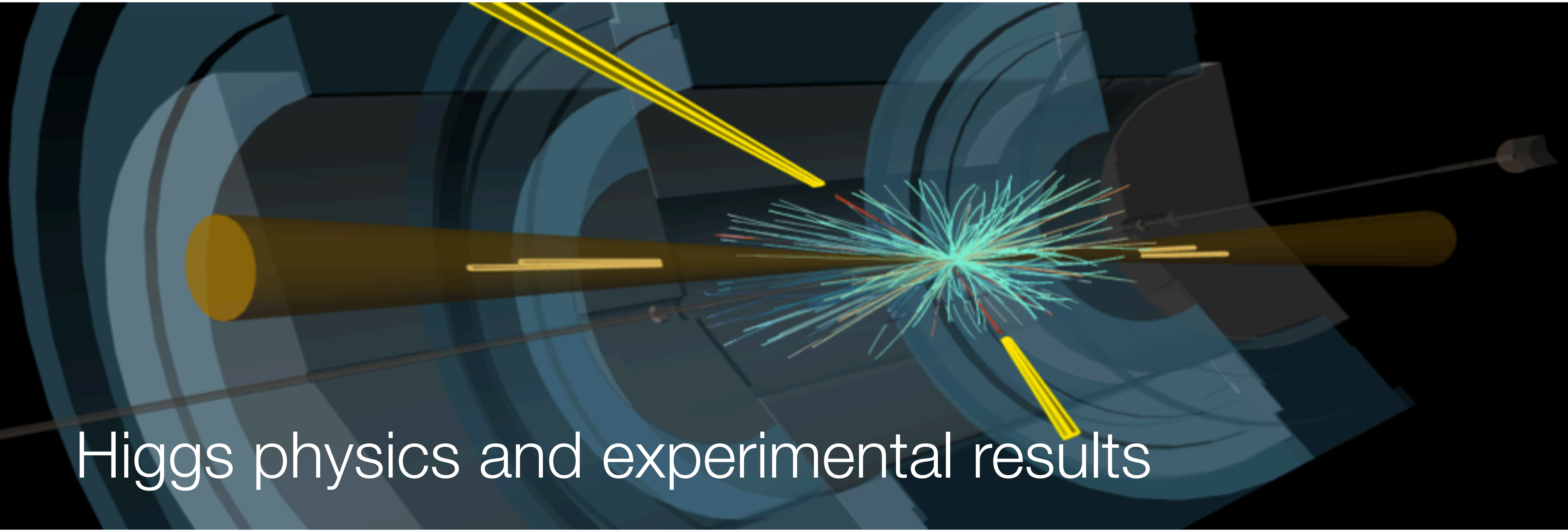


Higgs physics and experimental results

Bruno Lenzi

New Trends in High Energy Physics and QCD School, Natal, Brazil

23/10/2014

$H \to \gamma\gamma$: profile likelihood ratio

How to extract the signal? How significant it is?

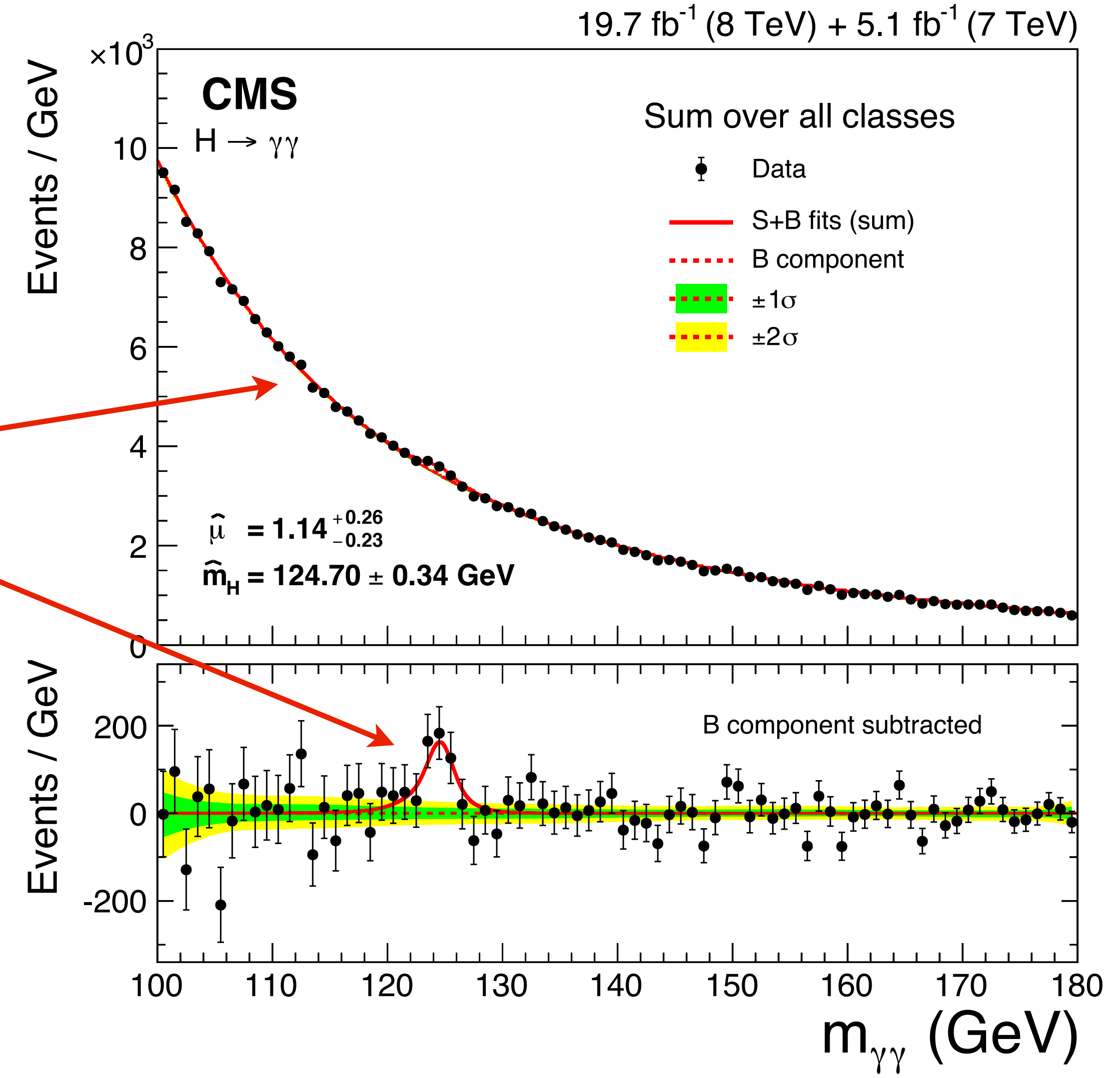
- Likelihood function (model of the data):

observable — nuisance parameters

$$\mathscr{L}(\mu,\theta) = \prod_{events} f_s \psi_s(m_{\gamma\gamma};\theta) + (1-f_s)\psi_b(m_{\gamma\gamma};\theta)$$

signal, bkg pdfs

parameter of interest (signal strength):
$\mu = \sigma/\sigma_{SM}$ ($\propto f_s$)



Claim a discovery when $\mu = 0$ rejected (at 5σ)

Profile likelihood ratio

How to extract the signal? How significant it is?

- Likelihood function (model of the data):

$$\mathscr{L}(\mu,\theta) = \prod_{events} f_s\psi_s(m_{\gamma\gamma};\theta) + (1-f_s)\psi_b(m_{\gamma\gamma};\theta)$$

  - Nuisance parameters: all that you needed to add to describe your data
    - Some are fully determined by the data, others are constrained by external information (ideally measurements) → systematics uncertainties

- Profile likelihood ratio: $q_\mu = -2\log\frac{\mathscr{L}(\mu,\hat{\hat{\theta}}_\mu)}{\mathscr{L}(\hat{\mu},\hat{\theta})}$

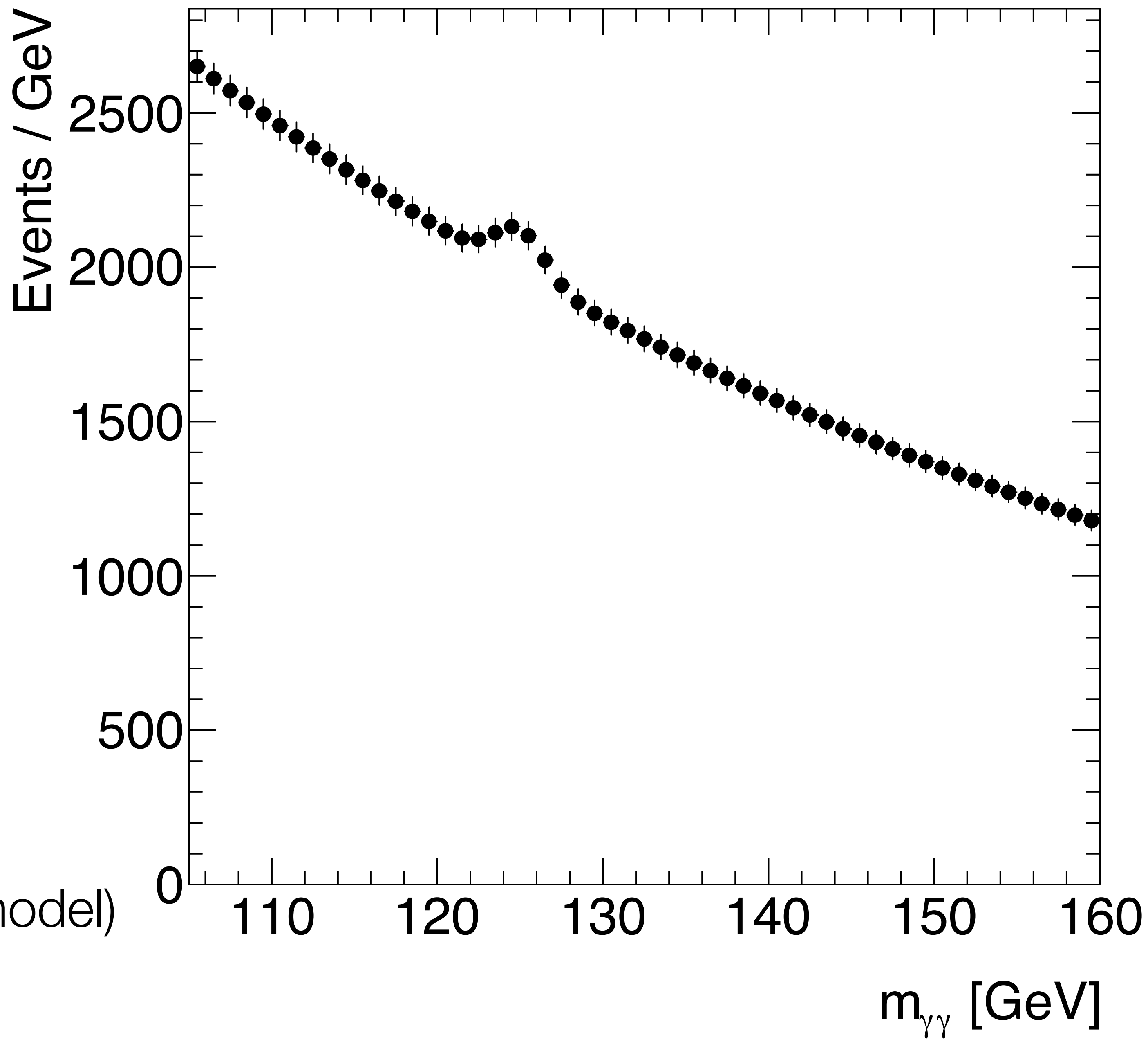
$$\frac{\mathscr{L} \text{ maximized with } \mu \text{ fixed}}{\mathscr{L} \text{ maximized with } \mu \text{ free}}$$

  - Asymptotically → χ^2 with 1 degree of freedom
  - "Easy" to incorporate systematic uncertainties

$H \to \gamma\gamma$: toy example

$$G(x,\bar{x},\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\bar{x})^2}{2\sigma^2}}$$

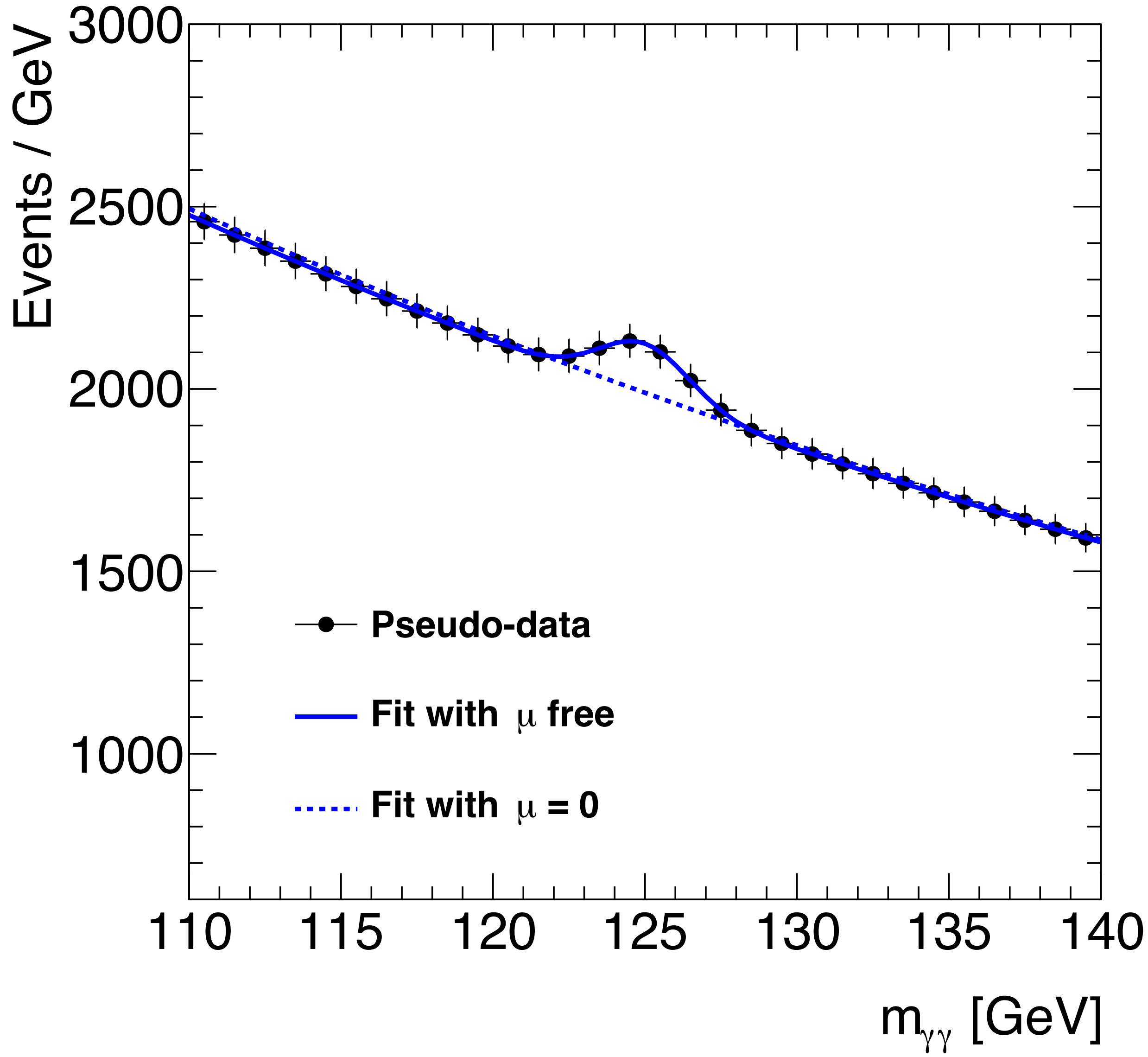
- $N_s = N_s^{SM} \times \mu$; $N_s^{SM} = 560$, $\mu = 1$
- $N_B = 100k$
- $\psi_s = G(m_{\gamma\gamma}, m_H, \sigma_m)$;
  $m_H = 125$ GeV, $\sigma_m = 1.5$ GeV
- $\psi_b = \exp(-\xi \times m_{\gamma\gamma}) / \mathrm{Norm}$
- Parameter of interest: μ
- Nuisance parameters: ξ, N_B
- Asimov dataset
  (single representative dataset of the model)

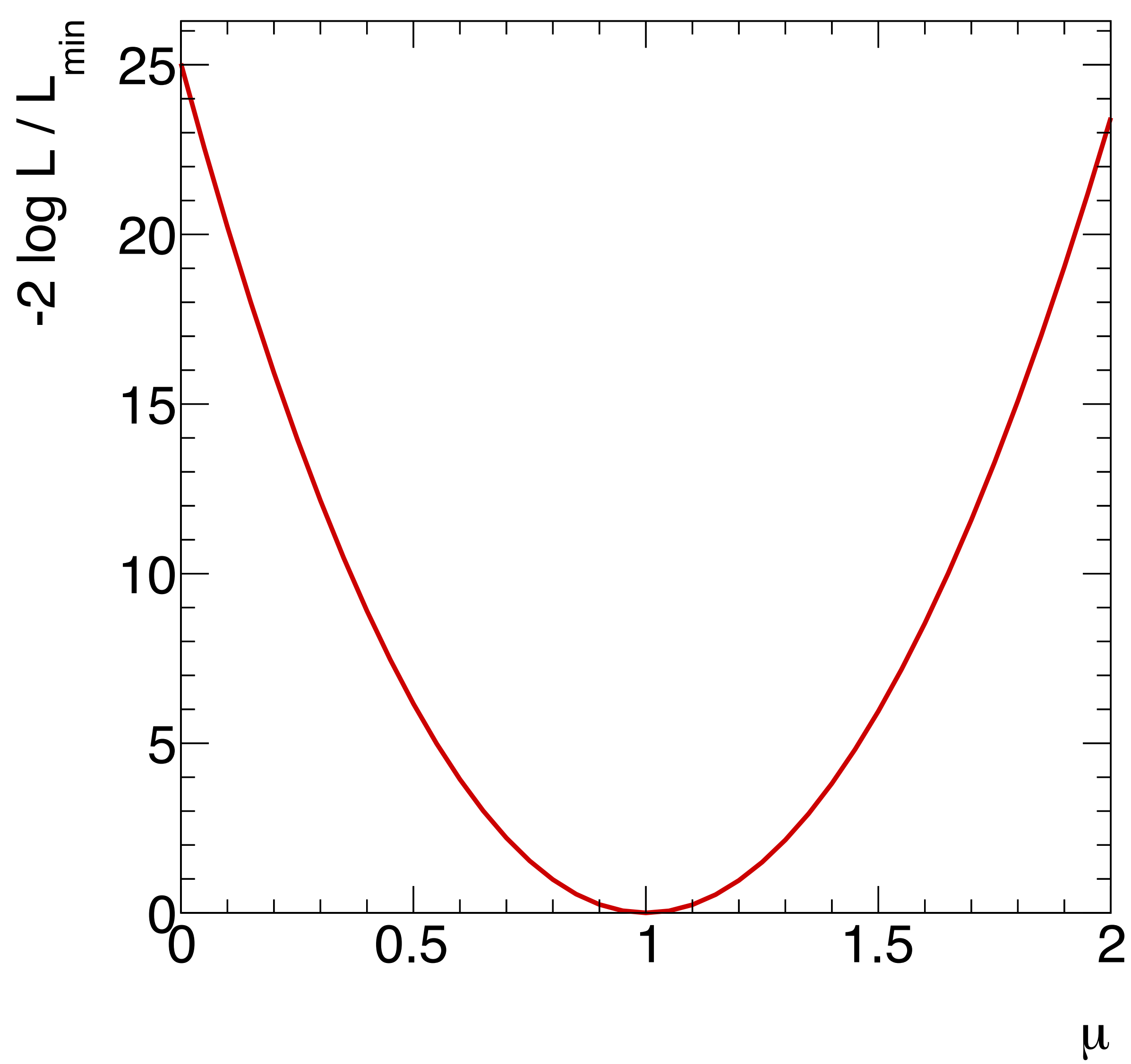


$H \to \gamma\gamma$: toy example, profile likelihood ratio

Profile likelihood ratio: $$q_\mu = -2\log\frac{\mathscr{L}(\mu,\hat{\hat{\theta}}_\mu)}{\mathscr{L}(\hat{\mu},\hat{\theta})}$$

