Школа по информационным технологиям ОИЯИ

Joint Institute for Nuclear Research

SCIENCE BRINGS NATIONS TOGETHER

At The Frontiers of Particle Physics

Sergei Shmatov (MLIT JINR, Dubna)
shmatov@jinr.ru   shmatov@cern.ch

MLIT, JINR, Dubna

16-20 October, 2023

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?
  - ✓ Monte Carlo tools
  - ✓ Reconstruction of physics objects
  - ✓ Reconstruction of physics processes
  - ✓ Physics Analysis and Statistics
- Something else?

What Do Particle Physicists Do?

Some eternal questions

People have long asked,

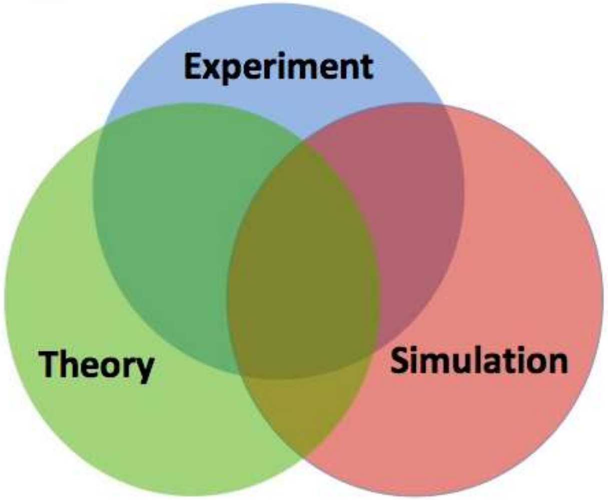
- "What is the world made of?”
- "What holds it together?”

Physicists hope to fill in their answers to these questions through the analysis of data from High Energy Physics experiments

Particle Physics Tools

Particle physics or high energy physics is the study of fundamental particles and forces that constitute matter (c) Wiki

- Where can I get elementary particles?
  - ✓ in Nature (cosmic sources, earth sources, i.e. natural radioactivity)
  - ✓ man-made sources (reactors, accelerators)
- How can you catch particles ⇒ detector facilities
- What is needed for data processing?
  - ✓ algorithms and software for reconstruction of physics objects and processes
- What is needed for data analysis?
  - ✓ Theory
  - ✓ Monte Carlo Tools
  - ✓ Statistics Tools

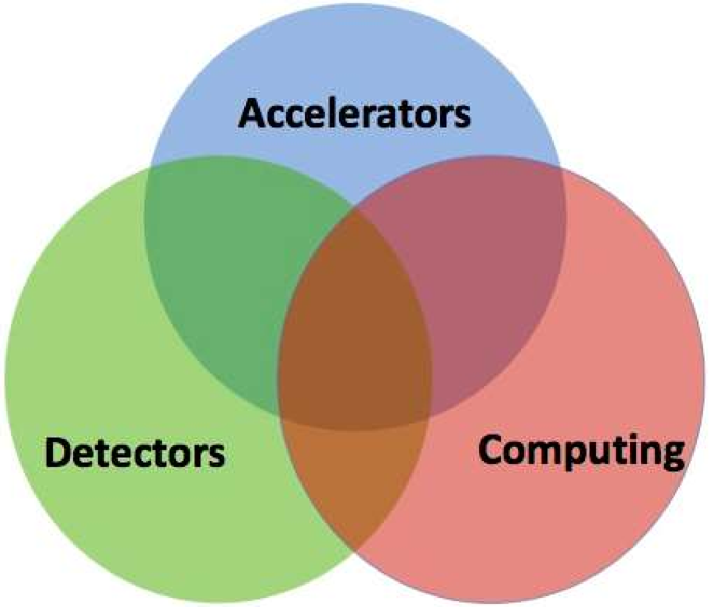


Along Three Paths

Information Technologies

Essential Parts of the Success

Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles



Detectors : gigantic instruments that record the resulting particles as they “stream” out from the point of collision.

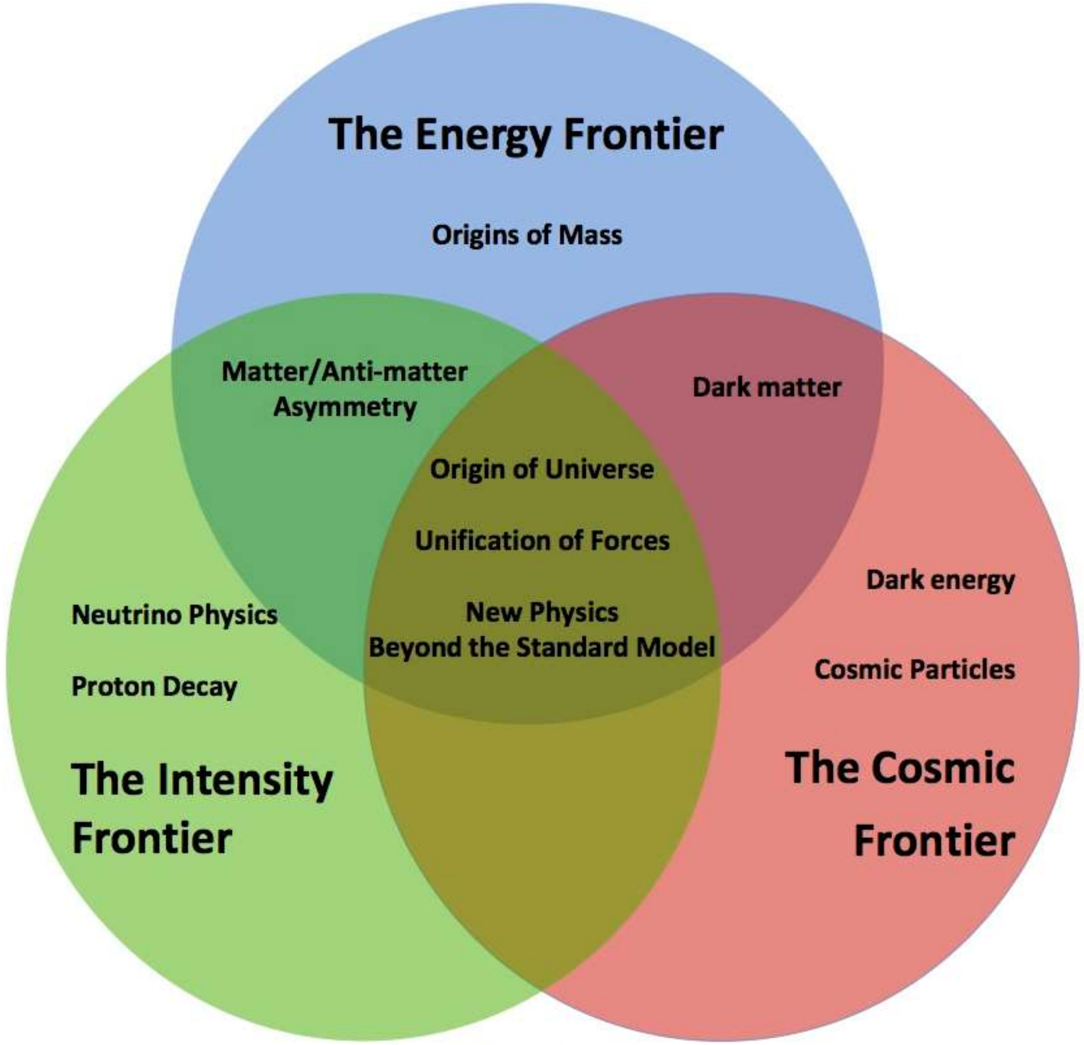
Computing : to collect, store, distribute and analyse the vast amount of data produced by these detectors

It's been a global effort, a global success. It has only been possible because of the extraordinary achievements of the experiments, infrastructure and the grid computing“ (c) Rolf Heuer, the Director General of CERN, when the discovery of the Higgs

Collaborative Science on Worldwide scale : thousands of scientists, engineers, technicians and support sta**ff to design, build and operate these complex** “machines”.

Particle (High Energy) Physics Frontiers

- **The Energy Frontier**, using high-energy colliders to discover new particles and directly probe the architecture of the fundamental forces.
- **The Intensity Frontier**, using intense particle beams to uncover properties of neutrinos and observe rare processes that will tell us about new physics beyond the Standard Model.
- **The Cosmic Frontier**, using underground experiments and telescopes, both ground and space based, to reveal the natures of dark matter and dark energy and using high-energy particles from space to probe new phenomena.

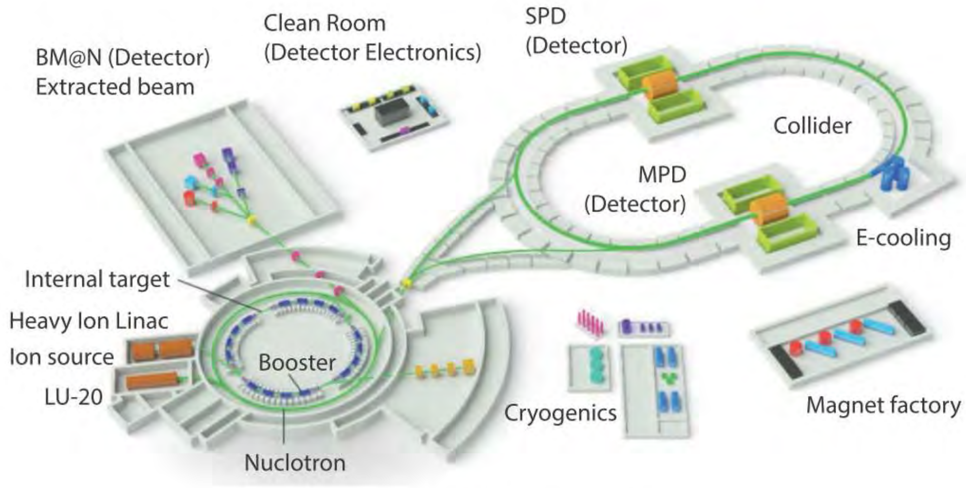


Physics Frontiers

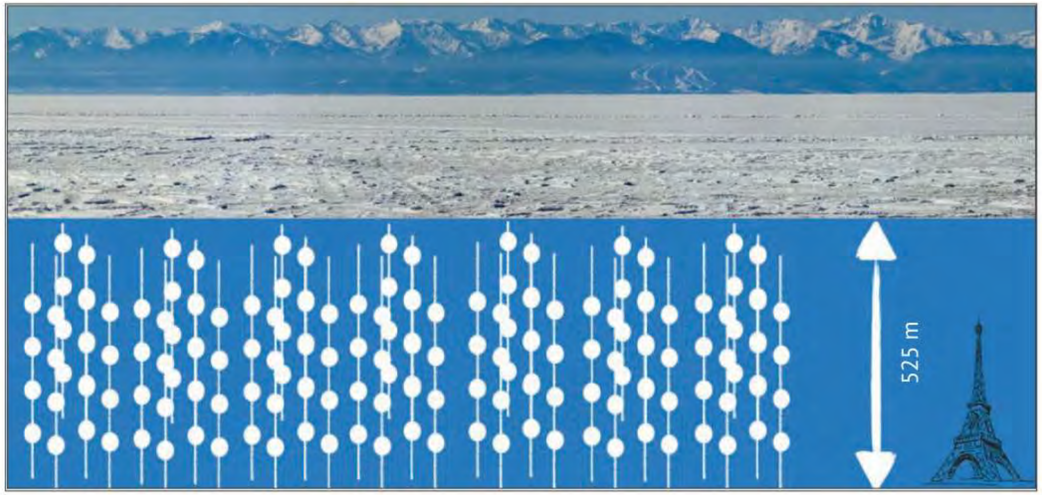
JINR in Particle Frontiers

JINR LONG-TERM DEVELOPMENT STRATEGIC PLAN UP TO 2030 AND BEYOND

- RELATIVISTIC HEAVY-ION PHYSICS AT NICA
- JINR PARTICIPATION IN FOREFRONT EXTERNAL EXPERIMENTS OFF-SITE
  - LHC, SPS, RHIC, and at facilities under construction, as for example the FAIR facility
- NICA SPIN PHYSICS
- PARTICLE PHYSICS AT THE LHC AND BEYOND
  - Accelerator-based research and frontier accelerator technologies (LHC, SPS, NICA, FAIR, etc)
  - Neutrino physics and astroparticle physics (Baikal-GVD, JUNO, NOvA, DUNE, etc)
  - Multi-messenger astronomy including gravitational wave detection (Baikal-GVD, TAIGA, VIRGO, etc)



The NICA accelerator complex



Baikal-GVD (Gigaton Volume Detector)

Why High Energy is Needed?

Particle physics have focused on the inner space frontier, pursuing the questions of the construction of matter and the fundamental forces at the smallest scale accessible.

Wavelength of probe radiation should be smaller than the object to be resolved

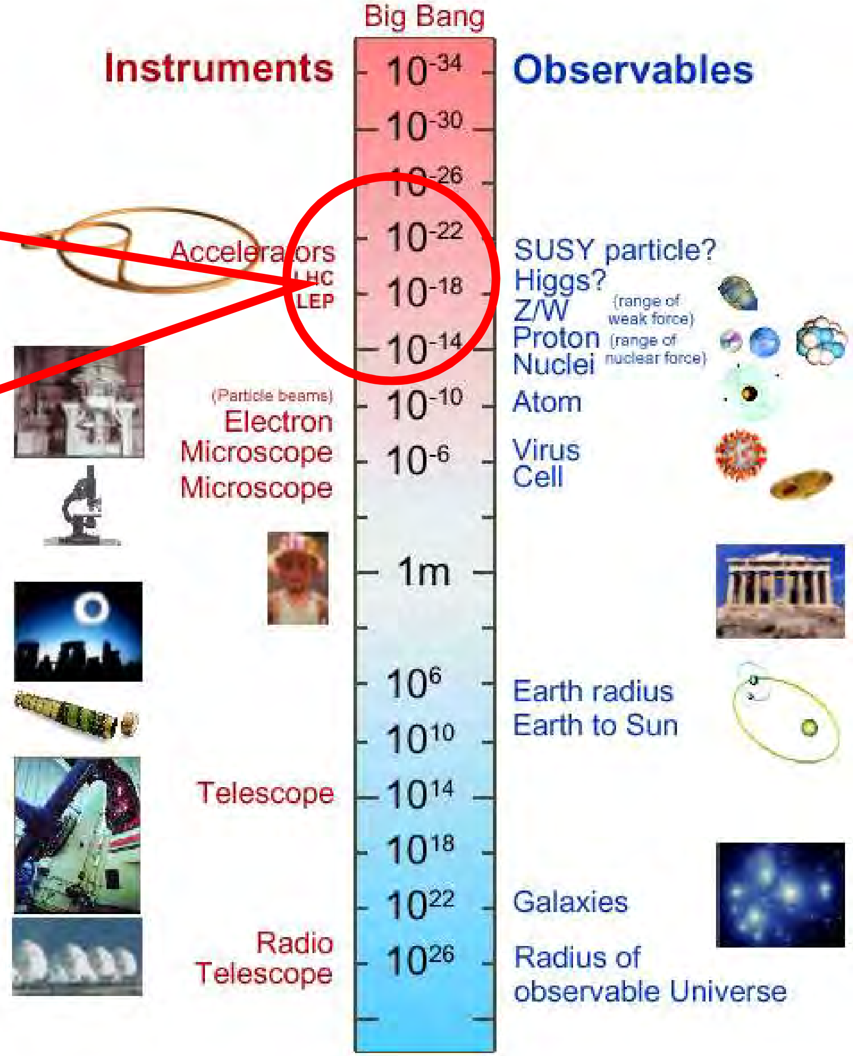
$$\lambda << \frac{h}{p} = \frac{hc}{E}$$

Object	Size	Energy of Radiation
Atom	10^{-10} m	0.00001 GeV (electrons)
Nucleus	10^{-14} m	0.01 GeV (alphas)
Nucleon	10^{-15}m	0.1 GeV (electrons)
Quarks	?	> 1 GeV (electrons)

Radioactive sources give energies in the range of MeV

Need accelerators for higher energies.

"electronic eyes"

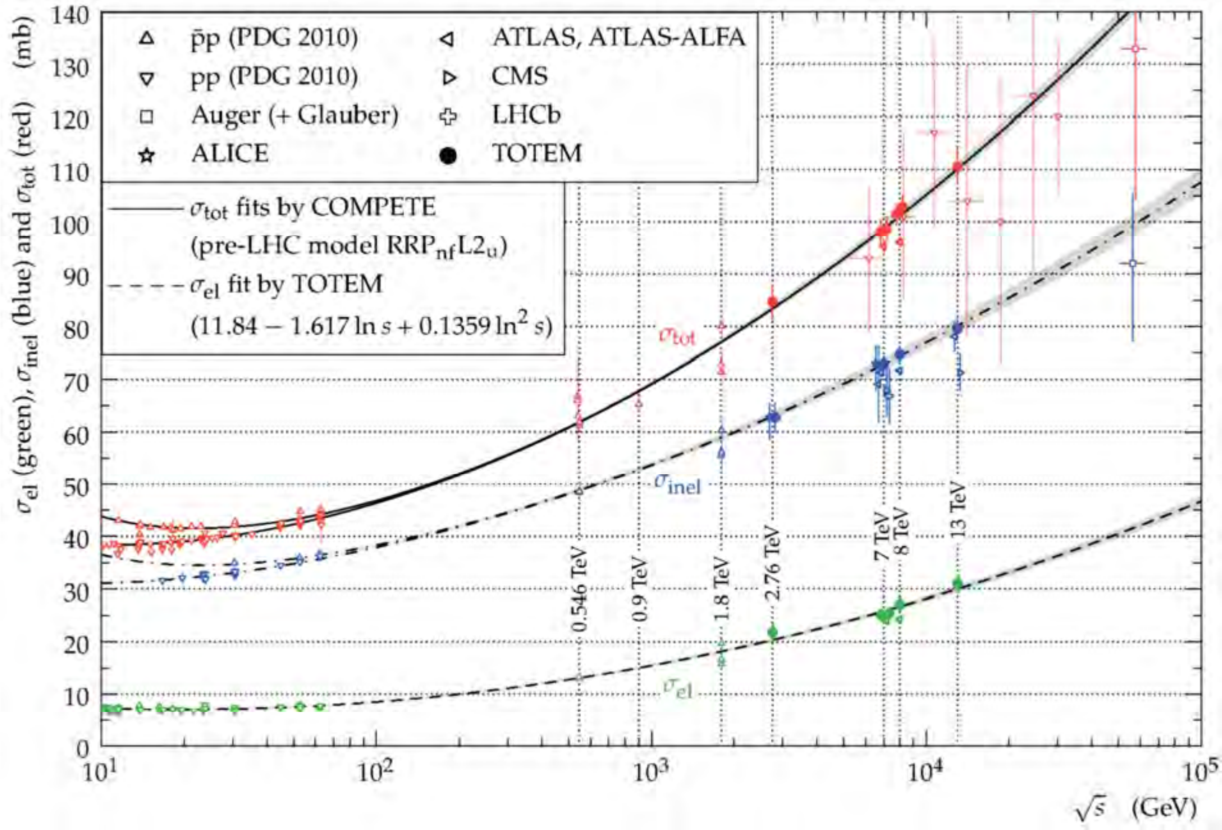


Energy and Intensity

- **Luminosity** L is a measure of how many interactions of **cross section** s can be created per unit time

$$L\sigma = \frac{dN}{dt} \qquad N = \sigma \int L\, dt = \sigma\, L_{\mathrm{int}}$$

  - L_{int} is integrated luminosity, an important factor of production for colliders
  - $[L] = cm^{-2}\ s^{-1}$, $[L_{int}] = cm^{-2}$ (1 barn $=10^{-24}$ cm; 1 $pb^{-1}=10^{36}\ cm^{-2}$)



- For equal-sized head-on Gaussian beams in a collider

$$L = \frac{f_{\mathrm{rev}}\, h\, N_1\, N_2}{4\pi\sigma_x\sigma_y}$$

  - $\sigma_{x,y}$ are rms beam sizes, h is number of bunches

Colliding 100 mm 7.5×10^9 proron bunches at 100 kHz for 1 year gives about 1 pb^{-1} of integrated luminosity

Luminosity vs Energy

Highest energies can be reached with proton colliders

Machine	Year	Beams	Energy (√s)	Luminosity
SPPS (CERN)	1981	pp	630-900 GeV	$6.10^{30}cm^{-2}s^{-1}$
Tevatron (FNAL)	1987	pp	1800-2000 GeV	10^{31}-$10^{32}cm^{-2}s^{-1}$
SLC (SLAC)	1989	e^+e^-	90 GeV	$10^{30}cm^{-2}s^{-1}$
LEP (CERN)	1989	e^+e^-	90-200 GeV	10^{31}-$10^{32}cm^{-2}s^{-1}$
HERA (DESY)	1992	ep	300 GeV	10^{31}-$10^{32}cm^{-2}s^{-1}$
RHIC (BNL)	2000	pp /AA	200-500 GeV	$10^{32}cm^{-2}s^{-1}$
LHC (CERN)	2009	pp (AA)	7-14 TeV	10^{33}-$10^{34}cm^{-2}s^{-1}$

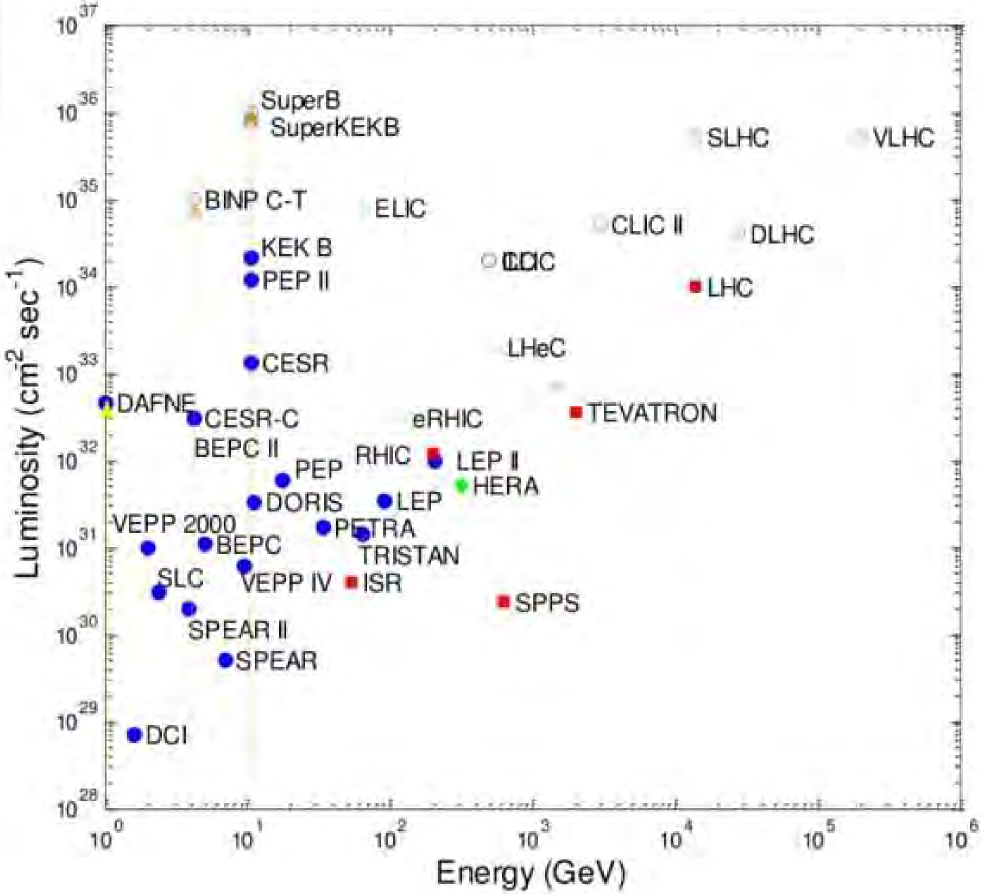
Luminosity = number of events/cross section/sec

Limits on circular machines (except the expense)

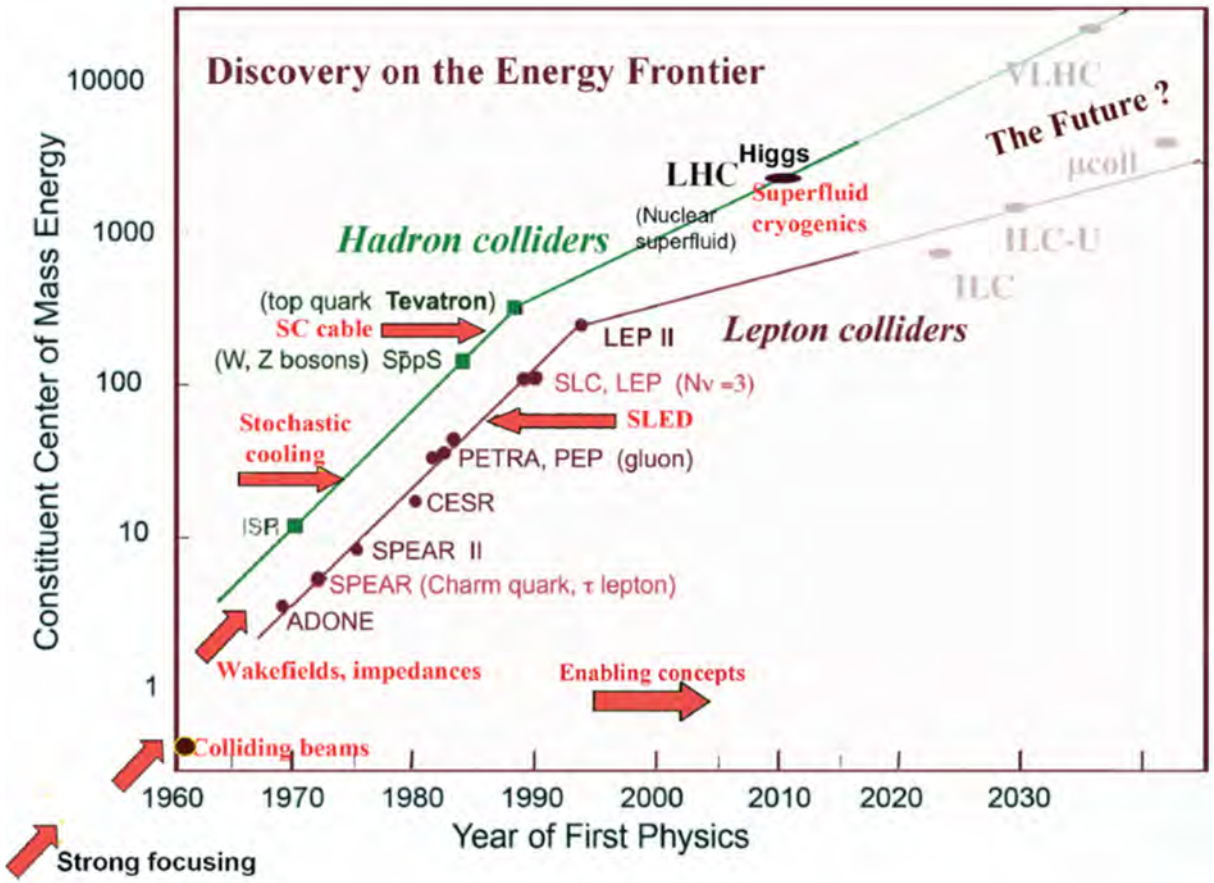
- Proton colliders: Dipole magnet strength $\rightarrow$ superconducting magnets
- Electron colliders: Synchrotron radiation/RF power

Limits on linear machines

- the device's length

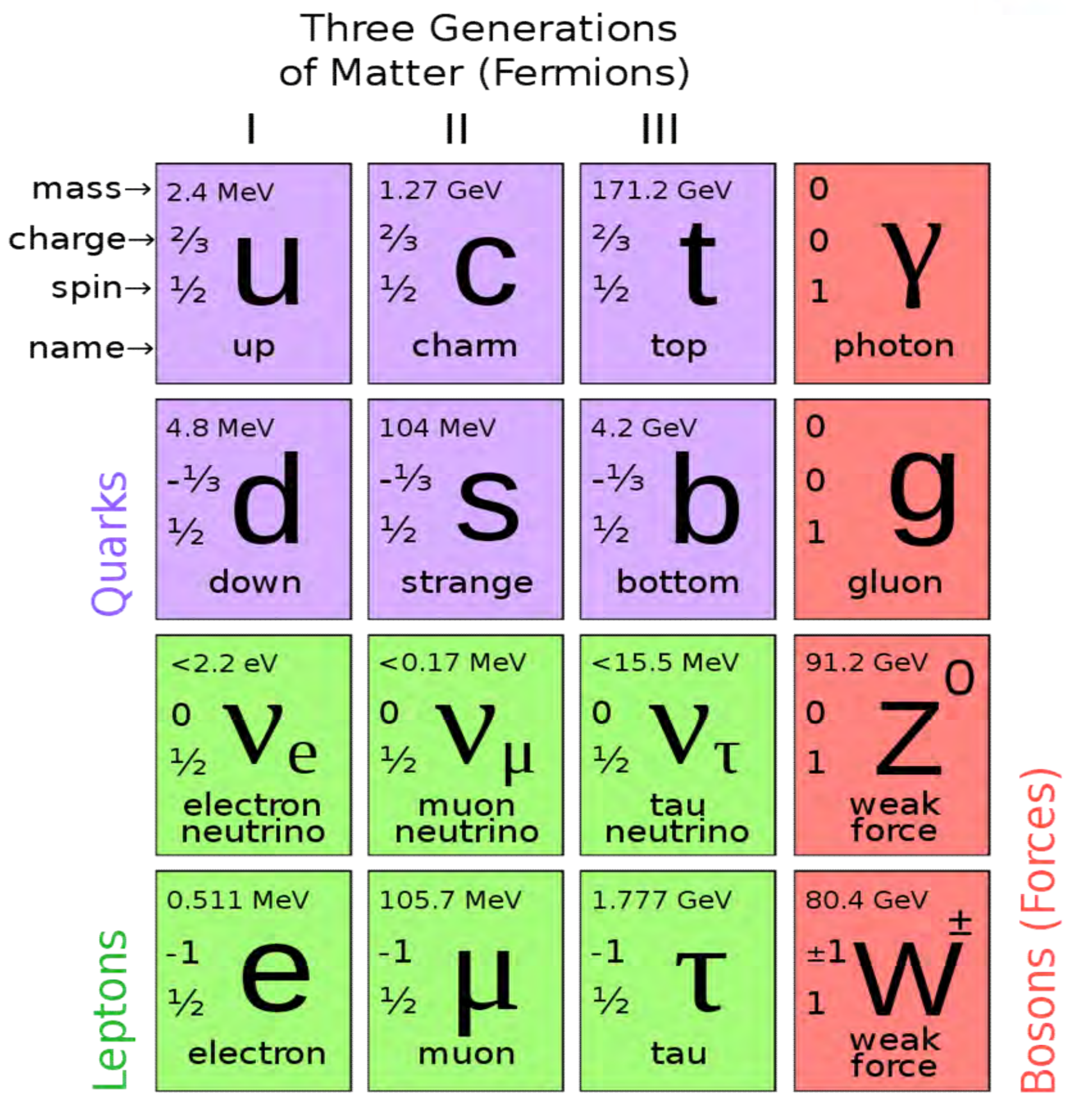


Do we really need more and more accelerator facilities?



What we had before LHC?

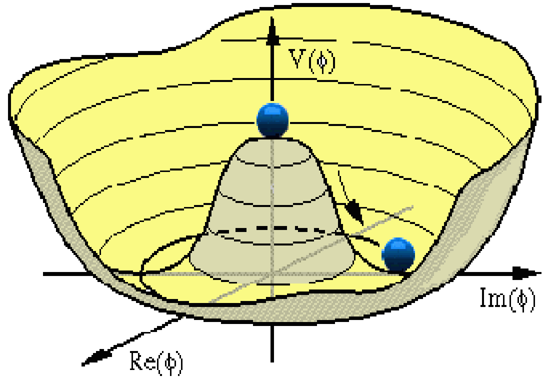
1900s: e discovered (cathode ray tube)
γ interpreted as a particle
1930s: μ discovered (cosmic rays)
1950s: ν_e observed (nuclear reactor)
ν_μ discovered (BNL)
1960s: 1st evidence for quarks
u and d observed (SLAC)
s observed (BNL)
1970s: ***standard model is born***
c discovered (SLAC, BNL)
τ observed (SLAC)
b observed (FNAL)
1980s: W and Z observed (CERN)
1990s: t quark observed (FNAL)
2000s: ν_τ observed (FNAL)



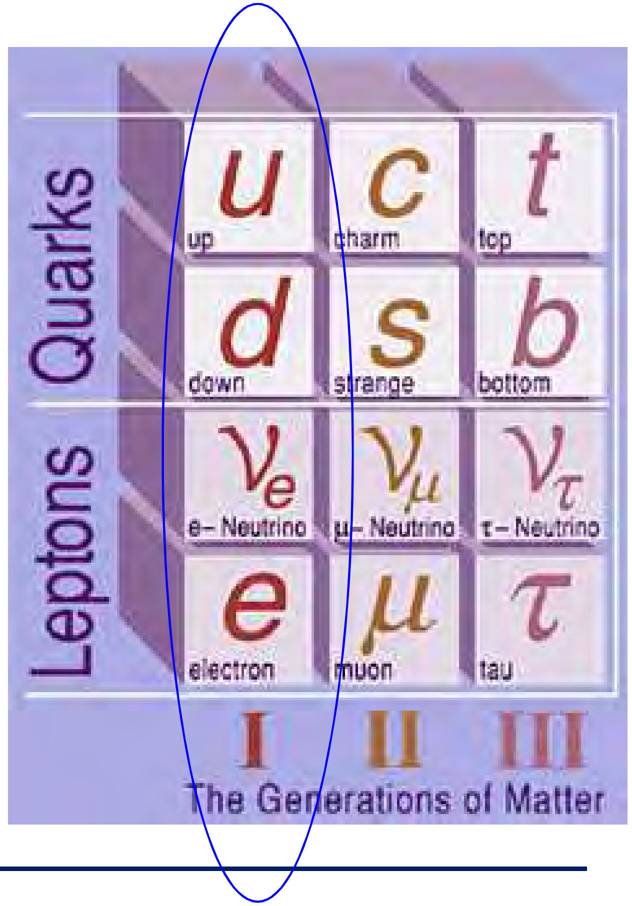
SM is fully completed, expect for Higgs boson

Is the Standard Model as Good as it Looks? or…

- What about a mass generation mechanism?
  - ✓ Higgs bosons? (Now – Yes)



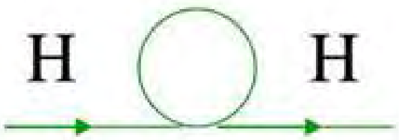
- Three generation of particles:
  - ✓ why 3 (they can not be fixed in the framework of SM)?
  - ✓ why do we need all of them?



