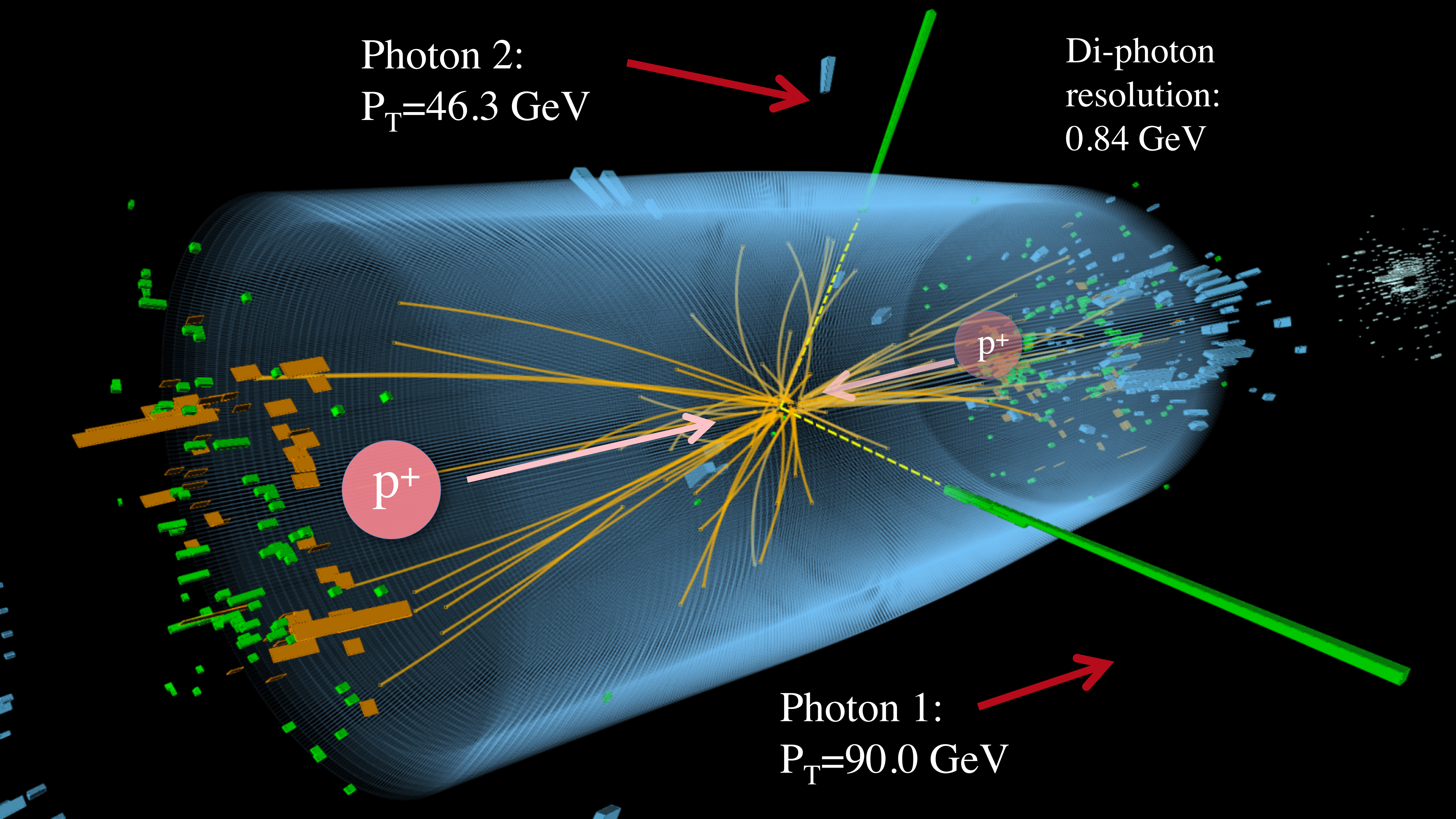
Higgs Boson: Discovery and Properties

PURSUE Day 2

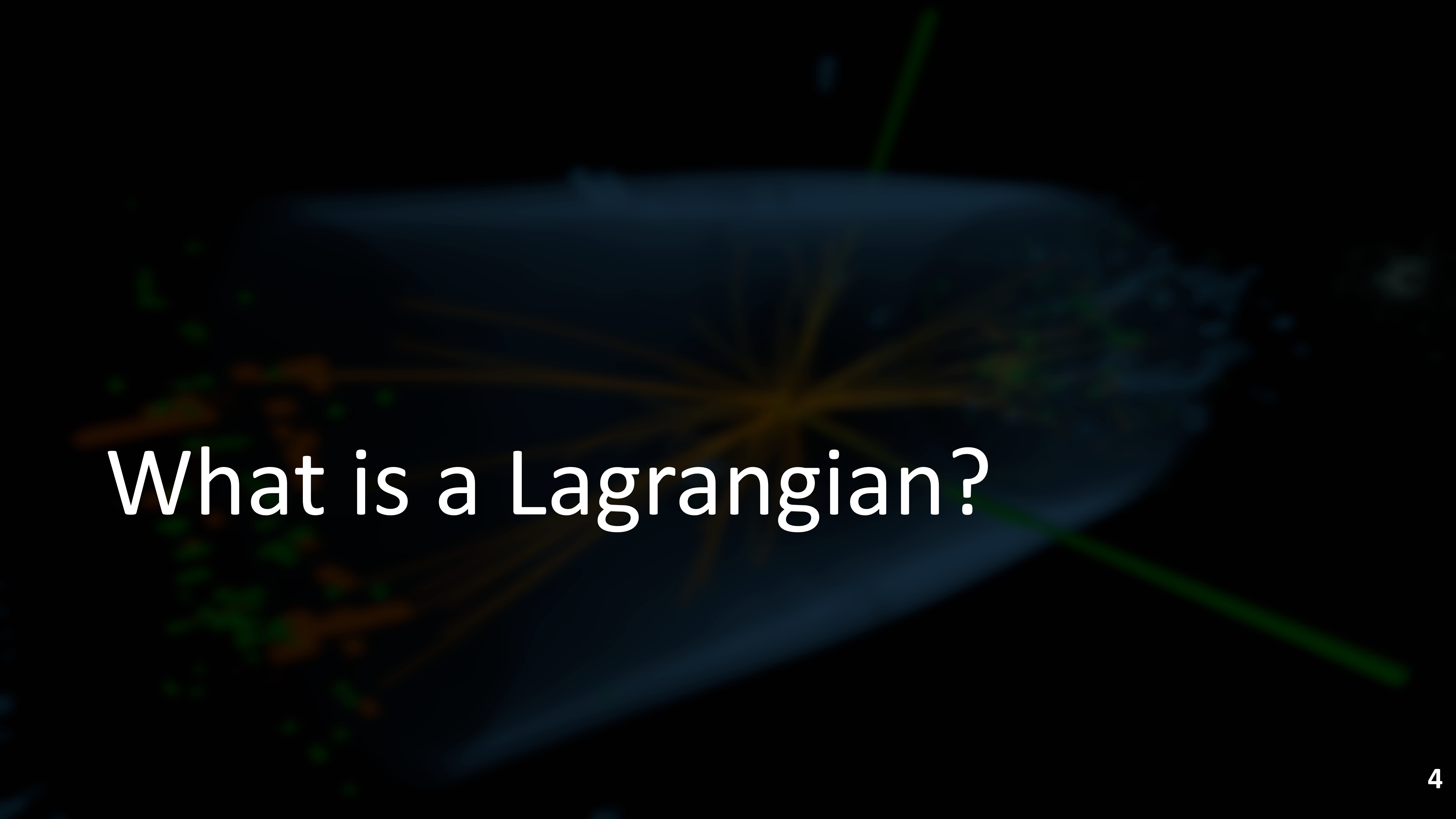
Tuesday, June 6, 2023

Christopher Palmer (UMD)


Photon 2:
P_T=46.3 GeV
Di-photon
resolution:
0.84 GeV
p+
p+
Photon 1:
P_T=90.0 GeV

Outline

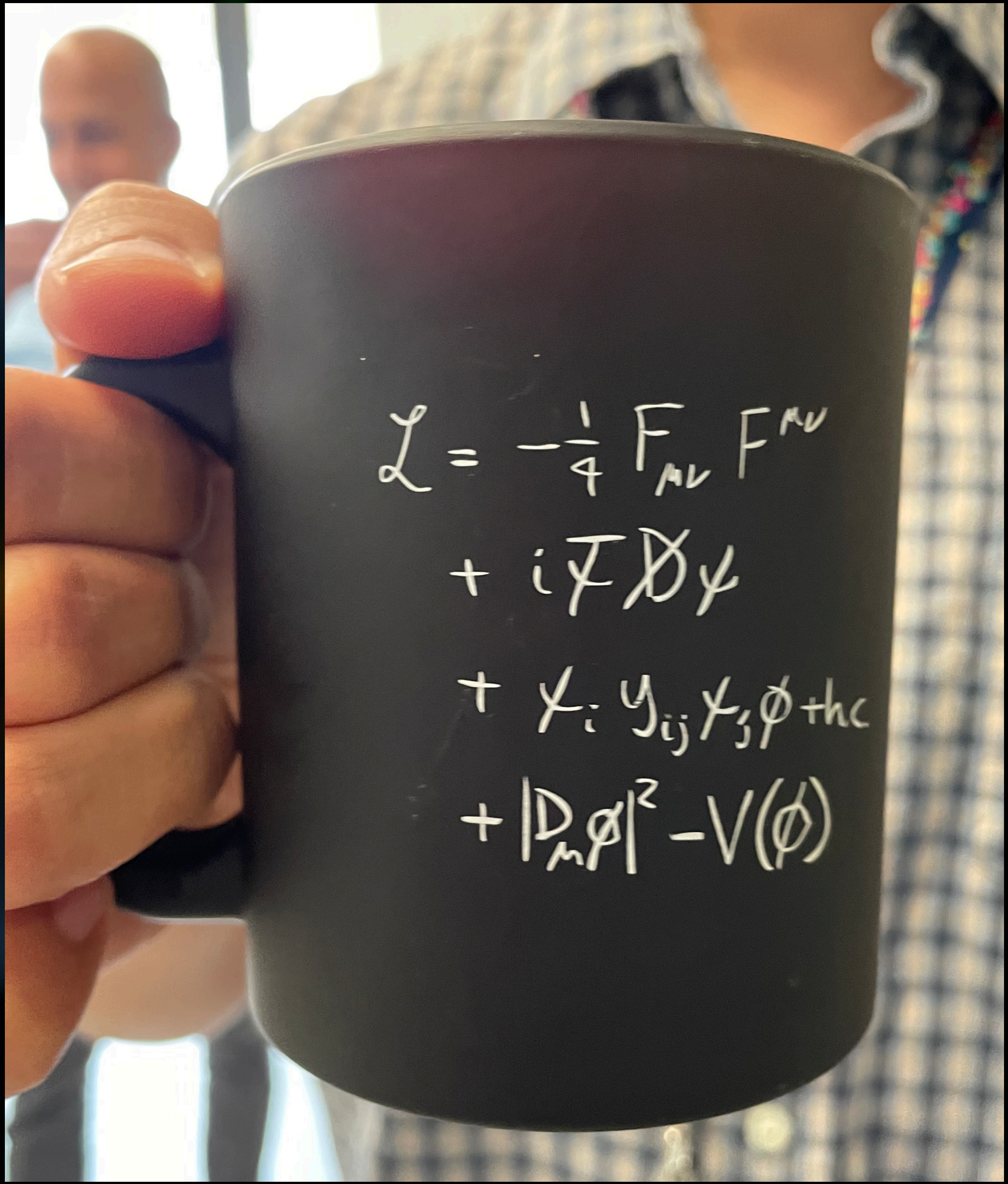
- Why have a Higgs boson?
- LHC accelerator and CMS detector
- How to make a Higgs boson?
- How do Higgs bosons decay?
- Discovery channels
- More observations!



What is a Lagrangian?

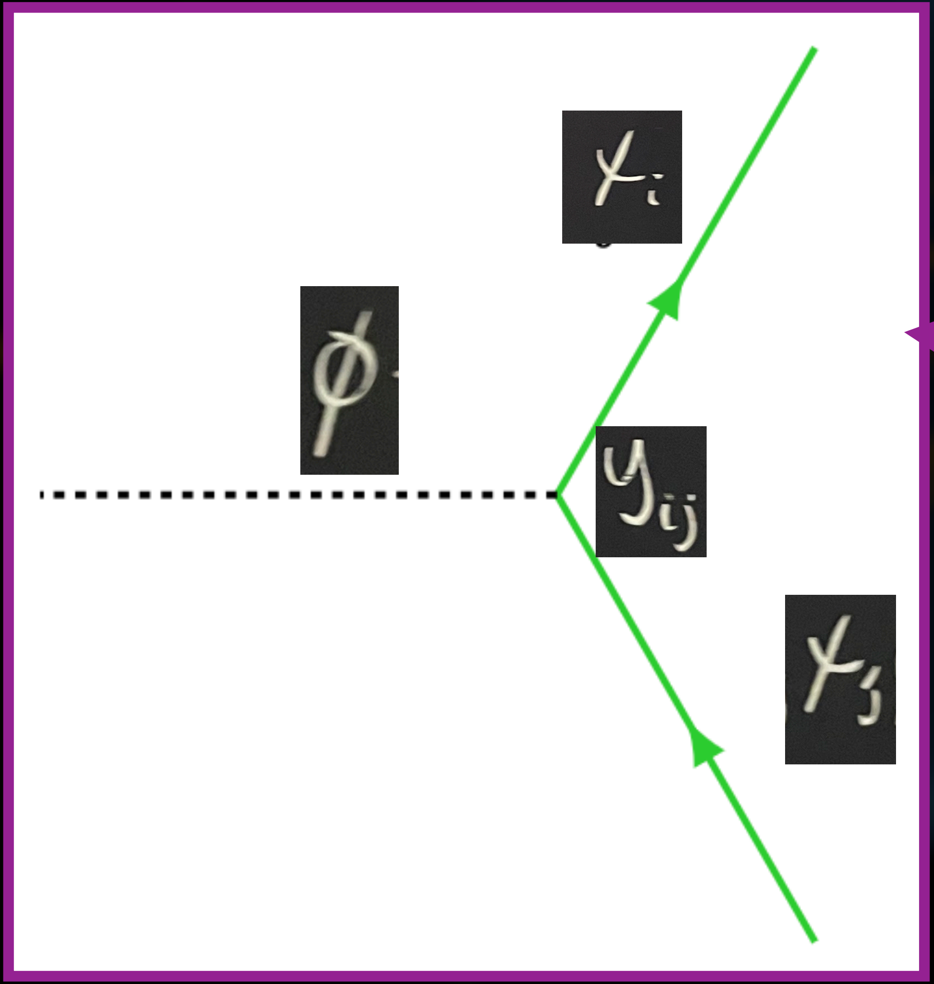
Lagrangians

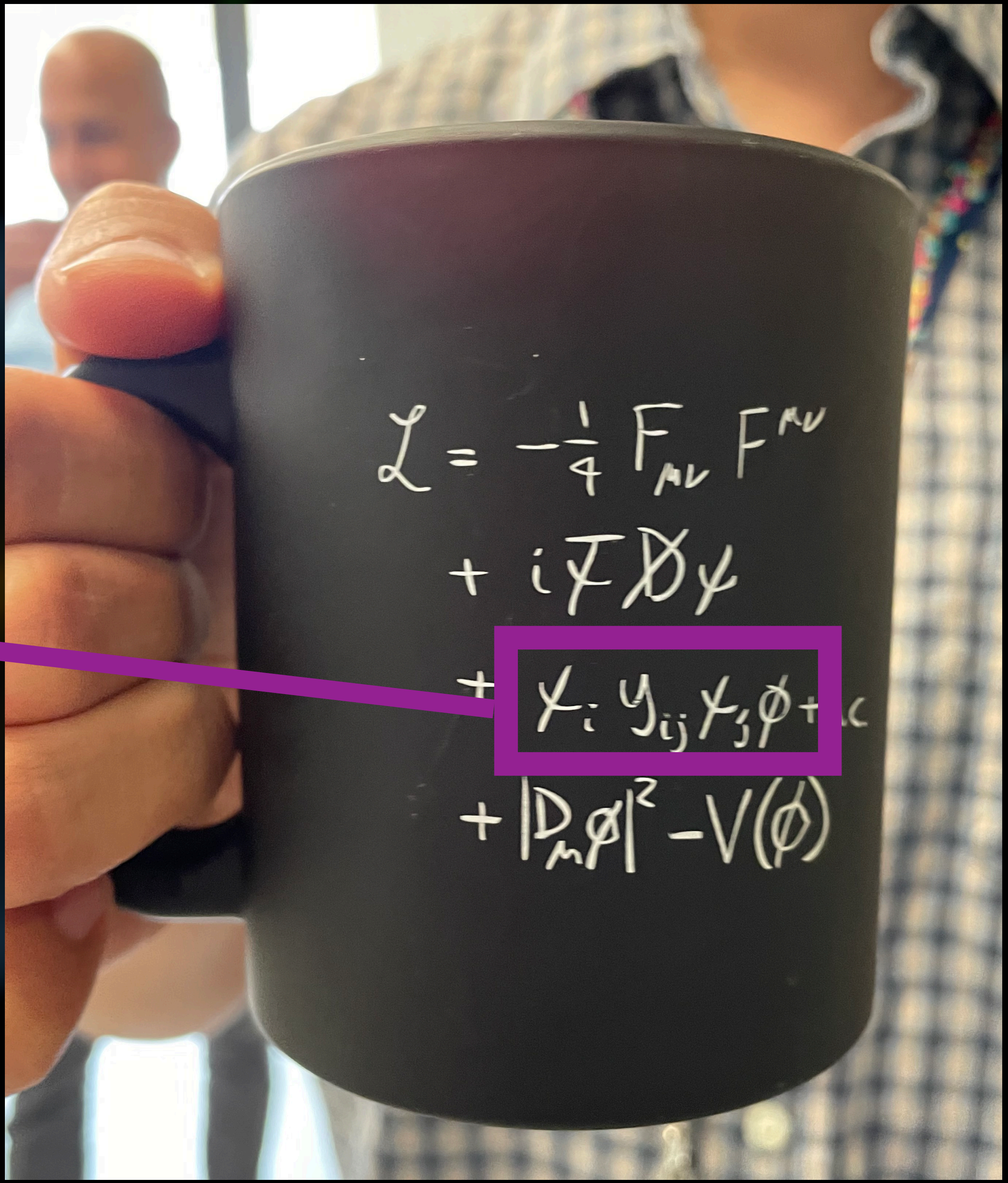
- Formally: they contain all the interactions and particles of a Quantum Field Theory (QFT), and they say what interactions are allowed and at what coupling "strength".
- Informally: they let experimentalists know how to draw pictures.

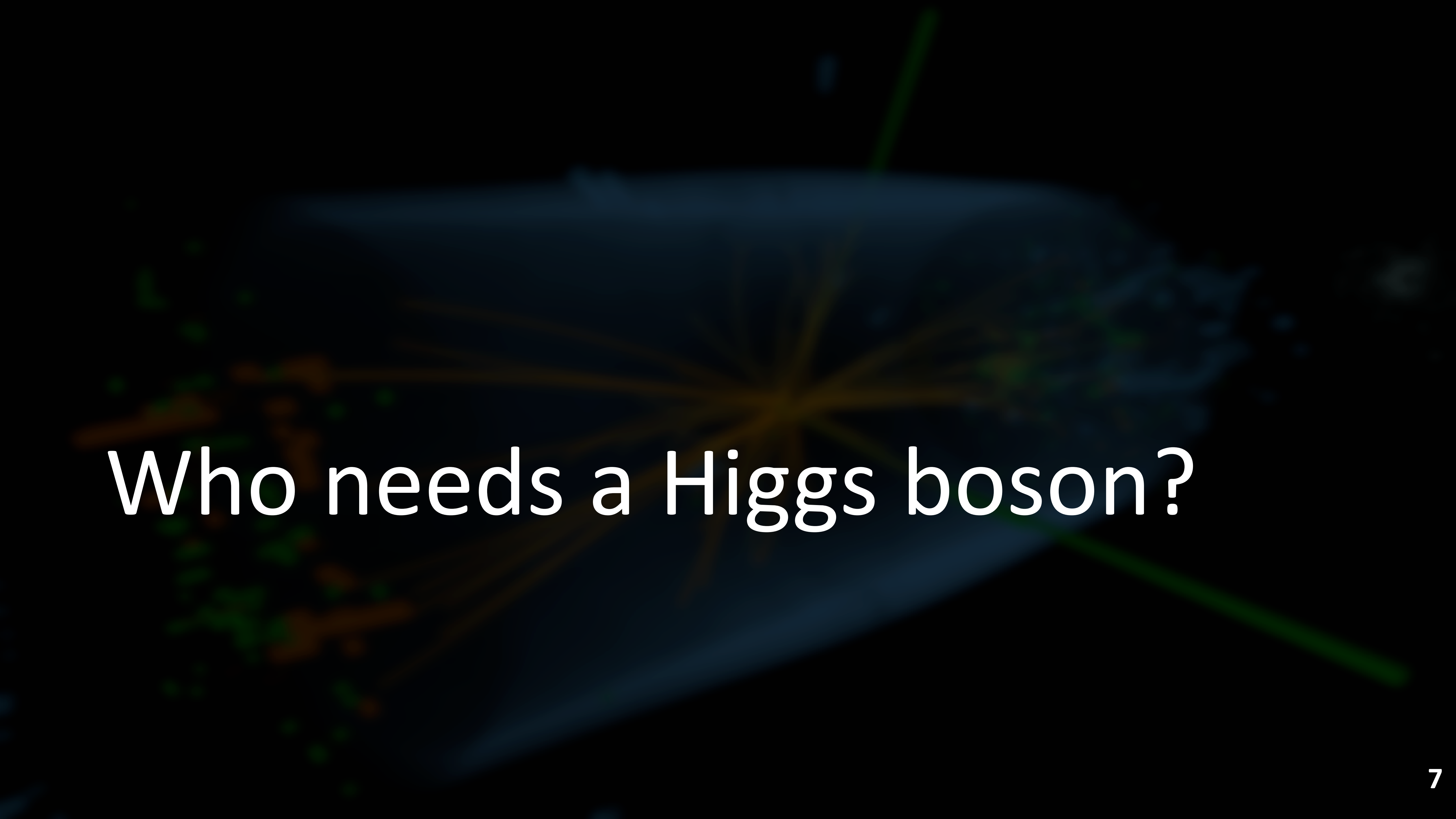


The Higgs field, ϕ

- Turn that into a picture!



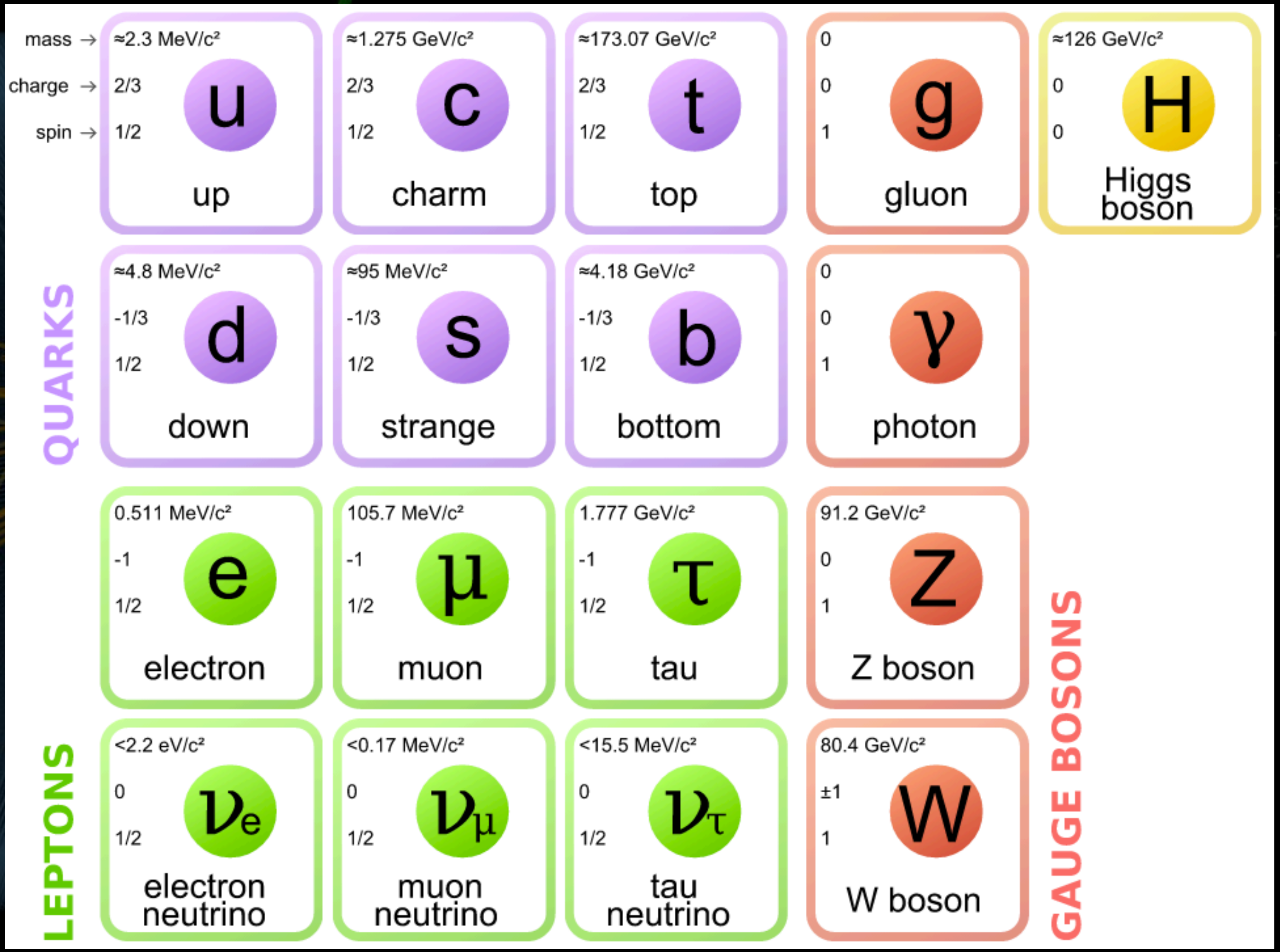




Who needs a Higgs boson?

Standard Model of Particle Physics

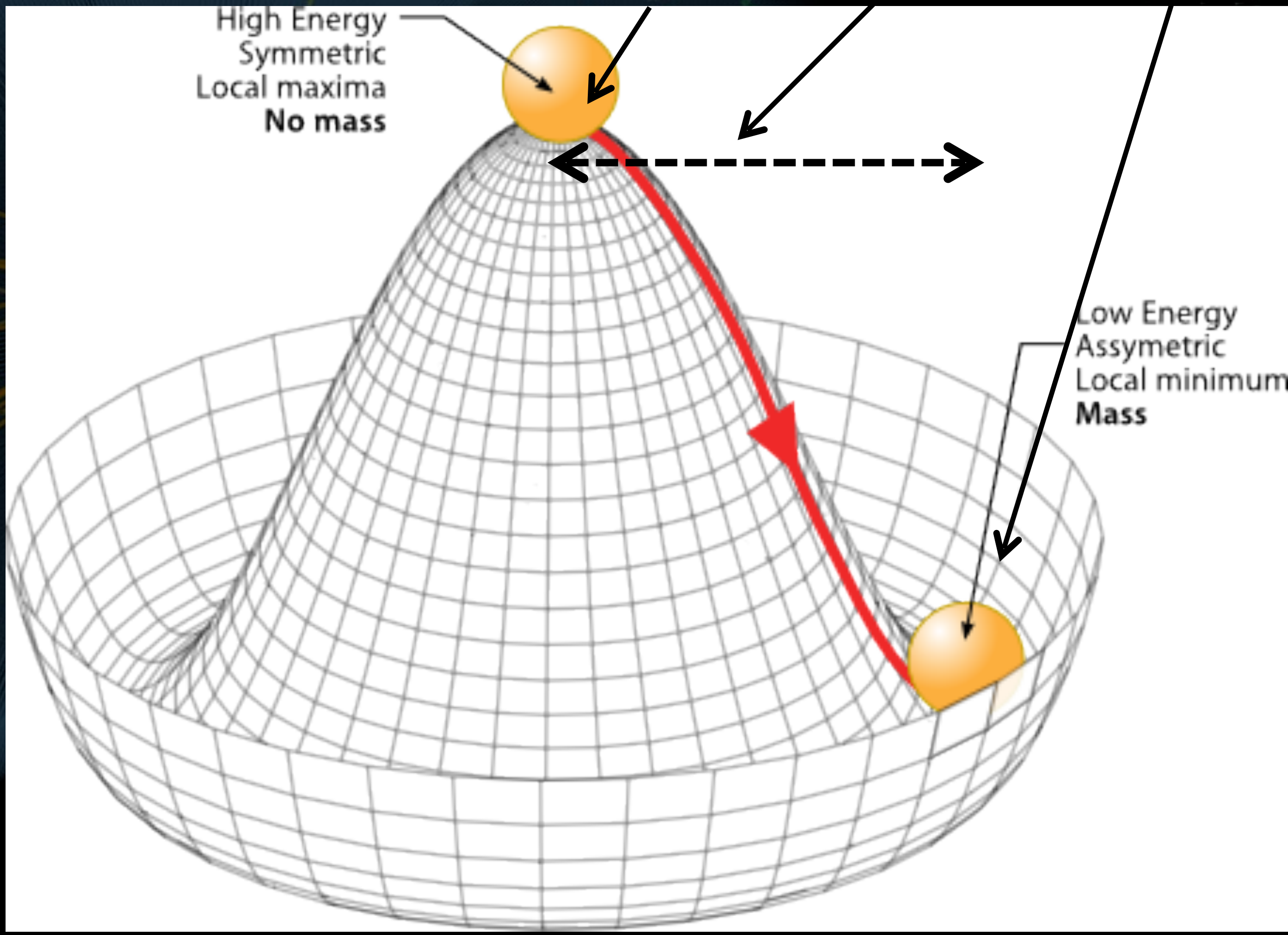
- Generations
  - Fermions organized by increasing mass
- Gauge bosons
  - Mediate forces
- Quarks
  - Glued together by gluons
  - E.g. proton, neutron
- Leptons
  - No strong interaction



Spontaneous Symmetry Breaking

- Falling out of the symmetry and into the minimum of the potential creates the massive Higgs boson, h.
- The minimum is at the vacuum expectation value or vev.

