Study of the Higgs Field

Andrei Gritsan

Johns Hopkins University

July 28, 2017

Johns Hopkins University QuarkNet Physics Workshop

The Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013

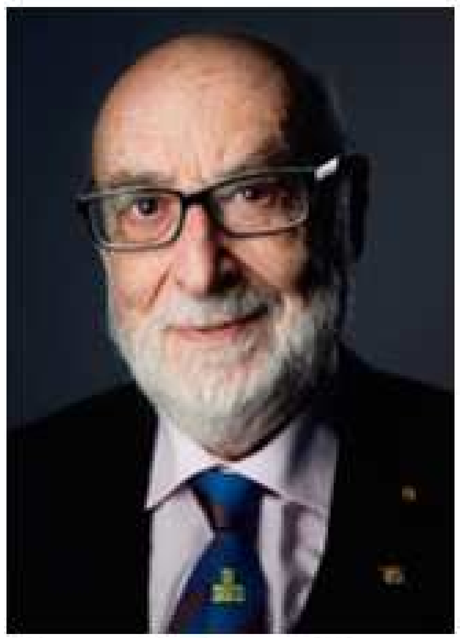


Photo: A. Mahmoud

François Englert

Prize share: 1/2

Photo: A. Mahmoud

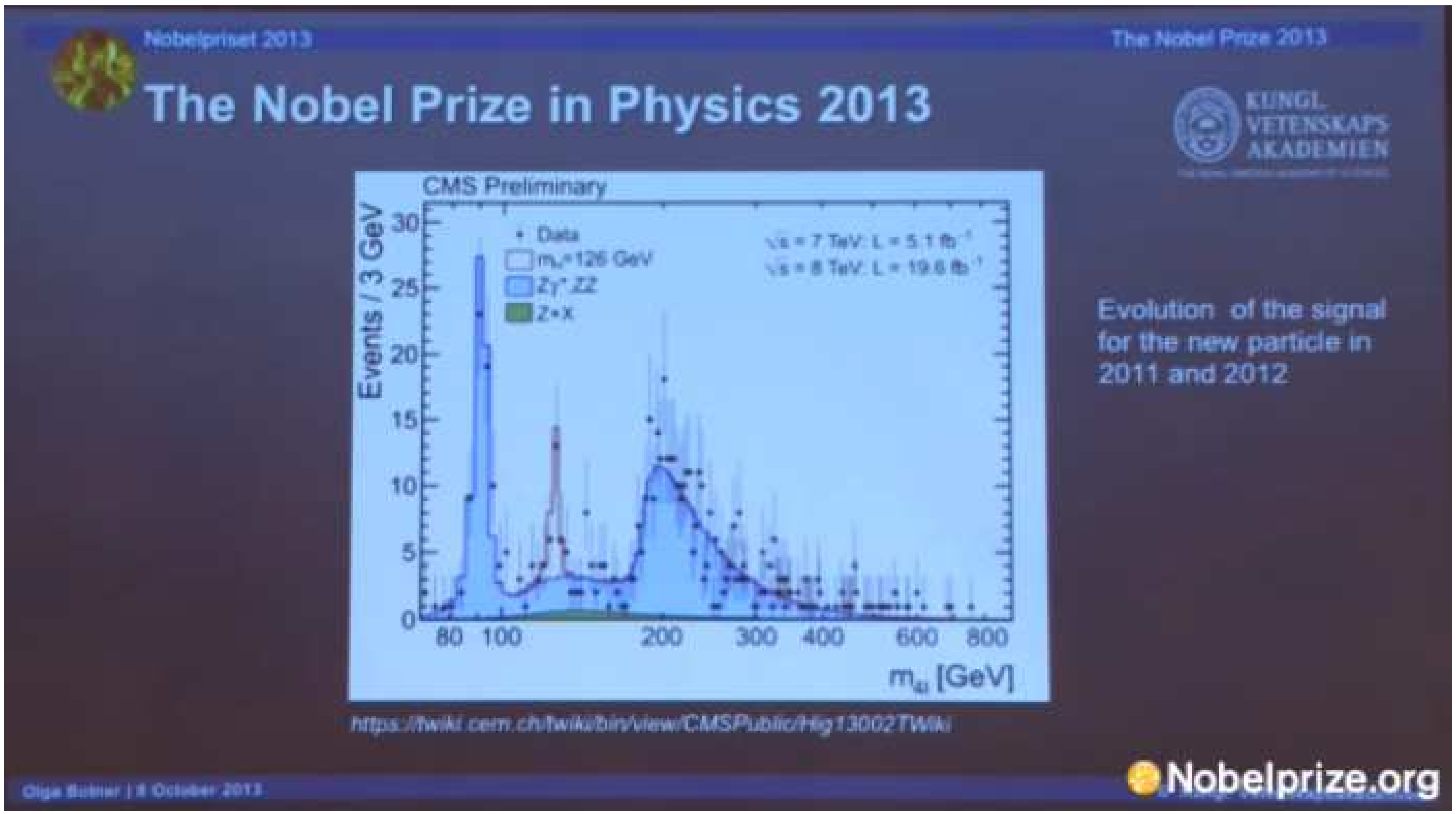
Peter W. Higgs

Prize share: 1/2

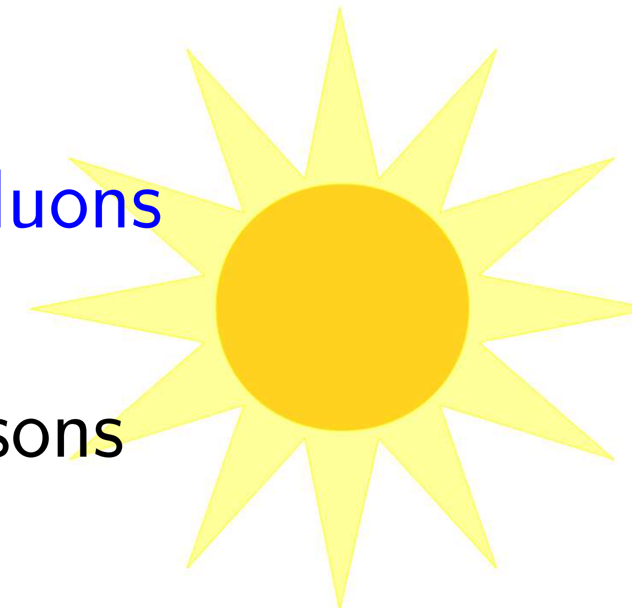
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

The Higgs Particle

- The Nobel prize for the Higgs mechanism
  - theoretical idea ∼50 years ago
- This idea became the reality with the Higgs particle
  - experimental discovery



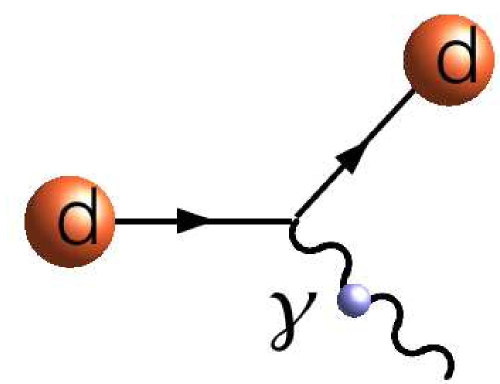
How many Bosons did we know in 2012?



- We knew 12 bosons: photon, Z^0, W^+, W^-, 8 gluons

- Photons (γ) are massless vector (spin=$\hbar$=1) bosons

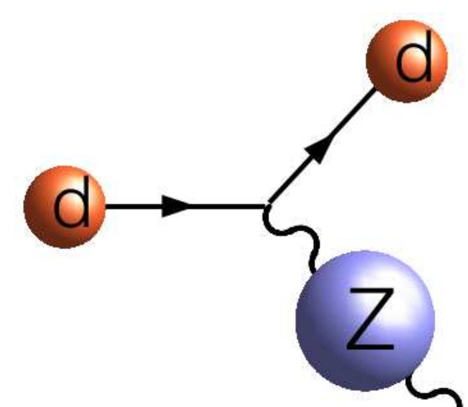
- Z^0 and $W^\pm$ are heavy $\rightarrow$ weak force



- Gauge bosons in unified electro-weak theory
  after spontaneous symmetry breaking

$$|\gamma\rangle\ = \cos\theta_W|B^0\rangle + \sin\theta_W|W^0\rangle$$ light (massless)

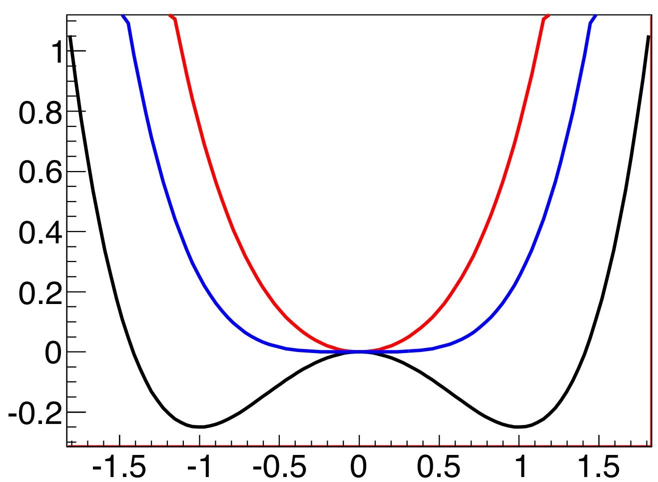
$$|Z^0\rangle = \sin\theta_W|B^0\rangle + \cos\theta_W|W^0\rangle$$ heavy

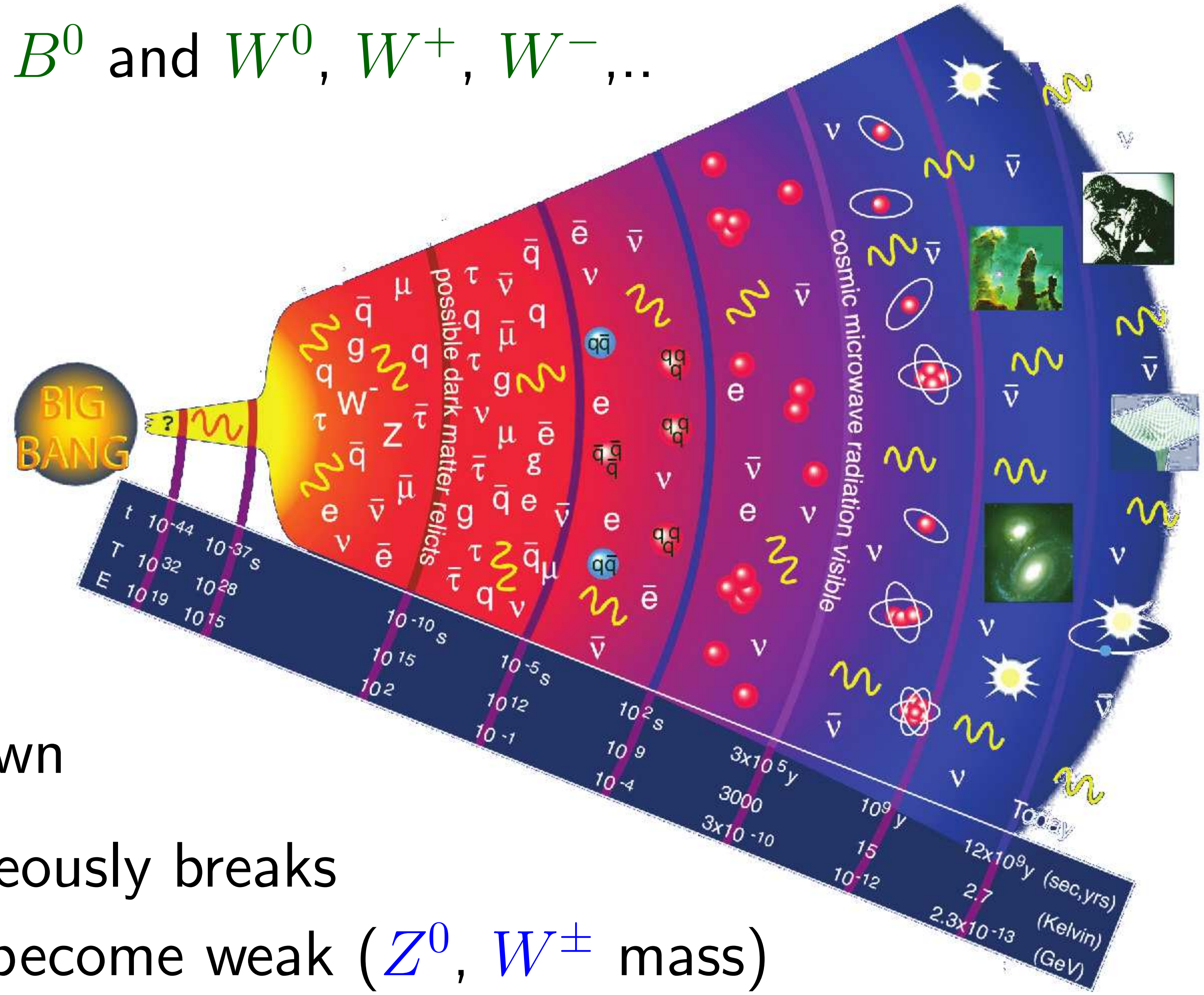


θ_W - Weak mixing (Weinberg) angle

Path from Light to Heavy

- Early moments of the Universe
  - massless particles: B^0 and W^0, W^+, W^-,..
  - all forces unify



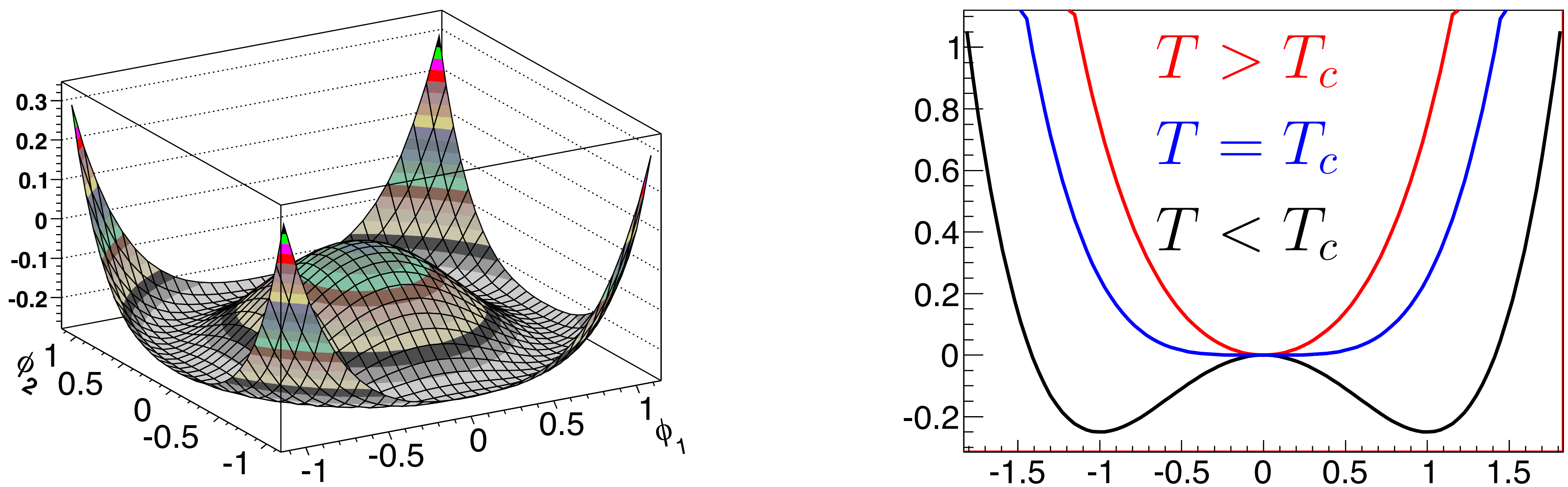


- As Universe cools down
  - symmetry spontaneously breaks
  - weak interactions become weak (Z^0, $W^\pm$ mass)
  - Higgs field – possible mechanism

The Englert-Brout-Higgs Mechanism

- Symmetry spontaneously breaks near minimum (vacuum) energy of Higgs field $(\phi_1, \phi_2, \phi_3, \phi_4)$

$$V = \frac{1}{4}\lambda\left[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right]^2 + \frac{1}{2}\mu^2\left[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right]$$



- Higgs particle described by one component of the Higgs field

$$h = \phi_1 - v$$

- The other Higgs field components ϕ_2, ϕ_3, ϕ_4 couple to Weak bosons Z^0, W^-, W^+ and generate mass, longitudinal polarization (not γ)

Idea - the Higgs Field

- Empty space filled with invisible "force" – the Higgs field

Idea - the Higgs Field

- The Higgs field clusters around the particle – gives mass

Idea - the Higgs Field

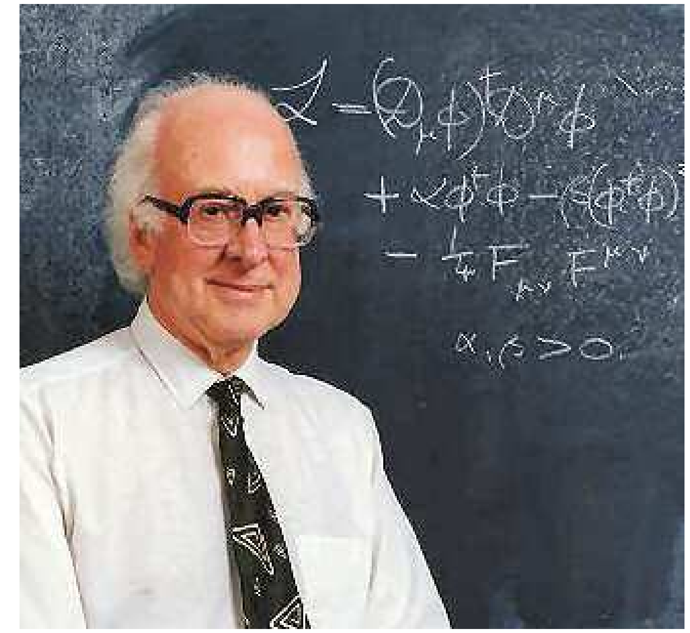
- Pass energy into the Higgs field (no particle)

Idea - the Higgs Field

- The Higgs particle cluster created from the Higgs field

What is Higgs?

