Школа по информационным технологиям ОИЯИ

Joint Institute for Nuclear Research

SCIENCE BRINGS NATIONS TOGETHER

At The Frontiers of Particle Physics

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Content

Lecture 1. At The Frontiers of Particle Physics

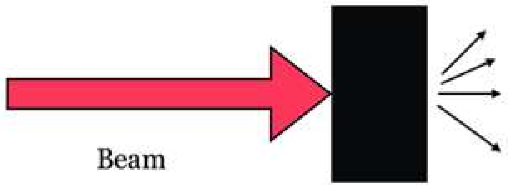
- What does Particle Physics do?
- How does Particle Physics do?
  - ✓ Physics Tools
  - ✓ Why do we need accelerator facilities?
  - ✓ Do we need more and more new accelerator facilities?
- Where Particle Physics Frontiers are (mainly LHC examples)
  - ✓ Selected hot points of particle physics
  - ✓ Is new physics really needed?

Lecture 2. Data Analysis in High Energy Physics (18 October)

- How do we achieve results?
  - ✓ Event Selection
  - ✓ Reconstruction of physics objects
  - ✓ Reconstruction of physics processes
  - ✓ Physics Analysis (Statistics and Monte Carlo tools)
- Something else?

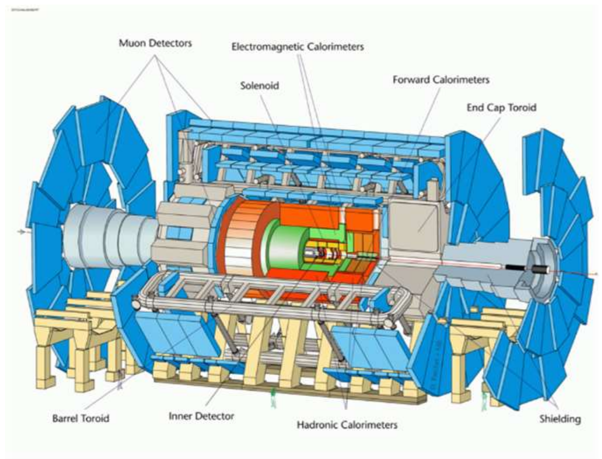
Examples of Experimental Facilities

$$E_{cm} = \sqrt{4E_1E_2}$$

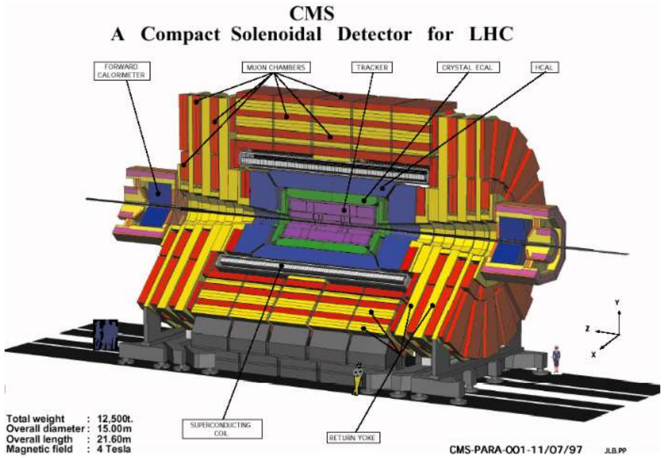


$$E_{cm} = \sqrt{2m_{target}E_{beam}}$$

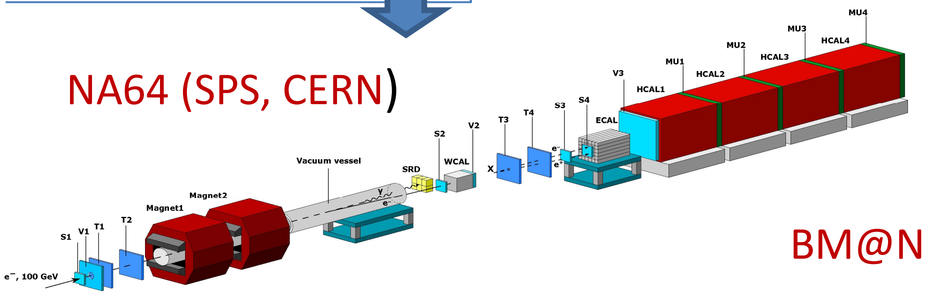
ATLAS (LHC, CERN)



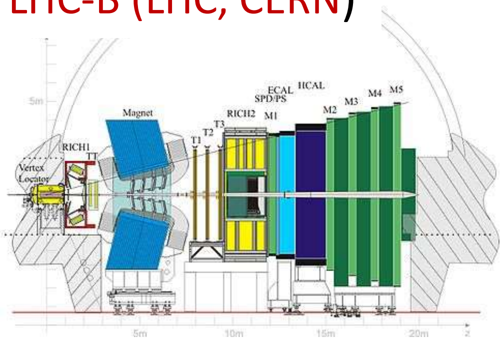
CMS (LHC, CERN)



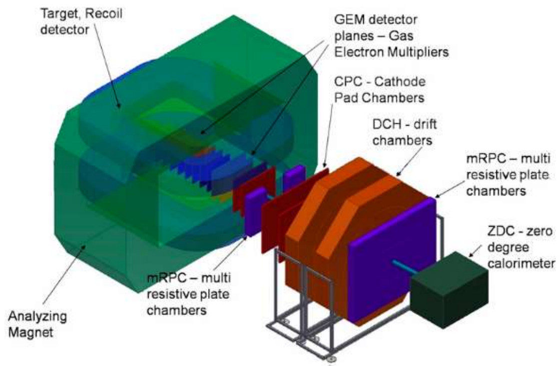
NA64 (SPS, CERN)



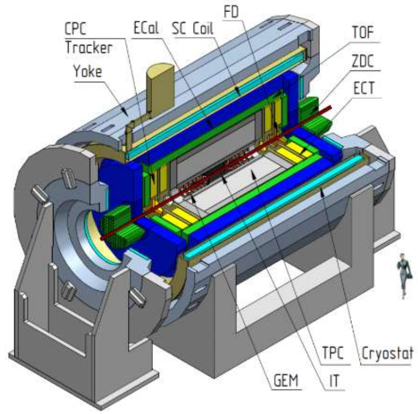
LHC-B (LHC, CERN)



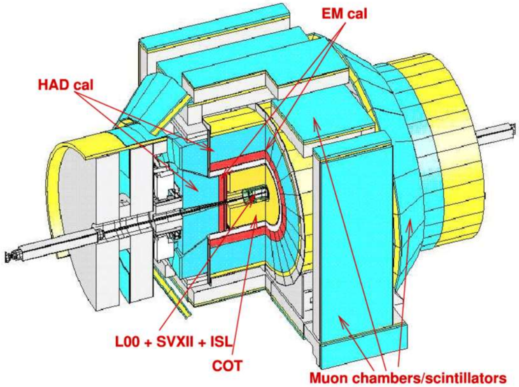
BM@N (NICA, JINR)



MPD (NICA, JINR)



CDF (Tevatron, FLab)



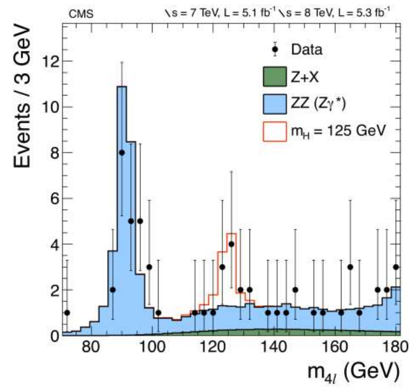
Scale without preservation of proportions

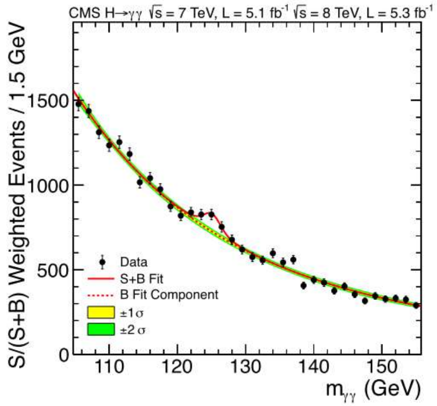
What do physicist want to see?

Higss Boson

From design

to discovery





4 July 2012

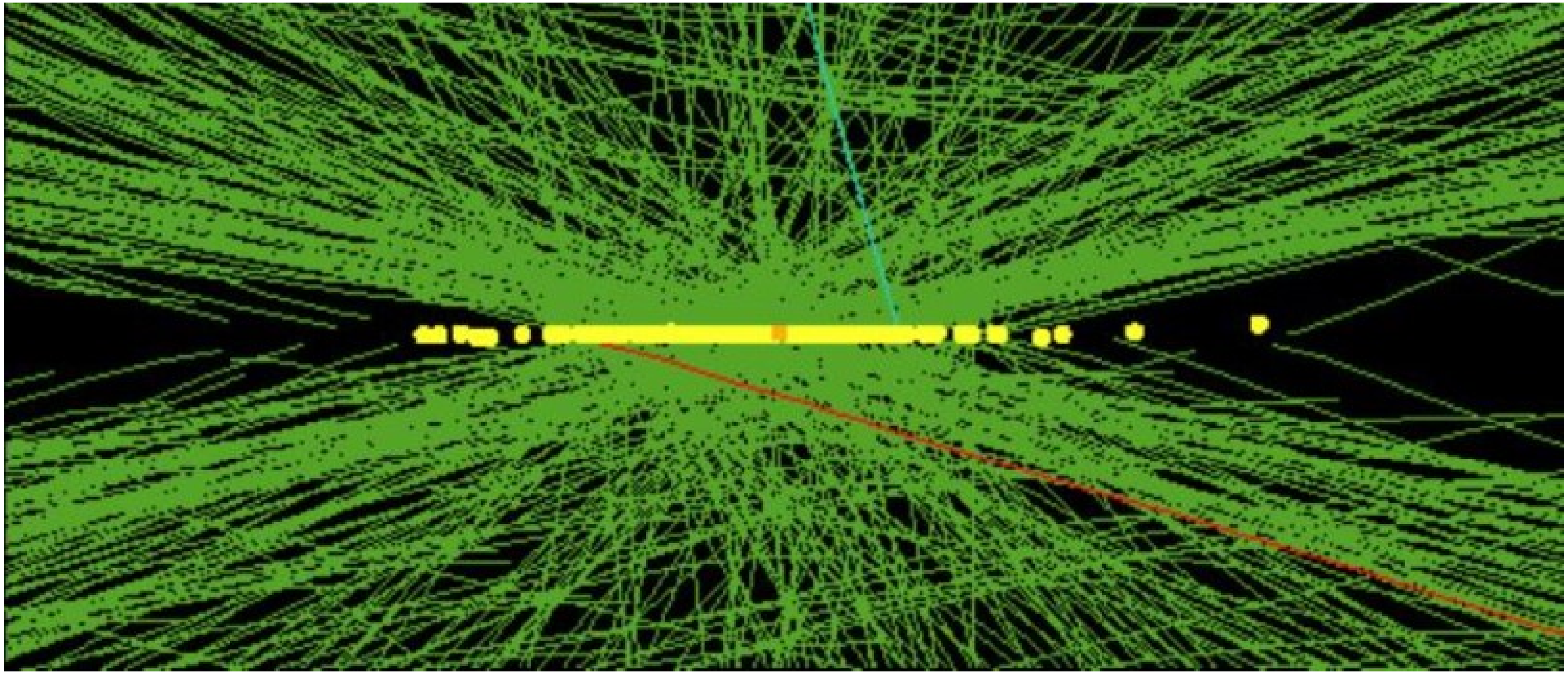
Higgs announcement at CERN

	Int. Luminosity at 7, 8 TeV	mH [GeV]	Expected [st. dev.]	Observed [st. dev.]
ATLAS	10.7 fb^{-1}	126.0 ± 0.6	4.6	5.0
CMS	10.4 fb^{-1}	125.3 ± 0.6	5.9	4.9

What do they actually see?

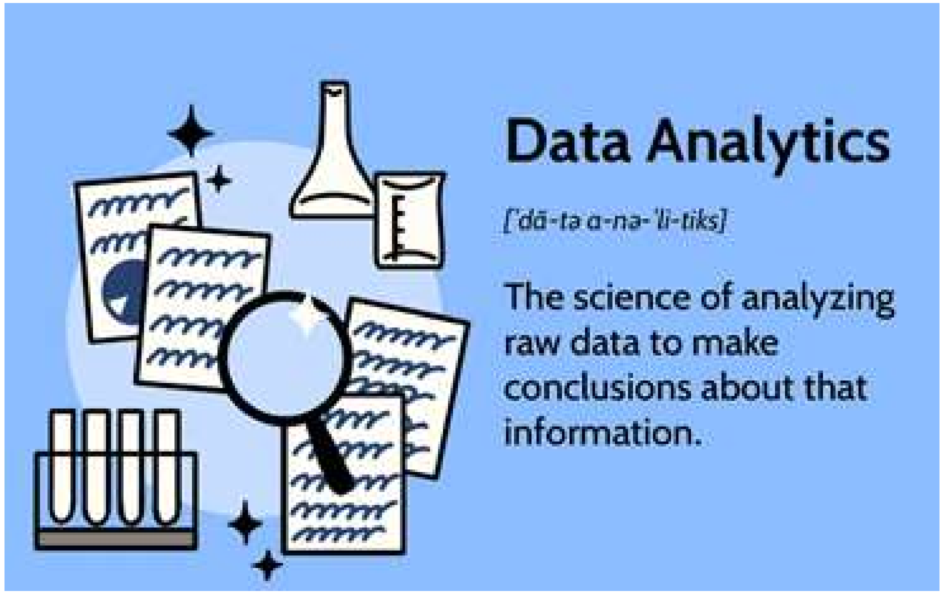
Real CMS Event with High Pile-up

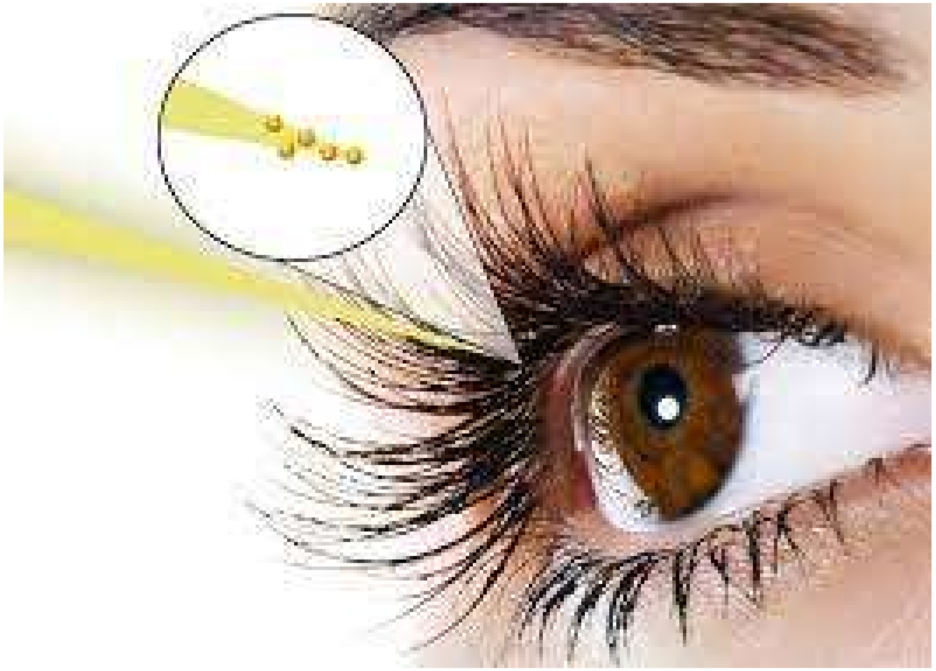
High pileup event with 78 reconstructed vertices taken in 2012 by CMS



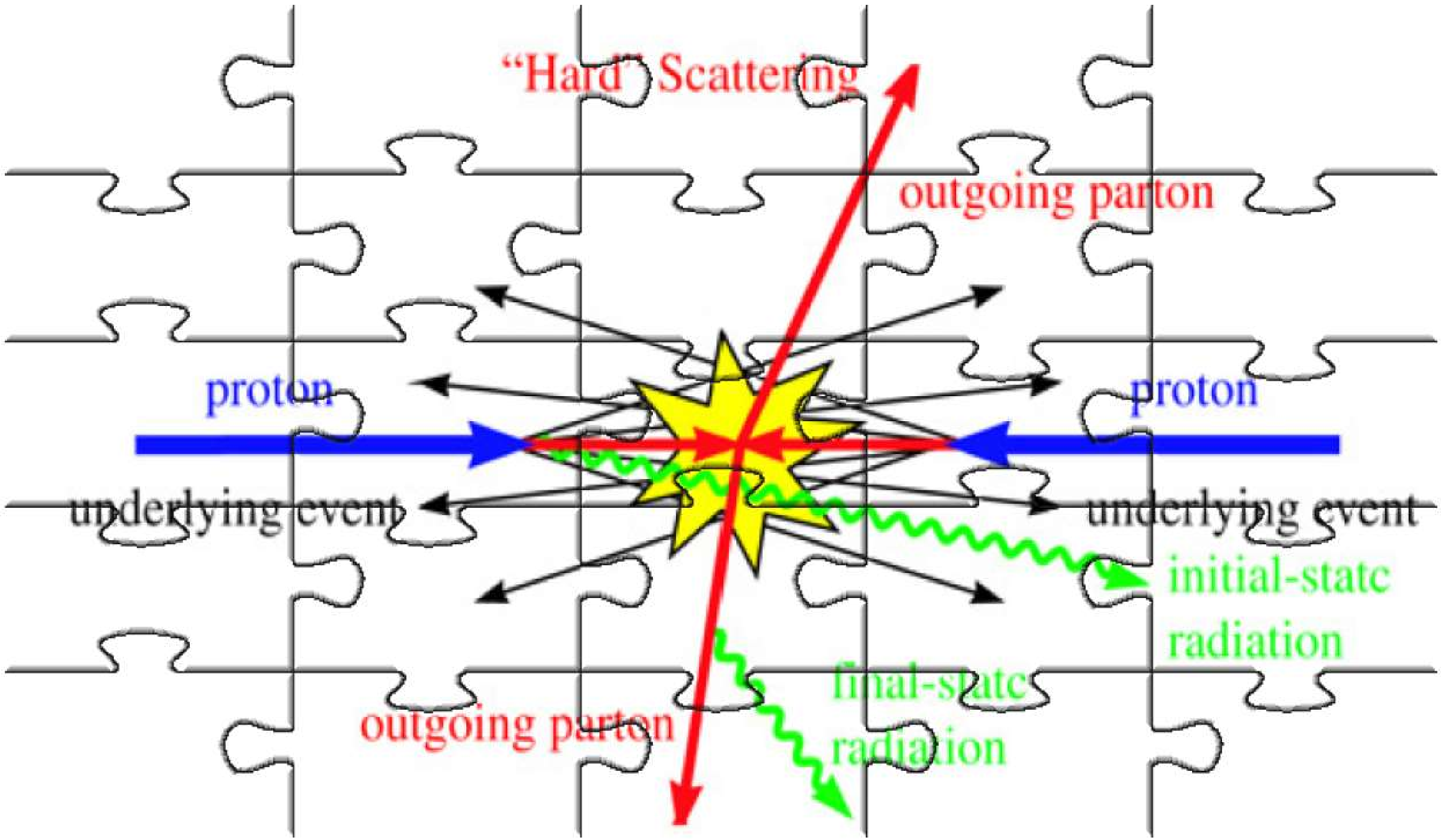
What is happening and and what we can do about it…

- Physics objects
- Event Selection
- Reconstruction and Processing
- Data Analysis



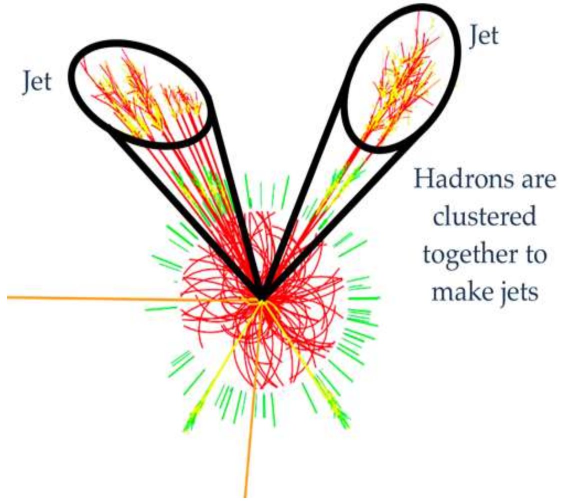


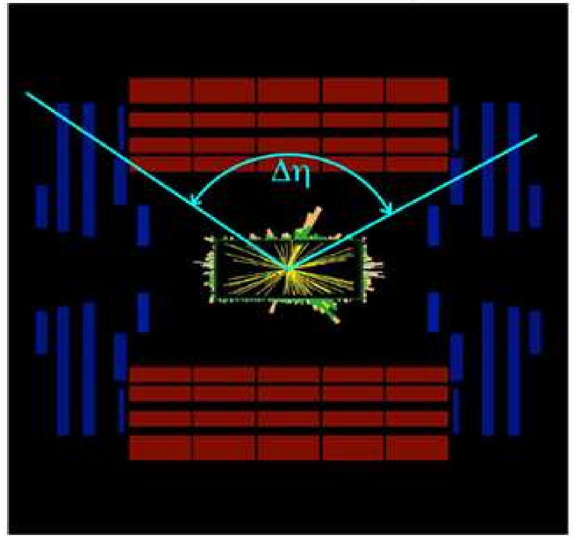
Mosaic of Collisions



Physics Objects

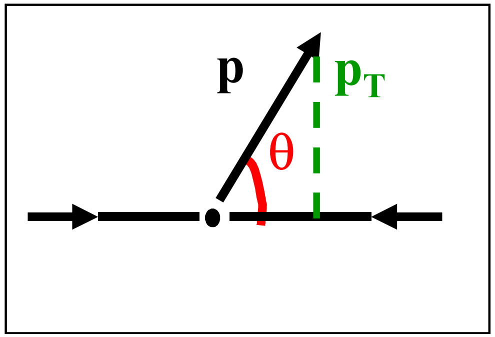
- Muons (transverse momentum p_T)
- Electrons (energy and tr. momentum p_T)
- Photons (energy)
- Jets (energy and coordinates)
- …..
- Missing energy and p_T
  - vectorial sum of all transverse momentum

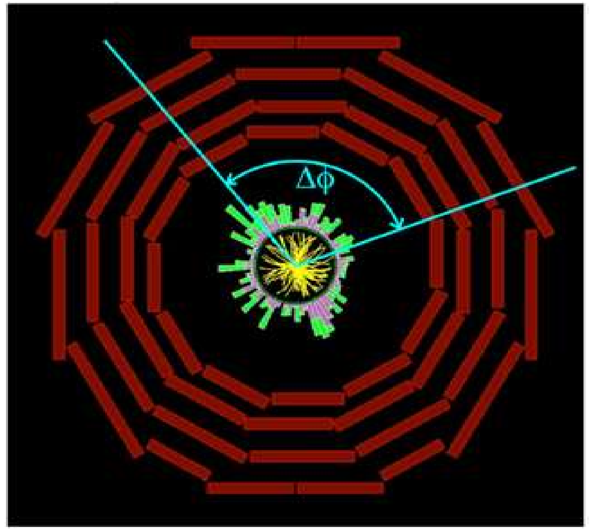




Kinematic Variables

- Transverse momentum p_T (energy)
  - particles that escape detection have p_T=0
  - total visible p_T = 0
- Longitudinal momentum p_Z and energy E_Z
  - particles that escape detection have p_T=0
  - visible p_Z is not conserved (not so usefull variable)
- Angles
  - azimuthal and polar angles
  - polar angle θ is not Lorenz invariant ⇒
  - rapidity y
  - or (or m=0) pseudorapidity η





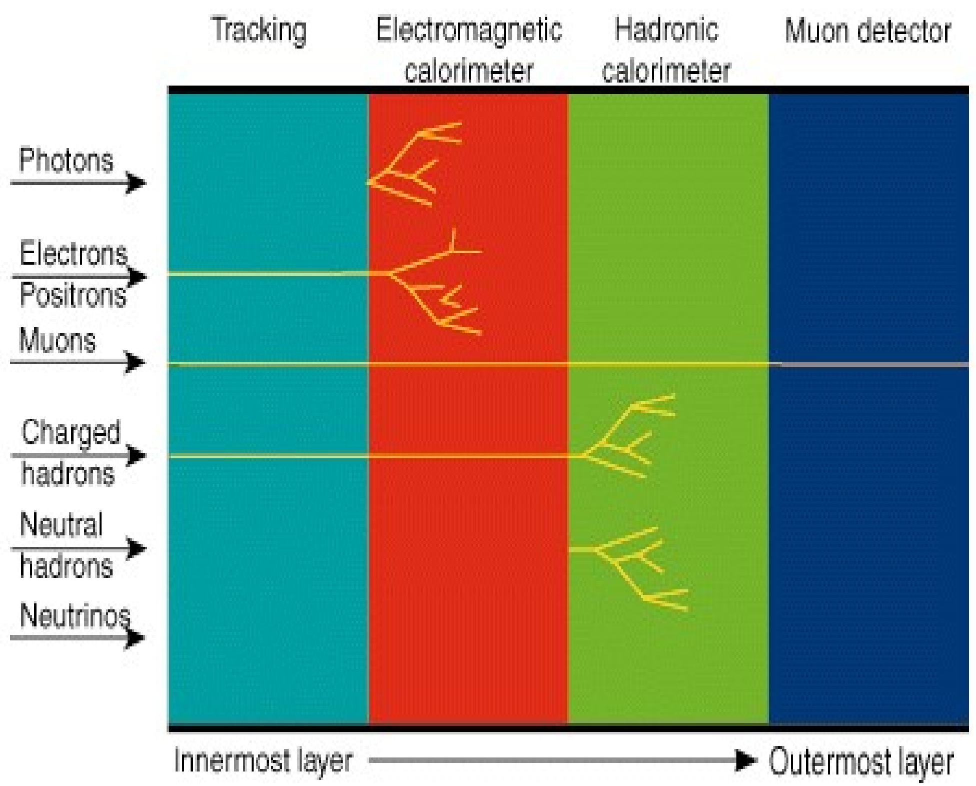
$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

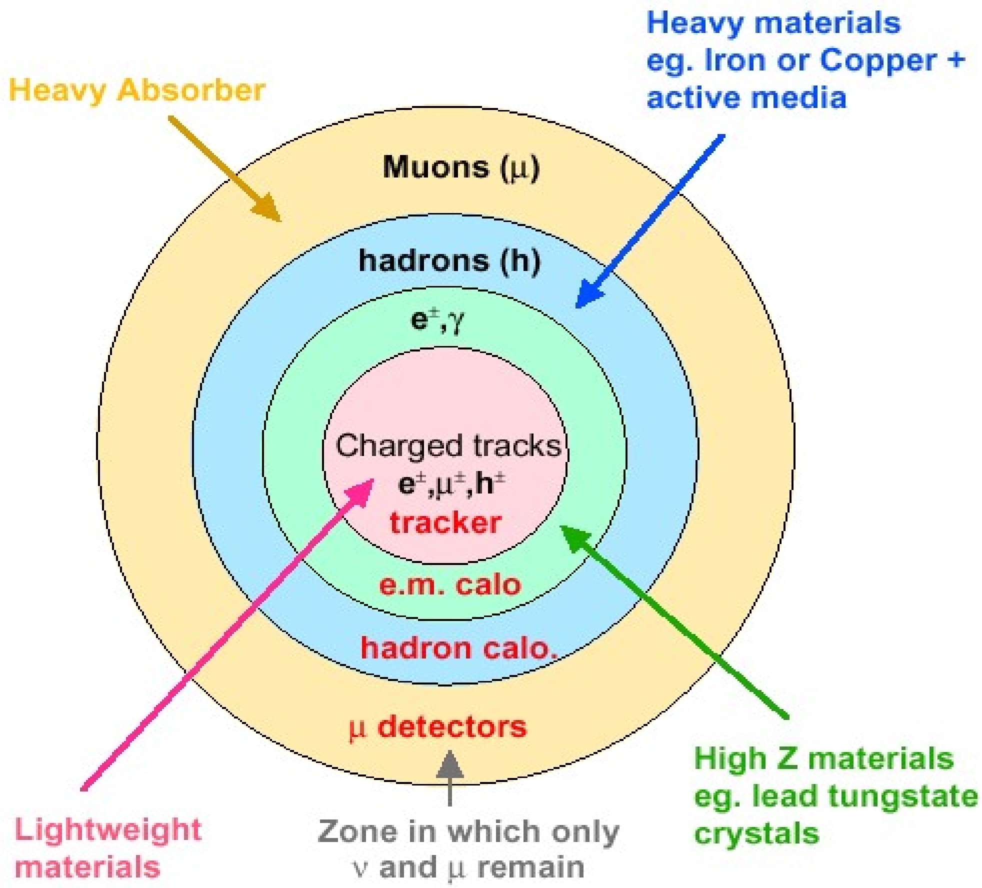
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

4π-experiments cover 360^0 over ϕ and large pseudorapidity range, |η| ≤ 5.0 (0.8^0)

Modus Operandi for Experiments

Onion structure of detector layers placed in B-field



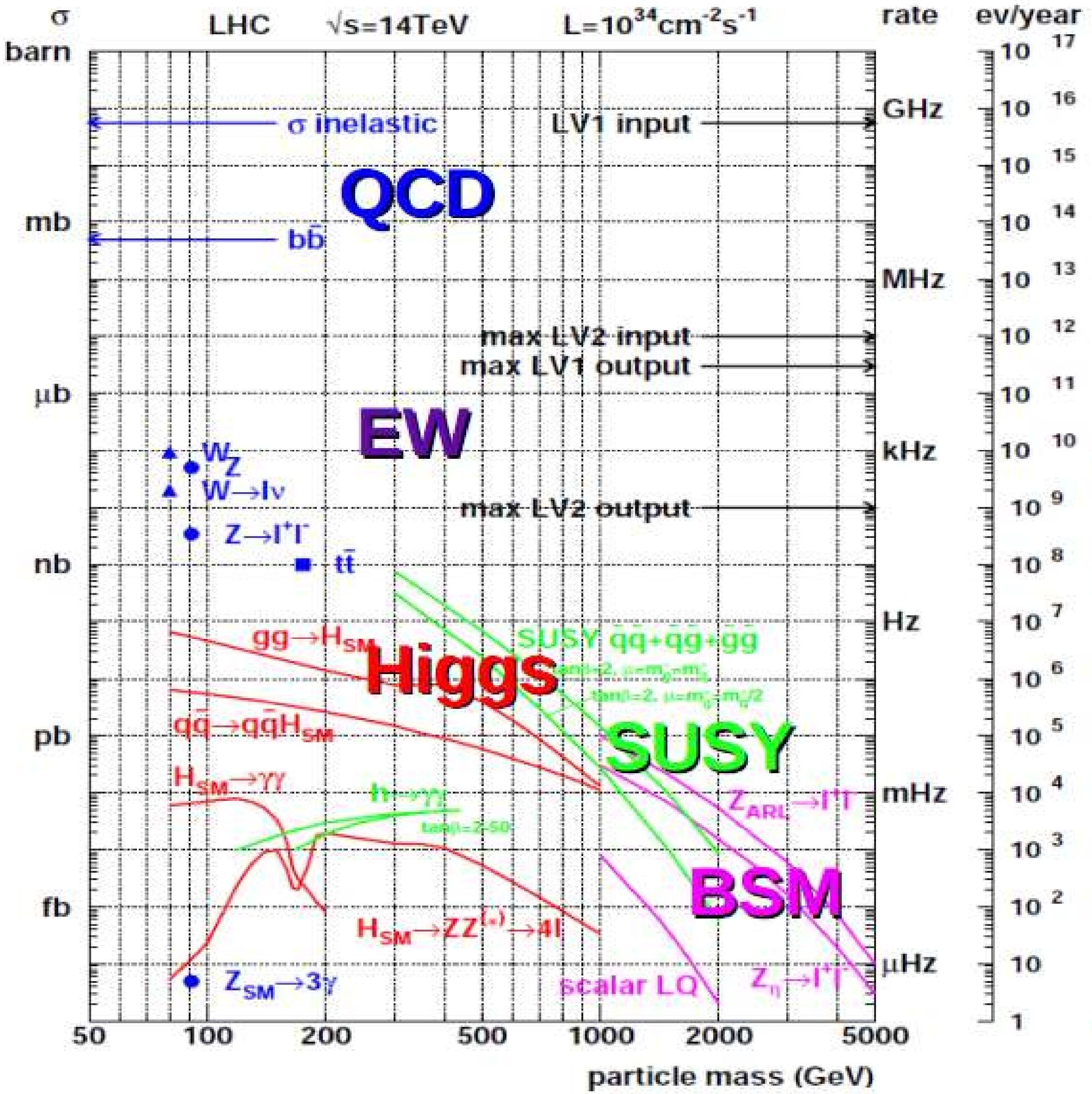


Each layer identifies and measures (or remeasures) the energy of particles unmeasured by the previous layer

No single detector can determine identity and measure energies/momenta of all particles

Event Selection and Data Flow

Physics Processes at LHC



- SM processes:

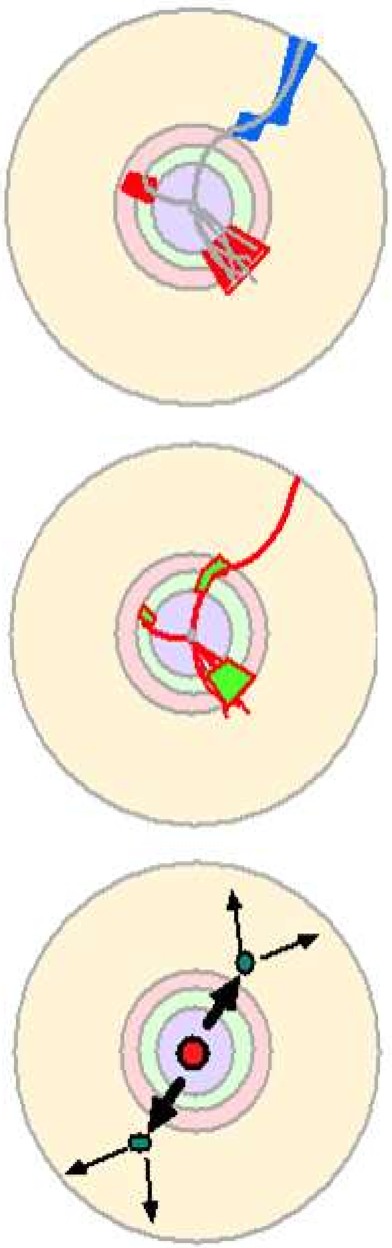
  $\sigma \sim 1/(100\ \text{MeV})^2$

10^{-8} !

- New Physics:

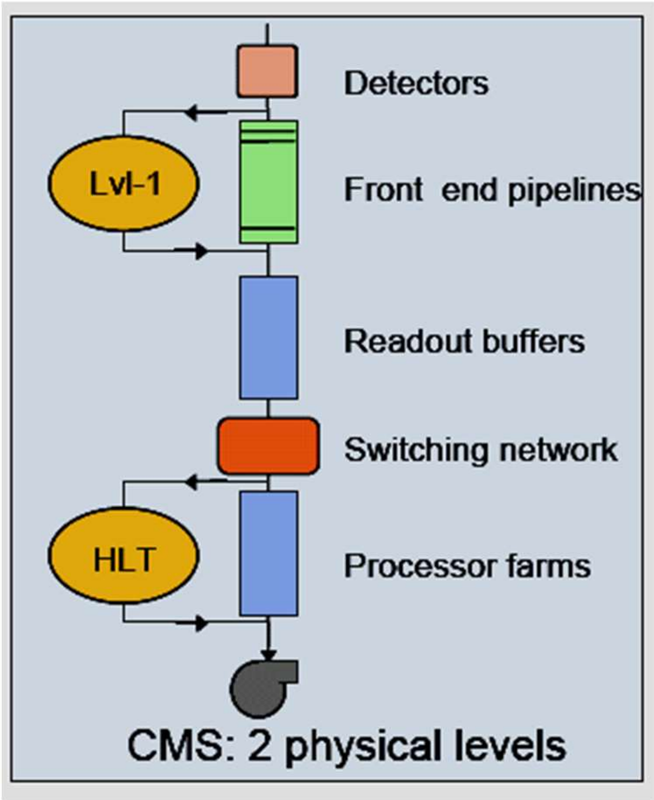
  $\sigma \sim 1/(1\ \text{TeV})^2$

Multi-Layer Selection and Triggering

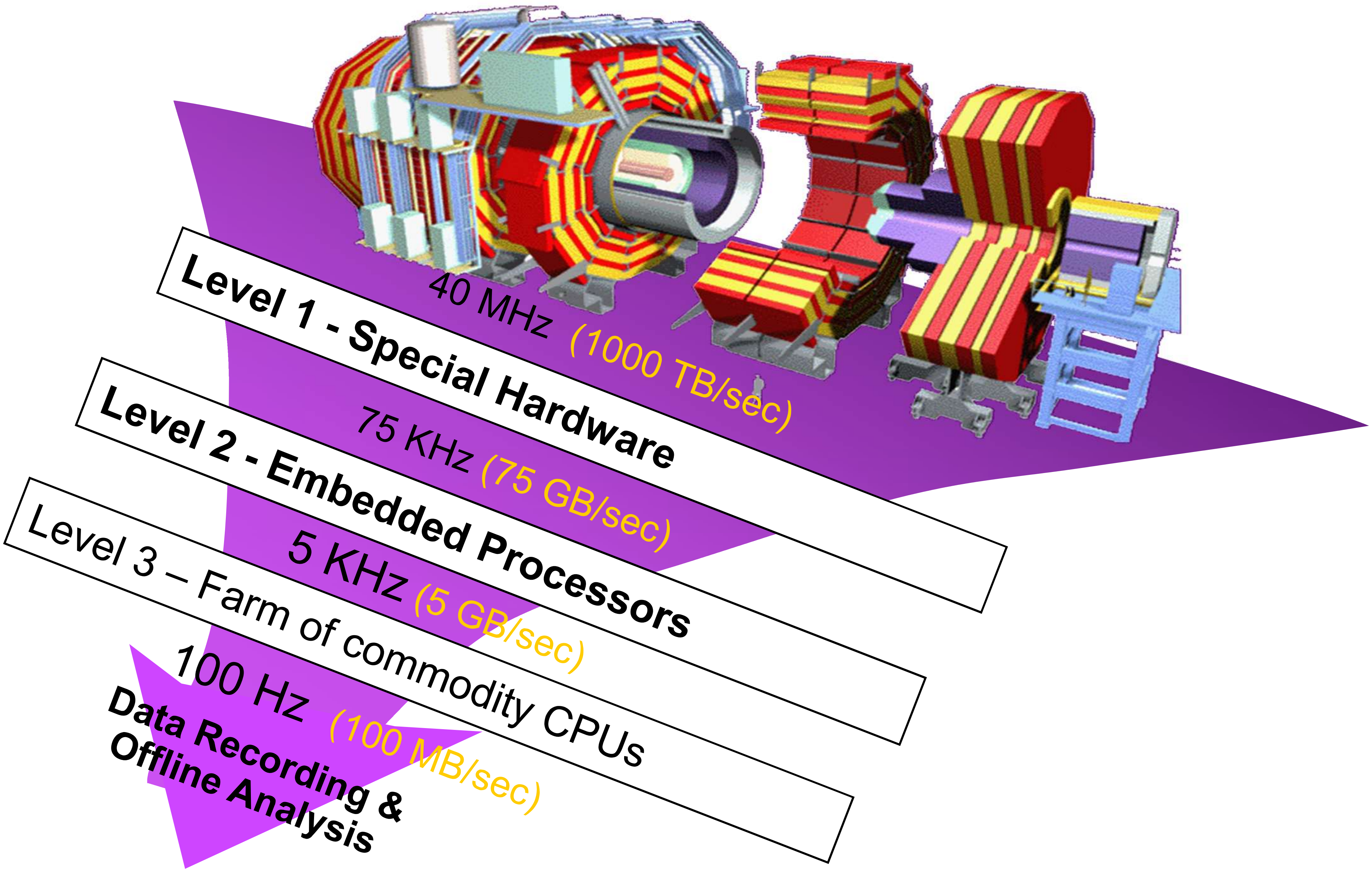


- **Level-1:**
  Hardware selection is comprised of custom electronics that process data from detectors, rough cutoffs

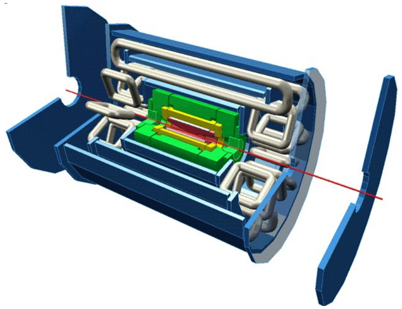
- **High Level Trigger:**
  Software selection based on reconstruction of physics objects, event topology

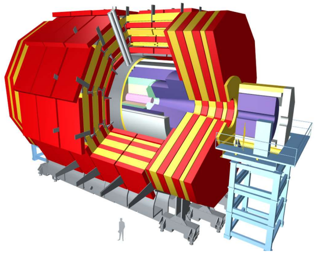


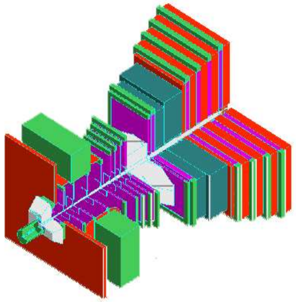
Trigger Rates

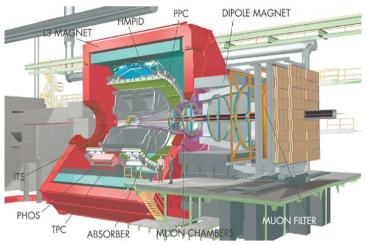


Data Flows









	Level-1 kHz	Event MByte	Storage MByte/s
ATLAS	100	1	100
CMS	100	1	100
LHCb	400	0.1	20
ALICE	1	25	1500