$\mathscr{L}$ maximized with μ fixed
—
$\mathscr{L}$ maximized with μ free





H → γγ: toy example, profile likelihood ratio

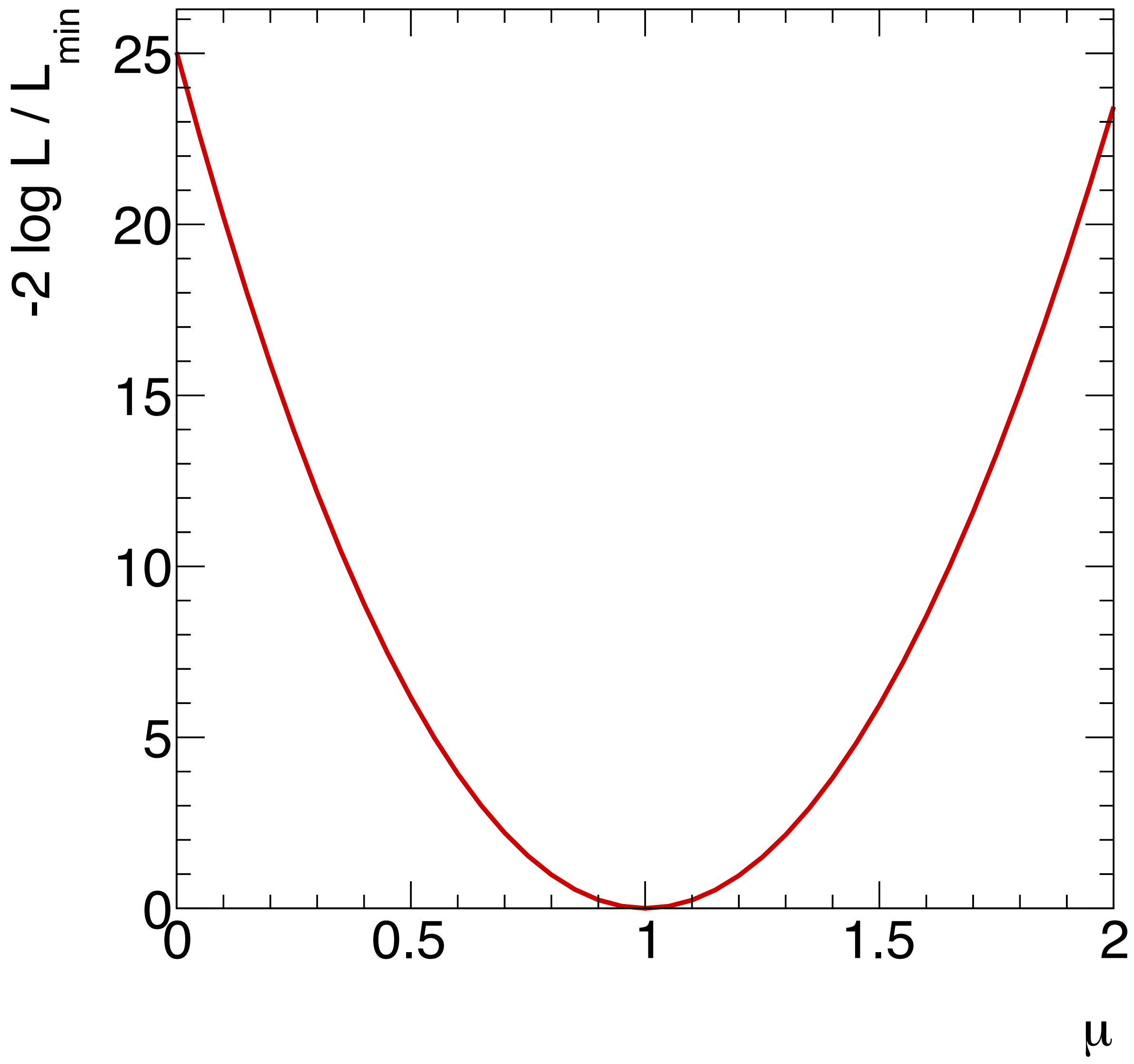
Profile likelihood ratio: $q_\mu = -2\log\frac{\mathscr{L}(\mu,\hat{\hat{\theta}}_\mu)}{\mathscr{L}(\hat{\mu},\hat{\theta})}$

$\frac{\mathscr{L} \text{ maximized with } \mu \text{ fixed}}{\mathscr{L} \text{ maximized with } \mu \text{ free}}$

Asymptotic approximation:

$$q_0 = -2\log\frac{\mathscr{L}(0;\theta_{\mu=0})}{\mathscr{L}(\hat{\mu};\hat{\theta})} \rightarrow \left(\frac{\hat{\mu}}{\sigma}\right)^2 = Z^2$$

5σ significance!



H → γγ: toy example, profile likelihood ratio

Profile likelihood ratio: $q_\mu = -2\log\dfrac{\mathscr{L}(\mu,\hat{\hat{\theta}}_\mu)}{\mathscr{L}(\hat{\mu},\hat{\theta})}$

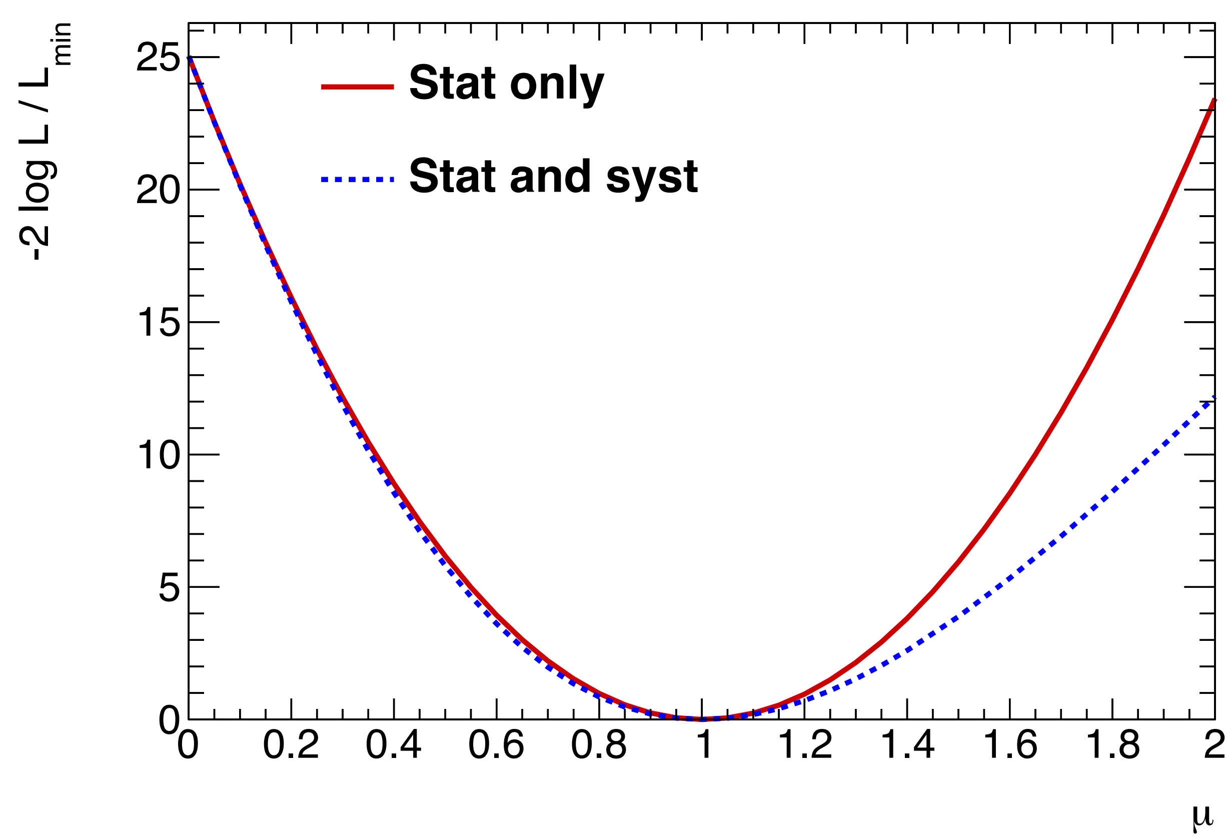
$\dfrac{\mathscr{L} \text{ maximized with } \mu \text{ fixed}}{\mathscr{L} \text{ maximized with } \mu \text{ free}}$

Systematic uncertainties incorporated by adding parameters to $\mathscr{L}$, constrained by external information (in the form of pdfs). E.g.:

constant

$$\mu \to \mu\,(1+\delta_N\theta_N)$$
$$\mathscr{L} \to \mathscr{L}\cdot G(\theta_N,0,1)$$

constraint or penalty term



H → γγ: toy example, profile likelihood ratio

Profile likelihood ratio: $q_\mu = -2\log \frac{\mathscr{L}(\mu, \hat{\hat{\theta}}_\mu)}{\mathscr{L}(\hat{\mu}, \hat{\theta})}$ $\frac{\mathscr{L} \text{ maximized with } \mu \text{ fixed}}{\mathscr{L} \text{ maximized with } \mu \text{ free}}$

Systematic uncertainties incorporated by adding parameters to $\mathscr{L}$, constrained by external information (in the form of pdfs). E.g.:

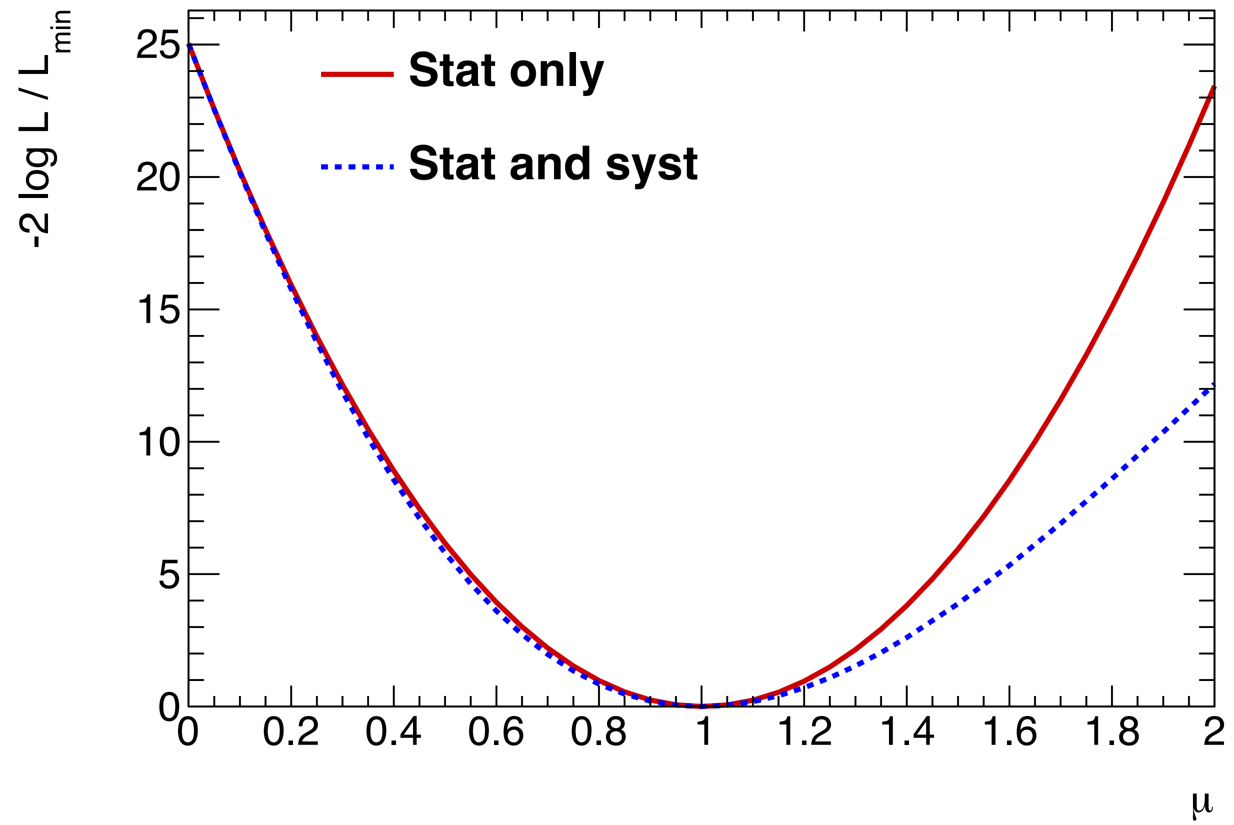
$$\mu \to \mu\,(1 + \delta_N \theta_N)$$
$$\mathscr{L} \to \mathscr{L} \cdot G(\theta_N, 0, 1)$$

constant

constraint or penalty term

No impact on Z!

- No change for μ = 0 or μ free (not always true)



$H \to \gamma\gamma$: toy example, profile likelihood ratio

Profile likelihood ratio: $q_\mu = -2\log \frac{\mathscr{L}(\mu, \hat{\hat{\theta}}_\mu)}{\mathscr{L}(\hat{\mu}, \hat{\theta})}$ $\frac{\mathscr{L} \text{ maximized with } \mu \text{ fixed}}{\mathscr{L} \text{ maximized with } \mu \text{ free}}$

Systematic uncertainties incorporated by adding parameters to $\mathscr{L}$, constrained by external information (in the form of pdfs).

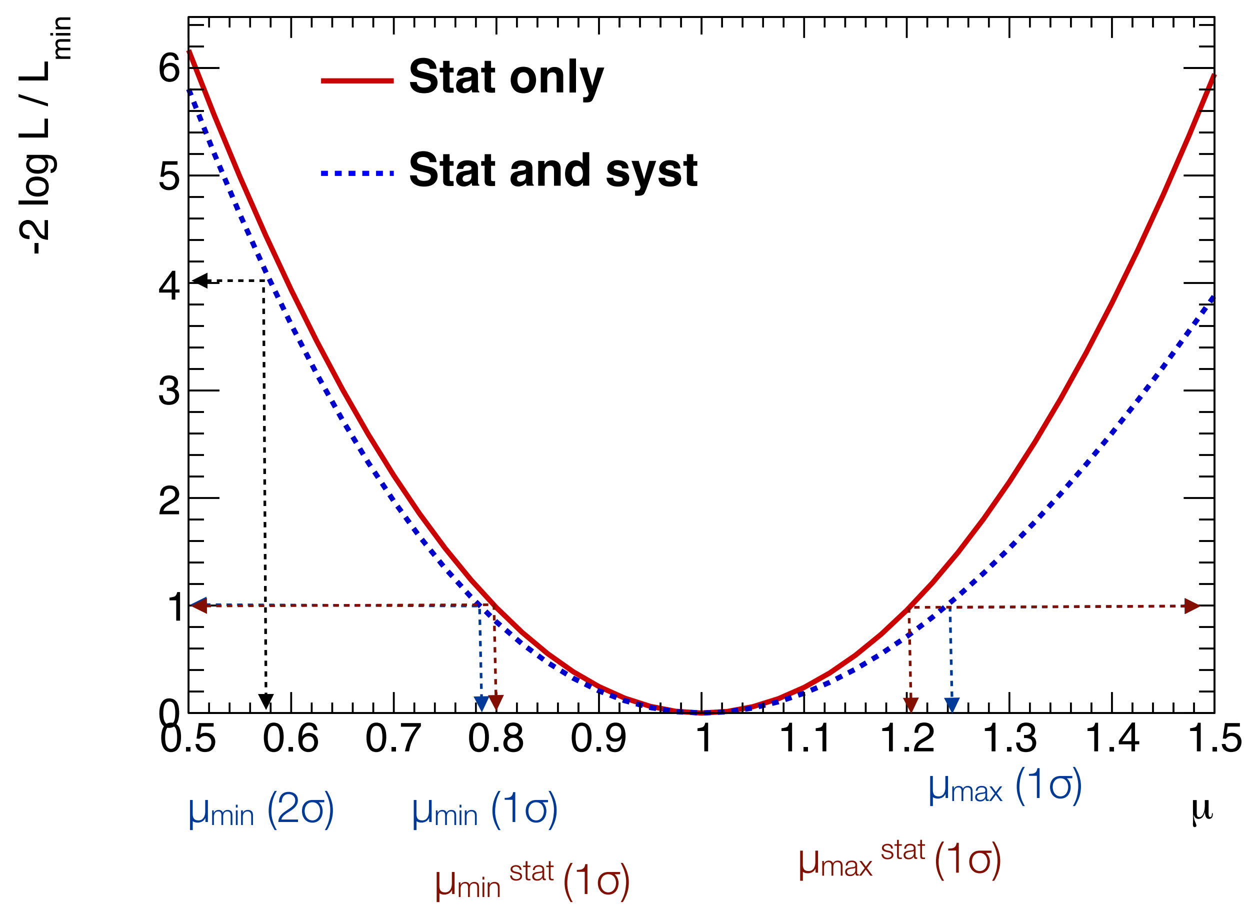
$$\text{Stat error } (1\sigma): \mu_{min} \leq \hat{\mu} \leq \mu_{max}$$

$$\text{Total error } (1\sigma): \mu_{min} \leq \hat{\mu} \leq \mu_{max}$$

$$\text{Syst}: (\text{total})^2 - (\text{stat})^2$$

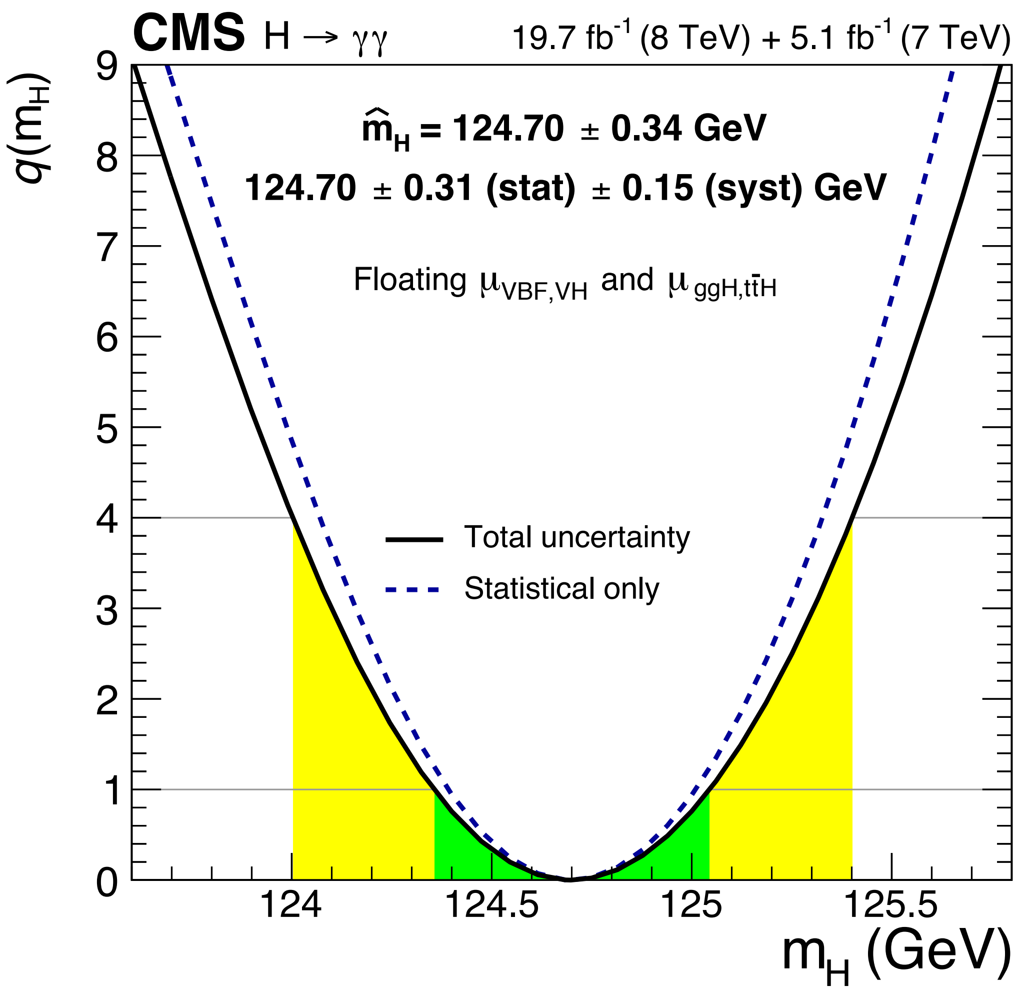
Increase error on μ:
- $\mathscr{L}$ more flexible

