The 5th Force

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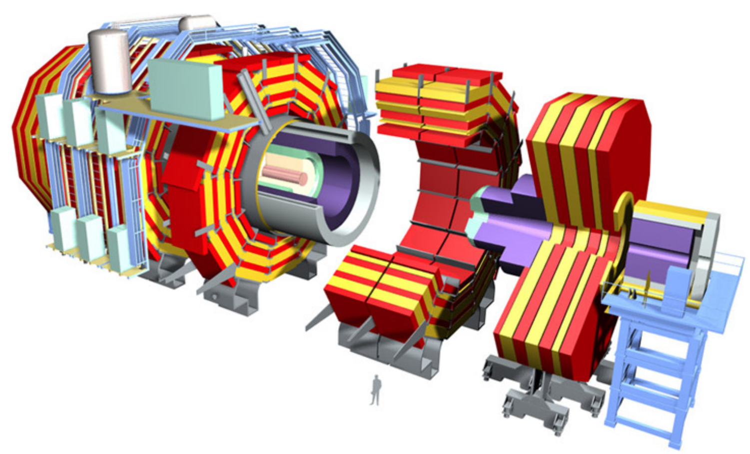
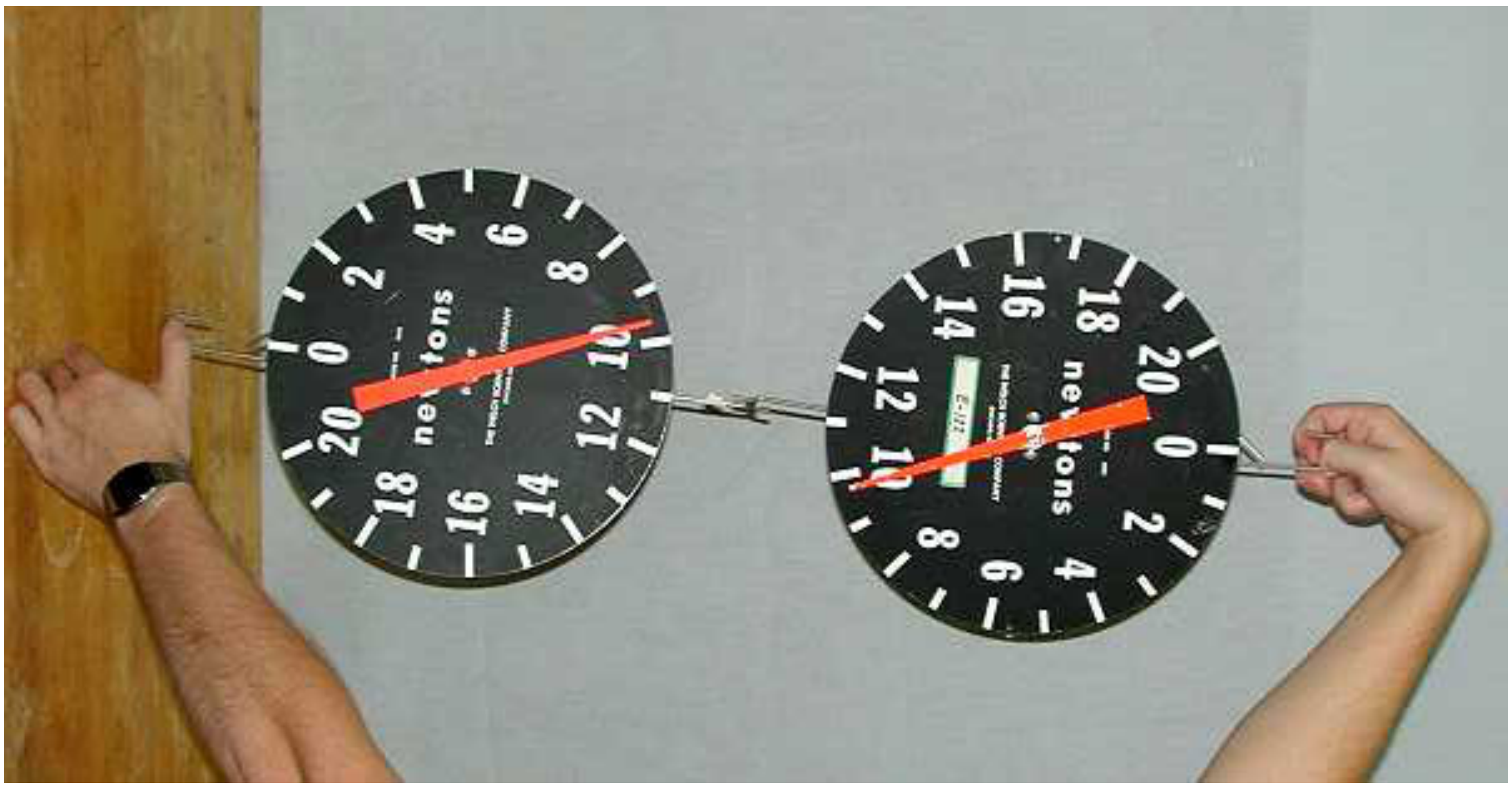


July 26, 2023

Johns Hopkins University

Johns Hopkins University QuarkNet Physics Workshop

How Many Forces do we know?



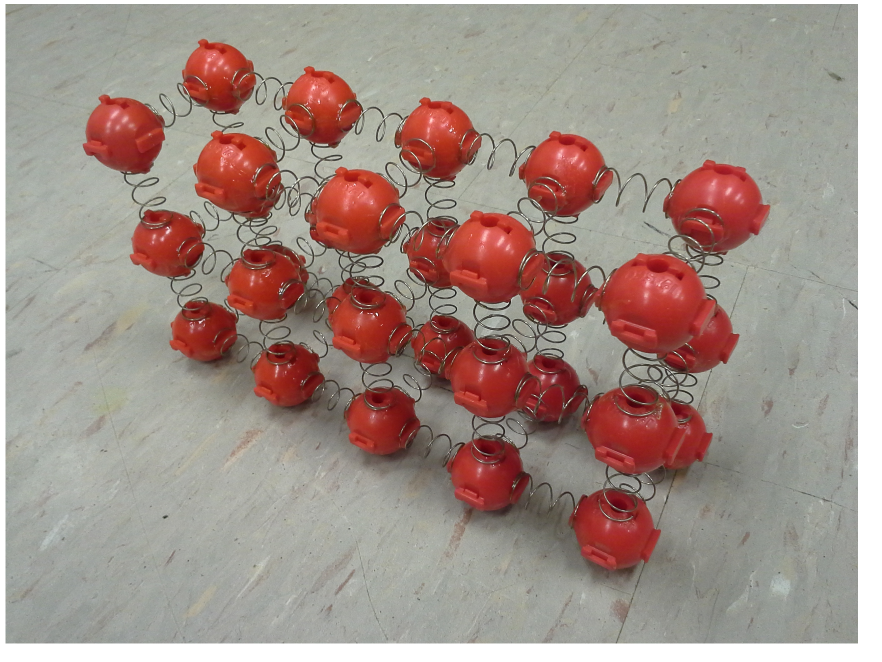
How Many Forces do we know?

- Quick Google search revealed 7 forces:
  - Frictional force
  - Tension force
  - Normal force
  - Air Resistance force
  - Applied force
  - Spring force
  - Gravitational force
  - …

How Many Fundamental Forces do we know?

- Quick Google search revealed 7 forces:
  - Frictional force
  - Tension force
  - Normal force
  - Air Resistance force
  - Applied force
  - Spring force
  - Gravitational force
  - …

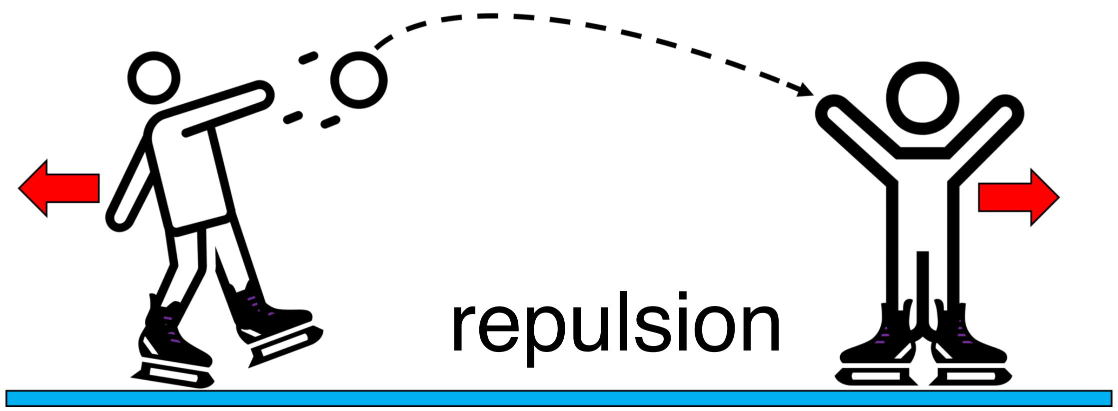
Not fundamental forces (electro-magnetic origin) — refers to: Frictional force, Tension force, Normal force, Air Resistance force, Applied force, Spring force

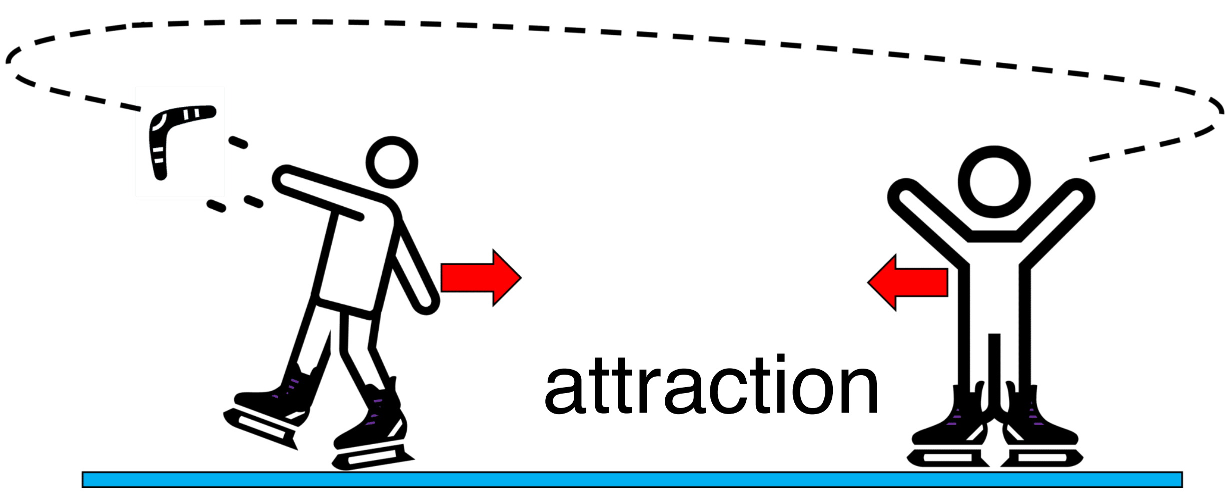


What is Force?

- A force is a push or pull upon an object resulting from the object's interaction with another object

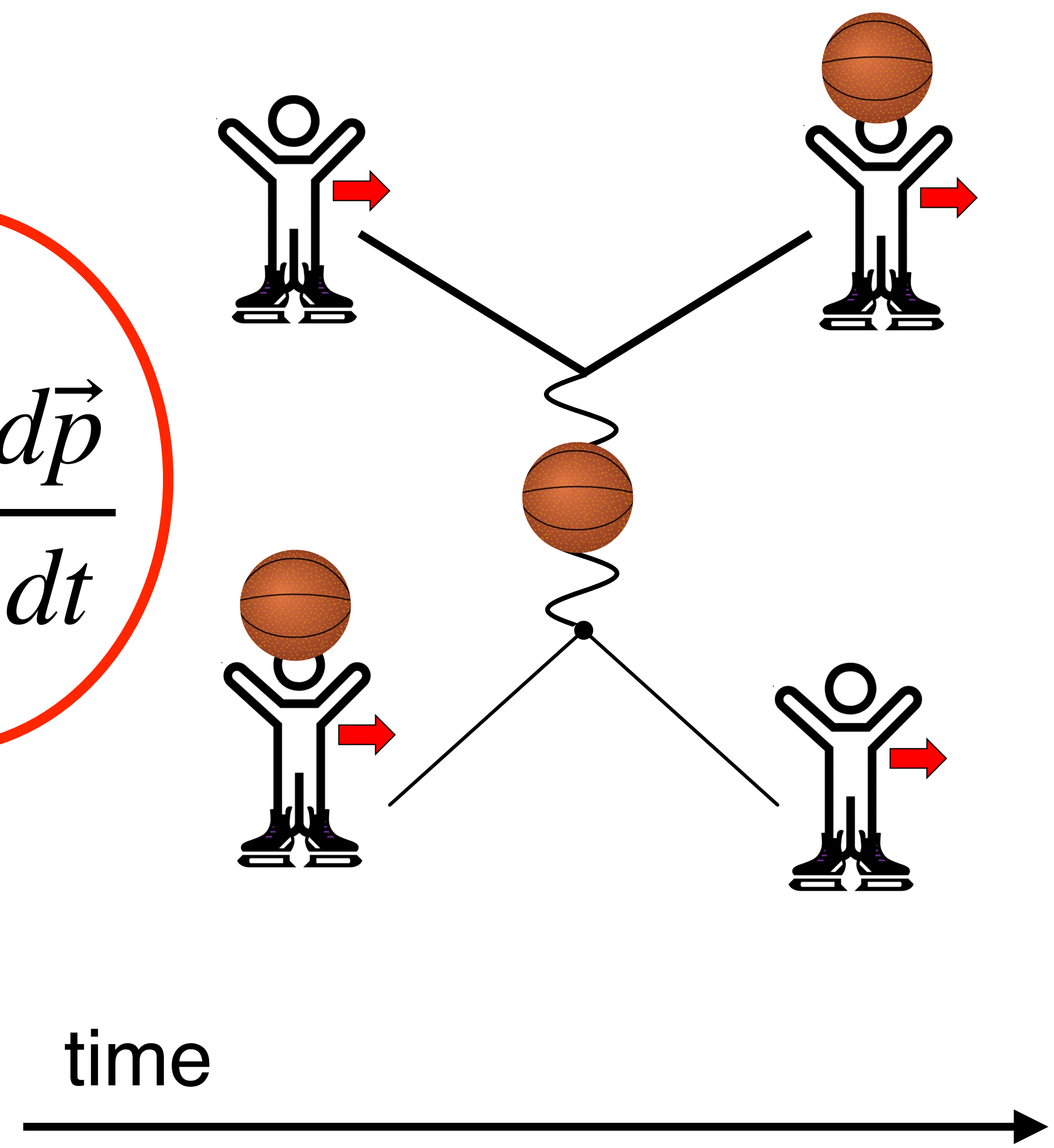
classical example of two skaters throwing ball to each other:





force

$$\vec{F} = \frac{d\vec{p}}{dt}$$



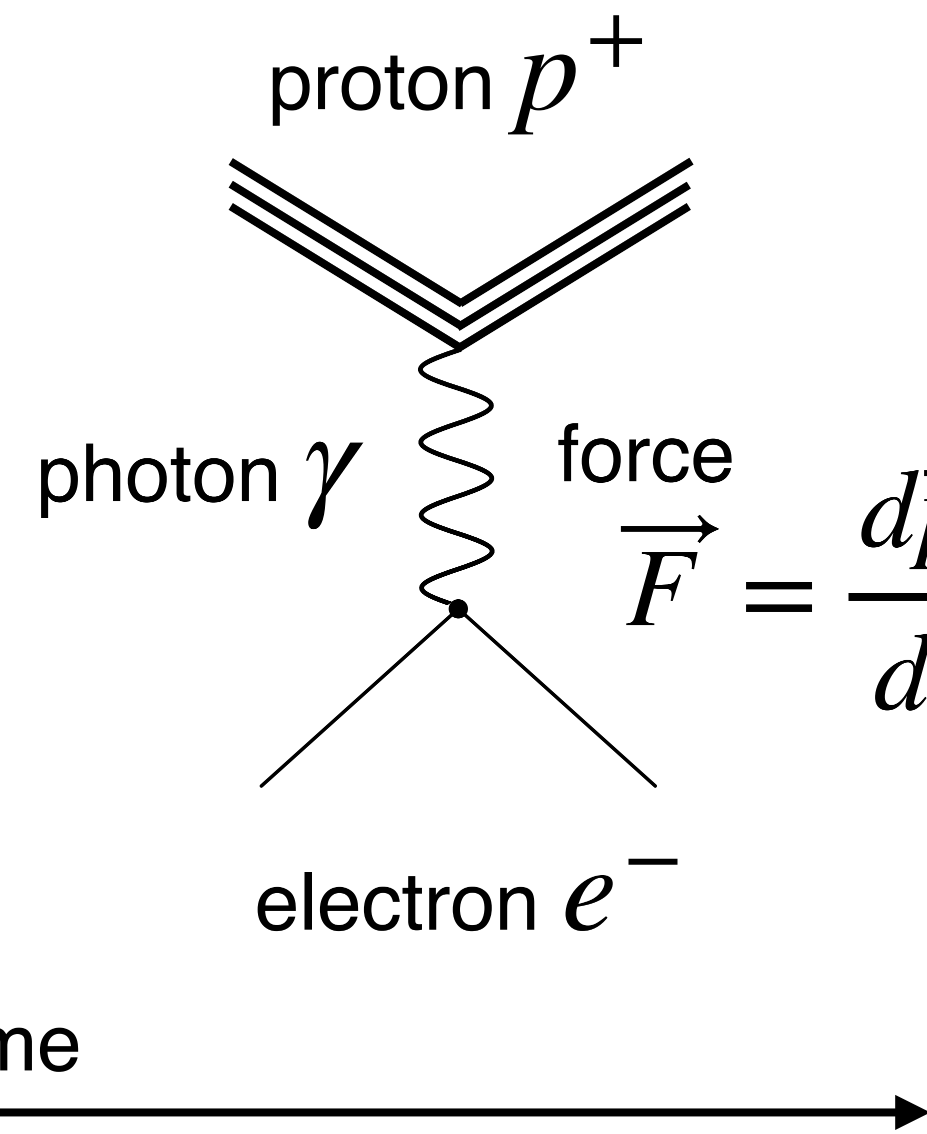
What is Force?

- A force is a push or pull upon an object resulting from the object's interaction with another object

— A fundamental force results from a fundamental interaction

Electromagnetic Interaction:

Force is not necessarily a single photon exchange



$$\vec{F} = \frac{d\vec{p}}{dt}$$

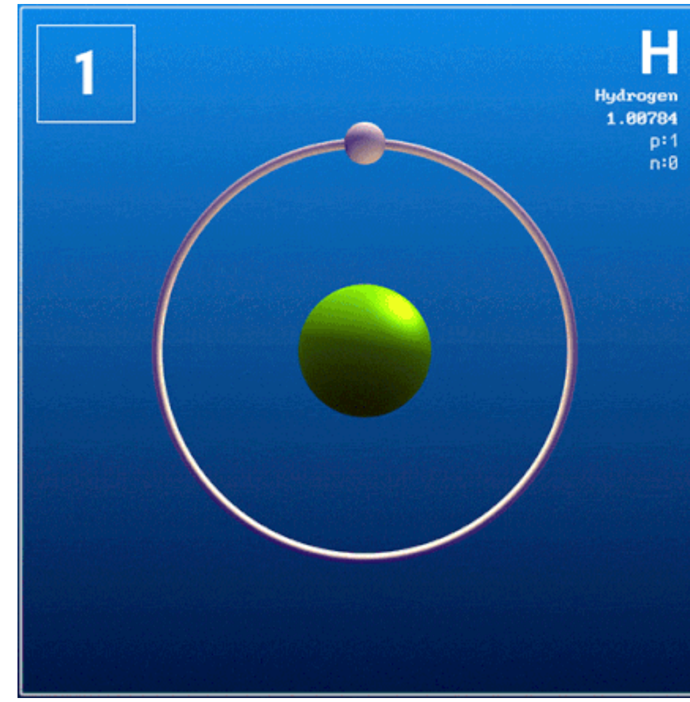
EM Interactions: Hydrogen Atom

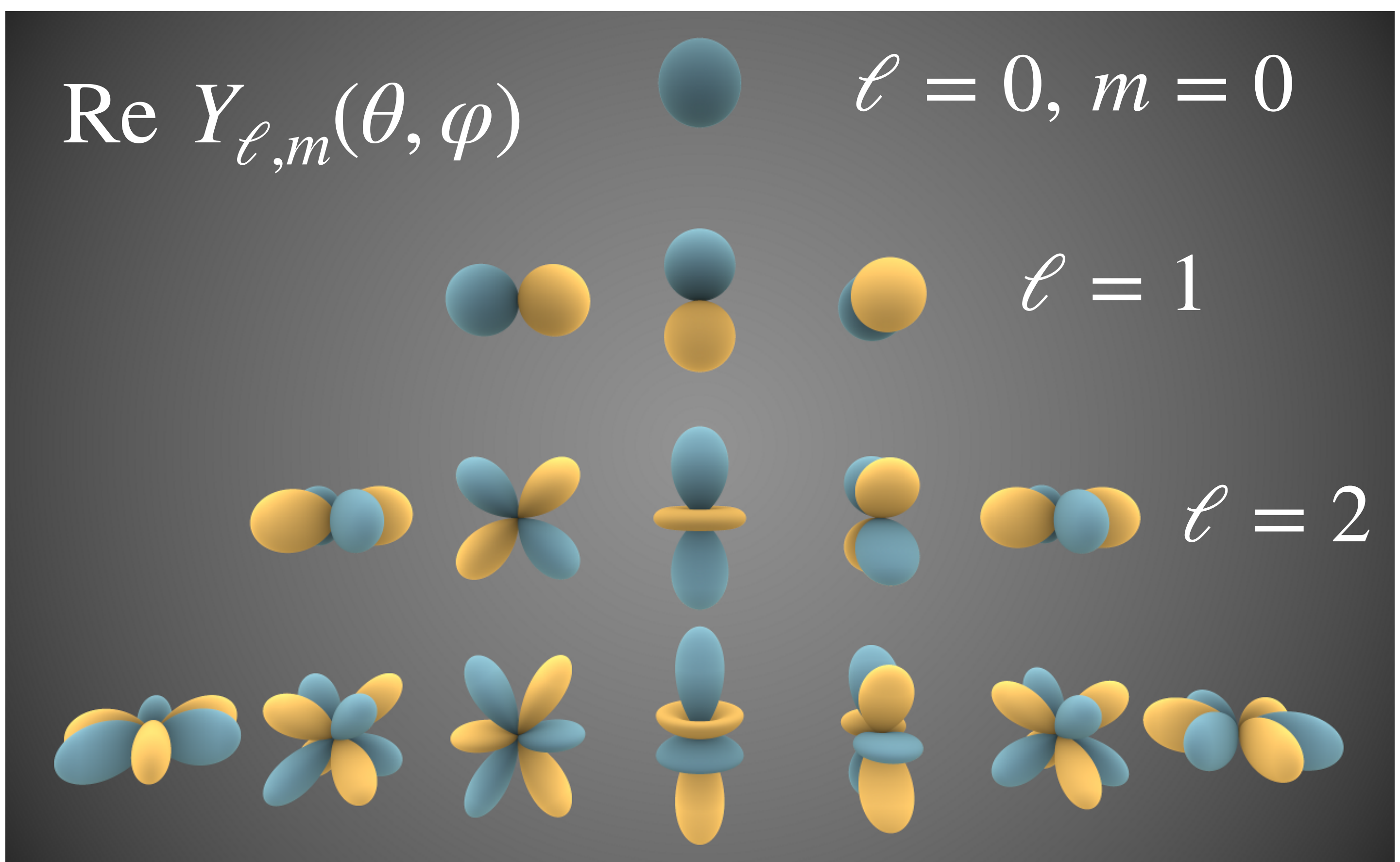
$$\psi_{n,\ell,m}(r,\theta,\varphi) \propto R_{n,\ell}(r)\, Y_{\ell,m}(\theta,\varphi)$$

$$|m| \le \ell = 0,1,2,3,\ldots \; < n$$

Probability to find electron in (r,θ,φ)

$$|\psi_{n,\ell,m}(r,\theta,\varphi)|^2$$





$$Y_0^0(\theta,\varphi) = \frac{1}{2}\sqrt{\frac{1}{\pi}}$$

$$Y_1^{-1}(\theta,\varphi) = \frac{1}{2}\sqrt{\frac{3}{2\pi}}\,\sin\theta\, e^{-i\varphi}$$

$$Y_1^0(\theta,\varphi) = \frac{1}{2}\sqrt{\frac{3}{\pi}}\,\cos\theta$$

$$Y_1^1(\theta,\varphi) = \frac{-1}{2}\sqrt{\frac{3}{2\pi}}\,\sin\theta\, e^{i\varphi}$$

$$Y_2^{-2}(\theta,\varphi) = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\,\sin^2\theta\, e^{-2i\varphi}$$

