Experiments at Circular Electron-Positron Collider

Proposition for JINR Project

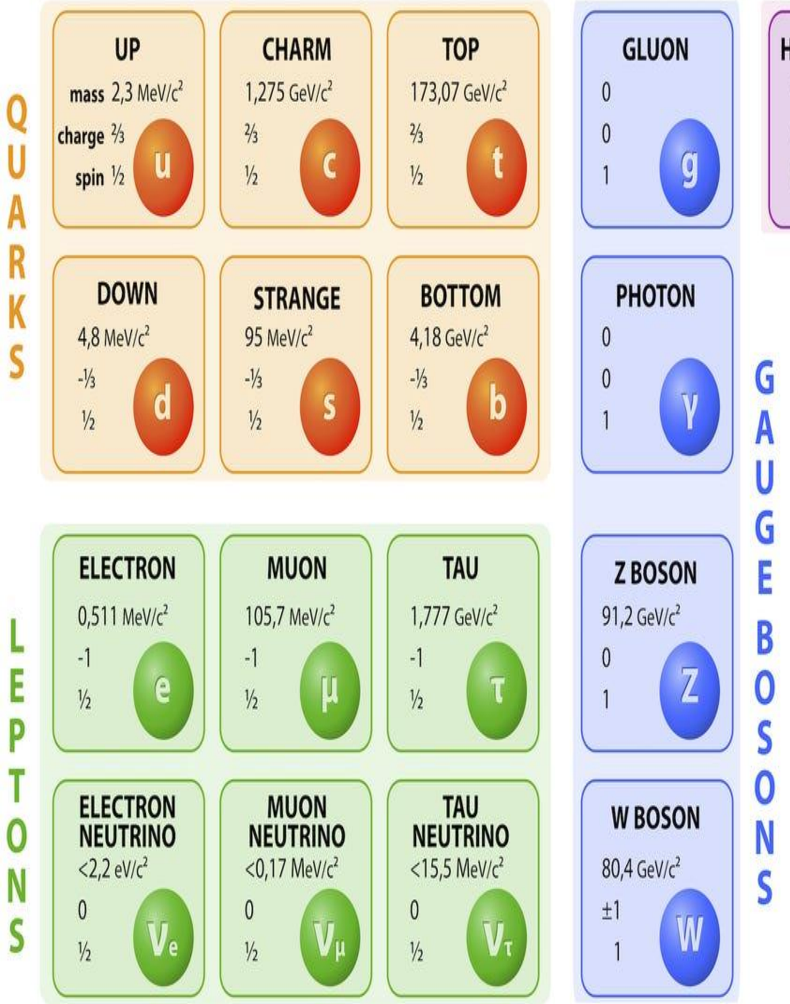
Yuri Davydov[1)] Yuri Kulchitsky[1),2)]

[1)] JINR, Dubna [2)] IP NASB, Minsk, Belarus

31.10.2024 seminar DLNP, JINR, Dubna

STANDARD MODEL

- **The SM describes the fundamental constituents of matter and their interactions**
- The **SM** of particle physics is the theory describing **3 of the 4 known fundamental forces (electromagnetic, weak and strong interactions** — *excluding gravity*) in the universe and classifying all known elementary particles

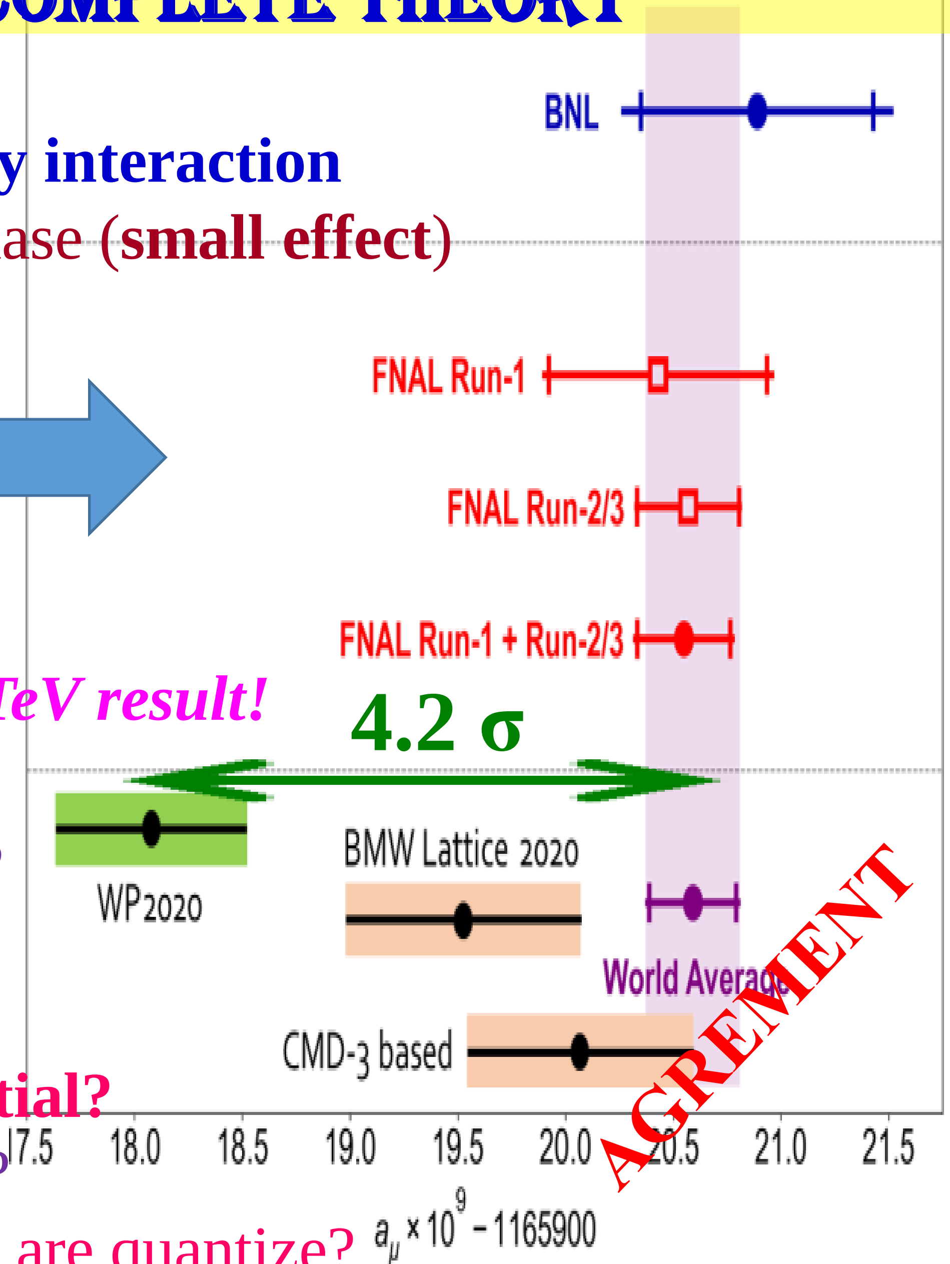


- **Quantum chromodynamics sector** $\mathcal{L}_{\mathrm{QCD}} = \sum_{\psi} \bar{\psi}_i \left(i\gamma^\mu (\partial_\mu \delta_{ij} - i g_s G^a_\mu T^a_{ij}) \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a,$
- **Electroweak sector** $\mathcal{L}_{\mathrm{EW}} = \sum_{\psi} \bar{\psi}\gamma^\mu \left(i\partial_\mu - g' \frac{1}{2} Y_{\mathrm{W}} B_\mu - g \frac{1}{2} \vec{\tau}_{\mathrm{L}} \vec{W}_\mu \right) \psi - \frac{1}{4} W^{\mu\nu}_a W^a_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu},$
- **Higgs sector** $\mathcal{L}_{\mathrm{H}} = \left| \left(\partial_\mu + \frac{i}{2} \left(g' Y_{\mathrm{W}} B_\mu + g \vec{\tau} \vec{W}_\mu \right) \right) \varphi \right|^2 - \frac{\lambda^2}{4} \left(\varphi^\dagger \varphi - v^2 \right)^2.$
- **Yukawa sector** $\mathcal{L}_{\mathrm{Yukawa}} = \overline{U}_{\mathrm{L}} G_{\mathrm{u}} U_{\mathrm{R}} \varphi^0 - \overline{D}_{\mathrm{L}} G_{\mathrm{u}} U_{\mathrm{R}} \varphi^- + \overline{U}_{\mathrm{L}} G_{\mathrm{d}} D_{\mathrm{R}} \varphi^+ + \overline{D}_{\mathrm{L}} G_{\mathrm{d}} D_{\mathrm{R}} \varphi^0 + \mathrm{h.c.},$

Interaction / Property	Gravitational	Weak	Electromagnetic	Strong	
		Electroweak		Fundamental	Residual
Acts on:	Mass - Energy	Flavor	Electric charge	Color charge	Atomic nuclei
Particles experiencing:	All particles	quarks, leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (Not yet observed)	W^+, W^- and Z^0	γ (photon)	Gluons	Mesons
Strength at the scale of quarks:	10^{-41}(predicted)	10^{-4}	1	60	Not applicable to quarks
Strength at the scale of protons/neutrons:	10^{-36}(predicted)	10^{-7}	1	Not applicable to hadrons	20

STANDARD MODEL PROBLEMS: AN INCOMPLETE THEORY

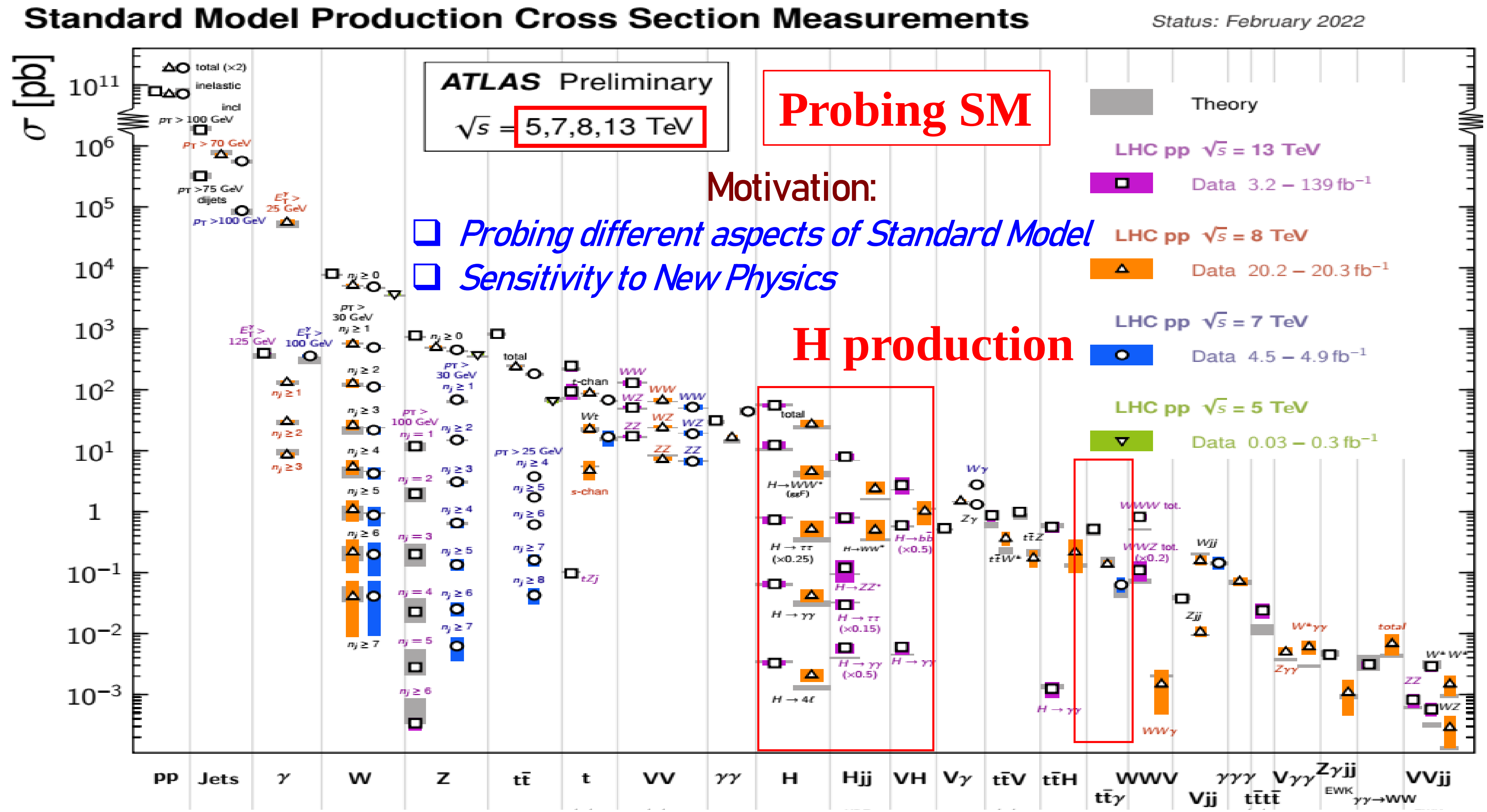
- ❑ Unknown nature of **Dark Matter**
- ❑ **Very small cosmological constant** and **very weak gravity interaction**
- ❑ **CP violation Cabibbo–Kobayashi–Maskawa** (CKM) phase **(small effect)**
- ❑ **Particle–antiparticle asymmetry in the Universe**
- ❑ **Problem of neutrino masses, mixing, oscillations**
- ❑ **Muon (g-2) μ anomaly** (**3.5σ→4.2σ** BNL):
  CMD-3 $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ → ***new theoretical calculation!***
- ❑ **B-anomalies (4.5σ): semi-leptonic B-decays**
- ❑ **CDF W-mass anomaly** (**7σ**): ***new ATLAS & CMS at 13 TeV result!***



- ➢ **What is a generation?** Why there are only 3 generations?
- ➢ What is a nature of **quark-lepton analogy**?
- ➢ **Are there additional gauge symmetries?**
- ➢ **What is responsible for a formation of the Higgs potential?**
- ➢ **Why gravity is so weak comparing** to other interactions?
- ➢ **What is responsible for gauge symmetries**, why charges are quantize?
- ➢ **To which accuracy the Charge, Parity & Time reversal symmetry (CPT) is exact?**

SM PRODUCTION CROSS SECTION MEASUREMENTS

ATL-PHYS-PUB-2023-039
ATL-PHYS-PUB-2022-009



ATLAS/CMS Results

1. **Higgs boson discovery**
2. **Systematic study of pp-processes at 0.9 – 13.6 TeV & comparison with SM predictions**
3. **There was no discovery of the MSSM particles at 10 TeV region**
4. **There was no discovery of exotic models particles**

Conclusion:
No BSM physics at 10 TeV

Review of Particle Physics, *PTEP* 2022 083C01
Part 9: QCD; *Figure 9.1*

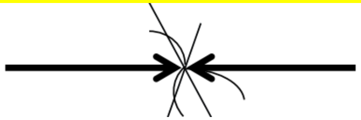
ATLAS: Summary of SM and fiducial production cross-section measurements in pp interactions at √s=5, 7, 8, 13 TeV, corrected for branching fractions, compared to the corresponding theoretical expectations

$$\mu_{if} = (\sigma_i/\sigma_i^{SM}) \times (B_f/B_f^{SM})$$

The inclusive Higgs boson production rate relative to the SM prediction is measured to be

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.})$$

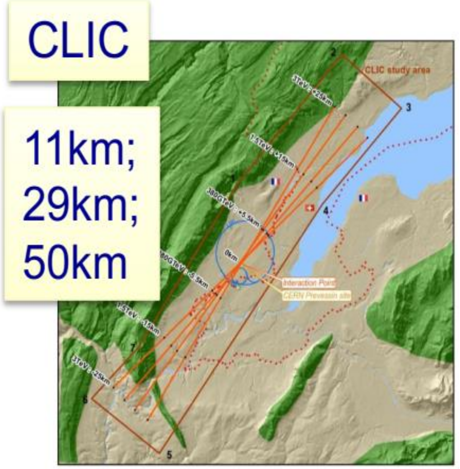
FUTURE COLLIDERS



❖ ILC (Japan):

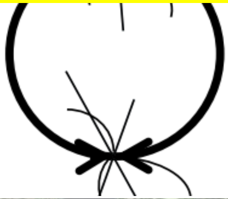
- Linear collider with high-gradient superconducting acceleration
- Ultimate: 0.5-1(?) TeV
- To secure funding: reduce cost by starting at 250 GeV (H factory)

❖ CLIC (CERN):

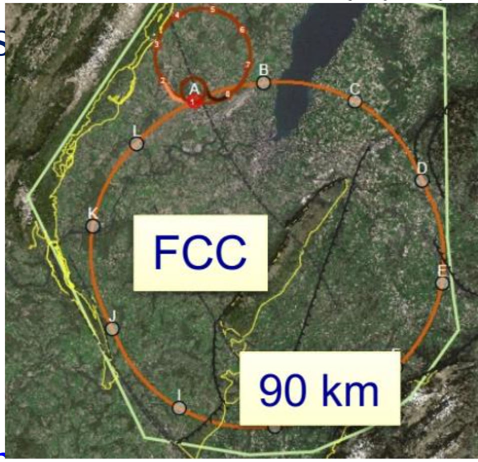


- Linear collider with high gradient normal-conducting acceleration
- Ultimate: multi-TeV (3) e^+e^- collisions
- Use technology to overcome challenges
- Stages, for physics and funding

❖ FCC-ee/FCC-hh (CERN):



- Protons to extend energy frontier
- **90 km** ring with 16T magnets
- Use FCC-hh tunnel for e^+e^- collider
- Technology for ee: **standard**



❖ CEPC/SppC

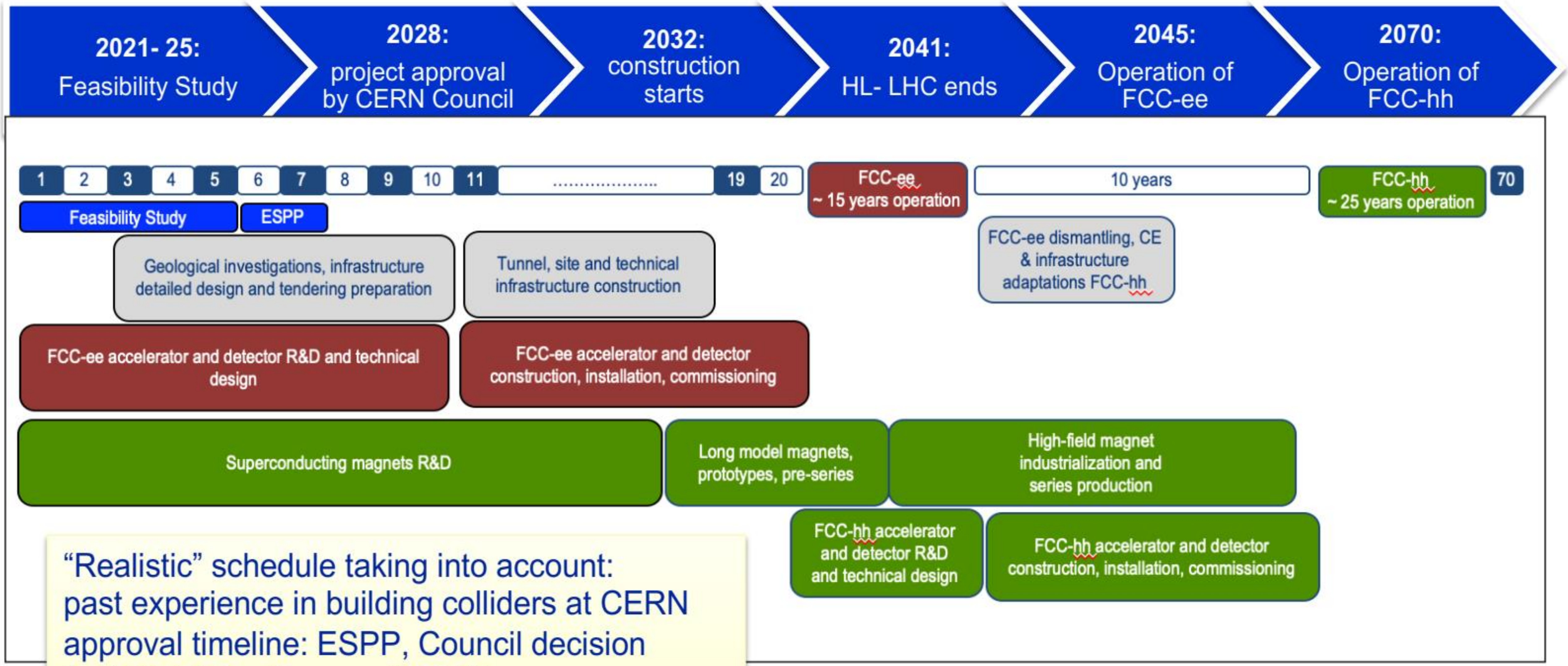
- Essentially an FCC-ee, then hh with
  a. more conservative luminosity estimates
  b. in China

❖ Outliers:

- “Low-field” (7T) magnets @FCC (?)
- Muon Collider (?)

FCC INTEGRATED PROGRAM - TIMELINE

FCCee Conceptual Design Study started in **2014** leading to **Conceptual Design Report** in **2018**



"Realistic" schedule taking into account:
past experience in building colliders at CERN
approval timeline: ESPP, Council decision
that HL-LHC will run until 2041
Can be accelerated if more resources available

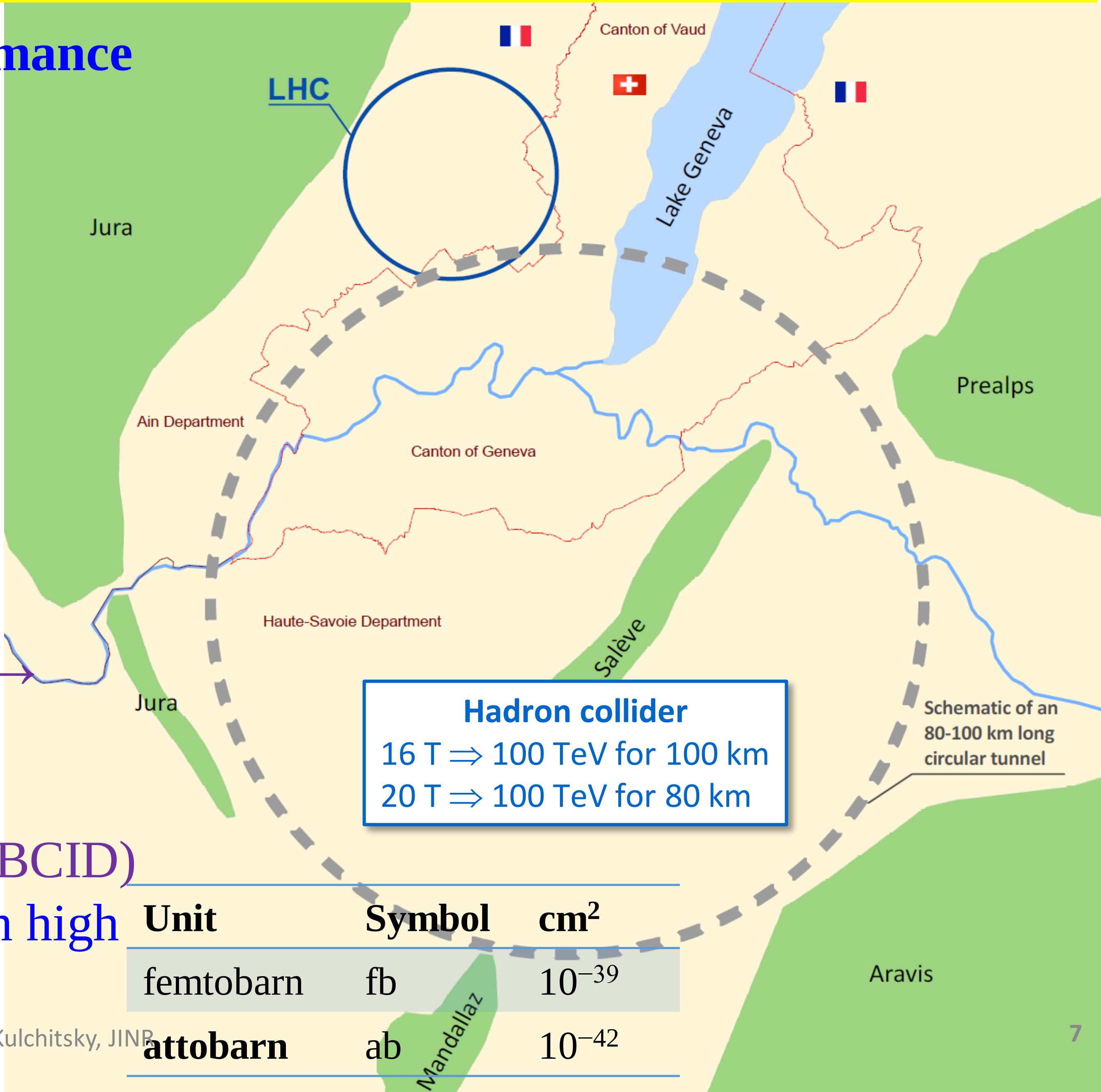
FCC INFRASTRUCTURE & OPERATION

Future Circulated Collider (FCC) performance

- Center of mass energy: **100 TeV**
- Peak luminosity ultimate: **≤ 30x10^{34}**
- Bunch Crossing **<5 ns**
- Integrated luminosity ultimate **~1000 fb^{-1}** (average per year)
- 25 years operation, leading to **~20 ab^{-1}**

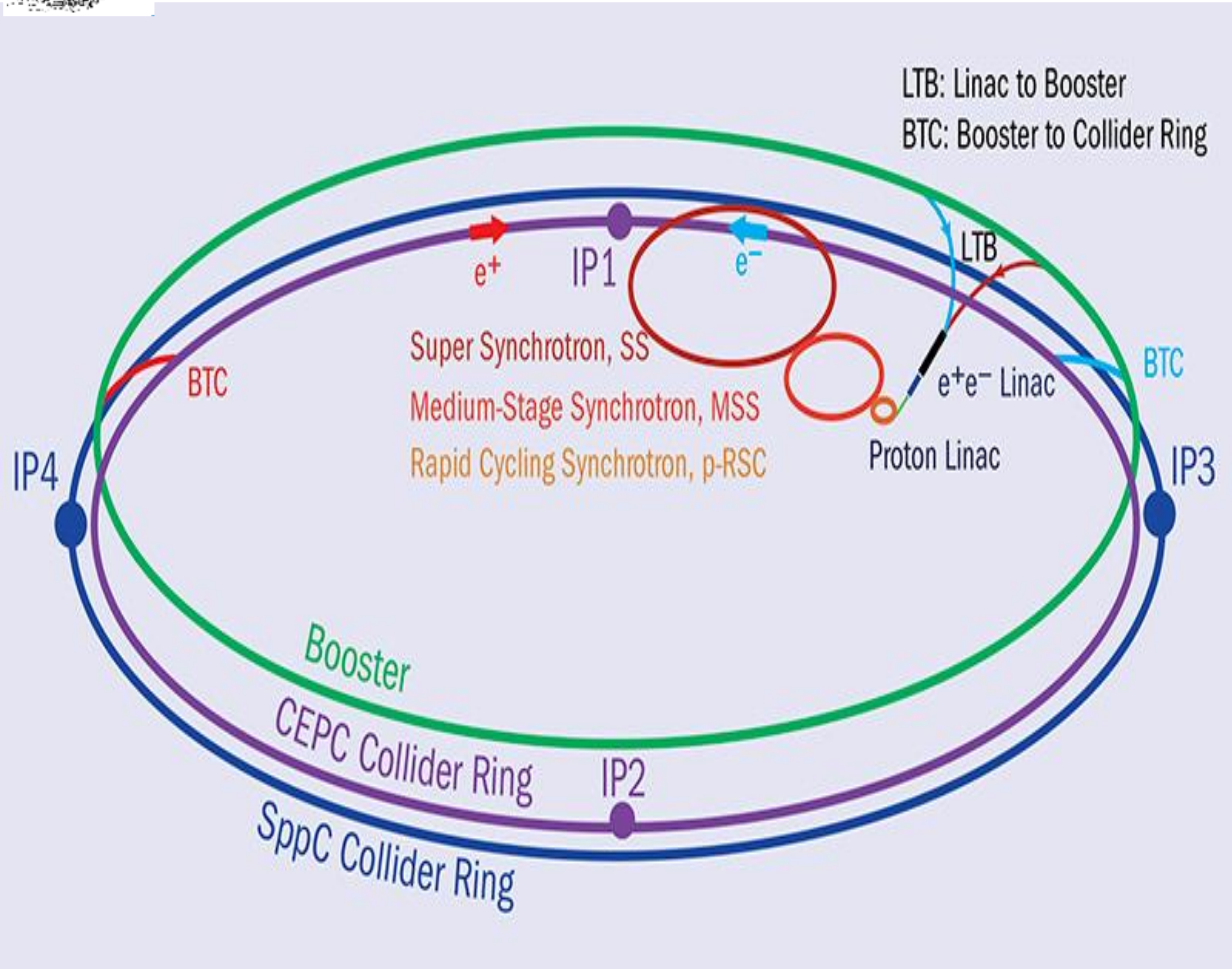
Consequence on detectors

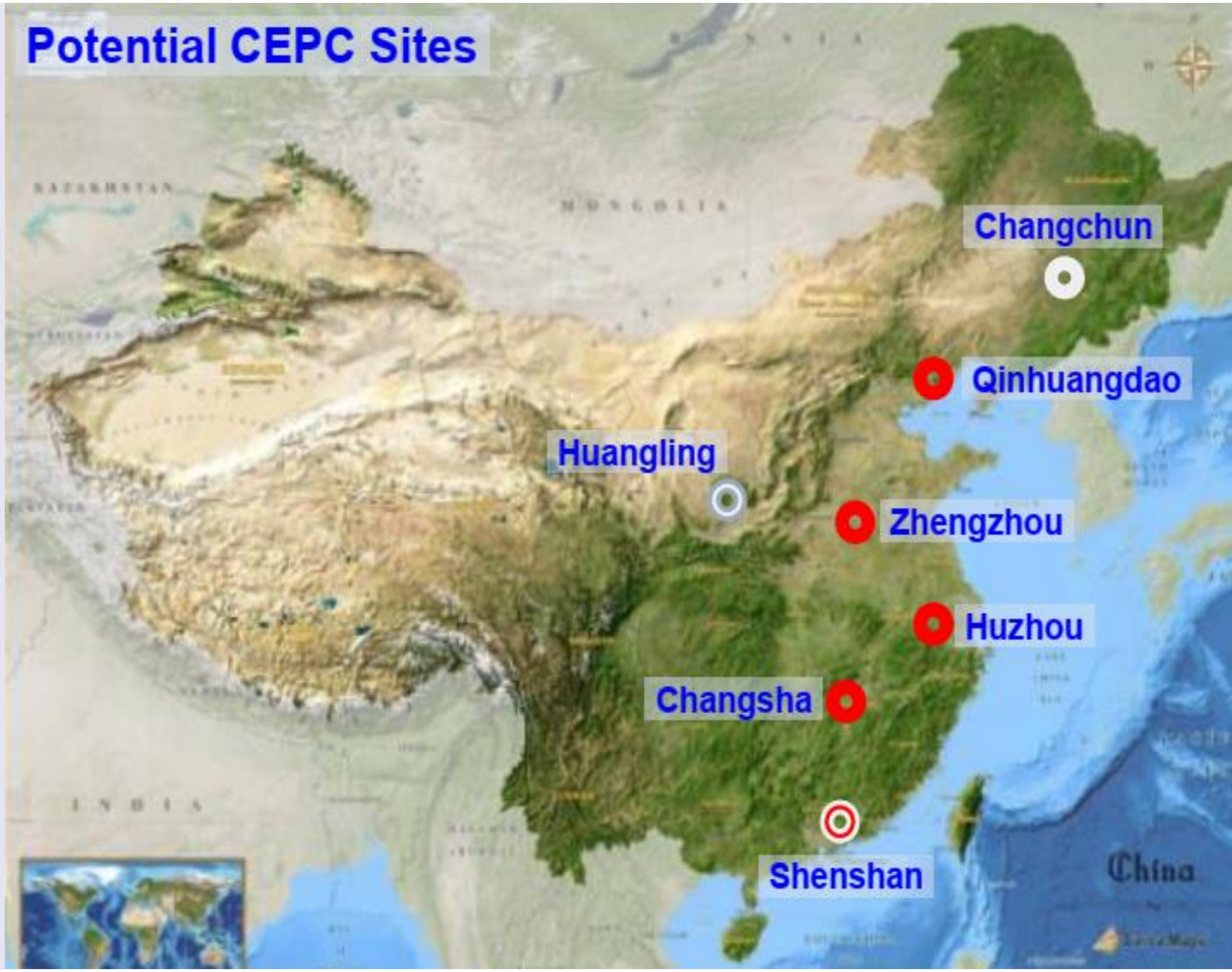
- Boosted objects → up to **|η|=6** coverage
- High pileup and fast Bunch-Crossing (BC) → very fast and granular detectors
- Momentum resolution **≈15% at p_T=10 TeV**
- **~1 ns** sharp Bunch-Crossing Identification (BCID)
- Particle flow capability for calorimeters with high granularity **25 mrad^2**
- Fine timing against pileup → **< 100 ps**



Unit	Symbol	cm^2
femtobarn	fb	10^{-39}
attobarn	ab	10^{-42}

CIRCULATED ELECTRON-POSITRON COLLIDER (CEPC)



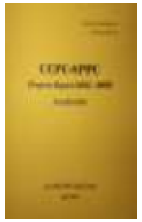


- The **CEPC** was proposed by the **Chinese HEP community in September 2012**
- The **CEPC** aims to start operation in 2035, as a **Higgs/Z/W/top factory**
- The **CEPC** to produce **Higgs/Z/W/top** for **high precision Higgs**, **EW measurements**, studies of **flavor physics** & **QCD**, probes of **BSM physics**

CIRCULATED ELECTRON-POSITRON COLLAIDER (CEPC) MILESTONES

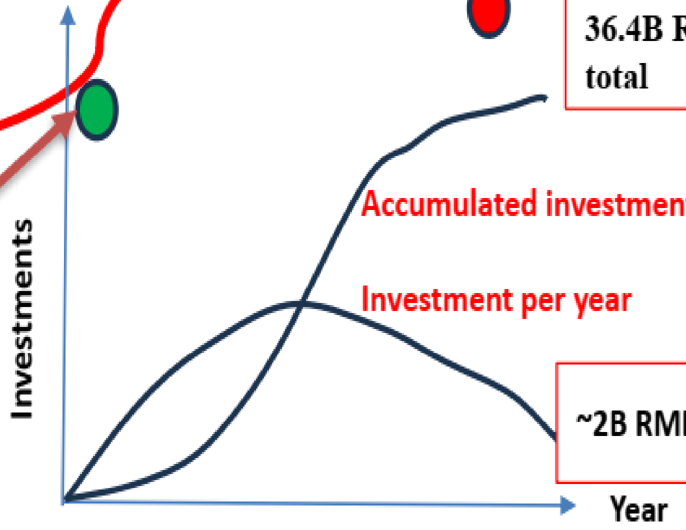
Year	2012	2013	2015	2017	2018	2023	2025	2027	2030	2035

CEPC kickoff meeting in Sept. 2013



Proposal (2025) for CEPC entering 15th five year plan

EDR is the critical path towards CEPC construction starting around 2027



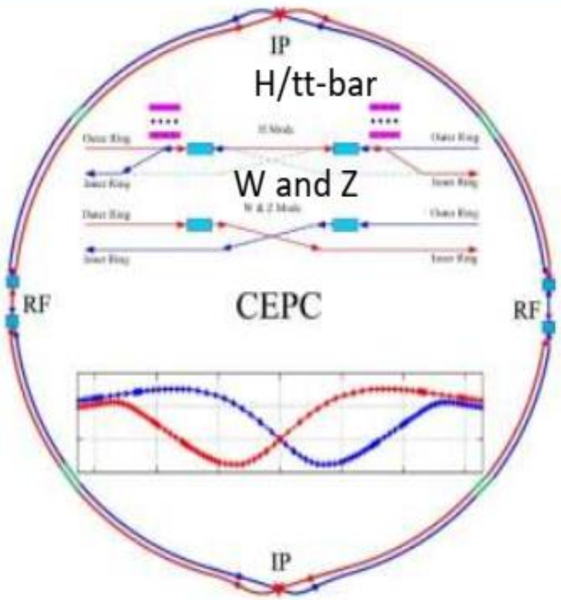
36.4B RMB total

~2B RMB/year

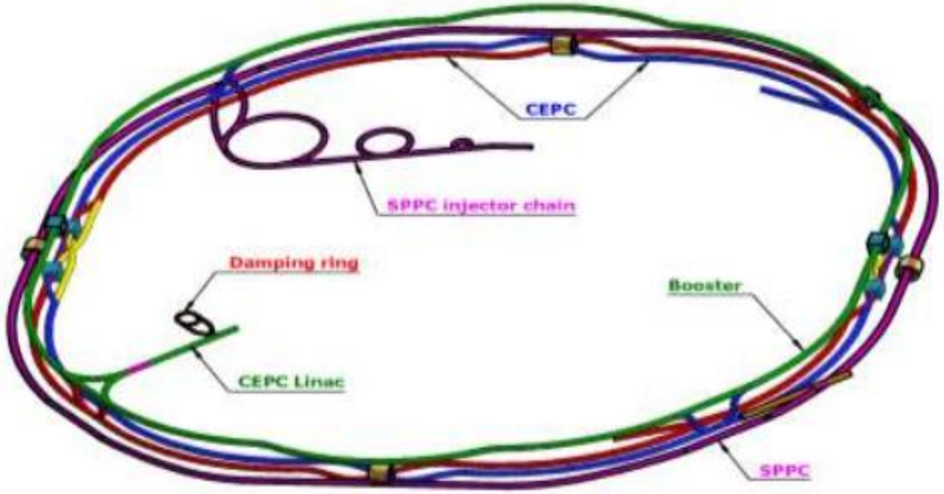
2012.9 CEPC proposed
2013.9
2015.3 Pre-CDR
2017.4 Progress report
2018.11 CDR
2023.12 TDR
2024 ~ 2027 EDR start of construction
~2035 Completion

CEPC Higgs Factory and SppC Layout

CEPC as a Higgs Factory: H, W, Z, upgradable to ttbar, followed by a SppC (a Hadron collider) ~125TeV
30MW SR power per beam (upgradable to 50MW) , high energy gamma ray 100Kev~100MeV

