Particle physics experiments
Current status

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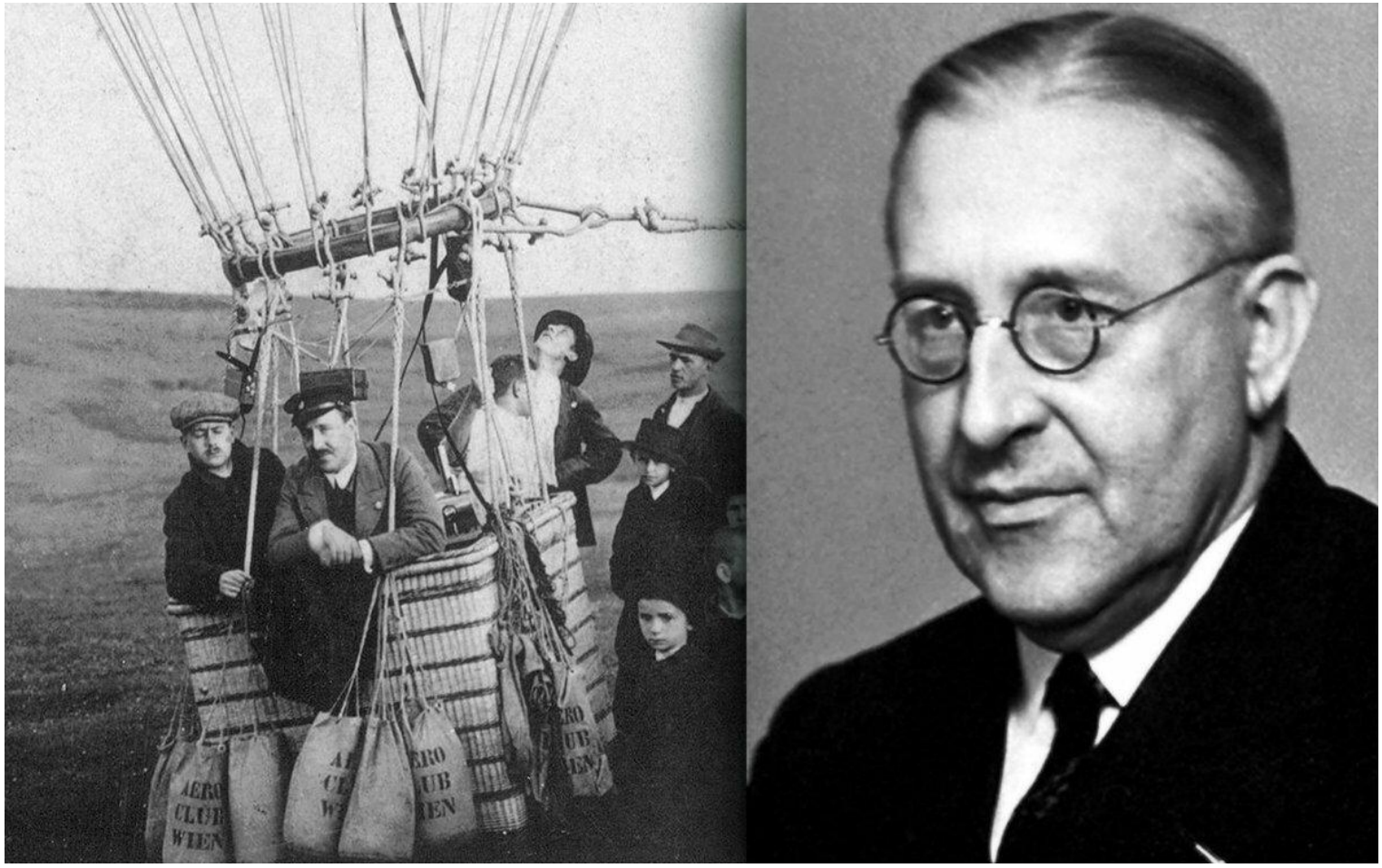
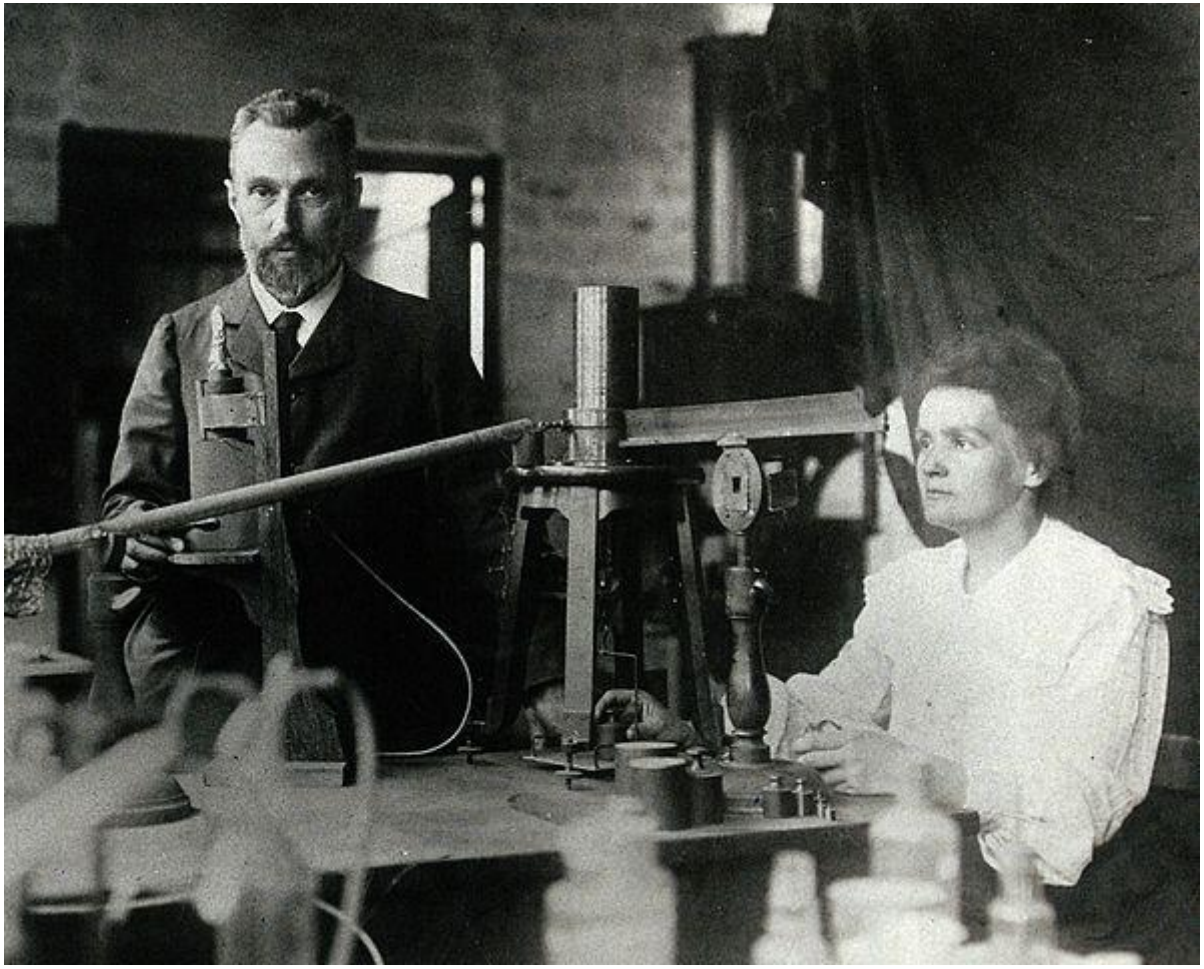
5 July 2022: LHC Run-3 first beam

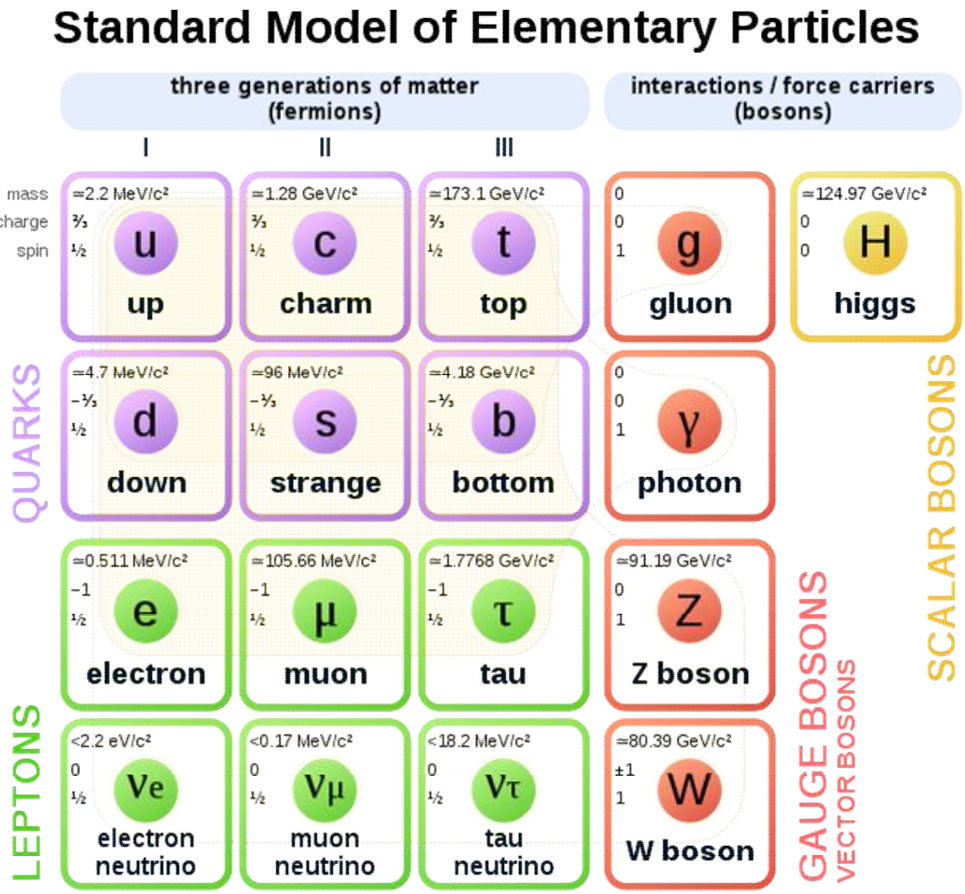
1911: Victor Hess discovery of cosmic rays



1896: H.Becquerel and M.Curie discovery of radioactivity



Standard Model is now a complete theory. All particles are known.



Where we study particles

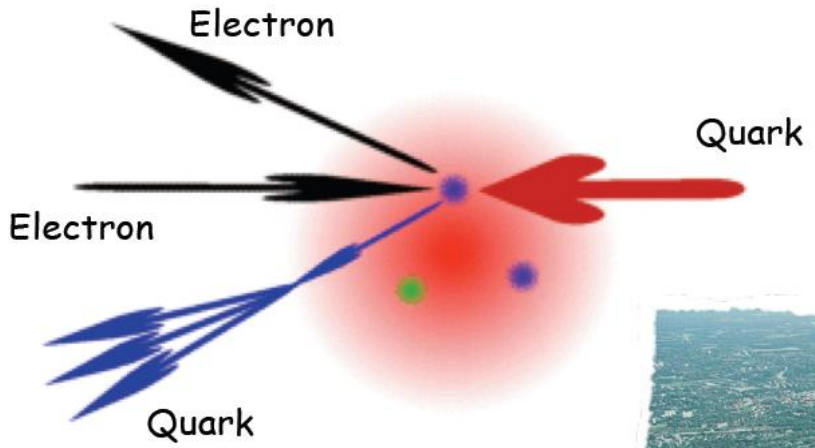
- How we produce particles?
  - From energy!
  - $E = mc^2$
- Sources of energy:
- Radioactivity
  - Energy up to ~10 MeV
- Cosmic rays
  - Up to 10^8 TeV, but VERY low flux
- Accelerators and colliders
  - 14 TeV now, 100 TeV in ~40 years
- Main directions of collider development:
  - Maximum energy
  - Maximum fluxes (luminosity)

Experiments of past decades

Recent major collider experiments

- HERA: H1, Zeus
  (DESY, Hamburg, 1992-2007)
  - ep collider, 27+920 GeV
- LEP: ALEPH, DELPHI, L3, OPAL
  (CERN, Geneva, 1989-2000)
  - e+e- collider, 91-209 GeV
- Tevatron: CDF, D0
  (Fermilab, Chicago, 1986-2011)
  - p+p- collider, 2000 GeV

HERA experiments



$\sqrt{s} = 310\ GeV$

$L = 5 \cdot 10^{30}\ cm^{-2}\ s^{-1}$

HERA, DESY [1991-2007]

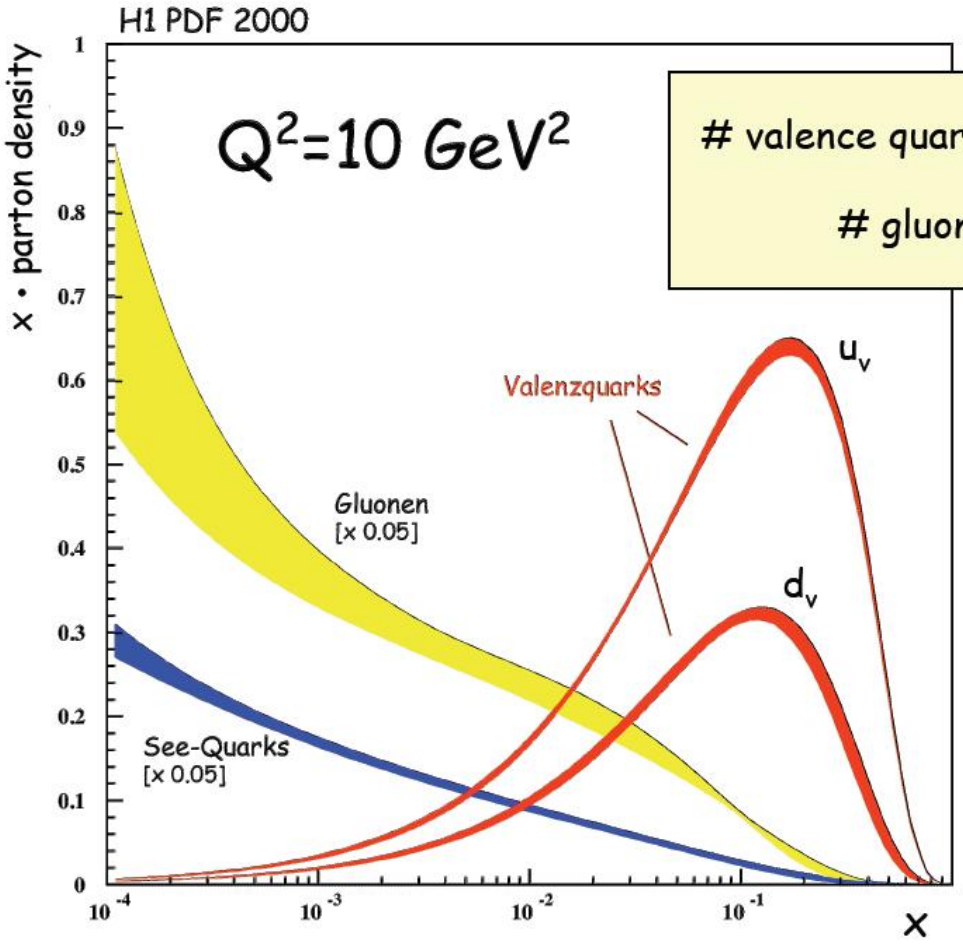
Proton:

$m_p = 1\ GeV$

$m_q = 3\text{-}6 MeV$

$\sum m_q/m_p = 0.01$?

