Hunting for elusive particles at LHC: Start of Run II

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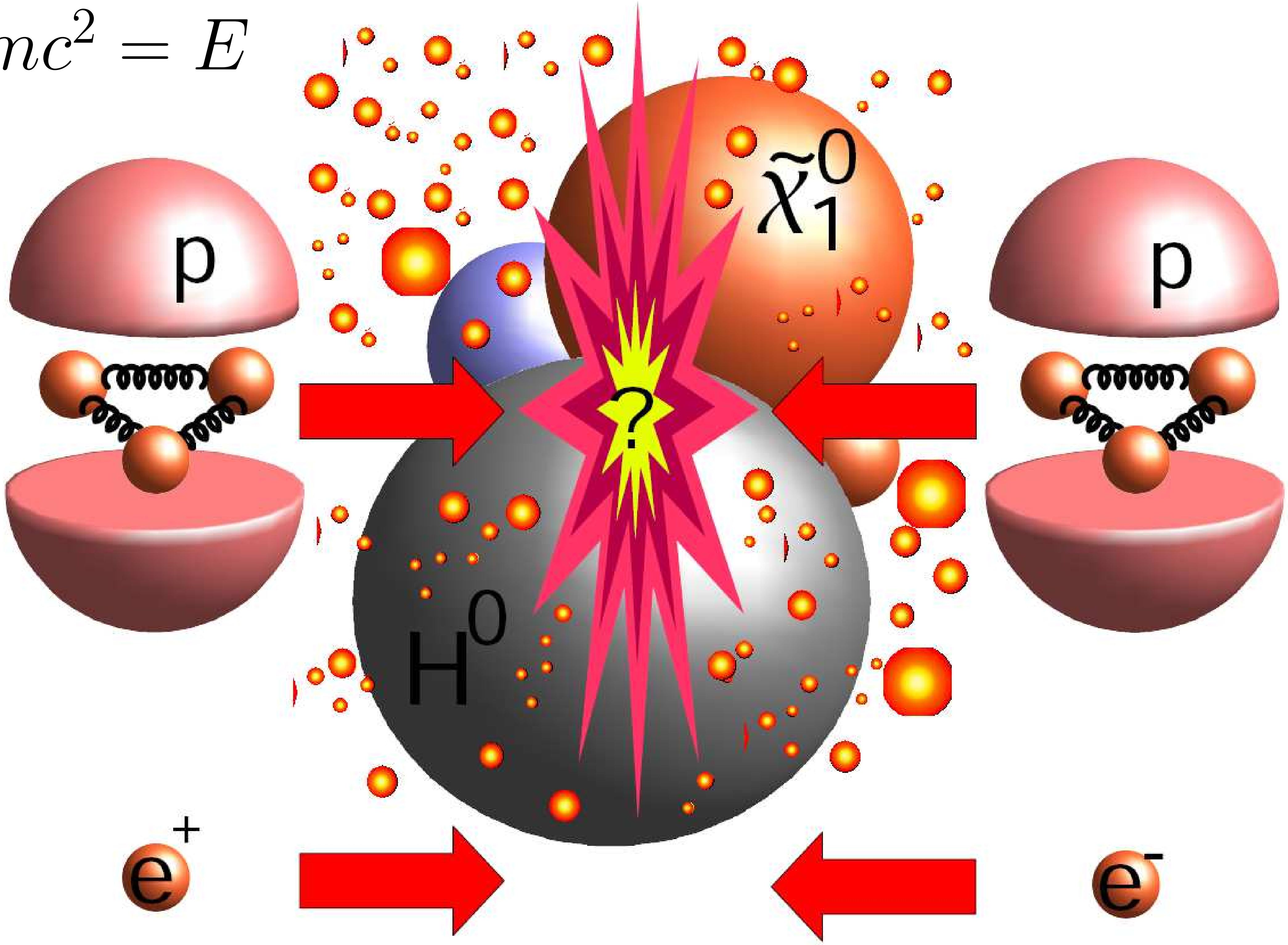
Johns Hopkins University QuarkNet Physics Workshop

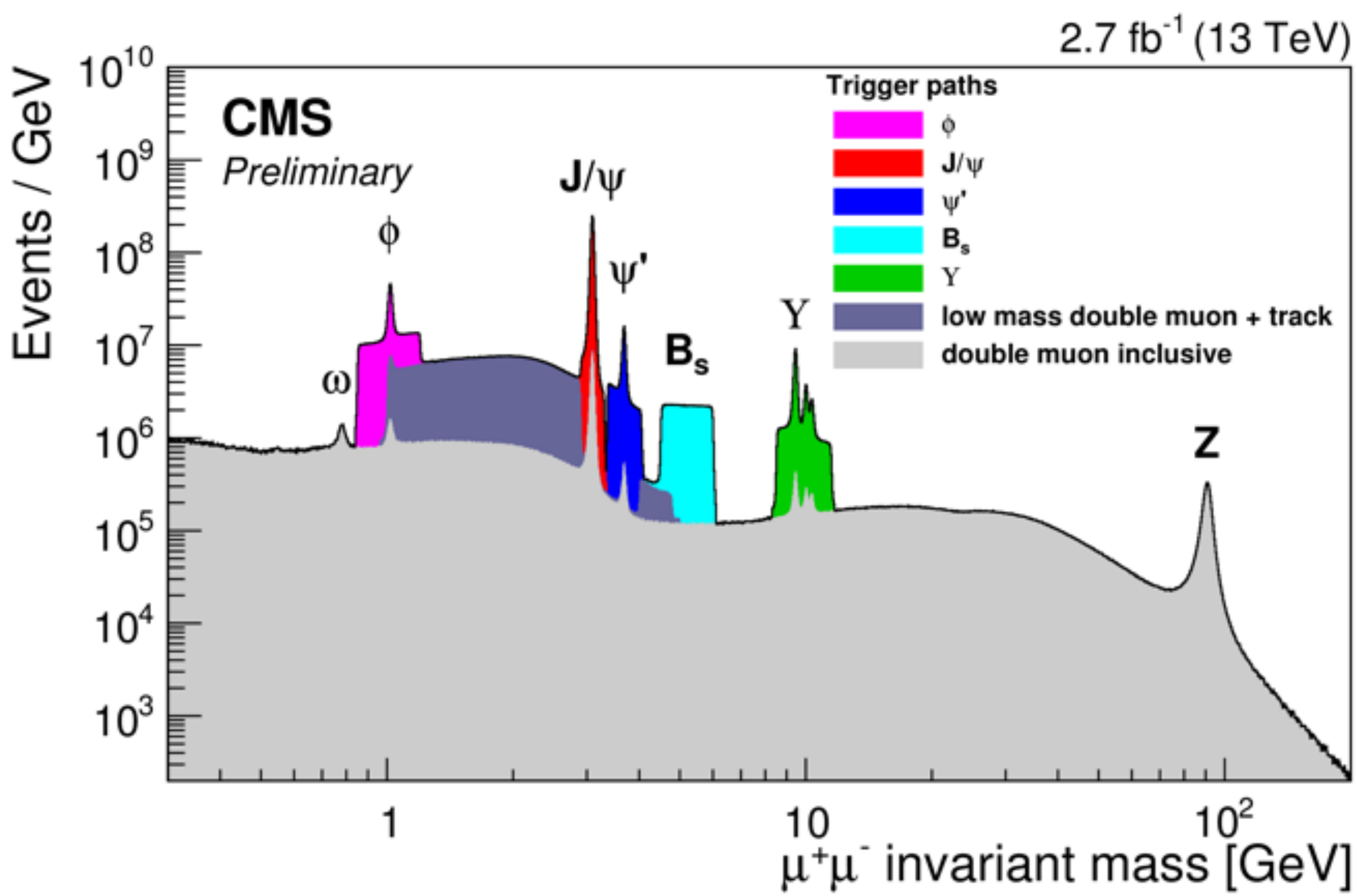
Reaching Highest Energy

- $mc^2 = E$



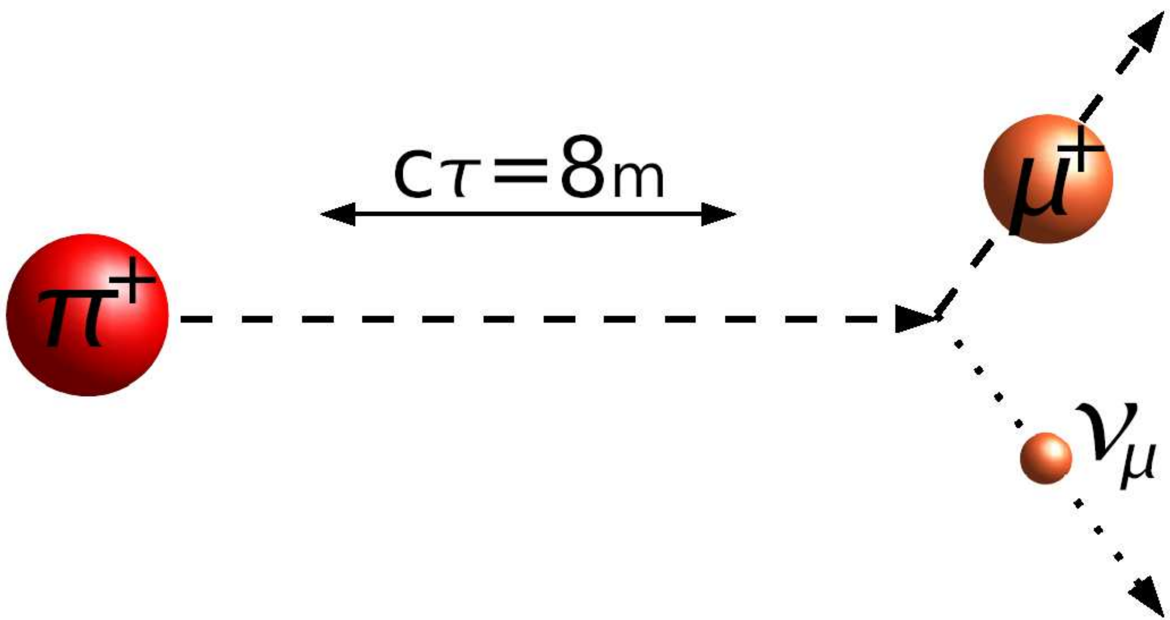
Particles → Resonances → “Bumps”

- We often see particles as “resonances”
  - most particles are not stable
  - reconstruct from their decay products

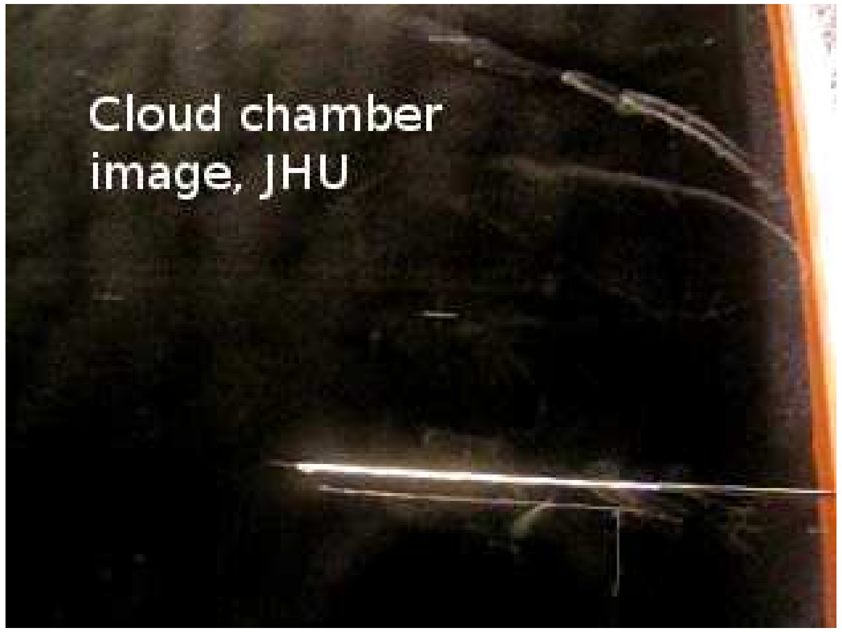


How do We "See" Particles

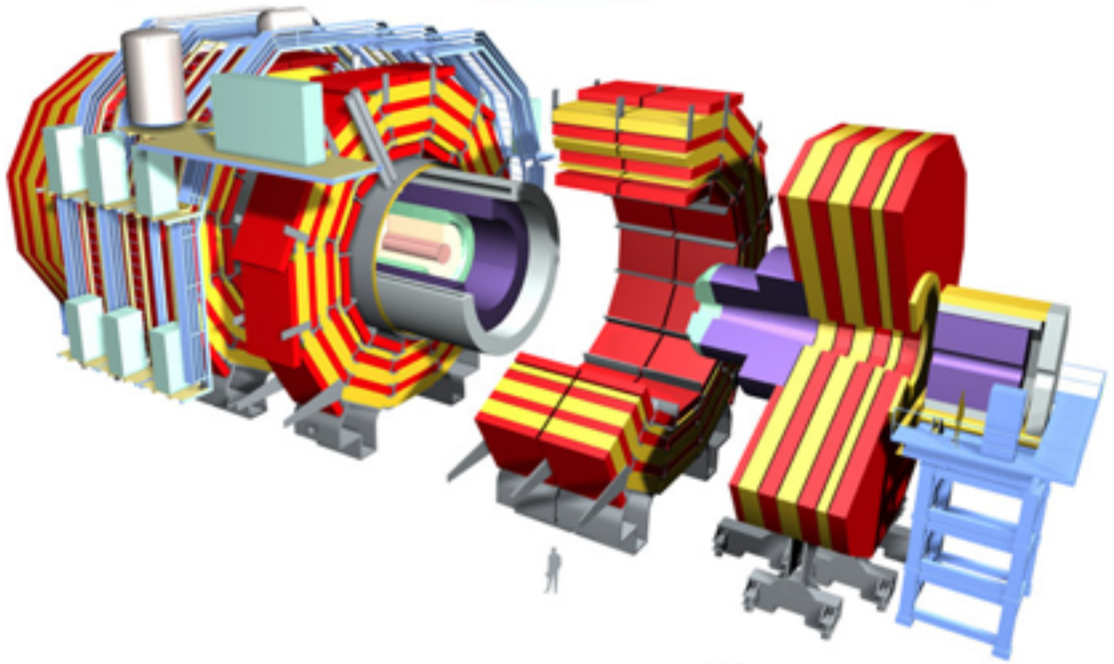
- We "see" semi-stable particles by "tracks" in matter:



- Table-top illustrations



- Complex multi-ton detectors



Particle Data Group: pdg.lbl.gov

$\pi^\pm$ $I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^\pm \to \ell^\pm \nu \gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

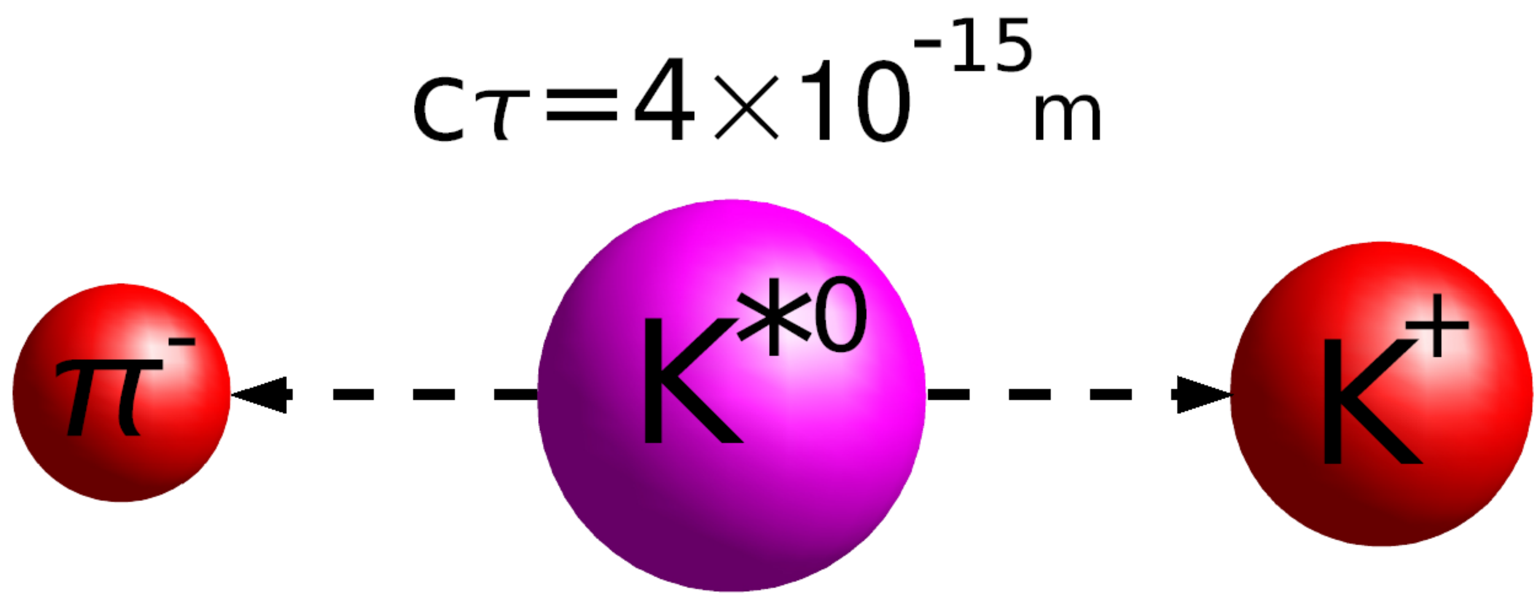
π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$		$< 5 \times 10^{-6}$	90%	70

