Results from the Higgs Searches at the LHC

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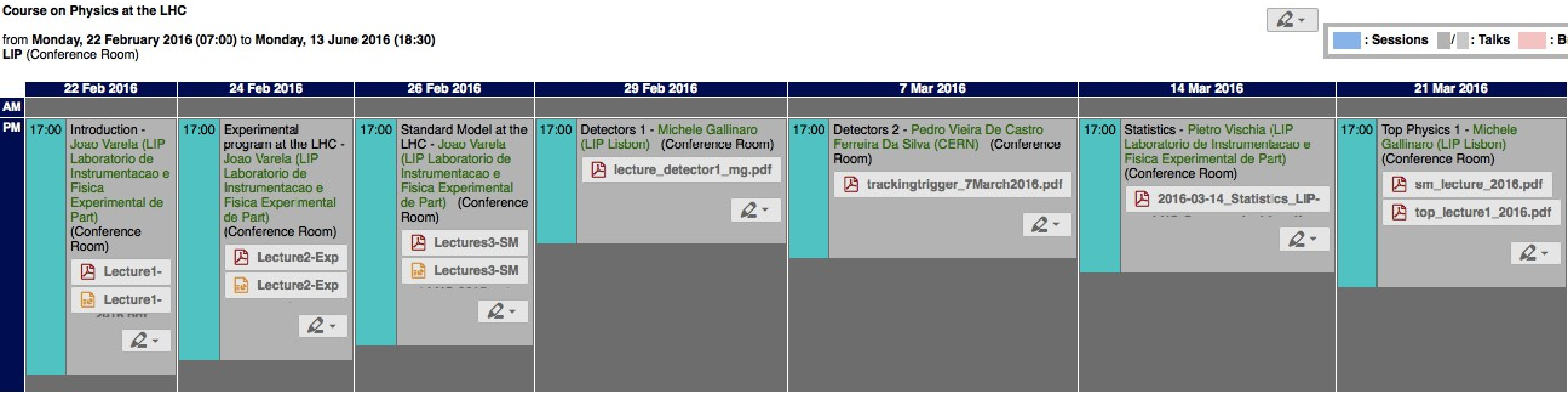
Up to now



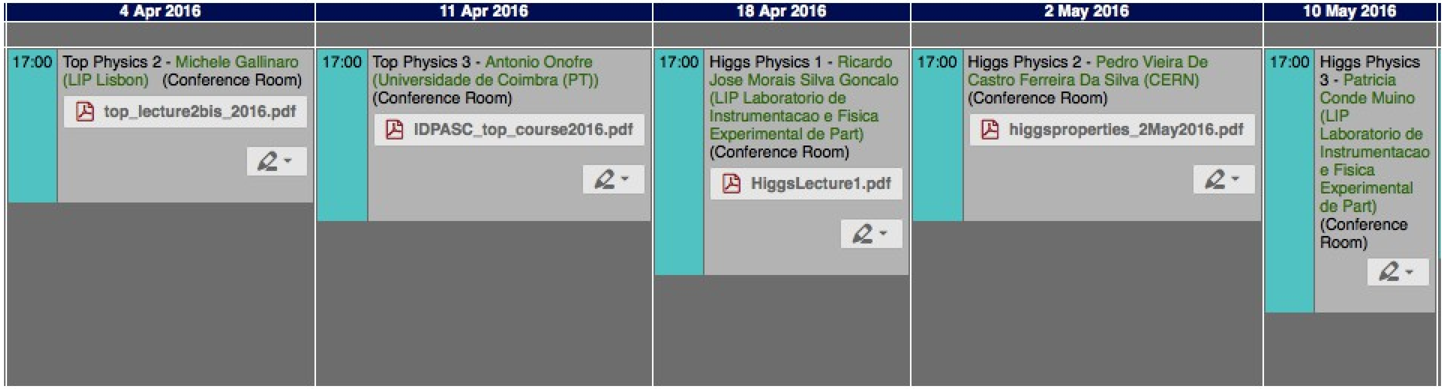
Course on Physics at the LHC

from **Monday, 22 February 2016 (07:00)** to **Monday, 13 June 2016 (18:30)**
LIP (Conference Room)

🟦 : Sessions ▨/▨ : Talks 🟥 : B

	22 Feb 2016	24 Feb 2016	26 Feb 2016	29 Feb 2016	7 Mar 2016	14 Mar 2016	21 Mar 2016
AM							
PM	17:00 Introduction - Joao Varela (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part) (Conference Room) Lecture1- Lecture1-	17:00 Experimental program at the LHC - Joao Varela (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part) (Conference Room) Lecture2-Exp Lecture2-Exp	17:00 Standard Model at the LHC - Joao Varela (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part) (Conference Room) Lectures3-SM Lectures3-SM	17:00 Detectors 1 - Michele Gallinaro (LIP Lisbon) (Conference Room) lecture_detector1_mg.pdf	17:00 Detectors 2 - Pedro Vieira De Castro Ferreira Da Silva (CERN) (Conference Room) trackingtrigger_7March2016.pdf	17:00 Statistics - Pietro Vischia (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part) (Conference Room) 2016-03-14_Statistics_LIP-	17:00 Top Physics 1 - Michele Gallinaro (LIP Lisbon) (Conference Room) sm_lecture_2016.pdf top_lecture1_2016.pdf

- LHC, detectors, statistics, top physics and first lectures of Higgs
- Now: how we go from the detector to an specific analysis, step by step

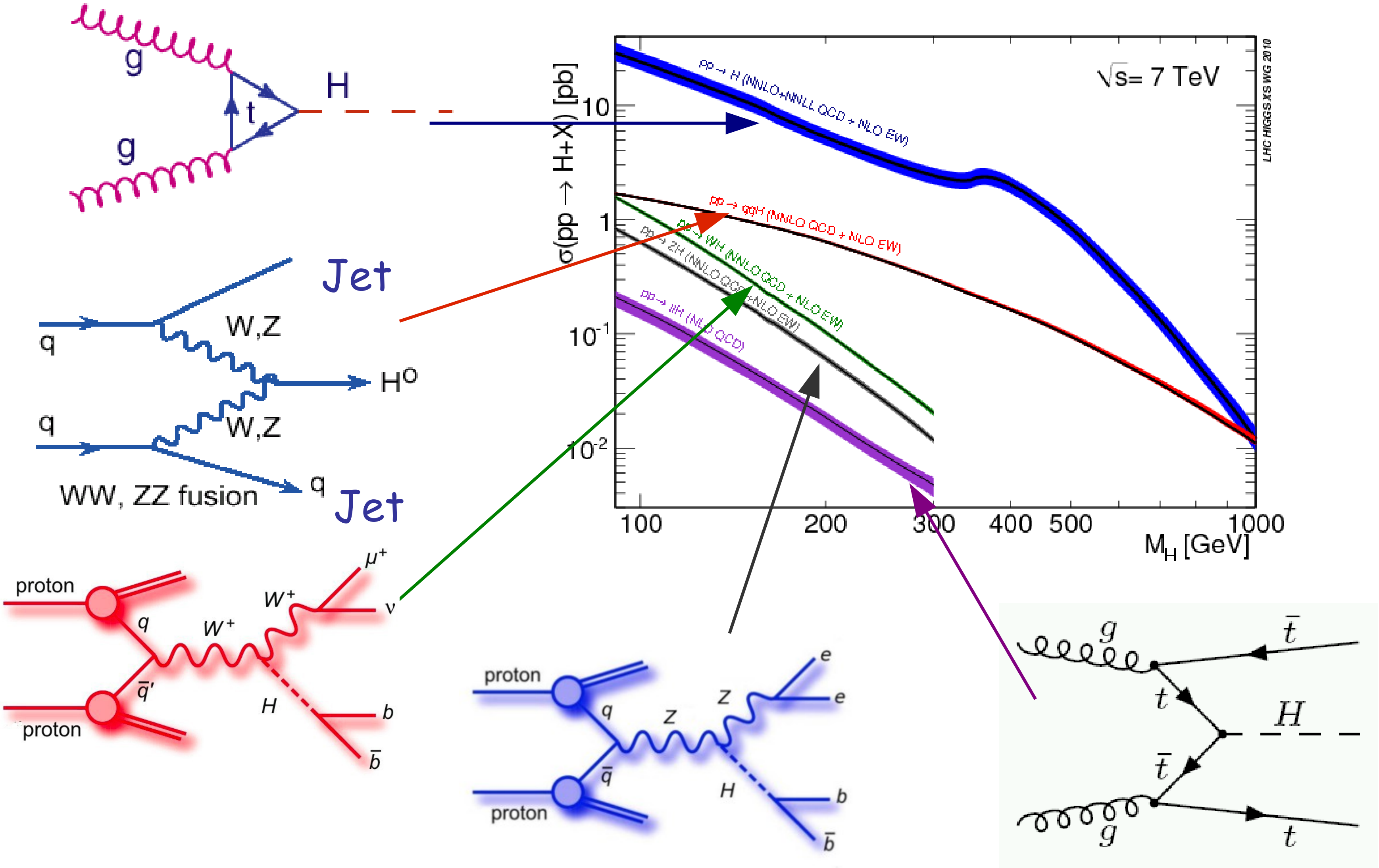


	4 Apr 2016	11 Apr 2016	18 Apr 2016	2 May 2016	10 May 2016
	17:00 Top Physics 2 - Michele Gallinaro (LIP Lisbon) (Conference Room) top_lecture2bis_2016.pdf	17:00 Top Physics 3 - Antonio Onofre (Universidade de Coimbra (PT)) (Conference Room) IDPASC_top_course2016.pdf	17:00 Higgs Physics 1 - Ricardo Jose Morais Silva Goncalo (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part) (Conference Room) HiggsLecture1.pdf	17:00 Higgs Physics 2 - Pedro Vieira De Castro Ferreira Da Silva (CERN) (Conference Room) higgsproperties_2May2016.pdf	17:00 Higgs Physics 3 - Patricia Conde Muino (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part) (Conference Room)

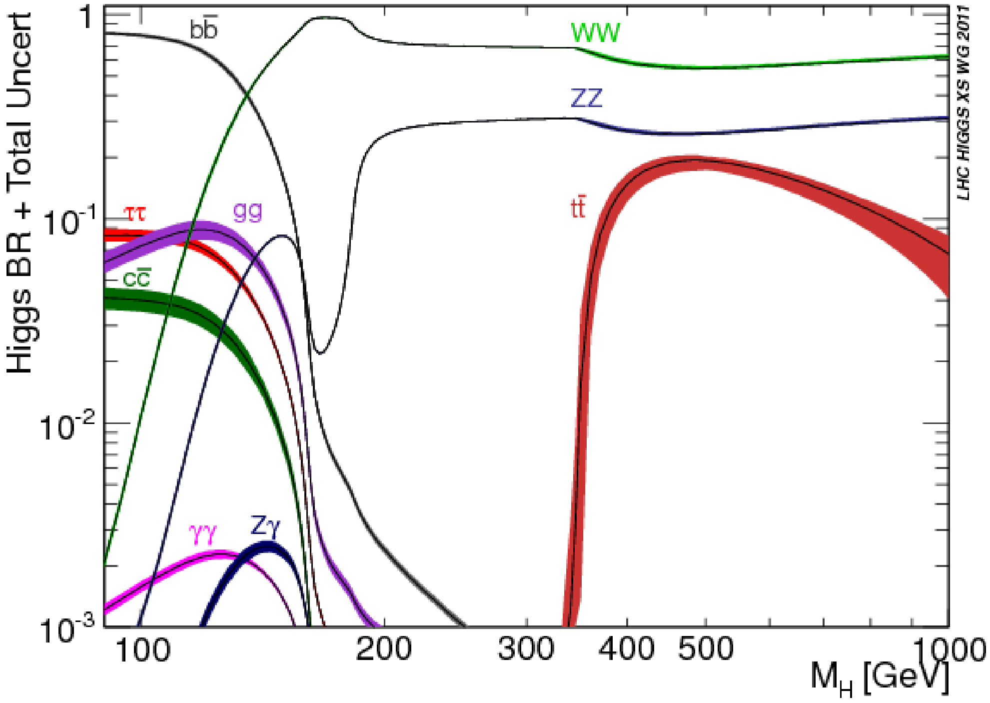
Overview

- Reminder
    - Production and decay modes at the LHC
    - The LHC, the ATLAS and CMS detectors
- Challenges and difficulties of the Higgs boson study at the LHC
- Photon reconstruction and the searches in the $H\to\gamma\gamma$ channel
- Electrons, muons and the $H\to ZZ\to\ell\ell\,\ell'\ell'$
- The $H\to WW\to\ell\nu\ell\nu$ channel
    - Jets, missing transverse energy
    - Background measurement
    - Fits
    - Vector boson fusion

Higgs production



Higgs decays

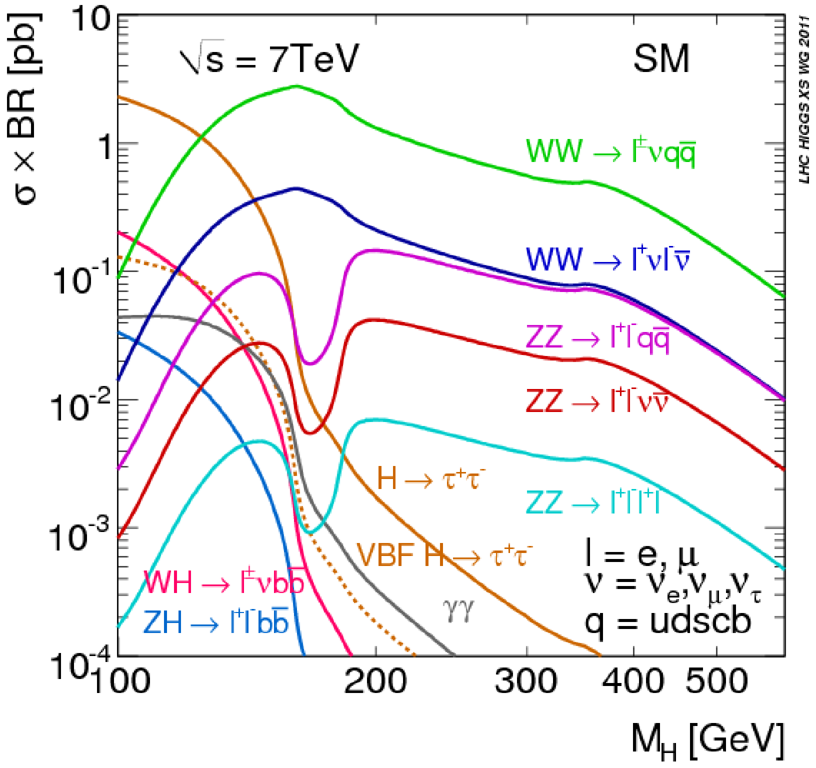


- 5 different decay modes
  - High mass: ZZ, WW
  - Low mass: bb, γγ, WW, ZZ, ττ
- Low mass very challenging
  - Large backgrounds

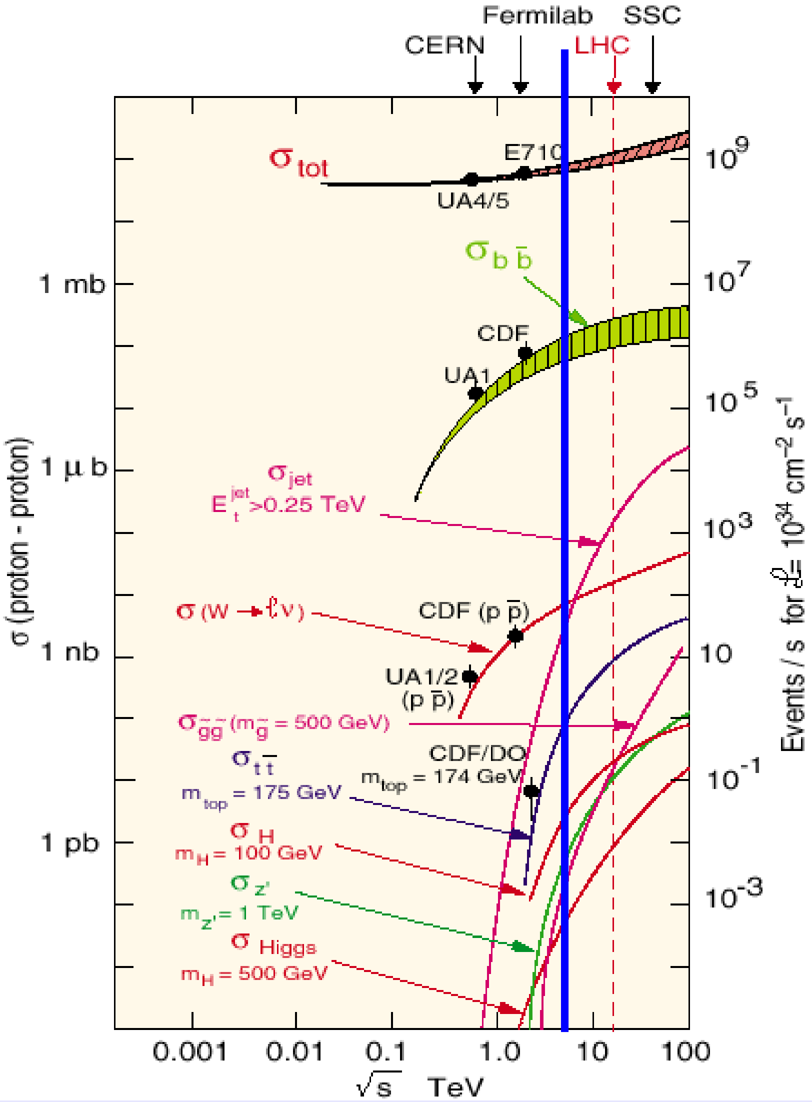
Best mass resolution: H→γγ, H→ZZ→llll

Analysis 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:

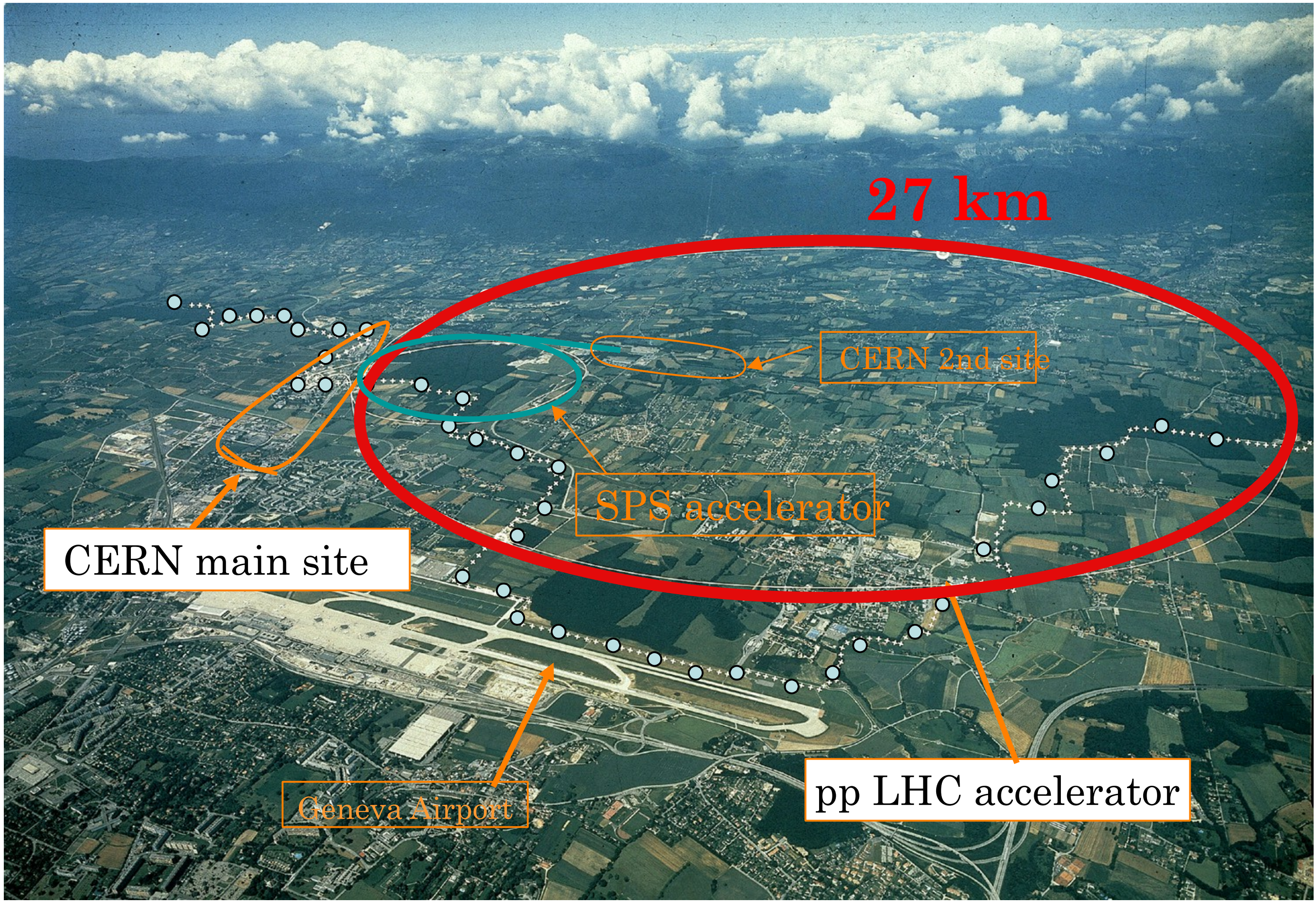
~ 10^3 x $\sigma(bb)$

- ~10^7 x $\sigma(W \rightarrow \mu\nu)$
- ~10^8 x $\sigma(tt)$
- ~$5\text{x}10^{10}$ x $\sigma(H)$ (m_H ~ 100 GeV)

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

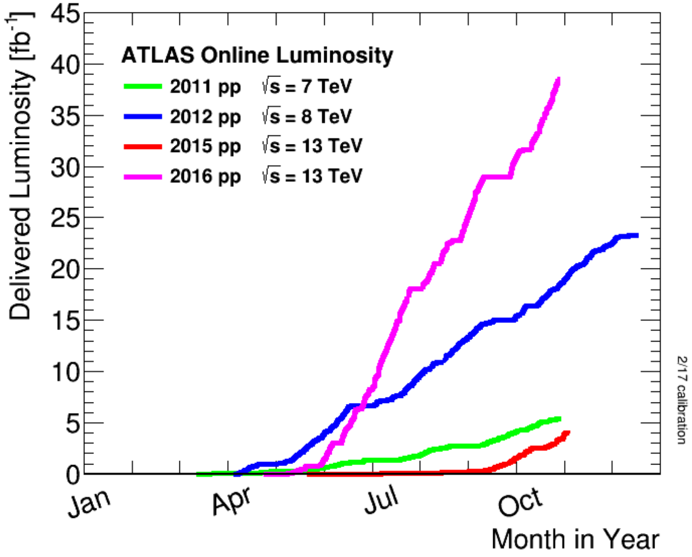
- Most interactions produce jets
  - Either quarks or gluons
- Need to identify clear signatures that distinguish the processes of interest from this background

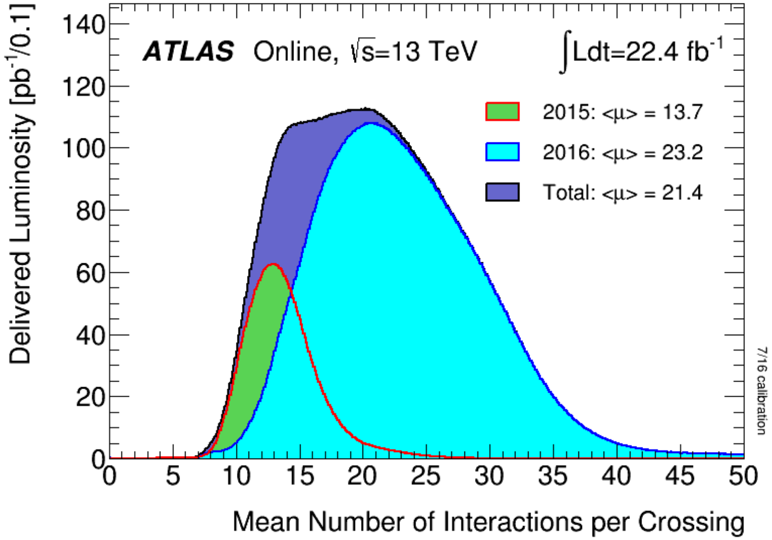
The Large Hadron Collider

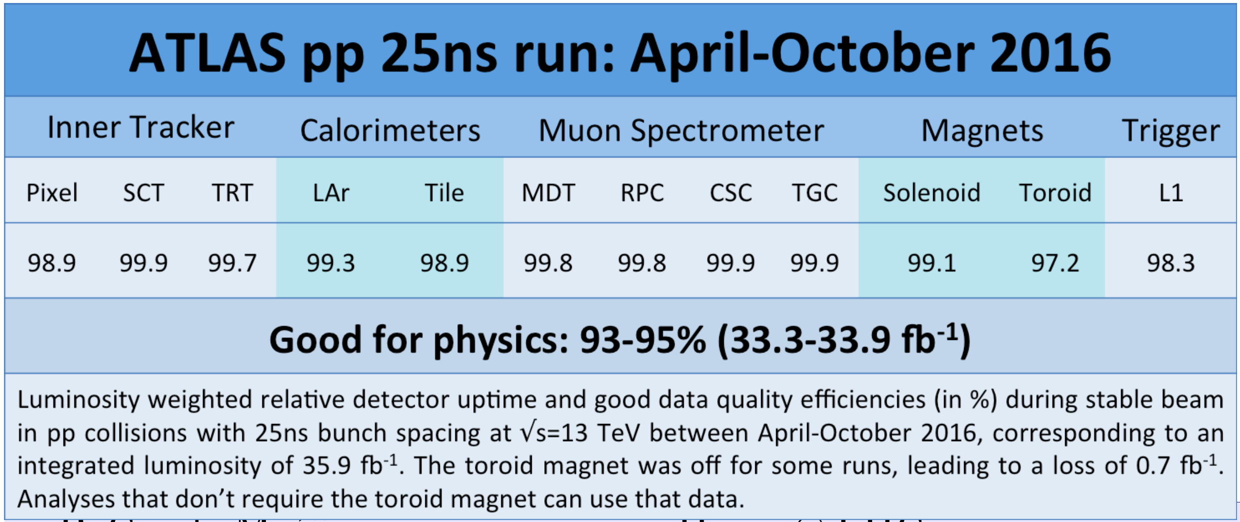


- pp collisions at
  7 TeV in 2010/11
  8 TeV in 2012
  13 TeV in 2015/16
- 40 MHz p bunch crossing rate
- Up to ~40 collisions per bunch crossing!
- Four experiments: ATLAS, CMS, LHCb, ALICE

LHC delivered data







ATLAS pp 25ns run: April-October 2016

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets		Trigger
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid	L1
98.9	99.9	99.7	99.3	98.9	99.8	99.8	99.9	99.9	99.1	97.2	98.3

Good for physics: 93-95% (33.3-33.9 fb^{-1})

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at √s=13 TeV between April-October 2016, corresponding to an integrated luminosity of 35.9 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.7 fb^{-1}. Analyses that don't require the toroid magnet can use that data.