- Yukawa hierachy (explanation of mass patterns for quarks and leptons)
- A lot of free parameters: gauge couplings, Yukawa coupling constants, CKM-mixing angles, Higgs vacuum expectation value, etc (in total, 26)

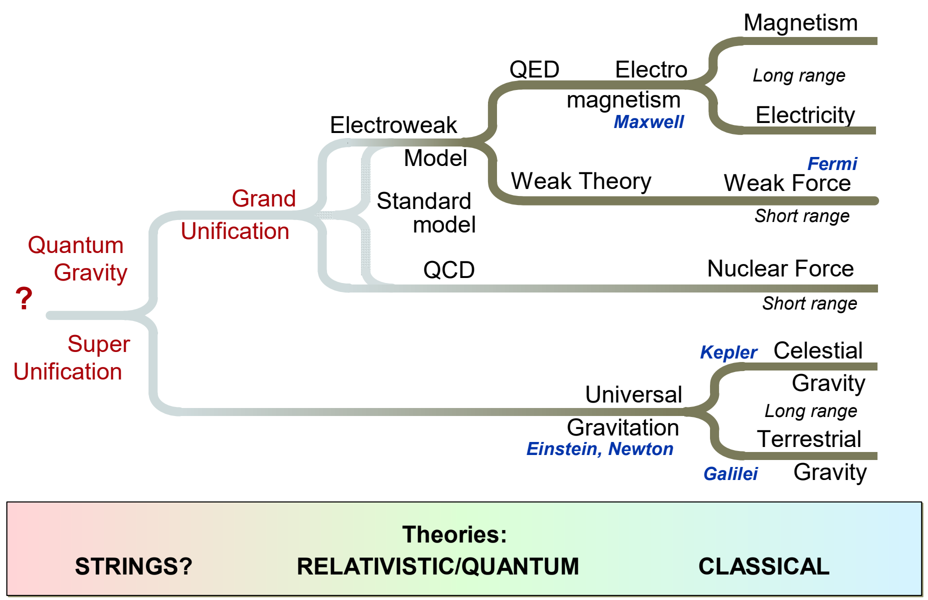
… why do we believe in something beyond Standard Model?

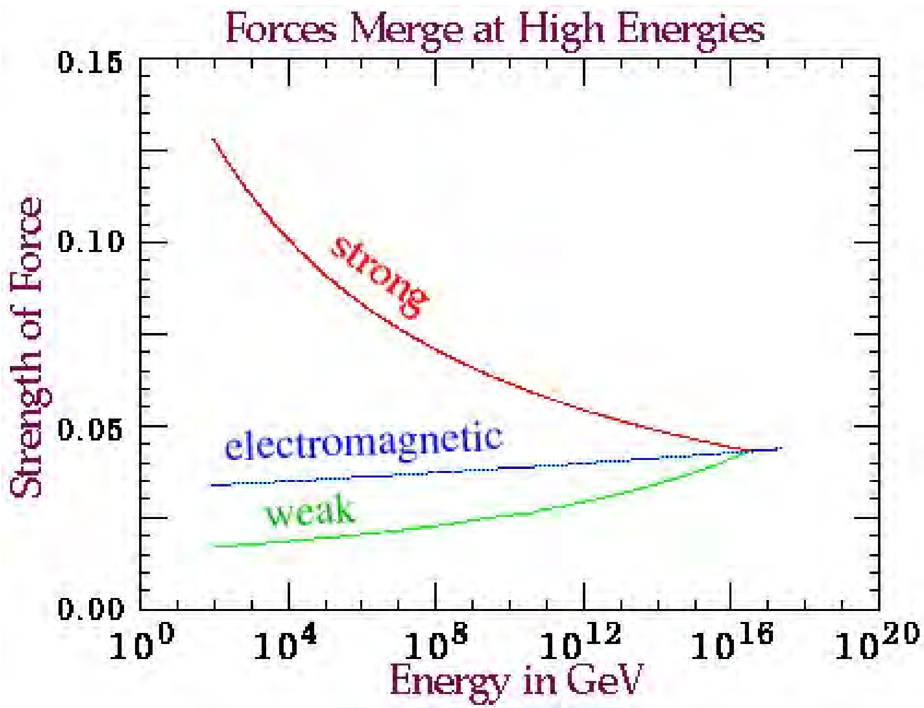
- Where is a gravity?
- Hierarchy problem
  - ✓ fine tuning of higgs mass is needed to "neutralize" contribution from high order corrections
  - ✓ huge gap between Electroweak (10^2 GeV) and Planck scale (10^{19} GeV) scales), Gravity/EW ~ $10^{19}/10^2$ GeV?



$\Delta m_H^2 \sim \Lambda^2$

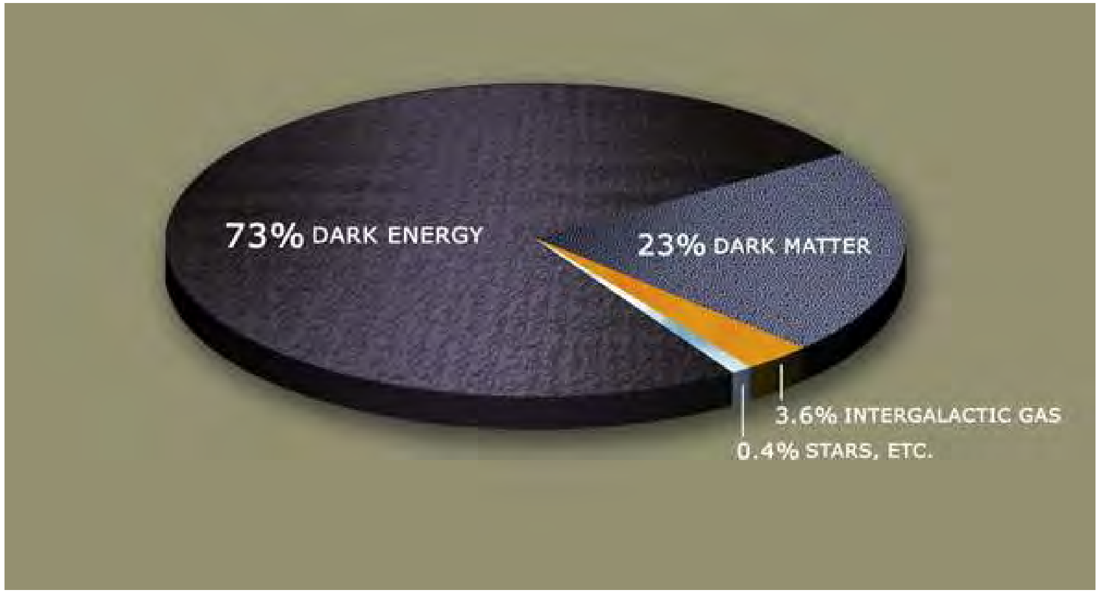
- Unification of Forces





Related Cosmological and Astrophysical Problems

- Dark Matter: what does it consist of?
- CP-violation in Early Universe

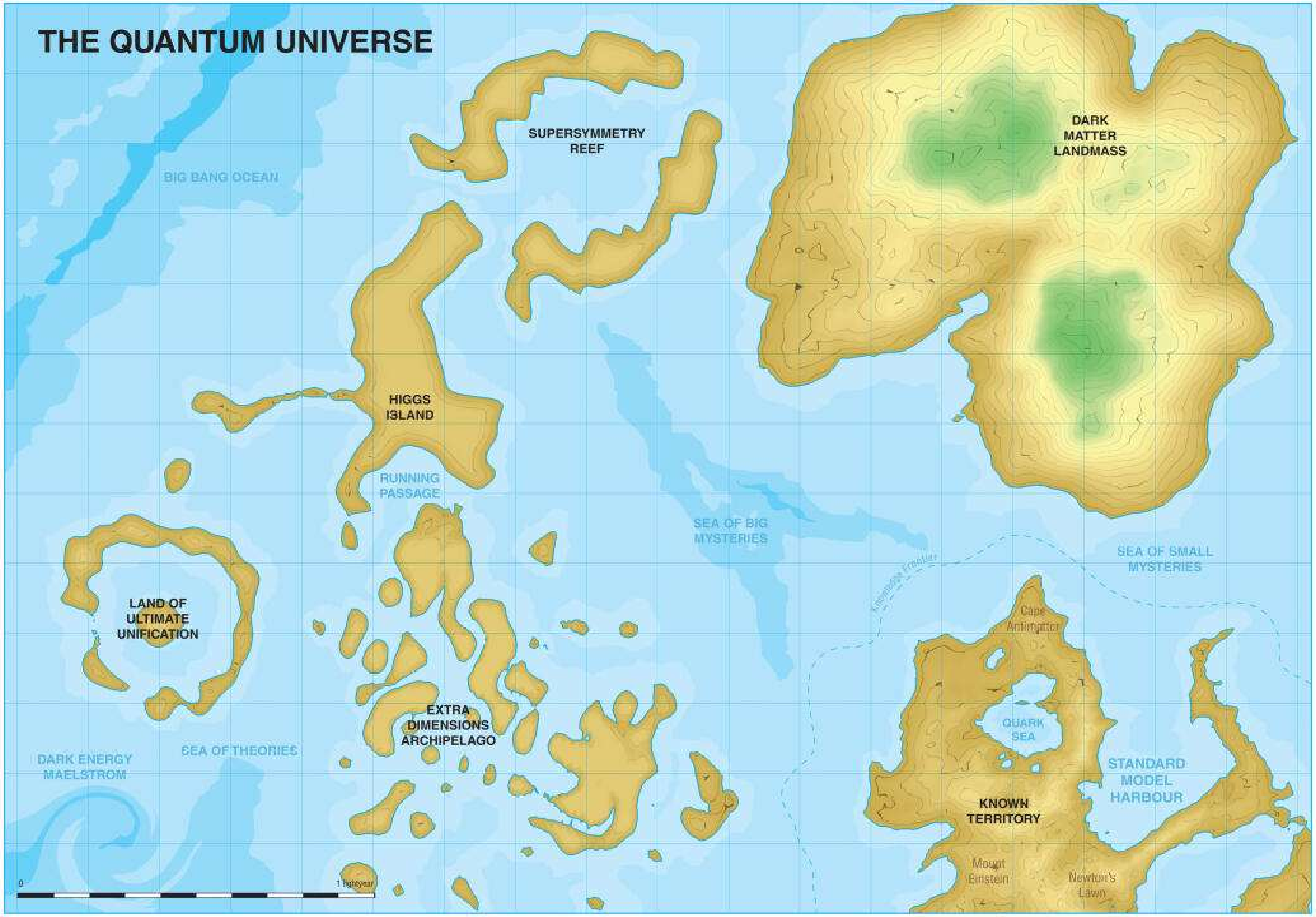


Well, the Standard Model is not a ultimate theory!

The 11 Greatest Unanswered Questions of Physics (Discover, 2002), 6 are LHC related

1. What is dark matter ?
2. What is dark energy ?
3. How were the heavy elements from iron to uranium made ?
4. Do neutrinos have mass ?
5. Where do ultrahigh-energy particles come from ?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures ?
7. Are there new state of matter at ultrahigh temperate and dentisity ?
8. Are protons unstable ?
9. What is gravity ?
10. Are there additional dimensions ?
11. How did the universe begin ?

What do we hope to see beyond the SM?



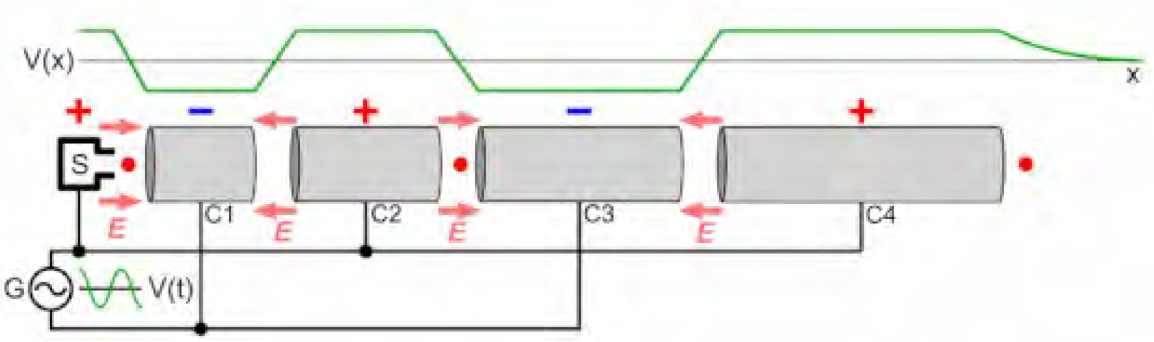
How we can escape beyond the Standard Model $SU(3)_c \times SU(2) \times U(1)$?

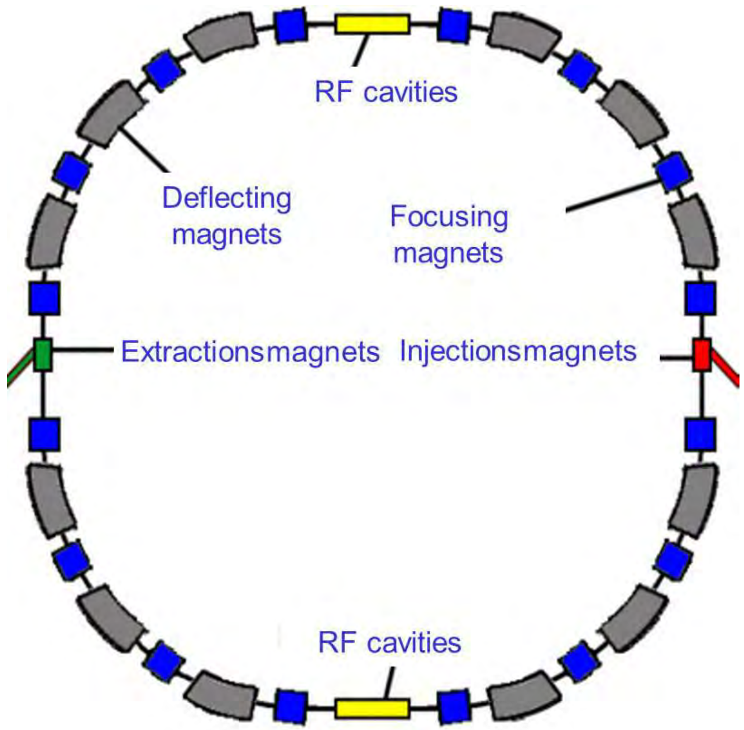
- Simplest extension of SM (based on SM gauge group)
  - ✓ 4 generation of fermions, q*, l*…
- Extended gauge sector
  - ✓ ExQCD (colorons, axigluons, diquarks etc)
  - ✓ ExEW (W’, Z’, …)
  - ✓ GUT (leptoquarks)
- Extended Higgs Sector
  - ✓ Higgs Doublet Models (HDM)
  - ✓ Higgs in ED, Higgs-Radion mixing, composite Hig… …ype)
- Hierarchy problem
  - ✓ SUSY (s-particles, LSP из RPV/split/GM SUSY…)
  - ✓ Extra dimensions (ED)
    - КК-modes of particles SM, KKPV, FCNC…
    - microscopic black holes (semi-classical, string balls, quantum black holes)
  - ✓ Technicolor (technibosons and technifermions, leptoquarks …)
  - ✓ Compositeness
- Dark Matter (EFT)

Will be discussed in details someday

How do we intend to observe all this (which accelerator is better?)?

Types of particle accelerators
- ✓ linear and circular accelerator
- ✓ e+e-, ep, pp, ppbar, pA, AA, …

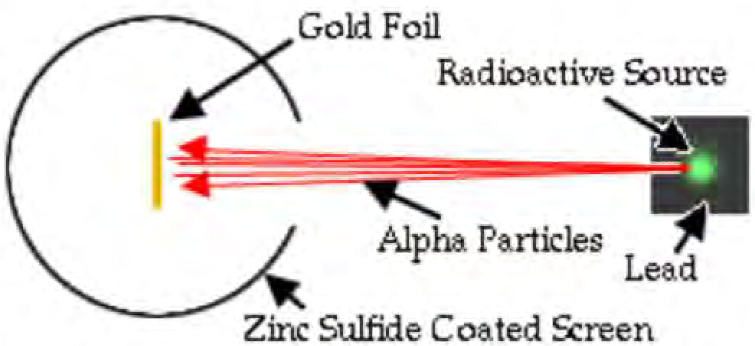




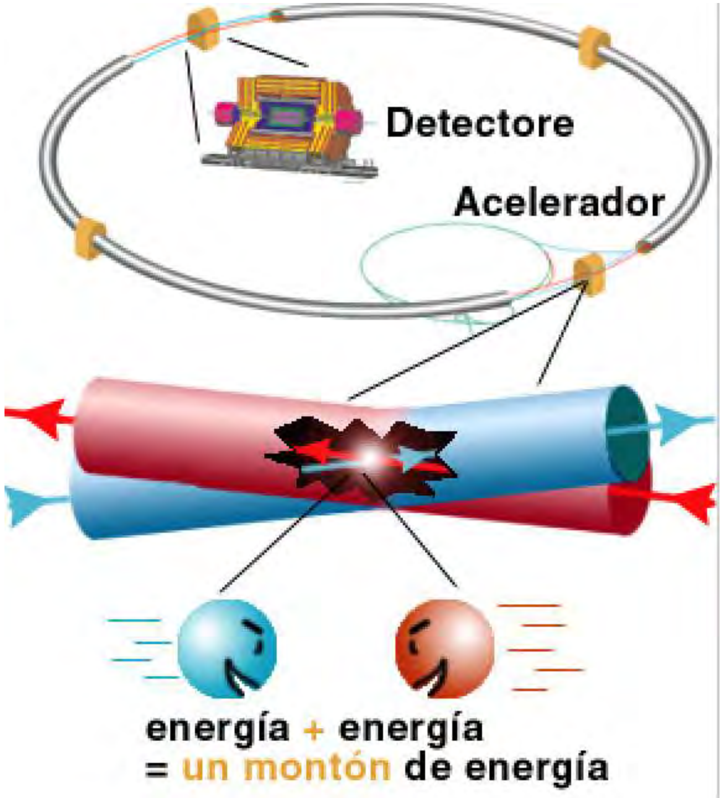
Fixed Target or Colliders?

First High Energy Physics Experiments:
Beam on fixed target!

High Energy Physics Experiments since mid 70's:
Colliding beams!



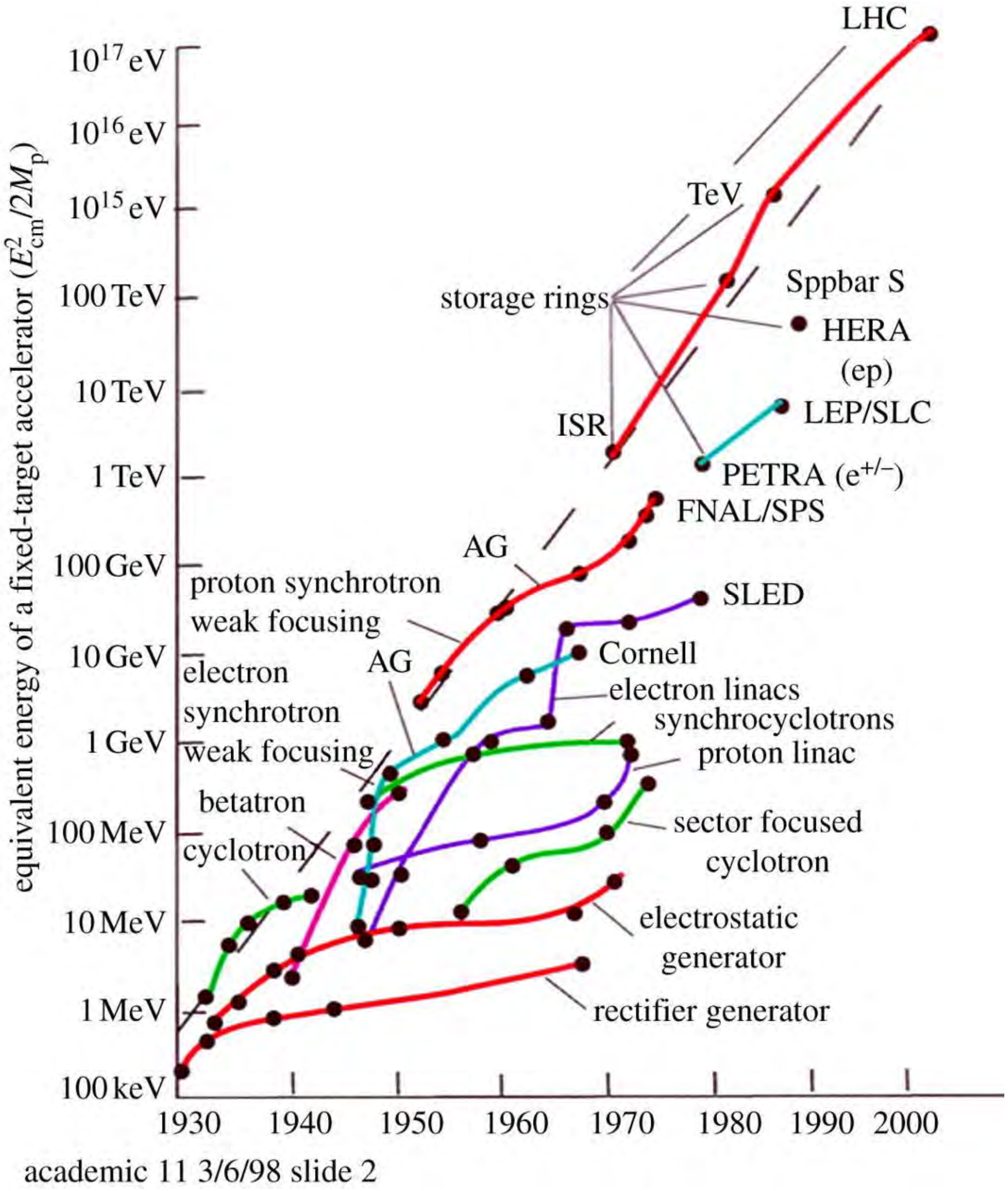
Rutherford experiment (1909)



Centre of mass energy squared $s=2E_1m_2$

Centre of mass energy squared $s=4E_1E_2$

…plus secondary beams such as neutrinos…

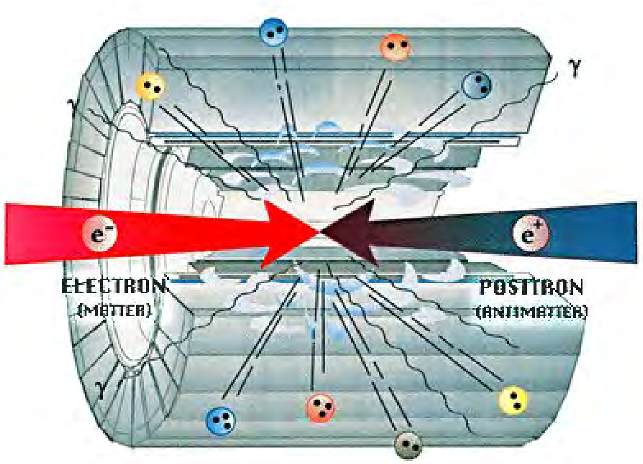

LHC
10^{17} eV
10^{16} eV
10^{15} eV
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
100 keV
equivalent energy of a fixed-target accelerator ($E^2_{cm}/2M_p$)
TeV
storage rings
Sppbar S
HERA
(ep)
LEP/SLC
ISR
PETRA ($e^{+/-}$)
FNAL/SPS
AG
proton synchrotron
weak focusing
SLED
Cornell
electron
synchrotron
weak focusing
AG
electron linacs
synchrocyclotrons
proton linac
betatron
cyclotron
sector focused
cyclotron
electrostatic
generator
rectifier generator
1930
1940
1950
1960
1970
1980
1990
2000
academic 11 3/6/98 slide 2

Why Hadron (pp) Collider?

Electron-Position Collider: clean signature

Synchrotron Radiation:

$$P = \frac{2\, e^2\, c}{3\, R^2} \left(\frac{E}{mc^2}\right)^4$$



CERN LEP： R=4.5km, E_{beam} ~ 100 GeV

CERN LHC： R=4.5km, E_{beam} ~ 7000 GeV

$$\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$$

How much energy do we really need?

- The simplest answer is .. as much as possible (construction restriction, technologies, price..)

- Different approach is .. more than Tevatron energy of 1.8 TeV (vague claim)

- Real life
  - ✓ Higgs boson
    - $m_H < 1$ TeV from theory (SM unitarity requires)
    - $m_H > 114.1$ GeV from LEP
    - $156 < m_H < 177$ GeV from Tevatron

    ⇒ need a machine to discover/exclude Higgs from ≈ 120 GeV to 1 TeV

  - ✓ $m_{SUSY} \sim$ TeV
  - ✓ $m_{BSM} > 0.5$ TeV from theory and from Tevatron

    ⇒ need a machine to explore a range of of up a several TeV

⇓

need a energy scan

Machine of Discovery

Factorization hypothesis

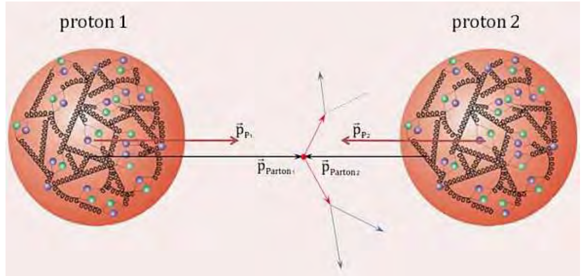
Fragmentation function

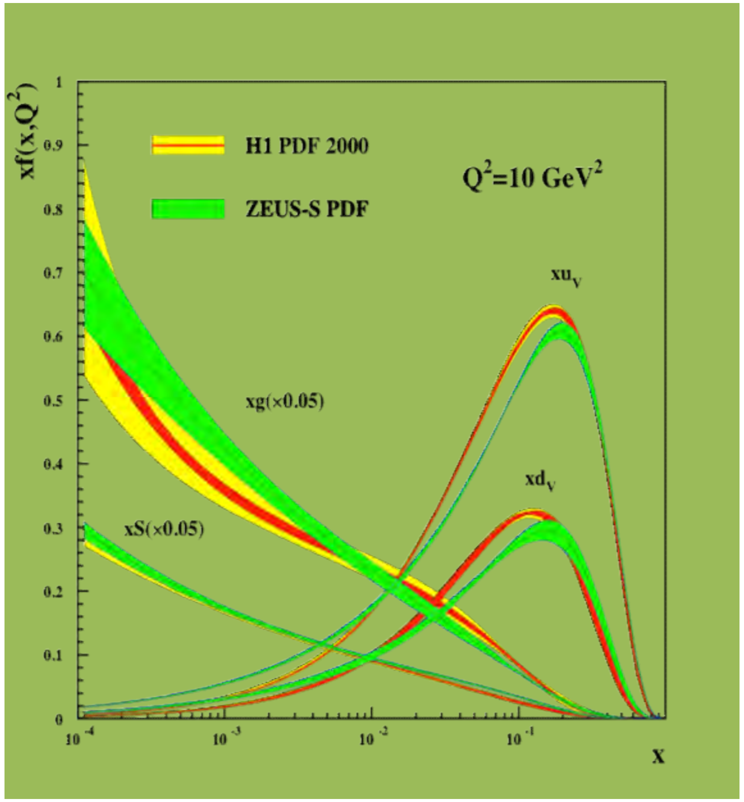
$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}\left(x_a, Q^2\right) \otimes f_{b/B}\left(x_b, Q^2\right) \otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt} \otimes D_{h/c}\left(z_c, Q^2\right)$$

Parton distributions

Parton density functions (PDFs)

cross section of hard processes





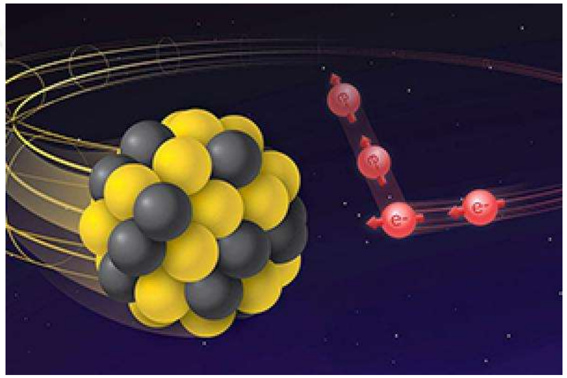
effective centre-of-mass energy $\sqrt{\hat{s}}$ smaller than $\sqrt{s}$ of colliding beams:

$$\left.\begin{aligned}\vec{p}_a &= x_a\,\vec{p}_A\\ \vec{p}_b &= x_b\,\vec{p}_B\end{aligned}\right\}\quad p_A = p_B = 7\ \text{TeV}\quad \sqrt{\hat{s}} = \sqrt{x_a x_b s} \approx x\sqrt{s}$$

if $x_a \approx x_b$

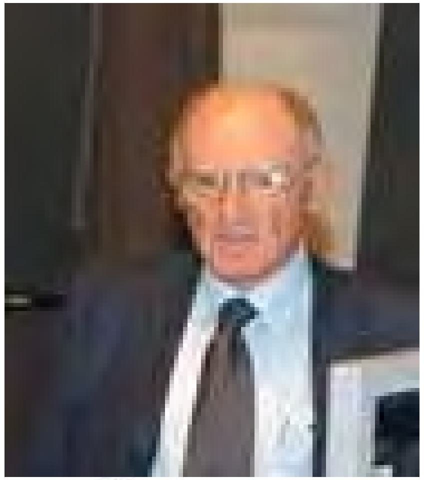
$\rightarrow$ to produce m $\approx$ 100 GeV x ~ 0.01

to produce m $\approx$ 5 TeV x ~ 0.35



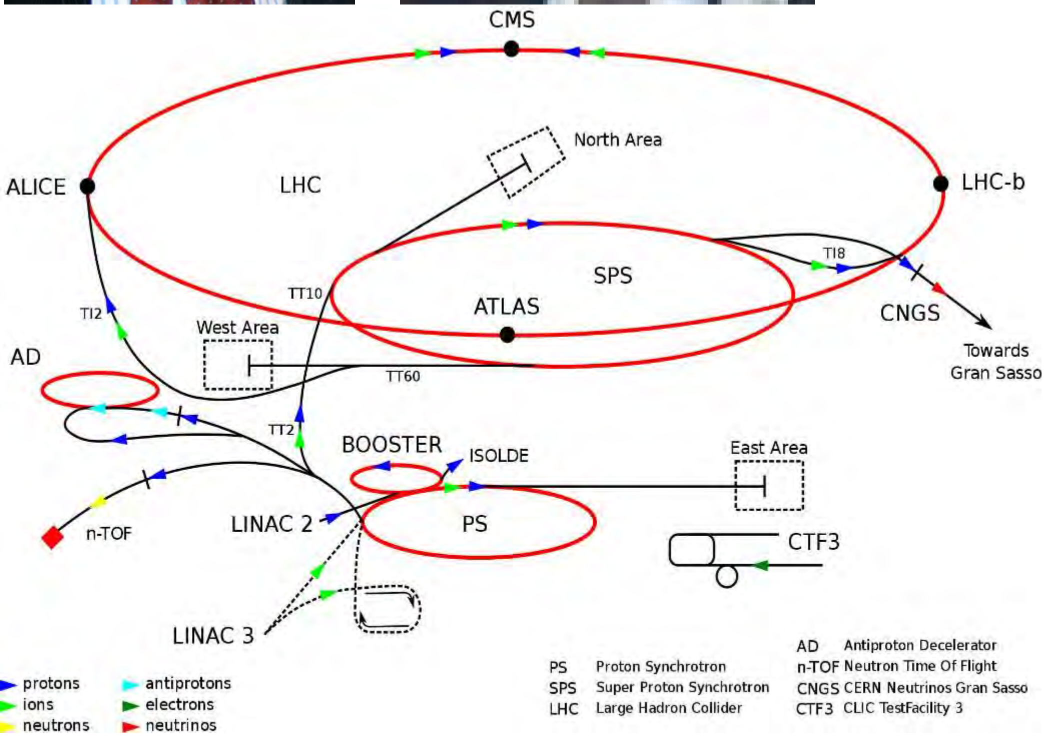
Large Hadron Collider at CERN

Carlo Rubbia   Giorgio Brianti



1984 (Lausanne): the fist LHC Working Group for LHC conception

December 16, 1991: LHC Project was approved by CERN Council



- High Energy ⇒ factor 7 increase w.r.t. past accelerators
- High Luminosity (# events/cross section/time) ⇒ factor 100 increase

