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

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University of Chicago

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 ?

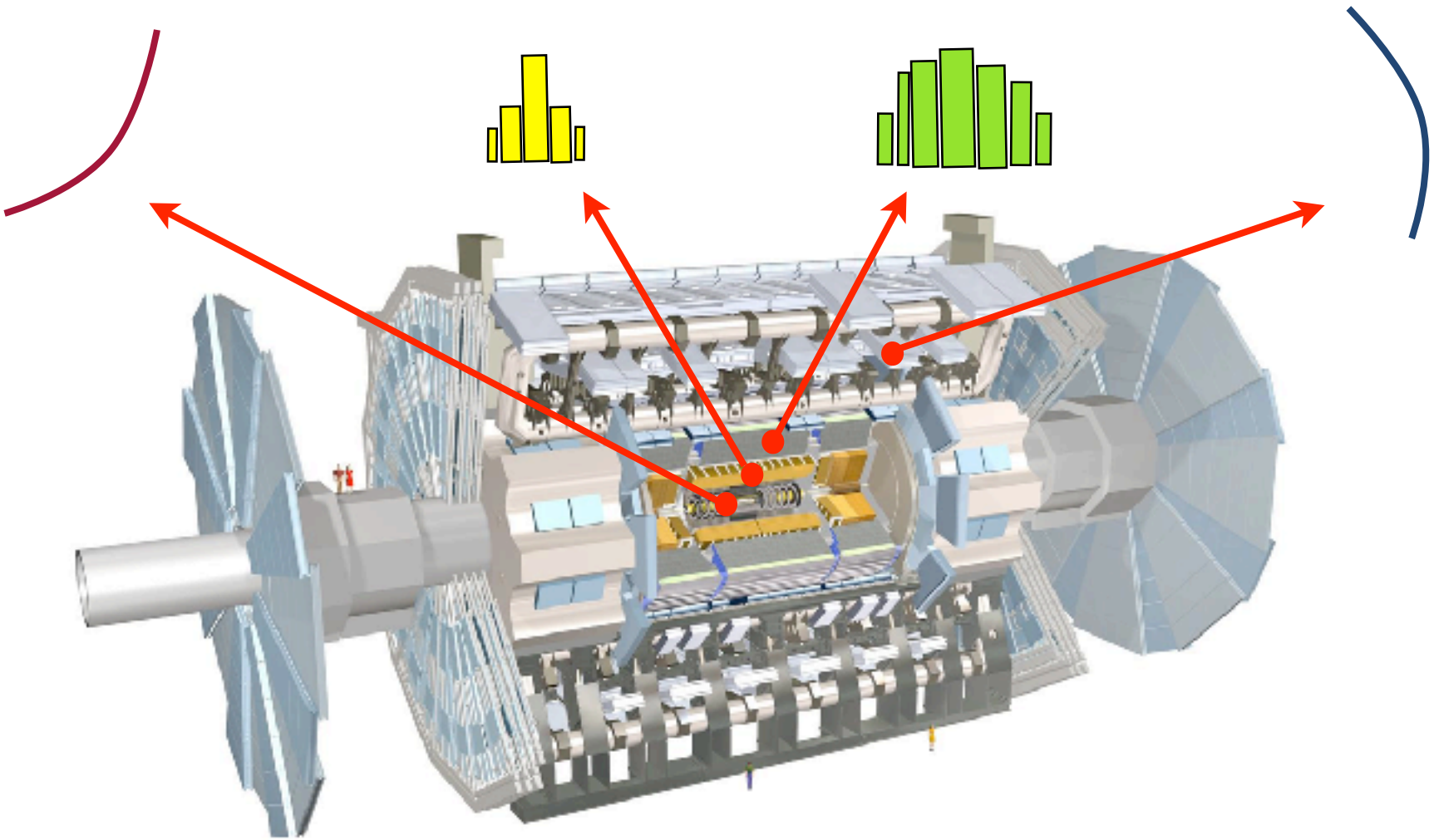
The Basic Outputs:

Inner Tracking System

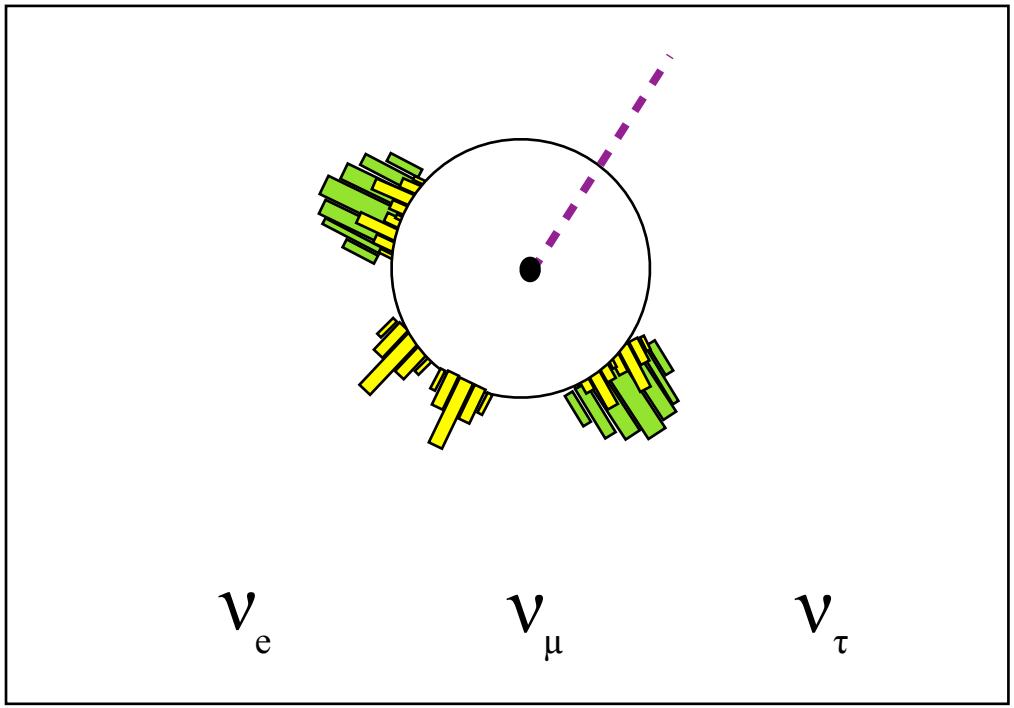
Electro-Magnetic Calorimeter

Hadronic Calorimeter

Muon Tracking System



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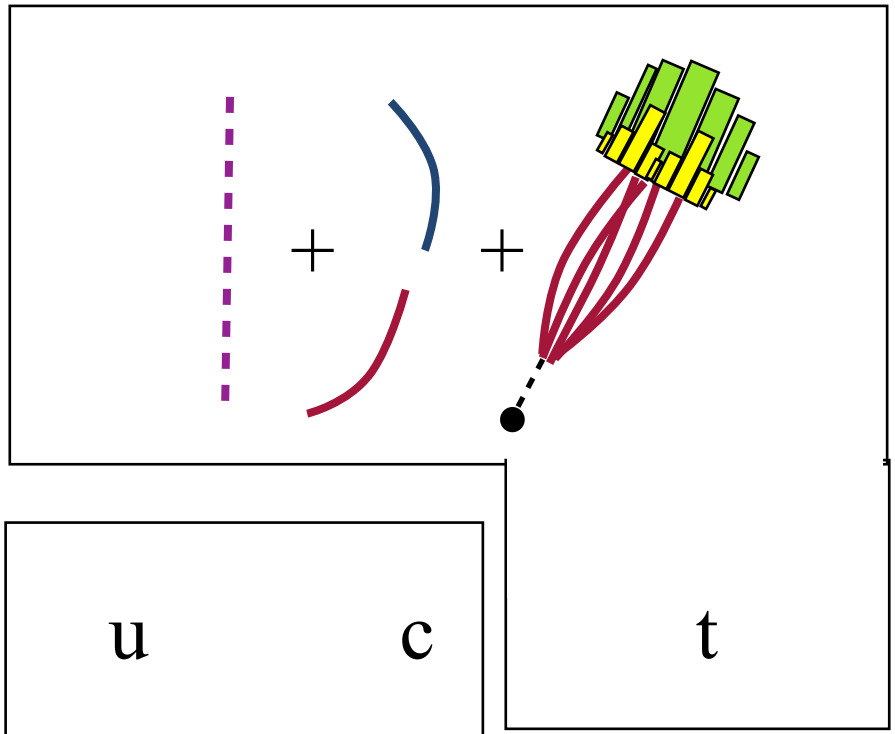
ν_μ
ν_τ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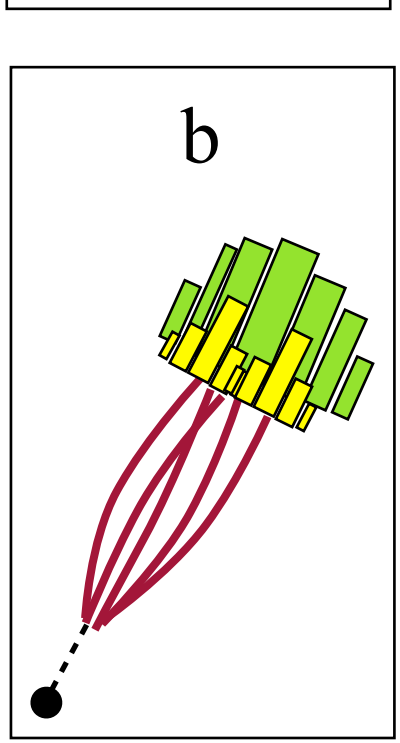
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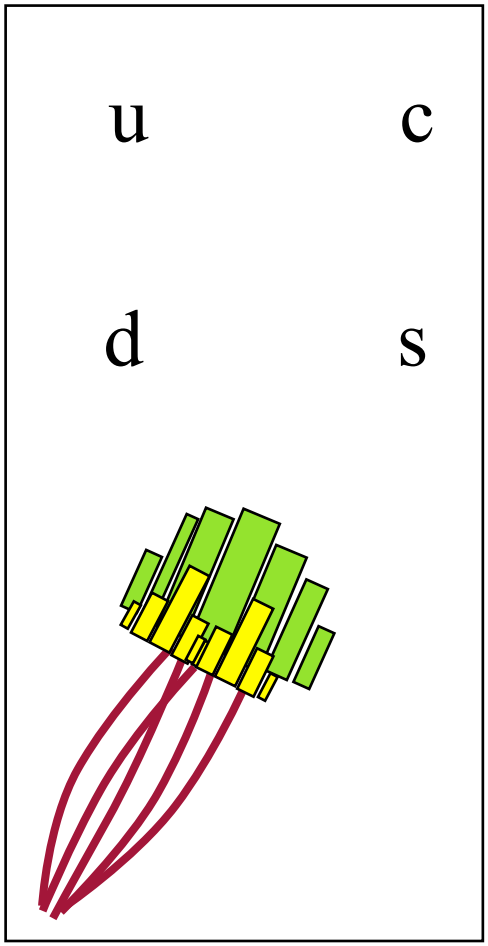
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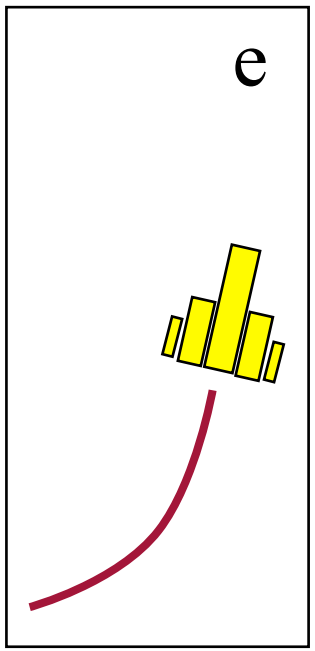
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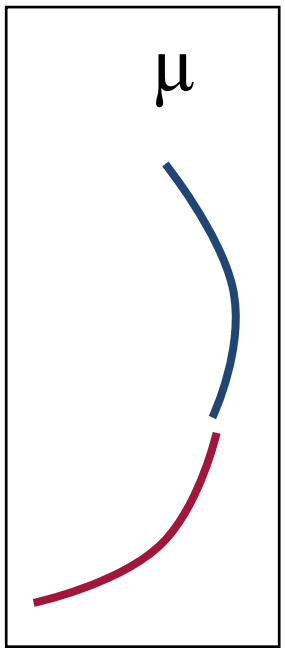
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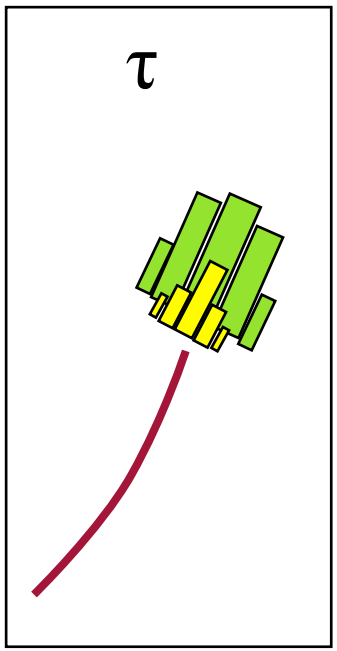
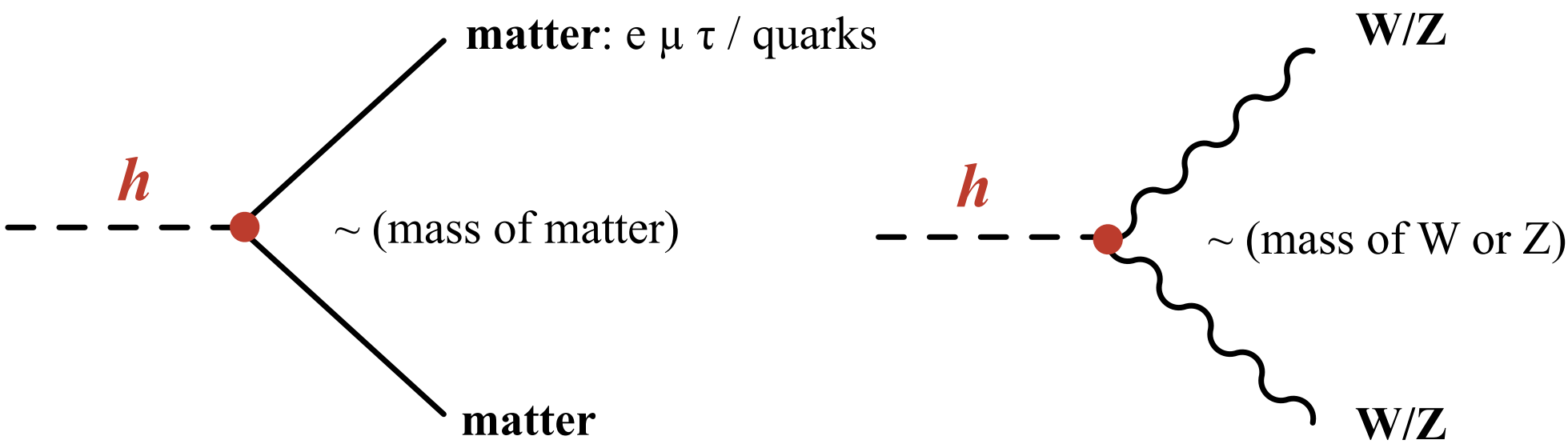

τ

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/gluons)

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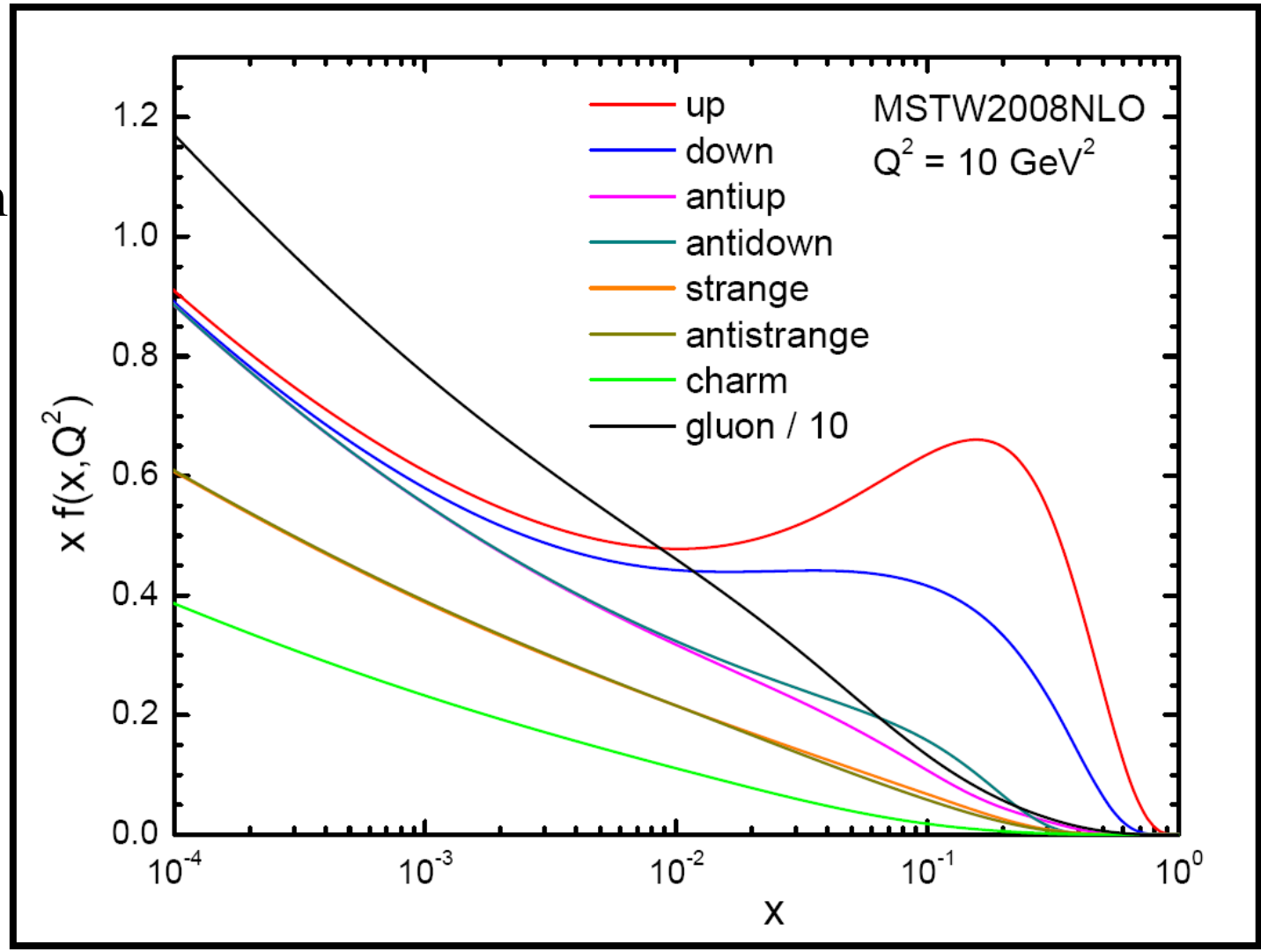

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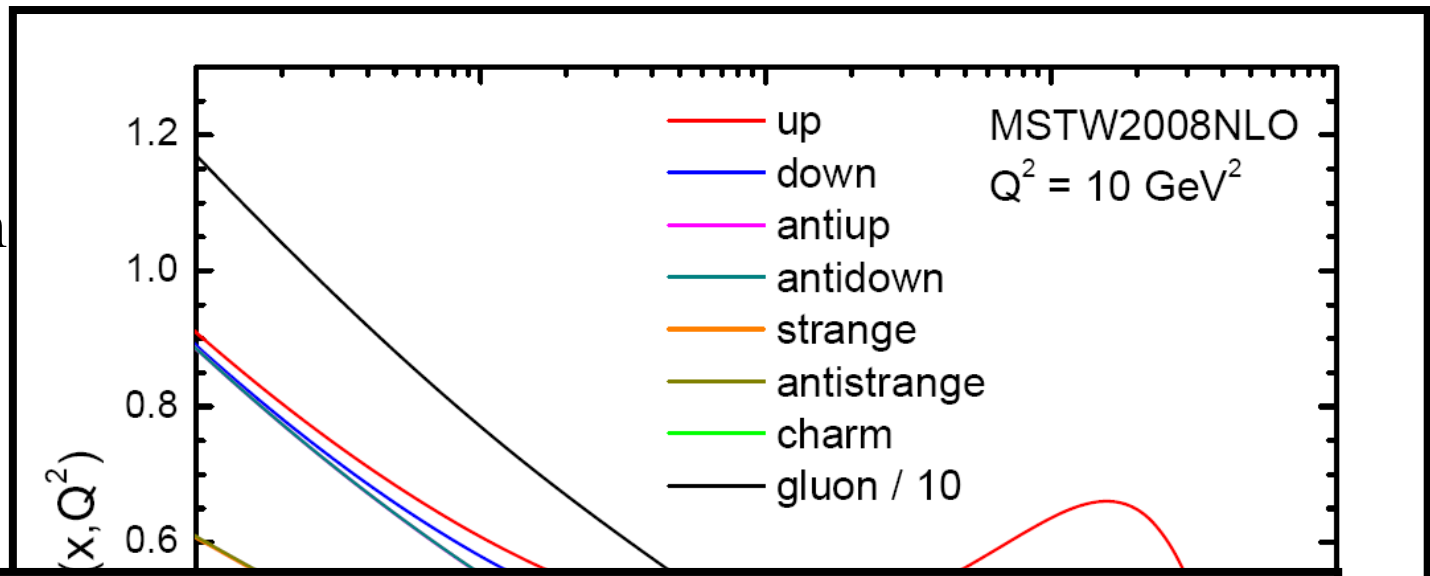
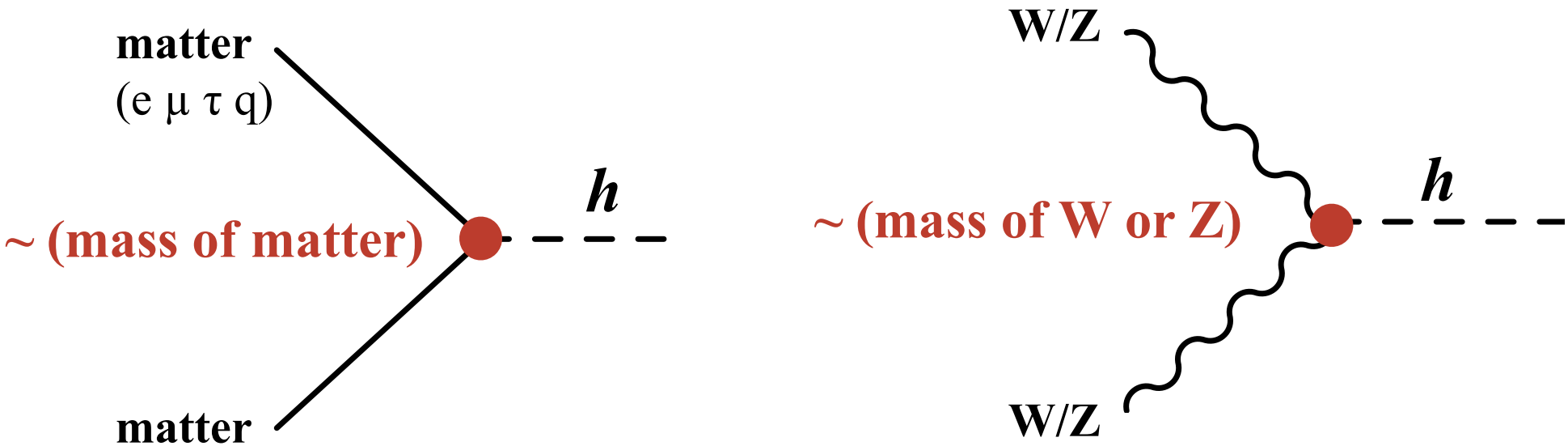


Higgs interactions (couplings) matter known:



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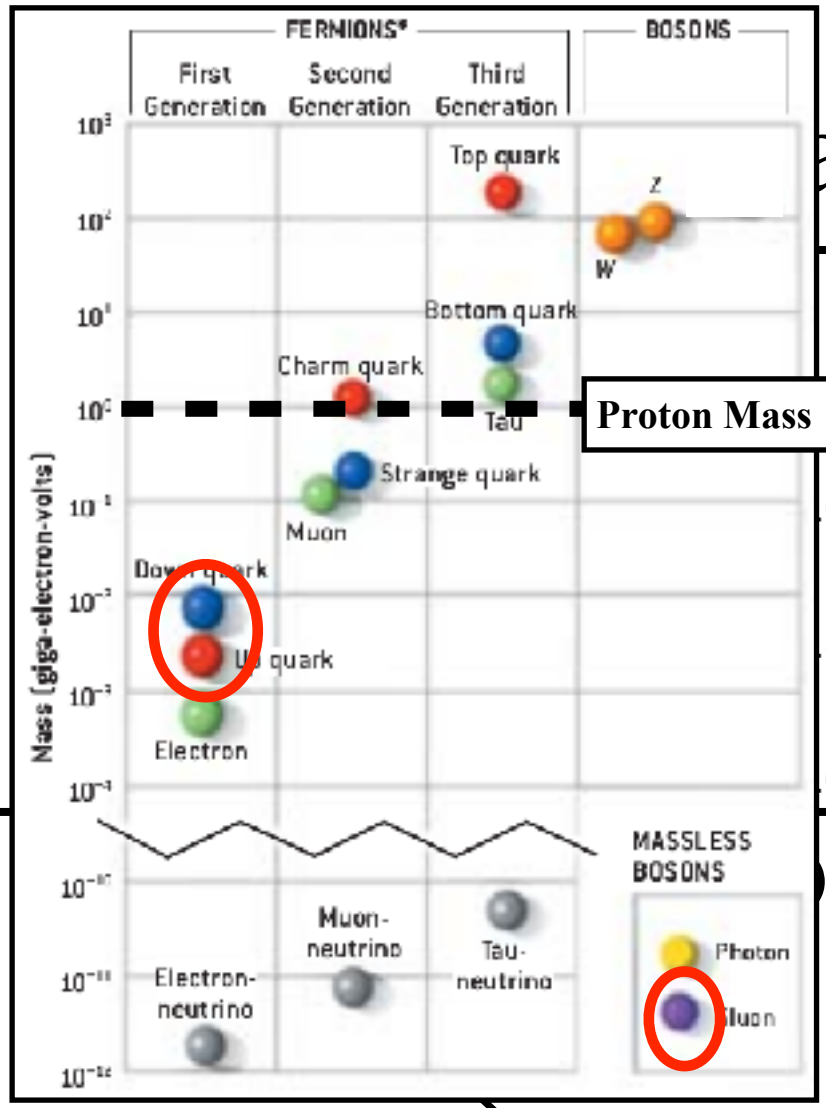

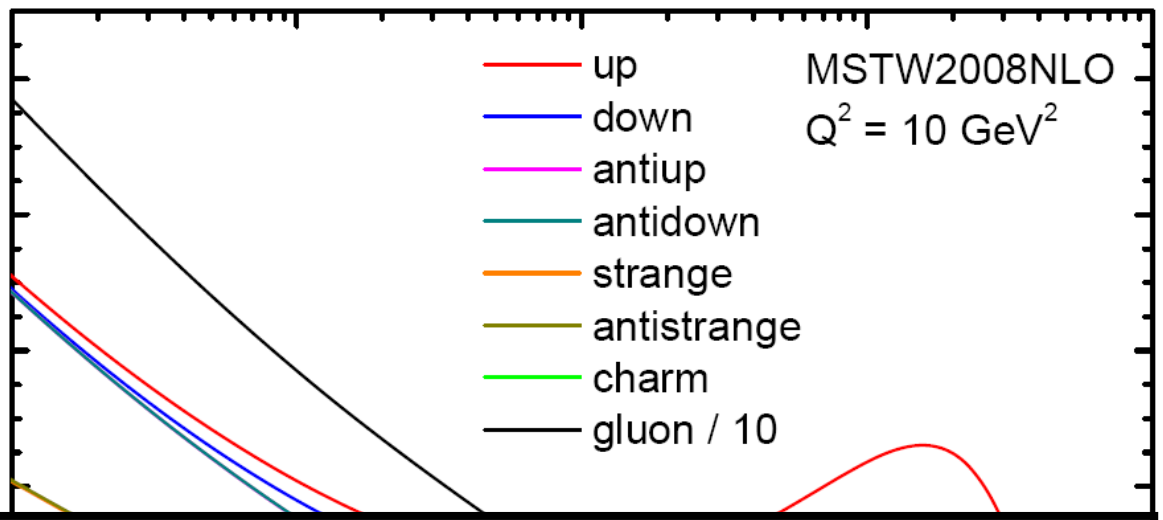

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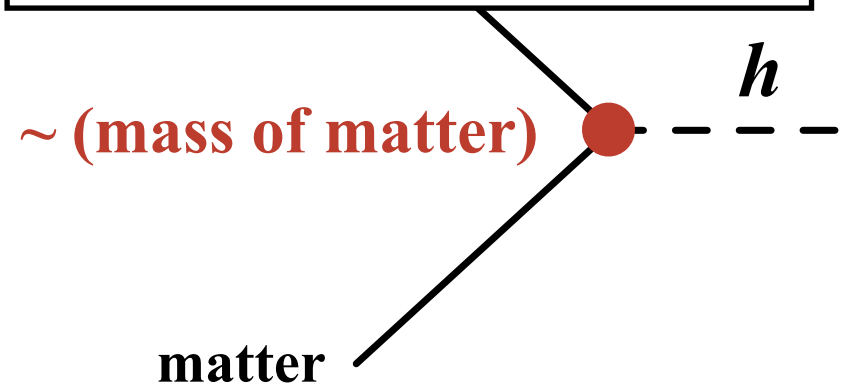
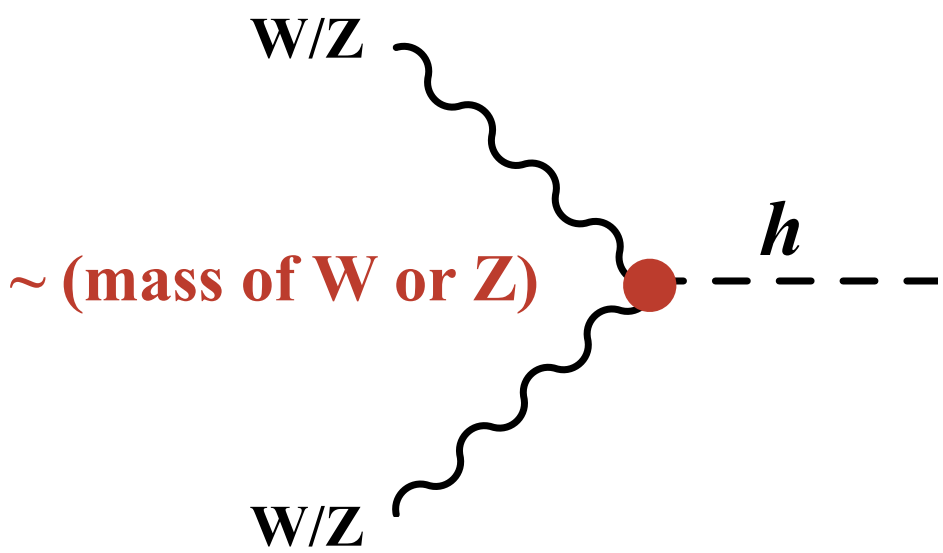
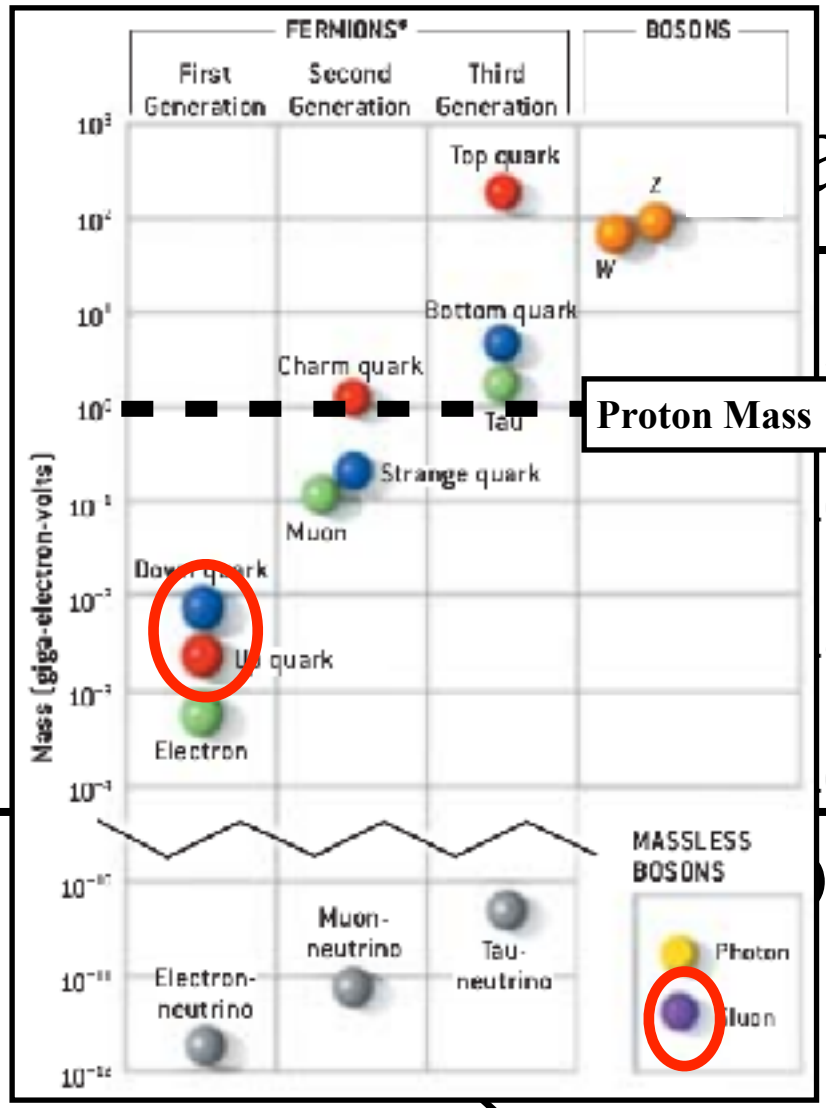


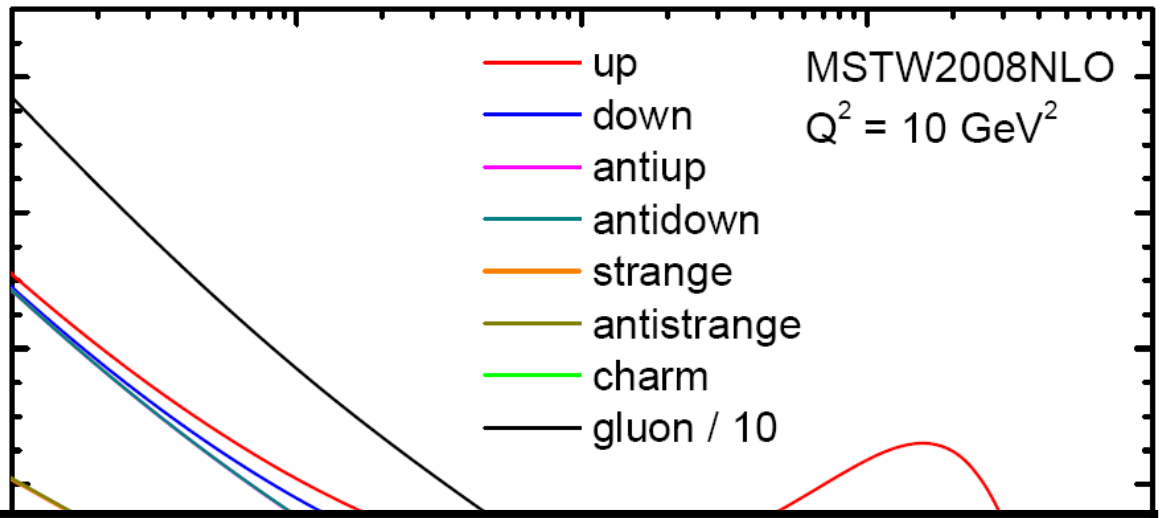


All things that exist in the proton light !