- There are several phenomena:
  - Peter Higgs
  - Higgs mechanism
  - Higgs field
  - Higgs particle (boson)



- People sometimes confuse these phenomena
  - especially the last two
- We have hard evidence for two:
  - 1964 article by Peter Higgs in *Physics Review Letters*
  - 2012 discovery of a new Boson by CMS and ATLAS

More on the History of the Higgs Mechanism

- In fact, there are several names of the Higgs mechanism:
  - Brout-Englert-Higgs mechanism
  - Higgs-Brout-Englert-Guralnik-Hagen-Kibble mechanism
  - Anderson-Higgs mechanism
  - Higgs mechanism is just simpler
  - all for authors of independent papers on the topic

- Partly due to ironic history with the paper by Higgs:
  - rejected from European *Physics Letters*
    "of no obvious relevance to physics"
  - added a reference to predicting a new particle

More on the History of the Higgs Mechanism

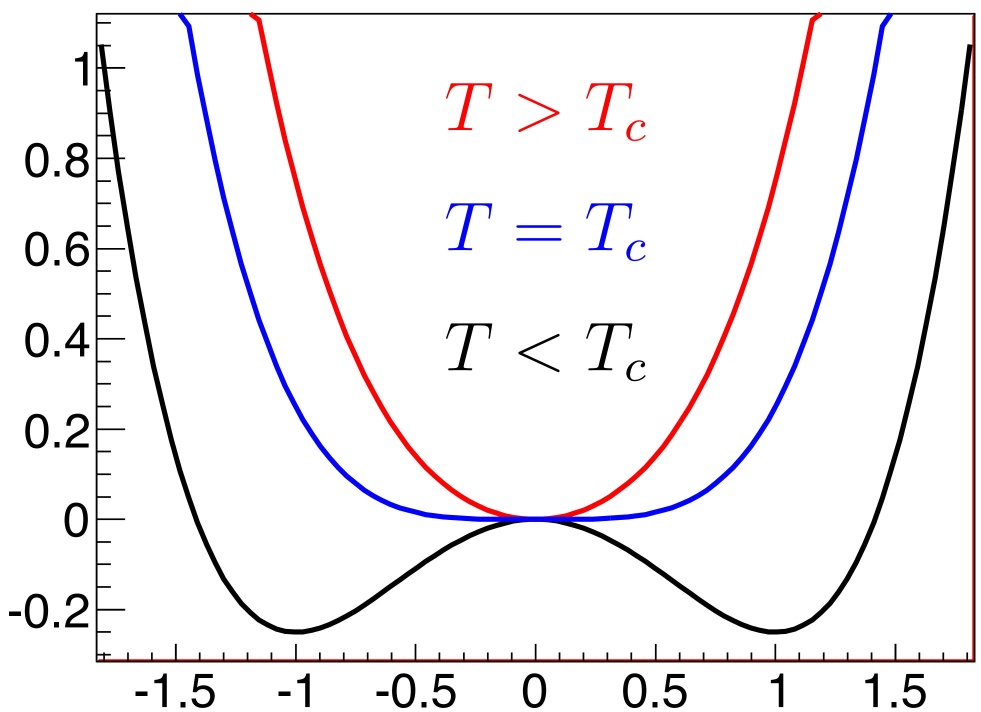
1950: Ginzburg- Landau model of superconductivity

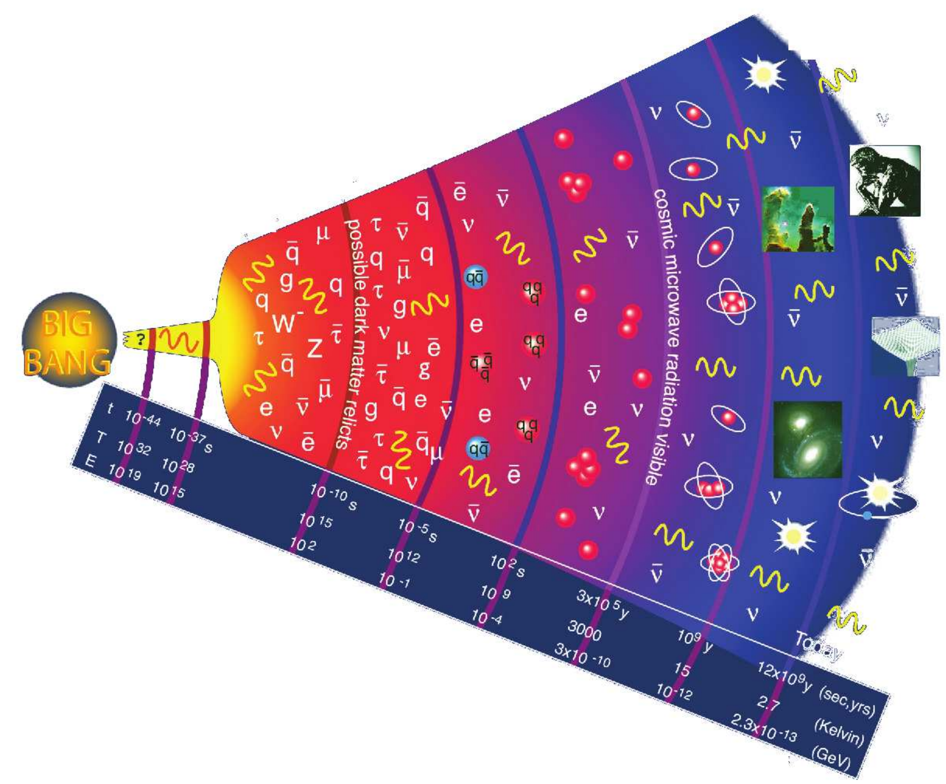
1959-60: Nambu- Goldstone bosons in spontaneous symmetry breaking

1962: P. Anderson - nonrelativistic example

1964: R. Brout & F. Englert; P. Higgs; G. Guralnik & C. R. Hagen & T. Kibble

1967: Incorporated into Standard Model by S. Weinberg and A. Salam





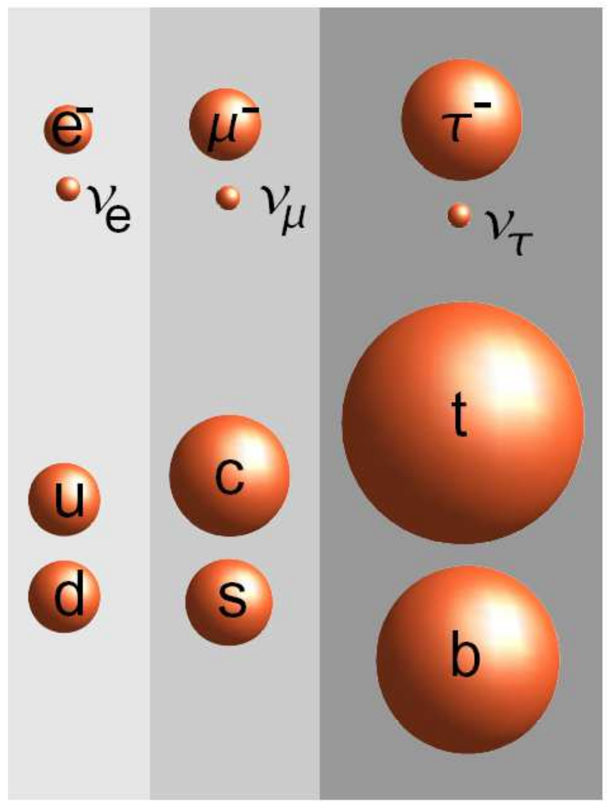
All Elementary Particles get Mass from Higgs Field

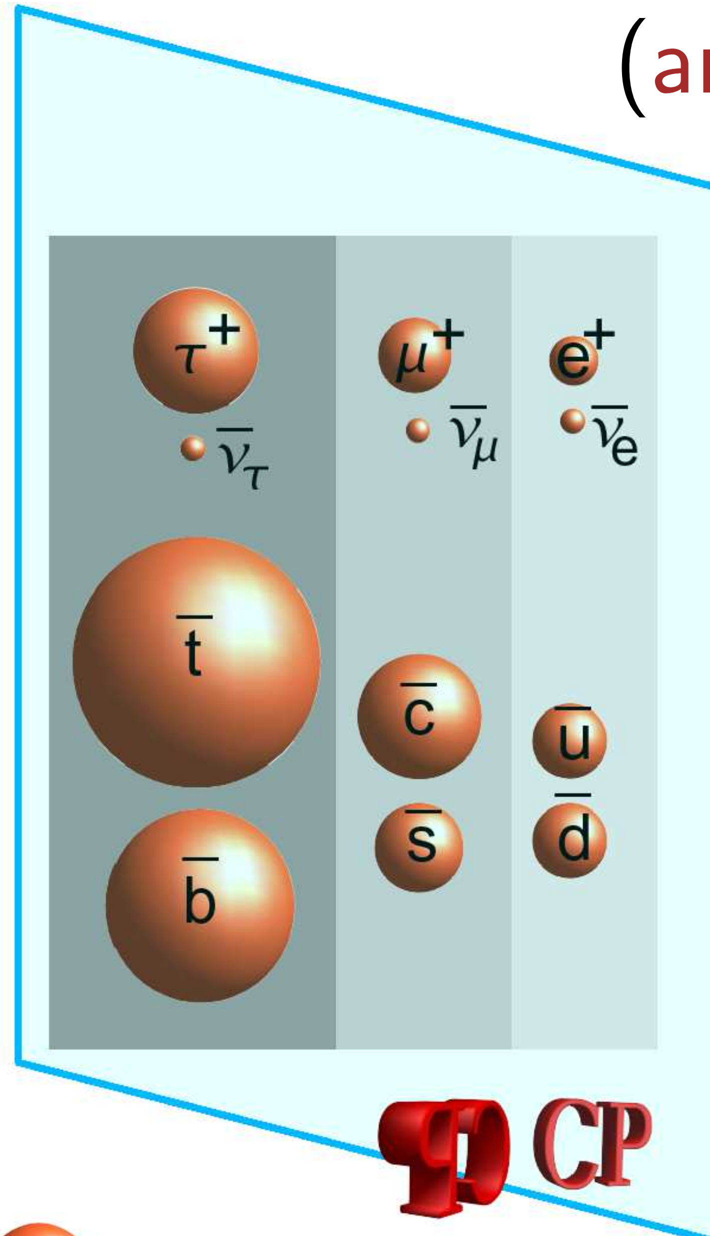
- Fermions $S = \frac{\hbar}{2}$ (matter)

(anti-matter)

leptons

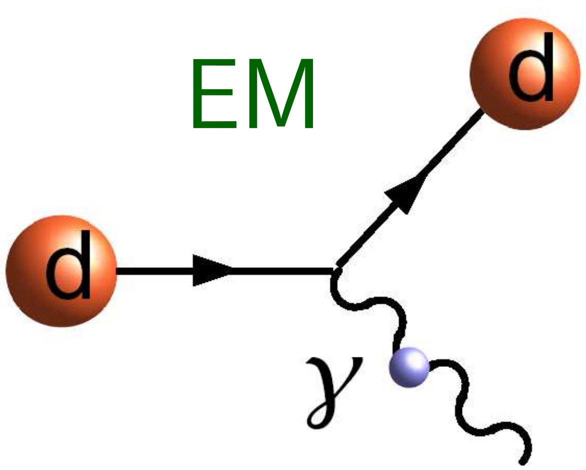
quarks



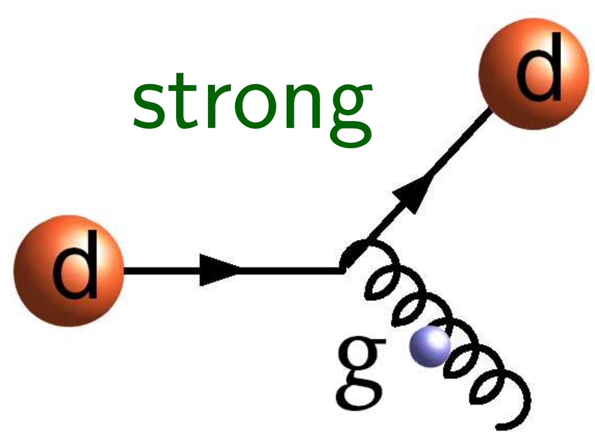


- Bosons $S = \hbar$ (force carries):

EM



strong

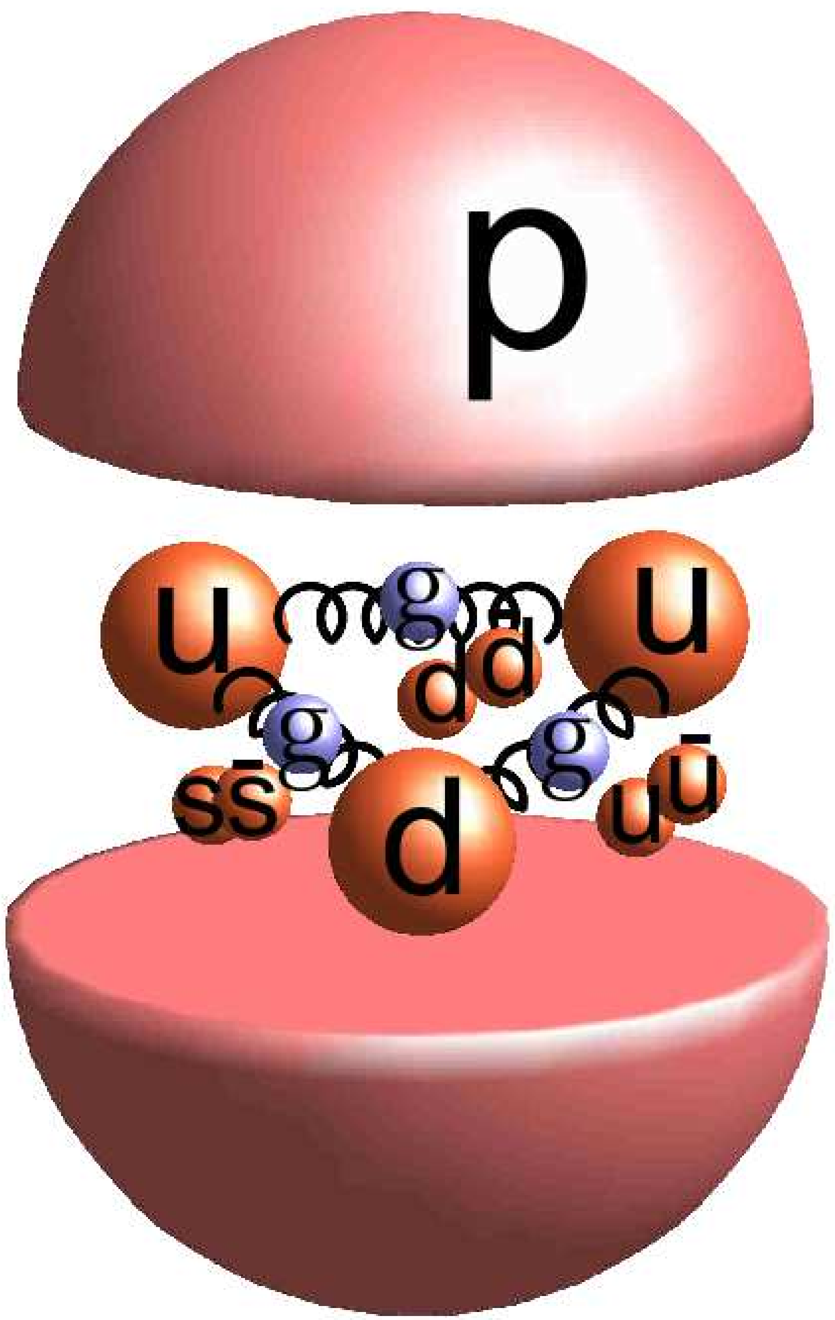


$\leftarrow$ massless

(weak force bosons mass)

Mass of Matter

- Most of our mass is protons and neutrons
  - most mass is energy of quark-gluon soup: $m_p c^2 = E$



