Standard Model of Particle Physics

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Higgs Properties

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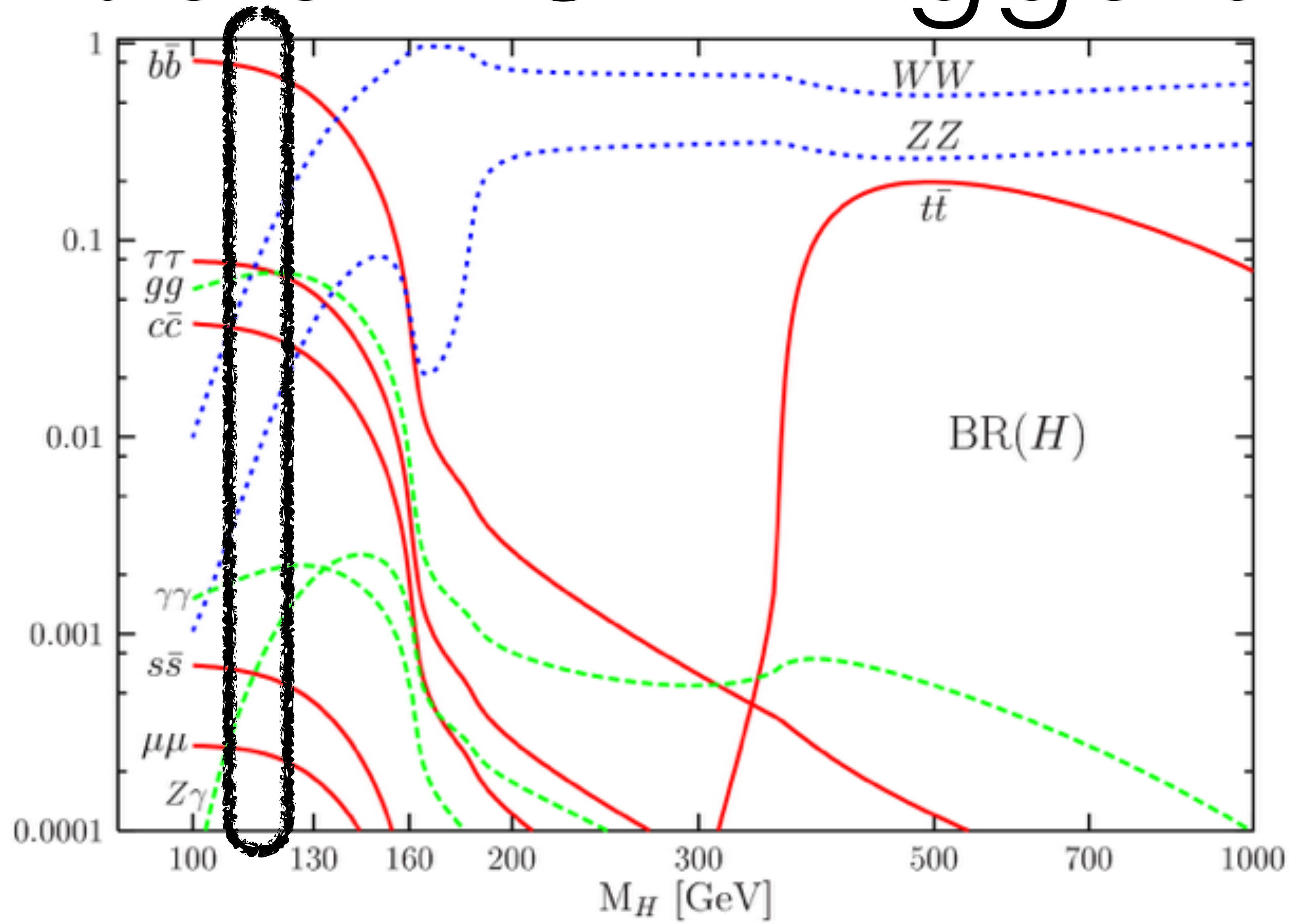
6. Juli 2016

Big thank you to Prof. S. Lai!
(this is inspired by his lecture)

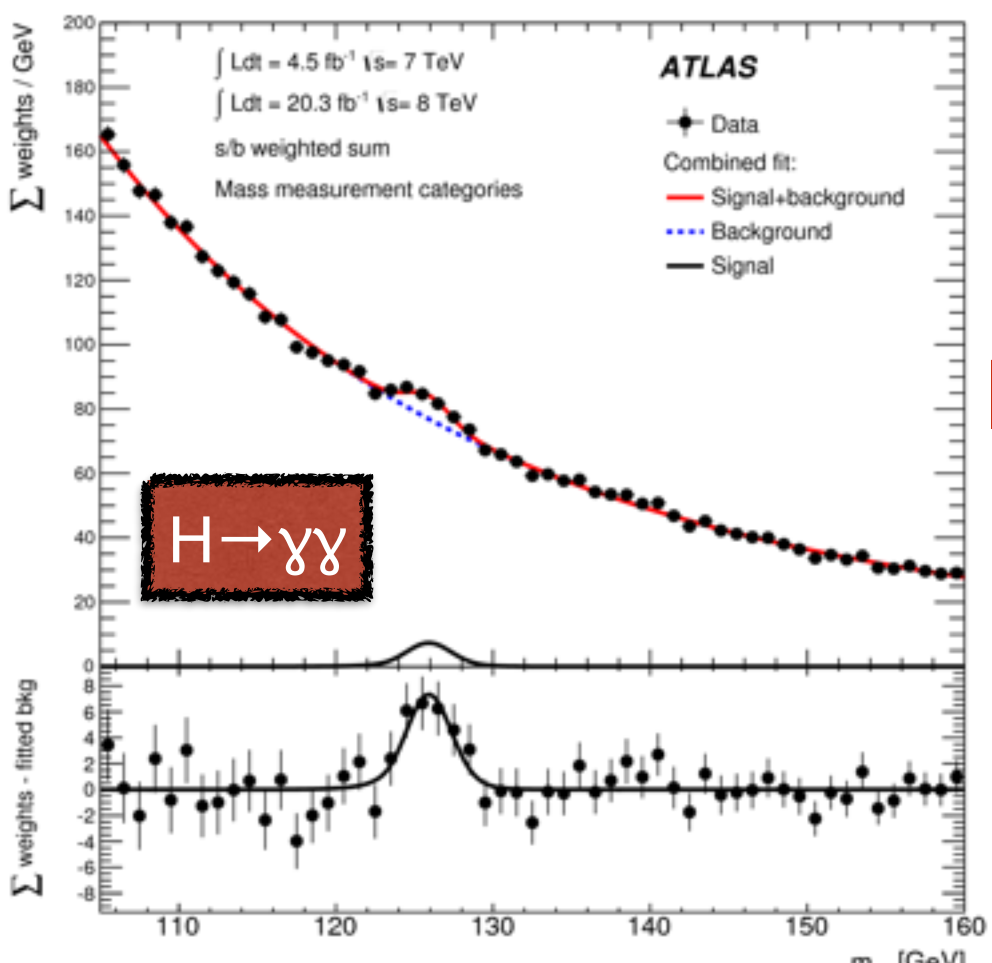
New particle = SM Higgs boson?



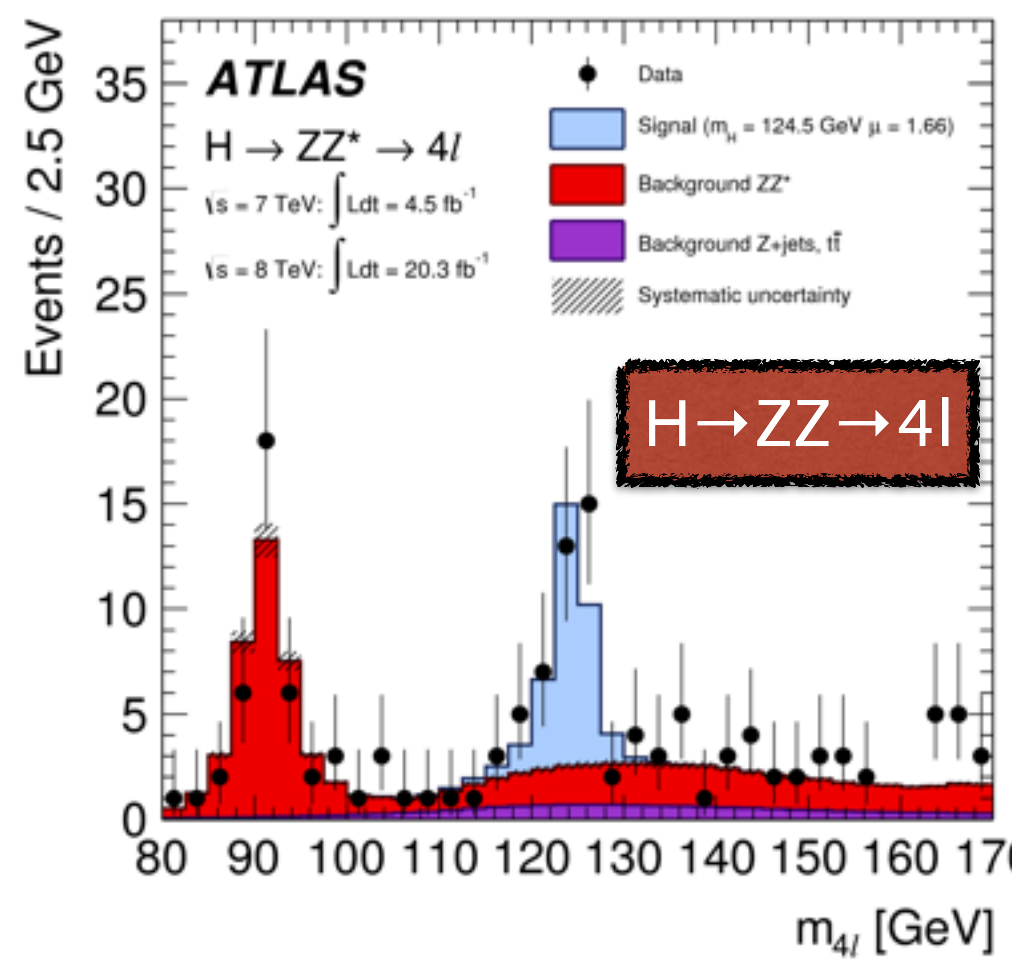
- Interesting mass range, but: What is the mass exactly?
- Observed H → bosons, what about fermions?
- Spin & couplings?
- Production modes?

Mass Distributions

- High mass resolution: only **H→ɣɣ** and **H→ZZ→4l** matter
- Low resolution:
  - **H→$\tau\tau$** and **H→WW→lνlν** suffer from final state neutrinos
  - **H→bb** measured in jets (less precise than photons and leptons)



high mass resolution channels



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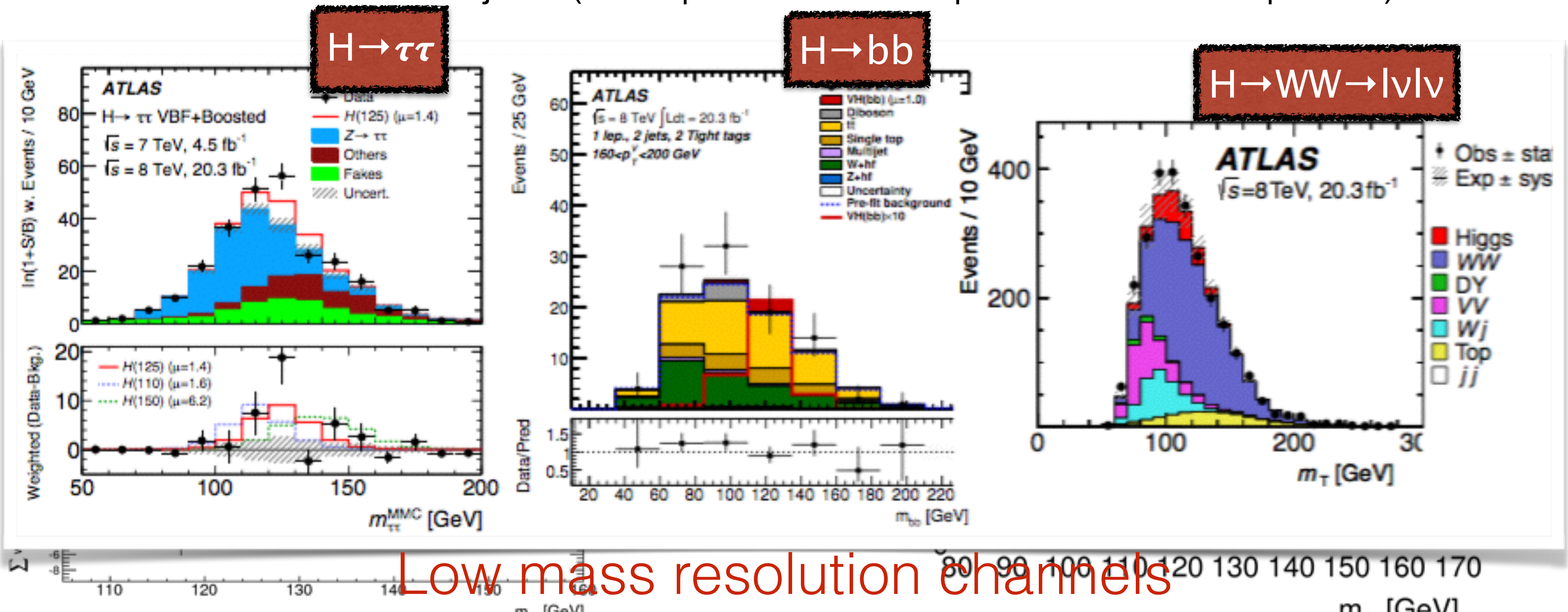
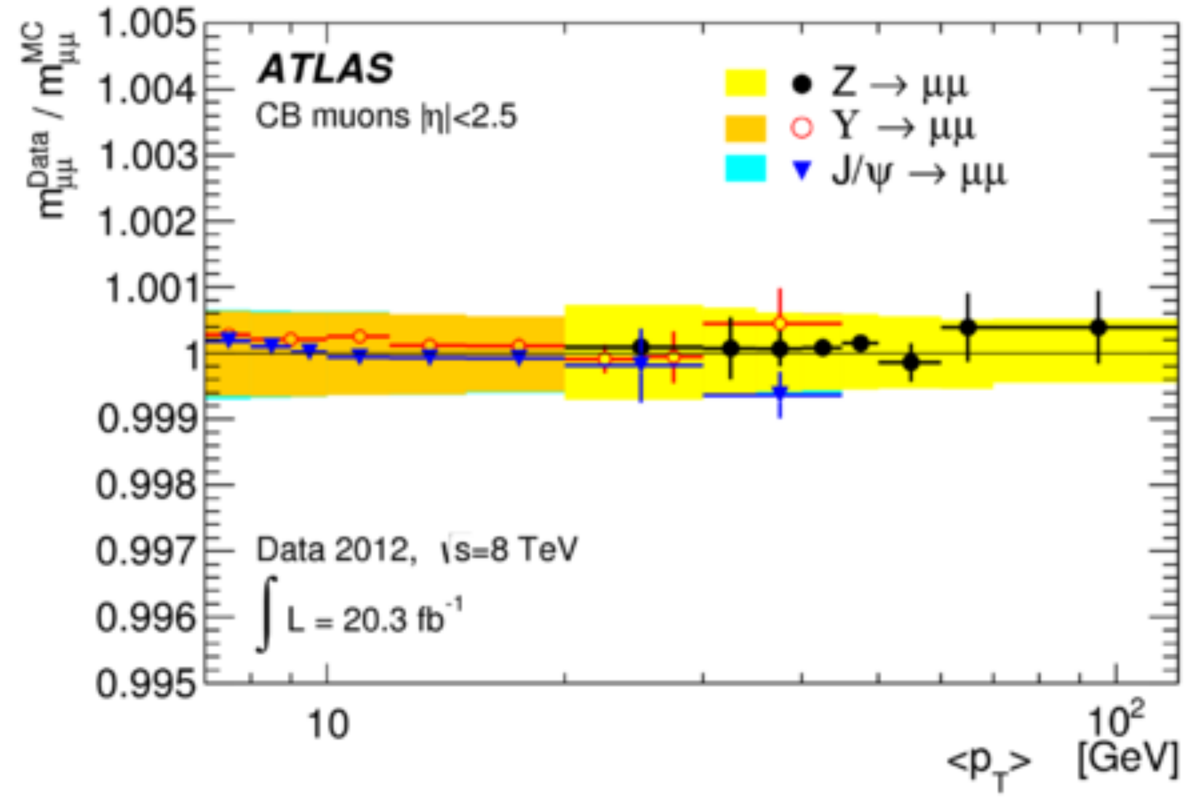


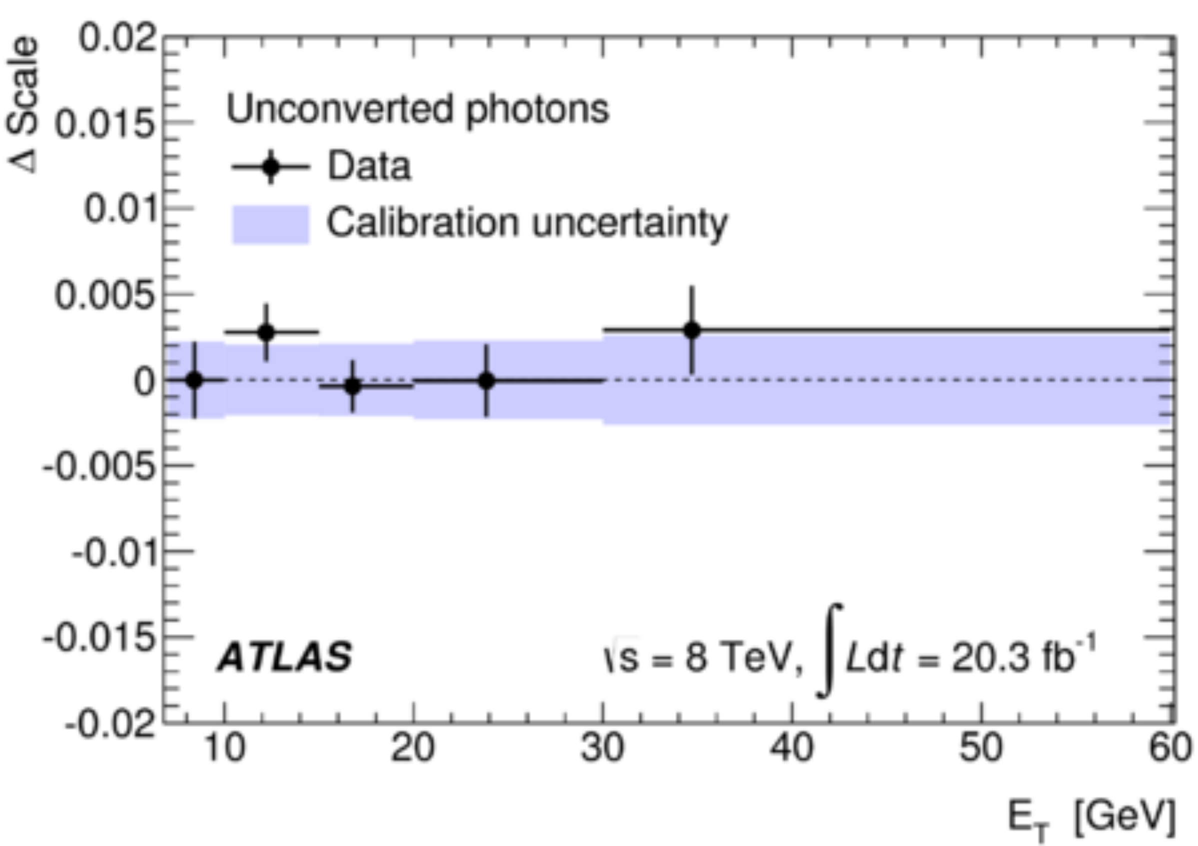
Low mass resolution channels

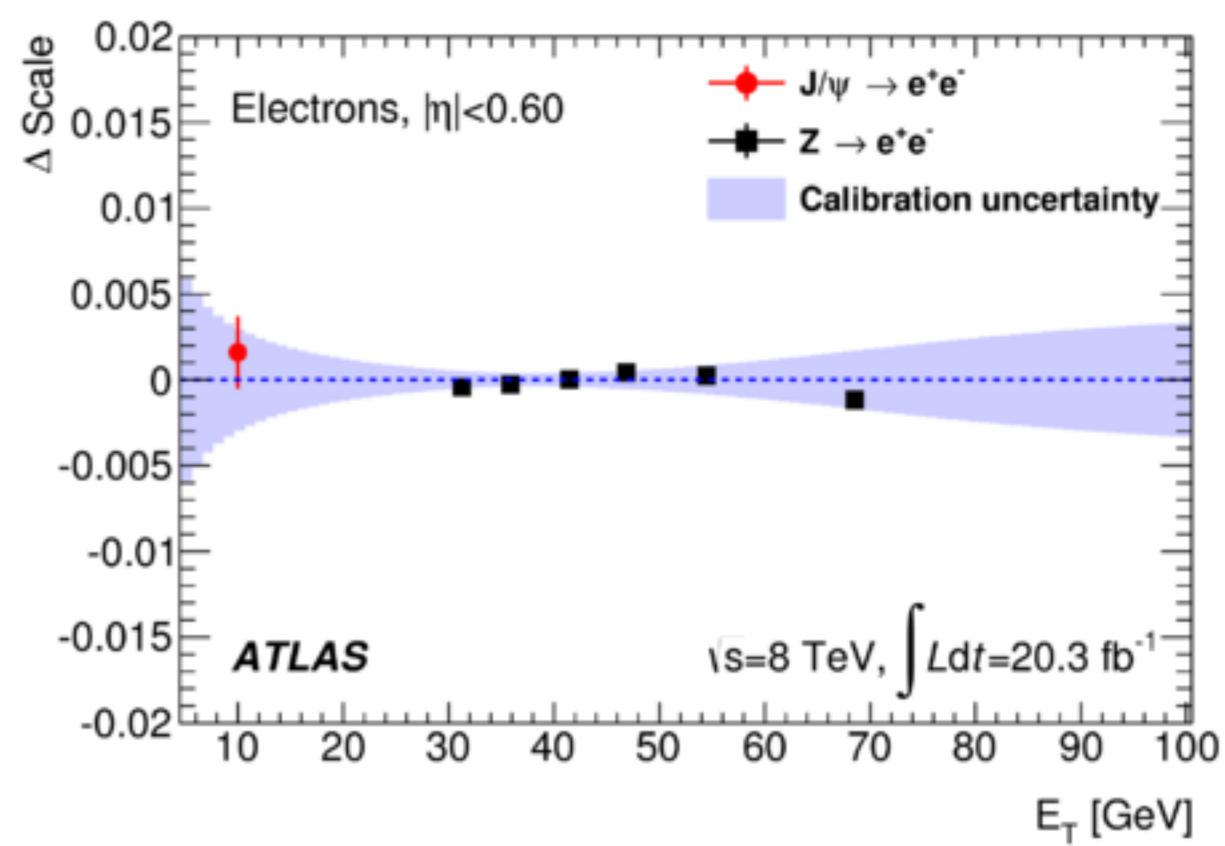
Measuring the mass: Calibration of inputs

Good understanding the energy/momentum scale for photons, electrons and muons is critical!

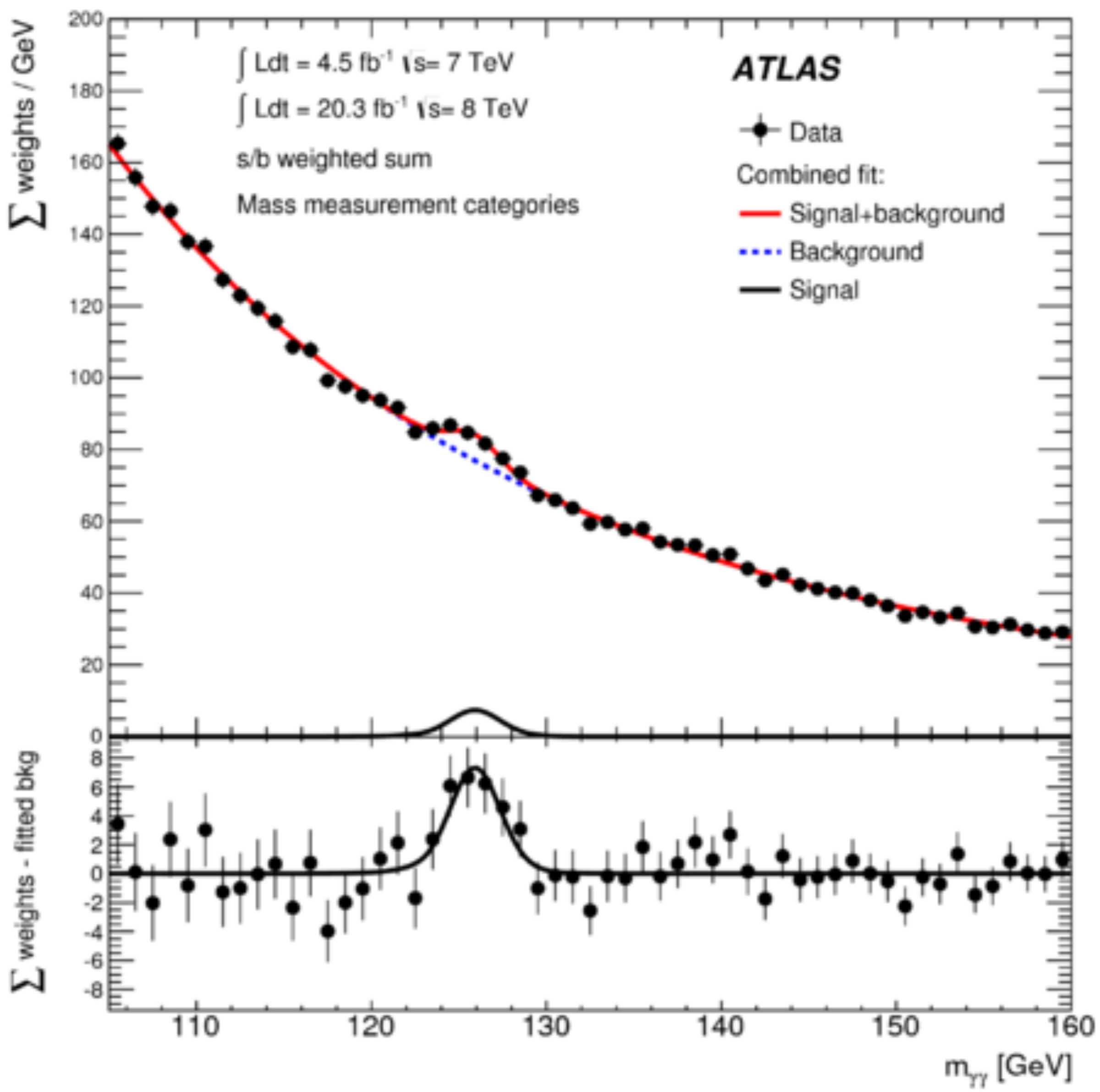
- use Z→μμ/ee, J/Ψ→μμ/ee for μ and e calibration
- also useable for photons + Z→llɣ
- in-depth calorimeter knowledge

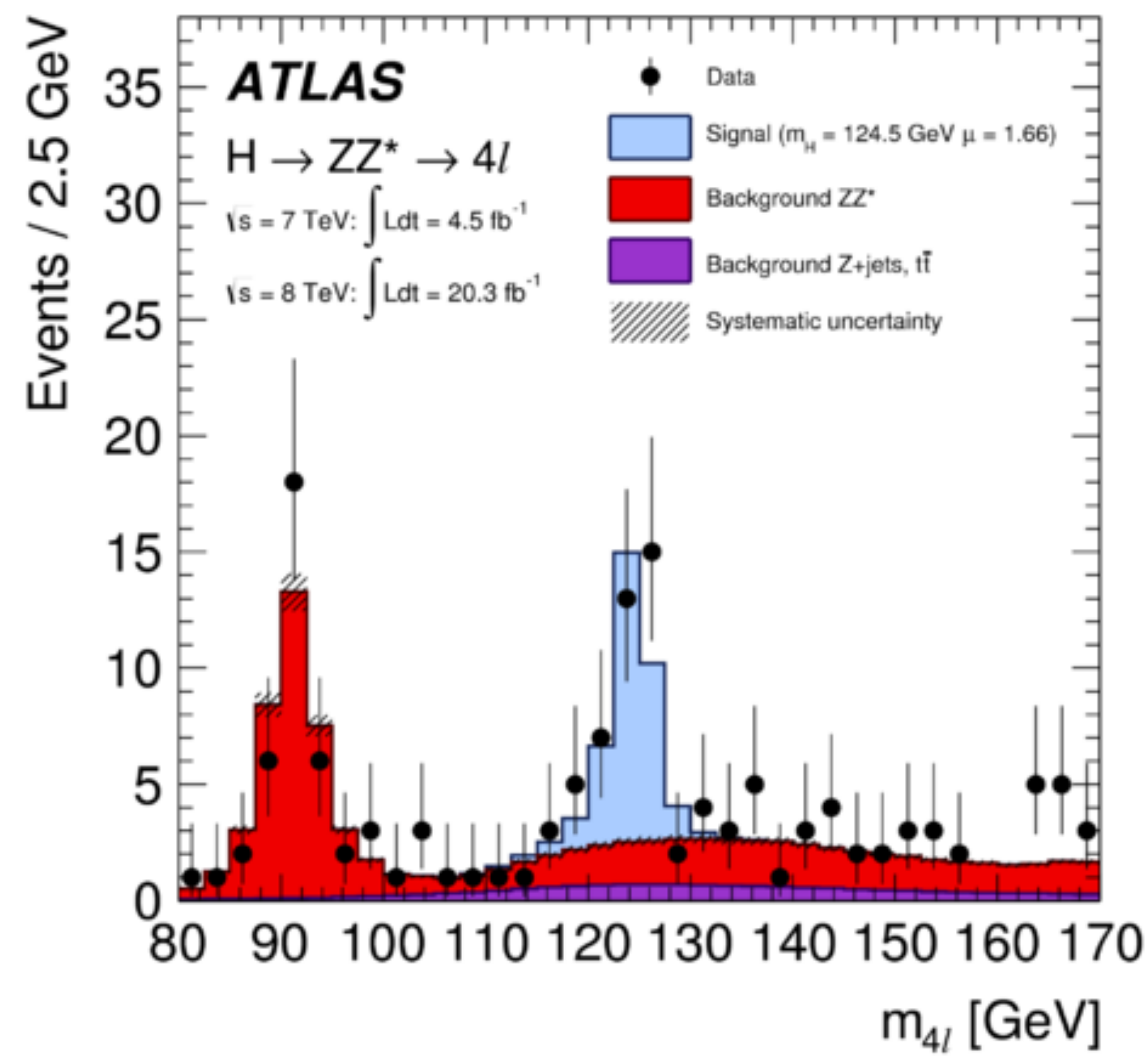






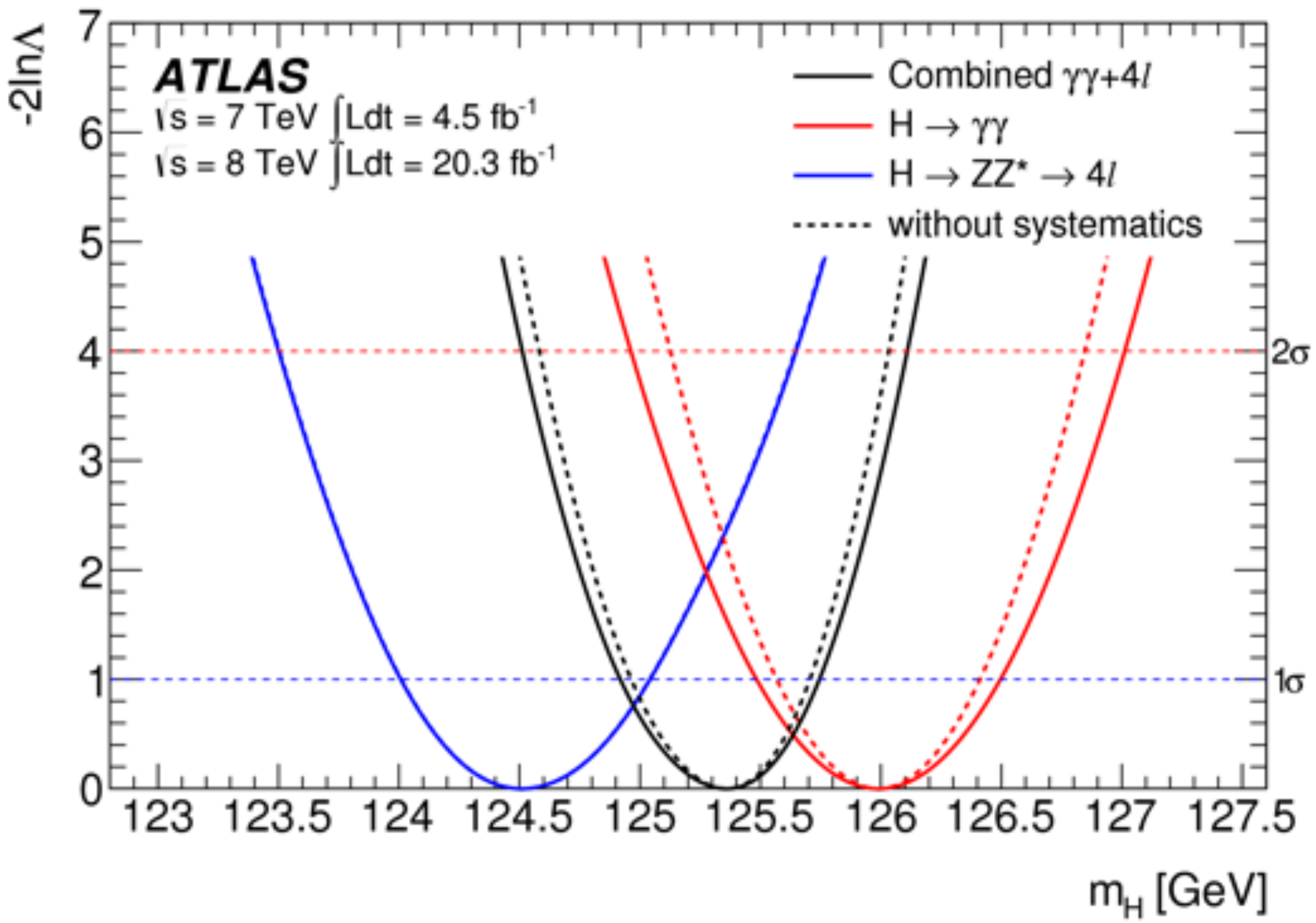
The mass spectra





- Use maximum likelihood estimator for m_H
- NB: Each channel has more than 1 category (2 plots = simplification!)