35.6 fb^{-1} 13 TeV pp collisions

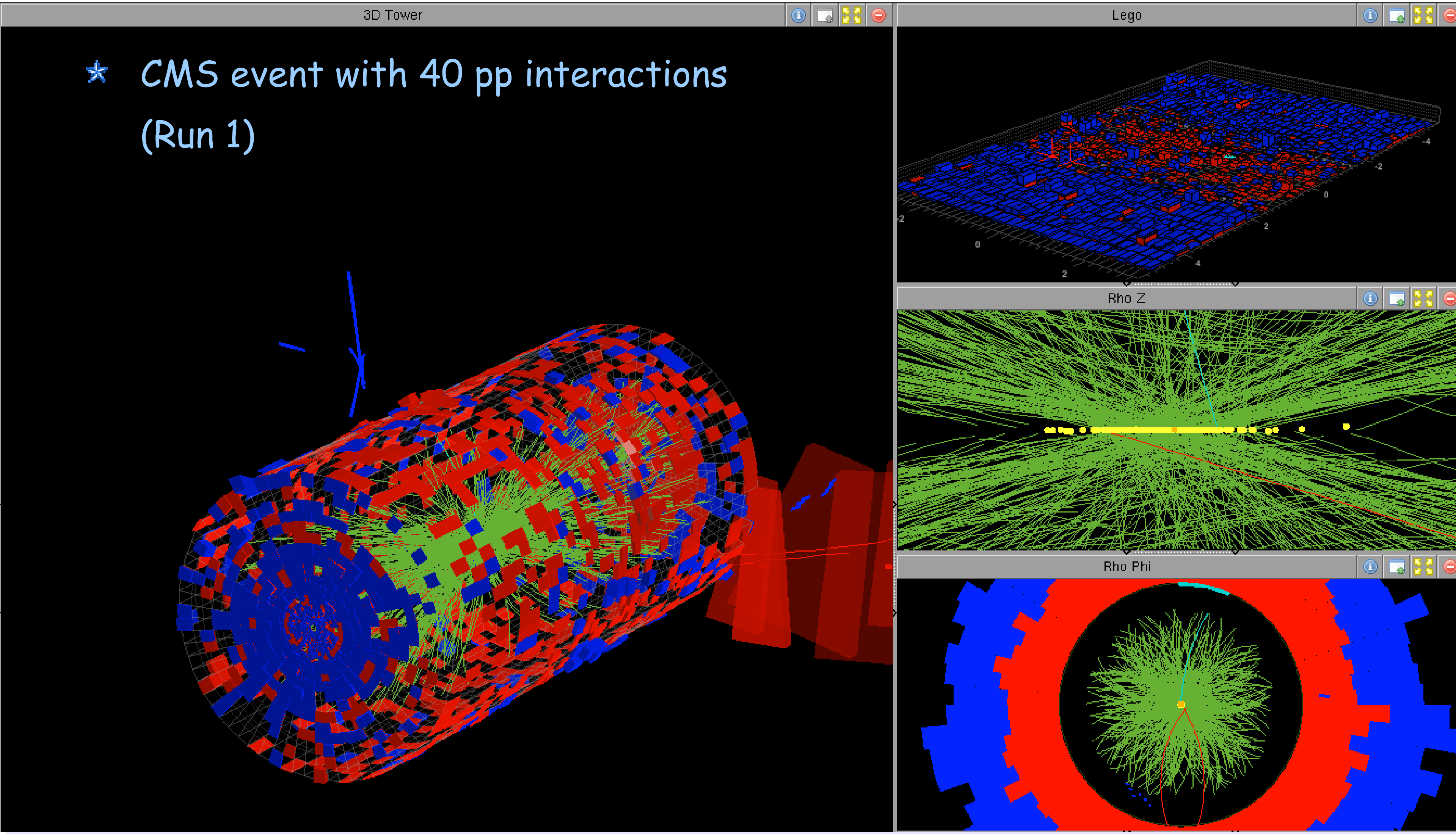
20.8 fb^{-1} 8 TeV pp collisions

5.2 fb^{-1} 7 TeV pp collisions

~93-95% of the delivered luminosity was good for physics!

Pile-up

- CMS event with 40 pp interactions (Run 1)



Pile-up

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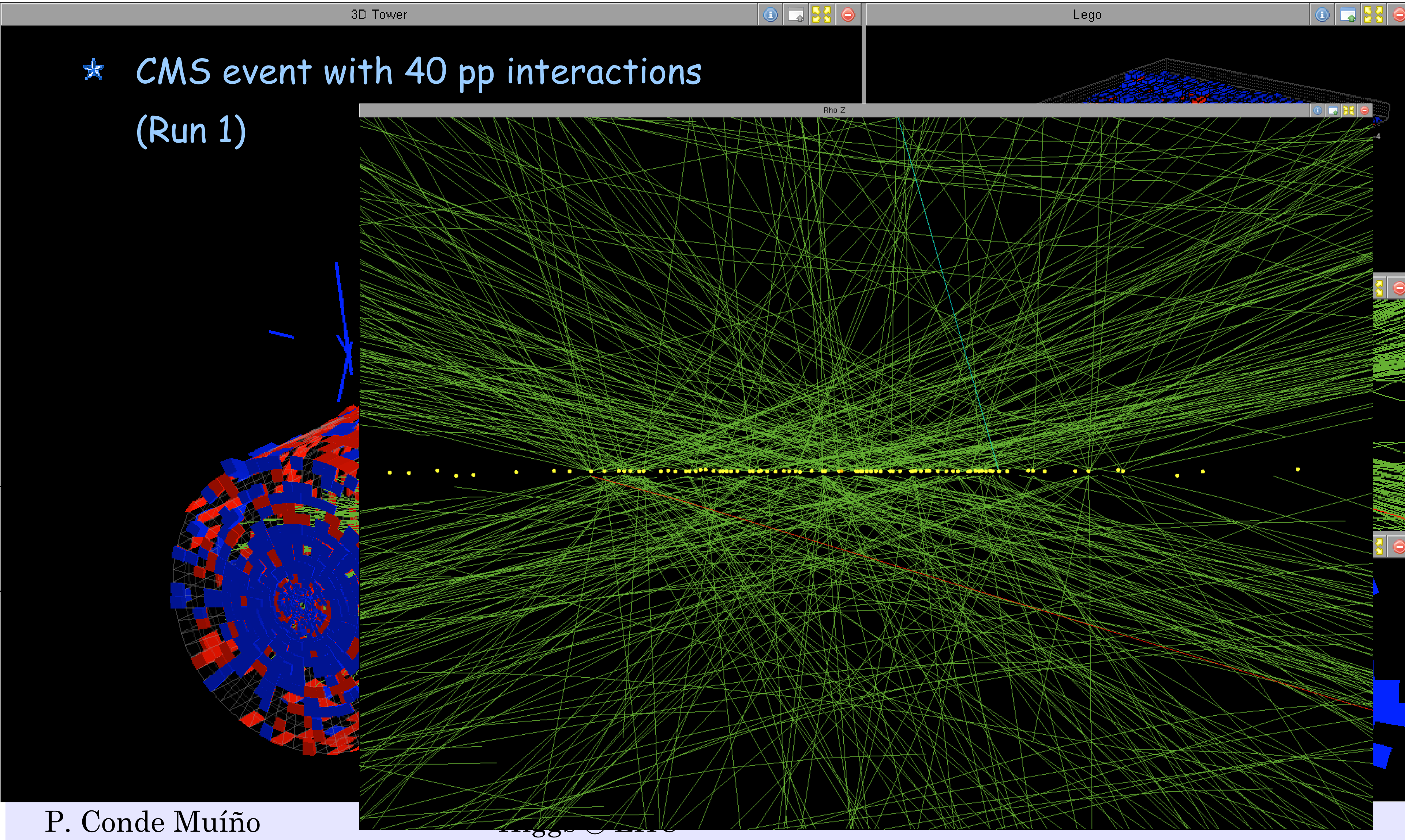
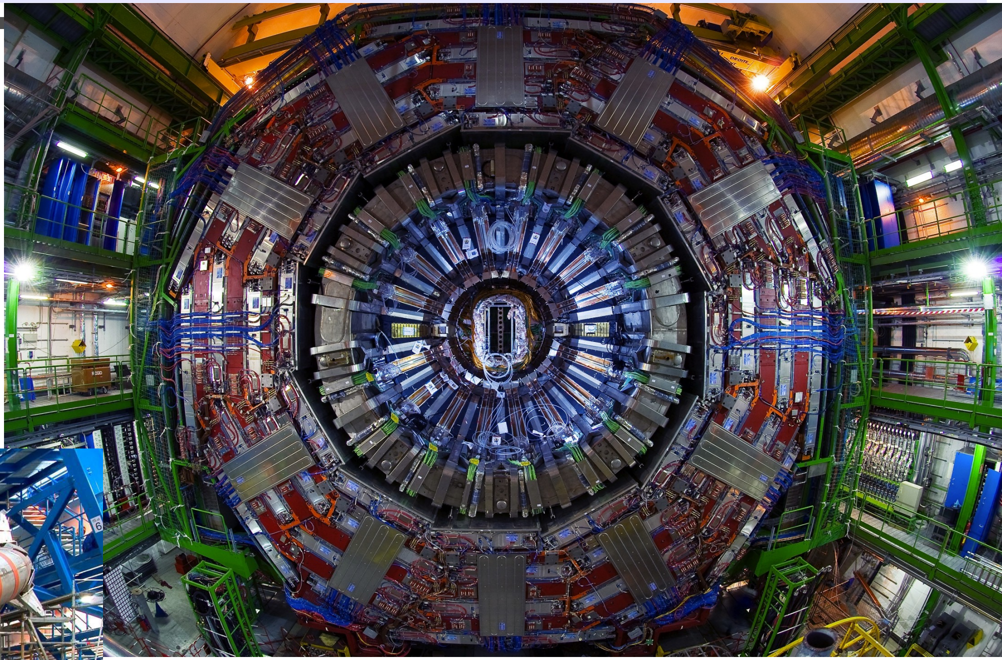
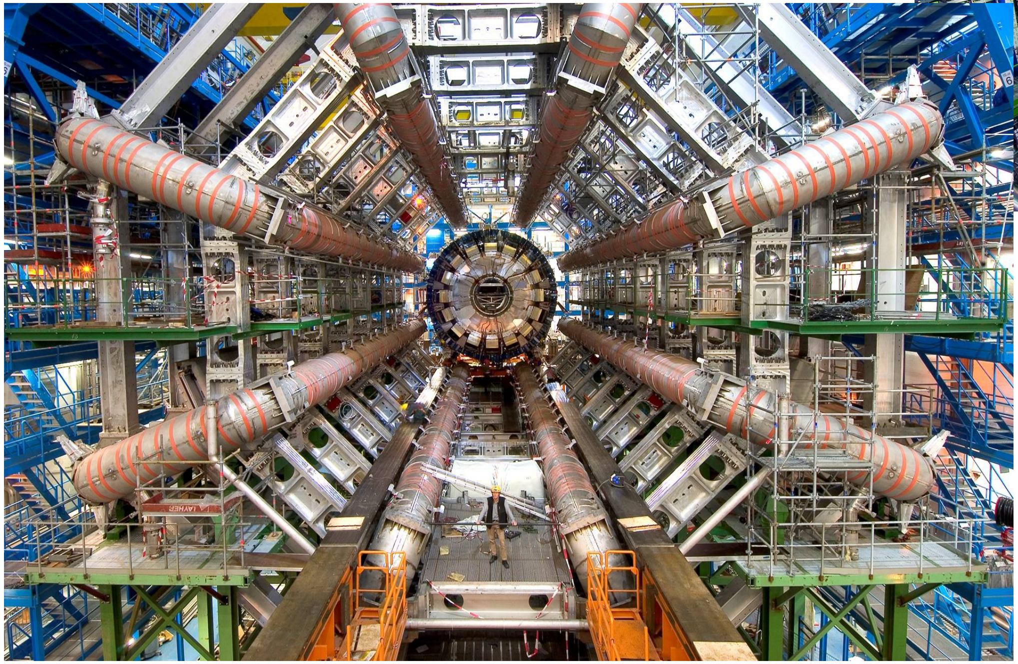
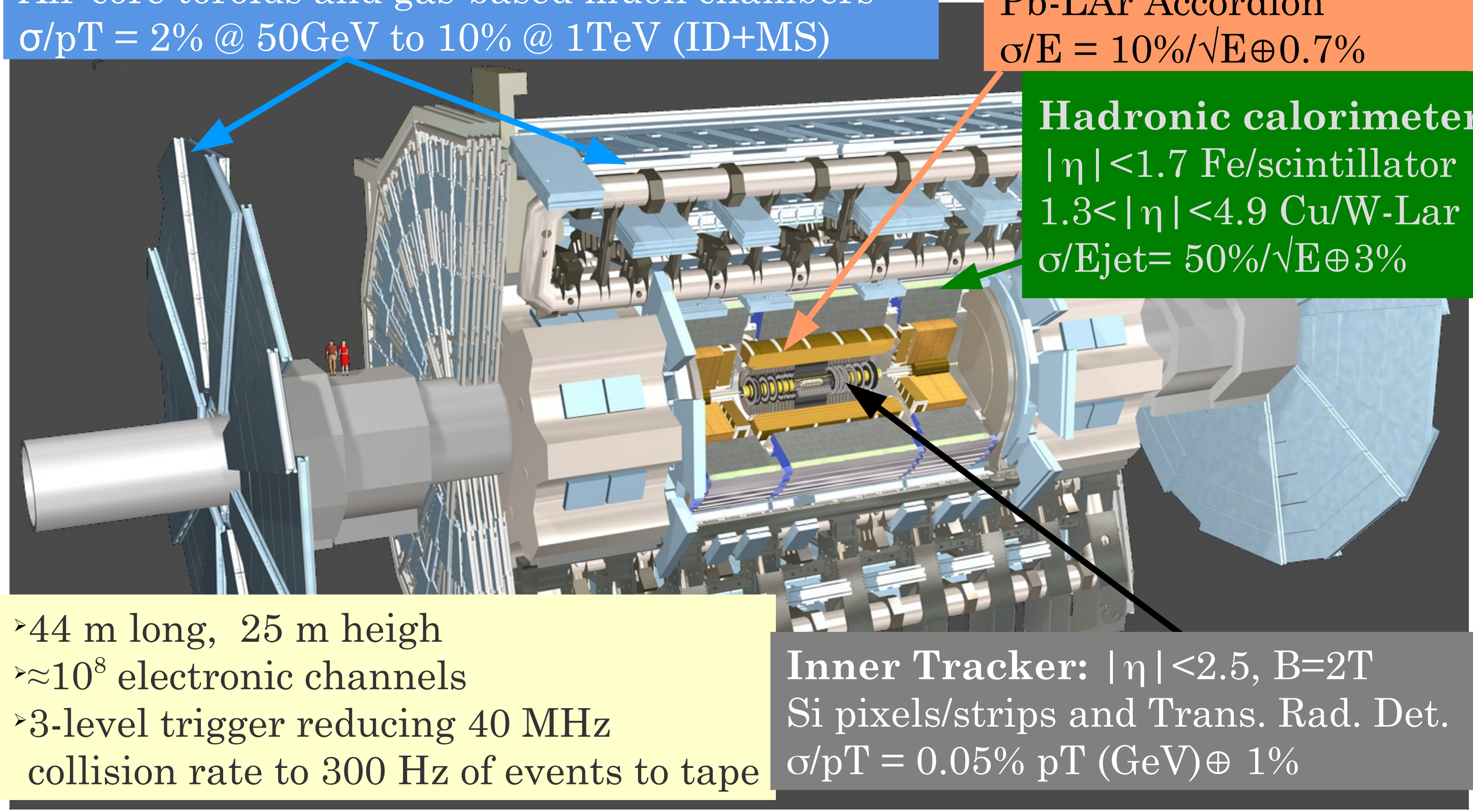


The ATLAS and CMS detectors





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)

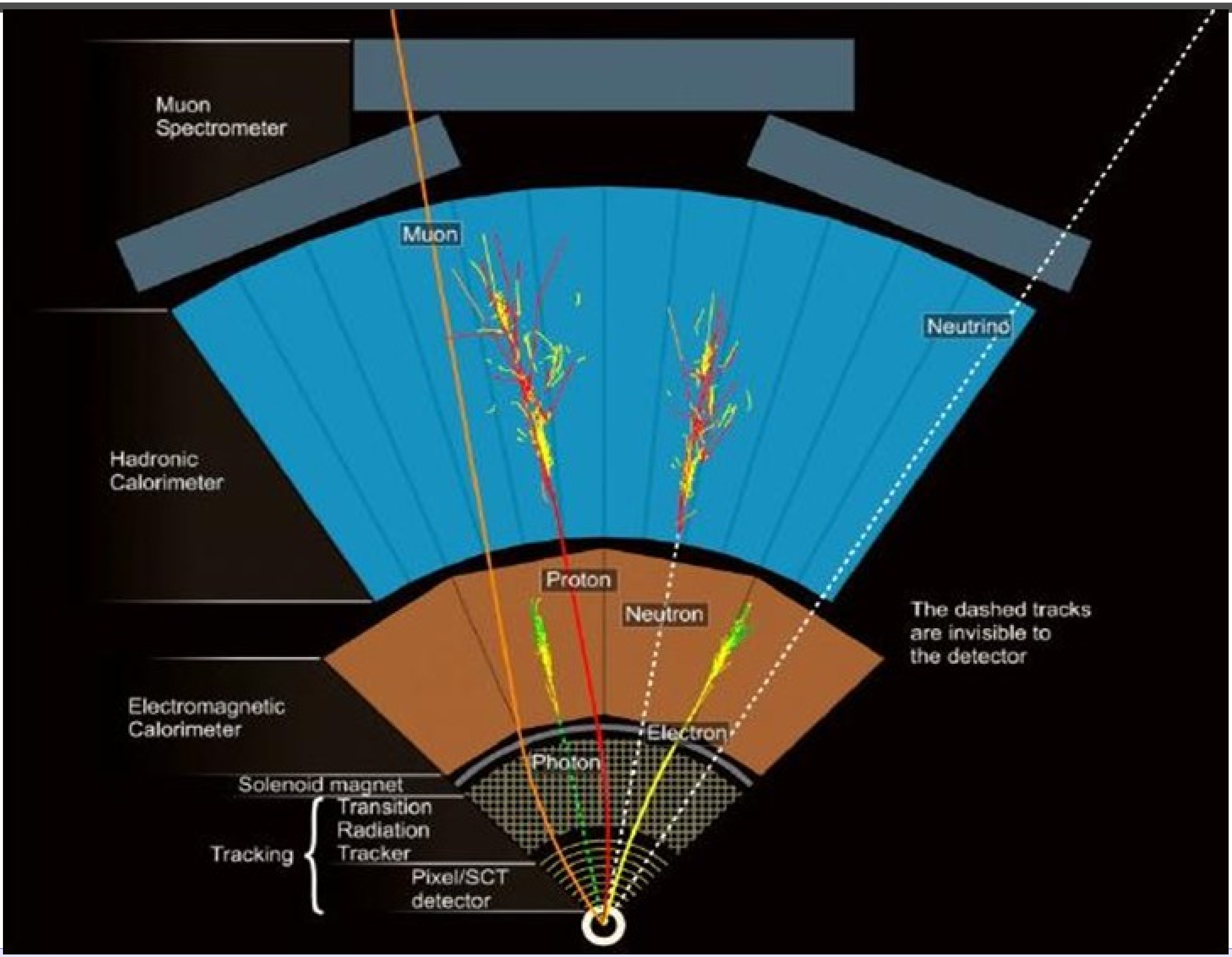
EM calorimeter: |η|<3.2
Pb-LAr Accordion
σ/E = 10%/√E⊕0.7%

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

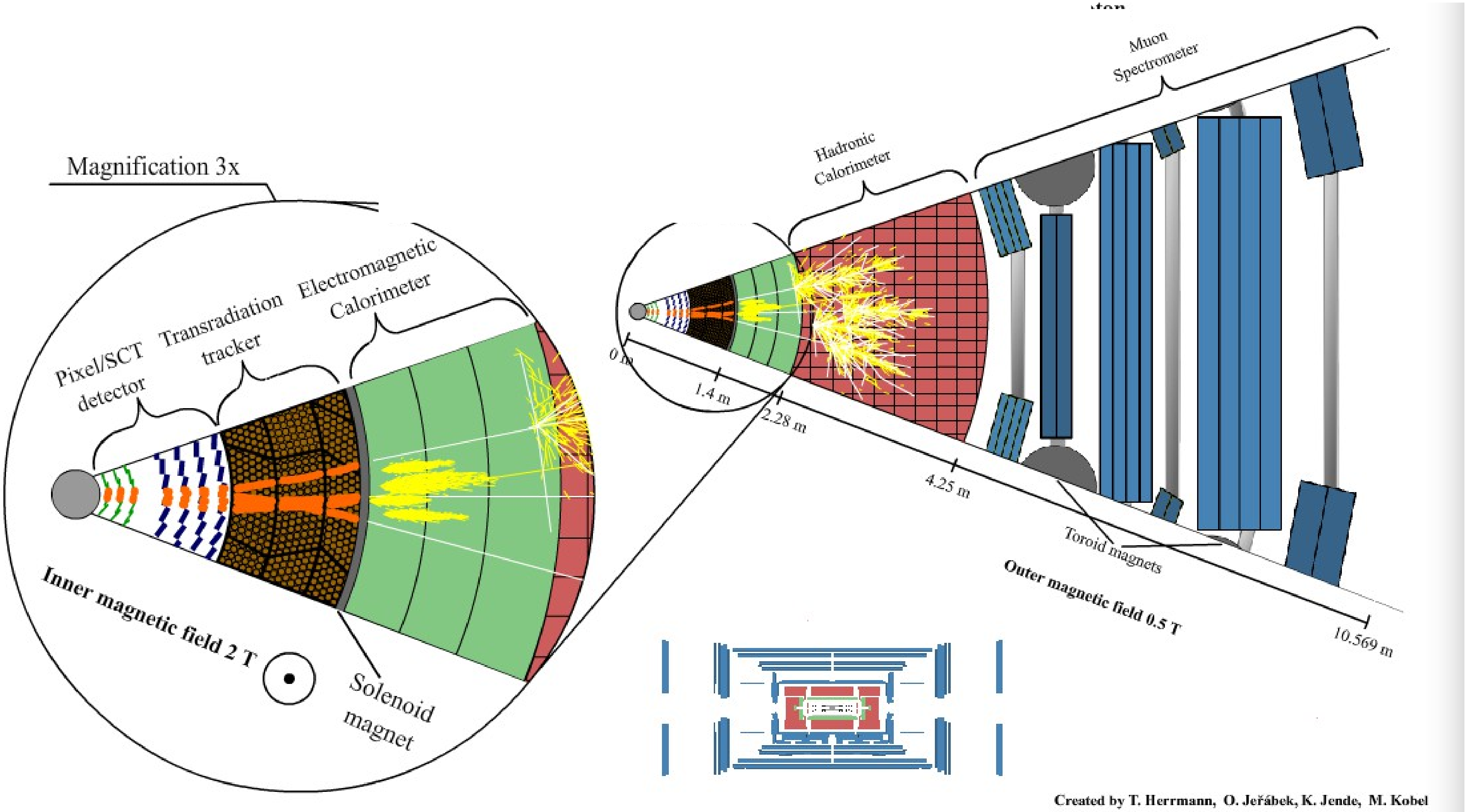
Inner Tracker: |η|<2.5, B=2T
Si pixels/strips and Trans. Rad. Det.
σ/pT = 0.05% pT (GeV)⊕ 1%

