Status of detector development for CEPC experiments and JINR participation

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JINR

Workshop ”Physics at future high-energy electron-positron colliders”

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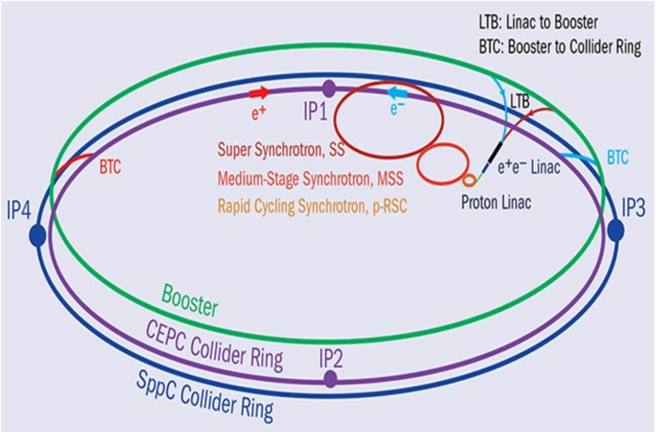
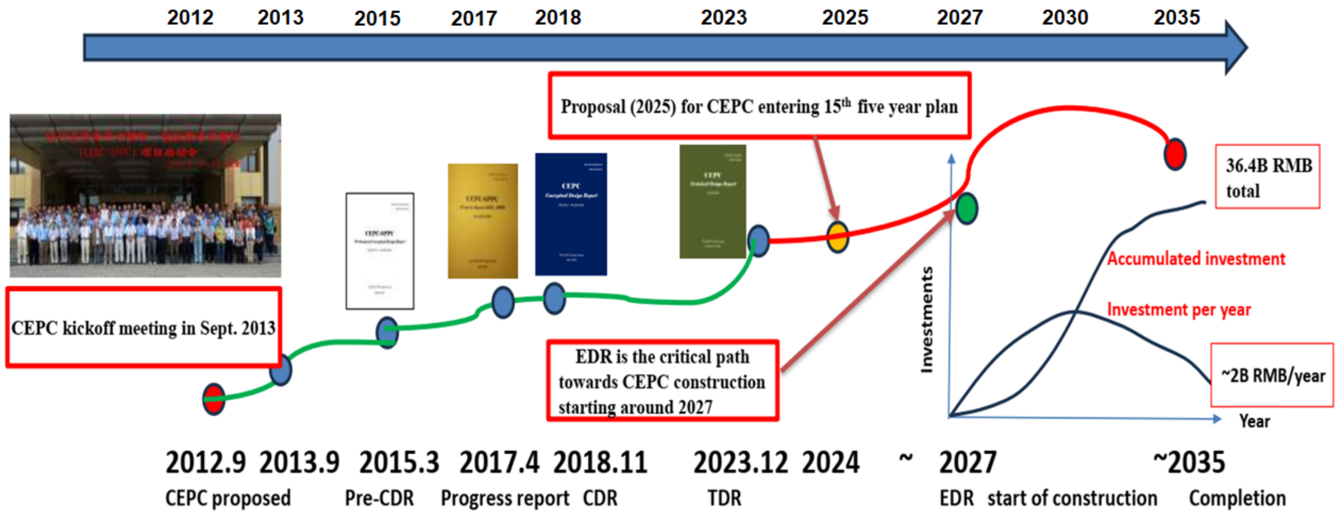
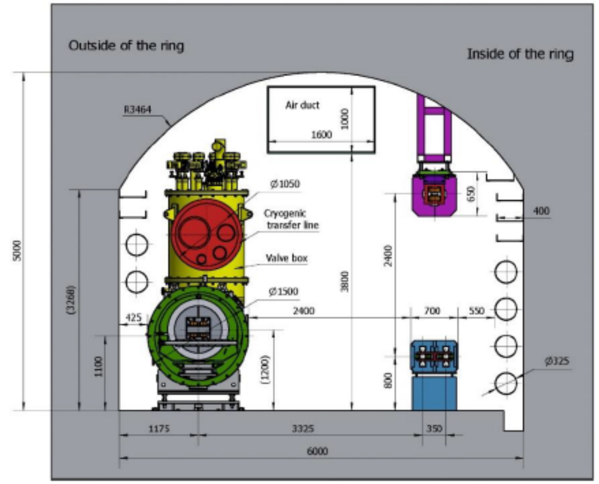
CEPC layout

- **Circular collider:** Higher luminosity than a linear collider
- **100km circumference:** Optimal total cost
- **Shared tunnel:** Compatible design for CEPC and SppC
- **Switchable operation: Higgs, W/Z, top**
- **Accelerator complex:** Linac, a 100 km booster and a collider ring







Common tunnel for booster/collider & SppC

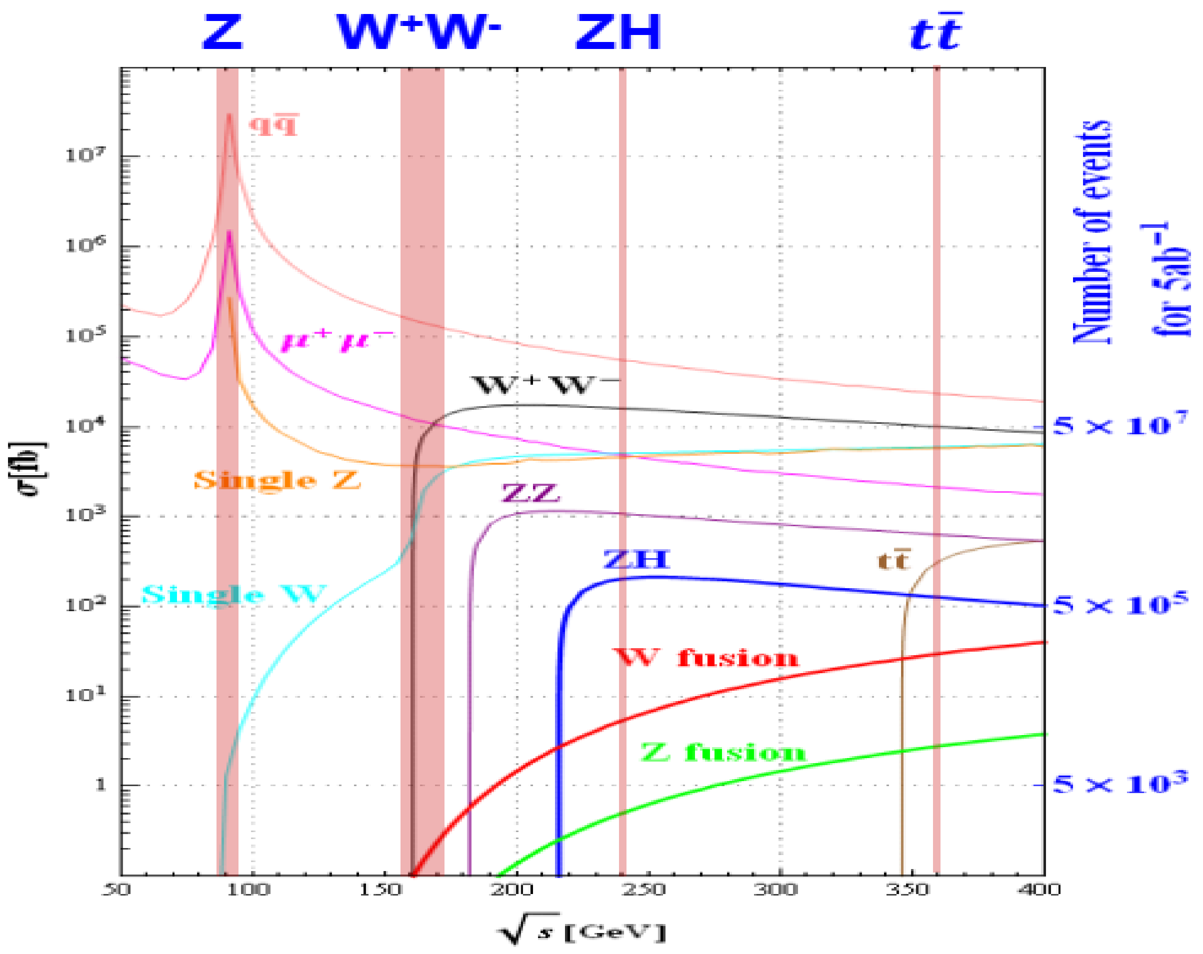
CEPC has strong advantages among mature electron-positron Higgs factories (design report delivered),

•**Earlier data**: collision expected in 2030s (vs. FCC-ee ~ 2040s), **larger tunnel cross section**（ee, pp coexistence)

