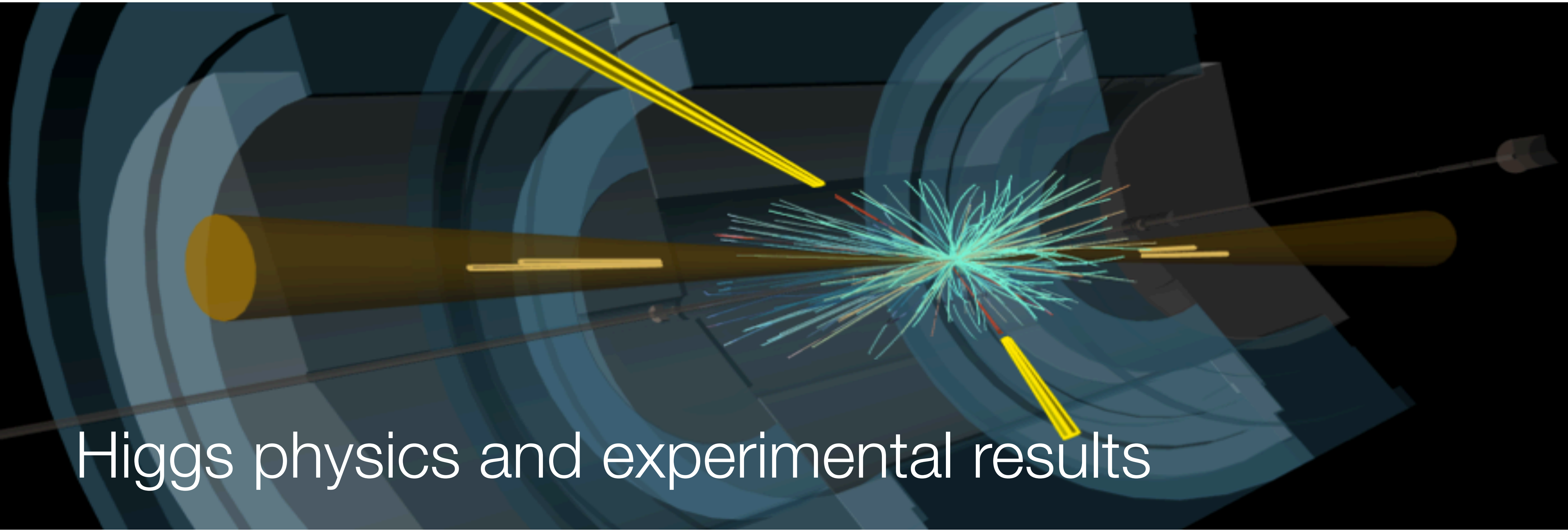


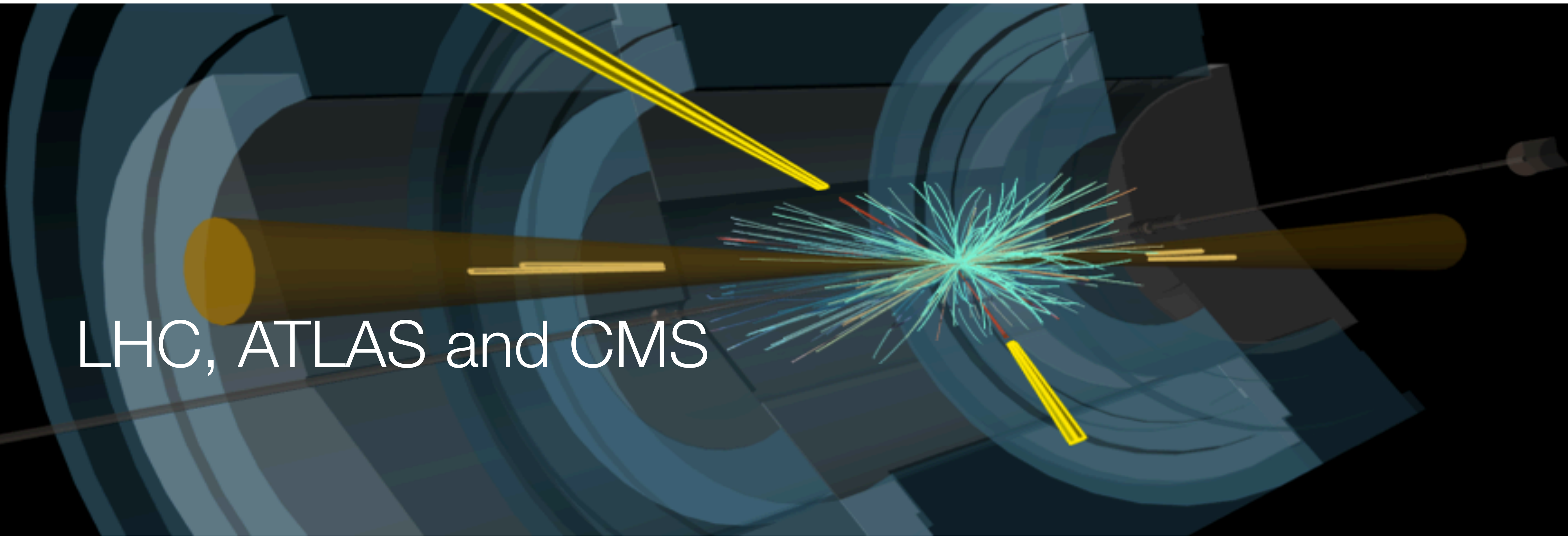
Higgs physics and experimental results

Bruno Lenzi

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

22/10/2014

LHC, ATLAS and CMS

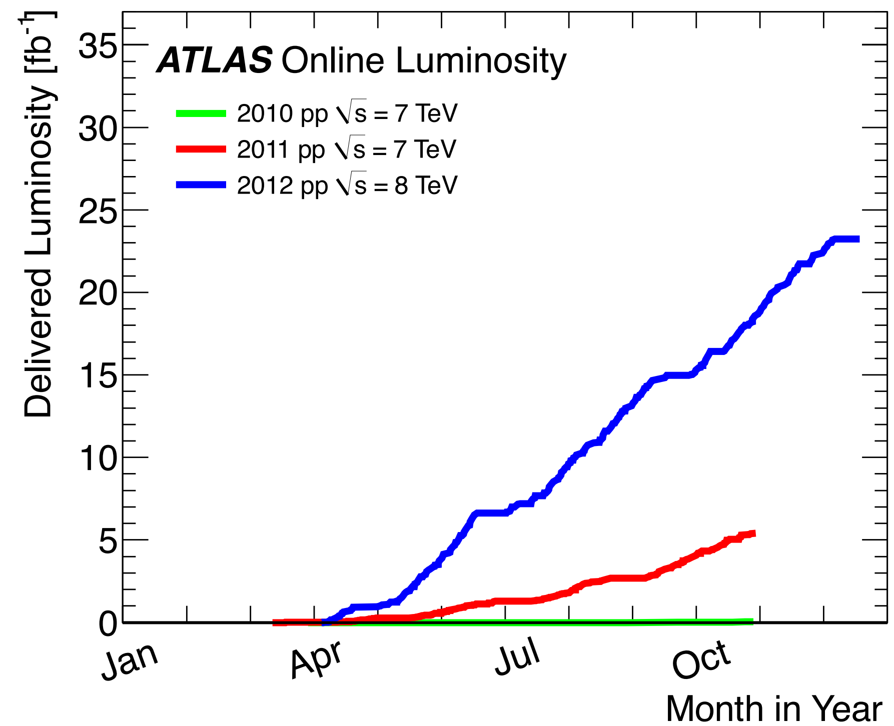


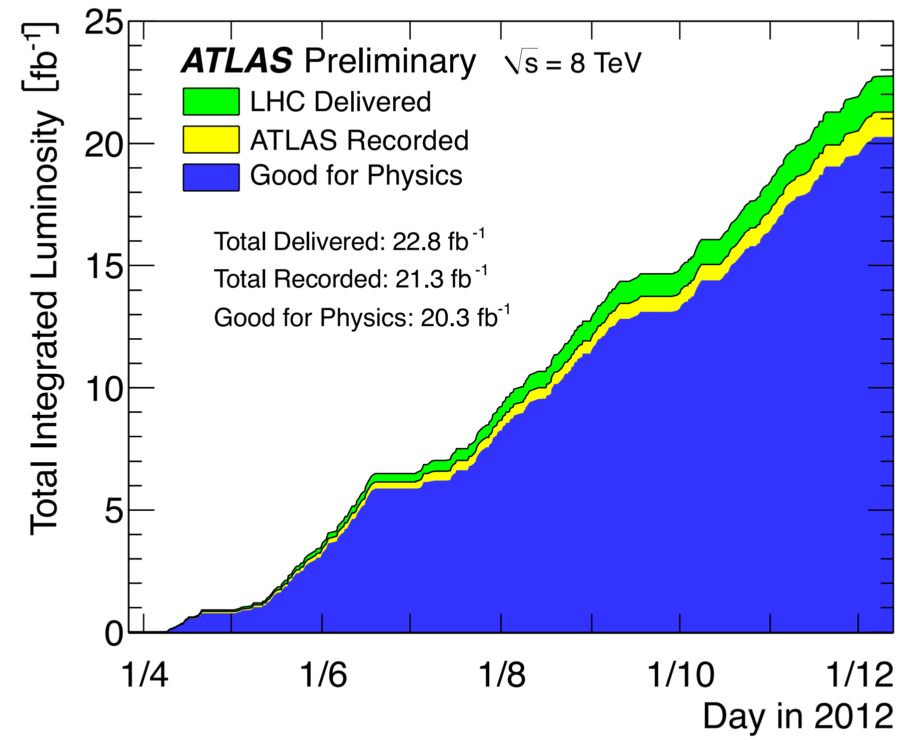
LHC: delivered luminosities

- LHC performance beyond expectations!
  - Higher luminosity → more pileup
    (additional interactions per bunch crossing)

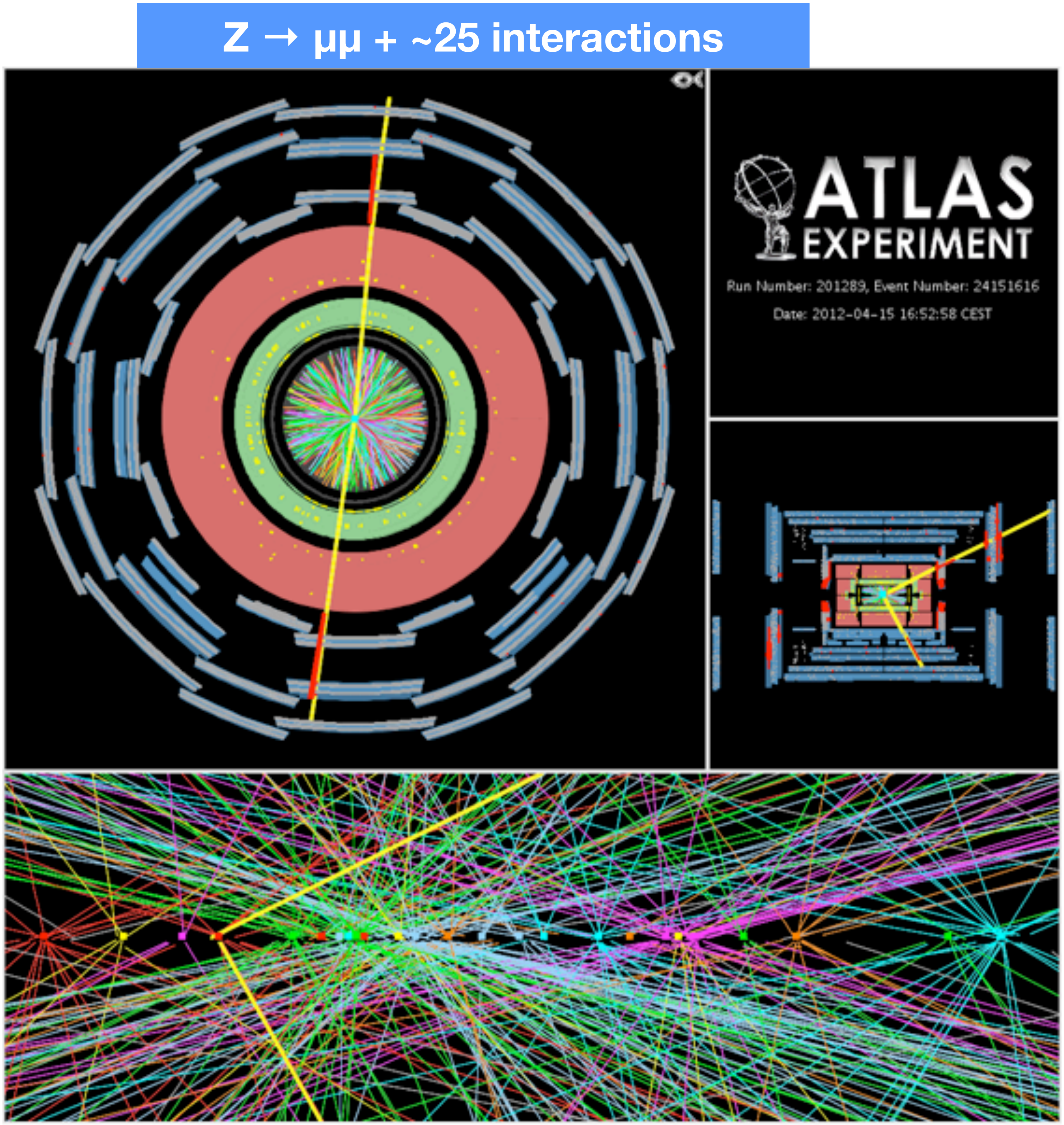
$$N_{events} = \sigma \times \text{lumi}$$

- Detector efficiency > 90%



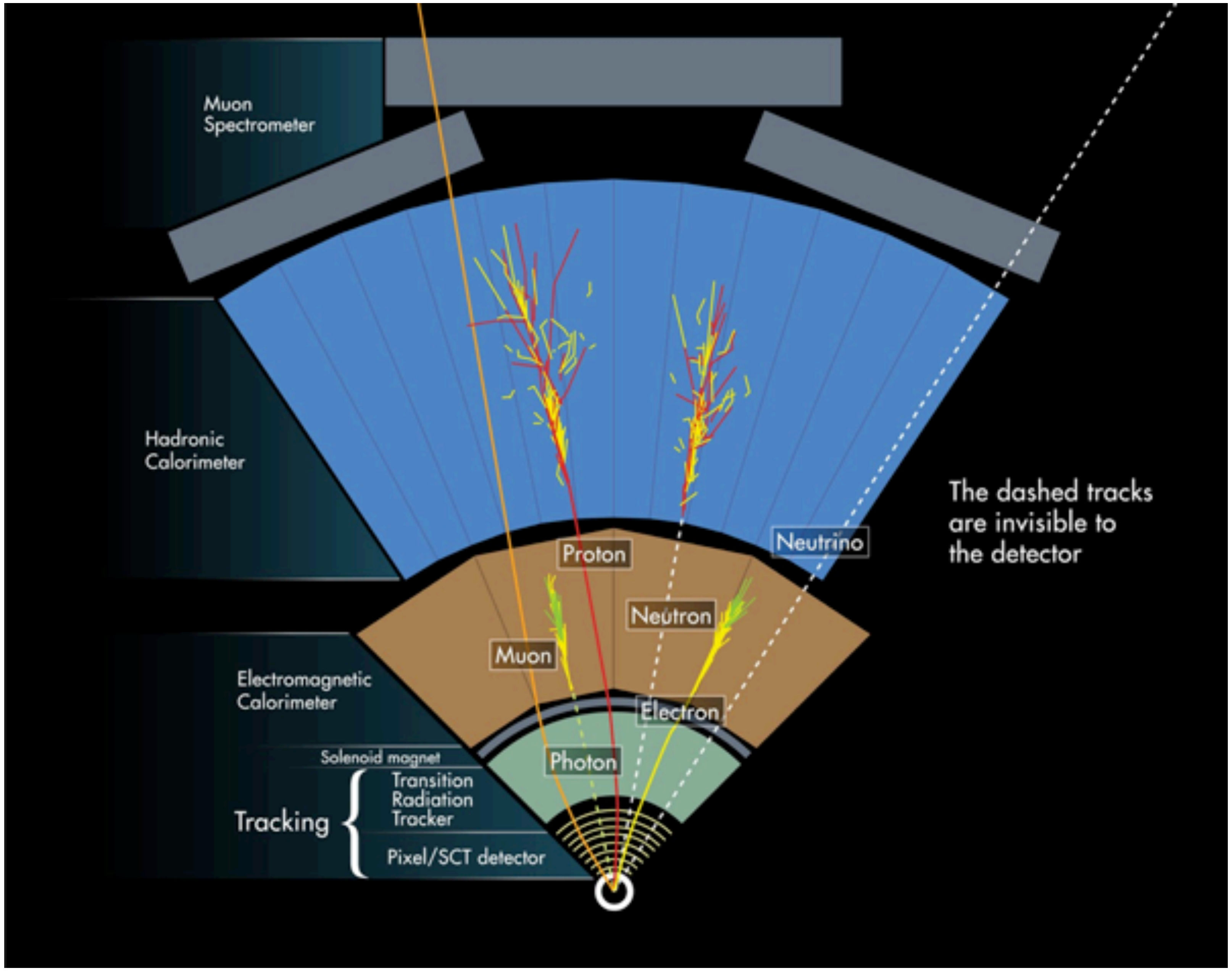


LHC collisions and pile-up



- Collisions at 40 MHz, events recorded @ ~300 Hz, ~90% used for analyses
- Multiple collisions per LHC bunch crossing (~20 in 2012)
- Experimental conditions beyond detector design capabilities
- Clean signatures: leptons (e,μ) and photons
- Increasingly difficult: (b-)jets, taus, missing transverse energy

LHC collisions and pile-up



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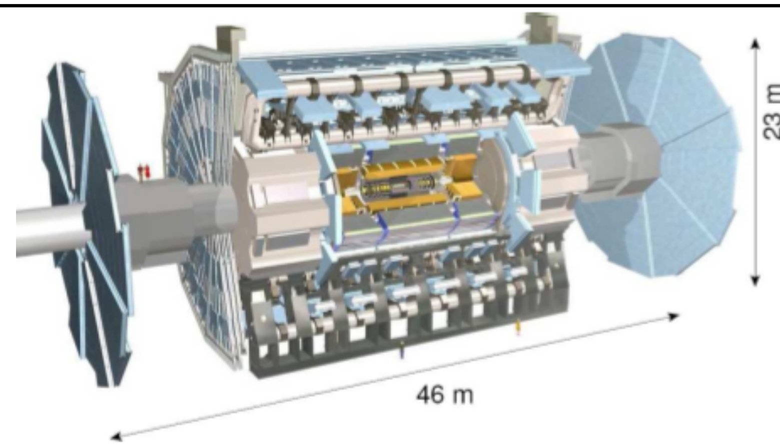
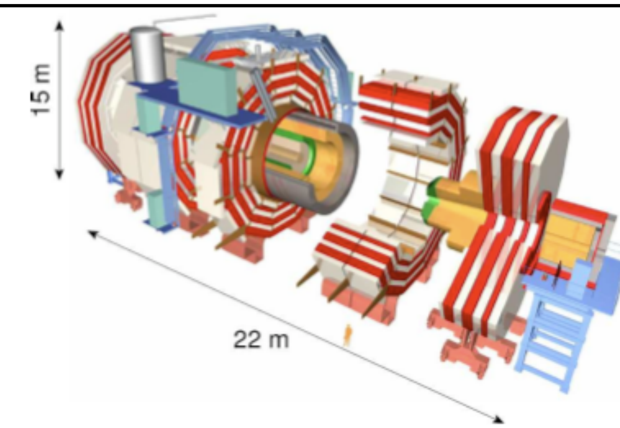
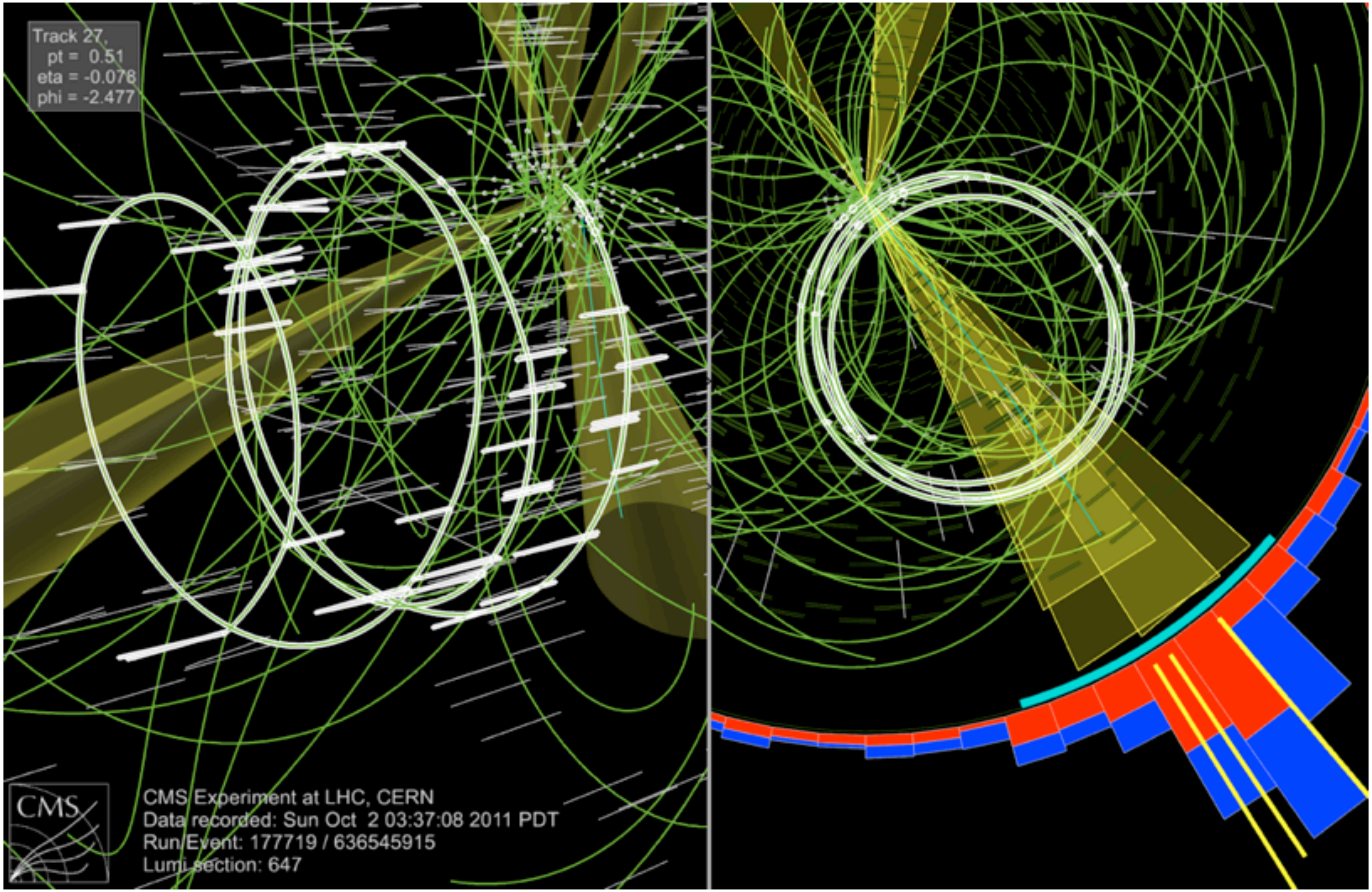
The ATLAS and CMS experiments

Marumi Kado

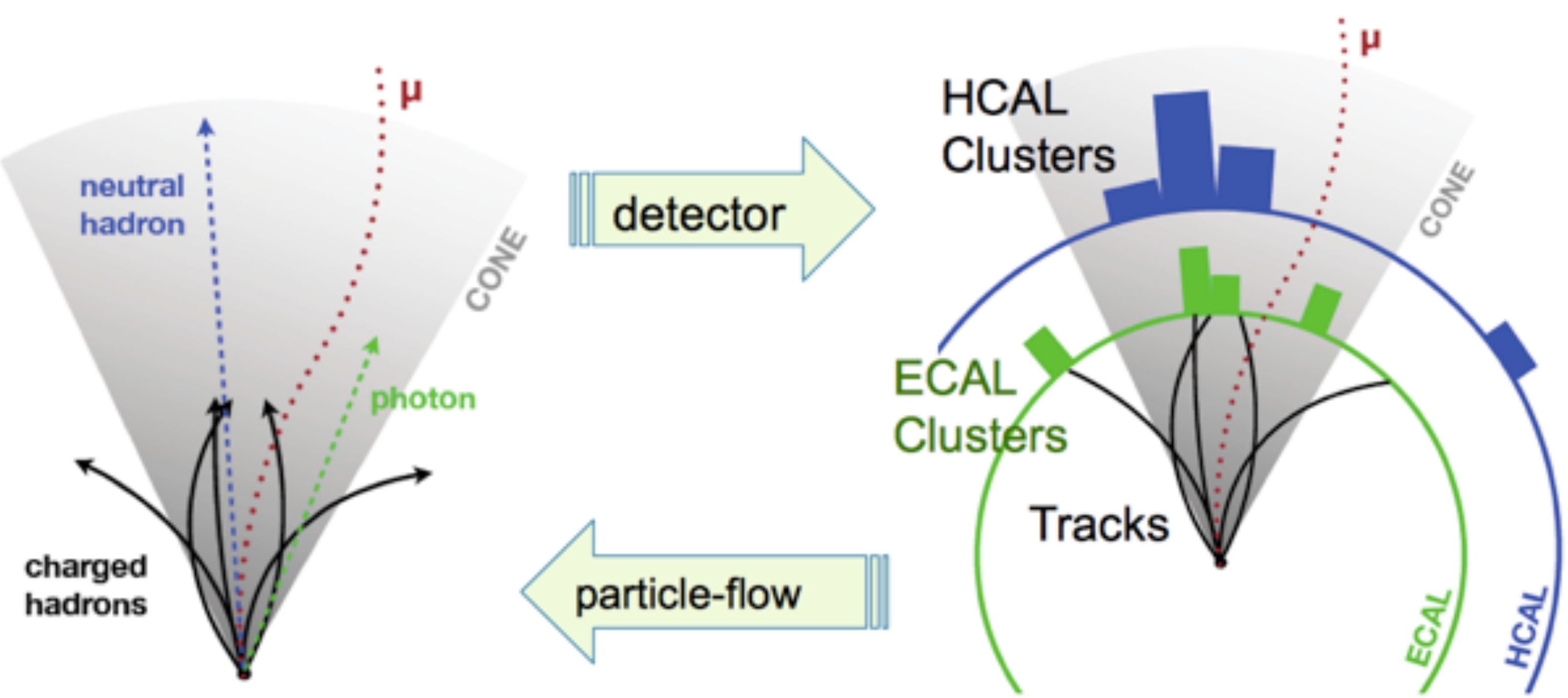
Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5\times10^{-4}p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5\times10^{-4}p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