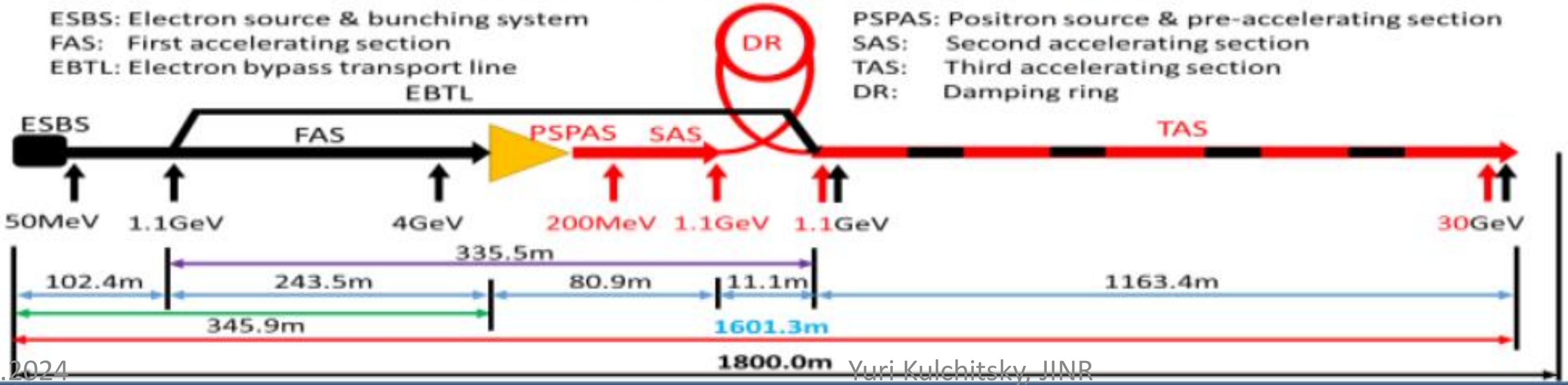


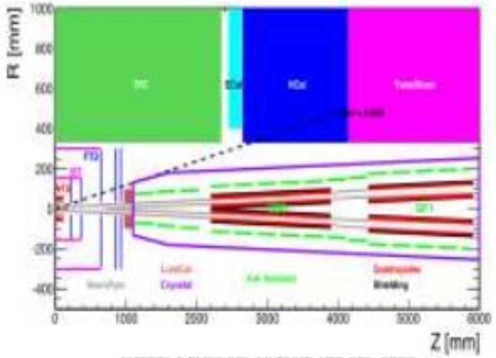
CEPC collider ring (100km)

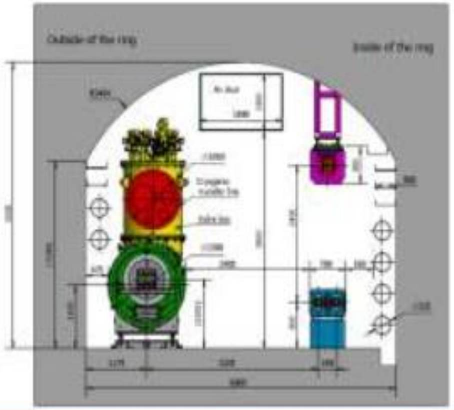


CEPC booster ring (100km)

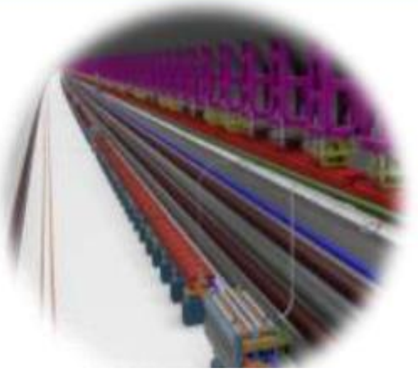
CEPC TDR S+C-band 30GeV linac injector







CEPC/SppC in the same tunnel



CEPC ACCELERATOR SYSTEM PARAMETERS

Linac

Parameter	Symbol	Unit	Baseline
Energy	E_e/E_{e+}	GeV	**30**
Repetition rate	f_{rep}	Hz	100
Bunch number per pulse			1 or 2
Bunch charge		nC	1.5 (3)
Energy spread	σ_E		1.5×10^{-3}
Emittance	ε_r	nm	6.5

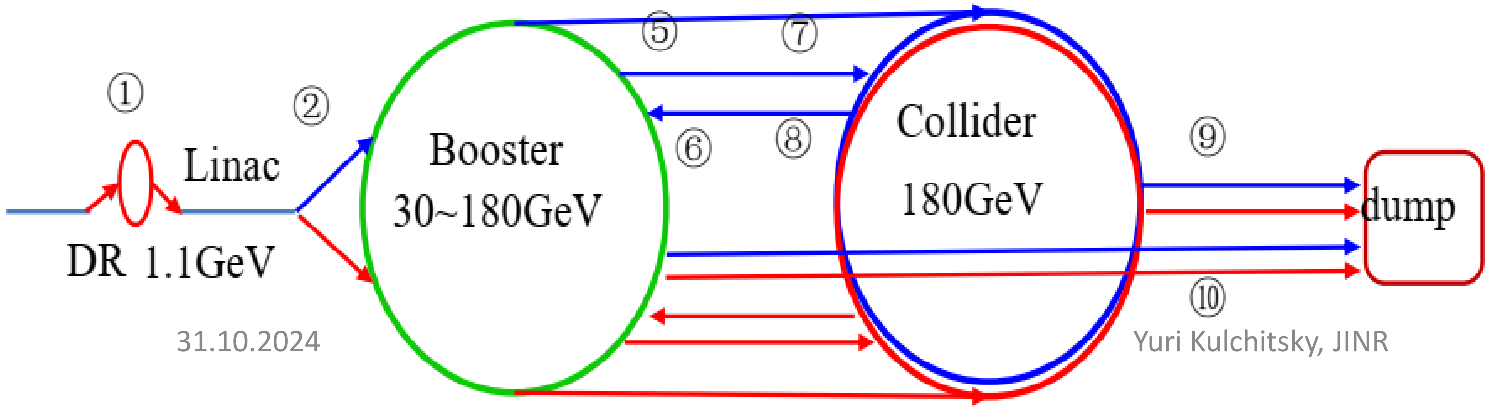
Booster

		tt	*H*		*W*	*Z*	
		Off axis injection	Off axis injection	On axis injection	Off axis injection	Off axis injection	
Circumfer.	km	**100**					
Injection energy	GeV	**30**					
Extraction energy	GeV	**180**	**120**		**80**	**45.5**	
Bunch number		35	268	261+7	1297	3978	5967
Maximum bunch charge	nC	0.99	0.7	20.3	0.73	0.8	0.81
Beam current	mA	0.11	0.94	0.98	2.85	9.5	14.4
SR power	MW	0.93	0.94	1.66	0.94	0.323	0.49
Emittance	nm	2.83	1.26		0.56	0.19	
RF frequency	GHz	1.3					
RF voltage	GV	9.7	2.17		0.87	0.46	
Full injection from empty	h	0.1	0.14	0.16	0.27	1.8	0.8

Collider

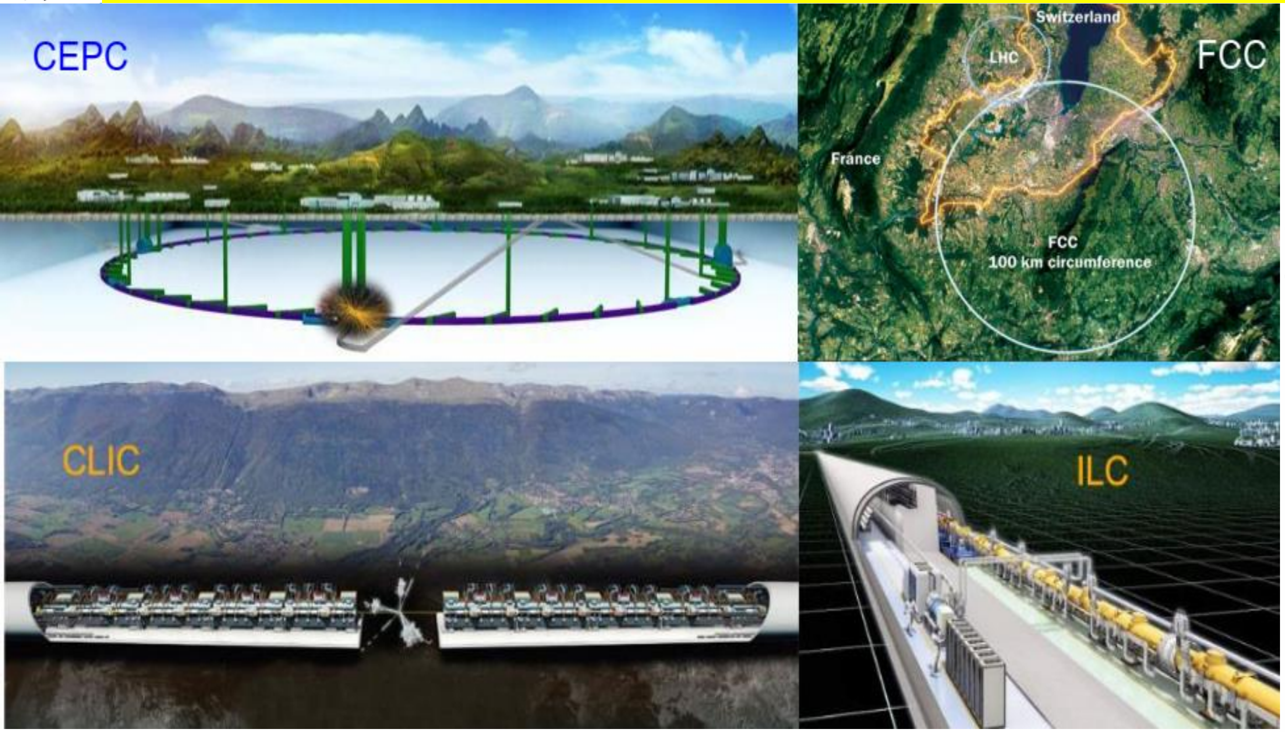
	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	**100.0**			
SR power per beam (MW)	**30**			
Energy (GeV)	**120**	**45.5**	**80**	**180**
Bunch number	268	11934	1297	35
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF frequency (MHz)	650			
Luminosity per IP (10^{34} cm^{-2} s^{-1})	**5.0**	**115**	**16**	**0.5**

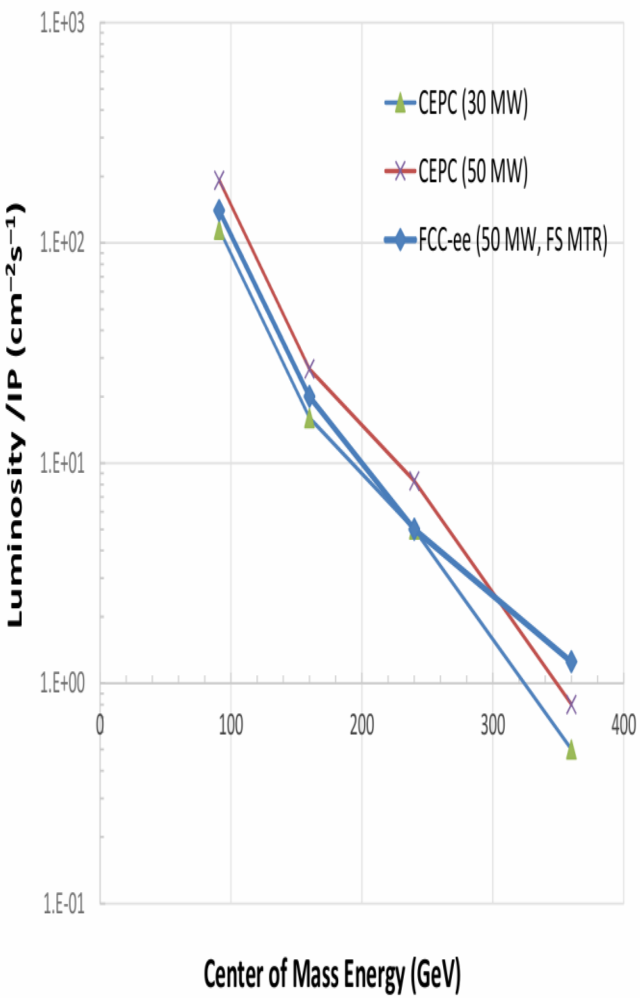
Transport lines

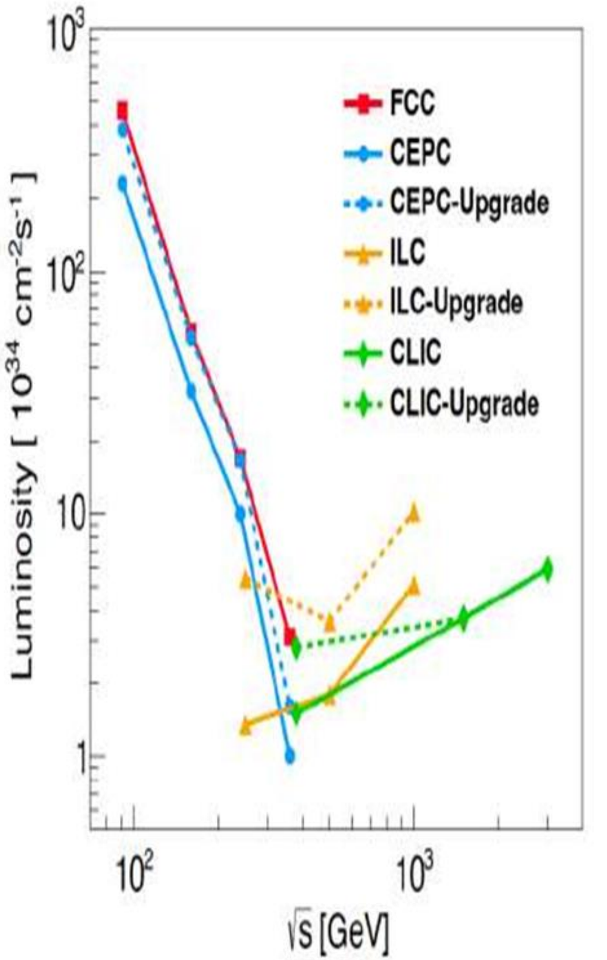


CEPC Technical Design Report (TDR) includes:
1) CEPC Accelerator TDR
2) CEPC Detector TDRrd (rd=reference design)
will be released by June 2025

COMPARISON OF HIGGS FACTORIES: CIRCULAR VS LINEAR







CEPC versus **FCC-ee**

- **Earlier data: collisions in 2035 (vs. ~2045)**
- **Large tunnel size (ee & pp coexistence)**
- **Lower construction cost**

CEPC versus **Linear Colliders**

- **Higher luminosity: precision for H&Z**
- **Upgrade for pp collider**

The **synchrotron radiation** (SR) power of **30 MW** per beam it can achieve a luminosity of **5 e^{34} /cm^2/s** (Intg. Lum. of 13 ab^{-1} for **2** interaction points over a **decade**) producing **2.6x10^6 H-bosons**. Increasing the **SR power to 50 MW** per beam expands the CEPC's capability to generate **4.3x10^6 H-bosons**,

CEPC OPERATION PLAN & GOALS

Higgs – top priority!

Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. per IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. per year (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30	0.5	0.13	0.65	0.4×10^6

* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs.

** Detector solenoid field is 2 Tesla during Z operation, 3Tesla for all other energies.

*** Calculated using 3,600 hours per year for data collection.

PHYSICS GOALS OF CEPC & SPPC

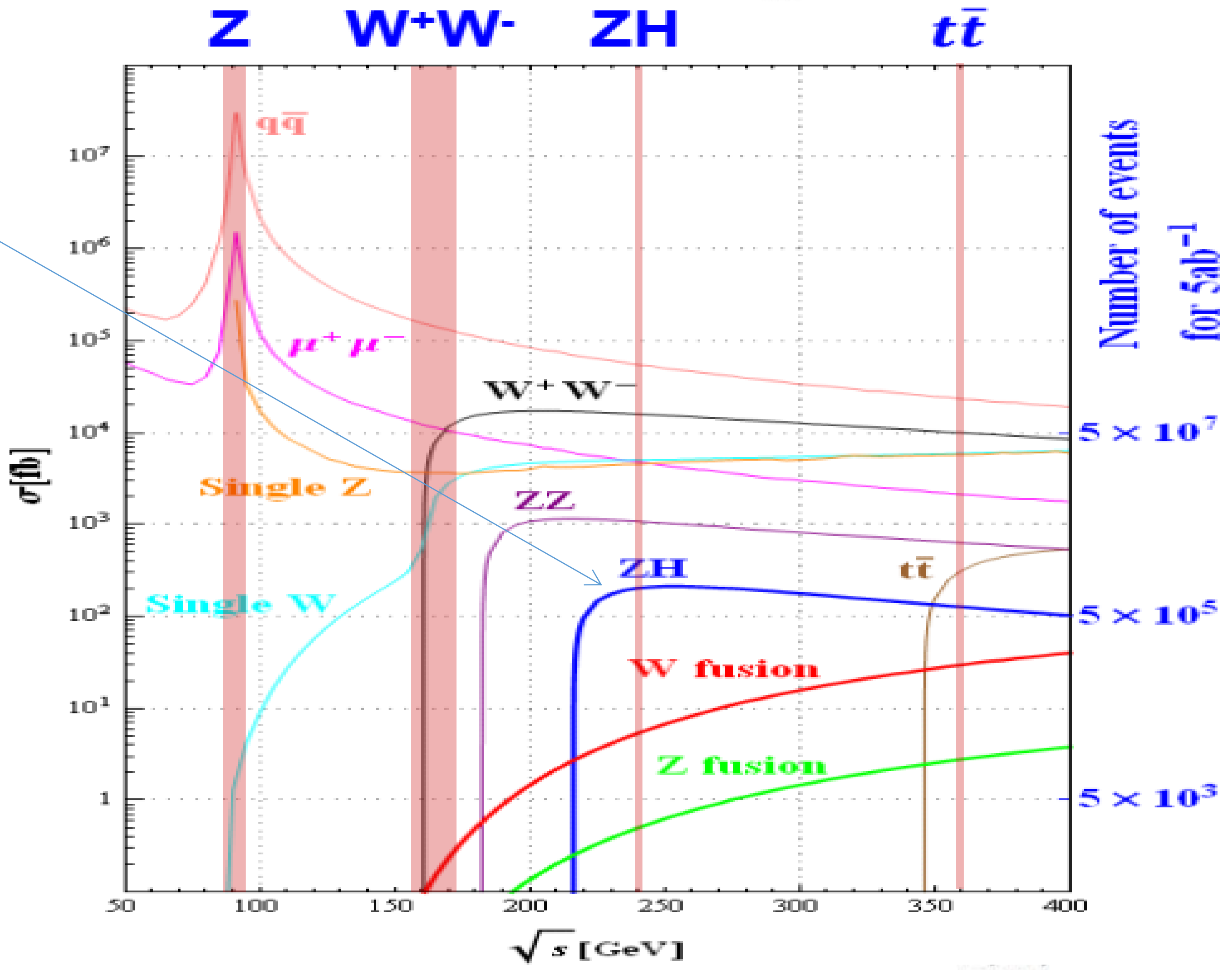
Circular Electron-Positron Collider

- **91** (Z), **160** (WW), **240** (ZH), **360** (tt) GeV
- **Higgs Factor (>10^6 Higgs bosons):**
  - **Precision study of Higgs** (m_H, main quantum numbers JPC, couplings),
  - **Complementary** to **Linear** colliders,
  - Looking for hints of **BSM physics:**
    - **Dark Matter,**
    - **ElectroWeak phase transition** (EWPT),
    - **Long-Lived Particles (LLP),** …
- **Z & W factory (>10^{12} Z_0):**
  - **Precision test of SM,**
  - **Rare decays**, …
- **Flavor factory: b, c, t and QCD studies**

Super proton-proton Collider

- **~125 TeV + Complementary to CEPC;**
- **Directly search for new physics BSM**
- **Precision test of SM**

CEPC-SppC was proposed by Chinese scientists in September 2012, after H-Boson was discovered at CERN



X-sections for SM physics processes

PHYSICS AT CEPC: I

The Higgs boson has a special role in the quest to answer some of the most profound questions

- These questions include the
  - nature of **the *EW phase transition*** that governed the ***evolution of the early Universe***
  - **why the *gravitational*** *force is* ***so weak*** **compared** with other forces in nature.
    - It is possible that the **EW phase transition** could have caused the **observed baryon asymmetry of the Universe** and therefore provide an explanation for the baryon asymmetry problem. It could also have generated **observable gravitational waves**
- The **Higgs boson in e^+e^- collisions** is ***practically free of systematic uncertainties*** that limit the measurements at the **HL-LHC**
- ***Precise measurements of the Higgs boson properties*****,** along with those of the mediators of the weak interaction will provide critical tests of the ***underlying fundamental physics principles of the SM*** and are ***vital in the exploration of new physics BSM***

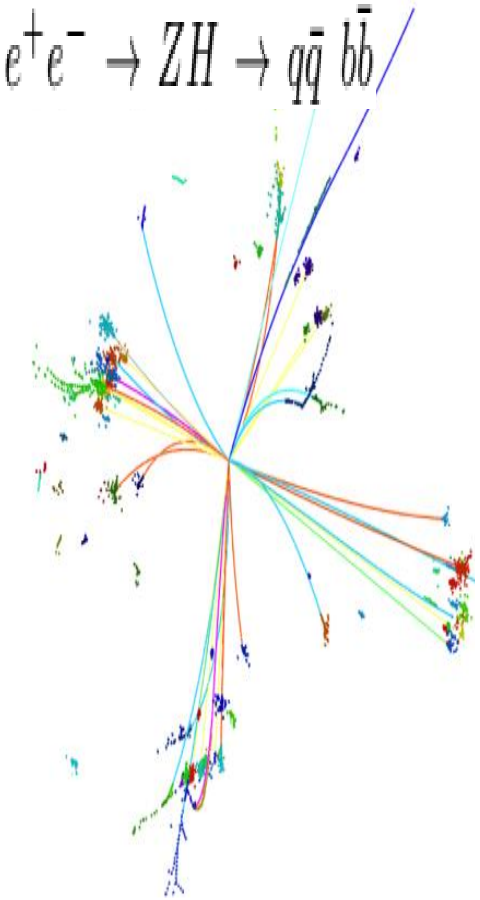
- The Experiments at **CEPC** will
  - measure the ***Higgs boson properties*** in ***greater detail*** and in ***a model-independent way***
  - ***reach a new level of precision*** for the ***measurements of the W, Z bosons properties***
  - allow ***the search for potential unknown decay modes***
  - Also, ***could uncover deviations from the SM predictions*** and ***reveal the existence of new particles*** that ***are beyond the reaches of direct searches at the current experiments***.

PHYSICS AT CEPC: II

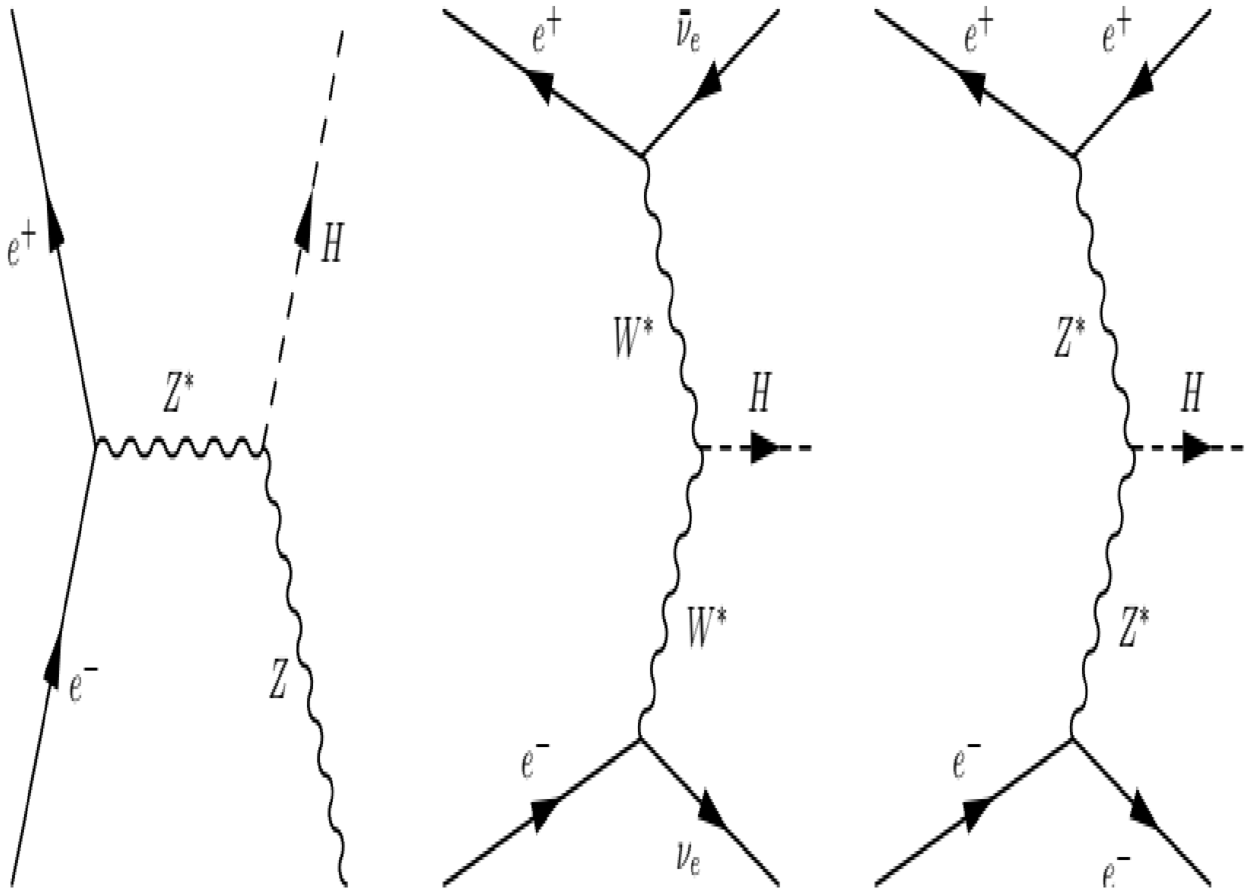
- The ***precision Higgs boson measurements*** could potentially ***reveal crucial physics mechanism*** that determines ***the nature of the EW phase transition***.
  - It will be ***another milestone*** in our ***understanding of the early history of our Universe***, &
  - could hold the key to unlock the ***origin of the matter and antimatter asymmetry*** in the Universe
  - These results could test the ideas that explain ***the vast difference between the energy scales associated with the EW and gravitational interaction.***
- The **CEPC** will also search for a ***variety of new particles.***
- Running as both a **Higgs factory and a Z factory**, the ***exotic decays of Higgs and Z bosons are sensitive vehicles the search of new physics***, such as those with ***light new particles.***
- ***The dark matter*** can be searched for through ***its direct production and its indirect effects on the precision measurements***.
- The **CEPC**, as ***B and τ-charm factories***, can perform studies that help to understand **the origin of different species of matter and their properties.**
- The **CEPC** is also an excellent facility to perform ***precise tests of the theory of the strong interaction***

PRECISION HIGGS PHYSICS AT THE CEPC

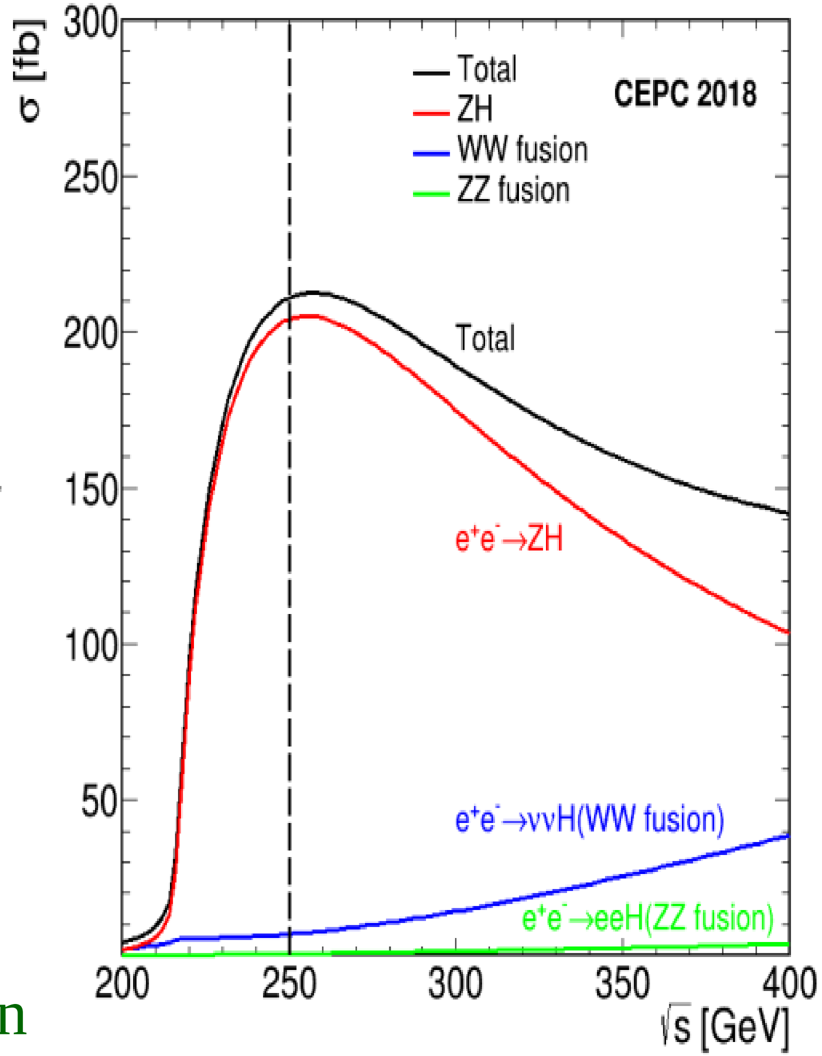
Chinese Physics C43, 4 (2019) 043002



A simulated $e^+e^- \to ZH \to q\bar{q}b\bar{b}$ event reconstructed with the Arbor algorithm



Feynman diagrams of the Higgs boson production processes: $e^+e^- \to ZH$ (ZH associate production or Higgsstrahlung) and VBF $e^+e^- \to \nu\bar{\nu}H$ (WW fusion), $e^+e^- \to e^+e^-H$ (ZZ fusion)



Production cross sections of $e^+e^- \to ZH$ and $e^+e^- \to \nu\bar{\nu}H$ as functions of energy

MEASUREMENT OF HIGGS BOSON WIDTH AND X-SECTION

Chinese Physics C43, 4 (2019) 043002

$$\Gamma_H = \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}$$

Decay mode	Branching ratio	Relative uncertainty
$H \to b\bar{b}$	57.7%	+3.2%, −3.3%
$H \to c\bar{c}$	2.91%	+12%, −12%
$H \to \tau^+\tau^-$	6.32%	+5.7%, −5.7%
$H \to \mu^+\mu^-$	2.19×10^{-4}	+6.0%, −5.9%
$H \to WW^*$	21.5%	+4.3%, −4.2%
$H \to ZZ^*$	2.64%	+4.3%, −4.2%
$H \to \gamma\gamma$	2.28×10^{-3}	+5.0%, −4.9%
$H \to Z\gamma$	1.53×10^{-3}	+9.0%, −8.8%
$H \to gg$	8.57%	+10%, −10%
Γ_H	4.07 MeV	+4.0%, −4.0%

Process	Cross section	Events in 5.6 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	204.7	1.15×10^6
$e^+e^- \to \nu_e\bar{\nu}_e H$	6.85	3.84×10^4
$e^+e^- \to e^+e^- H$	0.63	3.53×10^3
Total	212.1	1.19×10^6
Background processes, cross section in pb		
$e^+e^- \to e^+e^- (\gamma)$ (Bhabha)	850	4.5×10^9
$e^+e^- \to q\bar{q}(\gamma)$	50.2	2.8×10^8
$e^+e^- \to \mu^+\mu^-(\gamma)$ [or $\tau^+\tau^-(\gamma)$]	4.40	2.5×10^7
$e^+e^- \to WW$	15.4	8.6×10^7
$e^+e^- \to ZZ$	1.03	5.8×10^6
$e^+e^- \to e^+e^- Z$	4.73	2.7×10^7
$e^+e^- \to e^+\nu W^- / e^-\bar{\nu} W^+$	5.14	2.9×10^7

- Even with **10^6 H**-boson events, **statistical uncertainties** are expected to be **dominant** and thus **systematic uncertainties**

- **In contrast to hadron collisions, e+e− collisions are unaffected by underlying events and pile-up effects.**
- **Theoretical calculations** are **less dependent on higher order QCD radiative corrections.**
- **More precise tests of theoretical predictions** can be performed and **will provide sensitive probes to BSM**.

HIGGS PHYSICS: BACKGROUND PROCESSES

Apart from the Higgs boson production, other SM processes include **$e^+e^- \to e^+e^-$** (Bhabha scattering), **$e^+e^- \to Z\gamma$** (initial-state radiation return), **$e^+e^- \to WW/ZZ$** (diboson), **$e^+e^- \to e^+e^-Z$ & $e^+e^- \to e^+\nu W^-/e^-\bar{\nu} W^+$** (single boson).

Cross sections of main SM processes of e^+e^- collisions vs energy.

The calculations include initial-state radiation.

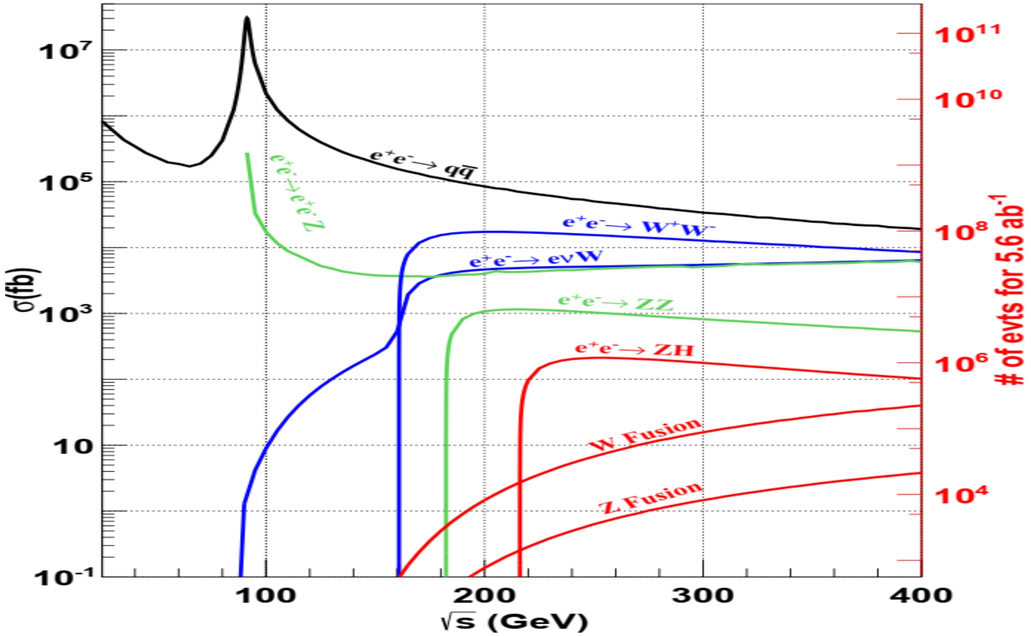
The W and Z fusion processes refer to **$e^+e^- \to \nu\nu H$, $e^+e^- \to e^+e^-H$** production.

Many of these processes can lead to ***identical final states*** & interfere:

$e^+e^- \to e^+\nu W^- \to e^+\nu_e e^-\bar{\nu}_e$

$e^+e^- \to e^+e^-Z \to e^+e^-\nu_e\nu_e$

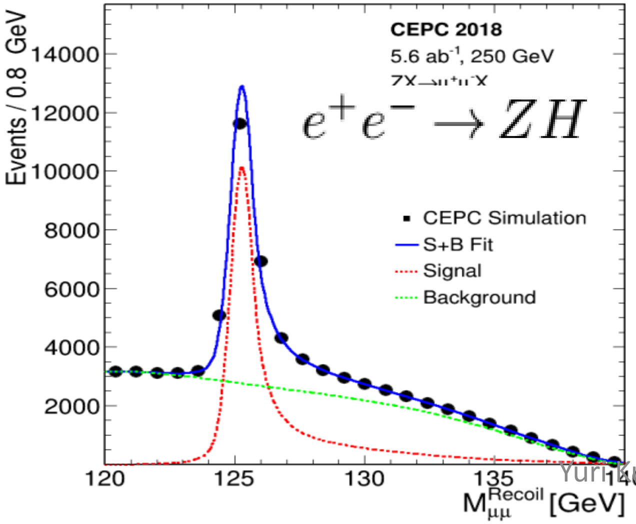
have the same final state after the decays of the **W** or **Z** bosons.

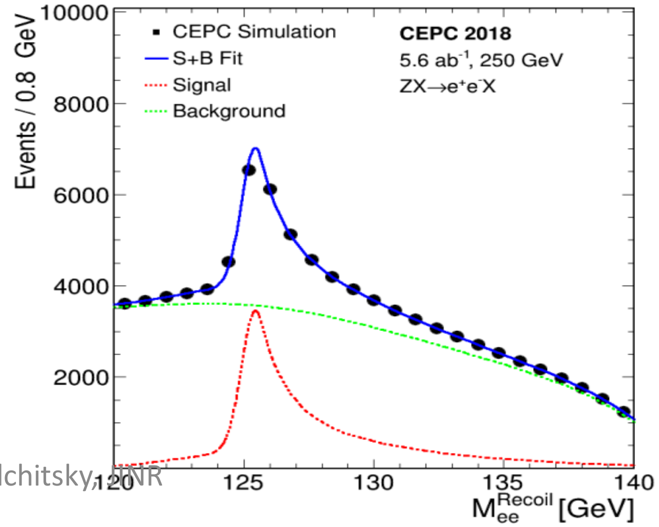


Higgsstrahlung event where the Z boson decays to a pair of visible fermions (ff), the mass of the system **recoiling** against the Z boson, commonly known as the **recoil mass**, can be calculated assuming the event has a total energy and zero total momentum:

$$M^2_{recoil} = \left(\sqrt{s} - E_{ff}\right)^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$

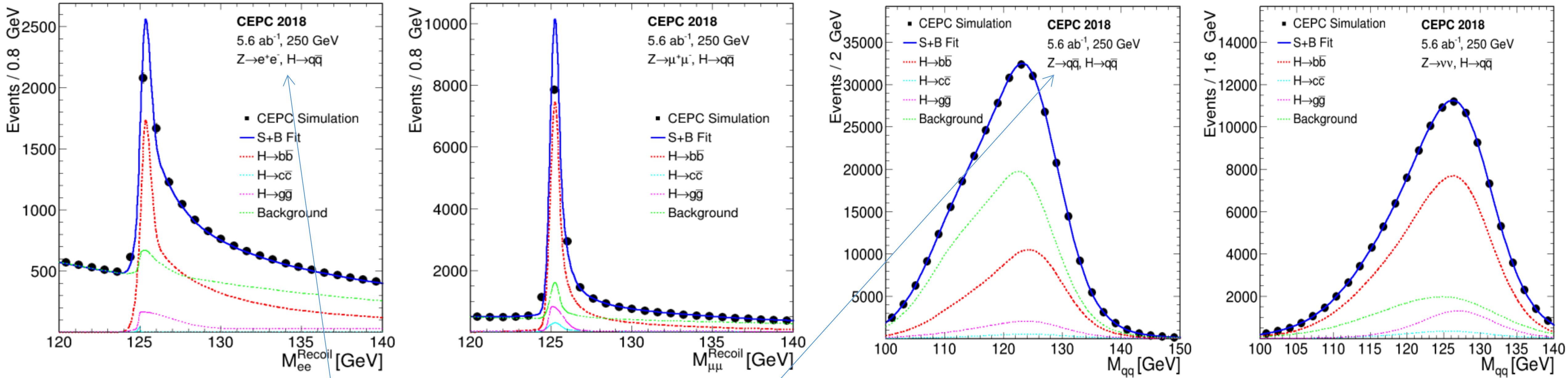
Here, E_{ff}, p_{ff} and m_{ff} are the total energy, momentum and invariant mass of the fermion pair. The M_{recoil} distribution should show a peak at the Higgs boson mass **m_H** for **$e^+e^- \to ZH$** and **$e^+e^- \to e^+e^-H$** processes.