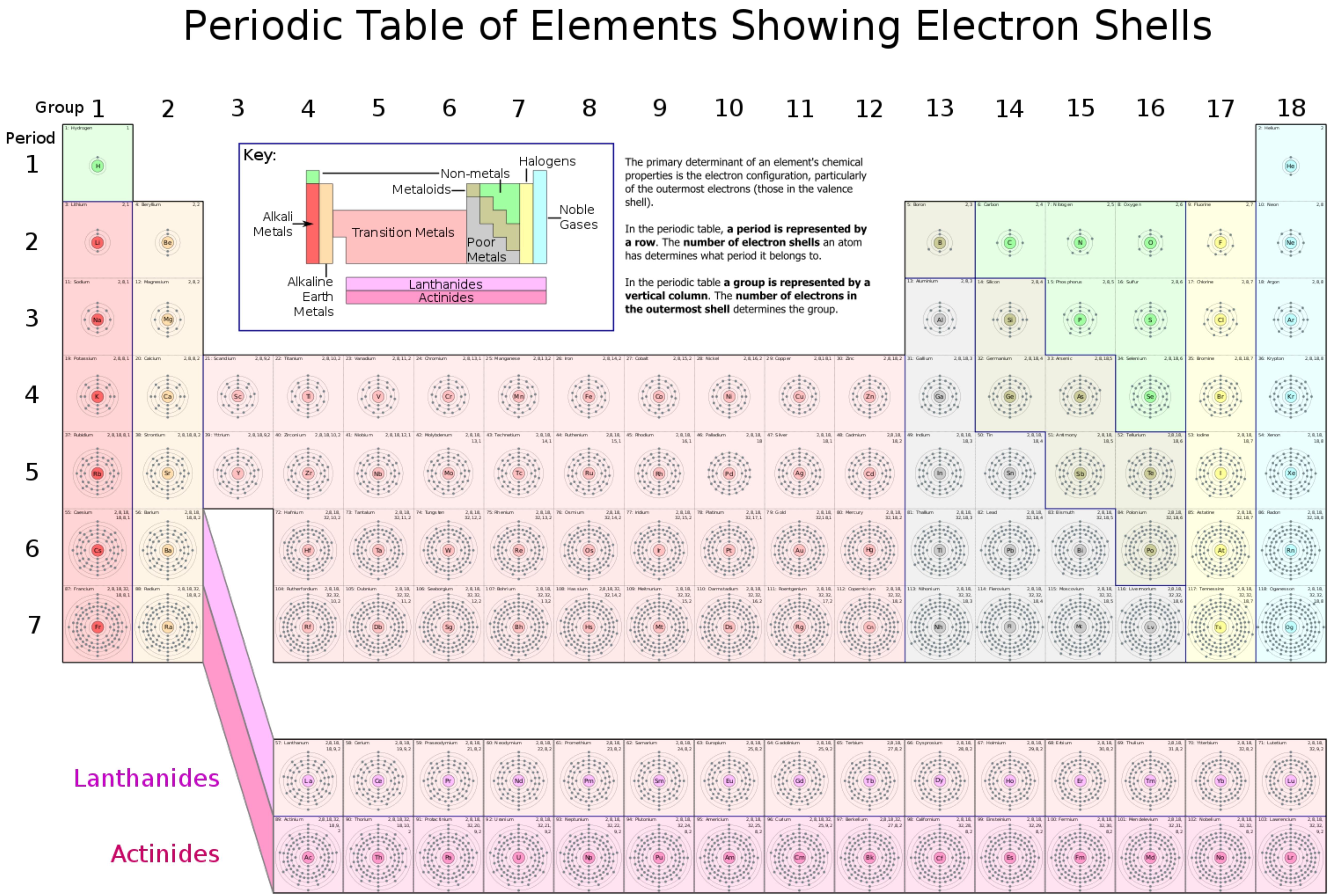
$$Y_2^{-1}(\theta,\varphi) = \frac{1}{2}\sqrt{\frac{15}{2\pi}}\,\sin\theta\,\cos\theta\, e^{-i\varphi}$$

$$Y_2^0(\theta,\varphi) = \frac{1}{4}\sqrt{\frac{5}{\pi}}\,(3\cos^2\theta - 1)$$

$$Y_2^1(\theta,\varphi) = \frac{-1}{2}\sqrt{\frac{15}{2\pi}}\,\sin\theta\,\cos\theta\, e^{i\varphi}$$

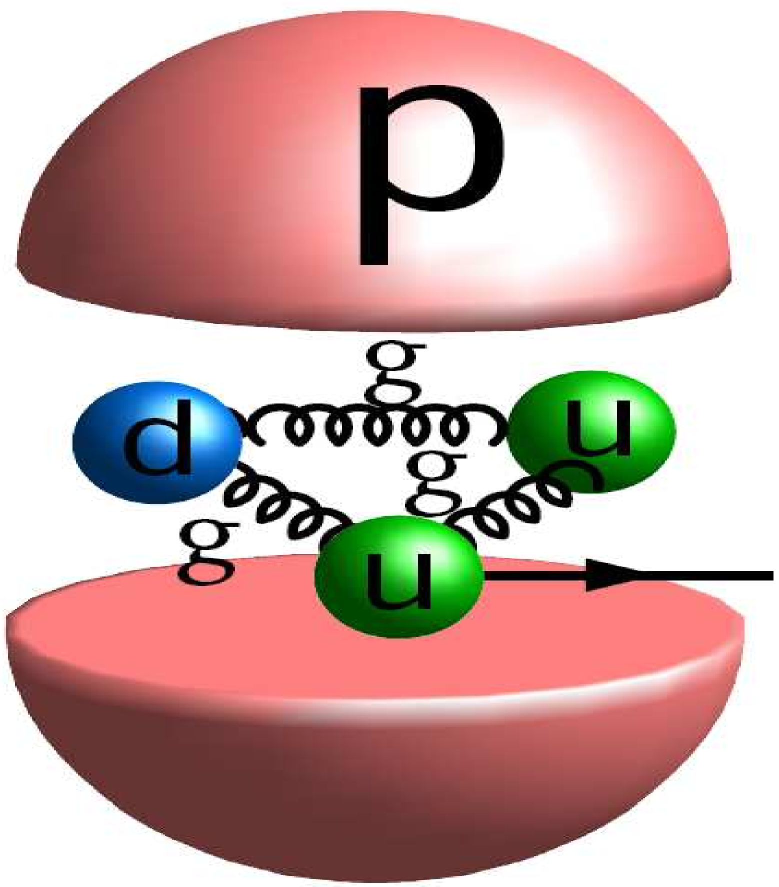
$$Y_2^2(\theta,\varphi) = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\,\sin^2\theta\, e^{2i\varphi}$$

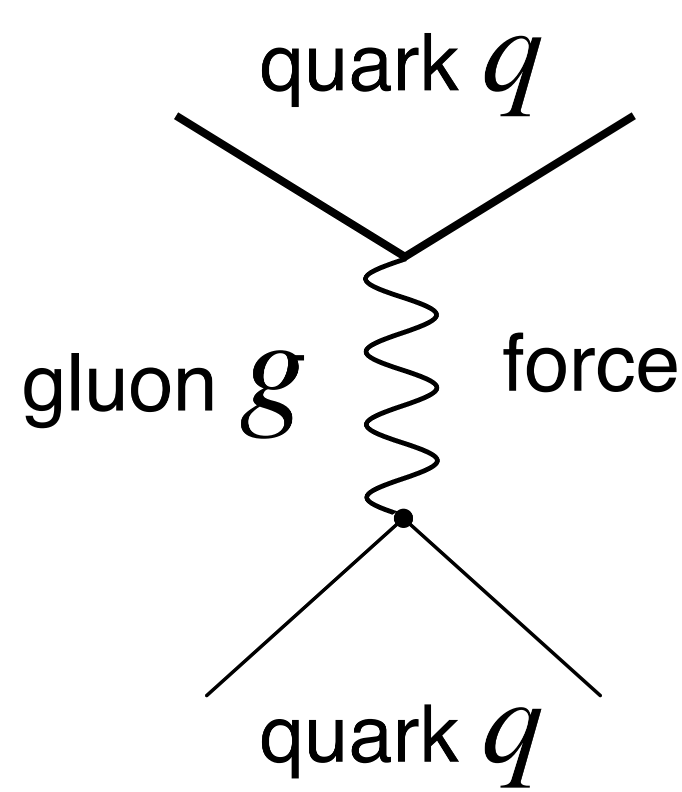
EM Interactions: Atoms and Molecules



Strong Nuclear Force

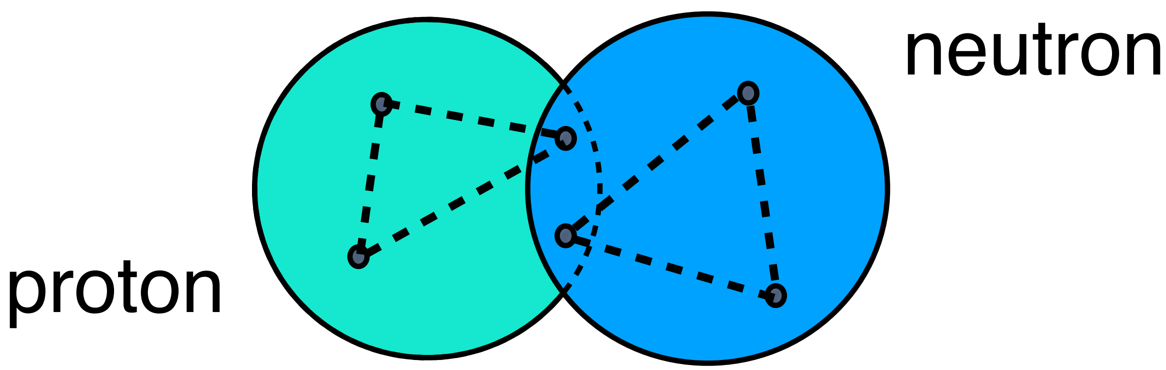
- Nucleus is held together by the strong nuclear force



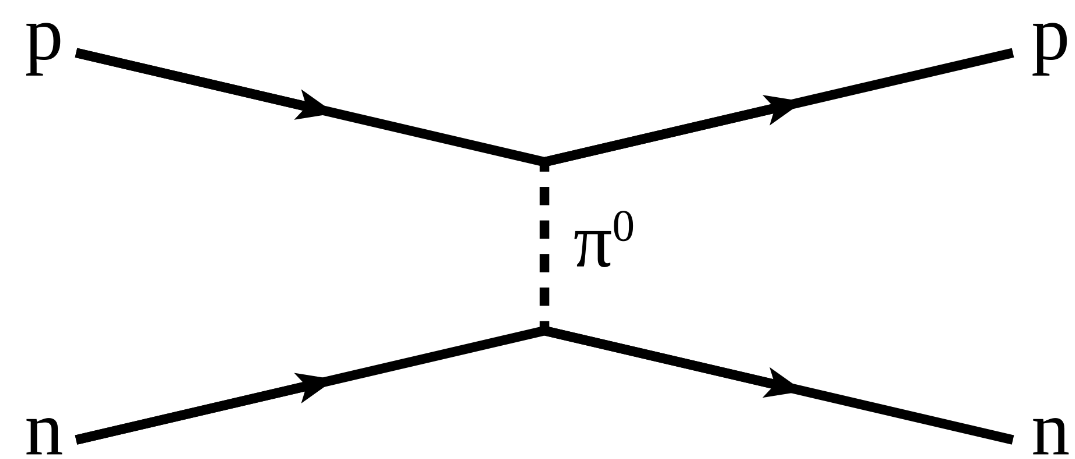


Strong Nuclear Force

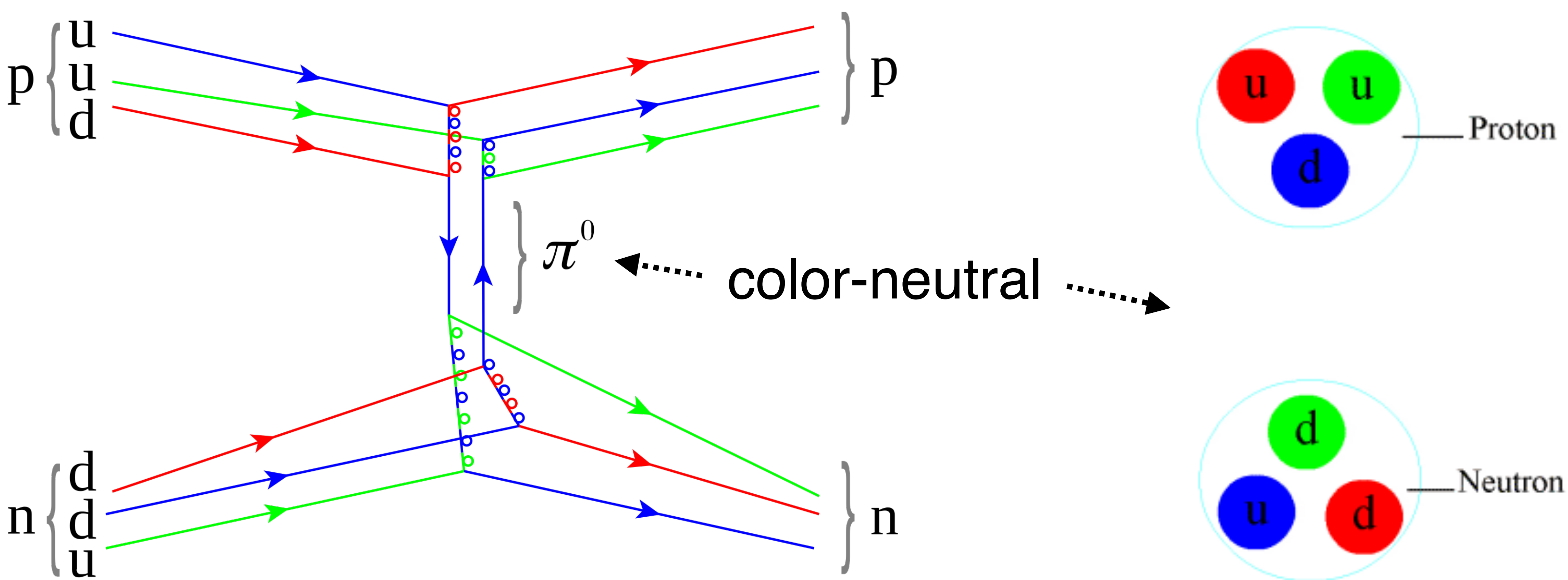
It gets more complicated, but gluons still connect it all:



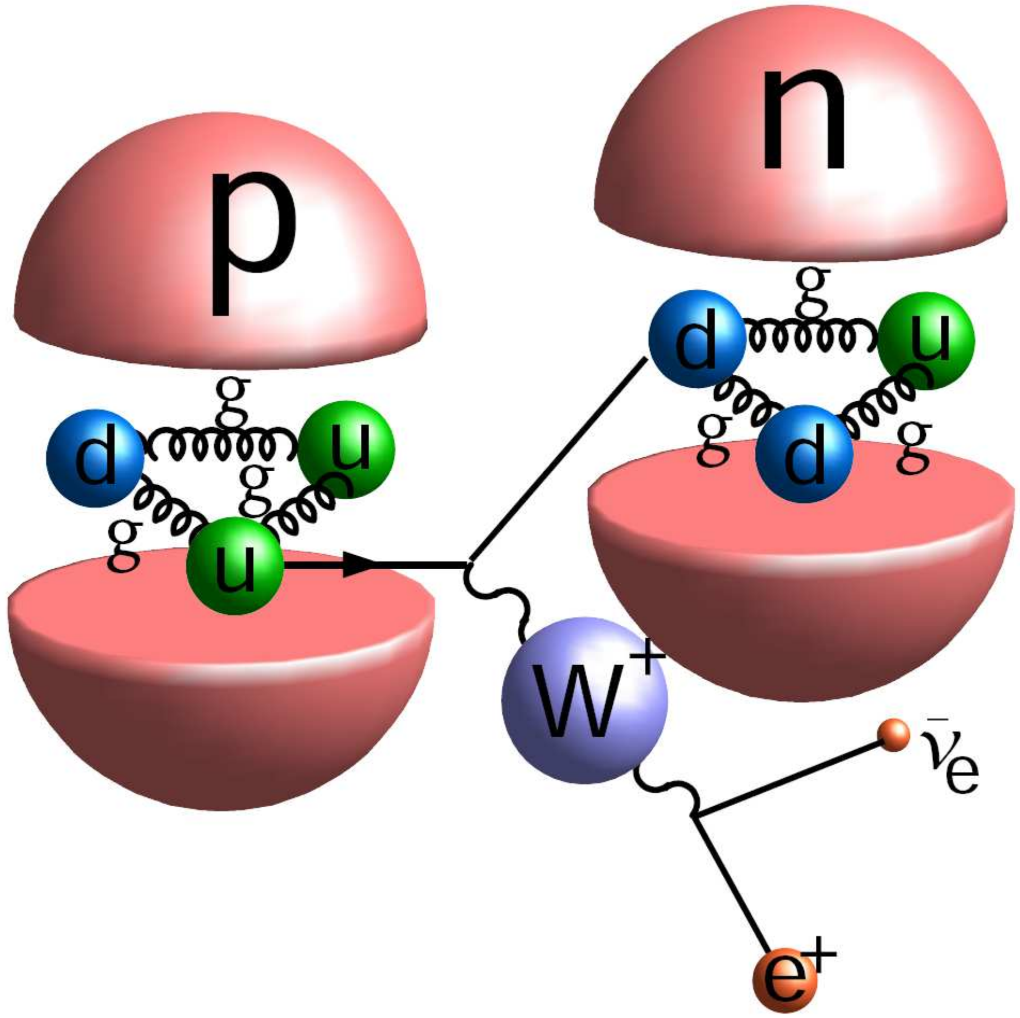
quark exchange



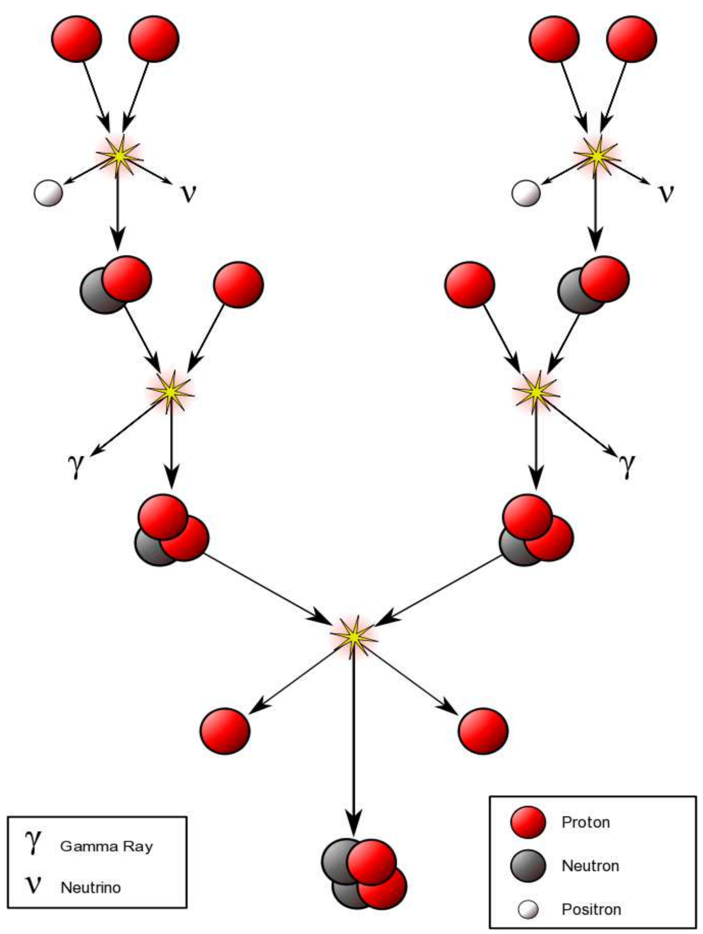
meson exchange



Weak Nuclear Force



Nuclear fusion (e.g. Sun):