How do We "See" Particles

- Most particles live too short to be "seen" directly
  - "see" decay products:



- Time (decay) and energy (resonance) amplitudes:

$$A(t) = A(0)e^{iE_0 t/\hbar}e^{-\Gamma_0 t/2\hbar} \quad \Rightarrow \quad |A(t)|^2 \propto e^{-\Gamma_0 t/\hbar} = e^{-t/\tau_0}$$

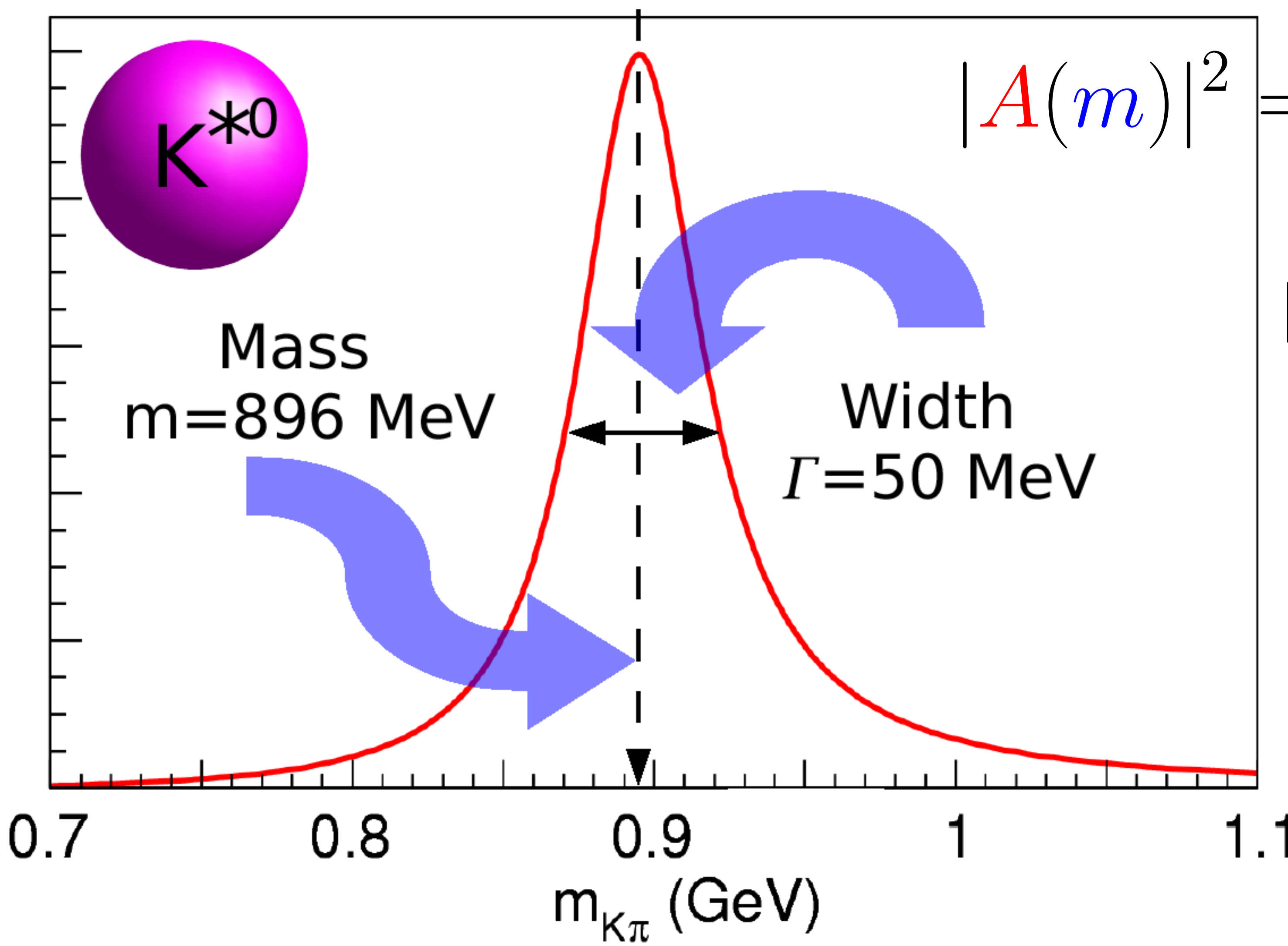
$$A(E) = \int A(t)e^{iEt/\hbar}\mathrm{d}t = \frac{C}{(E - E_0) - i\Gamma_0/2} \qquad \Gamma_0 = \frac{\hbar}{\tau_0}$$

"Resonance"

- The Uncertainty Principle $\Gamma_0 \times \tau_0 = \hbar$

  compare: $\Delta E \times \Delta t \sim \hbar$

- Probability $\propto \; |A(m)|^2$



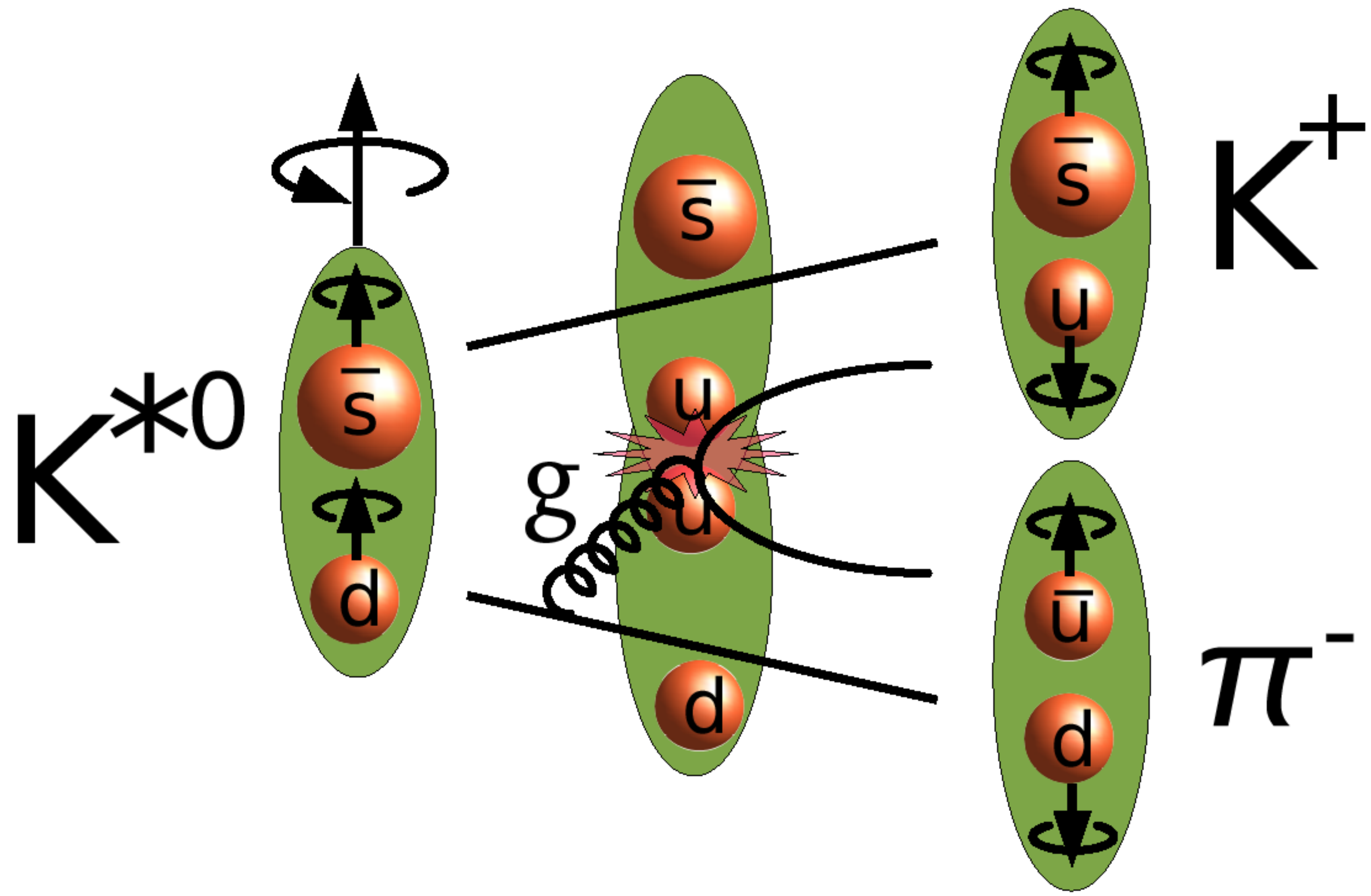
$$|A(m)|^2 = \left|\frac{C}{(m - m_0) - i\Gamma_0/2}\right|^2$$

Breit-Wigner resonance

Decay Dynamics

- Unstable particles decay

  Feynman diagram:

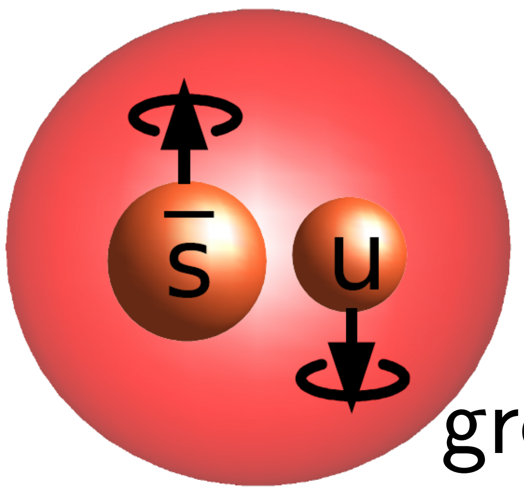


- Decay ⇒ study elementary particles and interactions

  (this "strong" decay is mostly understood)

"Periodic Table" of Mesons

- Quark-antiquark make up a Meson:

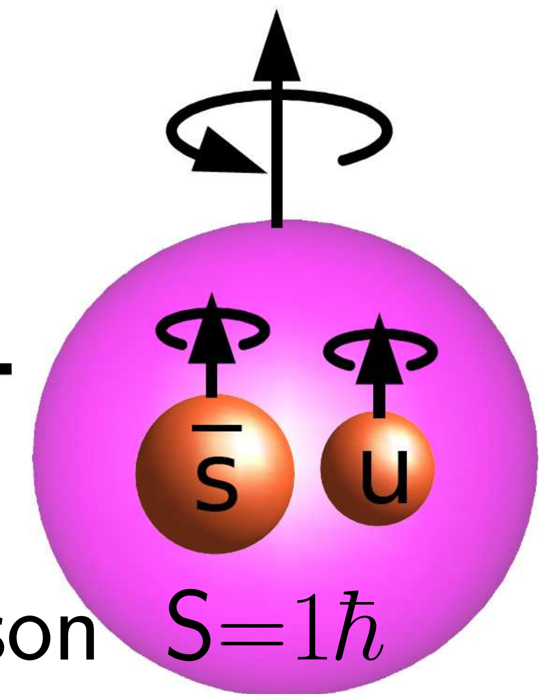


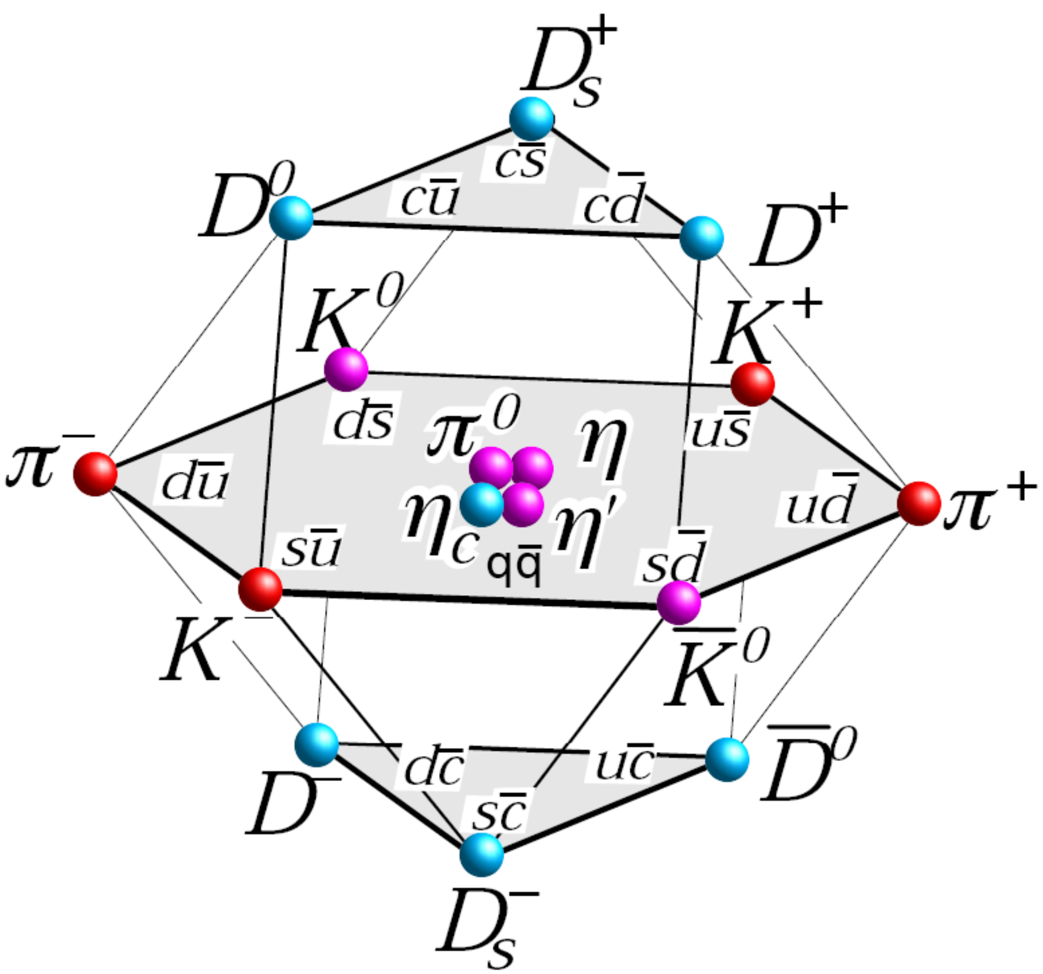
K^+

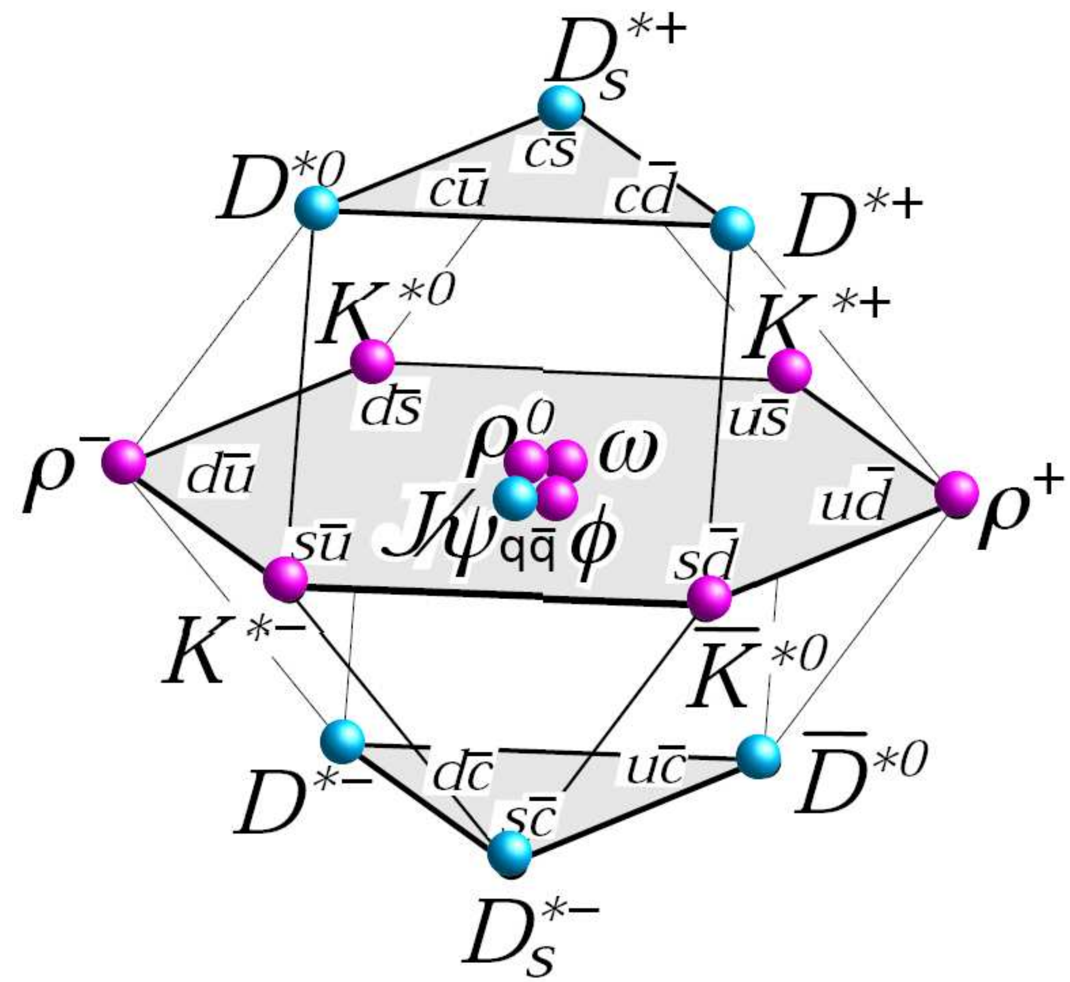
ground state (L=S=0)