⇒ small of a coupling to Higgs

⇒ small of a probability to produce Higgs





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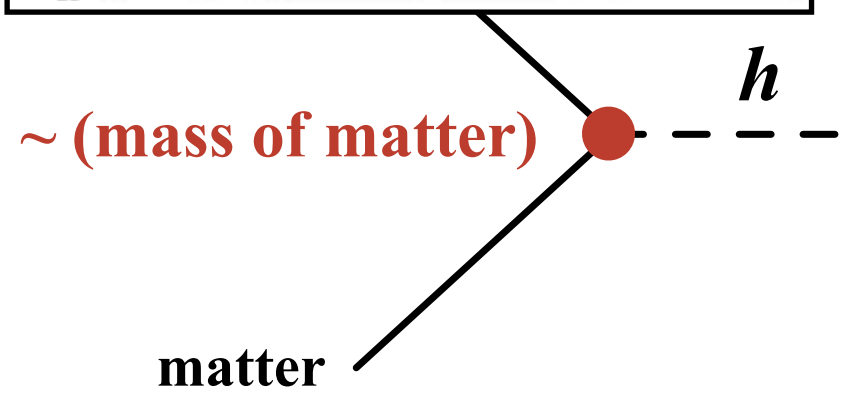

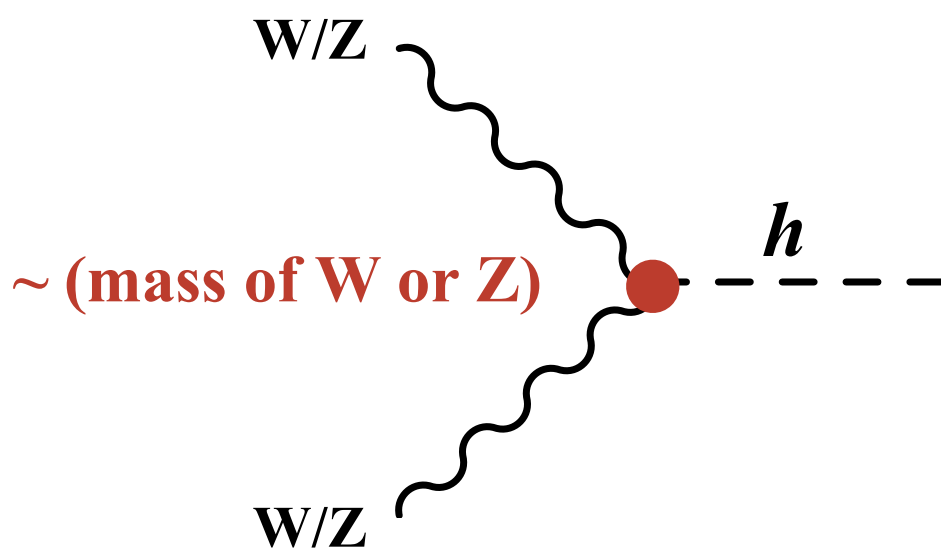

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⇒ small of a coupling to Higgs
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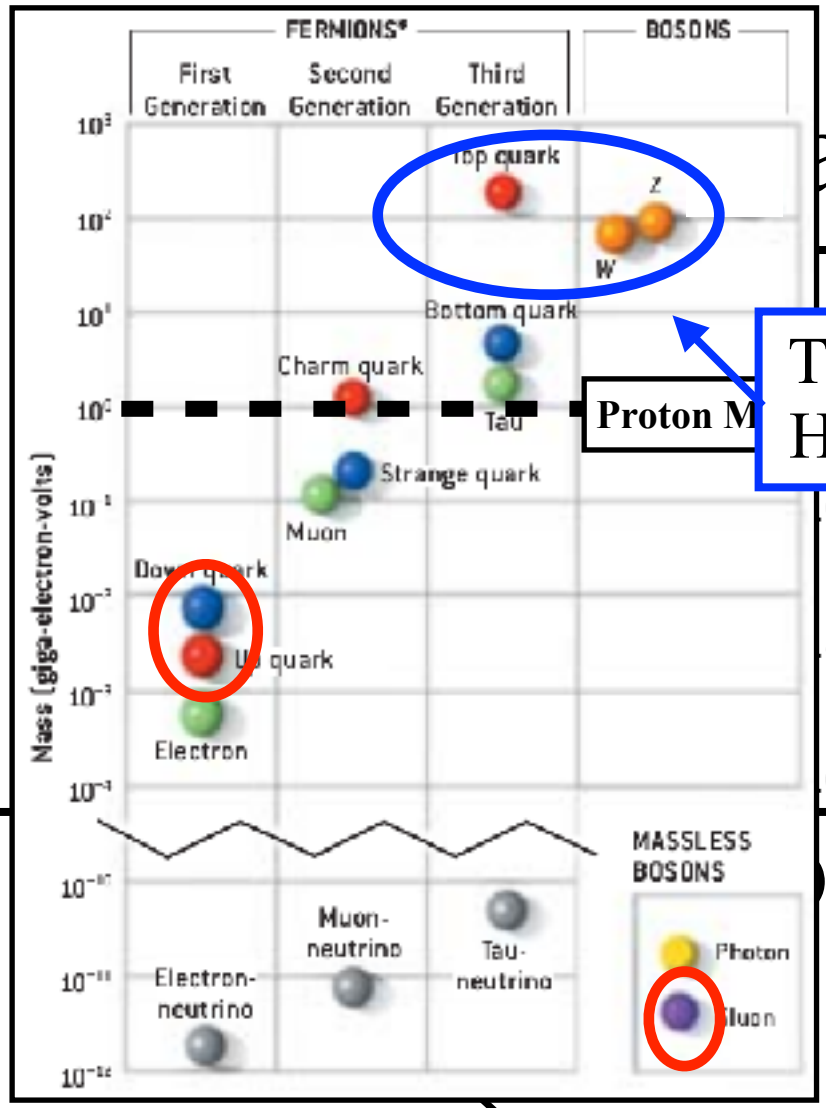
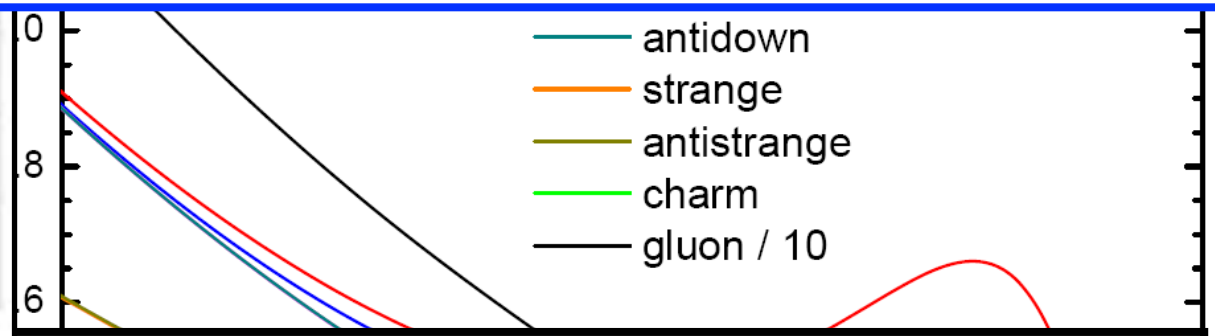
Top quark / W / Z are heaviest things in theory
Have the highest probability of producing Higgs





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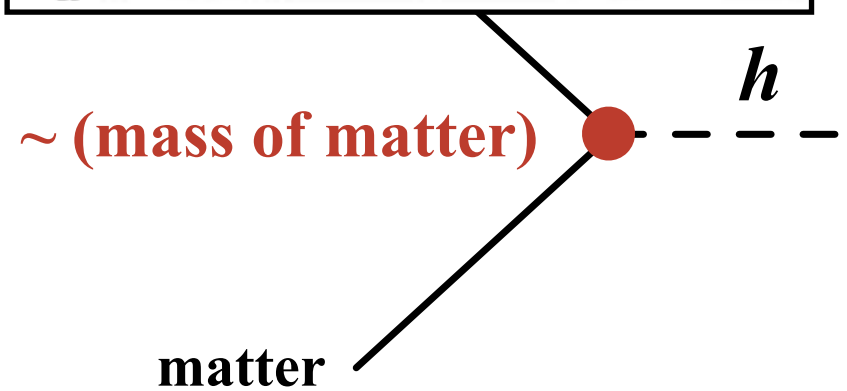
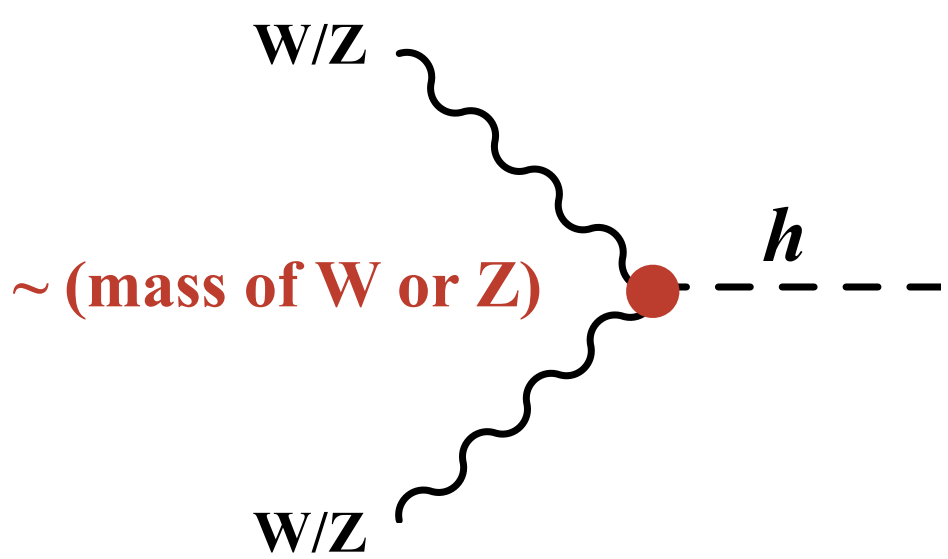
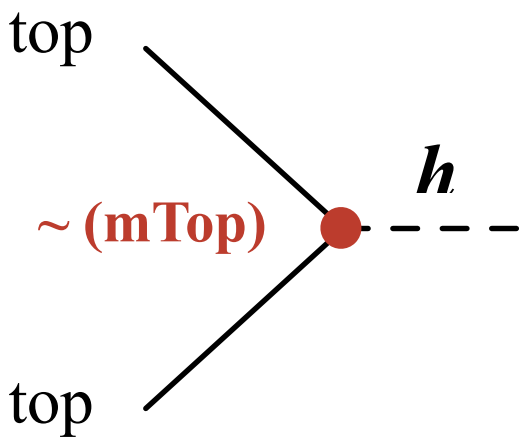
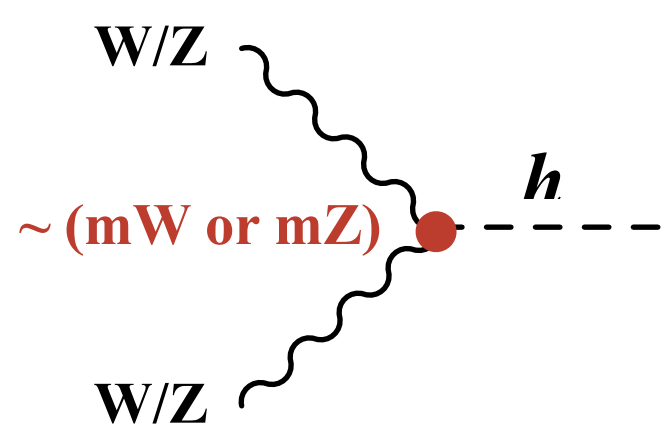




How to Make Higgs Bosons

We really want to use processes like:





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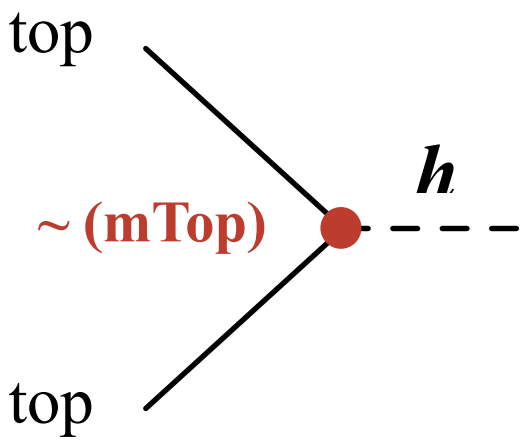

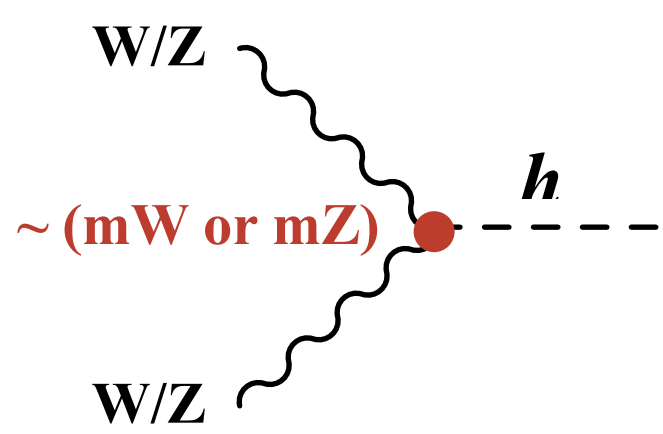

Problem is we don't have Top/W/Z colliders

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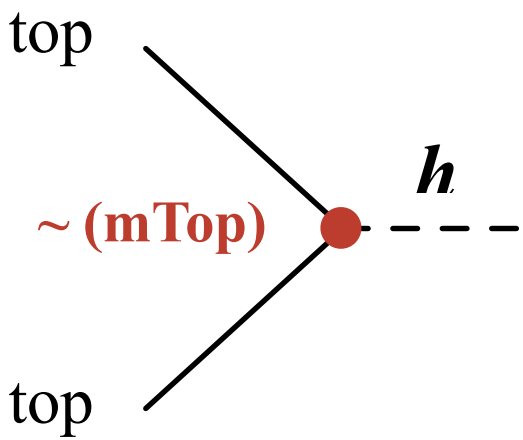

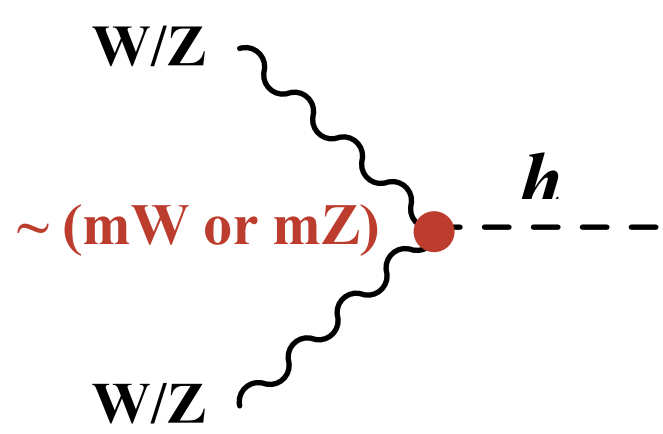

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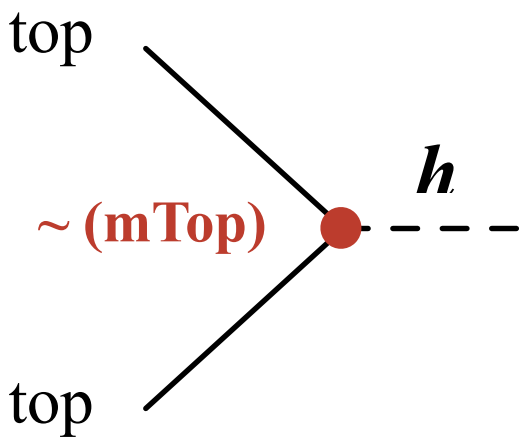

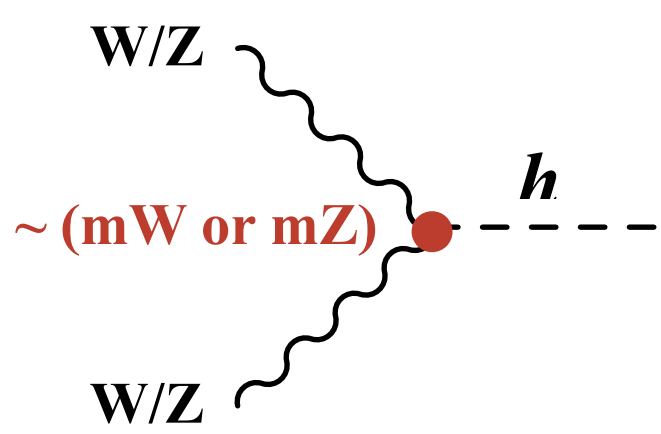

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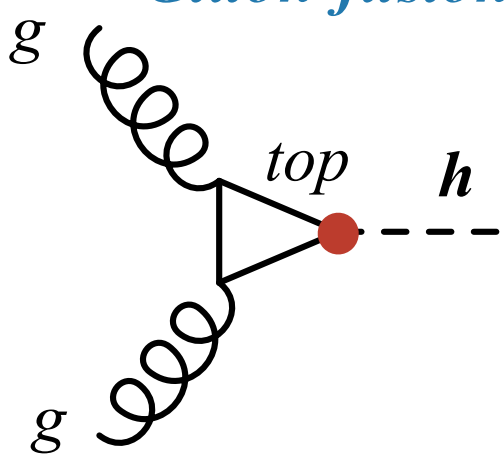
Gluon-fusion



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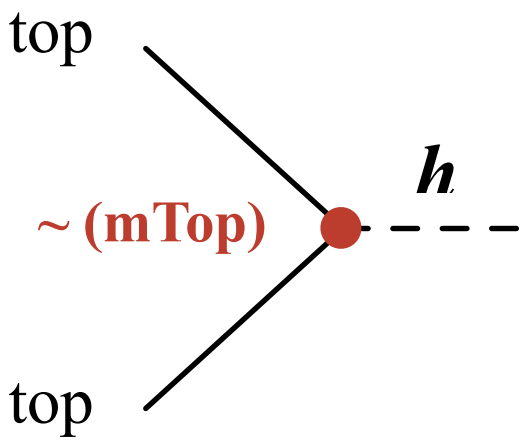

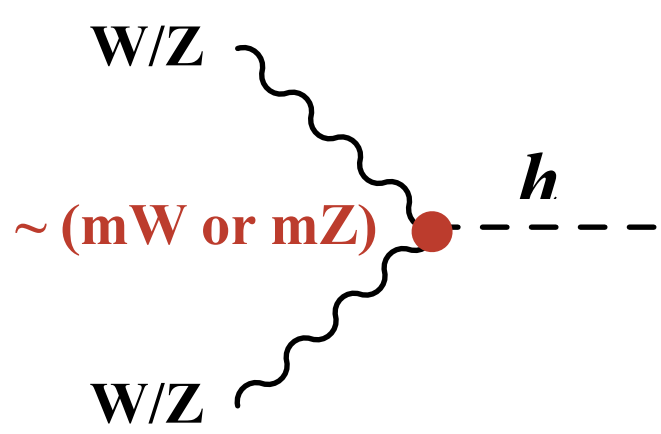

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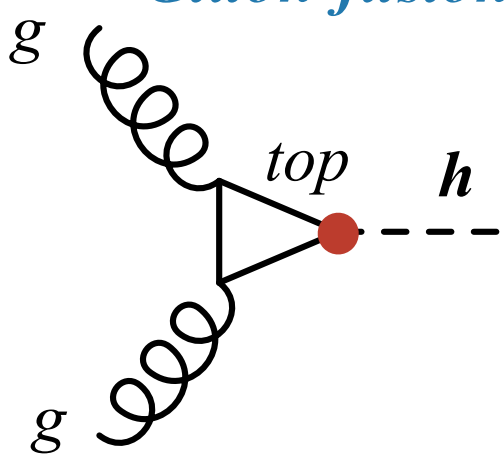
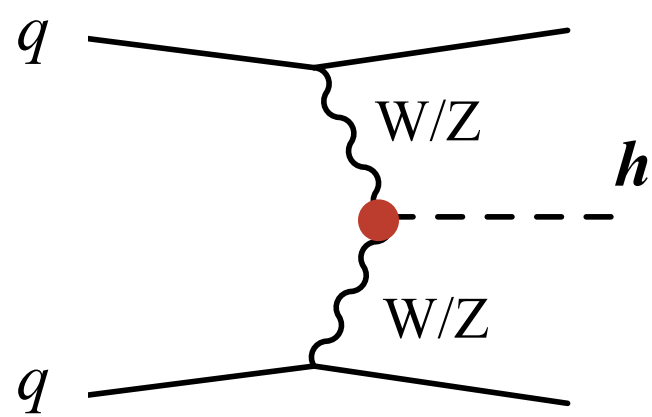


Vector-Bosons Fusion



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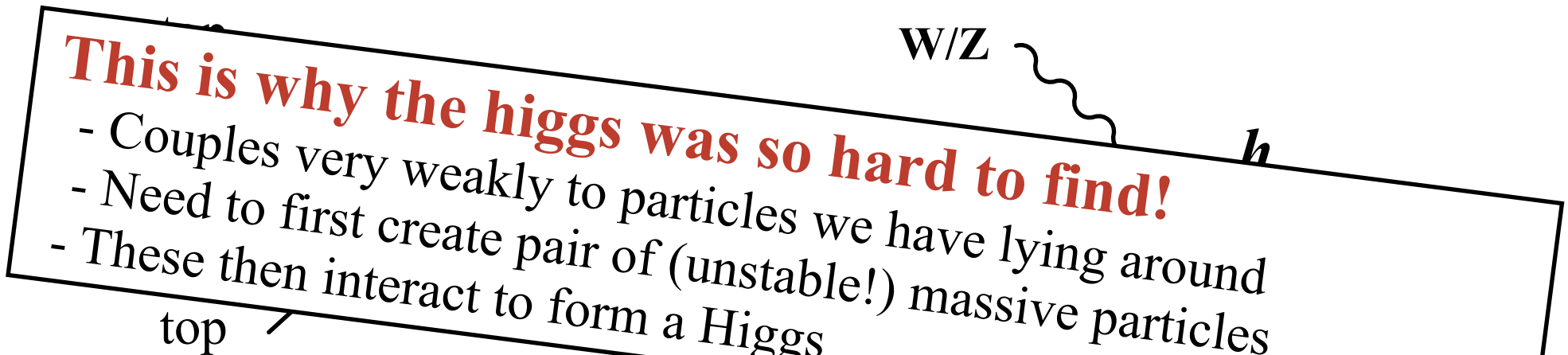

This is why the higgs was so hard to find!

- 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

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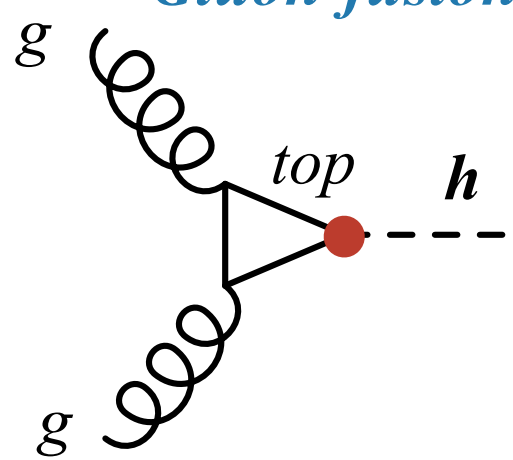

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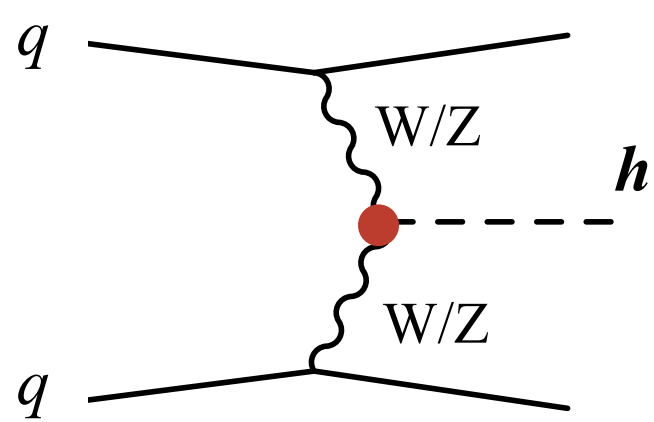
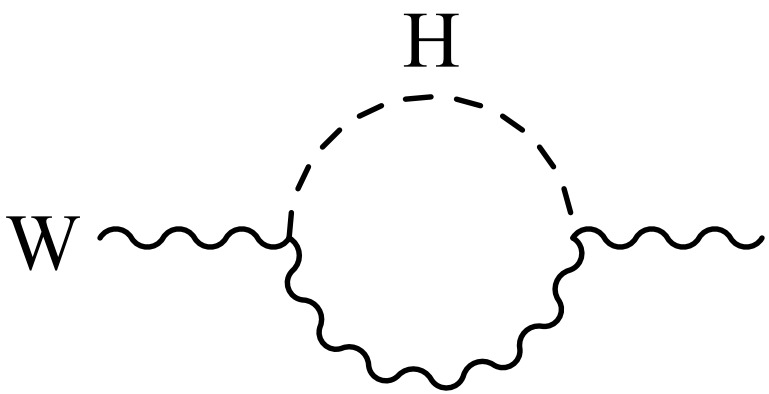
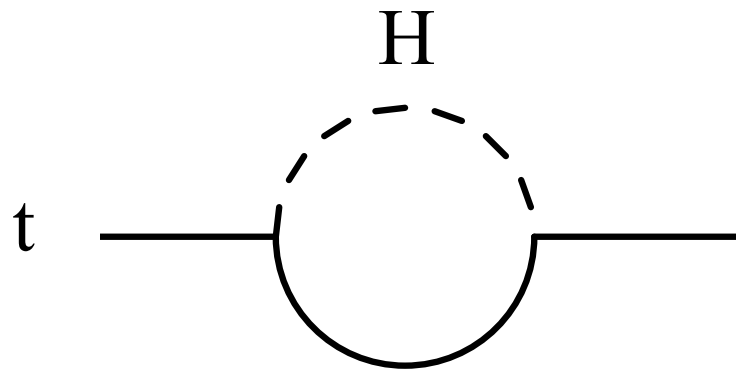


Where to look for the Higgs Boson ?

Mass constraints pre-LHC





50 < mH < 150 GeV (95%)

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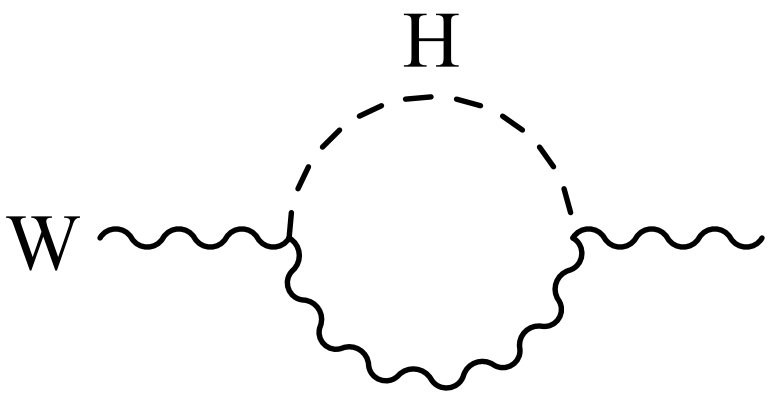

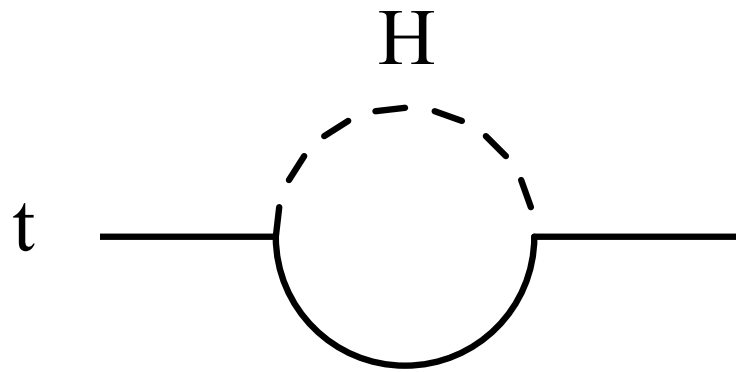

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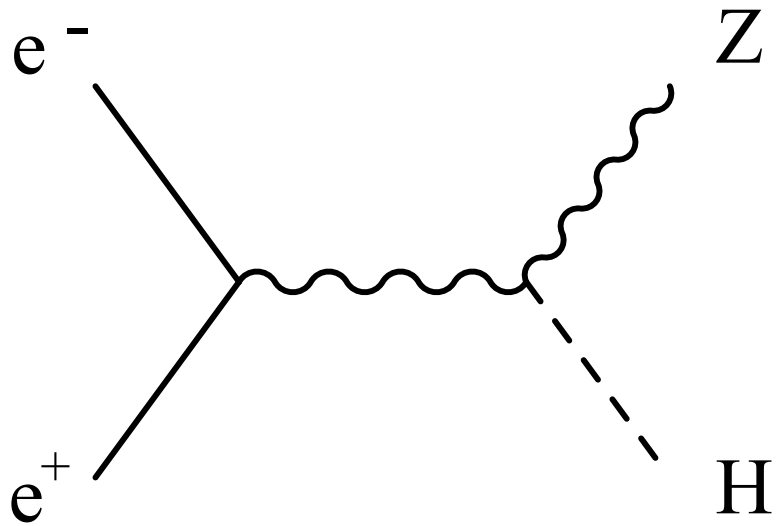
Limits from direct search Large Electron-Positron collider (LEP)



mH > 115 GeV

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Higgs Boson quickly decays to other particles.

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

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$$Branching\ Ratio = \frac{\text{h} \dashrightarrow \text{P} + \text{P}}{\sum_{i}^{\text{possibilities}} \left(\text{h} \dashrightarrow i + i \right)}$$

(for particle P)

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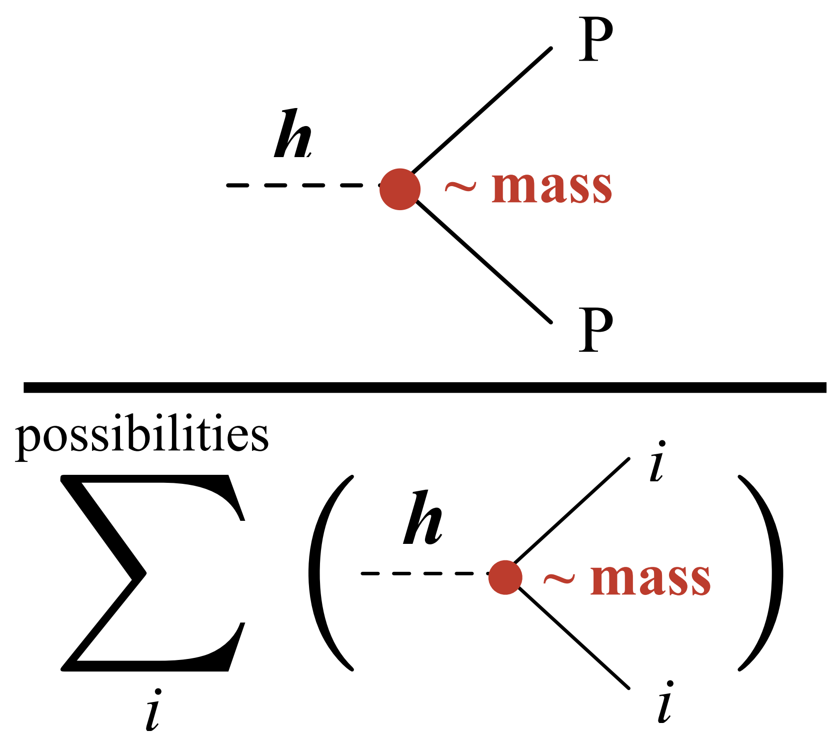

Higgs wants to decay to heaviest particle around (provided: $m_X < m_H/2$)

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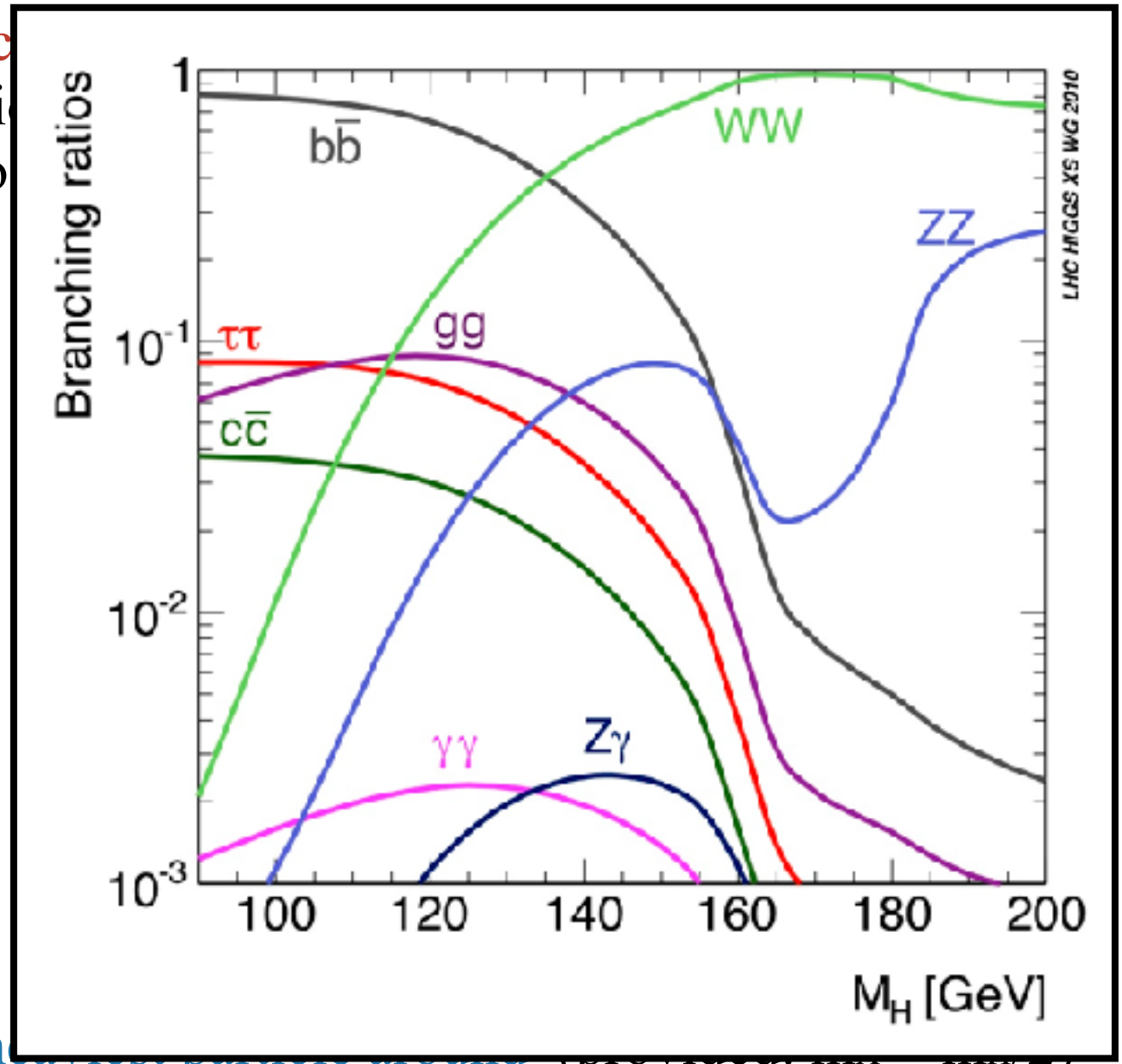

Branching Ratio
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Higgs wants to decay to h