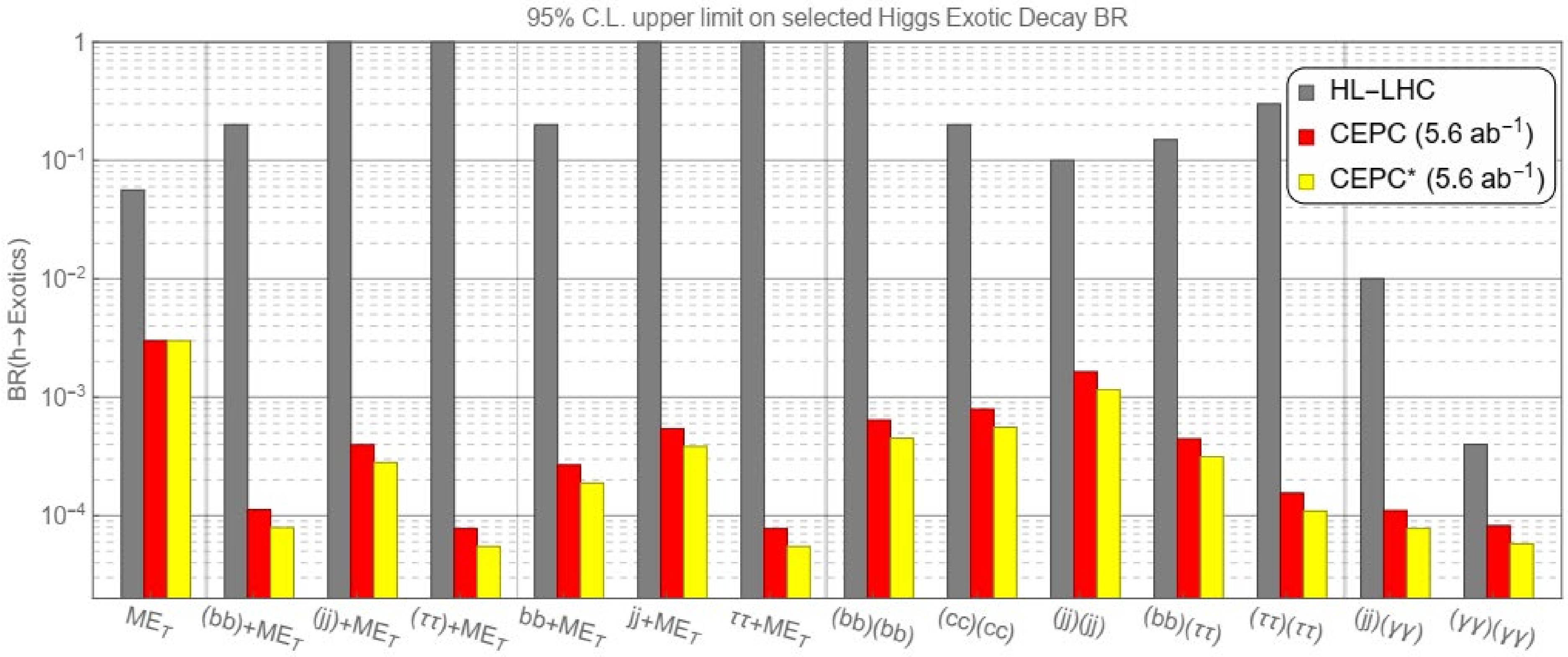
•**Higher precision** vs.linear colliders with more Higgs & Z; potential for **proton collider upgrade**.

Physics goals of CEPC

- ❑ **91** (Z), **160** (WW), **240** (ZH), **360** (tt) GeV
- ❑ **Higgs Factory (>10⁶ 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**



Branching of selected Higgs boson exotic 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

CEPC operation plans for first 10 years

SR Power Per Beam	Luminosity/IP [$\times 10^{34} cm^{-2}s^{-1}$]		
	H	Z	W^+W^-
12.1 MW	-	26	-
30 MW	5.0	-	16
50 MW	8.3	-	26.7

- **The first 10-year operation** includes: the Higgs mode, Low-Lumin Z mode, and W^+W^- mode.
- The accelerator may be upgraded for high lumi-Z mode and/or $t\bar{t}$ mode after 10 years operation, subject to physics needs
- The reference detector is only designed for the first 10 years operation. There may be future upgrade of the detector if the accelerator is to be upgraded

CEPC operation plan and goals

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.

Requirements on Detector Design

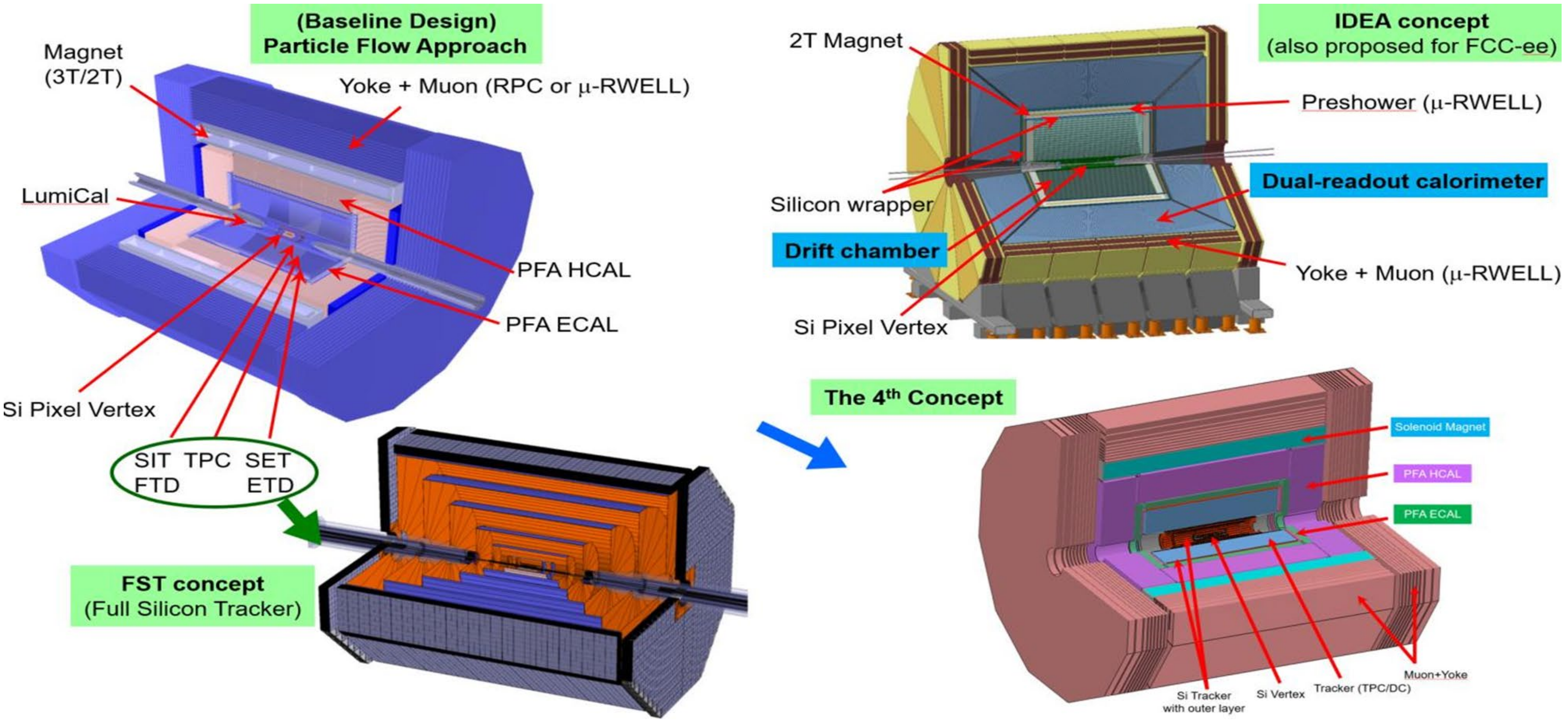
- The detectors should be able to operate for at least 10 years in Higgs mode, or better ~18 years of HZ, Z, W^+W^-, and $t\bar{t}$ productions.

- The detectors should be optimized to operate at the CEPC base clock frequency of 43.3 MHz (or period = 23.1 ns).

- The system needs to select and record interesting physics events.
  - In Higgs mode and L/IP (50 MW) = 8.3×10^{34} $cm^{-2}s^{-1}$:
    beam-beam crossing rate ~ 1.34 MHz, ZH ~16.6 mHz, $q\bar{q}$ ~ 5.0 Hz
  - In Z mode and L/IP (50 MW) = 1.92×10^{36} $cm^{-2}s^{-1}$:
    beam-beam crossing ~ 39.3 MHz, visible Z ~ 66 kHz

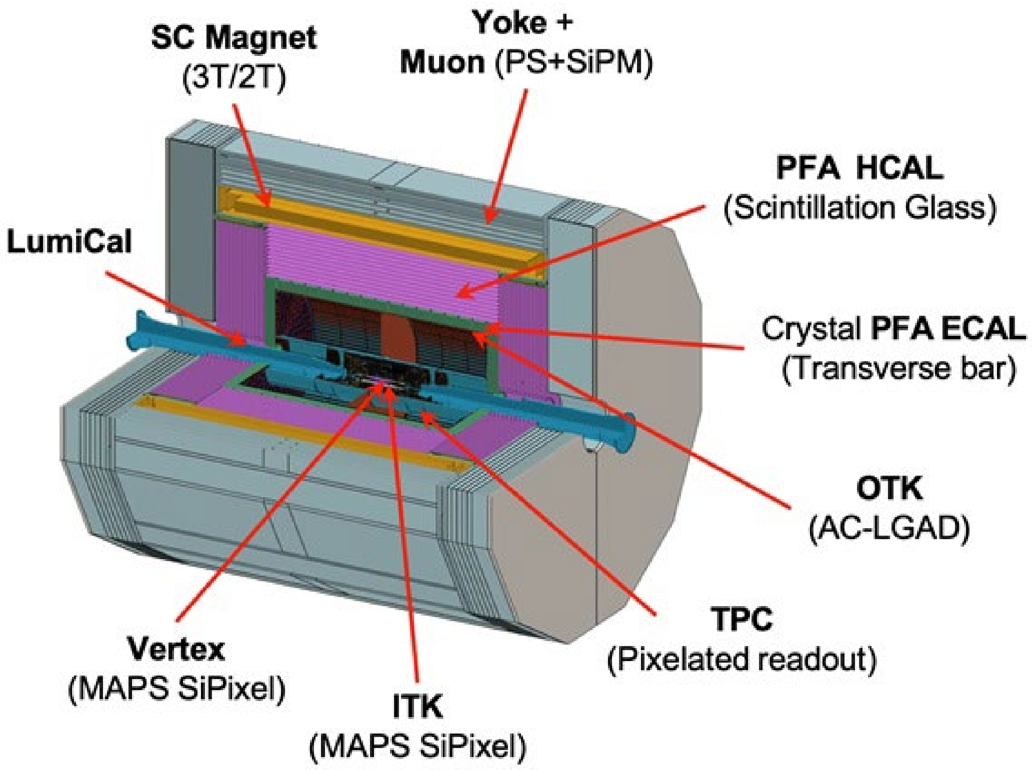
- Detectors can endure radiation damage and noise hit rates.
  - For example, in the Higgs mode at the Vertex detector:
    max noise hit rate ~ 0.6 MHz / cm^2, max TID ~2.1 Mrad/year
  - The background study is very preliminary. The value can be off by an order of magnitude.
  - It is relatively relaxed environment comparing to a hadron collider. Radiation resistance and noise hit rate should not be huge problems.