HERA: parton densities



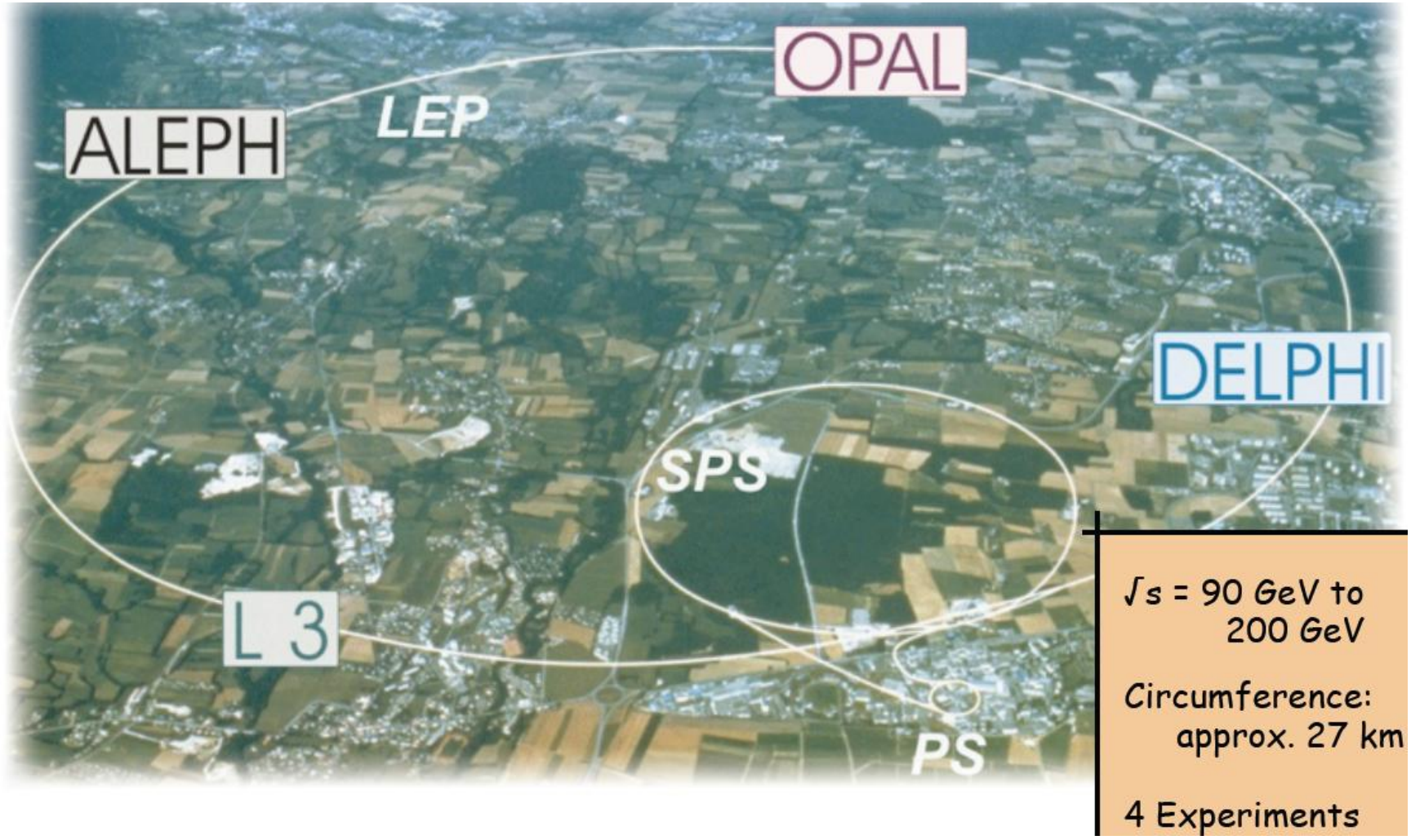
$$\#\ \text{valence quarks} = \int u_v(x) + d_v(x)\,dx = 3$$