— This weak interaction changes structure of the matter

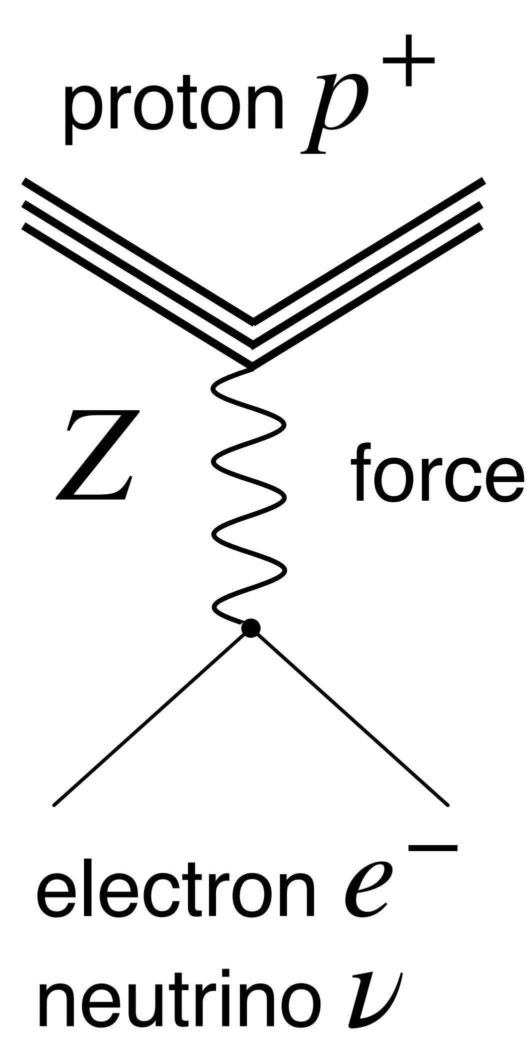
— One could argue if it is more than force (not just pull or push)

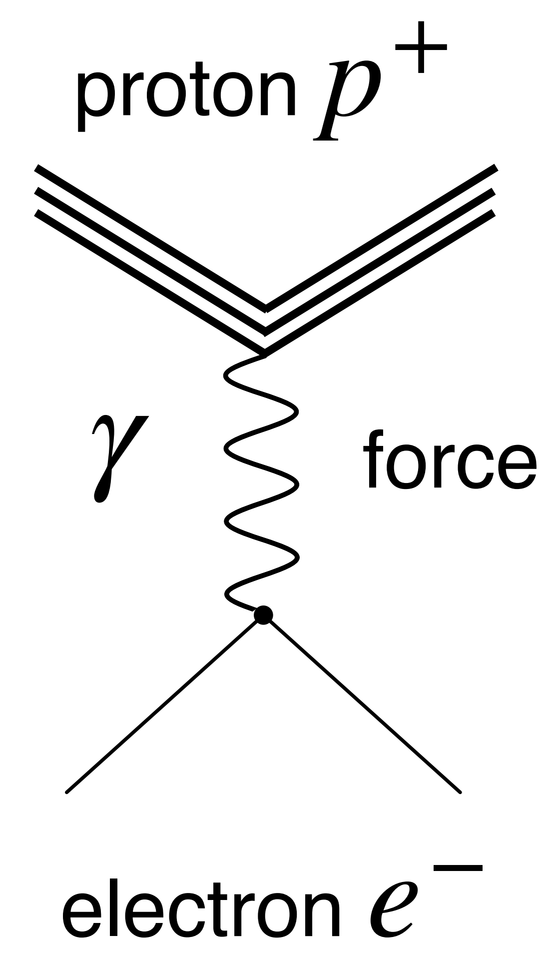
Weak Nuclear Force

— This weak interaction changes structure of the matter

— One could argue if it is more than force (not just pull or push)

— One can still have pure weak force:





Gravitational Force

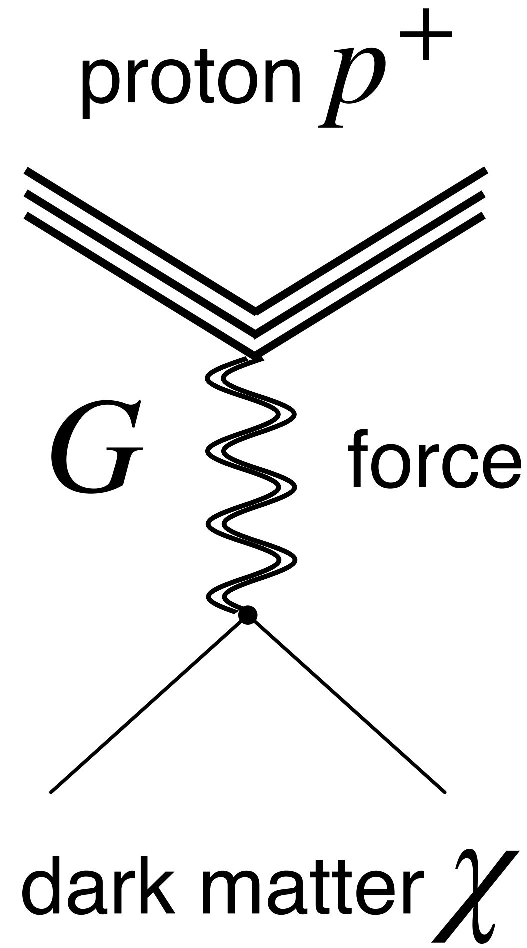
— Gravitational force is the weakest at elementary particle level

— Adds up to a large force on the scale of the planets
(when other forces cancel)

— Dark matter revealed only through gravitational interactions so far…

expect at elementary level:

quantum theory of gravity
is still in development…



Elementary Particles

- Until recently, all known elementary particles were of two types:

$$S = \frac{\hbar}{2}$$

Fermions (half-integer spin)
occupy space (Fermi statistics: exclusion princ.)
constitute matter (quarks, leptons)

$$S = 1\hbar$$

Bosons (integer spin)
carry interactions (γ photons, g gluons, $W^{\pm}, Z$)

- One can create compose particles of any spin $S = \frac{N\hbar}{2}, \; N = 0,1,2,..$

for example π^0 meson made of $q\bar{q}$ has $S = 0$

but there was no elementary particle with no spin, until recently

Elementary Particles

- Spin = 0 — H boson (discovered in 2012)
- Spin = $\frac{\hbar}{2}$ — $e^{\pm}, \mu^{\pm}, \tau^{\pm}, \nu_e, \nu_\mu, \nu_\tau$, quarks… matter
- Spin = $\hbar$ — $\gamma, Z, W^+, W^-, g_1, g_2, g_3, g_4, g_5, g_6, g_7, g_8$ interactions
- Spin = $\frac{3\hbar}{2}$ — Not known (may be supersymmetric particle, e.g. gravitino)
- Spin = $2\hbar$ — Not discovered, expect graviton G
- Arguments for higher Spin to be composite particles…

Elementary Particles: Interactions

- Spin = $\hbar$ $\quad \gamma, Z, W^+, W^-, g_1, g_2, g_3, g_4, g_5, g_6, g_7, g_8$

EM: γ

weak interactions: Z, W^+, W^-

strong interactions (gluons with color charge): $g_1, g_2, g_3, g_4, g_5, g_6, g_7, g_8$

- Spin = $2\hbar$ $\quad$ Not discovered, expect graviton G

gravity: G

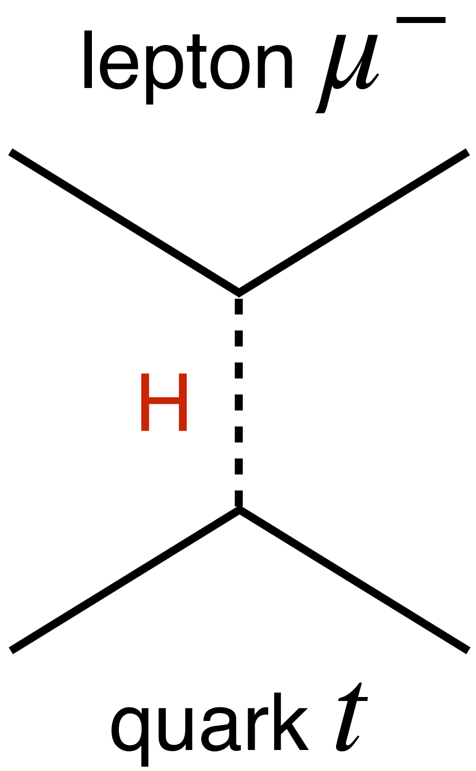
Elementary Particles: Interactions

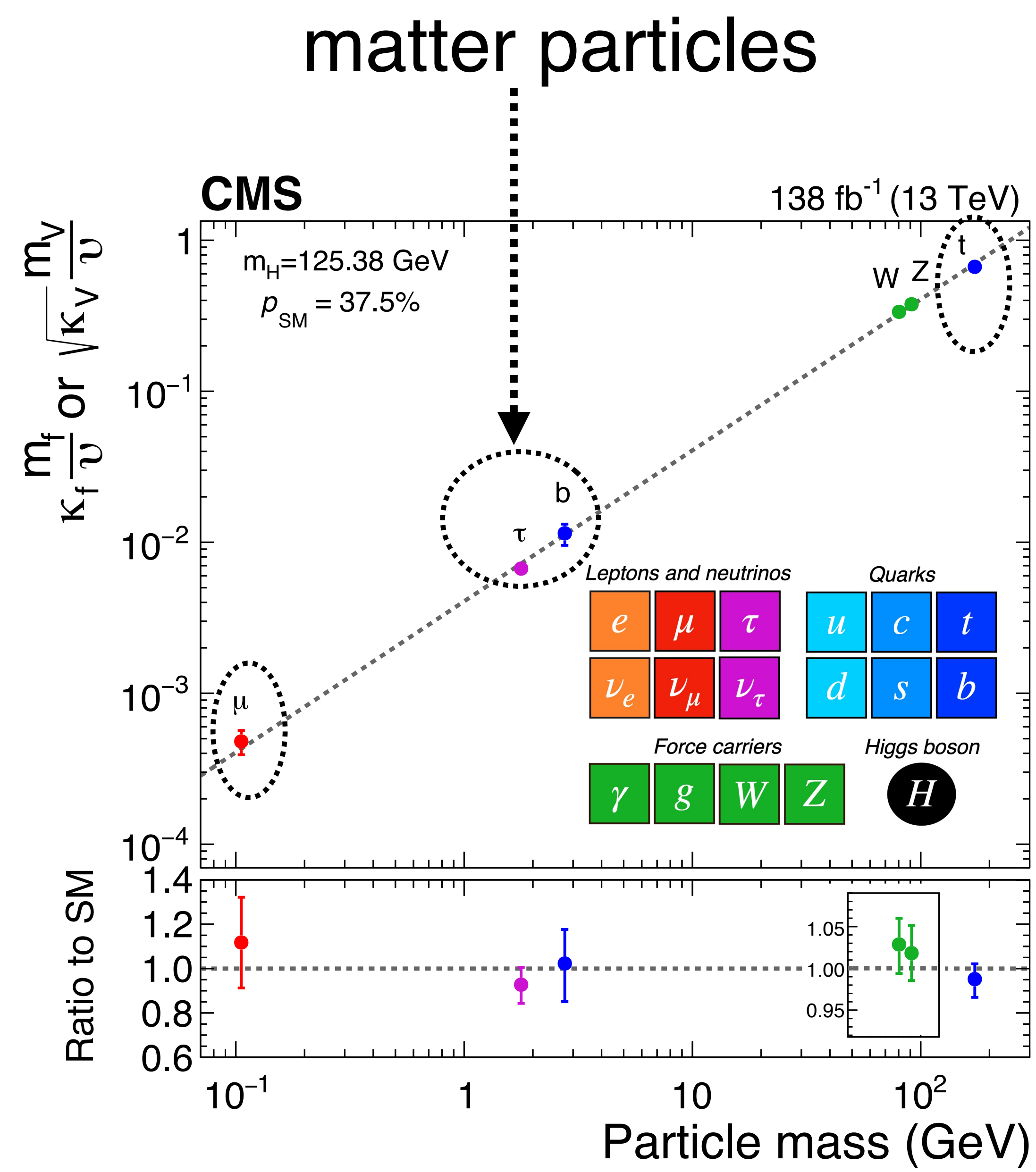
- Spin = 0 — H boson
  - (carrier of) the 5th force (kind of interaction)
- Spin = $\hbar$ — $\gamma, Z, W^+, W^-, g_1, g_2, g_3, g_4, g_5, g_6, g_7, g_8$
  - γ: EM
  - Z, W^+, W^-: weak interactions
  - $g_1, \ldots, g_8$: strong interactions (gluons with color charge)
- Spin = $2\hbar$ — Not discovered, expect graviton G
  - gravity

Higgs Boson is the 5th Force!

- H boson carries interaction between matter particles

Created in the laboratory (LHC):





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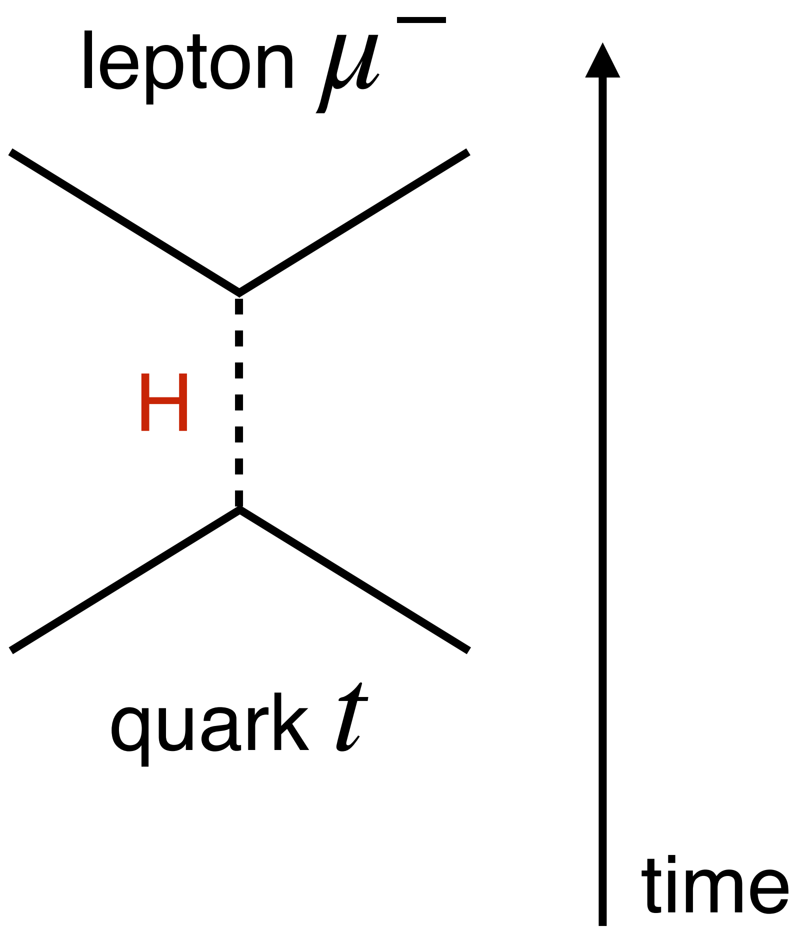

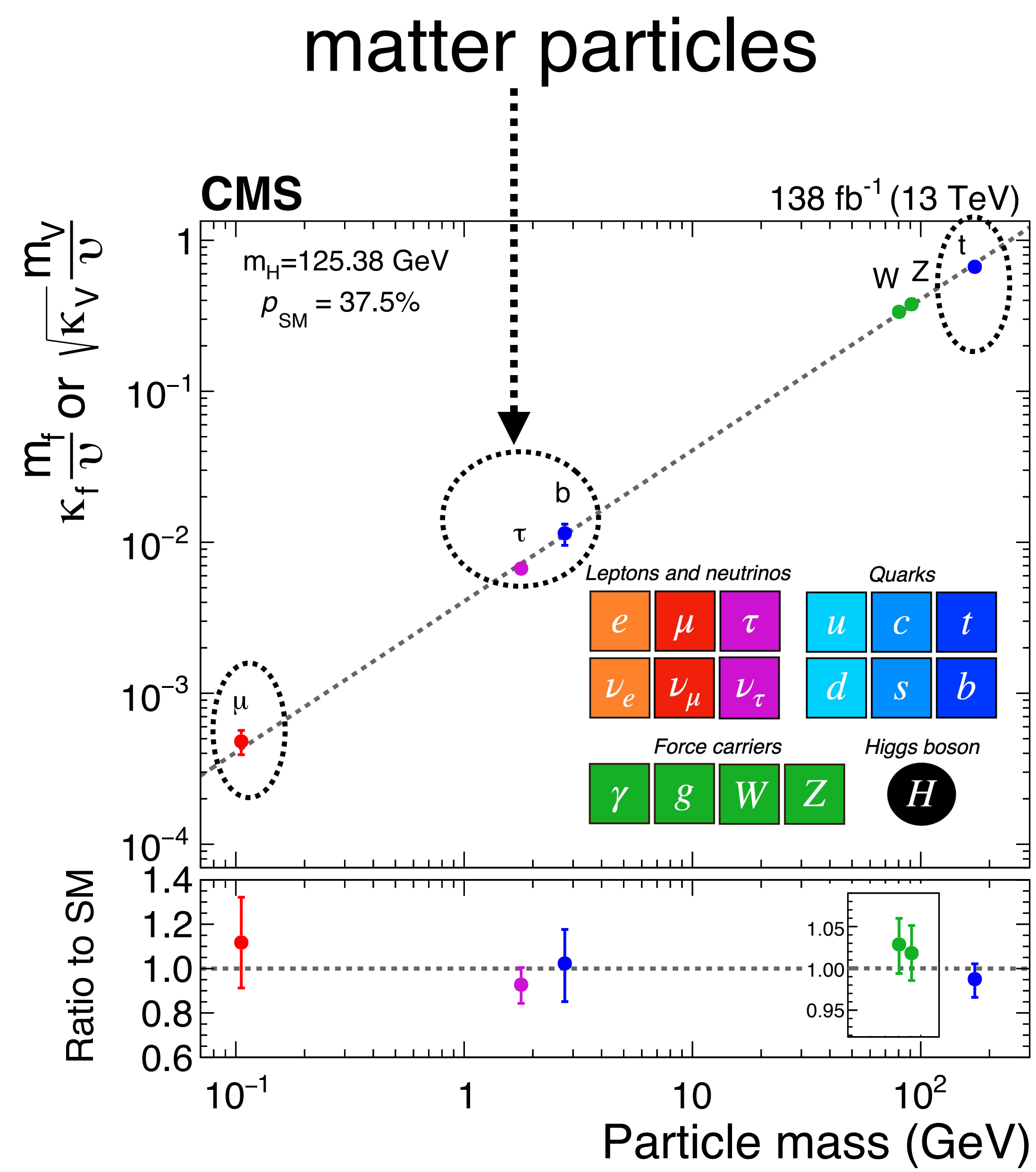

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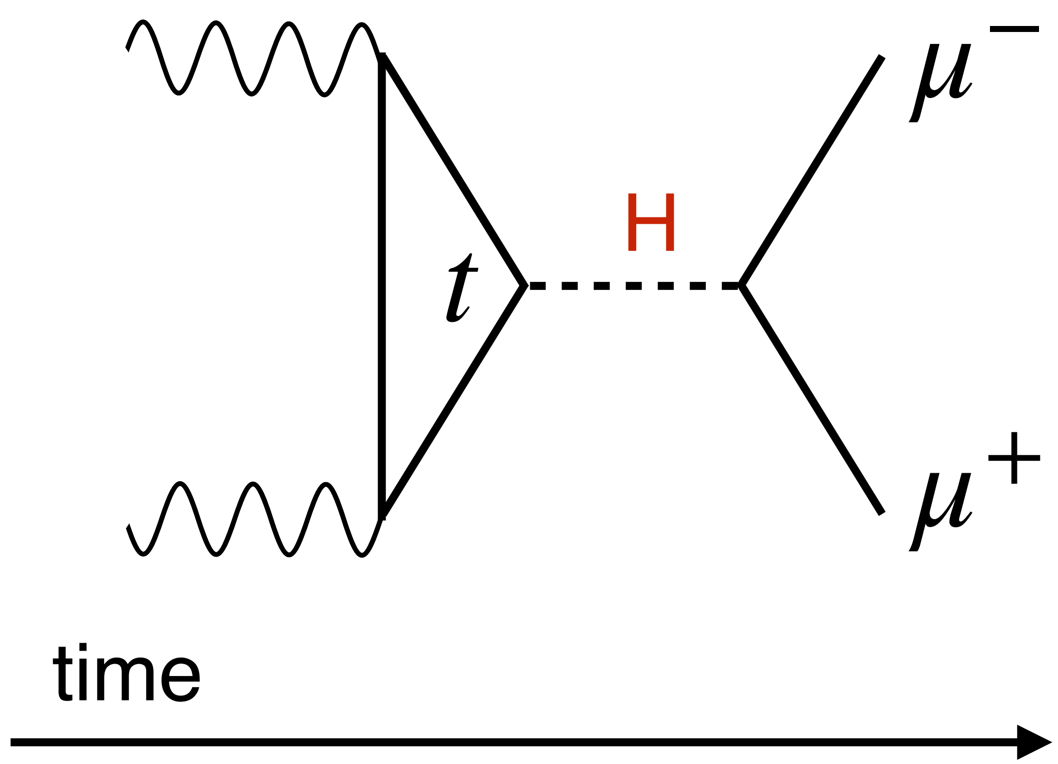
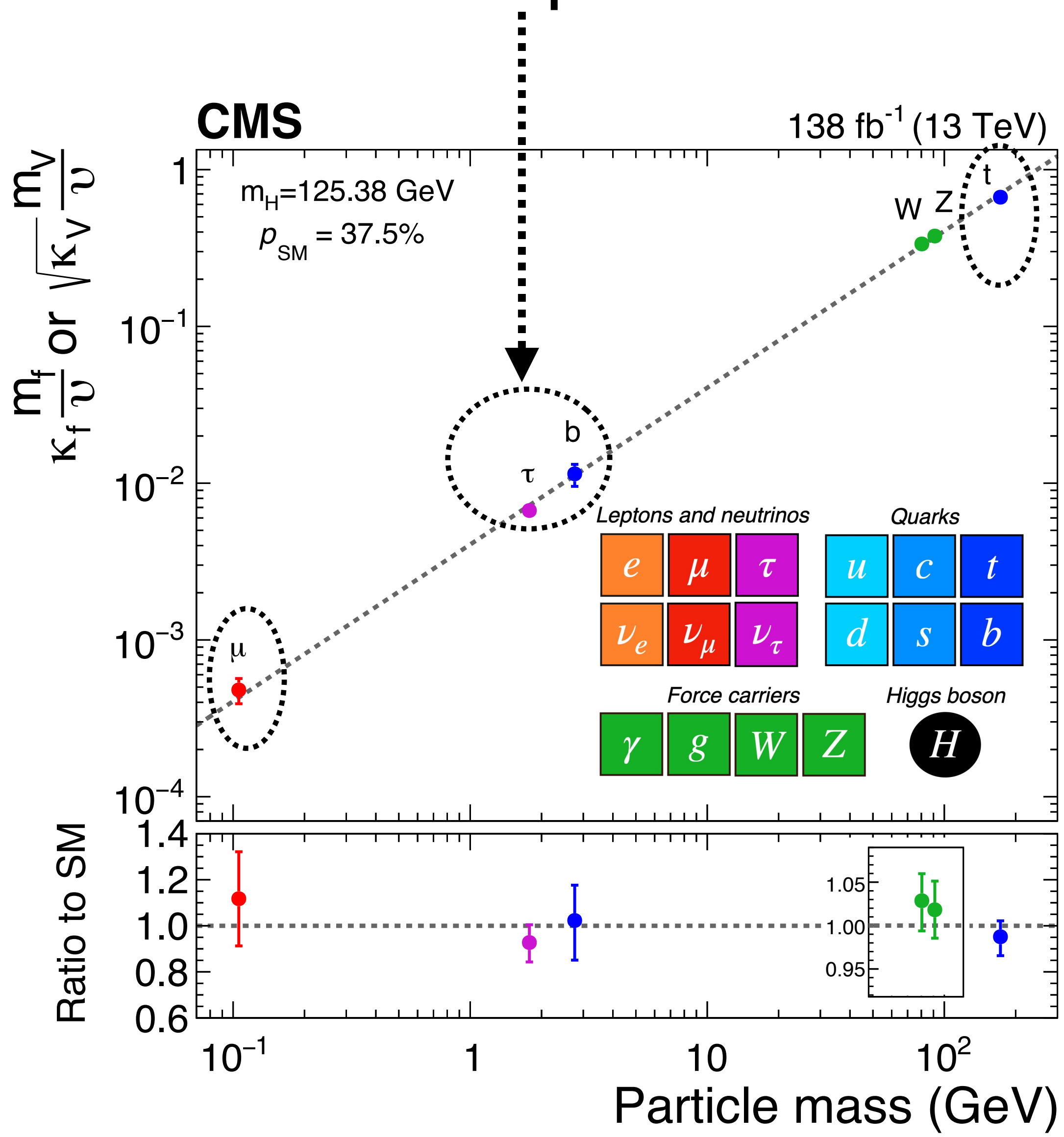


