How and Why to go Beyond the Discovery of the Higgs Boson

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http://hep.uchicago.edu/~johnda/ComptonLectures.html

Lecture Outline

April 1st: Newton's dream & 20th Century Revolution

April 8th: Mission Barely Possible: QM + SR

April 15th: The Standard Model

April 22nd: Importance of the Higgs

April 29th: Guest Lecture

May 6th: The Cannon and the Camera

May 13th: ***The Discovery of the Higgs Boson***

May 20th: Problems with the Standard Model

May 27th: Memorial Day: No Lecture

June 3rd: Going beyond the Higgs: What comes next ?

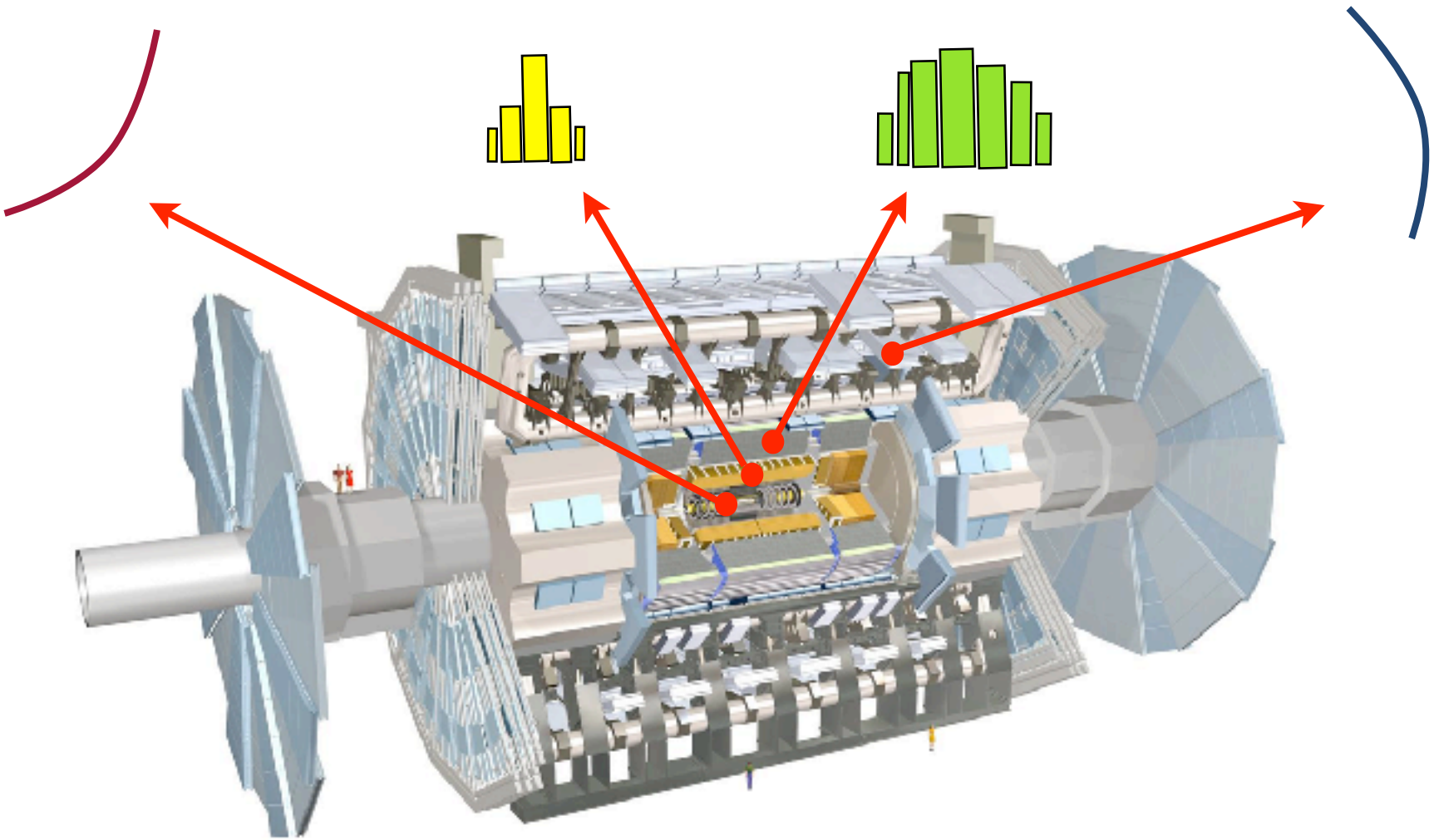
The Basic Outputs:

Inner Tracking System

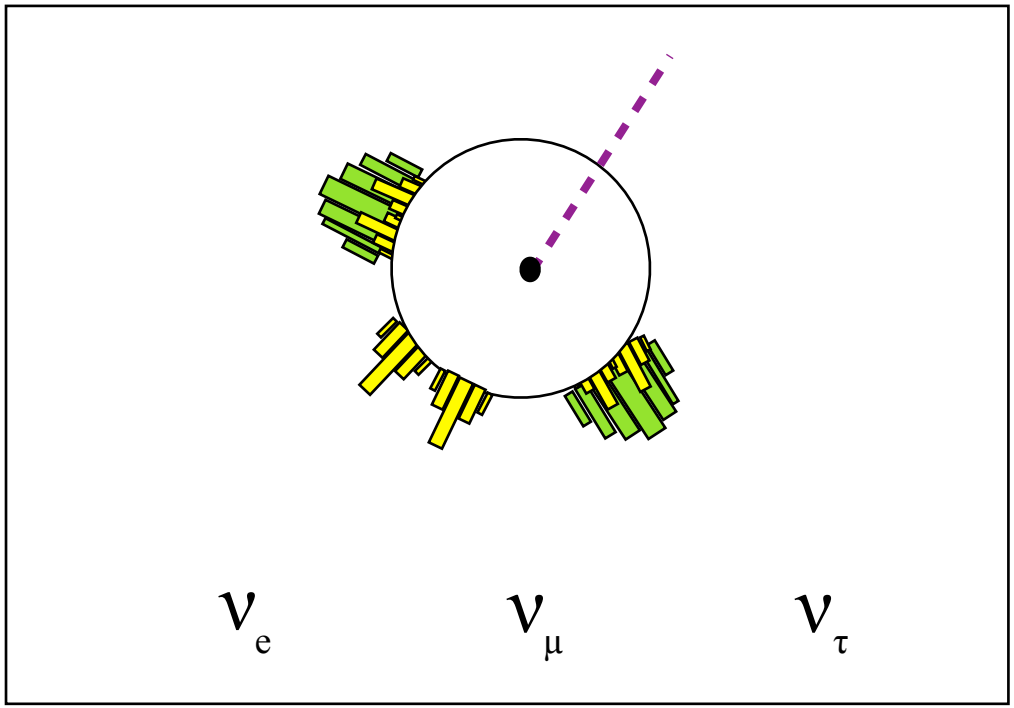
Electro-Magnetic Calorimeter

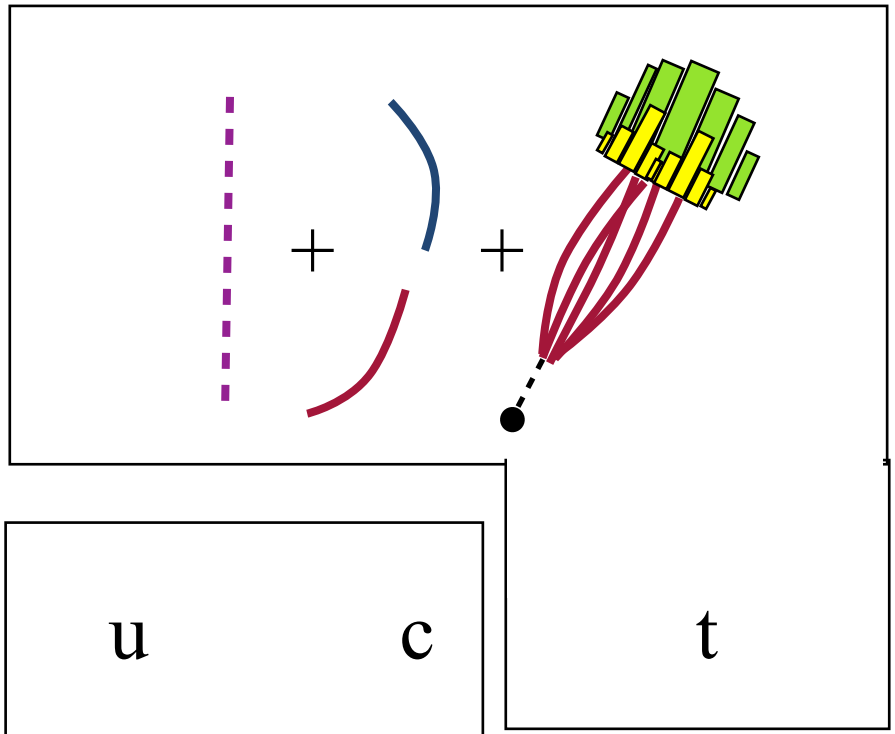
Hadronic Calorimeter

Muon Tracking System



A lot of work goes into making/understanding these basic outputs.


ν_e
ν_μ
ν_τ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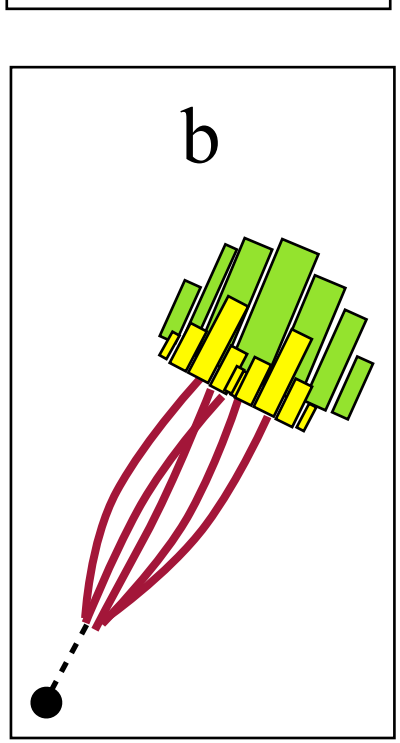
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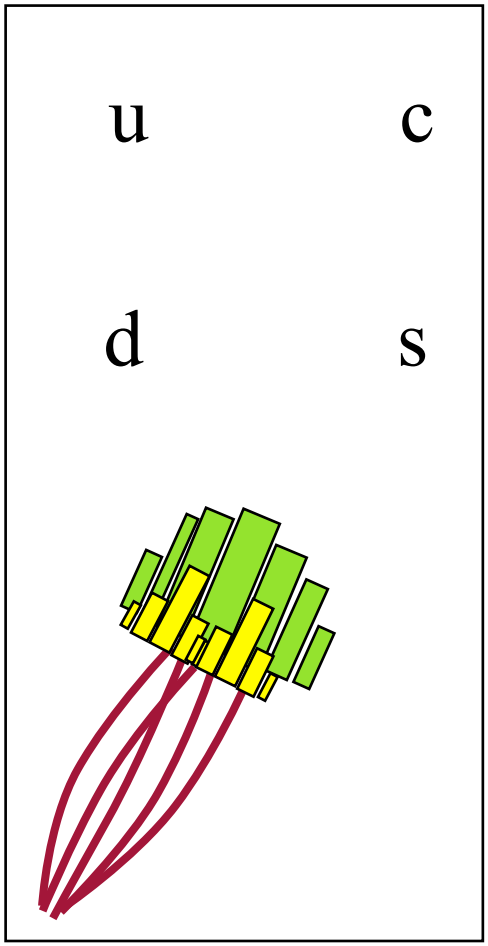
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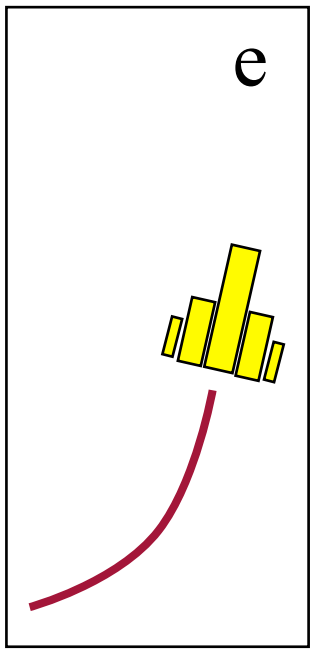
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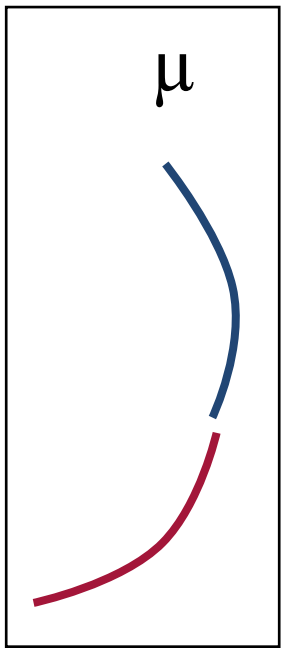
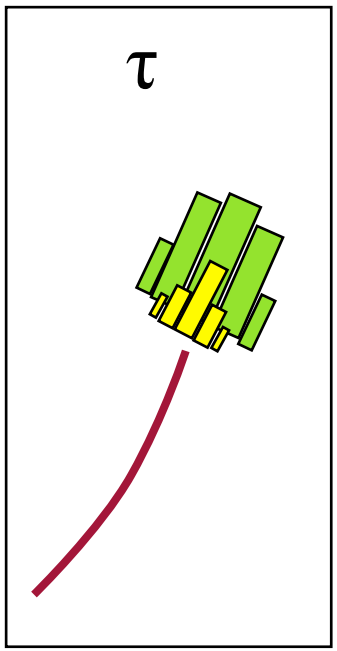