ATLAS results

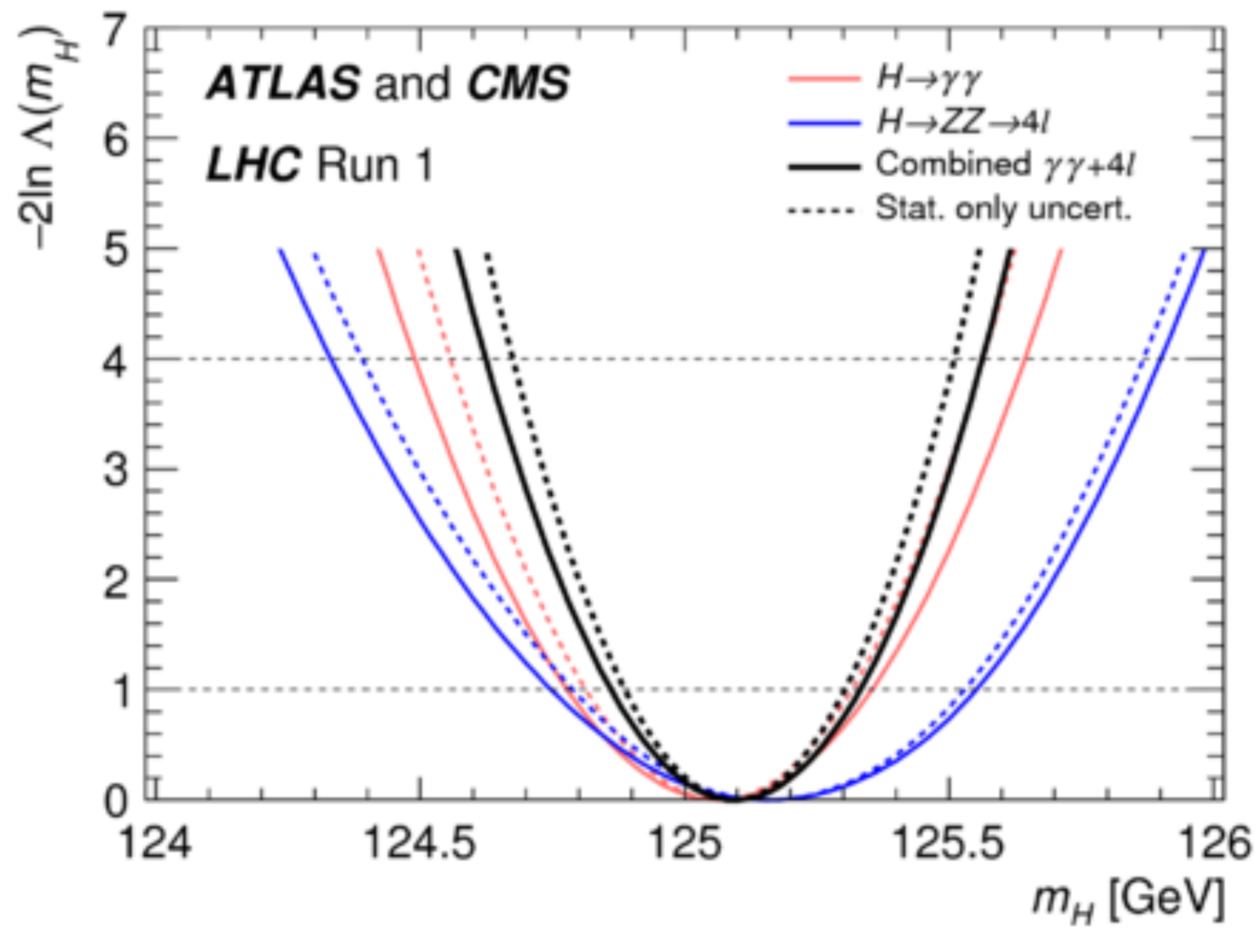


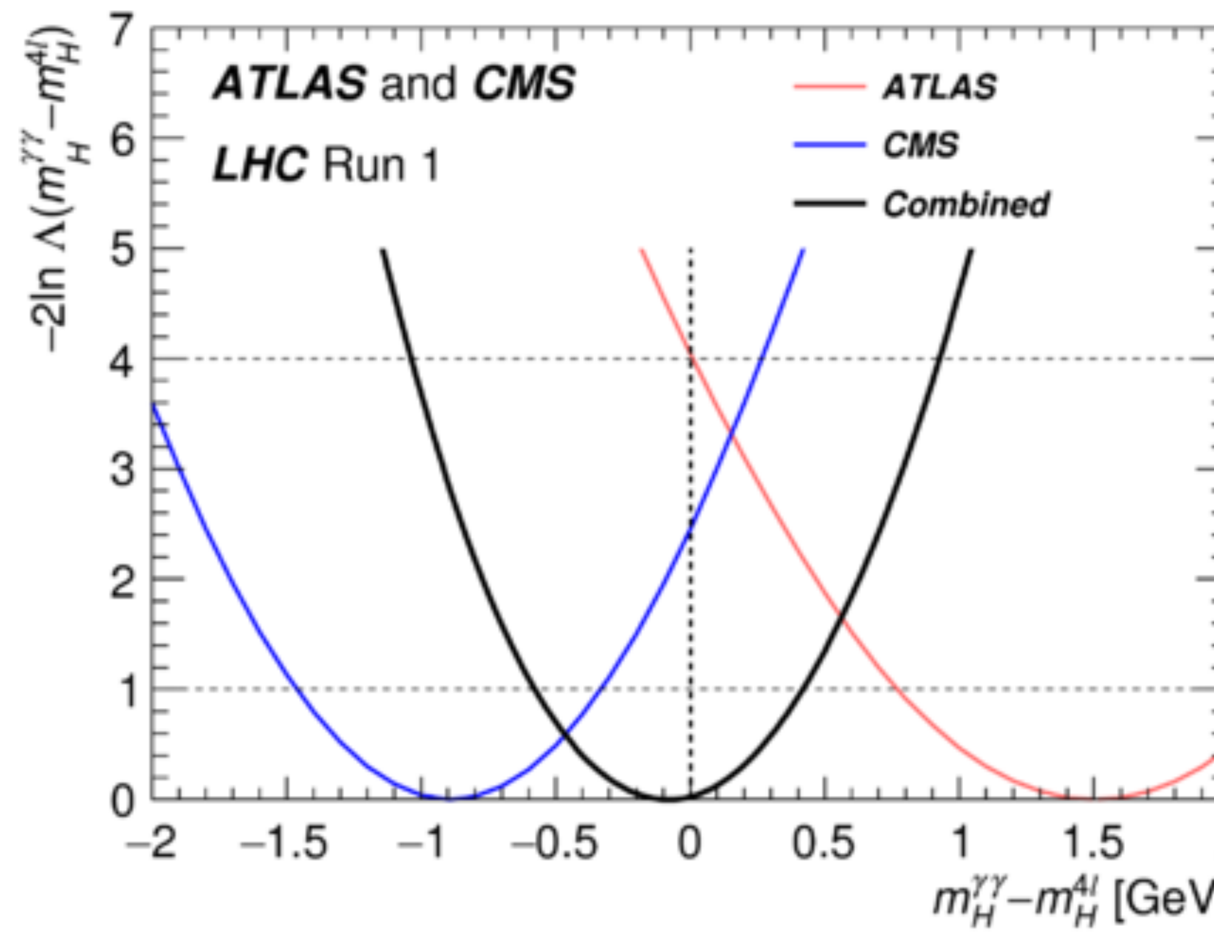
Systematic	Uncertainty on m_H [MeV]
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr cell nonlinearity (layer 2)	60
LAr cell nonlinearity (layer 1)	30
LAr layer calibration (barrel)	50
Lateral shower shape (conv)	50
Lateral shower shape (unconv)	40
Presampler energy scale (barrel)	20
ID material model ($\lvert\eta\rvert < 1.1$)	50
$H \to \gamma\gamma$ background model (unconv rest low p_{Tt})	40
$Z \to ee$ calibration	50
Primary vertex effect on mass scale	20
Muon momentum scale	10
Remaining systematic uncertainties	70
Total	180

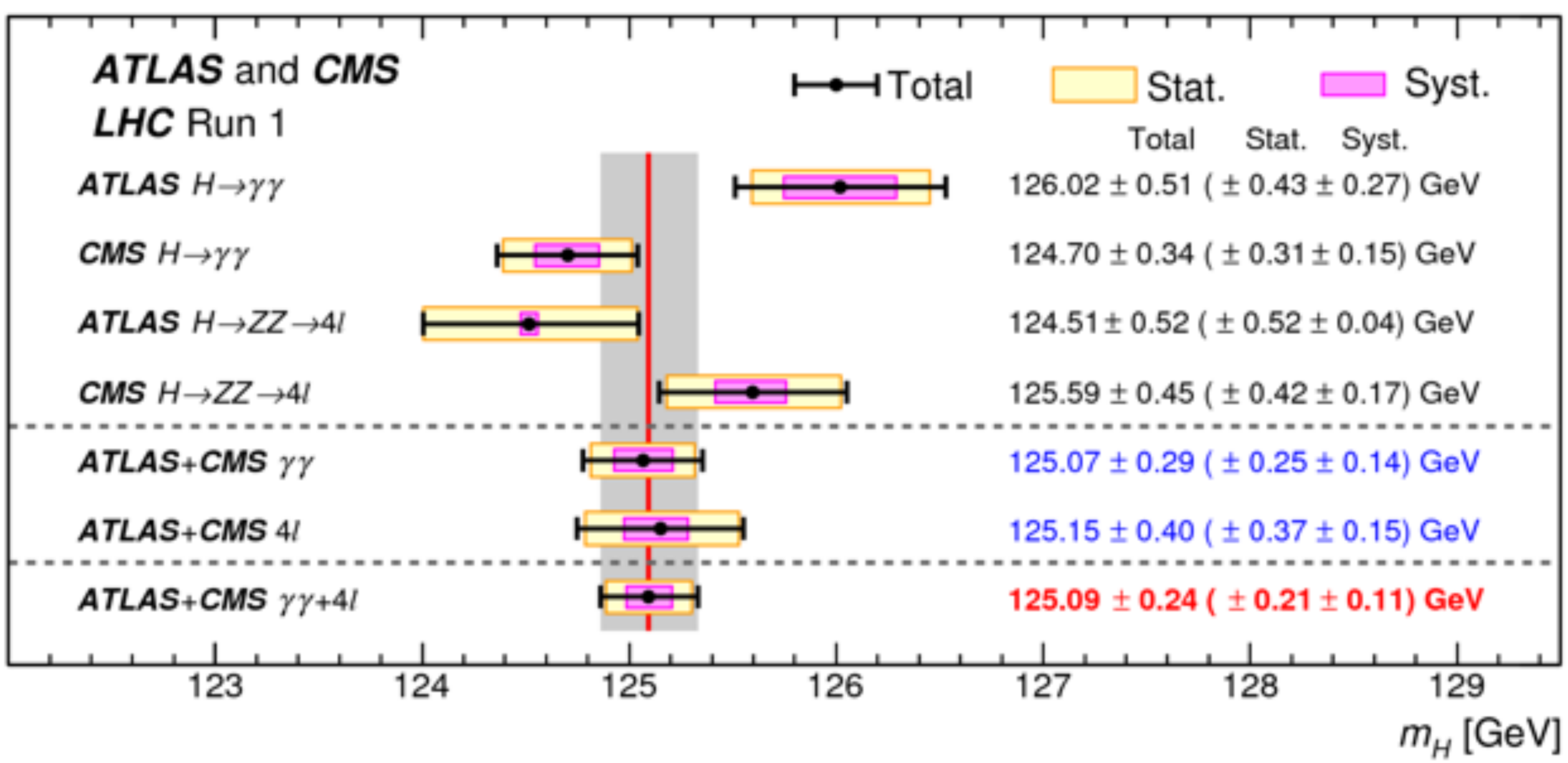
Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZ$llll	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

ATLAS measurement (stat. limited!)

CMS ATLAS combination

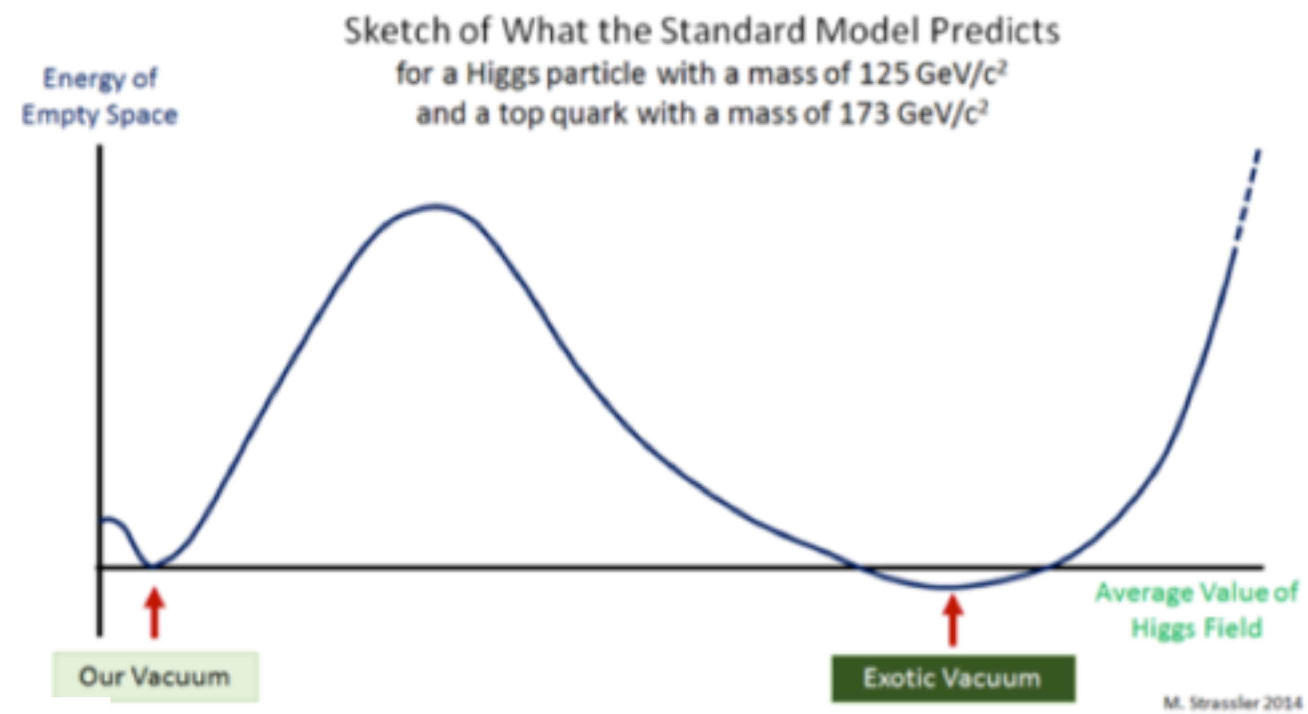




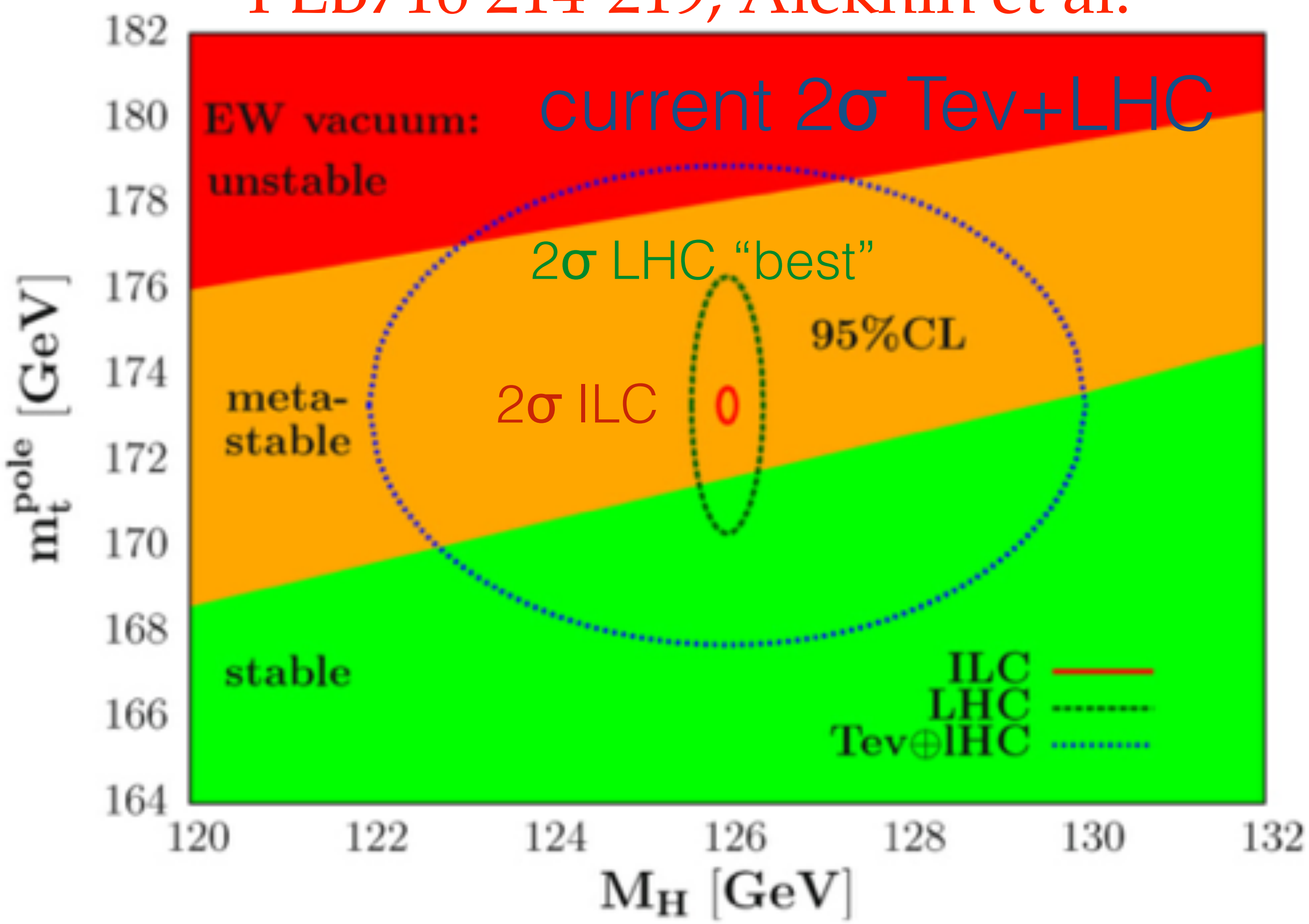


Mass measurements and electro weak vacuum stability?

Extrapolation to planck scale: is the electro weak vacuum stable?
Depends critically on values of m_{top} and m_H.



PLB716 214-219, Alekhin et al.

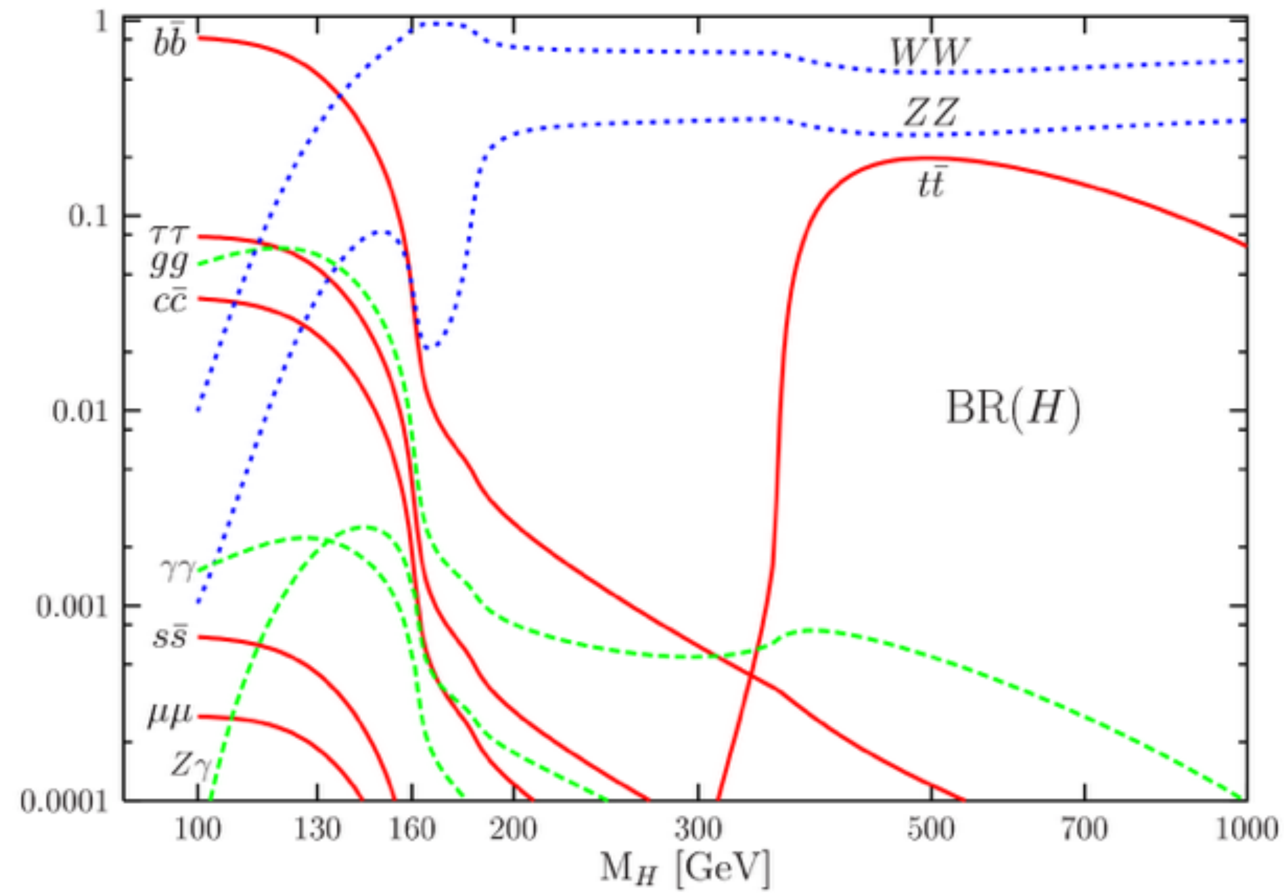


Still consistent with stable vacuum
Need more precise measurements, e.g. ILC

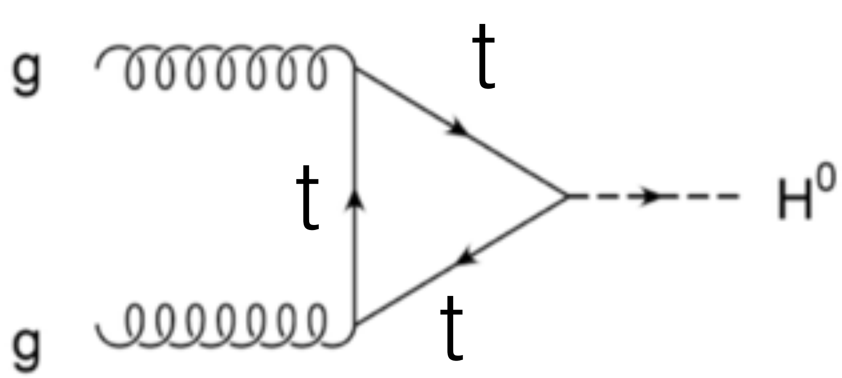
if meta-stable, maybe life-time of EWV longer than age of universe???

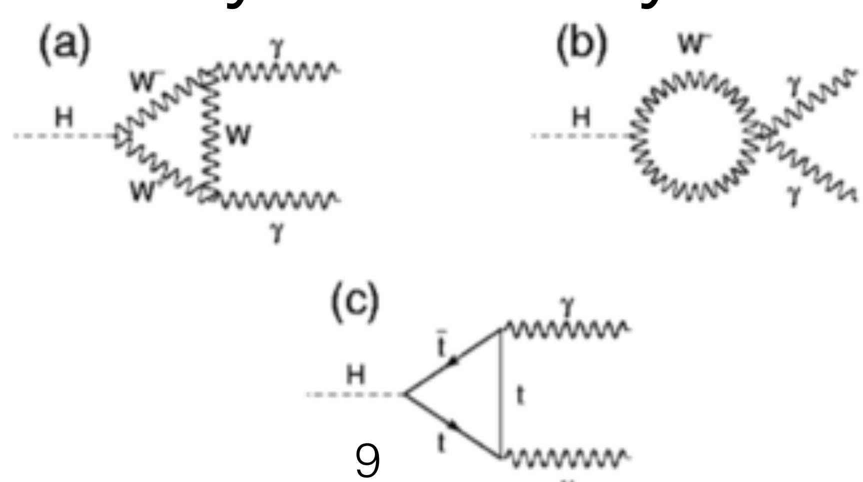
Couplings to bosons AND fermions?

Observation of new particle by ATLAS/CMS decaying to γγ, ZZ, WW (all bosons)



- particle is a boson
- particle couples to vector bosons
- coupling to fermions only indirectly seen in loops:





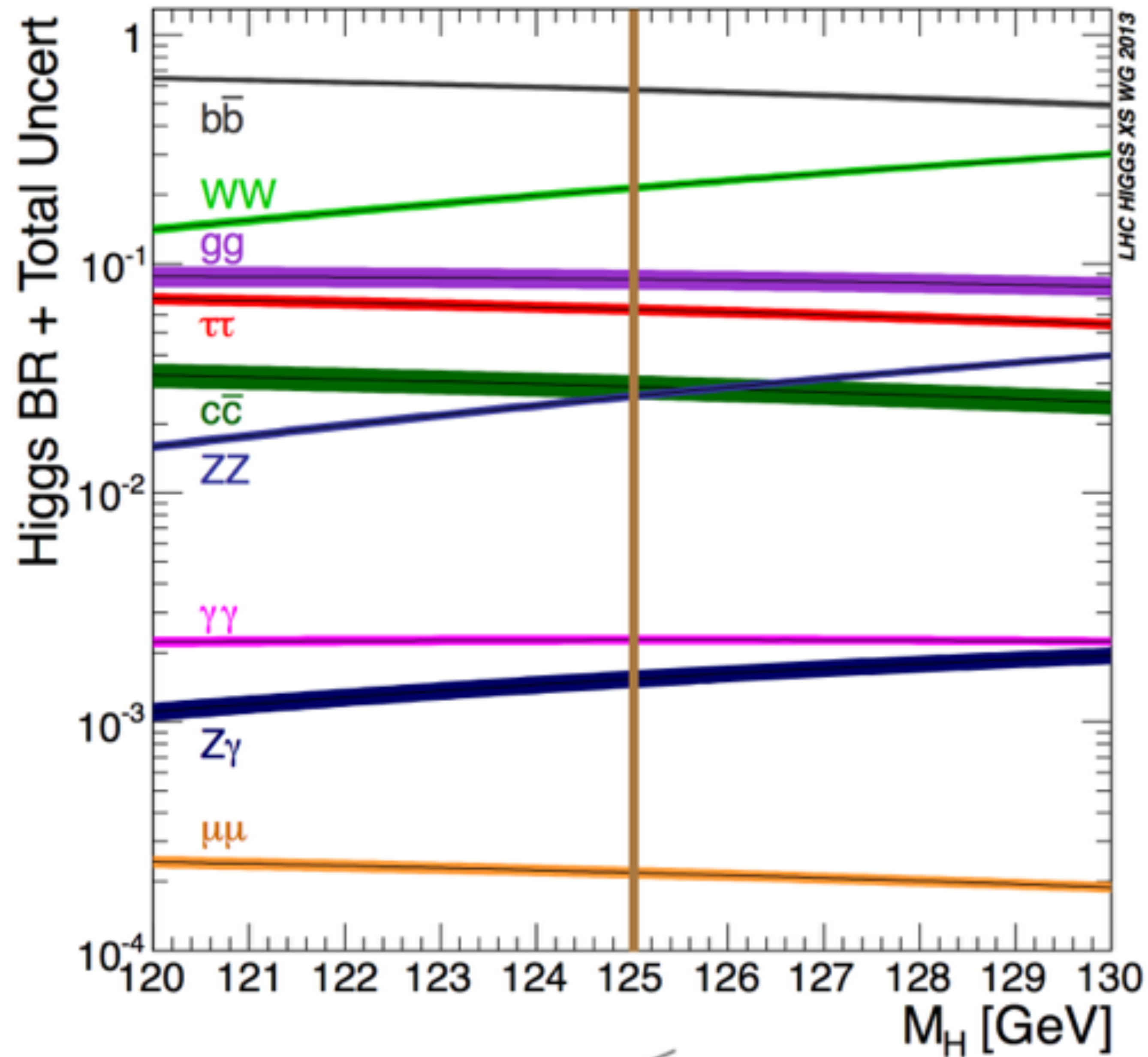
Search for H→ff important to establish direct Higgs to fermion couplings!

