Results from the Higgs Searches at the LHC

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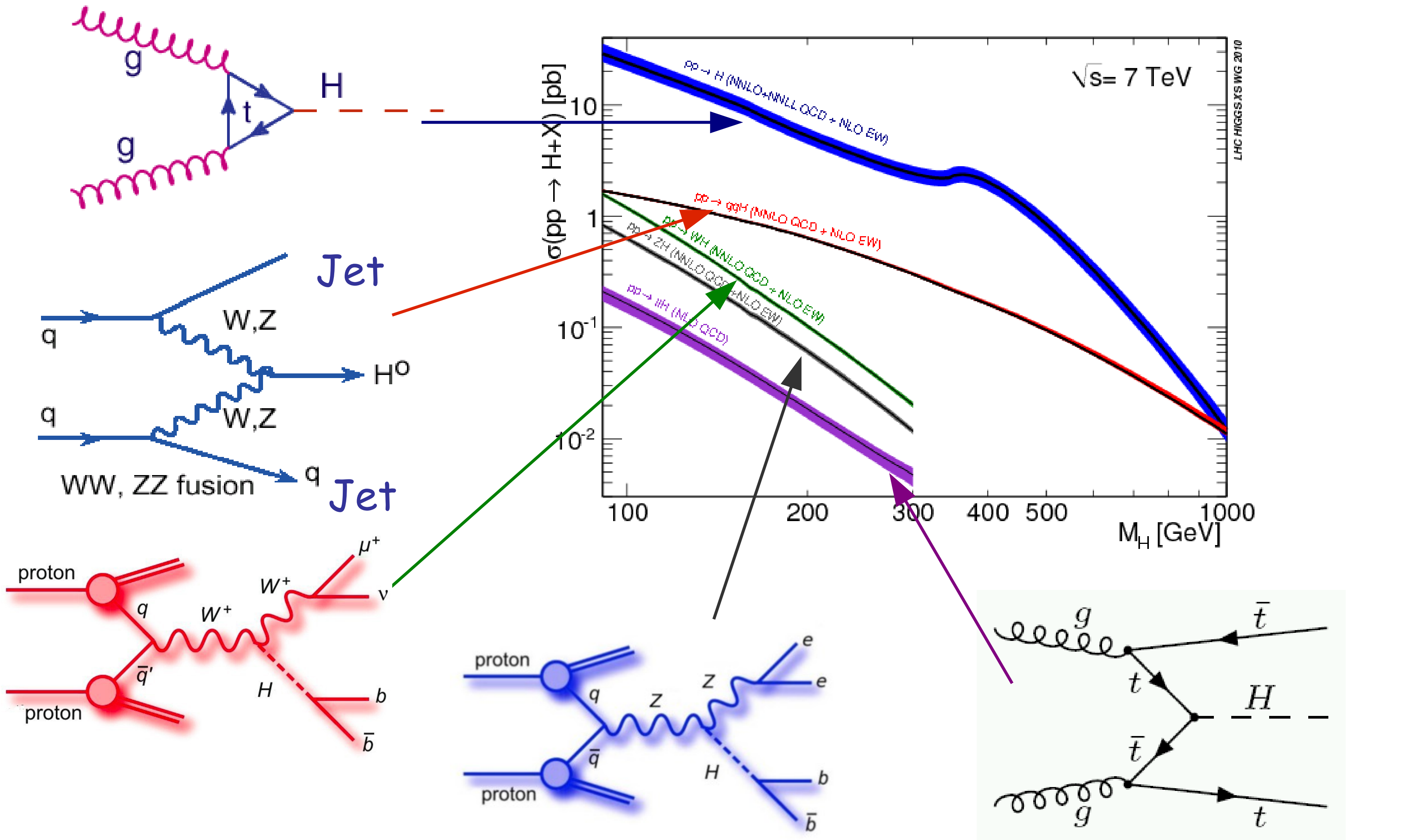
LIP

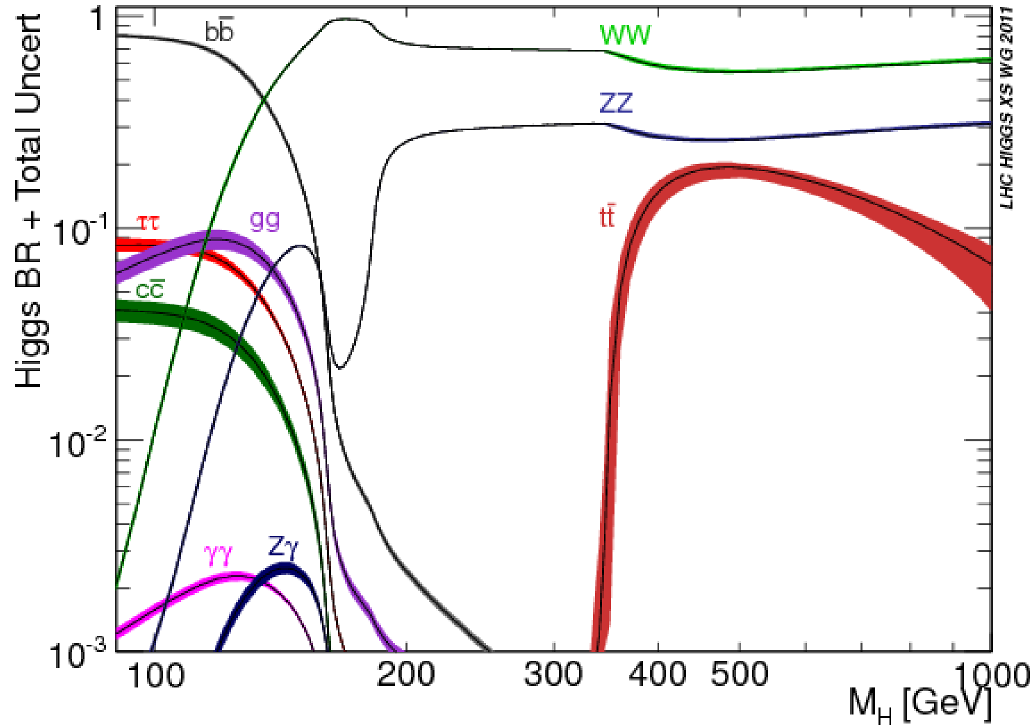
Overview

- Production and decay modes at the LHC
- Higgs searches: example of the $H \to WW$ channel at ATLAS
- Summary of the main results at ATLAS and CMS
  - Will cover most sensitive channels

Higgs production



Higgs decays

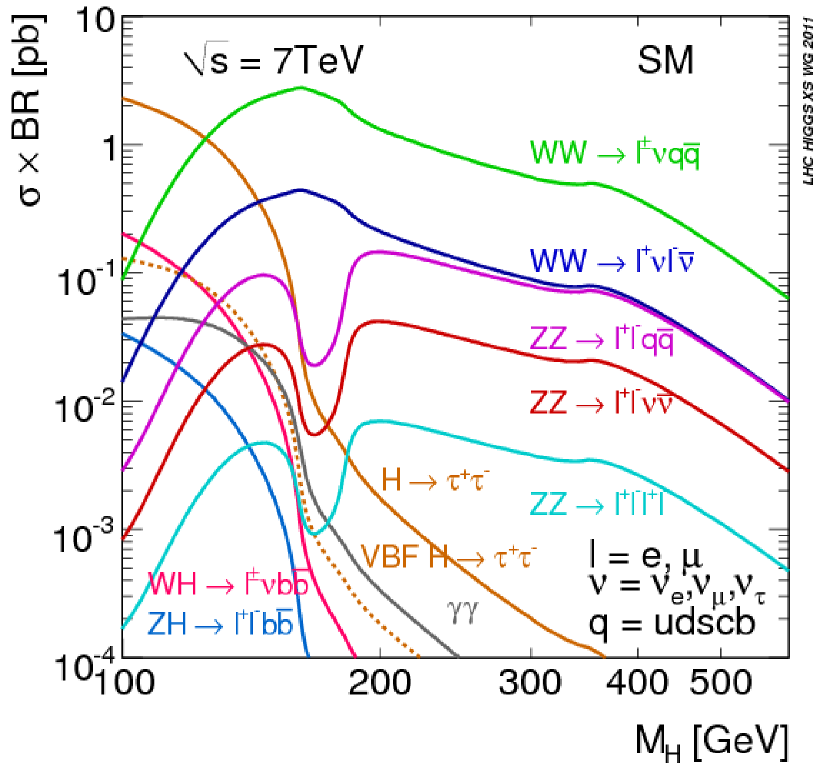


- 5 different decay modes
  - High mass: ZZ, WW
  - Low mass: bb, γγ, WW, ZZ, ττ
- Low mass very challenging
  - Large backgrounds

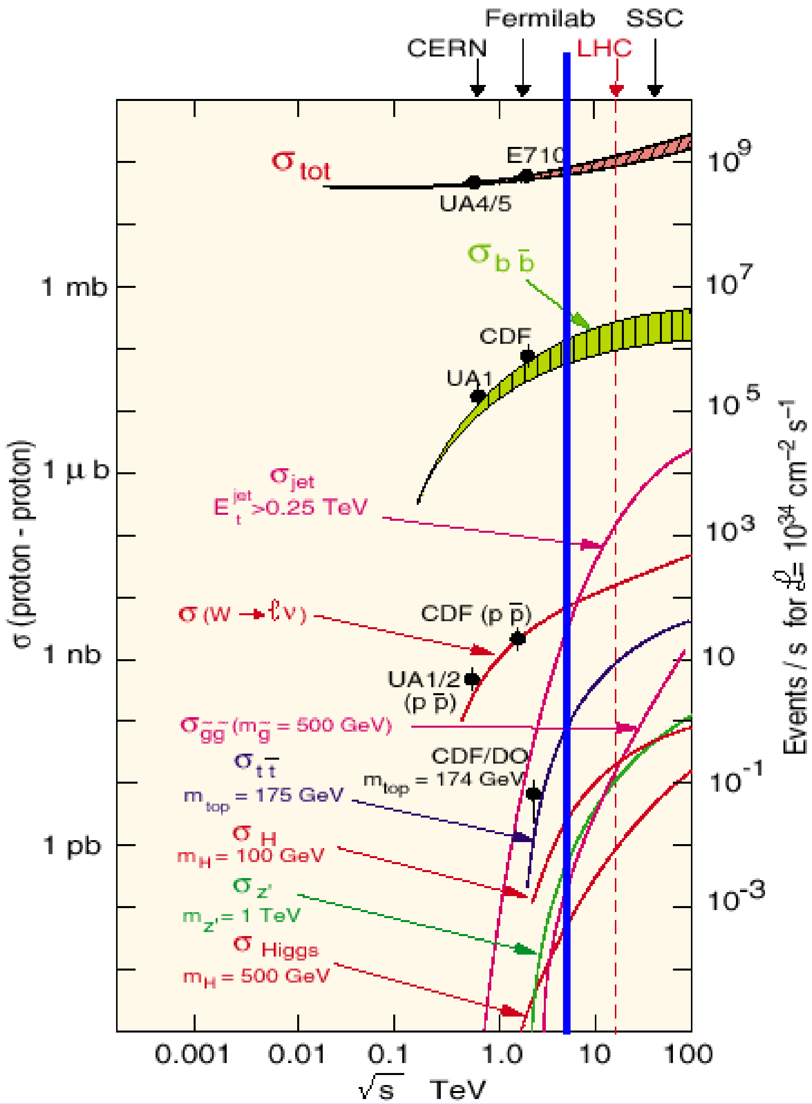
Best mass resolution: H→γγ, H→ZZ→llll

Search channel

- It normally implies a production mode plus a decay mode, characterized by some experimental signatures



Cross sections at the LHC



Total production cross section at LHC:

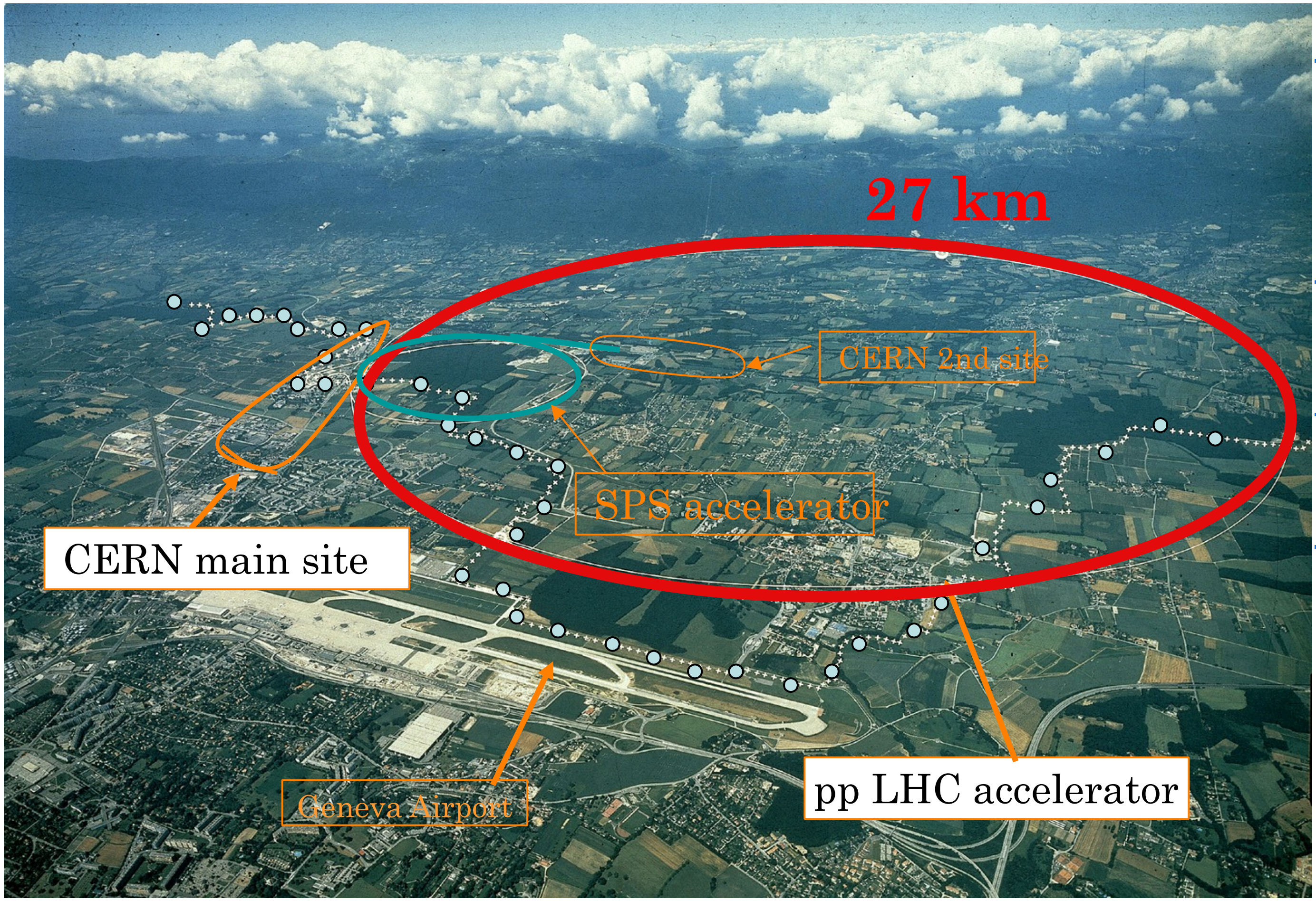
~ 10^3 x σ(bb)

- ~10^7 x σ(W→μν)
- ~10^8 x σ(tt)
- ~5×10^{10} x σ(H) (m_H ~ 100 GeV)

σ(di-jet) for jets with E_T > 7 GeV is ~ 50% of σ(tot)

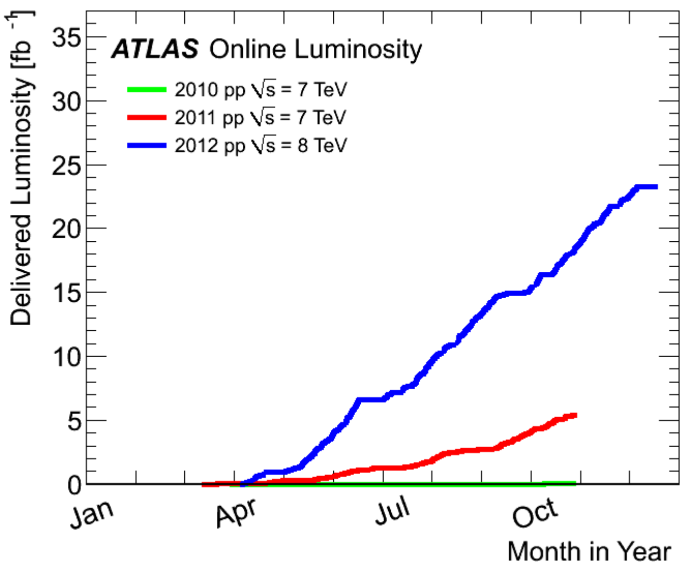
- Most interactions produce jets
  - Either quarks or gluons
- Need to identify clear signatures that distinguish the processes of interest from this background

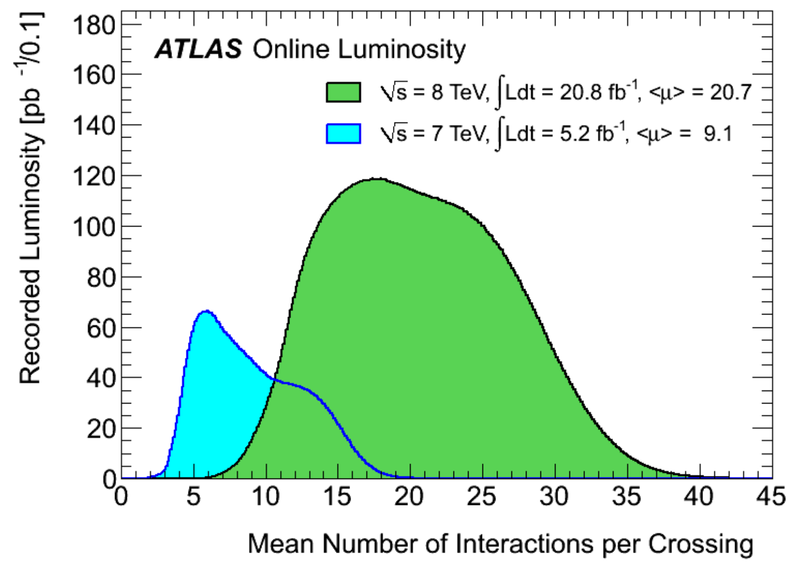
The Large Hadron Collider



- pp collisions at
  - 8 TeV in 2012
  - 7 TeV in 2010/11
- 20 MHz p bunch crossing rate
- Up to ~40 collisions per bunch crossing!
- Four experiments: ATLAS, CMS, LHCb, ALICE

LHC delivered data (2011-2012)

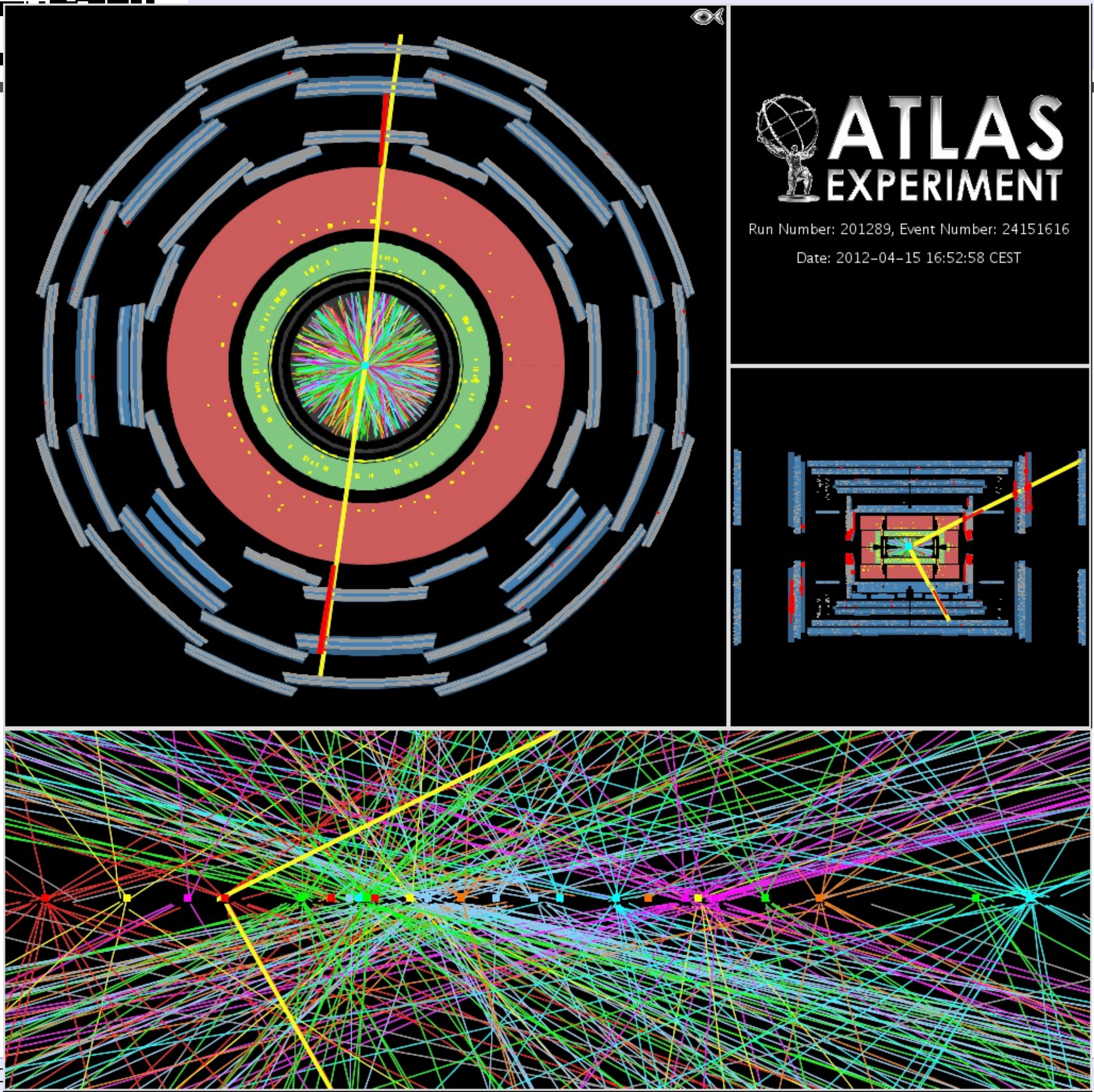




ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.4	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.8%										
Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb^{-1} of recorded data.										

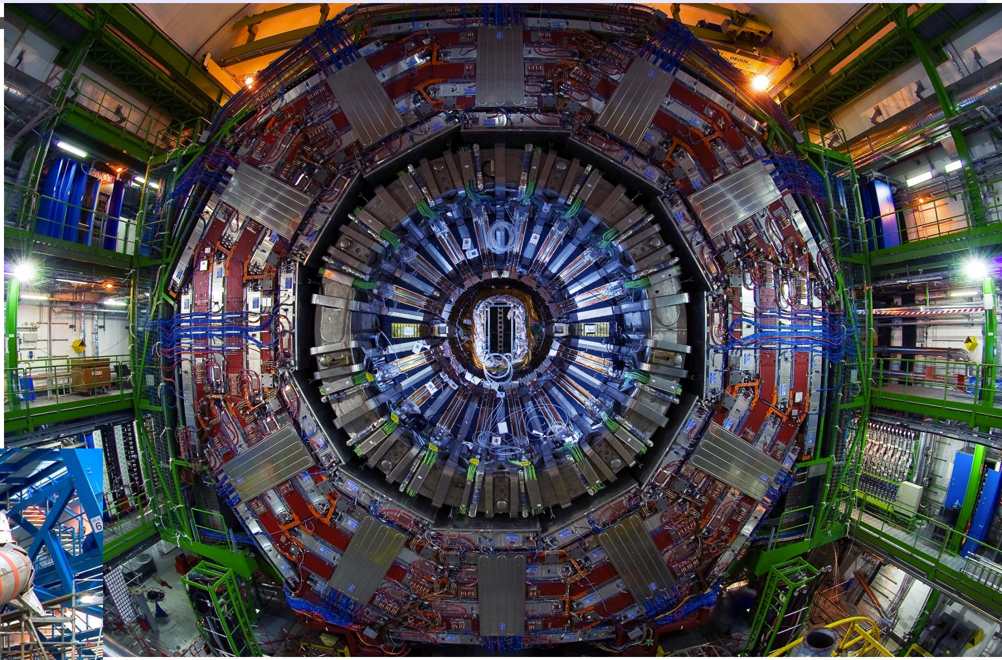
- 20.8 fb^{-1} 8 TeV pp collisions
- 5.2 fb^{-1} 7 TeV pp collisions
- 95.8% physics quality data

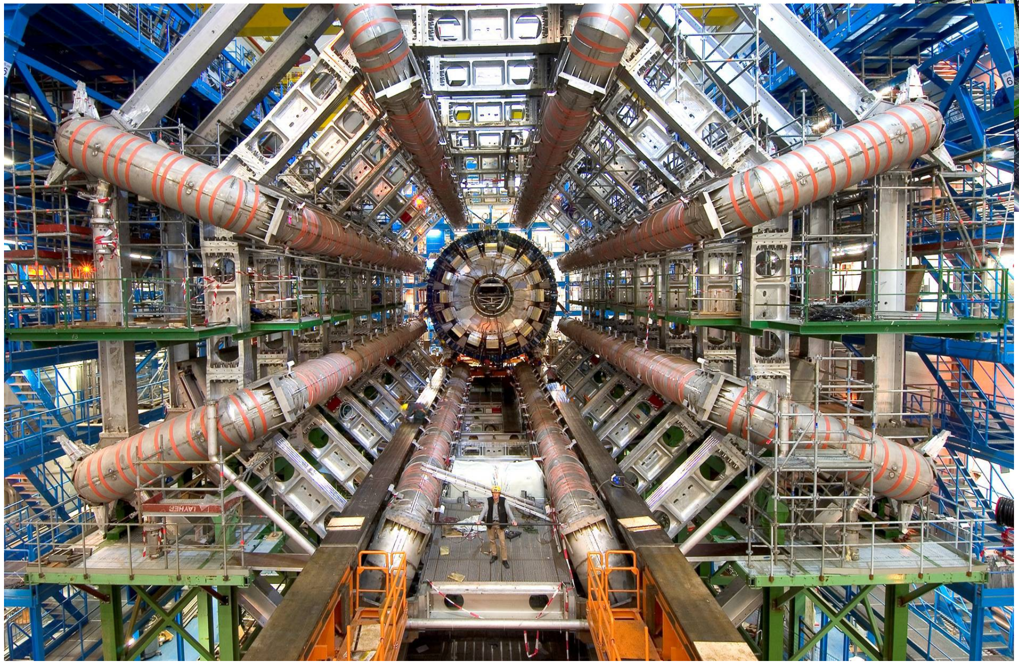
Pile-up



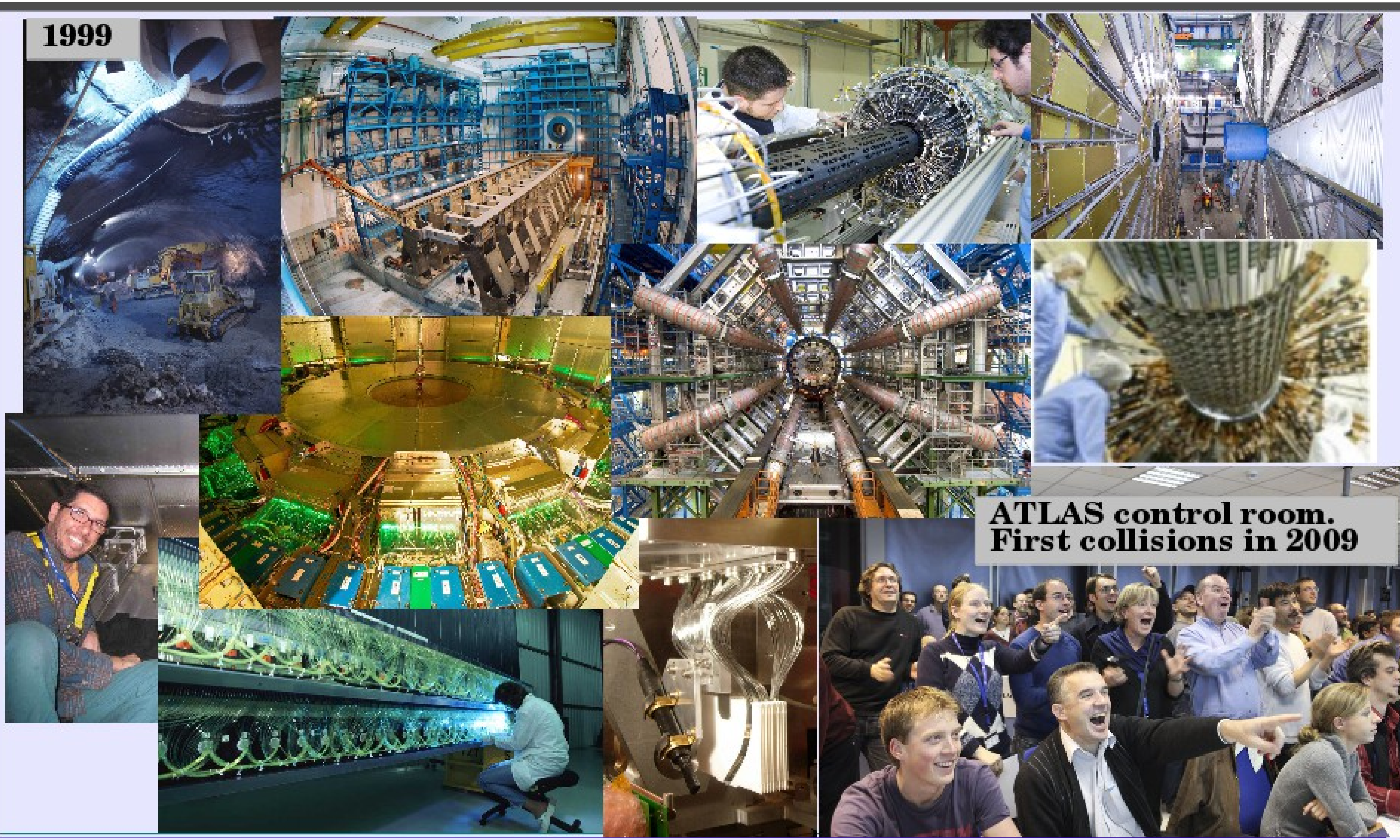
- $Z \rightarrow \mu\mu$ event with 25 additional interactions
- Typical average event in the second half of 2012

The ATLAS and CMS detectors



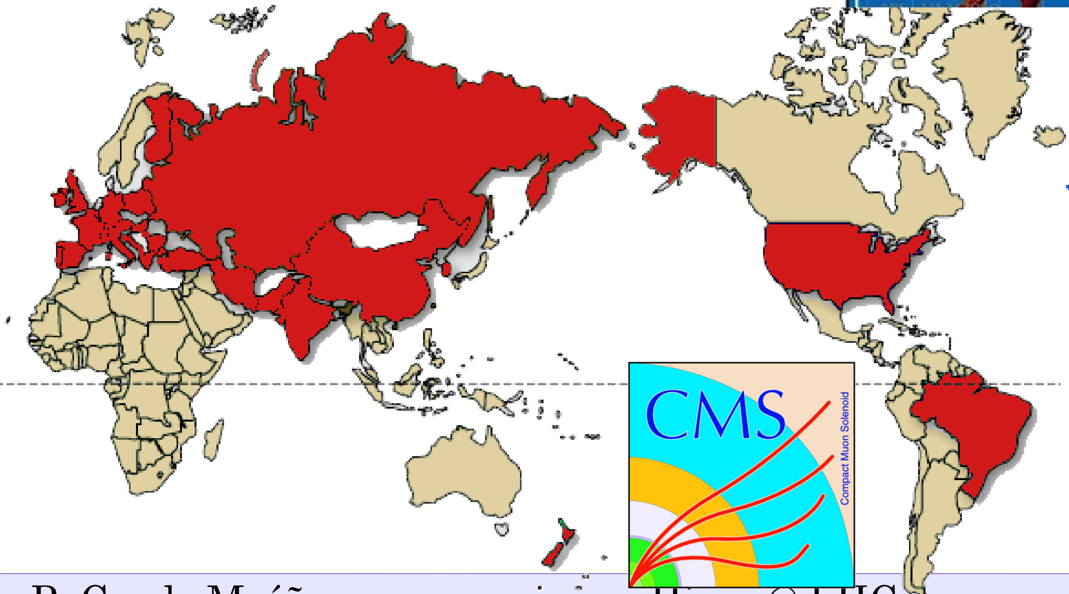


More than 20 years of continuous work...