$$\#\ \text{gluons} = \int g(x)\,dx > 30$$

"x" is the fraction of proton momentum carried by parton

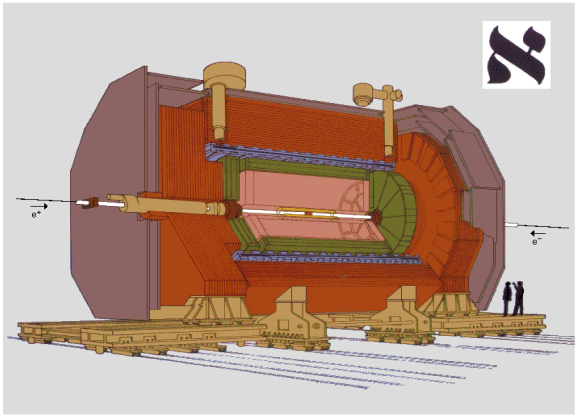
Proton is gluon dominated

The LEP collider

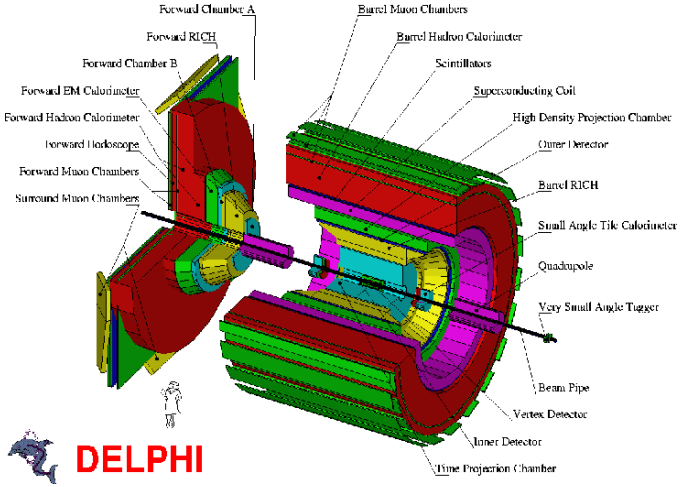


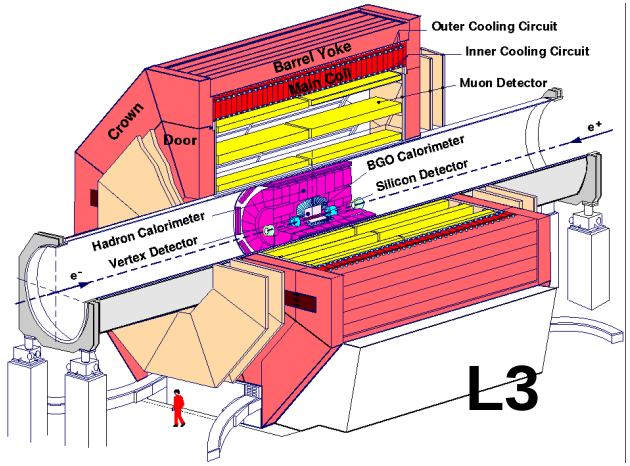
…same view 20 years later…

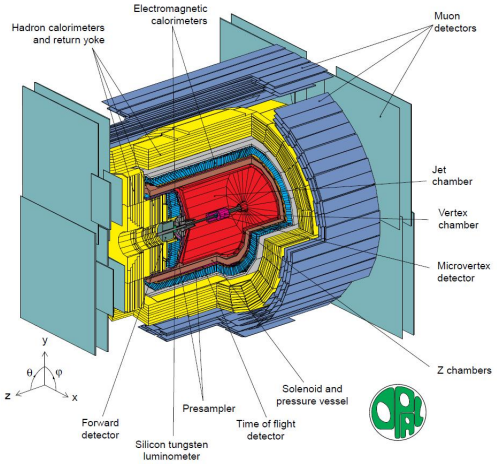
The LEP detectors



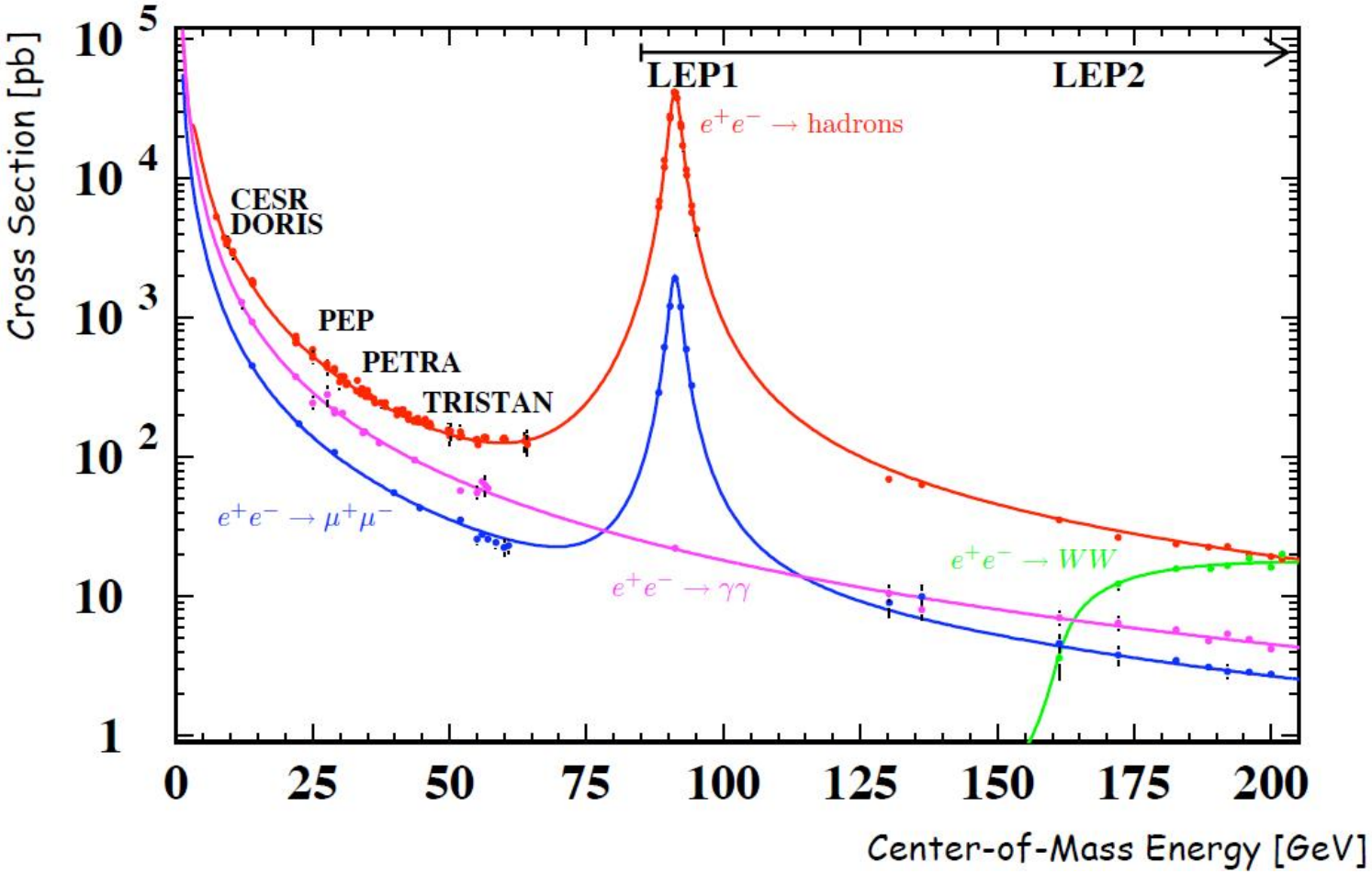
The ALEPH Detector



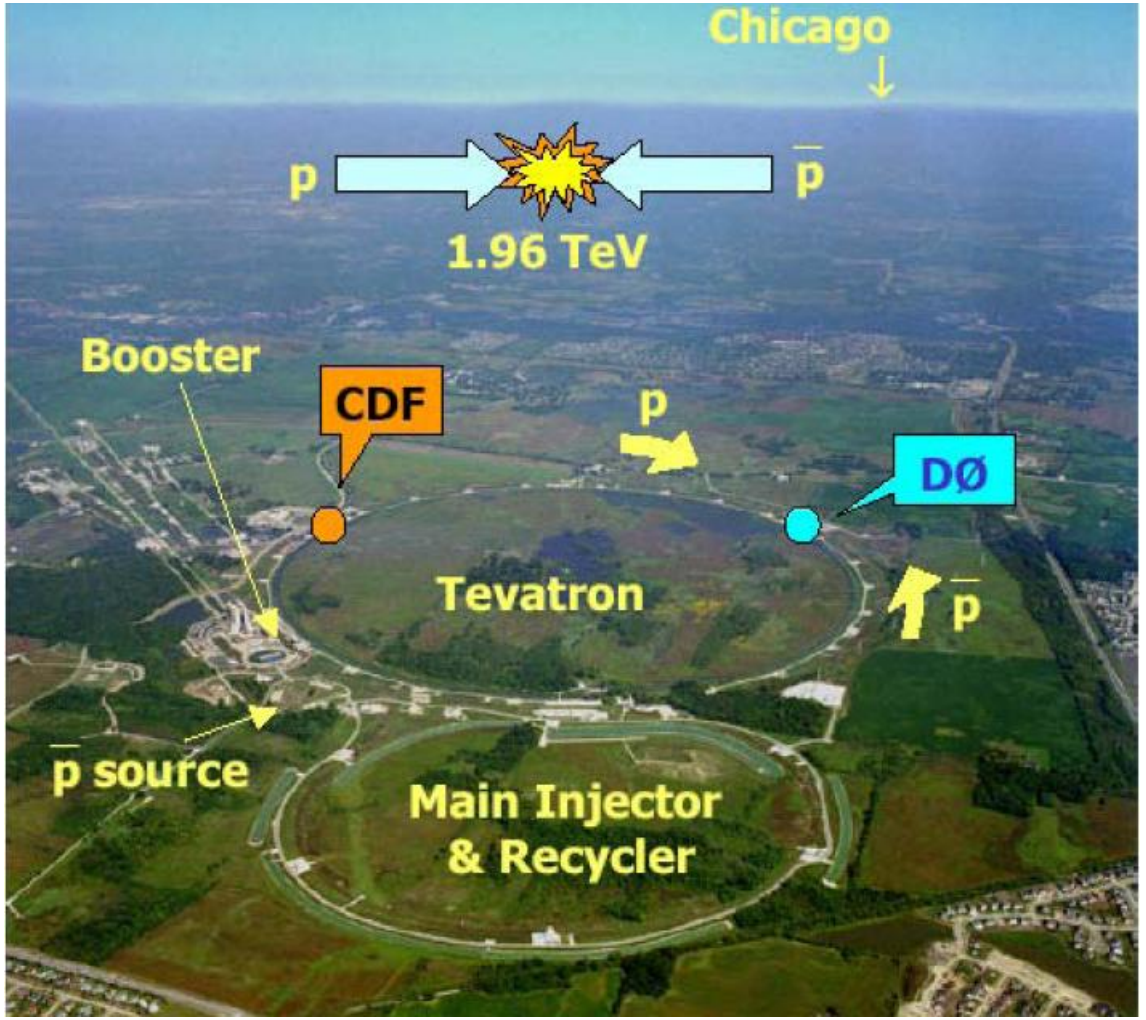




e^+e^- annihilation: LEP and before

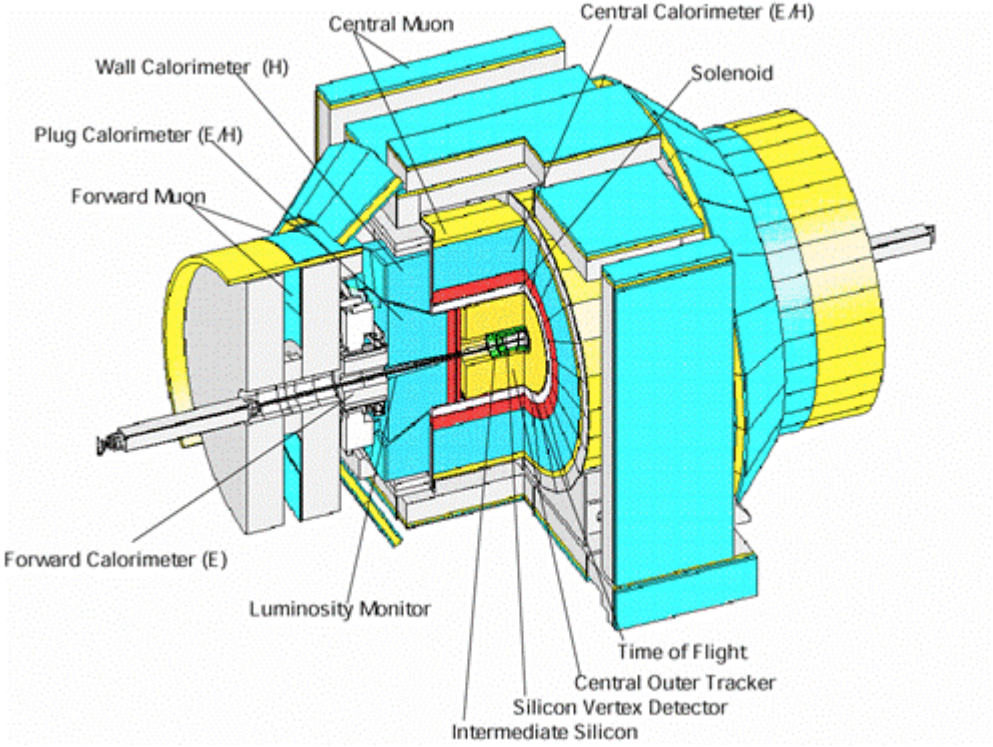


Tevatron collider

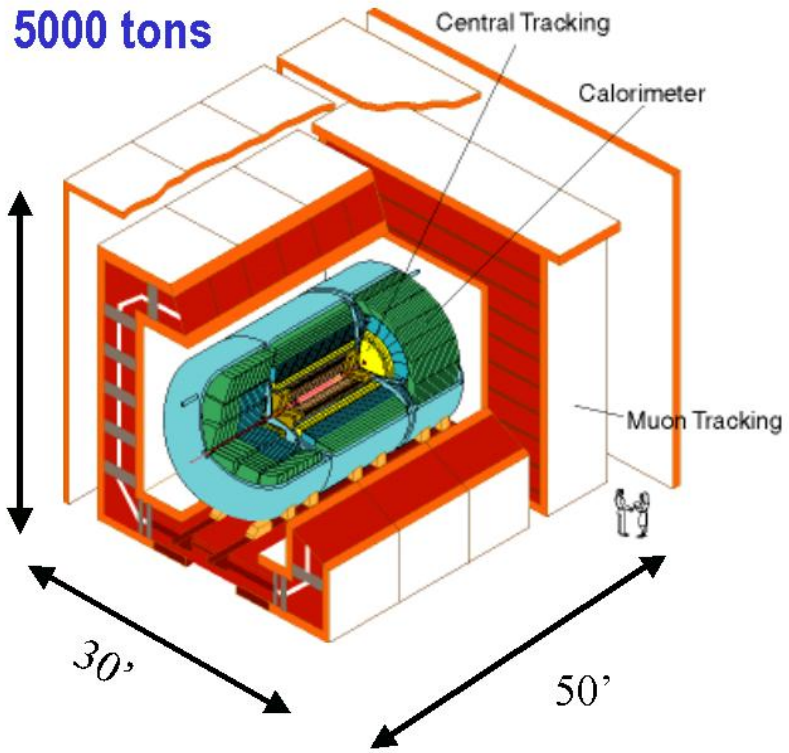


Tevatron experiments

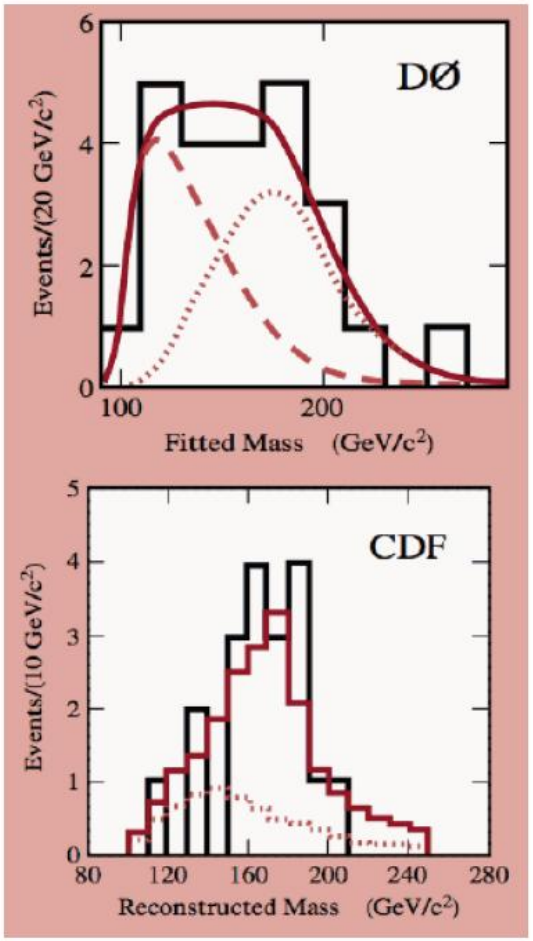
CDF

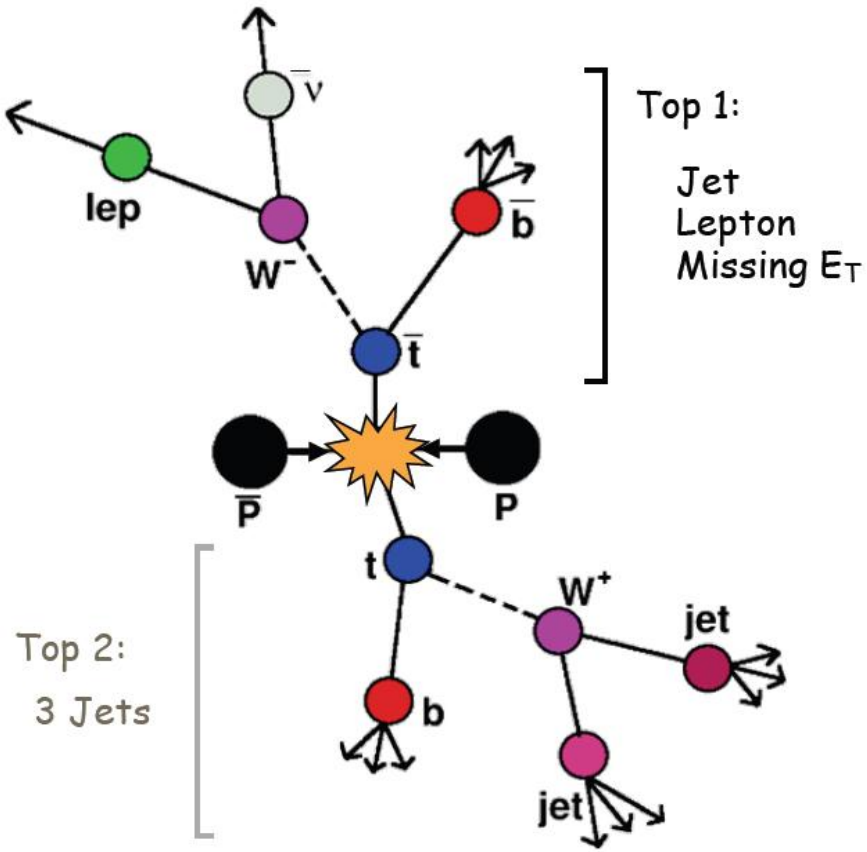


D0



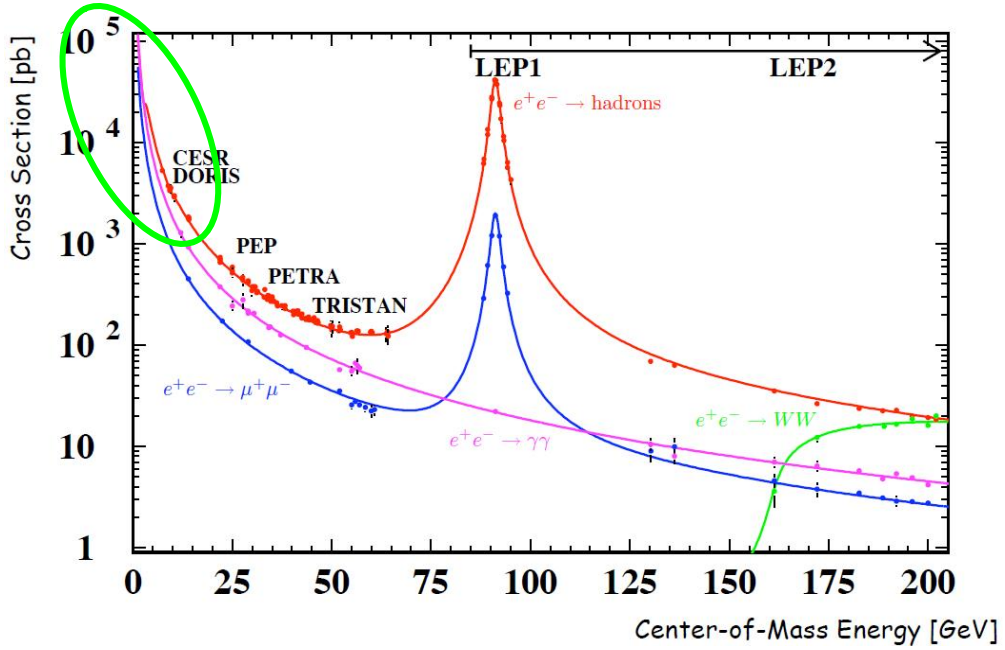
Discovery of the top quark (1995)