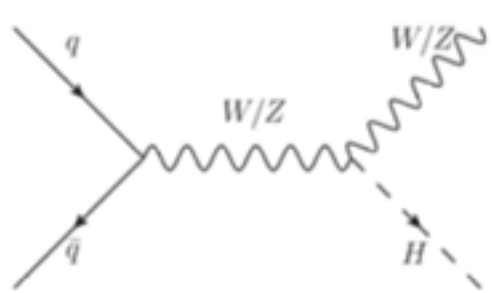
H→ff searches

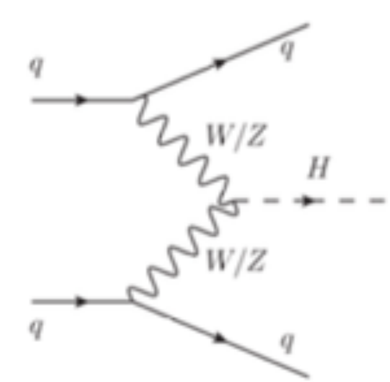
Advantage: large branching ratios

Disadvantage: bb and **ττ** are hard to distinguish from jet background

Use more distinct production processes to decrease backgrounds







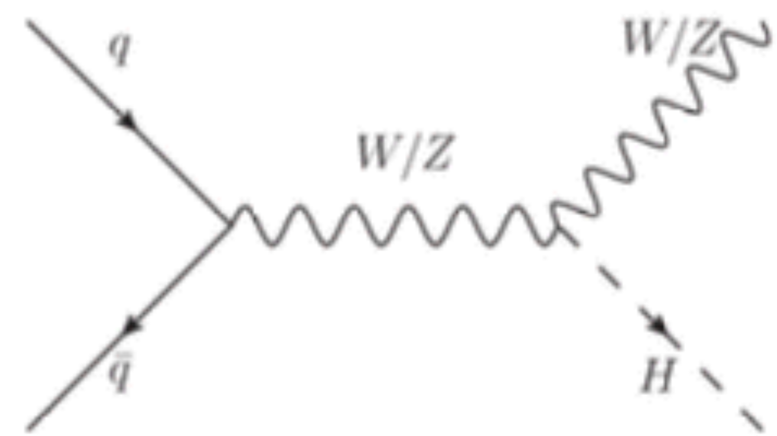
WH/ZH production for H→bb

- leptonic or neutrino decay products of W/Z reduce backgrounds

VBF production for H→ττ

- VBF jets (forward & separated) help distinguish signal from background

CMS H→bb



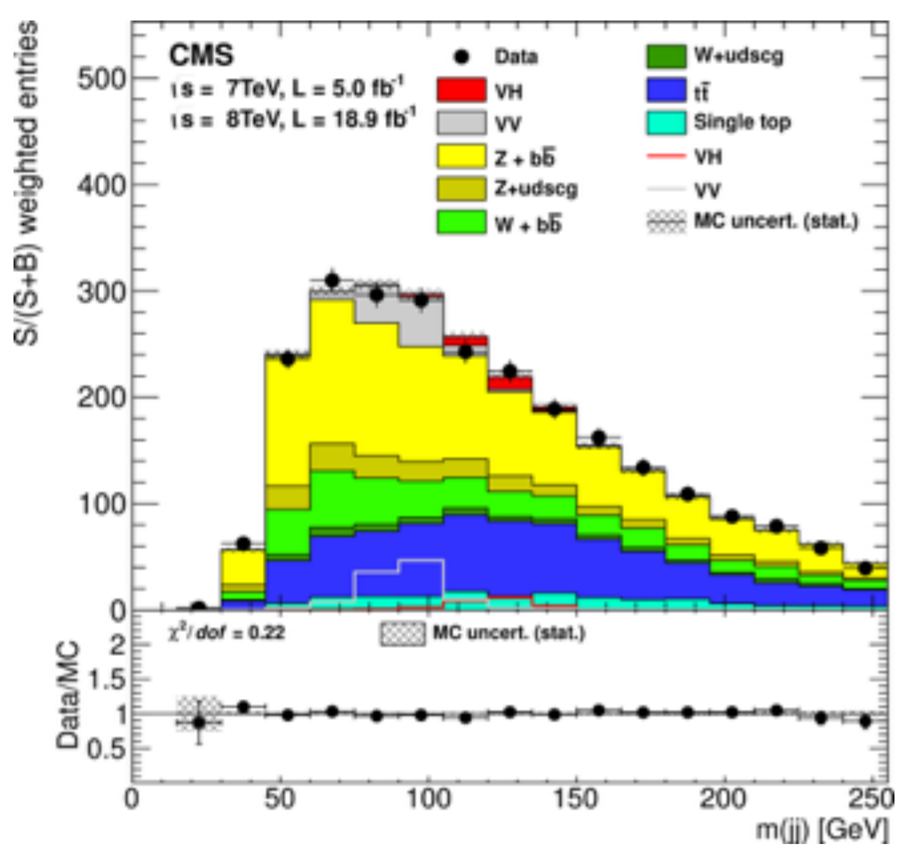
Main decay modes:

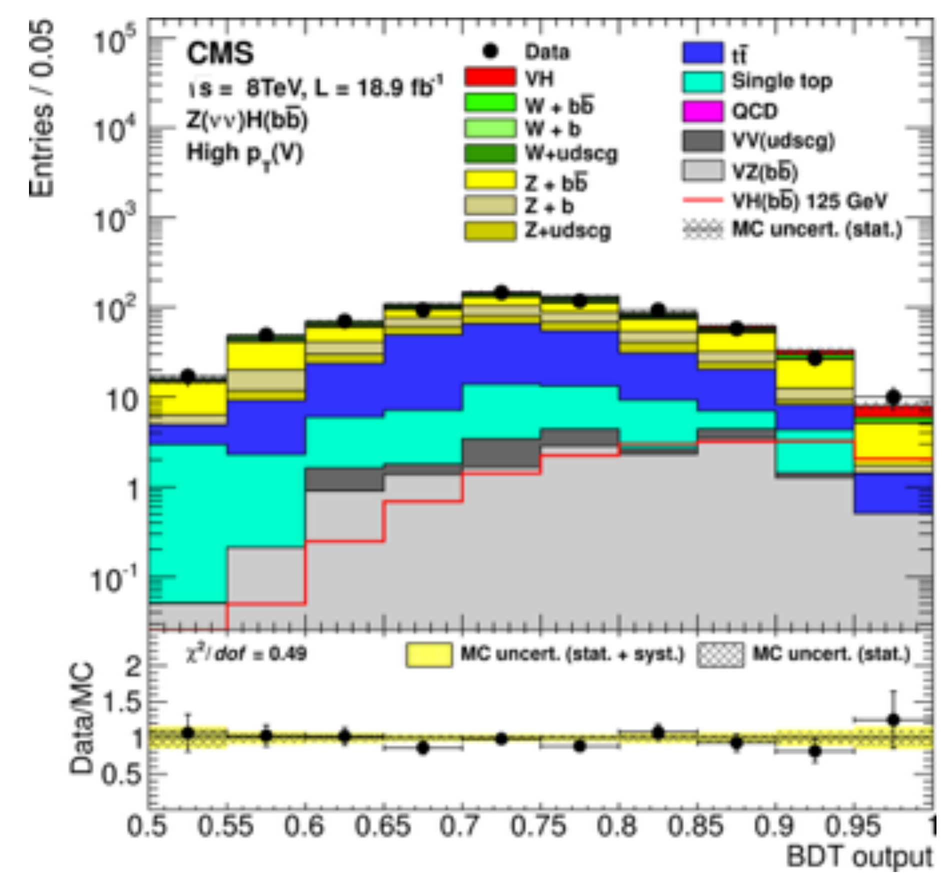
WH→lνb, ZH→l⁺l⁻bb, ZH→ννbb

Require: 2 b-tagged jets and
1 lepton + E_T^{miss} or oppositely charged lepton pair in Z mass window or large E_T^{miss}

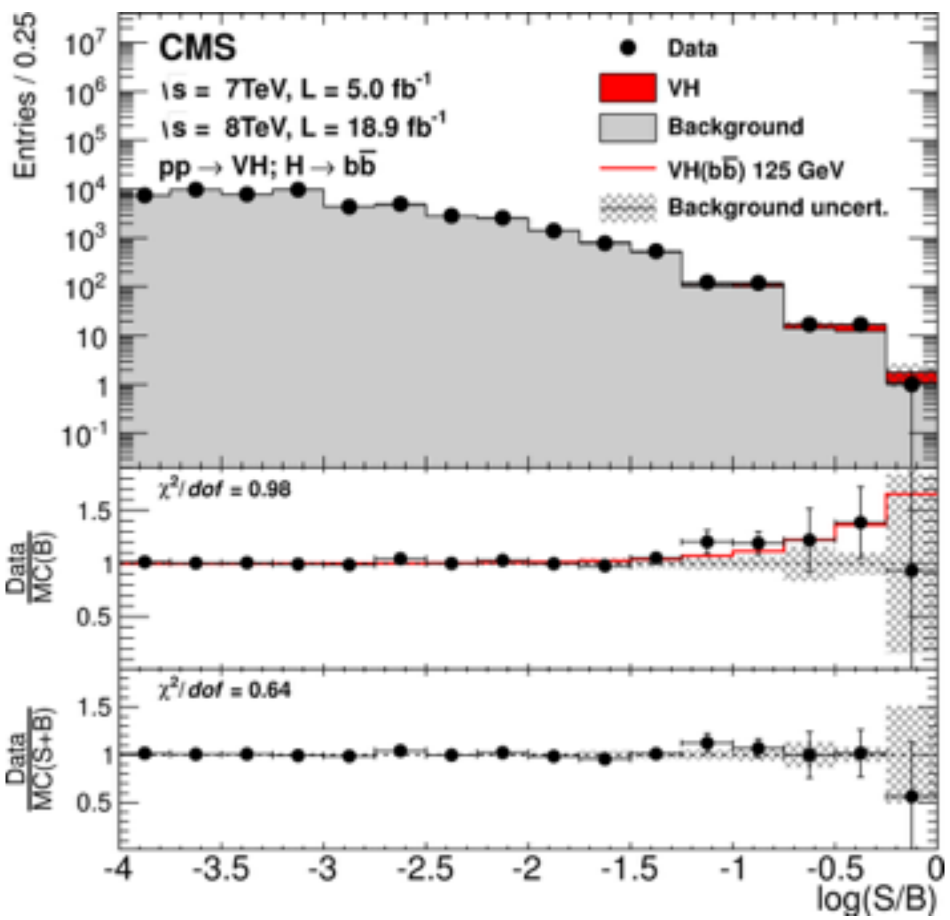
Split in categories of p_T^V (V=W/Z), exploit differing signal to background ratios

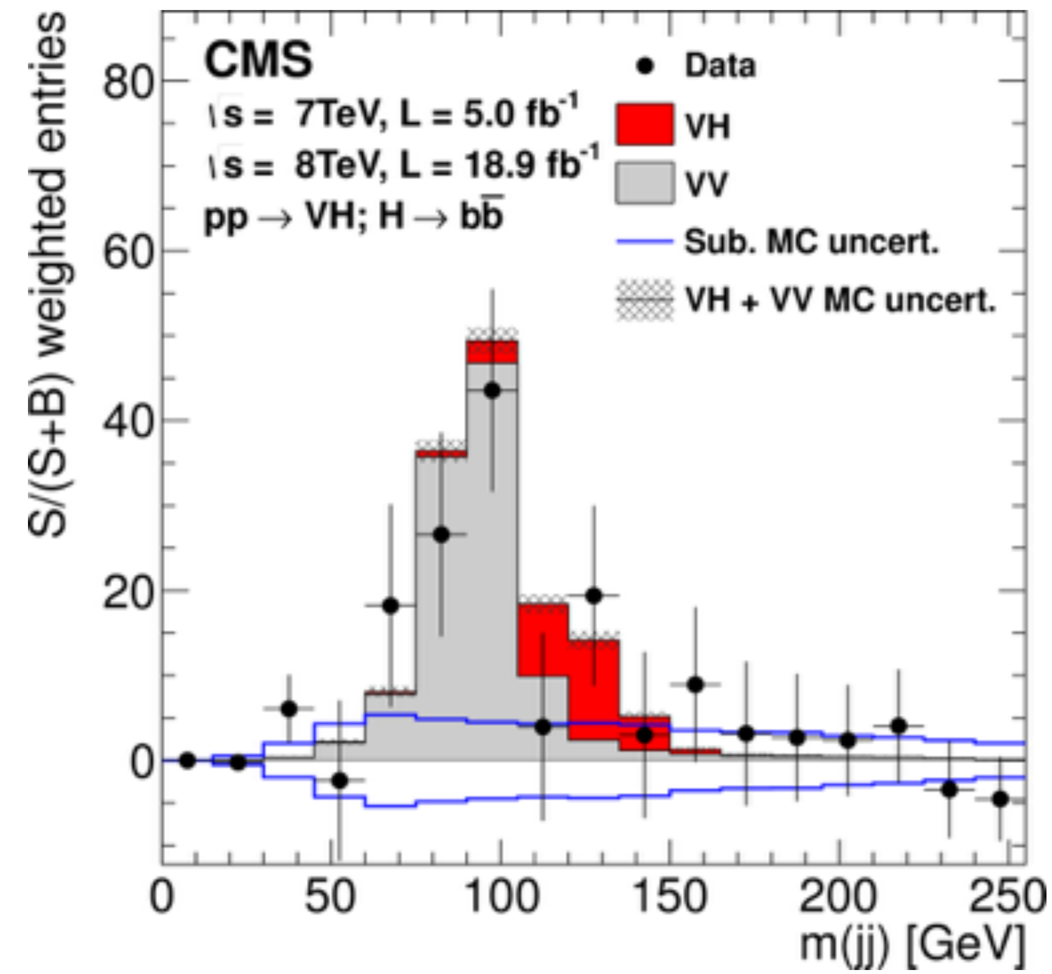
In each category use BDT to separate signal from background,
using m_{bb}, p_T^V, b-tagging, angular separation





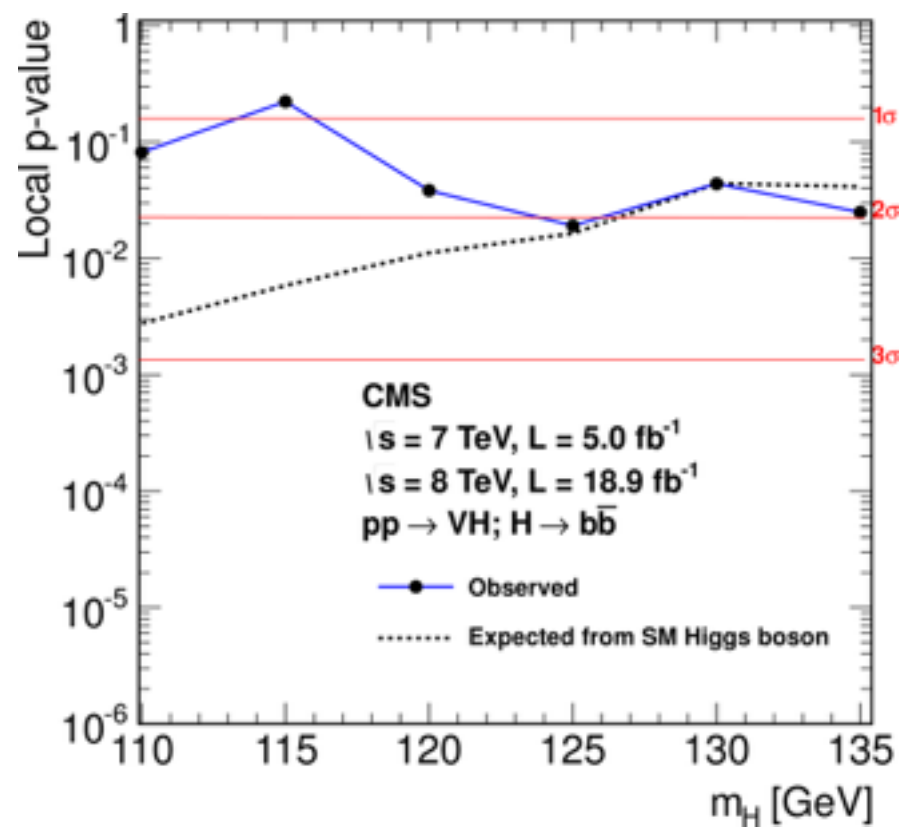
CMS H→bb





“Hint of a signal”

corresponds to 2.1σ

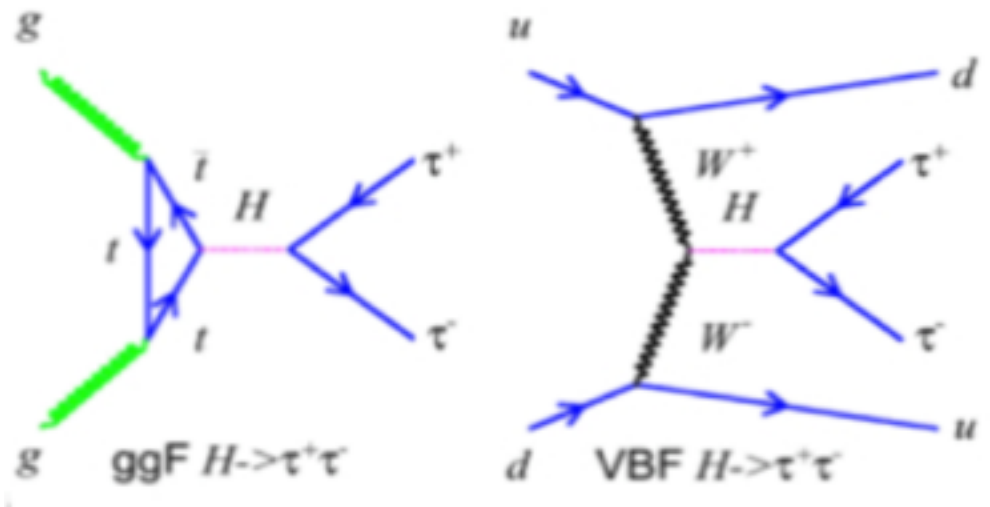


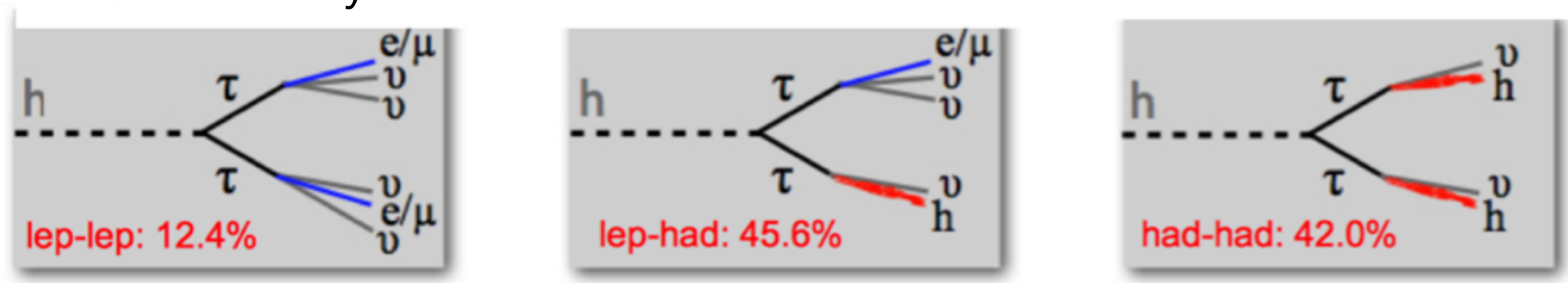
Signal strength

$\mu = 1.0 \pm 0.5$

ATLAS H→ττ

Exploit:
Production ggF and VBF
All tau decay combinations



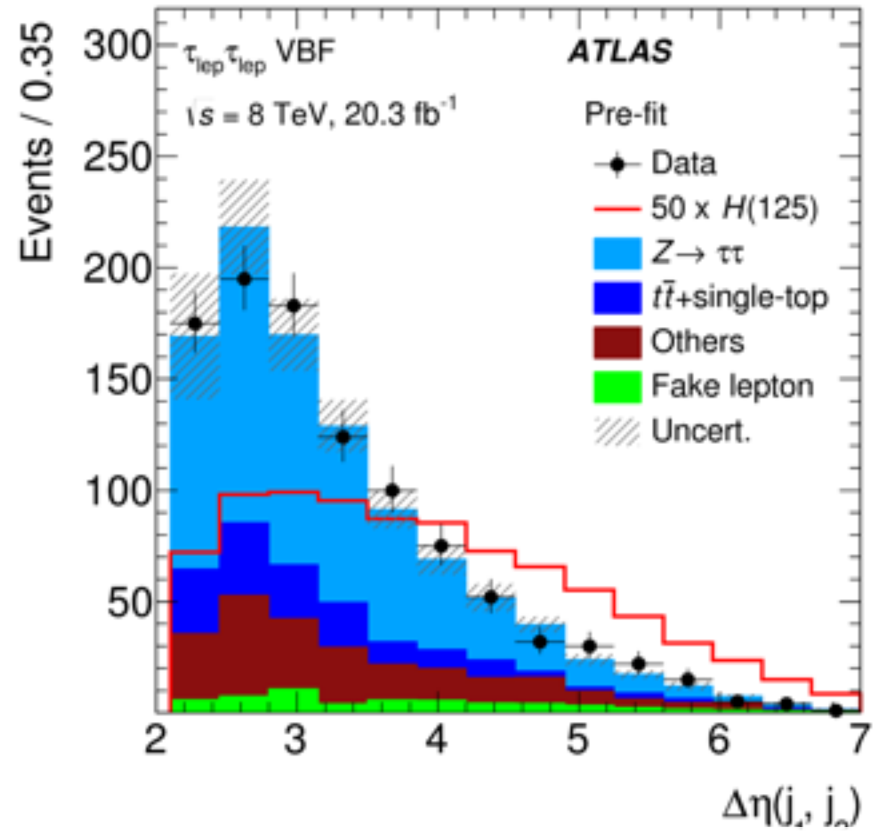


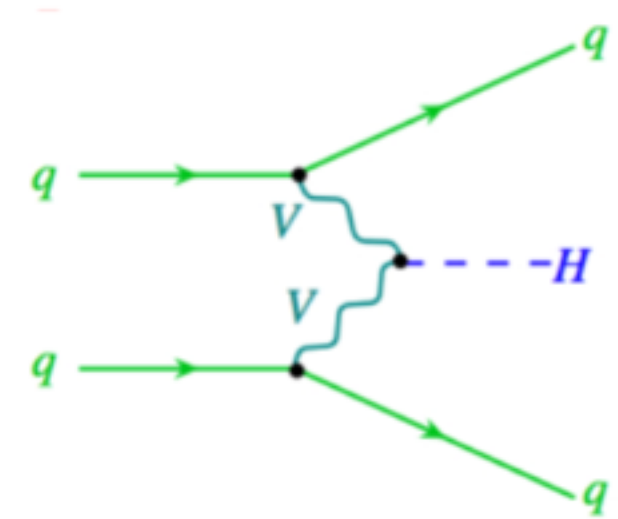
- categorize events into categories sensitive to ggF and VBF production
- build boosted decision tree based on kinematic variables to separate signal from background

Event categories

VBF category

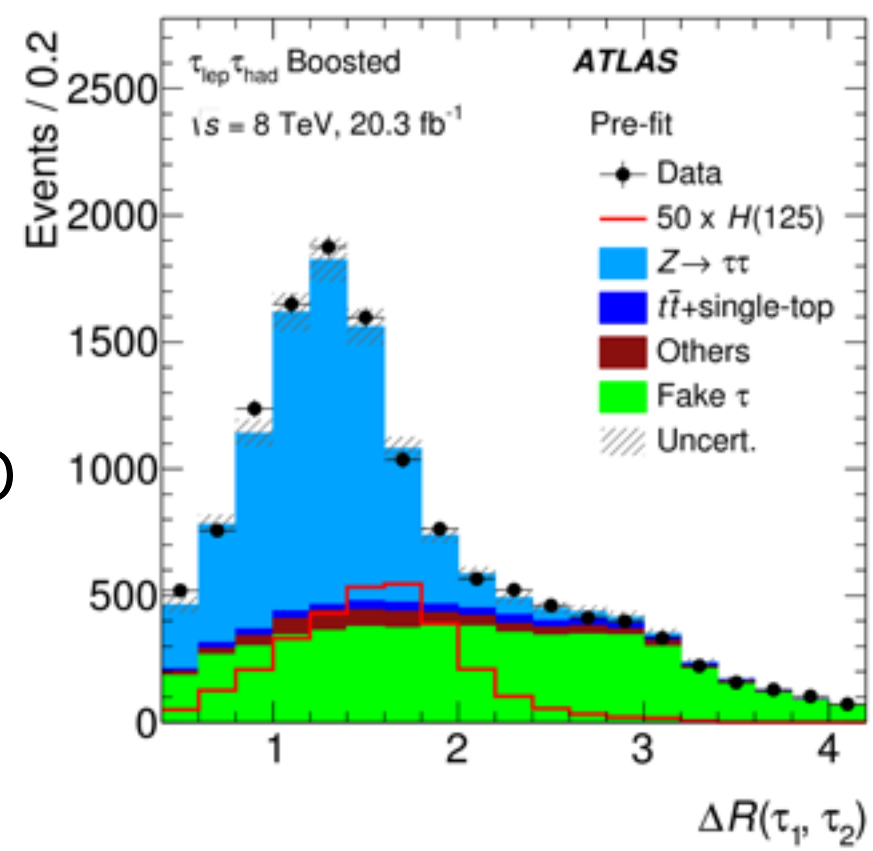
- 2 high p_T jets
- large separation in η
- better S/B ratio

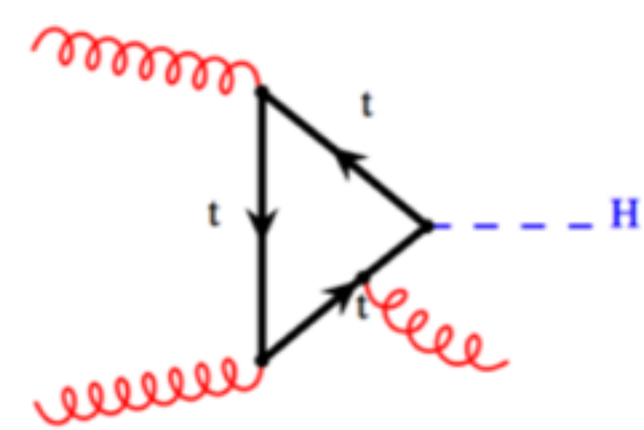




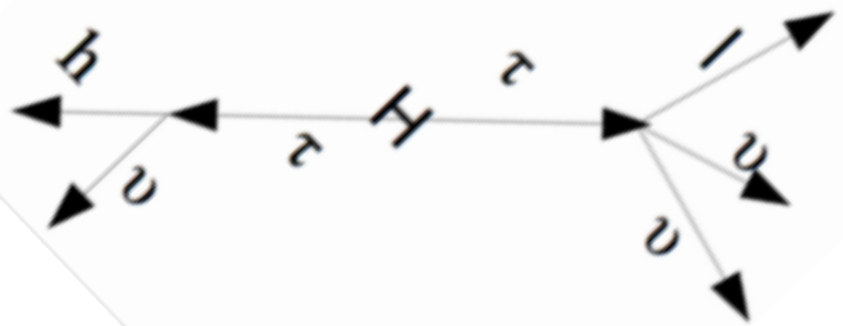
Boosted category

- sensitive to ggF events with extra jets
- Higgs at higher p_T to balance jets = "boosted" = taus closer together

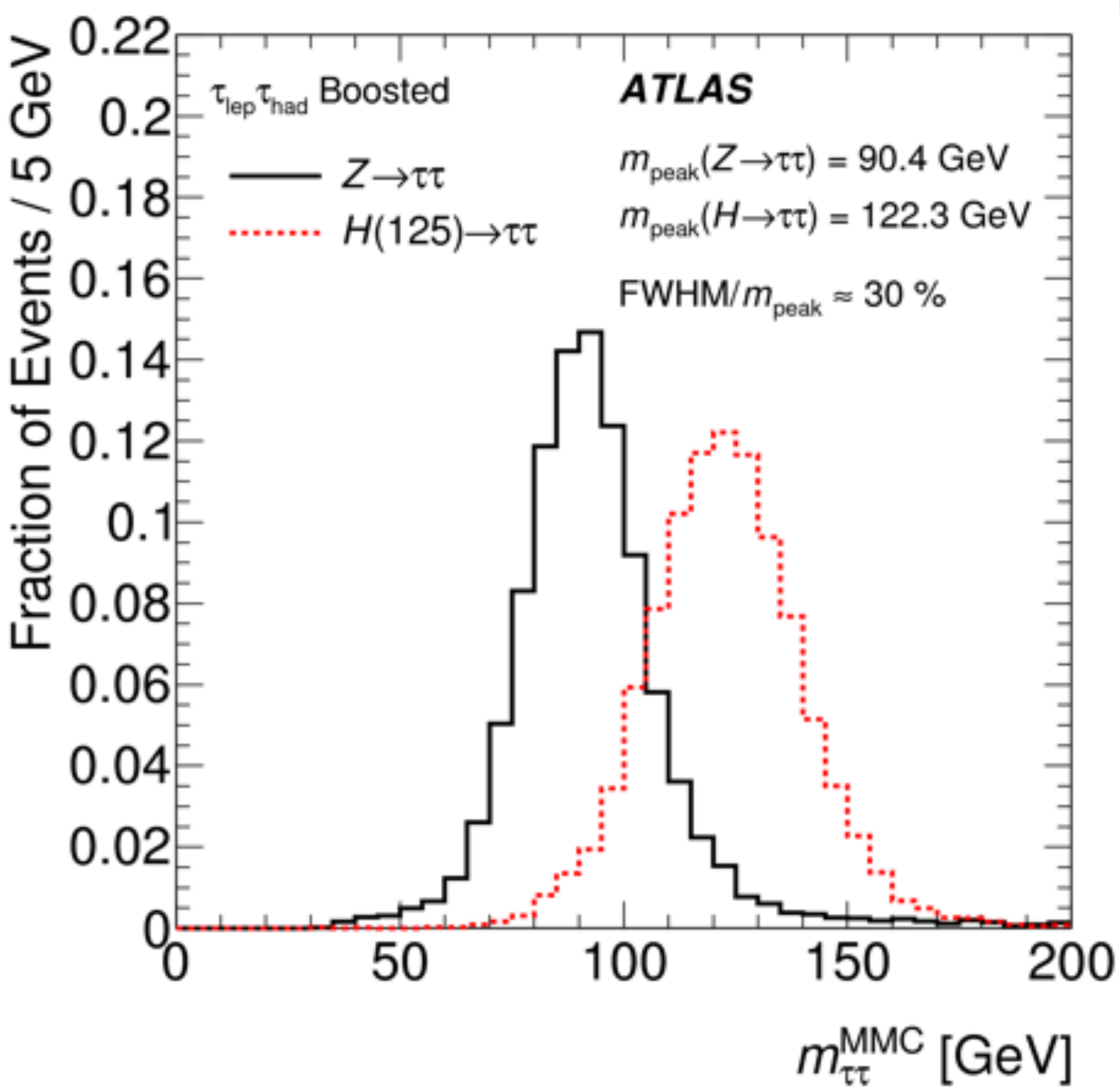




Di-tau mass reconstruction



Due to undetected neutrinos mass met fully constrained.
Need to infer through E_T^{miss}



Missing Mass calculator (MMC)

- Assumes E_T^{miss} only due to neutrinos
- takes into account the most probable neutrino kinematics to reconstruct di-tau mass

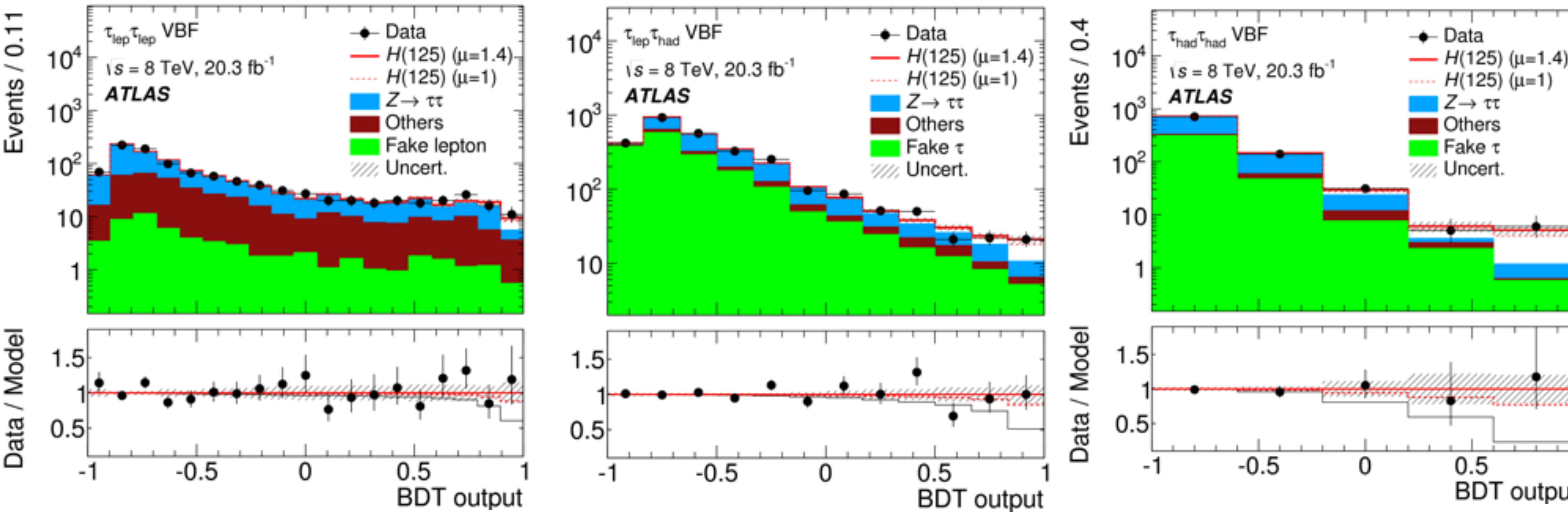
Typical resolution for $Z\rightarrow\tau\tau$

