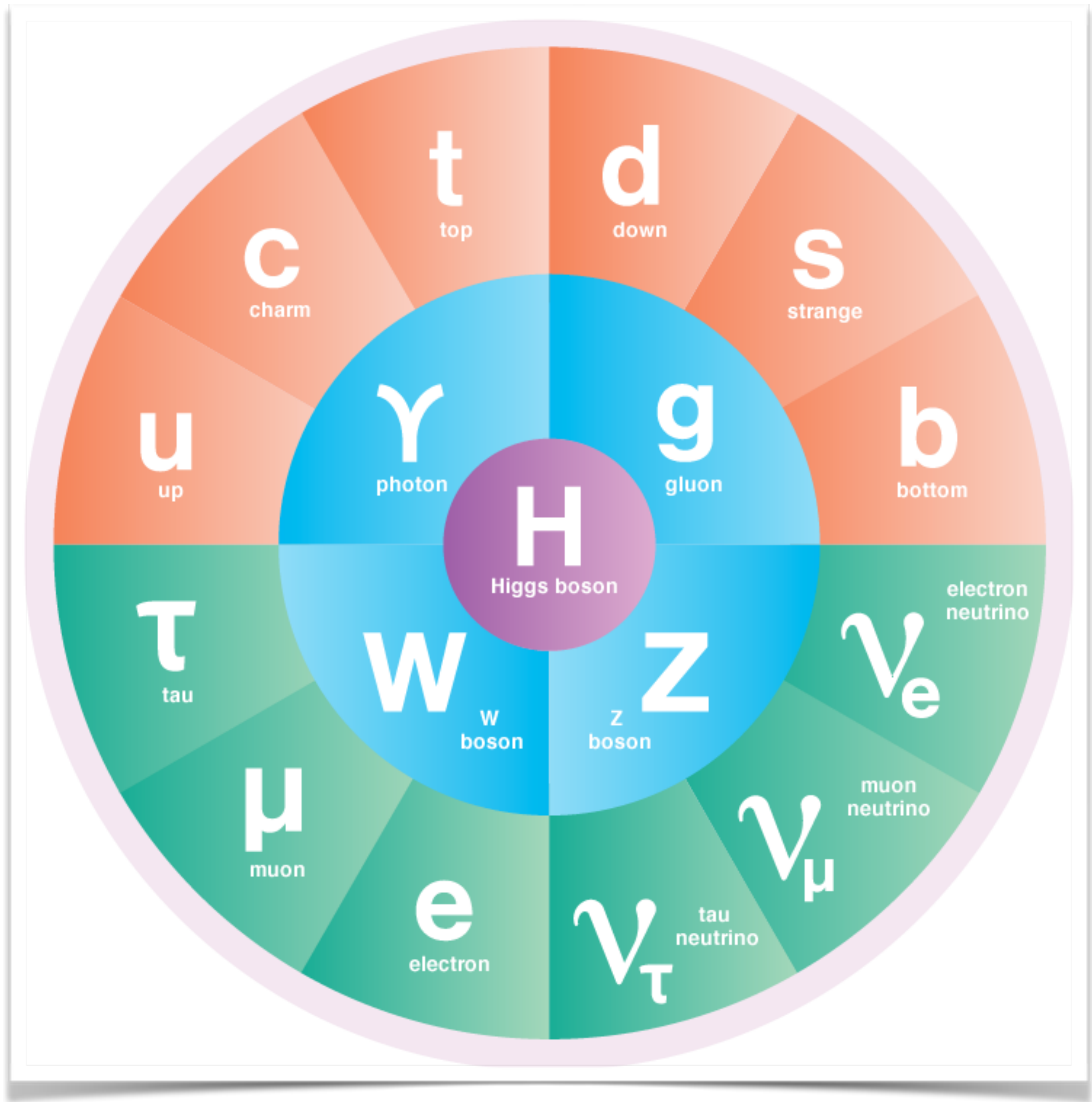
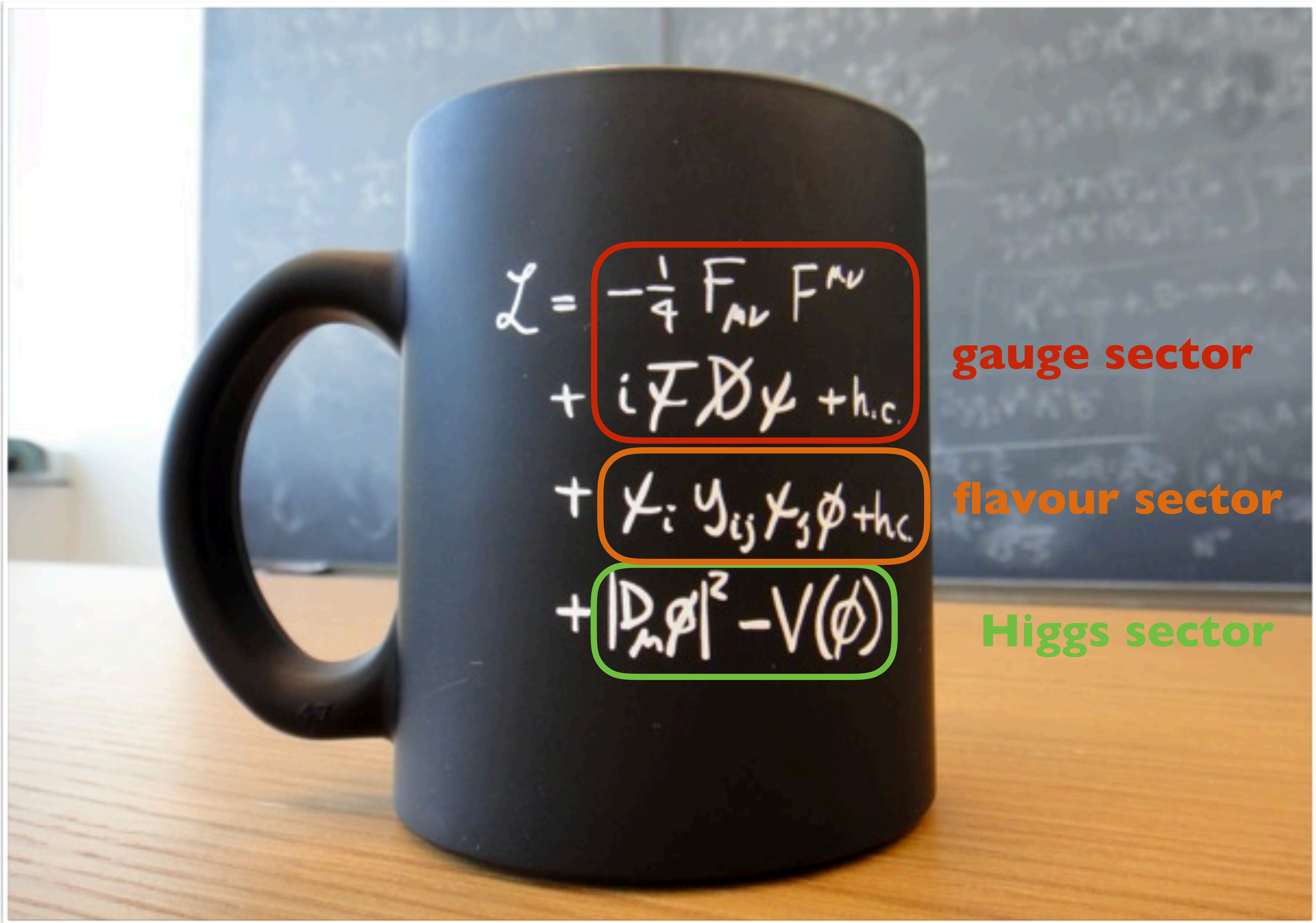
Higgs Flavor Physics: Interactions of the Higgs with Quarks



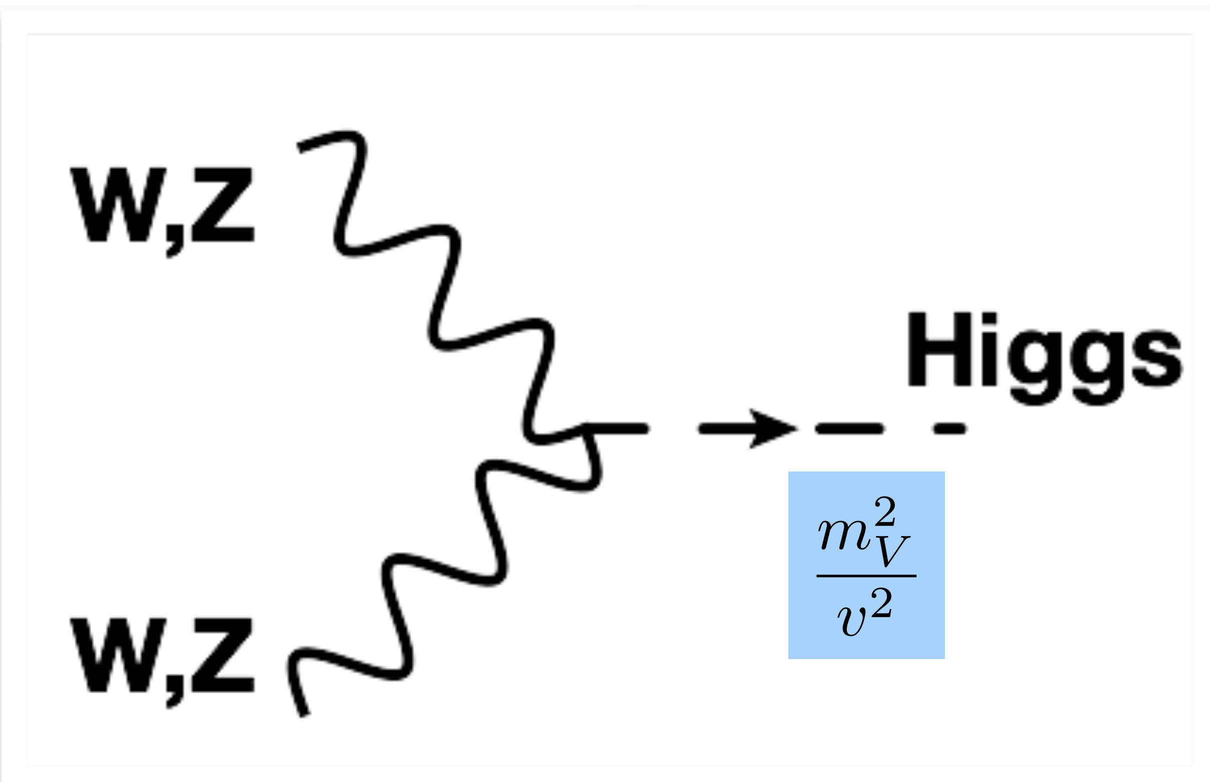
Heather M. Gray

The Standard Model Lagrangian



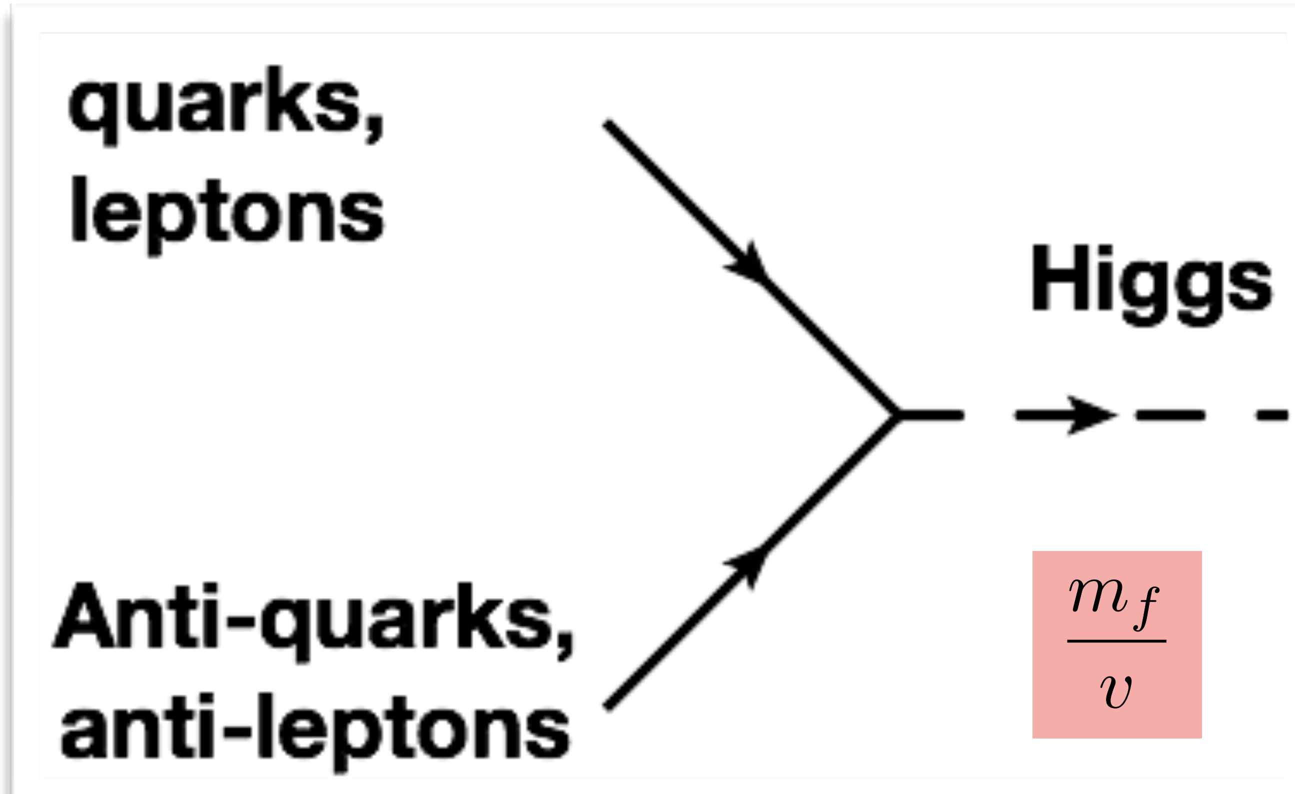
Higgs couples to all fermions and bosons

Coupling to bosons

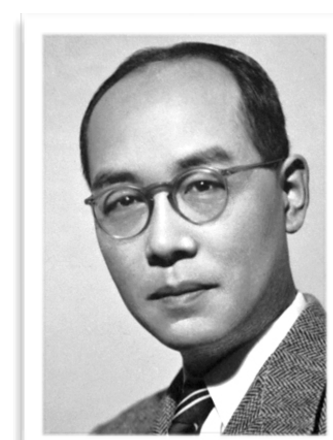


Defined by the Lagrangian
Typically what we think about when we talk about the Higgs mechanism

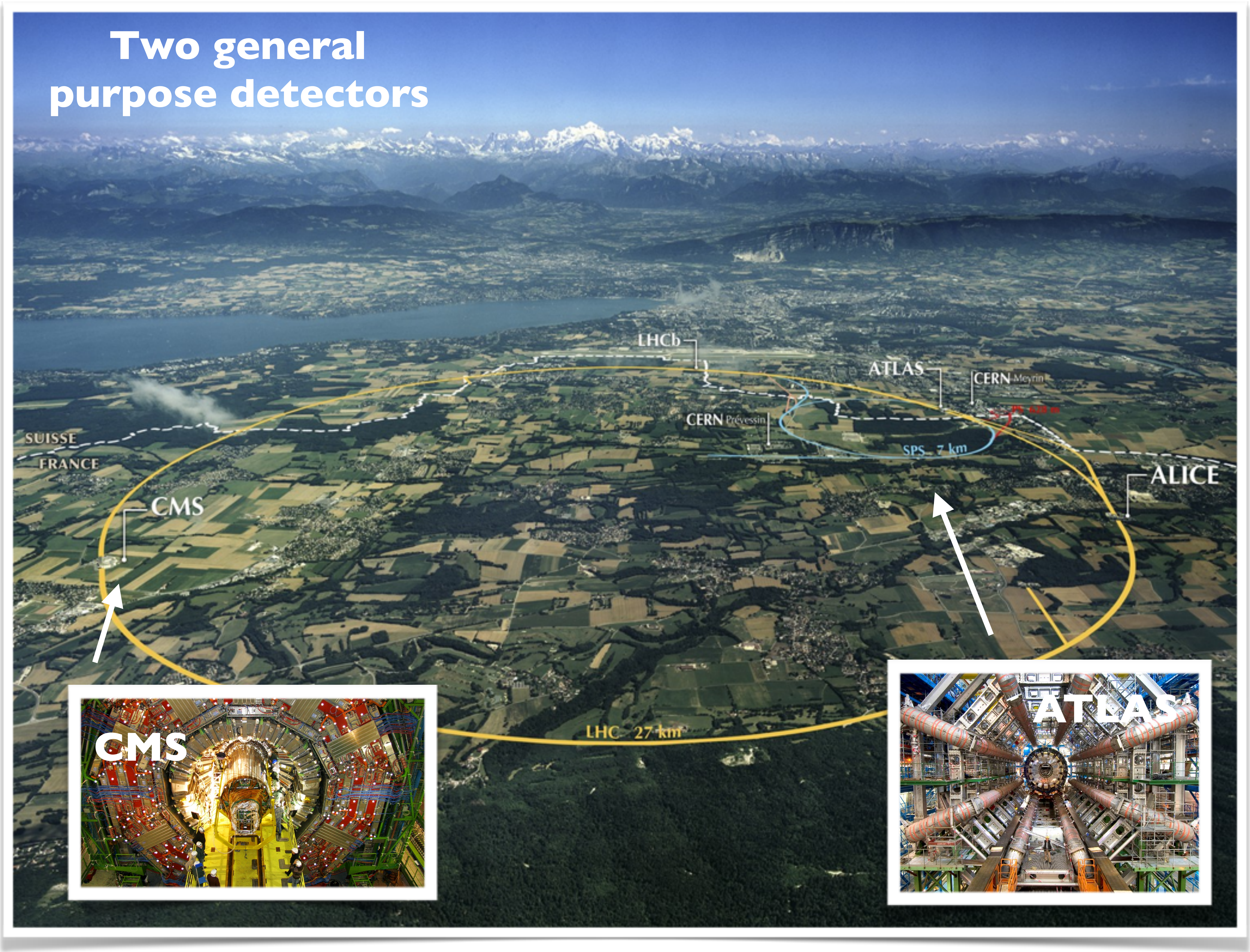
Coupling to fermions



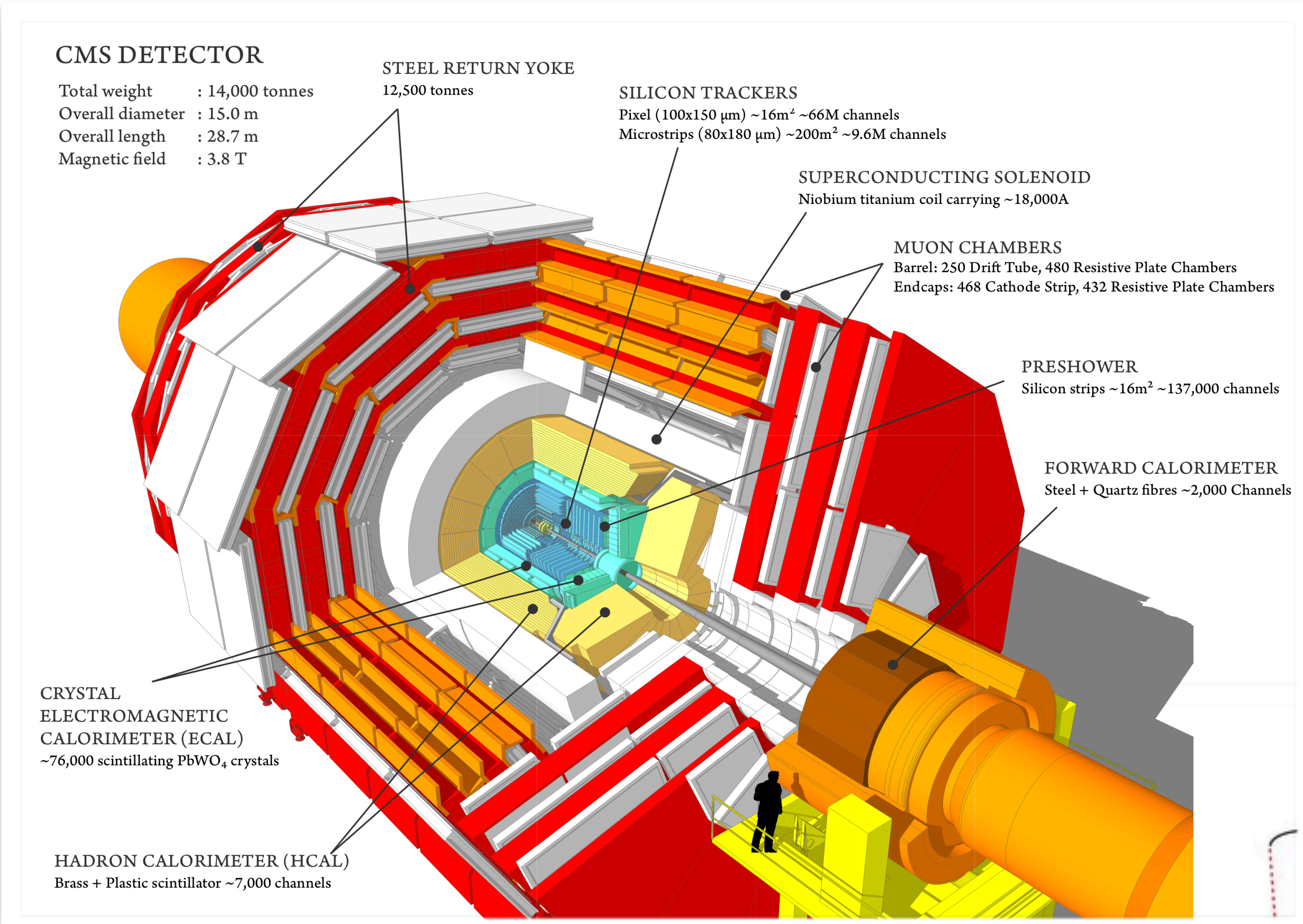
Depends on the fermion mass
Also called Yukawa couplings



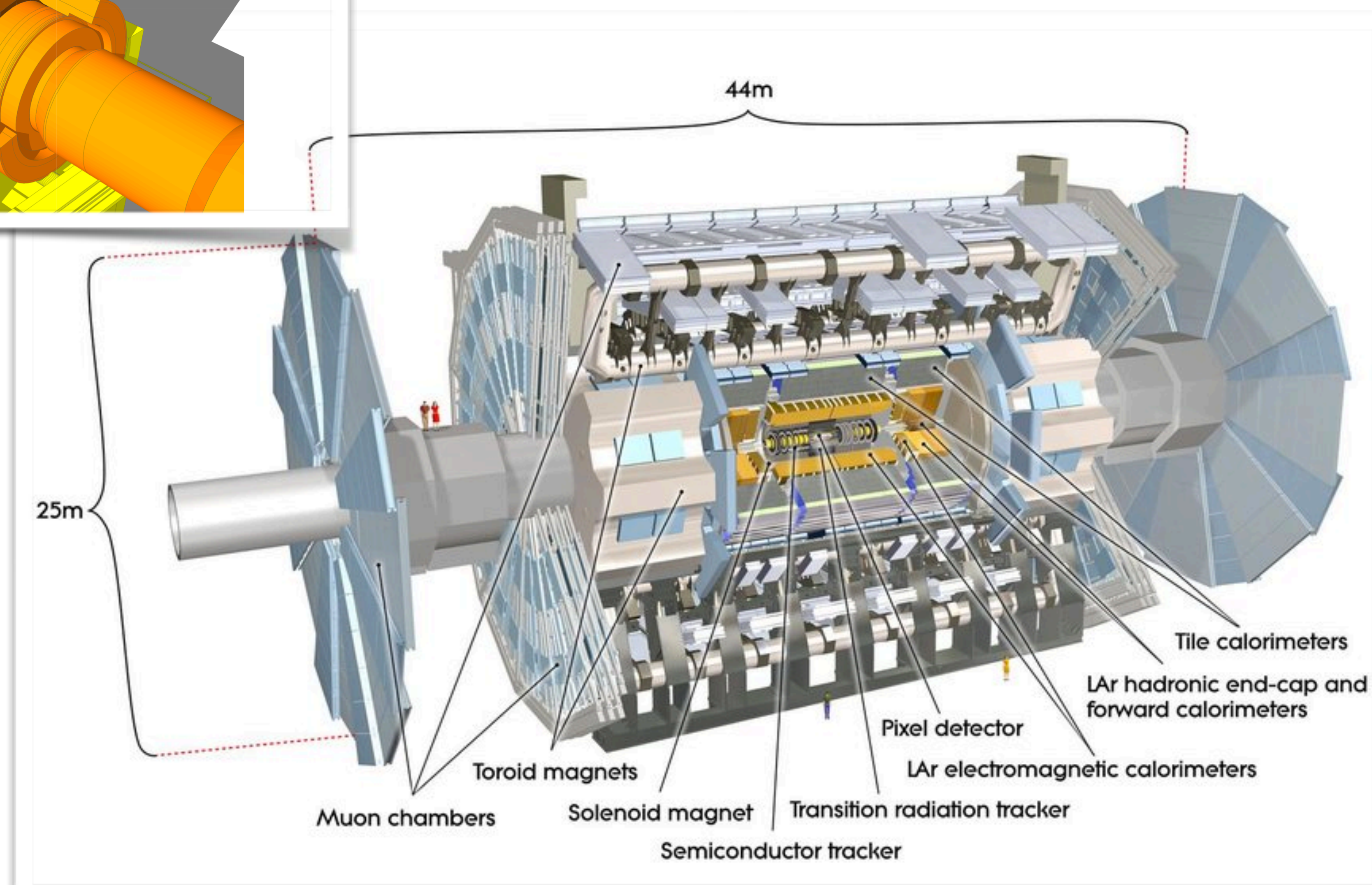
The Large Hadron Collider (LHC)