Linac: 50 MeV → PSB: 1.4 GeV → PS: 28 GeV → SPS: 450 GeV → LHC: 7 TeV

LHC Parameters

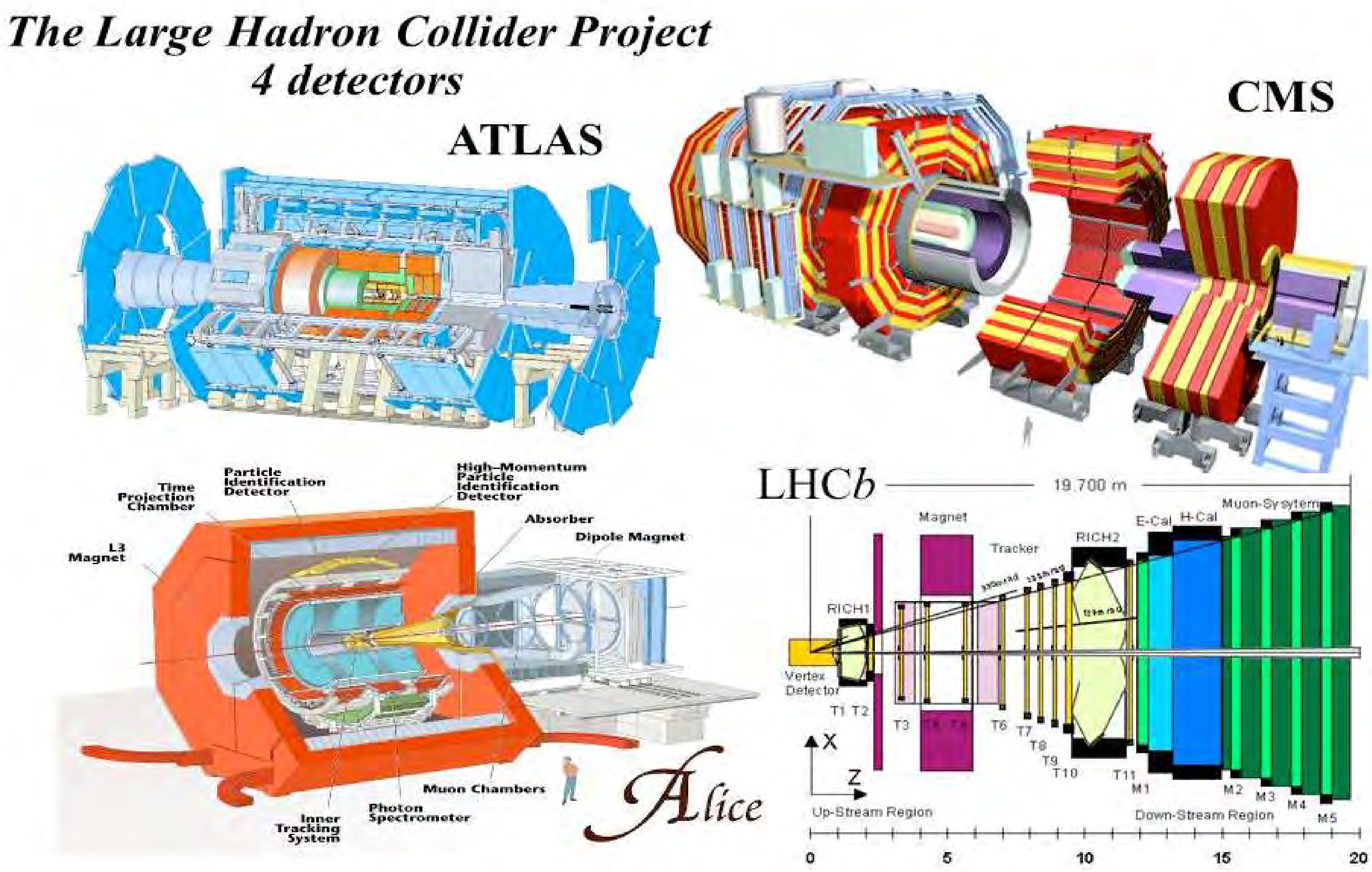
Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1×10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

(*) Energy per nucleon

LHC is 100m underground
LHC is 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC: 40 million proton-proton collisions per second
LHC: Luminosity 100 fb^{-1}/year (after start-up phase)

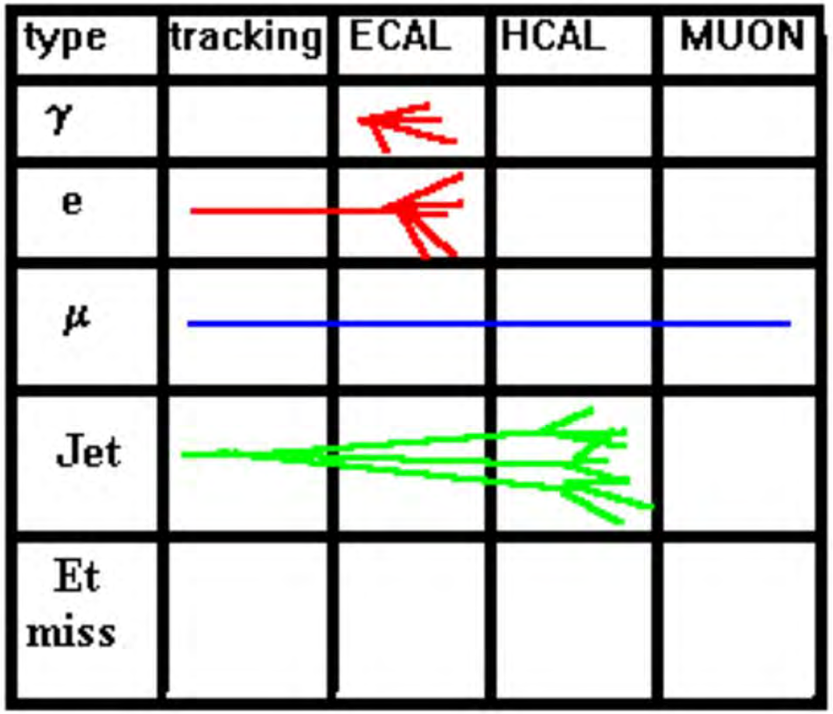
The LHC Experiment at CERN

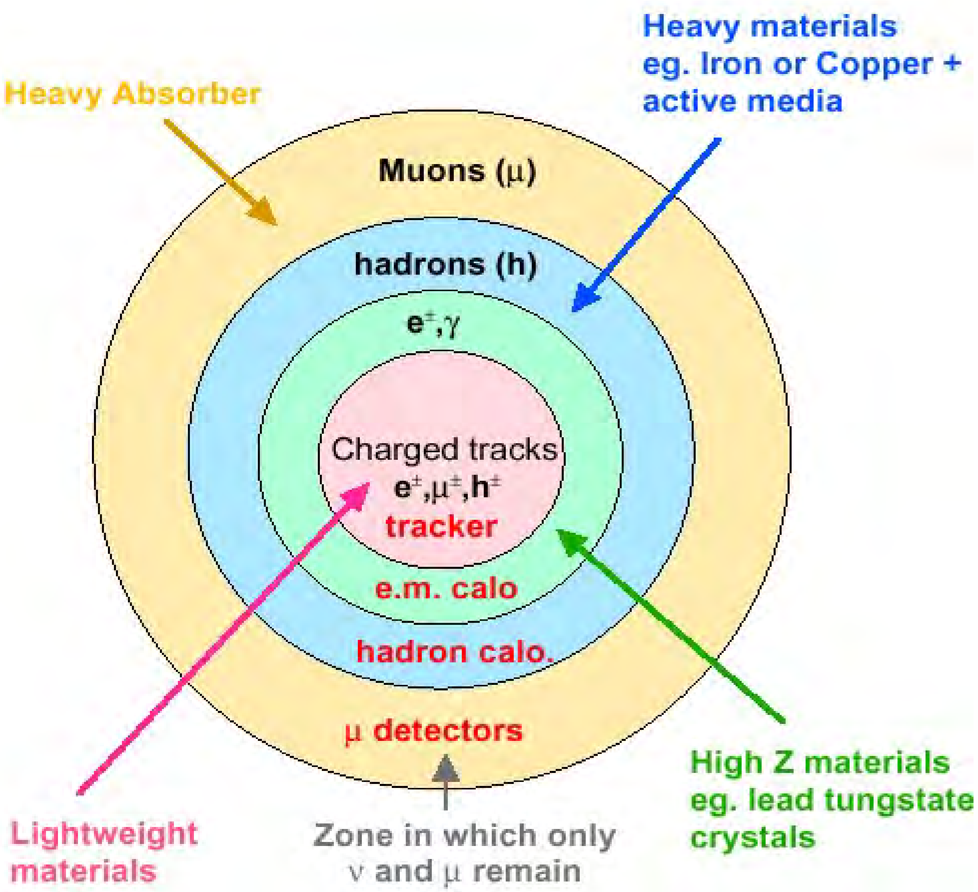
Experimental Facilities



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

Challenges to the Detector

LHC detectors must have

- Fast response, otherwise too large pile-up. Typical response time 20-50 ns
  - pile-up of 25-50 minimum bias events

  $\rightarrow$ very challenging readout electronics
- high granularity to minimize probability that pile-up particles be in the same detector element as interesting object

  $\rightarrow$ large number of electronic channels, high cost
- a robust and redundant Muon system
- the best possible e/g calorimeter ECAL that consistent with Muon System
- a highly efficient Tracking system consistent that with Muon System and ECAL
- a hermetic calorimeter system
- high radiation resistant e.g. in forward calorimeters: up to 10^{17} n/cm^2 in 10 years of LHC operation
- good PID (particle identification)
- good E, p_T resolution

Precision Muon Spectrometer $\sigma / pT \sim 10$ % at 1 TeV/c

Fast response for trigger

Good p resolution (e.g., A/Z' $\rightarrow \mu\mu$, H -> 4μ)

EM Calorimeters $\sigma / E \sim 10\% / \sqrt{E(GeV)}$

excellent electron/photon identification

Good *E* resolution (e.g., H$\rightarrow\gamma\gamma$)

Hadron Calorimeters

Good jet and E_T miss performance

(e.g., H $\rightarrow\tau\tau$) $\sigma / E \sim 50\% / \sqrt{E(GeV)} \oplus 0.03$

Inner Detector

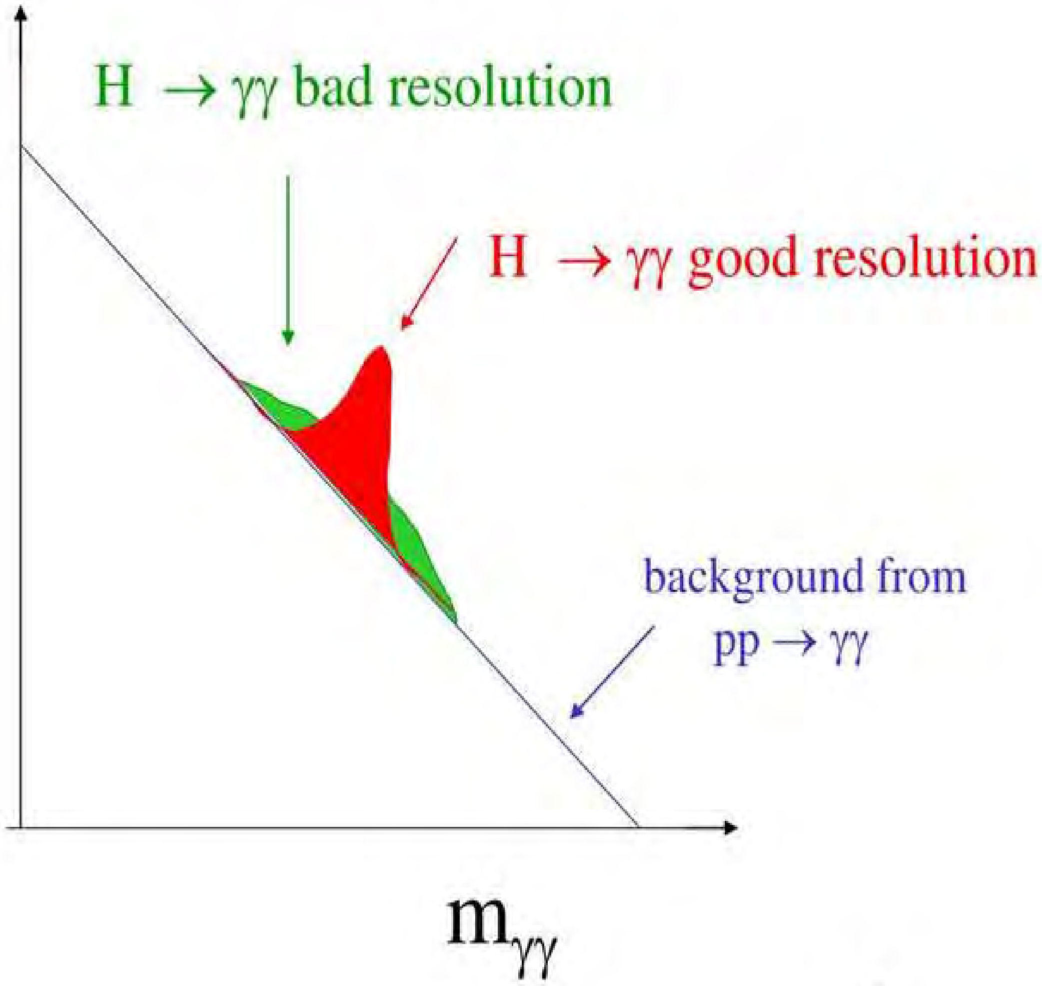
$\sigma / p_T \sim 5 \bullet 10^{-4}\, p_T \oplus 0.001$

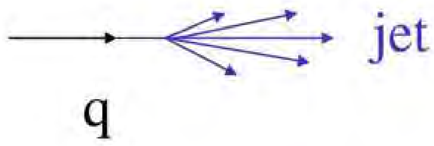
Good impact parameter res.

(e.g., H $\rightarrow$ bb)

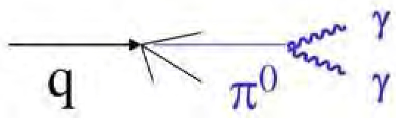
Challenge to the Detector (Example)

Example : $H \rightarrow \gamma\gamma$

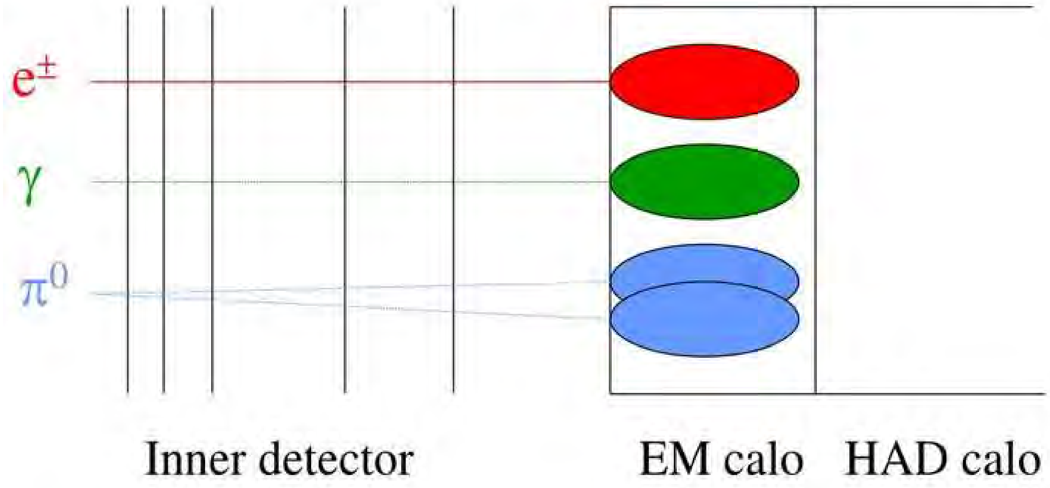




number and p_T of hadrons in a jet have large fluctuations



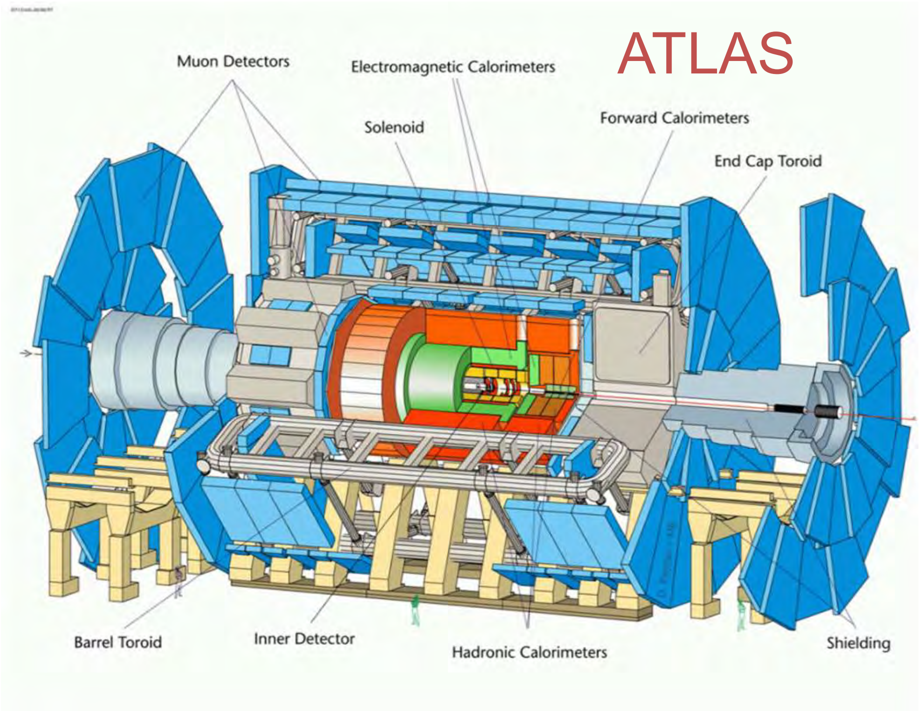
in some cases: one high-p_T π^0; all other particles too soft to be detected

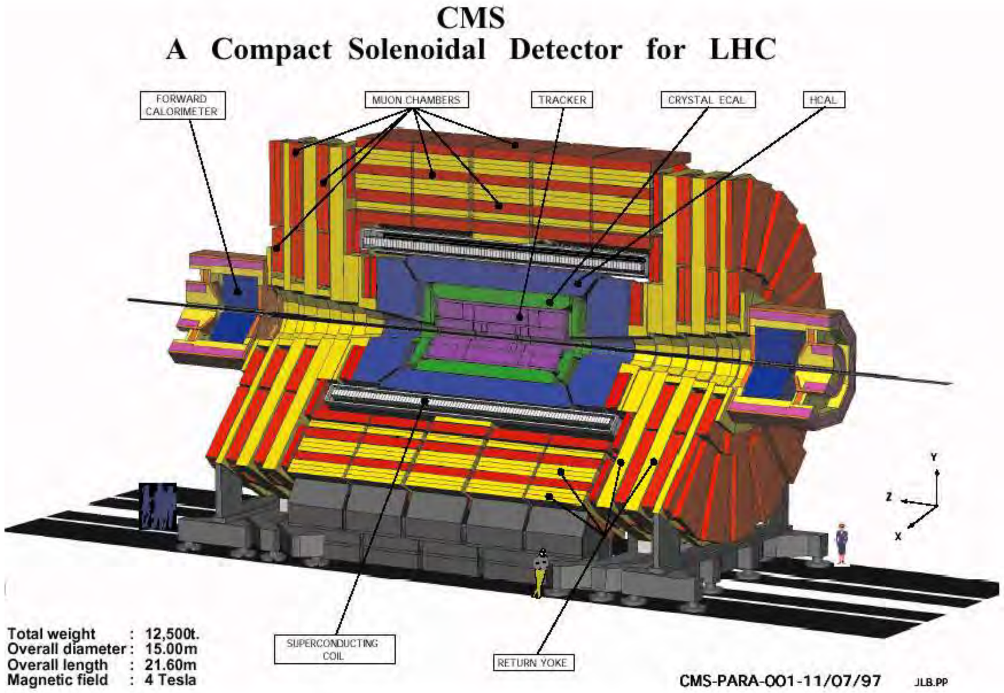


d (γγ) < 10 mm in calorimeter → QCD jets can mimic photons. Rare cases, however:

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

ATLAS and CMS Experiments





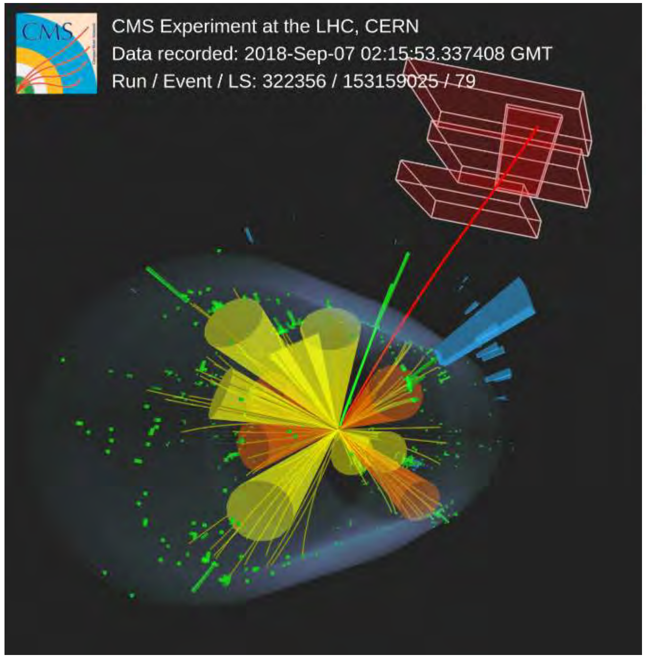
Weight	*7000 t*	*Weight*	*12 500 t*
Diameter	*25 m*	*Diameter*	*15 m*
Length of toroid	*26 m*	*Length*	*21.6 m*
Total Length	*46 m*	*B-field*	*4 Tesla*
B-field	*2 Tesla*		

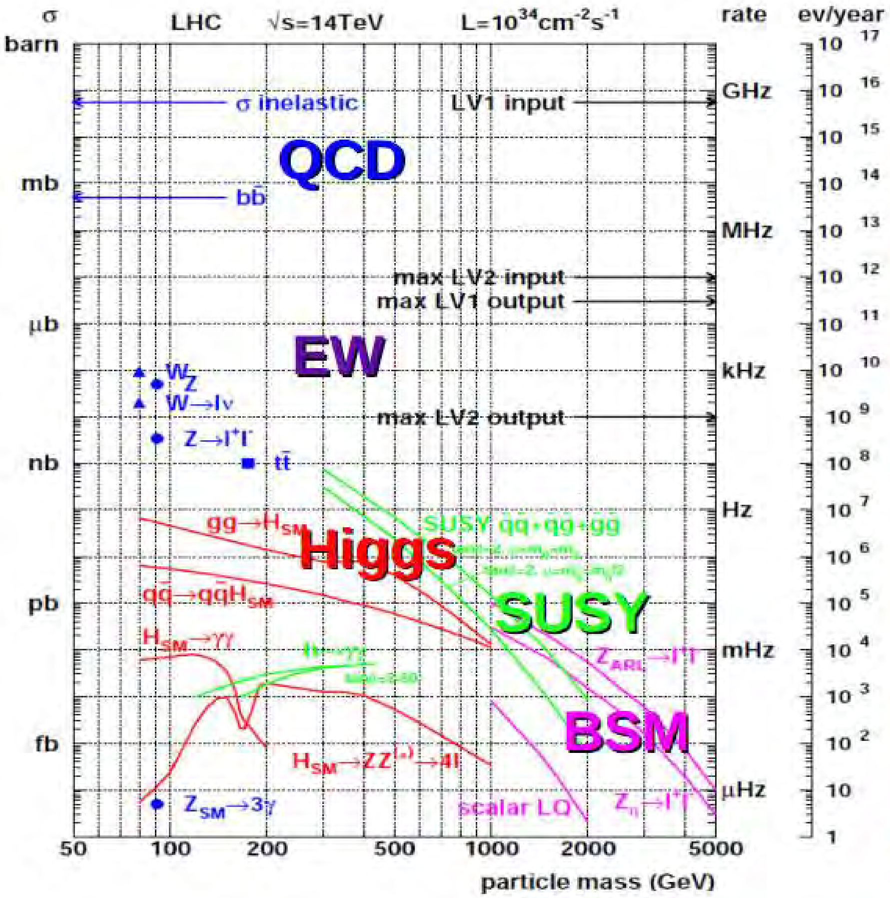
Detector systems are designed to measure:

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

IT SCHOOL JINR

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:

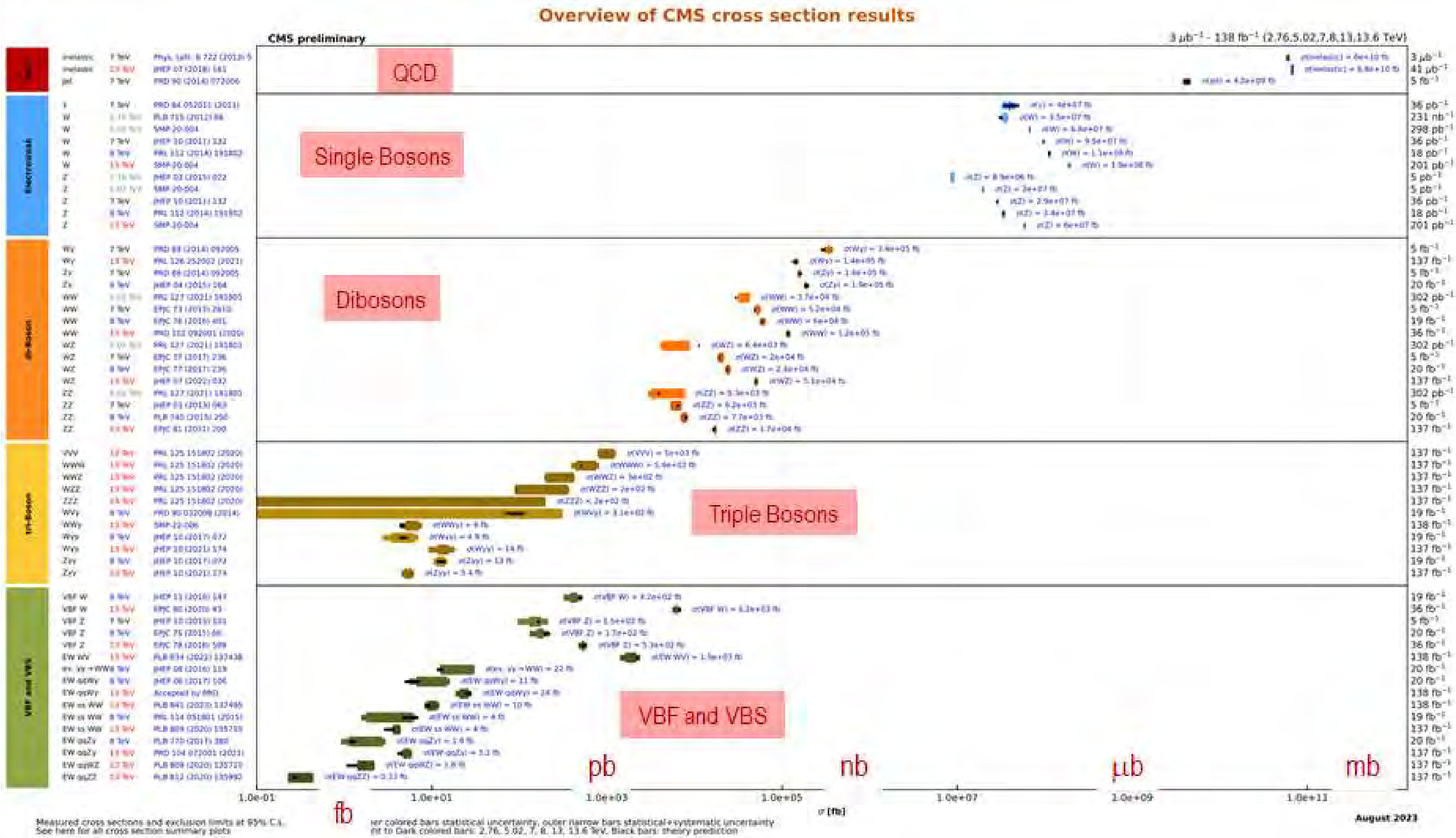
- W bosons: 12 billion
- Z bosons: 2.8 billion
- Top quarks: 300 million
- B quarks: 40 trillion
- Higgs bosons: 7.7 million

Summary of Standard Model Tests with EWK Bosons

Summaries of CMS cross section measurements

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

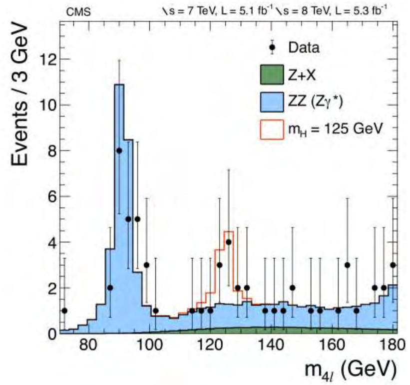
plots are updated for Summer 2023 Conferences

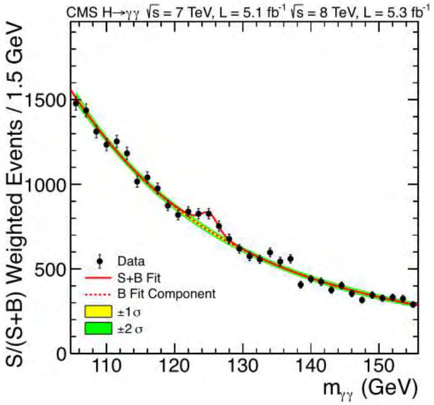


Higgs Physics

From design

to discovery





4 July 2012

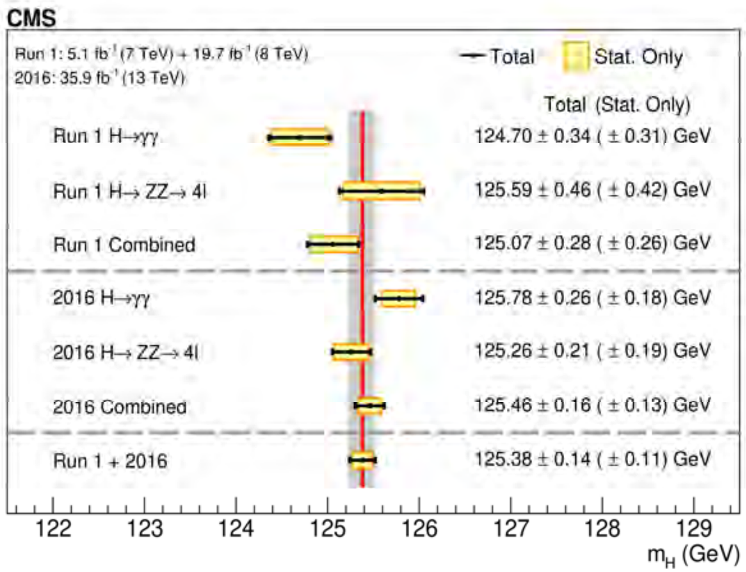
Higgs announcement at CERN

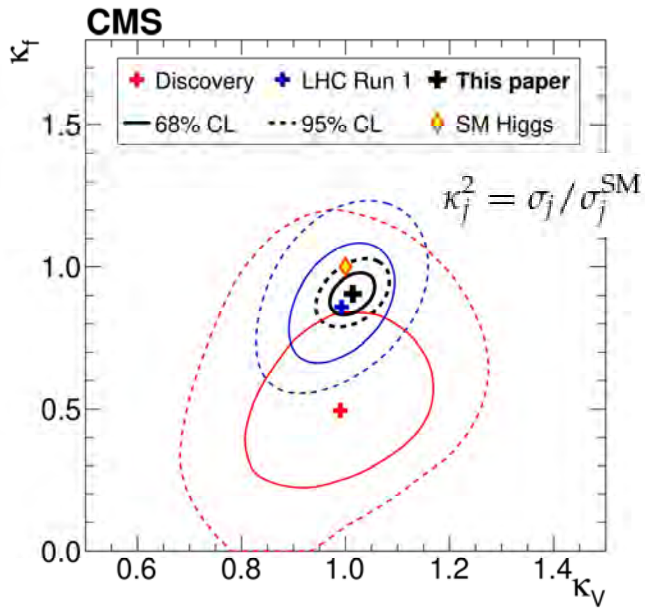
	Int. Luminosity at 7, 8 TeV	mH [GeV]	Expected [st. dev.]	Observed [st. dev.]
ATLAS	10.7 fb^{-1}	126.0 ± 0.6	4.6	5.0
CMS	10.4 fb^{-1}	125.3 ± 0.6	5.9	4.9

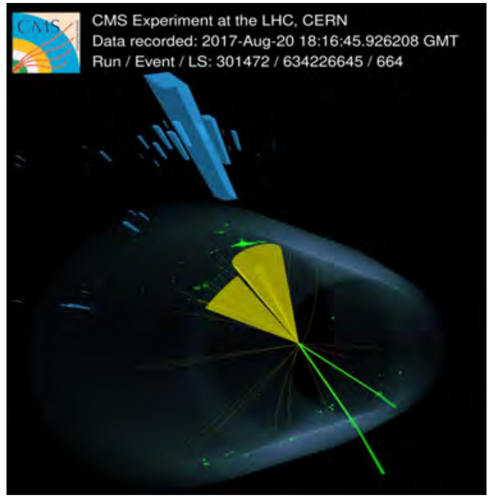
Higgs Portrait after 10 Years

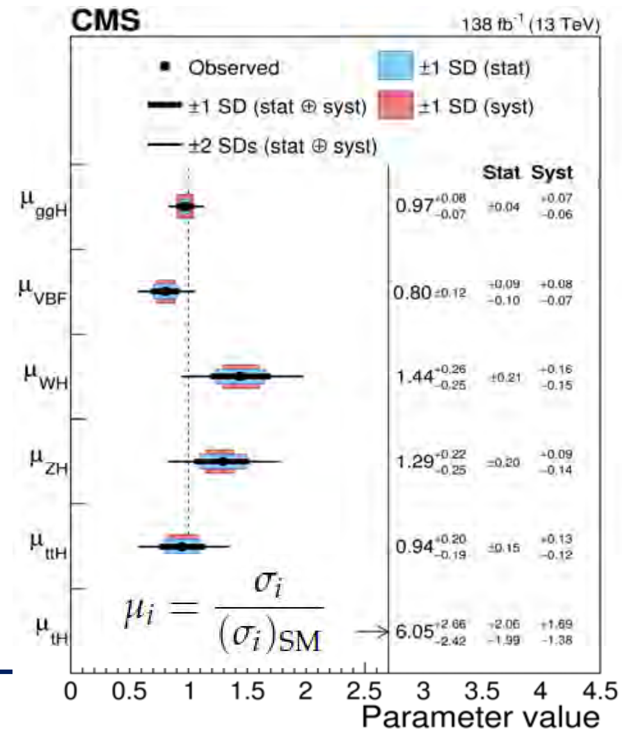
During Run 2 of the LHC the experimental collaborations started to employ the combined data for precision measurements of Higgs properties (mass, width, couplings, CP, rare decays)

- 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% (!)