Particle identification



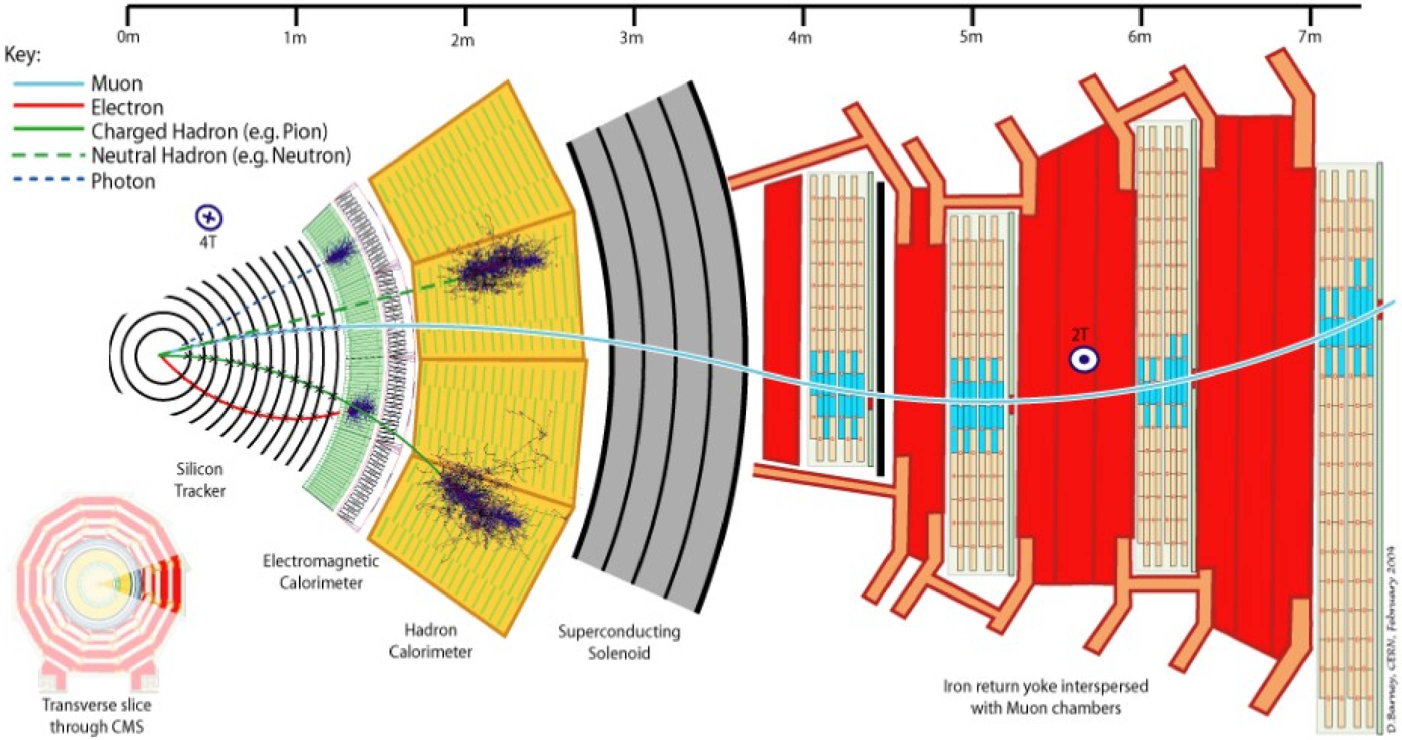
Jets

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



Created by T. Herrmann, O. Jeřábek, K. Jende, M. Kobel

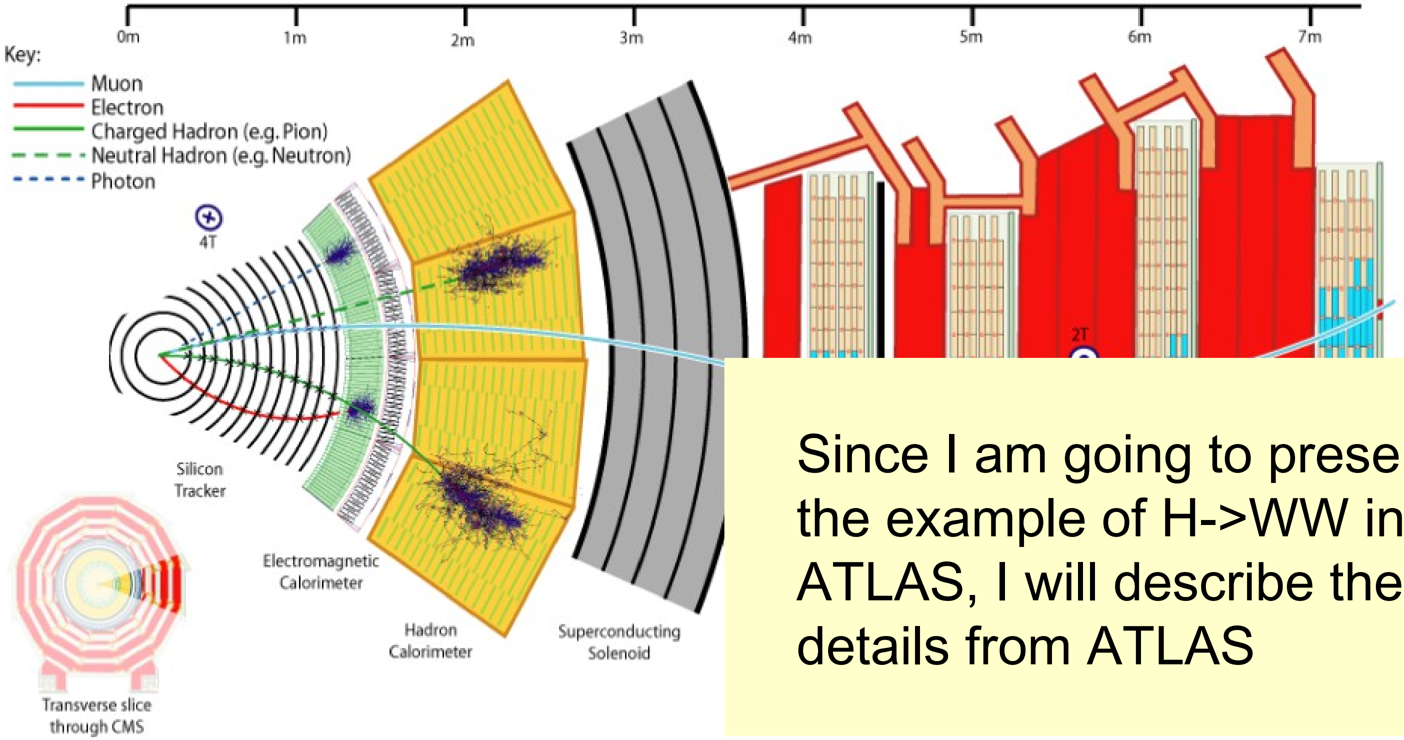
Particle identification @CMS



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)

From the detector to physics

- The detector gives us a list of bites that contain the electronic record of the bunch crossing

```
0x01e84c10:    0x01e8 0x8848 0x01e8 0x83d8 0x6c73 0x6f72 0x7400 0x0000
0x01e84c20:    0x0000 0x0019 0x0000 0x0000 0x01e8 0x4d08 0x01e8 0x5b7c
0x01e84c30:    0x01e8 0x87e8 0x01e8 0x8458 0x7061 0x636b 0x6167 0x6500
0x01e84c40:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c50:    0x01e8 0x8788 0x01e8 0x8498 0x7072 0x6f63 0x0000 0x0000
0x01e84c60:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c70:    0x01e8 0x8824 0x01e8 0x84d8 0x7265 0x6765 0x7870 0x0000
0x01e84c80:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c90:    0x01e8 0x8838 0x01e8 0x8518 0x7265 0x6773 0x7562 0x0000
0x01e84ca0:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cb0:    0x01e8 0x8818 0x01e8 0x8558 0x7265 0x6e61 0x6d65 0x0000
0x01e84cc0:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
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0x01e84ce0:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cf0:    0x01e8 0x87ec 0x01e8 0x85d8 0x7363 0x616e 0x0000 0x0000
0x01e84d00:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d10:    0x01e8 0x87e8 0x01e8 0x8618 0x7365 0x7400 0x0000 0x0000
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0x01e84d30:    0x01e8 0x87a8 0x01e8 0x8658 0x7370 0x6c69 0x7400 0x0000
0x01e84d40:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d50:    0x01e8 0x8854 0x01e8 0x8698 0x7374 0x7269 0x6e67 0x0000
0x01e84d60:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d70:    0x01e8 0x875c 0x01e8 0x86d8 0x7375 0x6273 0x7400 0x0000
0x01e84d80:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d90:    0x01e8 0x87c0 0x01e8 0x8718 0x7377 0x6974 0x6368 0x0000
```
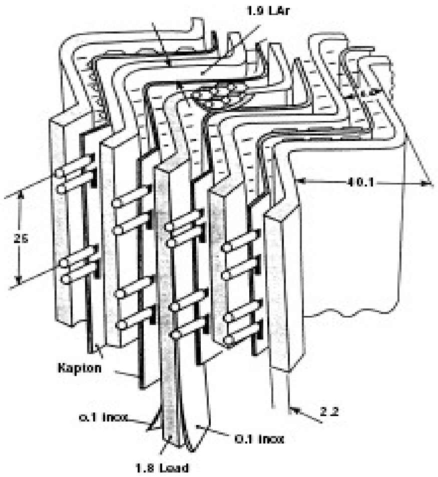
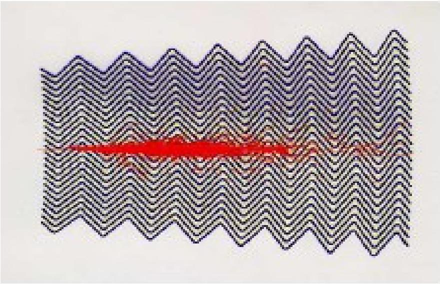
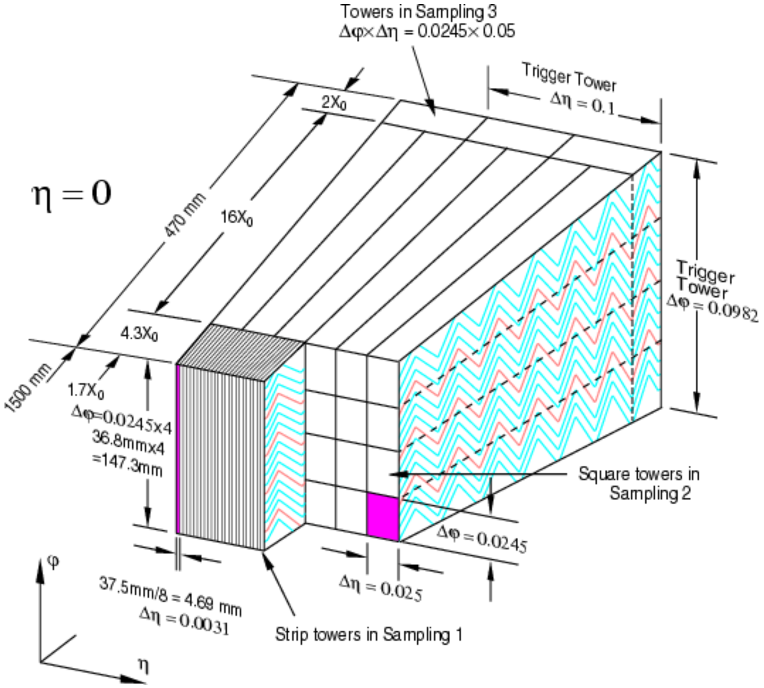

- How to get useful information from there?
- How to identify particles and measure its properties?
- How can we "see" a Higgs boson with this?

How to reconstruct e/γ:ATLAS example

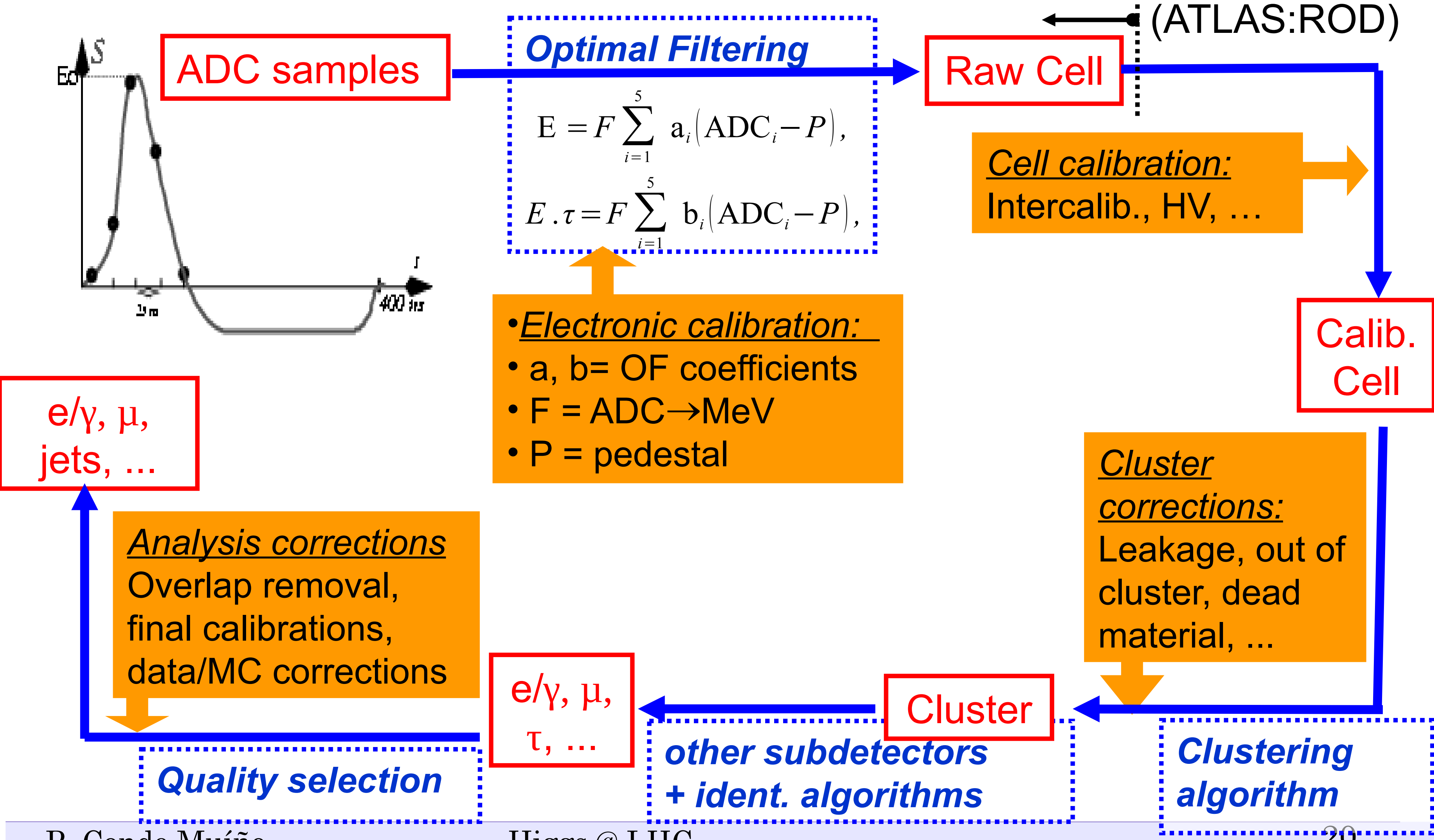
- LAr read out system: from the detector to the deposited energy
- Clustering algorithms
- Calibrations
- Photon/e identification algorithms







Reconstructing energy (calorimeter)



ADC samples

Optimal Filtering

$$E = F \sum_{i=1}^{5} a_i \left(ADC_i - P \right),$$

$$E.\tau = F \sum_{i=1}^{5} b_i \left(ADC_i - P \right),$$

Raw Cell

(ATLAS:ROD)

- *Electronic calibration:*
- a, b= OF coefficients
- F = ADC→MeV
- P = pedestal

Cell calibration:
Intercalib., HV, …

Calib. Cell

Cluster corrections:
Leakage, out of cluster, dead material, ...

Cluster

Clustering algorithm

other subdetectors + ident. algorithms

e/γ, μ, τ, …

Analysis corrections
Overlap removal, final calibrations, data/MC corrections

Quality selection

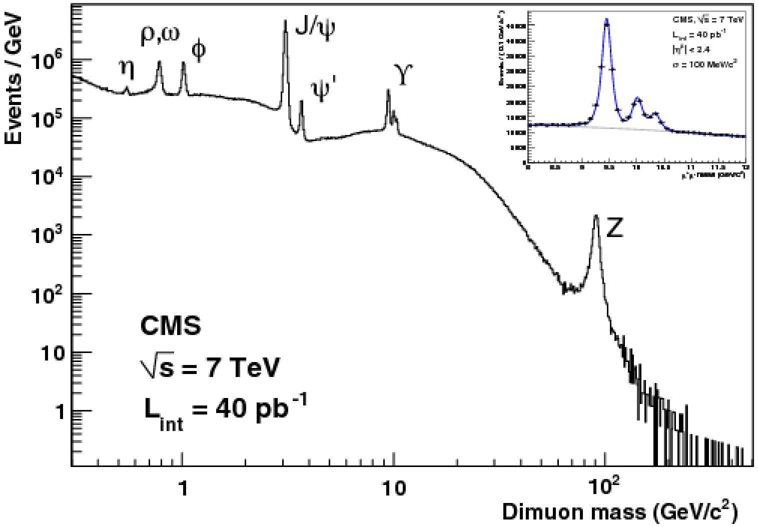
e/γ, μ, jets, ...

Particle reconstruction

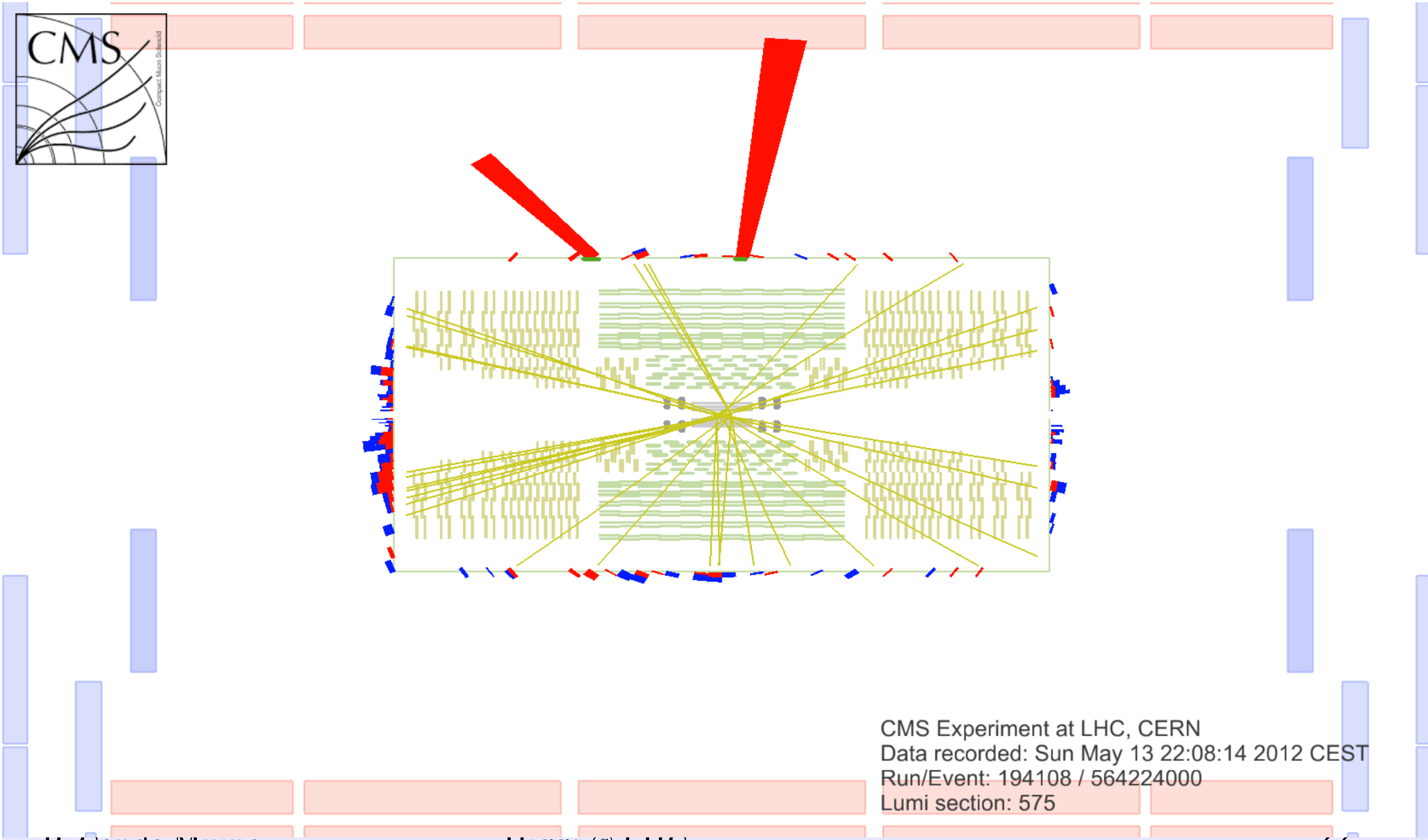
- From the properties of the particles produced in its decay we can infer the properties of the Higgs boson

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

- 20 years of particle physics in one single plot



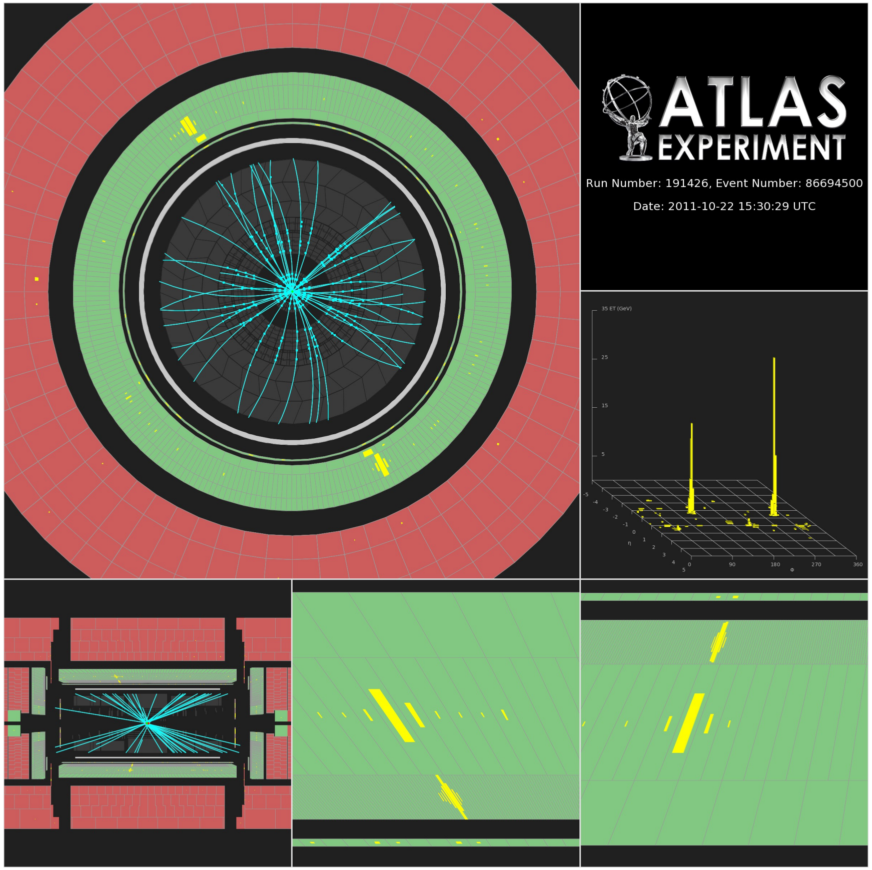
Run 1 analysis: H→γγ



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



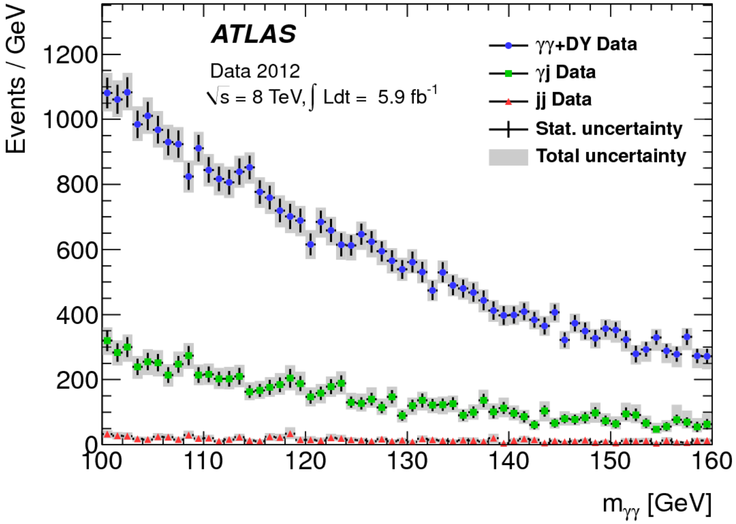
H→γγ candidate event

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

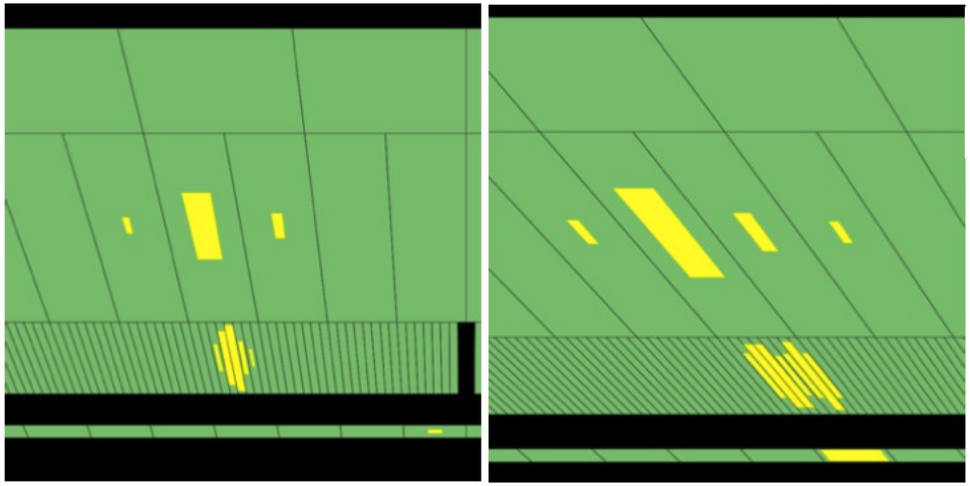
Main background:

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

Background composition



γ identification



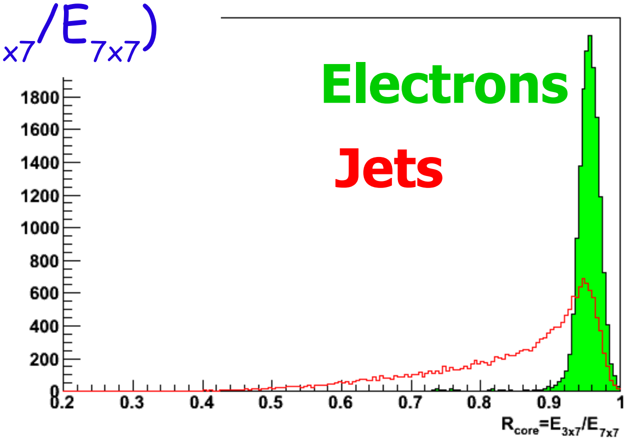
Photon

π^0

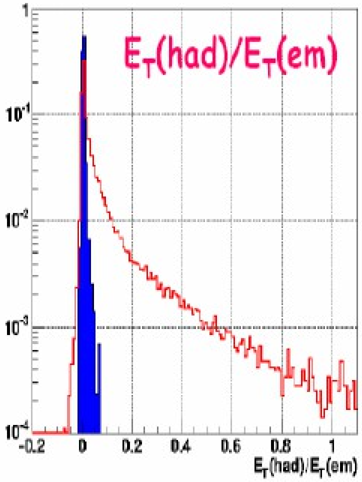
Definitions

- Identification performed by applying cuts over discriminating variables (shower shapes) from the calorimeter layers.
- There is a ‘loose’ and ‘tight’ selection of cuts.
- Cuts are binned in η, and by converted/unconverted photons.