Current experiments

e^+e^- annihilation, again

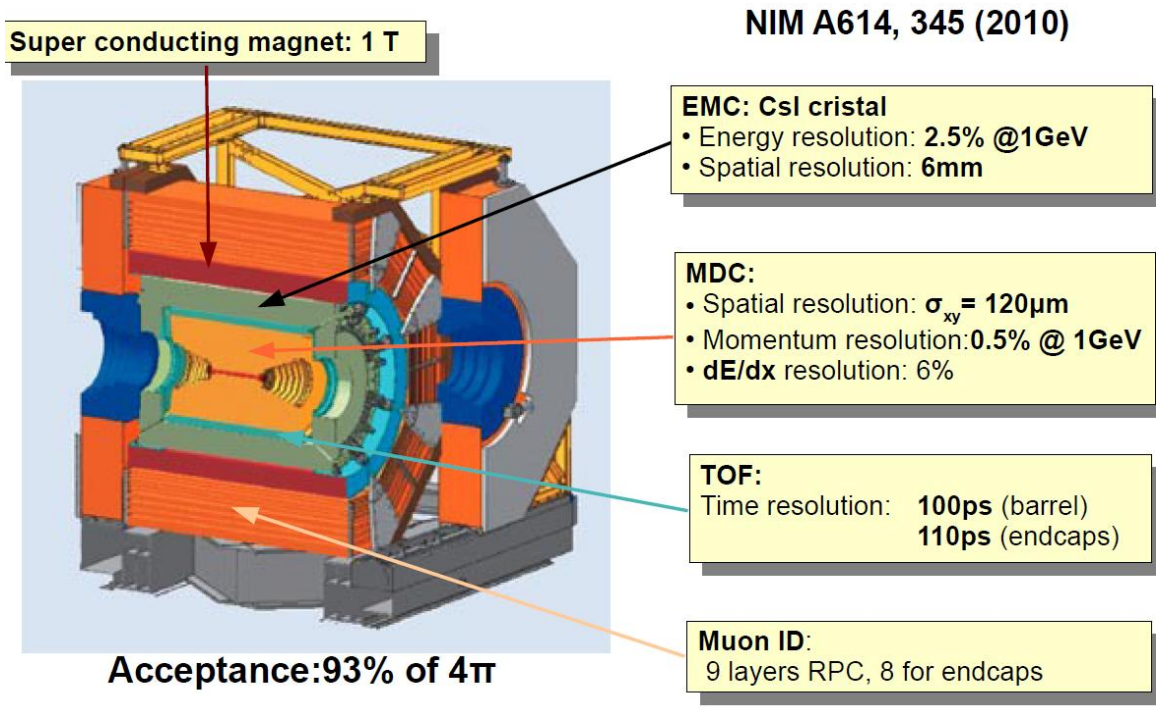


Large cross-section at low energies allows
to build factories and produce huge amount
of c-quarks (D-mesons) and b-quarks (B-mesons)

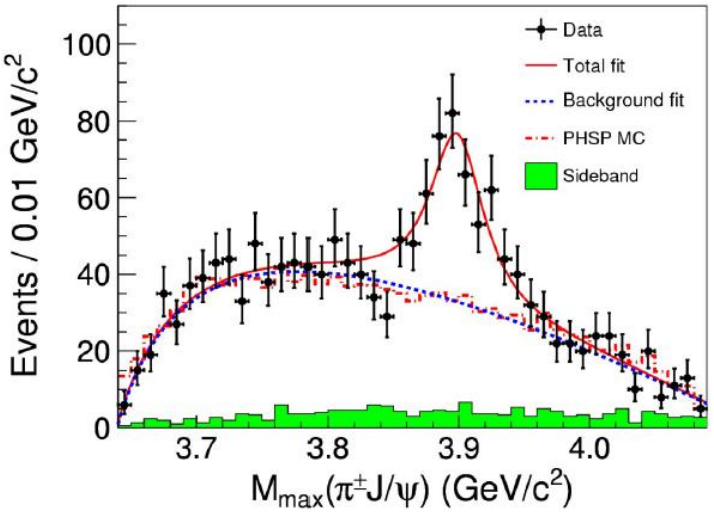
BESIII experiment at BEPC-II collider

BESIII experiment

- Collision energy
  - 2.0 – 4.9 GeV
  - Plan: 5.6 GeV
- Luminosity
  - 1.0×10^{33} cm^{-2} s^{-1}
- Circumference
  - 237m
- Statistics:
  - 10×10^{9} J/ψ
  - 0.4×10^{9} ψ'
  - 3 fb^{-1} at ψ'' (20M $e^+e^- \rightarrow$ DD)
  - Plan: 20 fb^{-1}



Discovery of tetraquarks at BESIII



$e^+e^- \to \pi^+\pi^- J/\Psi$ at 4260 MeV

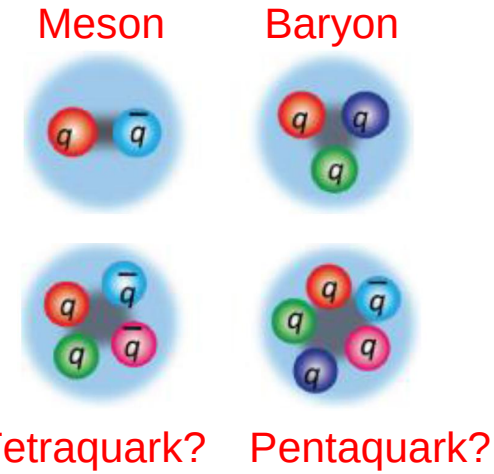
M = 3899.0±3.6±4.9 MeV

Γ = 46±10±20 MeV

Fraction=(21.5±3.3±7.5)%

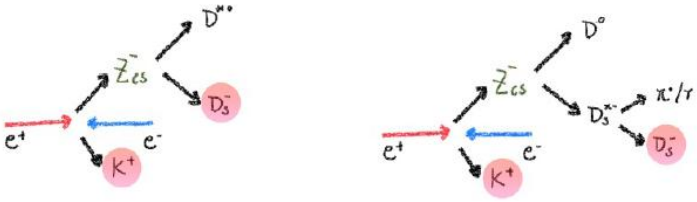
Significance > 8σ

- In the conventional quark model the hadrons are either mesons (quark-antiquark) or baryons (3 quarks)
- The decay $Z_c \to \pi^\pm J/\psi$ can be only explained if Z_c consists of 2 quarks and 2 antiquarks



Discovery of a strange tetraquark

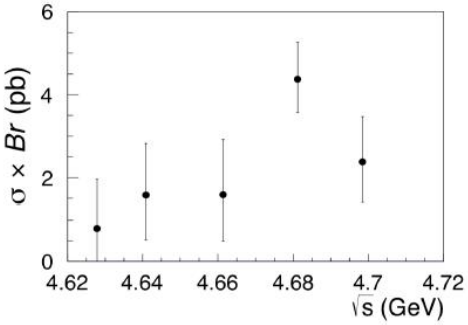
$e^+e^- \to K^+(D_S^- D^{*0} + D_S^{*-} D^0)$



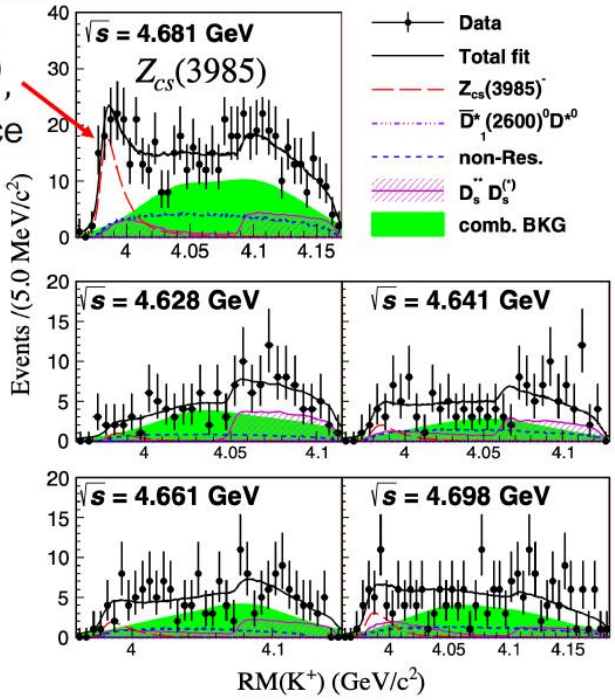
Enhancement not explained by $D_S^{**} D_S^{(*)}$, neither by interference

- Added a new resonance in the fit, assuming $J^P=1^+$
- Significance: 5.3σ
- Minimal quark content $c\bar{c}s\bar{u}$?
- Similar to $Z_{cs}(4000)$ seen by LHCb (widths differ)

PRL127, 082001 (2021)



Coupling with Y state
$e^+e^- \to Y \to K Z_{cs}(3895)$
?

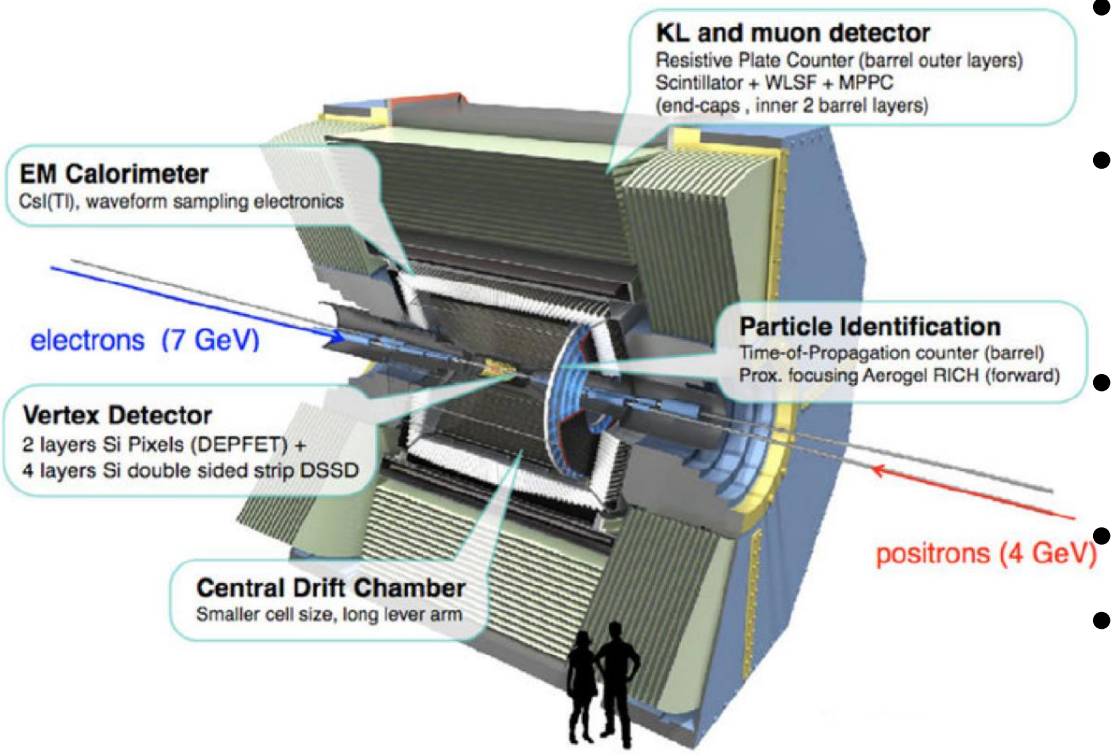


PRL126, 102001 (2021)

$m_{\rm pole}[Z_{cs}(3985)^-] = (3982.5^{+1.8}_{-2.6} \pm 2.1)\ {\rm MeV}/c^2,$

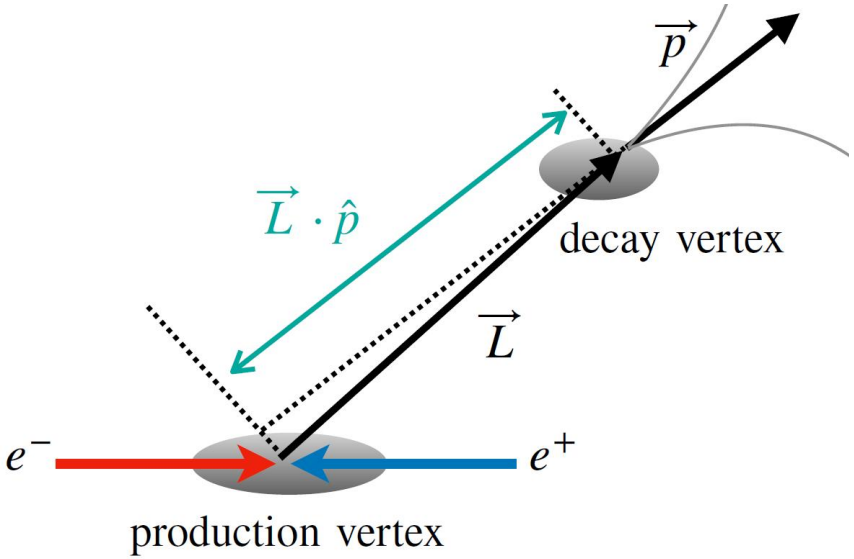
$\Gamma_{\rm pole}[Z_{cs}(3985)^-] = (12.8^{+5.3}_{-4.4} \pm 3.0)\ {\rm MeV}.$