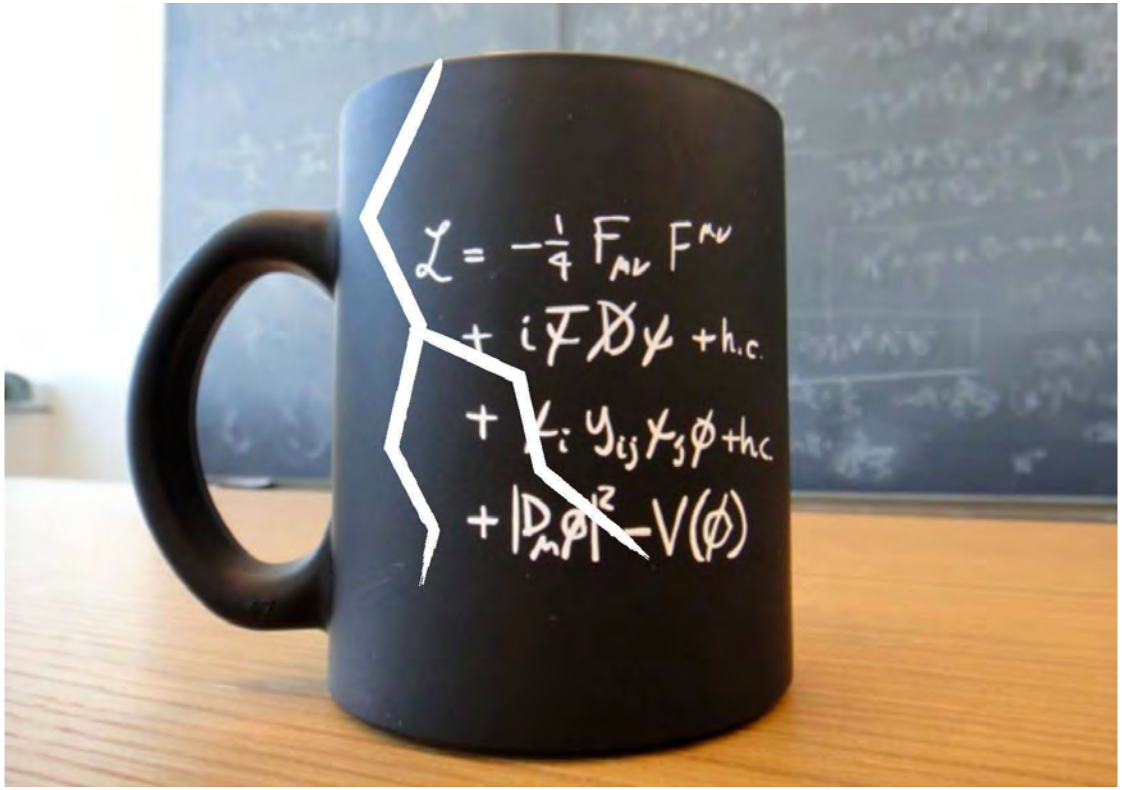




- Precisions of cross section and branching ratio measurements in combined channel are down to 8.5% level
- We have ~6-30% accuracy for measurements of couplings
- The absolute value of a width $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV is getting closer to the SM expectations (4.1 MeV). We still need to improve 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?

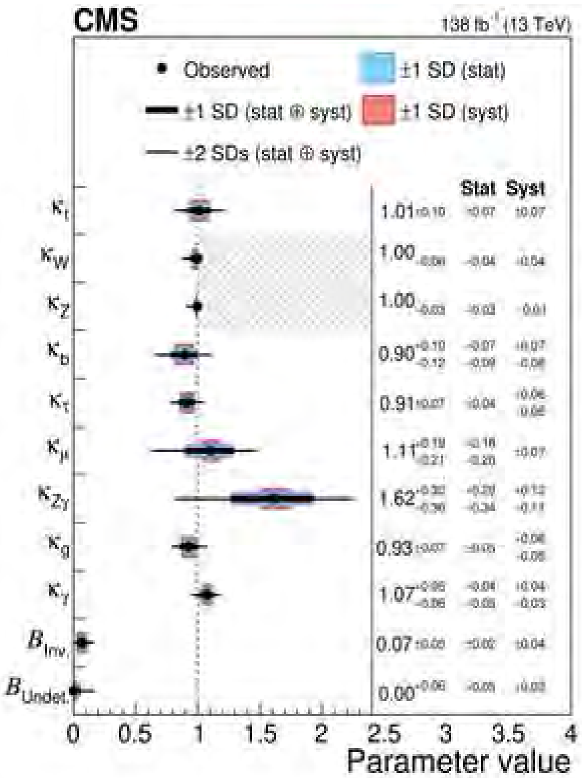


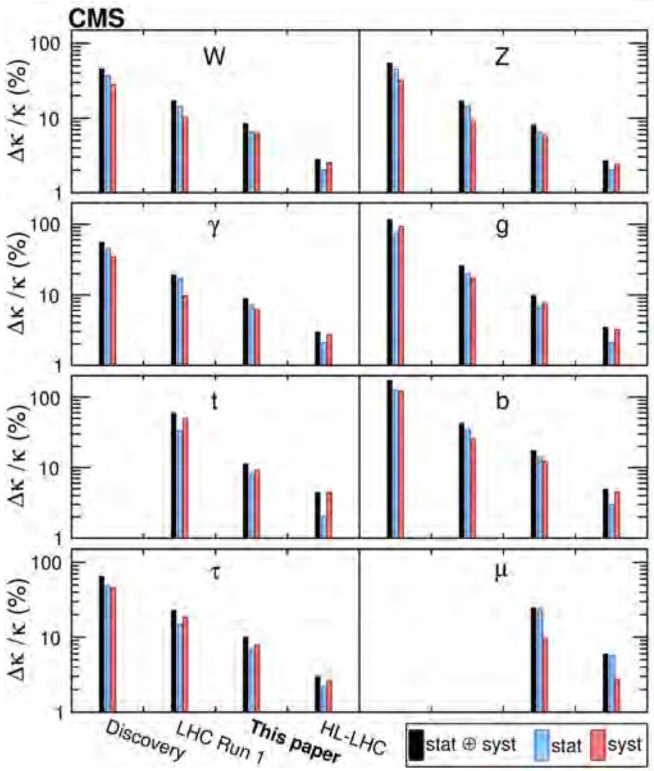
A room in Higgs Sector

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

EPJC 79 (2019) 421

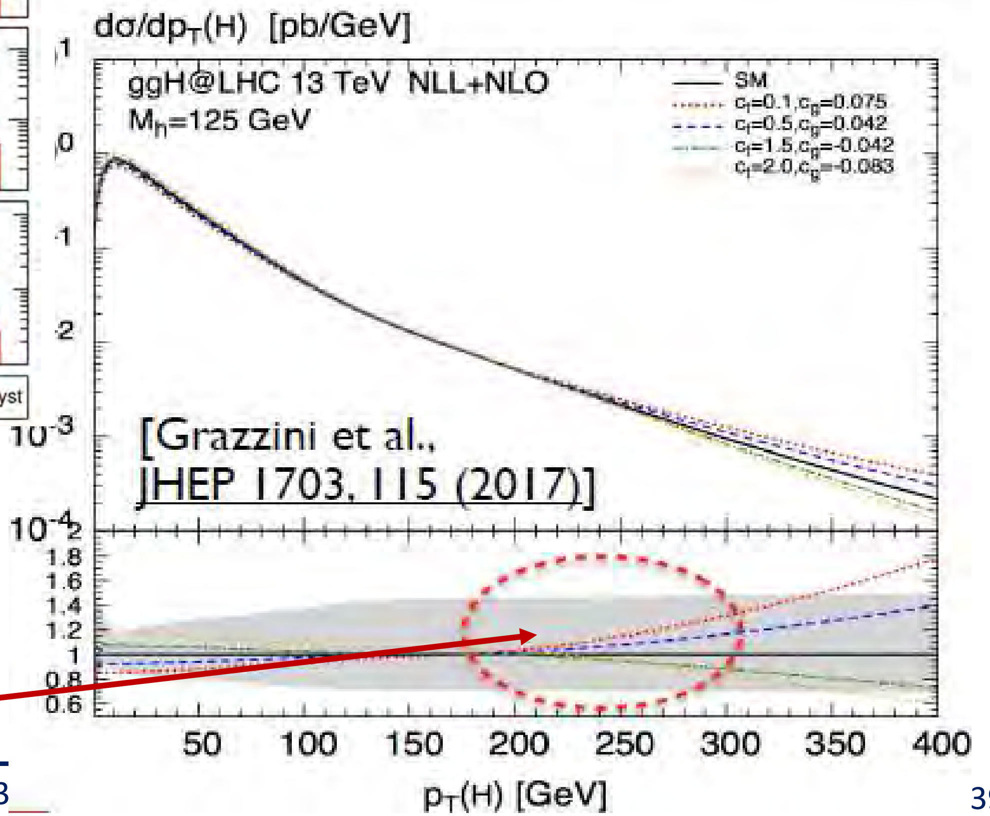
Summary of Higgs Couplings Measurements





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

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	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

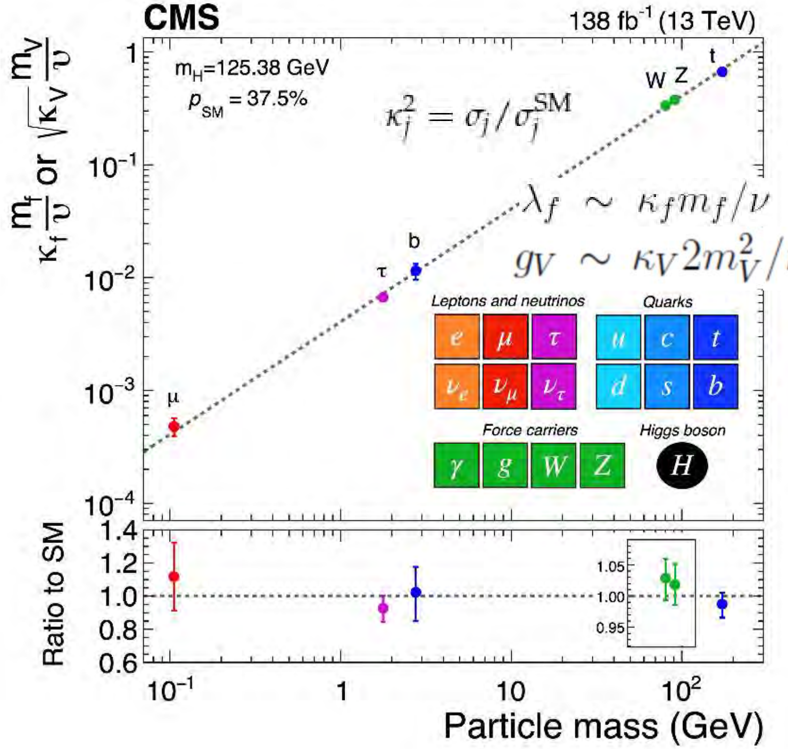


- Measurements precision continuous increasing
- Search for new higgs states and other BSM
  - ✓ BSM effects on in the differential distributions

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)



$$\kappa_j^2 = \sigma_j / \sigma_j^{SM}$$

$$\lambda_f \sim \kappa_f m_f / \nu$$

$$g_V \sim \kappa_V 2 m_V^2 / \nu$$

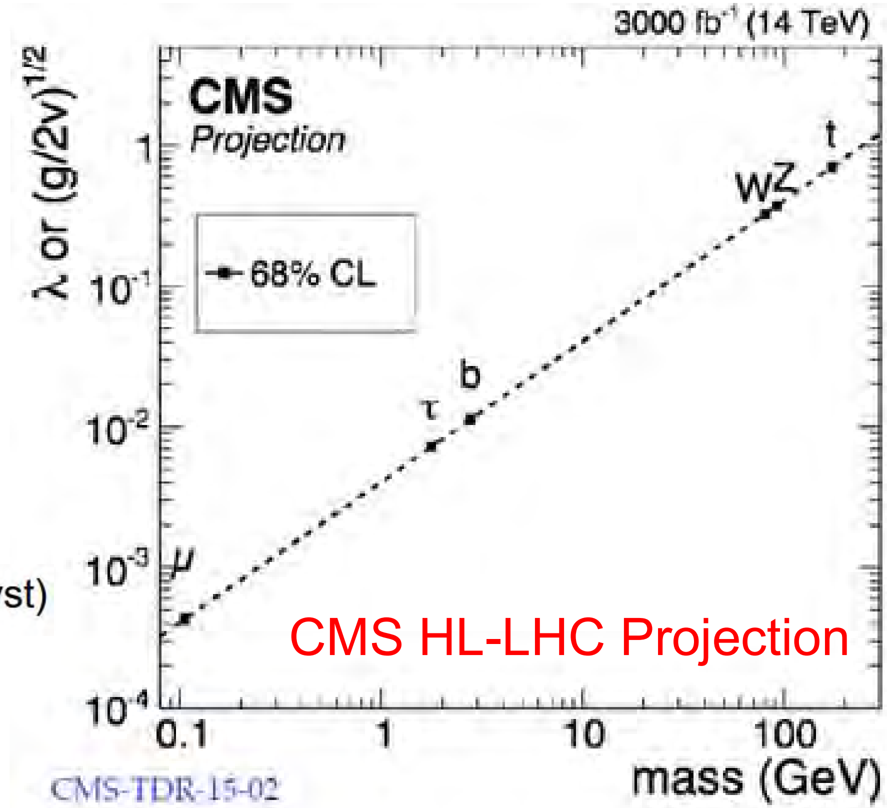
$$\mathcal{B}_{SM}(H \to e^+e^-) \approx 9 \cdot 10^{-9}$$

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

μμ: 3σ

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

JHEP 01 (2021) 148



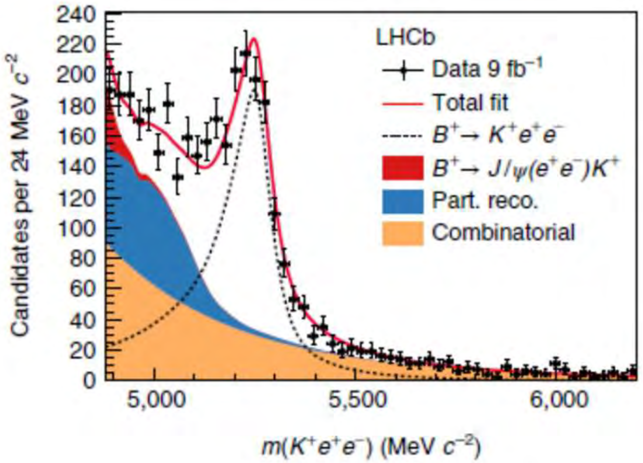
We do not know and will not know until the end of the LHC whether the coupling of the Higgs h_{125} to 1st generation fermions is in a “standard” way or not.

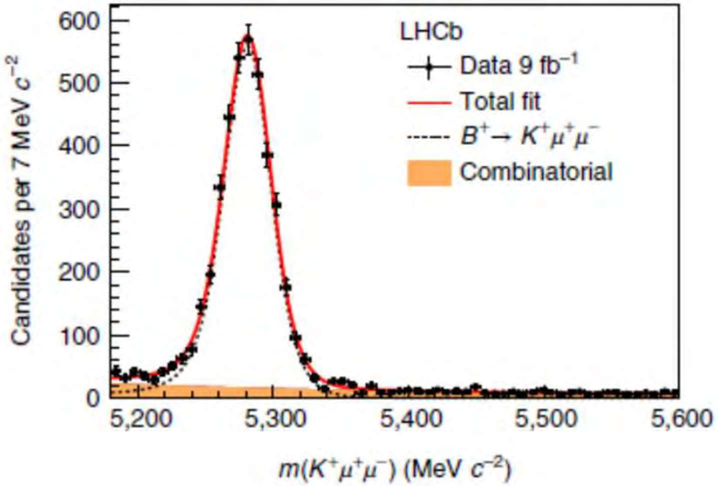
If we have no Extra Higgses! (rare decays are enhanced within Extended Higgs Sectors)

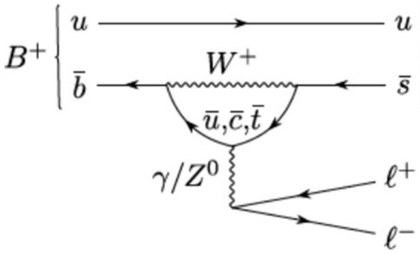
Lepton universality in beauty-quark decays

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

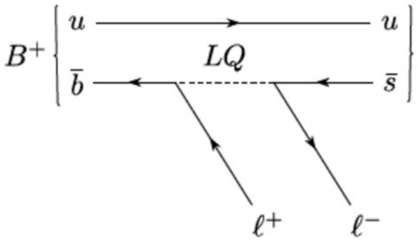
All QCD effects cancel in ratios.
Small $\mathcal{O}(1\%)$ radiative corrections.





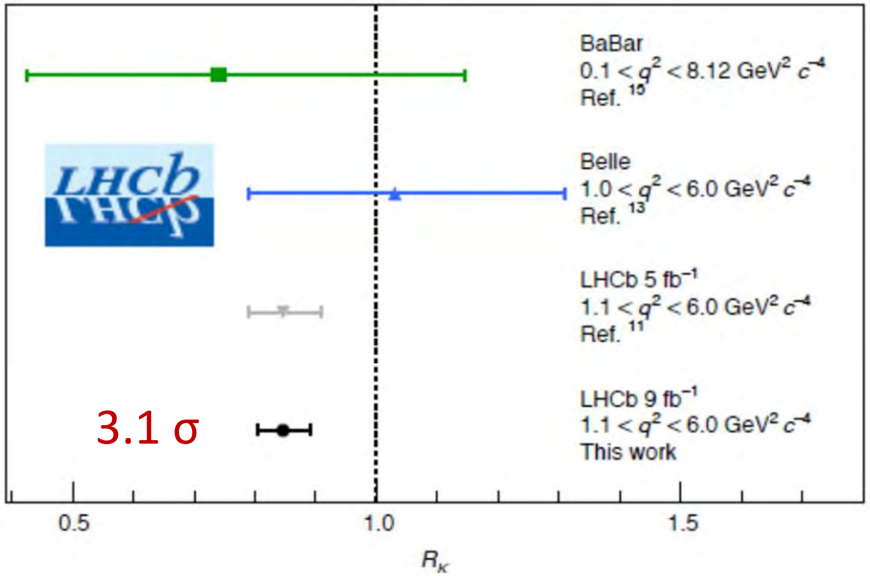


SM



NP

arXiv:2103.11769
Nature 18, 277 (2022)



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

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

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

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

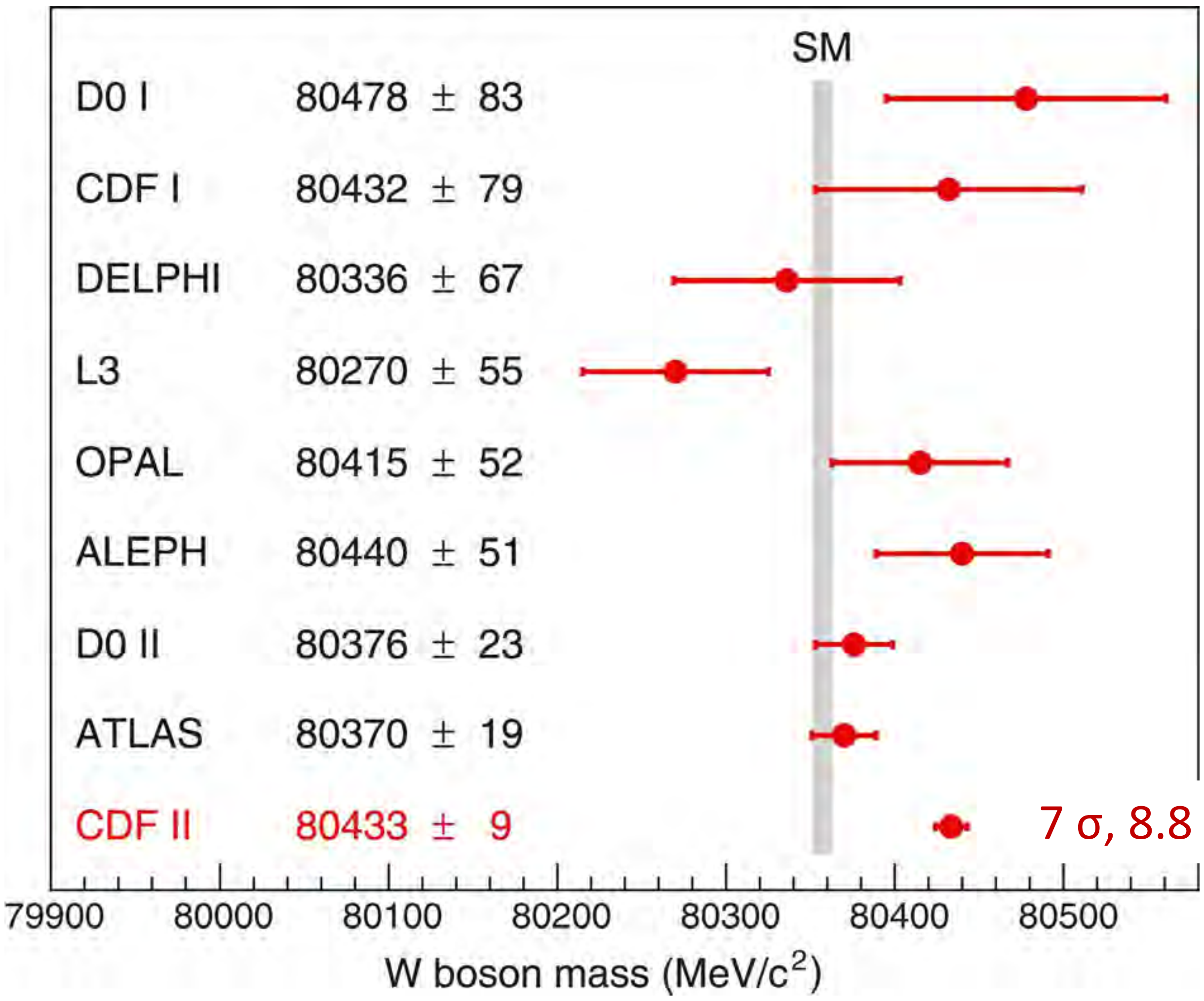
$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2\,c^{-4}) = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

Control uncertainties by measuring double ratios:

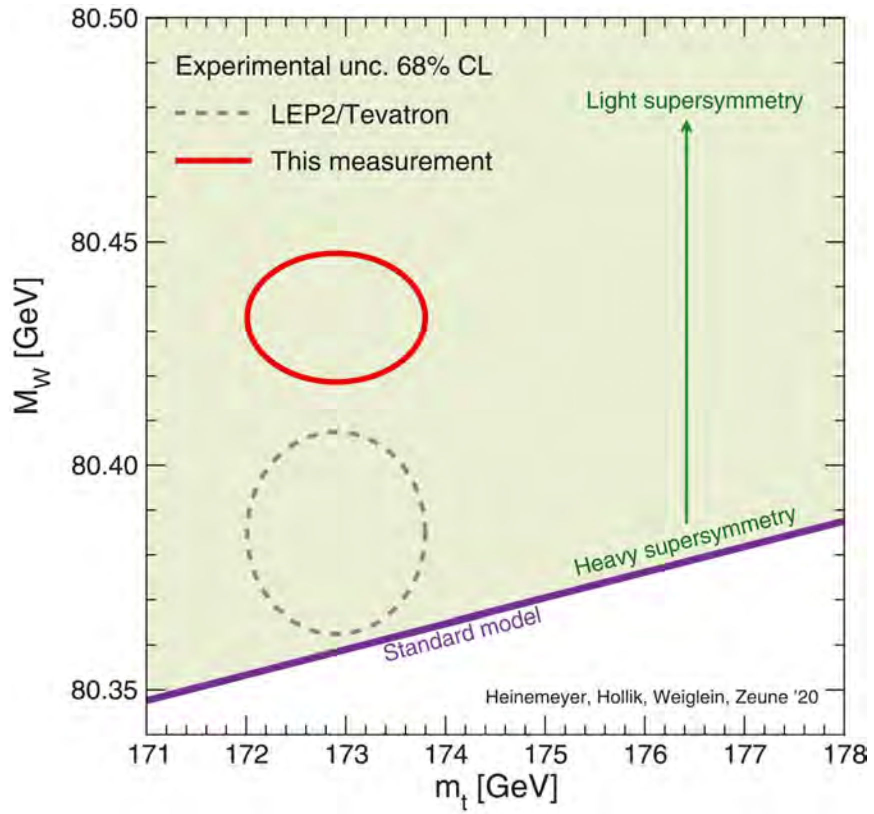
$$R_X \equiv \frac{\mathcal{B}\left(B \to X \mu\mu\right)}{\mathcal{B}\left(B \to X\, J/\psi\,(\to \mu\mu)\right)} \frac{\mathcal{B}\left(B \to X\, J/\psi\,(\to ee)\right)}{\mathcal{B}\left(B \to X ee\right)} = 1_{(SM)}$$

W boson mass with the CDF II detector

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



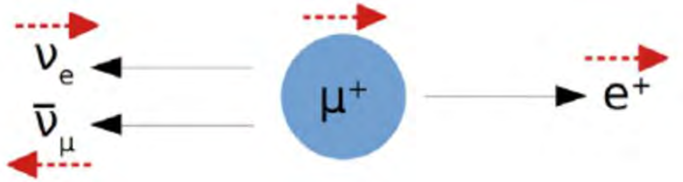
7 σ, 8.8 fb^{-1}

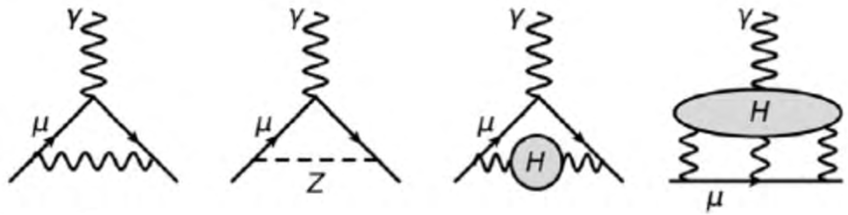


Science Vol 376, 170-176 (2022)

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

Fermilab Muon g – 2 Experiment





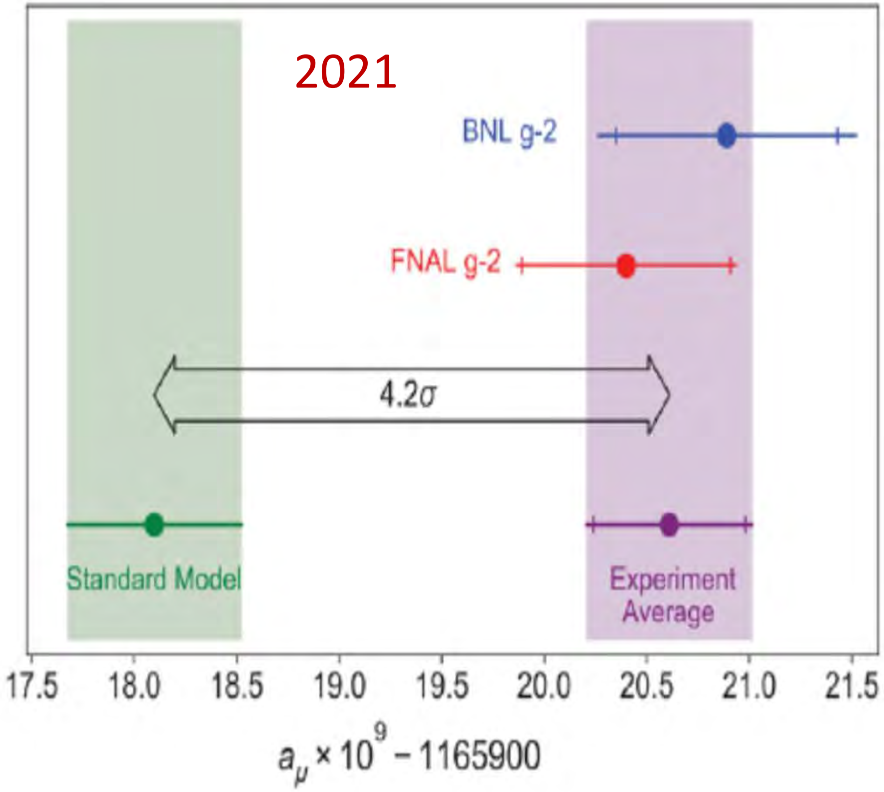
for J=1/2

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

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

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

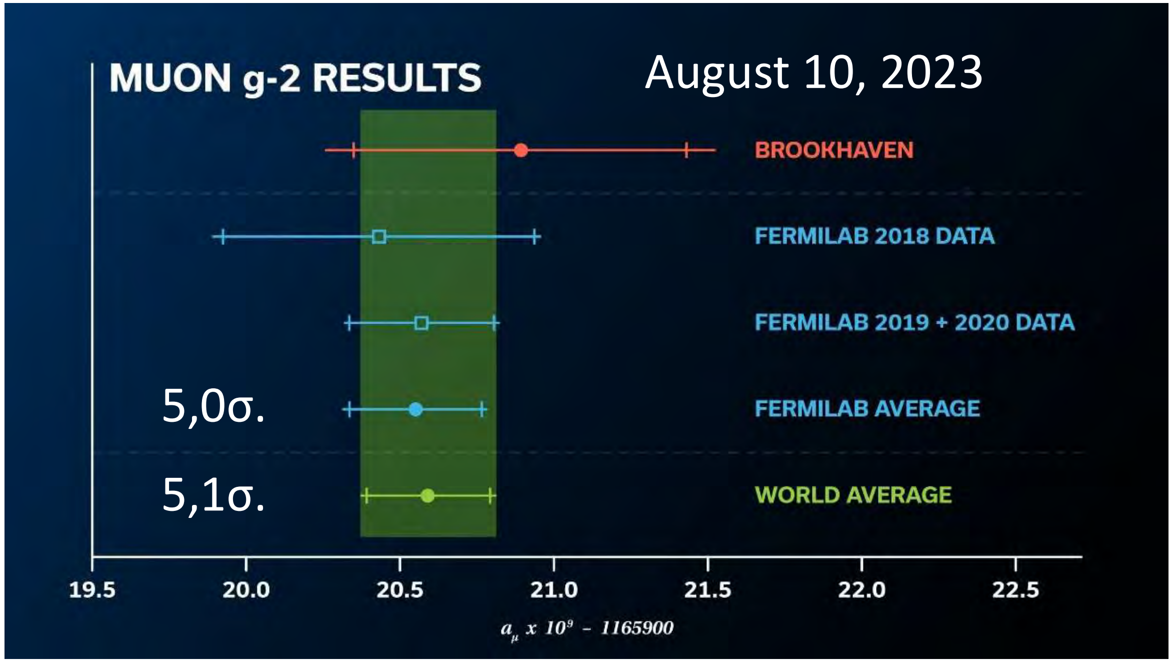
$$1{,}000{,}000 \ : \ 60 \ : \ 1.3 \ : \ \propto \left(m_\mu/m_X\right)^2$$