Shower containment in sampling 2 (E_{3x7}/E_{7x7})

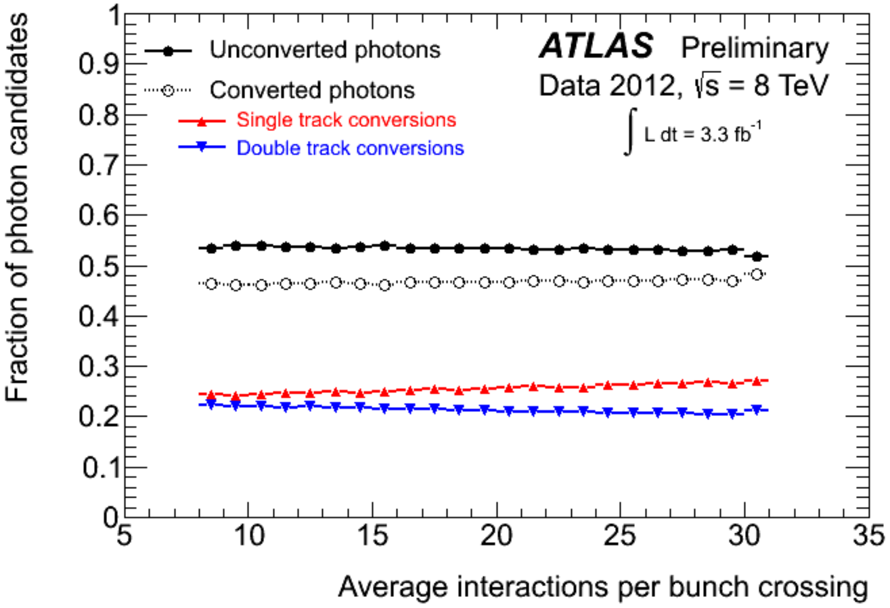


Hadronic leakage



γ identification

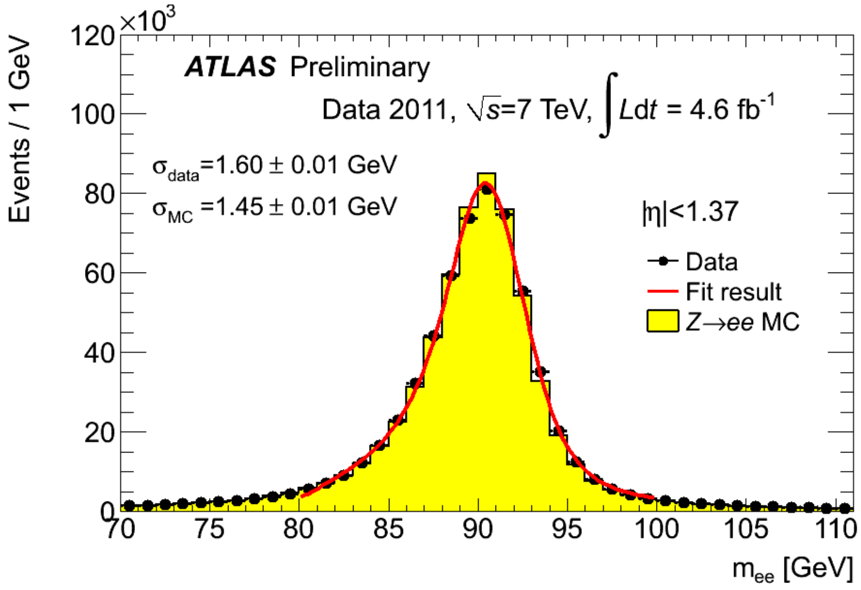
- Normal photons → unconverted
- Converted photons: γ →e+e-
    - After interaction with material in front of the calorimeter
    - Can have one or two tracks.
- Pileup can lead to misreconstructing unconverted photons as converted γ
    - 3% migration of 2-track to 1-track conversions.
    - Fraction of converted vs unconverted photon candidates stable to 1% between extreme pileup values.



γ energy measurement

- Calorimeter E response studied with Z, J/ψ and W decays
  - γ/e showers very similar
  - Study e showers using Z decays
- Data versus MC differences observed
  - Width: due to resolution of the energy calibration
  - Mean peak position: energy scale
- Derive corrections for the MC as a function of electron/photon η, p_T
  - Reduce systematic uncertainties!

Performance in 2013:

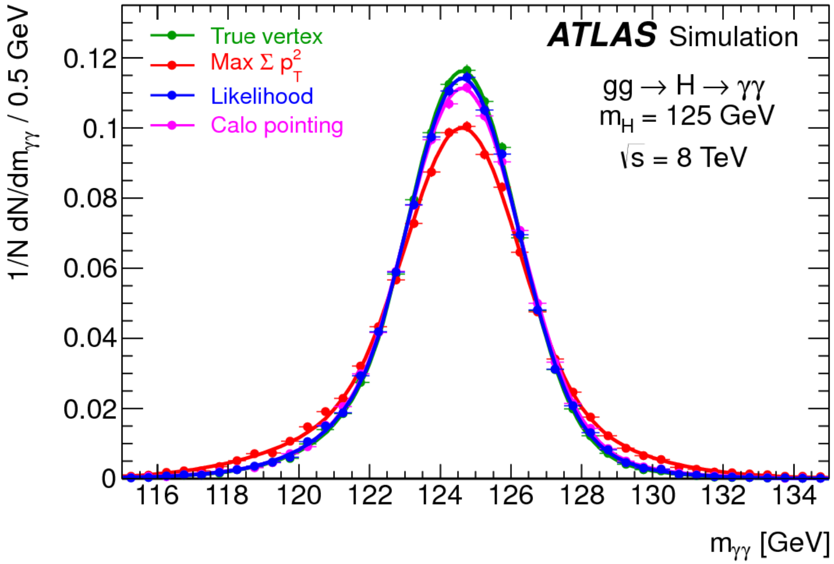


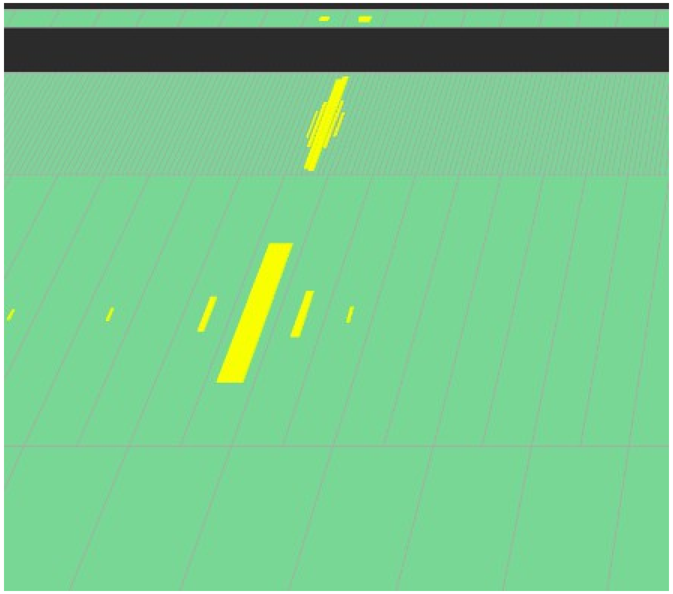
- Energy scale at m_Z known to ~ 0.5%
- Excellent mass resolution
  - 1.6-3.1 GeV
- Linearity better than 1%

γ association to primary vertex

- Use calorimeter segmentation to associate γ to primary vertex

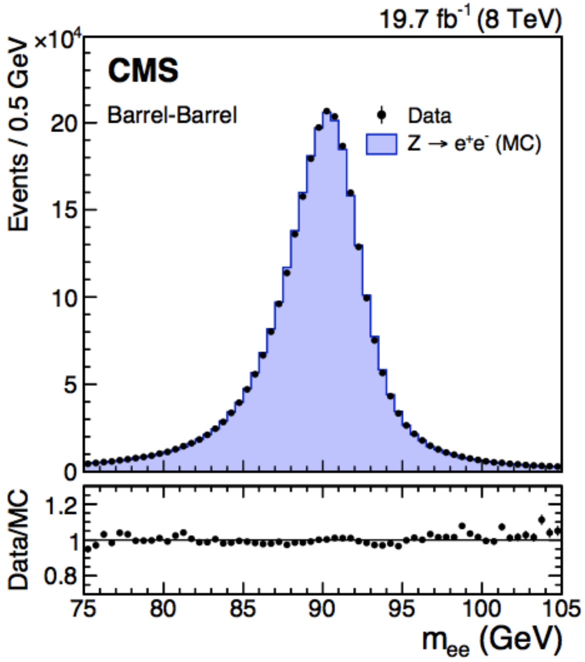
$\sigma_z \sim 15$ mm

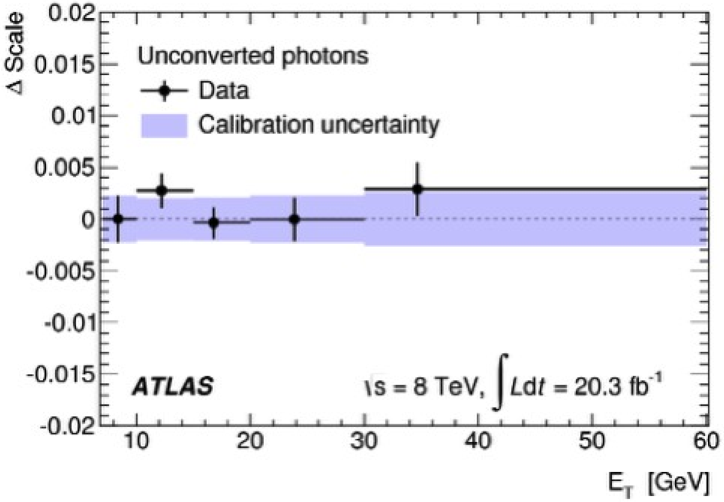




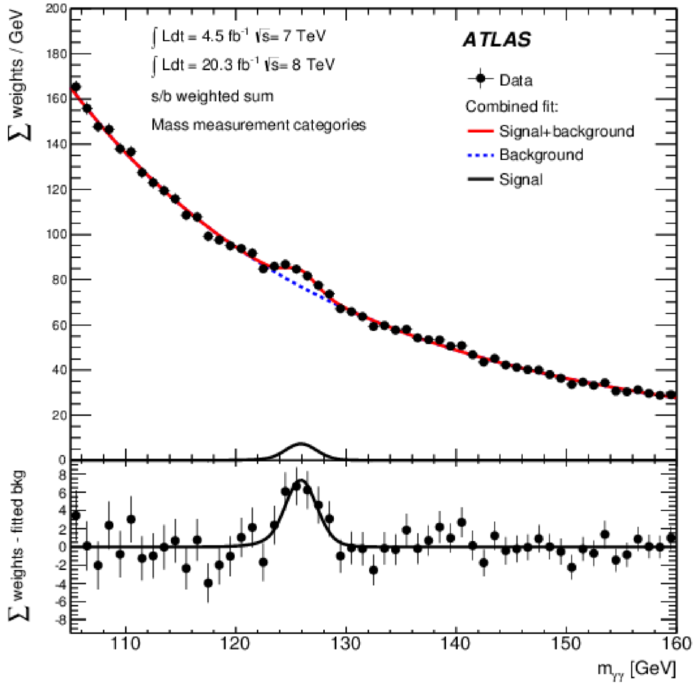
Improved γ identification & calibration

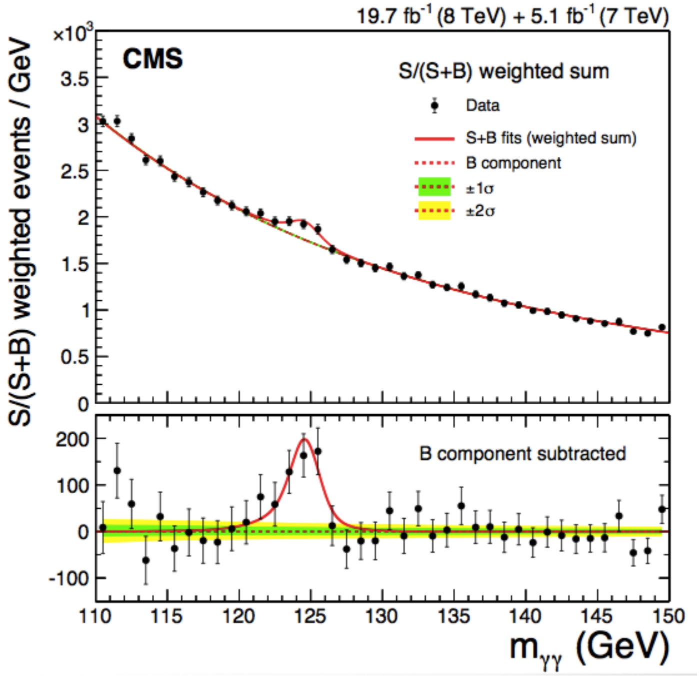
- Both, ATLAS and CMS, improved their photon energy measurement and identification procedures
- Validated the energy scale and systematics with data





Run 1: 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

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

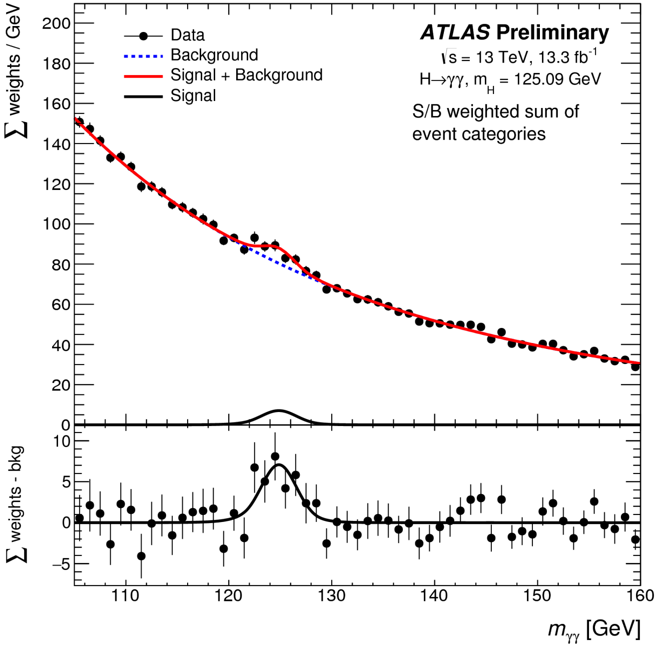
- Background fluctuation probability ~ 10^{-8}

Higgs re-discovery at 13 TeV

ATLAS-CONF-2016-067

- $H \rightarrow \gamma\gamma$

13.3 fb^{-1} pp collisions @ 13 TeV

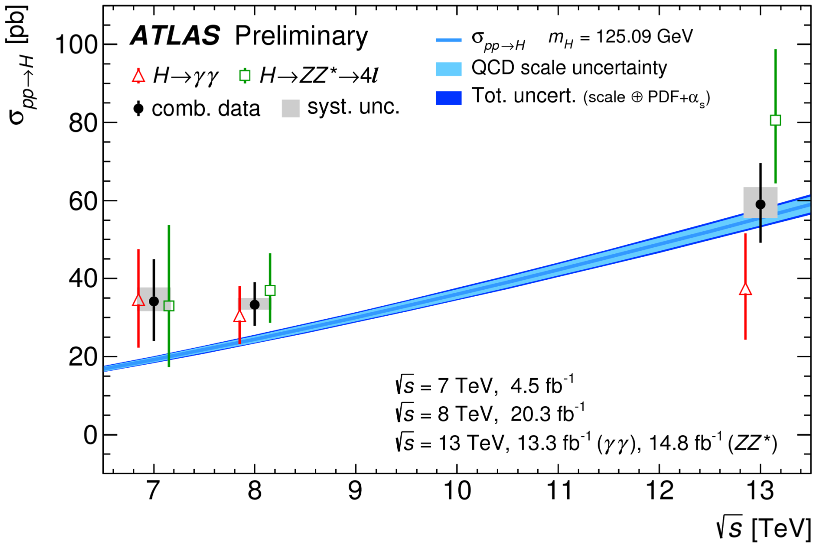


$$\sigma_{\text{fid}} = 47.0 \pm 13.9\,(\text{stat.}) \pm 5.4\,(\text{syst.})\ \text{fb}$$

SM prediction $62.8^{+3.4}_{-4.4}$ fb

ATLAS-CONF-2016-081

- Cross section as a function of the pp center of mass energy



	Measurement at 13 TeV	SM prediction at 13 TeV
σ (pb)	$59.0^{+9.7}_{-9.2}$(stat)$^{+4.4}_{-3.5}$(syst)	$55.5^{+2.4}_{-3.4}$
μ	$1.13^{+0.18}_{-0.17}$	1

Differential cross sections in H → γγ

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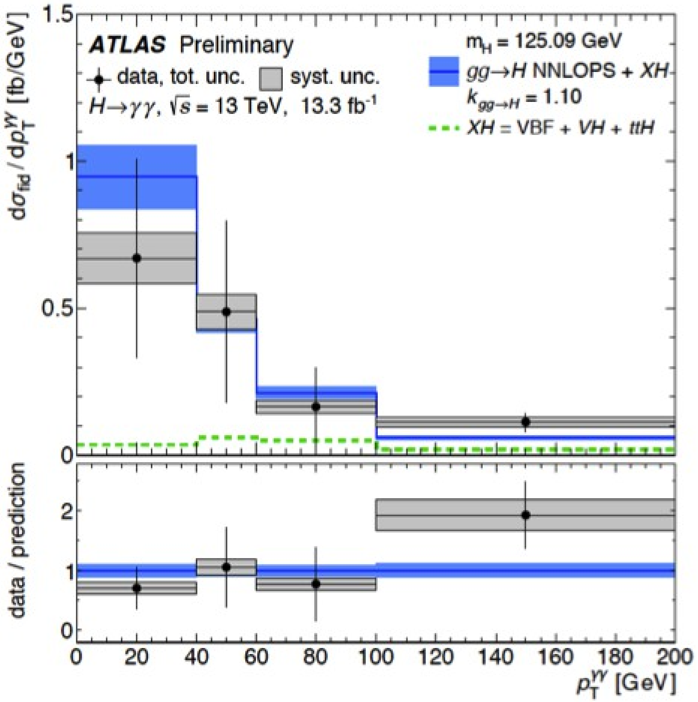
- $H \rightarrow \gamma\gamma$ differential cross section as a funtion of $p_T^{\gamma\gamma}$

Agreement with theory

Slightly harder pT in data



H→γγ & H→4ℓ combination @ 13TeV

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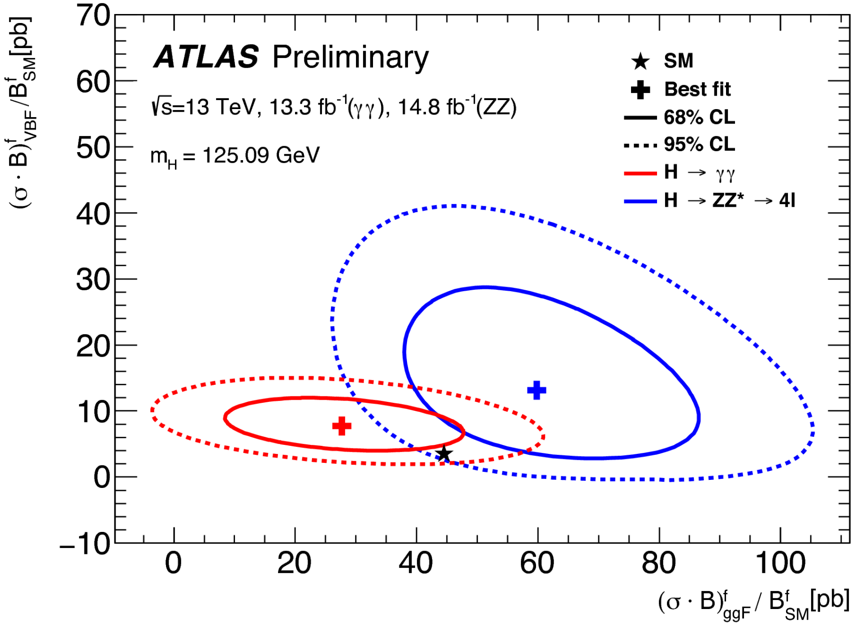
- Fitted VBF and ggF contours

  Dominant systematics:

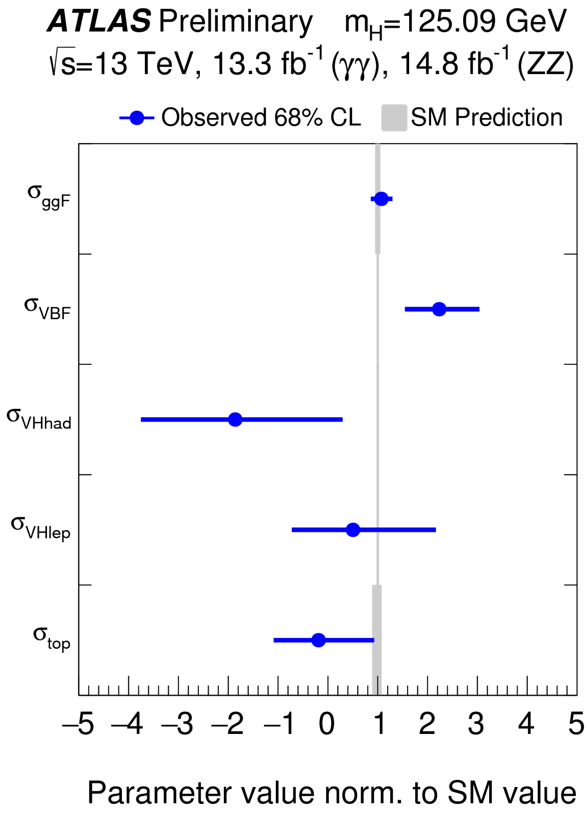
  e/γ energy resolution, γ identification efficiency