ATLAS and CMS detectors

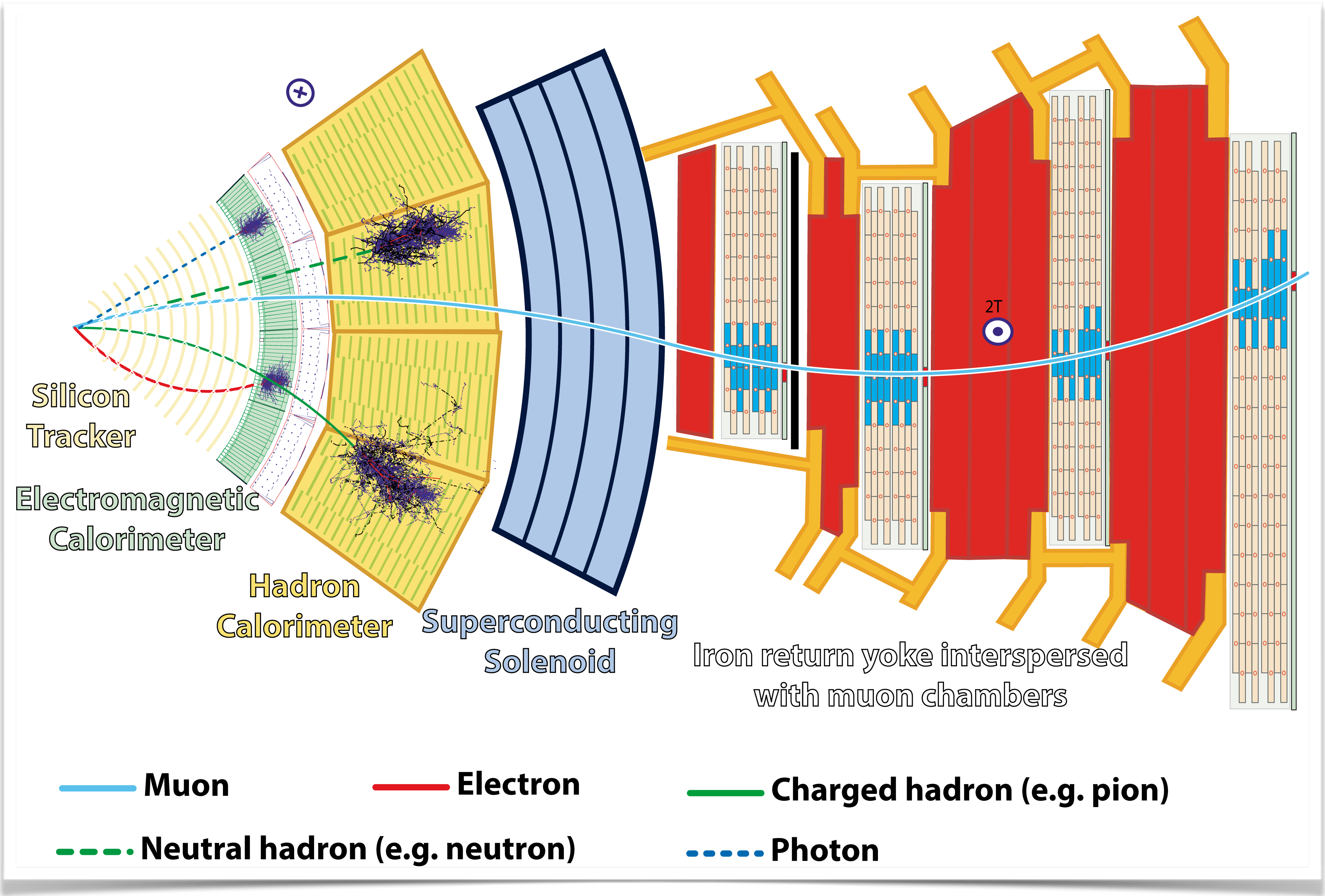


CMS



ATLAS

Detecting elementary particles



4 July 2012: Higgs (In)dependence Day

Nobel prize in 2013 for Higgs and Englert

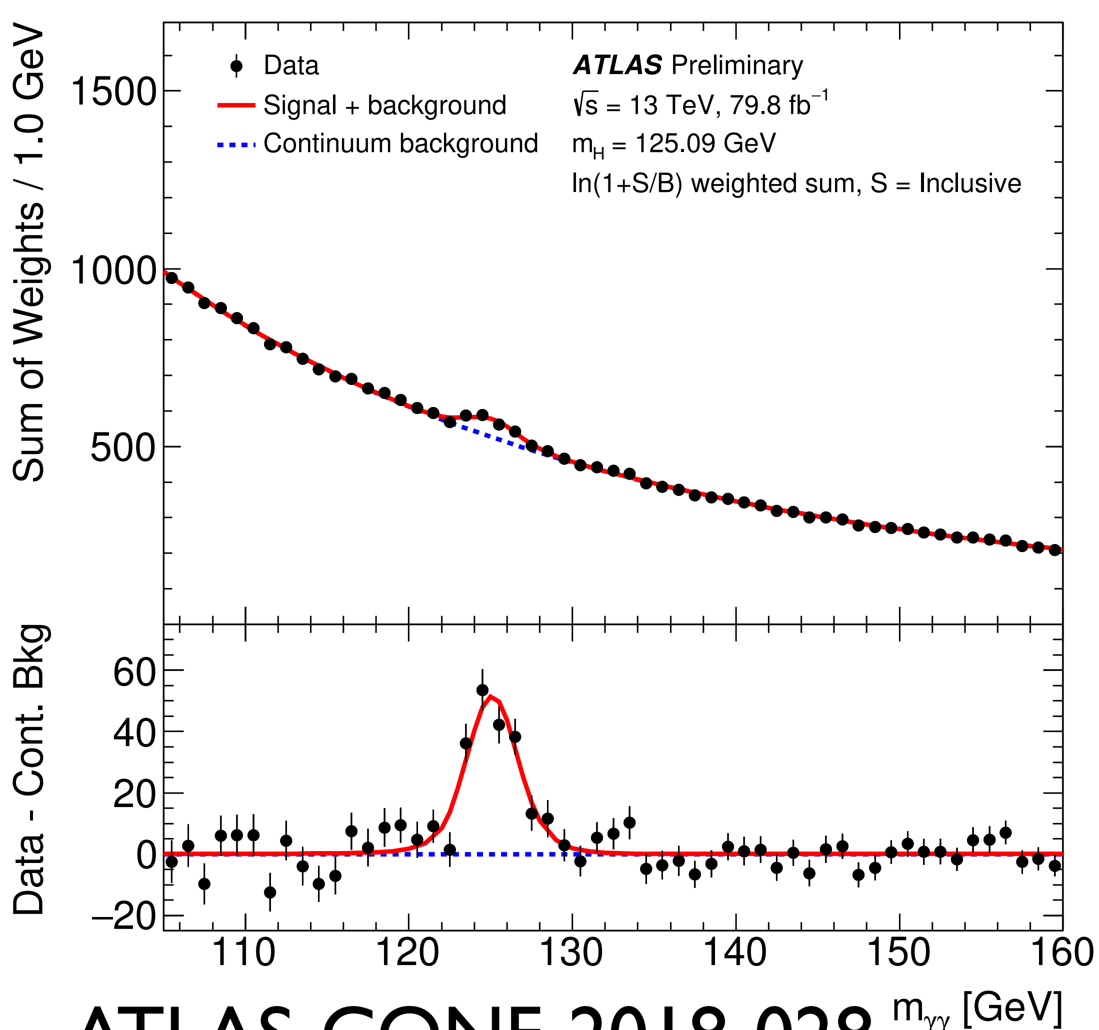
Discovery Channels: H→γγ and H→ZZ→4l

- The Higgs boson discovery relies on the diphoton and ZZ decay modes
- Does not mean that we've established the coupling to quarks

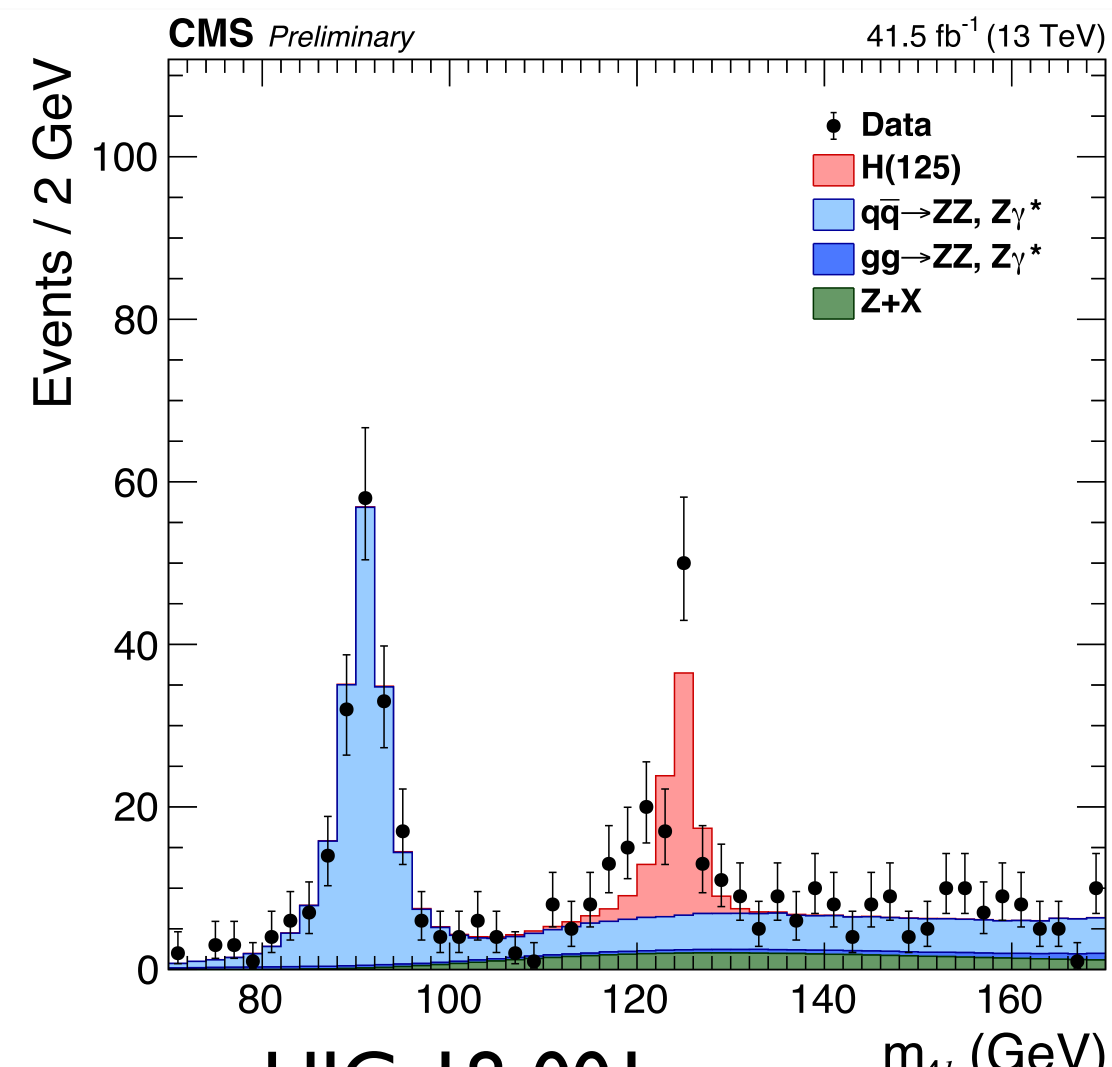
$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$$

$1.06 \pm 0.08\ (\text{stat.})\ ^{+0.08}_{-0.07}\ (\text{exp.})\ ^{+0.07}_{-0.06}\ (\text{theo.})$

$1.00 \pm 0.10(\text{stat})^{+0.08}_{-0.06}(\text{exp. syst})^{+0.07}_{-0.05}(\text{th. syst})$

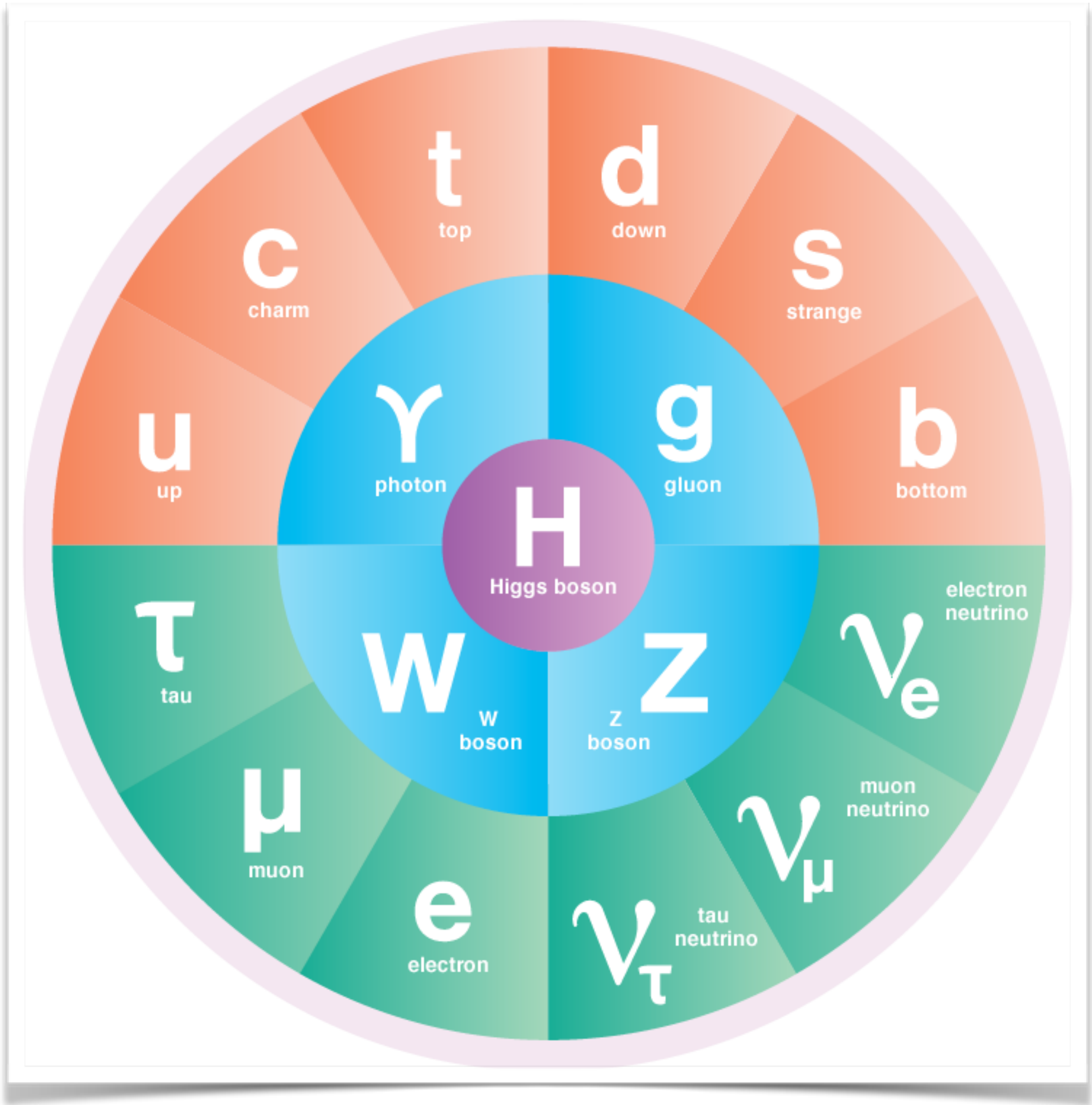


ATLAS-CONF-2018-028



HIG-18-001

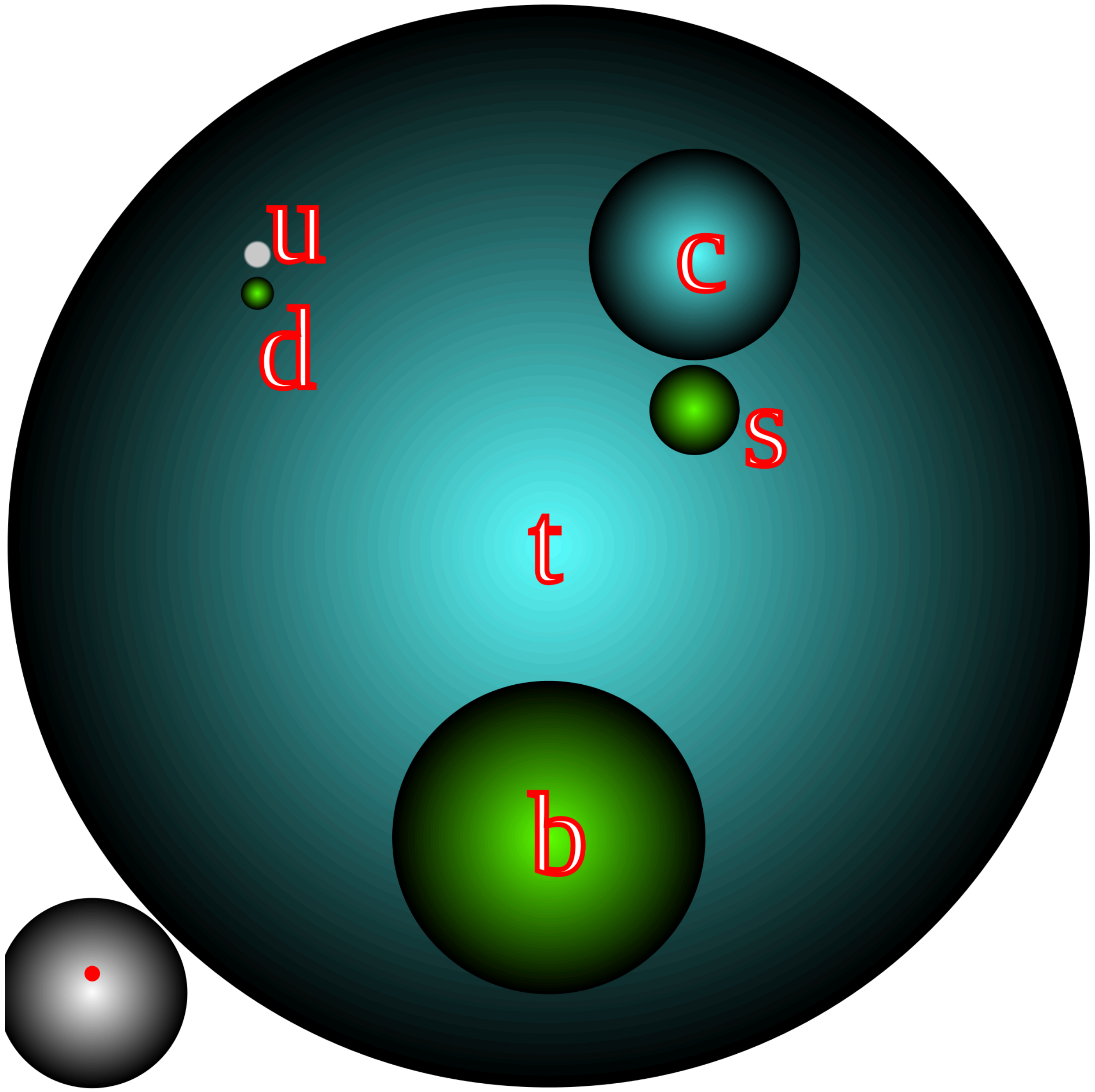
Reminder: The Standard Model

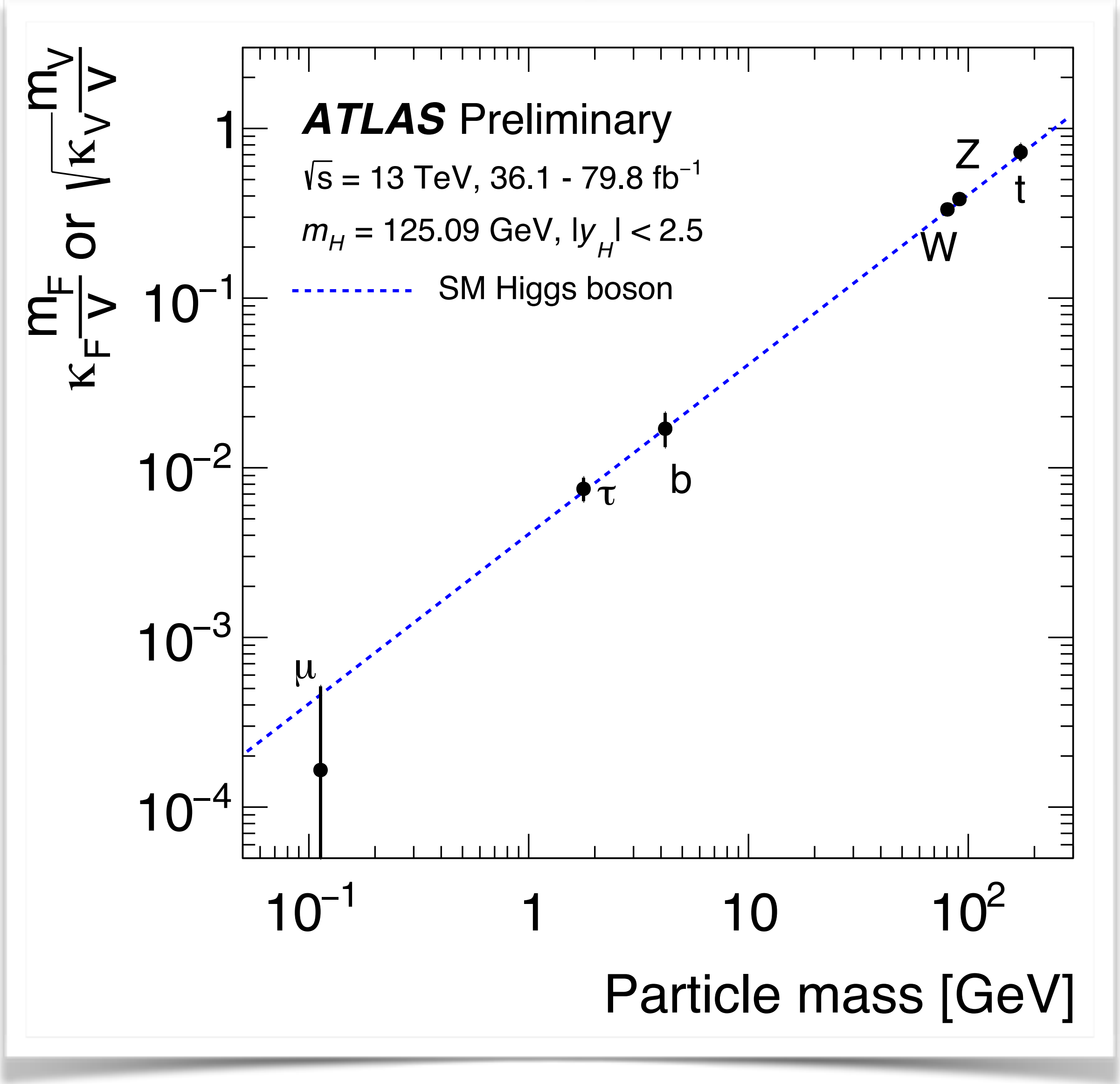


Higgs couples to all particles with mass (i.e. all except gluons and photons)

Question: How did we observe the $H \rightarrow \gamma\gamma$ decay?