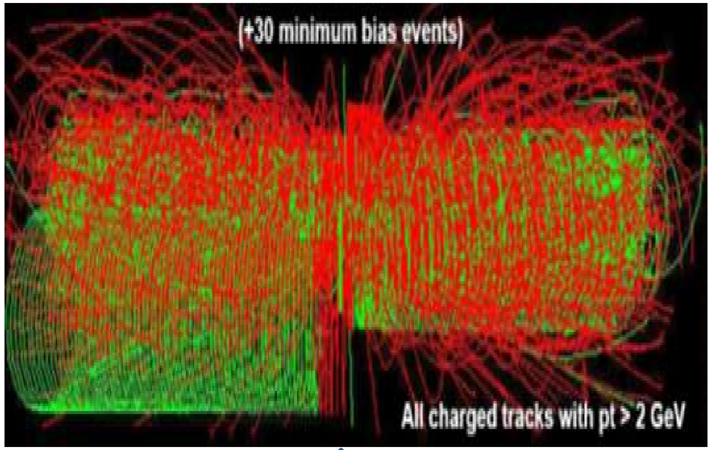
~ 3PB/year

Big Data/GRID Computing

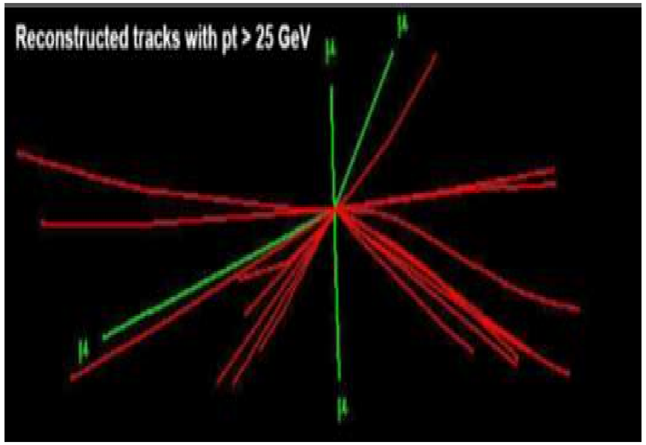
Data Processing and Analysis

RAW Data

Reconstruction

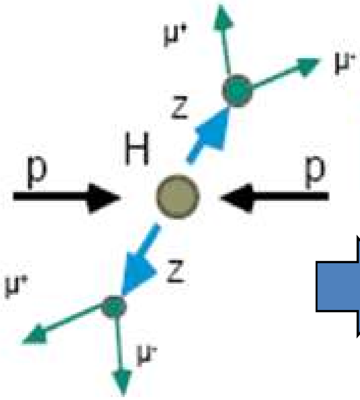


Event Selection

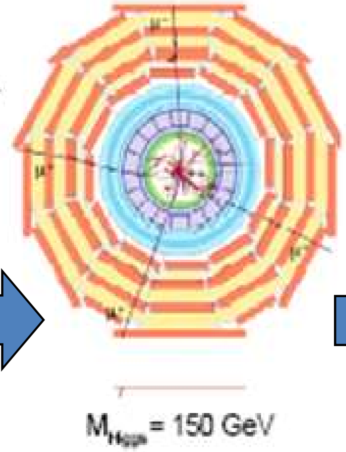


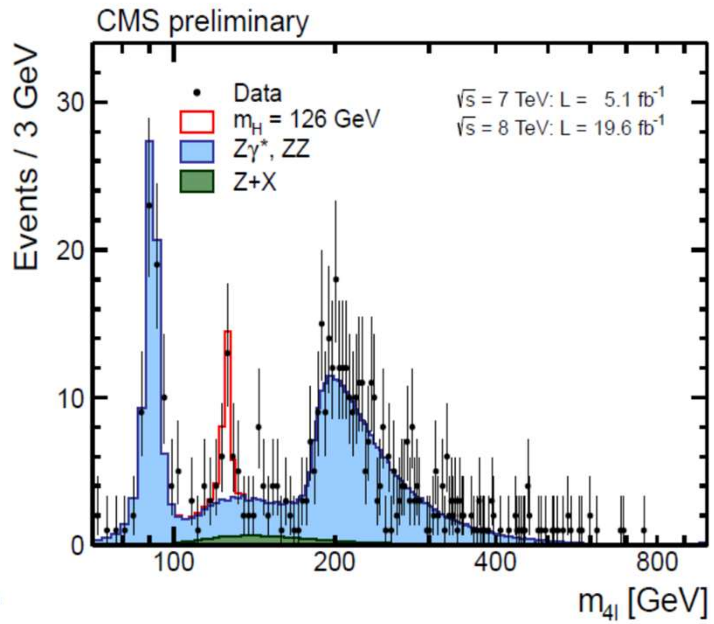
Calibration/Condition/etc
Data Bases

Theory/
Monte Carlo
Simulation

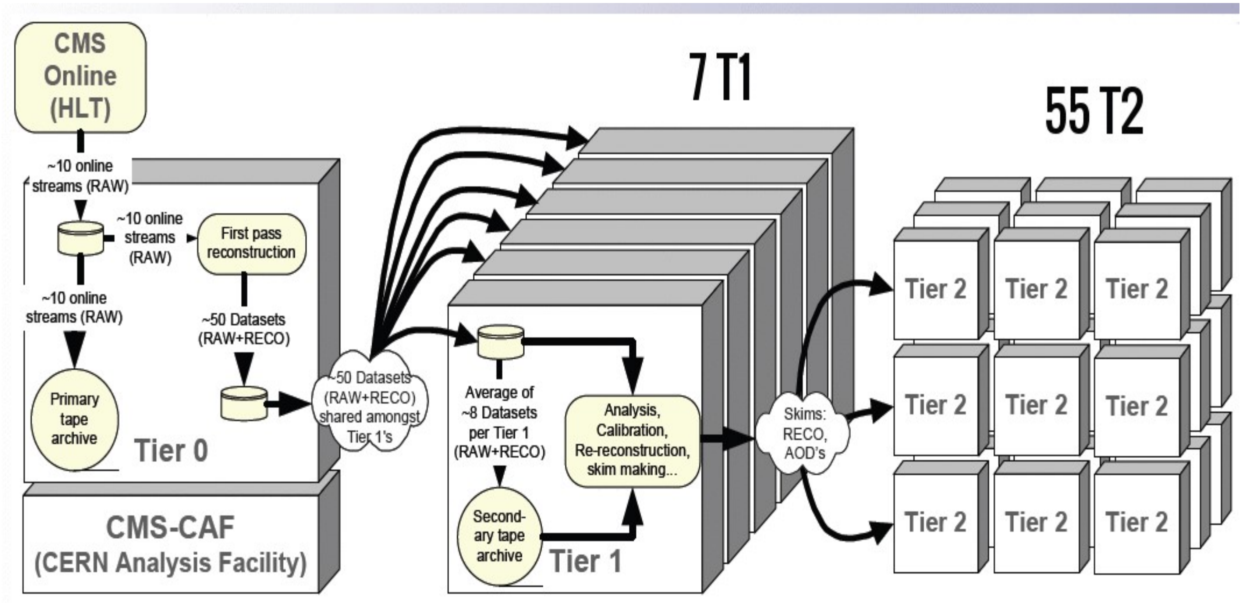


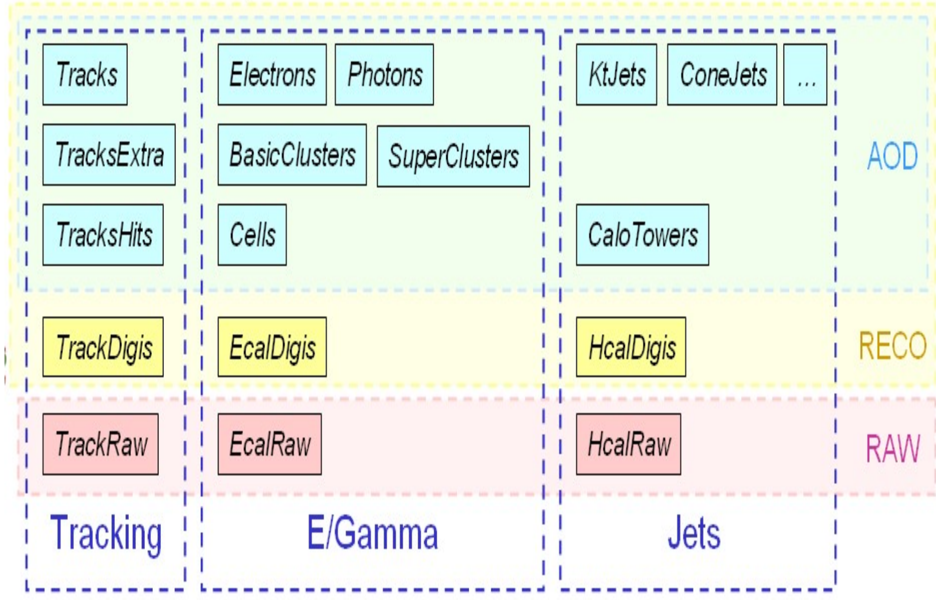
Detector Response
Simulation



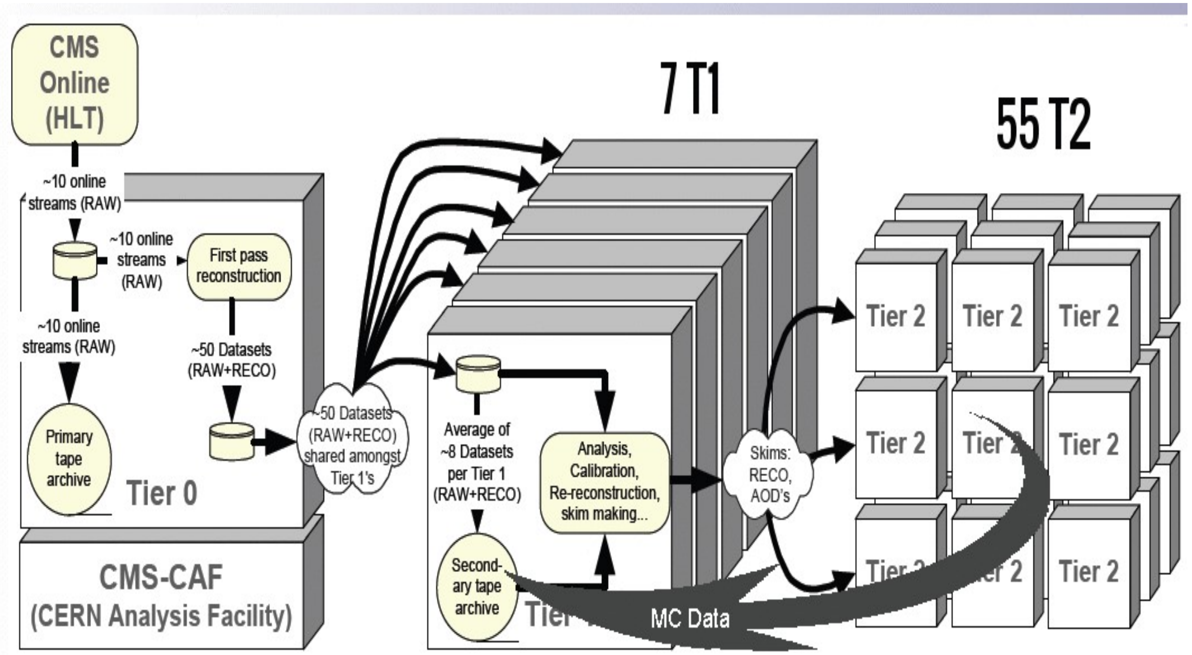


Data Model and Data Flow through Tiers



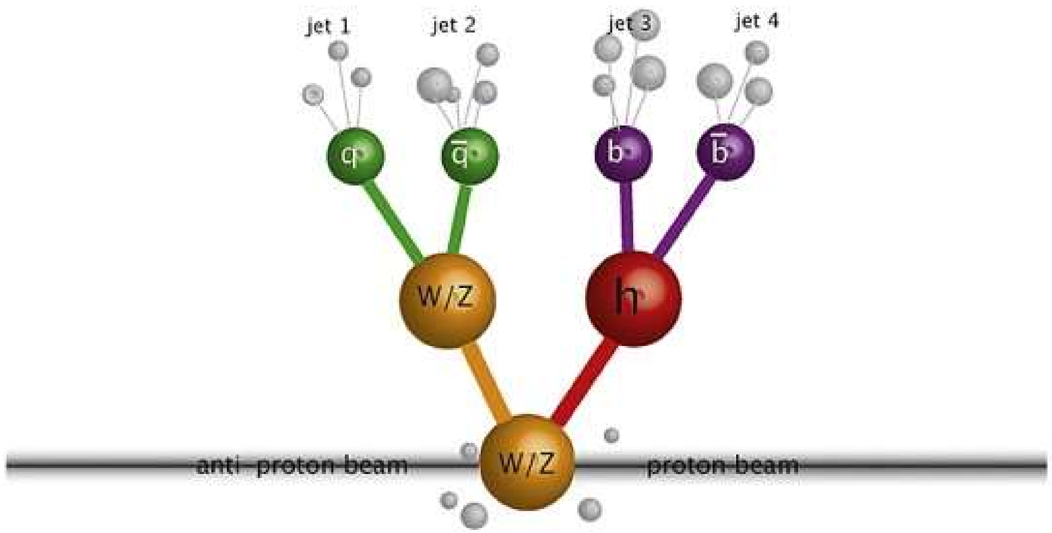


- T0 ⇒ T1
  - ✓ scheduled, time-critical, will be continuous during data-taking periods
  - ✓ reliable transfer needed for fast access to new data, and to ensure that data is stored safely
- T1 ⇒ T1:
  - ✓ redistributing data, generally after reprocessing (e.g. processing with improved algorithms)
- T1 ⇒ T2:
  - ✓ Data for analysis at Tier-2s

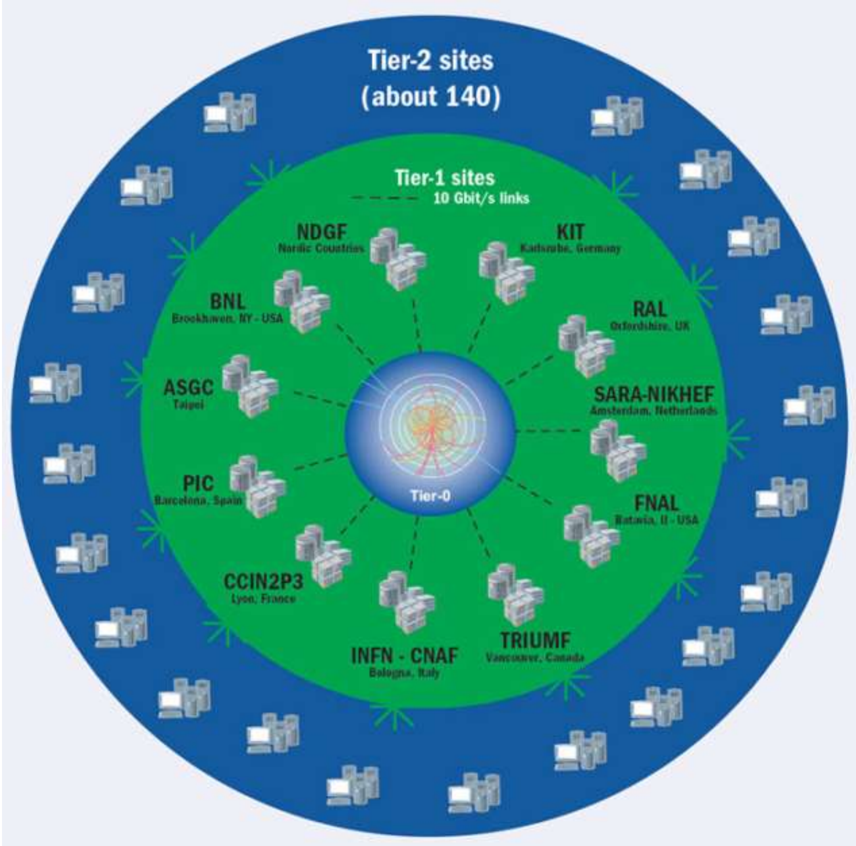


Event Reconstruction

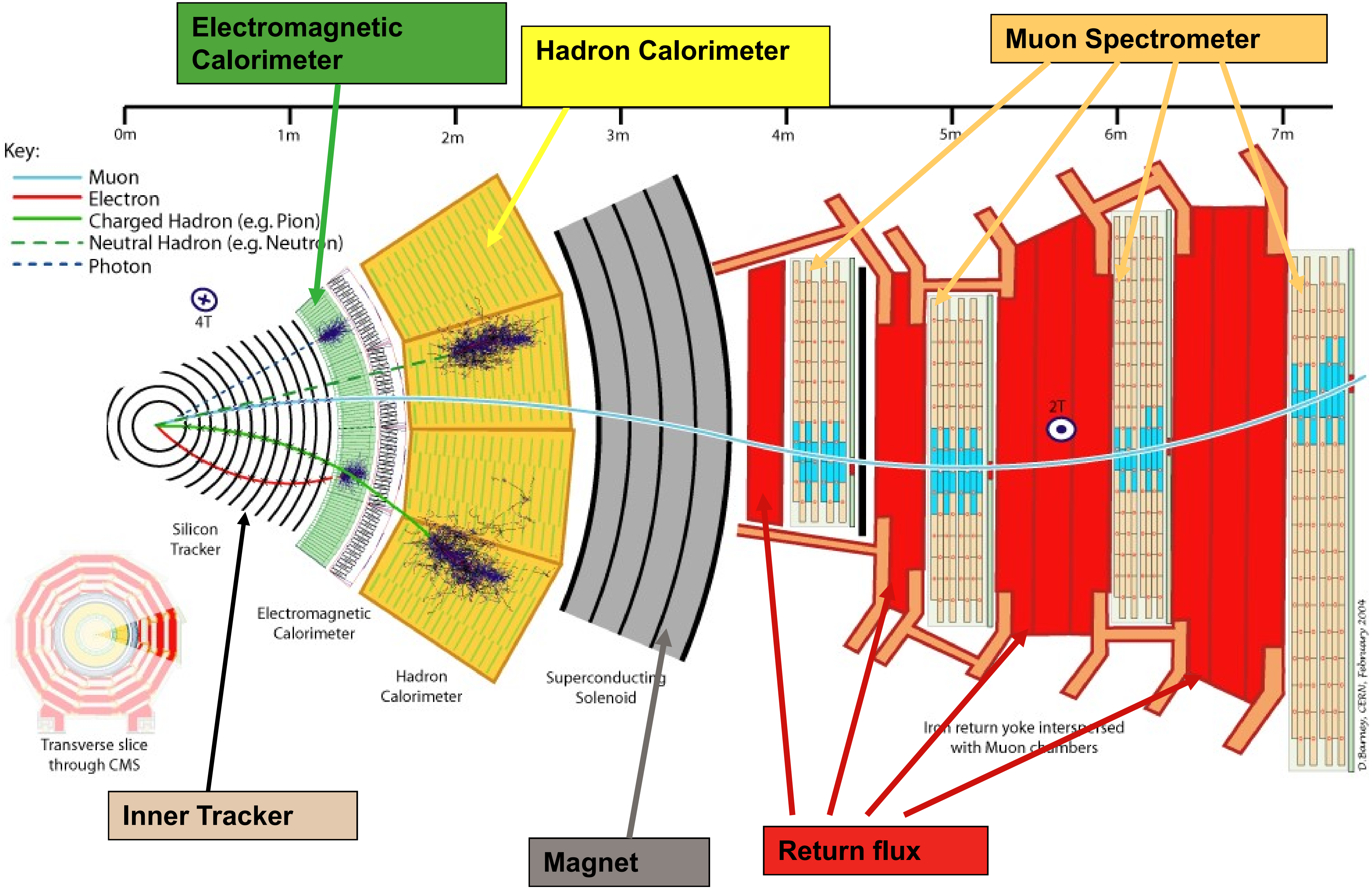
- Reconstruction (mathematical methods/algorithms/SW)
  - ✓ physics objects - stable particles (e, μ, γ), clusters of particles (energy), vertexes, etc
  - ✓ unstable particles/ physics processes



- Data Processing

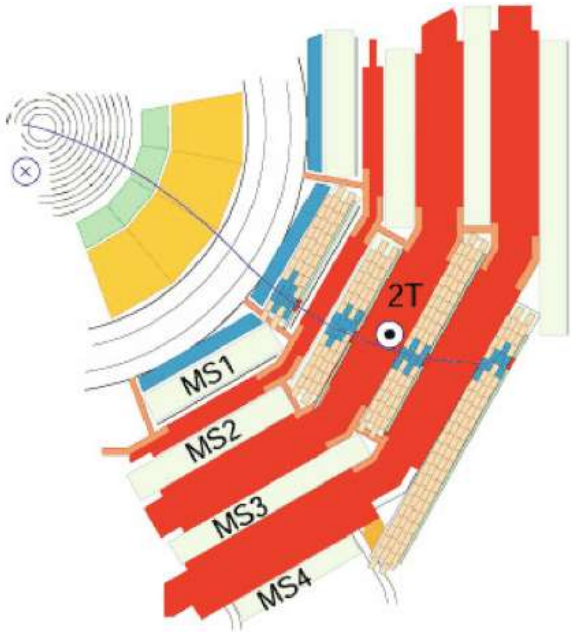


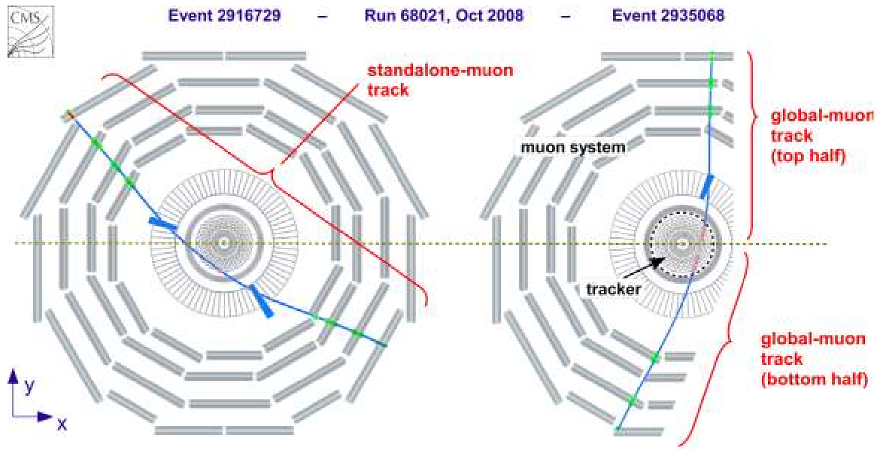
Particles in Detectors

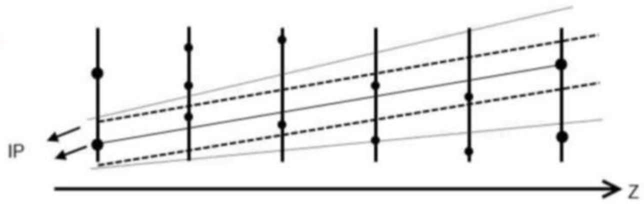


Muon Track and Dumuons Reconstruction

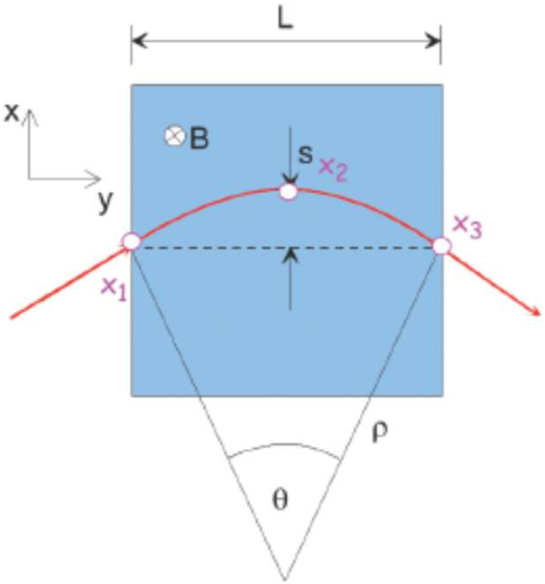
CMS Muon System shows a excellent performance to detect different resonances

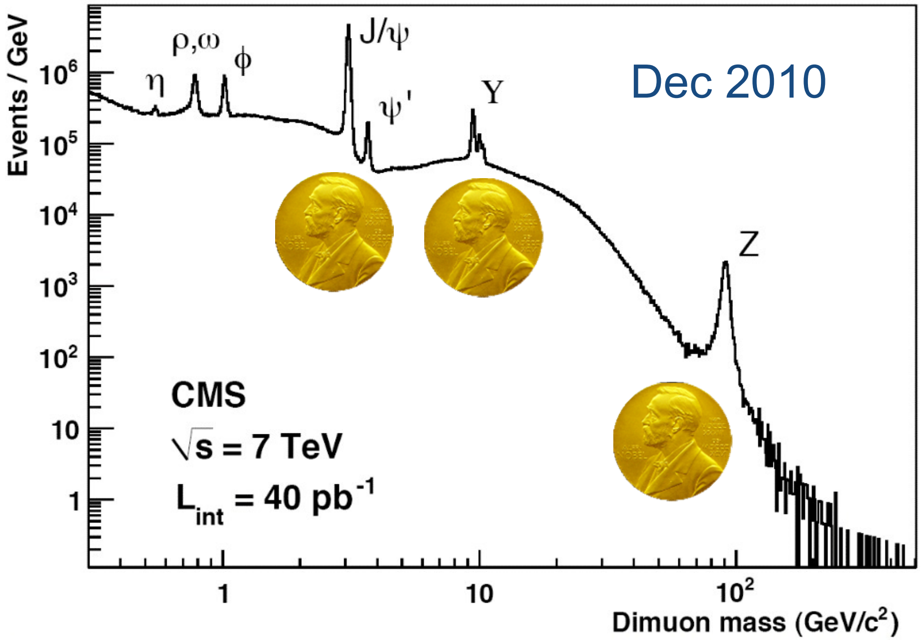






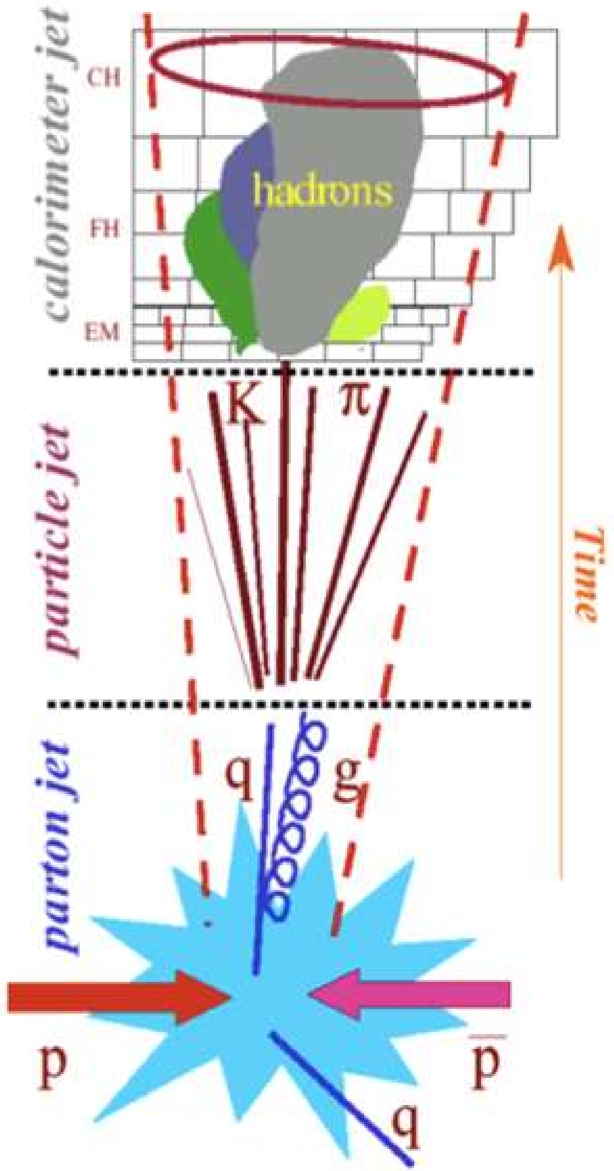
$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_x p_T}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$





https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsMUO

Jet Finding



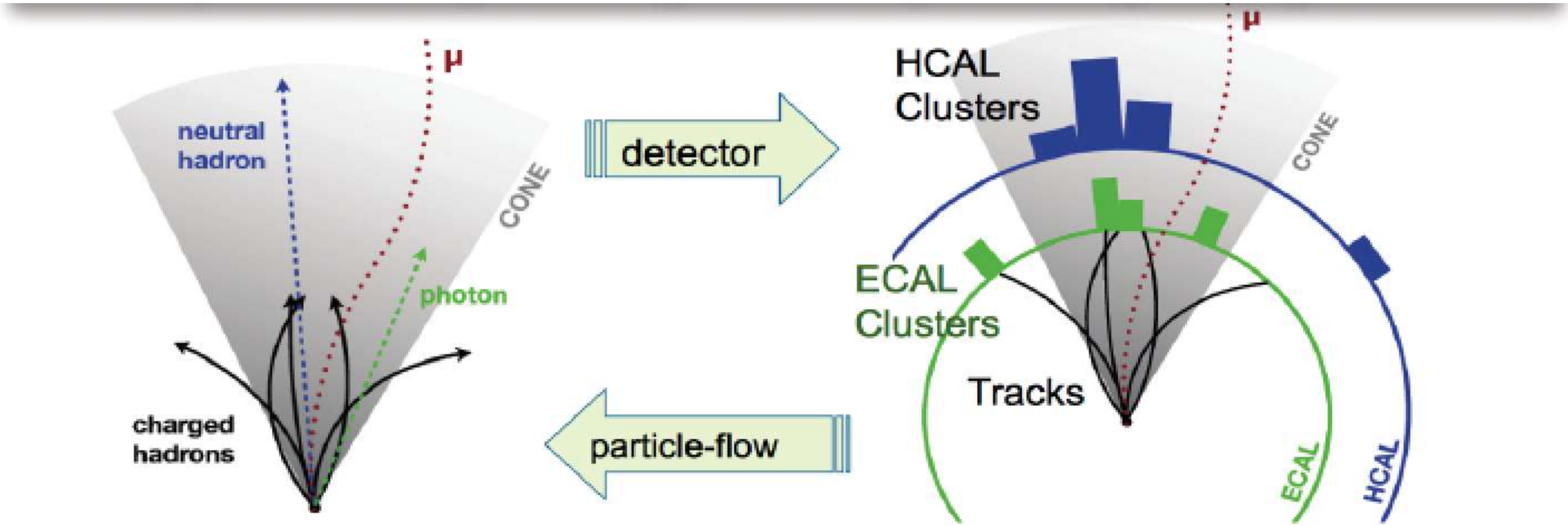
- **Calorimeter jet (cone)**
  - jet is a collection of energy deposits with a given cone *R*: $R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$
  - cone direction maximizes the total E_T of the jet
  - various clustering algorithms

→ correct for finite energy resolution
→ subtract underlying event
→ add out of cone energy

- **Particle jet**
  - a spread of particles running roughly in the same direction as the parton after hadronization

Global Event Reconstruction

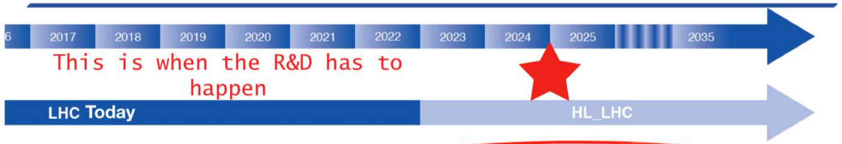
Using all information of the detector together for optimal measurement



- Optimal combination of information from all subdetectors
- Returns a list of reconstructed particles
  - e,μ,γ, charged and neutral hadrons
    - Used in the analysis as if it came from a list of generated particles
    - Used as building blocks for jets, taus , missing transverse energy , isolation and PU particle identification

Machine Learning

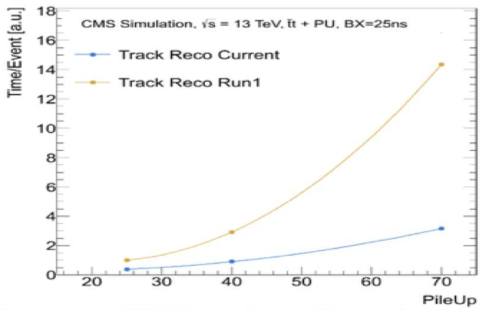
HL-LHC: elephant in the room



- ~40 collisions/event
- ~10 sec/event processing time
- (at best)Same computing resources as today

- ~200 collisions/event
- ~minute/event processing time(*)
- (at best)Same computing resources as ...

- *Flat budget vs. more needs =* ***current rule-based reconstruction algorithms will not be sustainable***
- ***Adopted solution:*** *more granular and complex detectors → more computing resources needed → more problems*
- ***Modern Machine Learning might be the way out***

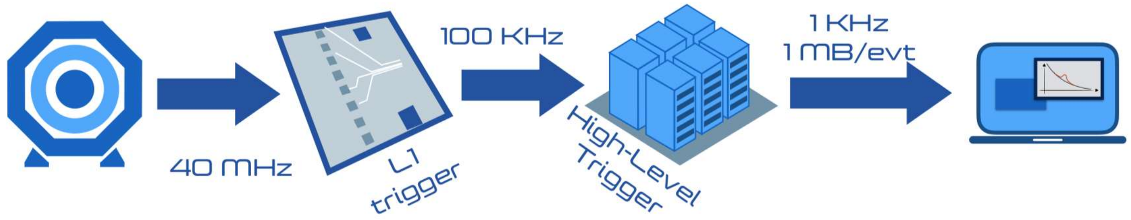


4

(*)With nowadays software development

The LHC Big Data Problem

- *Too many data, too large data -> need to filter online*

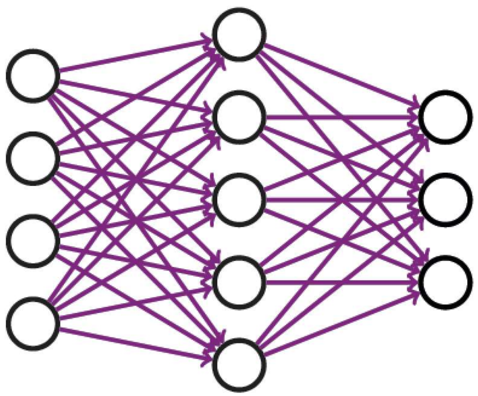


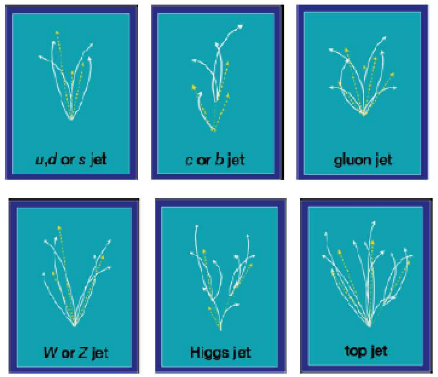
- *The solution to the HL-LHC problem: modern Machine Learning as a fast shortcut between the data and the right answer (the outcome of our traditional & slow algorithms)*

DEEP LEARNING TECHNIQUES

Deep neural networks

based on many low-level features with large training data sets to classify jets

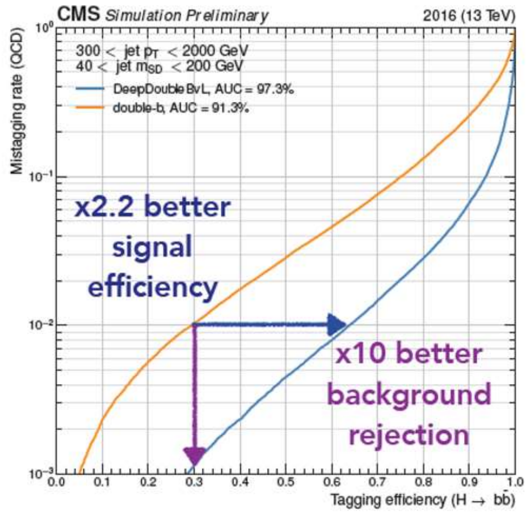




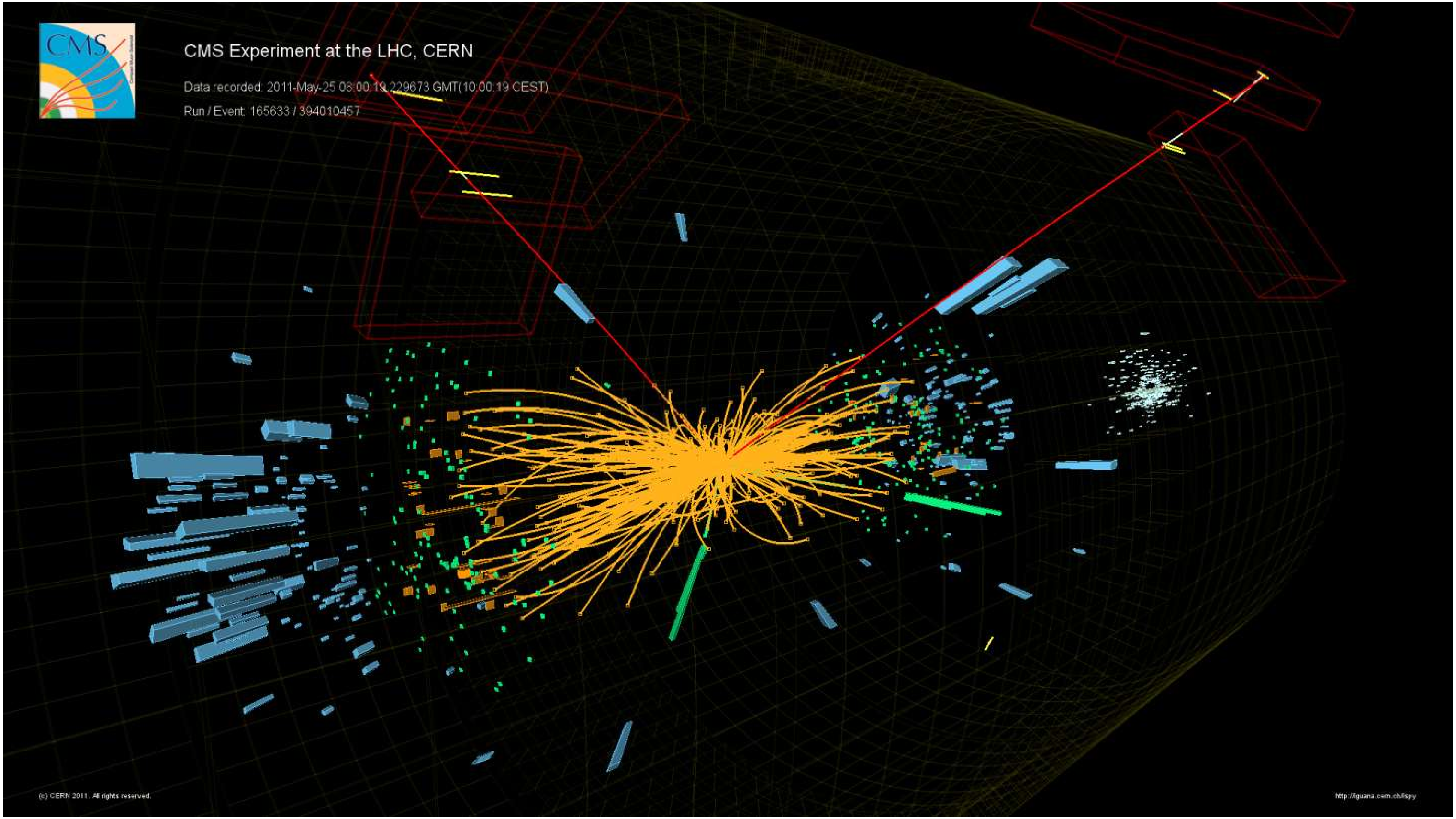
DP-2018/033

DEEP DOUBLE-B TAGGER

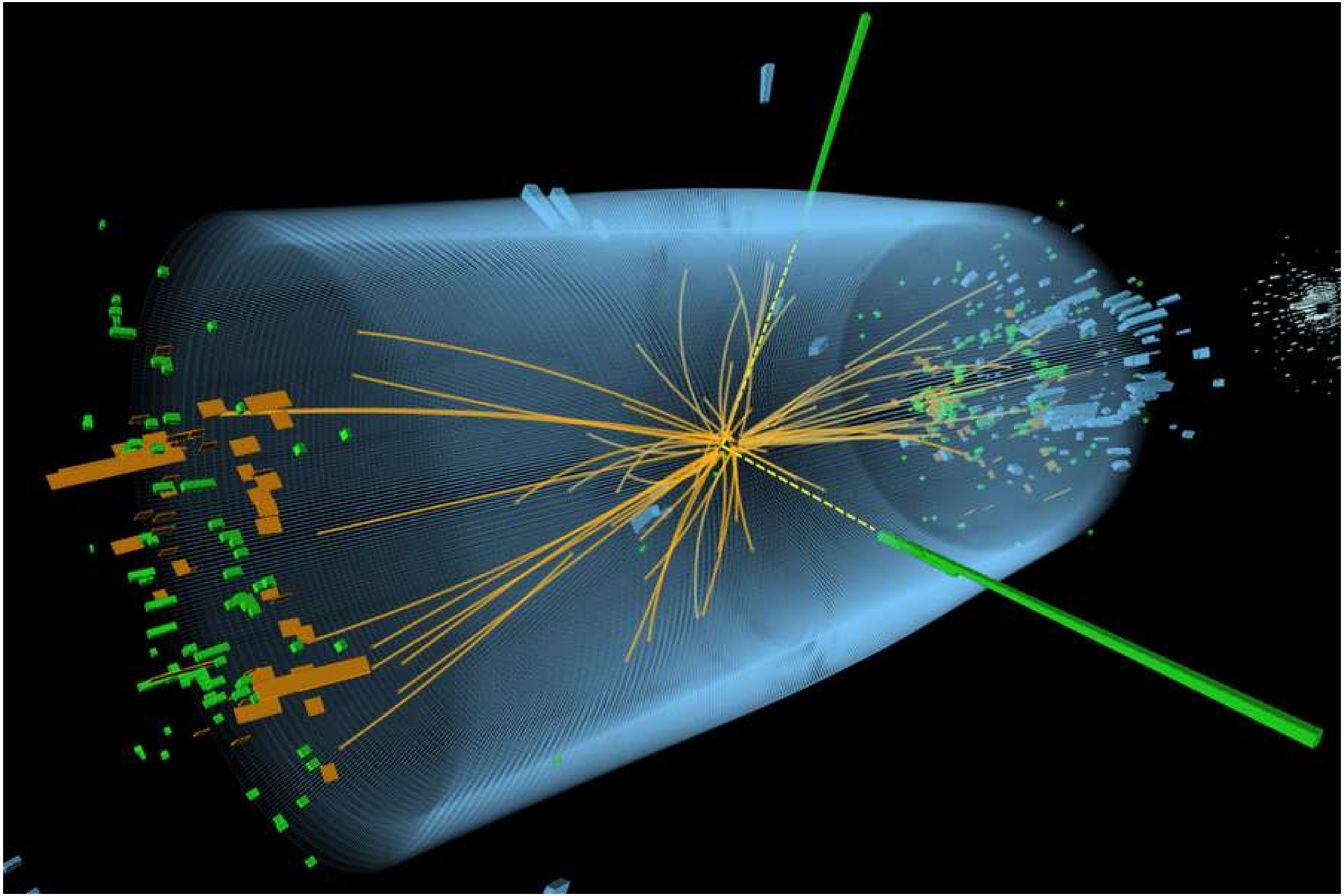
- Large performance gain over previous algorithm