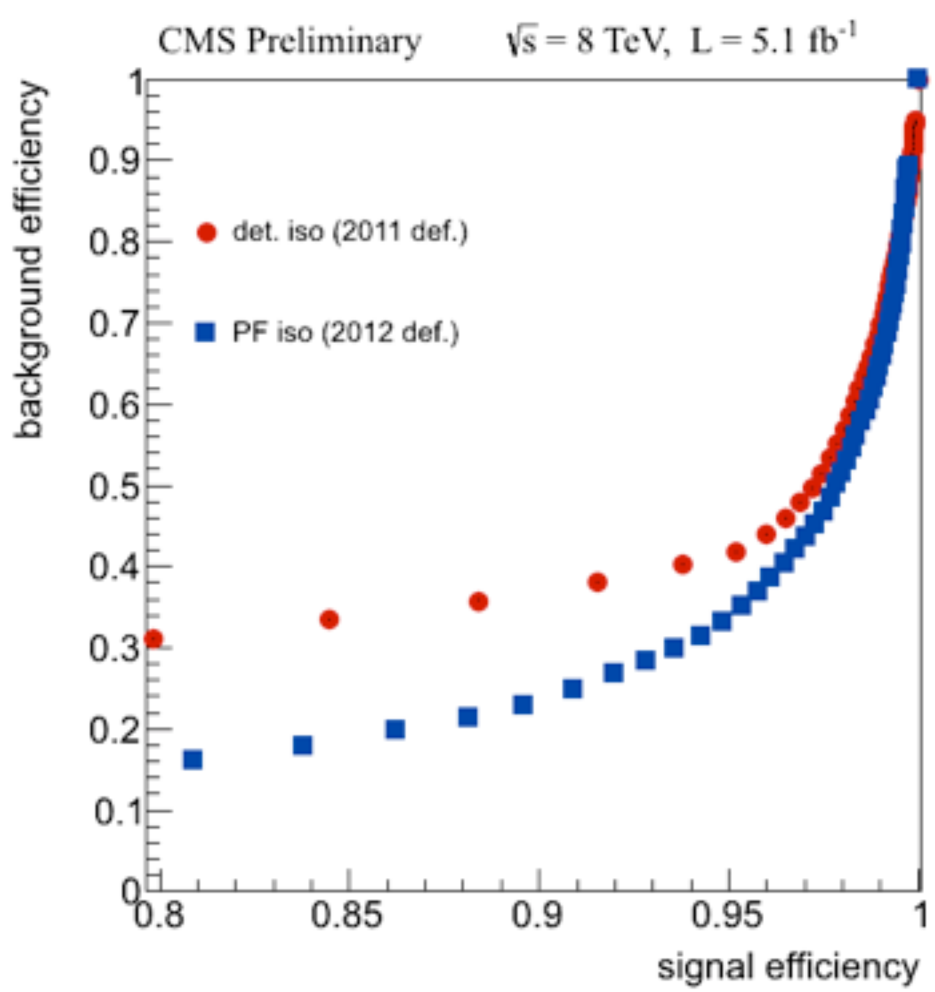
Detector challenges: low P_T charged particles



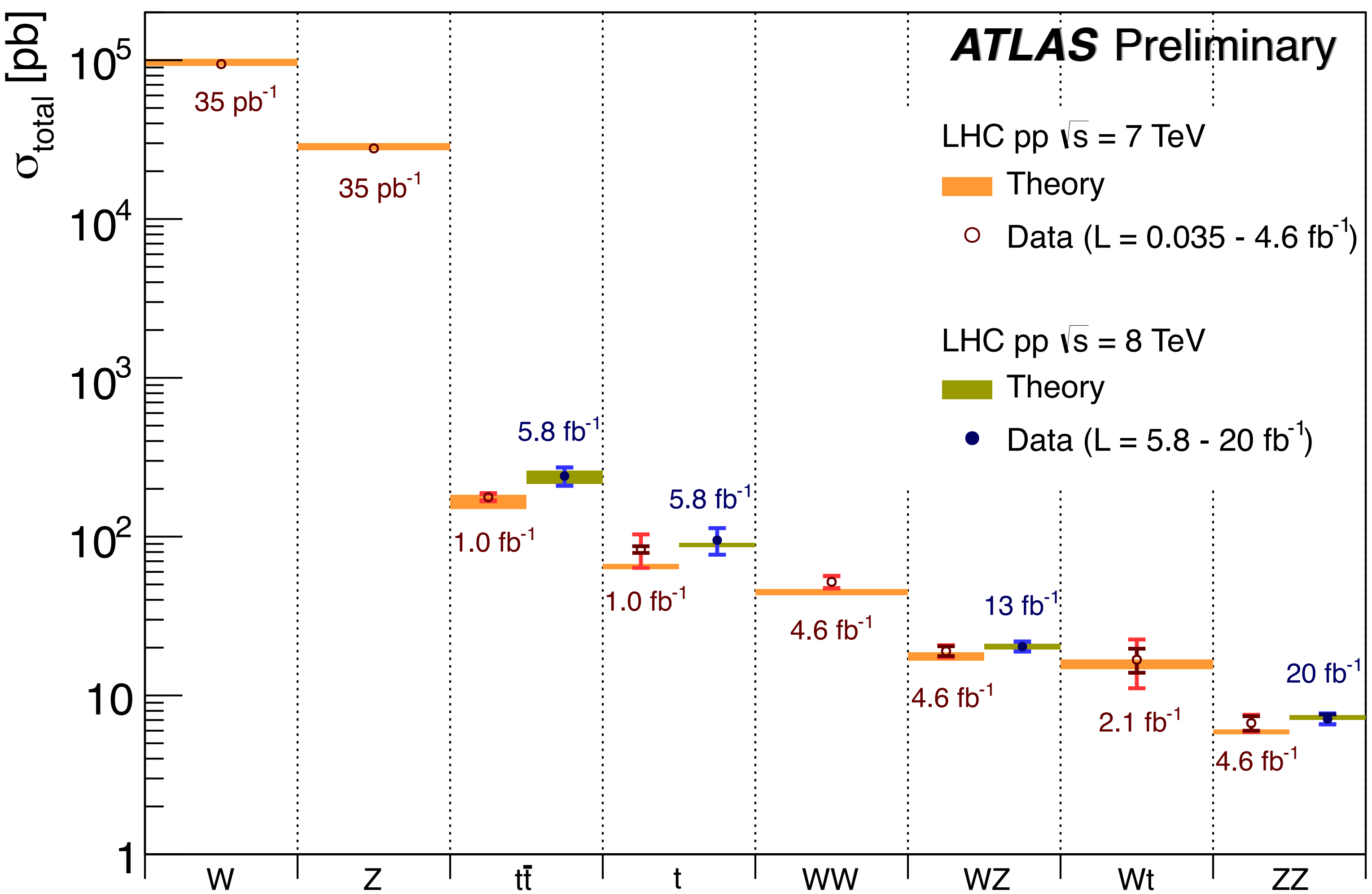
Techniques: particle-flow and isolation

- Particle-flow: combine the information from several detectors
  - Can improve resolution and pileup rejection
- Isolation: activity around the particle
  - Leptons and photons from H, W, Z decays vs. jets

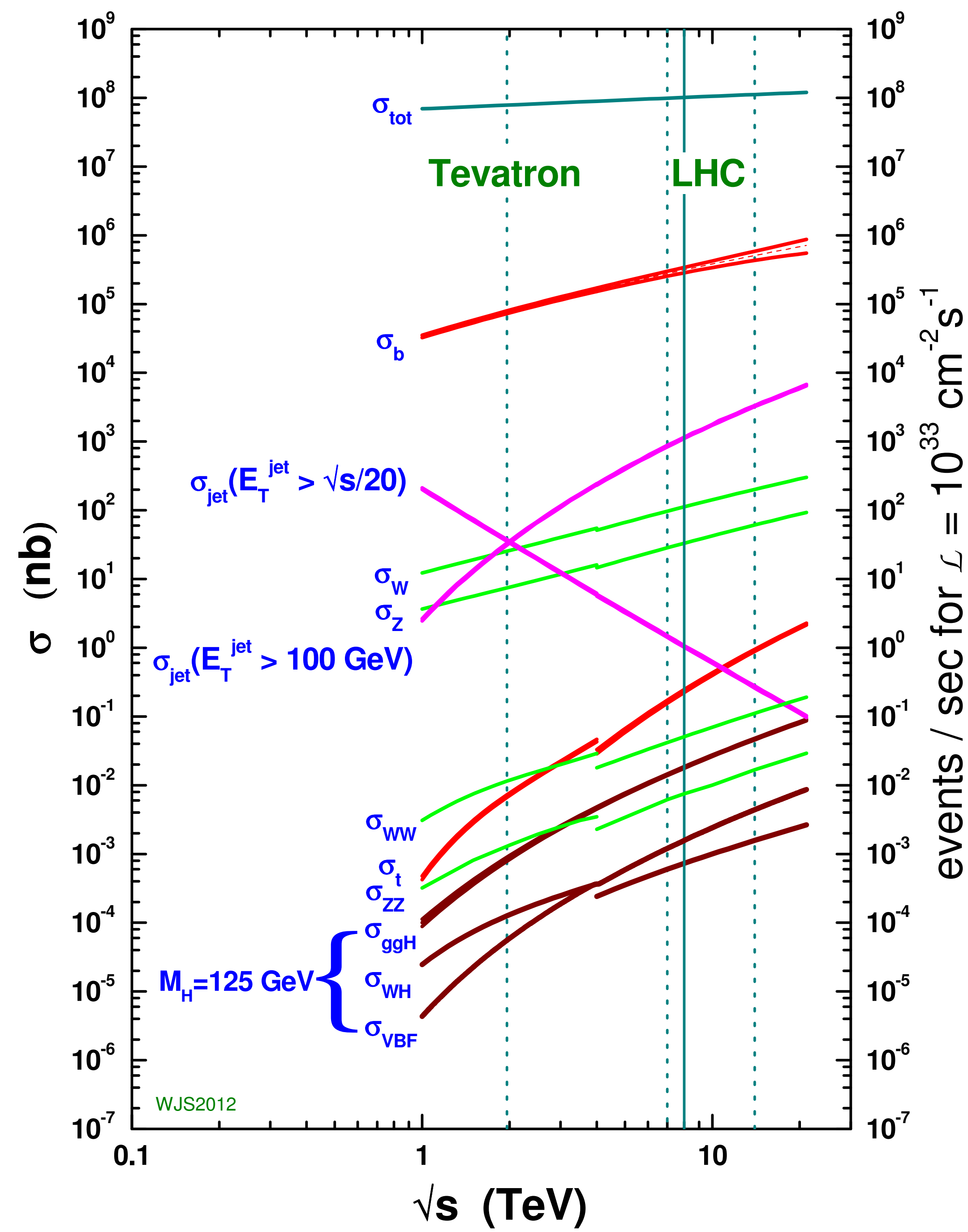




http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html



proton - (anti)proton cross sections

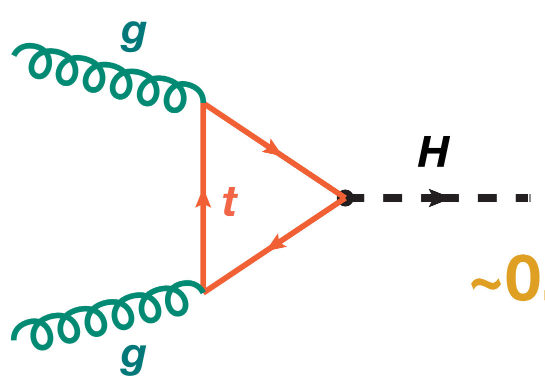


1 Higgs boson produced every 10^{10} events ...and many others look-alike

The SM Higgs boson at the LHC

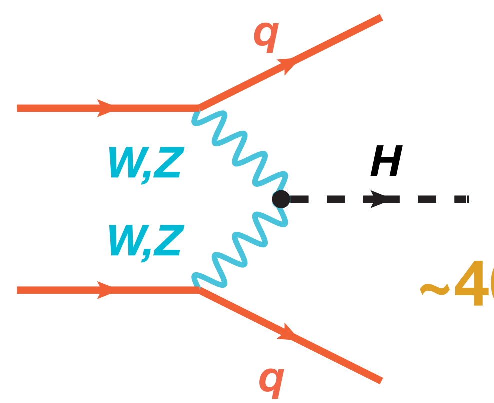
Production mechanisms (events produced)

Gluon-fusion



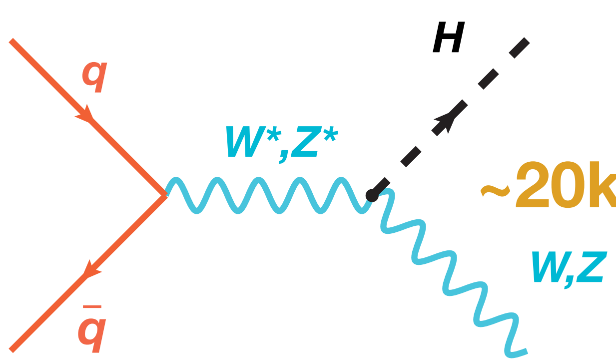
~0.5M

Vector boson fusion (VBF)



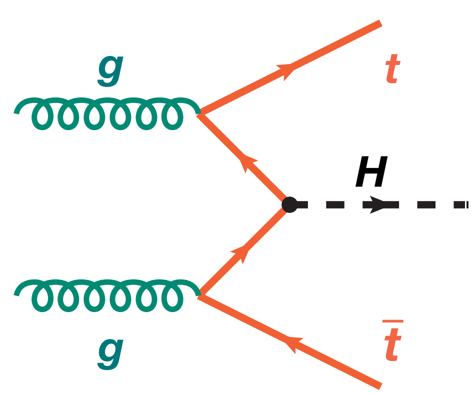
~40k

Associated with W / Z



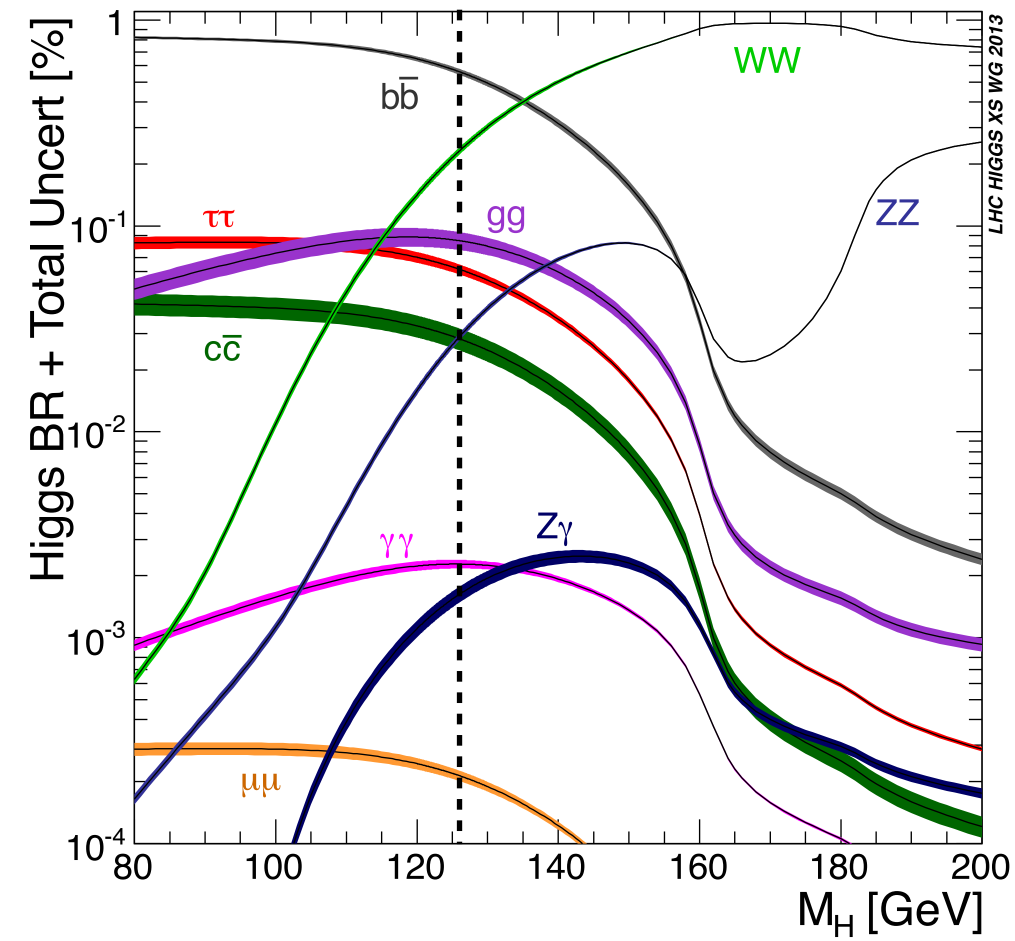
~20k/10k

Associated with tt (or bb)

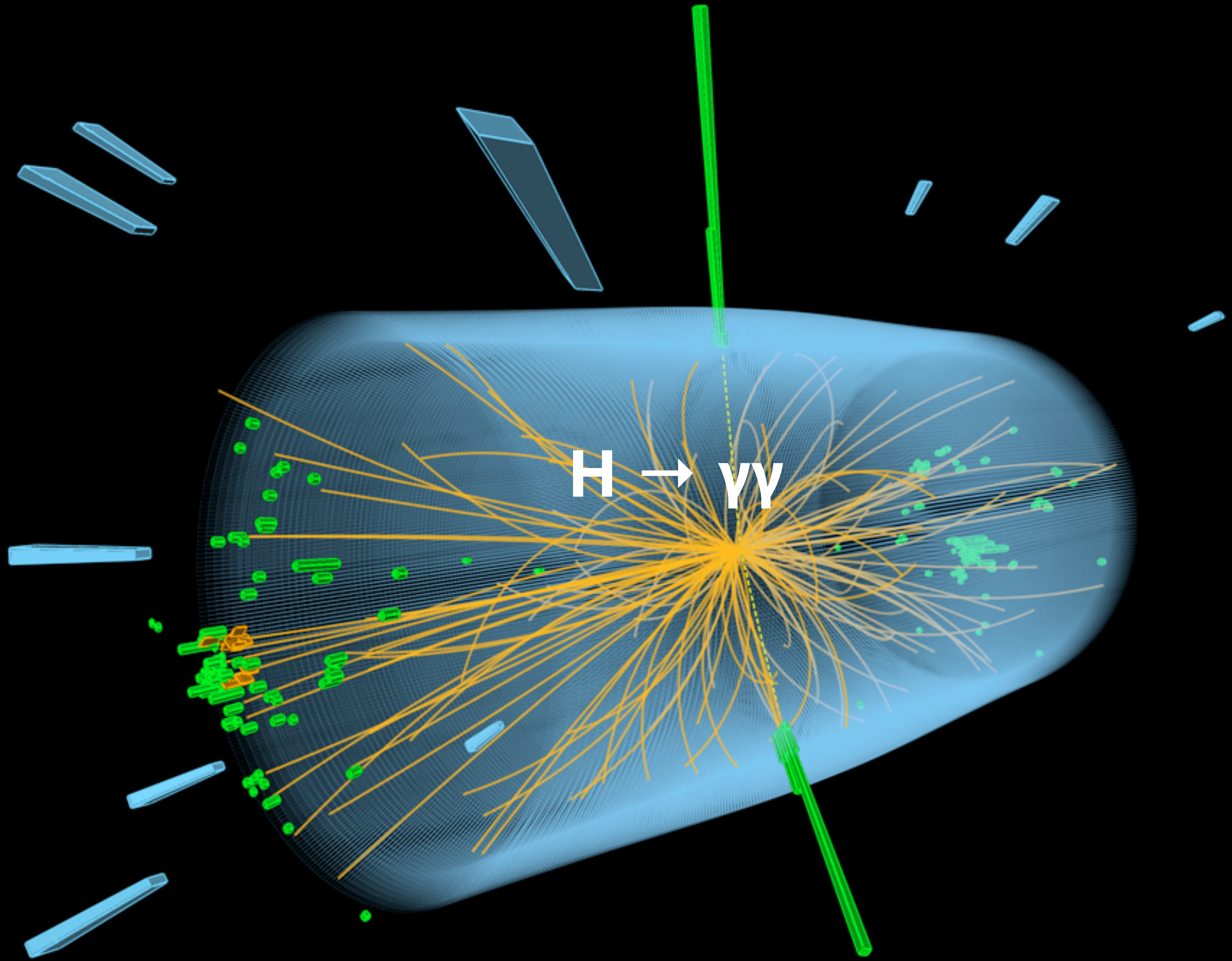


~3k/5k

Decay modes



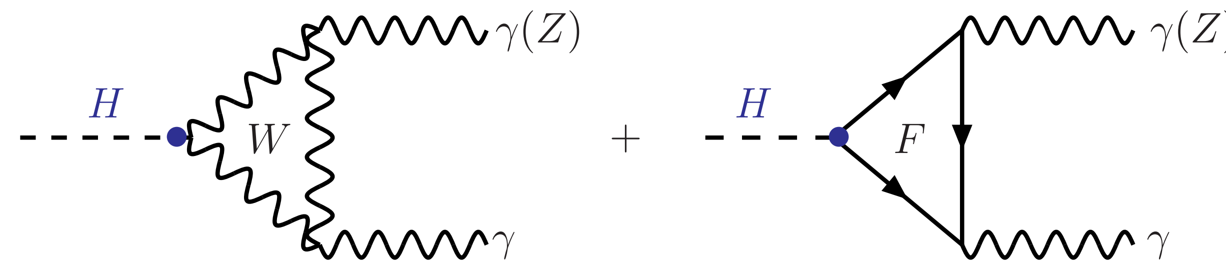
- Main channels (bosonic): H → γγ, H → ZZ* → 4ℓ, H → WW* → ℓνℓν
- Fermionic modes (associated production): (VBF) H → ττ, (W/Z) H → bb
- Rare decays: H → Zγ, H → μμ


H → γγ

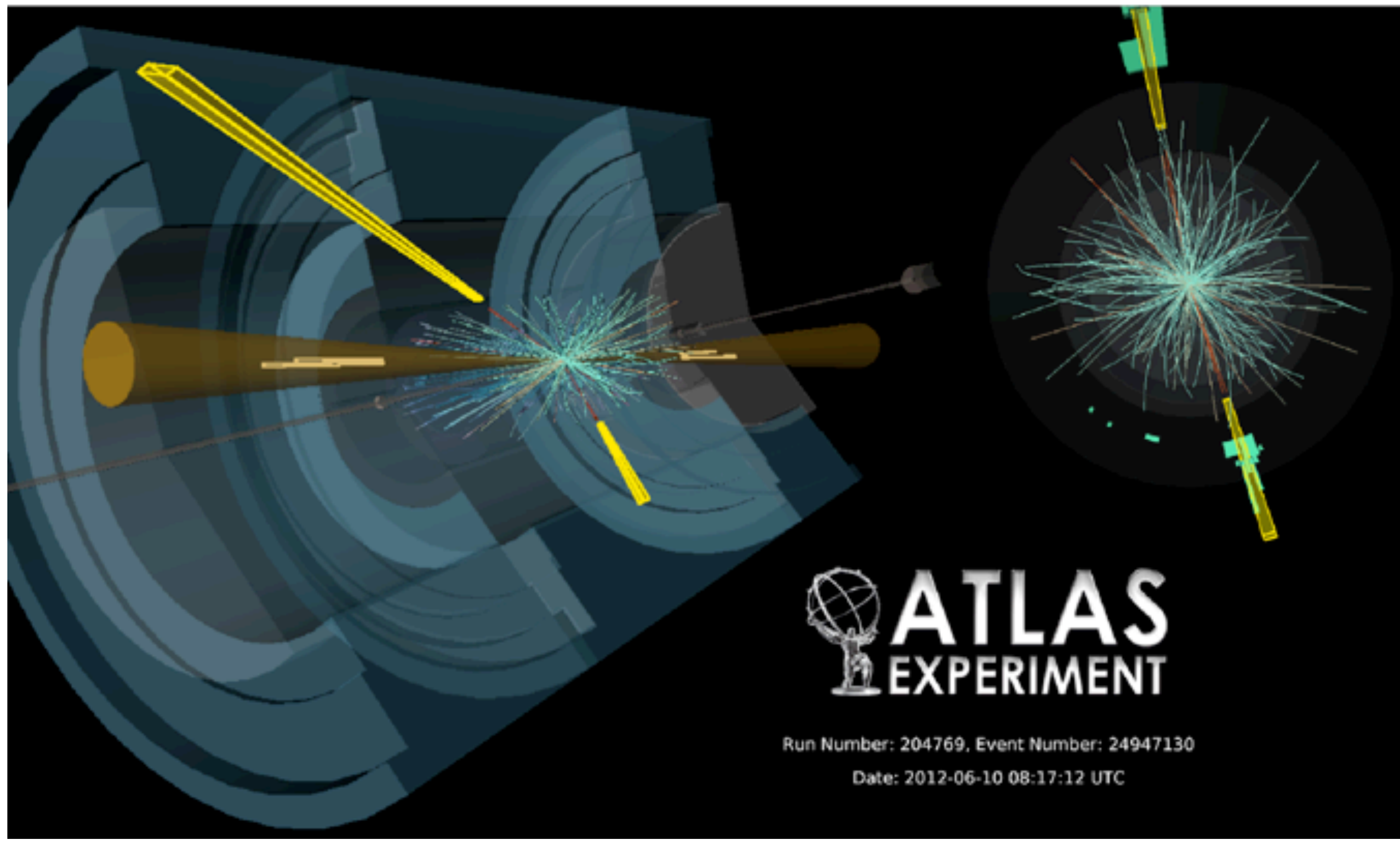
H → γγ

σ X BR ~ 50 fb @ 125.5 GeV

- Loop decay, low BR ~ 0.2%



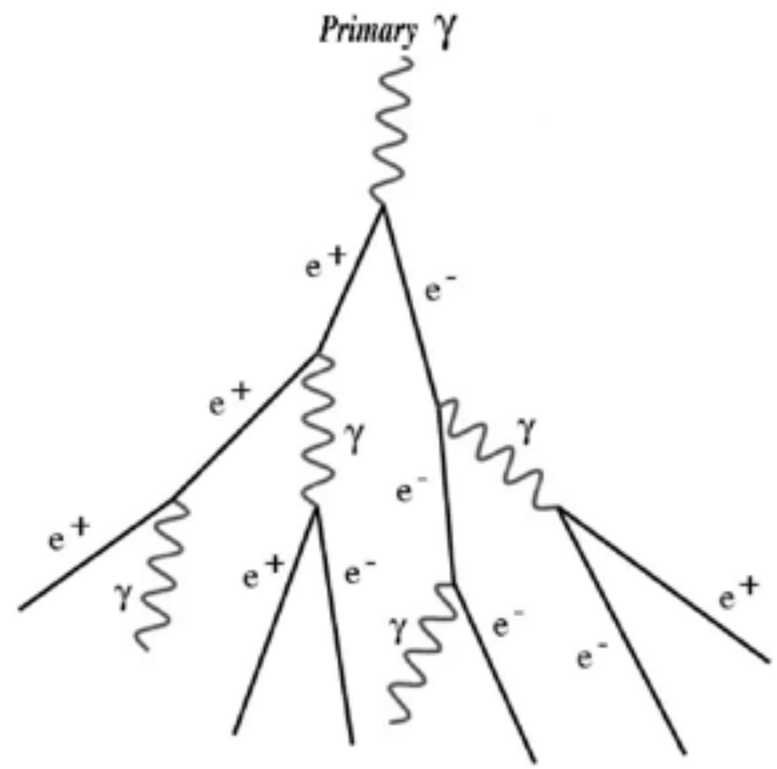
- Simple topology
  - Two isolated energetic photons
- ...requiring excellent performance
  - Large backgrounds (excellent γ ID)
  - Signal: narrow peak (good mass resolution)



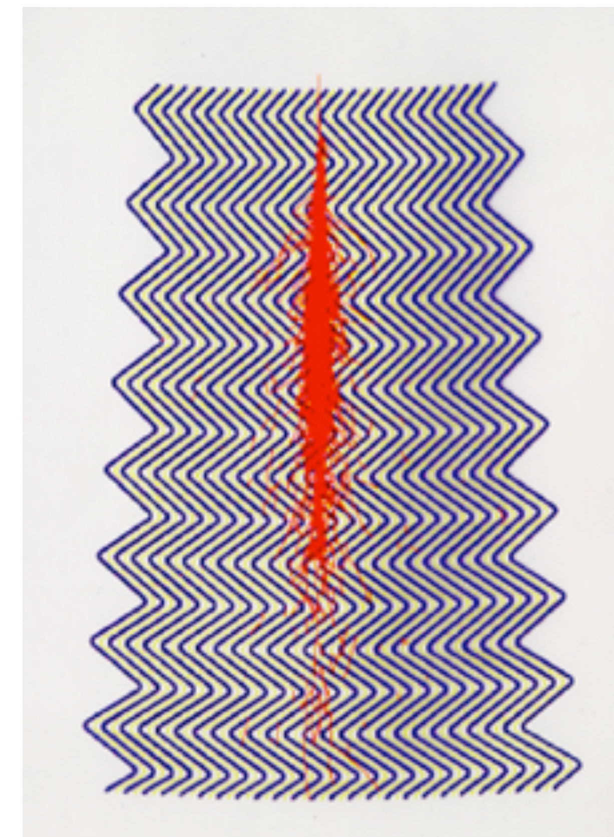
$\sigma(m_{\gamma\gamma})$ ~ 1%
S/B ~ 3%