Coupling vs Mass



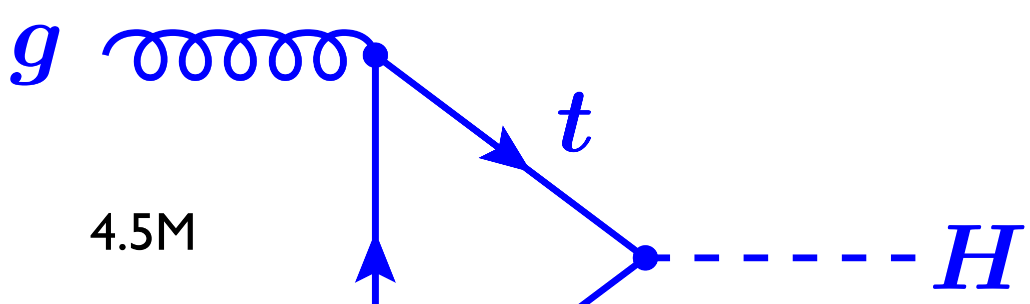


ATLAS-CONF-2018-031

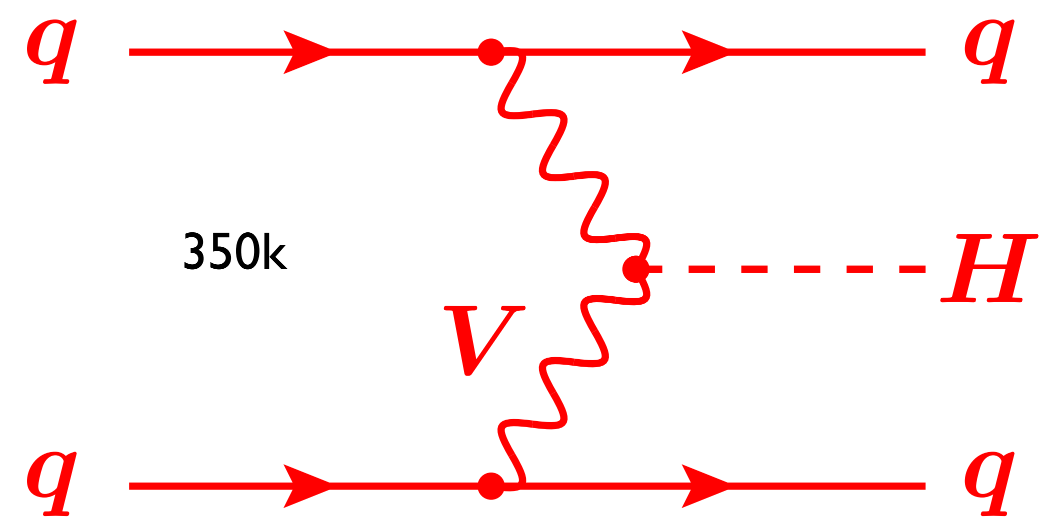
The Higgs Boson at the LHC

#Higgs produced at 13 TeV

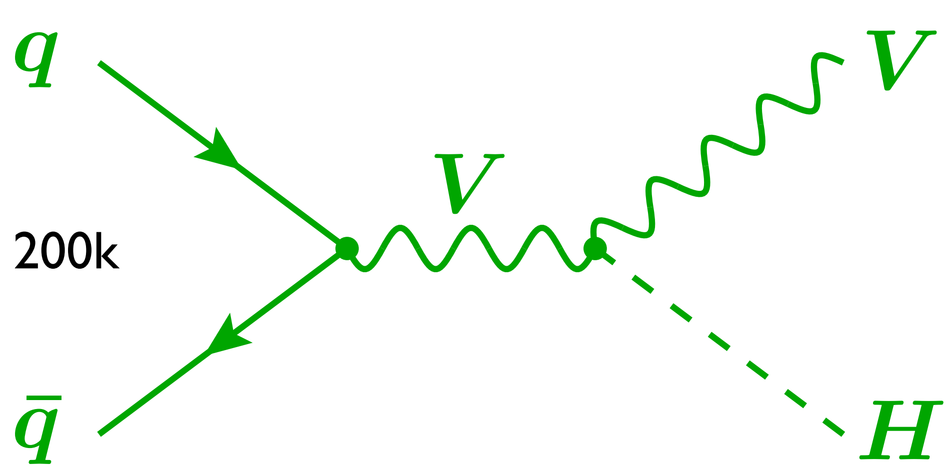
Production



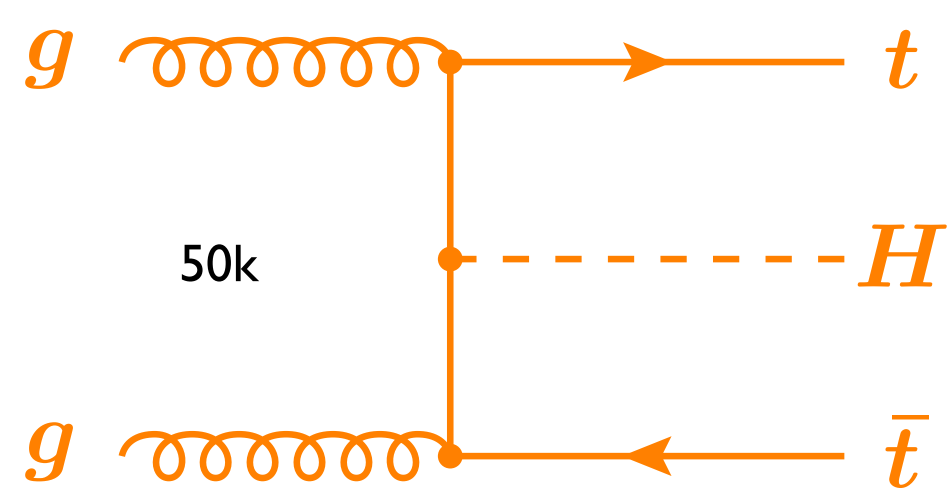
Main production channel



2 forward jets, little central hadronic activity



Tag W and Z decays



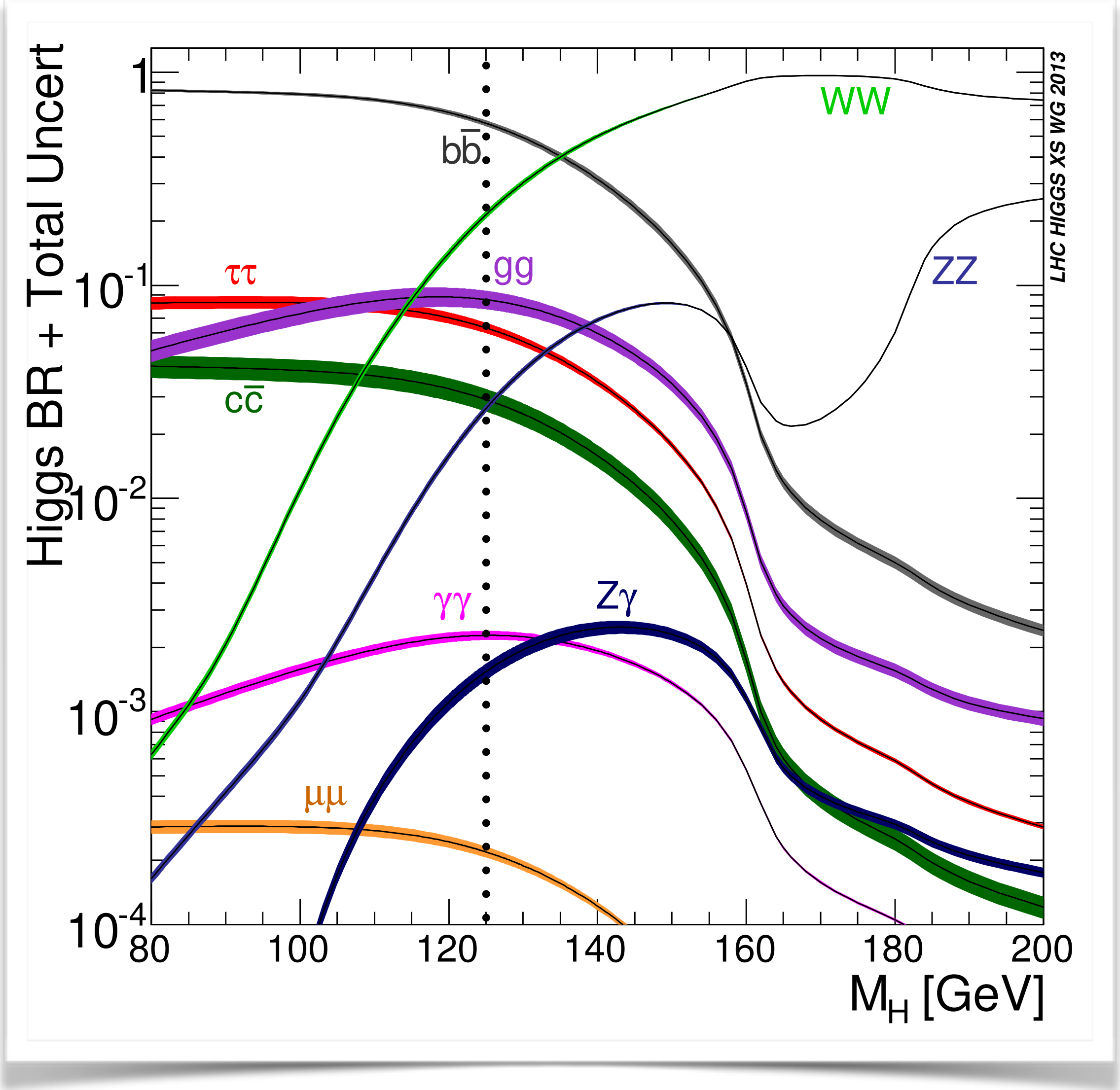
Tag 2 top quarks

Higgs Boson Decays

5 main channels at the LHC

Decay branching fractions for $m_H = 125$ GeV

- $H \to bb$: 58 %
- $H \to WW^*$: 21%
- $H \to \tau^+\tau^-$: 6.3%
- $H \to ZZ^*$: 2.6%
- $H \to \gamma\gamma$: 0.2%



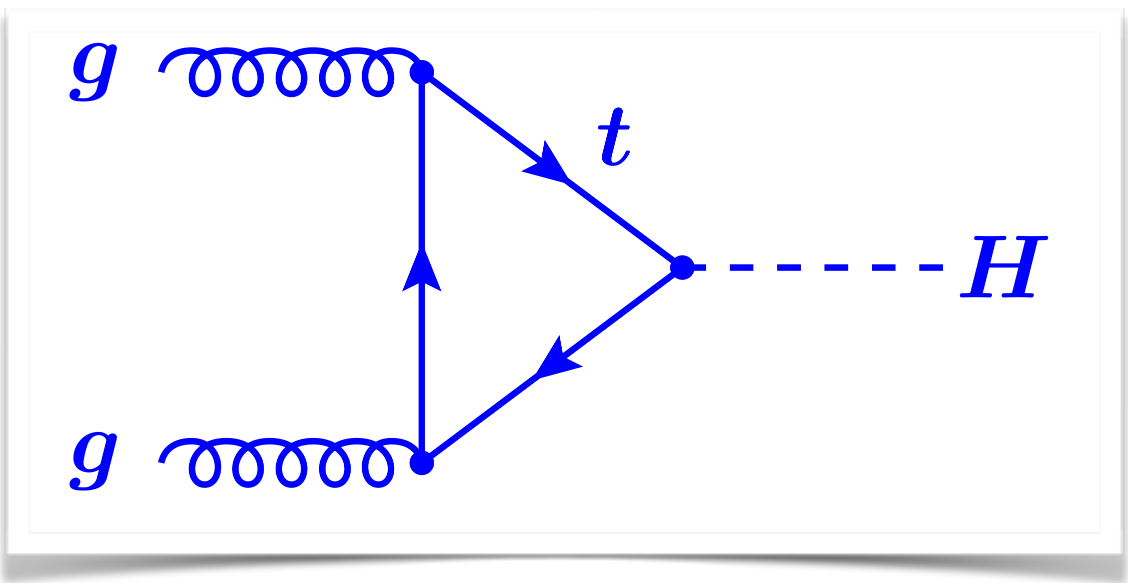
No branching ratio to top quark

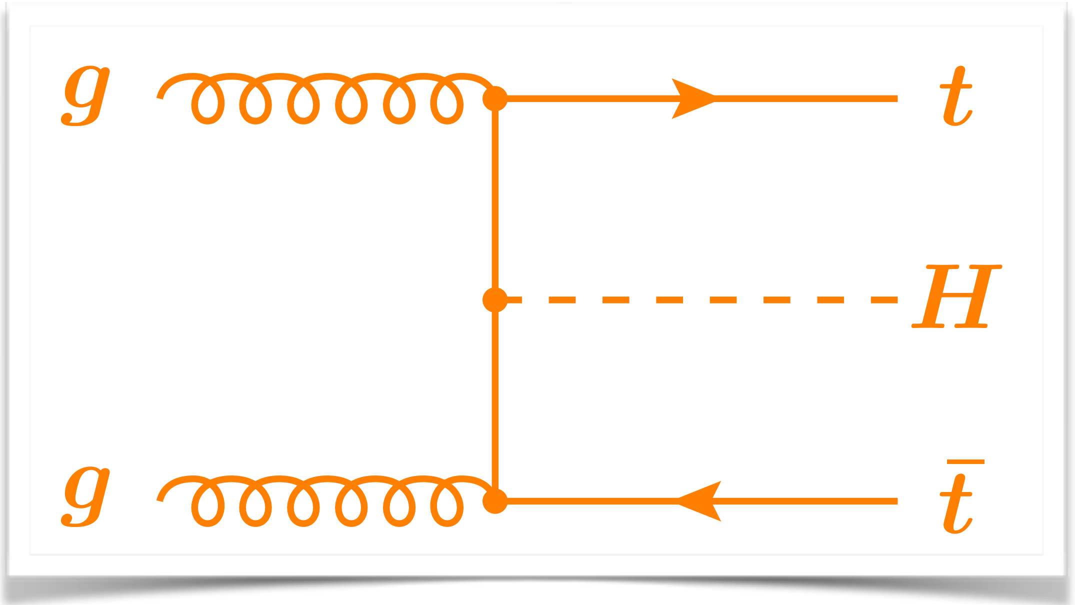
Note: BR to strange, up and down lie below the plot

Top Quark

Already done?

ggF was the production mode used for the Higgs discovery

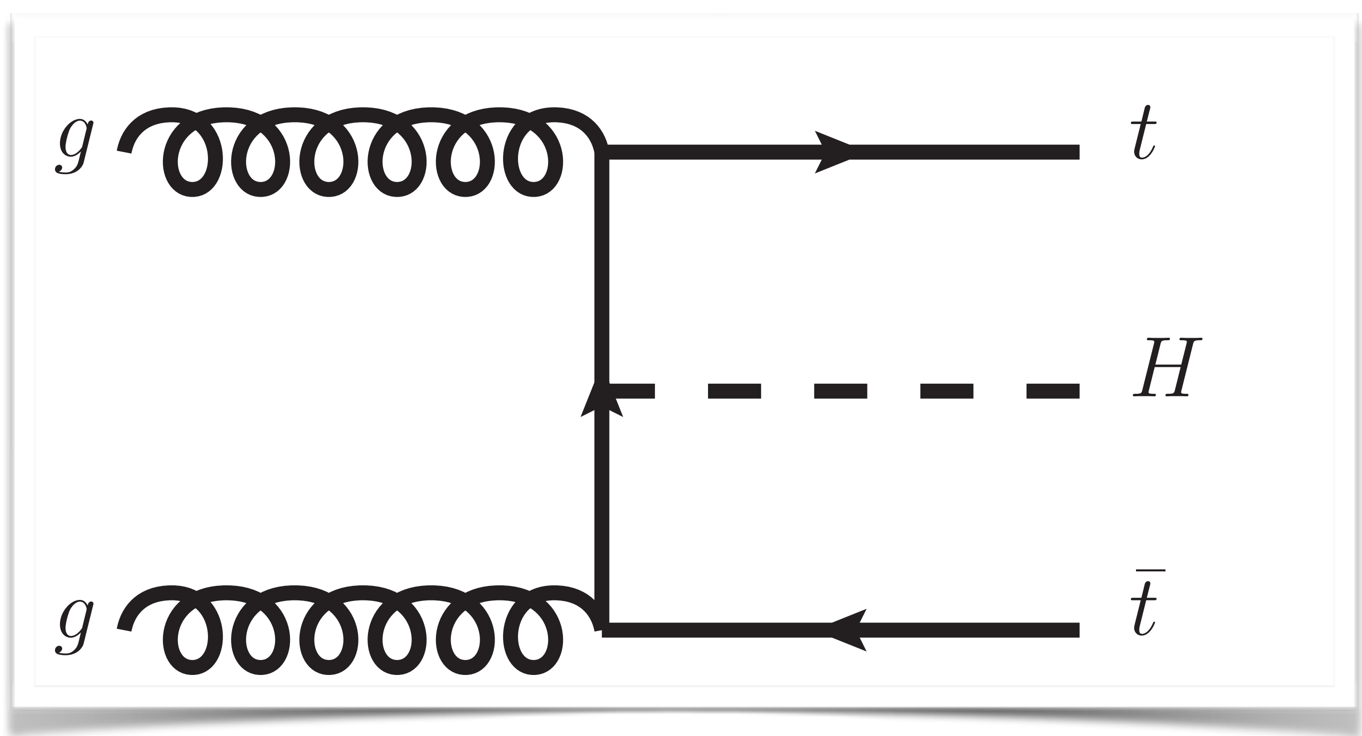




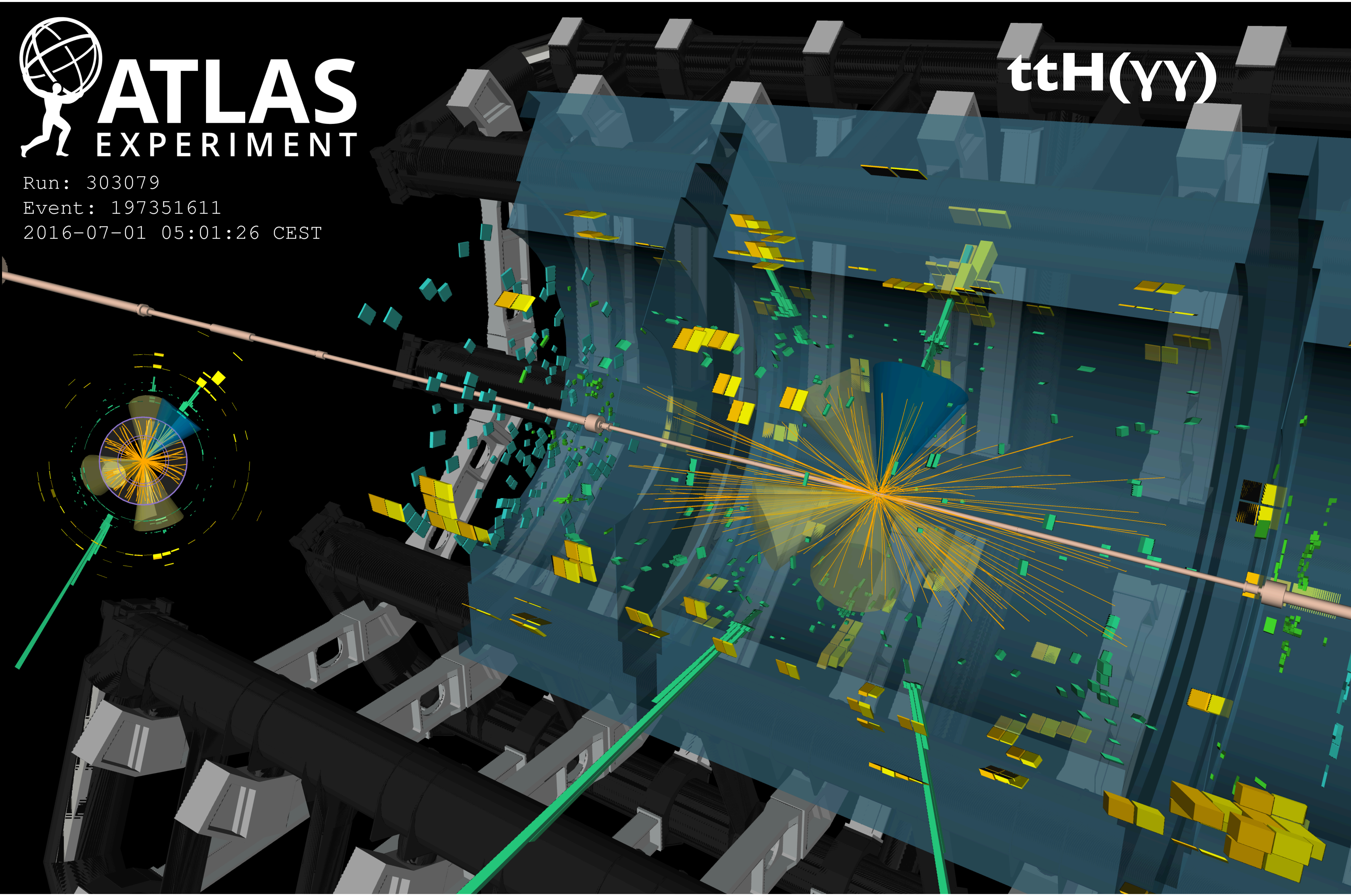
But … we can't see inside the loops
Could contain some new particle other than the top quark
With ttH production, we can observe the top quark directly

ttH

- Tiny cross-section of 0.5 pb (100x smaller than ggF)
  - Need to combine information from multiple top and Higgs decays
- Group these into four analyses according to the Higgs decays: γγ, ZZ, bb, multilepton*
  - Top quarks decay to a W boson and b quark
    - All channels include at least two b-jets from the top decay (+ 2W's)
- Busy final states!