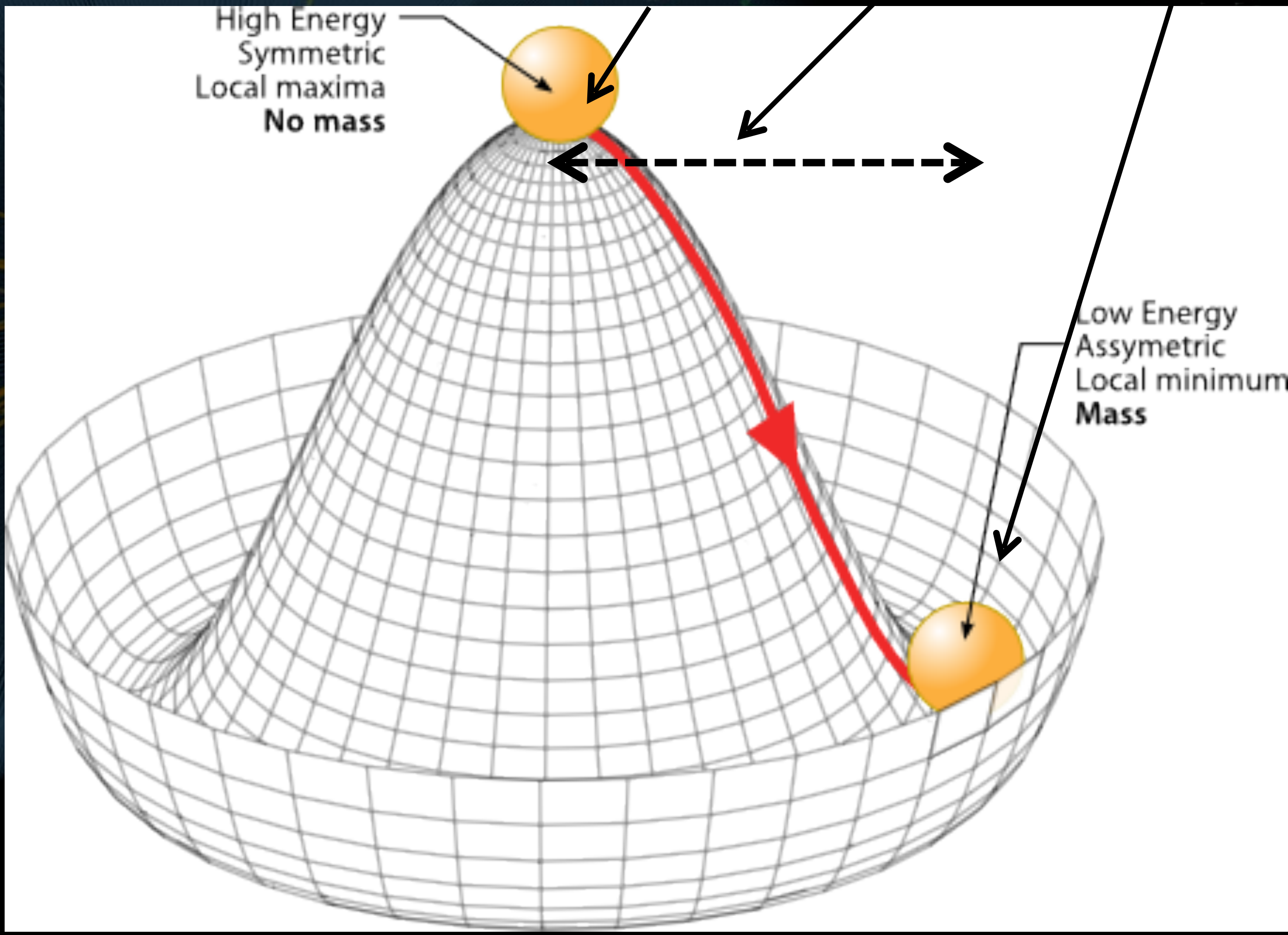
$$\phi(x) \rightarrow vev + h(x)$$



The Brout-Englert-Higgs (BEH) Mechanism

- In the summer of 1964 three papers were submitted for publication tweaking the problem.
- Within a few years (1971) the BEH mechanism was integrated into electroweak theory.

$$\phi(x) \rightarrow vev + h(x)$$

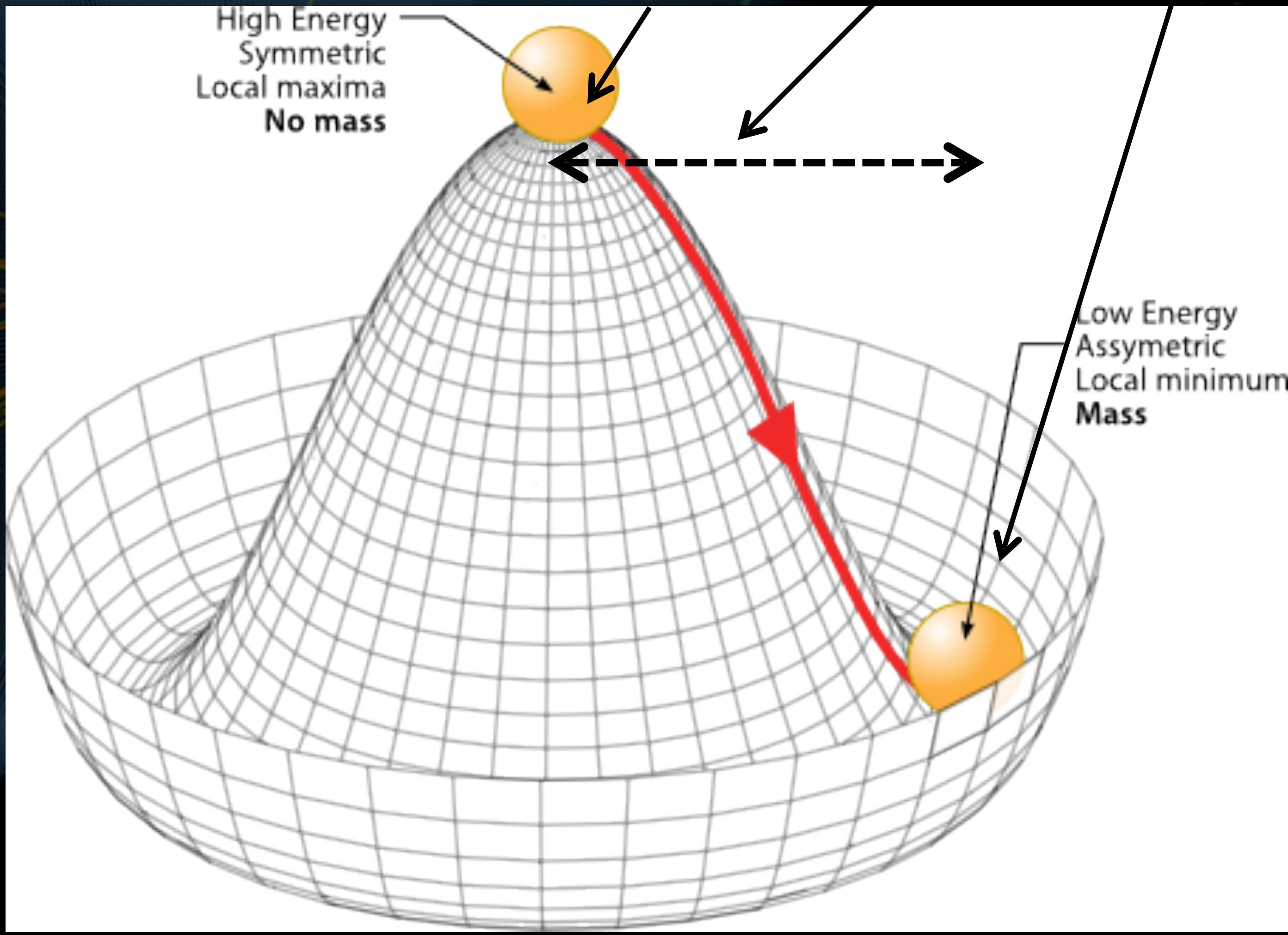


The Brout-Englert-Higgs (BEH) Mechanism

- Punchline: Where there was the Higgs field interacting, there is now a constant plus a Higgs boson.

$$\psi_i y_{ij} \psi_j \phi$$

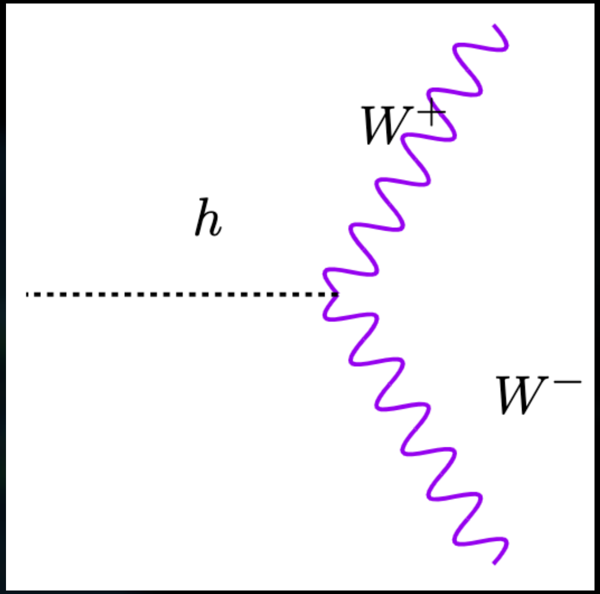
$$\phi(x) \rightarrow vev + h(x)$$

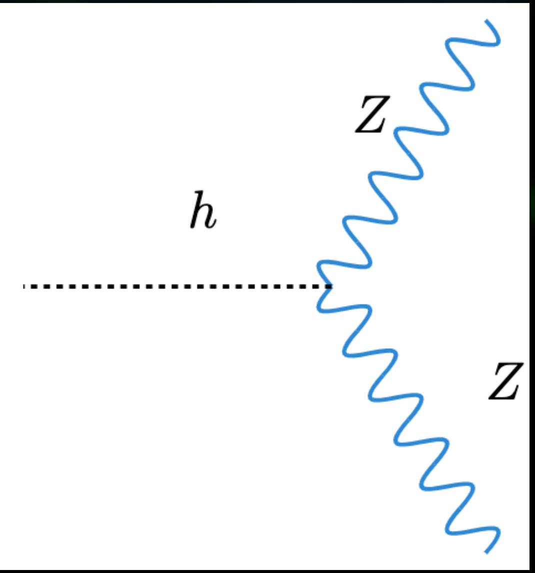


$$\psi_i y_{ij} \psi_j (v + h)$$

SM Predictions (from BEH)

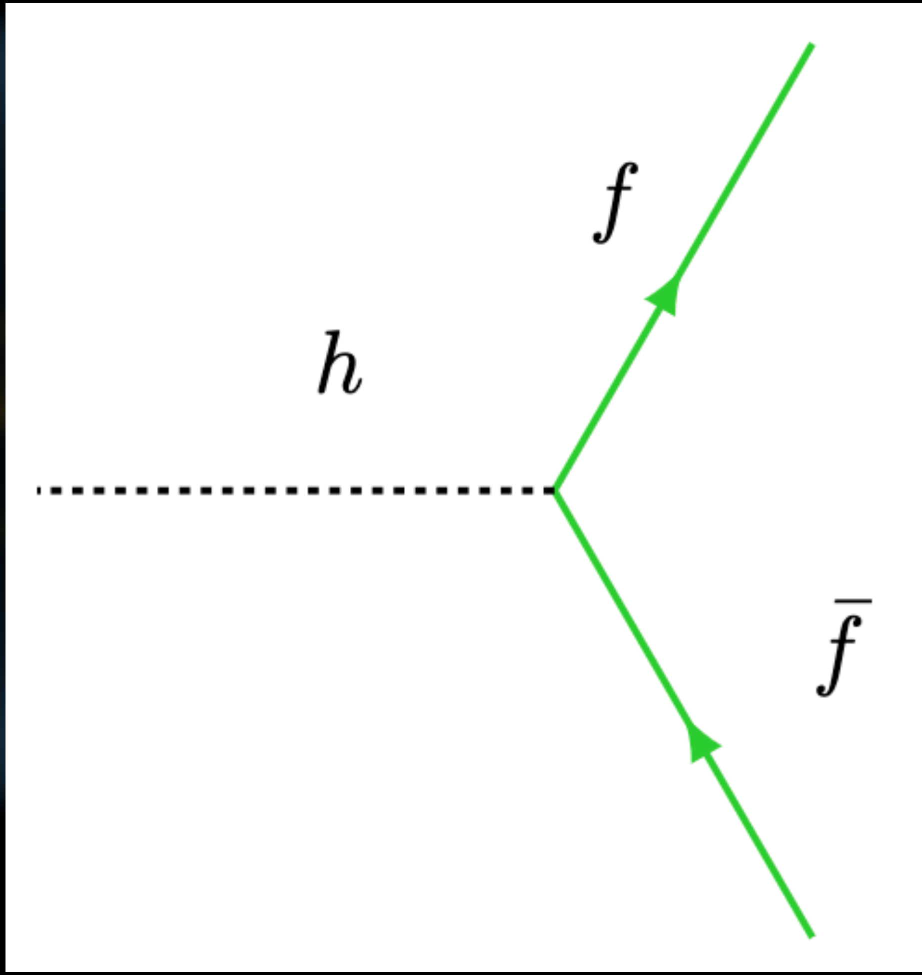
- The existence of three massive weak bosons (2 charged, $W^{\pm}$ & 1 neutral, Z)
- The existence of a massive Higgs boson that interacts with the weak bosons.
    - The mass of the Higgs boson is not predicted.
- The Higgs boson's interactions with weak bosons are foundational elements of the theory, which motivate the entire mechanism.
- The Higgs boson has self-interaction.





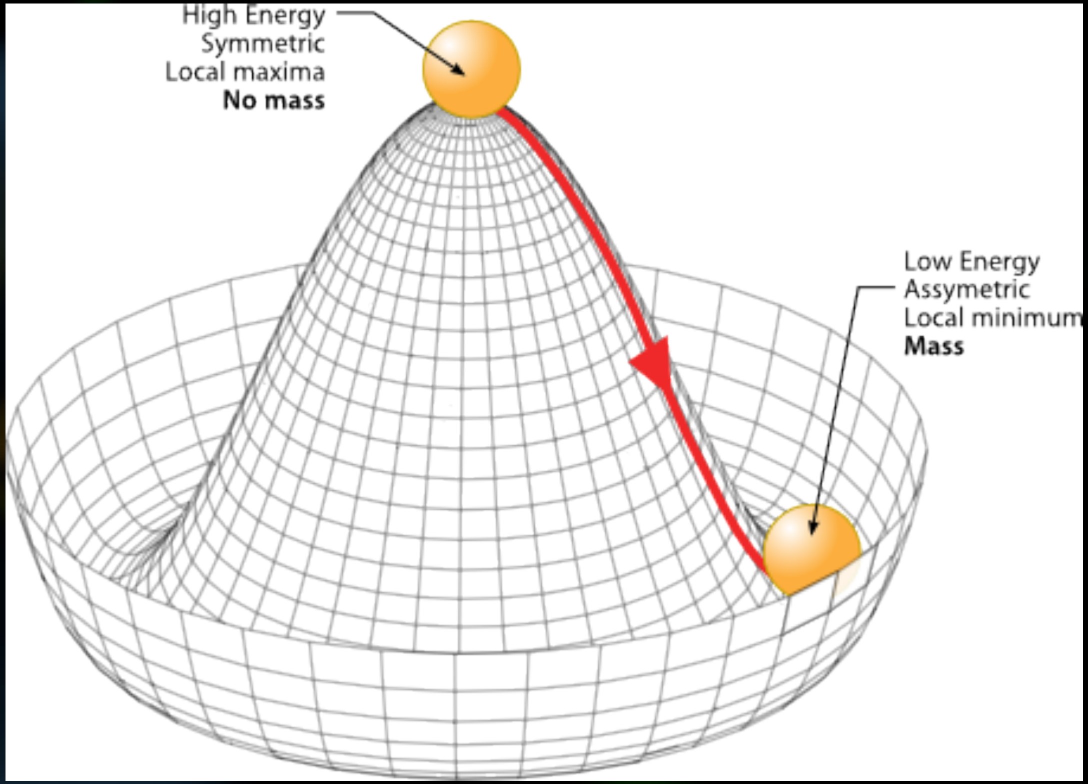
Predictions of the BEH Mechanism

- A SM Higgs boson couples to all massive fermions via Yukawa coupling.
  - After the symmetry is hidden (or broken) the Higgs field can give mass to fermions as well.
  - The Higgs boson coupling to fermions is proportional to mass.
  - Heavier particles interact with the Higgs boson with larger coupling.



The Higgs Potential, $V(\phi)$

- The Higgs field must obey the Higgs potential.



- $\phi = \begin{pmatrix} \phi_0 \\ 0 \end{pmatrix}$

$$V_{SM}(\phi) = -\frac{\mu^2}{2}\phi_0^2 + \frac{\lambda}{4}\phi_0^4$$

- $\phi_0(x) \rightarrow v + h(x)$

The Higgs Potential, $V(\phi)$

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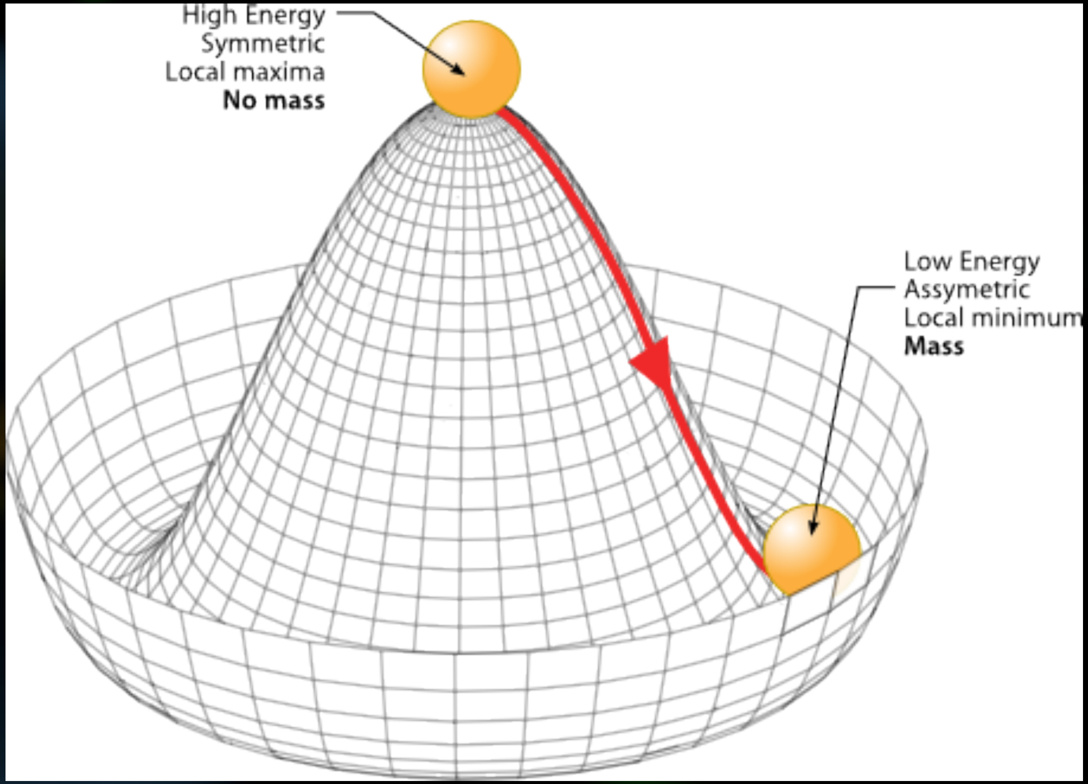


$$V_{SM}(h) = -\frac{\mu^2}{2}(v+h)^2 + \frac{\lambda}{4}(v+h)^4$$

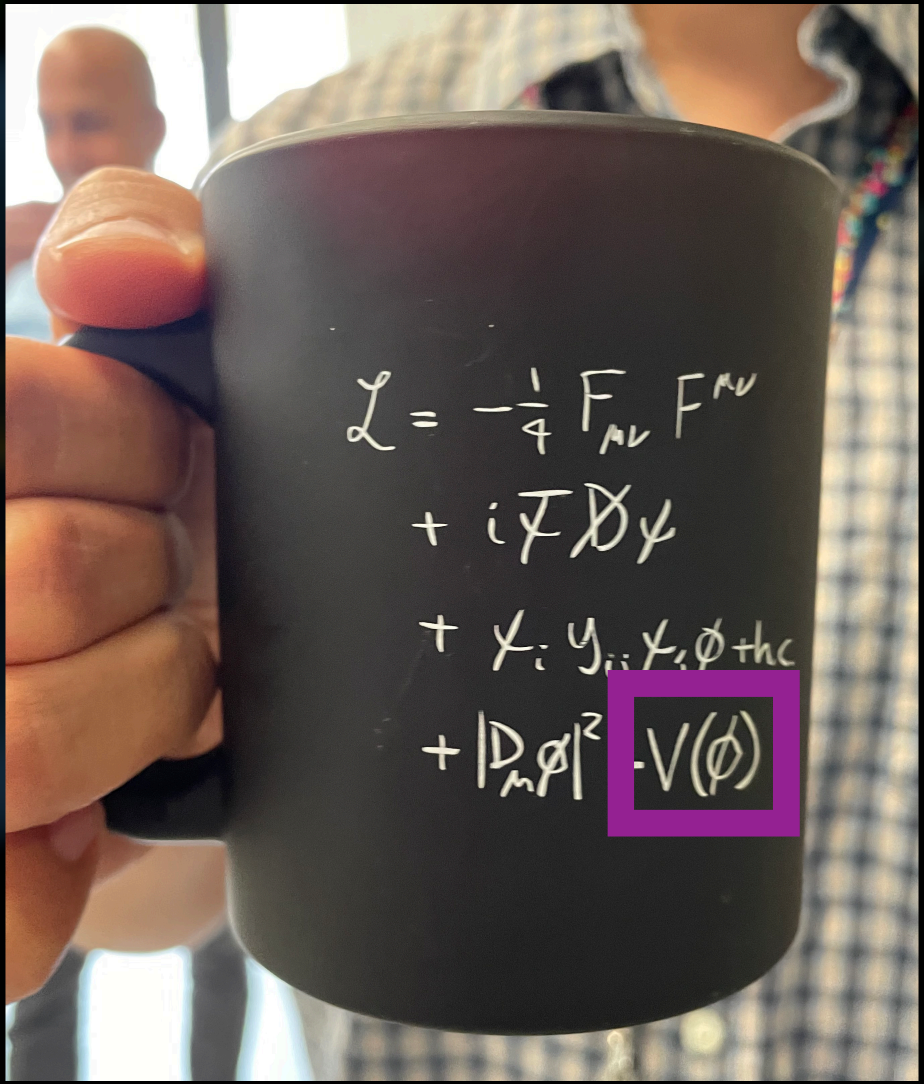
The Higgs Potential, $V(\phi)$

- The Higgs field must obey the Higgs potential.

$$V_{SM}(\phi) = -\frac{\mu^2}{2}\phi_0^2 + \frac{\lambda}{4}\phi_0^4$$

- $\phi_0(x) \rightarrow v + h(x)$

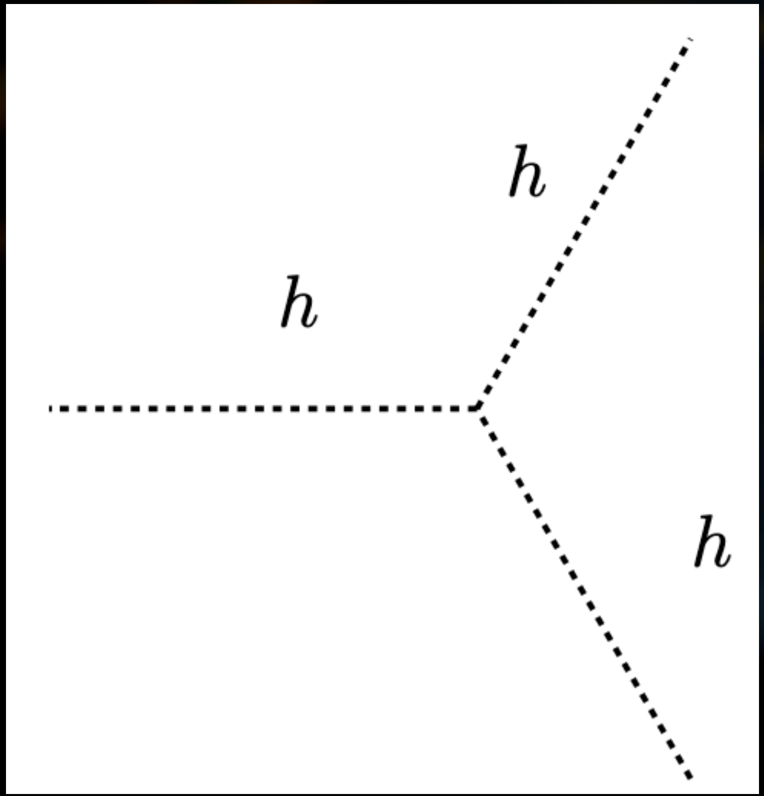
$$V_{SM}(h) = \ldots + \lambda v h^3 + \frac{\lambda}{4}h^4$$

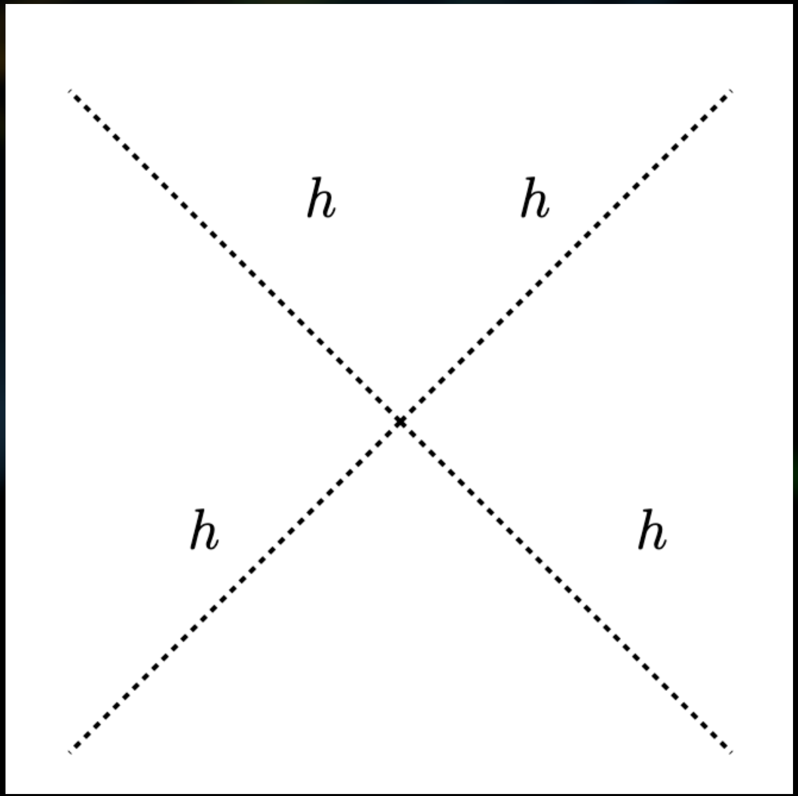


The Higgs Potential, $V\left(\phi\right)$

- These terms correspond to "self-coupling" interactions.