Electromagnetic calorimetry

- Challenges:
  - Energies from few GeV to TeV
  - Trigger capabilities
  - Precise position meas. (η, ϕ)
  - Jet rejection factor ~10^4
- Important characteristics:
  - Shower containment (> 20 X_0)
  - Good uniformity and stability vs. time and pileup (rad. hardness)
  - Fast signals and low noise
  - Fine segmentation



Schema of EM shower development



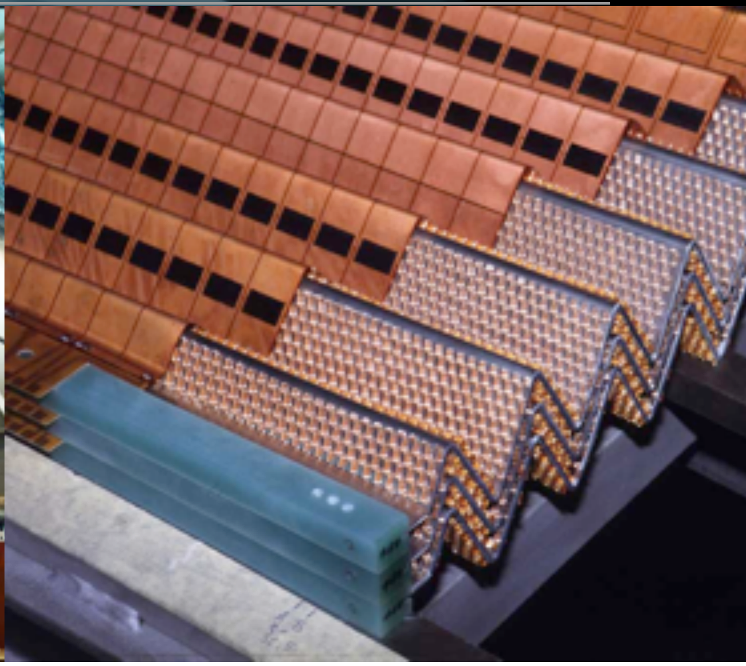
Simulated EM shower in ATLAS calorimeter

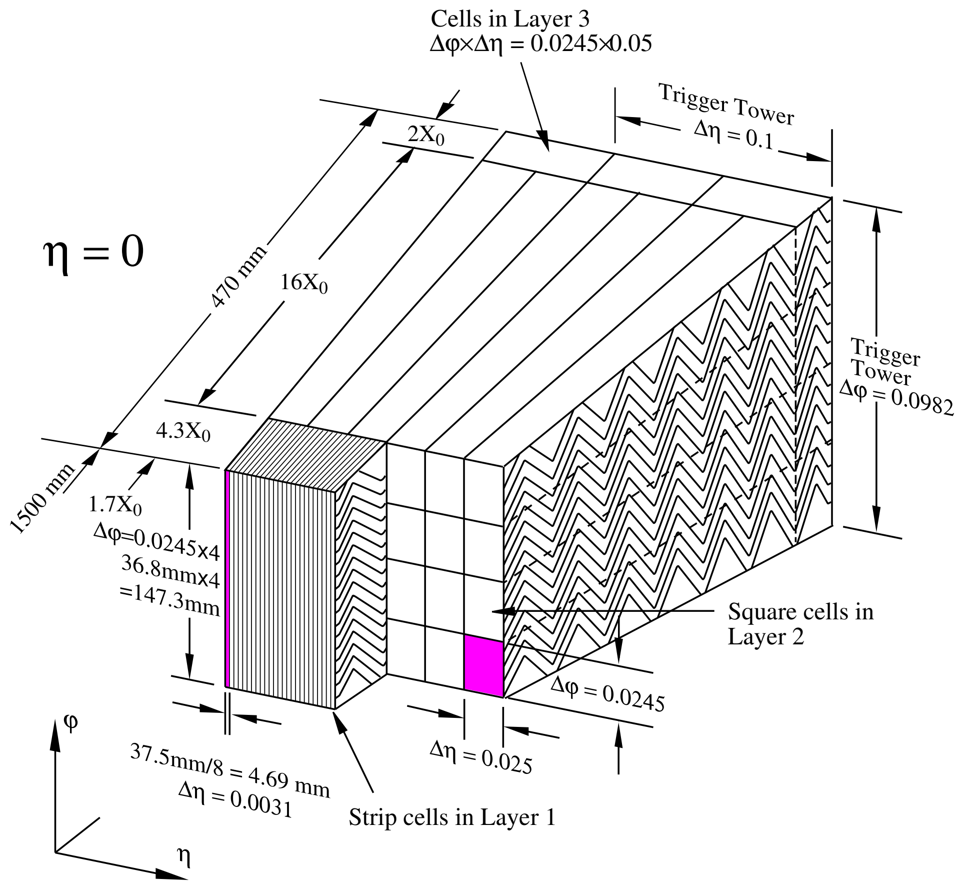
ATLAS EM calorimeter

- Lead - liquid argon calorimeter
  - High stability, radiation hard
- Accordion-shape electrodes
  - Fast extraction of (ionization) signals without cracks
- Energy resolution ($f_{sampling}$ ~ 20%):

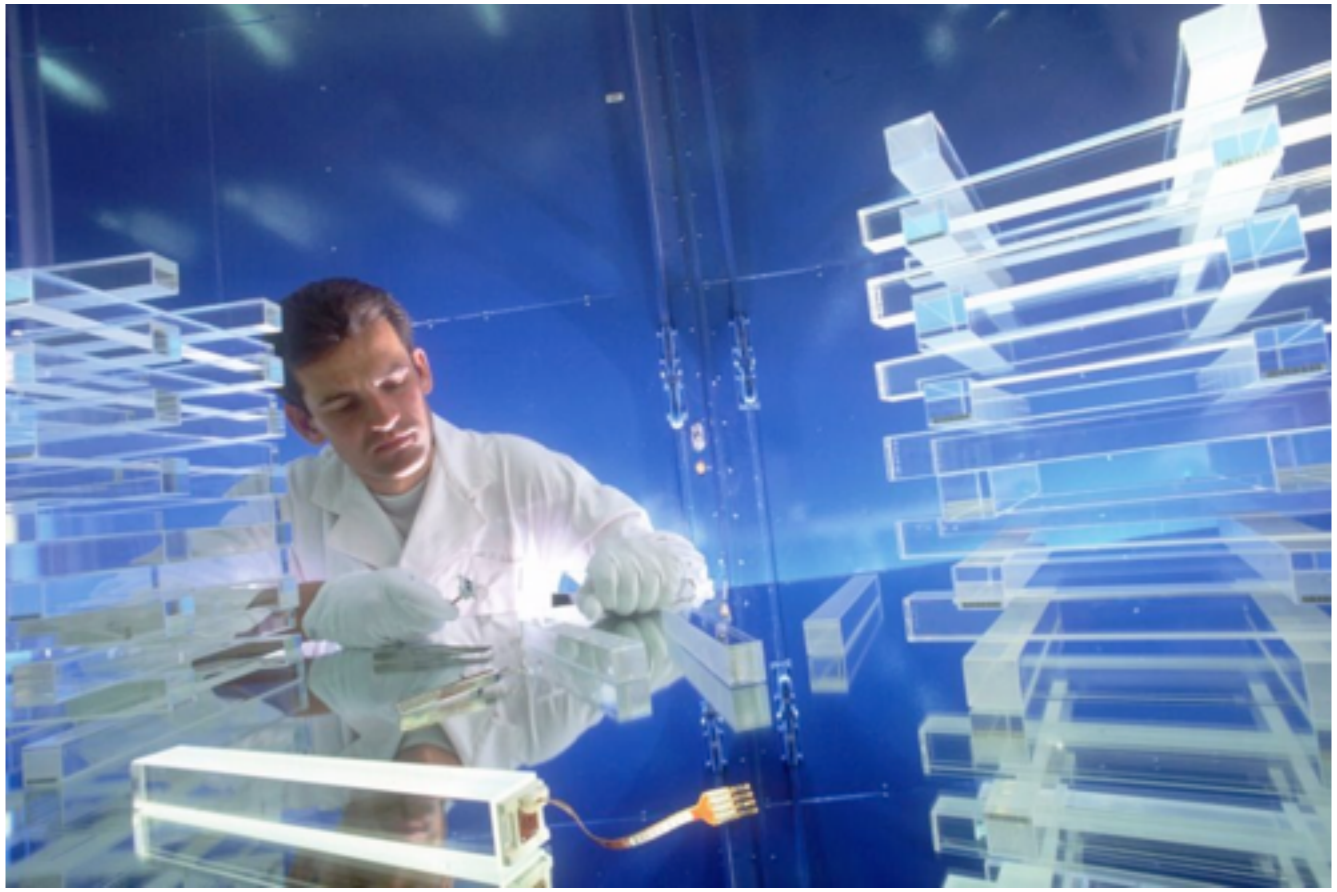
$$\frac{\sigma_E}{E} = \frac{\sqrt{10\%}}{E(\text{GeV})} \oplus \frac{0.2\ \text{GeV}}{E} \oplus 0.7\%$$

- Fine lateral segmentation, 3 layers in depth (+ pre-sampler)
  - Strips of ~4mm in η to reject $\pi^0 \to \gamma\gamma$
  - γ direction (“pointing”)



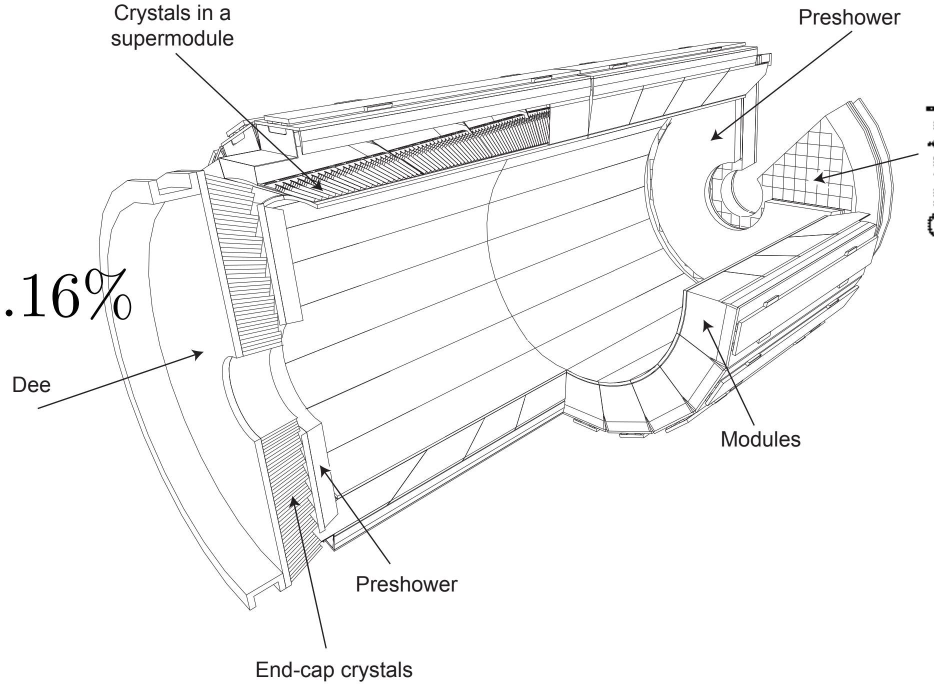


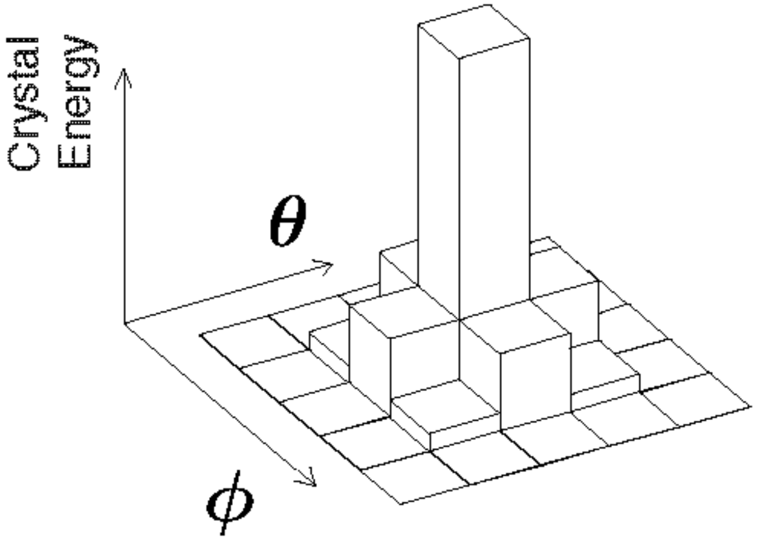
CMS EM Calorimeter



- Lead tungstate crystals (~75k)
  - Dense (22-23 cm long) and small Molière radius (~2-3 x 2-3 cm)
  - Scintillation light (few ns)
  - Sensitive to temperature variations and radiation
- Homogeneous calorimeter, exceptional energy resolution

$$\frac{\sigma_E}{E} = \frac{\sqrt{2.8\%}}{E(\mathrm{GeV})} \oplus \frac{0.16\ \mathrm{GeV}}{E} \oplus 0.16\%$$

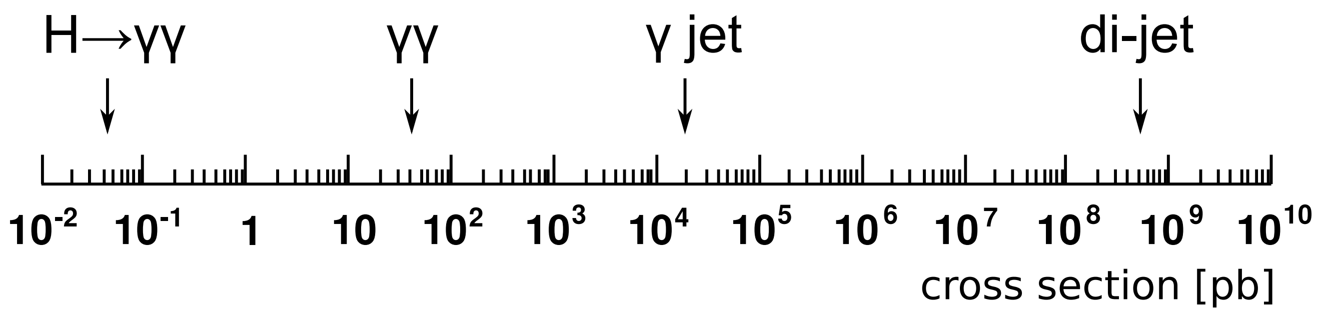


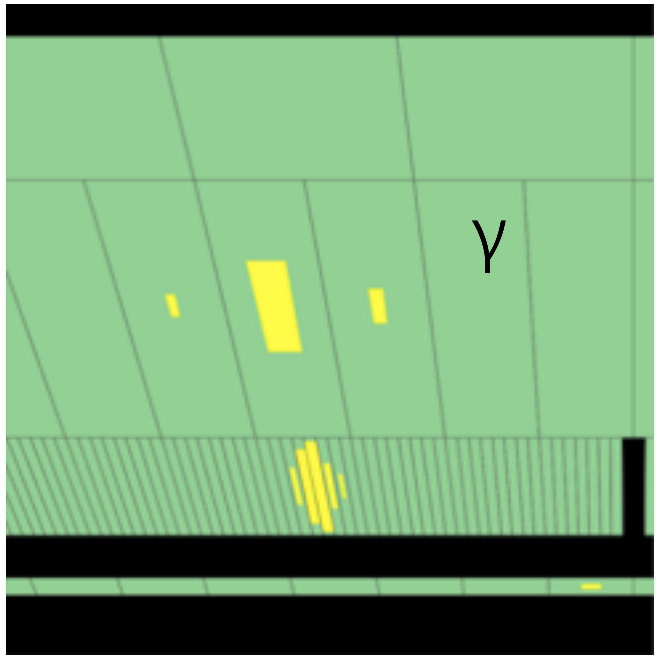


Photon identification

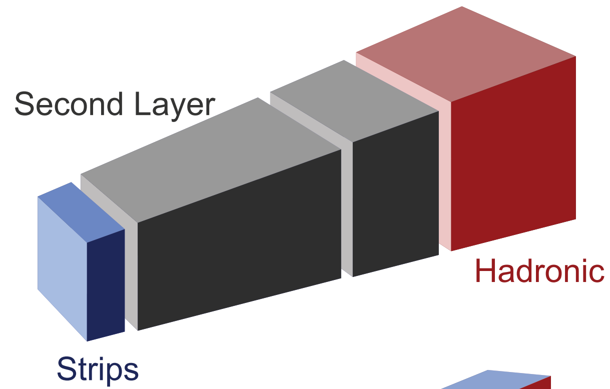
thanks to Jamie Saxon

Goal: high γ efficiency, jet ($\pi^0 \rightarrow \gamma\gamma$) rejection factors ~$10^4$



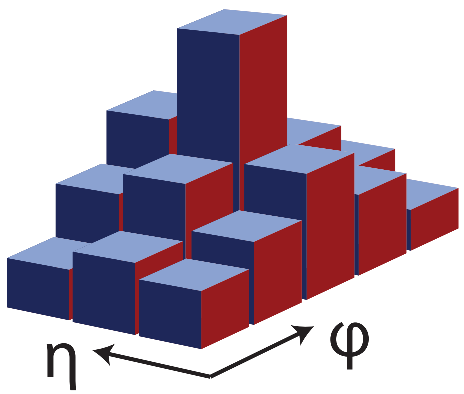


- No hadronic activity

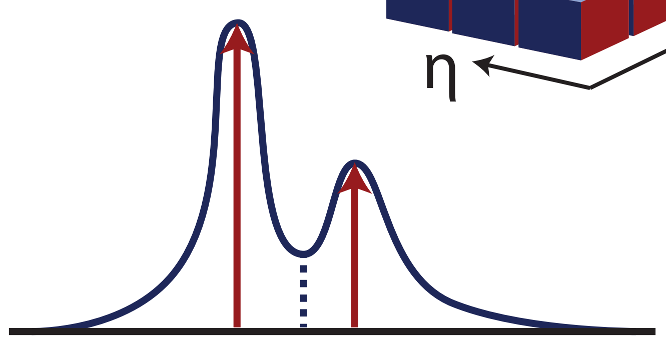


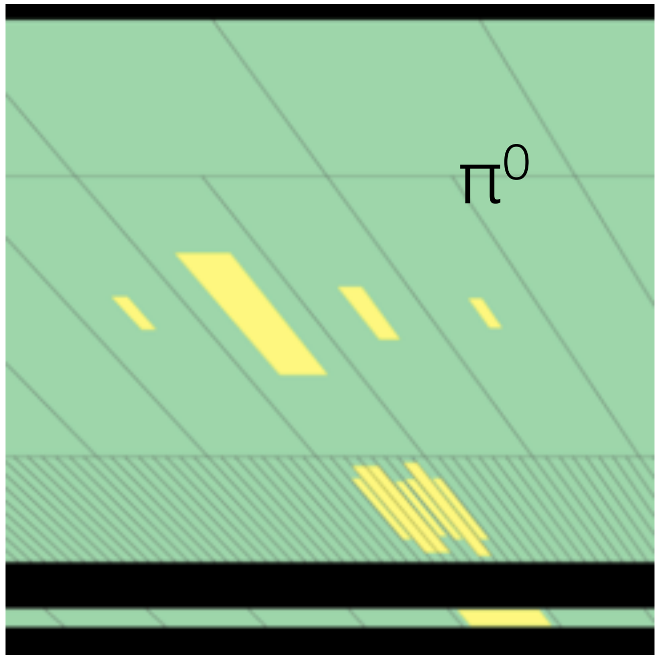
VS

- Narrow showers



- No second maxima

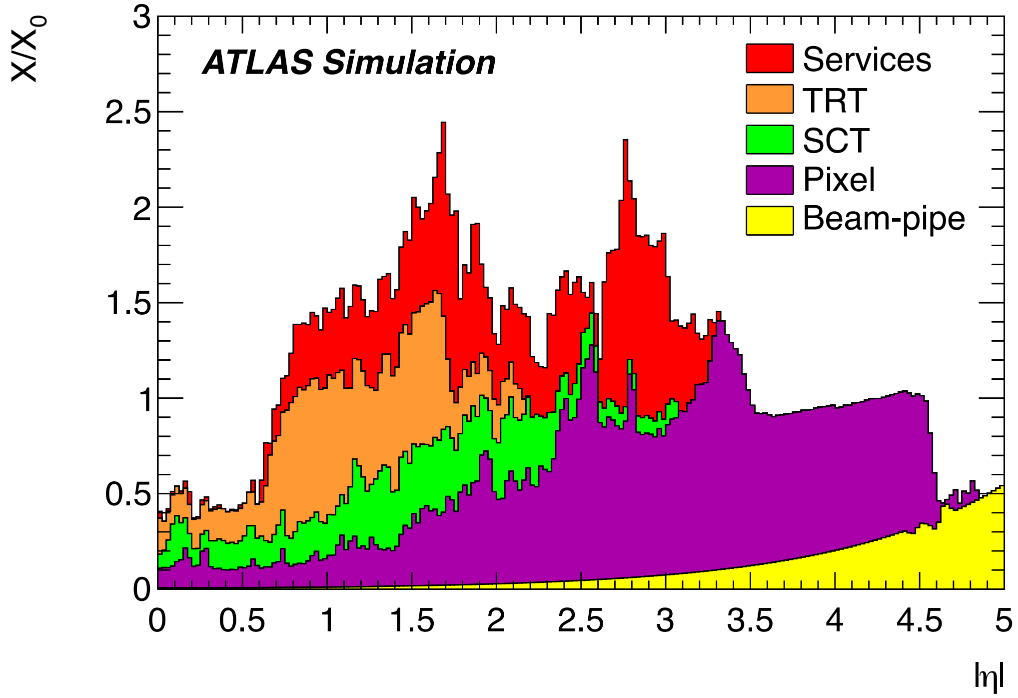




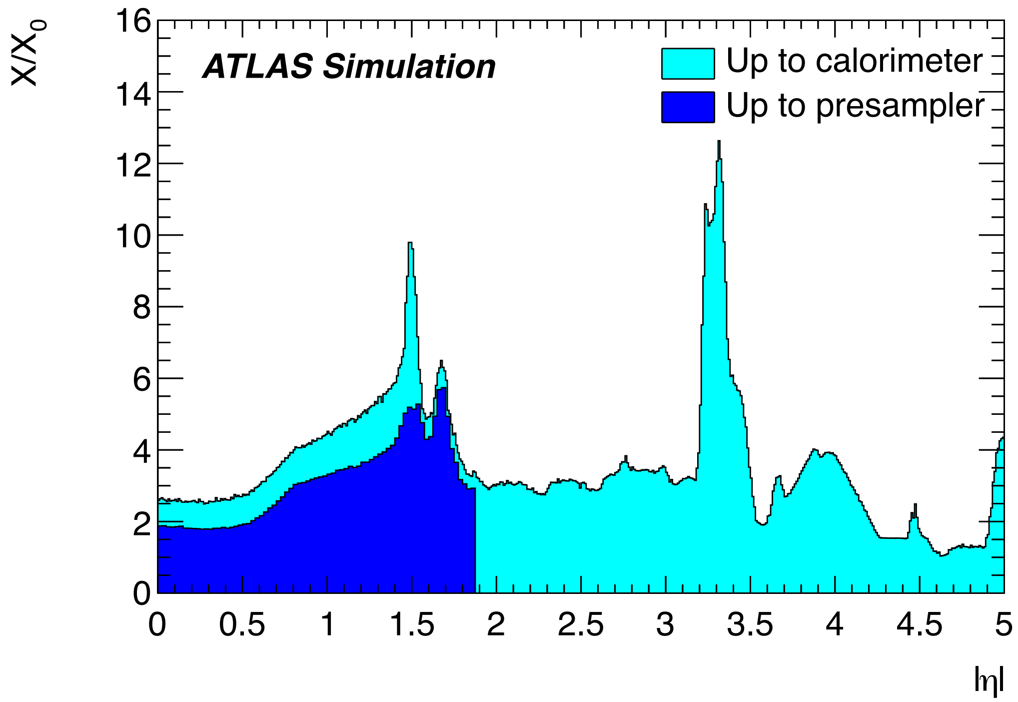
Material in front of calorimeters

Large amounts of material in front of the calorimeter from tracker and services

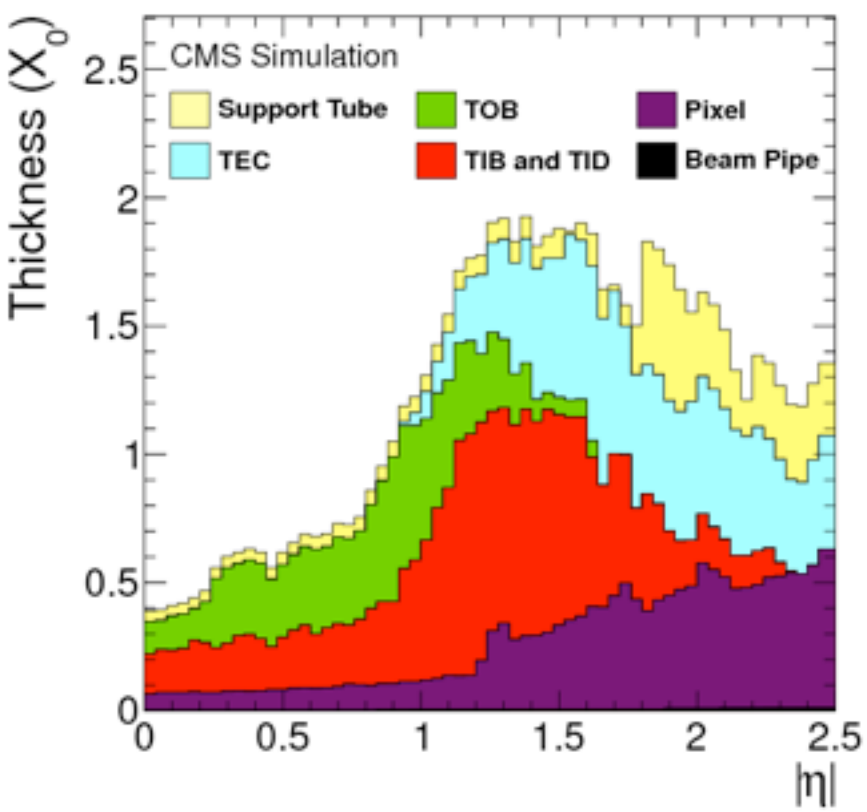
arXiv:1407.5063



+ cryostat!