μ

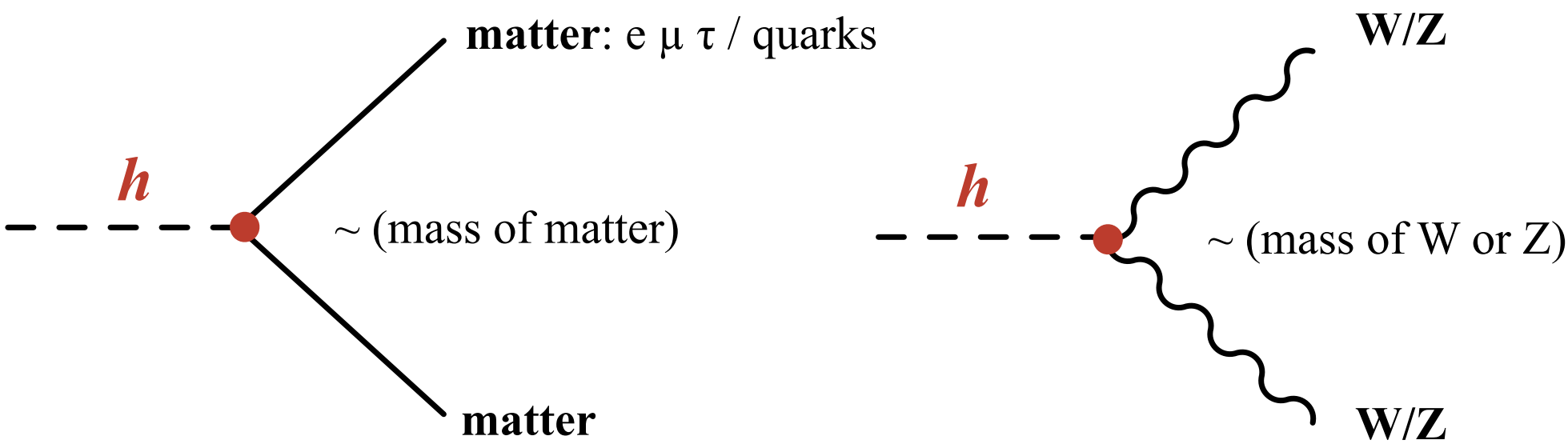

τ

Reminder: *The Higgs Boson*

What do we know about the Higgs Particle: ***A Lot***

Higgs is excitations of v-condensate

$\Rightarrow$ Couples to matter / W/Z just like v



Spin: 0 ~~1/2~~ ~~1~~ ~~3/2~~ ~~2~~

Only thing we don't (*didn't!*) know is the value of mH

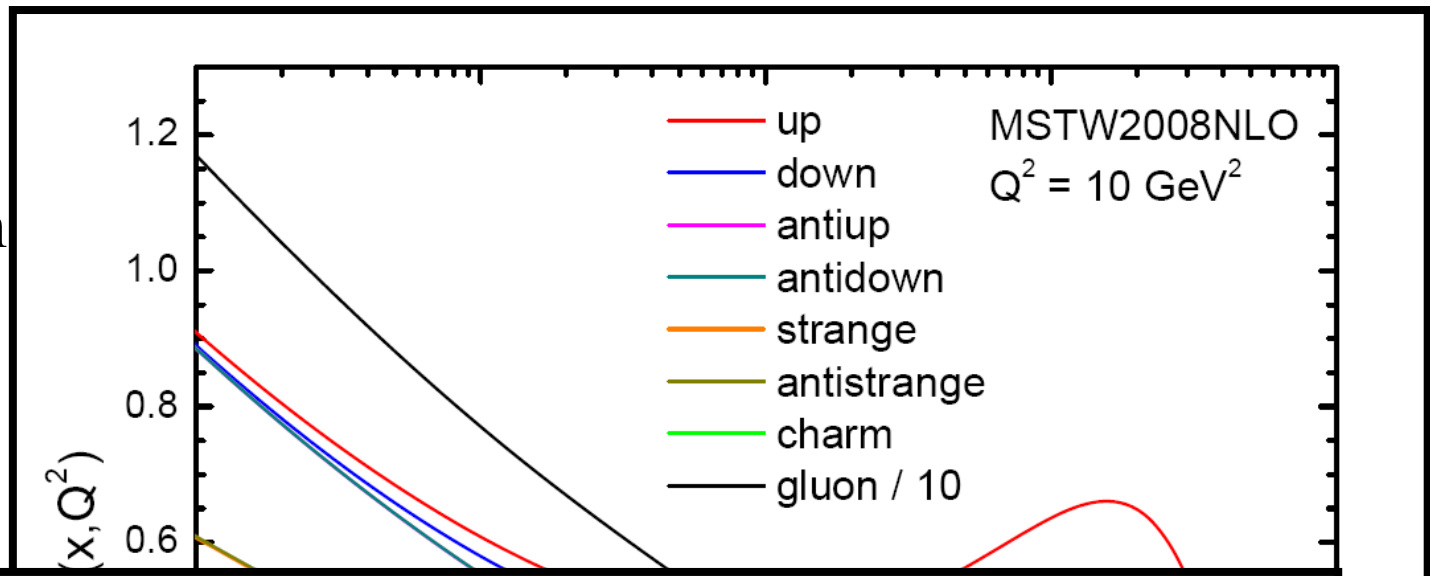
Today's Lecture

The Discovery of the Higgs Boson

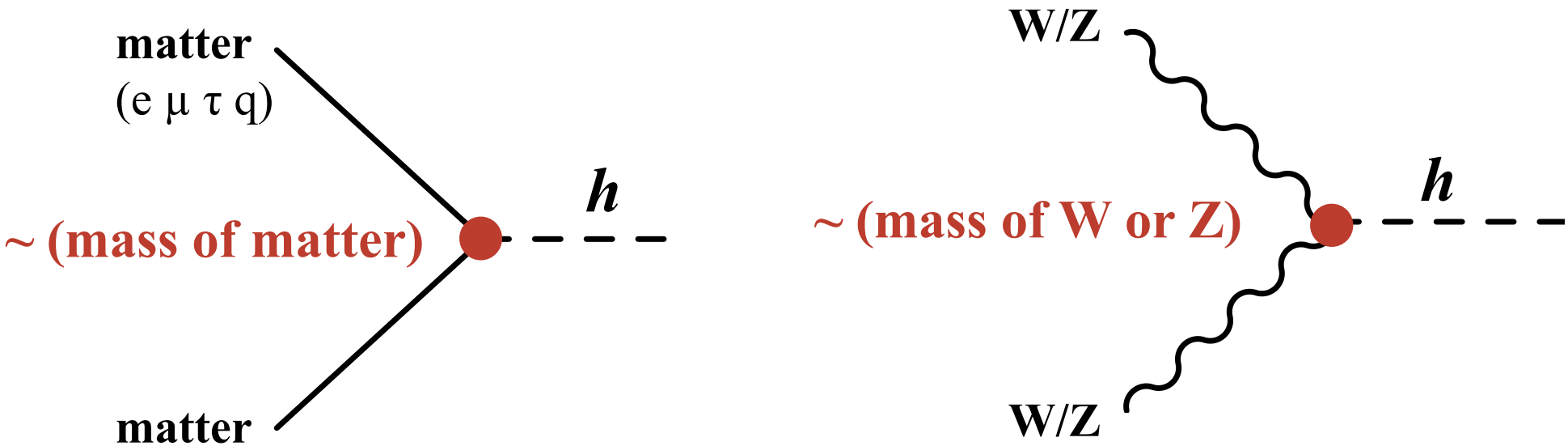
How to Make Higgs Bosons ?

Collide Protons !

(Really Quarks/gluon

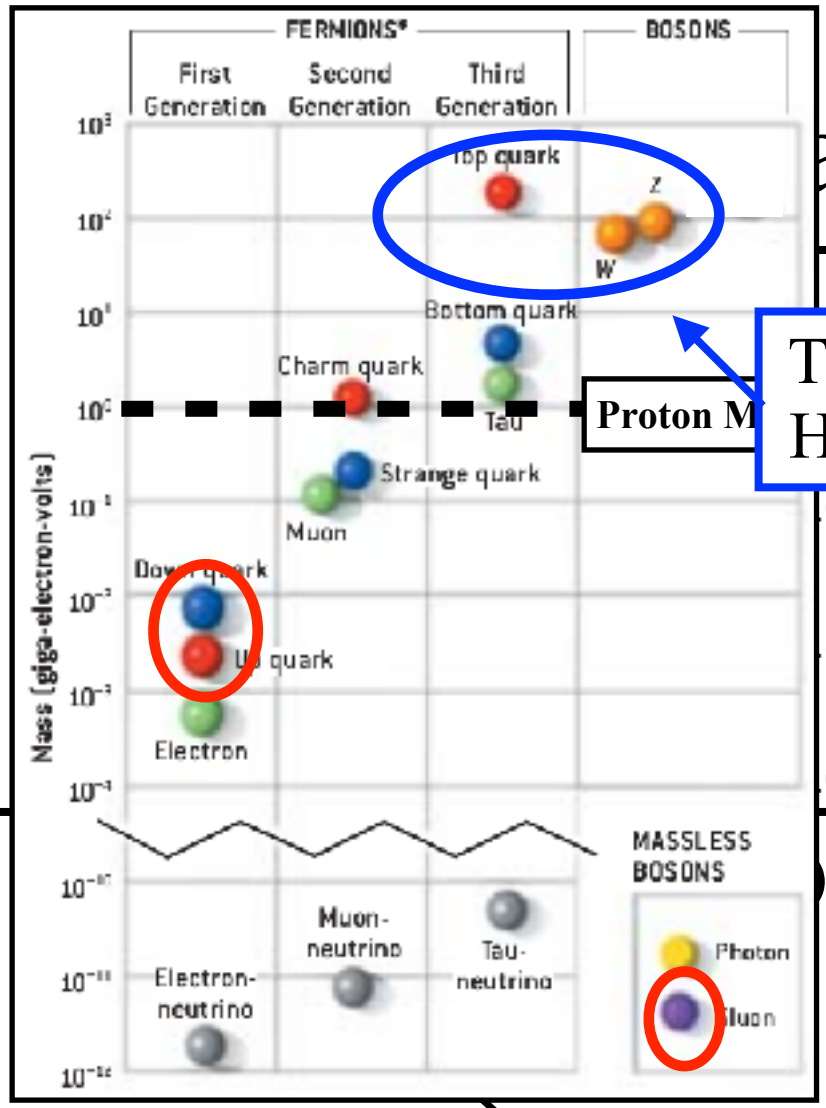


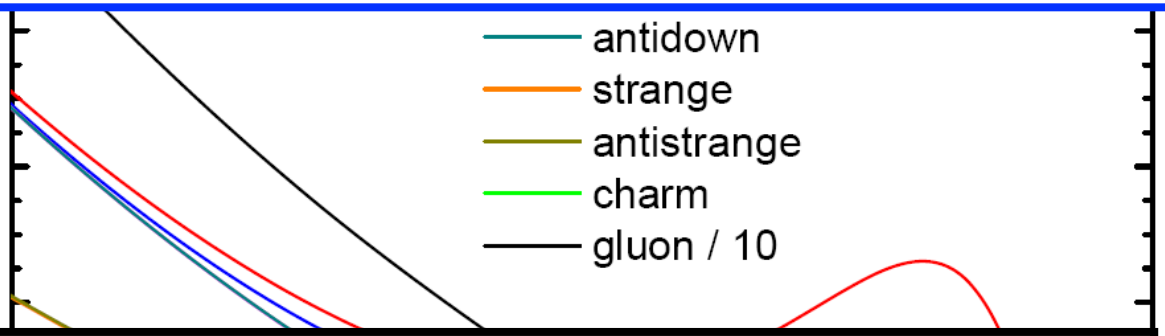
Higgs interactions (couplings) matter known:



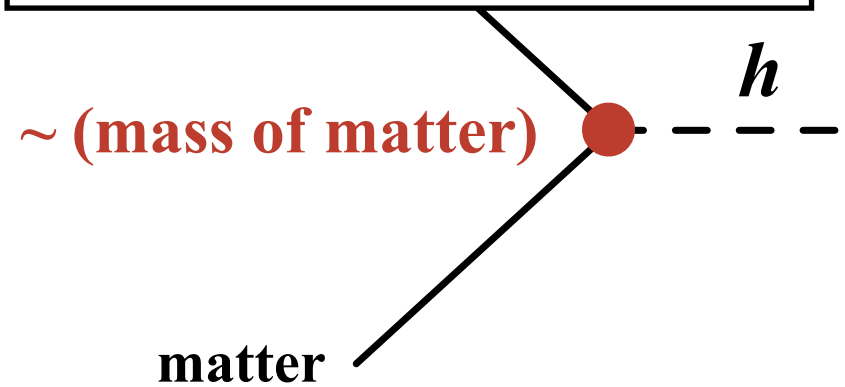
All things that exist in the proton light !
⇒ small of a coupling to Higgs
⇒ small of a probability to produce Higgs

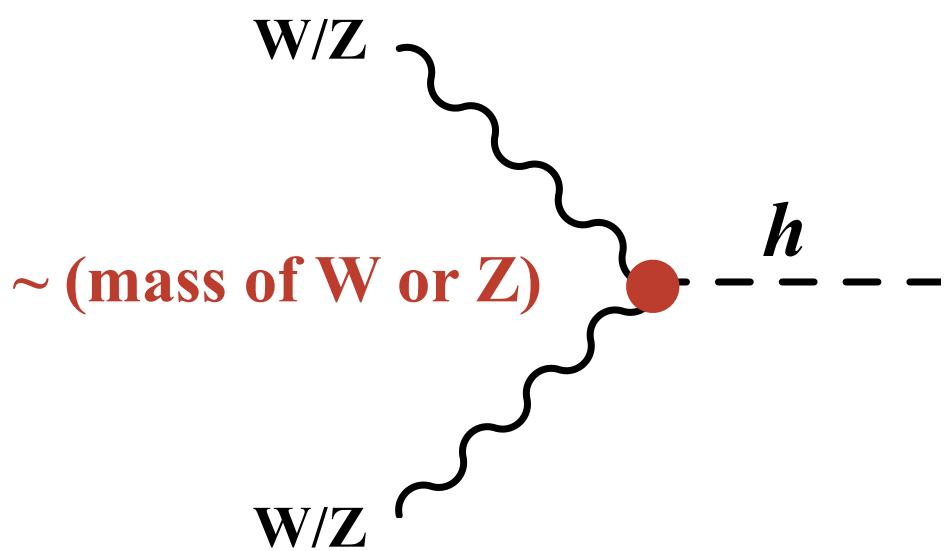
Top quark / W / Z are heaviest things in theory
Have the highest probability of producing Higgs





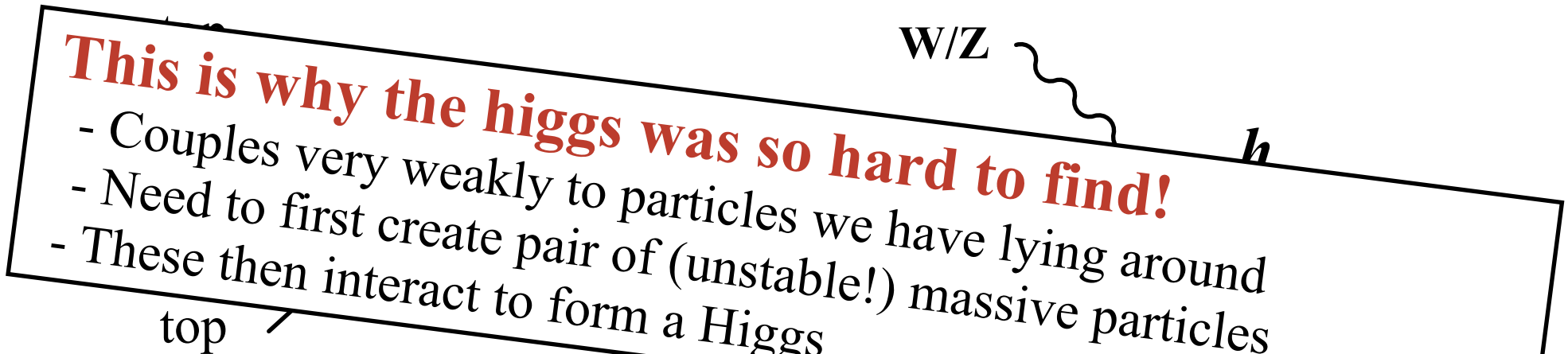
matter known:





How to Make Higgs Bosons

We really want to use processes like:



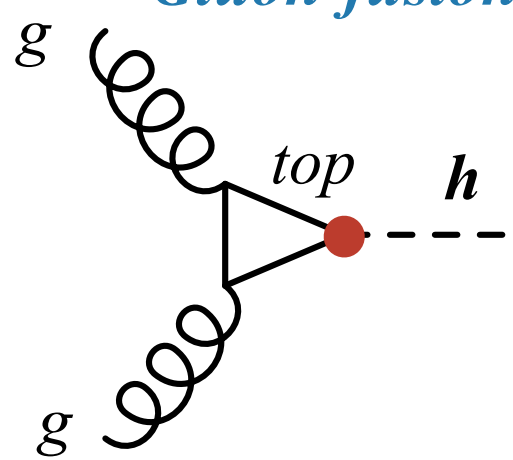
This is why the higgs was so hard to find!

- Couples very weakly to particles we have lying around
- Need to first create pair of (unstable!) massive particles
- These then interact to form a Higgs

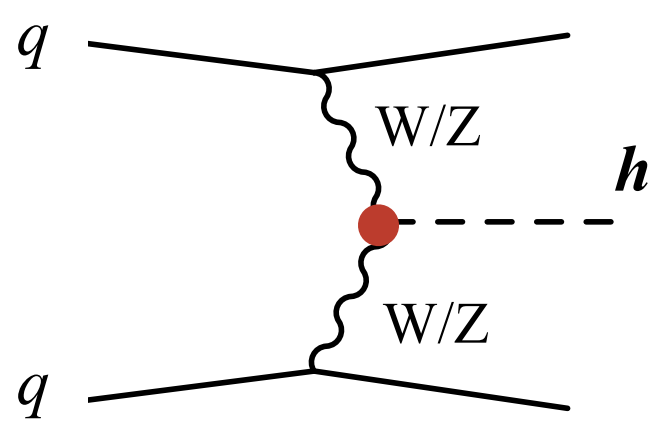
Problem is we don't have Top/W/Z colliders

⇒ ***Have to make tops and W/Z from protons first***

Gluon-fusion

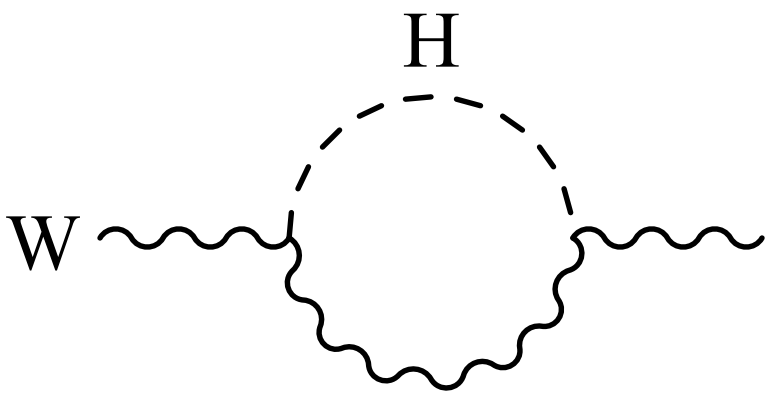


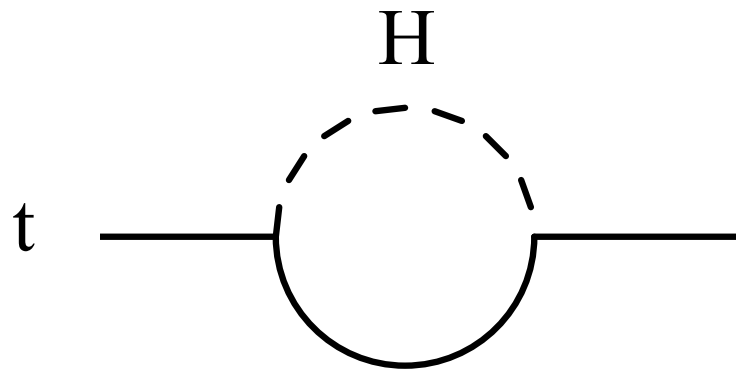
Vector-Bosons Fusion



Where to look for the Higgs Boson ?