channel	mass resolution
lep-lep	16%
lep-had	16%
had-had	14%

MMC mass is the most separating in BDT

BDT outputs

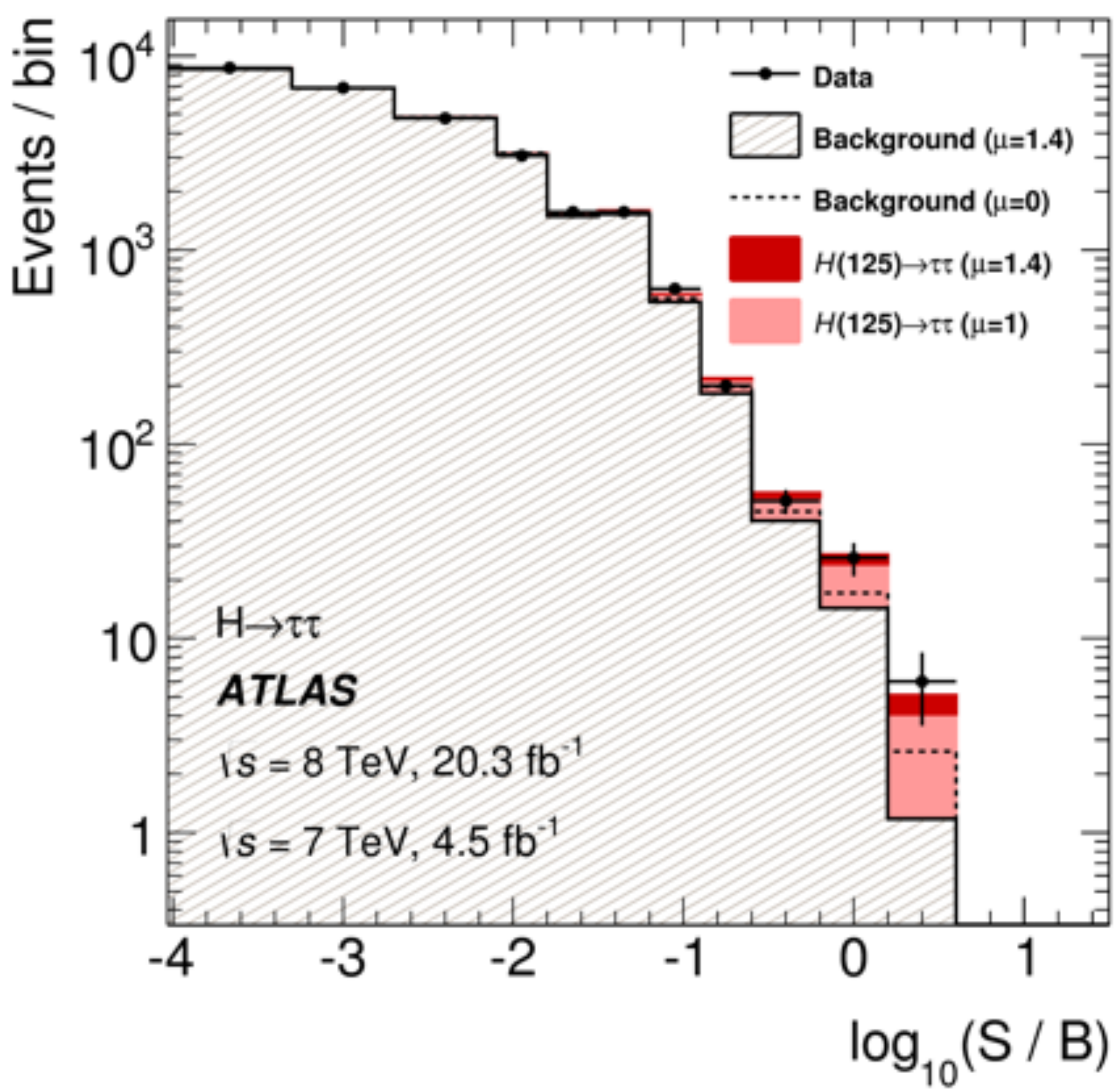
lep lep | lep had | had had

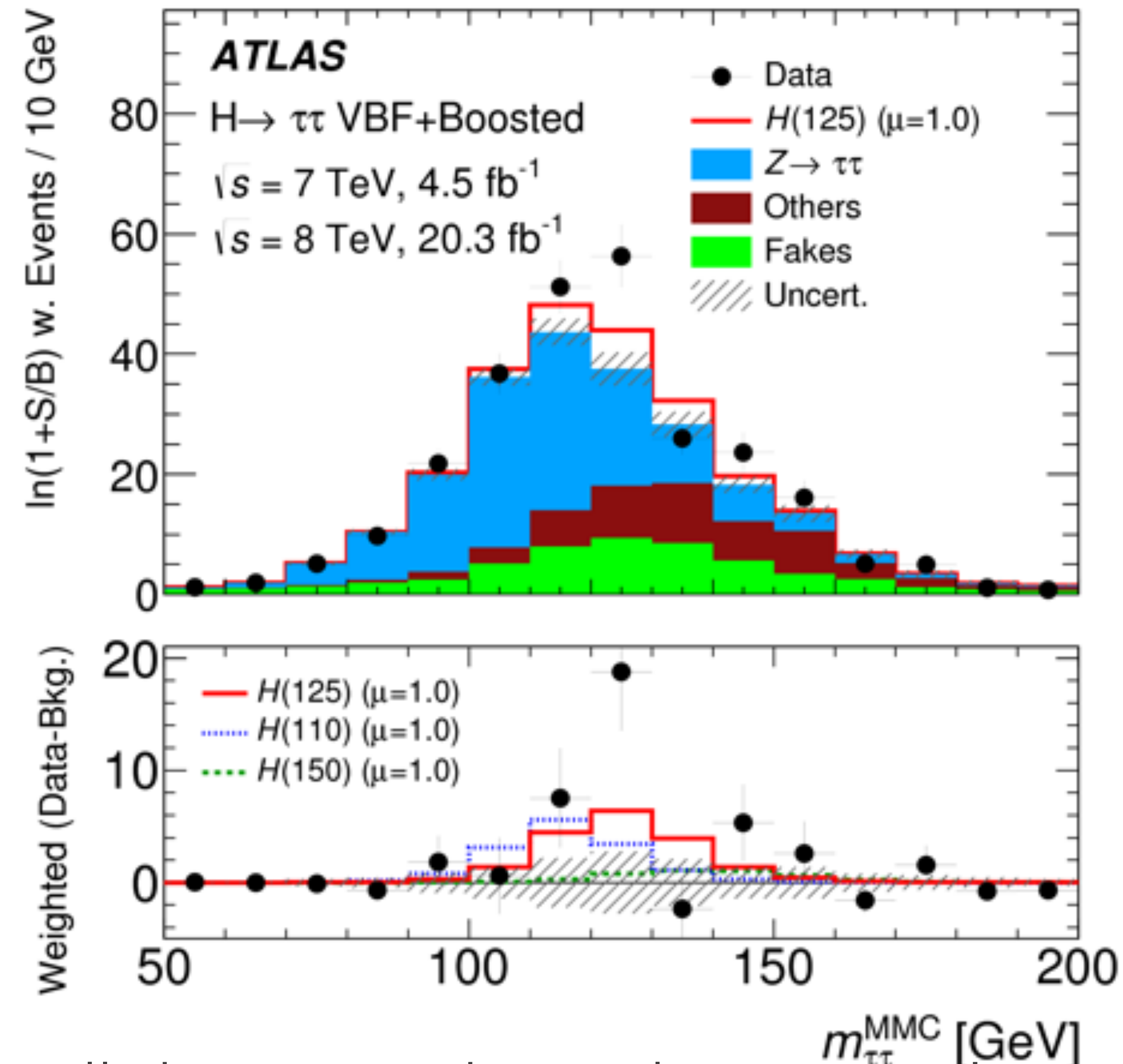


Clear excess of data above background prediction

Excess consistent with SM Higgs prediction

Results





Significant excess of events seen across all datasets, channels, categories

observed (expected) significance corresponds to **4.5σ (3.5σ)**

best fit signal strength is **μ= σ/σSM = 1.42+0.44-0.38**

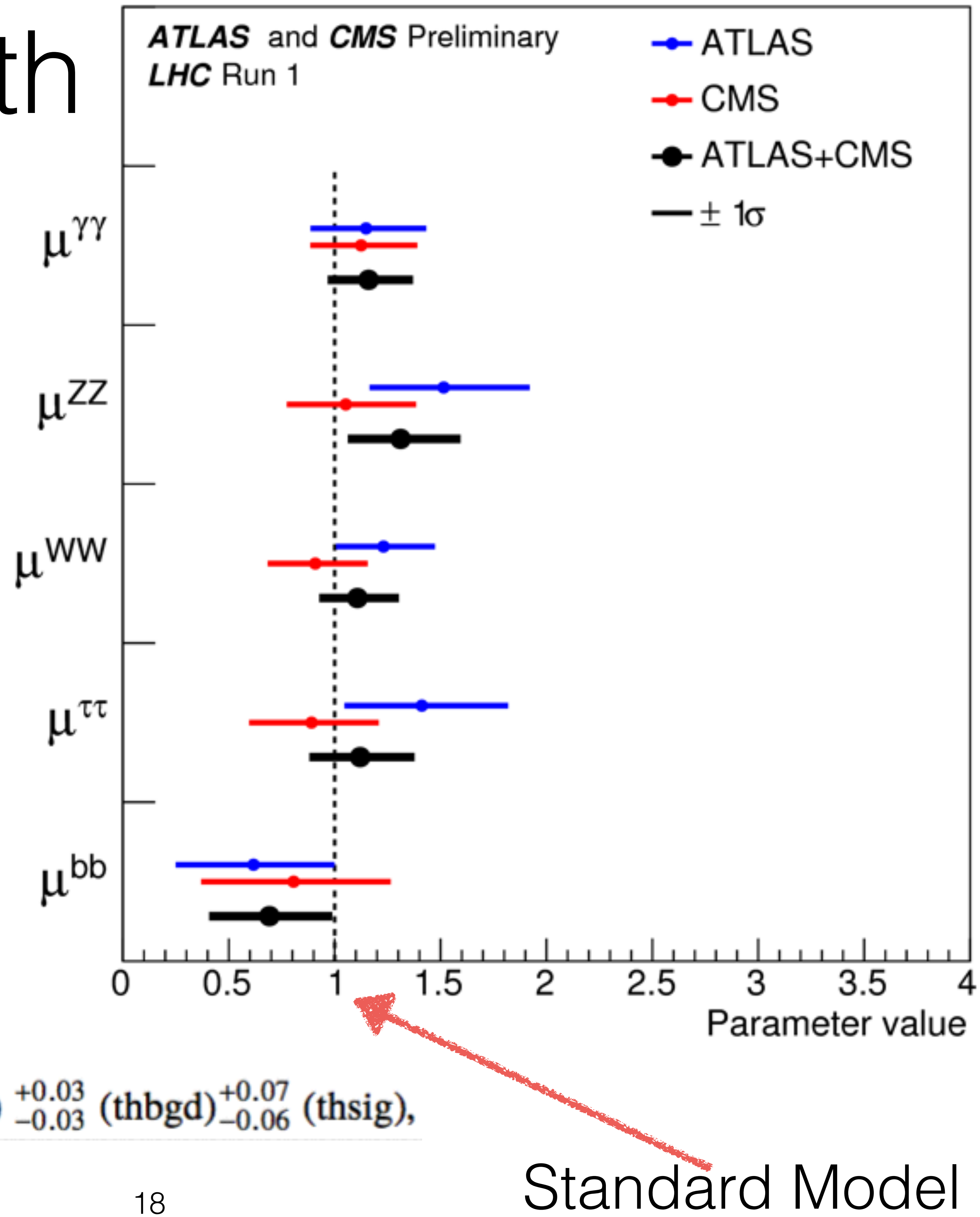
CMS: **3.2σ (3.7σ)** evidence for H→ττ decays

CMS/ATLAS combination:
5.5σ
—> Discovery!

Signal strength summary

- Signal strength
  μ=measured/SM

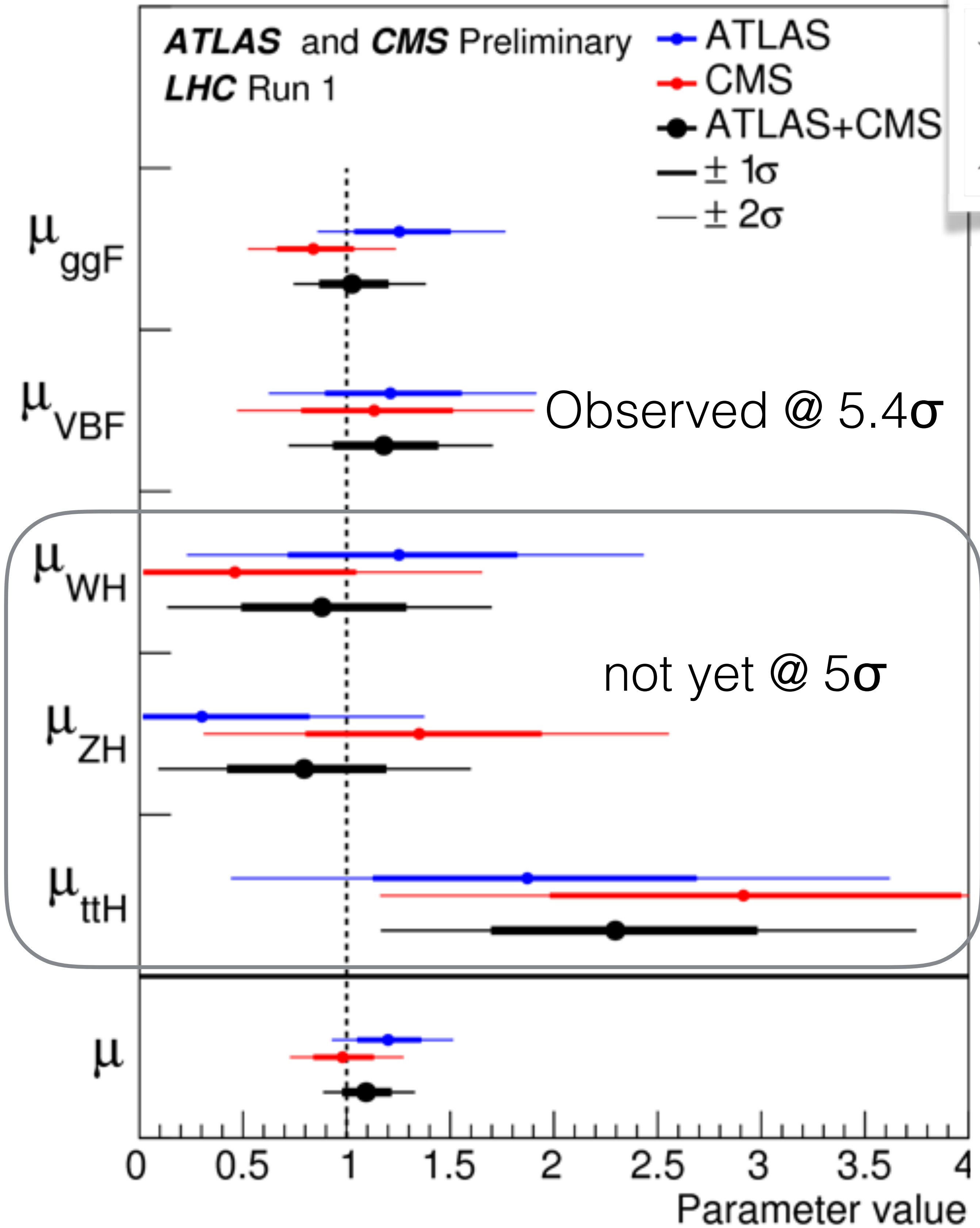
- all channels seem to be consistent with the SM expectation

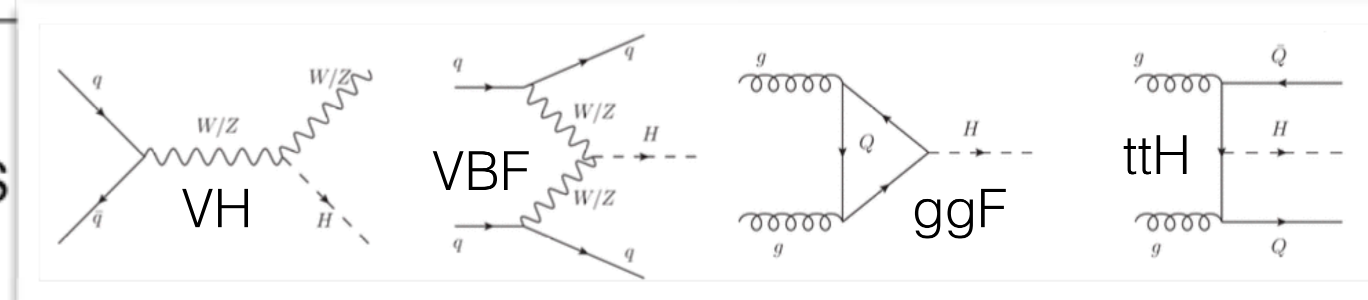


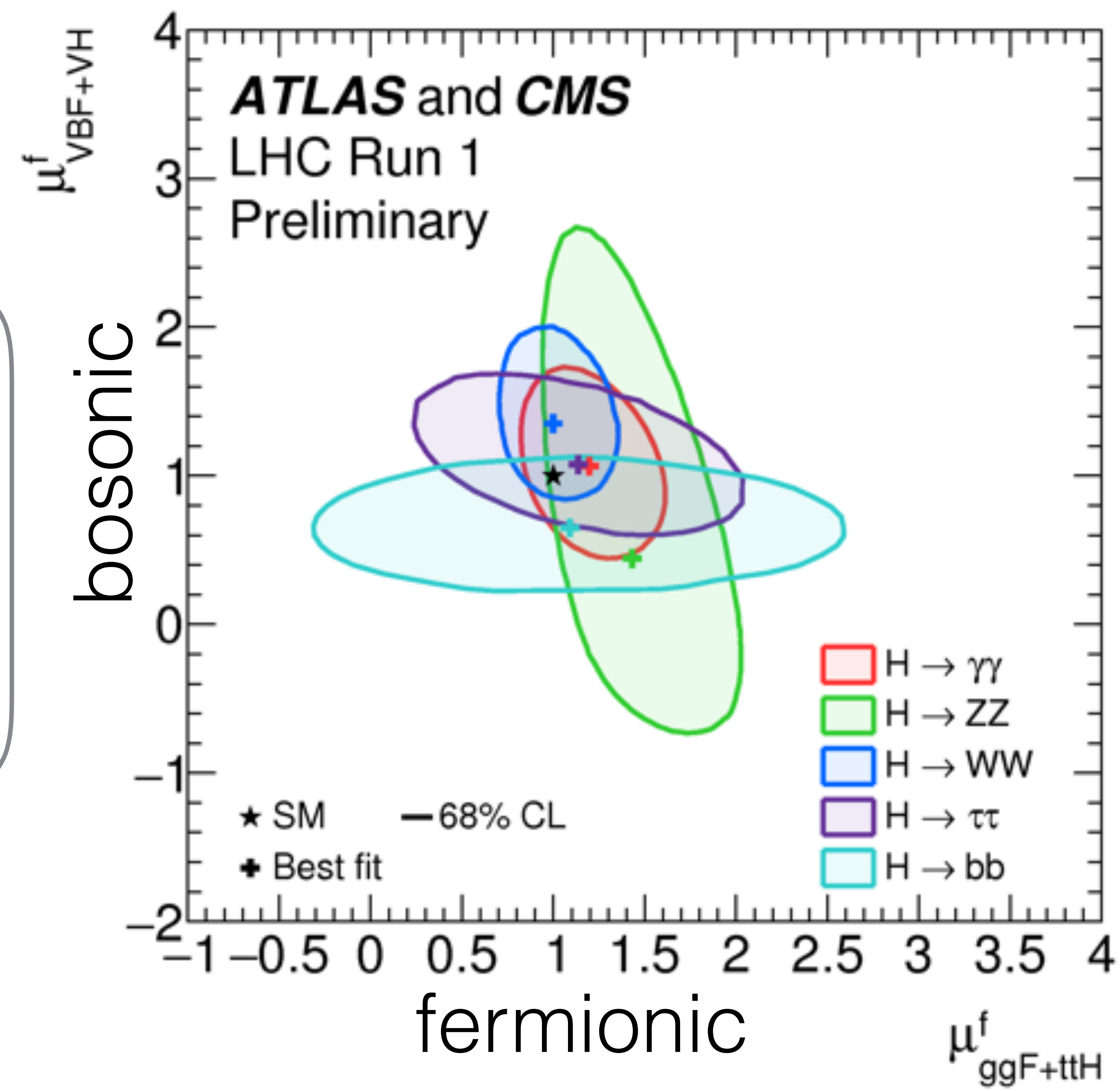
global ATLAS+CMS:

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\ (\text{stat})\ ^{+0.04}_{-0.04}\ (\text{expt})\ ^{+0.03}_{-0.03}\ (\text{thbgd})^{+0.07}_{-0.06}\ (\text{thsig}),$$

Higgs production

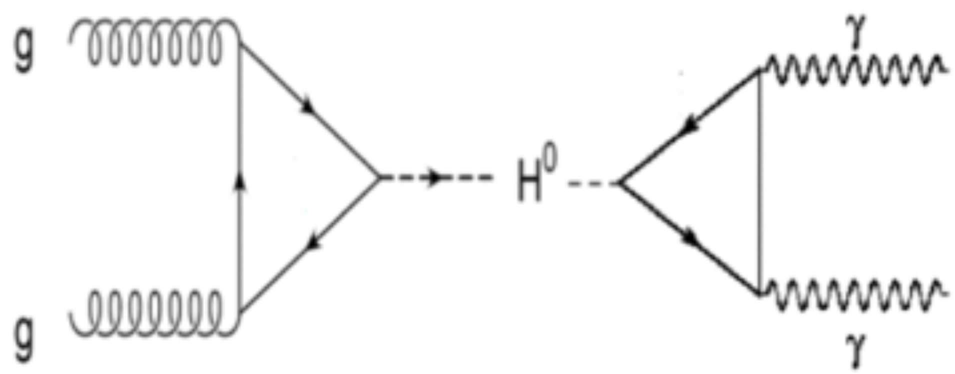


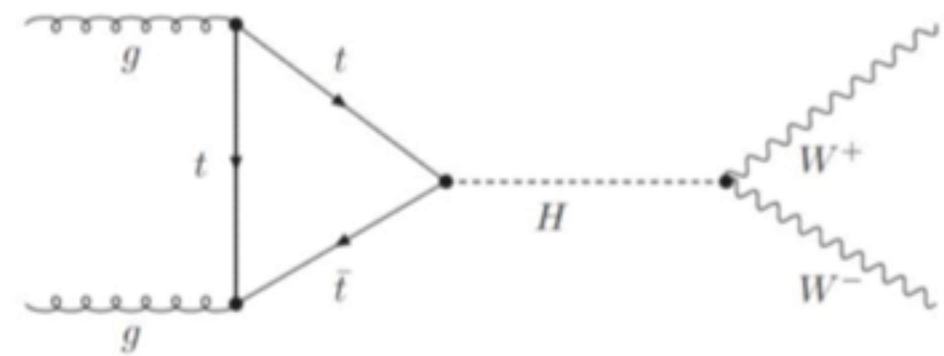




Higgs boson coupling scale factors

Measurements so far are always mixing different production processes, production and decay, and tree vs loop level Higgs couplings, e.g.:





production & decay mix fermion/boson & tree/loop mix

Can separate out effects by using coupling scale factors κ_i

$$g_{Hff} = \frac{\sqrt{2}m_f}{\upsilon}, \qquad g_{HVV} = \frac{2m_V^2}{\upsilon} \quad \Rightarrow \quad g_{Hff} = \boxed{\kappa_f} \cdot \frac{\sqrt{2}m_f}{\upsilon}, \quad g_{HVV} = \boxed{\kappa_V} \cdot \frac{2m_V^2}{\upsilon}$$

SM: $\kappa_i = 1$

Scale factors

$$(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

Introduce parameter κ_i, κ_f parametrizing new physics

SF for ii, ff

Example: ggH → γγ

$$(\sigma \cdot \mathrm{BR})\,(gg \to \mathrm{H} \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(gg \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}$$

SF for total width

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases} \qquad \frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma_{\mathrm{WW}^{(*)}}^{\mathrm{SM}}} = \kappa_W^2 \qquad \frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{\mathrm{SM}}} = \kappa_t^2$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^2(\kappa_W, \kappa_Z, m_H) \qquad \frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma_{\mathrm{ZZ}^{(*)}}^{\mathrm{SM}}} = \kappa_Z^2 \qquad \frac{\Gamma_{gg}}{\Gamma_{gg}^{\mathrm{SM}}}$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_W^2 \qquad \frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{\mathrm{SM}}} = \kappa_b^2 \qquad \frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{\mathrm{SM}}} = \kappa_t^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_Z^2 \qquad \frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{\mathrm{SM}}} = \kappa_\tau^2 \qquad \frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{\mathrm{SM}}} = \kappa_b^2$$

$$\frac{\sigma_{t\bar{t}\mathrm{H}}}{\sigma_{t\bar{t}\mathrm{H}}^{\mathrm{SM}}} = \kappa_t^2 \qquad \frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{\mathrm{SM}}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Fundamental parameters:

$\kappa_W,\ \kappa_Z,\ \kappa_b,\ \kappa_\tau,\ \kappa_t$

also useful to fix parameters to same value:

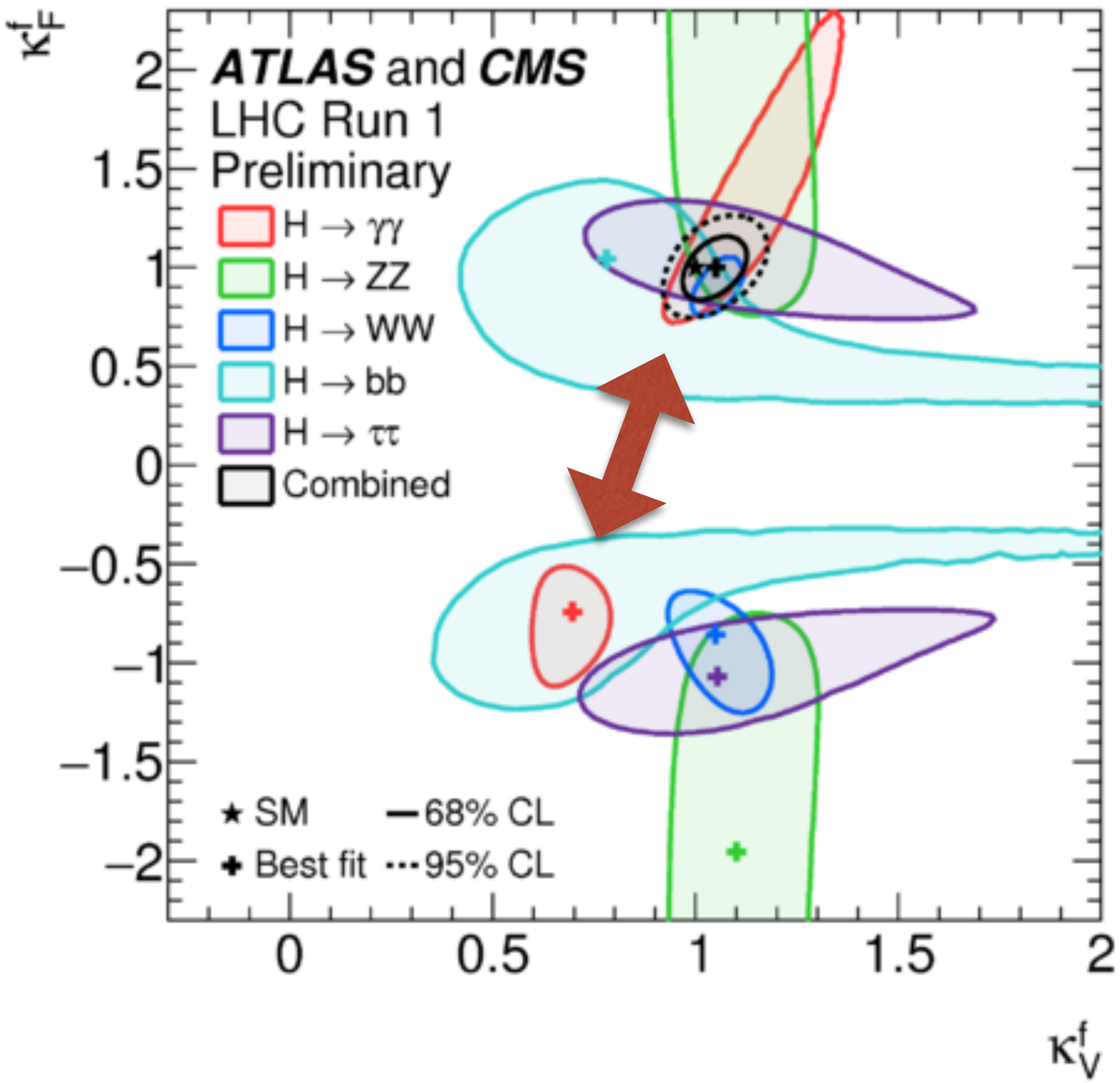
$$\kappa_V = \kappa_W = \kappa_Z$$

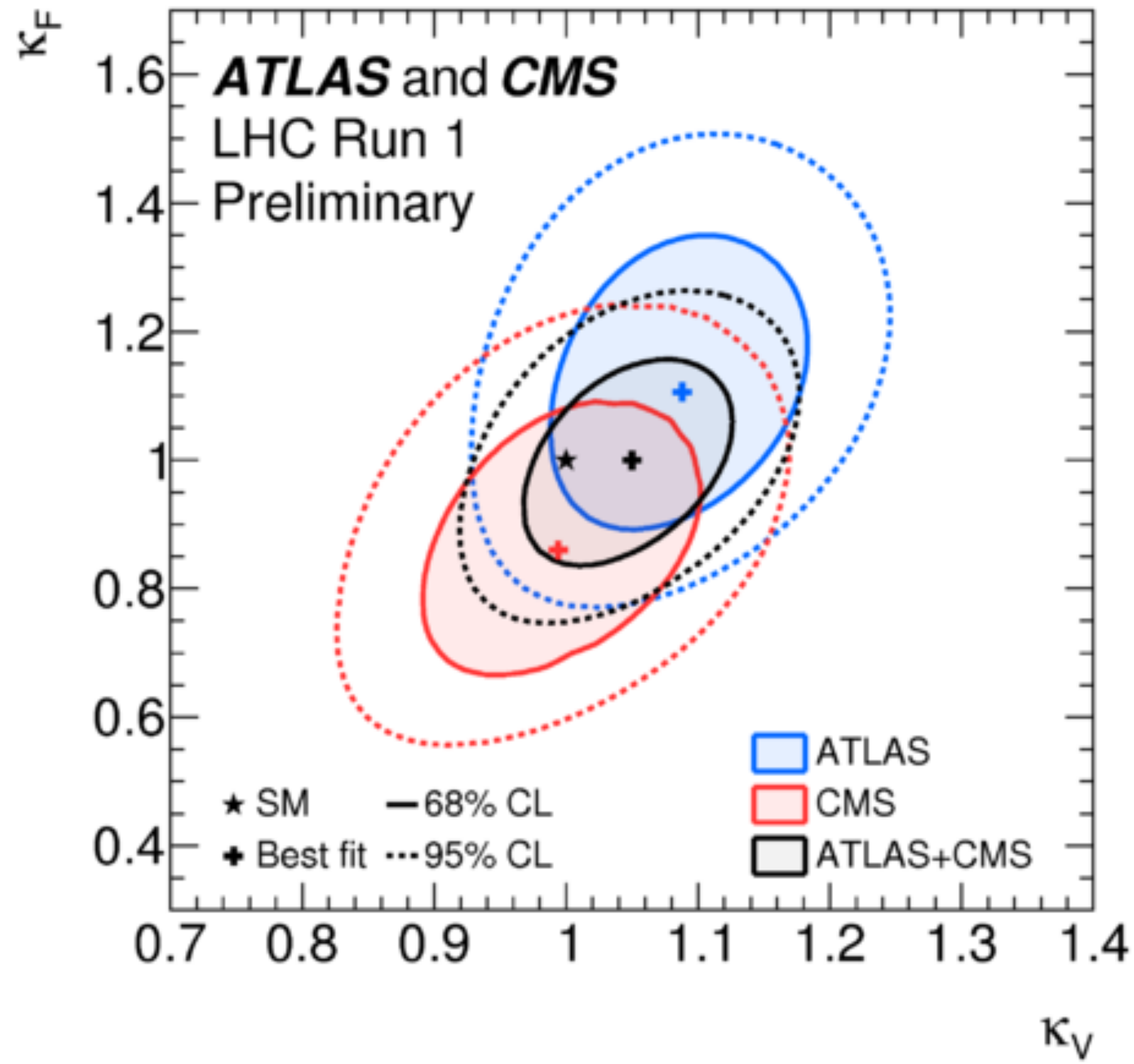
$$\kappa_V = \kappa_\tau = \kappa_t$$

e.g. to test boson vs fermion

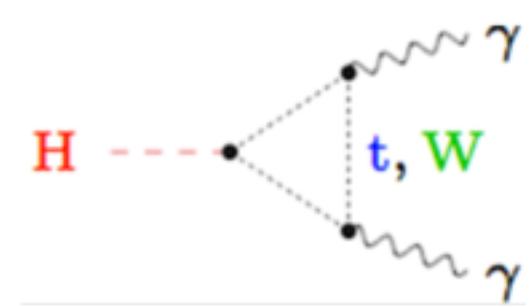
Higgs boson couplings

Define κ_V positive: most processes are **not** sensitive to relative sign of κ_F