The inclusive recoil mass spectra of **$e^+e^- \to ZX$** candidates for **$Z \to \mu^+\mu^-$** and **$Z \to e^+e^-$.** No attempt to identify X is made. The markers and their uncertainties (too small to be visible) represent expectations from a CEPC dataset of 5.6 ab^{-1}, whereas the solid blue curves are the fit results. The dashed curves are the signal and background components.

HIGGS PHYSICS: ZH PRODUCTION WITH $H \to b\bar{b}/c\bar{c}/gg$

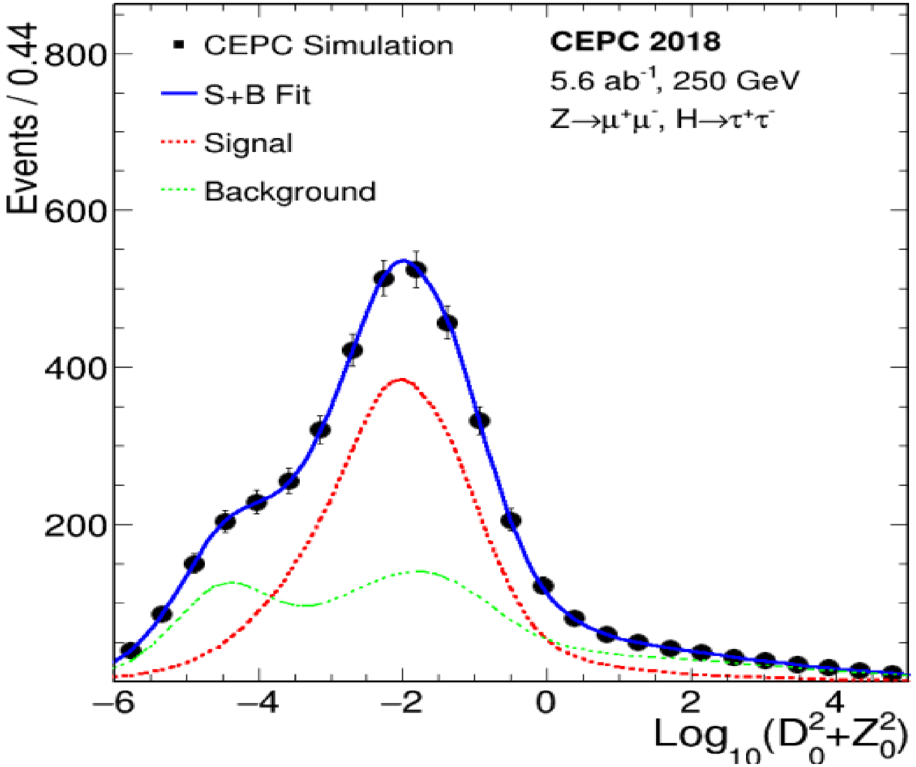


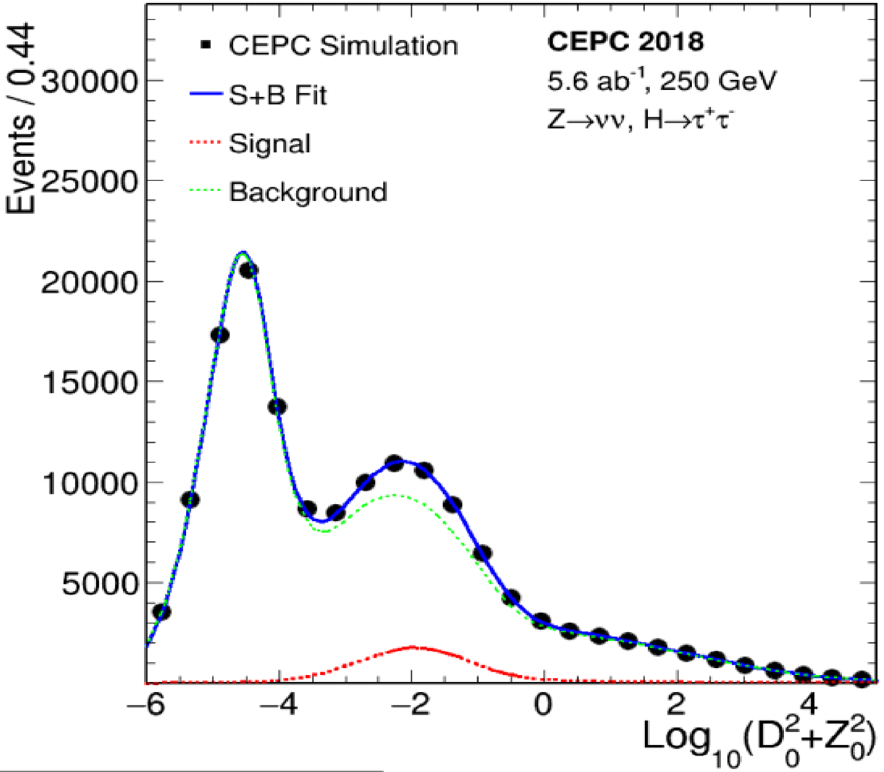
ZH production with **$H \to b\bar{b}/c\bar{c}/gg$**: the recoil mass distributions of **$Z \to e^+e^-$ & $Z \to \mu^+\mu^-$**; the dijet mass distributions of Higgs boson candidates for **$Z \to q\bar{q}$ & $Z \to \nu\bar{\nu}$**. The markers and their uncertainties represent expectations from a CEPC dataset of 5.6 ab^{-1} whereas the solid blue curves are the fit results. The dashed curves are the signal and background components. Contributions from other decays of the Higgs boson are included in the background.

Z decay mode	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$
$Z \to e^+e^-$	1.3%	12.8%	6.8%
$Z \to \mu^+\mu^-$	1.0%	9.4%	4.9%
$Z \to q\bar{q}$	0.5%	10.6%	3.5%
$Z \to \nu\bar{\nu}$	0.4%	3.7%	1.4%
Combination	0.3%	3.1%	1.2%

- Expected **relative precision** on **σ(ZH)×BR** for the **$H \to b\bar{b}/c\bar{c}/gg$** decays from a CEPC dataset of 5.6 ab^{-1}.
- Combining all Z boson decay modes studied, a relative statistical precision for **σ(ZH)×BR** of **0.3%, 3.3% and 1.3%** can be achieved for the **$H \to b\bar{b}/c\bar{c}/gg$** decays, respectively

HIGGS PHYSICS: THE INVISIBLE DECAY OF THE HIGGS BOSON: H →INV





Distributions of the impact parameter variable of the **leading tracks from 2-tau candidates** in the **Z-decay** mode: **$Z\to\mu^+\mu^-$ &$Z\to\nu\bar{\nu}$**. Here **D_0** and **Z_0** are the transverse & longitudinal impact parameters.

ZH final state studied		Relative precision on $\sigma\times$BR	Upper limit on BR($H\to$ inv)
$Z\to e^+e^-$	$H\to$ inv	339%	0.82%
$Z\to\mu^+\mu^-$	$H\to$ inv	232%	0.60%
$Z\to q\bar{q}$	$H\to$ inv	217%	0.57%
Combination		143%	0.41%

Expected relative precision on **σ(ZH)× BR(H→inv)** and **95% CL** upper limit on **BR(H→inv)** from a CEPC dataset of 5.6 ab^{-1}. Subtracting the SM **$H\to ZZ^*\to\nu\nu\bar{\nu}\bar{\nu}$** contribution, a 95% CL upper limit of **0.30%** on **BR^{BSM}_{inv}**, the **BSM** contribution to the **H→inv** decay can be obtained..

- The sensitivity of the **BR(H→inv)** measurement is studied for the **$Z\to l^+l^-$** and **$Z\to q\bar{q}$** decay modes.
- The **$H\to ZZ^*\to\nu\nu\bar{\nu}\bar{\nu}$** decay (**$Br=1.06\times10^{-3}$**) is used to model the **H→inv** decay both in the context of the **SM and BSM.** This is made possible by the fact that the Higgs boson is narrow scalar so that its production and the decay can be treated separately.
- The main background is SM ZZ production with one of the Z bosons decay invisibly and the other decays visibly.

The SM makes specific predictions for the H-boson couplings to the SM fermions, **g_{SM}(Hff)**, and to the SM gauge bosons, **g_{SM}(HVV)**. The potential deviations from the SM are parameterized as:

$$\kappa_f = \frac{g(Hff)}{g_{\rm SM}(Hff)}, \quad \kappa_V = \frac{g(HVV)}{g_{\rm SM}(HVV)},$$

with κ_i =1 being the SM prediction. The rates of the H production and decays are modified accordingly.

$$\sigma(ZH) = \kappa_Z^2 \cdot \sigma_{\rm SM}(ZH)$$

$$\sigma(ZH) \times {\rm BR}(H \to ff) = \frac{\kappa_Z^2 \kappa_f^2}{\kappa_\Gamma^2} \cdot \sigma_{\rm SM}(ZH) \times {\rm BR}_{\rm SM}(H \to ff)$$

$$\kappa_\Gamma^2 (\equiv \Gamma_H / \Gamma_H^{\rm SM})$$

κ^2_Γ parameterizes the change in the Higgs width due to both the coupling modifications and the presence of BSM decays

- **It is possible that the Higgs boson can decay directly into new particles or have BSM decays to SM particles.**

➢ ***In this case, two types of new decay channels should be distinguished:***

I. **Invisible decay.** This is a specific channel in which H **decay into new physics particles** which are **invisible** in the detector. The CEPC sensitivity to this decay channel is quantified by the upper limit on **BR^{BSM}_{inv}**.

II. **Exotic decays.** These include **all the other new physics channels**. Whether they **can be observed,** what **precision? In one extreme**, the final states can be **very distinct,** and the rate can be well measured. **In the another extreme,** they can be **completely swamped by the background**. Without the knowledge of the final states and the corresponding expected CEPC sensitivity, **the exotic decays are accounted for by treating the Higgs boson width Γ_H as an independent free parameter in the interpretation.**

$$\kappa_b, \kappa_c, \kappa_g, \kappa_W, \kappa_\tau, \kappa_Z, \kappa_\gamma, \kappa_\mu, {\rm BR}_{\rm inv}^{\rm BSM}, \Gamma_H$$

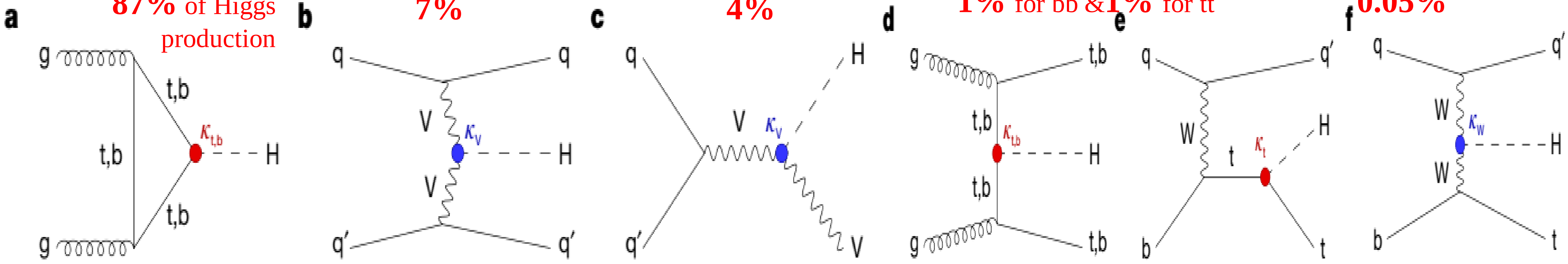
$$\kappa_b, \kappa_c, \kappa_g, \kappa_W, \kappa_Z, \kappa_\gamma, \kappa_\tau = \kappa_\mu$$

These 10 & 7 parameters are useful for studies at hadron colliders as the Higgs boson total width cannot be measured with good precision. The interpretation of the CEPC results is also performed using this reduced set to allow for direct comparisons with the expected HL-LHC sensitivity.

The κ_i parameters do not include all possible effects of new physics either.

FEYNMAN DIAGRAMS FOR HIGGS BOSON PRODUCTION & DECAY

87% of Higgs production | **7%** | **4%** | **1%** for bb & **1%** for tt | **0.05%**

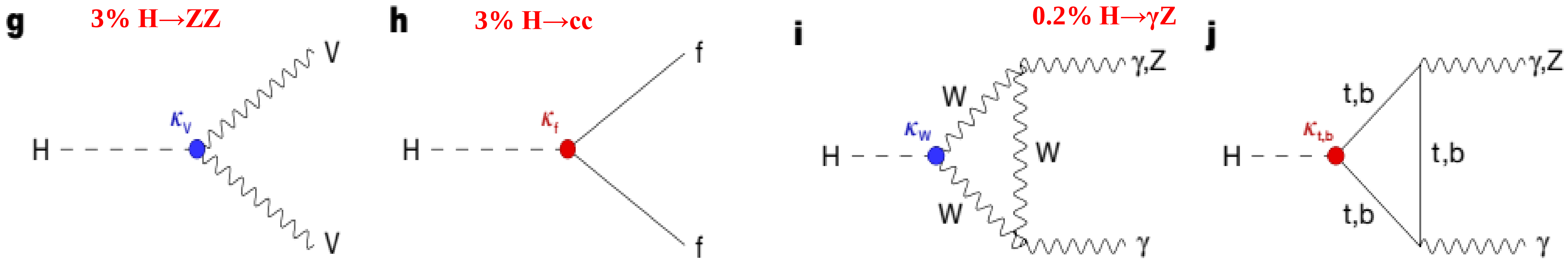


Higgs boson production in **ggH (a)** and **VBF (b)**, associated production with a W or Z (V) boson **(VH; c)**, associated production with a top or bottom quark pair **(ttH or bbH; d)**; associated production with a top quark **(tH; e, f)**

22% H→WW
3% H→ZZ

56% H→bb
3% H→cc

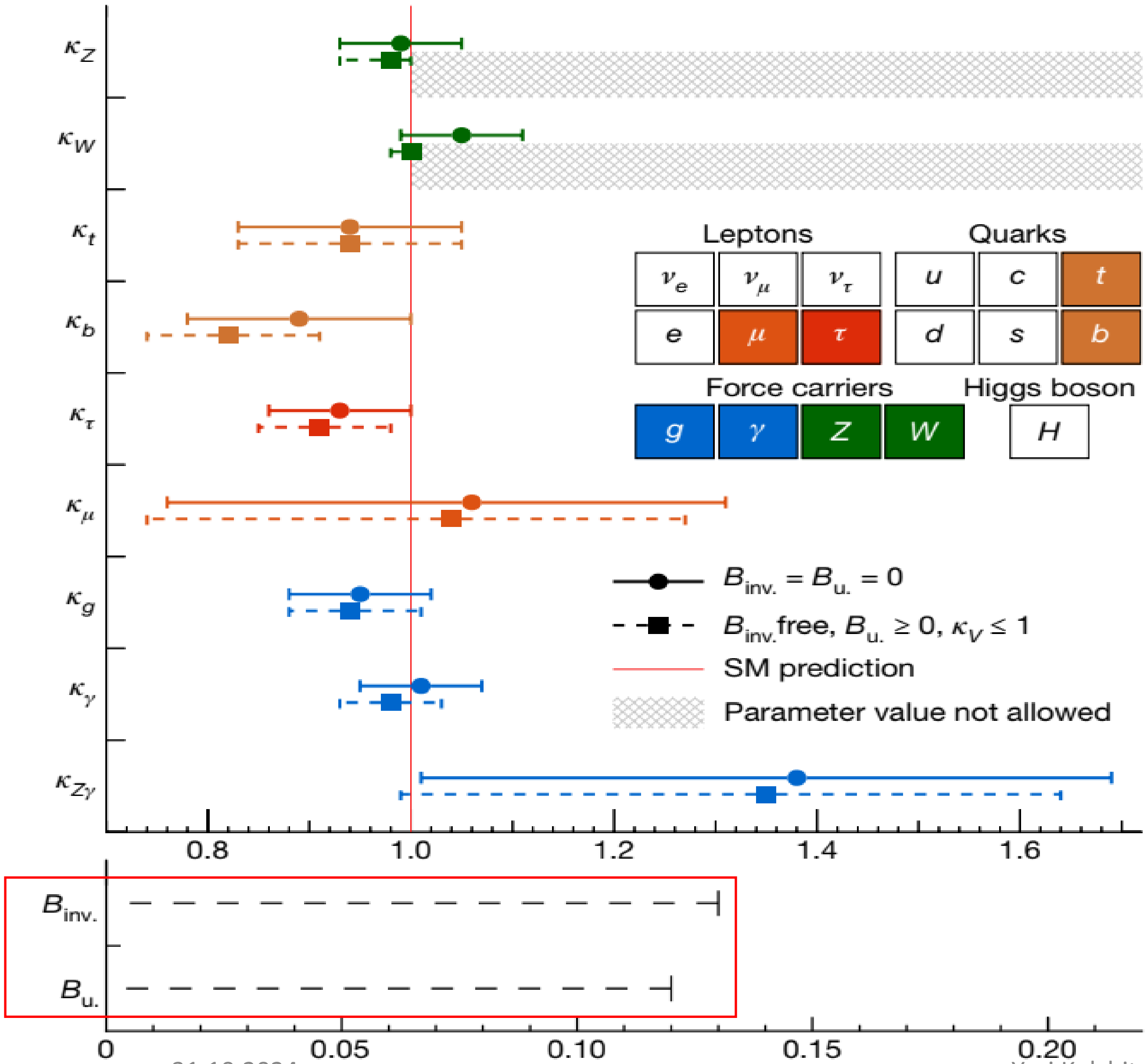
0.2% H→γγ
0.2% H→γZ



Higgs boson decays into **heavy vector boson pairs (g), fermion–antifermion pairs (h)** and photon pairs or **Zγ (i,j).**

The Higgs boson is predicted to decay almost instantly, with a lifetime of 1.6×10^{-22} seconds

COUPLING STRENGTH MODIFIERS



Reduced coupling strength modifiers and their uncertainties per particle type with effective photon, $Z\gamma$ and gluon couplings.

- The scenario in which $\boldsymbol{B_{inv.} = B_{u.} = 0}$ is assumed is shown as solid lines with circle markers. The *p* value for compatibility with the SM prediction is 61% in this case.
- The scenario in which $\boldsymbol{B_{inv.}}$ and $\boldsymbol{B_{u.}}$ are allowed to contribute to the total Higgs boson decay width while assuming that $\boldsymbol{\kappa_V \leq 1}$ and $\boldsymbol{B_{u.} \geq 0}$ is shown as dashed lines with square markers.
- **The lower panel shows the 95% CL upper limits on $B_{inv.}$ and $B_{u.}$.**

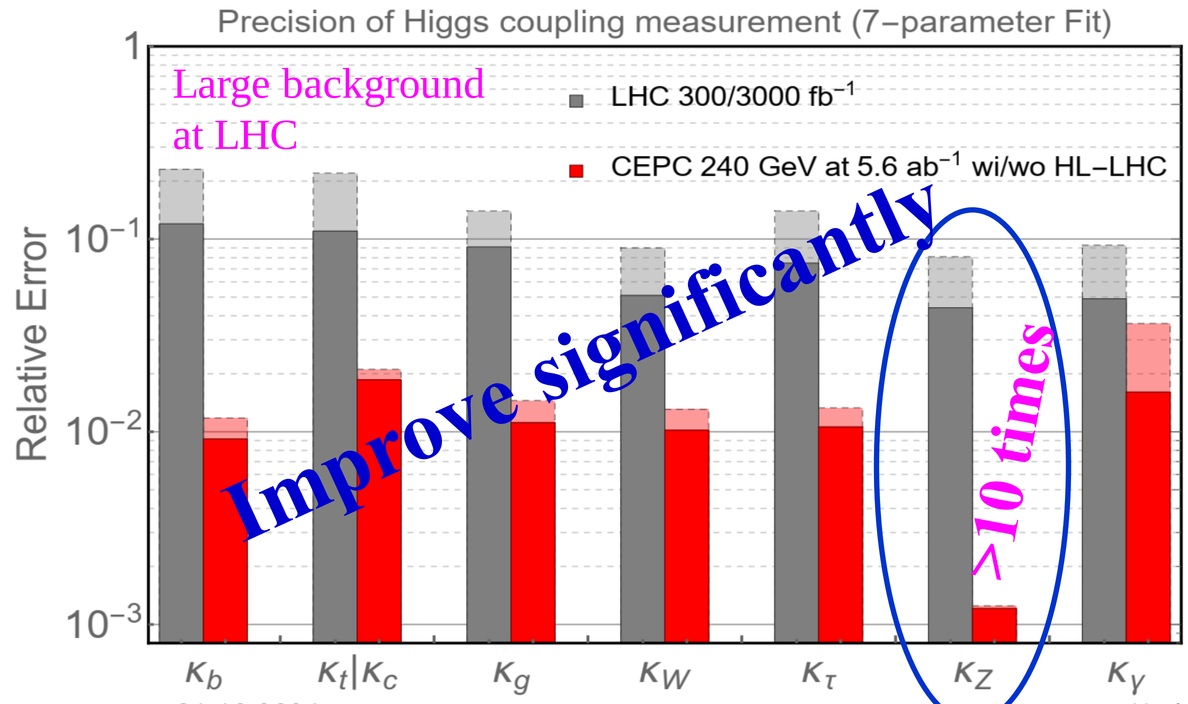
HIGGS PHYSICS: COUPLING FITS IN THE κ-FRAMEWORK

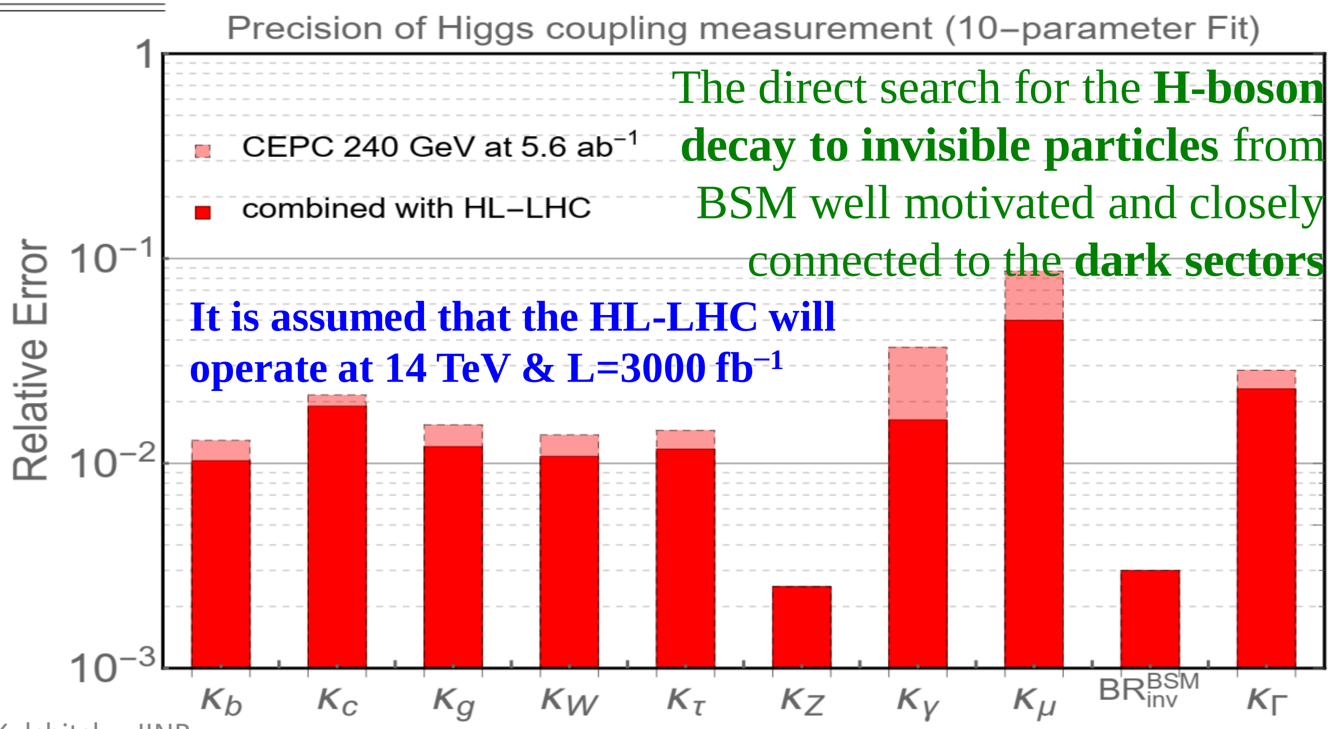
Relative coupling measurement precision and the 95% CL upper limit on BR^{BSM}_{inv}

Quantity	10-parameter fit		7-parameter fit	
	CEPC	CEPC+HL-LHC	CEPC	CEPC+HL-LHC
κ_b	1.3%	1.0%	1.2%	0.9%
κ_c	2.2%	1.9%	2.1%	1.9%
κ_g	1.5%	1.2%	1.5%	1.1%
κ_W	1.4%	1.1%	1.3%	1.0%
κ_τ	1.5%	1.2%	1.3%	1.1%
κ_Z	0.25%	0.25%	0.13%	0.12%
κ_γ	3.7%	1.6%	3.7%	1.6%
κ_μ	8.7%	5.0%		
BR^{BSM}_{inv}	$<0.30\%$	$<0.30\%$		
Γ_H	2.8%	2.3%		

Systematic uncertainties are under much better control at CEPC

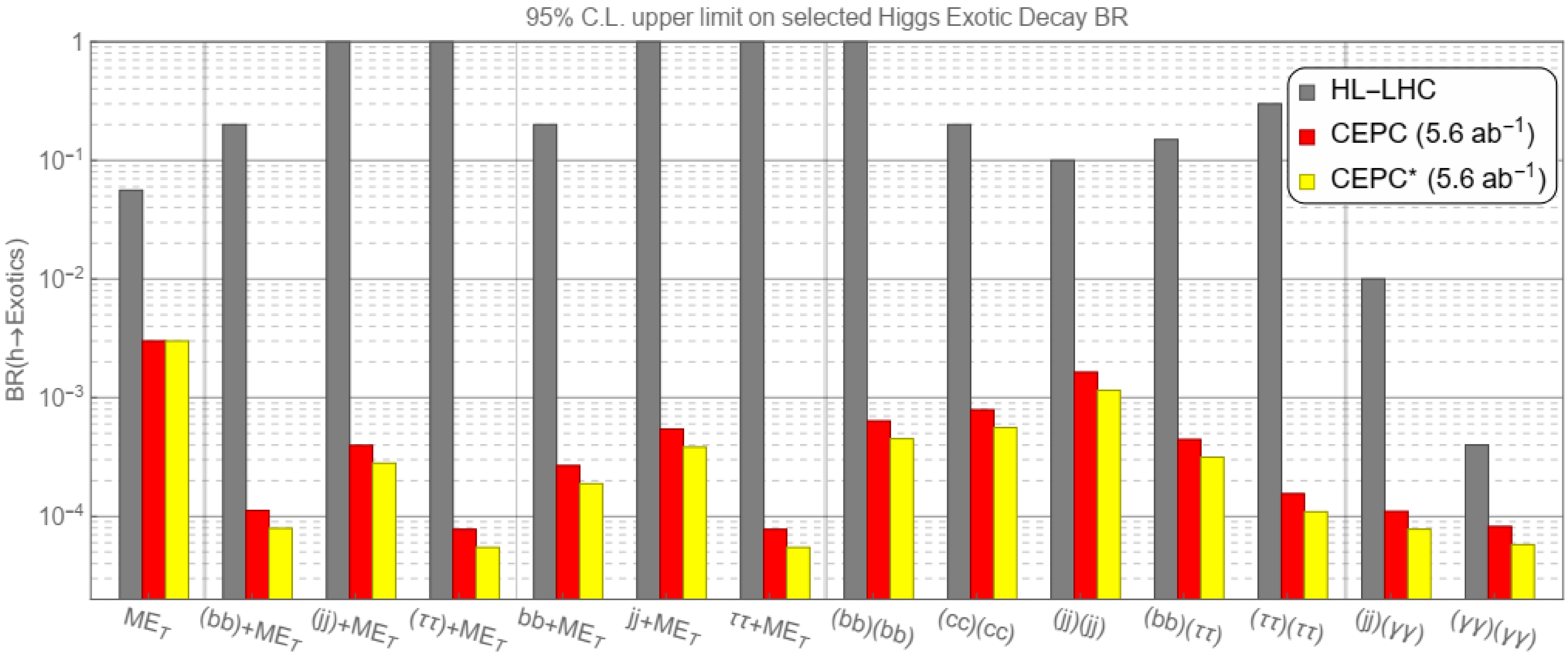
Coupling measurement precision from the 10-parameter fit and 7-parameter fit for the CEPC, and corresponding results after combination with the HL-LHC. All the numbers refer to are relative precision except for $\mathbf{BR^{BSM}_{inv}}$ for which the 95% CL upper limit are quoted respectively. Some entries are left vacant for the 7-parameter fit as they are not dependent parameters under the fitting assumptions.





The results of the 7 and 10 parameter fits and comparison with the HL-LHC.

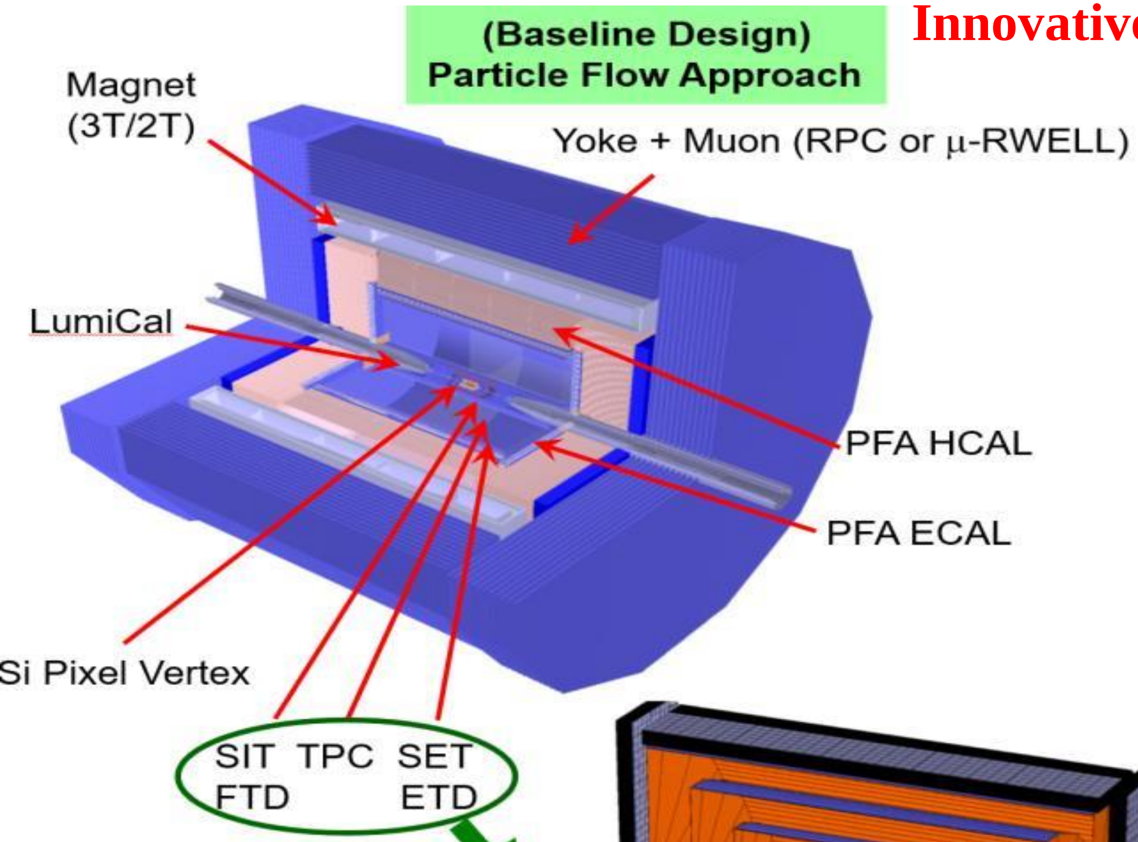
BRANCHING OF SELECTED HIGGS BOSON DECAYS

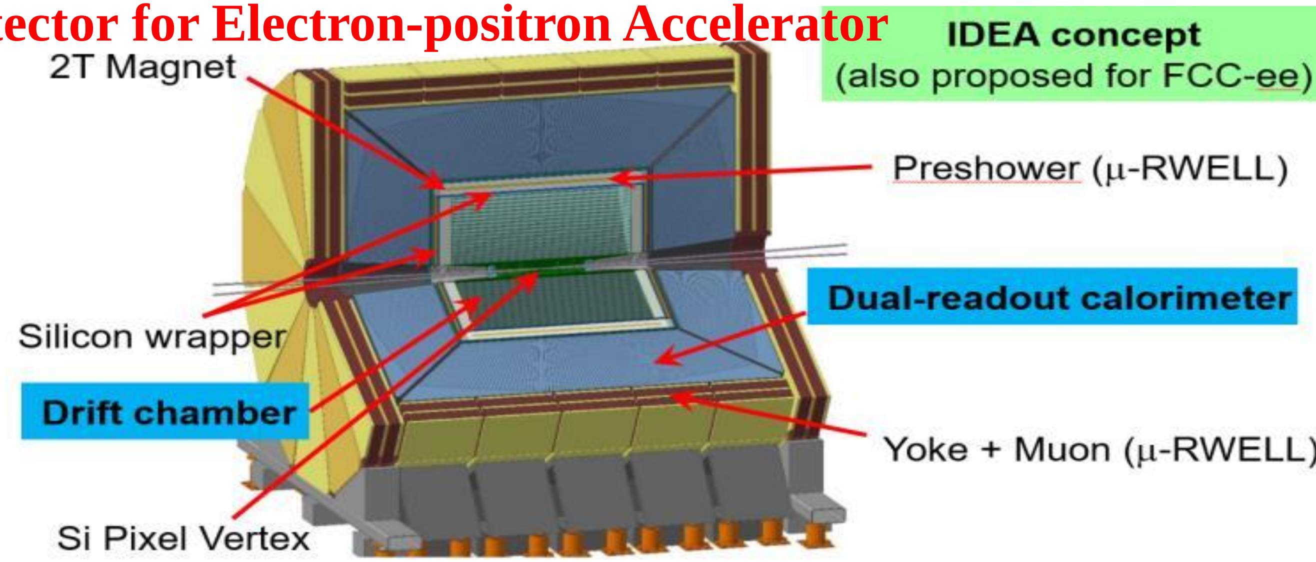


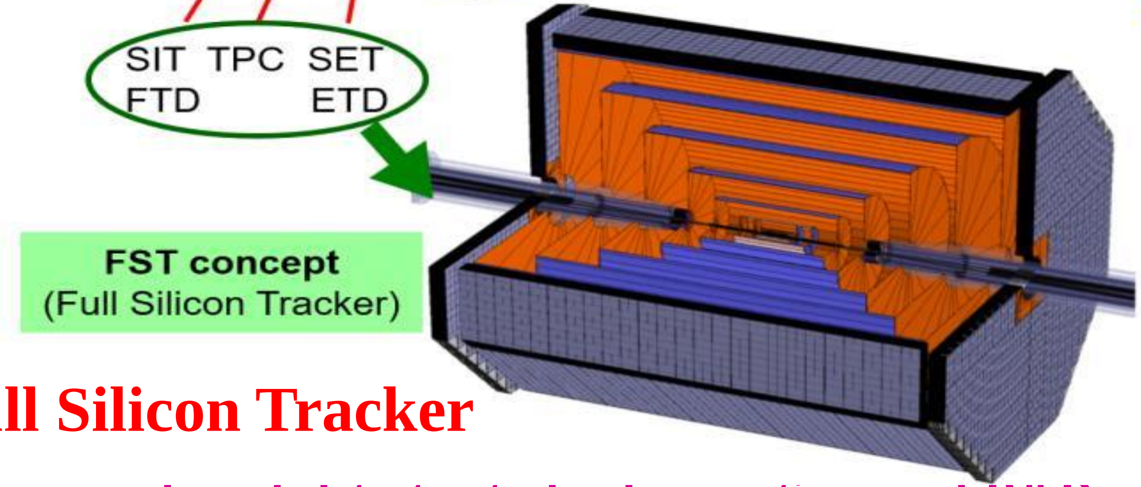
- The 95% CL upper limit on selected Higgs exotic decay branching fractions at **HL-LHC and CEPC**.
- **The red bars correspond to the results using only leptonic decays of the spectator Z-boson.**
- **The yellow bars** further include extrapolation with **the inclusion of the hadronic decays** of the spectator Z-boson
- Several vertical lines are drawn in this figure to **divide different types of Higgs boson exotic decays**.