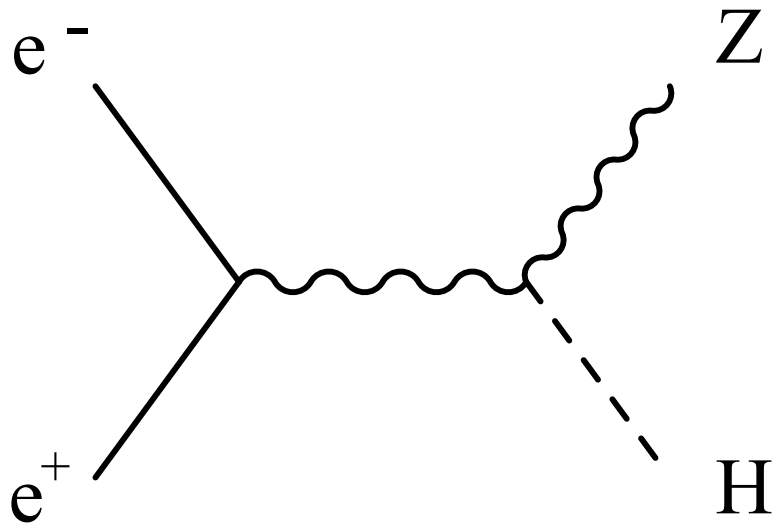
Mass constraints pre-LHC





50 < mH < 150 GeV (95%)

Limits from direct search Large Electron-Positron collider (LEP)



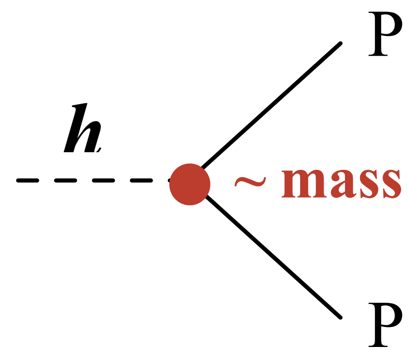
mH > 115 GeV

How to look for the Higgs Boson ?

Higgs Boson quickly decays to other particles.

- Basic Higgs interactions control how the Higgs can decay
- Fraction of decays to particular particle is: ***Branching Ratio***

Branching Ratio =
(for particle P)



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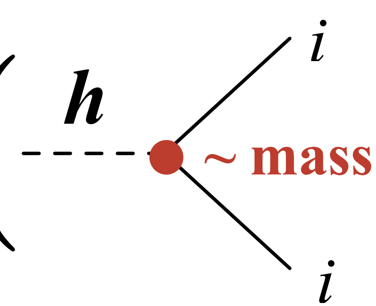
$\sum_{i}^{\text{possibilities}}$ (



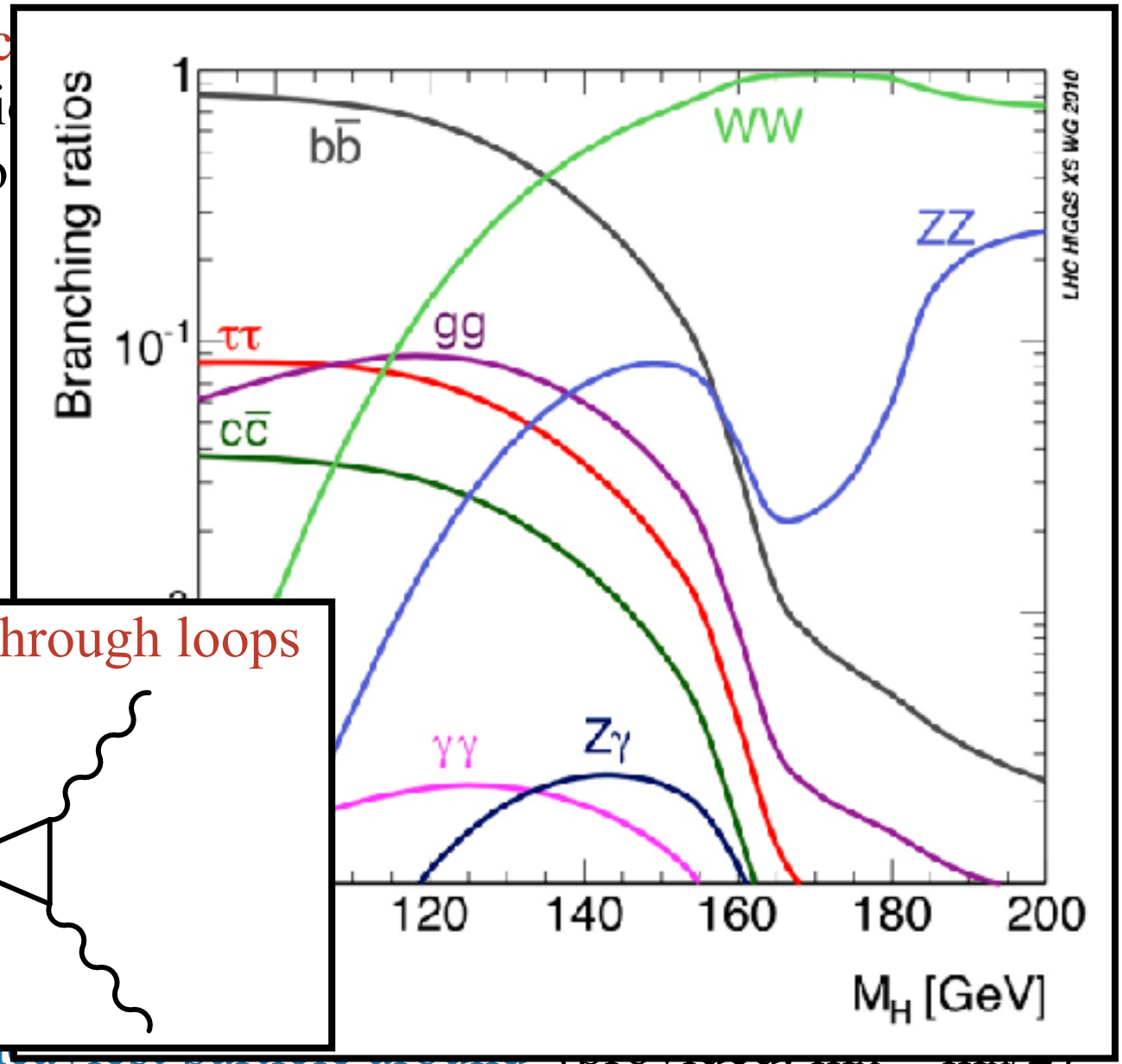
)

Higgs wants to decay to heaviest particle around (provided: $m_X < m_H/2$)

How to look for the Higgs Boson ?

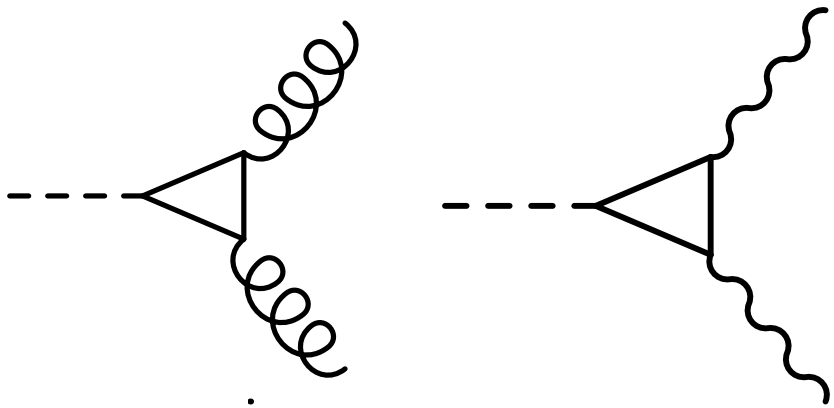
Higgs Boson quickly dec

- Basic Higgs interacti
- Fraction of decays to



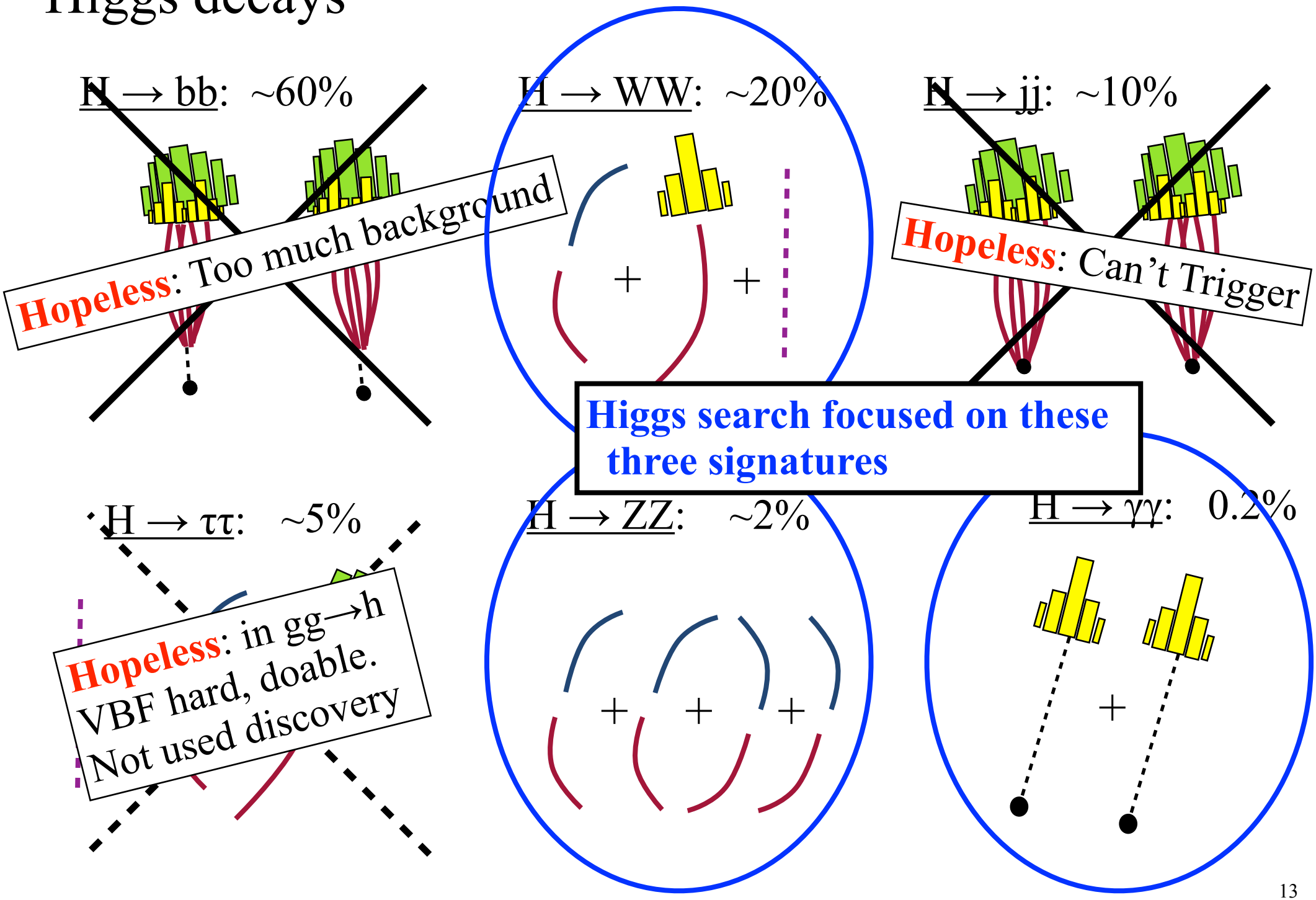
Branching Ratio

$m_\gamma/m_g = 0$ ***but*** h→γγ/gg through loops



Higgs wants to decay to heaviest particle around (provided $m_H > 2m_X$)

Higgs decays



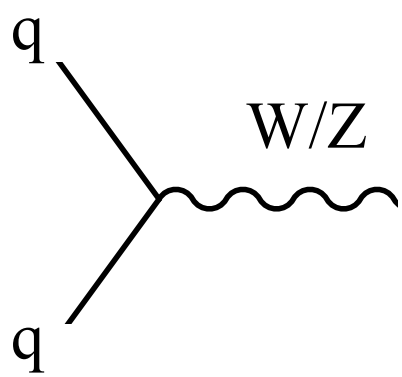
How much data do we need ?

Estimate out how often we make a Higgs.

Warm-up: *How often do we make a W/Z ?*

$$\sigma_{W/Z} \sim \frac{\alpha_W}{(m_{W/Z})^2} \sim \left(\frac{1}{50}\right)\left(\frac{1}{100}\right)^2 \text{ GeV}^{-2}$$

$$\sim 2 \cdot 10^{-6} \text{ GeV}^{-2}$$

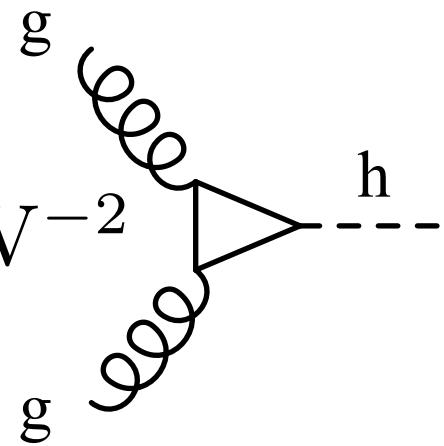


$\sigma_{pp} \sim \text{GeV}^{-2} \Rightarrow$ 1 W/Z for every 1 million proton collisions

How much data do we need ?

First estimate out how often we make a Higgs.