K^{*+}

Vector meson

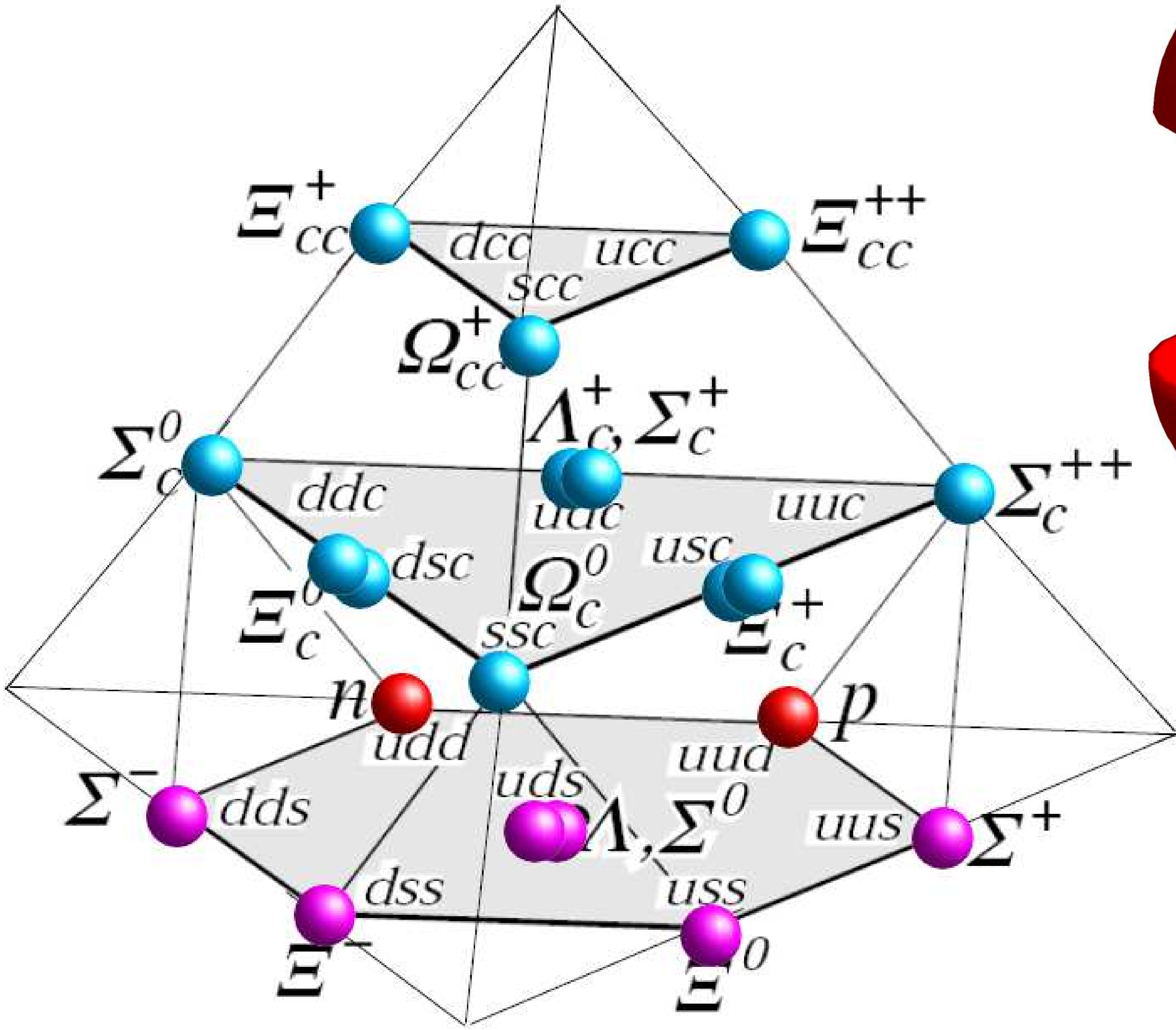


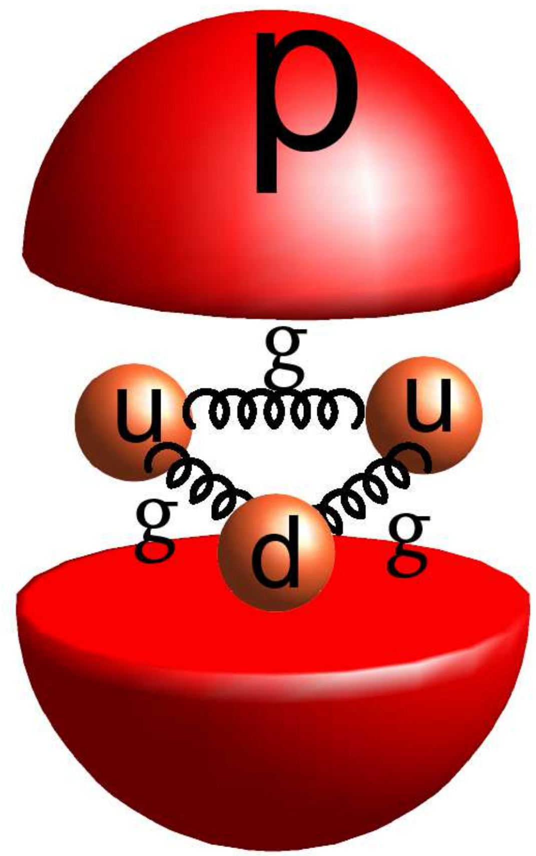




“Periodic Table” of Baryons: Proton, Neutron,...

- Three quarks make up a Baryon:





Particle Data Group: Proton

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014) and 2015 update

N BARYONS
$(S = 0, I = 1/2)$

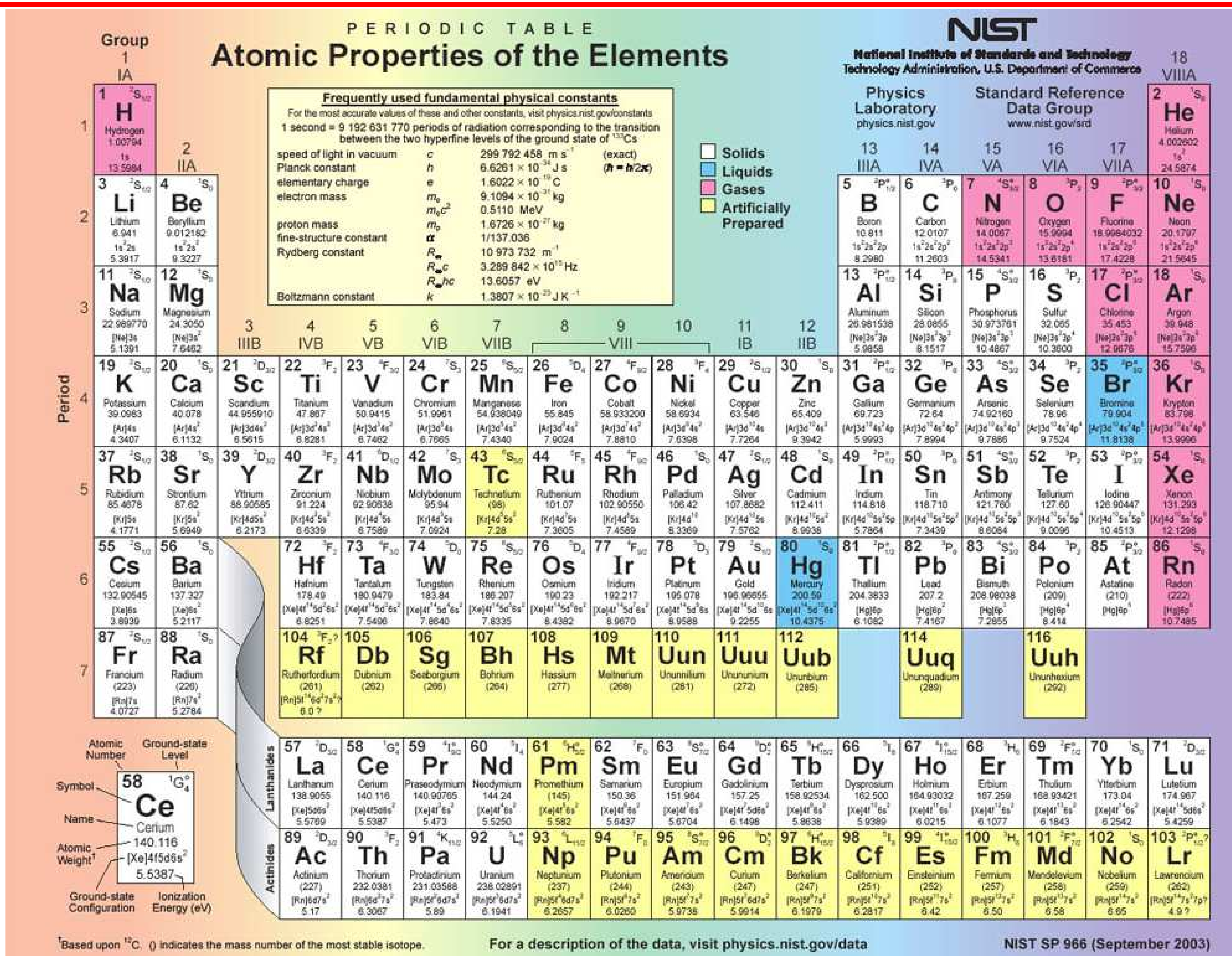
$p, N^+ = uud; \quad n, N^0 = udd$

p

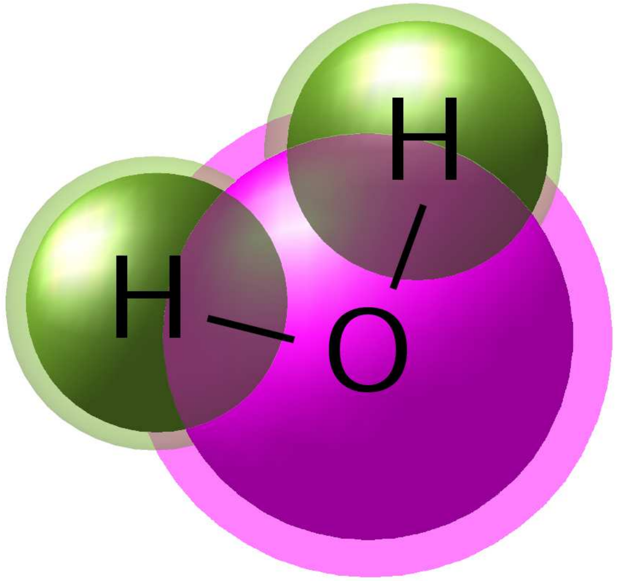
$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

Mass $m = 1.00727646681 \pm 0.00000000009$ u
Mass $m = 938.272046 \pm 0.000021$ MeV [a]
$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 0.99999999991 \pm 0.00000000009$
$|q_p + q_{\overline{p}}|/e < 7 \times 10^{-10}$, CL = 90% [b]
$|q_p + q_e|/e < 1 \times 10^{-21}$ [c]
Magnetic moment $\mu = 2.792847356 \pm 0.000000023\ \mu_N$
$(\mu_p + \mu_{\overline{p}}) / \mu_p = (0 \pm 5) \times 10^{-6}$
Electric dipole moment $d < 0.54 \times 10^{-23}\ e\,$cm
Electric polarizability $\alpha = (11.2 \pm 0.4) \times 10^{-4}$ fm^3
Magnetic polarizability $\beta = (2.5 \pm 0.4) \times 10^{-4}$ fm^3 (S = 1.2)
Charge radius, μp Lamb shift = 0.84087 ± 0.00039 fm [d]
Charge radius, $e p$ CODATA value = 0.8775 ± 0.0051 fm [d]
Magnetic radius = 0.777 ± 0.016 fm
Mean life $\tau > 2.1 \times 10^{29}$ years, CL = 90% [e] ($p \to$ invisible mode)
Mean life $\tau > 10^{31}$ to 10^{33} years [e] (mode dependent)

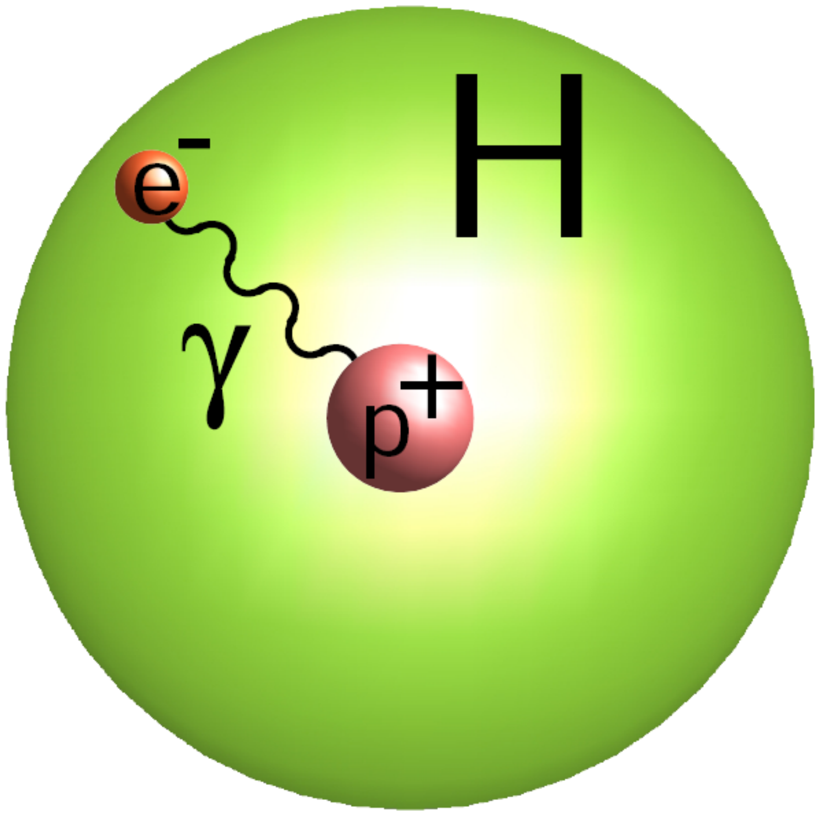
Like Periodic Table of Atoms



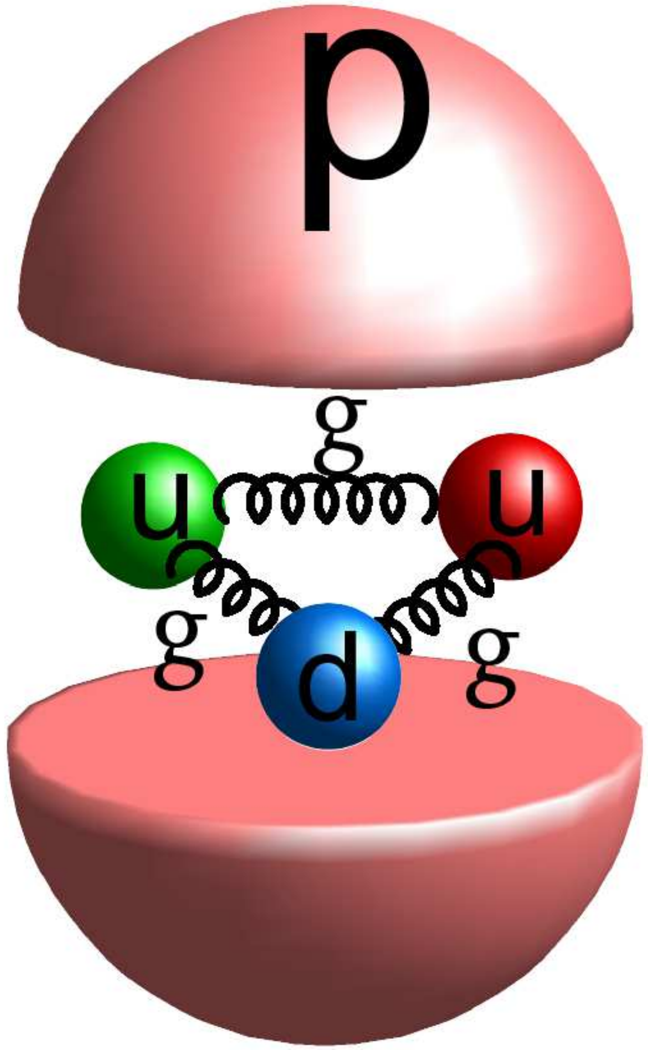
From large to small to elementary



Molecules



Atoms



Nucleus

Particle Data Group: Quarks

QUARKS

The *u*-, *d*-, and *s*-quark masses are estimates of so-called "current-quark masses," in a mass-independent subtraction scheme such as $\overline{\mathrm{MS}}$ at a scale $\mu \approx 2$ GeV. The *c*- and *b*-quark masses are the "running" masses in the $\overline{\mathrm{MS}}$ scheme. For the *b*-quark we also quote the 1S mass. These can be different from the heavy quark masses obtained in potential models.