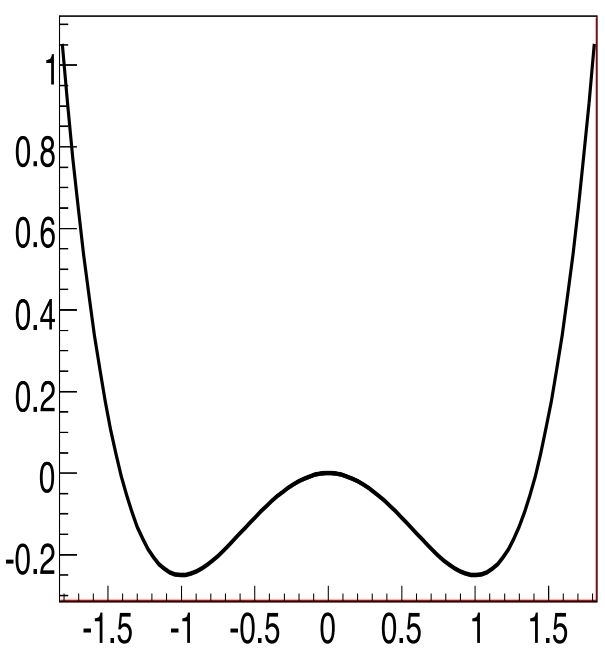
Mass from quark-glue soup energy:
$m_p c^2 = 938$ MeV $\simeq 1.7 \times 10^{-27}$ kg

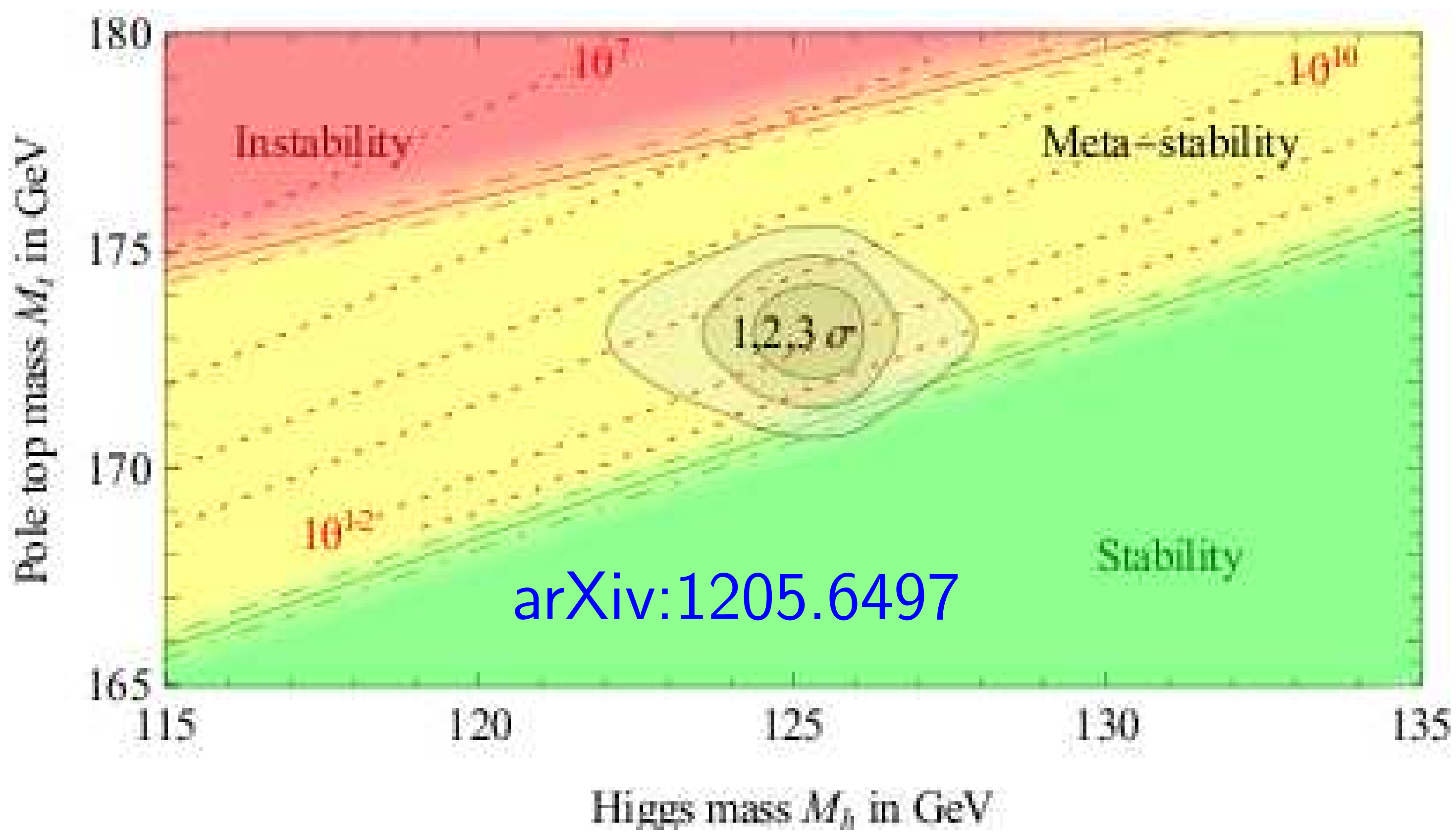
Mass from the Higgs field:
$m_u c^2 \sim 3$ MeV, $m_d c^2 \sim 5$ MeV

but Higgs field is very important

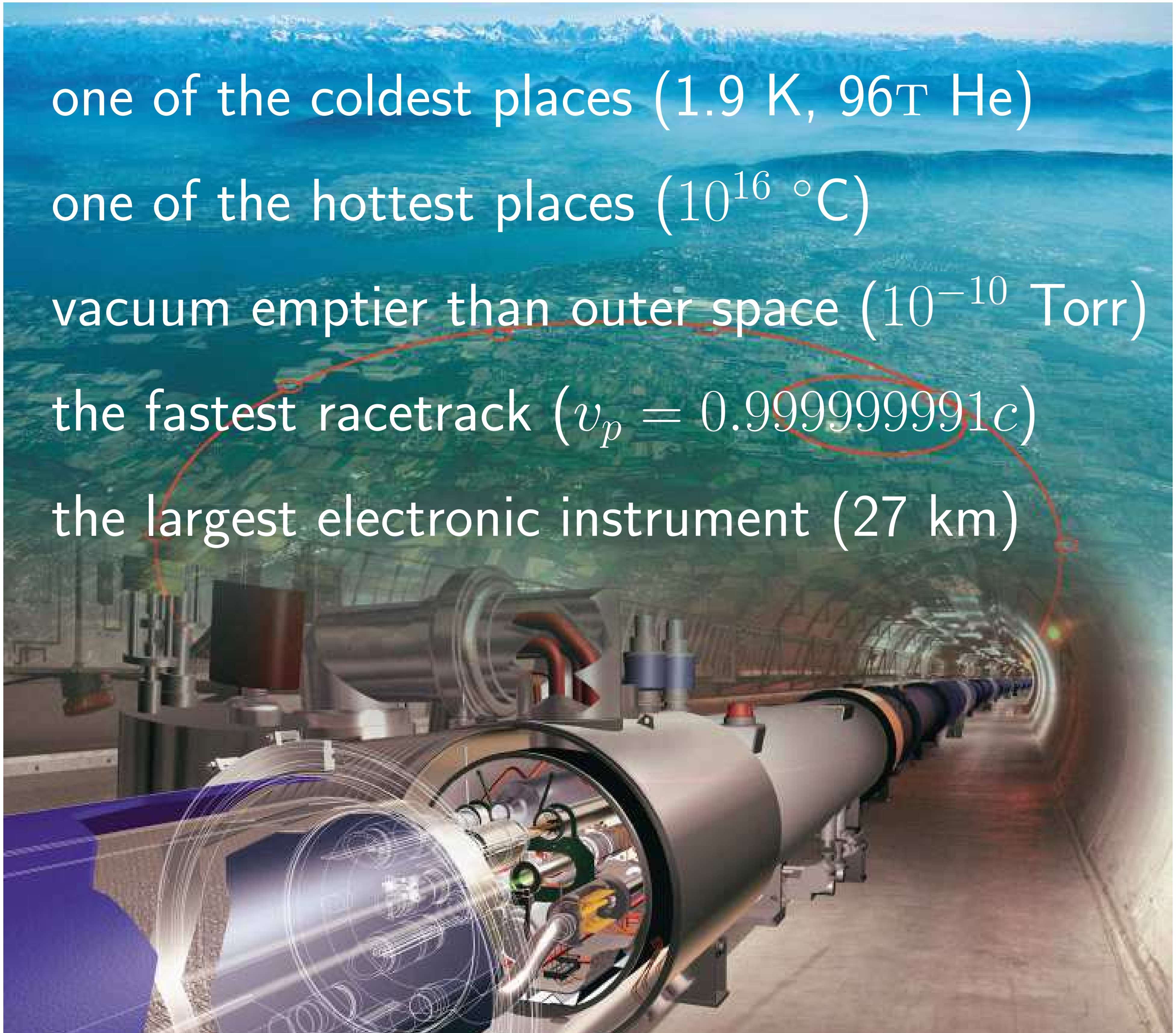
Stability of the Vacuum

- Higgs self-coupling $\lambda < 0$ at higher scale
  - may tunnel thru "potential barrier" $\Rightarrow$ unstable Universe
  - tunneling time $>$ Universe lifetime $\Rightarrow$ metastable Universe
  - for $m_H \sim$ 126 GeV$/c^2$ and SM Higgs field $\Rightarrow$ metastable





The Large Hadron Collider



one of the coldest places (1.9 K, 96T He)

one of the hottest places (10^{16} °C)

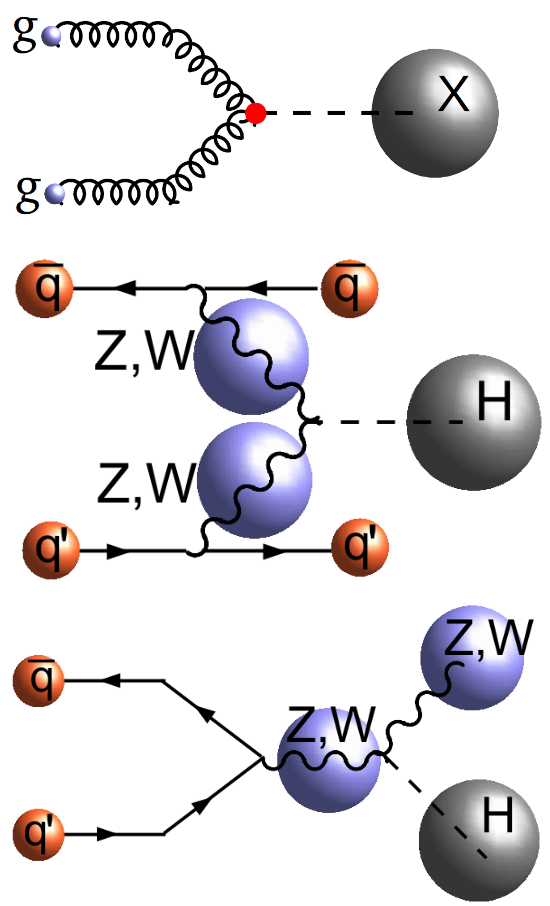
vacuum emptier than outer space (10^{-10} Torr)

the fastest racetrack ($v_p = 0.99999999 1c$)

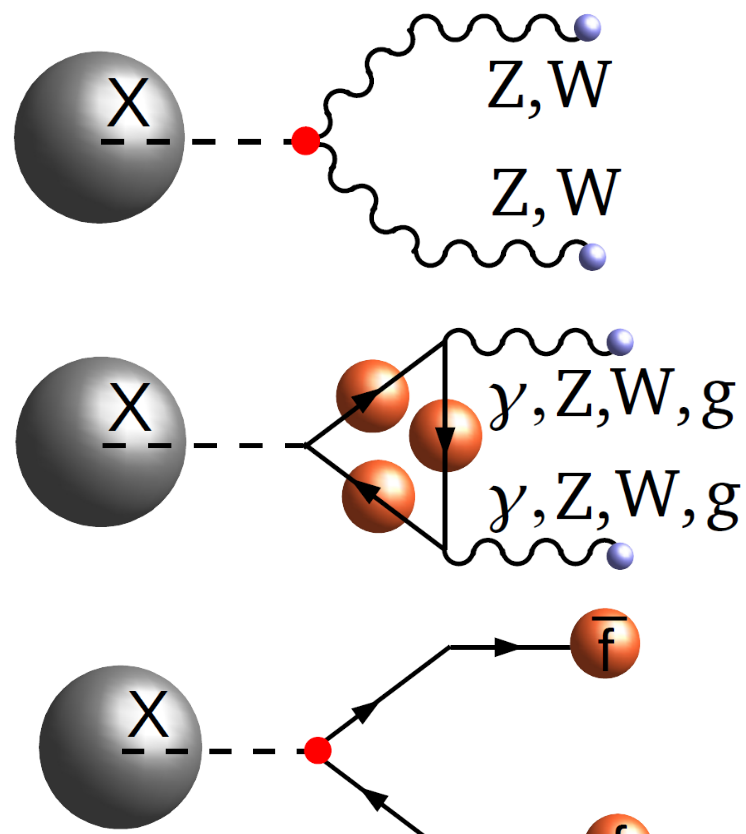
the largest electronic instrument (27 km)