CEPC detector designs



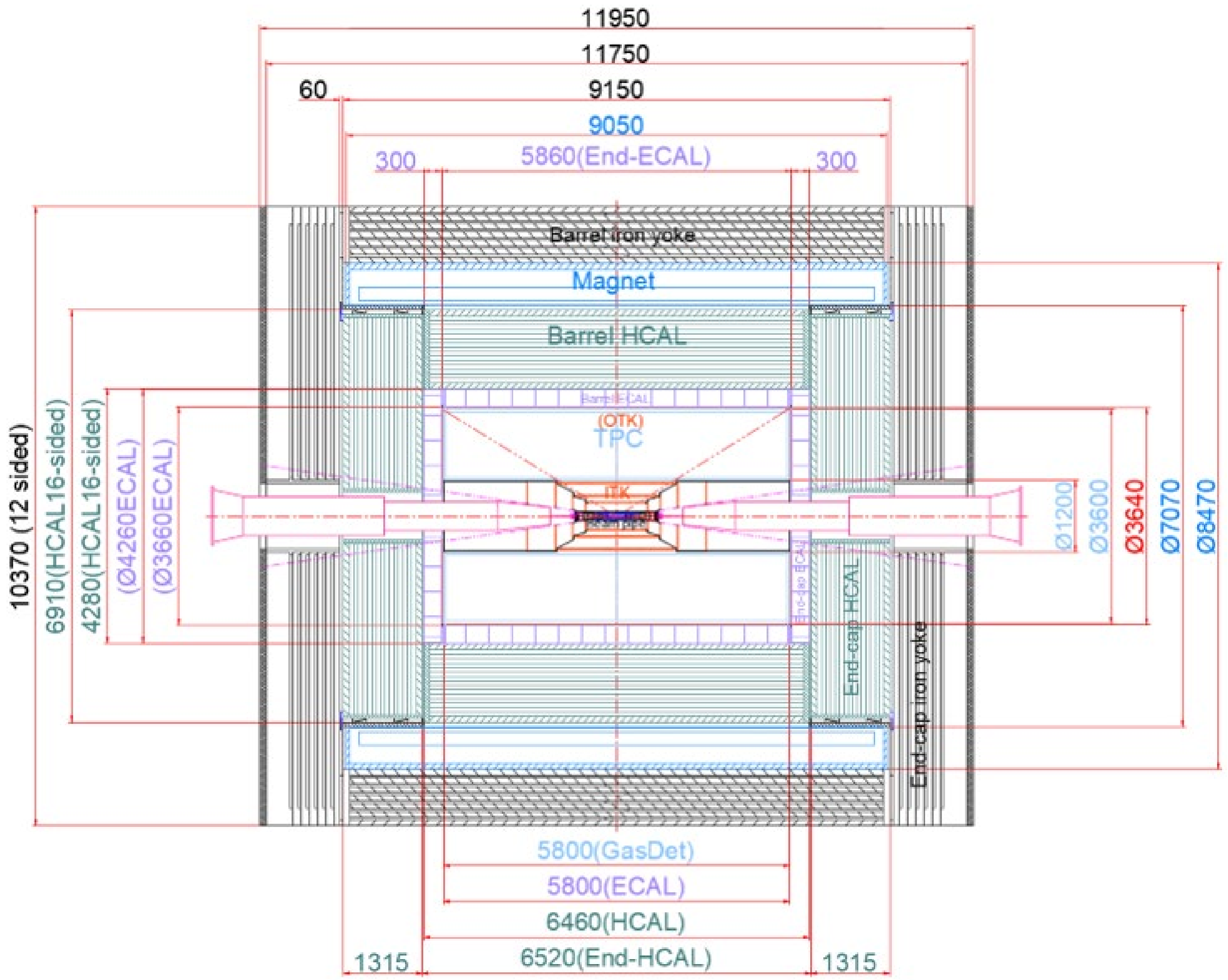
CDR baseline, *arXiv:1811.10545*

Reference detector concept



- **Ultra-low-mass vertex detector:** four inner layers utilize 65 nm large-area single-layer **stitched sensors**, with the innermost detector radius reaching **11 mm,** + a double-layer ladder structure.
- **ITK:** based on **monolithic HV-CMOS pixel sensors**, 3 barrel layers and 4 disk layers at each endcap, **~20 m²**.
- **TPC: pixelated** readout, **500×500μm²**
- **OTK:** one barrel layer and two endcap disk layers, based on **AC-LGAD** to measure **timing and position**
- **PFA-oriented calorimetry:** high-granularity homogeneous **crystal** ECAL and novel **glass scintillator** HCAL
- **Superconducting solenoid** → **3 T** magnetic field.
- **Muon** detectors in the return yoke.
- **LumiCal**: an AC-LGAD silicon wafer layer and a calorimeter utilizing LYSO crystals.

CEPC ref-TDR detector geometry

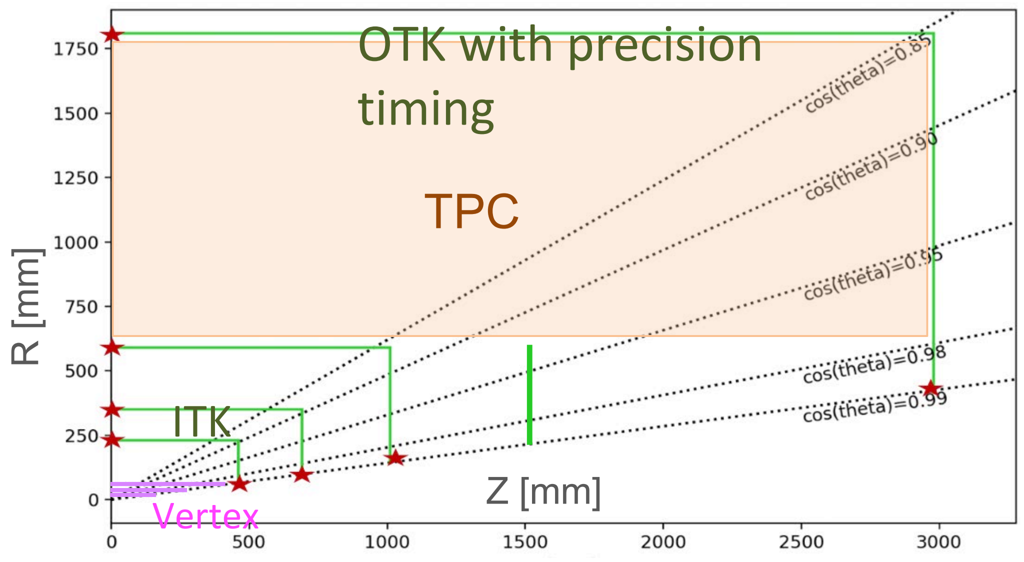


Tracker

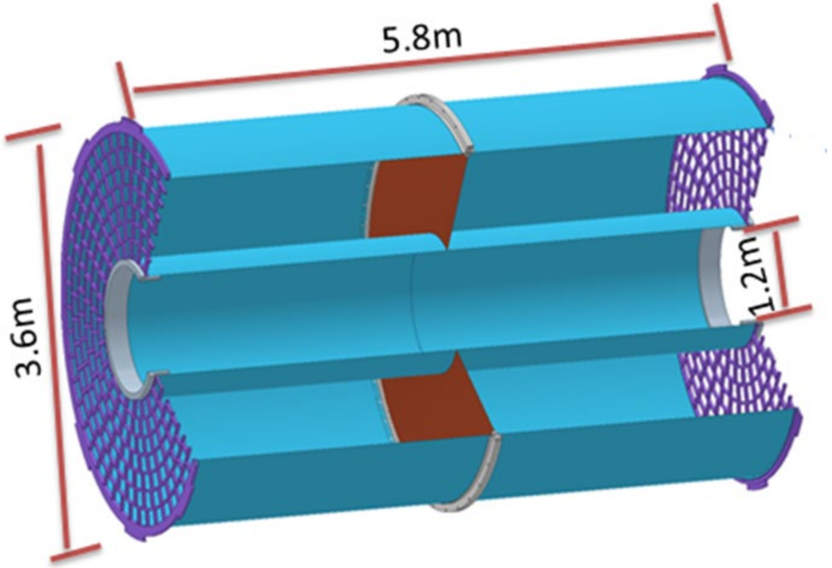
- Inner silicon tracker (ITK)
  - Spatial resolution:
    Barrel: σ_φ< 10 μm (bending), σ_z< 50 μm
    Endcap: σ_φ< 10 μm (bending), σ_r< 100 μm
  - Material budget: <1% X_0 per layer
  - Operate at high luminosity Z-pole mode:
    A few ns timing resolution to tag 23 ns bunches
  - Cost effectiveness: ~20 m^2 area

- Outer silicon tracker (OTK) with precision timing
  - Spatial resolution: σ_φ< 10 μm (bending)
  - Material budget: 1-2% X_0
  - Timing resolution: σ_t<50 ps
  - Cost effectiveness: ~85 m^2 area

The CEPC tracker system includes several detectors: the Vertex Detector, Inner Silicon Tracker, Time Projection Chamber (TPC), and Outer Silicon Tracker.