Example of h → ZZ → 2e 2μ

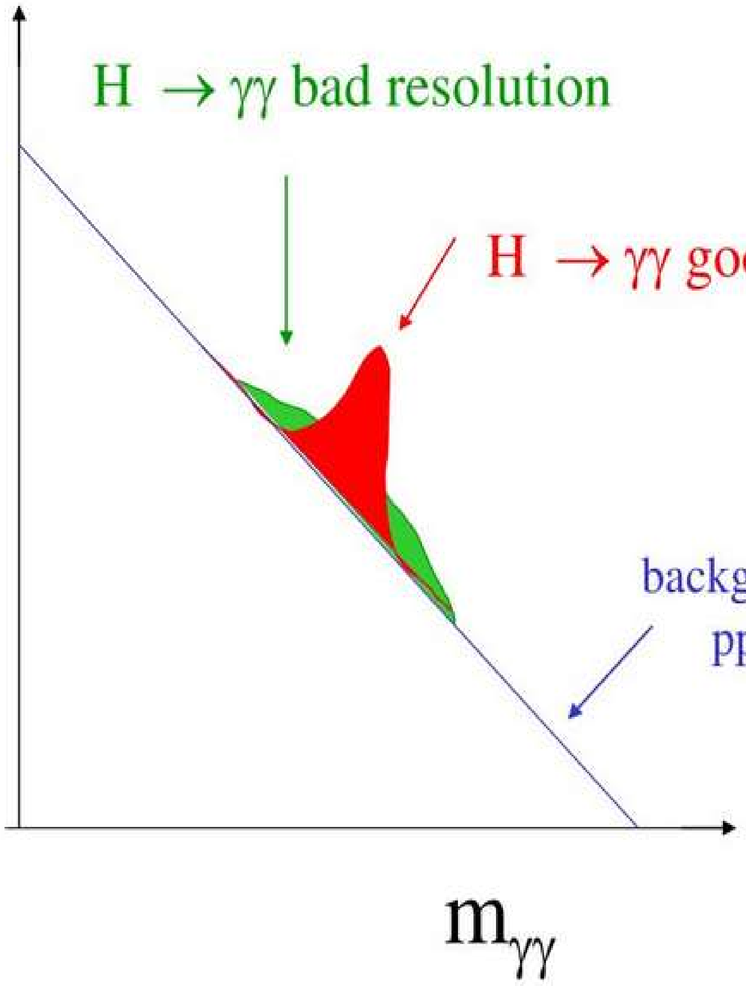


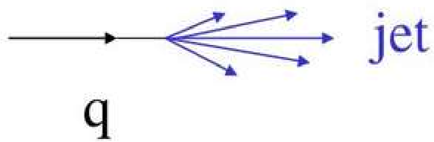
Example of h → 2γ



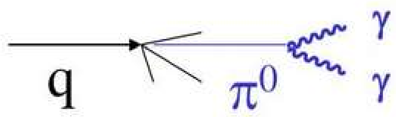
Challenge to the Detector/SW (Example)

Example : $H \rightarrow \gamma\gamma$

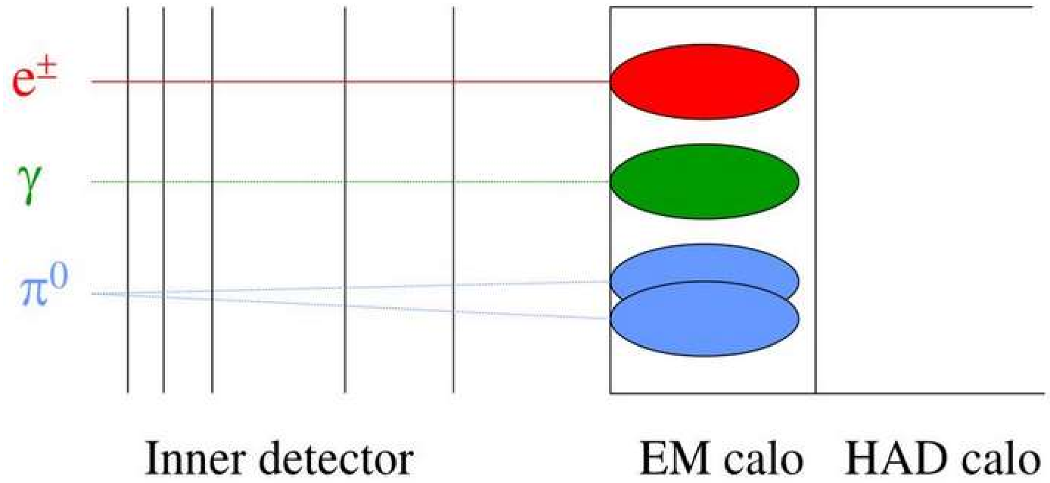




number and p_T of hadrons in a jet have large fluctuations



in some cases: one high-p_T π^0; all other particles too soft to be detected

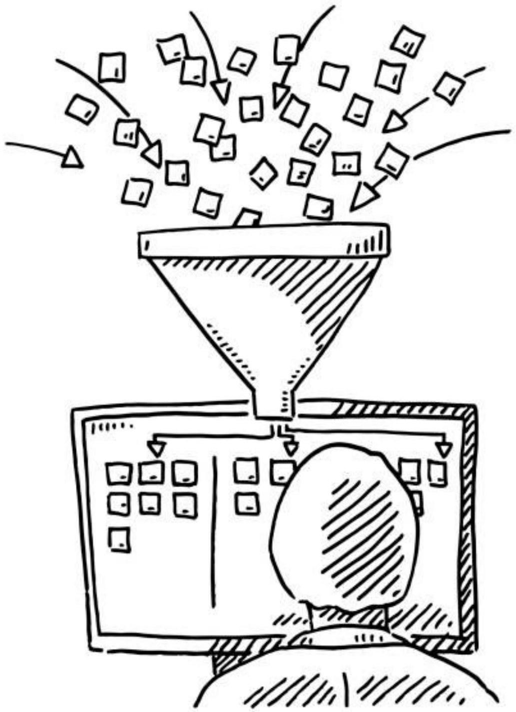


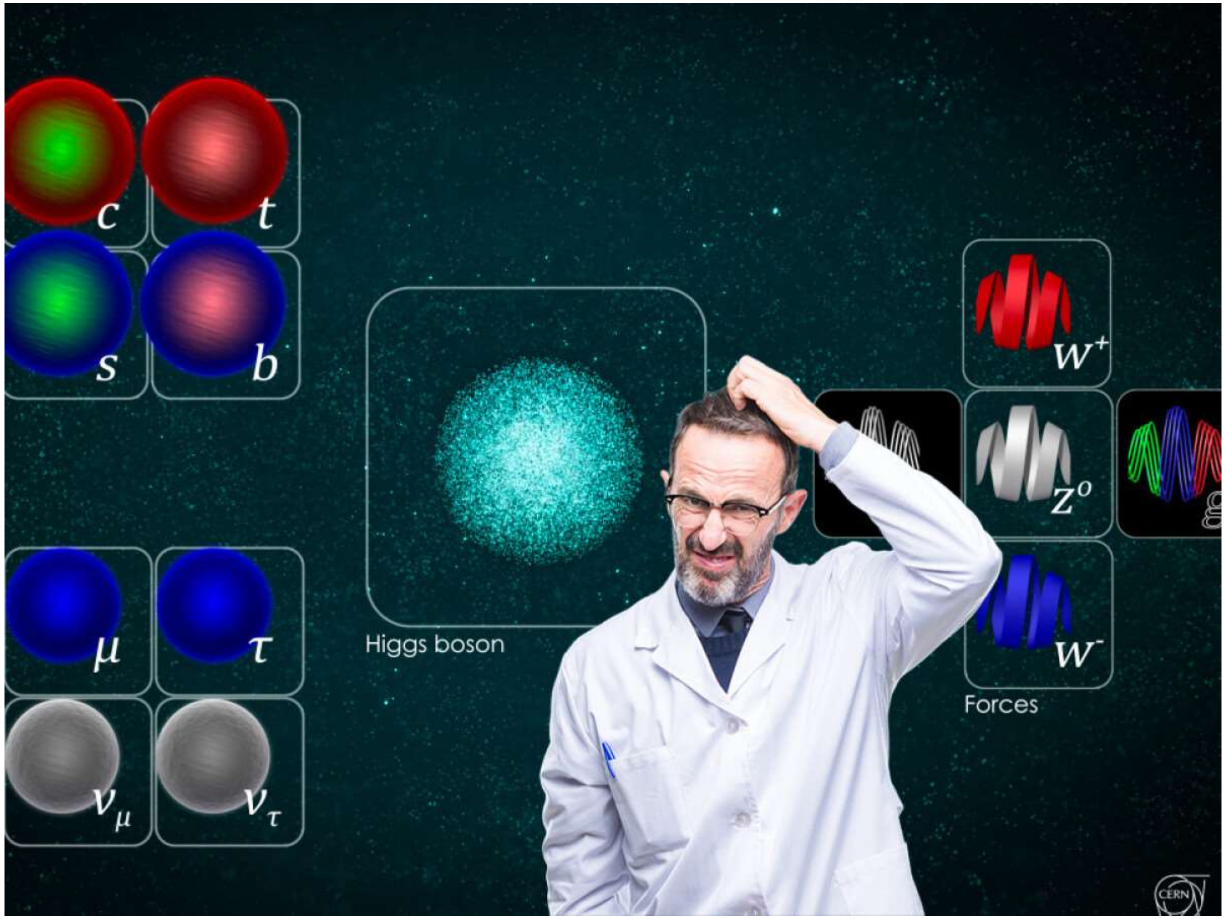
d $(\gamma\gamma)$ < 10 mm in calorimeter → QCD jets can mimic photons. Rare cases, however:

$$\frac{\sigma_{jj}}{\sigma(H \rightarrow \gamma\gamma)} \sim 10^8 \qquad m_{\gamma\gamma} \sim 100 \text{ GeV}$$

Data Analysis

- Data vs Theory ⇒ which theories you believe vs. reject
- Significance of final results ⇒ do you trust your analysis or not?

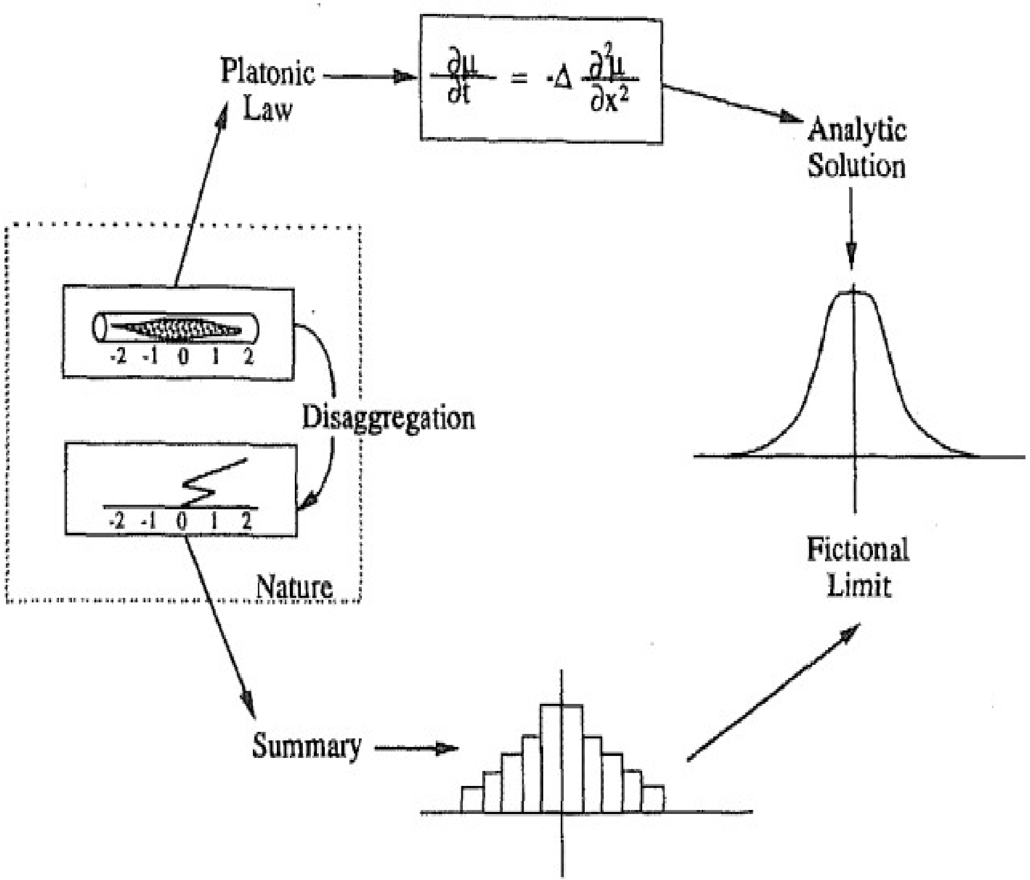




Data Analysis: Theory and Modeling (Monte Carlo Simulation)

Digital Twin of Experiments

- physics in a collision point
- models of detector systems
- response from detectors including digitization
- processing of MC data (simulation of data flow)



Chain of Simulation

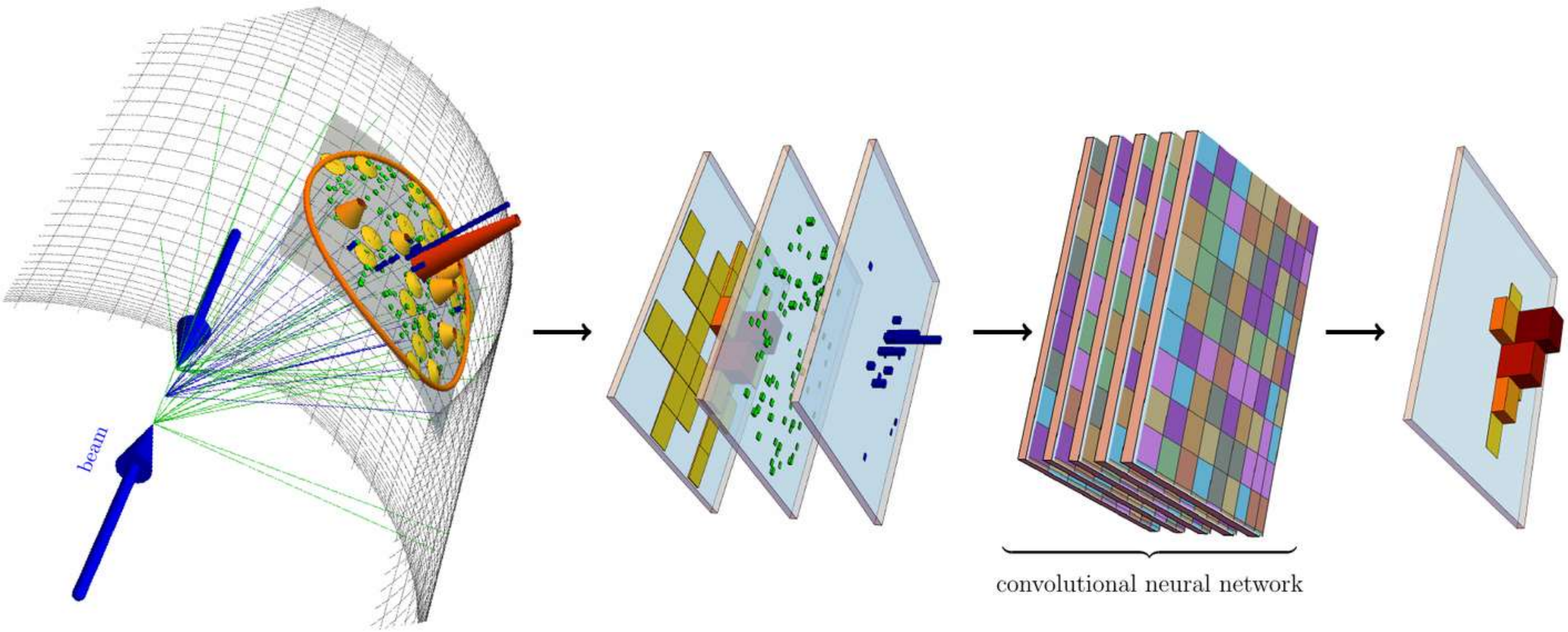
LHE Data

Physics Processes
(Event Generators)

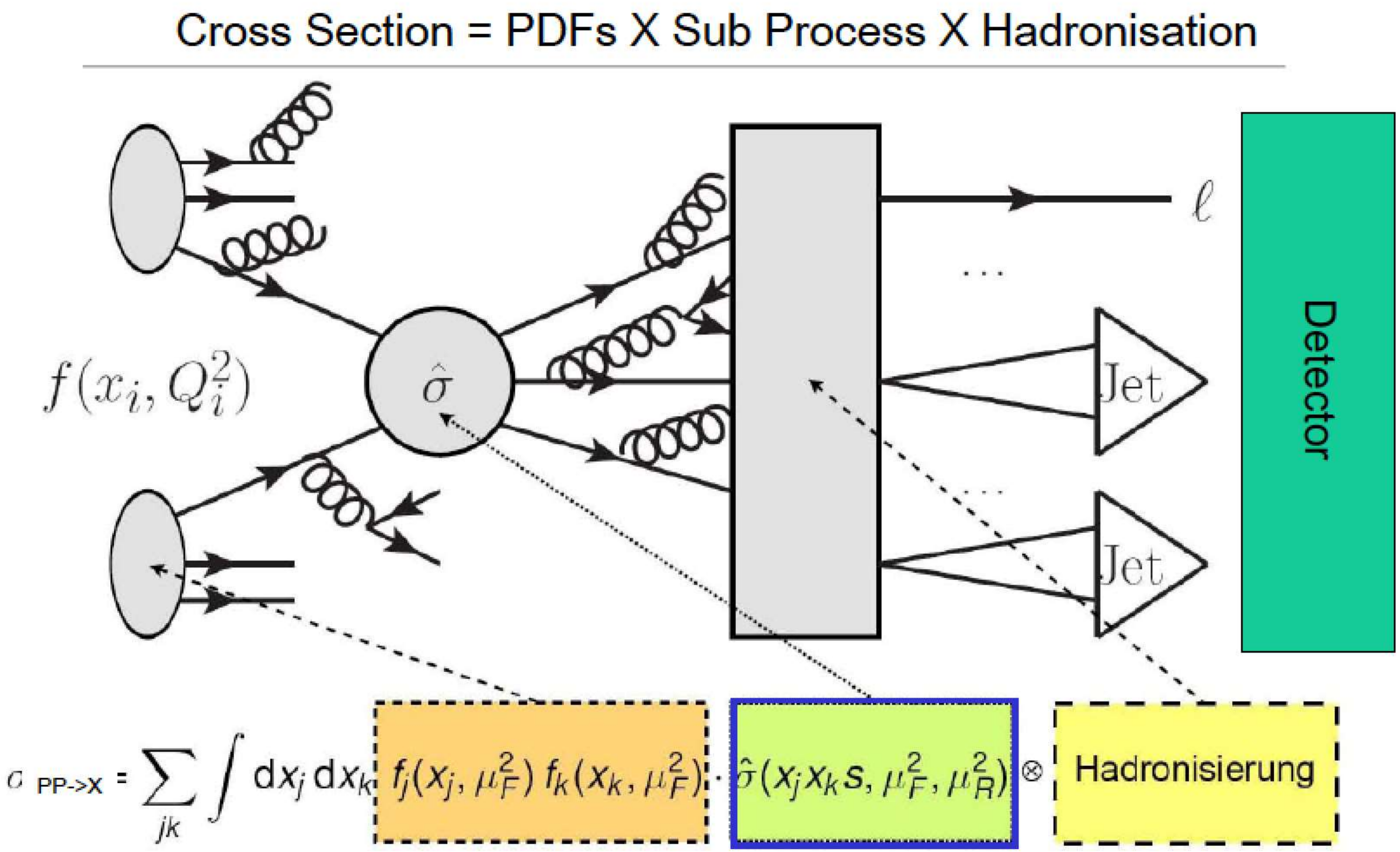
Detector Response
(tracing a particle through matter)

RAW Data

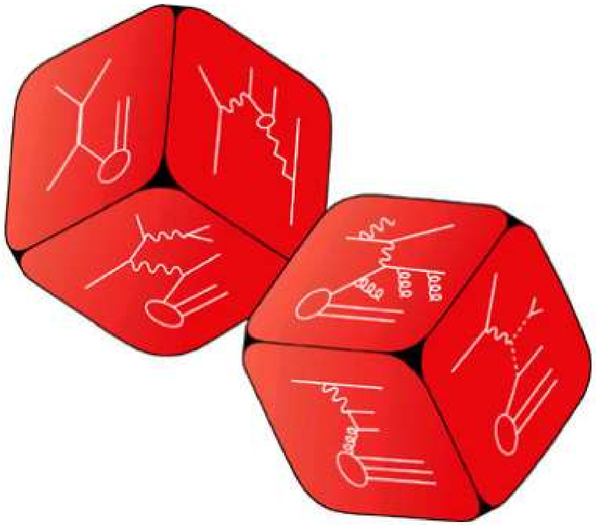
Reconstruction



Theory of Collisions



Event Generators



Three general-purpose generators:

- HERWIG
- PYTHIA
- SHERPA

Many others good/better at some specific tasks.

Generators to be combined with detector simulation (GEANT)

accelerator/collisions ⇔ event generator
detector/electronics ⇔ detector simulation

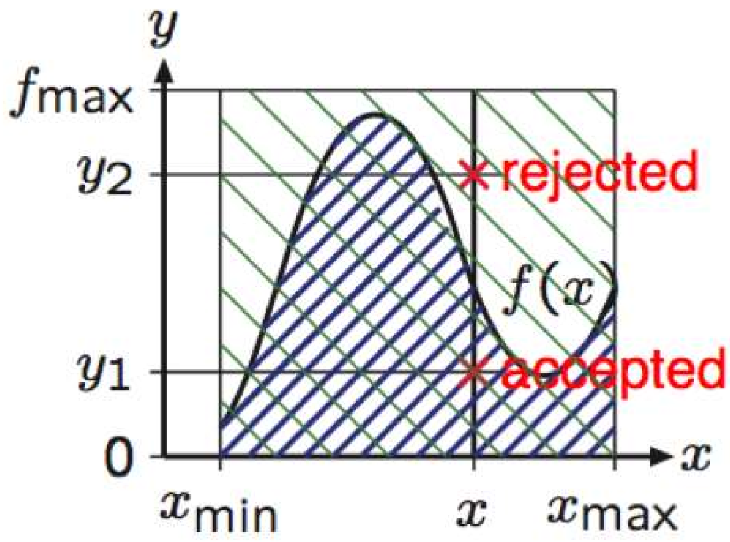
to be used to
- predict event rates and topologies
- simulate possible backgrounds
- study detector requirements
- study detector imperfections

Hit-and-miss Monte Carlo

If $f(x) \leq f_{\max}$ in $x_{\min} < x < x_{\max}$

use interpretation as an area

1. select
   $x = x_{\min} + R\,(x_{\max} - x_{\min})$
2. select $y = R\,f_{\max}$ (new R!)
3. while $y > f(x)$ cycle to 1



Integral as by-product:

$$I = \int_{x_{\min}}^{x_{\max}} f(x)\,\mathrm{d}x = f_{\max}\,(x_{\max} - x_{\min})\,\frac{N_{\text{acc}}}{N_{\text{try}}} = A_{\text{tot}}\,\frac{N_{\text{acc}}}{N_{\text{try}}}$$

Binomial distribution with $p = N_{\text{acc}}/N_{\text{try}}$ and $q = N_{\text{fail}}/N_{\text{try}}$,

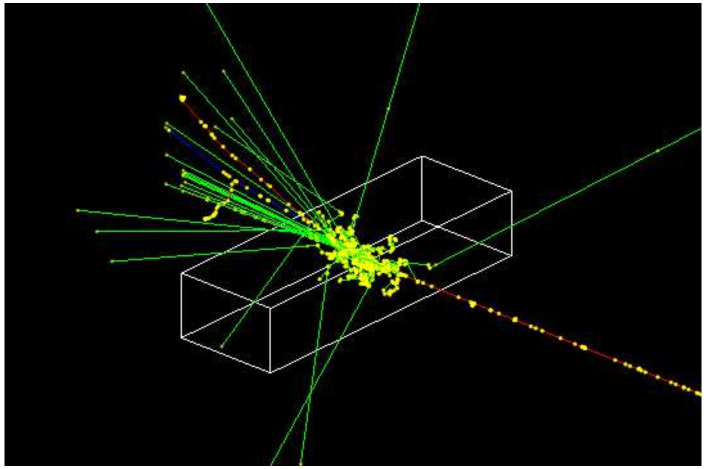
so error

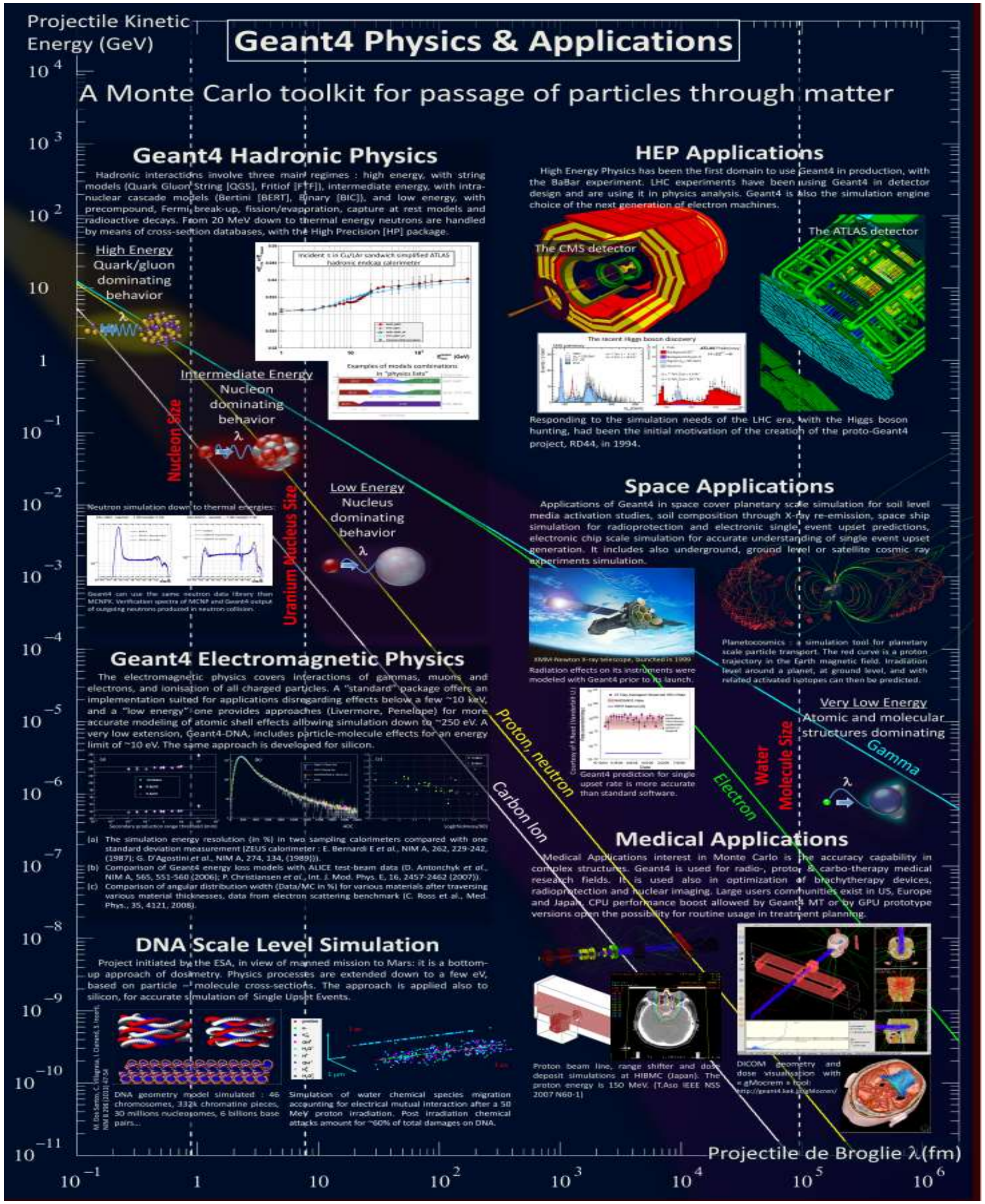
$$\frac{\delta I}{I} = \frac{A_{\text{tot}}\,\sqrt{p\,q/N_{\text{try}}}}{A_{\text{tot}}\,p} = \sqrt{\frac{q}{p\,N_{\text{try}}}} = \sqrt{\frac{q}{N_{\text{acc}}}} \longrightarrow \frac{1}{\sqrt{N_{\text{acc}}}} \quad \text{for} \;\; p \ll 1$$

Detector Modeling

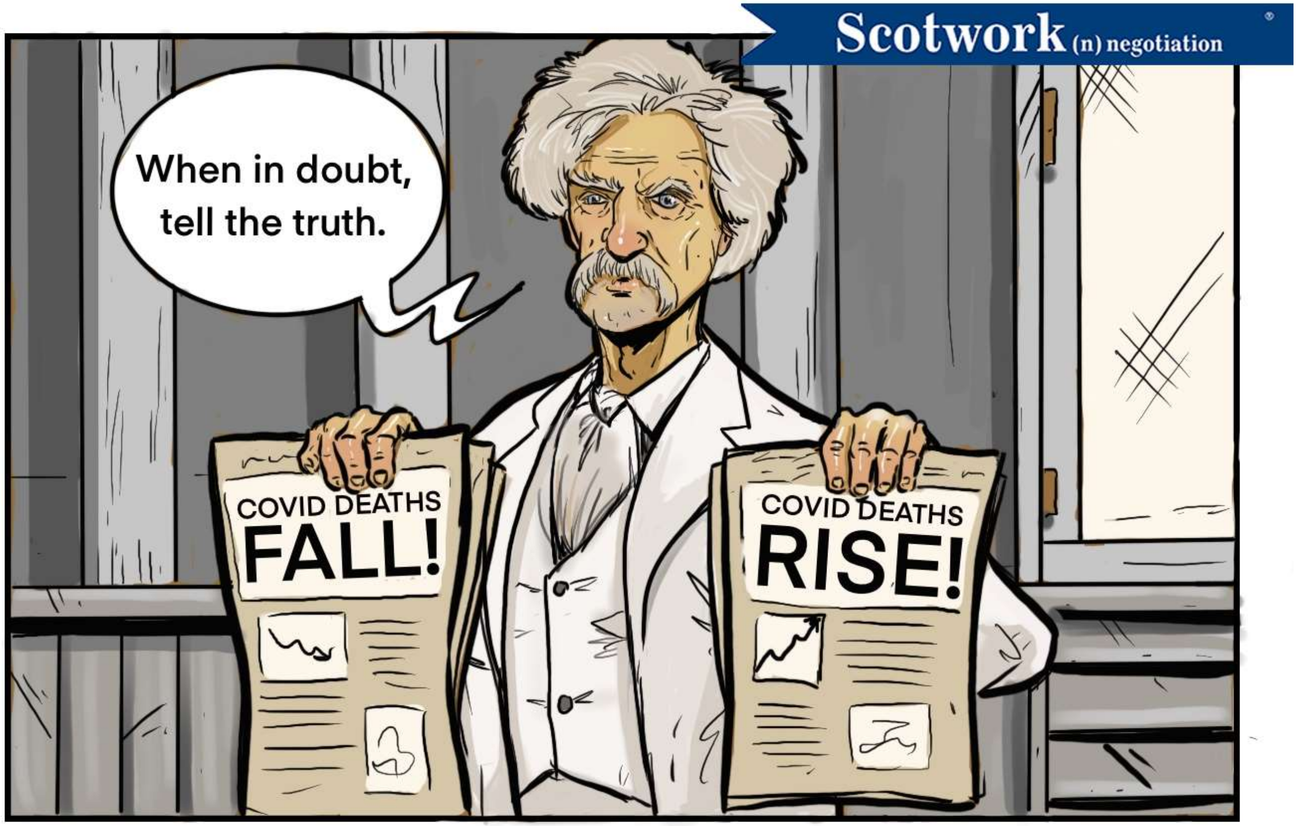
GEANT4

- Toolkit created by CERN to simulate the passage of particles through matter.
- Designed to make the physics used transparent within the toolkit, handle a wide range of geometries, and enable an easy adaptation of different physics to fit the application.





Data Analysis: Statistics



There are three kinds of lies: lies, damned lies, and statistics (c) Benjamin Disraeli

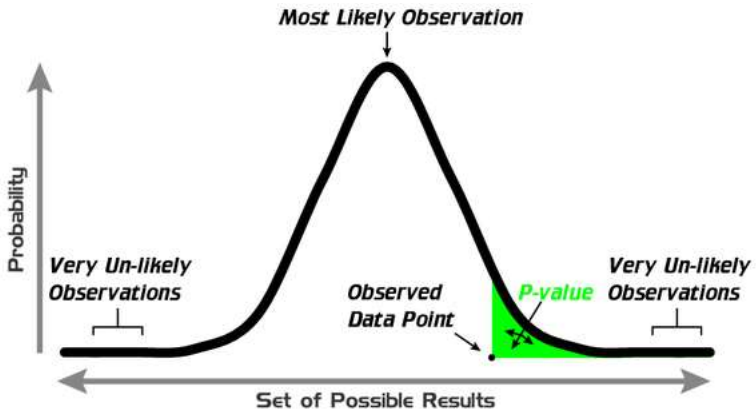
Статистический анализ

Событие (результат) называется "статистическими значимым", если оно вряд ли произошло случайно

p-value - вероятность получить результат, такой как наблюдается (или выше) в предположении, что нуль-гипотеза верна

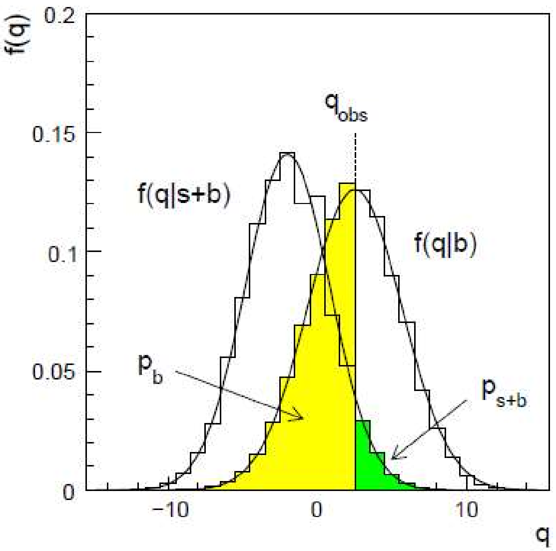
$\Rightarrow$ в нашем случае вероятность, того, что флуктуация фона достигли (или превысили) наблюденное значение

$$p = P(\, n \geq n_{obs} \mid b \,)$$



Нуль-гипотеза – основная проверяемая гипотеза (фон)

$\Rightarrow$ Нулевая гипотеза отвергается, когда значение p-value меньше уровня стат. значимости α (по соглашению <0.05)



Масштабный фактор (strength factor)

$$\mu = \frac{\sigma}{\sigma_{SM}} < \mu^{95\%} \text{ at } 95\% \text{ C.L., e.g. } \mu^{95\%} = 1 \Rightarrow \text{exclusion}$$

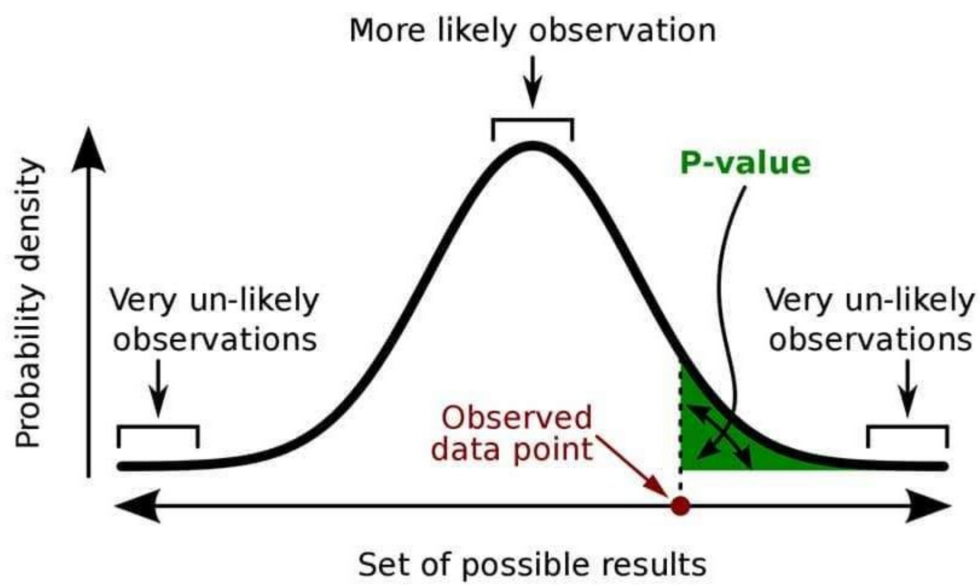
σ_{SM} – сечение бозона Хиггса в СМ, σ - гипотетическое сечение бозона Хиггса

$$CL_S(\mu^{95\%}) = \frac{CL_{S+B}}{CL_B} = \frac{P(q_\mu > q_\mu^{obs} \mid B + \mu^{95\%} \times S)}{P(q_\mu > q_\mu^{obs} \mid B\ )} = 0.05$$

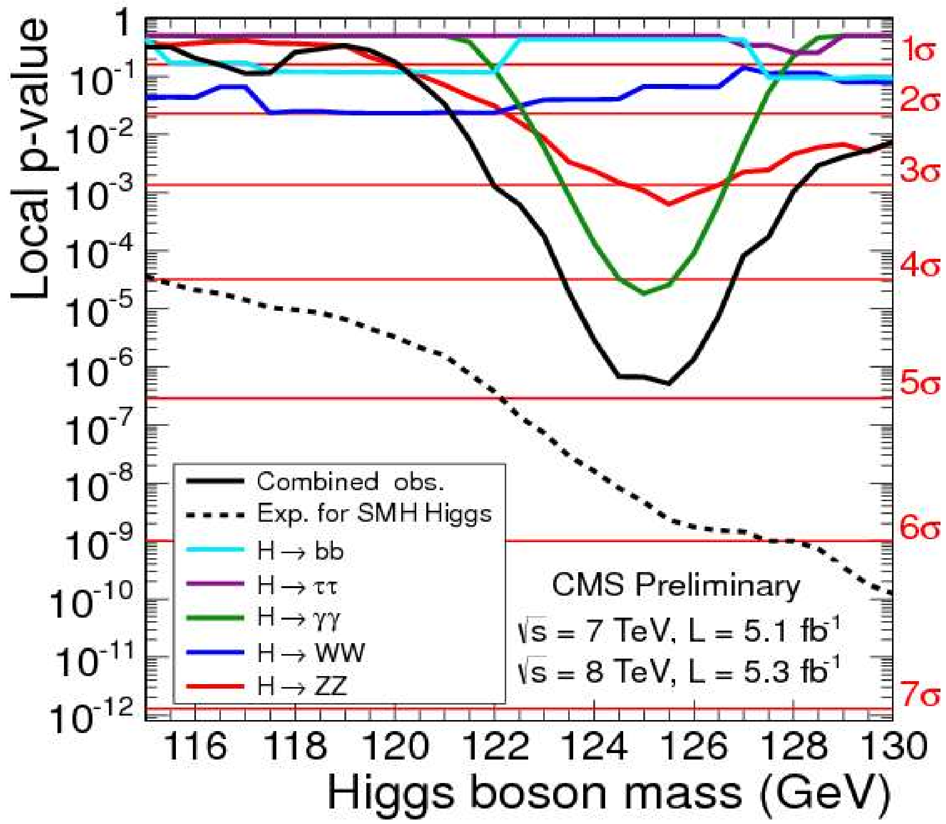
$$q_\mu = -2 \ln \frac{\mathcal{L}(\text{data} \mid \mu, \hat{\hat{\theta}}_\mu)}{\mathcal{L}(\text{data} \mid \hat{\mu}, \hat{\theta})},$$

Significance of Discovery

The probability that an observed excess was a statistical fluctuation of the background (p-value)

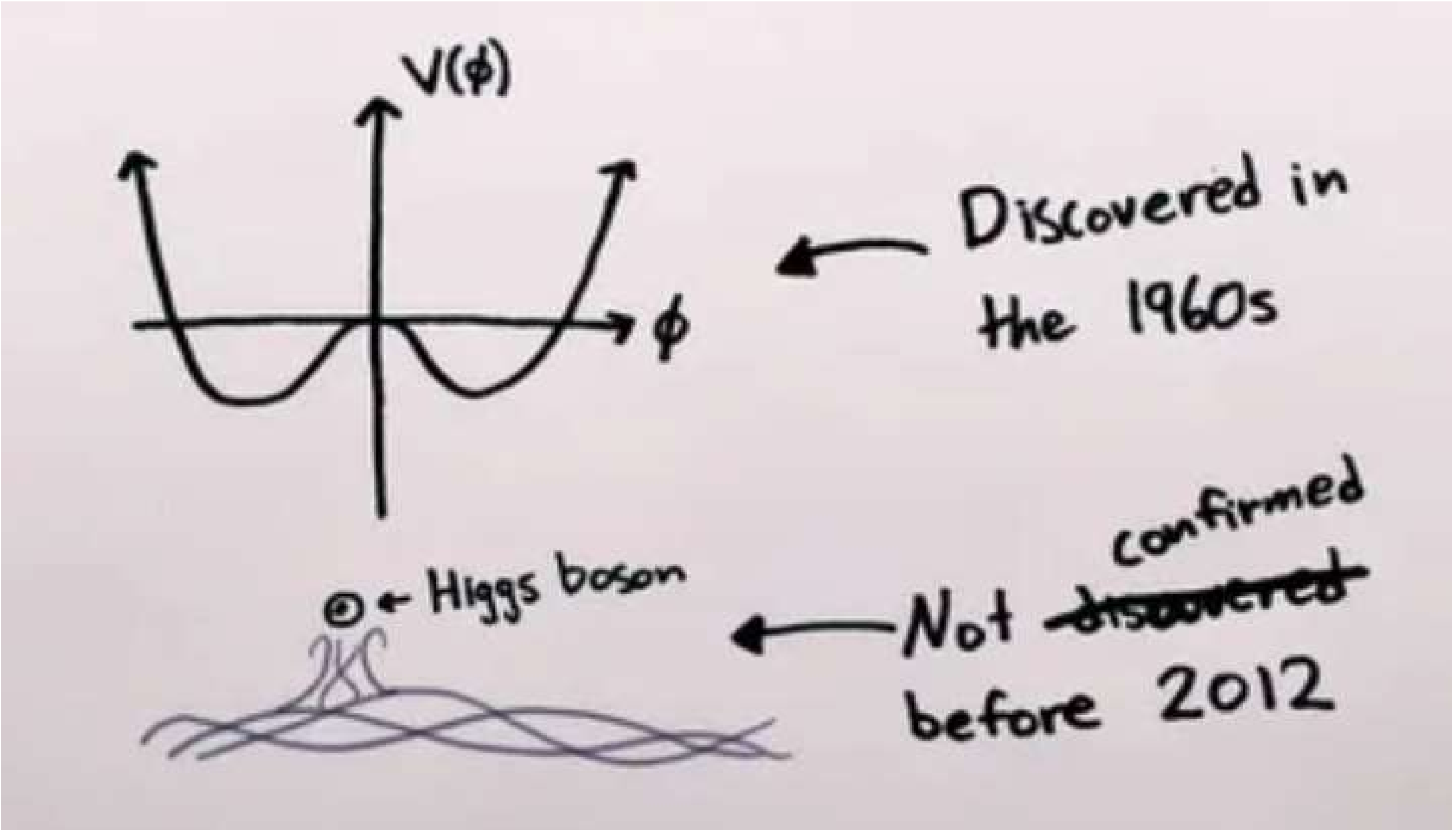


A **p-value** (shaded green area) is the probability of an observed (or more extreme) result assuming that the null hypothesis is true.