  Theory: ggF acceptance in events with fixed number of jets

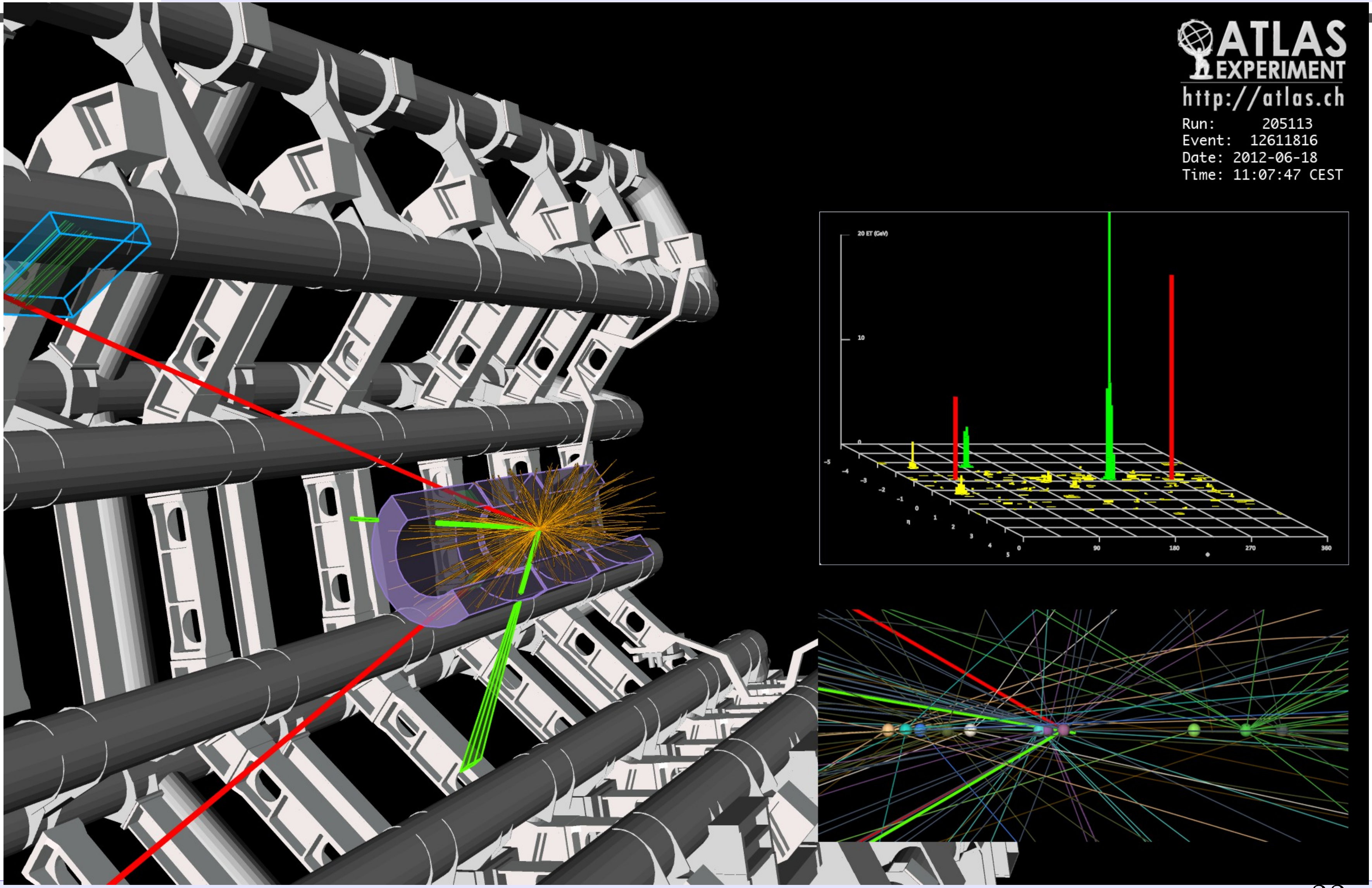


- Production cross sections assuming SM BR:

  Compatibility with SM: p_{SM} = 21%



H→ZZ→4ℓ analysis



H→ZZ→4ℓ analysis

arXiv:1207.7214

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

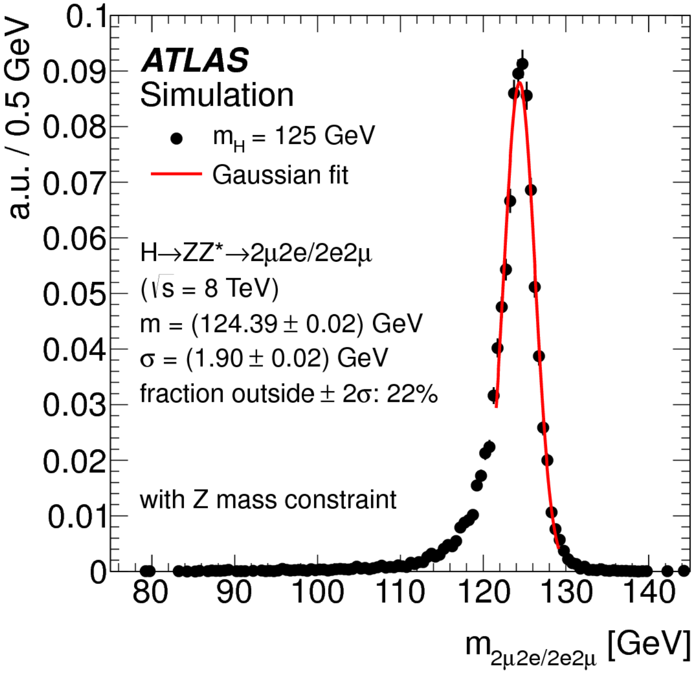
Excellent mass resolution

- 1.6-2.4 GeV (4μ, 4e)

Very good e/μ reconstruction efficiency

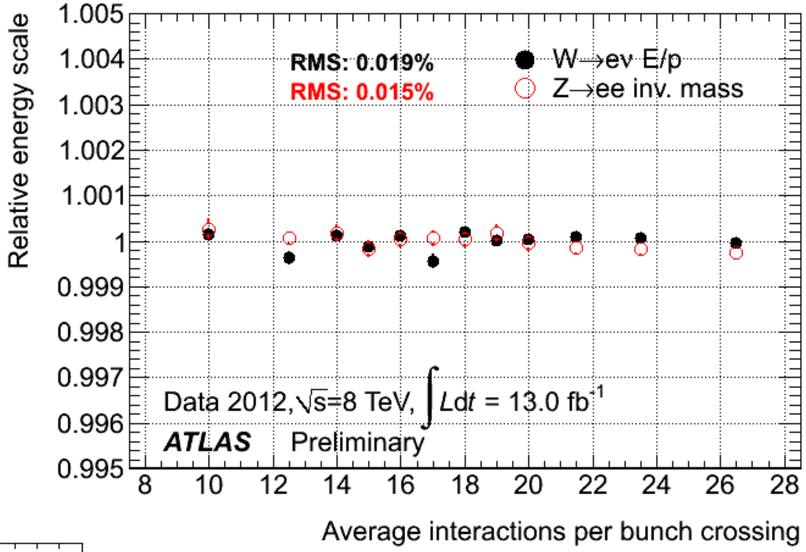
- ~97% for muons with p_T>6 GeV
- ~98% (95%) for e reconstruction (identification)

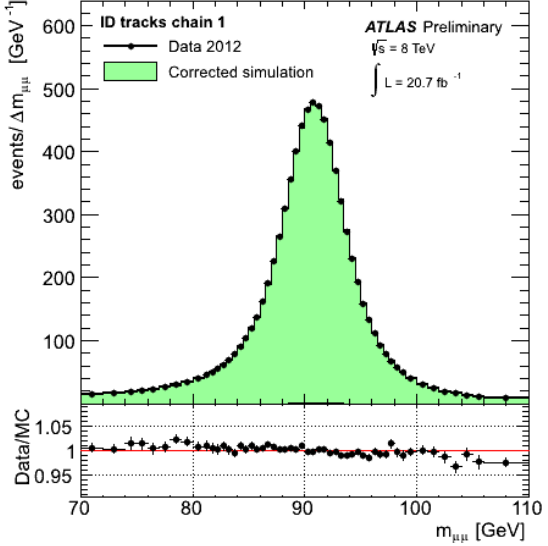
Discriminating variable: $m_{4\ell}$

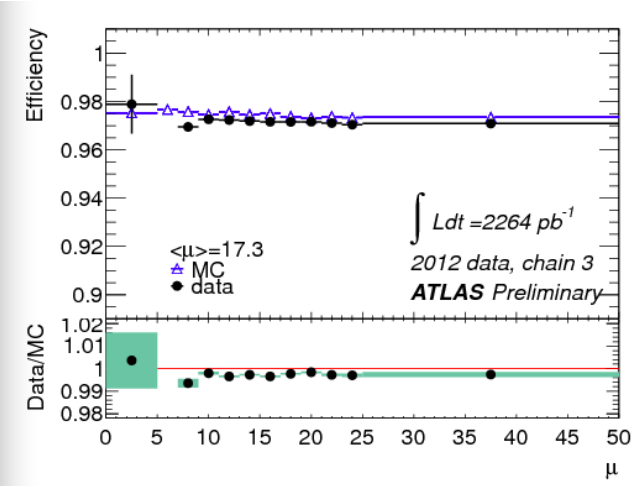


e and μ reconstruction

- 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

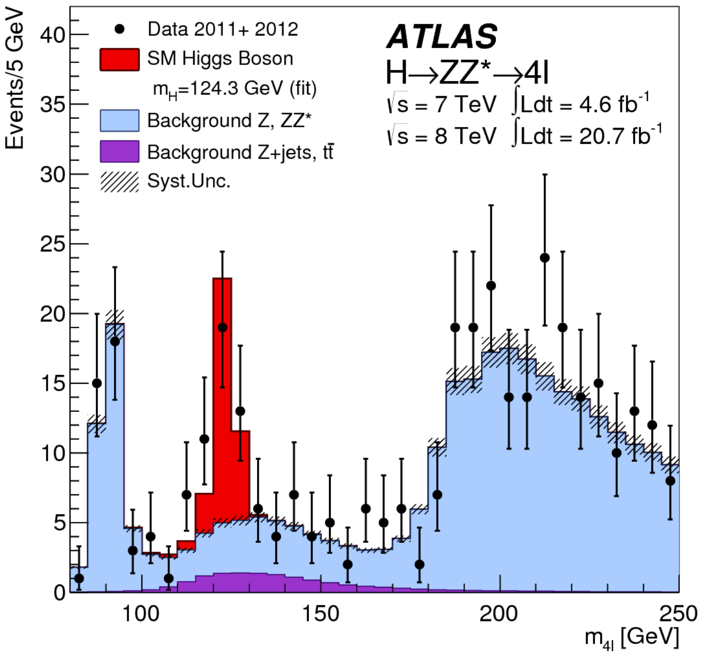


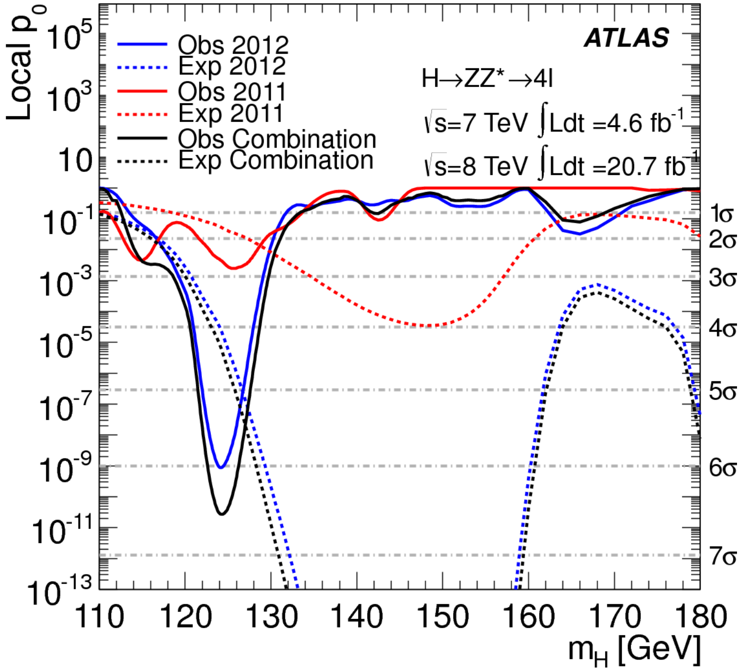




H→ZZ→4ℓ results

- 4ℓ mass spectrum (7+8 TeV)



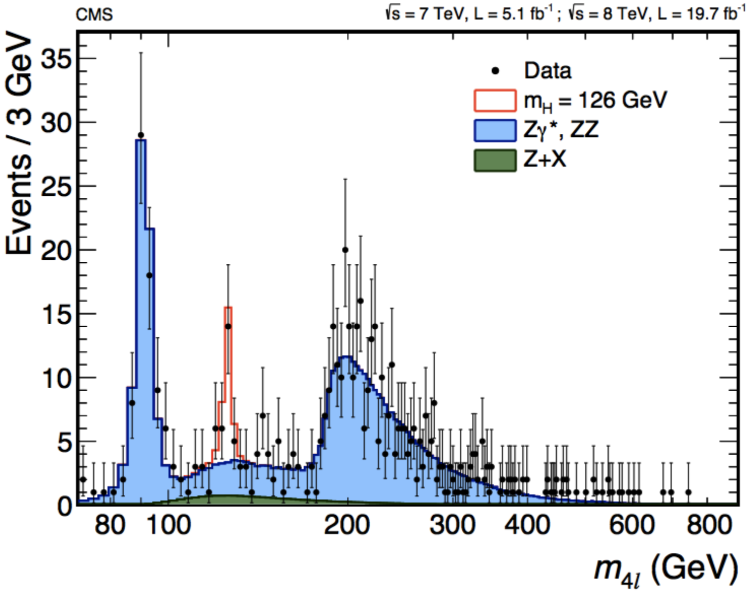


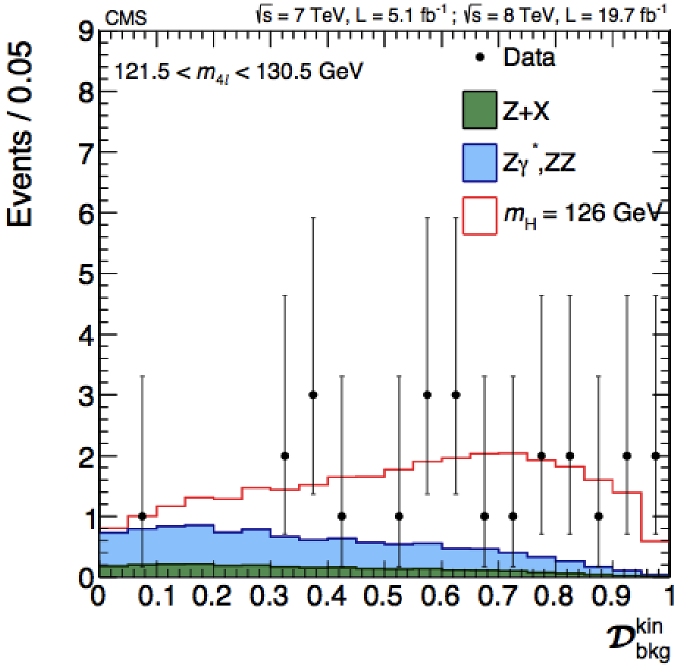
- Best fit mass: $m_H = 124.3^{+0.6}_{-0.5}\,(\text{stat})\,^{+0.5}_{-0.3}\,(\text{sys})\ \text{GeV}$
- Minimum combined p_0 value for m_H= 124.3 GeV

  Expected p_0: 5.7×10^{-6} (4.4 σ)

  Observed p_0: 2.7×10^{-11} (6.6 σ)

CMS H→ZZ→4ℓ results

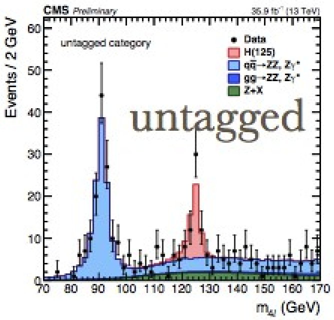


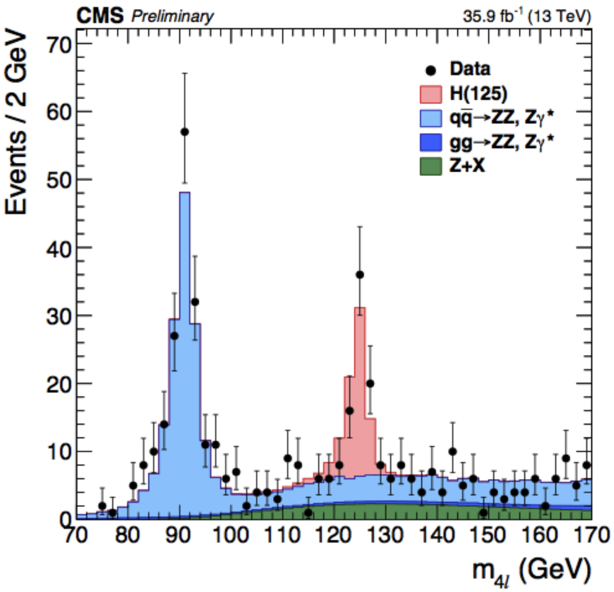


- Kinematic discriminant to further separate signal and background

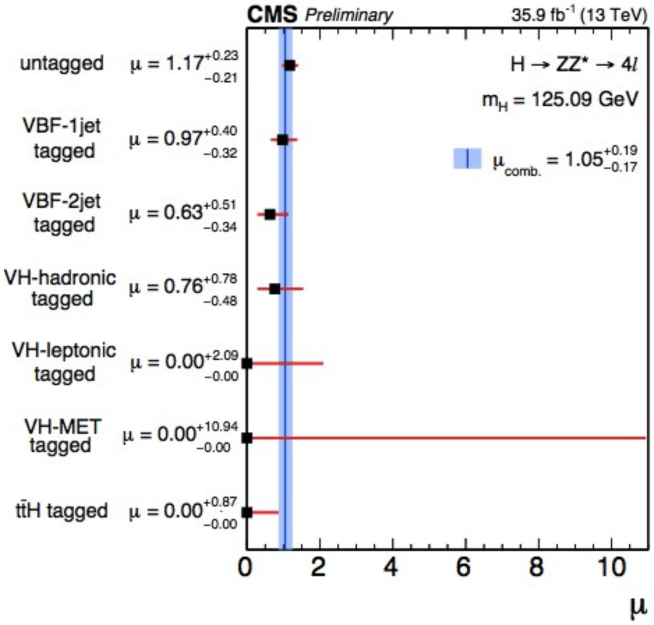
$$K_D(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi, m_{Z_1}, m_{Z_2}) = \mathcal{P}_{sig}/(\mathcal{P}_{sig} + \mathcal{P}_{bkg})$$

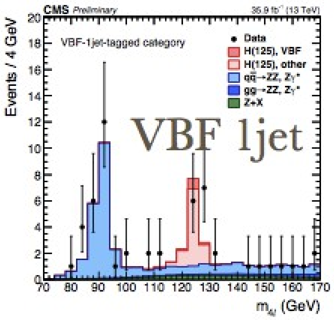
CMS Run 2 $H \to ZZ \to 4\ell$ results

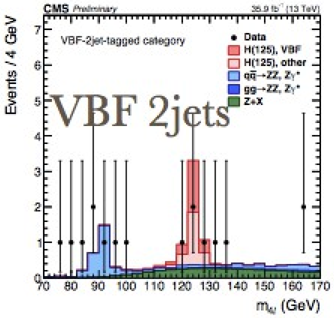


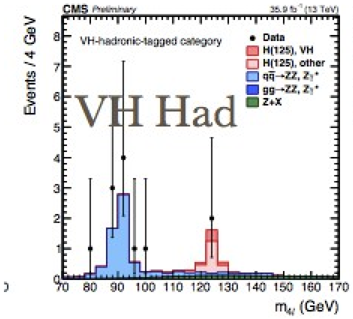


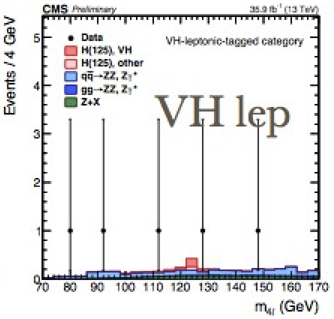
μ per category

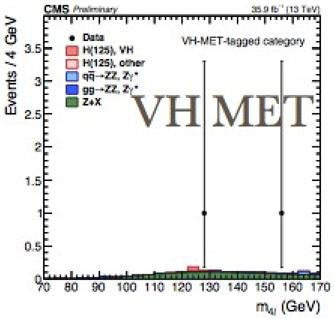


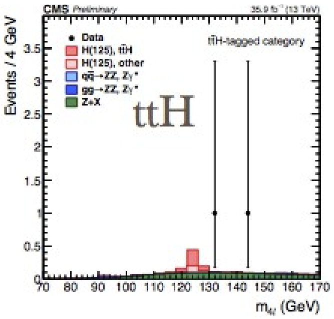




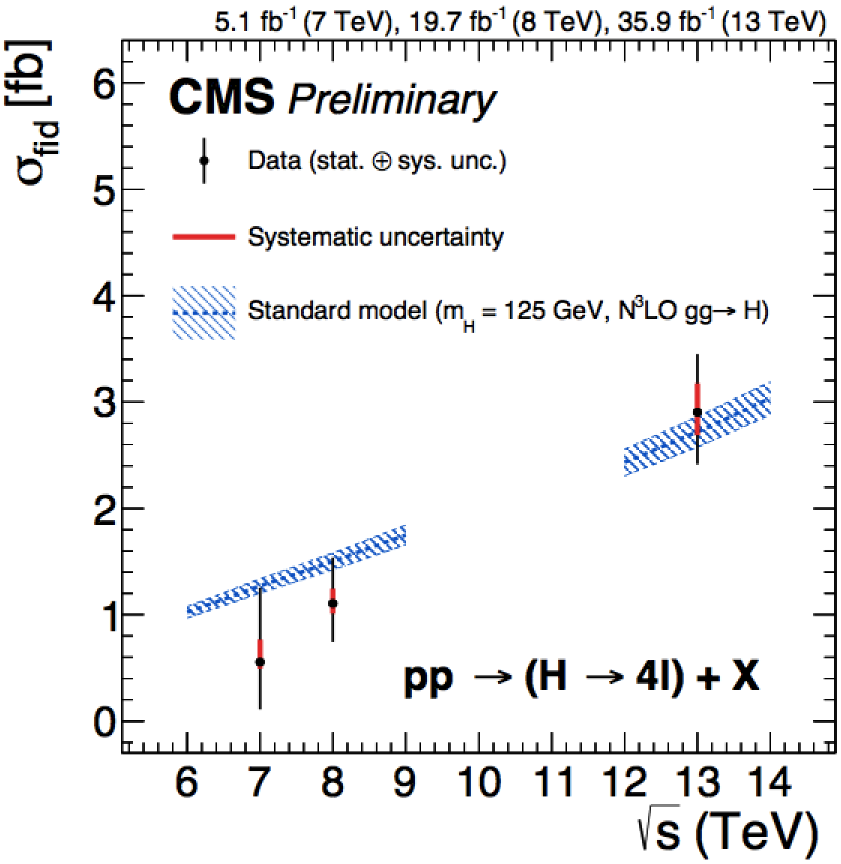


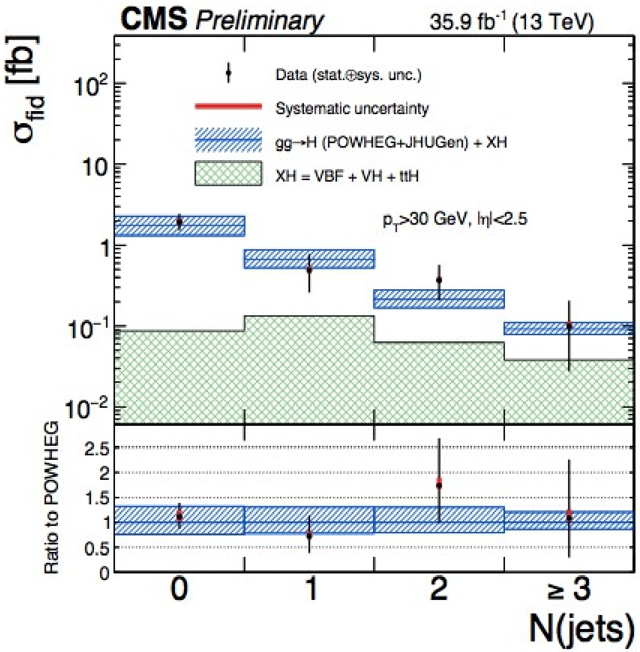






CMS Run 2 H→ZZ→4ℓ results



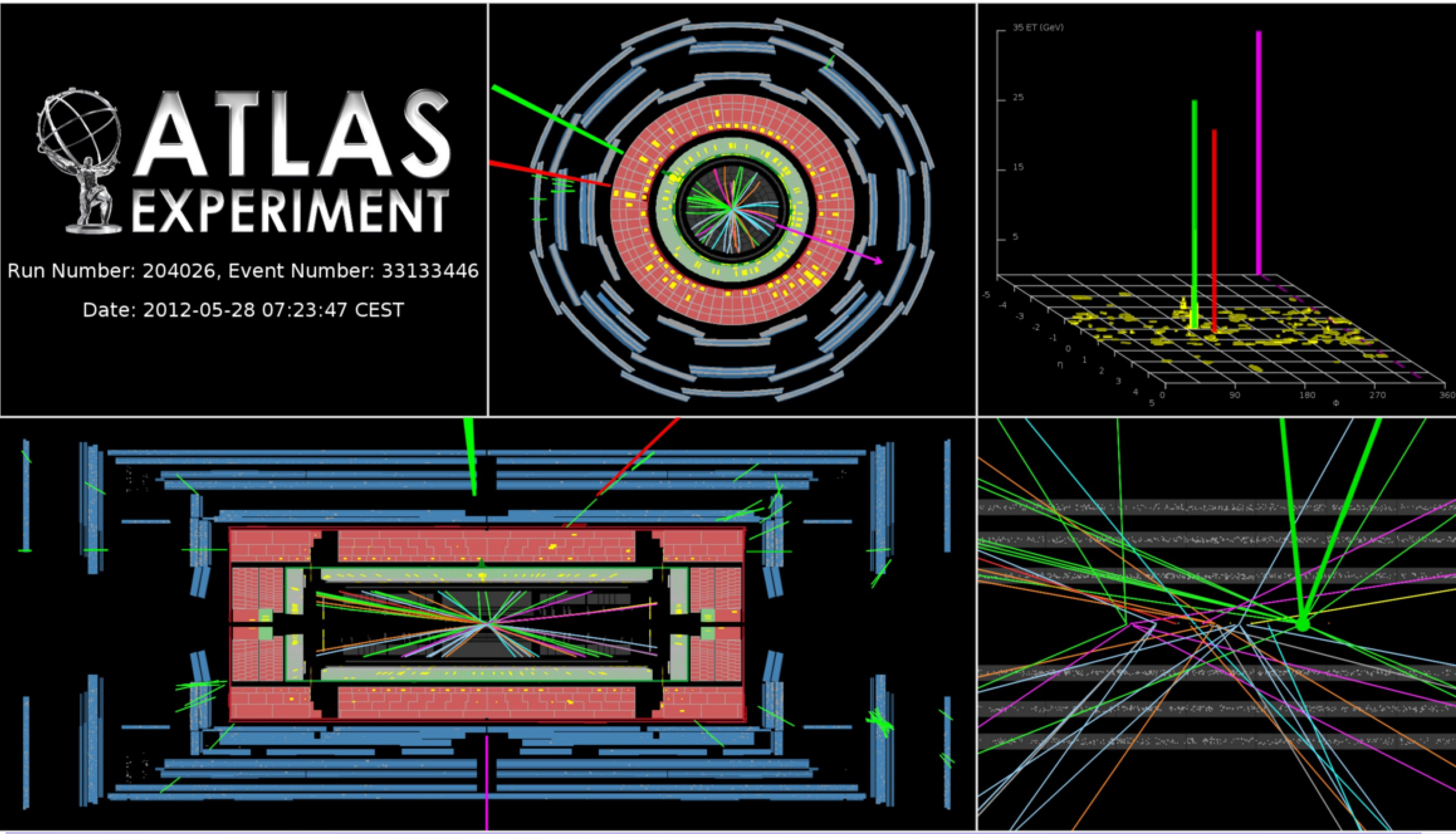


$m_H = 125.26 \pm 0.20(\text{stat.}) \pm 0.08(\text{sys.})$ GeV

Compared to

$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{sys.})$ GeV from Run1 ATLAS+CMS (4l+ γγ) combination