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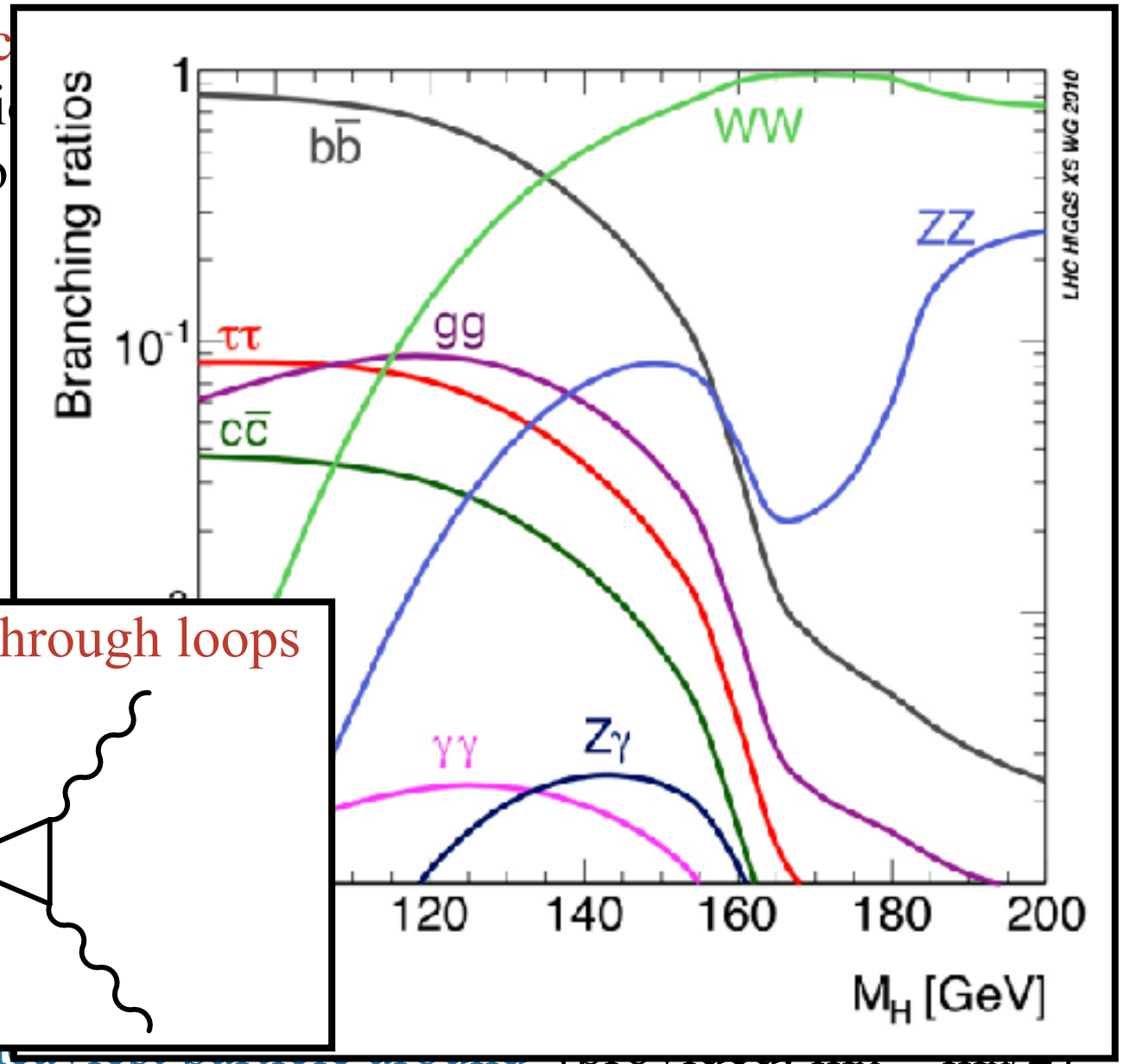
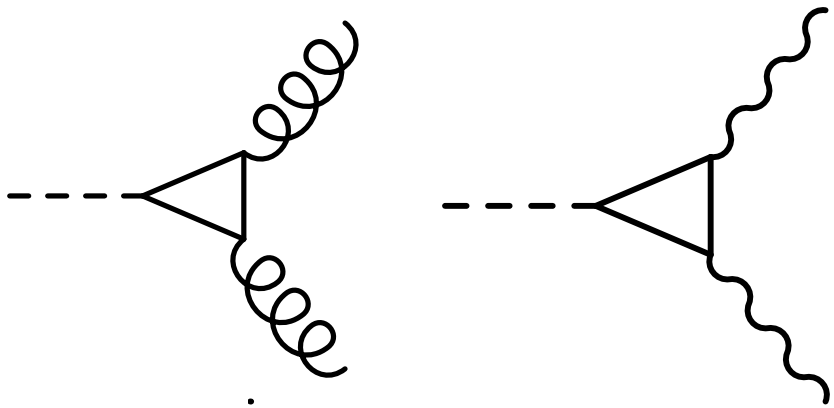


Branching Ratio

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



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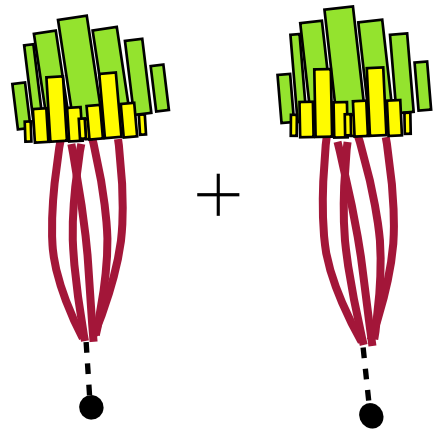
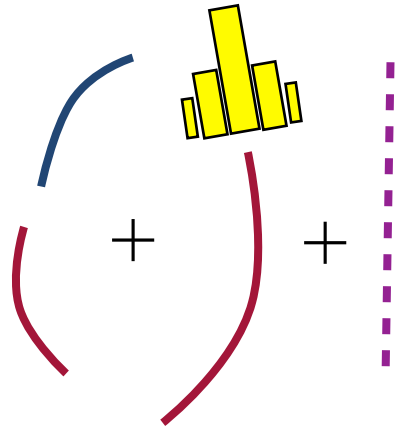
Higgs decays

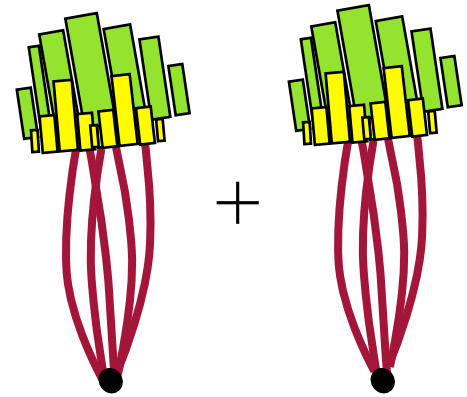
H → bb: ~60%



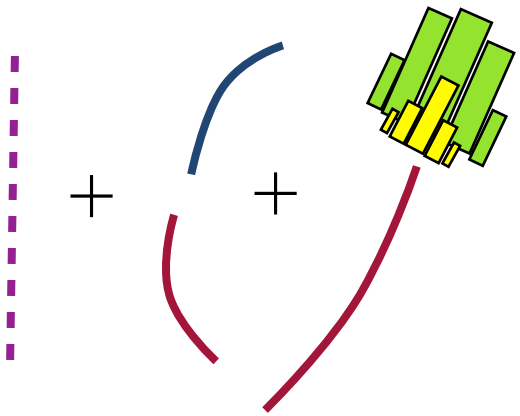
H → WW: ~20%



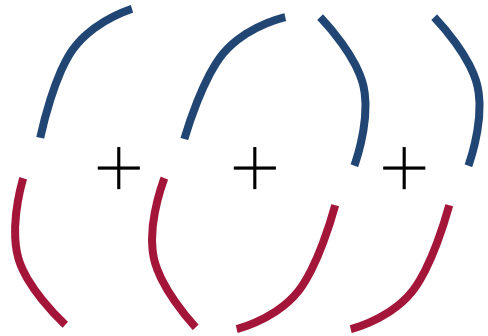
H → jj: ~10%



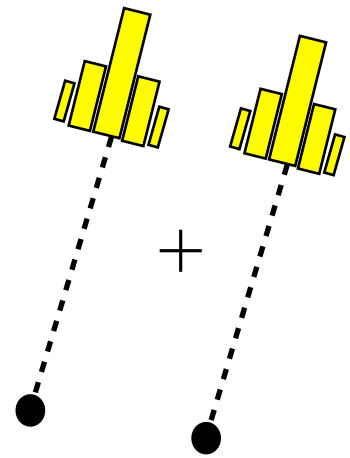
H → ττ: ~5%



H → ZZ: ~2%

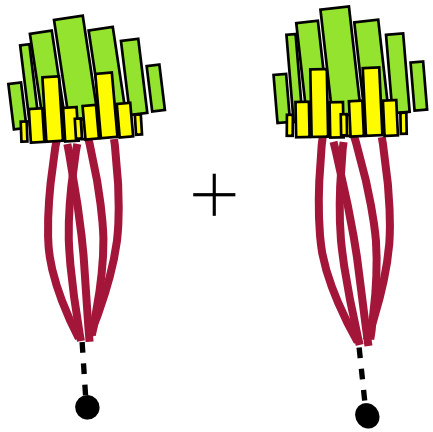


H → γγ: 0.2%

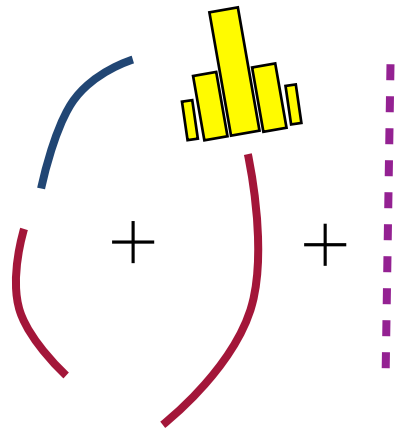


Higgs decays

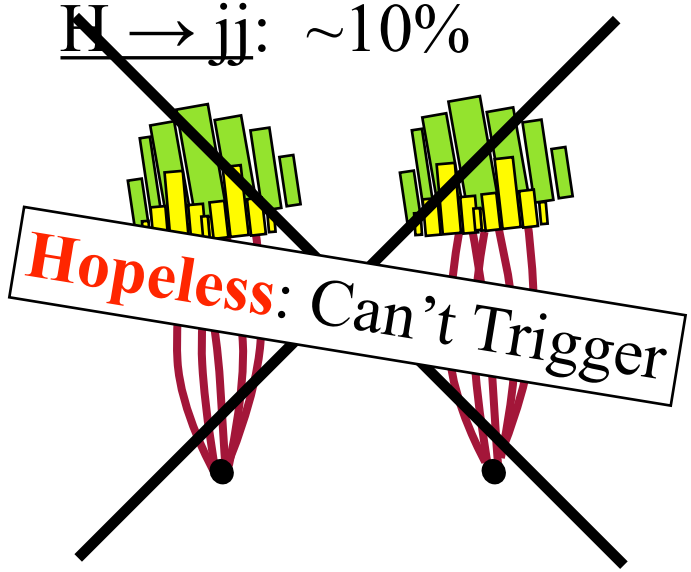
H → bb: ~60%



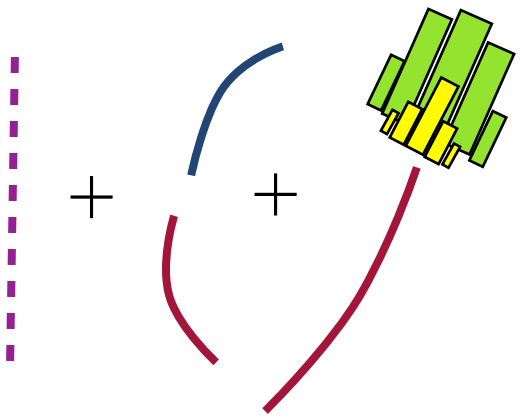
H → WW: ~20%



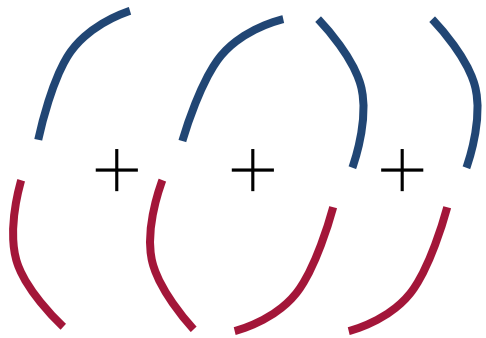
H → jj: ~10%



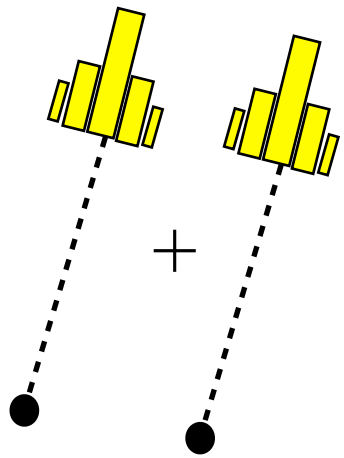
H → ττ: ~5%



H → ZZ: ~2%



H → γγ: 0.2%



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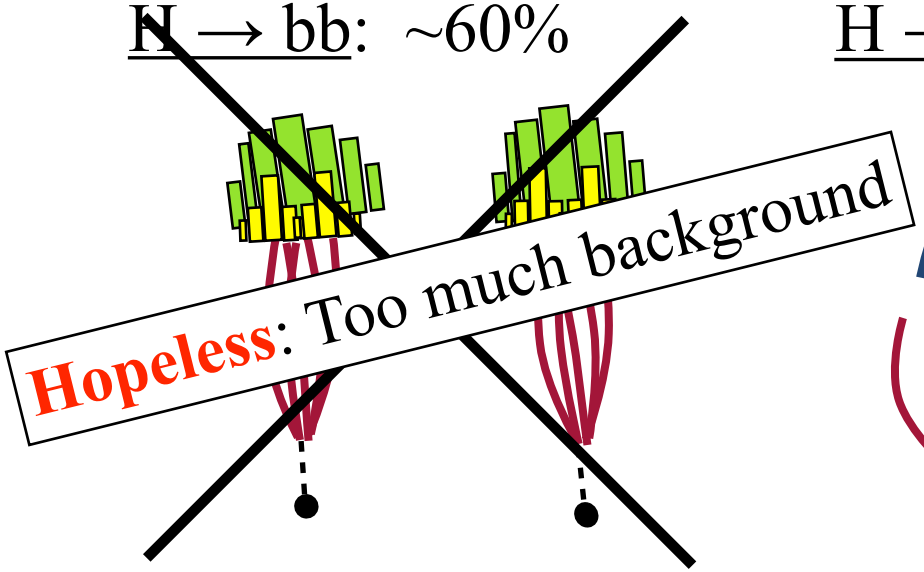
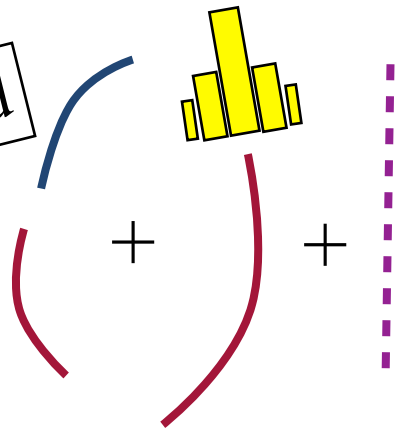
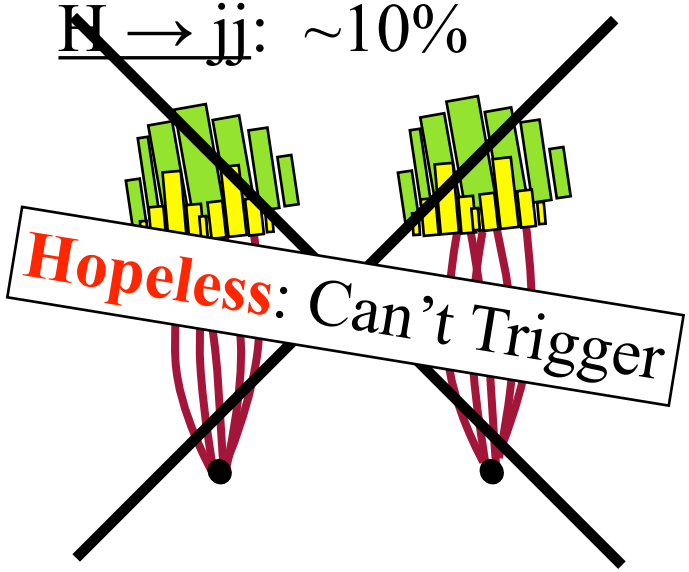


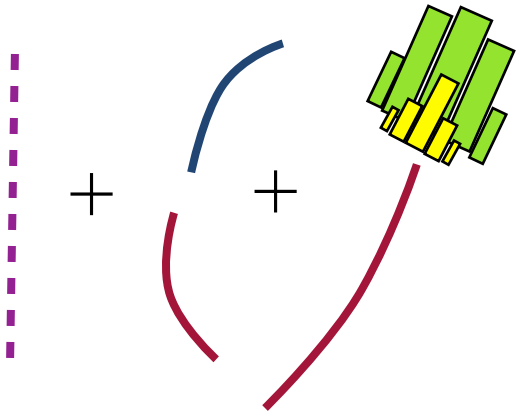
H → WW: ~20%



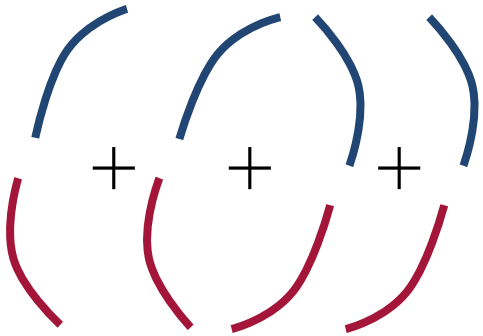
H → jj: ~10%



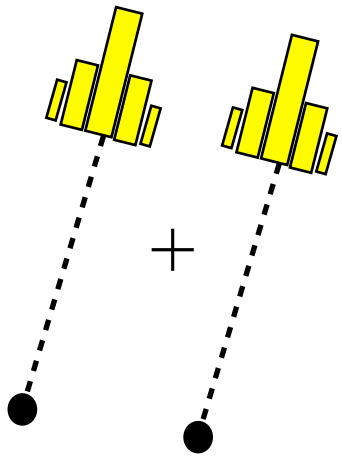
H → ττ: ~5%



H → ZZ: ~2%



H → γγ: 0.2%



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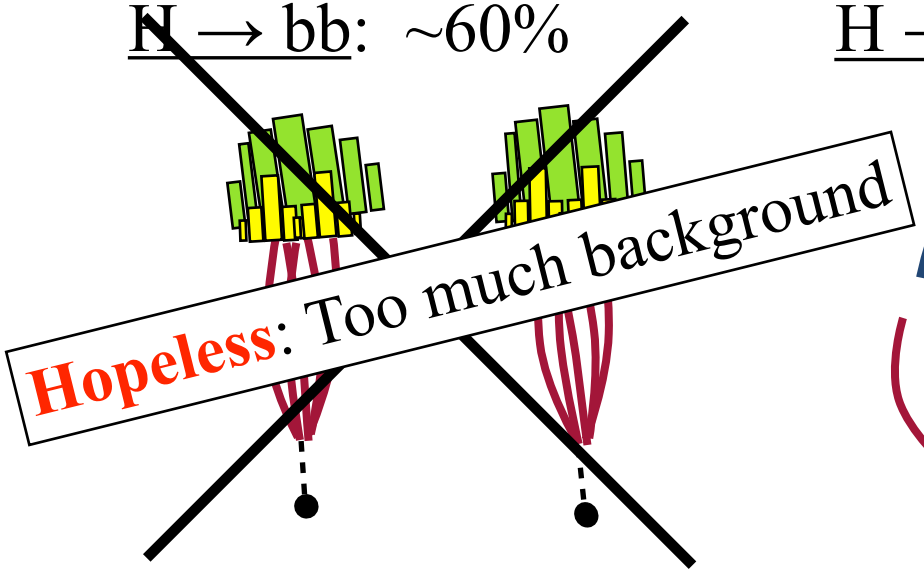

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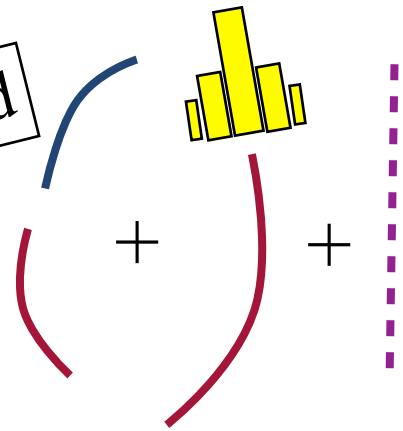

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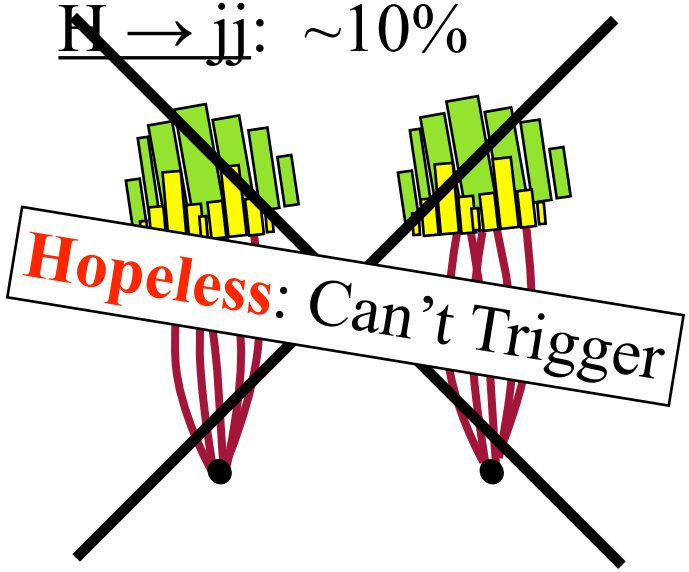

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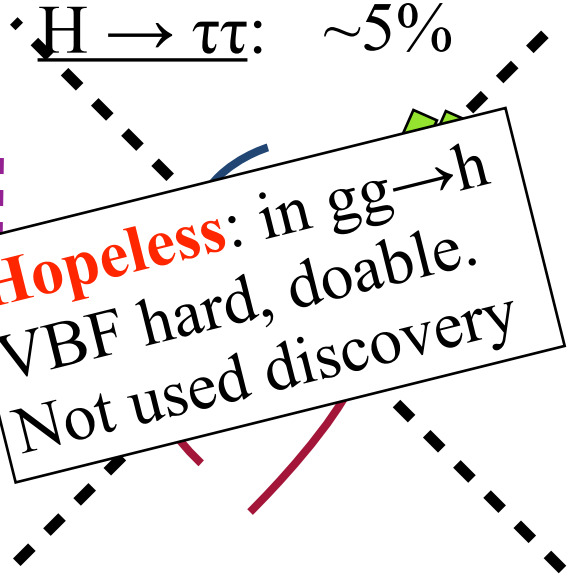

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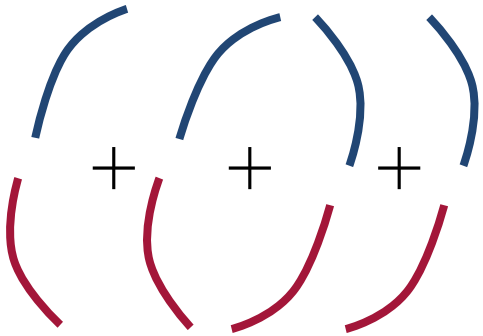

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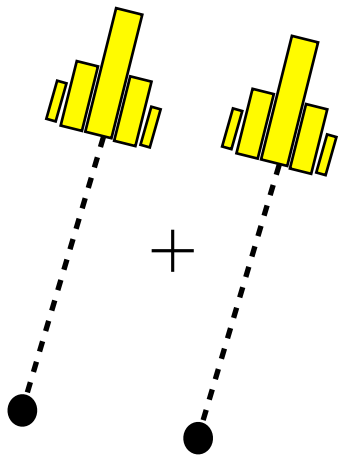
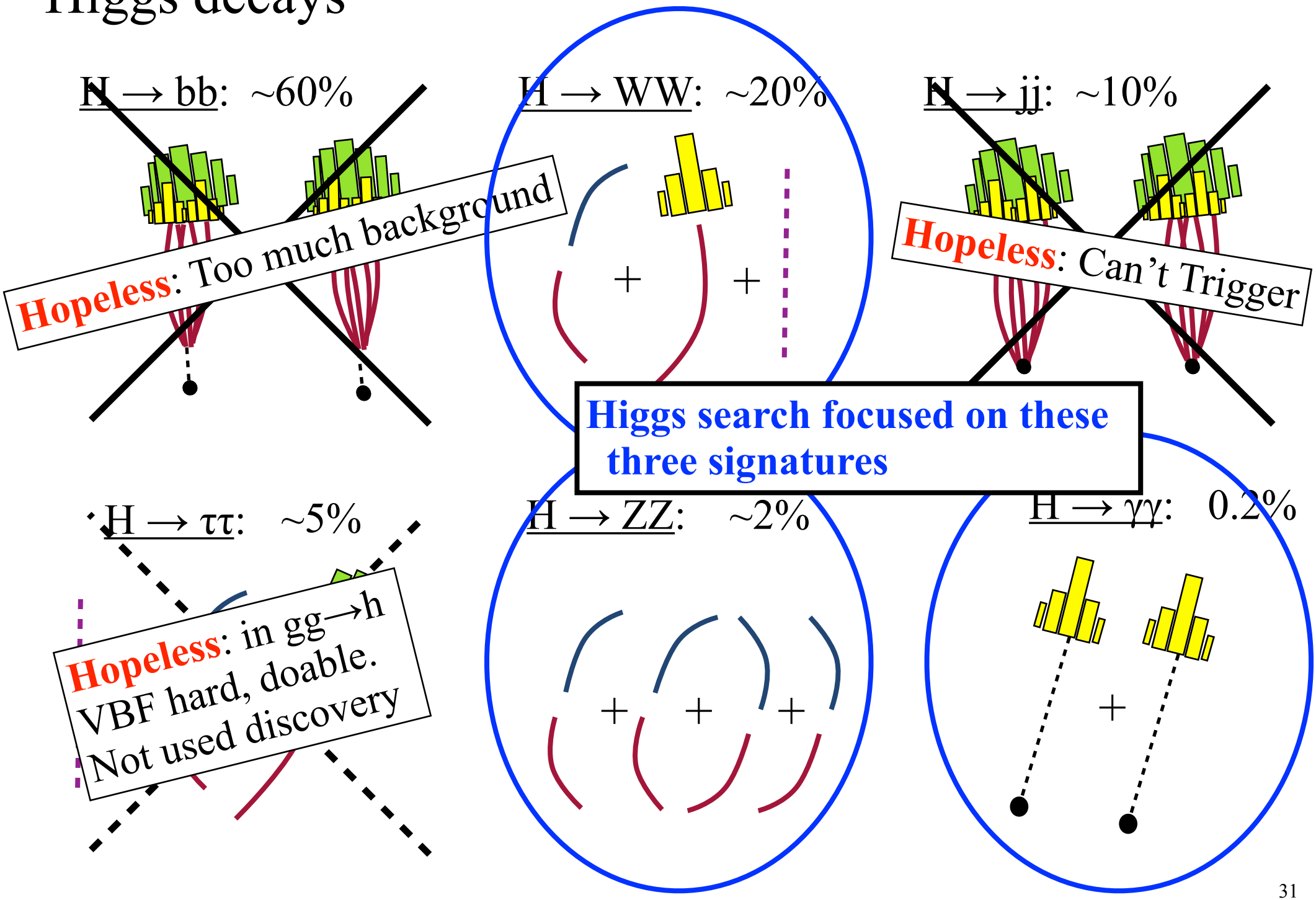


Higgs decays



How much data do we need ?

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Estimate out how often we make a Higgs.

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

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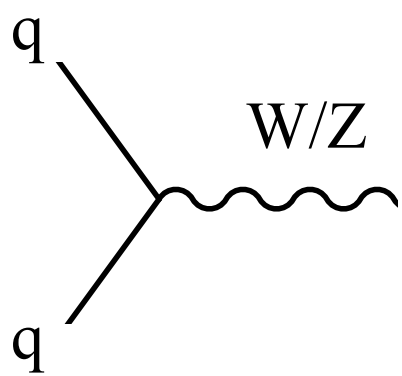
Warm-up: *How often do we make a W/Z ?*

$\sigma_{W/Z}$



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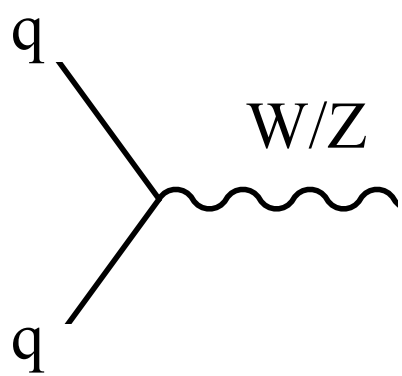
$$\sigma_{W/Z} \sim \frac{\alpha_W}{(m_{W/Z})^2}$$



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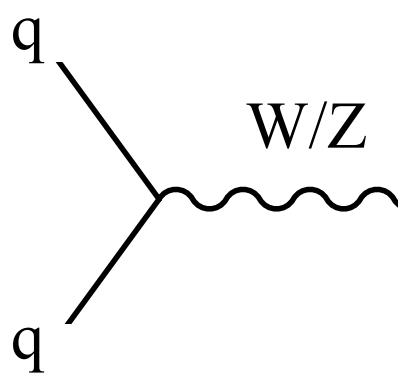
$$\sigma_{W/Z} \sim \frac{\alpha_W}{(m_{W/Z})^2} \sim \left(\frac{1}{50}\right)\left(\frac{1}{100}\right)^2 \text{GeV}^{-2}$$



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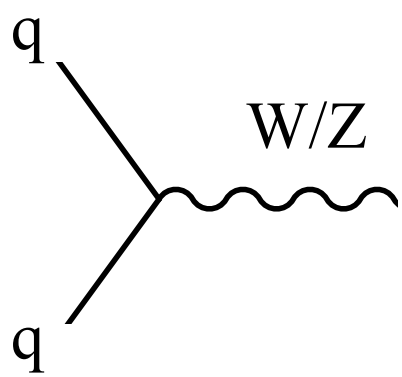
$$\sigma_{W/Z} \sim \frac{\alpha_W}{(m_{W/Z})^2} \sim \left(\frac{1}{50}\right)\left(\frac{1}{100}\right)^2 \text{ GeV}^{-2}$$

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



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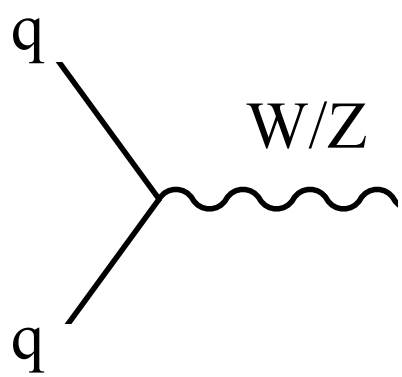

$\sigma_{pp} \sim \text{GeV}^{-2} \Rightarrow$ 1 W/Z for every 1 million proton collisions

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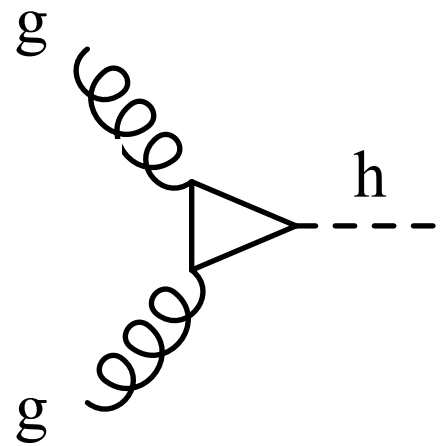
Same game for the Higgs

σ_{H}



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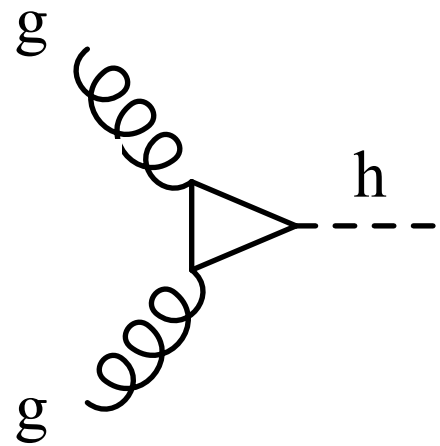
$$\sigma_H \sim \frac{1}{16\pi^2} \frac{\alpha_S^2 \alpha_W}{(m_H)^2}$$



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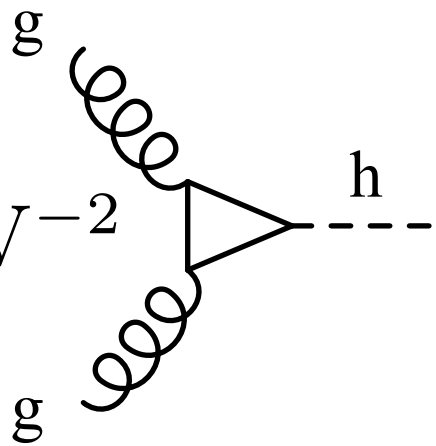
$$\sigma_H \sim \frac{1}{16\pi^2}\frac{\alpha_S^2\alpha_W}{(m_H)^2} \sim \frac{1}{160}\left(\frac{1}{10}\right)^2\left(\frac{1}{50}\right)\left(\frac{1}{100}\right)^2 \text{ GeV}^{-2}$$



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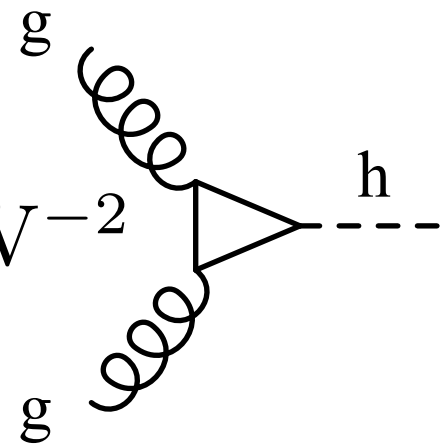

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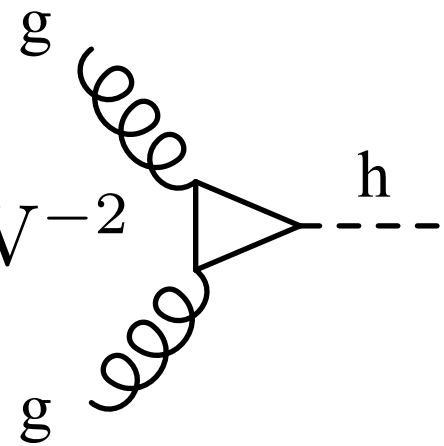

$\sigma_{pp} \sim \text{GeV}^{-2} \Rightarrow$ 1 Higgs for every billion proton collisions

How much data do we need ?