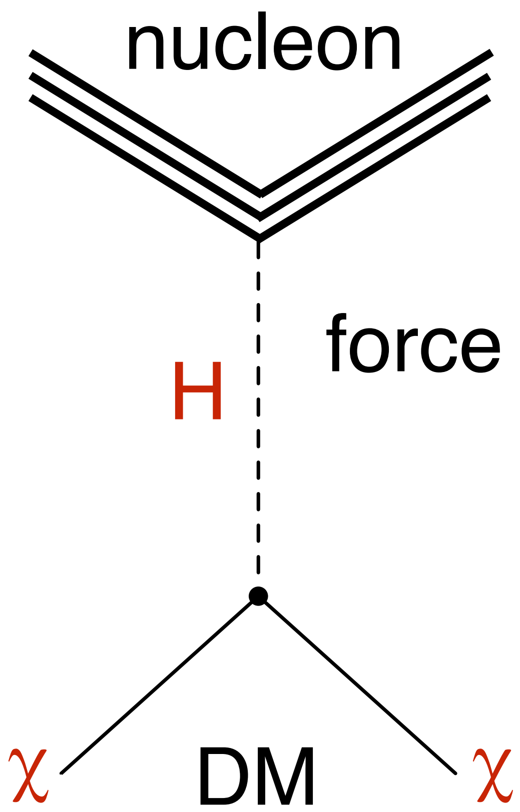
matter particles



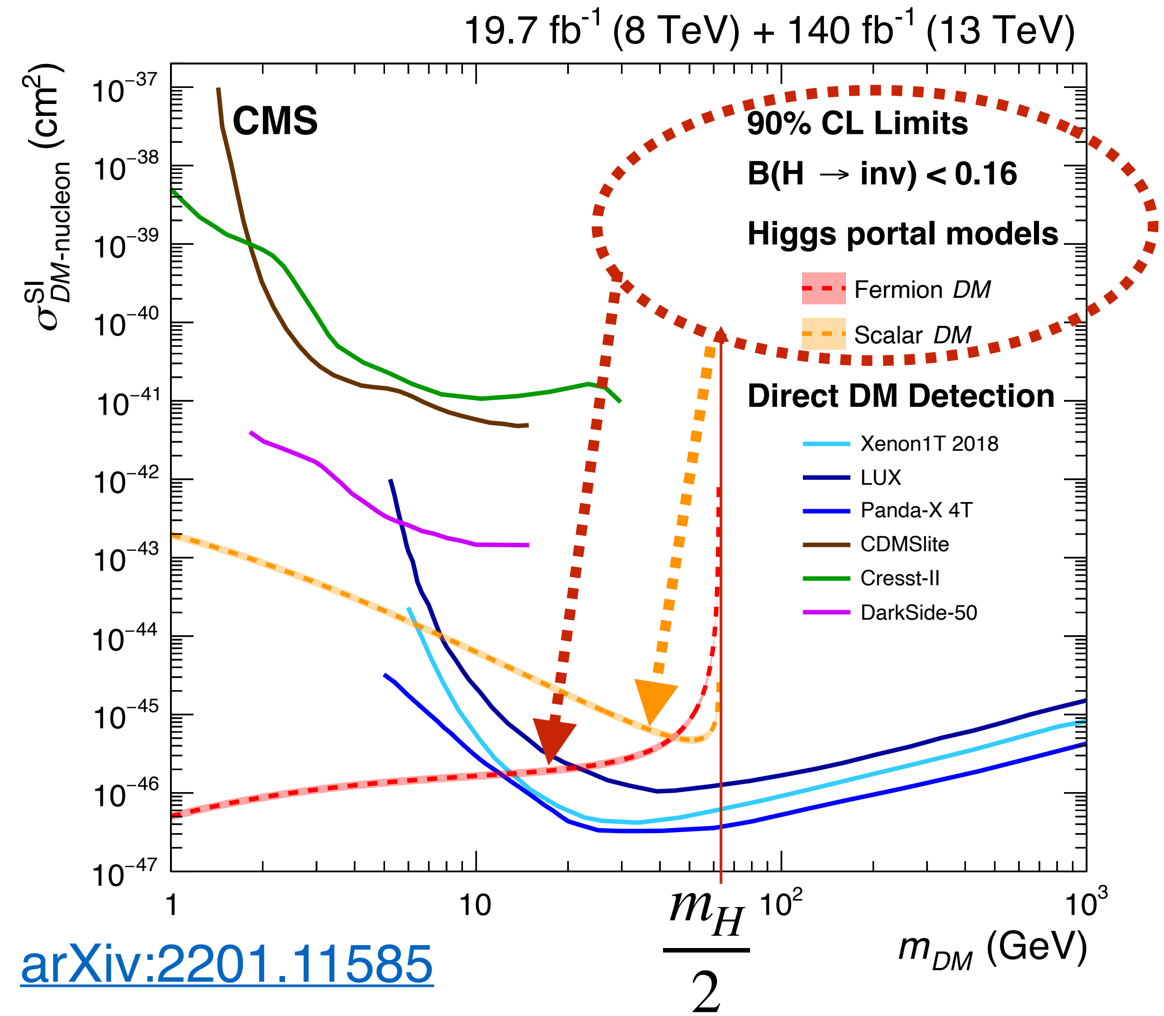
Higgs Boson is the 5th Force!

- H boson may become the only quantum connection to dark matter (χ) (besides gravity)

direct detection of dark matter:



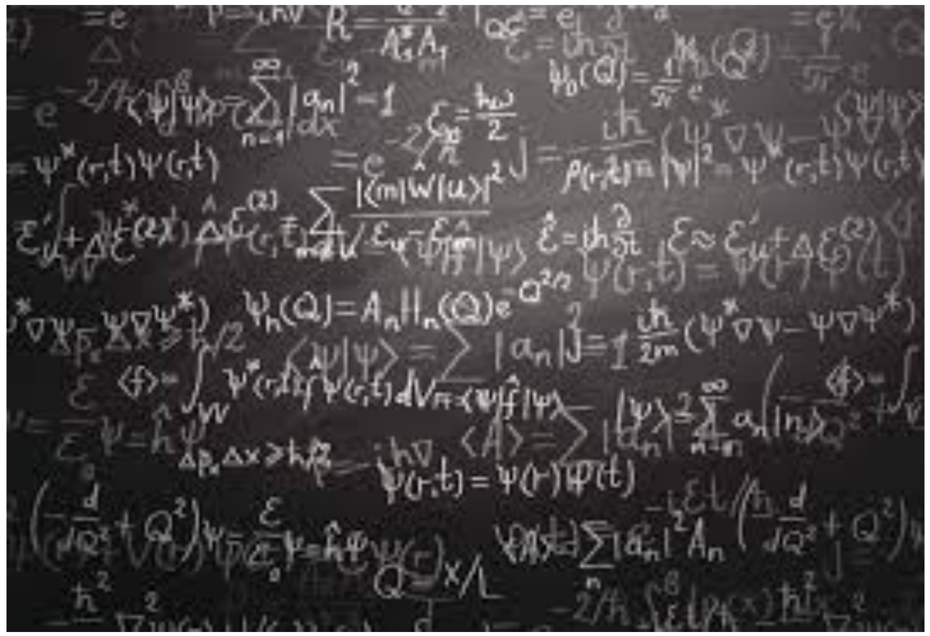
- Competitive (or better) with direct detection of dark matter: H→ $\chi\chi$ (invisible)

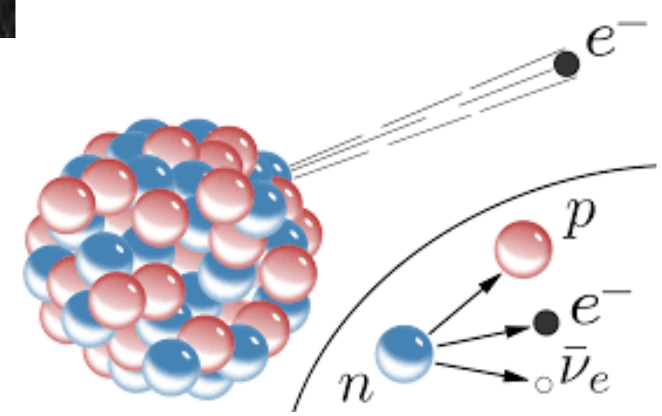


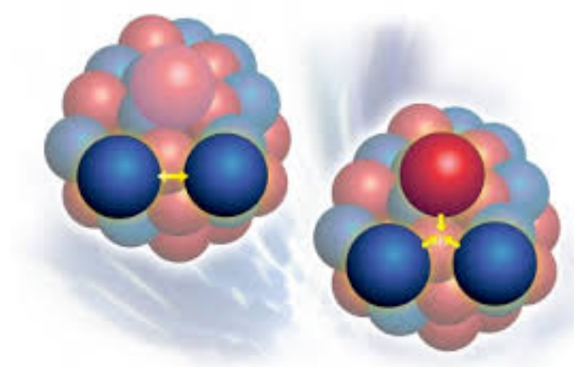
arXiv:2201.11585

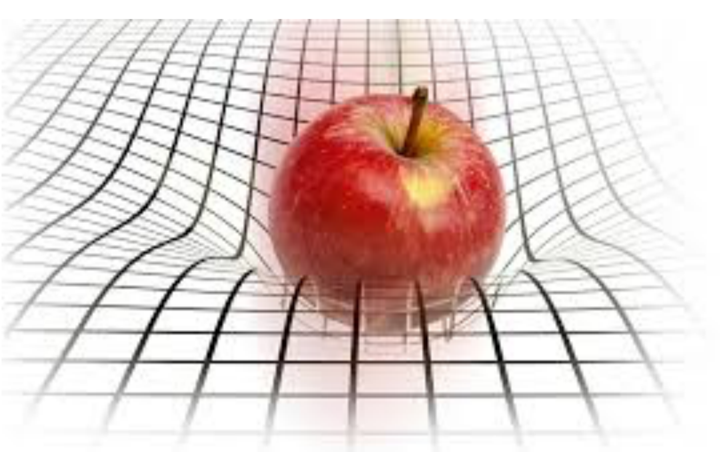
- Search for dark matter (χ) H→ $\chi\chi$ (invisible)

The 4 Forces









Gravity

Weak

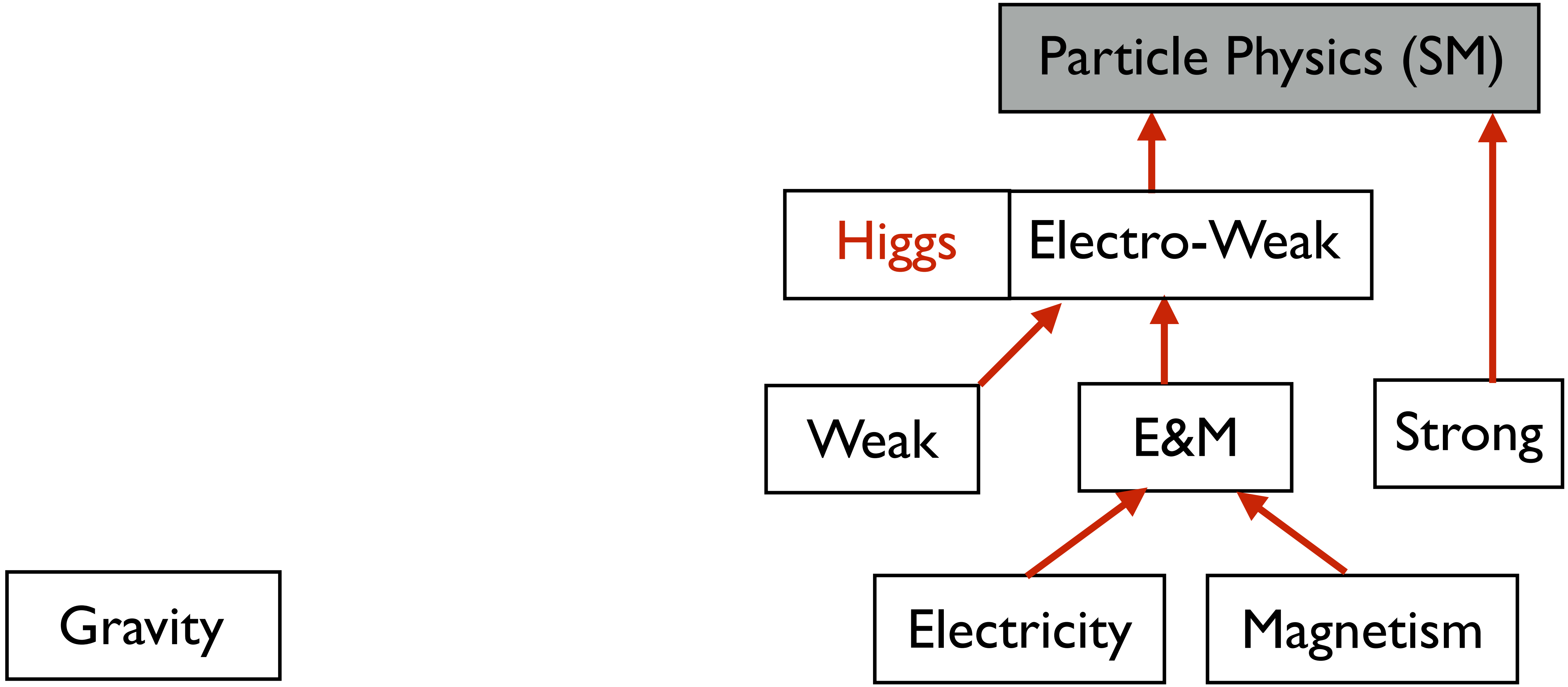
E&M

Strong

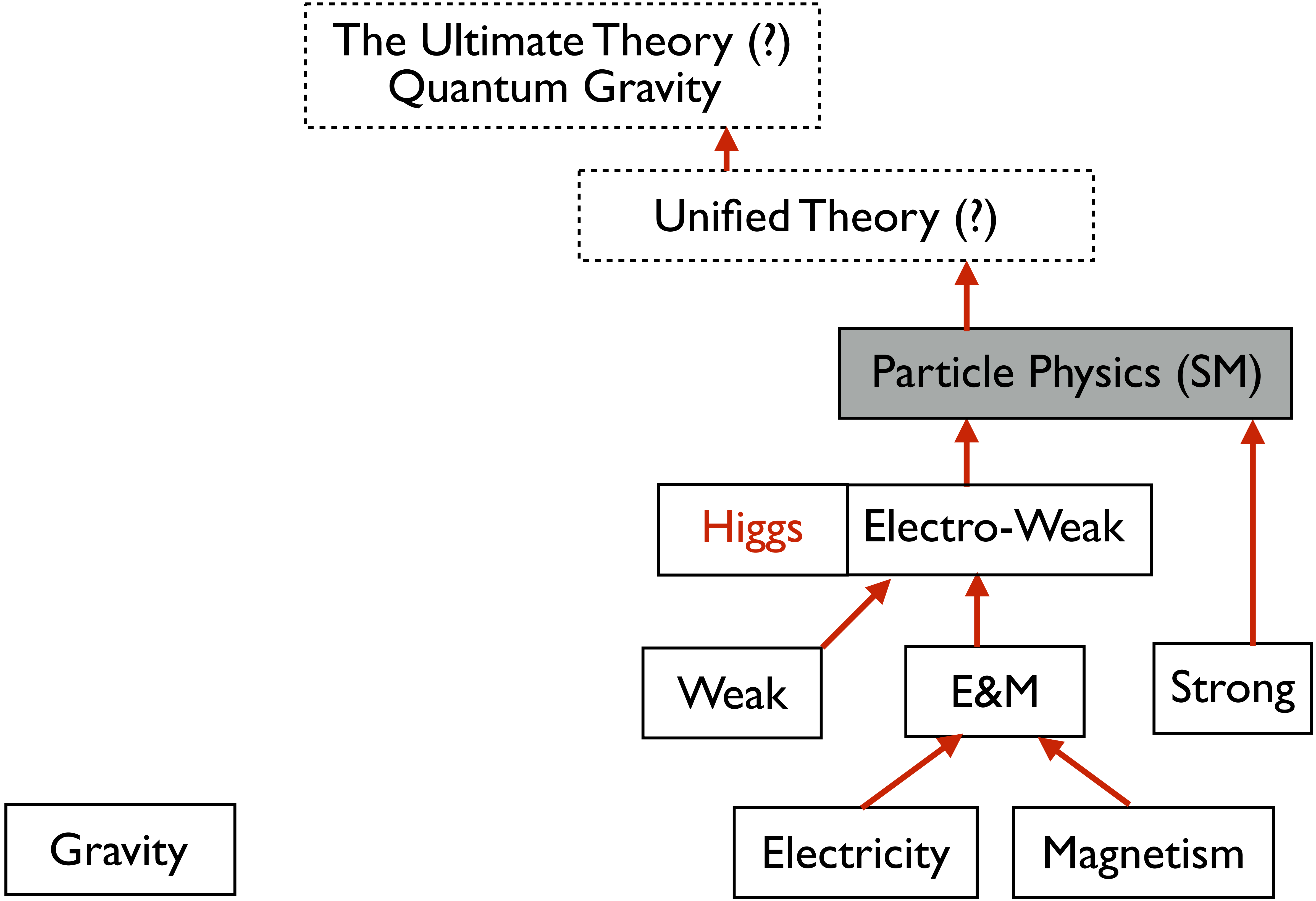
Electricity

Magnetism

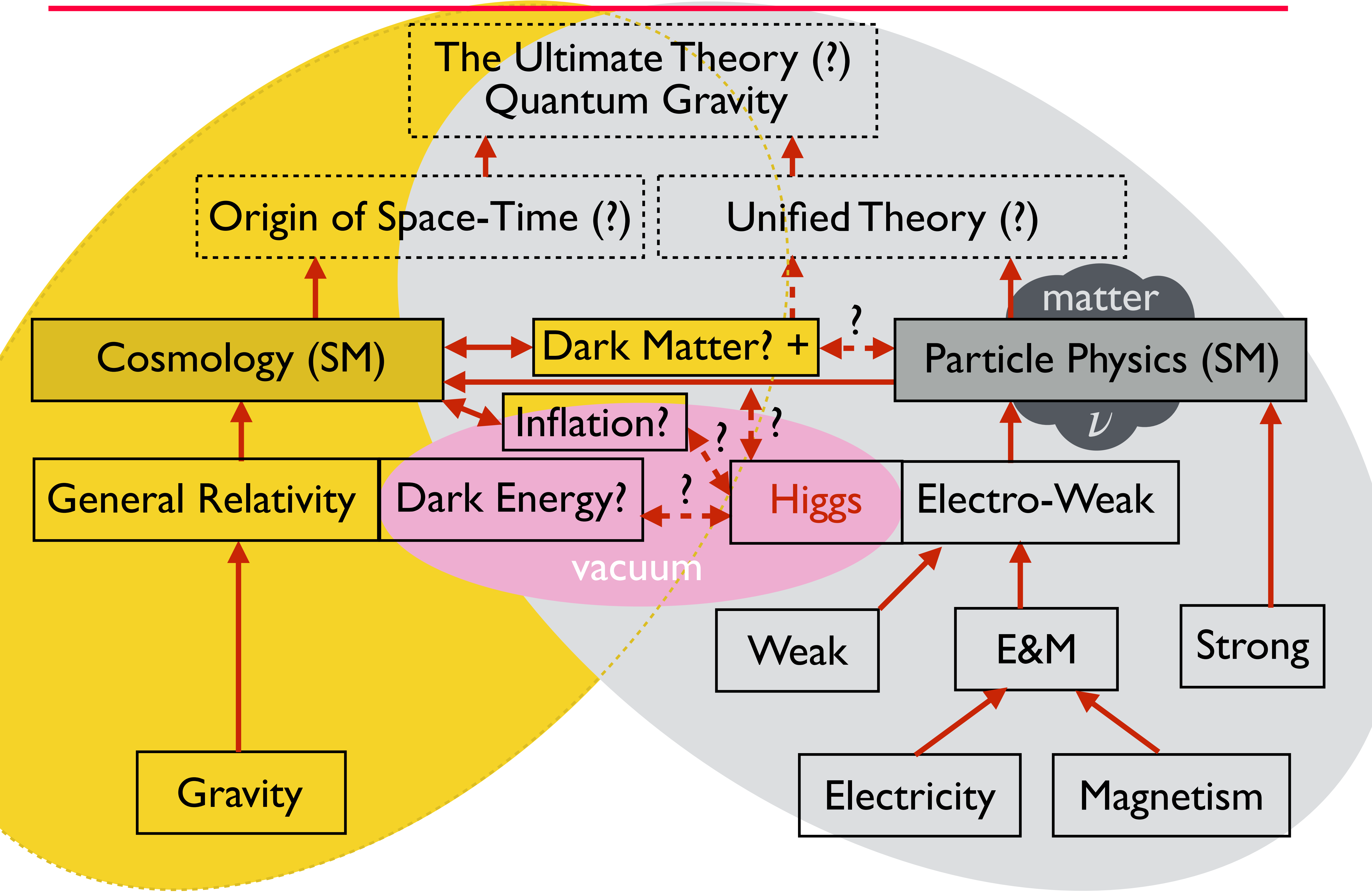
The 5 Forces


Particle Physics (SM)
Higgs
Electro-Weak
Weak
E&M
Strong
Gravity
Electricity
Magnetism