*Mostly WW + ττ

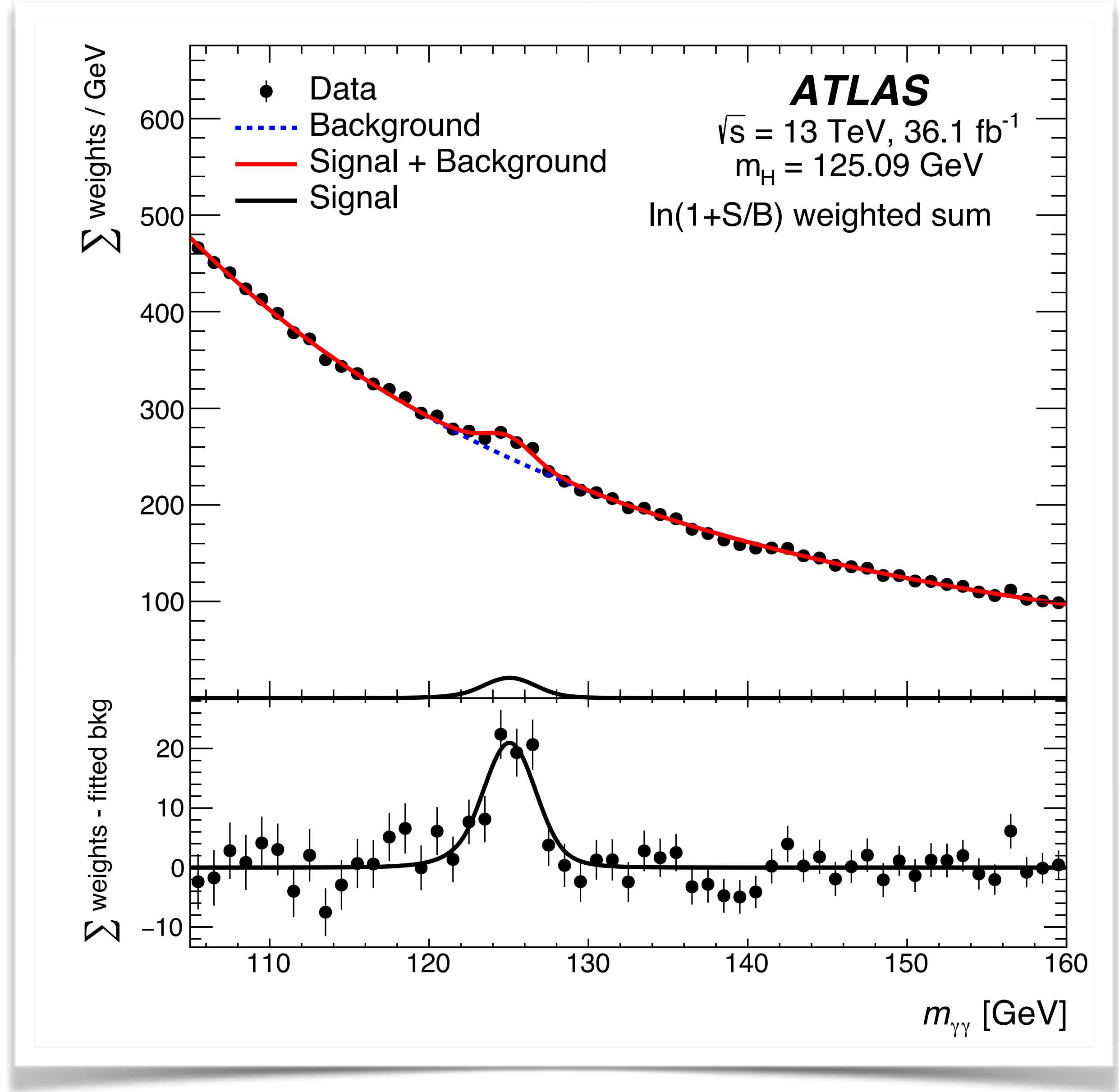


PLB784 (2018) 173

Analysis Overview

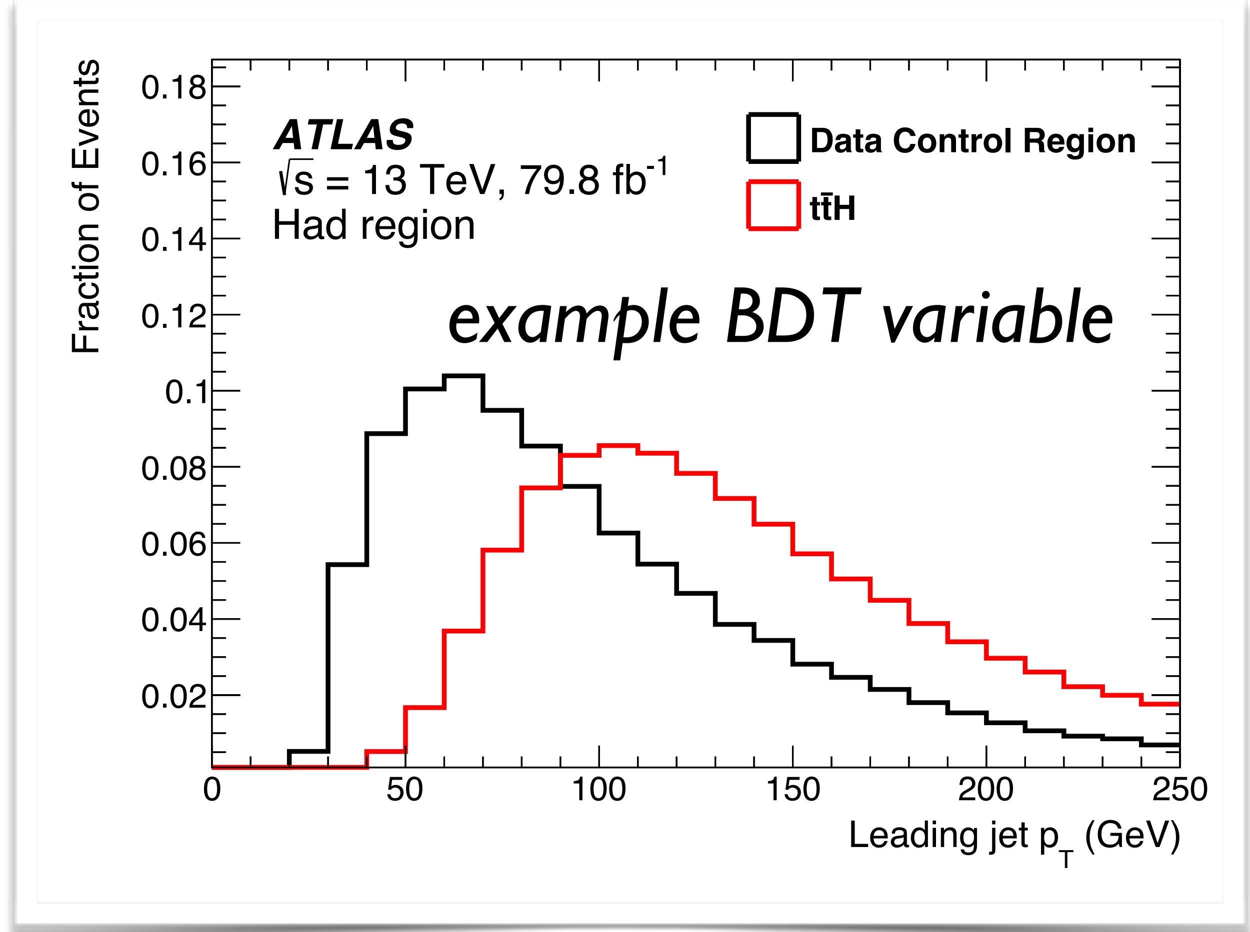
Expect events to contain two b-jets, two photons, 0-2 leptons and 4-0 jets

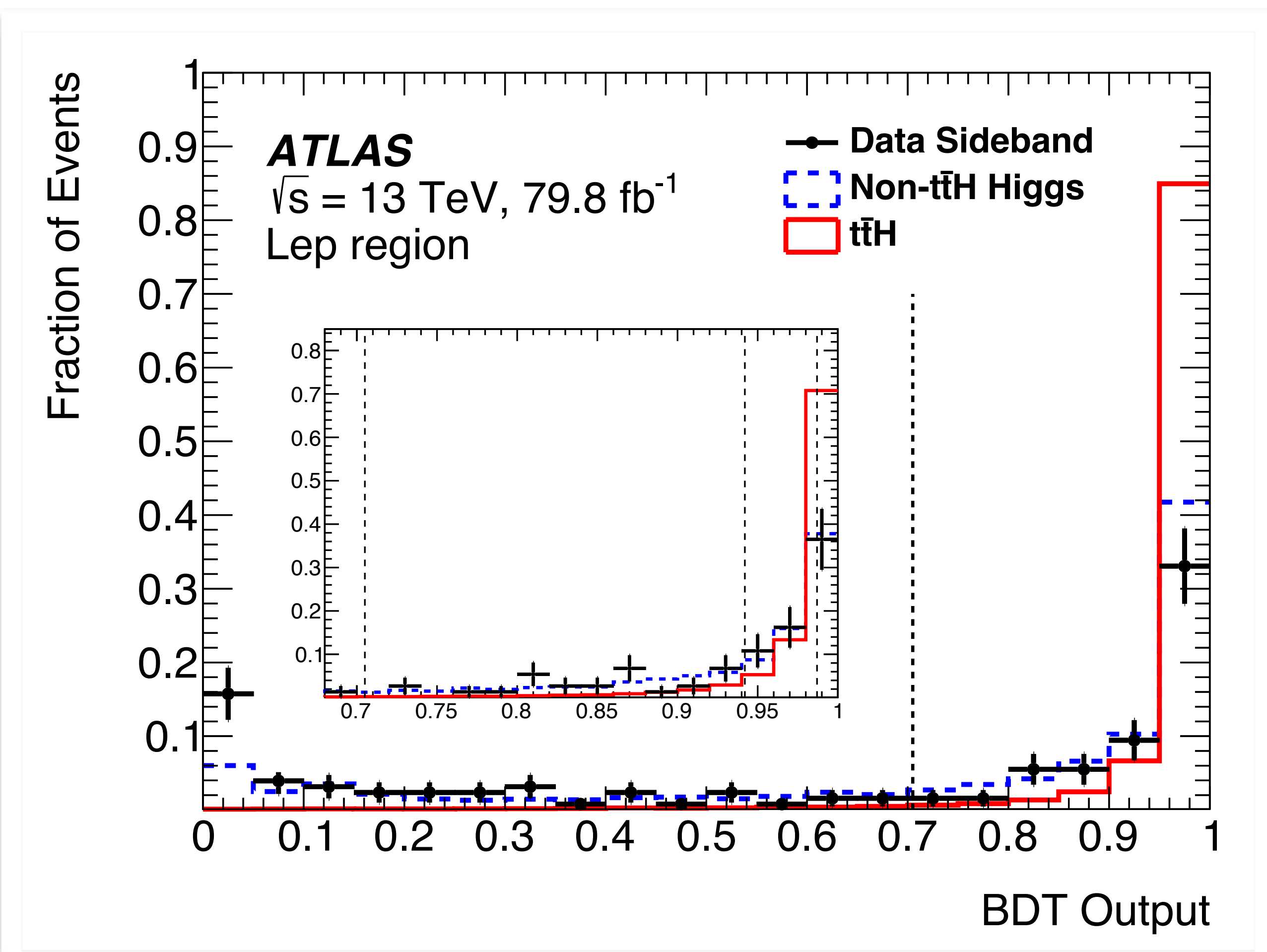
- Select events with two photons and at least one b-jet
- Define two channels
  - **Leptonic**: at least one lepton
  - **Hadronic**: no leptons
- Train a BDT in each channel and define 7 categories using the BDT
- Fit diphoton mass in each category
- Background estimation from data sidebands

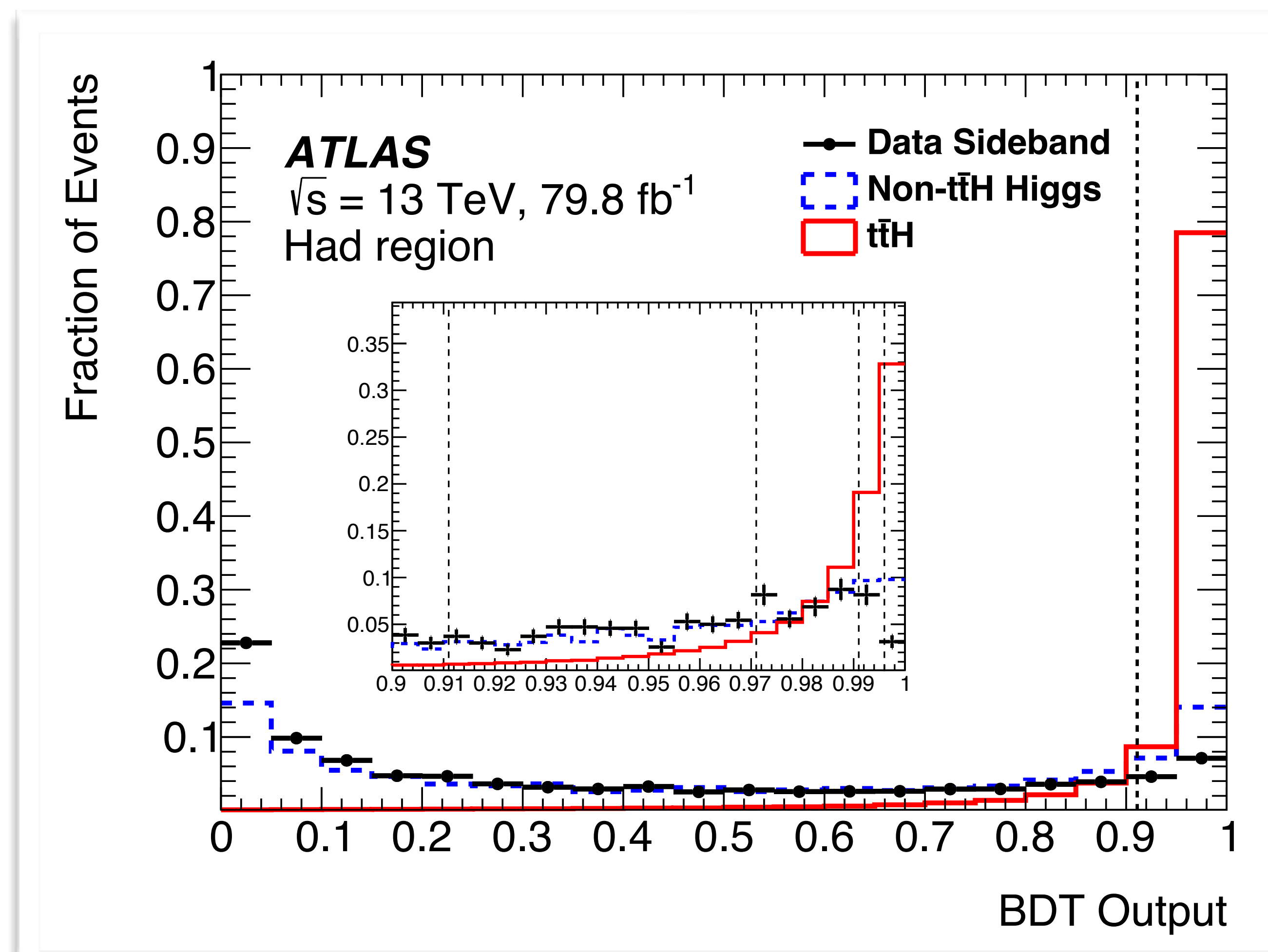


Channel Definition

- BDTs are trained using ttH signal and background from data control regions
- Mostly kinematic variables for jets and photons (p_T, η, φ) also b-tagging, MET
- Define 3 categories for the leptonic channel and 4 categories for the hadronic channel

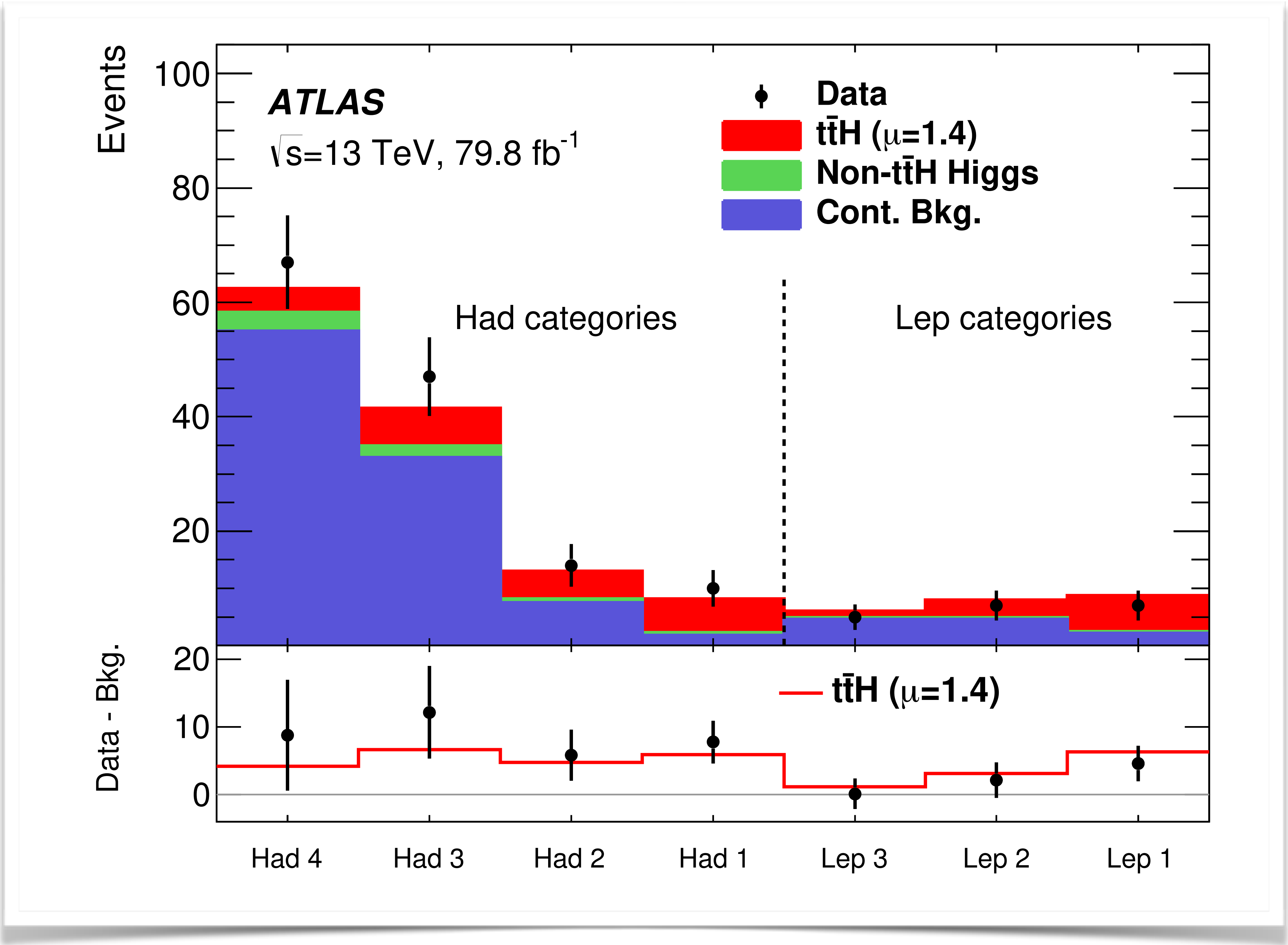






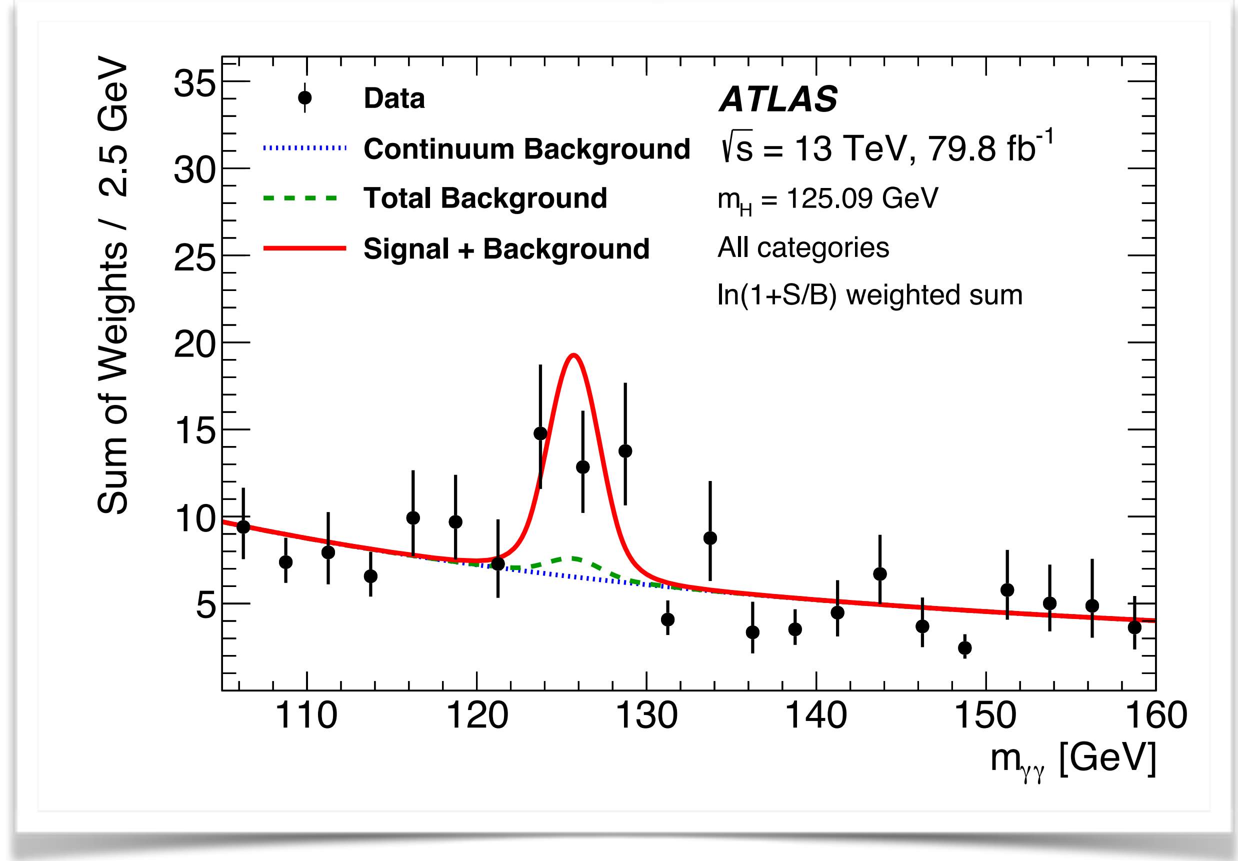
Event Yields

- Number of events in data in each analysis category in mass window containing 90% of expected signal



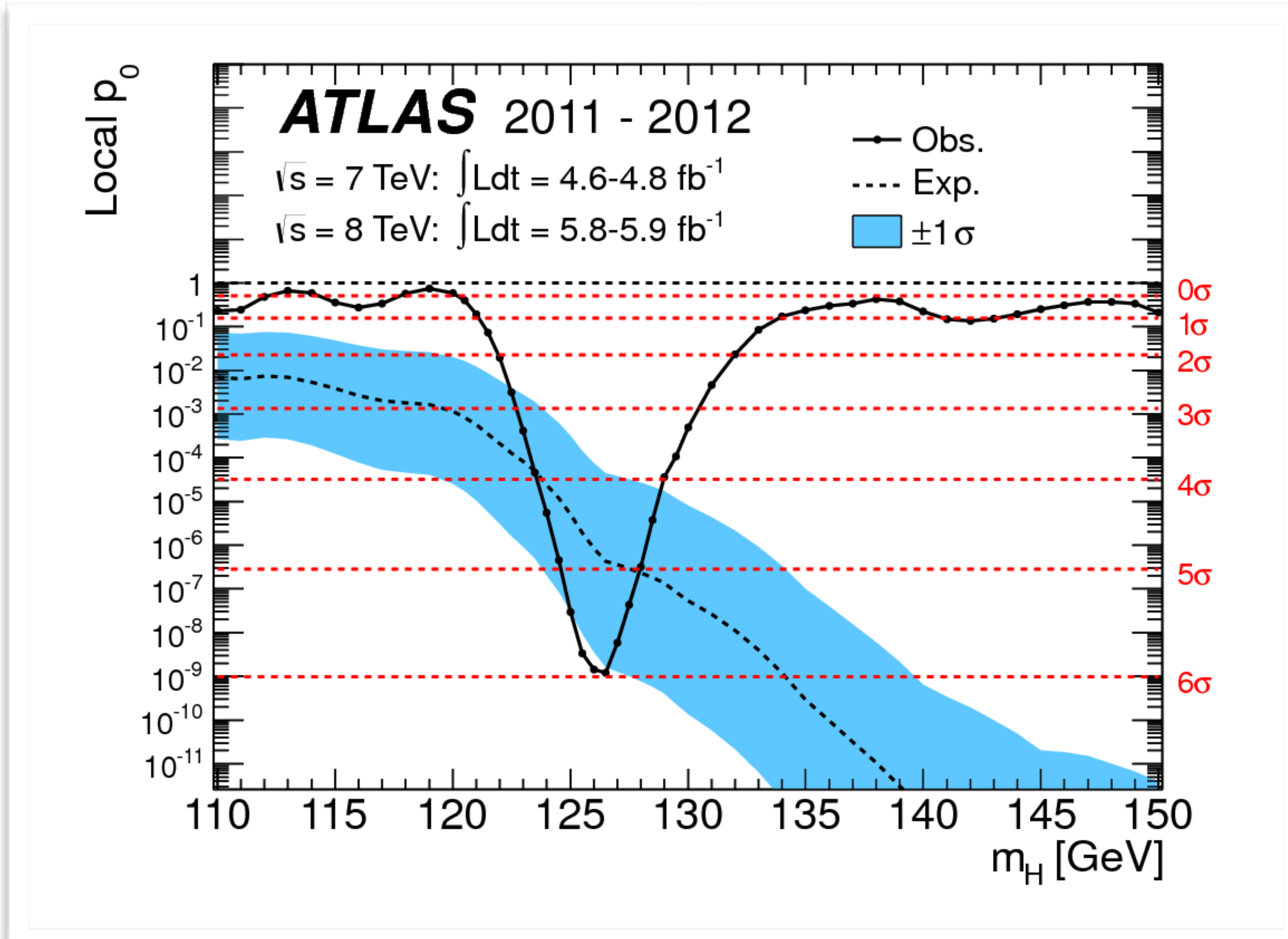
Results

- Peak in diphoton mass distribution at 125 GeV
- A fit over the seven categories yields 36±12 ttH(γγ) events
- $\mu = 1.4^{+0.5}_{-0.4}$
- Total background includes other Higgs production mechanisms
- 50% sensitivity improvement compared to the previous ATLAS publication with the same luminosity (largely due to