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

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

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



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

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

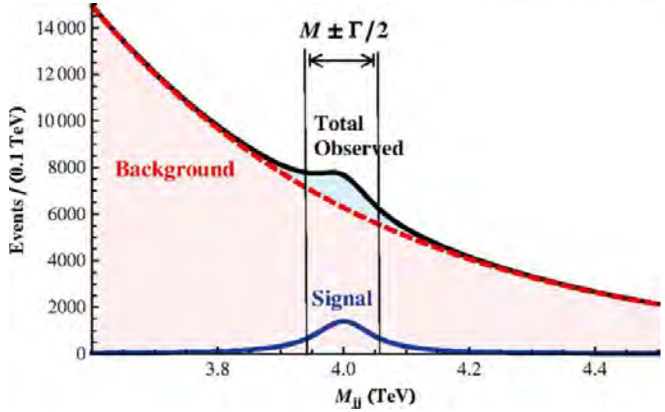
- BSM-Higgs Physics
  - ✓ Searches for the new Higgs states (from extended Higgs sector including SUSY)
  - ✓ Probes for the New Physics with h_{125} (Higgs as a tool for new discovery)

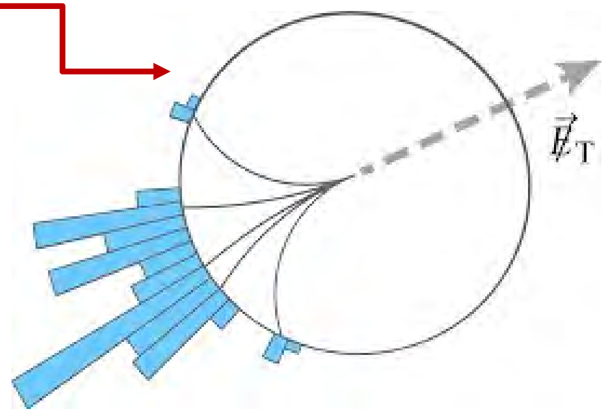
Extra Higgses, Dark Matter, Flavour Universality Violation

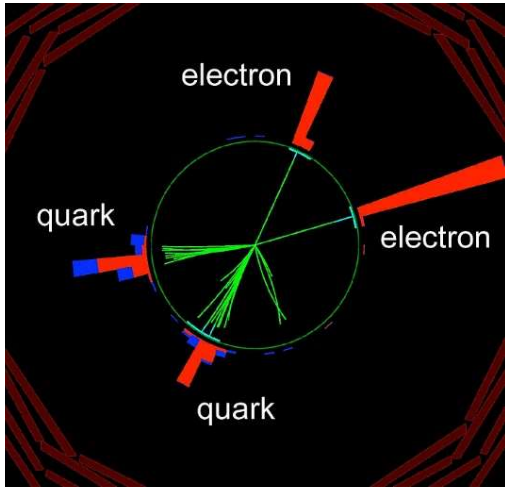
- Precision Tests of SM
  - ✓ Measurements of the W/Z, Drell-Yan (+ n jets) x-sections and angular characteristics
  - ✓ Search for rare decays of B-mesons
  - ✓ Observations of other rare process in top sector within SM (Wtb couplings, CP violating top quark couplings, flavor-changing neutral current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

Conventional Signals

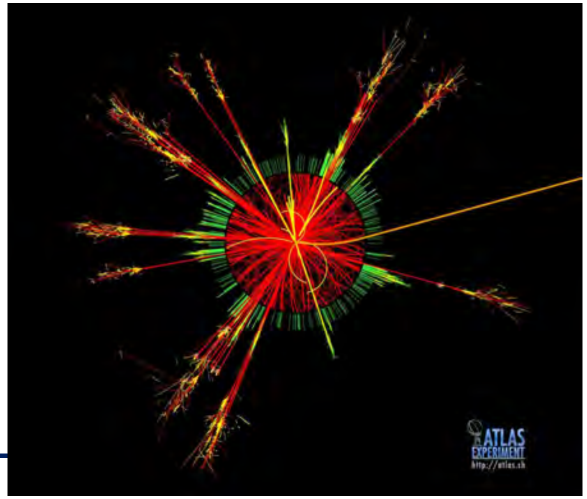
- Heavy Resonances (extended gauge models, extra dimensions, technicolor) ⇒ dileptons, dijets, diphotons, ttbar, WZ
- Non-Resonant Signals
- Mono-particle + Missing ET (extended gauge models, extra dimensions, technicolor, SUSY) ⇒ mono-jet + MET, mono-photon + MET, mono-lepton + MET
- Microscopic Black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



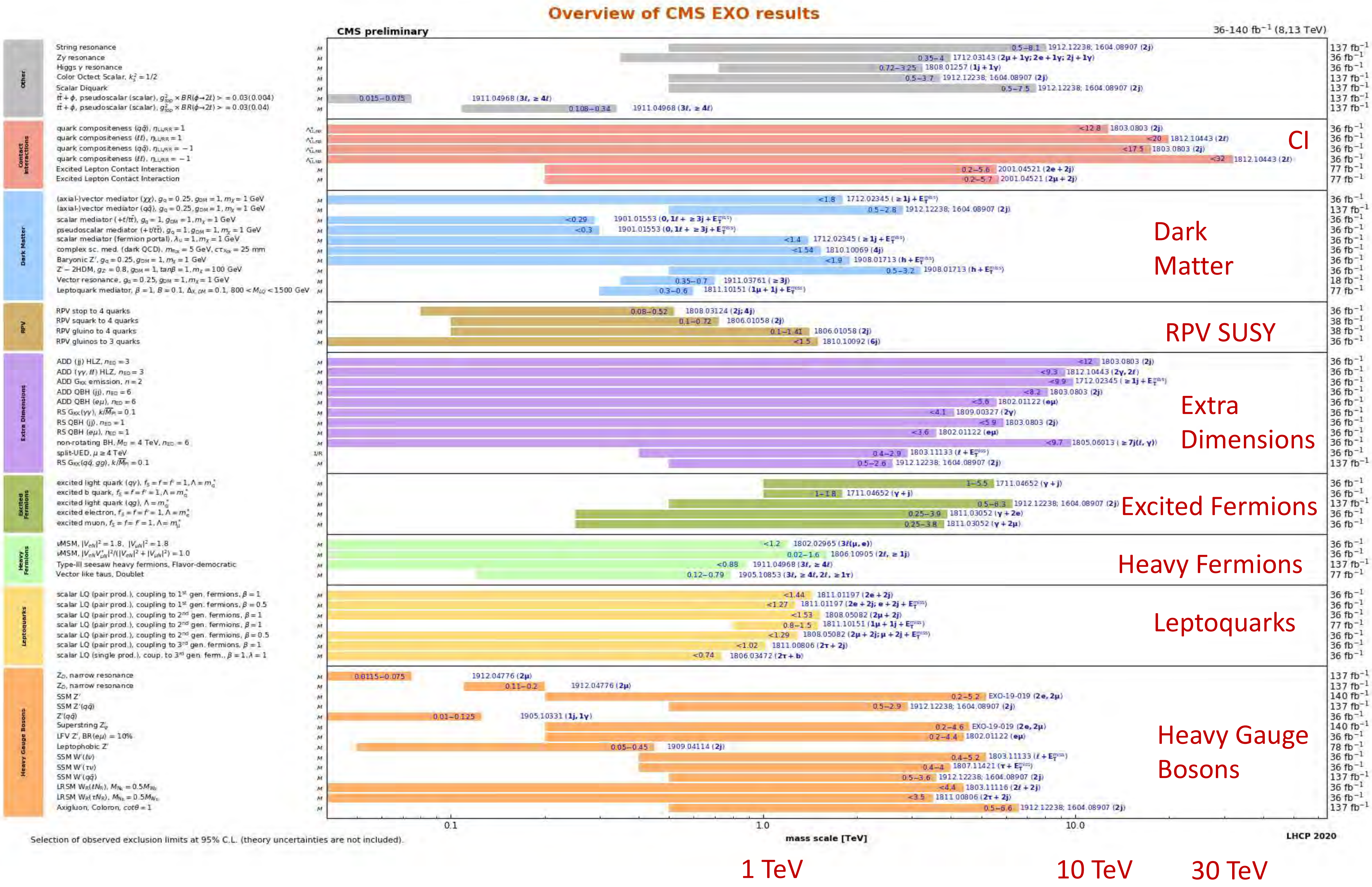




- Leptoquarks ⇒ lepton + jet
- 4th Generation ⇒ leptons/jets, dilepton



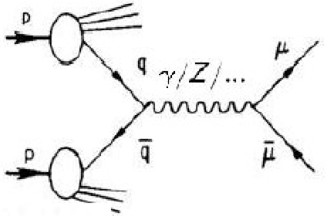
Direct Search for BSM: Conventional Signals



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

Searches for Heavy Resonances

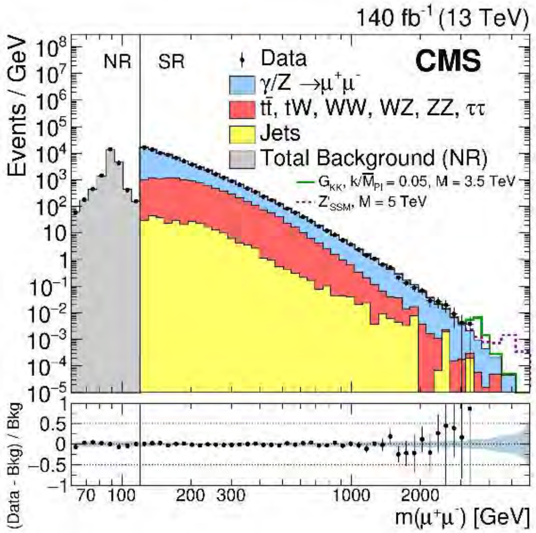
New Physics ($Z'/Z_{KK}/G_{KK}$) contributions to SM processes

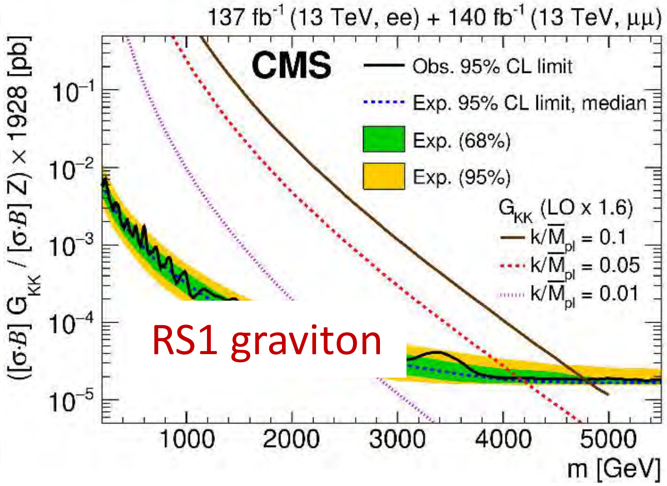


$$R_\sigma = \frac{\sigma(pp \to Z' + X \to l^+l^- + X)}{\sigma(pp \to Z^0 + X \to l^+l^- + X)}$$

Dileptons, full RUN2 data

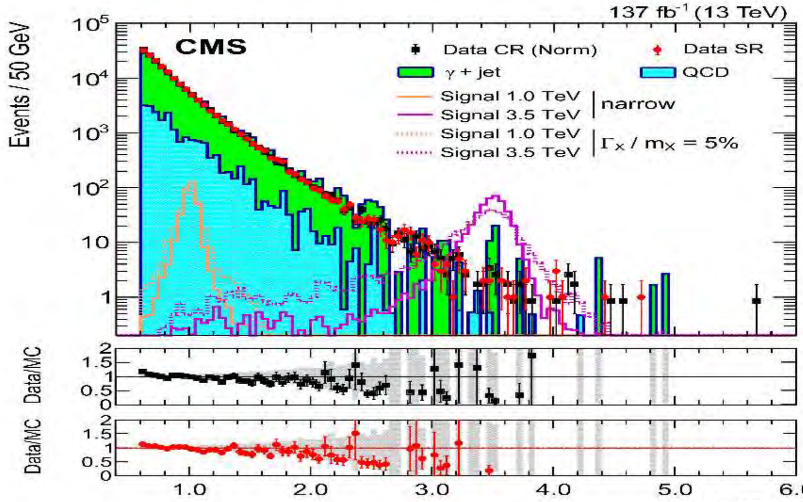
JHEP 07 (2021) 208

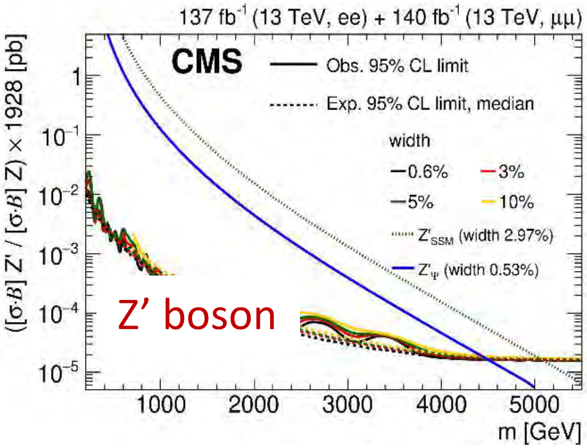


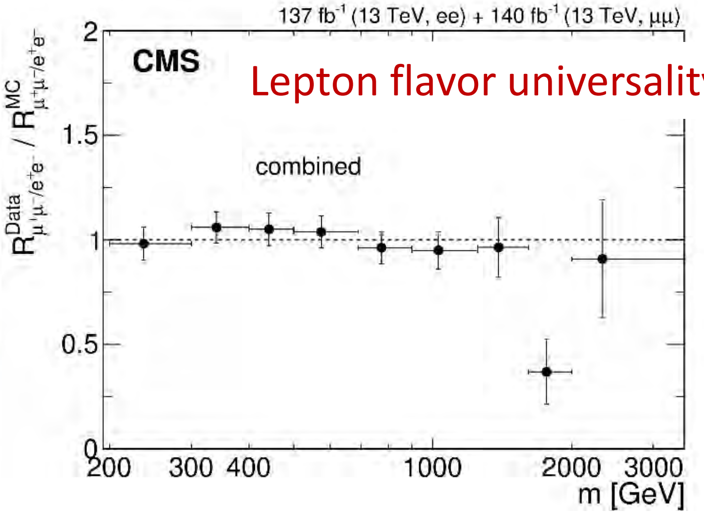


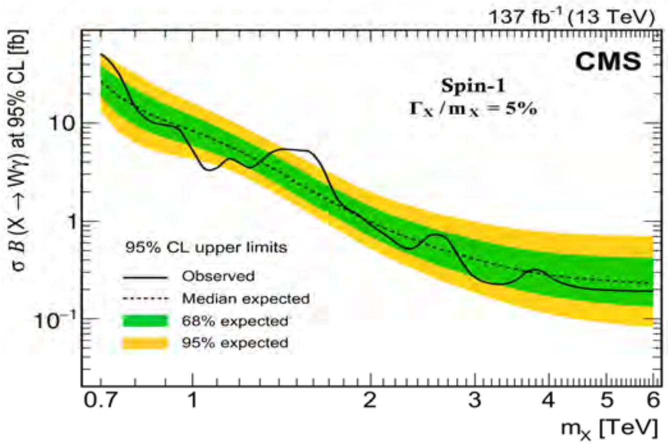
Wγ, full RUN2 data

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

What does Brazilian Flag mean?

Dimuon example

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

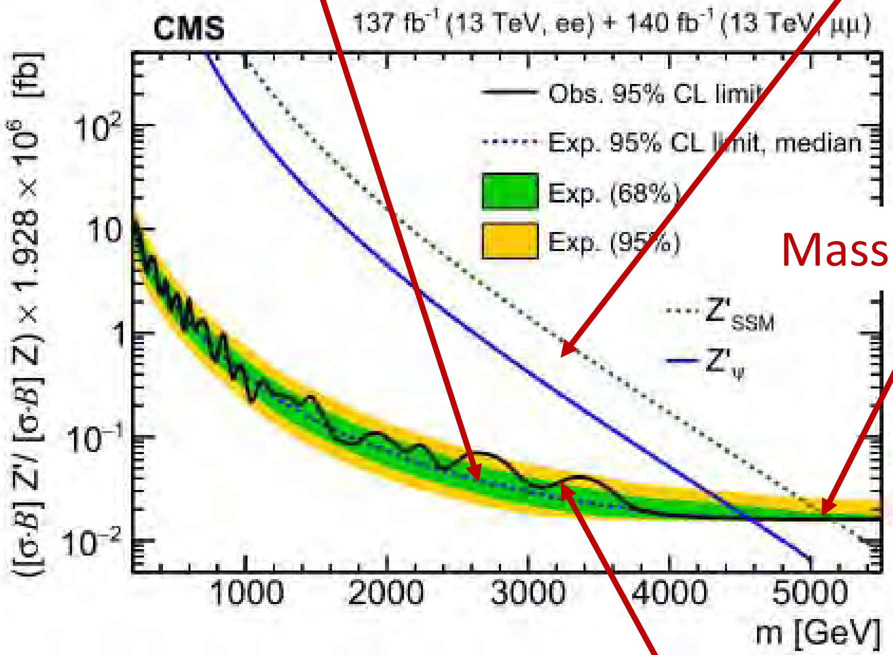
Extended gauge models

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

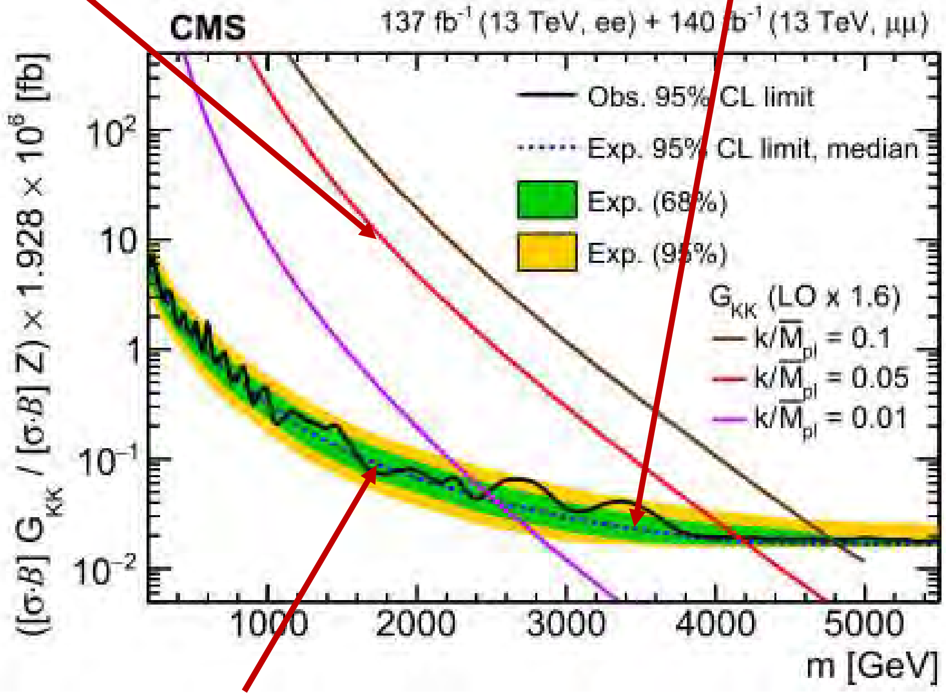
SM predictions

BSM predictions

SM predictions



Mass limit



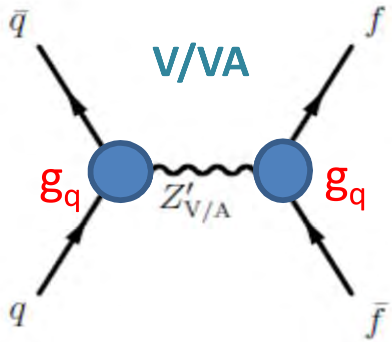
Model-independent limits on cross section (in narrow width approximation, NWA)

Channel	Z'_{SSM} Obs. [TeV]	Z'_{SSM} Exp. [TeV]	Z'_{ψ} Obs. [TeV]	Z'_{ψ} 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	$k/\overline{M}_{Pl} = 0.01$ Obs. [TeV]	$k/\overline{M}_{Pl} = 0.01$ Exp. [TeV]	$k/\overline{M}_{Pl} = 0.05$ Obs. [TeV]	$k/\overline{M}_{Pl} = 0.05$ Exp. [TeV]	$k/\overline{M}_{Pl} = 0.1$ Obs. [TeV]	$k/\overline{M}_{Pl} = 0.1$ 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

Example of Dark Matter Searches in Dijets + Dileptons

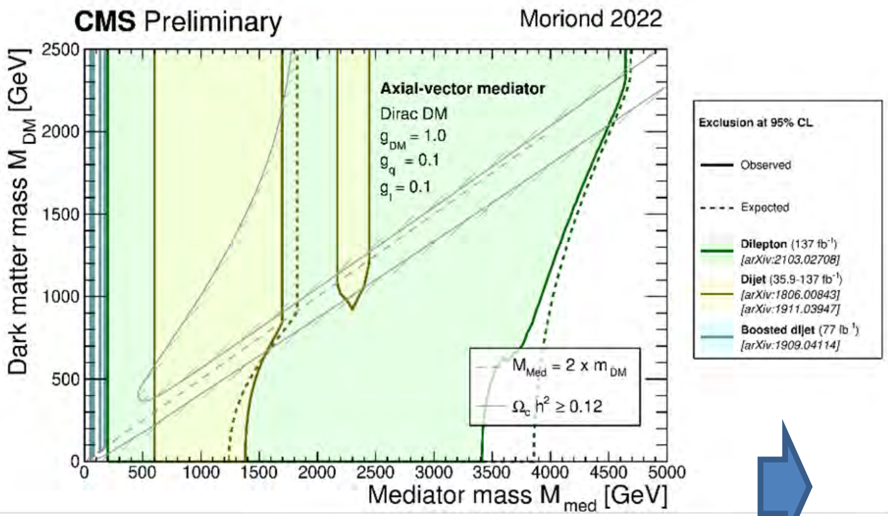
We consider a model that assumes the existence of a single DM particle that interacts with the SM particles through a spin-1 mediator, which can be either a vector or axial-vector boson.

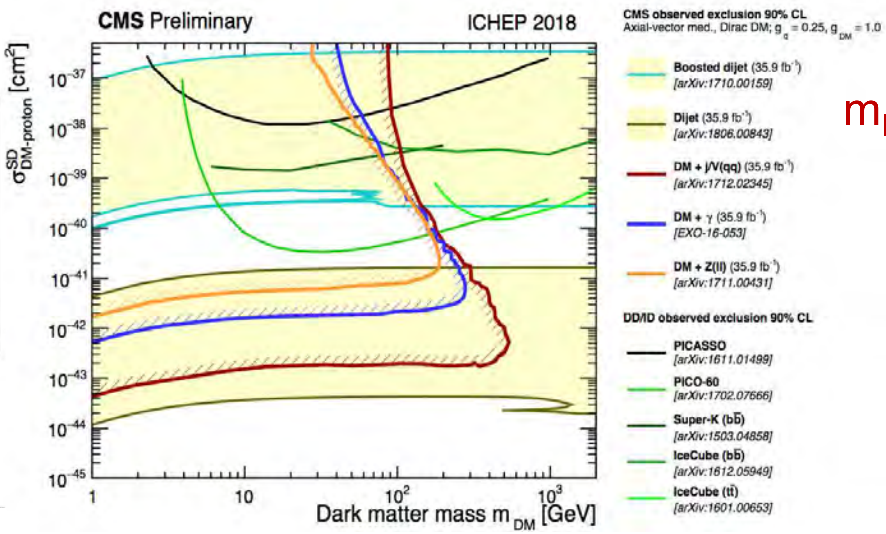


- vector mediator with small couplings to leptons, $g_{DM} = 1.0$, $g_q = 0.1$, $g_l = 0.01$
- axial-vector mediator with equal couplings to quark and leptons: $g_{DM} = 1.0$, $g_q = g_l = 0.1$

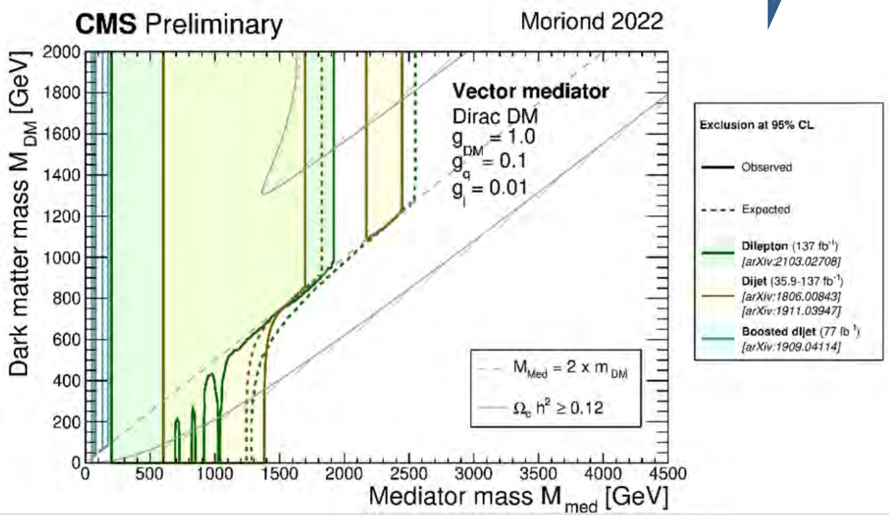
5 parameters:

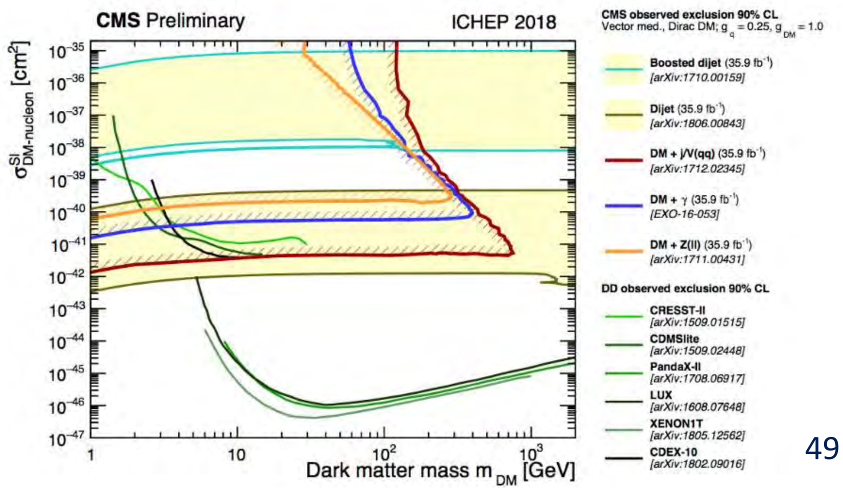
m_{DM}, m_{Med}, g_{DM}, g_l, g_q





DM-nucleon upper limits on the cross section

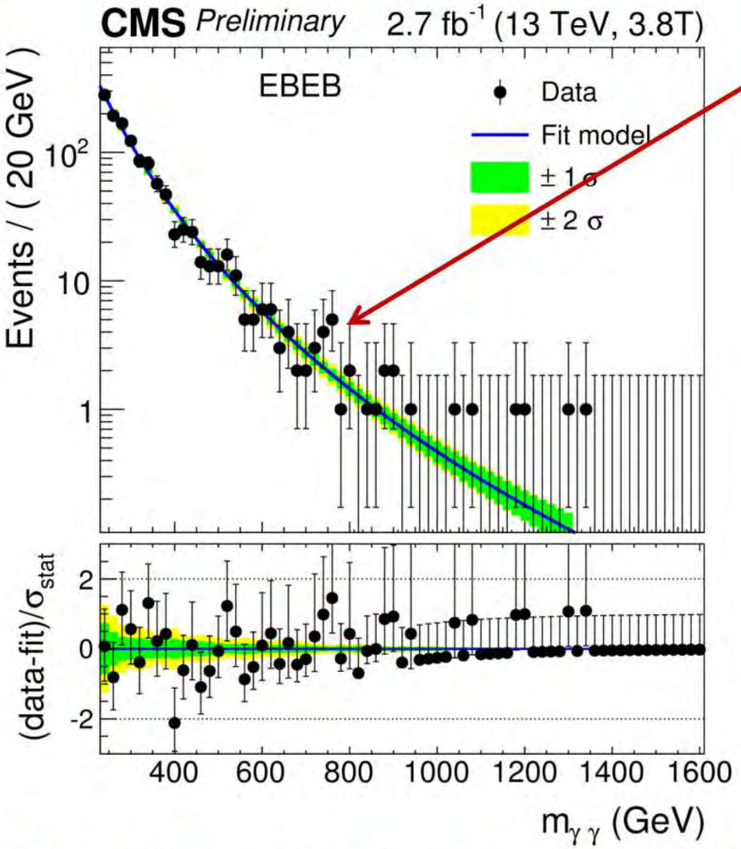




The case of the past days ($\gamma\,\gamma$ excess in LHC data)

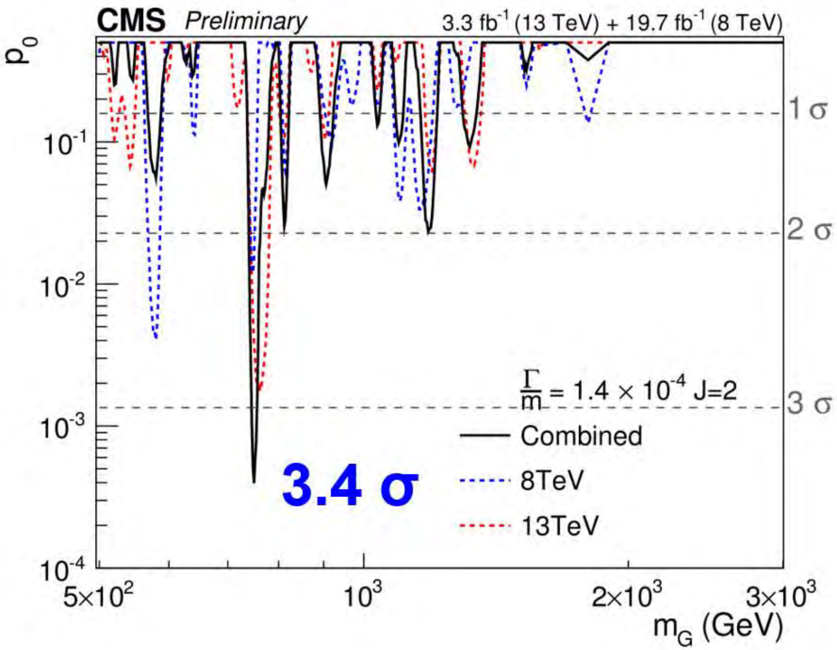
First intrigue @ 13 TeV: Excess in Diphotons

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:

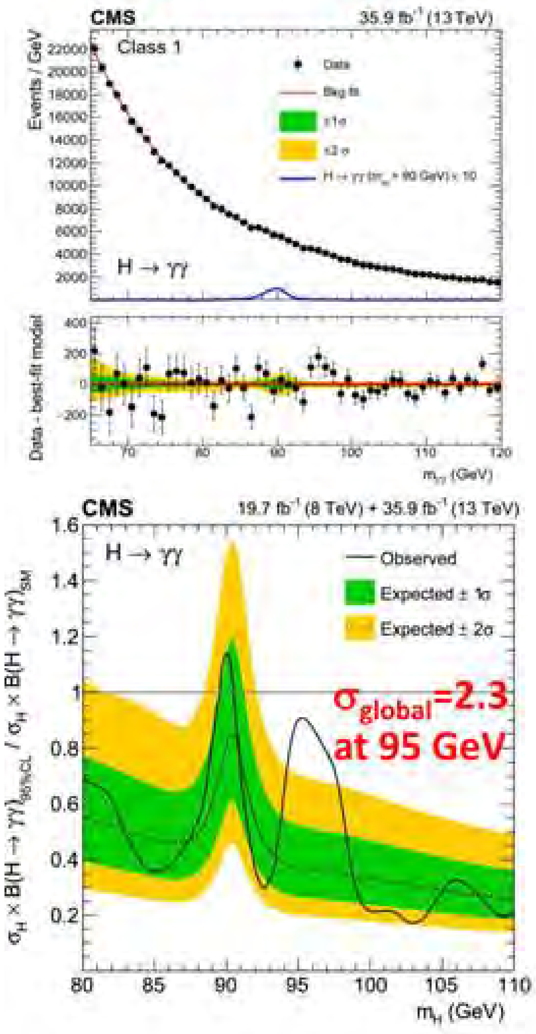


A lot of theoretical works attempt to explain this effect:
more 320 papers since Dec. 2015

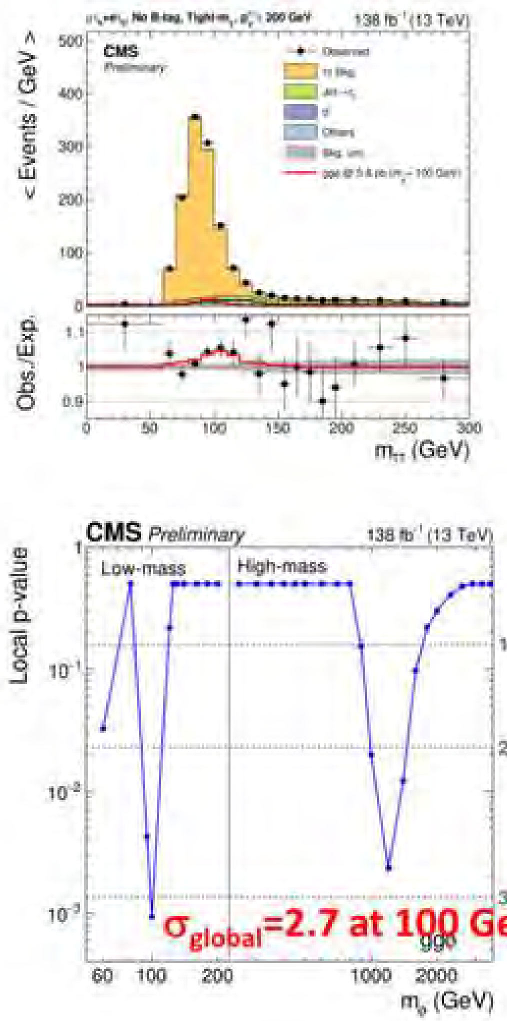
Need more data!