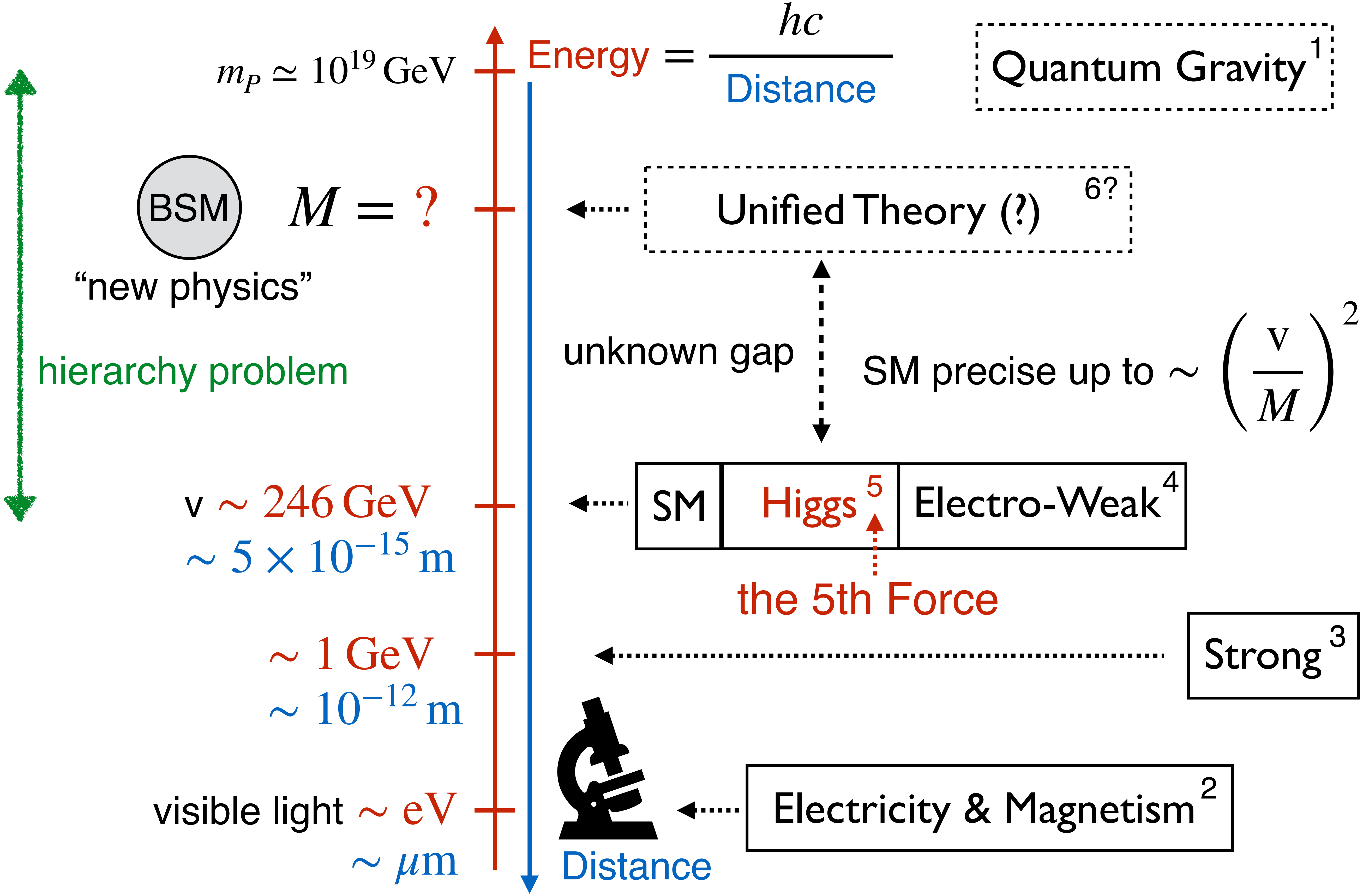
More Forces?


The Ultimate Theory (?)
Quantum Gravity
Unified Theory (?)
Particle Physics (SM)
Higgs
Electro-Weak
Weak
E&M
Strong
Gravity
Electricity
Magnetism

The Big Picture



Scales in Particle Physics



Crisis of the Standard Models

Study the Word
with a Telescope

Crisis of the Standard Models (SM)
of Particle Physics & Cosmology

(turn of the XXth century)

understanding the matter

— Dark matter?

— Baryogenesis? (matter over antimatter)

baryon number violation (p decay?)

CP violation? non-equilibrium?

— Are neurinos special? …

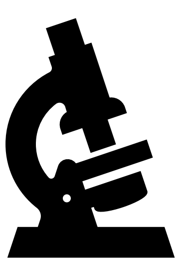
understanding the vacuum

— Higgs field and masses (hierarchy problems)

(vacuum stability)

— Dark energy?

— Inflation?

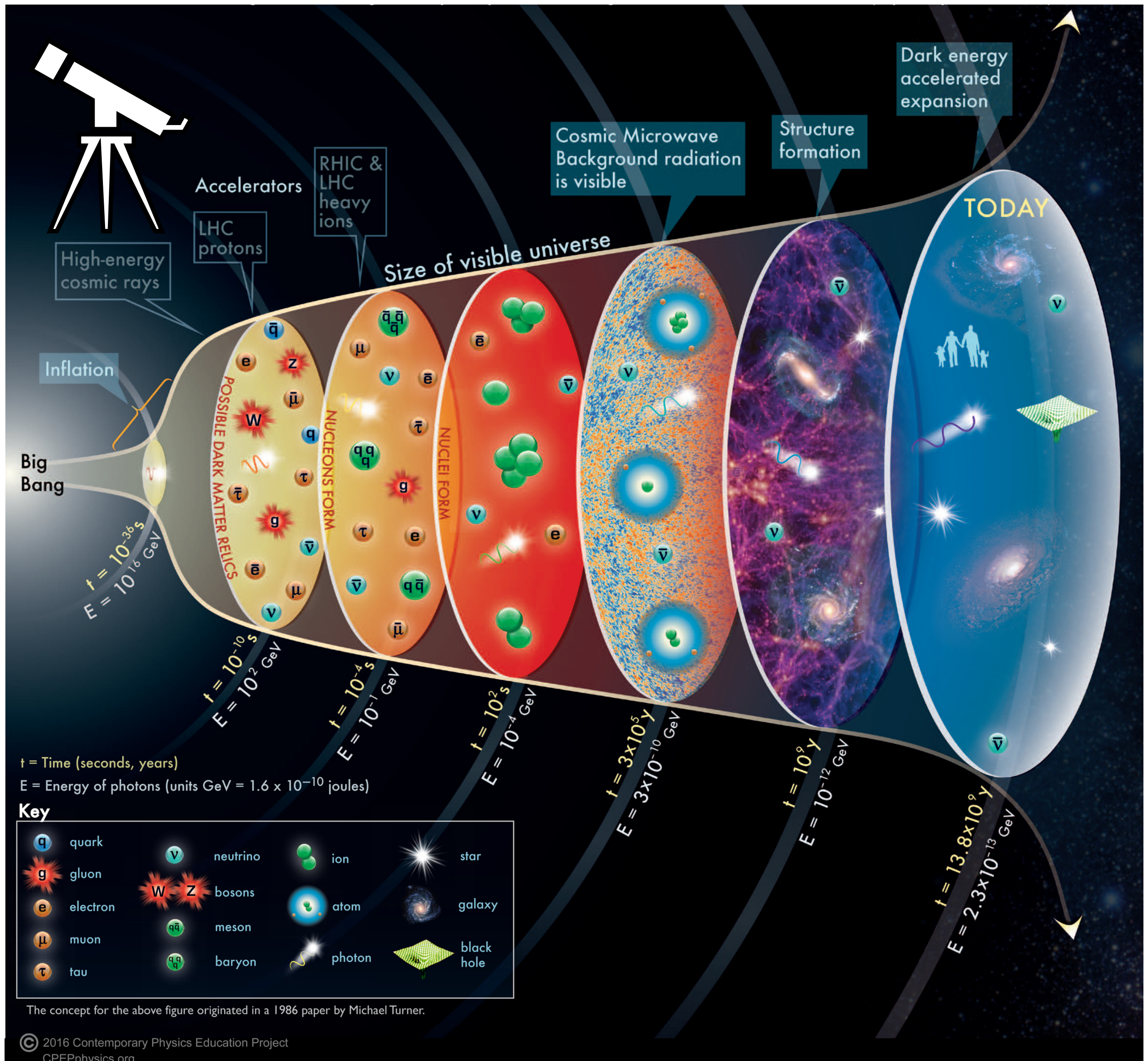


Microscope to look deep: the LHC experiments

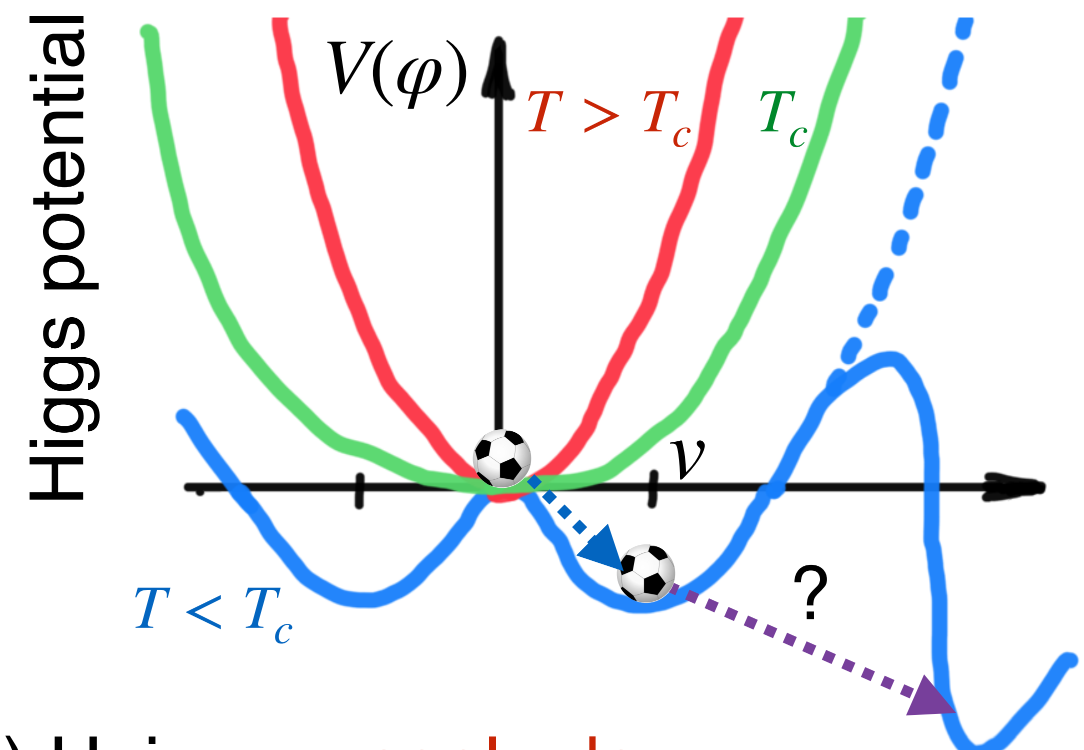
The Higgs Field in the SM

SM Higgs field $\varphi = \begin{pmatrix} G^+ \\ (v + H^0 + iG^0)/\sqrt{2} \end{pmatrix} \Rightarrow H^0$ + mass of Z, W^+, W^-

LHC goal: excite the vacuum (Higgs field φ)$\Rightarrow$ create the H^0 boson



$$V(\varphi) = \mu^2 \varphi^\dagger \varphi + \lambda^2 (\varphi^\dagger \varphi)^2$$

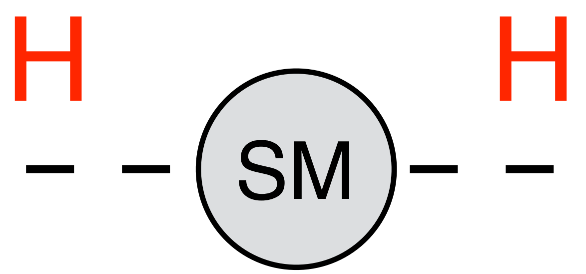


(1) Universe cools down

(2) symmetry spontaneously breaks

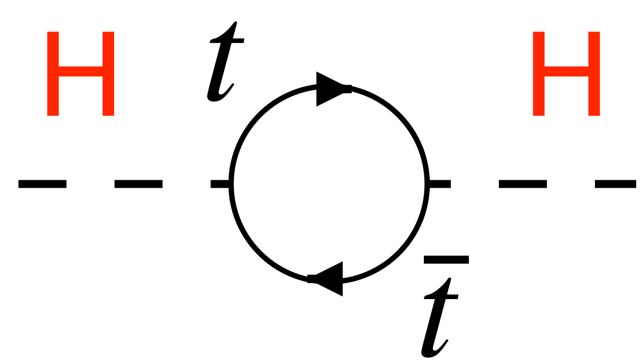
Hierarchy Problem

- quantum corrections:



$\Rightarrow \quad \Delta m_H^2 \to \infty$

for example:



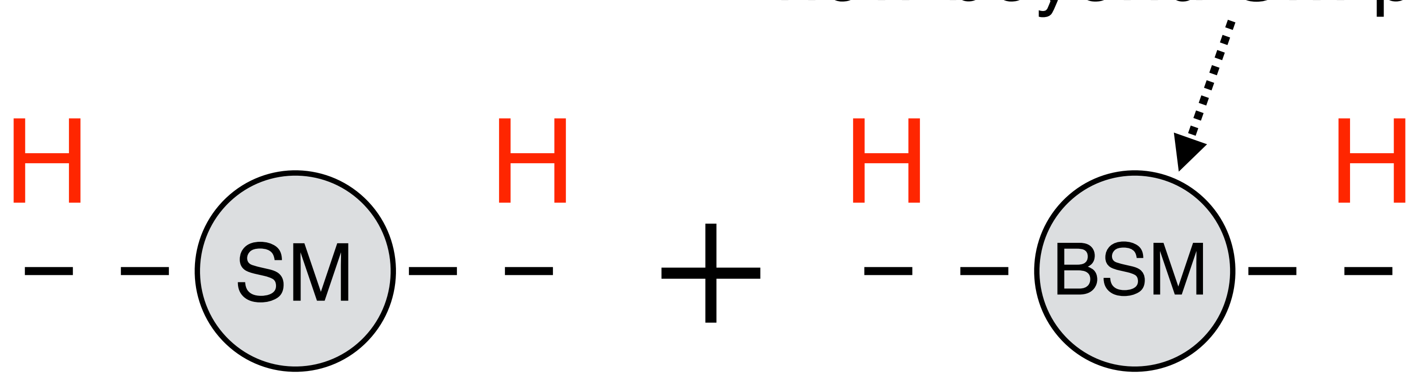
SM cannot predict m_H - measure

$$m_H = 125.26 \pm 0.20 \pm 0.08 \text{ GeV} \lll m_P$$

- one of possible solutions:

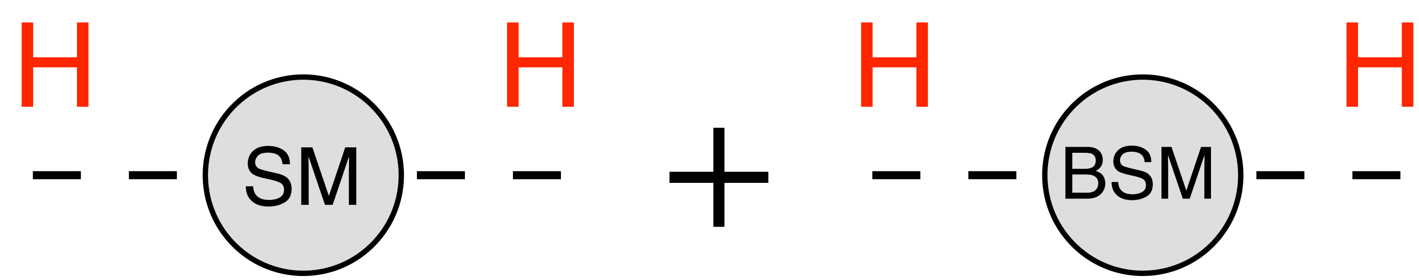
new beyond SM particles

corrections cancel:

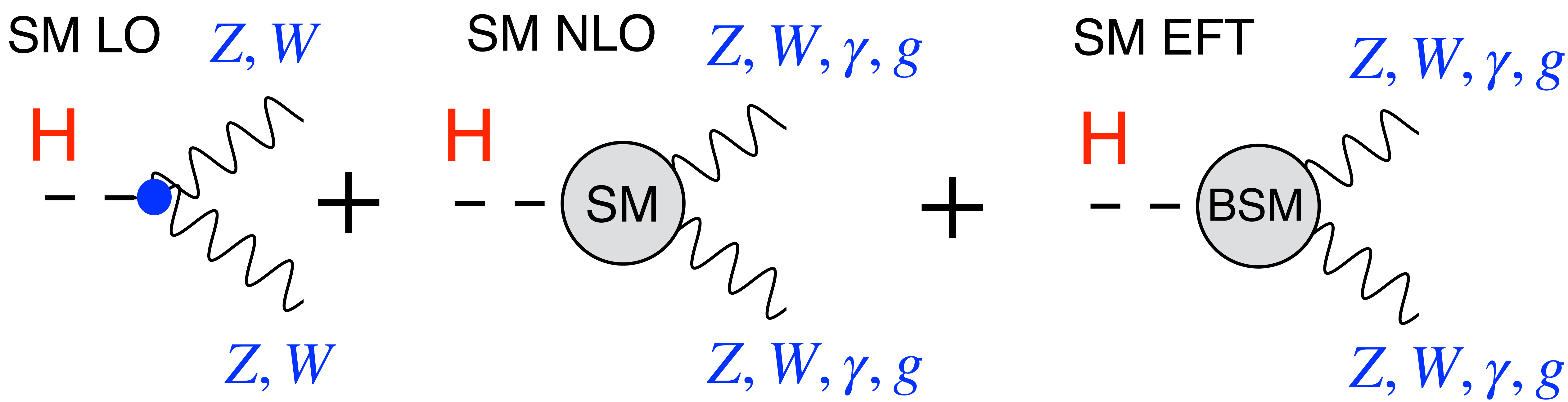


Implications of the Hierarchy Problem

If BSM contributes:



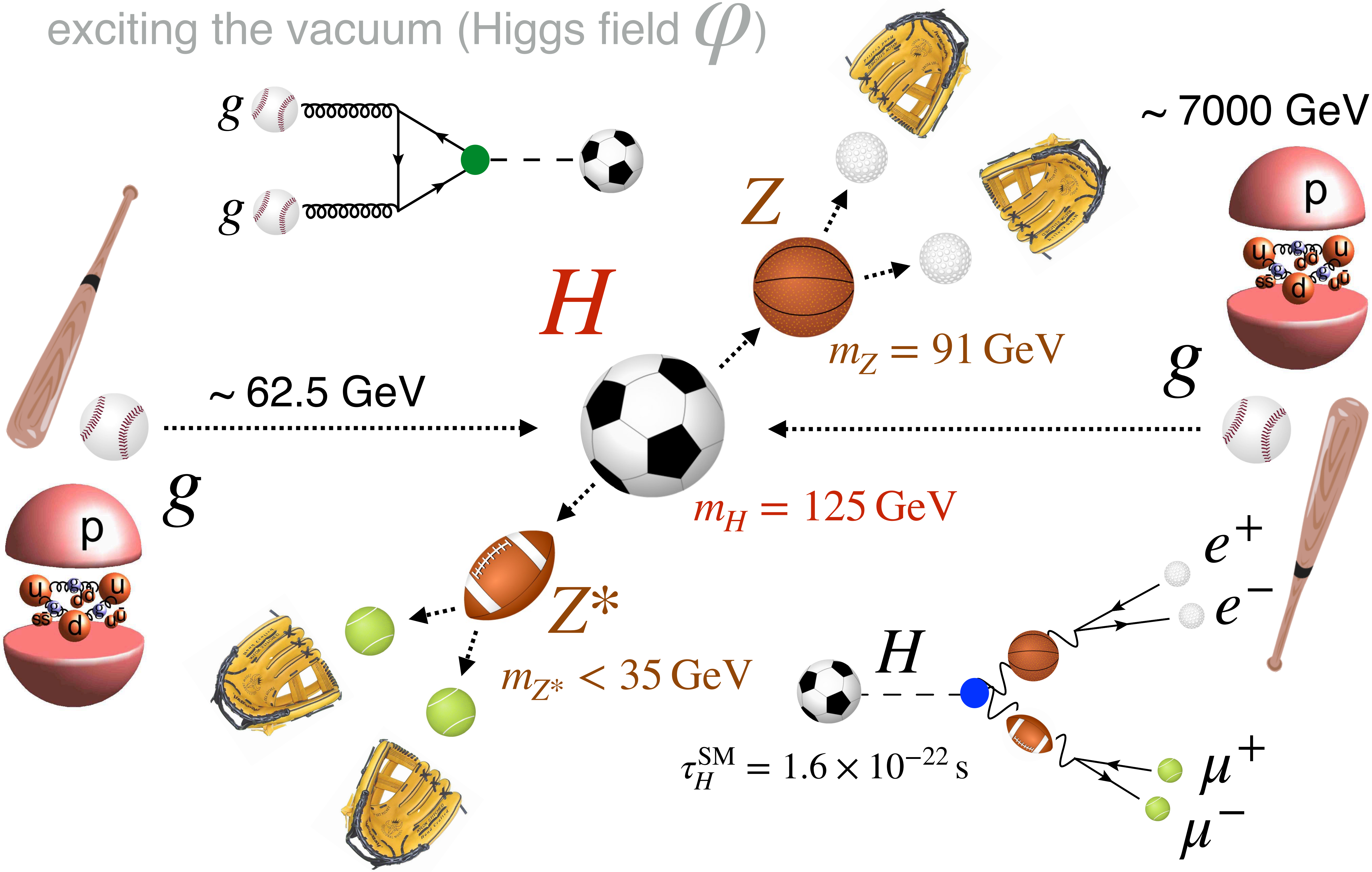
- We should see something like this:



- This motivates us to study Higgs boson to high precision

Our Microscope in a Nutshell

exciting the vacuum (Higgs field φ)