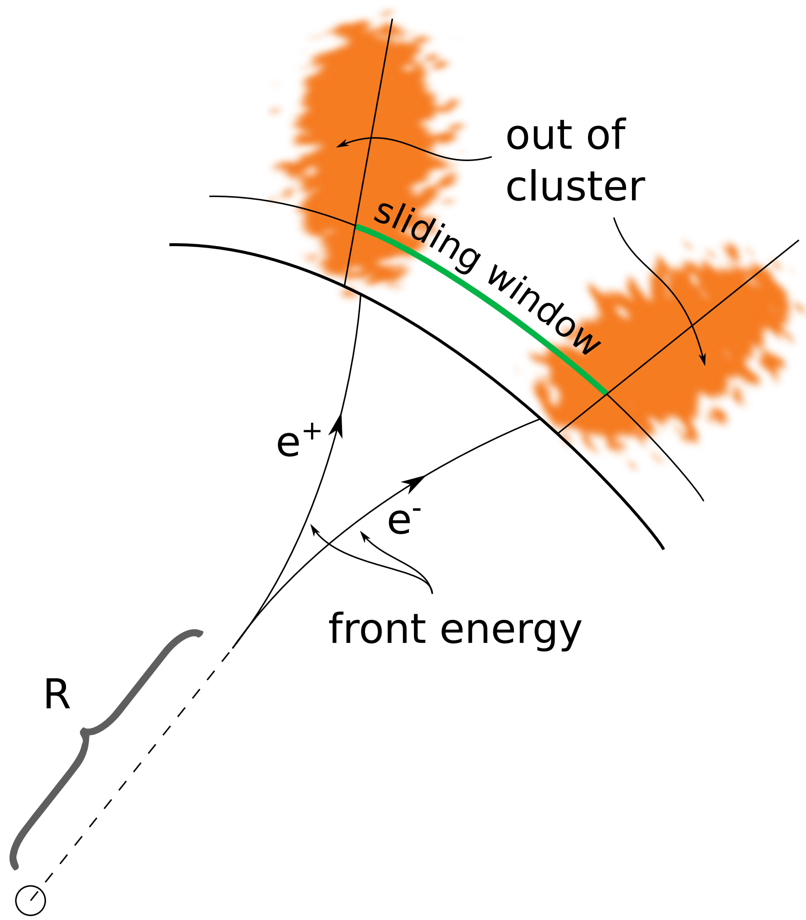
arXiv:1306.2016

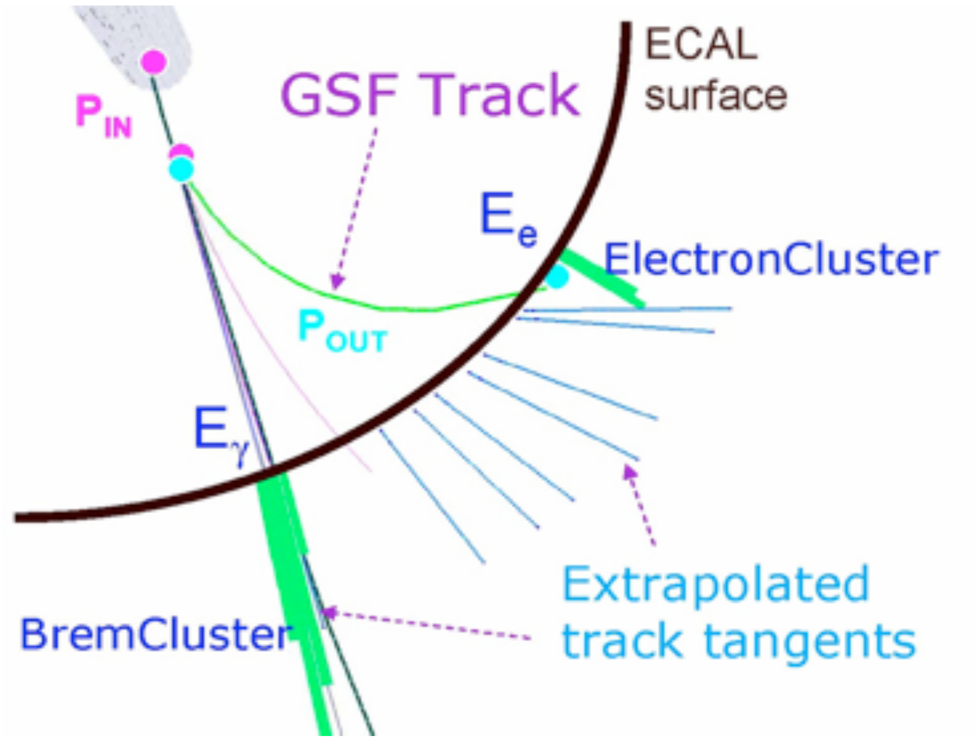


Material in front of calorimeters

Large amounts of material in front of the calorimeter from tracker and services

- Photons convert to e^+e^- (which open in B field), bremsstrahlung for $e^\pm$
- EM showers start earlier and become wider in the calorimeter
- Some energy is lost in front





Energy measurement

A. Correct for non-uniformities (inter-calibration, time-dependence, ...)

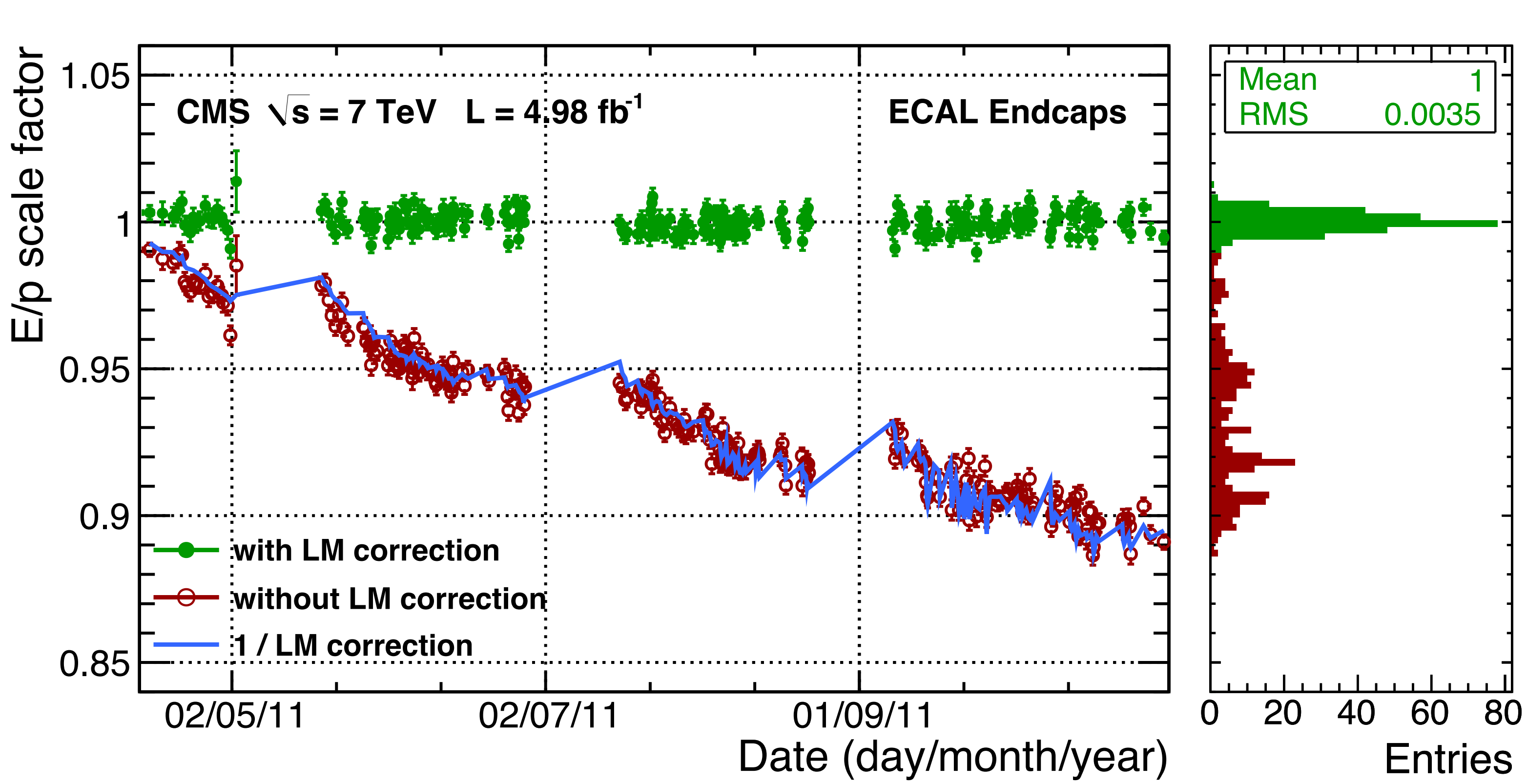
- ATLAS: stable over time (0.05%), CMS: E-flow, $\pi^0/\eta \rightarrow \gamma\gamma$, E/p, laser monitoring

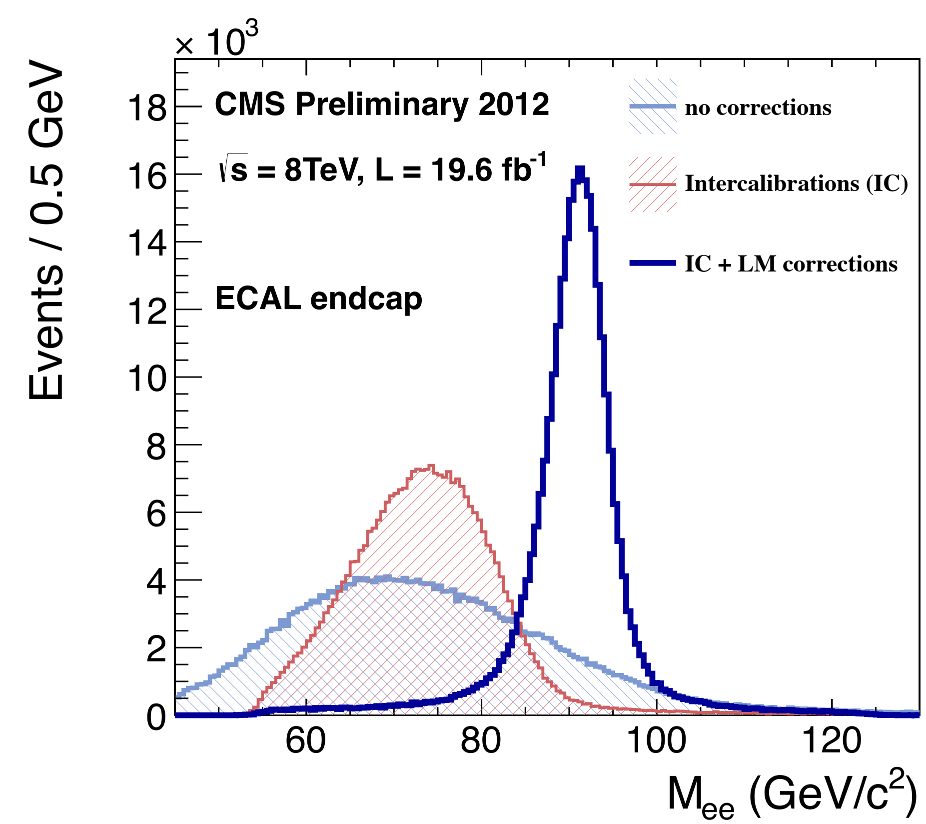
B. Correct for Ecalo < Eparticle

- BDT using E, position, shower profile, conversion info, trained on simul. data

C. In-situ calibration using resonances like $Z \rightarrow ee$

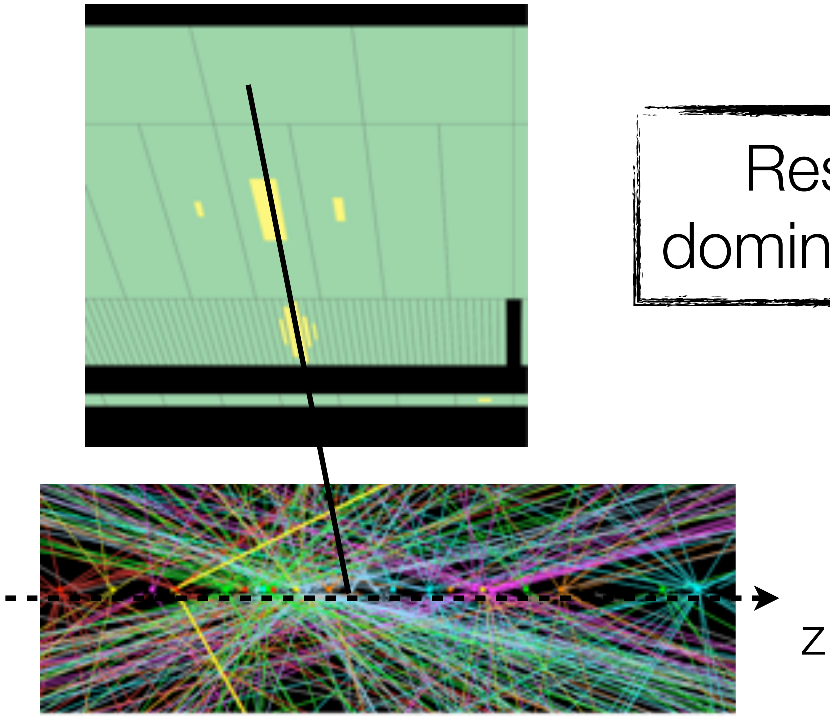
- Estimate of energy scale uncertainty and resolution (for $E_T^e \sim 40$ GeV)



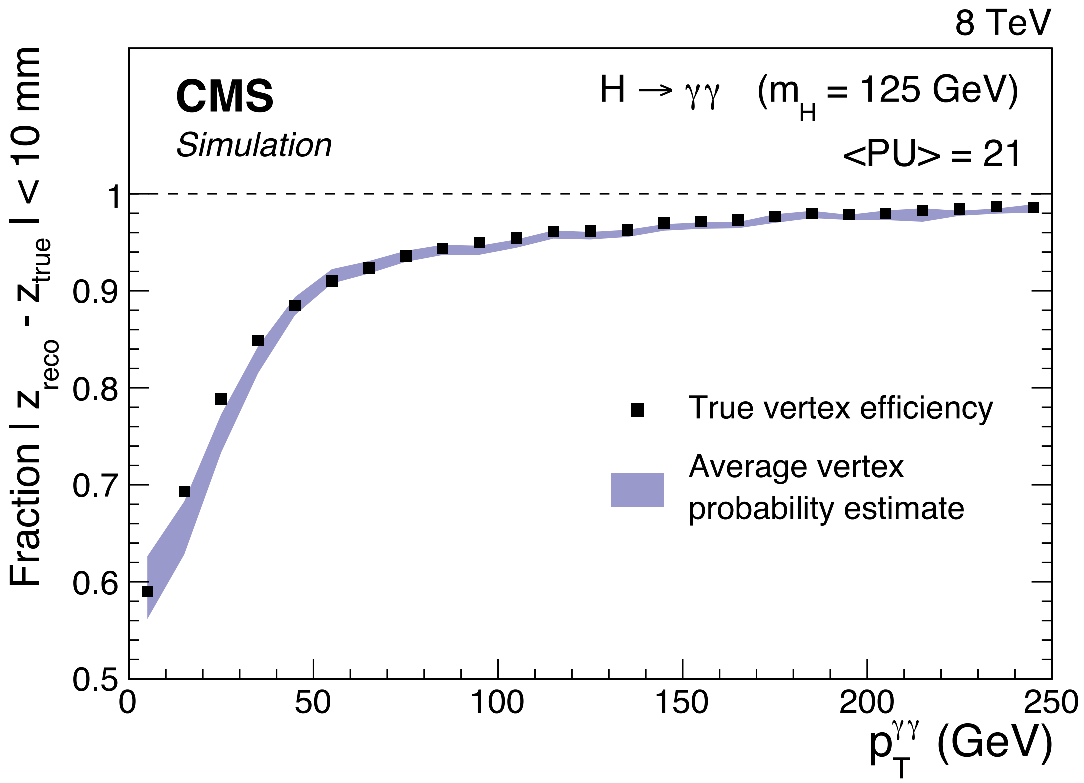


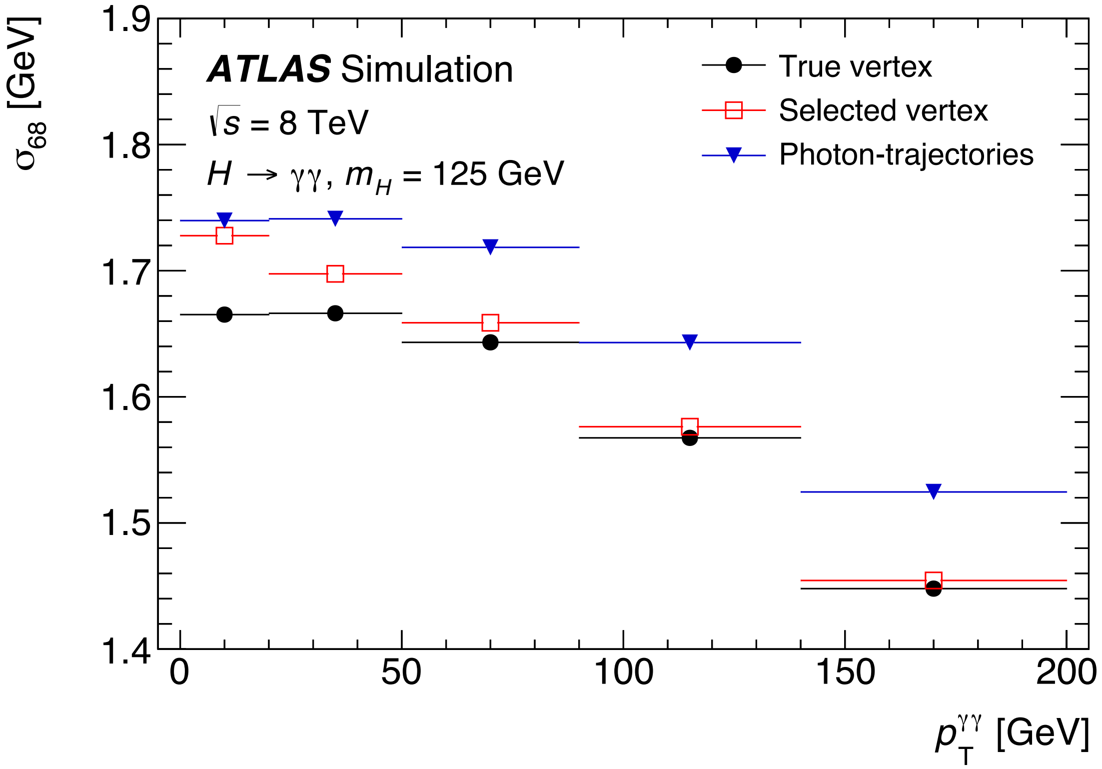
H → γγ: invariant mass reconstruction

- Energy and impact points from calo
- LHC beam spread (~6 cm) would add 1.4 GeV smearing → vertex located using:
  - Longitudinal segmentation of calorimeter (ATLAS)
  - Conversion tracks
  - Tracks from recoil / underlying event



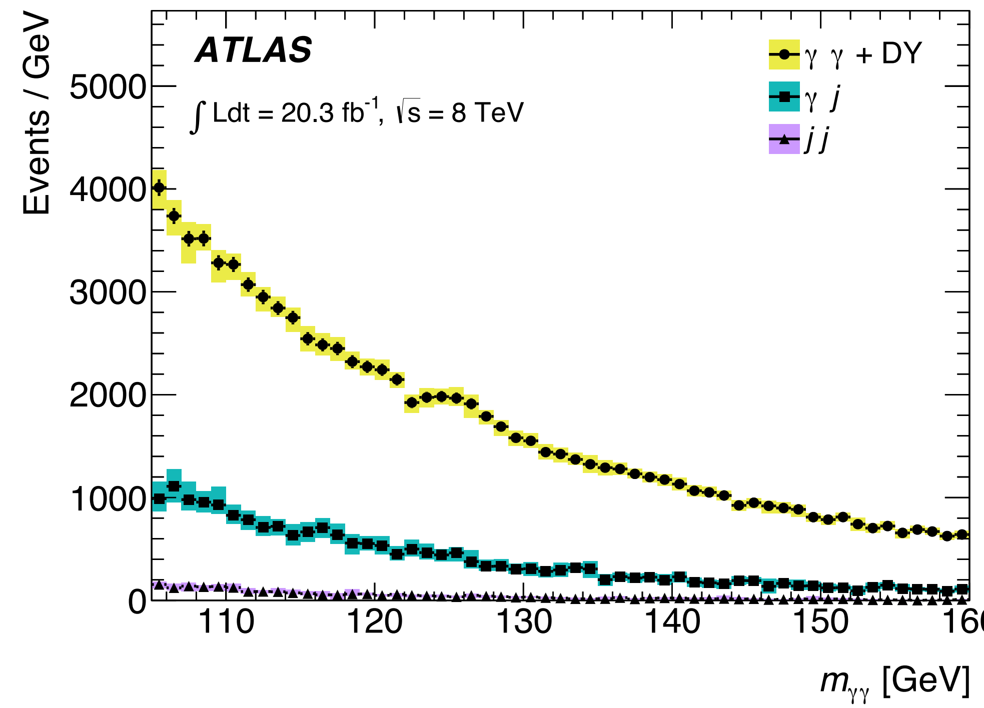
Resolution dominated by σ_E

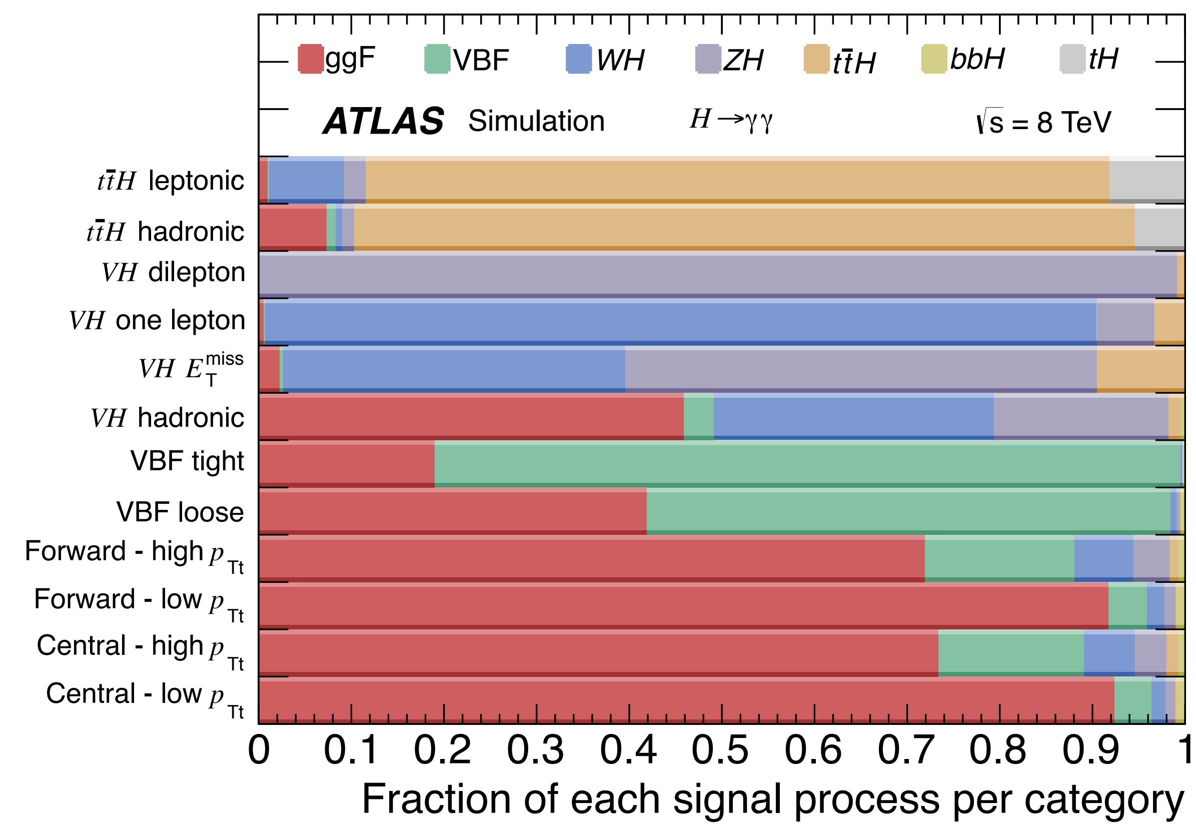




H → γγ: analysis strategy

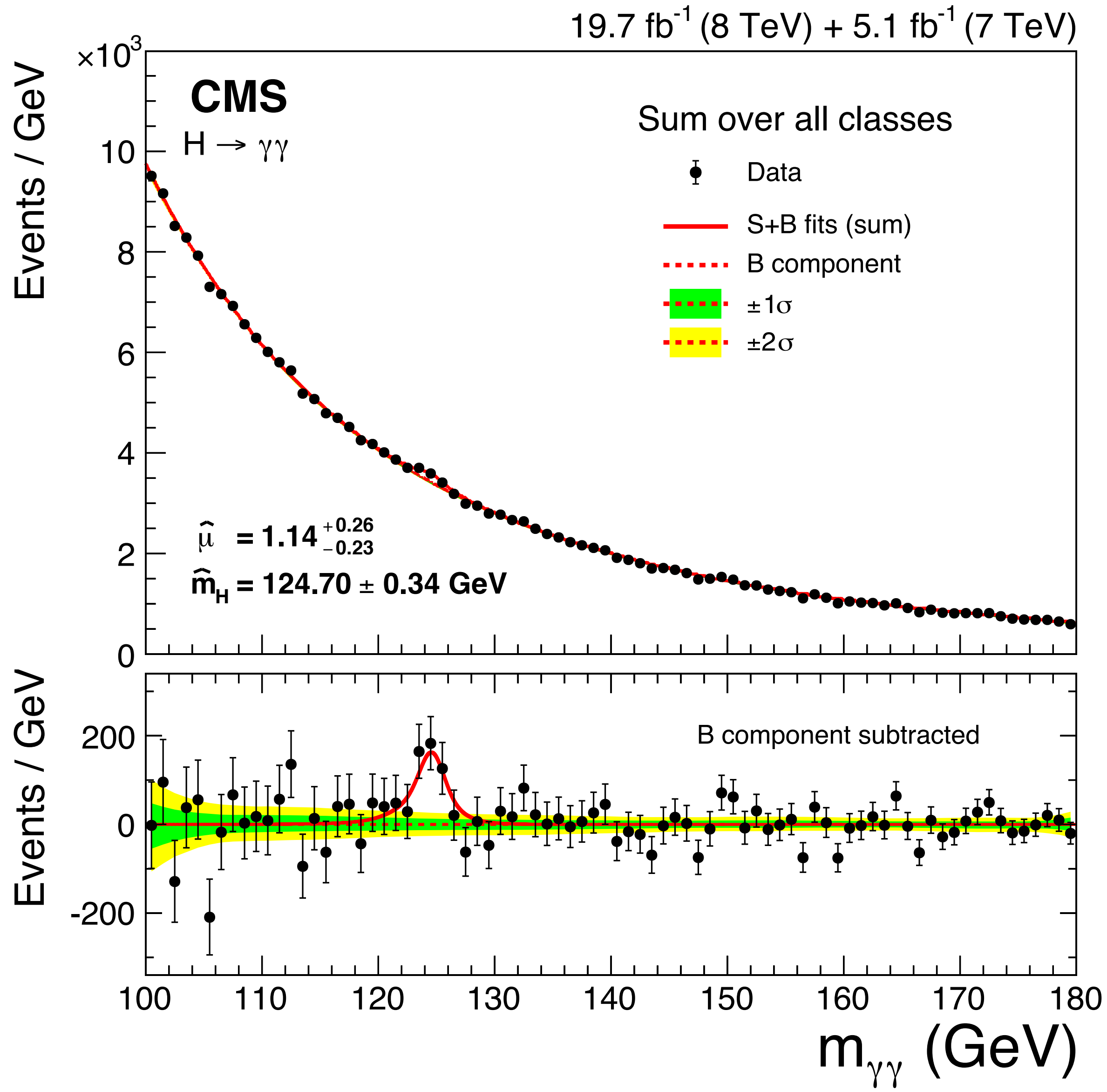
- Select clean γγ sample (purity ~75%)
- Reconstruct $m_{\gamma\gamma}$
- Split events in categories
  - Improve sensitivity
    - Resolution and S/B vary with e.g. η
  - Access to production modes
    - Leptons and jets for ttH
    - W/Z → ℓ, ν or jets
    - Forward jets to tag VBF





H → γγ: a look at the data

How to extract the signal? How significant it is?



H → γγ: profile likelihood ratio

How to extract the signal? How significant it is?