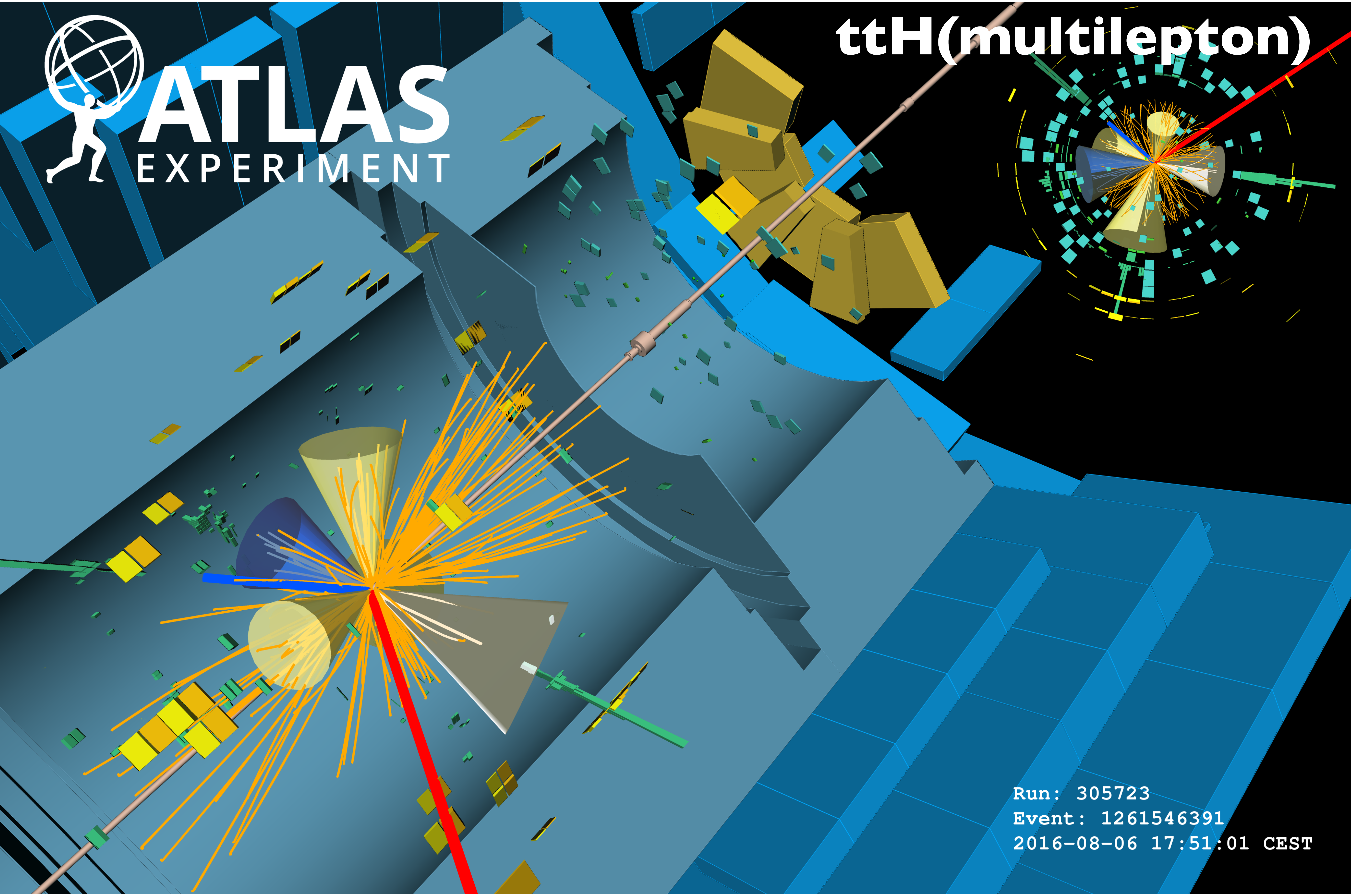


	Observed	Expected
Had	3.8σ	2.7σ
Lep	1.9σ	2.5σ
Comb	4.1σ	3.7σ

Reminder: p-value in the Higgs Discovery



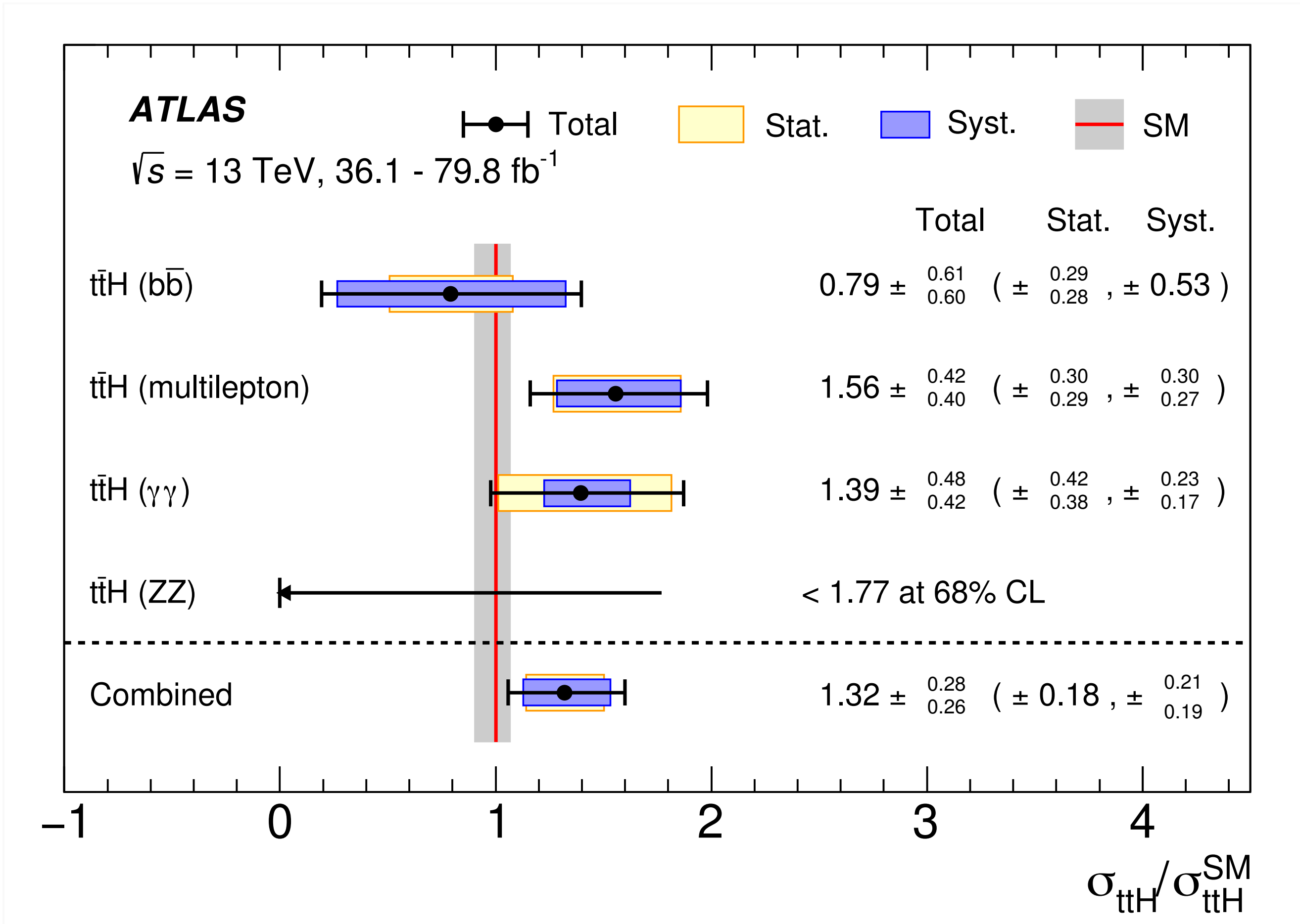
- Local p-value vs m_H
- Dotted line is expected p-value for a SM Higgs with that mass
- Warning: "Look-elsewhere" effect
  - When asking how likely something is, need to take into account how many places you've looked



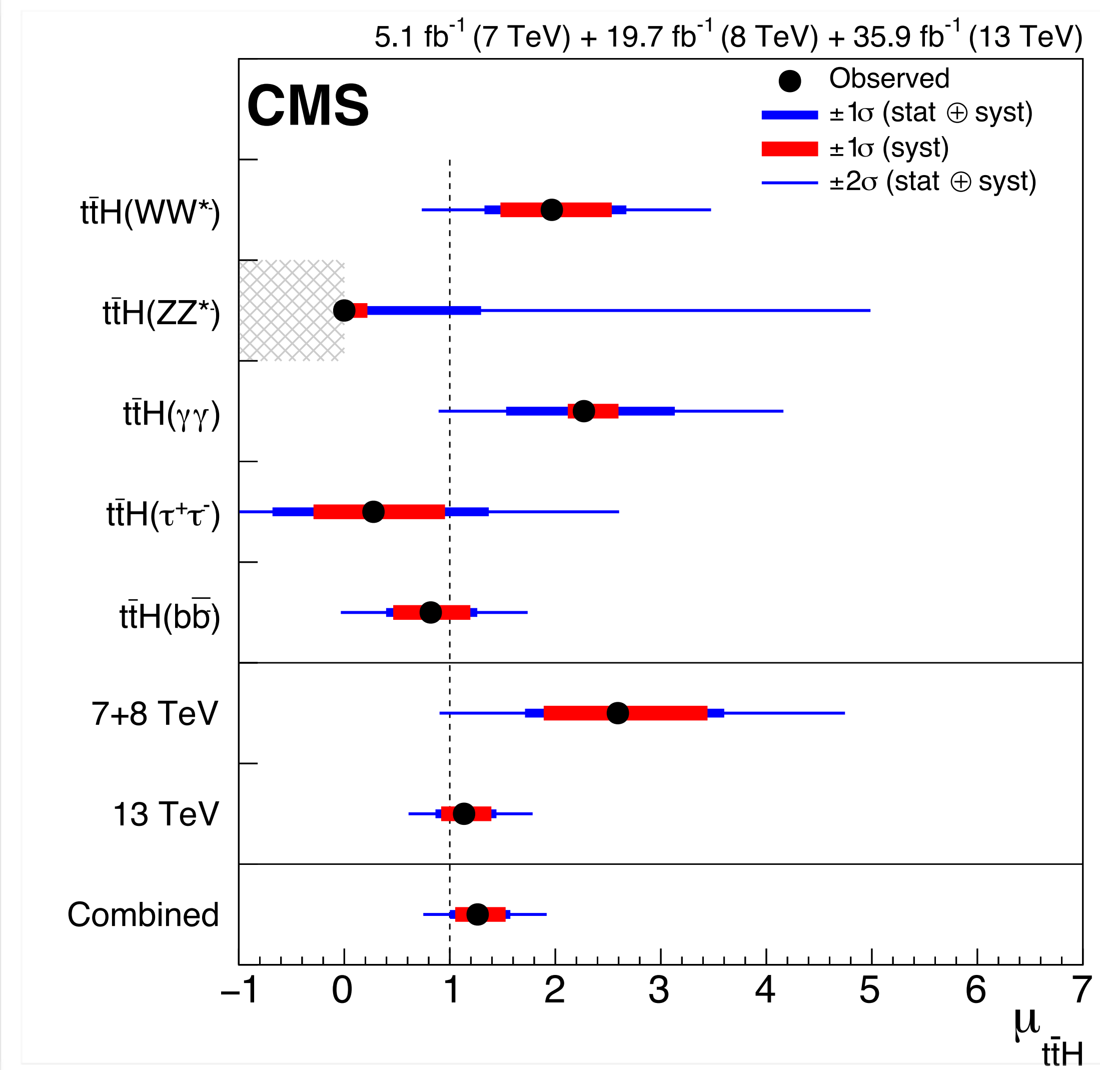
PRD97 (2018) 072003

Observation of ttH Production

PLB 784 (2018) 173
PRL 120 231801



Observed significance: 6.3σ
Expected significance: 5.1σ



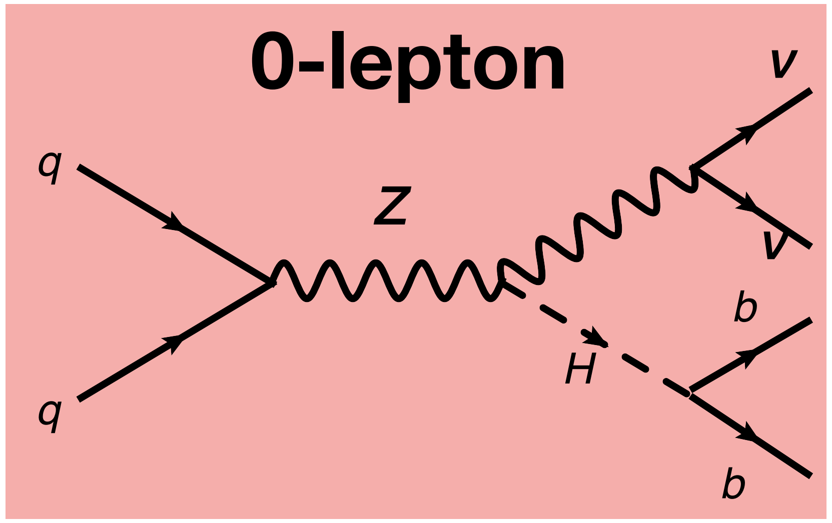
Observed significance: 5.2σ
Expected significance: 4.2σ

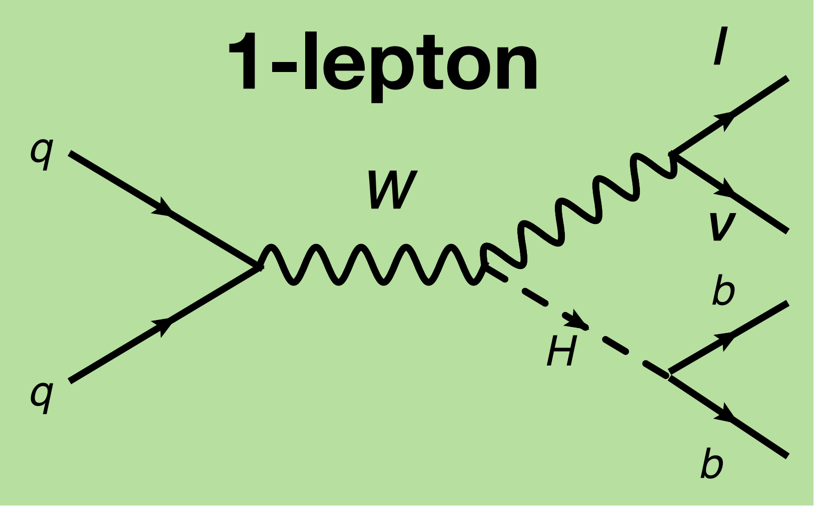
Bottom Quarks

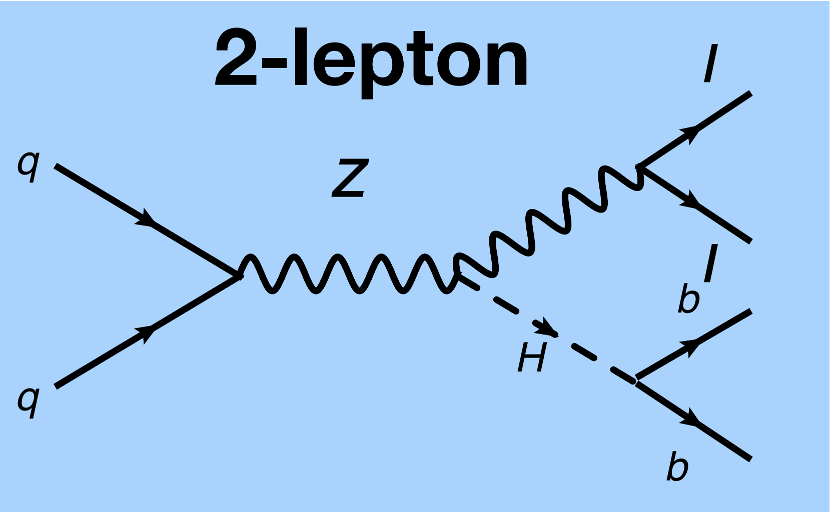
H→bb

JHEP 12 (2017) 024
JHEP 01 (2015) 069
ATLAS-CONF-2018-036

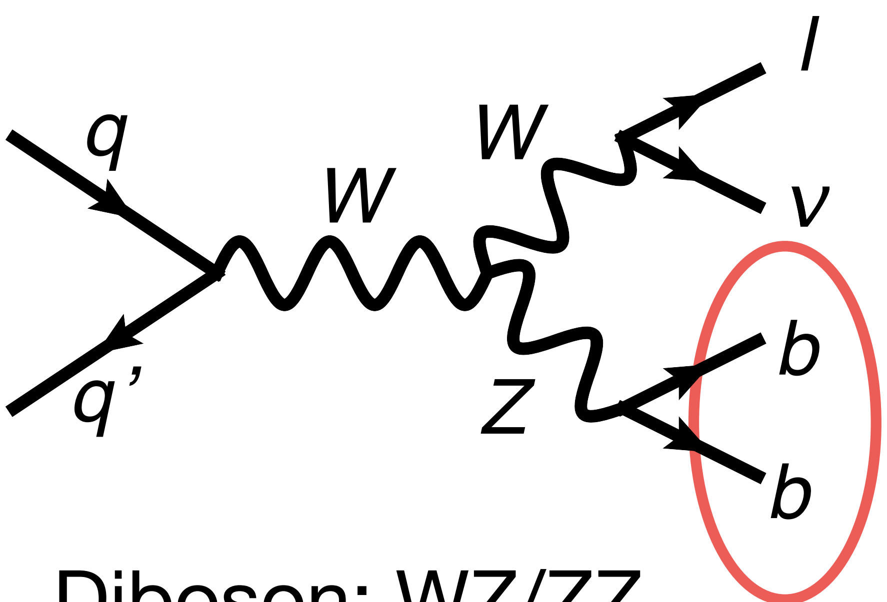
- Largest branching ratio (58%), large backgrounds
- Production modes studied VBF, VH, ttH, (ggF)
  - ggF is swamped by large QCD dijet production
- Most powerful channel is VH (V=W, Z)
- Three channels
  - 0-lepton: Z(νν)H(bb)
  - 1-lepton: W(lν)H(b)
  - 2-lepton: Z(ll)H(bb)
- Events contain two b-jets and 0-2 leptons