u

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$m_u = 2.3^{+0.7}_{-0.5}$ MeV Charge $= \frac{2}{3}\,e$ $I_z = +\frac{1}{2}$

$m_u/m_d = 0.38$–0.58

d

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$m_d = 4.8^{+0.5}_{-0.3}$ MeV Charge $= -\frac{1}{3}\,e$ $I_z = -\frac{1}{2}$

$m_s/m_d = 17$–22

$\overline{m} = (m_u + m_d)/2 = 3.5^{+0.7}_{-0.2}$ MeV

s

$I(J^P) = 0(\frac{1}{2}^+)$

$m_s = 95 \pm 5$ MeV Charge $= -\frac{1}{3}\,e$ Strangeness $= -1$

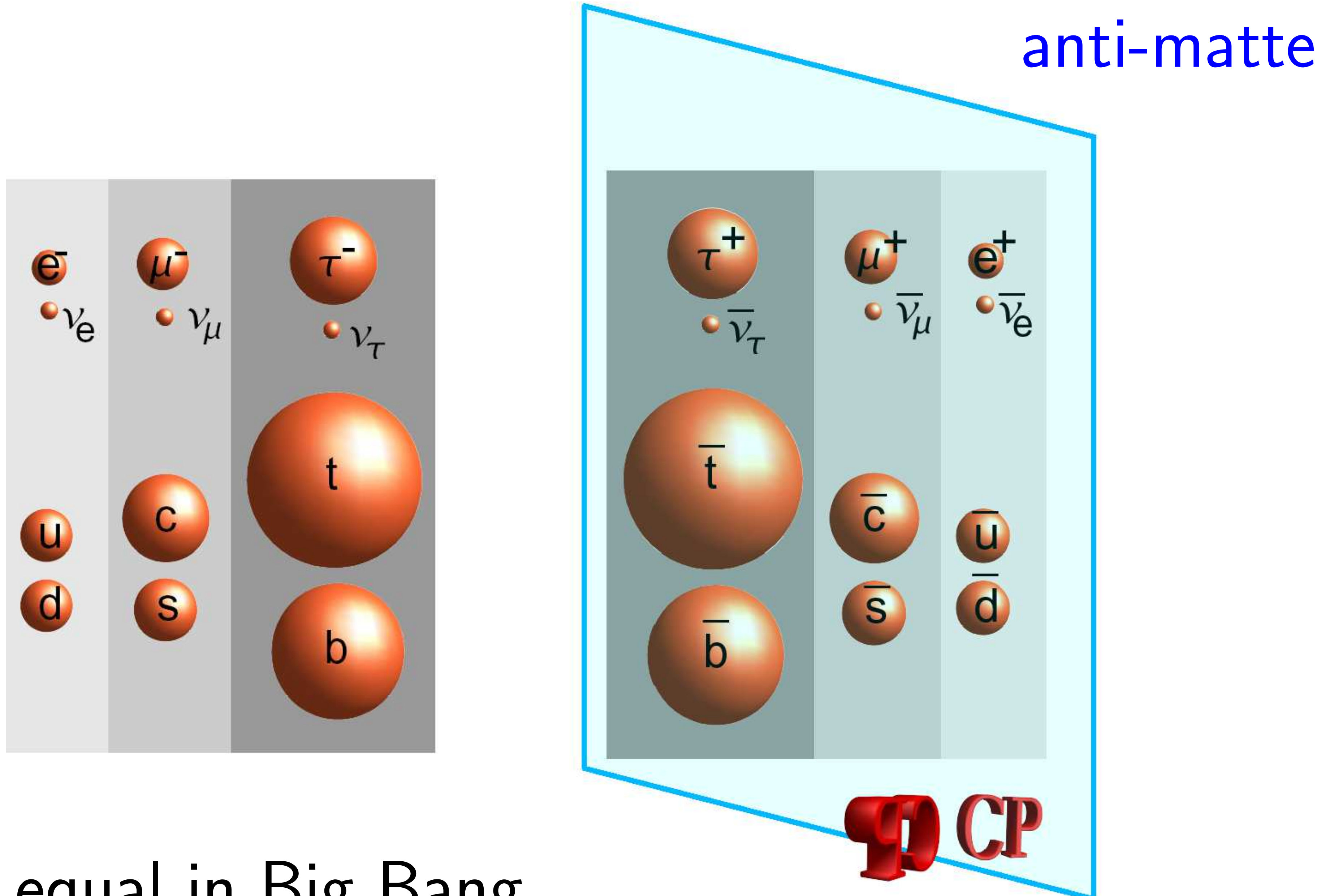
m_s / $((m_u + m_d)/2) = 27.5 \pm 1.0$

Anti-Matter: Mirror Object of Matter

- matter

leptons

quarks



- Produced equal in Big Bang

energy $\rightarrow$ matter $+$ antimatter

anti-matter should behave differently than matter

Particle Data Group: Bosons

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014) and 2015 update

GAUGE AND HIGGS BOSONS

γ (photon) $I(J^{PC}) = 0,1(1^{--})$

Mass $m < 1 \times 10^{-18}$ eV
Charge $q < 1 \times 10^{-35}$ e
Mean life τ = Stable

---

g or gluon $I(J^{P}) = 0(1^{-})$

Mass $m = 0$ [a]
SU(3) color octet

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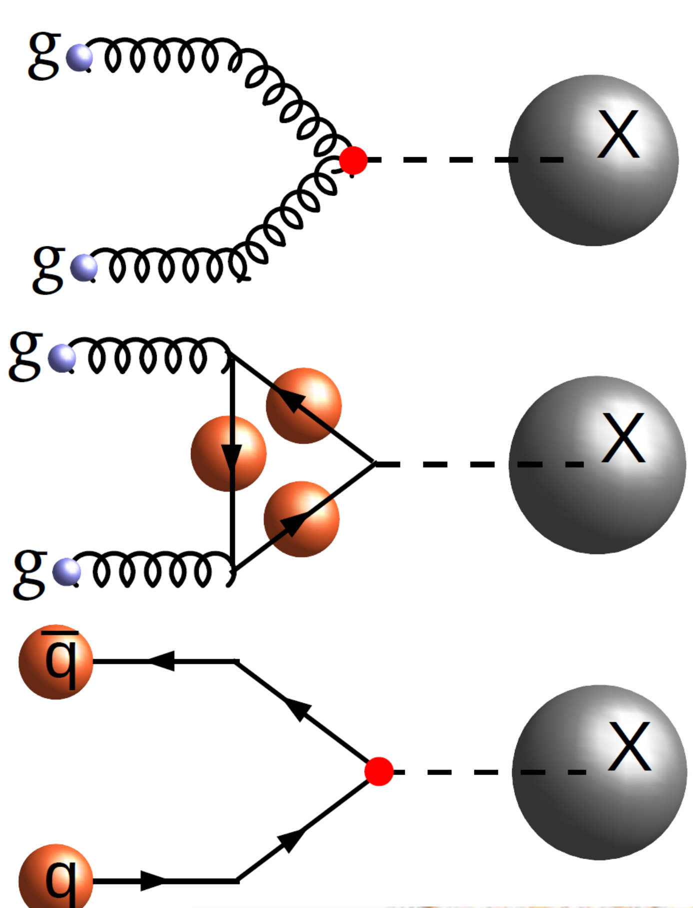
graviton $J = 2$