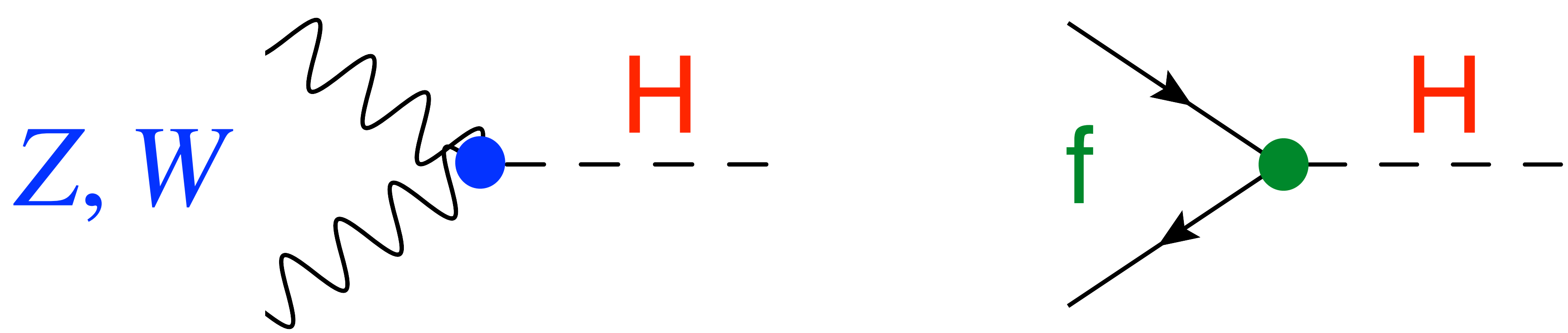


What we knew before 2012

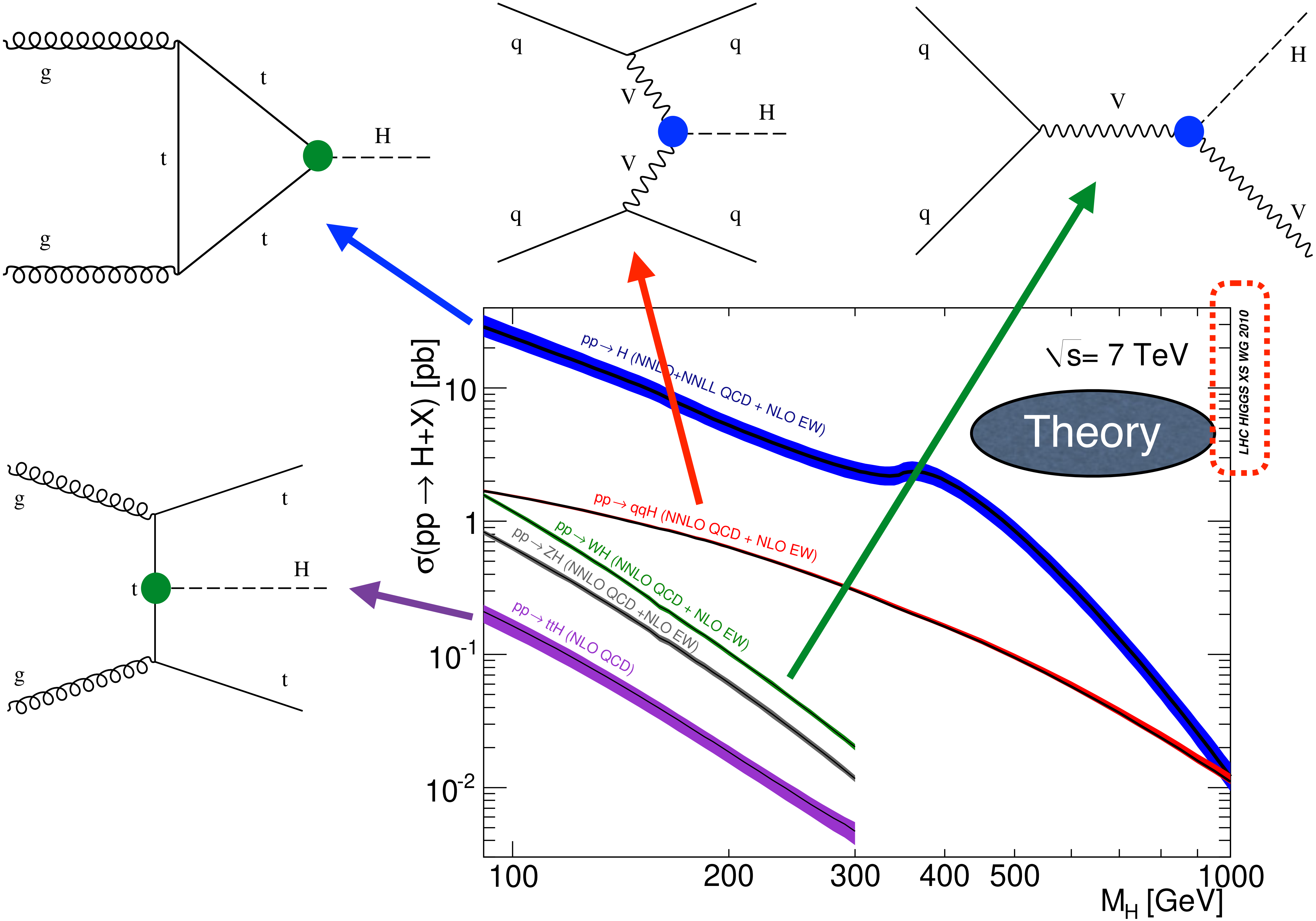
- — We did not know if the Higgs field (or boson) existed!
- — Even if it were, was it the Standard Model Higgs boson?
- — We did not know the mass! (there were indirect SM constraints)

- Two diagrams relevant to H in early days of LHC, couple to mass:

- Flip the time direction to produce it:



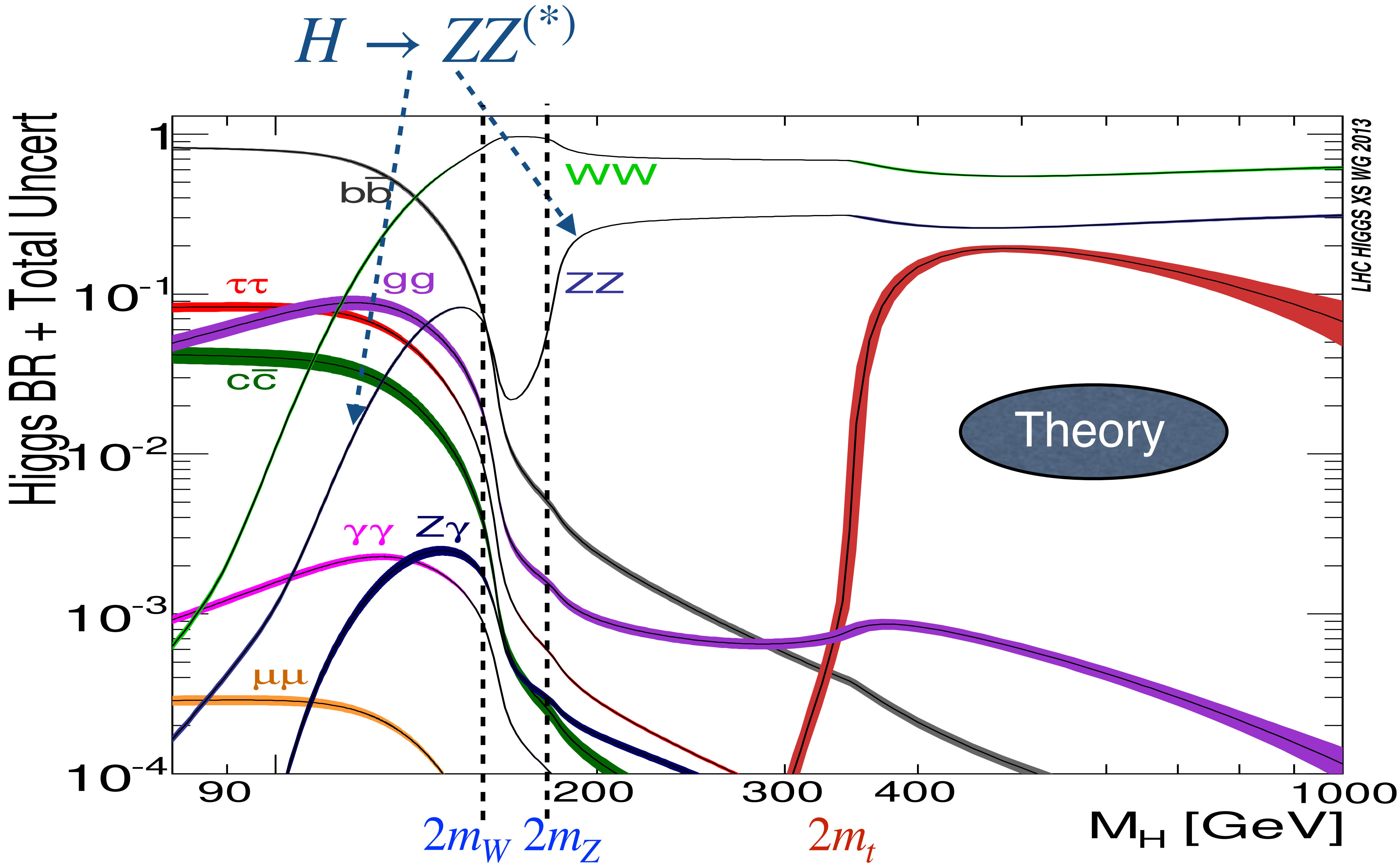
Producing the SM Higgs boson

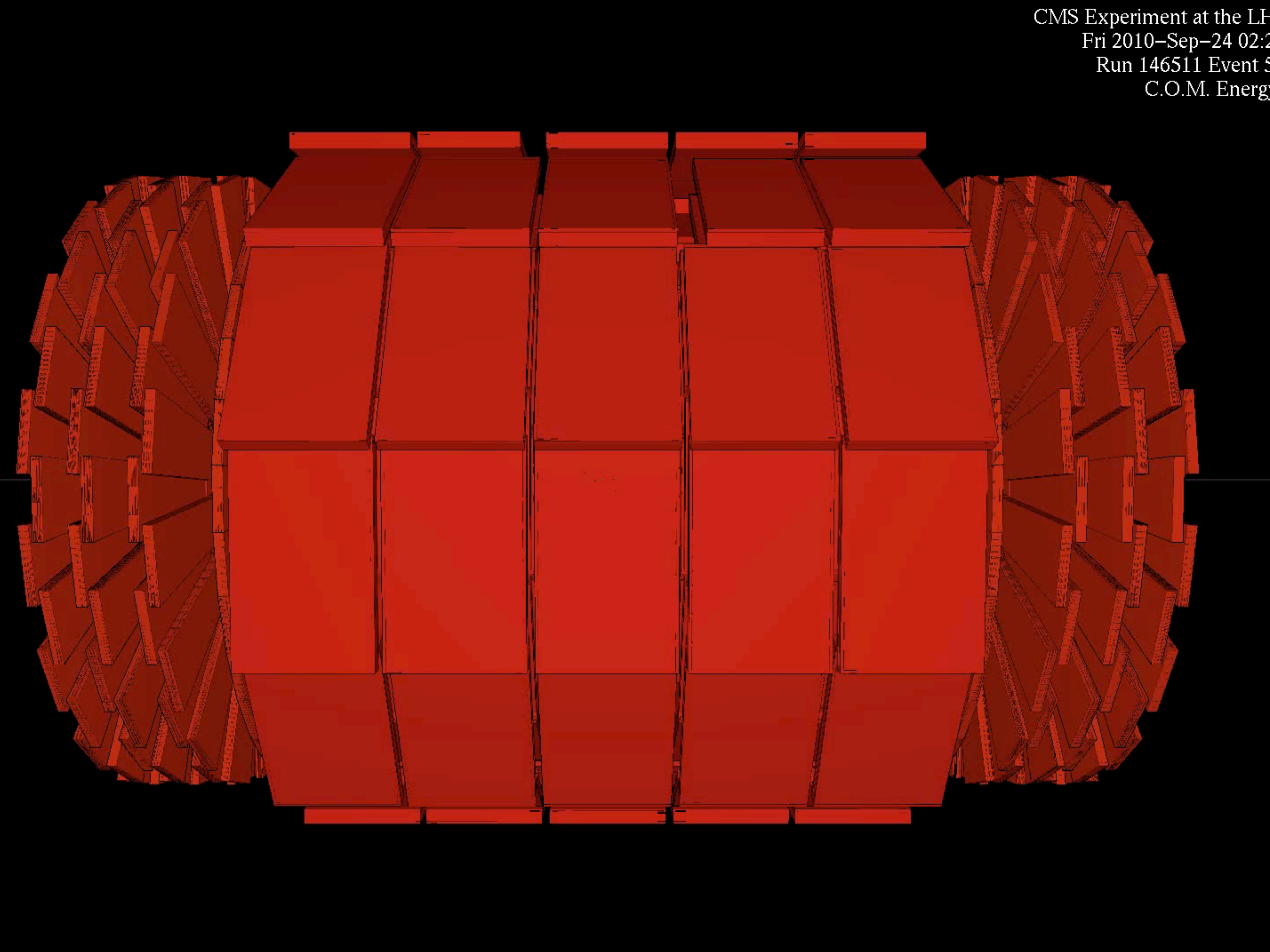


Decay of the SM Higgs boson

- Golden channel both below $2m_W$ and above $2m_Z$ threshold
  best signal / background

$H \to ZZ^{(*)}$

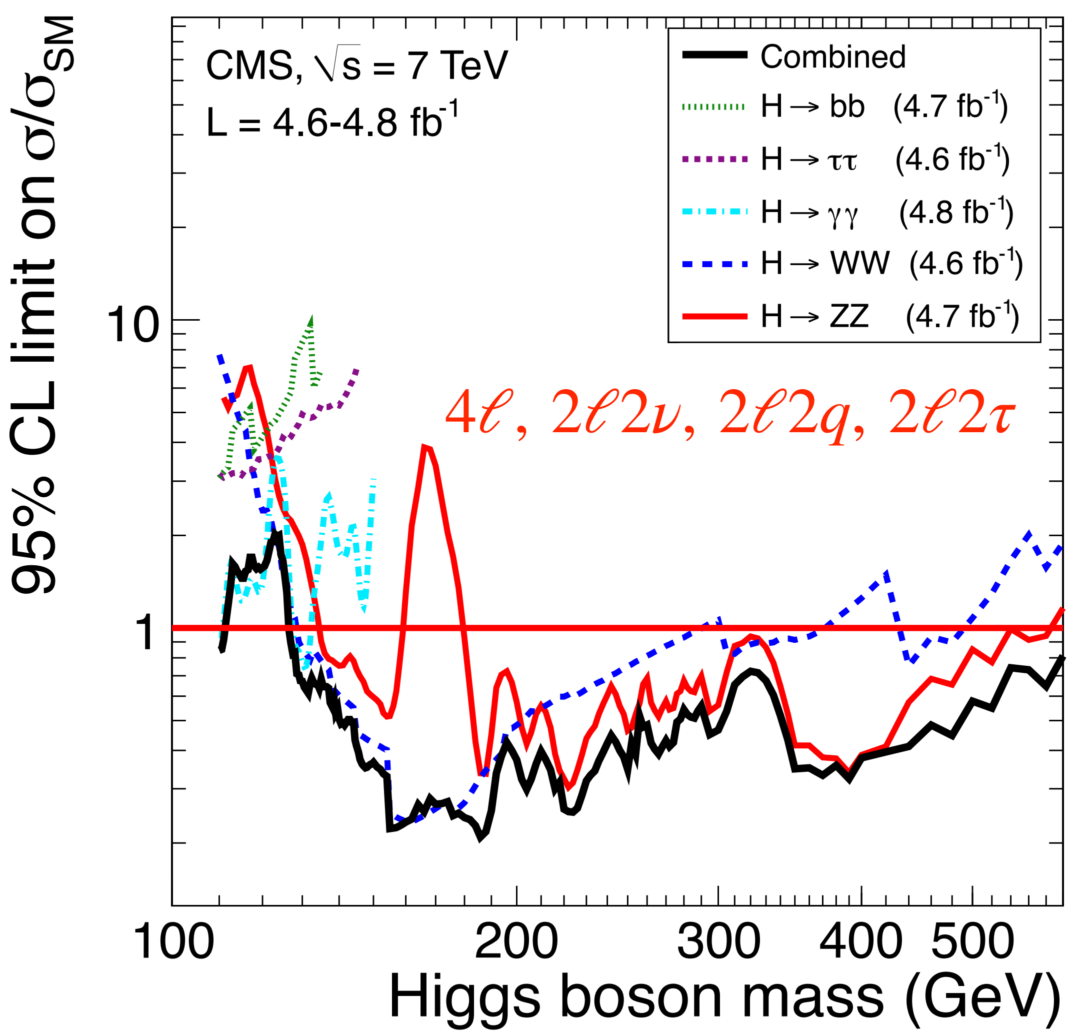


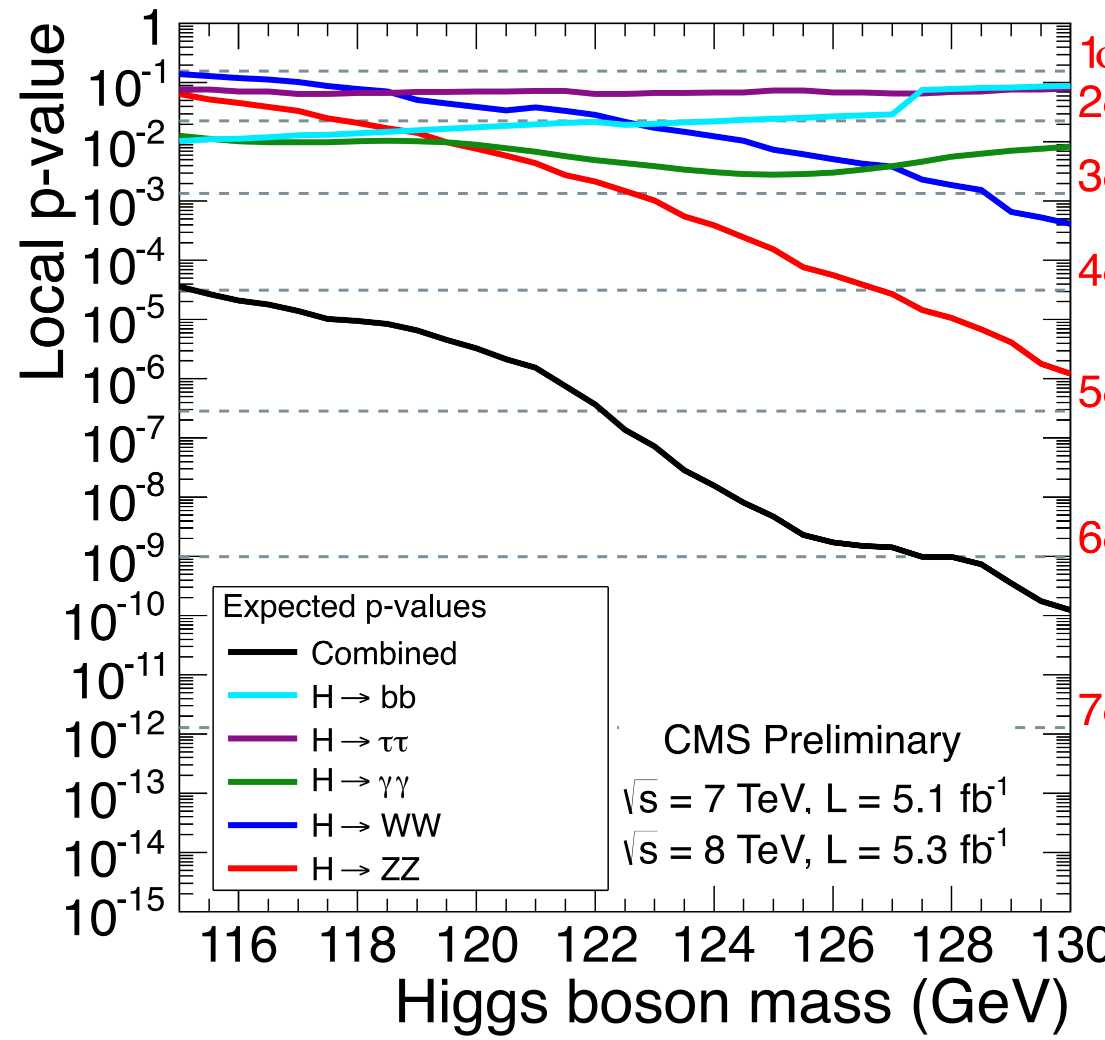

CMS Experiment at the LH
Fri 2010–Sep–24 02:2
Run 146511 Event 5
C.O.M. Energ

CMS on Track for Discovery

- In December 2011
  excluded SM Higgs
  $127 < m_H < 600$ GeV
  tantalizing hint $m_H \sim 125$ GeV

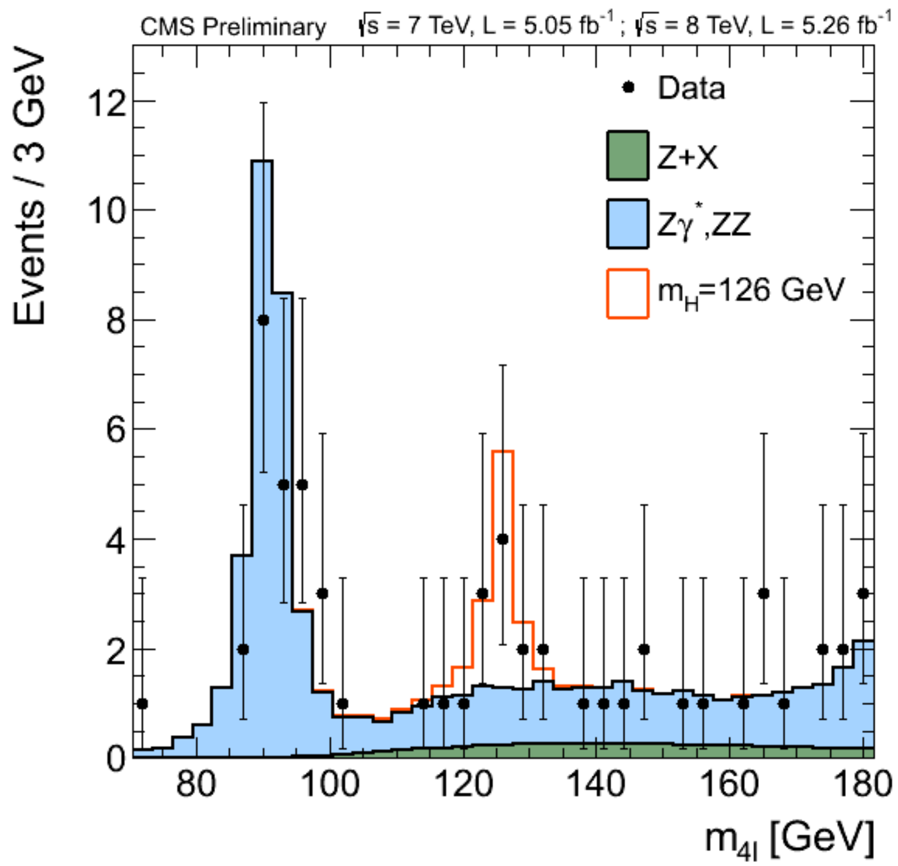
- In July 2012
  expect for SM Higgs
  up to 6σ observation
  $H \to ZZ^{(*)}, \gamma\gamma, WW^{(*)}, b\bar{b}, \tau\tau$