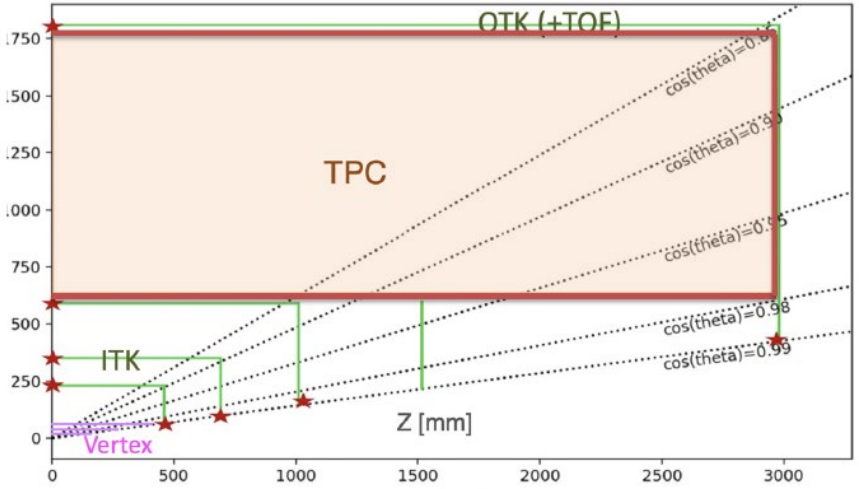


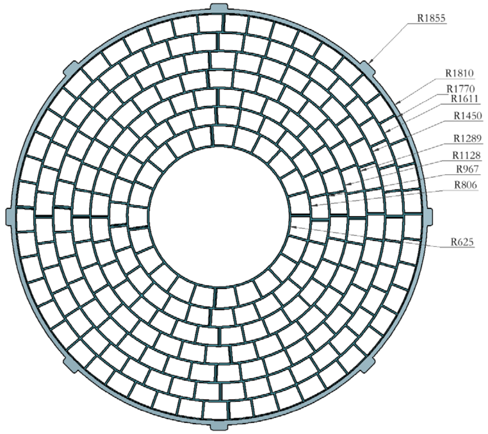
CEPC Gaseous Tracker: Pixelated readout TPC



Pixelated TPC is baseline detector as main tracker in CEPC ref-TDR. Data reading is carried out on the basis of the Micromegas detector.. The simulation framework has been developed using Garfied++ and Geant4.

- Aiming to Higgs and low luminosity Z run at future e+e- collider
- Radius of TPC from 0.6 m to 1.8 m, readout size 500µm x 500µm
- Ultra light material budget of the barrel and endplate
- Beam-induced backgrounds studied based on Garfield++ and CEPCSW



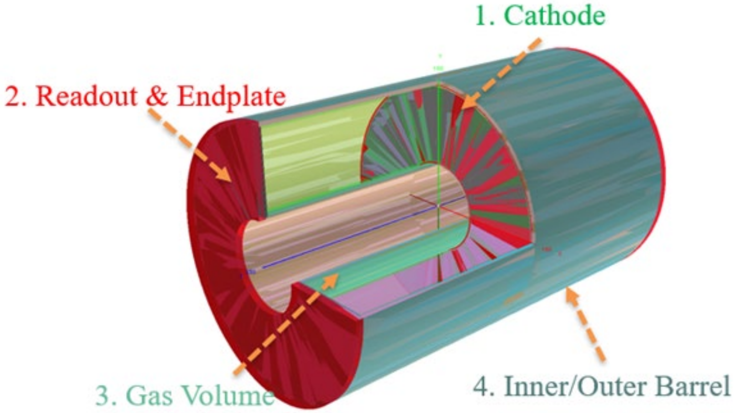


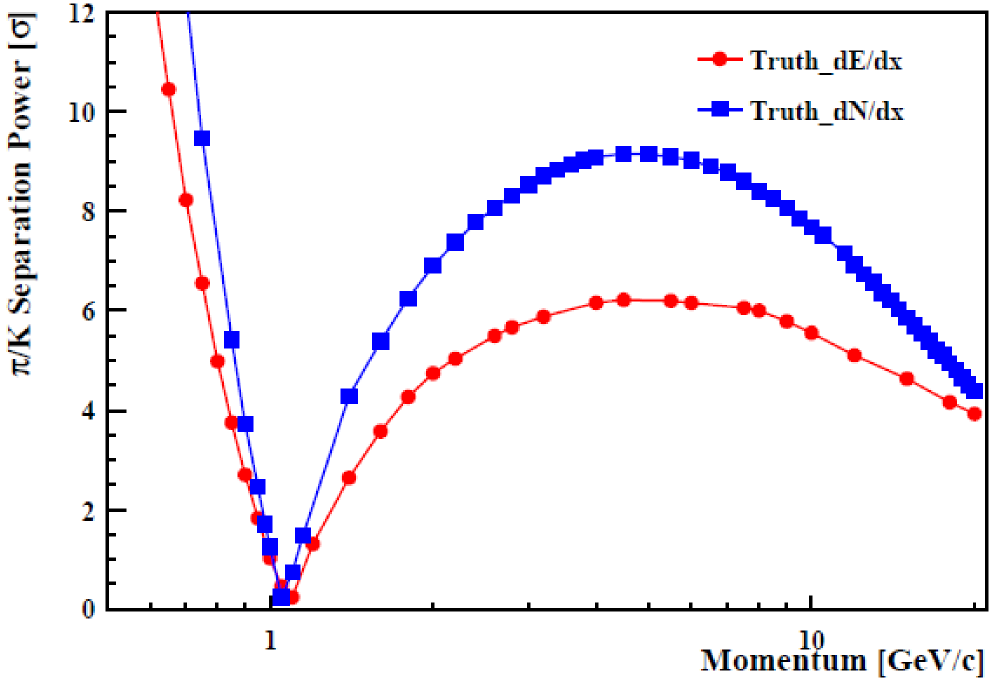
TPC detector	Key Parameters
Modules per endcap	248 modules /endplate
Module size	206mm×224mm×161mm
Geometry of layout	Inner: 1.2m Outer: 3.6m Length: 5.9m
Potential at cathode	- 62,000 V
Gas mixture	T2K: Ar/CF4/iC4H10=95/3/2
Maximum drift time	34µs @ 2.75m
Cooling	Water cooling circulation system
Detector modules	Pixelated Micromegas

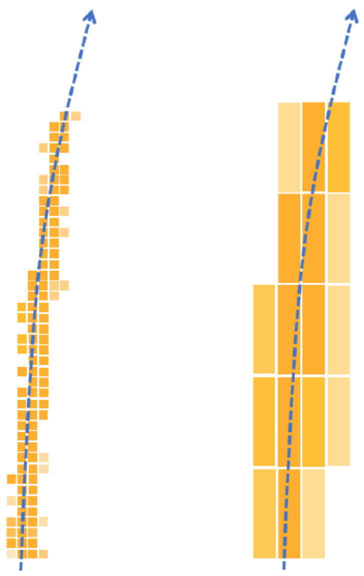
PID with dn/dx

- dn/dx: Count the number of pixels with small-pixel-size readout
- dE/dx: Measure the total energy loss

  dn/dx has much better PID by getting rid of fluctuations from energy deposition and amplification