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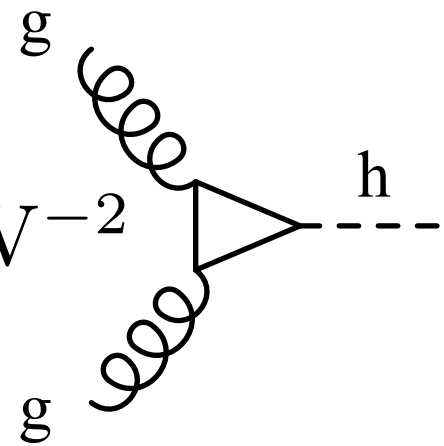
Same game for the Higgs



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Good target: $\sim 100 \frac{h \to \gamma\gamma}{\text{year}}$

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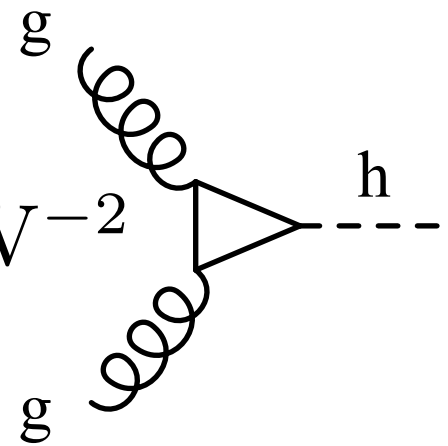

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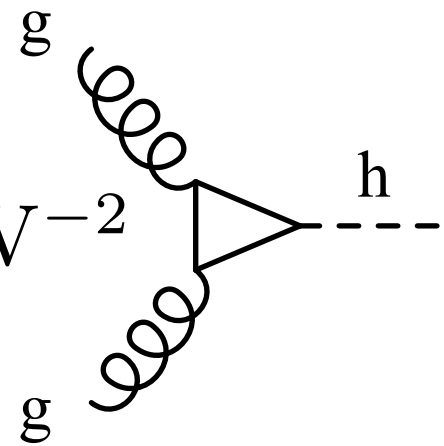

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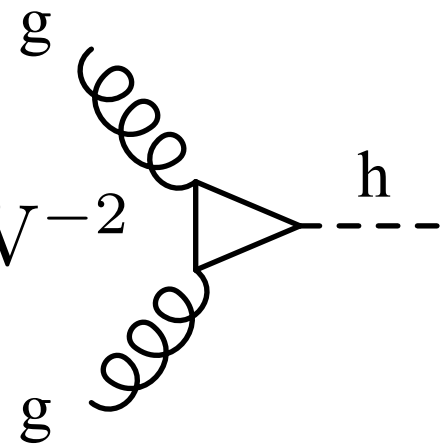

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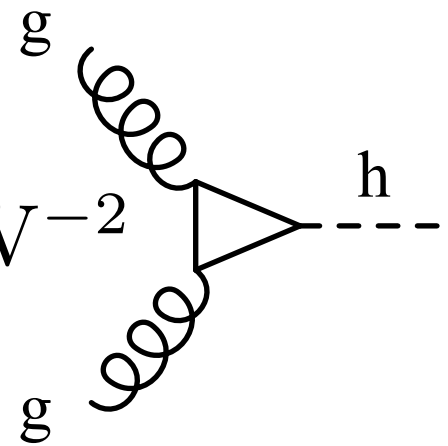

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$\Rightarrow$ need billion proton collisions per second

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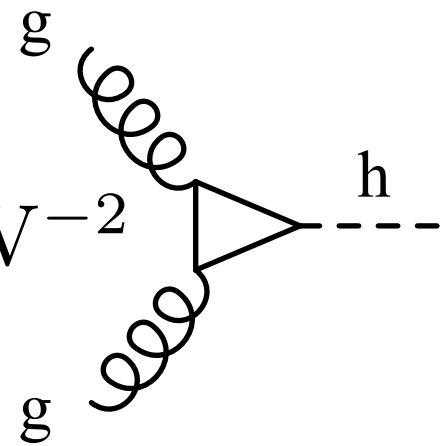

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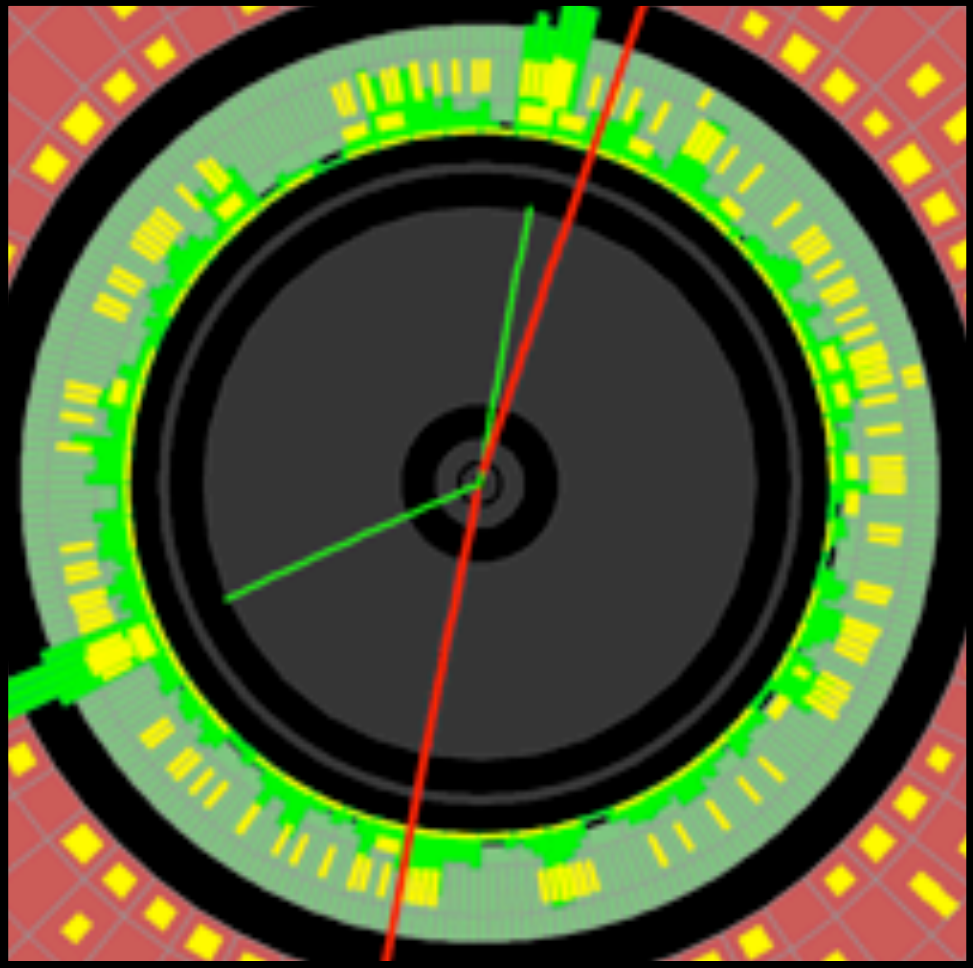
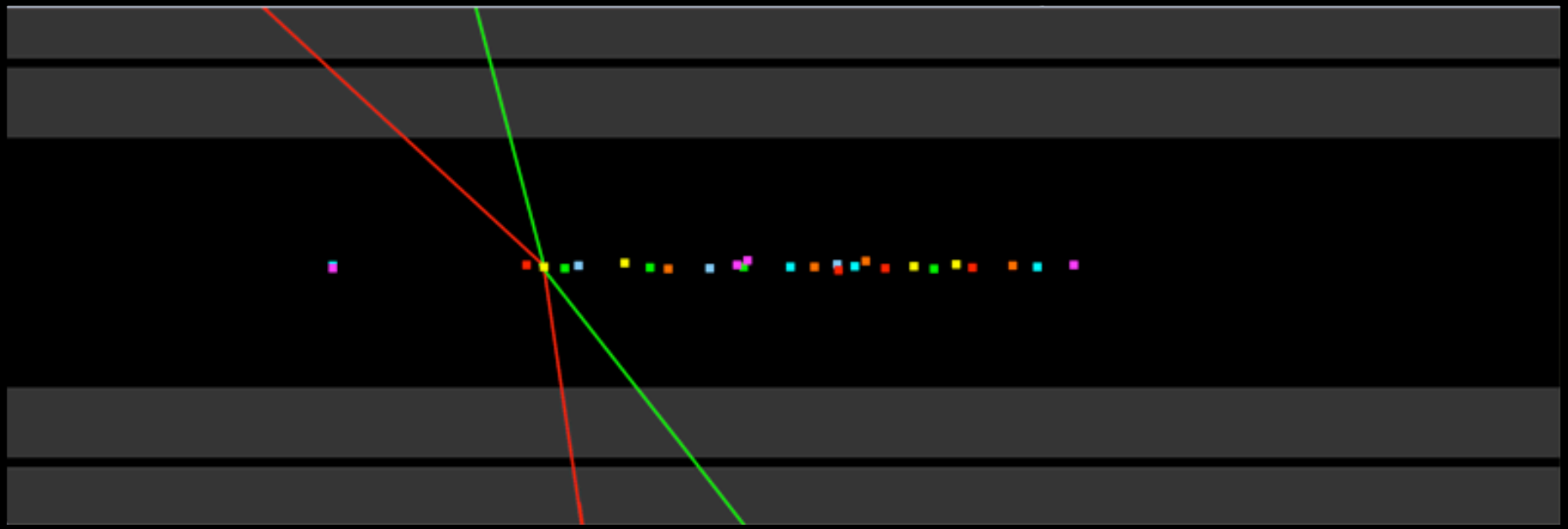
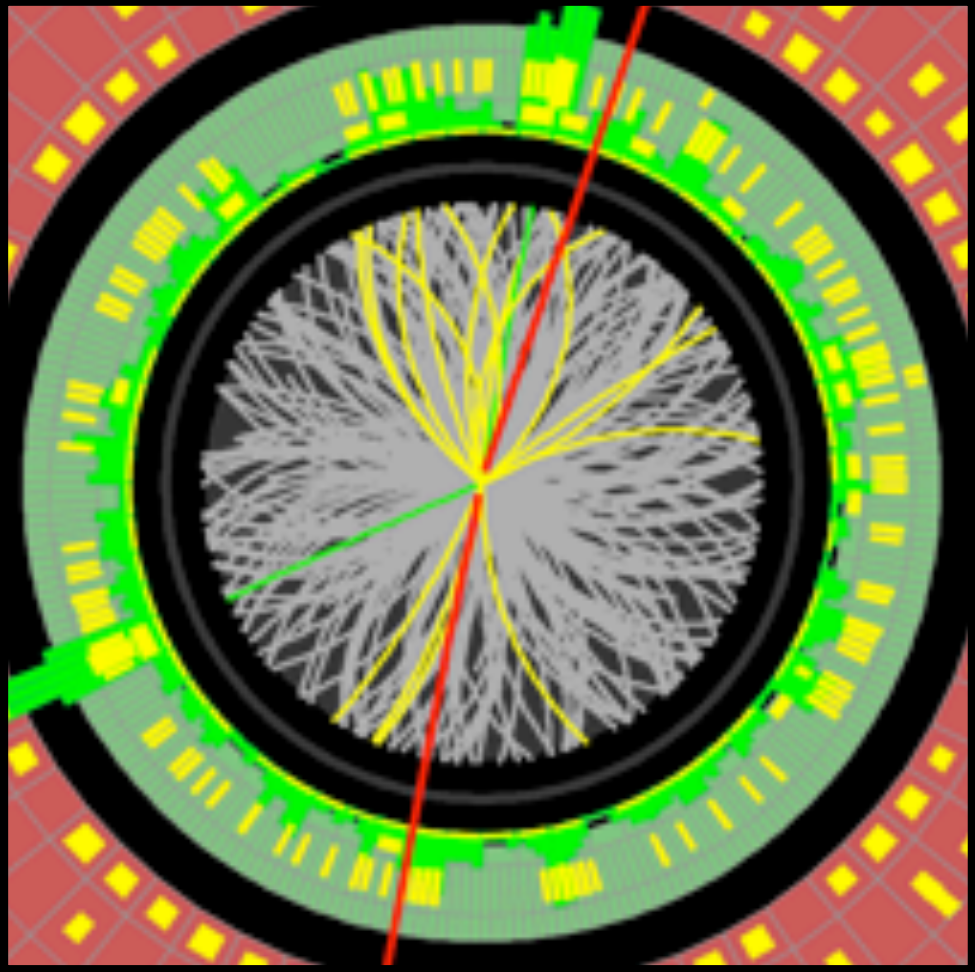
$\Rightarrow$ need billion proton collisions per second

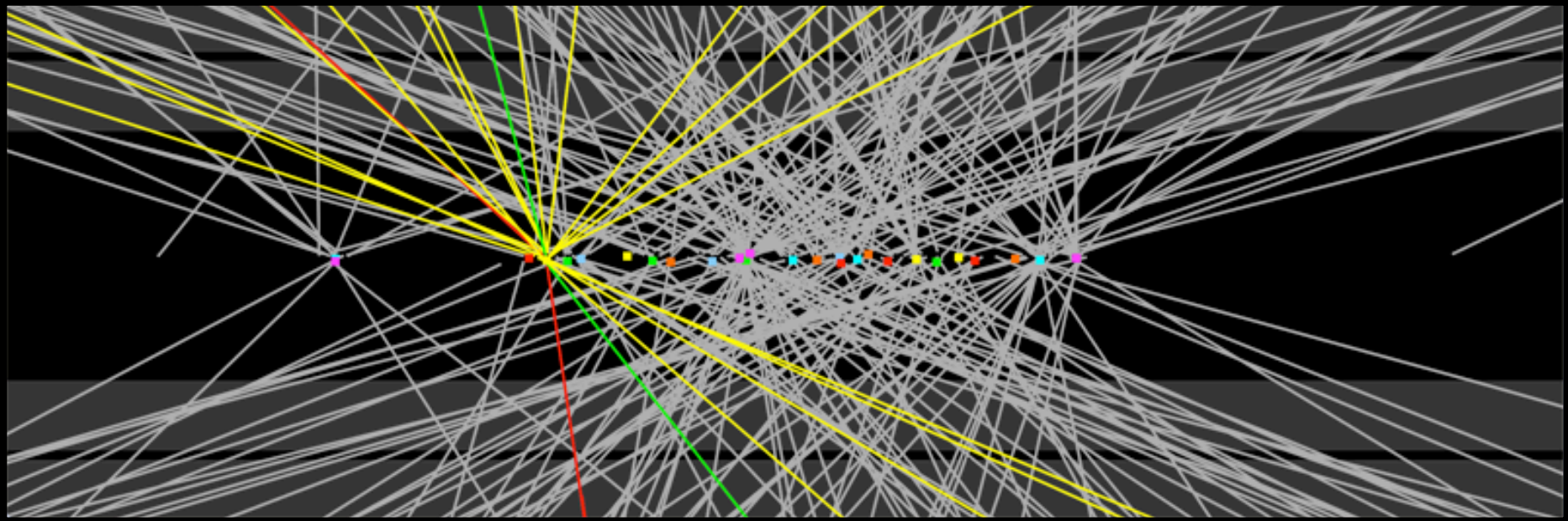
Only have beams crossing 40 million times per second …

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

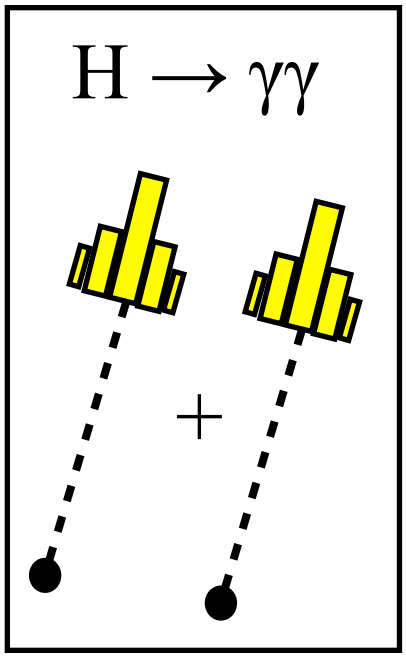


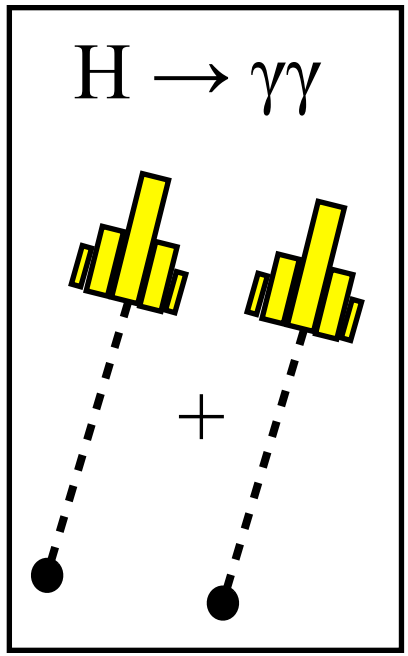




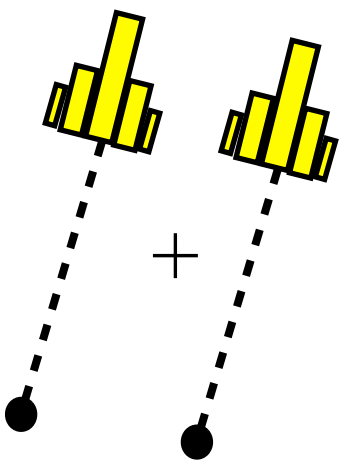


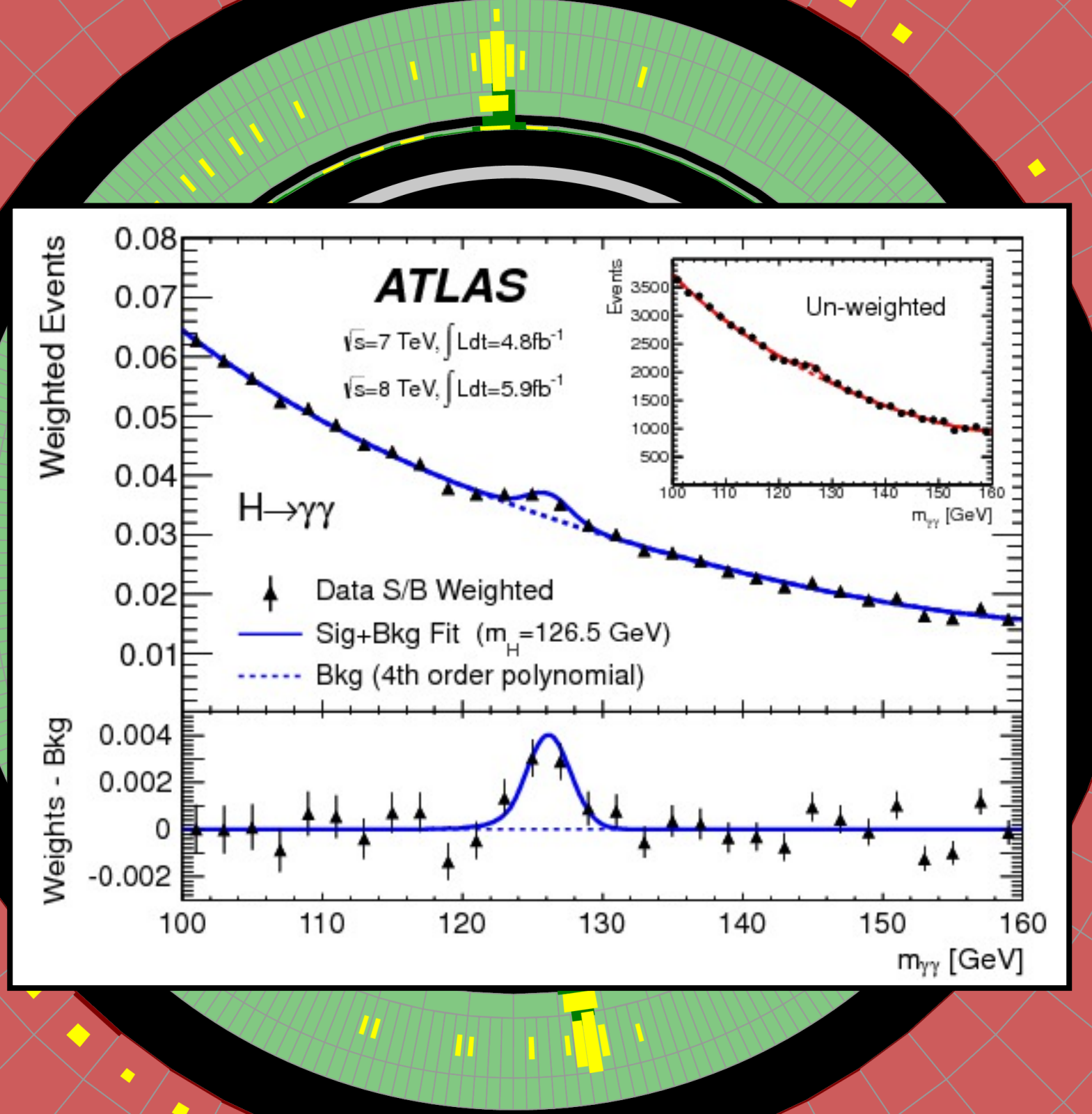
Higgs Discovery

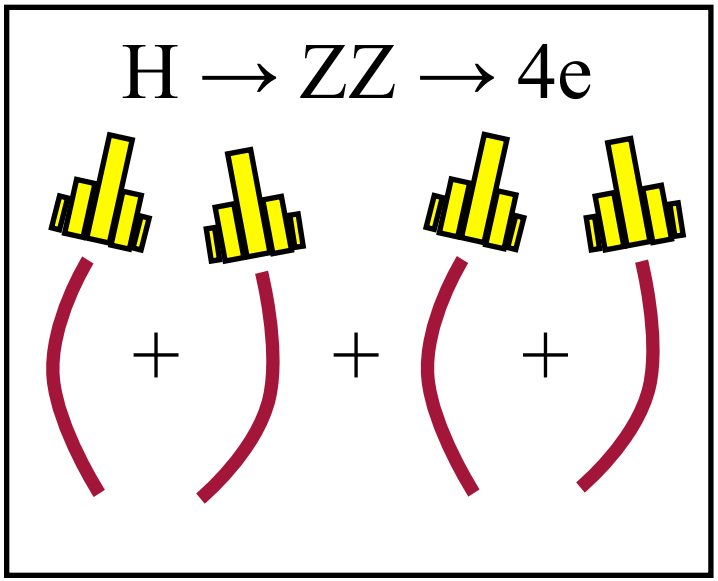

H → γγ
+

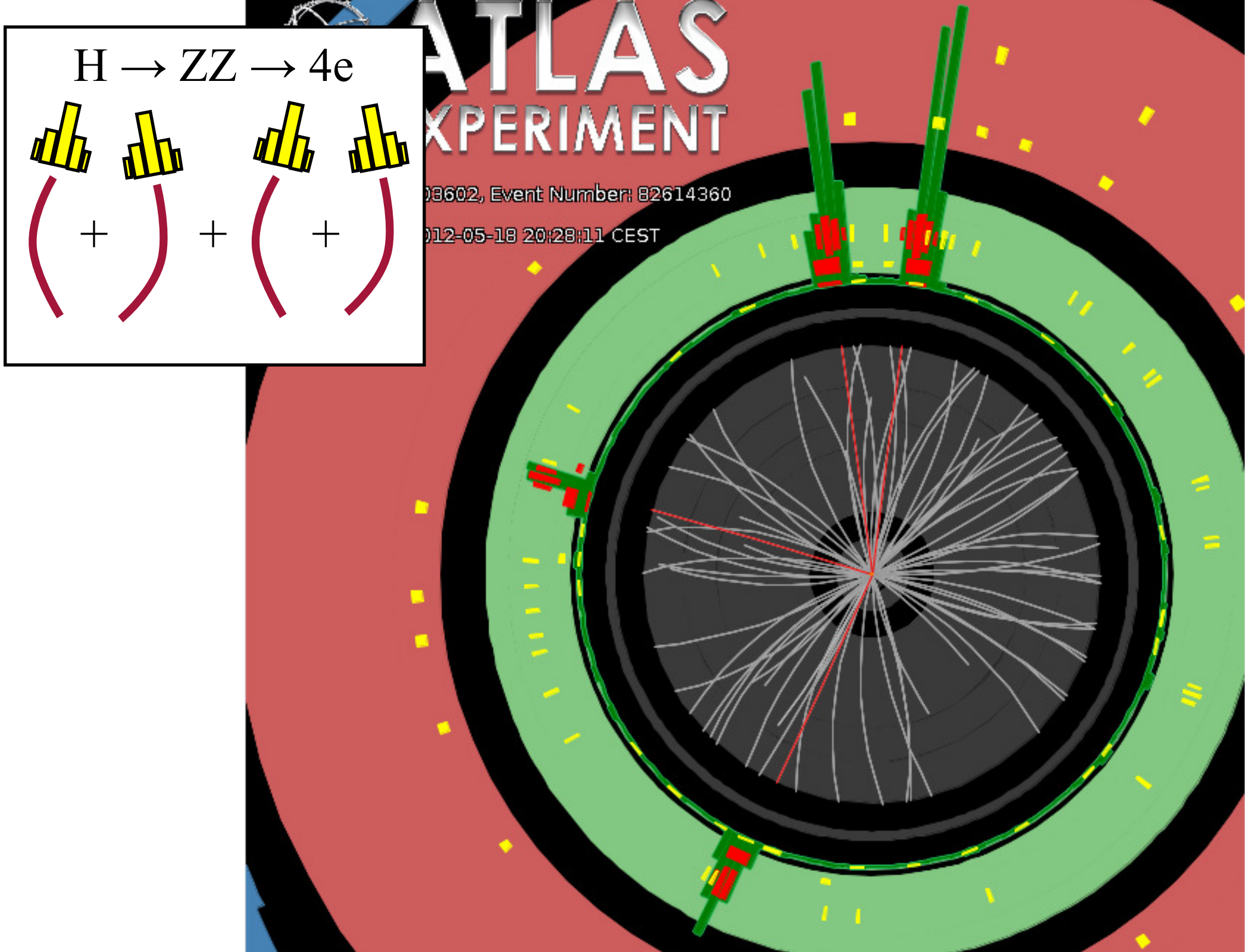

H → γγ
+

$H \rightarrow \gamma\gamma$

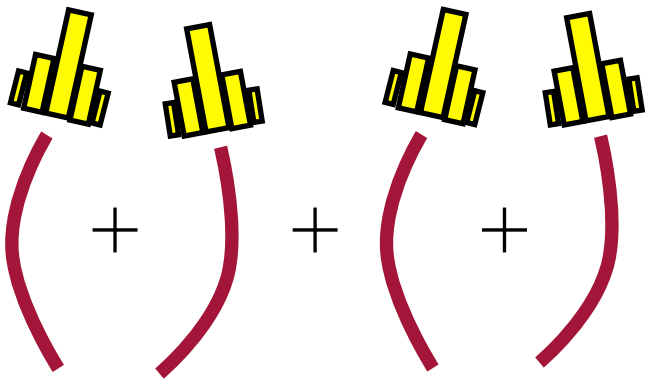


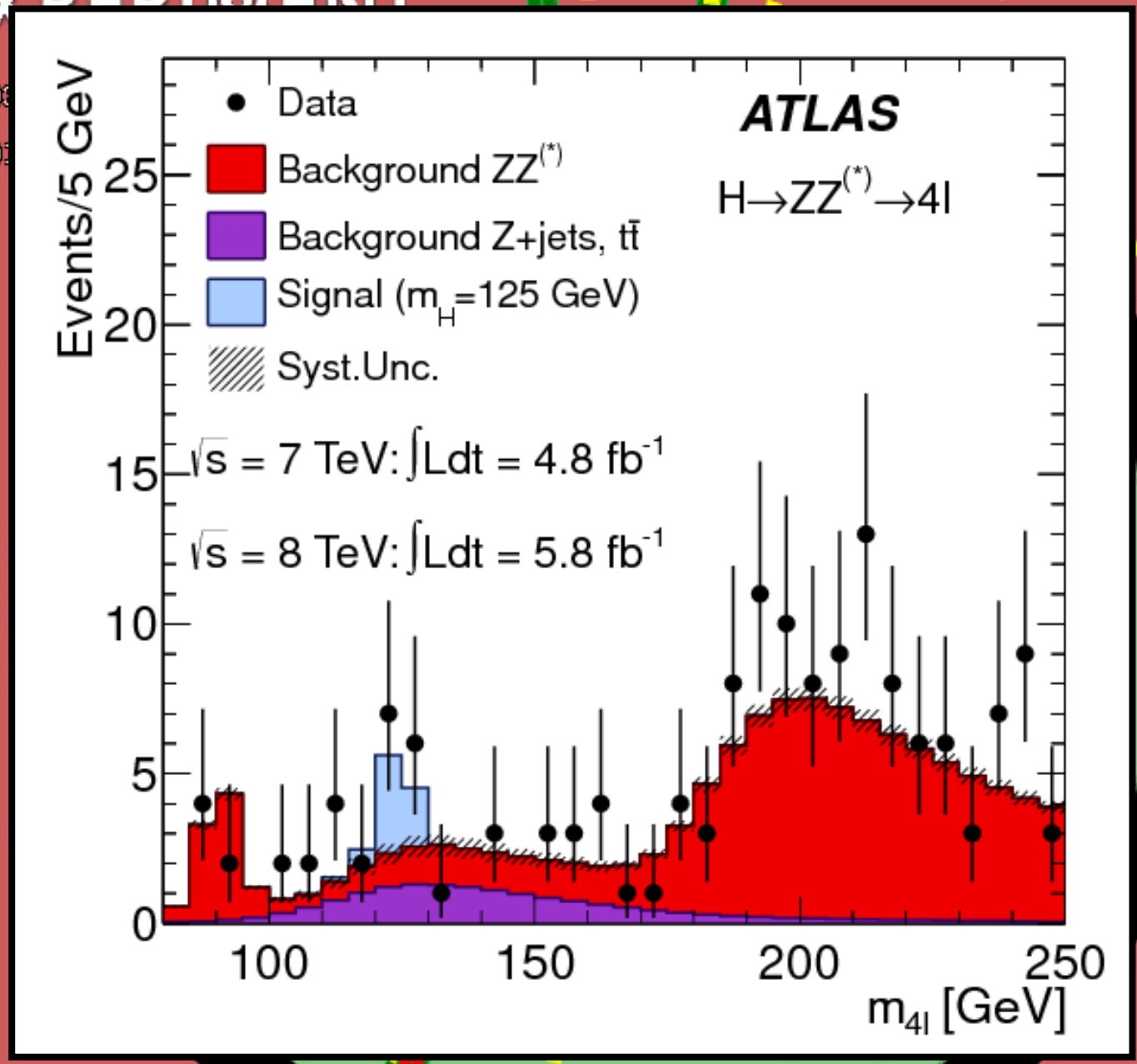


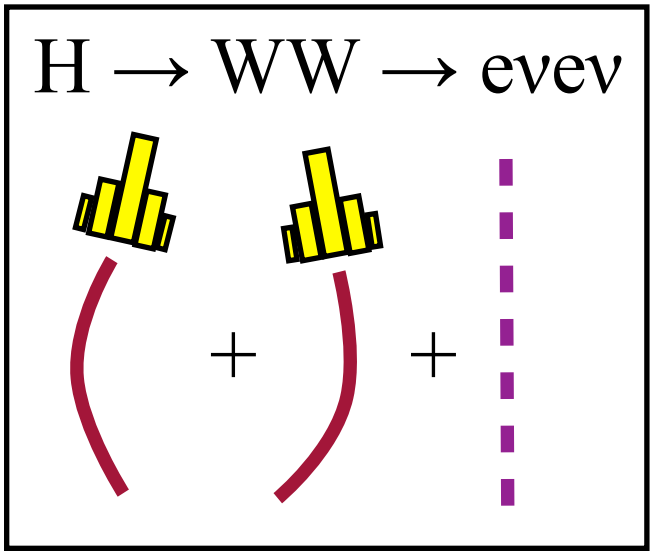

H → ZZ → 4e
+
+
+

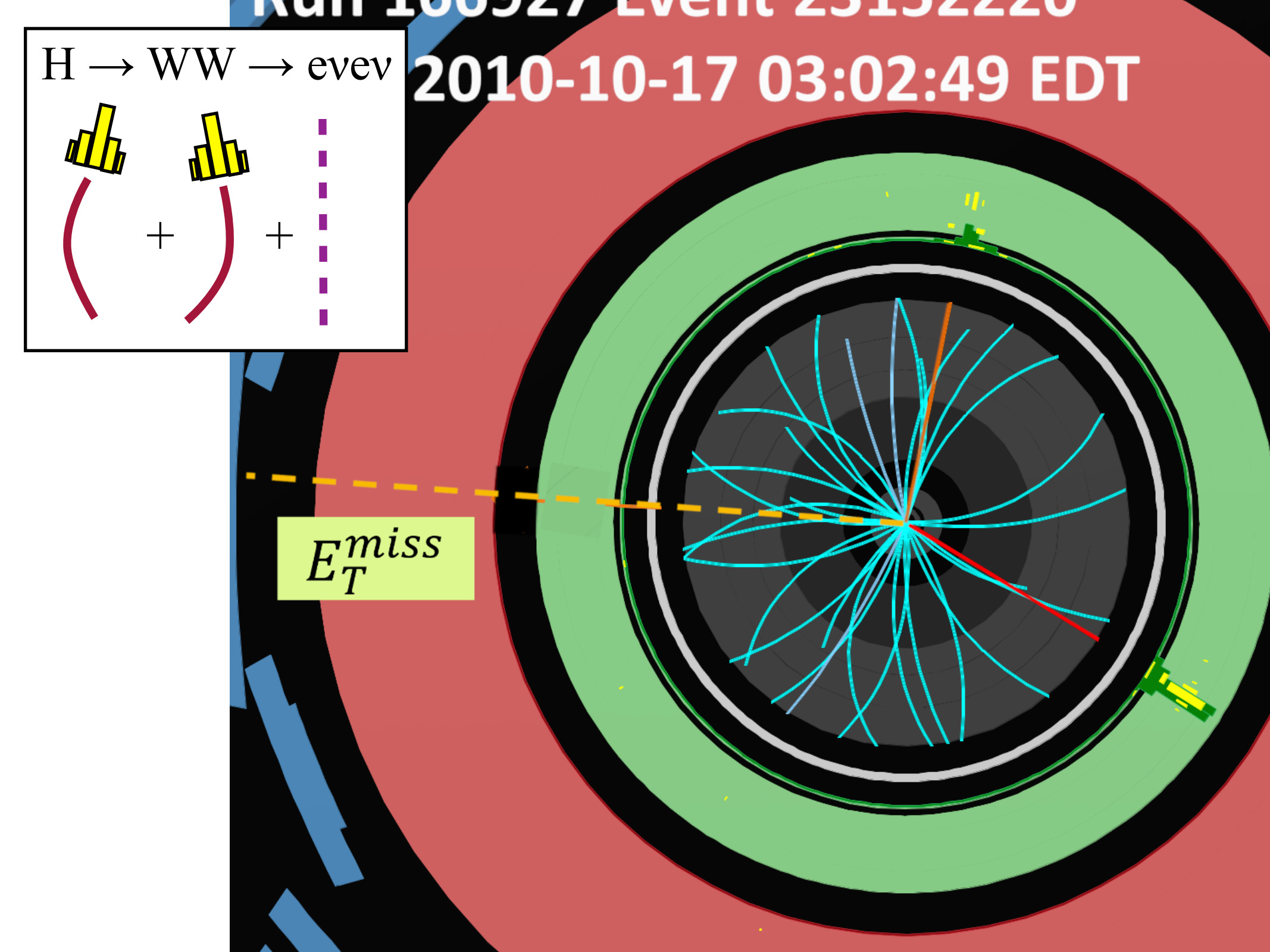

H → ZZ → 4e
+
+
+
ATLAS
XPERIMENT
03602, Event Number: 82614360
012-05-18 20:28:11 CEST

$H \rightarrow ZZ \rightarrow 4e$





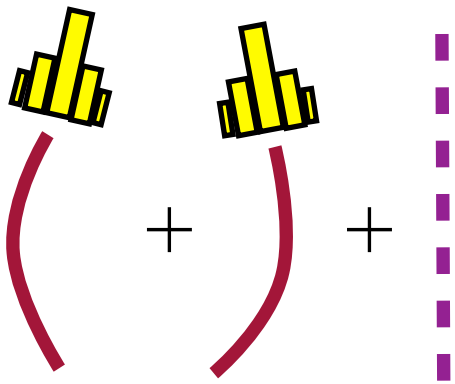

H → WW → evev
+
+


H → WW → evev
+
+
Run 166927 Event 23152220
2010-10-17 03:02:49 EDT
E_T^{miss}

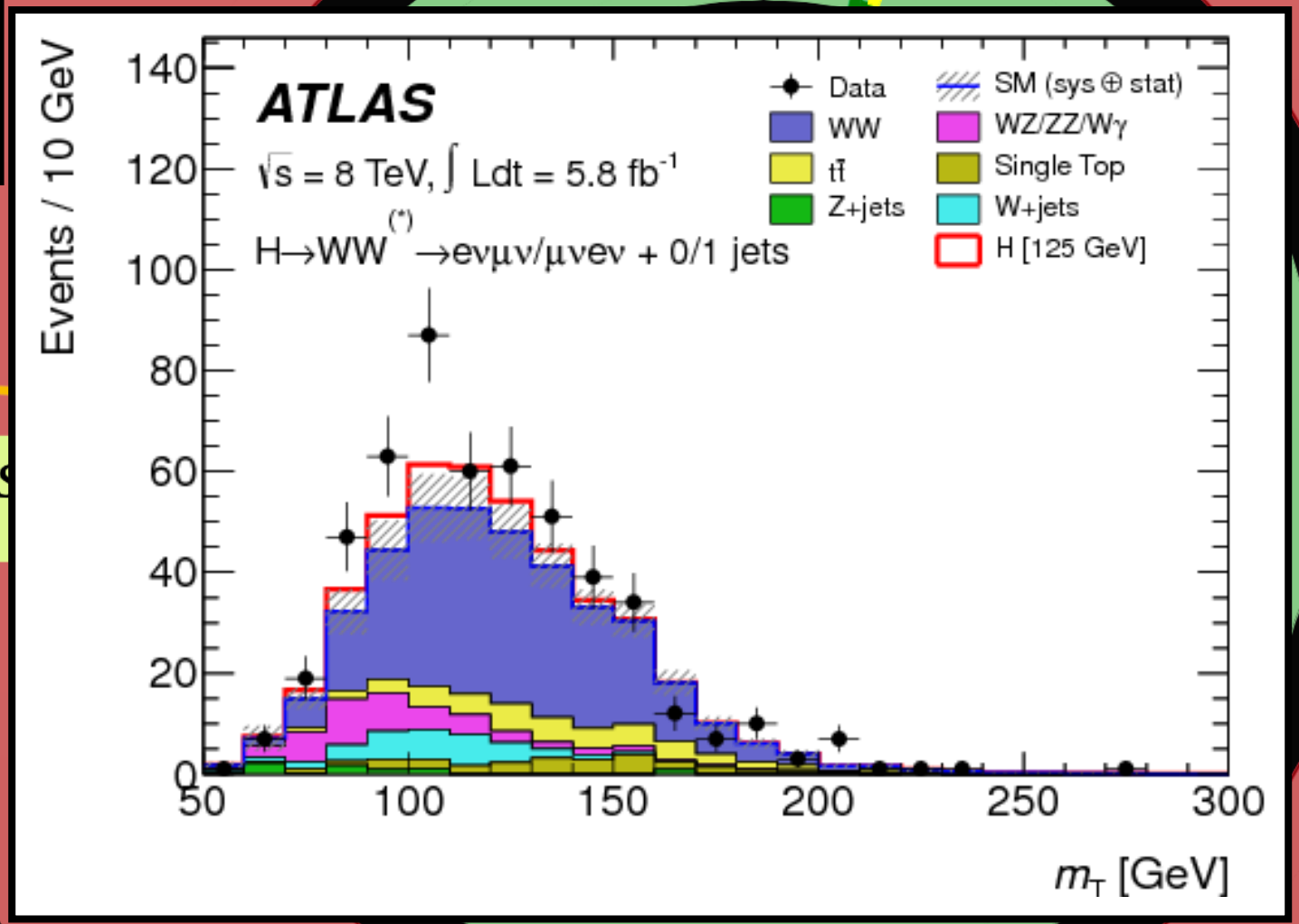
Run 166927 Event 2315222

2010-10-17 03:02:49 EDT

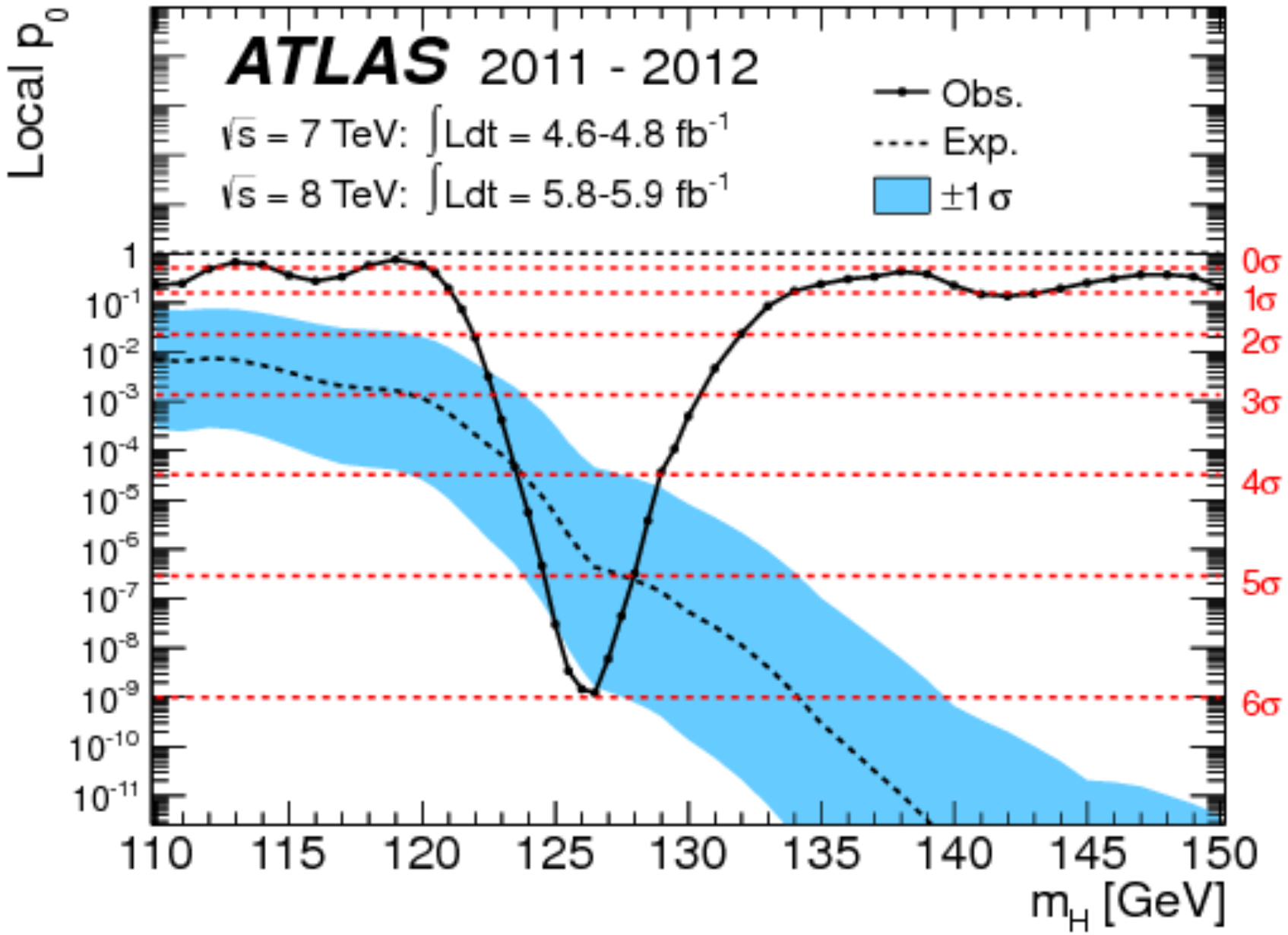
$H \rightarrow WW \rightarrow e\nu e\nu$