Same game for the Higgs



$$\sigma_H \sim \frac{1}{16\pi^2}\frac{\alpha_S^2\alpha_W}{(m_H)^2} \sim \frac{1}{160}\left(\frac{1}{10}\right)^2\left(\frac{1}{50}\right)\left(\frac{1}{100}\right)^2 \text{ GeV}^{-2}$$

$$\sim 1 \cdot 10^{-10} \text{ GeV}^{-2}$$

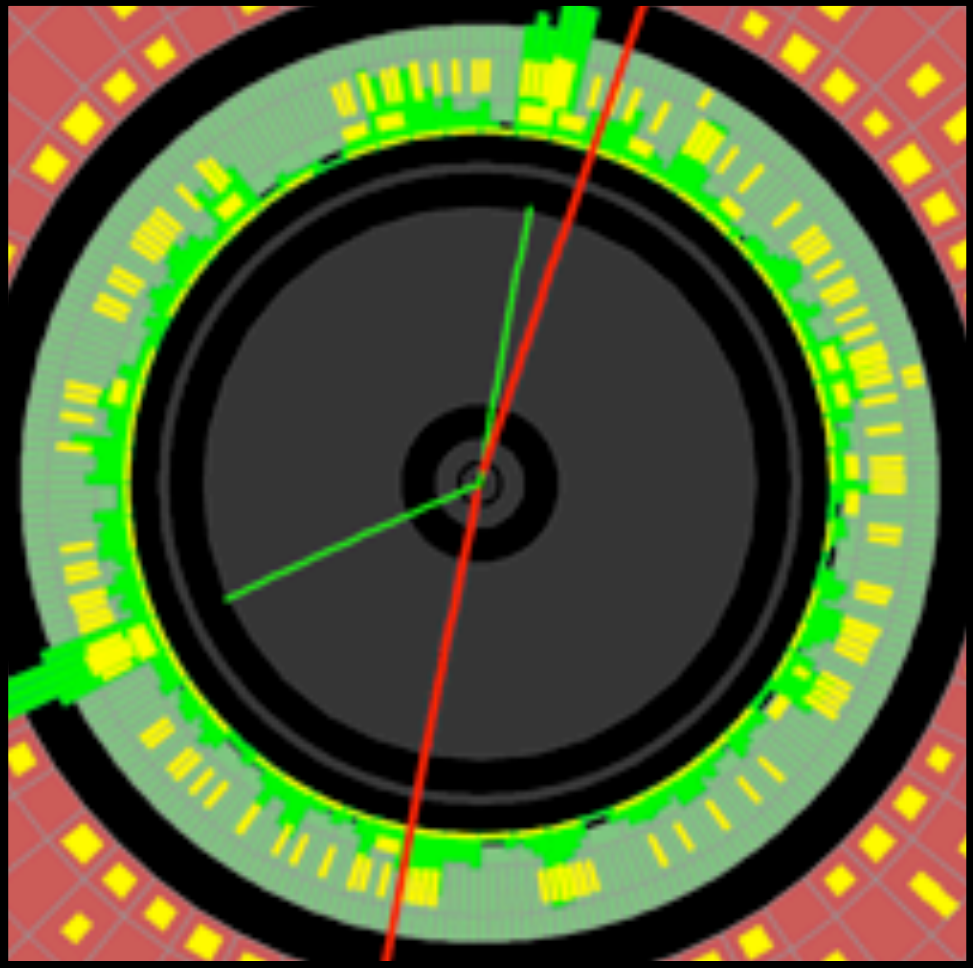
$\sigma_{pp} \sim \text{GeV}^{-2} \Rightarrow$ 1 Higgs for every billion proton collisions

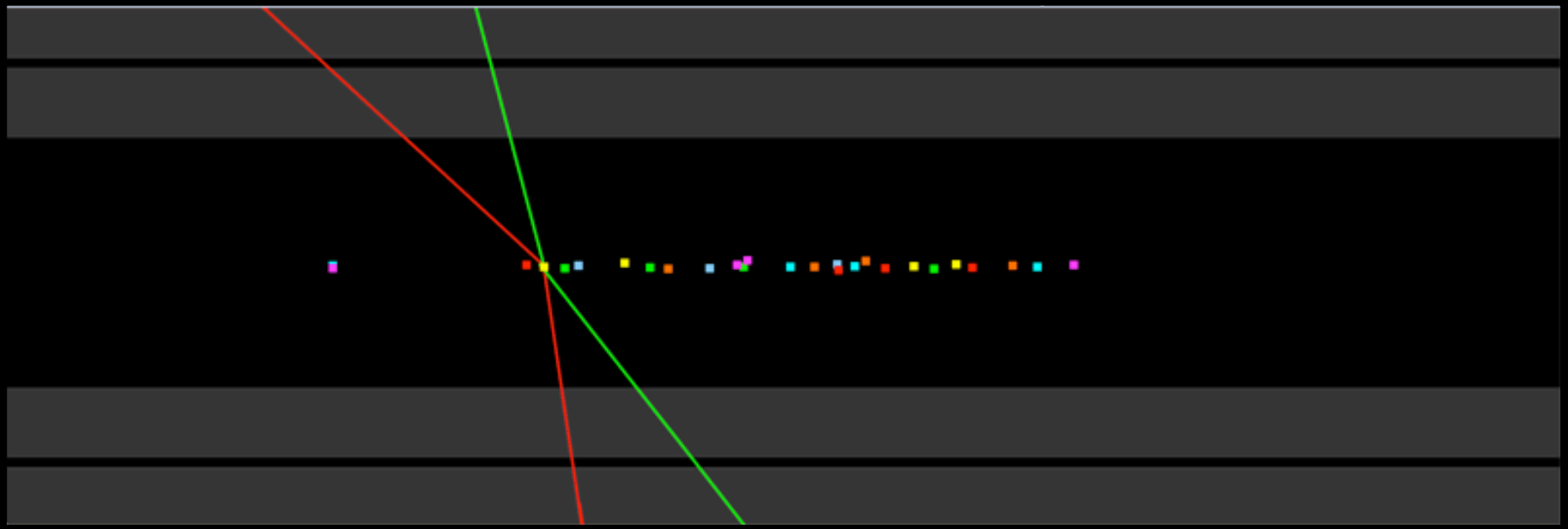
Good target: $\sim 100 \frac{h\to\gamma\gamma}{\text{year}} \sim 10^5 \frac{h}{\text{year}} \frac{\text{year}}{\epsilon\cdot 10^7 \text{s}} \sim 1 \frac{h}{\text{second}}$

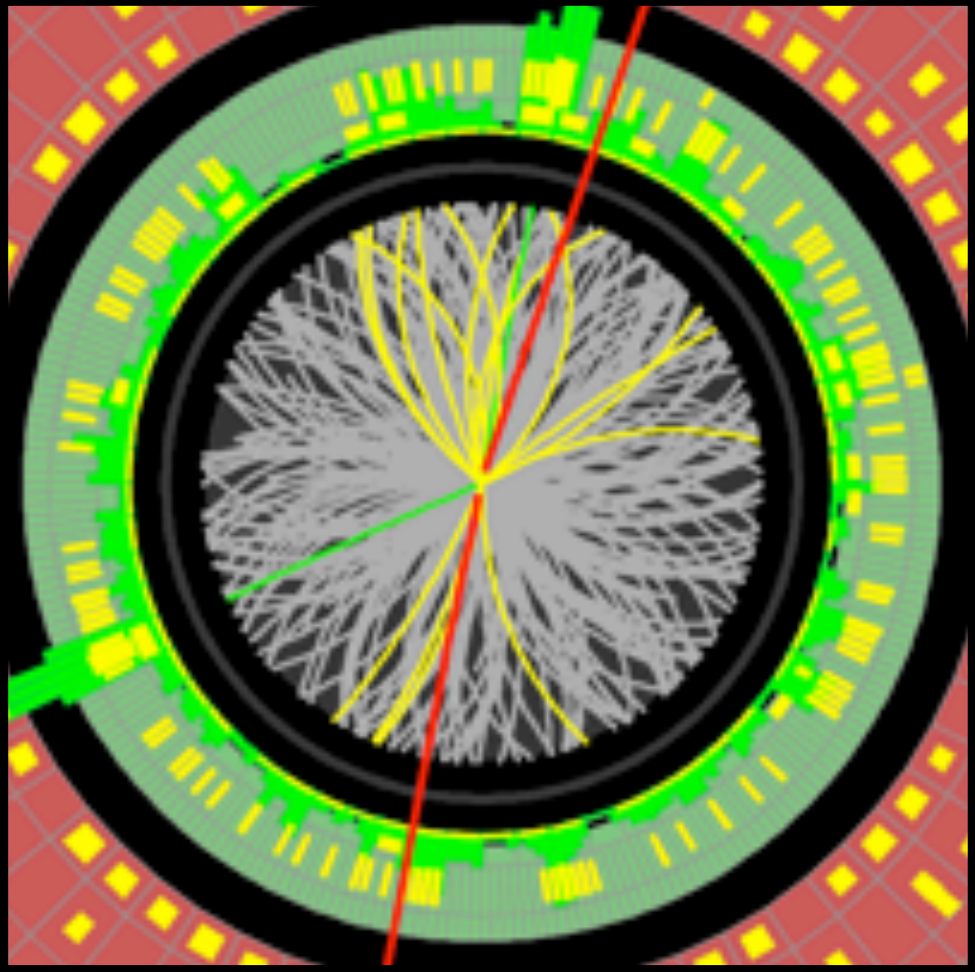
$\Rightarrow$ need billion proton collisions per second

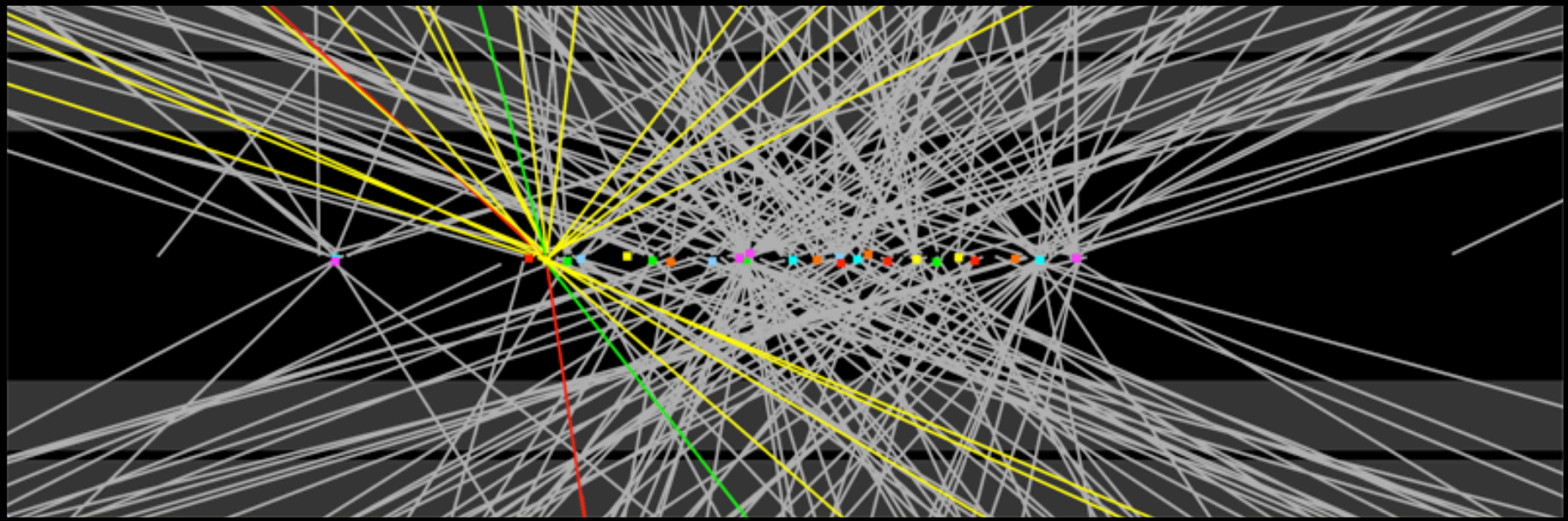
Only have beams crossing 40 million times per second …