500 x 500 μm^2
Readout size

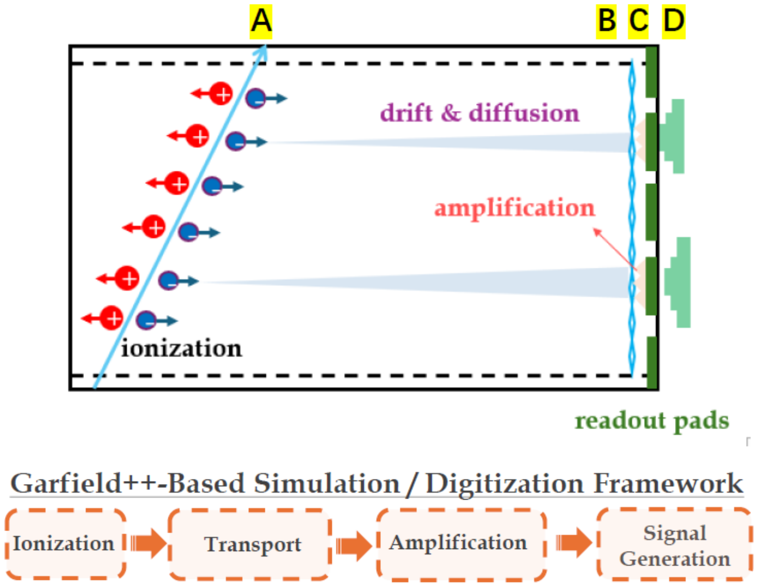
1x6 mm^2
Pad

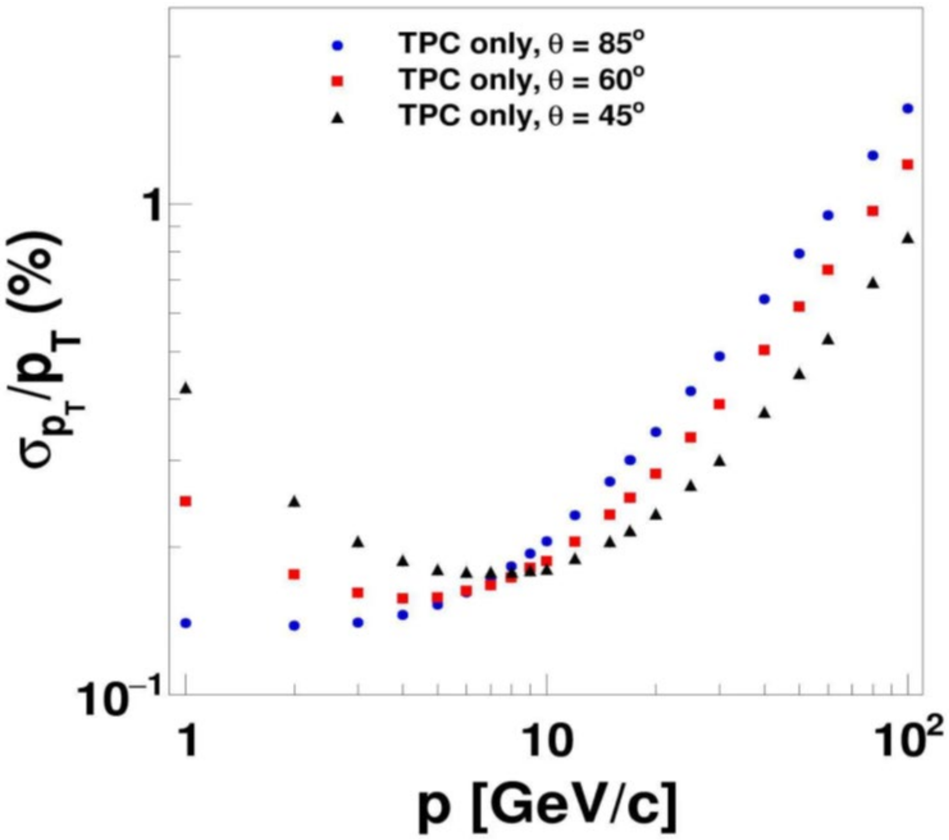
Yu. Davydov

Simulation and performance

Simulation:

- With the full TPC geometry
- Ionization simulated with Garfield++
- Drift and diffusion from parameterized model based on Garfield++

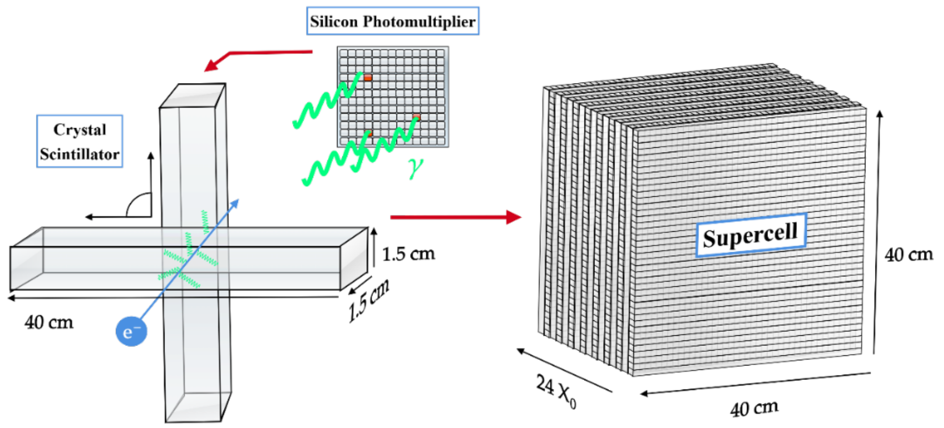




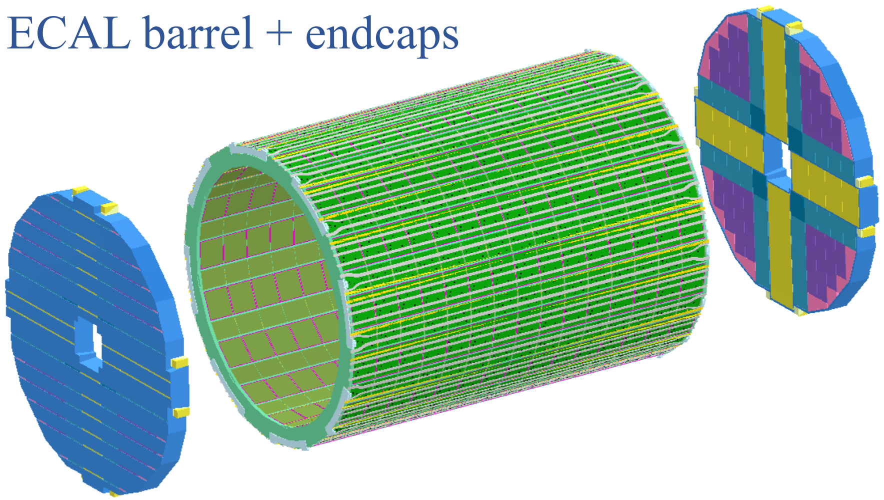
Crystal ECAL

- Compatible for PFA: Boson mass resolution (BMR) < 4%
- Optimal EM performance: $\sigma_E/E < 3\%/\sqrt{E}$
- A new option: R&D activities started since 2019
- Long crystal bars in orthogonal arrangement
  - Minimum longitudinal dead material
  - Significant reduction of readout channels
  - 3D positioning with two-sided SiPM readout

ECAL module schematics



ECAL barrel + endcaps



- ECAL design features: high granularity, modularity and hermeticity
  - Nominal crystal bar dimensions: 15×15×~400 mm^3
  - Transverse (effective) granularity: 15×15 mm^2
  - Total depth of 24 X_0 with 18 longitudinal layers
- ECAL barrel: 480 modules (411k channels, ~17.9 m^3 crystals)
- ECAL endcaps: 224 modules (160k channels, ~6.3 m^3 crystals)

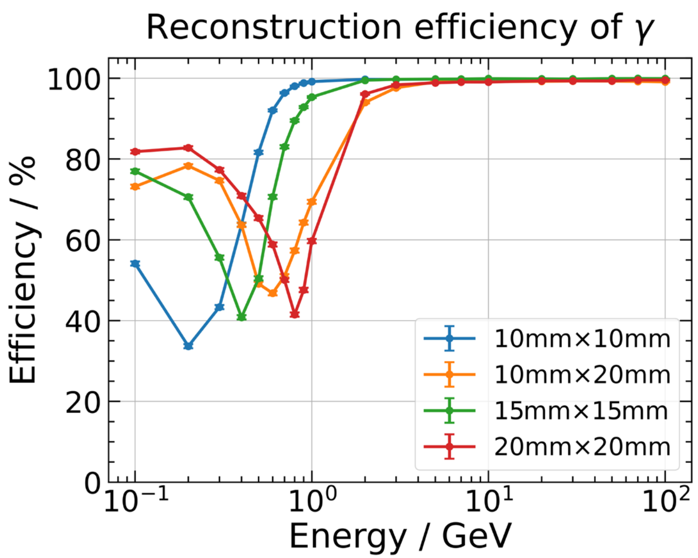
ECAL granularity optimization

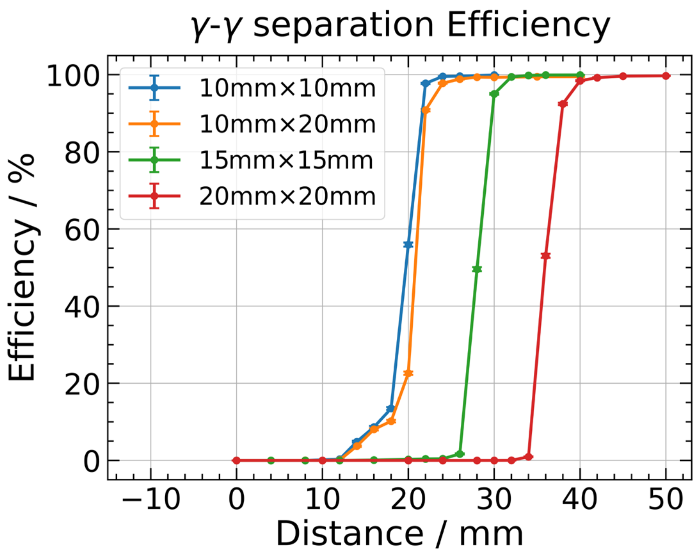
- Four typical scenarios of transverse granularity investigated

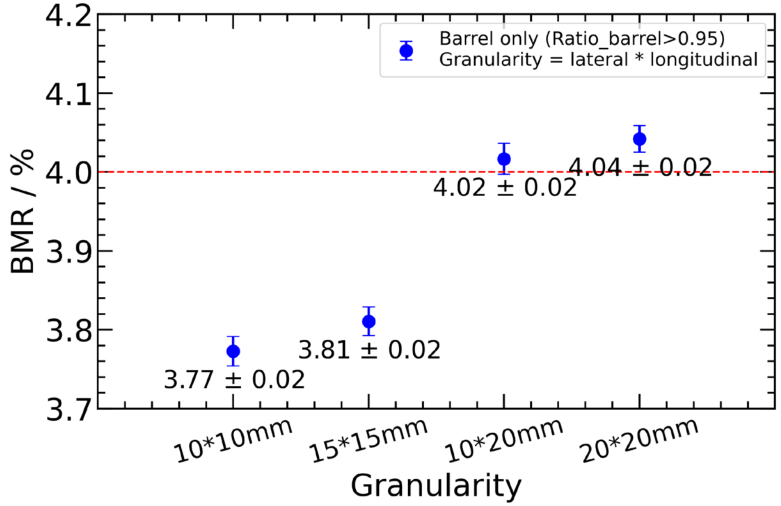
  10×10mm, 10×20mm, 15×15 mm and 20×20mm