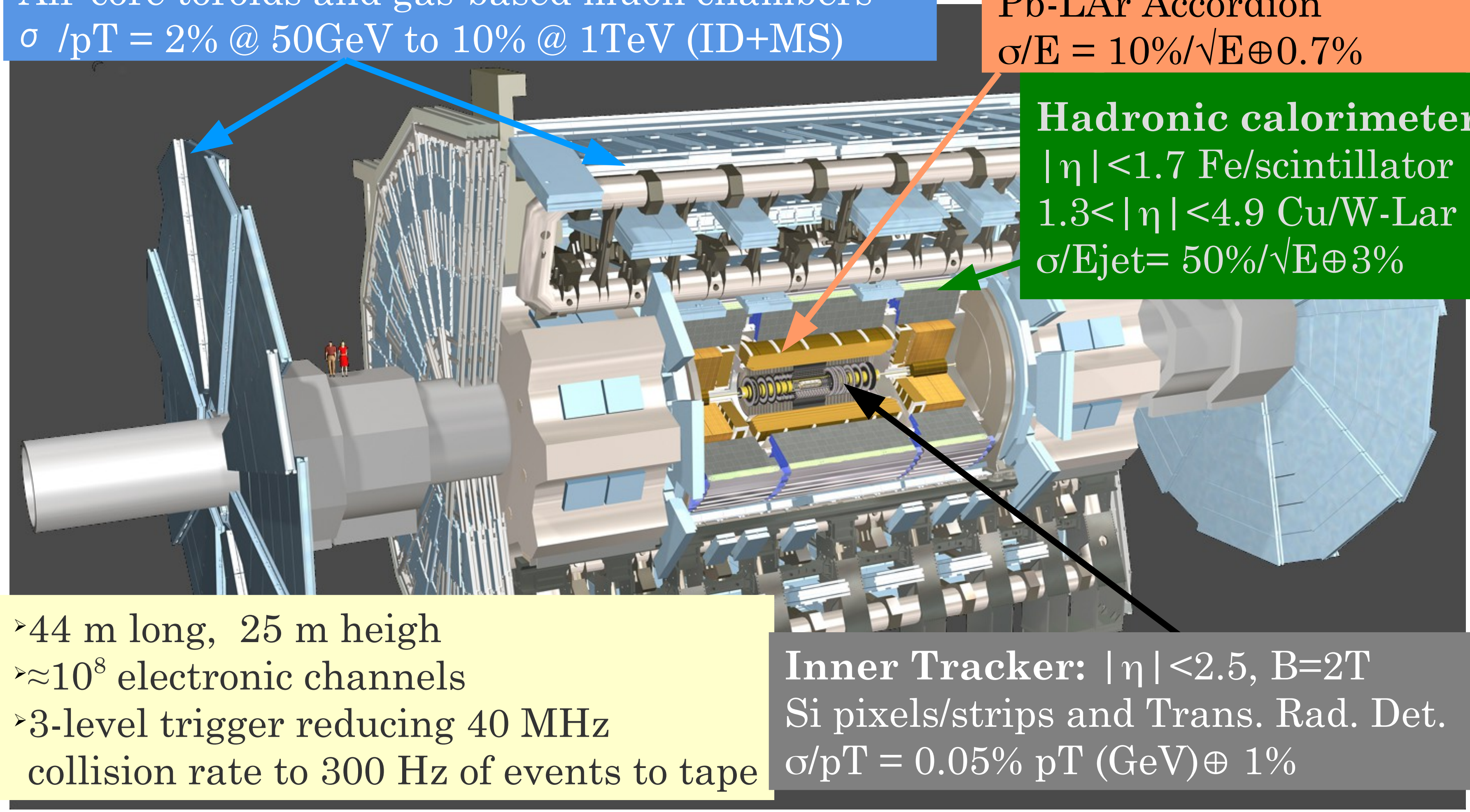
ATLAS and CMS Collaborations

- Each of them composed of
  - >4000 members
  - >3000 physicists
  - ~180 institutions
  - ~40 countries



- Examples of a truly global collaboration!

The ATLAS detector



Muon Spectrometer: |η|<2.7
Air-core toroids and gas-based muon chambers
σ /pT = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

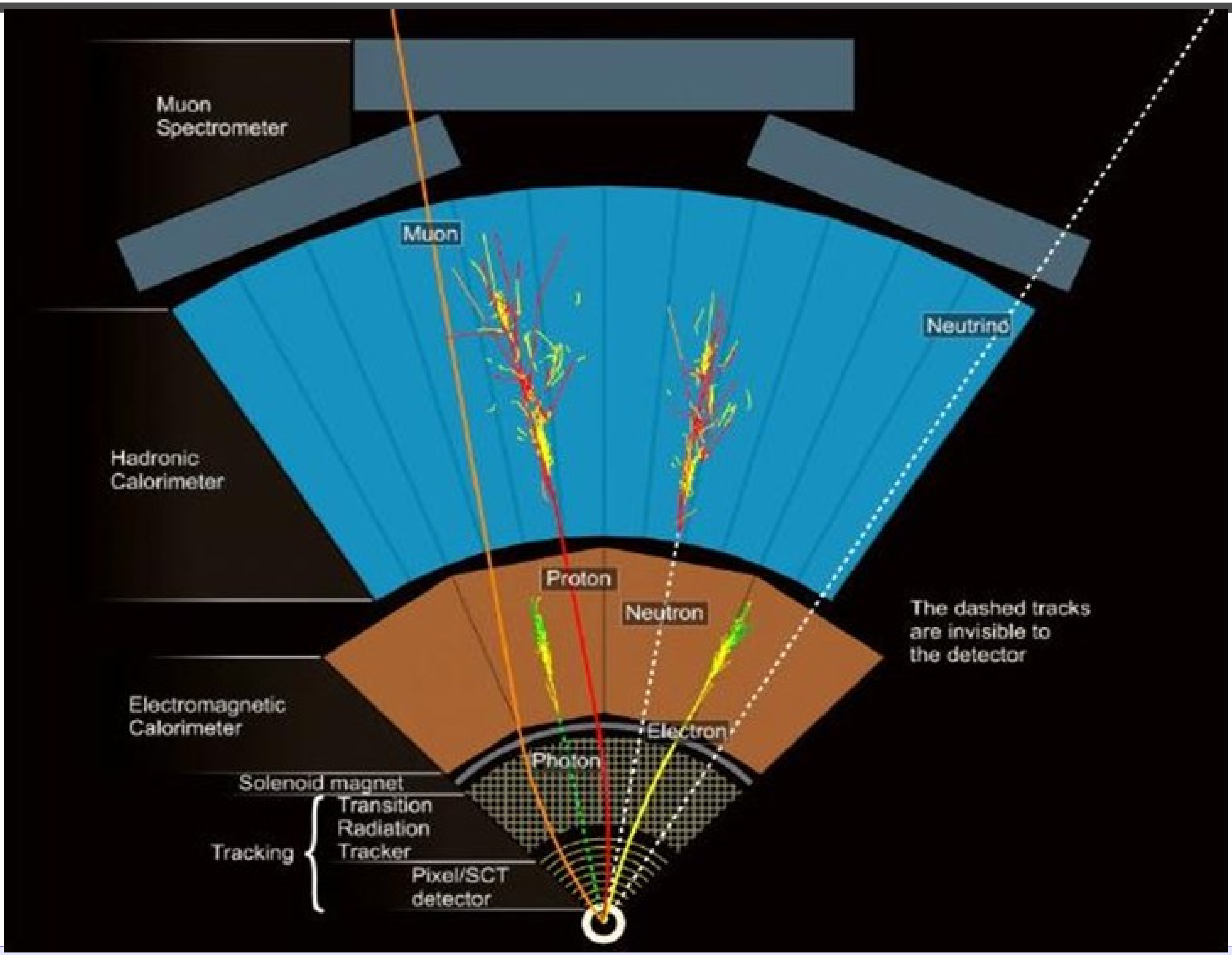
EM calorimeter: |η|<3.2
Pb-LAr Accordion
σ/E = 10%/√E⊕0.7%

Hadronic calorimeter:
|η|<1.7 Fe/scintillator
1.3<|η|<4.9 Cu/W-Lar
σ/Ejet= 50%/√E⊕3%

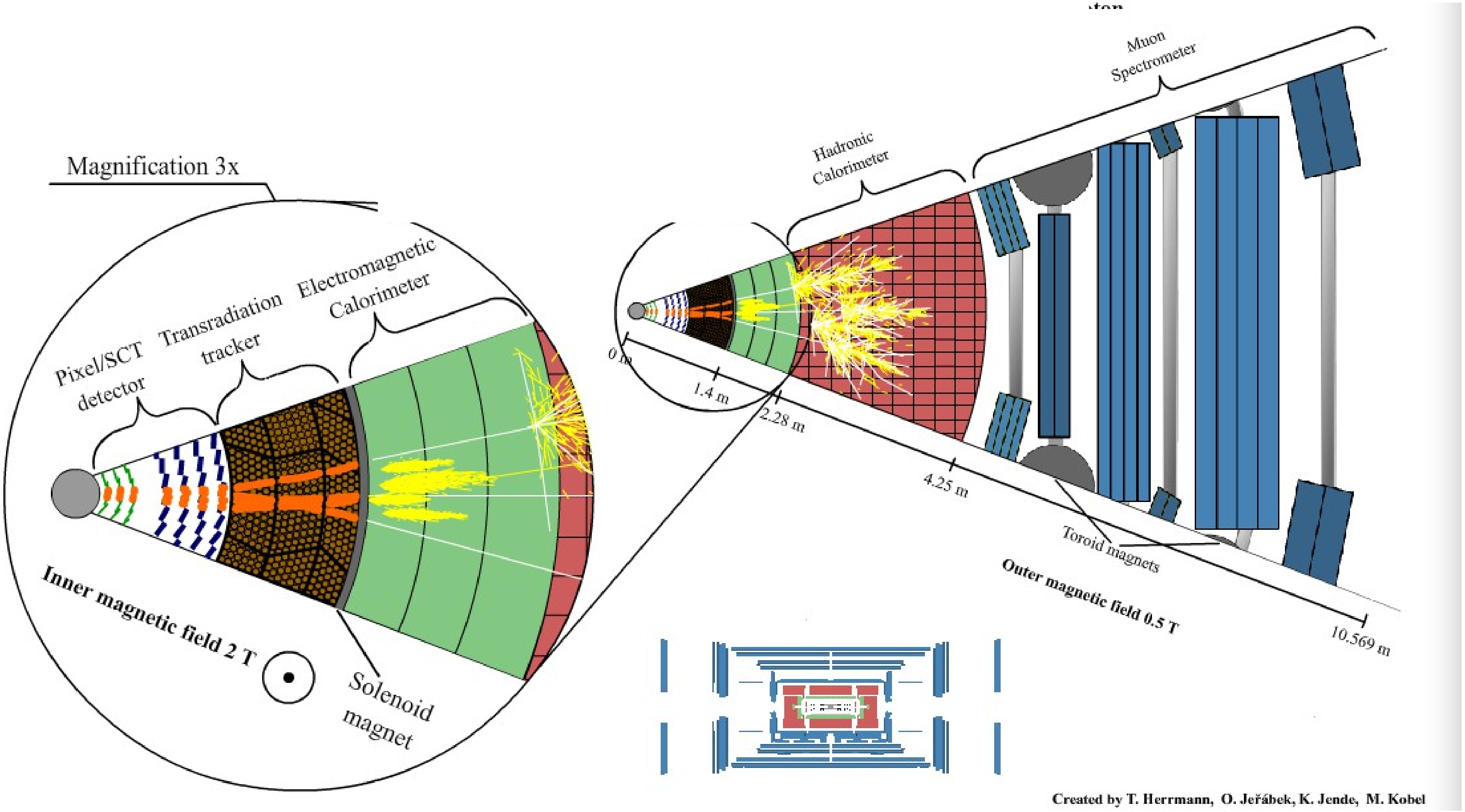
- 44 m long, 25 m heigh
- ≈10^8 electronic channels
- 3-level trigger reducing 40 MHz collision rate to 300 Hz of events to tape

Inner Tracker: |η|<2.5, B=2T
Si pixels/strips and Trans. Rad. Det.
σ/pT = 0.05% pT (GeV)⊕ 1%

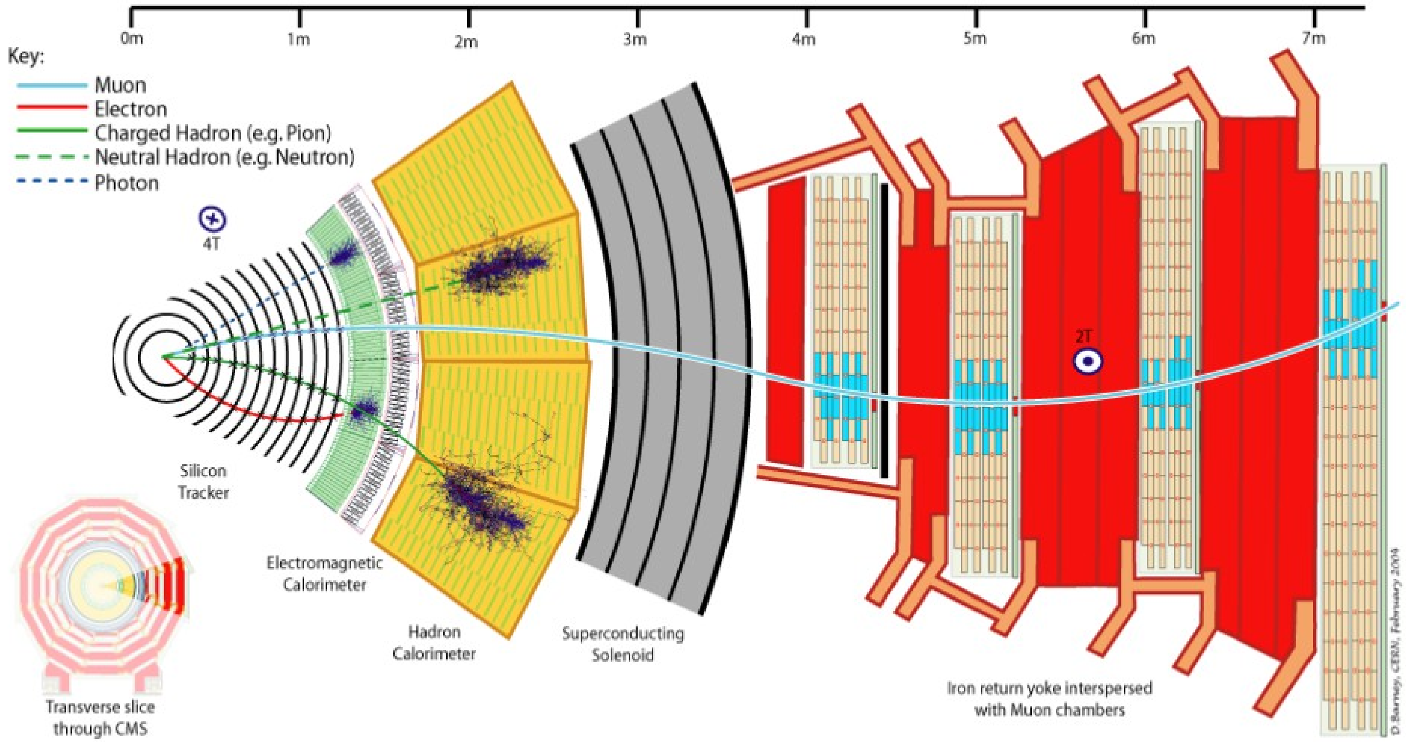
Particle identification



- Quarks/gluons hadronize producing a colimated spray of particles: jets



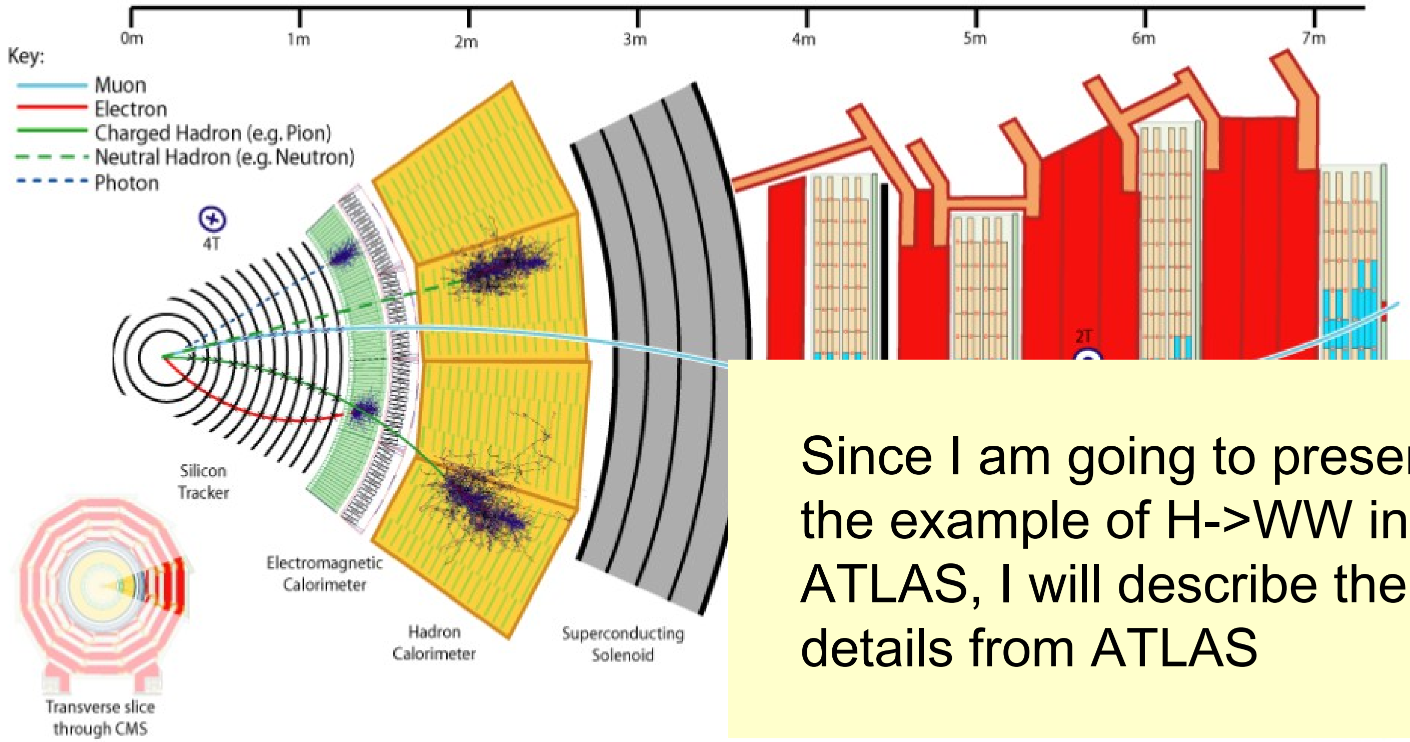
Particle identification @CMS



Global Event Description—Particle flow algorithm

- Combines and links signals from different sub-detectors
- Provides optimal event description for a list of particles (e, μ, γ, hadrons, missing transverse energy)

Particle identification @CMS



Since I am going to present the example of H->WW in ATLAS, I will describe the details from ATLAS

Global Event Description—Particle flow algorithm

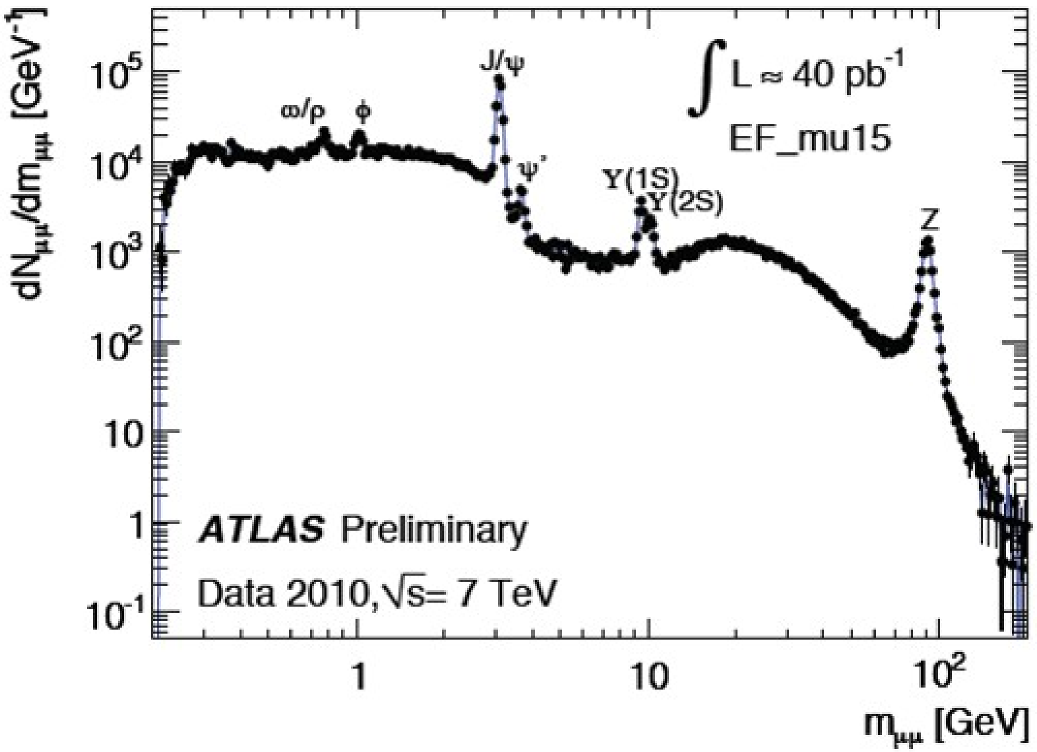
- Combines and links signals from different sub-detectors
- Provides optimal event description for a list of particles (e, μ, γ, hadrons, missing transverse energy)

Particle reconstruction

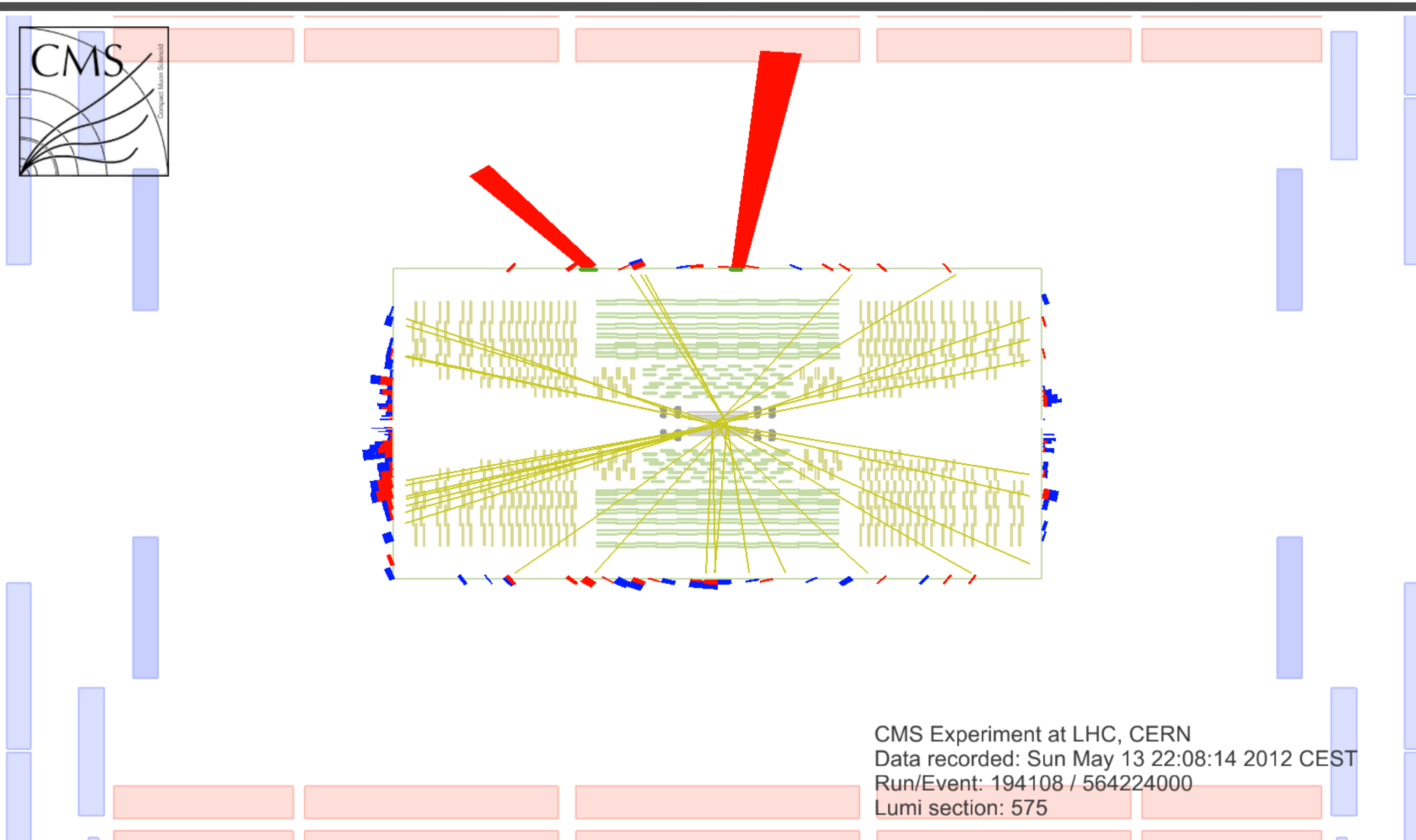
- From the properties of the particles produced in its decay we can infer the properties of the Higgs boson

$$E^2 = (mc^2)^2 + (pc)^2$$

- 20 years of particle physics in one single plot

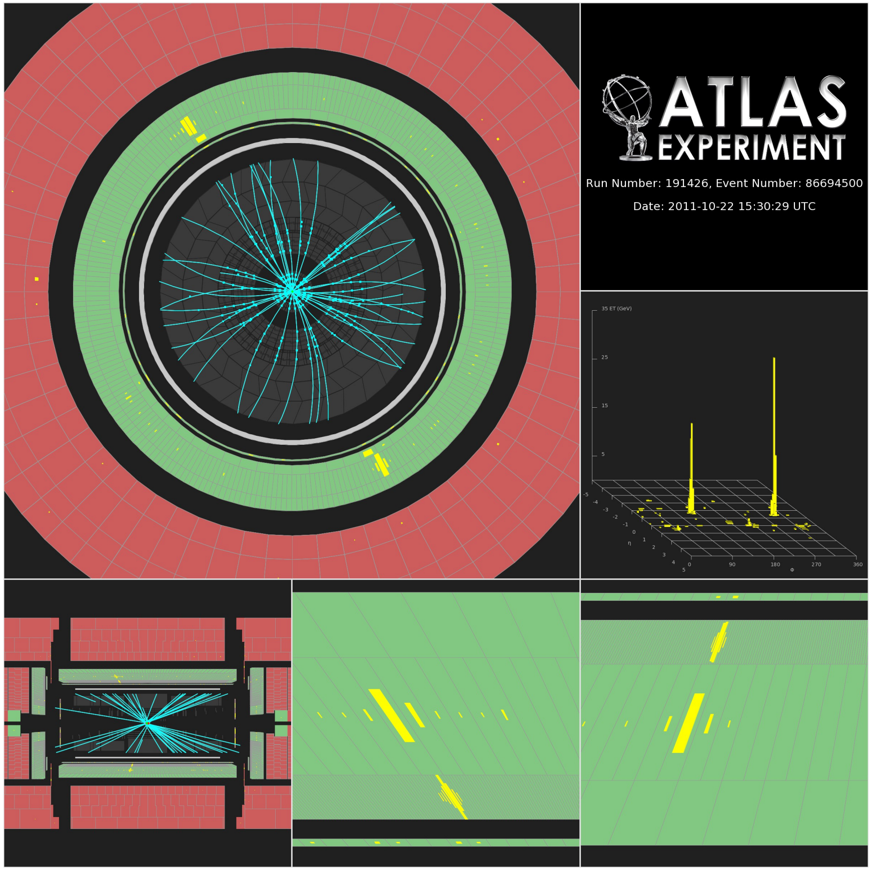


H→γγ


CMS Experiment at LHC, CERN
Data recorded: Sun May 13 22:08:14 2012 CEST
Run/Event: 194108 / 564224000
Lumi section: 575