(zoom)



Higgs mass measurement

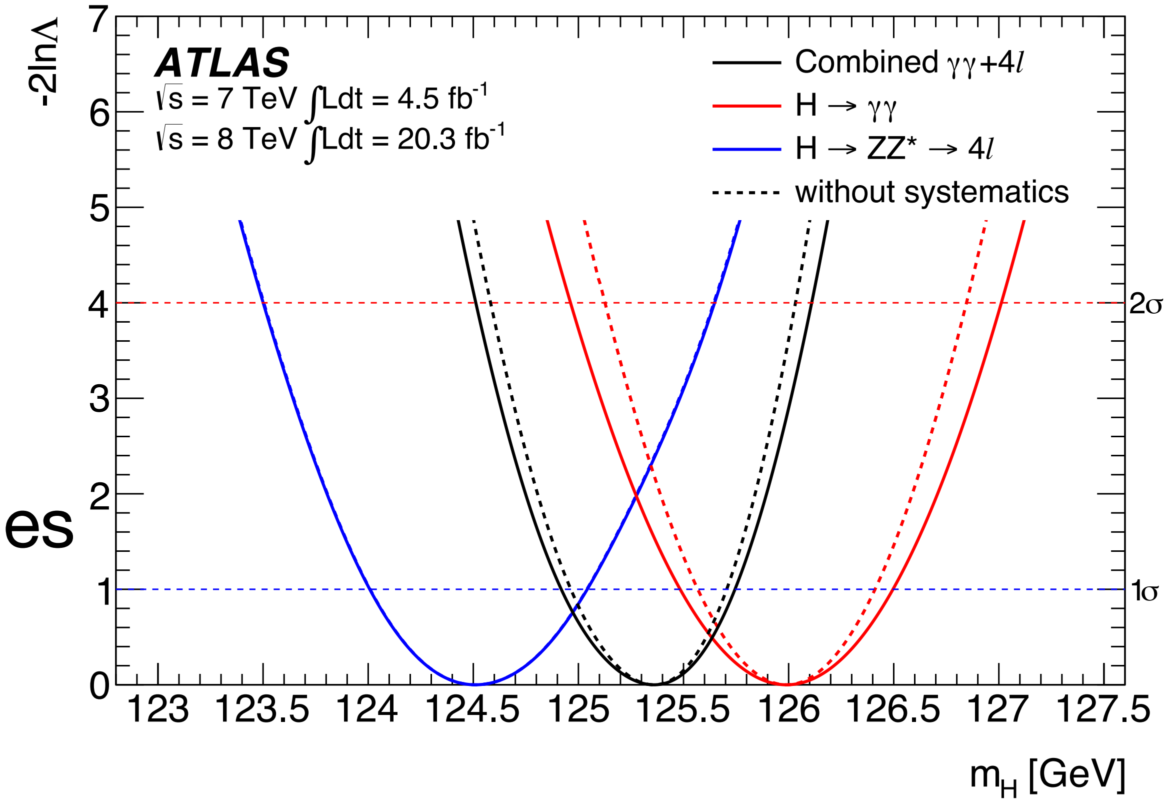
- H → γγ: systematic uncertainties from energy scale
  - e → γ extrapolations, non-linearities
  - Huge effort to reduce by factor 2-3



Higgs mass measurement

Known to ~1% at discovery, ~0.3% now

- H → γγ: systematic uncertainties from energy scale
  - e → γ extrapolations, non-linearities
  - Huge effort to reduce by factor 2-3
- H → 4ℓ: dominated by statistical uncertainties
- Compatibility: 2.0σ (ATLAS), 1.6σ (CMS)
  - Shifts in opposite directions

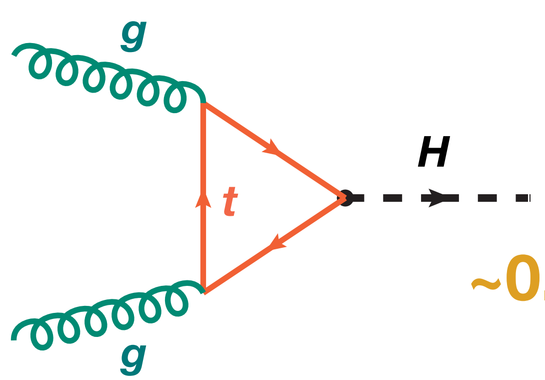


	ATLAS	CMS
$H \to \gamma\gamma$	125.98 ± 0.42 (stat) ± 0.28 (sys)	124.70 ± 0.31 (stat) ± 0.15 (sys)
$H \to ZZ^* \to 4\ell$	124.51 ± 0.52 (stat) ± 0.04 (sys)	125.6 ± 0.4 (stat) ± 0.2 (sys)
Combined	125.36 ± 0.37 (stat) ± 0.18 (sys)	$125.03^{+0.26}_{-0.27}$ (stat) $^{+0.13}_{-0.15}$ (sys)
	125.36 ± 0.41	$125.03^{+0.29}_{-0.31}$

The SM Higgs boson at the LHC

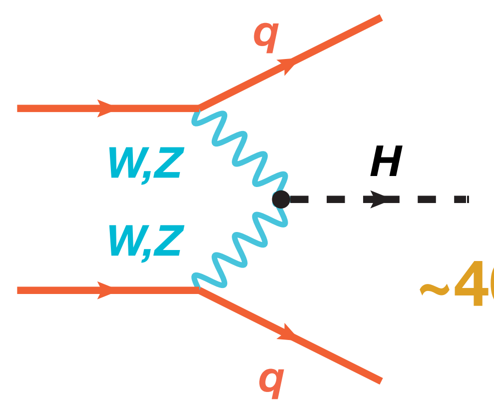
Production mechanisms (events produced)

Gluon-fusion



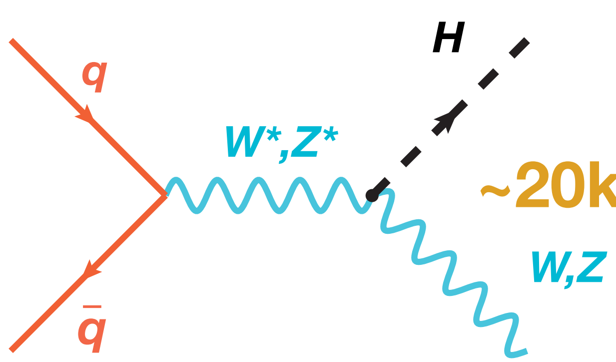
~0.5M

Vector boson fusion (VBF)



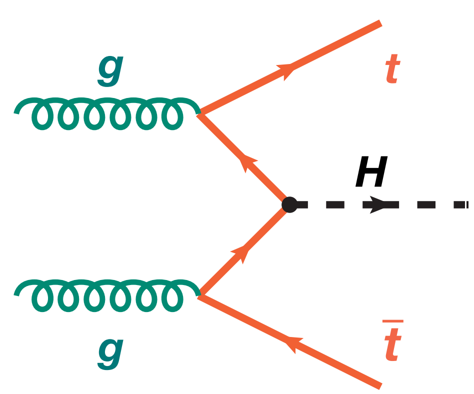
~40k

Associated with W / Z



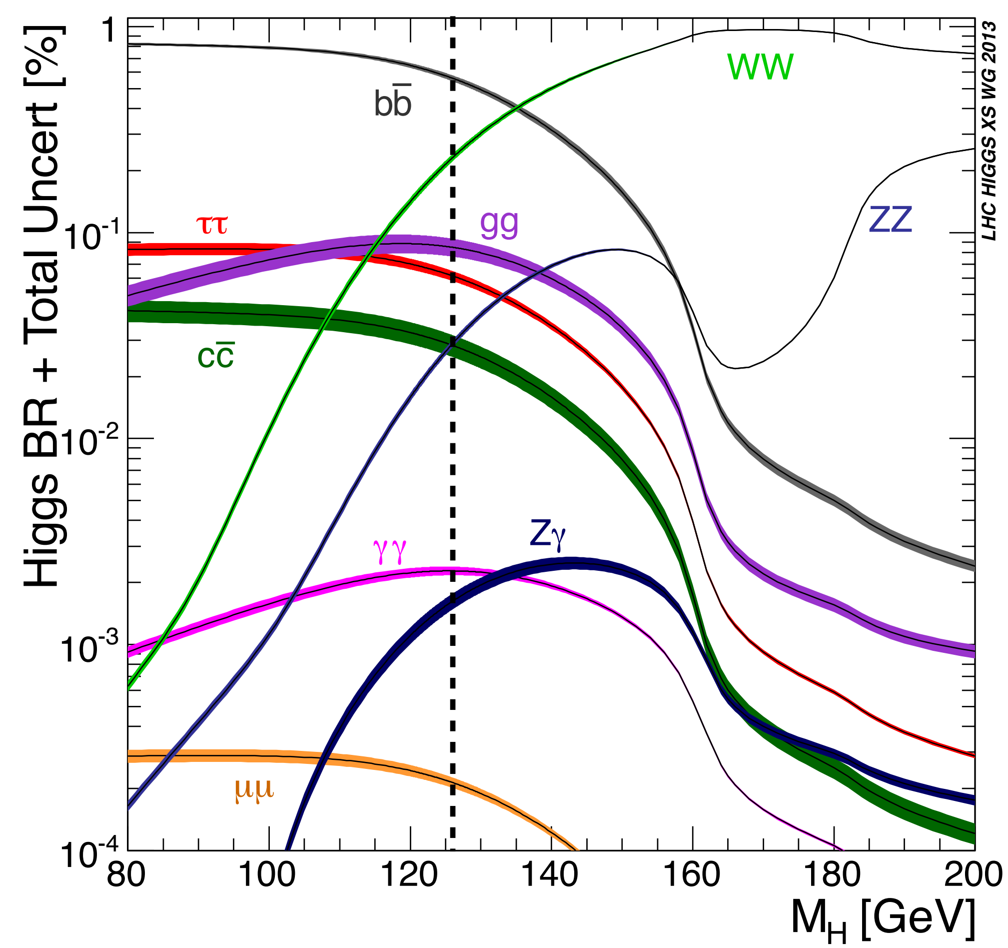
~20k/10k

Associated with tt (or bb)



~3k/5k

Decay modes

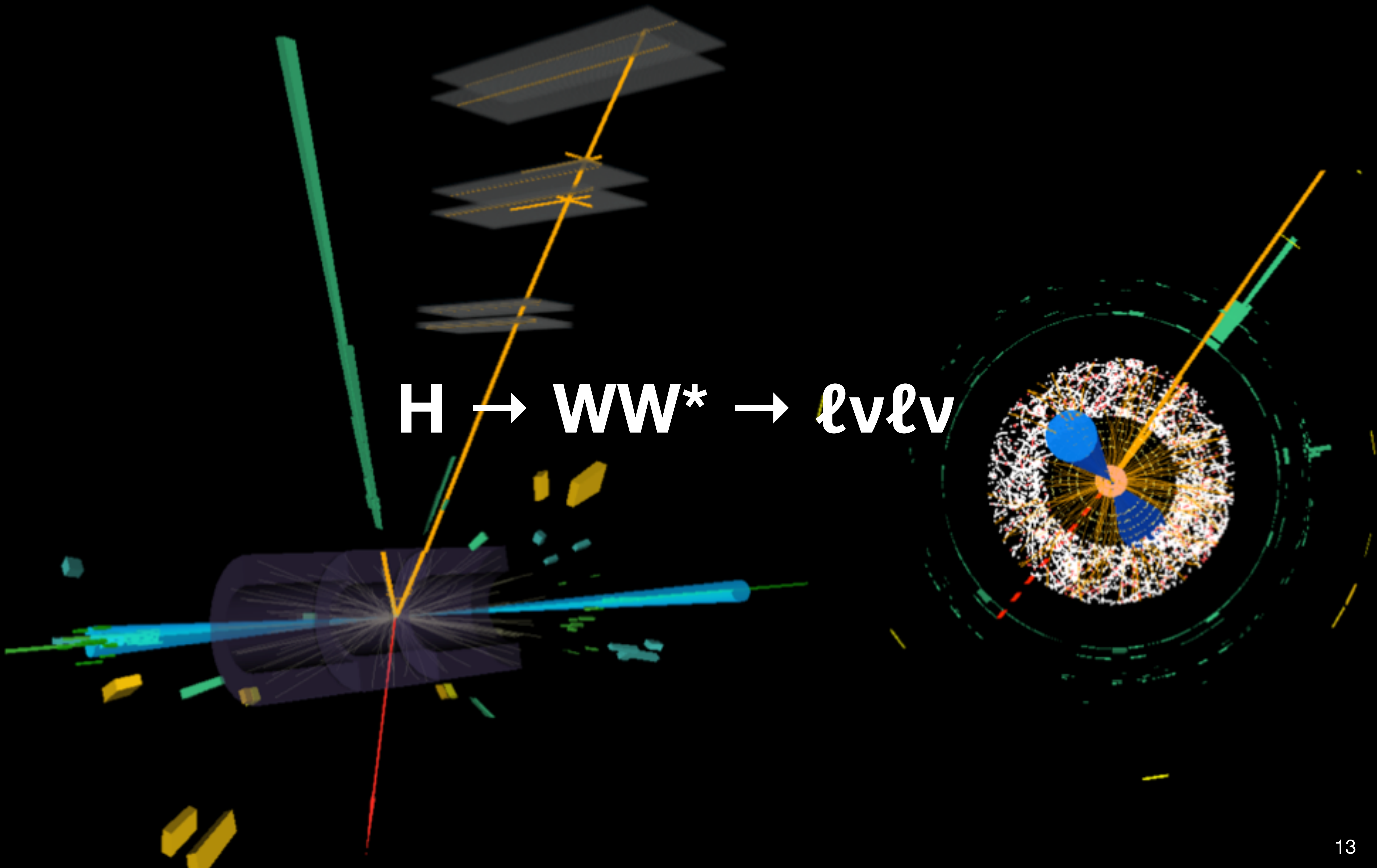


- Main channels (bosonic): H → γγ, H → ZZ* → 4ℓ, H → WW* → ℓνℓν
- Fermionic modes (associated production): (VBF) H → ττ, (W/Z) H → bb
- Rare decays: H → Zγ, H → μμ

ATLAS EXPERIMENT

Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET

$H \rightarrow WW^{*} \rightarrow \ell\nu\ell\nu$

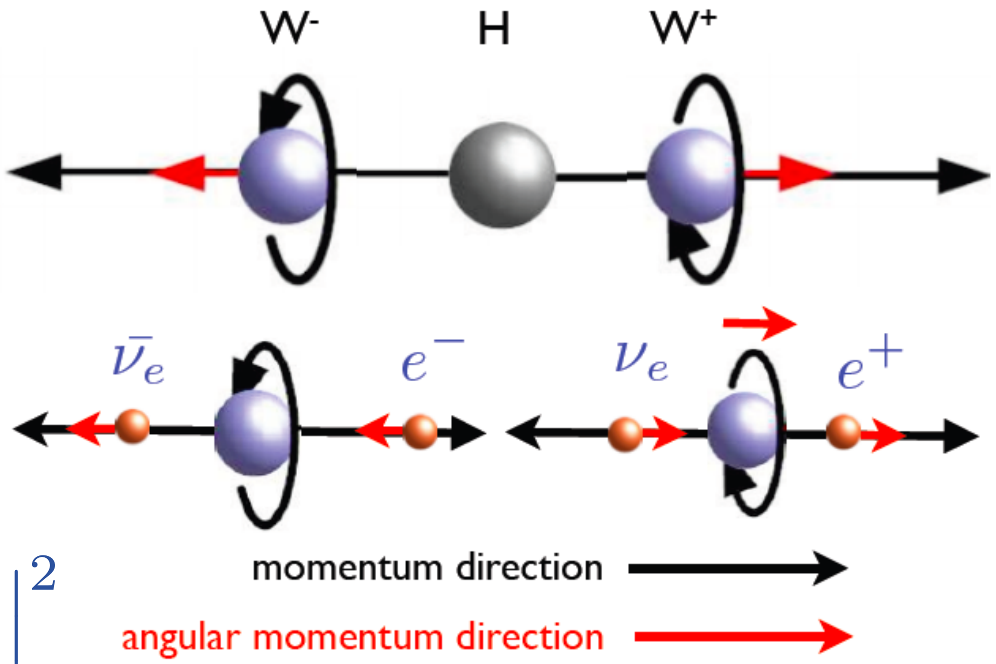


H → WW* → ℓνℓν: analysis strategy

σ X BR ~ 200 fb @ 125.5 GeV

- Signature: opposite-sign leptons (e,μ) and large missing transverse energy
  - Higgs is a scalar
    - Leptons emitted with small Δϕ
  - Limited mass resolution from ν's
    - Transverse mass as main discriminant:

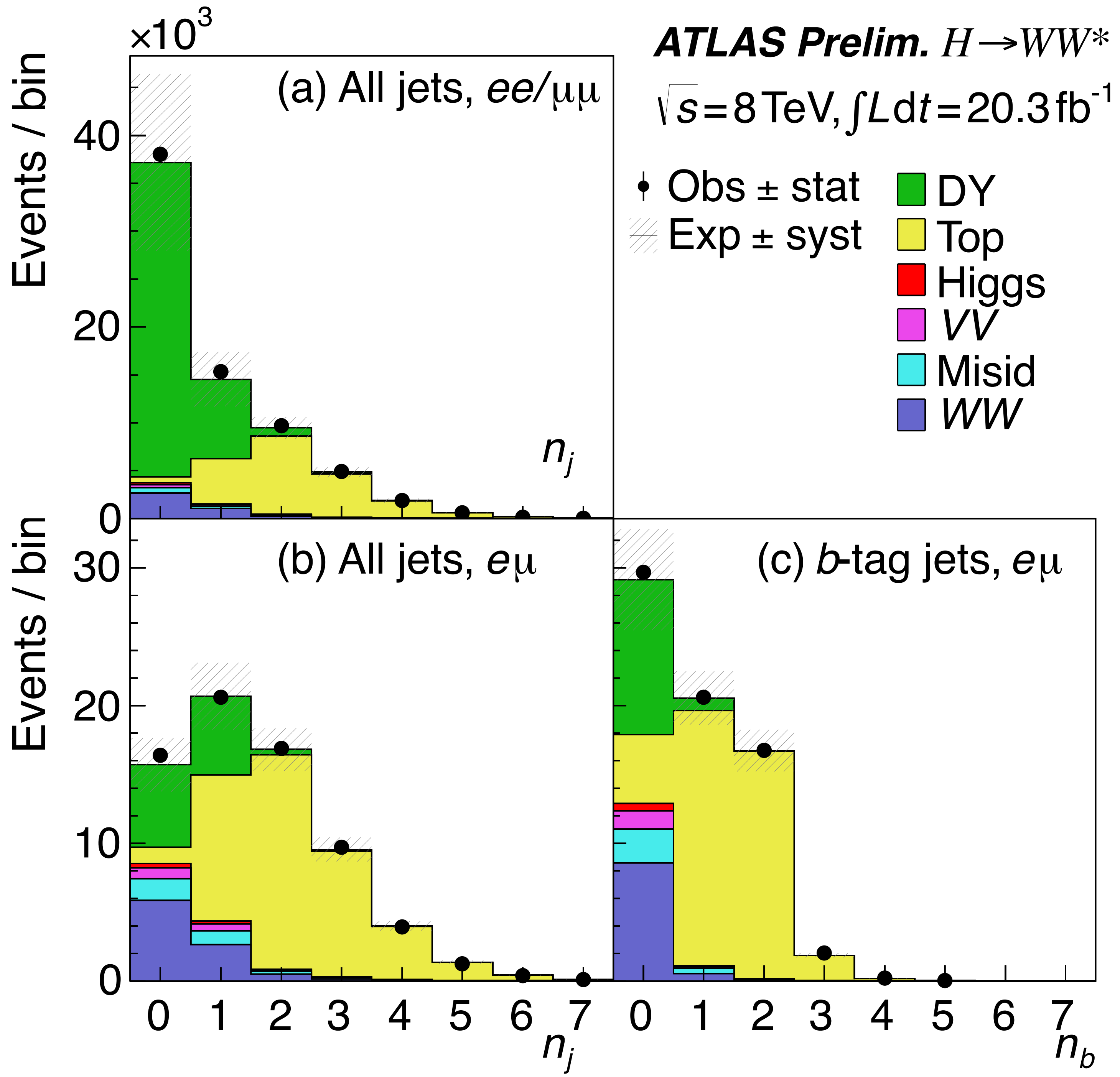
$$m_T^2 = \left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left|\vec{p_{T_{\ell\ell}}} + \vec{E_T^{\text{miss}}}\right|^2$$



  - Large backgrounds: WW, W+jets, top, Z/γ*, di-bosons
    - Mostly data-driven
- Data split according to jet multiplicity
  - 0/1 jets: ggF signal, WW background
  - 2 or more jets: VBF signal, top background

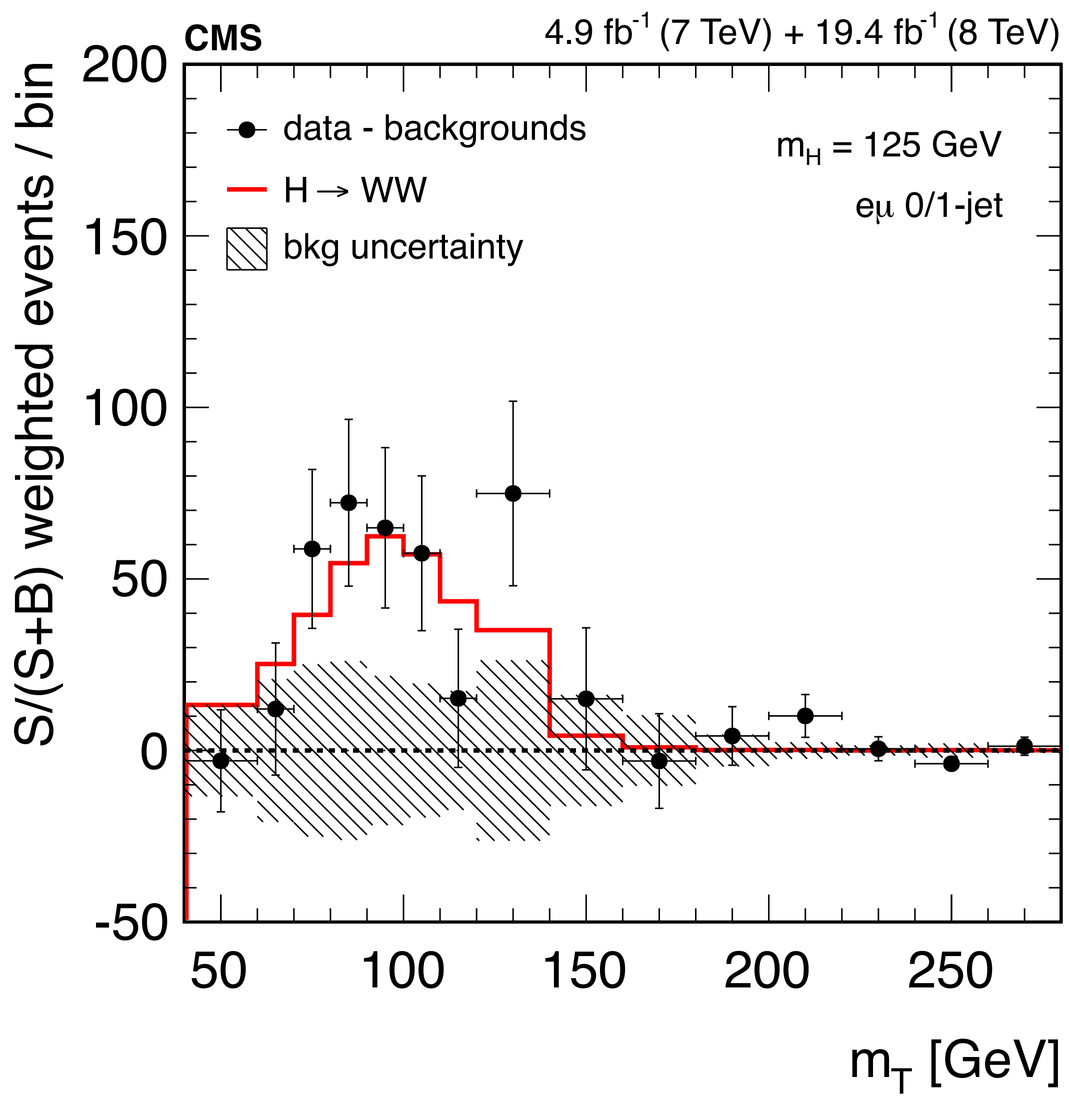
H → WW* → ℓνℓν: analysis strategy

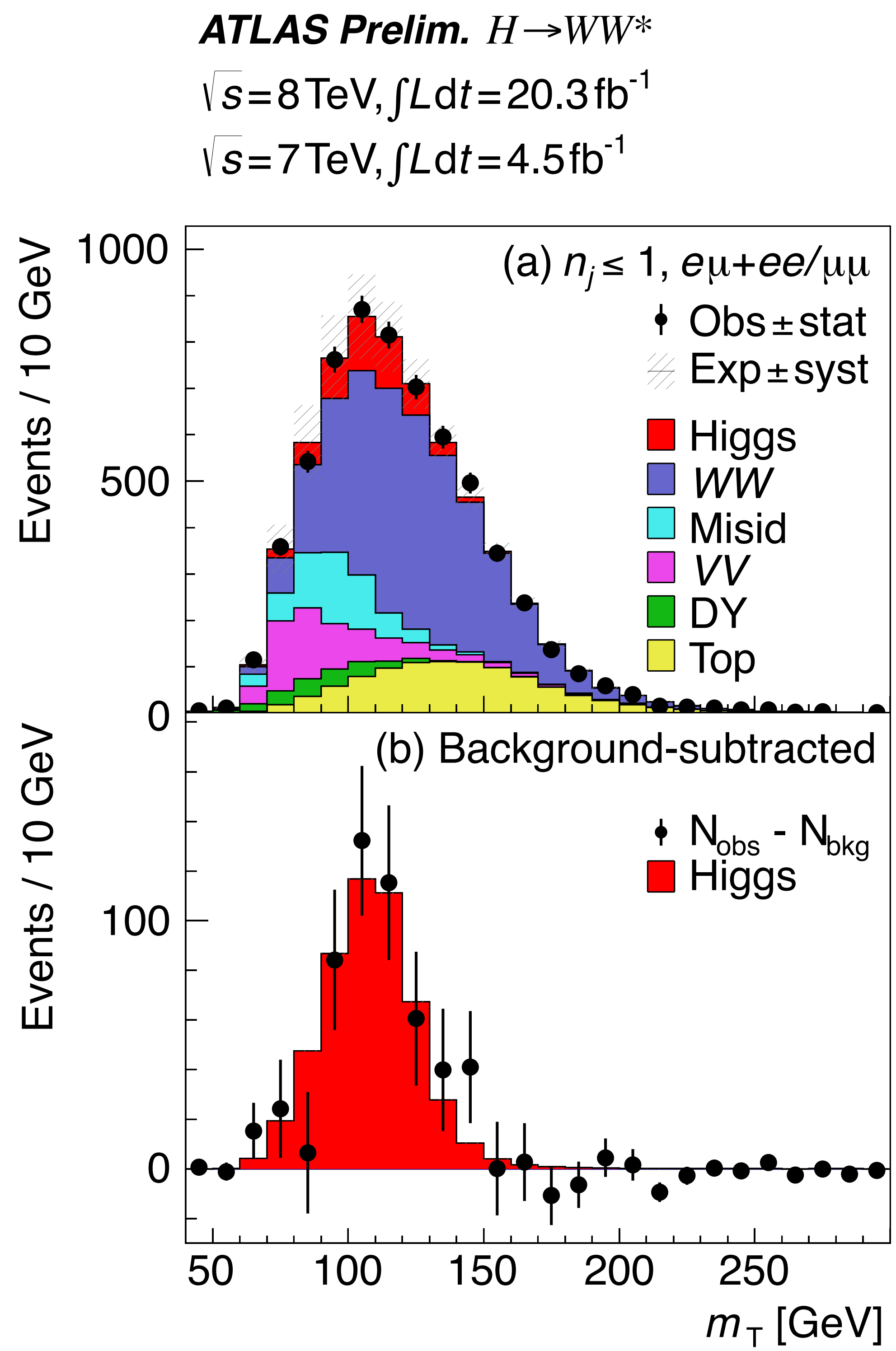
- Data split according to jet multiplicity
  - 0/1 jets:
    - ggF signal
    - WW / Z backgrounds
  - 2 or more jets
    - VBF signal
    - top background



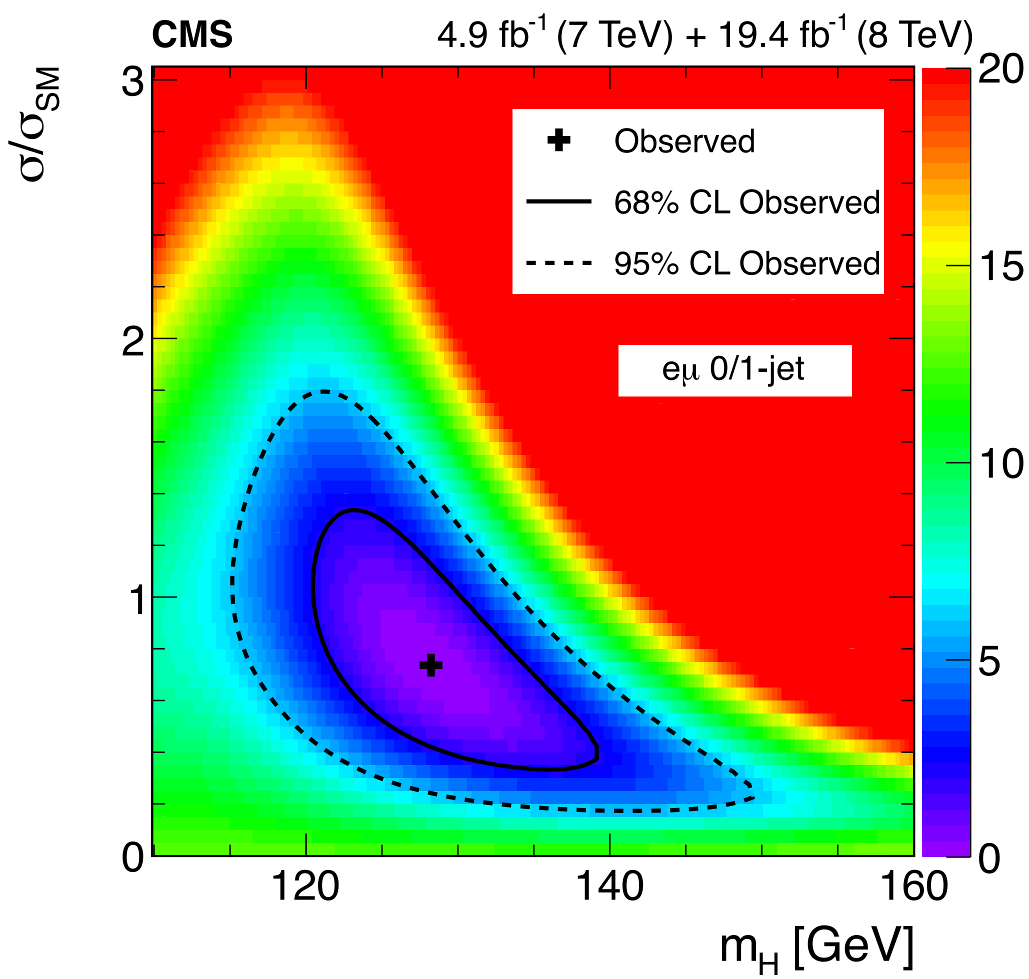
H → WW* → ℓνℓν: a look at the data

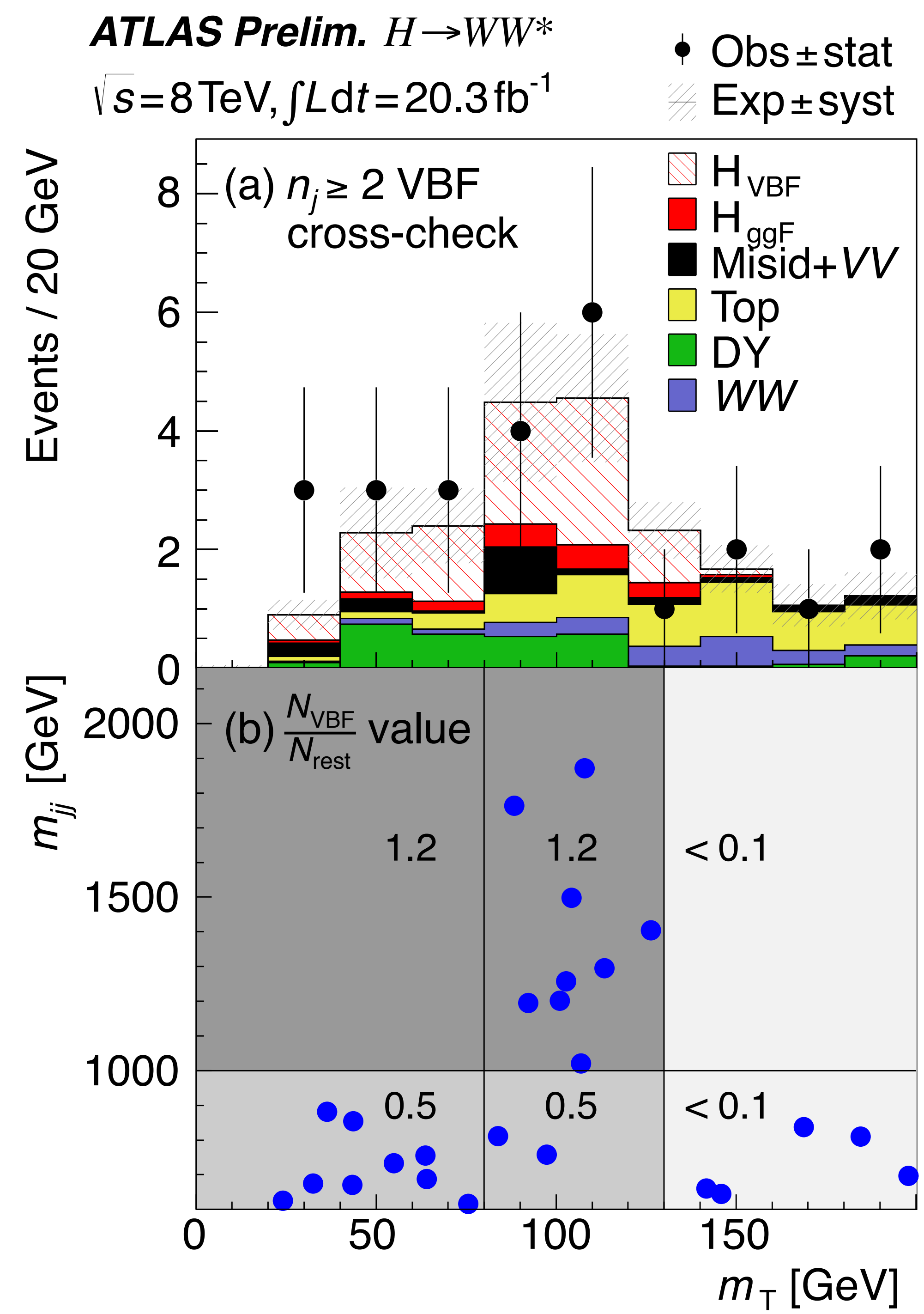
	Z_{obs}	Z_{exp}	μ
ATLAS	6.1	5.8	$1.08^{+0.22}_{-0.20}$
CMS	4.3	5.8	$0.72^{+0.20}_{-0.18}$