- Figures of merit

  Single photon reconstruction, separation power and jet performance

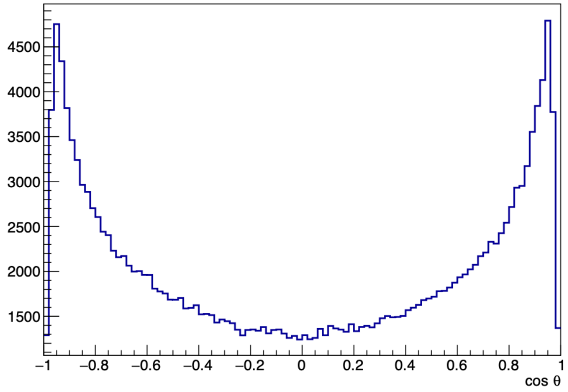




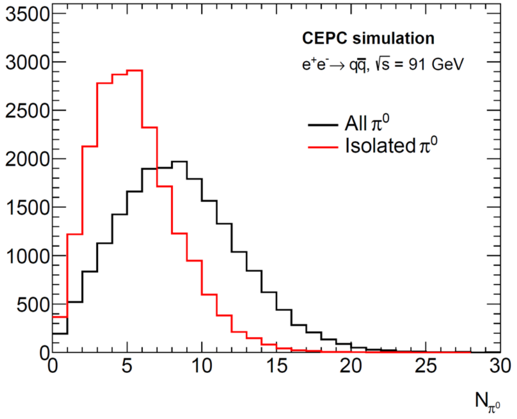


ECAL calibration schemes and precision

- ECAL in-situ calibration based on collision data
  - Bhabha events: 14k events/h at Z-pole for a central barrel module
  - $Z \rightarrow e^+e^-$ events: calibrations for inter-calibration of modules and absolute energy scale
  - π^0 calibration: 40 kHz production rate at Z-pole ($e^+e^- \rightarrow q\bar{q}$); selection of isolated π^0
  - MIP calibration: muons and also “punch-through” hadrons in ECAL (MIP tracking algorithm)
- Calibration precision: target 1% (channel-wise)
  - Contribution of 0.3% to the constant term from 1% of inter-channel calibration precision



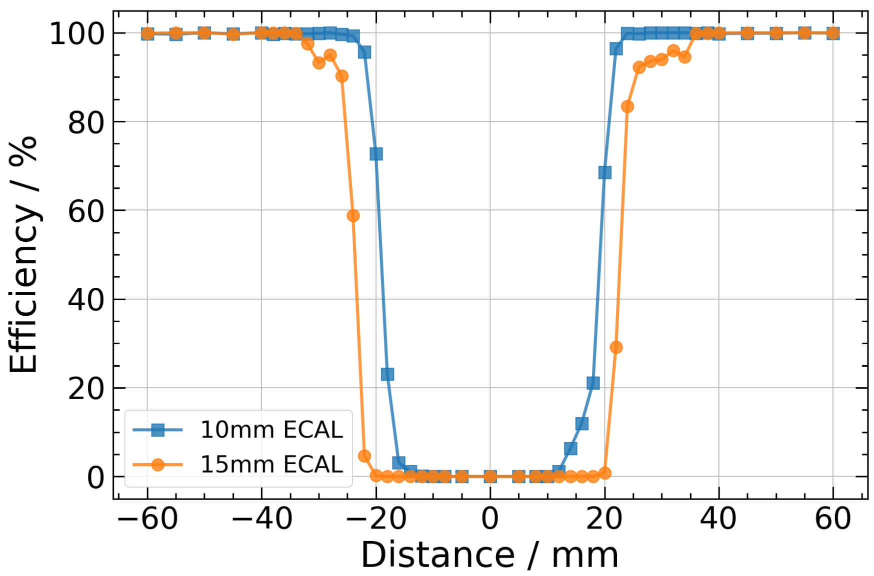
Angular distribution of Bhabha events at 91 GeV



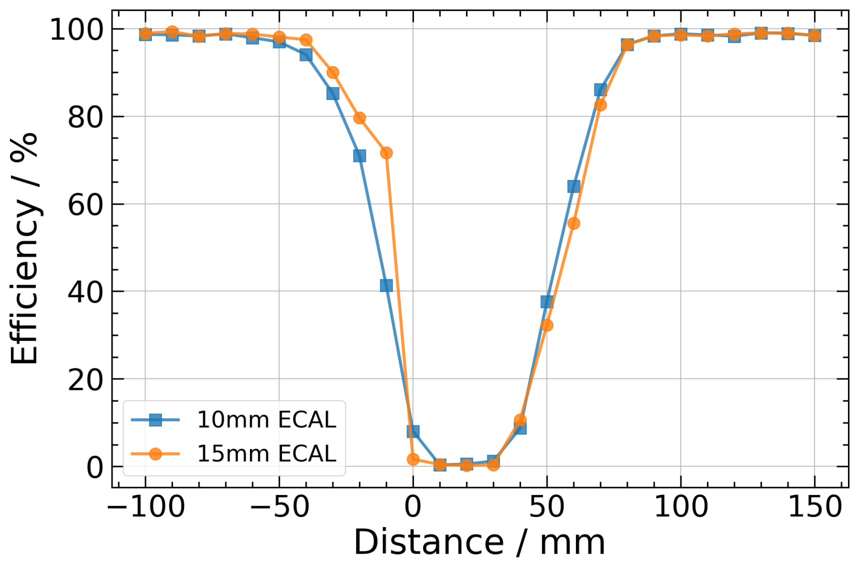
π^0 distributions in barrel ECAL at 91 GeV

ECAL separation power

- CyberPFA: a new PFA developed for the ECAL design with long crystal bars
- Promising separation power: key performance in particle flow
  - Two photons: shows slightly degraded performance in separation efficiency
  - Photon-pion: 15 mm crystal granularity shows similar performance to 10mm granularity



γ-γ separation, 5 GeV



γ-π separation for 5 GeV γ and π^-

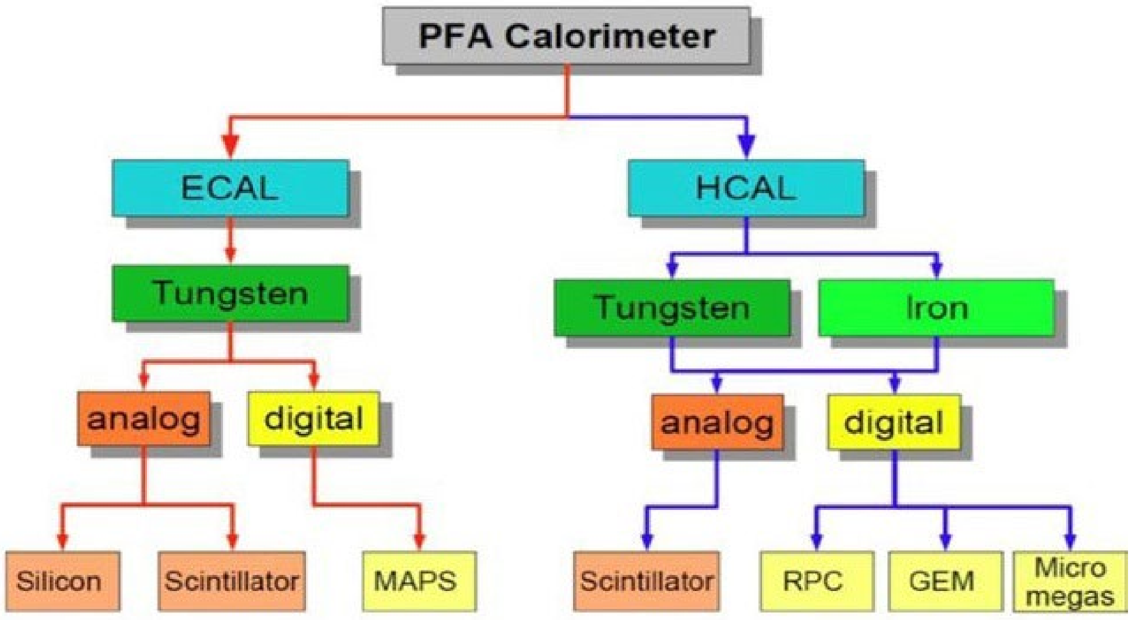
Physics requirements of HCAL

CEPC as Higgs/W/Z bozon factory require:

Boson mass resolution (BMR)<4% (critical for qqH and qqZ separation using recoil mass to di-jet)
Improve BMR to <3% (motivated by BSM&Flavor Physics)
The Particle Flow Approach (PFA) calorimeter concept was proposed (high granularity, good track finding, good energy resolution)

Three options for HCAL were considered

- RPC-DHCAL, SDHCAL, 48 layers
- Plastic scintillator-AHCAL, PS-HCAL, 40 layers
- Glass Scintillator-AHCAL, GS-HCAL, 48 layers