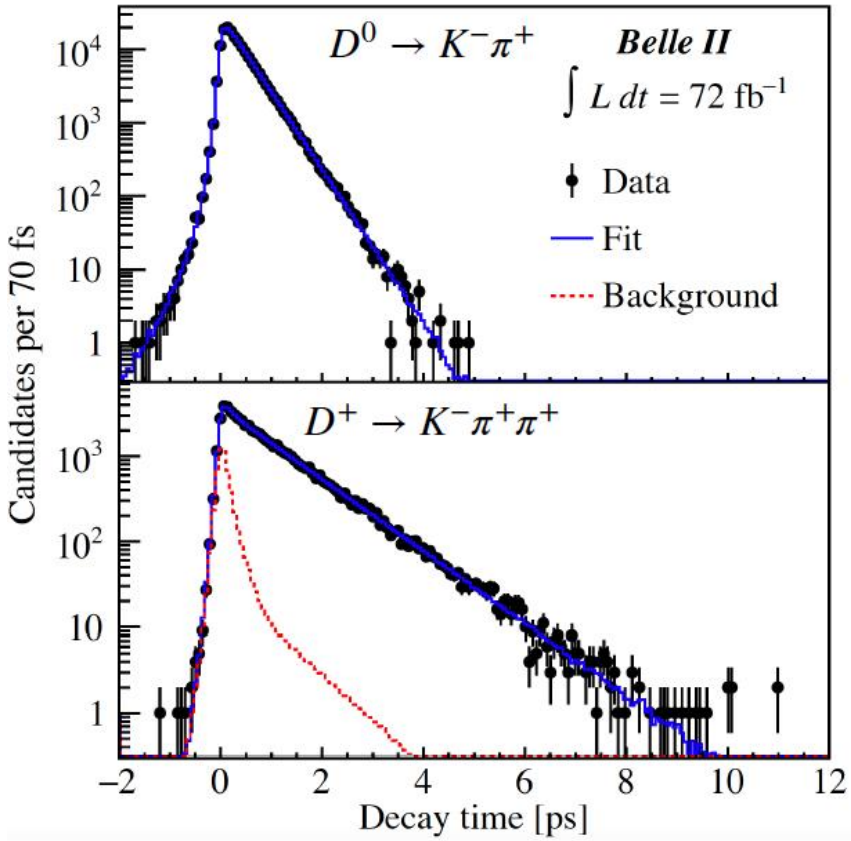
Belle II B-factory (Tsukuba, Japan)



- Asymmetric e^+e^- collisions 4+7 GeV
- Maximum production of $e^+e^- \rightarrow \Upsilon \rightarrow BB$
- Collected 0.43 ab^{-1} (0.5×10^9 B-pairs)
- Plan: 50 ab^{-1}
- Previous Belle experiment (1999-2010): 0.7 ab^{-1}, 0.8×10^9 B-pairs

Measurement of charm lifetime





World-best measurements:

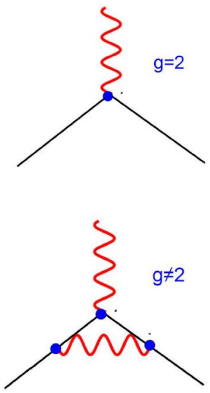
$$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8 \text{ fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1 \text{ fs}$$
$$\tau(\Lambda_c^+) = 203.2 \pm 0.9 \pm 0.8 \text{ fs}$$

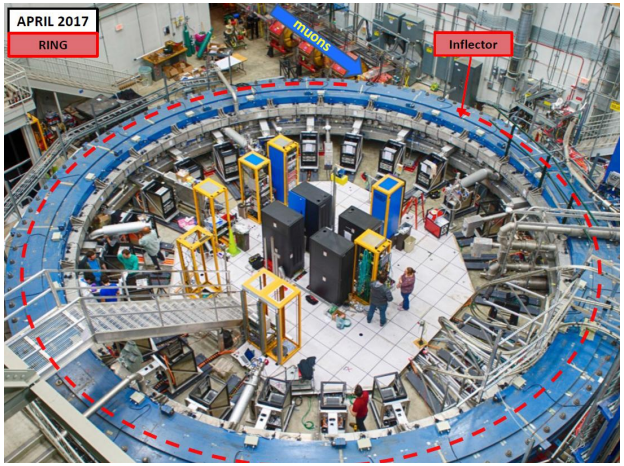
Before we go to LHC…

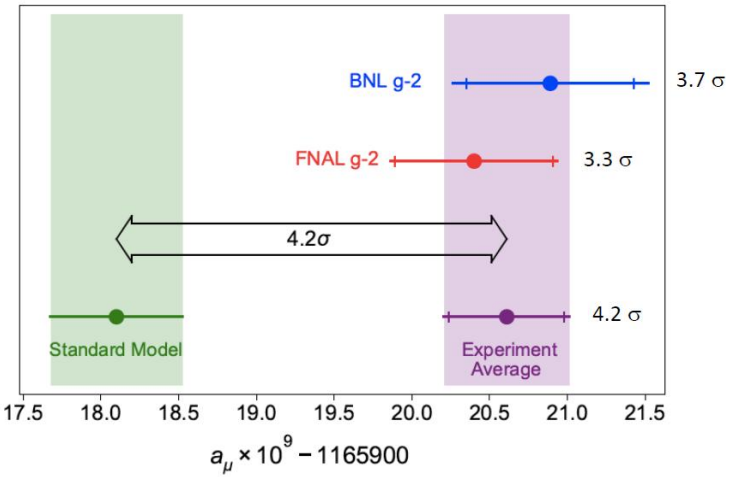
Non-collider experiments

- Neutrino physics
  - Reactors
  - Accelerators
  - Cosmic rays
  - Radioactivity (neutrinoless double β-decay)
- Astroparticle physics (ultra-energetic cosmic rays)
- Dark matter searches
- Many other fields

Fermilab muon g-2 experiment







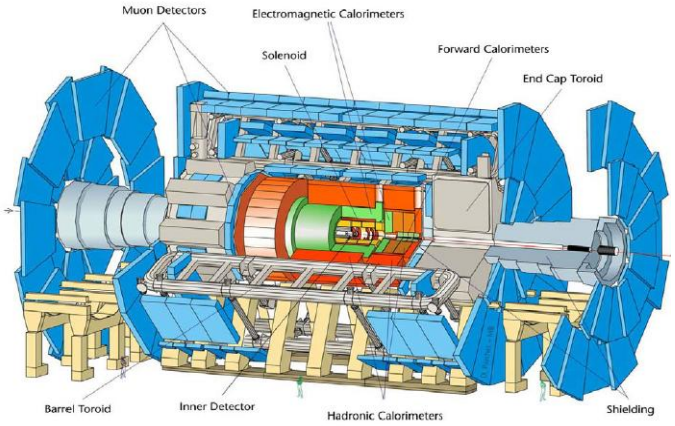
- Anomalous magnetic moment of leptons can be measured and theoretically calculated to fantastic precision: 10^{-12} for electron, 10^{-9} for muon
- Fermilab muon g-2 experiment is currently taking data
- First (small) piece of data in combination with BNL result gives 4.2σ discrepancy with theoretical calculation
- New physics??

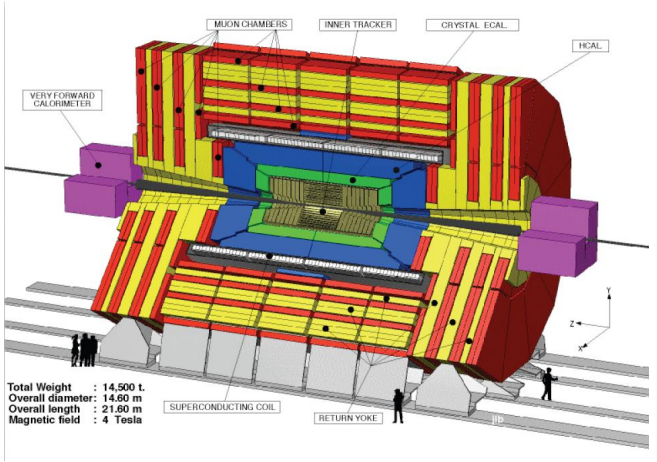
The LHC collider

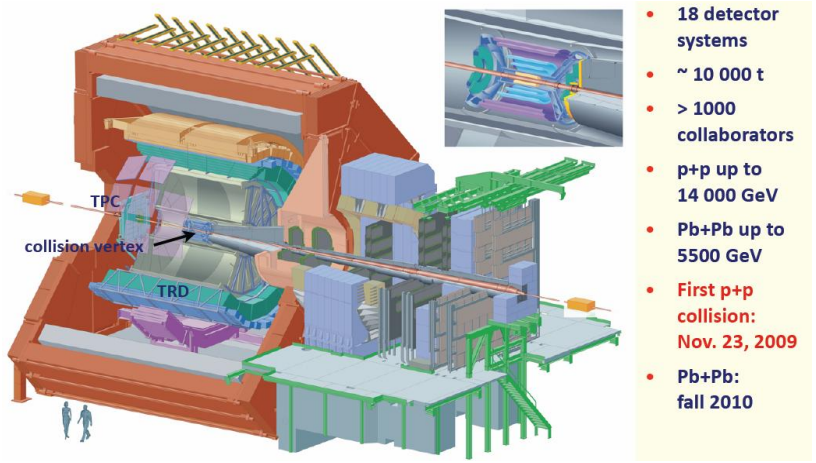
LHC history

- 1984: conceptual ideas
- 1995: budget approved
- 1999: civil engineering work started
- 2008: first beam
- 2010: first useful data (7 TeV)
- 2012: Higgs boson discovered (8 TeV)
- 2015-2018: Run-2 (13 TeV, 140fb^{-1})
- 2022-2025: Run-3 (13.6 TeV, ~300fb^{-1})
- 2029-2032: Run-4 ("HL-LHC", ~3000fb^{-1})
- 2035?: Run-5? Higher energy?