$\Rightarrow$ **Need ~25 proton collisions per crossing !**



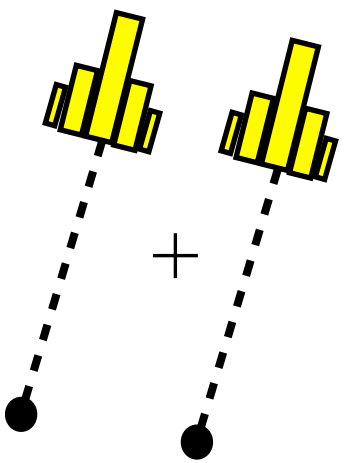


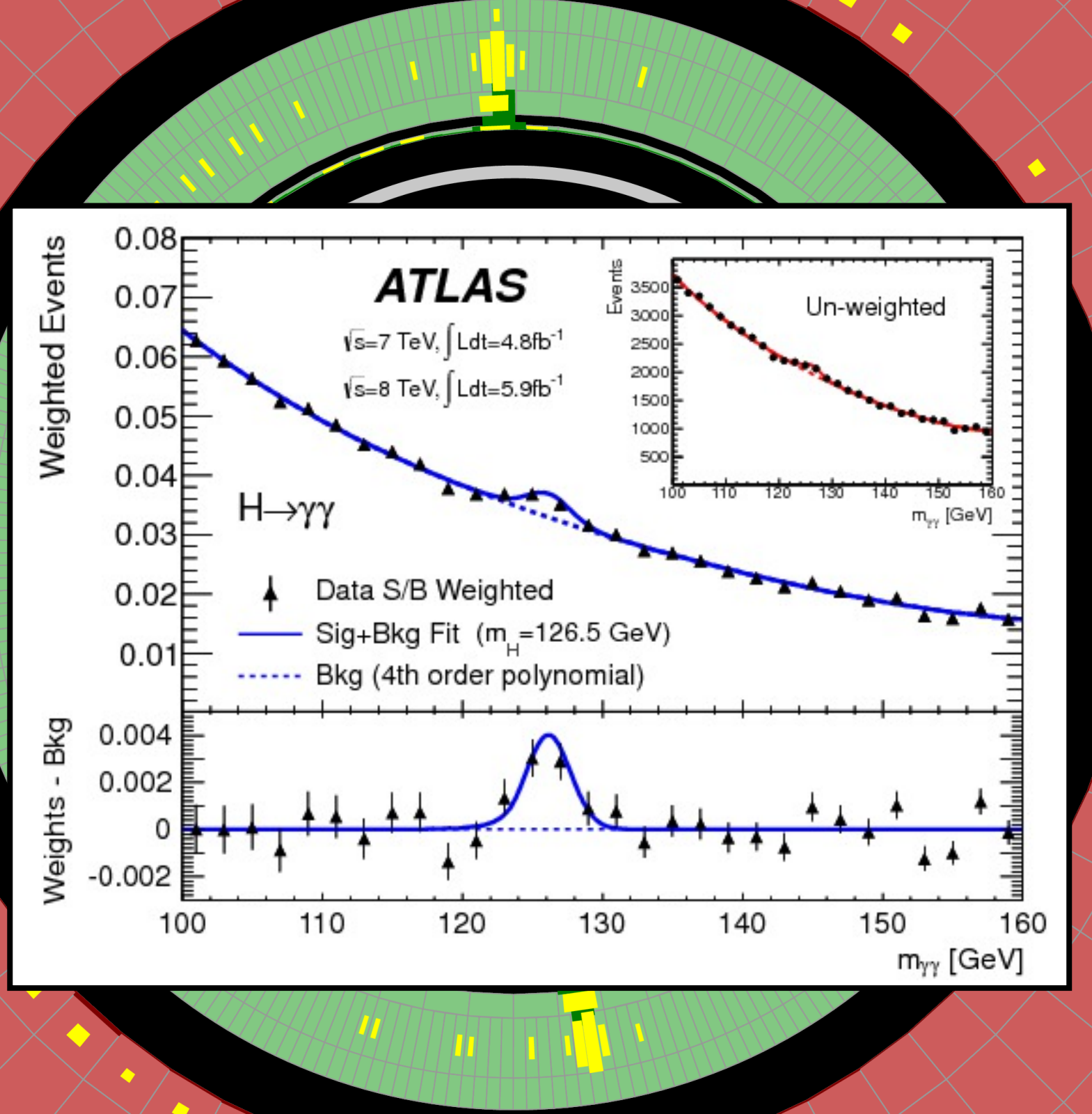




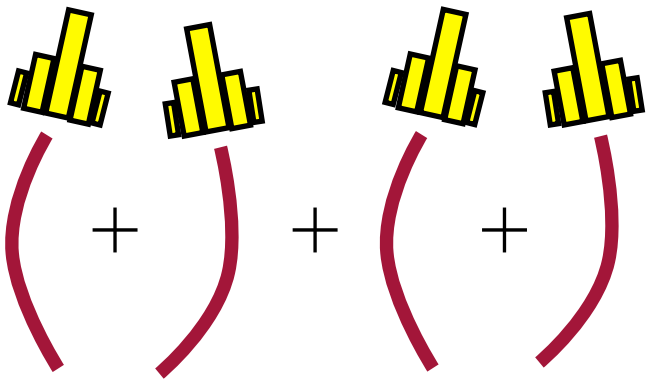
Higgs Discovery

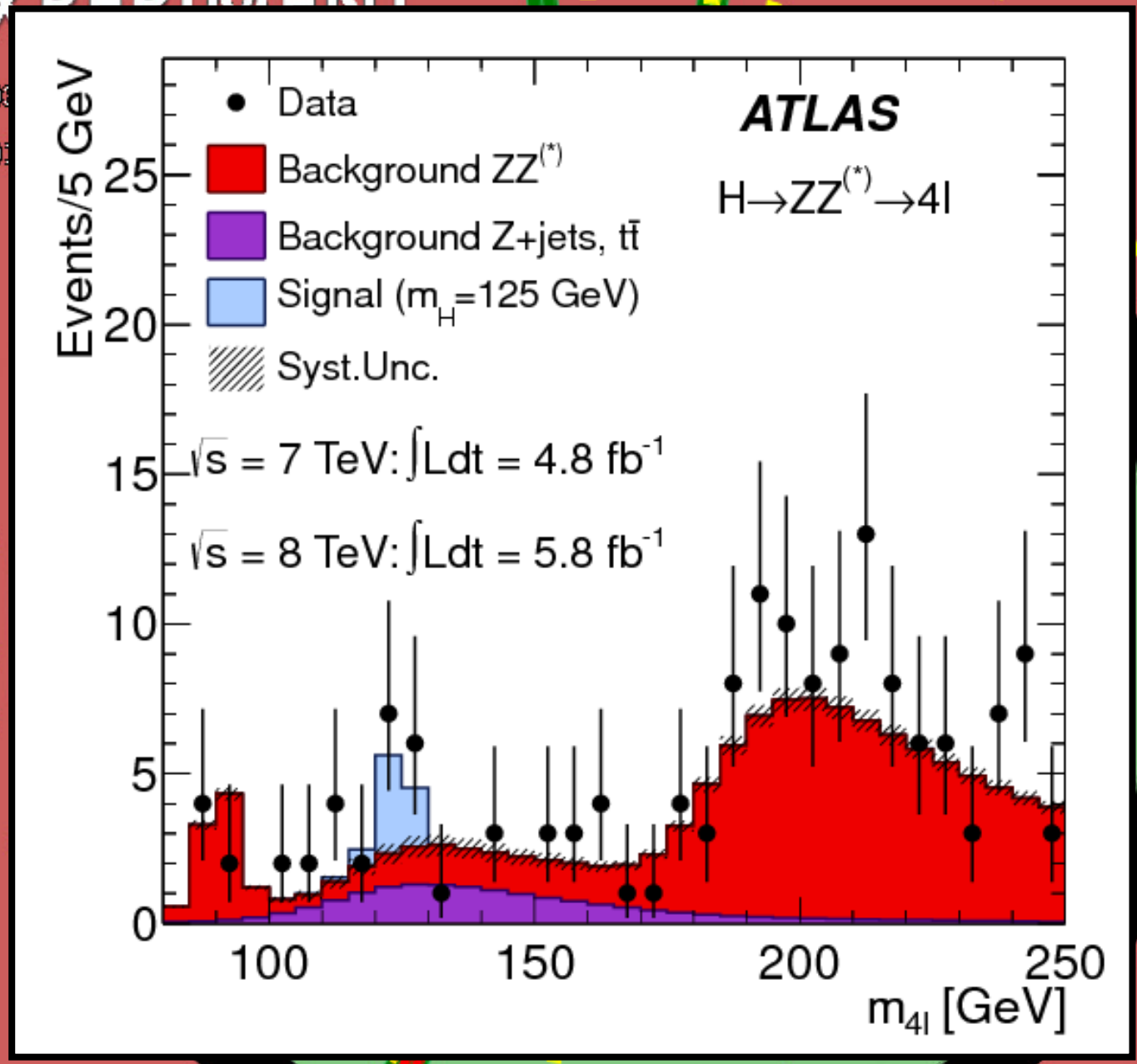
$H \rightarrow \gamma\gamma$





$H \rightarrow ZZ \rightarrow 4e$

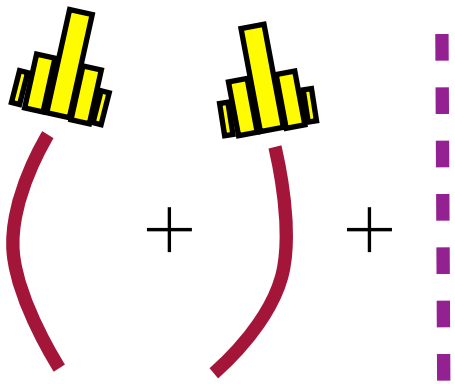




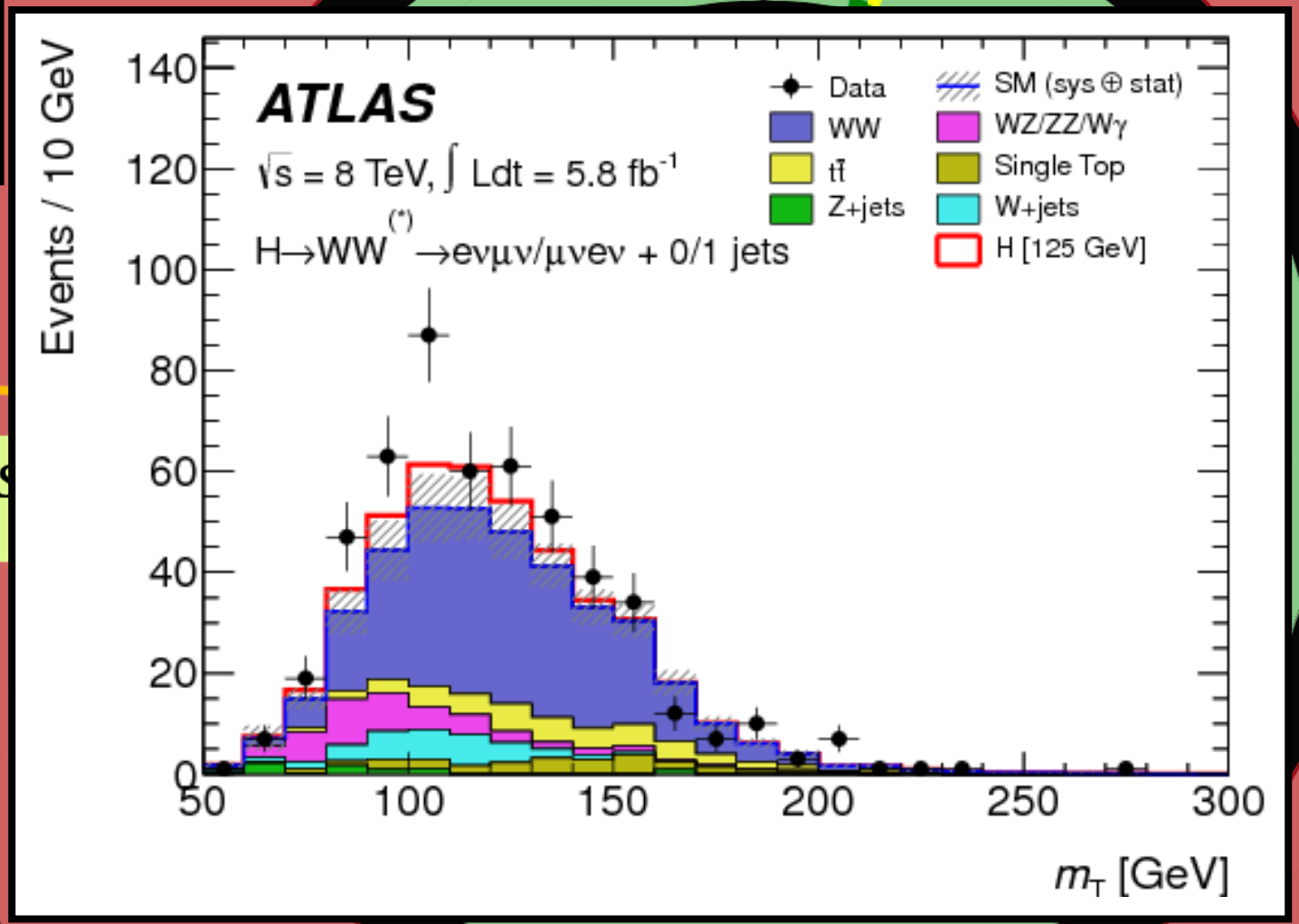
Run 166927 Event 2315222

2010-10-17 03:02:49 EDT

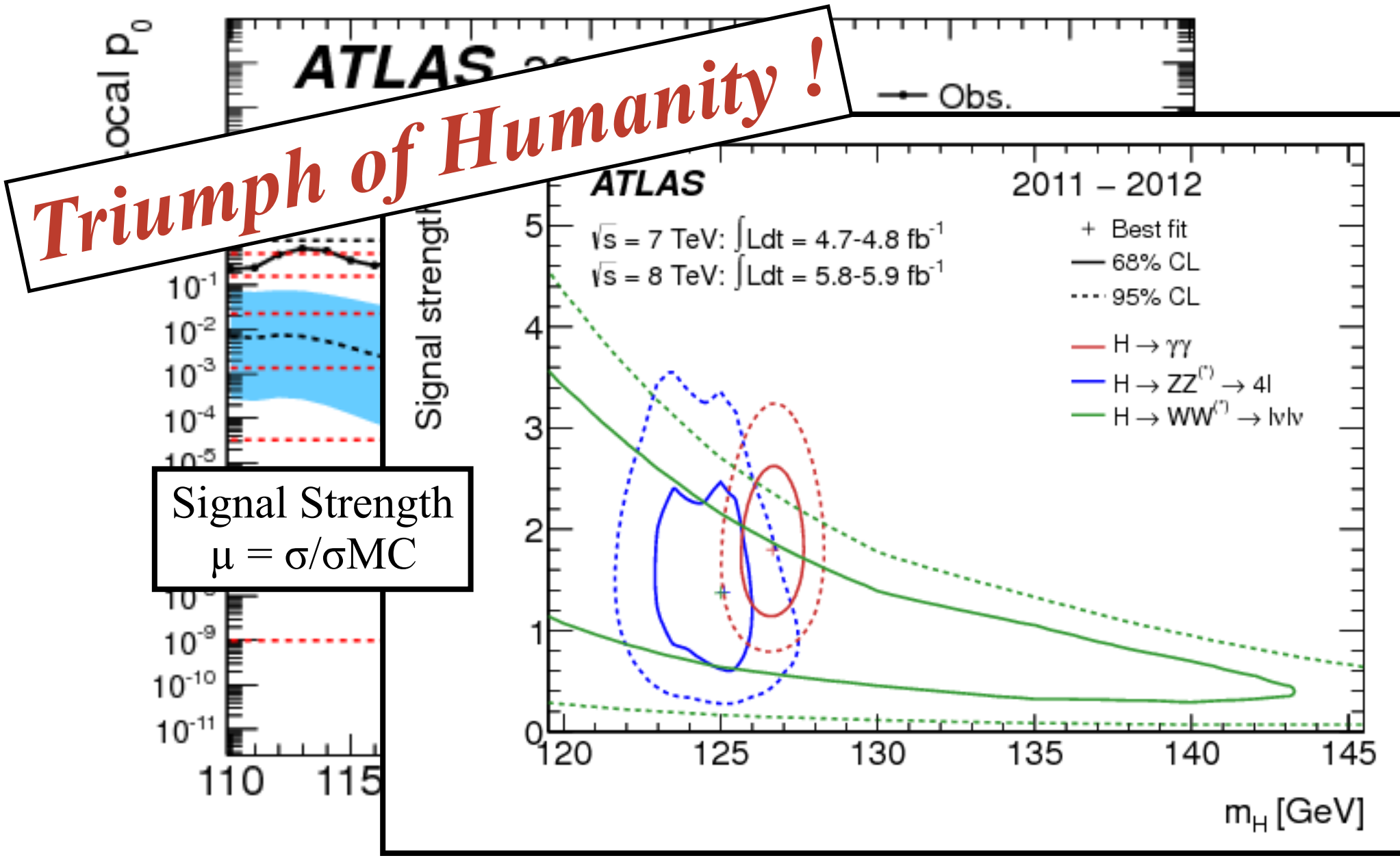
$H \rightarrow WW \rightarrow e\nu e\nu$