Some Selected Recent Excitements from LHC

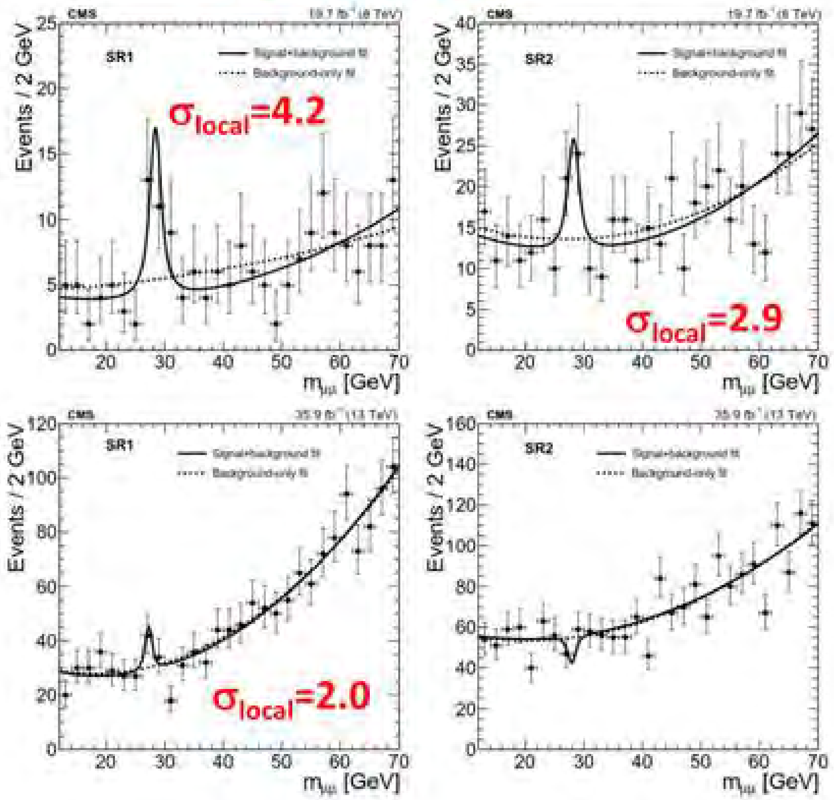
- **Light X→γγ**



- **Light X→ττ**



- **Light X→μμ**

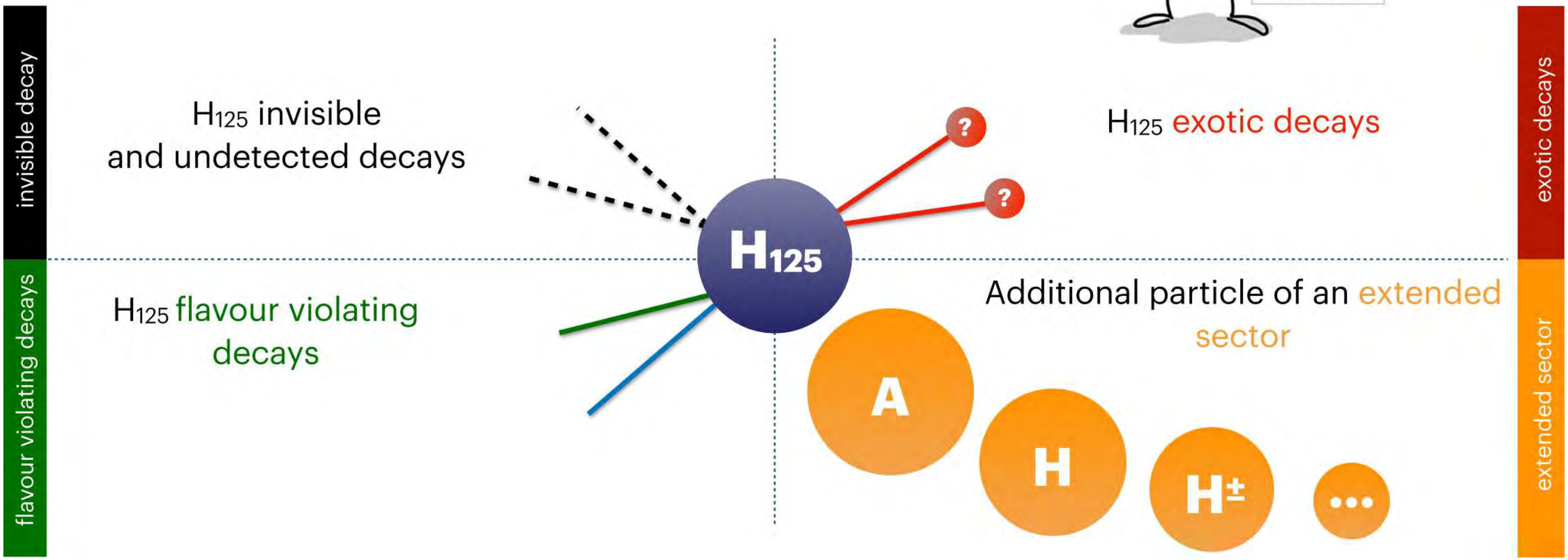


A. Nikitenko

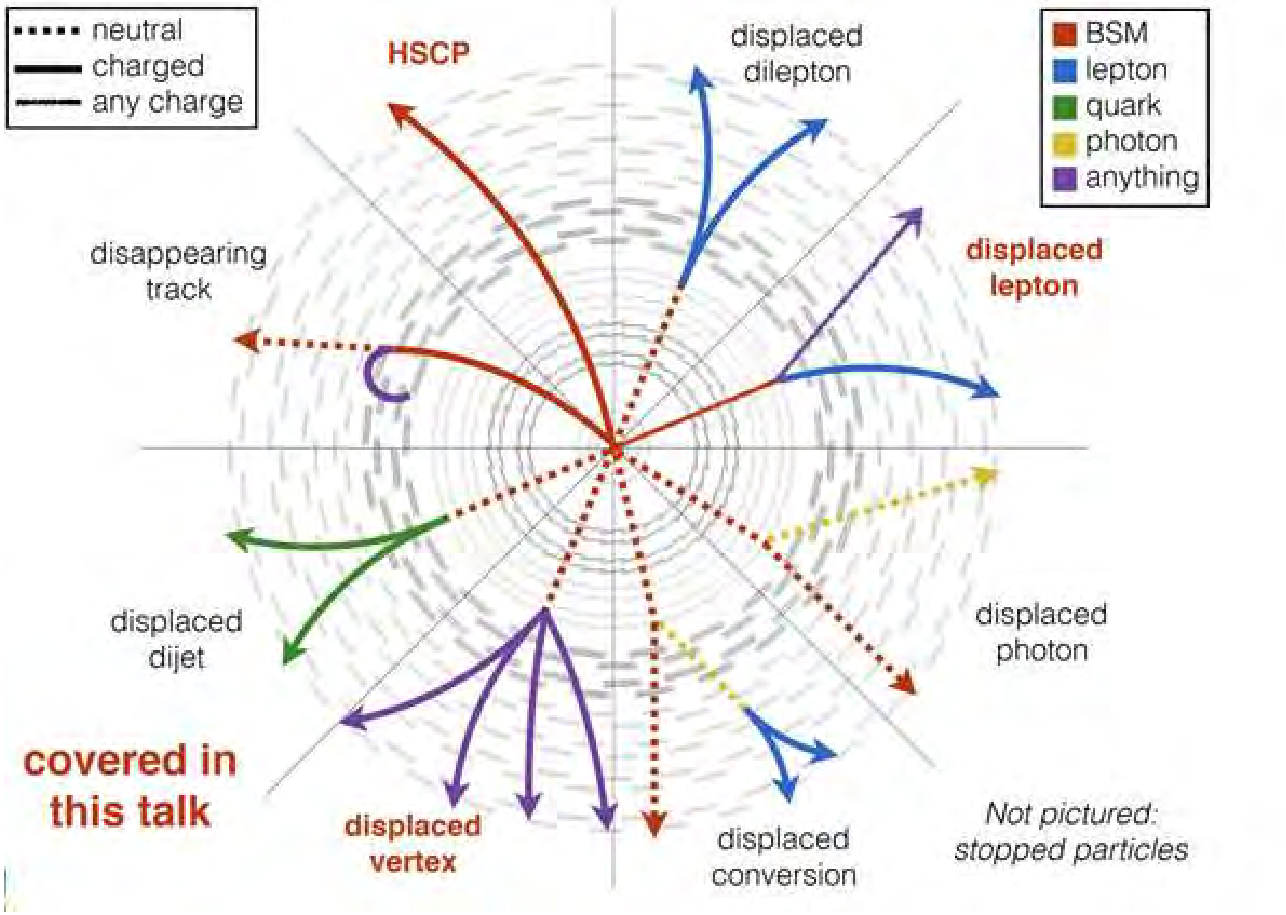
The Physics of the Dimuons at the LHC
Dubna, Russia, 23-24 June, 2022

RUN3 is a perfect judge for these challenges!

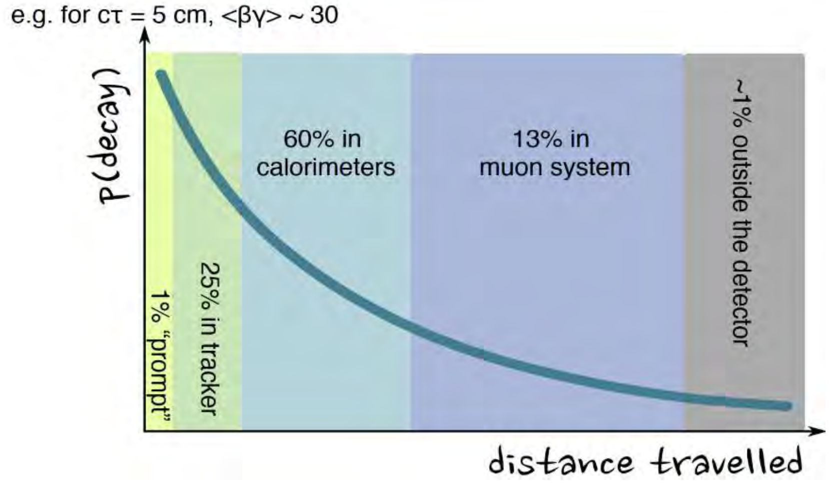
Higgs Boson as a Tool to Search for the New Physics



Direct Search for BSM: LLP Non-conventional Signals



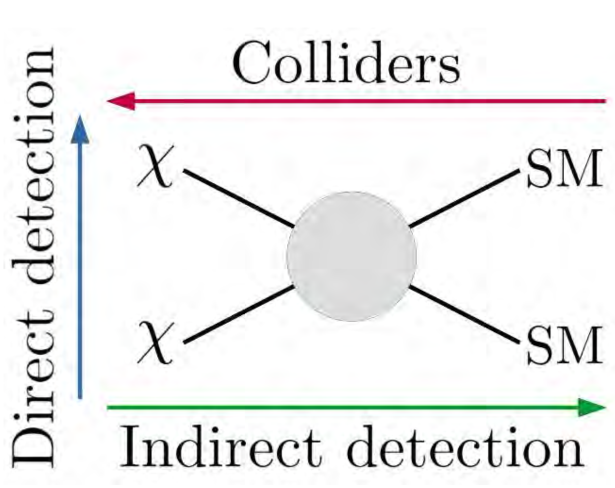
LLPs may have decay lengths up to several meters, hence traveling through the inner detector layers without leaving any trace

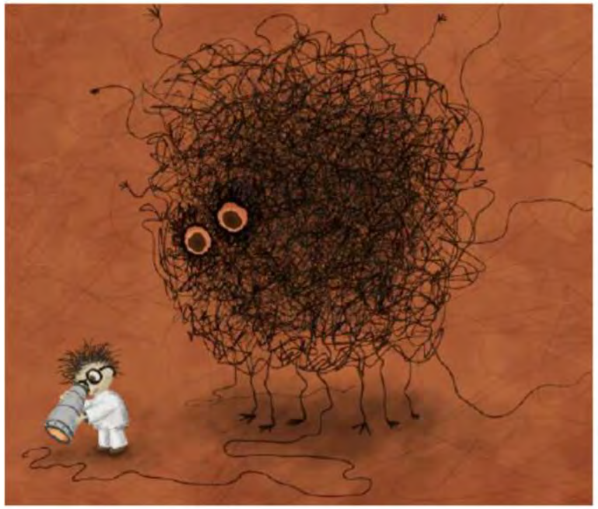


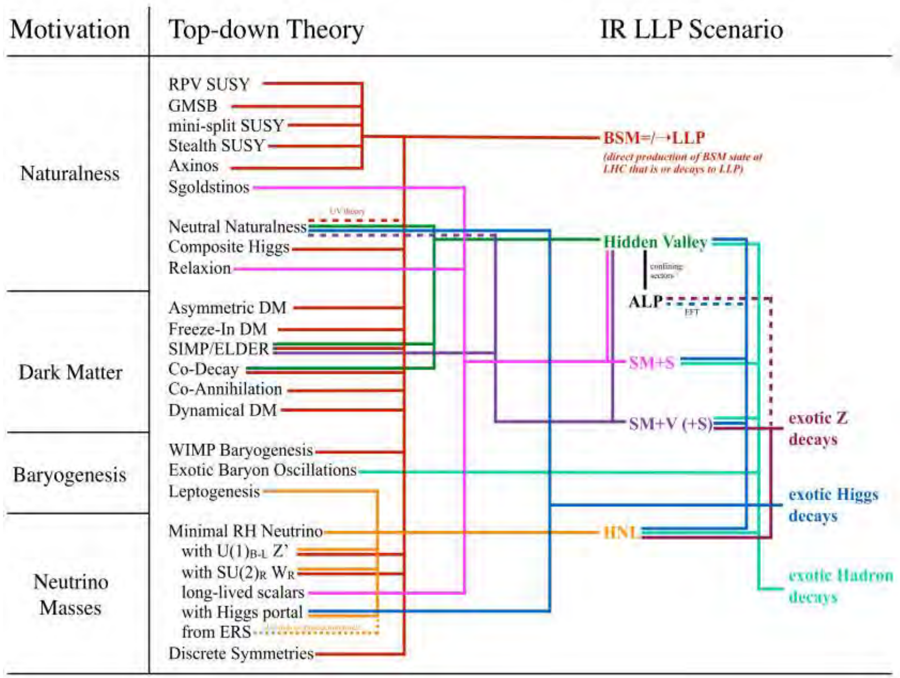
- a proper lifetime $c\tau_0$ is greater than or comparable to the characteristic size of the (sub)detectors
- small $c\tau_0$ that comparable to the inner tracker size, no displaced tracks → "standard" prompt decay
- intermediate $c\tau_0$ → LLP
- very large/infinite large $c\tau_0$ → stable particles,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

Inelastic Dark Matter at the LHC/LLP

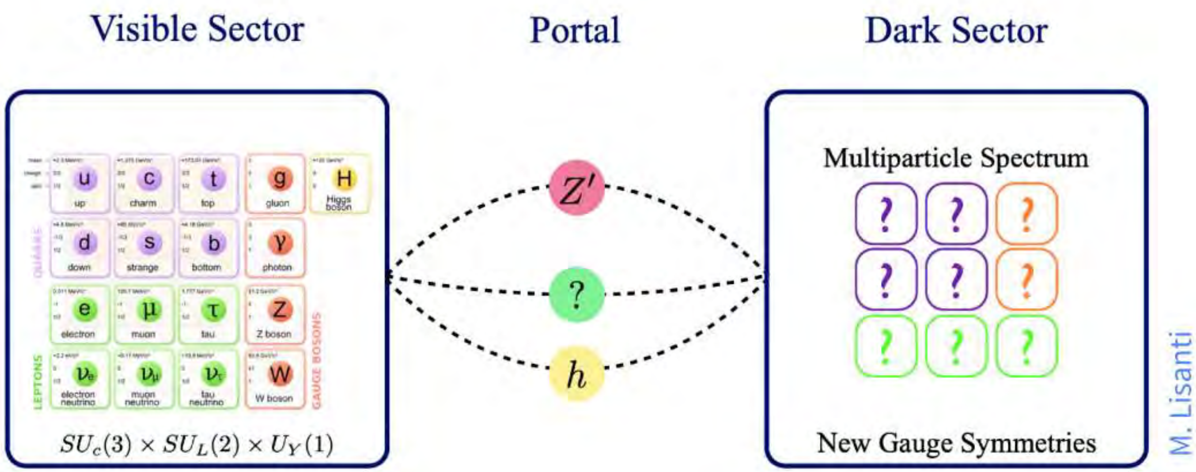
- inelastic dark matter: relic particles that cannot scatter elastically off of nuclei the dark sector
- particles continue traveling for a long time and traverse several meters (Long-Lived Particles) before tunneling back into our visible universe (quarks or leptons)





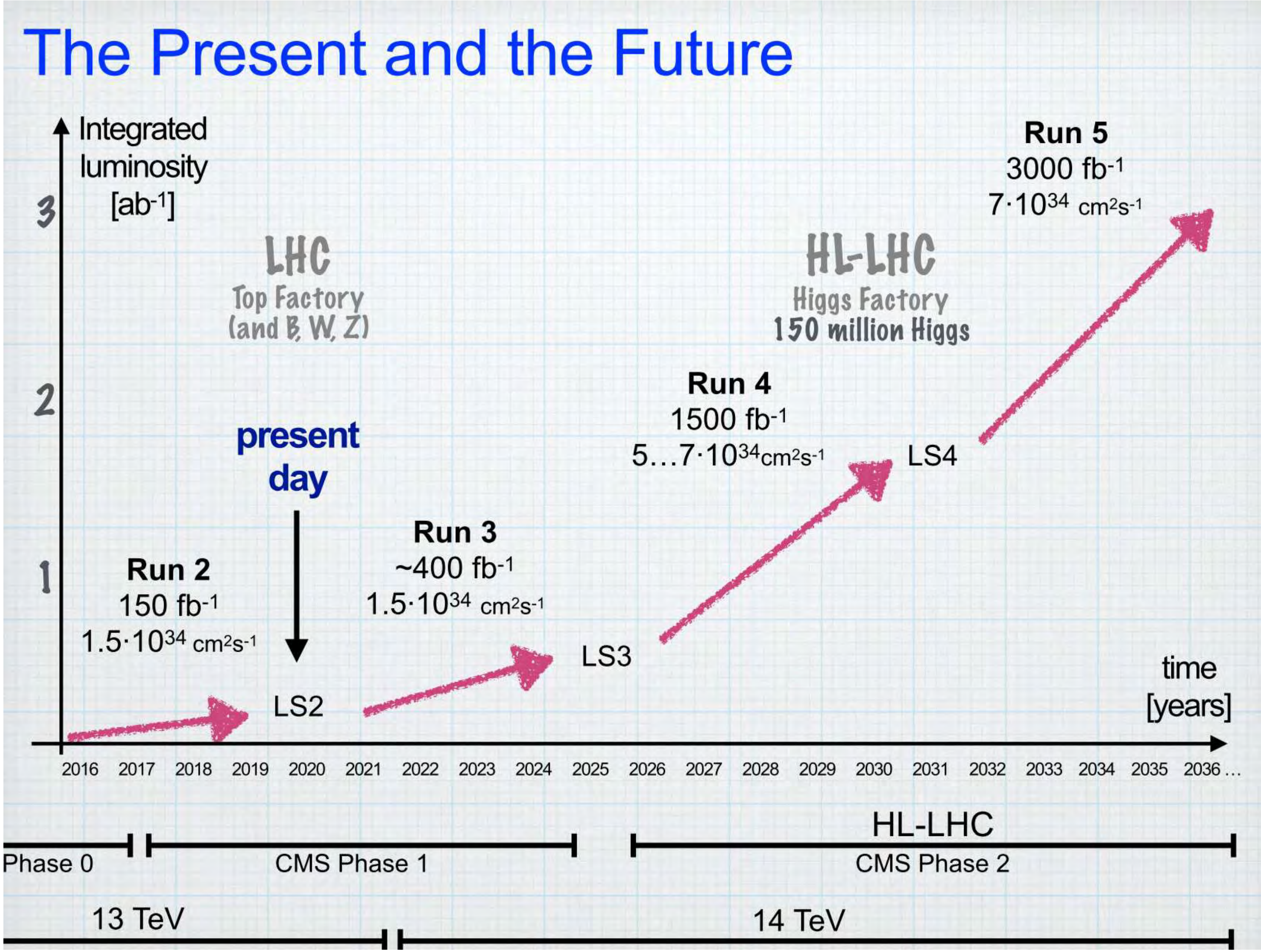


https://arxiv.org/abs/1901.04040



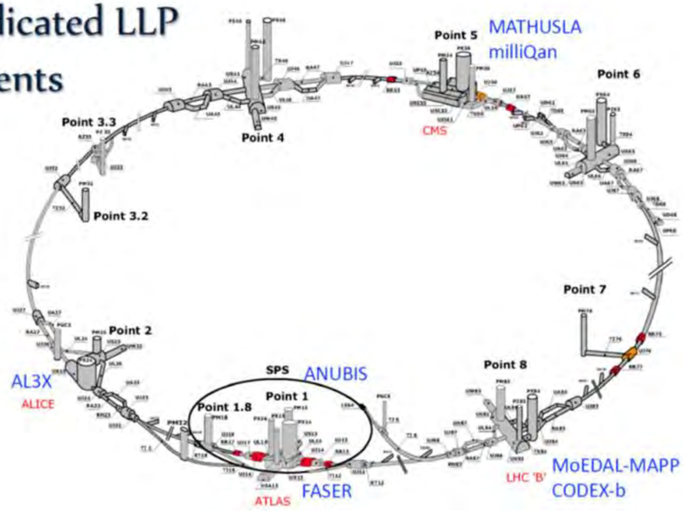
LHC Prospects and beyond

LHC/High-Luminosity Timescale



LHC Satellite Experiments

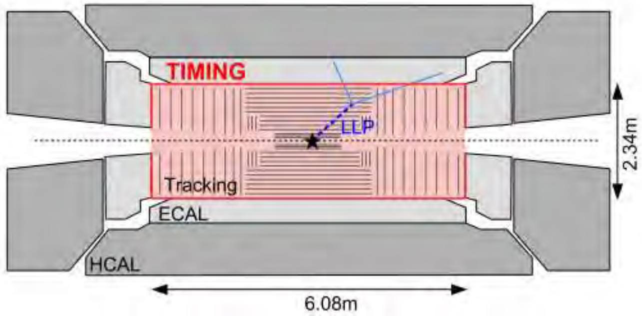
LHC dedicated LLP experiments



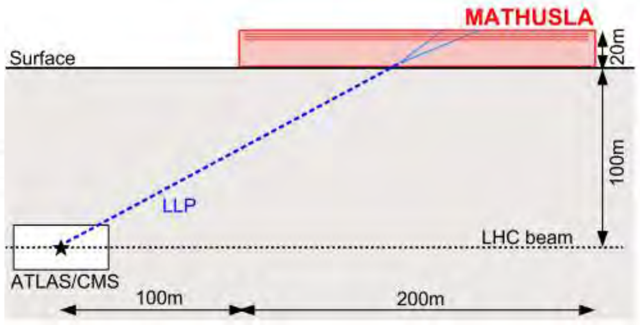
Phys. Rev. D 99 (2019) 015021

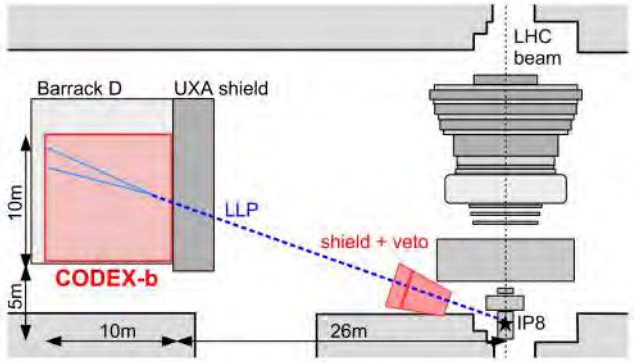
https://arxiv.org/abs/1901.04040

CMS/ATLAS

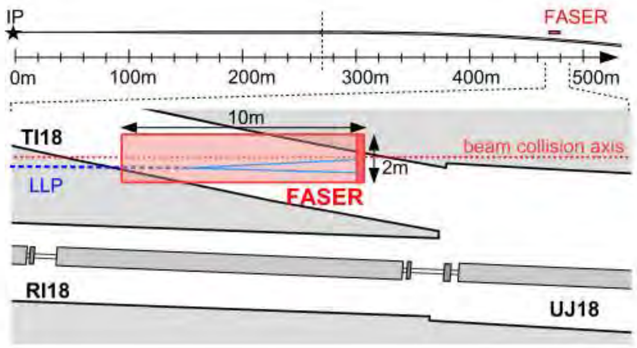


CMS

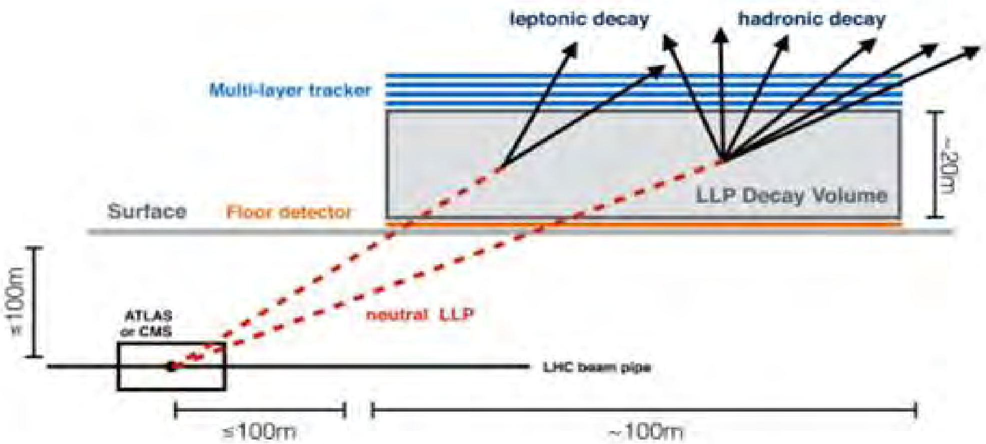


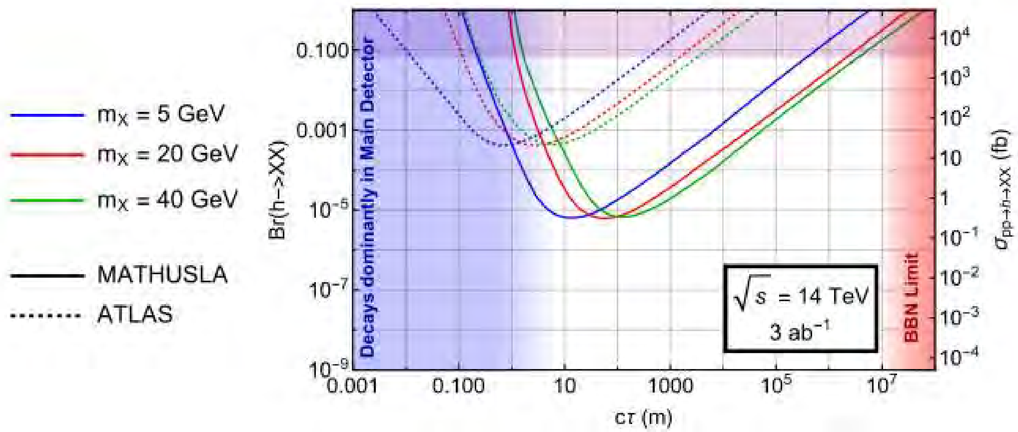


LHCb



ATLAS





Future Circular Colliders (100 TeV pp)

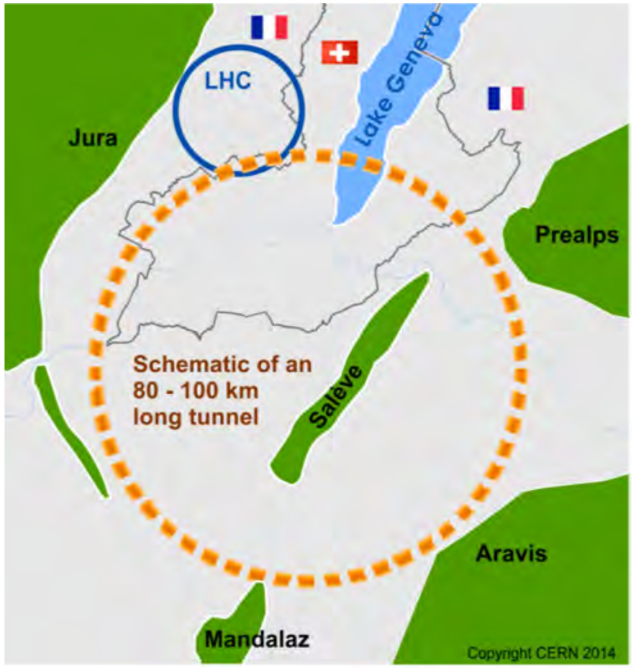
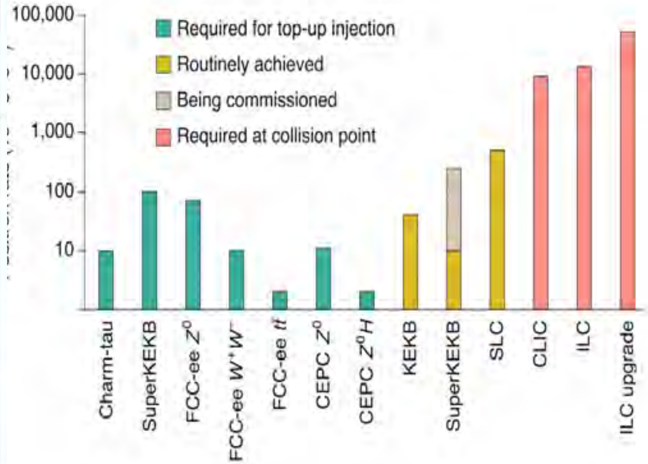
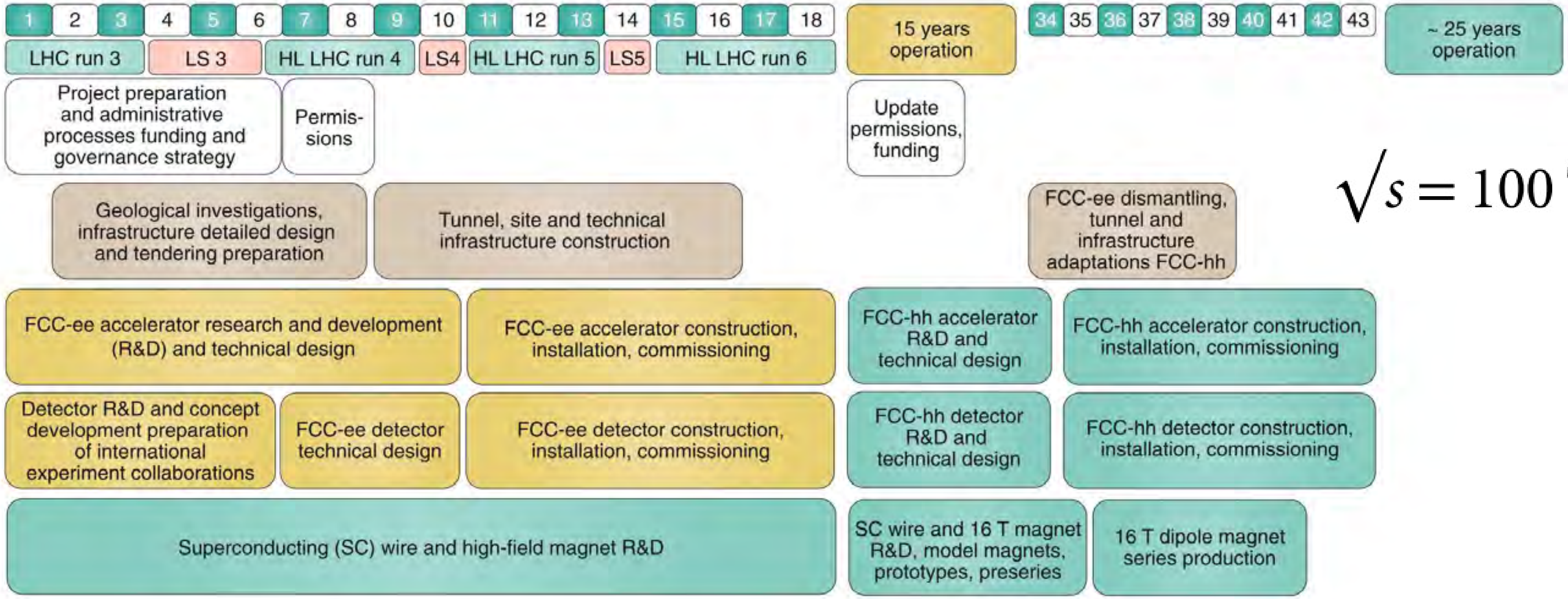