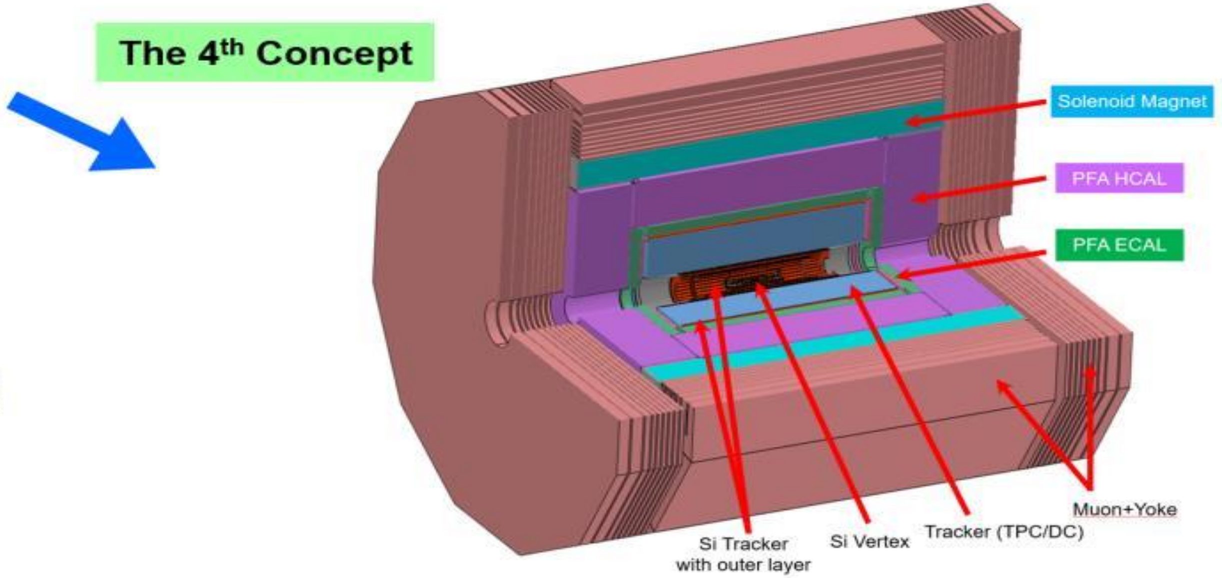
CEPC DETECTORS DESIGNS

Innovative Detector for Electron-positron Accelerator









Full Silicon Tracker

Large number of detector technology options and R&D projects on-going. Need to converge technology options towards a CEPC reference detector TDR**:** Start preparation in January 2024; Release of ref-TDR in June 2025. International detector collaborative efforts: HL-LHC detector R&D efforts help to prepare teams for CEPC detectors. **Detector Research & Development (DRD) collaboration (DRD: 1-8).**

DRD COLLABORATIONS (1-8)

1. Gaseous

e.g.
time/spatial resolution;

environment friendly gases

2. Liquid

e.g.
Light/charge readout;

low background materials

3. Semiconductor

e.g.
CMOS pixel sensors;

High time resolution (10s ps)

4. PID & Photon

e.g.
spectral range of photon sensors;

Time resolution

5. Quantum

quantum sensors
- R&D, incl. beyond QFTP in conventional detectors

6. Calorimetry

e.g.
Sandwich;
noble liquid;
optical

7. Electronics

e.g.
ASICs;
FPGAs;
DAQ

8. Integration

tracking detector mechanics

DETECTORS CONCEPTS

Parameters of the ***International Large Detector (ILD)*** *[1,2]* & the ***CEPC detector concepts***

Concept	ILD	CEPC baseline	IDEA
Tracker	TPC/Silicon	TPC/Silicon or FST	Drift Chamber/Silicon
Solenoid B-Field (T)	3.5	3	2
Solenoid Inner Radius (m)	3.4	3.2	2.1
Solenoid Length (m)	8.0	7.8	6.0
L* (m)	3.5	2.2	2.2
VTX Inner Radius (mm)	16	16	16
Tracker Outer Radius (m)	1.81	1.81	2.05
Calorimeter	PFA	PFA	Dual readout
Calorimeter λ_I	6.6	5.6	7.5
ECAL Cell Size (mm)	5	10	-
ECAL Time resolution (ps)	-	200	-
ECAL X_0	24	24	-
HCAL Layer Number	48	40	-
HCAL Absorber	Fe	Fe	-
HCAL λ_I	5.9	4.9	-
DRCAL Cell Size (mm)	-	-	6.0
DRCAL Time resolution (ps)	-	-	100
DRCAL Absorber	-	-	Pb or Cu or Fe
Overall Height (m)	14.0	14.5	11.0
Overall Length (m)	13.2	14.0	13.0

An alternative detector

Time Projection Chamber (TPC)

L* is the distance between the IP and the final focusing quadrupole magnet

*The **baseline concept** was developed from the **ILD concept**, **optimized** for the **CEPC** collision environment*

It employs an ***ultra high granular calorimetry system*** to efficiently separate the final state particle showers, a ***low material tracking system*** to minimize the interaction of the final state particles in the tracking material, and a ***large volume 3T solenoid*** that encloses the entire calorimetry system

A ***Dual Readout calorimeter*** to achieve the ***excellent energy resolution*** for both the electromagnetic and hadronic showers

1. Linear Collider ILD Concept Group - Collaboration, T. Abe et al., The International Large Detector: Letter of Intent, arXiv:1006.3396 [hep-ex]
2. H. Abramowicz et al., The International Linear Collider Technical Design Report, Volume 4: Detectors, arXiv:1306.6329 [physics.ins-det].

DETECTOR PERFORMANCE AT CEPC: I

To deliver the physics program **CEPC detector concepts** must meet the **stringent performance requirements**

- **The detector designs are guided by the principles of**
  - **large and precisely defined solid angle coverage,** excellent particle identification, precise particle energy/momentum measurement, efficient vertex reconstruction, **superb jet reconstruction** and measurement as well as **the flavor tagging.**

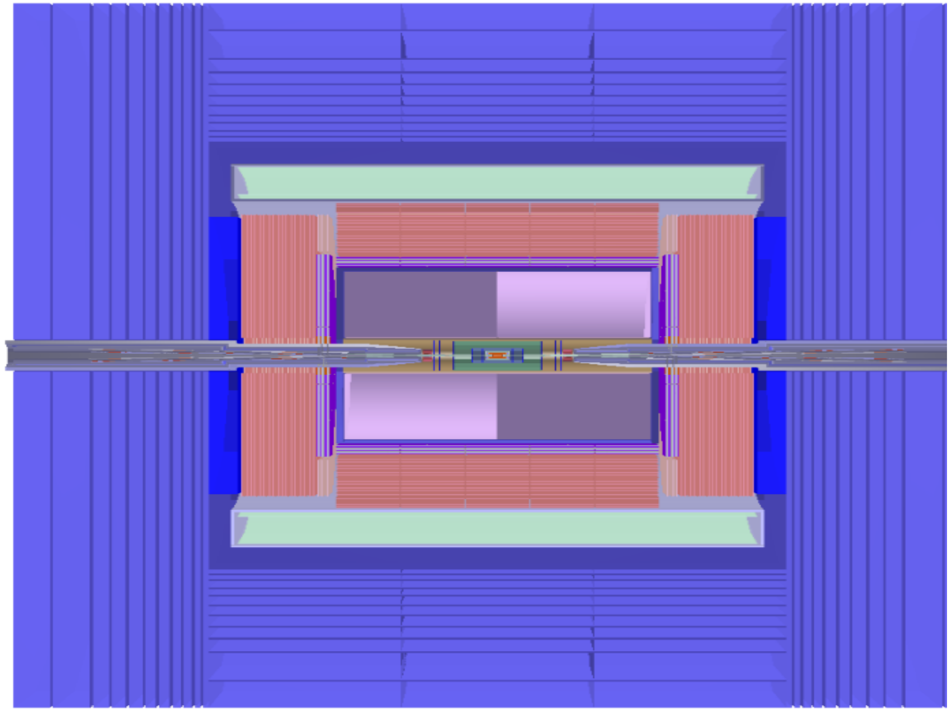
✓ Two primary detector concepts are described, a **baseline** with **two approaches to the tracking systems**, and an *alternative* with a **different strategy for meeting the jet resolution requirements**.

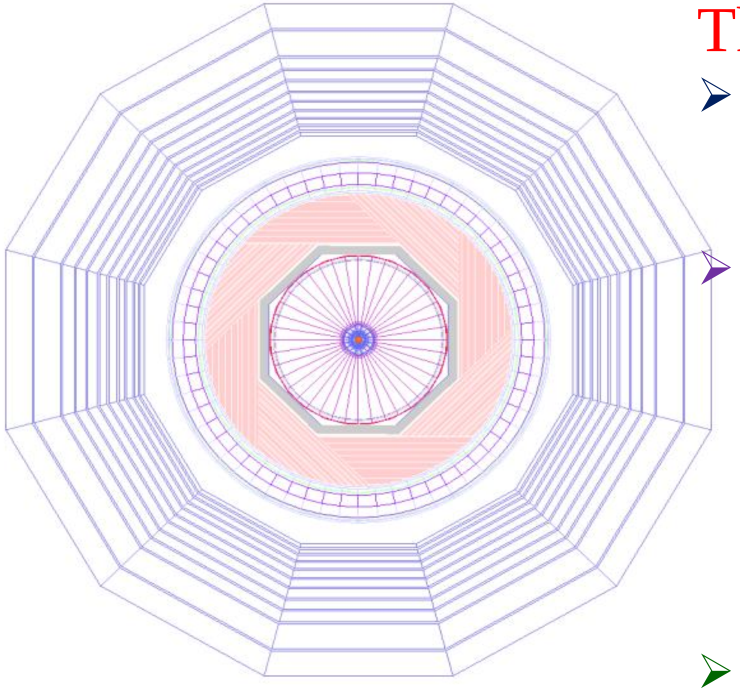
- The **baseline detector concept** incorporates **the particle flow principle** with
  - a **precision vertex detector**, a *Time Projection Chamber (TPC)*, a *silicon tracker*, a *high granularity calorimetry system*, a **3 Tesla** superconducting solenoid followed by, a *muon detector embedded in a flux return yoke*.
- **The alternative concept** is based on
  - a **precision vertex detector,** a drift chamber tracker, **a dual readout calorimetry,** a **2 Tesla** solenoid, and a muon detector.
- The **baseline detector concept** has been studied in detail **through realistic simulation** and the **results demonstrate** that it can **deliver the performance necessary to achieve the physics goals of the CEPC**

DETECTOR PERFORMANCE AT CEPC: II

- To develop the detector concepts into **full-scale technical designs** for the planned detectors, a set of **critical R&D tasks** has been identified.
  - Prototypes of key detector components will be built and tested.
  - Mechanical integration, thermal control and data acquisition schemes must be developed.
  - Industrialization of the detector component fabrication will be pursued.
- **International collaborations** will need to be formed ***before the detector designs can be finalized*** and the ***technical design reports can be developed***.
- The **CEPC** will be a world-class multifaceted scientific facility for research, education, **and international collaboration**.
- **CEPC** will be a center for discoveries and innovation and a magnet for attracting top scientists from all over the world to work together to understand the fundamental nature of our Universe.
- The **CEPC** will also provide **leading educational opportunities for universities and research institutions** in China and **around the world.**
- The **CEPC** together with its possible upgrade, the **Super proton-proton Collider**, will firmly place China at the forefront of the cutting-edge research and exploration in fundamental physics for the **next half century.**
- ✓ **CEPC** will have profound impacts on **science, economy and society** that will reverberate across the world.

CEPC: BASELINE DETECTOR CONCEPT





The **baseline concept** employs

- **high granular sampling ECAL and HCAL, providing 3-dimensional spatial and the energy information.**
- The ECAL is composed of **30 longitudinal layers** of alternating **silicon sensors and tungsten absorbers**, splitting into **two** sections of different absorber thickness. The total absorber length at θ=90^o is 8.4 cm, or equivalently 24 radiation lengths (X_0).
- Transversely, each sensor layer is segmented into **10x10 mm²** cells.
- The **HCAL** uses **steel as absorbers and scintillator** titles or **gaseous detectors such as RPCs as sensors**. It has **40** longitudinal layers, each consists of a **2.5** cm steel absorber. The total steel thickness is about 100 cm at θ=90^o, corresponding to 5.6 interaction lengths. Like the **ECAL, the HCAL** is segmented into **10x10 mm²** cells transversely.

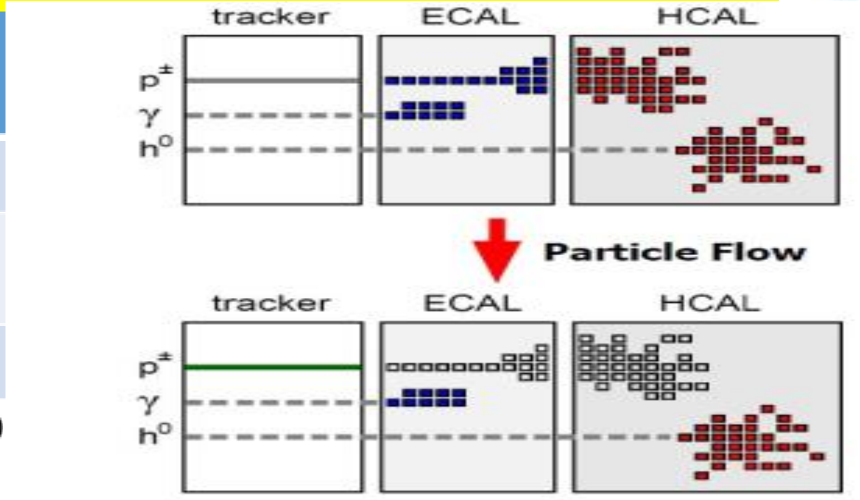
The Baseline detector concept:

- **Barrel:** The detector is composed of ***a silicon pixel vertex detector***, ***a silicon inner tracker***, ***a TPC***, ***a silicon external tracker***, ***an ECAL***, ***an HCAL***, ***a solenoid of 3 Tesla*** and ***a return yoke with embedded a muon detector***.
- **Forward:** ***Five pairs of silicon tracking disks*** are installed to enlarge the tracking acceptance 0.99<|cos(θ)|< 0.996

The **calorimetry system** provides good energy measurements for **neutral particles: ~16%/√E/GeV** for **photons** and **60%/√E/GeV** for **neutral hadrons. A jet** energy resolution of **3–5% are expected for jet energies 20 – 100 GeV.**

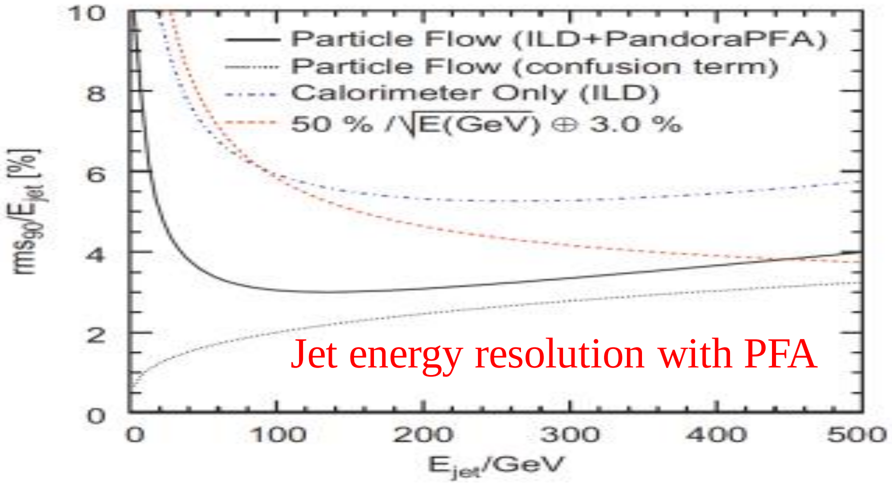
Components in jets	Sub-Detectors	Energy fraction (average) within a jet*	(Typical) Sub-detector Resolution
charged particles ($X^{\pm}$)	Tracker	$\sim 62\%\ E_j$	$10^{-4}E^2{}_X$
photons (γ)	ECAL	$\sim 27\%\ E_j$	$0.15\sqrt{E_\gamma}$
neutral hadrons (h)	ECAL+HCAL	$\sim 10\%\ E_j$	$0.55\sqrt{E_h}$

*Measurements of jet fragmentation at LEP (and ~1% by neutrinos)



Particle Flow Algorithm (PFA)

- To achieve unprecedented jet energy resolution of **~30%/√E$_{jet}$**
- Choose a sub-detector best suited for each particle in a jet
- Charged particles measured in tracker
- Photons in ECAL and neutral hadrons in HCAL
- Separation of close-by particles in the calorimeters
- **PFA-oriented calorimeters**: high granularity (1~10 million channels)



Jet energy resolution with PFA

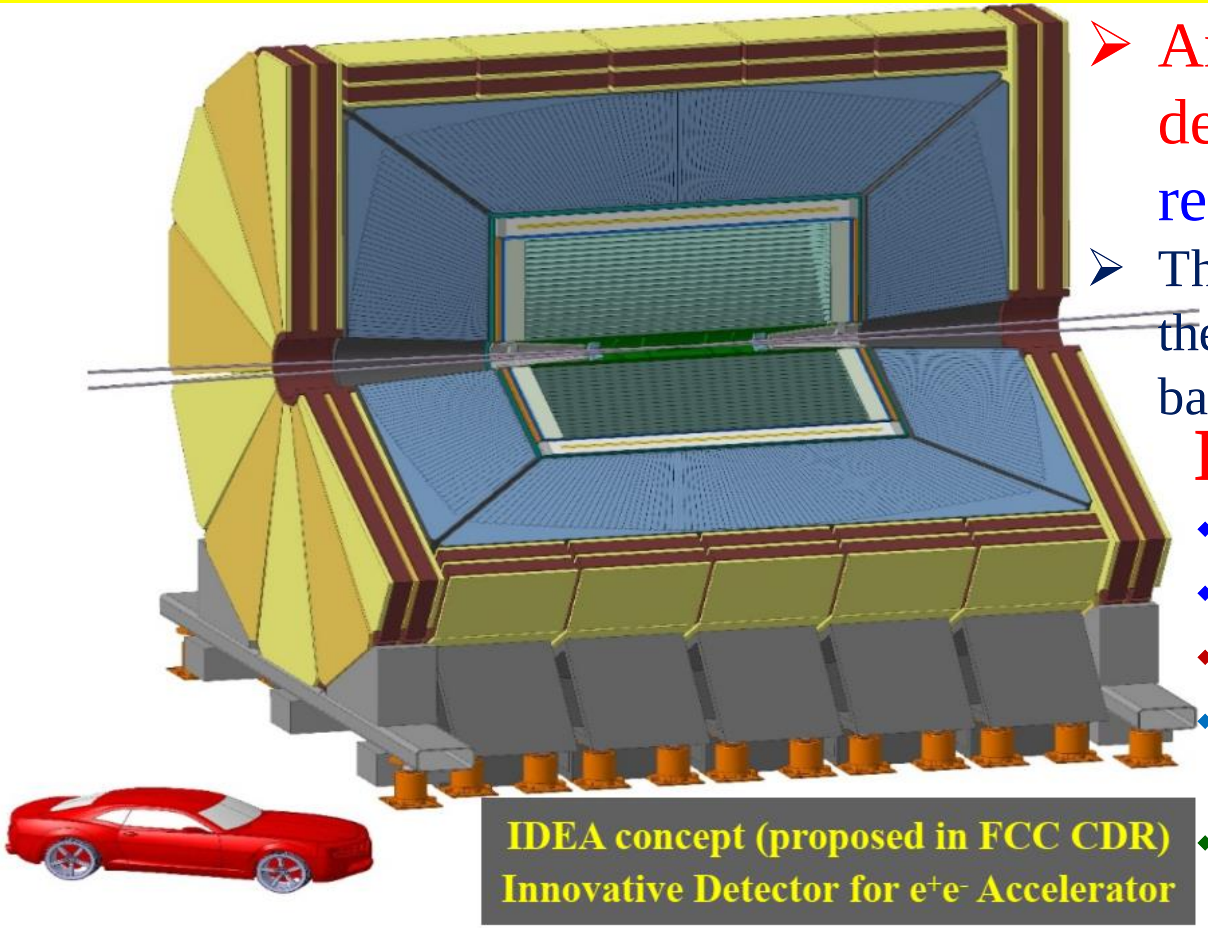
$$\sigma^2_{\rm jet} = \sigma_{h^\pm} + \sigma^2_\gamma + \sigma^2_{h^0} + \sigma^2_{\rm confusion} + \sigma^2_{\rm threshold} + \sigma^2_{\rm losses}$$

Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07^2\ E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	$0.16^2\ E_{jet}$
Confusion	Required for 30%/√E		$\leq 0.24^2\ E_{jet}$

18%/√E

- Jet energy resolution will be dominated by the intrinsic resolution at low jet energies
- Jet energy resolution of 3-4% required to separate W/Z peak not suitable for CEPC: worse resolution should be still tolerable

INNOVATIVE DETECTOR FOR ELECTRON-POSITRON ACCELERATOR (IDEA)



- An alternative detector concept, **IDEA**, has been designed for a **CEPC**. It is being adopted as a reference detector for FCC-ee
- The concept design attempts to **economize** on the overall cost of the detector and proposes **different technologies** than the baseline concept for some of the detector subsystems

Innovative, more cost-effective concept:

- Silicon vertex detector
- Short-drift, ultra-light wire chamber
- **Dual-readout calorimeter**
- Thin and light solenoid coil inside calorimeter system: Small magnet ⇒ small yoke
- Muon system made of 3 layers of μ-RWELL detectors in the return yoke

- The **IDEA detector** concept could be an excellent choice for one of the **IP**s:: Very good momentum measurement; Outstanding PID with cluster counting from the drift chamber; **Excellent calorimetry**; Precise and efficient muon detector; Very appealing upgrade options! (DR EM crystal calorimeter, LGADs for the Si wrapper)
- Need for **significant R&D in the next 4-5 years**: A lot of ongoing activities on all IDEA sub-detectors; Profiting from several national funding schemes, EU projects, etc.; Several international colleagues have joined these efforts

PHYSICS PROCESSES USED AS BENCHMARKS

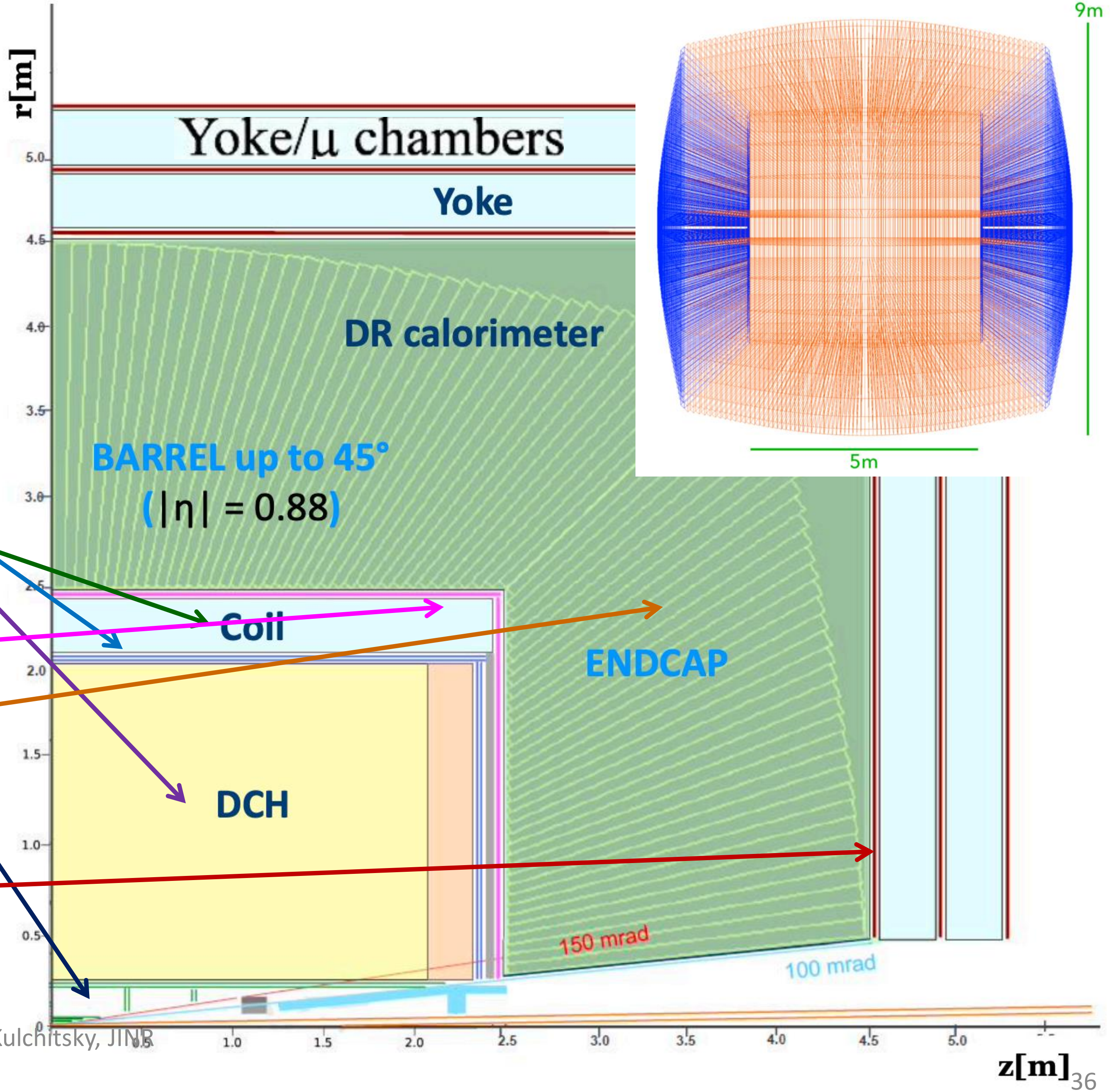
Physics **processes and key observables** used as benchmarks for setting **the requirements and the optimization of the CEPC detectors**

- **$\Delta(1/p_T)$**
  - high precision measurement at the end of tracker
- **$\sigma_{r\Phi}$**
  - finely segmented vertex detector
- **σ^{jet}_E/E**
  - excellent Jet energy resolution
- **$\sigma^{e/\gamma}_E/E$**
  - Good em energy resolution
- Challenging requirements for detector materials

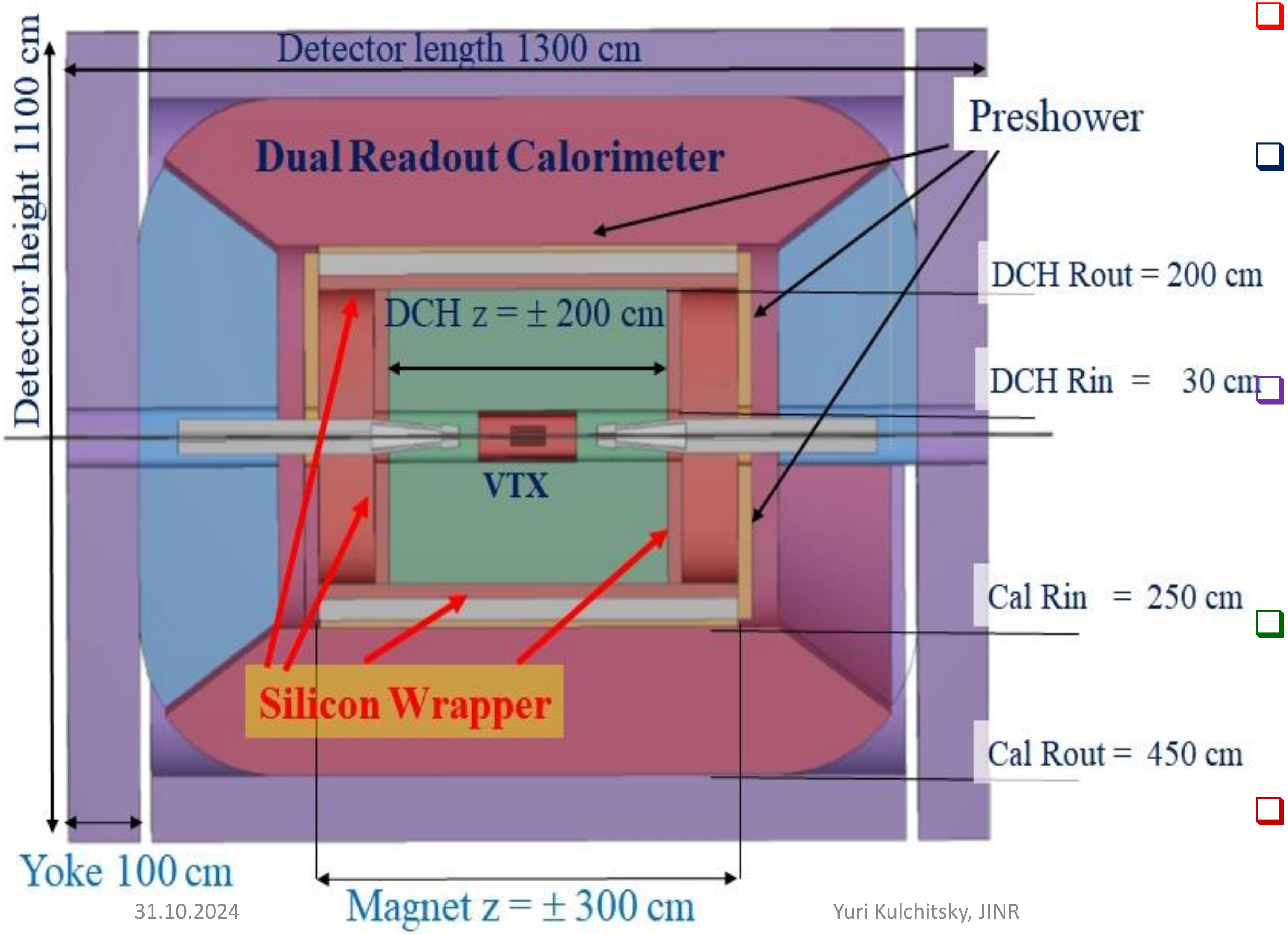
Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) =$ $2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} =$ $5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E =$ $3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E =$ $\frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

THE IDEA DETECTOR LAYOUT

- **Beam pipe:** R~1.0 cm
- **Vertex:** 5 MAPS layers, R = 1.37 – 31.5 cm
- **Drift Chamber:** 112 layers, 4 m long, R = 35 – 200 cm
- **Outer Silicon wrapper: Si** strips
- **Superconducting solenoid coil: 2 T, R ~ 2.1 – 2.4 m**
  0.74 X_0, 0.16 λ @ 90°
- **Preshower:** ~1 X_0
- **Dual-Readout Calorimetry: 2m /7λ_{int};** Preshower **μ-Rwell**
- **Yoke +**
- **Muon chambers**
  - μ-Rwell



THE IDEA DETECTOR LAYOUT



- A key element of IDEA is a **thin, 30 cm, and low mass, 0.8 X_0,** solenoid with a magnetic field 2T
- The low mass and thickness of the solenoid allows it to be located between the tracking volume and the calorimeter without a significant performance loss
- The low-magnetic field is optimal as it minimizes the impact on emittance growth and allows for manageable fields in the compensating solenoids
- It puts stringents constraints on the tracker design required to achieve the necessary momentum resolution
- IDEA has consequently adopted a large low-mass cylindrical drift chamber has its main tracker

❑ ***The following R&D program is being pursued in order to address and clarify several issues:***

- **Absorber material** choice, current candidates: ***lead, brass and iron;***
- ***Machining* and *assembly procedure*** for modules of **10x10 cm^2** cross section;
- **Development of a modular, projective solution** for a **4π calorimeter** concerning both the construction of *single modules* and the *design and construction of a full detector*;
- ***Identification of adequate solid-state photo-sensors*** in order to ***independently optimize*** both ***Cerenkov*** *and* ***scintillation light*** *detection*
- ***Readout granularity*** (i.e. identify the ***optimal fiber grouping*** into a ***single readout channel***);

1. **DREAM Collaboration**, R.Wigmans, The DREAM project: Towards the ultimate in calorimetry, NIM A617 (2010) 129–133.
2. N.Akchurin et al., The electromagnetic performance of the **RD52** fiber calorimeter, NIM A735 (2014) 130–144.
3. **RD52 (DREAM) Collaboration**, R.Wigmans, New results from the **RD52** project, NIM A824 (2016) 721–725.
4. N.Akchurin et al., Particle identification in the longitudinally unsegmented **RD52** calorimeter, NIM A735 (2014) 120–129

5.5: Dual-readout calorimeter

Franco Bedeschi bed@fnal.gov, INFN - Sezione di Pisa, Universita' di Pisa and Scuola Normale Superiore
Roberto Ferrari roberto.ferrari@cern.ch, INFN - Sezione di Pavia and University of Pavia

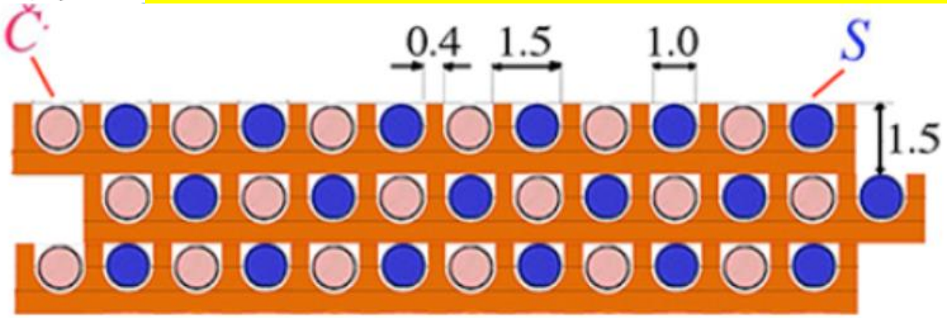
CEPC Physics & Detector TDR: Dual-Readout Calorimeter II

❑ ***The following R&D program is being pursued in order to address and clarify several issues:***

- ***Identification of a tailored front-end electronics***, likely composed by an **ASIC** and an **FPGA** *chip*, in order to extract in real time both charge and time information (*a time resolution of 100 ps allow to identify the shower starting point inside the calorimeter with a precision of 6 cm*);
- ***Particle ID performance with PFA***, with and without a ***longitudinal segmentation***;
- ***Development and validation of full and fast simulations*** of both ***test beam modules*** and an ***integrated 4π detector;***
- ***Assessment of the performance*** for the *most relevant physics channels* (W, Z, H decays).

5.5: Dual-readout calorimeter
Franco Bedeschi bed@fnal.gov, INFN - Sezione di Pisa, Universita' di Pisa and Scuola Normale Superiore
Roberto Ferrari roberto.ferrari@cern.ch, INFN - Sezione di Pavia and University of Pavia

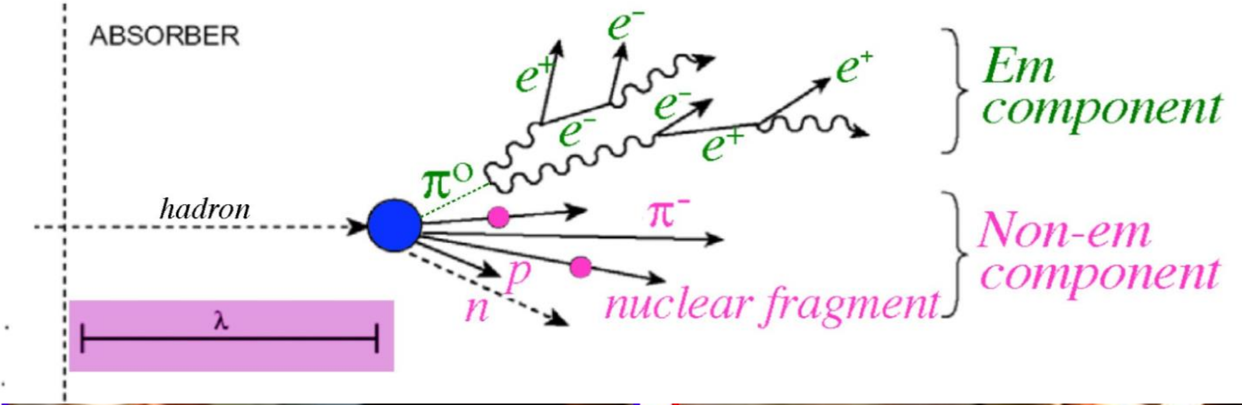
IDEA DETECTOR: DUAL READOUT CALORIMETRY



Alternate
- ✓ Cherenkov fibers
- ✓ **Scintillating fibers**

Dual-Readout calorimetry **allows to remove** fluctuations by correcting for $\mathbf{f_{em}}$ event-by-event using two readout channels with different **h/e**

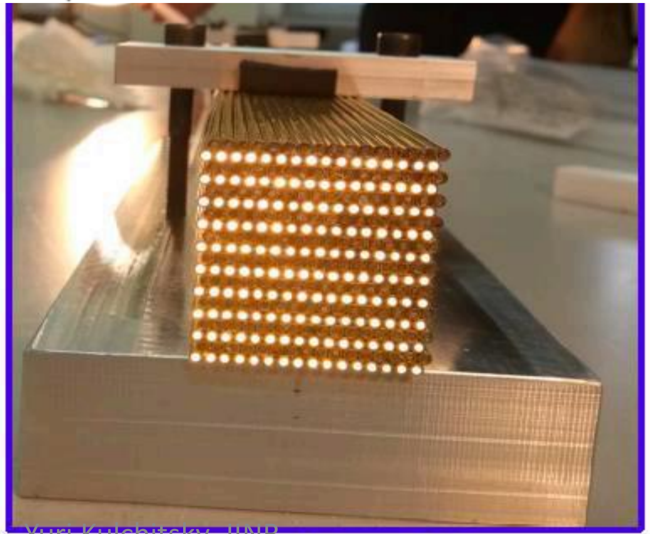
- ❑ **Measure simultaneously:**
  - ➢ Scintillation signal (**S**)
  - ➢ Cherenkov signal (**C**)
- ❑ Calibrate both signals with e^-
- ❑ Unfold event by event f_{em} to obtain corrected energy



$$S = E\left[f_{em} + (h/e)_S(1 - f_{em})\right]$$

$$C = E\left[f_{em} + (h/e)_C(1 - f_{em})\right]$$

$$E = \frac{S - \chi C}{1 - \chi} \quad \text{with:} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

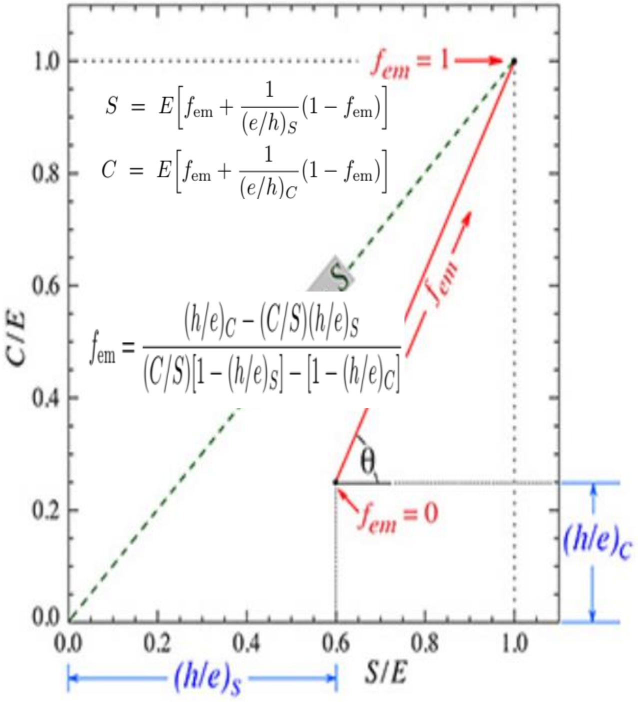


Scintillation fibers

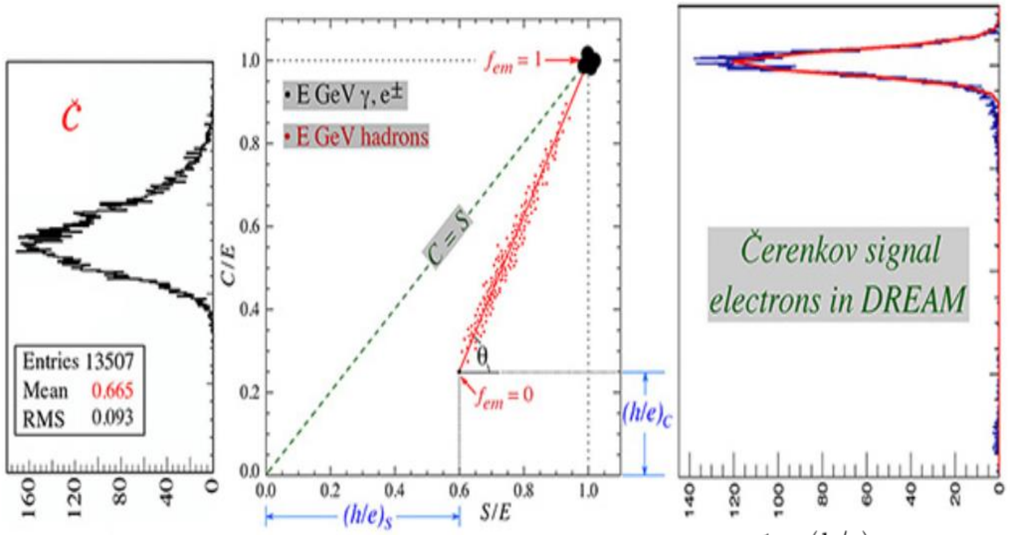
Cherenkov fibers

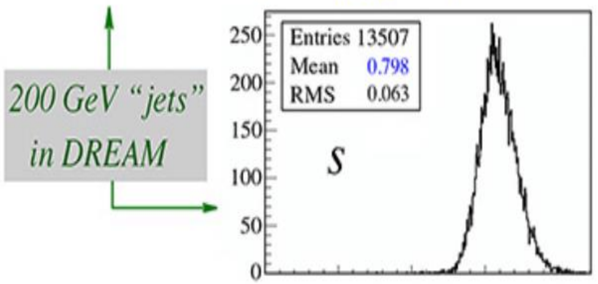
S. Lee, M. Livan, R. Wigmans, Dual-Readout Calorimetry, arXiv:1712.05494

The DR calorimetry has emerged as a technique for measuring the properties of high-energy hadrons and hadron jets



The data points for hadron showers detected with a dual-readout calorimeter are located around the straight (red) line in this diagram. The data points for em showers in this calorimeter are clustered around the point where this line intersects the C=S line.