E_T^{mis}



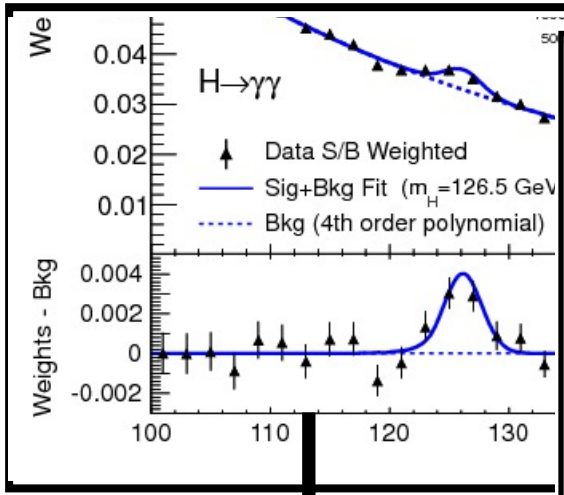
Putting It All Together

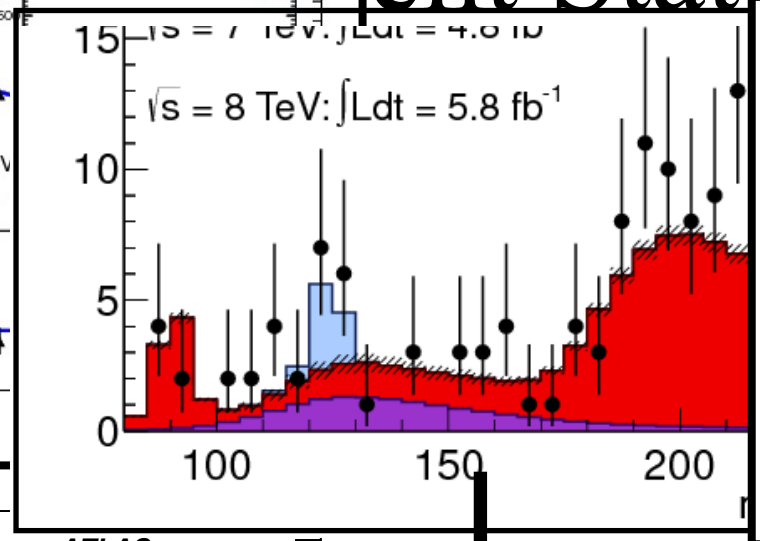


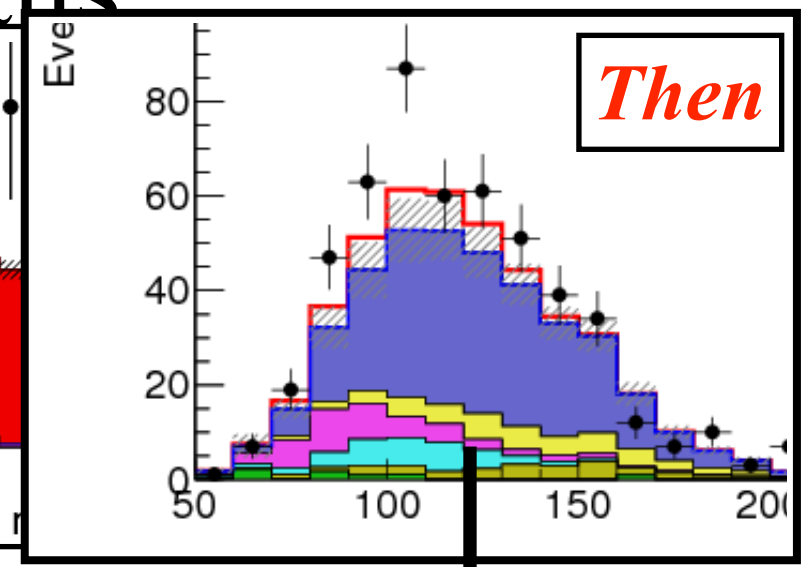
Higgs Post-Discovery

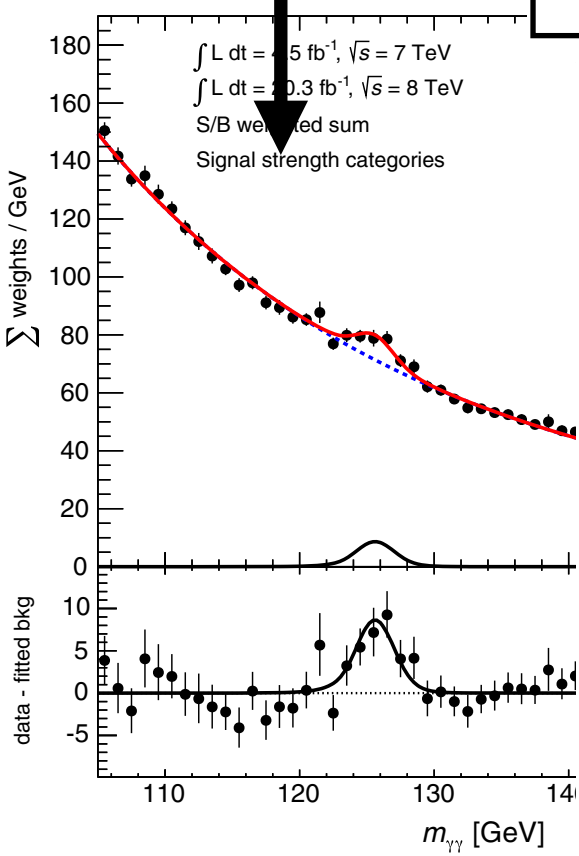
What We Know and Where We are Going

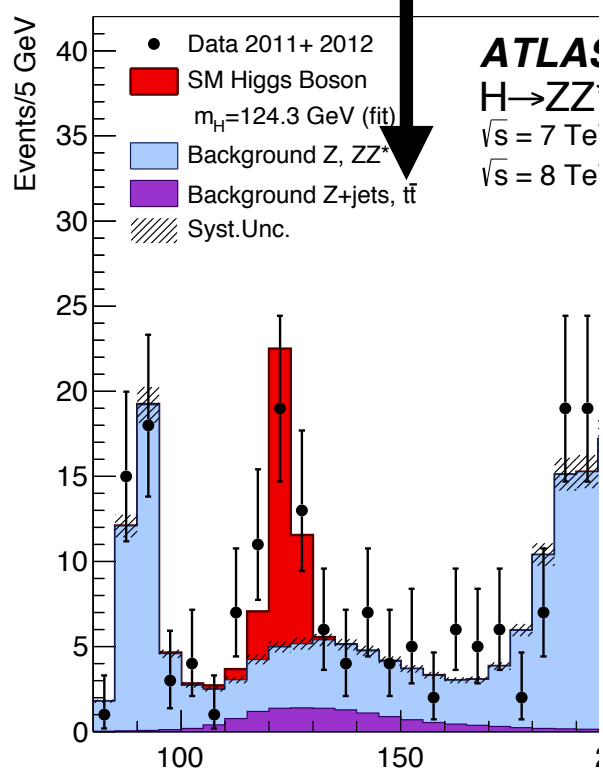
Current Status

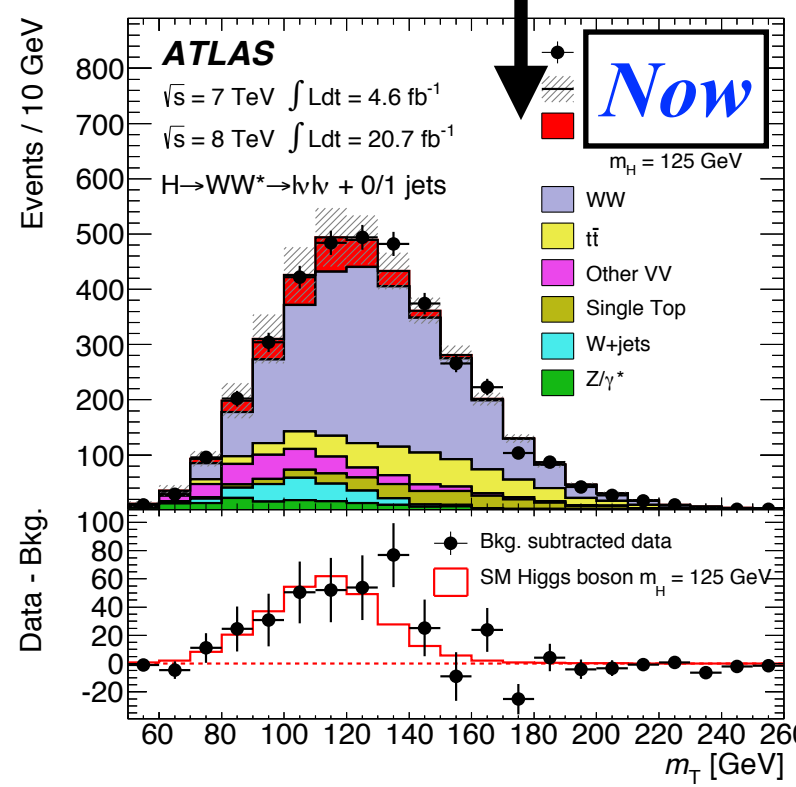












Higgs Program Beyond Discovery

Establish signals in harder channels:

h→ττ (done) / direct h→tt *(close)* / h→bb *(close)*

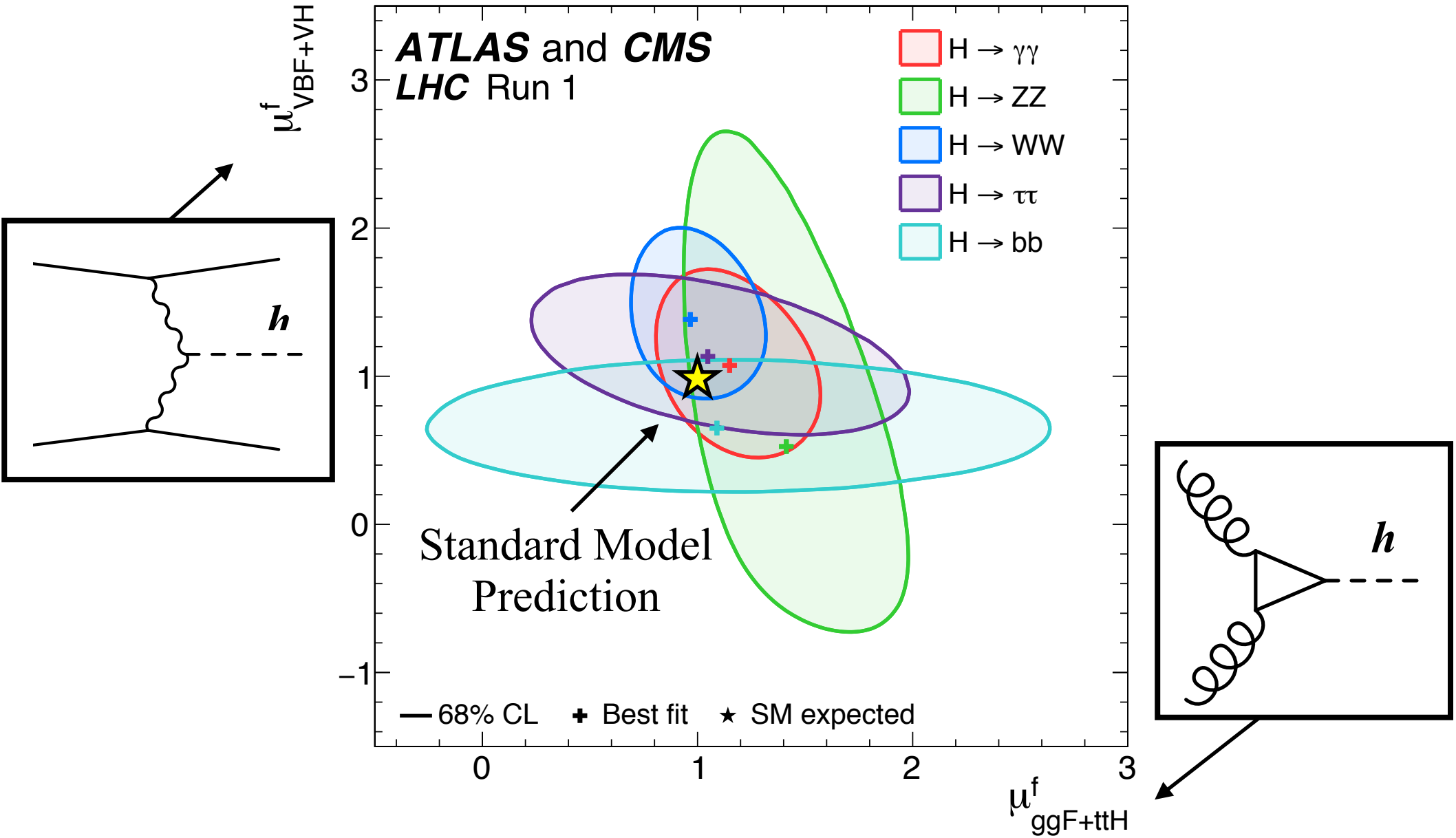
Compare measured/predicted interaction strengths

- Study production cross sections and branching ratios

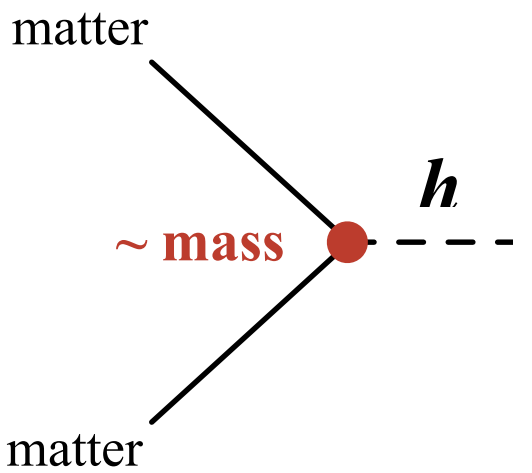
Measure Spin of new particle

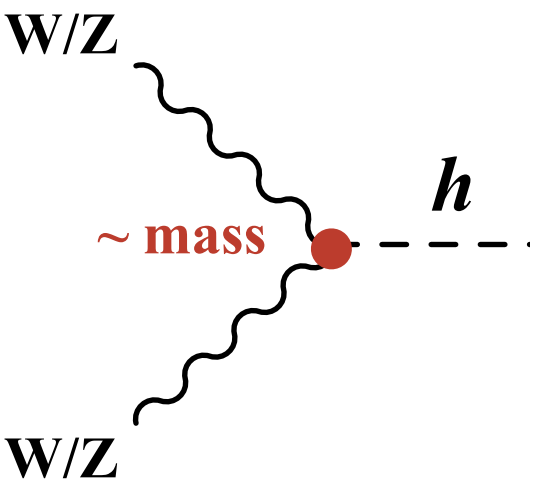
Search for un-predicted decays

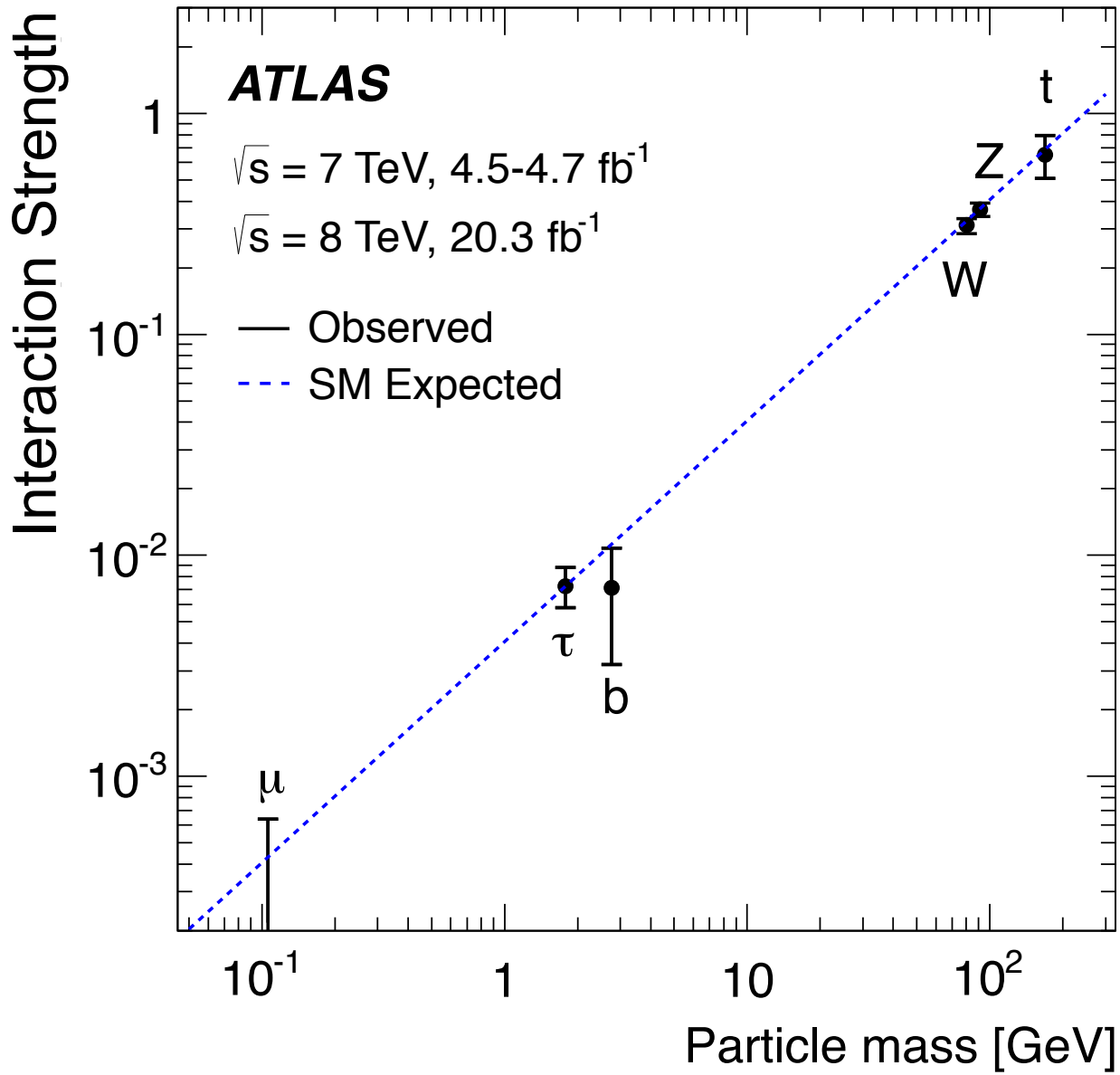
Results: Production Cross Section



Results: Interaction Strengths



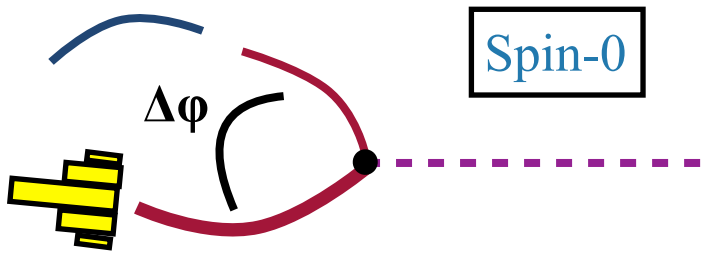




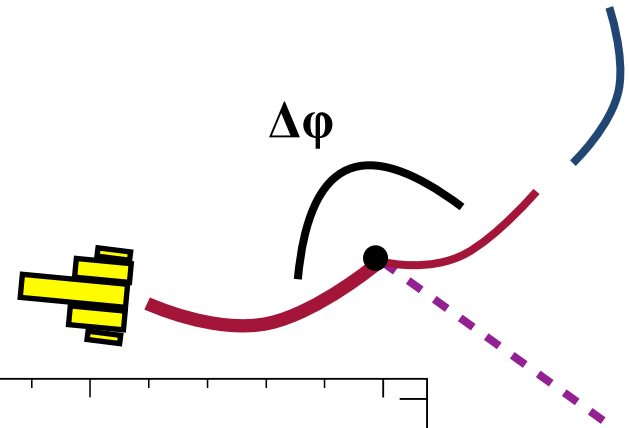
Results: Spin

- Massive Spin 1 resonance cannot decay to $\gamma\gamma$ (QM+Relativity)
- Use decay angle to separate spin 0 and 2

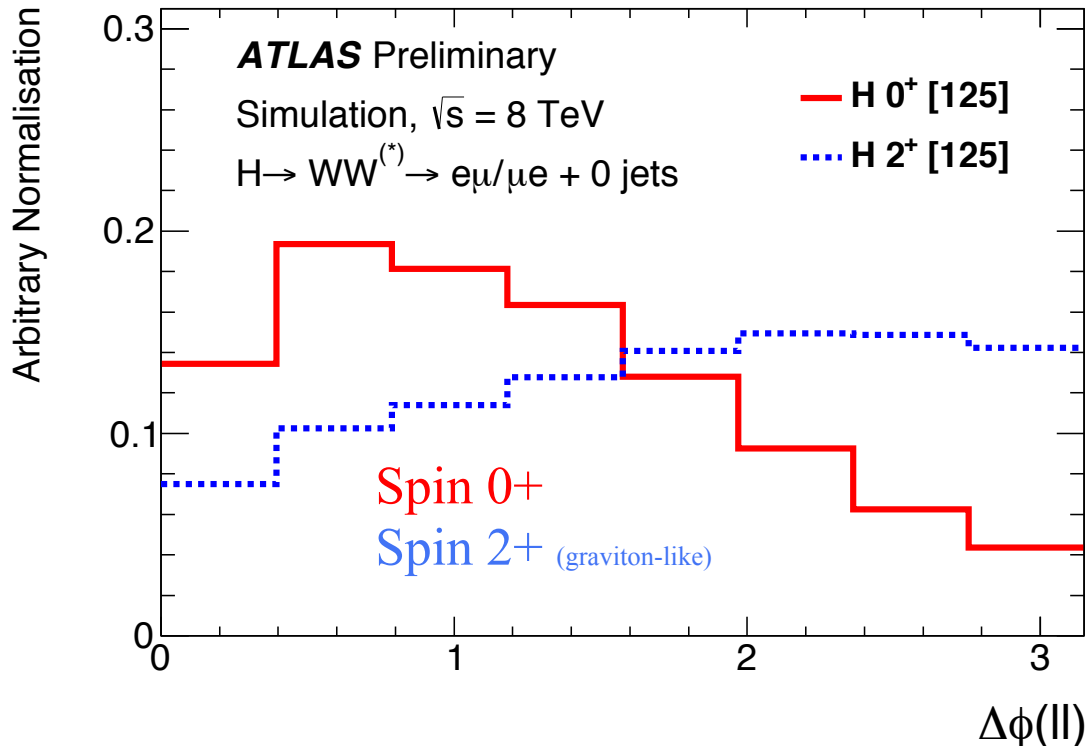
$H \rightarrow WW \rightarrow e\nu\mu\nu$