H→γγ analysis

arXiv:1207.7214

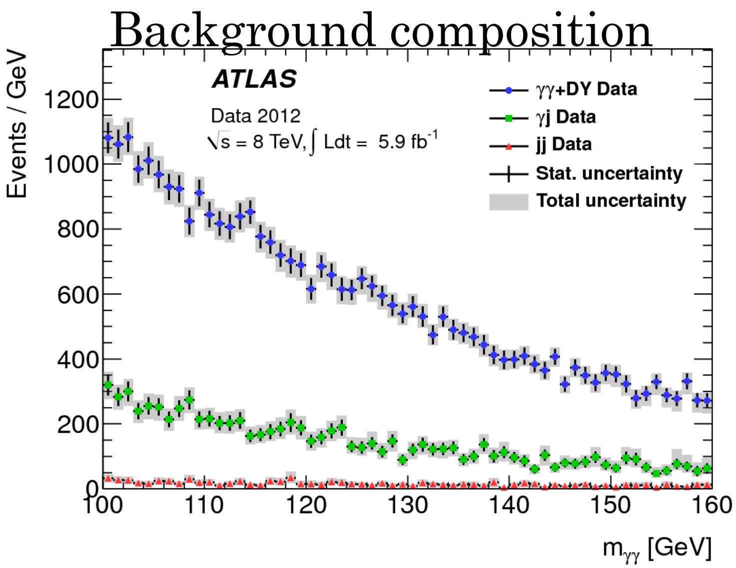


H→γγ candidate event

- Two isolated photons
- Search for a narrow peak on a large continuum

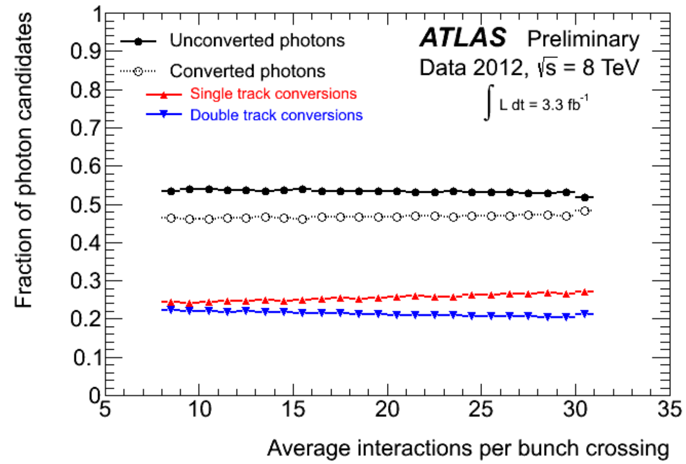
Main background:

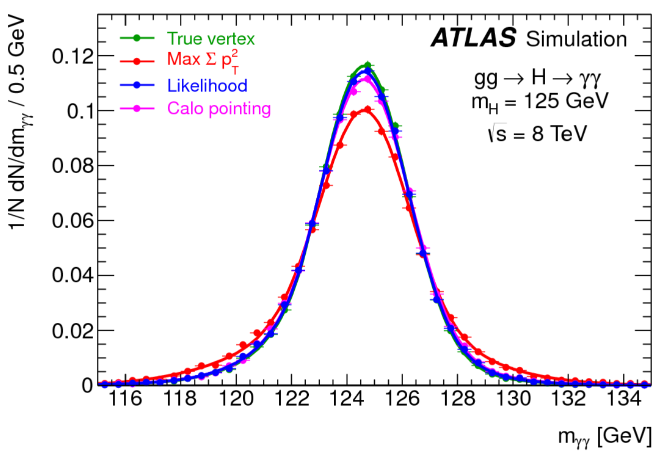
- Continuum γγ production
- γ+jet, jet+jet

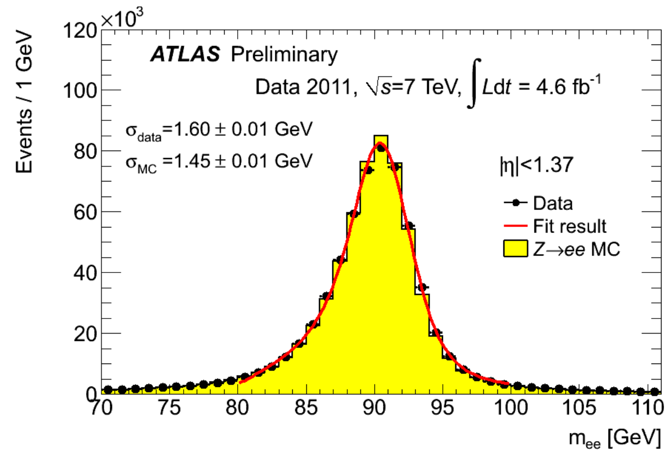


γ identification & energy measurement

- Stable photon ID peformance with pile-up
- Calorimeter E response studied with Z, J/ψ and W decays
  - Energy scale at m_Z known to ~ 0.5%
  - Linearity better than 1%
- Excellent mass resolution (1.6-3.1 GeV)
  - Use calorimeter segmentation to associate γ to primary vertex (σ_z ~ 15 mm)







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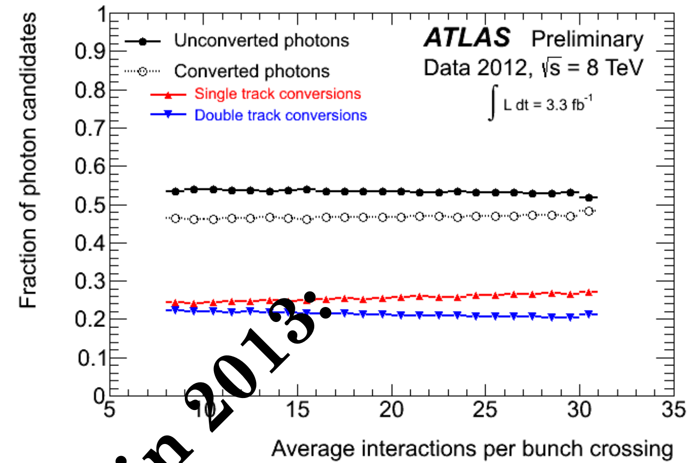
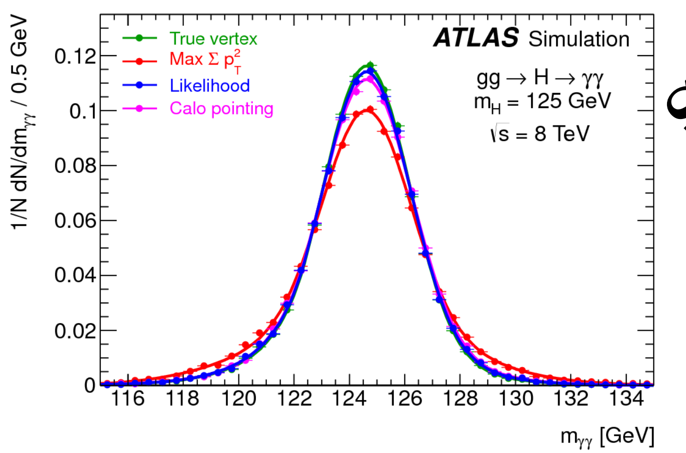
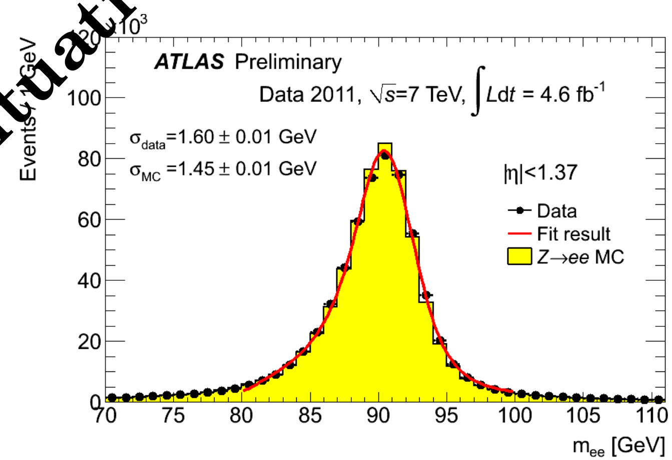


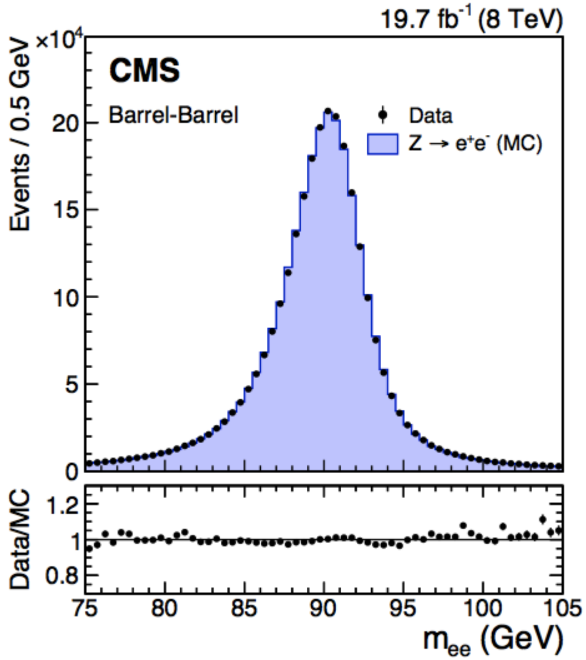
Situation in 2013:

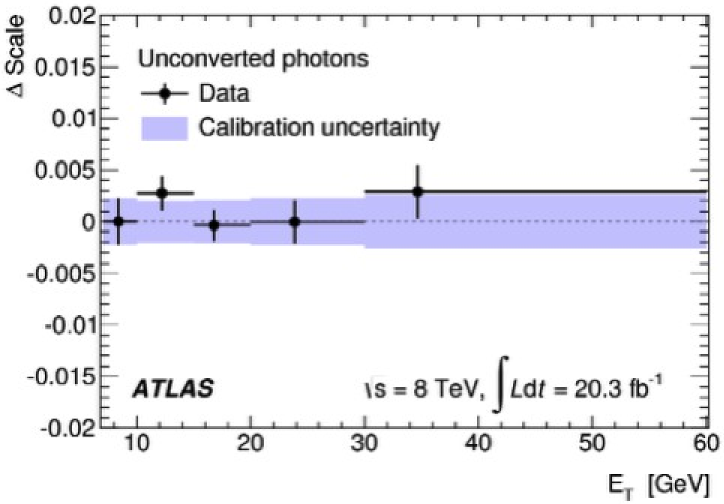




Improved photon identification & calibration

- Both, ATLAS and CMS, improved their photon energy measurement and identification procedures
- Validated the energy scale and systematics with data

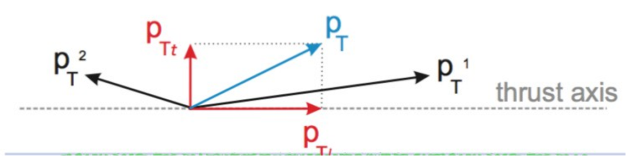


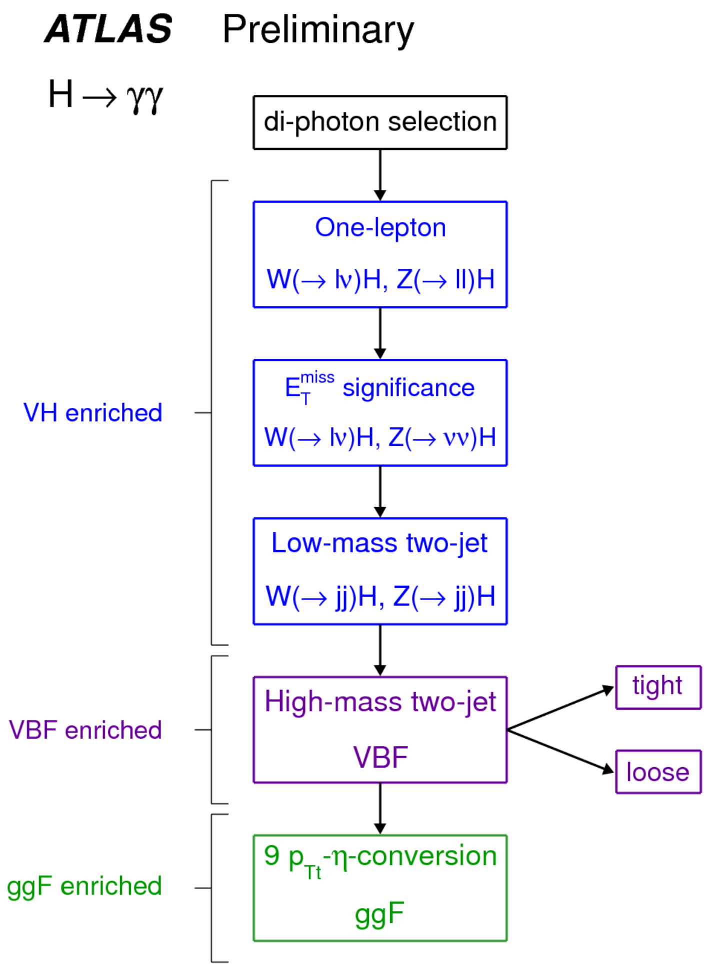


H→γγ analysis categories

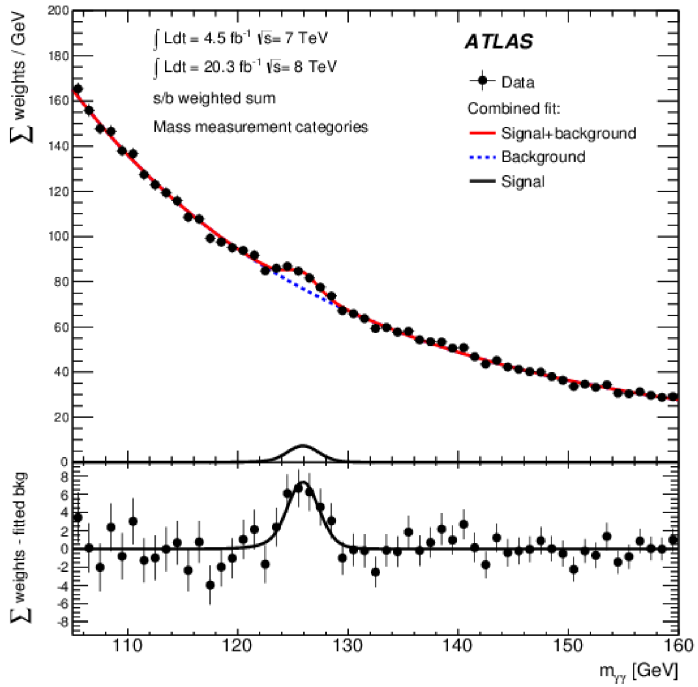
Different analysis categories based

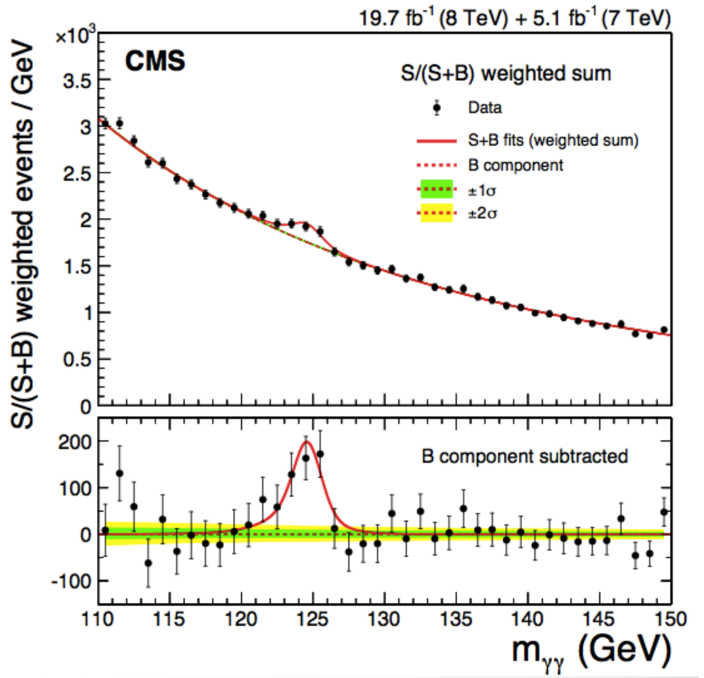
- Converted/unconverted photons
- Photon location in the detector
- Di-photon transverse momentum with respect to thrust
- Production mechanism
    - VBF: use BDT
    - VH enriched
    - ggF enriched





H→γγ results





- Best fit results:

ATLAS

m_H = 125.98 ± 0.42 (stat) ± 0.28 (syst) GeV

$\mu = \sigma/\sigma_{SM}$ = 1.29± 0.30

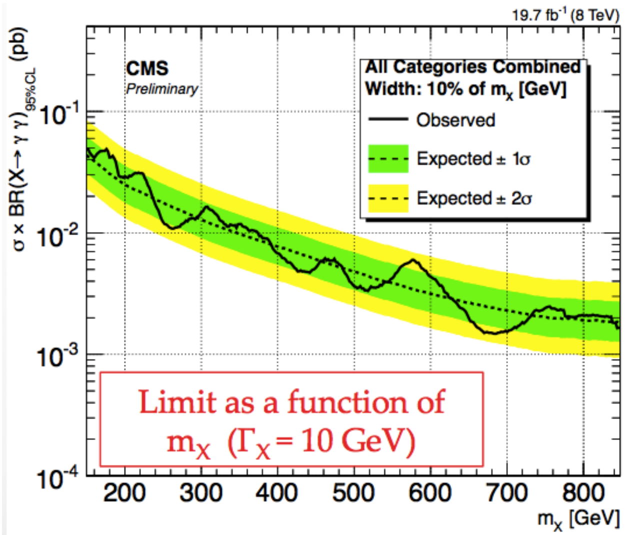
CMS

m_H = 124.7 ± 0.31 (stat) ± 0.15 (syst) GeV

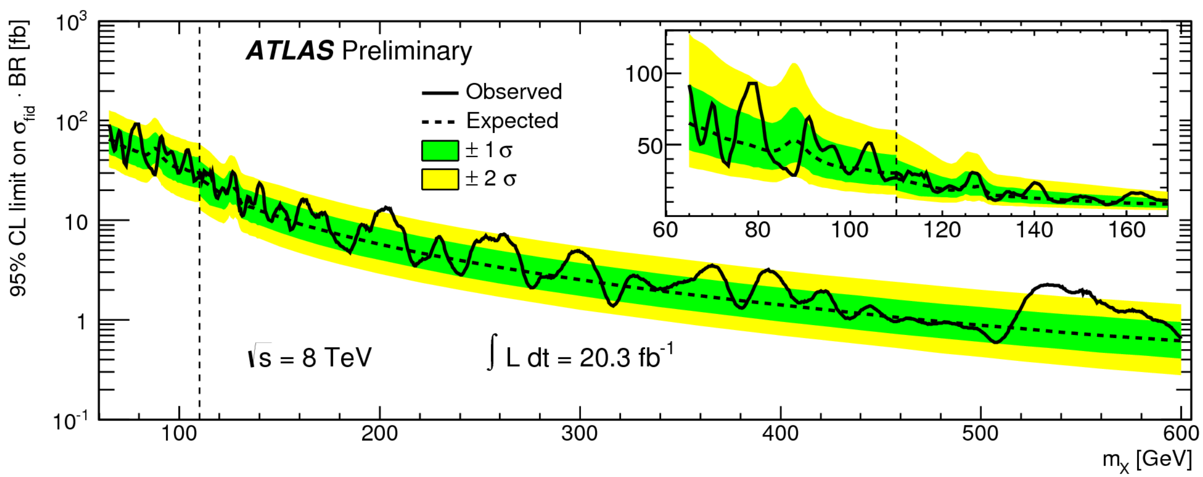
$\mu = \sigma/\sigma_{SM} = 1.14^{+0.26}_{-0.23}$

- Background fluctuation probability ~ 10^{-8}

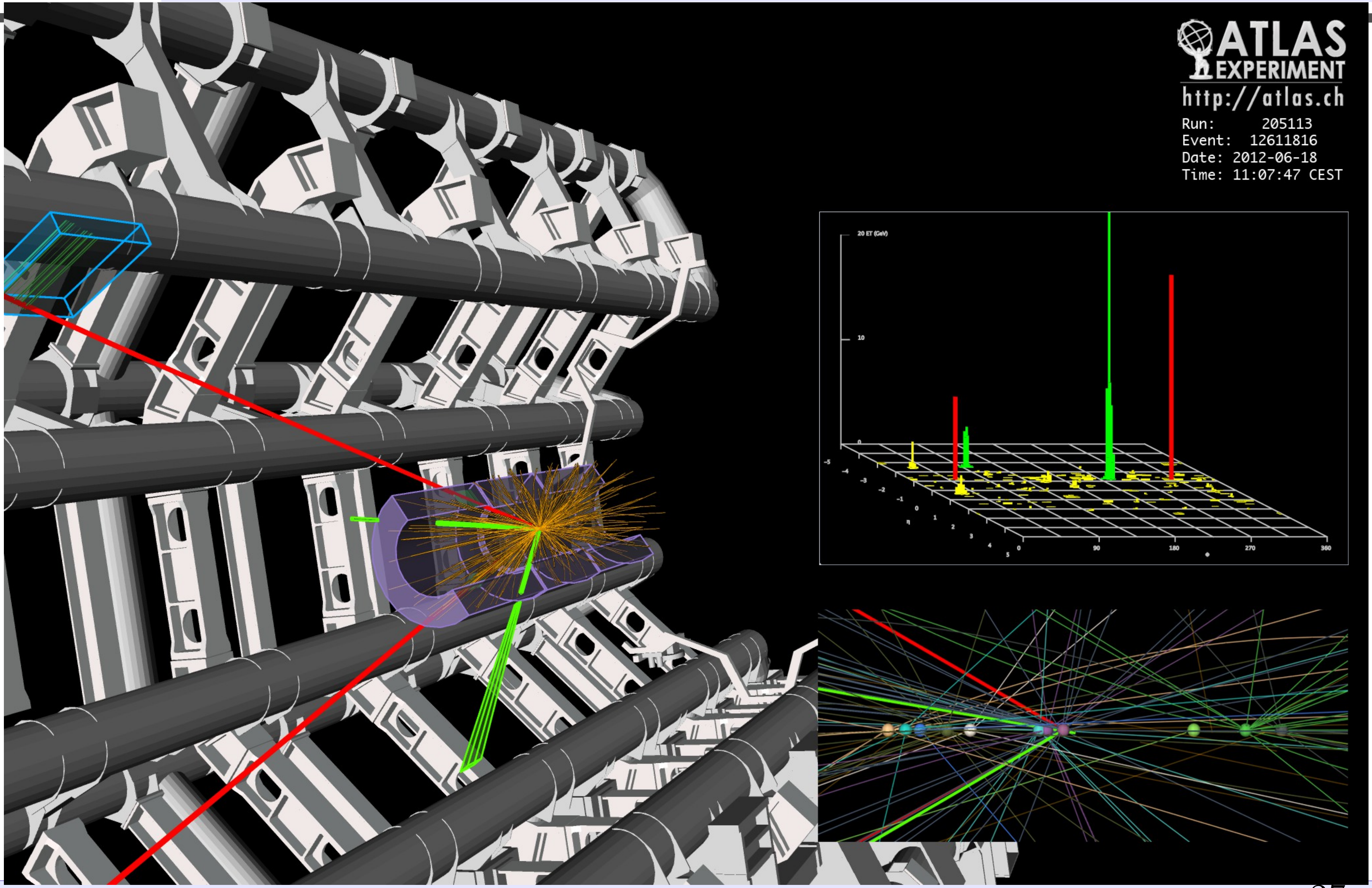
H→γγ high mass Higgs searches



- No additional new resonances found
- Limits imposed as a function of the mass of the new particle
  - Assuming narrow resonances



H→ZZ→4ℓ analysis



H→ZZ→4ℓ analysis

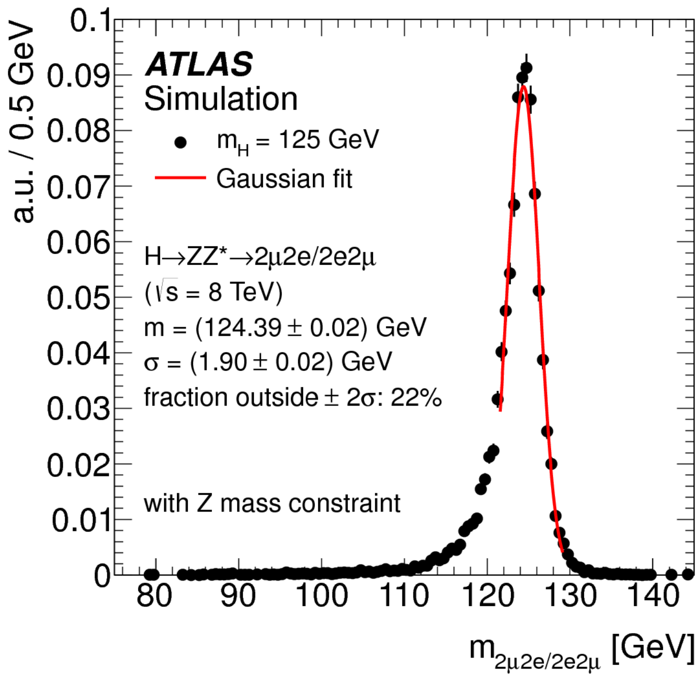
Selection:

- 4 isolated leptons with high p_T
- Z mass constraint on one l pair

Main backgrounds:

- Continuum $ZZ^* \to 4\ell$ production
- Z+jets, tt

Discriminating variable: $m_{4\ell}$



Excellent mass resolution

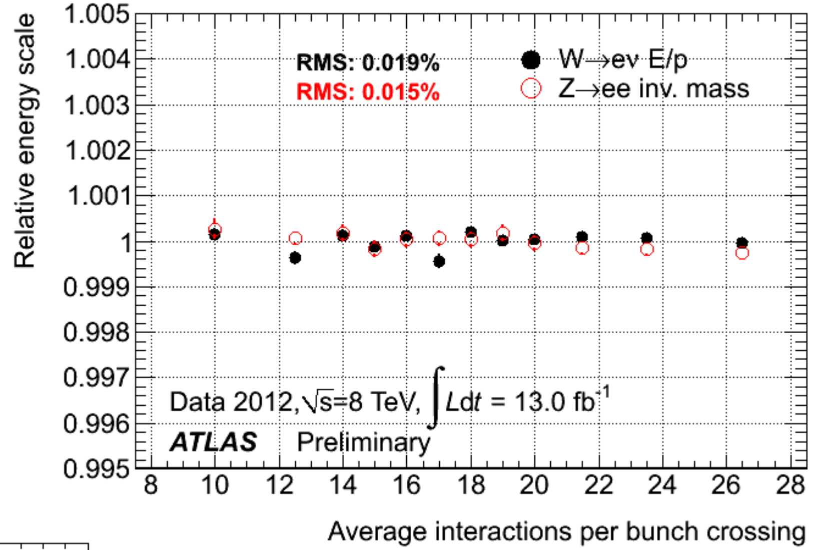
- 1.6-2.4 GeV (4μ, 4e)

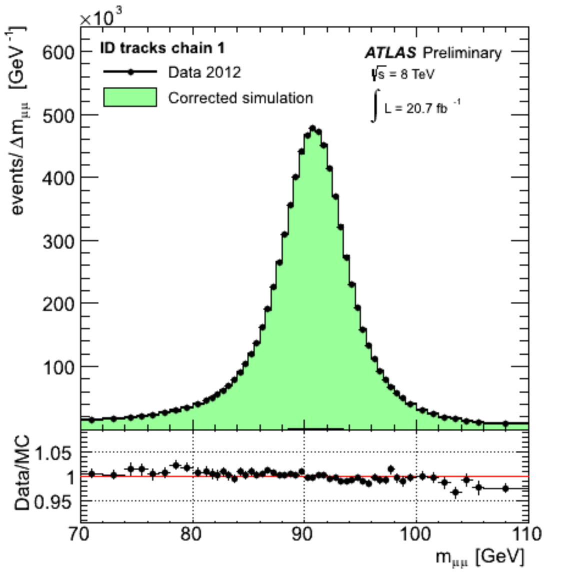
Very good e/μ reconstruction efficiency

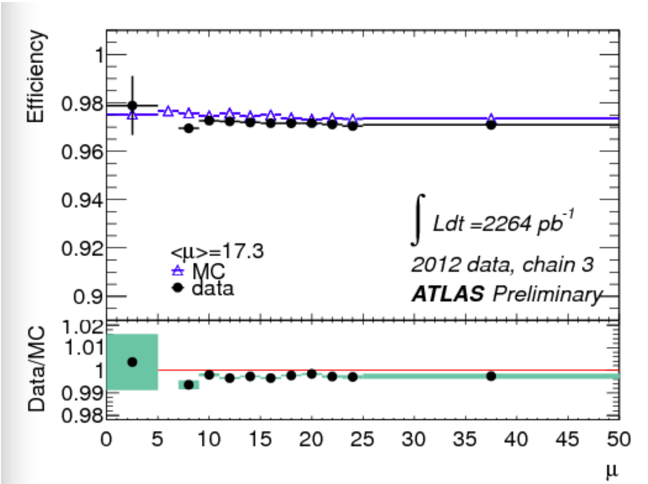
- ~97% for muons with p_T>6 GeV
- ~98% (95%) for e reconstruction (identification)

e and μ reconstruction

- Electrons: combine shower shape information from calorimeter with tracking information (including transition-radiation in TRT)
- Muons: combined tracks in inner detector and muon chambers
- MC simulation corrected to reproduce the detector resolution, energy scale and efficiency precisely

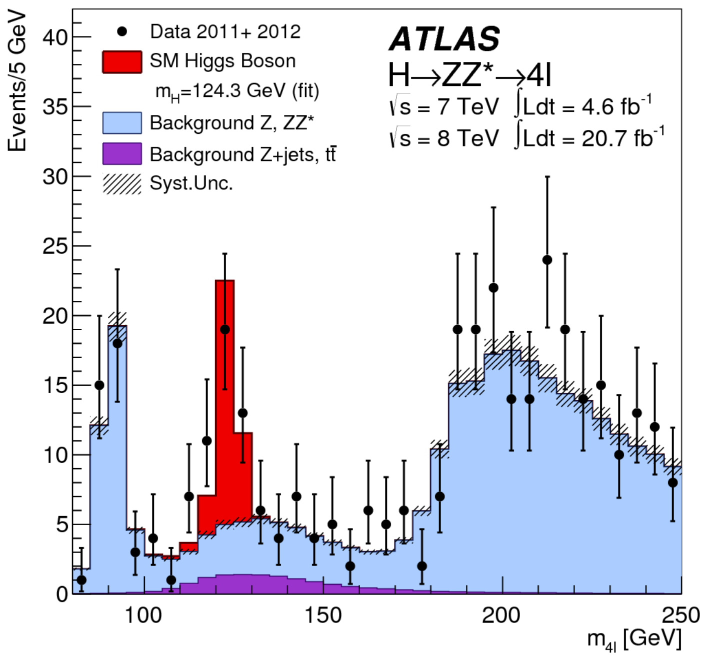


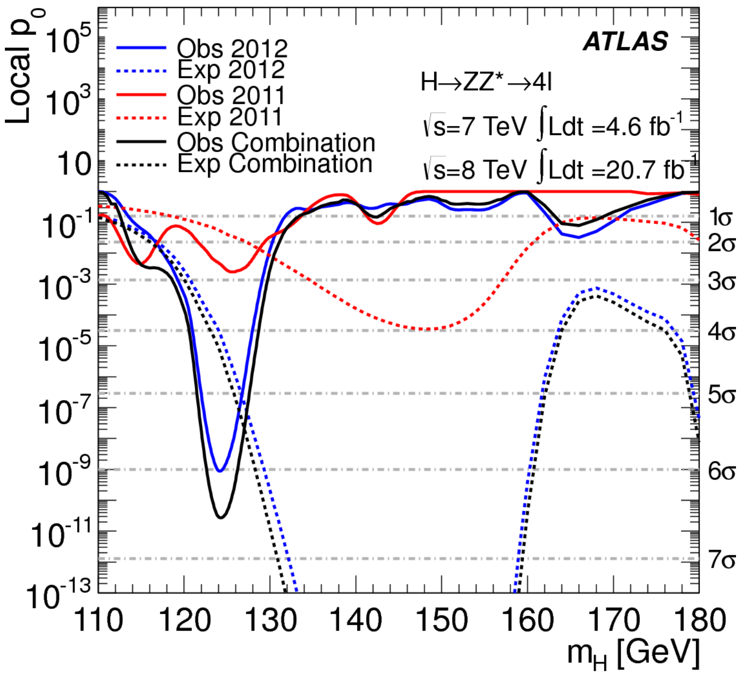




H→ZZ→4ℓ results

- 4ℓ mass spectrum (7+8 TeV)