Destructive interference in **H→γγ**
decay loop breaks degeneracy



Higgs boson couplings

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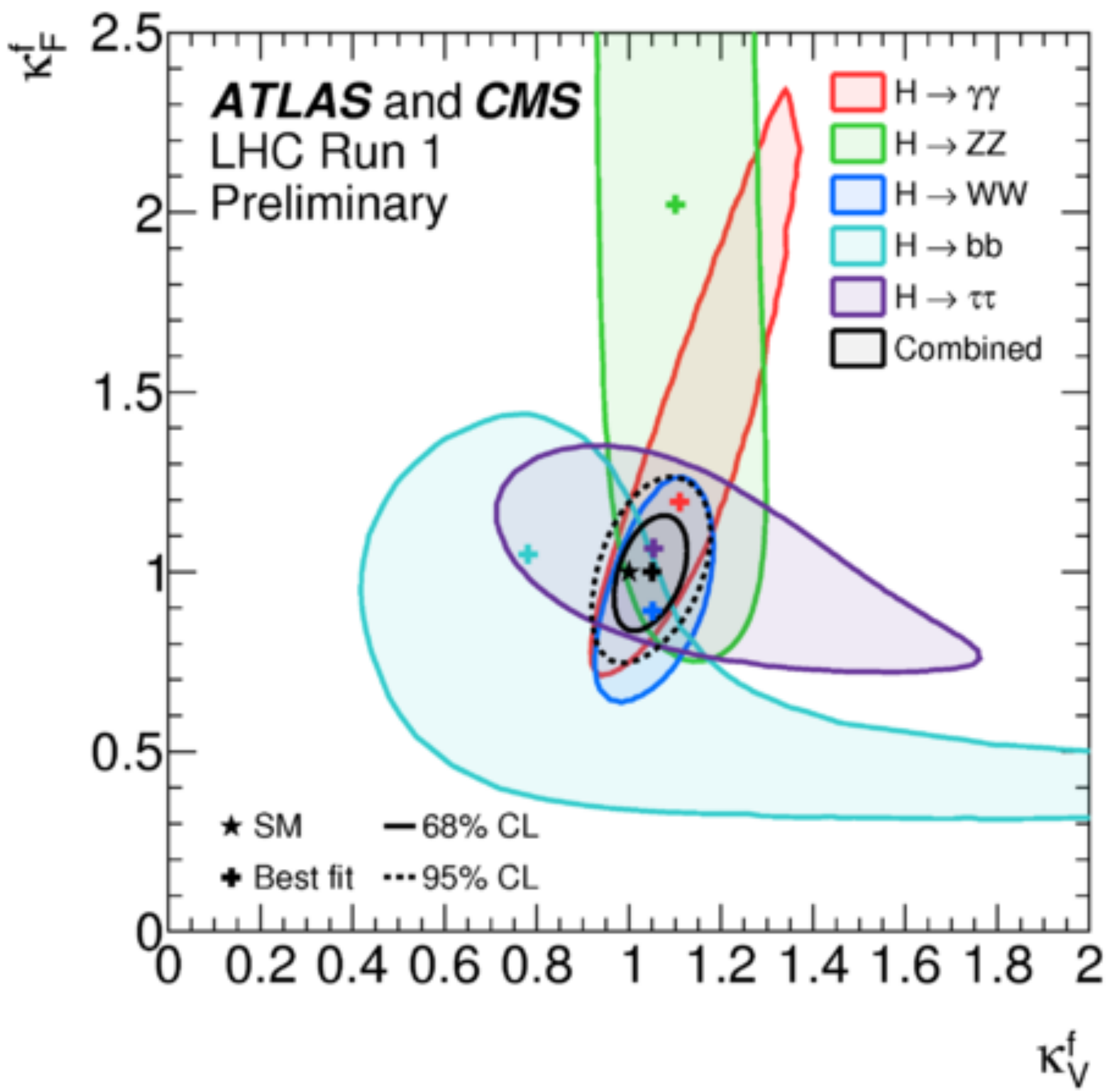
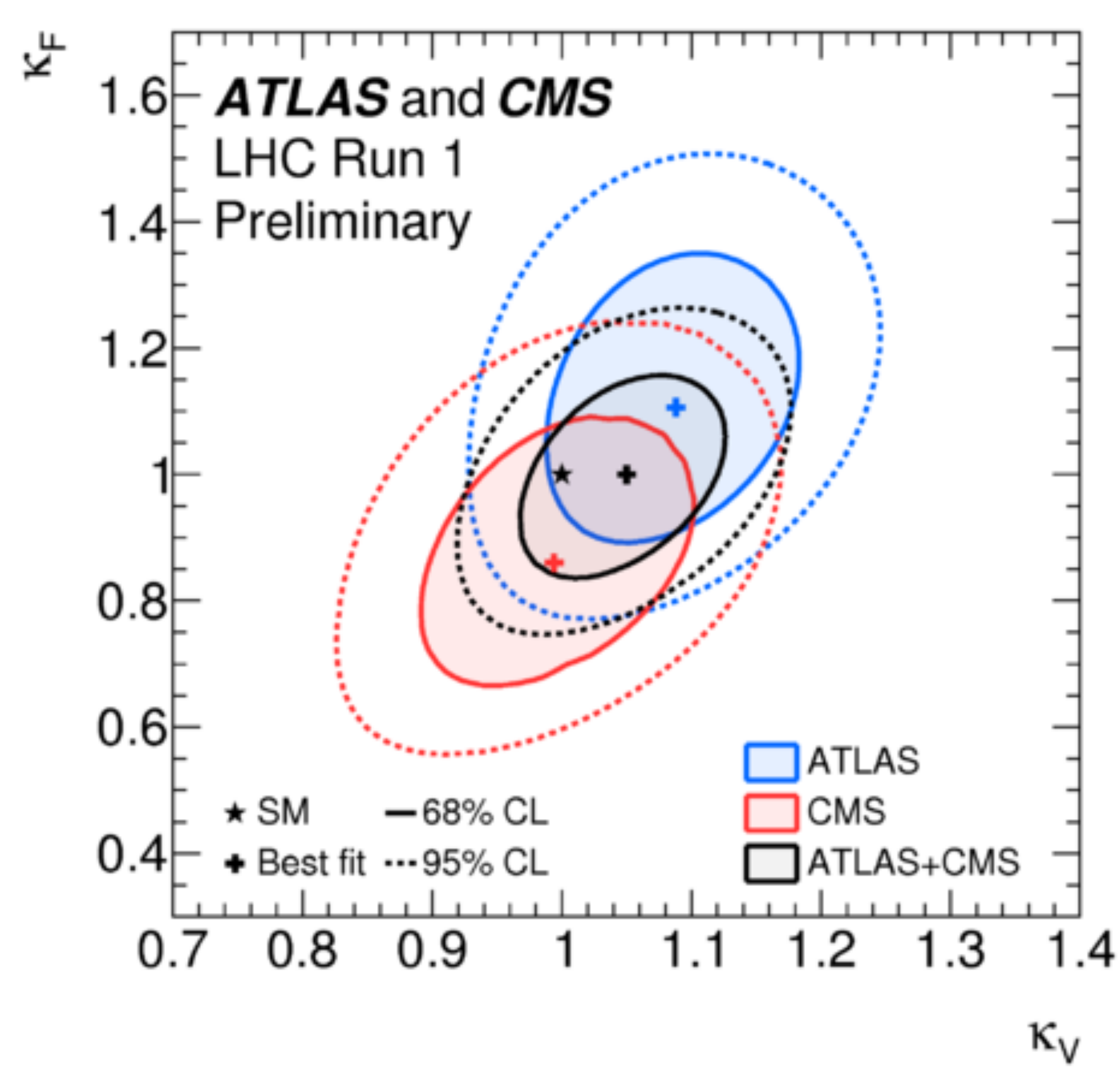
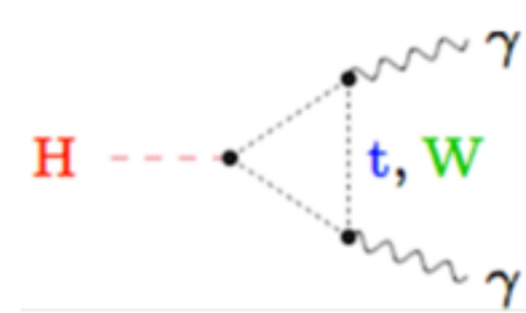
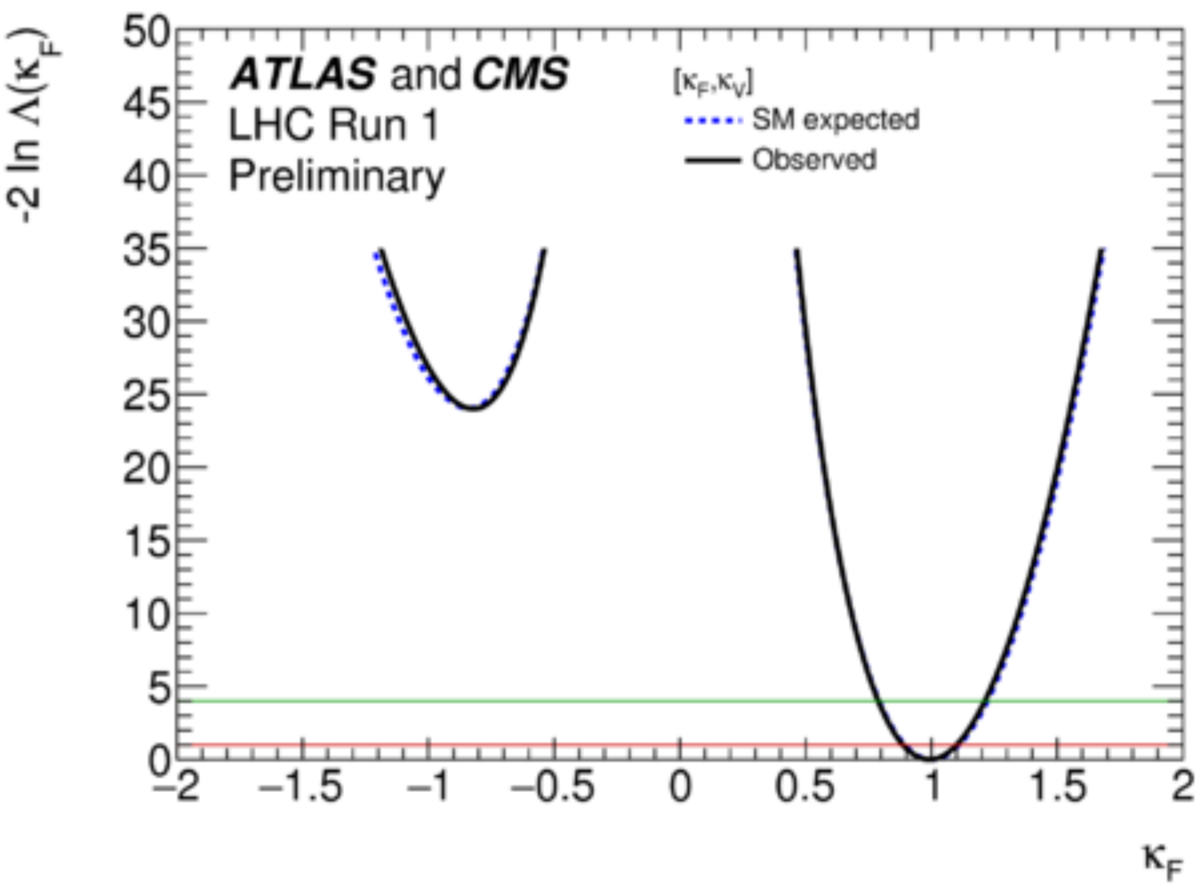


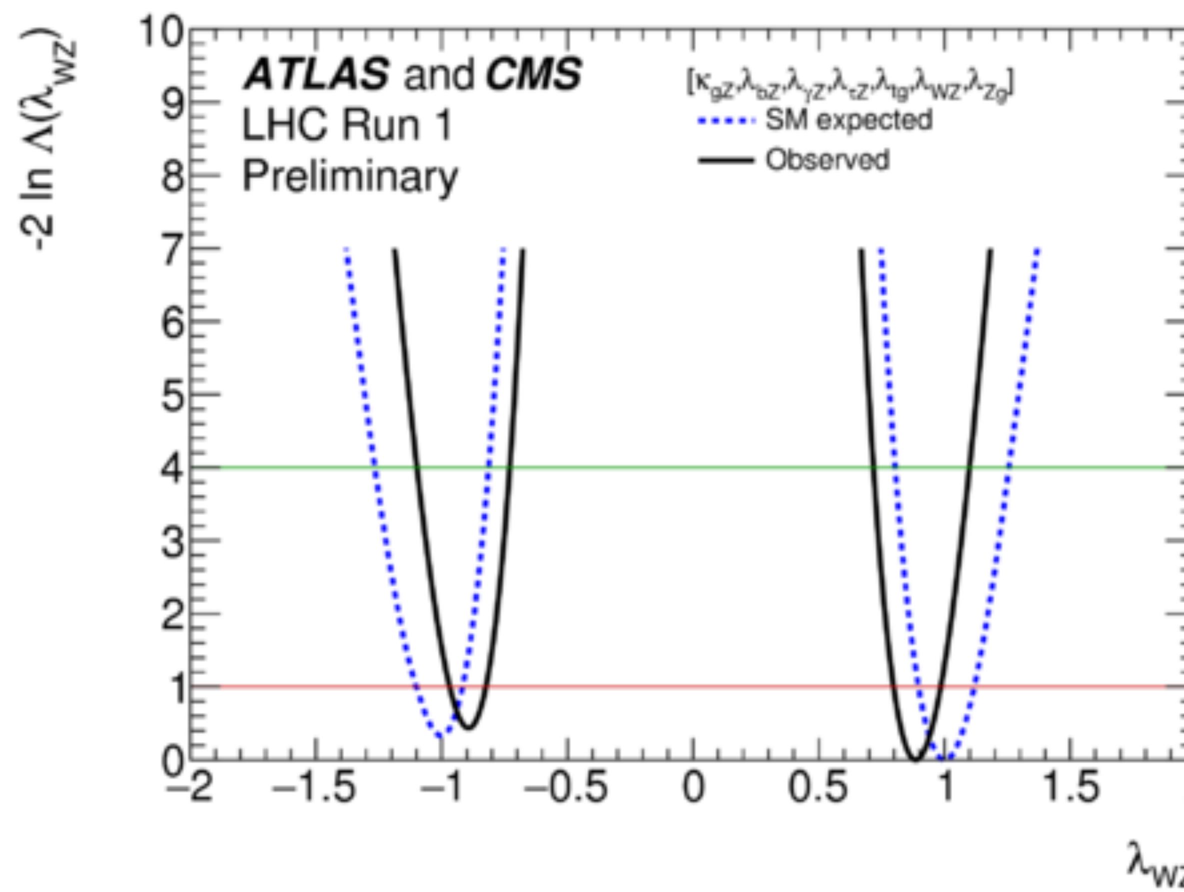


Destructive interference in **H→γγ** decay loop breaks degeneracy



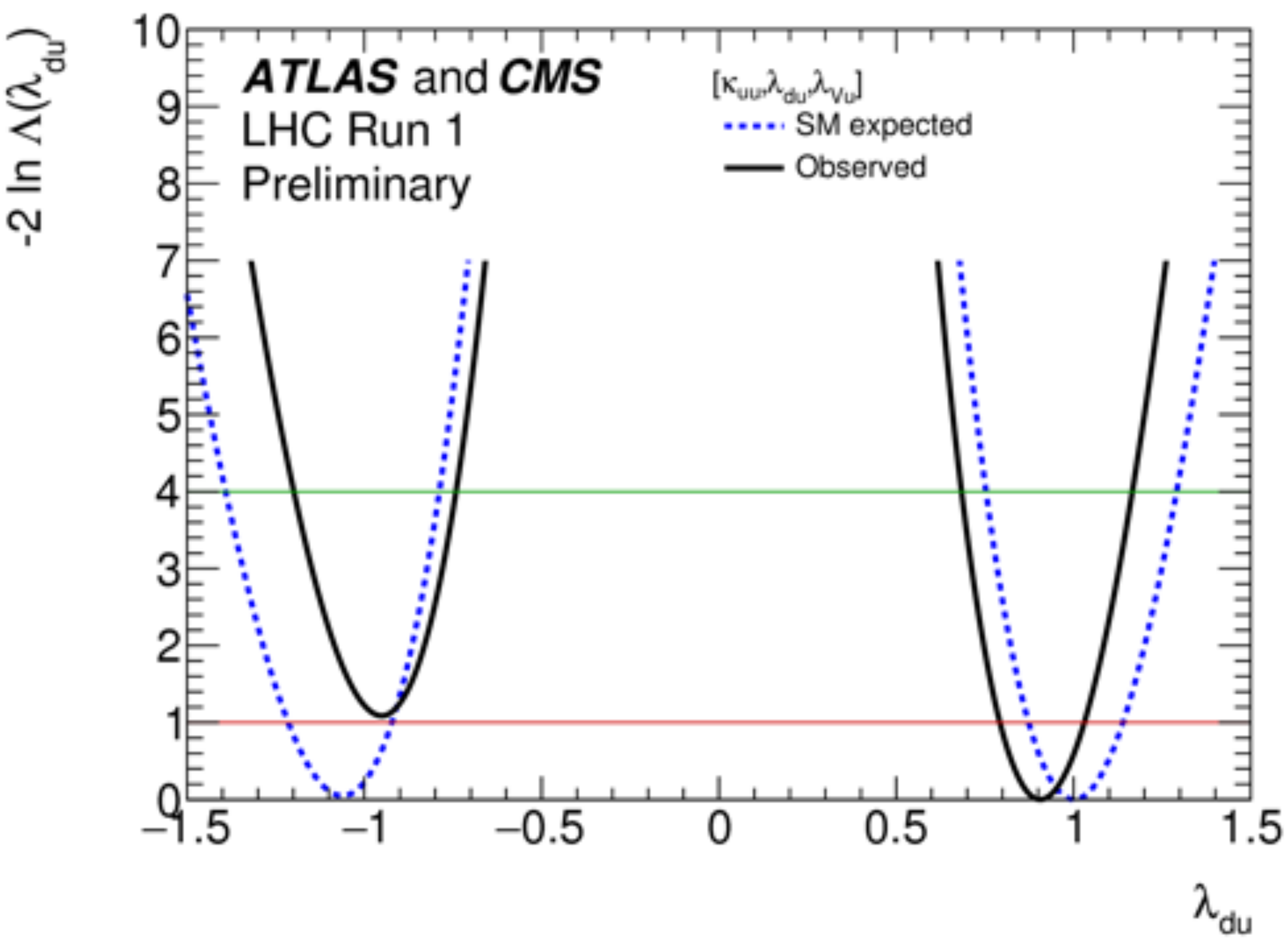
Higgs boson coupling



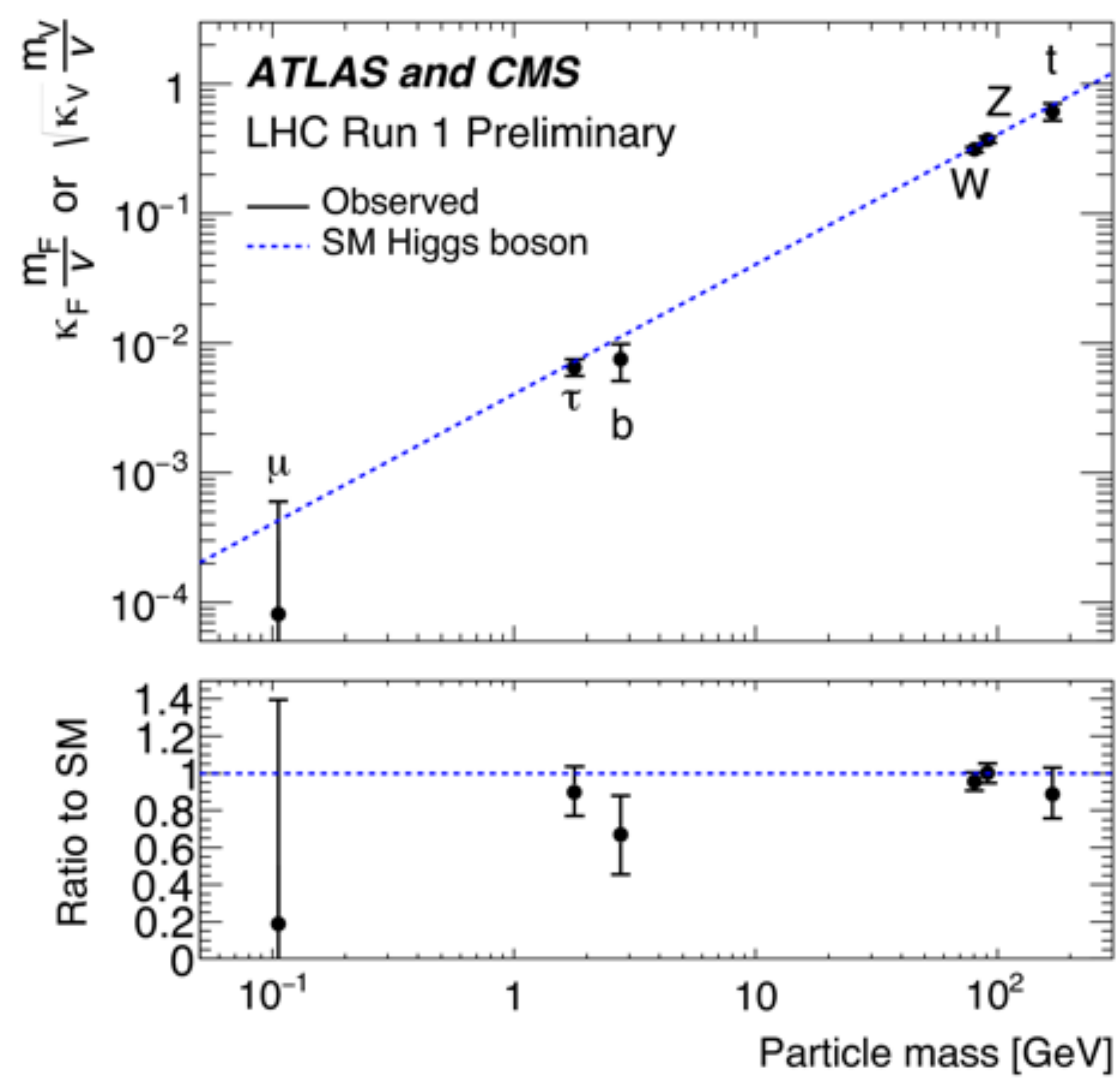


$\lambda_{WZ} = \kappa_W / \kappa_Z$

Higgs boson coupling

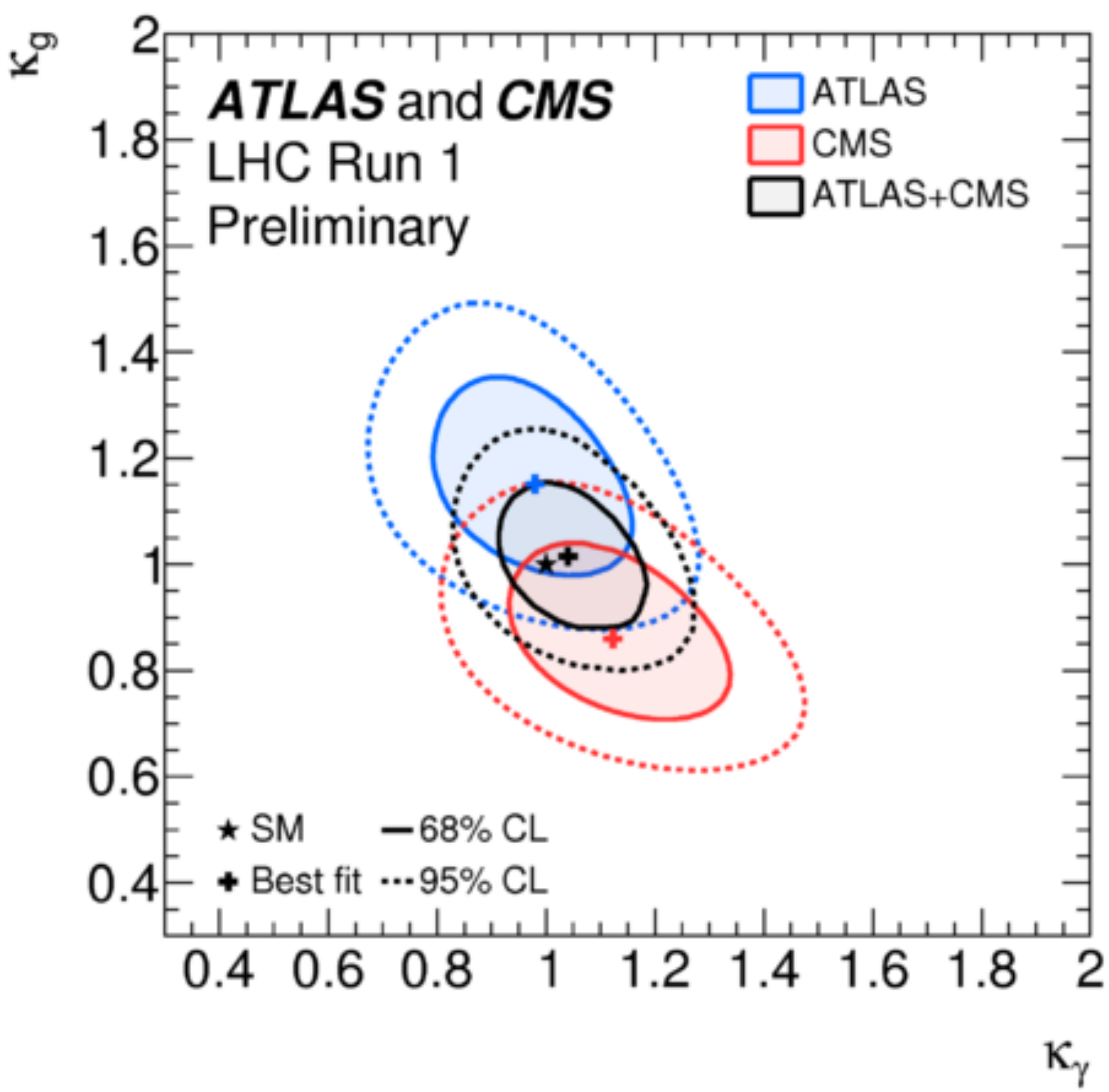


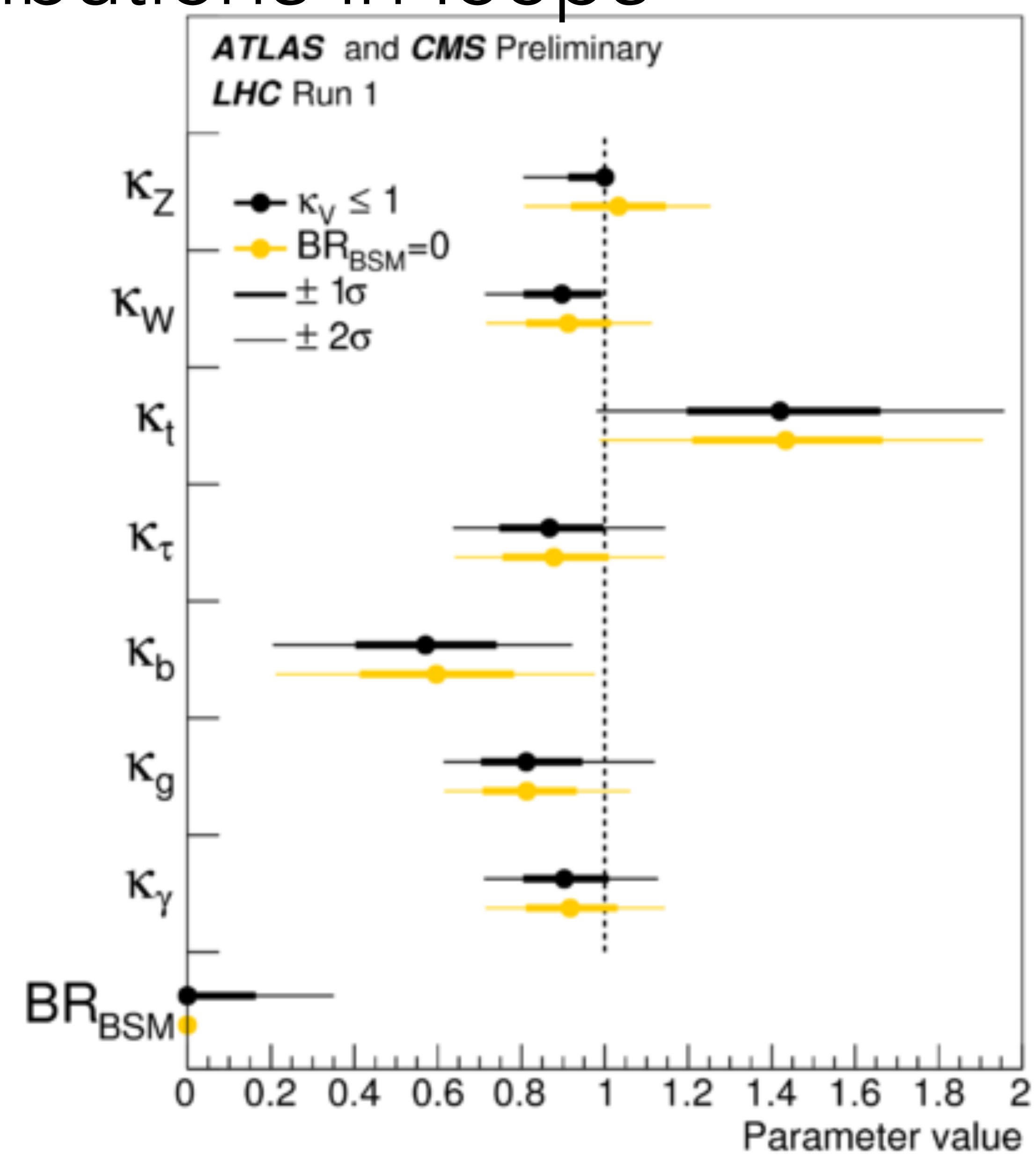
Test down-type to up-type fermion coupling



Non-SM contributions?

Effective Higgs-gluon or Higgs-photon couplings can be altered by non-SM contributions in loops





Consistent with SM

Spin and parity

Portrait of Peter Higgs by Ken Currie, 2008

- SM Prediction for the Higgs boson: $J^P = 0^+$
- Simple Alternate Hypotheses:
  Pseudoscalar: $J^P = 0^-$
  Vector, Pseudovector: $J^P = 1^-, 1^+$
  Tensor/Pseudotensor: $J^P = 2^{+/-}$
- Complex Alternate Hypotheses: admixture state
  i.e. $|\text{Higgs}\rangle = \alpha\,|\text{even-parity}\rangle + \beta\,|\text{odd-parity}\rangle$

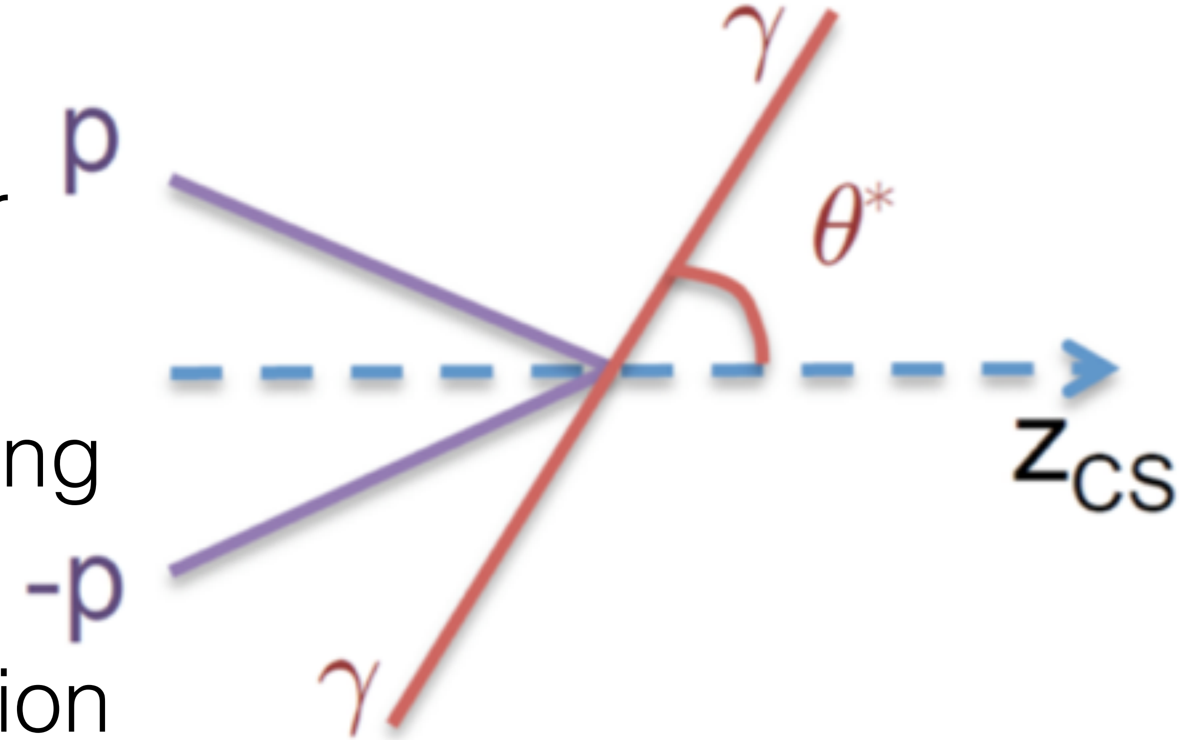
  ????
- Likelihood ratio (based-upon hypotheses) often the final test statistic

NB: Particle is a boson, otherwise decays to $\gamma\gamma$, ZZ,WW (conservation of angular momentum)

Landau-Yang Theorem: $S \neq 1$ if it decays to di-photon

Collins-Soper Frame

- use Higgs boson rest-frame
- define Collins-Soper axis as bisector between two proton vectors
- Collins-Soper angle: between outgoing photon and axis
- minimizes effect of initial state radiation

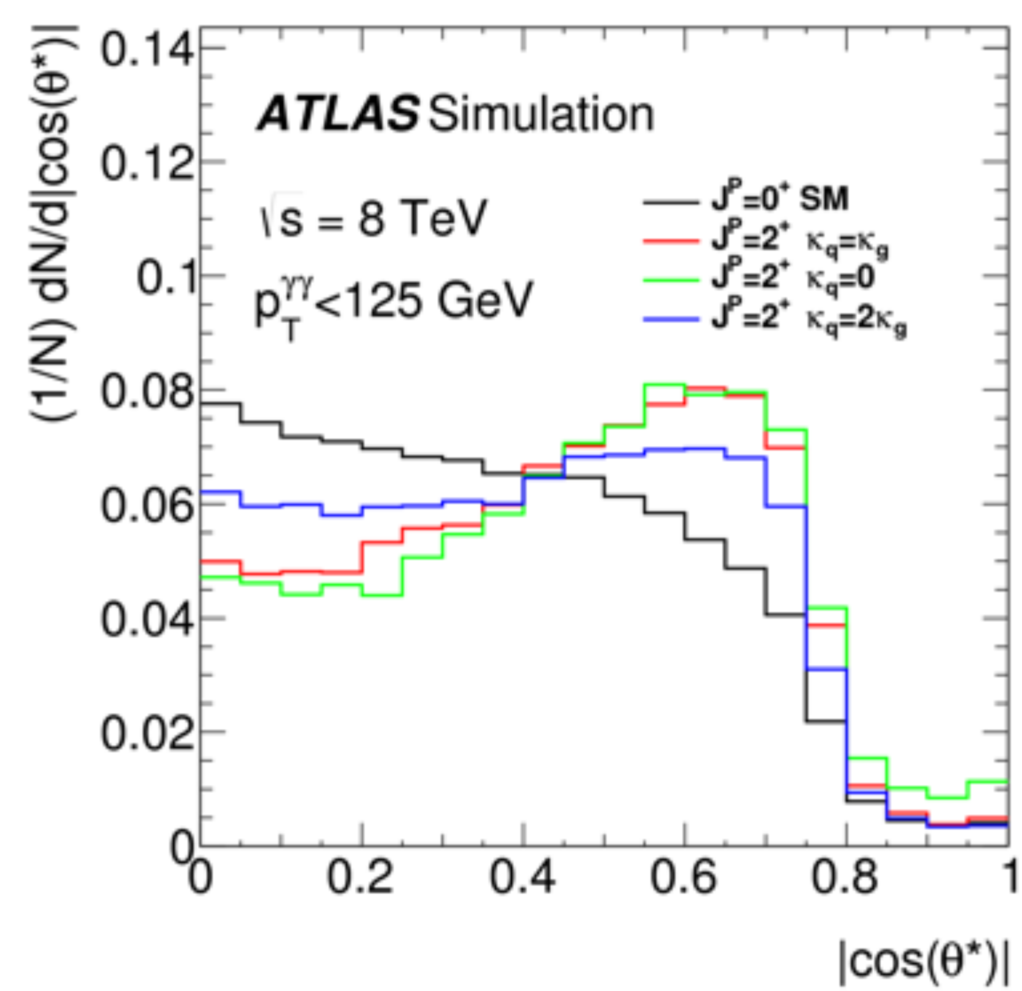


$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}}\frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