Mass $m < 6 \times 10^{-32}$ eV

Hunting for New Particles

Producing New Particles

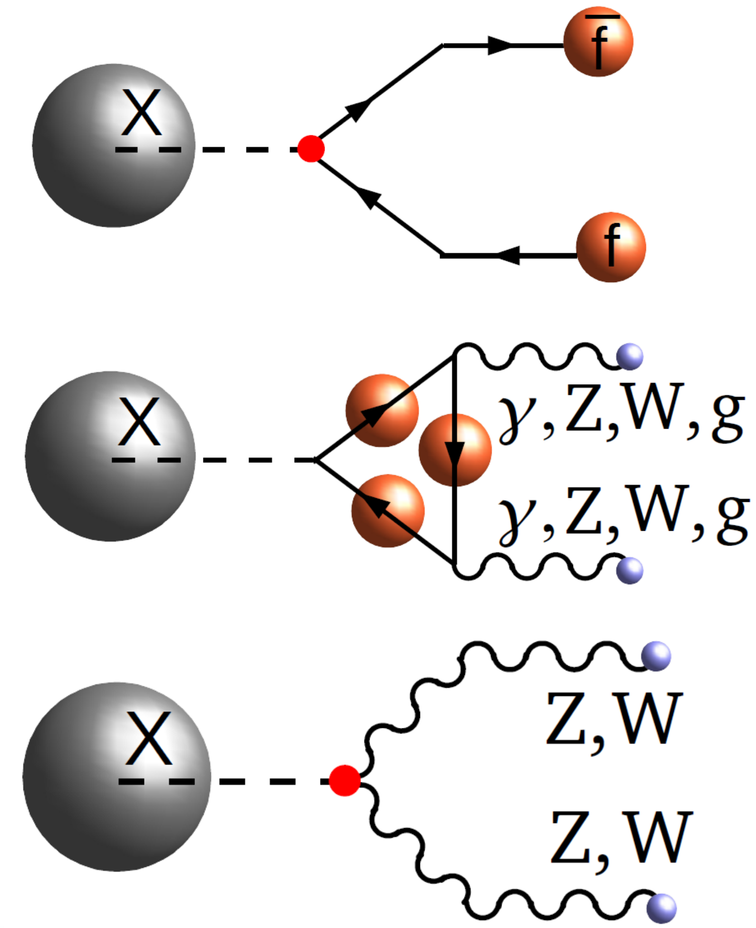
Produce a resonance

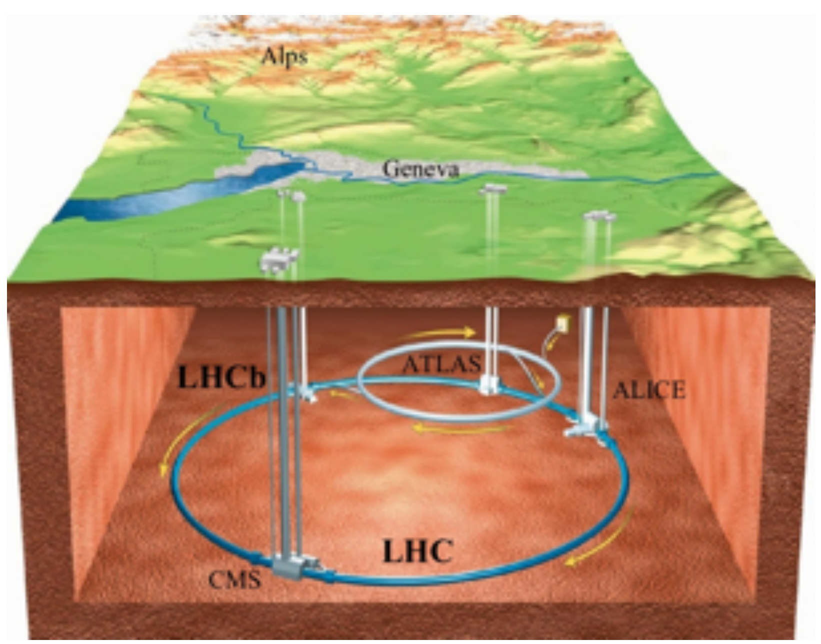


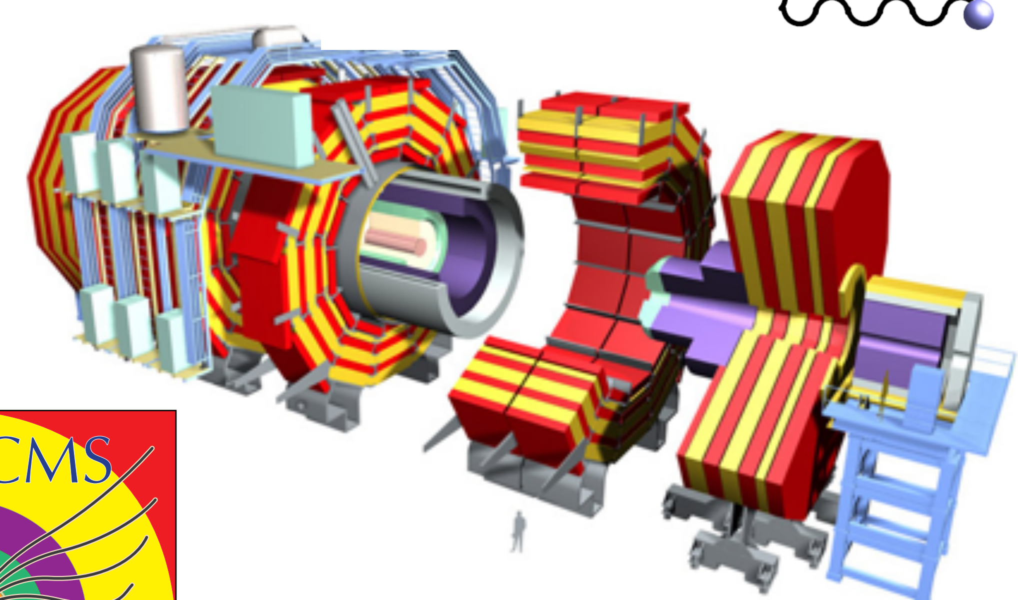
$$? \; x_{\mu\nu}T^{\mu\nu} \; ?$$

$$? \; XV_{\mu}V^{\mu} \; ?$$

Detect its decay

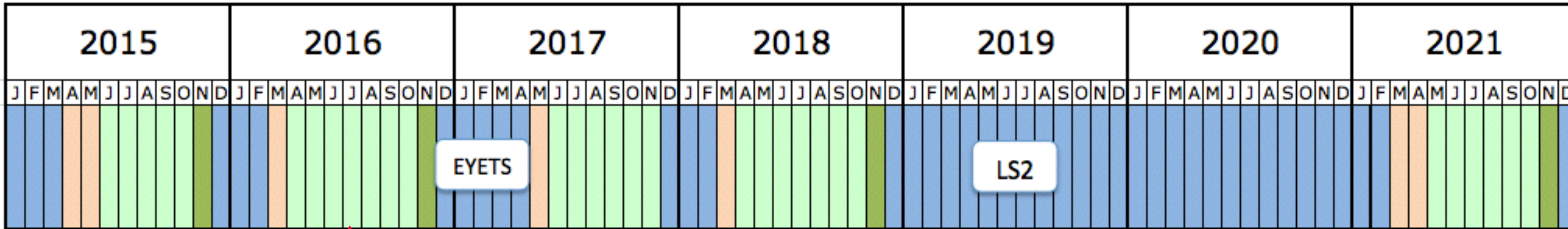


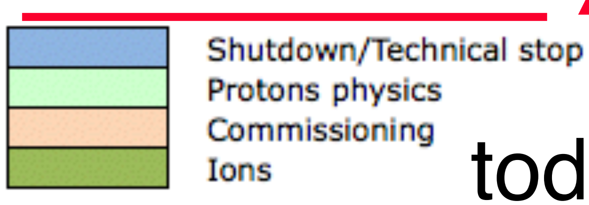




LHC schedule: 10 year plan

- LHC E_{pp}=13 TeV, Phase-1 thru 2023/24





today

Run-2

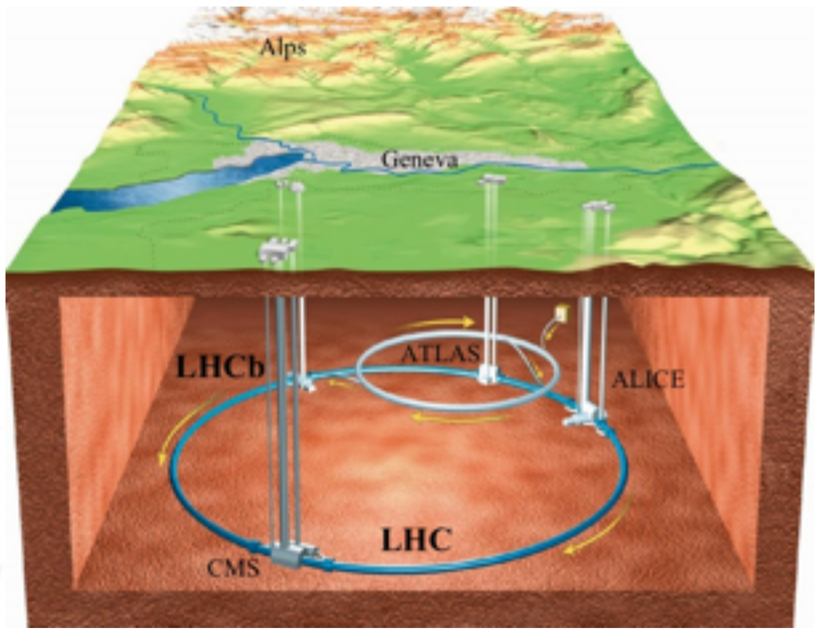
Run-3 thru 2023/24

~17 fb^{-1} today

~30-40 fb^{-1}

~100 fb^{-1}

~300 fb^{-1}

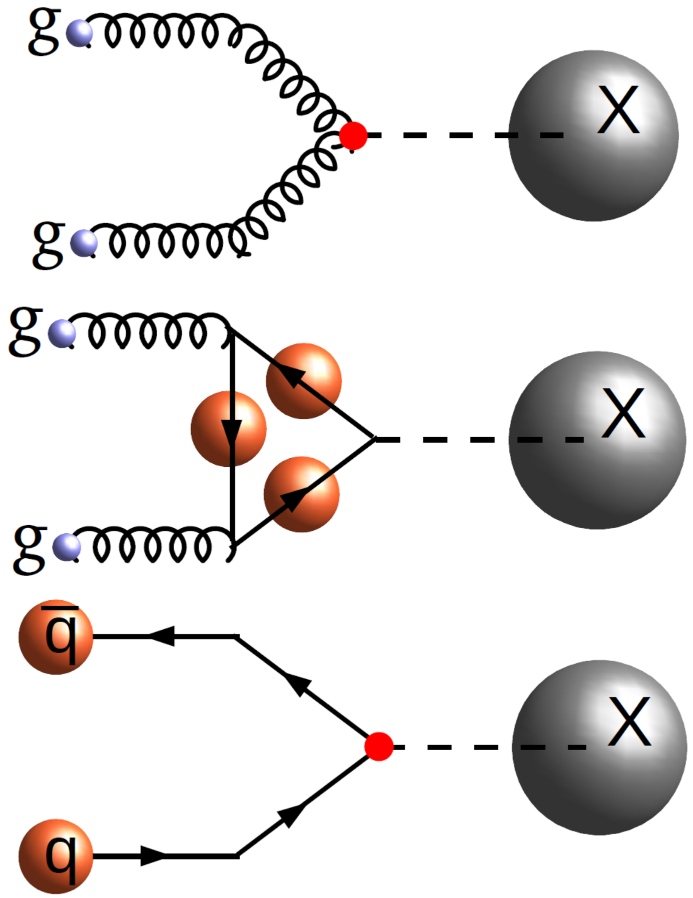


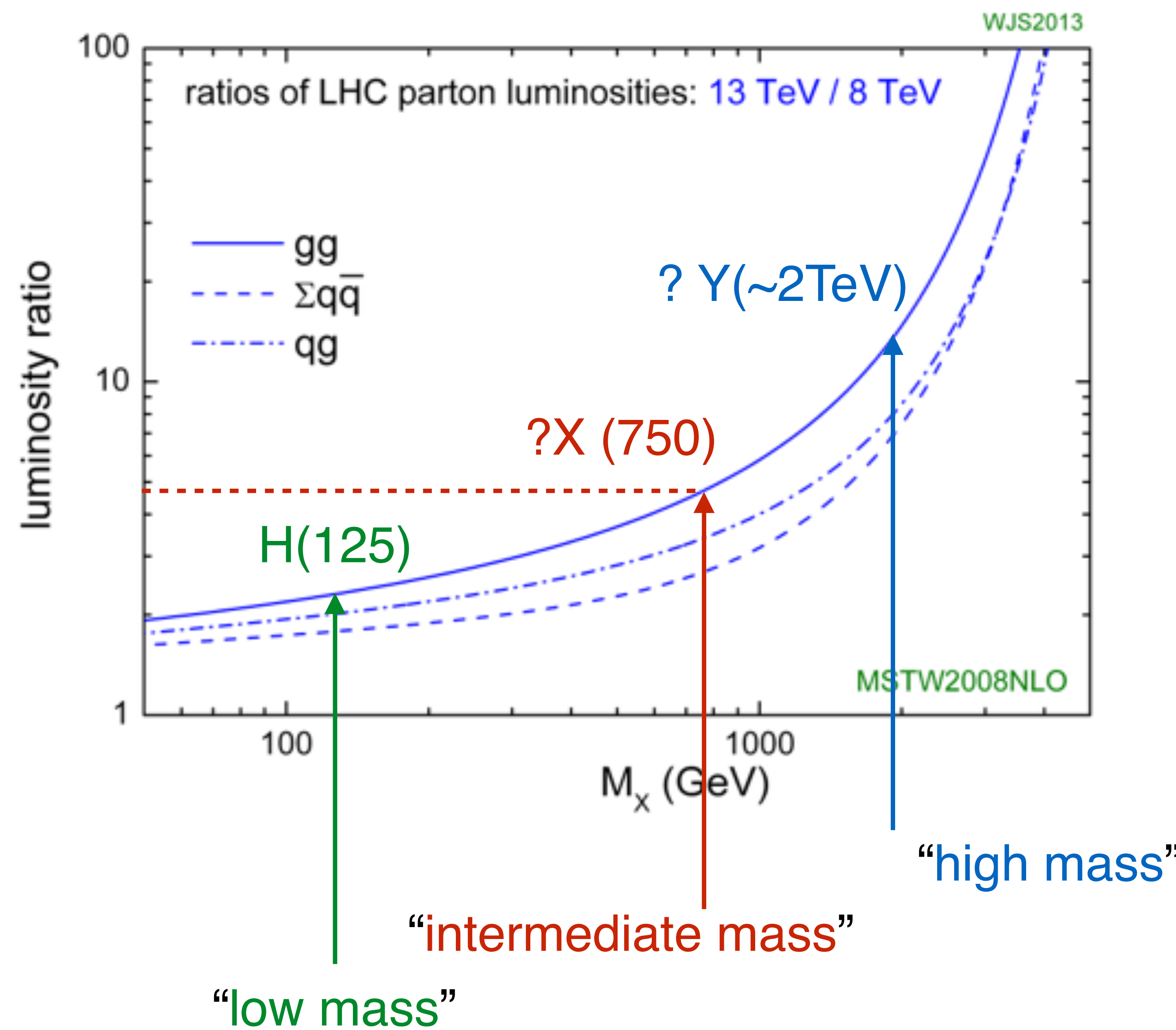
- Phase-2 with Run-4 plan to start in 2026, Snowmass: ~3000 fb^{-1}

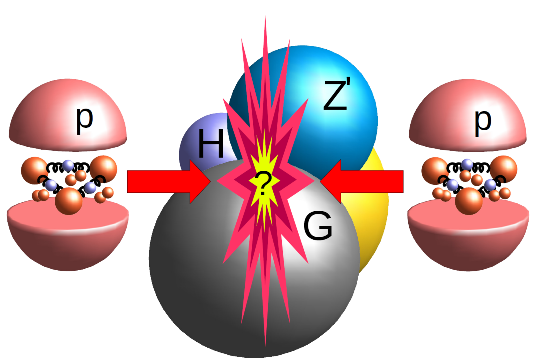
- Legacy: Run-1 (2010-2012) ~25 fb^{-1} at 7 and 8 TeV

Resonances in LHC Run-2 vs Run-1

Produce a resonance







~3 fb^{-1} in Run-2 at 13 TeV (2015)

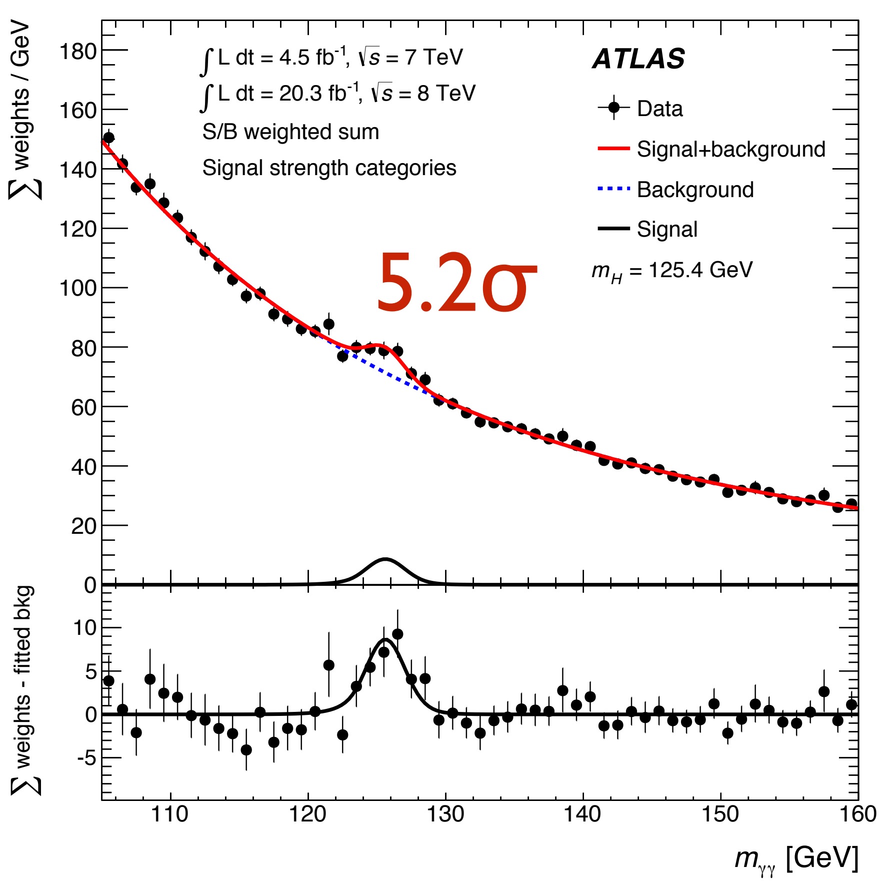
~30-40 fb^{-1} in Run-2 at 13 TeV (2016)

compared to ~20 fb^{-1} in Run-1 at 8 TeV (2012)

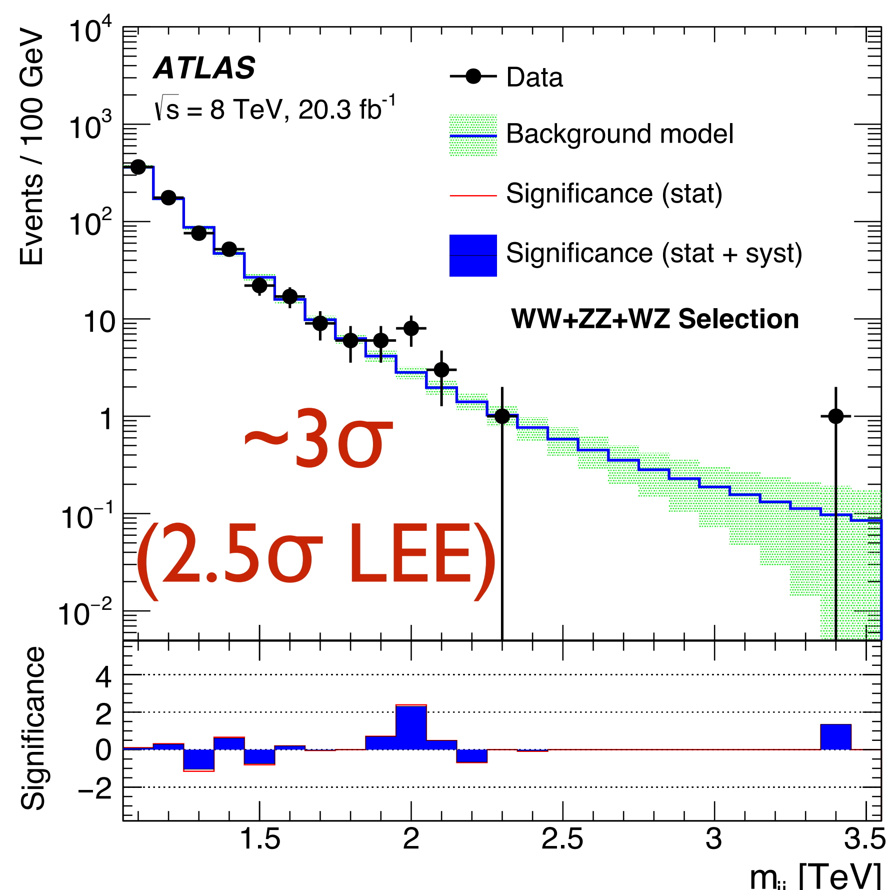
Hints of Bumps from ATLAS

- H(125) is one particle surely discovered
- Several hints in either Run I or Run II excited interest
  - especially when ATLAS and CMS saw something similar

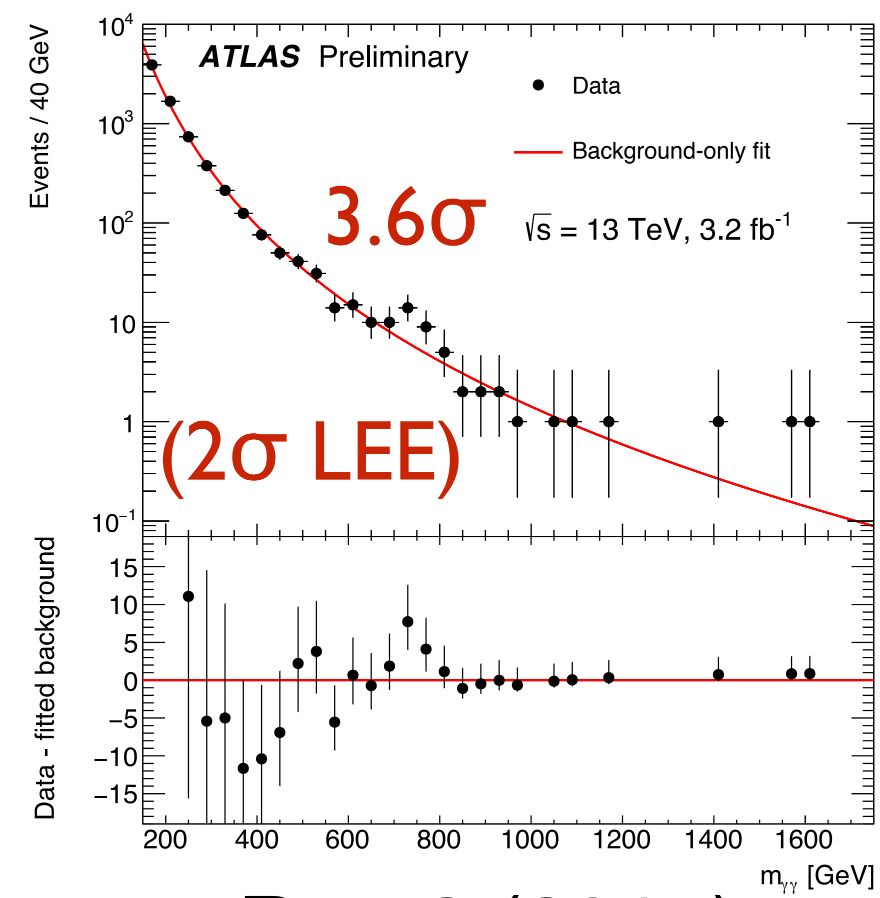
$H(125)^0 \to \gamma\gamma$ | ? $X(2000) \to ZZ, WW, ZW$ | ? $X(750) \to \gamma\gamma$