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

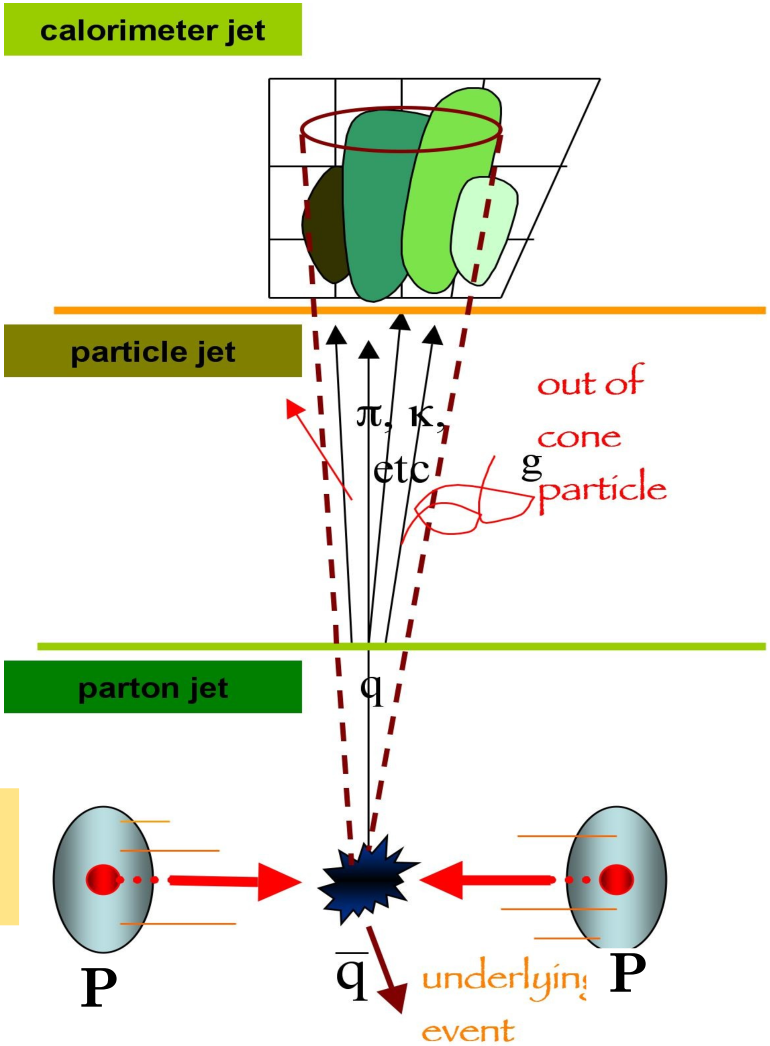


Jets reconstruction and calibration

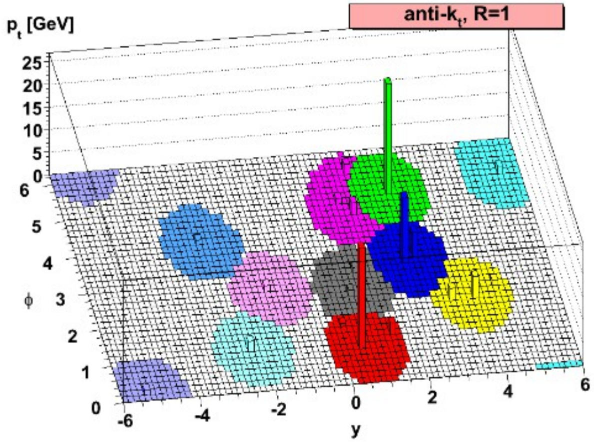
- Complex underlying physics
  - spectator interactions
  - initial and final state gluons
  - energy from different pp interactions
  - different types of jets: light quarks, gluons, b/c/↔

- Complex detector properties:
  - non-linear energy response
  - non-instrumented regions, dead material
  - invisible energy

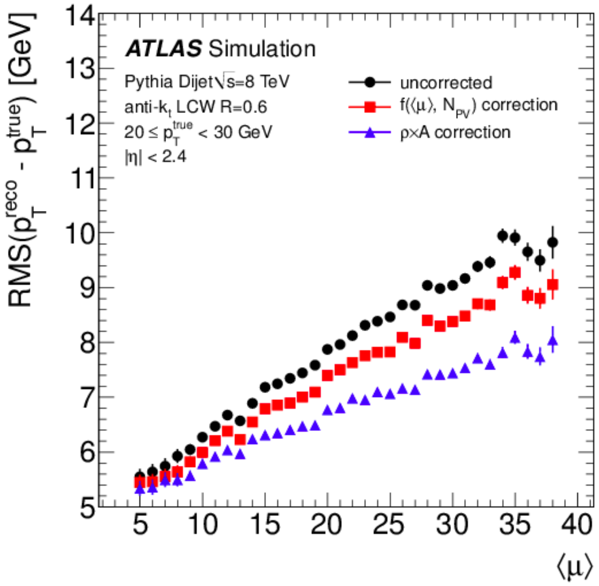
- Algorithm effects:
  - Out of cone radiation, infrared safeness

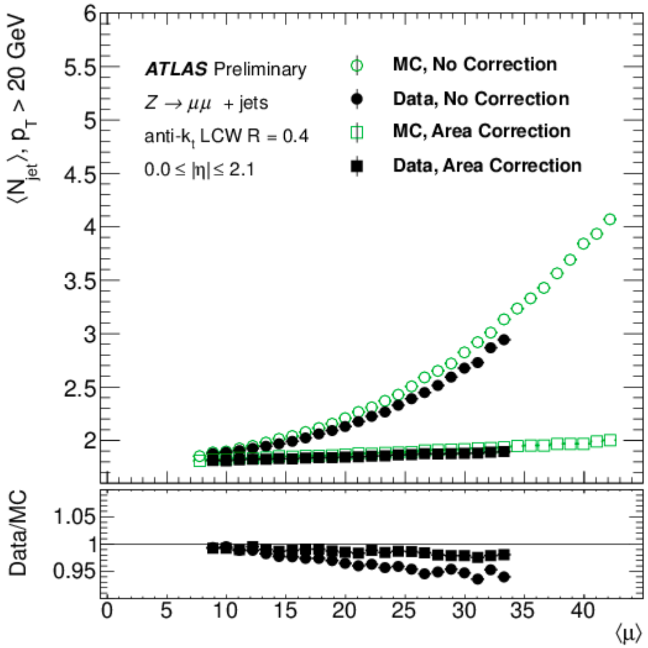


Jet Reconstruction

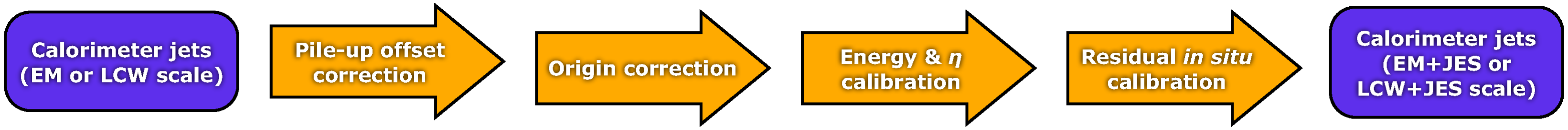


- Use Anti-kT with R = 0.4
  - Constituents: 3D clusters in calorimeter
- Calibrate to hadronic scale
- Sensitive to pile-up
  - Apply pile-up corrections





Jet energy scale uncertainty



Calorimeter jets (EM or LCW scale)

Pile-up offset correction

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

Origin correction

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

Energy & η calibration

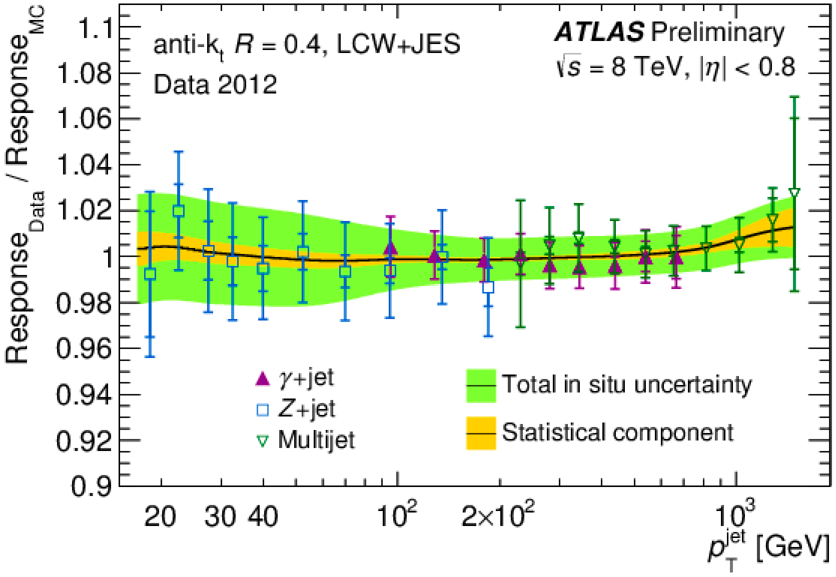
Calibrates the jet energy and pseudorapidity to the particle jet scale. Derived from MC.

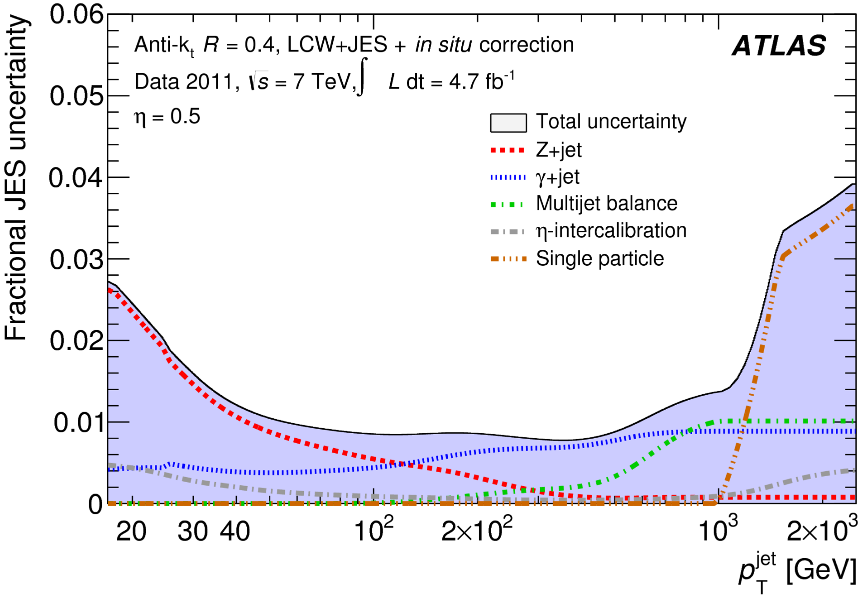
Residual *in situ* calibration

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

Calorimeter jets (EM+JES or LCW+JES scale)

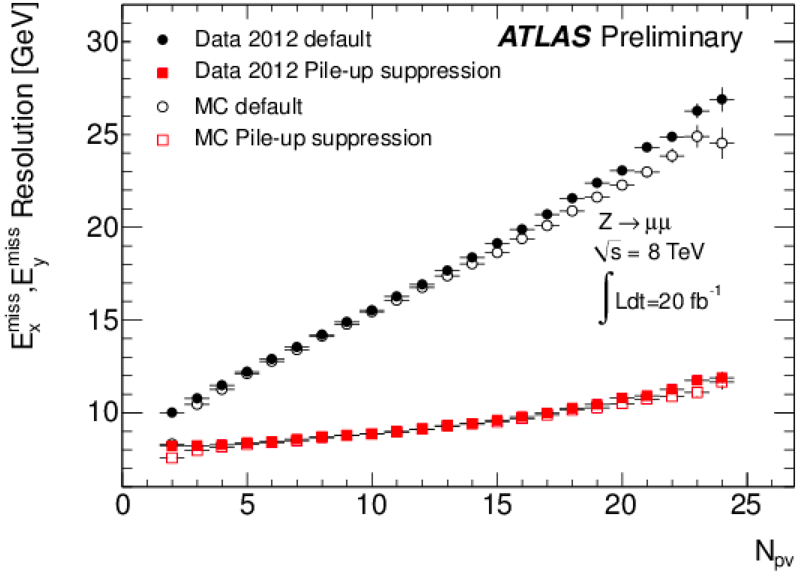
- JES uncertainty dominated by in-situ uncertainties

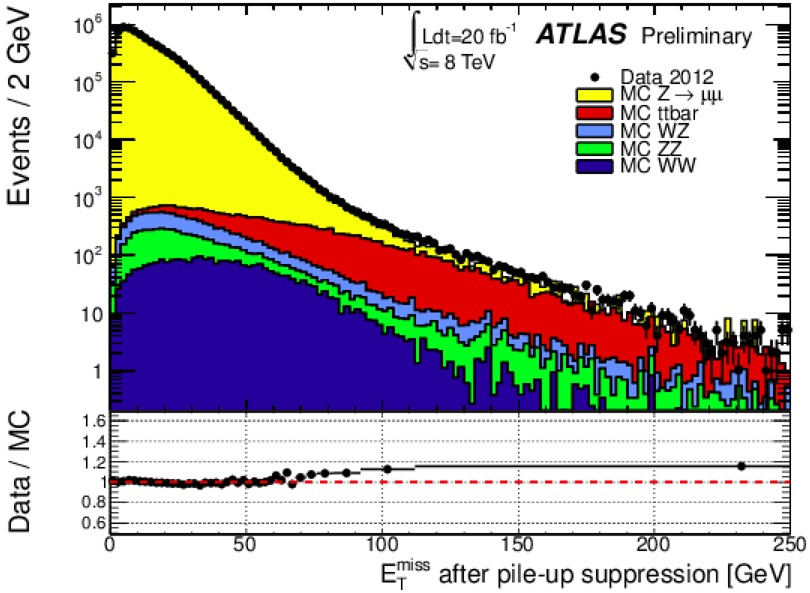




Missing E_T performance

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





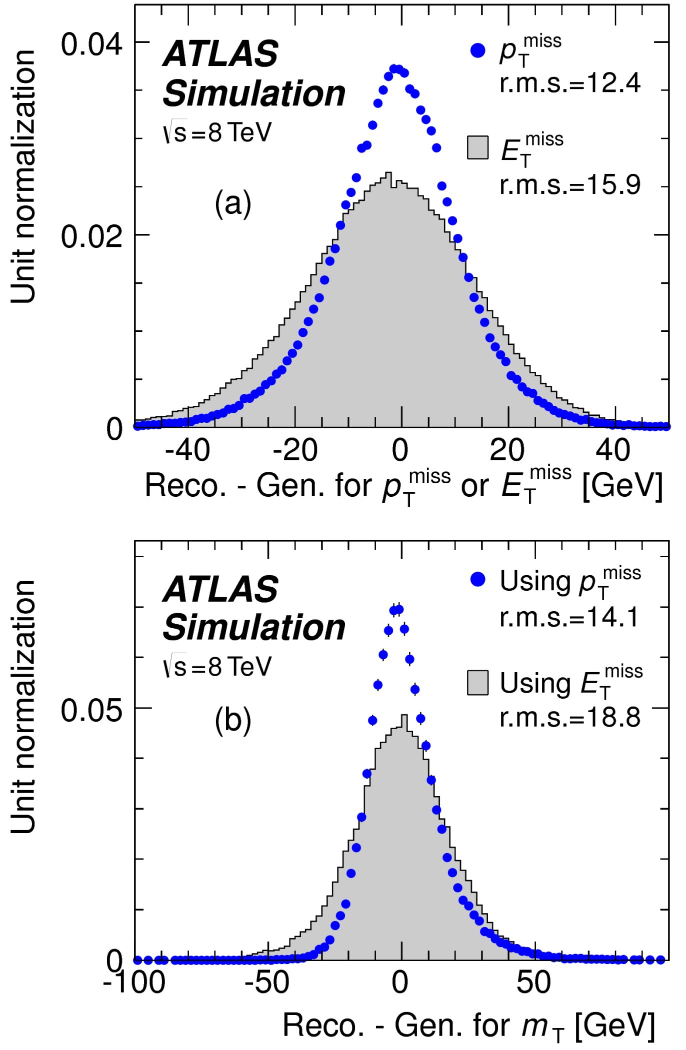
- ETmiss resolution worsens significantly with increasing pile-up
  - Correct it using tracking information
- Good data-MC agreement

E_T^{miss} on the H→WW→lνlν search

$$\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}} = -\left(\sum_{\mathrm{selected}} \boldsymbol{p}_{\mathrm{T}} + \sum_{\mathrm{soft}} \boldsymbol{p}_{\mathrm{T}} \right),$$

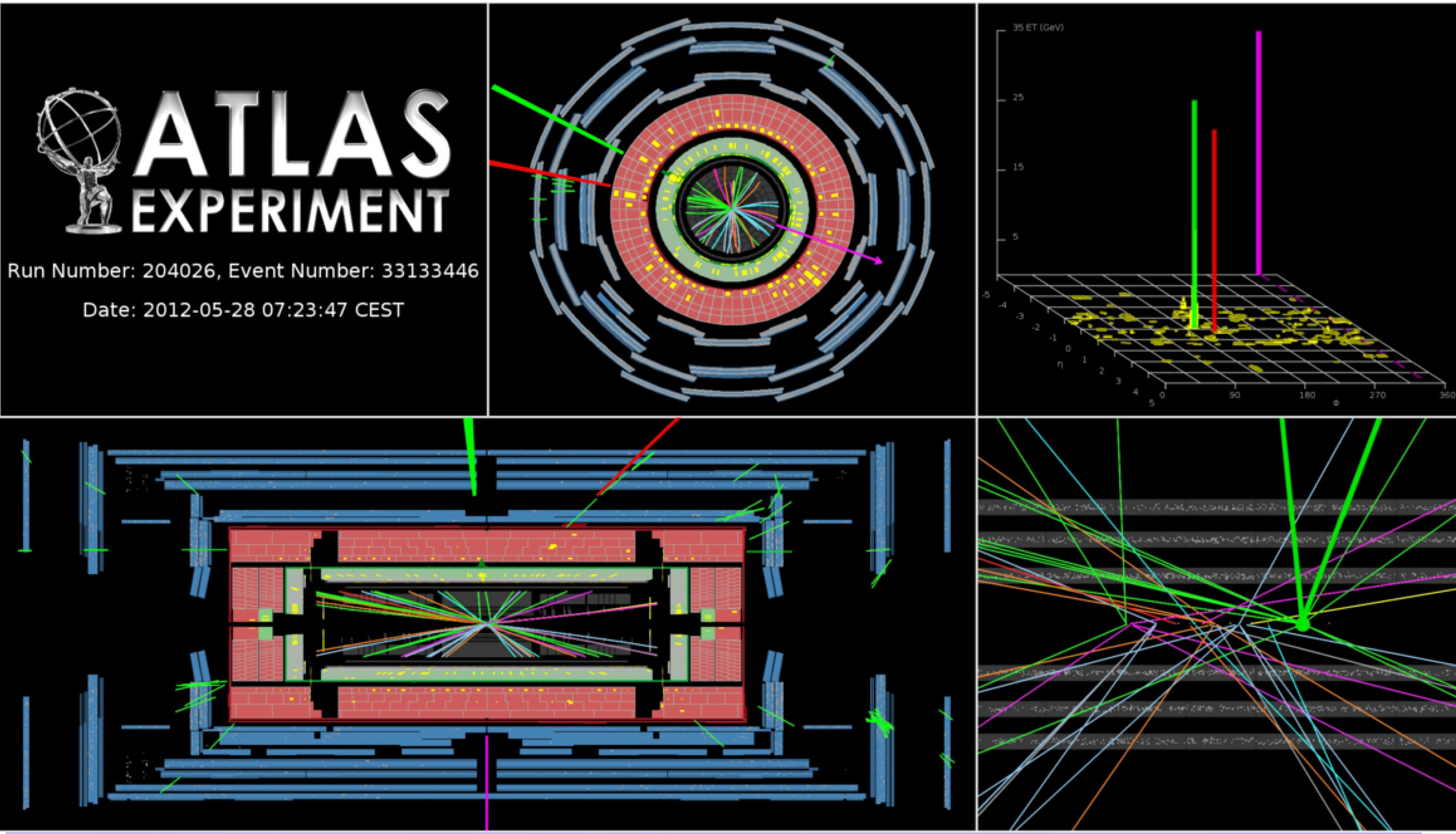
- Calorimeter based E_T^{miss}
  - Large rapidity coverage, sensitive to neutral particles
  - Soft term: calibrated calorimeter clusters
- p_T^{miss}:
  - Soft term calculated using tracking
  - Improves resolution by ~20%
- $p_T^{miss,track}$: $$p_{\mathrm{T}}^{\mathrm{miss,track}} = -\sum p_{\mathrm{T}}^{\mathrm{tracks}}$$
  - Used in the same flavour channel
  - Aligns $p_T^{miss,track}$ to the jets in DY events