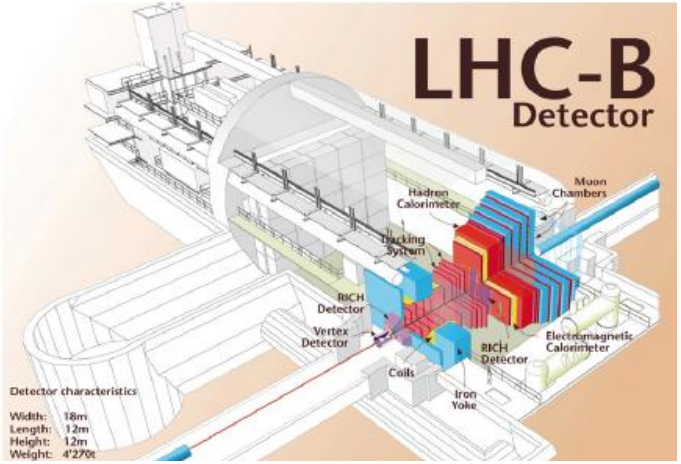
Major LHC experiments



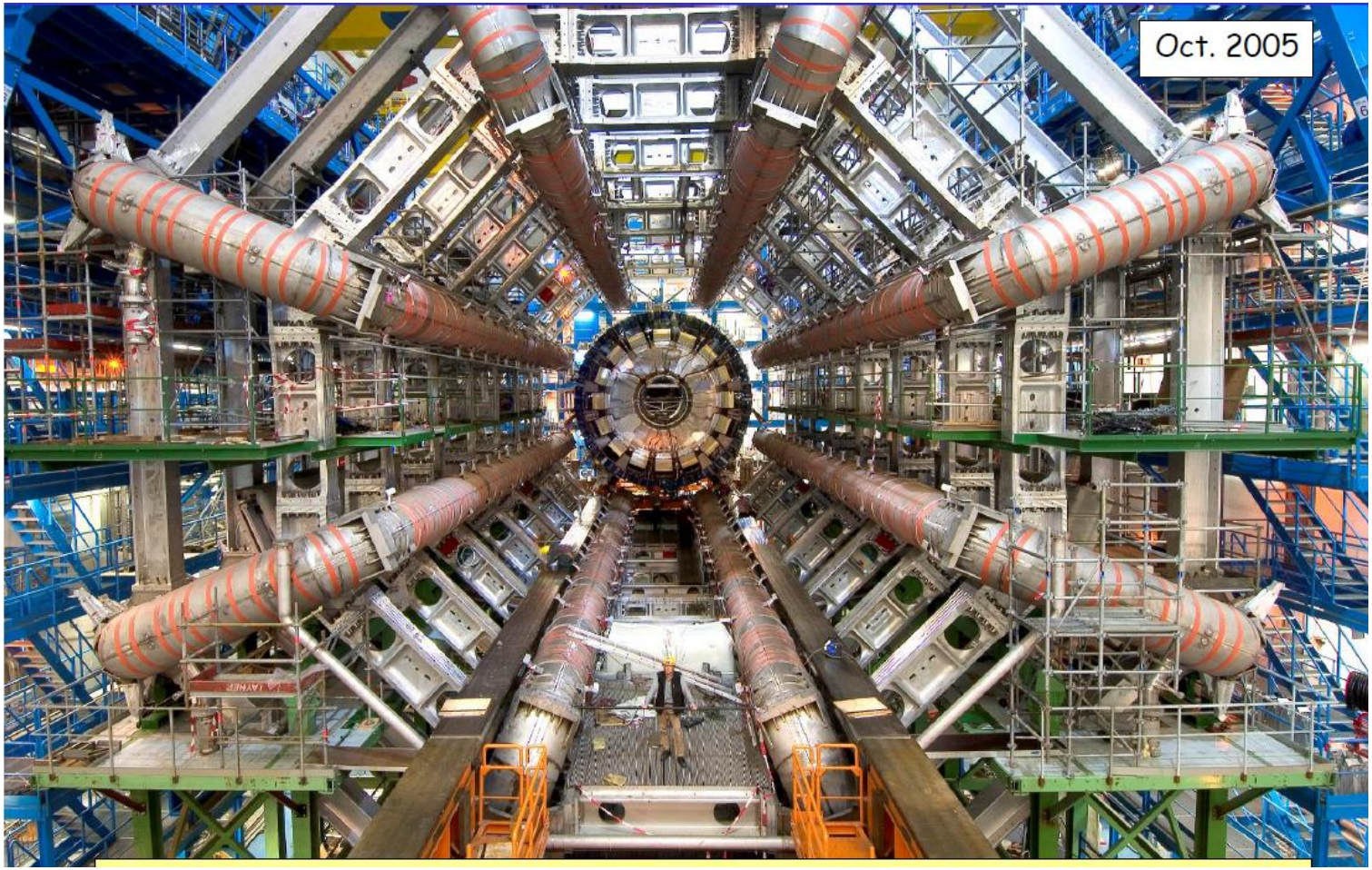




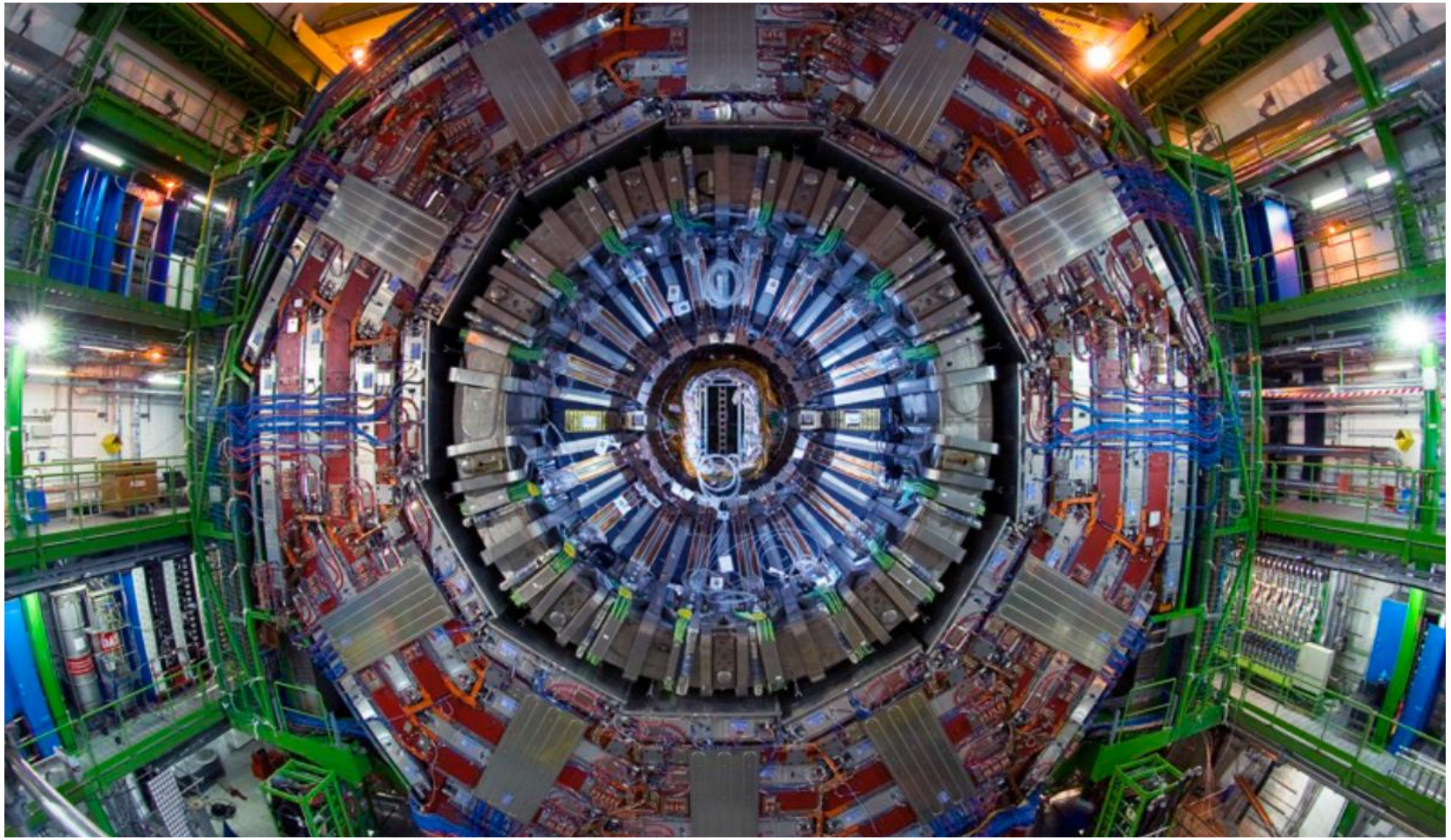
- 18 detector systems
- ~ 10 000 t
- > 1000 collaborators
- p+p up to 14 000 GeV
- Pb+Pb up to 5500 GeV
- First p+p collision: Nov. 23, 2009
- Pb+Pb: fall 2010



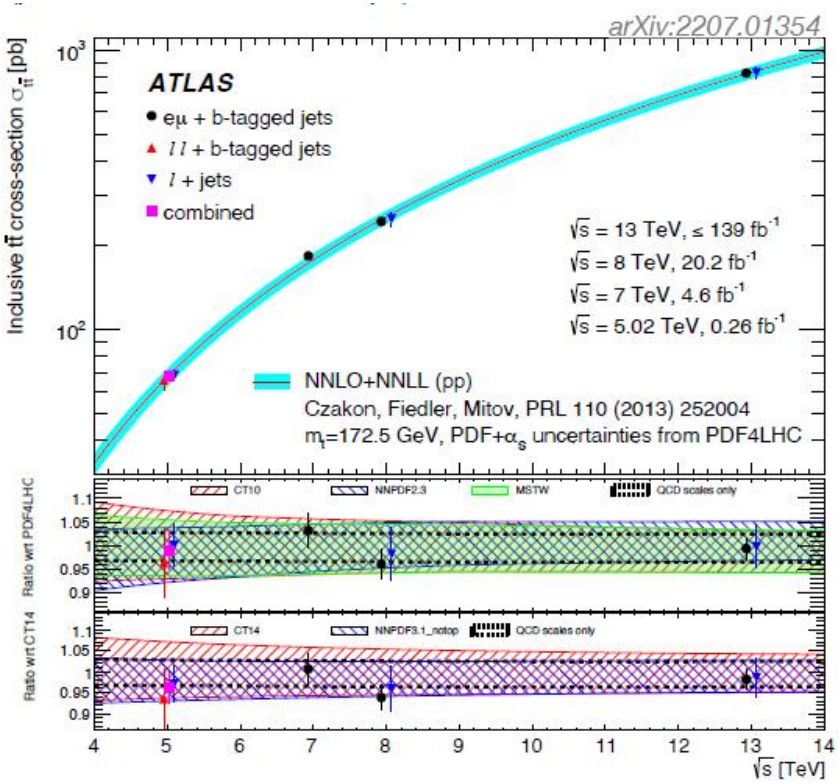
ATLAS

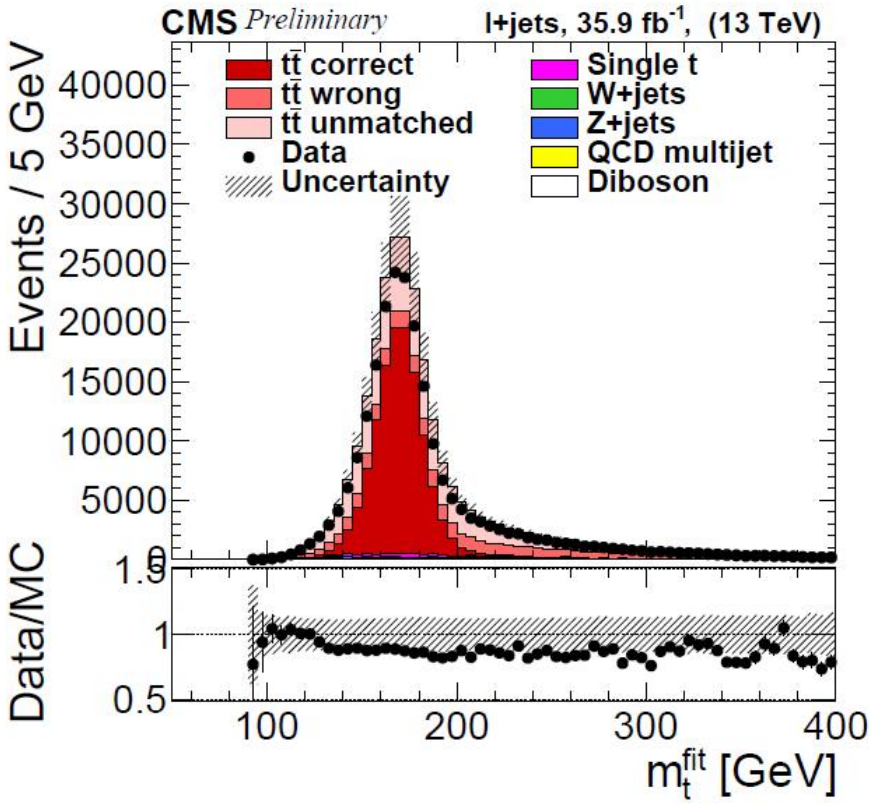


CMS



Top physics in ATLAS and CMS



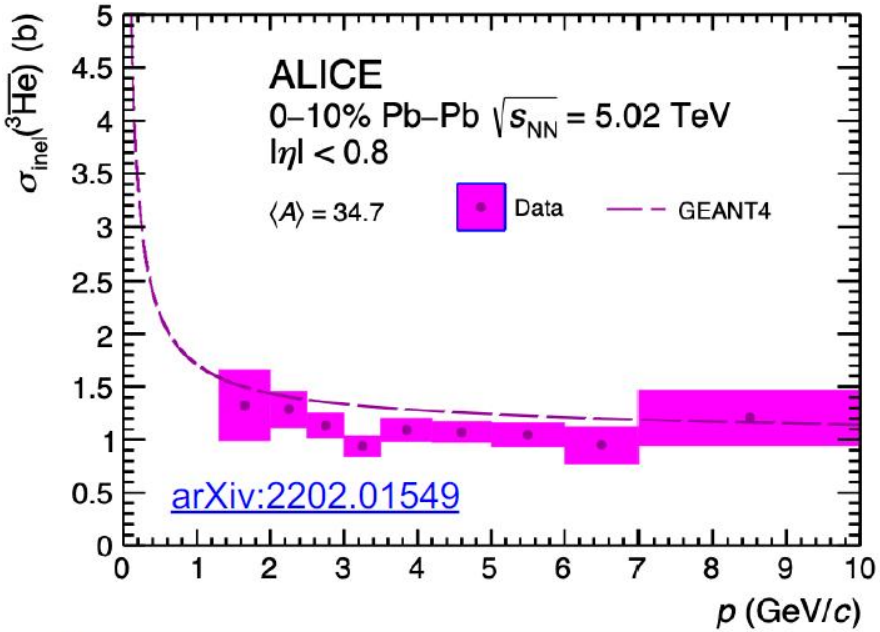


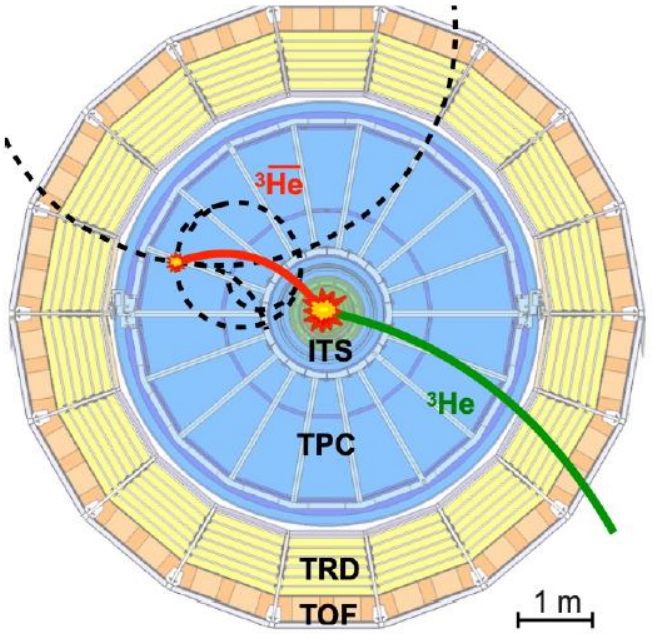
Recent ATLAS result:
$\sigma_{tt}(5TeV) = 67.5 \pm 2.7$ pb

Recent CMS result:
$m_t = 171.77 \pm 0.38$ GeV

ALICE

ALICE measurement of antihelium absorption



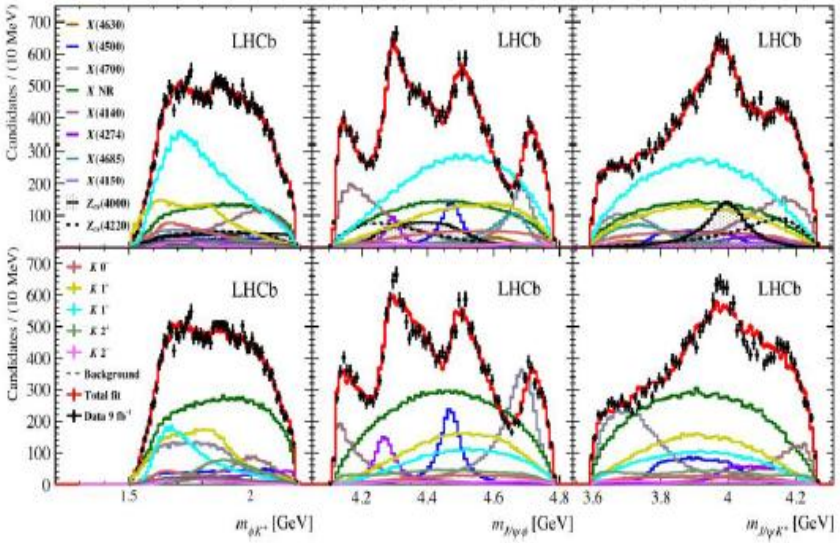


- Novel technique to use detector material as $\bar{d}$ and ^3He absorber: measure σ_{inel}
  - First measurement for $\overline{^3He}$