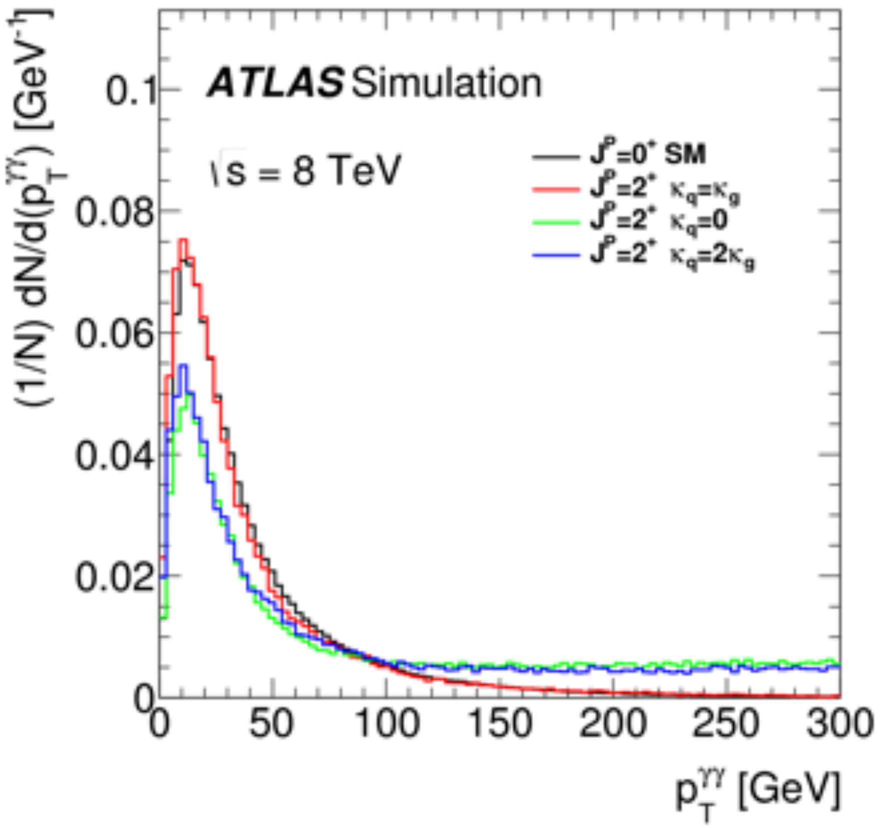
Before selection:
S=0: isotropic (flat distribution)
S=2: depends on qq/gg fractions

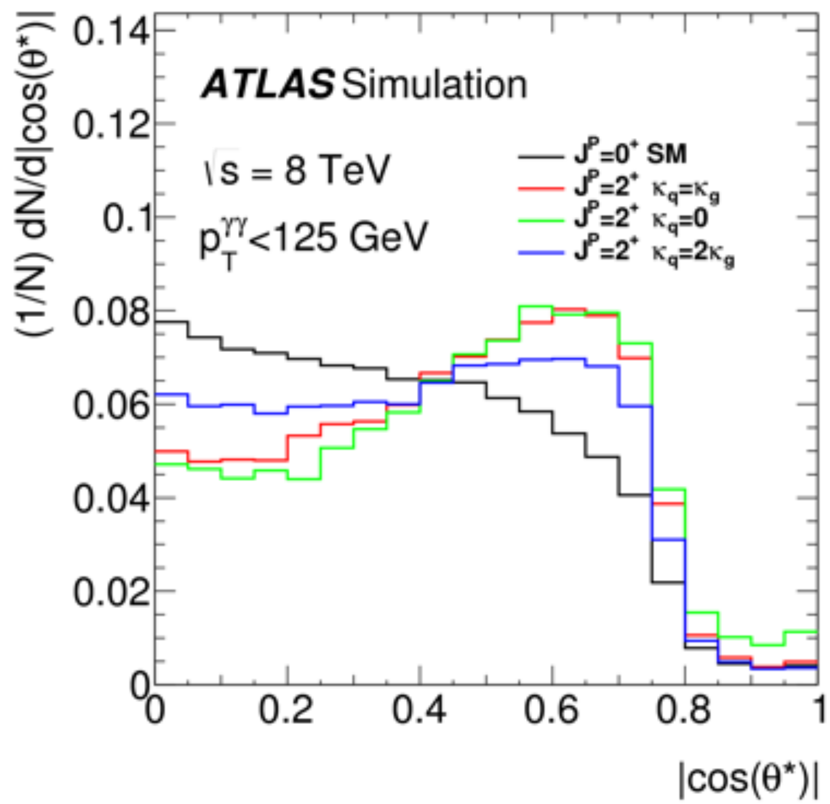
$$100\%\ gg\ :\ \frac{dN}{d\cos\theta^*} = 1 - 6\cos^2\theta^* + \cos^4\theta^*$$

$$100\%\ q\bar{q}\ :\ \frac{dN}{d\cos\theta^*} = 1 - \cos^4\theta^*$$



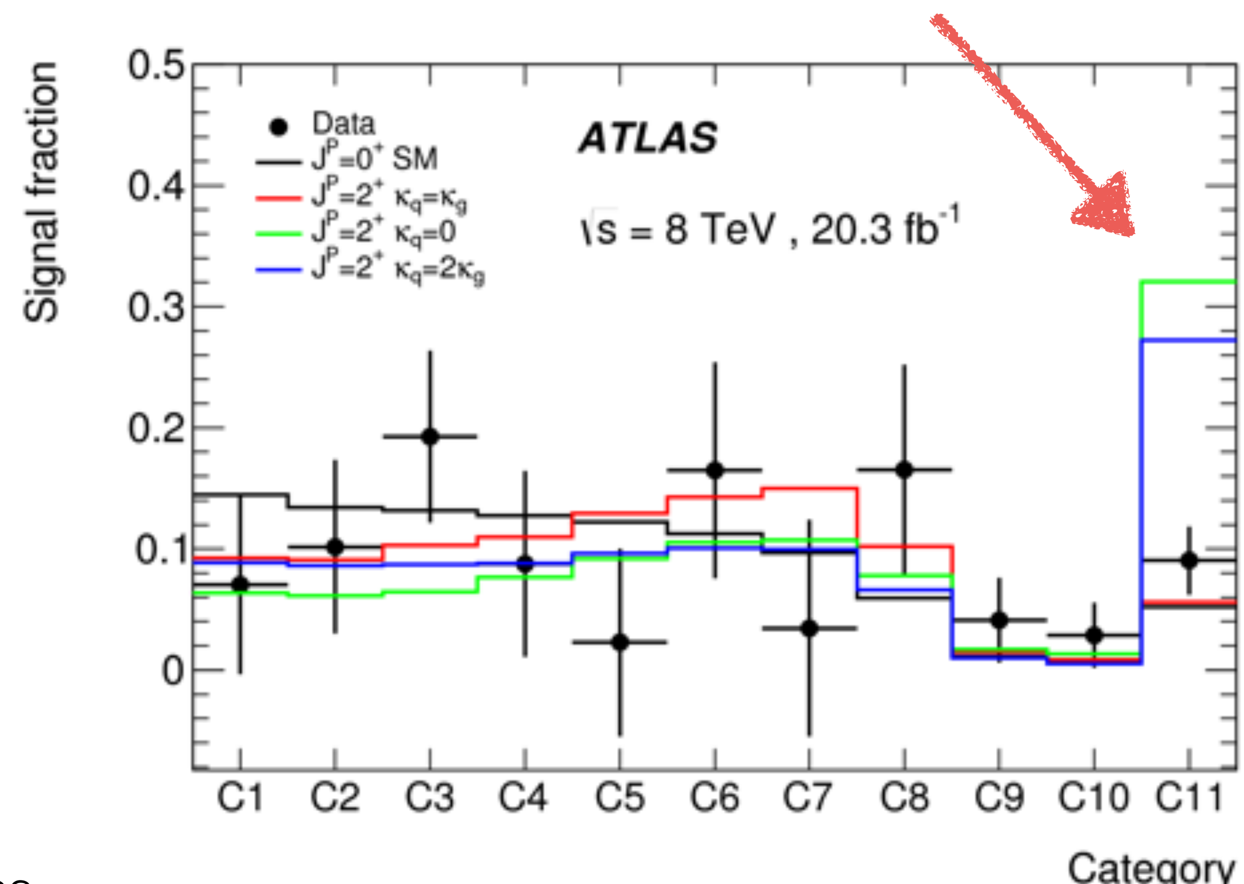
Distributions





Check distributions of p_T $^{\gamma\gamma}$ and $|\cos(\theta^*)|$

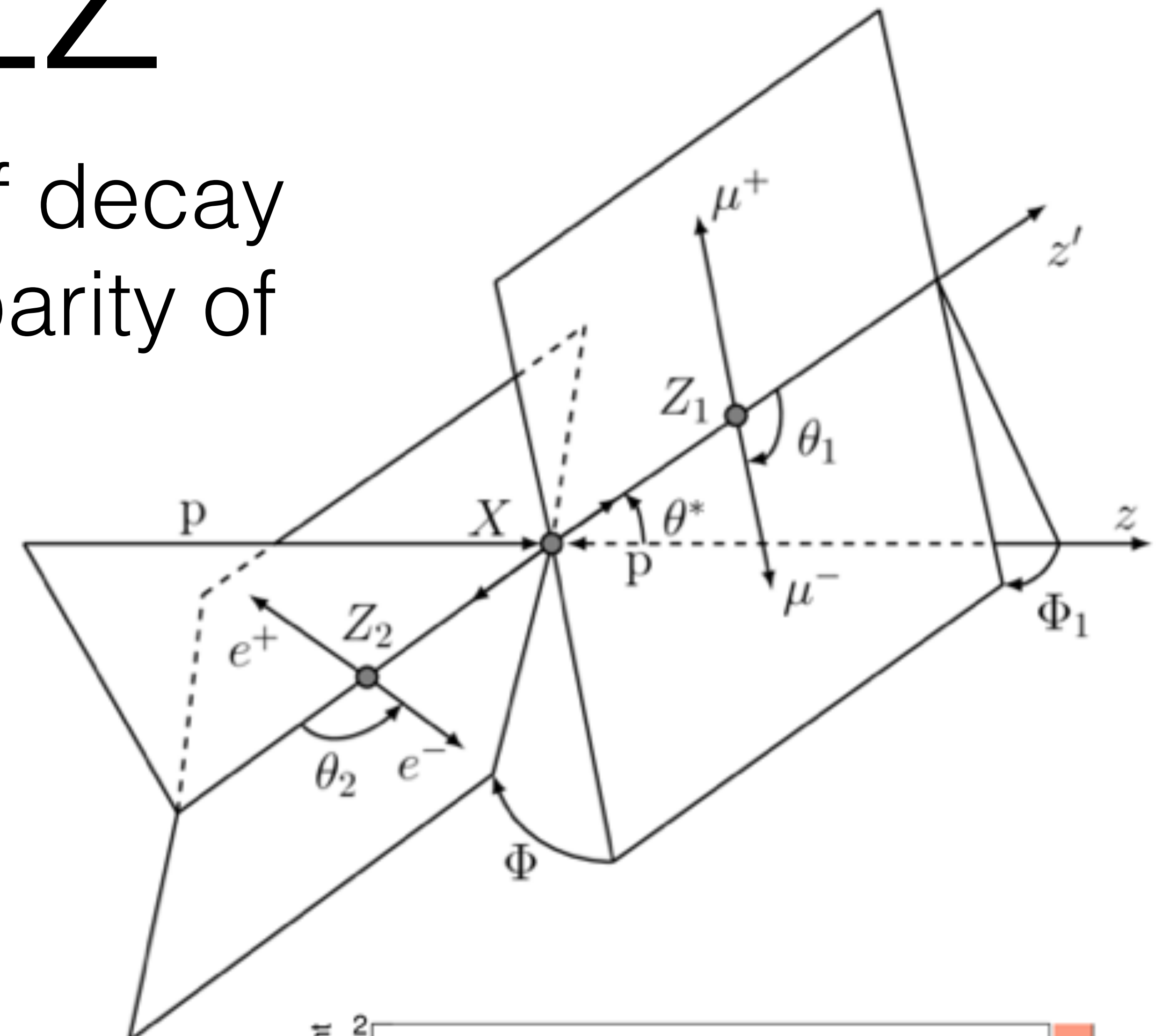
high p_T category



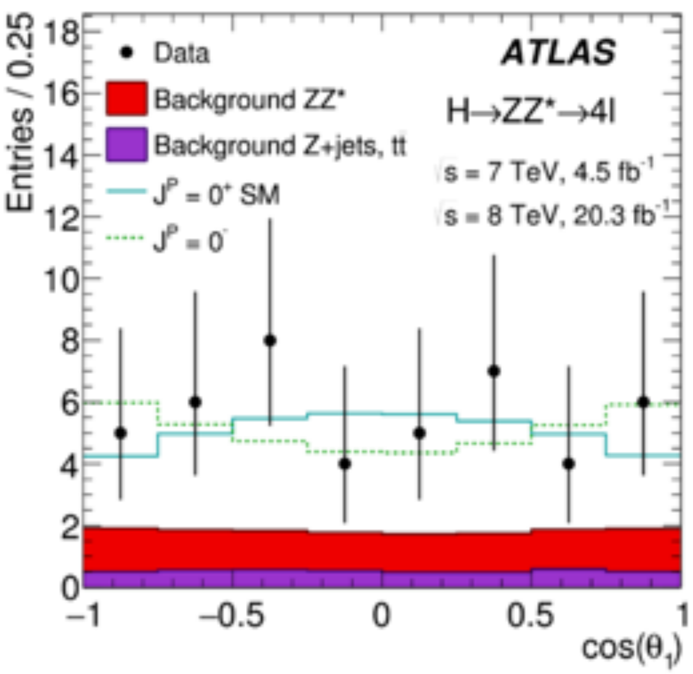
Use background subtracted distributions

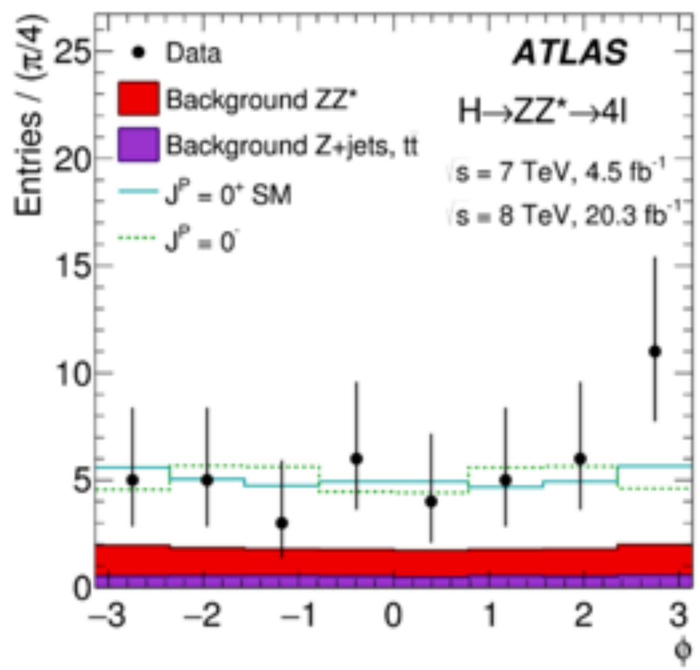
Form LLH ratio for hypothesis

H→ZZ

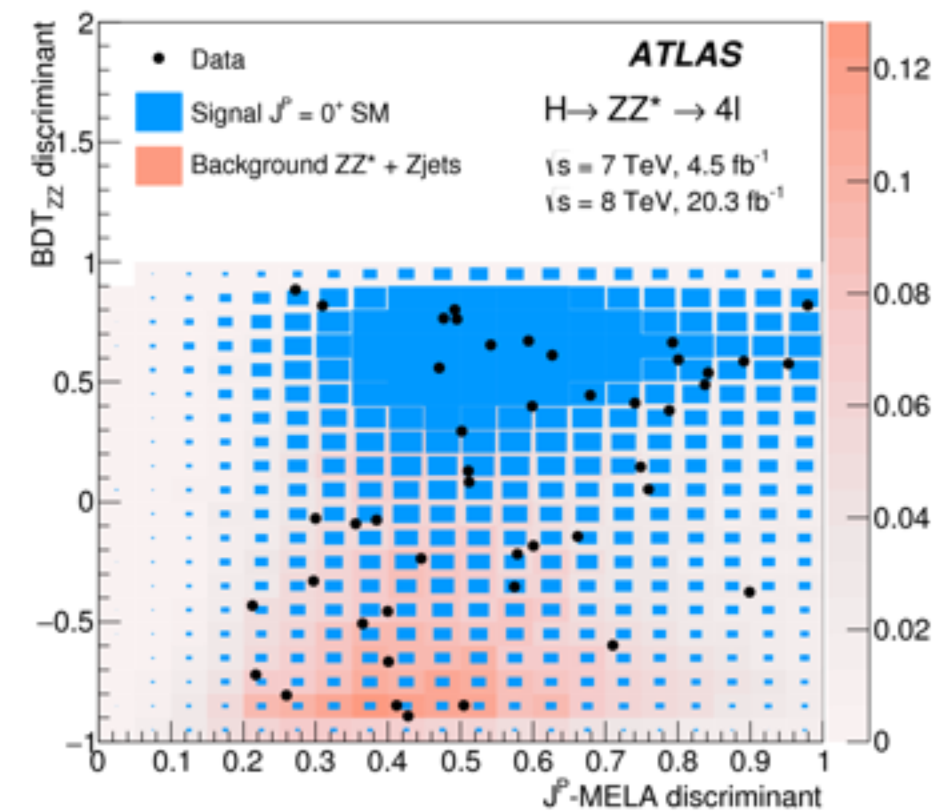


Exploit full angular correlations of decay products, very sensitive to spin/parity of parent particle

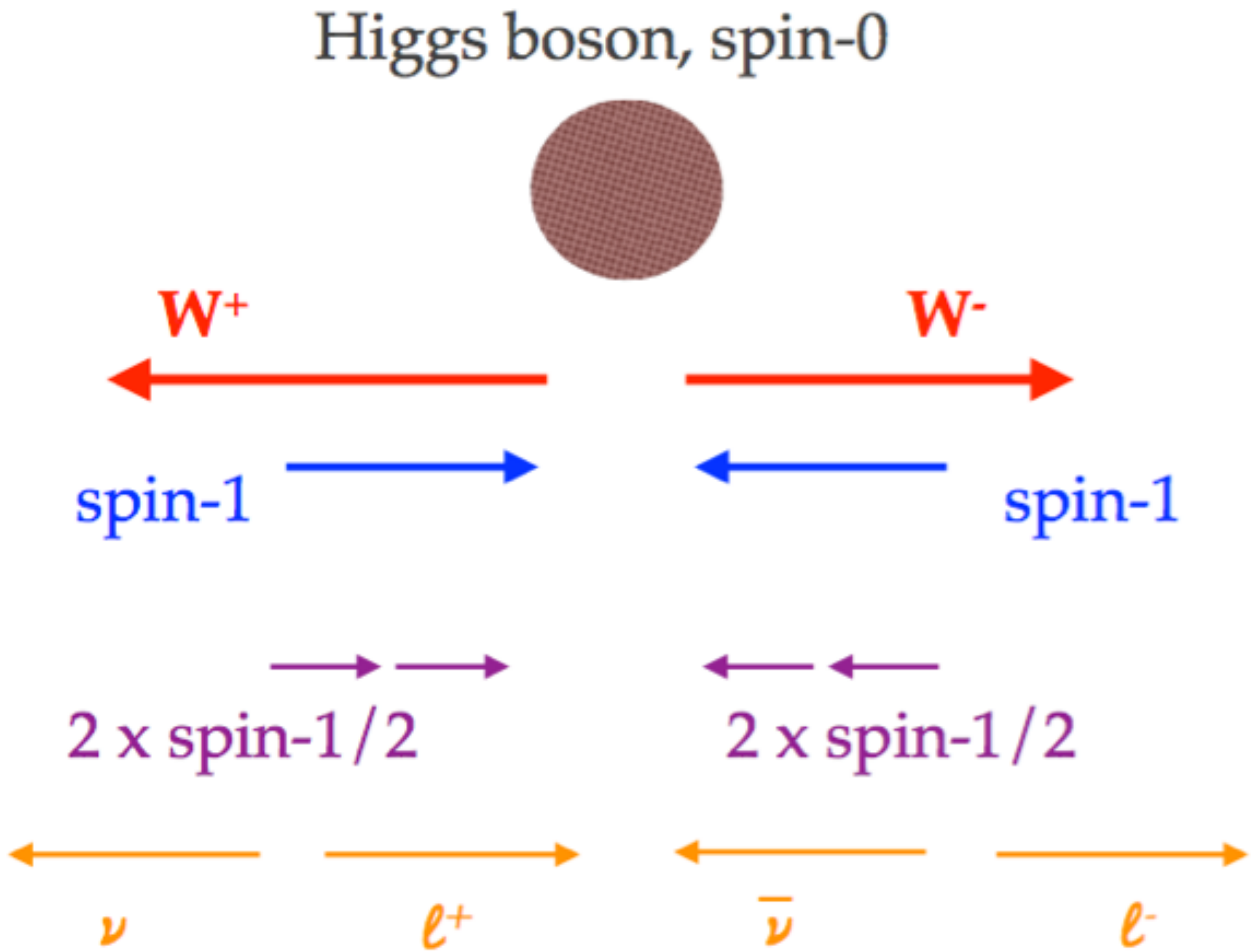


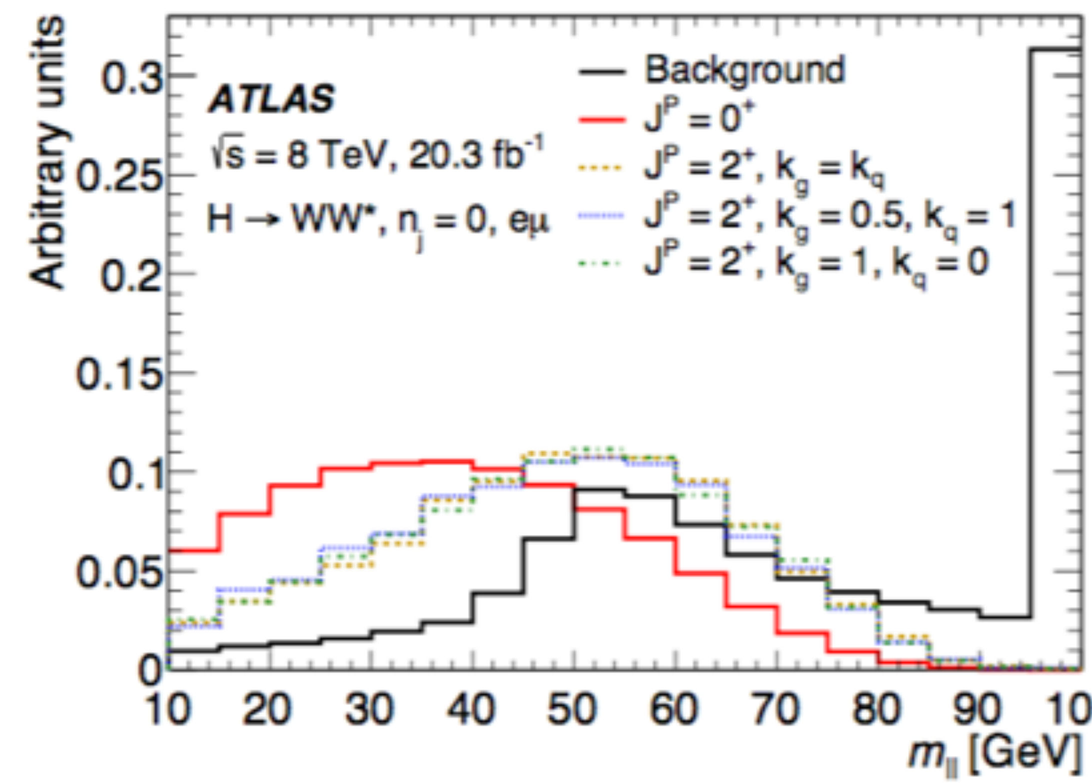


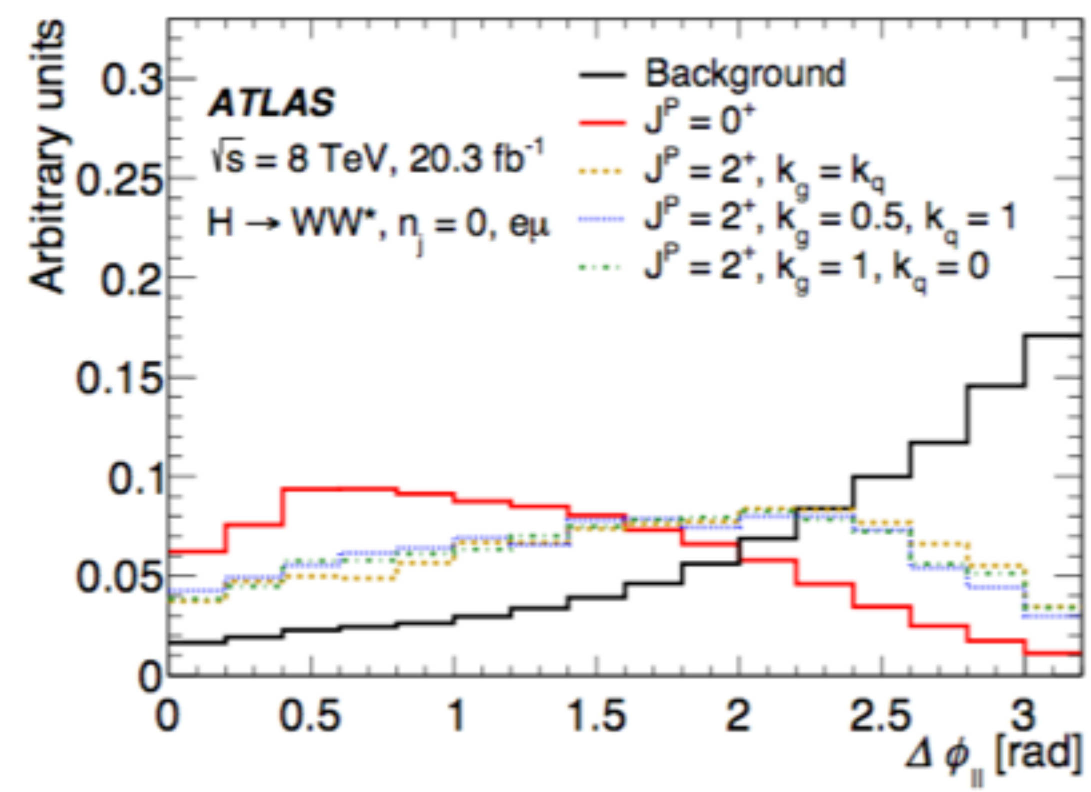
Combine kinematics into MV-discriminant
train in different hypotheses



H→WW



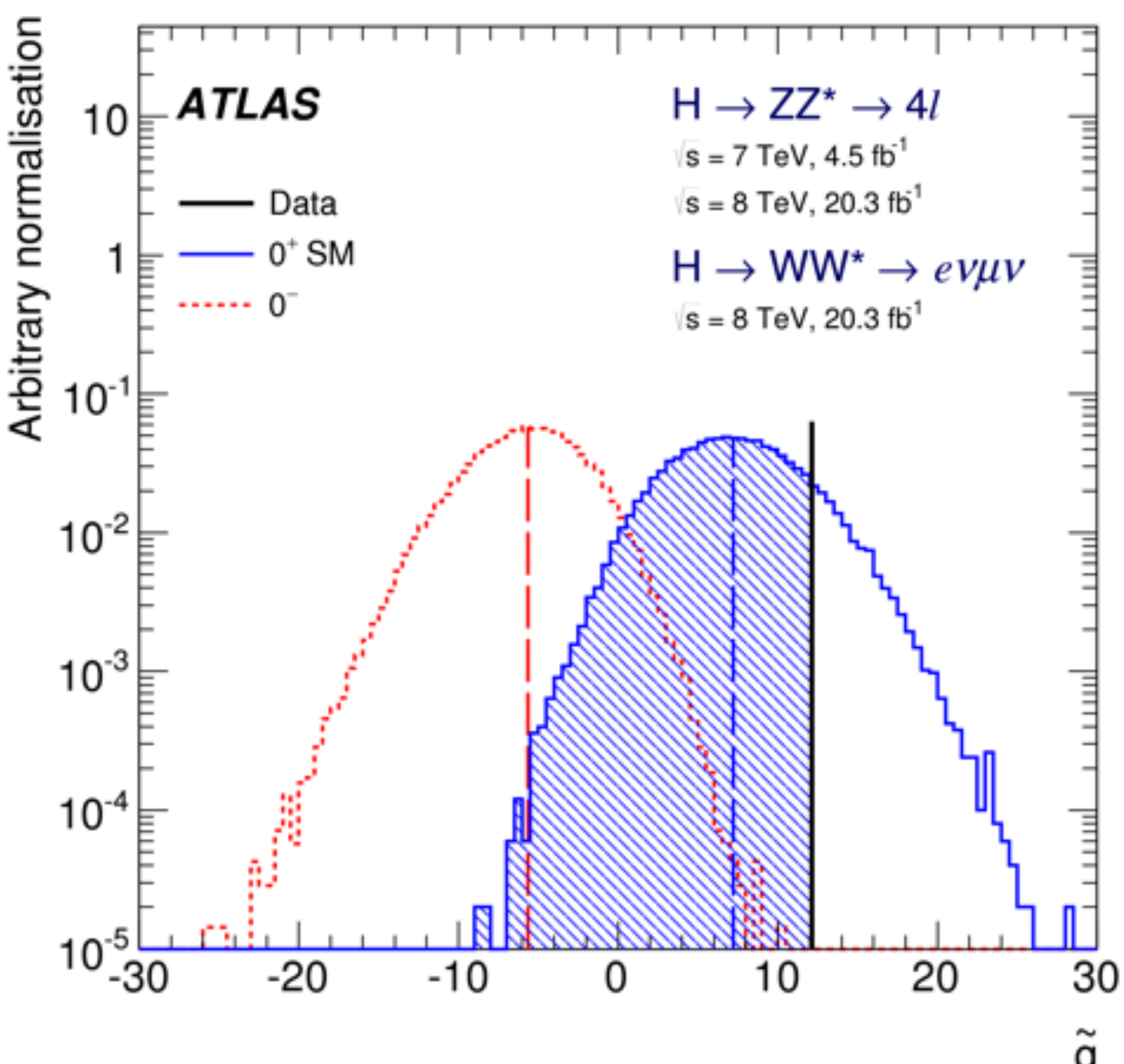


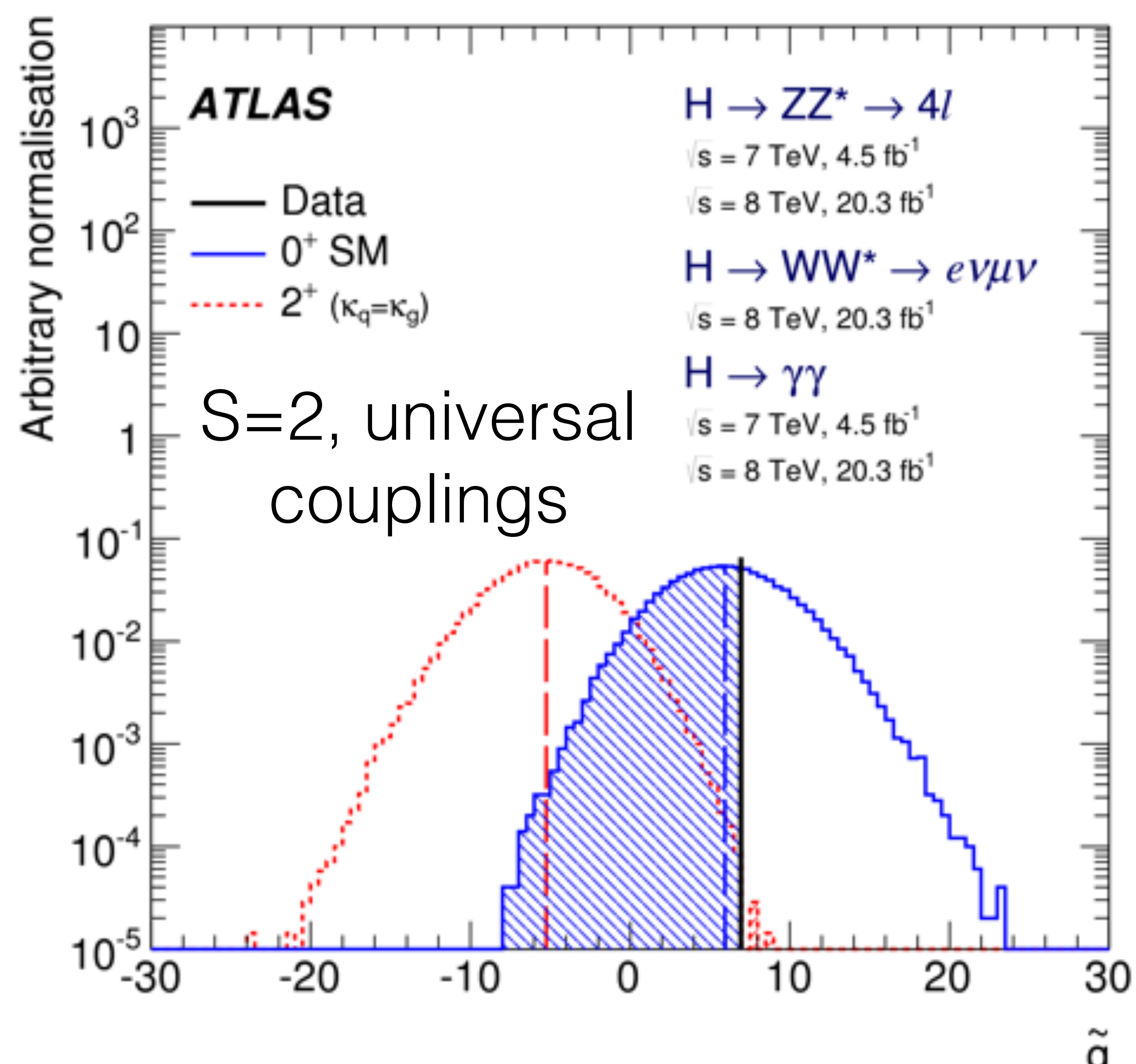


For s=0, both charged leptons emitted in same direction preferentially
—> can be exploited