Table 1 | Run plan for the FCC-ee

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





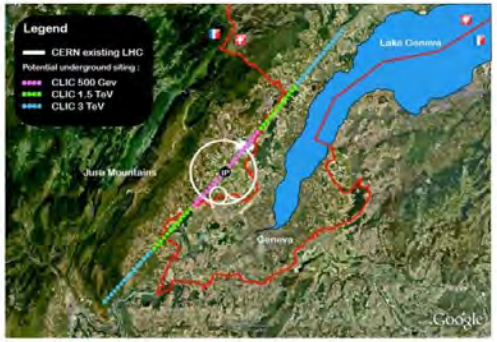
$$\sqrt{s} = 100\ \text{TeV}$$

The launch point is 2020

Nature Physics 16, 402–407 (2020)

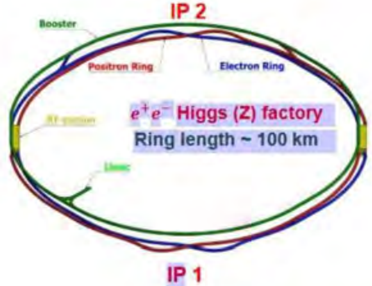
e+e- Colliders

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}

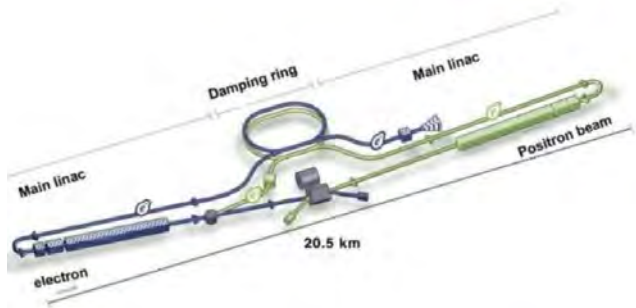
Circular Electron Positron Collider (CEPC)



	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}

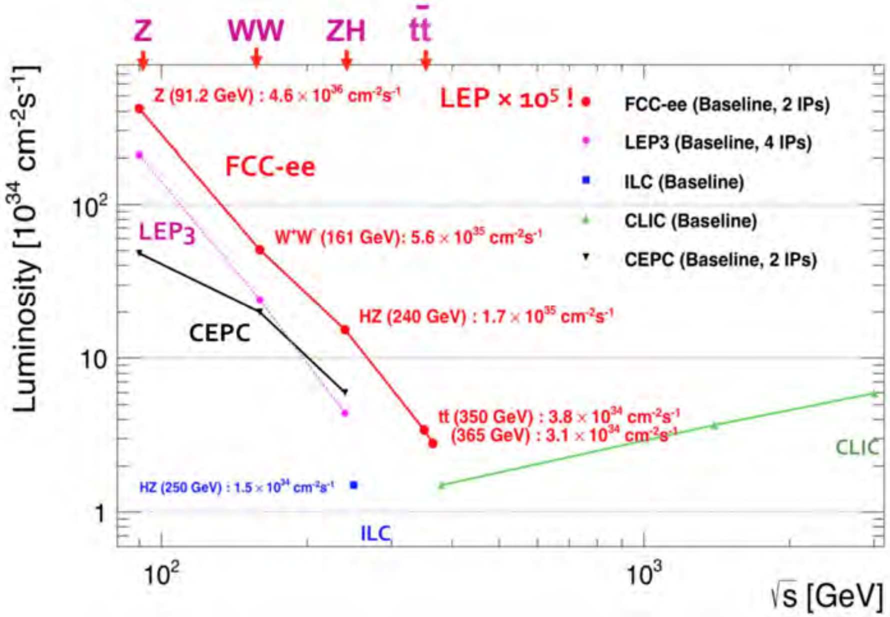
(CEPC Study Group, arXiv:1809.00285, 1811.10545)

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)



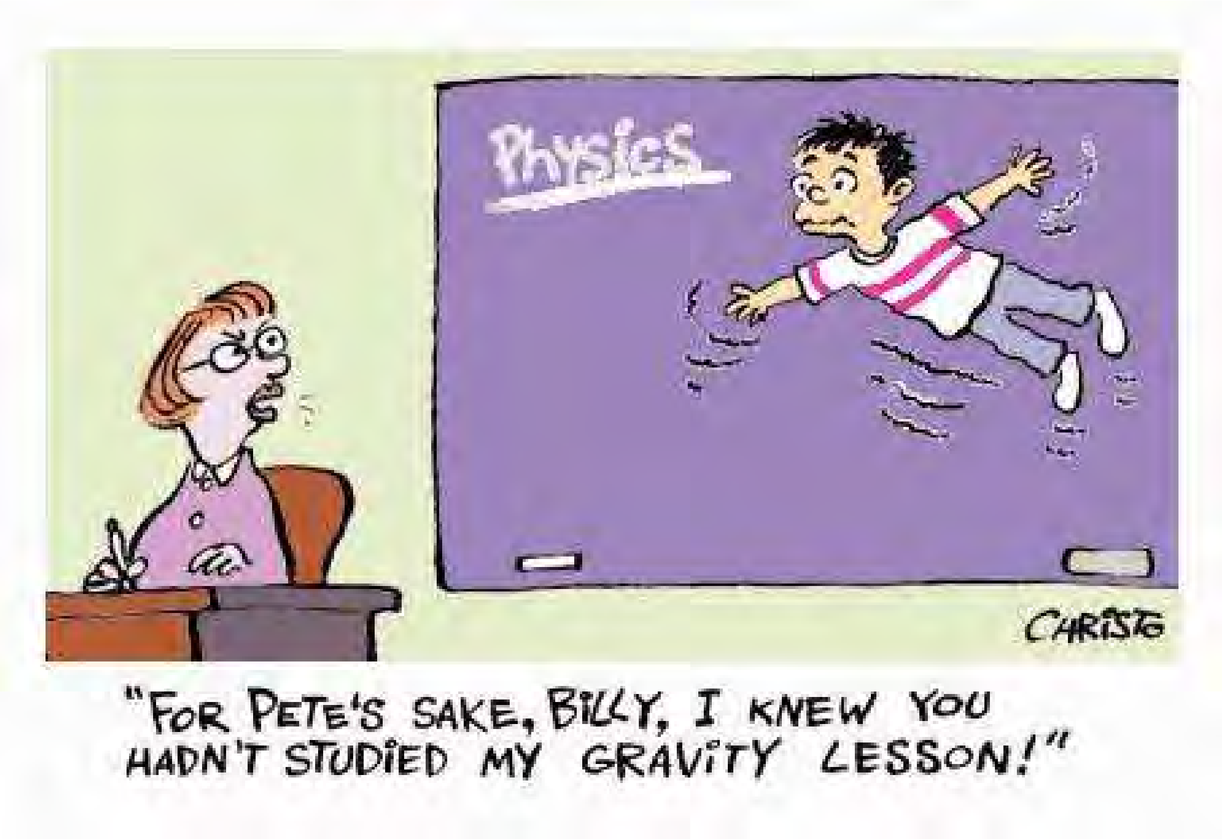
Higgs boson is found

Standard Model works

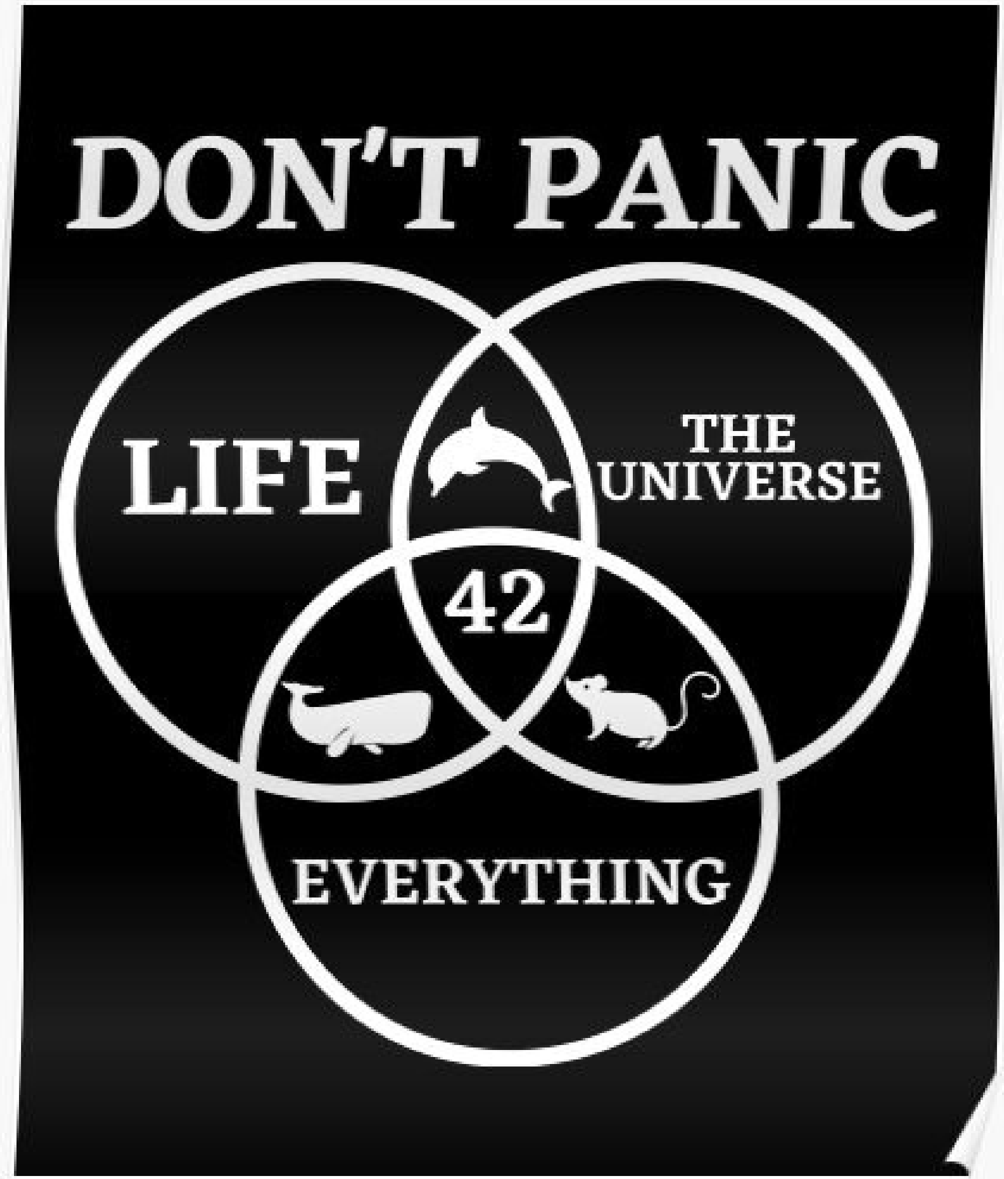
Extensive Searches for New Physics

- 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



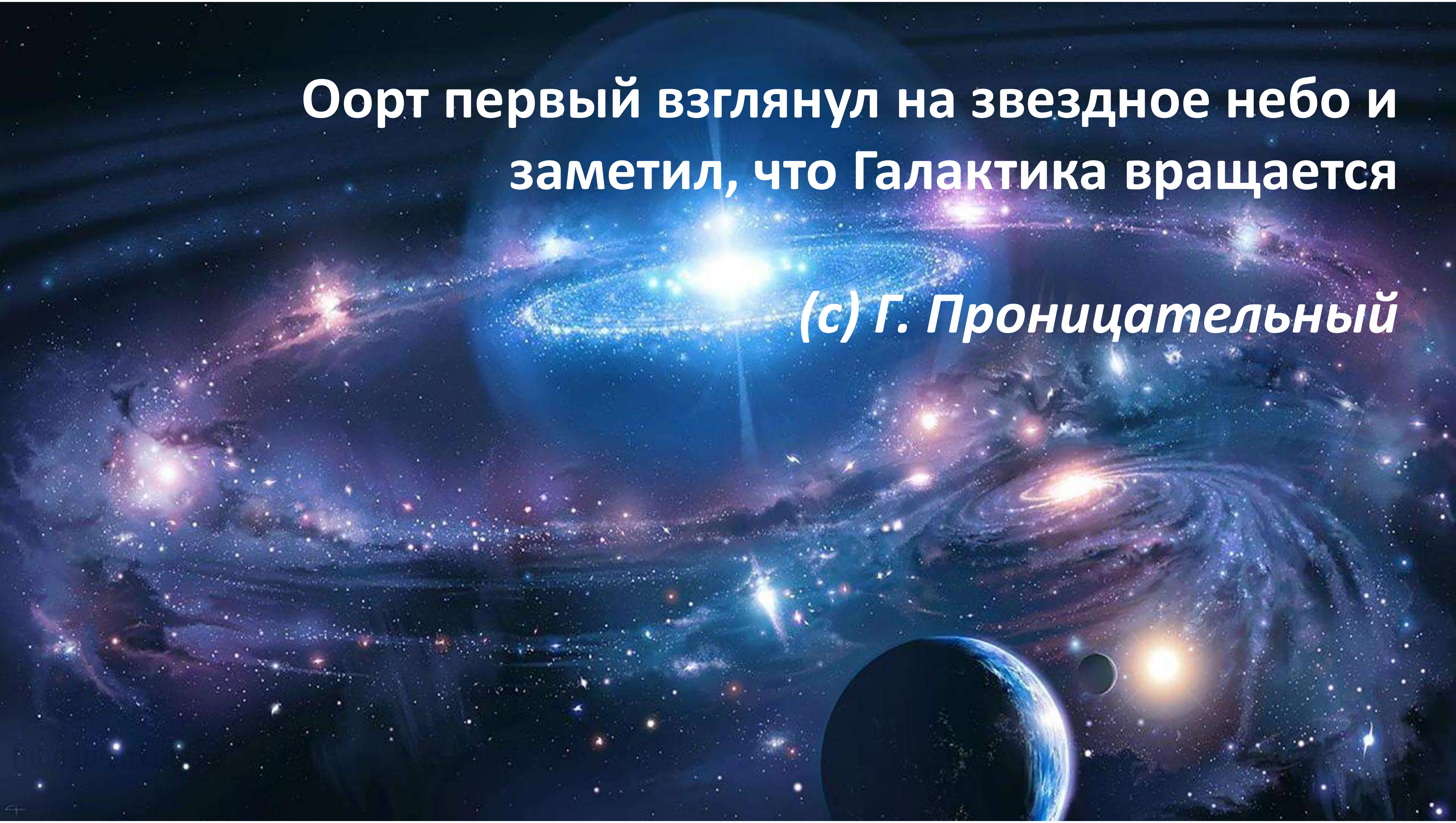
Anyway…



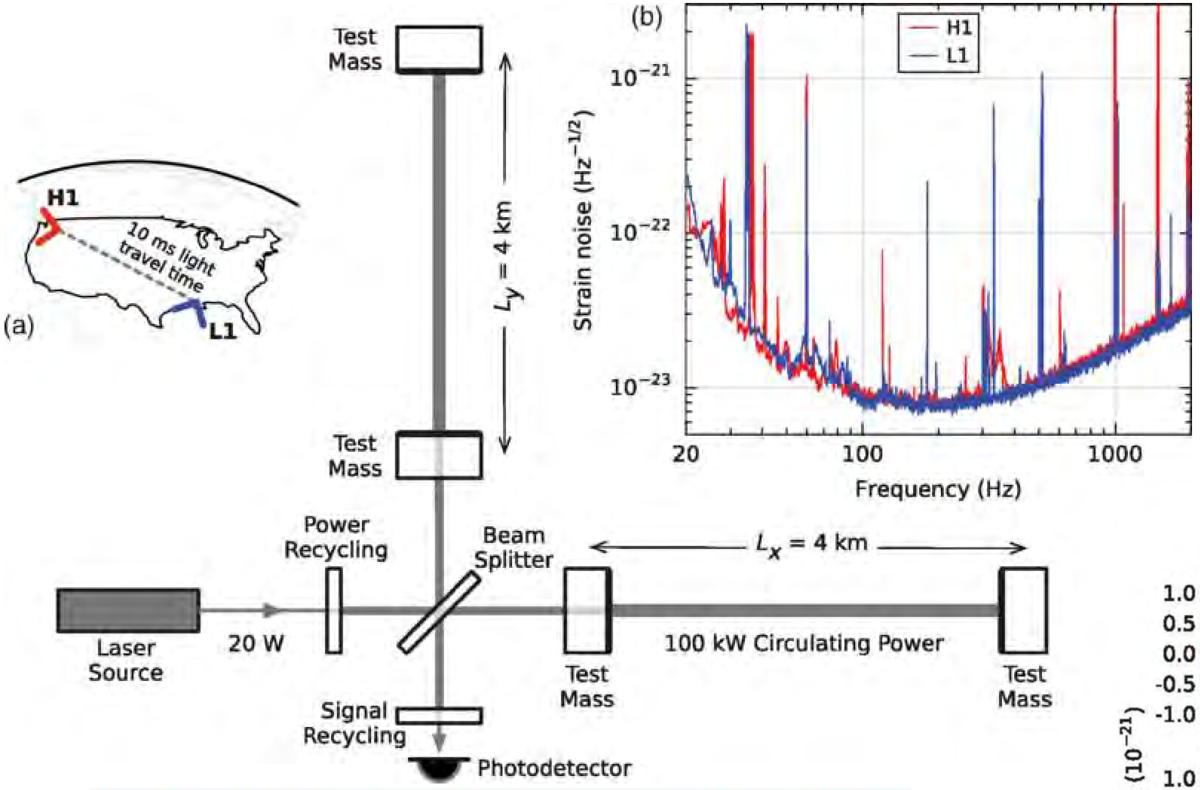
The Hitchhiker's Guide to the Galaxy
by Douglas Adams

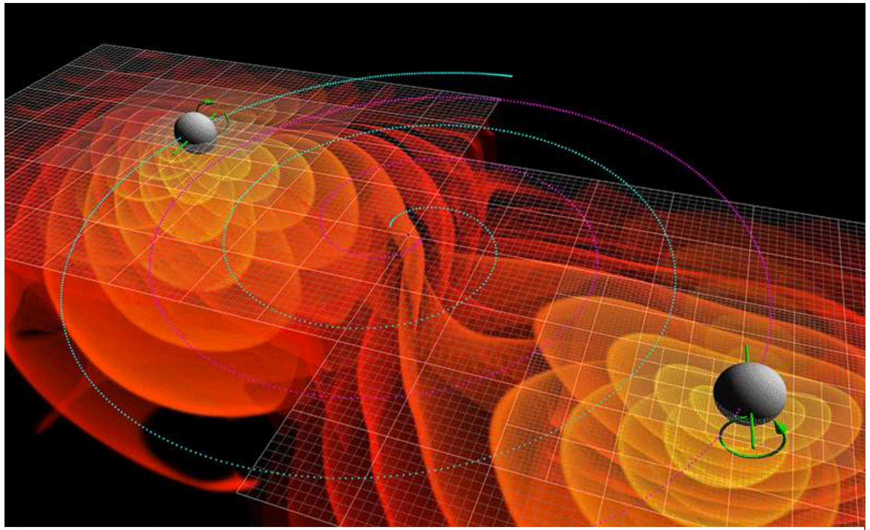
Оорт первый взглянул на звездное небо и заметил, что Галактика вращается

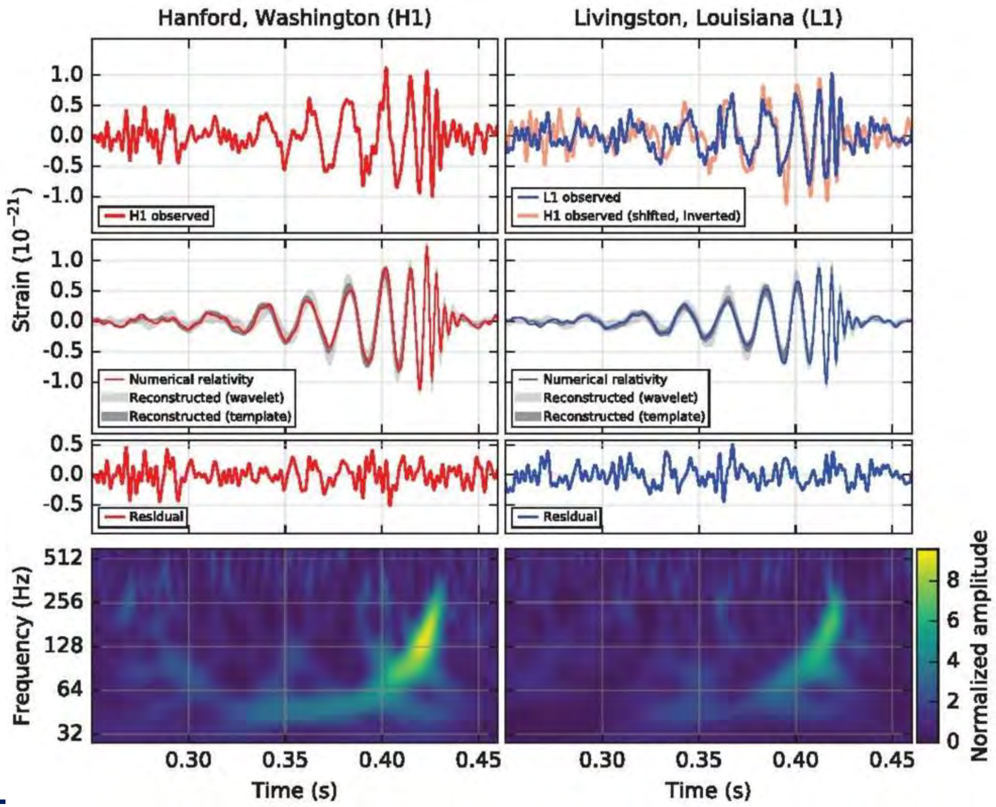
(с) Г. Проницательный



Observation of Gravitational Waves







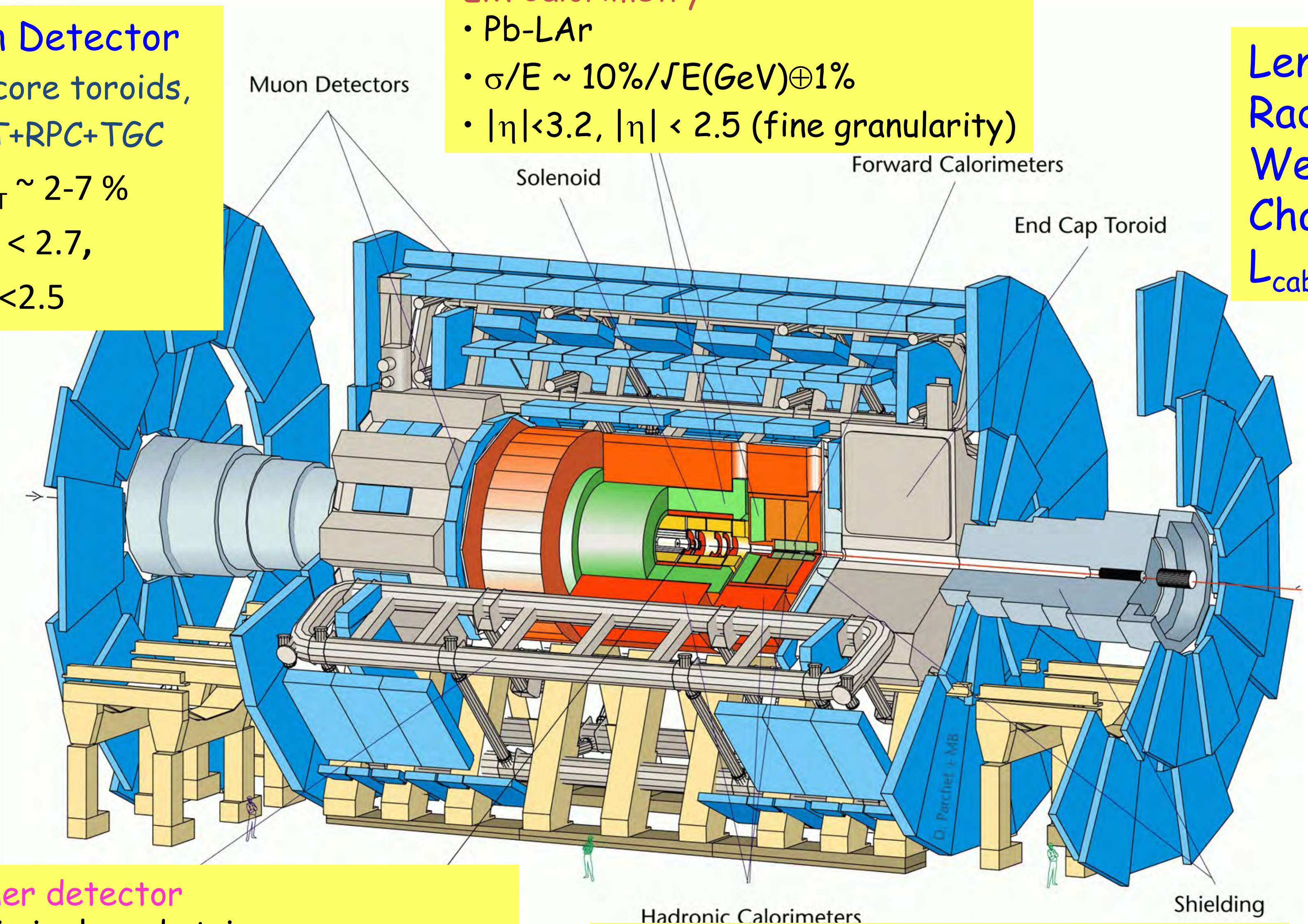
THANK YOU FOR YOUR ATTENTION!

The ATLAS Experiment

Muon Detector
- air-core toroids, MDT+RPC+TGC
- $\sigma/p_T \sim 2\text{-}7\ \%$
- $|\eta| < 2.7$,
- $|\eta| < 2.5$

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

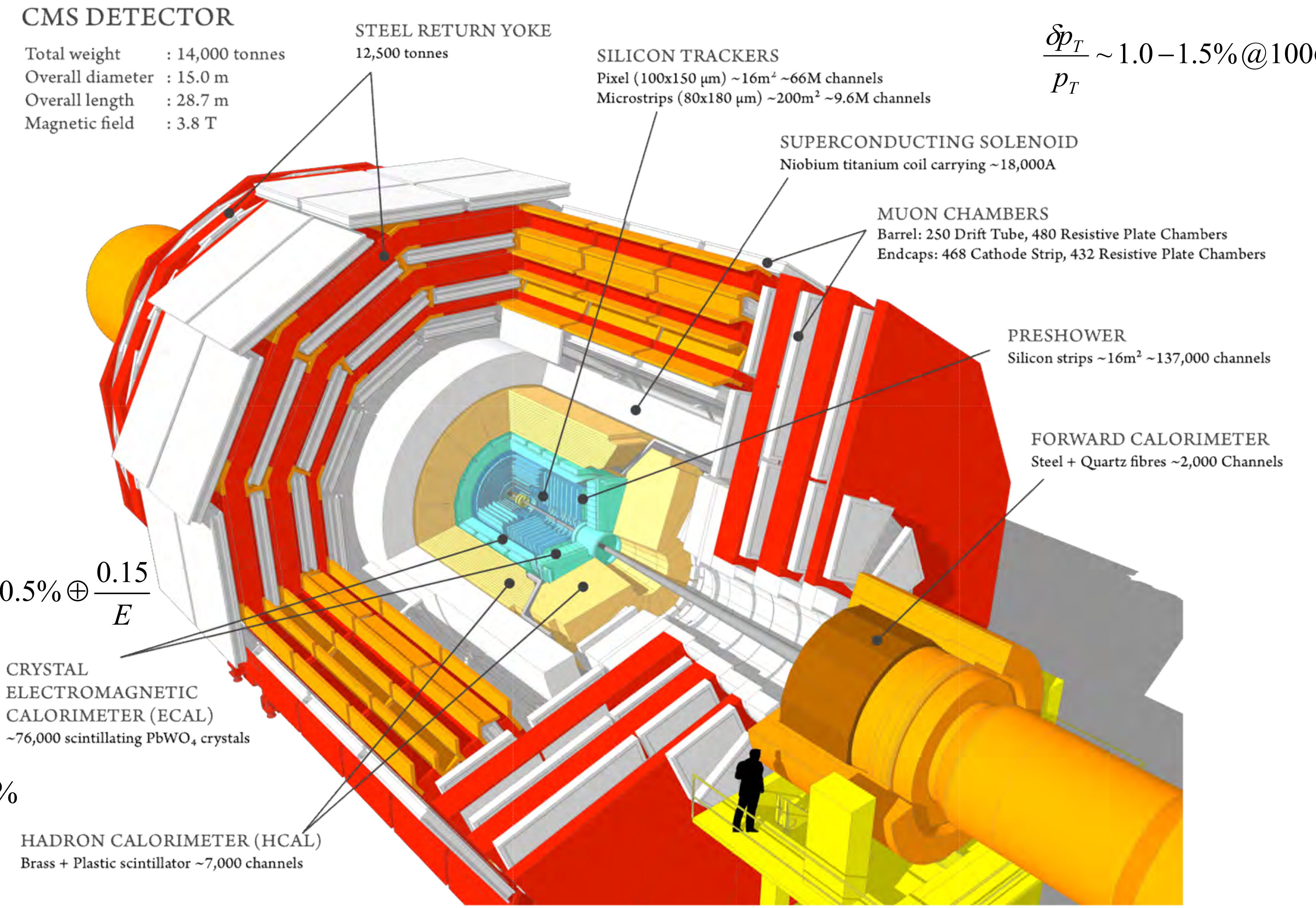
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
Channels: ~ 10^8
L_{cable}: ~ 3000 km



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)
- $\sigma/E \sim 50\%/\sqrt{E(GeV)} \oplus 3\%$
- $|\eta|<3$