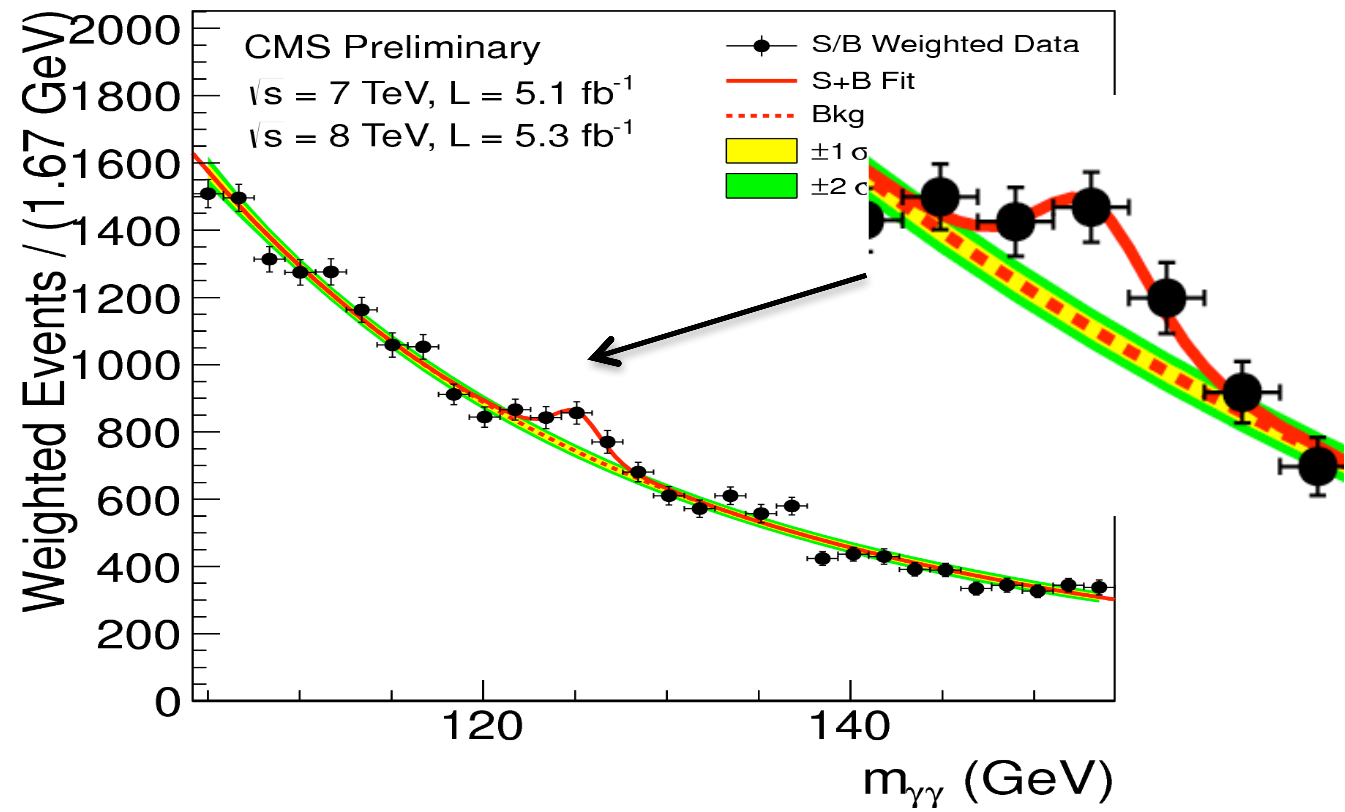


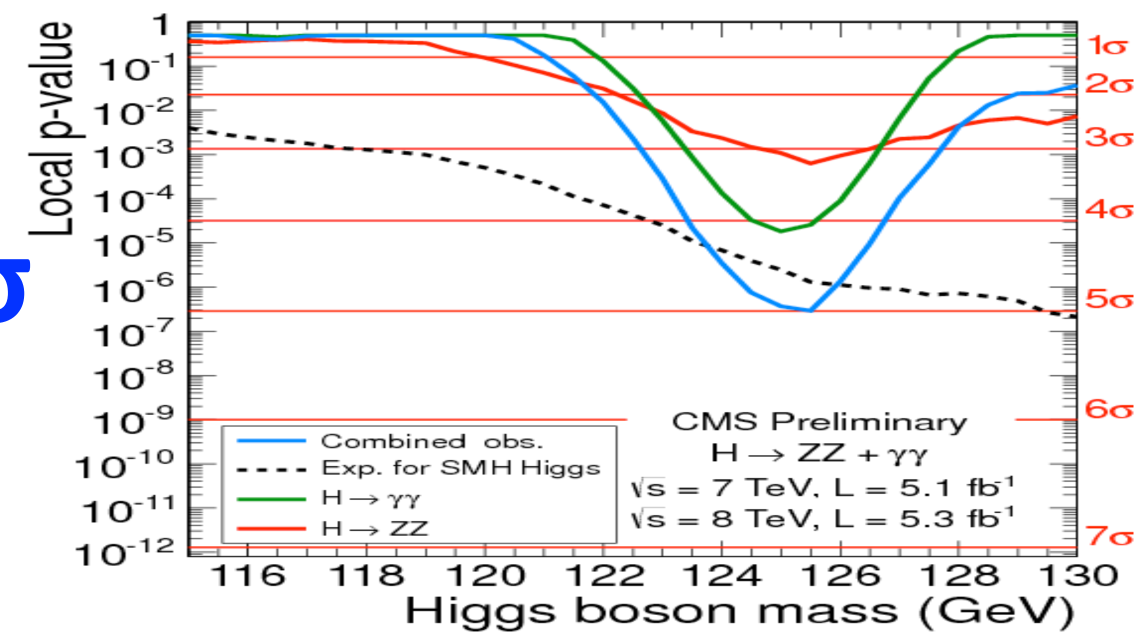


“Opened the box” on June 14, 2012 (at CERN)

Two channels ZZ and 2γ combined

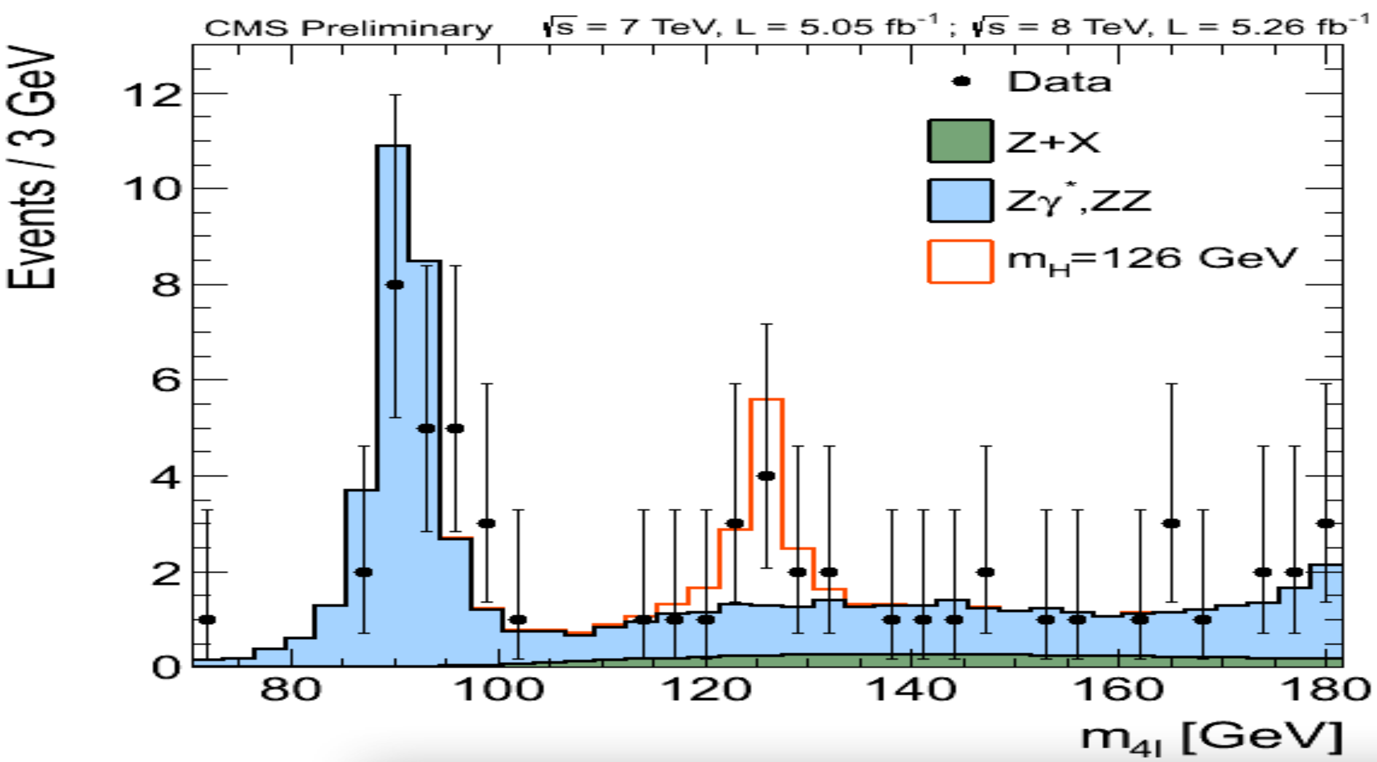


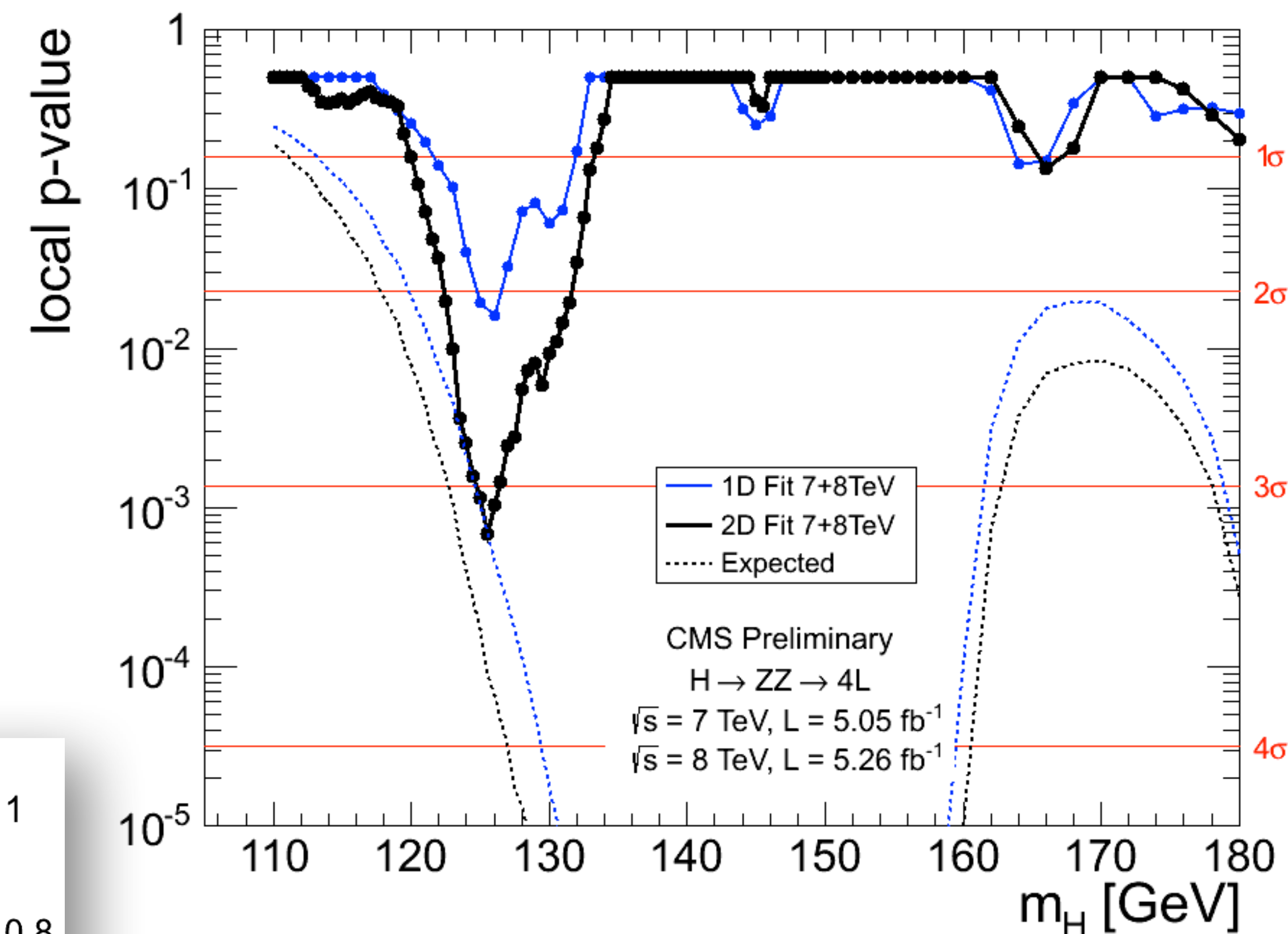


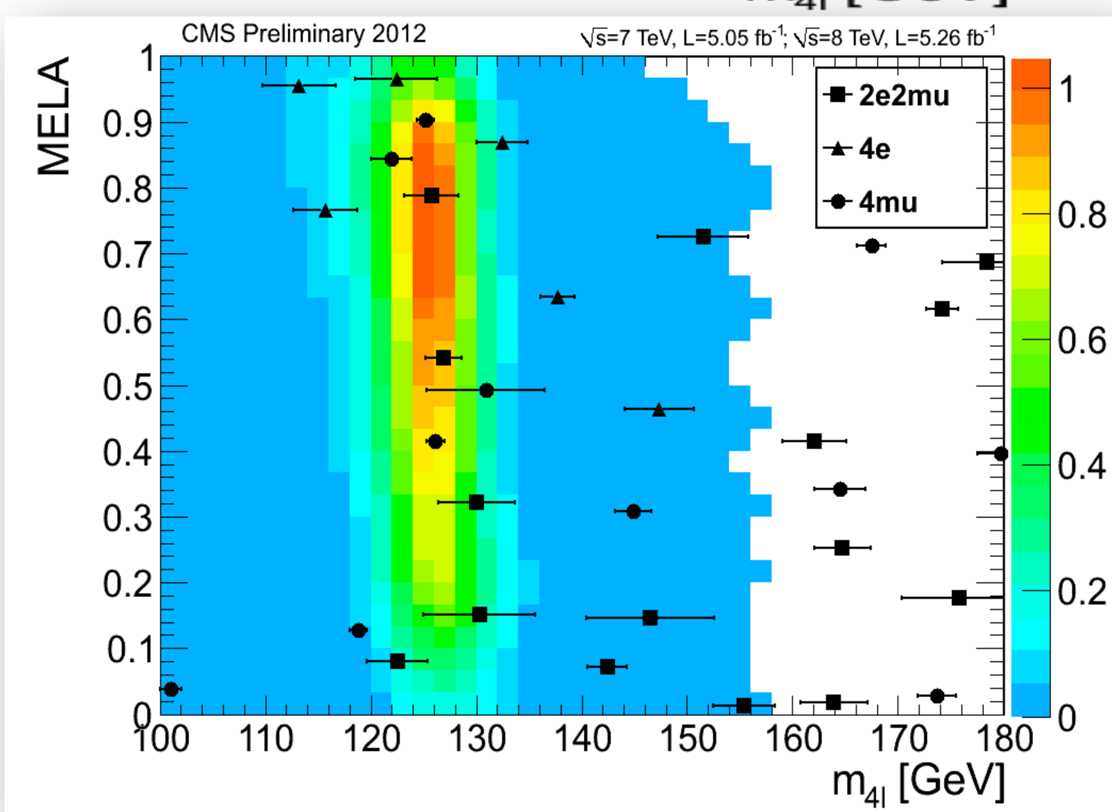


- **Comb. significance: 5.0 σ**
- **Expected 4.7 σ**

Observed local excess of events







Expected significance at 125.5 GeV :

3.8 σ

Observed significance at 125.5 GeV:

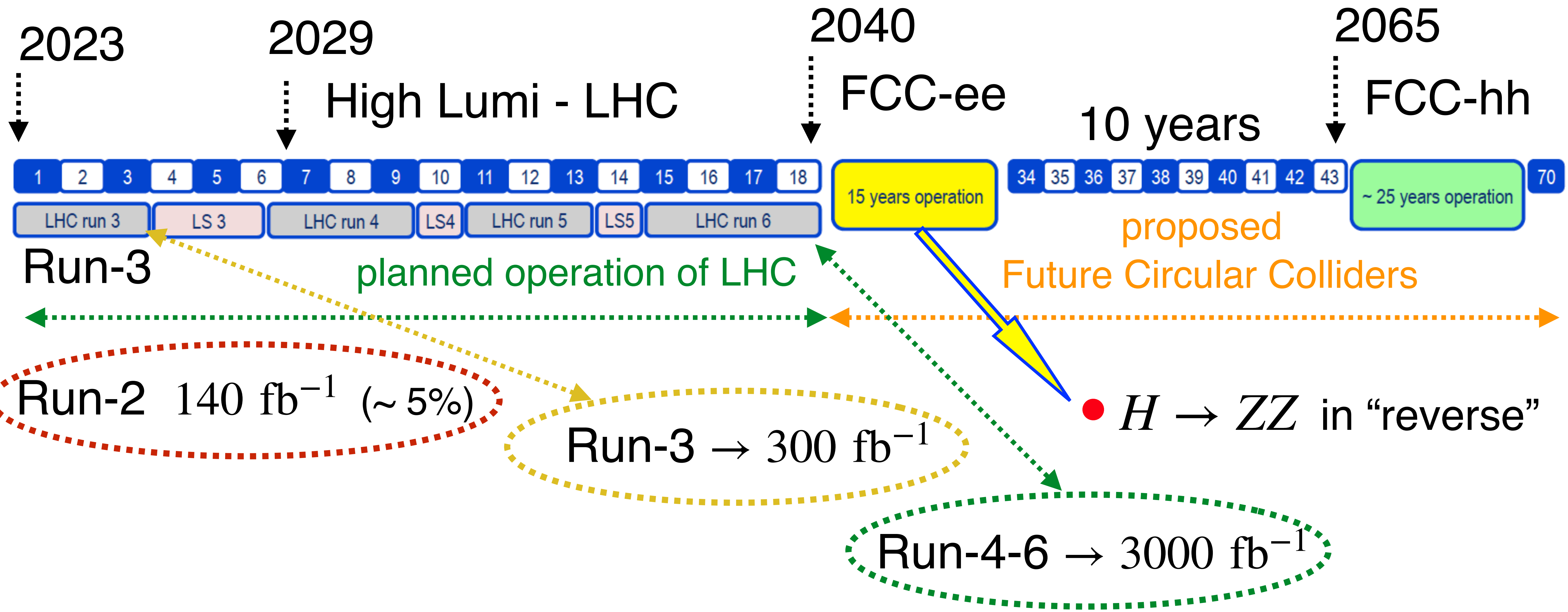
3.2 σ

June 15, 2012

The Higgs boson: 2012

Future Directions

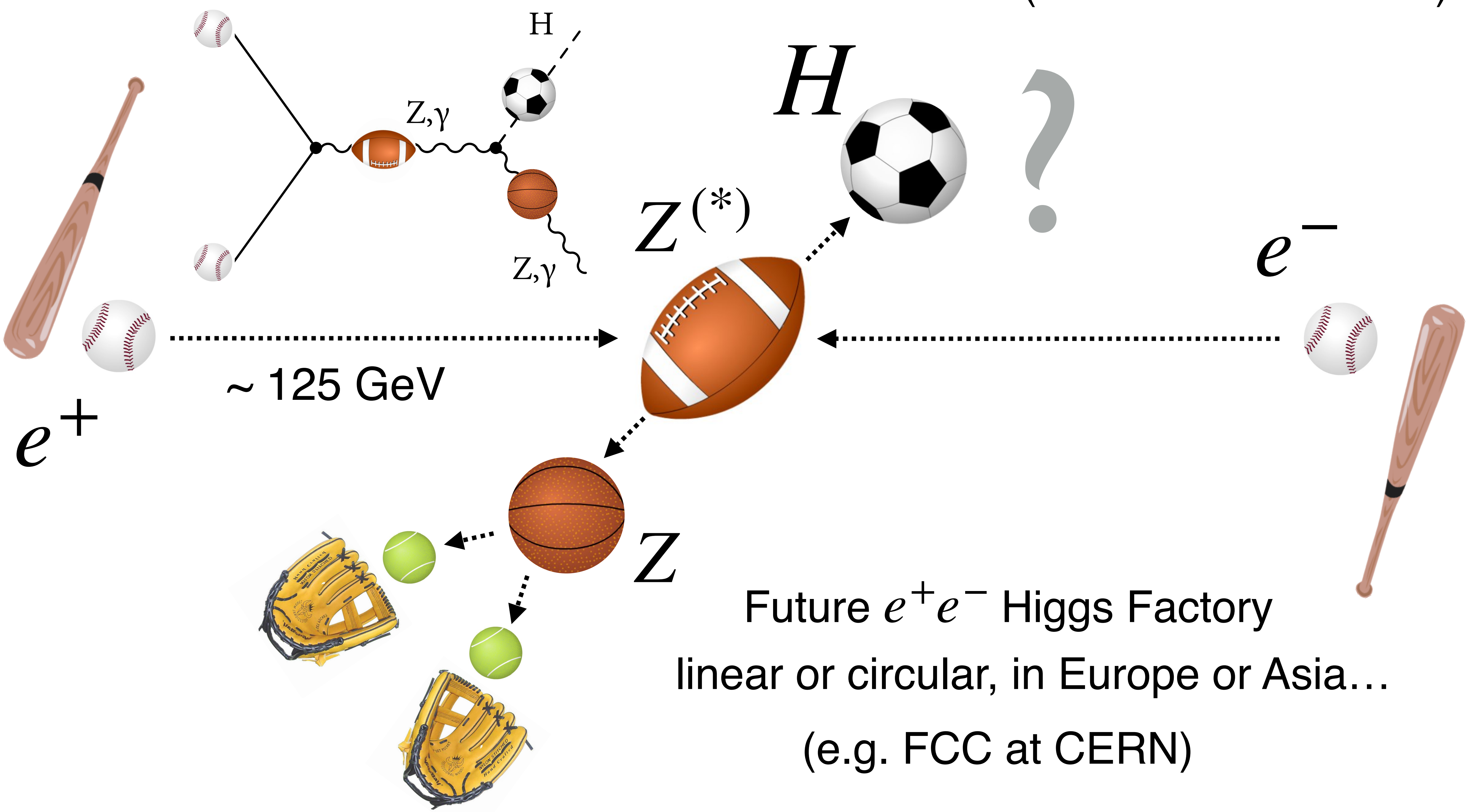
LHC Run-3 and Beyond



The Next Microscope (Proposed Collider)