- Likelihood function (model of the data):

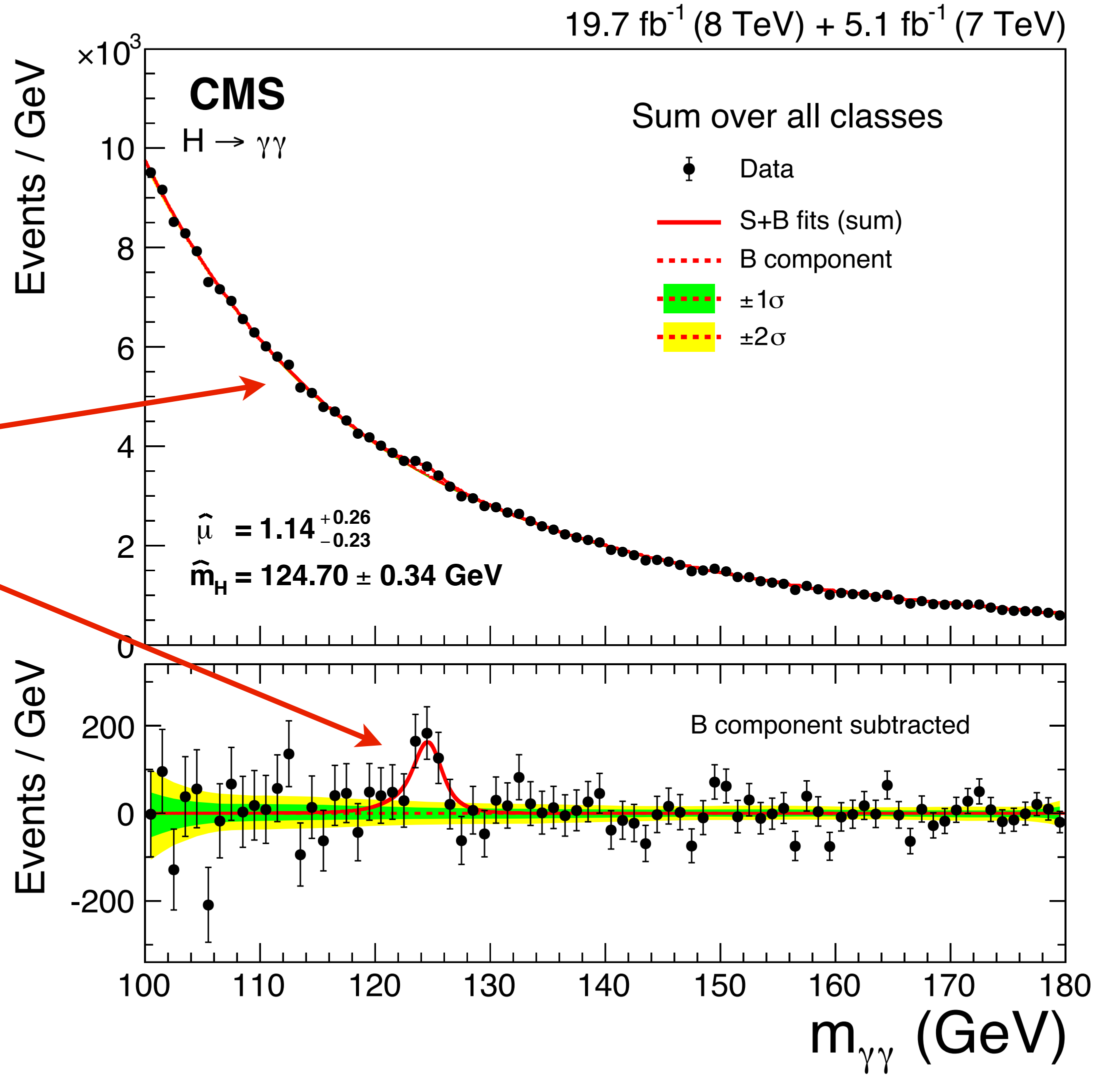
observable — nuisance parameters

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

signal, bkg pdfs

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

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



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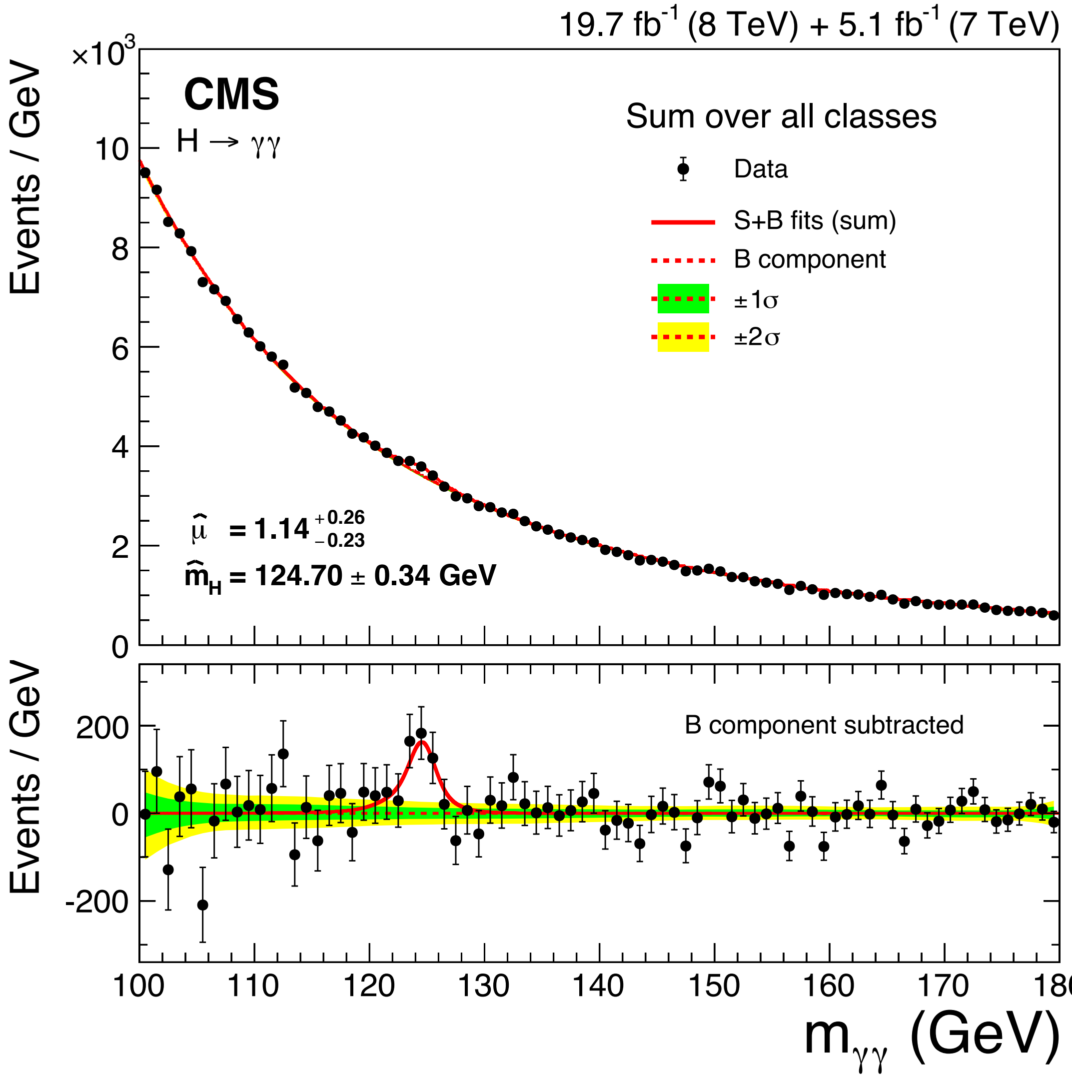
$$\mathscr{L}(\mu,\theta) = \prod_{events} f_s\psi_s(m_{\gamma\gamma};\theta) + (1-f_s)\psi_b(m_{\gamma\gamma};\theta)$$

- Profile likelihood ratio:

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

$\mathscr{L}$ maximized with μ fixed

$\mathscr{L}$ maximized with μ free



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

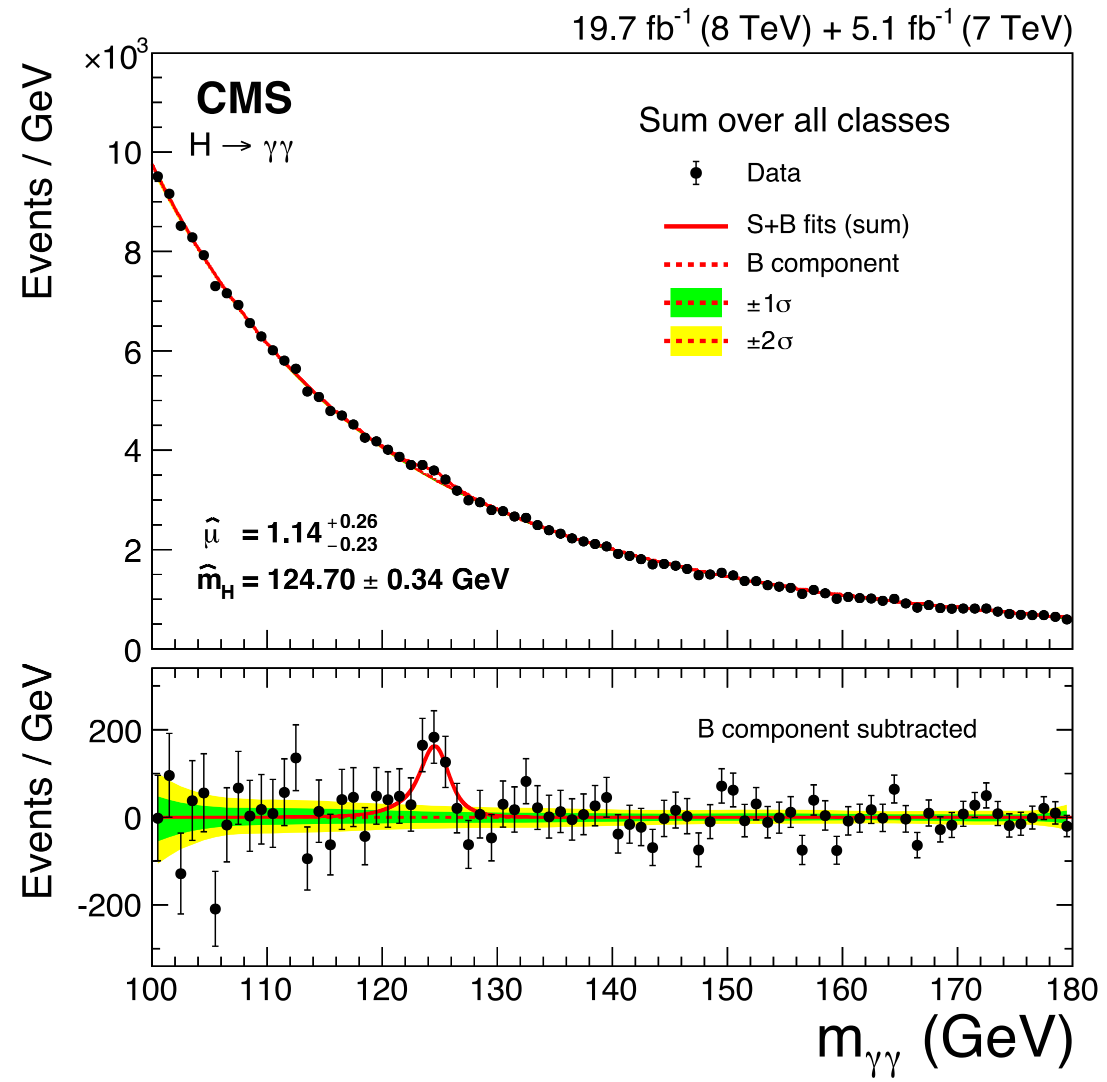
- Profile likelihood ratio:

$$\tilde{q}_\mu = -2\log\frac{\mathscr{L}(\mu,\hat{\theta}_\mu)}{\mathscr{L}(\hat{\mu},\hat{\theta})}\ ,\ 0\le\hat{\mu}\le\mu$$

- Asymptotic approximation:

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

$$(\text{but } \hat{\mu}<0 \rightarrow q_0 = 0)$$

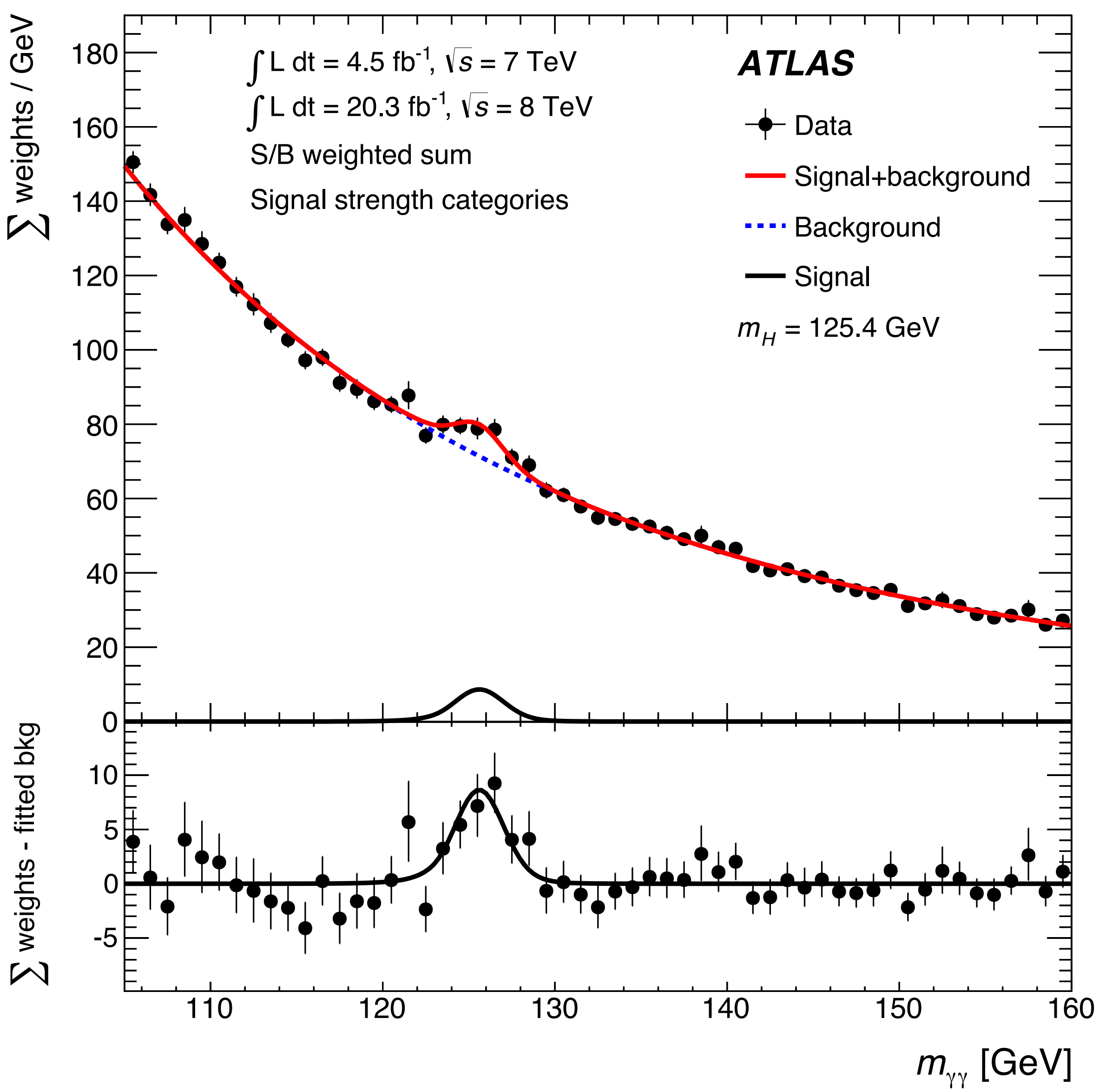


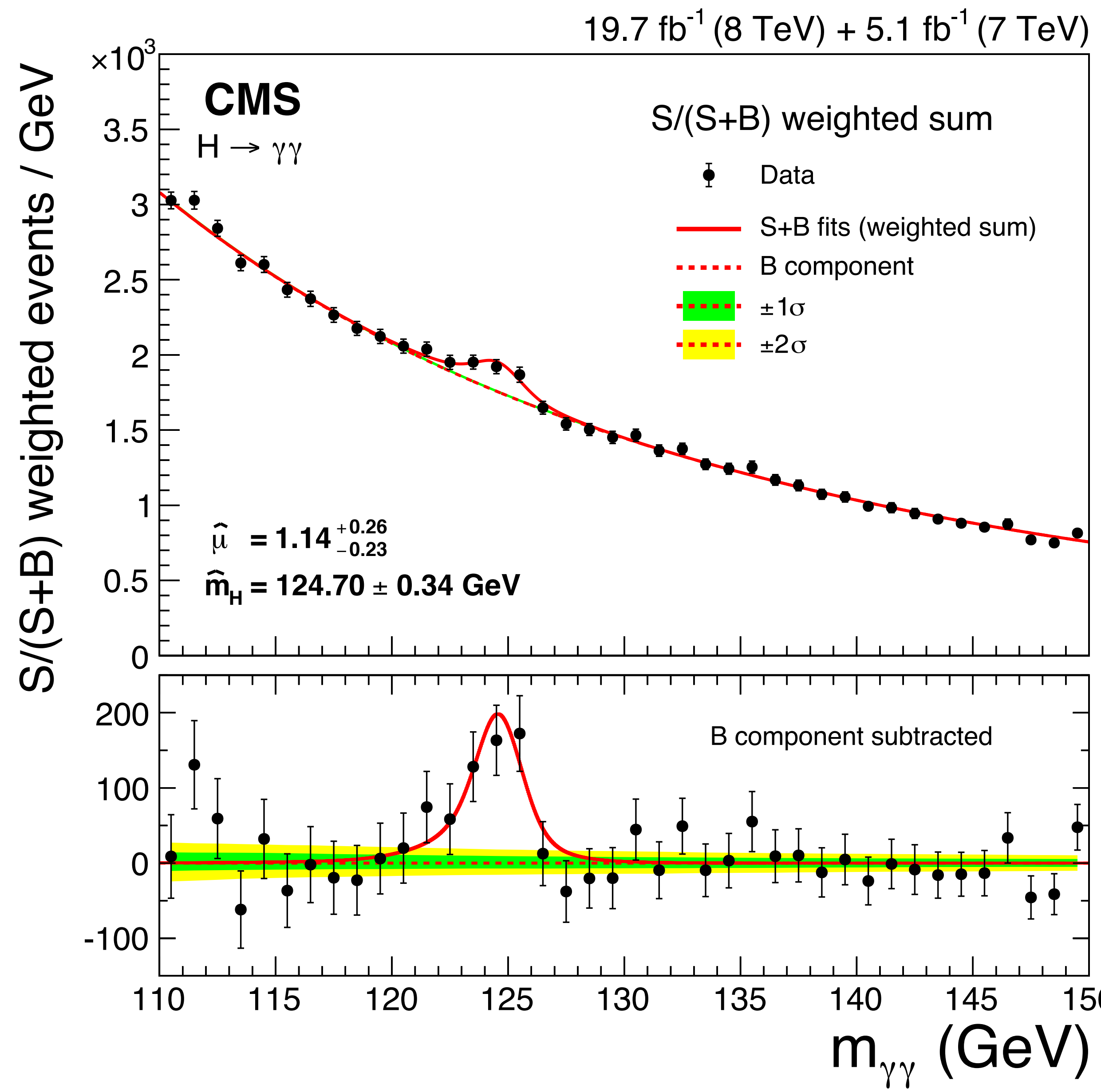
Equivalent to: $\Delta\chi^2 = \chi^2 - \chi^2_{min}$
(with 1 d.o.f)

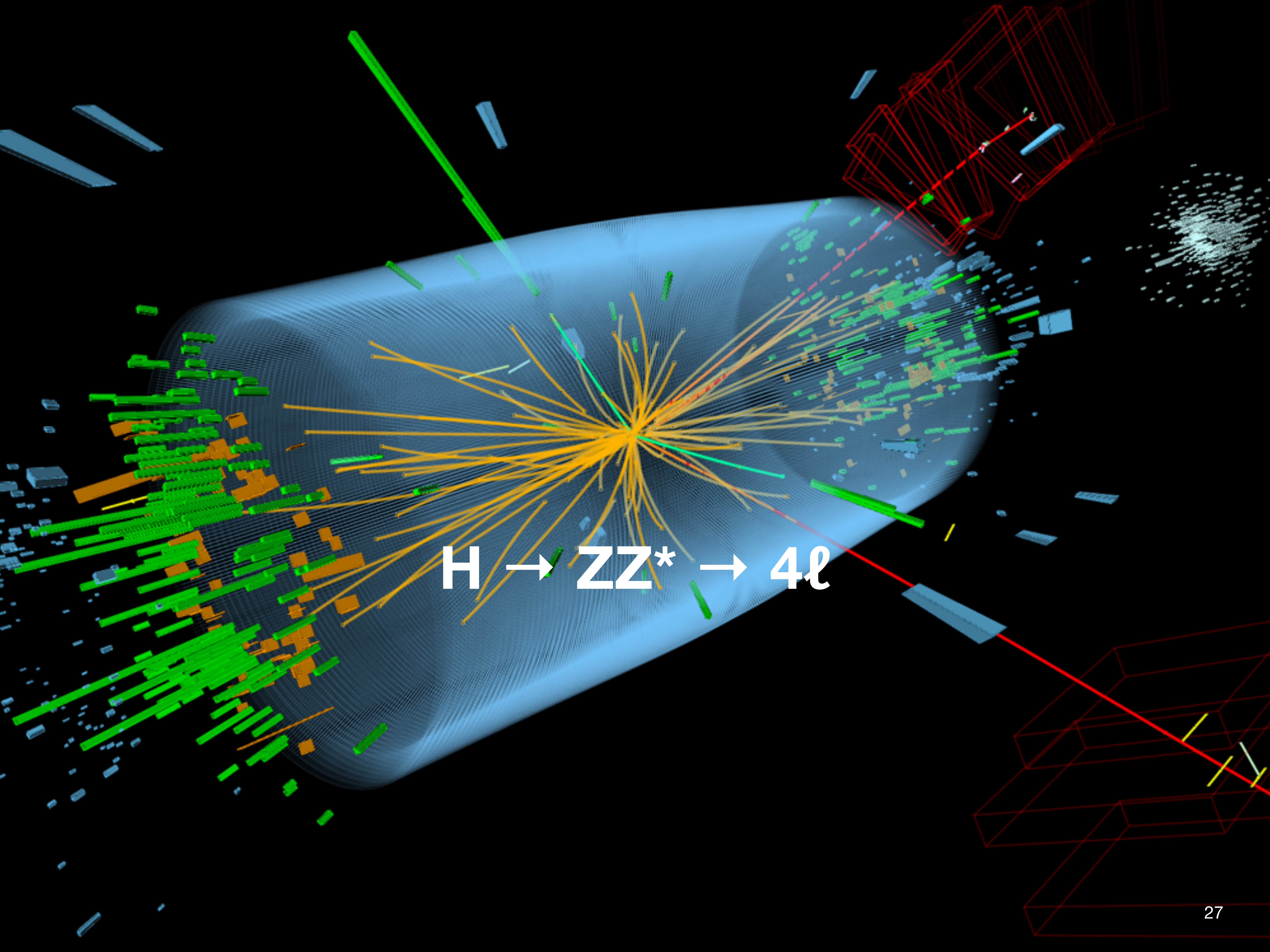
H → γγ: a look at the data

	Z_{obs}	Z_{exp}	μ
ATLAS	5.2	4.6	1.17 ± 0.27
CMS	5.7	5.2	$1.14^{+0.26}_{-0.3}$

Enhancing the signal with weights from the categories



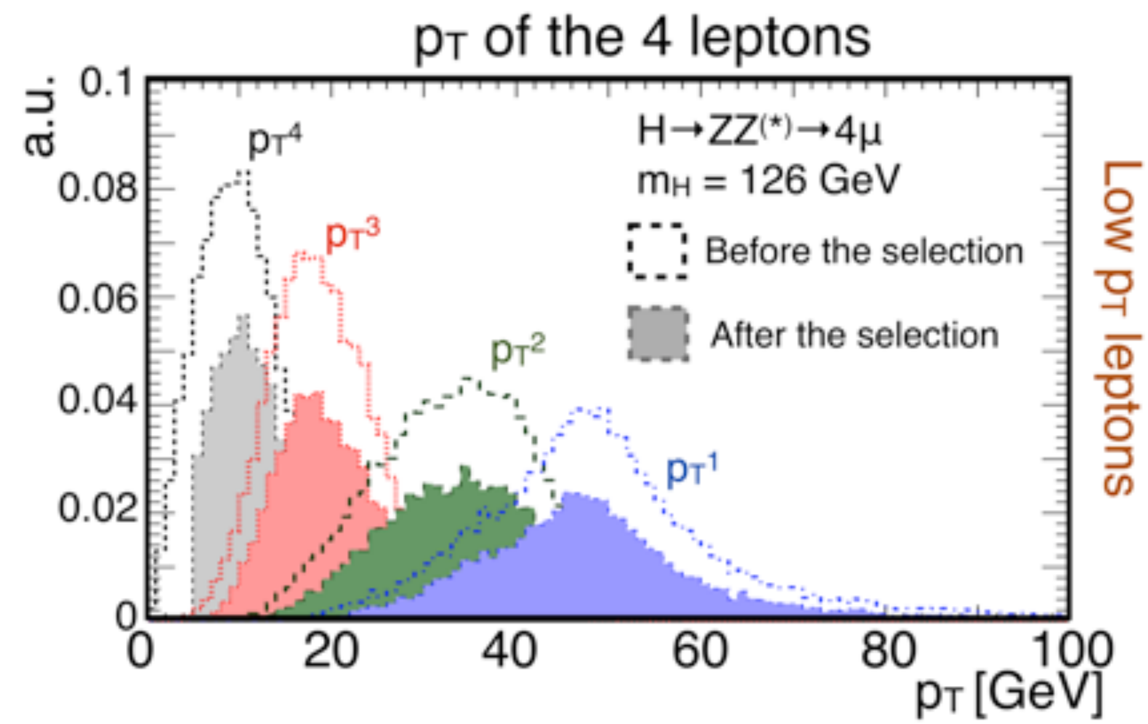



H → ZZ* → 4ℓ

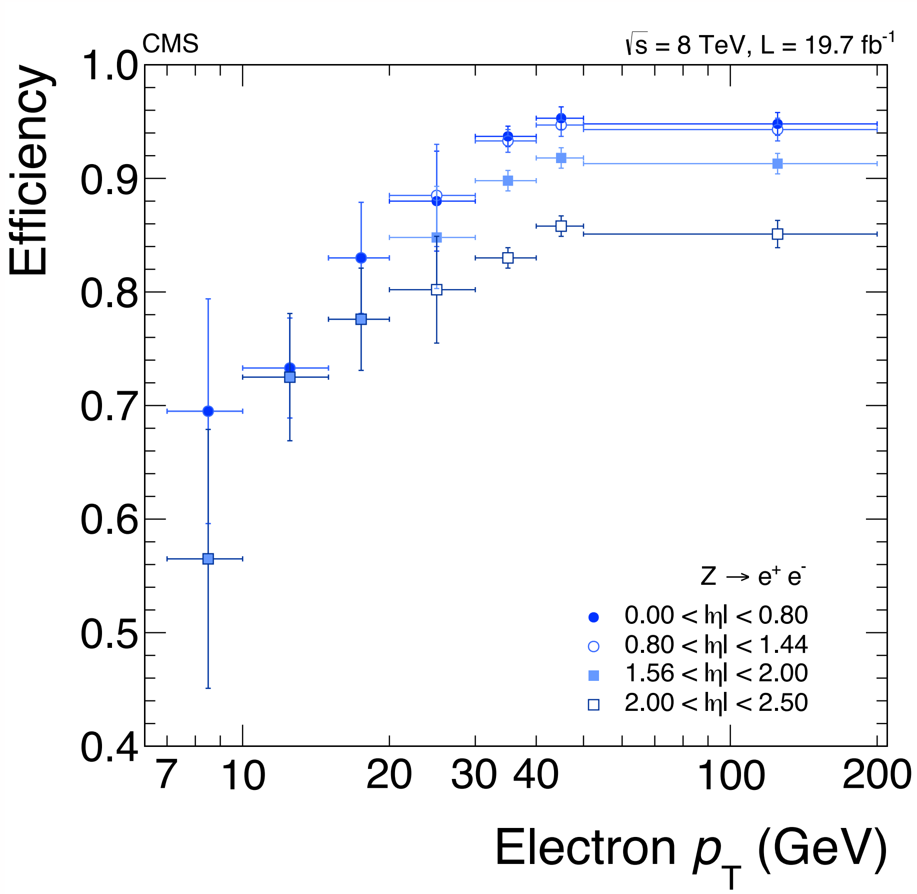
$H \to ZZ^* \to 4\ell$

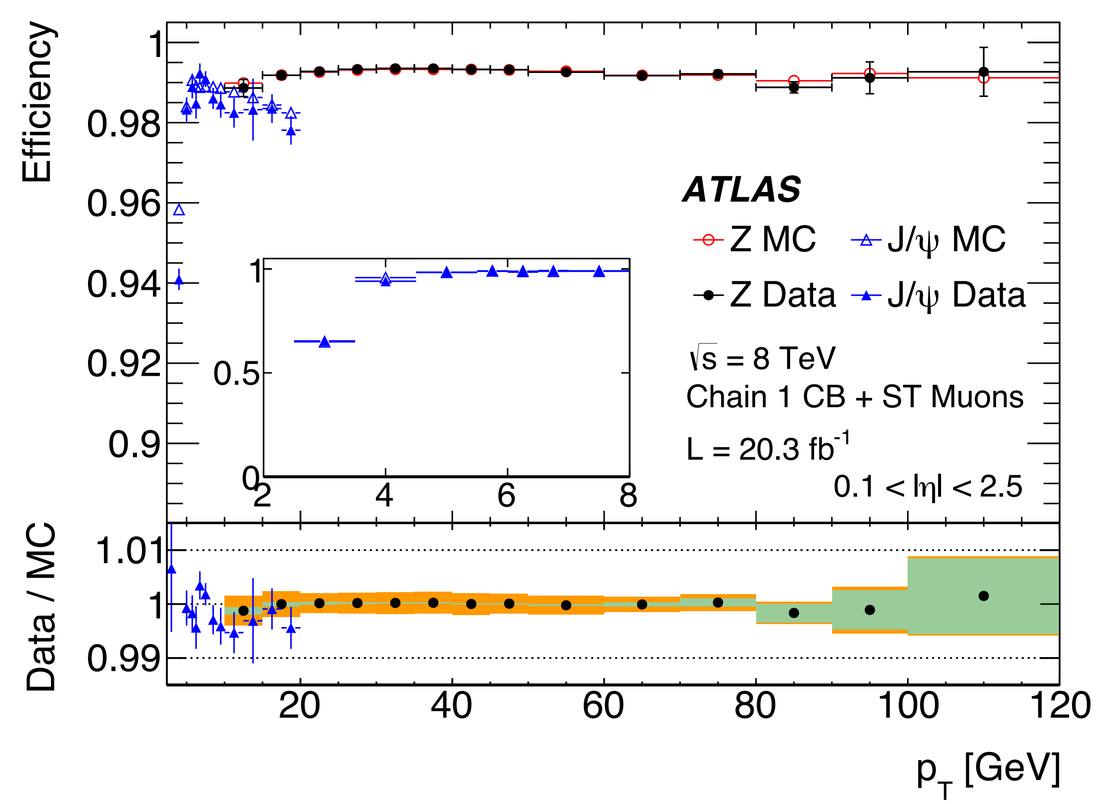
σ X BR ~ 2.9 fb @ 125.5 GeV

- "Golden channel" but very small rates
  - BR($Z \to \ell\ell$) ~ 3.3%
  - Need very high efficiency for e^- and μ down to low P_T (~5 GeV)