Spin-0



Spin-2

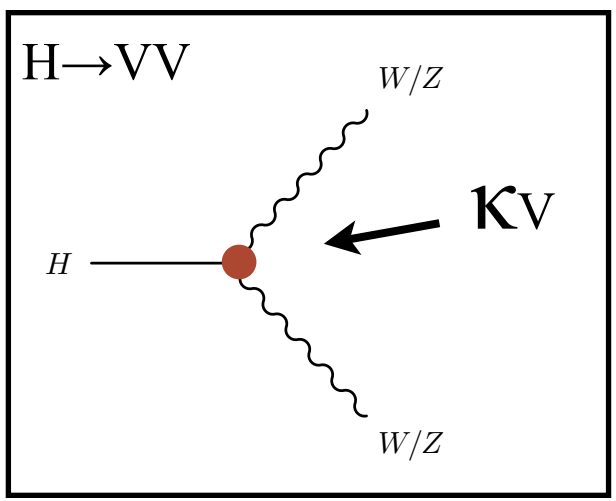


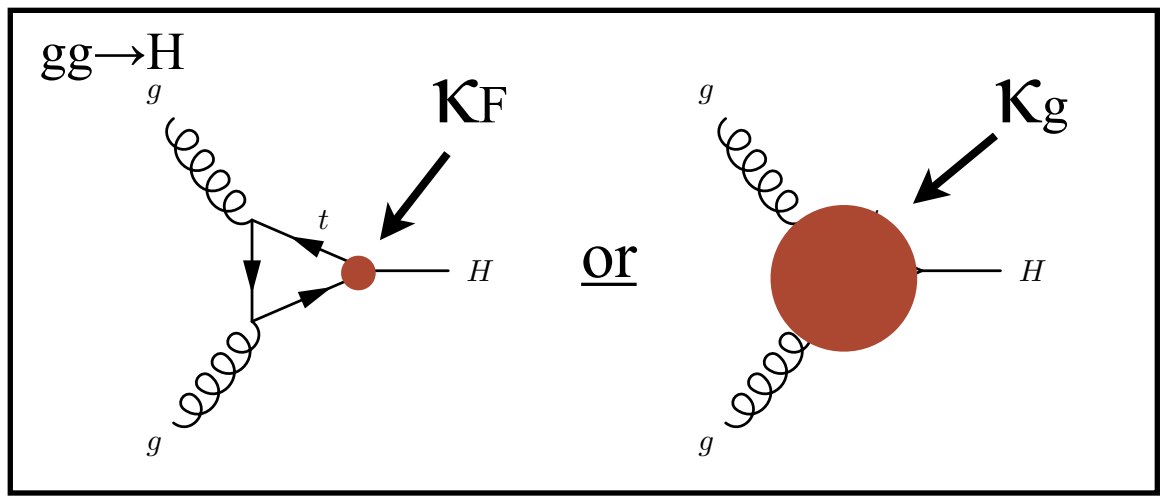
Compatibility w/SM Higgs Couplings

Current statistics allow a limited number of tests of data w.r.t expectation.

In practice introduce coupling modifiers "κ", where κ = 1 is SM.

Examples:

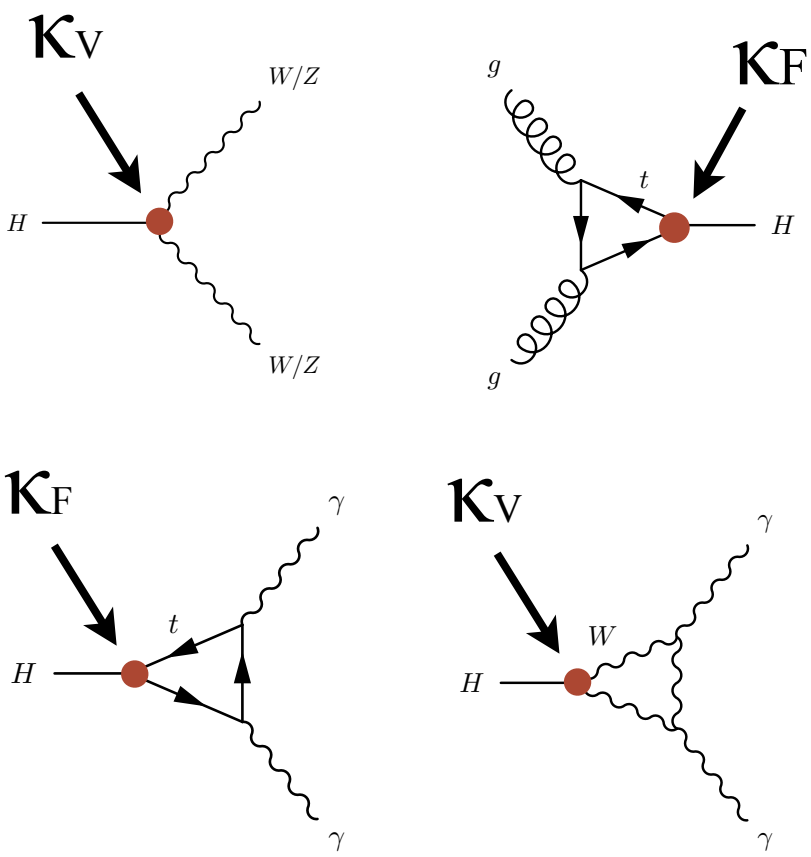


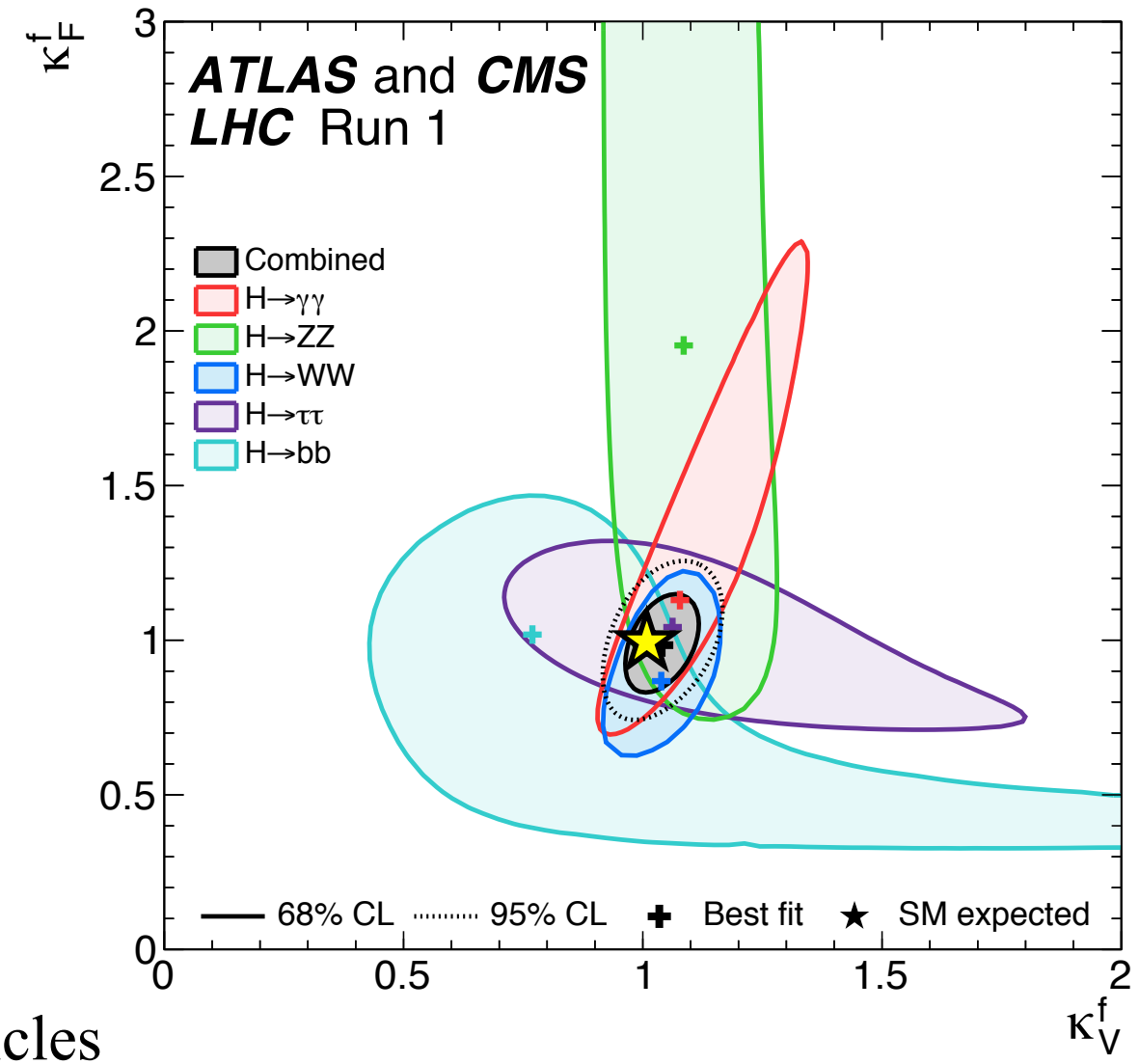


Test against few specific benchmark scenarios.

Compatibility w/SM Higgs Couplings

Test for differences in boson and fermion couplings: assume ($\kappa_W = \kappa_Z$)



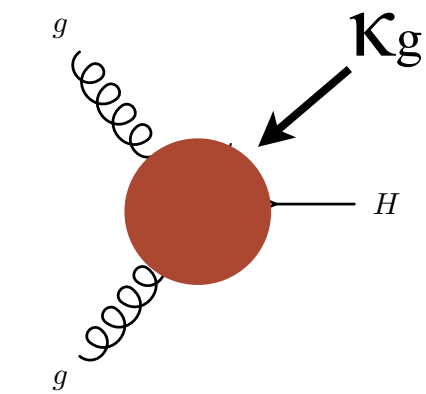


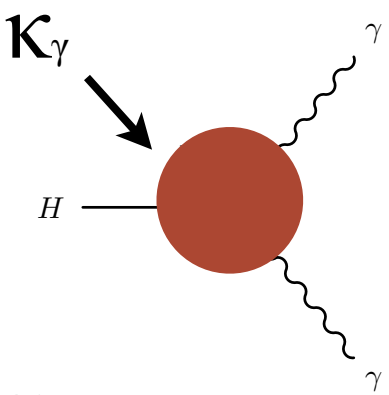
Assume:

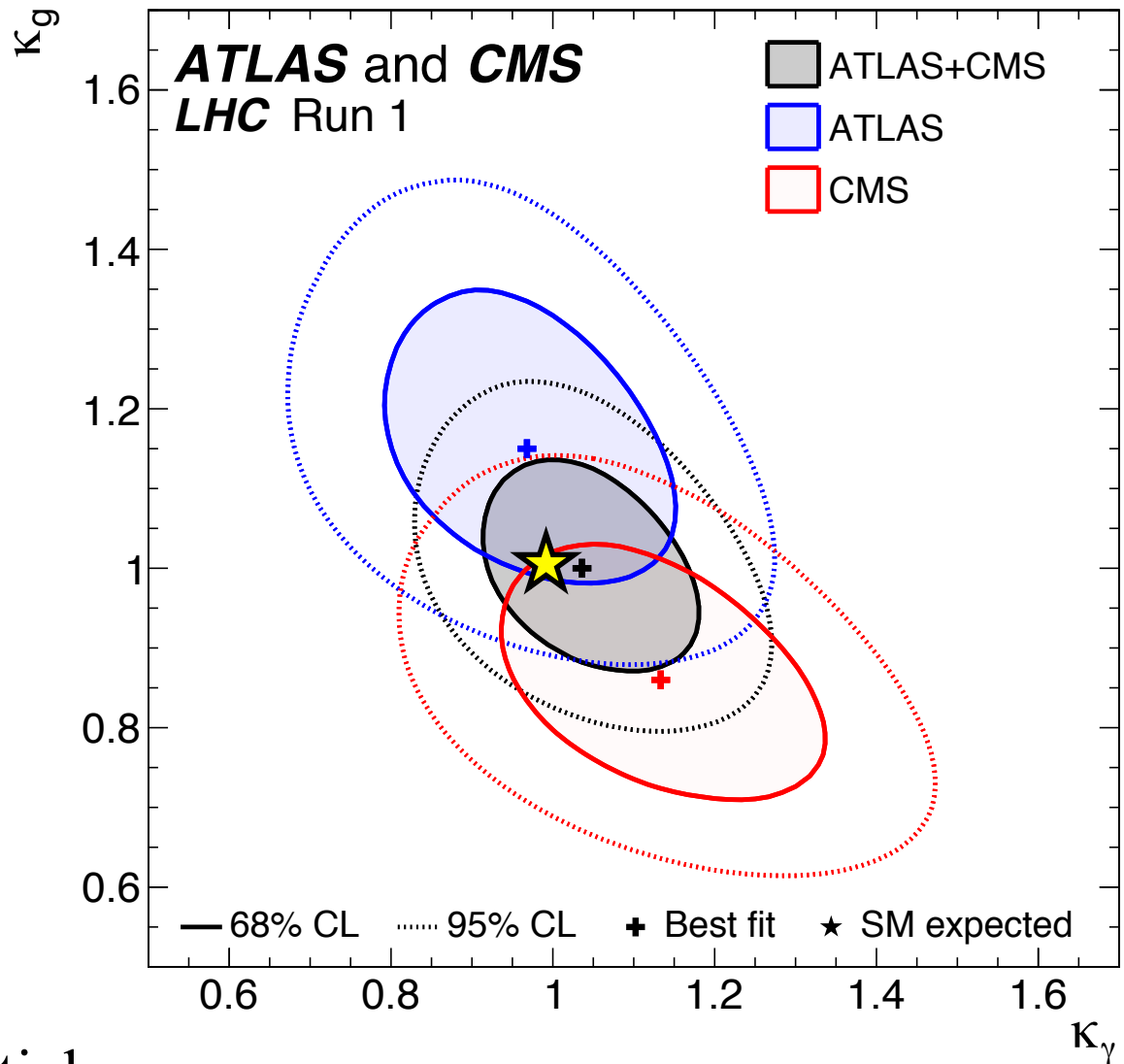
- no decays to unknown particles

Compatibility w/SM Higgs Couplings

Test loops diagrams





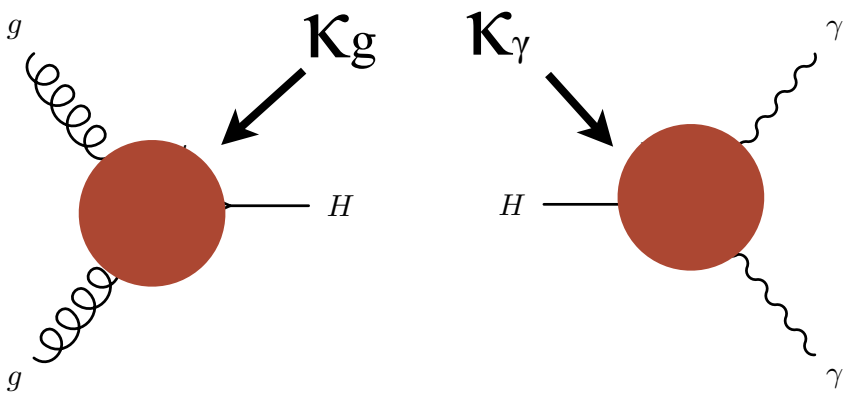


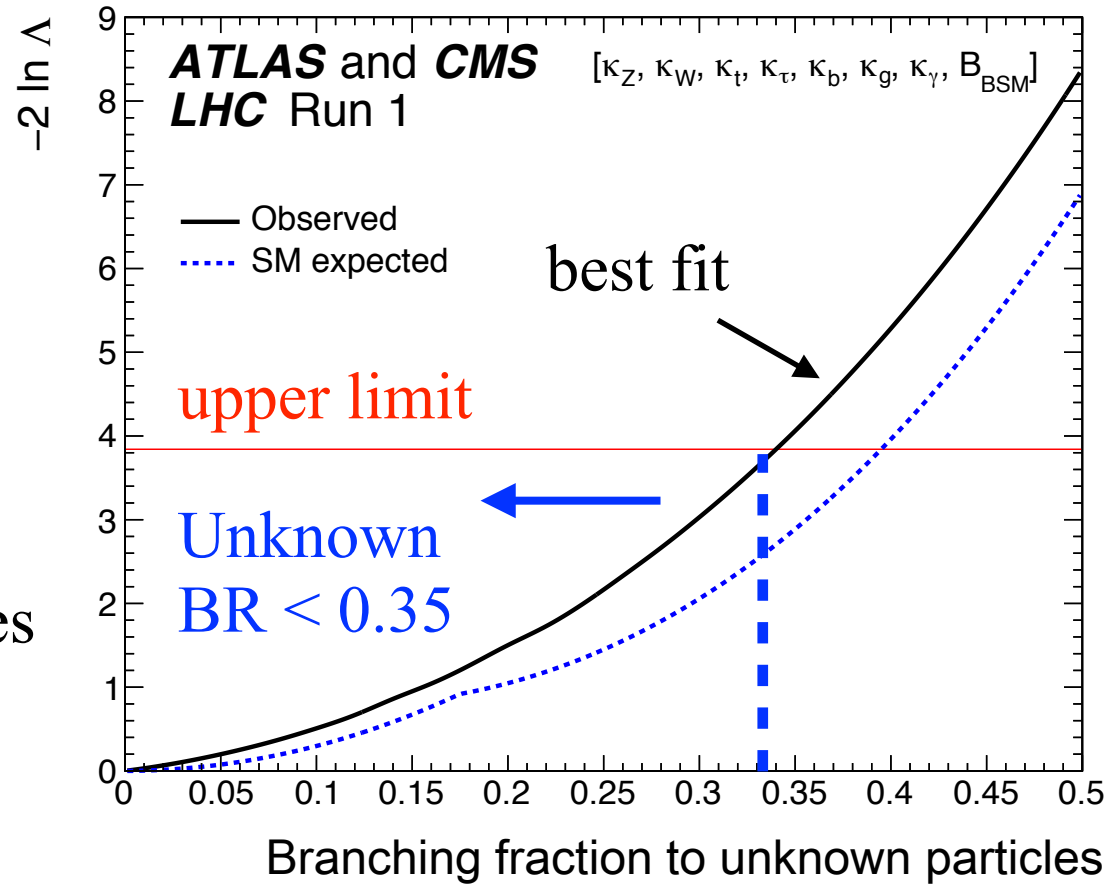
Assume:

- $\kappa F = \kappa V = 1$
- no decays to unknown particles

Compatibility w/SM Higgs Couplings

Test loops diagrams and unknown decays





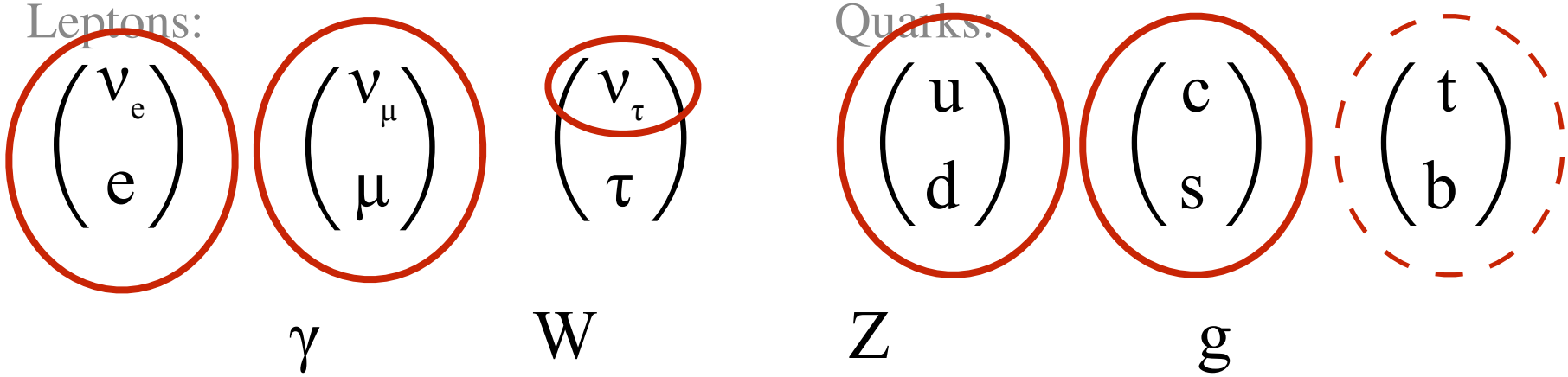
Allow decays to unknown particles

Assume:

- $\kappa F = \kappa V = 1$

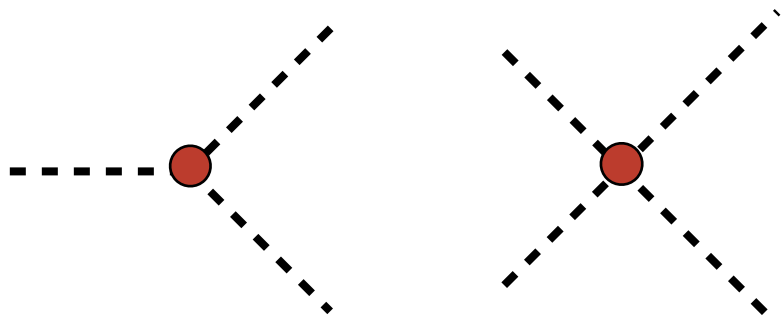
What we don't know

- If established couplings modified at level of ≤ 20%
- If Higgs decays in unexpected way ≤ 30% of the time
- Lots of un-observed interactions



- Very important unobserved interaction: H

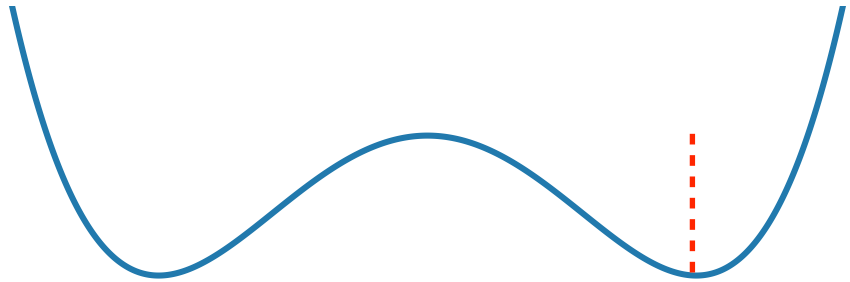
Higgs self-interaction:



Measure Potential with *hh*

Energy of Higgs field: *Higgs potential*

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



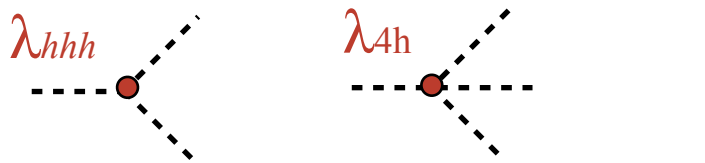
Expanding about minimum: $V(\phi) \to V(v+h)$

$$\frac{\mu}{\sqrt{\lambda}} \equiv v \quad 246 \text{ GeV}$$

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

$$= V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4$$

Higgs mass term



hh-production *hhh*-production

Standard Model:

$$\lambda_{hhh} = \frac{m_h^2}{2v^2}$$

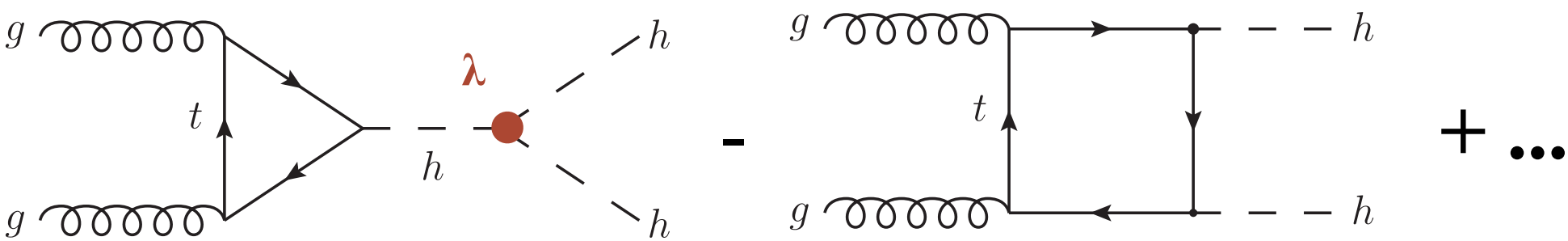
- Shape of potential gives relationship between λ_{hhh} and m_h, v
- Measuring λ_{hhh} important probes the shape of the Higgs potential
- *hh* production interesting because it measures λ_{hhh}

SM *hh* Production at the LHC

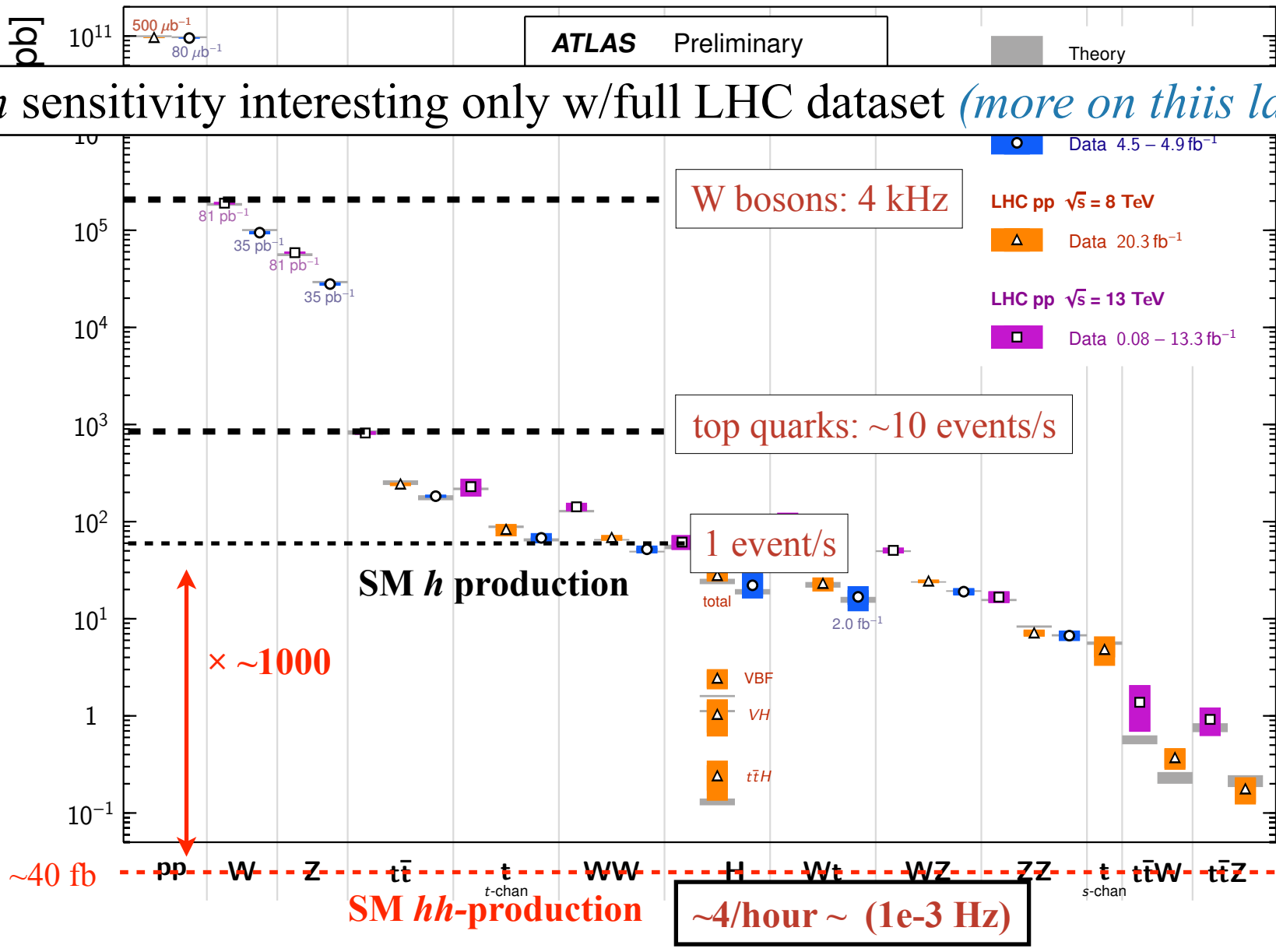
Small in Standard Model

- Leading *hh* diagrams higher order in series (have extra vertices)
- 2 heavy particles (fraction of proton energy needed larger)
- Two diagrams with relative minus sign

Production Diagrams:

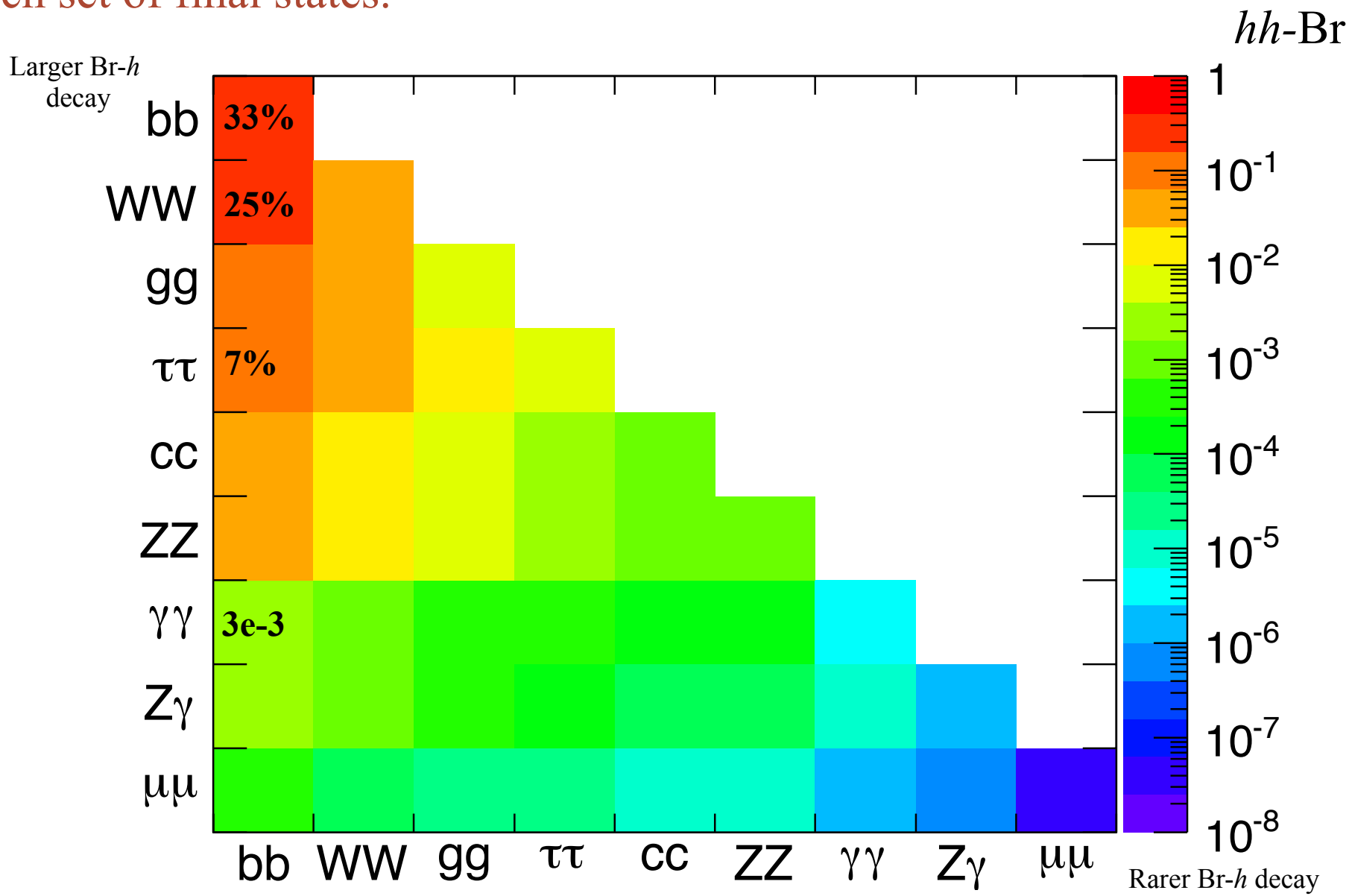


SM *hh* sensitivity interesting only w/full LHC dataset *(more on thiis later)*



hh Decay

Rich set of final states.



Di-Higgs

Ultimate goal in the program to measure the Higgs

- Direct probe of shape of Higgs potential
- Deep connections w/fundamental problems associated to the Higgs boson.

Pick up here next time.