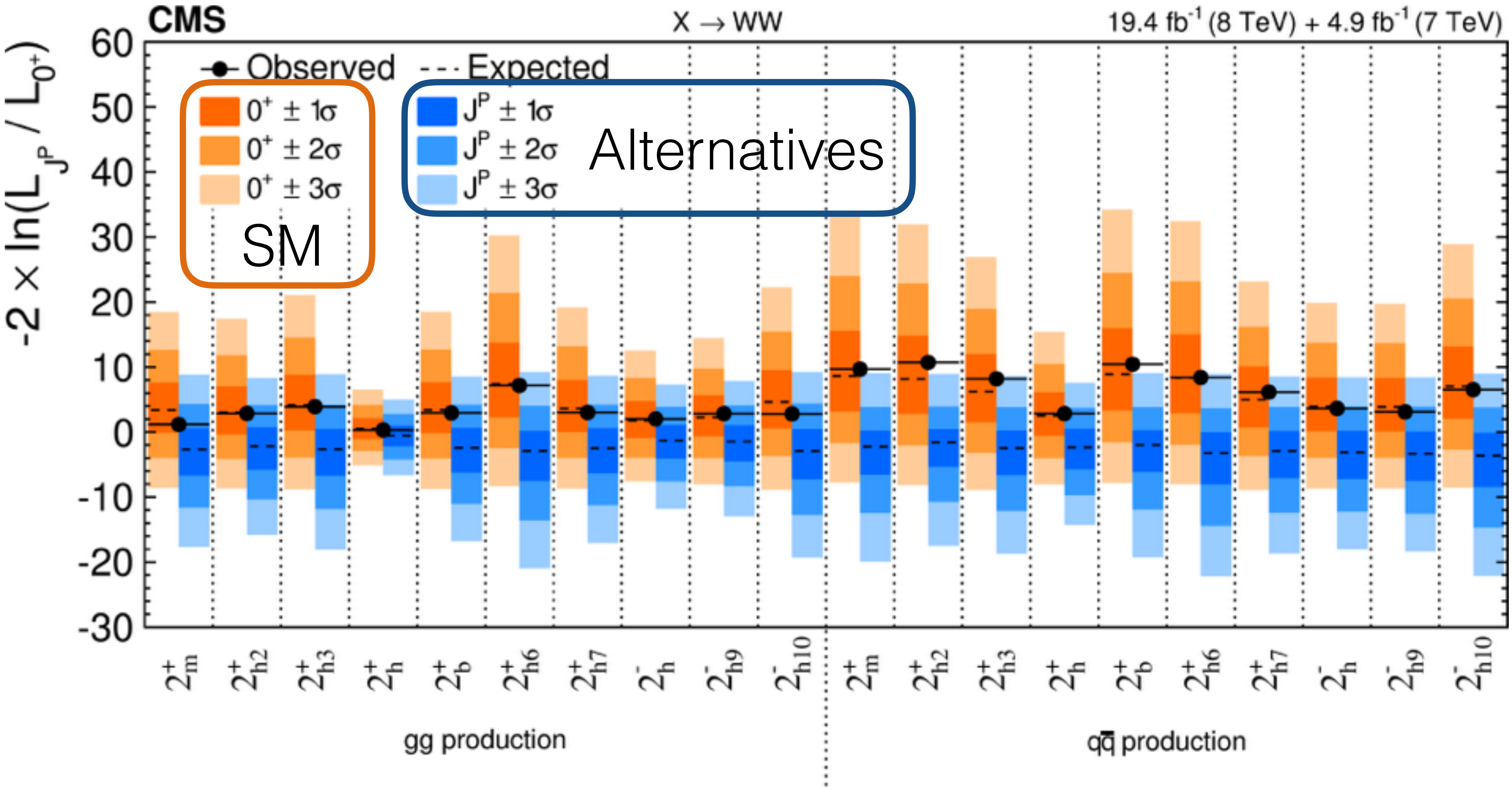
Hypothesis testing

Form likelihood ratios for different hypothesis vs the SM one.
Use CL_S (see last week) to exclude



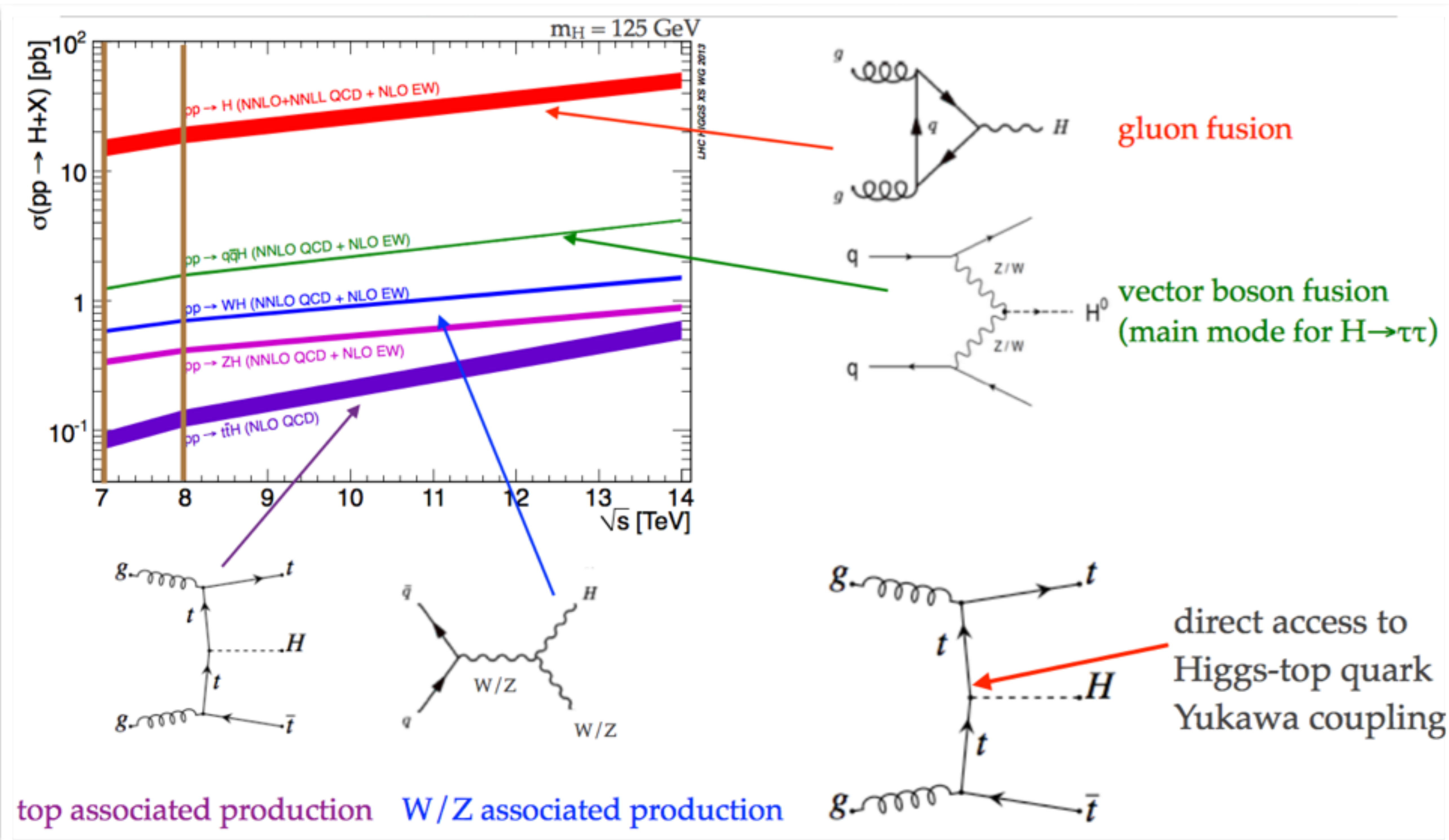


CMS results



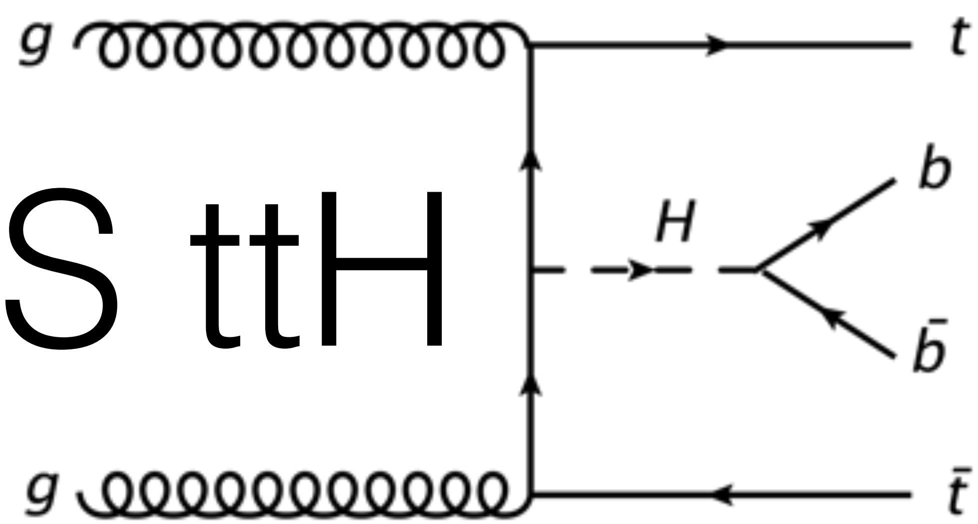
all data point to QNs consistent with the SM Higgs boson
non-SM admixture states not fully excluded

Higgs production and ttH



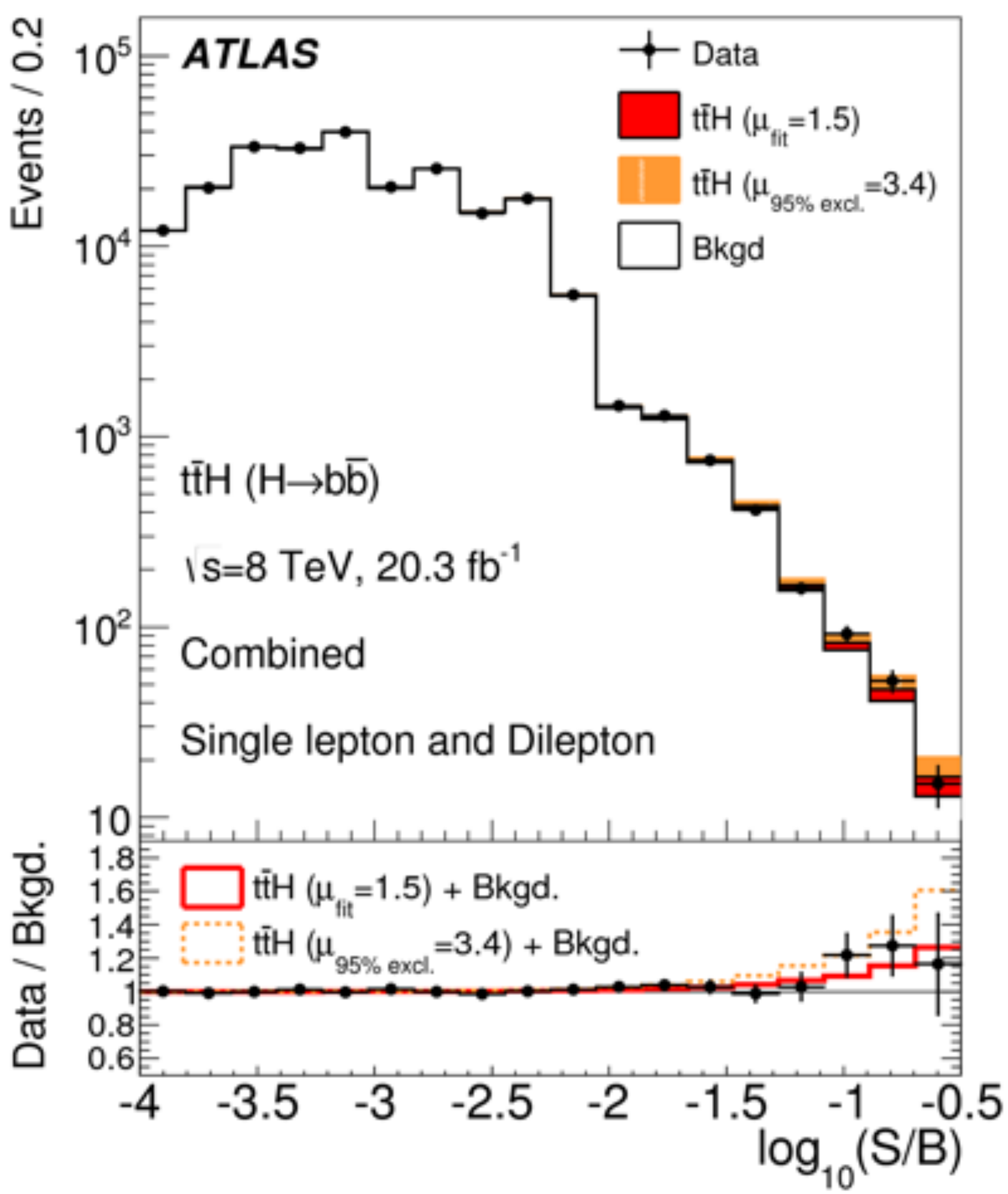
Slide by S. Lai

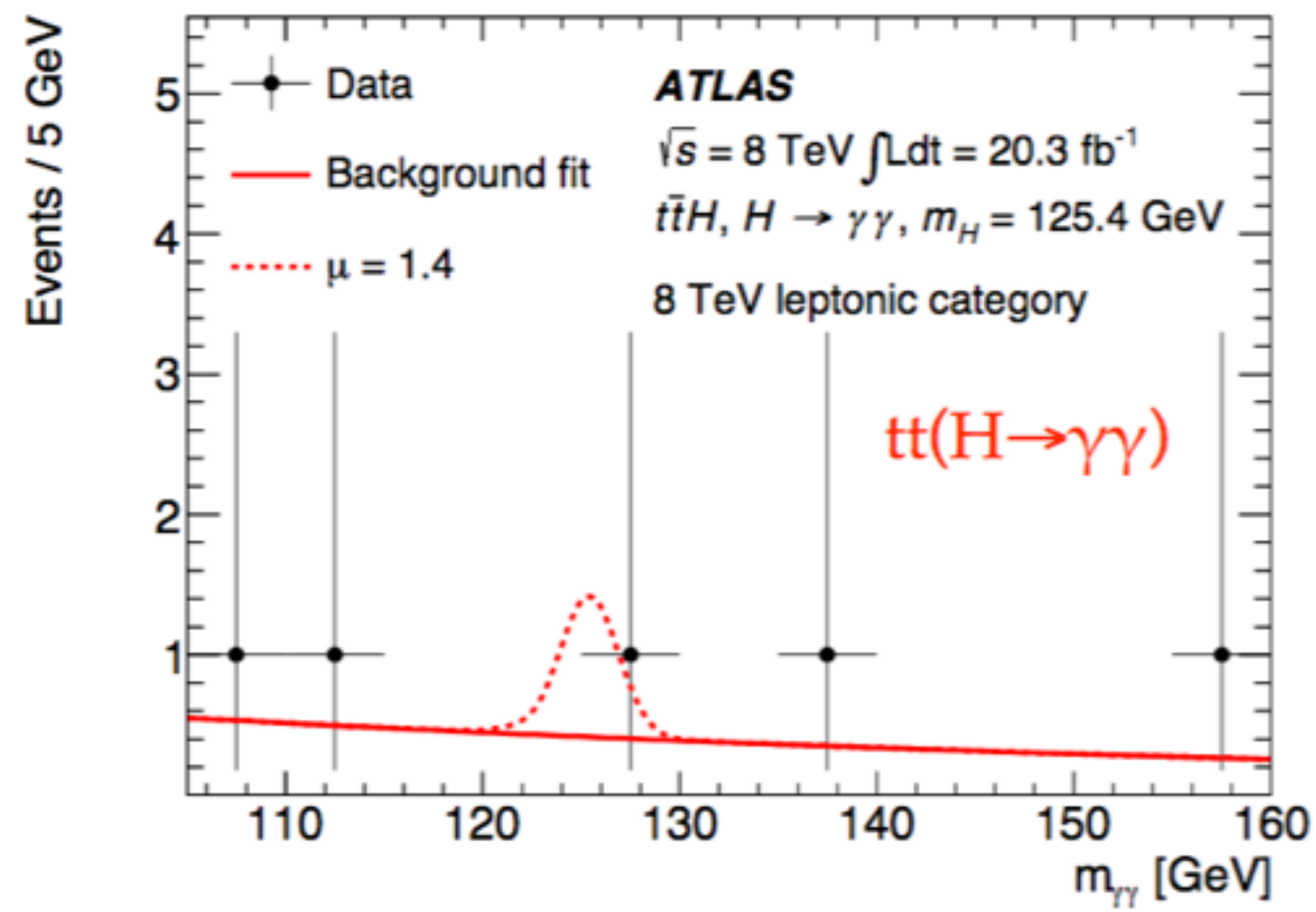
ATLAS ttH



Higgs and 2 tops in final state —> spectacular signature

Problem: low cross-section, top pair background



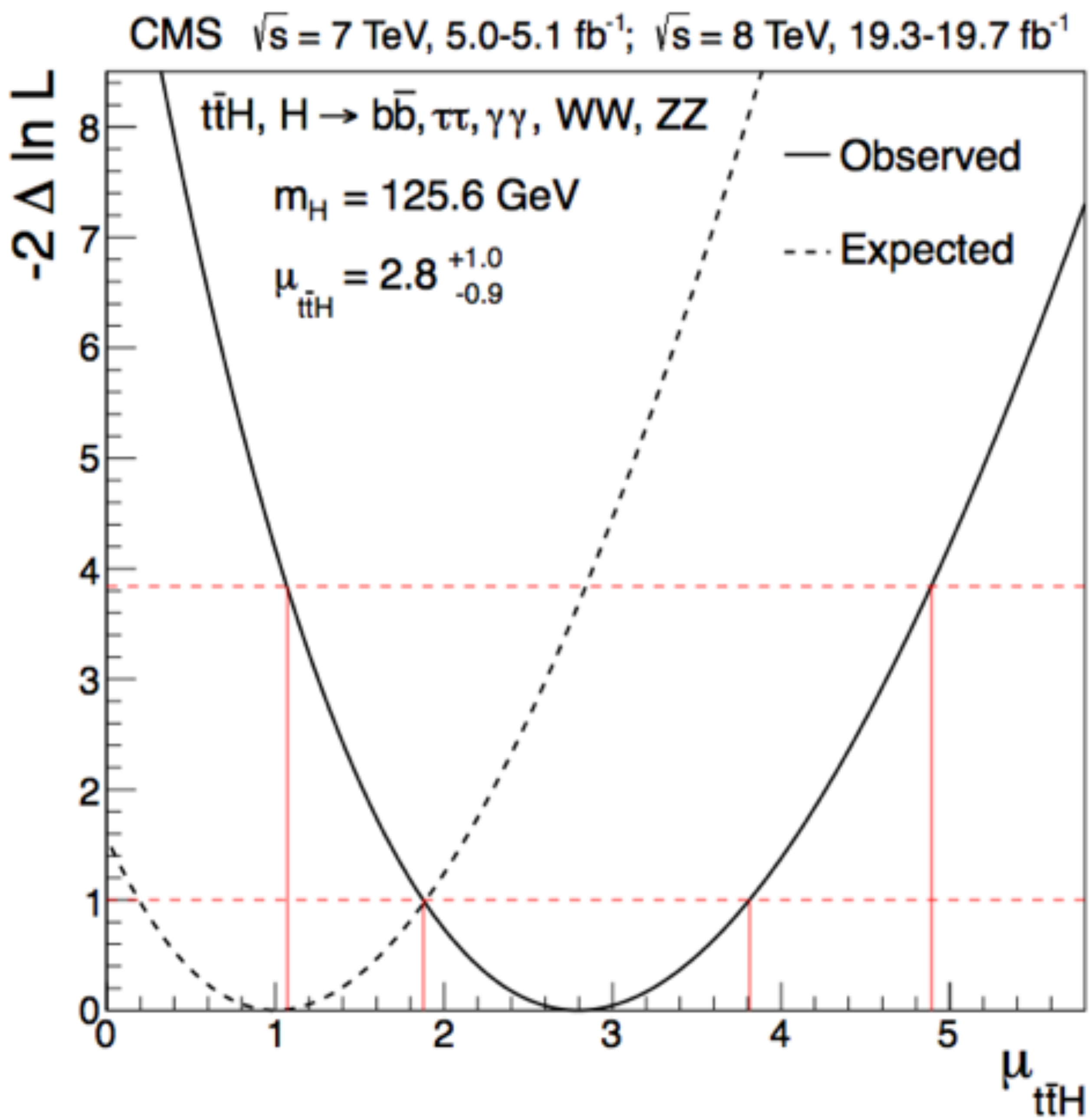


95% observed (expected) limits on signal strength

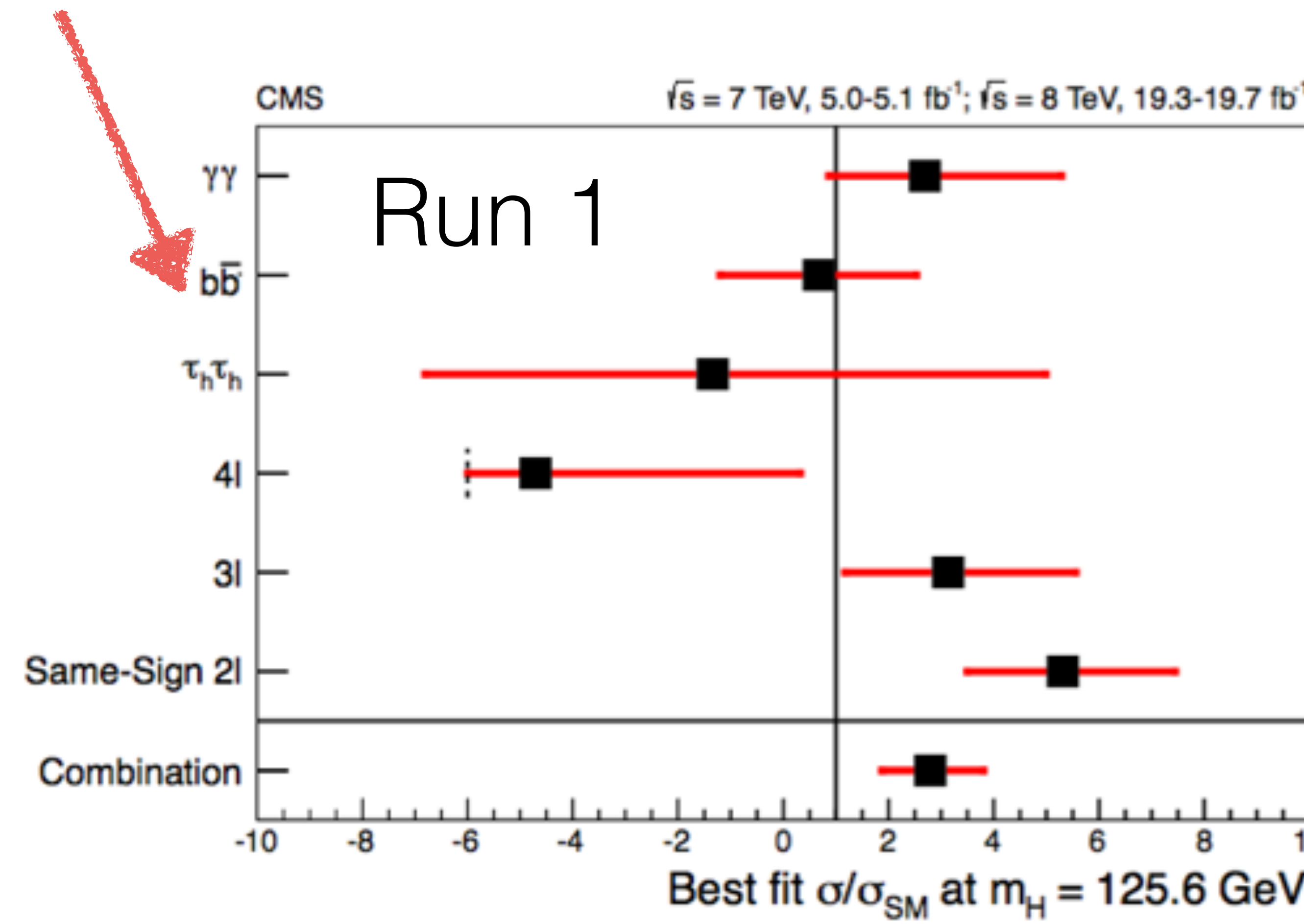
6.7 (4.9) x SM for tt(H→γγ)

4.1 (2.6) x SM for tt(H→bb)