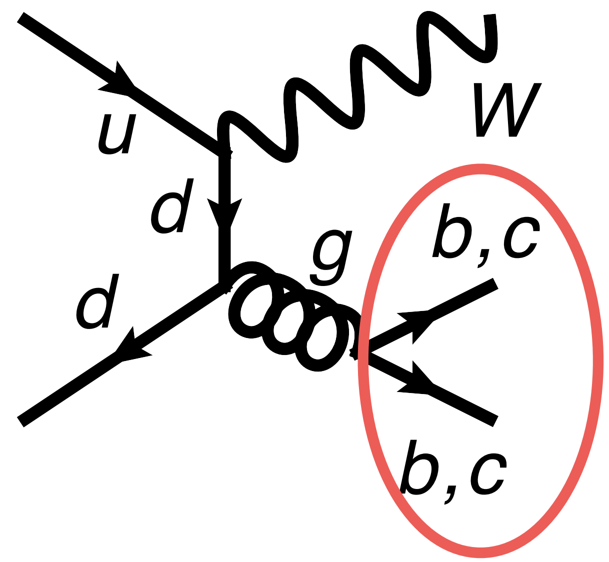




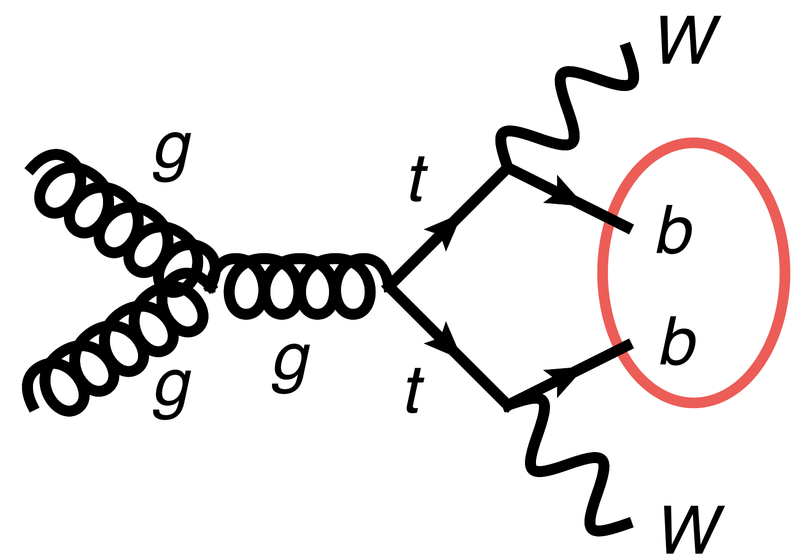
Backgrounds



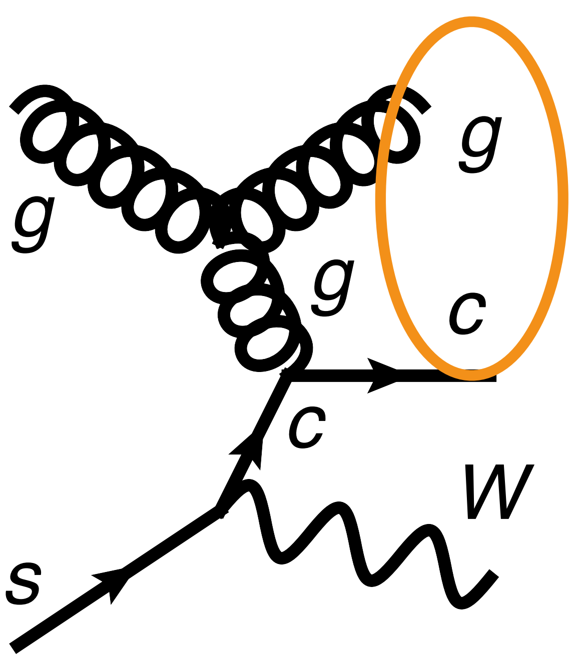
Diboson: WZ/ZZ



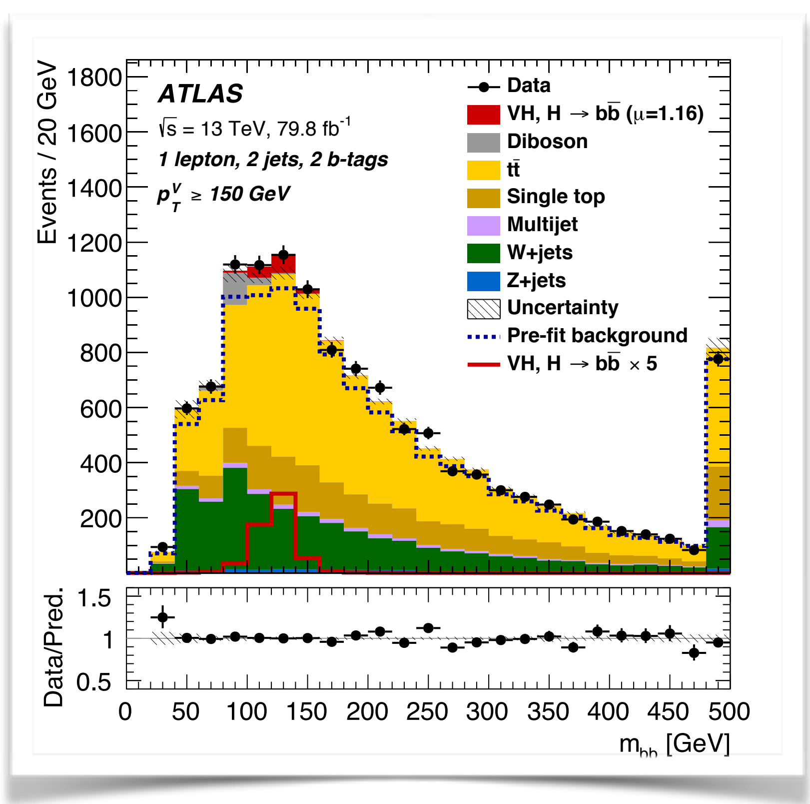
V+bb
V+cc
gluon splitting

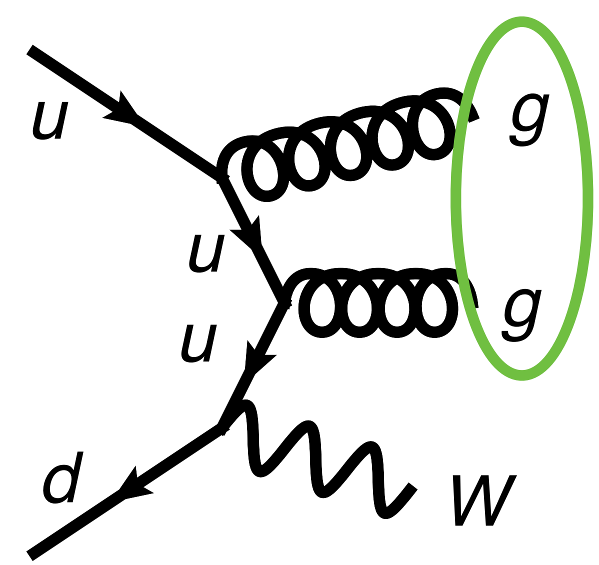


ttbar



W+c

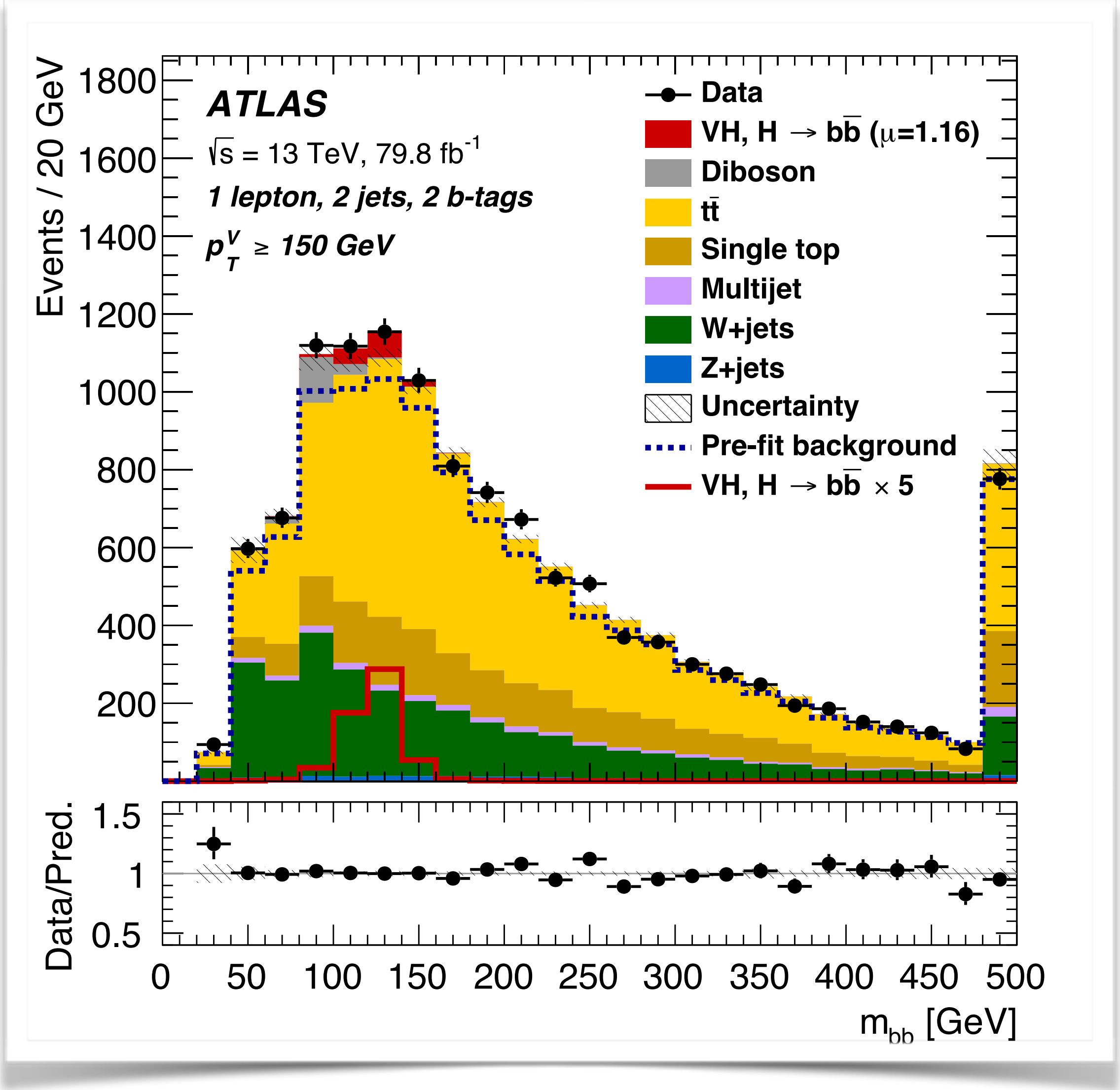


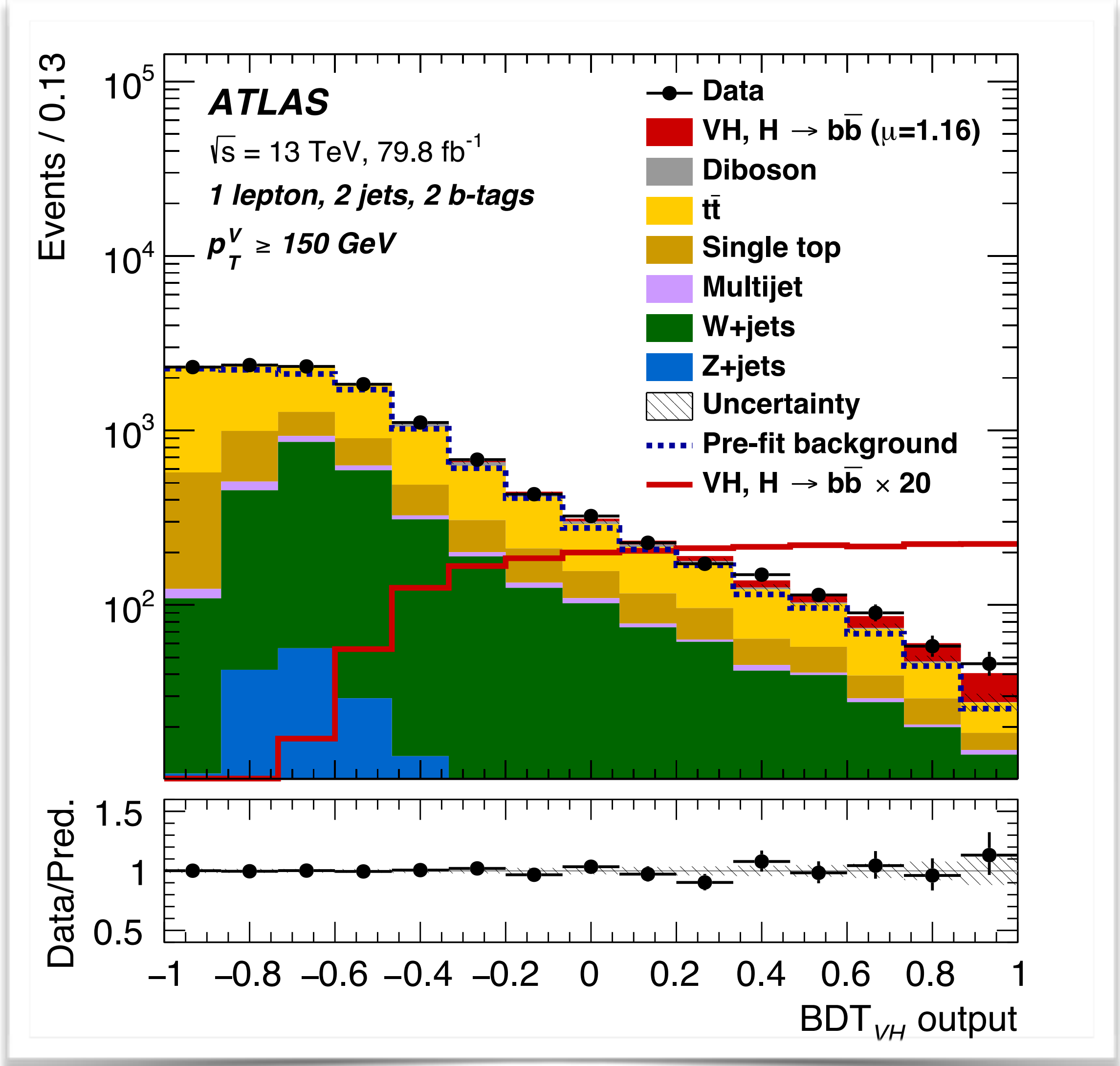


W+light

Signal Extraction

- Lepton or MET triggers
- Two b-jets
- Boosted decision tree (BDT) to extract Higgs from large V+jets and tt backgrounds
- Complex profile likelihood fit to extract signal and constrain backgrounds





Boosted Decision Trees

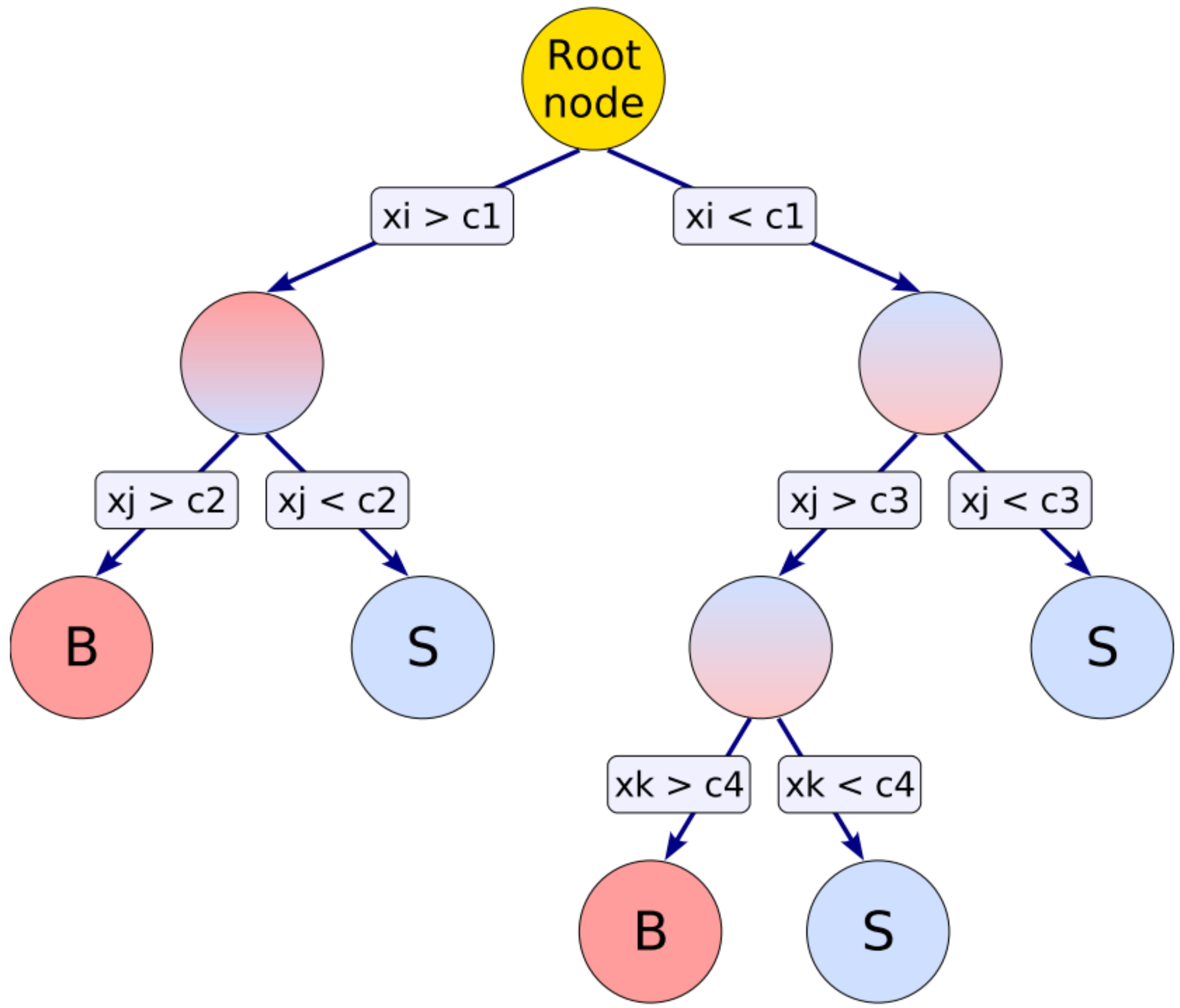


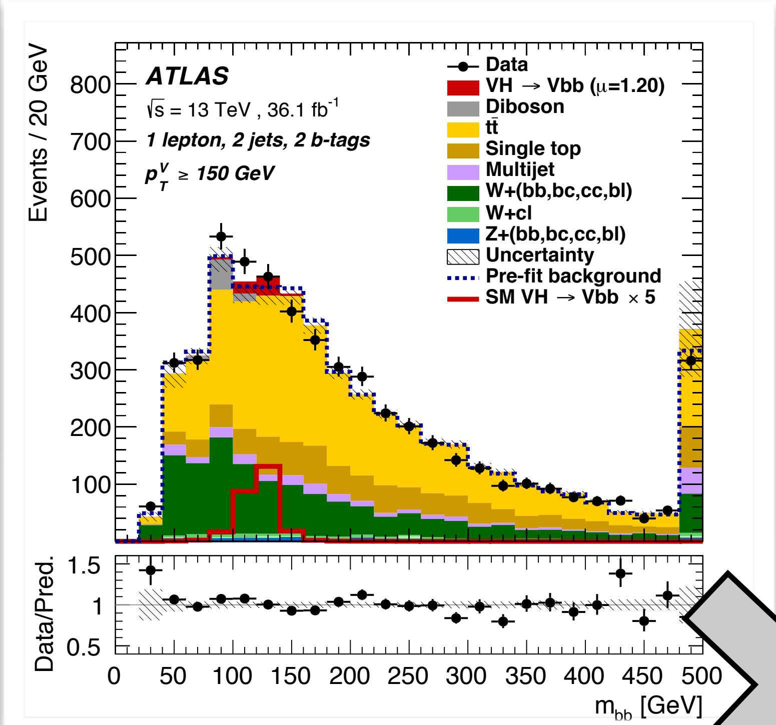
Figure 18: Schematic view of a decision tree. Starting from the root node, a sequence of binary splits using the discriminating variables x_i is applied to the data. Each split uses the variable that at this node gives the best separation between signal and background when being cut on. The same variable may thus be used at several nodes, while others might not be used at all. The leaf nodes at the bottom end of the tree are labeled "S" for signal and "B" for background depending on the majority of events that end up in the respective nodes. For regression trees, the node splitting is performed on the variable that gives the maximum decrease in the average squared error when attributing a constant value of the target variable as output of the node, given by the average of the training events in the corresponding (leaf) node (see Sec. 8.12.3).

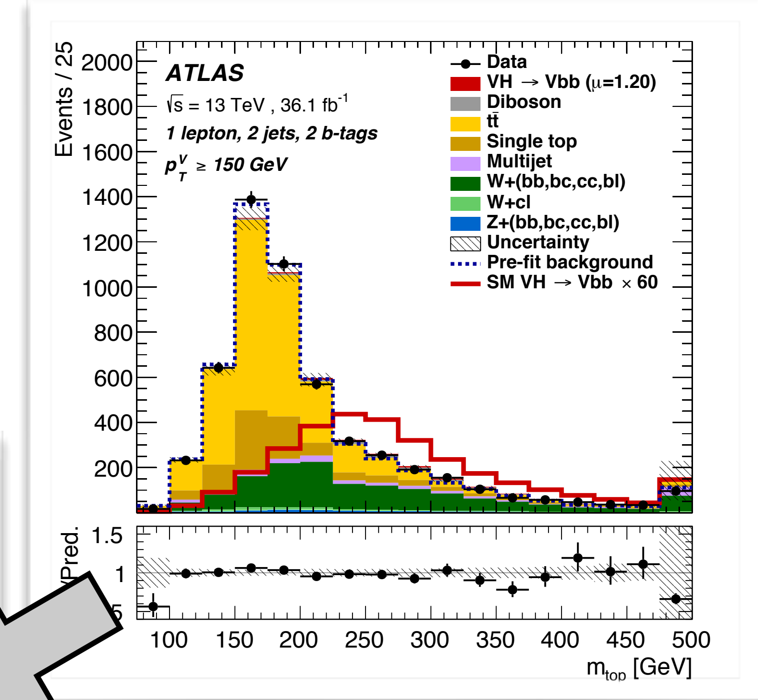
http://tmva.sourceforge.net/docu/TMVAUsersGuide.pdf

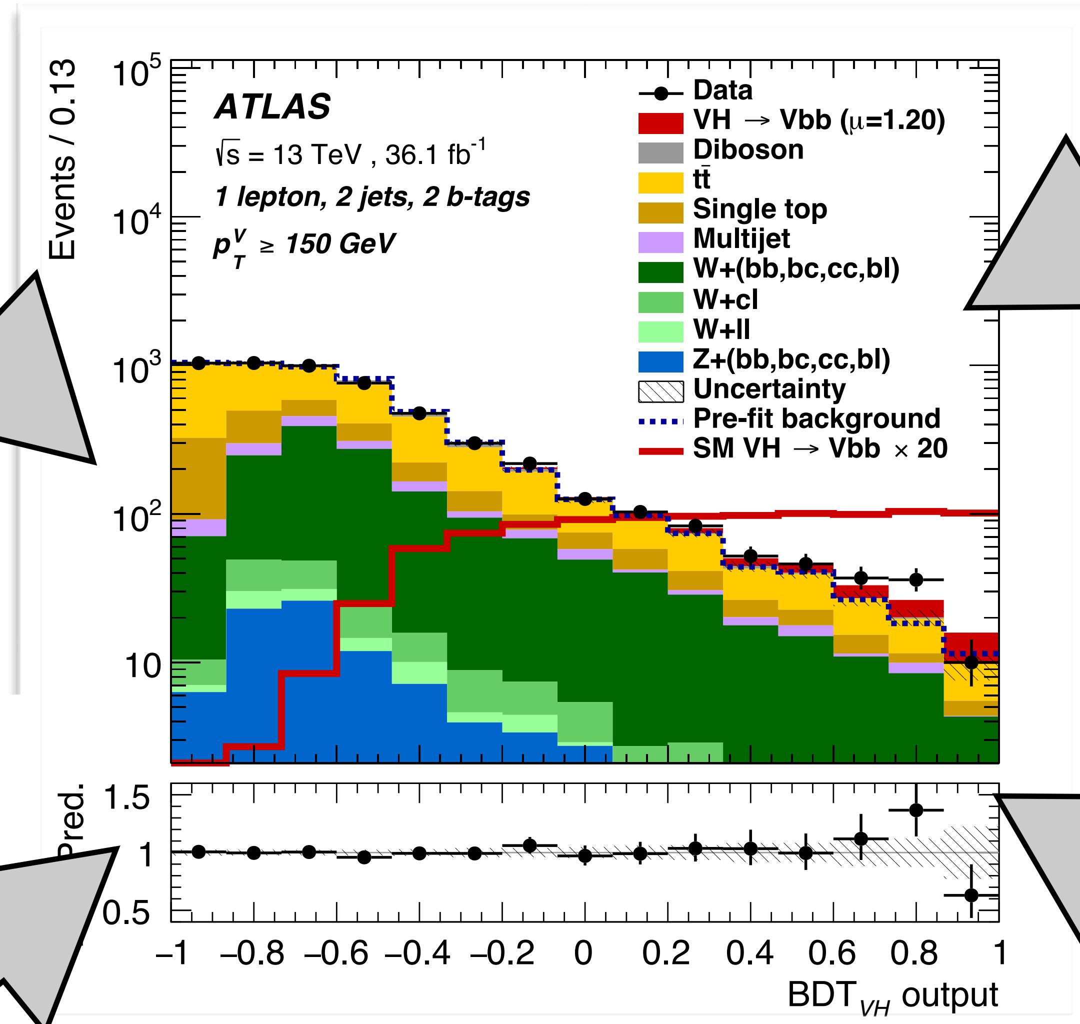
BDT construction

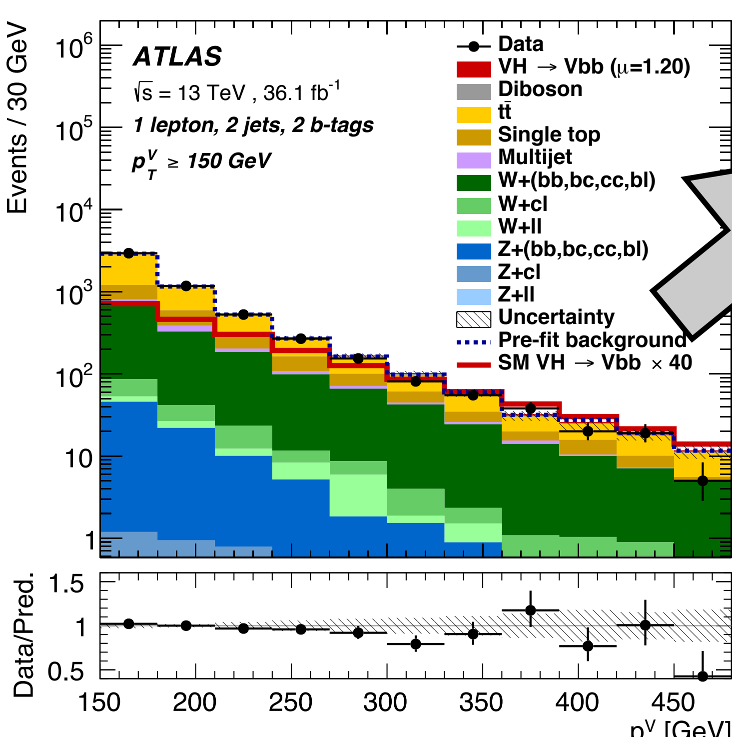
HIGG-2016-29

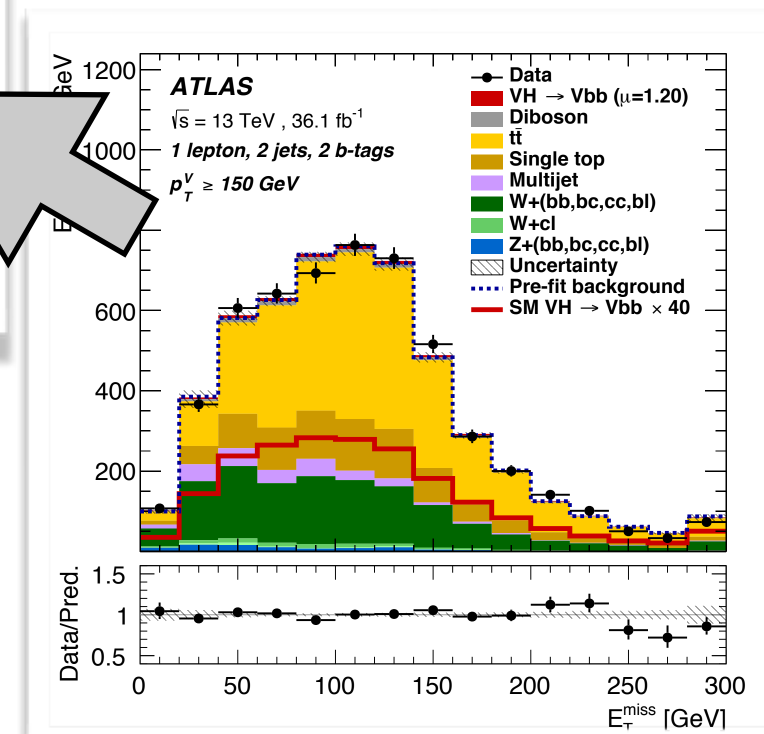
(previous analysis version)