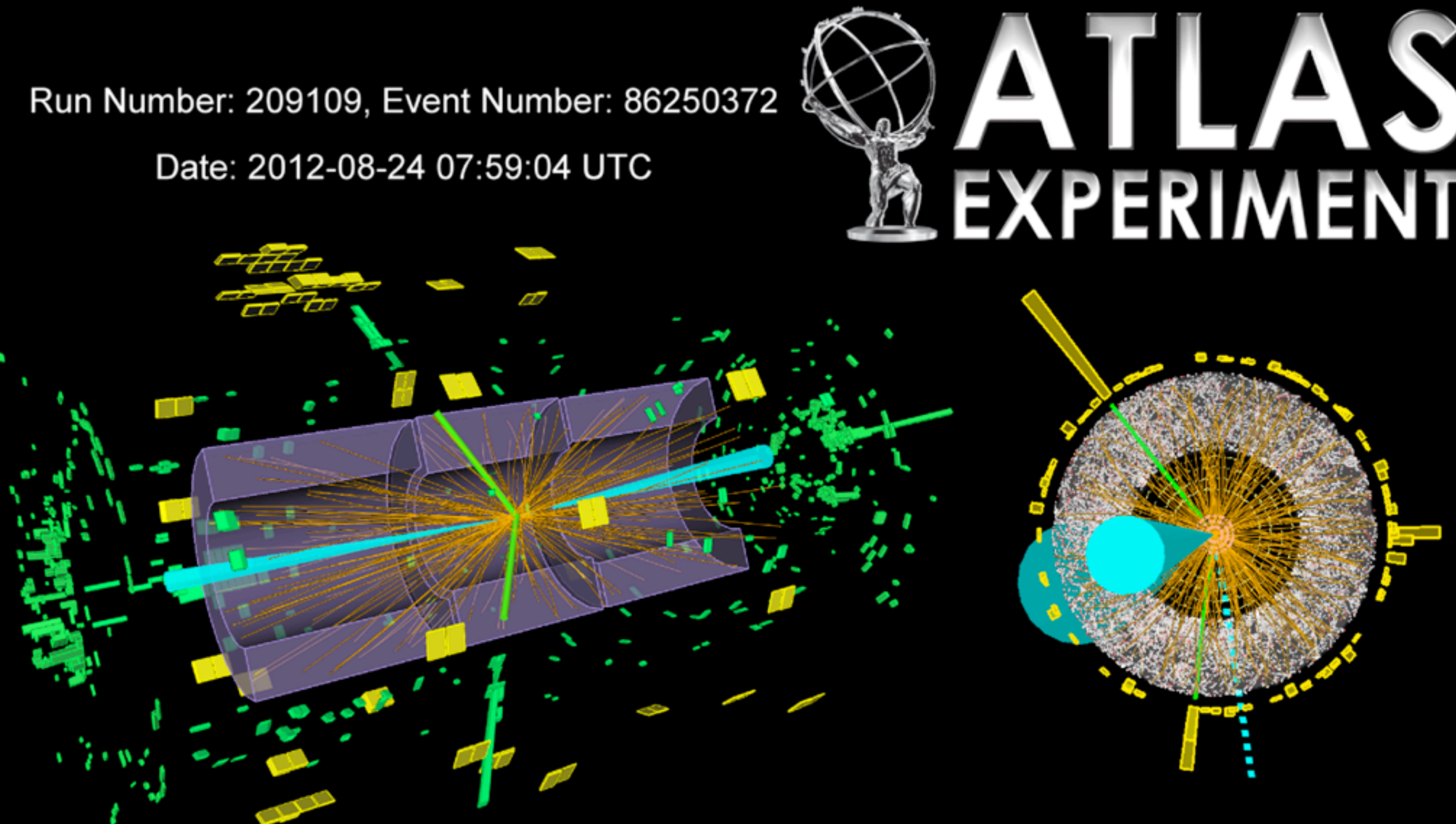
H → WW* → ℓνℓν: a look at the data





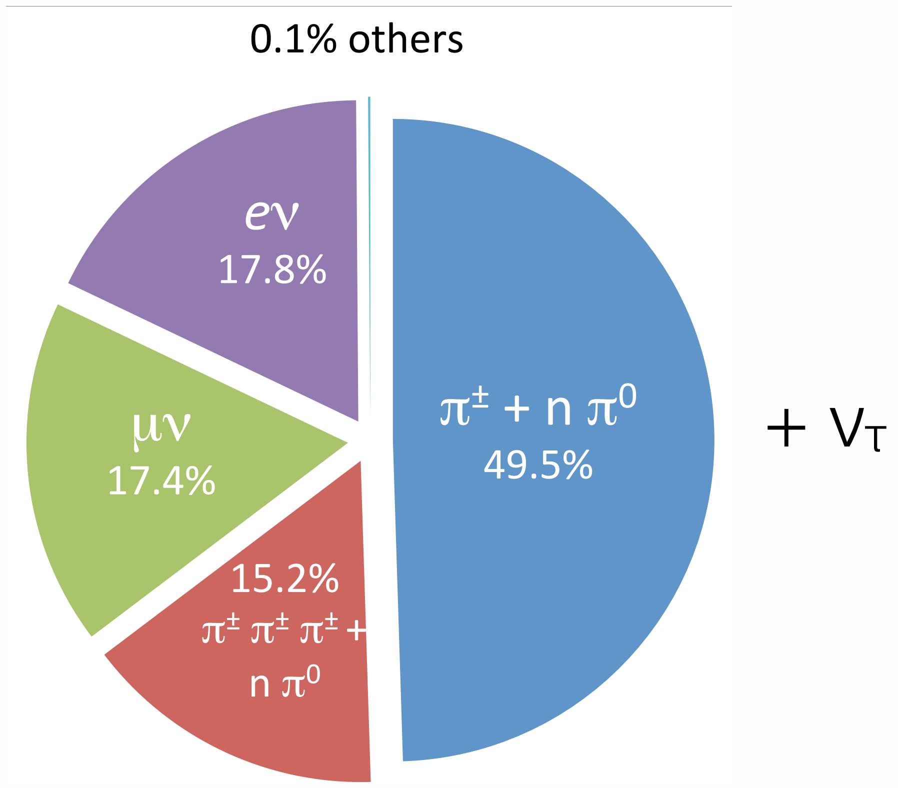
- ATLAS: VBF signal enhanced using BDT
  - 3.2σ observed (2.1 expected)
- CMS VBF: 1.3σ observed (2.1 expected)

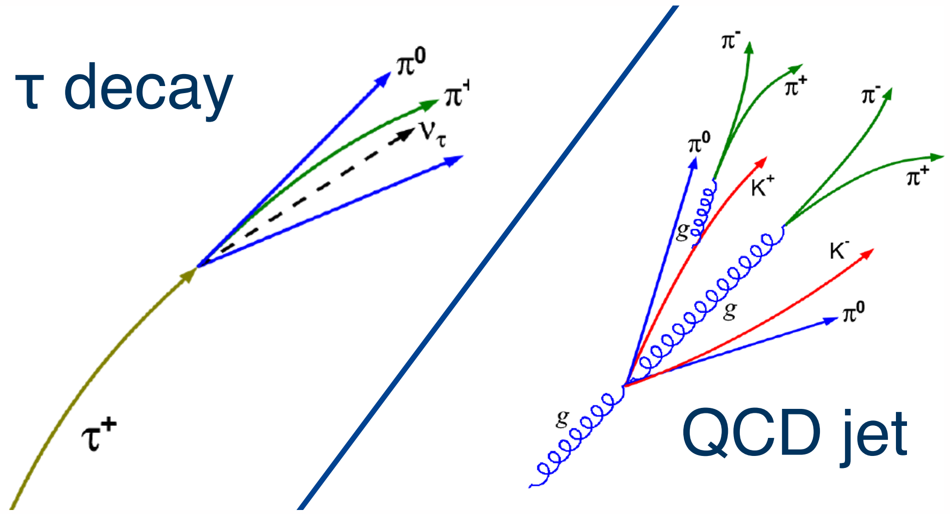
$H \rightarrow \tau\tau$



Tau decays and reconstruction

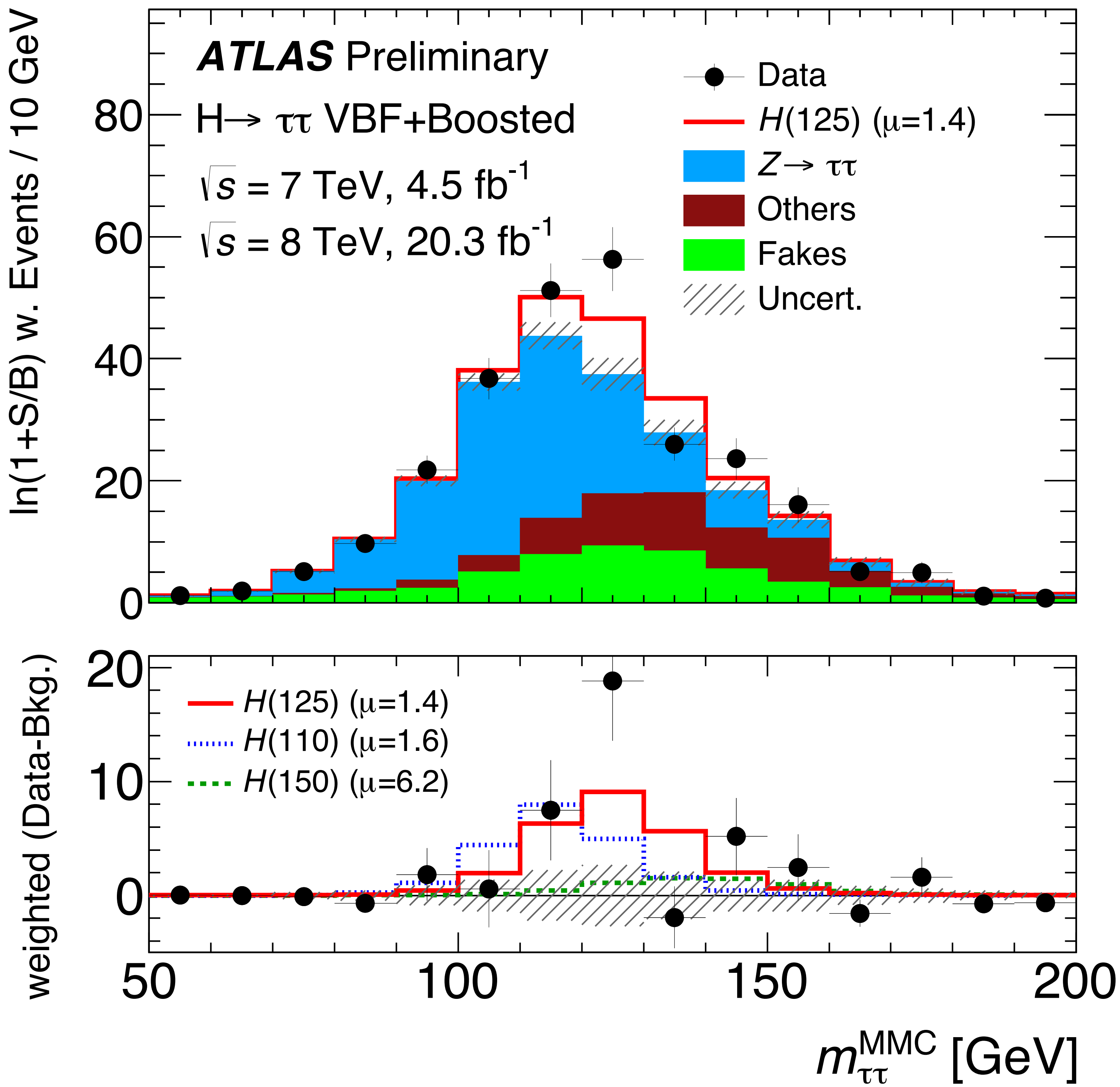
- Challenges:
  - Hadronic τ identification
  - $m_{\tau\tau}$ reconstruction (ν in final state) → σ_m ~15-20%
    - Decay products ~ collinear
- Backgrounds from Z, W+jets, top, multijets (mostly estimated from data)
  - e.g.: Z → τ τ from Z → μμ in data, replacing μ by simulated τ
- Exploit "associated" production (split by N-jets)
  - VBF, W/Z H, boosted ggH





Efficiency: ~60% mis ID: ~1%

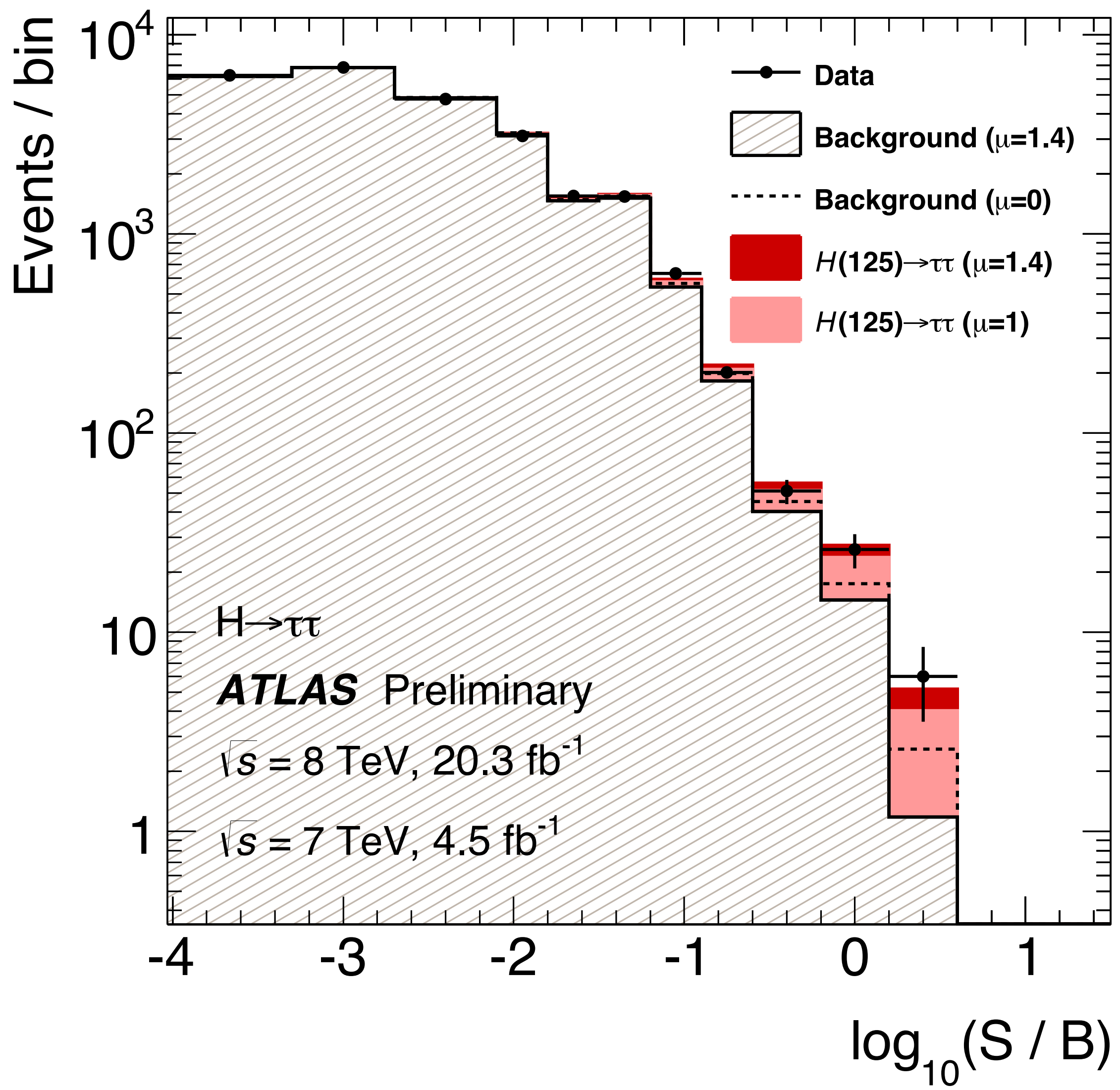
H → ττ: a look at the data

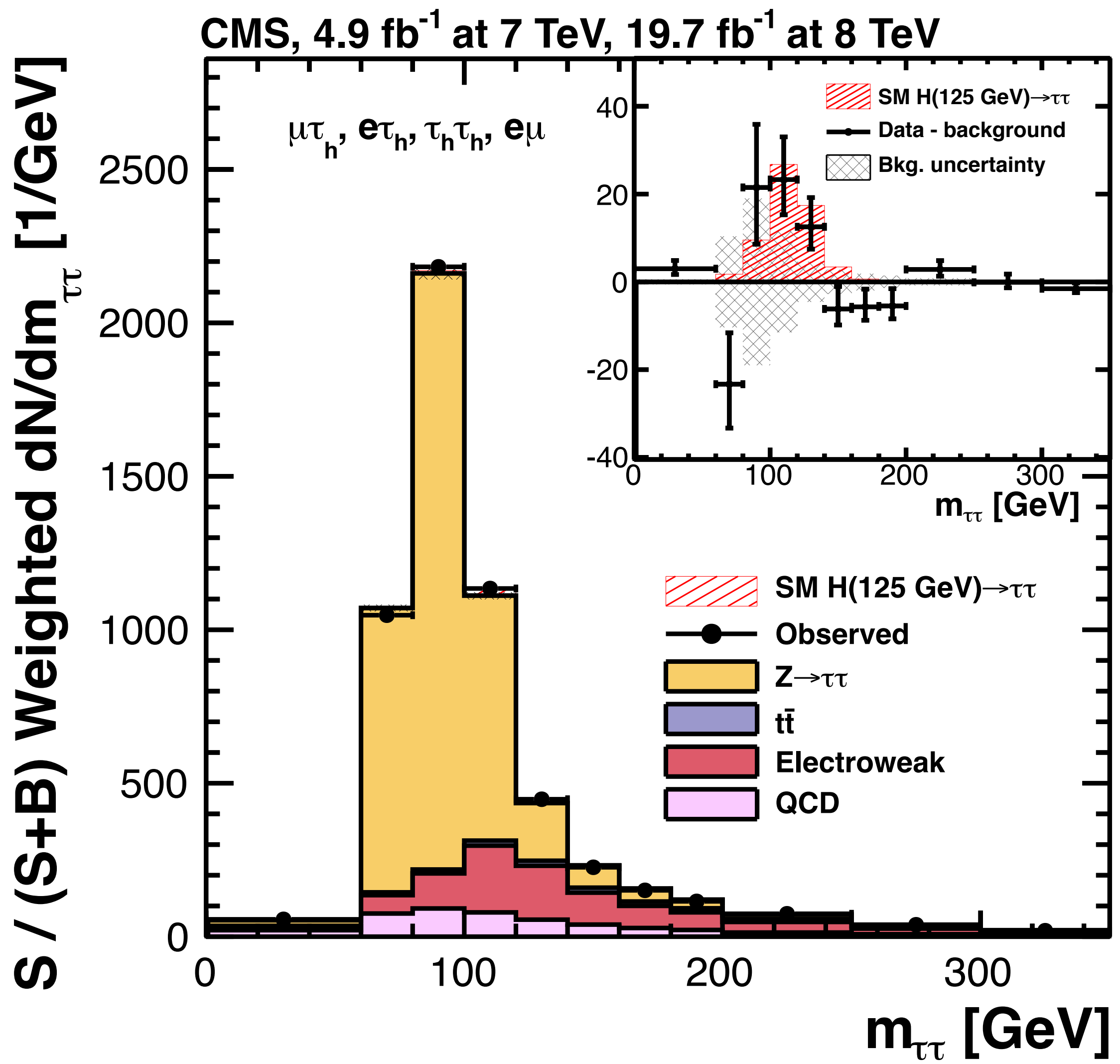


- Low mass resolution:
  - Small separation from Z → τ τ
  - No precise Higgs mass determination
- Analysis optimised to m_H = 125 GeV
  - $m_{\tau\tau}$ is one of the inputs in the BDT discriminant against the background