MC sample for ggF $H \rightarrow WW^*$



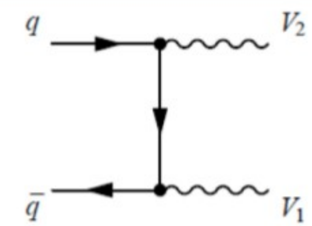
Phys. Lett. B 726 (2013), pp. 88-119

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

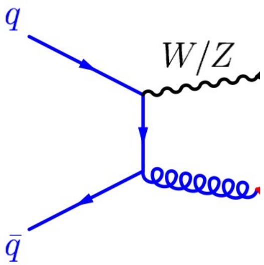


Main backgrounds

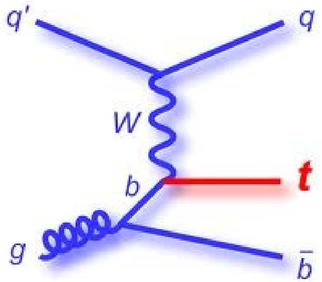
- Di-boson production
  WW, WZ, ZZ

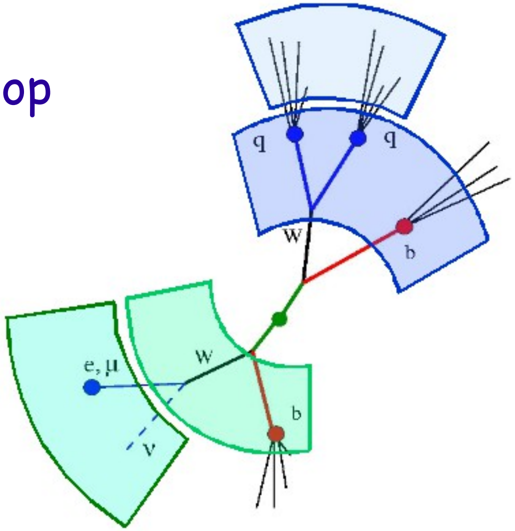


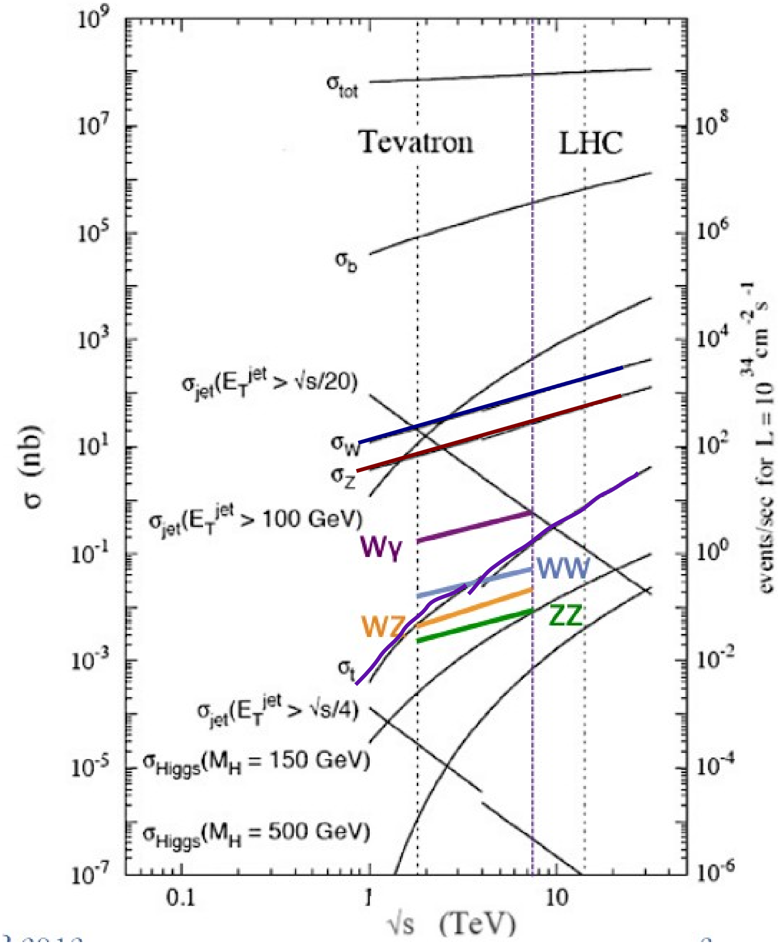
- Others: W+jets, Wγ, Drell-Yan



- Top production:
  t-tbar
  Single top

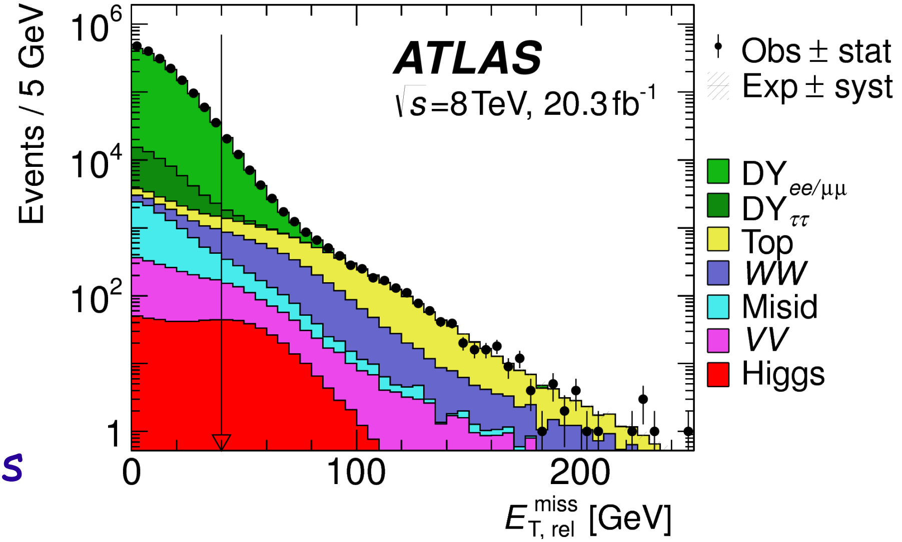




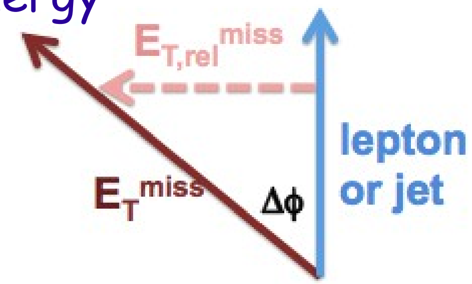


Event selection

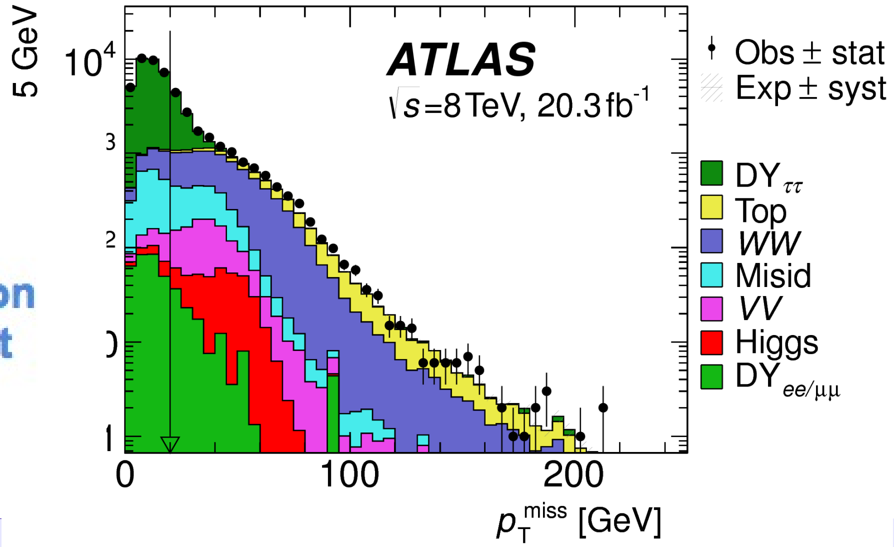
- Exploit the properties of the Higgs events to separate the signal from the backgrounds
- Different channels affected by different backgrounds
    - Small selection differences in opposite/same flavour final states



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

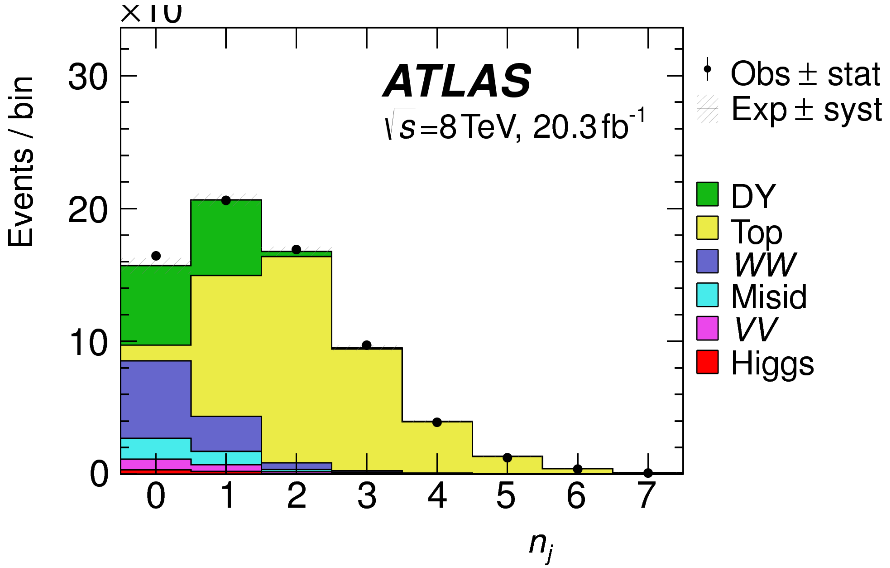


Use calorimeter and tracking systems

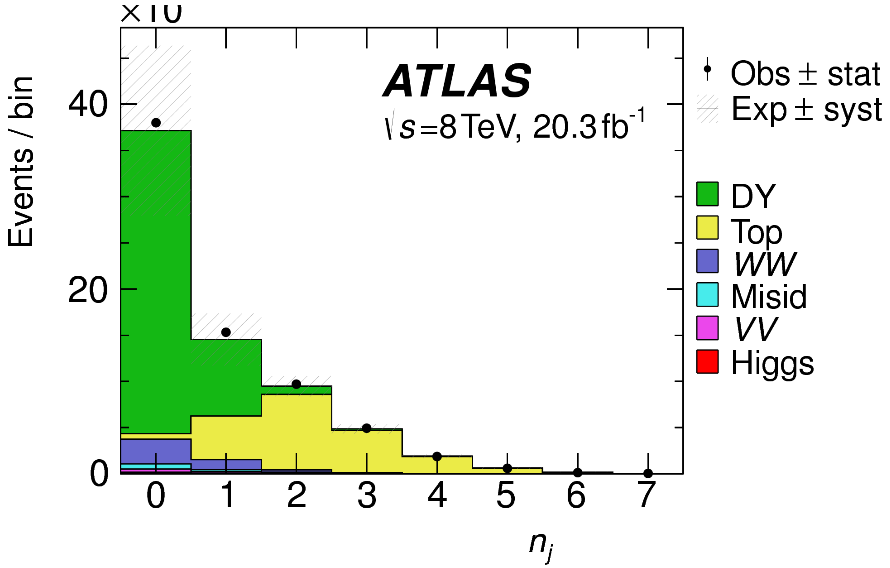


Analysis categories

- Different flavour final state

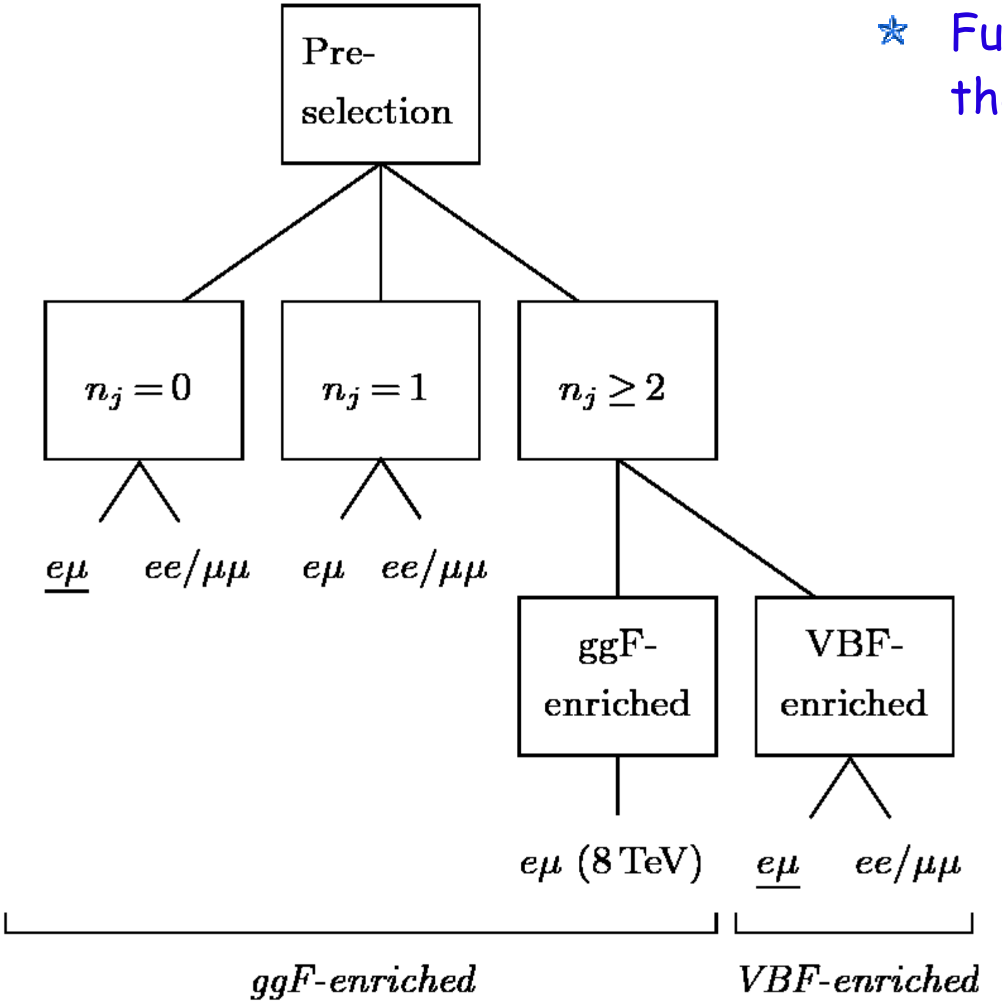


- Same flavour final state



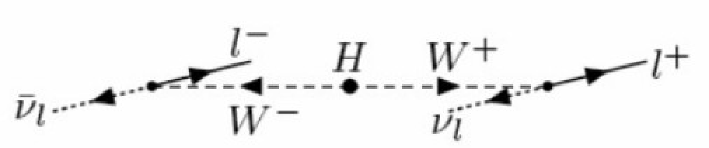
- Consider separately different categories: 0, 1, 2 jets
  - Sensitive to different production mechanisms
    - Gluon gluon fusion dominates the 0-jet category
    - VBF dominate the 2-jet category
  - Affected by different backgrounds

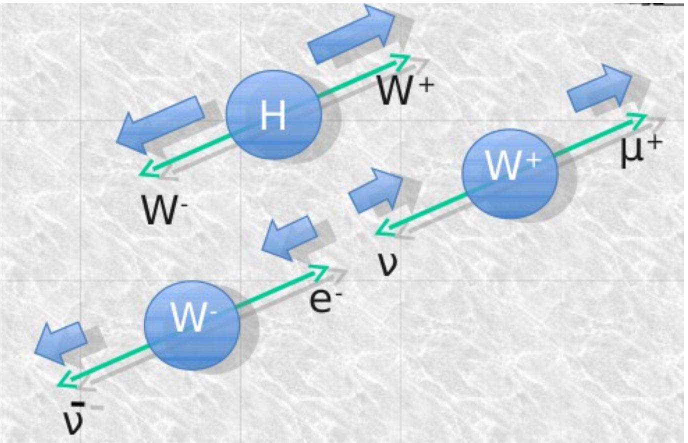
Analysis categories

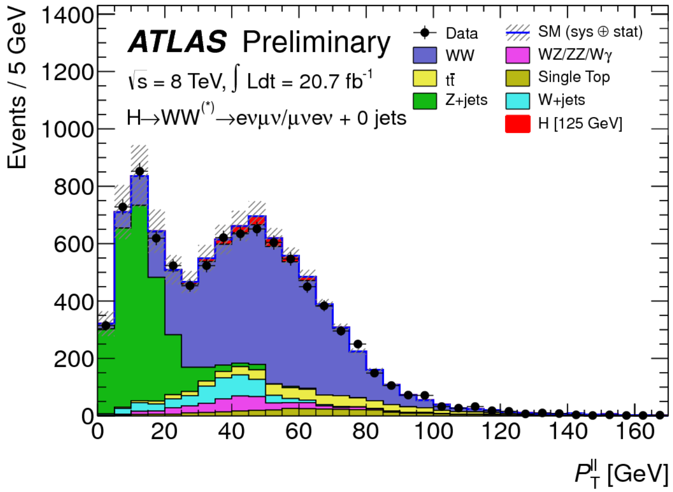


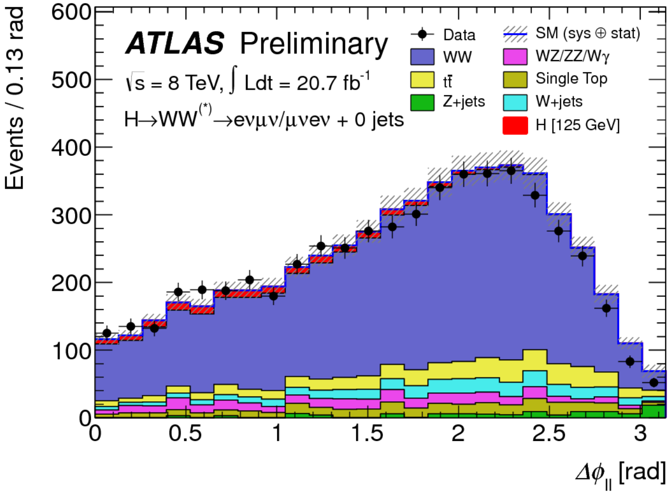
- Further selection will depend on the analysis category

Further selection

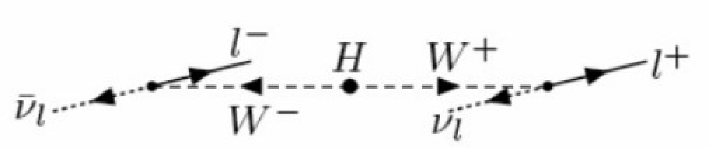


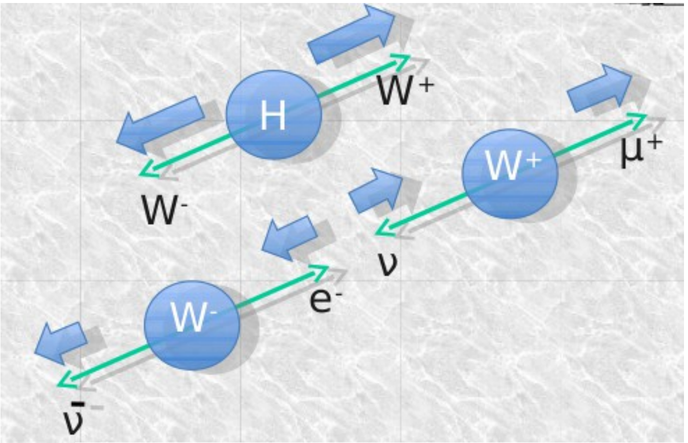


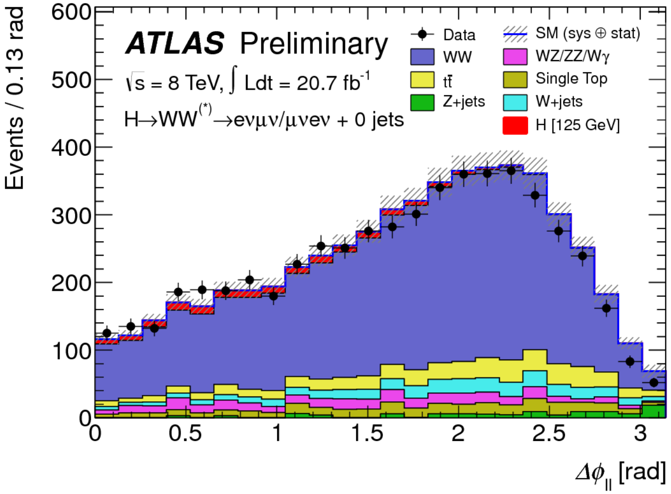


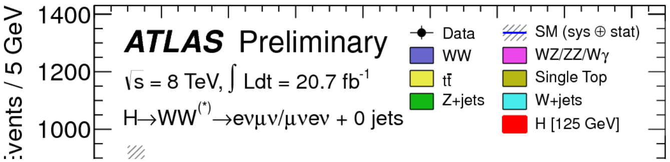


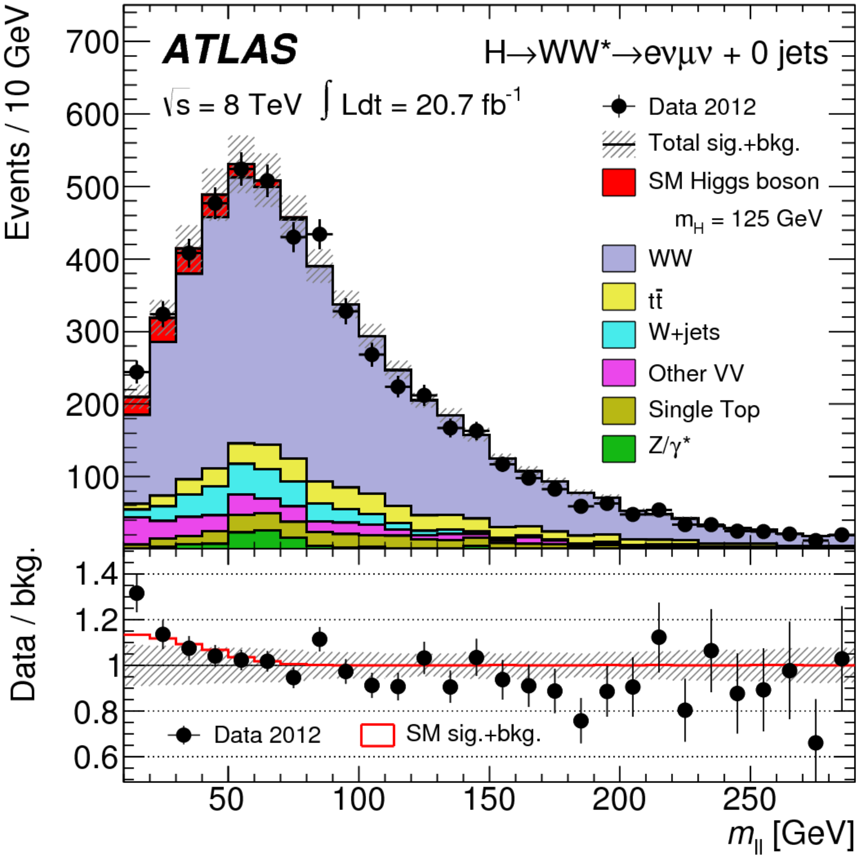
Further selection





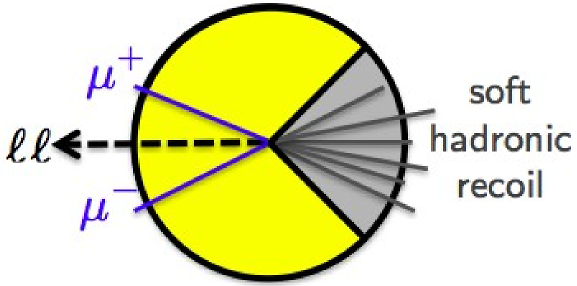


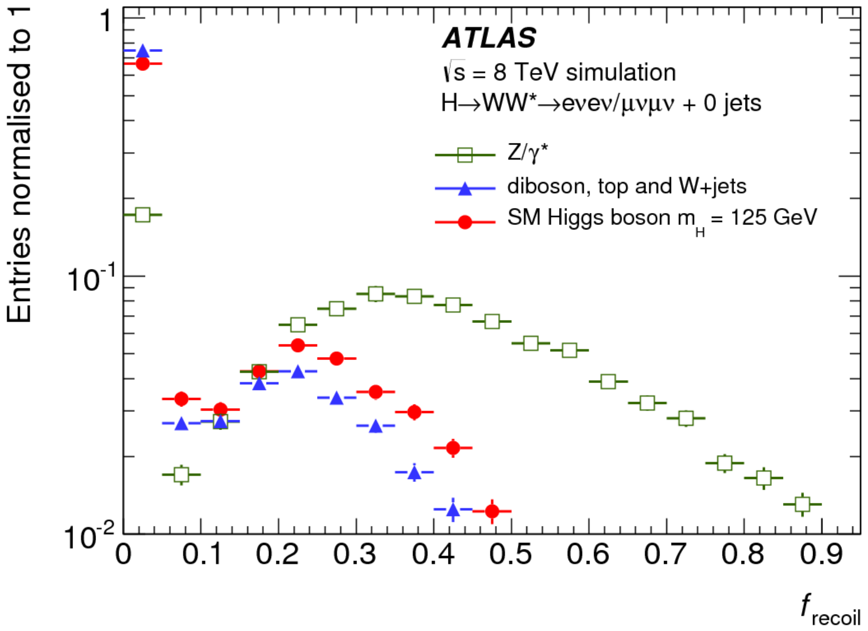




Further selection (II)