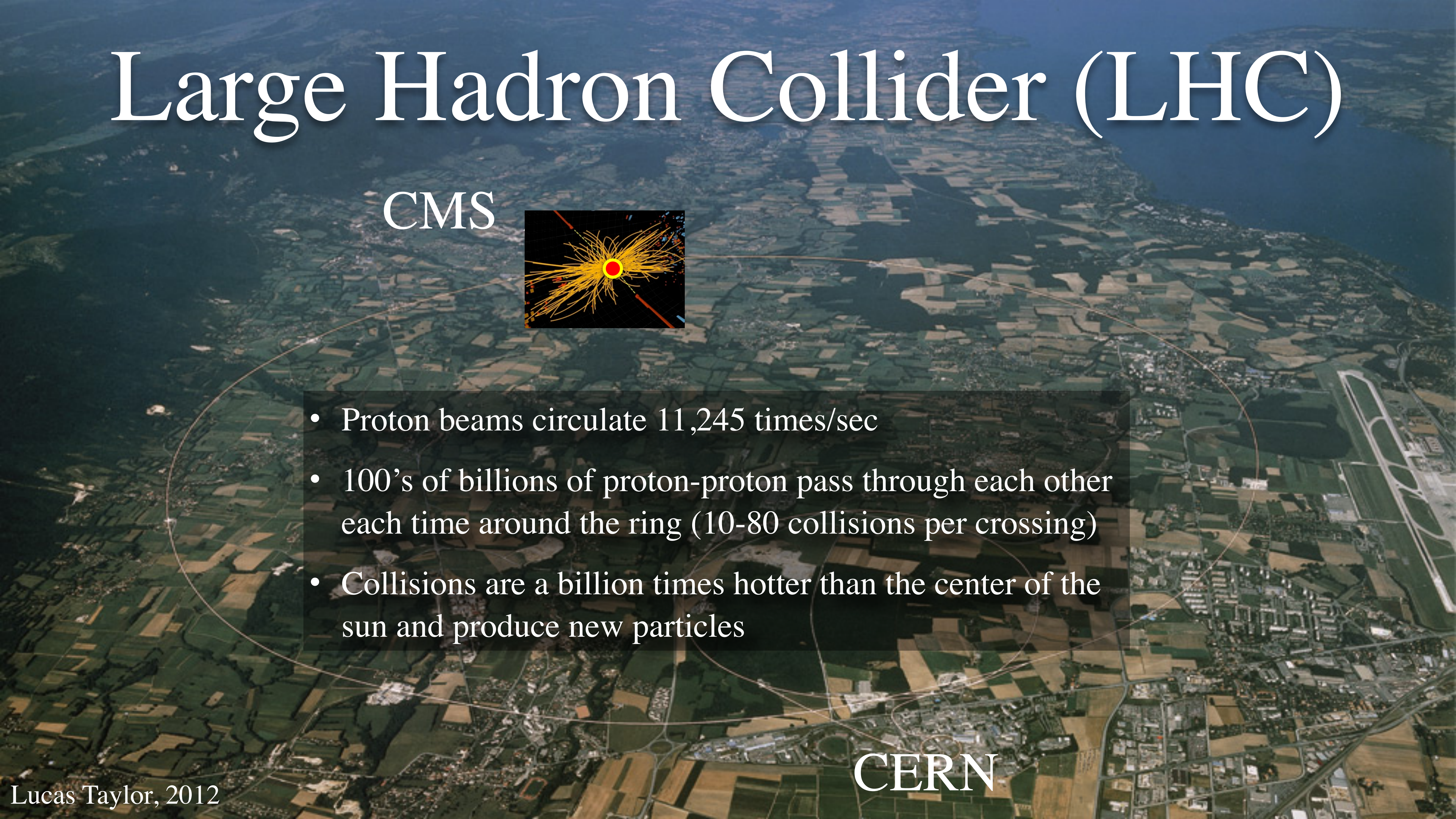
$$V_{SM}\left(h\right) = \ldots + \lambda v h^3 + \frac{\lambda}{4} h^4$$





LHC and CMS

Large Hadron Collider (LHC)

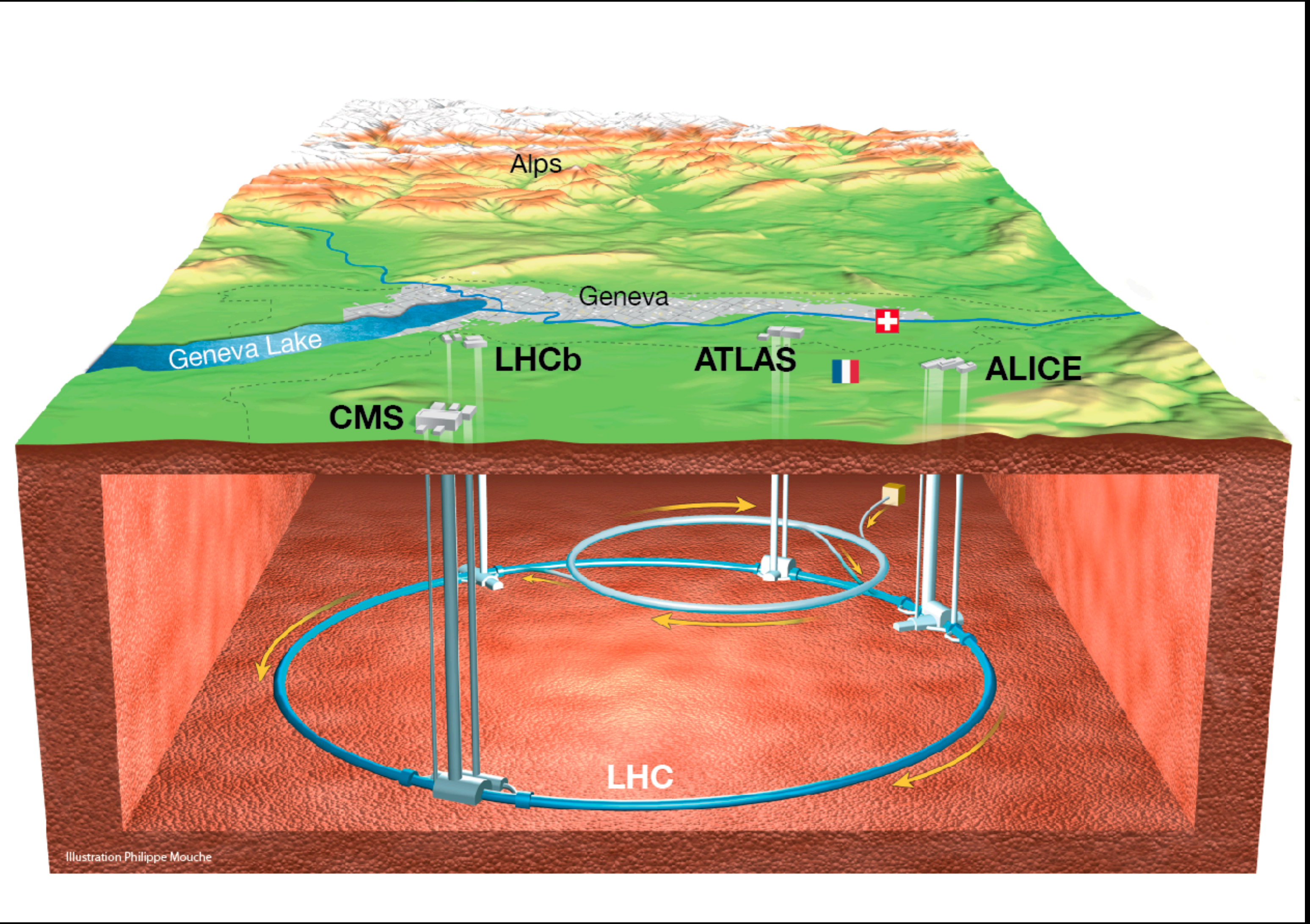


- Proton beams circulate 11,245 times/sec
- 100's of billions of proton-proton pass through each other each time around the ring (10-80 collisions per crossing)
- Collisions are a billion times hotter than the center of the sun and produce new particles

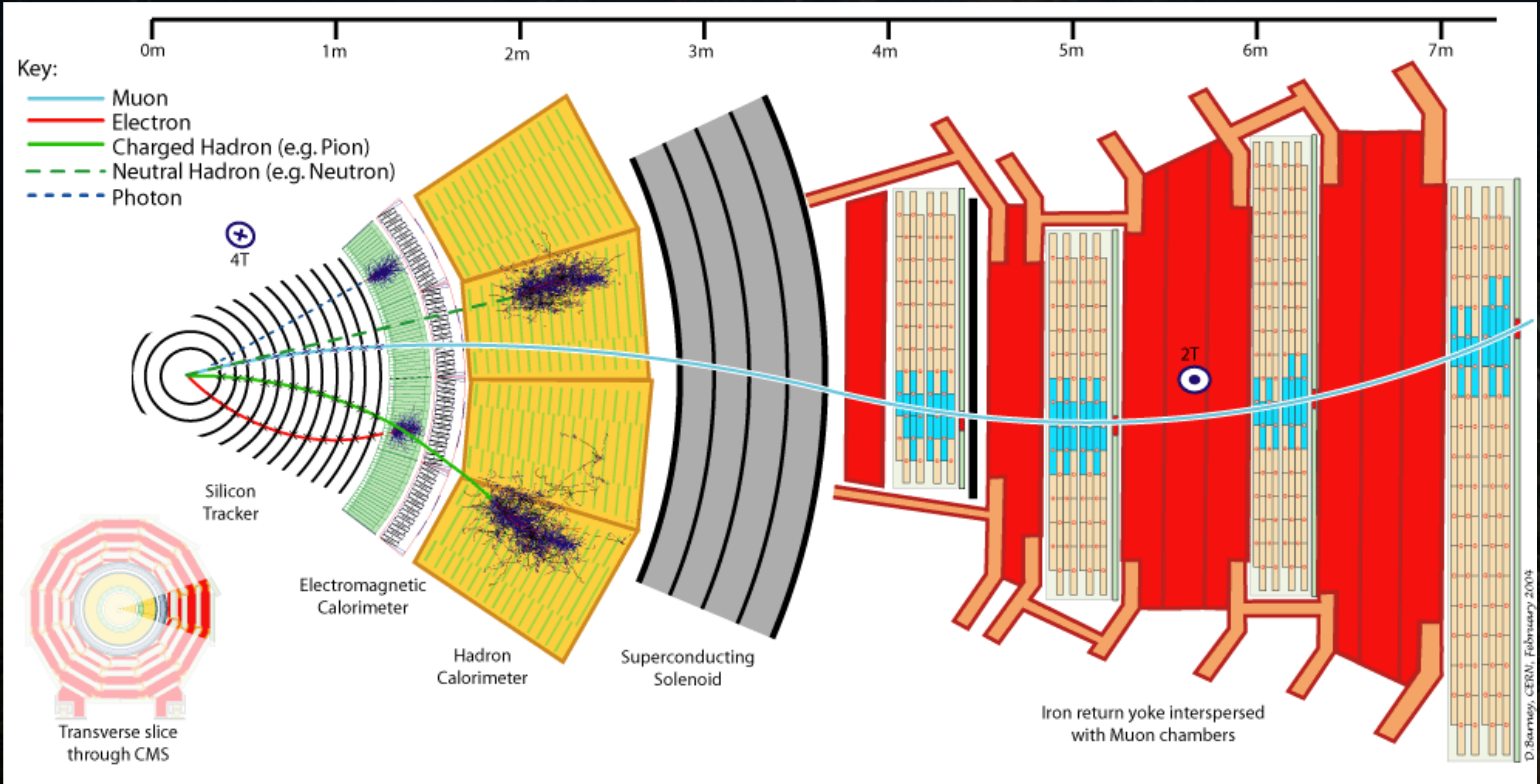
Lucas Taylor, 2012

Large Hadron Collider (LHC)

- 27 km in circumference
  - Experiments 50-175 meters underground
- Accelerates two proton (or lead ion) beams
  - In bunches of ~10^{11}
  - To 3.5 TeV in 2011
  - To 4 TeV in 2012
  - To 6.5 TeV in 2015-2018
- CMS and ATLAS are general purpose detectors
- ALICE and LHCb are specialized for heavy ion and b-physics.

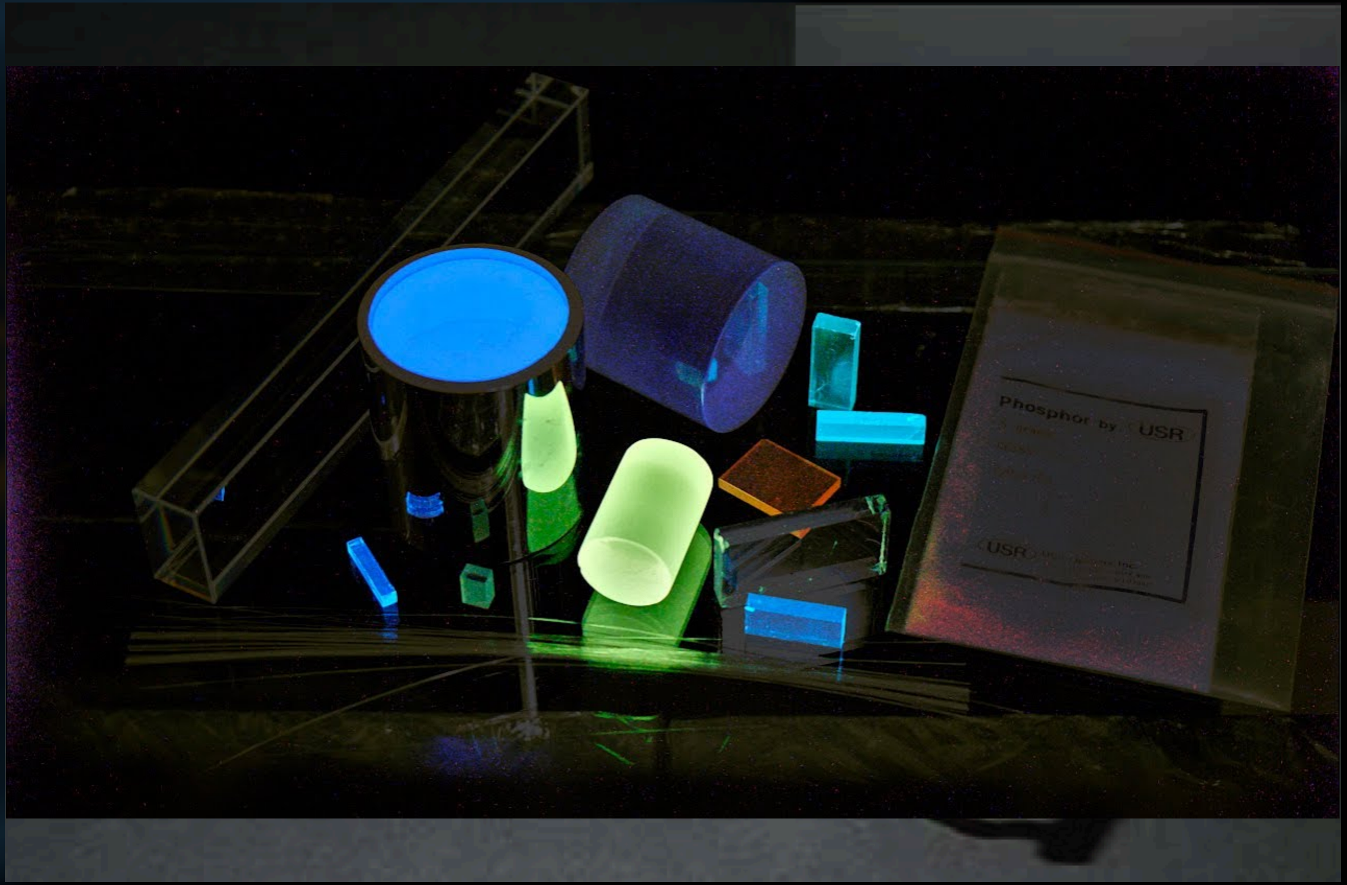


Particle Detection in CMS



Electromagnetic Calorimeter (ECAL)

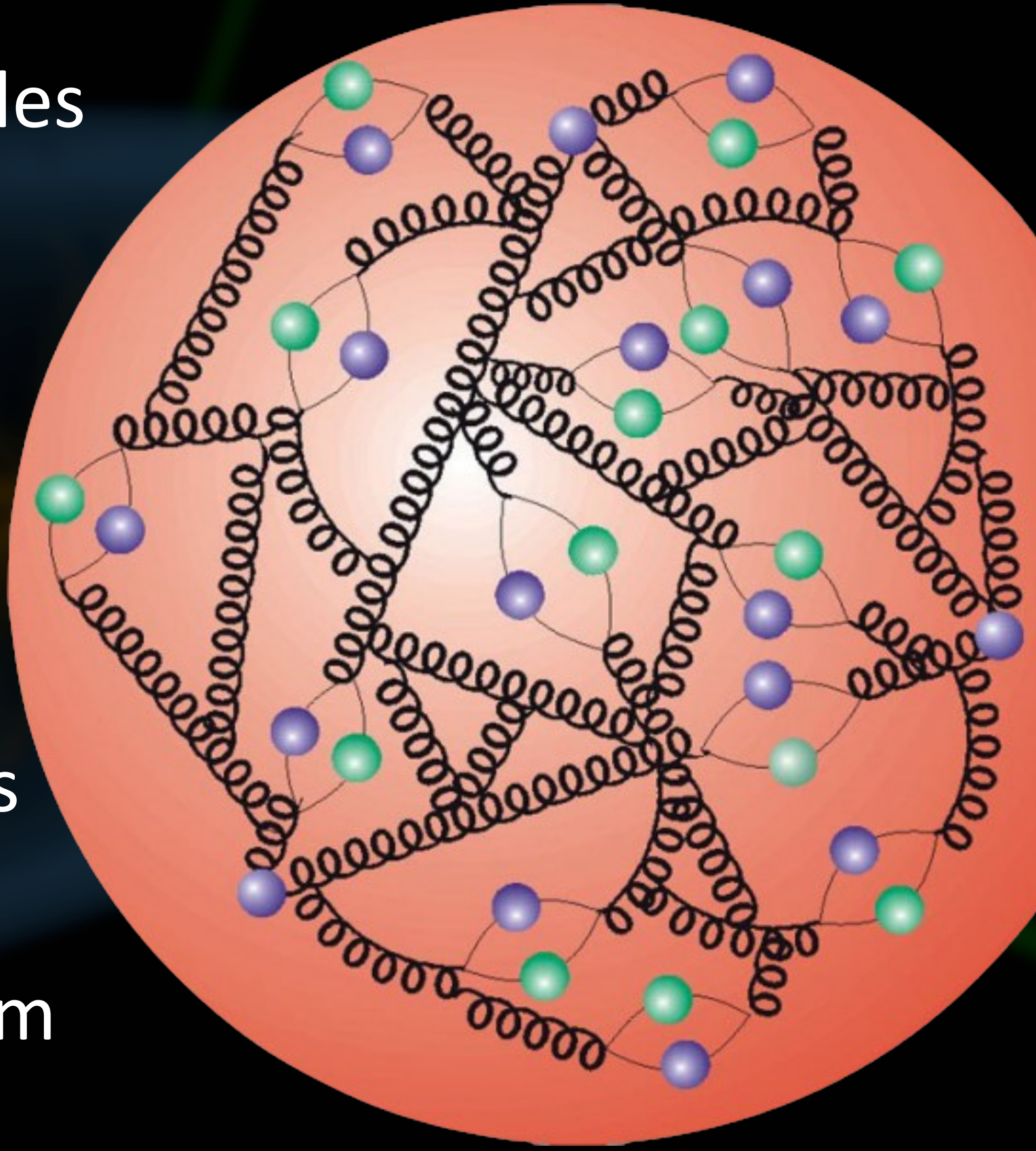
- Nearly all the energy of electrons and photons is deposited in the ECAL.
- Made of ~76,000 lead-tungstate crystals.
- The crystals induce electromagnetic showers and emit blue light after showering. That light is collected from the back side.
- The amount of light collected is converted to energy estimates.
- 23 cm long in the barrel
- ~26 radiation lengths



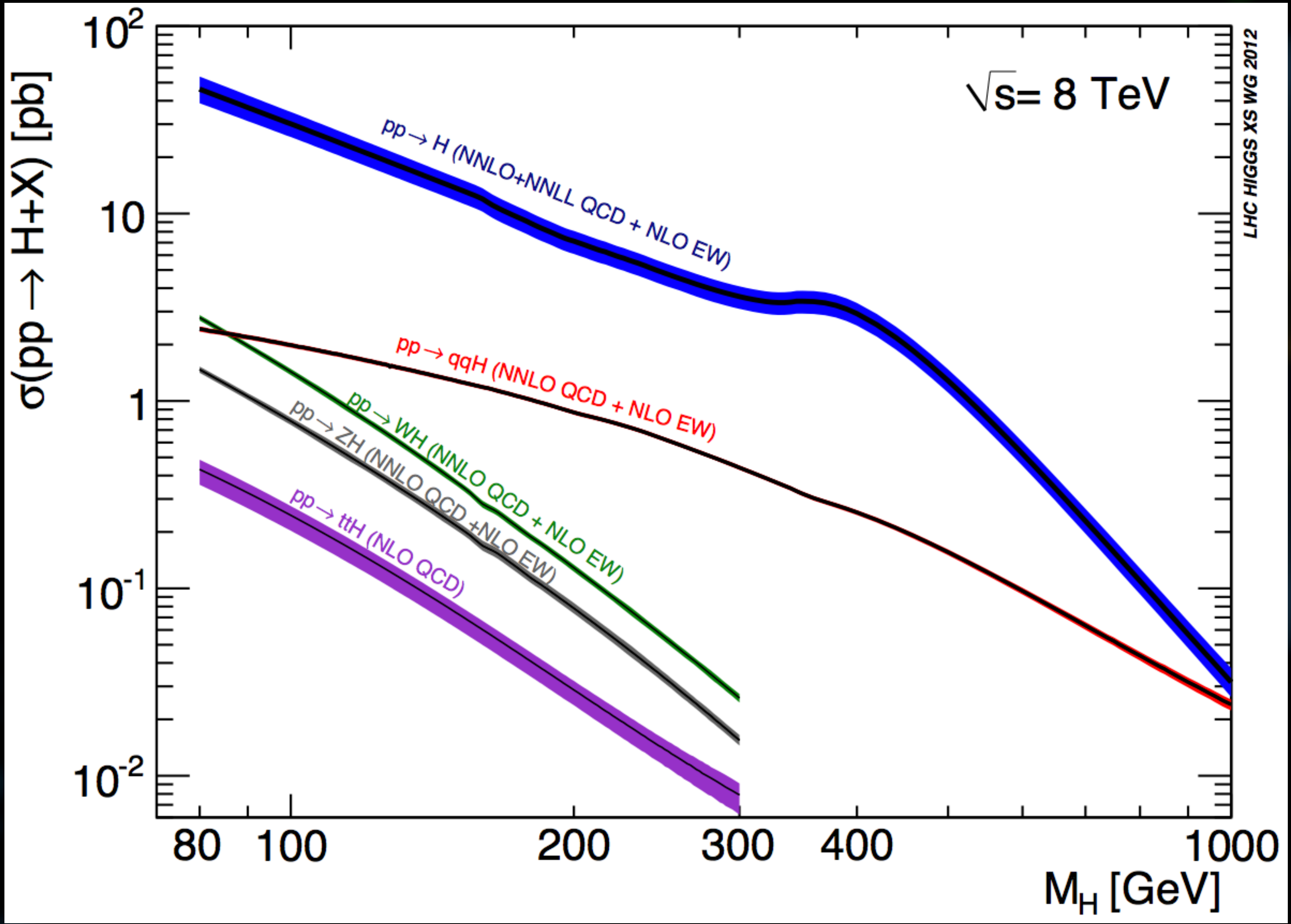
The Life and Death of a Higgs boson at LHC

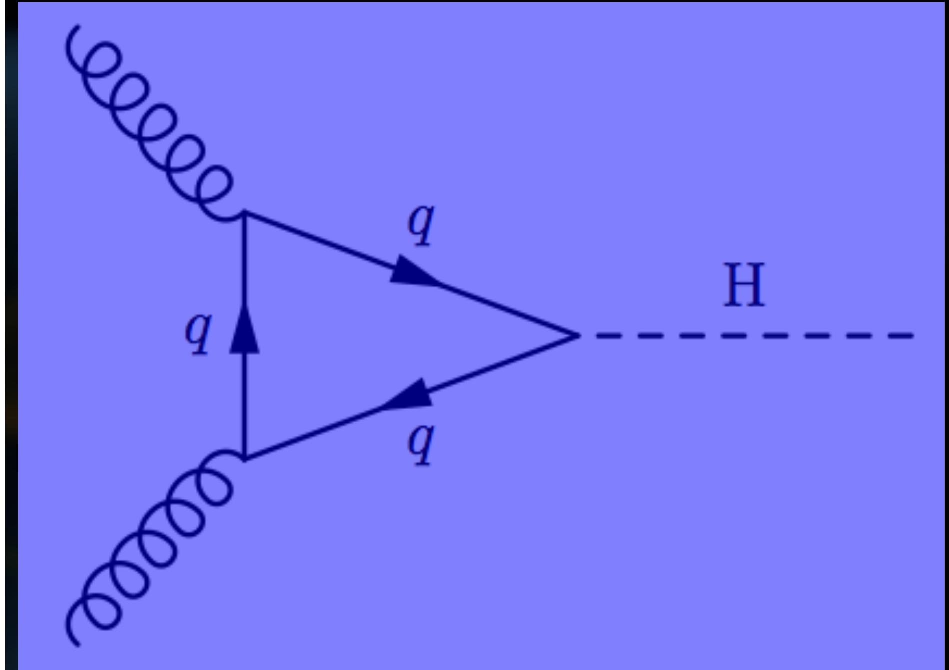
The Inside of a Proton

- Protons are not fundamental particles
- Made up of three “valence” quarks
  - Two up and one down
  - Electric charge is +1
  - One of each color
- Gluons
  - Bind hadrons in “colorless” states
- “Sea” quarks
  - Created continuously in pairs from gluons