Discovery of $H \to ZZ$ enabled plans for $e^+e^- \to Z^* \to ZH$

($H \to ZZ$ in "reverse")



Future e^+e^- Higgs Factory

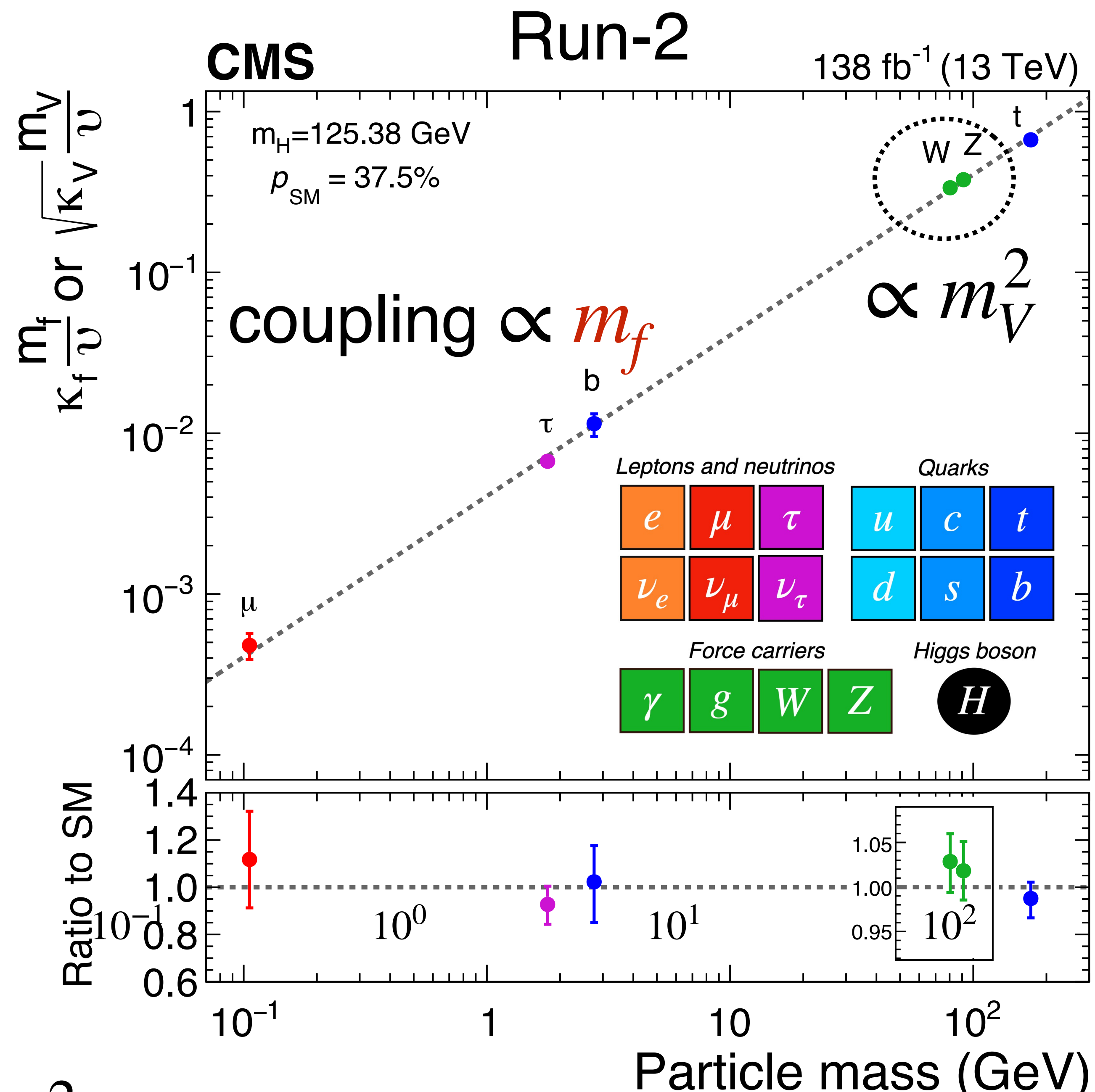
linear or circular, in Europe or Asia…

(e.g. FCC at CERN)

What we want to know about the 5th force

- Couples to matter-energy

  rates as ~ expected - - - - ▶



- Mass: quantum corrections

- Lifetime:

  faster decay to new states?

  to dark matter?…

- Quantum numbers?

  expect $J^{PC} = 0^{++}$ as vacuum

- New source of CP violation?

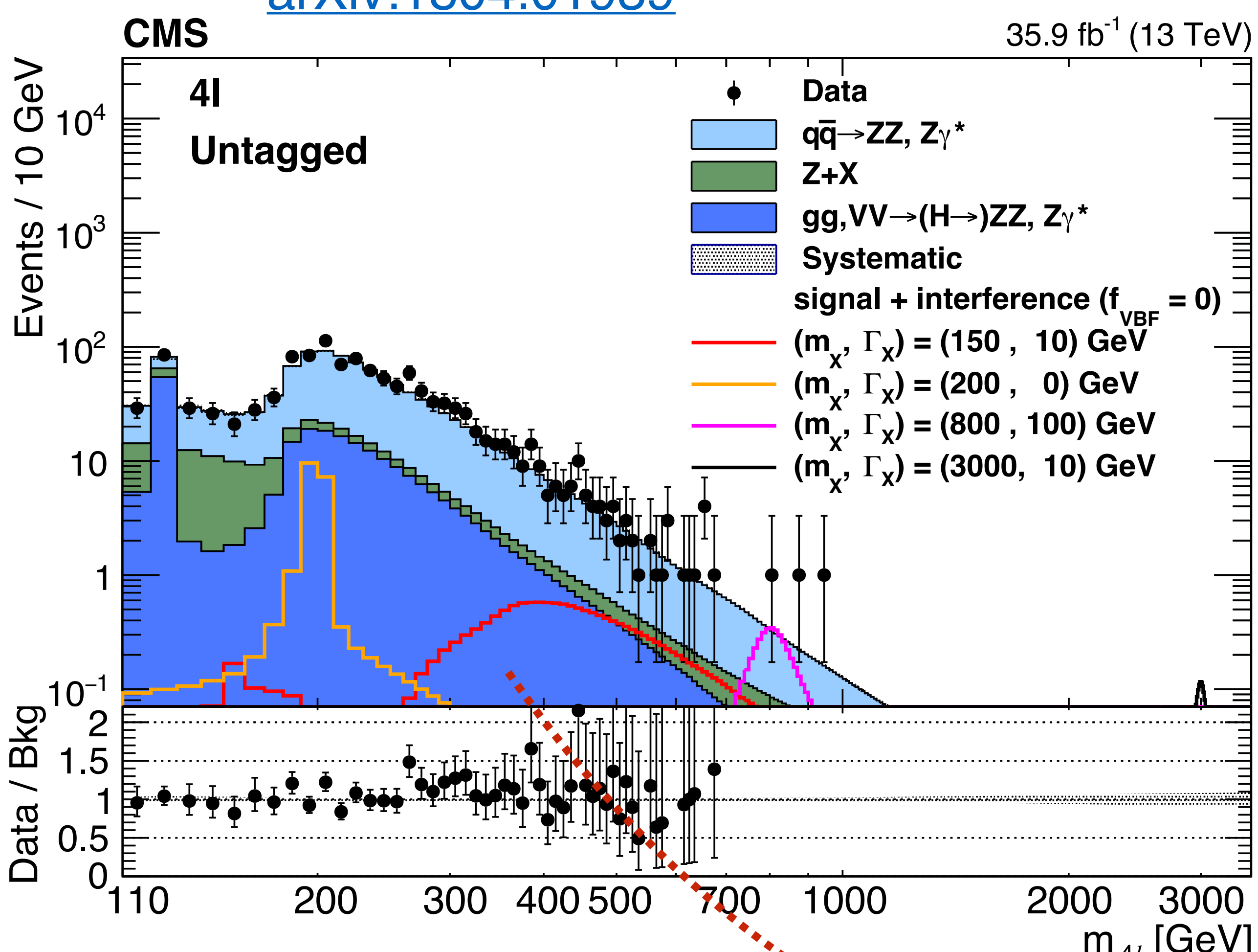
- Any hints of EFT effects $\sim \left(\frac{\text{v}}{M}\right)^2$?… $\Rightarrow$ study full kinematics

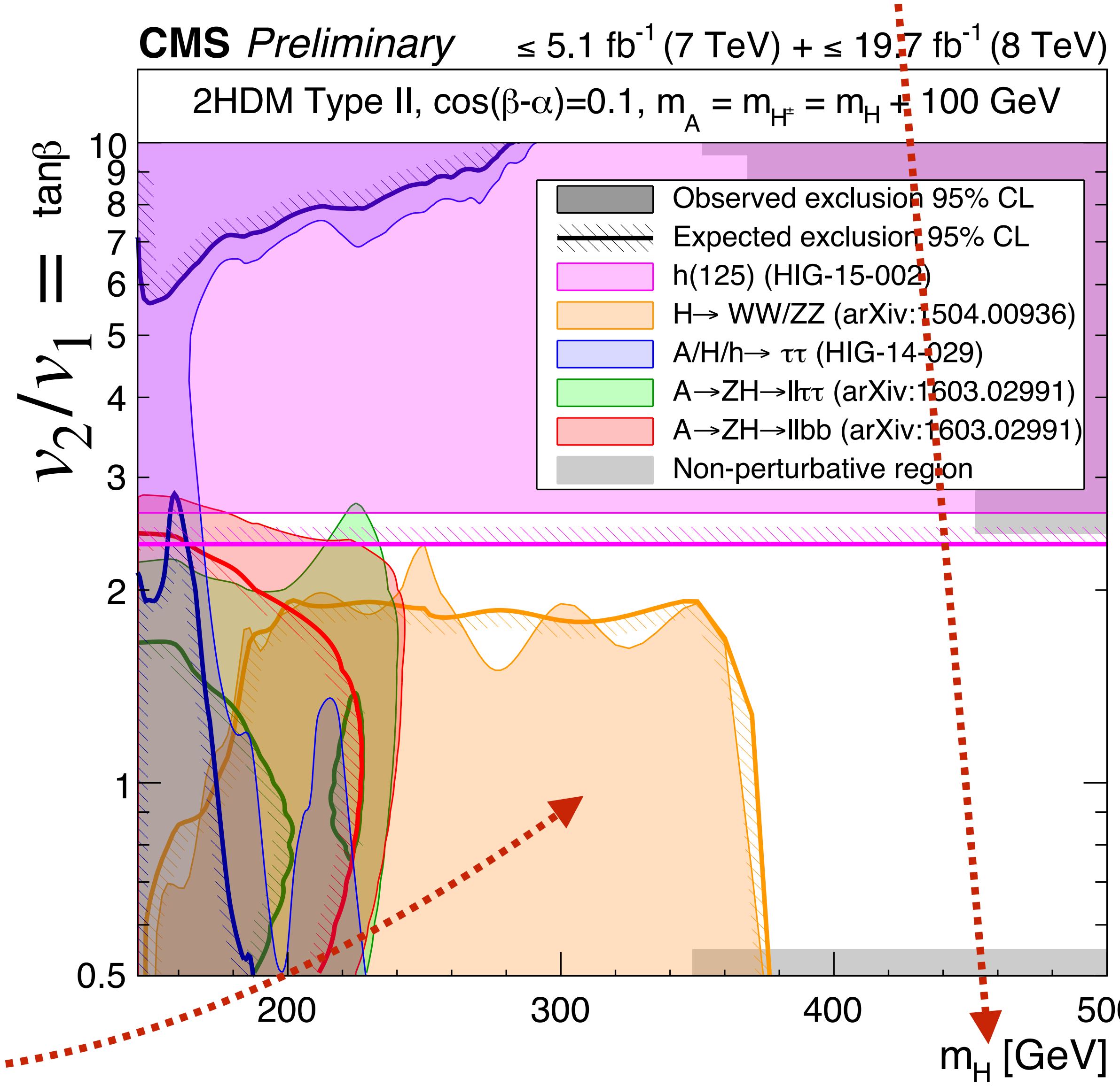
- Higgs field(s) and potential? $\Rightarrow$ new states or HHH interaction

What if there are more Higgs Fields?

- SM Higgs field $\varphi = \begin{pmatrix} G^+ \\ (v + H^0 + iG^0)/\sqrt{2} \end{pmatrix} \Rightarrow H^0$ + mass of Z, W^+, W^-
- What if 2 Higgs fields $\varphi_1, \varphi_2 \Rightarrow$ mass of Z, W^+, W^- + $H^0, H^\pm, H', A$ (new)

arXiv:1804.01939

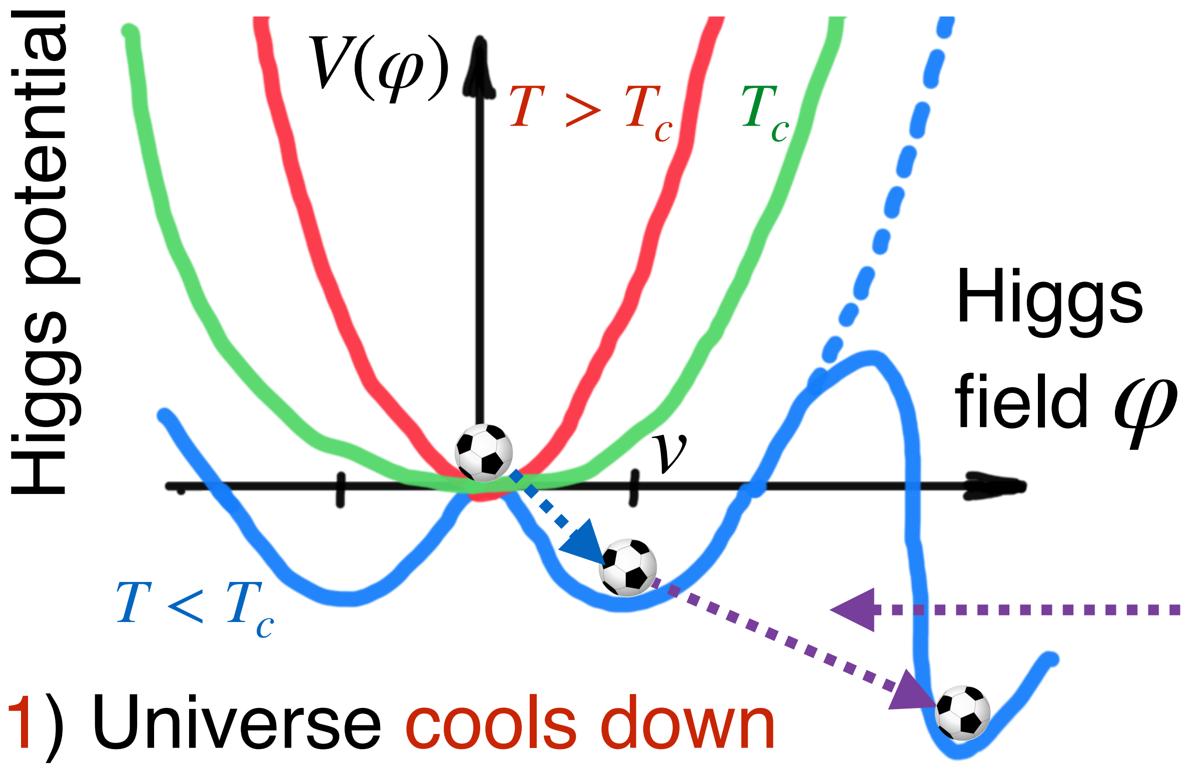




$H' \to ZZ \to 4\ell,\ 2\ell 2q,\ 2\ell 2\nu$ exclude

Higgs Potential and Stability of the Vacuum

$$V(\varphi) = \mu^2\varphi^\dagger\varphi + \lambda^2(\varphi^\dagger\varphi)^2$$

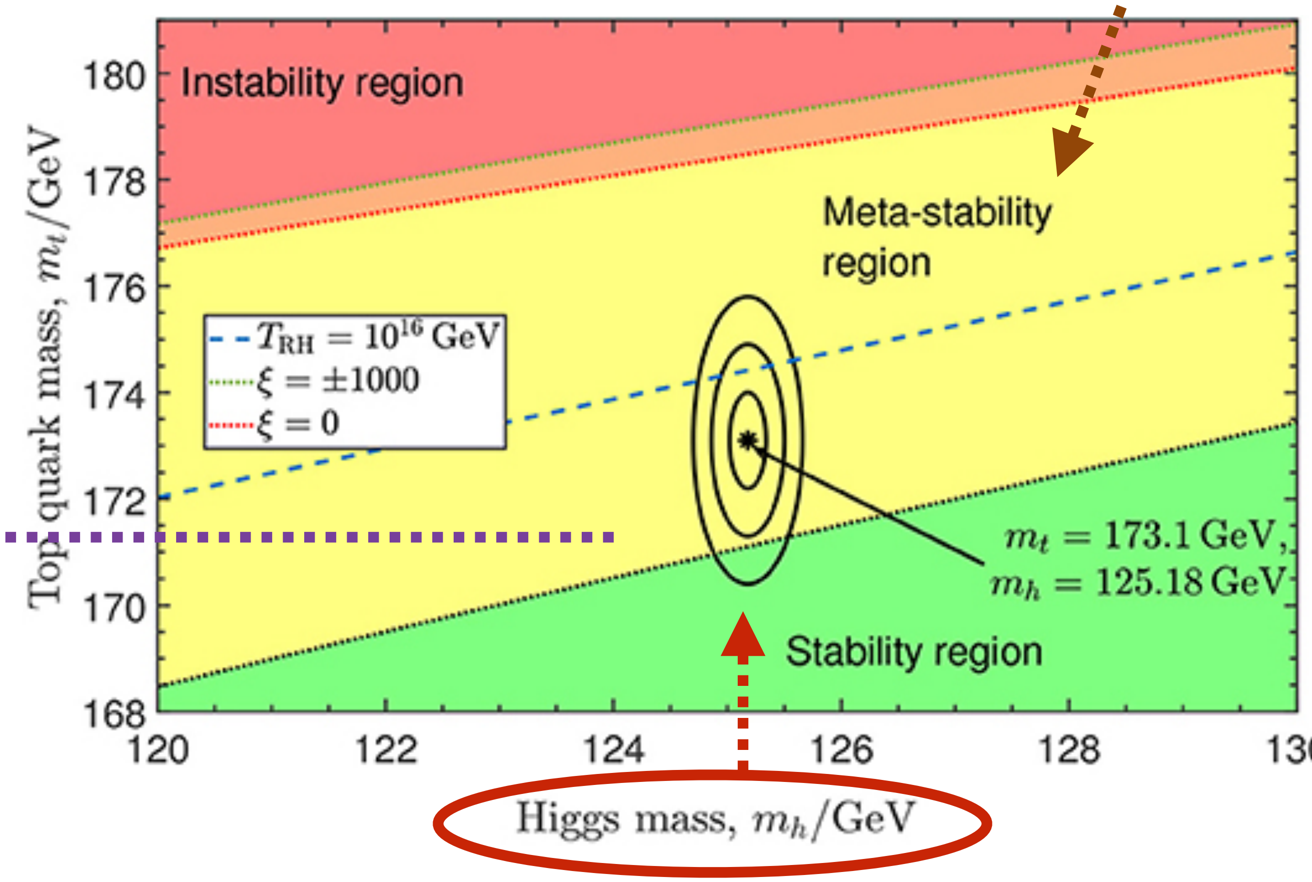


(1) Universe cools down

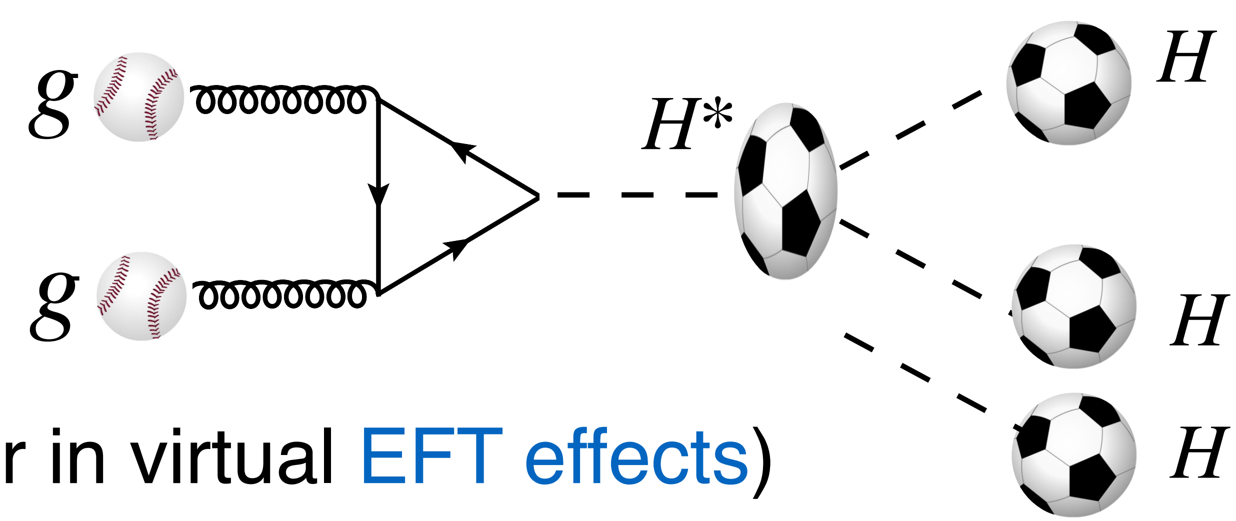
(2) symmetry spontaneously breaks

(3) tunnel away?

- Quantum corrections ⇒ metastable vacuum
  — assume SM up to very large M



- First steps to test Higgs potential $V(\varphi)$
  $+(\varphi^\dagger\varphi)^3 \ldots ?$
  — test $HHH(H)$ interaction
  — need more data, new facilities…



(or in virtual EFT effects)