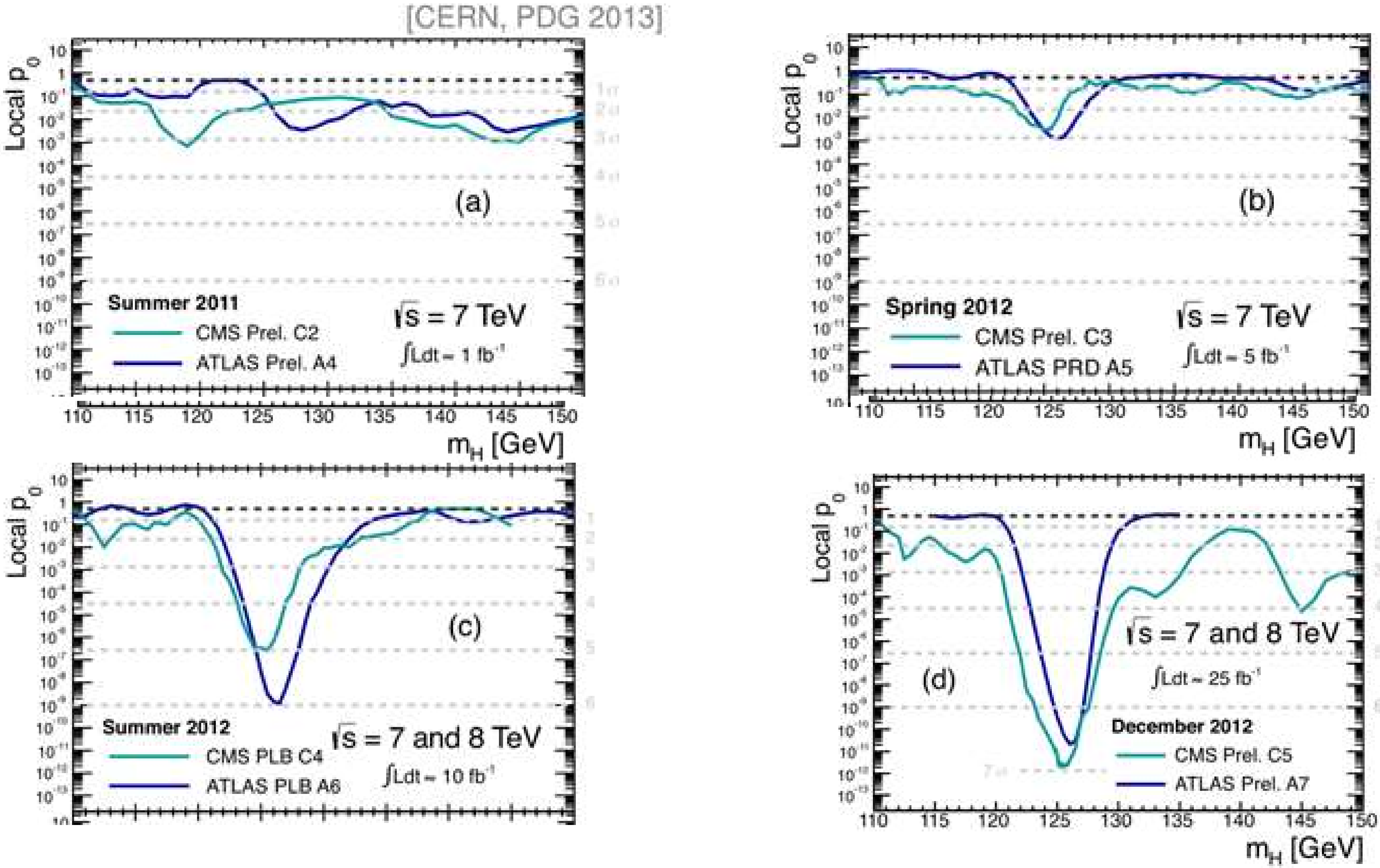
Notable values for an excess in particle physics are **3σ, or p-value = 0.0013**; and **5σ, or p-value = 2.87 x 10^{-7}**. **When we have an excess of 3σ we talk about an evidence, and when we have an excess of 5σ, we are facing a discovery**.

… and as a result…



Story at Higgs Discovery

[CERN, PDG 2013]



IT SCHOOL JINR

What does Brazilian Flag mean?

Dimuon example

$$R_\sigma = \frac{\sigma(pp \to Z' + X \to l^+l^- + X)}{\sigma(pp \to Z^0 + X \to l^+l^- + X)}$$

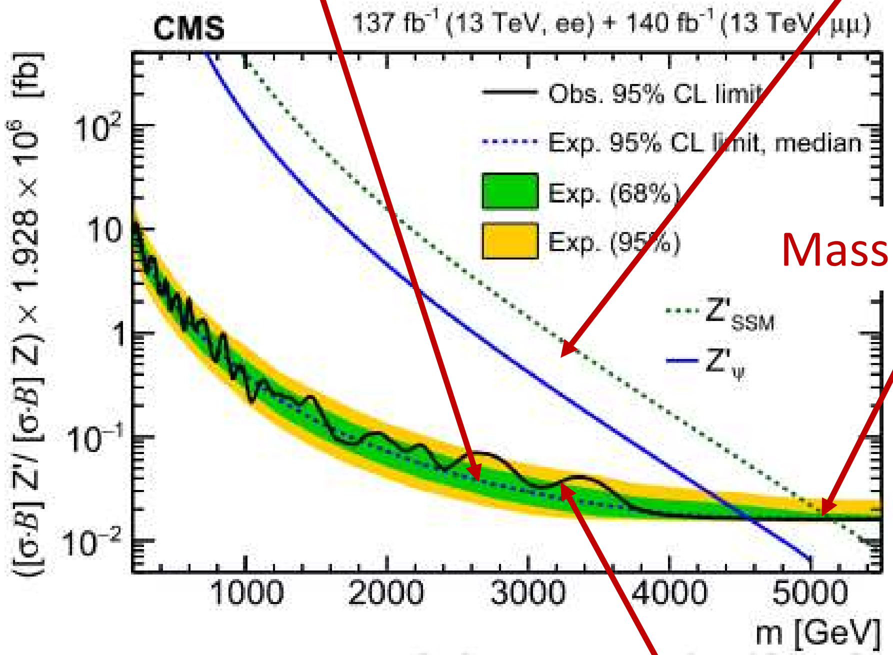
Extended gauge models

Models of low-energy gravity (RS1-type scenario of ED)

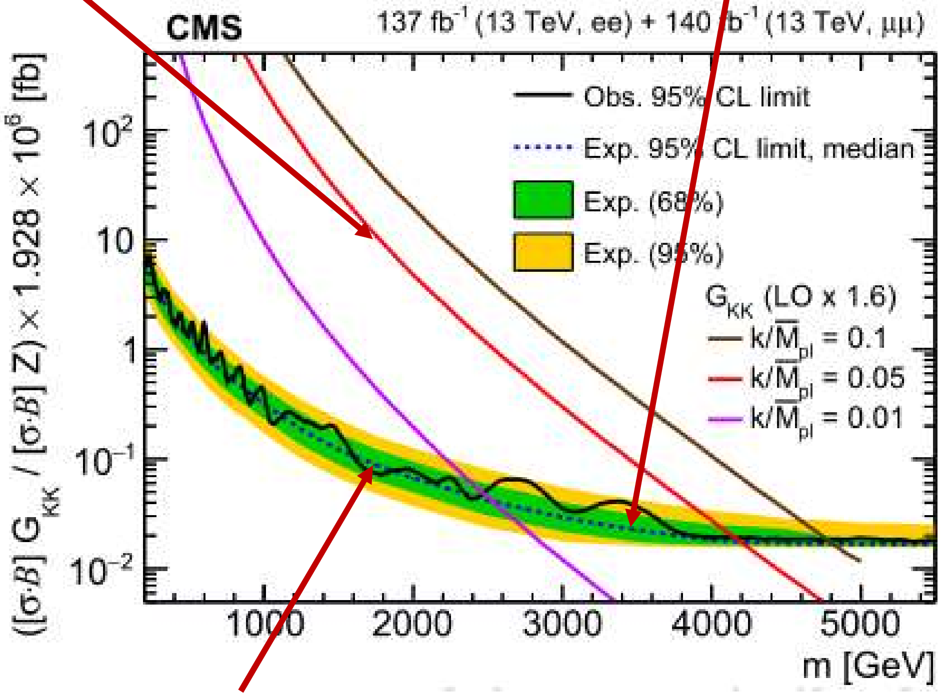
SM predictions

BSM predictions

SM predictions



Mass limit



Model-independent limits on cross section (in narrow width approximation, NWA)

Channel	Z'_{SSM}		Z'_ψ	
	Obs. [TeV]	Exp. [TeV]	Obs. [TeV]	Exp. [TeV]
e e	4.72	4.72	4.11	4.13
$\mu^+\mu^-$	4.89	4.90	4.29	4.30
e e + $\mu^+\mu^-$	5.15	5.14	4.56	4.55

Channel	$k/\overline{M}_{Pl} = 0.01$		$k/\overline{M}_{Pl} = 0.05$		$k/\overline{M}_{Pl} = 0.1$	
	Obs. [TeV]	Exp. [TeV]	Obs. [TeV]	Exp. [TeV]	Obs. [TeV]	Exp. [TeV]
e e	2.16	2.29	3.70	3.83	4.42	4.43
$\mu^+\mu^-$	2.34	2.32	3.96	3.96	4.59	4.59
e e + $\mu^+\mu^-$	2.47	2.53	4.16	4.19	4.78	4.81

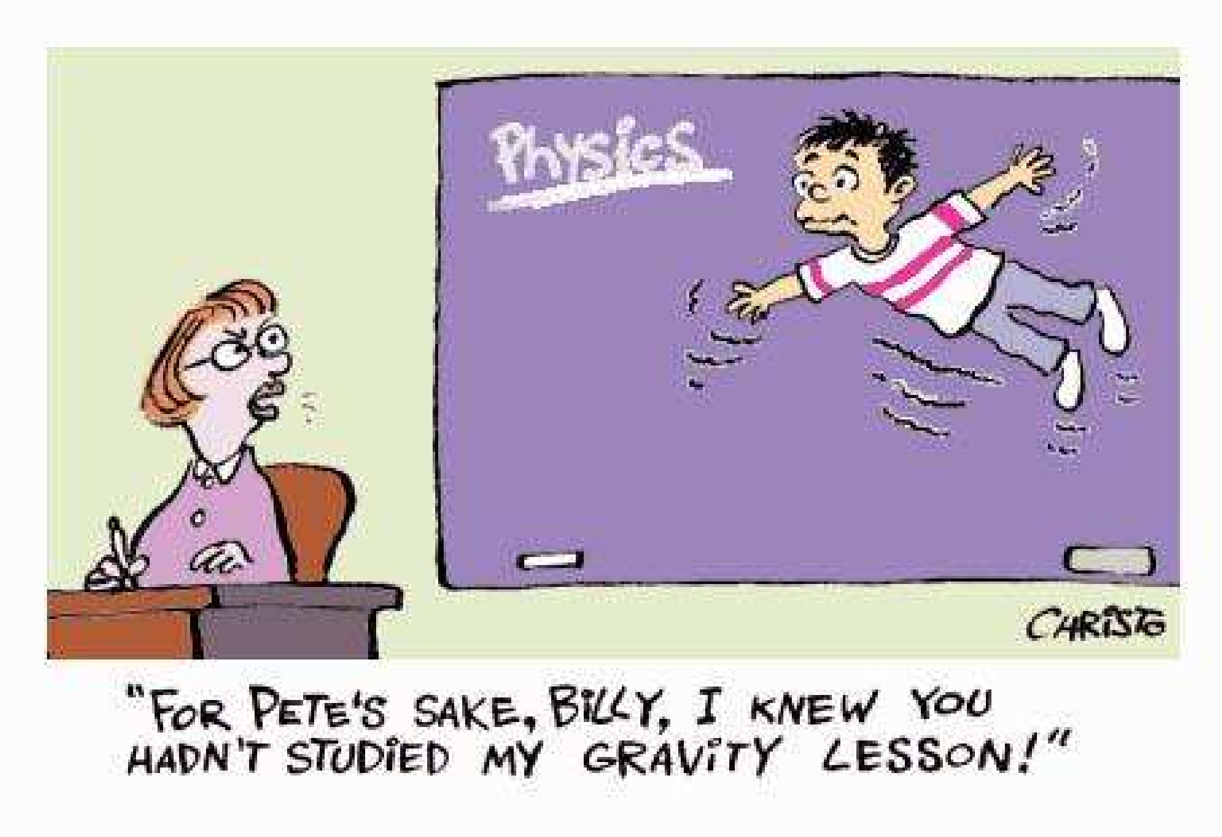
Higgs boson is found

Standard Model works

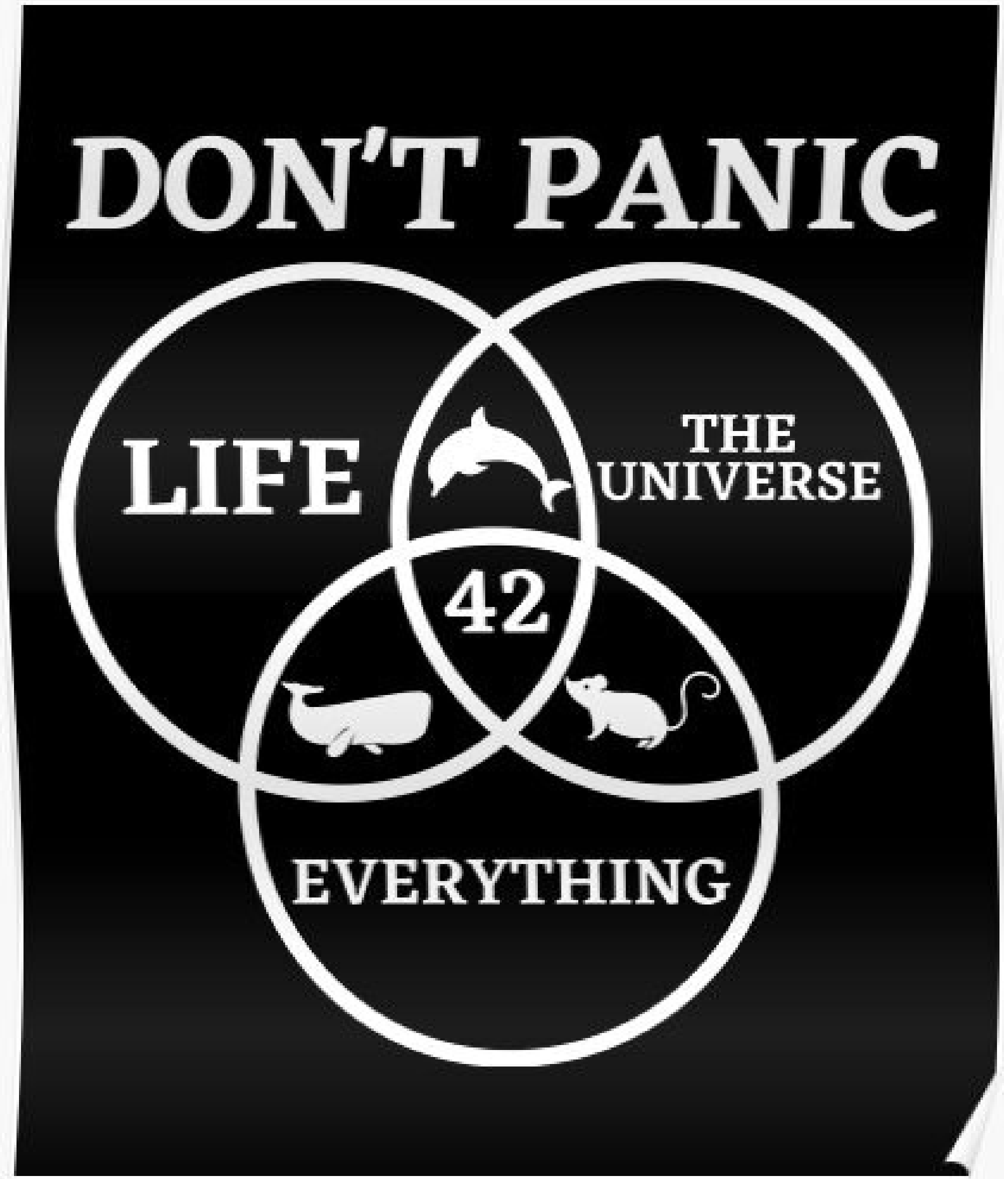
Extensive Searches for New Physics

- No significant signals
- A set of hints
- A number of future projects

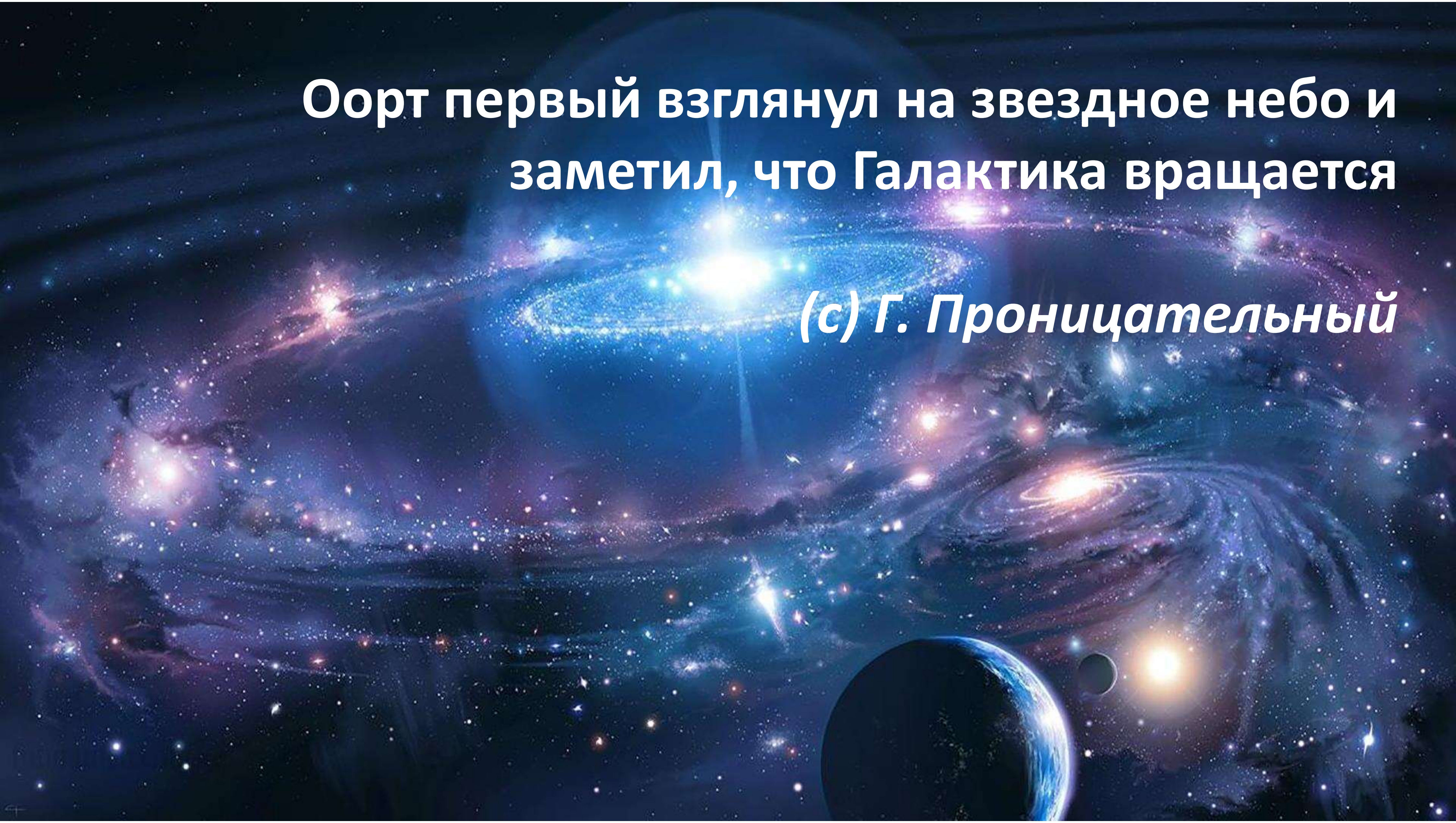
Particle physics isn’t going to die — even if the LHC finds no new particles



Anyway…



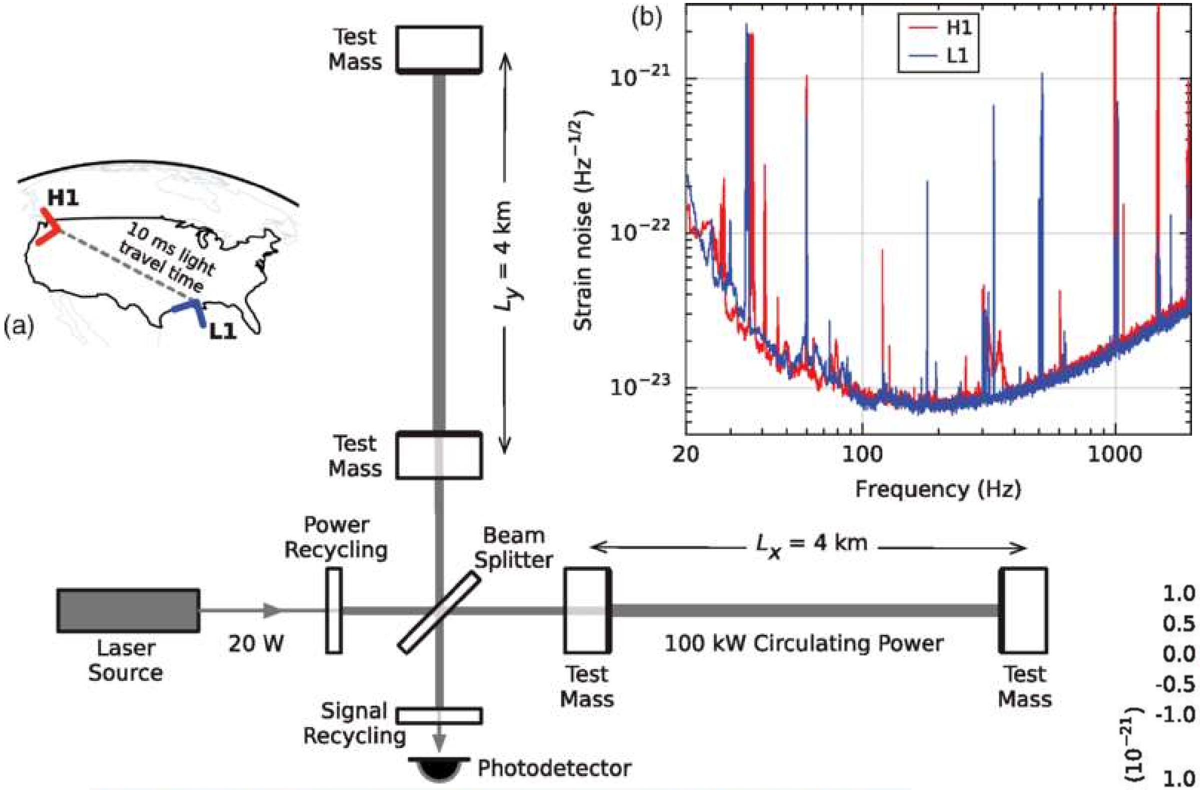
The Hitchhiker's Guide to the Galaxy
by Douglas Adams

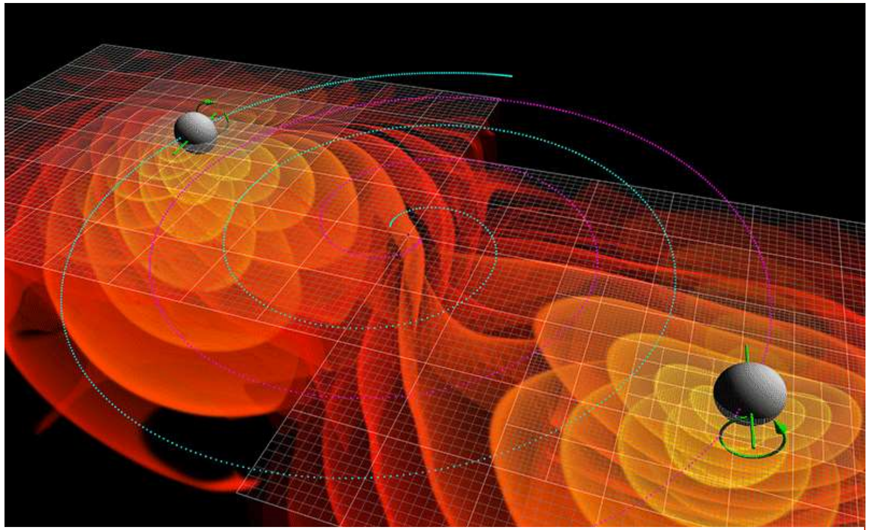


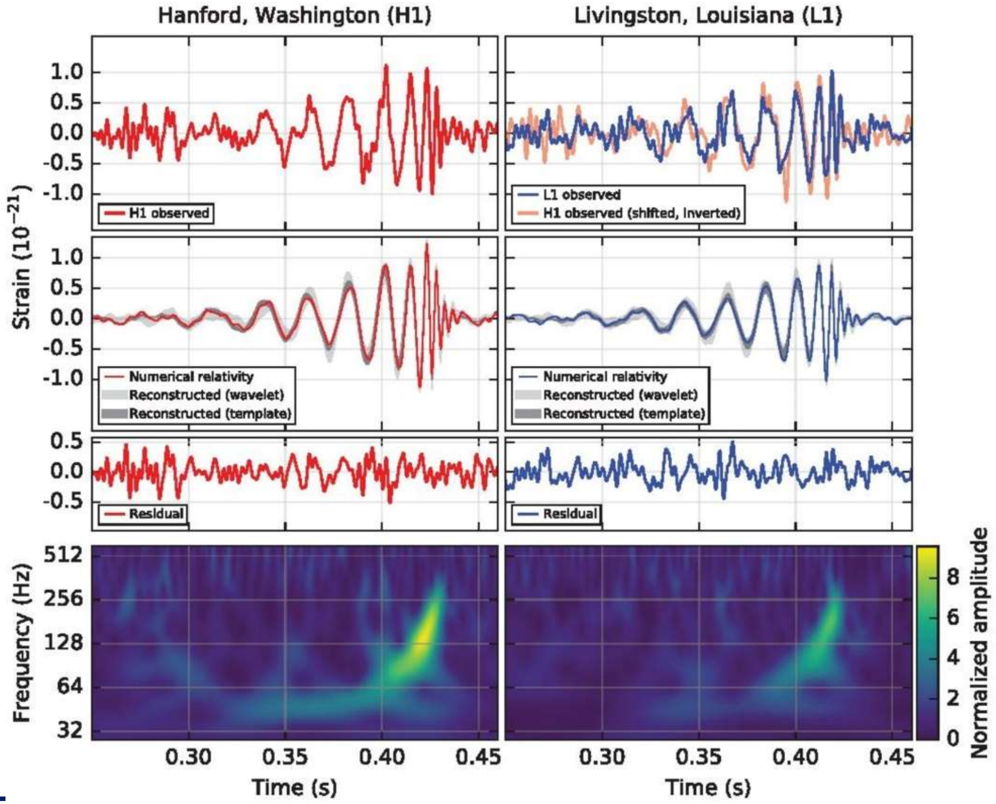
Оорт первый взглянул на звездное небо и заметил, что Галактика вращается

(с) Г. Проницательный

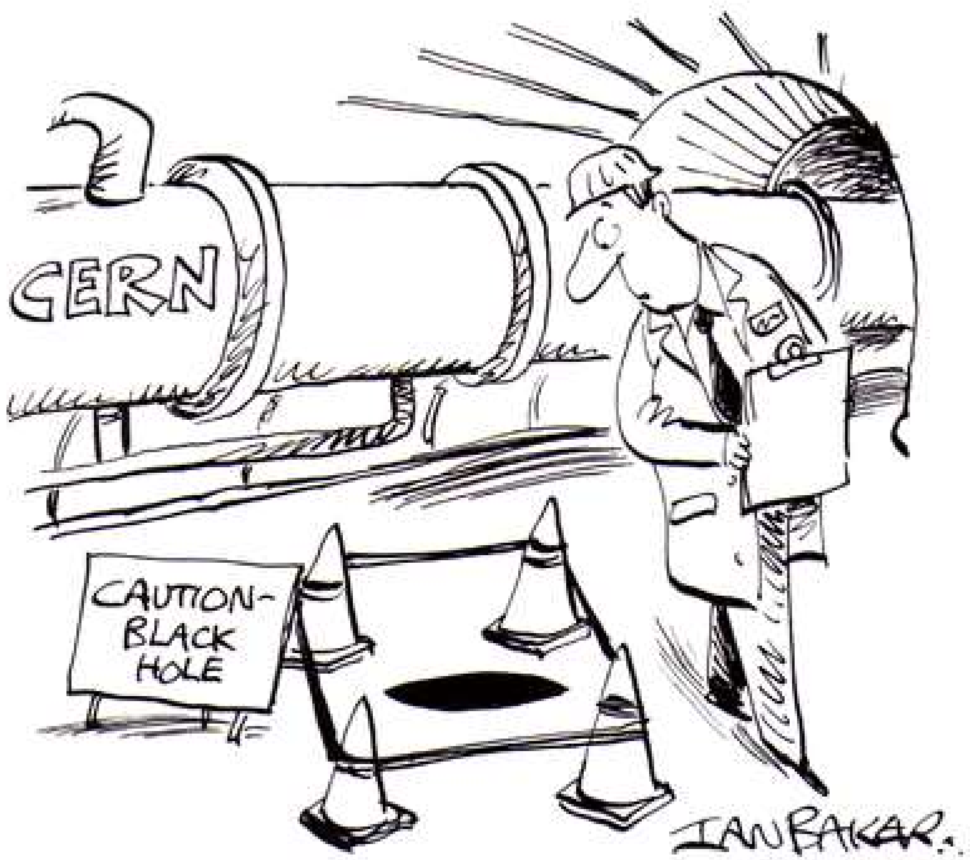
Observation of Gravitational Waves

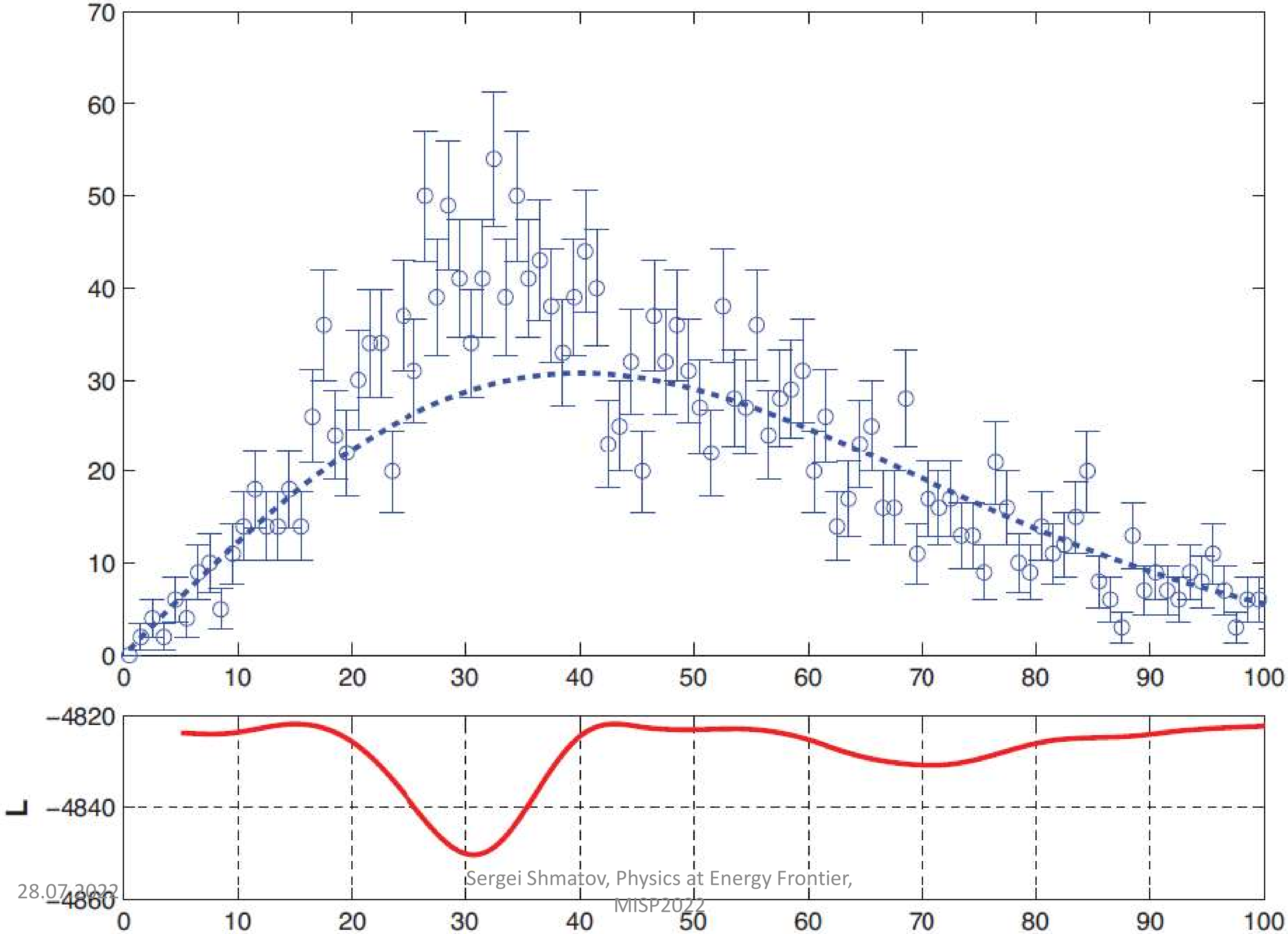


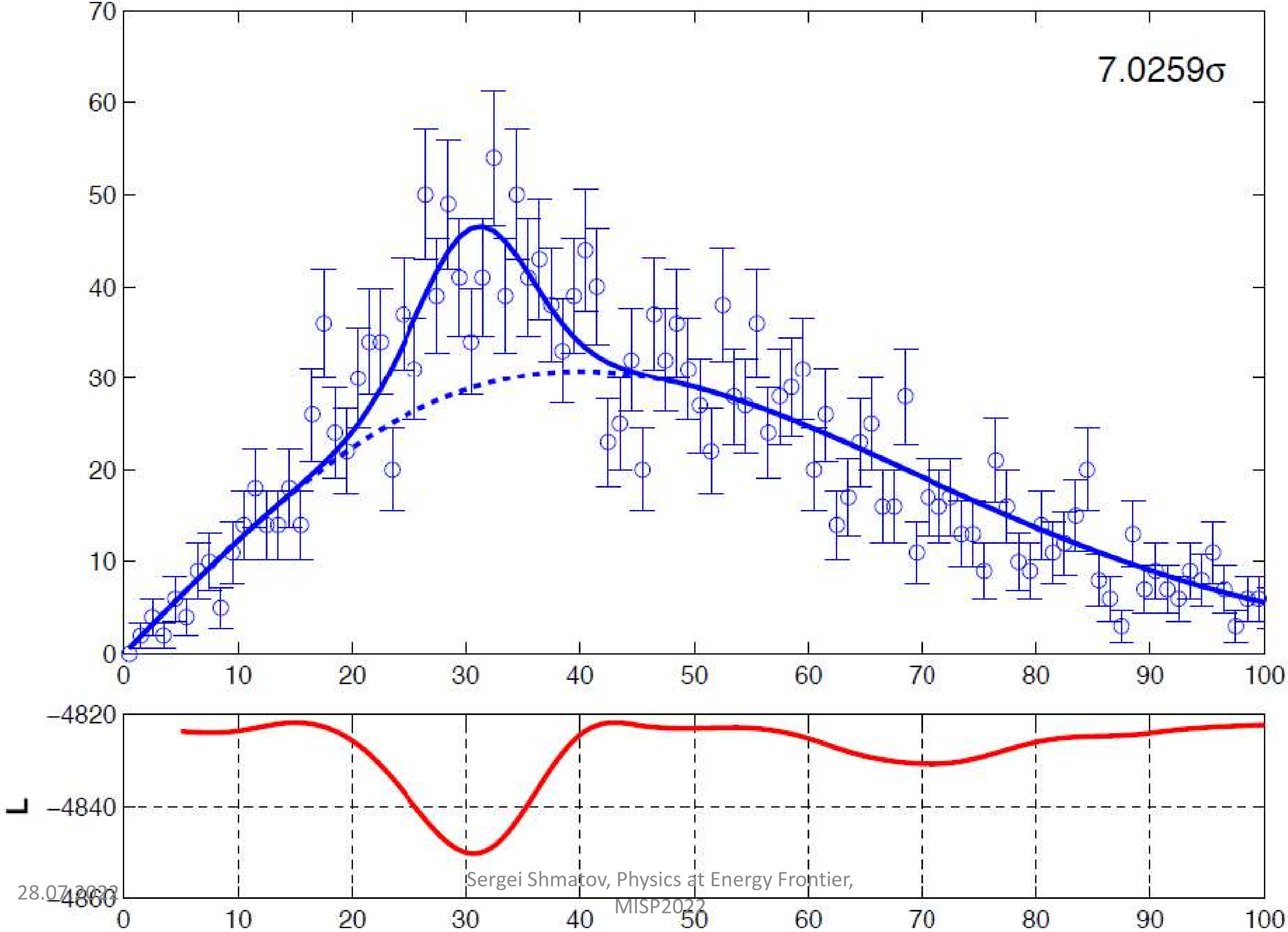


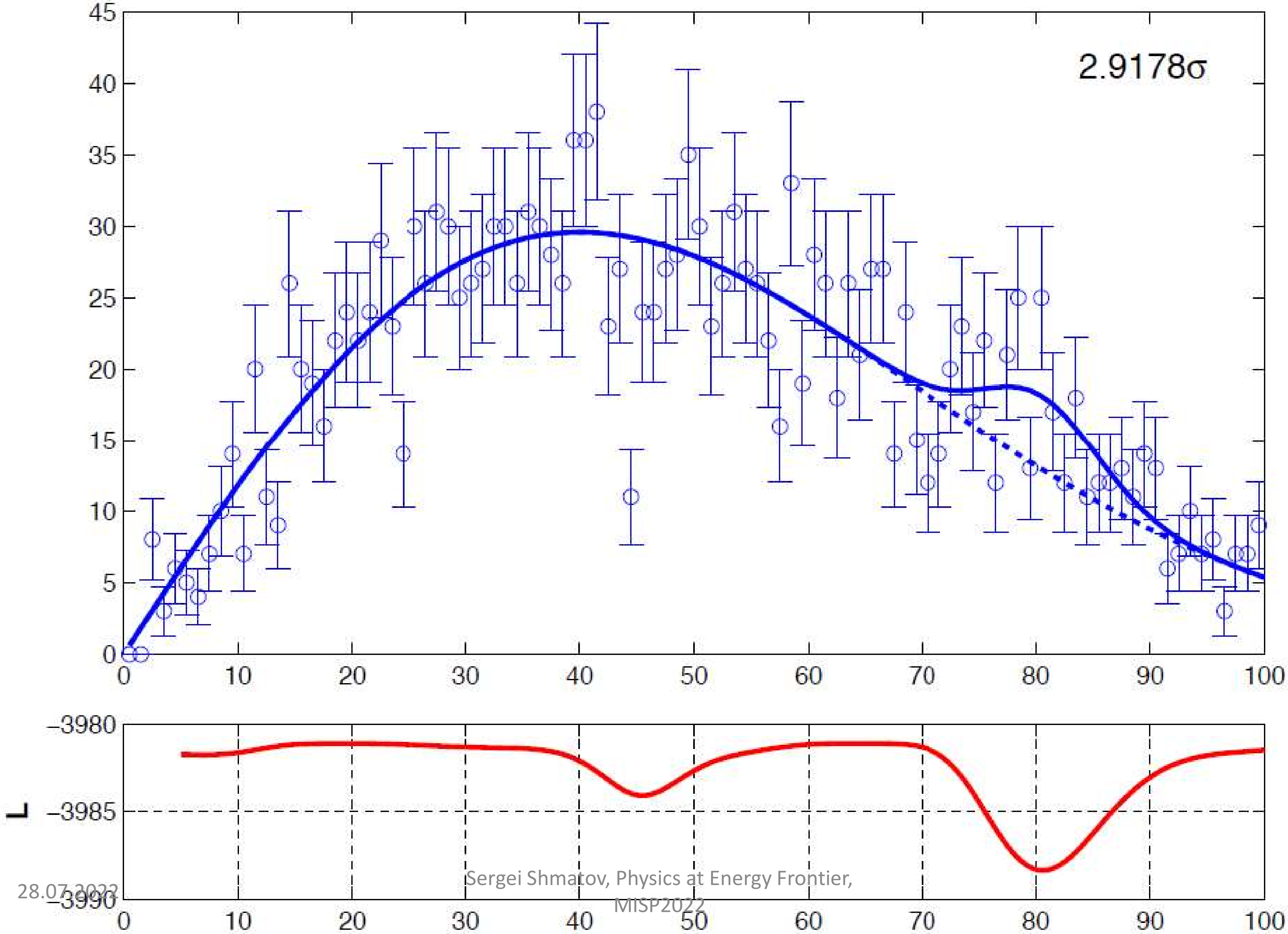


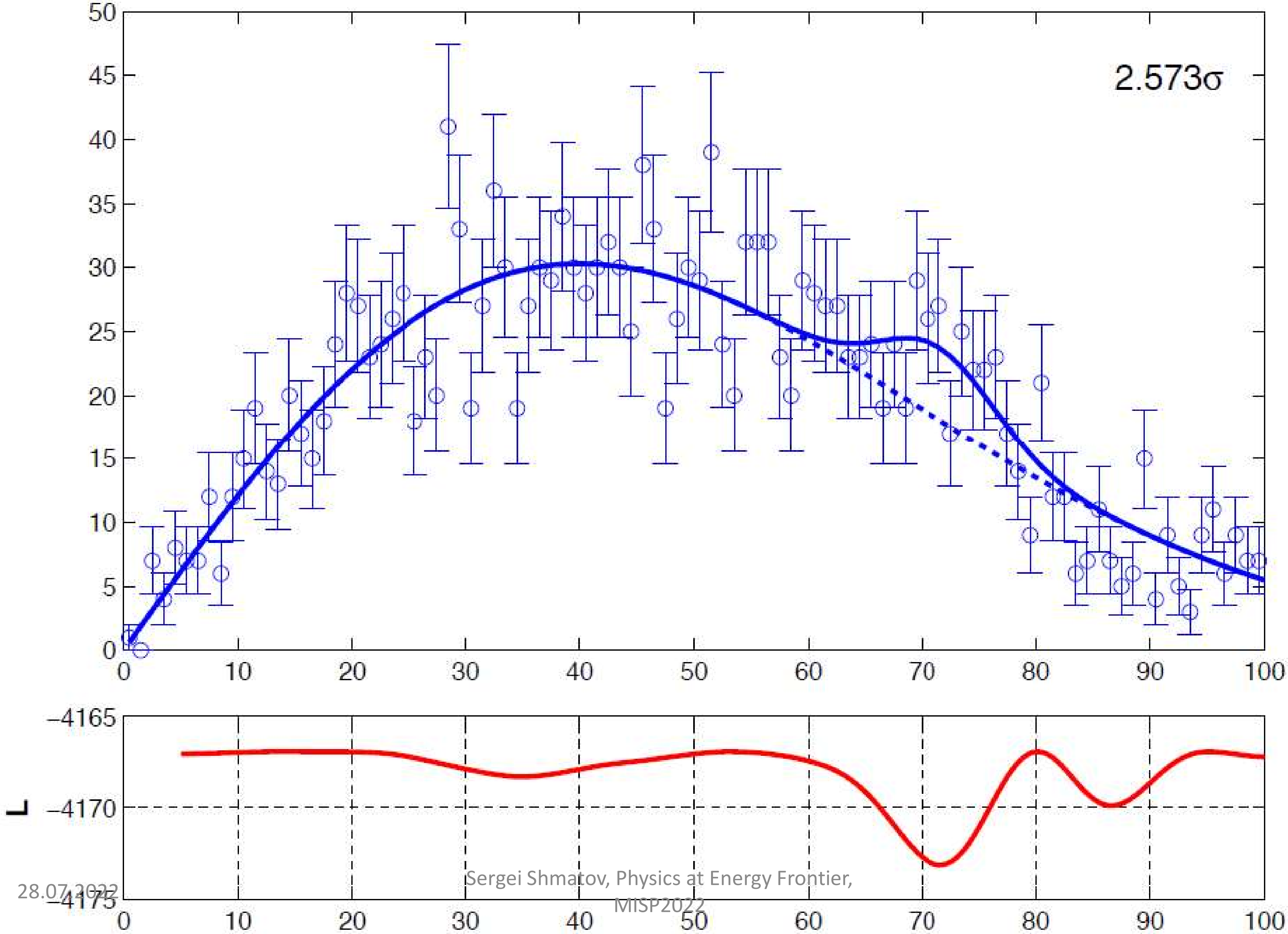
THANK YOU FOR YOUR ATTENTION!