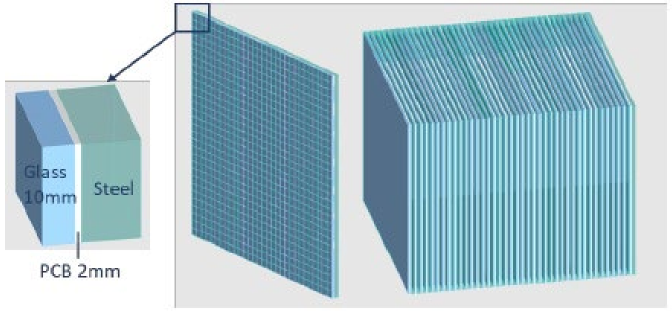


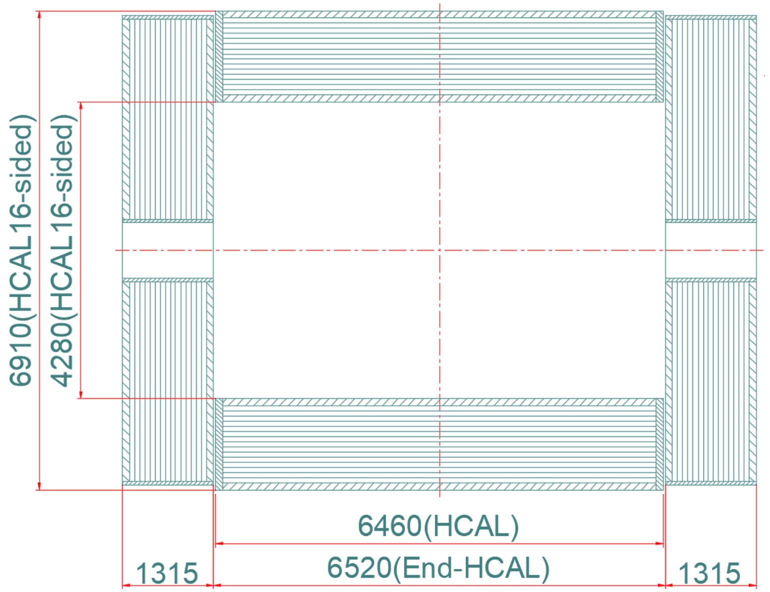
CDR baseline, *arXiv:1811.10545*

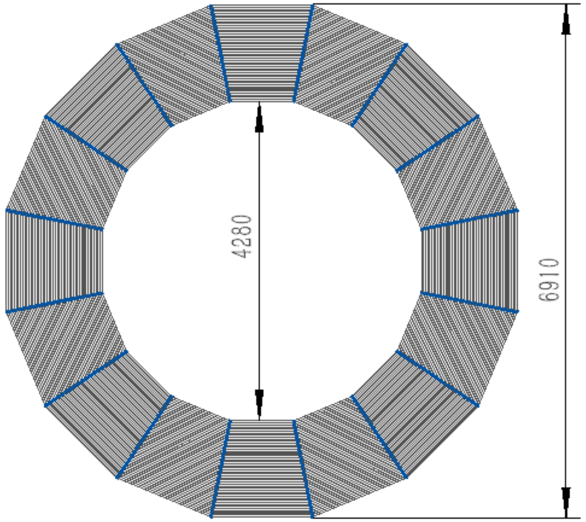
Design of the GS-HCAL

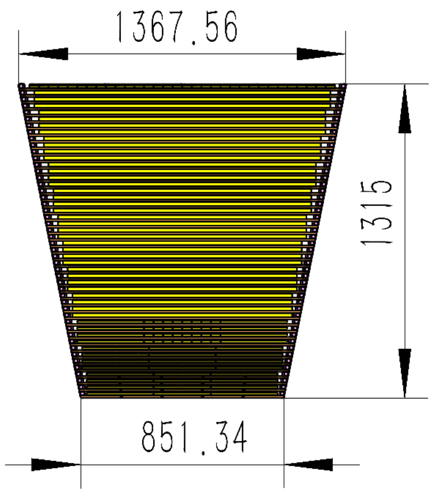
- GS-HCAL: One Barrel (16 wedges) and Two Endcaps
  - Thickness of the Barrel : 1315 mm
  - Inner radius of the Barrel : 2140mm
  - Barrel length along beam direction : 6460 mm
  - Number of Layers : 48 (6 λ_I)

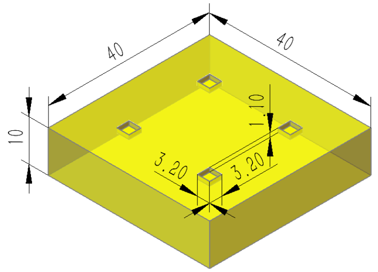
GS-HCAL
Fe: 13.8mm/171.5mm=0.0805 λ_I
GS: 10.2mm/242.8mm=0.0425 λ_I
PCB: 1.2mm/492.2mm=0.0024 λ_I
Sampling fraction ~ 31%











HCAL Performance

4.2 GS-HCAL Physics Performance (C4)

- **Hadron Energy Resolution (full simu. + digitization):**
  - MC Sample: $ee \to ZH \to \nu\nu gg$ @ 240GeV
  - Tracker (Si + TPC) + Crystal ECAL + GS-HCAL, Cyber PFA Reconstruction
- **BMR (H→gg) = 3.87% (barrel), 6% (endcap)**

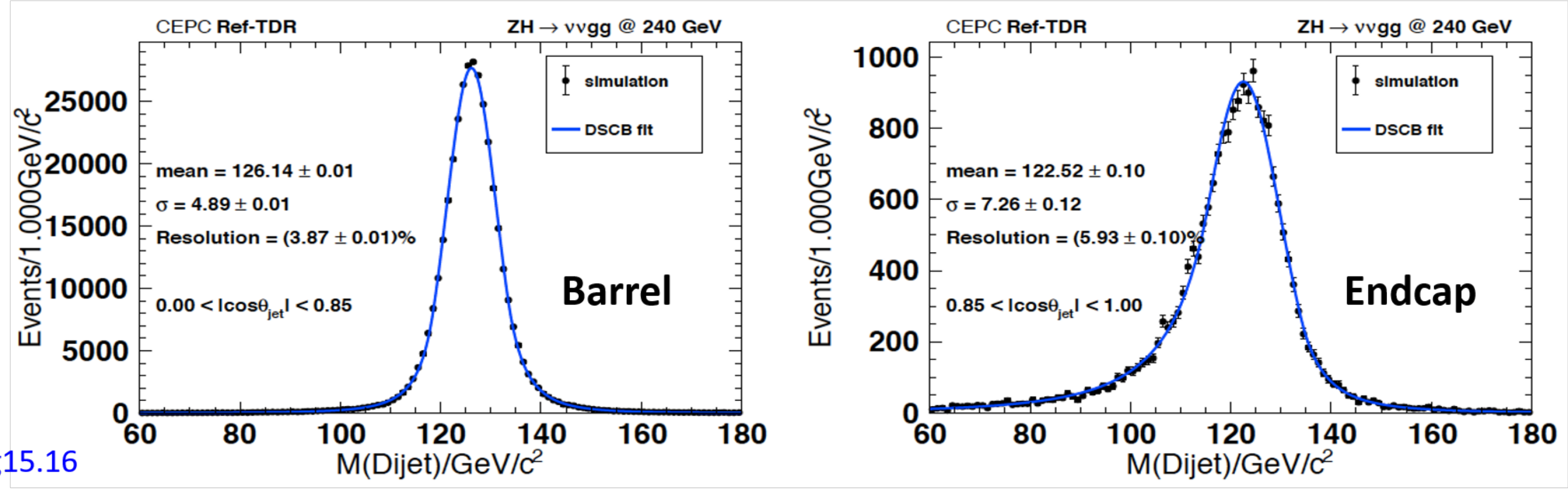


Fig15.16

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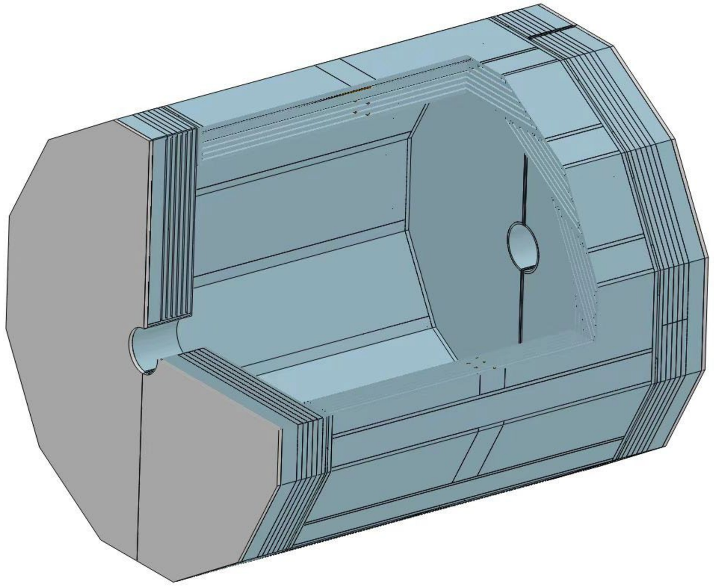
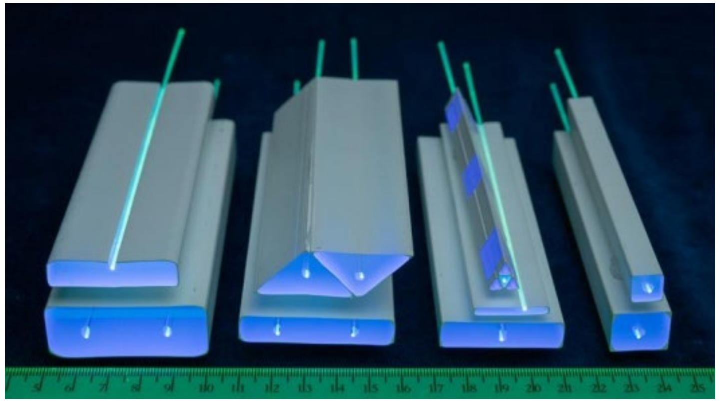
From report of Haijun Yang