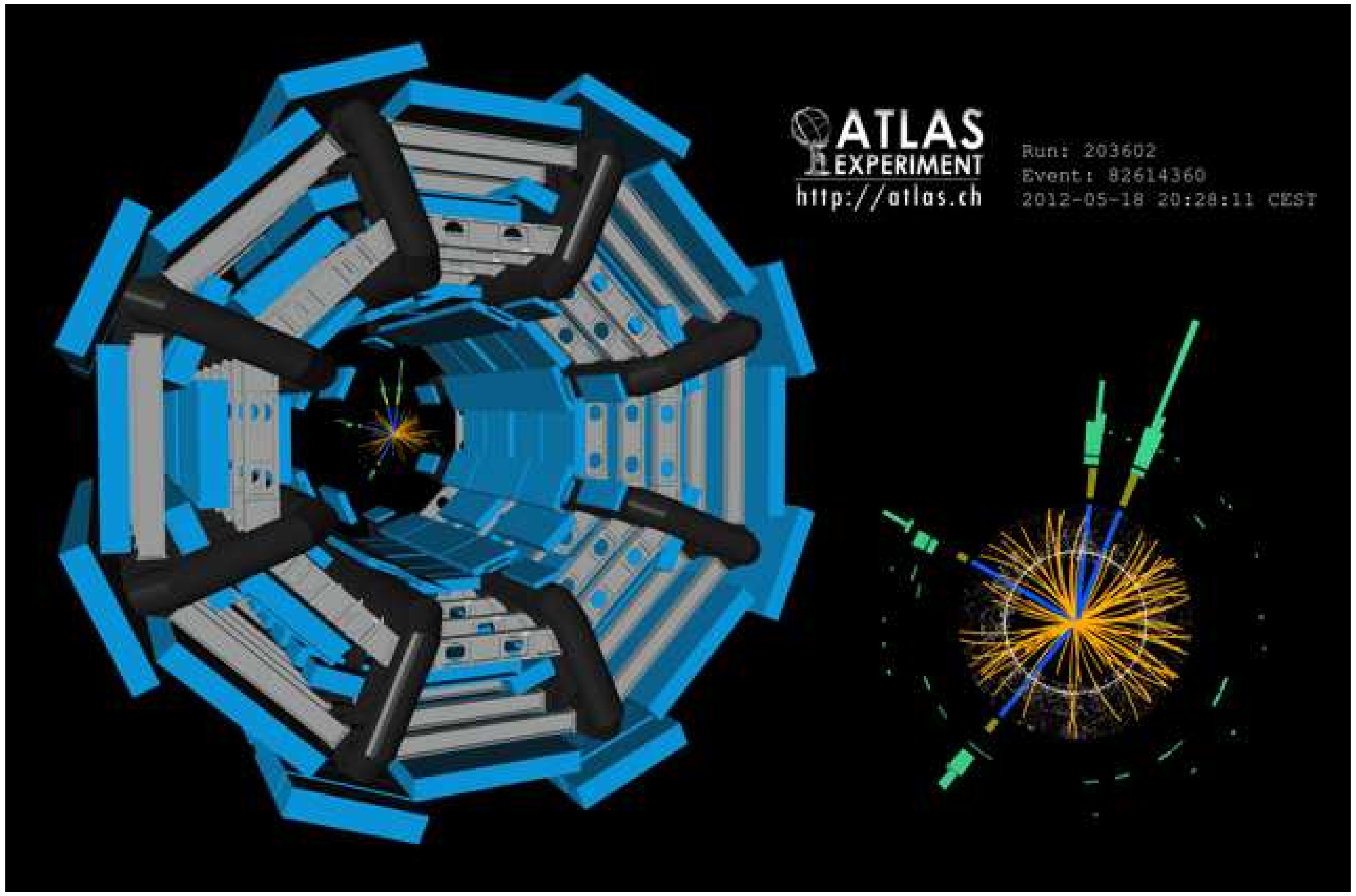
Low pT leptons

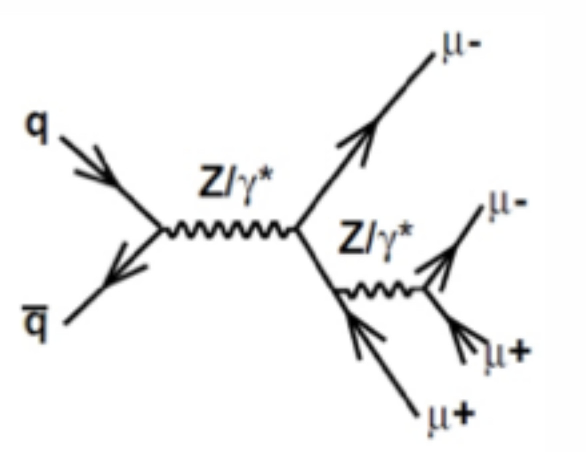


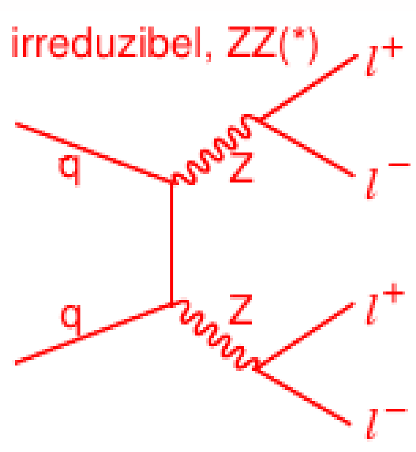


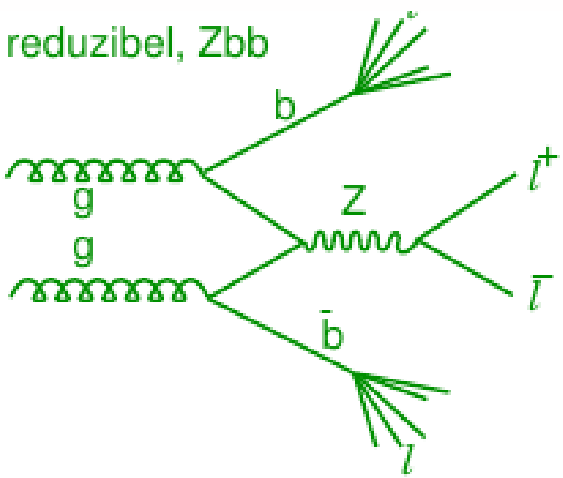
$H \to ZZ^* \to 4\ell$

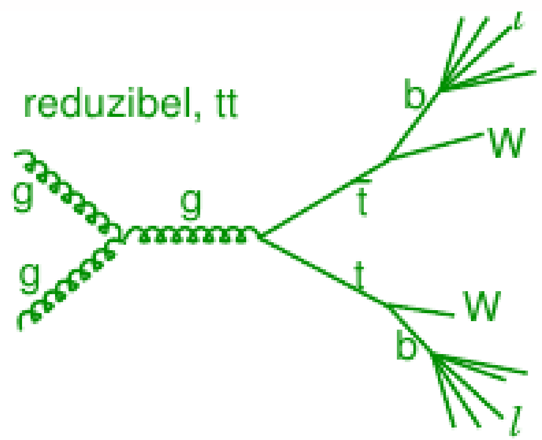
- "Golden channel" but very small rates
  - Signature: 2 pairs of oppositely charged, same flavour leptons
    - Leading $m_{\ell\ell}$ close to m_Z
- Narrow peak ($\sigma_{m4\ell} \sim$ 1.6-2 GeV) on top of smooth background (S/B ~ 1)
  - Main backgrounds:









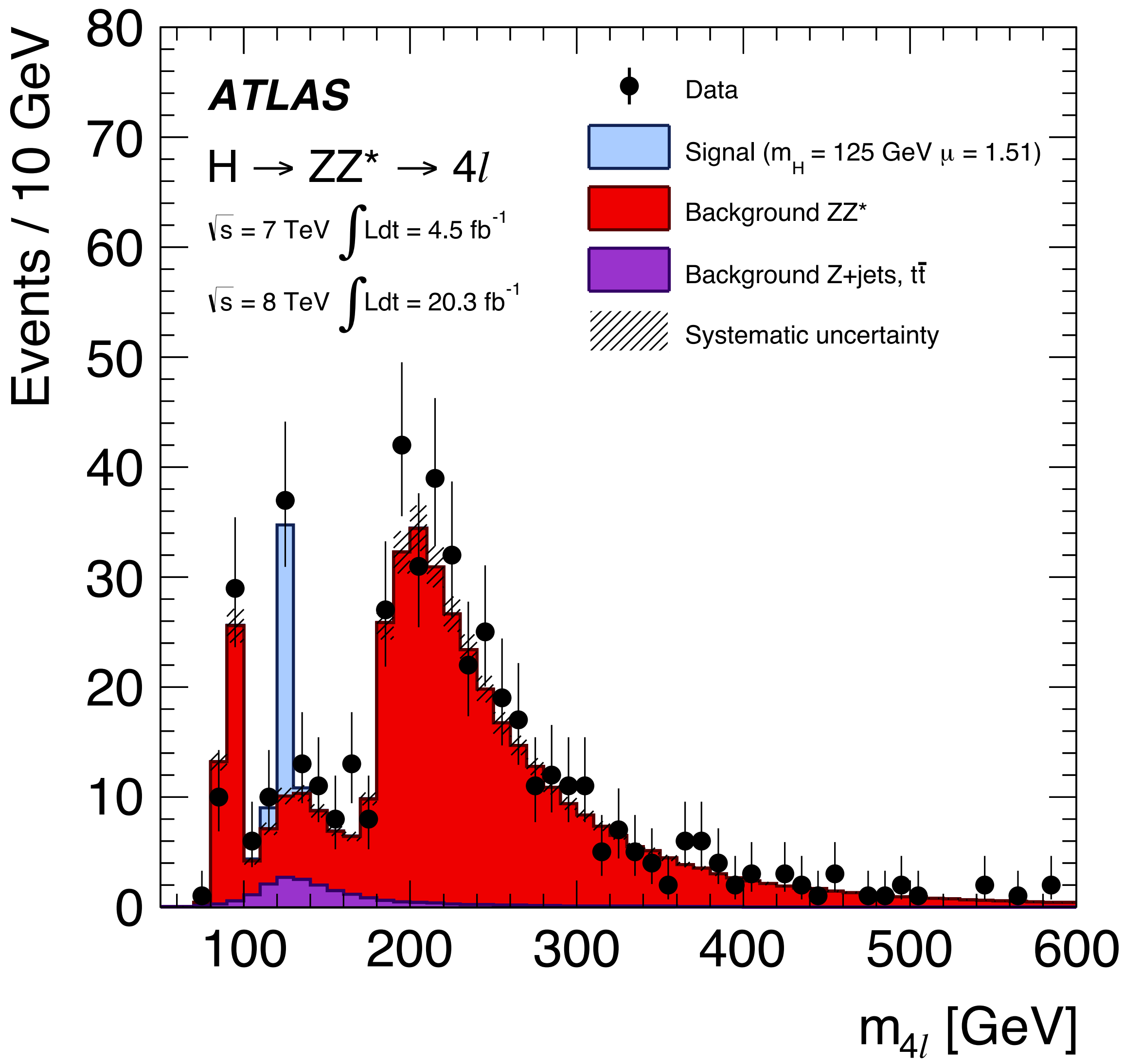


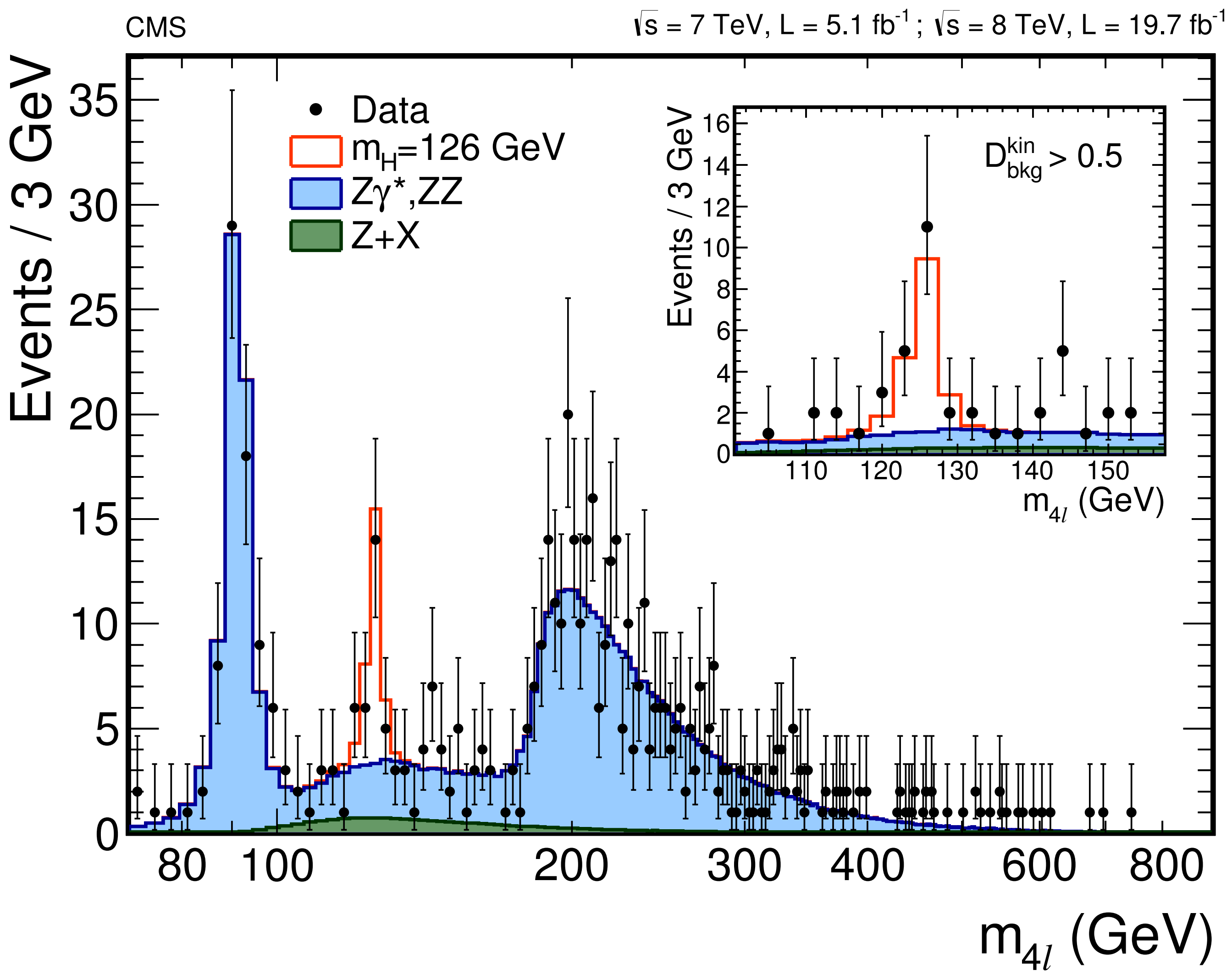
from NLO MC

normalized from control regions

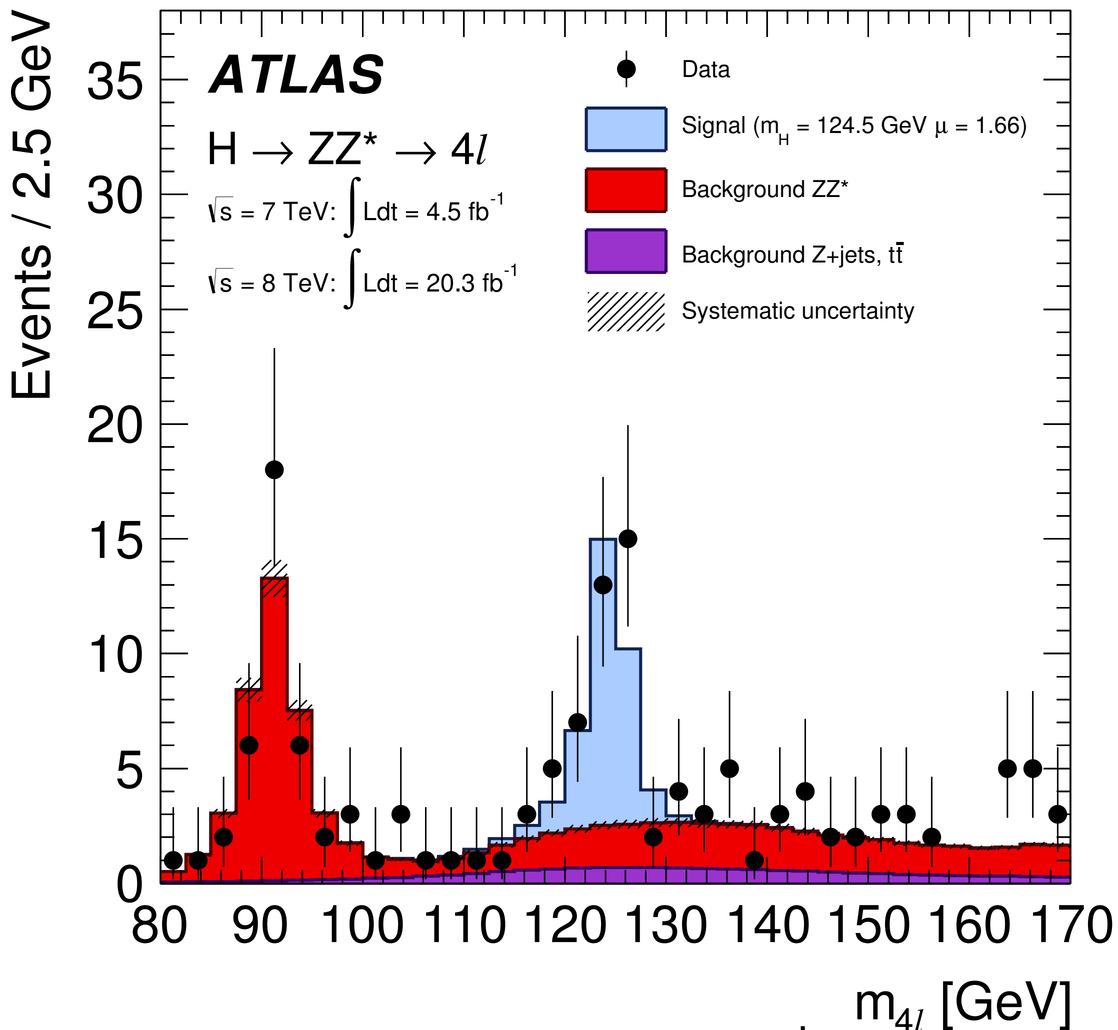
H → ZZ* → 4ℓ: a look at the data

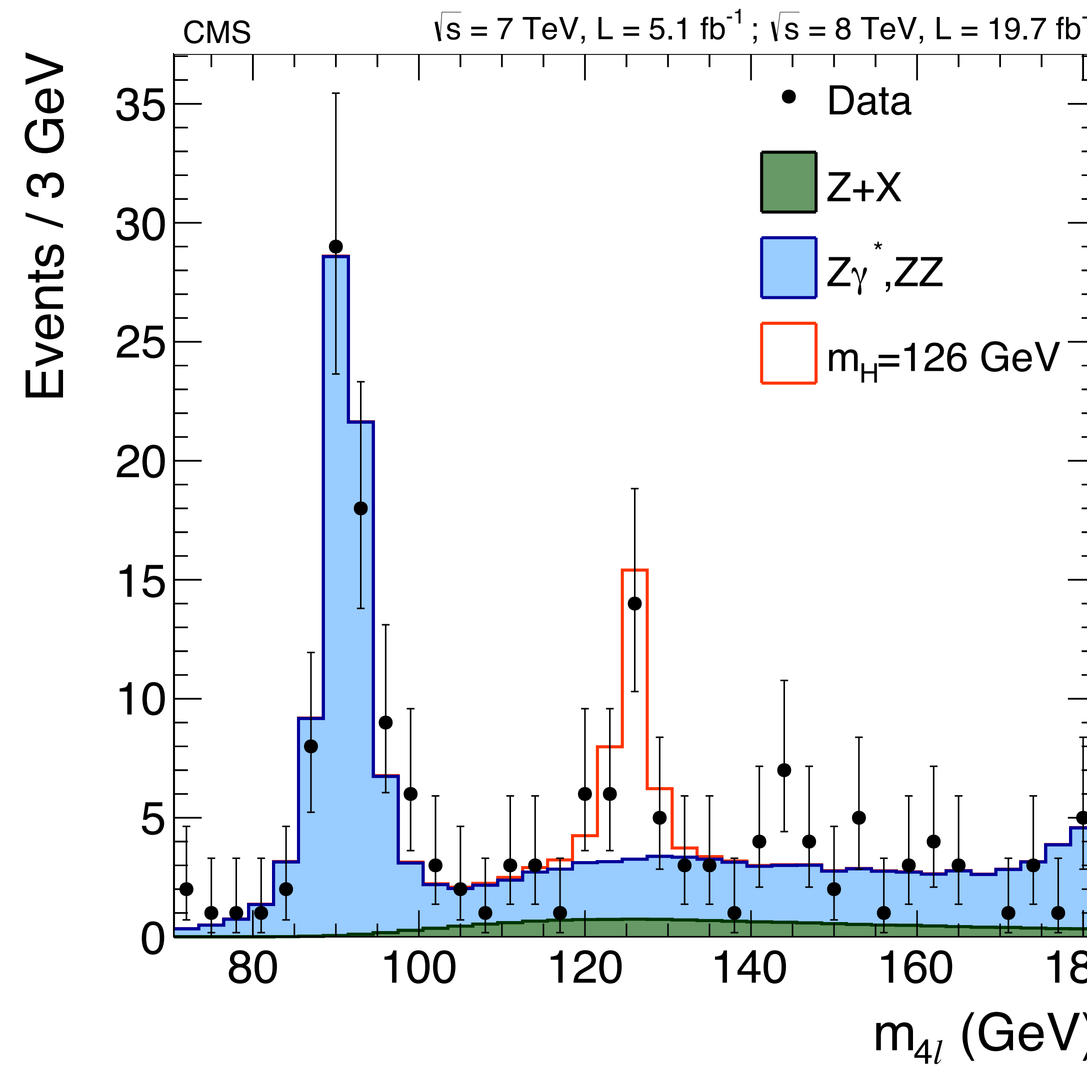
Handful of events but clean peak!