Run-1



Run-1

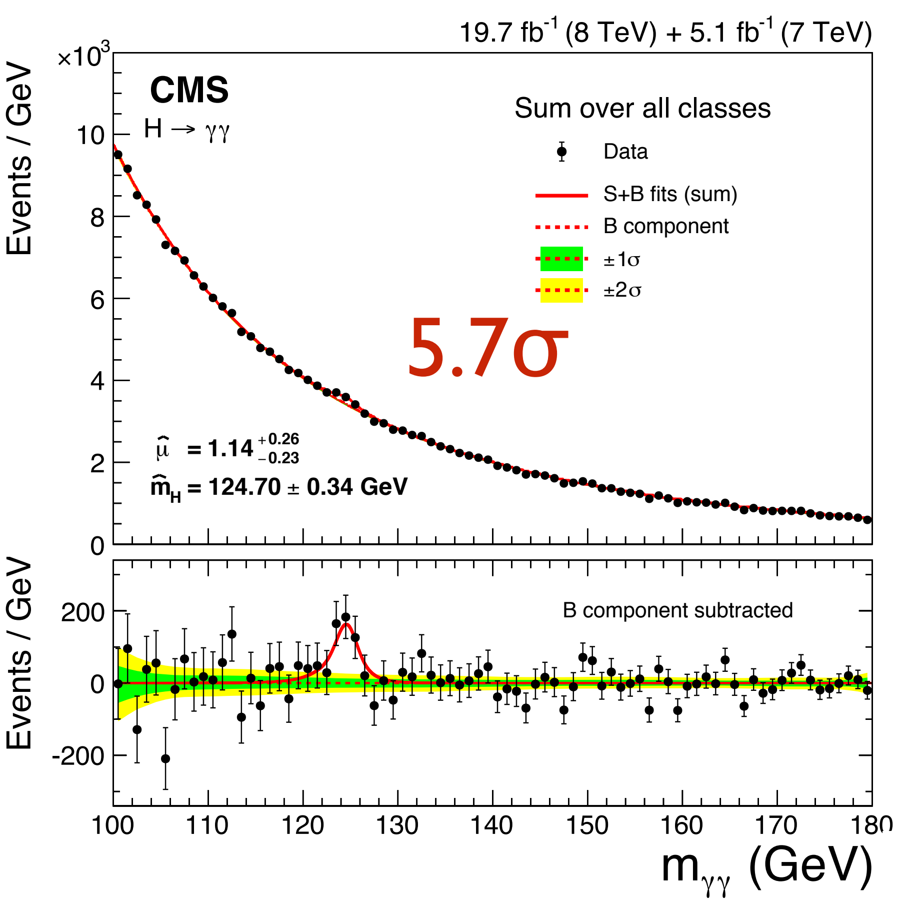


Run-2 (2015)

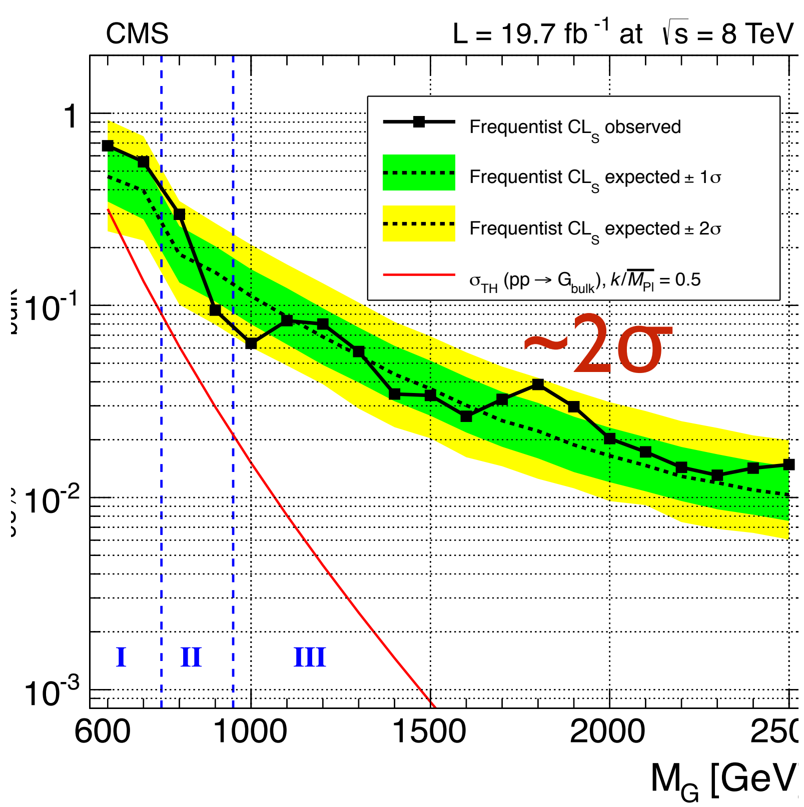
Hints of Bumps from CMS

- H(125) is one particle surely discovered
- Several hints in either Run I or Run II excited interest
  - especially when ATLAS and CMS saw something similar

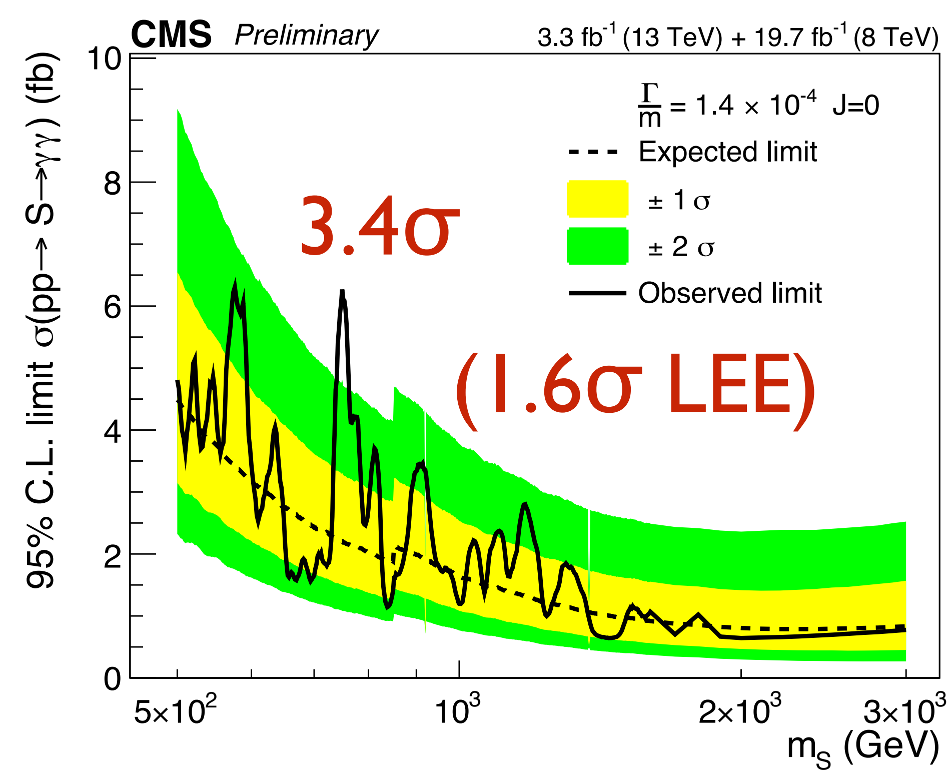
$H(125)^0 \rightarrow \gamma\gamma$? $X(2000) \rightarrow ZZ, WW, ZW$? $X(750) \rightarrow \gamma\gamma$



Run-1

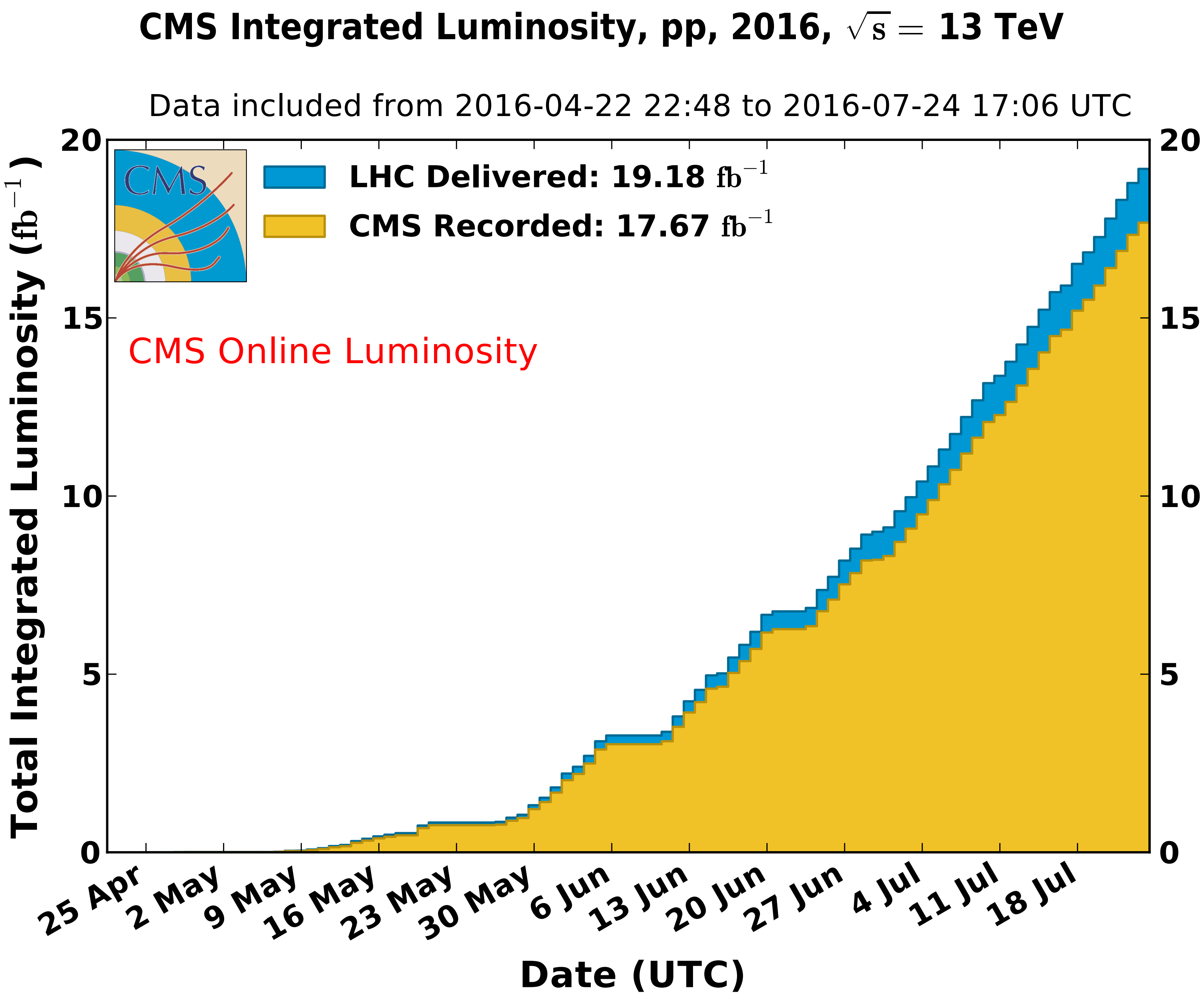


Run-1



Run-2 (2015)

LHC Luminosity in 2016



~3 fb^{-1} in Run-2 at 13 TeV (2015)

~30-40 fb^{-1} in Run-2 at 13 TeV (2016)

compared to ~20 fb^{-1} in Run-1 at 8 TeV (2012)

Hunting for the Higgs Boson

H(125)

The H(125)^0 Resonance: 2012-2013


"All the News That's Fit to Print"

The New York Times

Late Edition

Today, sunny to partly cloudy, rather hot, high 92. Tonight, mostly clear, low 72. Tomorrow, mostly sunny, hot and humid, high 90. Weather map appears on Page B16.

VOL. CLXI . . No. 55,823 — © 2012 The New York Times — NEW YORK, THURSDAY, JULY 5, 2012 — $2.50

Oil Backed Up, Iranians Put It On Idled Ships

Subterfuge at Tankers as Embargo Tightens

By THOMAS ERDBRINK and CLIFFORD KRAUSS

BANDAR ABBAS, Iran — The hulking tanker Neptune was floating aimlessly this week in the warm waters of the Persian

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

SHIFT RENEWS CRITICISM

Move Aligns Him With Conservative Voices Within His Party

Physicists Find Elusive Particle Seen as Key to Universe

...ed the discovery of a subatomic particle that looks like the Higgs boson.

...if Rare Species Play Along

...LIFEBOAT

...te. It turns out that ...an be a turnoff for ... was time to bring in ...he seemed mystified ...cheetah's eagerness ...assume a mating po-

thing but.

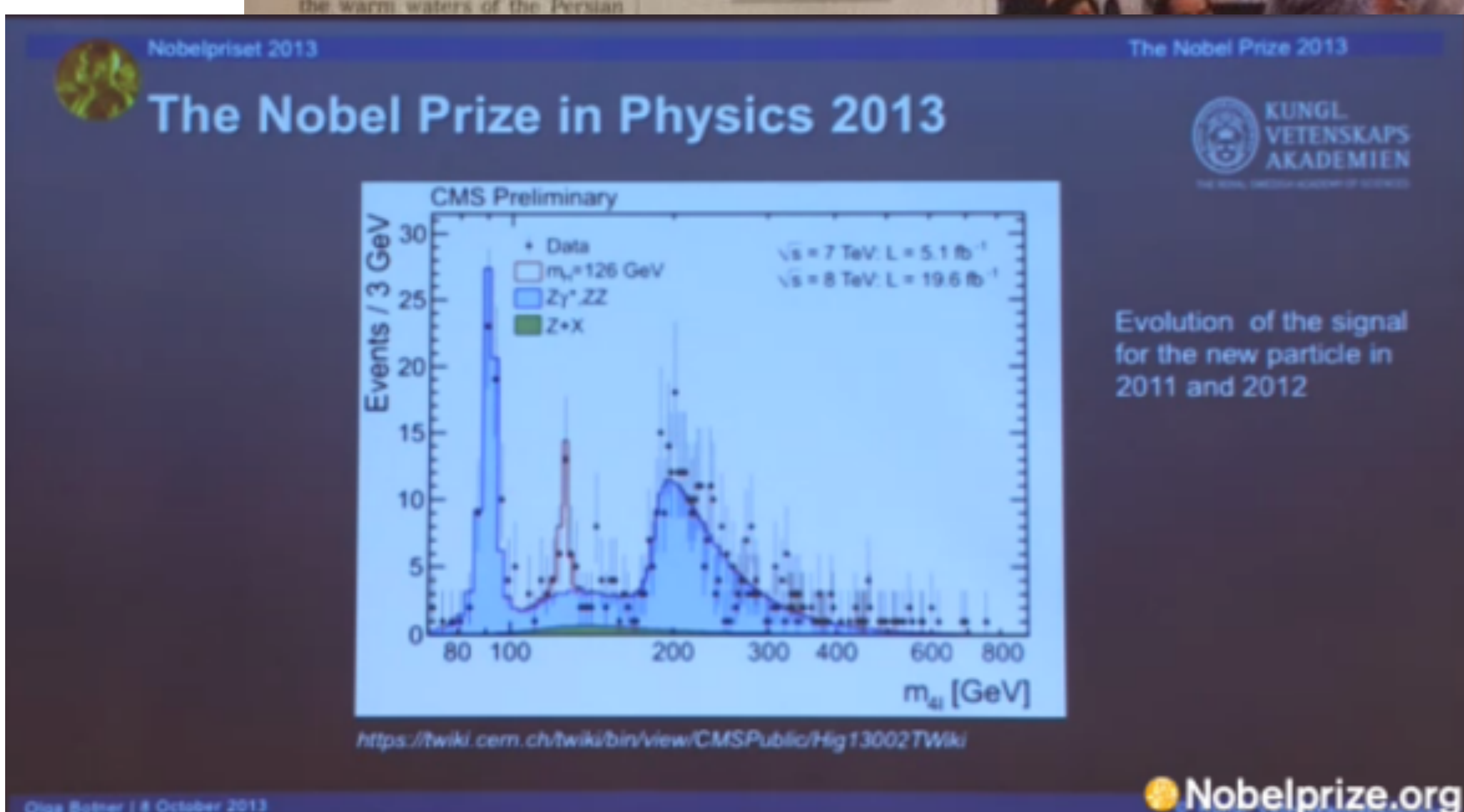
Eighty-three percent of those species in North American zoos are not meeting the targets set for maintaining their genetic diversity, the Association of Zoos and Aquariums reports. In the case of cheetahs, fewer than 20 percent of those in North American zoos have been able to reproduce.