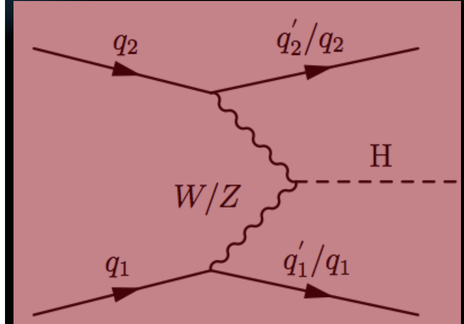


SM Higgs Production at LHC

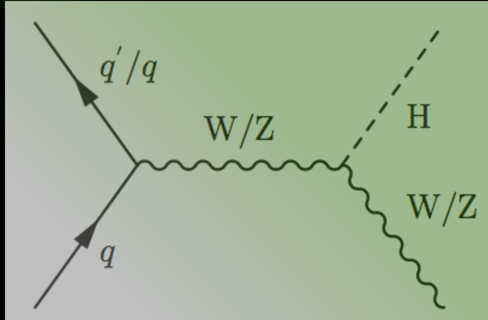




(a) Gluon Fusion



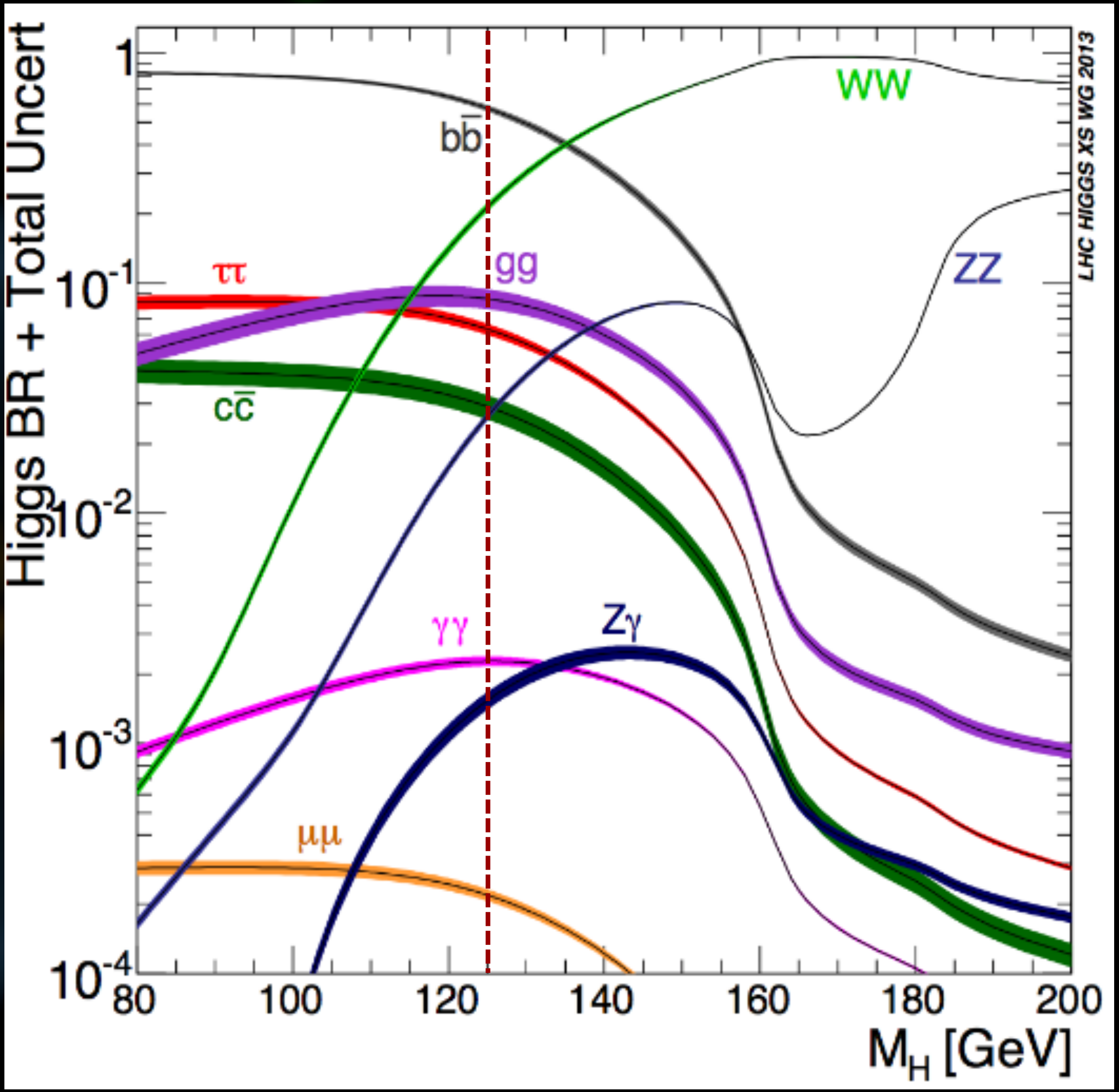
(b) Vector Boson Fusion



(c) Higgsstrahlung

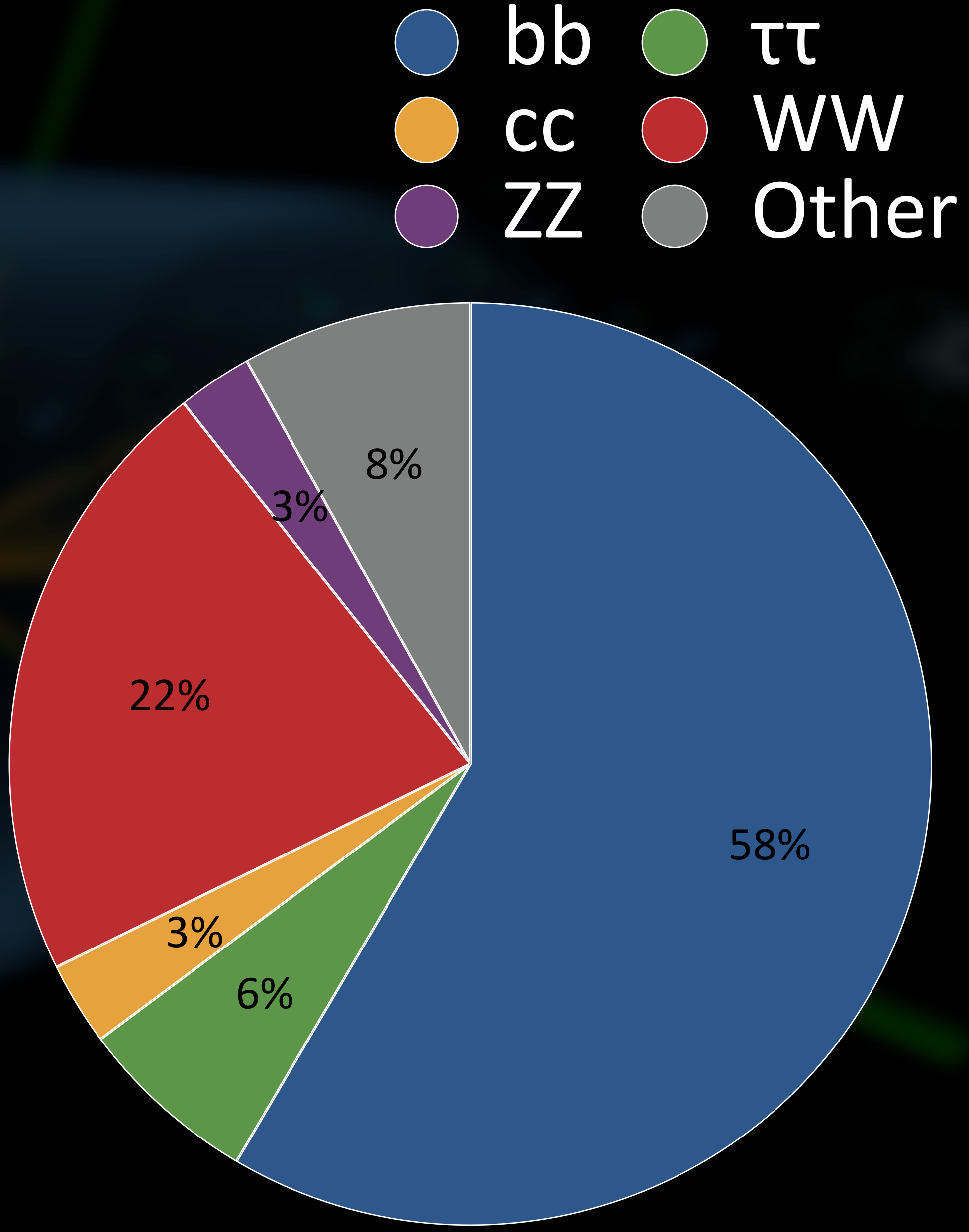
SM Higgs Decay

- Before the observation of the Higgs boson, we didn't know the mass.
- A particle (X) that decays to two identical particles needs enough mass (Y+Y), $2m_Y < m_X$.



SM Higgs Decay

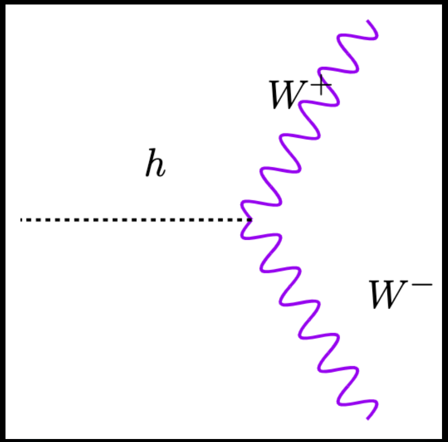
- A particle (X) that decays to two identical particles (Y+Y) needs enough mass, $2m_Y < m_X$.
- No decays to top quarks.
- Largest channels not always the keys to observation.

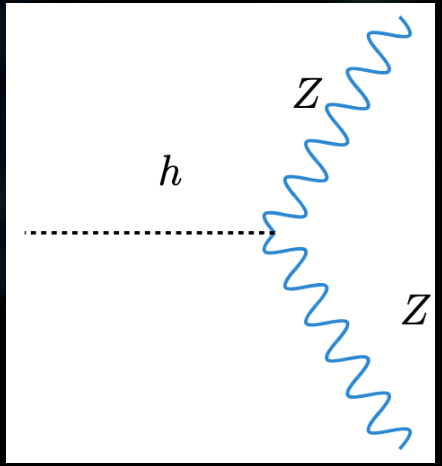


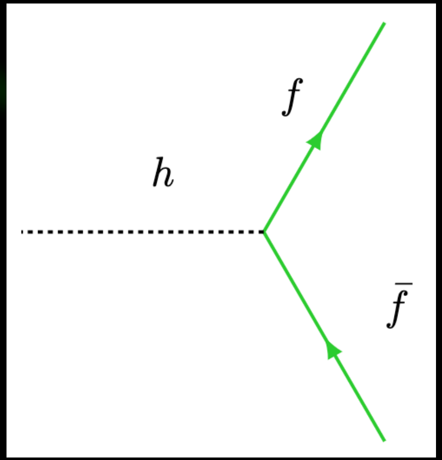
Higgs decays to two photons

Decay to two photons?

- The Higgs boson does not couple directly to photons.

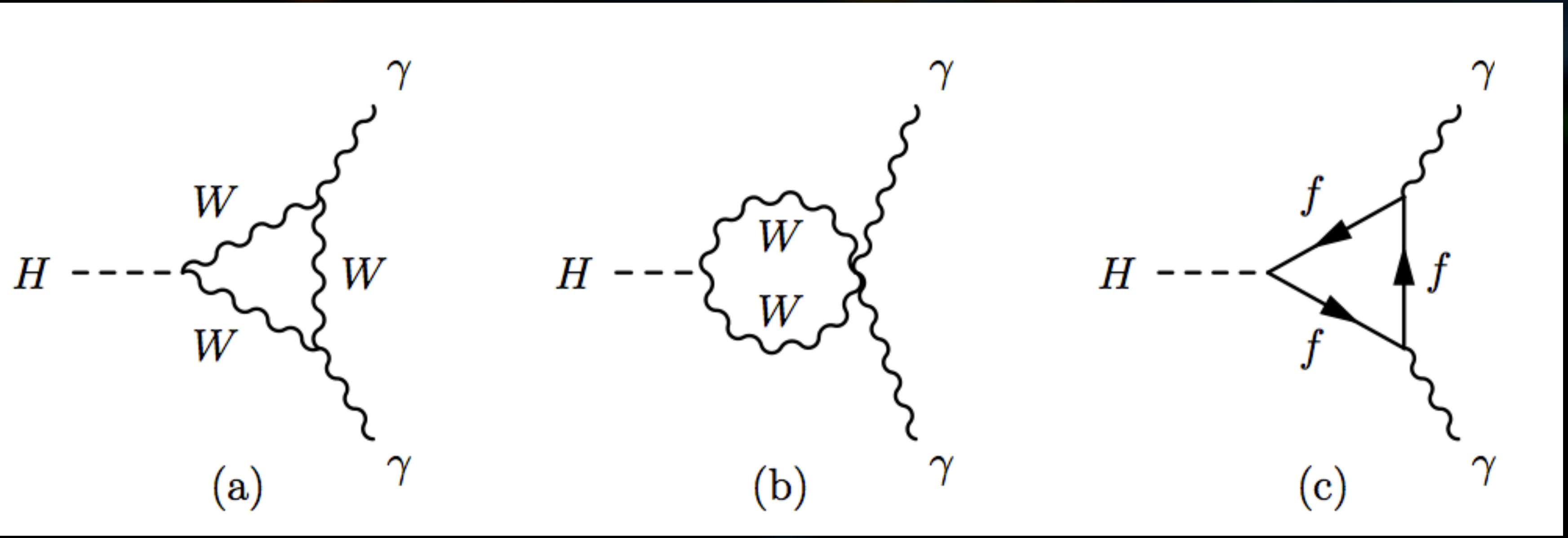


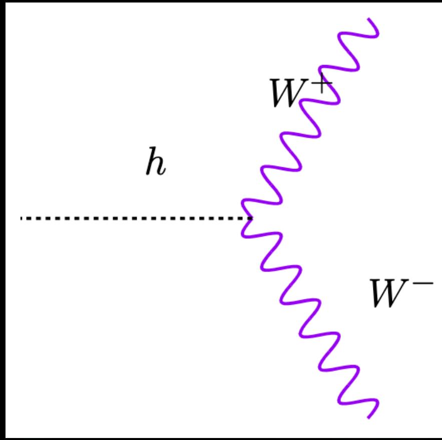


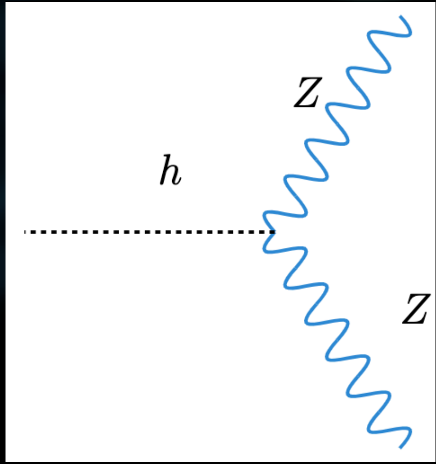


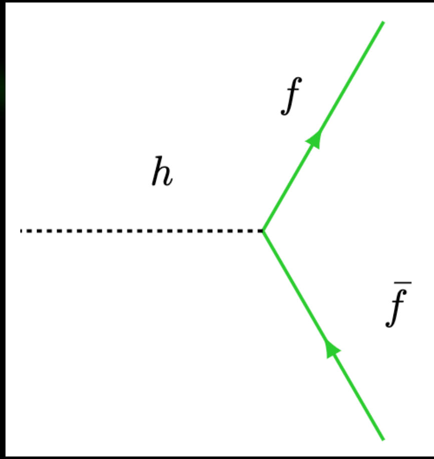
Decay to two photons?

- The Higgs boson does not couple directly to photons.
- The final state can be two photons with an intermediate charged loop. (BR~0.2%)









Higgs to Two Photons Invariant Mass

- This is a very important result of special relativity.
  - Otherwise… it keeps the speed of particles less than c.
- Can you use it to compute the diphoton invariant mass?

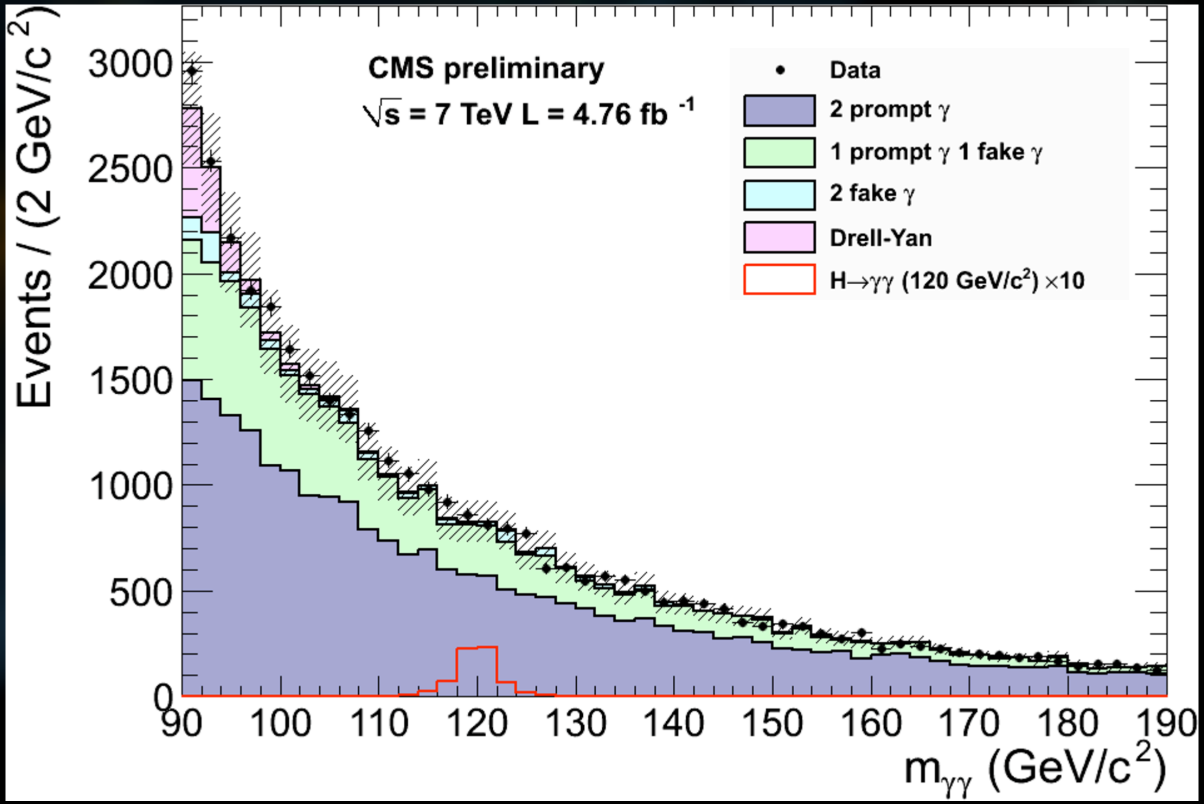
$$m^2 = E^2 - \overrightarrow{p} \cdot \overrightarrow{p}$$

$$\begin{aligned} m_{\gamma\gamma}^2 &= E_{\gamma\gamma}^2 - \overrightarrow{p}_{\gamma\gamma} \cdot \overrightarrow{p}_{\gamma\gamma} \\ &= E_1^2 + E_2^2 + 2E_1E_2 \\ &\quad - \left(E_1^2 + E_2^2 + 2E_1E_2\hat{p}_1 \cdot \hat{p}_2\right) \\ &= 2E_1E_2\left(1 - \cos\theta_{12}\right) \end{aligned}$$

Higgs to Two Photons Analysis Strategy

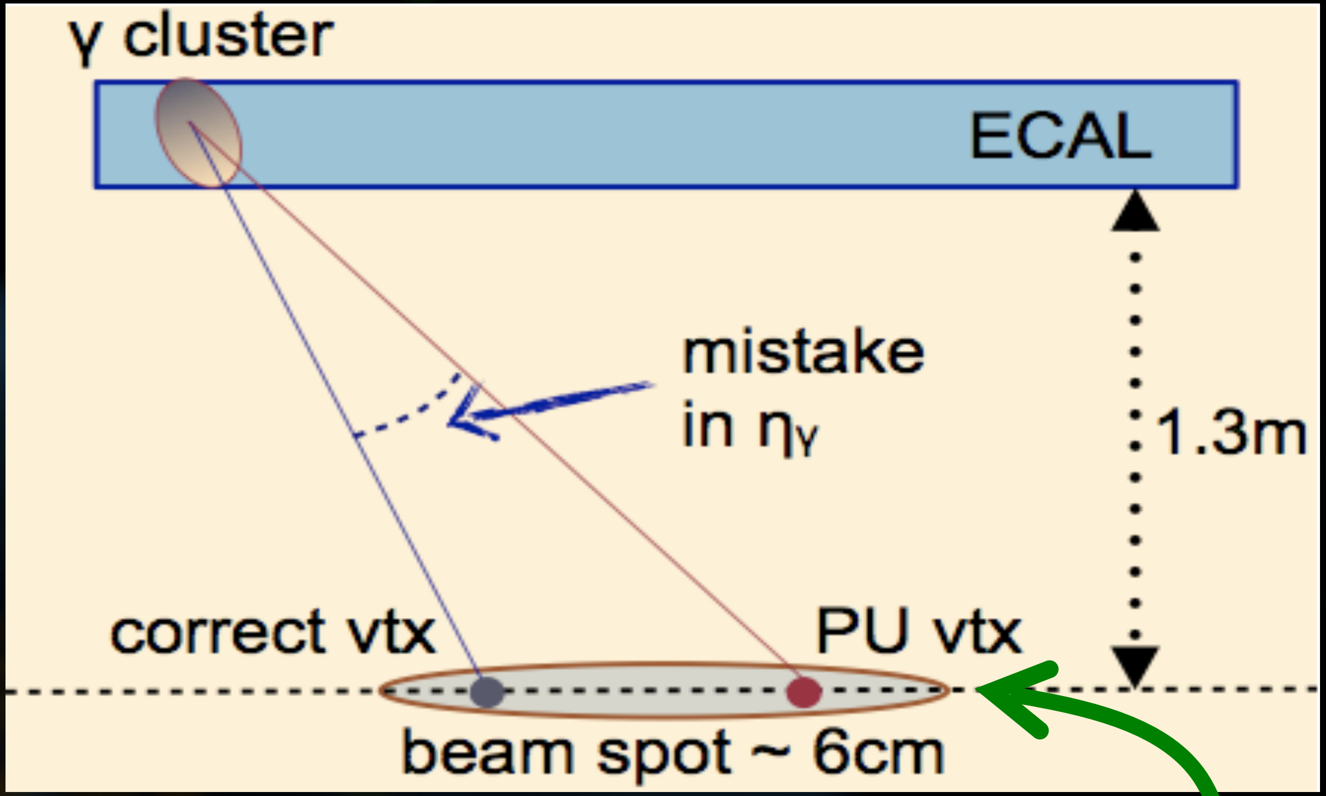
- Very good resolution (ECal!)
- Reasonably large branching ratio
- Very large background (tiny S/B)
- Estimate background with fits of the data
- Divide data into event classes
  - With resolution estimates
  - With higher S/B production mode tags

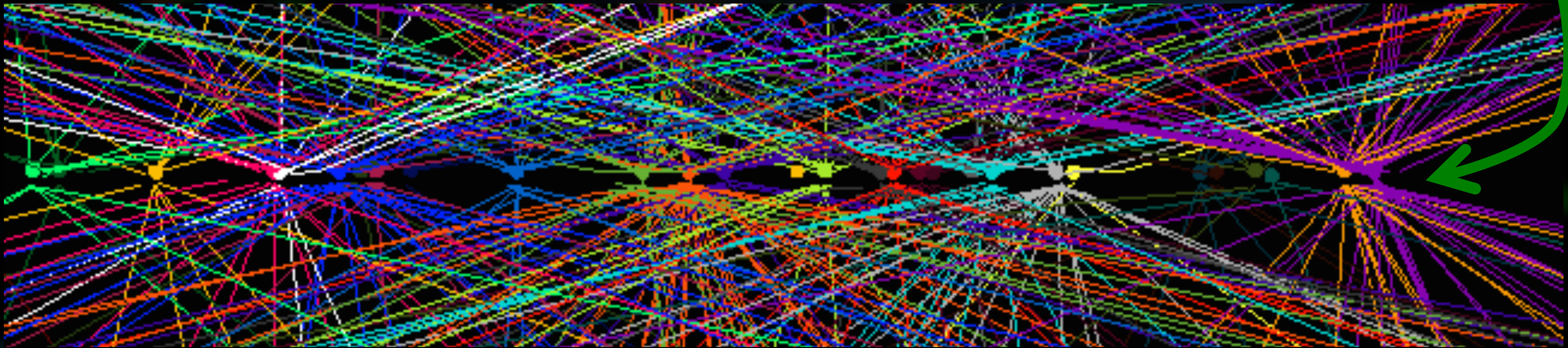
$$m_{\gamma\gamma} = \sqrt{2E_1E_2\left(1 - \cos\theta_{12}\right)}$$



Vertex Selection

- Many proton-proton interactions per event (~20/ event in 2012 data)
- Choosing the incorrect vertex deteriorates mass resolution via opening angle

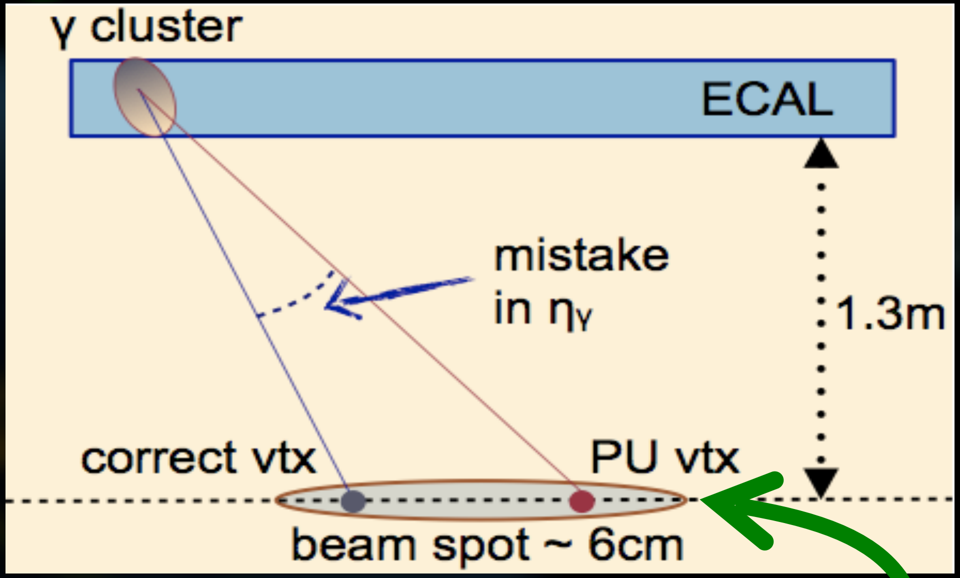


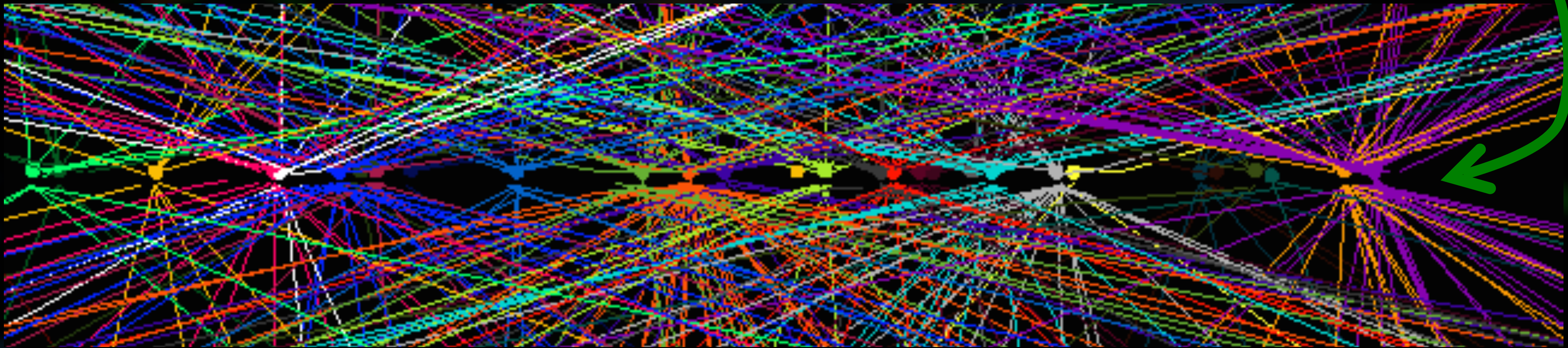


Vertex Selection

$$m_{\gamma\gamma} = \sqrt{2E_1E_2\left(1-\cos\theta_{12}\right)}$$

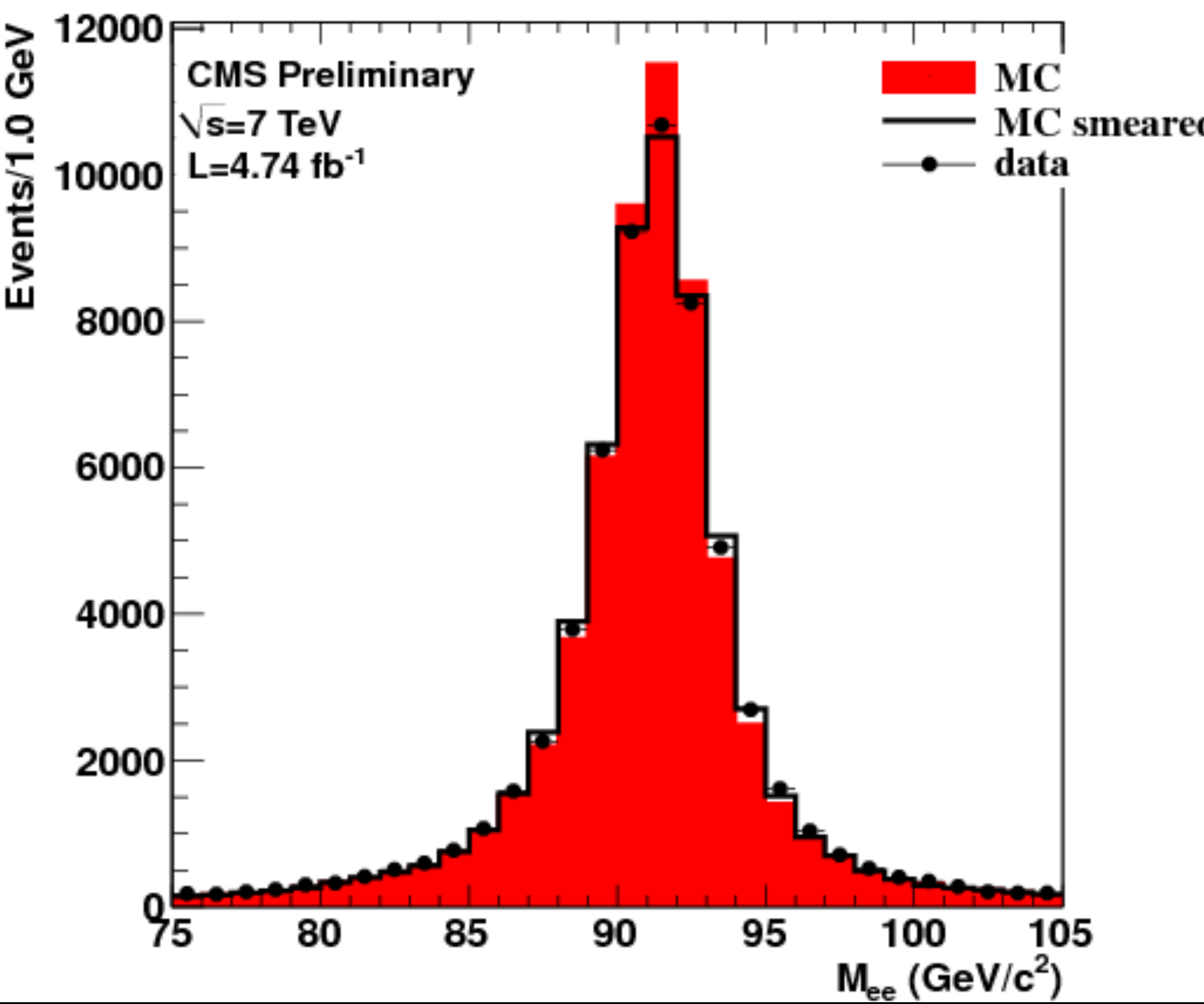
- Boosted Decision Tree (BDT) used to compare and choose.
  - Sum of track $|p_T^2|$
  - Compatibility of tracks to di-photon
  - Available conversion information
- ~83% efficient