Study of the H⁰ boson

Produce

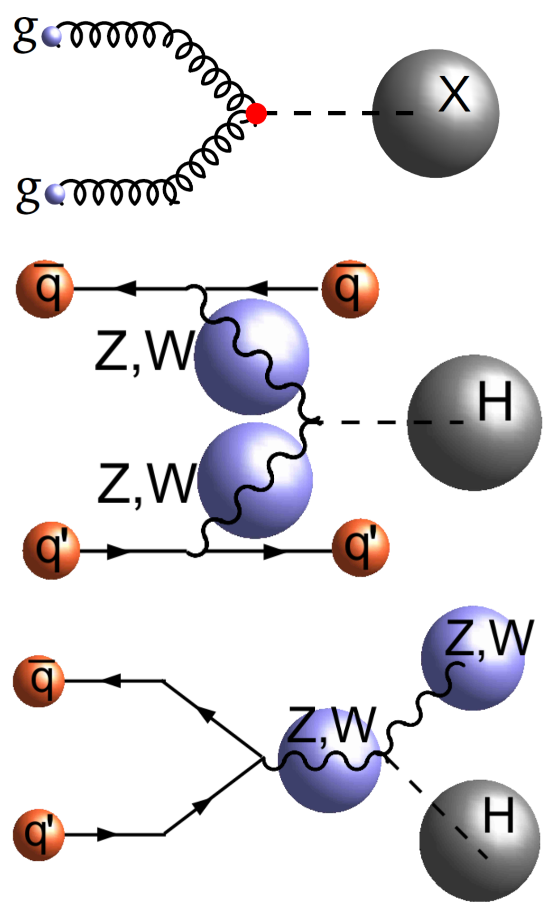


Detect

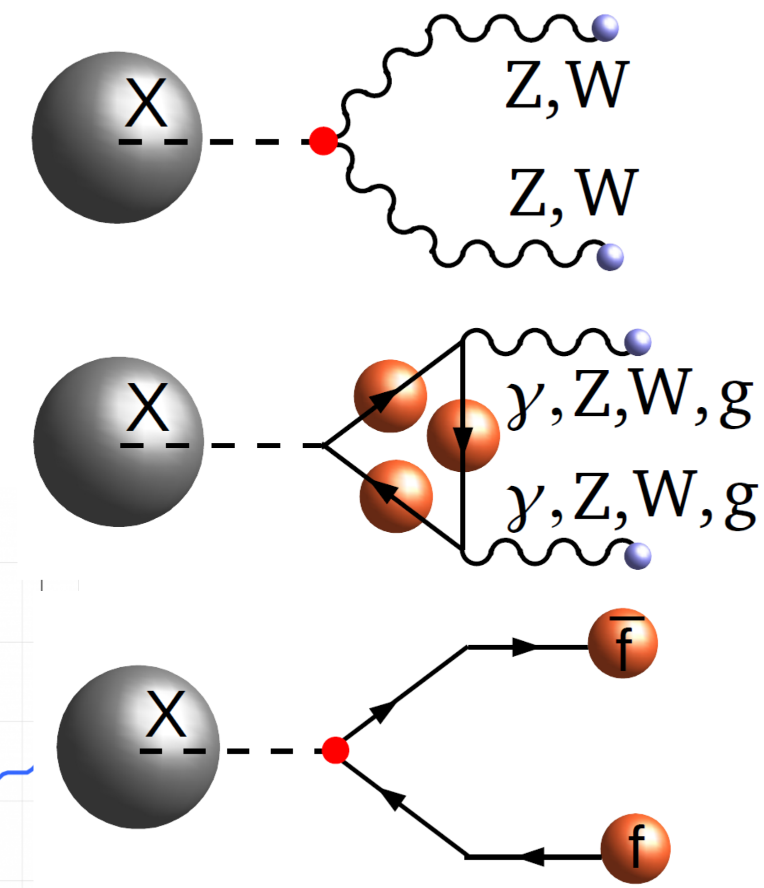


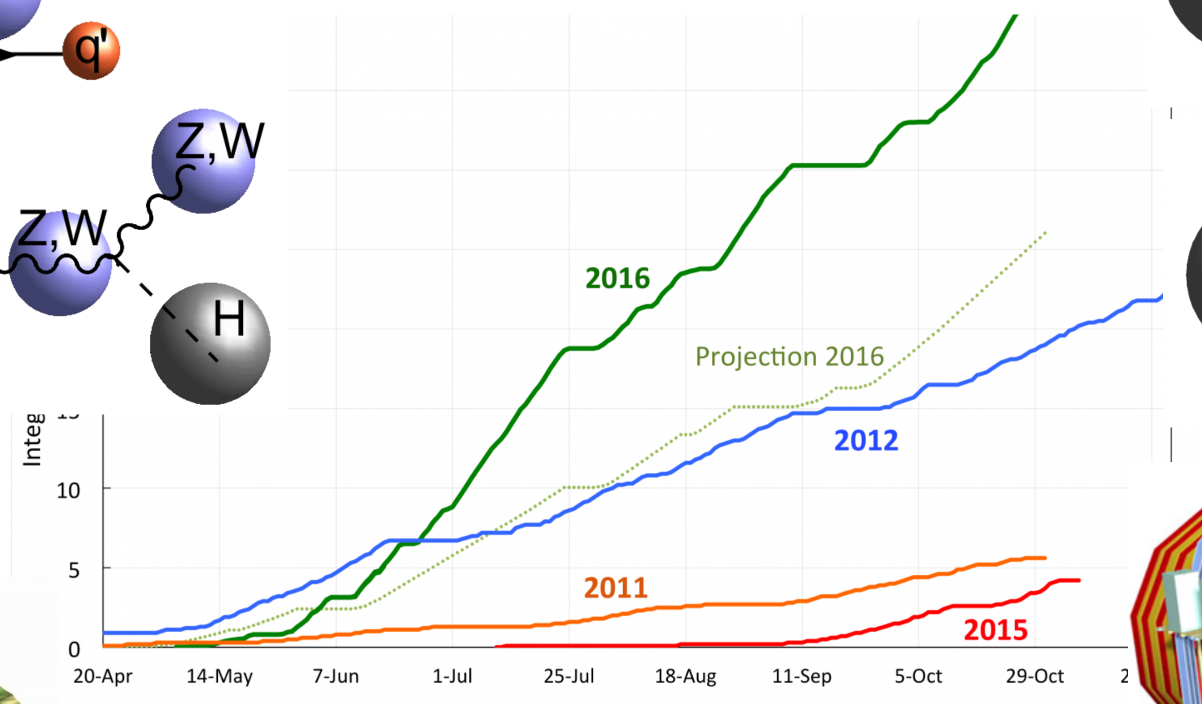
Study of the H^0 boson

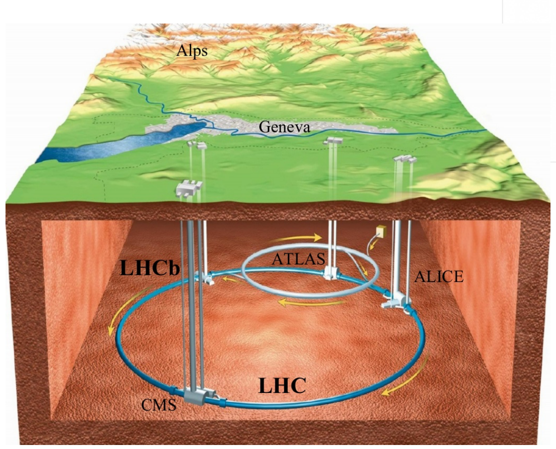
Produce

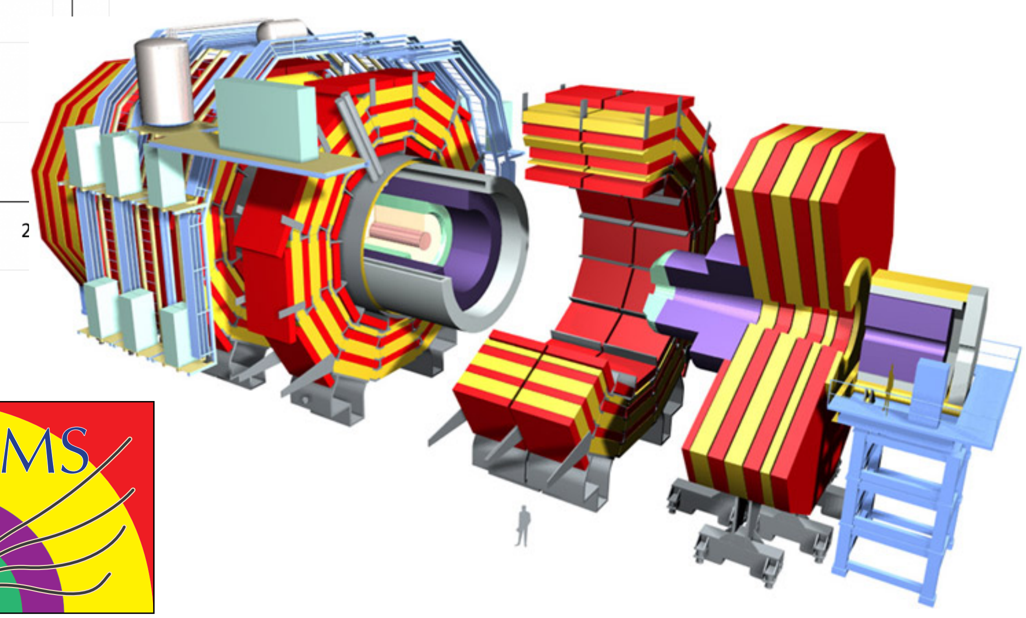


Detect



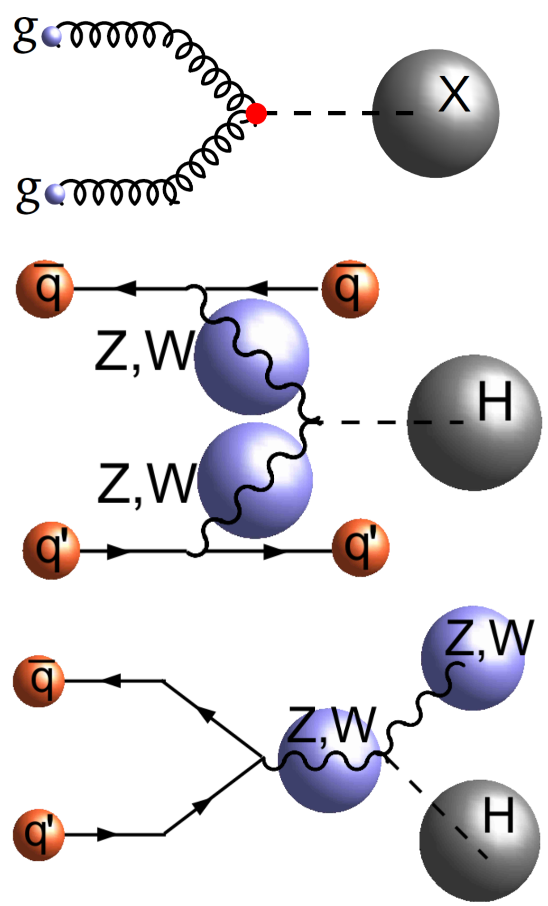






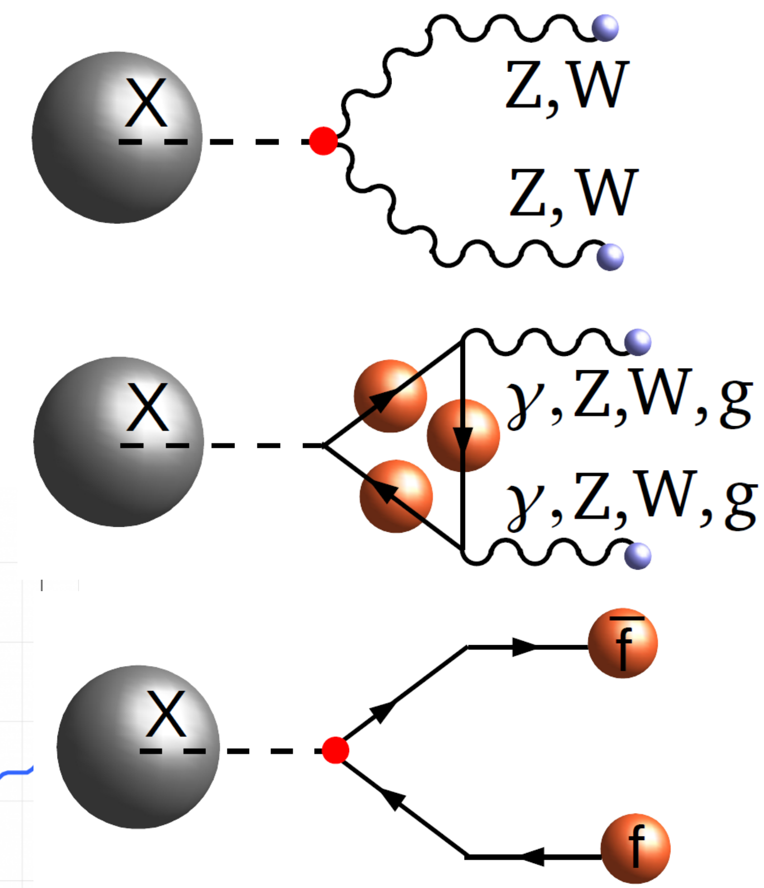
Study of the H^0 boson

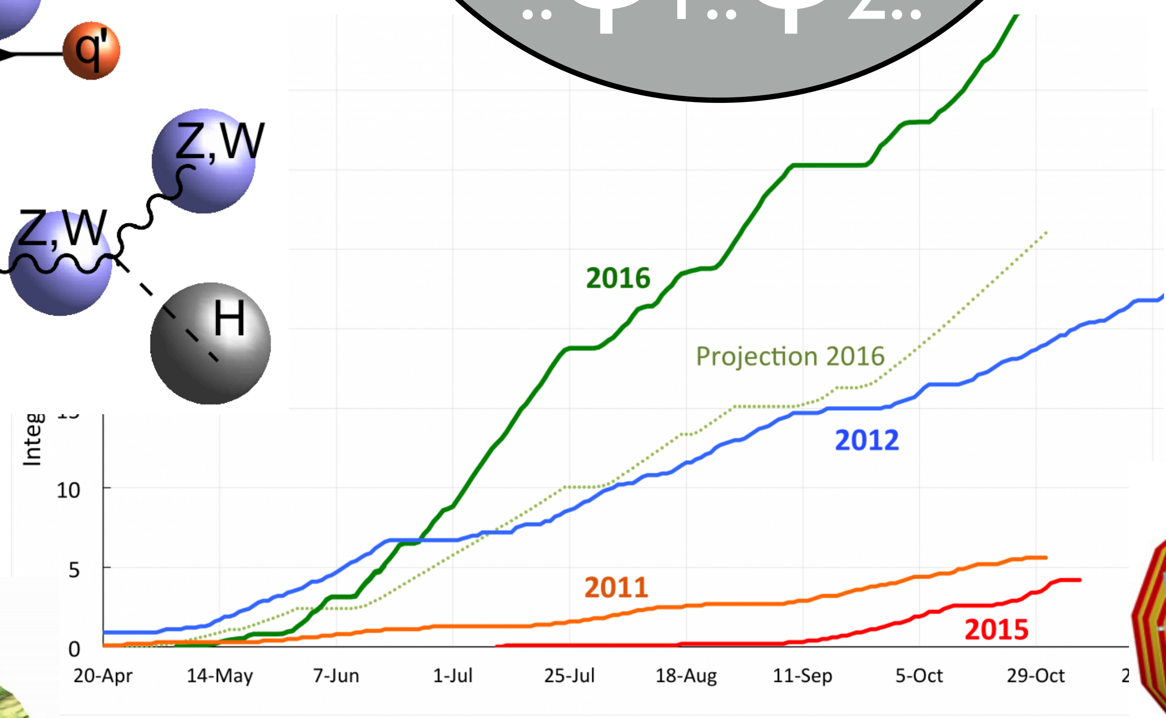
Produce

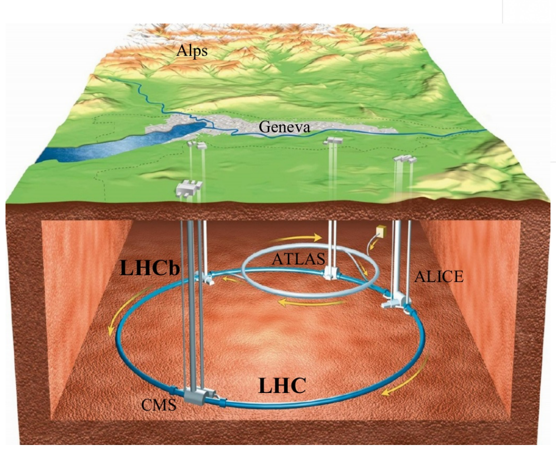


$$\ldots$$
$$? \; +|D_\mu\varphi|^2$$
$$+\psi_i y_{ij} \psi_j \varphi + h.c.$$
$$-V(\varphi) \; ?$$
$$..\varphi_1..\varphi_2..$$