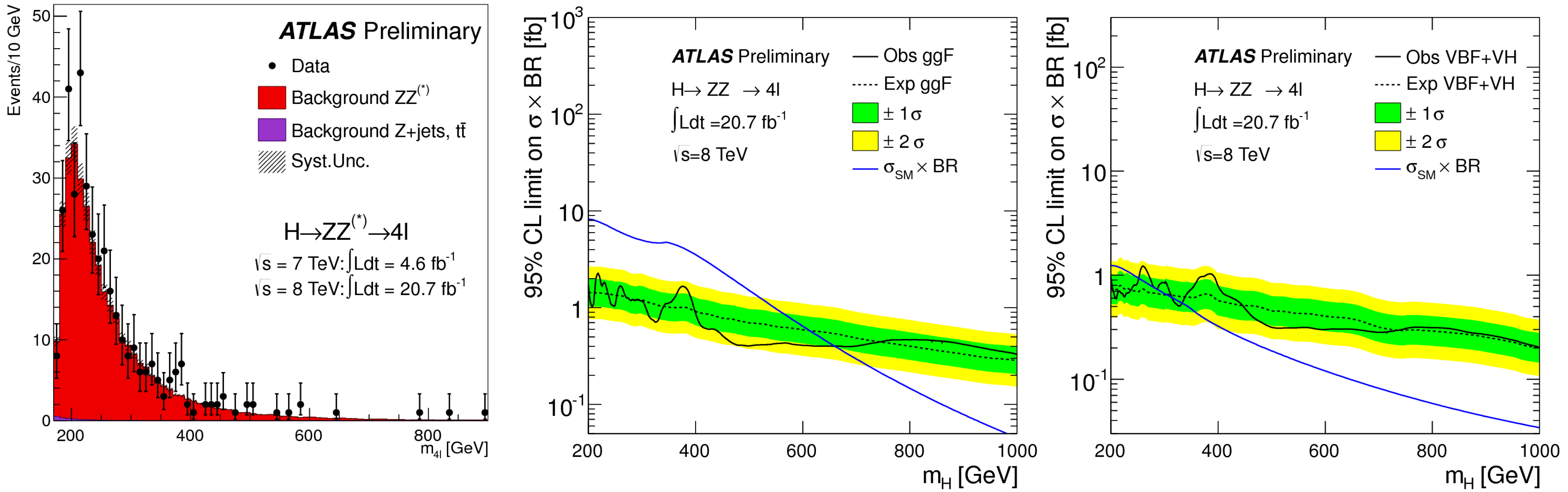


- Best fit mass: $m_H = 124.3^{+0.6}_{-0.5}\,(\text{stat})\,^{+0.5}_{-0.3}\,(\text{sys})$ GeV
- Minimum combined p0 value for m_H= 124.3 GeV

  Expected p0: $5.7\text{x}10^{-6}$ (4.4 σ)

  Observed p0: $2.7\text{x}10^{-11}$ (6.6 σ)

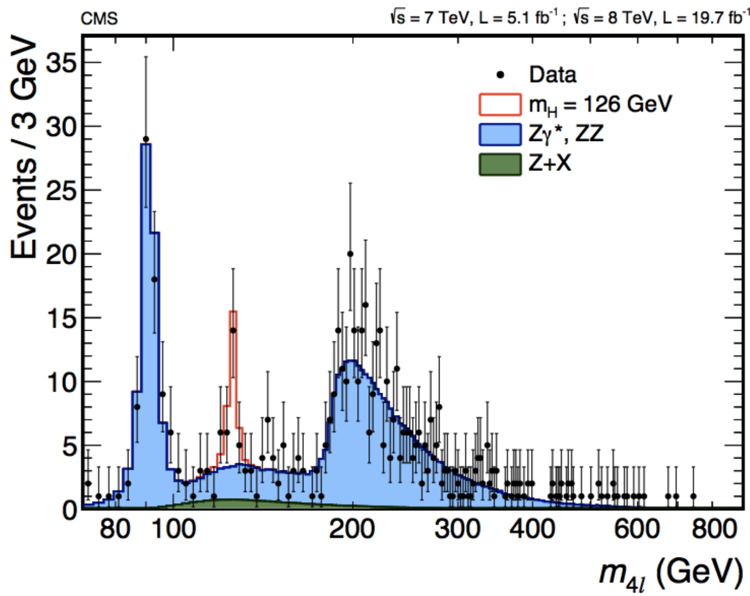
H→ZZ→4ℓ results larger masses

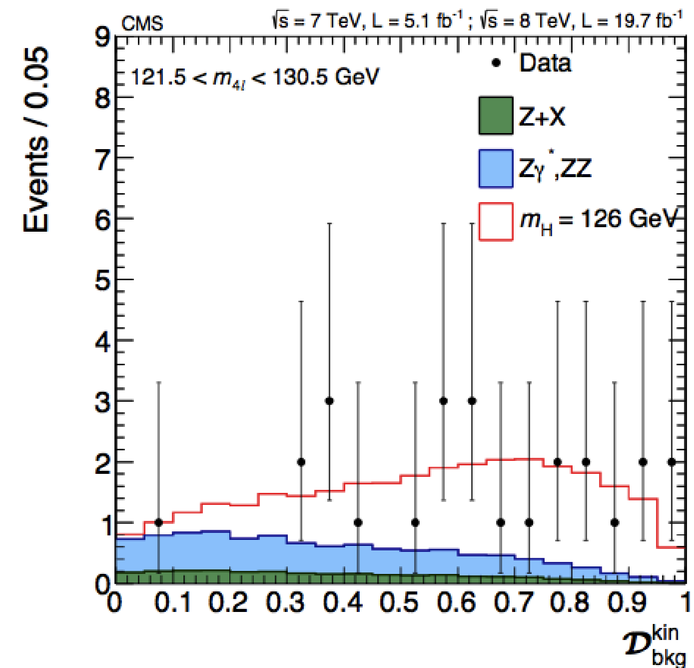


Search for other SM Higgs-like resonance in a large mass regime

- Assume SM width
- Test independently VBF and ggF to allow constraint new resonances that might have different production rates

CMS H→ZZ→4ℓ results

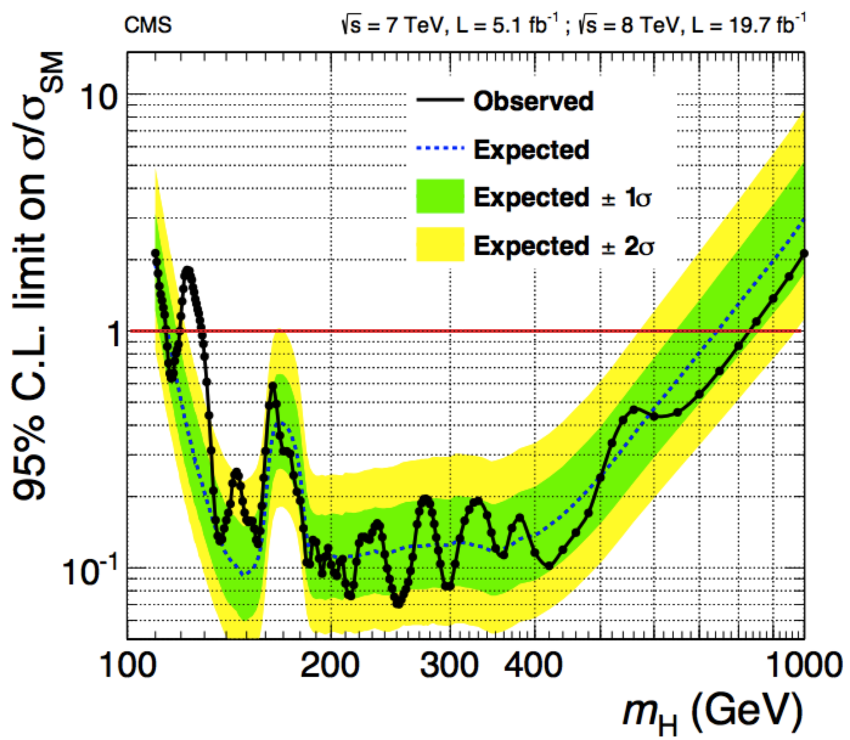


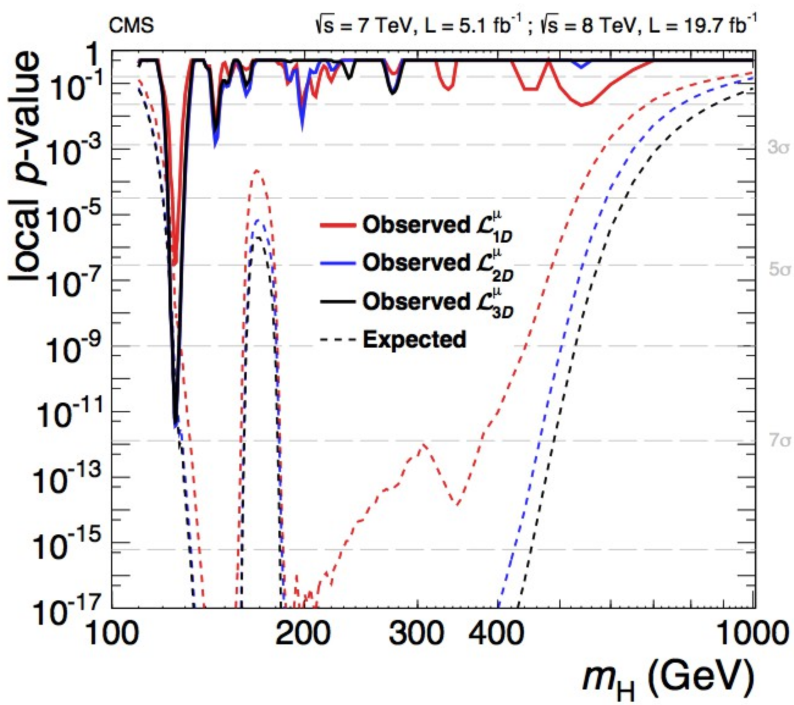


- Kinematic discriminant to further separate signal and background

$$K_D(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi, m_{Z_1}, m_{Z_2}) = \mathcal{P}_{sig}/(\mathcal{P}_{sig} + \mathcal{P}_{bkg})$$

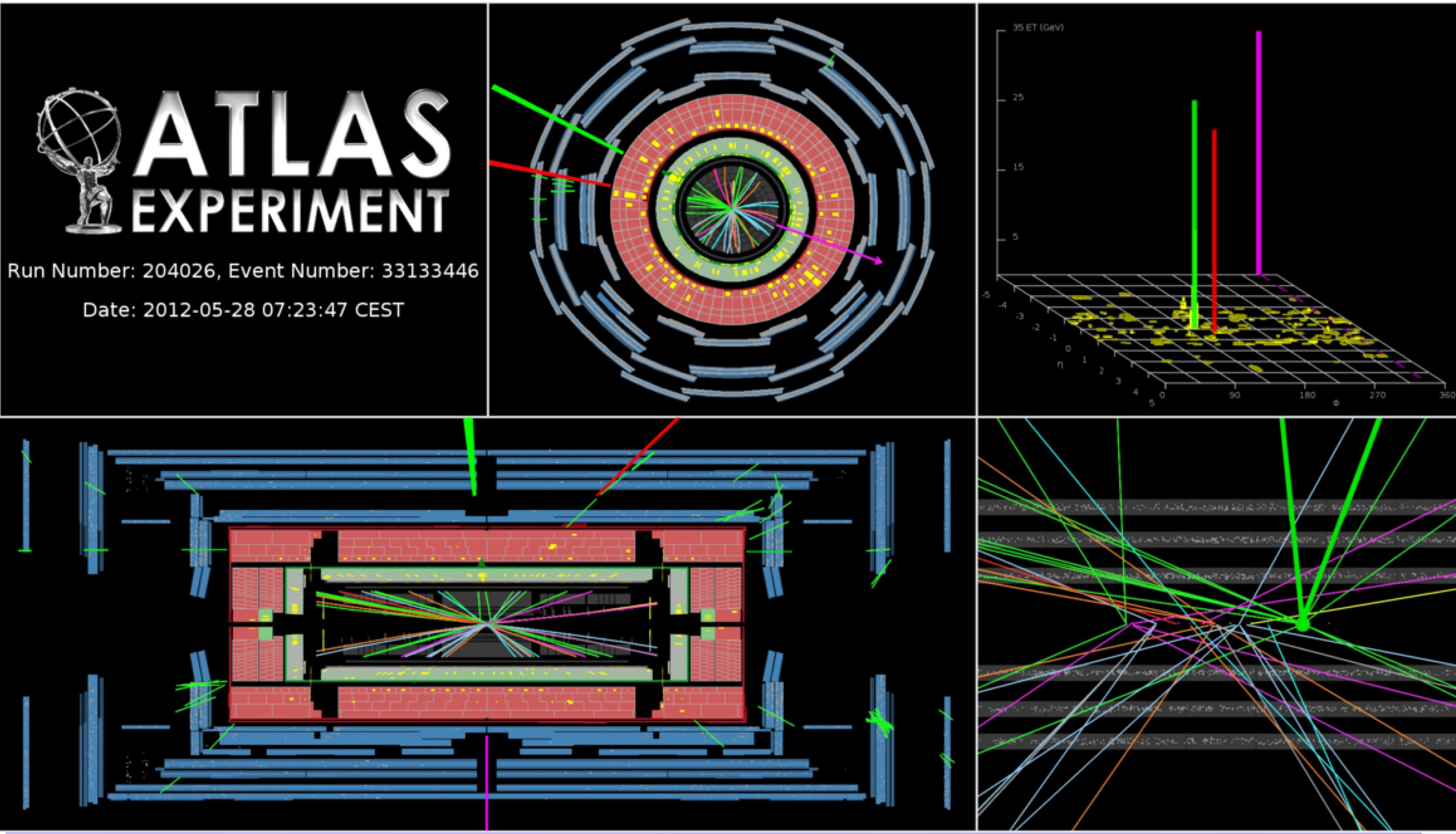
CMS H→ZZ→4ℓ results





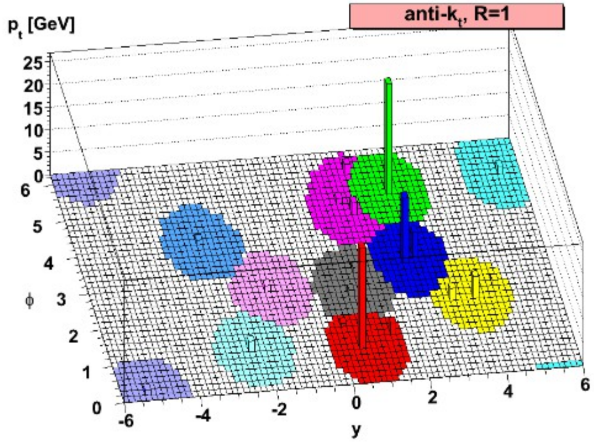
- Clear signal observed, compatible with SM expectations
- Best mass fit: $m_H = 125.6 \pm 0.4\,(\text{stat.}) \pm 0.2\,(\text{syst.})\,\text{GeV}$
- Signal strength: $\mu = \sigma/\sigma_{SM} = 0.93^{+0.26}_{-0.23}\,(\text{stat.})^{+0.13}_{-0.09}\,(\text{syst.})$

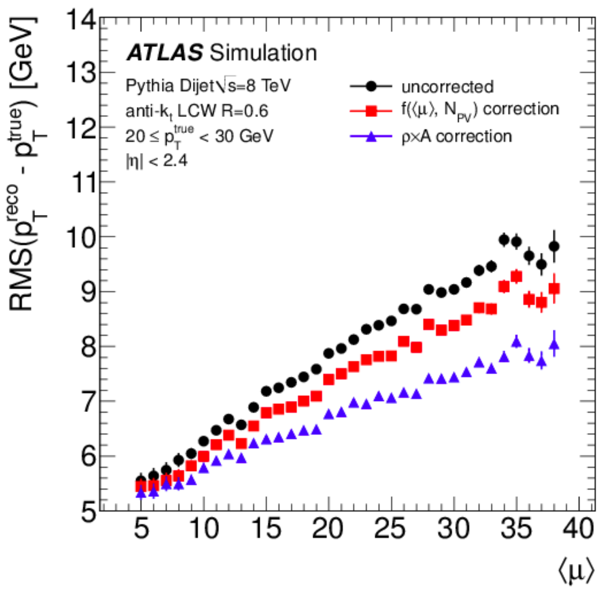
$H \rightarrow WW \rightarrow l\nu l\nu$

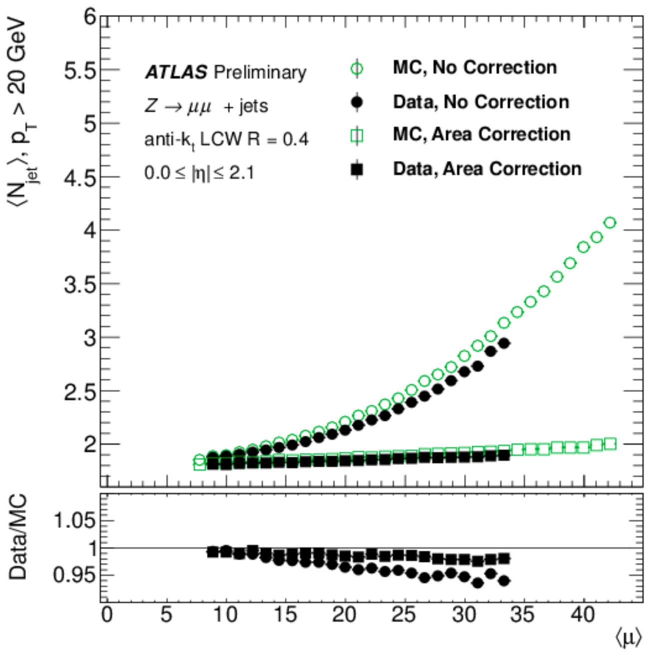


Jet Reconstruction

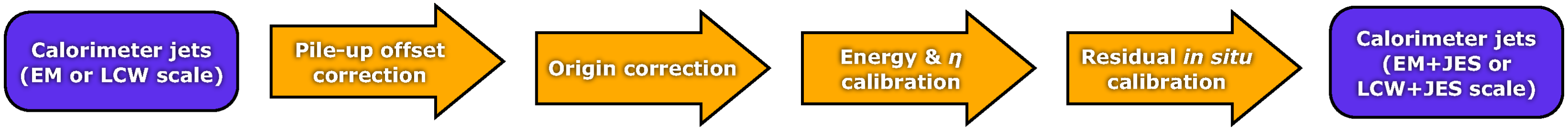
- Use Anti-kT with R = 0.4
  - Constituents: 3D clusters in calorimeter
- Calibrate to hadronic scale
- Sensitive to pile-up
  - Apply pile-up corrections







Jet energy scale uncertainty



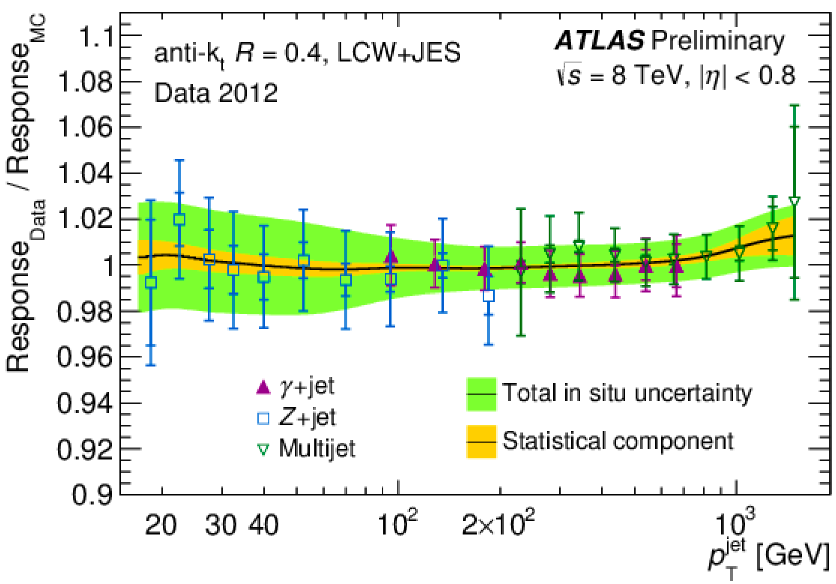
Corrects for the energy offset introduced by pile-up. Depends on μ and N_{PV}. Derived from MC.

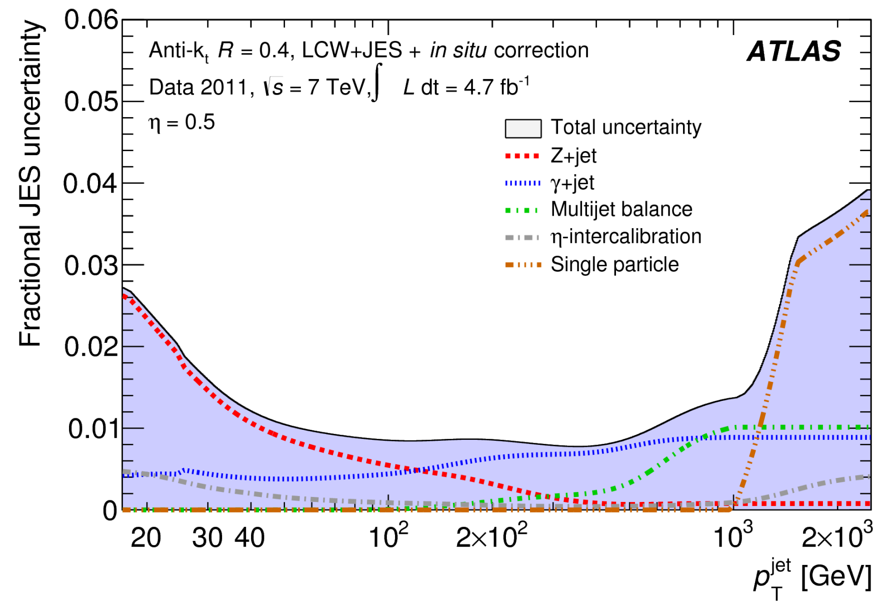
Changes the jet direction to point to the primary vertex. Does not affect the energy.

Calibrates the jet energy and pseudorapidity to the particle jet scale. Derived from MC.

Residual calibration derived using *in situ* measurements. Derived in data and MC. Applied only to data.

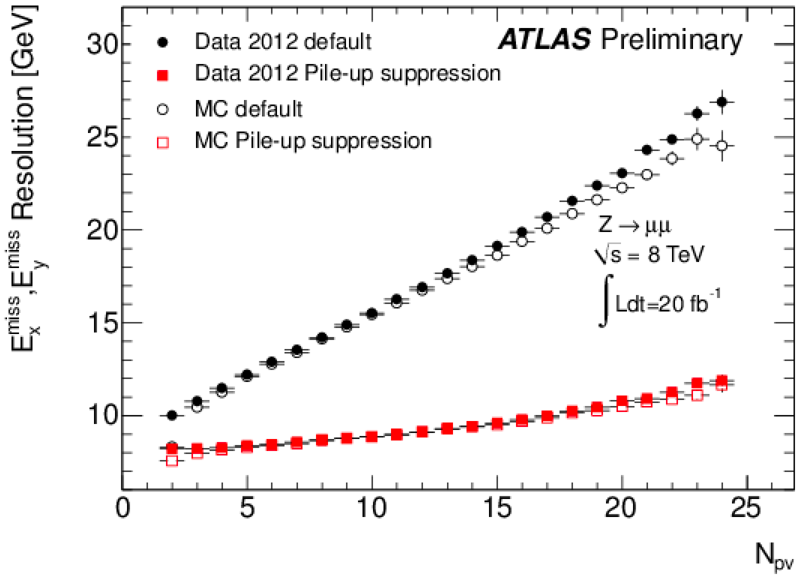
- JES uncertainty dominated by in-situ uncertainties

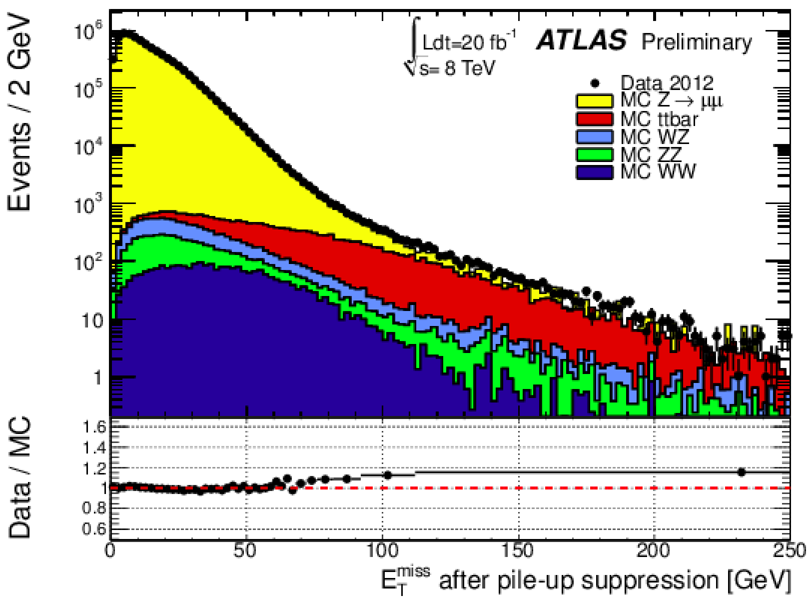




Missing ET performance

- Calculated as the sum of the energy of all the identified objects (e, γ, μ, τ, jets) and energy not associated to objects





- ETmiss resolution worsens significantly with increasing pile-up
  - Correct it using tracking information
- Good data-MC agreement

E_T^{miss} on the H→WW→lνlν search

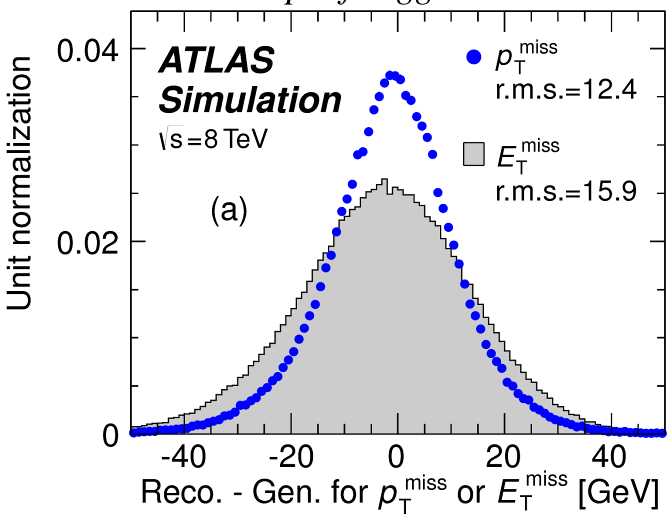
$$E_{\mathrm{T}}^{\mathrm{miss}} = -\left(\sum_{\mathrm{selected}} p_{\mathrm{T}} + \sum_{\mathrm{soft}} p_{\mathrm{T}} \right),$$

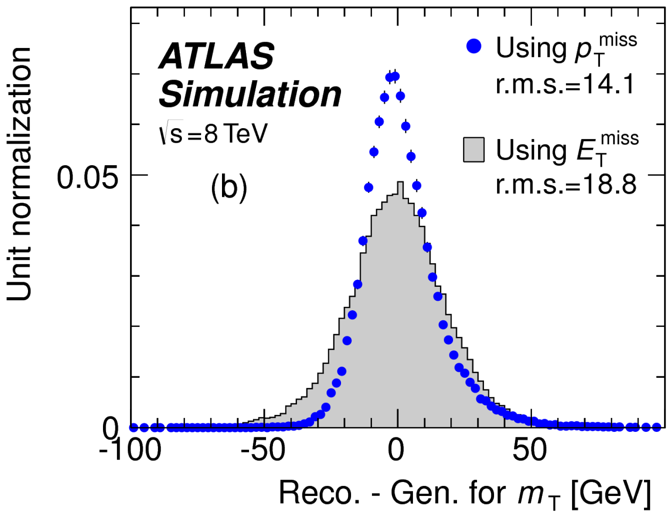
- Calorimeter based E_T^{miss}
  - Large rapidity coverage, sensitive to neutral particles
  - Soft term: calibrated calorimeter clusters
- p_T^{miss}:
  - Soft term calculated using tracking
  - Improves resolution by ~20%
- $p_T^{miss,track}$:

$$p_{\mathrm{T}}^{\mathrm{miss,track}} = -\sum p_{\mathrm{T}}^{\mathrm{tracks}}$$

  - Used in the 0-ℓ to further reduce Drell-Yan
  - Aligns $p_T^{miss,track}$ to the jets in DY events