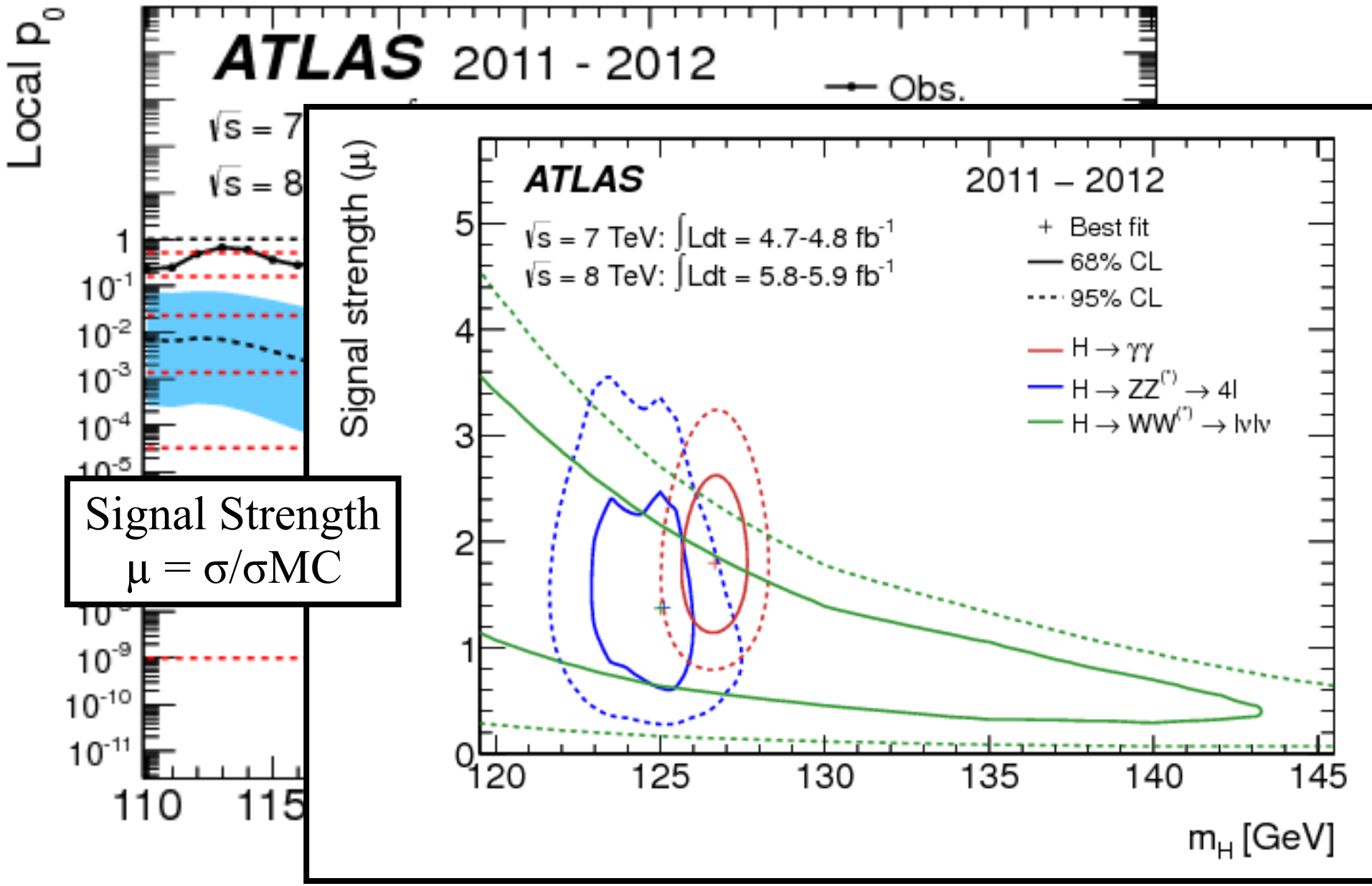
E_T^{mis}



Putting It All Together

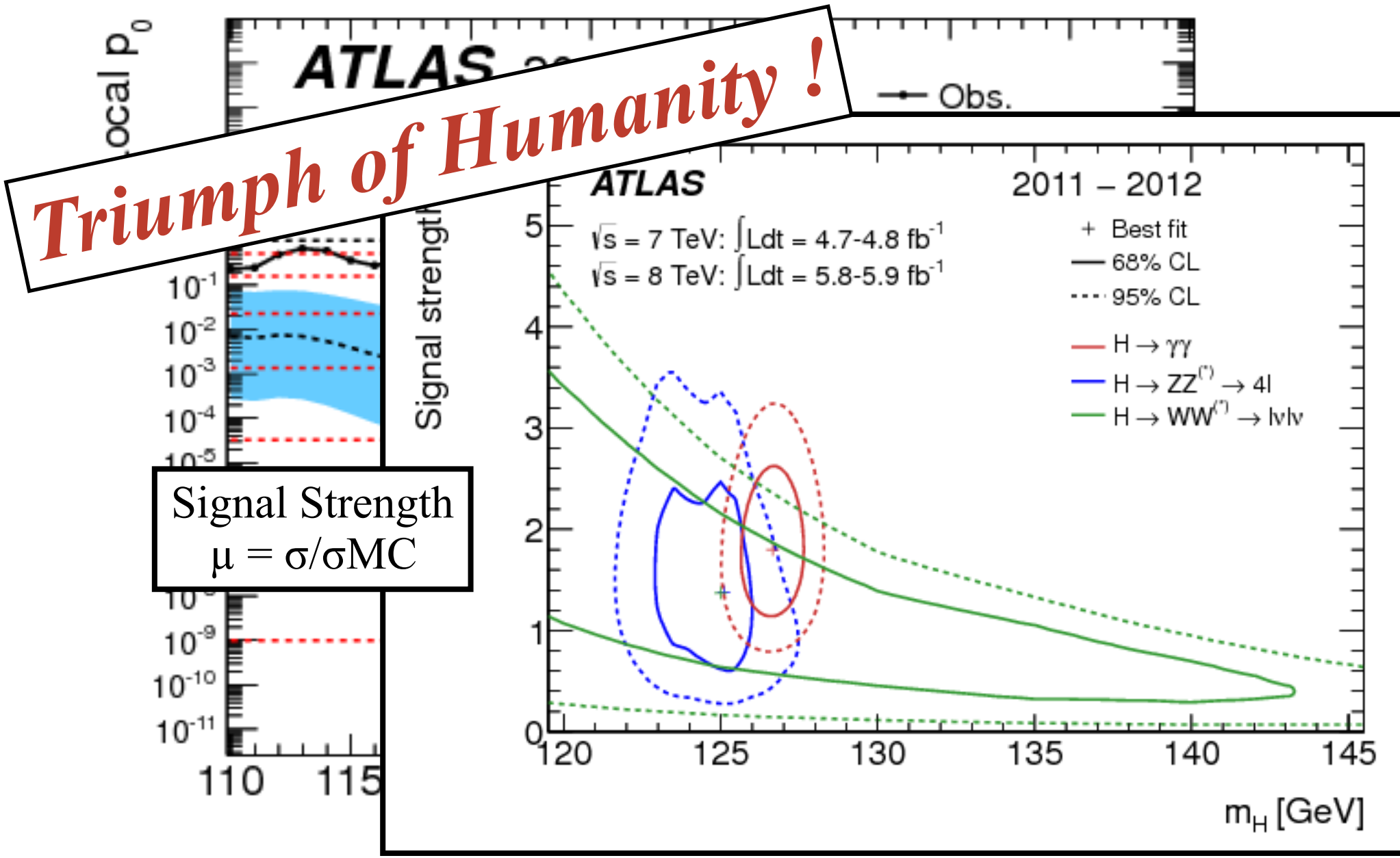


Putting It All Together



Signal Strength
$\mu = \sigma/\sigma_{MC}$

Putting It All Together

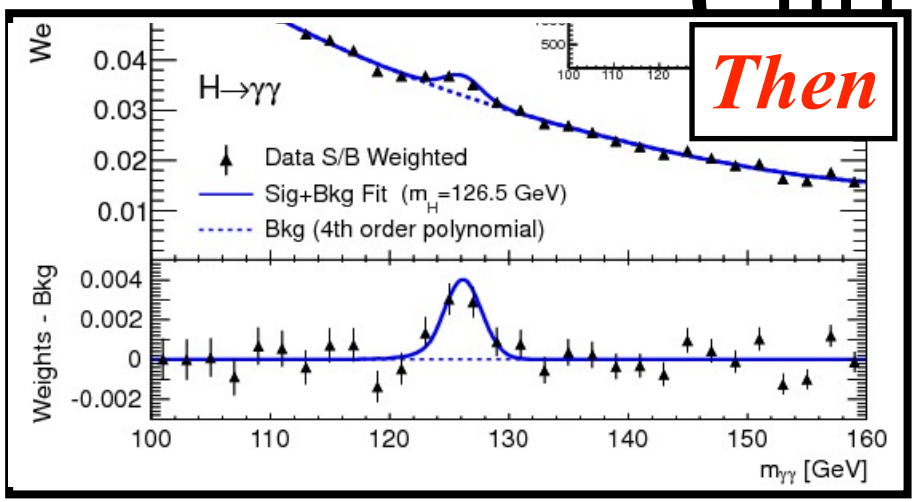


Higgs Post-Discovery

What We Know and Where We are Going

Current Status

Current Status



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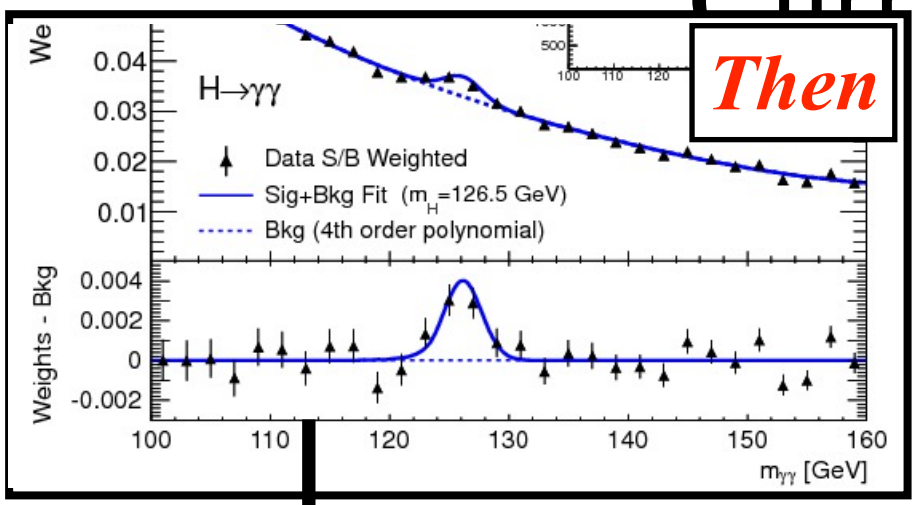

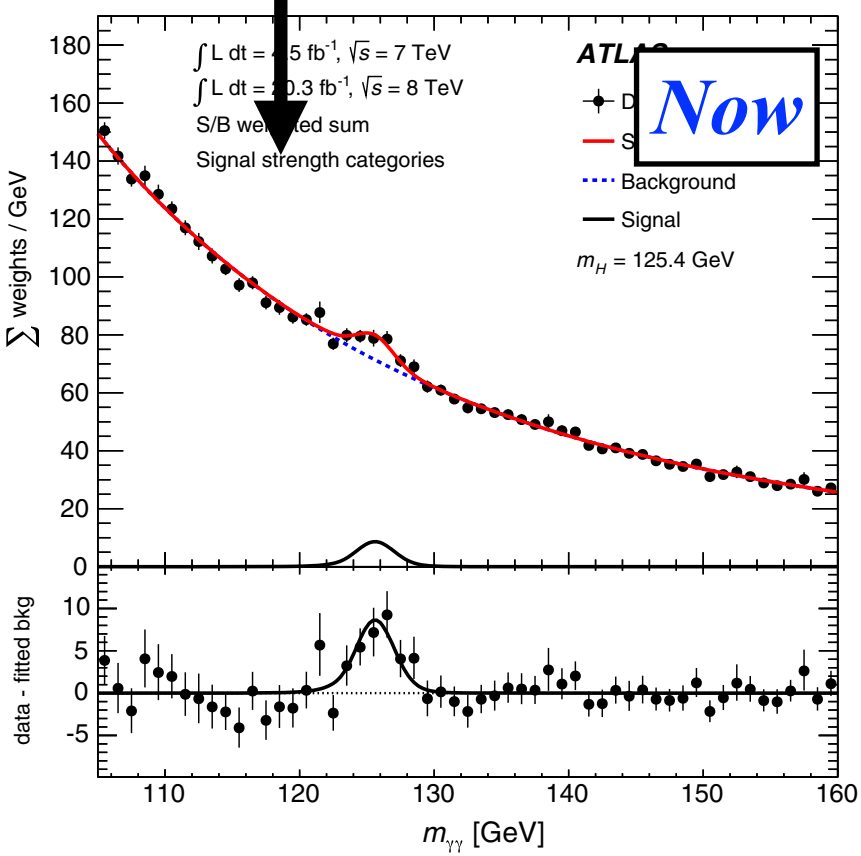

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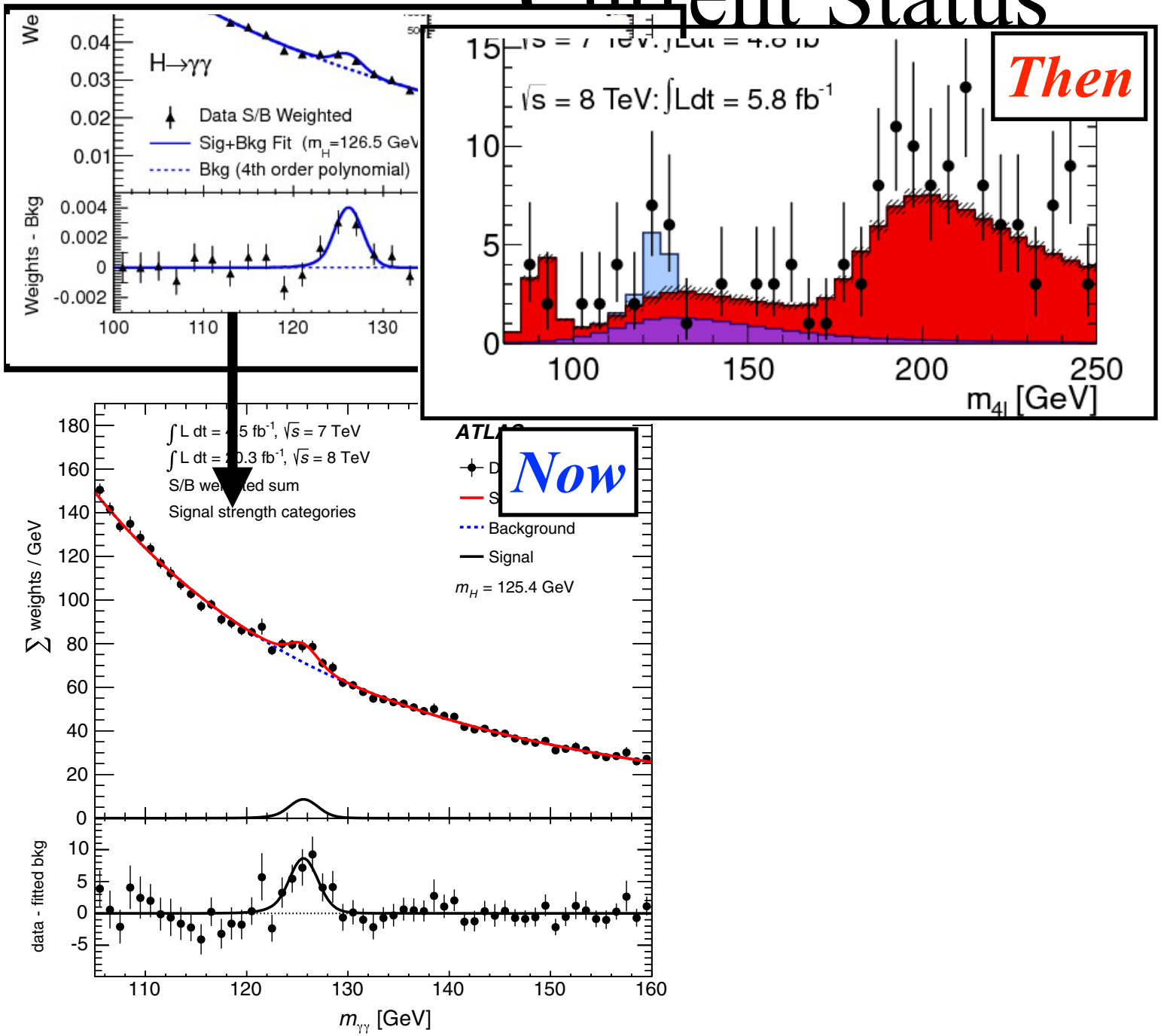

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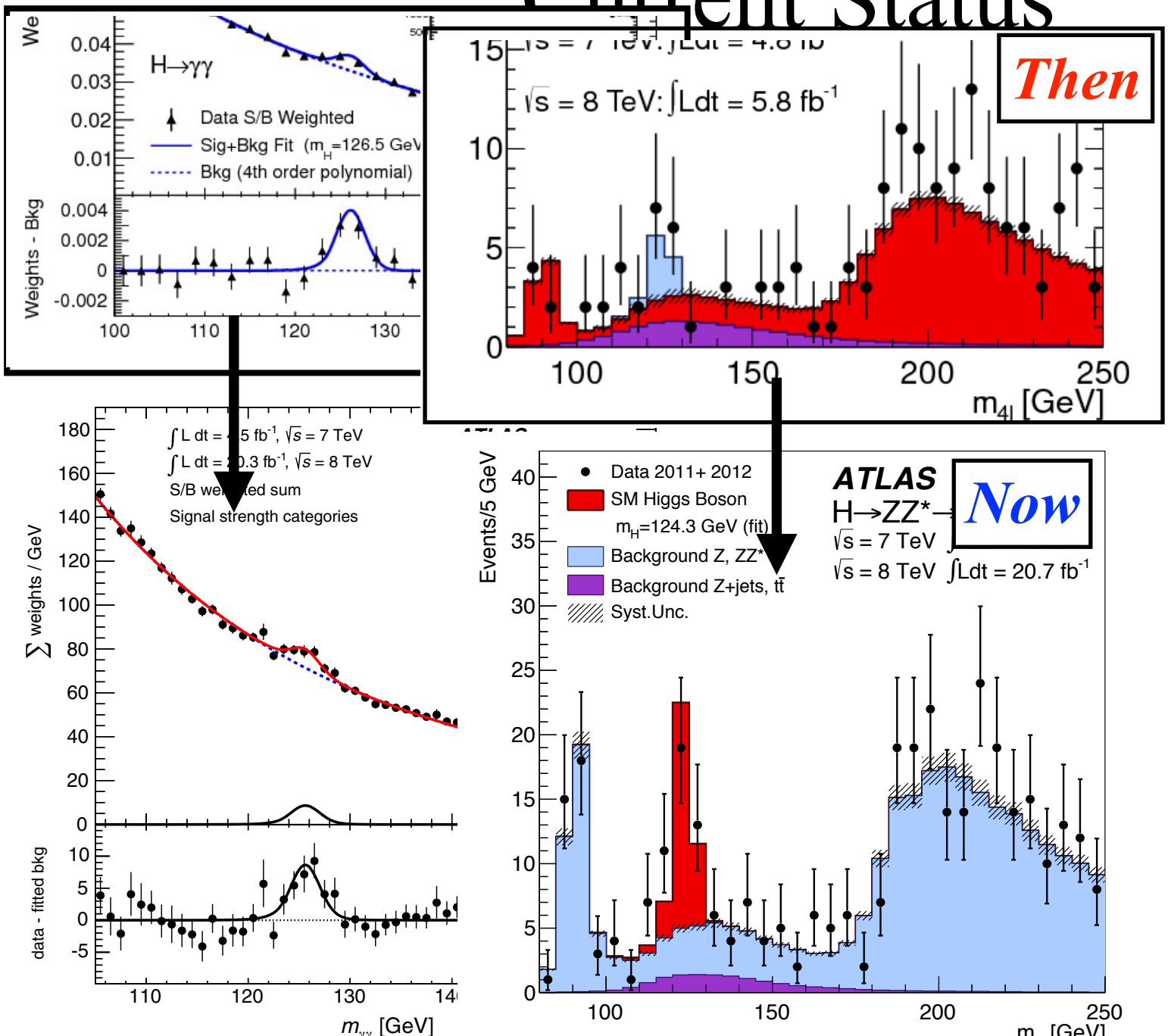

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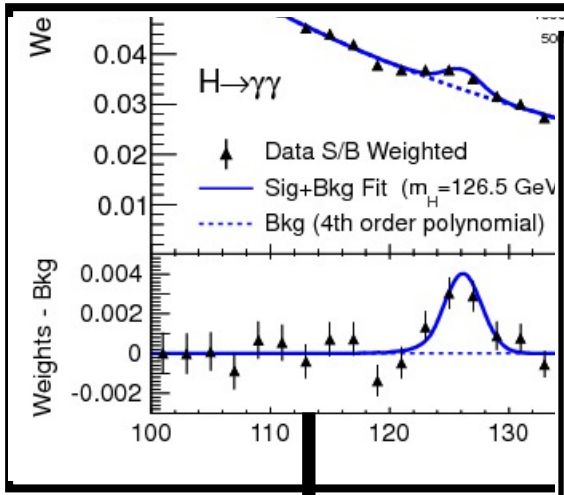
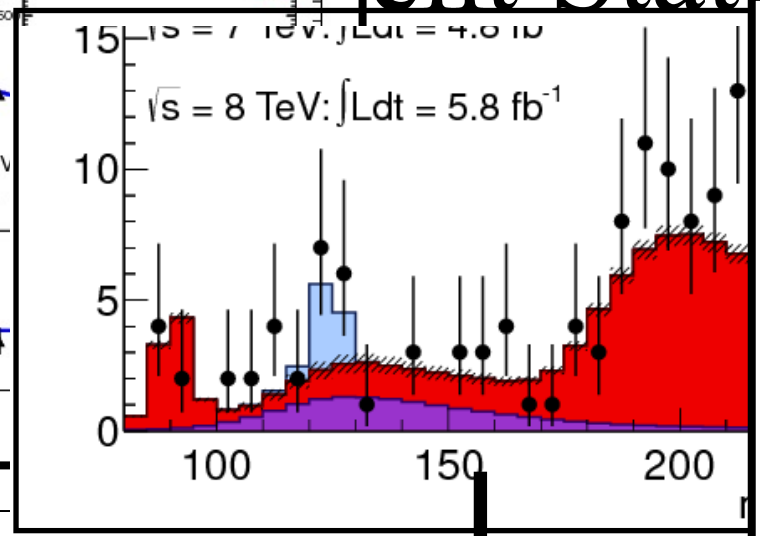
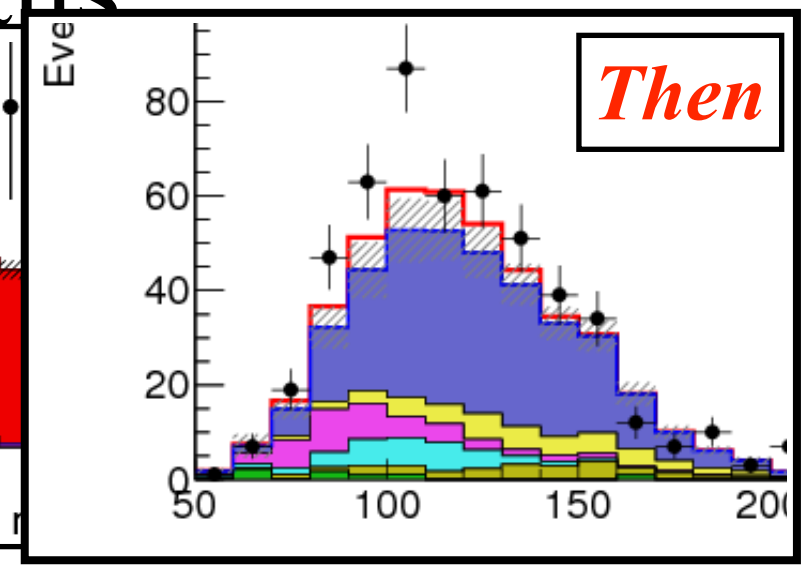
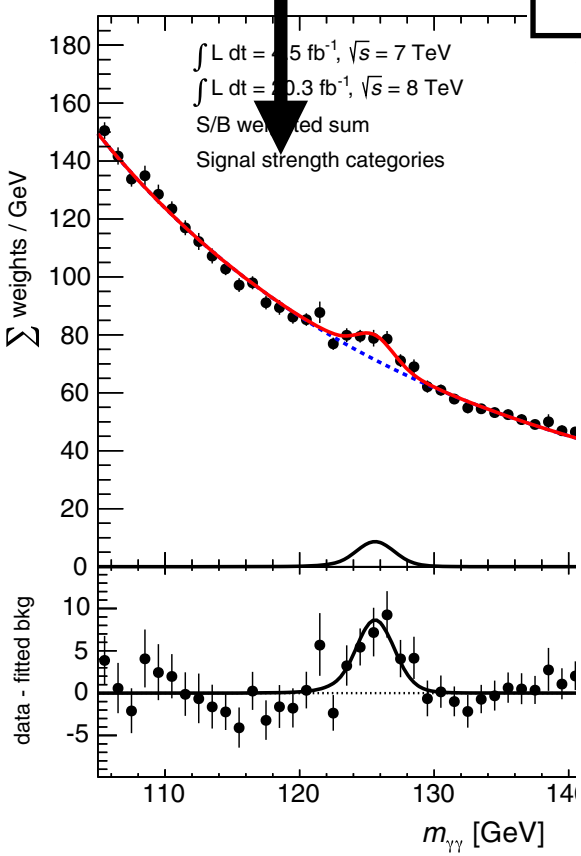
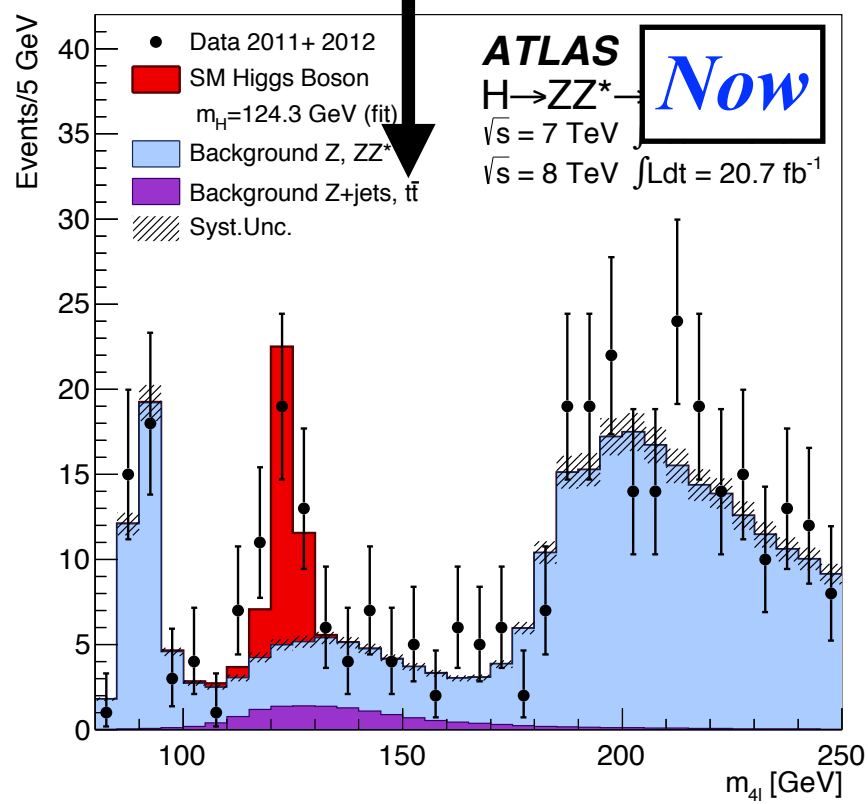