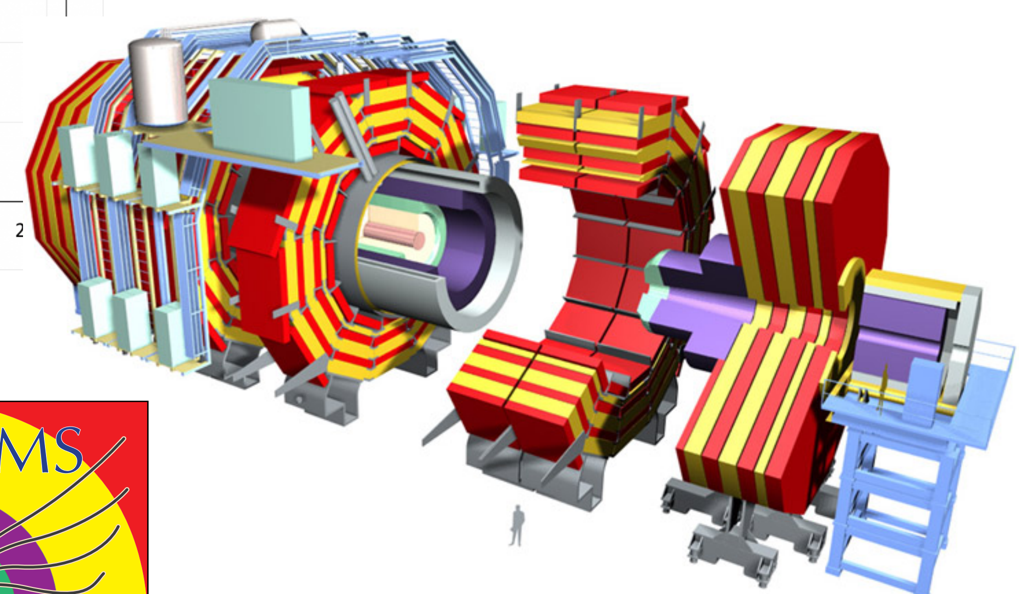
Detect





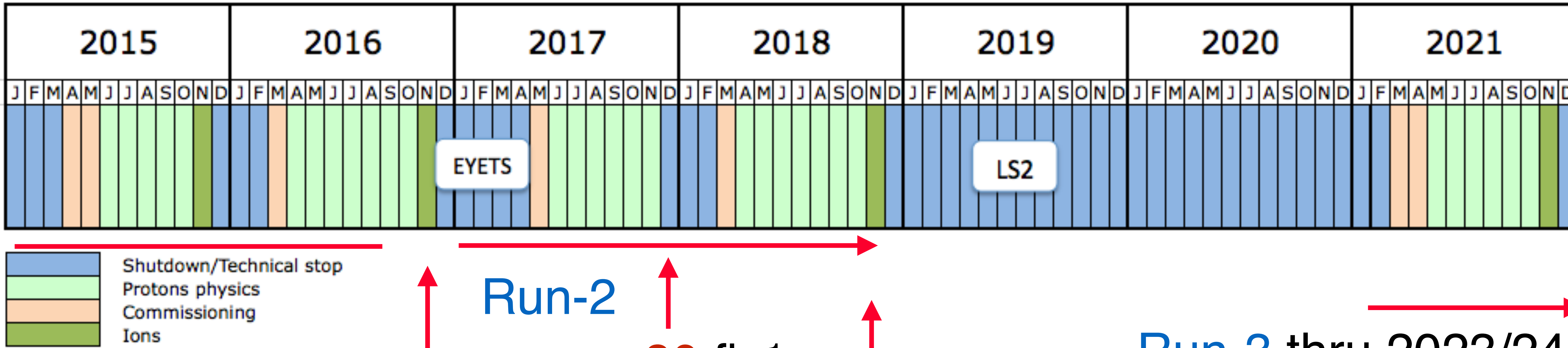


CMS



LHC schedule: 10 year plan

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



Run-2

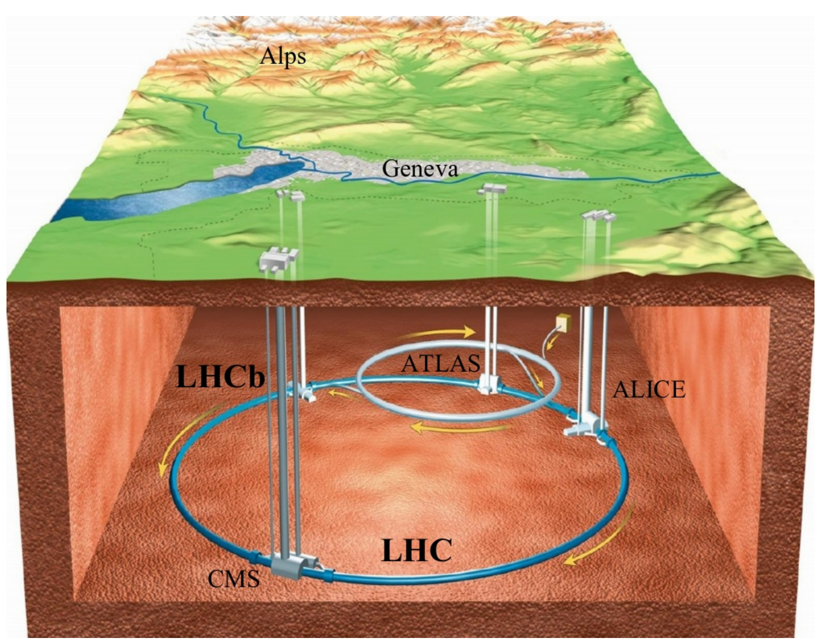
~40 fb^{-1}

~80 fb^{-1}

~120 fb^{-1}

Run-3 thru 2023/24

~300 fb^{-1}

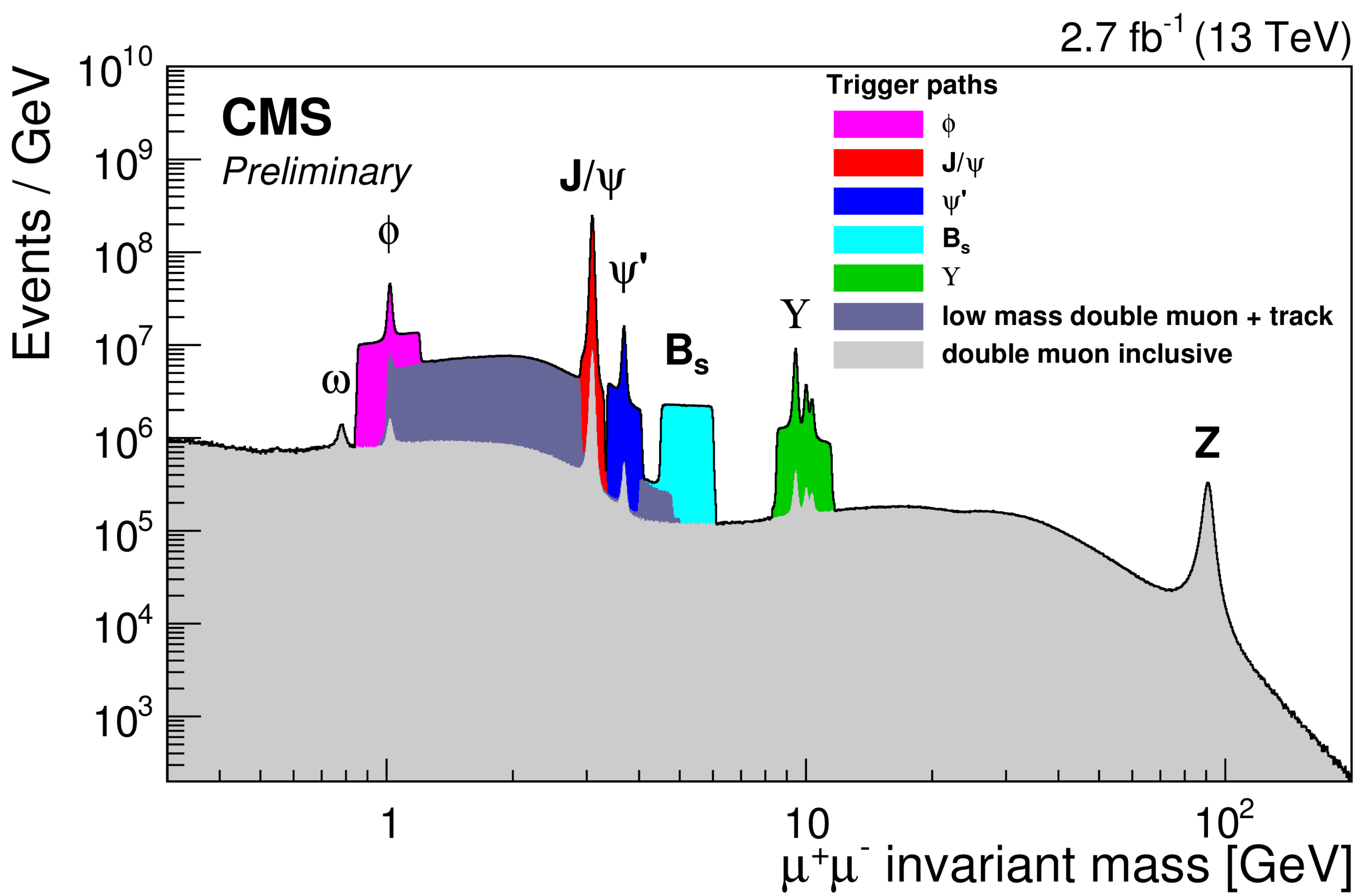


- Phase-2 with Run-4 plan to start in 2026, Snowmass: ~3000 fb^{-1}

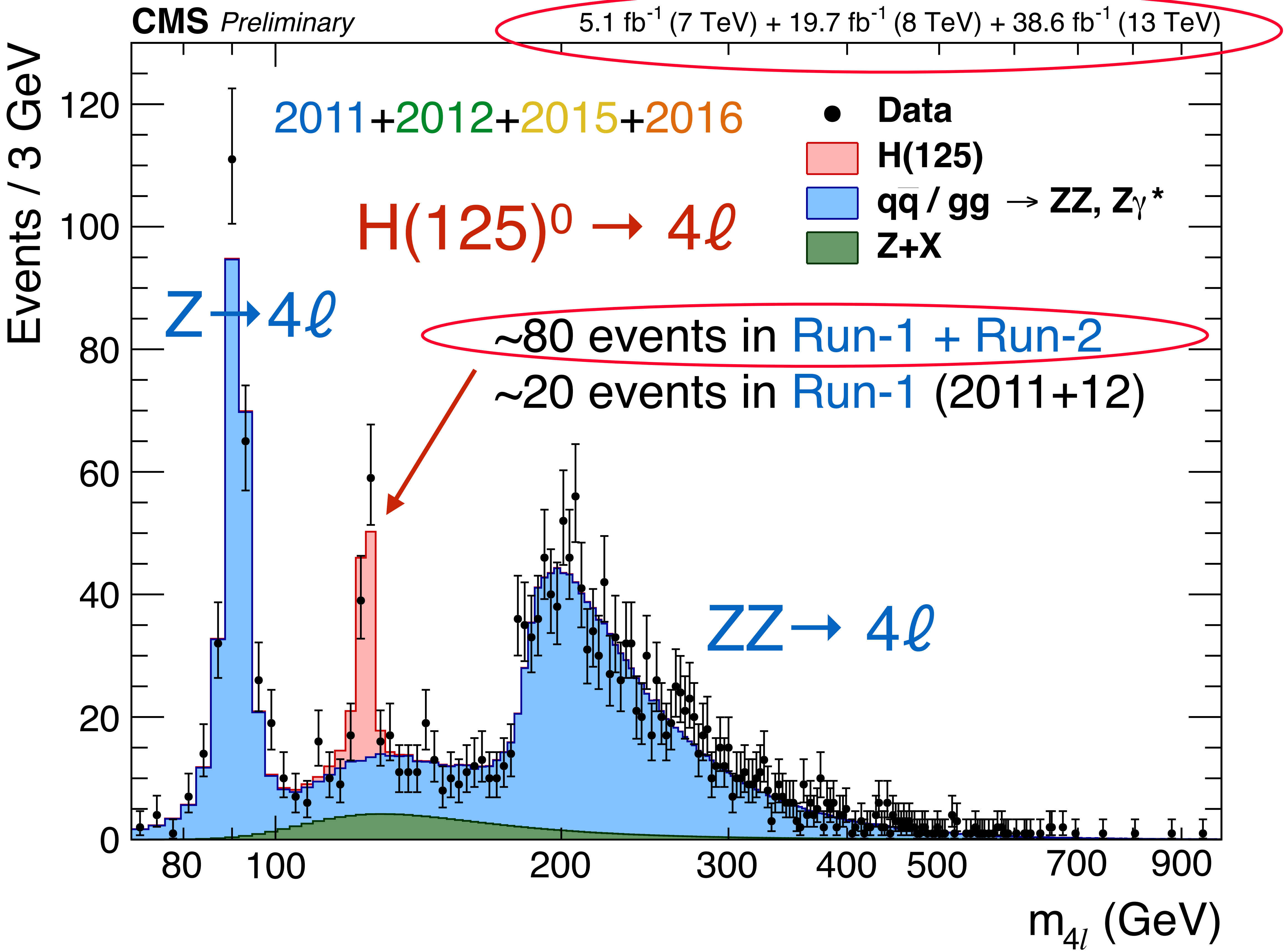
- Legacy: Run-1 (2010-2012) ~25 fb^{-1} at 7 and 8 TeV

Particles → Resonances → "Bumps"

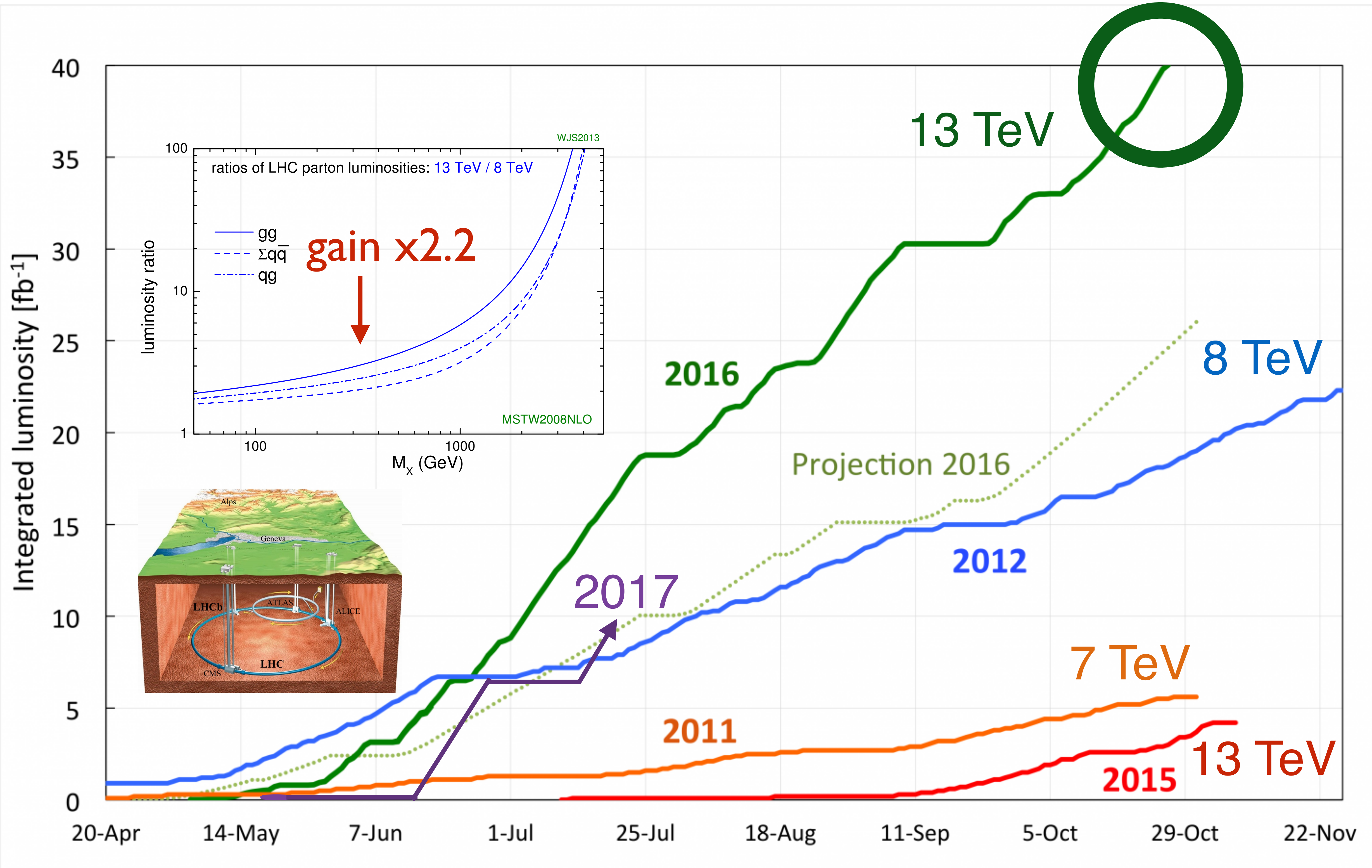
- We often see particles as "resonances"
  - most particles are not stable
  - reconstruct from their decay products