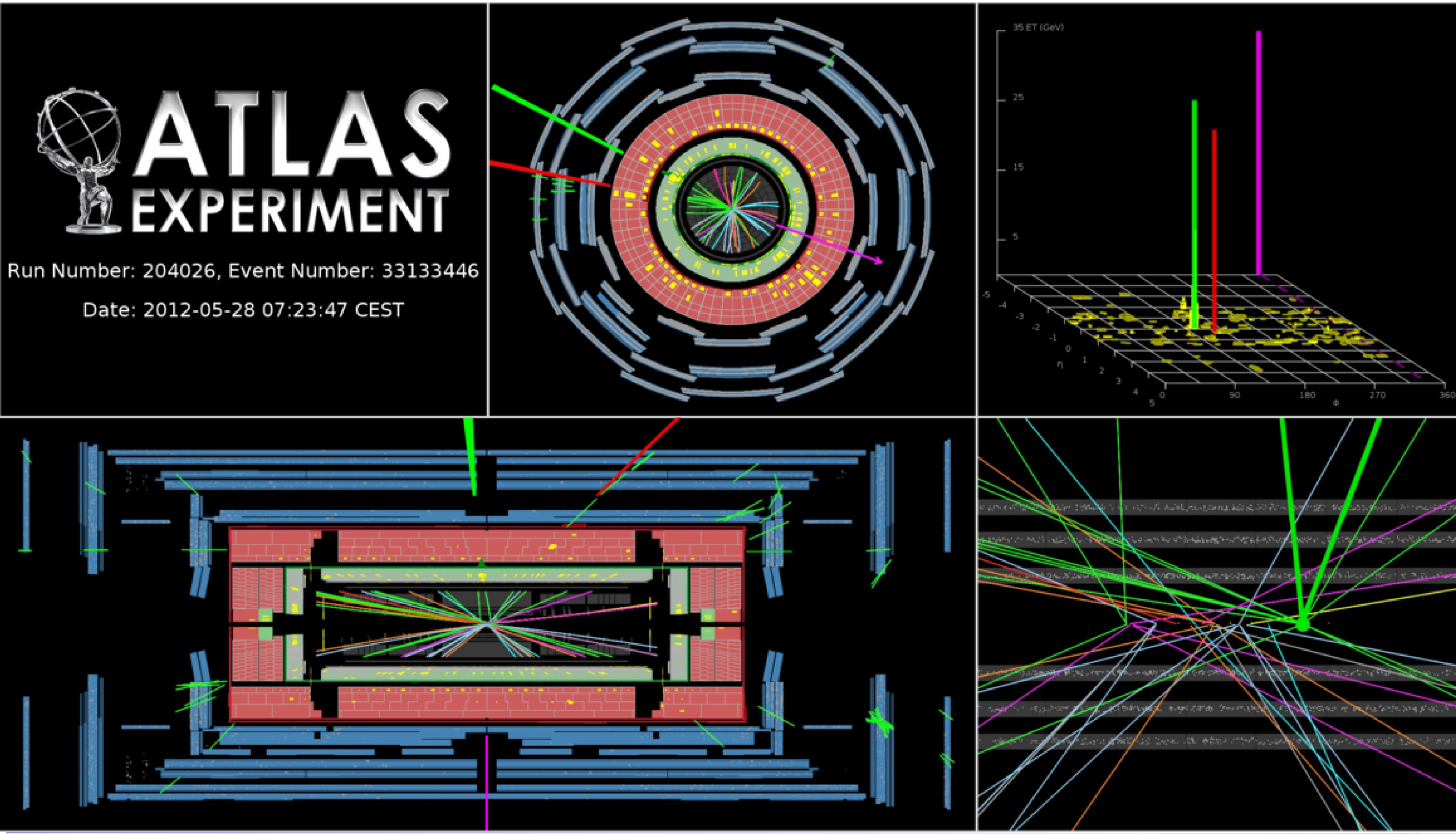
MC sample for ggF H → WW*





$H \to WW \to l\nu l\nu$

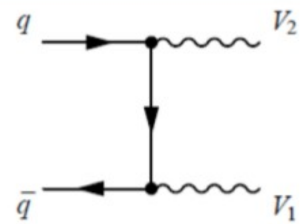
Phys. Lett. B 726 (2013), pp. 88-119



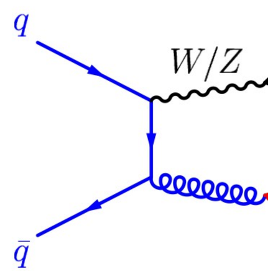
Main backgrounds

- Di-boson production

  WW, WZ, ZZ



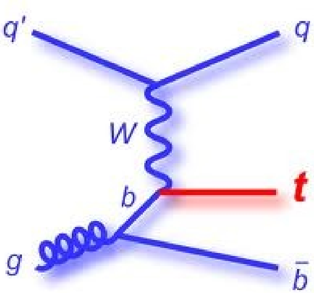
- Others: W+jets, Wγ, Drell-Yan

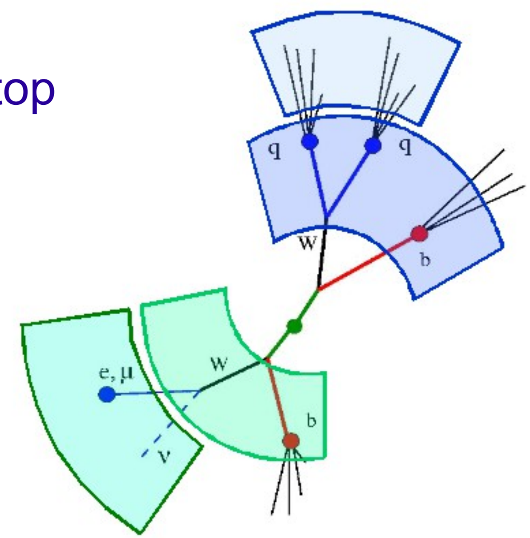


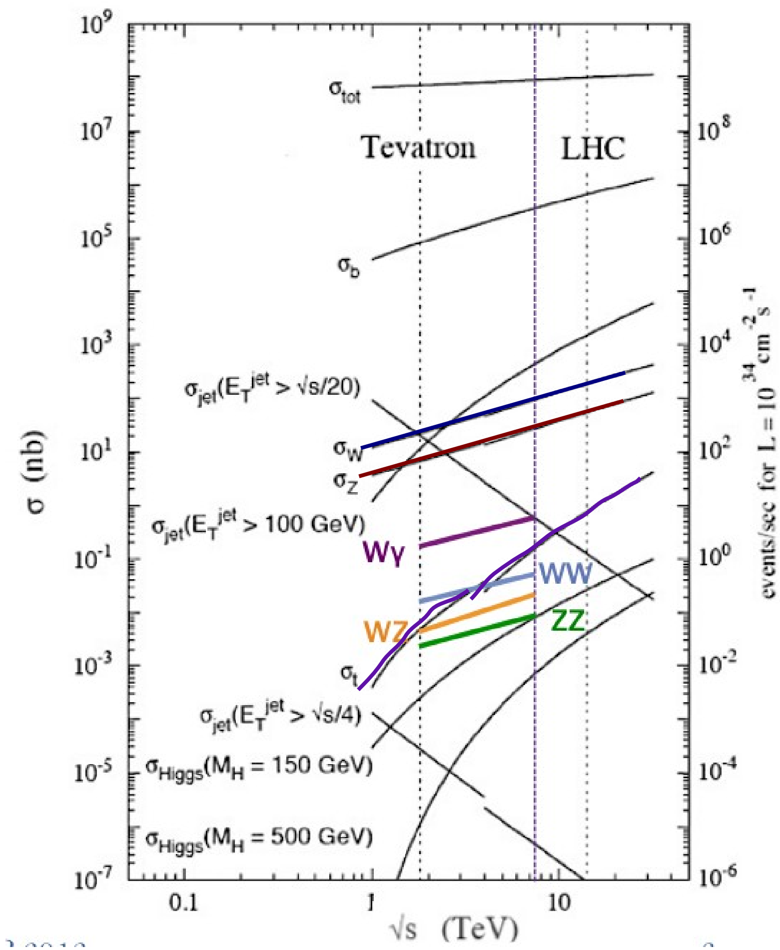
- Top production:

  t-tbar

  Single top

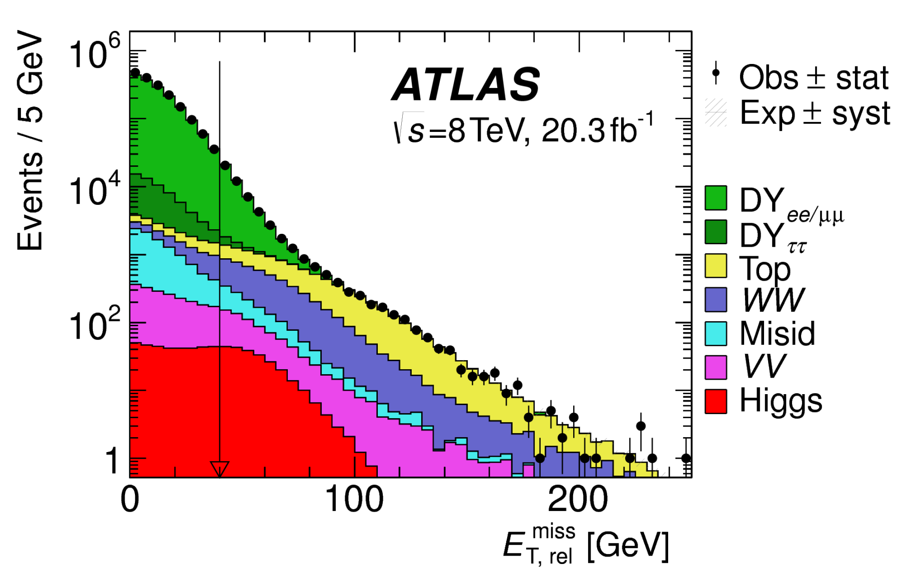


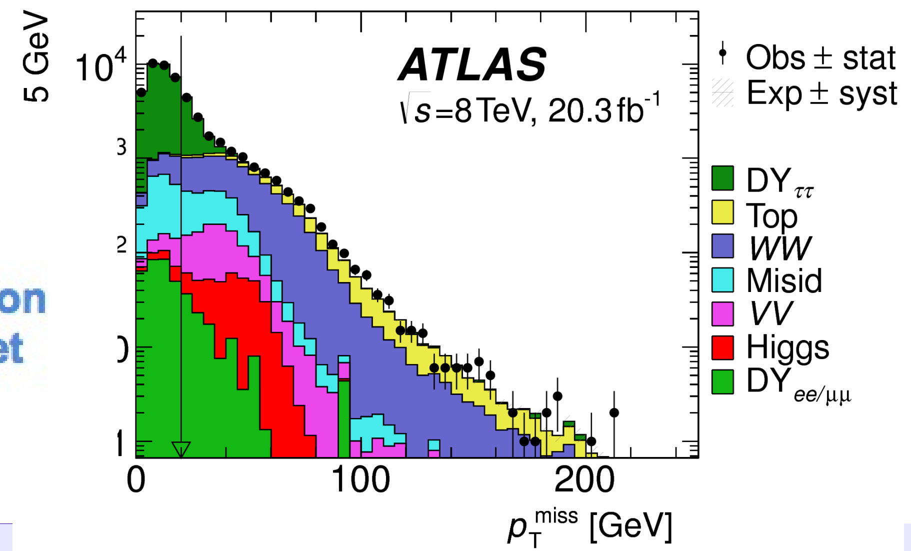




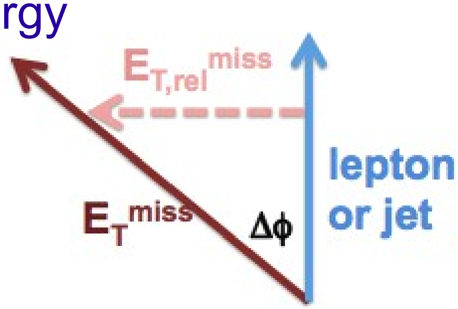
Event selection

- Exploit the properties of the Higgs events to separate the signal from the backgrounds
- Different channels affected by different backgrounds
  - Small selection differences in opposite/same flavour final states





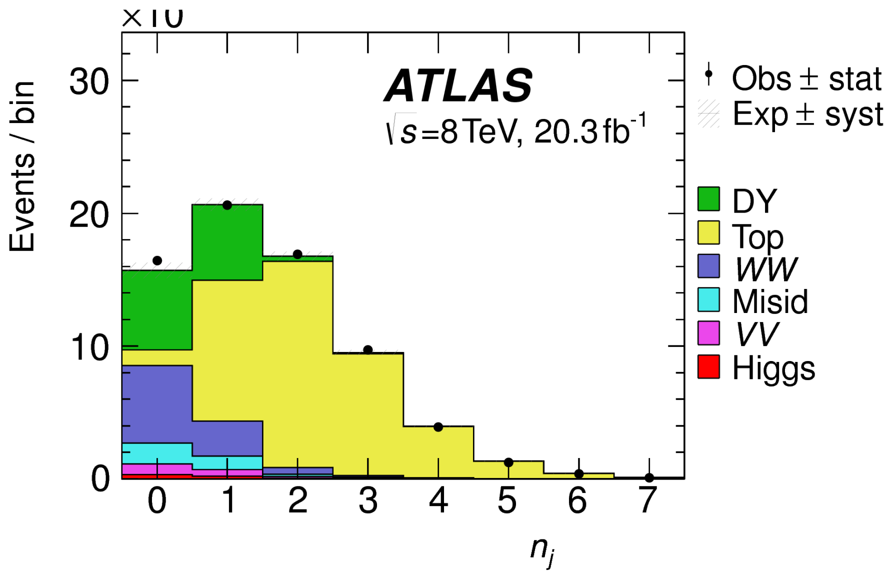
- Reject Z/Drell-Yan background
  - Require large missing transverse energy



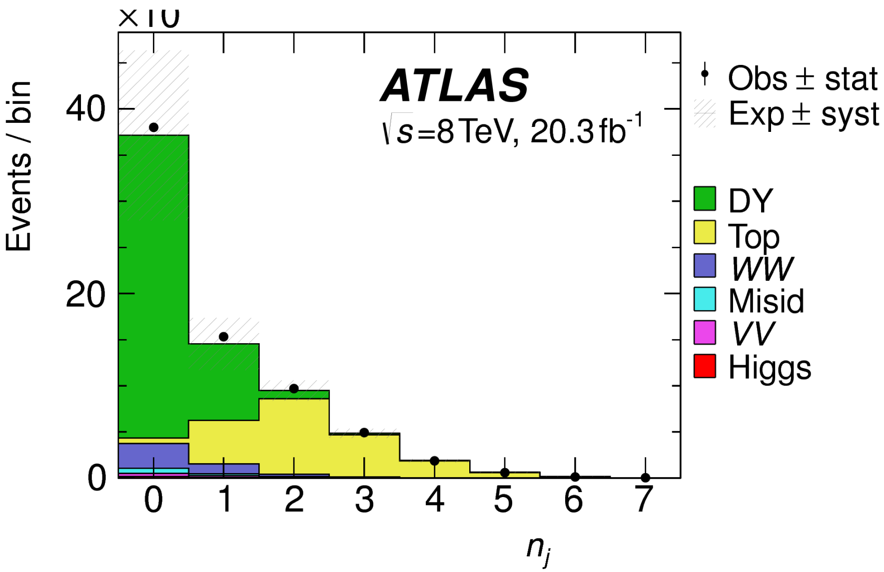
Use calorimeter and tracking systems

Analysis categories

- Different flavour final state

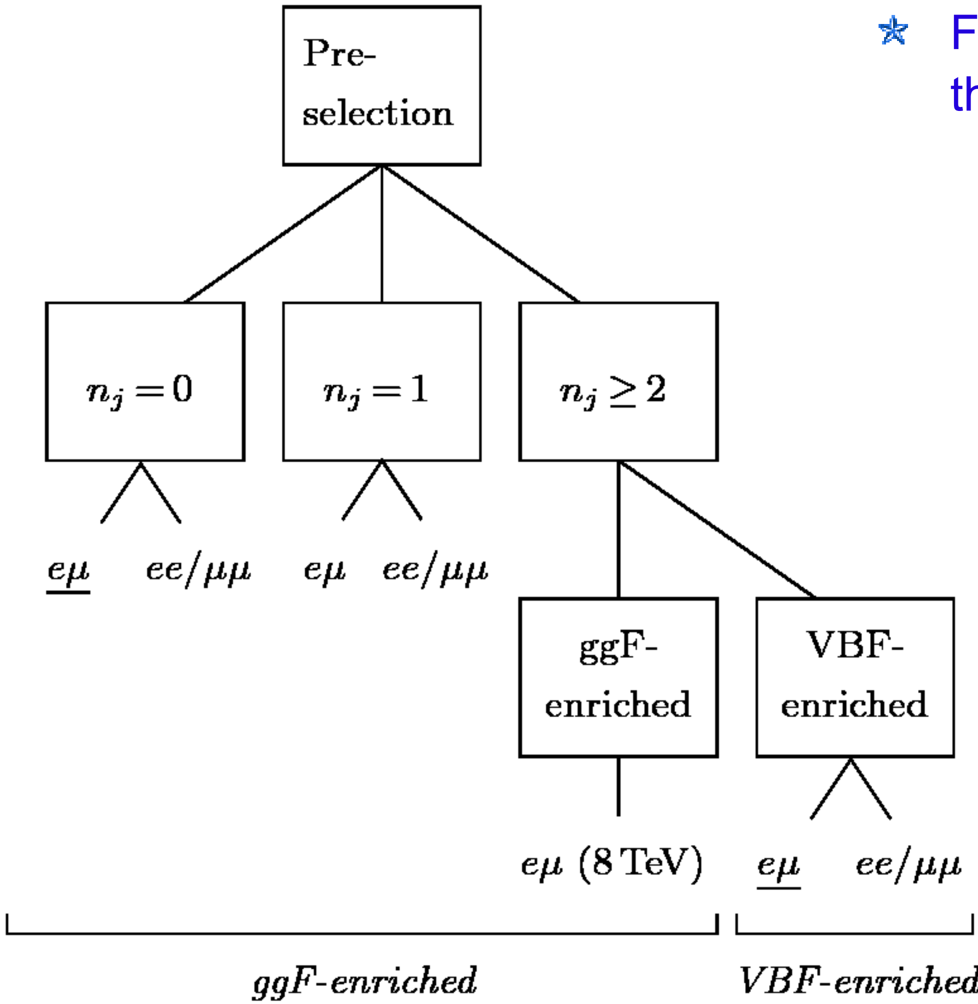


- Same flavour final state



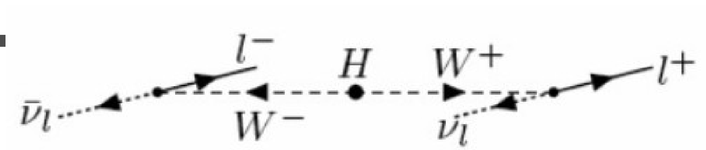
- Consider separately different categories: 0, 1, 2 jets
  - Sensitive to different production mechanisms
    - Gluon gluon fusion dominates the 0-jet category
    - VBF dominate the 2-jet category
  - Affected by different backgrounds

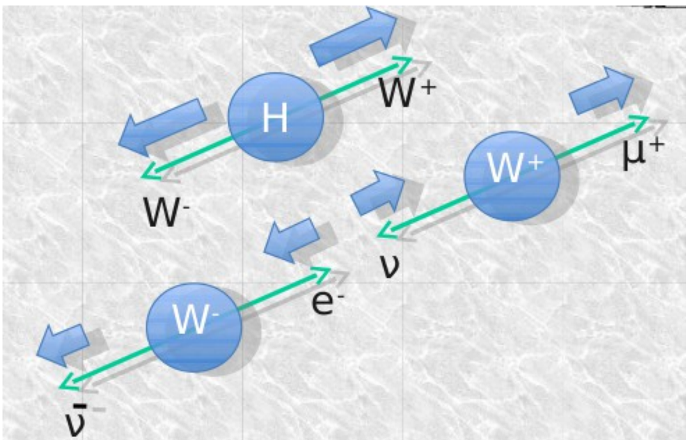
Analysis categories

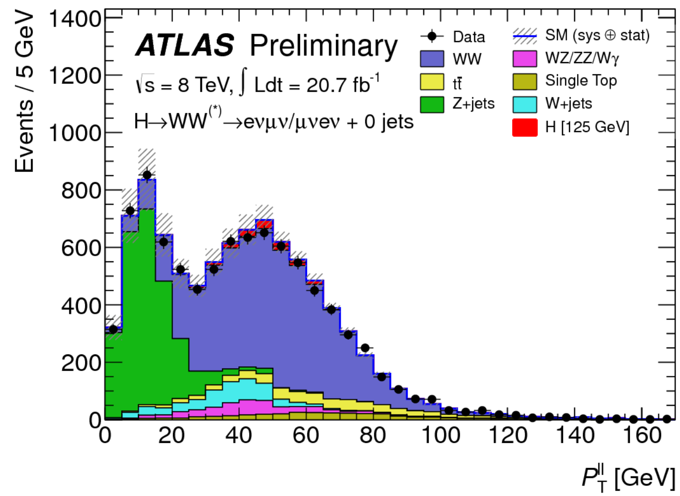


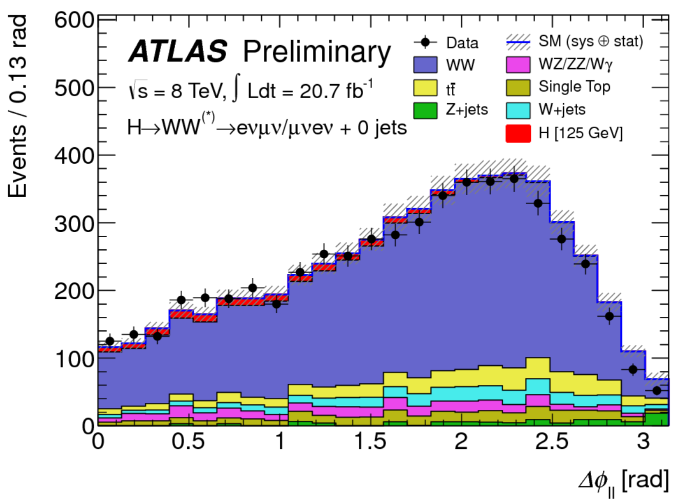
- Further selection will depend on the analysis category

Further selection

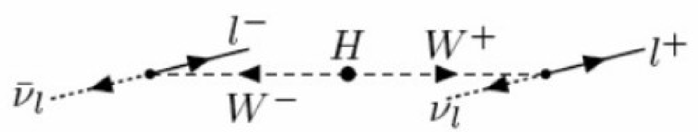


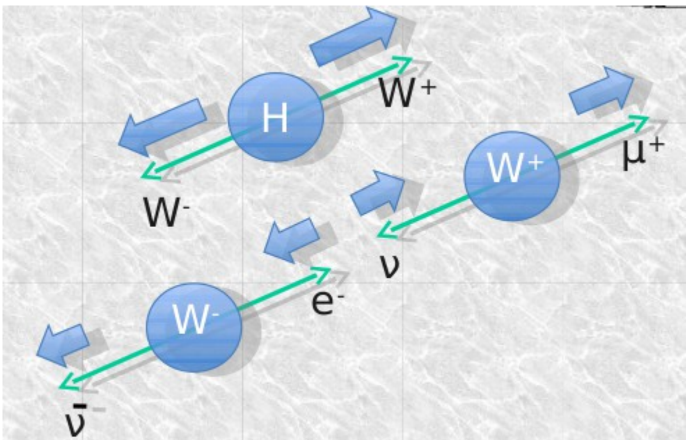


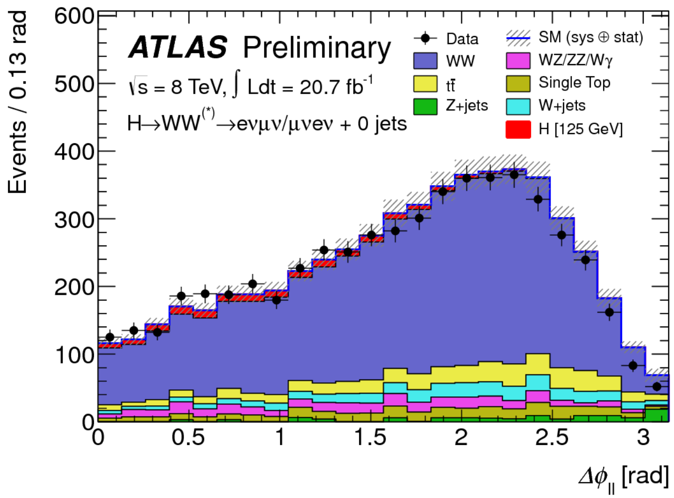


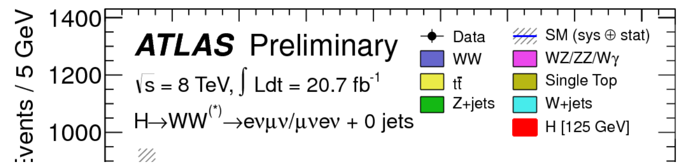


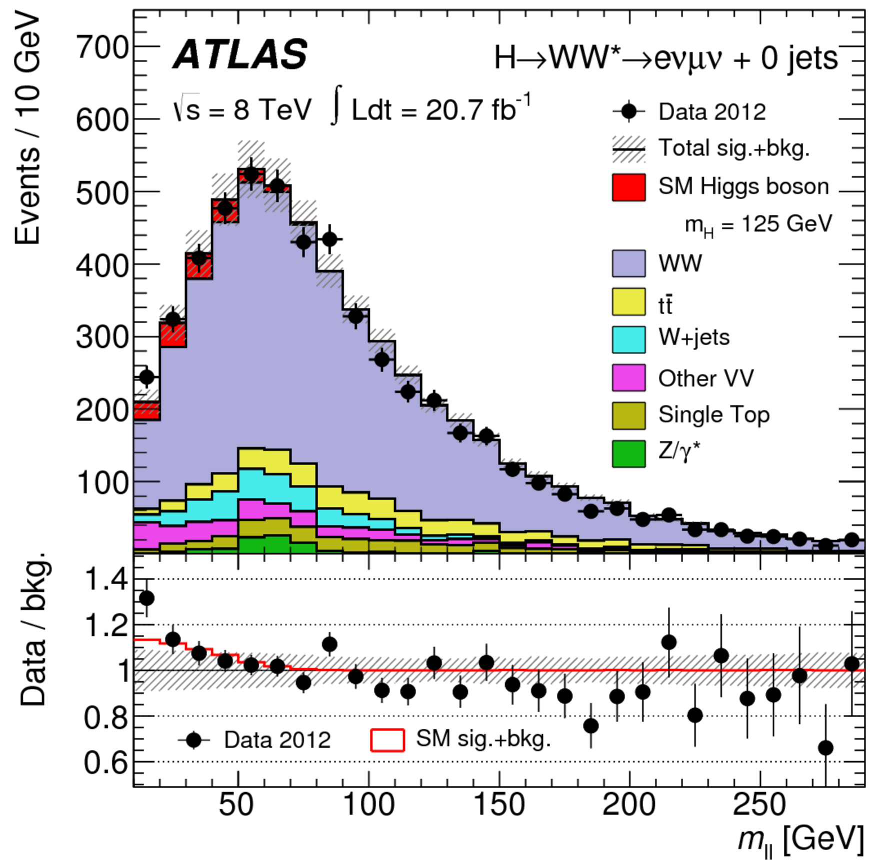
Further selection





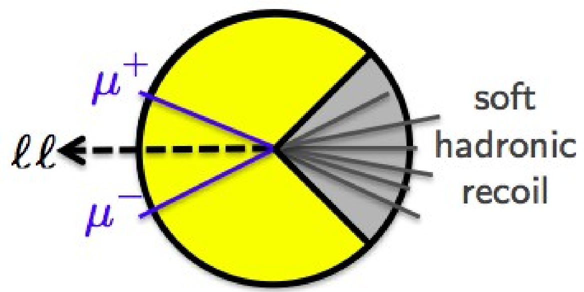




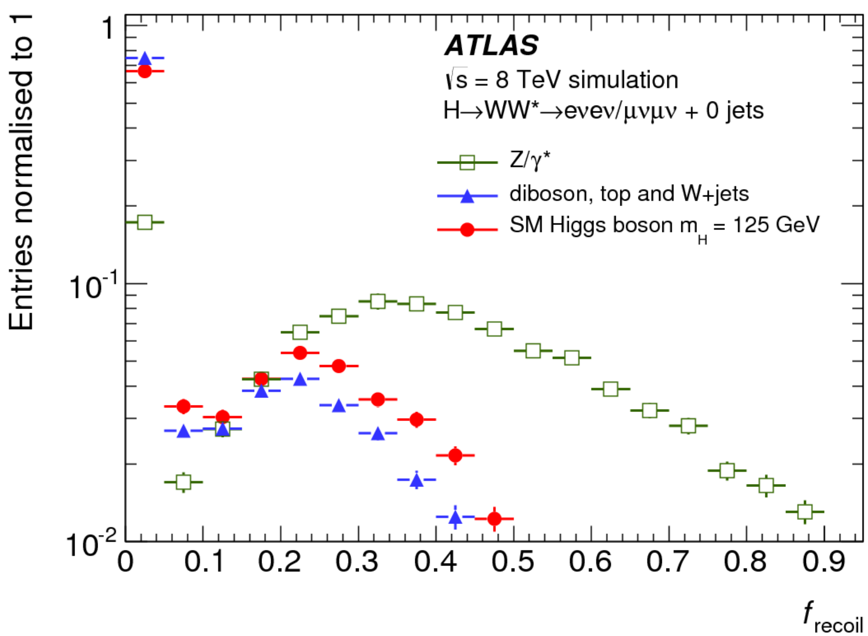


Further selection (II)

- Same flavour final state:
  - Drell-Yan background still large
    - Affected by pile-up
    - Hard to model it with MC
  - Use recoil energy for further rejection



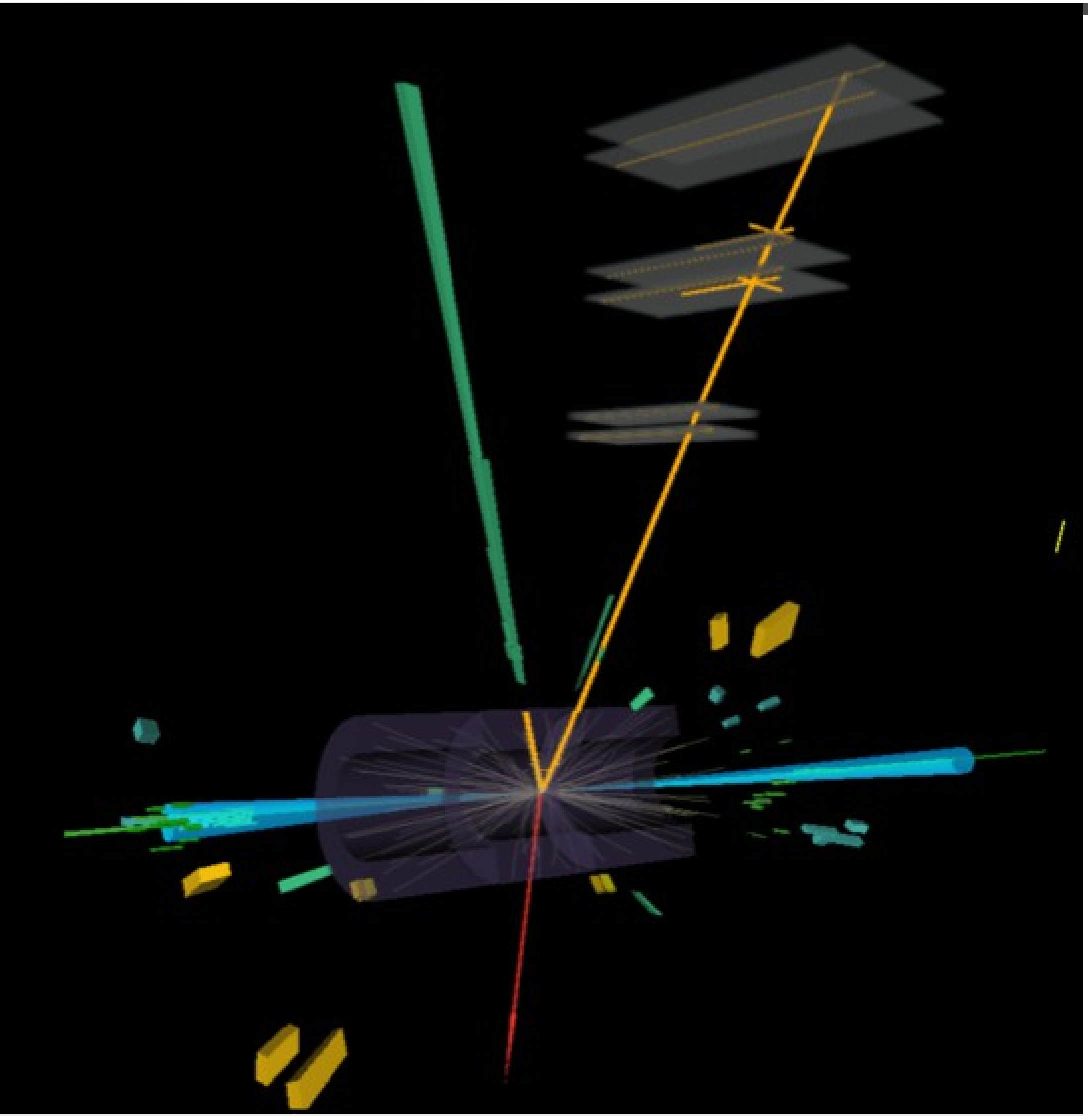
$$f_{\rm recoil} = \frac{|\sum |{\rm JVF}| \times \vec{p_{\rm T}}|}{p_{\rm T}^{\ell\ell}}$$



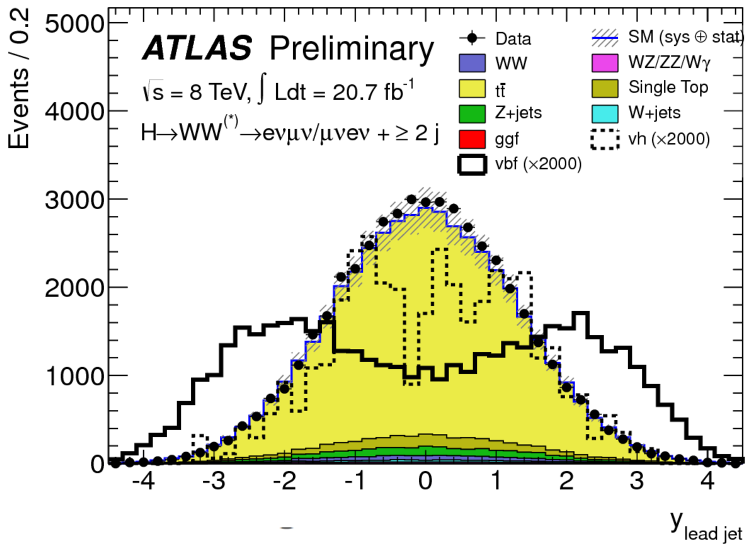
- Require

$f_{\rm recoil} < 0.05/0.2$ for 0/1-jet.