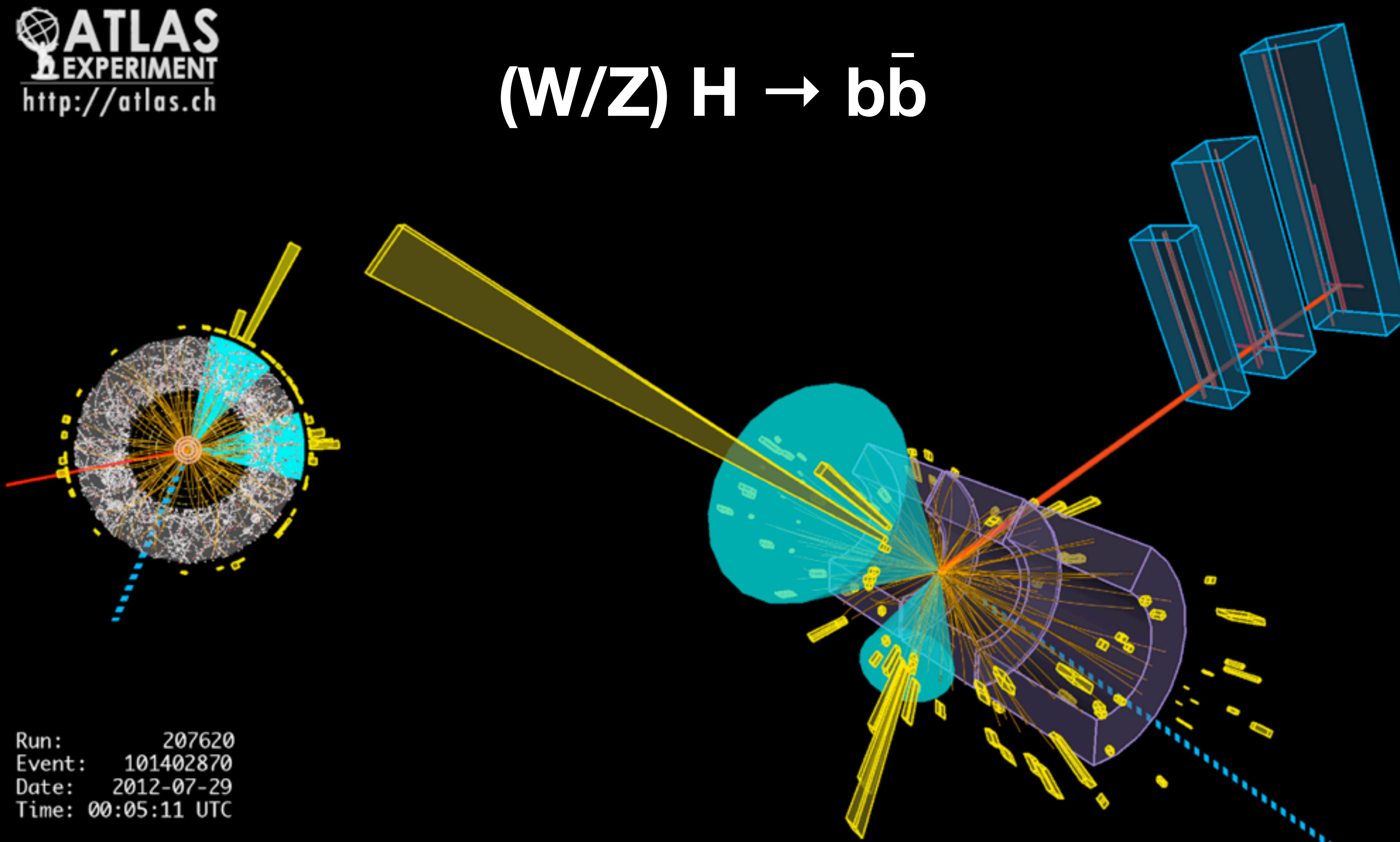
H → ττ: a look at the data

	Z_{obs}	Z_{exp}	μ
ATLAS	4.5	3.5	$1.42^{+0.44}_{-0.38}$
CMS	3.0	3.7	0.78 ± 0.27



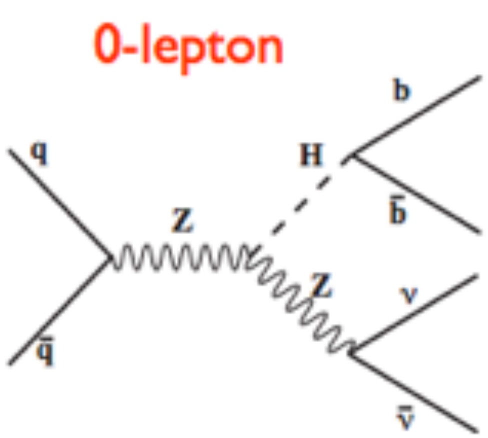


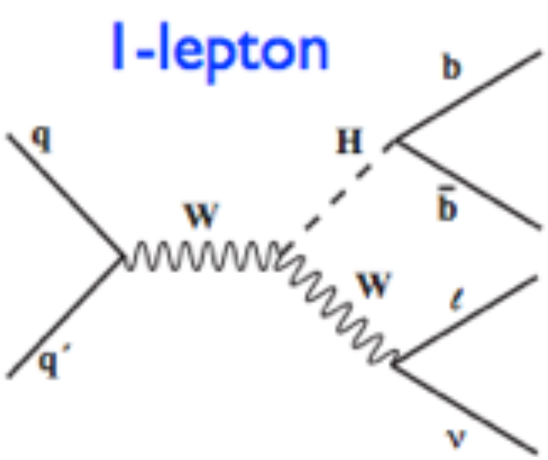
(W/Z) H → $b\bar{b}$

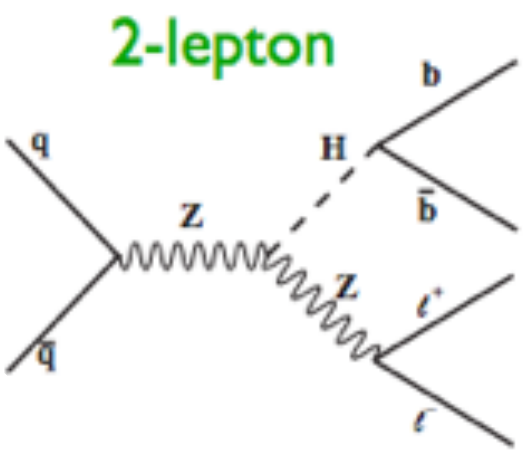

ATLAS EXPERIMENT
http://atlas.ch
Run: 207620
Event: 101402870
Date: 2012-07-29
Time: 00:05:11 UTC

(W/Z) H → $b\bar{b}$

- Huge backgrounds from QCD
    - Exploit associated production with W/Z decaying to leptons and neutrinos
        - Provides trigger
        - Reduces QCD multi-jet background



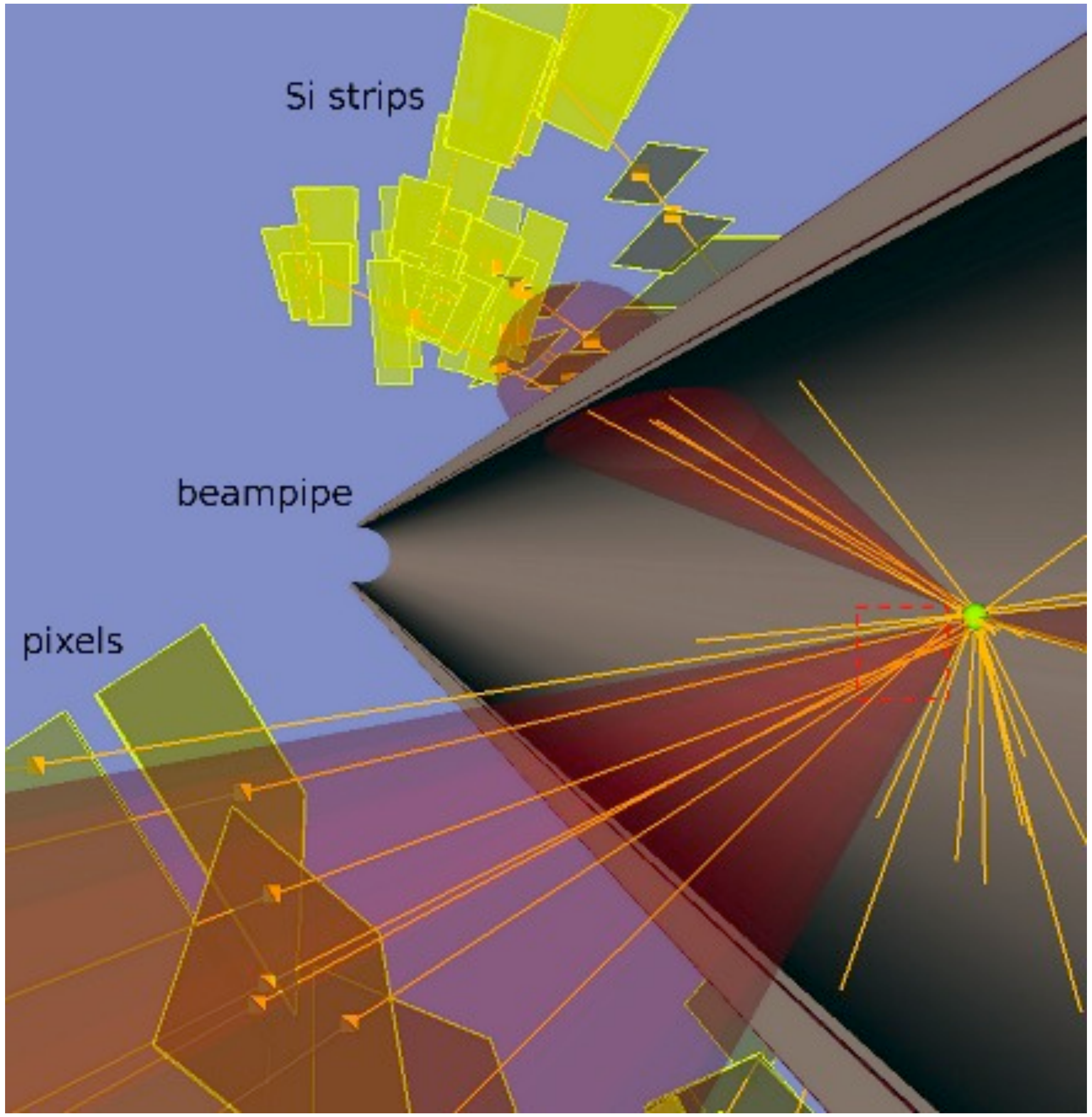




(W/Z) H → $b\bar{b}$

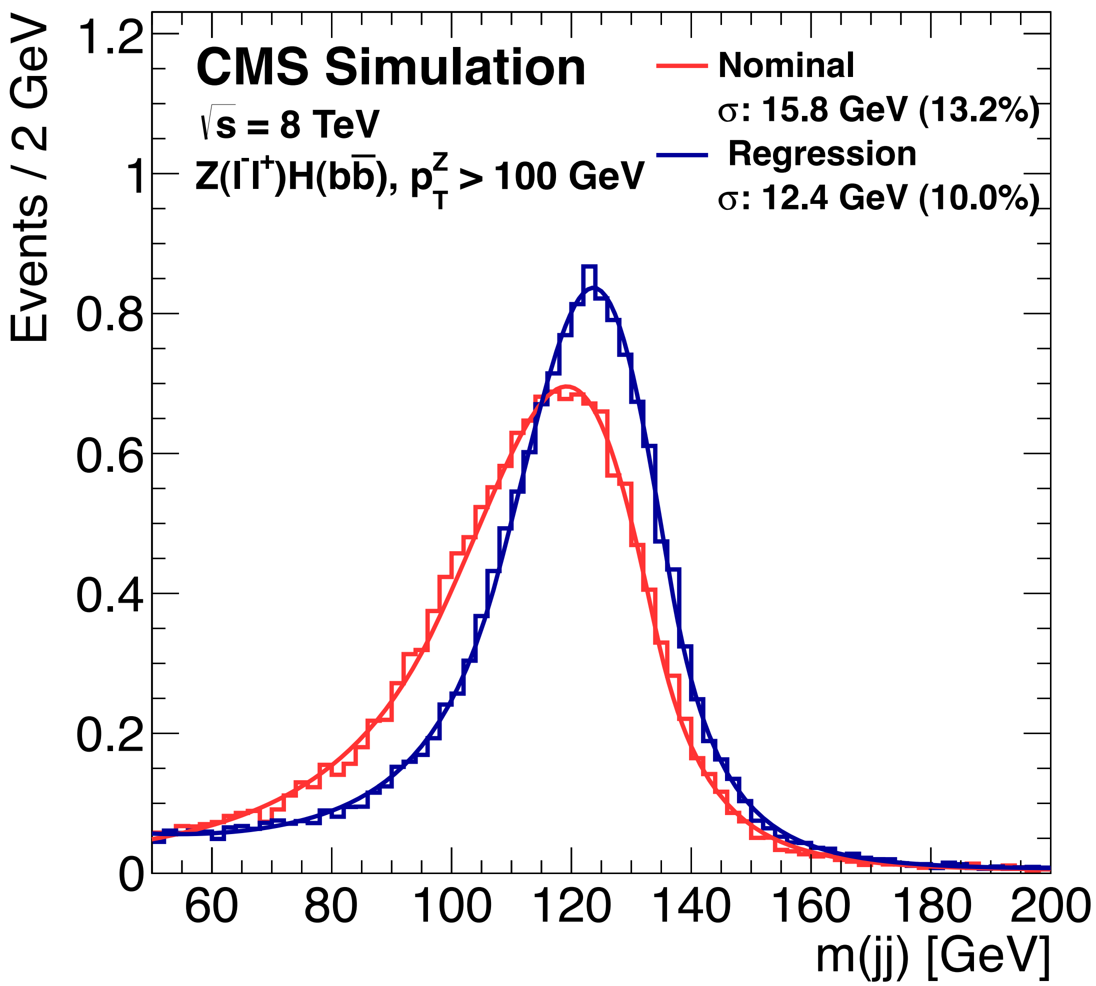
- Huge backgrounds from QCD
  - Exploit associated production with W/Z decaying to leptons and neutrinos
- 2 b-tagged jets (displaced vertices)

(CMS)	b	c	light [%]
Loose	85	32	10
Medium	70	15	1
Tight	50	6	0.1



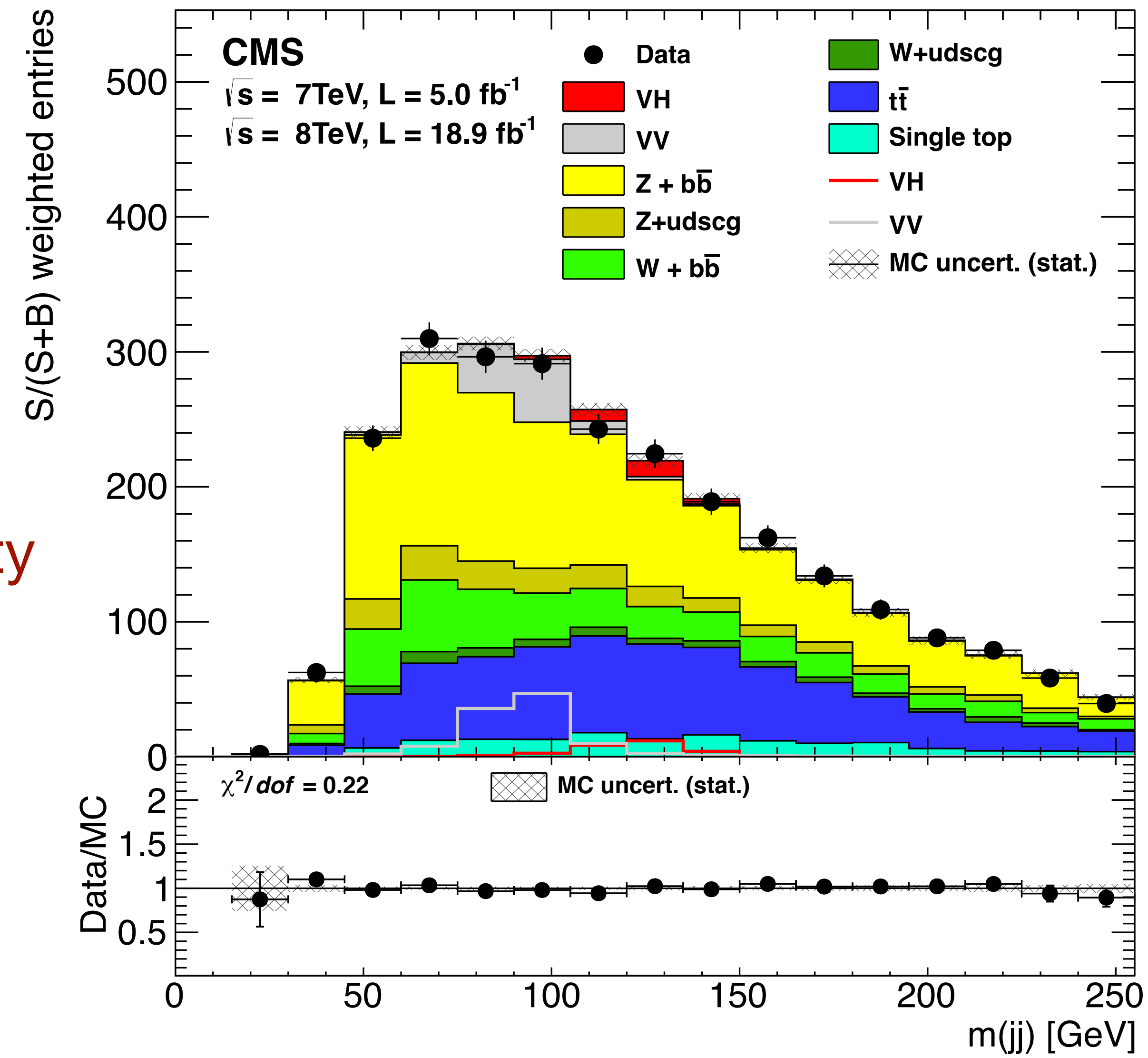
(W/Z) H → $b\bar{b}$

- Huge backgrounds from QCD
  - Exploit associated production with W/Z decaying to leptons and neutrinos
- 2 b-tagged jets (displaced vertices)
- m_{bb} resolution ~ 10%
  - ~30% improvement from multivariate regression techniques and inclusion of soft-muons (b → μ, b → c → μ)