LHCb

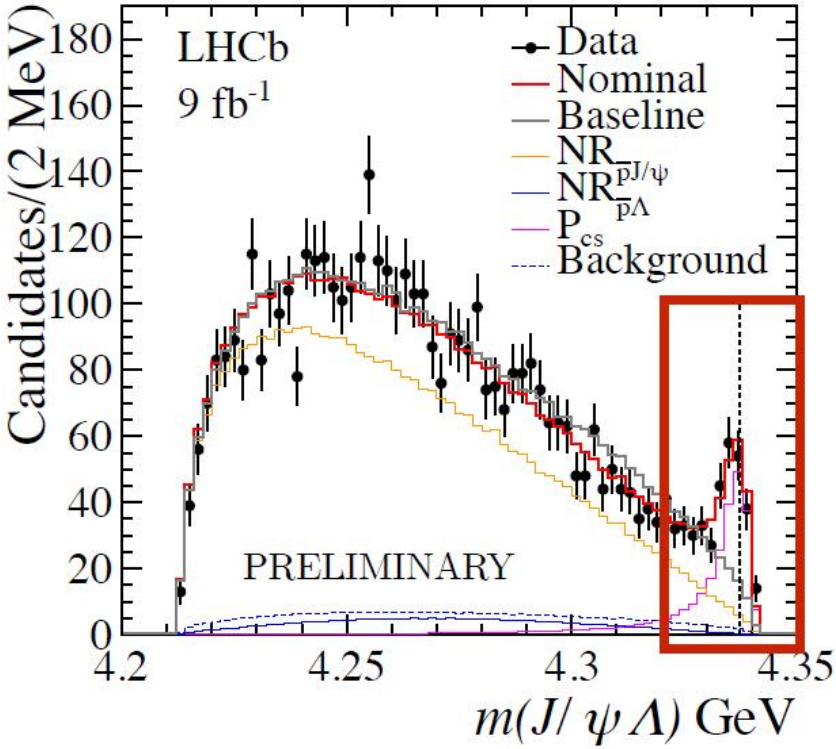
LHCb tetra- and pentaquarks

$B^+ \to J/\psi\phi K^+$



$Z_{cs}(4000)^+$

$B^- \to J/\psi\Lambda\bar{p}$



Confirmation of BESIII strange tetraquark Zcs (and observation of many other tetraquarks and pentaquarks)

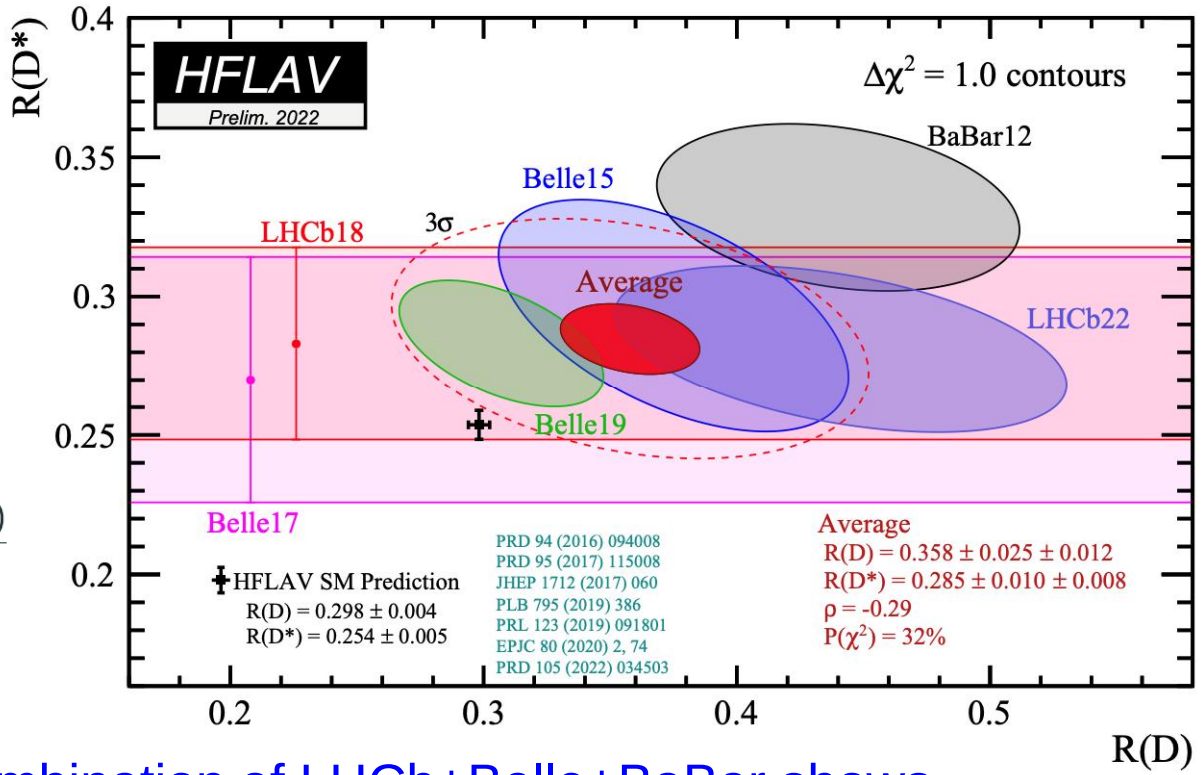
First strange pentaquark: $P^{\Lambda}_{\psi s}(4438)^0$ $(c\bar{c}uds)$

Lepton universality test in B→τ/μ/e

$$R(D) = \frac{\mathcal{B}(B^0 \to D\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D\ell\nu_\ell)}$$

$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^*\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^*\ell\nu_\ell)}$$