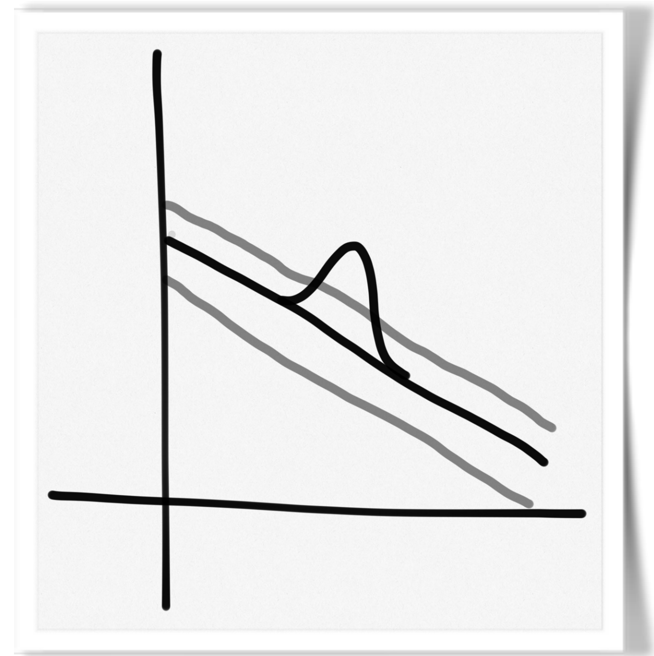




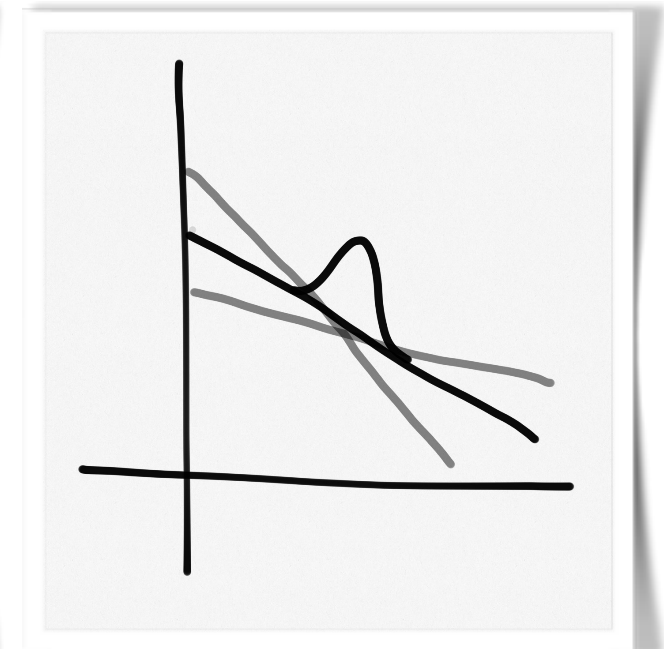
Systematic uncertainties

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.014
Leptons		0.009
b-tagging	b-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

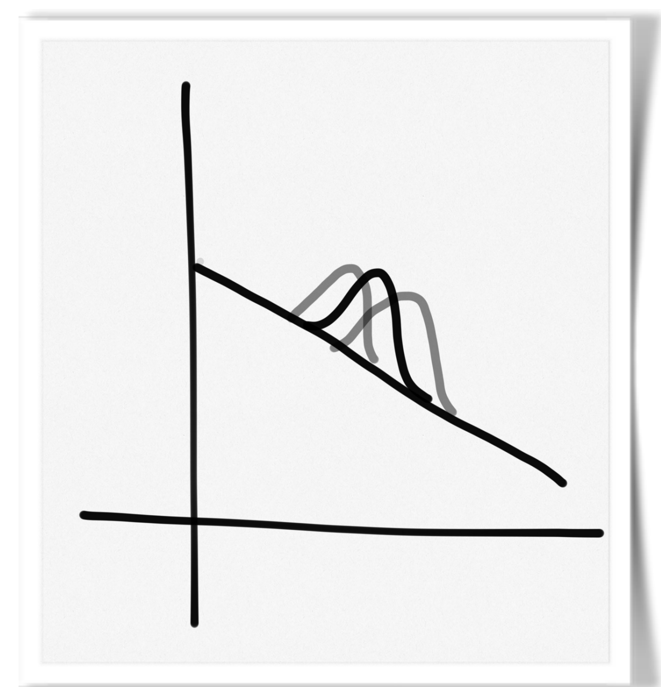
background normalisation



background shape

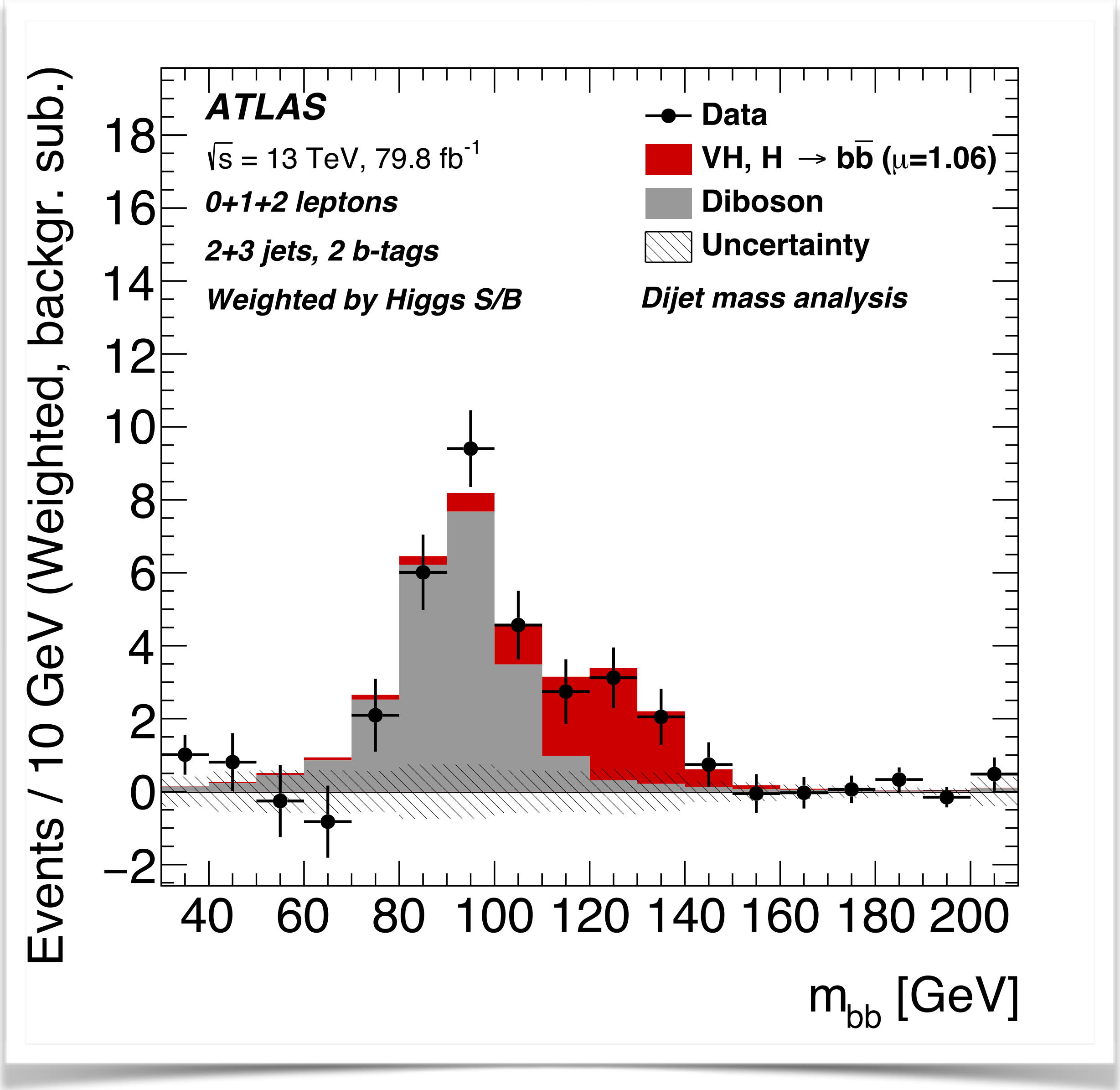


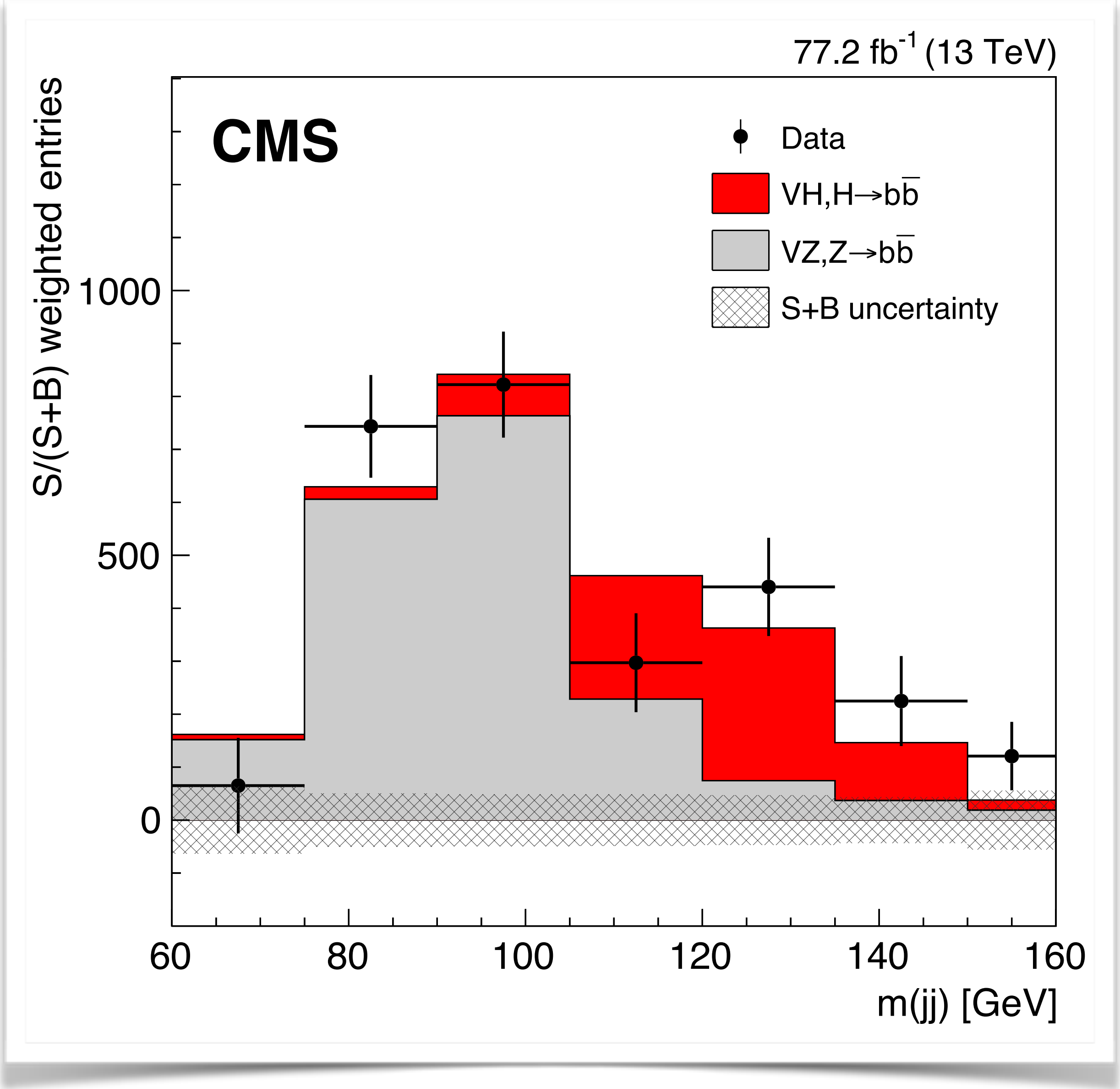
signal scale



Seeing the H→bb

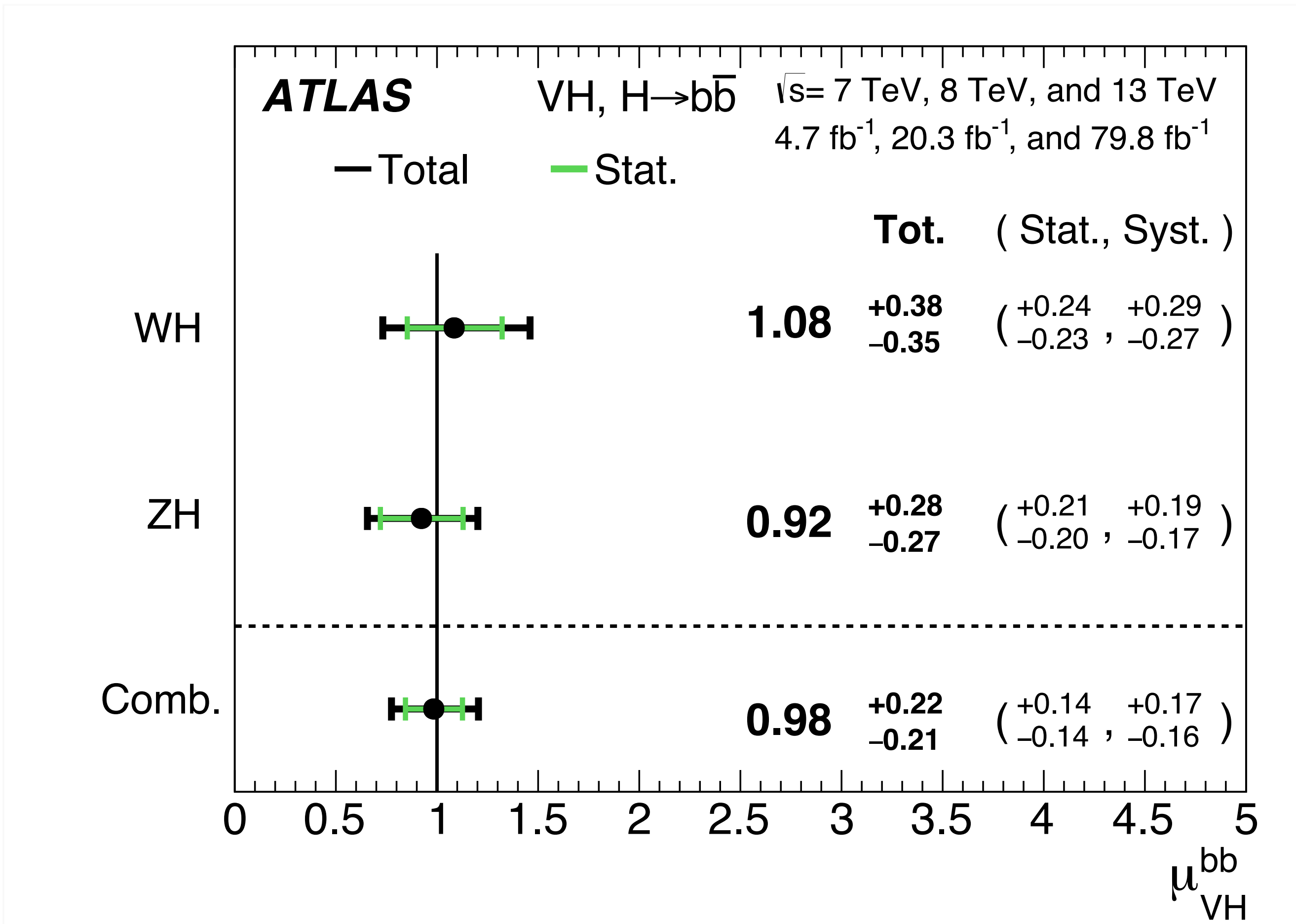
HIGG-2018-04



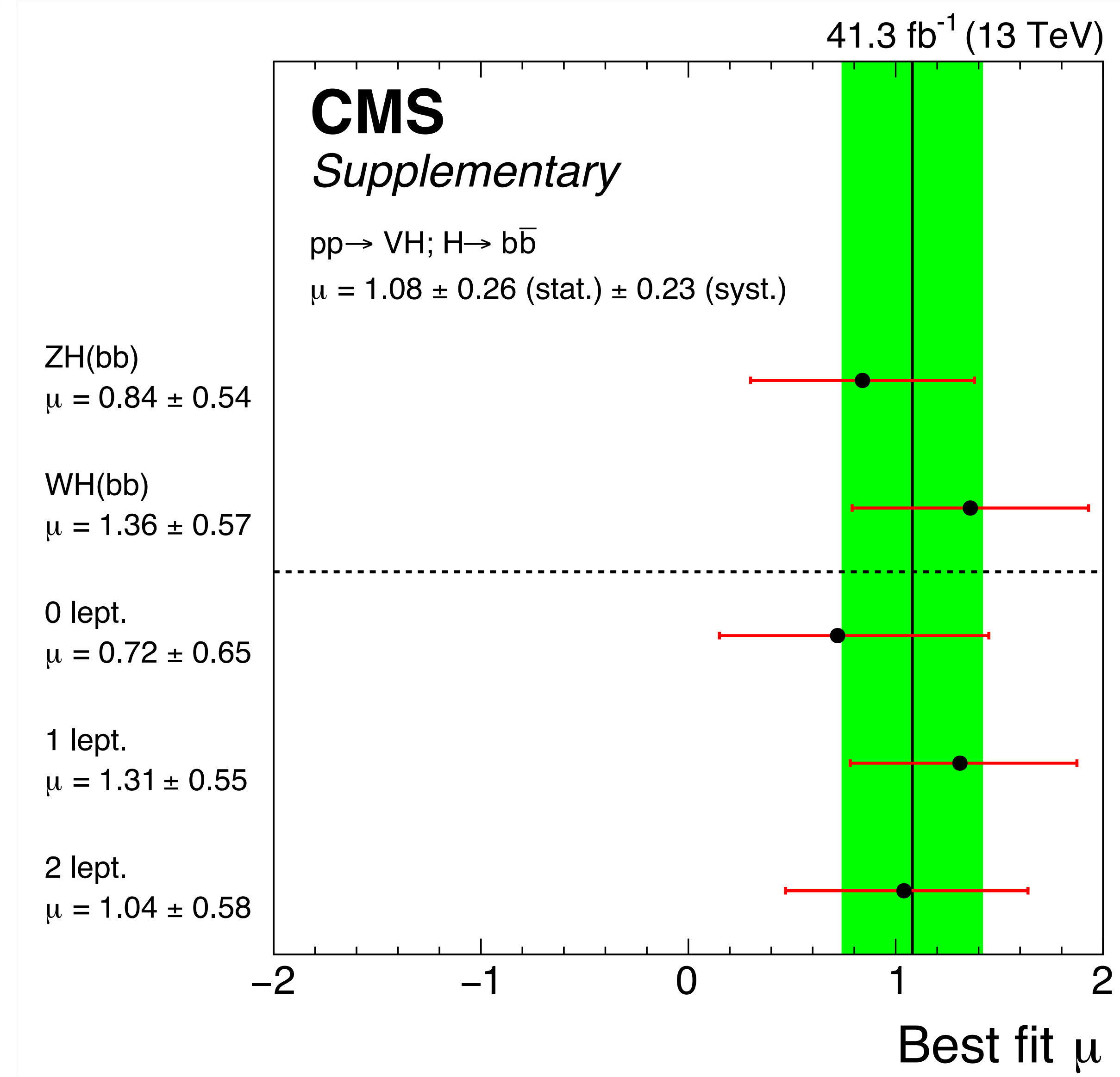


VH→bb Results

HIGG-2016-29
HIG-16-044



4.9σ (4.3σ exp)[3]

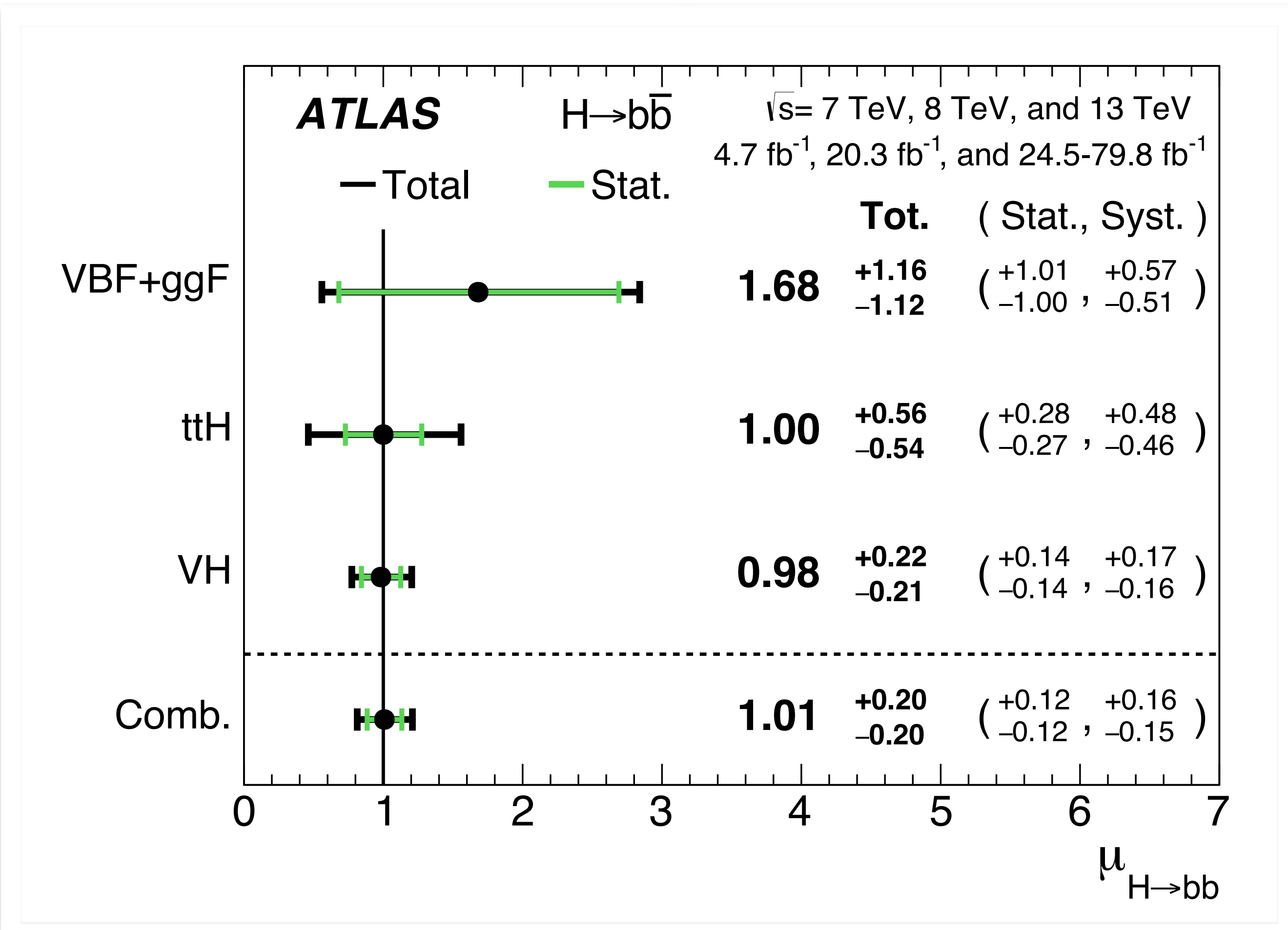


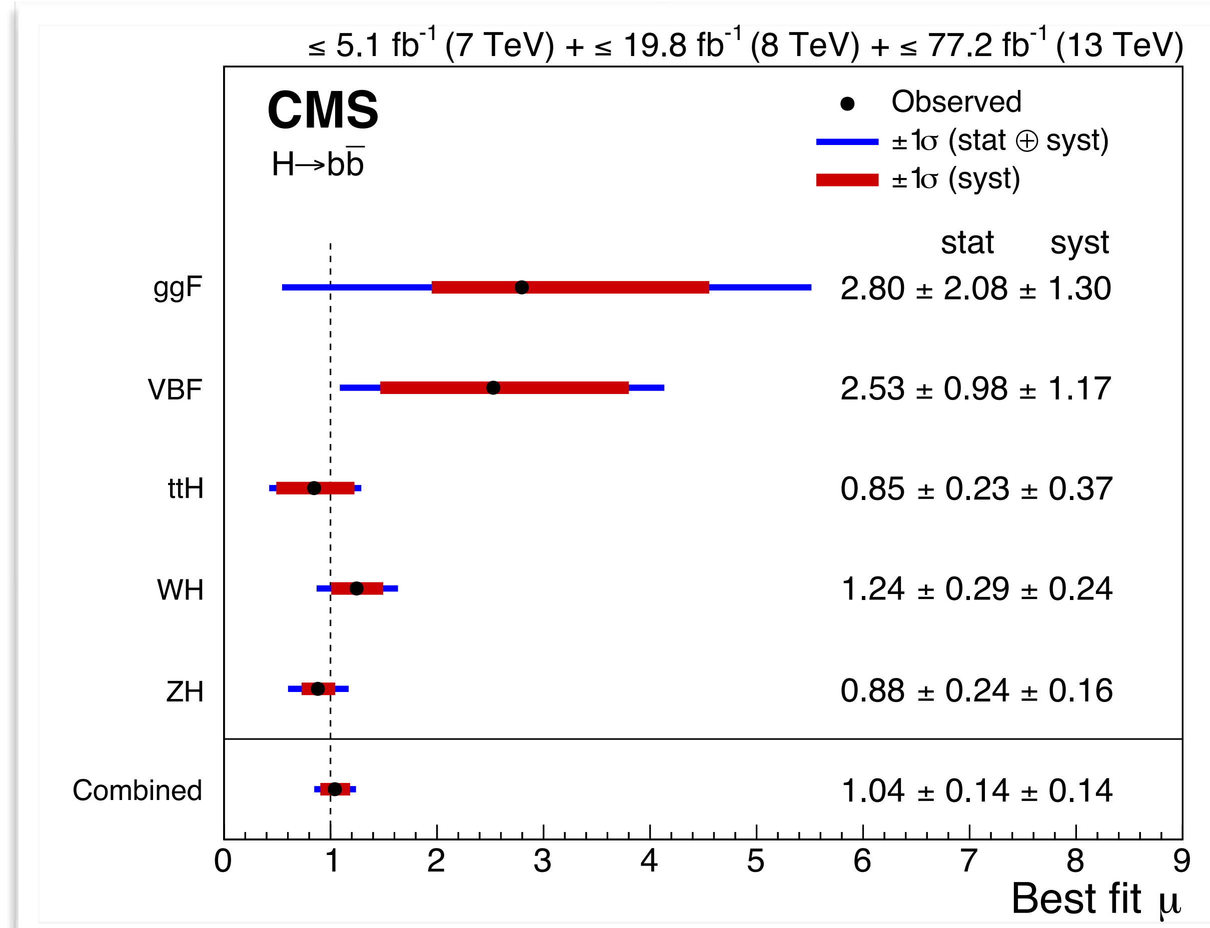
4.8σ (4.9σ exp)[1+2]