CEPC muon detector

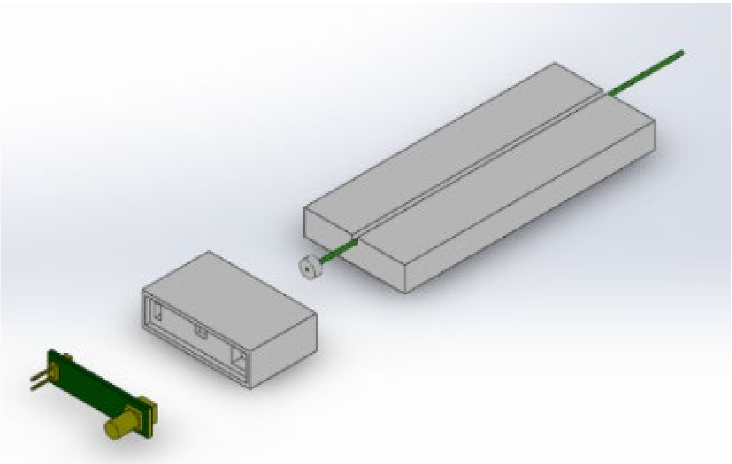
- Solid angle coverage: $0.98 \times 4\pi$
- Detection efficiency: $> 95\%$ (at least 3 layers)
- Fake $\pi \rightarrow \mu$ @ $30\ \mathrm{GeV}/c$: $< 1\%$
- Position resolution: $\sim 1\ cm$
- Time resolution: $\sim 1\ ns$
- Rate capability: $\sim 50\ \mathrm{Hz}/cm^2$



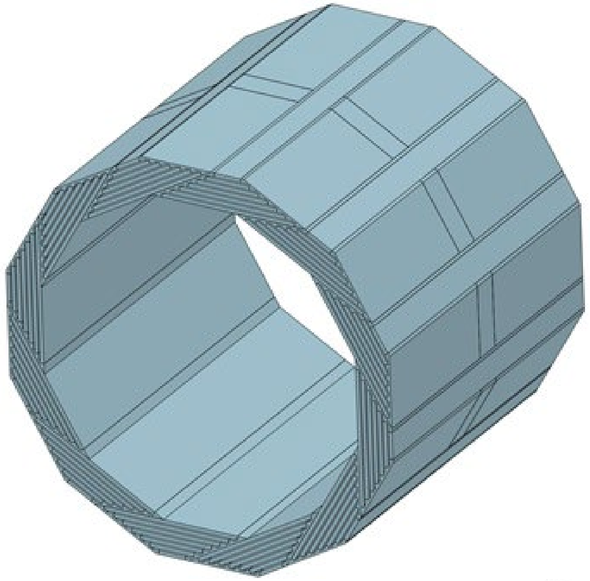


Muon detector is designed for muon identification, but not limited to this:

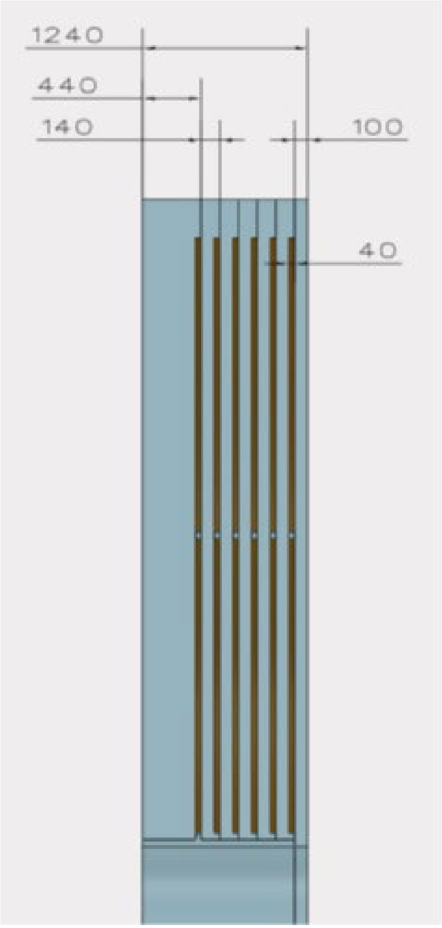
- Could be used to detect the leakage of HCAL
- Can be used for trigger
- Can be used to search for Long-lived particles

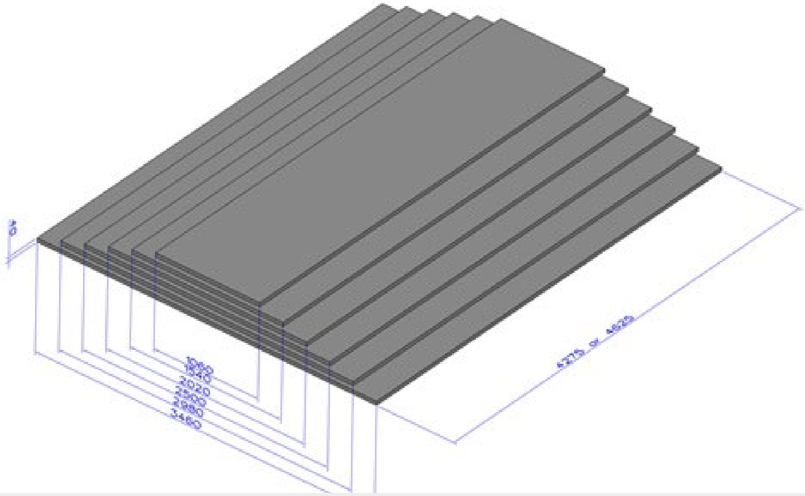


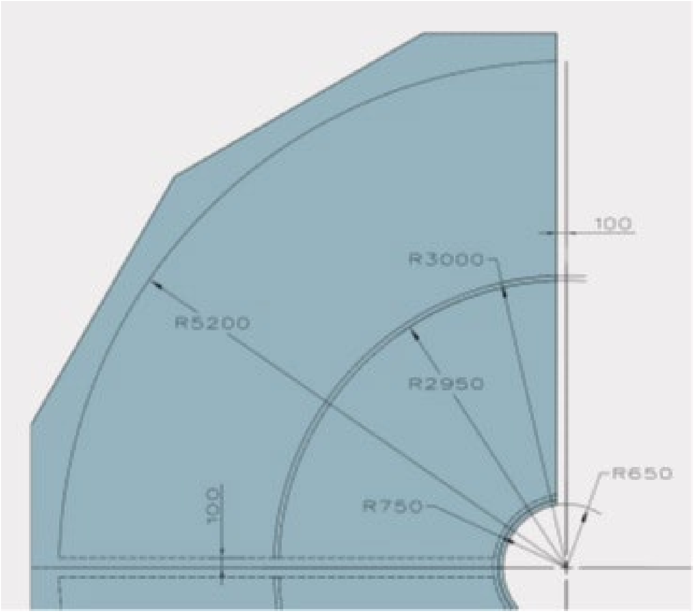
Muon detector design

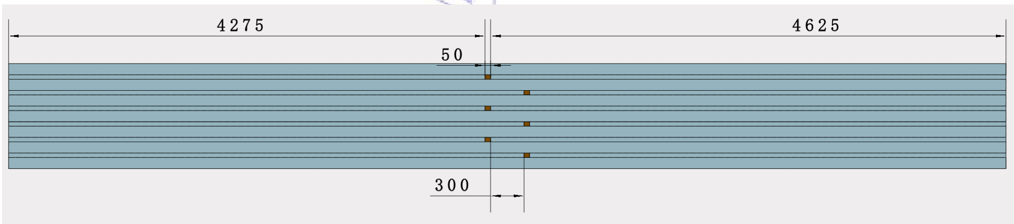


- Barrel: 6 layers, 2 long modules per layer, helix dodecagon
- Endcaps: 6 layers, 4 sectors per layer, two modules (inner and outer) per sector
- Large area modules with long PS bars.
- $43k$ channels, $4.8 \times 10^3\ m^2$ area, and $119\ km$ long fiber, in total.



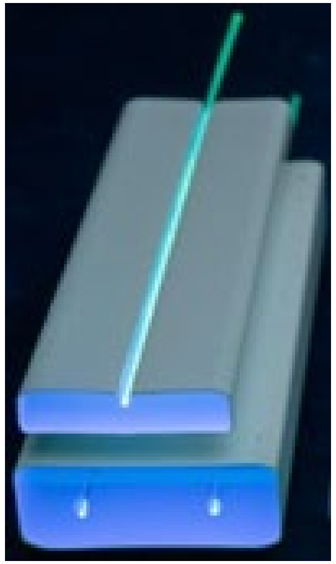






Muon detector challenges

- Long detector module: $> 4m$, due to the large size of the muon detector.
- Plastic scintillation degradation
- How to achieve the required efficiency and the time resolution from a long PS bar?
  - Kuraray fiber has an attenuation length of $> 3.5m$.
  - The key is to increase the light yield and the light collection



Ways to improve light yield:

- Increasing scintillator fluorescence for more light yields
- Fiber embedding into hole, ~40% LY increase
- Diameter of fiber, 1.2 mm → 2.0 mm, x2.8 times LY increase
- Optical glue can increase the N_{pe} by 25-30%

Our plans for participation in CEPC

Physics program:	See a few talks later today
HCAL:	Group members have great experience in design, construction, commissioning hadron calorimeter of the ATLAS experiment at the LHC, in development of calibration methods
ECAL:	We have extensive experience in testing crystals, studying their radiation resistance, developing and manufacturing crystal calorimeters, and studying their parameters.
TPC:	DLNP has well developed lab and experienced staff for development of Micromegas detectors
Muon detector:	Group has big expertize in development and construction of muon detectors for CDF and Mu2e at Fermilab, Comet at J-PARC.

Summary

- The preparation of the CEPC project is progressing successfully and is approaching the stage of readiness of the TDR and the creation of international collaborations. A decision on whether to begin construction of the collider is expected in about a year (?)

- The JINR group plans to join the work on preparing the CEPC project and actively participate in the development of the physics research program at the collider, in R&D for the creation and development of calibration methods for hadron and electromagnetic calorimeters, a muon detector, and a pixelated TPC

Thank you for your attention!