70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90 100
−4820
L −4840
−4860
0 10 20 30 40 50 60 70 80 90 100

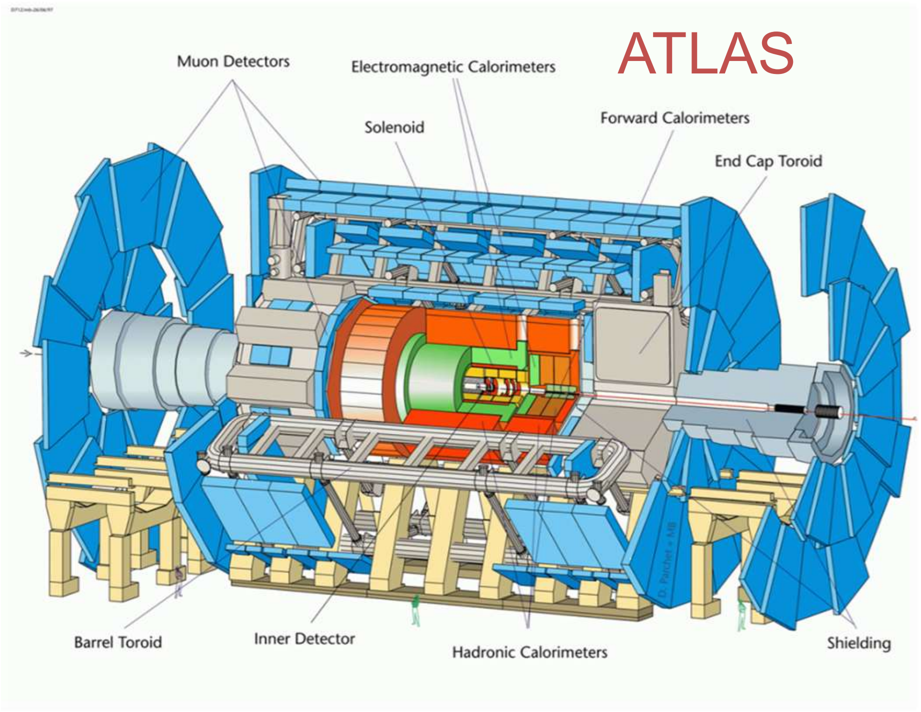

7.0259σ
L


2.9178σ
45
40
35
30
25
20
15
10
5
0
0 10 20 30 40 50 60 70 80 90 100
L
−3980
−3985
−3990
0 10 20 30 40 50 60 70 80 90 100

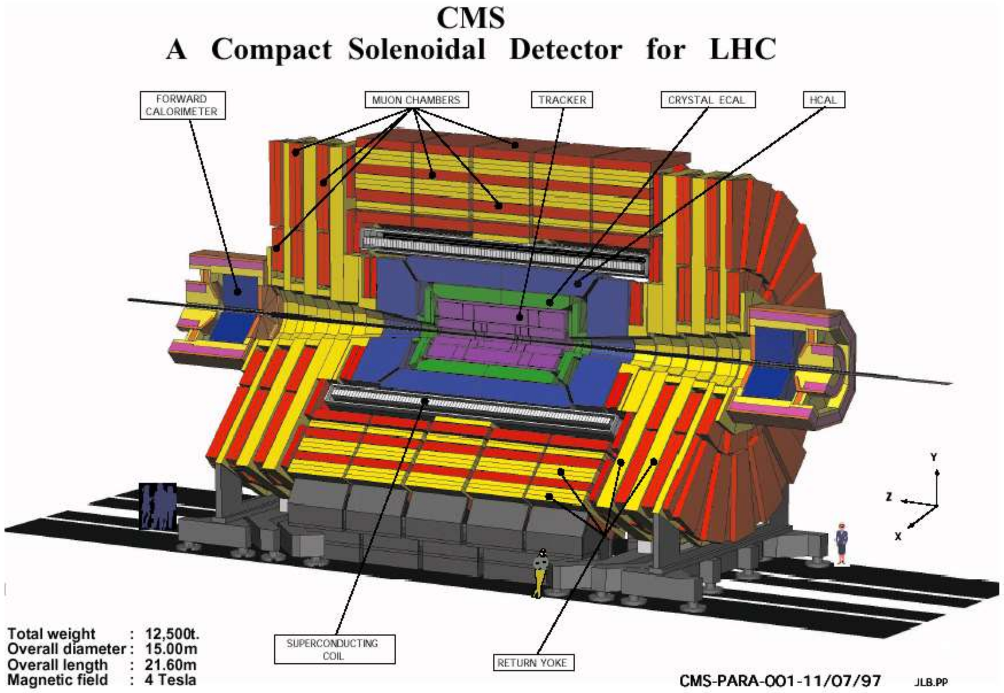

2.573σ
L

ATLAS and CMS Experiments

ATLAS



CMS



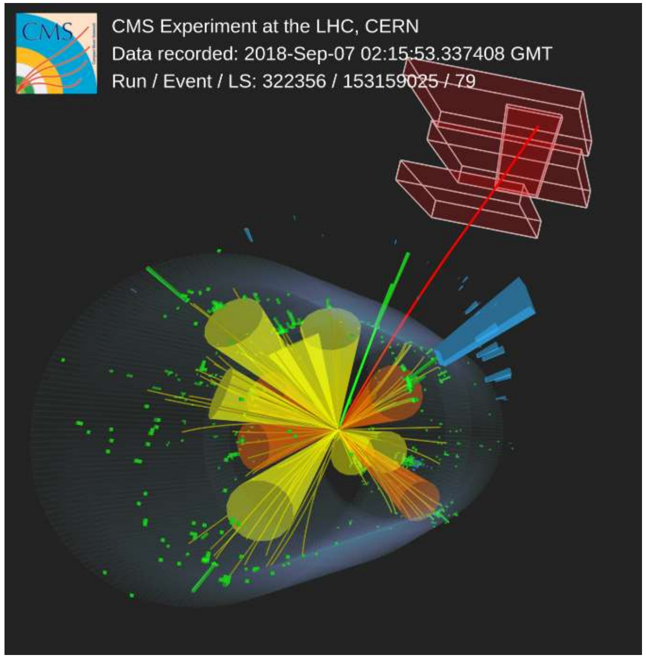
Weight	*7000 t*
Diameter	*25 m*
Length of toroid	*26 m*
Total Length	*46 m*
B-field	*2 Tesla*

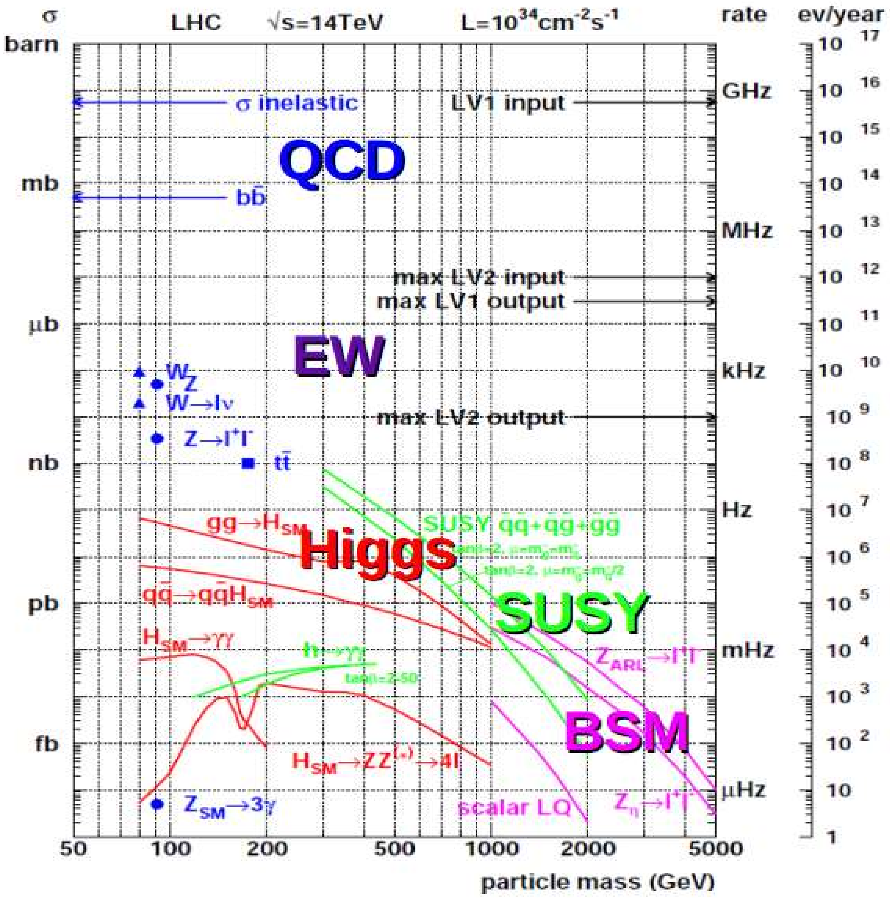
Weight	*12 500 t*
Diameter	*15 m*
Length	*21.6 m*
B-field	*4 Tesla*

Detector systems are designed to measure:

energy and momentum of photons, electrons, muons, and jets up to a few TeV

What do we know today about the Standard Model from LHC?





- SM processes:

  $\sigma \sim 1/(100\ \text{MeV})^2$

10^{-8} !

- New Physics:

  $\sigma \sim 1/(1\ \text{TeV})^2$

During Run 2 the LHC produced 10^{16} collisions

Large samples of various particles produced:

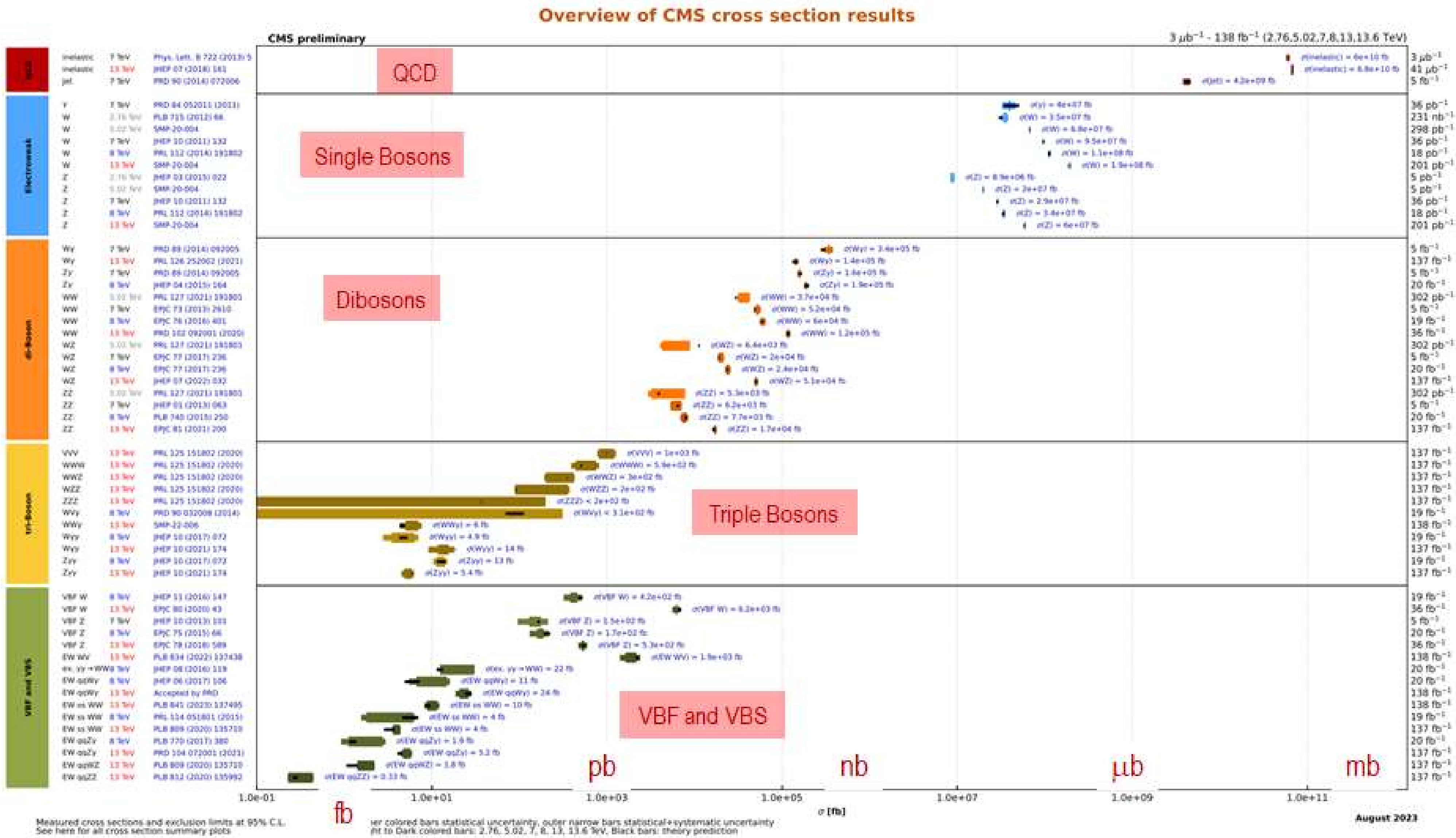
- W bosons: 12 billion
- Z bosons: 2.8 billion
- Top quarks: 300 million
- B quarks: 40 trillion
- Higgs bosons: 7.7 million

Summary of Standard Model Tests with EWK Bosons

Summaries of CMS cross section measurements

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

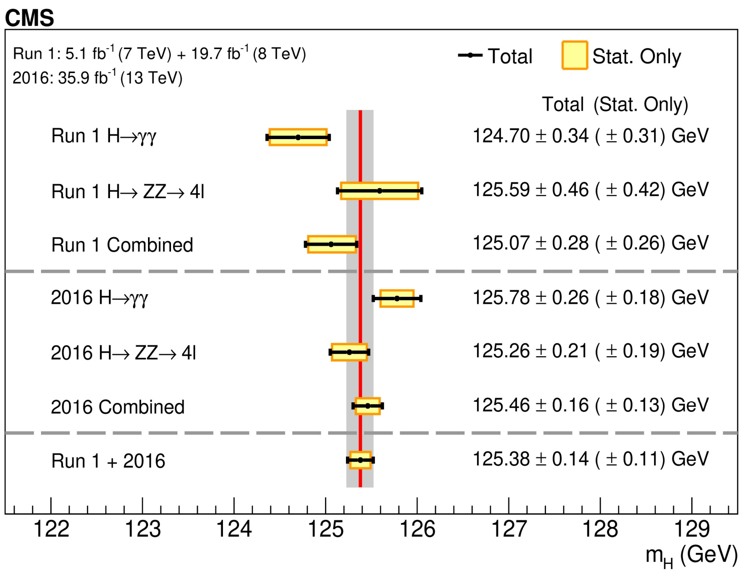
plots are updated for Summer 2023 Conferences

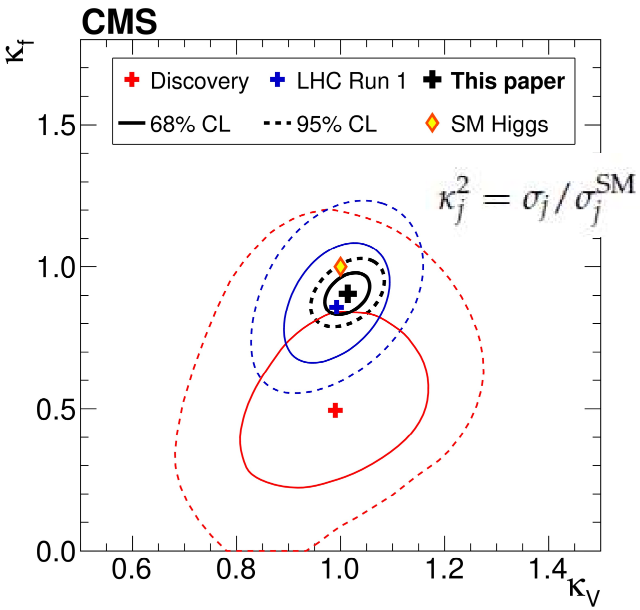


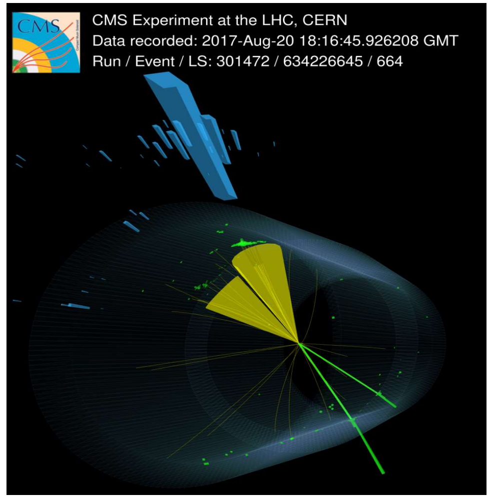
Higgs Portrait after 10 Years

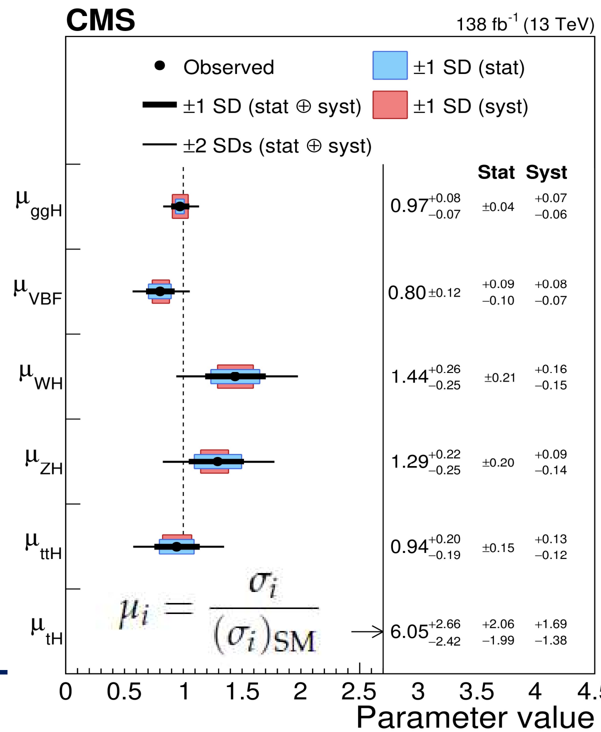
During Run 2 of the LHC the experimental collaborations started to employ the combined data for precision measurements of Higgs properties (mass, width, couplings, CP, rare decays)

- All main production mechanisms are observed, including h → bbar, ttH, VH
- Mass of Higgs boson m_h is measured with an accuracy of 0.1% (!)





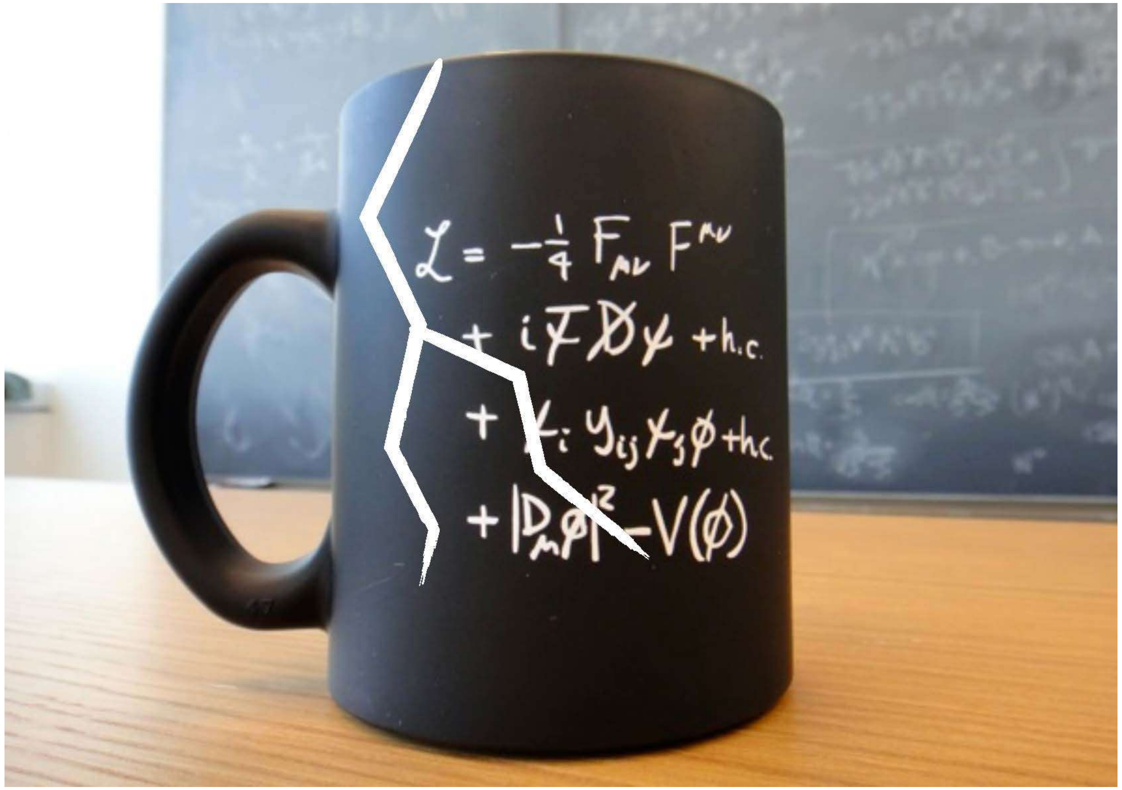




- Precisions of cross section and branching ratio measurements in combined channel are down to 8.5% level
- We have ~6-30% accuracy for measurements of couplings
- The absolute value of a width $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV is getting closer to the SM expectations (4.1 MeV). We still need to improve an accuracy.
- Spin, parity, differential distributions do not contradict the SM

What do we have as a result?

Why we are still expecting the New Physics?



A room in Higgs Sector

… but the current accuracy of Higgs coupling measurements is still insufficient to reject BSM Higgs hypothesis

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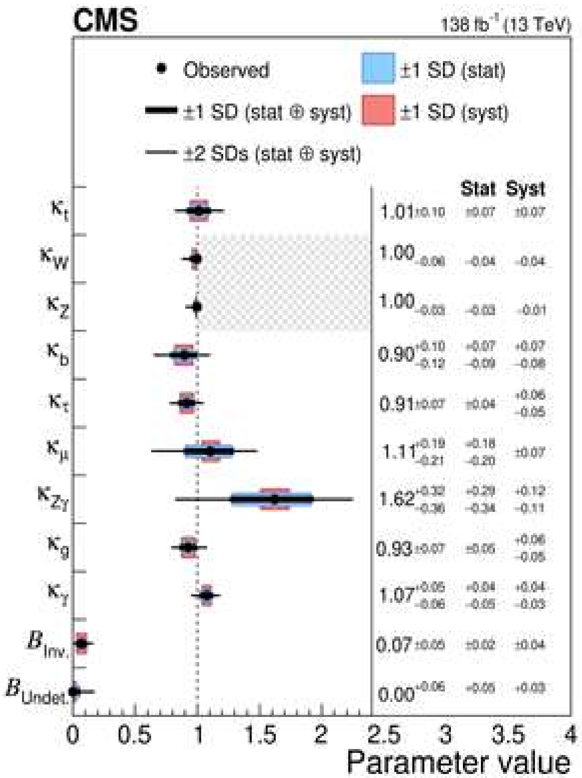
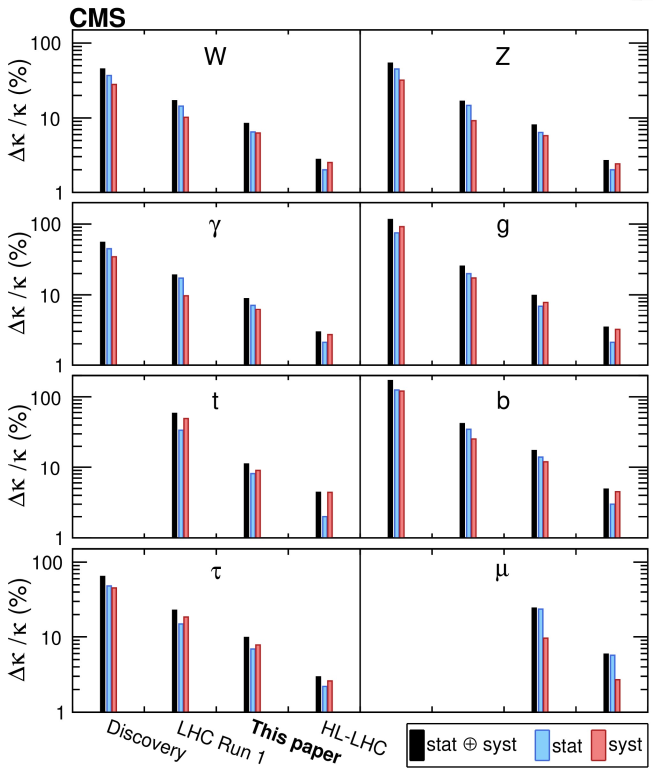
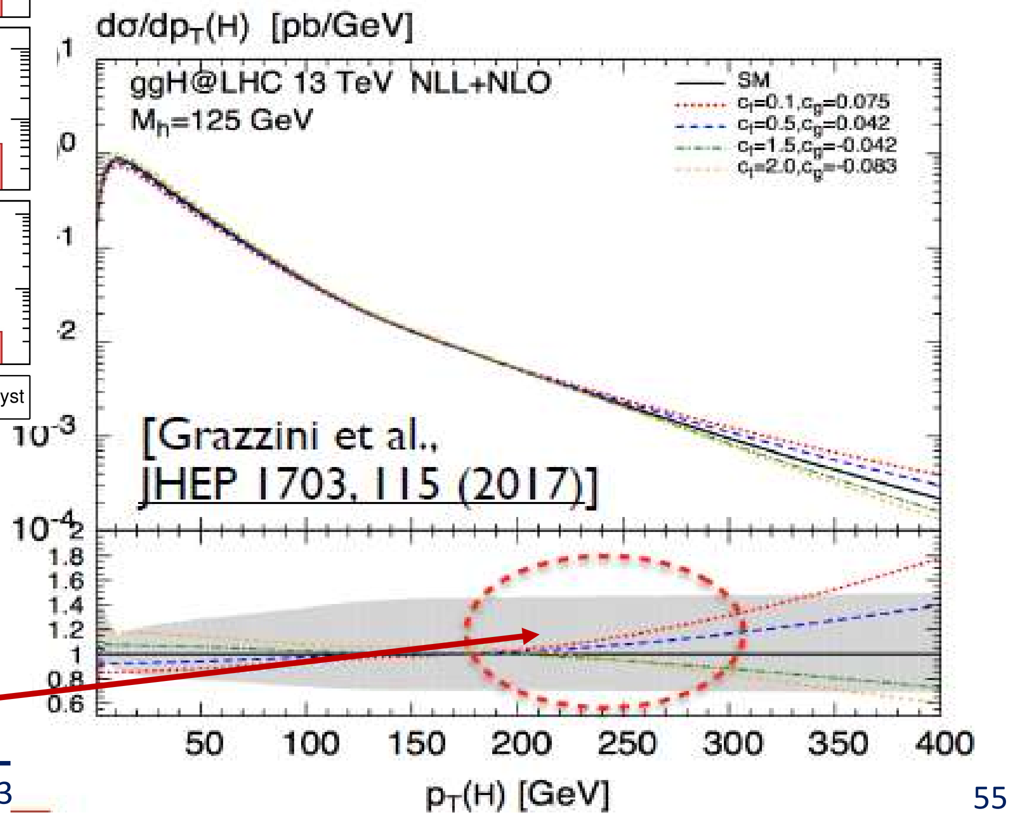
Summary of Higgs Couplings Measurements

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
ecoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$





The 95% CL upper limit on $\mathcal{B}_{\mathrm{Undet.}}$ is found to be <0.16

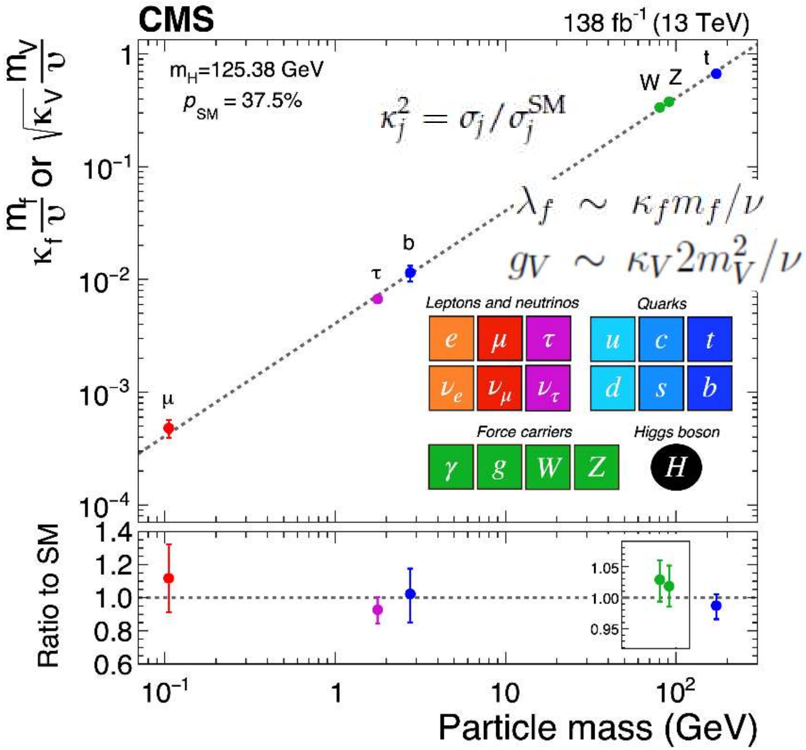


- Measurements precision continuous increasing
- Search for new higgs states and other BSM
  - ✓ BSM effects on in the differential distributions

Another Hint from the Higgs: Flavour Universality

The properties of the Higgs h_{125} agree fully with SM in decay into

- gauge bosons
- 3rd generation fermions (t/b/τ)
- and do not conflict with results for the 2nd generation (no deviations in cc/μμ decays after RUN2)



$$\mathcal{B}_{\rm SM}(H \to e^+e^-) \approx 9 \cdot 10^{-9}$$

$$\mathcal{B}_{\rm SM}(H \to \mu^+\mu^-) \approx 2{,}2 \cdot 10^{-4}$$

μμ: 3σ

$1.19^{+0.40}_{-0.39}$ (stat)$^{+0.15}_{-0.14}$ (syst)

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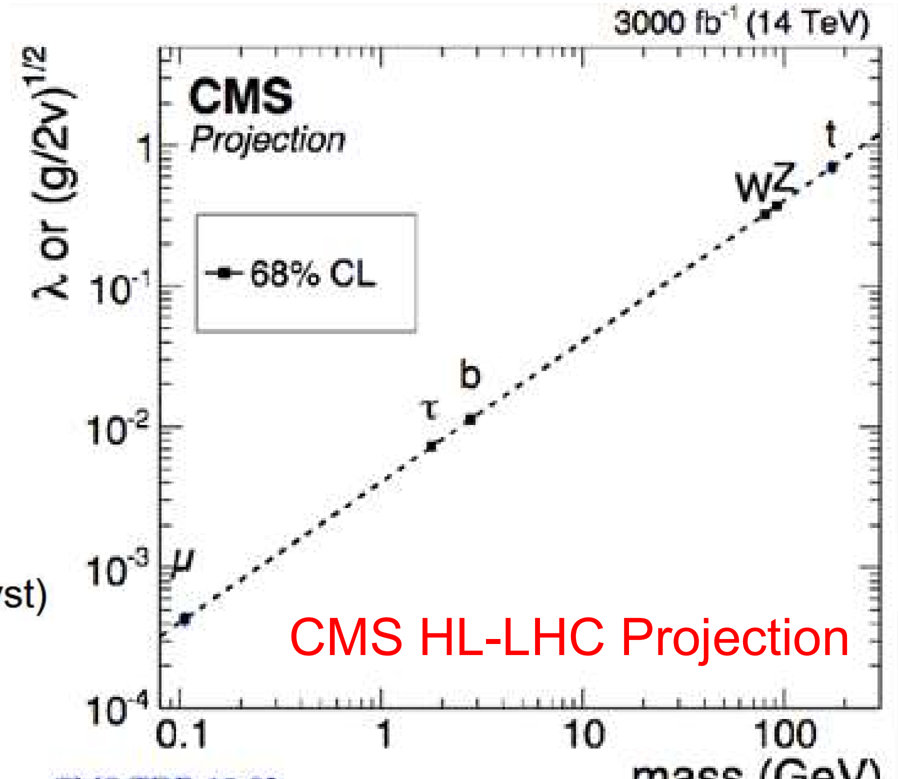


CMS-TDR-15-02

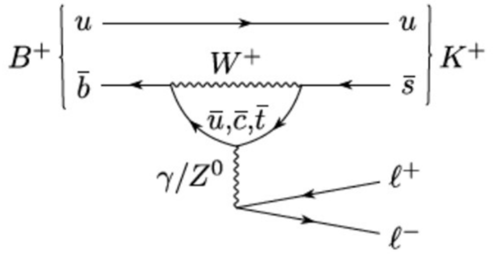
We do not know and will not know until the end of the LHC whether the coupling of the Higgs h_{125} to 1st generation fermions is in a "standard" way or not.

If we have no Extra Higgses! (rare decays are enhanced within Extended Higgs Sectors)

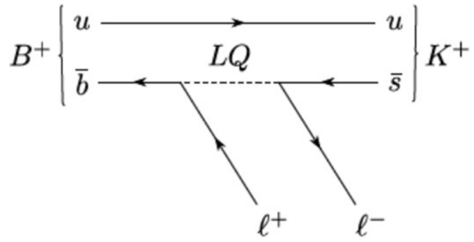
Lepton universality in beauty-quark decays

$$R_X \equiv \frac{\mathcal{B}(B \to X \mu^+\mu^-)}{\mathcal{B}(B \to X e^+e^-)} = 1 \text{ in the SM}$$

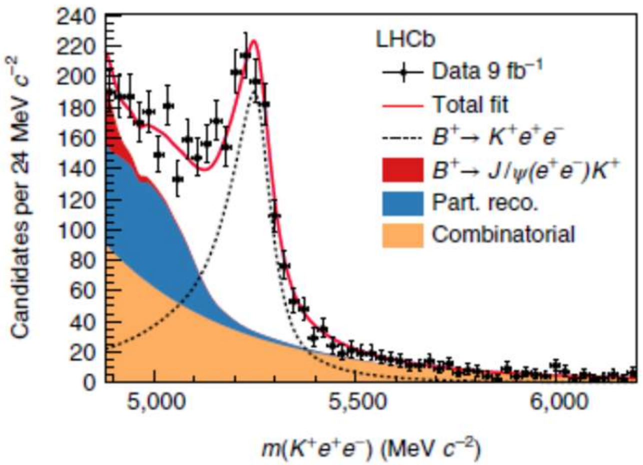
All QCD effects cancel in ratios.
Small $\mathcal{O}(1\%)$ radiative corrections.