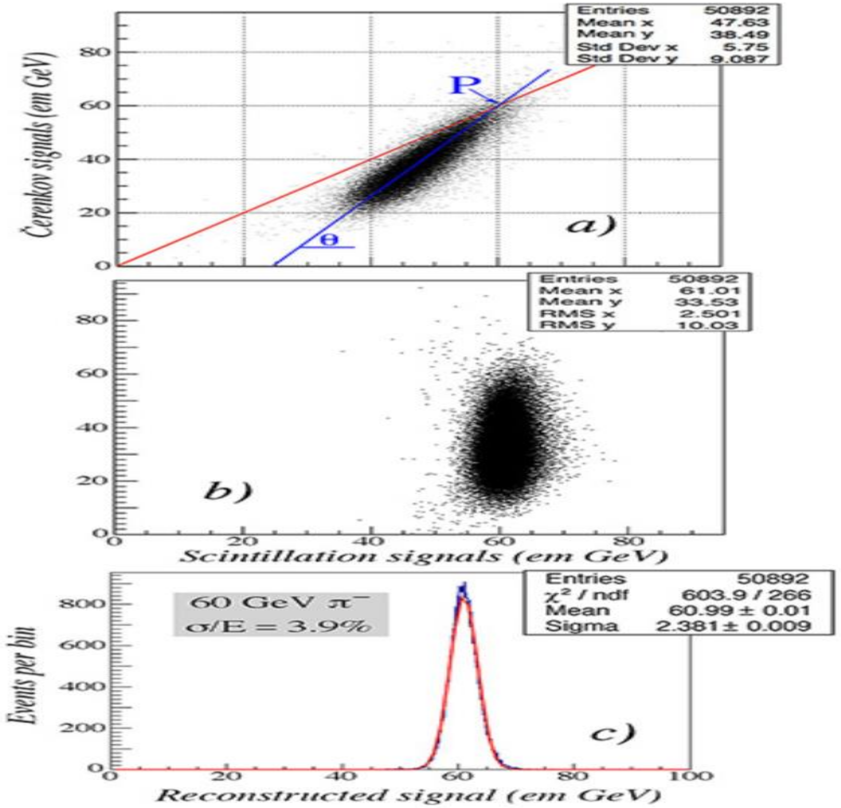




$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

$$E = \frac{S - \chi C}{1 - \chi}$$

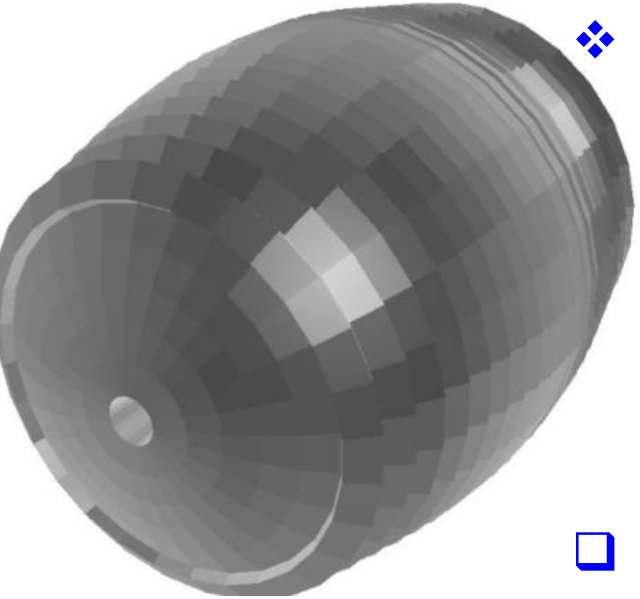
The hadron events are clustered around the straight (red) line, the electron events around the point (1,1). Experimental signal distributions measured in the scintillation and Cerenkov channels for **200 GeV jets** with the **DREAM** fiber calorimeter. Also shown is a typical (Cerenkov) response function measured for electrons in **DREAM**.



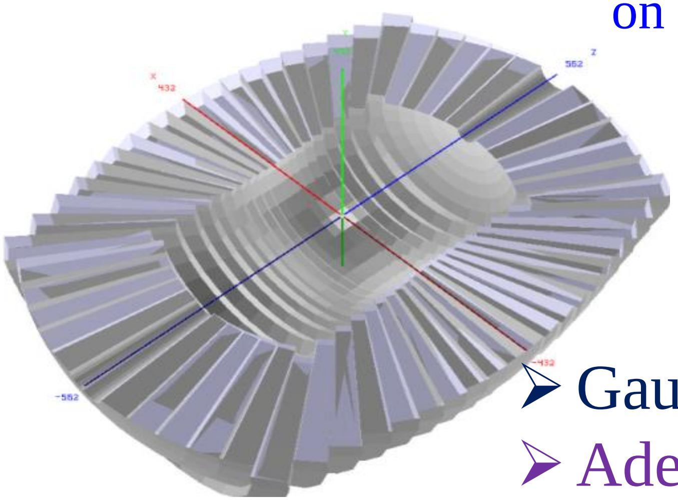
Signal distributions of the Dual-Readout lead fiber calorimeter for 60 GeV pions. Scatter plot of the 2 types of signals as recorded for these particles and rotated over an θ=30° around the point where the 2 lines from diagram a intersect. Projection of the latter scatter plot on the x-axis.

IDEA DETECTOR: DUAL READOUT CALORIMETRY

Full GEANT4 implementation of the DR calorimeter

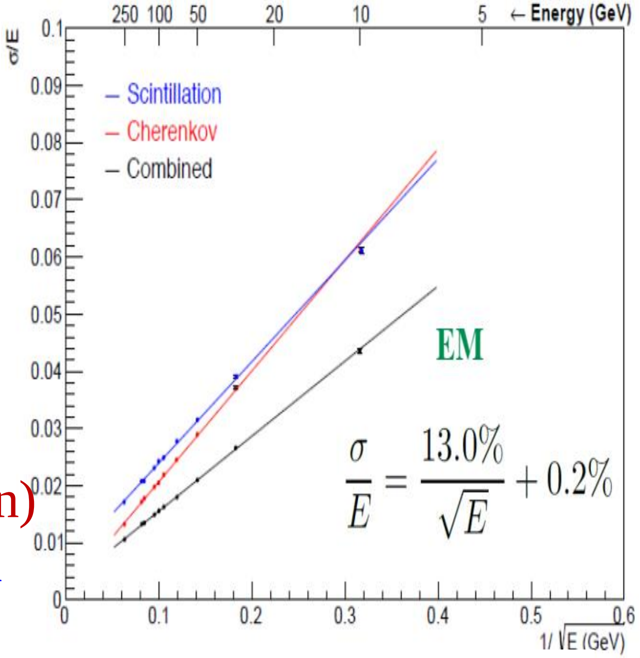


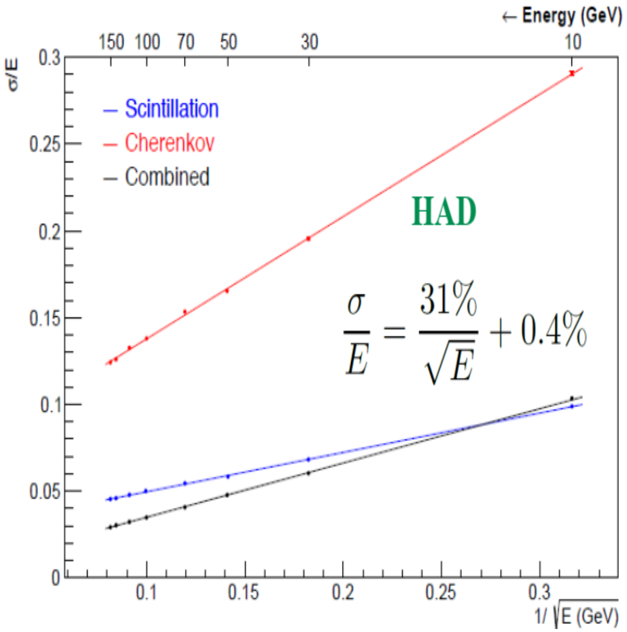
- International collaboration:
  1. TTU (USA),
  2. Sussex (UK),
  3. Universities (Korea),
  4. Chile,
  5. Princeton,
  6. Maryland (USA),
  7. CERN (crystal extension)
- EM prototype built and tested on beams (DESY/CERN)

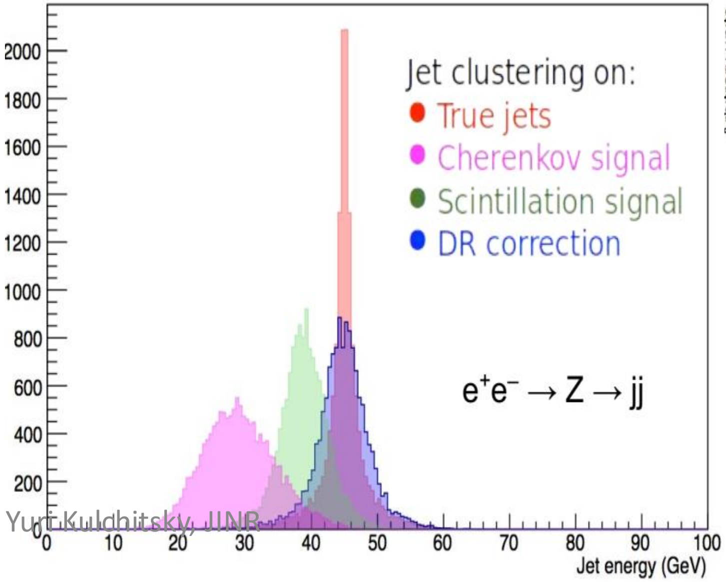


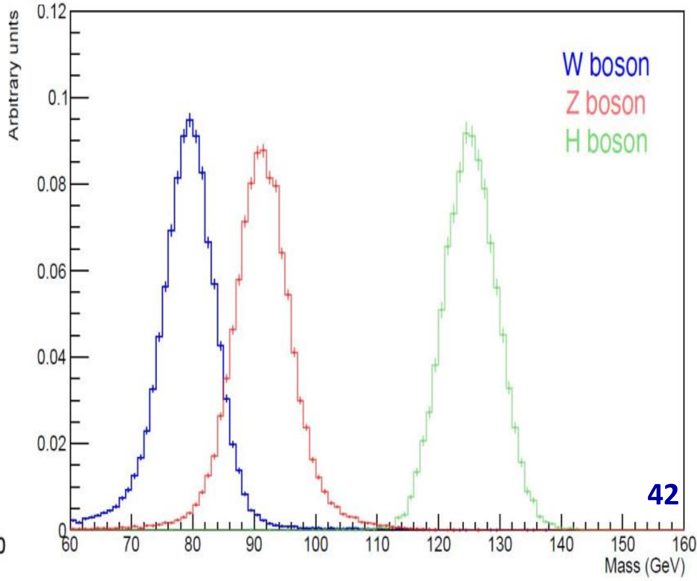
- Gaussian resolution
- Adequate separation of **W/Z/H**

Geant 4: ***good resolutions averaged over η and φ***

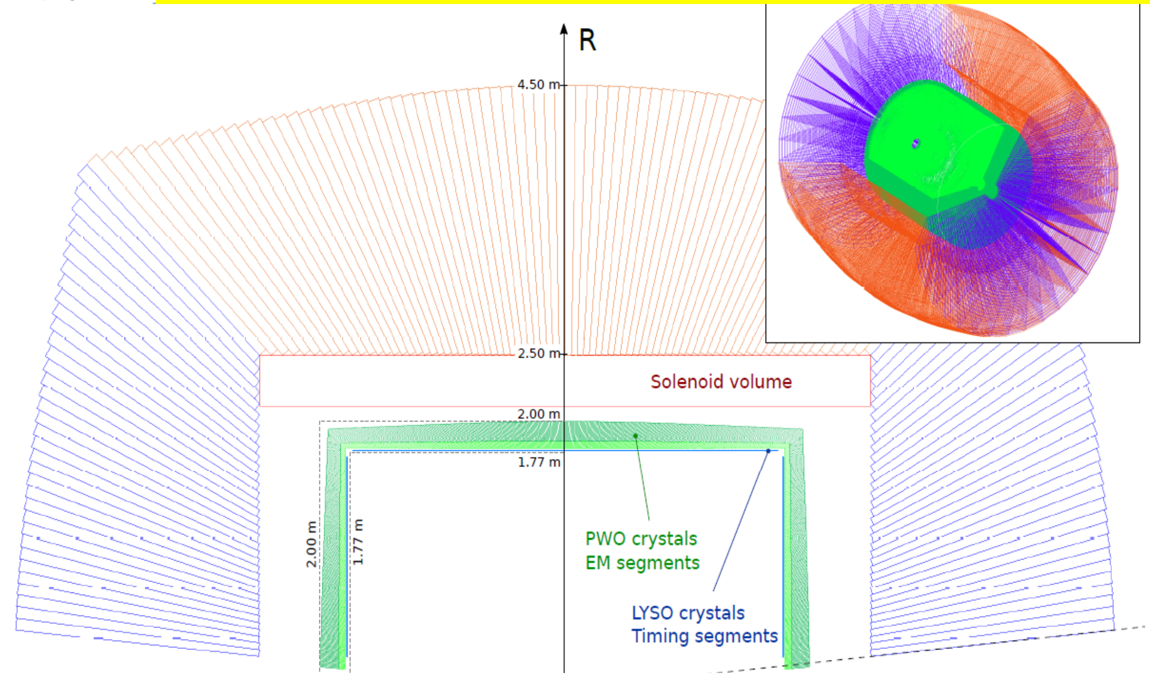








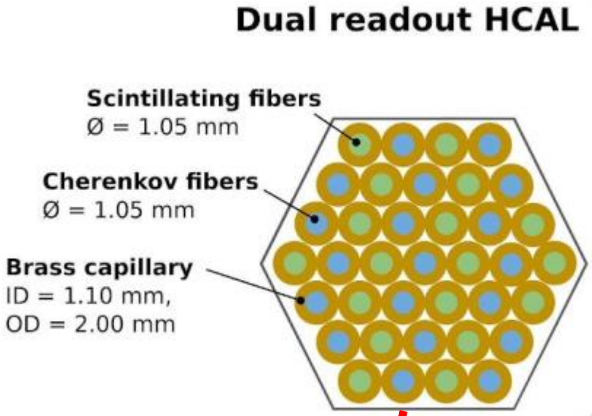
IDEA DETECTOR: CRYSTAL ECAL OPTION

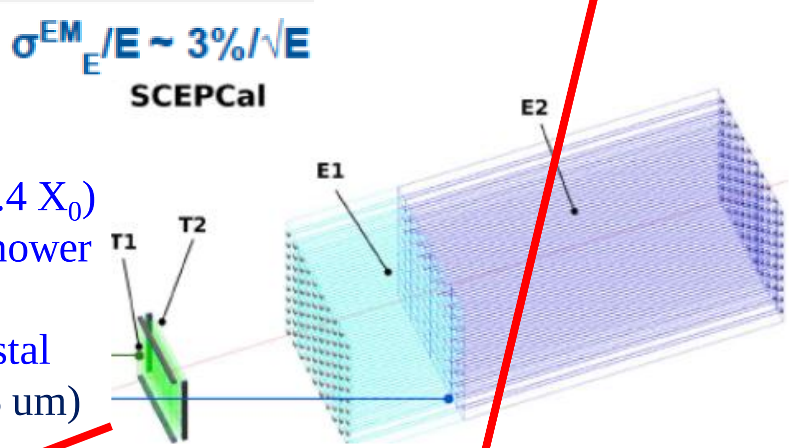


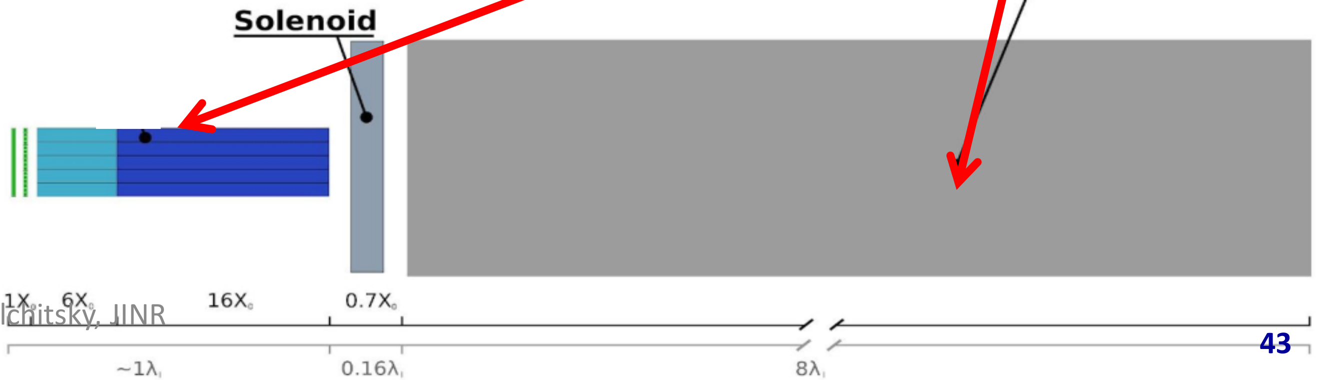
Geometry built from projective towers

- O(100M) fibres embedded in absorber in longitudinal direction
- Absorber material being investigated (copper, brass, steel)
- Tower geometries, based on chessboard or honeycomb layout of fibres, available
- High transverse granularity:: Excellent angular resolution, Lateral shape sensitivity
- No longitudinal segmentation out of the box
- For both EM and HAD calorimetry:: Option with dedicated crystal ECAL in front

- **ECAL ~20 cm PbWO4**
  - 2 layers: 6+16 X0
  - $\sigma_{EM} \approx$ **3%/√E**
  - Dual readout (DR) with filters
- Timing layer
  - LYSO 20 – 30 ps
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (10-15 um)
- Particle flow (PF) for jets
- **ECAL layer:**
  - PbWO crystals
  - front segment 5 cm (~5.4 X_0)
  - rear segment for core shower
  - (15 cm ~16.3 X_0)
  - **10x10x200 mm³** of crystal
  - **5x5 mm²** SiPMs (10-15 um)



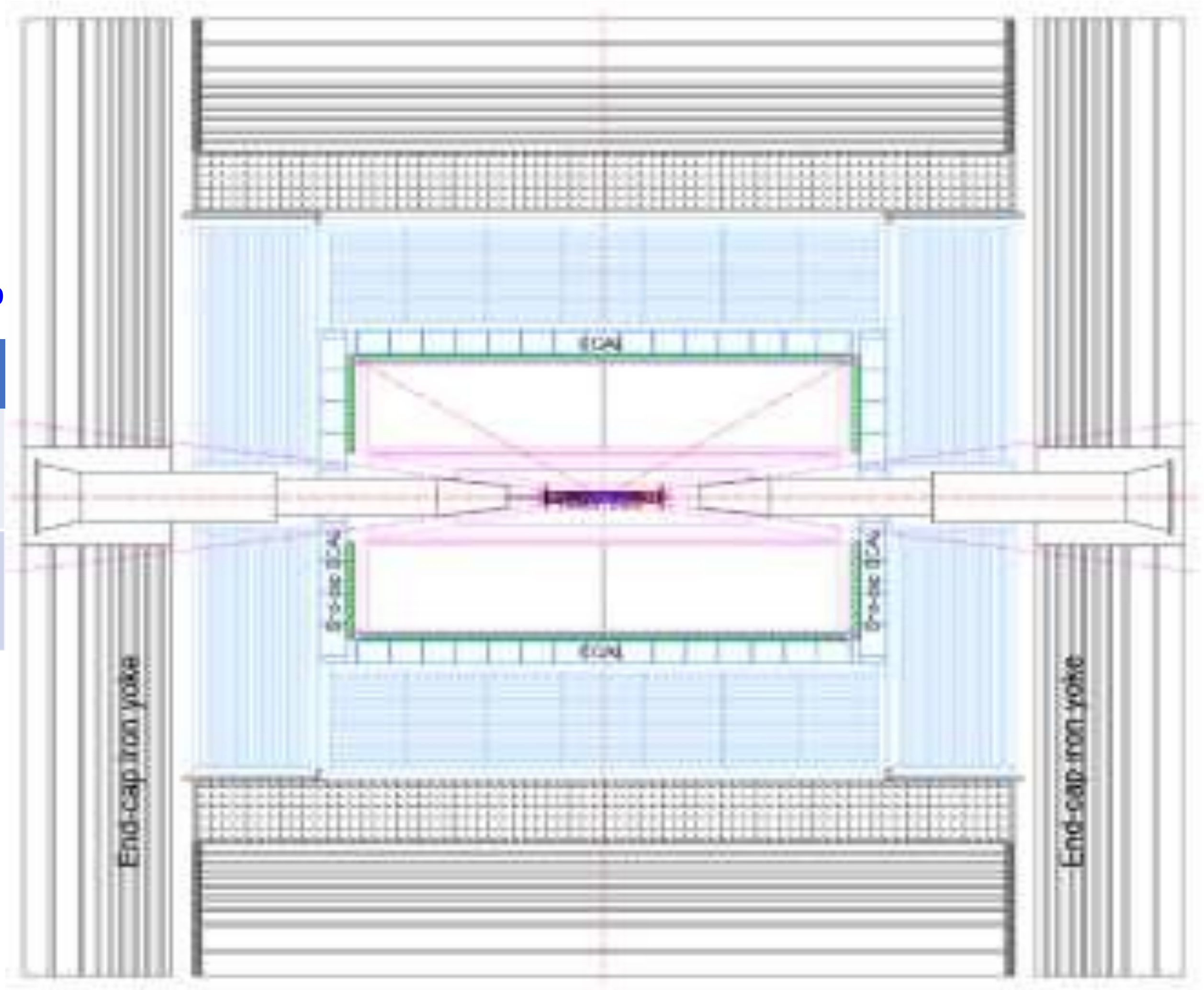


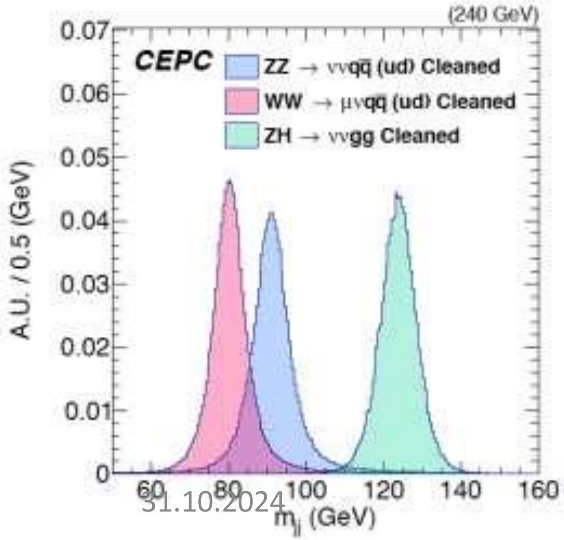


CEPC DETECTOR: IDEA OF THE "4TH CONCEPT"

- **Requirements:** boson mass resolution **(BMR ~3%)**
- **Challenges:** Support Particle flow with = High granularity & High precision
- Novel detector design based on Particle Flow Algorithm (PFA) calorimeter to improve the BMR from **4% to 3%**

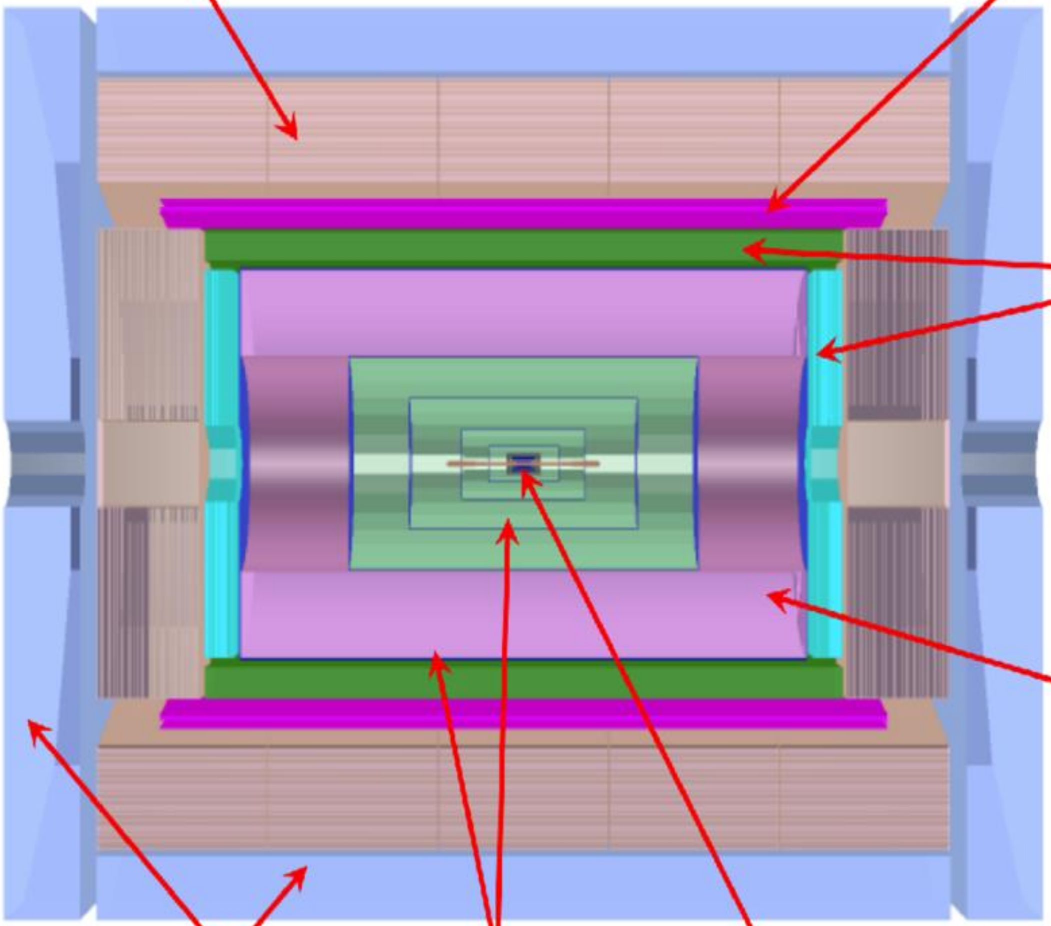
Detector	Key parameter	World level	4th concept
PFA based EM calorimeter	EM shower E resolution	~ 15-20%/√E	<3%/√E
PFA based Hadron calorimeter	Single hadron E resolution	~ 50-60%/√E	~40%/√E





- Silicon combined with gaseous chamber as the tracker and PID
- **ECAL** based on crystals with timing for 3D shower profile for PFA and EM energy
- Scintillation glass **HCAL** for better hadron sampling and energy resolution

CEPC DETECTOR: IDEA OF THE "4TH CONCEPT"



Scint Glass PFA HCAL

Advantage: Cost efficient, high density

Challenges: Light yield, transparency, massive production.

Solenoid Magnet (3T / 2T) Between HCAL & ECAL

Advantage: the HCAL absorbers act as part of the magnet return yoke.

Challenges: thin enough not to affect the jet resolution (e.g. BMR); stability.

Crystal ECAL

Advantage: better π^0/γ reconstruction.

Challenges: minimum number of readout channels; compatible with PFA calorimeter; maintain good jet resolution.

A Drift chamber that is optimized for PID

Advantage: Work at high luminosity Z runs

Challenges: sufficient PID power; thin enough not to affect the moment resolution.

- Excellent e/gamma energy resolution
- PID capability
- Better hadronic energy resolution
- Magnet in much reduced size

JINR: THE MAIN TASKS

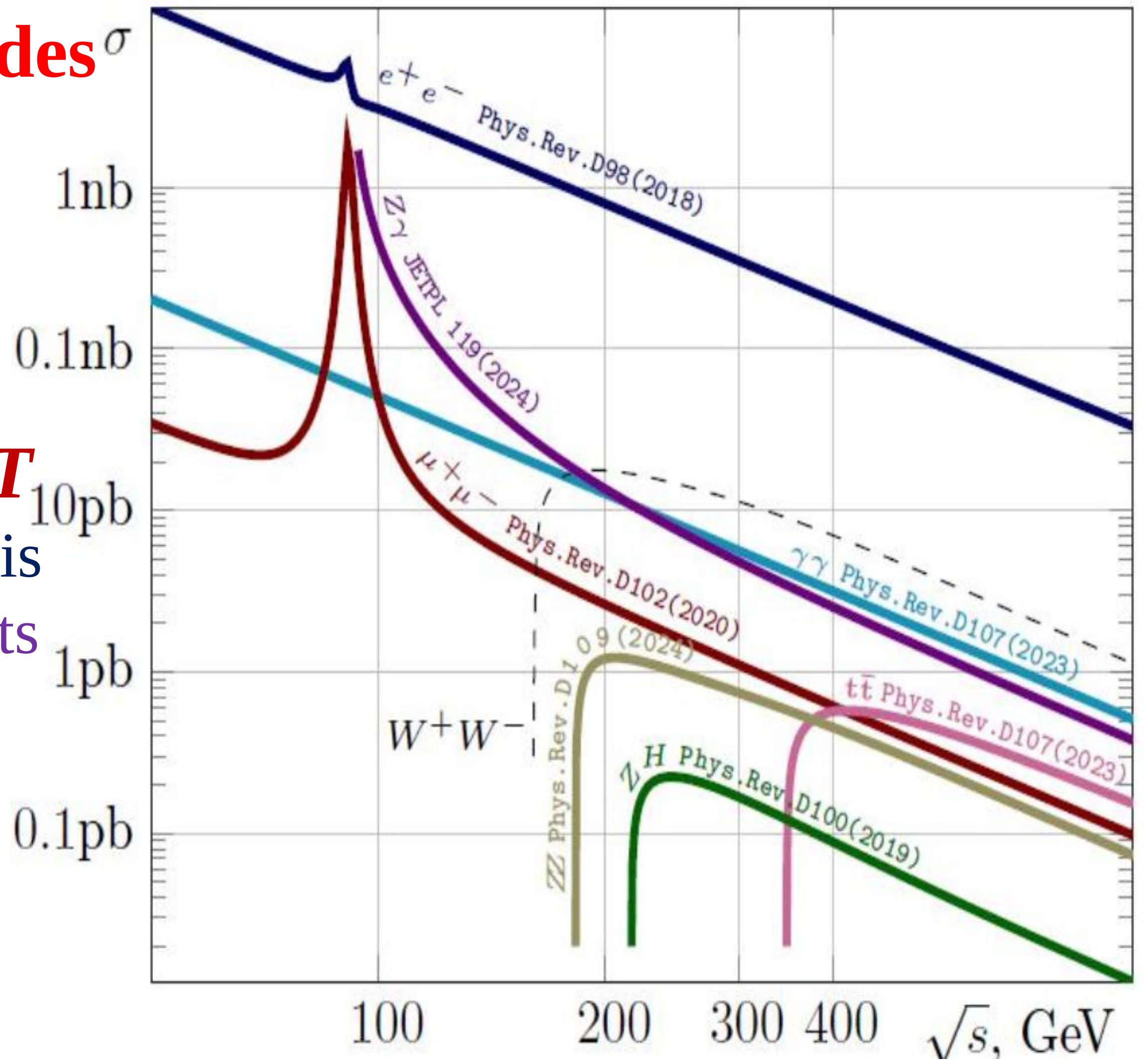
JINR Participation in Experiments at CEPS (preferable in the IDEA experiment)

- **Hardware contribution** to experiments (MHPD have good experience in experiments: ATLAS, CDF, mu2e, Comet, …): MHPD team
  1. Double Readout Hadronic calorimeter
  2. Crystal Electromagnetic calorimeter
  3. Forward calorimeter for Luminosity measurement
  4. Micro-Resistive WELL (μ-RWELL) muon system
  5. Monte Carlo simulations for detector development
- **The physics program** preparation: G.Lykasov, V.Lyubushkin, I.Boyko, Y.Kulchitsky, ...
  1. **Precision Higgs boson physics (**based on ***$5x10^6$ $e^+e^- \to ZH$ at 240-250 GeV),***
  2. **New physics BSM**,
  3. **Flavor Physics** (B physics, C physics)
- **Theoretical support** of the CEPC Physics program: A. Arbuzov, …
- **Development** of event generators (SANC, …): L.Kalinovskaya + SANC team
- **Precision calculations** of experimental observables: L.Kalinovskaya, I.Boyko, …
- **Participation** in a code development for data preparation and analysis

JINR: THEORETICAL SUPPORT (I.R. BOYKO)

JINR group has developed the computer codes

- **e+e- initial state:**
  - MC generator ***ReneSANCe***
  - MC integrator ***MCSANCee***
- **γγ initial state:** MC integrator ***SANCphot***
- **semi-analytic programs *Zfitter* and *DIZET***
  - were the main tools for LEP1/LEP2 data analysis
  - new versions prepared for the future experiments



SANC advanced features

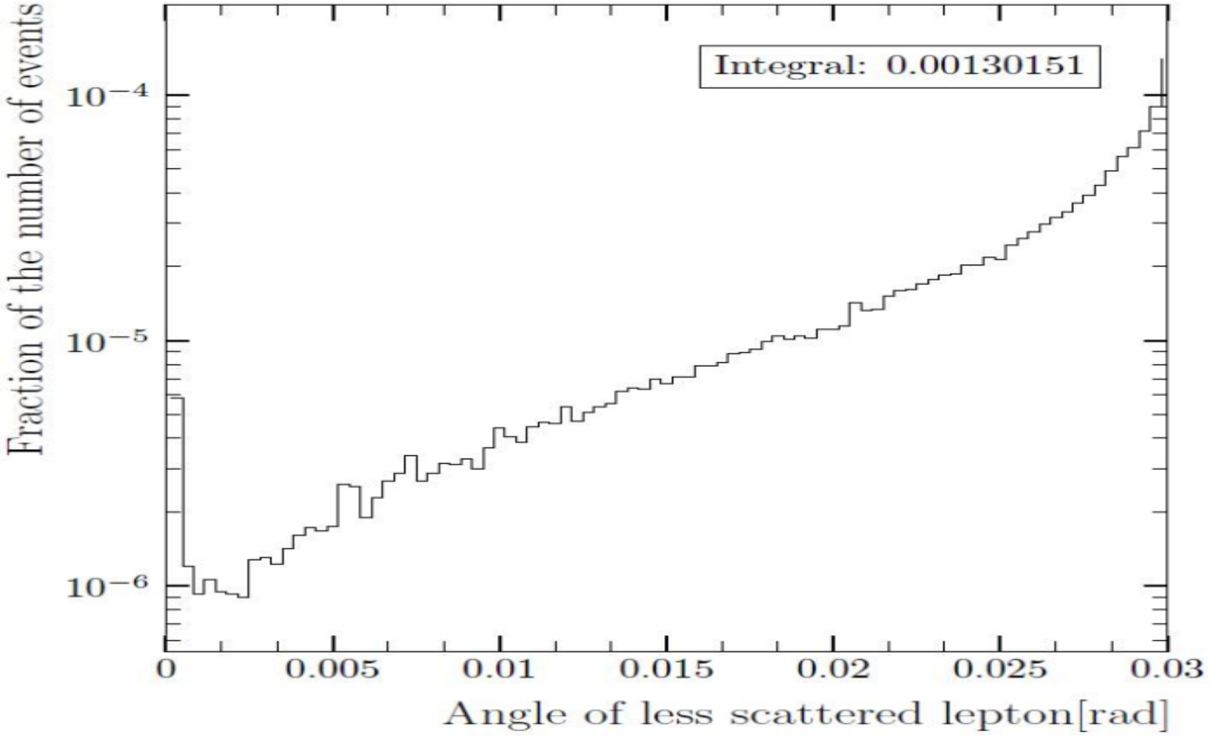
- full one-loop electroweak corrections,
- higher order corrections,
- fully massive case,
- accounting for polarization effects,
- full phase space operation.

JINR calculations of e^+e^- SM annihilation processes. The cross sections are given for polar angles 10^o-170^o in the final state.

JINR: LUMINOSITY INVESTIGATION (I.R. BOYKO)

Luminosity measurement with precision $<10^{-4}$ is necessary for e^+e^- experiments

- Traditionally, **BabaYaga and BHLUMI** have been used for theoretical estimation of luminosity,
- **ReneSANCe:** Simulation of **Bhabha** and other processes used for luminosity monitoring, taking into account initial and final state polarization in the full phase space.
- $e^+e^- \to e^+e^-$ **SABS** (Small Angle Bhabha Scattering)
- $e^+e^- \to e^+e^-$ (all angles)
- $e^+e^- \to \mu^+\mu^-$
- $e^+e^- \to \gamma\gamma$



Luminosity in ReneSANCe

- DONE: 1-loop for all processes,
- DONE: leading 2-loop contributions. They include EW corrections at $O(G_\mu^2)$ and the mixed EWxQCD at $O(G_\mu \alpha_s)$
- UNDER DEVELOPMENT: complete 2- loop for all lumi processes

The Luminosity determination for LEP experiments was re-analyzed in Chin.Phys.C48, 4, 043002 (2024)

- Beam scattering down to zero angle has been considered, thank to SANC feature of the full phase space.
- The conclusion is that by neglecting very small scattering angles, LEP experiments have underestimated their luminosity by 1.3 ppm
- The effect is comparable to the overall LEP experimental precision.