2-jet analysis



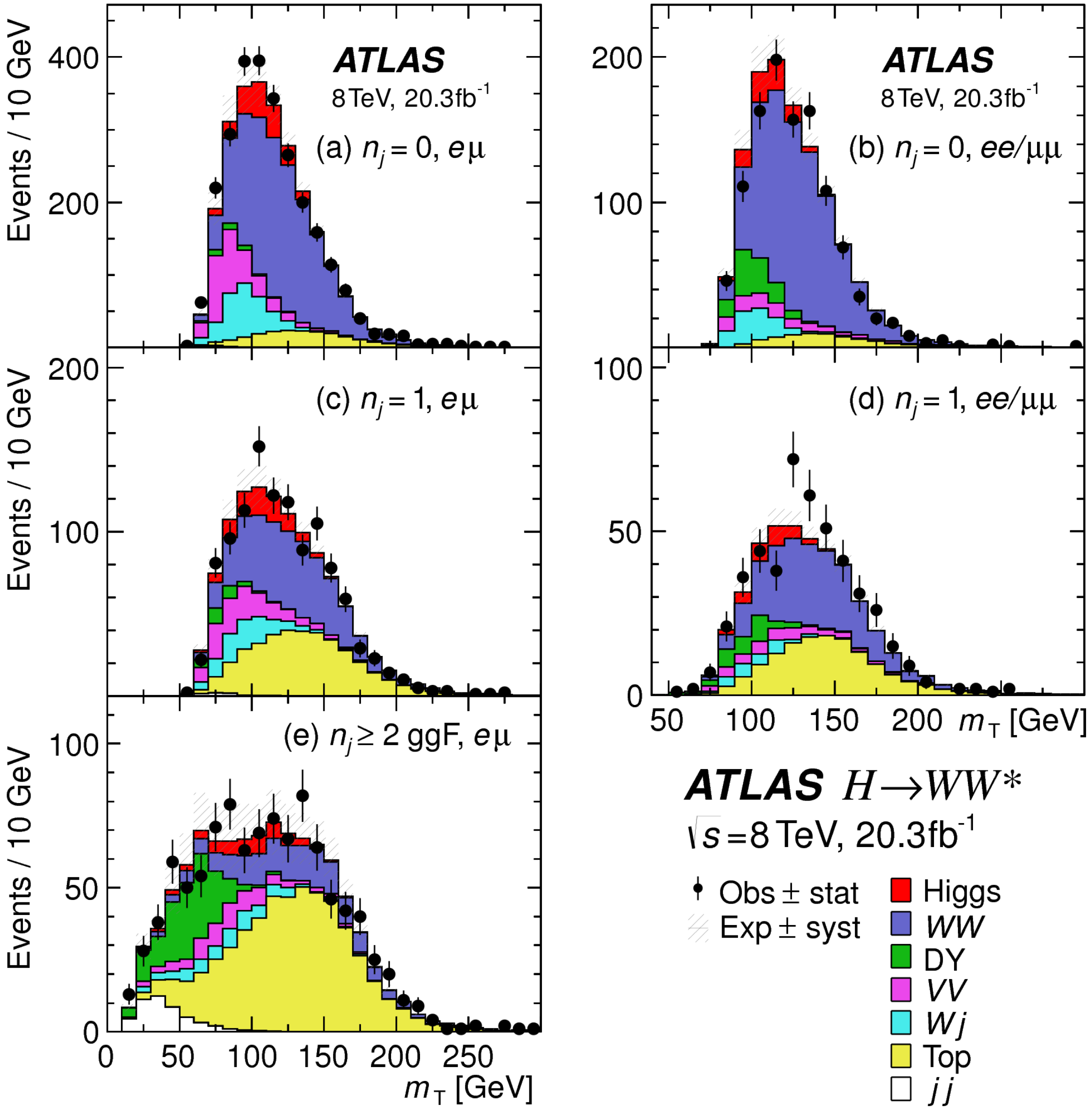
- Dominated by VBF
- Large rapidity gap between jets



$$|\Delta y_{jj}| > 2.8$$

$$m_{jj} > 500\ \text{GeV}$$

Transverse mass



- Define the transverse mass:

$$m_T = \sqrt{(E_T^{\ell\ell} + |\vec{p}_T^{miss}|)^2 - (\vec{p}_T^{\ell\ell} + \vec{p}_T^{miss})^2}$$

- Equivalent to the mass, but considering only transverse components
- Sensitive to the Higgs mass in the high edge

Background estimation

- Since it is not possible to reconstruct a narrow peak backgrounds have to be measured carefully!

$$B_{\mathrm{SR}}^{\mathrm{est}} = B_{\mathrm{SR}} \cdot \underbrace{N_{\mathrm{CR}}/B_{\mathrm{CR}}}_{\text{Normalization } \beta} = N_{\mathrm{CR}} \cdot \underbrace{B_{\mathrm{SR}}/B_{\mathrm{CR}}}_{\text{Extrapolation } \alpha}$$

Category	WW			Top			Misid.			VV			Drell-Yan $ee/\mu\mu$			Drell-Yan $\tau\tau$		
	N	E	V	N	E	V	N	E	V	N	E	V	N	E	V	N	E	V
$n_j = 0$																		
$e\mu$	●	○	○	●	○	○	●	●	●	●	○	○	○	○	○	●	○	○
$ee/\mu\mu$	●	○	○	●	○	○	●	●	●	○	○	○	●	●	○	●	○	○
$n_j = 1$																		
$e\mu$	●	○	○	●	○	○	●	●	●	●	○	○	○	○	○	●	○	○
$ee/\mu\mu$	●	○	○	●	○	○	●	●	●	○	○	○	●	●	○	●	○	○
$n_j \geq 2$ ggF																		
$e\mu$	○	○	○	●	○	○	●	●	●	○	○	○	○	○	○	●	○	○
$n_j \geq 2$ VBF																		
$e\mu$	○	○	○	●	○	○	●	●	●	○	○	○	○	○	○	●	○	○
$ee/\mu\mu$	○	○	○	●	○	○	●	●	●	○	○	○	●	●	○	●	○	○

- Define control regions for each backgrounds
  - Pure in that background
  - Kinematically as similar as possible to signal region
- Use CR to normalize the different backgrounds
  - Global fit
- Extrapolate to the signal region

W+jets and QCD background

W+jets:

- Control sample: one loosely identified lepton
- Transfer factor to signal region evaluated with a data sample dominated by QCD jets
    - Probability of a jet faking a lepton
- ~25% to ~40% uncertainty depending on the analysis category
    - Dominated by jet flavour composition in QCD versus W+jet events

QCD

- Control sample with two anti-identified leptons
- Transfer factor estimated with data

Same charge control region

Category	W+jets yield N_{Wj}		Multijets yield N_{jj}	
	OC	SC	OC	SC
$n_j = 0$	278 ± 71	174 ± 54	9.2 ± 4.2	5.5 ± 2.5
$n_j = 1$	88 ± 22	62 ± 18	6.1 ± 2.7	3.0 ± 1.3
$n_j \geq 2$ ggF	50 ± 22	-	49 ± 22	-
$n_j \geq 2$ VBF	3.7 ± 1.2	-	2.1 ± 0.8	-

Diboson backgrounds

Dibosons (Wγ, ZZ, WZ)

- Different flavour

  Use normalization control region

$$\beta_{0j} = 0.92 \pm 0.07\,(\mathrm{stat.})$$

$$\beta_{1j} = 0.96 \pm 0.12\,(\mathrm{stat.})$$

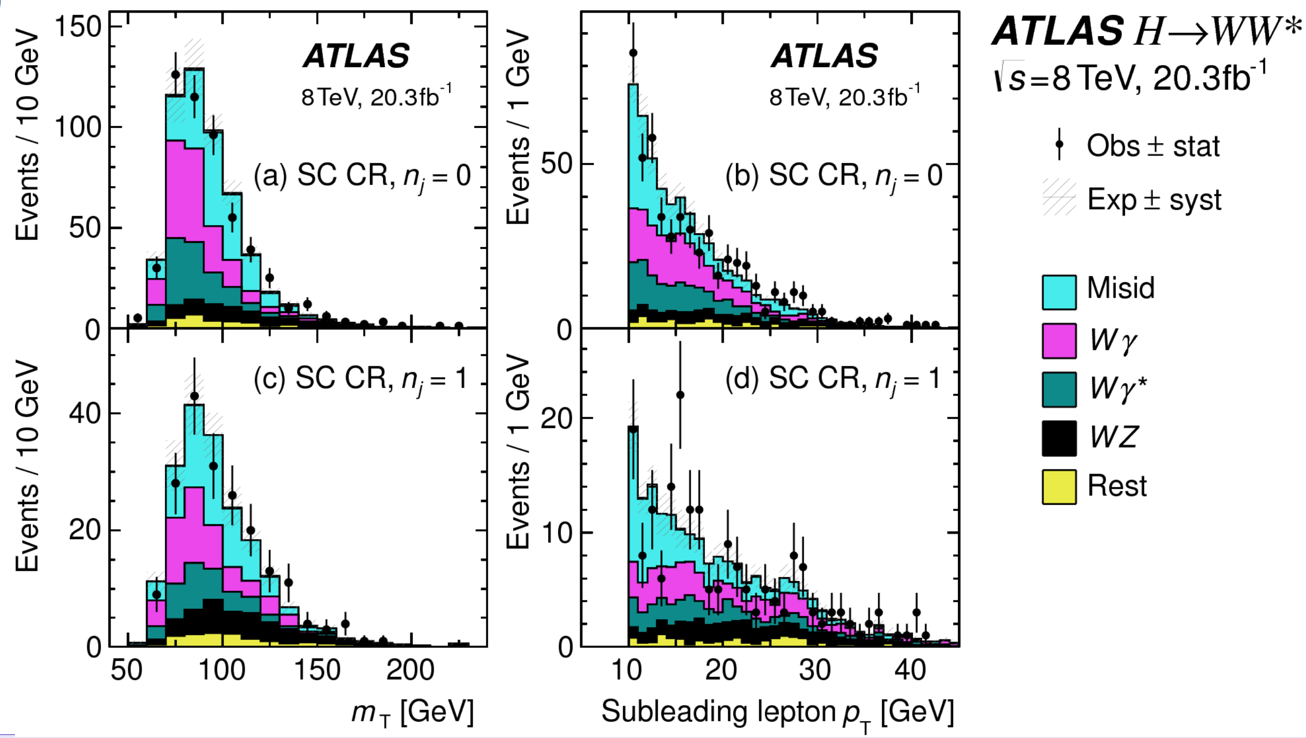
- Same flavour: use MC for normalization

  Validated with the same sign region

Diboson background composition and modelling from MC

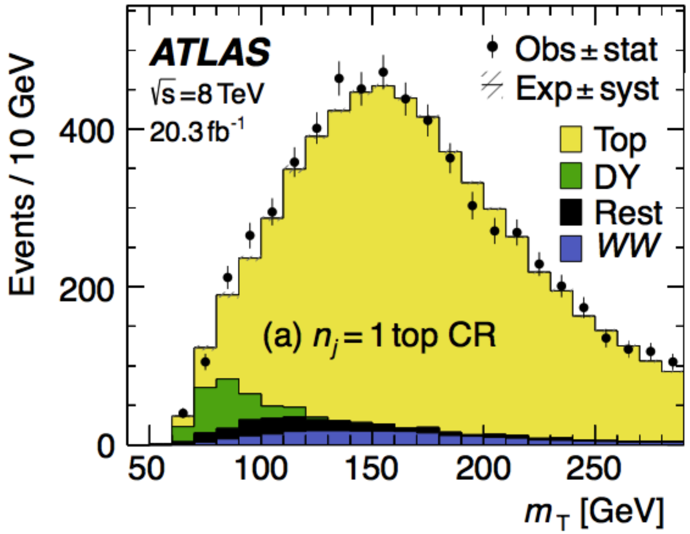
Uncertainty dominated by jet scale (jet bin classification)

Same sign control region



Top quark background estimation

Top control region



Top:

- Includes t-tbar and single top (Wt, qt)
- Control sample: remove jet multiplicity or b-tagging conditions depending on the channel

Details for the 0-jet channel:

- Remove jet multiplicity cut

$$B^{\mathrm{est}}_{\mathrm{top},0j} = N_{\mathrm{CR}} \cdot \underbrace{B_{\mathrm{SR}}/B_{\mathrm{CR}}}_{\alpha^{0j}_{\mathrm{MC}}} \cdot \underbrace{\left(\alpha^{1b}_{\mathrm{data}}/\alpha^{1b}_{\mathrm{MC}}\right)^2}_{\gamma_{1b}}$$

$$\beta^{0j}_{\mathrm{top}} = 1.08 \pm 0.02\,(\mathrm{stat.})$$

$$\left(\alpha^{1b}_{\mathrm{data}}/\alpha^{1b}_{\mathrm{MC}}\right)^2 = 1.006$$

- Small overlap (<3%) of the SR and CR in 0-jet category
- Purity in top quark events: 74%
- Corrected by data/MC differences with a correction factor extracted b-tagged events
  - Jet energy scale and resolution effects
  - Two jets in t-tbar events

WW background estimation

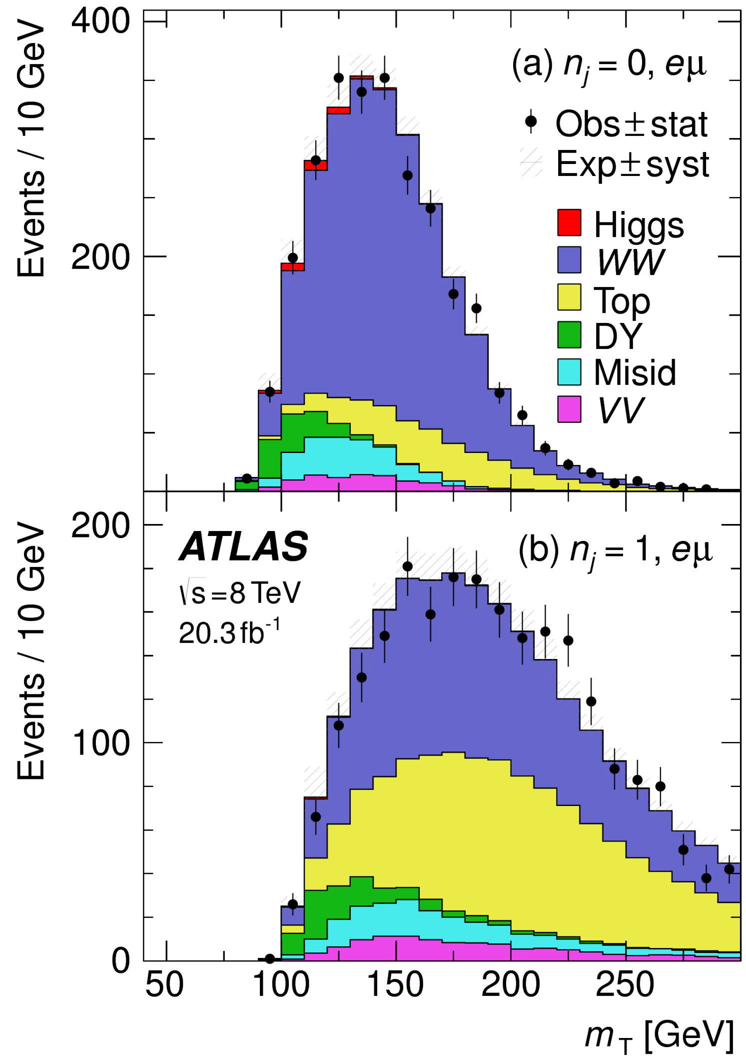
WW:

- Invert $\Delta\phi_{\ell\ell}$ cut, require $55<m_{\ell\ell}<110$ GeV
- Uncertainty dominated by extrapolation to SR

  Due to theoretical uncertainties (limited accuracy of the MC predictions: PDF, QCD factorization and renormalization scales, ...)

$$\beta^{0j}_{WW} = 1.22 \pm 0.03\,(\text{stat.}) \pm 0.10\,(\text{syst.})$$

$$\beta^{1j}_{WW} = 1.05 \pm 0.05\,(\text{stat.}) \pm 0.24\,(\text{syst.})$$



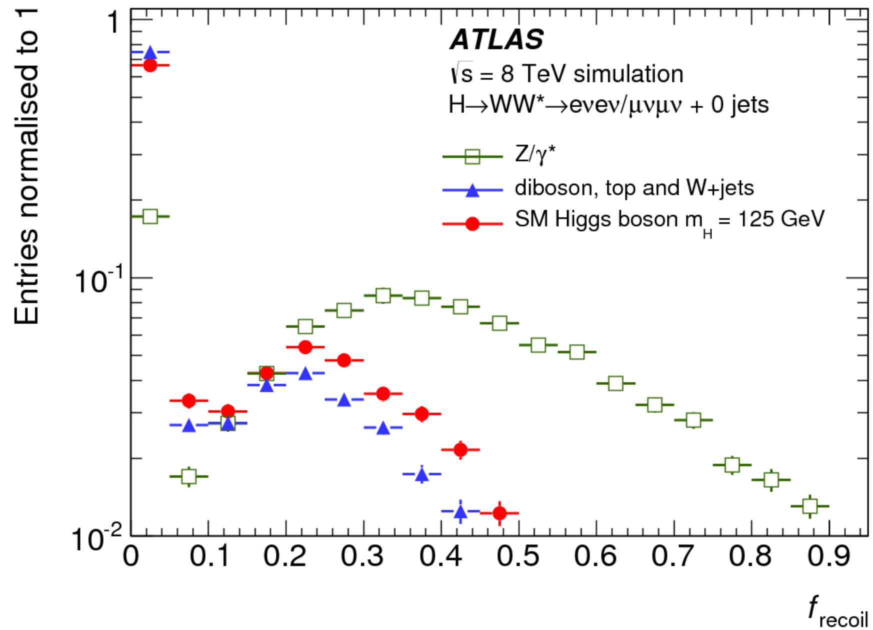
Z/γ* background

- Count events before/after f_{recoil} cut

$$N^{data}_{pass} = N^{Z/\gamma^*}_{pass} + N^{non\text{-}Z/\gamma^*}_{pass}$$

$$N^{data} = \frac{N^{Z/\gamma^*}_{pass}}{\epsilon^{Z/\gamma^*}} + \frac{N^{non\text{-}Z/\gamma^*}_{pass}}{\epsilon^{non\text{-}Z/\gamma^*}}$$

- Solve for N^{Z/γ^*}_{pass}



- Where:

  $\varepsilon^{non\text{-}Z/\gamma*}$ - fraction of eμ + μe data events passing the cut (pure in non-Z /γ*)

  $\varepsilon^{Z/\gamma*}$ - fraction of ee + μμ events passing the cut in the Z peak (dominated by Z/γ*)

- Systematics:

  Compute differences between true and measured efficiencies

  ~50% for 0-jet and ~45% for 1-jet analysis

Leading systematic uncertainties

(a) Uncertainties on N_{sig} (in %)

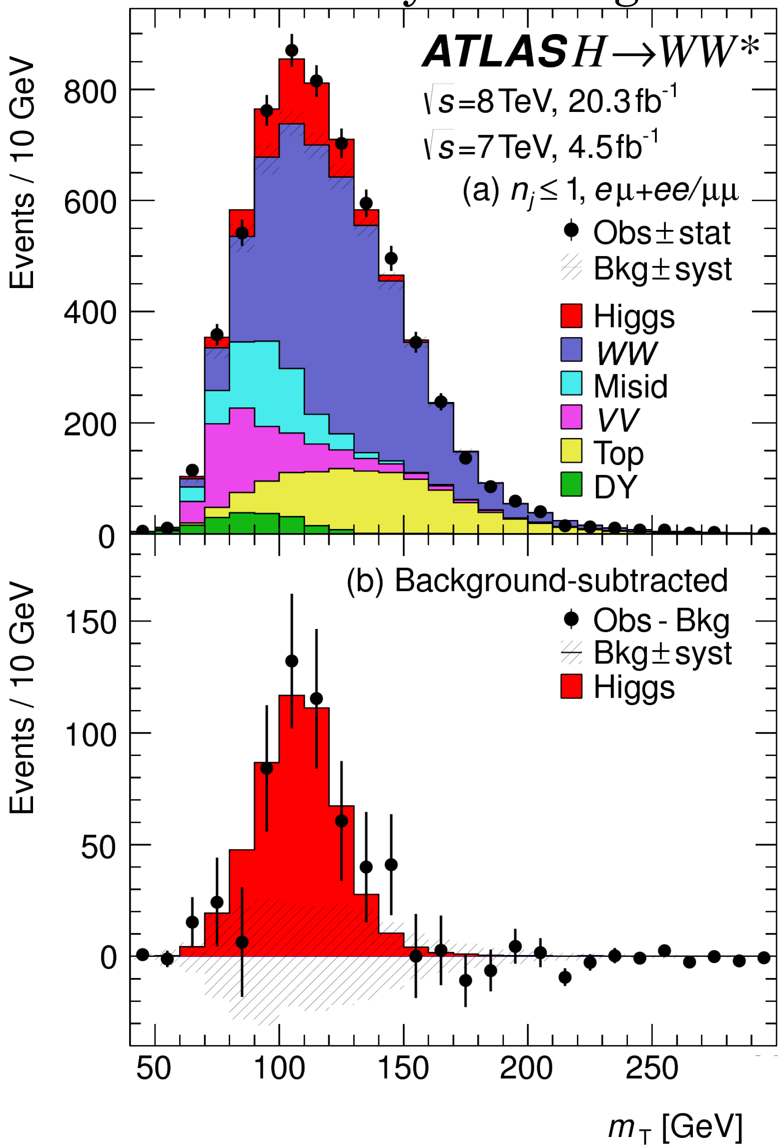
	$n_j = 0$	$n_j = 1$	$n_j \geq 2$ ggF	$n_j \geq 2$ VBF
ggF H, jet veto for $n_j = 0$, ϵ_0	8.1	14	12	-
ggF H, jet veto for $n_j = 1$, ϵ_1	-	12	15	-
ggF H, $n_j \geq 2$ cross section	-	-	-	6.9
ggF H, $n_j \geq 3$ cross section	-	-	-	3.1
ggF H, total cross section	10	9.1	7.9	2.0
ggF H acceptance model	4.8	4.5	4.2	4.0
VBF H, total cross section	-	0.4	0.8	2.9
VBF H acceptance model	-	0.3	0.6	5.5
$H \to WW^*$ branch. fraction	4.3	4.3	4.3	4.3
Integrated luminosity	2.8	2.8	2.8	2.8
Jet energy scale & reso.	5.1	2.3	7.1	5.4
$p_{\text{T}}^{\text{miss}}$ scale & resolution	0.6	1.4	0.1	1.2
f_{recoil} efficiency	2.5	2.1	-	-
Trigger efficiency	0.8	0.7	-	0.4
Electron id., iso., reco. eff.	1.4	1.6	1.2	1.0
Muon id., isolation, reco. eff.	1.1	1.6	0.8	0.9
Pile-up model	1.2	0.8	0.8	1.7

(b) Uncertainties on N_{bkg} (in %)

WW theoretical model	1.4	1.6	0.7	3.0
Top theoretical model	-	1.2	1.7	3.0
VV theoretical model	-	0.4	1.1	0.5
$Z/\gamma^* \to \tau\tau$ estimate	0.6	0.3	1.6	1.6
$Z/\gamma^* \to ee$, $\mu\mu$ est. in VBF	-	-	-	4.8
Wj estimate	1.0	0.8	1.6	1.3
jj estimate	0.1	0.1	1.8	0.9
Integrated luminosity	-	-	0.1	0.4
Jet energy scale & reso.	0.4	0.7	0.9	2.7
$p_{\text{T}}^{\text{miss}}$ scale & resolution	0.1	0.3	0.5	1.6
b-tagging efficiency	-	0.2	0.4	2.0
Light- and c-jet mistag	-	0.2	0.4	2.0
f_{recoil} efficiency	0.5	0.5	-	-
Trigger efficiency	0.3	0.3	0.1	-
Electron id., iso., reco. eff.	0.3	0.3	0.2	0.3
Muon id., isolation, reco. eff.	0.2	0.2	0.3	0.2
Pile-up model	0.4	0.5	0.2	0.8

Signal extraction

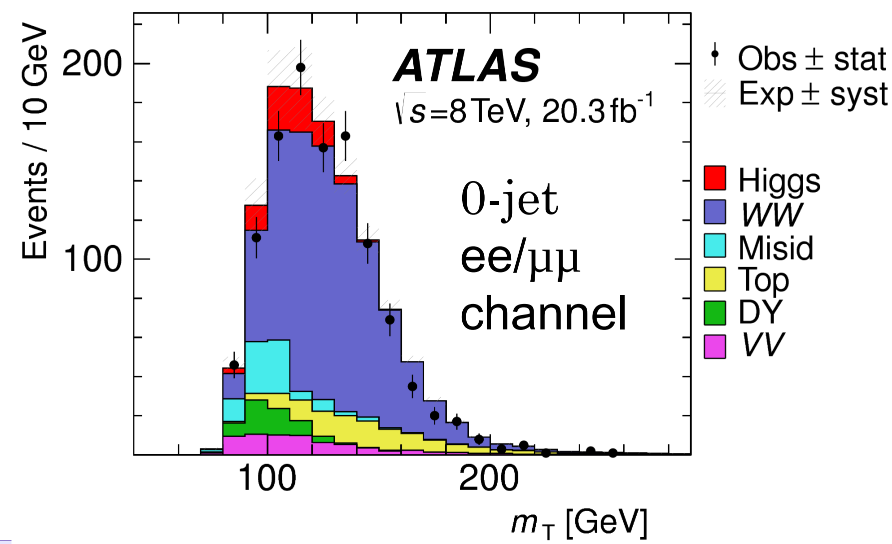
All analysis categories

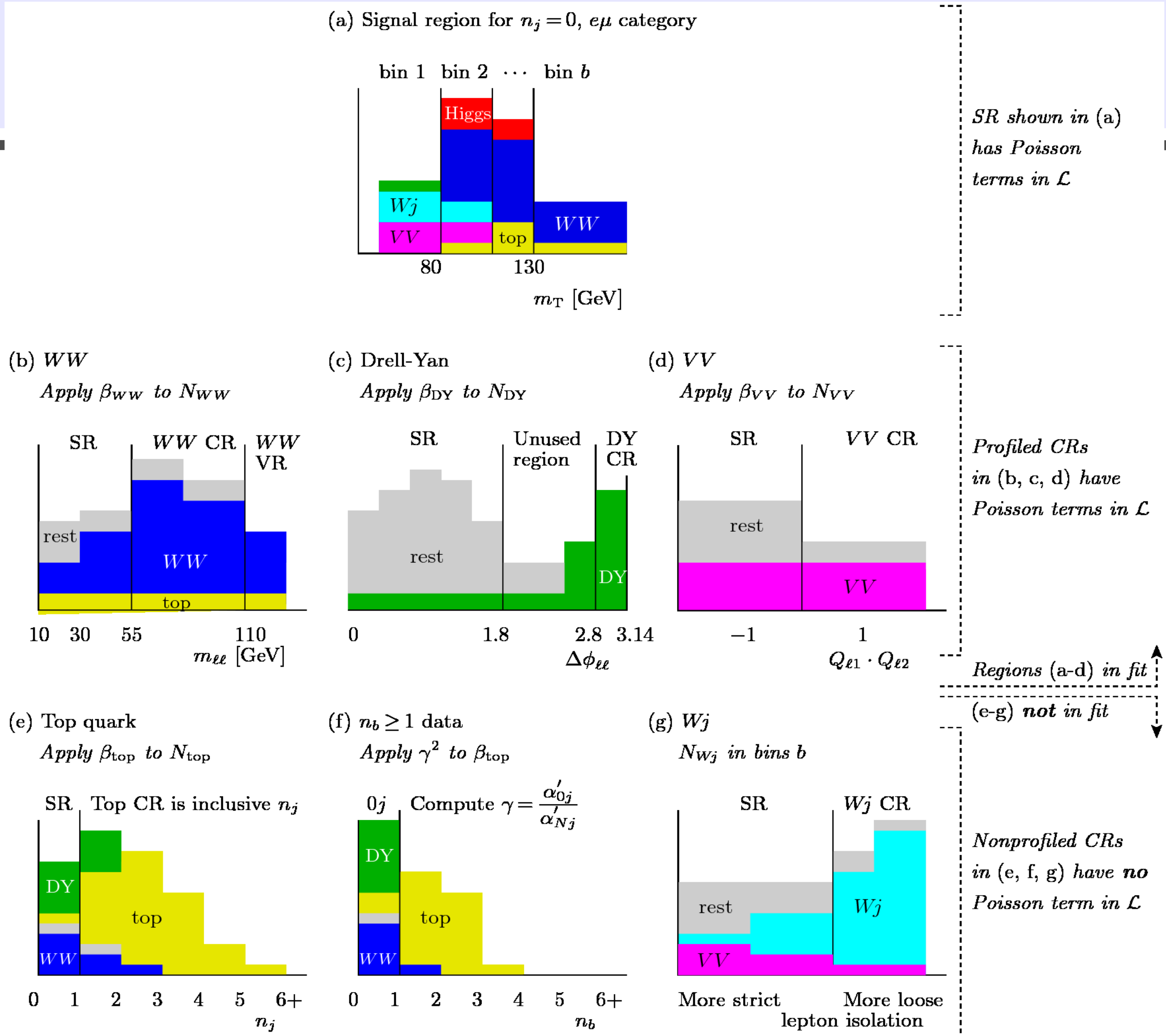


- Fit the transverse mass

$$m_T = \sqrt{(E_T^{\ell\ell} + |\vec{p}_T^{miss}|)^2 - (\vec{p}_T^{\ell\ell} + \vec{p}_T^{miss})^2}$$