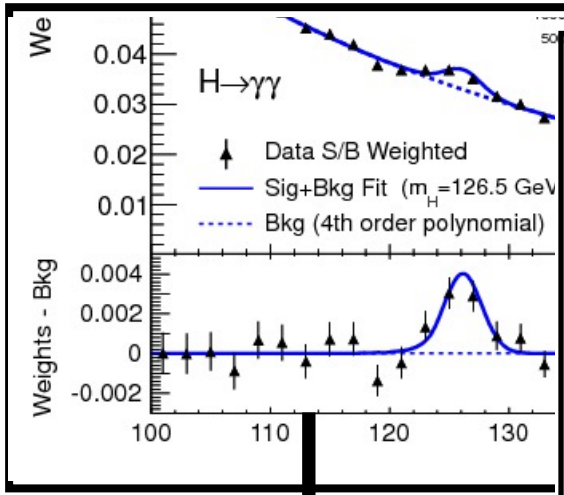


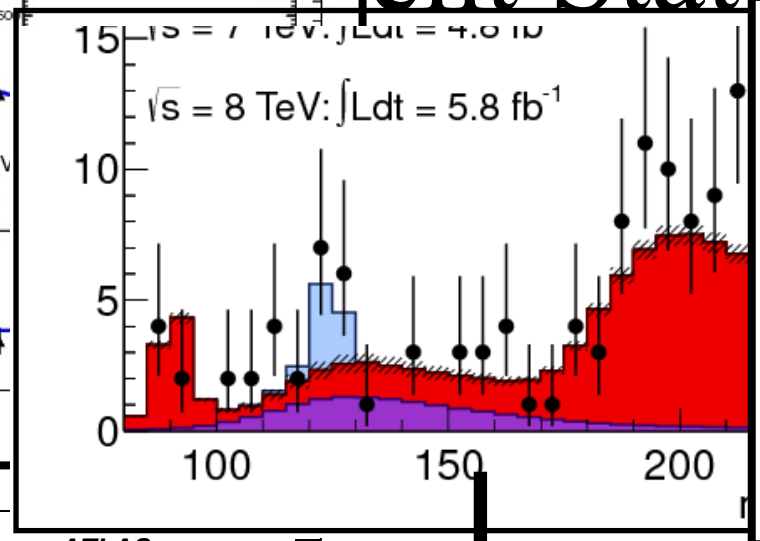


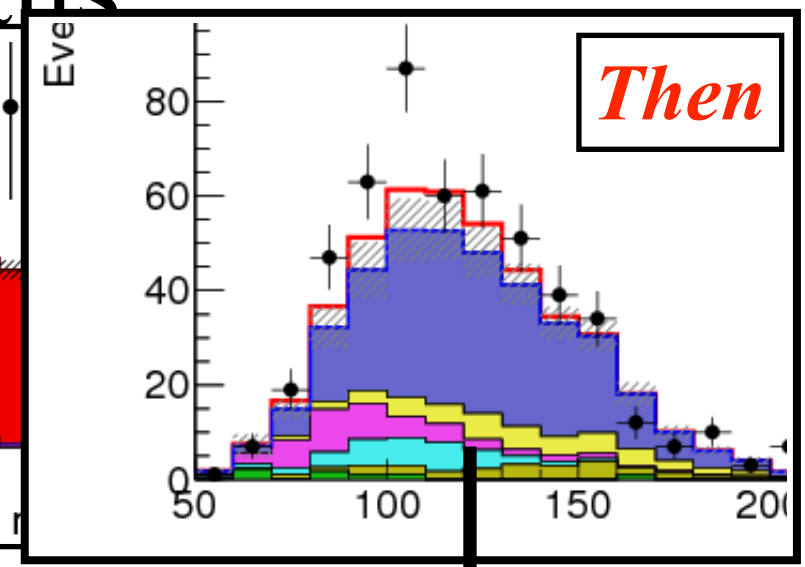


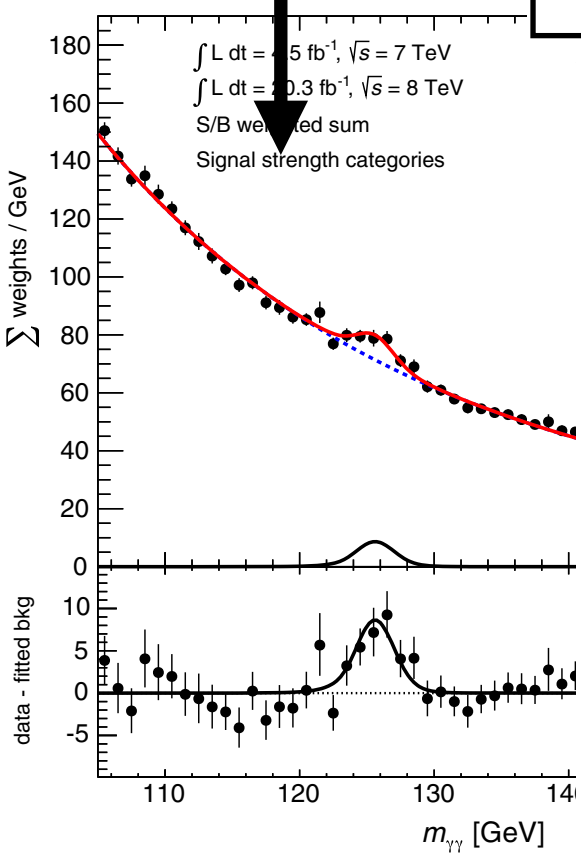


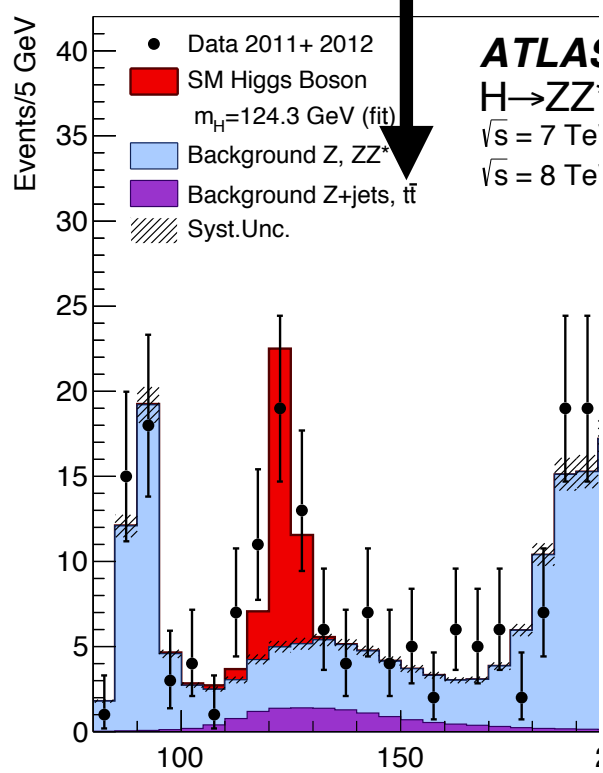
Current Status

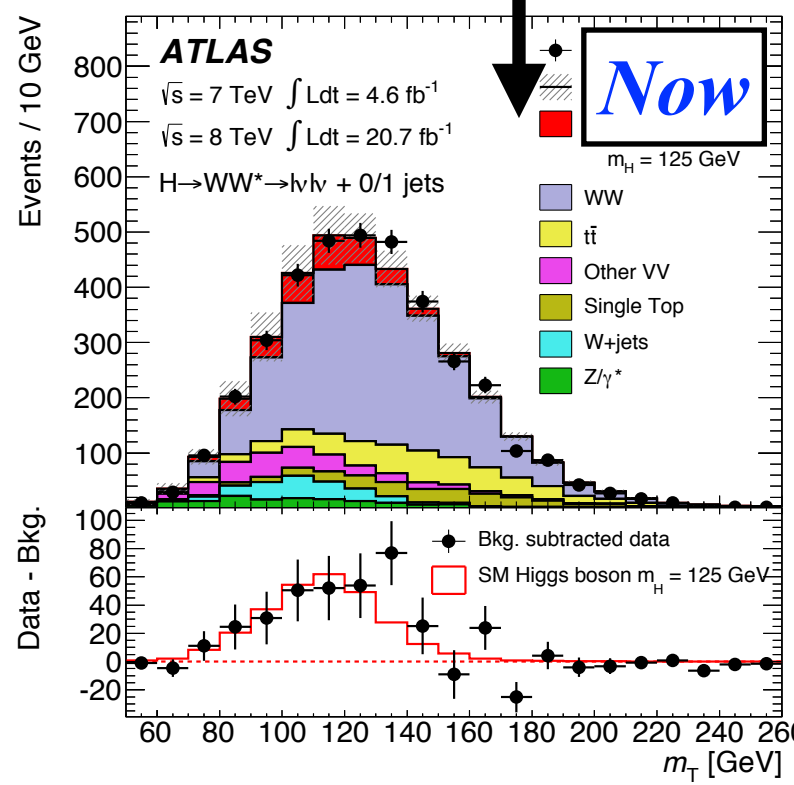












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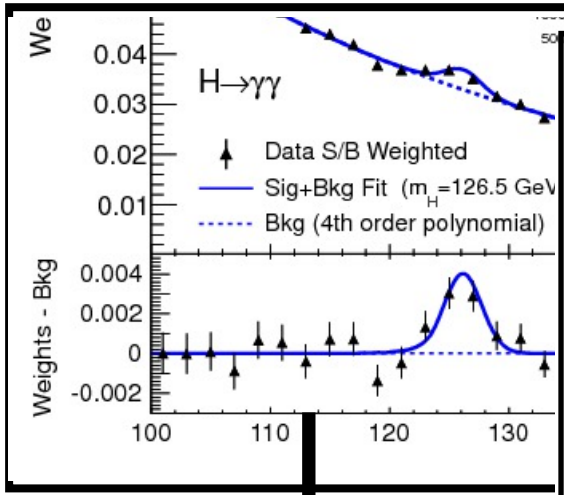
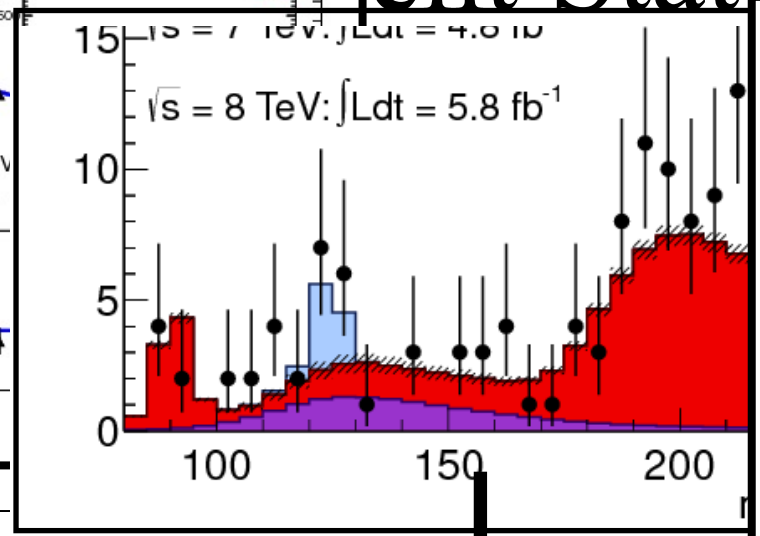
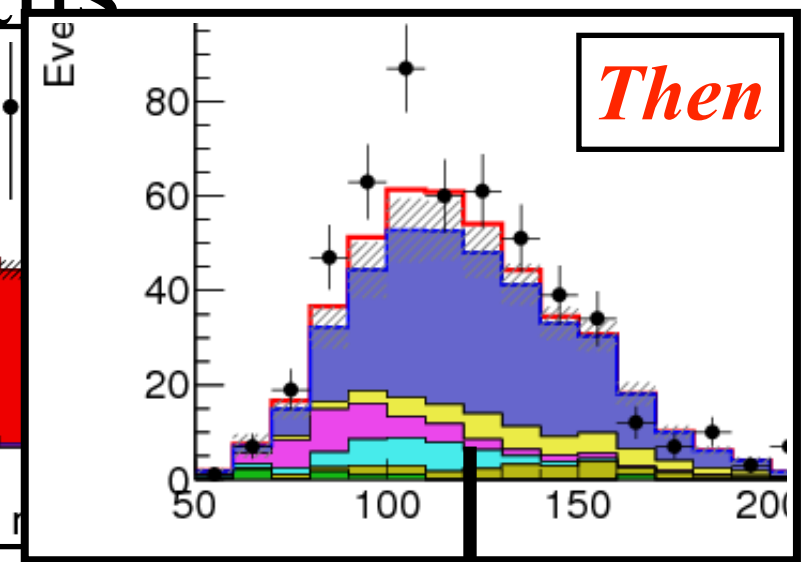
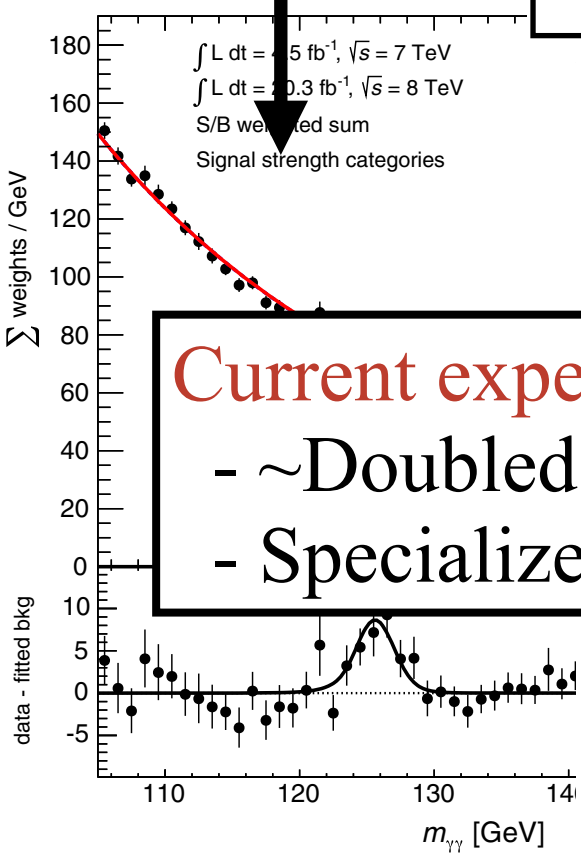
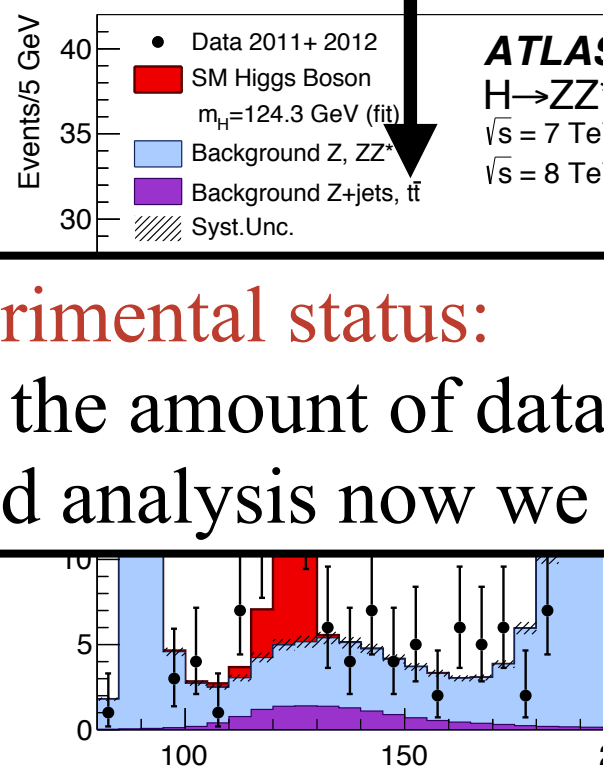
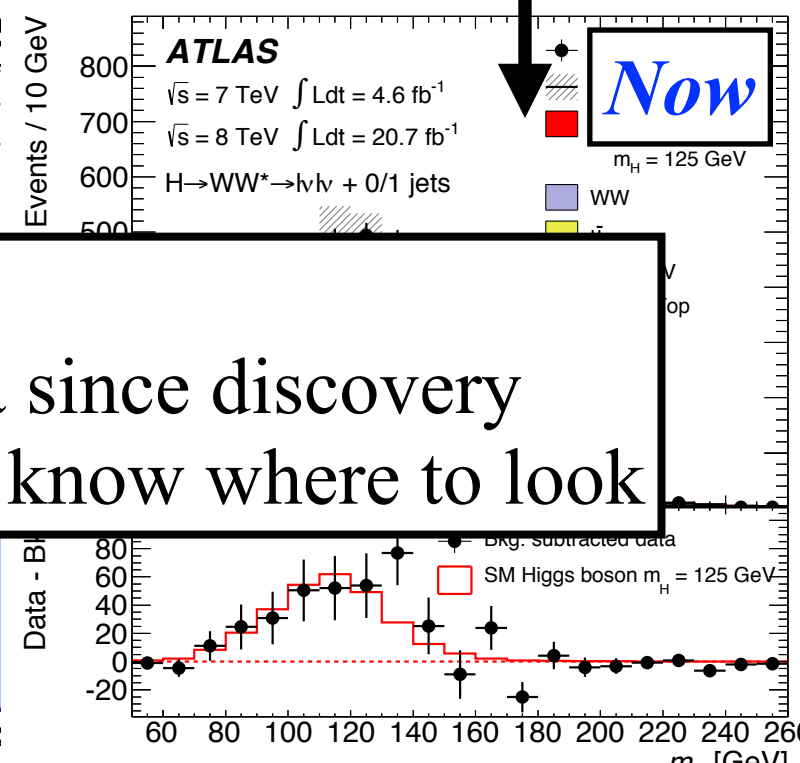












Current experimental status:

- ~Doubled the amount of data since discovery
- Specialized analysis now we know where to look

Higgs Program Beyond Discovery

Establish signals in harder channels:

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

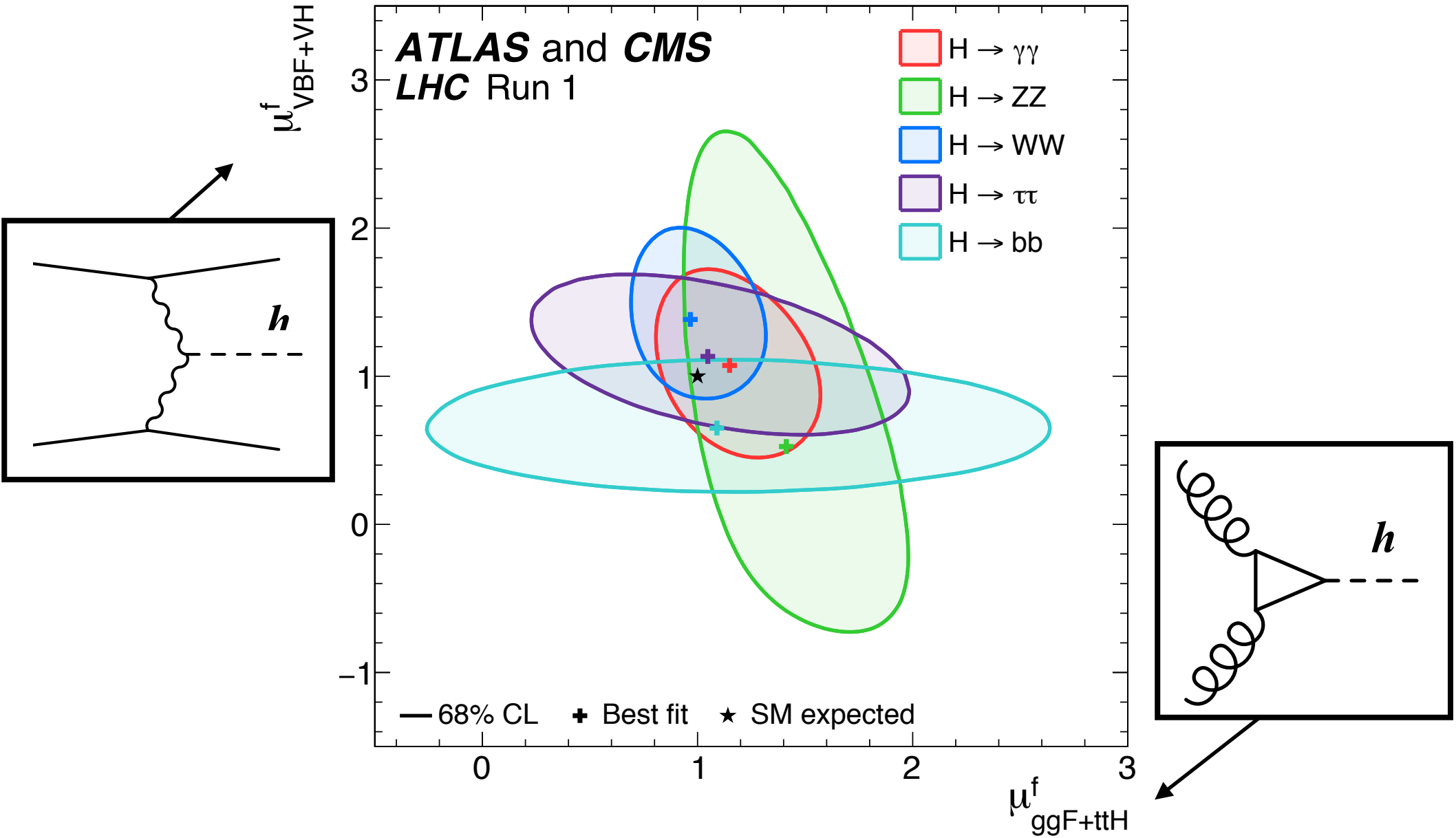
Compare measured/predicted interaction strengths

- Study production cross sections and branching ratios

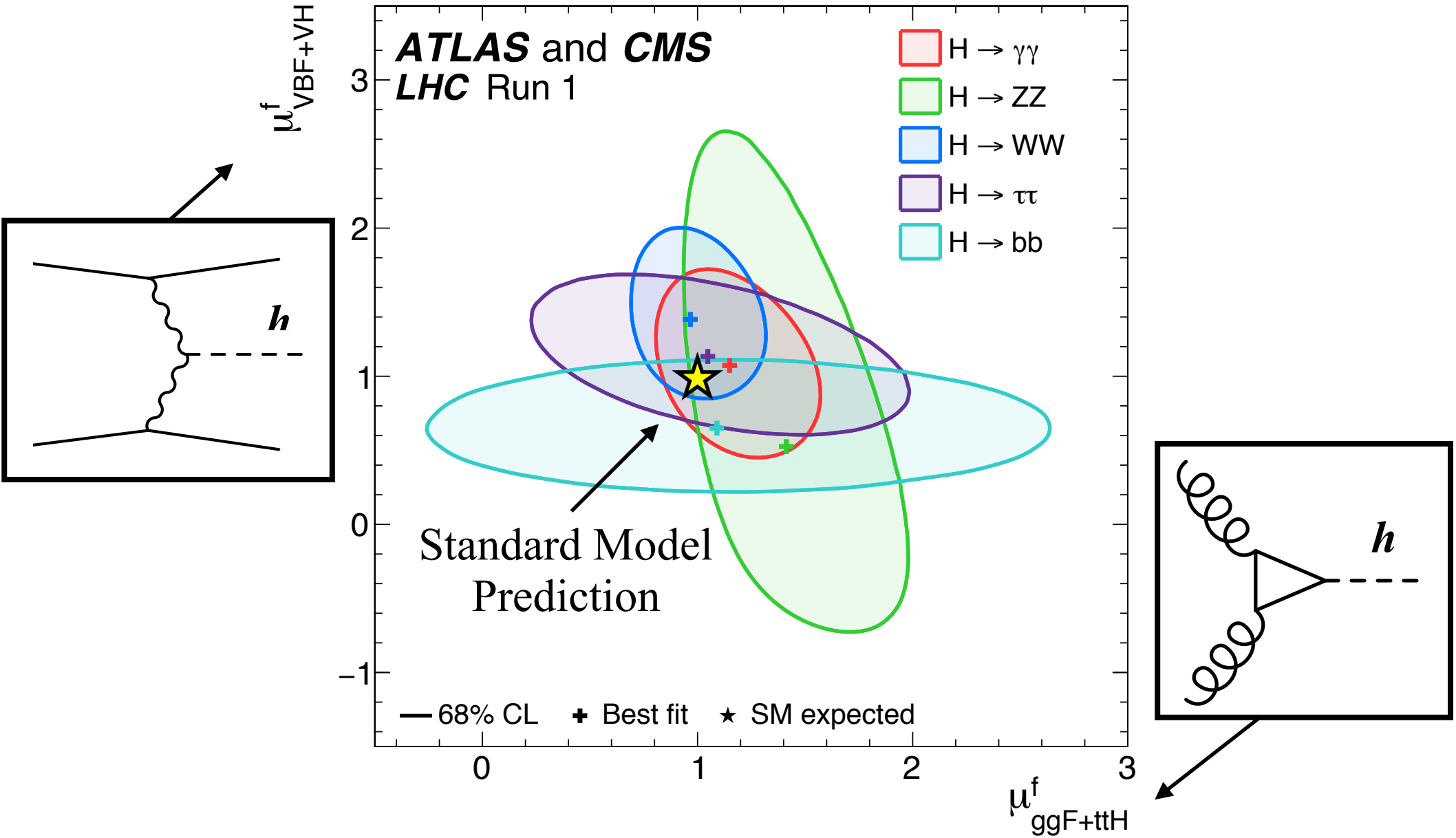
Measure Spin of new particle

Search for un-predicted decays

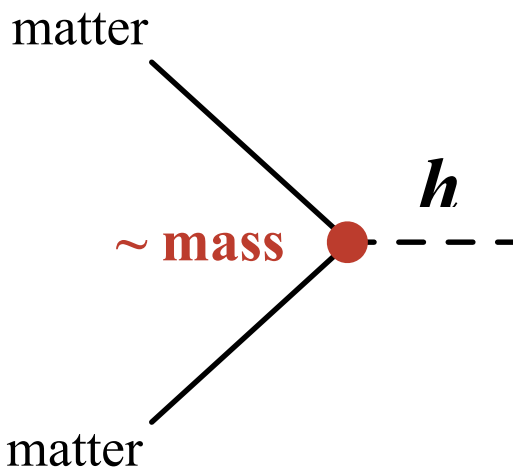
Results: Production Cross Section

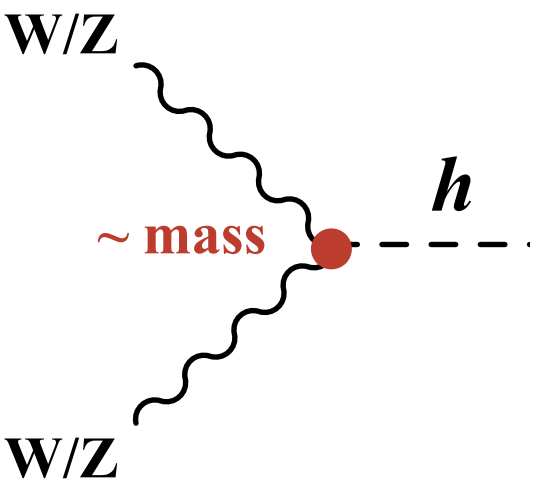


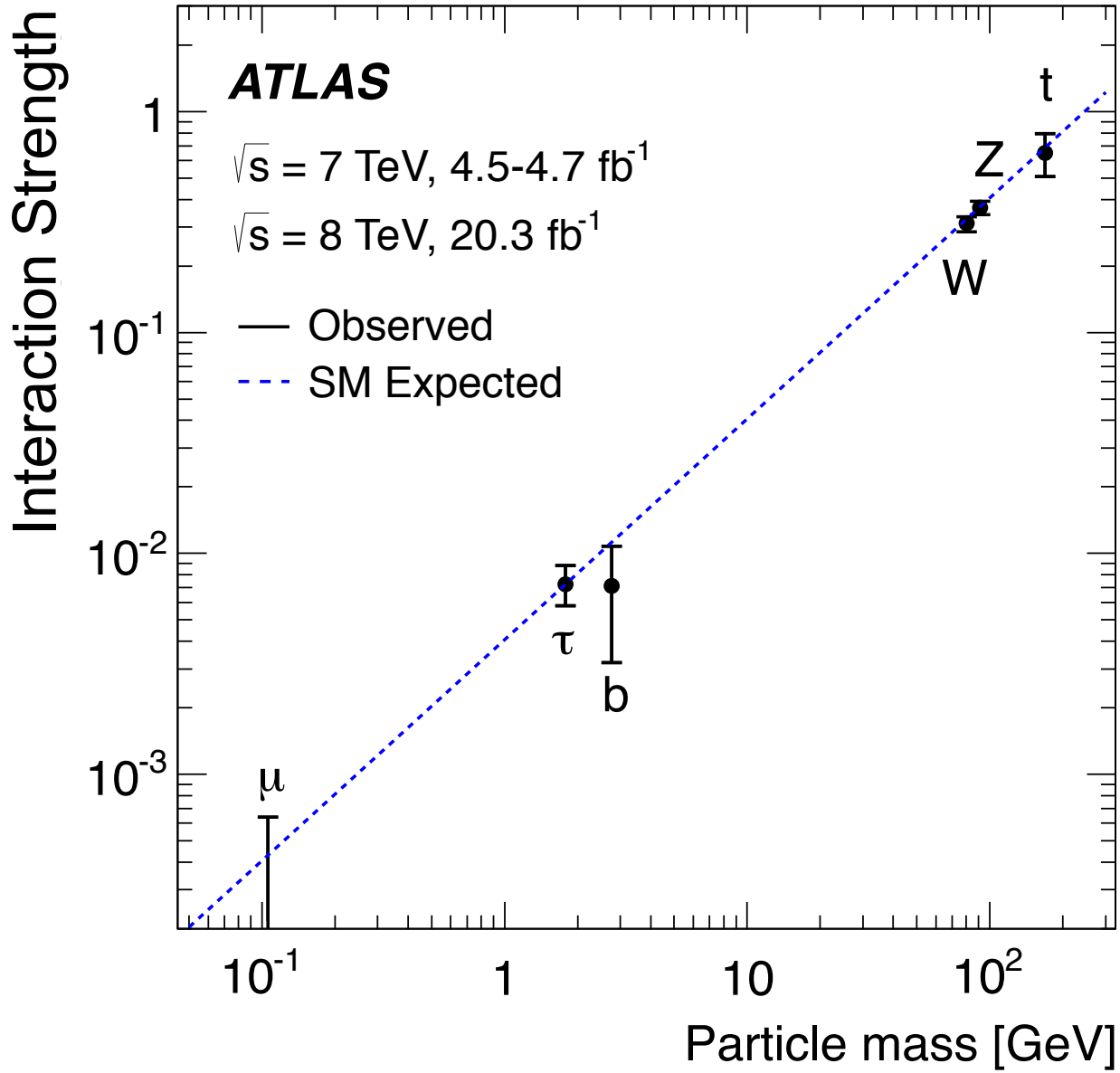
Results: Production Cross Section



Results: Interaction Strengths







Results: Spin

- Massive Spin 1 resonance cannot decay to $\gamma\gamma$ (QM+Relativity)

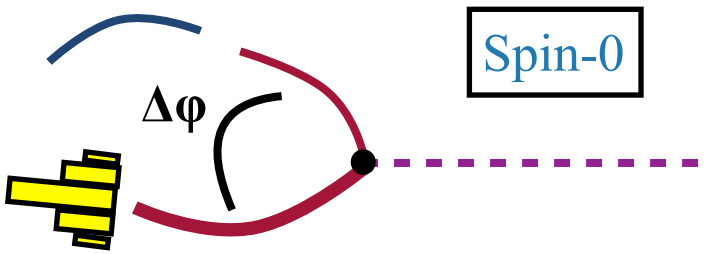
Results: Spin

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

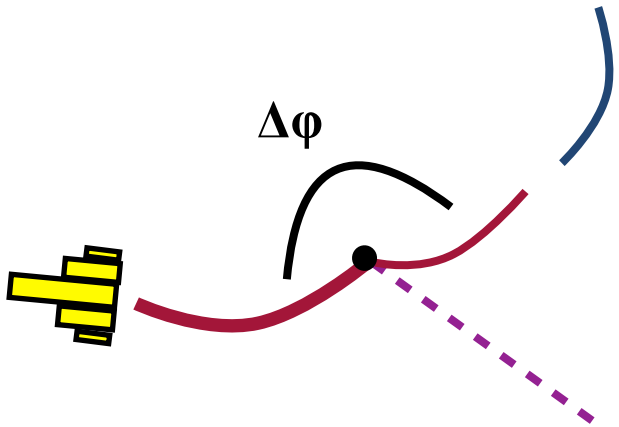
Results: Spin

- 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

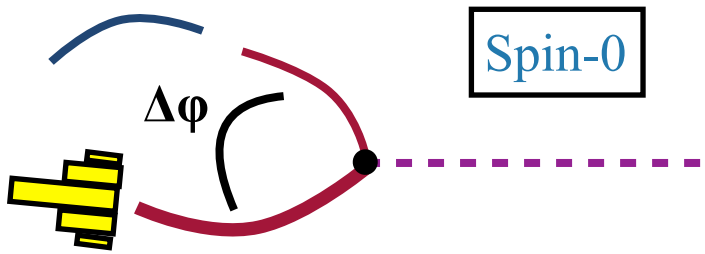


Spin-2

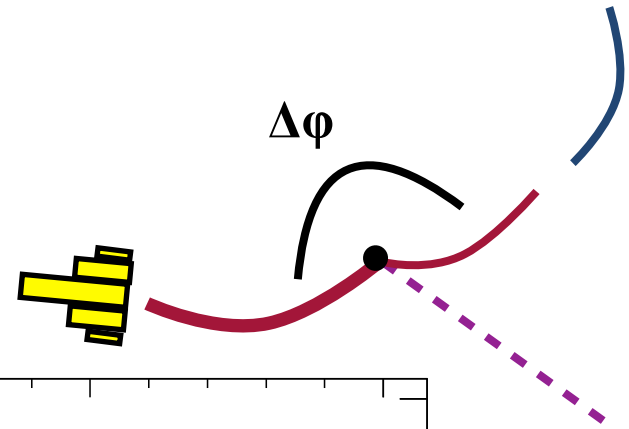
Results: Spin

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

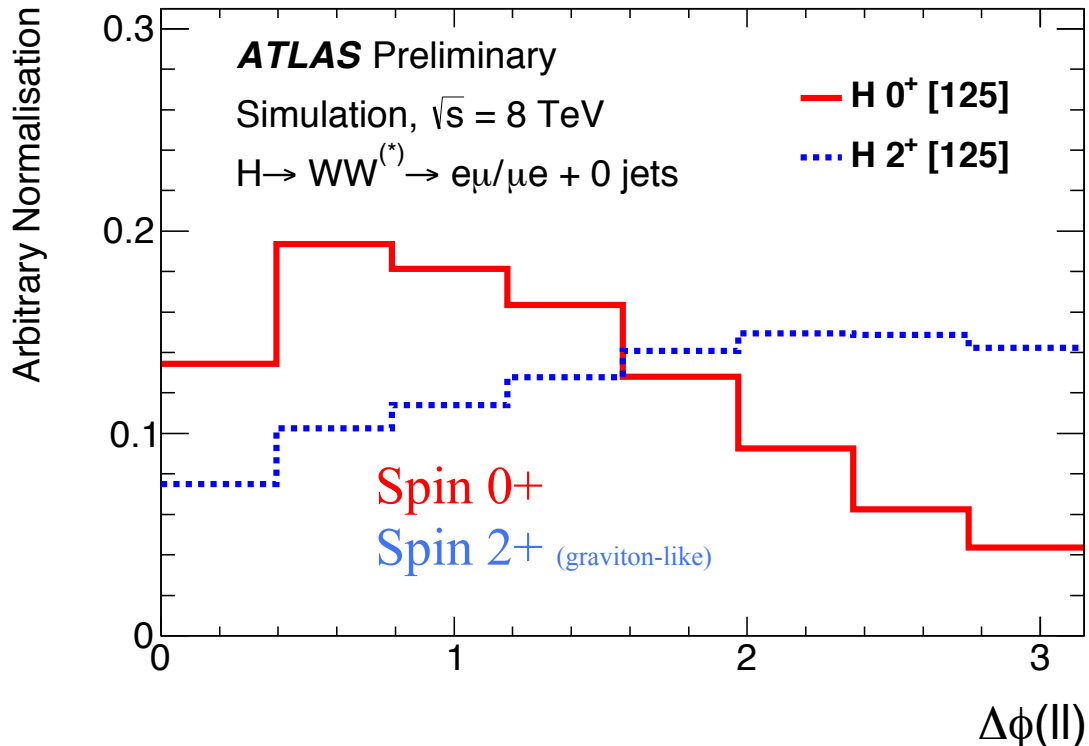
$H \rightarrow WW \rightarrow e\nu\mu\nu$



Spin-0



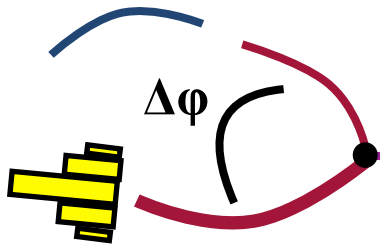
Spin-2



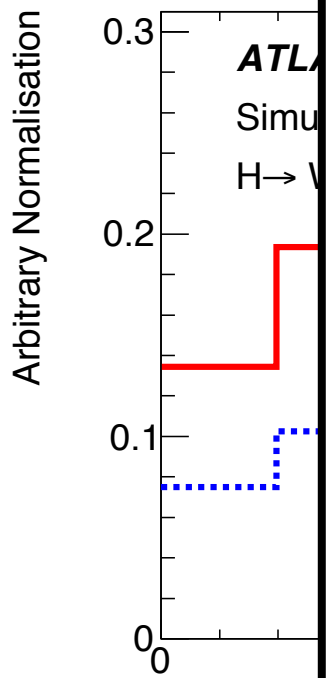
Results: Spin

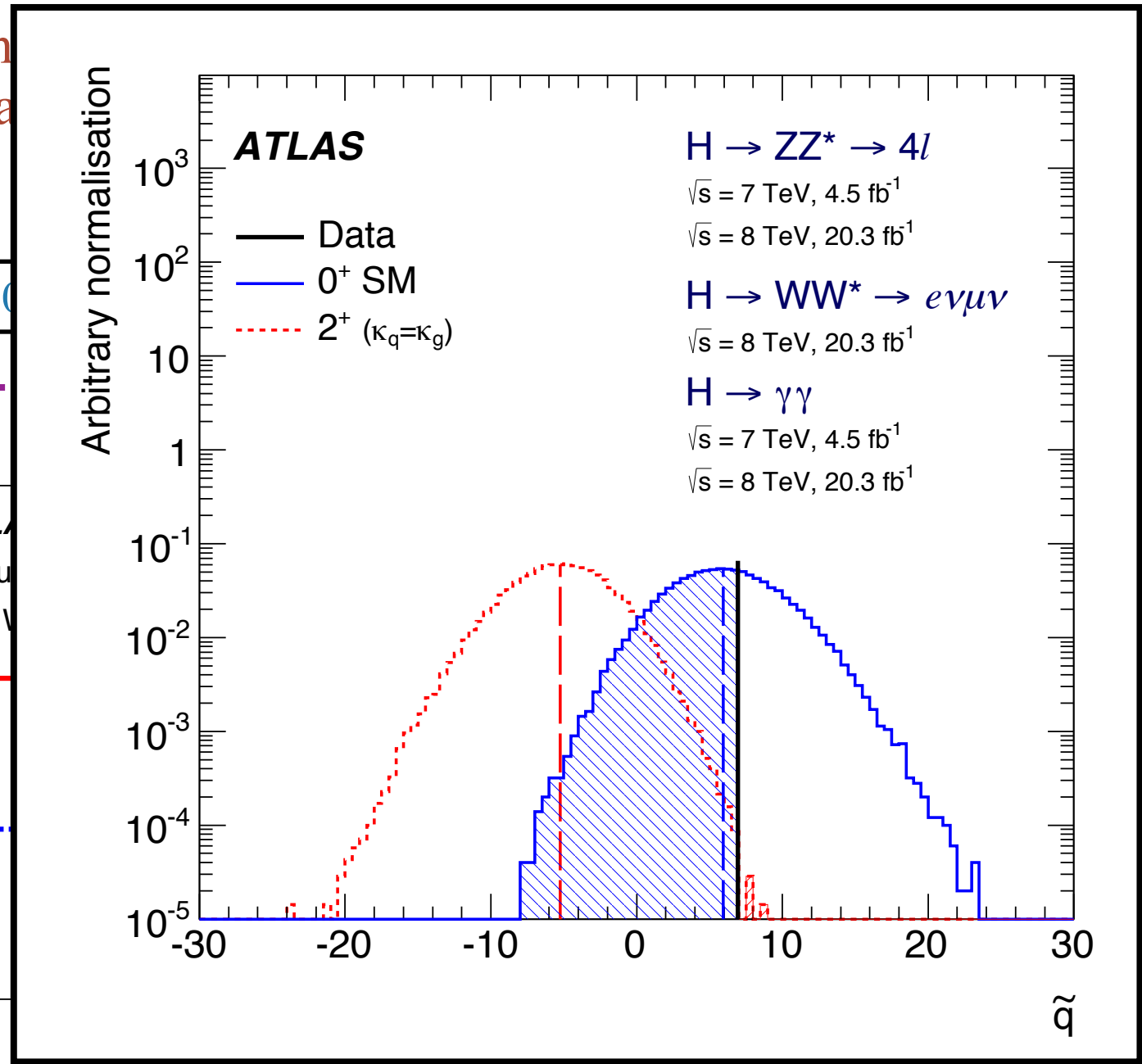
- Massive Spin 1 resonan
- Use decay angle to sepa

H → WW → eνμν



Spin-



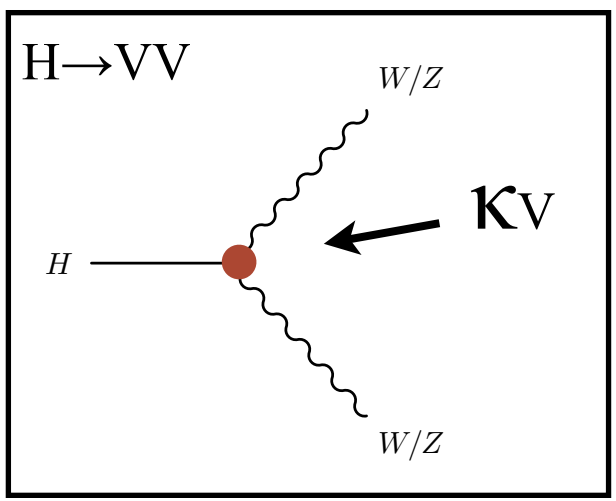


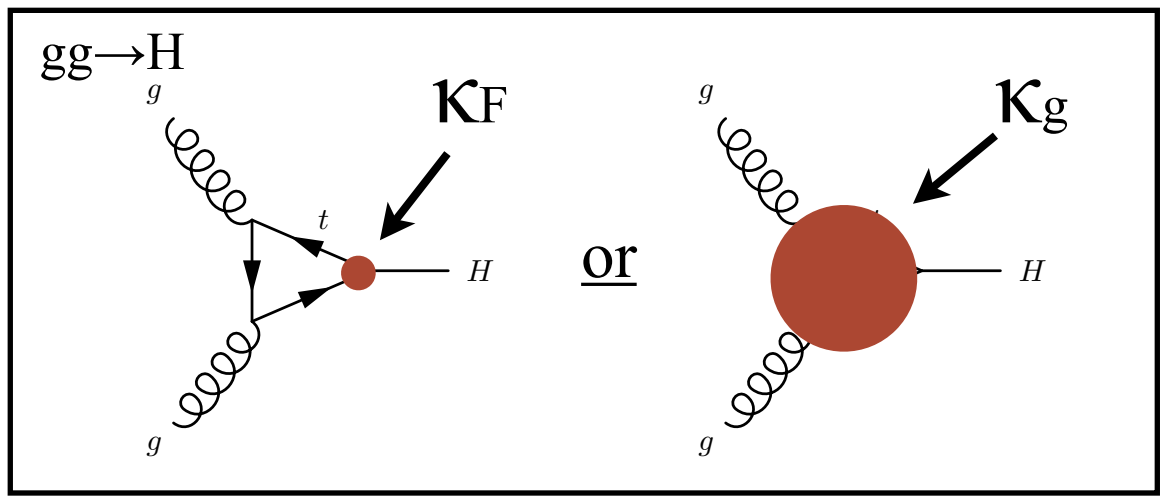
Compatibility w/SM Higgs Couplings

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:

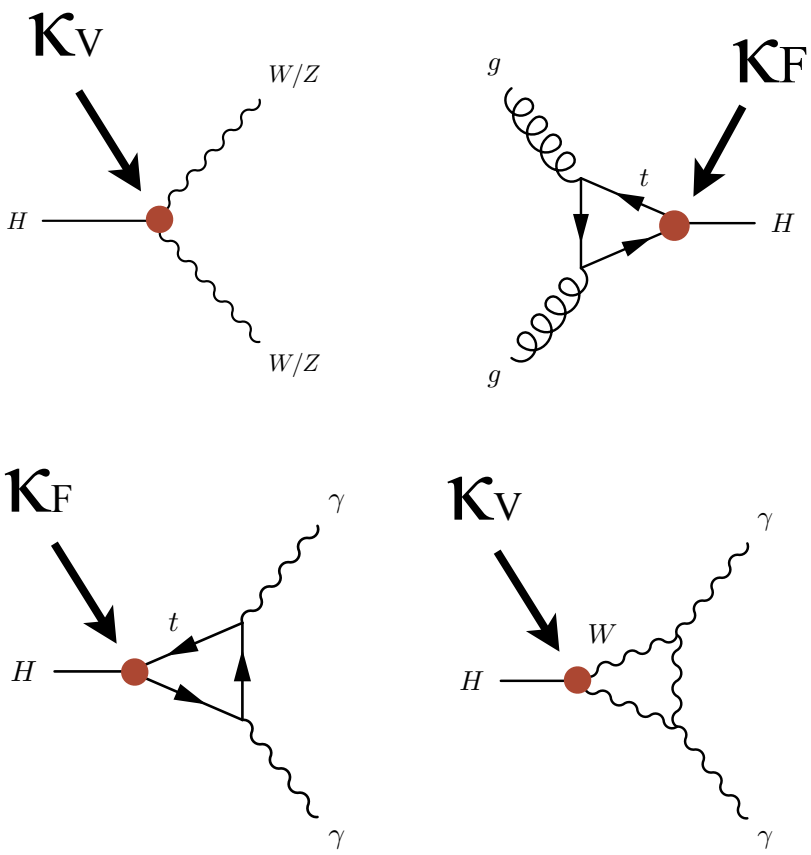




Test against few specific benchmark scenarios.