Observation of H→bb

HIGG-2018-04

HIG-18-016



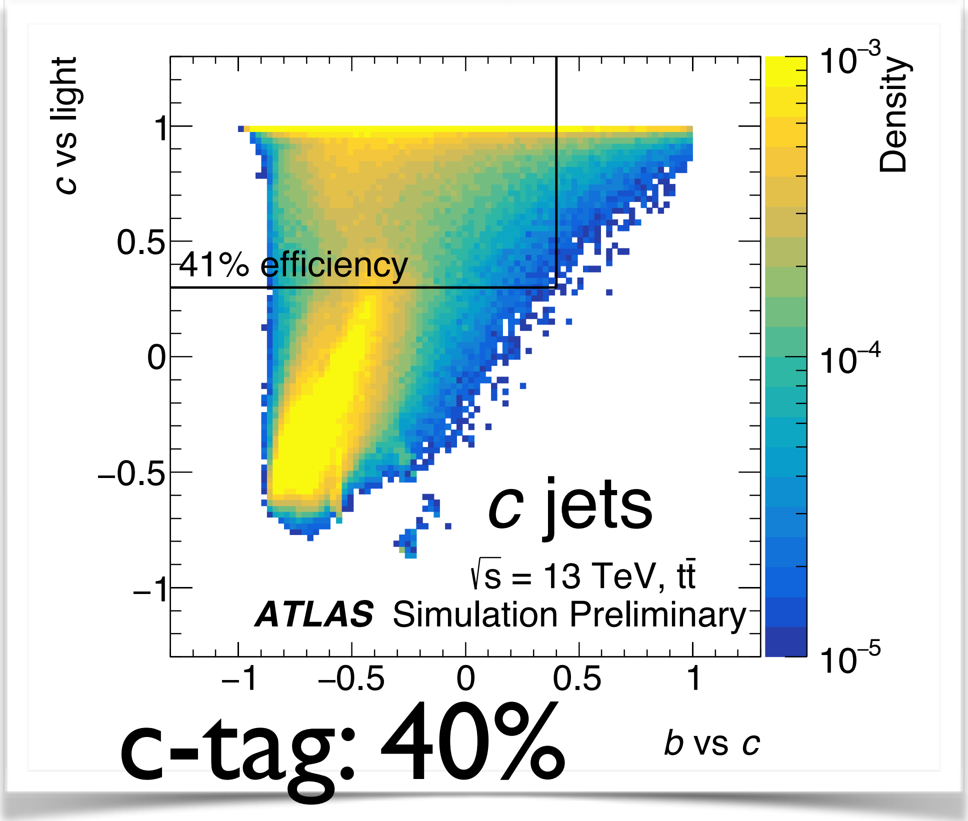


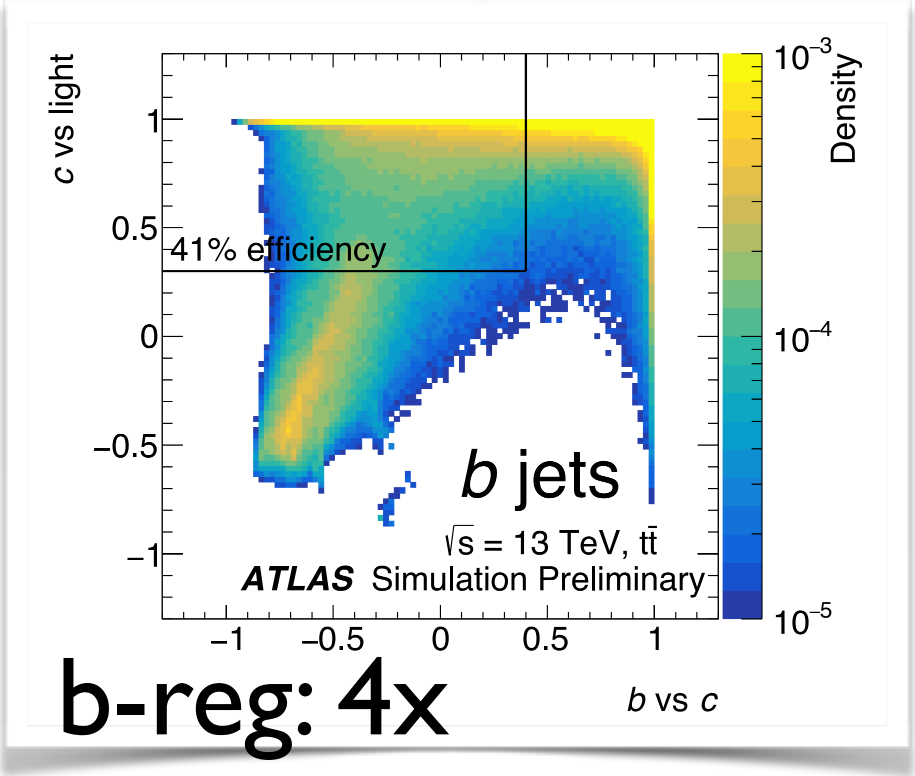
Charm Quarks

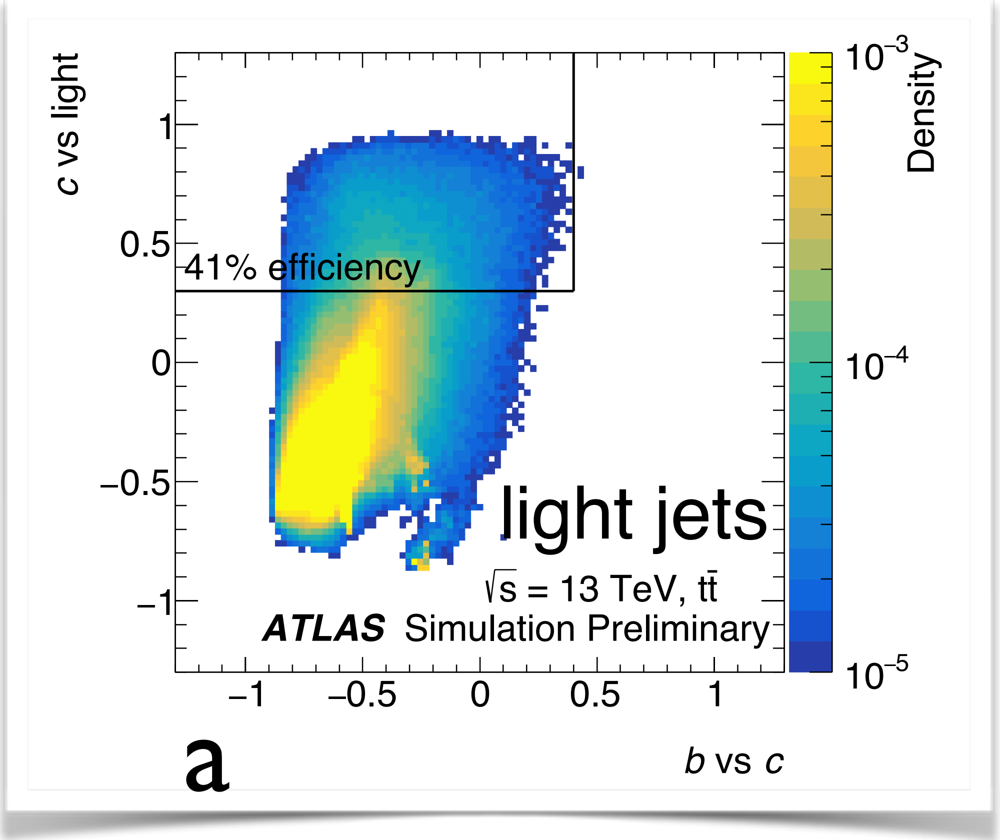
Higgs coupling to charm quarks

PRL 120 (2018) 211802

- We've observed the coupling of the Higgs to third generation quarks only
  - Rich flavour structure
- Can we probe the second generation quark coupling using charm?
- Crucial element
  - Efficient charm tagging
- Problem charm looks like both bottom and



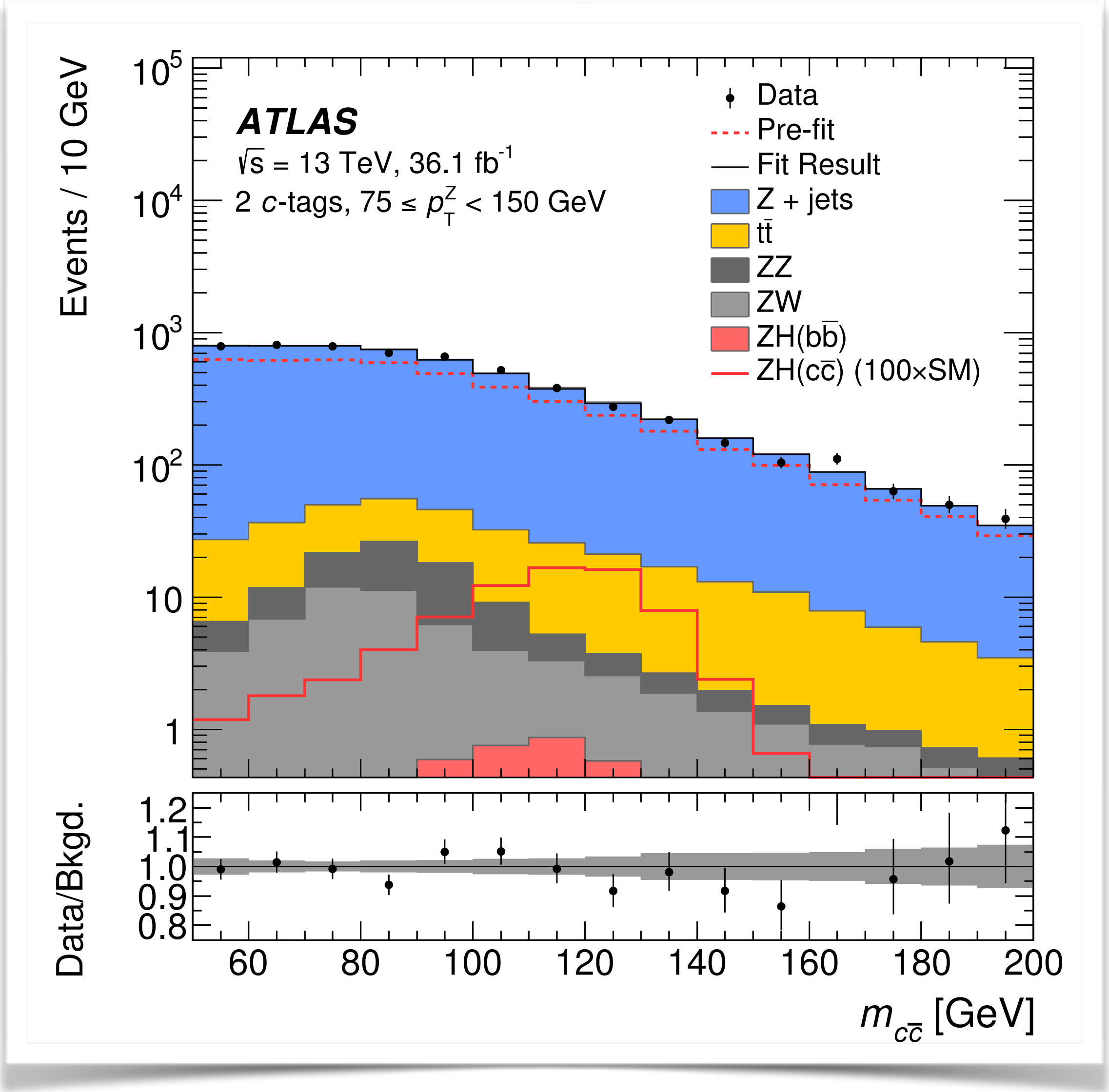


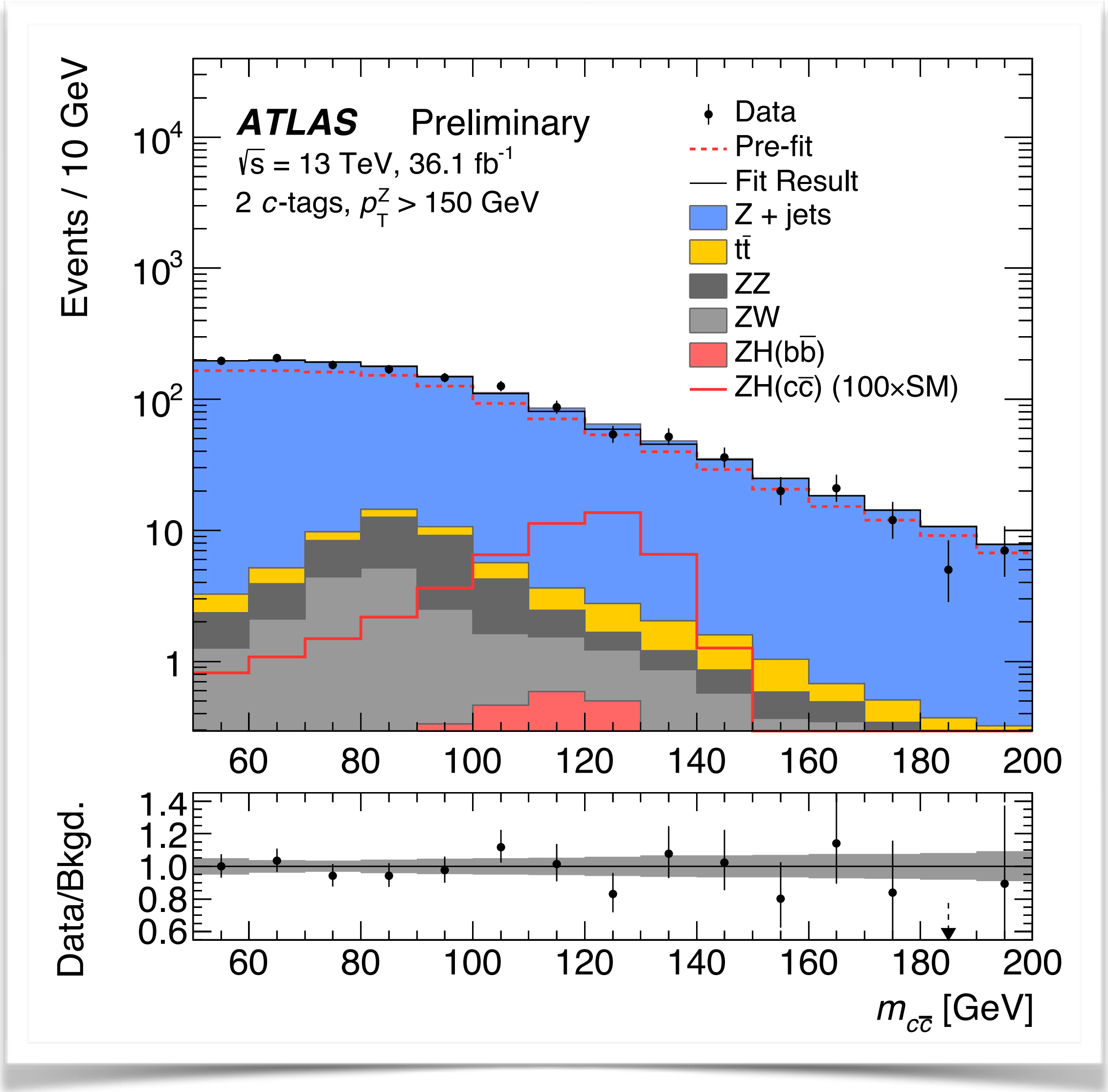


Higgs coupling to charm quarks

PRL 120 (2018) 211802

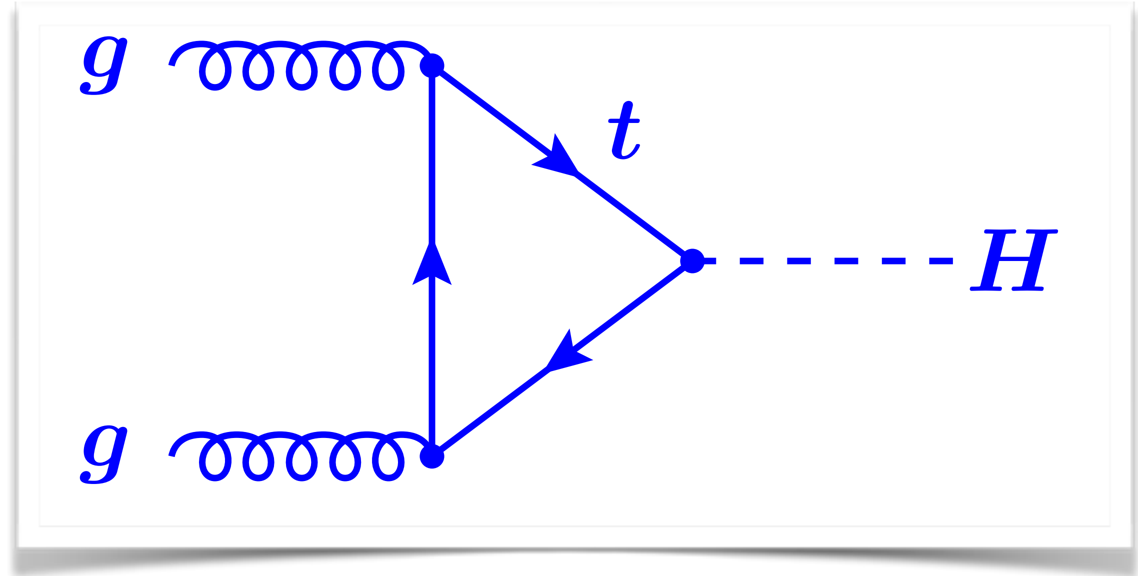
- Analogous but simplified strategy to VH(bb)
  - Only used 2-lepton; fit dijet invariant mass instead of BDT
- Obtain limit of ~100x SM with 36 fb^{-1}
  - Strongest direct limit on charm
  - Project to HL-LHC: ~6 x SM: need improved analysis

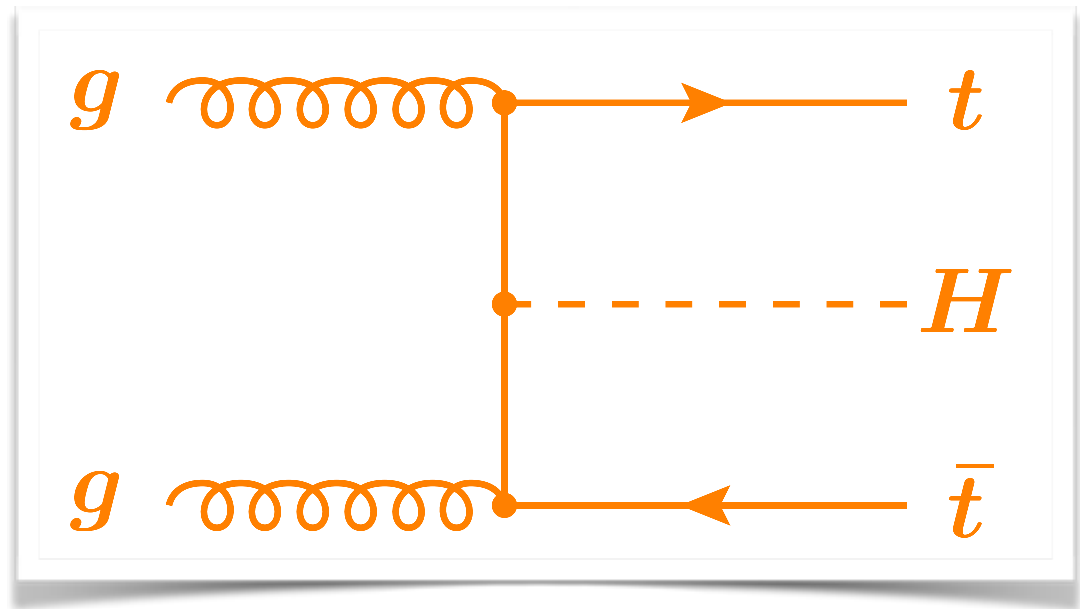


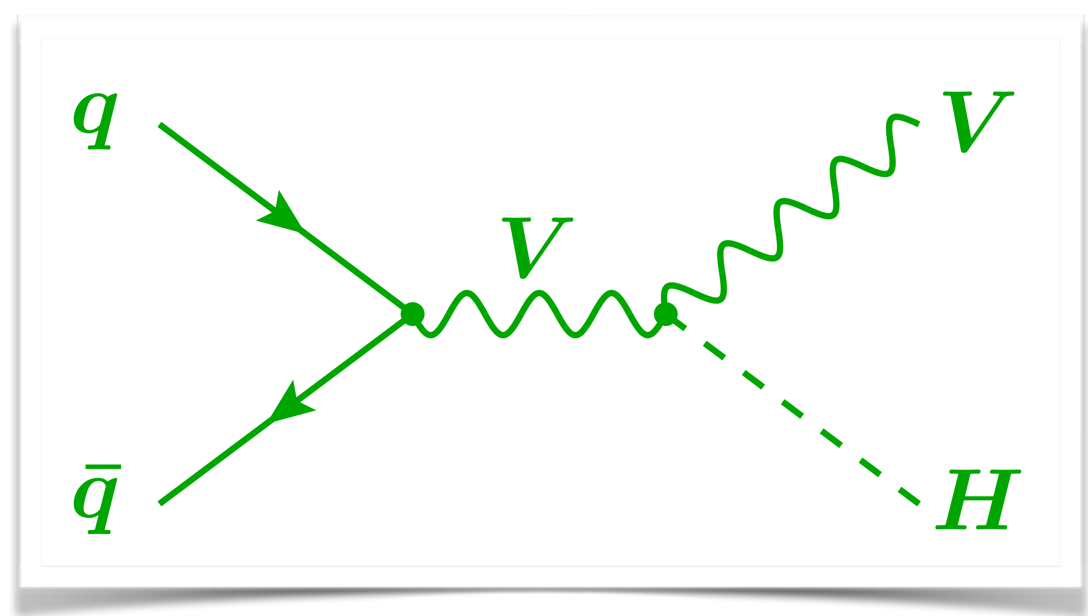


Summary Higgs-quark interactions

- **Top quark**
  - ggF: "top loop"
  - Higgs produced in association with a pair of top quarks
- **Bottom quark**
  - Higgs decay to bottom quarks
  - Large backgrounds: best production channel is when its produced in association with a vector boson
- **Charm quark**
  - Analog of bottom (change the decay)
  - Indirect: use J/ψγ
- Potentially some ideas for strange (not covered here)







Conclusion

- The discovery of the Higgs boson has opened up a new field of studying the properties of the Higgs and its interaction with particles
- This past year has been an exciting year as we've observed the Higgs interacting with top and bottom quarks
- We've also done preliminary studies into probing its interaction with charm
- So far, the Higgs is consistent with predictions from the Standard Model, but there's more to be probed and more data coming from the LHC