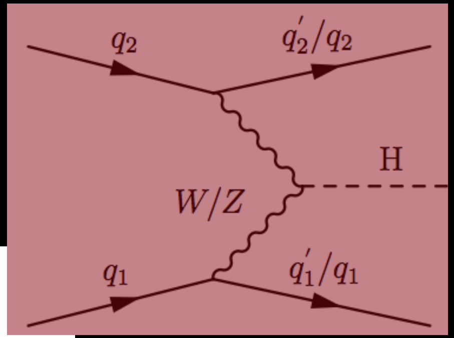


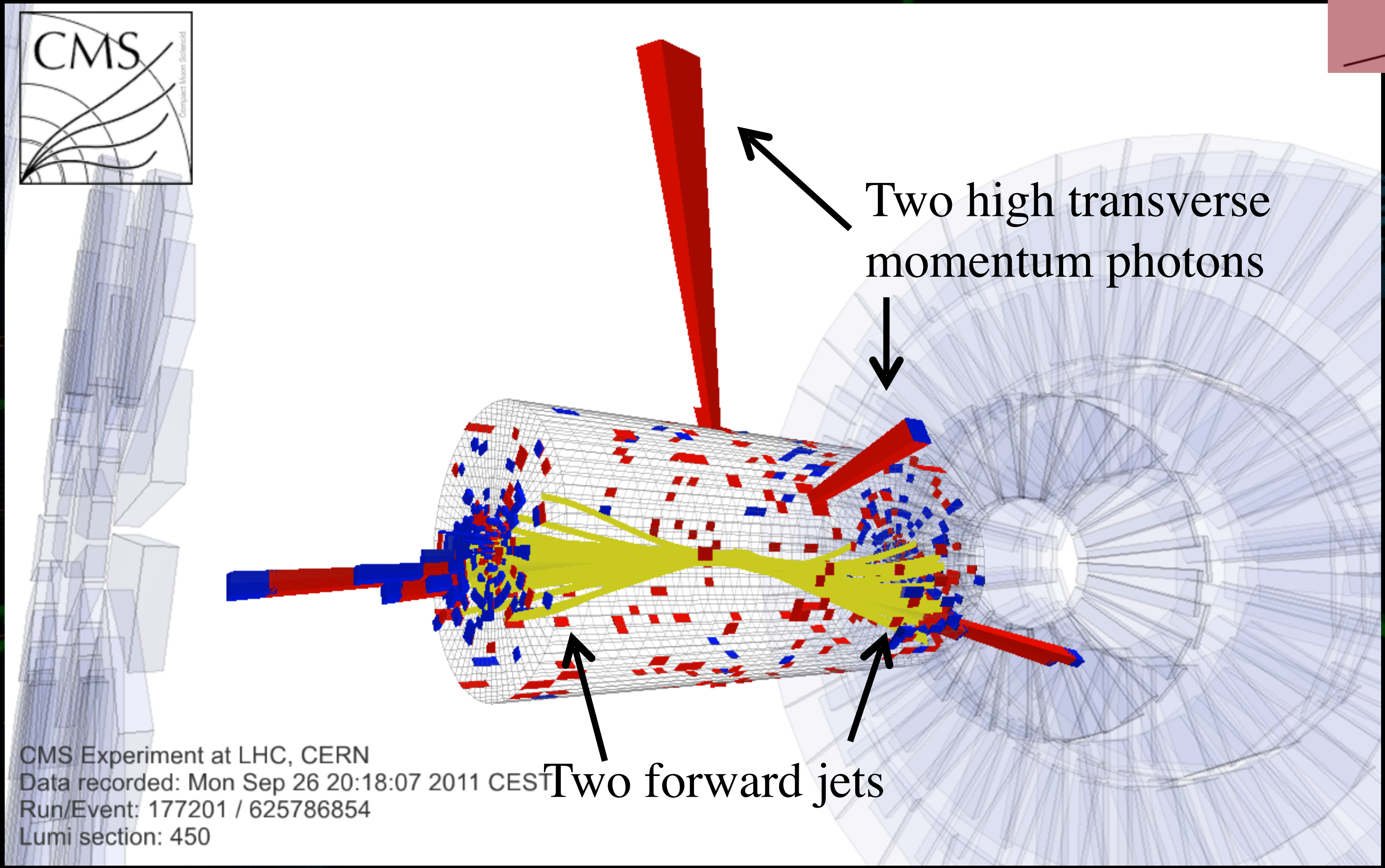
Photon Energy Determination

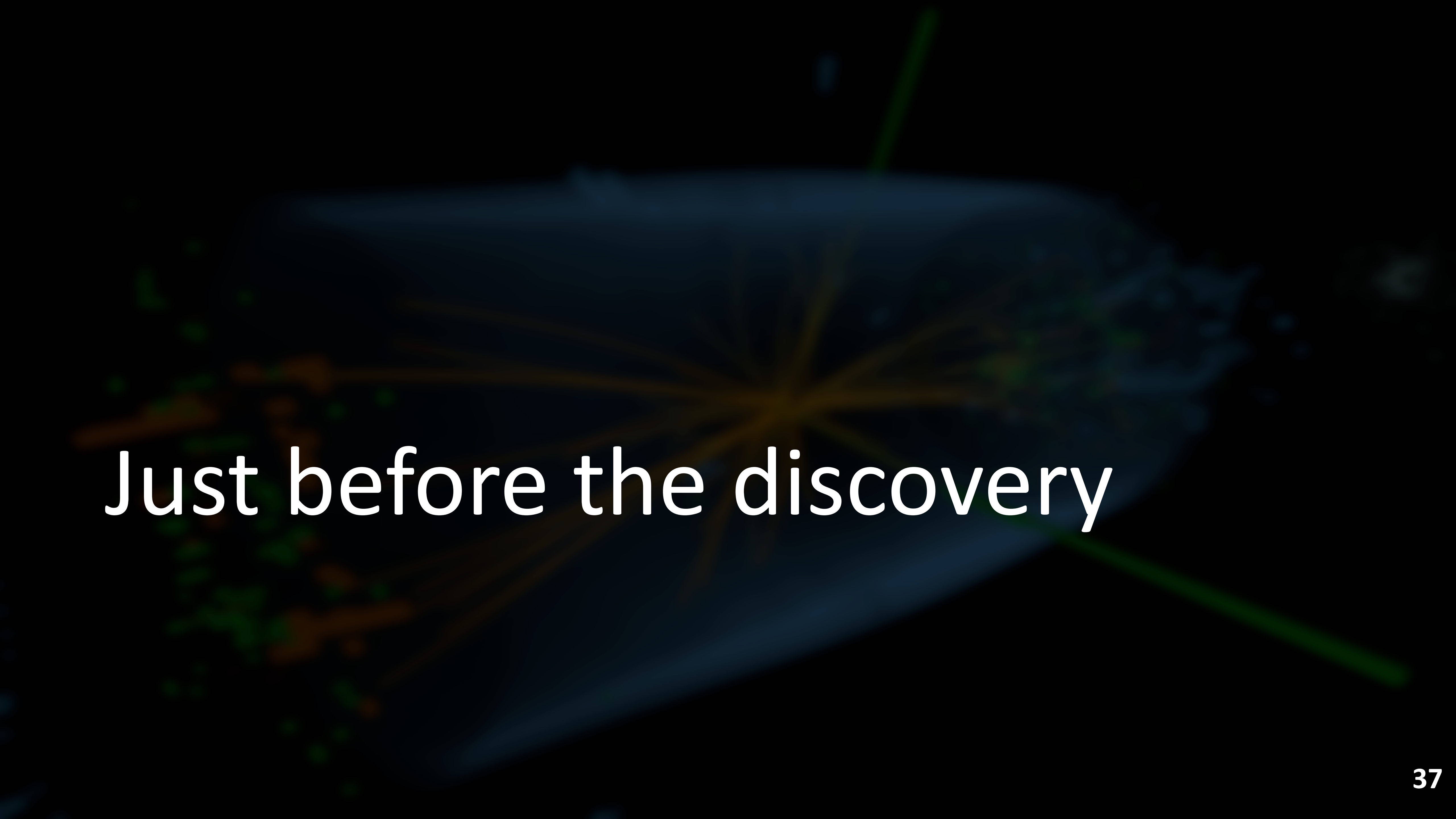
- ECAL calibration
  - Relative calibrations using π_0s and radial symmetry
  - Energy scale calibrated with Z to two electron events
- Energy regression
- Higgs to two photon specific regression providing energy and energy error estimates per photon



Di-jet Tag for VBF Production



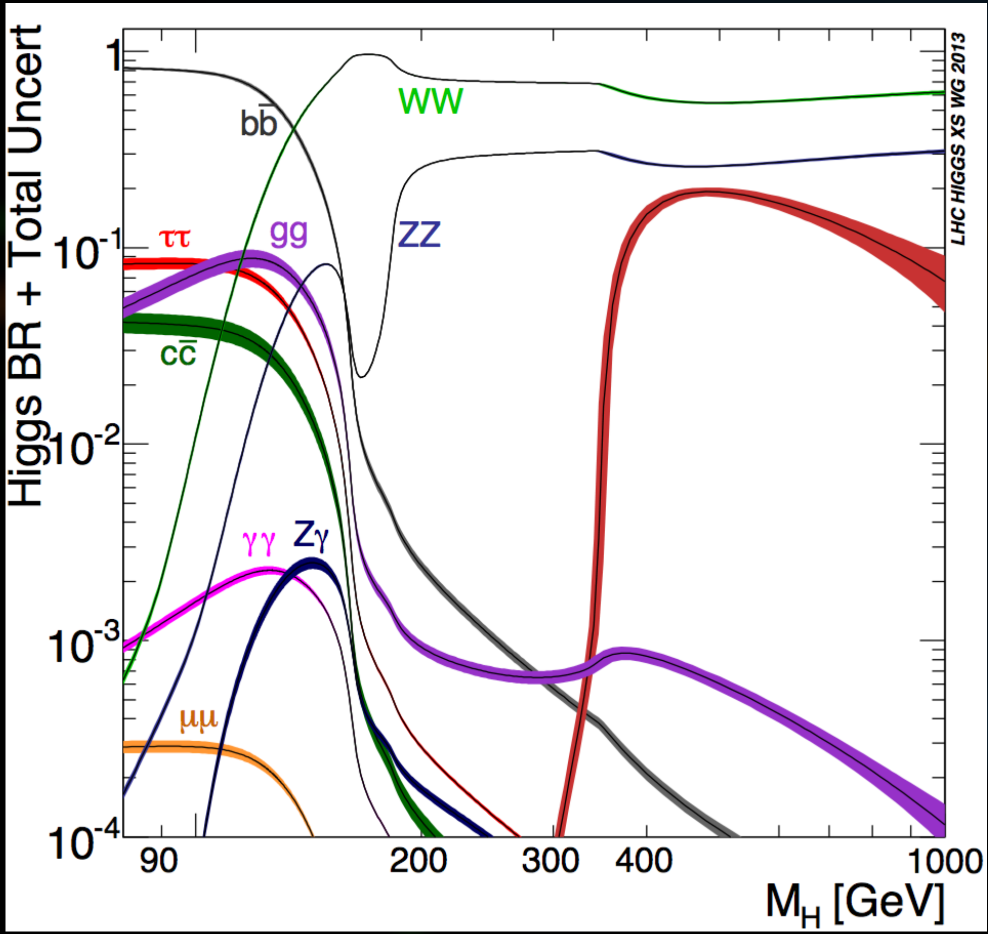


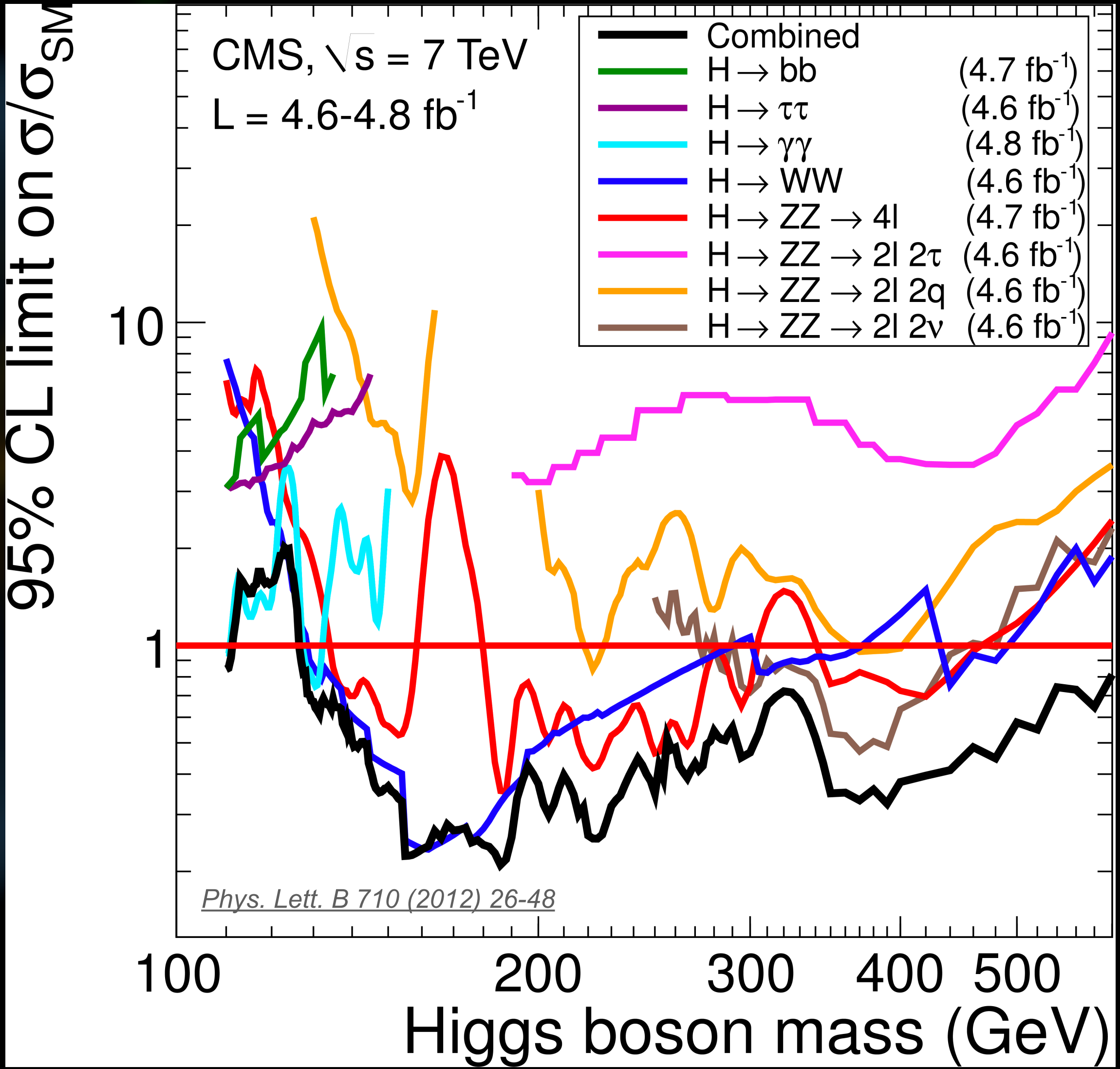


Just before the discovery

We looked at all masses

- WW and ZZ channels would have seen high mass Higgs in 2011.

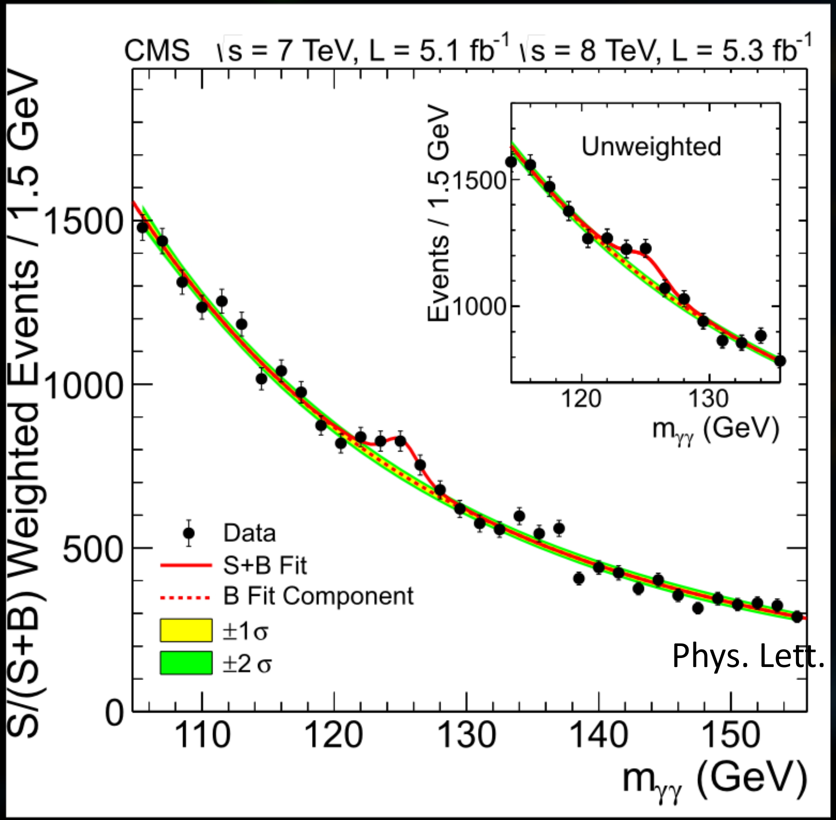


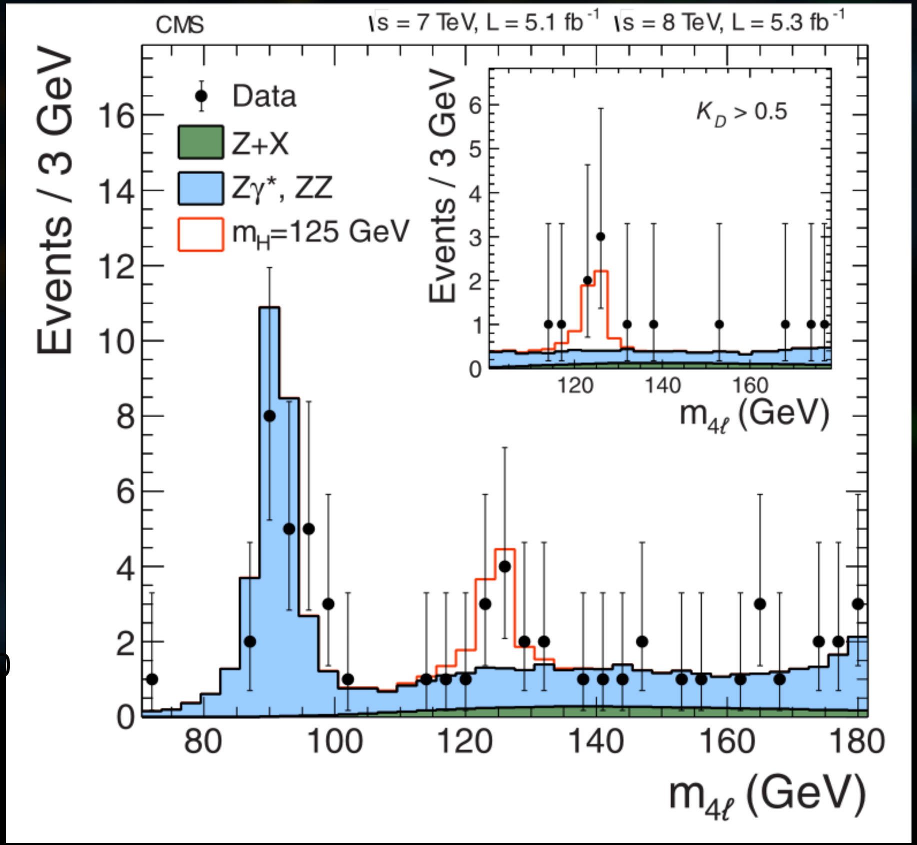


From Discovery to Now

July 4th, 2012: Higgs boson discovery

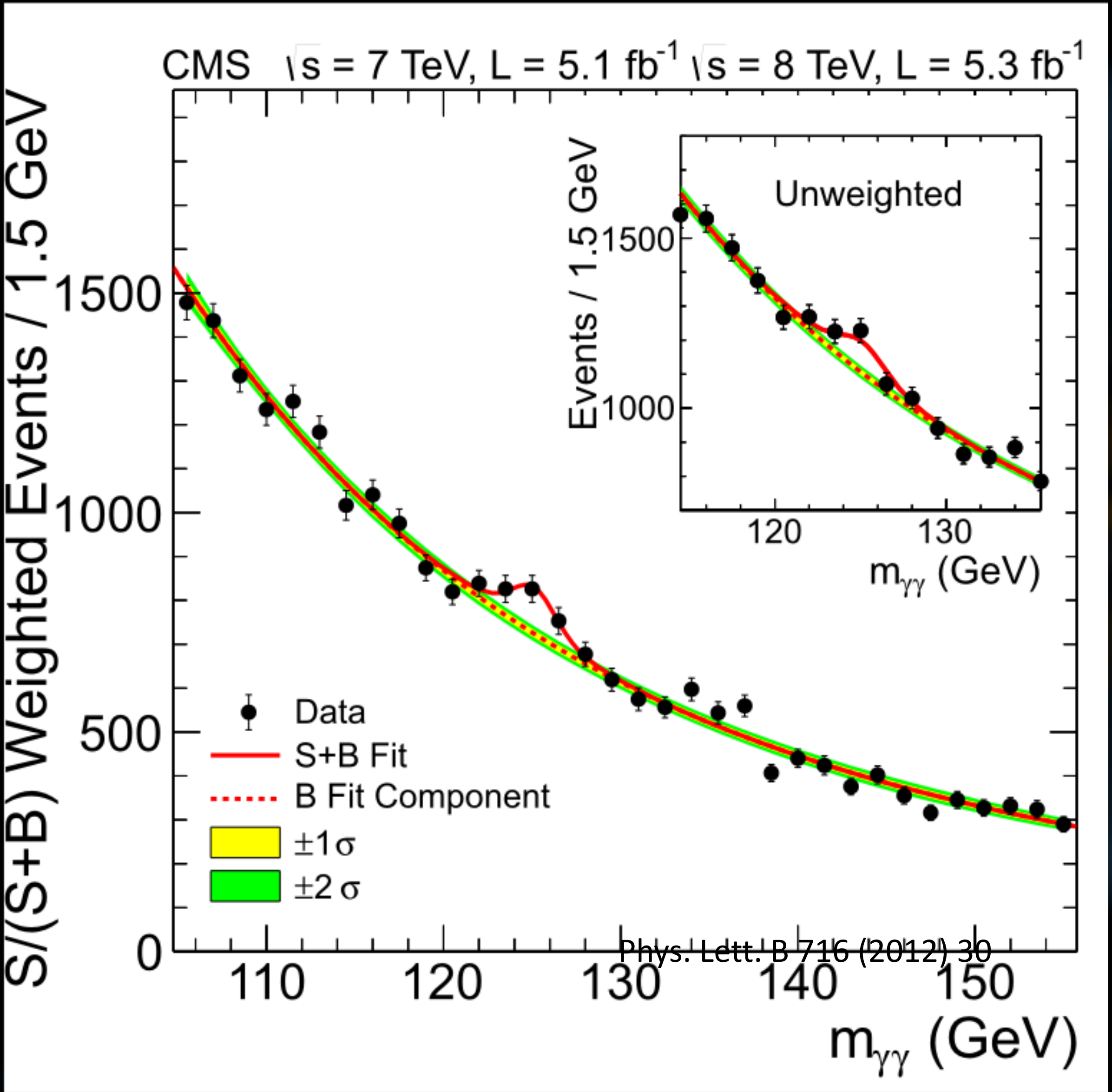
- Fully reconstructed Higgs boson decay channels with excellent mass resolution drove the discovery.
- Peter Higgs and François Englert won the 2013 Nobel Prize in physics.





Phys. Lett. B 716 (2012) 30

Discovery Data (~10fb^{-1})