Zoos must figure out how to

'I Think We Have It' Is Cheer of Day at Home of Search

By DENNIS OVERBYE

ASPEN, Colo. — Signaling a likely end to one of the longest, most expensive searches in the history of science, physicists said Wednesday that they had discovered a new subatomic particle



The Higgs Boson: $H(125)^0$

- Why discuss $H(125)^0$
  - — window to Beyond SM (extended sector, dark matter, etc)
  - — techniques applicable to any new particle…
  - — the only LHC discovery so far

- Follow PDG check-list
  - — mass
  - — lifetime
  - — width
  - — quantum numbers
  - — coupling strength

H^0 $J = 0$

Mass $m = 125.09 \pm 0.24$ GeV

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)
$WW^* = 0.81 \pm 0.16$
$ZZ^* = 1.15^{+0.27}_{-0.23}$ (S = 1.2)
$\gamma\gamma = 1.17^{+0.19}_{-0.17}$
$b\bar{b} = 0.85 \pm 0.29$
$\mu^+\mu^- < 7.0$, CL = 95%
$\tau^+\tau^- = 0.79 \pm 0.26$
$Z\gamma < 9.5$, CL = 95%
$t\bar{t}H^0$ Production $= 2.5^{+0.9}_{-0.8}$

H^0 DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
invisible	<58 %	95%	–

H^0 $J = 0$

In the following H^0 refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of H^0 and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

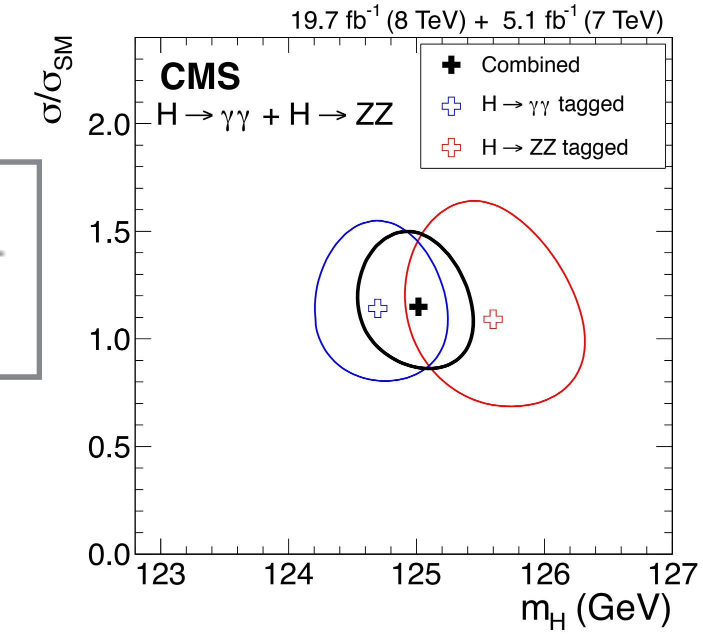
Mass of H(125)^0 in Run-1

- LHC combination:

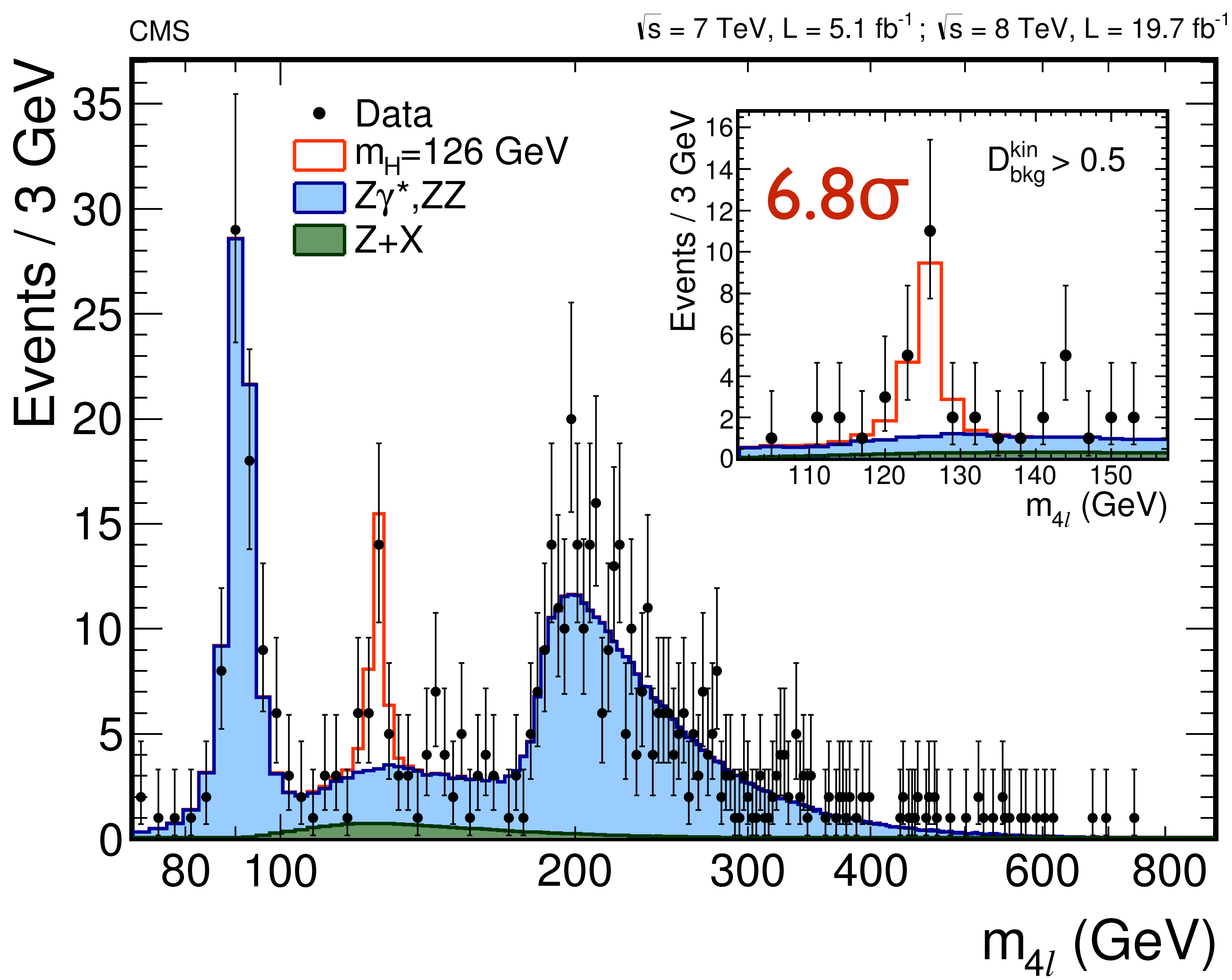
H^0 MASS

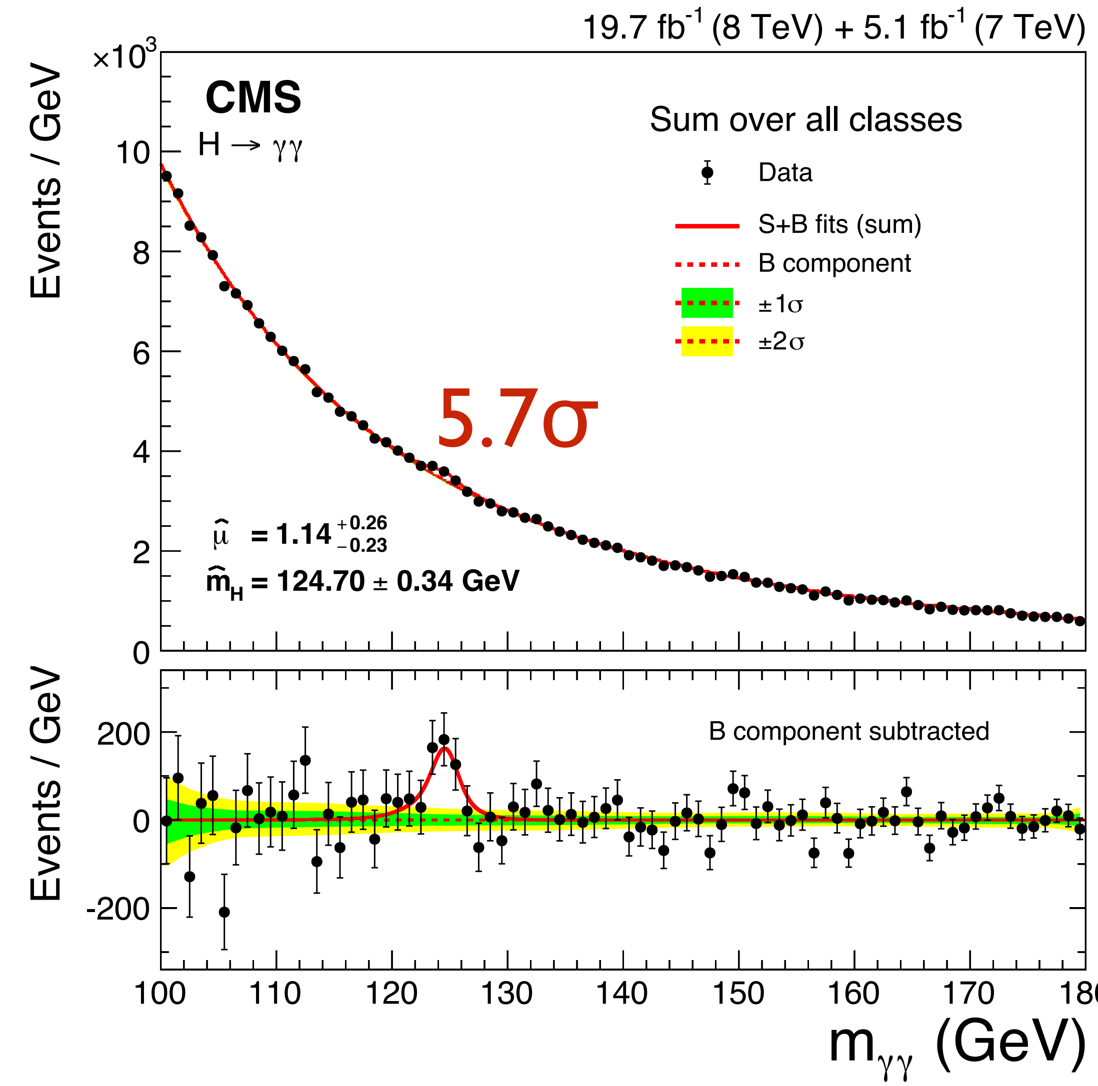
VALUE (GeV)		DOCUMENT ID		TECN	COMMENT
125.09±0.21±0.11	1,2	AAD	15B	LHC	*pp*, 7, 8 TeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