SUMMARY

- **CEPC** addressed **most pressing & critical science problems** in particle physics
  - Accelerator design & technology R&D are reaching maturity.
  - Accelerator ready for construction 3-5 years
- Reference detector **TDR** under preparation, to be completed by **2025**
- **A strong and experienced team**, backed by **IHEP and international teams**
- ✓ **Call for collaboration** and proposals once **CEPC** is approved
- Work with **government** and **funding agencies** to get support

- **Desirable areas of DLNP at JINR participation in CEPS experiments:**
- **Hardware contribution to experiments**
  - Double Readout Hadronic calorimeter
  - Crystal Electromagnetic calorimeter
  - Forward calorimeter for Luminosity measurement
  - Micro-Resistive WELL (μ-RWELL) muon system
  - Monte Carlo simulations for detector development
- Theoretical support of the CEPC Physics program
- The physics program preparation for CEPC experiments
- Development of event generators
- Precision calculations of experimental observables
- Participation in a cod development for data preparation and analysis

Thank You Very Much for Attention!

BACKUP SLIDES

CEPC SITE PREPARATIONS (3 CANDIDATES IN TDR)

COOPERATION JINR WITH CHINA INSTITUTES

3.07.24 в Шанхае: 2 заседание **Совместного координационного комитета** по сотрудничеству ОИЯИ и Китая

ОИЯИ имеет партнерские отношения с >40 китайскими институтами и университетами

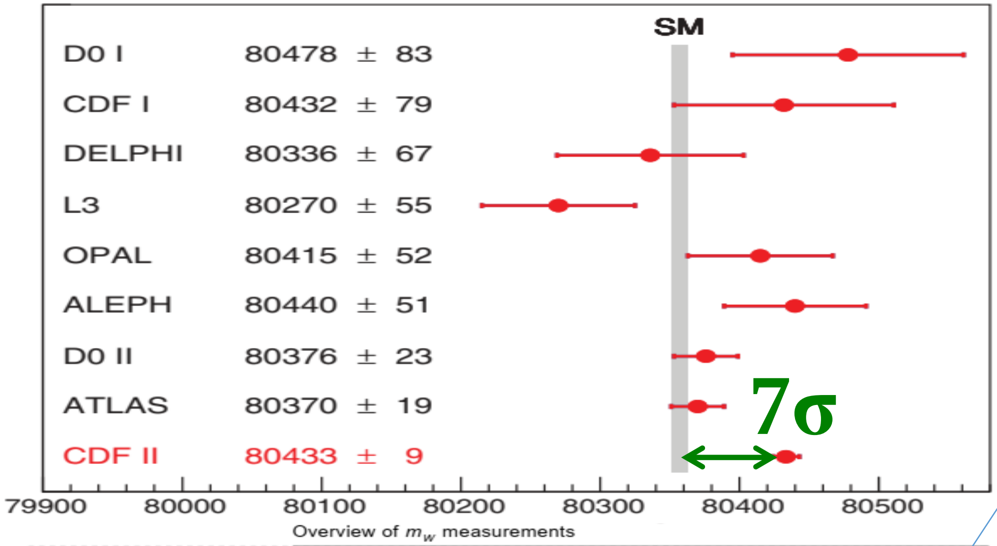
- **Комитет принял решение о начале реализации в 2024 году 8 совместных проектов:**
  1. теоретическую физику,
  2. разработку технологий для сверхбольшого глубоководного нейтринного телескопа,
  3. использование нейтронных пучков для решения фундаментальных и прикладных задач,
  4. синтез и изучение свойств сверхтяжелых элементов,
  5. разработку ускорительных технологий,
  6. создание монолитных кремниевых детекторов,
  7. сотрудничество в рамках подготавливаемого в КНР нейтринного эксперимента **JUNO**.
- Поддержка совместной программы академических обменов и проведения научных мероприятий.
- Использование платформы **DIRAC** Interware для построения распределенных вычислительных систем, в том числе с применением облачных ресурсов, позволяет обрабатывать данные **NICA, JUNO и BESIII**.
- Важным направлением сотрудничества ОИЯИ и КНР может стать радиобиология и медицина.
- Подчеркнут **прогресс** в сотрудничестве: стороны ведут **совместную** подготовку **экспериментов MPD и SPD на NICA,** продолжают сотрудничество в проектах **BESIII и JUNO**, в области физики тяжелых ионов, нейтронной физики, разработки медицинских ускорителей, теоретических исследований и др.

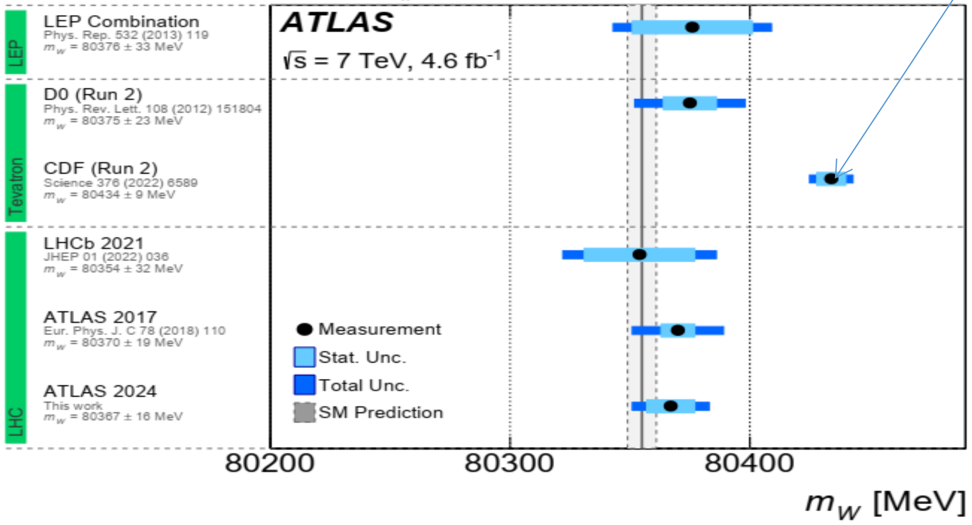
«Мы договорились о том, что в перспективе перечень направлений для совместных проектов может быть расширен, а число проектов может быть увеличено по мере развития сотрудничества и оценки реализации уже одобренных проектов», Директор ОИЯИ.

Measurement of the W boson mass: 7σ from SM prediction

PoS ICHEP2022 (2022) 898

CDF II Collaboration, High-precision measurement of the W boson mass with the CDF detector. ***PoS* ICHEP2022 (2022) 898**





The ATLAS Collaboration has reported a measurement

M_W=80370±7 (stat)±11(syst)±1(mod. syst)=80370±19 MeV

M_W=80366.5 ±9.8 (stat) ±12.5 (syst)=80366.5±15.9 MeV **2403.15085 [hep-ex]**

- **CDF II** measure the W boson mass, M_W, using data corresponding to **8.8 fb^{-1}** collected in proton-antiproton collisions at a **1.96 TeV** with the CDF II detector at the Fermilab Tevatron collider. A sample of approximately 4x10^6 **W** boson is used to obtain **M_W=80433.5±6.4(stat) ±6.9(syst) =80433.5±9.4 MeV.** The ***W*** bosons are identified using their decays to ***eν*** & ***μν*** and the mass is measured by fitting template distributions of transverse momentum and mass: $m_T = \sqrt{2p_T^{\ell} p_T^{\nu}(1 - \cos\Delta\phi)}$
- A comparison with the **SM expectation** of **M_W=80357±6 MeV,** treating the quoted uncertainties as independent, yields a difference with a significance of **7σ.** The suggests are:
  - **the improvements to the SM calculation or**
  - **of extensions to the SM**
- SM result includes the published estimates of the uncertainty (4 MeV) due to missing higher-order quantum corrections and the uncertainty (4 MeV) from other global measurements used as input to the calculation

ATLAS Collaboration, Measurement of the *W*-boson mass in pp collisions at √s =7 TeV with the ATLAS detector, ***Eur. Phys. J. C* 78 (2018) 2, 110, *Eur. Phys. J. C* 78 (2018) 11, 898 (erratum), arXiv:1701.07240; e-Print: 2403.15085 [hep-ex]**

A measurement of the mass of the W boson is presented based on proton–proton collision data recorded in 2011 at a **7 TeV** with the ATLAS detector at the LHC, and corresponding to **4.6 fb^{-1}** of integrated luminosity. The selected data sample consists of 7.8×10^6 candidates in the ***W→μν*** channel and 5.9×10^6 candidates in the ***W→eν*** channel.

ATLAS/CMS: Run-2 at 13 TeV **is 139/137 fb^{-1}**

FCC-EE MAIN MACHINE PARAMETERS

Parameter	4 years 5 x 10^{12} Z LEP x 10^5	Z	2 years > 10^8 WW LEP x 10^4	WW	3 years 2 x 10^6 H	H (ZH)	5 years 2 x 10^6 tt pairs	ttbar
beam energy [GeV]		45.6		80		120		182.5
beam current [mA]		1270		137		26.7		4.9
number bunches/beam		11200		1780		440		60
bunch intensity [10^{11}]		2.14		1.45		1.15		1.55
SR energy loss / turn [GeV]		0.0394		0.374		1.89		10.4
total RF voltage 400/800 MHz [GV]		0.120/0		1.0/0		2.1/0		2.1/9.4
long. damping time [turns]		1158		215		64		18
horizontal beta* [m]		0.11		0.2		0.24		1.0
vertical beta* [mm]		0.7		1.0		1.0		1.6
horizontal geometric emittance [nm]		0.71		2.17		0.71		1.59
vertical geom. emittance [pm]		1.9		2.2		1.4		1.6
vertical rms IP spot size [nm]		36		47		40		51
beam-beam parameter x_x / x_y		0.002/0.0973		0.013/0.128		0.010/0.088		0.073/0.134
rms bunch length with SR / BS [mm]		5.6 / 15.5		3.5 / 5.4		3.4 / 4.7		1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]		140		20		≥5.0		1.25
total integrated luminosity / IP / year [ab^{-1}/yr]		17		2.4		0.6		0.15
beam lifetime rad Bhabha + BS [min]		15		12		12		11

CEPC and other Accelerator Projects in China

Project name	Machine type	Location	Cost (B RMB)	Completion time
CEPC	Higgs factory Upto ttar energy	Led by IHEP, China	**36.4 (where accelerator 19)**	Around 2035 (starting time around 2027)
BEPCII-U	e+e-collider 2.8GeV/beam	IHEP (Beijing)	**0.15**	2025
HEPS	4th generation light source of 6GeV	IHEP (Huanrou)	**5**	2025
SAPS	4th generation light source of 3.5GeV	IHEP (Dongguan)	**3**	2031 (in R&D, to be approved)
HALF	4th generation light source of 2.2GeV	USTC (Hefei)	**2.8**	2028
SHINE	Hard XFEL of 8GeV	Shanghai-Tech Univ., SARI and SIOM of CAS (Shanghai)	**10**	2027
S3XFEL	S3XFEL of 2.5GeV	Shenzhen IASF	**11.4**	2031
DALS	FEL of 1GeV	Dalian DICP	-	(in R&D, to be approved,)
HIAF	High Intensity heavy ion Accelerator Facility	IMP, Huizhou	**2.8**	2025
CIADS	Nuclear waste transmutation	IMP, Huizhou	**4**	2027
CSNS-II	Spallation Neutron source proton injector of 300MeV	IHEP, Dongguan	**2.9**	2029

- **The total cost of the *accelerator projects under construction* is 39B RMB (5.5 M$);**
- **CEPC cost is 36.4B RMB (5.1 M$)**

LEPTON COLLIDERS

Location	Name (type[a])	Beam Energy[b] (GeV)	Luminosity[b] ($cm^{-2}s^{-1}$)	Operation Period
Stanford/SLAC, USA	CBX[c] (e^-e^- DR)	0.5	2×10^{28}	1963-1968
	SPEAR (SR)	4	1.2×10^{31}	1972-1988
	PEP (SR)	15	6×10^{31}	1980-1990
	SLC (LC)	49	2.5×10^{30}	1989-1998
	PEP-II (DR)	9 (e^-) 3.1 (e^+)	1.2×10^{34}	1998-2008
Frascati, Italy	AdA (SR)	0.25	5×10^{25} [d]	1961-1964
	ADONE (SR)	1.5	6×10^{29}	1969-1993
	DAΦNE (SR)	0.51	2.4×10^{32} 4.5×10^{32} [e]	1999-present
BINP, Russia	VEP-1 (e^-e^- DR)	0.16	5×10^{27}	1964-1968
	VEPP-2 (SR)	0.67	4×10^{28}	1966-1970
	VEPP-2M (SR)	0.7	5×10^{30} (@0.511)	1974-2000
	VEPP-3 (SR)	1.55	2×10^{27}	1974-1975
	VEPP-4M (SR)	6	2×10^{31}	1984-present
	VEPP-2000 (SR)	1	5×10^{31}	2010-present
Cambridge, USA	CEA Bypass (SR)	3	8×10^{27}	1971-1973
Orsay, France	ACO (SR)	0.54	1×10^{29}	1965-1975
	DCI (DR)	1.8	1.7×10^{30}	1977-1985
DESY, Germany	DORIS (SR)	5.6	3.3×10^{31}	1973-1993
	PETRA (SR)	23.4	2.4×10^{31} (@17.5)	1978-1986
CERN, Europe	LEP (SR)	104.5	1×10^{32}	1989-2000
Cornell, USA	CESR (SR)	5.5	1.3×10^{33}	1979-2008
KEK, Japan	TRISTAN (SR)	32	4.1×10^{31}	1986-1995
	KEKB (DR)	8 (e^-) 3.5 (e^+)	2.1×10^{34}	1998-2010
	SuperKEKB (DR)	7 (e^-) 4 (e^+)	8×10^{35} [f]	2016-present
IHEP, China	BEPC (SR)	2.4	1×10^{31} (@1.84)	1988-2004
	BEPC II (DR)	2.47	1×10^{33} (@1.89)	2009-present

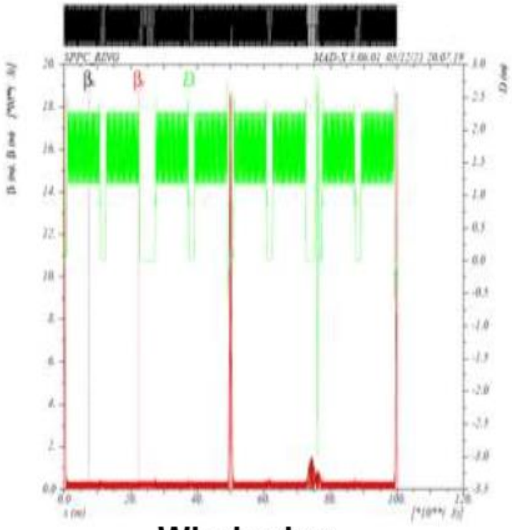
HADRON COLLIDERS

Location	Name (type[a])	Beam Energy[b] (GeV)	Luminosity[b] ($cm^{-2}s^{-1}$)	Operation Period
CERN, Europe	ISR (pp DR)	31.4	1.4×10^{32}	1971-1984
	$Sp\bar{p}S$ ($p\bar{p}$ SR)	315	6×10^{30}	1981-1991
	LHC (pp, ii, pi DR)	6800 (p) 2510/n (Pb) [c] 6500 (p) 2560/n (Pb) [c]	2.1×10^{34} 6.1×10^{27} 9×10^{29}	2009-present
Fermilab, USA	Tevatron ($p\bar{p}$ SR)	980	4.3×10^{32}	1987-2011
DESY, Germany	HERA (ep DR)	27.5 (e^-) 920 (p)	5.3×10^{31}	1992-2007
Brookhaven, USA	RHIC (pp, ii DR)	250 (p) 100/n (Au) [c]	2.5×10^{32} 1.6×10^{28}	2000-present
	EIC (ep, ei DR) [d]	18 (e^-) 275 (p) 18 (e^-) 110/n (Au) [c]	1×10^{34} 3×10^{30}	(under construction)

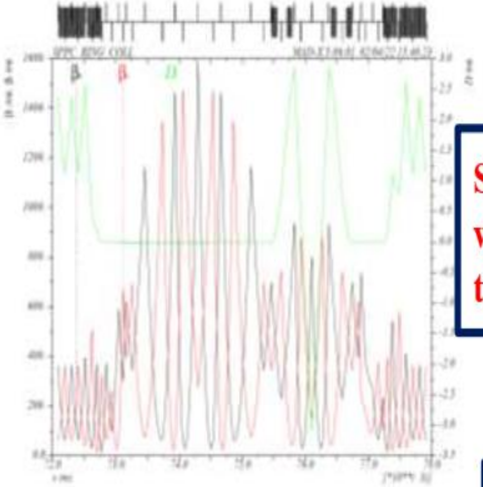
SPPC COLLIDER PARAMETERS

Main parameters		
Circumference	100	km
Beam energy	62.5	TeV
Lorentz gamma	66631	
Dipole field	20.00	T
Dipole curvature radius	10415.4	m
Arc filling factor	0.780	
Total dipole magnet length	65442.0	m
Arc length	83900	m
Total straight section length	16100	m
Energy gain factor in collider rings	19.53	
Injection energy	3.20	TeV
Number of IPs	2	
Revolution frequency	3.00	kHz
Revolution period	333.3	μs
Physics performance and beam parameters		
Initial luminosity per IP	4.3E+34	$cm^{-2}s^{-1}$
Beta function at initial collision	0.5	m
Circulating beam current	0.19	A
Nominal beam-beam tune shift limit pe	0.015	
Bunch separation	25	ns
Bunch filling factor	0.756	
Number of bunches	10080	
Bunch population	4.0E+10	
Accumulated particles per beam	4.0E+14	

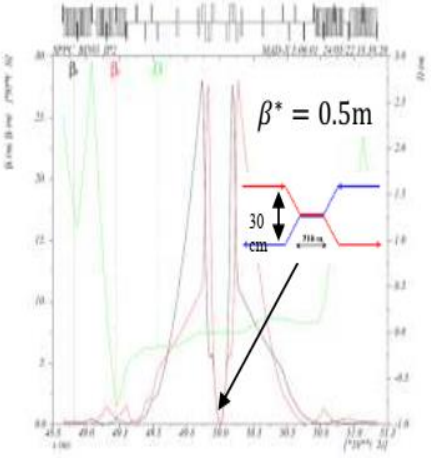
Lattice of SPPC



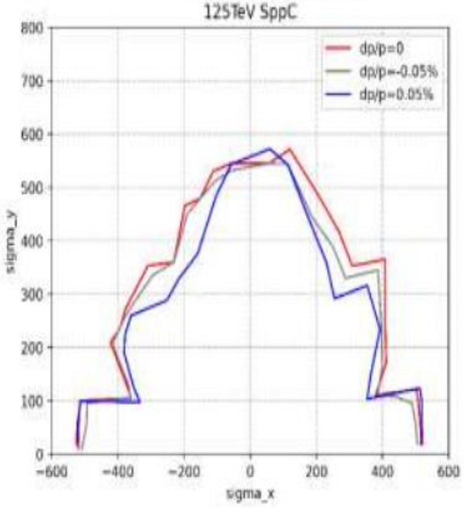
Whole ring



Collimation



IP



Dynamic Aperture

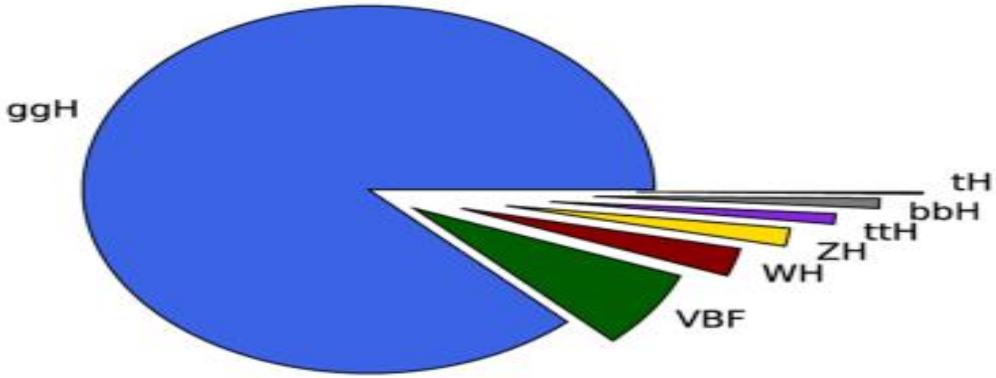
SppC is compatible with CEPC in the same tunnel

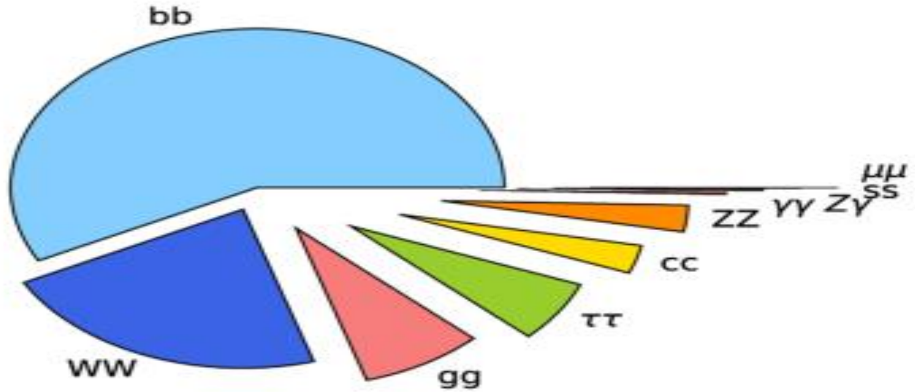
Ecm=125TeV with dipole field of 20T

The SM Higgs production x-sections and branching

Production mode	Cross section (pb)
ggH	48.31 ± 2.44
VBF	3.771 ± 0.807
WH	1.359 ± 0.028
ZH	0.877 ± 0.036
ttH	0.503 ± 0.035
bbH	0.482 ± 0.097
tH	0.092 ± 0.008

Decay channel	Branching fraction (%)
bb	57.63 ± 0.70
WW	22.00 ± 0.33
gg	8.15 ± 0.42
ττ	6.21 ± 0.09
cc	2.86 ± 0.09
ZZ	2.71 ± 0.04
γγ	0.227 ± 0.005
Zγ	0.157 ± 0.009
ss	0.025 ± 0.001
μμ	0.0216 ± 0.0004

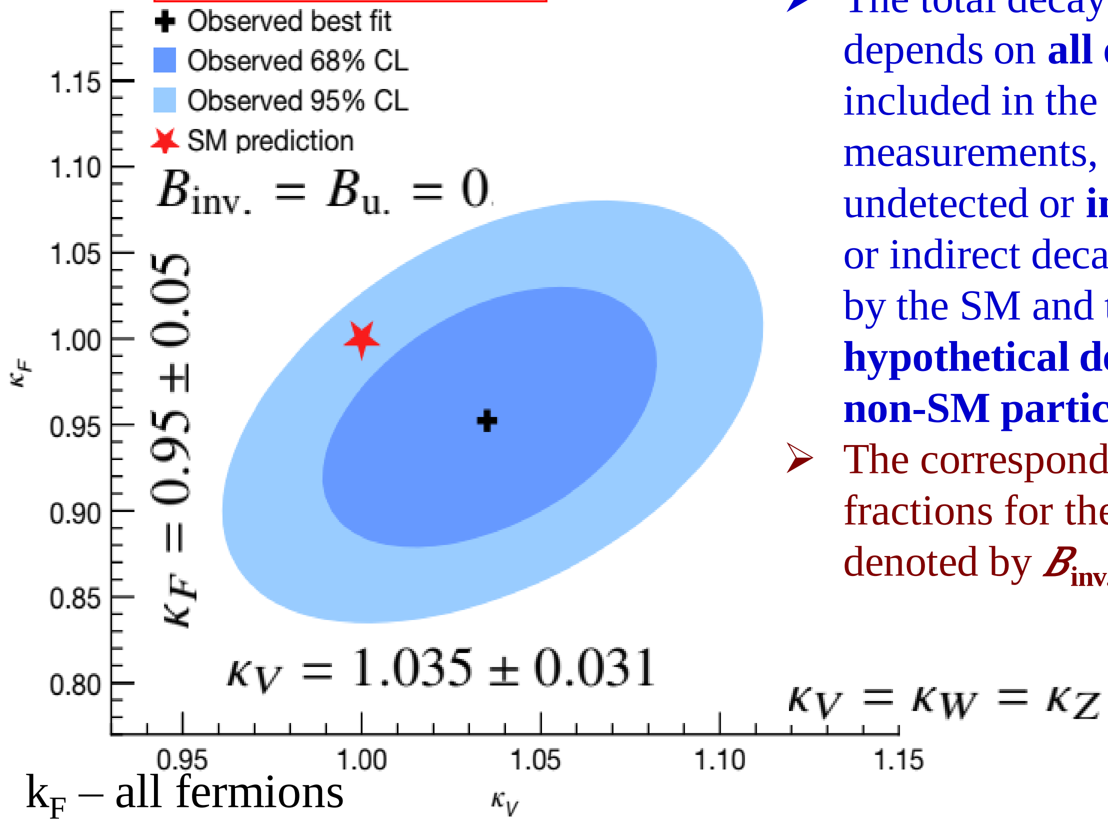




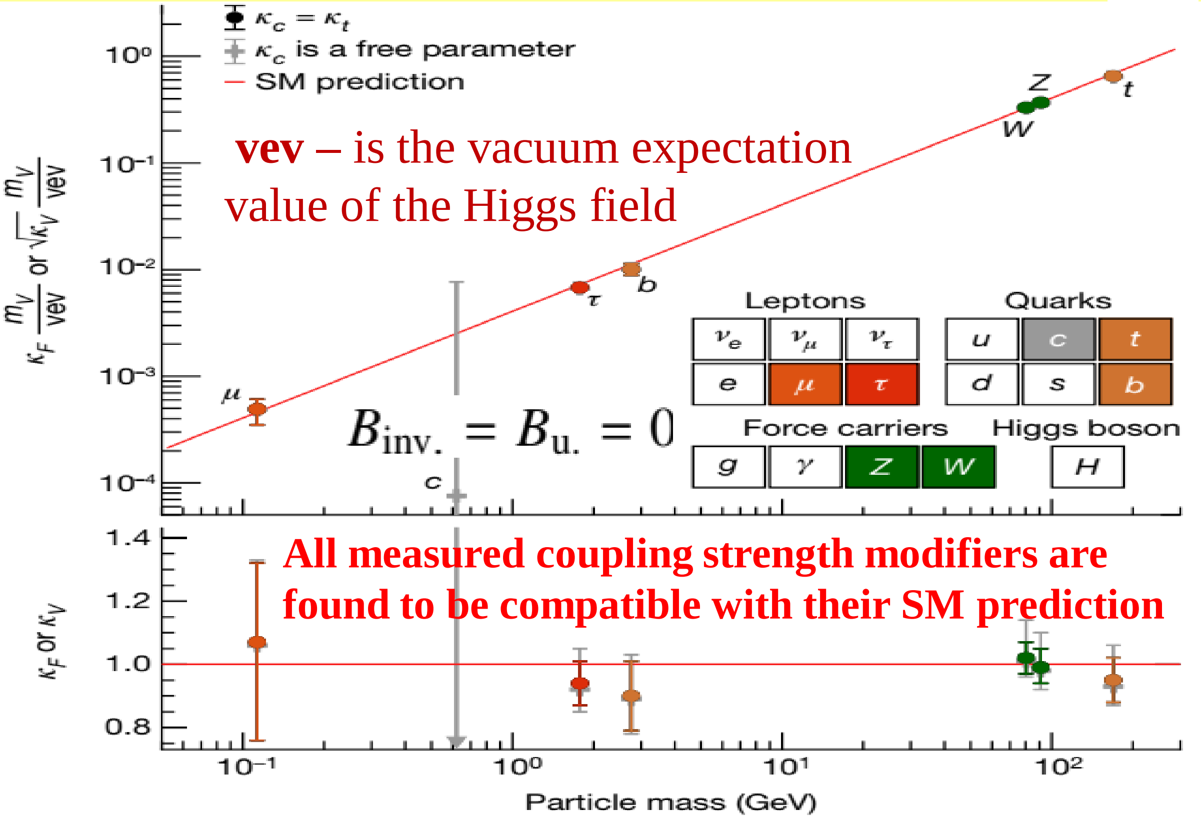
Theoretical cross-sections for each production mode and branching fractions for the decay channels, at 13 TeV for m_H=125.38 GeV

HIGGS BOSON COUPLING STRENGTH

the SM prediction of $\kappa_V = \kappa_F = 1$



- The total decay width depends on **all decay modes** included in the present measurements, currently undetected or **invisible**, direct or indirect decays predicted by the SM and the **hypothetical decays into non-SM particles.**
- The corresponding branching fractions for the two are denoted by $B_{inv.}$ **and** B_u



vev – is the vacuum expectation value of the Higgs field

All measured coupling strength modifiers are found to be compatible with their SM prediction

k_F – all fermions

Negative log-likelihood contours corresponding to 68% and 95% CL in the (κ_V, κ_F) plane. The p-value for compatibility of the combined measurement and the SM prediction is 14%

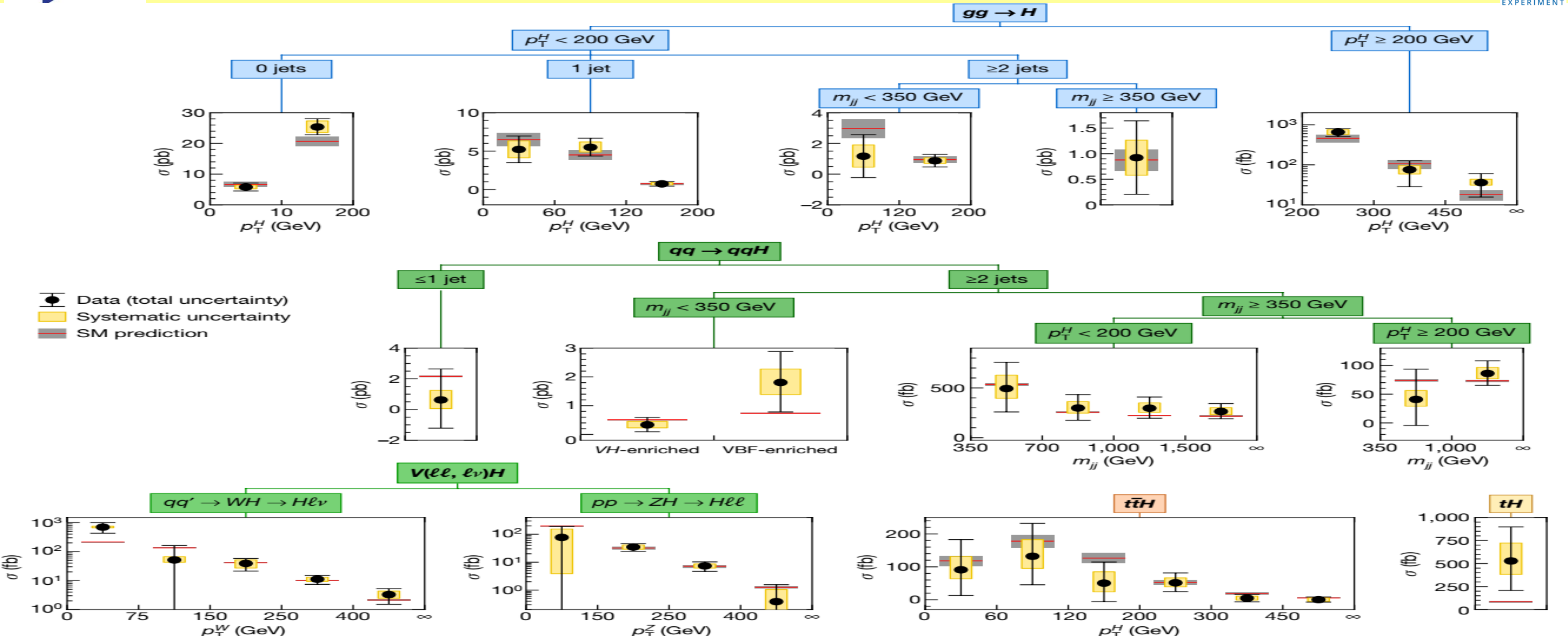
A coupling strength modifier $\boldsymbol{\kappa_p}$ for a production or decay process via the coupling to a given particle $\boldsymbol{p}$ is defined as

$$\kappa_p^2 = \sigma_p/\sigma_p^{SM} \qquad \kappa_p^2 = \Gamma_p/\Gamma_p^{SM}$$

$\boldsymbol{\Gamma_p}$ is the partial decay width into a pair of particles $\boldsymbol{p}$.

Reduced Higgs boson coupling strength modifiers and their uncertainties. They are defined as $\boldsymbol{\kappa_F m_F}$**/vev** for fermions ($\boldsymbol{F = t, b, \tau, \mu}$) and $\sqrt{\boldsymbol{\kappa_V}}\boldsymbol{m_V}$ **/vev** for vector bosons as a function of their masses $\boldsymbol{m_F}$ and $\boldsymbol{m_V}$. Two fit scenarios with $\kappa_c = \kappa_t$ (coloured circle markers), or κ_c left free-floating in the fit (grey cross markers) are shown. Loop-induced processes are assumed to have the SM structure, and Higgs boson decays to non-SM particles are not allowed. The lower panel shows the values of the coupling strength modifiers.

THE RESULTS OF THE SIMULTANEOUS MEASUREMENT IN 36 REGIONS

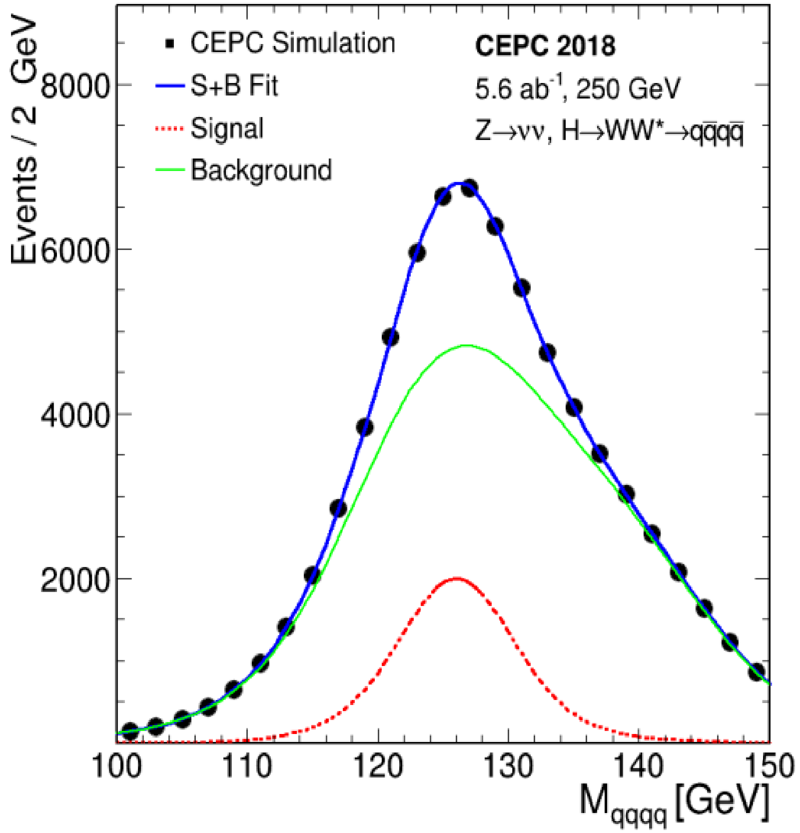


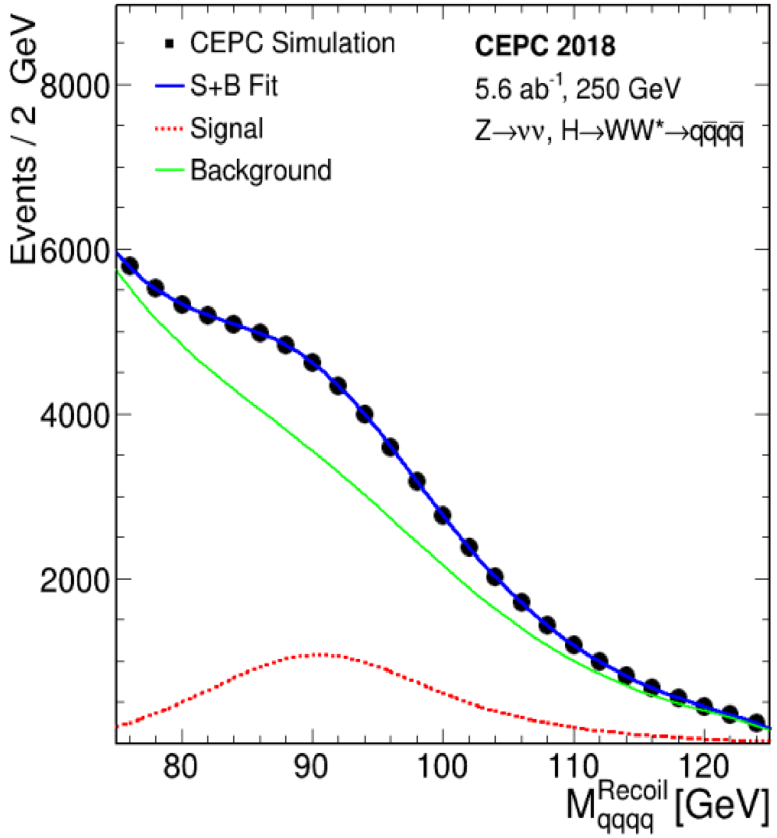
Observed and predicted Higgs boson production cross-sections in different kinematic regions. The *p* value for compatibility of the combined measurement and the SM prediction is 94%. Kinematic regions are defined separately for each production process, based on the jet multiplicity, the transverse momentum of the Higgs (**p_T^H**) and vector bosons (**p_T^W** and **p_T^Z**) and the two-jet invariant mass (m_{jj}). The ‘*VH*-enriched’ and ‘VBF-enriched’ regions with the respective requirements of **m_{jj} ∈ [60, 120) GeV** and **m_{jj} ∉ [60, 120) GeV** are enhanced in signal events from *VH* and VBF productions.

EW PHASE TRANSITIONS

- At least **two Cosmological phase transitions** are very probable to have happened since the beginning of the Universe, one of them being the **electroweak phase transition** responsible for the **breaking of the EW symmetry.**
- It is possible that the **EW phase transition** could have caused **the observed baryon asymmetry** of the Universe and therefore provide **an explanation for** the **baryon asymmetry problem.**
- **It could also have generated observable gravitational waves.**
- Both of these possibilities however hinge on the fact that the **EW phase transition** had been a **first-order phase transition**, which it is not according to the standard model.
- The SM predicts a crossover transition.