Compatibility w/SM Higgs Couplings

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

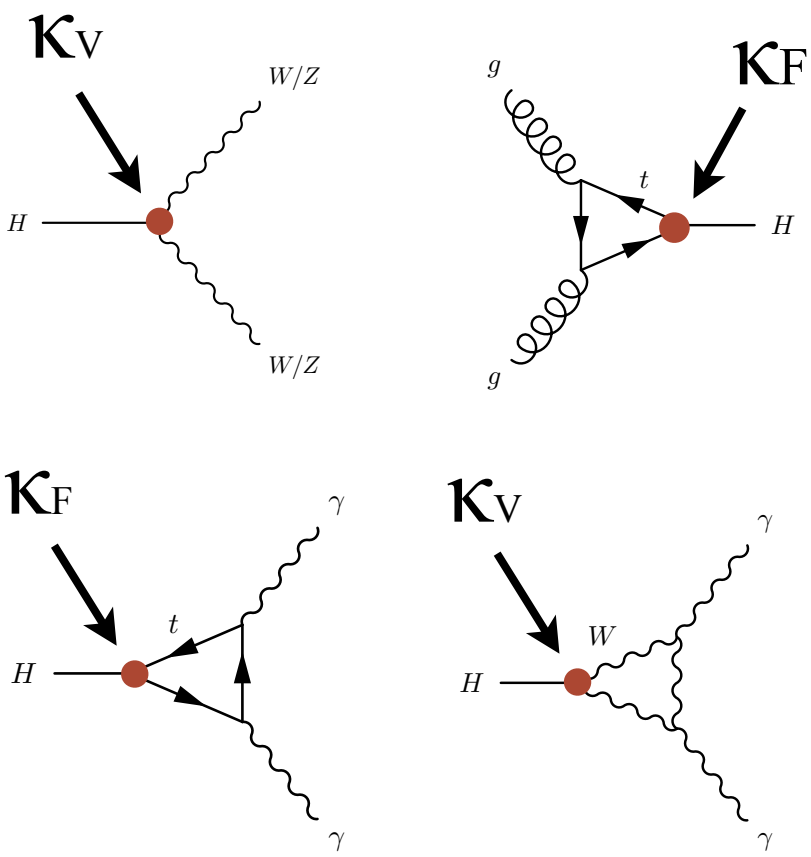


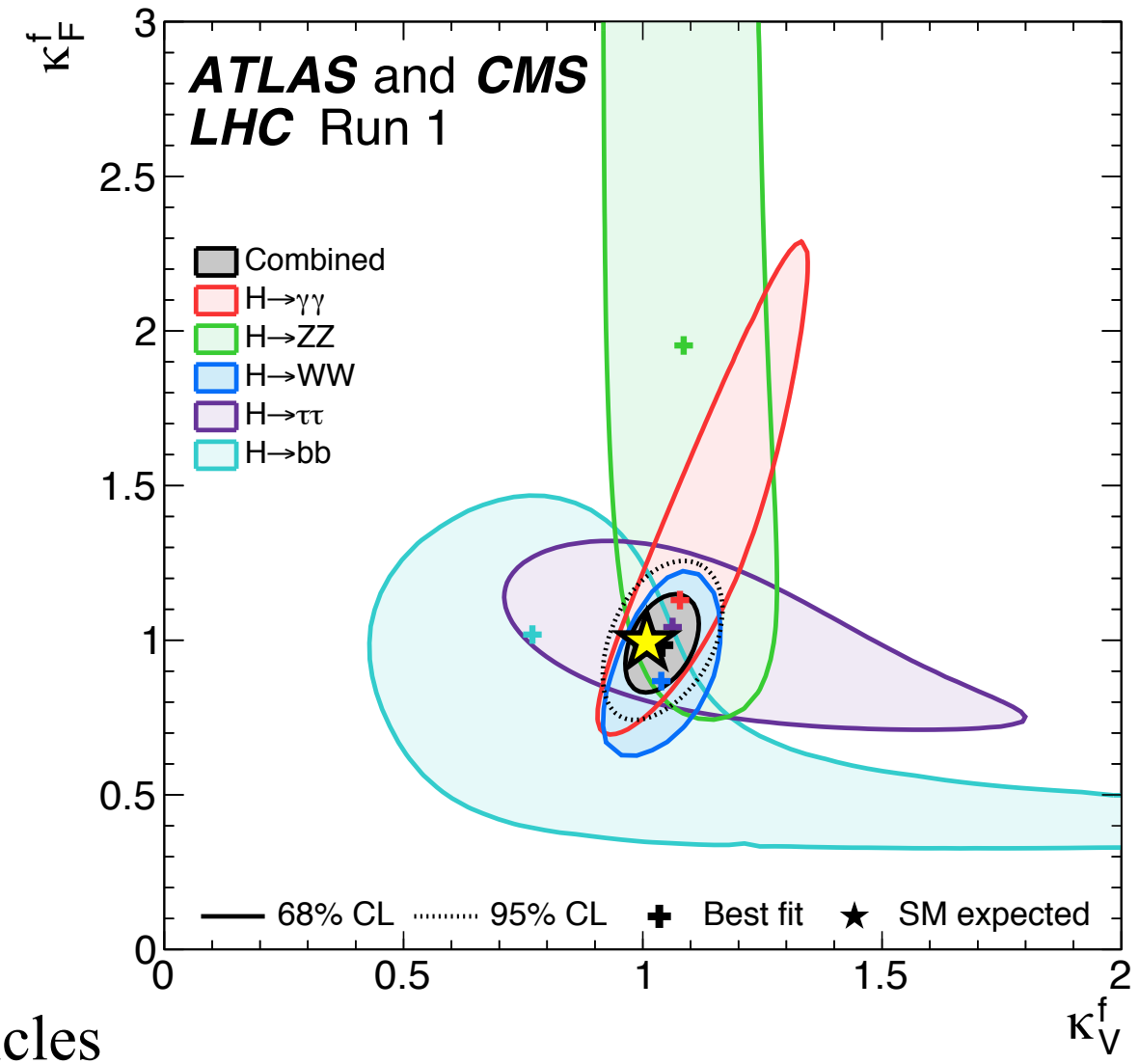
Assume:

- no decays to unknown particles

Compatibility w/SM Higgs Couplings

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



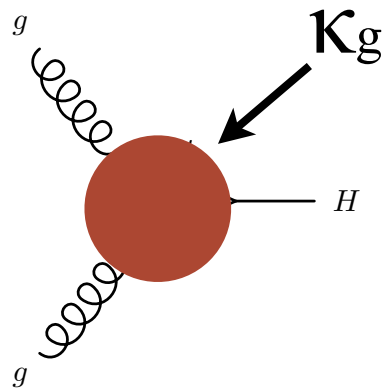


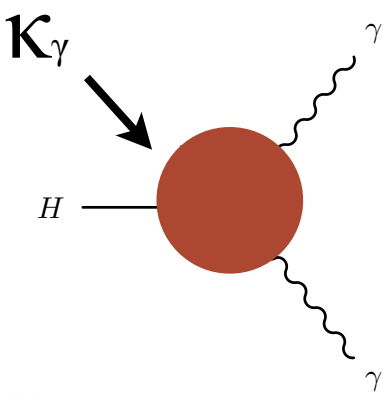
Assume:

- no decays to unknown particles

Compatibility w/SM Higgs Couplings

Test loops diagrams





Assume:

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Compatibility w/SM Higgs Couplings

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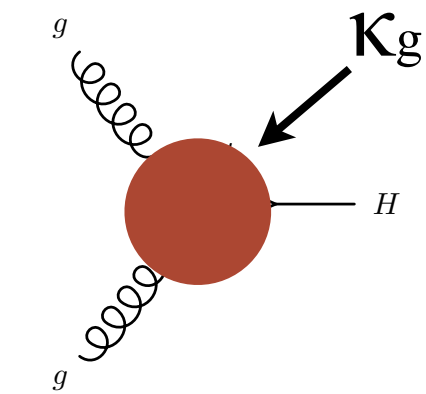

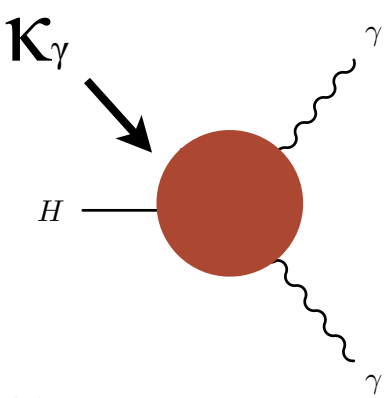

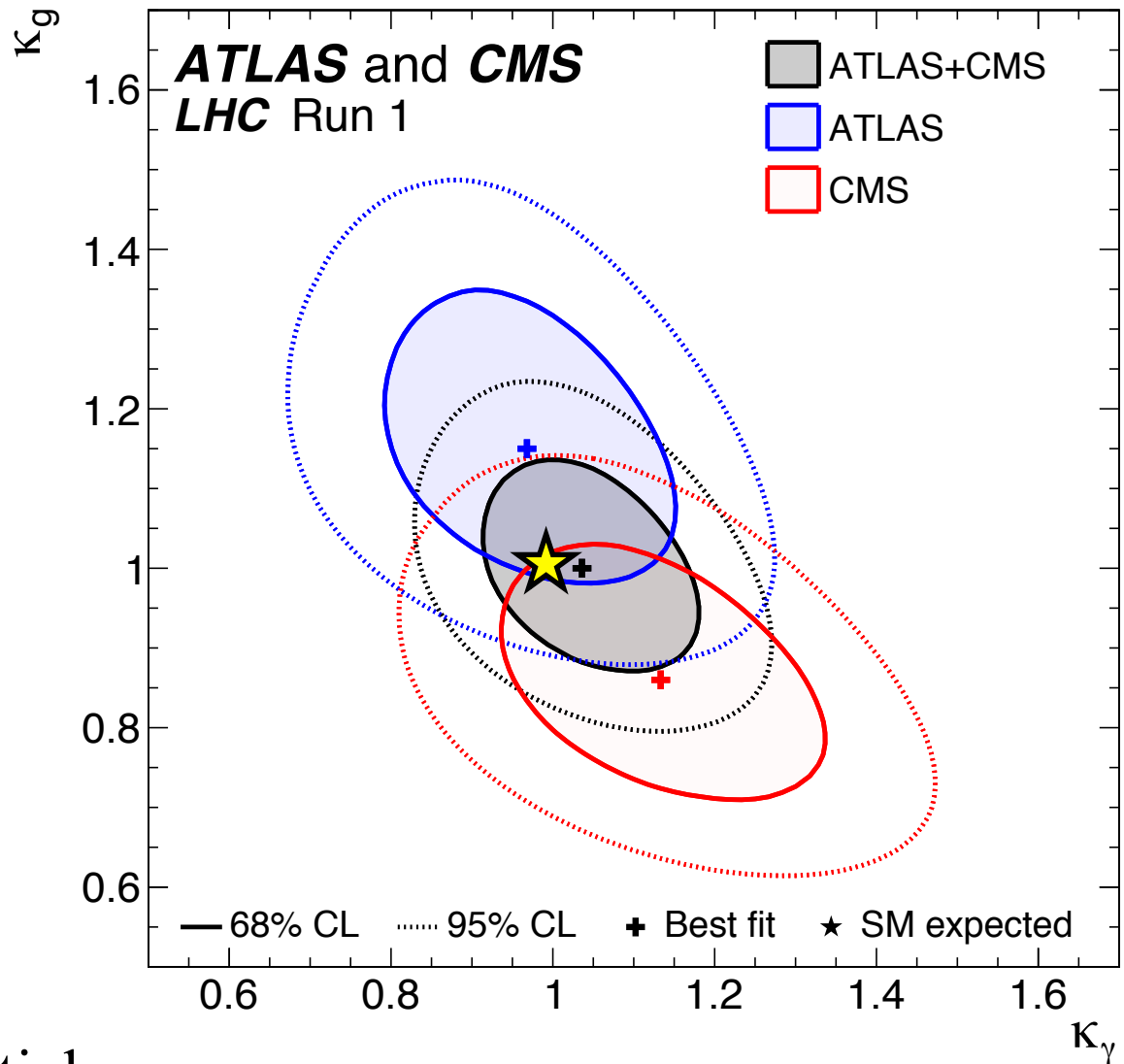

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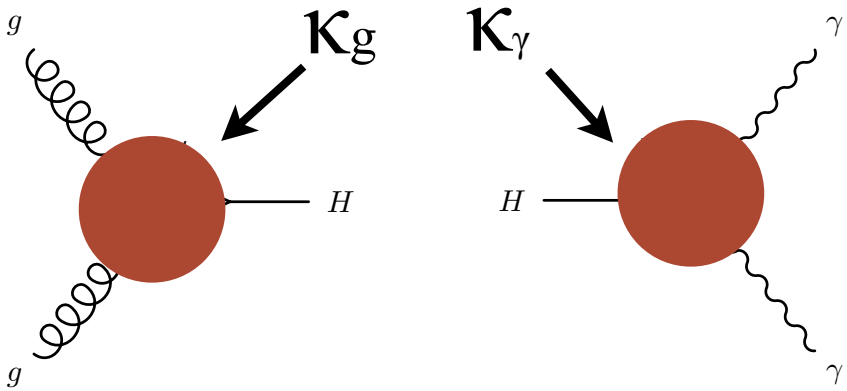

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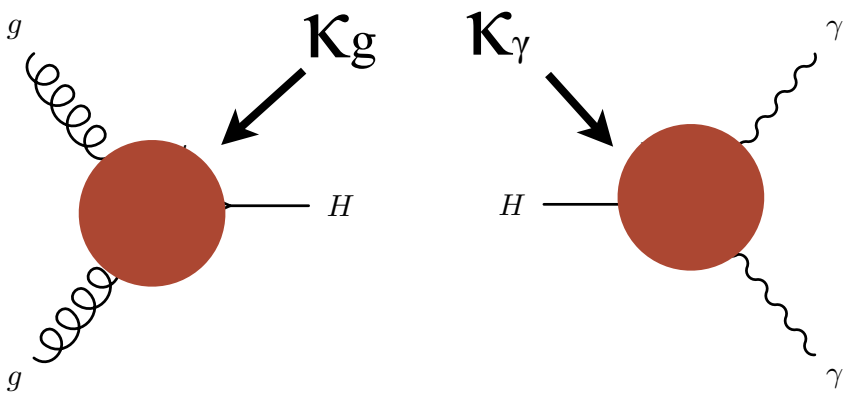

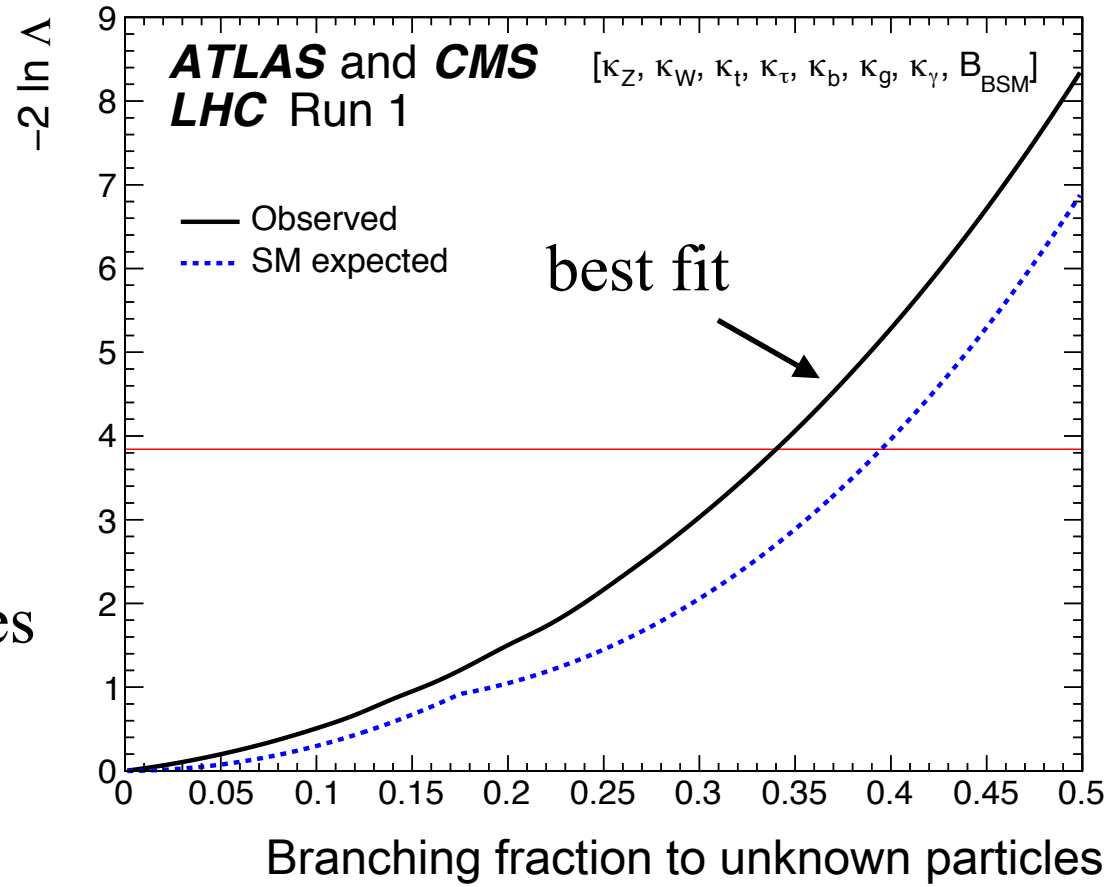

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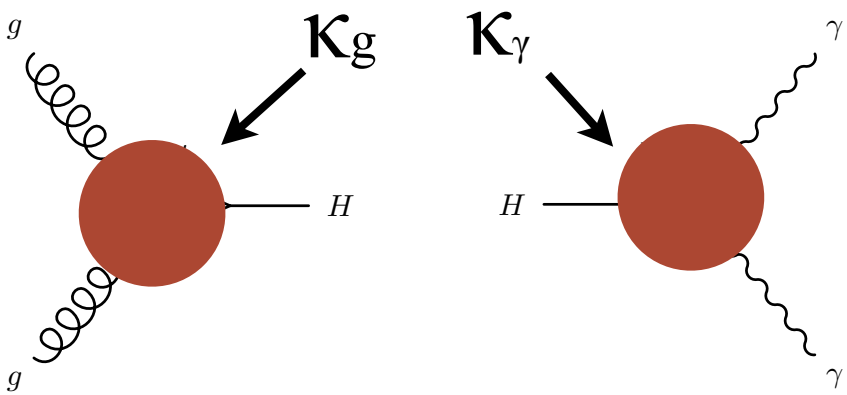

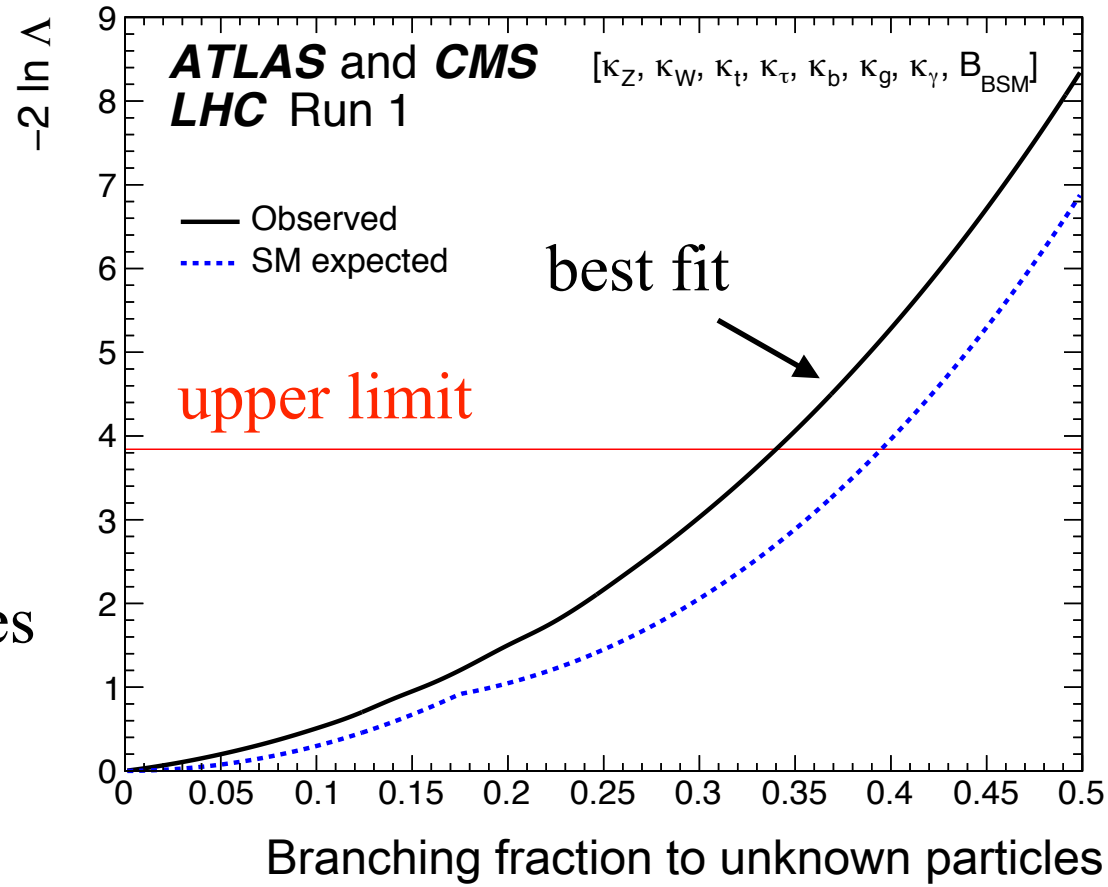

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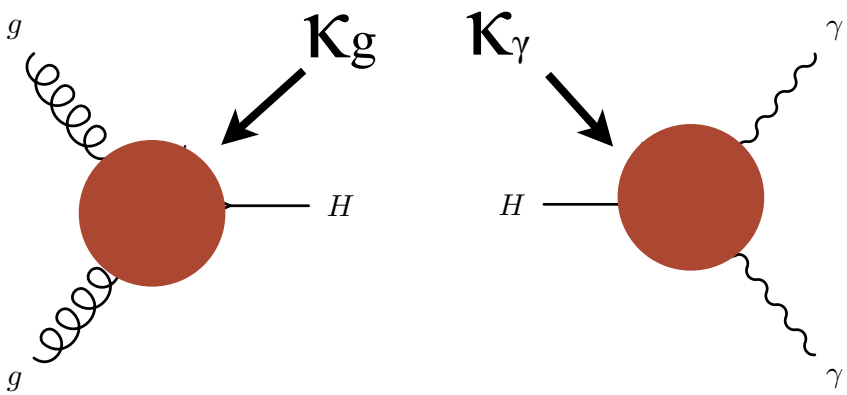

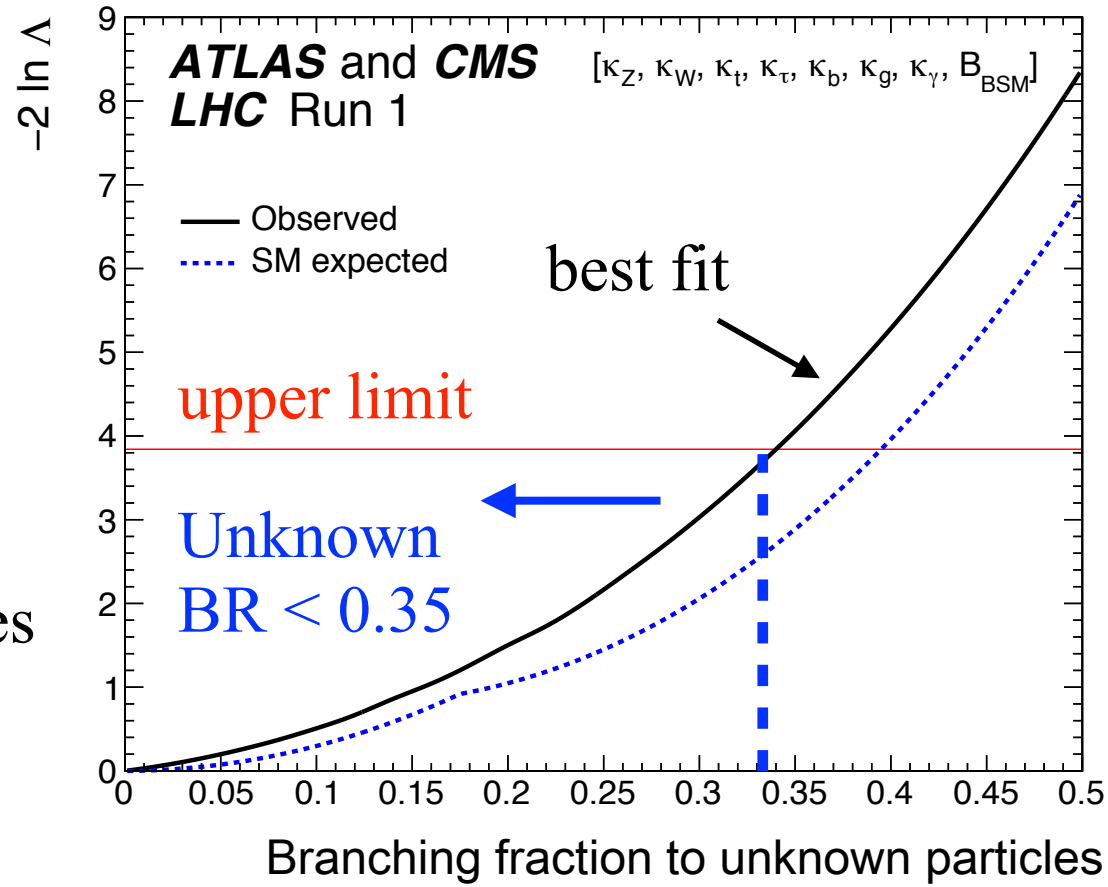

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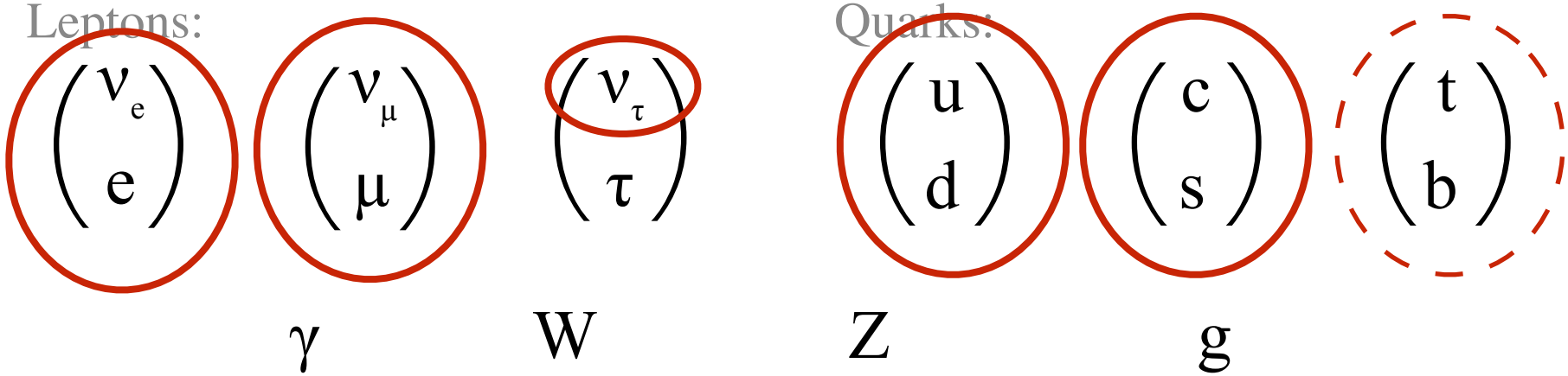

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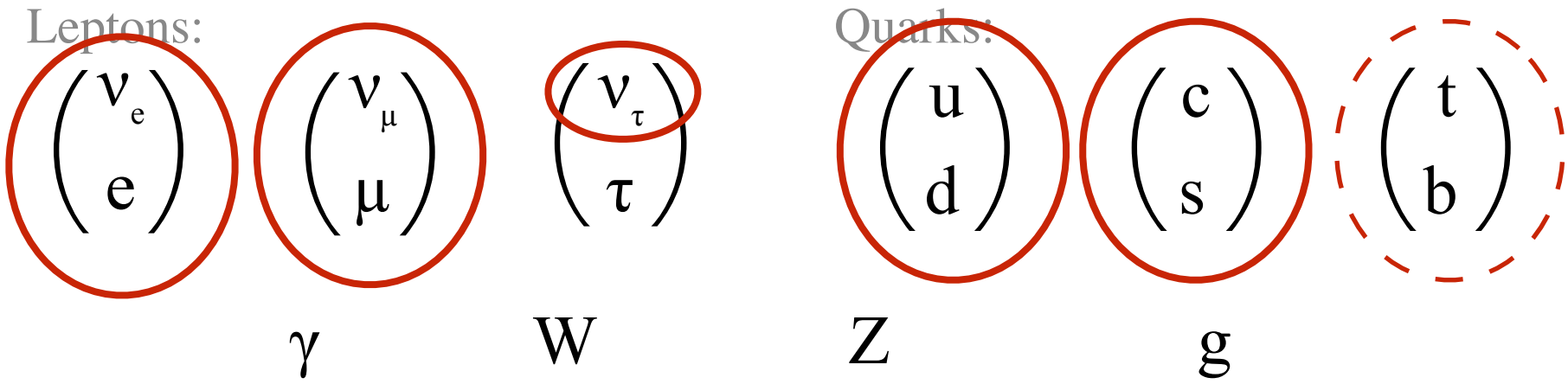

- Very important unobserved interaction: H

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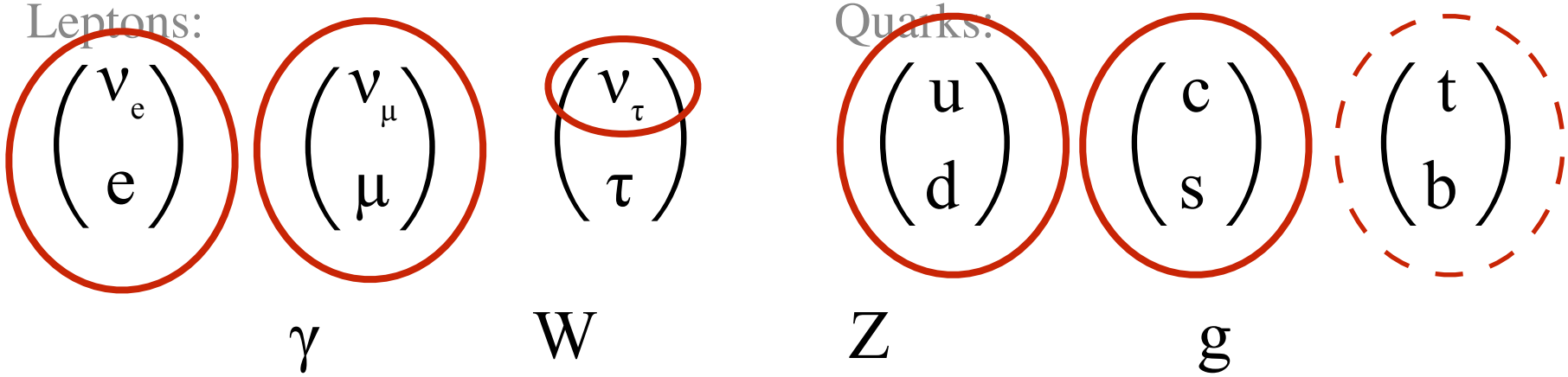