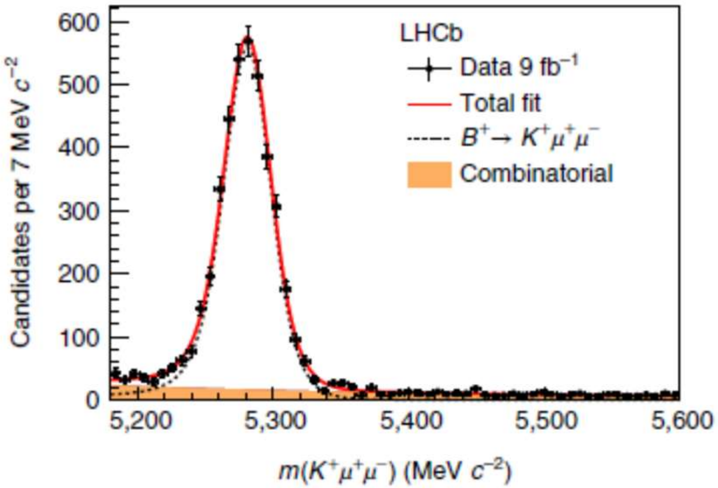


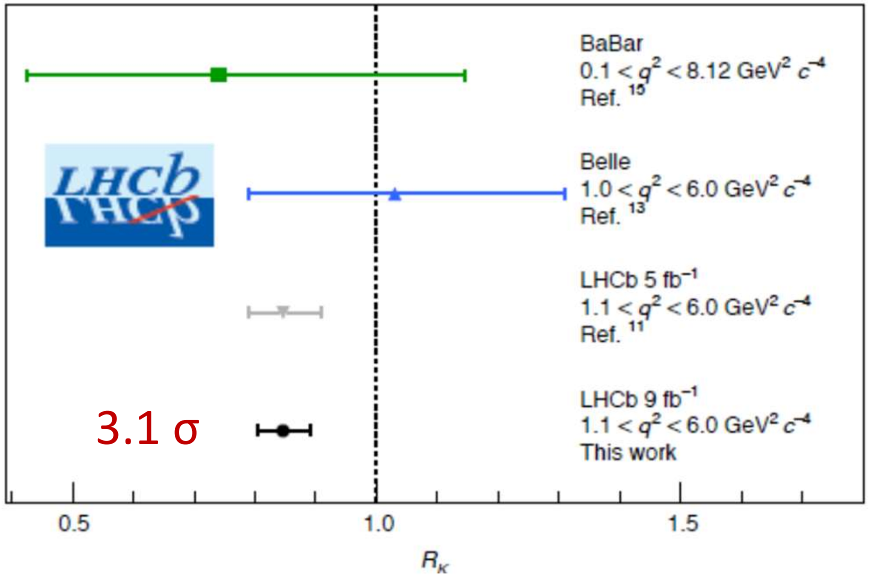
SM



NP







arXiv:2103.11769
Nature 18, 277 (2022)

- LHCb searches in B decays (90% CL limits):

$\mathcal{B}(B_s^0 \to e\mu) < 5.4 \times 10^{-9}$ [3 fb^{-1} JHEP03(2018)078]

$\mathcal{B}(B^+ \to Ke\mu^-) < 7 \times 10^{-9}$ [3 fb^{-1} hep-ex/1909.01010]

$\mathcal{B}(B_s^0 \to \tau\mu) < 3.4 \times 10^{-5}$ [3 fb^{-1} hep-ex/1905.06614]

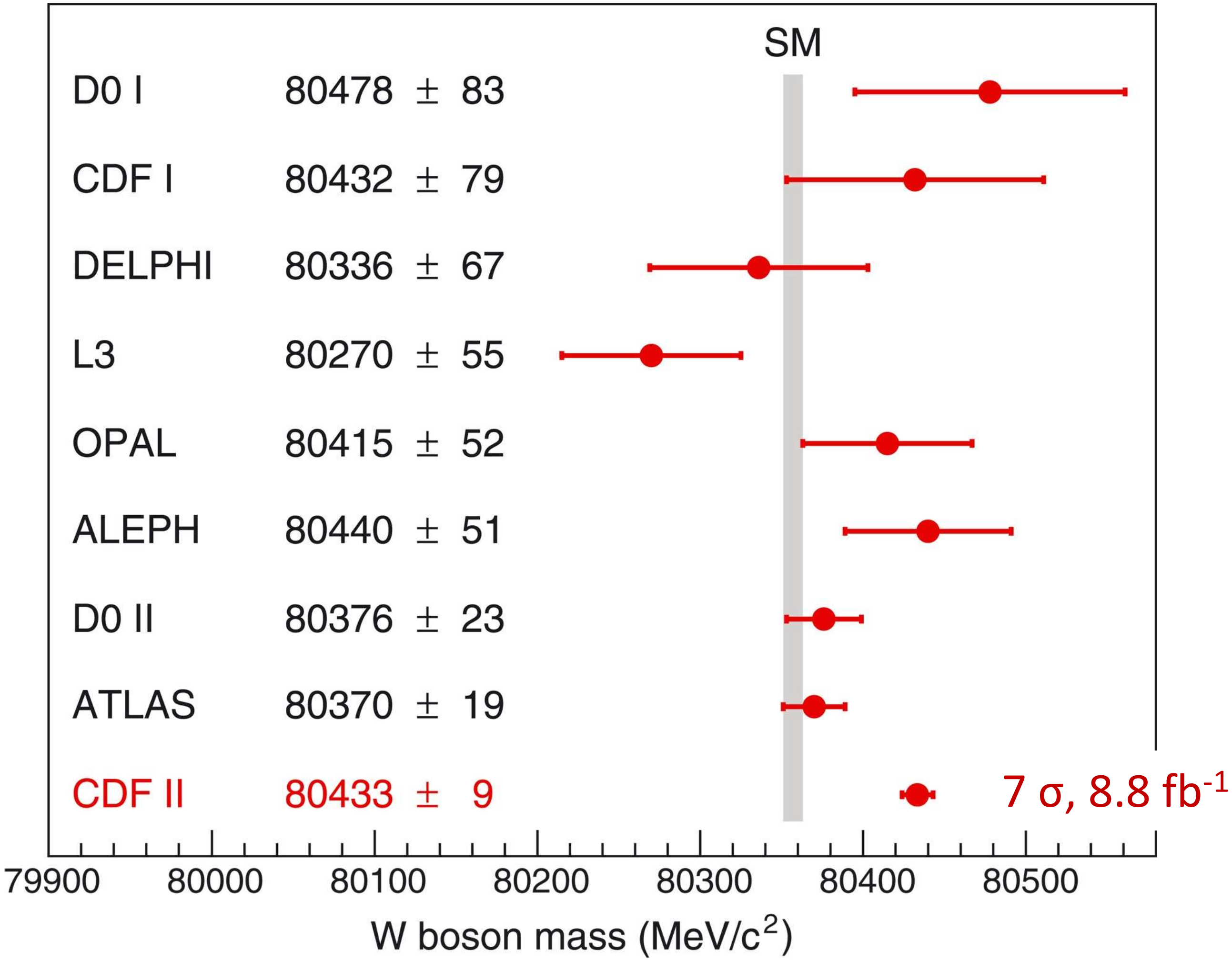
$$R_K(1.1 < q^2 < 6.0\,\text{GeV}^2 c^{-4}) = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

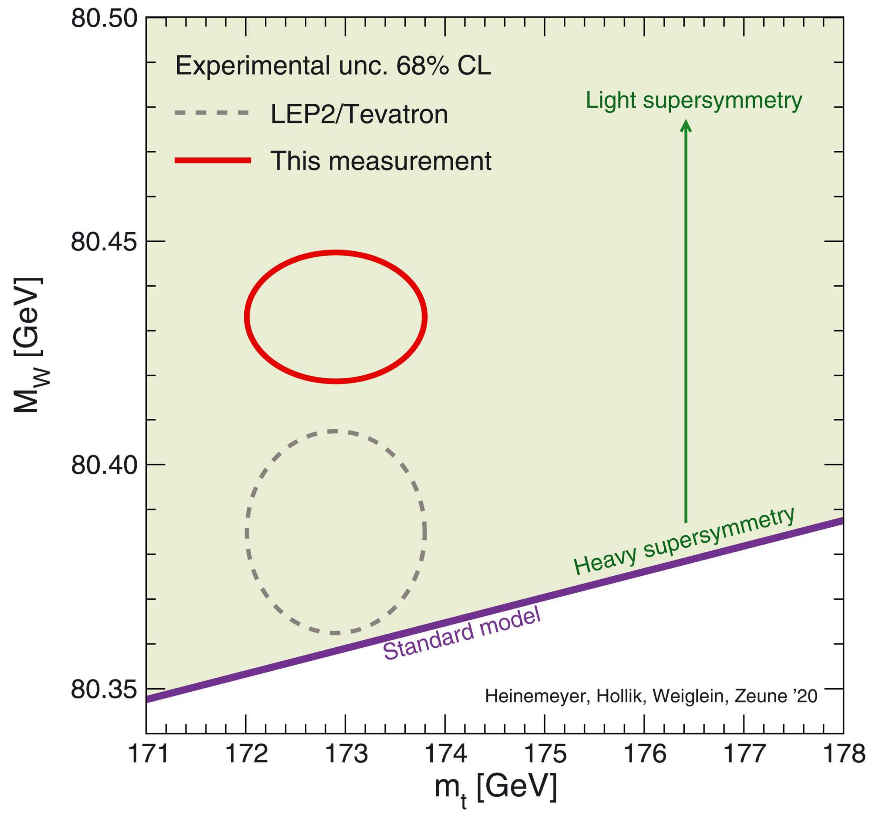
Control uncertainties by measuring double ratios:

$$R_X \equiv \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to X\, J/\psi\,(\to \mu\mu))}\,\frac{\mathcal{B}(B \to X\, J/\psi\,(\to ee))}{\mathcal{B}(B \to X ee)} = 1_{(SM)}$$

W boson mass with the CDF II detector

$W \to \mu\nu$ and $W \to e\nu$ decays.

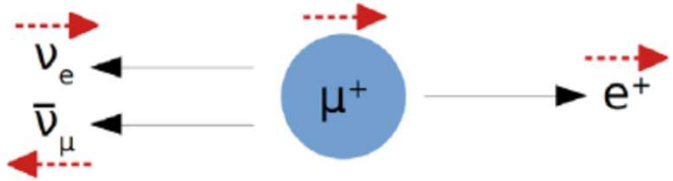


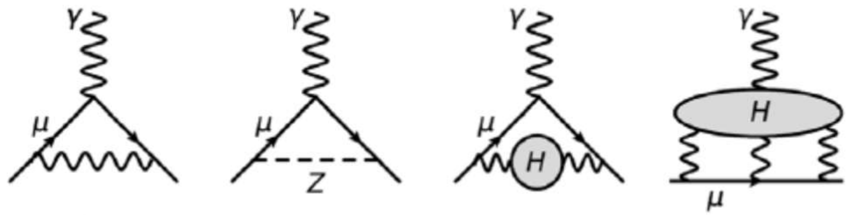


Science Vol 376, 170-176 (2022)

$$M_W = 80,433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}} = 80,433.5 \pm 9.4\ \text{MeV}/c^2$$

Fermilab Muon g – 2 Experiment





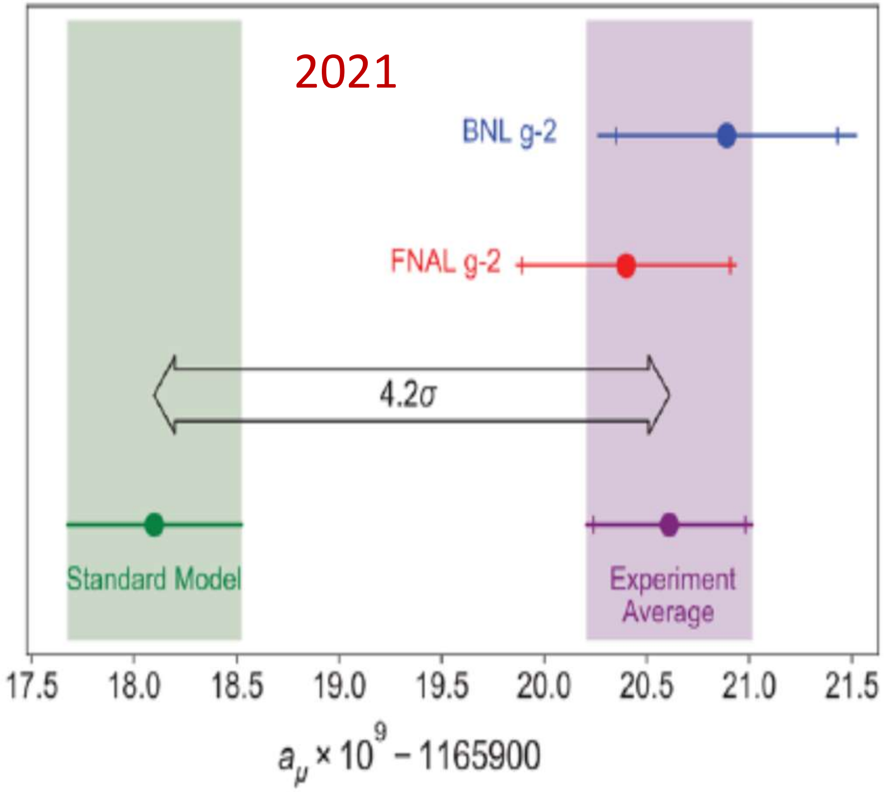
for J=1/2

$g = \mu/\mu_B J = 2$

$a_\mu = (g-2)/2$

$$a_\mu = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak} + a_\mu^{New\,Physics}$$

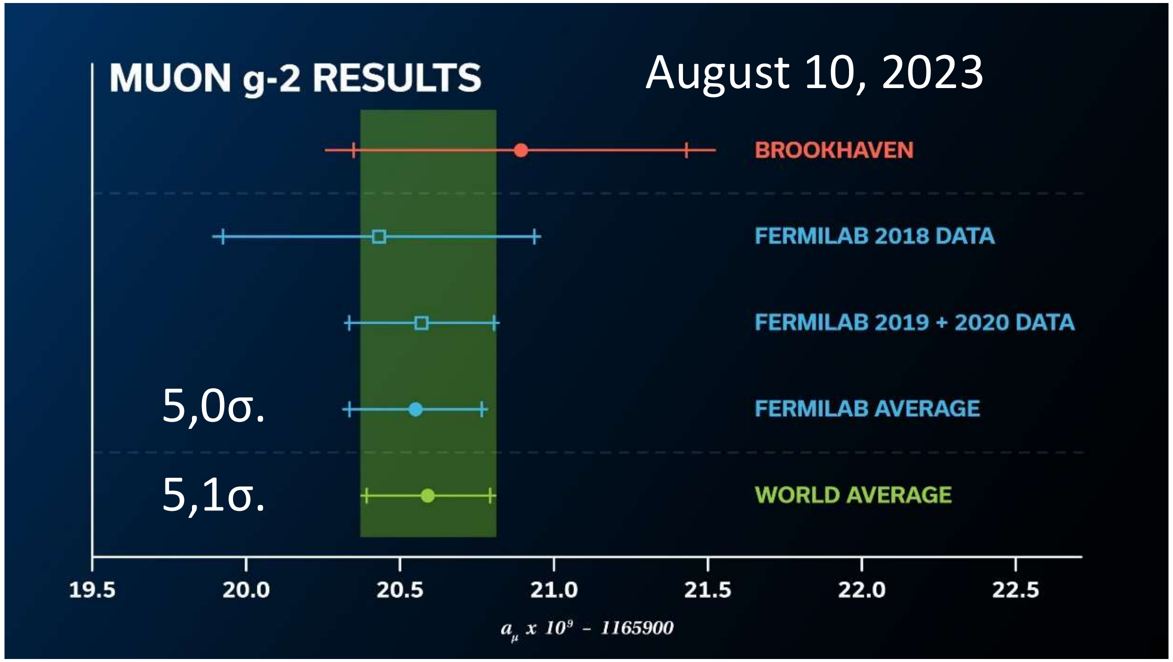
$$1{,}000{,}000 \;:\; 60 \;:\; 1.3 \;:\; \propto (m_\mu/m_X)^2$$



a_μ^{Th} [2020] $= 116\,591\,810(43) \times 10^{-11}$ (0.37 ppm)

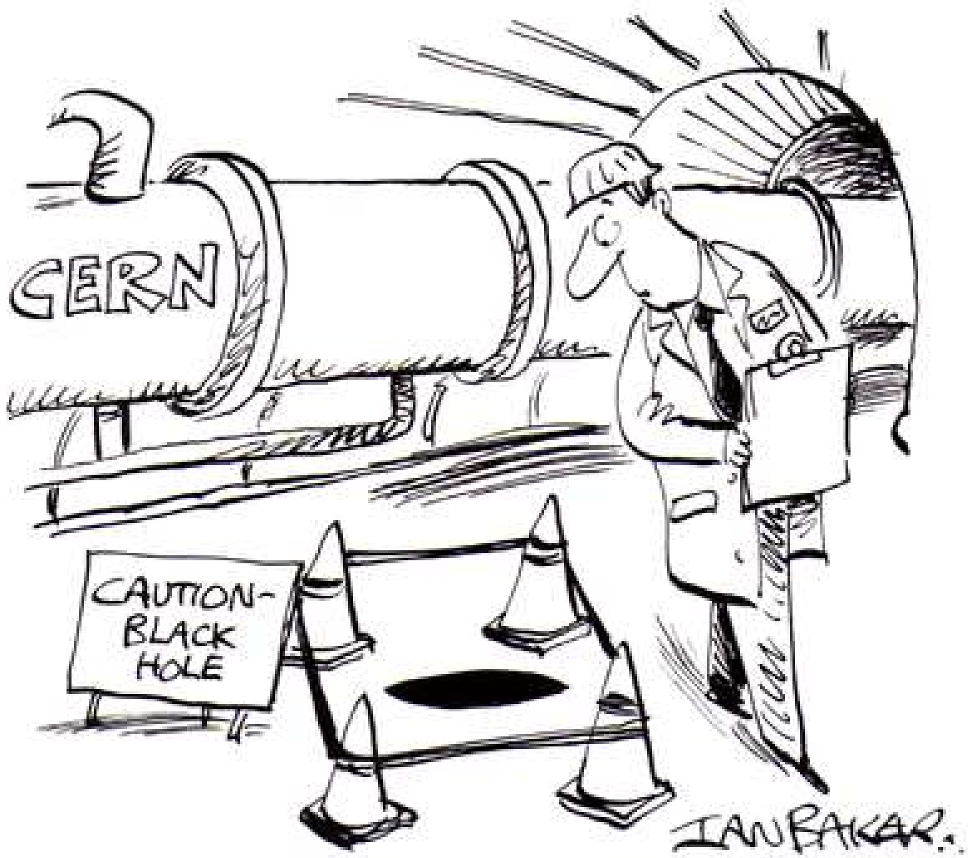
a_μ^{Exp} [2021] $= 116\,592\,061(41) \times 10^{-11}$ (0.35 ppm)

$a_\mu^{Exp} - a_\mu^{Th} = (251 \pm 59) \times 10^{-11}$ (4.2σ)



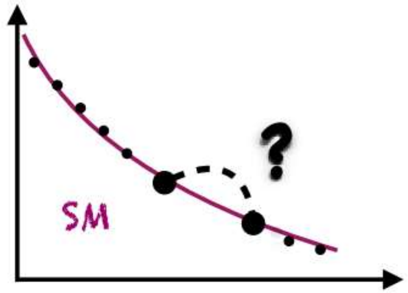
The new experimental result is:
g-2 = 0.00233184110 +/- 0.00000000043 (stat.) +/- 0.00000000019 (syst.), 0.2 ppm

THANK YOU FOR YOUR ATTENTION!



BSM Analyses in the LHC Collaborations

- Direct Searches for the Physics Beyond the SM
  - ✓ Conventional Signals, such as new resonances in dileptons/diphotons/ dijets spectra or non-resonant signals, combinations of physics objects (leptons/photons/jets) and MET/ b/t-jets tags, high-multiplicity events, etc



SUSY | Extended Gauge Sector | Extra Dimensions | CI/Excited Fermions/B3G

  - ✓ Non-conventional Signals, for example displaced vertices/leptons/lepton-jets/dileptons from Long-Lived Particles or emerging jets/leptons from boosted heavy objects, $m \ll p_T$ (i.e. high-p_T Z/W/h_{125} bosons)

Long-Lived Particles (Dark Matter/Non-standard SUSY/Neutrino Masses/etc) | Extended Higgs and Dark Matter Sectors

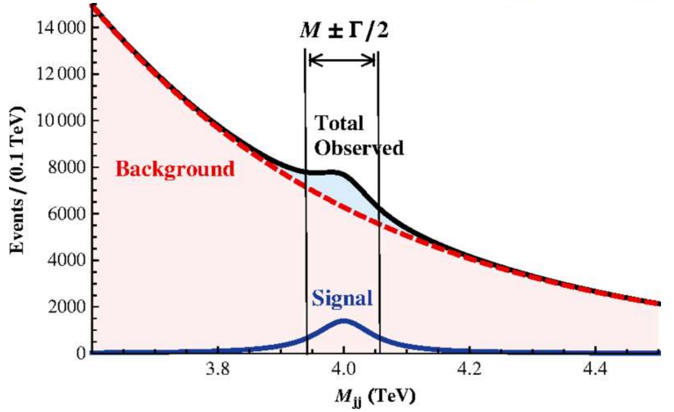
- BSM-Higgs Physics
  - ✓ Searches for the new Higgs states (from extended Higgs sector including SUSY)
  - ✓ Probes for the New Physics with h_{125} (Higgs as a tool for new discovery)

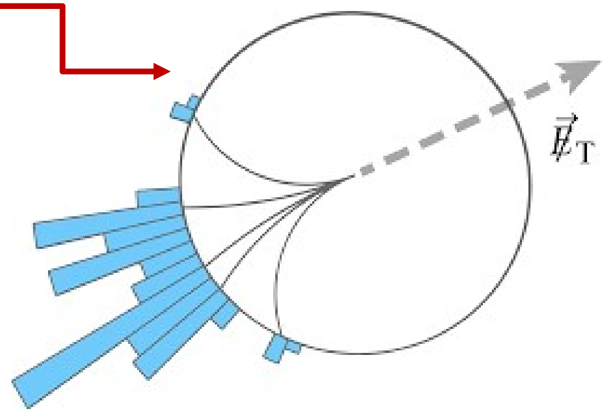
Extra Higgses, Dark Matter, Flavour Universality Violation

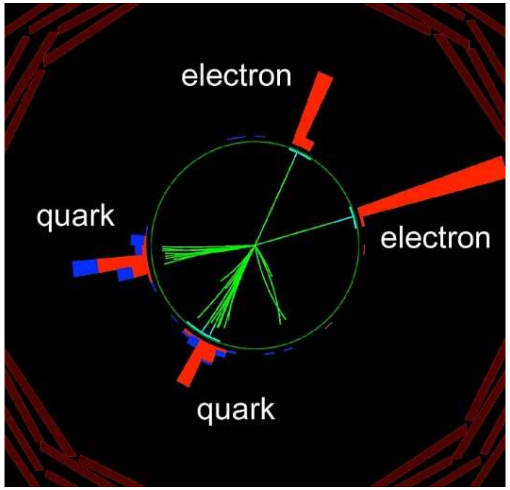
- Precision Tests of SM
  - ✓ Measurements of the W/Z, Drell-Yan (+ n jets) x-sections and angular characteristics
  - ✓ Search for rare decays of B-mesons
  - ✓ Observations of other rare process in top sector within SM (Wtb couplings, CP violating top quark couplings, flavor-changing neutral current interactions of the t-quark and h_{125})

Conventional Signals

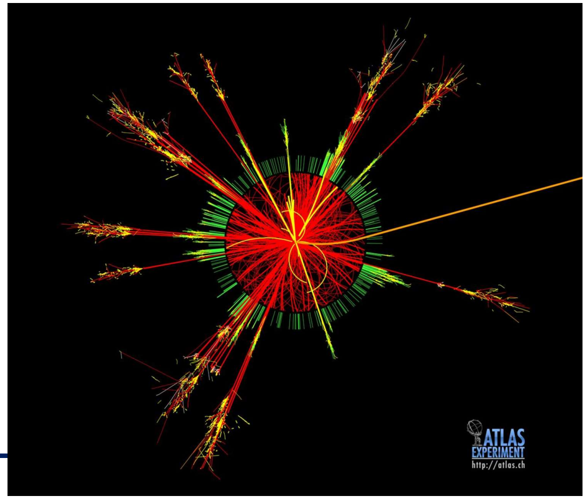
- Heavy Resonances (extended gauge models, extra dimensions, technicolor) ⇒ dileptons, dijets, diphotons, ttbar, WZ
- Non-Resonant Signals
- Mono-particle + Missing ET (extended gauge models, extra dimensions, technicolor, SUSY) ⇒ mono-jet + MET, mono-photon + MET, mono-lepton + MET
- Microscopic Black Holes (extra dimensions) ⇒ high-multiplicity events



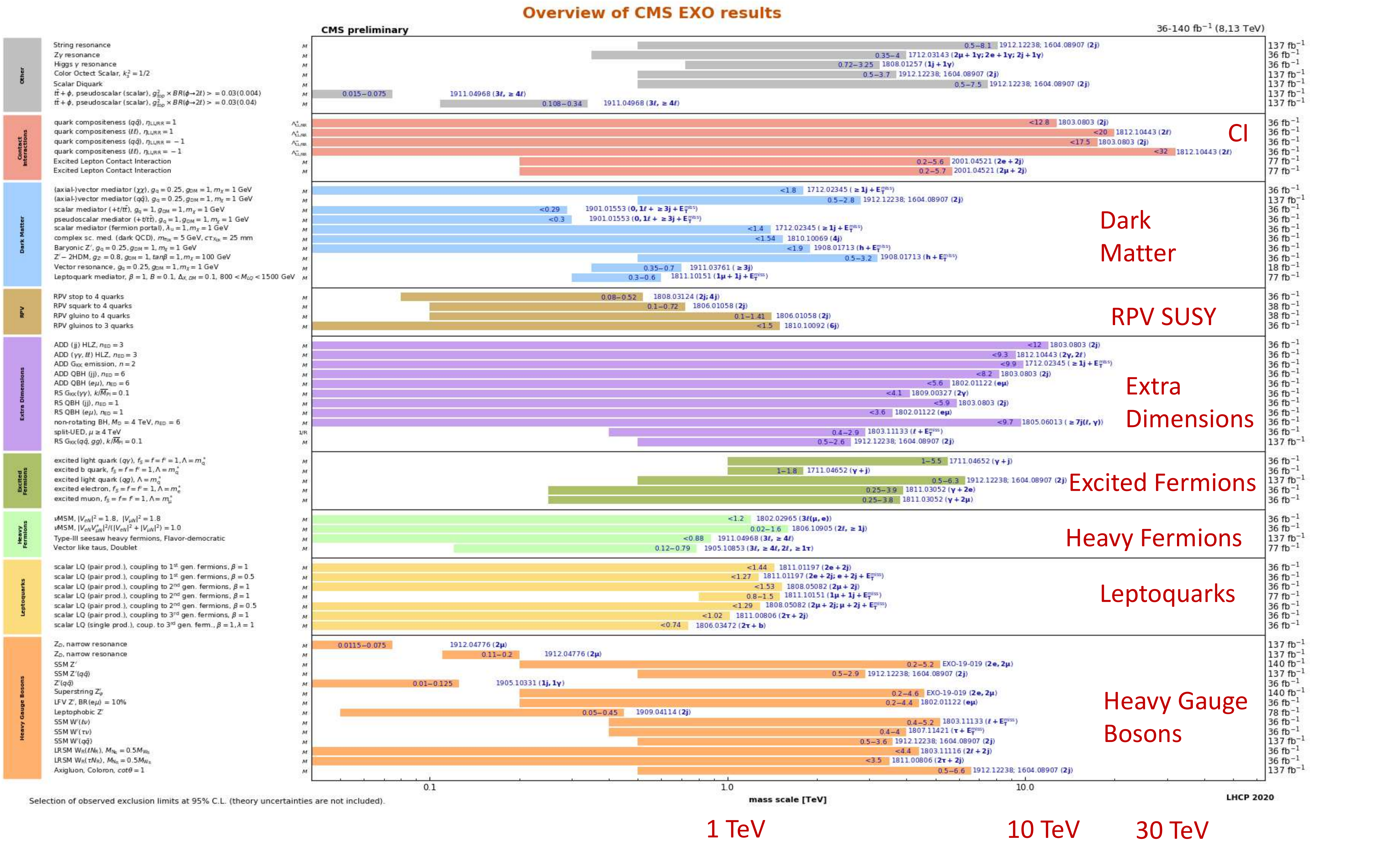




- Leptoquarks ⇒ lepton + jet
- 4^{th} Generation ⇒ leptons/jets, dilepton



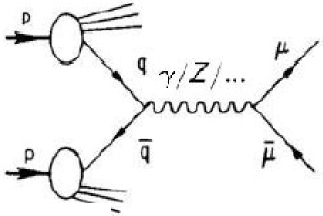
Direct Search for BSM: Conventional Signals



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

Searches for Heavy Resonances

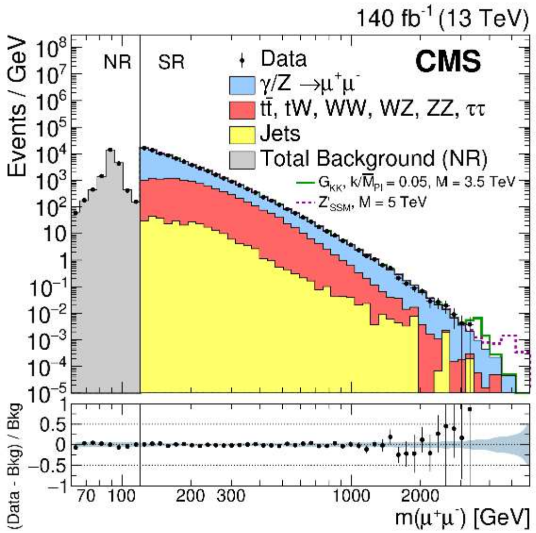
New Physics ($Z'/Z_{KK}/G_{KK}$) contributions to SM processes

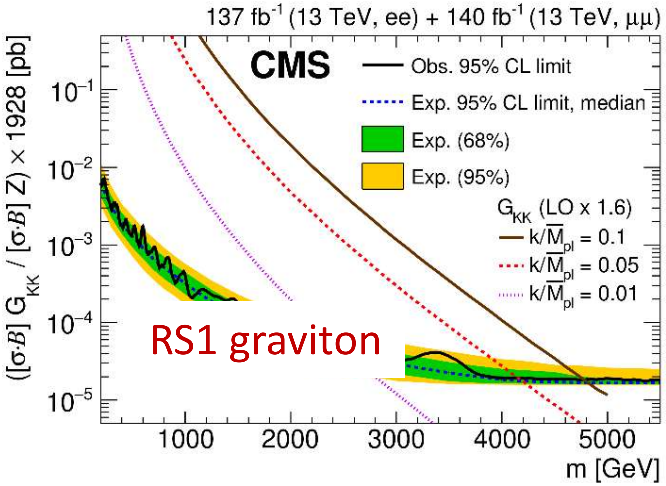


$$R_\sigma = \frac{\sigma(pp \to Z' + X \to l^+l^- + X)}{\sigma(pp \to Z^0 + X \to l^+l^- + X)}$$

Dileptons, full RUN2 data

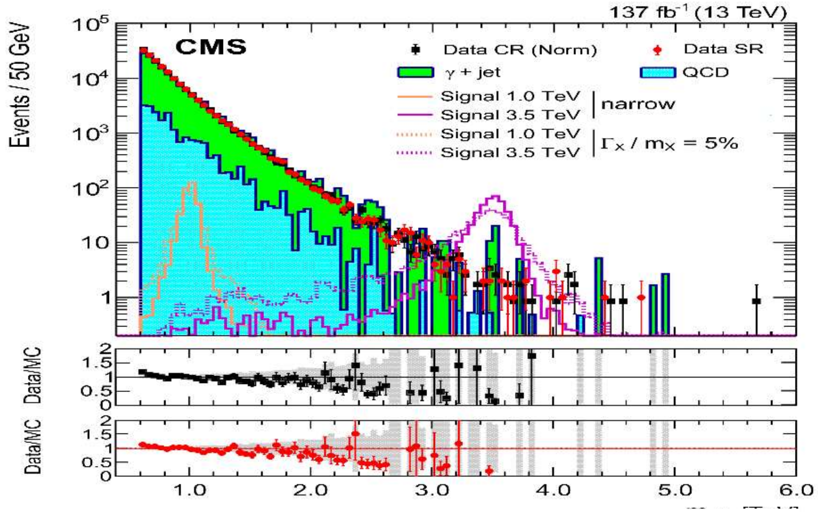
JHEP 07 (2021) 208

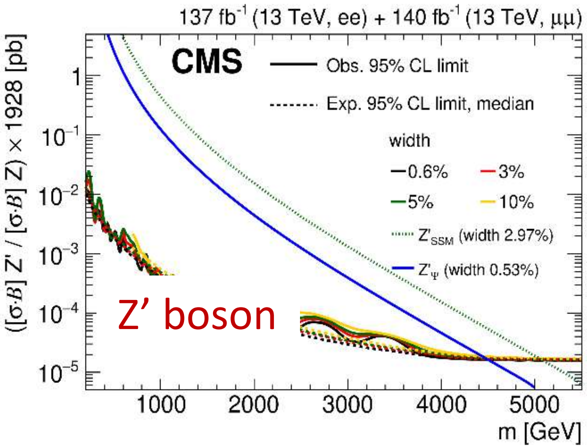


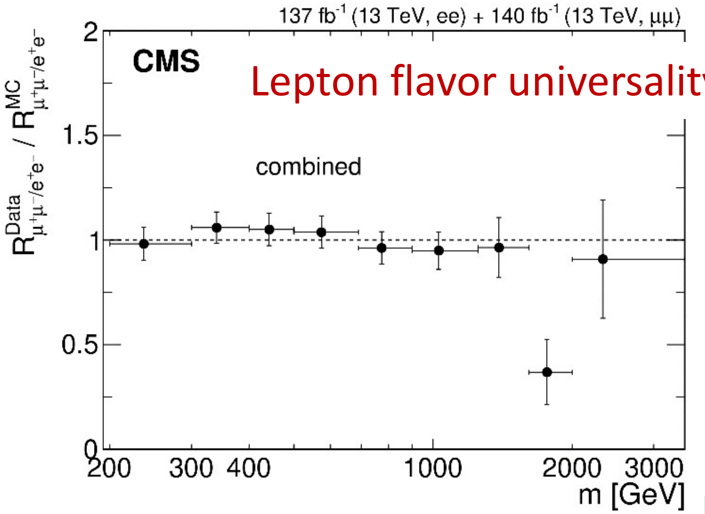


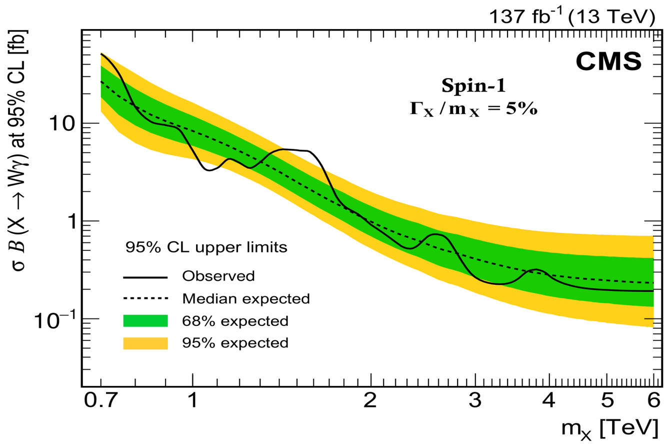
Wγ, full RUN2 data

PLB 826 (2022) 136888







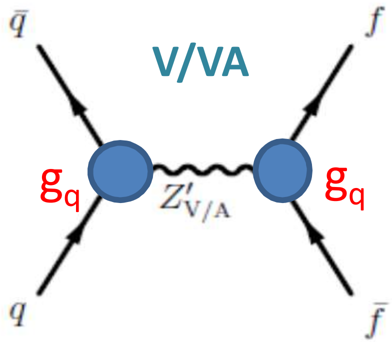


benchmark heavy scalar (vector) triplet bosons with masses between 0.75 (1.15) and 1.40 (1.36) TeV are excluded at 95% CL

Example of Dark Matter Searches in Dijets + Dileptons

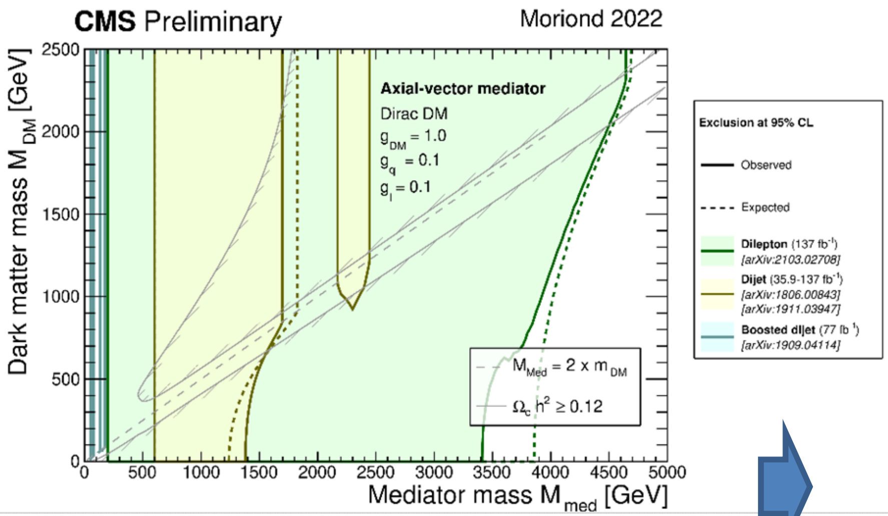
We consider a model that assumes the existence of a single DM particle that interacts with the SM particles through a spin-1 mediator, which can be either a vector or axial-vector boson.

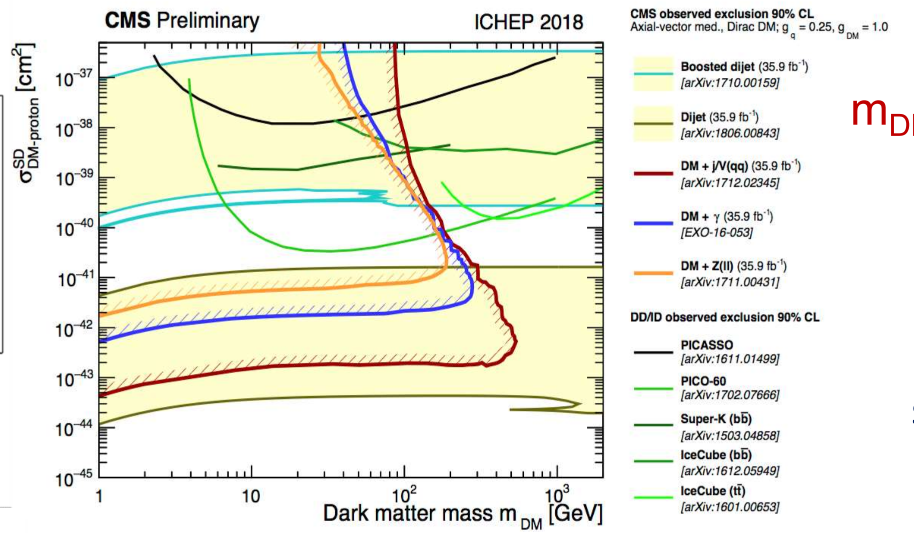
- vector mediator with small couplings to leptons, g_{DM} = 1.0, g_q = 0.1, g_l = 0.01
- axial-vector mediator with equal couplings to quark and leptons: g_{DM} = 1.0, g_q = g_l= 0.1



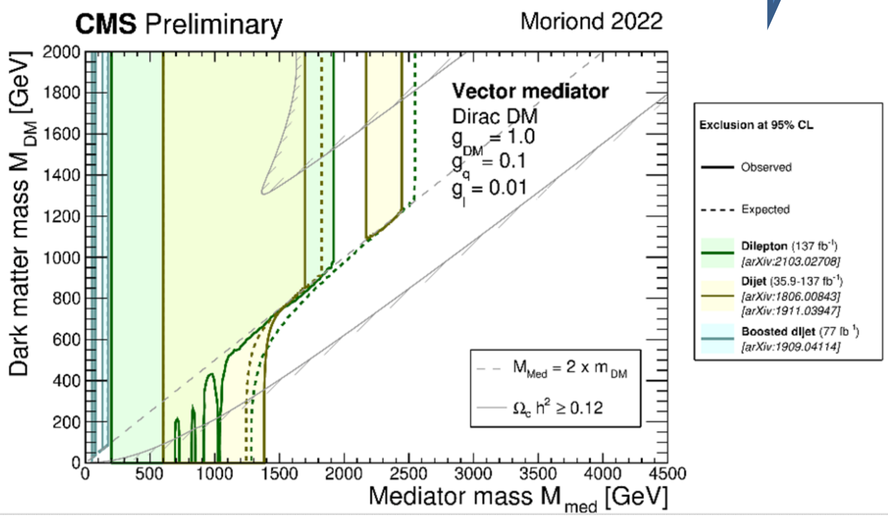
5 parameters:

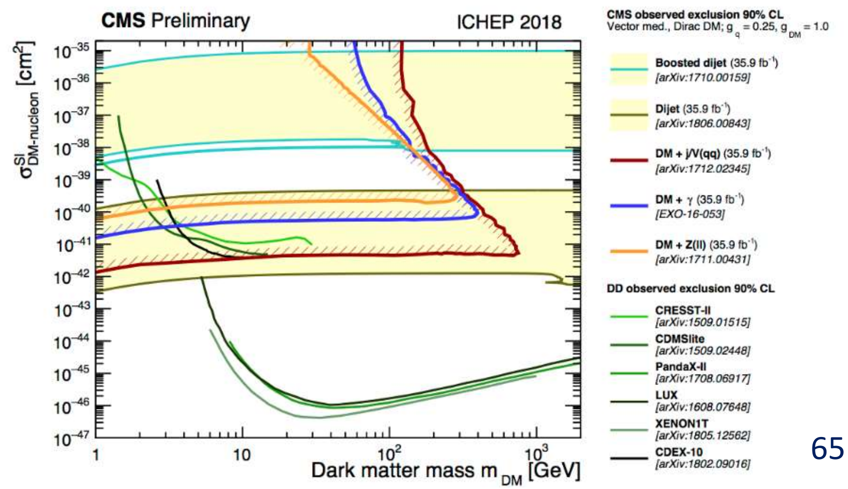
m_{DM}, m_{Med}, g_{DM}, g_l, g_q





DM-nucleon upper limits on the cross section

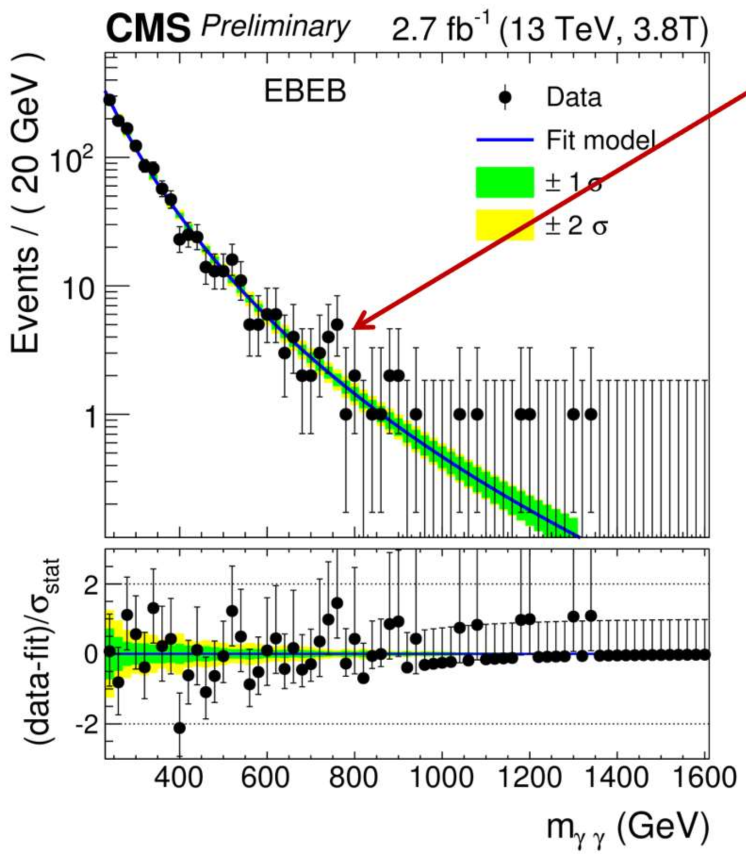




The case of the past days ($\gamma\gamma$ excess in LHC data)

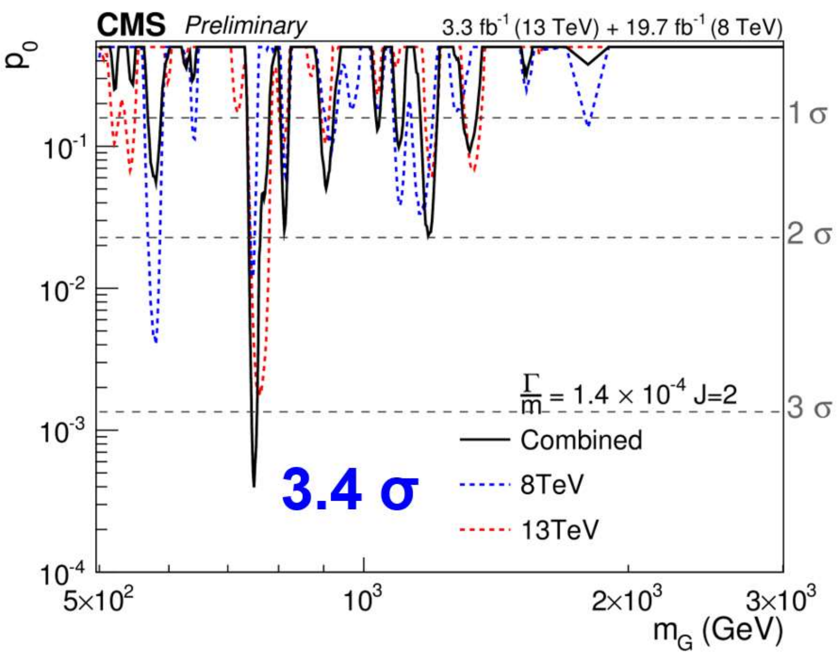
First intrigue @ 13 TeV: Excess in Diphotons

CMS-PAS-EXO-16-018



CMS sees excess in diphoton spectrum around ~750 GEV on 8+13 TeV data

✓ **3.4 σ (local) and 1.6 σ (global) for analysis of spin-0 and spin-2 states:**

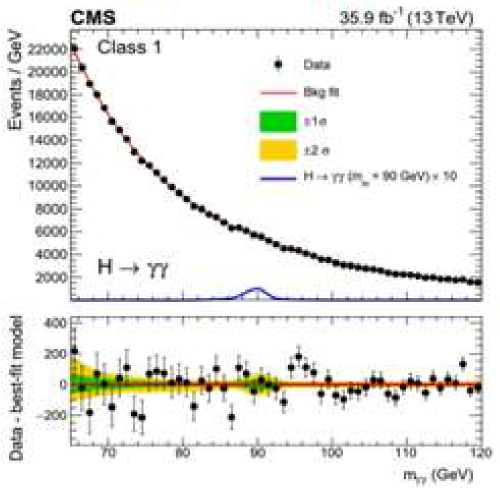


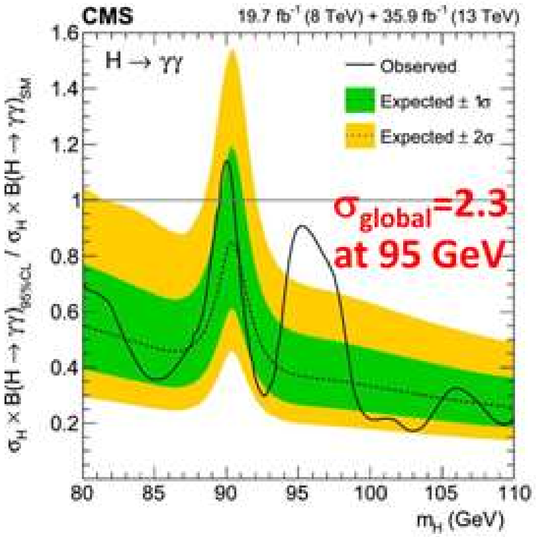
A lot of theoretical works attempt to explain this effect: more 320 papers since Dec. 2015

Need more data!