HIGGS PHYSICS: ZH PRODUCTION WITH $Z\to\nu\bar{\nu}$ & $H\to WW^*\to qq\bar{q}\bar{q}$





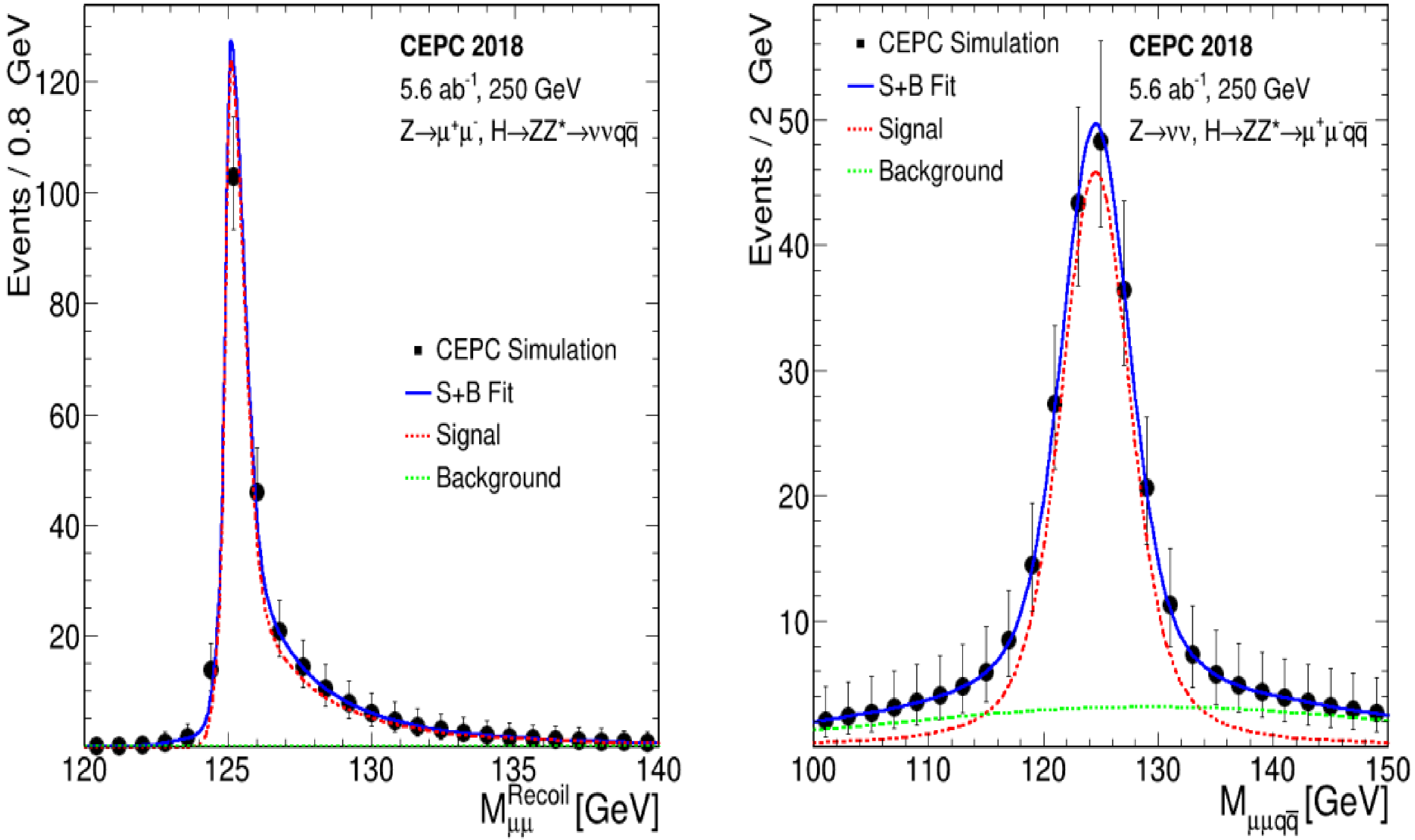
ZH final state		Precision
$Z\to e^+e^-$	$H\to WW^*\to \ell\nu\ell'\nu, \ell\nu q\bar{q}$	2.6%
$Z\to \mu^+\mu^-$	$H\to WW^*\to \ell\nu\ell'\nu, \ell\nu q\bar{q}$	2.4%
$Z\to \nu\bar{\nu}$	$H\to WW^*\to \ell\nu q\bar{q}, q\bar{q}q\bar{q}$	1.5%
$Z\to q\bar{q}$	$H\to WW^*\to q\bar{q}q\bar{q}$	1.7%
Combination		0.9%

Expected relative precision on the **σ(ZH)×BR(H→WW*)** measurement from a CEPC dataset of 5.6 ab^{-1}

ZH production with $Z\to\nu\bar{\nu}$ and $H\to WW^*\to qq\bar{q}\bar{q}$: distributions of the visible mass and the missing mass of selected events. The markers and their uncertainties represent the expected number of events in a CEPC dataset of 5.6 ab^{-1}, whereas the solid blue curves are the fit results. The dashed curves are the signal and background components. Contributions from other decays of the Higgs boson are included in the background.

- The combination of these decay final states leads to a precision of **0.9%.**
  - This is likely a conservative estimate as many of the final states of the **H →WW*** decay remain to be explored. Including these missing final states will no doubt improve the precision.

HIGGS PHYSICS: ZH PRODUCTION WITH H→ZZ*



ZH production with H→ZZ*: the recoil mass distribution of the **μ+μ−** system for **$Z\to\mu^+\mu^-$; $H\to ZZ^*\to\nu\nu q\bar{q}$;** the invariant mass distribution of the **$\mu^+\mu^-q\bar{q}$** system for **$Z\to\nu\nu$; $H\to ZZ^*\to\mu^+\mu^-q\bar{q}$.** The markers and their uncertainties represent the expected number of events in a CEPC dataset of 5.6 ab^{-1}, whereas the solid blue curves are the fit results. The dashed curves are the signal and background components. Contributions from other decays of the Higgs boson are included in the background.

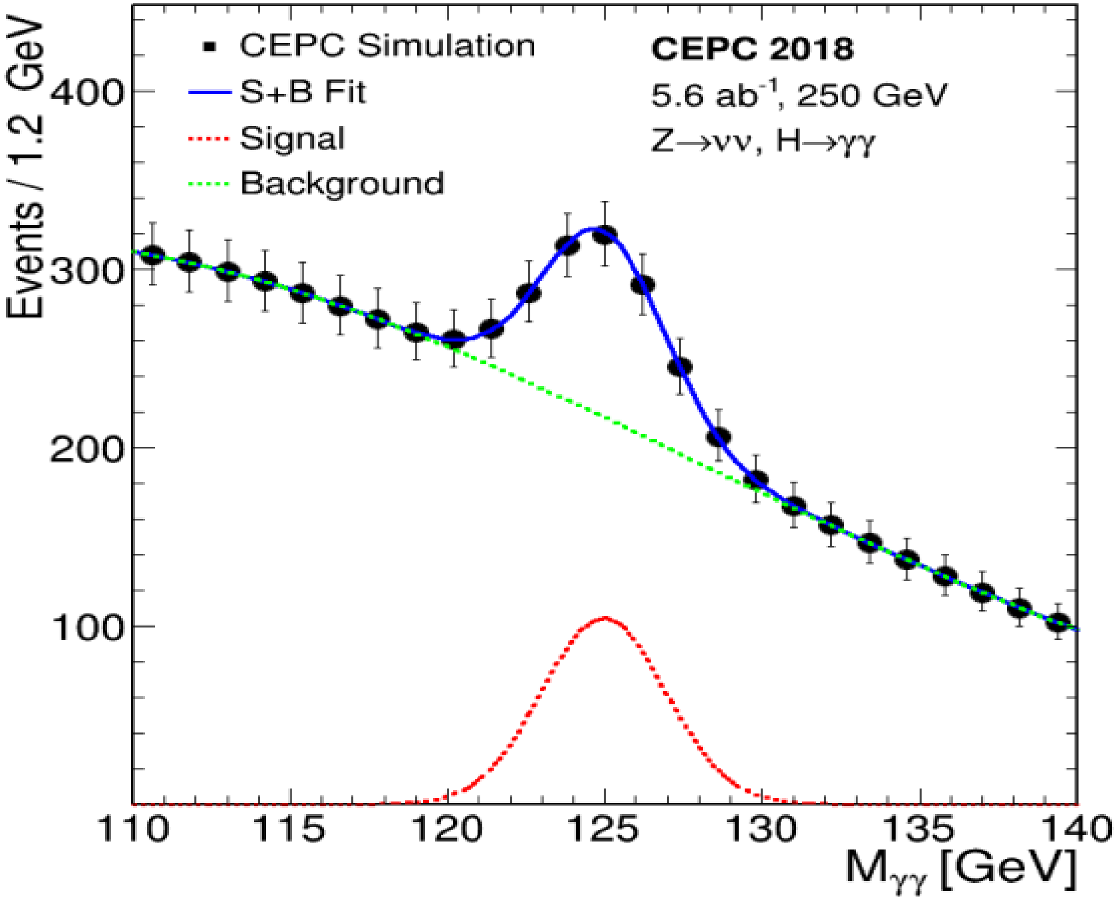
ZH final state		Precision
$Z\to\mu^+\mu^-$	$H\to ZZ^*\to\nu\bar{\nu}q\bar{q}$	7.2%
$Z\to\nu\bar{\nu}$	$H\to ZZ^*\to\ell^+\ell^-q\bar{q}$	7.9%
Combination		4.9%

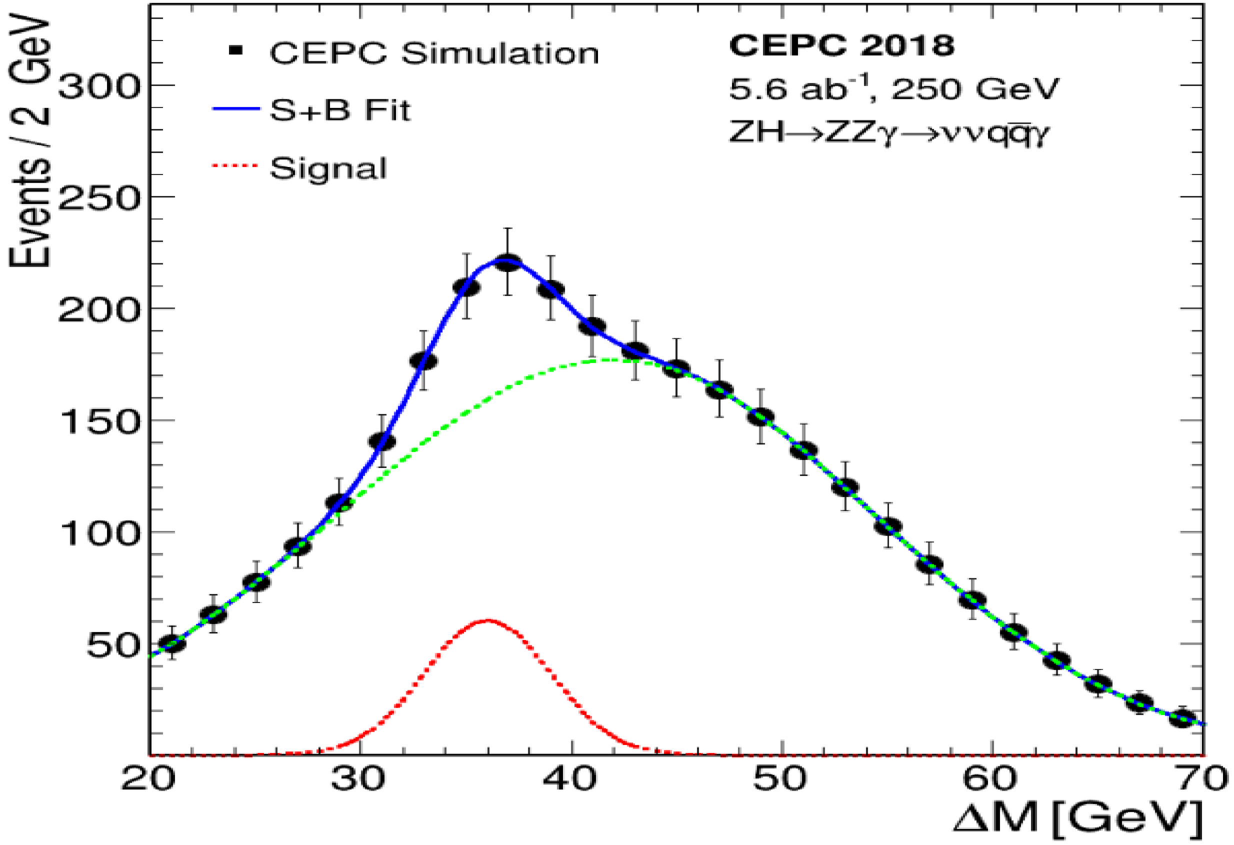
Expected relative precision on the σ(ZH)× BR(H→ZZ*) measurement from a CEPC at 5.6 ab^{-1}

The combination of these final states results in a precision of about 4.9%.

The sensitivity can be significantly improved considering that many final states are not included in the current study. In particular, the final state of **$Z\to q\bar{q}$, $H\to ZZ^*\to qq\bar{q}\bar{q}$** which accounts for a third of all **ZH→ZZZ*** decay is not studied. Moreover, there are further potential improvements by using multivariate techniques. The combination of these decay final states leads to a precision of 0.9%.

HIGGS PHYSICS: ZH PRODUCTION WITH $H\to\gamma\gamma$





ZH production with $H\to\gamma\gamma$: the diphoton invariant mass distribution for the **$Z\to\nu\bar{\nu}$** decay**.** The markers and their uncertainties represent the expected number of events in a CEPC dataset of 5.6 ab^{-1}, whereas the solid blue curves are the fit results. The dashed curves are the signal and background components. A relative precision of **6.2%** on $\sigma(ZH)\times BR(H\to\gamma\gamma)$ can be achieved.

The distribution of the mass difference **ΔM ($M_{q\bar{q}\gamma} - M_{q\bar{q}}$ & $M_{\nu\bar{\nu}\gamma} - M_{\nu\bar{\nu}}$)** of the selected **$e^+e^-\to ZH\to Z Z\gamma\to\nu\bar{\nu}q\bar{q}\gamma$** candidates expected in a dataset with an integrated luminosity of 5.6 ab^{-1}. The signal distribution shown is for the correct pairings of the Higgs boson decays.

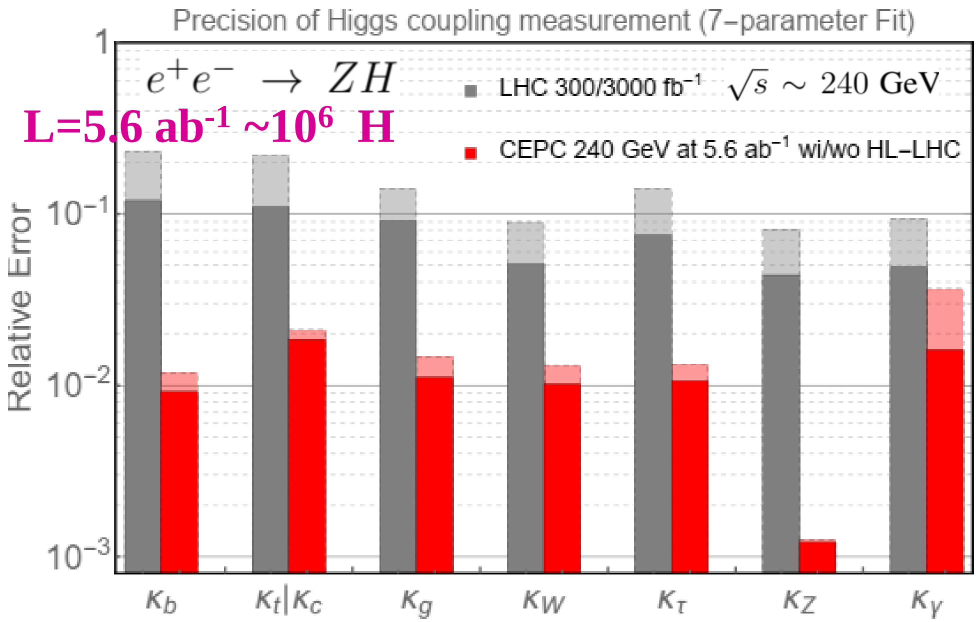
Similar to the **$H\to\gamma\gamma$** decay, the **$H\to Z\gamma$** decay in the SM is mediated by W-boson and top-quark loops and has a branching ratio of **0.154%**.

There is not a complete understanding of the nature of the EW phase transition.

- The discovery of a **spin zero Higgs boson**, the first elementary particle of its kind, has only sharpened these questions, ***and their resolution*** will necessarily involve new physics ***BSM***.
- The ***precision measurement of Higgs boson properties*** will be a critical component of any road map for high energy physics in the coming decades.
- BSM physics can lead to ***observable deviations in Higgs couplings*** relative to SM expectations

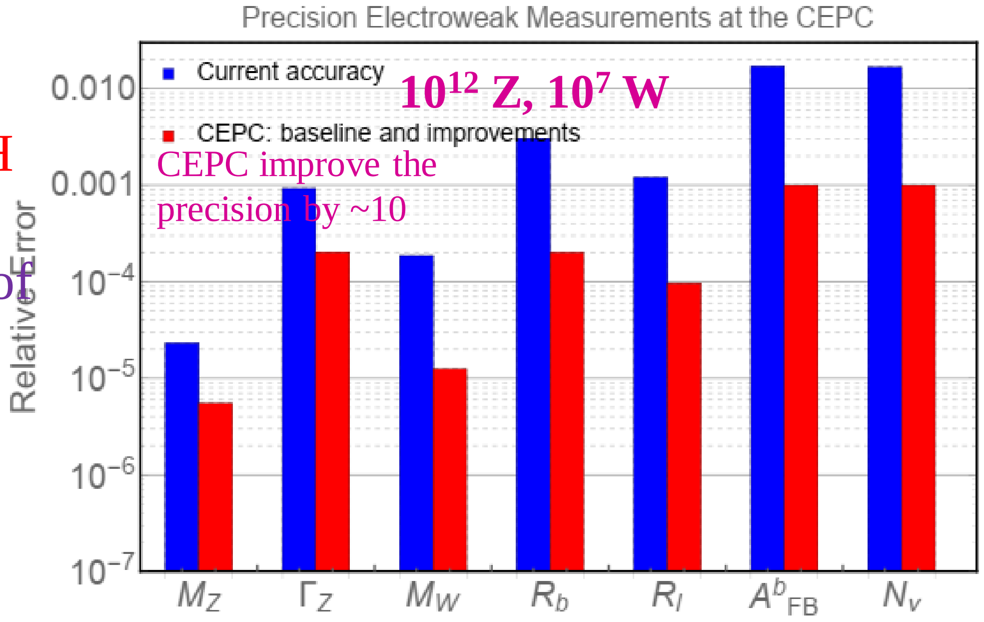
$$\delta = c\frac{v^2}{M_{\rm NP}^2}$$

v and $\mathbf{M_{NP}}$ are the vacuum expectation value of the H field & the typical mass scale of new physics. Need to probe new physics significantly beyond the LHC's reach requires measuring H couplings with ***sub-percent-level accuracy***



Higgs coupling extraction in the k-framework

- The **CEPC** has strong capability in detecting invisible decays of the H
- For **L=5.6 ab^{-1}**, it can **improve the accuracy** of the measurement of the **H invisible branching ratio** to **0.3%**, **more than 10 times better** than the precision for HL-LHC.

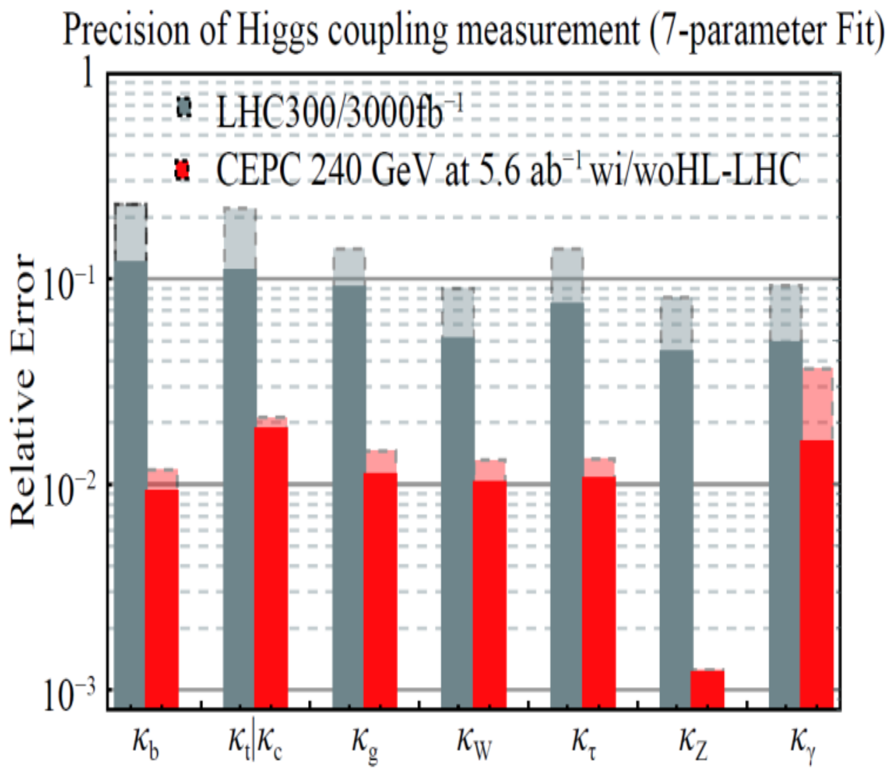


Projection for the precision of the Z-pole measurements

A lepton collider allows much better exclusive measurement of Higgs boson decay channels.

PHYSICS MOTIVATION

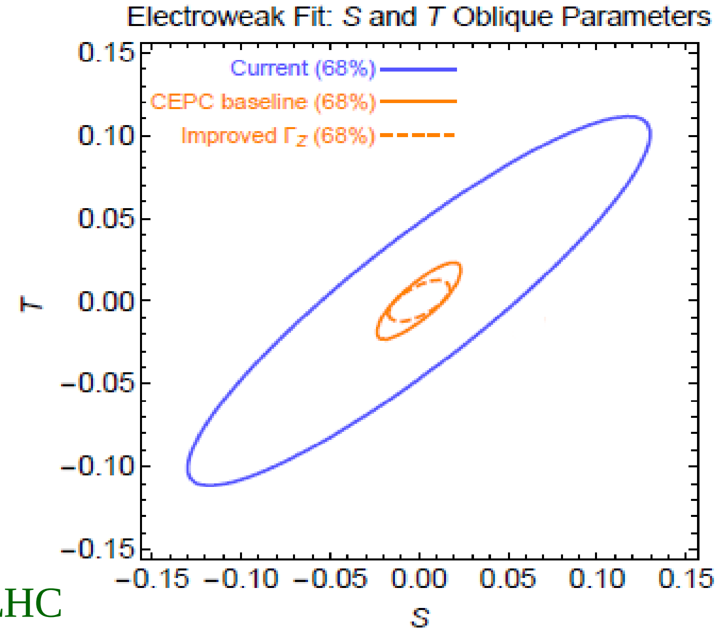
Higgs boson was discovered, but understanding its nature requires precision measurements of its properties at the (HL-)LHC or better at future lepton colliders, e.g. Higgs couplings:



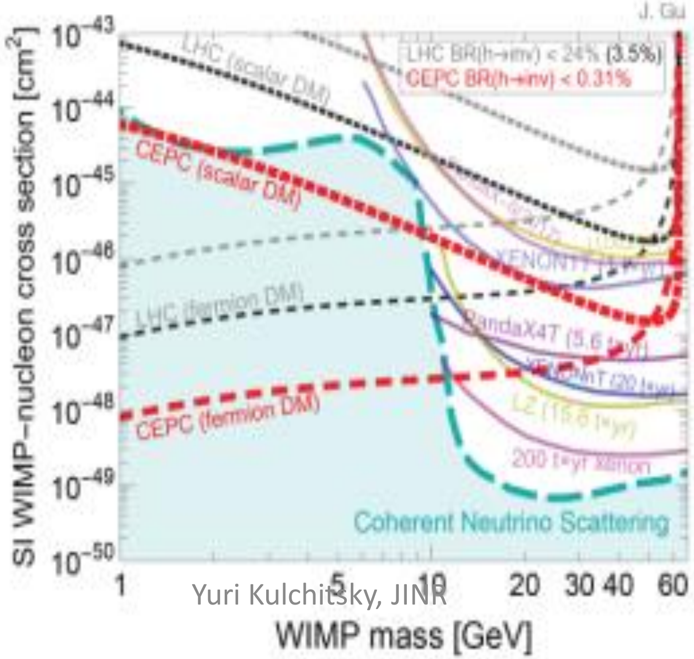
$$\kappa_f = \frac{g(hff)}{g(hff;\mathrm{SM})}$$

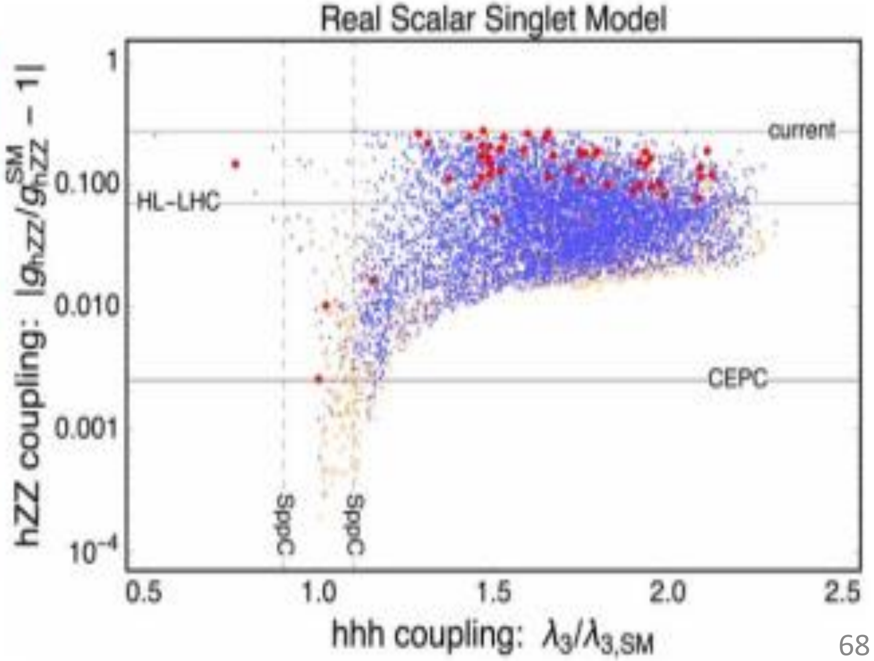
$$\kappa_V = \frac{g(hVV)}{g(hVV;\mathrm{SM})}$$

Anticipated accuracy on H-boson properties at CEPC & at LHC/HL-LHC



Electroweak measurement can be improved by a large factor

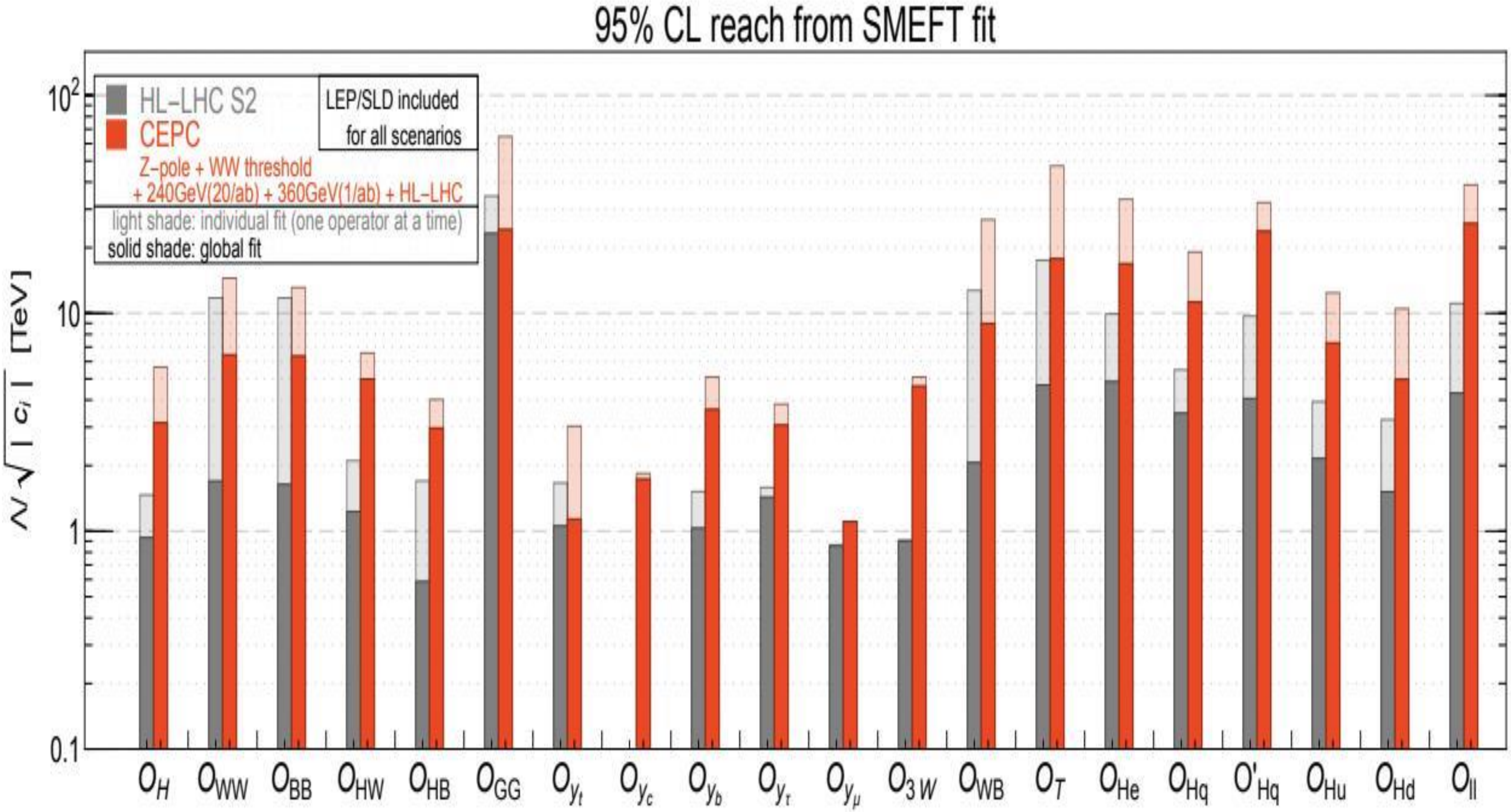




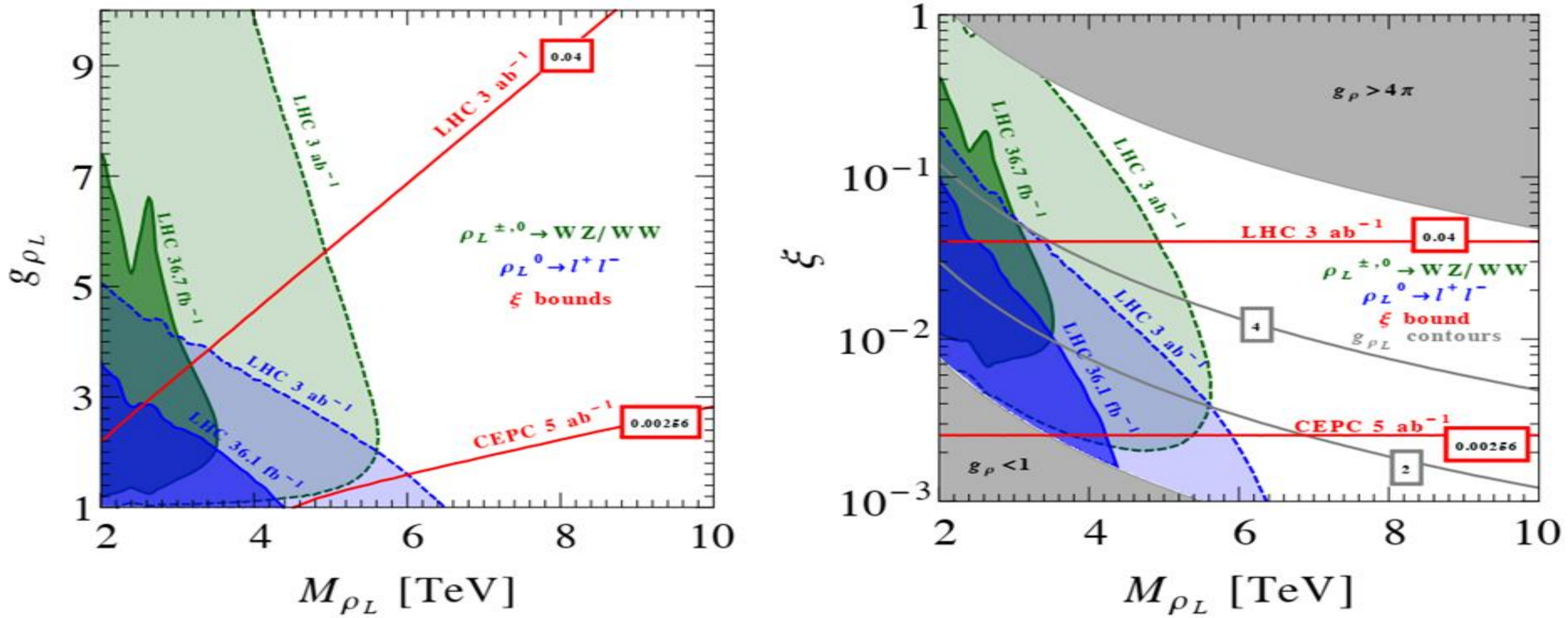
Direct or indirect probe to **dark matter and EWPT etc**, an order of magnitude more sensitive than the HL-LHC

CEPC can reveal new physics at energy >10 TeV

Energy scale probed



DIRECT AND INDIRECT PROBE TO NEW PHYSICS UP TO 10 TEV



- Potential coverage of composite-type ***global symmetry models*** in terms of ***resonance mass*** **$M_{\rho L}$** and ***coupling parameter*** **$g_{\rho L}$** ;
- ***Mixing parameter*** **$\xi \equiv v_2/f_2$** via direct searches at the **LHC** (**blue** & **green** *shaded regions*) and **precision Higgs measurement** constraints **(red lines).**

KEY SCIENTIFIC ISSUES AND TECHNOLOGICAL ROUTE

Physics ➡ Detector ➡ MDI ➡ Accelerator

New Physics
~10 TeV

- ✓ Dark Matter
- ✓ Extended Higgs
- ✓ Composite Higgs
- ✓ Supersymmetry
- ……

High Precision
~1%

- ✓ Higgs: 1%-0.1%
- ✓ EW : $O(10^2-10^3)$ vs current
- ✓ Flavor
- ……

Detector
Particle Flow

- ✓ High Granularity
- ✓ Good Resolution
- ✓ Reliable PID
- ……

Design & Implementation
Detector & Accelerator

- ✓ Multi-purposed Acc.
- ✓ New concept Detector
- ✓ Cost, added values
- ✓ Spill-over
- ……

- ✓ Management
- ✓ Collaboration
- ……

High Lumi.
$\sim 10^{34\text{-}36} cm^{-2}s^{-1}$

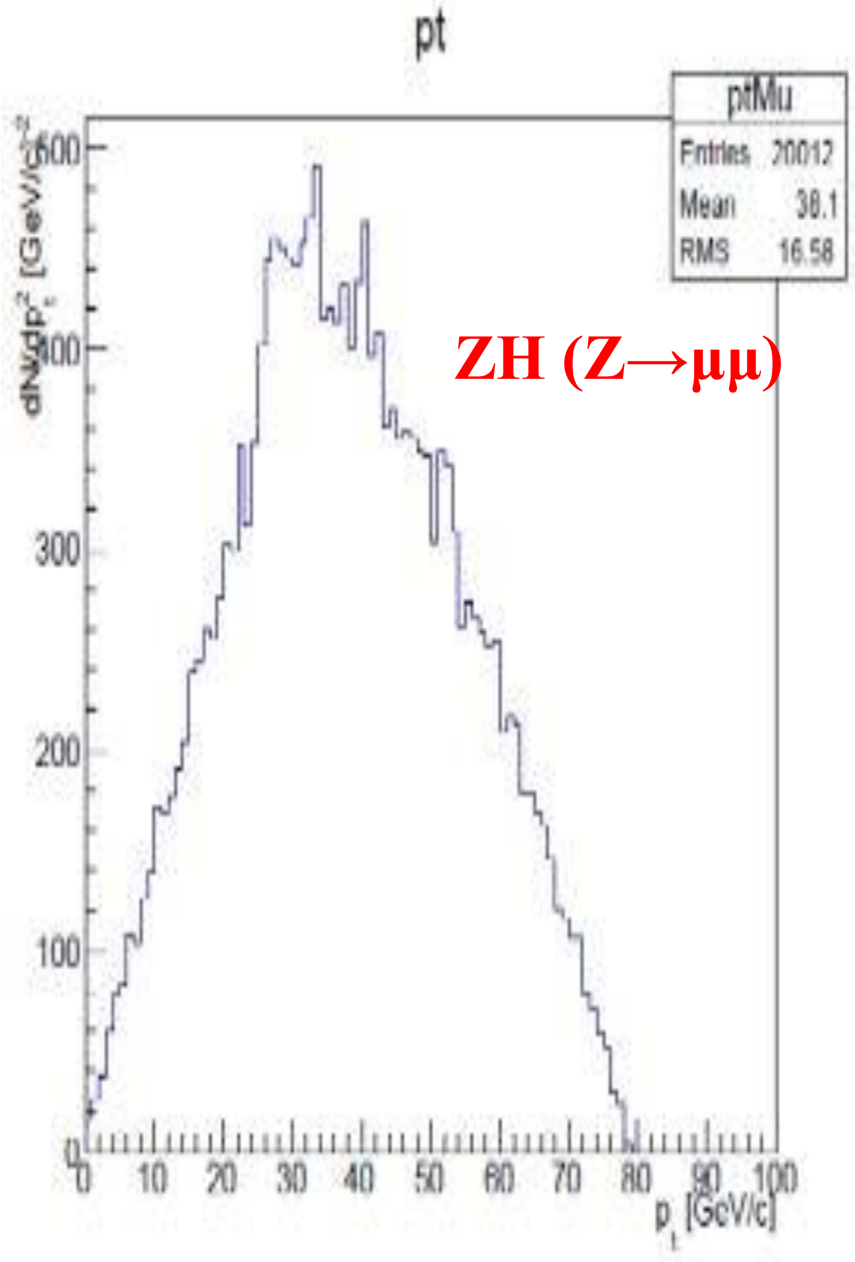
- ✓ Higgs: 20 ab^{-1}
- ✓ Z: 100 ab^{-1}
- ✓ W: 6 ab^{-1}
- ✓ Top: 1 ab^{-1}