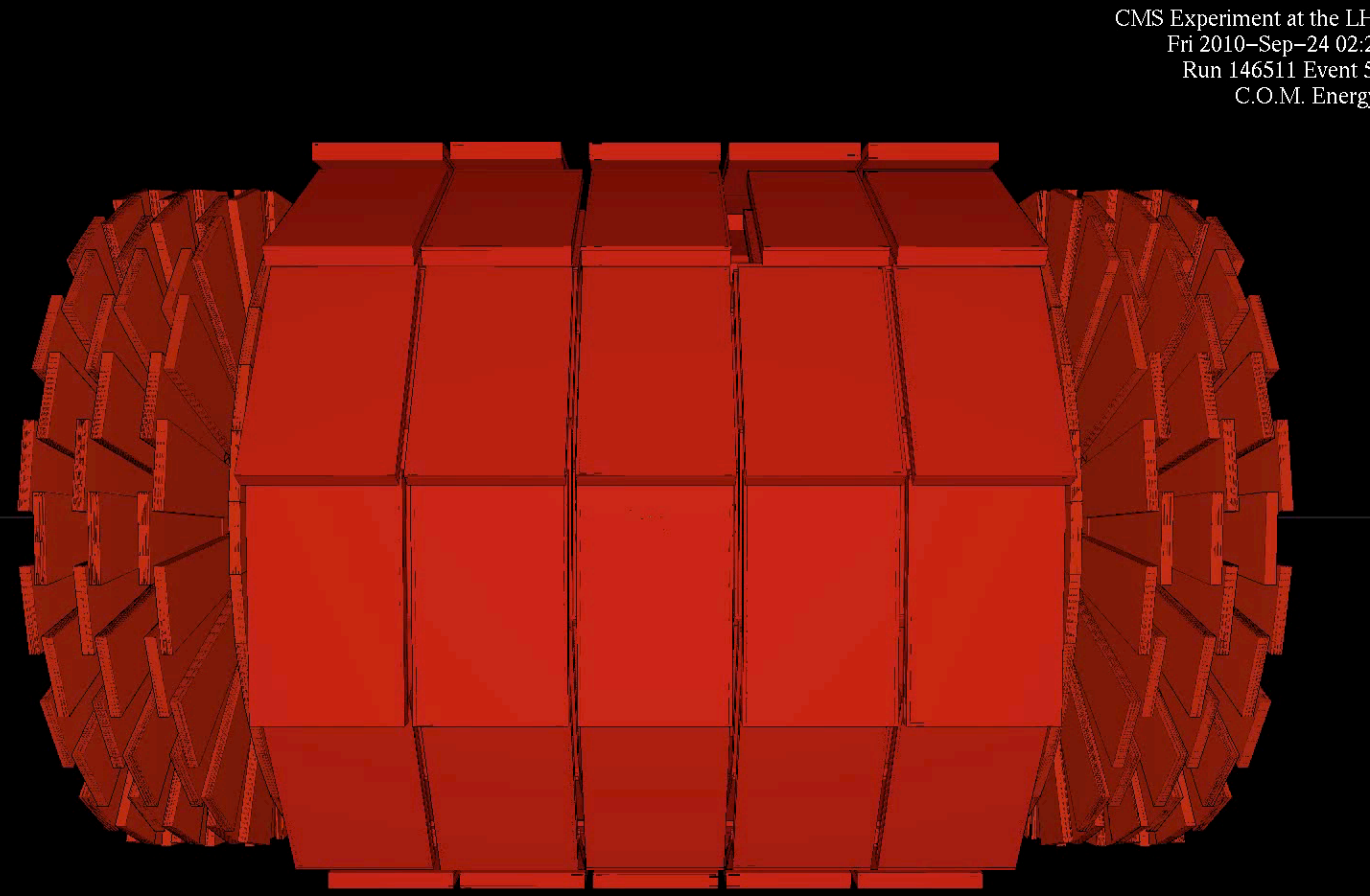
Higgs boson yield



Run-2 of LHC

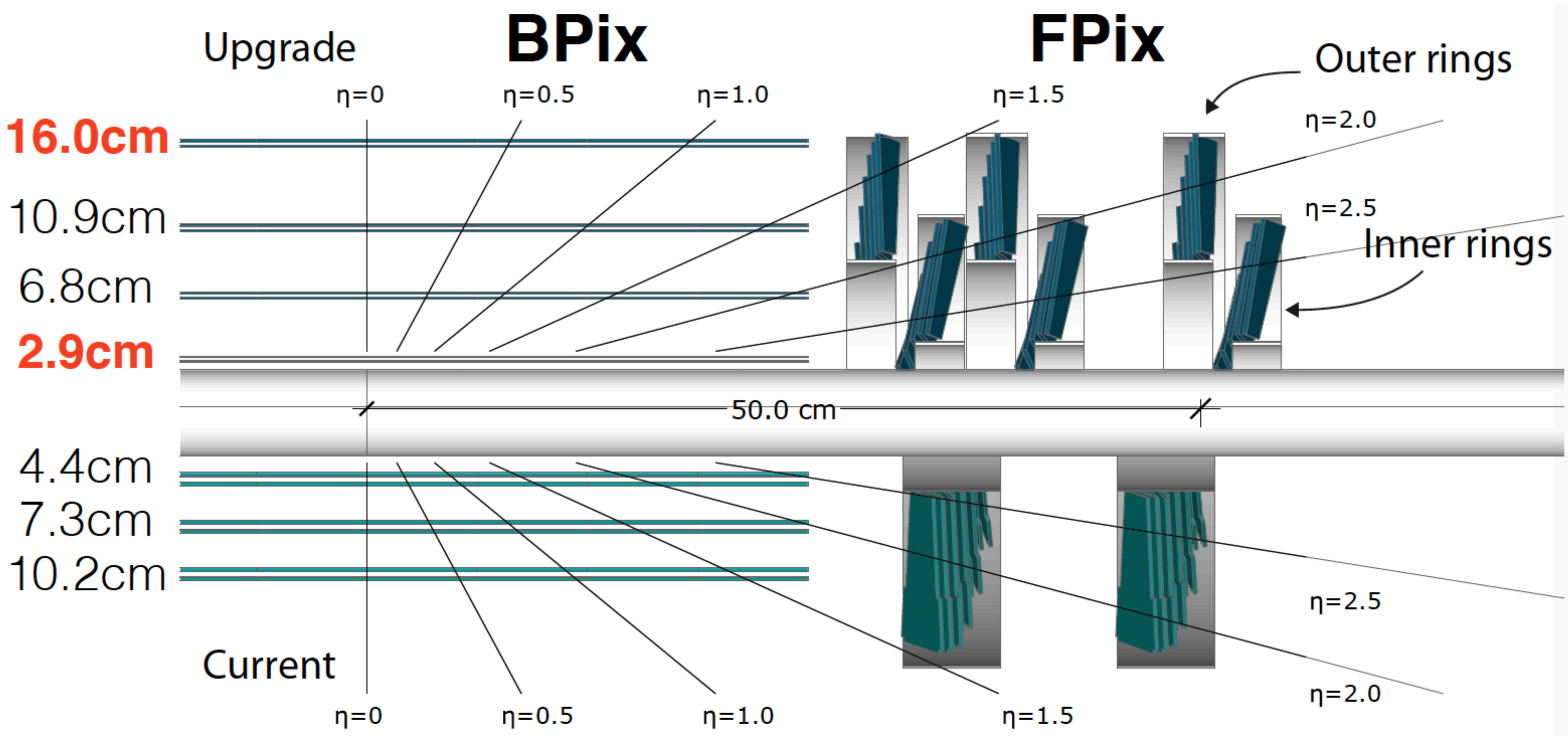


Integrated luminosity [fb^{-1}]
40
35
30
25
20
15
10
5
0
20-Apr
14-May
7-Jun
1-Jul
25-Jul
18-Aug
11-Sep
5-Oct
29-Oct
22-Nov
13 TeV
2016
8 TeV
Projection 2016
2012
2017
7 TeV
2011
13 TeV
2015
ratios of LHC parton luminosities: 13 TeV / 8 TeV
WJS2013
luminosity ratio
gg
Σqq̄
qg
gain x2.2
MSTW2008NLO
M_X (GeV)
100
10
1
100
1000
Alps
Geneva
LHCb
ATLAS
ALICE
CMS
LHC


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

New Pixel Detector in CMS Now (“Phase-1”)

- first stable beams on May 23, 2017



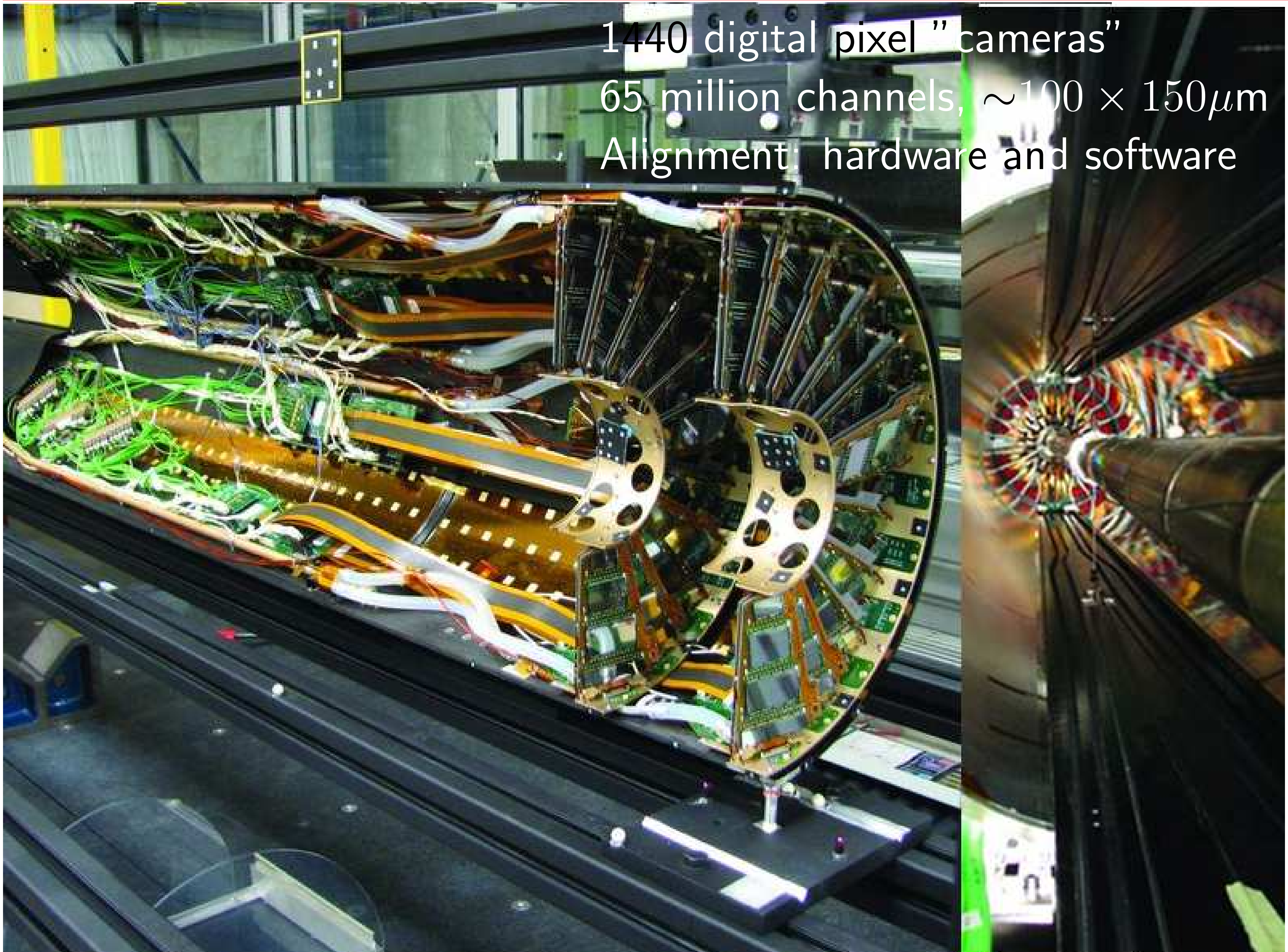
66 million channels in 1440 modules → 124 million channels in 1856 modules

The Silicon Pixel Detector

1440 digital pixel "cameras"

65 million channels, $\sim 100 \times 150 \mu$m

Alignment: hardware and software



Study of the Higgs field φ

...

? $+|D_\mu \varphi|^2$

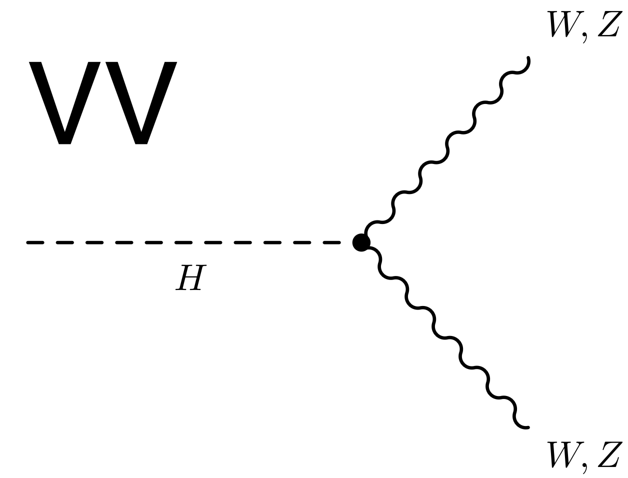
$+\psi_i y_{ij} \psi_j \varphi$ +h.c.

$-V(\varphi)$?

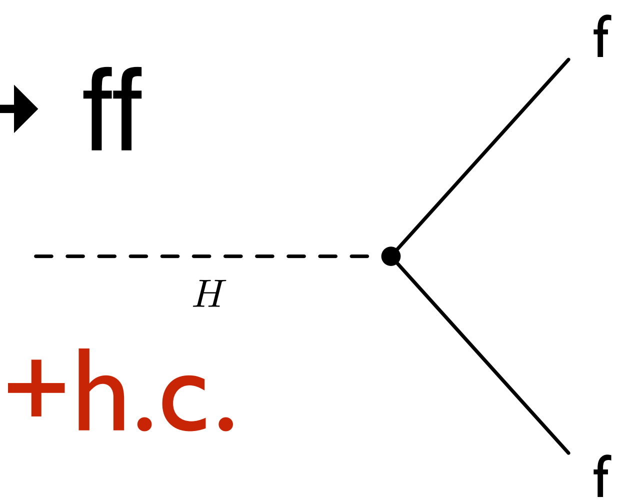
$..\varphi_1..\varphi_2..$

$H(125)^0 \rightarrow VV$

$|D_\mu \varphi|^2$



$H(125)^0 \rightarrow ff$



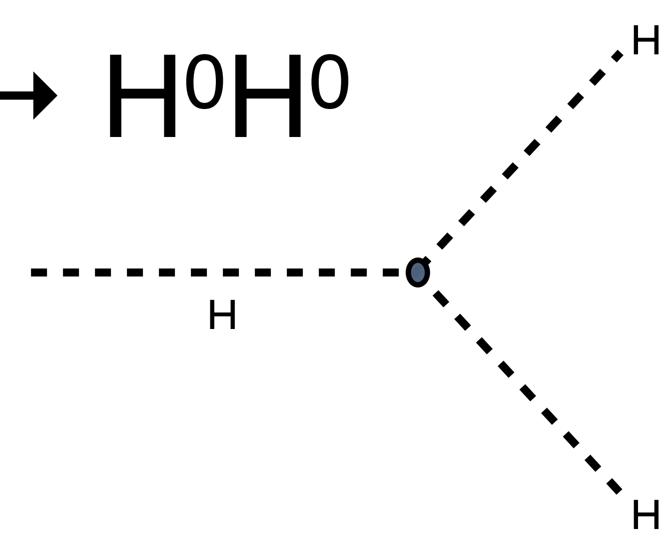
$\psi_i y_{ij} \psi_j \varphi$ +h.c.

$..\varphi_1..\varphi_2..$

more Higgs bosons

$H(125)^0, H, A, H^+, H^-$

$H(125)^0 \rightarrow H^0 H^0$

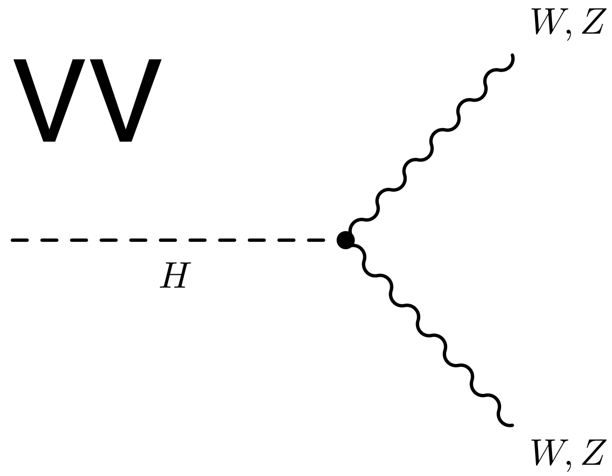


$V(\varphi)$

Study HVV or $|D_\mu\varphi|^2$

$H(125)^0 \rightarrow VV$

$|D_\mu\varphi|^2$

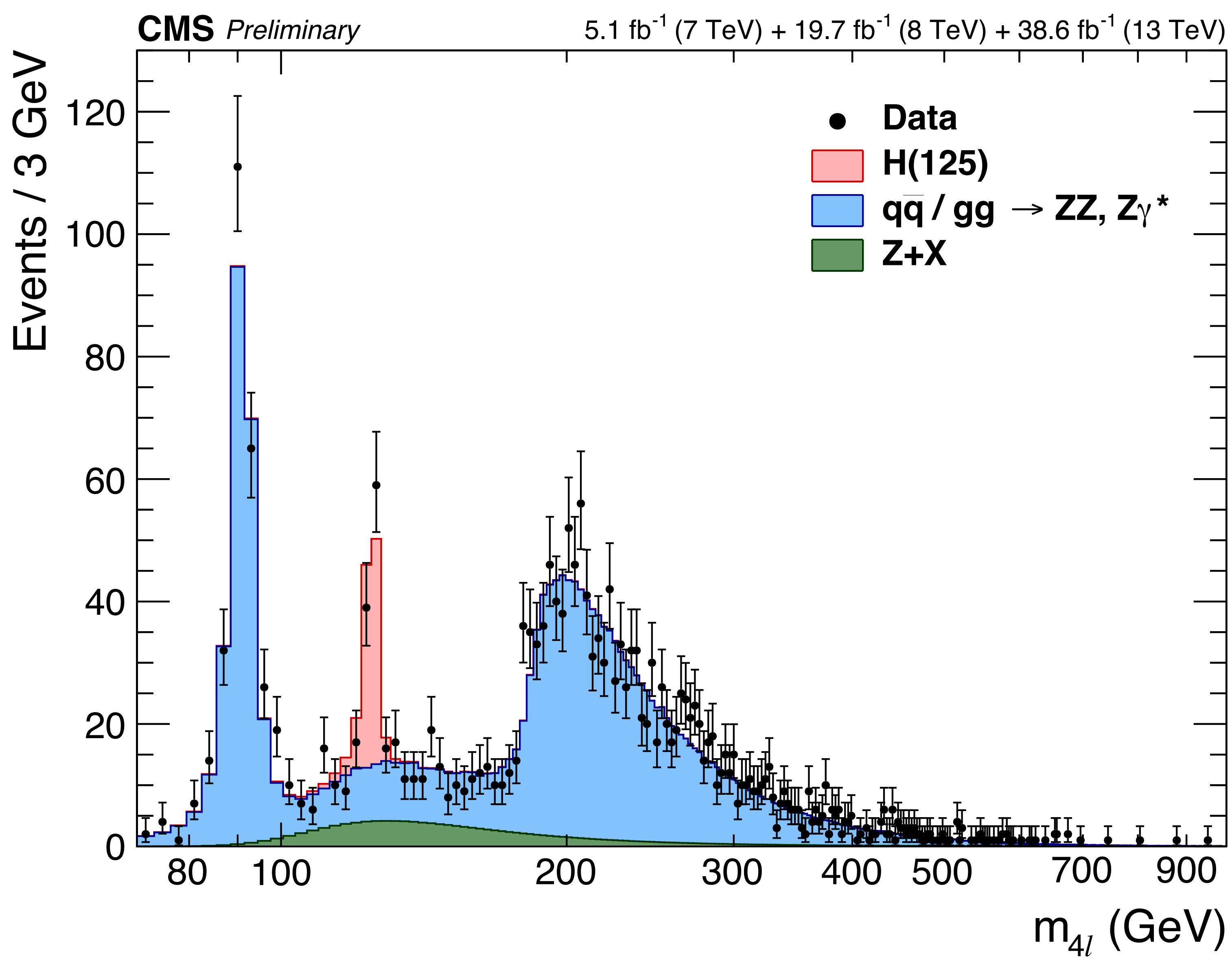


H^0 $J = 0$

pdg.lbl.gov
(LHC Run 1)