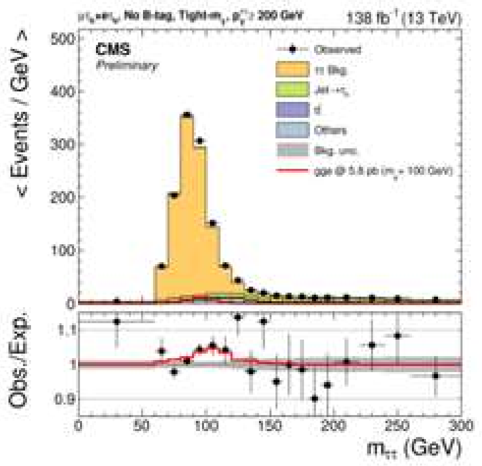
Some Selected Recent Excitements from LHC

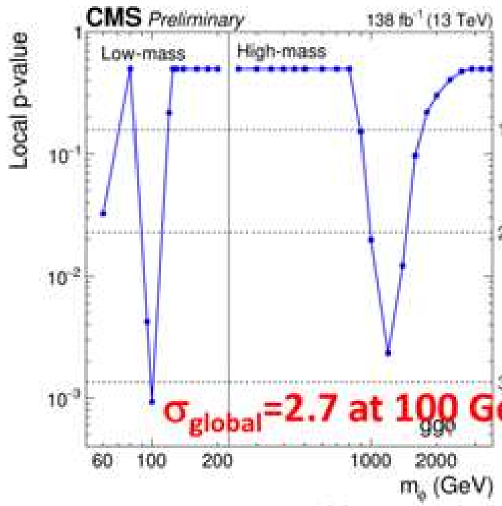
- **Light X→γγ**





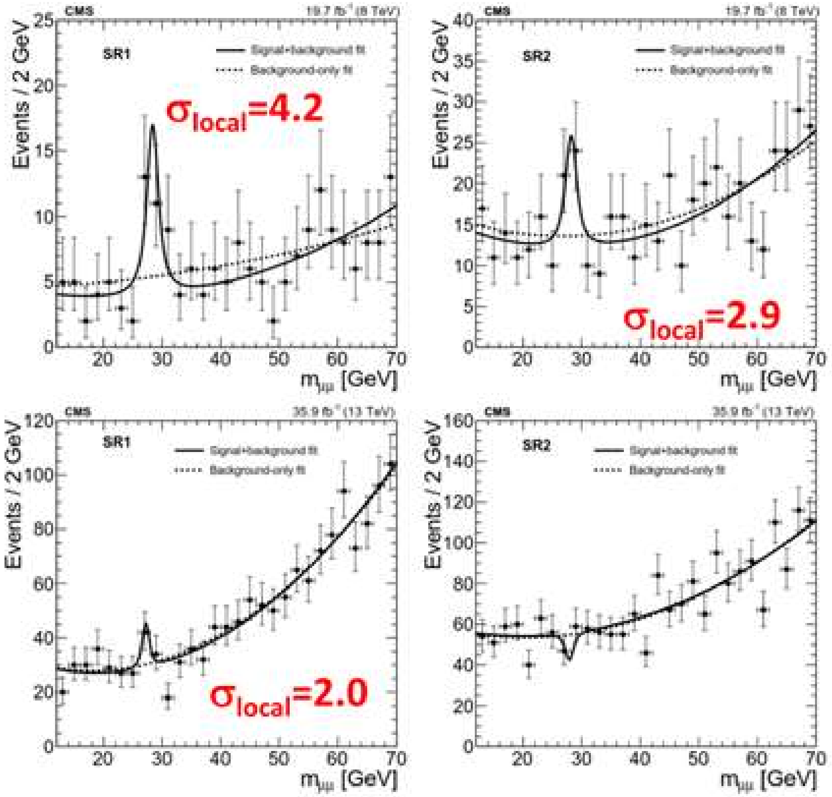
- **Light X→ττ**





σ_{global}=2.7 at 100 GeV, 2.3 at 95 GeV

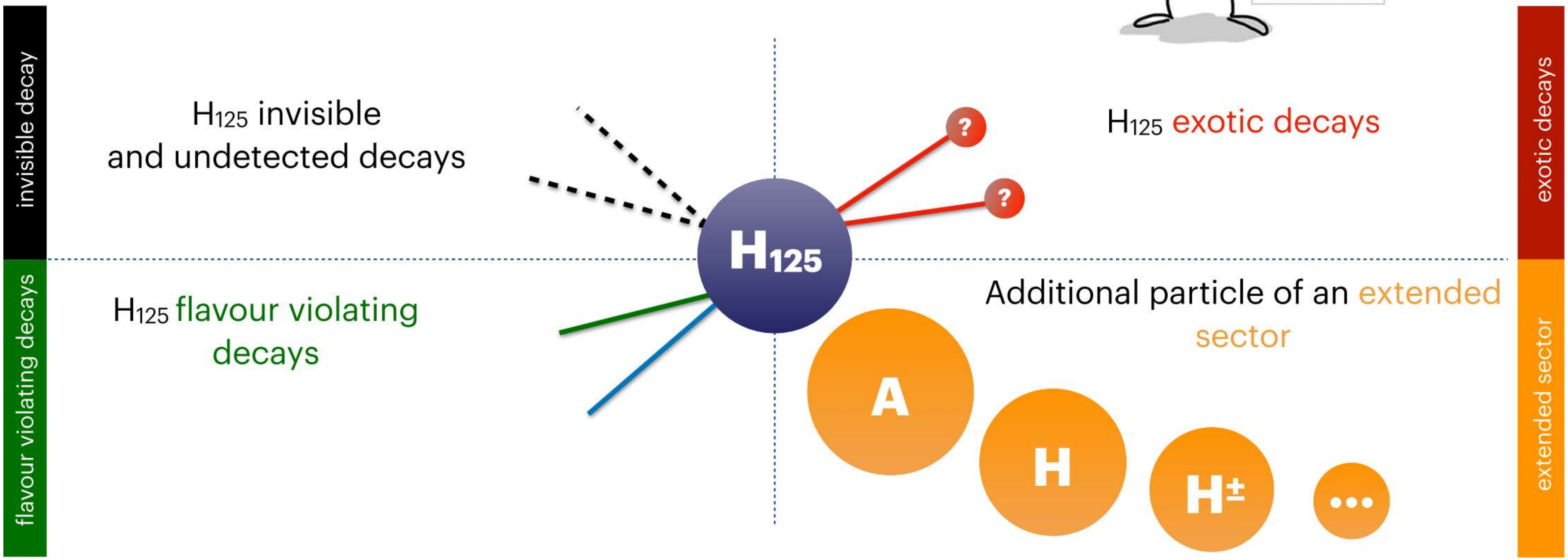
- **Light X→μμ**



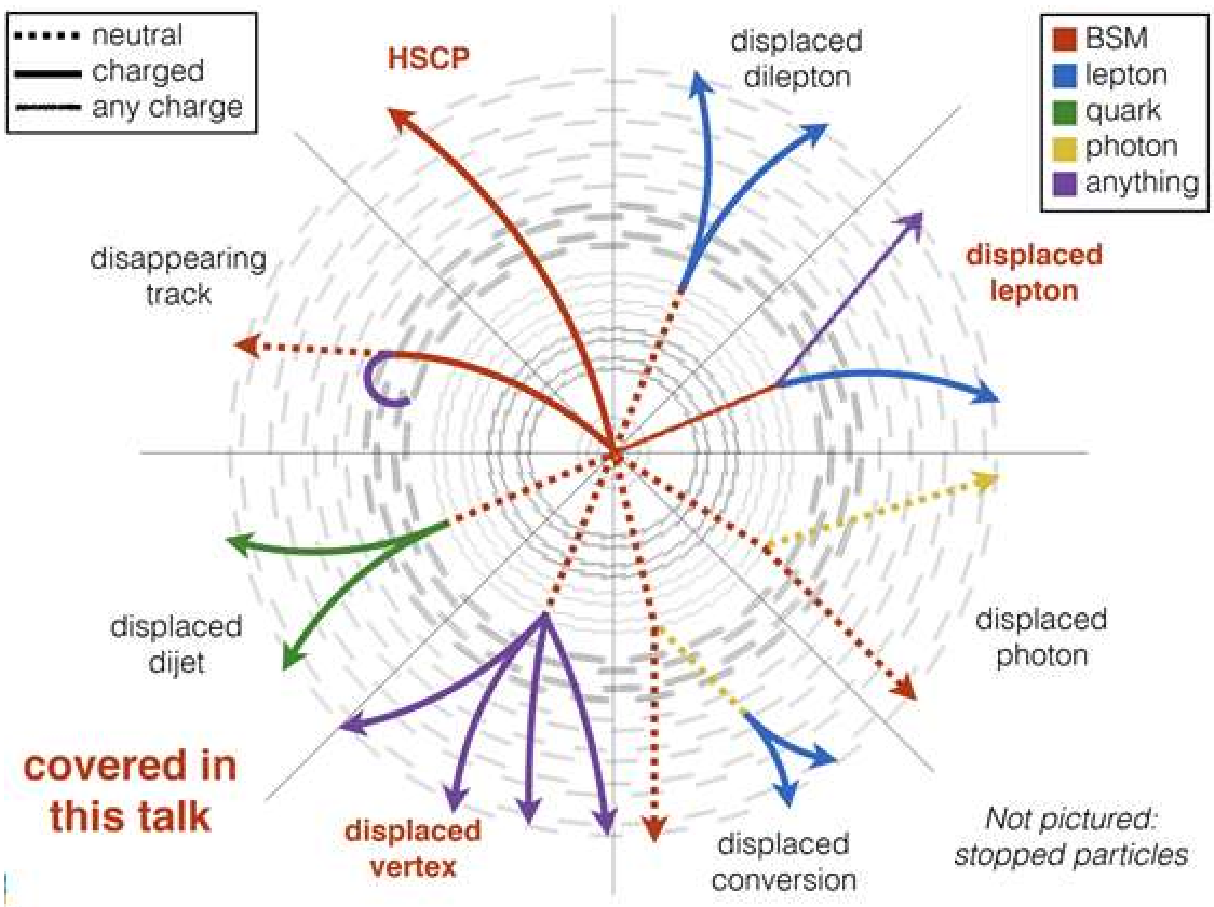
A. Nikitenko

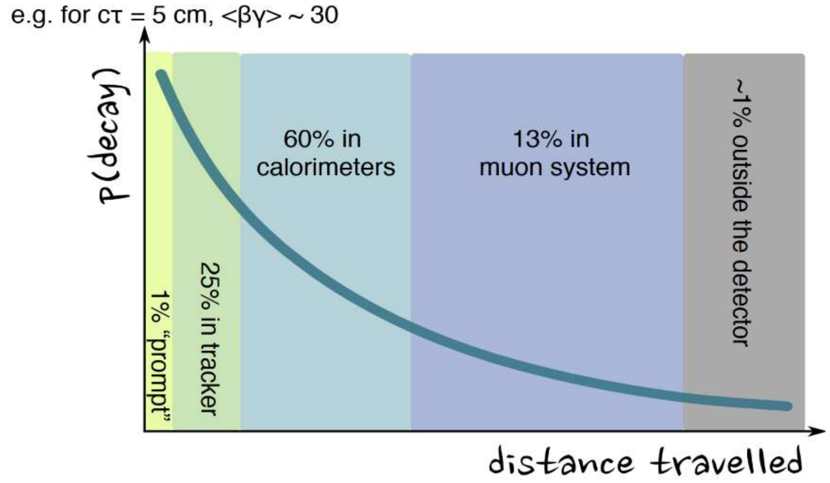
RUN3 is a perfect judge for these challenges!

Higgs Boson as a Tool to Search for the New Physics



Direct Search for BSM: LLP Non-conventional Signals



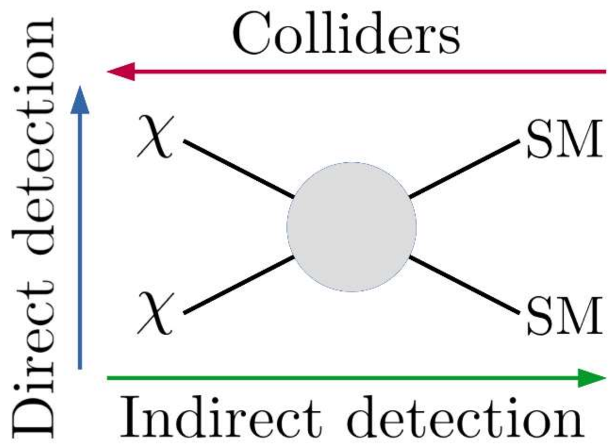


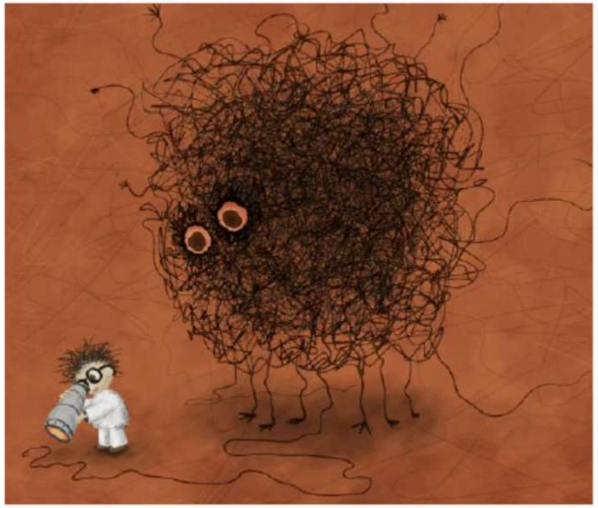
LLPs may have decay lengths up to several meters, hence traveling through the inner detector layers without leaving any trace

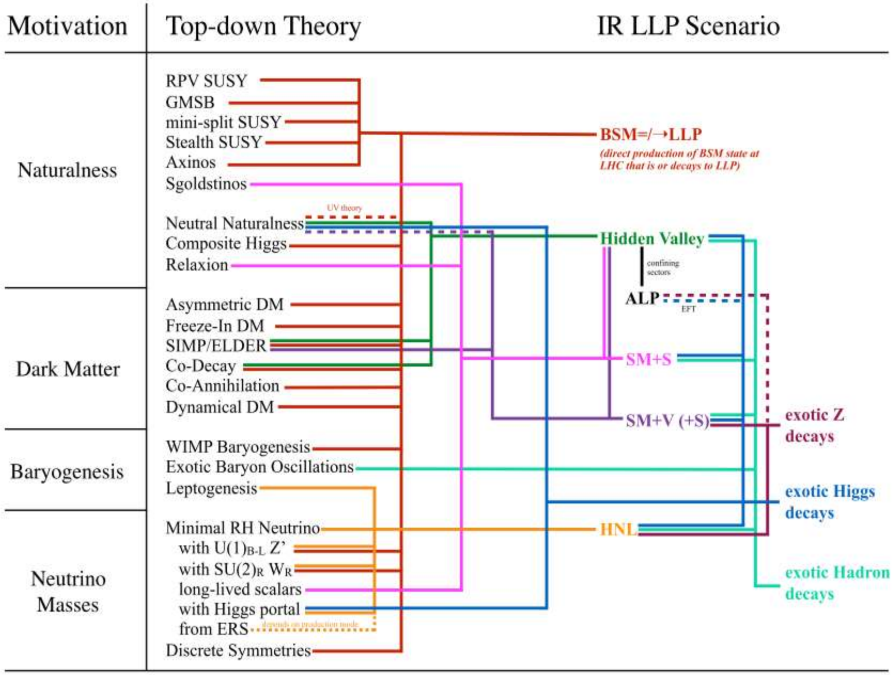
- a proper lifetime $c\tau_0$ is greater than or comparable to the characteristic size of the (sub)detectors
- small $c\tau_0$ that comparable to the inner tracker size, no displaced tracks → "standard" prompt decay
- intermediate $c\tau_0$ → LLP
- very large/infinite large $c\tau_0$ → stable particles, "standard" MET signatures

Inelastic Dark Matter at the LHC/LLP

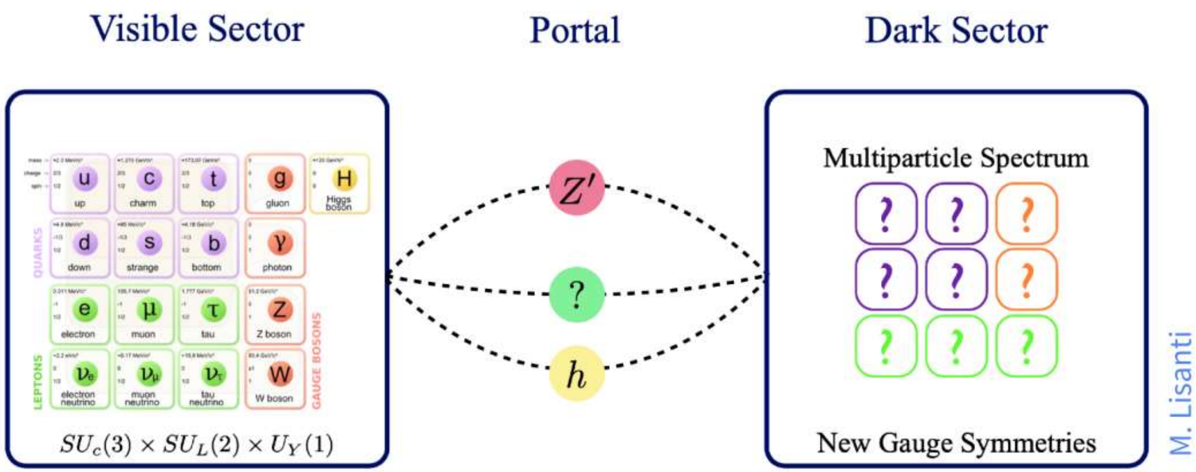
- inelastic dark matter: relic particles that cannot scatter elastically off of nuclei the dark sector
- particles continue traveling for a long time and traverse several meters (Long-Lived Particles) before tunneling back into our visible universe (quarks or leptons)





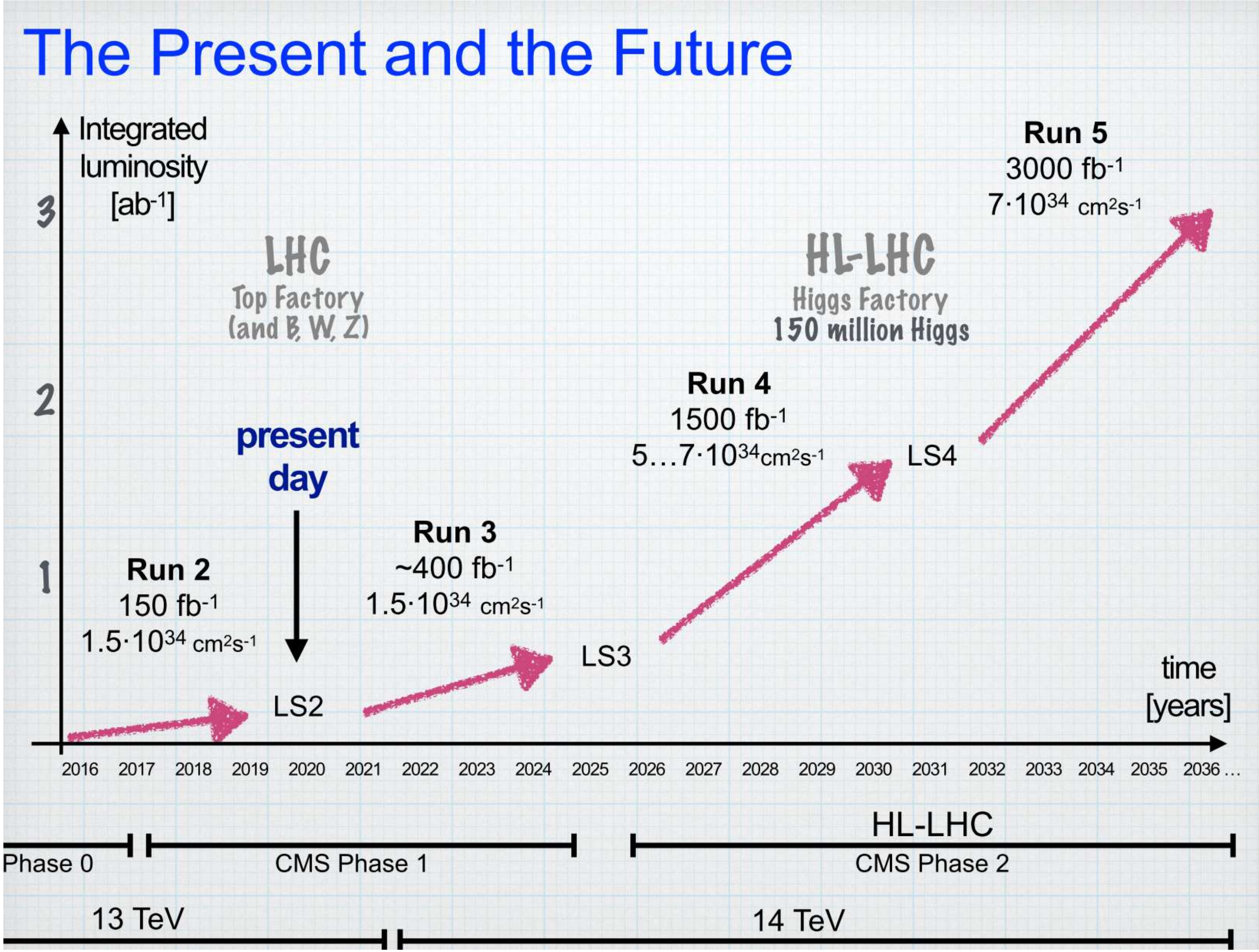


https://arxiv.org/abs/1901.04040



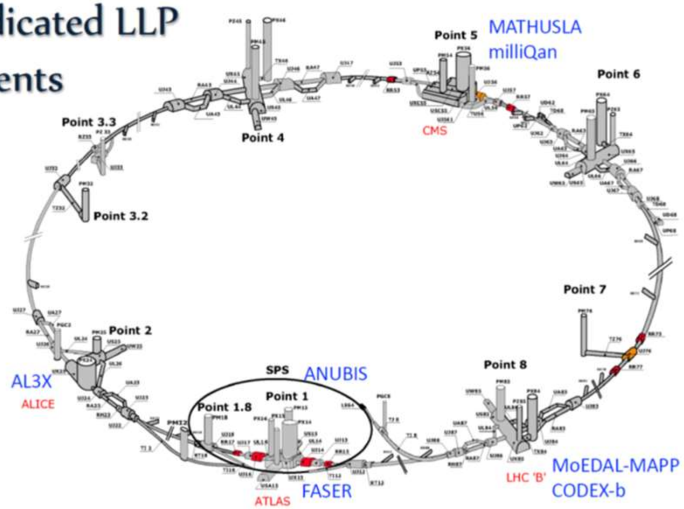
LHC Prospects and beyond

LHC/High-Luminosity Timescale



LHC Satellite Experiments

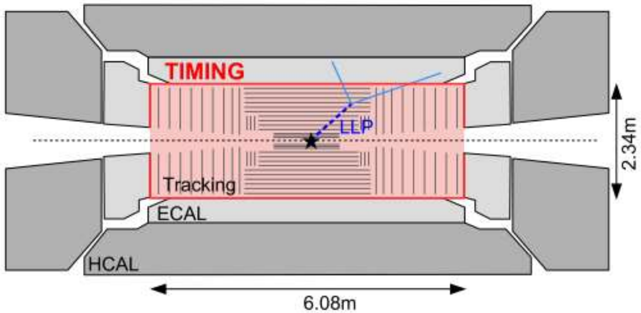
LHC dedicated LLP experiments



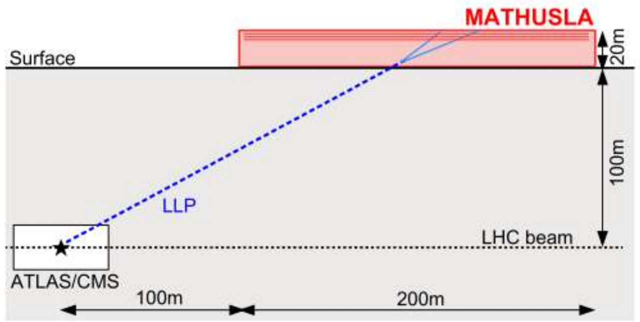
Phys. Rev. D 99 (2019) 015021

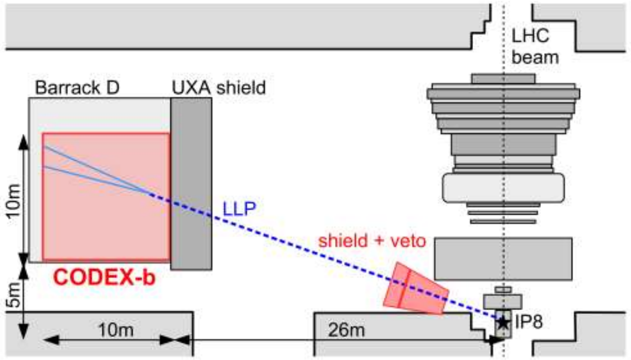
https://arxiv.org/abs/1901.04040

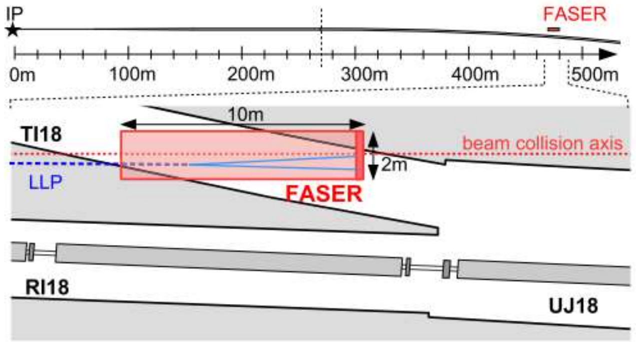
CMS/ATLAS



CMS

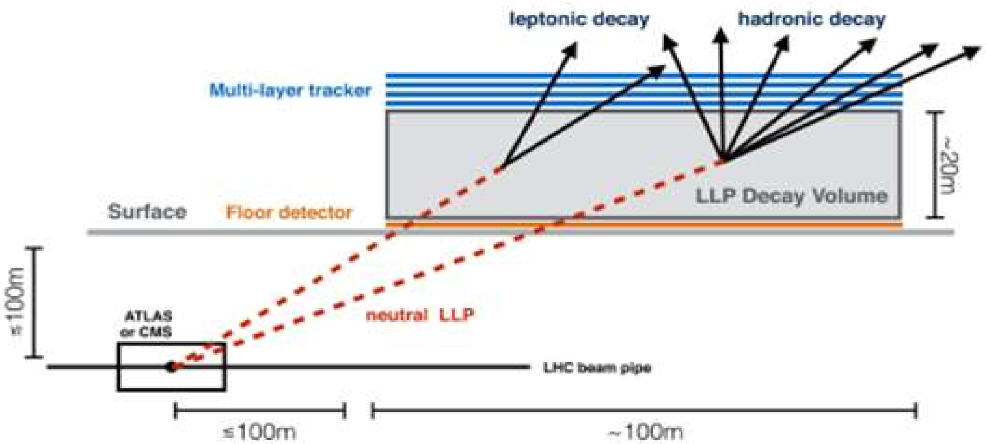


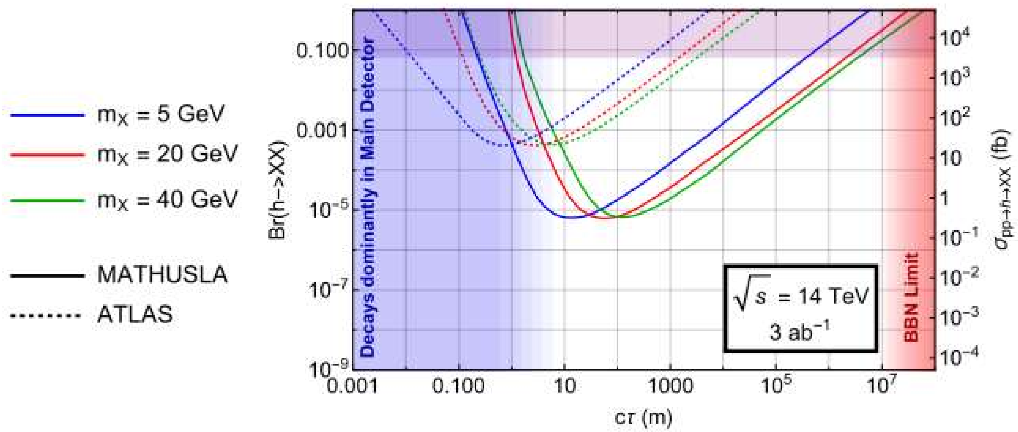




LHCb

ATLAS





Future Circular Colliders (100 TeV pp)

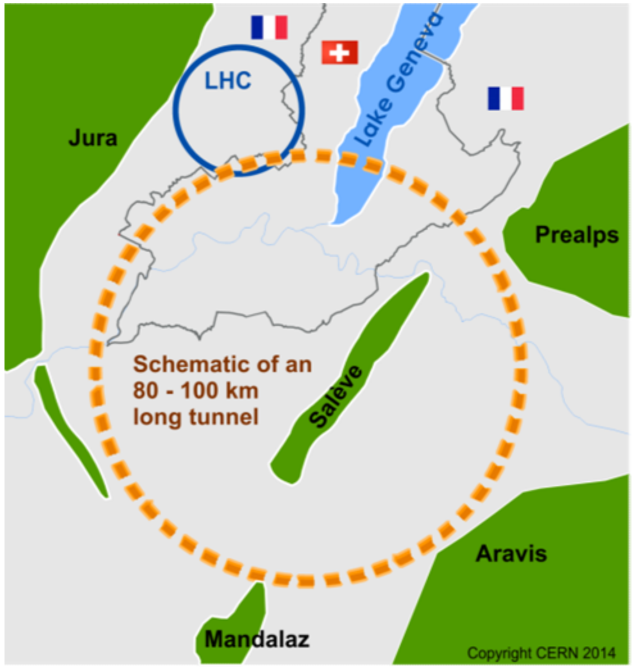
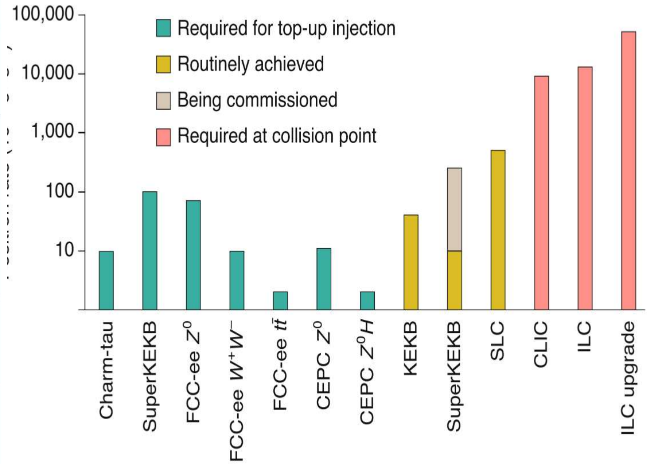
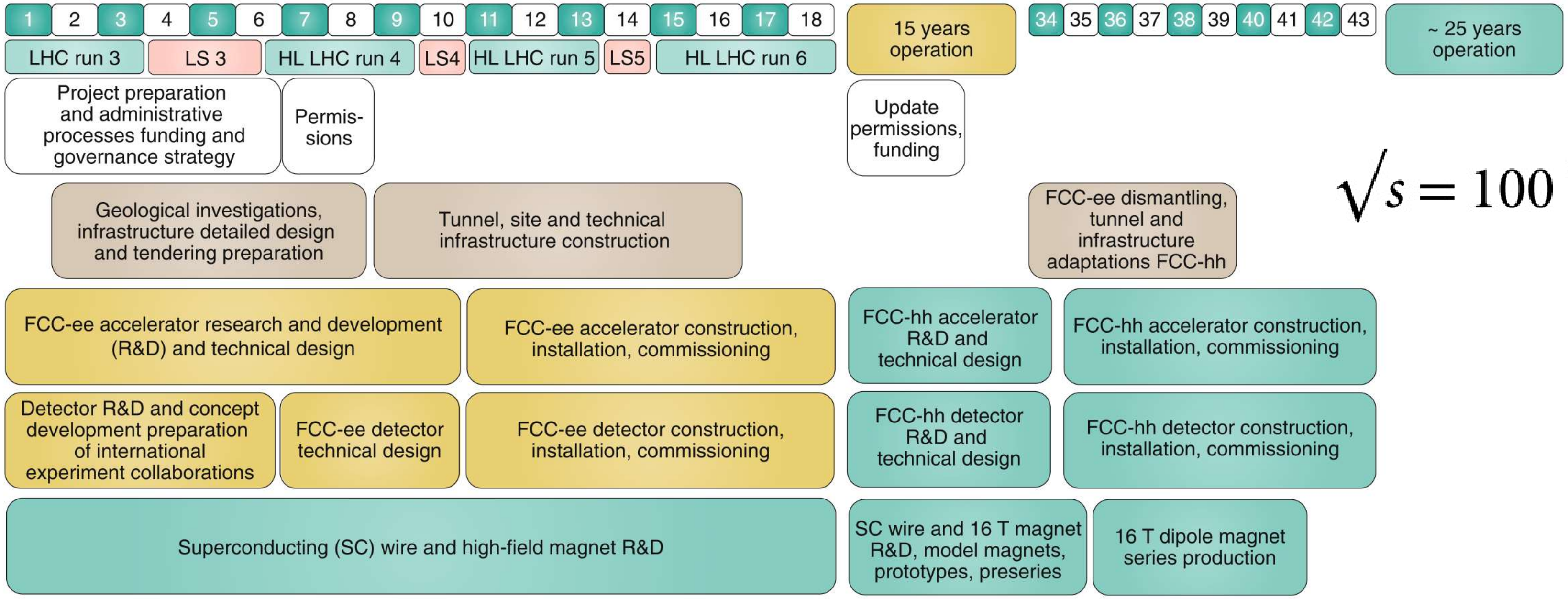


Table 1 | Run plan for the FCC-ee

FCC-ee phase	Run duration (yr)	$\sqrt{s}$ (GeV)	L_{int} (ab^{-1})	Event statistics
Z^0	4	88–95	150	3×10^{12} hadronic Z^0 decays
W^+W^-	2	158–192	12	3×10^8 W^+W^- pairs
Z^0H	3	240	5	10^6 Z^0H events
$t\bar{t}$	5	345–365	1.5	10^6 $t\bar{t}$ and 6×10^4 $H\nu\bar{\nu}$ events
H (optional)	3	125	21	Optional run on H resonance





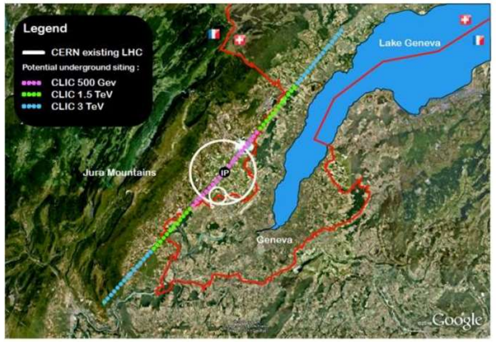
The launch point is 2020

$$\sqrt{s} = 100 \text{ TeV}$$

Nature Physics 16, 402–407 (2020)

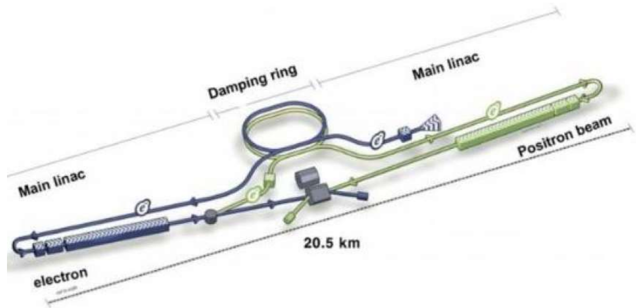
e+e- Colliders

Compact Linear Collider (CLIC)



	Collision energy	Integrated luminosity (unpolarized beams)
1st stage	380 GeV	1.0 ab^{-1}
2nd stage	1500 GeV	2.5 ab^{-1}
3rd stage	3000 GeV	5.0 ab^{-1}

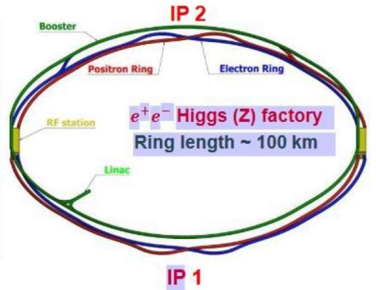
International Linear Collider (ILC)

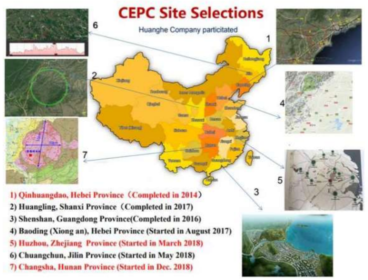


	Collision energy	Integrated luminosity (unpolarized beams)
1st stage	250 GeV	2.0 ab^{-1}
2nd stage	500 GeV	4.0 ab^{-1}
3rd stage	1000 GeV	5.4 ab^{-1}

(ILC Technical Design Report, arXiv:1306.6327, 1903.01629)

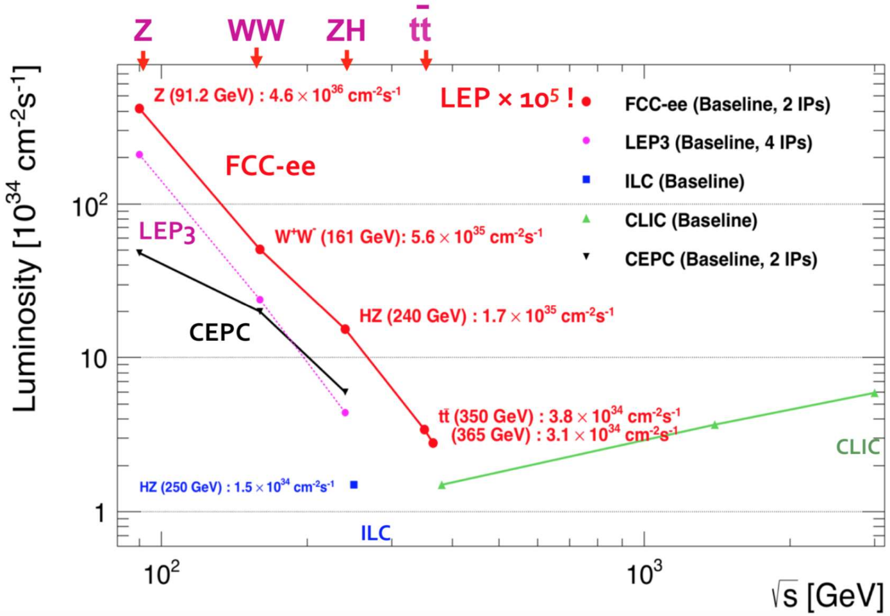
Circular Electron Positron Collider (CEPC)





	Collision energy	Integrated luminosity (unpolarized beams)
1st stage	90 GeV	16 ab^{-1}
2nd stage	180 GeV	2.6 ab^{-1}
3rd stage	240 GeV	5.6 ab^{-1}

(CEPC Study Group, arXiv:1809.00285, 1811.10545)