H → ZZ* → 4ℓ: a look at the data (zoom)





s+b

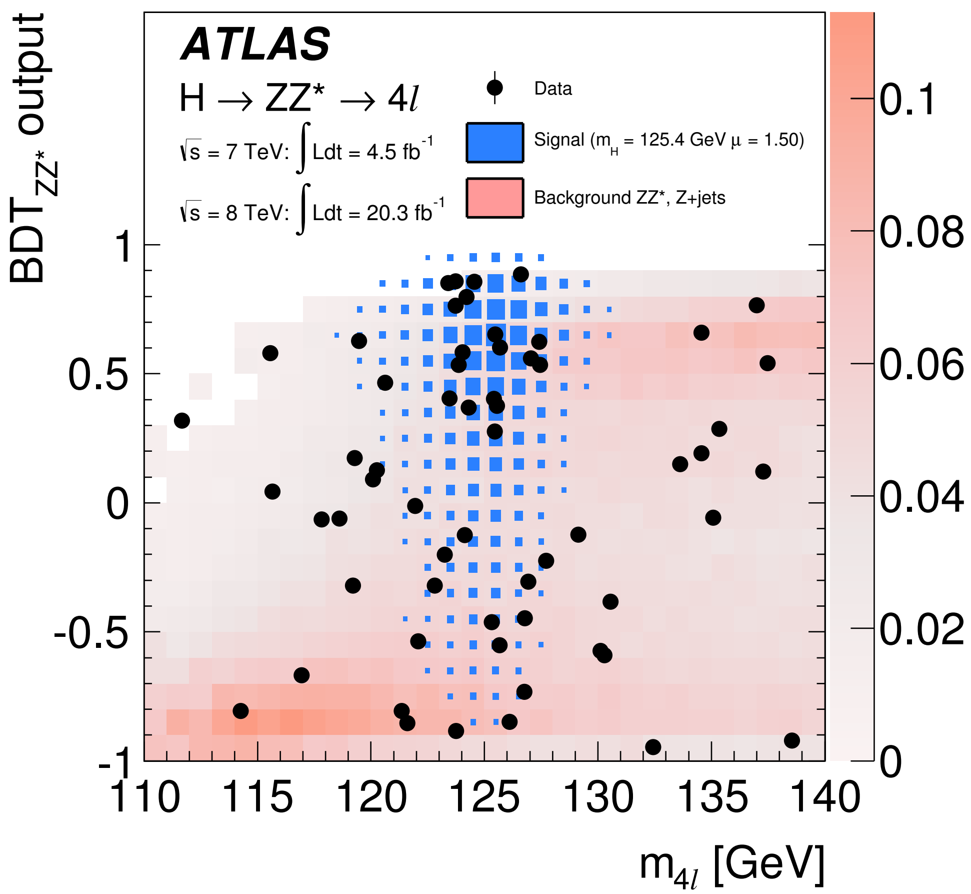
	s/b	expected	observed
4μ	1.7	9.80 ± 0.64	14
$2e2\mu$	1.5	6.72 ± 0.43	9
$2\mu2e$	1.5	5.24 ± 0.35	6
$4e$	1.4	4.75 ± 0.32	8
total	1.6	26.5 ± 1.7	37

Channel	4e	$2e2\mu$	4μ	4ℓ
ZZ background	1.1 ± 0.1	3.2 ± 0.2	2.5 ± 0.2	6.8 ± 0.3
Z + X background	0.8 ± 0.2	1.3 ± 0.3	0.4 ± 0.2	2.6 ± 0.4
All backgrounds	1.9 ± 0.2	4.6 ± 0.4	2.9 ± 0.2	9.4 ± 0.5
$m_H = 125$ GeV	3.0 ± 0.4	7.9 ± 1.0	6.4 ± 0.7	17.3 ± 1.3
$m_H = 126$ GeV	3.4 ± 0.5	9.0 ± 1.1	7.2 ± 0.8	19.6 ± 1.5
Observed	4	13	8	25

$H \rightarrow ZZ^* \rightarrow 4\ell$

- Full event kinematics!
  - Discriminant against ZZ* background improves sensitivity
  - 5 angles and 2 masses to measure spin/CP

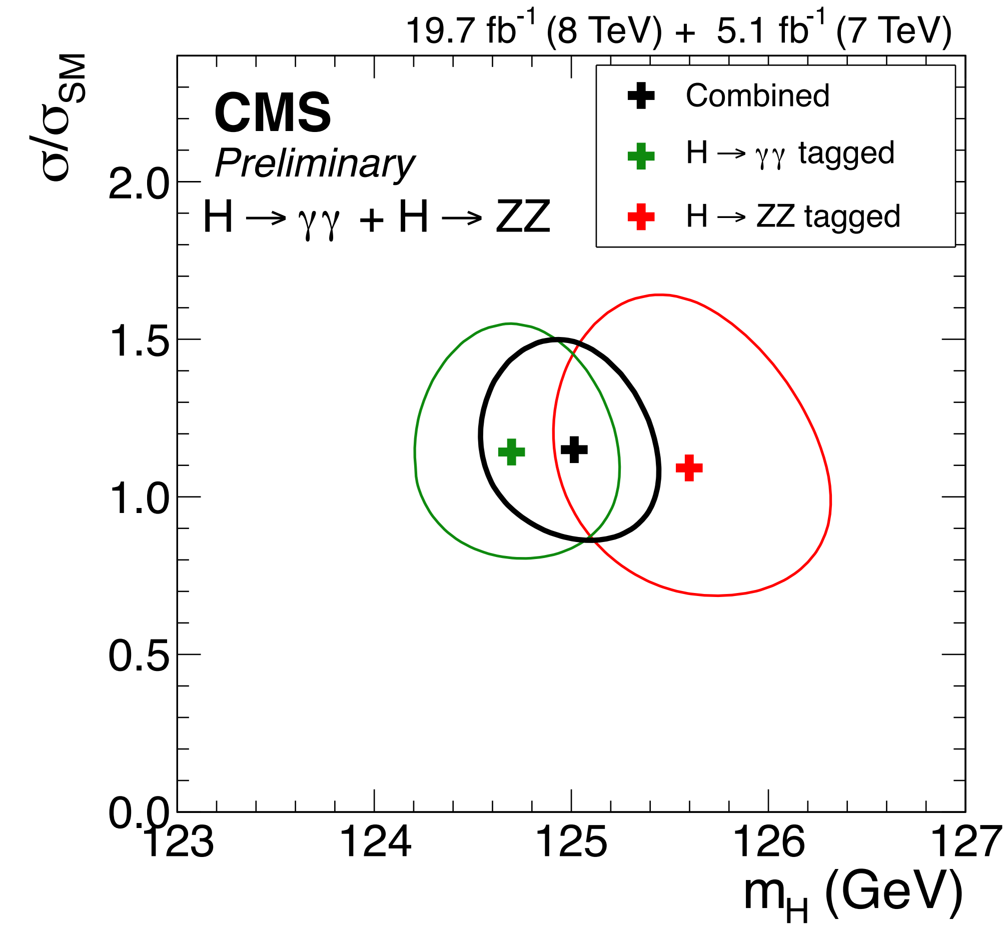
	Z_{obs}	Z_{exp}	μ
ATLAS	8.1	6.2	$1.44^{+0.40}_{-0.33}$
CMS	6.8	6.7	$0.93^{+0.29}_{-0.16}$



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

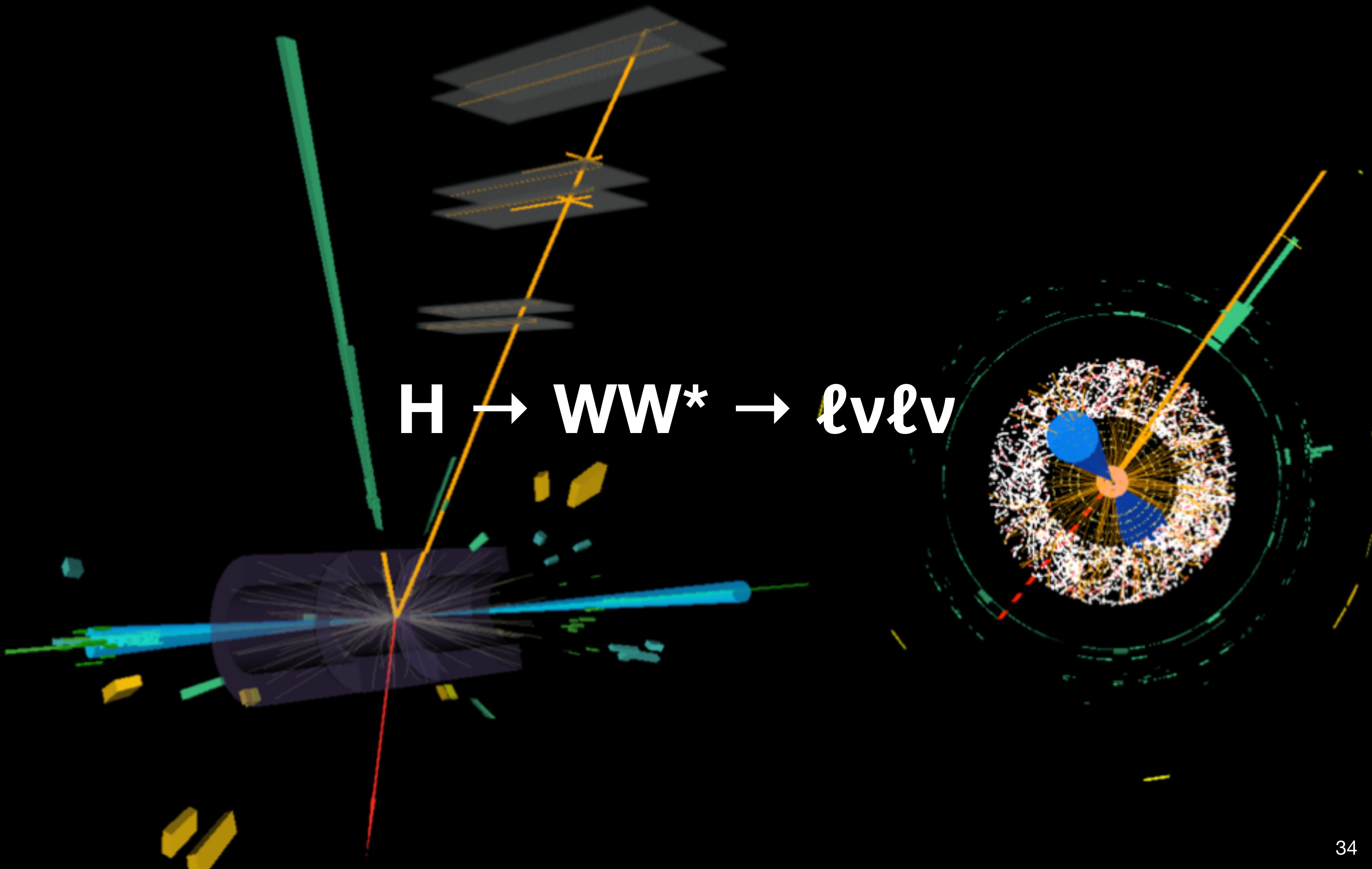


	ATLAS	CMS
$H \to \gamma\gamma$	125.98 ± 0.42 (stat) ± 0.28 (sys)	124.70 ± 0.31 (stat) ± 0.15 (sys)
$H \to ZZ^* \to 4\ell$	124.51 ± 0.52 (stat) ± 0.04 (sys)	125.6 ± 0.4 (stat) ± 0.2 (sys)
Combined	125.36 ± 0.37 (stat) ± 0.18 (sys)	$125.03^{+0.26}_{-0.27}$ (stat)$^{+0.13}_{-0.15}$ (sys)
	125.36 ± 0.41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

ATLAS EXPERIMENT

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

H → WW* → ℓνℓν

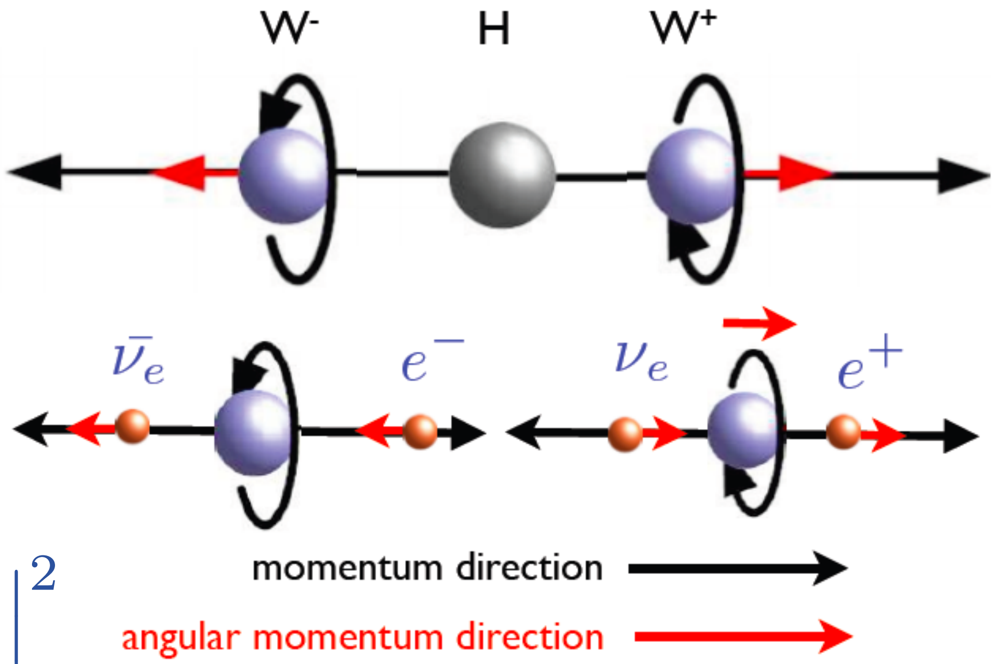


H → WW* → ℓνℓν: analysis strategy

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:

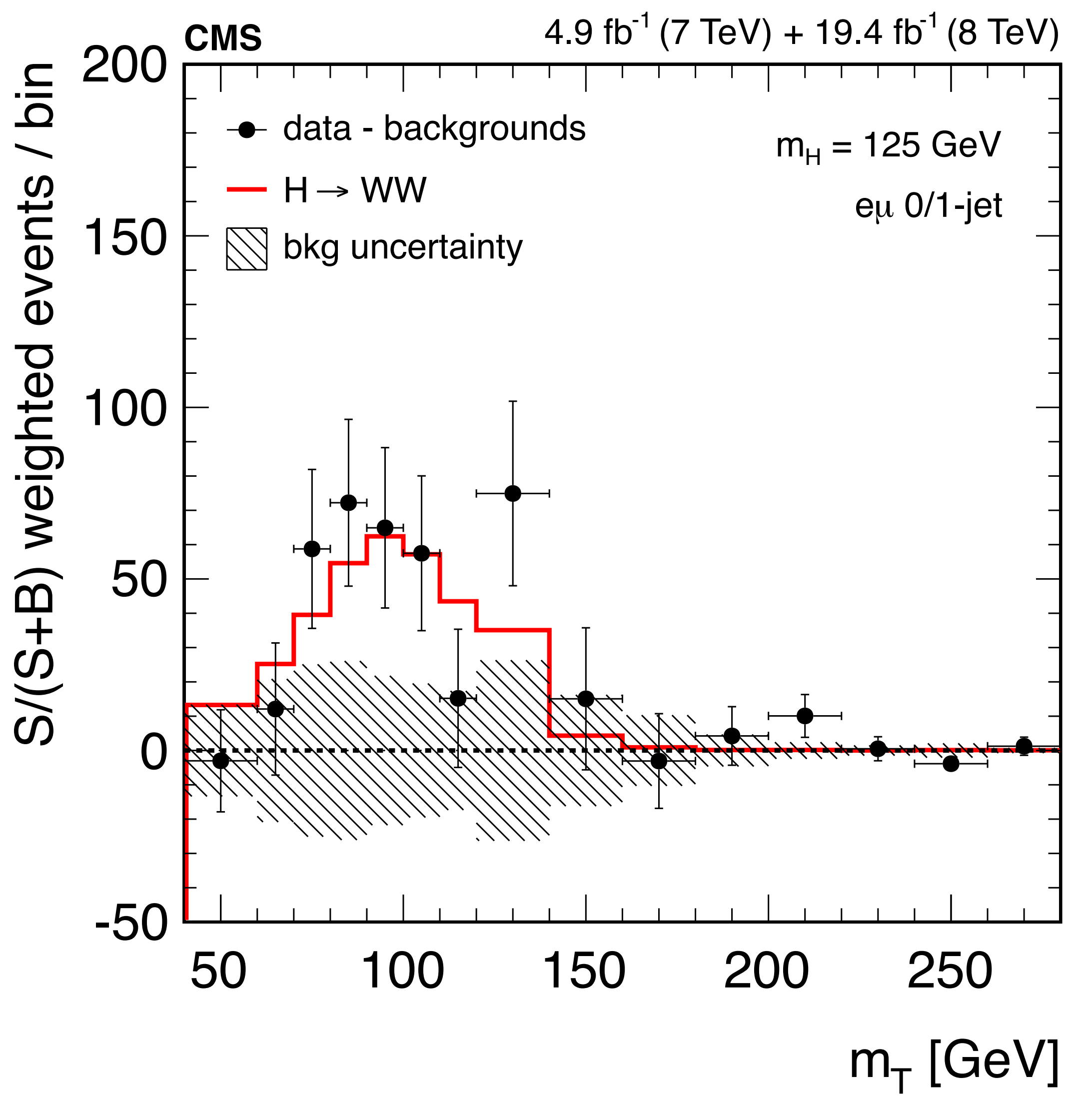
$$m_T^2 = \left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left|\vec{p_{T_{\ell\ell}}} + \vec{E_T^{\text{miss}}}\right|^2$$

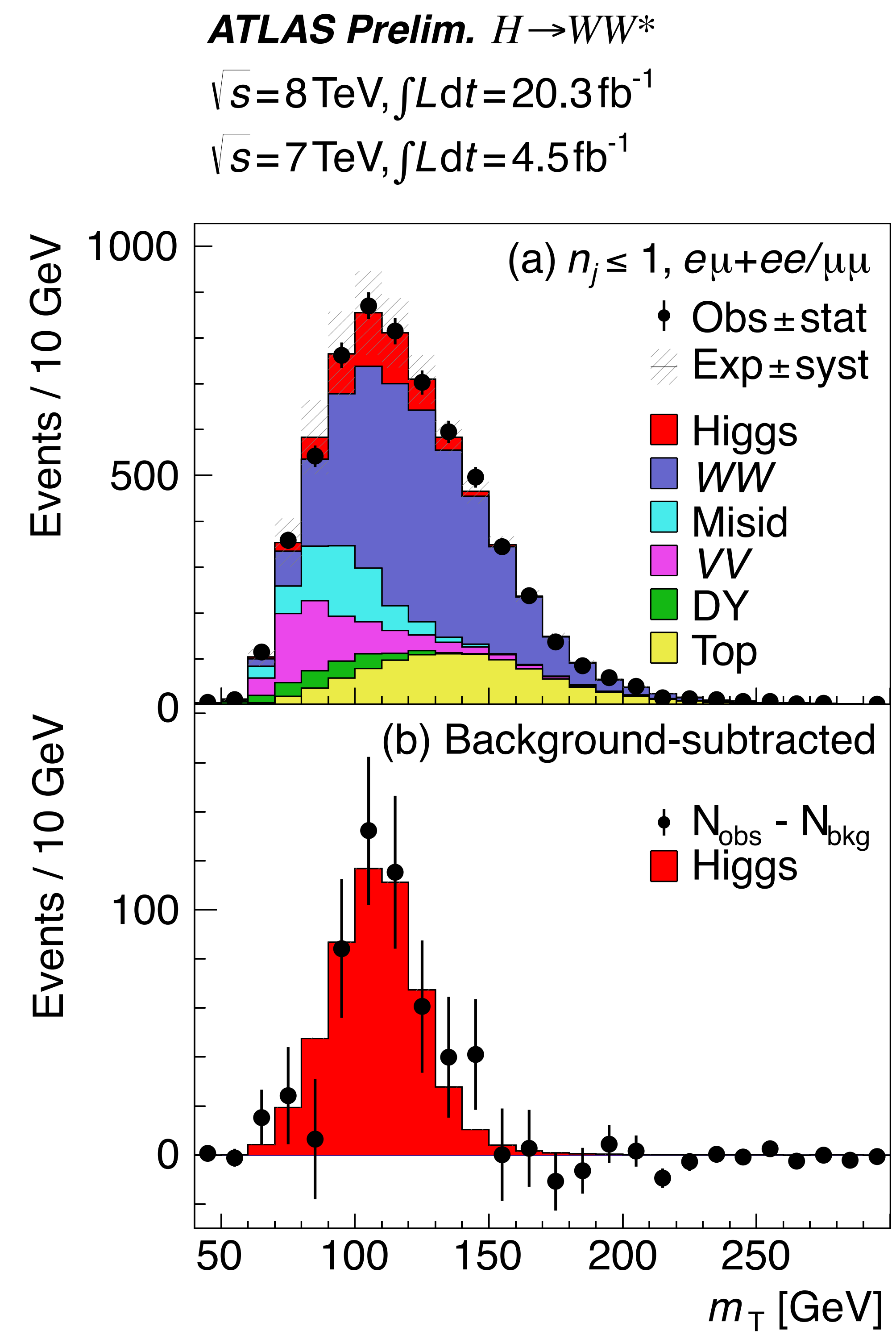


  - Large backgrounds: WW, W+jets, top, Z/γ*, di-bosons
    - Mostly data-driven
- Data split according to jet multiplicity
  - 0/1 jets: ggF signal, WW background
  - 2 or more jets: VBF signal, top background

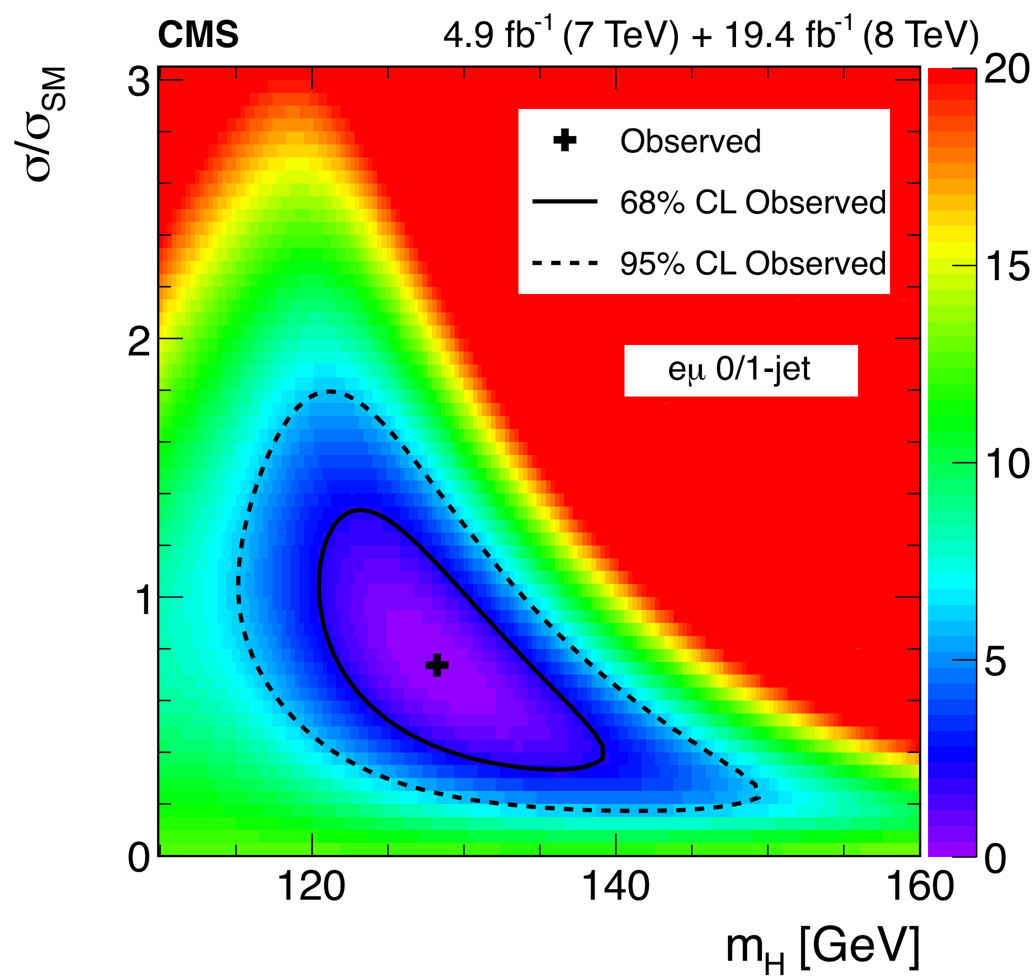
H → WW* → ℓνℓν: a look at the data

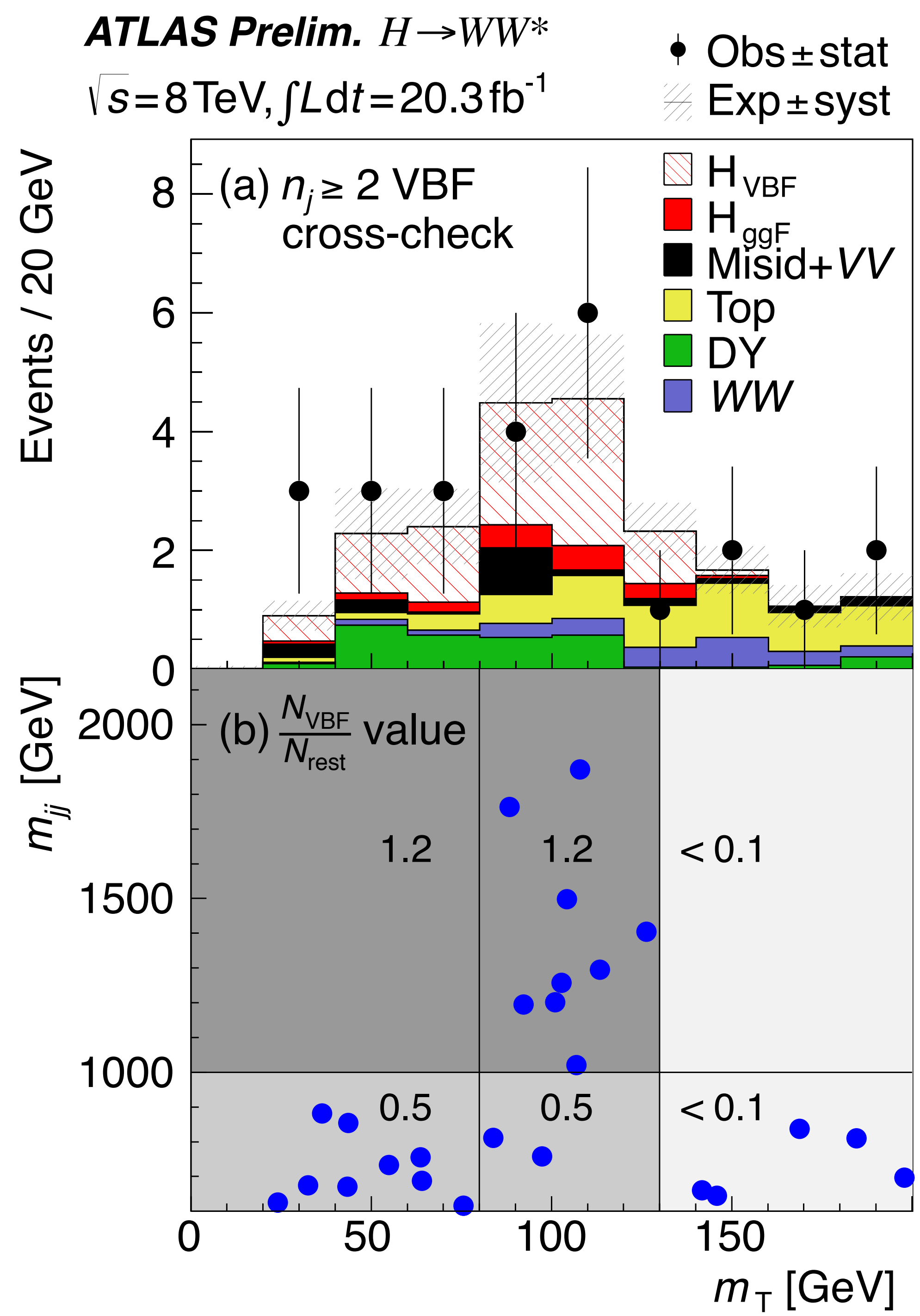
	Z_{obs}	Z_{exp}	μ
ATLAS	6.1	5.8	$1.08^{+0.22}_{-0.20}$
CMS	4.3	5.8	$0.72^{+0.20}_{-0.18}$