(W/Z) H → $b\bar{b}$

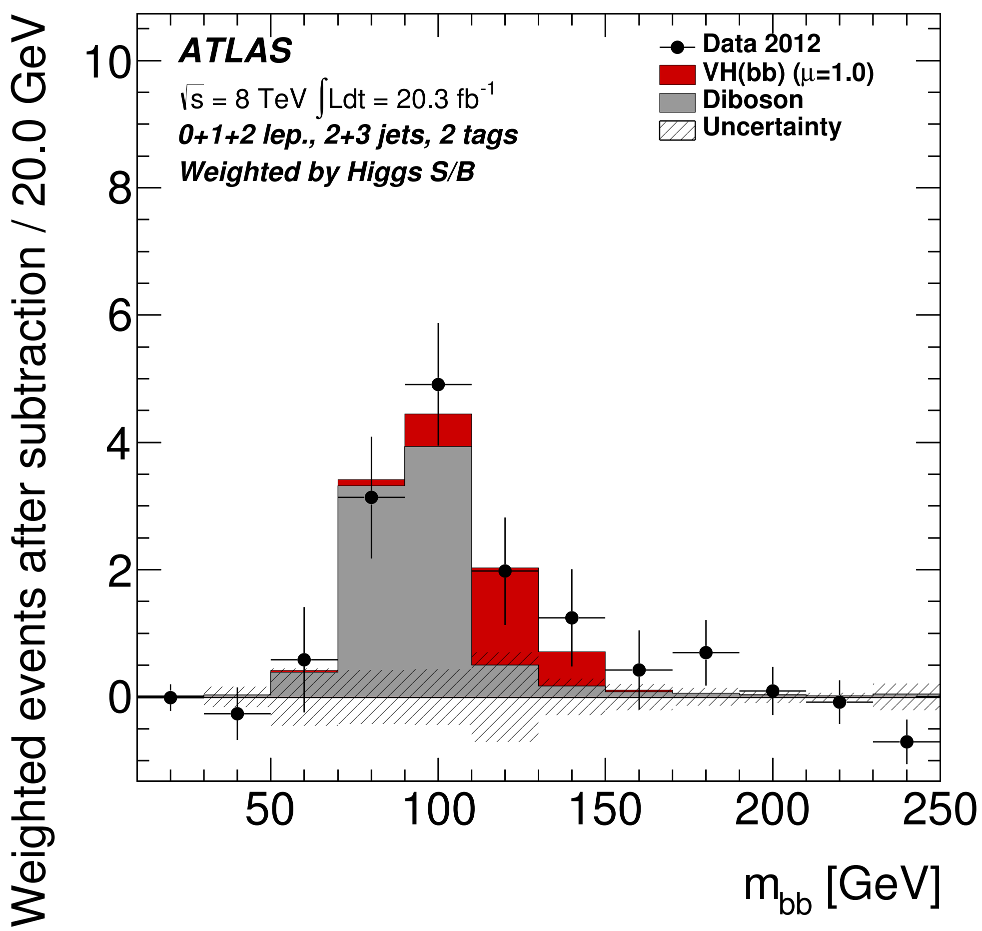
- Huge backgrounds from QCD
    - Exploit associated production with W/Z decaying to leptons and neutrinos
- 2 b-tagged jets (displaced vertices)
- m_{bb} resolution ~ 10%
- Split events in P_T(W/Z)
    - Boosted topologies, enhance sensitivity
- Challenge: control backgrounds
    - Di-boson, W/Z+jets (heavy flavour), top, multijets

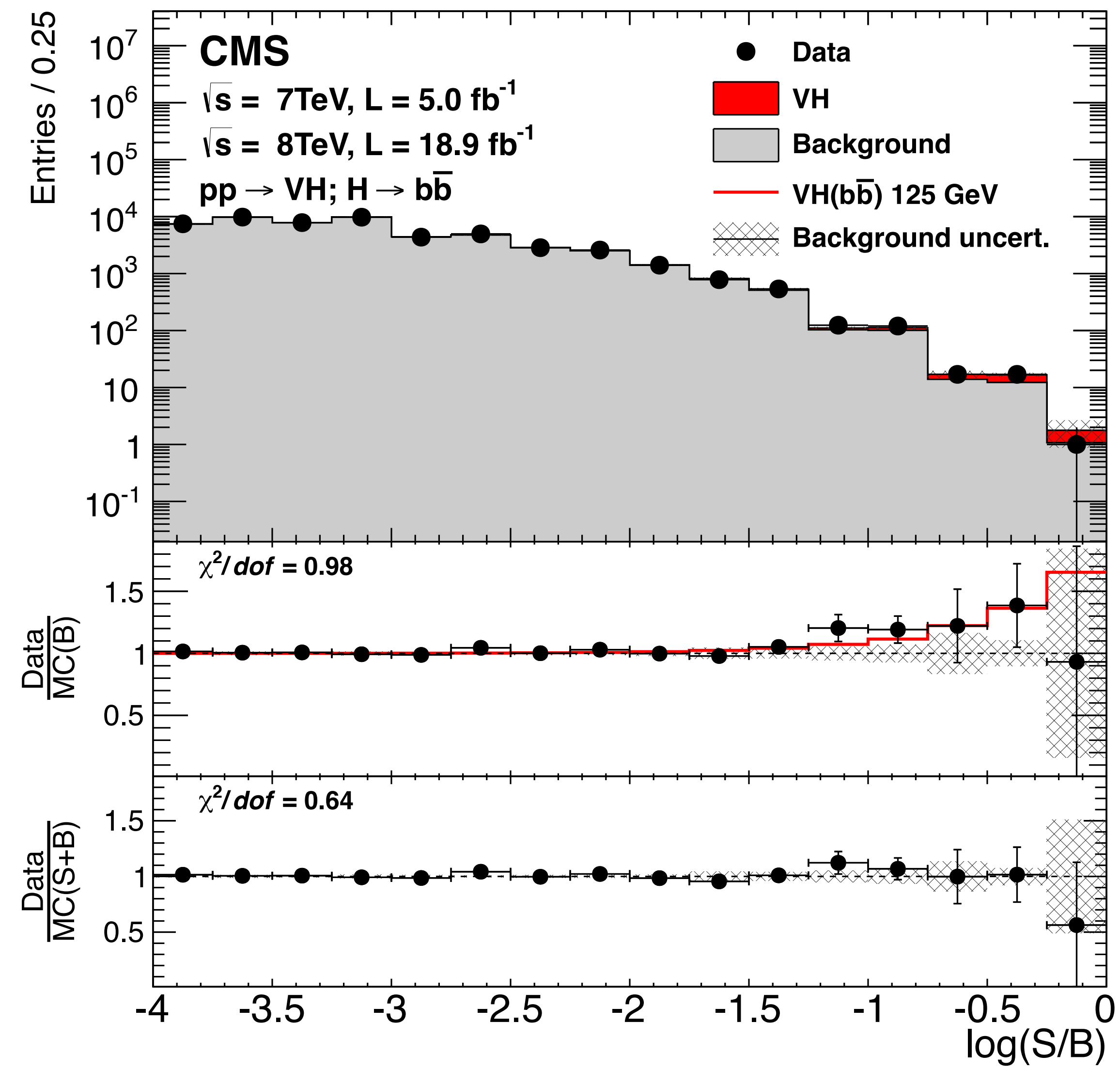


- Discriminant: BDT, including m_{bb}, number of jets, b-tagging score...

(W/Z) H → b$\bar{b}$: a look at the data

	Z_{obs}	Z_{exp}	μ
ATLAS	1.4	2.6	0.52 ± 0.4
CMS	2.1	2.1	1.0 ± 0.5

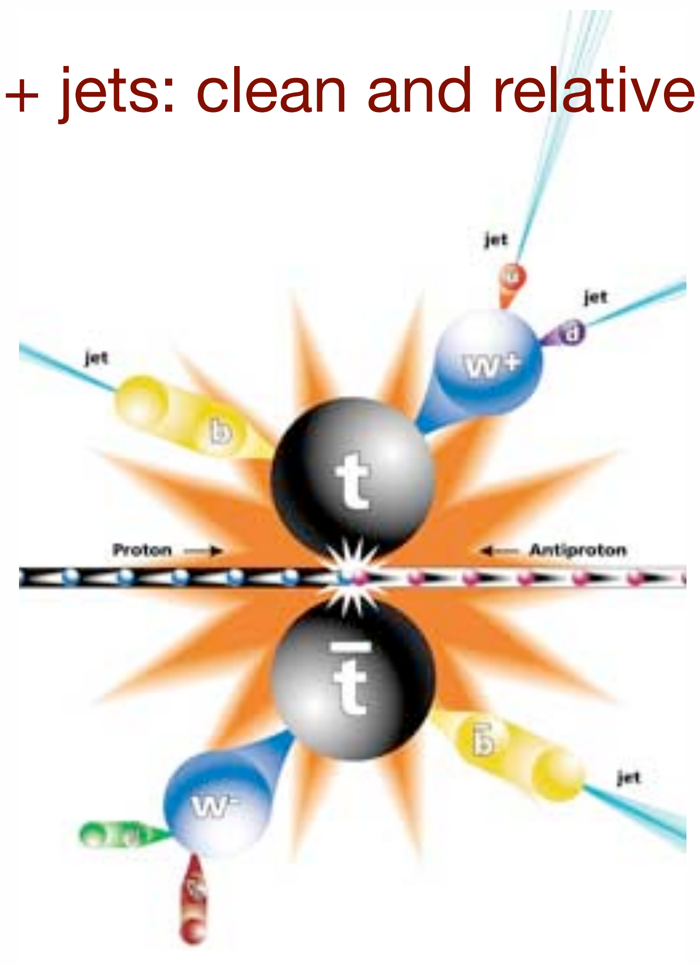


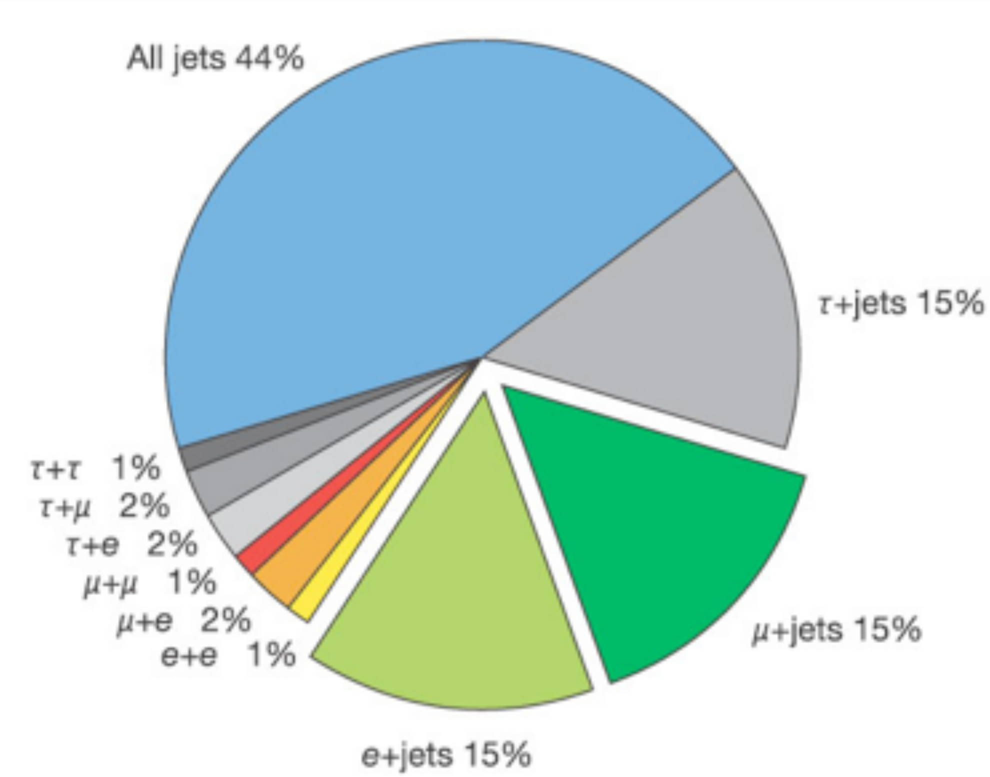


ttH

σ ~ 130 fb @ 125.5 GeV

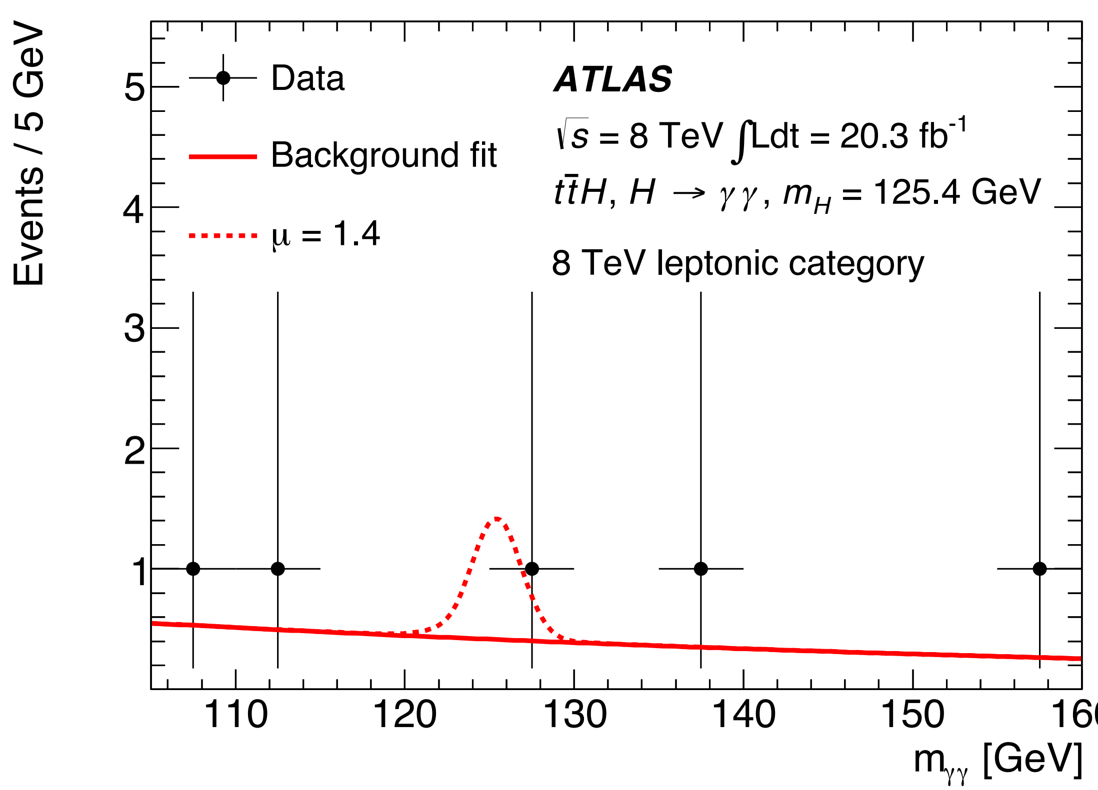
- Direct access to top Yukawa coupling (gluon-fusion is a loop process)
- Complex final states, determined by top-quark decays and Higgs decays
  - All jets: large BR but hard to disentangle from QCD multijets (H → γγ)
  - Fully leptonic tt: very clean but very low BR (H → bb)
  - Lepton + jets: clean and relatively abundant (H → bb, τ τ, WW, ZZ, γγ)