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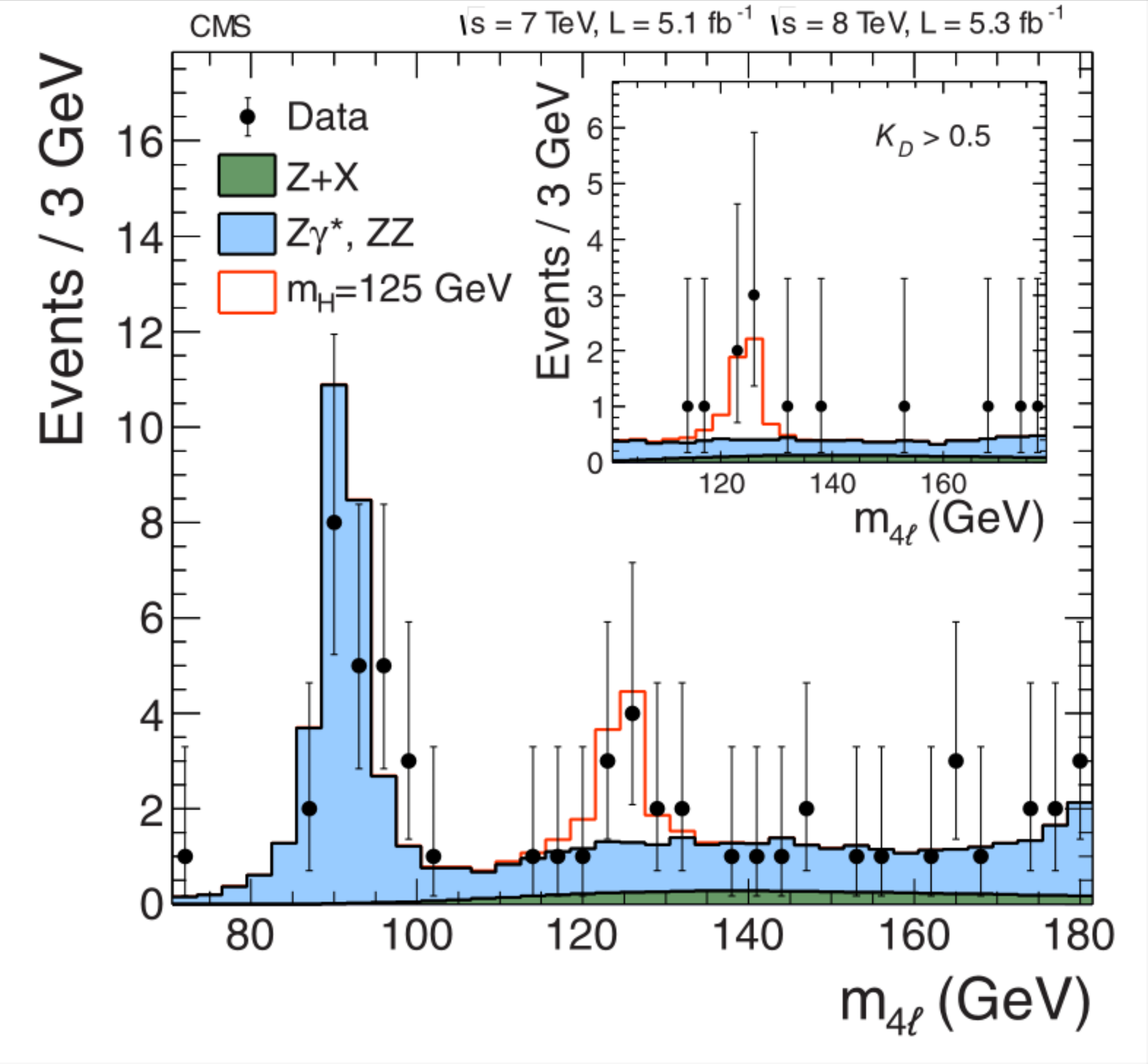
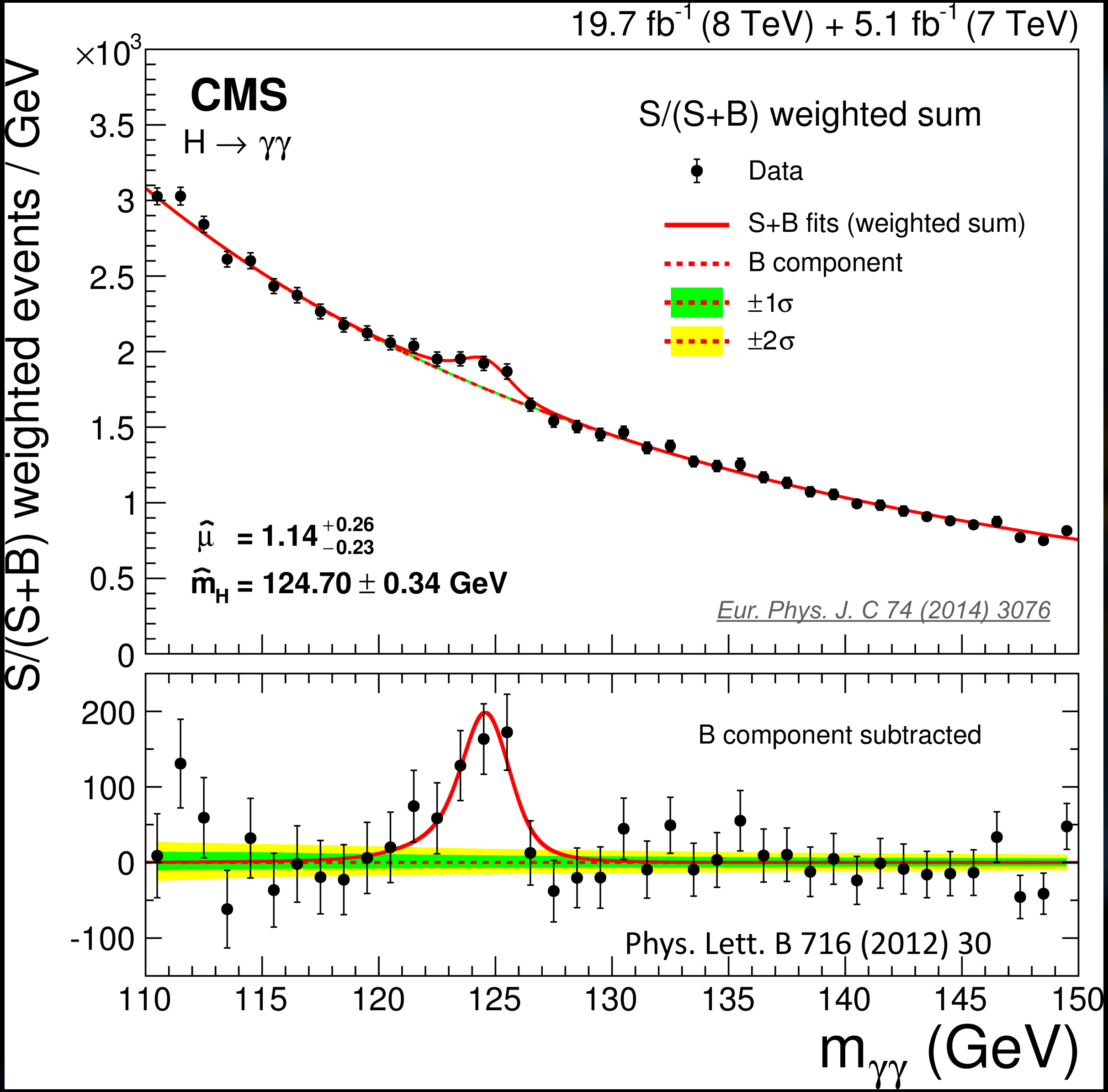
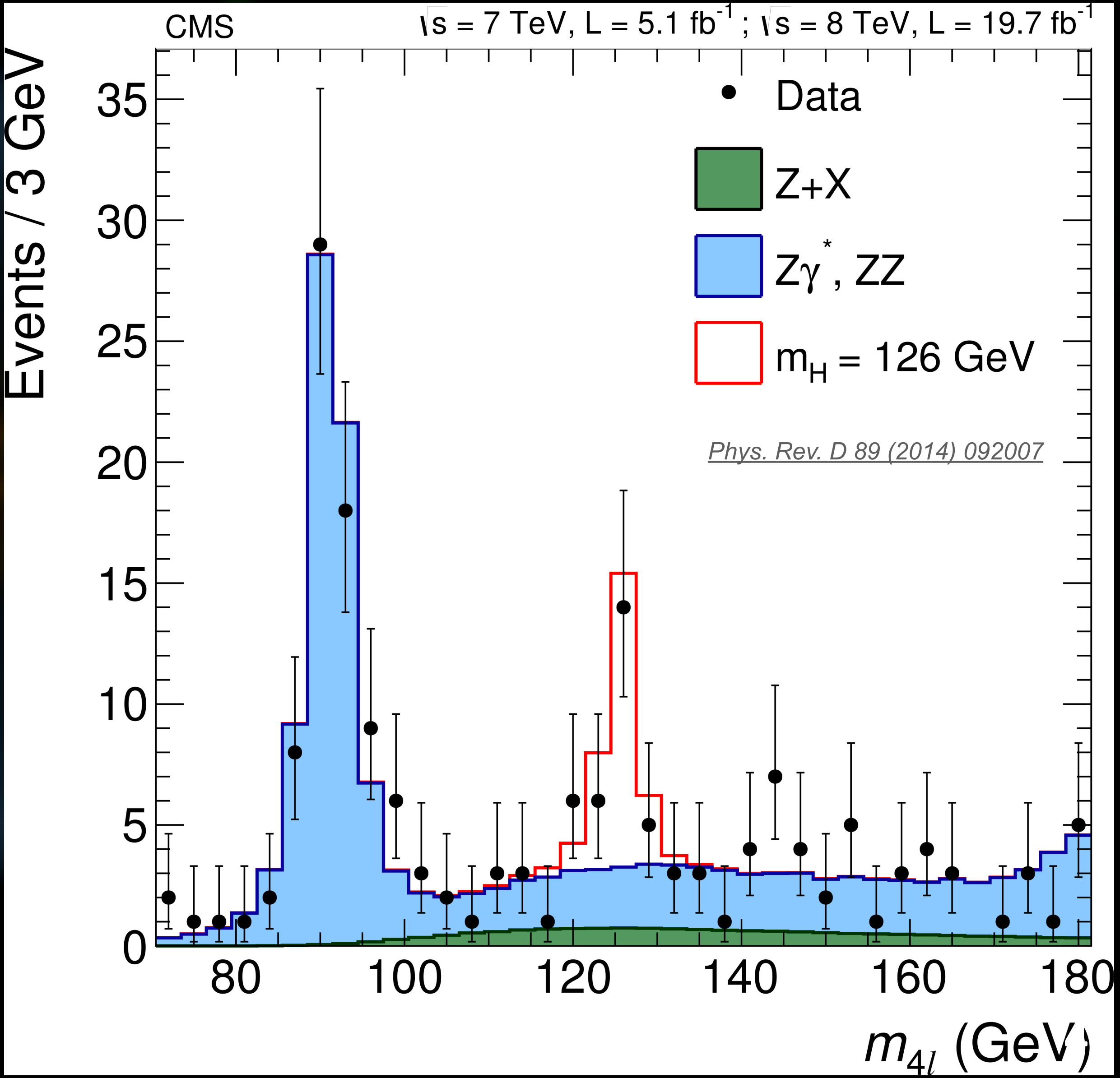
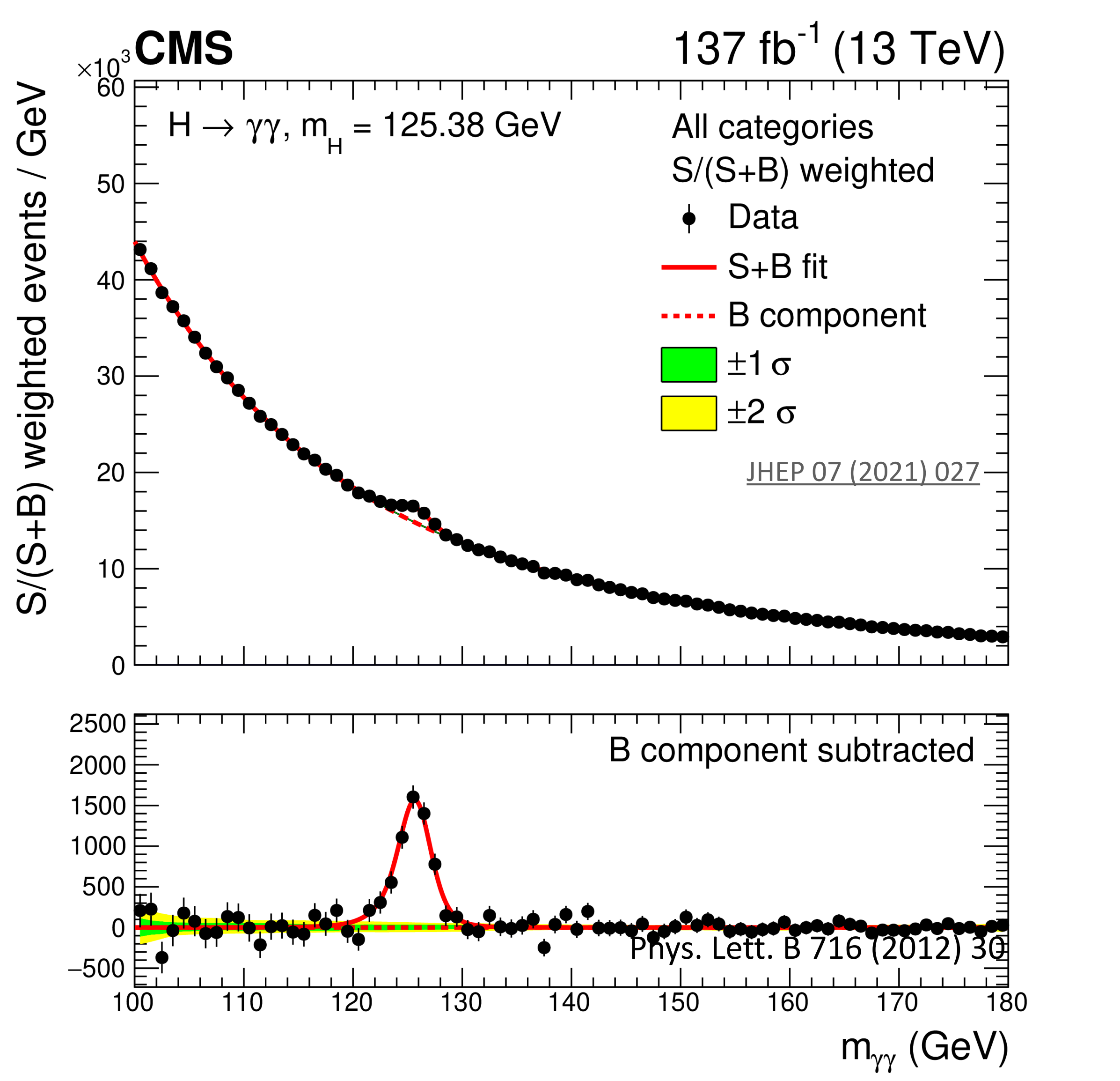


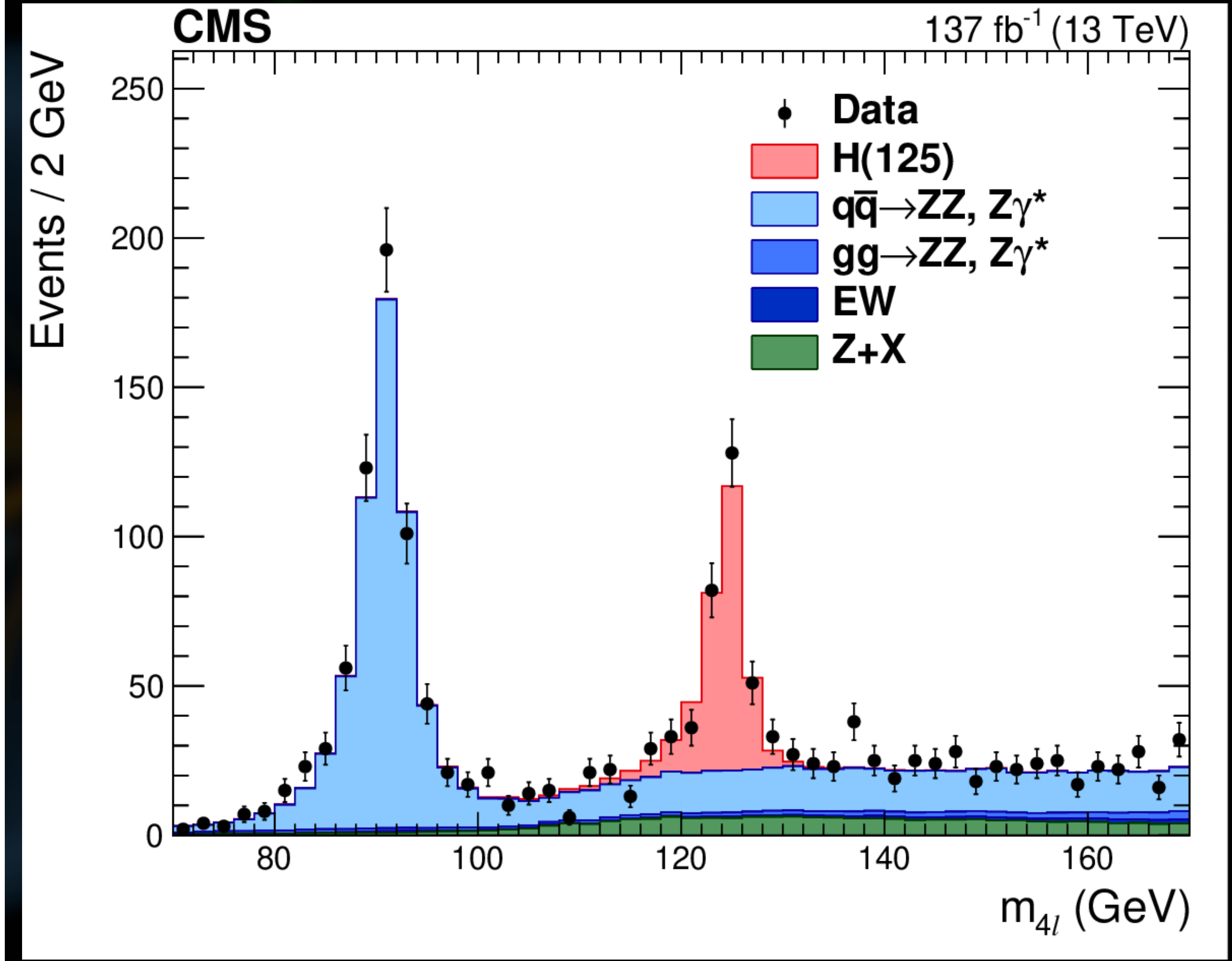
Full Run 1 Data (~25fb^{-1})





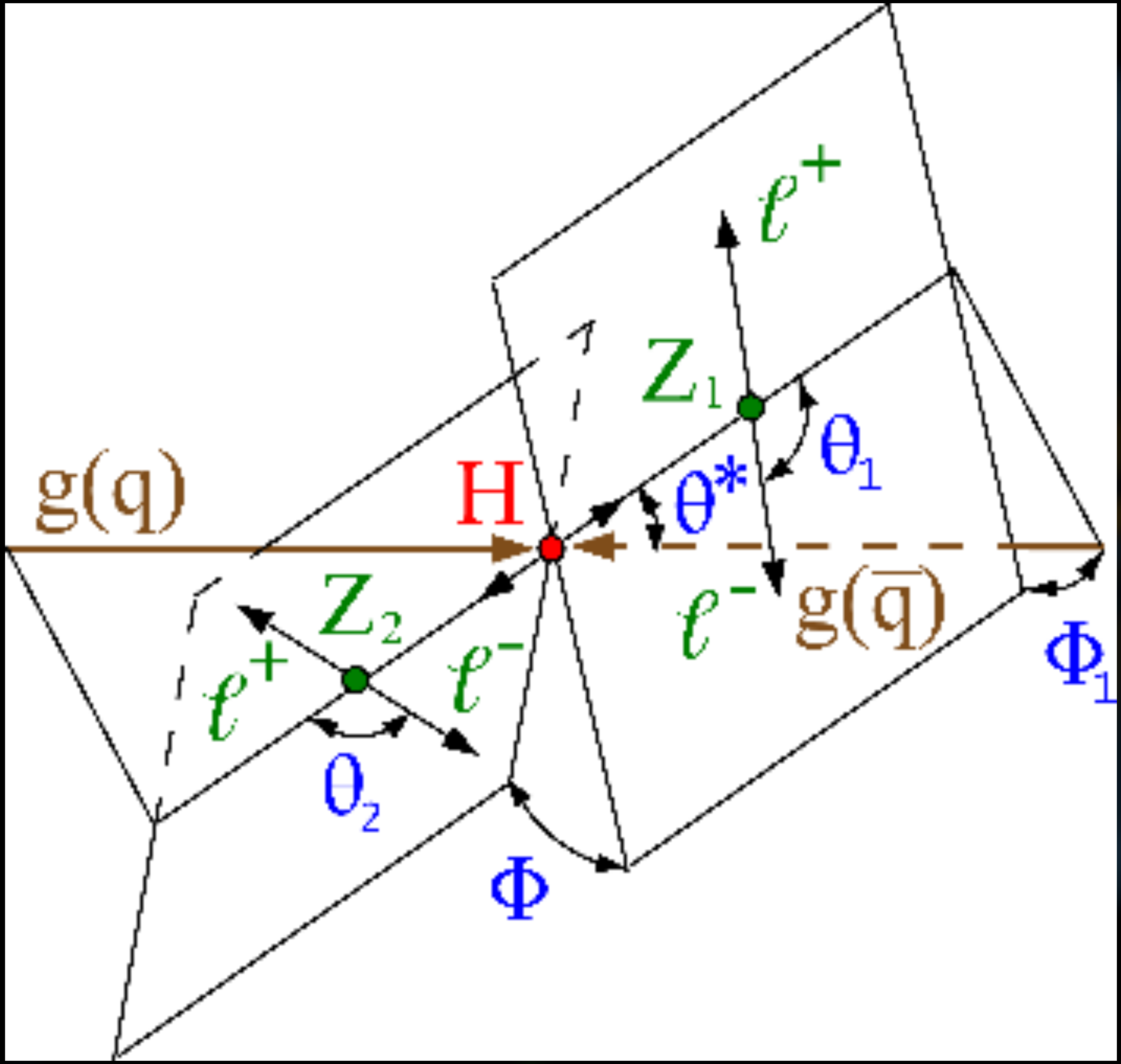
Full Run 2 Data (~140fb-1)