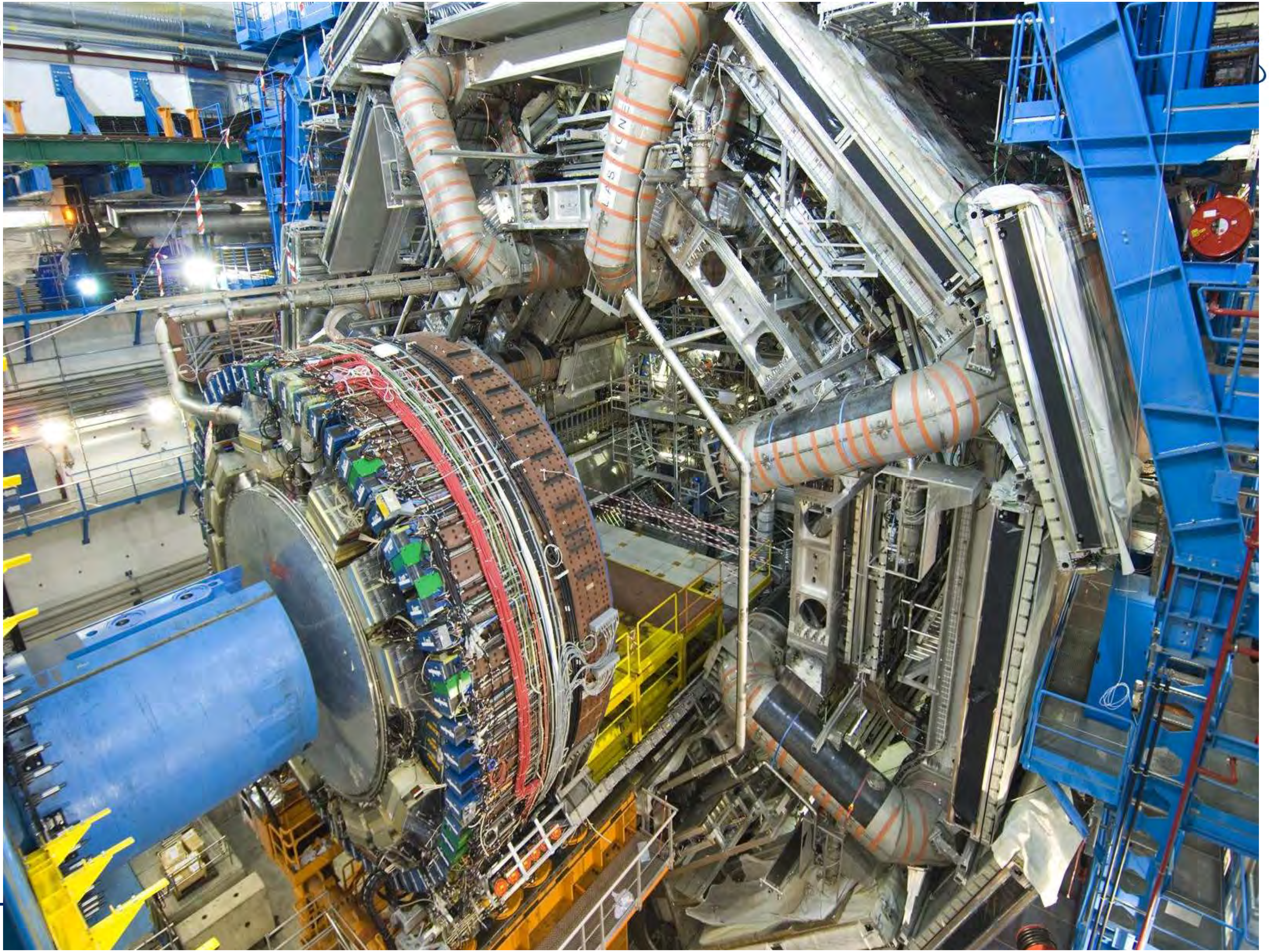
The CMS Experiment



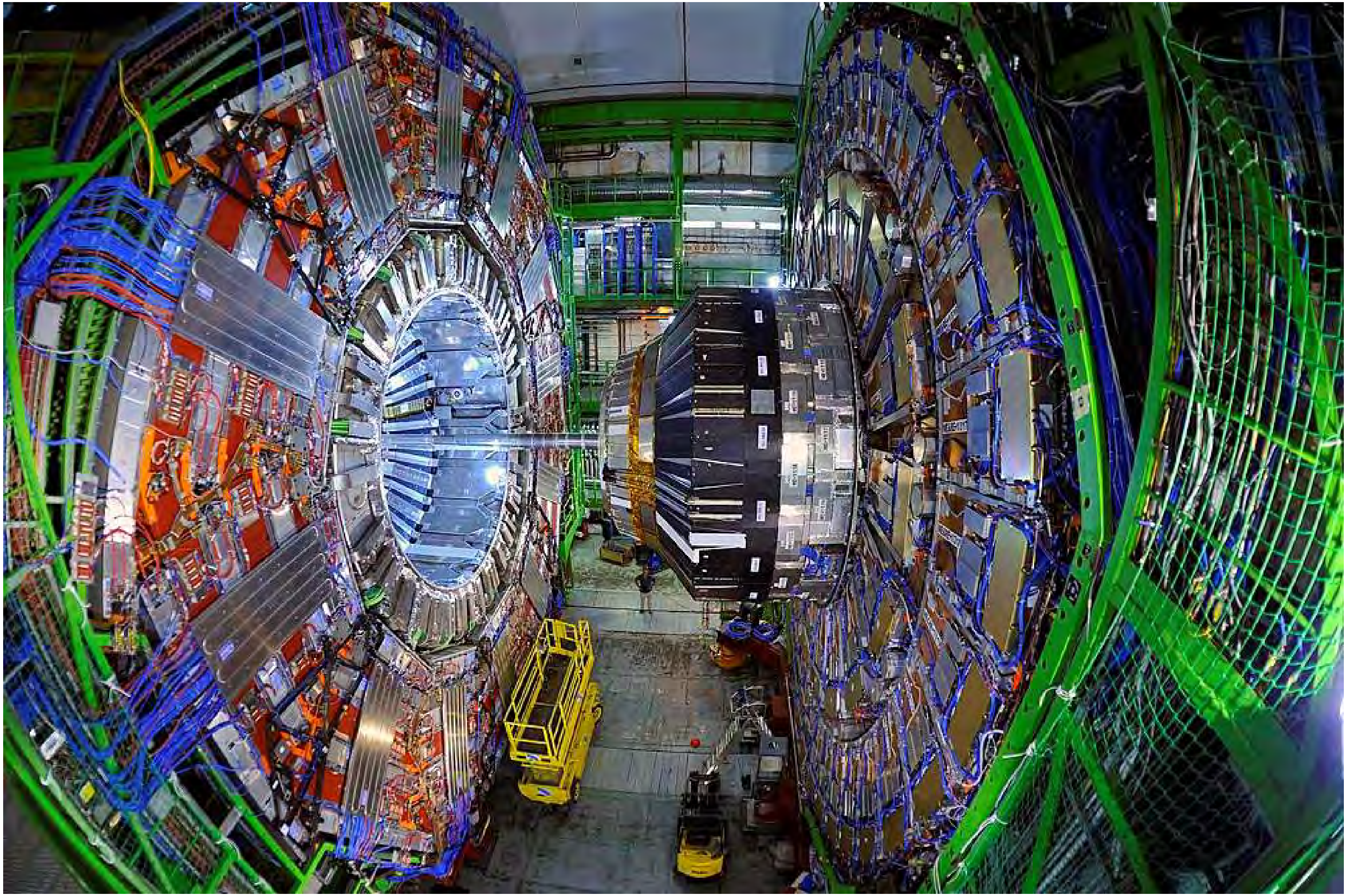
$$\frac{\delta p_T}{p_T} \sim 1.0 - 1.5\% @ 100 GeV$$

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

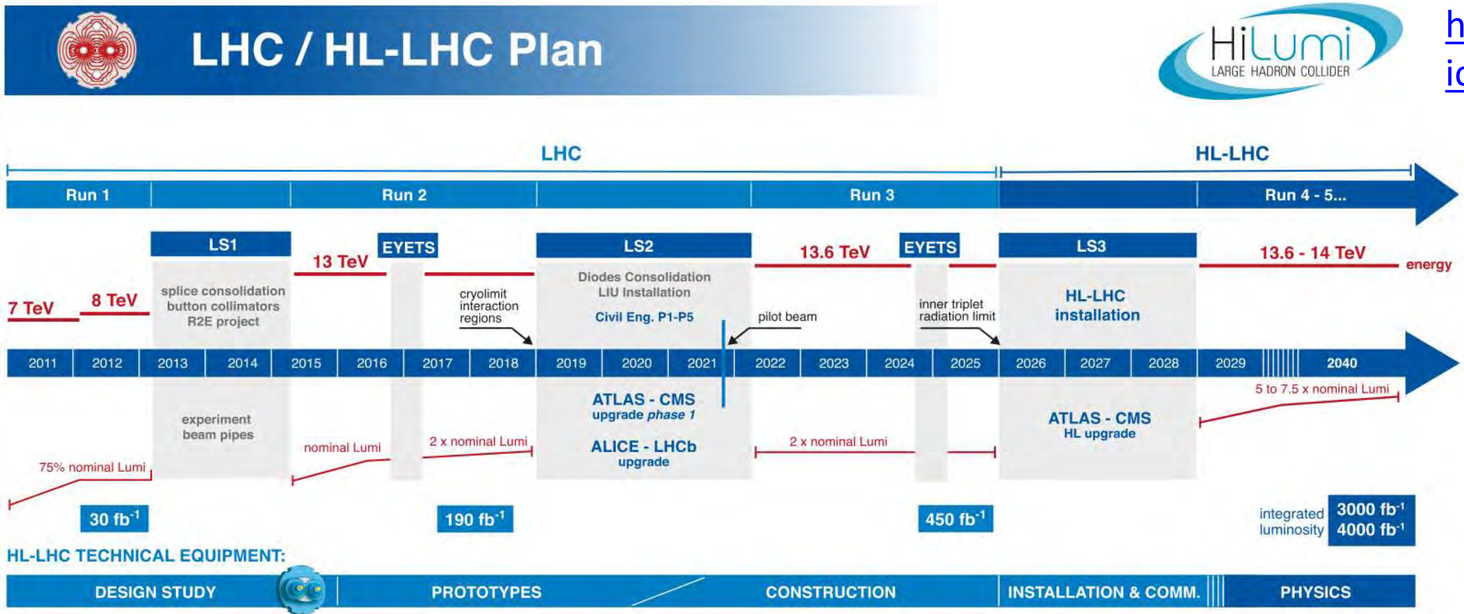
$$\frac{\sigma_E}{E} = \frac{120}{\sqrt{E}} \oplus 5\%$$



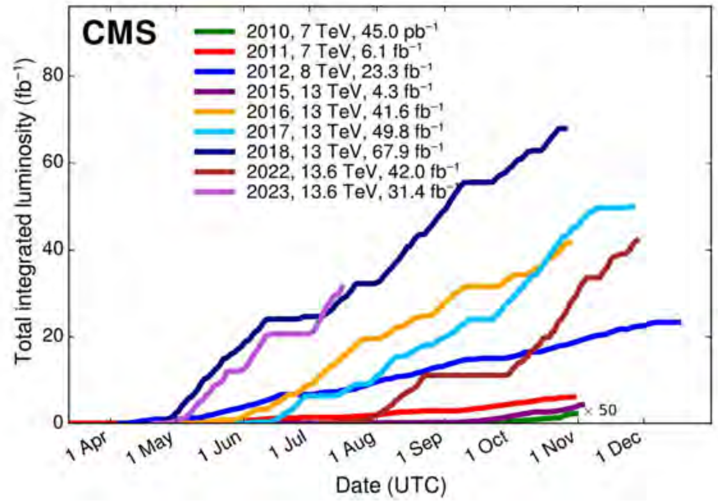
Open CMS



LHC Timeline and Data That We Have



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

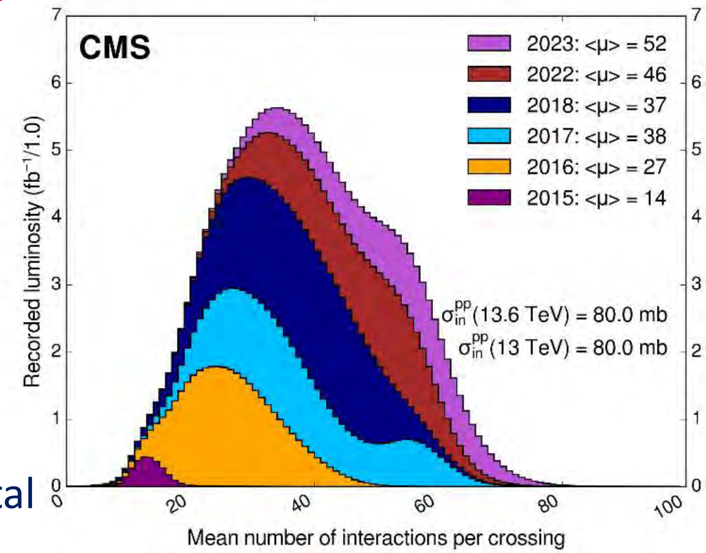


$L_{inst} = 2.1\times10^{34}\ cm^{-2}s^{-1}$

We are here

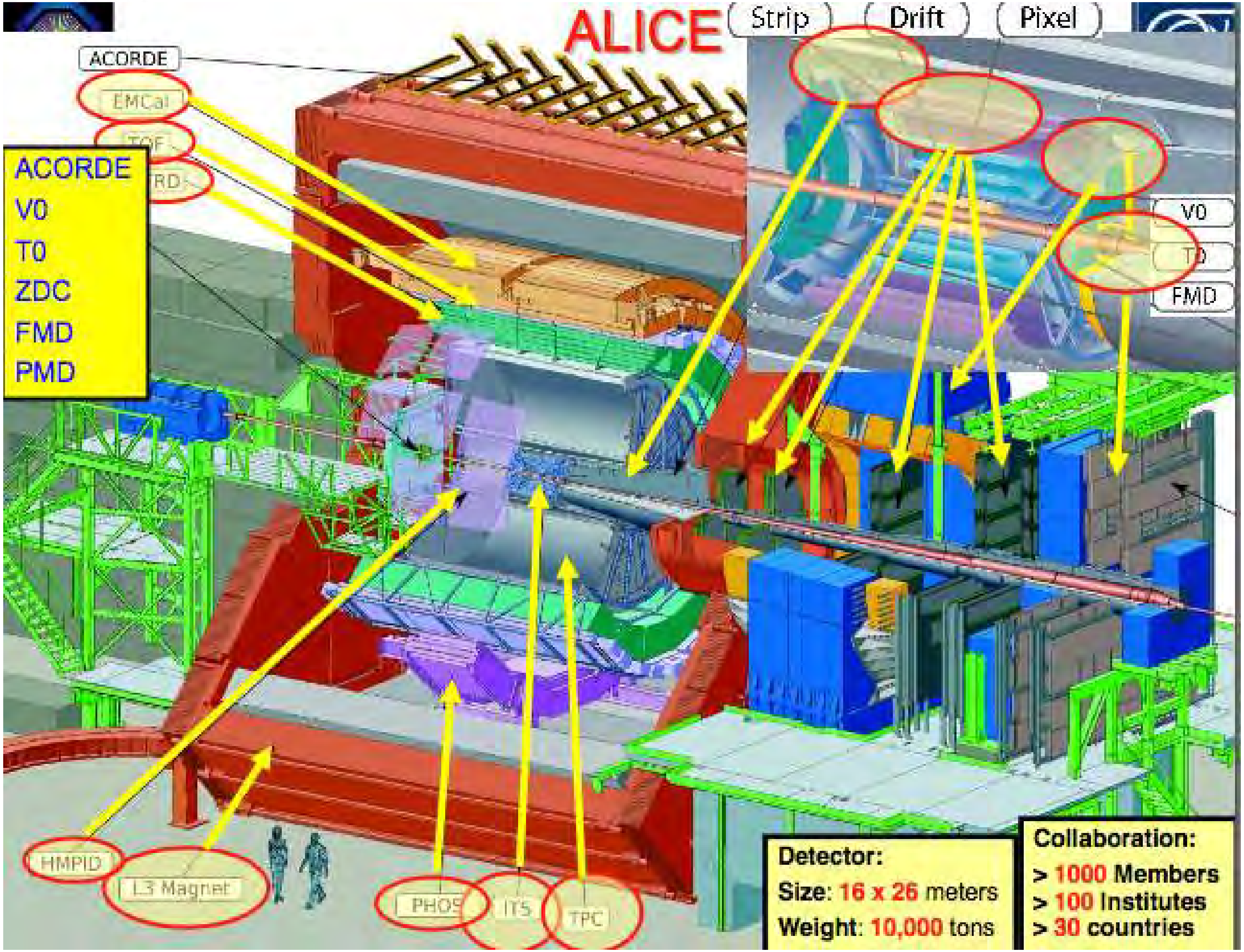
$L_{nisyt} = 7.5\times10^{34}\ cm^{-2}s^{-1}$

- 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)



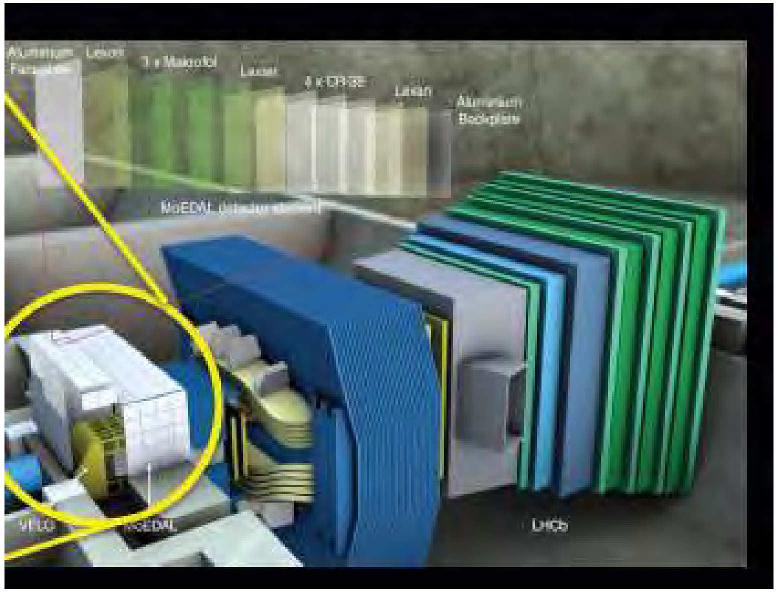
CMS Data Quality Information
https://twiki.cern.ch/twiki/bin/view/CMSPublic/DataQuality

The ALICE Experiment

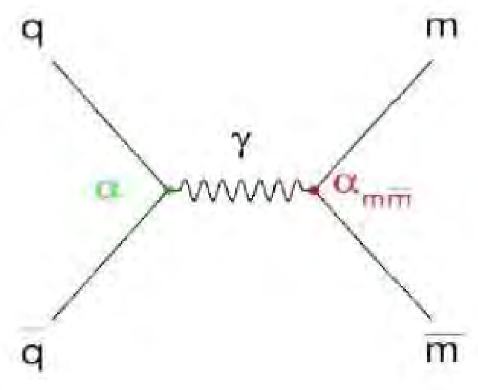


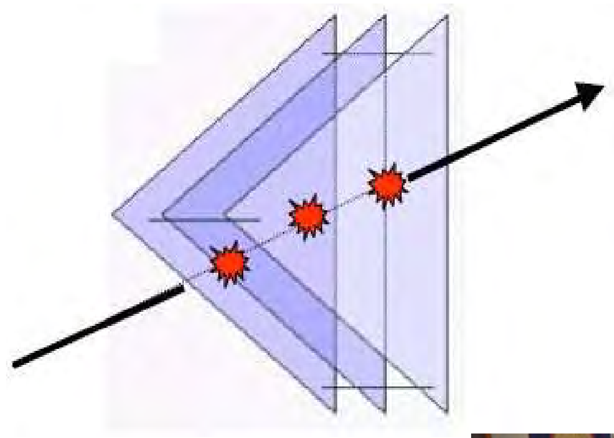
MoEDAL: Monopole and Exotics Detector at the LHC

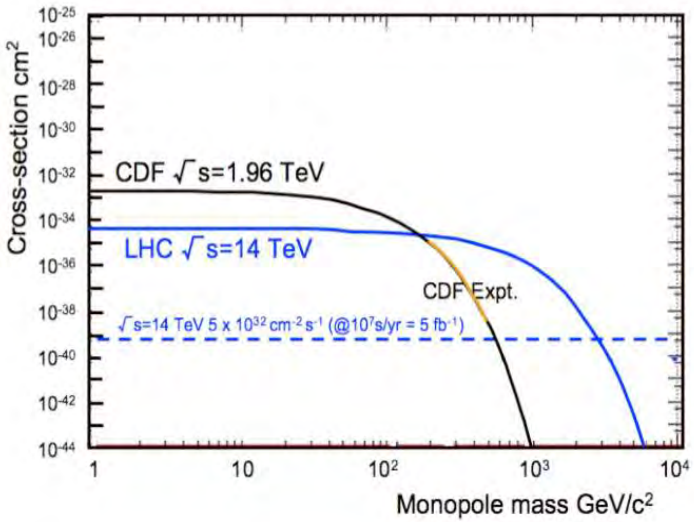
Heavy particles which carry “magnetic charge”
Could eg explain why particles have “integer electric charge”



Monopole production





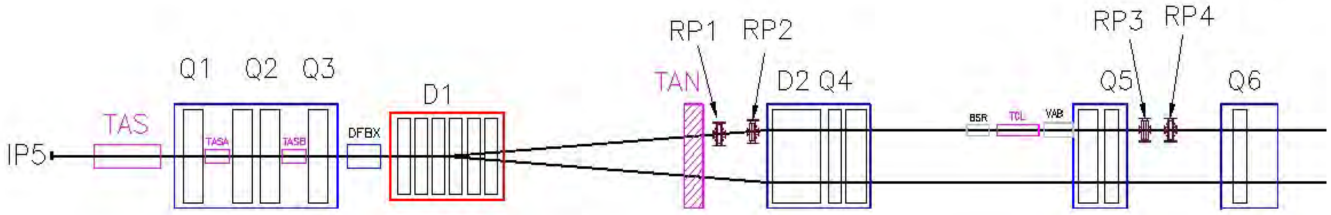


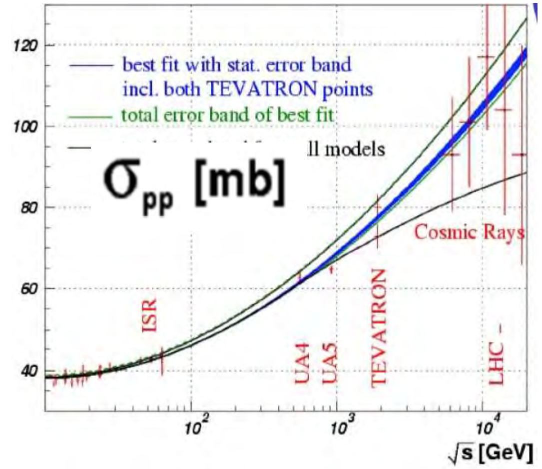
Remove the sheets after some running time and inspect for ‘holes’

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

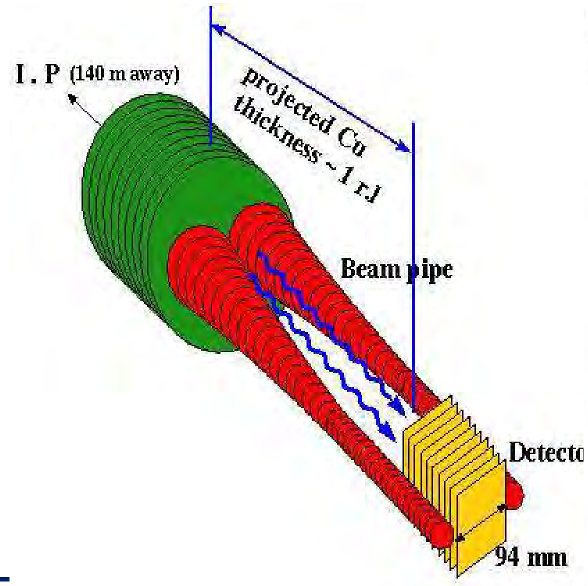
TOTal and Elastic cross section Measurement

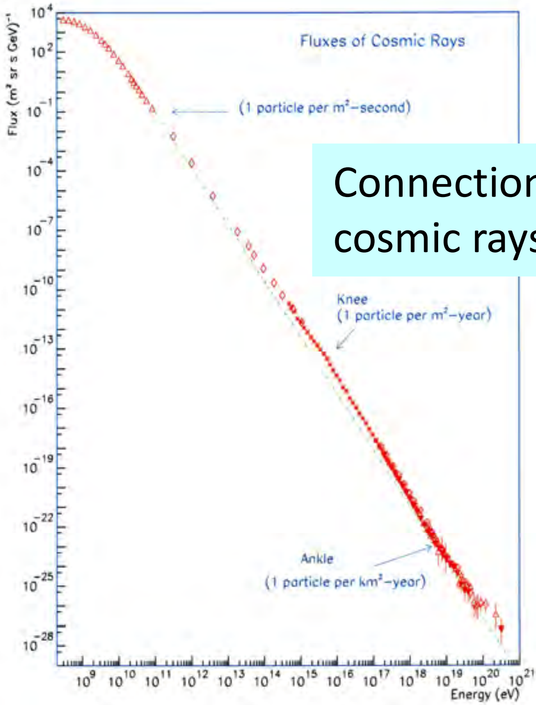




LHCf: measurement of photons and neutral pions in the very forward region of LHC

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

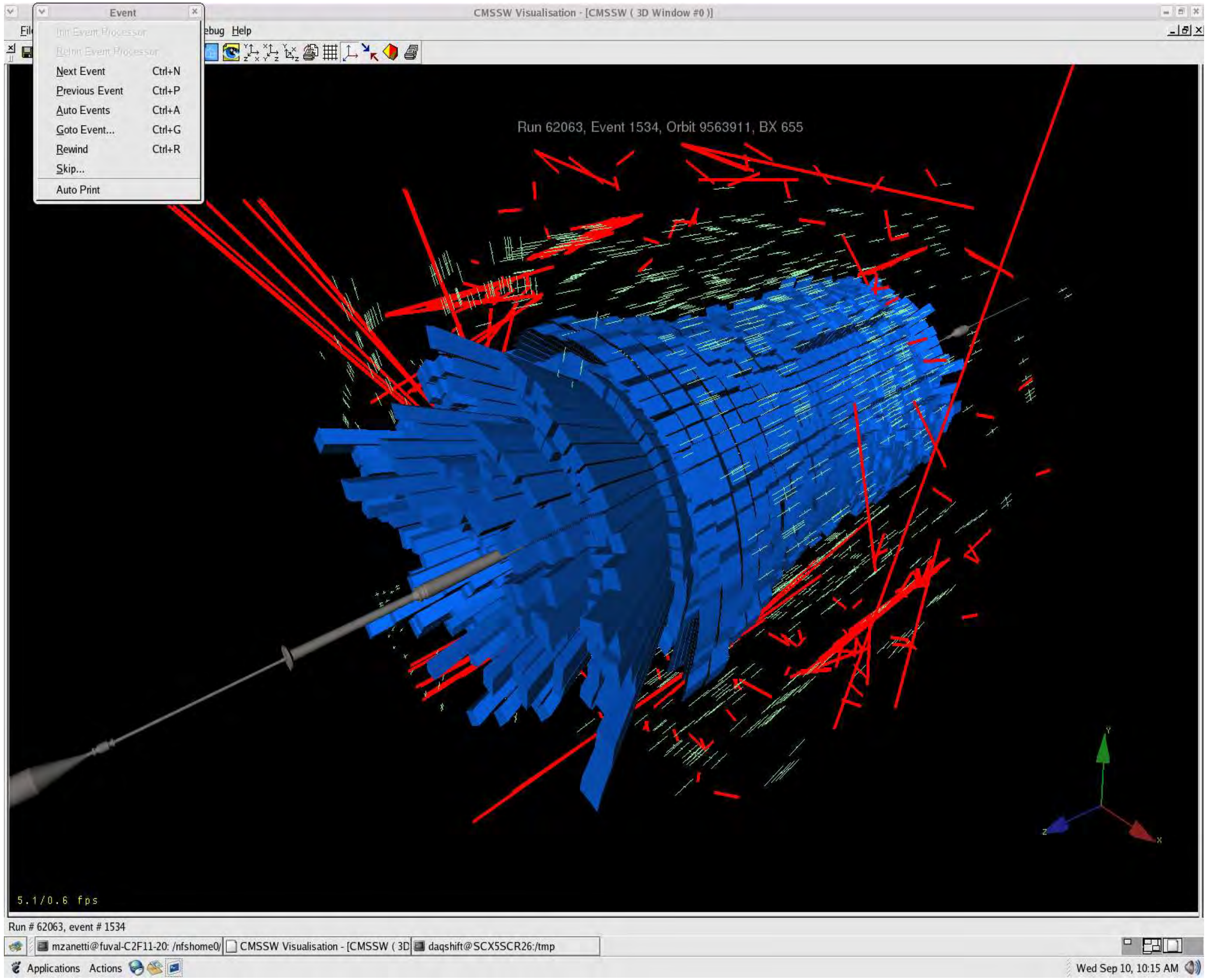




Connection with cosmic rays

LHC Start Up

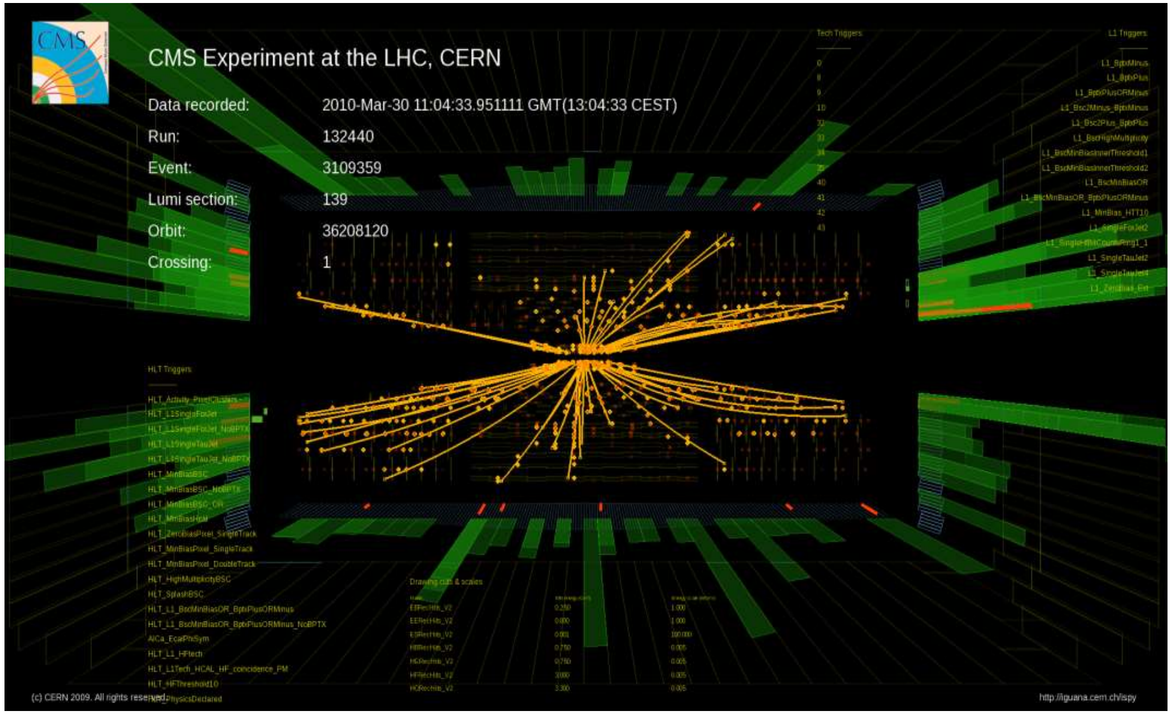
10 September 2008, 9:50, the first LHC beam event was recorded by CMS

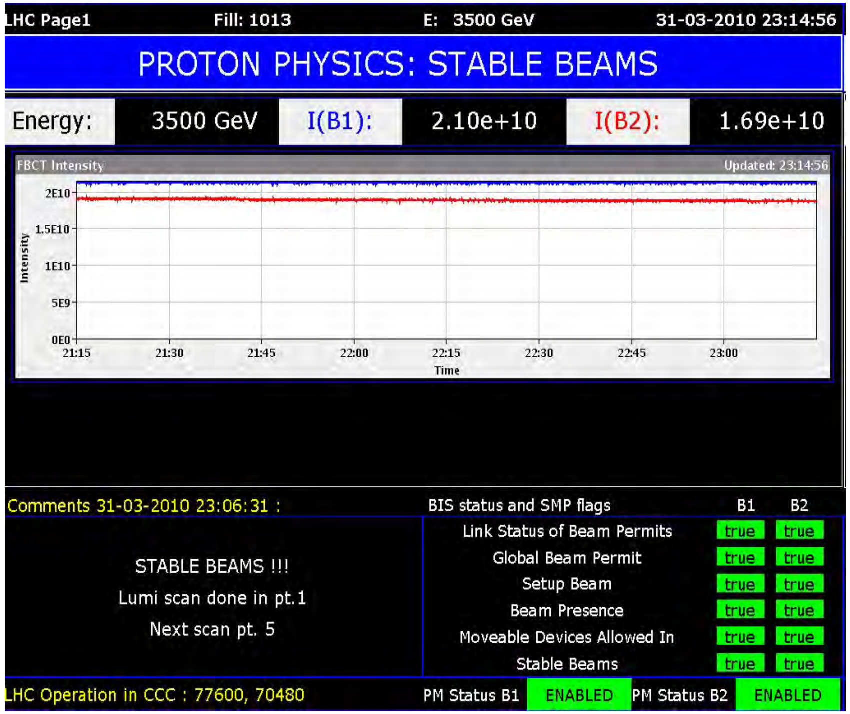


The First Collisions @ 7 TeV

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