$\ell = e, \mu$ for B-factories

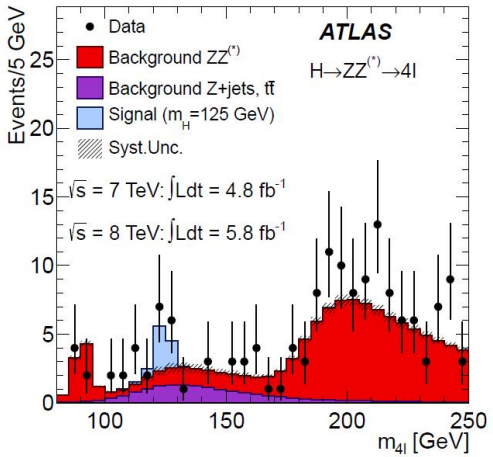


Combination of LHCb+Belle+BaBar shows more that 3σ deviation from SM

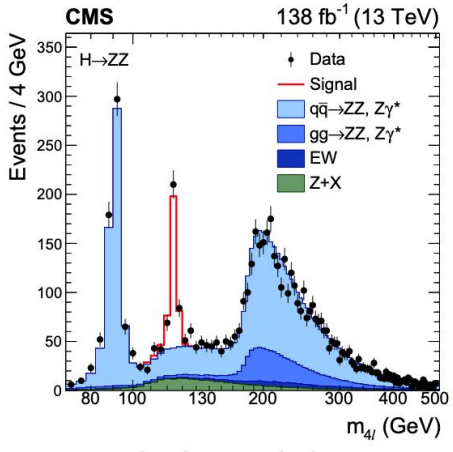
Higgs physics in ATLAS and CMS

H → ZZ

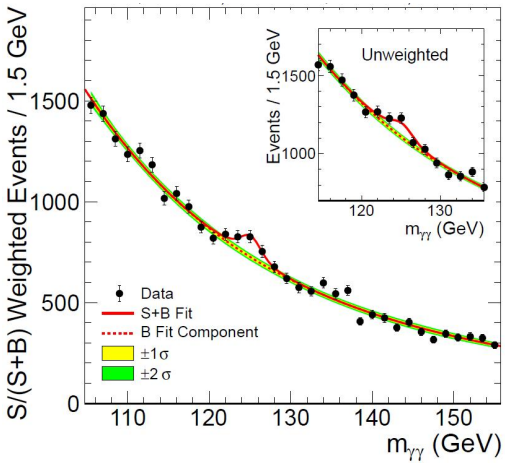
2012

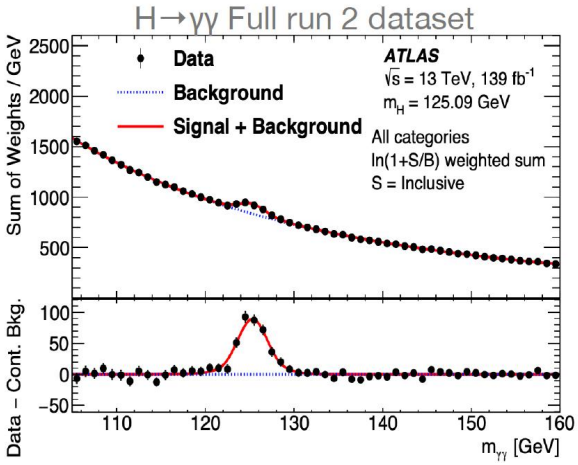


2022

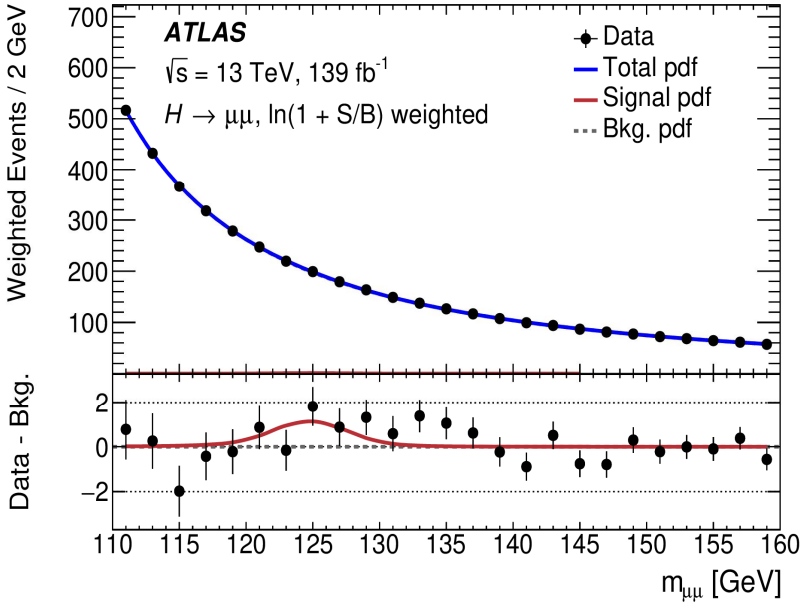


H → γγ

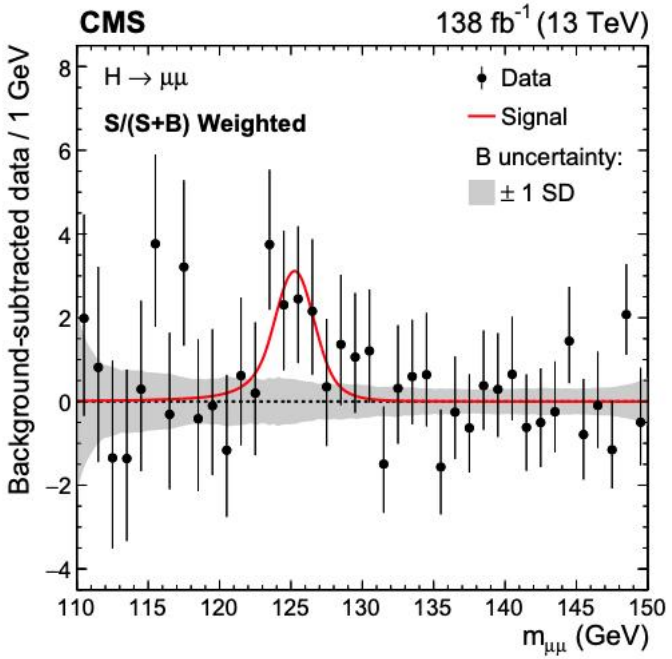




First evidences of H→μμ

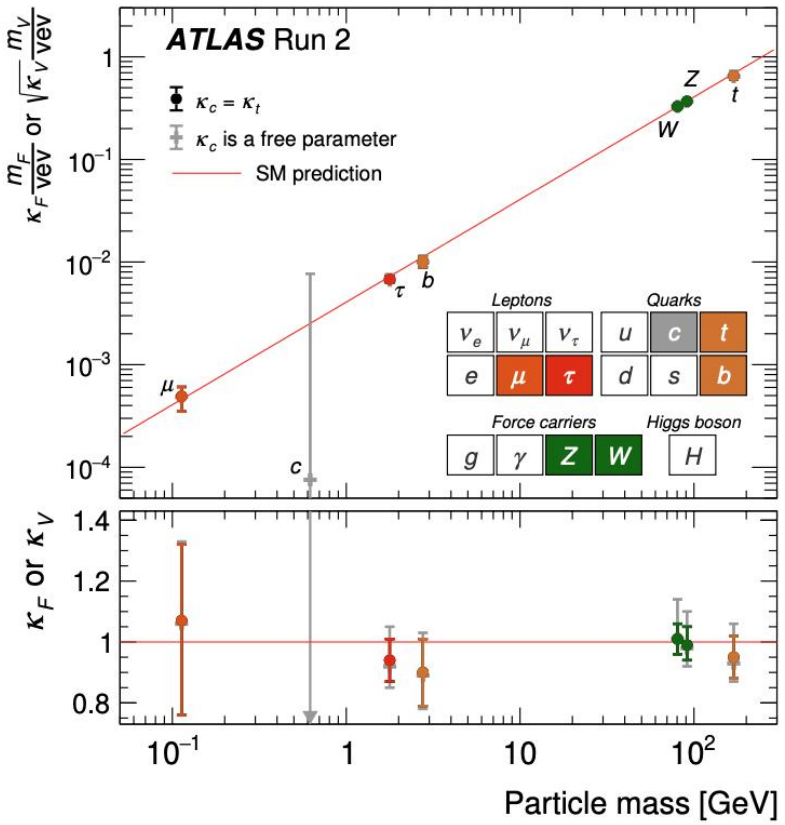


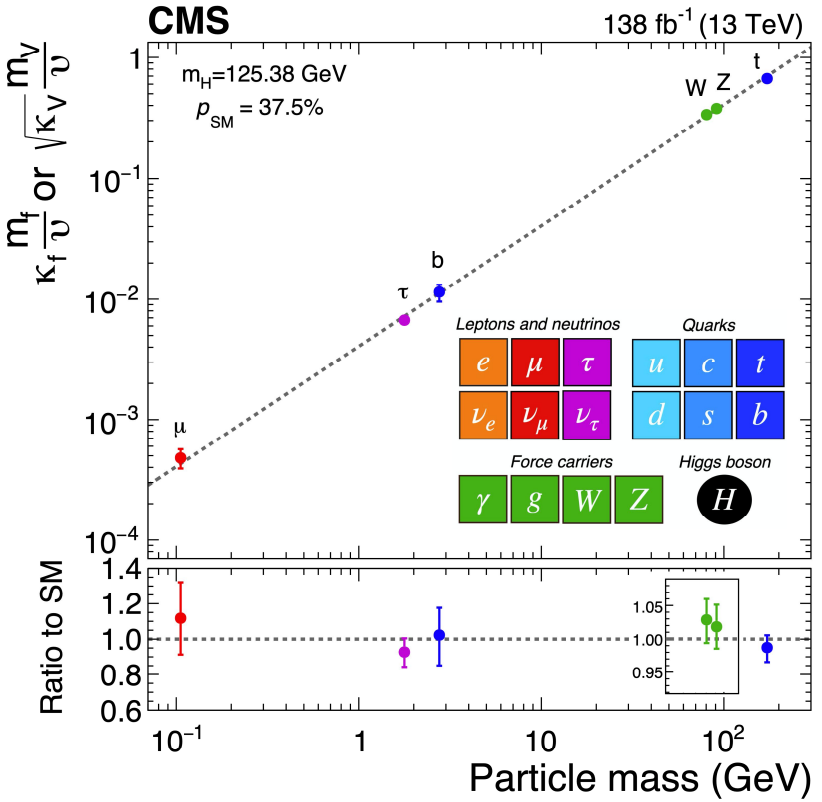
2σ effect



3σ effect

Mass dependence of Higgs force





Agreement of Higgs signal with theory prediction

ATLAS

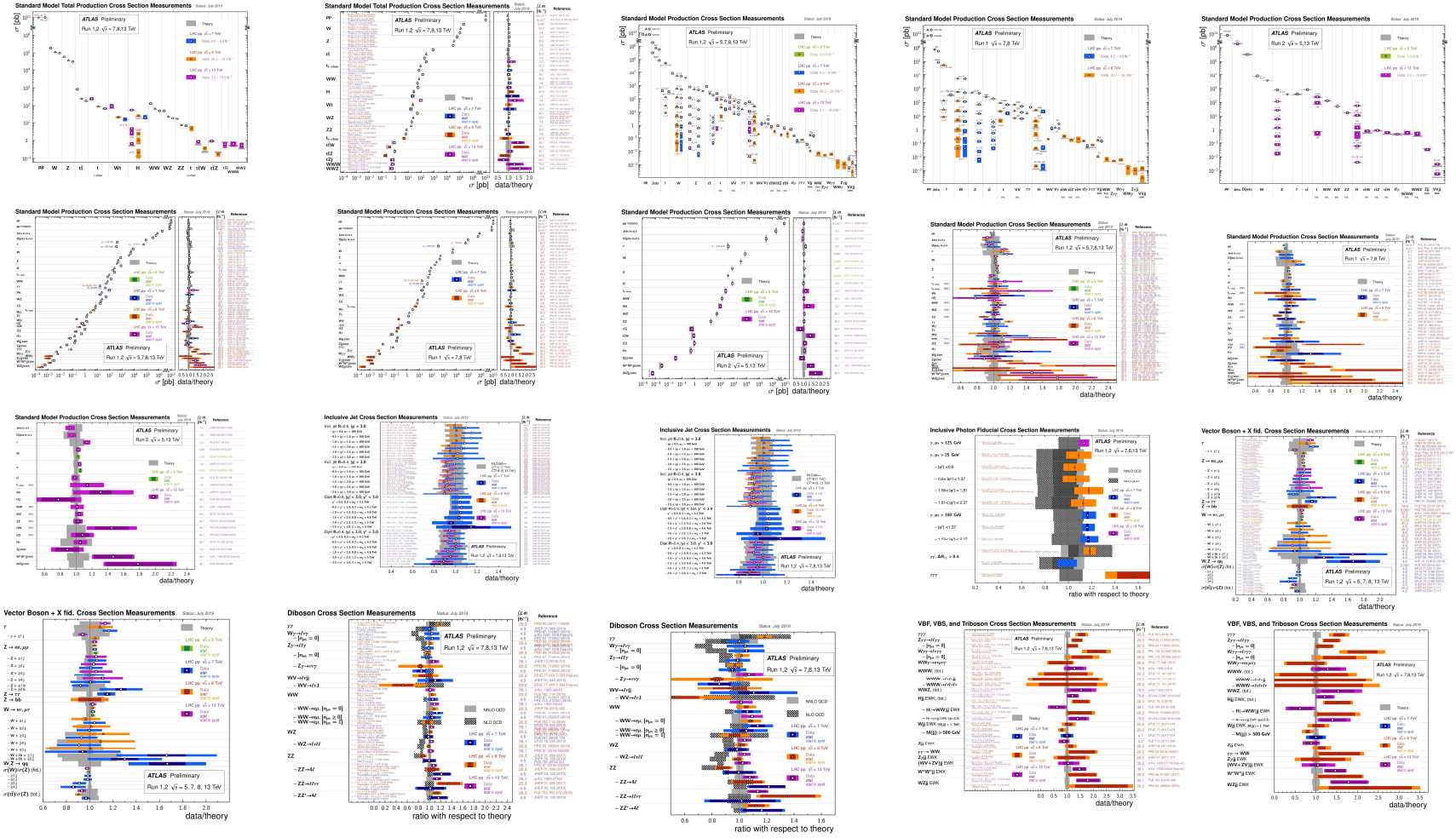
$\mu = 1.05 \pm 0.04\ (\text{th}) \pm 0.03\ (\text{exp}) \pm 0.03\ (\text{stat})$

CMS

$\mu = 1.002 \pm 0.036\ (\text{th}) \pm 0.033\ (\text{exp}) \pm 0.029\ (\text{stat})$

μ is the ratio of observed signal to theory prediction

All ATLAS results in one slide :-)

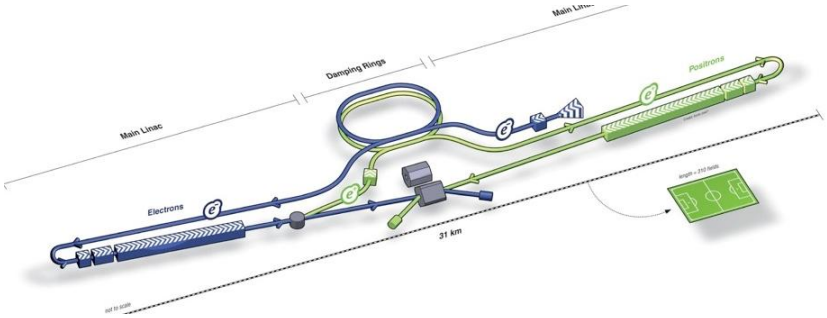


After LHC: what next?

- LHC energy upgrade: HE-LHC (33 TeV)
- Circular collider
  - e^+e^- 250-360 GeV
  - pp 100 TeV
- Linear collider
  - e^+e^- up to 3 TeV

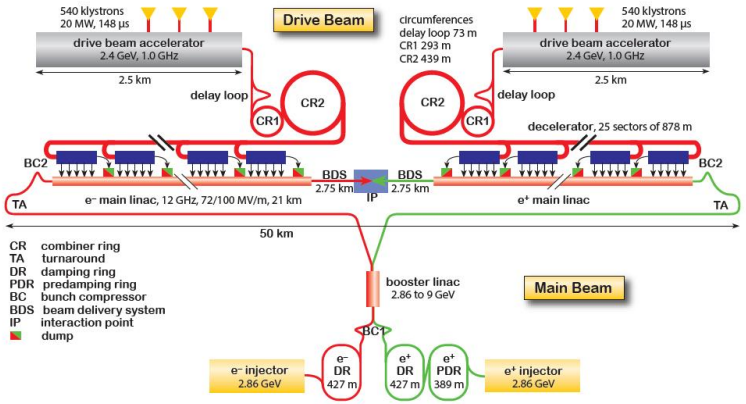
ILC (2030)

$ 4-5G



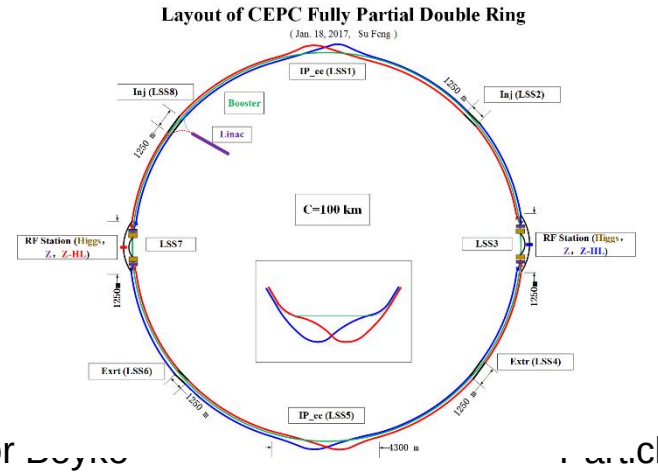
CLIC (2035)

$ 6.7G (380 GeV)
$13G (3000 GeV)



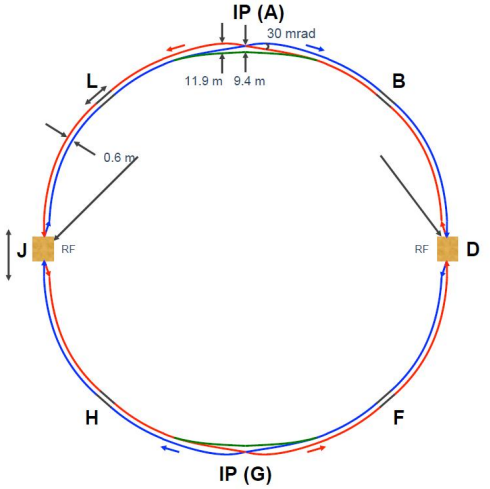
CEPC (2030)

$ 5.5G

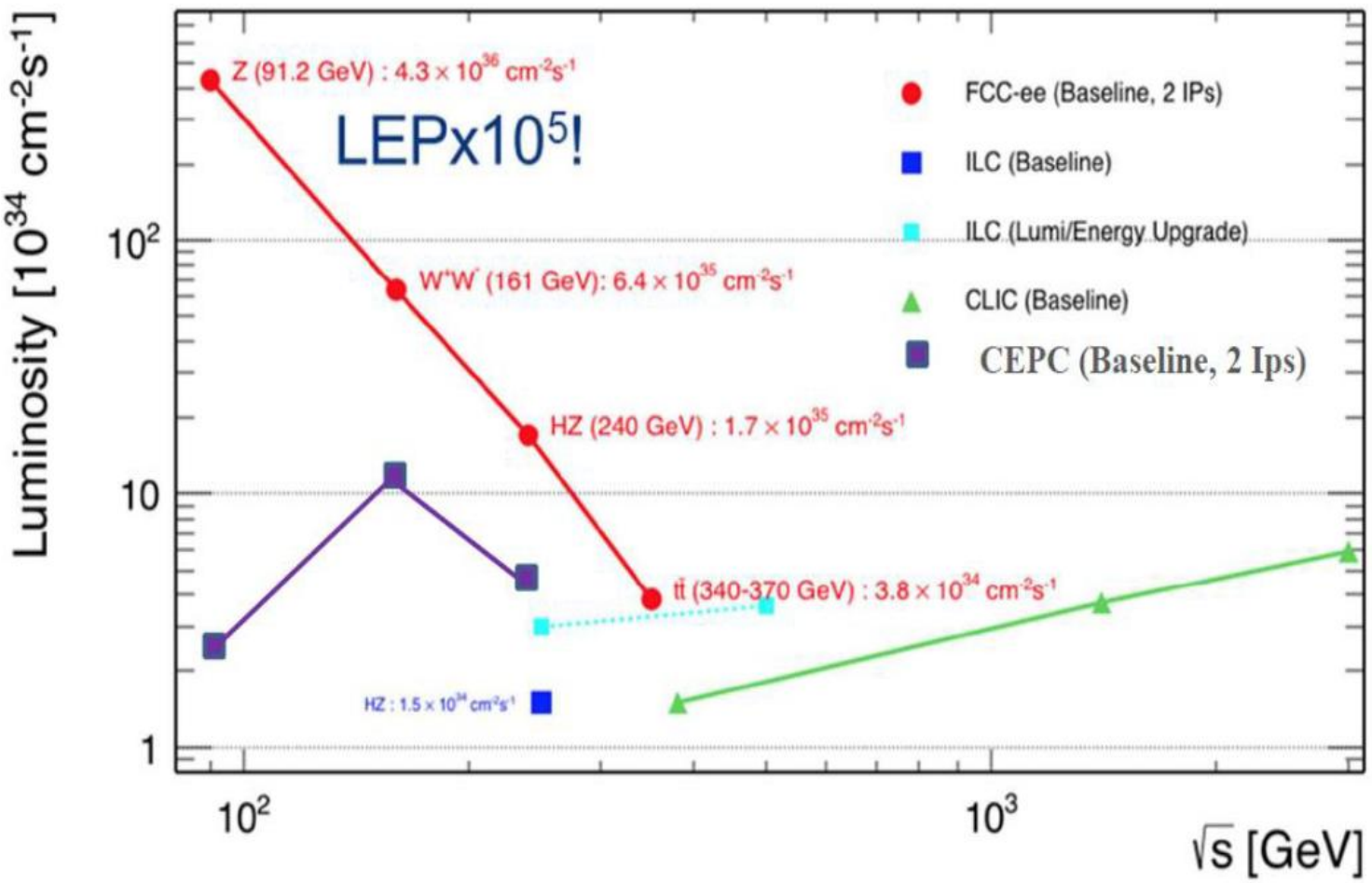


FCC-ee (2039)

$ 12G



Luminosity/energy



Summary

- Enormous amount of experimental studies is being carried out in all fields of particle physics
- Discovery of the Higgs boson was a triumph for both theory and experiment. Higgs physics is now entering the precision stage (few % level)
- Nearly all experiments show perfect agreement with the SM theory
  - Yet, there are few hints of possible deviations
- Planning has already started for the post-LHC era (2030s-2090s)