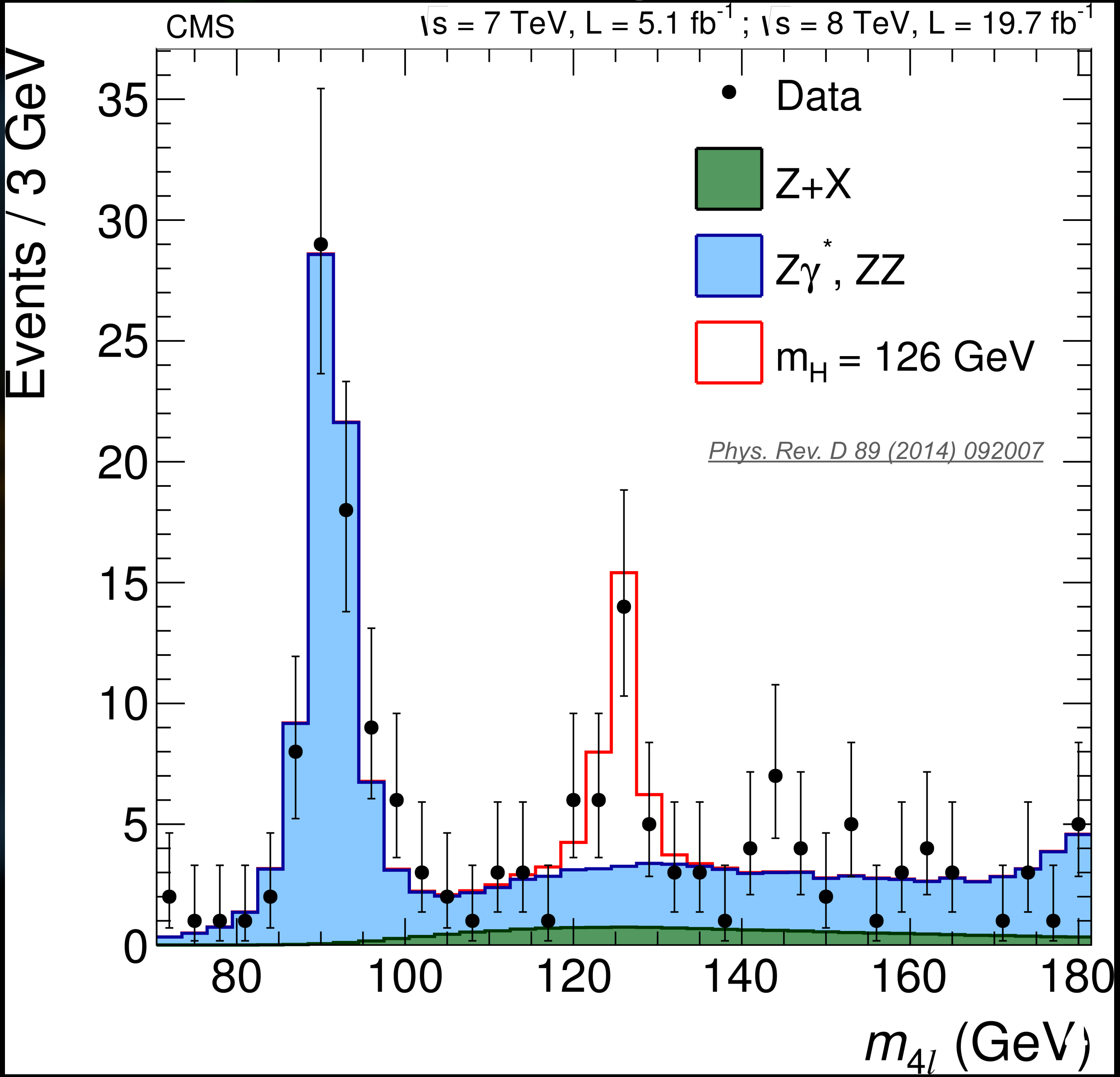




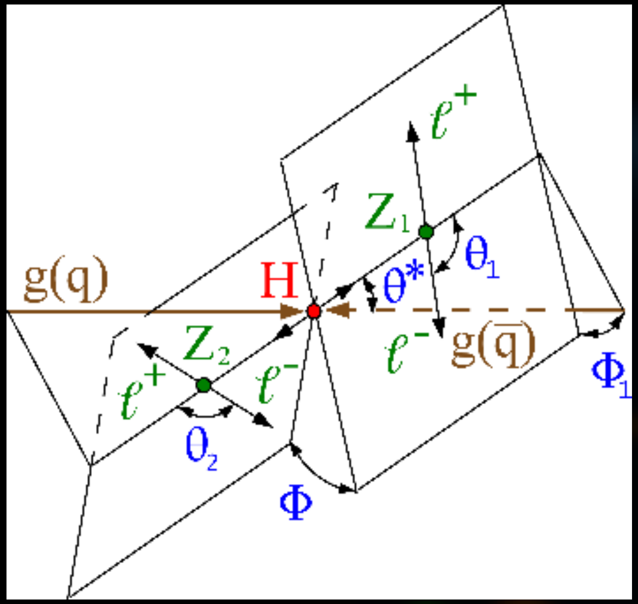
Some Properties

Run 1 $H \to ZZ \to 4\ell$ Properties

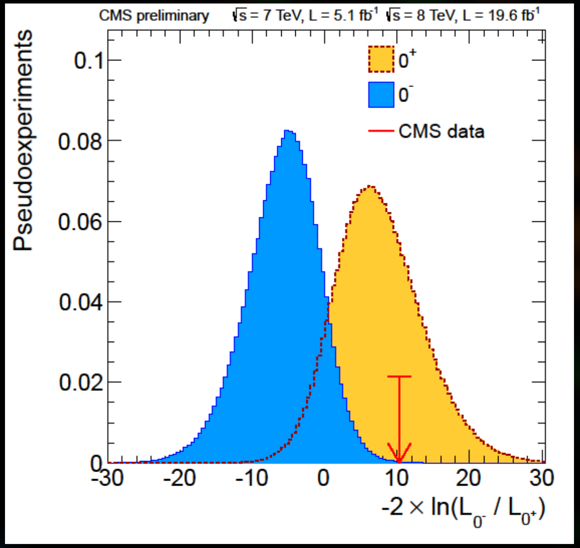


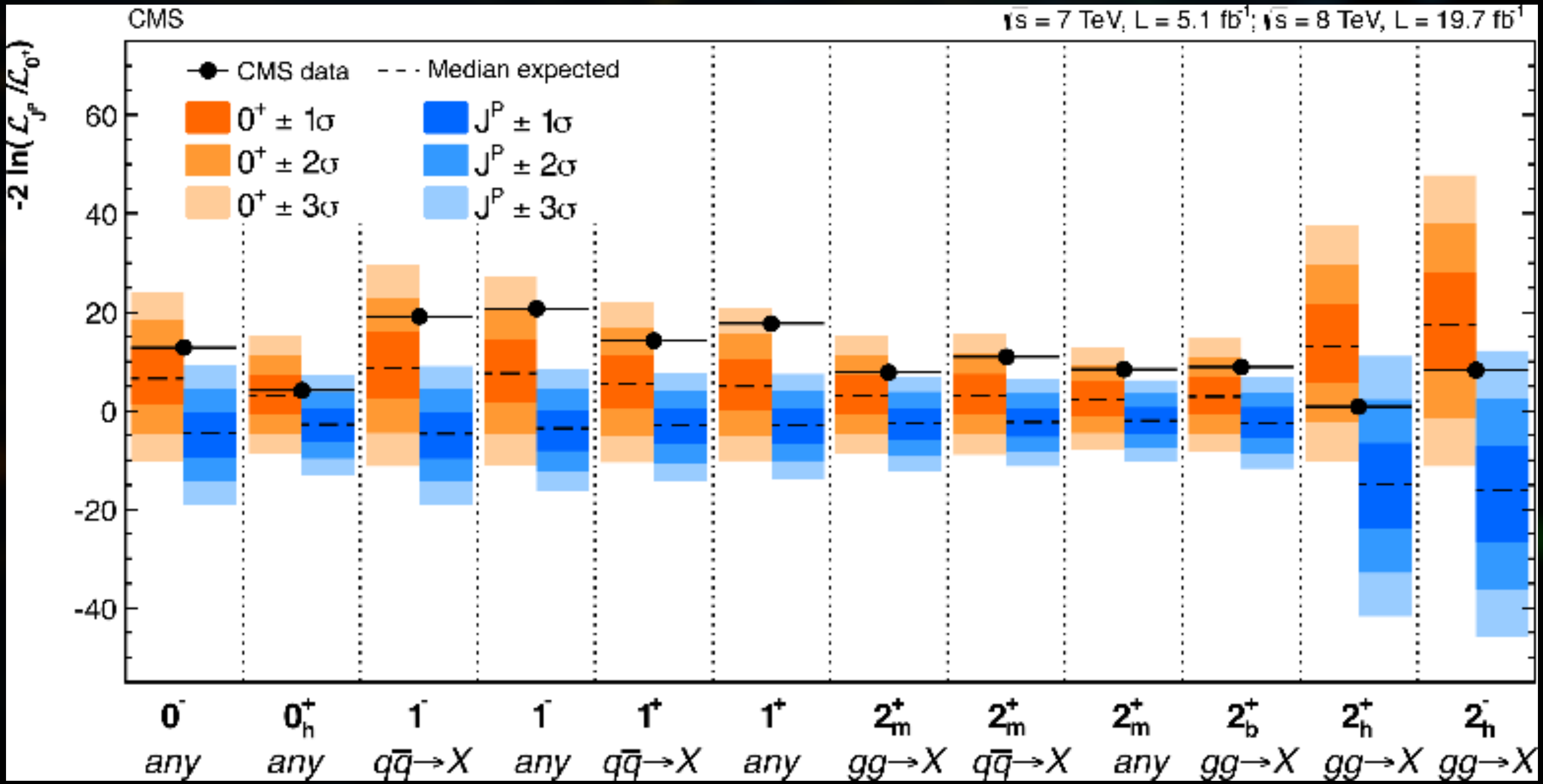


Higgs boson quantum numbers

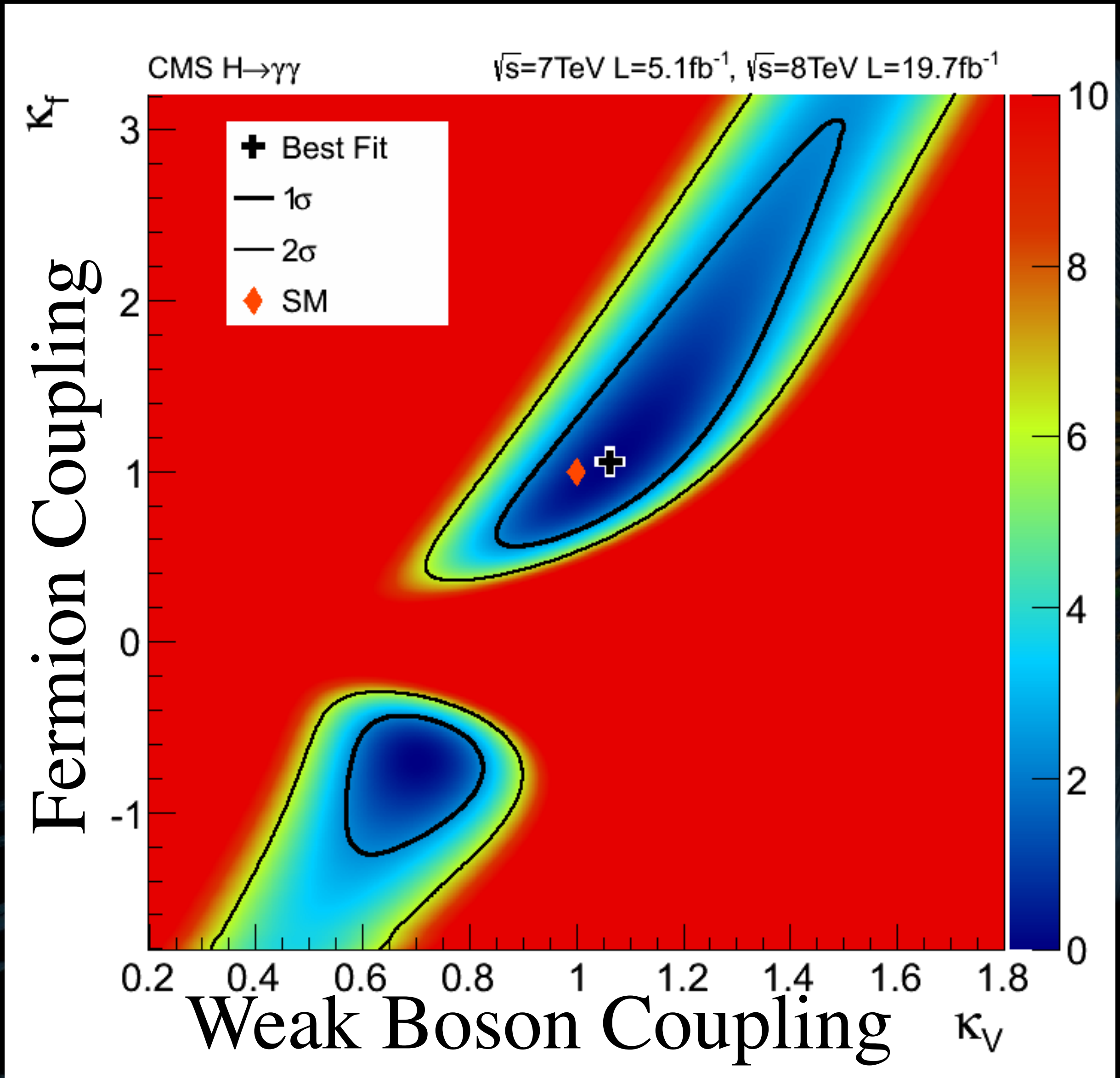


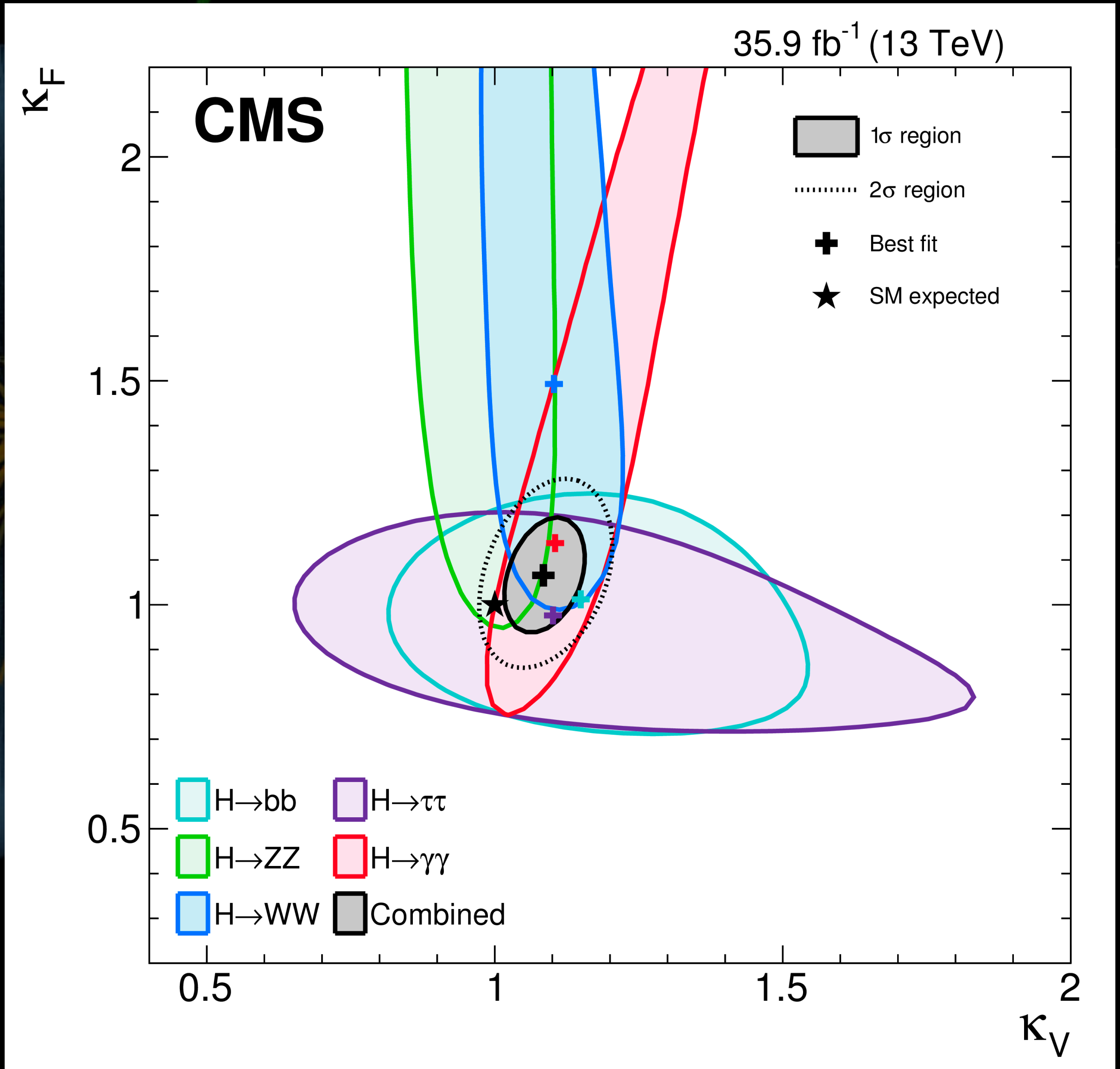
- How SM is this Higgs boson? (SM: spin-0, CP+)
- Using only 4-lepton events with full Run 1 dataset, the favored spin-parity was clear.





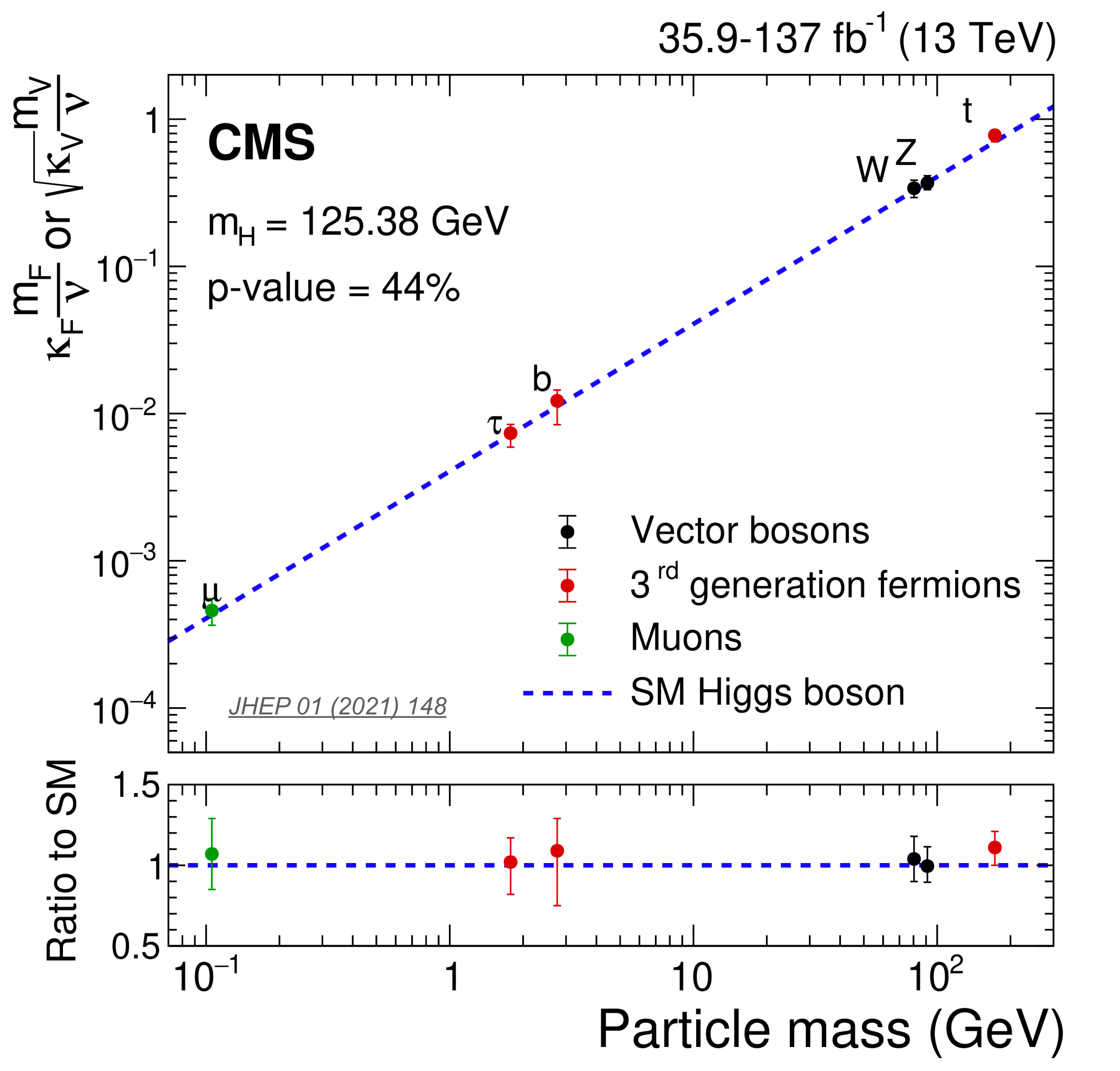
Measurement of Fundamental Couplings





Couplings so far!

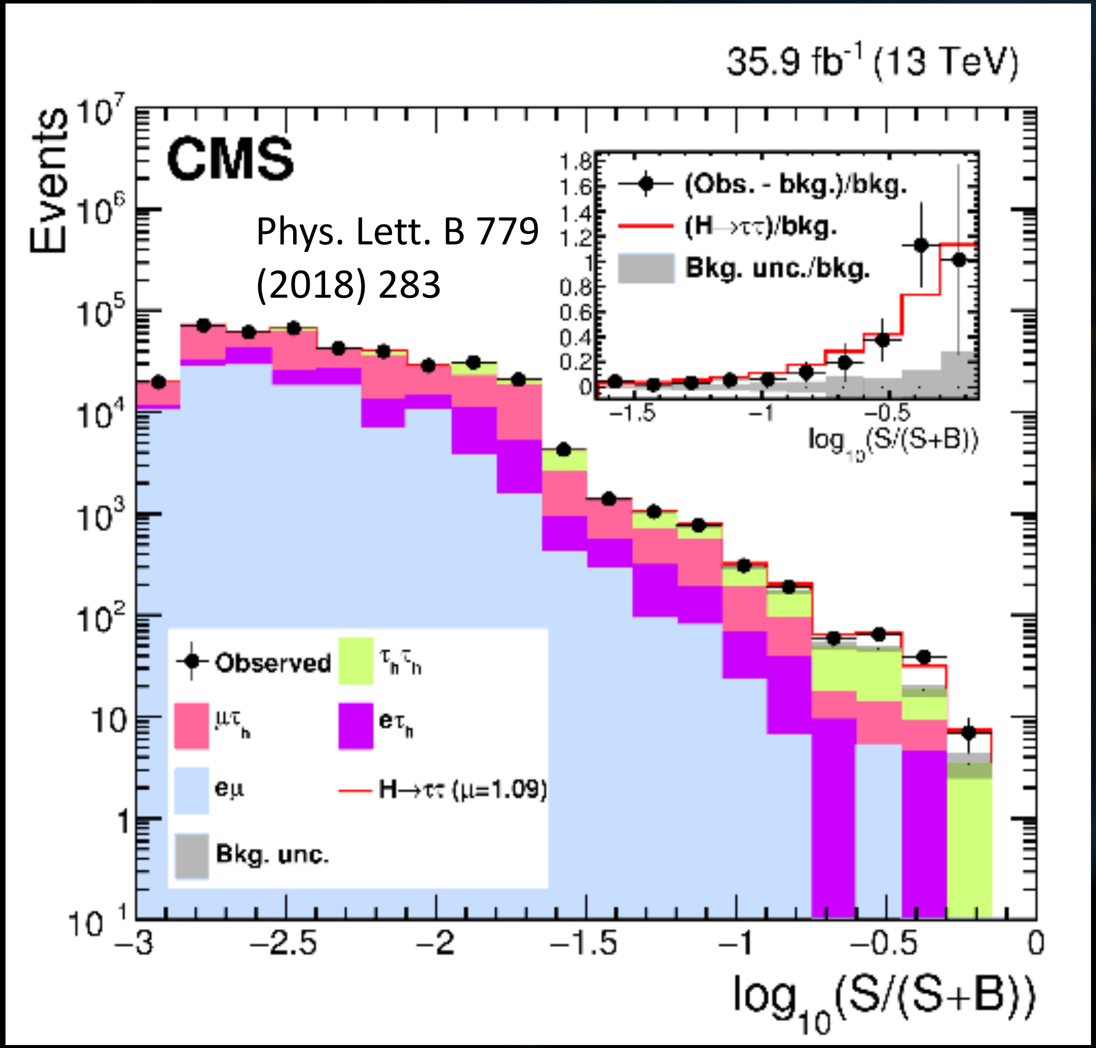
- All significant channels are fit together.
- Couplings to particles are allowed to float (not fixed to expected).
- Observed couplings are in line with SM expectations
  - Proportional to the mass!!

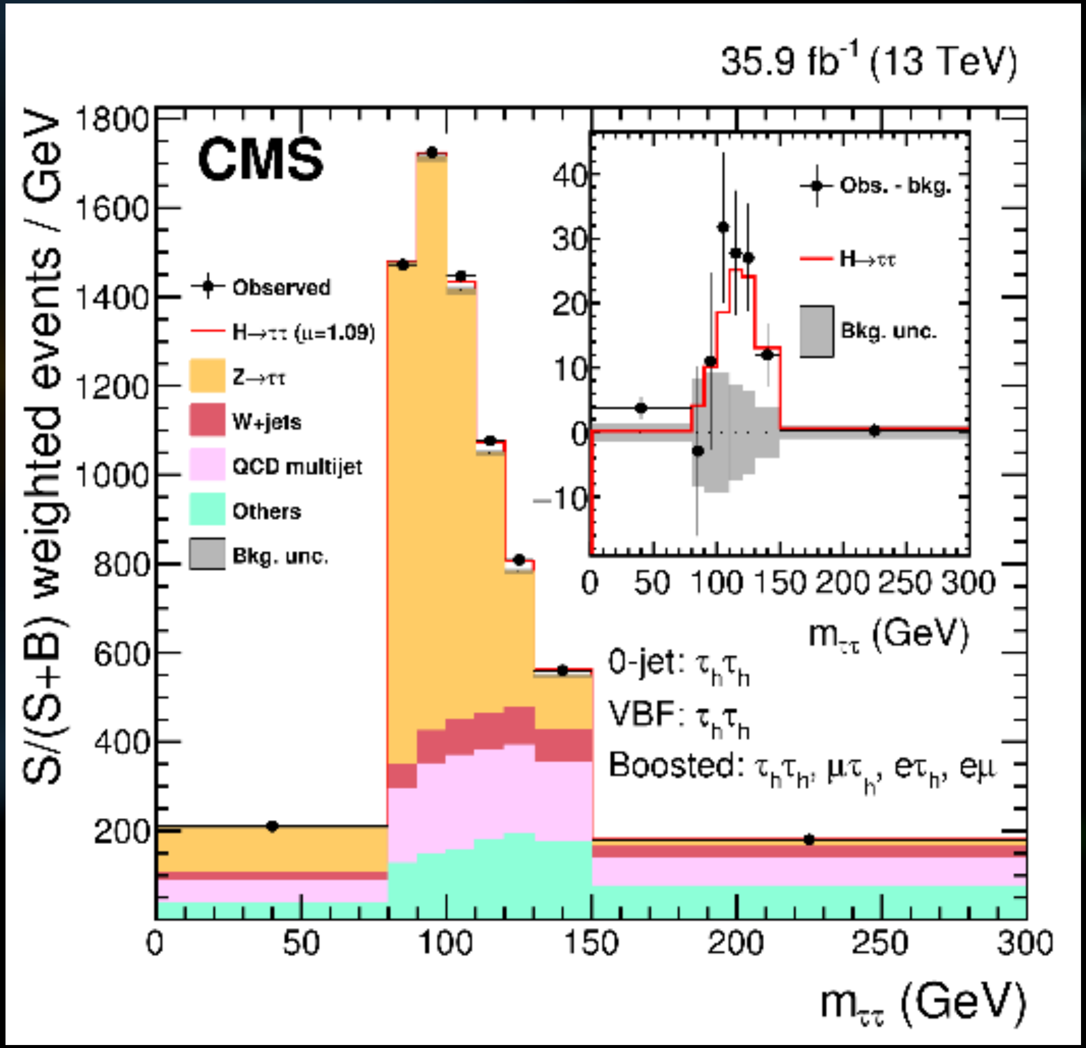


Other Channels

Observations of $H \to \tau\bar{\tau}$

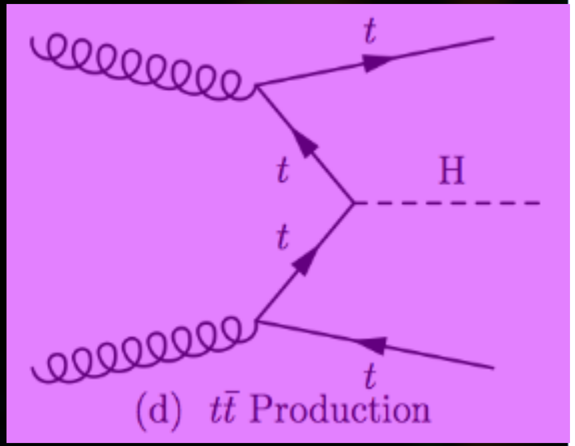
- 2016 data plus Run 1 combination: 5.9σ observed

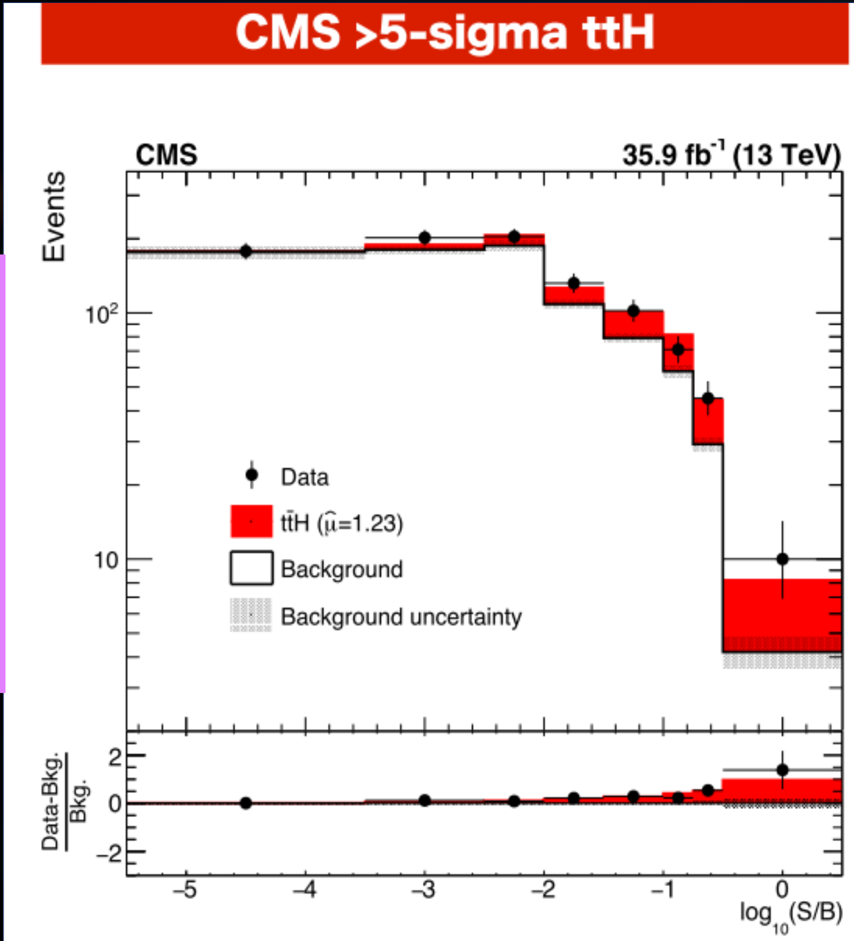


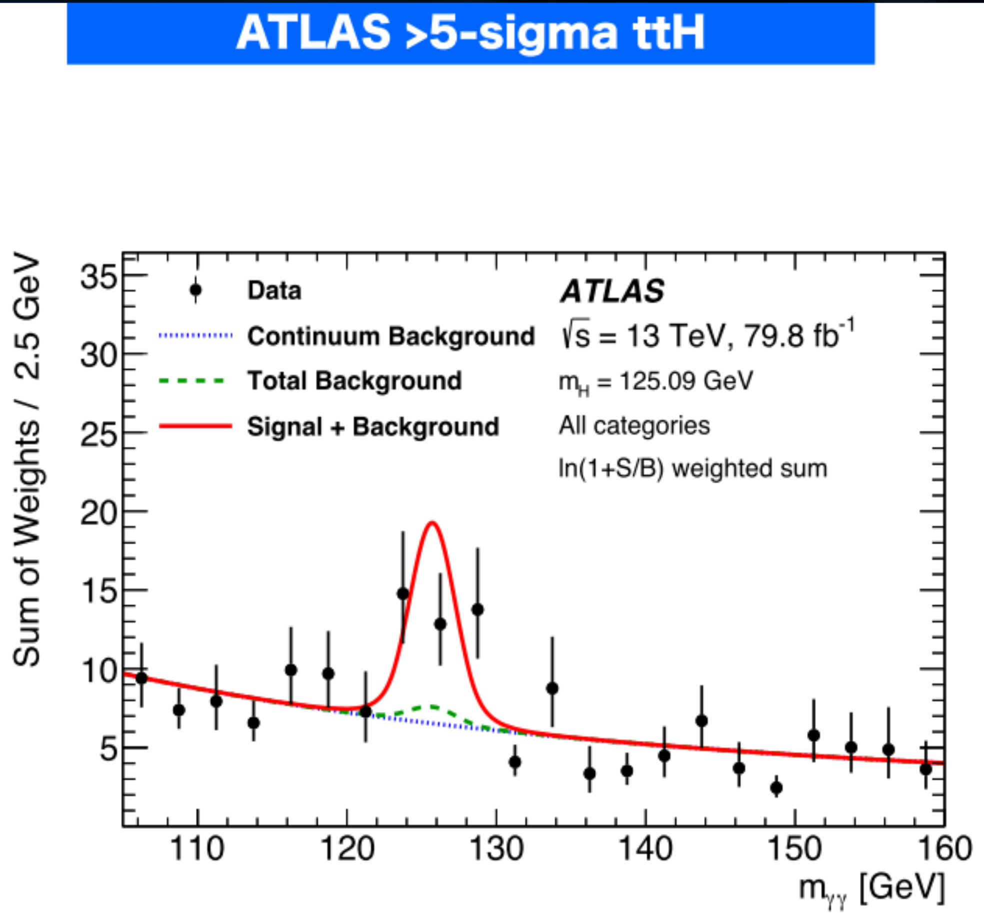


Observation of $t\bar{t}H$ Production

- Di-photon and two bottom quark channels were the most essential channels for this observation.

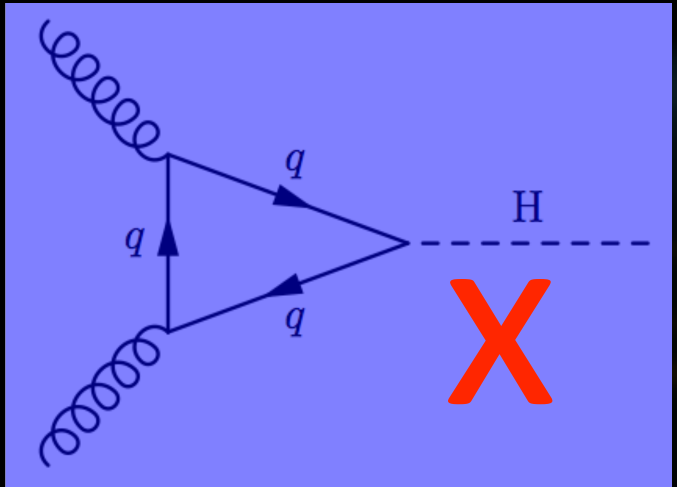




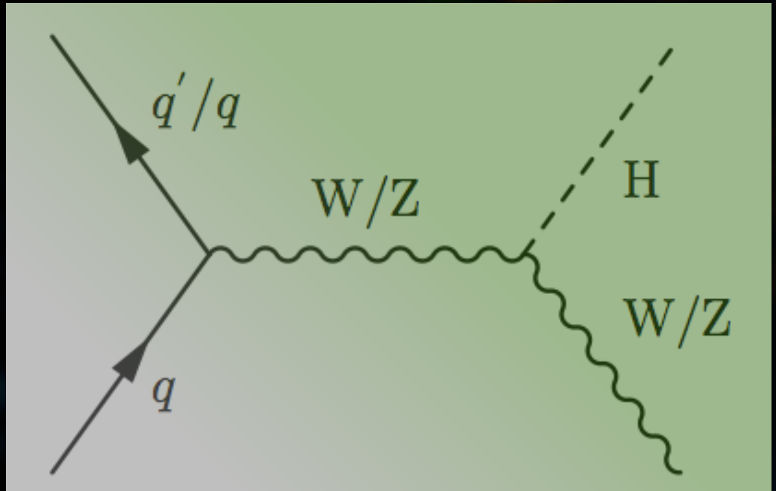


Finding *the* original channel

VHbb



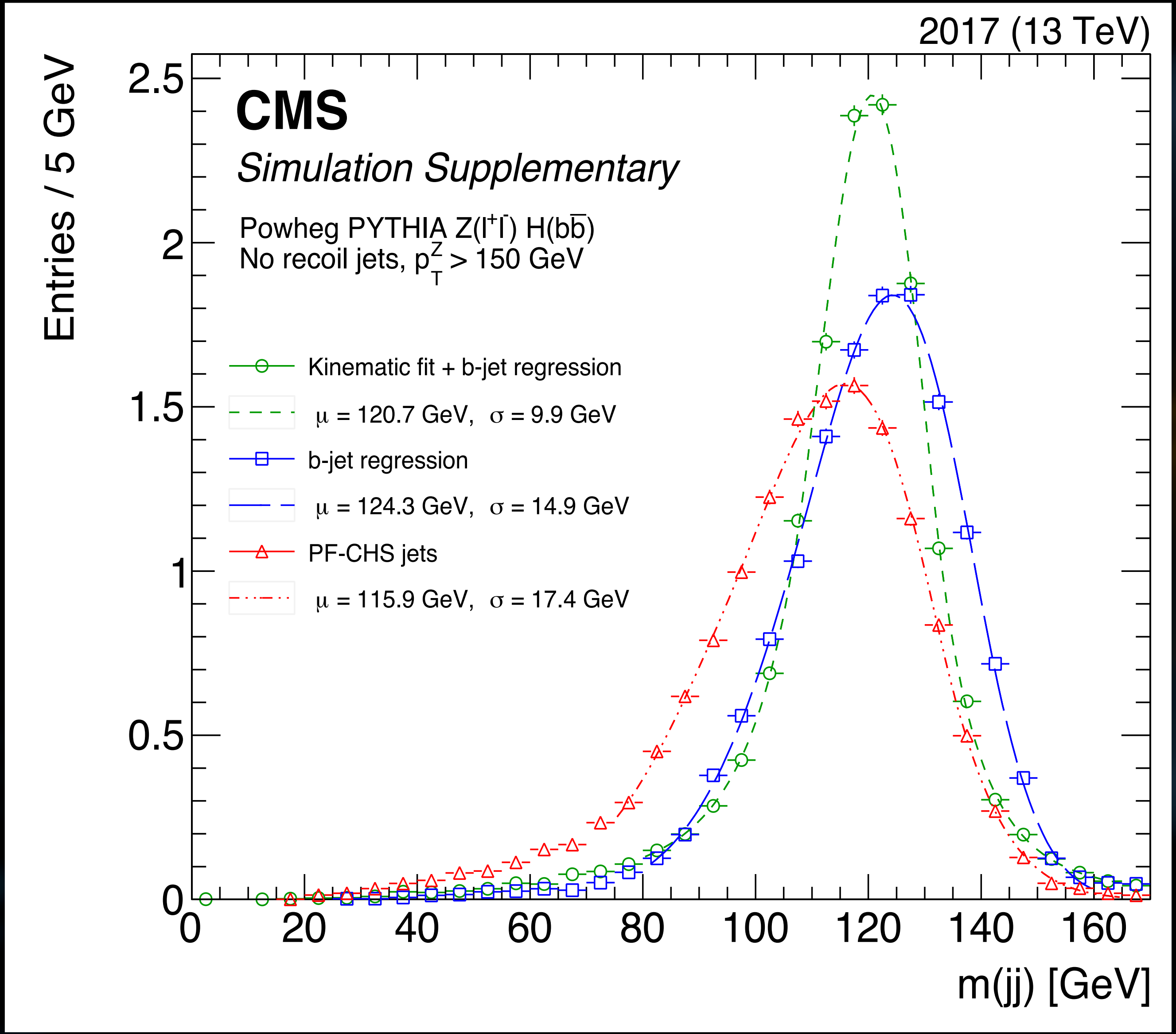
(a) Gluon Fusion

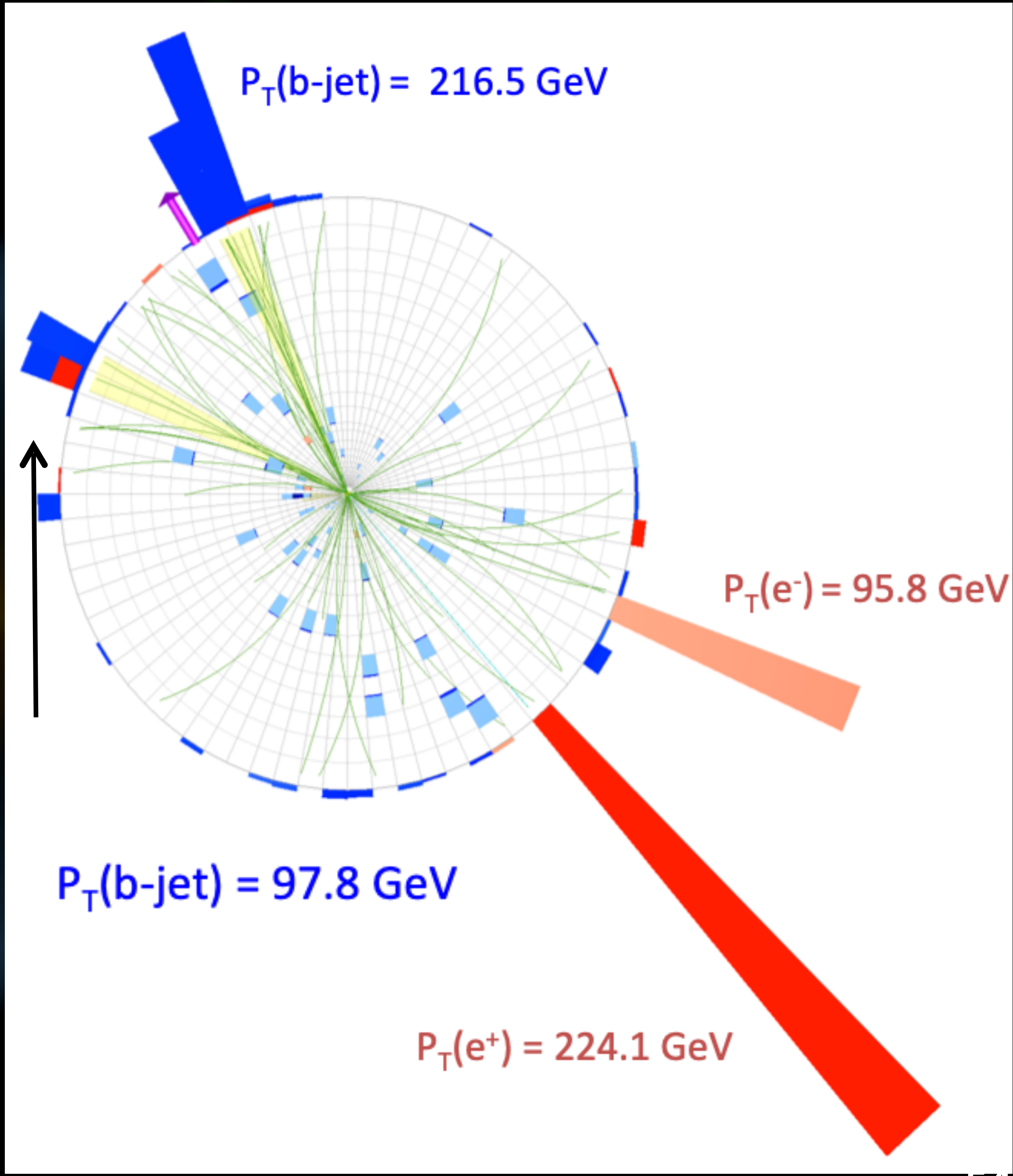


(c) Higgsstrahlung

- Two b-quark jets looks like almost any event with some combination of quarks and gluons.
  - We can’t anchor the analysis in bb.
- We need to tag the vector boson just to save the events on tape!
- That’s why we call it VHbb.