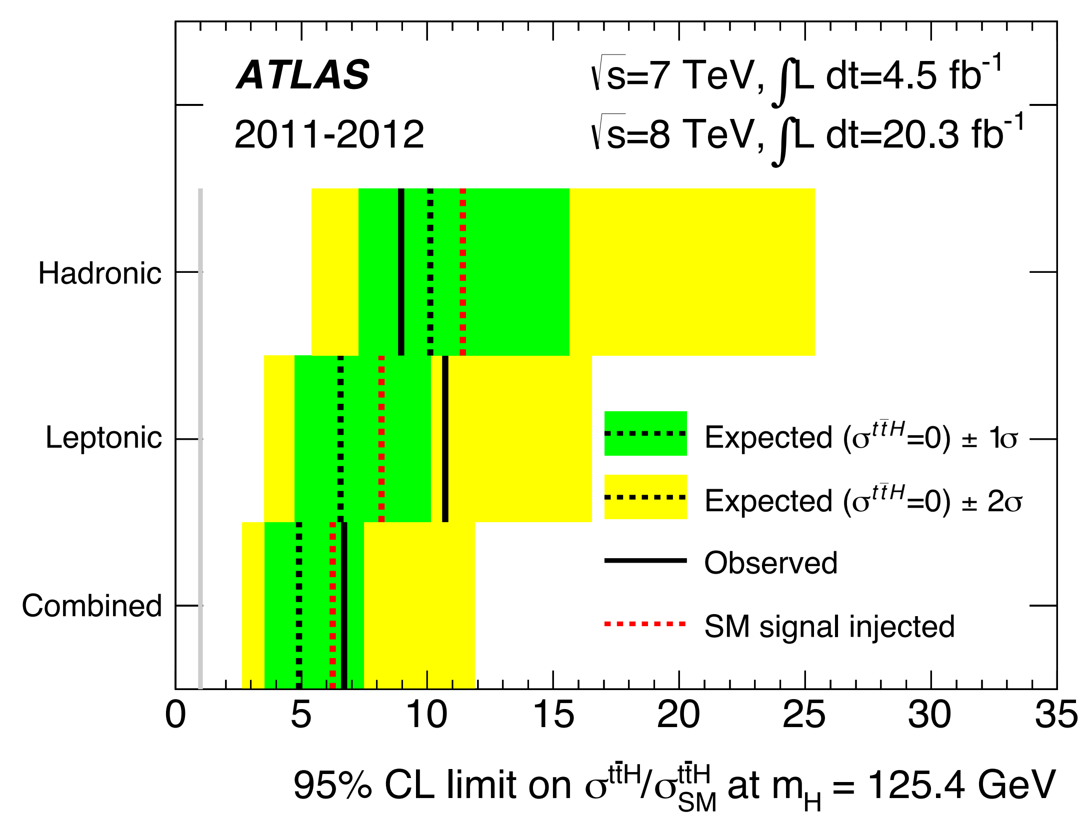




ttH, H → γγ

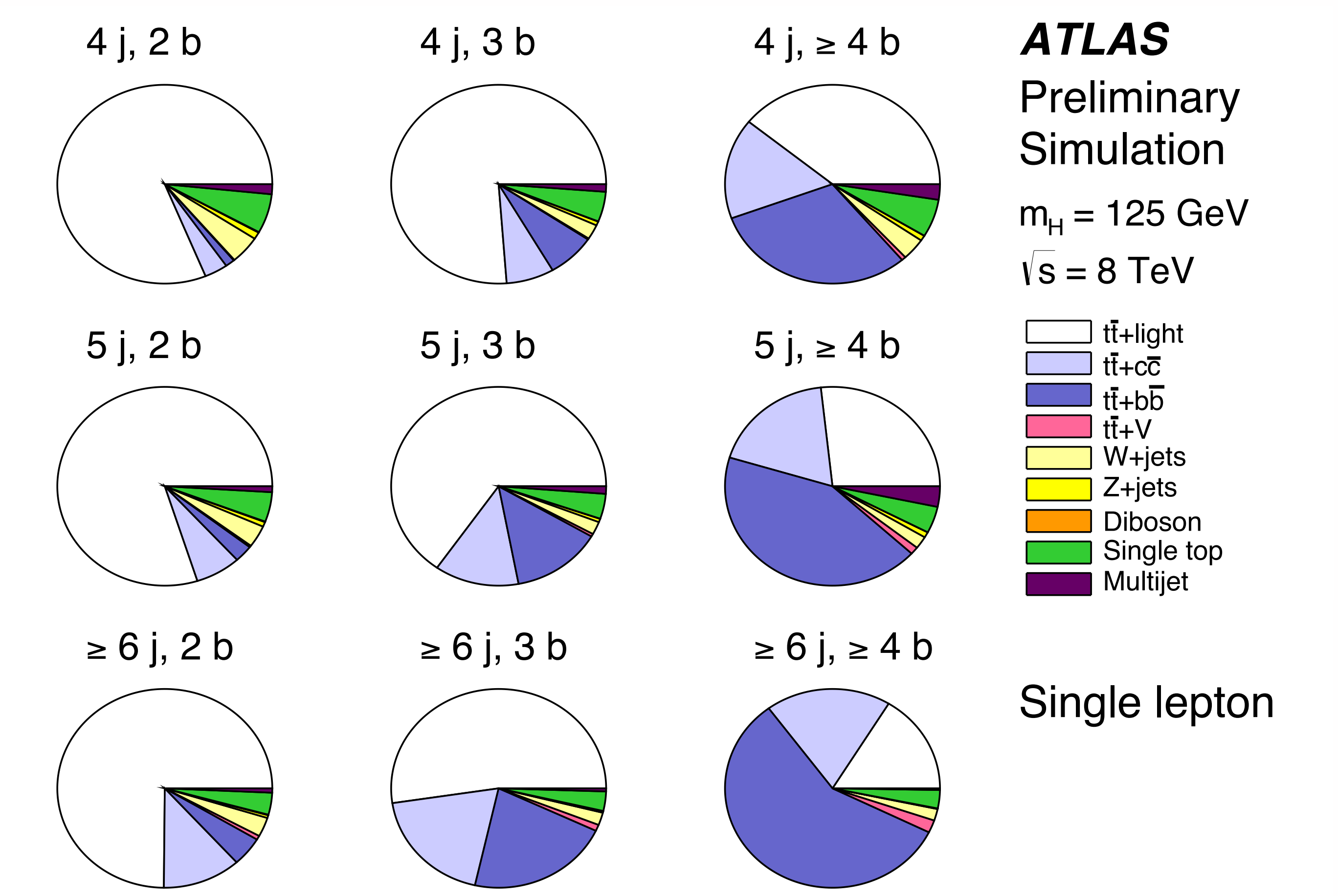
- Standard H → γγ analysis requiring additional leptons and/or jets to enrich the sample in ttH production
  - Very low statistics
  - Leptonic and hadronic categories with ~80% ttH purity
    - Small contamination from tH, WH (leptonic), gluon-fusion (hadronic)





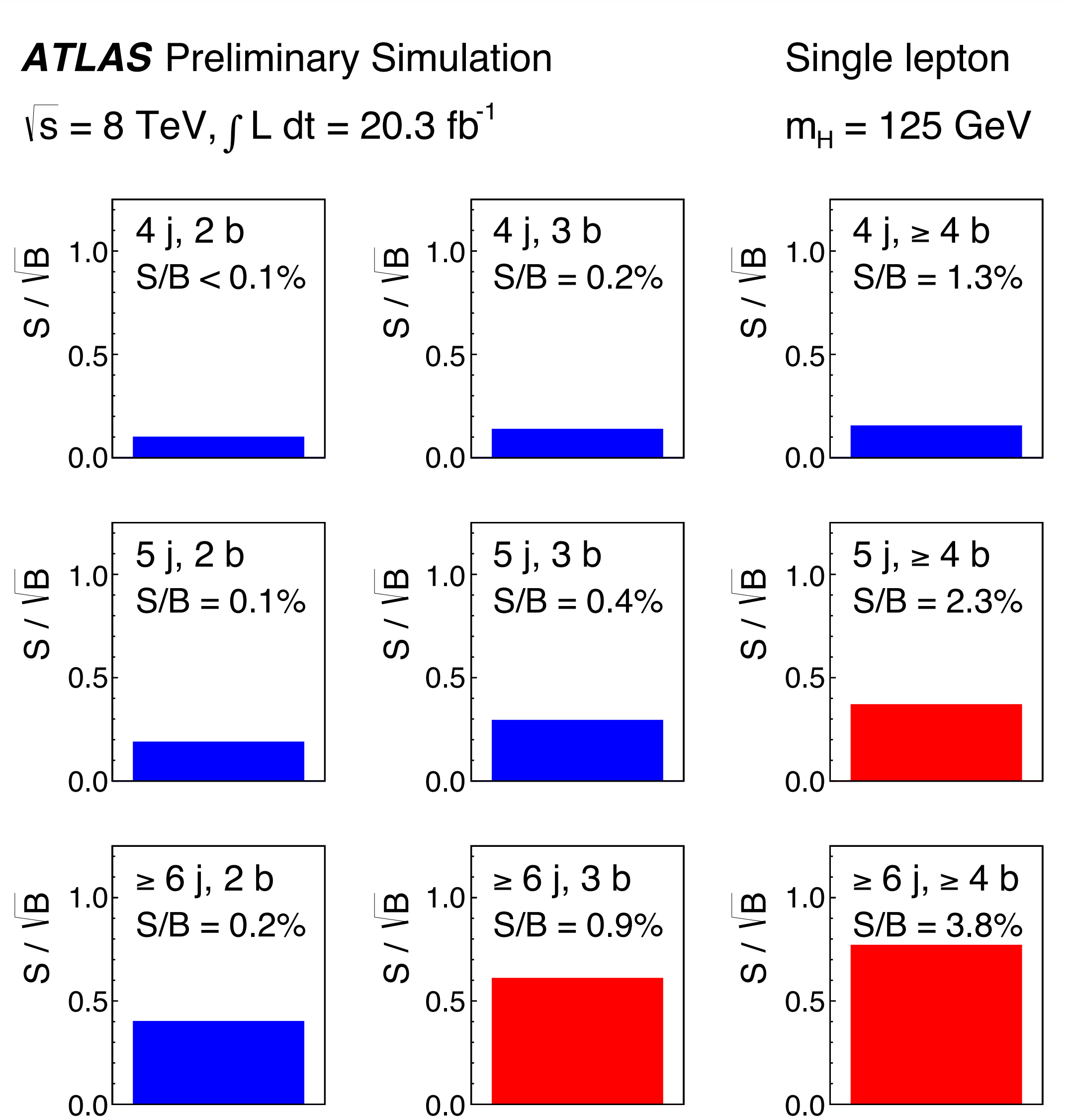
ttH, H → bb

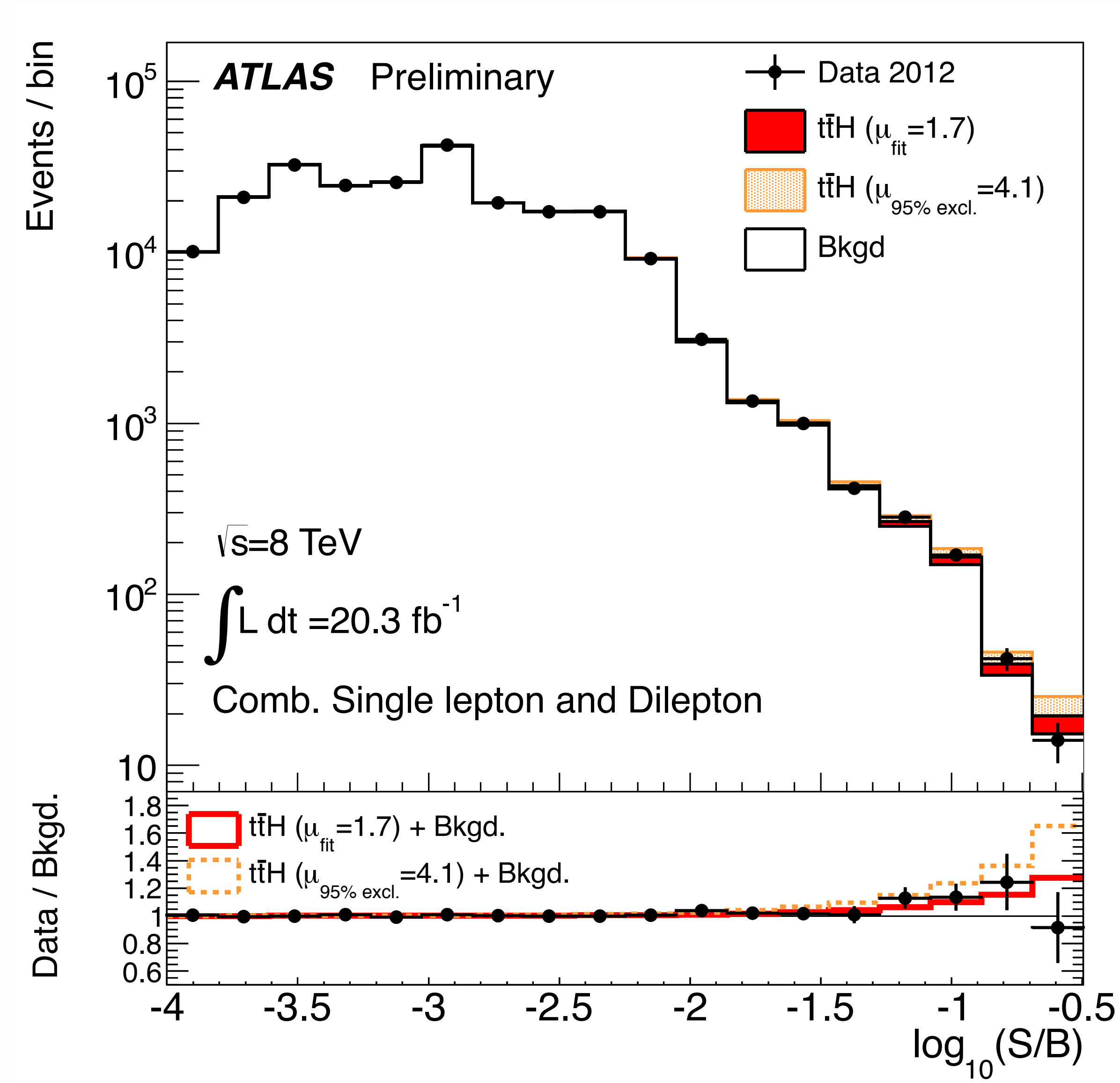
- Final states with one or both W's decaying to leptons
  - Trigger and discrimination against QCD
- Very complex final states, multiple possibilities to combine jets to reconstruct Higgs or top decays
  - m_{bb} is not a powerful discriminant



ttH, H → bb

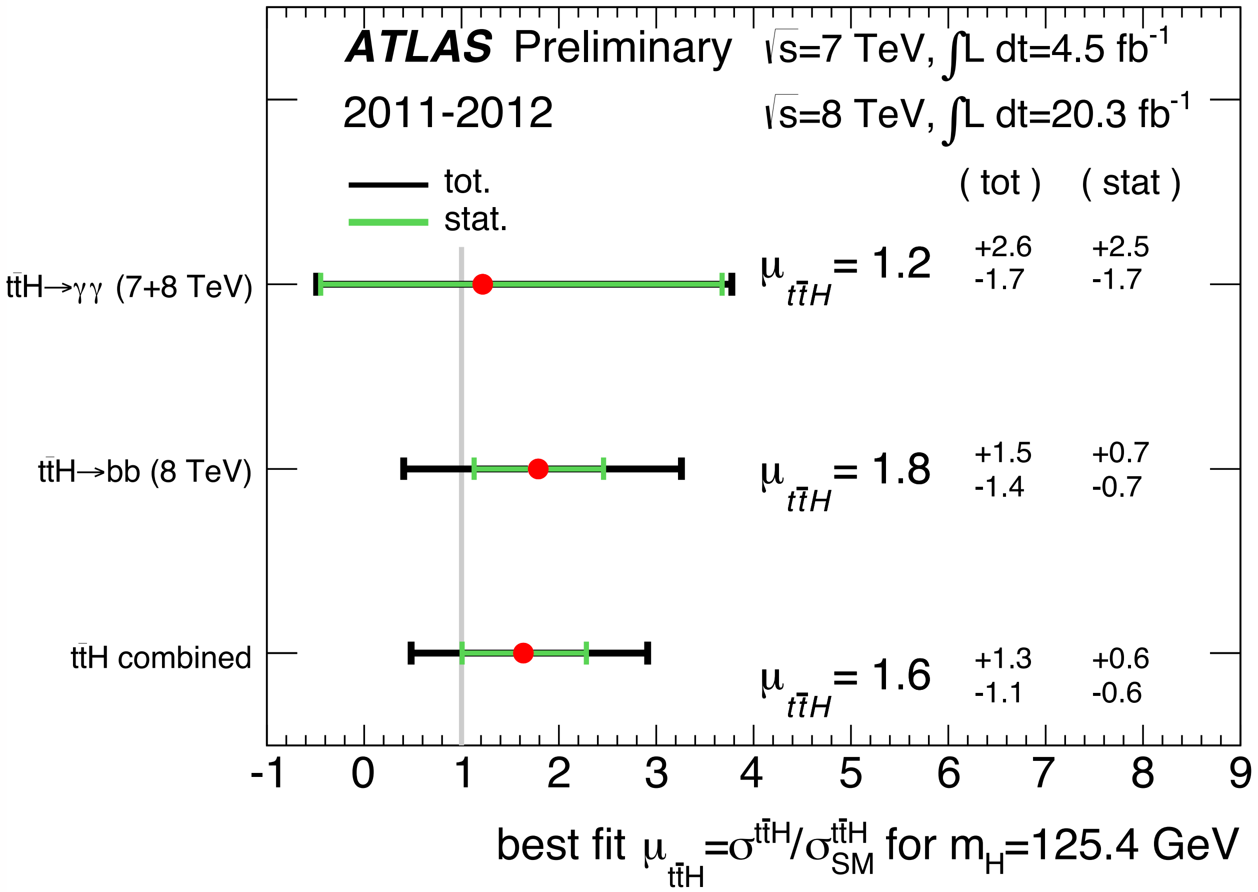
- No single final state with sensitivity: "divide and conquer"

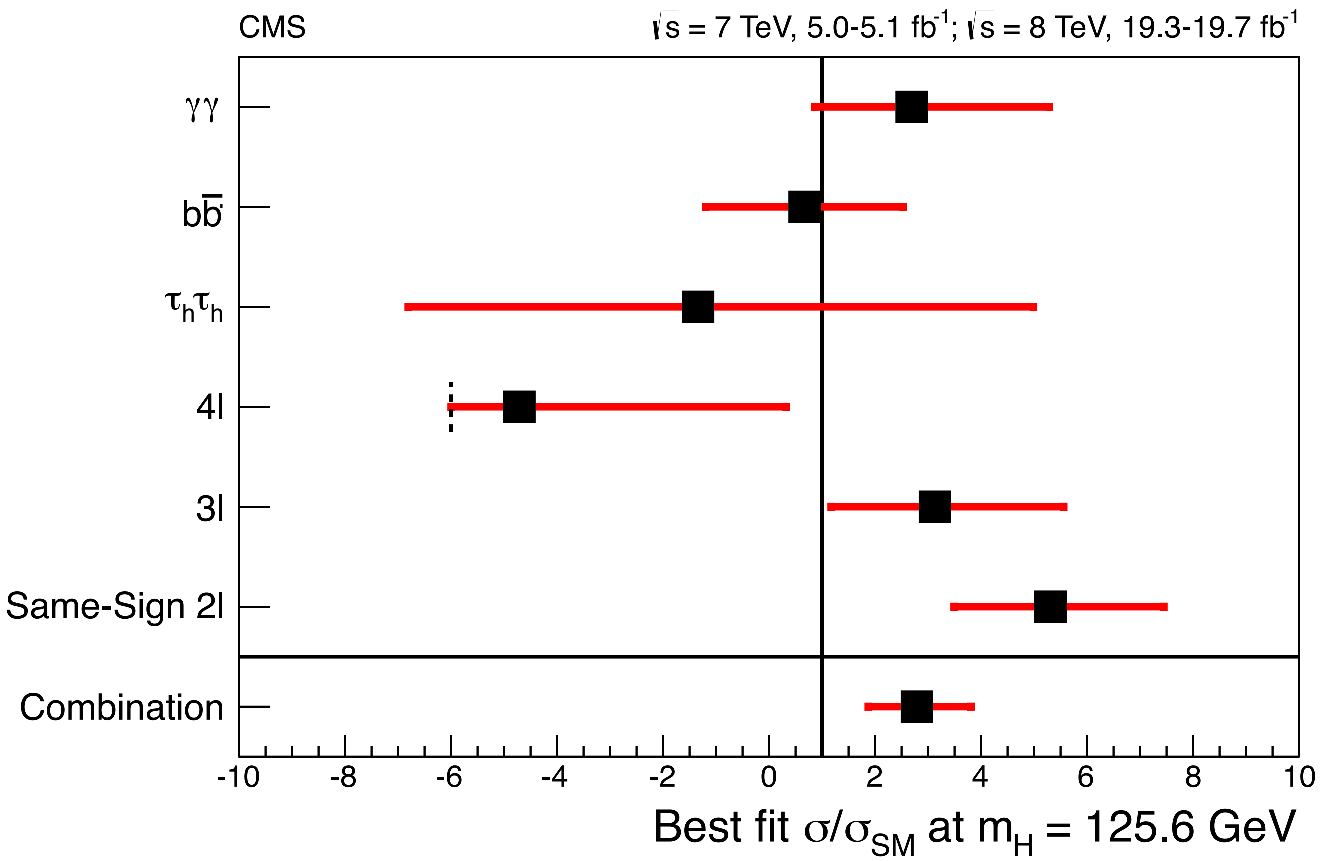




ttH combination

- ATLAS: 1.5σ observed (1.0σ expected)
- CMS: 3.5σ observed (1.2σ expected), 2.0σ above SM prediction
    - Large excesses in same-sign di-muon and γγ analyses





Rare decays: H → Zγ → ℓℓγ, H → μμ

σ X BR ~ 2.3 fb (~5 fb) @ 125.5 GeV

- Clean signatures
  - Leptons and low-E_T photon / opposite charged muons
- Low signal yields and large backgrounds, modeled by analytical functions
  - Z+γ (~80%) and Z+jet (~20%) / Drell-Yan (~95%)
- Limits @ 95% CL, m_H = 125.5 GeV: μ ≲ 10 / μ ≲ 7