Accelerator
2 IPs/100 km

- ✓ Switchable Operations
- ✓ Upgradability
- ✓ Large Piwinski angle with Crab-waist
- ……

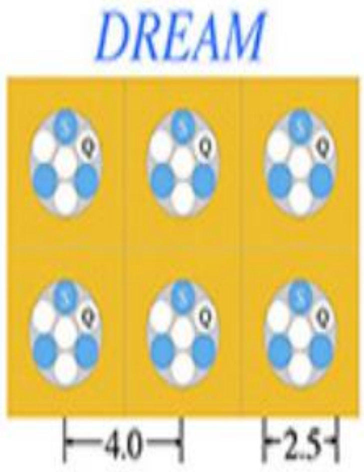
Operation mode	Z	W	Higgs
Center-of-mass energy (GeV)	91	160	240
Operation time (year)	2	1	10
Instantaneous luminosity/IP ($10^{34}cm^{-2}s^{-1}$)	115	16.0	5.0
Integrated luminosity (ab^{-1}, 2 IPs)	60	3.6	12
Event yield (30 MW)	2.5×10^{12}	1.0×10^{8}	2.5×10^{6}
Event yield (50 MW)	4.0×10^{12}	1.6×10^{8}	4.0×10^{6}

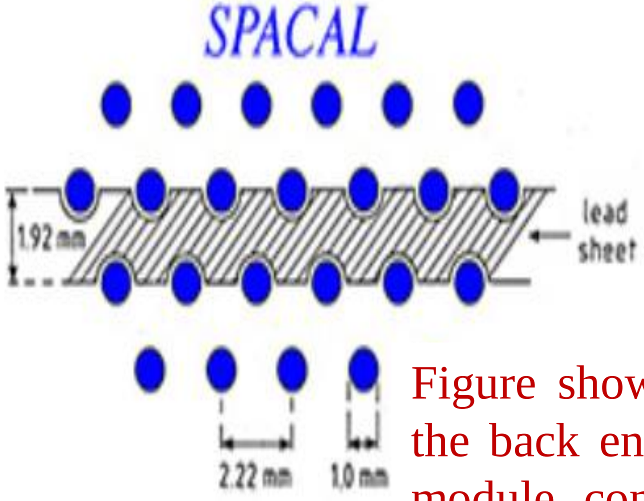
- Excellent **acceptance** and **luminosity control**
  - E.g. ECAL inner radius known at 15 μm
- **B ~ 2T** for beam emittance preservation
  - Maximize **tracking volume**
- Bunch spacing at Z pole ~ 25 ns
  - Limited **drift-time**
- **PID** & π^0 ID for HF/τ physics
  - dE/dx or TOF
- Muons in **ZH** events have rather small p_T
  - **Transparency** more relevant than asymptotic resolution



DUAL-READOUT CALORIMETERS

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \quad \text{with} \quad a = 0.027\sqrt{d/f_{samp}}$$





Compared RD52 with DREAM, the number of fibers per unit volume, and thus the sampling fraction, is approximately **twice as large in the RD52 calorimeter**. And since each fiber is now separately embedded in the absorber structure, the sampling frequency has also considerably increased. Since both factors determine the electromagnetic energy resolution, one should thus expect a substantial resolution improvement

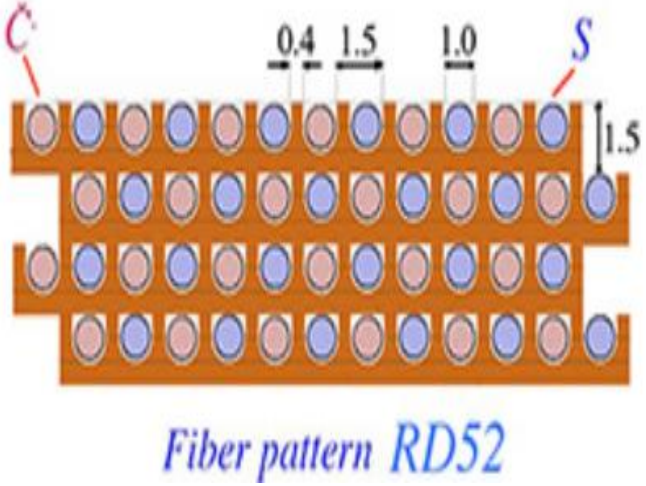
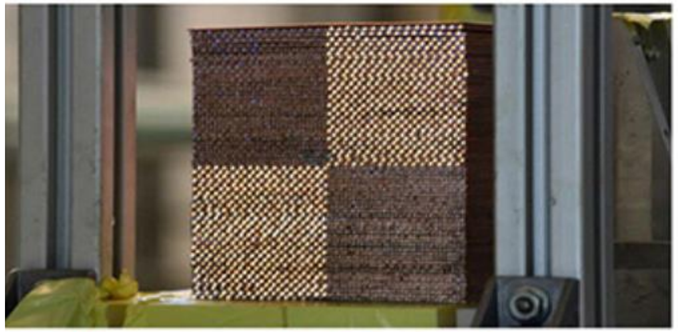
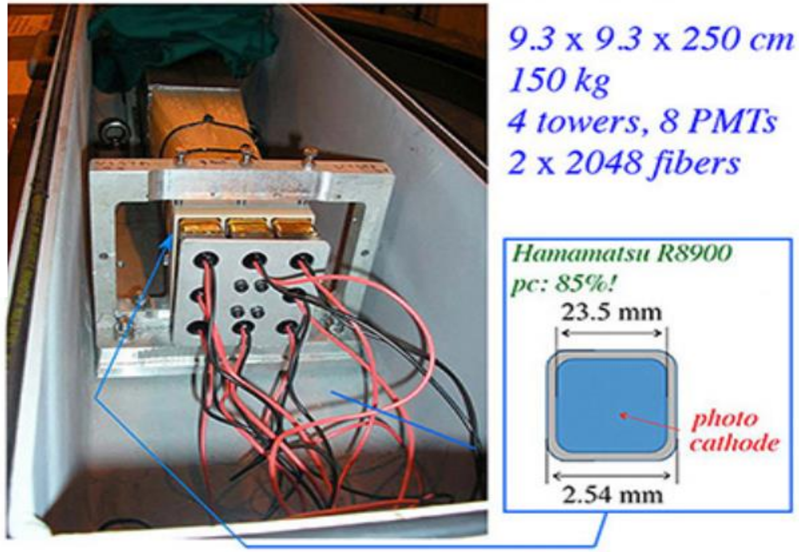


Figure shows pictures of the front face and the back end of a calorimeter module. Each module consists of four towers, and each tower produces a scintillation and a Cerenkov signal. The transverse dimension of the module was chosen such that the eight PMTs would fit within its perimeter, and the maximum fiber density was determined by the total photocathode surface of these PMTs (which corresponds to more than half of the module's lateral cross section)



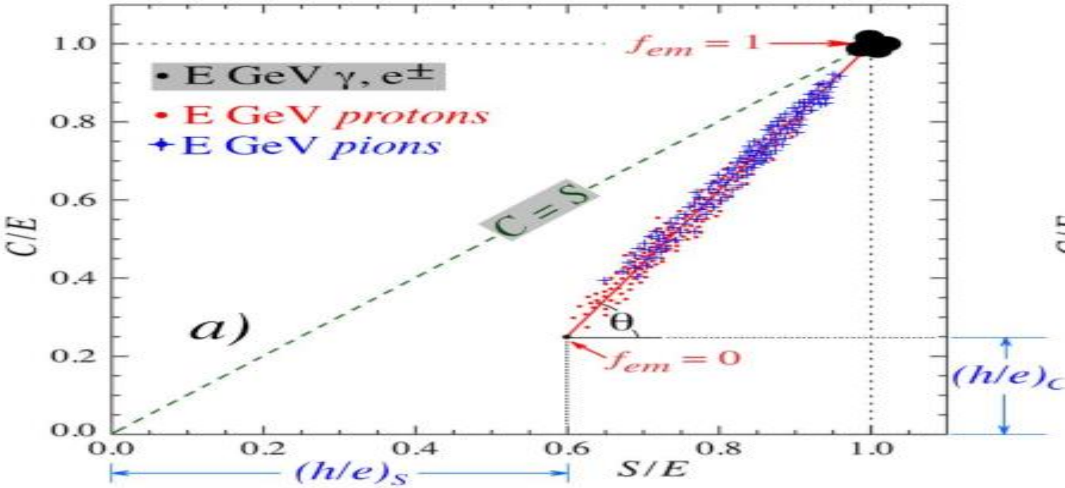


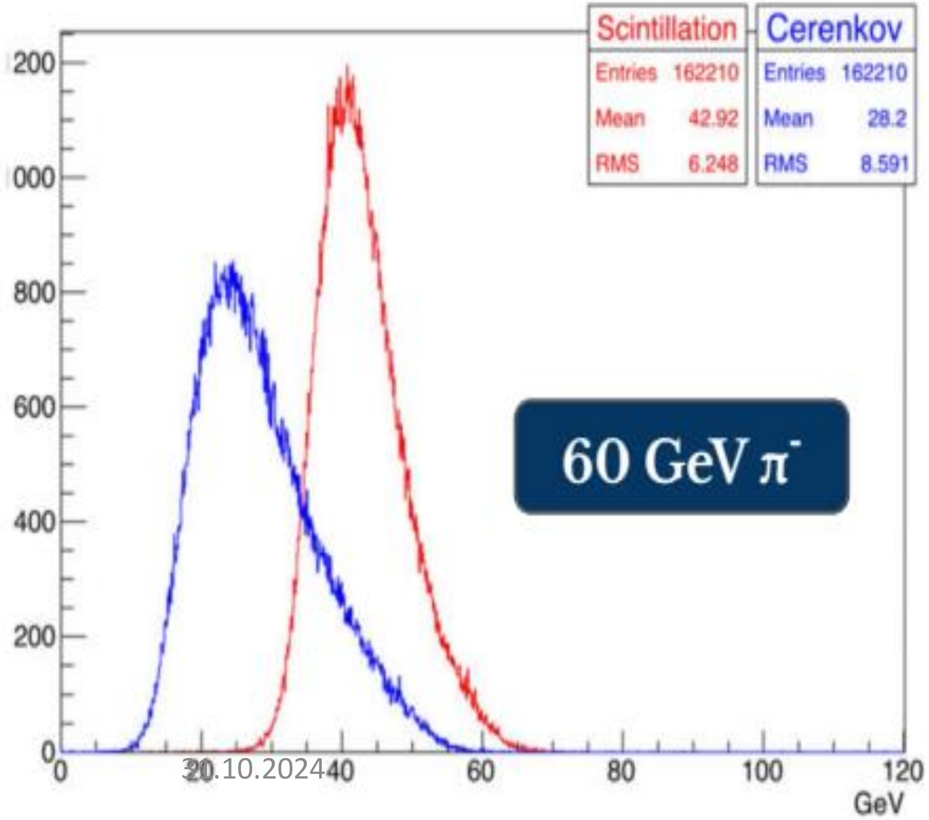
The structure of the **RD52** fiber calorimeter (copper based modules), compared to that of two other fiber calorimeters: DREAM [NIM A537, 5376 2005] and SPACAL [NIM A308, 4816 1991].

Front and rear view of one of the **RD52** fiber calorimeter modules. The tower structure is made visible by shining light on two of the eight fiber bunches sticking out at the back end. See text for more details.

DUAL READOUT CALORIMETRY

- Calibration with electrons of known energy for both **em** and **hadronic** showers
  - Potential to use as ECAL and HCAL combined
  - Universal for all hadron types
- Restored Gaussian and linear response to hadrons
- **Improved energy resolution**

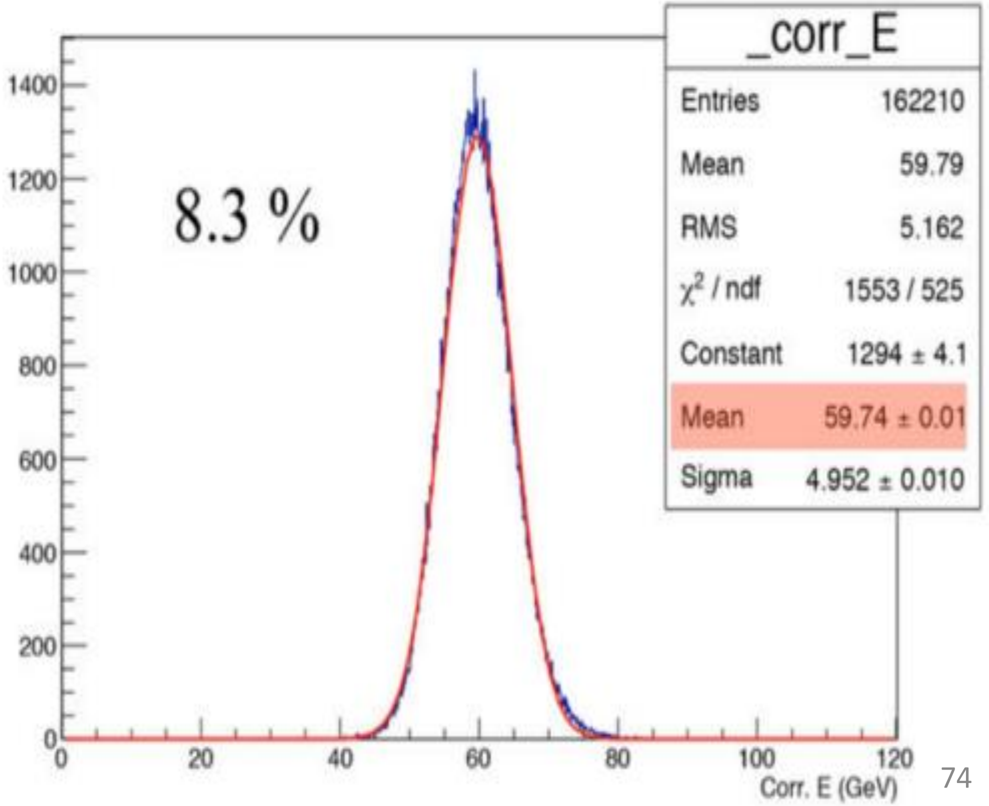




$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

$$E = \frac{S - \chi C}{1-\chi}$$

DR-formula



CEPC CALORIMETRY SYSTEM

Two technology options are being explored for the **CEPC calorimetry system**:

I. the **Dual-readout (DR) concept**

- The dual-readout approach aims for a **combined and homogeneous calorimeter with excellent performance for both electromagnetic and hadronic particle showers.**

II. the **Particle Flow Algorithm (PFA)** concept

- The PFA approach aims to develop **high-granularity electromagnetic and hadronic calorimeters** capable of **measuring individual particles in a jet.**

- **CEPC, Conceptual Design Report, Volume II - Physics & Detector,** IHEP-CEPC-DR-2018-02, IHEP-EP-2018-01, IHEP-TH-2018-01, The CEPC Study Group, October 2018, e-Print: 1811.10545 [hep-ex], 424 pages

Chapter 5: Calorimetry

5.3: Particle flow oriented electromagnetic calorimeter;

Jianbei Liu liujianb@ustc.edu.cn, University of Science and Technology of China, Hefei

Tao Hu hut@ihep.ac.cn, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing

5.4: Particle flow oriented hadronic calorimeter

Haijun Yang, haijun.yang@sjtu.edu.cn, Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai

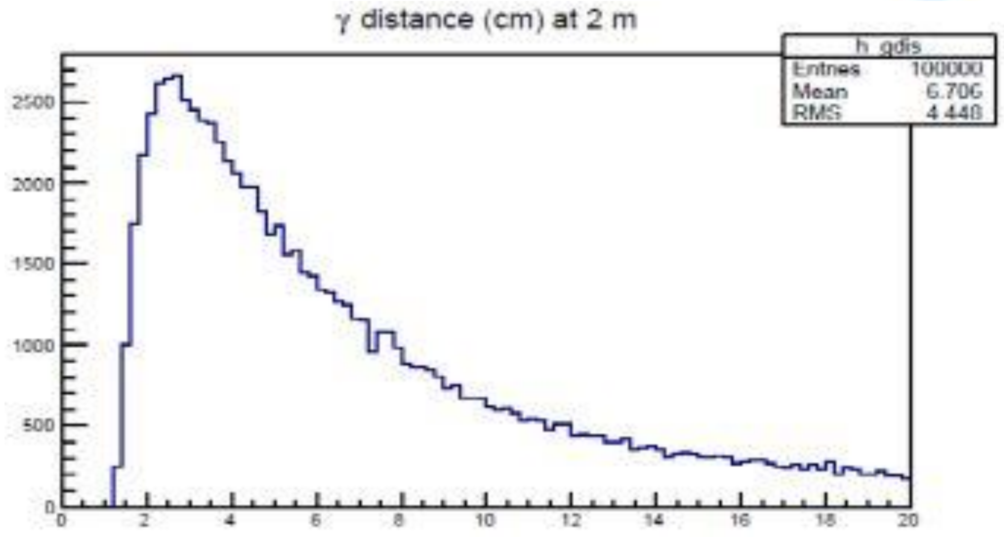
5.5: Dual-readout calorimeter

Franco Bedeschi bed@fnal.gov, INFN - Sezione di Pisa, Universita’ di Pisa and Scuola Normale Superiore

Roberto Ferrari roberto.ferrari@cern.ch, INFN - Sezione di Pavia and University of Pavia

❑ Requirements

- σ_{EM} ~ 10-15%/√E sufficient for Higgs physics
- σ_{jets} ~ 30-40%/√E to clearly identify W, Z, H in 2 jets decays
- Transverse granularity <1 cm for π^0 from τ and HF
- All electronics in the back to simplify cooling and services

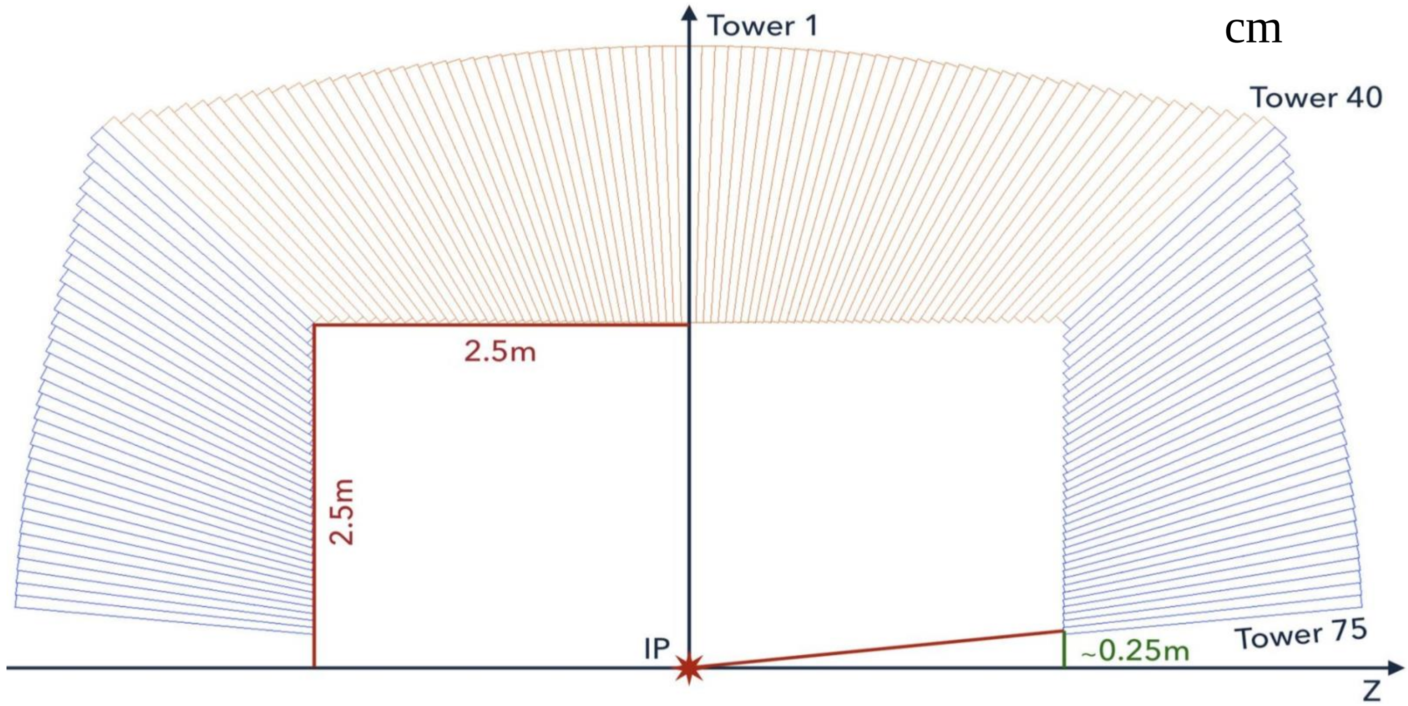


❑ Satisfied by a dual readout fiber calorimeter

- w/SiPM readout

❑ Baseline option

- **DR fiber calorimeter**
  - **~130 M fibers**
    - ✓ 1 mm ⌀, 1.5 mm pitch
- **Copper absorber**
- **75 projective towers x 36 slices**
  - ✓ Δϑ = 1.125°, Δϕ = 10.0°
  - ✓ ϑ coverage: ~0.100 rad
- **G4 simulation available**
  - ✓ Tuned to RD52 TB data



CEPC PHYSICS & DETECTOR TDR: PARTICLE FLOW ORIENTED ECAL

The CEPC ECAL *to have is required*

1. a **good intrinsic energy resolution,**
2. **precise energy measurement of electrons and photons**,
3. excellent shower imaging capability that would allow **to identify photons** from close-by showers, **reconstruct detailed properties of a shower** and **distinguish** electromagnetic showers from hadronic ones effectively.

- **Extensive and focused R&D** will be conducted on developing a **tungsten-based** (**Wolframium**) high-granularity sampling calorimeter with either **silicon or scintillator** as **active medium**.

❖ Design optimization and common R&D

1. **Optimization** of primary detector parameters **with full detector simulation;**
2. **Thermal studies** of detector and electronics components through both simulation

❖ Prototyping;

1. **Cooling design** based on the above studies and prototyping;
2. Development of technological prototypes to **address power, cooling and front-end electronics issues**;
3. **Design of detector modules**. Development of technology for **fabricating large-size detector modules.**

❖ Silicon-Tungsten ECAL

1. **Full characterization** of a physics Silicon-Tungsten ECAL prototype using its **existing test beam data.**

❖ Scintillator-Tungsten ECAL

1. Development of a SiPM-scintillator coupling scheme that allows very large dynamic range;
2. Development of technology of fabricating high-quality scintillator strips with required fine structures;
3. Design, construction and characterization of a small-size physics prototype

High granularity HCAL is an essential part of the PFA-based CEPC calorimetry system

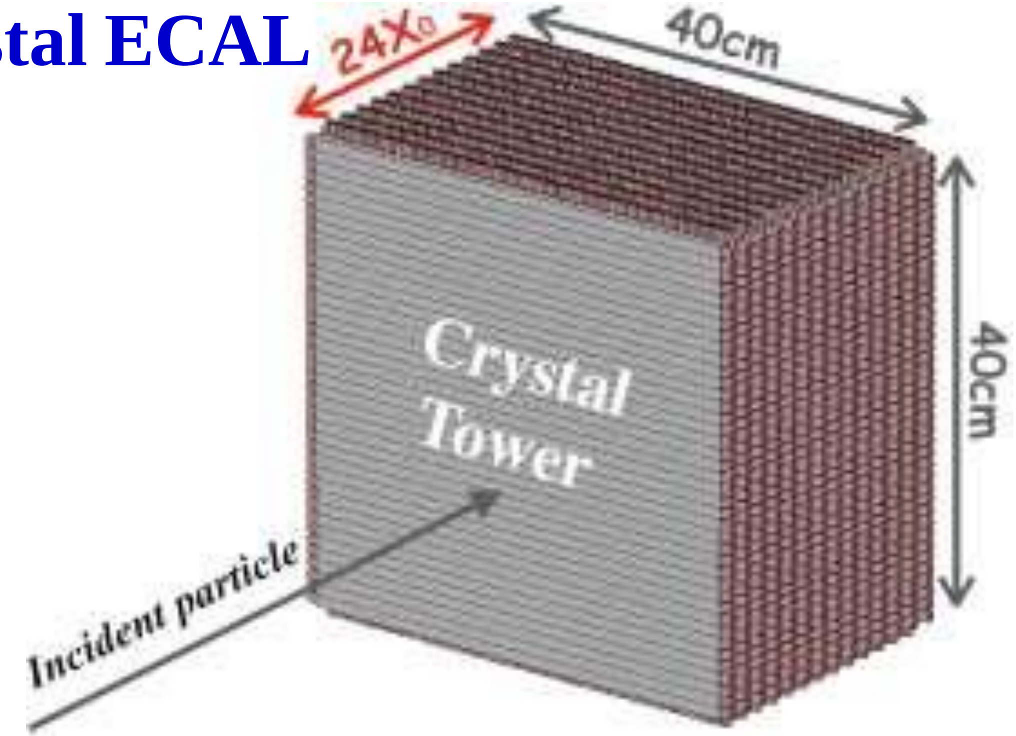
- **Currently R&D activ**ities for HCAL system includes **sampling calorimeters** with **stainless steel as the absorber** and **gaseous detector** (RPC or GEM) or **scintillator tiles** with embedded electronics **as active sensors**.
- Two technology options are considered, one is **SDHCAL** based on **gaseous detector** and the other is **AHCAL** based on **scintillator with SiPM.**
- **The future R&D plans** for **HCAL** system include design, construction and performance studies of various prototypes with the CALICE collaboration.

The following R&D program is being pursued in order to address and clarify several issues before the TDR

1. Make performance study of **SDHCAL** technological prototype based on RPC using MC and test beam data samples;
2. Design and construction of a small-size **AHCAL** prototype using **scintillator and SiPM,** make performance study with test beam and MC samples;
3. **Optimize the geometry and cell size** of **SDHCAL and AHCAL** designs;
4. **Design active cooling system** for both **SDHCAL and AHCAL** prototypes to address ASIC and frond-end electronics heating issues;
5. **Develop large size** Resistive Plate Chamber (**RPC)** (2-3 m^2), optimize gas distribution and circulation system to improve gas uniformity;
6. Develop **Multi-layer RPC** with excellent time resolution (~50 ps) which may help to **identify showers from neutrons;**
7. Explore ASIC chips with time information (PETIROC), design and develop corresponding PCB and front-end electronics;
8. Develop THGEM with very compact structure and stable operation.
9. Explore new types of SiPM (eg. NDL SiPM) with better performance/price ratio.

CALORIMETERS WITH PARTICLE FLOW ALGORITHM (PFA)

Crystal ECAL



Energy resolution $\frac{\sim 3\%}{\sqrt{E}} \oplus \sim 1\%$

Features

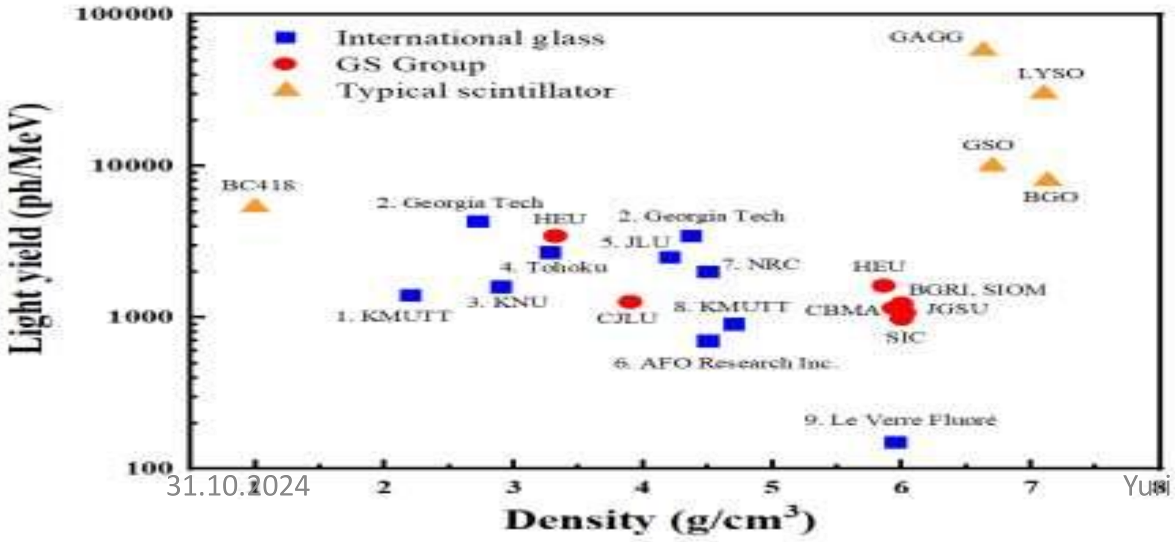
- ➢ **Good energy resolution**
- ➢ 3D shower info. with limited readout channel
- ➢ Shower separation < 4 cm

Main issues for R&D

- ➢ **Jet reconstruction and PFA algorithm**

Scintillation Glass HCAL

Energy resolution ~40%/√E ± ~ 2%

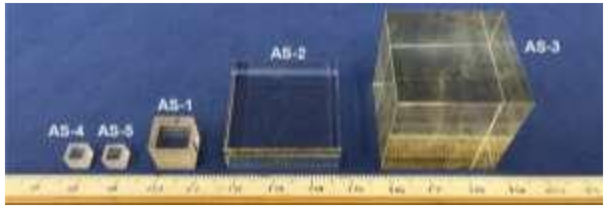


Features：

➢ Large sampling ratio at low cost

Main issues for R&D

➢ high density, high light yield, radiation hardness, production



DIGITAL ECAL CONCEPT

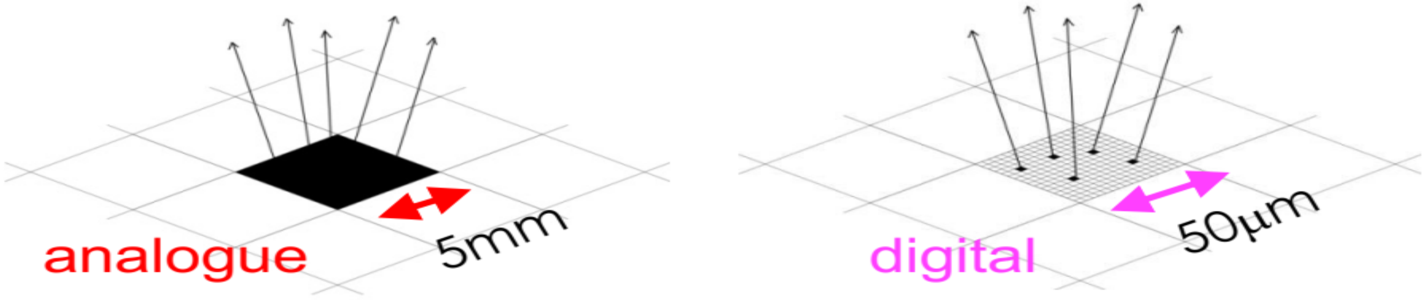
- Calorimeter samples energy between ~30 W absorber layers
- Analogue, e.g. CMS HGCAL (~ex-ILC), **sum energy** in 5x5 mm^2 Si cells
- Digital: **count every individual particle** in EM shower

Need ultra-small pixels! Ideally 1 particle/pixel → binary approach

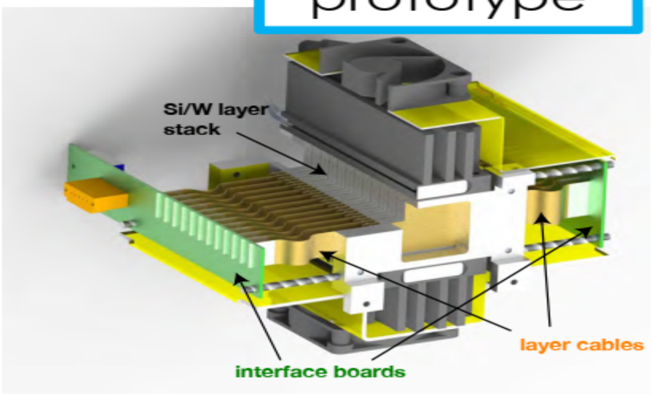
EM shower core density at 500GeV ~100/mm^2

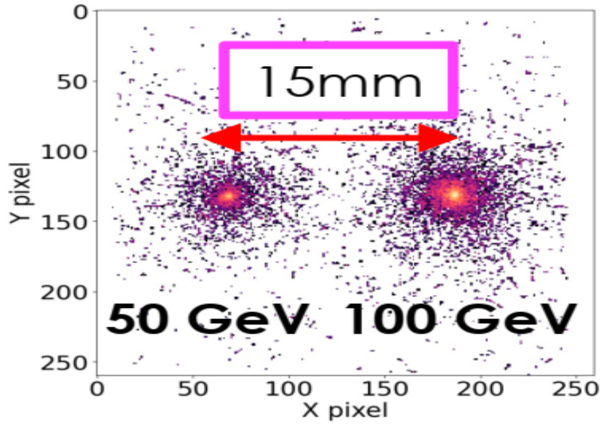
Pixels <100x100μm^2 for no saturation

~10^{12} pixels for ECAL barrel



EPICAL-2 prototype





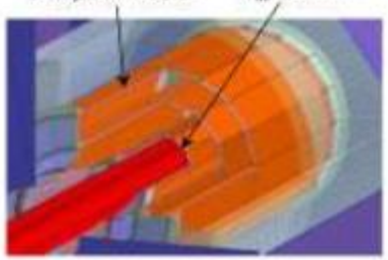
- Using CMOS MAPS, simpler construction,

+ expect lower cost

- A `tracking calorimeter', separates boosted decays, e.g. $\tau, \pi^0 \rightarrow \gamma\gamma$ …
- 20 X_0 prototype calorimeter in testbeams

VERTEX DETECTOR AND TRACKER

2 layers / ladder R_{in}~16 mm



Goal: σ(IP) ~ 5 μm for high P track

CDR design specifications

- Single point resolution ~ 3μm
- Low material (0.15% X_0 / layer)
- Low power (< 50 mW/cm²)
- Radiation hard (1 Mrad/year)

Silicon pixel sensor develops in 5 series:
JadePix, TaichuPix, CPV, Arcadia, CEPCPix

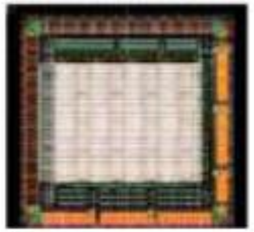
Develop **CEPCPix** for a CEPC tracke
basing on **ATLASPix3** CN/IT/UK/DE
TSI 180 nm HV-CMOS process

JadePix-3 Pixel size ~16×23 μm²

Tower-Jazz 180nm CIS process
Resolution 5 microns, 53mW/cm²

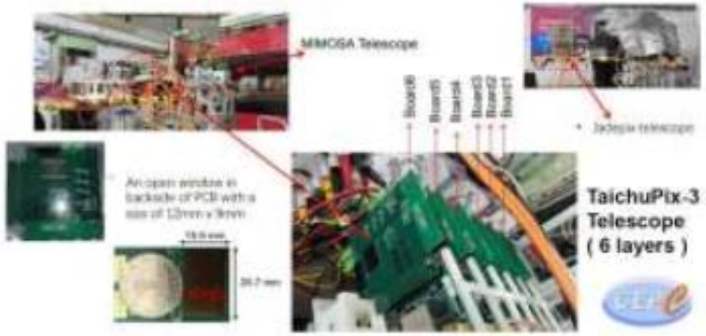
TaichuPix-3, FS 2.5x1.5 cm²
25×25 μm² pixel size

CPV4 (SOI-3D), 64×64 array
~21×17 μm² pixel size

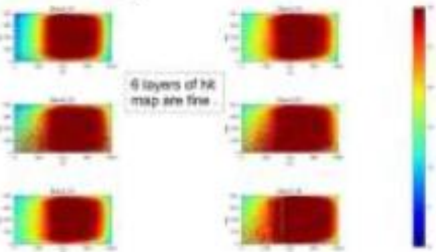


Arcadia by Italian groups
for IDEA vertex detector
LFoundry 110 nm CMOS

Full vertex detector prototype (TaichuPix-3, JadePix-3) has TB at DESY in Dec. 2022.

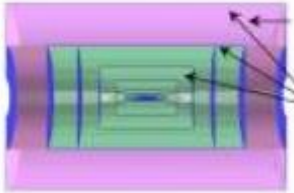


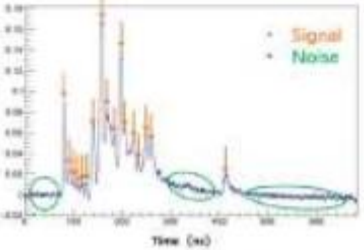
Hitmap of 4 GeV e⁺/e⁻ beam

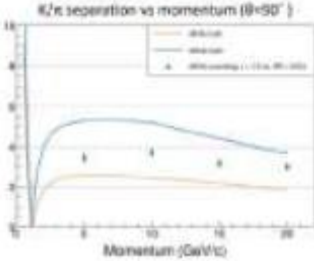


Goal: 3σ π/K separation up to ~20 GeV/c.

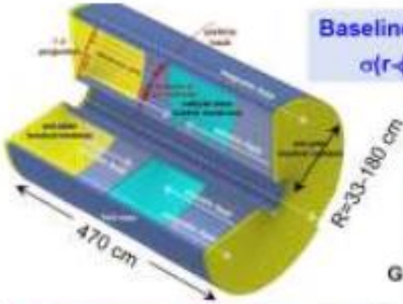
- Cluster counting method, or **dN/dx**, measures the number of primary ionization
- **Can be optimized specifically for PID**: larger cell size, no stereo layers, different gas mixture
- Garfield++ for simulation, realistic electronics, peak finding algorithm development



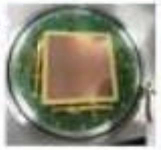


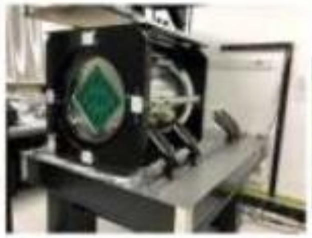


IHEP and Italian INFN groups have close collaboration and regular meetings.
IHEP joined the TB (led by INFN group) in 2021 and 2022



Baseline main tracker
σ(r-ϕ) ~100 μm

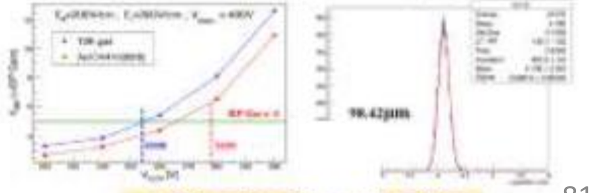




MOST 1 (IHEP+THU)

GEM-MM cathode TPC Prototype + UV laser beams Low power FEE ASIC

Challenge: Ion backflow (IBF) affects the resolution.
It can be corrected by a laser calibration at low luminosity, but difficult at high luminosity Z-pole.



σ < 100 μm for drift length of 27cm