VHbb

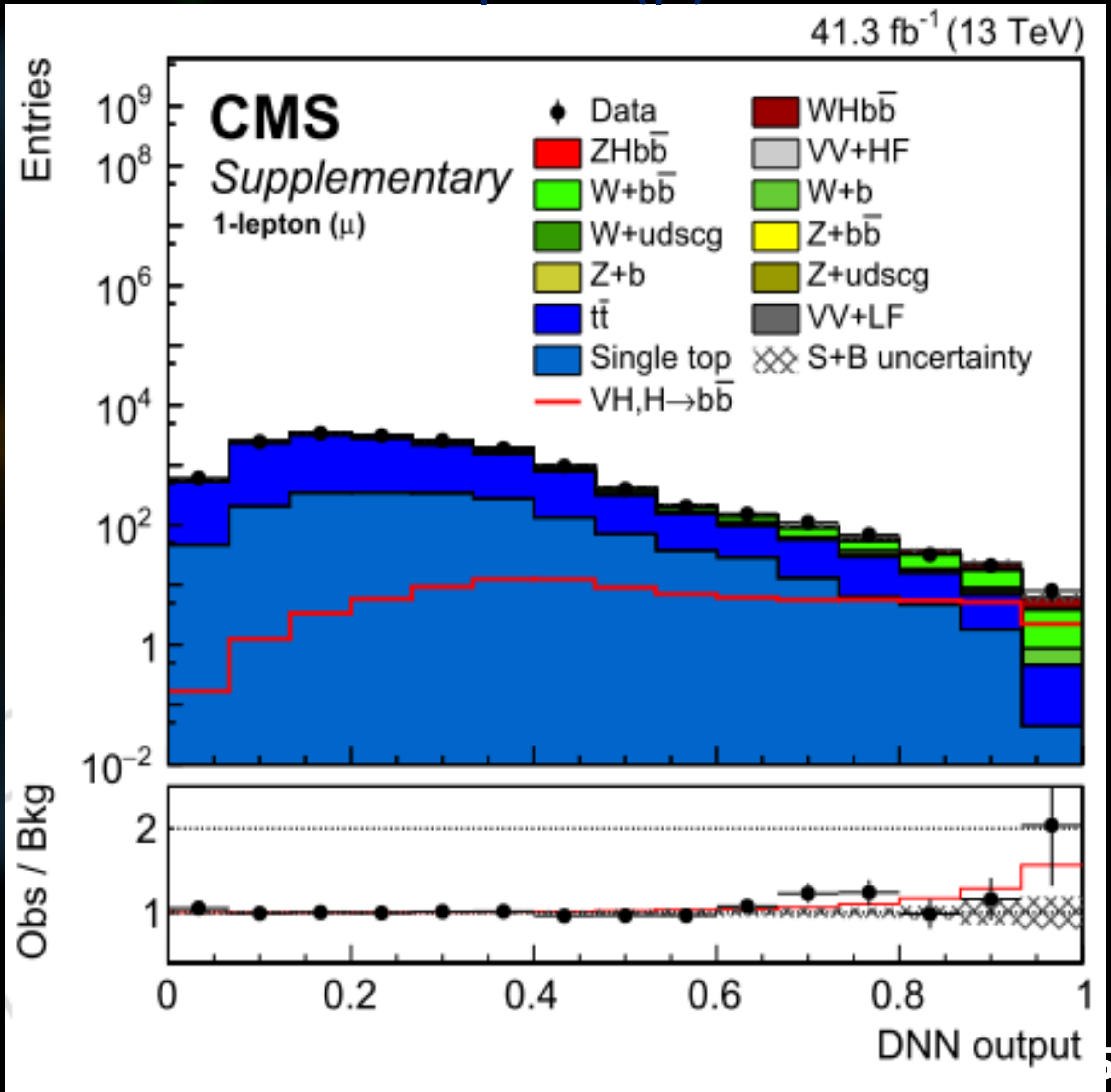

2017 (13 TeV)
CMS
Simulation Supplementary
Powheg PYTHIA Z(l+l-) H(bb̄)
No recoil jets, p_T^Z > 150 GeV
Kinematic fit + b-jet regression
μ = 120.7 GeV, σ = 9.9 GeV
b-jet regression
μ = 124.3 GeV, σ = 14.9 GeV
PF-CHS jets
μ = 115.9 GeV, σ = 17.4 GeV
Entries / 5 GeV
m(jj) [GeV]


P_T(b-jet) = 216.5 GeV
P_T(e-) = 95.8 GeV
P_T(b-jet) = 97.8 GeV
P_T(e+) = 224.1 GeV

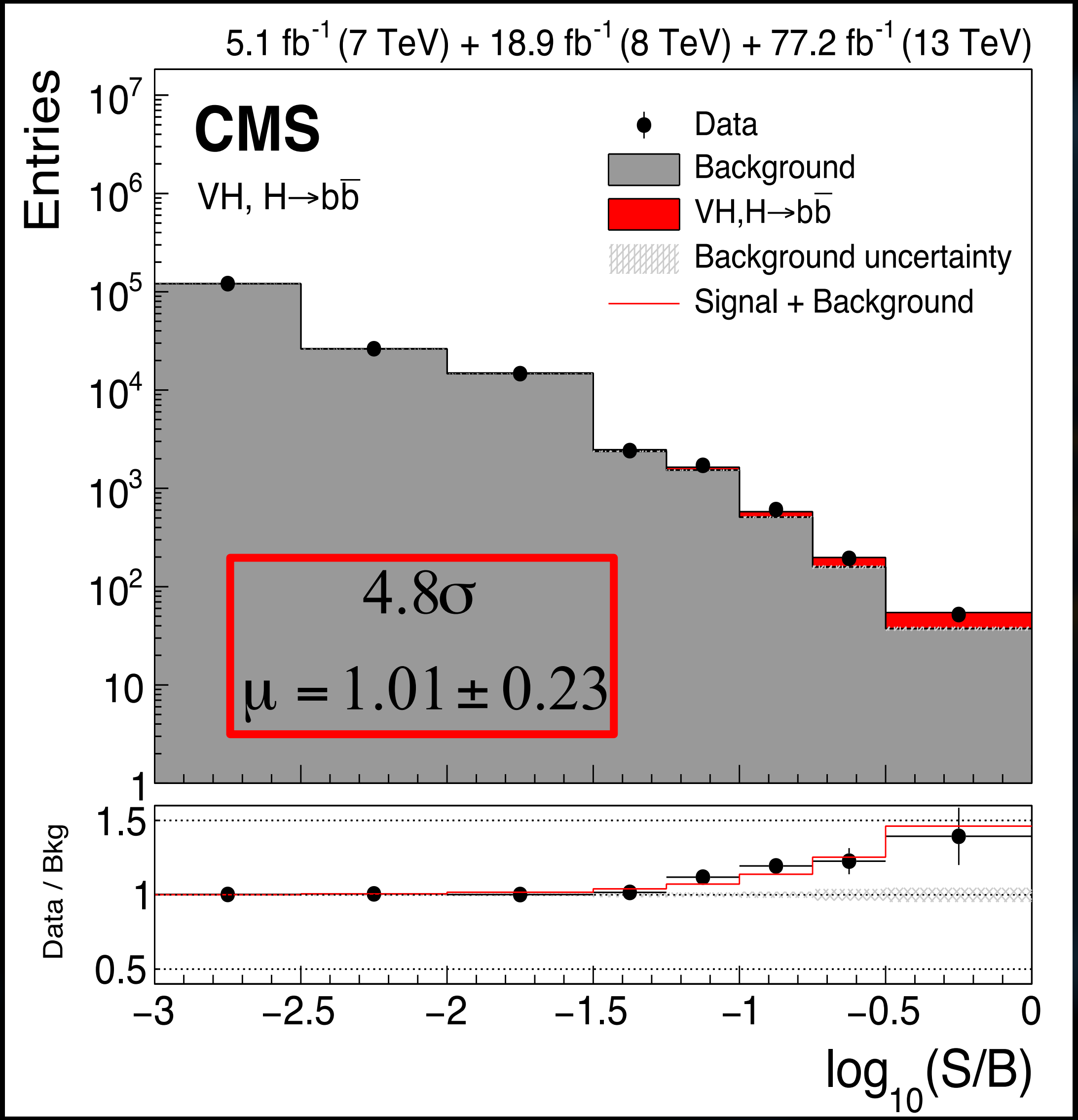
Signal vs Background discriminator

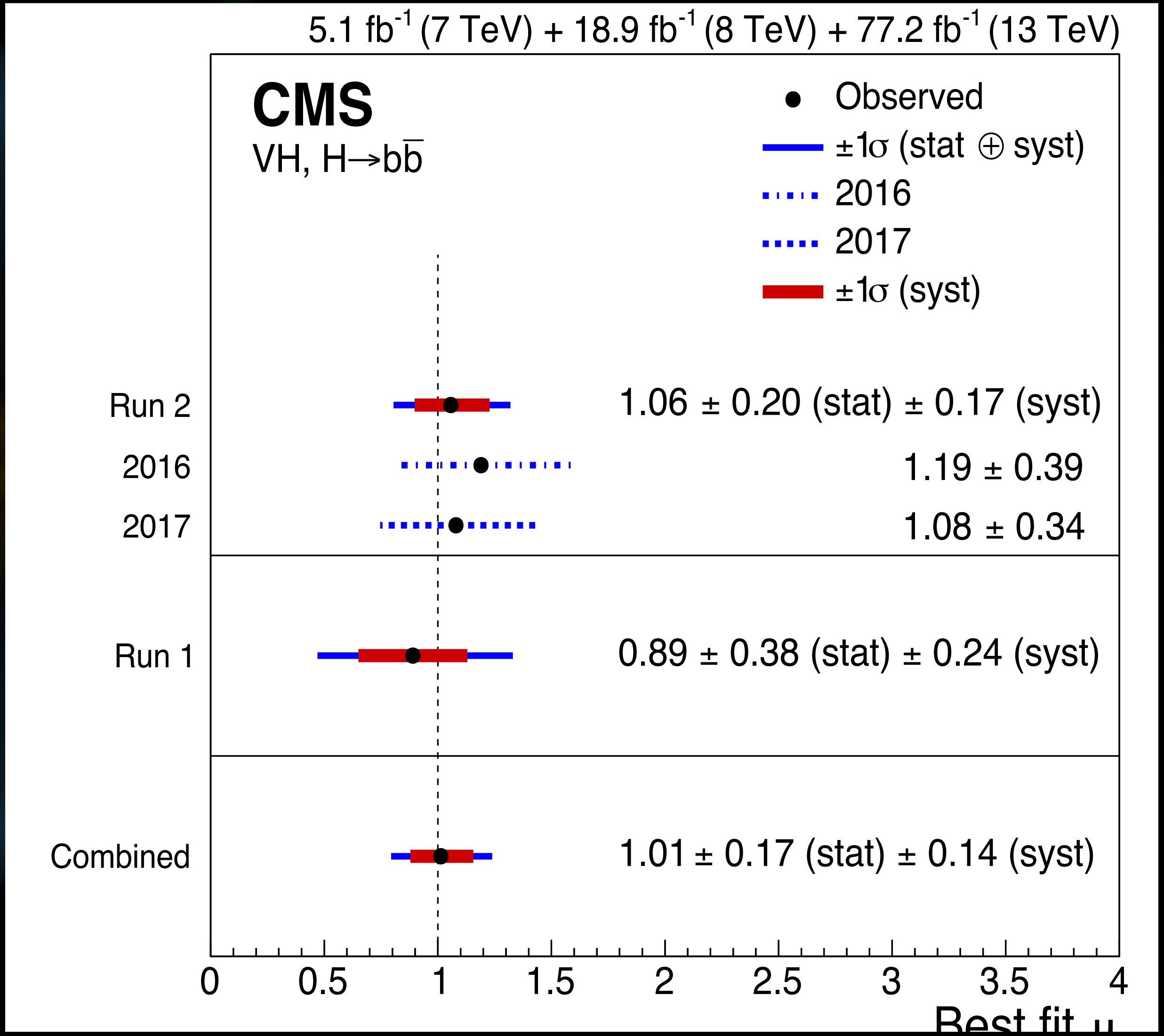
1-lepton (μ)

- DNN discriminator used to extract signal
- Input variables:
    - b-jet properties
    - H, V candidate kinematics
- Carefully validated through data/MC comparisons
- Optimized separately in each channel
- Performance optimization with blind analysis



Run 1+2016+2017 VHbb

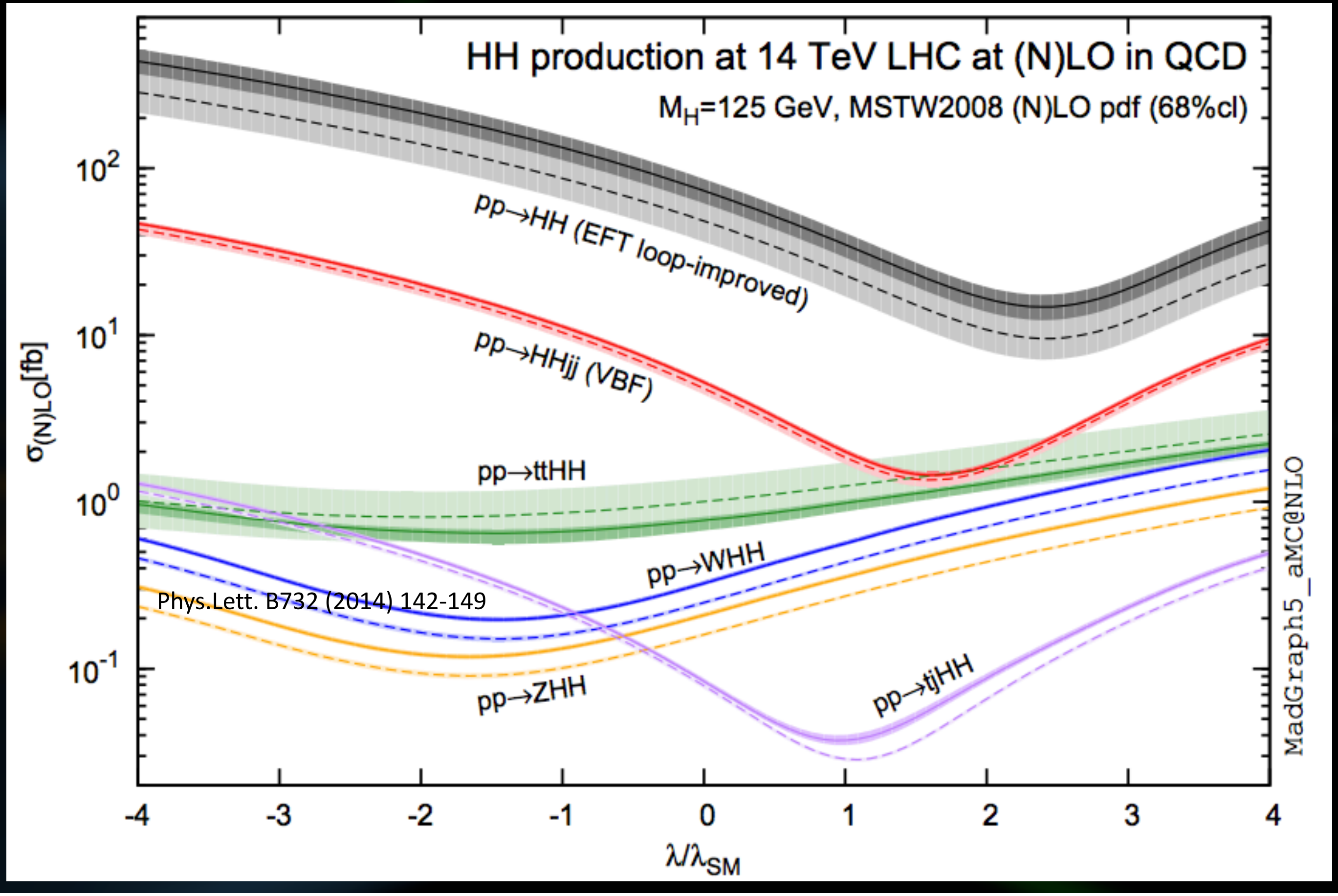


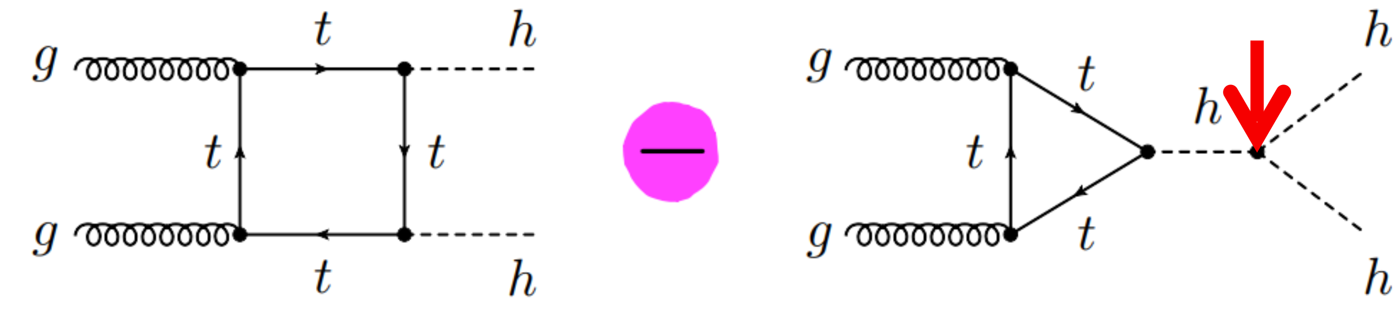


The Search for the Higgs Potential

Double Higgs Production

- At LO things are conceptually simple
- Only the right term below has triple-higgs vertex in it.
- The two terms below interfere destructively.
- The left—with two Yukawa couplings of the Higgs to the top—has a dominate cross section for SM triple-higgs coupling strength.



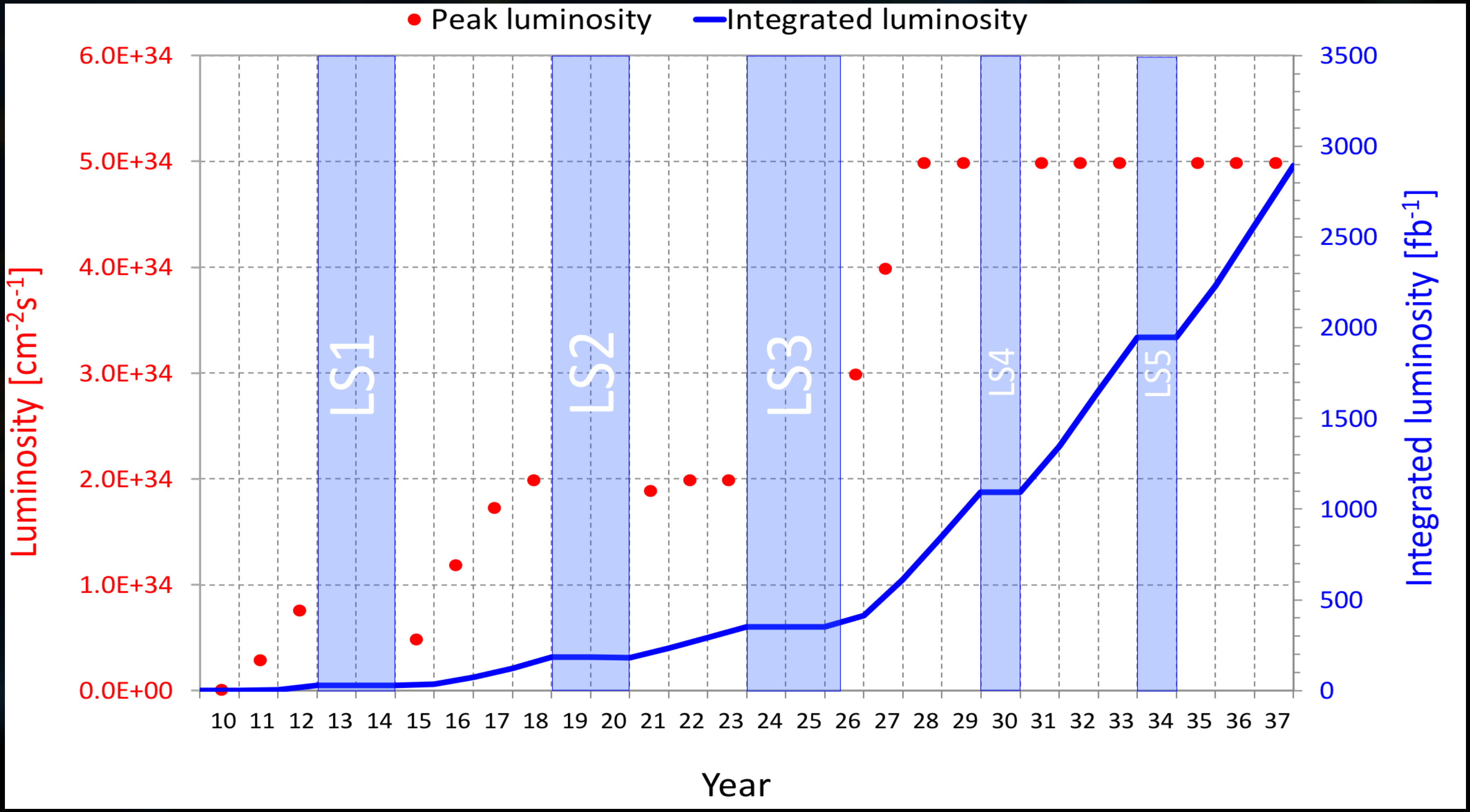


(Di-)Higgs Production at LHC

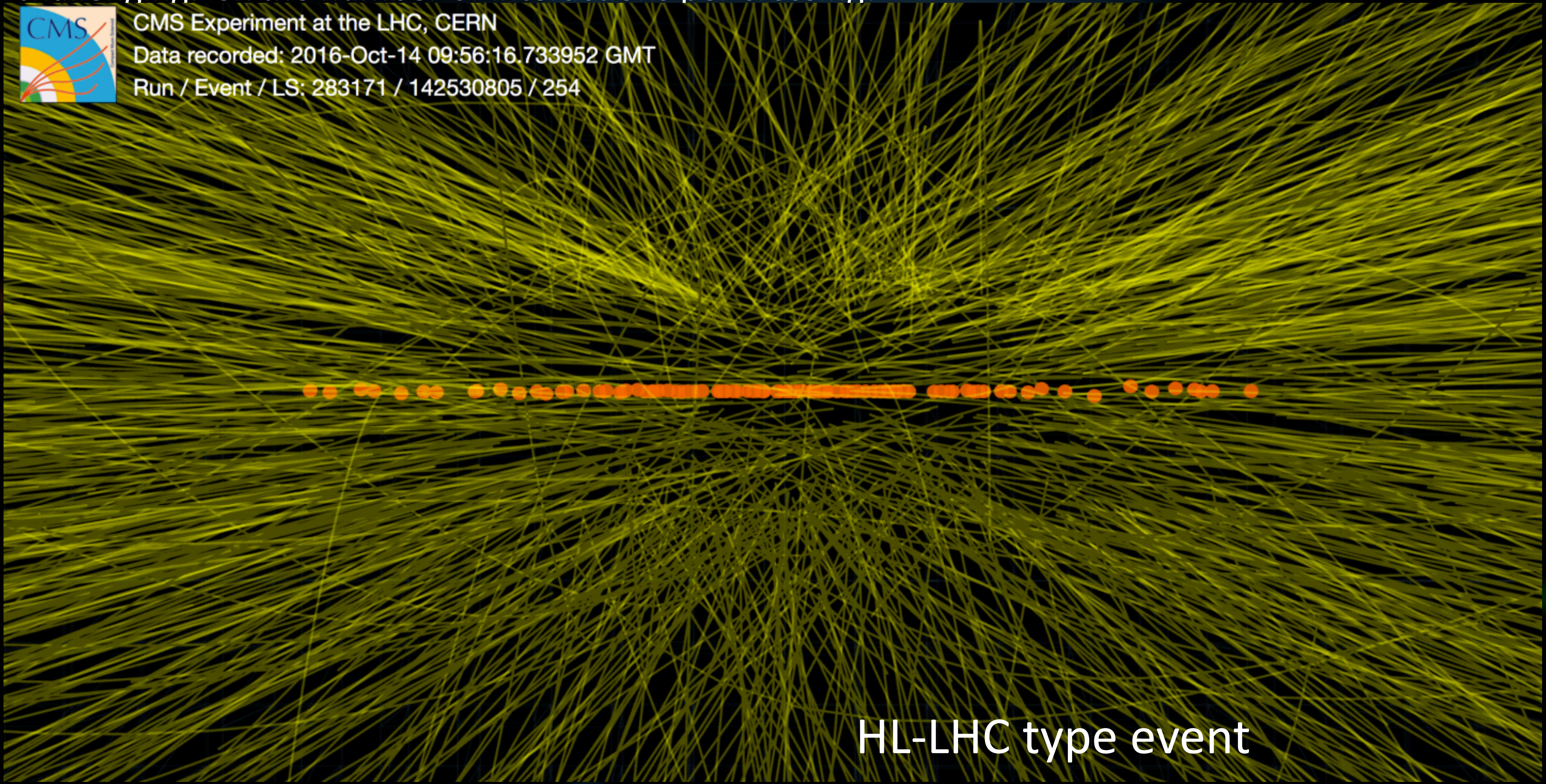
- σ(pp—>h) ~ 50 pb
- σ(pp—>hh) ~35 fb
  - (~1/1000th)

- Small cross section
  - need more data!!

Dataset	One Higgs	Two Higgs
HL-LHC (~3000/fb)	1.5e8	**1.1e5**
Run 2/3 (~140/fb)	7.1e6	4200
Run 1 (~25/fb)	5.7e5	192
Discovery (~10/fb)	2.3e5	69



- Searching for di-Higgs boson production is vitally important for getting close to estimating the self-coupling of the Higgs boson.
  - Double Higgs cross sections ~1/1000th of single Higgs
  - High Luminosity LHC should yield a huge dataset (20x Run 2)
  - Very challenging: 5x the number of interactions per crossing!



Summary

- The Higgs boson is the crown jewel of the electroweak sector of the SM.
- We have observed Higgs decays in many channels and all major production mechanisms.
- The future of the program is going to be finding the self-coupling strength, which will take creativity and LOTS of data.