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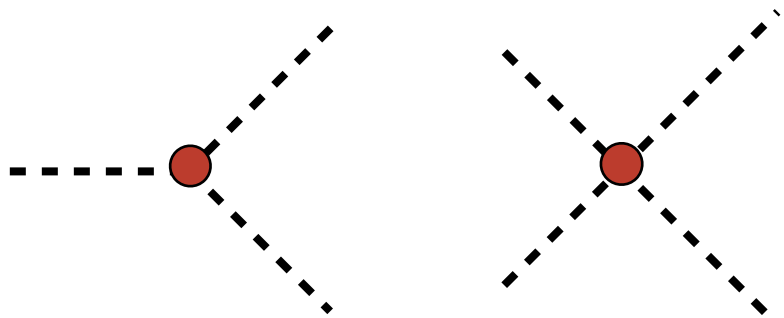
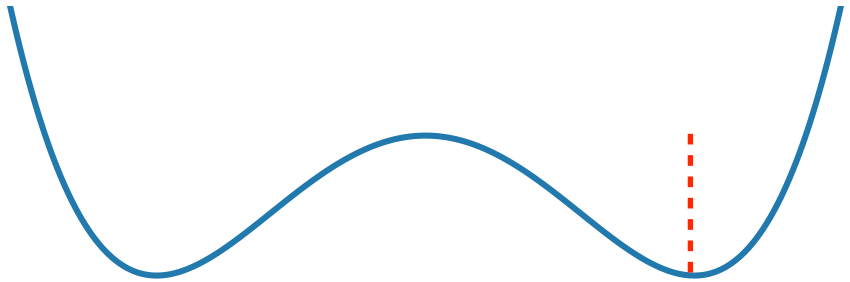
Higgs self-interaction:



Measure Potential with *hh*

Energy of Higgs field: *Higgs potential*

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



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

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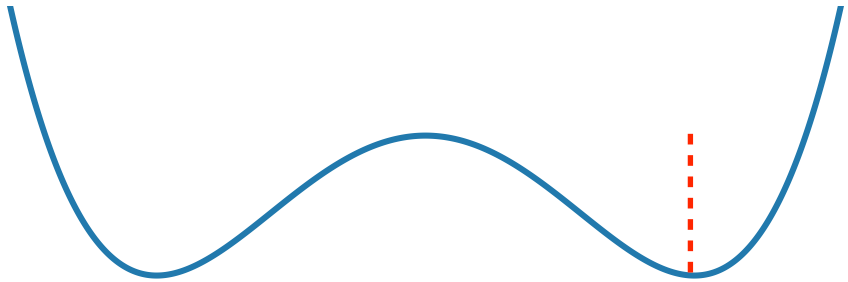

Expanding about minimum: $V(\phi) \to V(v+h)$

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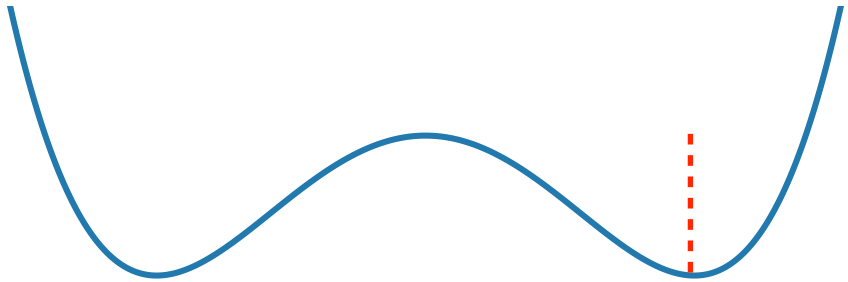

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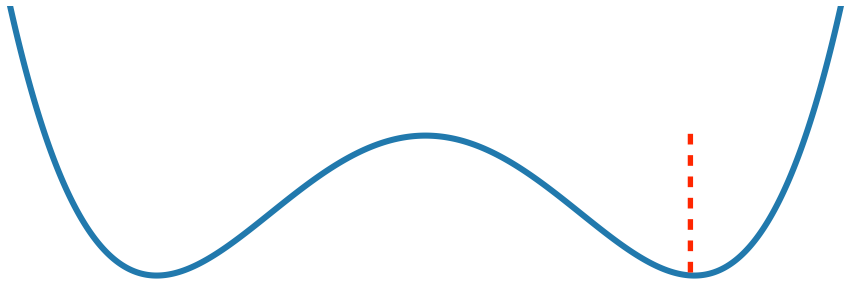

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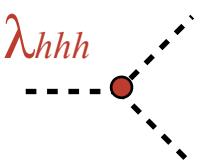

hh-production

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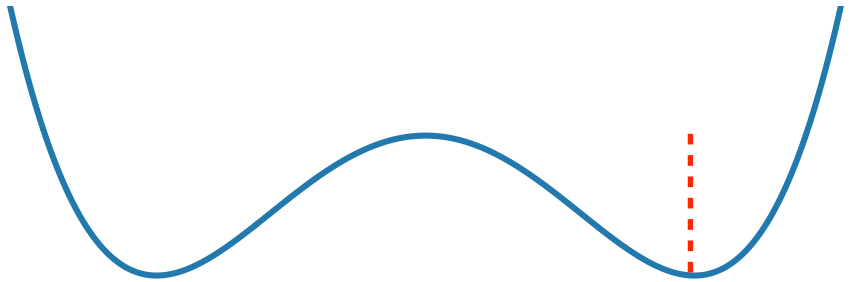

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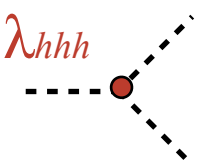

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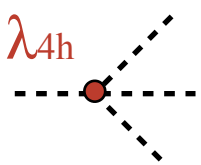
λ_{4h}



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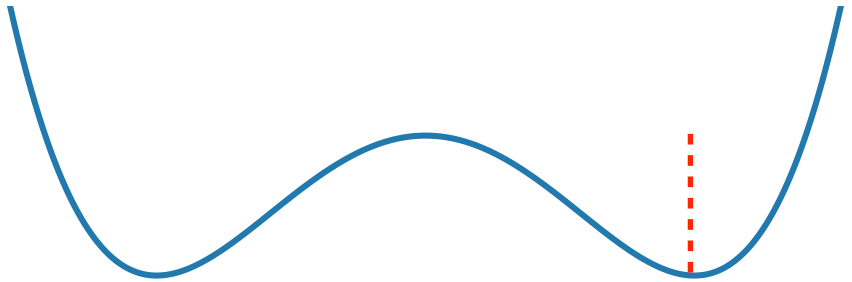

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λ_{hhh} λ_{4h}

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

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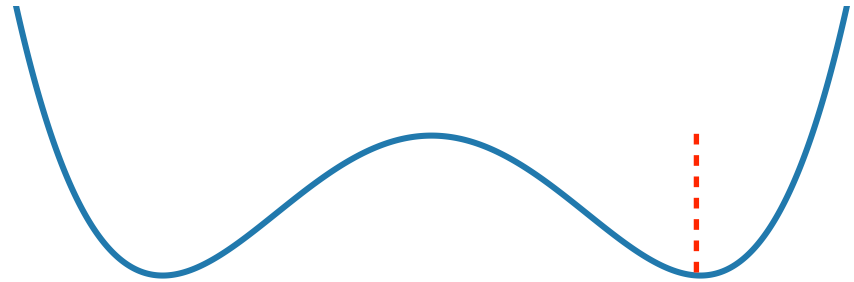

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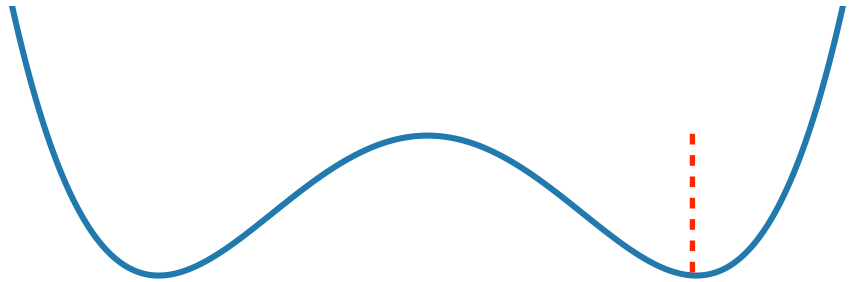

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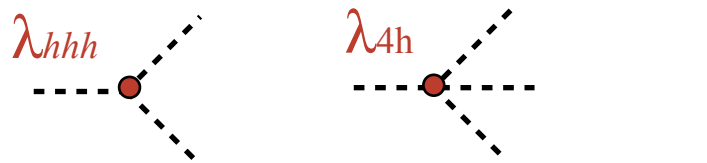

hh-production *hhh*-production

Standard Model:

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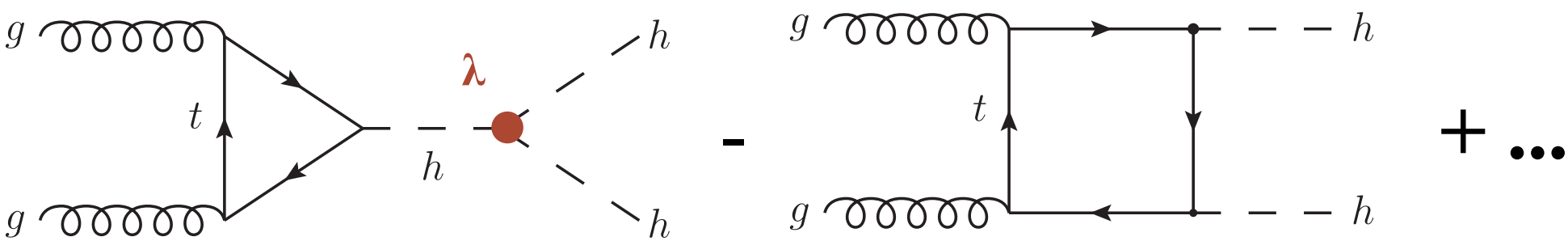
- Shape of potential gives relationship between λ_{hhh} and m_h, v
- Measuring λ_{hhh} important probes the shape of the Higgs potential
- *hh* production interesting because it measures λ_{hhh}

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:



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.

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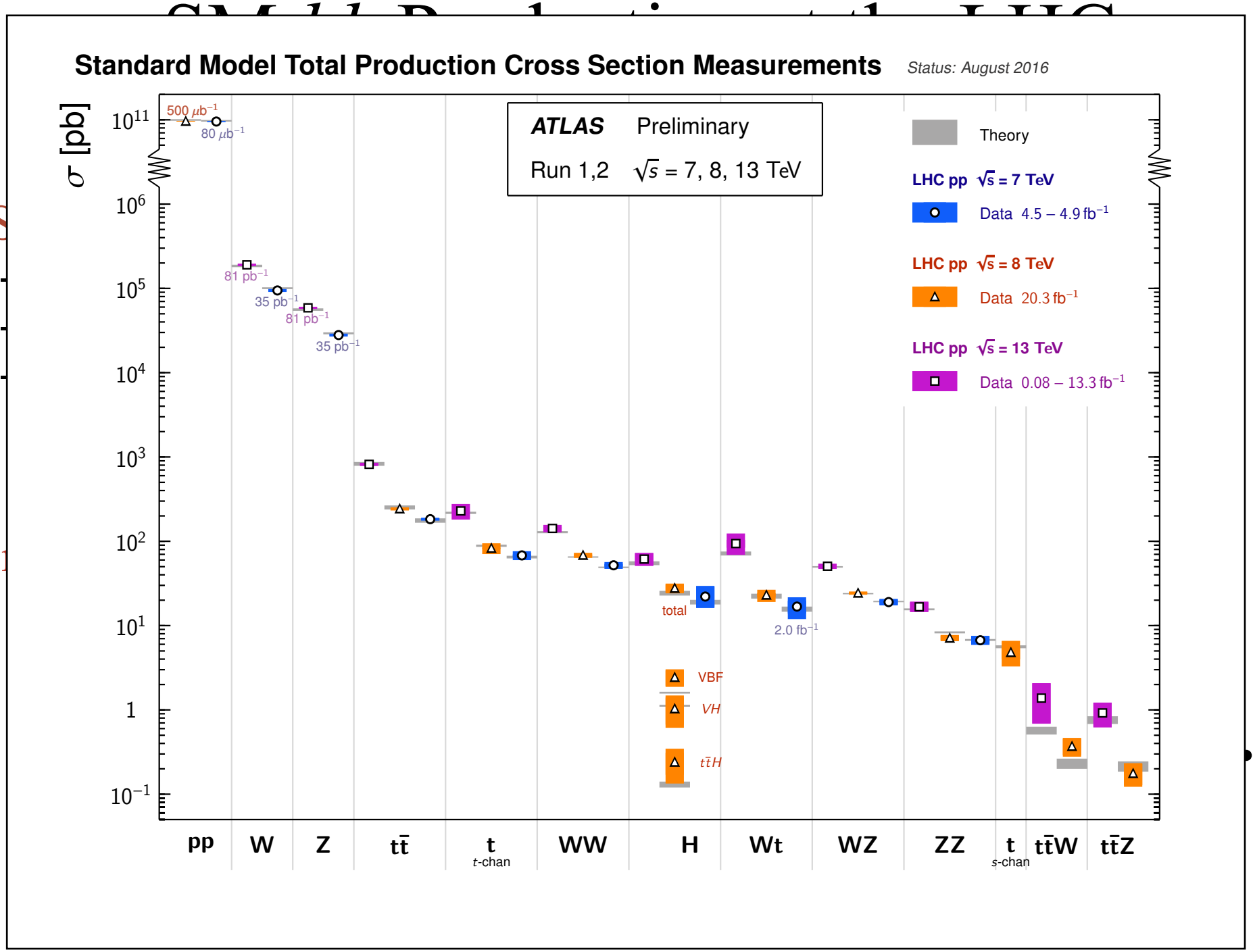
Pick up here next time.

Backup


Standard Model Total Production Cross Section Measurements
Status: August 2016
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb−1
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Data 0.08 – 13.3 fb−1
σ [pb]
500 μb−1
80 μb−1
81 pb−1
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81 pb−1
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total
2.0 fb−1
VBF
VH
tt̄H
pp
W
Z
tt̄
t
t-chan
WW
H
Wt
WZ
ZZ
t
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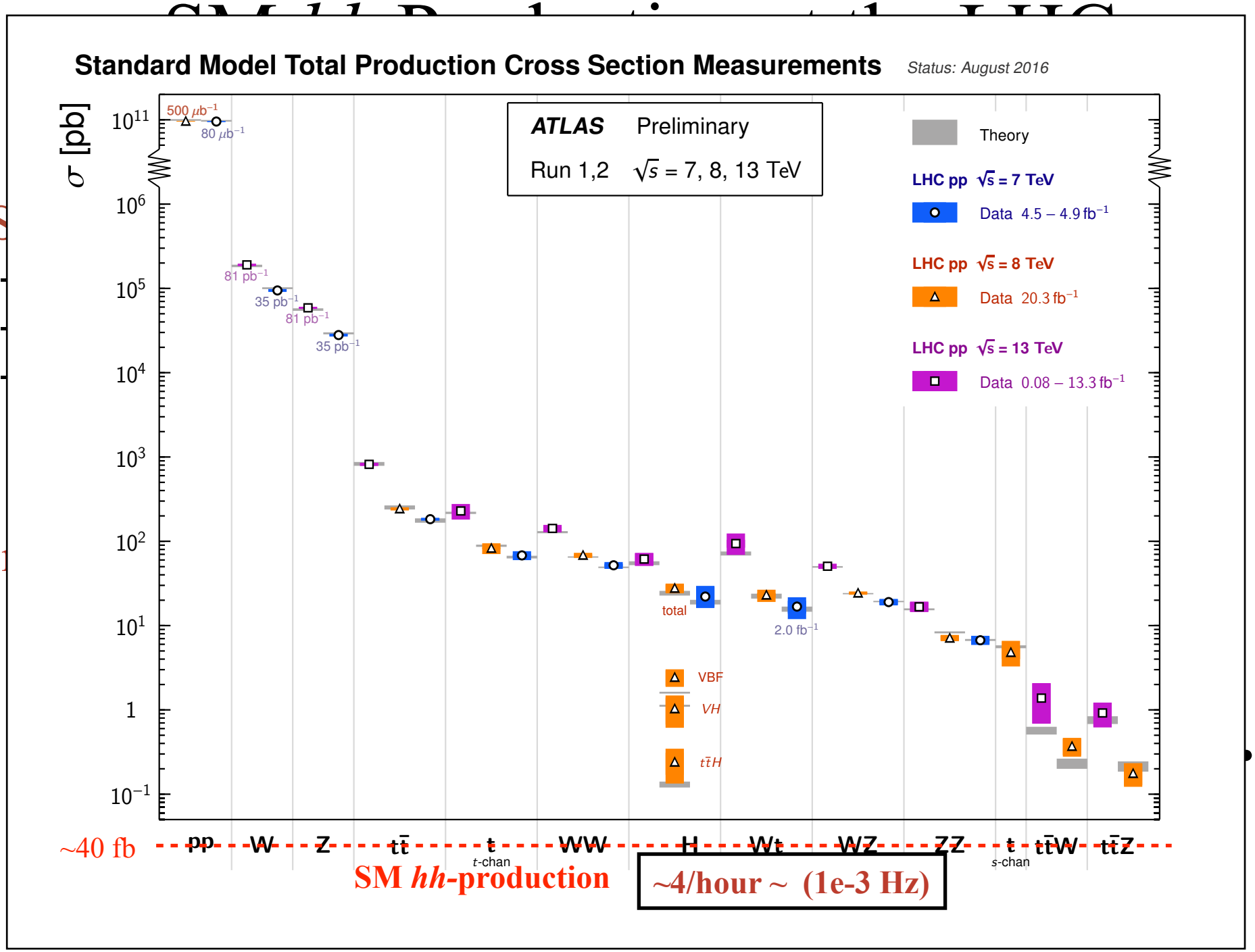
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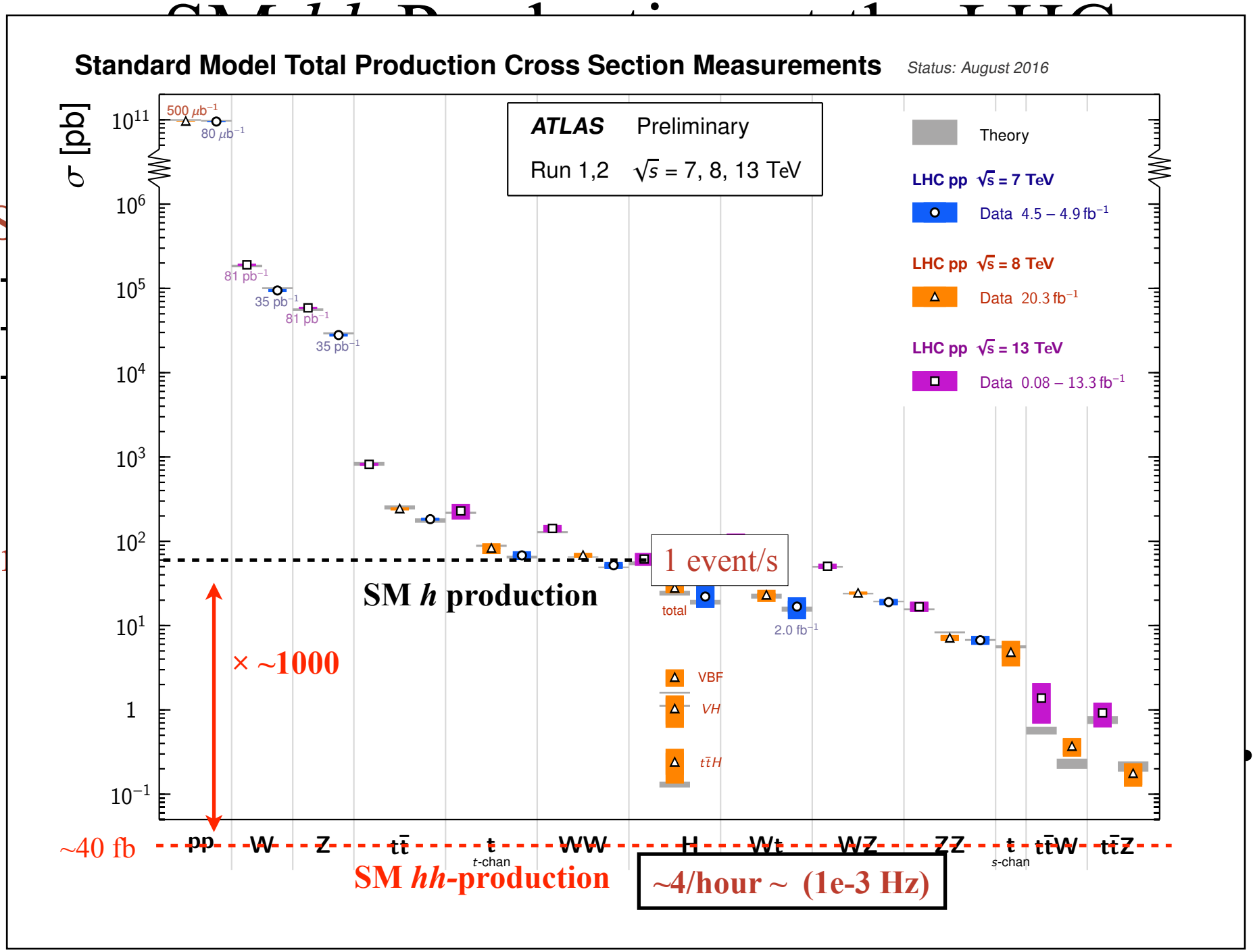
W
Z
tt̄
t
t-chan
WW
H
Wt
WZ
ZZ
t
s-chan
ttW
ttZ
~40 fb
SM hh-production
~4/hour ~ (1e-3 Hz)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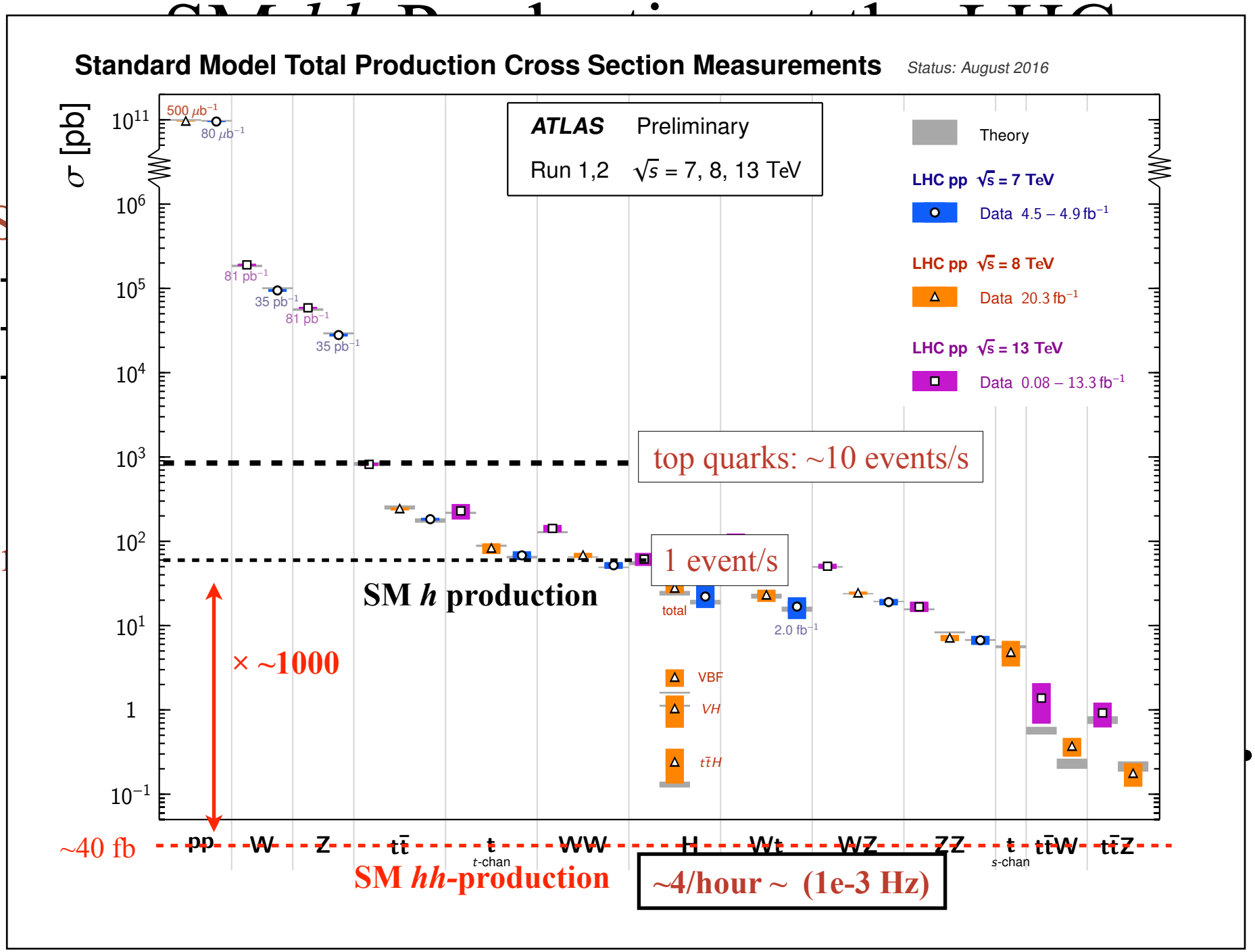
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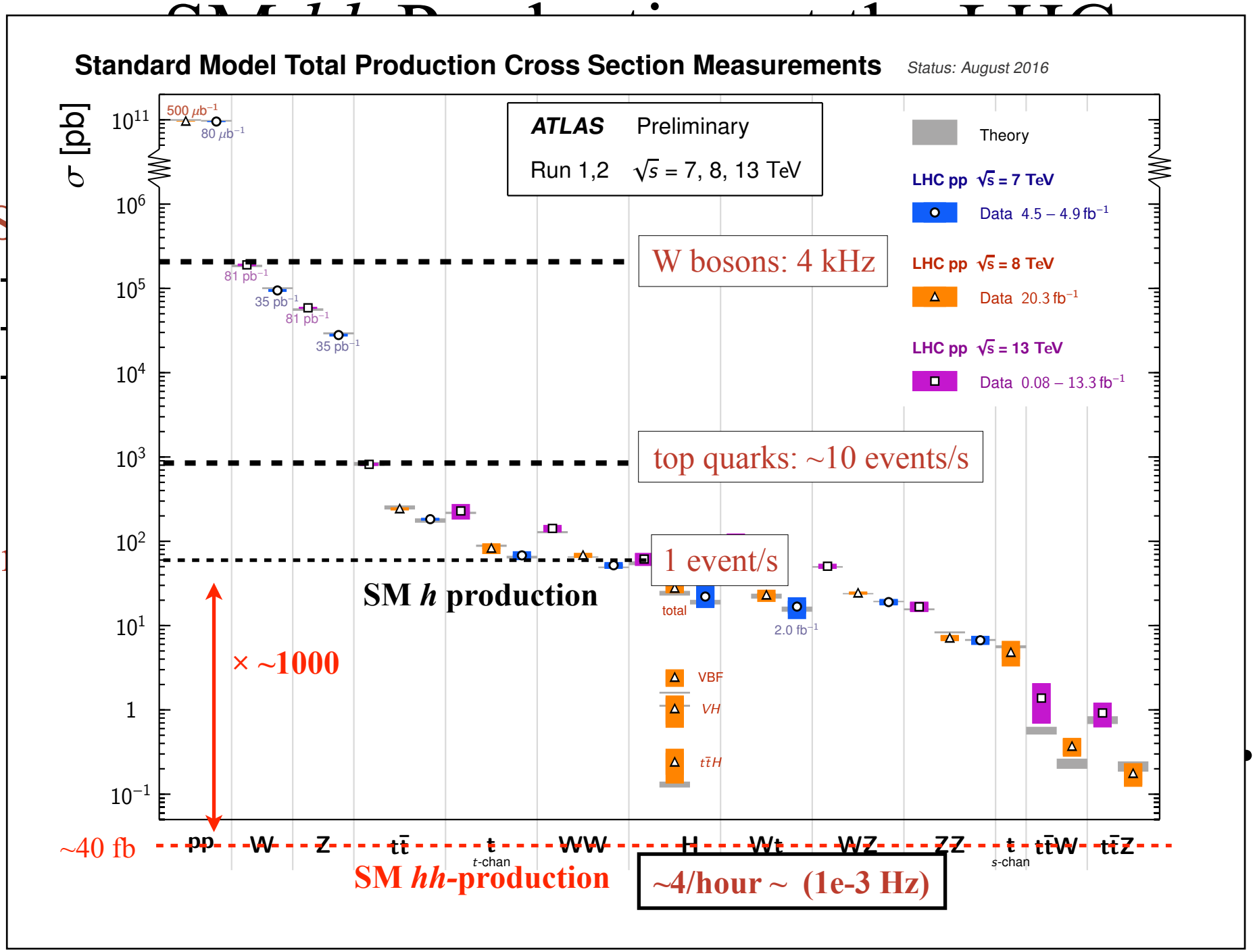
σ [pb]
top quarks: ~10 events/s
1 event/s
SM h production
× ~1000
~40 fb
SM hh-production
~4/hour ~ (1e-3 Hz)
pp
W
Z
tt̄
t
t-chan
WW
H
Wt
WZ
ZZ
t
s-chan
ttW
ttZ
total
VBF
VH
ttH
2.0 fb⁻¹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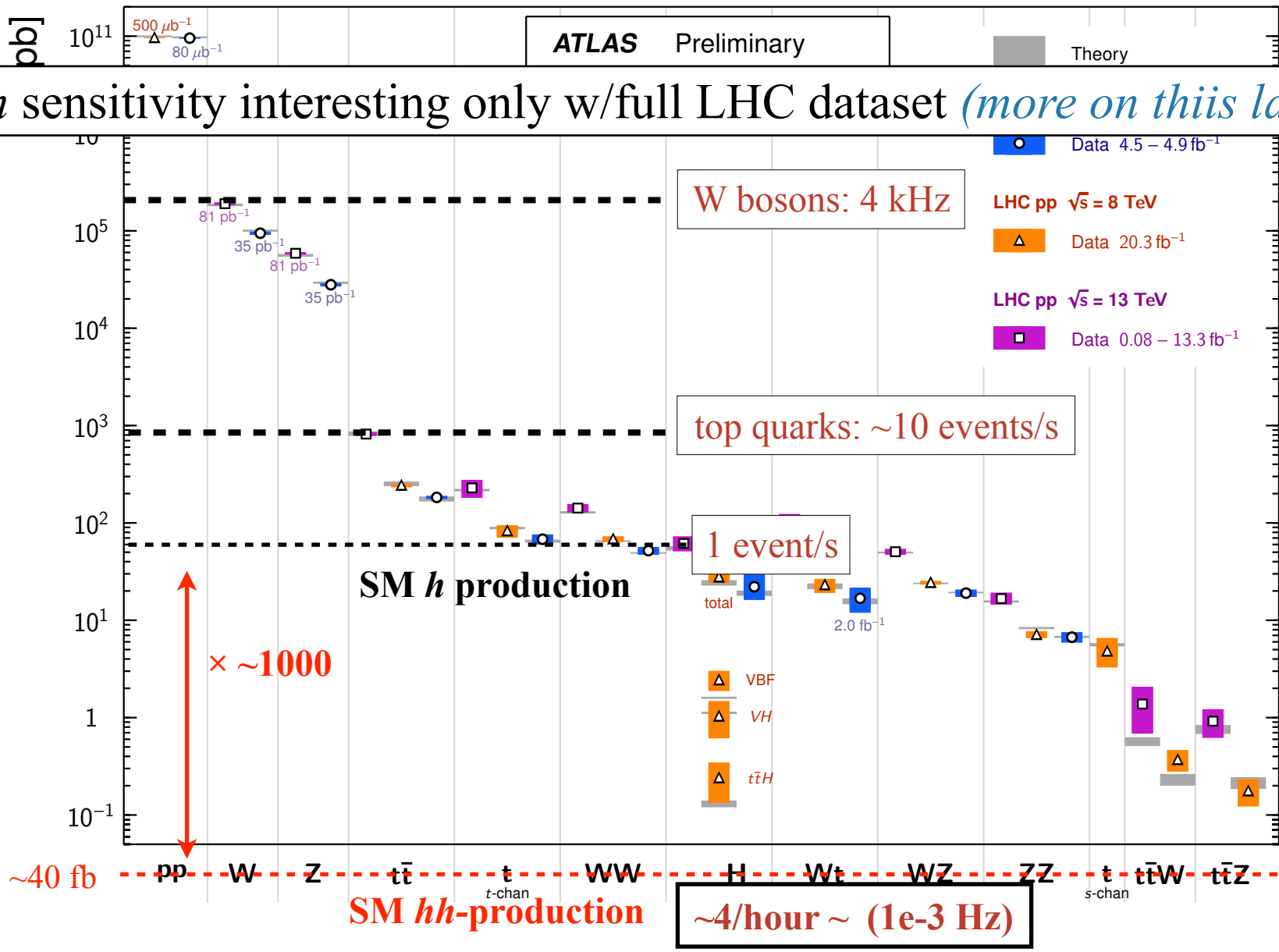
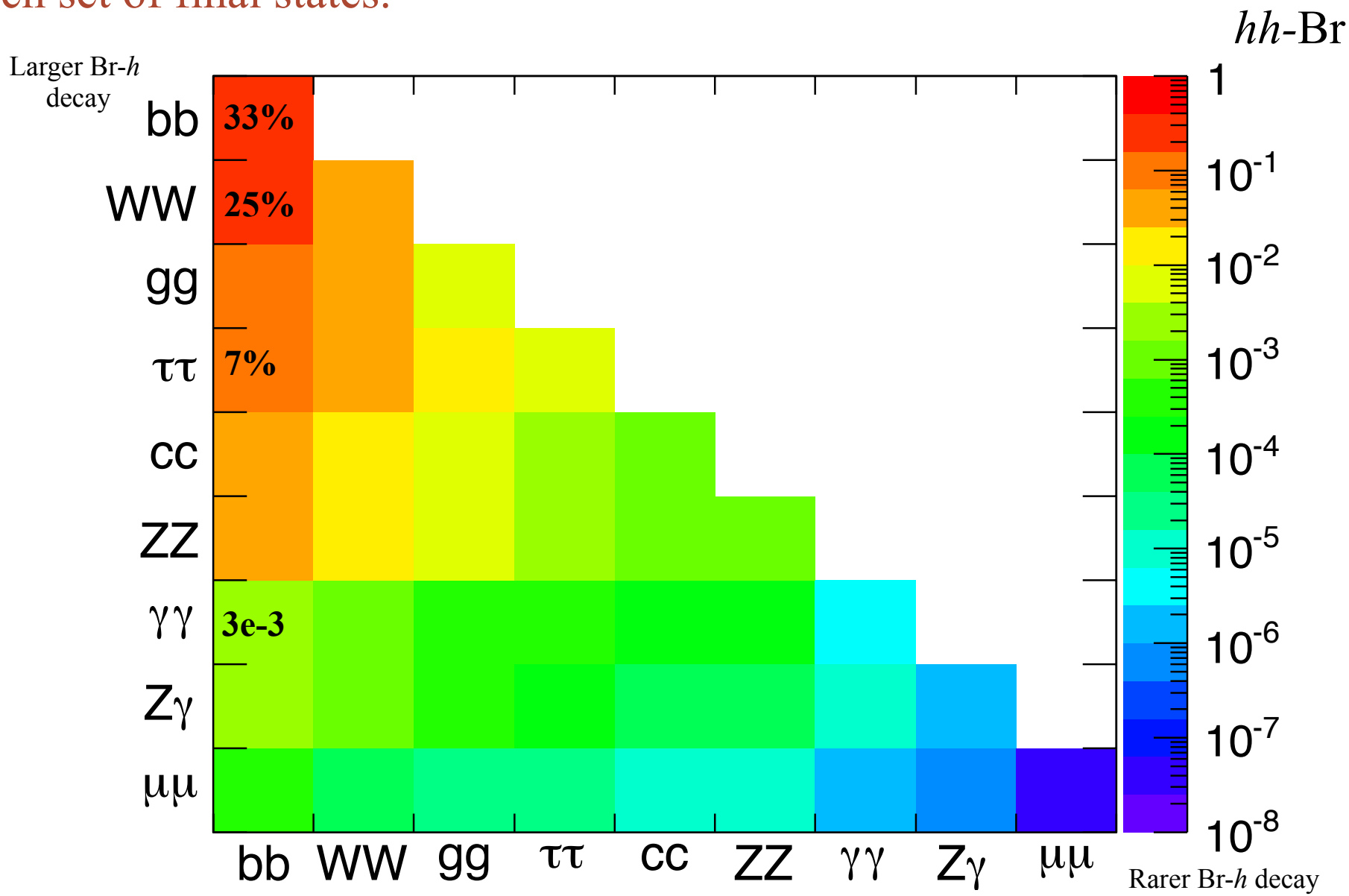
WZ
ZZ
t
s-chan
ttW
ttZ
total
VBF
VH
ttH

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



hh Decay

Rich set of final states.



Higgs Decay Rates