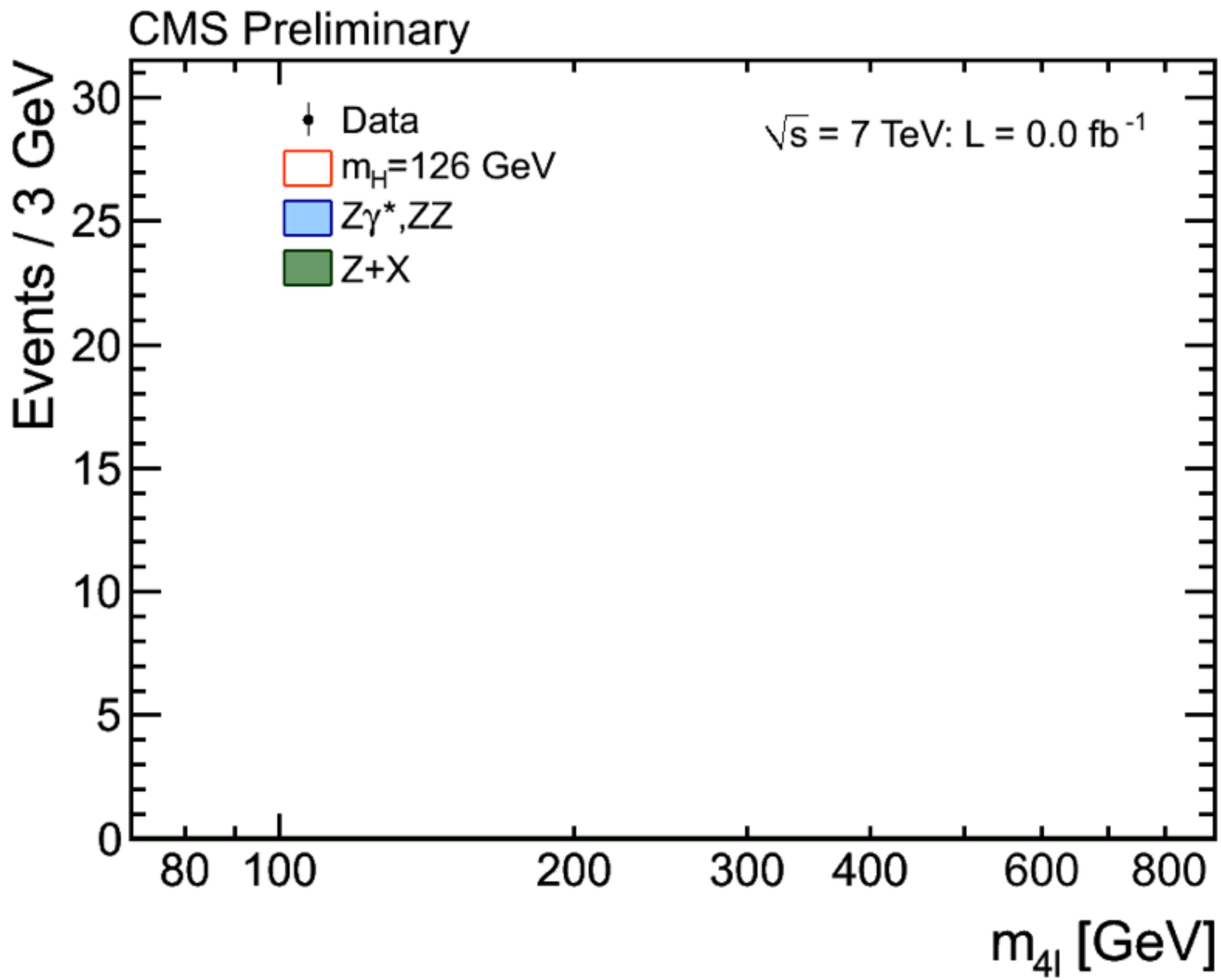


- **Mass** = position of two bumps
  H→ZZ, γγ





$H \to ZZ \to 4\ell$

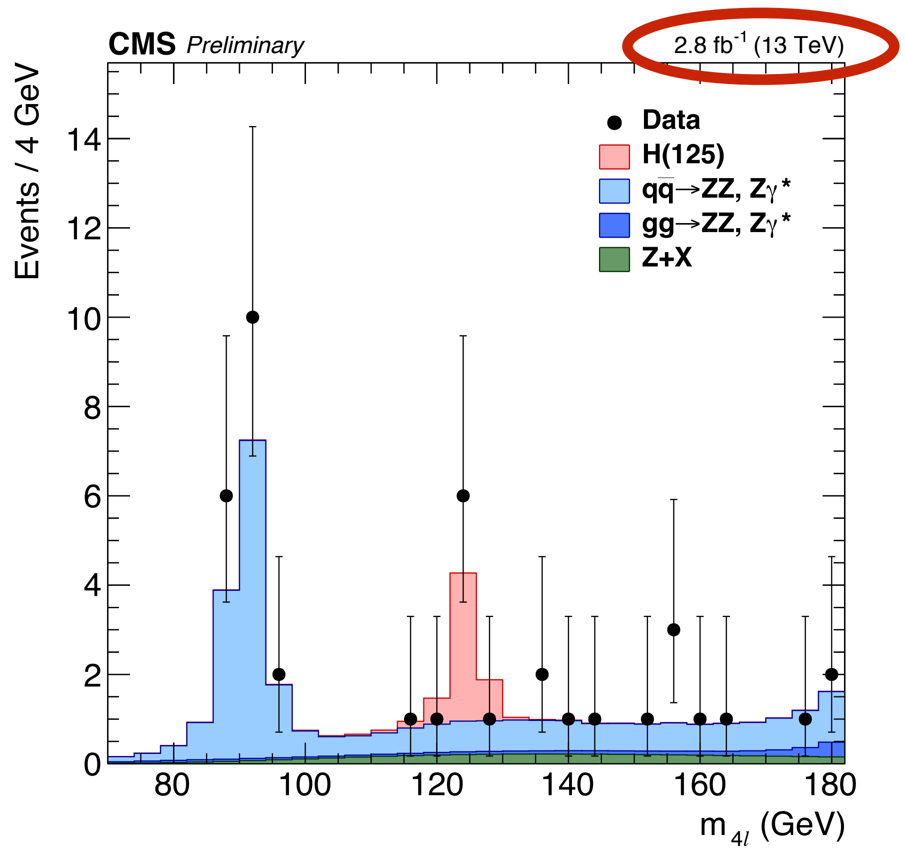


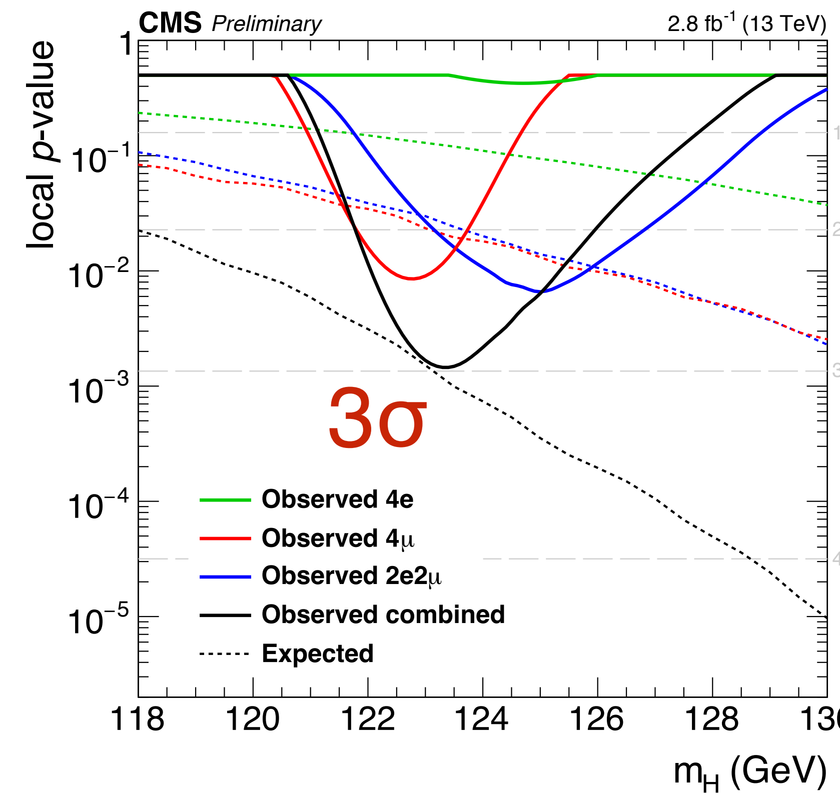
Re-discover $H(125)^0$ in Run-2 (2015 data)

$H^0 \rightarrow ZZ$

$\mu=0.82^{+0.57}_{-0.43}$

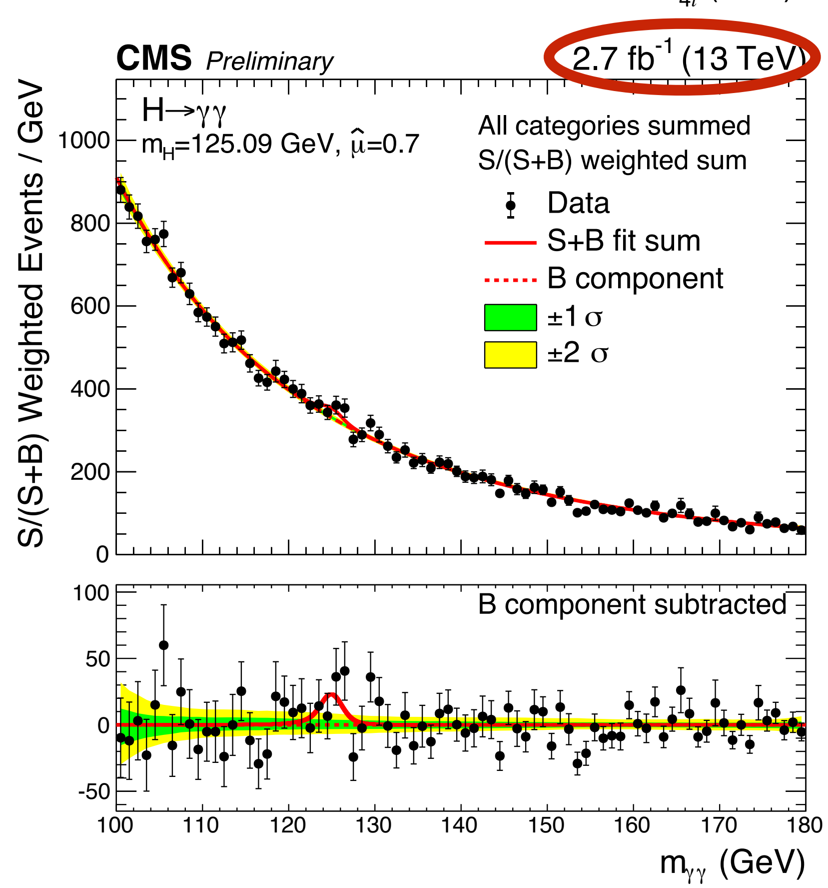
$m=123.4^{+0.8}_{-0.7}$ GeV

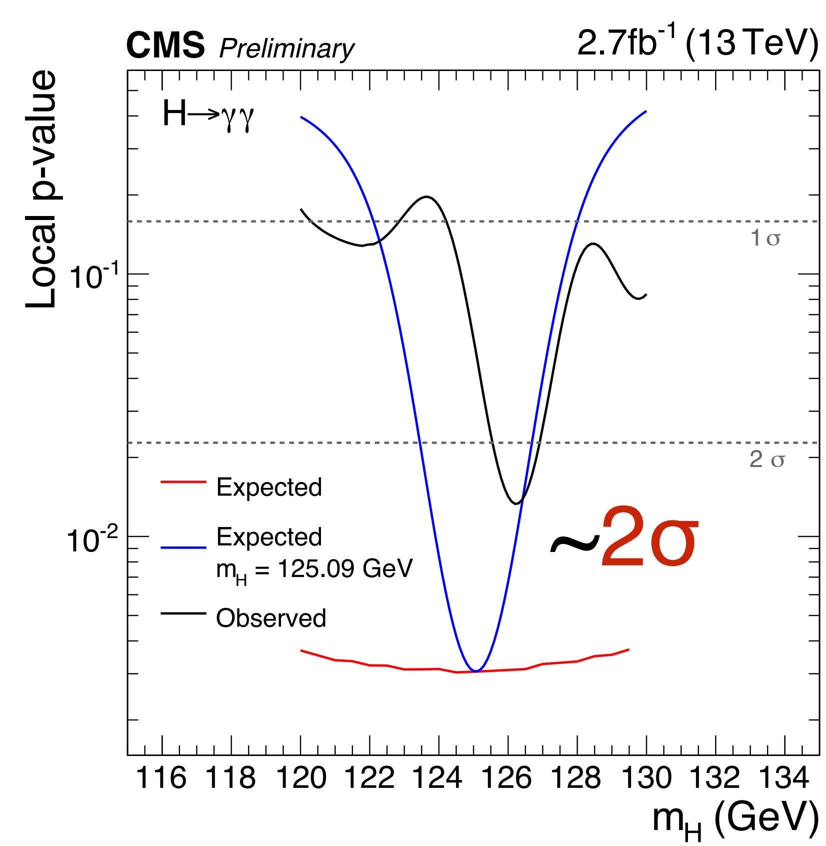




$H^0 \rightarrow \gamma\gamma$

$\mu=0.69^{+0.47}_{-0.42}$

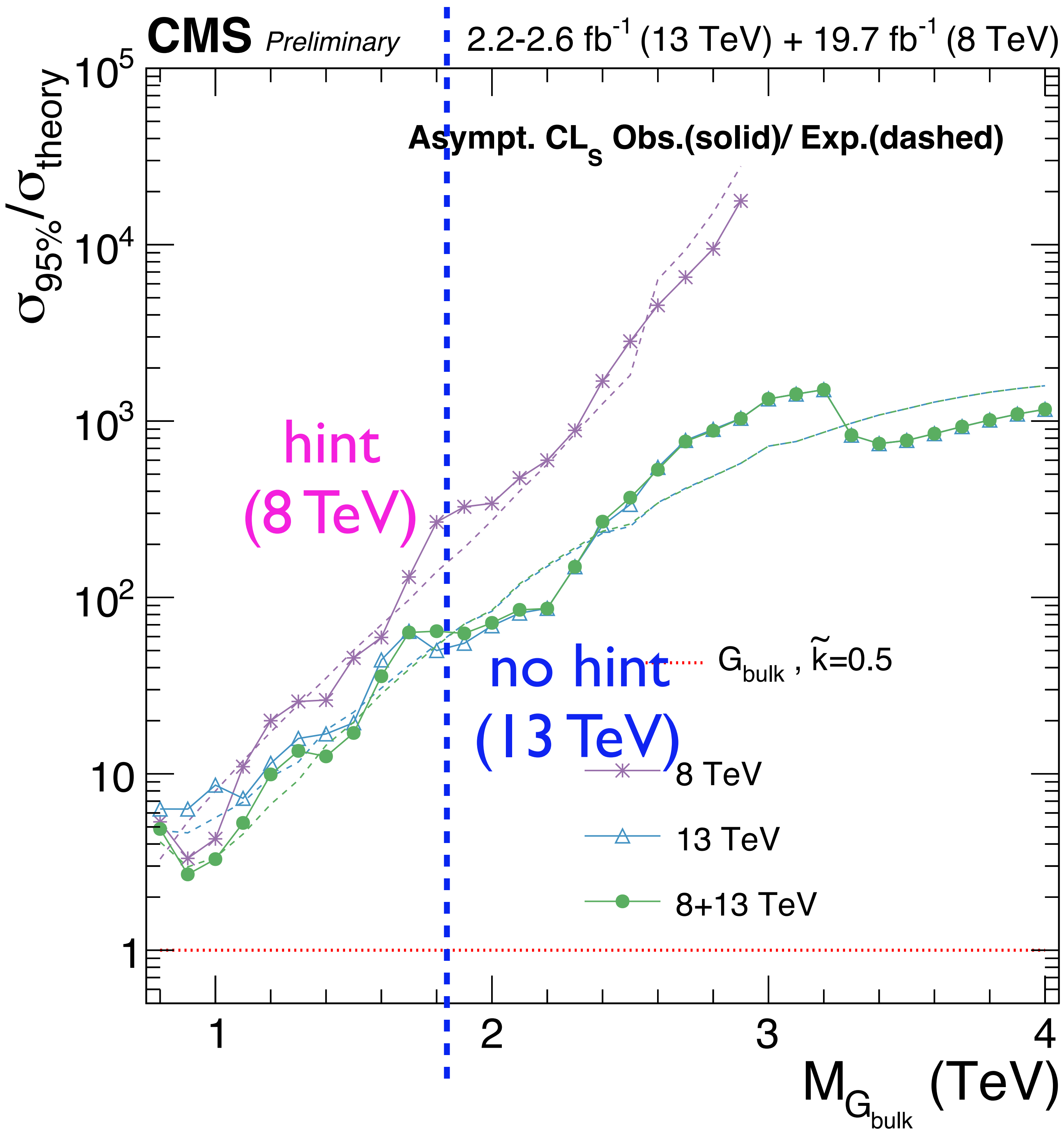




Hunting for ?X(~2000)
?X(750)

? X(~2000)

- Hints for X(2000) do not seem to be confirmed with new data

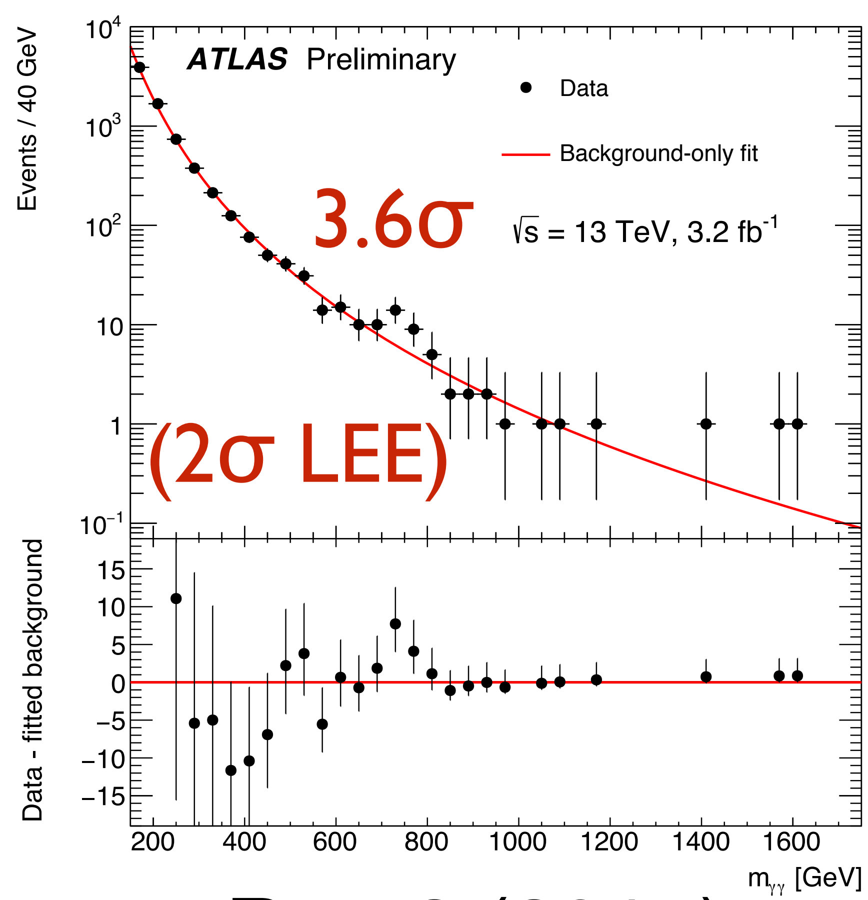


? X(750)

- Waiting for ICHEP conference in Chicago next week

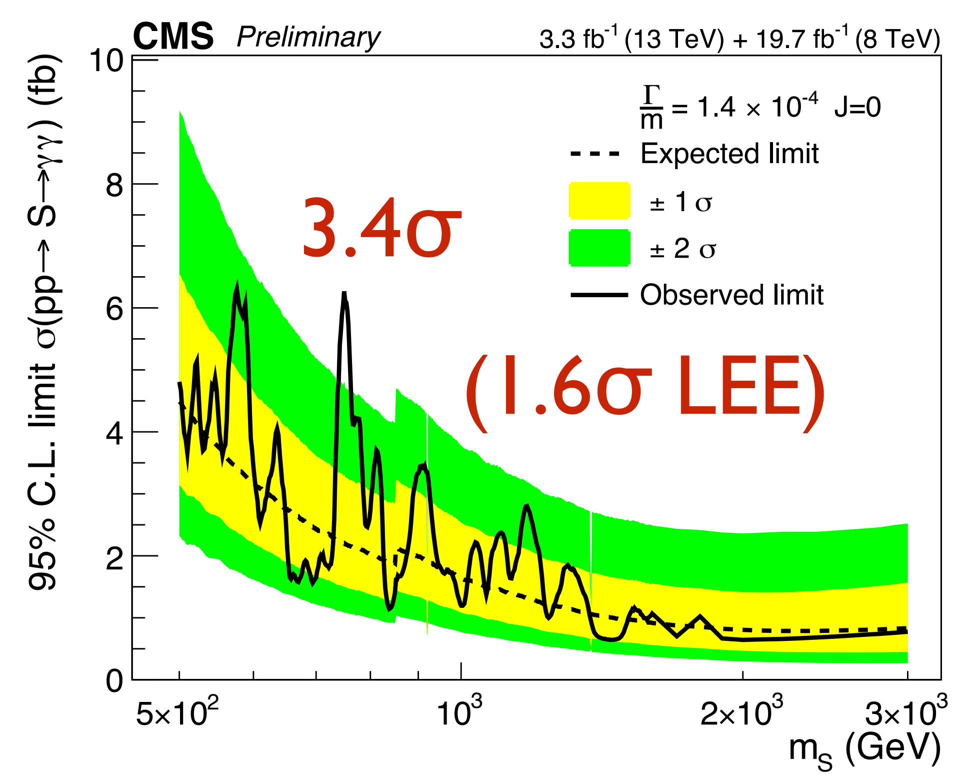
  new data from 2016 will tell …

? X(750)→ γγ on ATLAS



Run-2 (2015)

? X(750)→ γγ on CMS



Run-2 (2015)

38th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

AUGUST 3 - 10, 2016

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