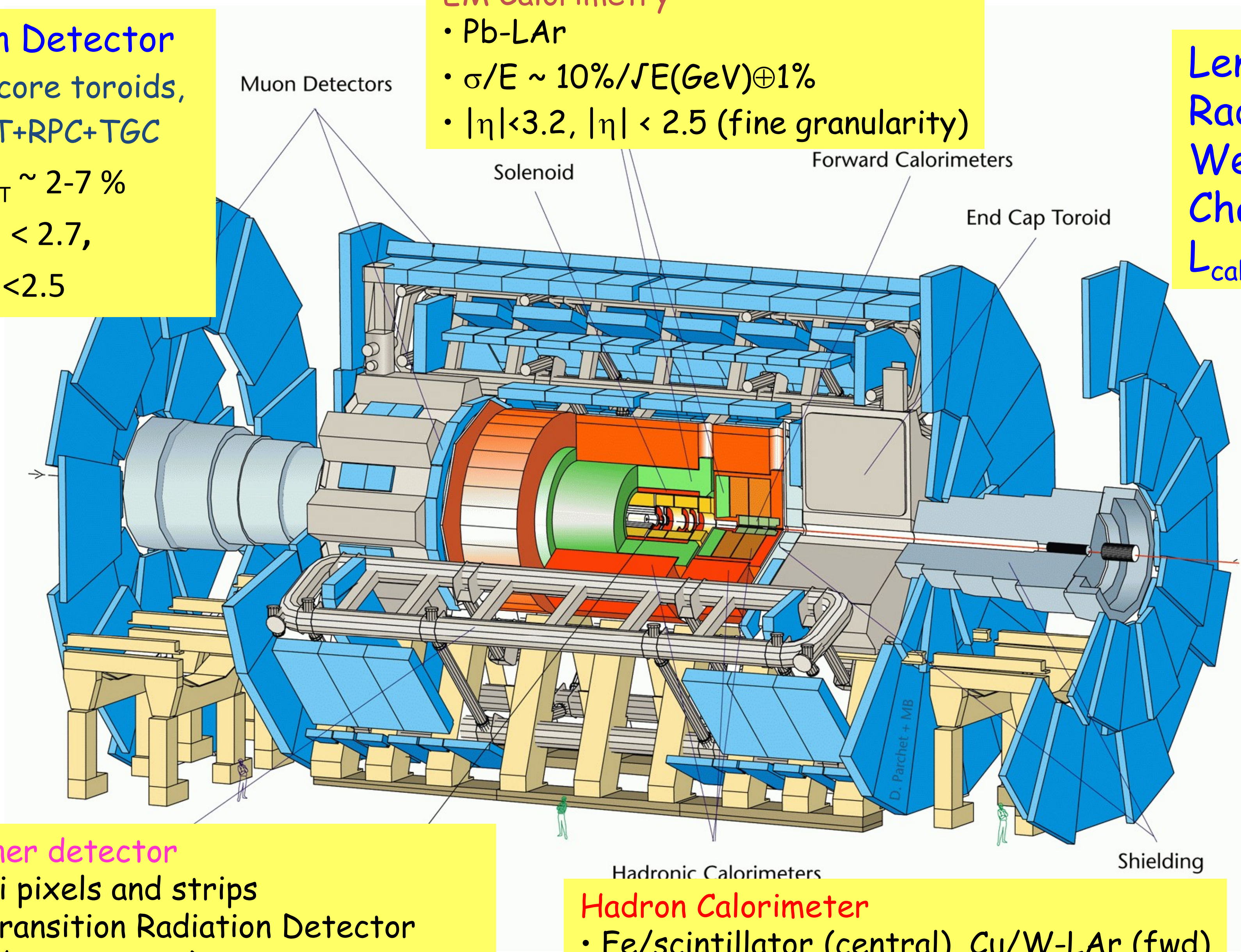


The ATLAS Experiment

Muon Detector
- air-core toroids, MDT+RPC+TGC
- σ/p_T ~ 2-7 %
- $|\eta|$ < 2.7,
- $|\eta|$<2.5

EM Calorimetry
- Pb-LAr
- $\sigma/E \sim 10\%/\sqrt{E(GeV)} \oplus 1\%$
- $|\eta|$<3.2, $|\eta|$ < 2.5 (fine granularity)

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
Channels: ~ 10^8
L_{cable}: ~ 3000 km

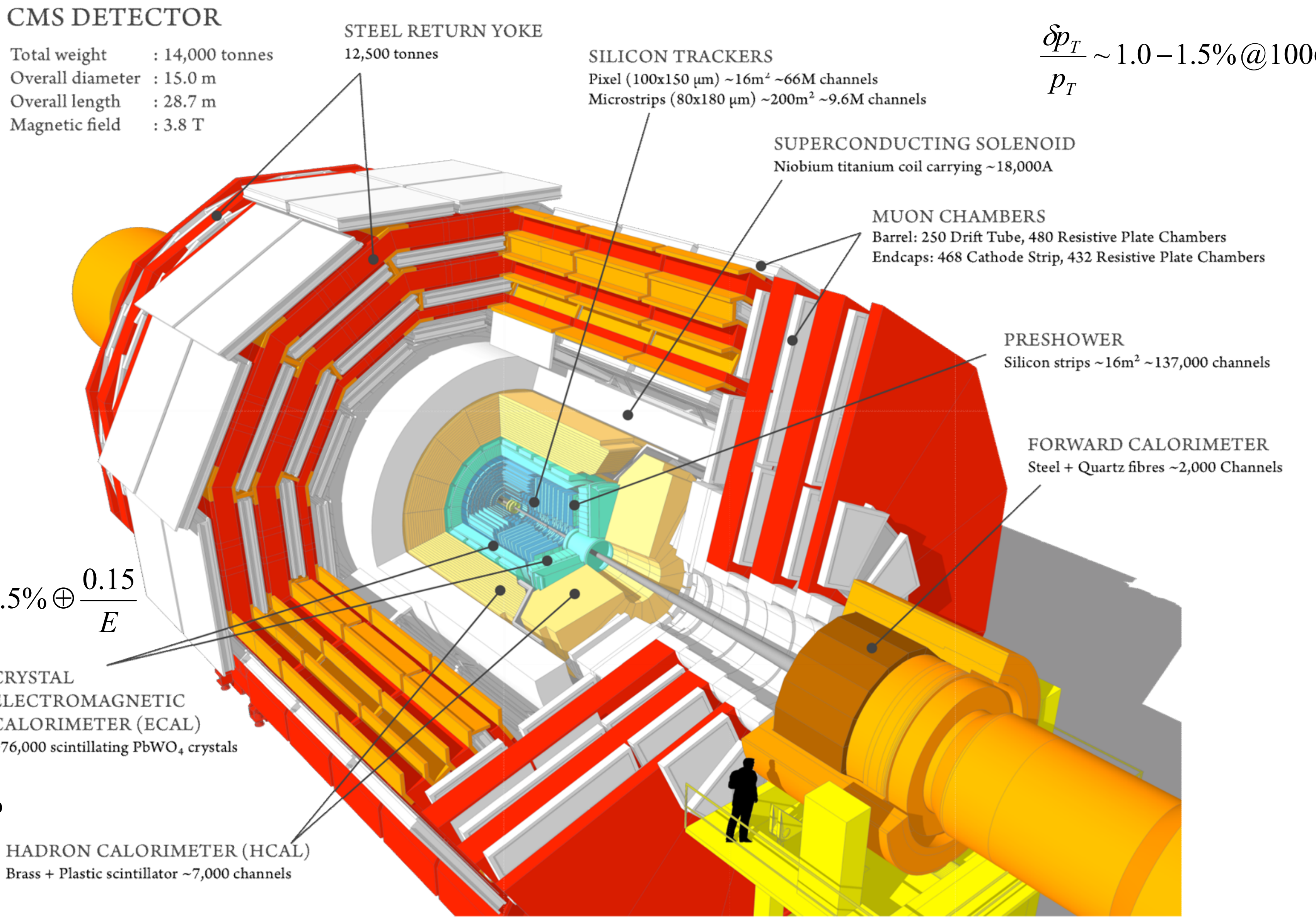


Inner detector
- Si pixels and strips
- Transition Radiation Detector (e/π separation)
- $\sigma/p_T \sim 0.05\%\, p_T(GeV) \oplus 0.1\%$;
- $|\eta|$ < 2.5, B=2 T(central solenoid)

Hadron Calorimeter
- Fe/scintillator (central), Cu/W-LAr (fwd)
- $\sigma/E \sim 50\%/\sqrt{E(GeV)} \oplus 3\%$
- $|\eta|$<3

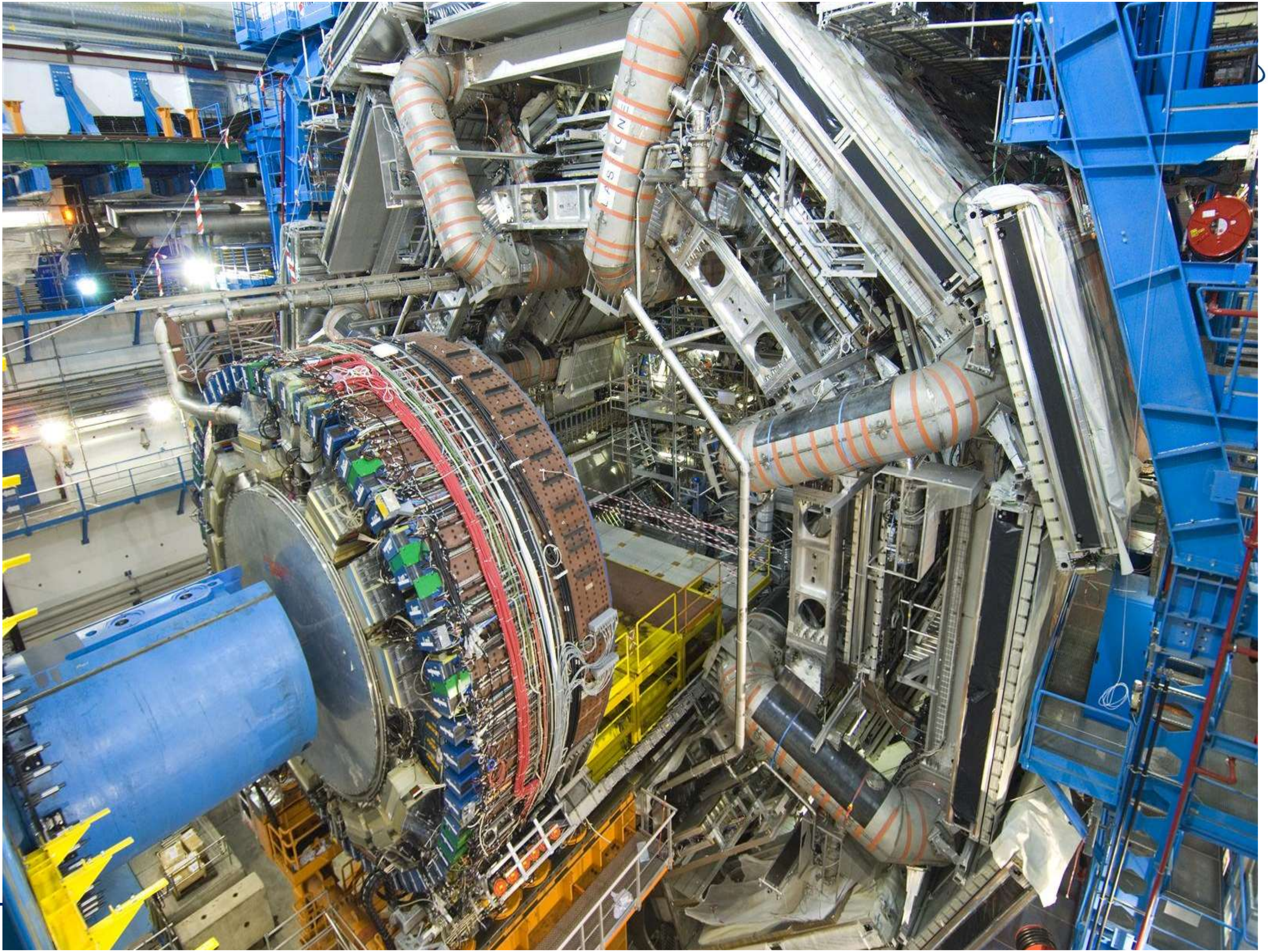
The CMS Experiment

$$\frac{\delta p_T}{p_T} \sim 1.0 - 1.5\% @ 100 GeV$$

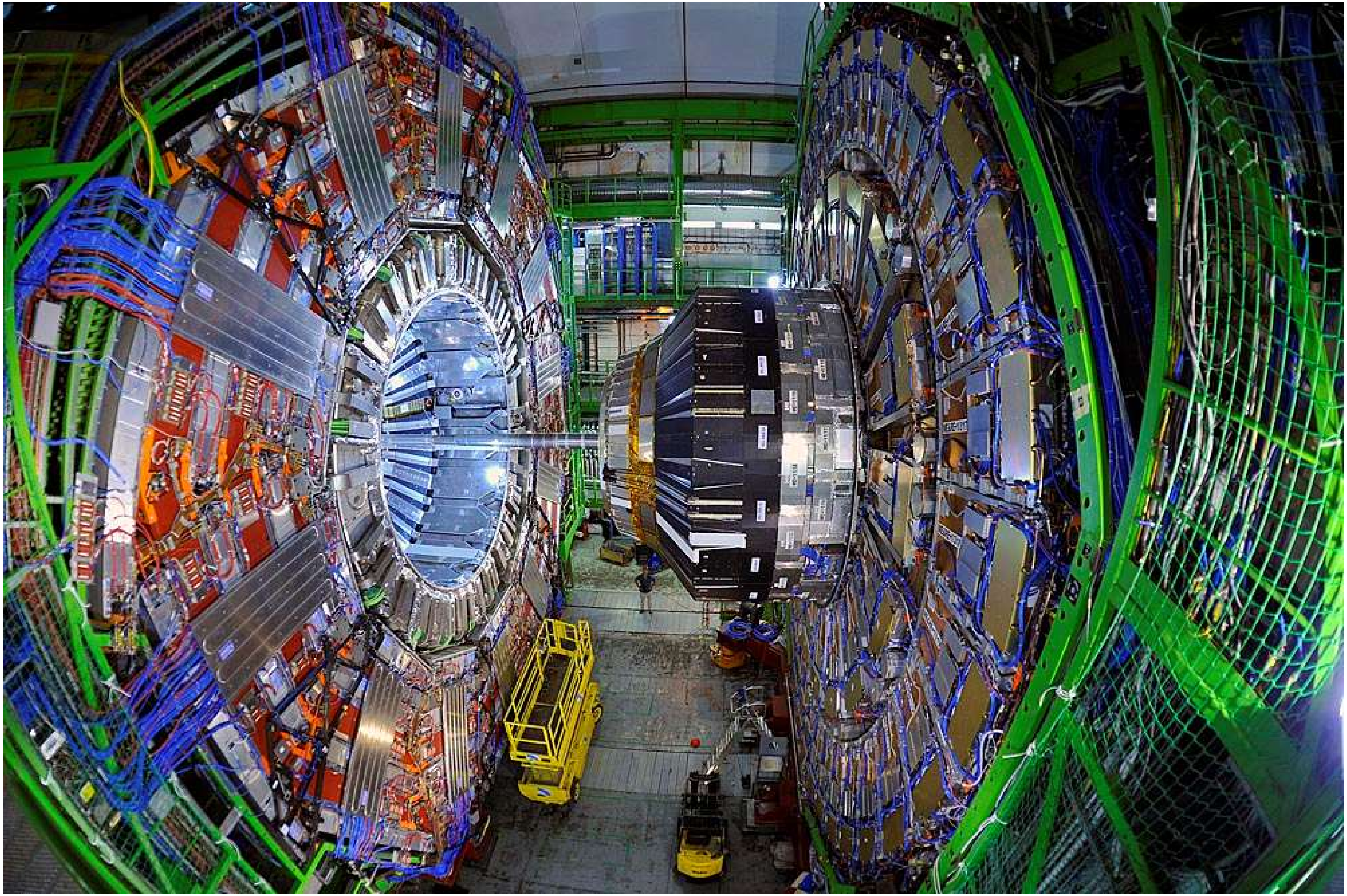


$$\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.5\% \oplus \frac{0.15}{E}$$

$$\frac{\sigma_E}{E} = \frac{120}{\sqrt{E}} \oplus 5\%$$

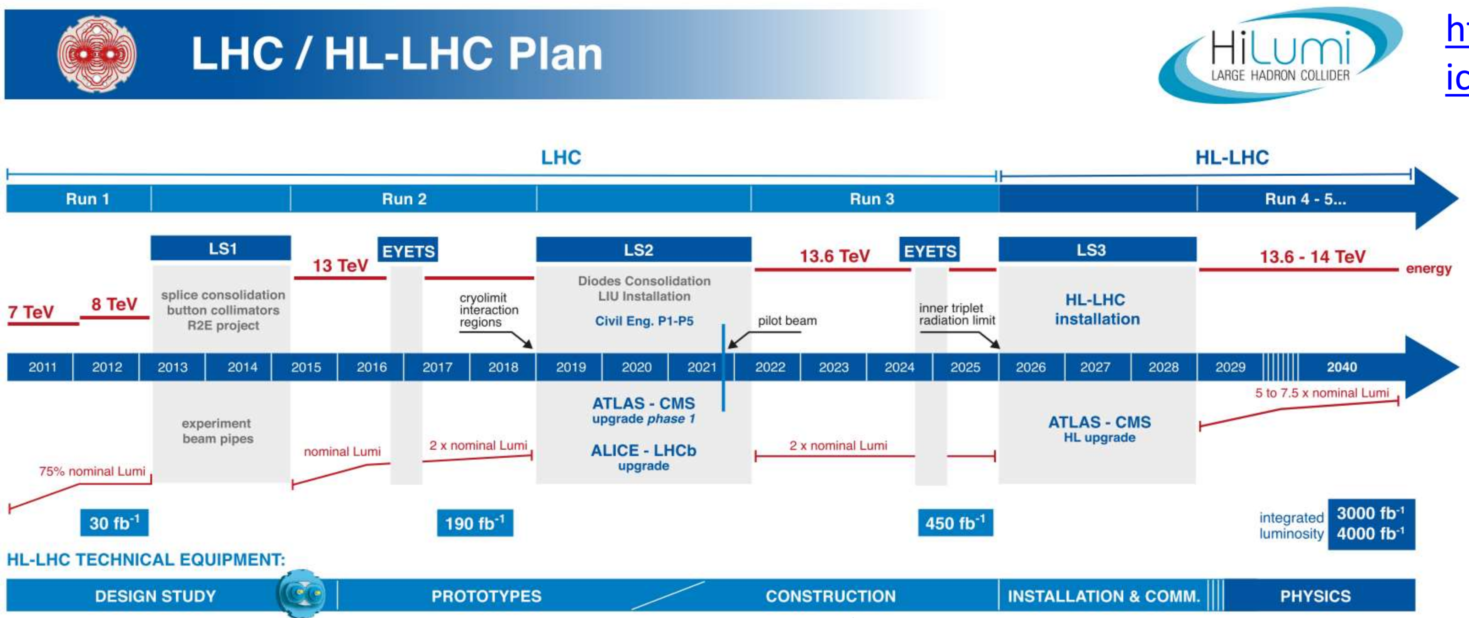


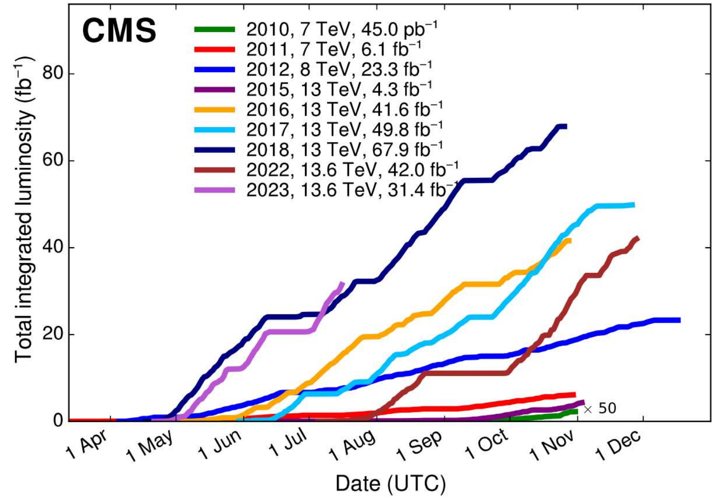
Open CMS



LHC Timeline and Data That We Have

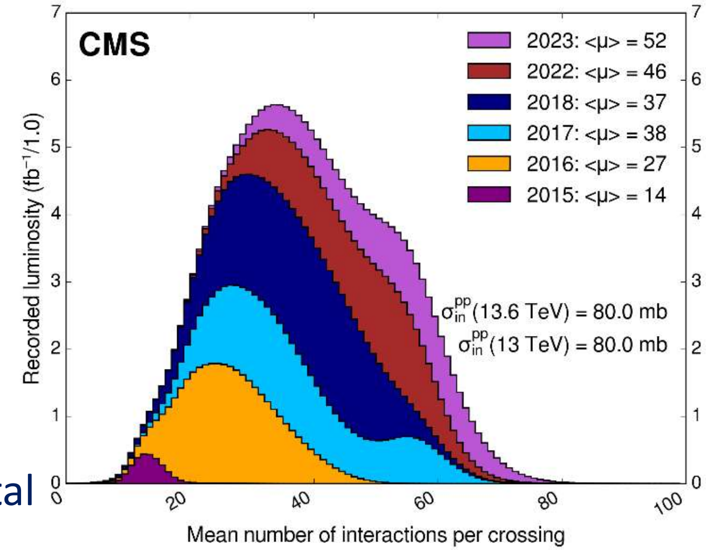
CMS Luminosity Information
https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults





$L_{inst} = 2.1\times10^{34}\ cm^{-2}s^{-1}$ $L_{nisyt} = 7.5\times10^{34}\ cm^{-2}s^{-1}$

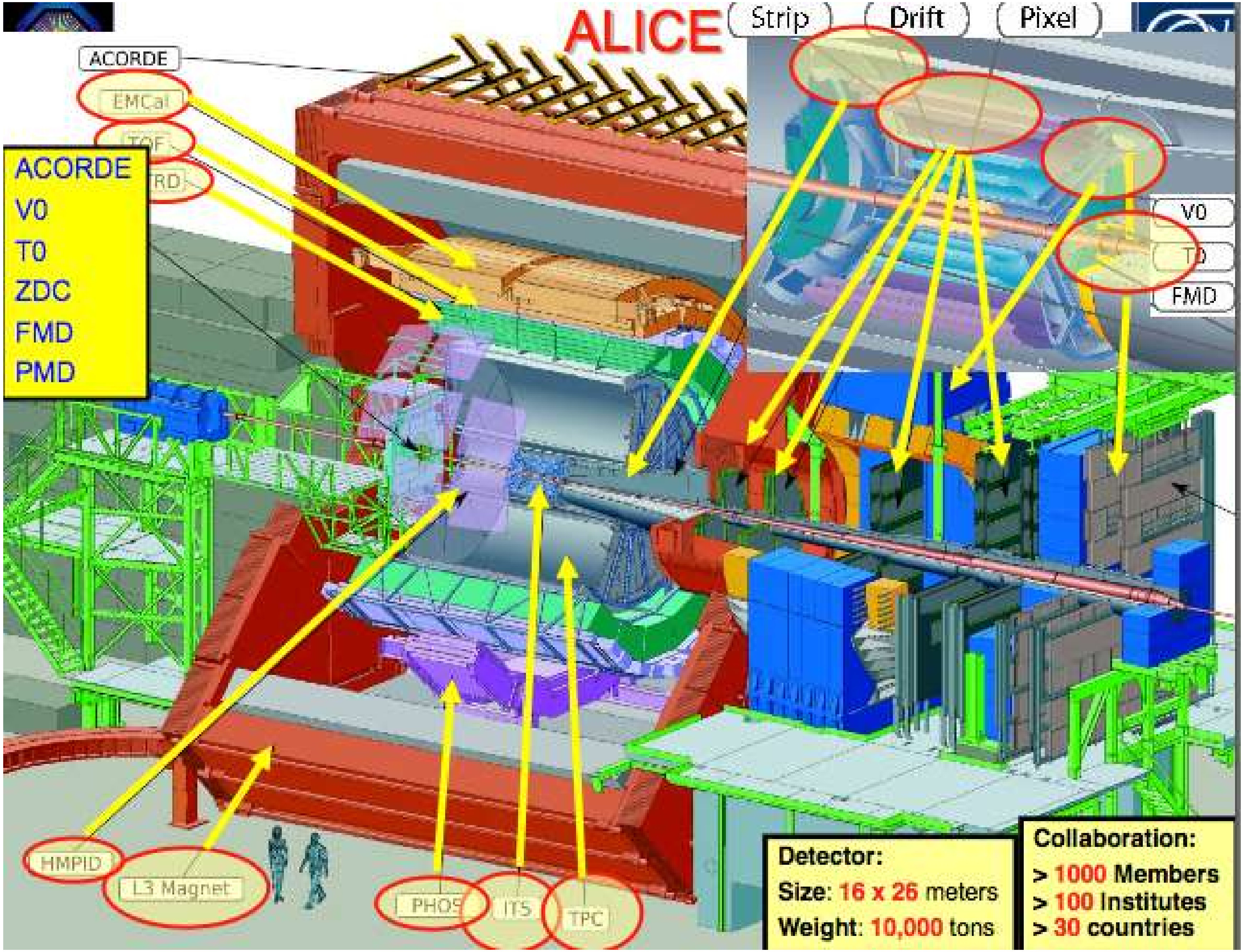
We are here



- CMS Dataset RUN2
  - ✓ ~163 fb^{-1} of proton-proton collisions @ 13 TeV is delivered
  - ✓ 151.78 fb^{-1} is recorded by CMS (data-taking efficiency ~93%)
- CMS Dataset RUN3
  - ✓ ~73.4 fb^{-1} is already delivered @ 13.6 TeV during the RUN3
  - ✓ 63.7 fb^{-1} is recorded by CMS (data-taking efficiency ~92%)
  - ✓ ~93% of collected data "good for physics" in 2023 (91% in 2022)
  - ✓ number of pp interactions per beam crossing (PU): $\langle\mu\rangle = 52$ for 2023
- ~260 fb^{-1} it is expected @ 13.6 TeV for the end of the RUN3 (450 fb^{-1}, in total for RUN1/2/3)
- pPb and PbPb Runs (see talk by Serguei Petrushanko)

CMS Data Quality Information
https://twiki.cern.ch/twiki/bin/view/CMSPublic/DataQuality

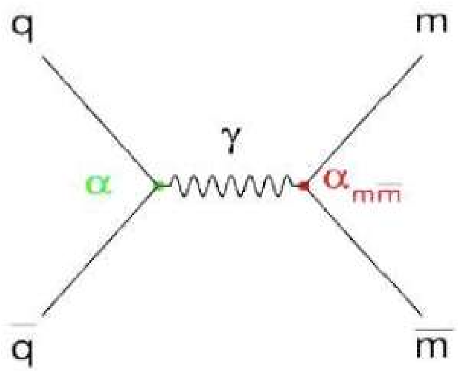
The ALICE Experiment

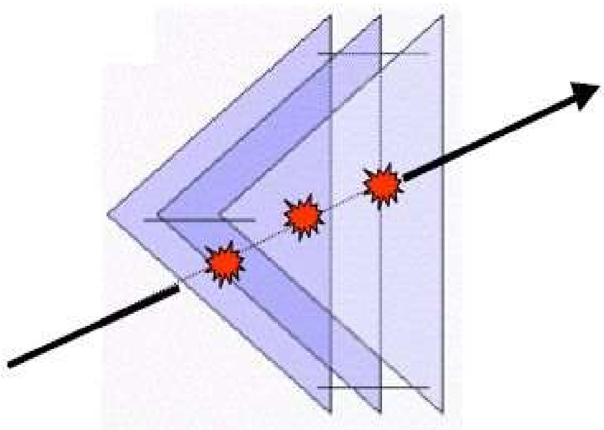


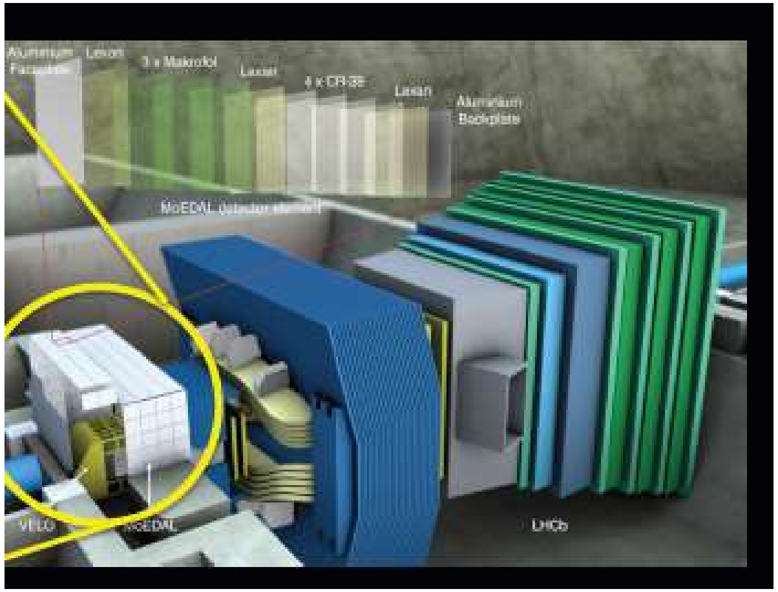
MoEDAL: Monopole and Exotics Detector at the LHC

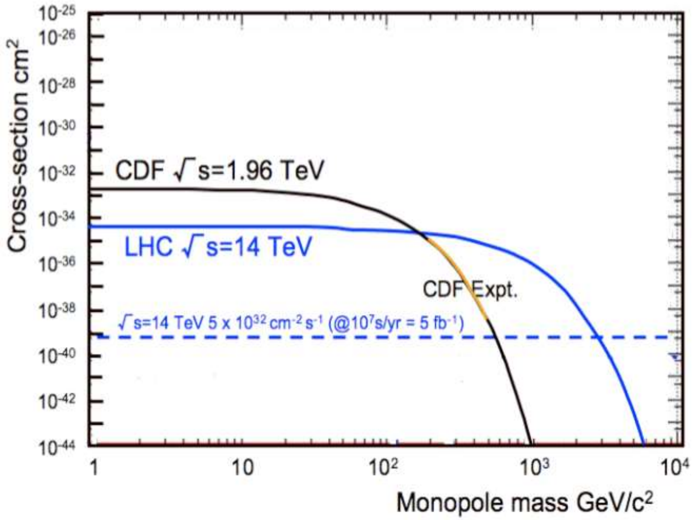
Heavy particles which carry “magnetic charge”
Could eg explain why particles have “integer electric charge”

Monopole production







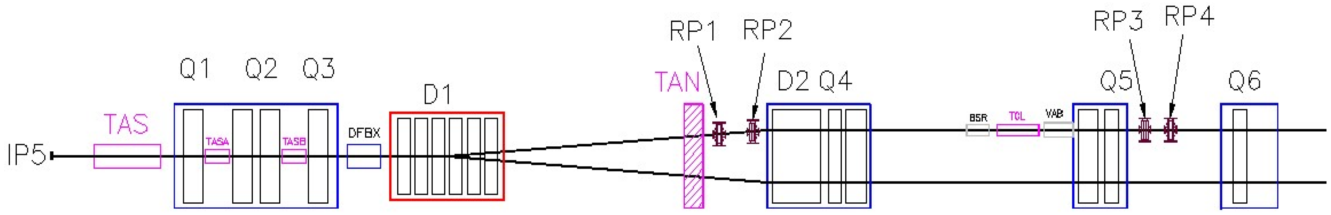


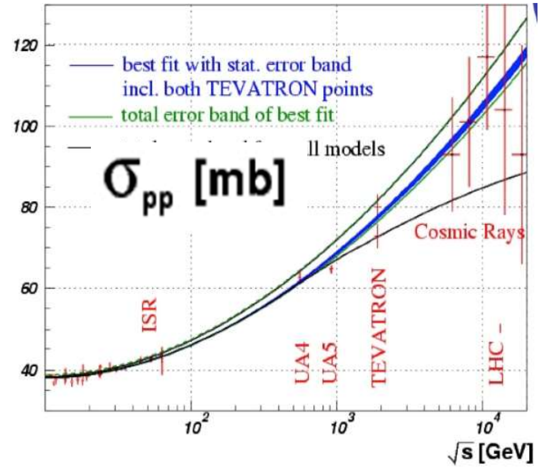
Remove the sheets after some running time and inspect for ‘holes’

A Few Smaller Experiments: TOTEM & LHCf

TOTEM: measuring the total, elastic and diffractive cross sections
Add Roman pots (and inelastic telescope) to CMS interaction regions (200 m from IP)
Common runs with CMS planned

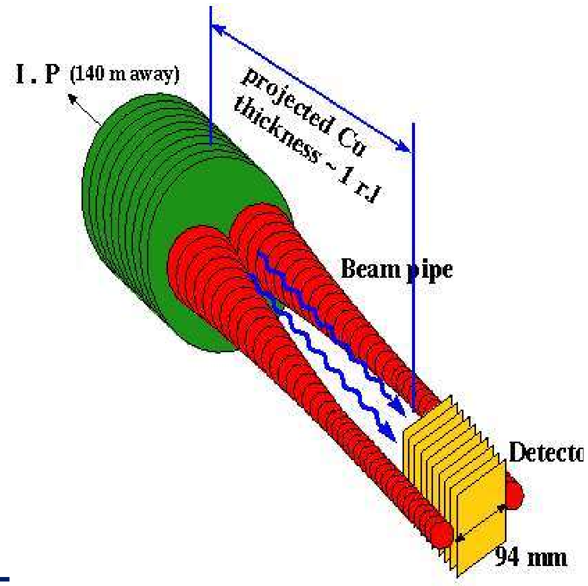
TOTal and Elastic cross section Measurement

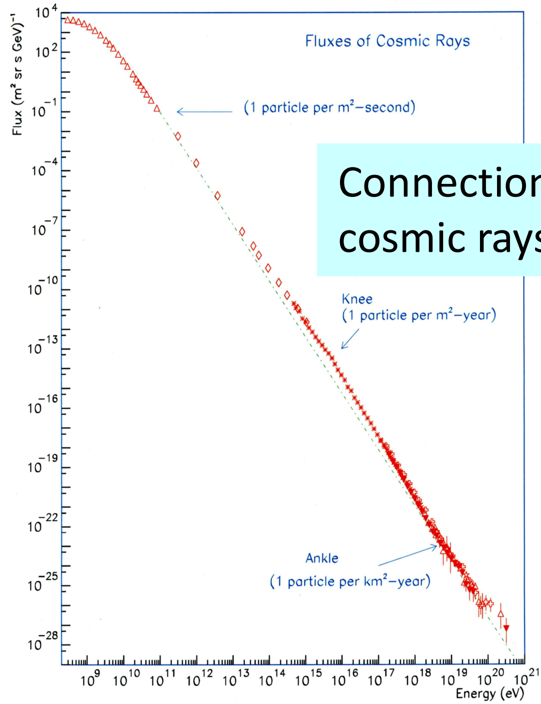




LHCf: measurement of photons and neutral pions in the very forward region of LHC

Add a EM calorimeter at 140 m from the Interaction Point (of ATLAS)

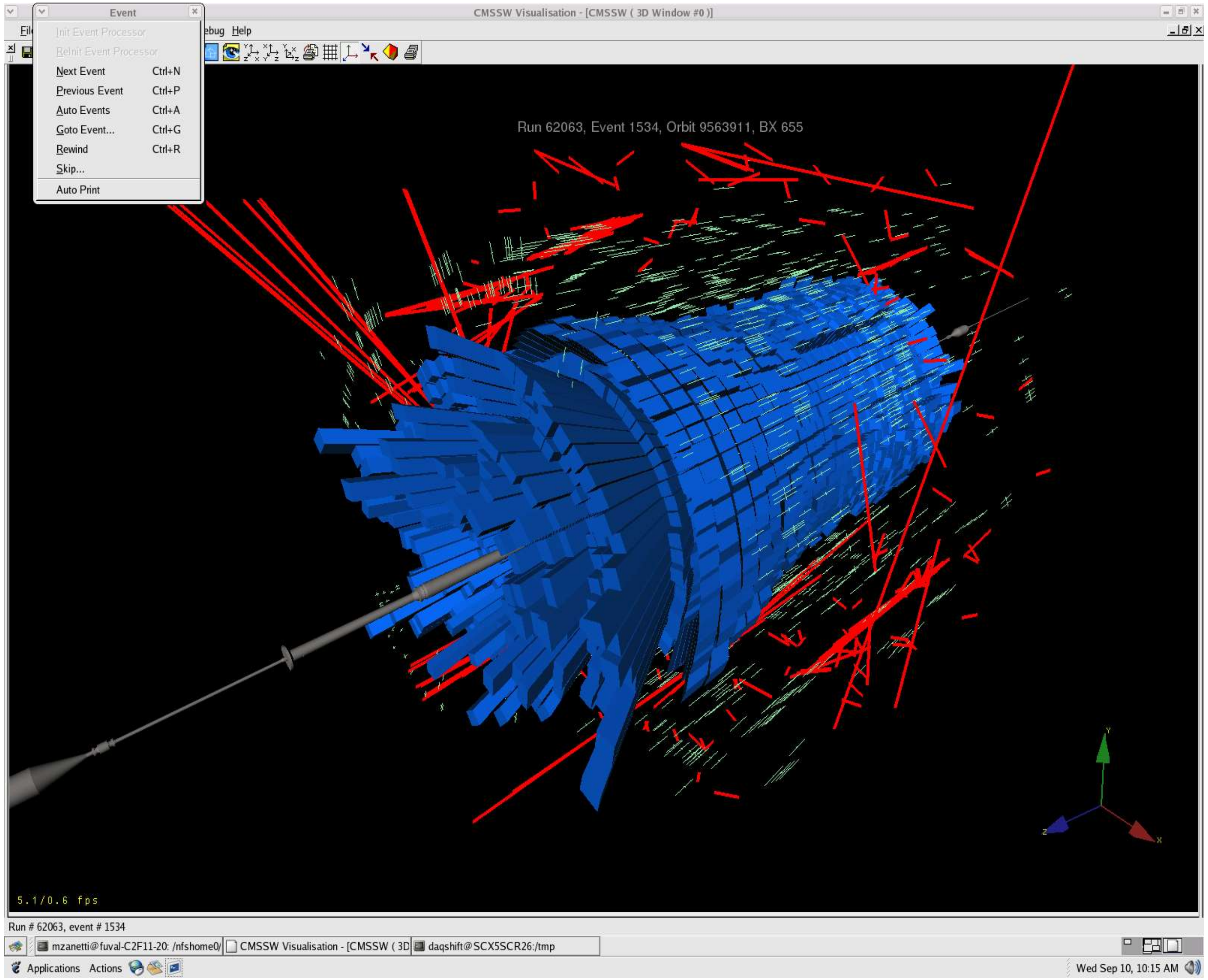




Connection with cosmic rays

LHC Start Up

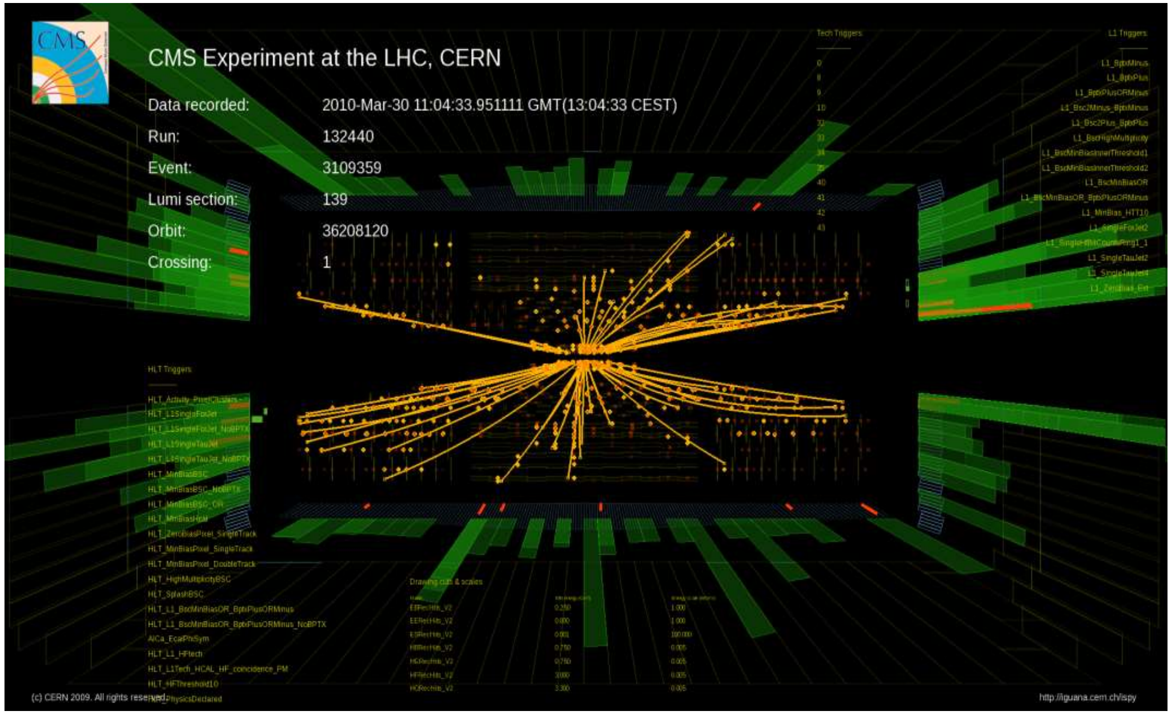
10 September 2008, 9:50, the first LHC beam event was recorded by CMS

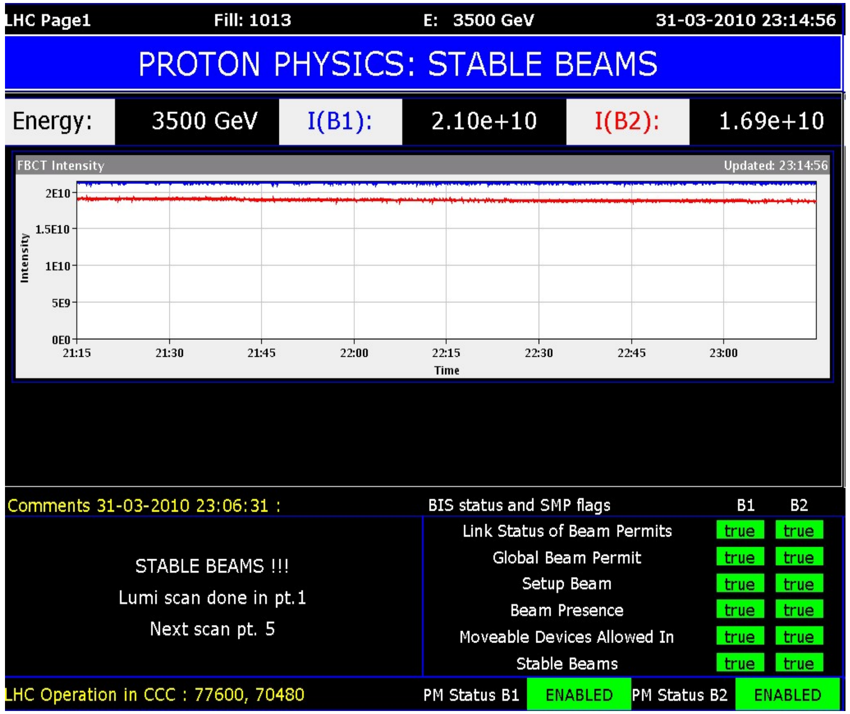


The First Collisions @ 7 TeV

The first collisions (3.5 TeV + 3.5 TeV) were happen on March 30th, 2010, at 13-00 (Geneve)

12:52 – CMS, 12:58 – ATLAS, 12:59 – LHCb, 13:01 – ALICE





14:30 Neutral pion decay was detected by CMS