CMS ttH



5 channels: bb, **ττ**, γγ, WW,ZZ

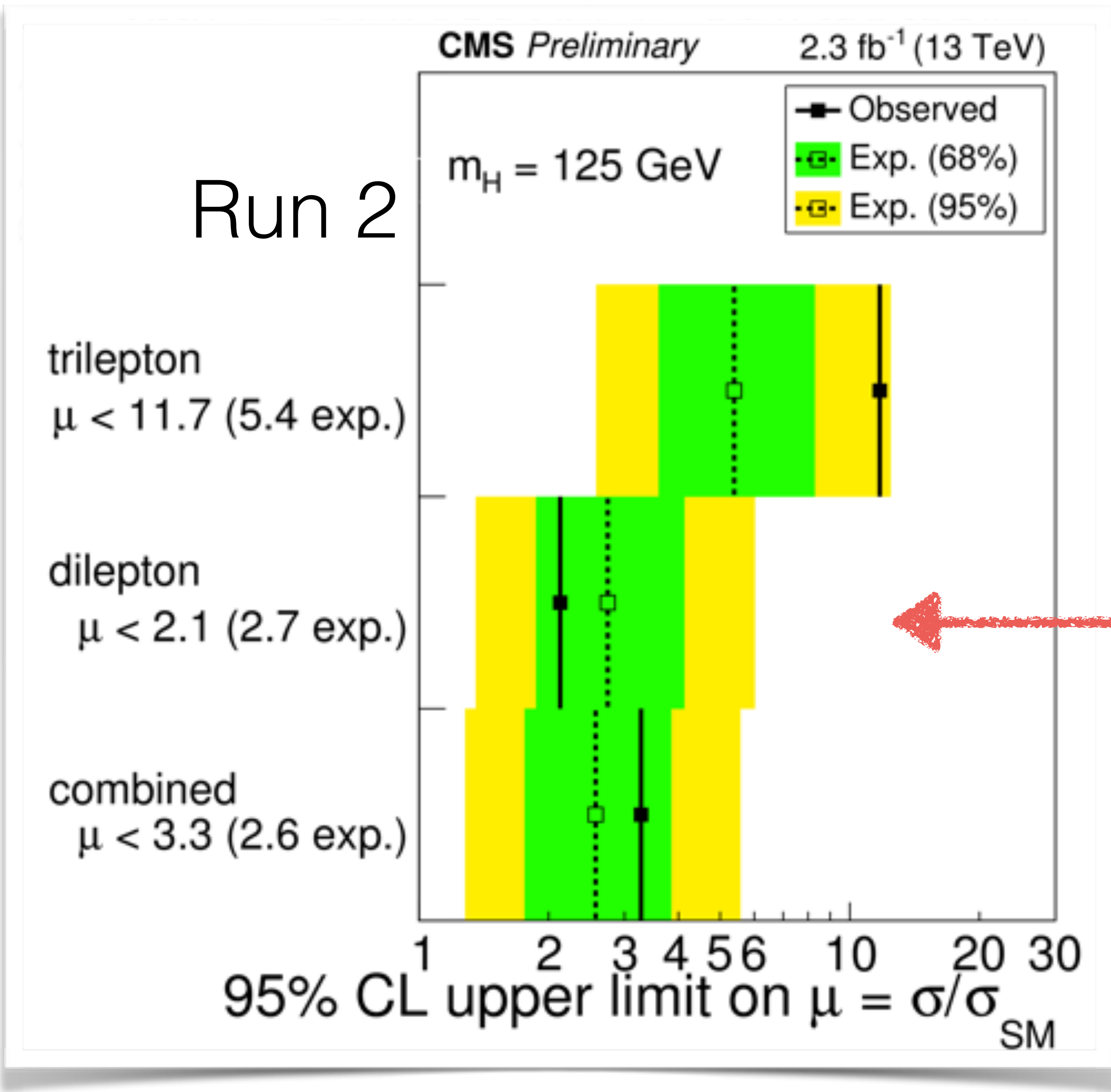


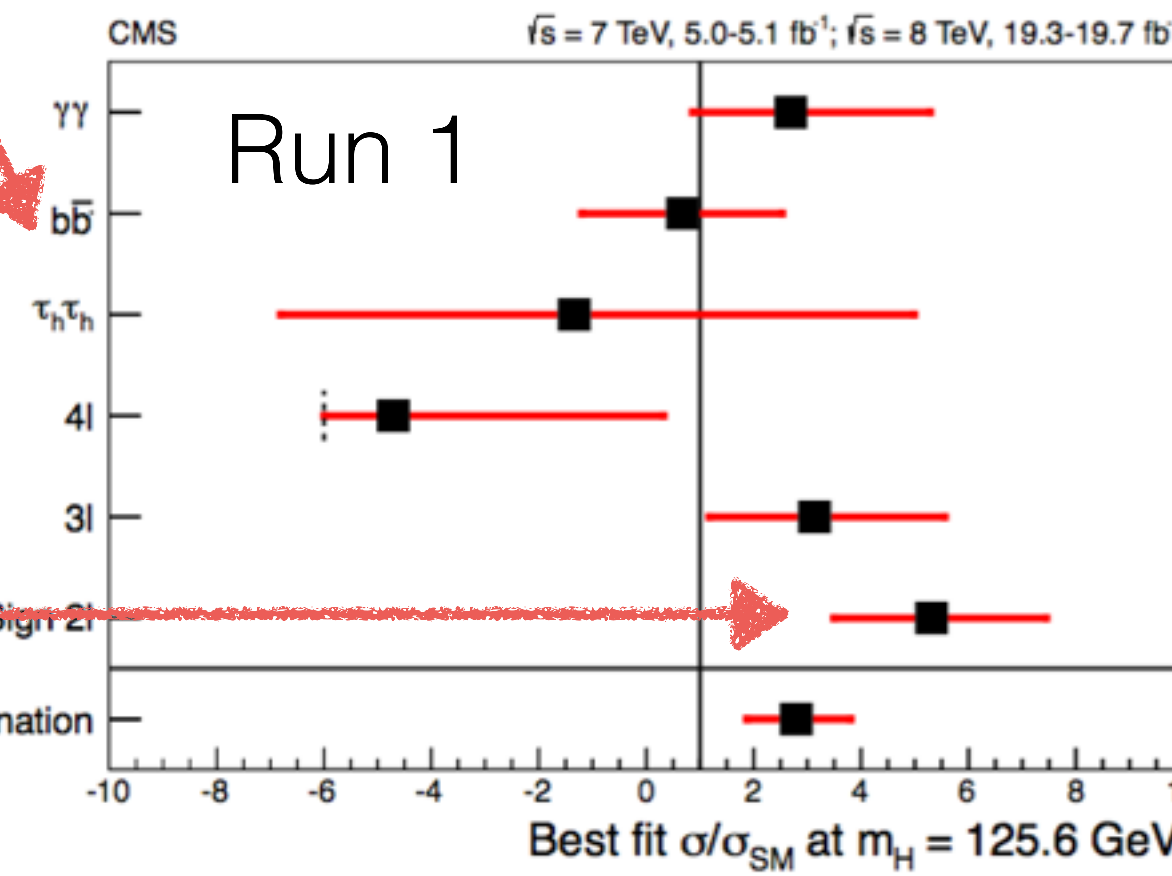
μ = 2.8±1.0

p-value: 3.4σ

CMS ttH

5 channels: bb, $\tau\tau$, $\gamma\gamma$, WW,ZZ

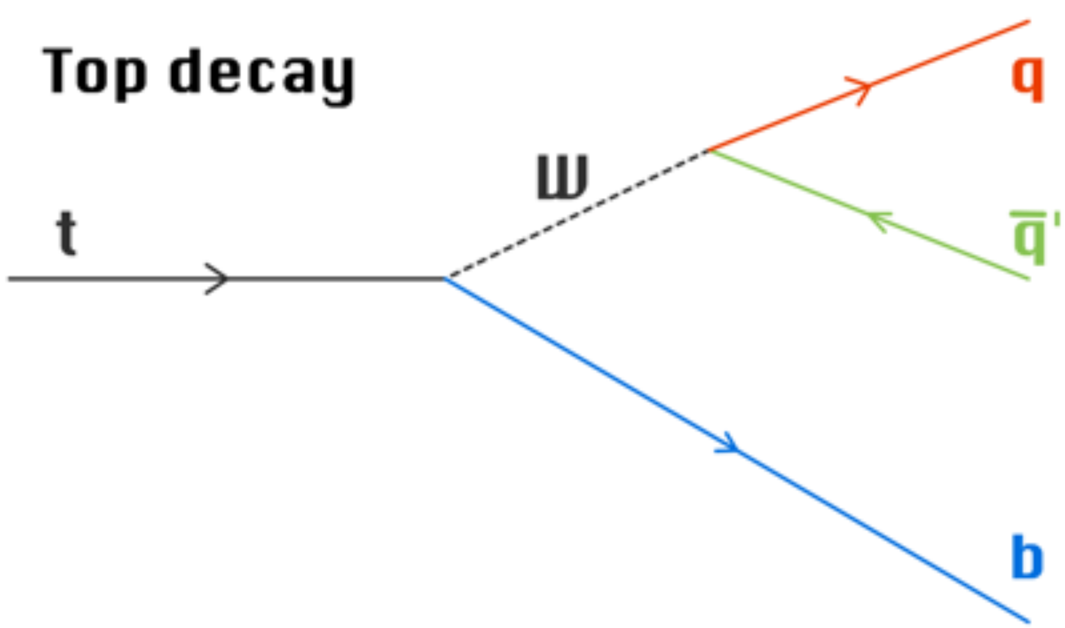


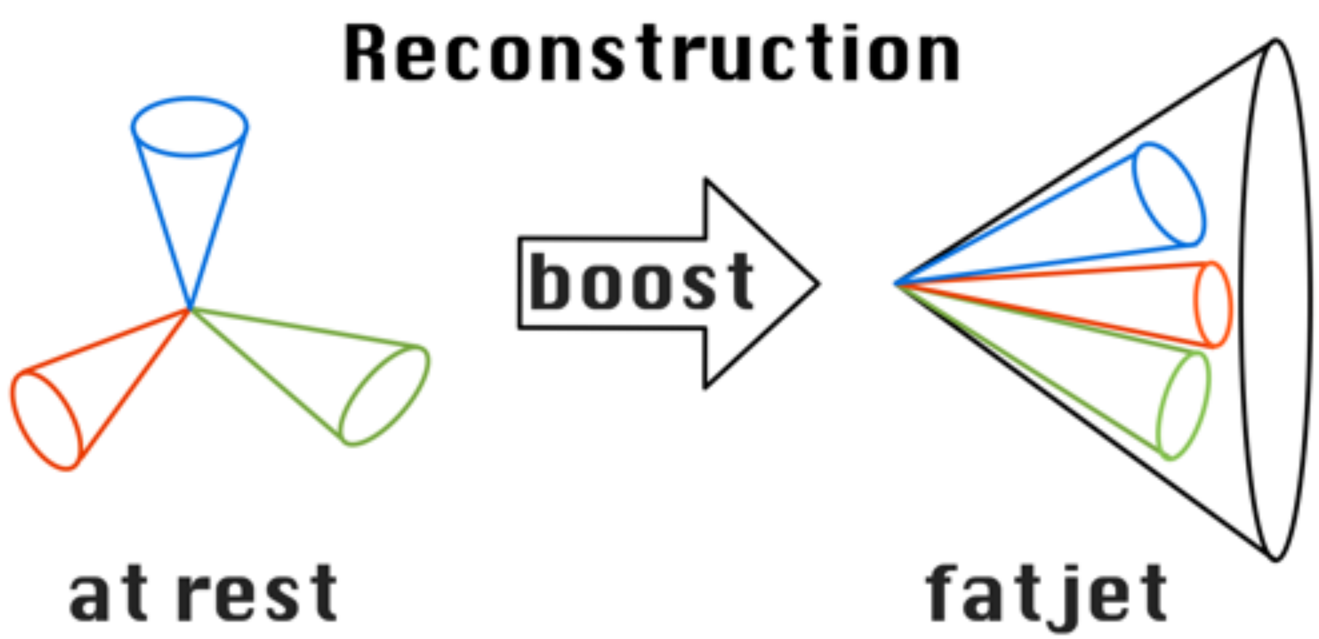


$\mu = 2.8 \pm 1.0$

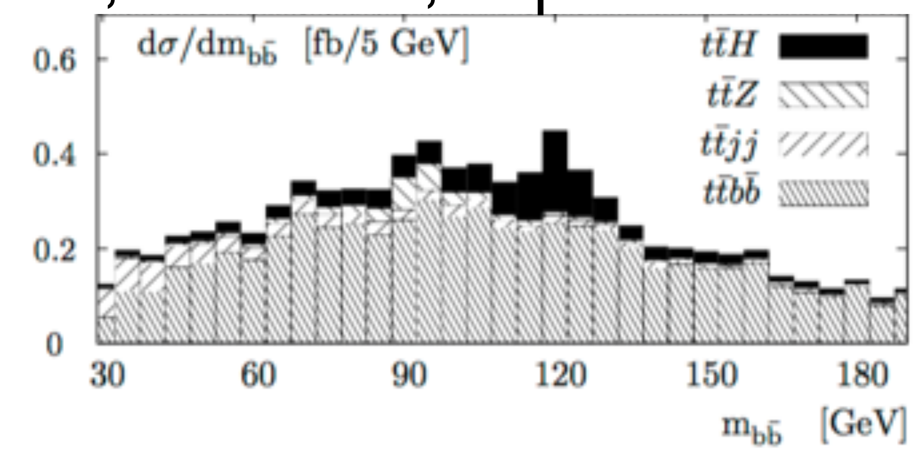
p-value: 3.4σ

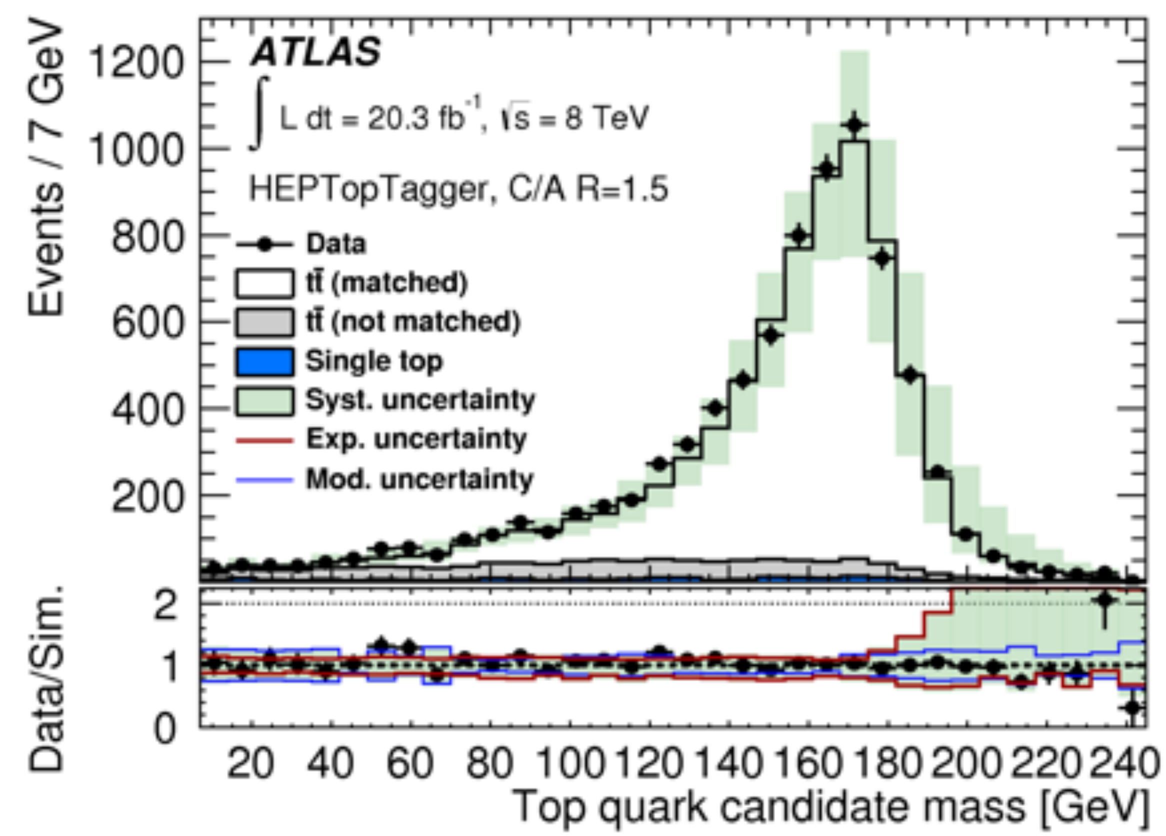
Fat jets for a light Higgs





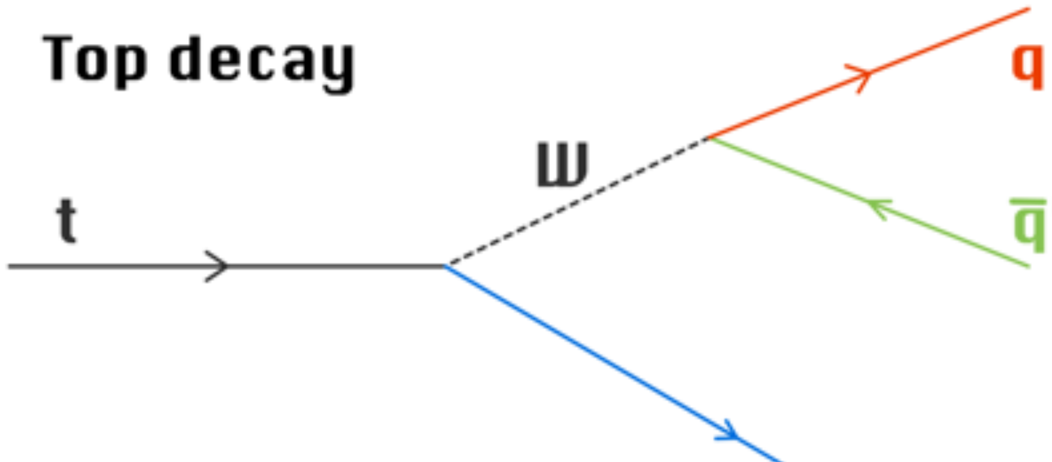
Plehn, Salam, Spannowsky

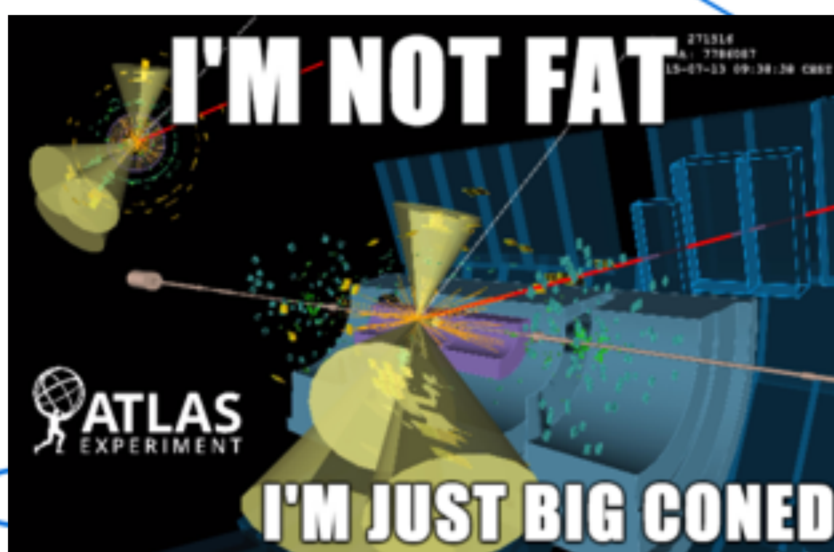




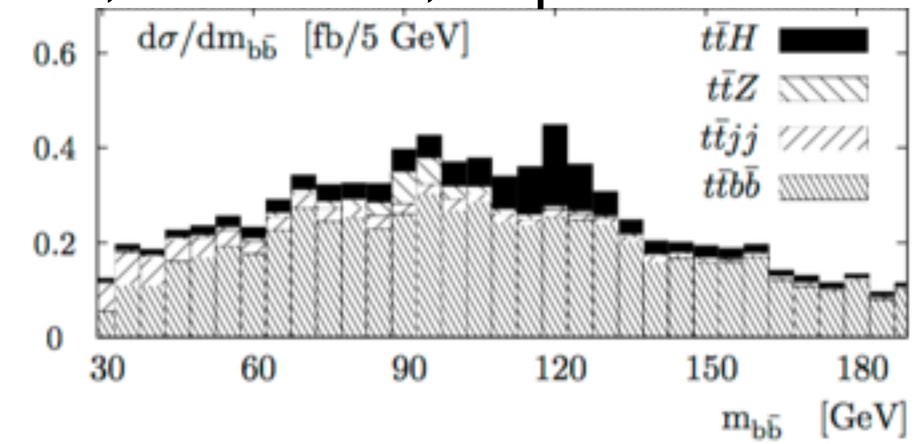
Hadronic tops with HEPTopTagger, method from HD theory, applied by HD experiment!

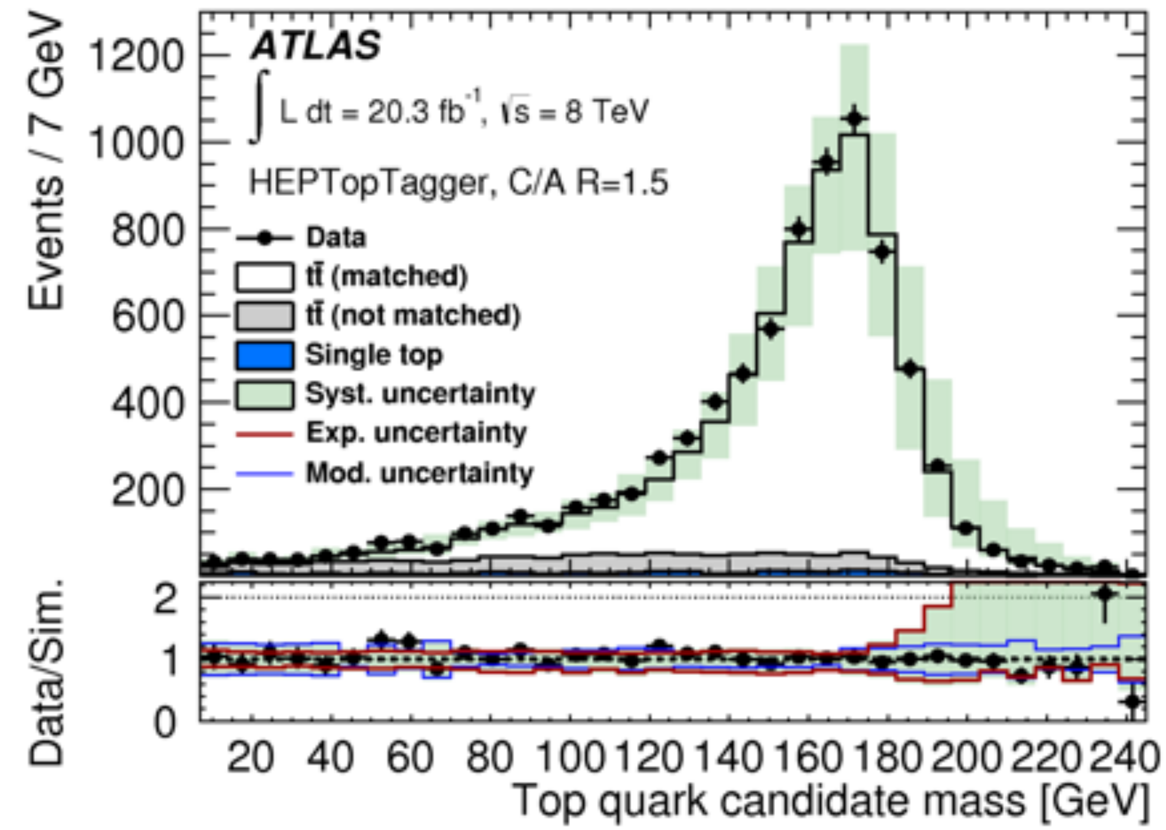
Fat jets for a light Higgs





Plehn, Salam, Spannowsky





Hadronic tops with HEPTopTagger, method from HD theory, applied by HD experiment!

Higgs self coupling

- Reminder, Higgs potential:

$$\mathcal{L}_{Higgs} = D_\mu\phi^\dagger D^\mu\phi - V(\phi)$$
$$V(\phi) = -\mu^2\phi^\dagger\phi + \frac{\lambda}{2}(\phi^\dagger\phi)^2$$

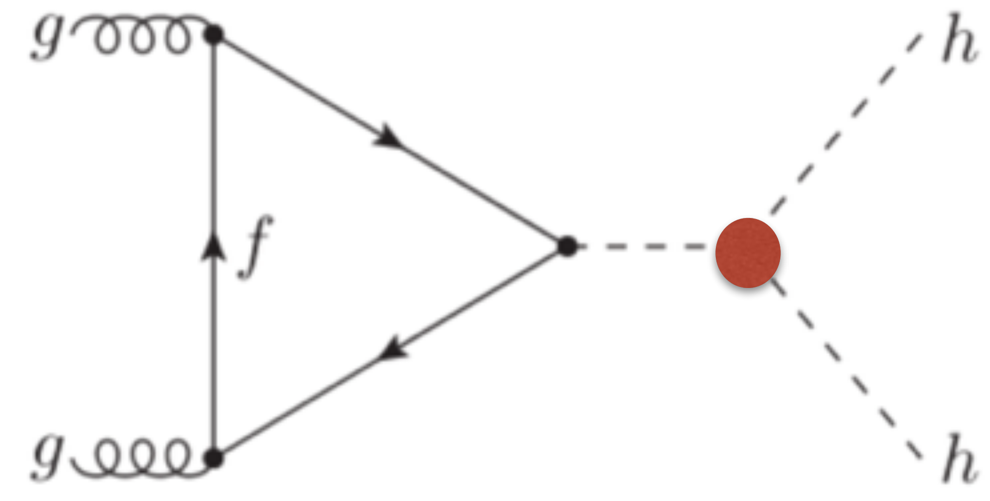
- What are the lambdas?

- After electroweak symmetry breaking can be expanded to:

$$\mathcal{V} = \frac{1}{2}M_h^2 h^2 + \lambda v h^3 + \frac{\tilde{\lambda}}{4}h^4$$

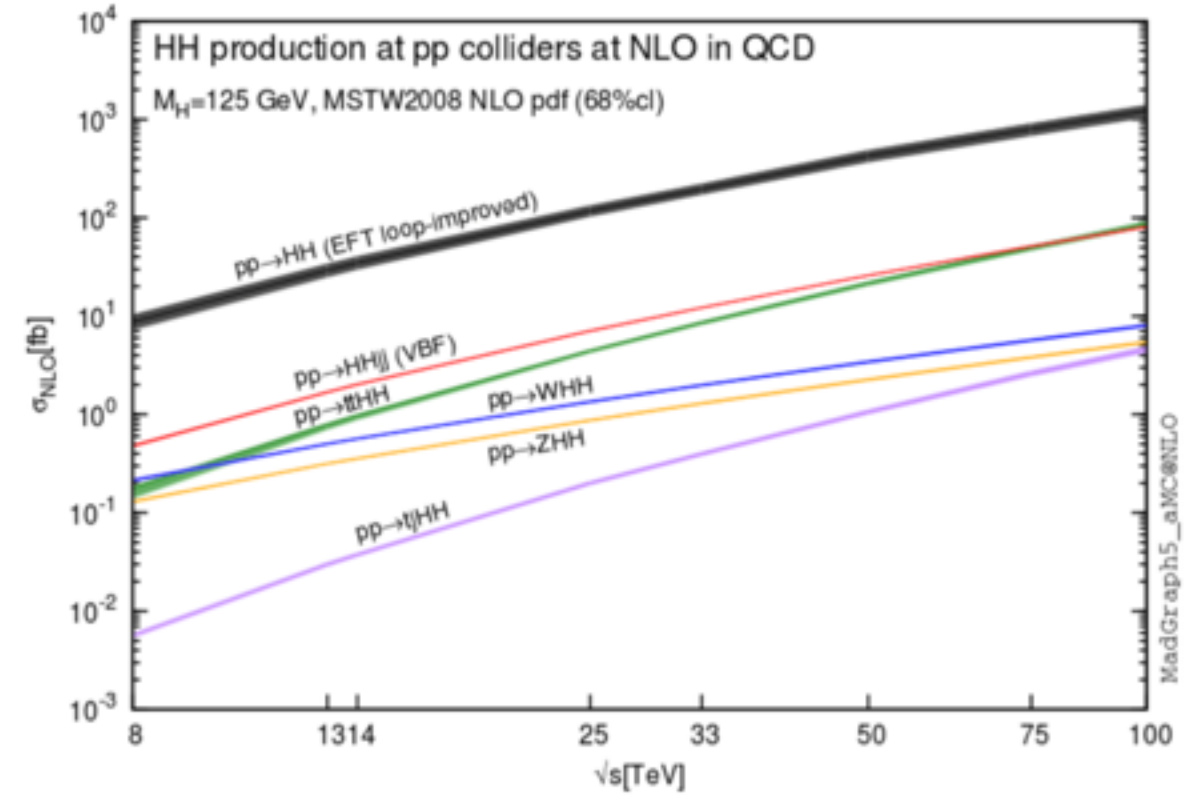
- SM expectation: $\lambda = \tilde{\lambda} = M_h^2/2v^2 \sim 0.13$ needs to be verified

Self coupling



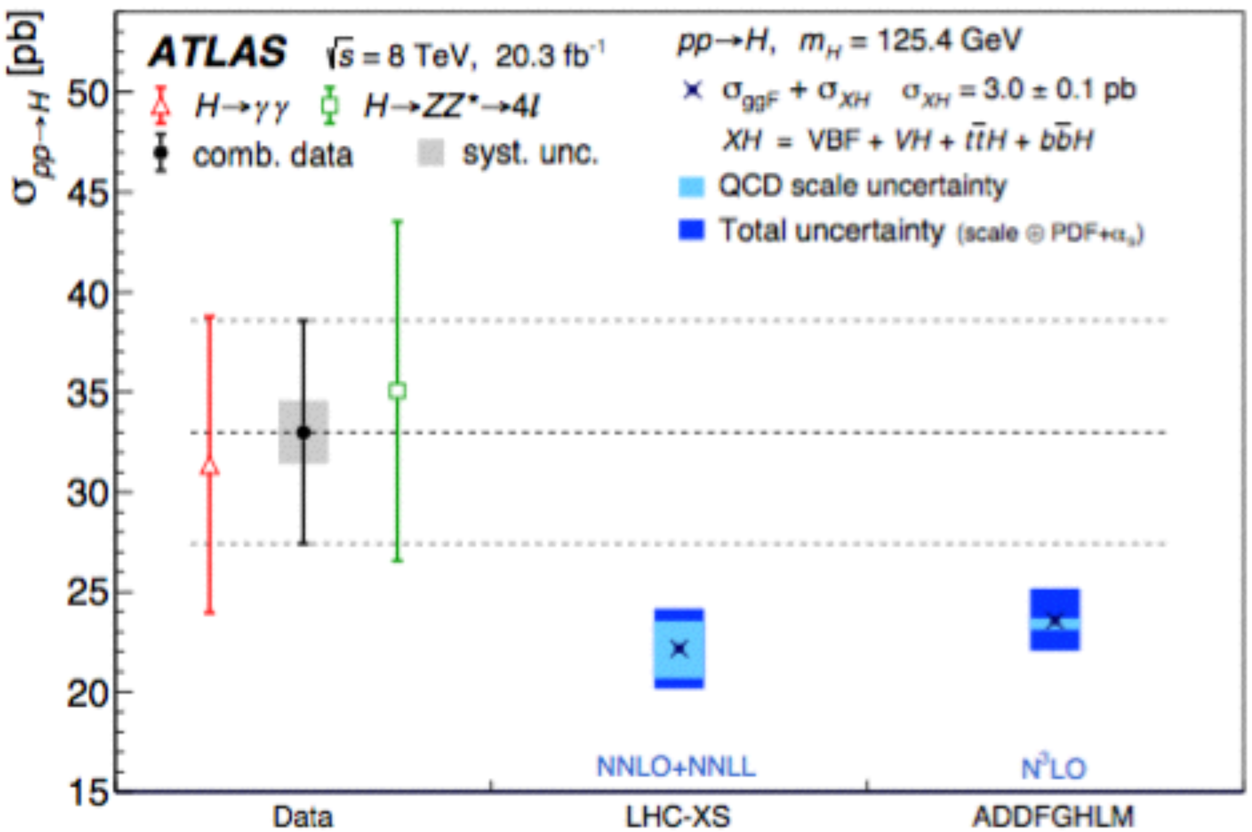
- h^3 term might be measurable at the high luminosity LHC, but need 14TeV and 3 ab^{-1} (= 3000 fb^{-1} !!!)

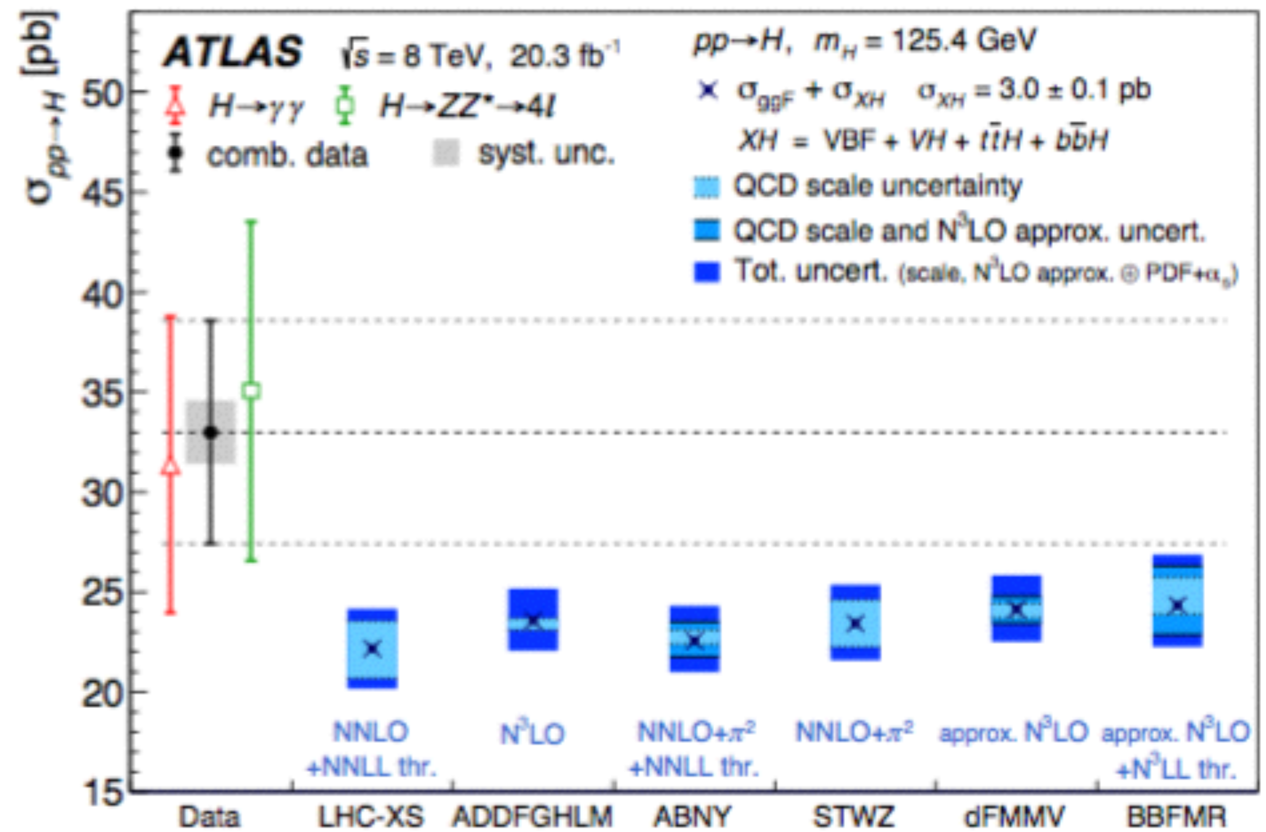
- Measure SM di-Higgs HH production



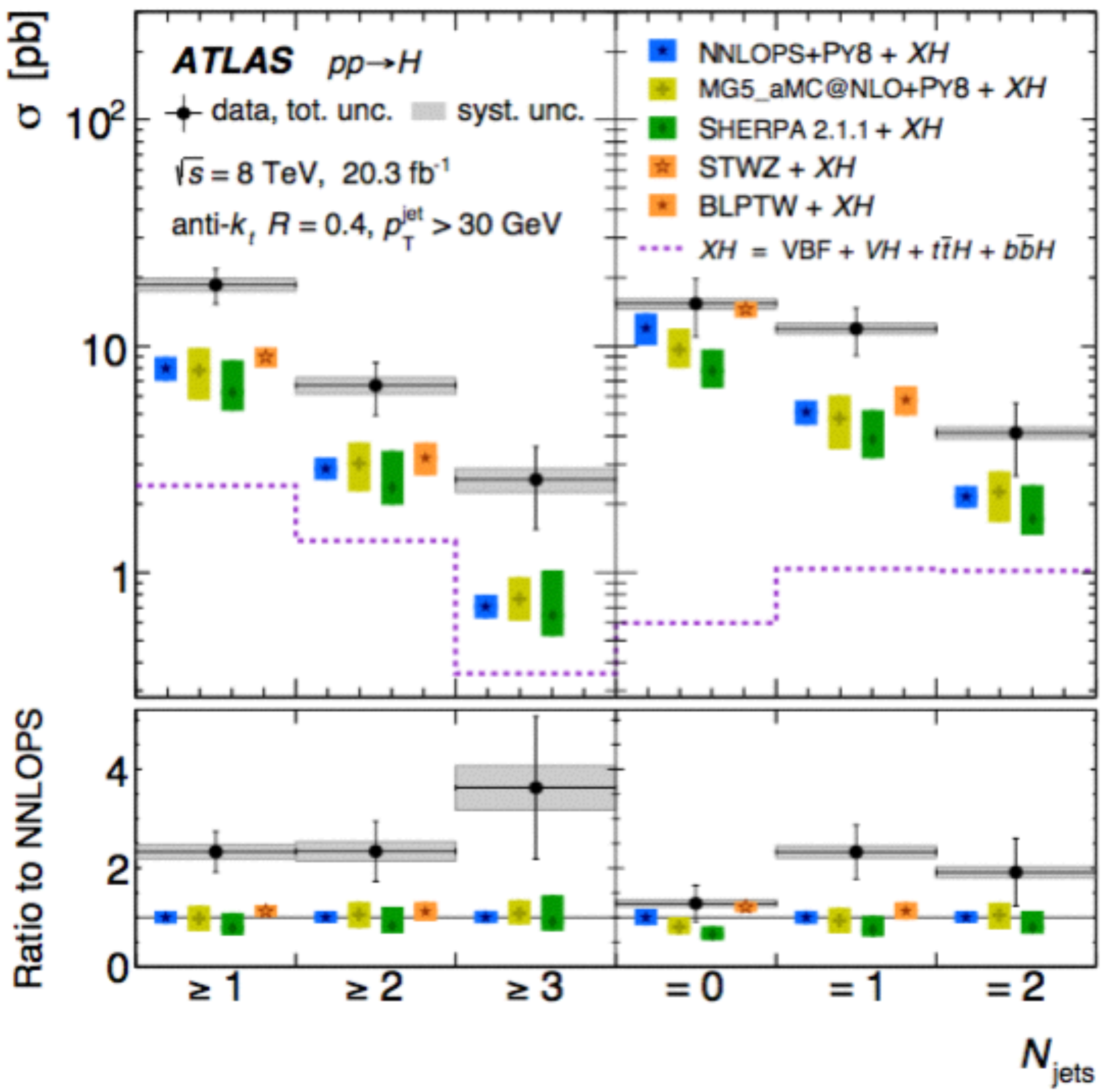
- Challenges: small cross section (—> need large BR: bb, WW,$\tau\tau$), large backgrounds

Total cross-section measurement





Differential measurements (N_{jet})



Differential measurement (p_T^H)