- Separate different analysis categories:
  0-, 1-, 2-jets
- Split signal region at m_{ll}= 30 GeV




(a) Signal region for $n_j = 0$, $e\mu$ category
bin 1 bin 2 ··· bin b
Higgs
Wj
VV
top
WW
80
130
m_T [GeV]
SR shown in (a) has Poisson terms in $\mathcal{L}$
(b) WW
Apply β_{WW} to N_{WW}
SR
WW CR
WW VR
rest
WW
top
10 30 55 110
$m_{\ell\ell}$ [GeV]
(c) Drell-Yan
Apply β_{DY} to N_{DY}
SR
Unused region
DY CR
rest
DY
0 1.8 2.8 3.14
$\Delta\phi_{\ell\ell}$
(d) VV
Apply β_{VV} to N_{VV}
SR
VV CR
rest
VV
−1 1
$Q_{\ell 1} \cdot Q_{\ell 2}$
Profiled CRs in (b, c, d) have Poisson terms in $\mathcal{L}$
Regions (a-d) in fit
(e-g) not in fit
(e) Top quark
Apply β_{top} to N_{top}
SR
Top CR is inclusive n_j
DY
top
WW
0 1 2 3 4 5 6+
n_j
(f) $n_b \geq 1$ data
Apply γ^2 to β_{top}
0j
Compute $\gamma = \frac{\alpha'_{0j}}{\alpha'_{Nj}}$
DY
top
WW
0 1 2 3 4 5 6+
n_b
(g) Wj
N_{Wj} in bins b
SR
Wj CR
rest
Wj
VV
More strict
More loose
lepton isolation
Nonprofiled CRs in (e, f, g) have no Poisson term in $\mathcal{L}$

Signal extraction

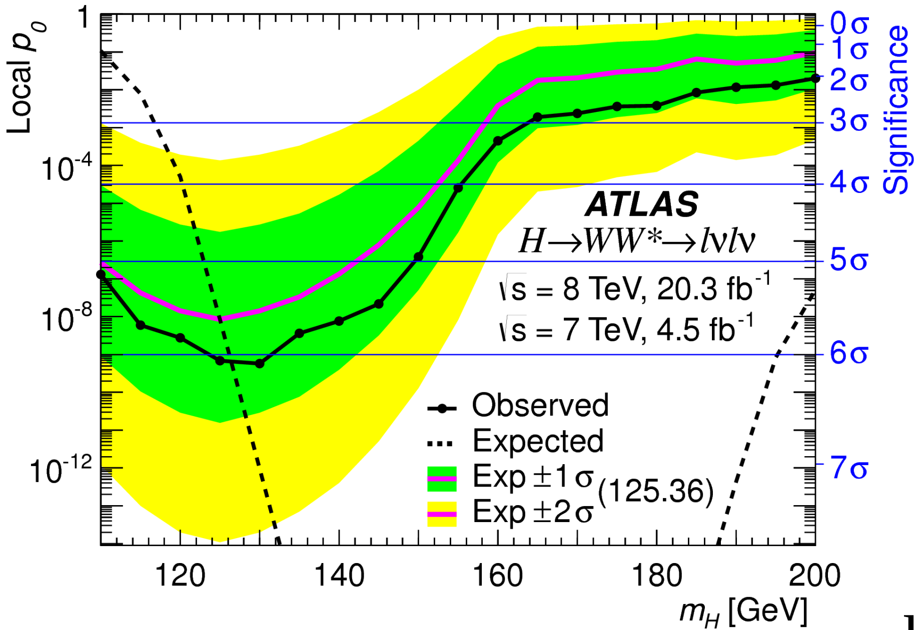
$$\mathcal{L} = \underbrace{\prod_{i,b}^{\text{Table XXIa}} f\left(N_{ib} \,\middle|\, \mu \cdot S_{ib} \cdot \prod_{r}^{\text{Syst. in Sec. V}} \nu_{br}(\theta_r) + \sum_{k}^{\text{Table I}} \beta_k \cdot B_{kib} \cdot \prod_{s}^{\text{Syst. in Sec. VII C}} \nu_{bs}(\theta_s)\right)}_{\text{Poisson for SR with signal strength } \mu\text{; predictions } S,\, B} \cdot \underbrace{\prod_{l}^{\text{Table XXIb}\,\bullet} f\left(N_l \,\middle|\, \sum_{k}^{\text{Table I}} \beta_k \cdot B_{kl}\right)}_{\text{Poisson for profiled CRs}} \cdot \underbrace{\prod_{t}^{\text{Syst. in }\{r,\,s\}} g(\vartheta_t|\theta_t)}_{\text{Gauss. for syst.}} \cdot \underbrace{\prod_{k}^{\text{Table I}} f(\xi_k \,|\, \zeta_k \cdot \theta_k)}_{\text{Poiss. for MC stats}}$$

- Global fit for all signal and background regions
- μ = signal strength
- Poisson terms for signal and background normalization
- Constraints of the systematic uncertainties

(a) Signal region categories

SR category i				Fit var.
n_j, flavor	$\otimes\, m_{\ell\ell}$	$\otimes\, p_T^{\ell 2}$	$\otimes\, \ell_2$	
$n_j = 0$				
$e\mu$	$\otimes\,[10, 30, 55]$	$\otimes\,[10, 15, 20, \infty]$	$\otimes\,[e, \mu]$	m_T
$ee/\mu\mu$	$\otimes\,[12, 55]$	$\otimes\,[10, \infty]$		m_T
$n_j = 1$				
$e\mu$	$\otimes\,[10, 30, 55]$	$\otimes\,[10, 15, 20, \infty]$	$\otimes\,[e, \mu]$	m_T
$ee/\mu\mu$	$\otimes\,[12, 55]$	$\otimes\,[10, \infty]$		m_T
$n_j \geq 2$ ggF				
$e\mu$	$\otimes\,[10, 55]$	$\otimes\,[10, \infty]$		m_T
$n_j \geq 2$ VBF				
$e\mu$	$\otimes\,[10, 50]$	$\otimes\,[10, \infty]$		O_{BDT}
$ee/\mu\mu$	$\otimes\,[12, 50]$	$\otimes\,[10, \infty]$		O_{BDT}

H→WW results

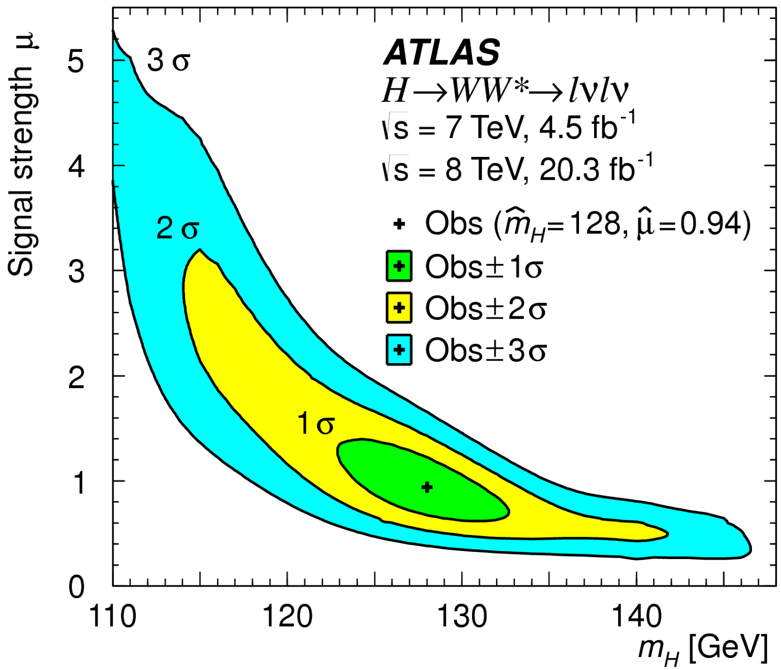


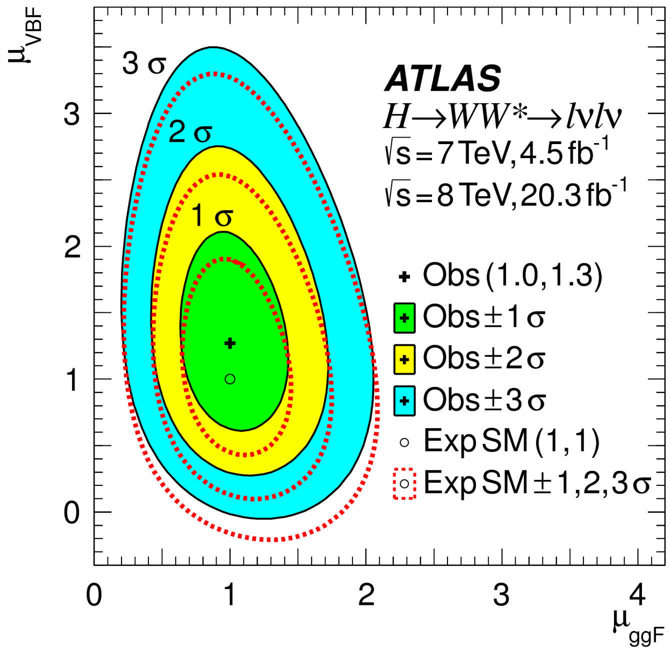
- p_0 = probability that the observed excess of events is due to a background fluctuation
- Minimum p^0 at 130 GeV (6.1σ)
- Same p0 at 125.36 GeV

  Expected 5.8σ
- Signal strength at 125.36 GeV:

$$\mu = 1.09\ ^{+0.16}_{-0.15}\,(\text{stat.})\ ^{+0.17}_{-0.14}\,(\text{syst.})$$

Signal strength

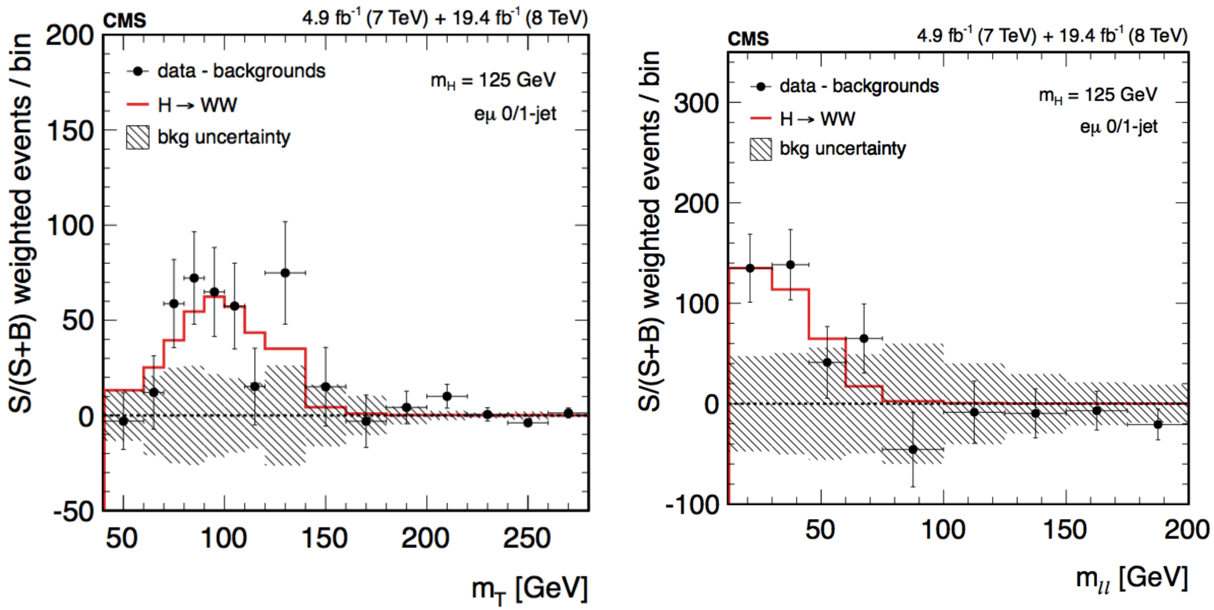




- Signal strength compatible with SM expectations

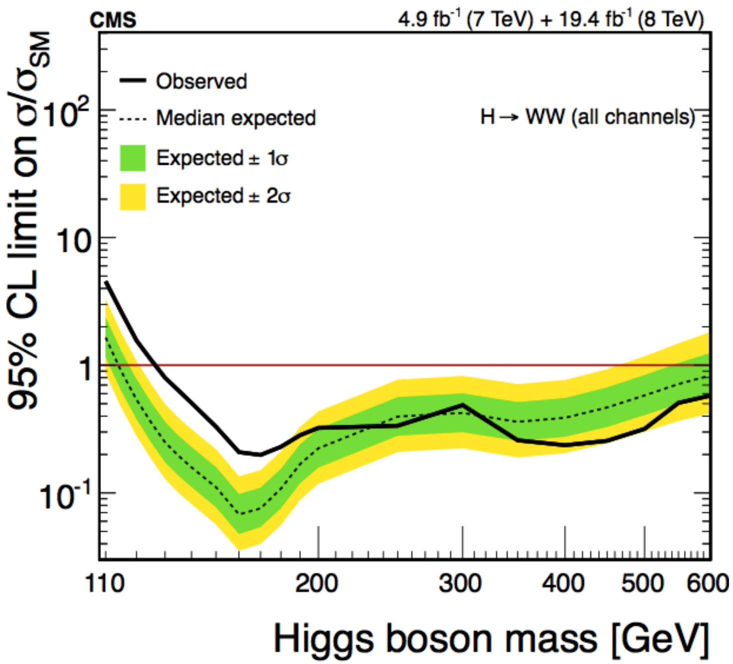
$$\begin{aligned} \mu_{\text{ggF}} &= 1.02 \pm 0.19 \; {}^{+0.22}_{-0.18} = 1.02 \; {}^{+0.29}_{-0.26} \\ \mu_{\text{VBF}} &= 1.27 \; {}^{+0.44}_{-0.40} \; {}^{+0.30}_{-0.21} = 1.27 \; {}^{+0.53}_{-0.45}. \\ & \qquad\quad (\text{stat.}) \; (\text{syst.}) \end{aligned}$$

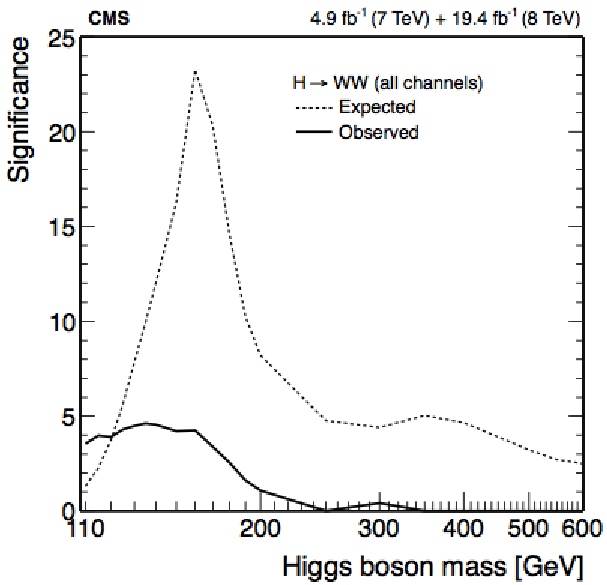
- m_T and m_{ll} after the final selection:



- In addition, they consider also a 3-lepton category (VH associated production)

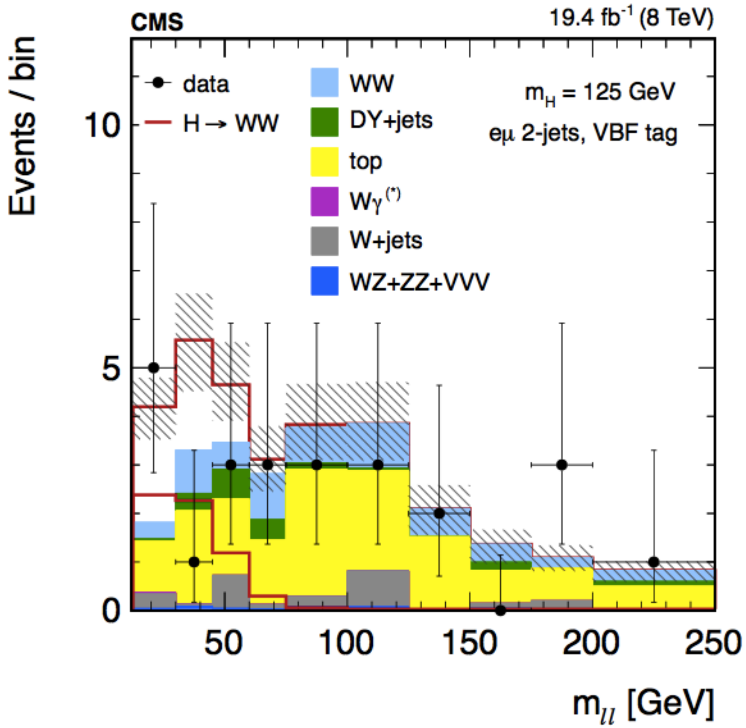
Combined results

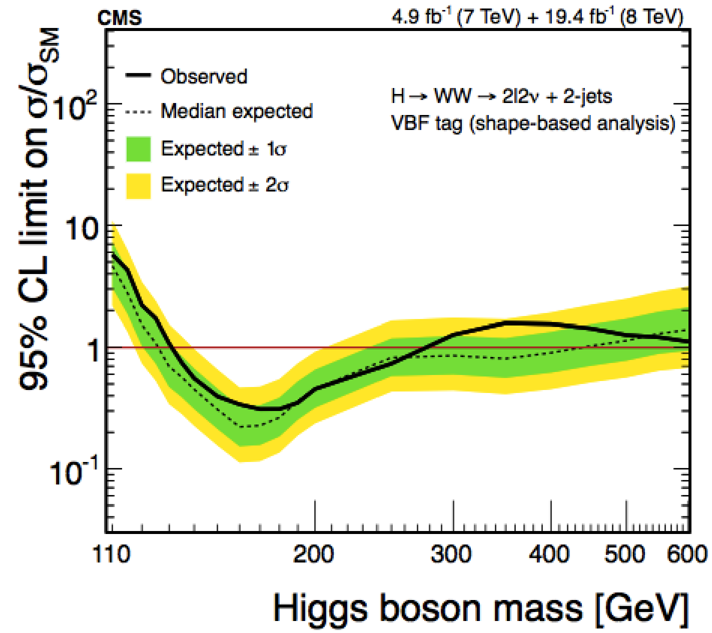




0/1-jet analysis $m_H = 125\,\text{GeV}$	95% CL limits on σ/σ_{SM} expected / observed	Significance expected / observed	σ/σ_{SM} observed
$(m_T, m_{\ell\ell})$ template fit (default)	0.4 / 1.2	5.2 / 4.0 sd	0.76 ± 0.21
$(m_R, \Delta\phi_R)$ parametric fit	0.5 / 1.4	5.0 / 4.0 sd	0.88 ± 0.25
Counting analysis	0.7 / 1.4	2.7 / 2.0 sd	0.72 ± 0.37

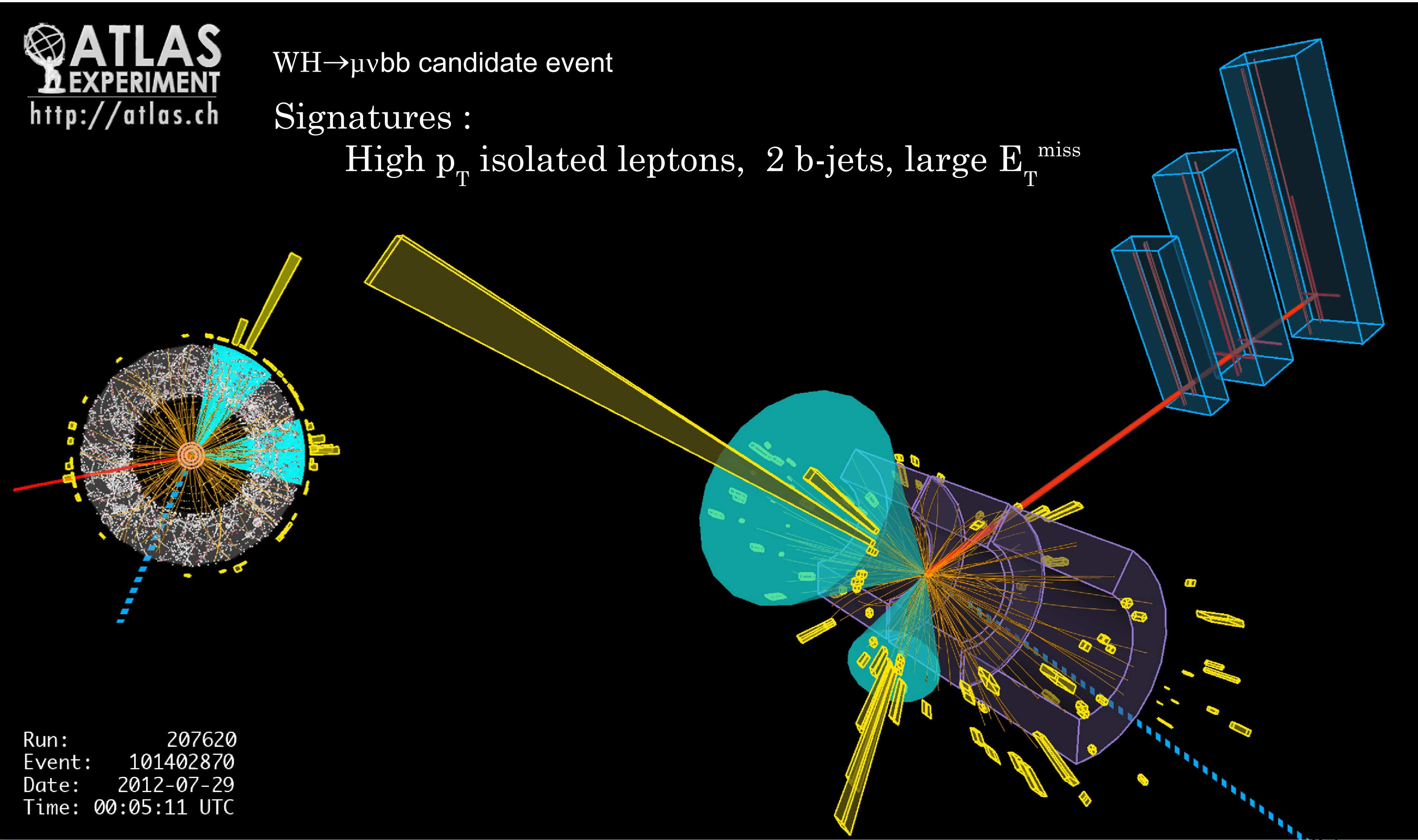
CMS H→WW VBF results



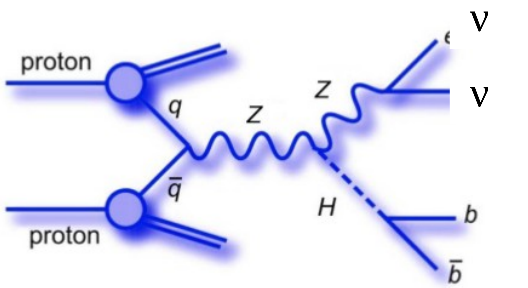


VBF analysis $m_H = 125\,\text{GeV}$	95% CL limits on σ/σ_{SM} expected / observed	Significance expected / observed	σ/σ_{SM} observed
Shape-based (default)	1.1 / 1.7	2.1 / 1.3 sd	$0.62^{+0.58}_{-0.47}$
Counting analysis	1.1 / 0.9	2.0 / —	$-0.35^{+0.43}_{-0.45}$

WH→μνbb candidate event

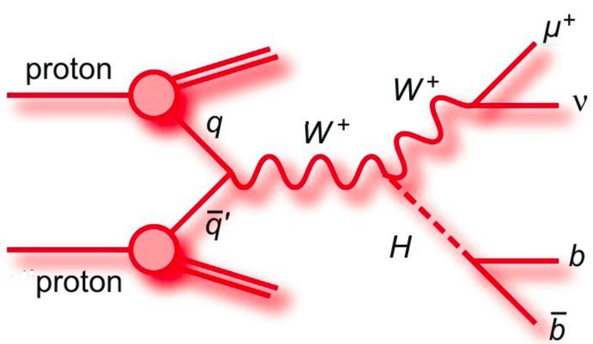


VH searches: 3 channels



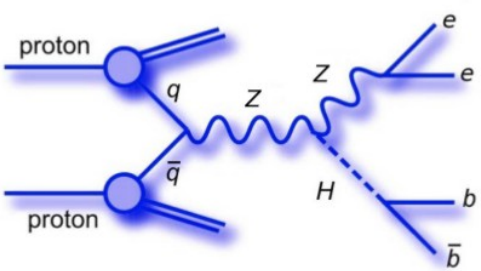
0-lepton:

- Large MET



1-lepton:

- 1 good lepton
- MET, m_T^W consistent with W boson decay



2-leptons:

- 2 good leptons
- No MET
- Di-lepton mass compatible with m_Z

Plus 2 good b-tagged jets

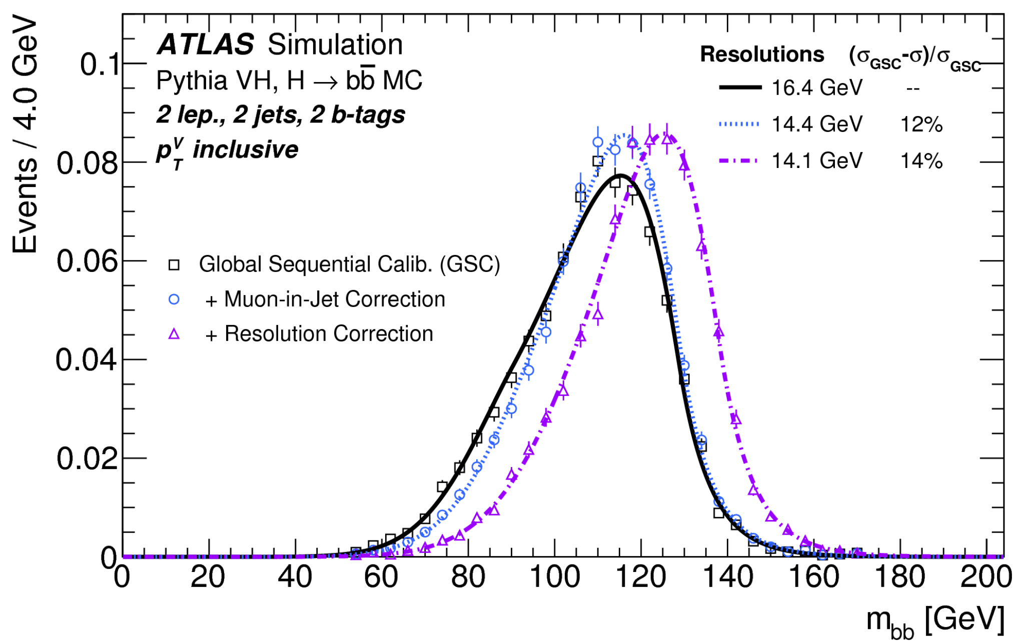
- anti-kT with R=0.4
- P_T^{j1}>45 GeV
  p_T^{j2}>20 GeV
- p_T^V dependent ΔR cut

Dominant backgrounds:

- Top
- V+heavy flavour jets

Signal mass resolution

- Improved mass resolution applying dedicated jet corrections
  - Correction for muons in b-decays
  - Correction for resolution effects (specific to Higgs decays)
  - Resolution extracted from a Bukin function fit



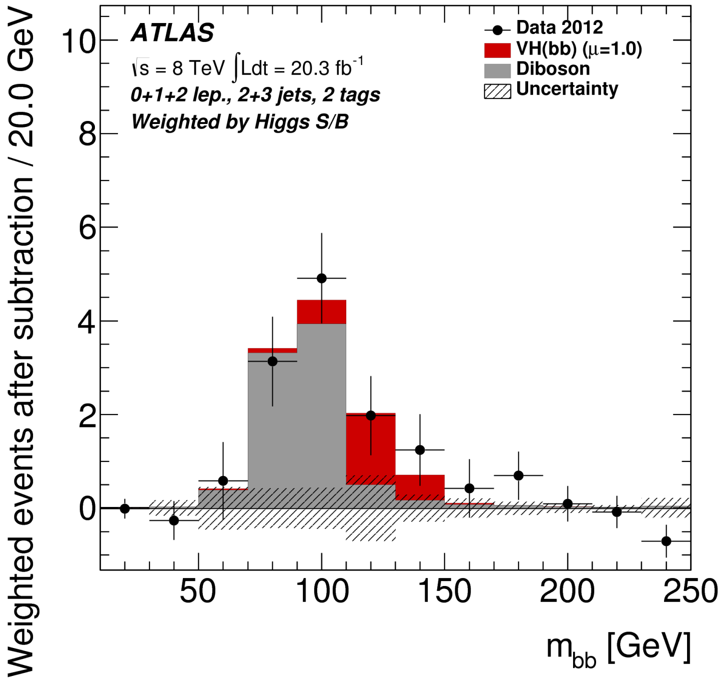
Fit validation: SM di-boson fit

- Fit strategy tested searching for the SM di-boson signal:

WZ+ZZ with Z→bb

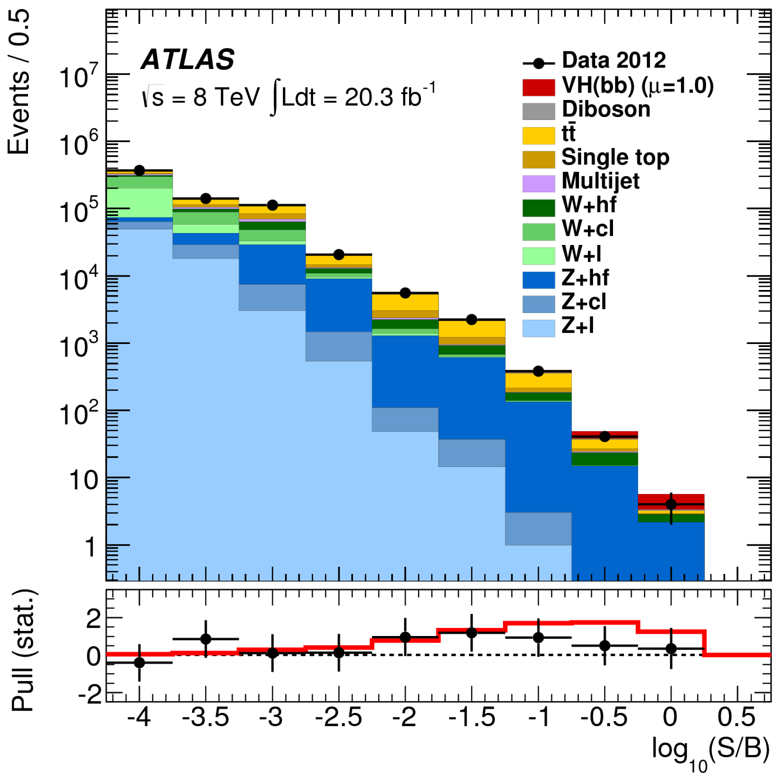
- Signal strength for the di-boson signal:

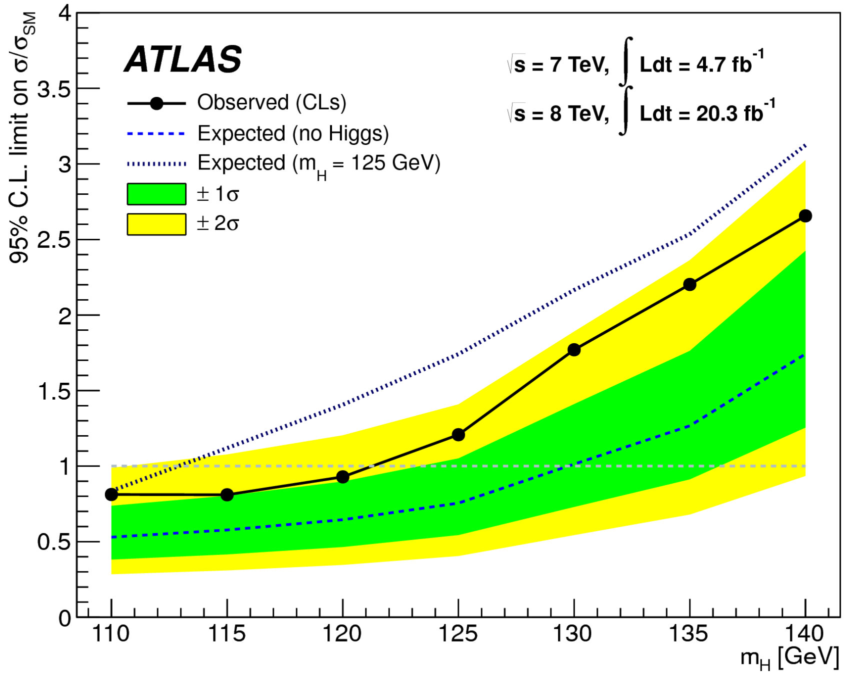
$$\mu_{VZ} = 0.74 \pm 0.09(\text{stat.}) \pm 0.14(\text{syst.})$$



VH ($H \rightarrow bb$) results

- Signal region divided in p_T^V and number of jets bins
- Combined m_{bb} fit to all signal and backgrounds regions

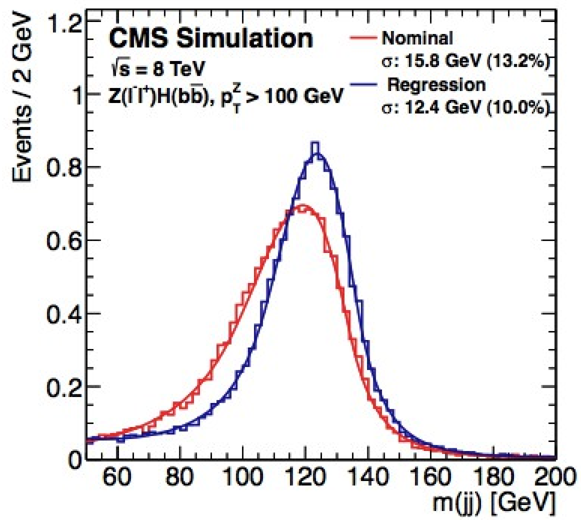




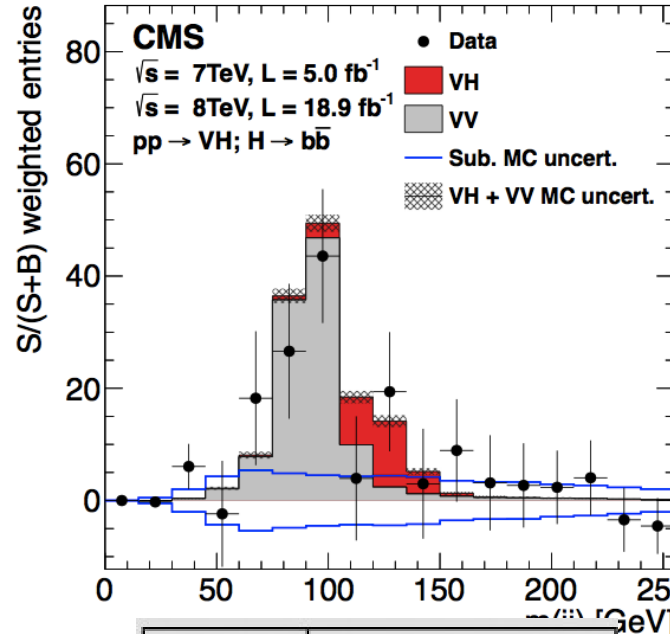
$$\mu = 0.52 \pm 0.32(\text{stat.}) \pm 0.24(\text{syst.})$$

CMS VH→bb

- BDT to
  - Improve mass resolution
  - Optimize signal to background separation

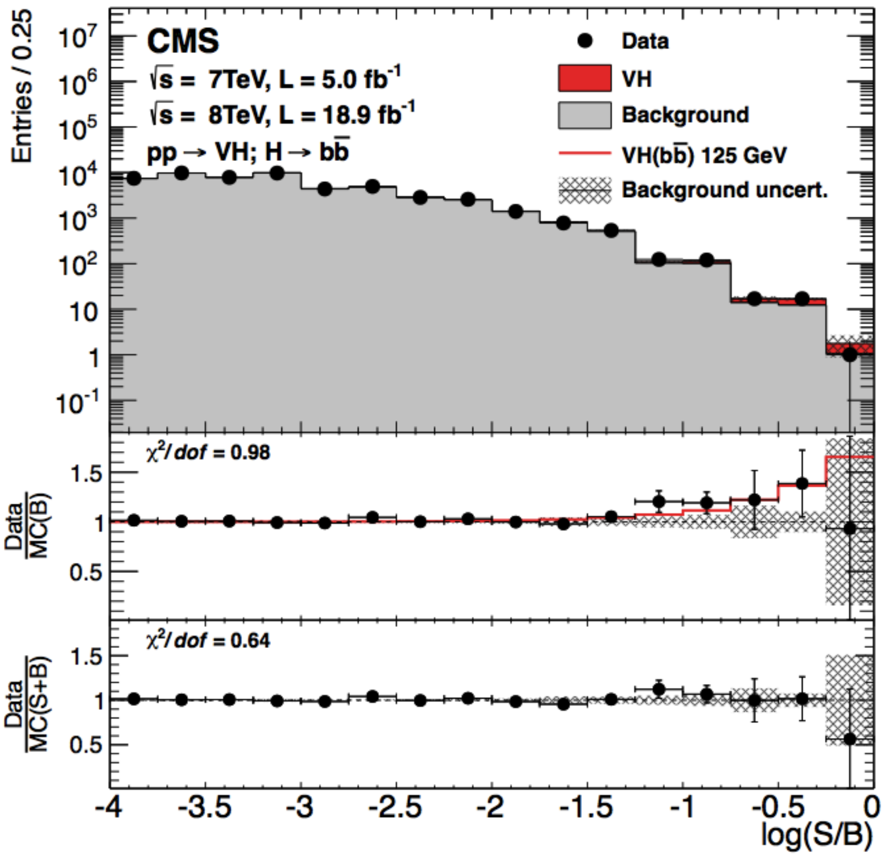


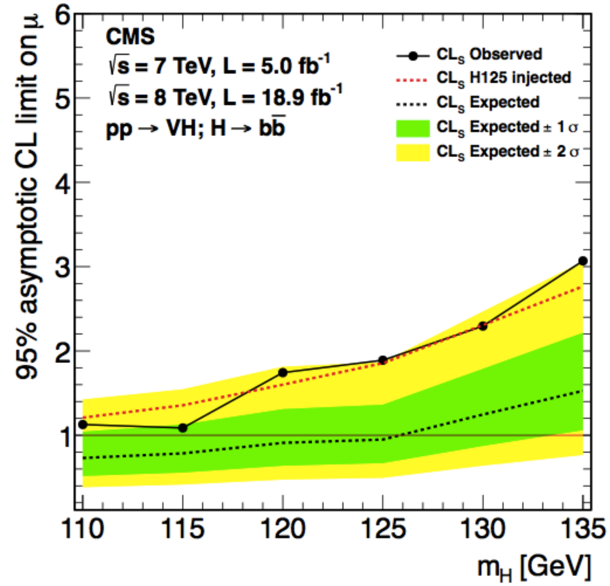
- VZ, with Z→bb, analysis:



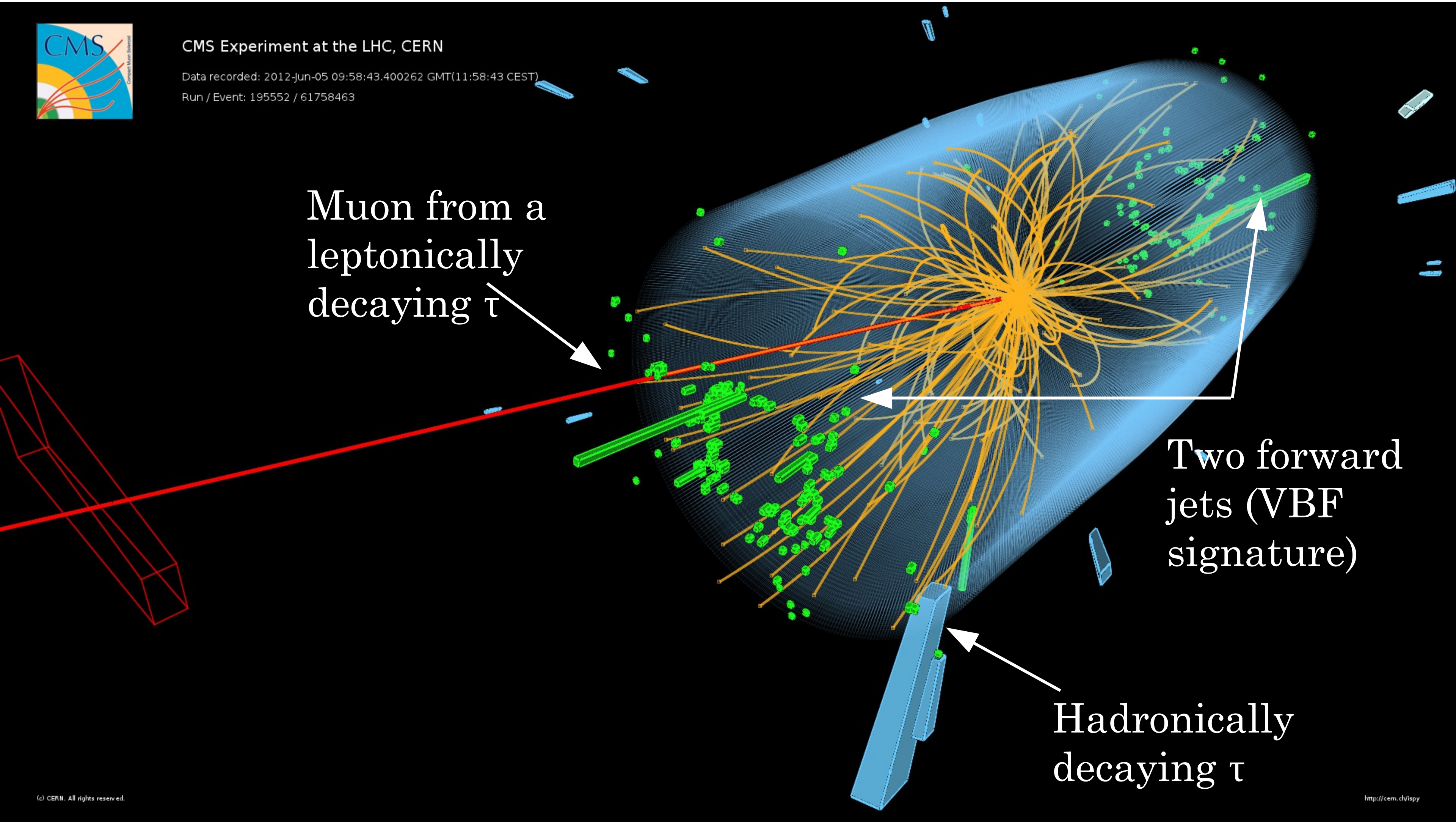
	BDT VZ(bb)
Exp. Sig	6.3 σ
Obs. Sig	7.5 σ
μ	$1.19^{+0.27}_{-0.23}$

CMS VH→bb results





- Excess of event observed at around 125 GeV
  - 2.1σ significance (local)
  - Compatible with a 125 GeV SM Higgs expectation


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-Jun-05 09:58:43.400262 GMT(11:58:43 CEST)
Run / Event: 195552 / 61758463
Muon from a leptonically decaying τ
Two forward jets (VBF signature)
Hadronically decaying τ
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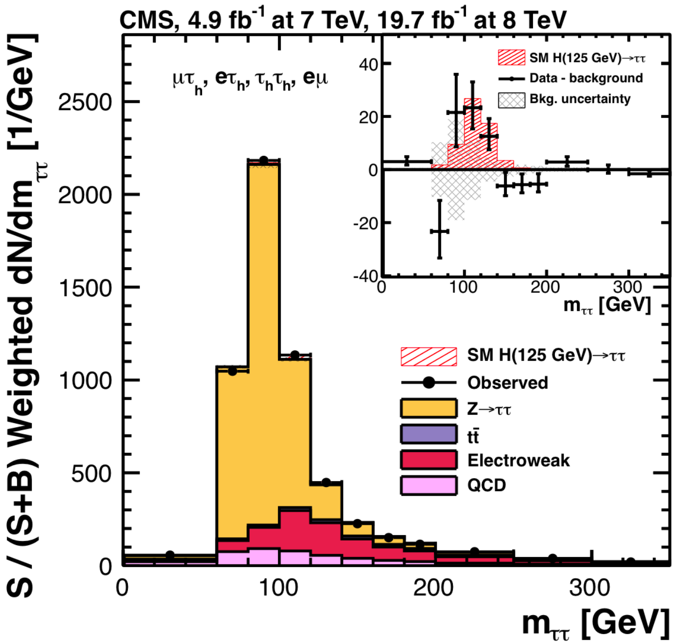
http://cern.ch/ispy

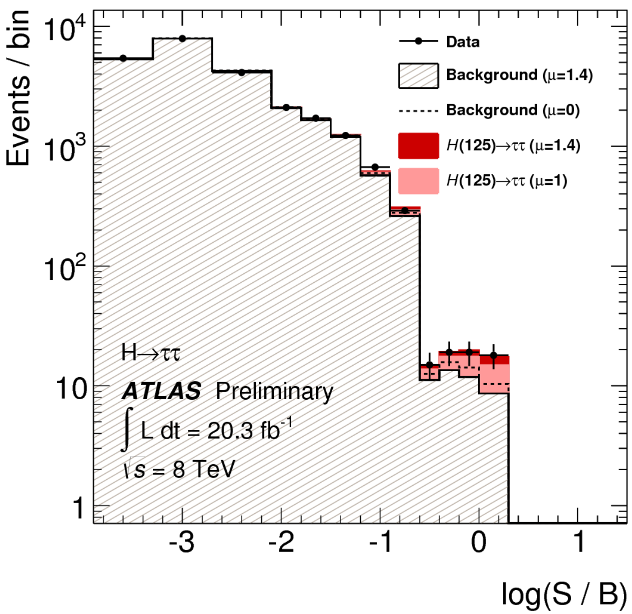
H→ττ results

- Using MVA to better disentangle signal from background

CMS ττ mass



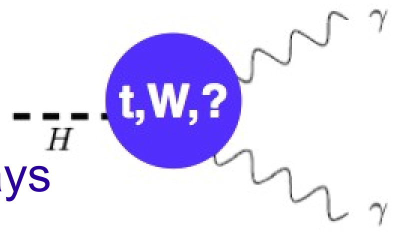
Combined BDT score for all the search channels

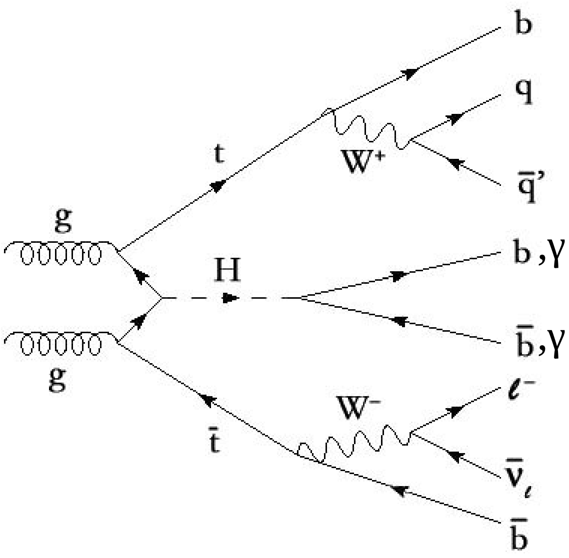


- Evidence for the Higgs decaying to ττ pairs in both experiments
- Signal strength: $\mu = \sigma/\sigma_{SM} = 1.4^{+0.5}_{-0.4}$ at ATLAS and 0.78±0.27 in CMS

Associated production ttH

- Very challenging channel
- Important to measure top to Higgs coupling directly
  - Indirect constraints from ggH production and Hγγ decays
  - Allows probing for New Physics contributions in the ggH and γγH vertices





ATLAS-CONF-2014-043
arXiv:1408.1682

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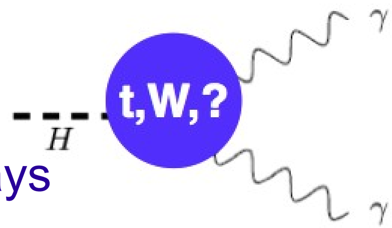
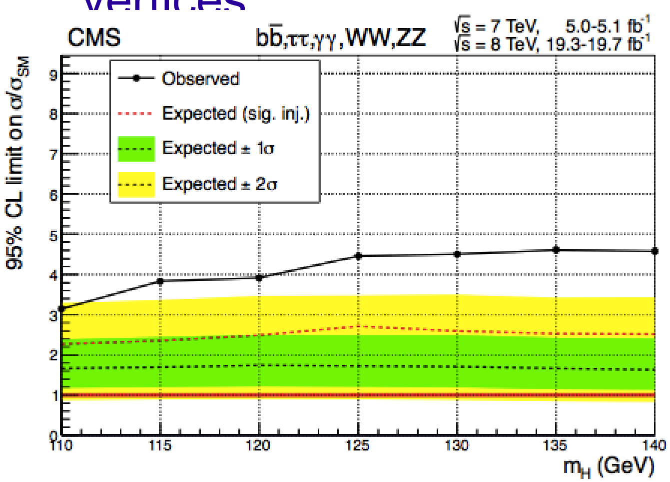
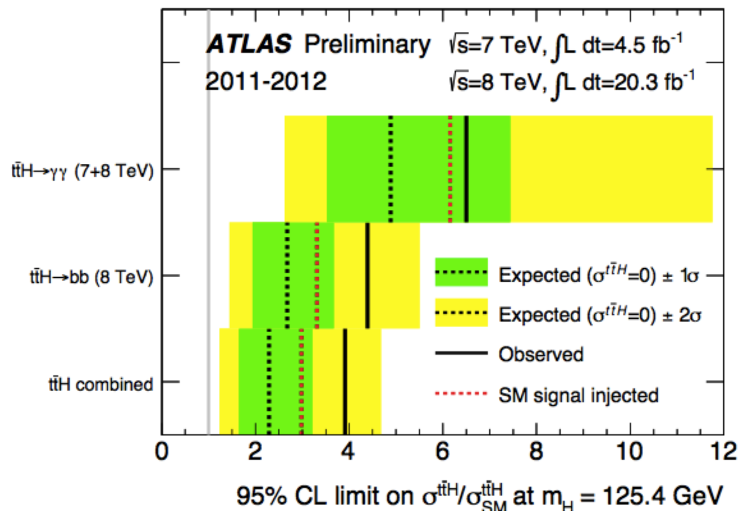






- CMS observes an excess of events corresponding to $\mu = 2.8 \pm 1$
- ATLAS best fit signal strength: $\mu = 1.6 \pm 0.6(\text{stat.})\, ^{+1.1}_{-1.0}\,(\text{syst.})$

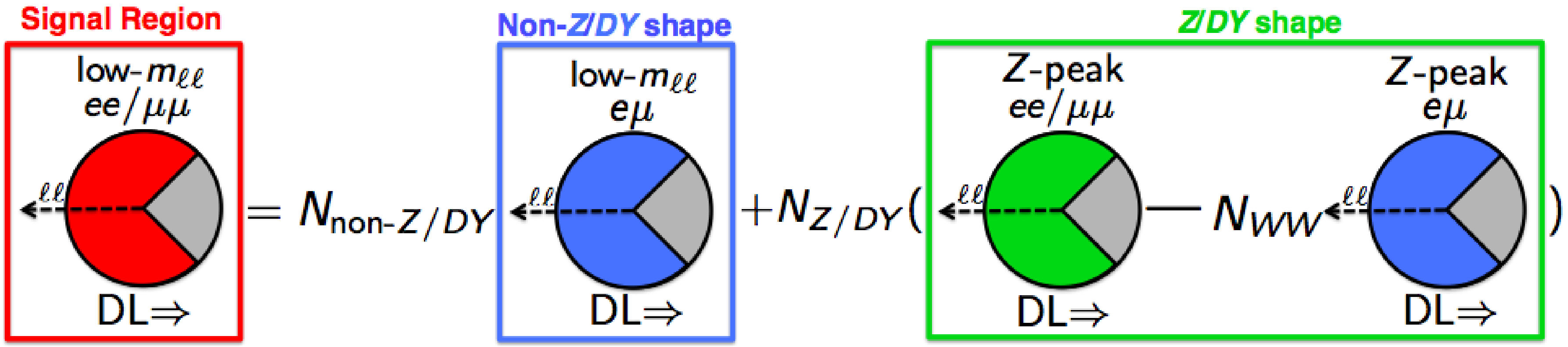
Summary and conclusions

- Both, ATLAS and CMS, collaborations observed a new boson in July 2012
  - Original observation based on 3 channels with partial statistics
  - Since then, statistics increased, and the analysis were refined
  - Signal observed in individual decay channels
  - Evidence of fermionic decays
    - $H \rightarrow \tau\tau$, $H \rightarrow bb$
- Work continues now to understand if this is the SM Higgs boson or any other boson
  - Measure all its properties accurately (production and decay rates, spin, C and P, …)
- Measurement of the new boson properties will be the subject of the next Higgs lecture

Backup

Pacman method - systematic uncertainties and advantages

- Assign systematic uncertainties on ϵ by computing difference between measured efficiencies and true efficiencies:
  - different flavour $\rightarrow$ same flavour extrapolation for $\epsilon^{\text{non-}Z/\gamma^*}$
  - Z peak $\rightarrow$ signal region extrapolation for ϵ^{Z/γ^*}
  - Largest systematic 27% on Z/γ^* efficiency.
- Final uncertainity on Z/γ^* estimate obtained by propagating:
  - Systematic uncertainties on the efficiencies.
  - Statistical uncertainty on the data.
  - $\sim$ 60% uncertainty for 0-jet and $\sim$ 80% uncertainty for 1-jet.
- Advantages of this method:
  - Uses directly the final signal region.
  - Estimate is insensitive to the presence of signal.
  - Does not rely on MC modelling.
  - Final uncertainty on the estimate dominated by data statistics.



H→γγ background modelling

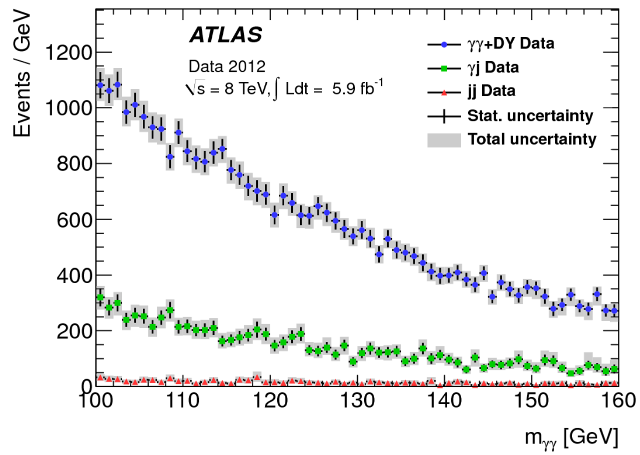
Background composition:

- Dominated by continuum γγ production (75%), followed by γ+jet, jet+jet

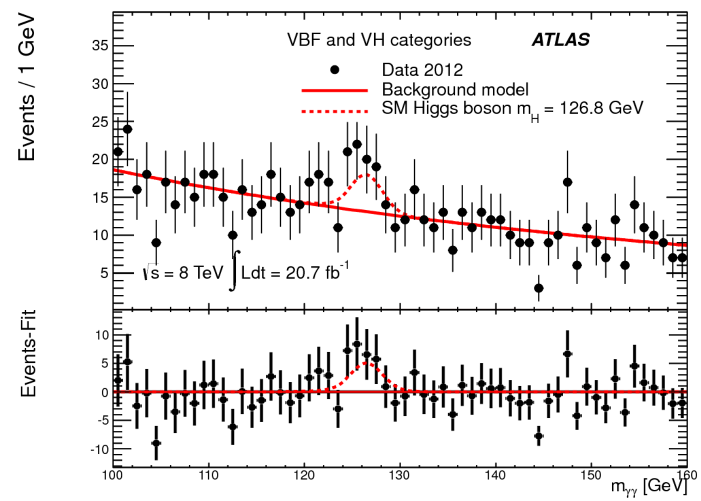
Background estimated by fitting the di-photon mass distribution

- Studied for each category with high-statistics MC before looking at data
- Considered: n-order Bernstein polynomial, exp(P2), exponential
- Choice based on largest expected sensitivity for 125 GeV signal

  Largest residual bias seen in MC experiments over 110-150 GeV taken as signal yield systematic



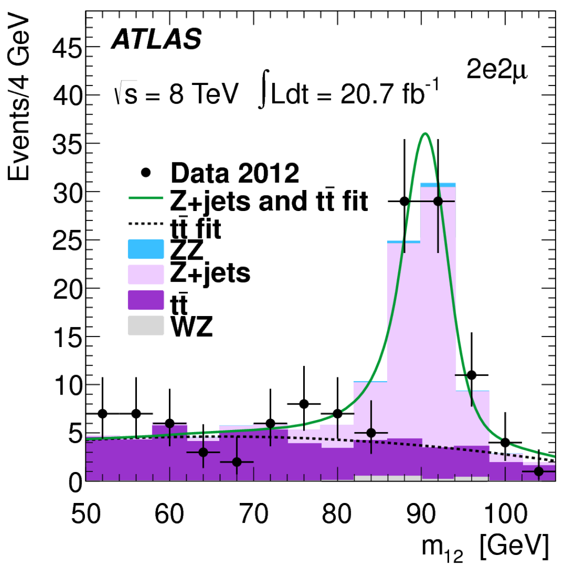
Example of a fit



Background estimation

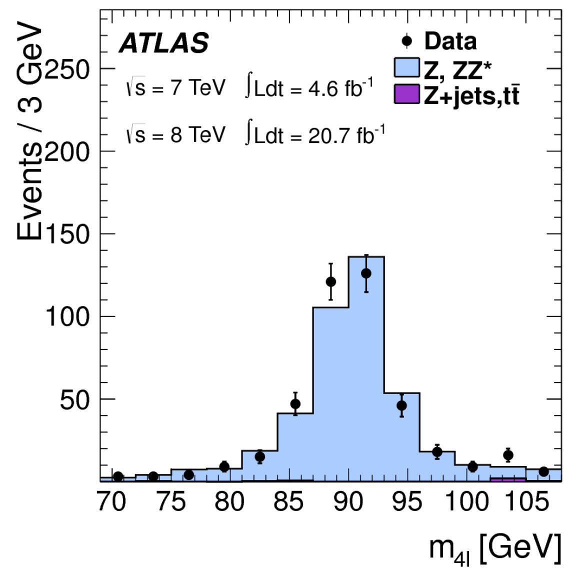
- ZZ continuum estimated with MC simulation
- Z+jets and tt backgrounds estimated using control regions
  - Transfer factors from control to signal regions from MC

Z+jets, tt control region:



- No isolation or transverse impact parameter requirements on the sub-leading lepton pair

Z→4ℓ control region:

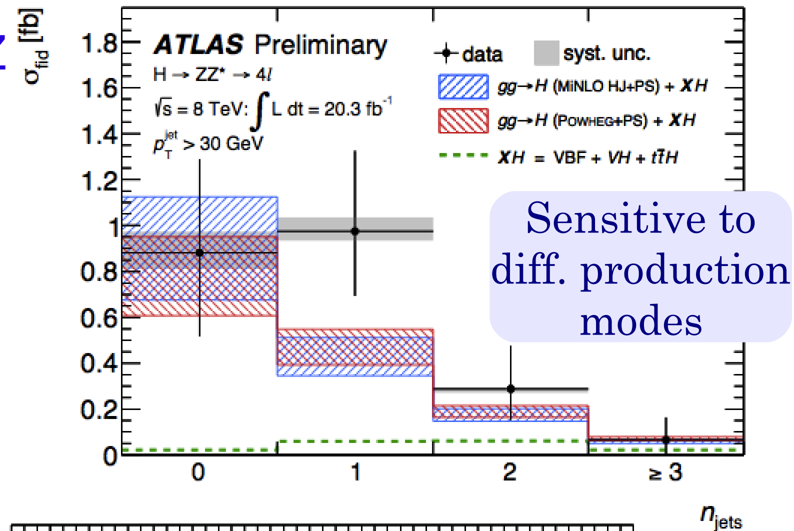


- Relax invariant mass requirements on the lepton pairs

Differential fiducial cross sections

- Calculated differential cross sections in many different variables in H→γγ and H→ZZ
  - Test theoretical predictions
  - Sensitive to new physics effects

H→ZZ



H→γγ