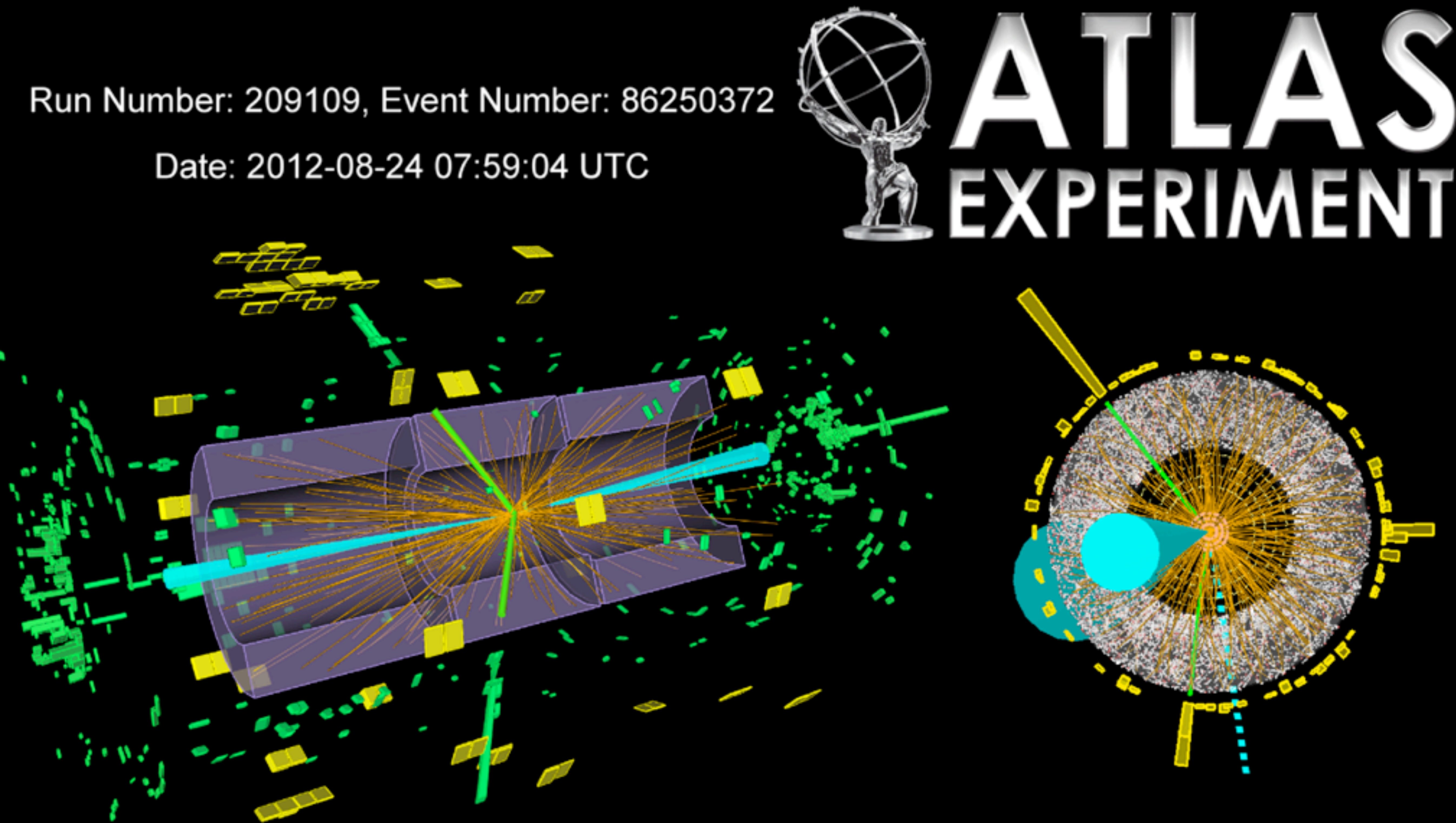
H → WW* → ℓνℓν: a look at the data





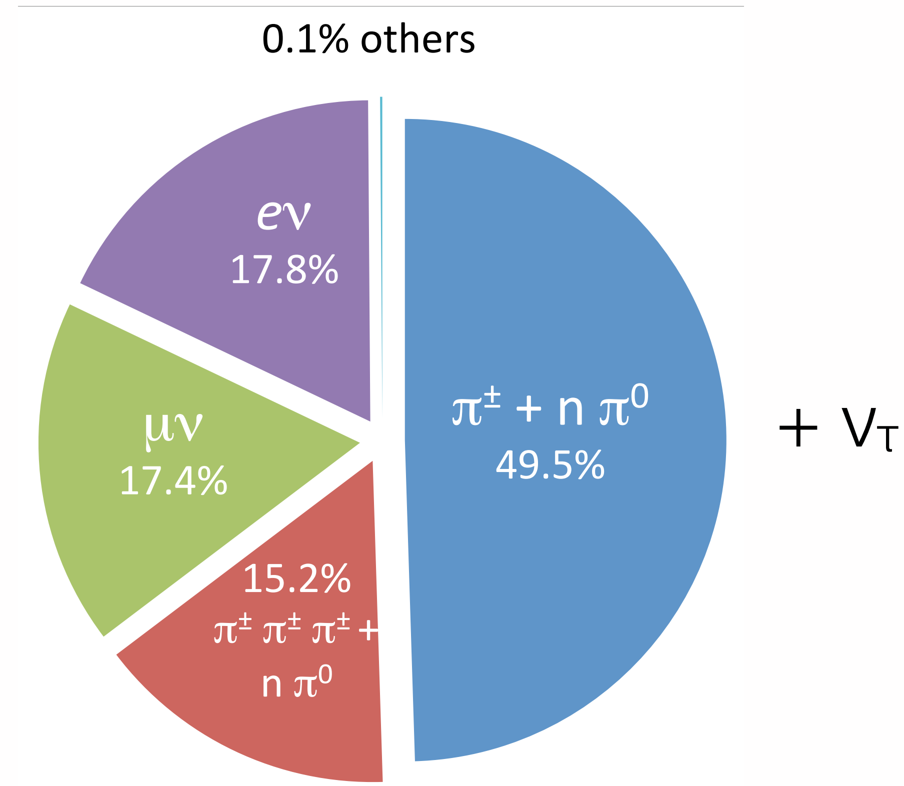
- ATLAS: VBF signal enhanced using BDT
  - 3.2σ observed (2.1 expected)
- CMS VBF: 1.3σ observed (2.1 expected)

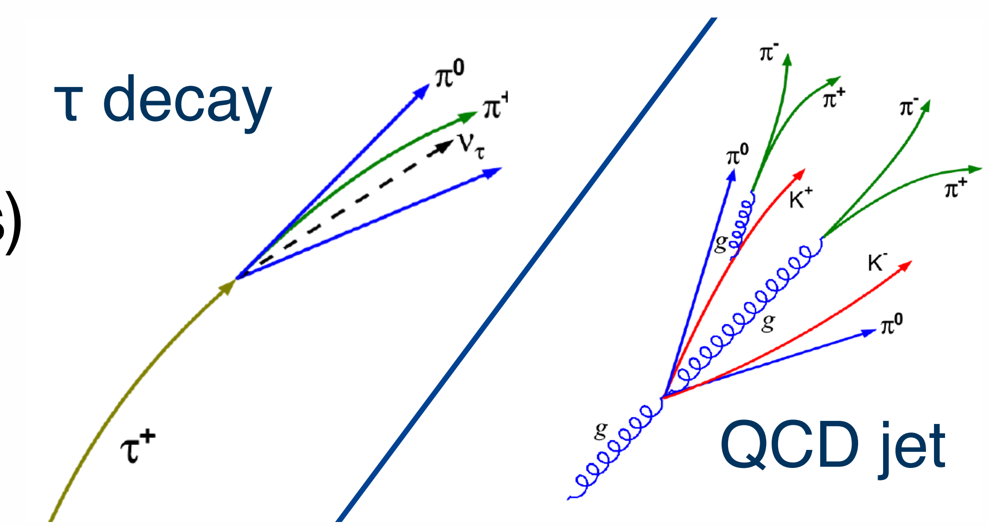
$H \rightarrow \tau\tau$



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



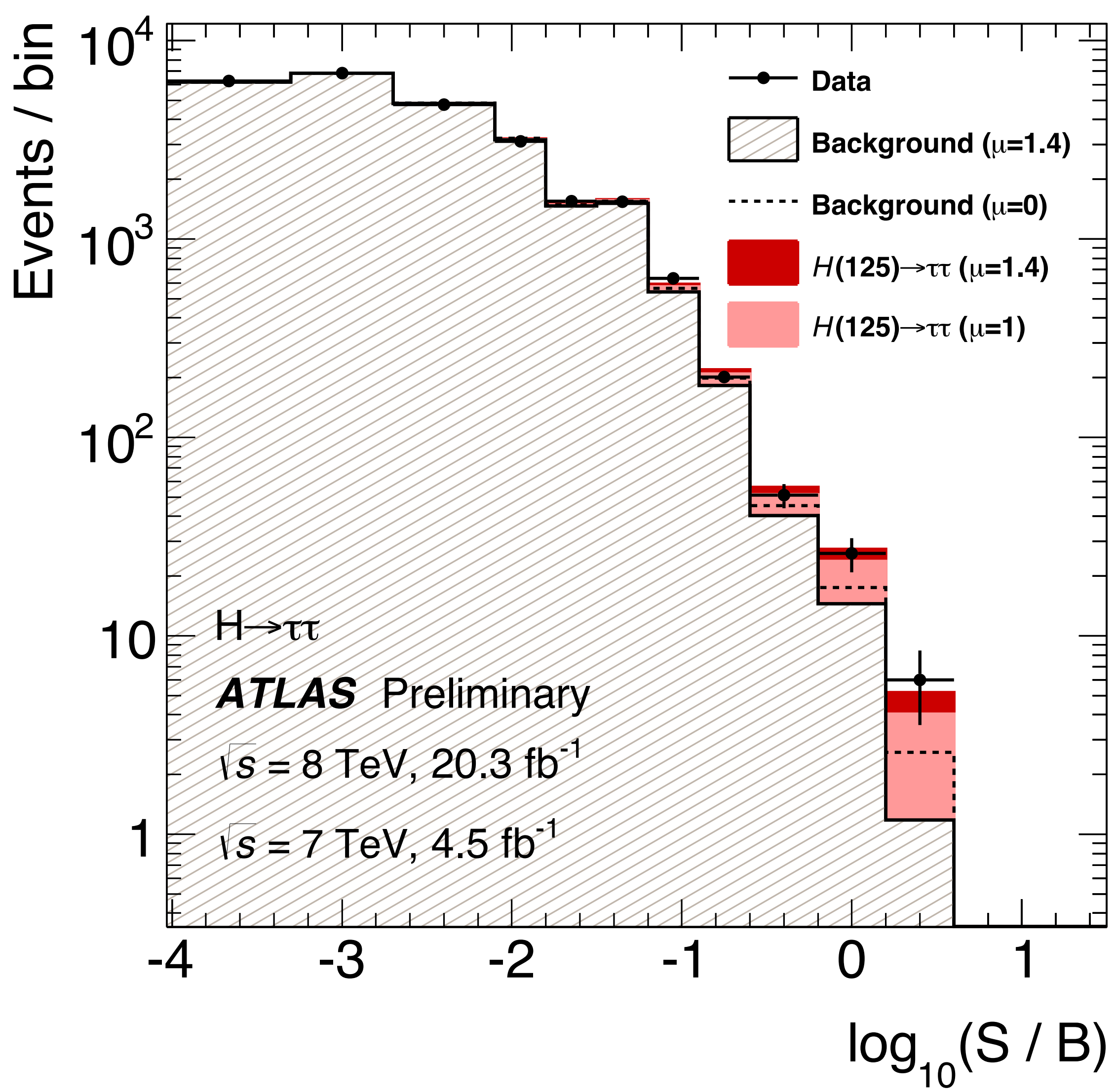


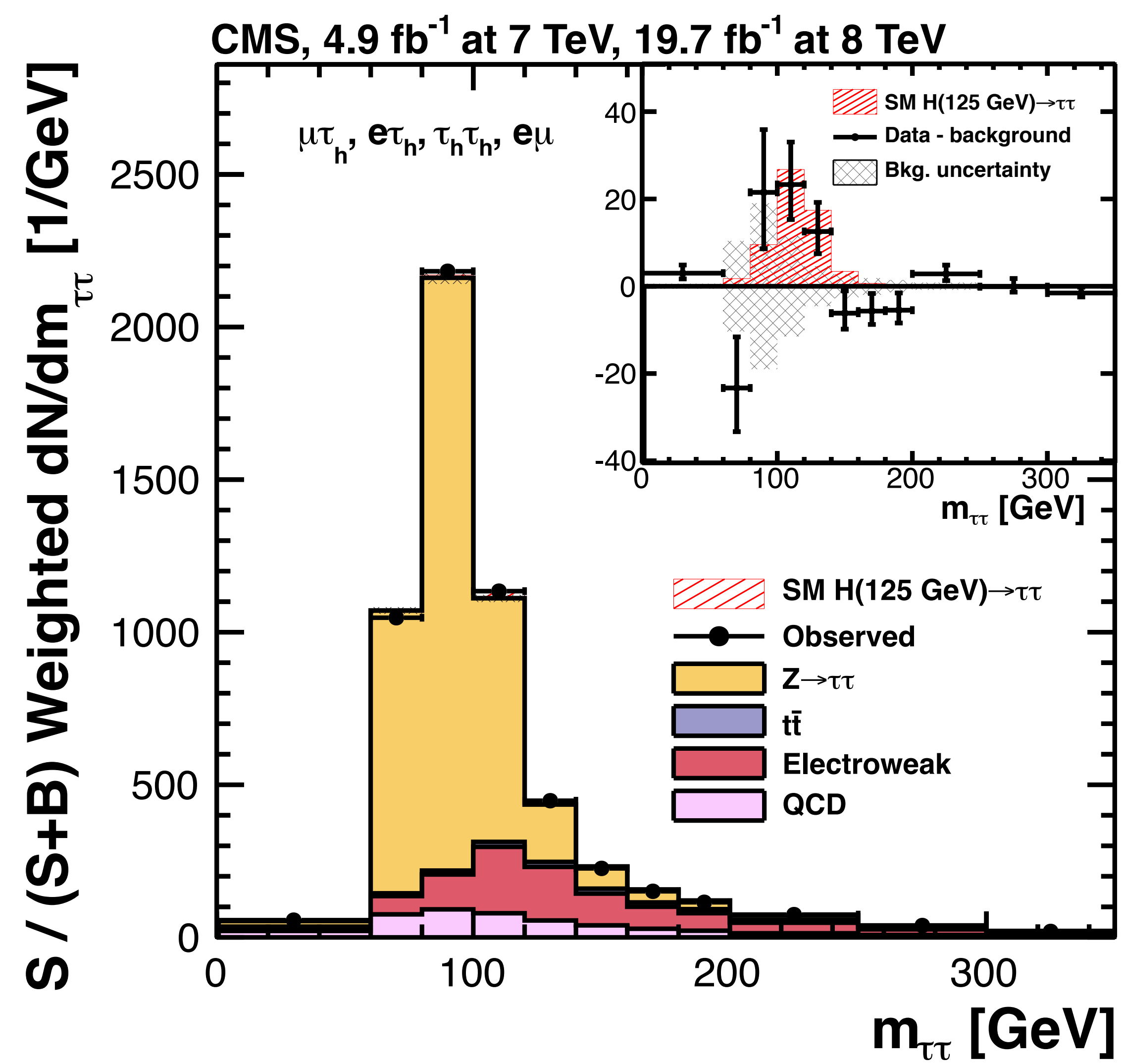
Efficiency: ~60%

mis ID: ~1%

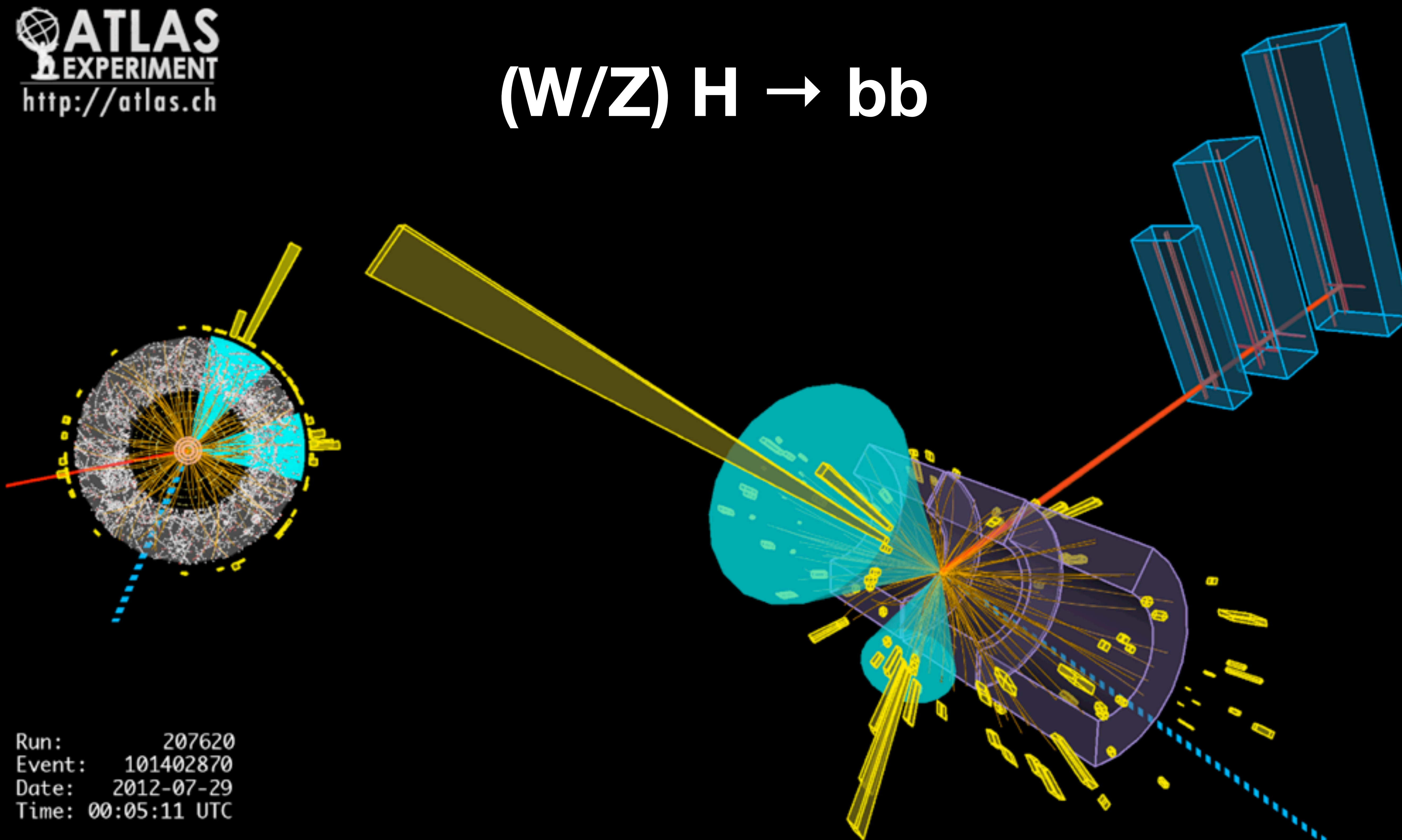
H → ττ: a look at the data

	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



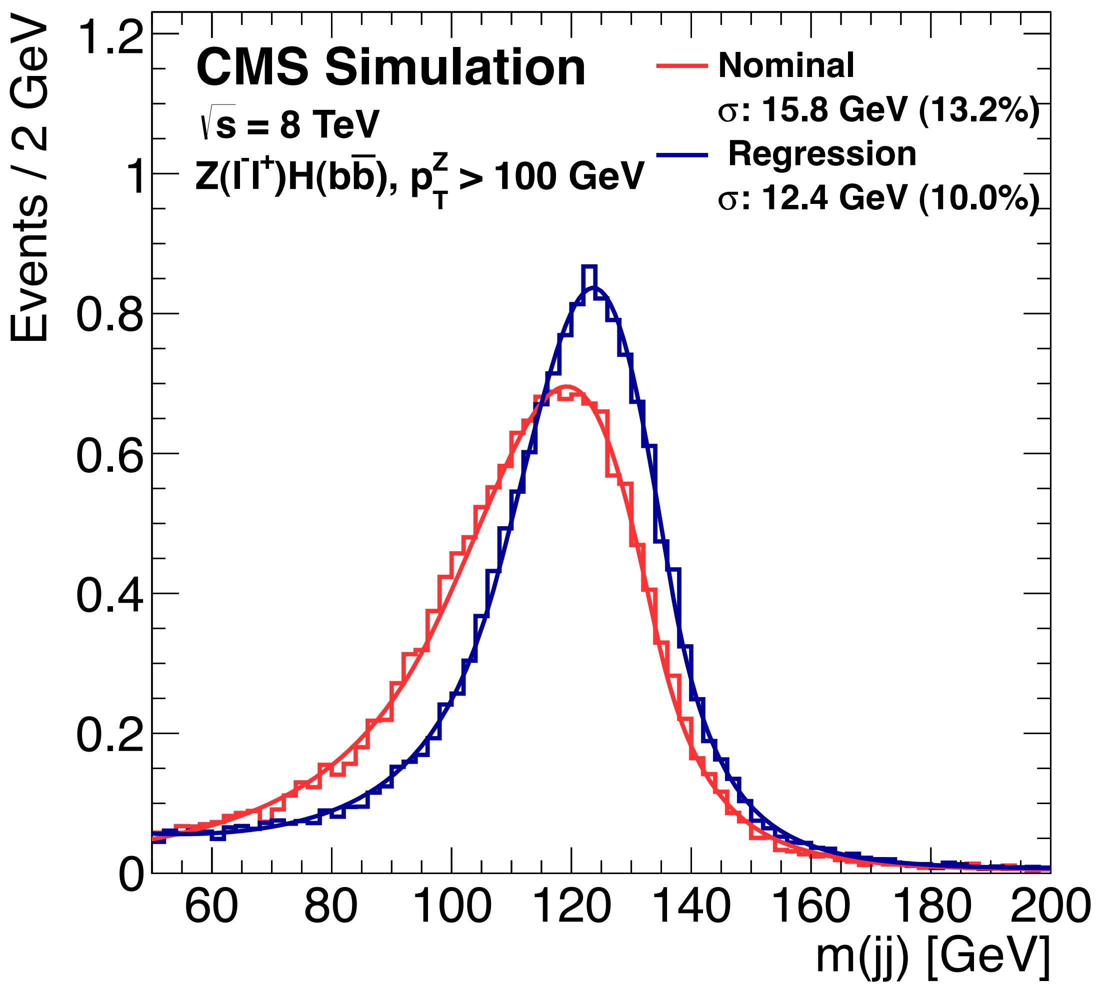


(W/Z) H → bb


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

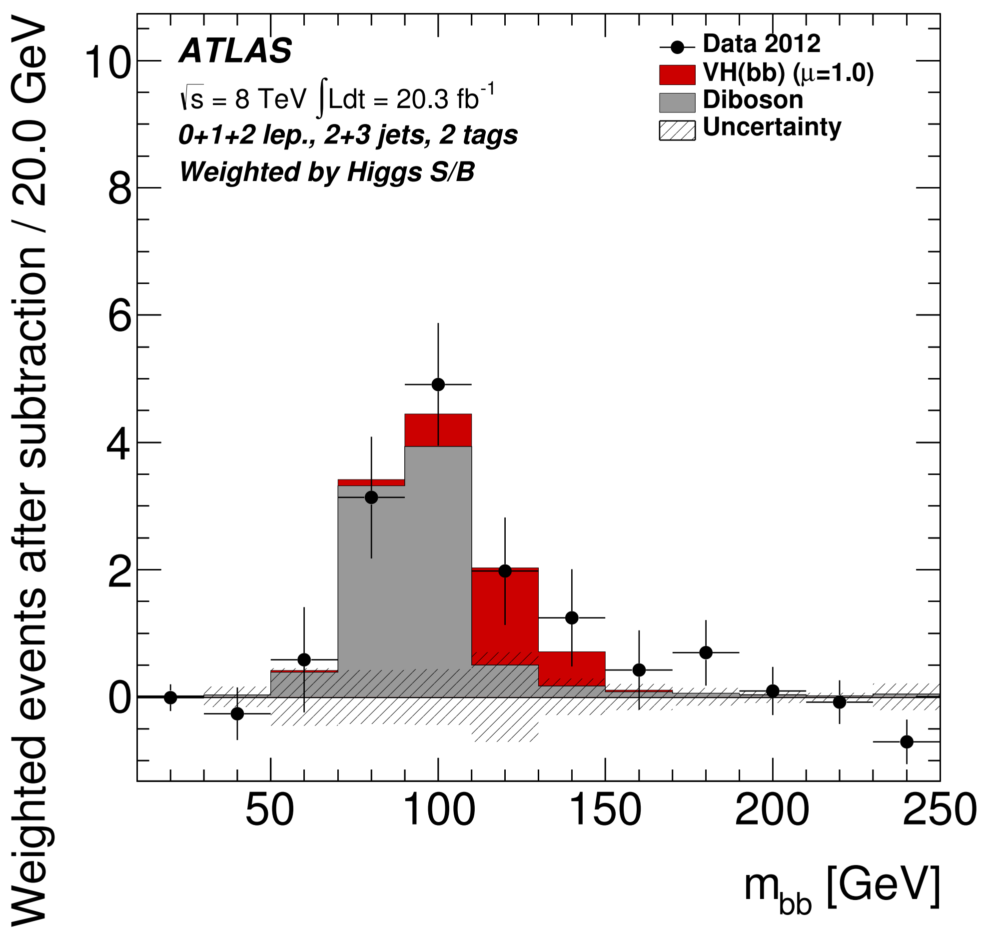
(W/Z) H → $b\bar{b}$

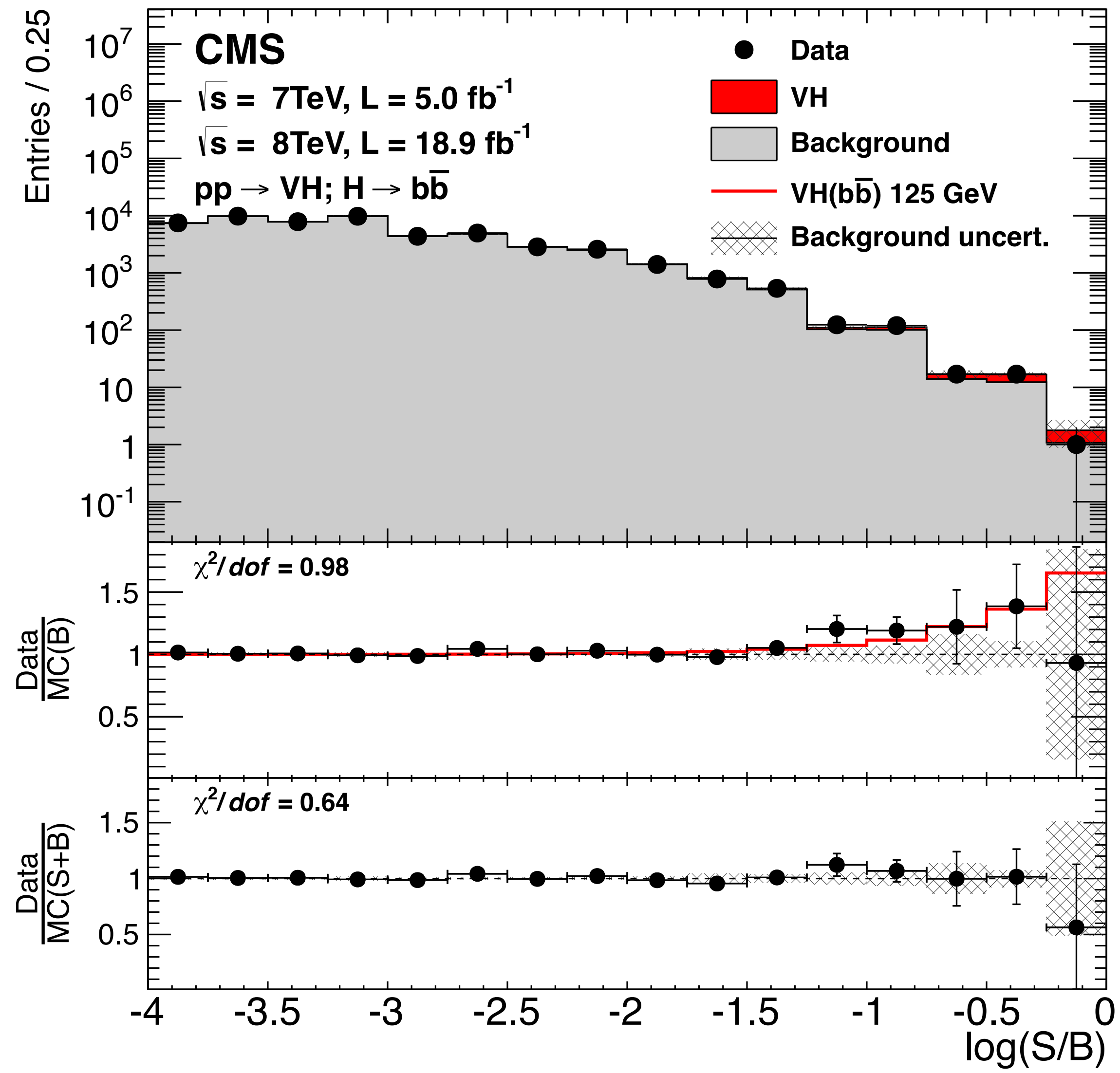
- Huge backgrounds from QCD
    - Associated production with W/Z decaying to leptons and neutrinos
- 2 b-tagged jets (displaced vertices)
- m_{bb} resolution ~ 10%
- Split events in P_T(W/Z)
    - Boosted topologies, enhance sensitivity
- Backgrounds: di-boson, W/Z+jets (heavy flavour), top, multijets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



(W/Z) H → bb: 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





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