Mass $m = 125.09 \pm 0.24$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

CMS (Run 2): $m_H = 125.26 \pm 0.20(\mathrm{stat}) \pm 0.08(\mathrm{syst})$ GeV

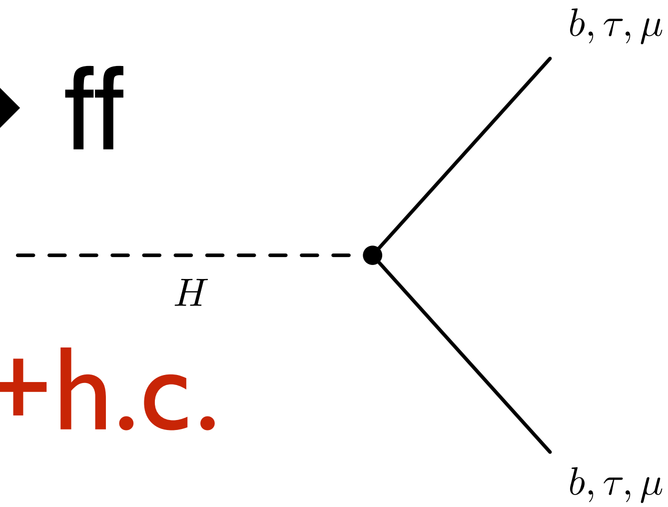


Follow PDG check-list

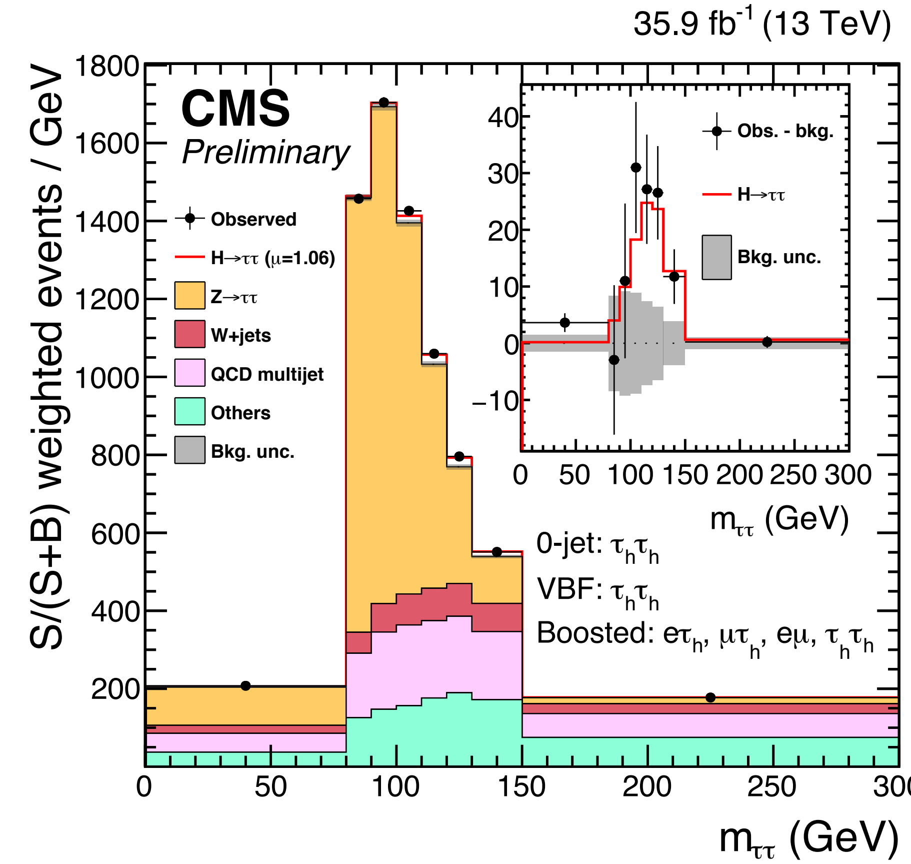
- mass
- lifetime
- width
- quantum numbers
- coupling strength

Study Hff or $\psi_i y_{ij} \psi_j \varphi$

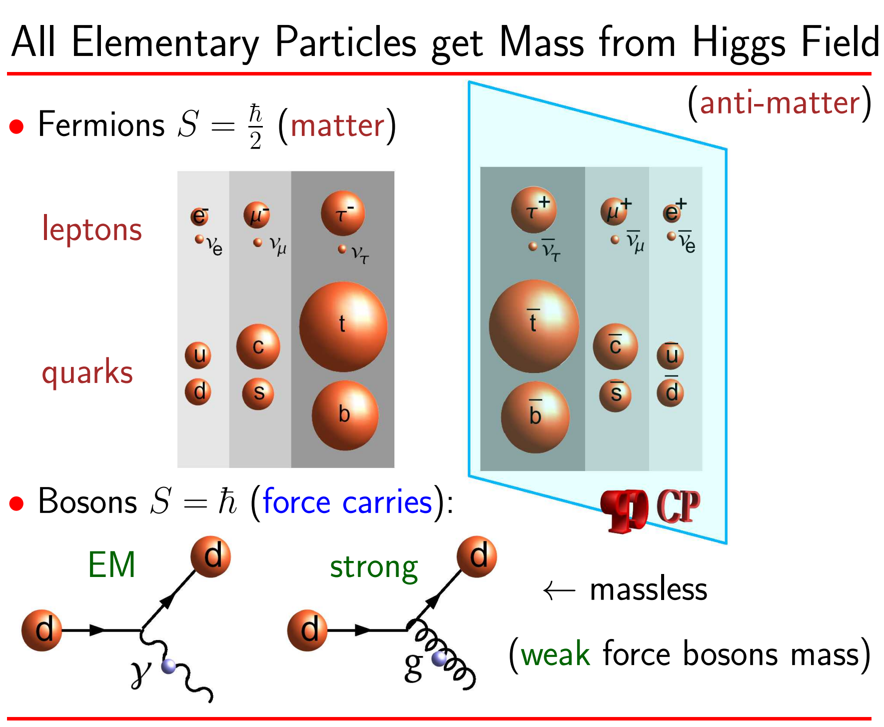
$H(125)^0 \rightarrow ff$

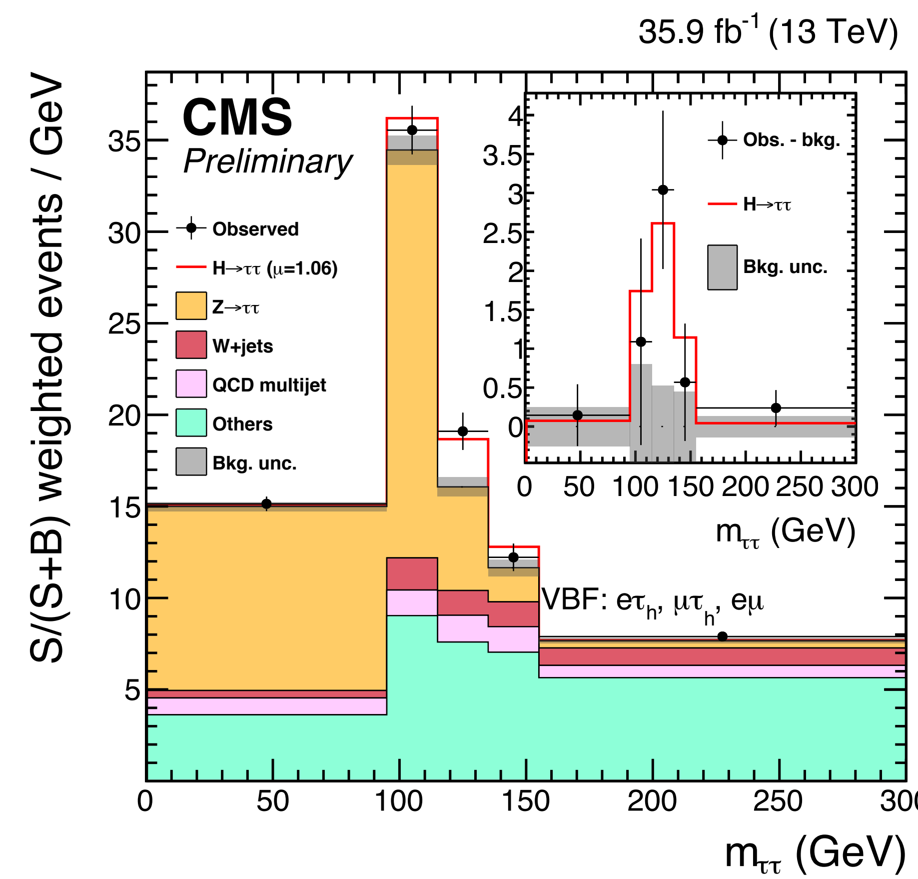


$\psi_i y_{ij} \psi_j \varphi$ +h.c.



Discovery of $H(125)^0 \rightarrow \tau\tau$

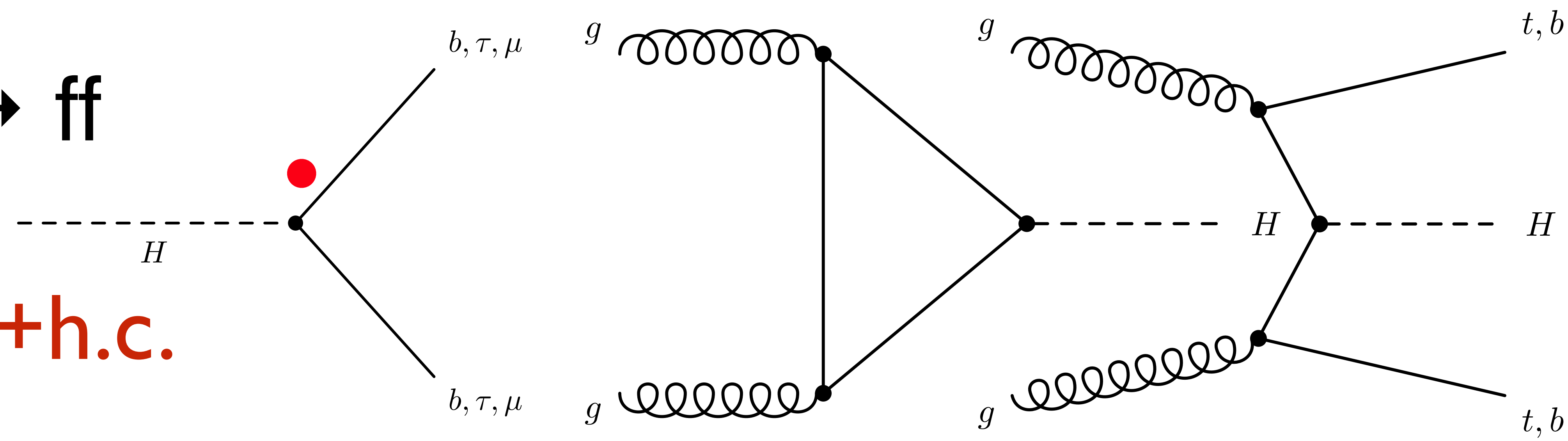




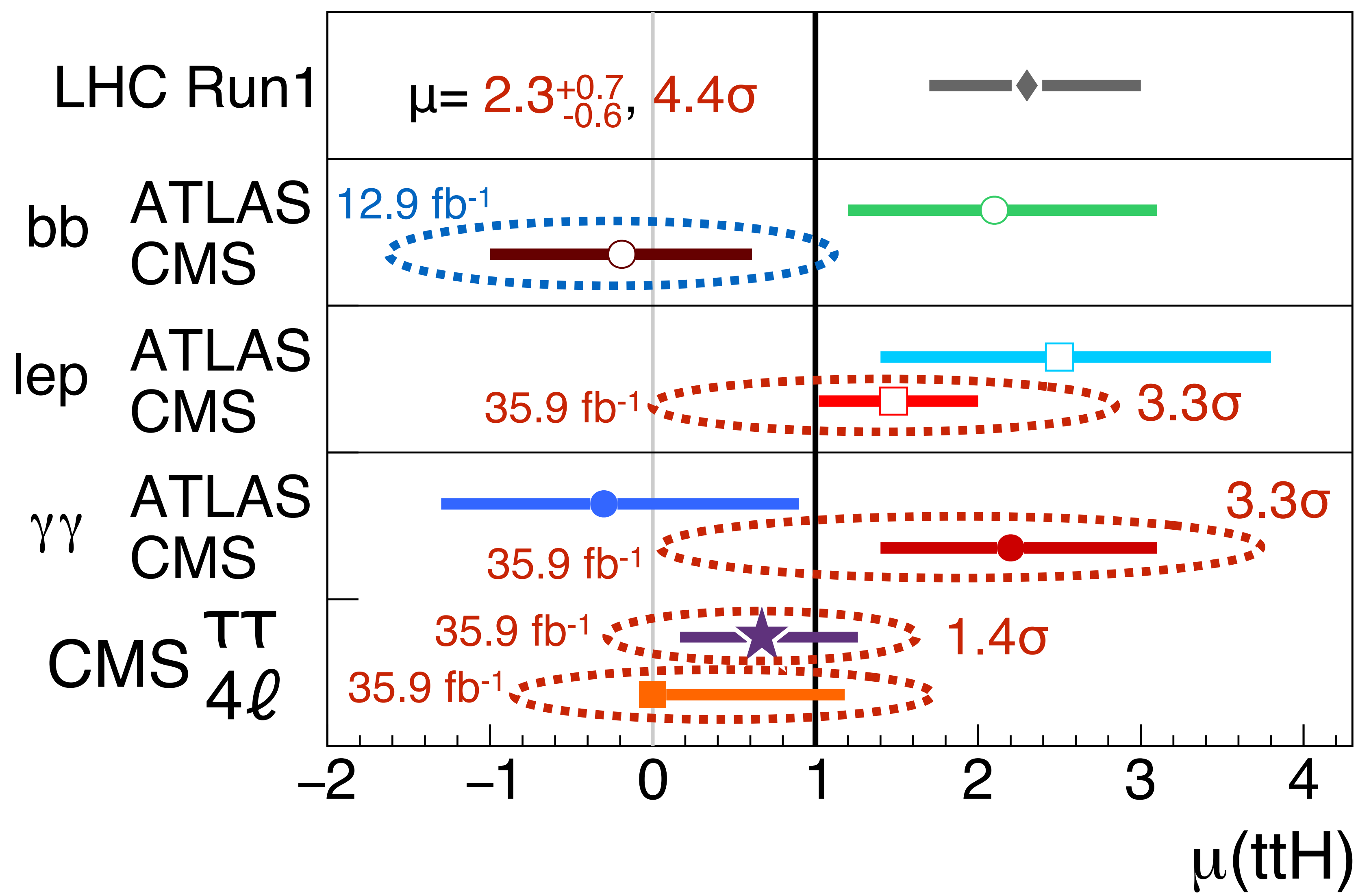
Study Hff or $\psi_i y_{ij} \psi_j \varphi$

$H(125)^0 \rightarrow ff$

$\psi_i y_{ij} \psi_j \varphi$ +h.c.

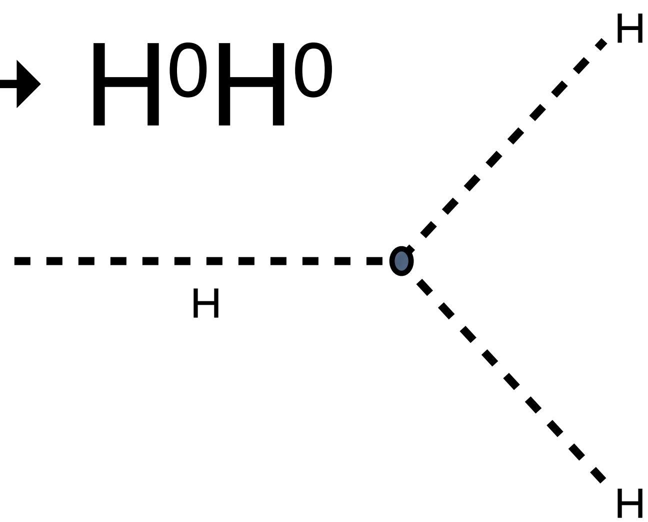


Strong evidence for ttH(125)^0



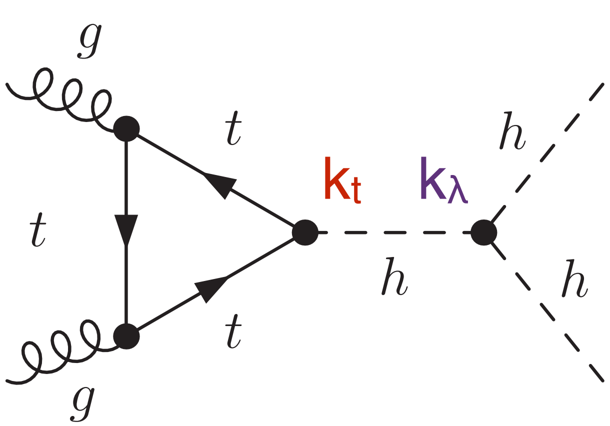
Study HHH or V(φ)

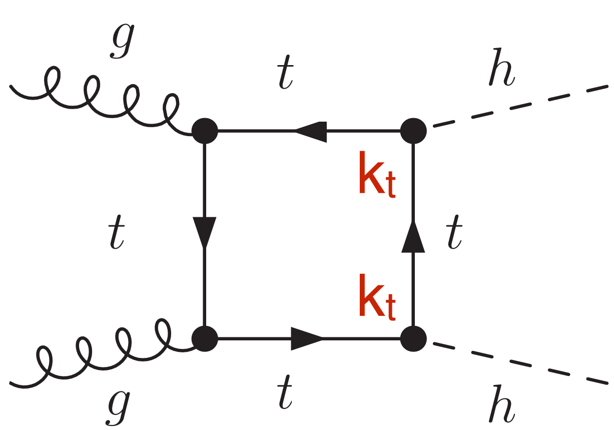
$H(125)^0 \rightarrow H^0H^0$

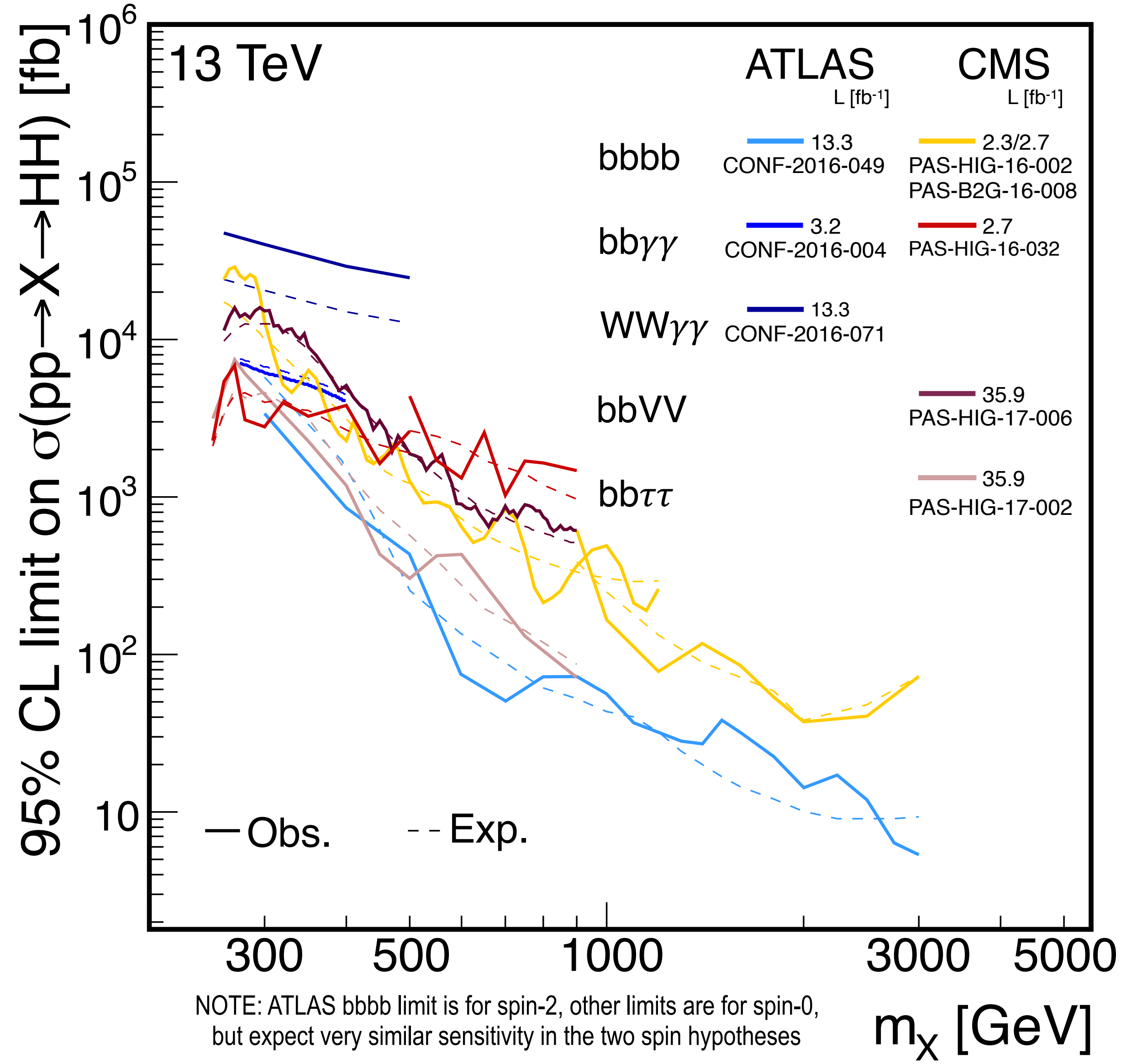


V(φ)

only limits so far
need HL-LHC (3000 fb^{-1})
to find SM H^0H^0 production







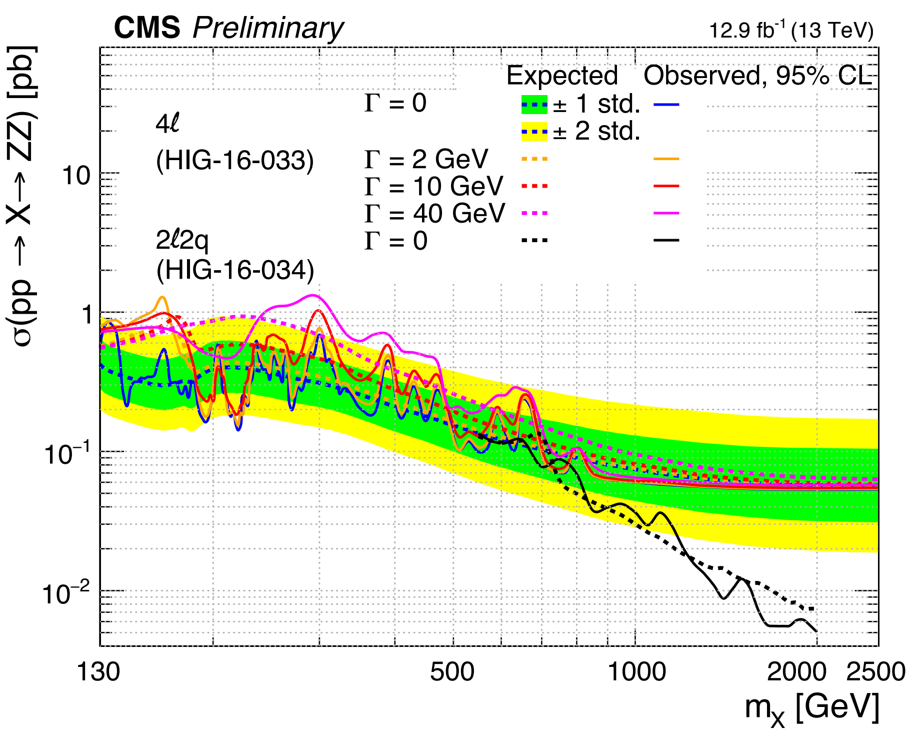
HH→(bb)+(bb/WW/ZZ/ττ/γγ)

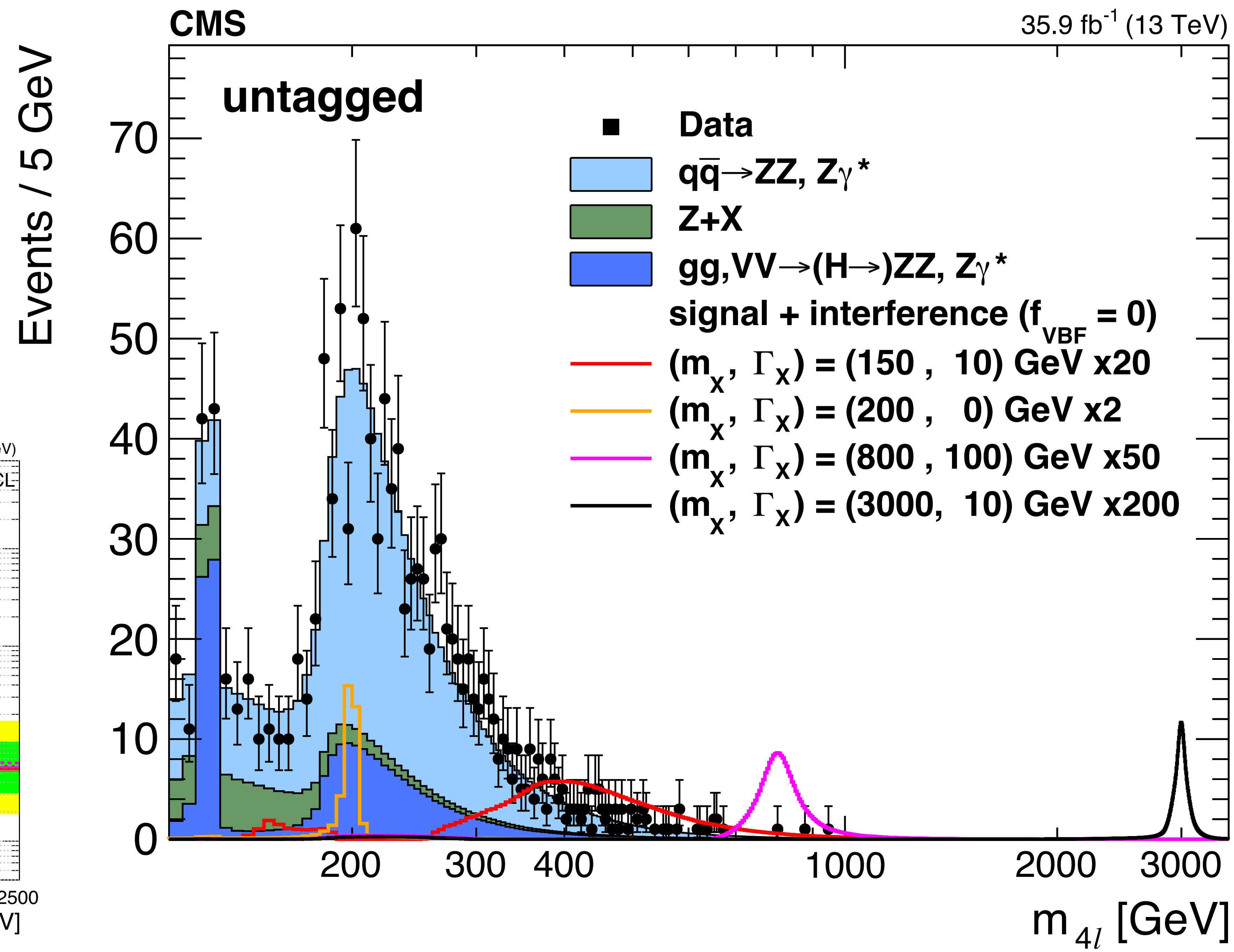
Search for more Higgs bosons: $\varphi_1, \varphi_2 \ldots$

more involved Higgs field $..\varphi_1..\varphi_2..$

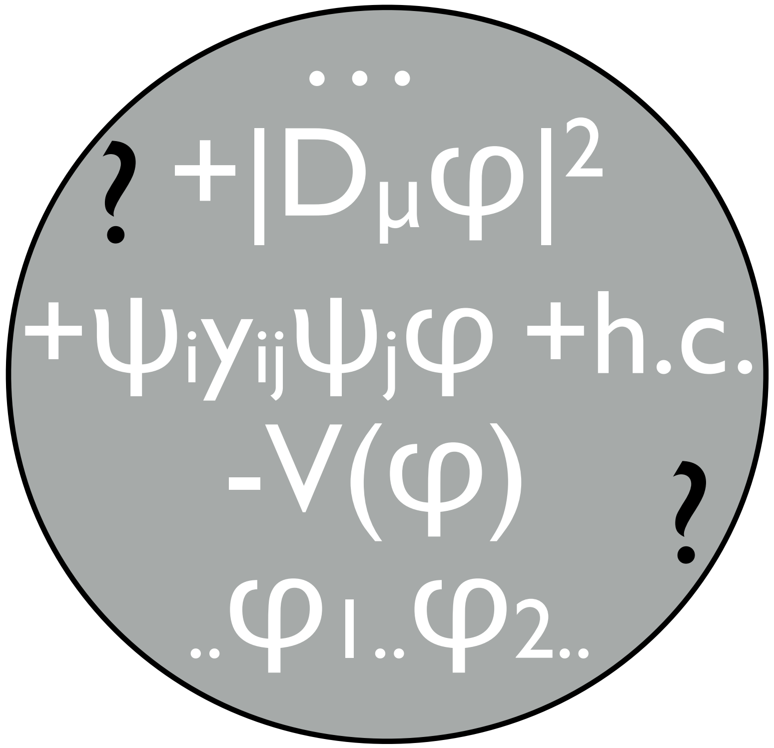
more Higgs bosons, $H(125)^0, H, A, H^+, H^-$

nothing found yet



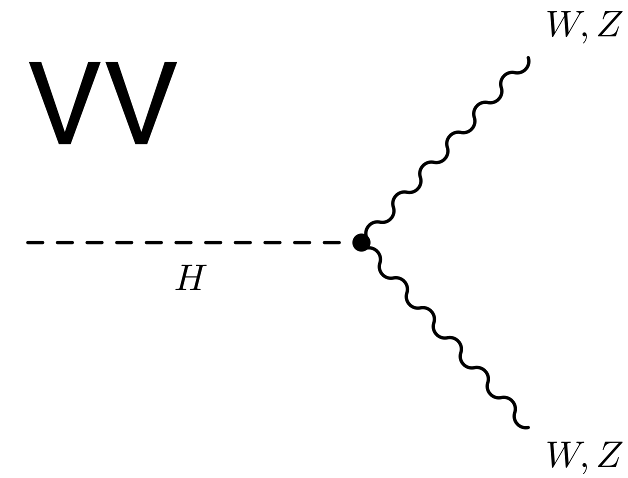


Study of the Higgs field φ



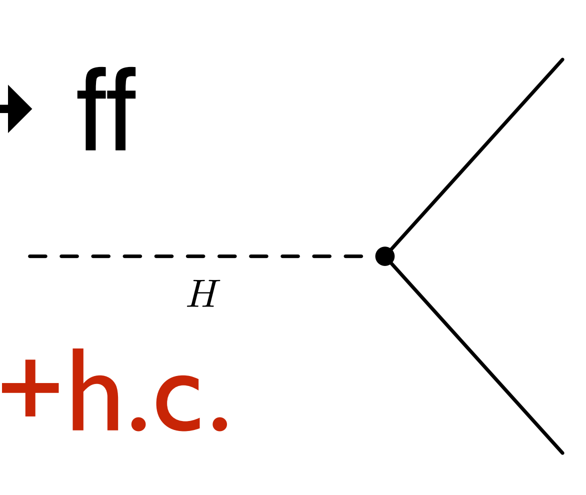
$H(125)^0 \rightarrow VV$

$|D_\mu\varphi|^2$



$H(125)^0 \rightarrow ff$

$\psi_i y_{ij} \psi_j \varphi$ +h.c.



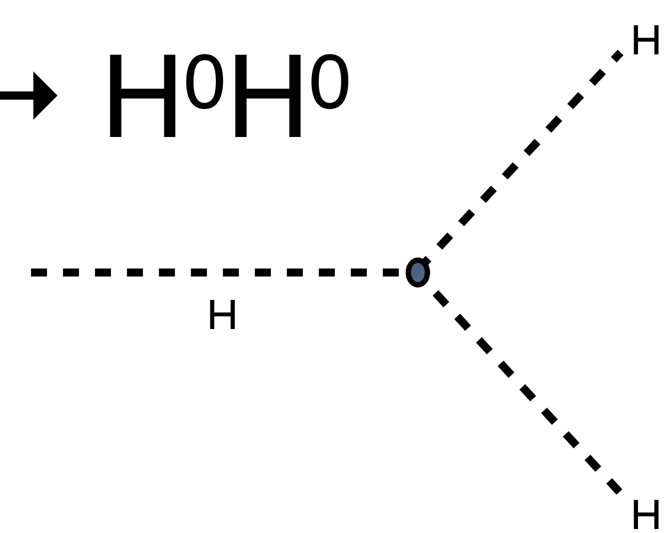
$..\varphi_1..\varphi_2..$

more Higgs bosons

$H(125)^0, H, A, H^+, H^-$

$H(125)^0 \rightarrow H^0 H^0$

$V(\varphi)$



Study of the Higgs field φ

- $H(125)^0$ is a completely new state of matter-energy

— the major LHC discovery so far

— yet it is just an extinct particle

— what remains in the Higgs field

— it is all around us

— gives mass to fermions, bosons

— its potential remains to be tested, implication for our existence

$$\begin{gathered} \ldots \\ ?\ +|D_\mu\varphi|^2 \\ +\psi_i y_{ij}\psi_j\varphi + h.c. \\ -V(\varphi)\quad ? \\ ..\varphi_1..\varphi_2.. \end{gathered}$$