- 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



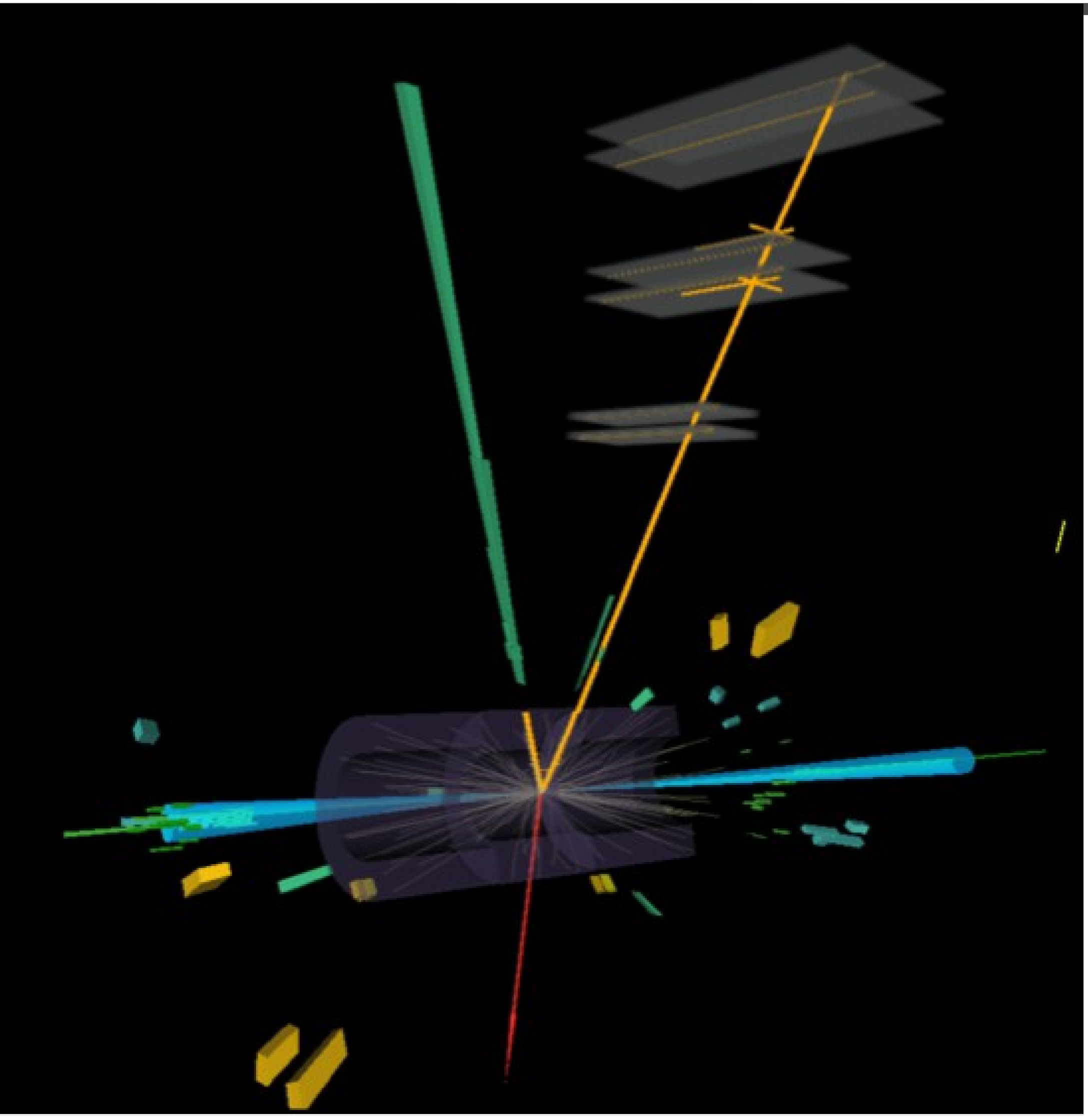


$$f_{\text{recoil}} = \frac{\left|\sum |\text{JVF}| \times \vec{p_T}\right|}{p_T^{\ell\ell}}$$

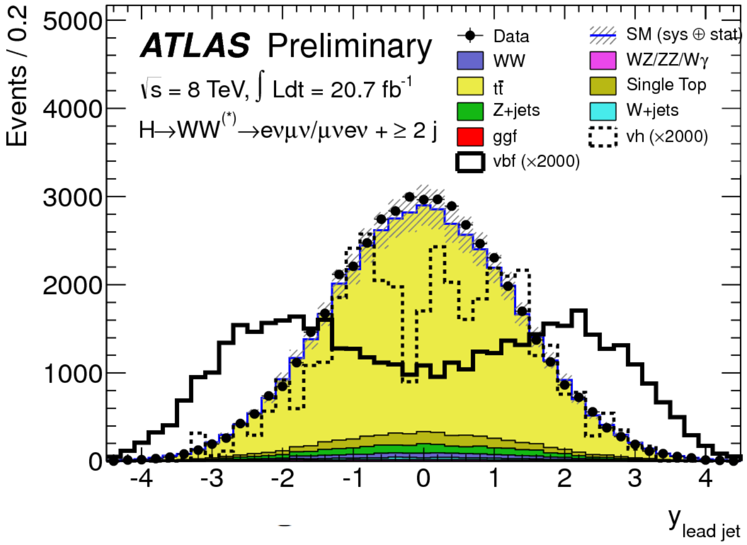
- Require

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

2-jet analysis



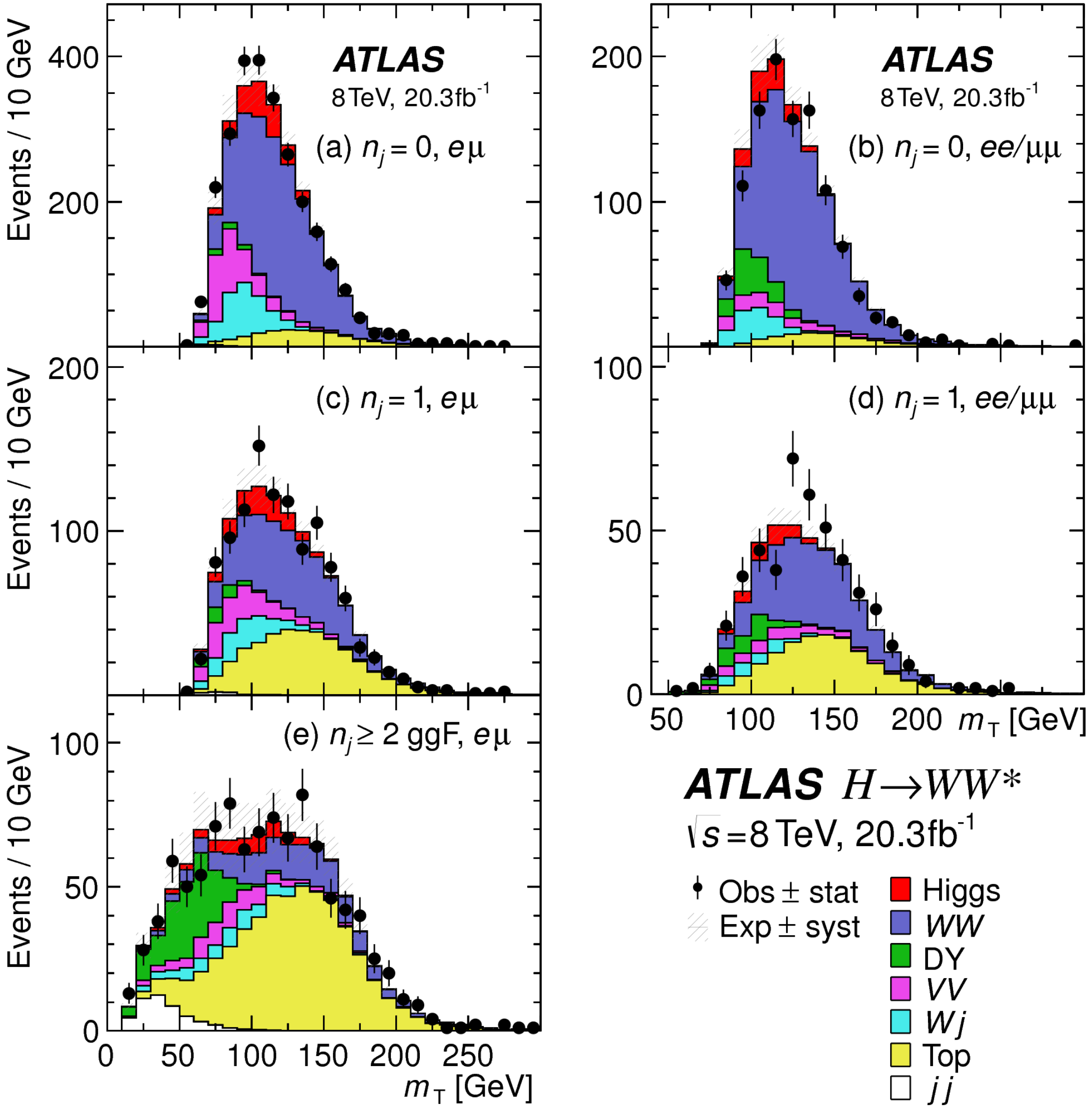
- Dominated by VBF
- Large rapidity gap between jets



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

$$m_{jj} > 500\,\mathrm{GeV}$$

Transverse mass



- Define the transverse mass:

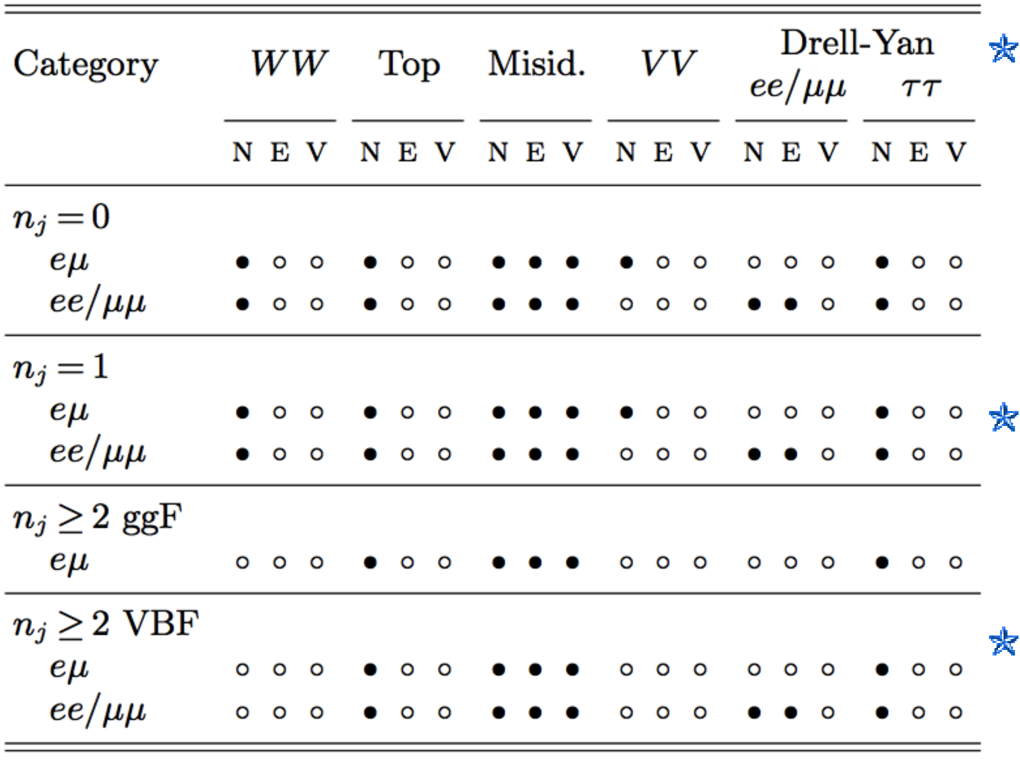
$$m_T = \sqrt{(E_T^{\ell\ell} + |\vec{p}_T^{miss}|)^2 - (\vec{p}_T^{\ell\ell} + \vec{p}_T^{miss})^2}$$

- 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					
													$ee/\mu\mu$			$\tau\tau$		
	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 background
  - 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

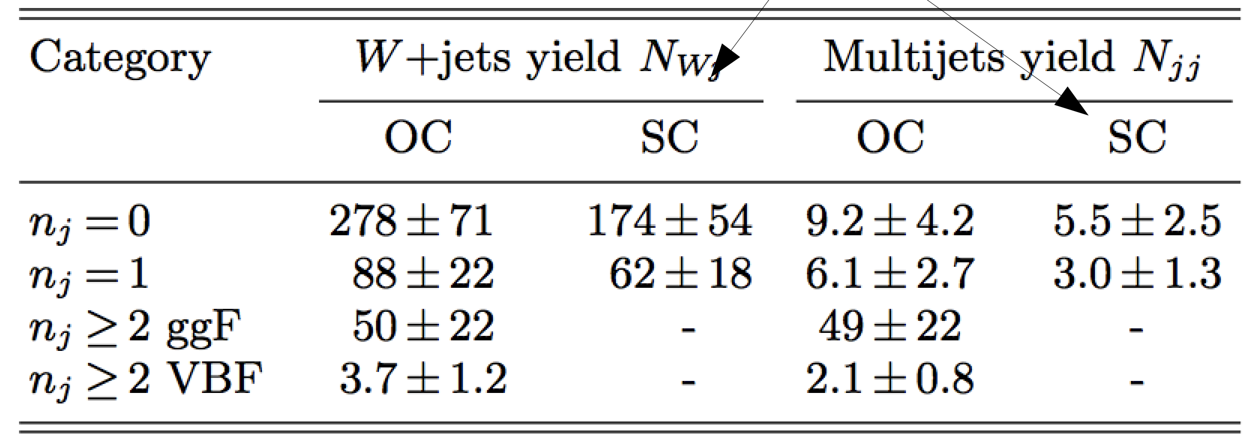
W+jets and QCD background

W+jets:

- Control sample: one loosely identified lepton
- Transfer factor to signal region evaluated with a QCD dominated jets data sample
  - 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

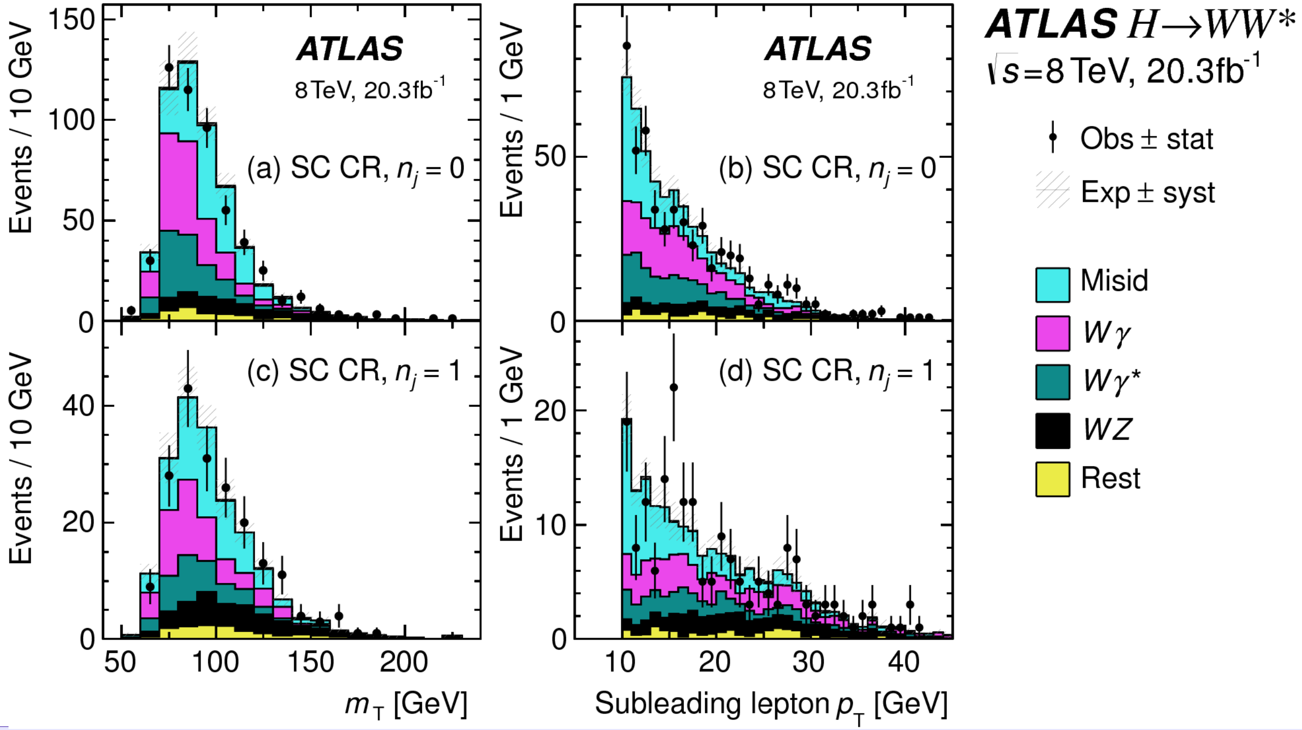
$$\beta_{0j} = 0.92 \pm 0.07\,(\text{stat.})$$

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

- Same flavour: use MC for normalization

  Validated with the same sign region

Same sign control region



Diboson background composition and modelling from MC

Uncertainty dominated by jet scale (jet bin classification)

Top quark background estimation

Top:

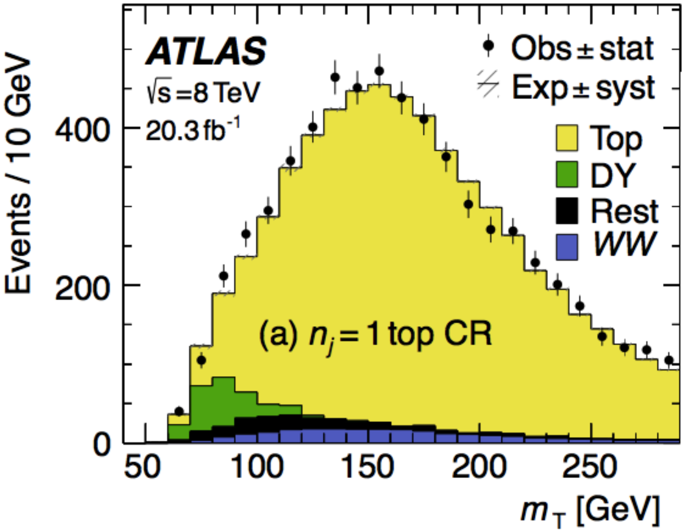
- Includes t-tbar and single top (Wt, qt)
- Control sample: remove jet multiplicity or b-tagging conditions depending on the channel

Details for the 0-jet channel:

- Remove jet multiplicity cut

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

Top control region



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

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

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

WW background estimation

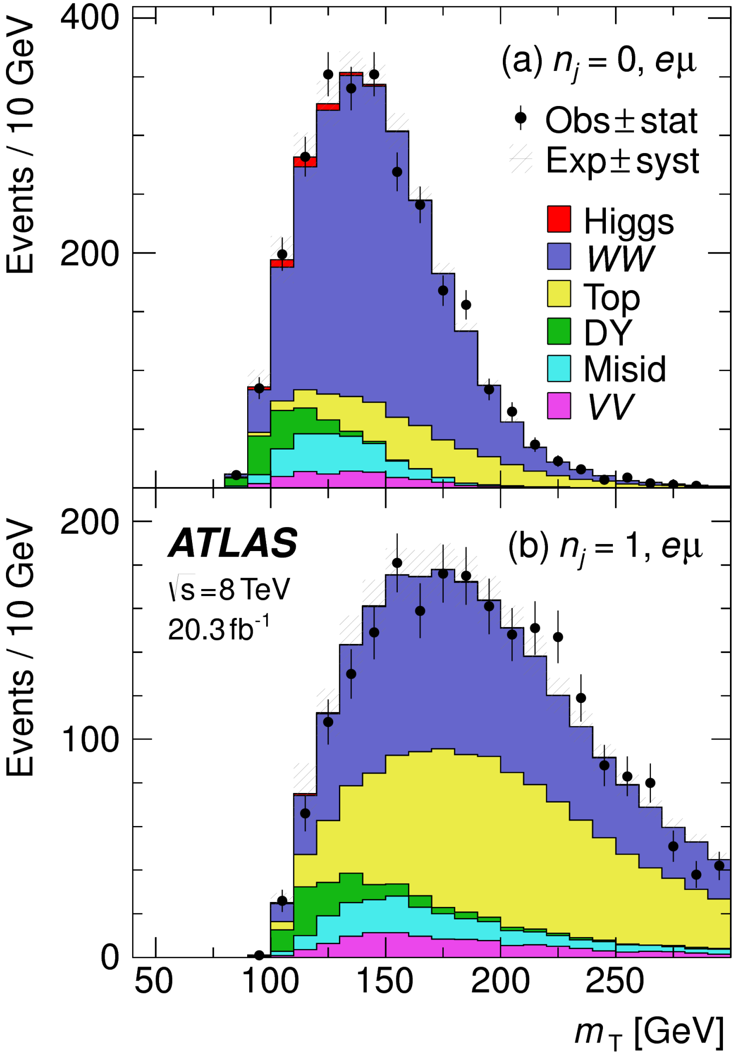
WW:

- 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, ...)

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

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



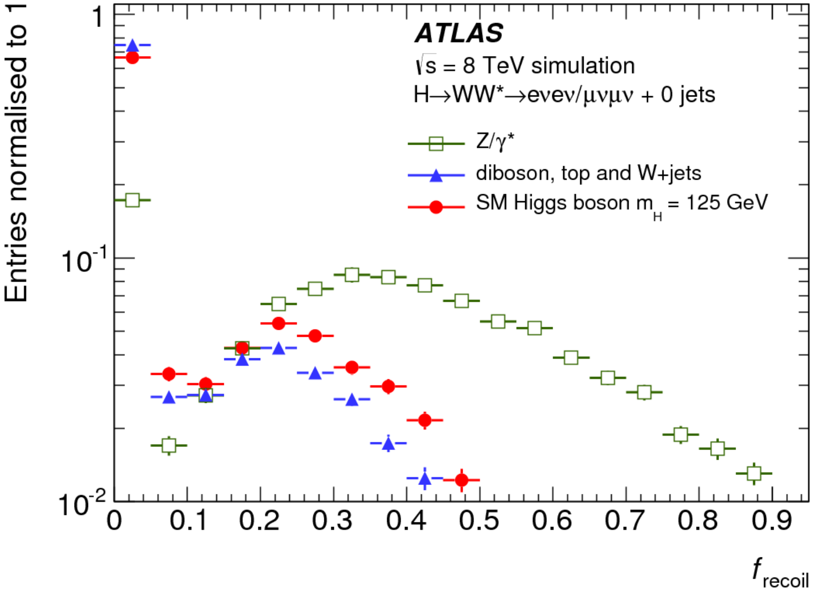
Z/γ* background

- 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 %)

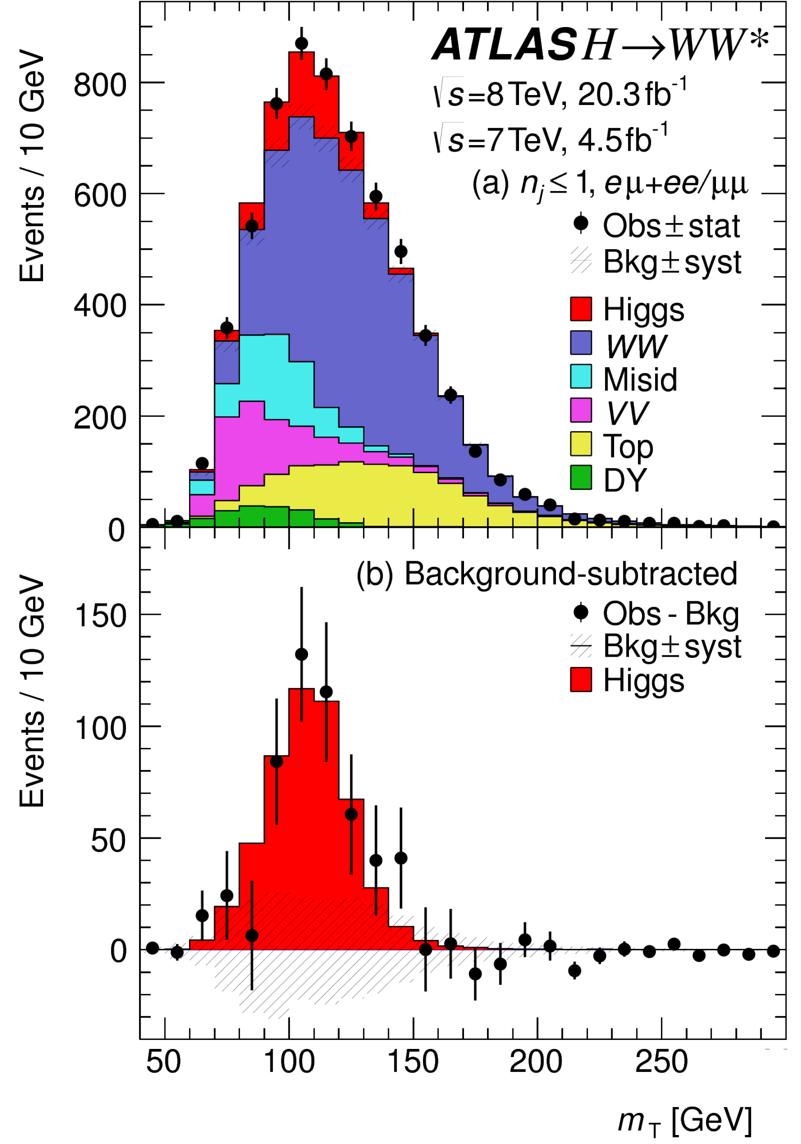
	$n_j = 0$	$n_j = 1$	$n_j \geq 2$ ggF	$n_j \geq 2$ VBF
ggF H, jet veto for $n_j = 0$, ϵ_0	8.1	14	12	-
ggF H, jet veto for $n_j = 1$, ϵ_1	-	12	15	-
ggF H, $n_j \geq 2$ cross section	-	-	-	6.9
ggF H, $n_j \geq 3$ cross section	-	-	-	3.1
ggF H, total cross section	10	9.1	7.9	2.0
ggF H acceptance model	4.8	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
$p_{\mathrm{T}}^{\mathrm{miss}}$ 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
$p_{\mathrm{T}}^{\mathrm{miss}}$ 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



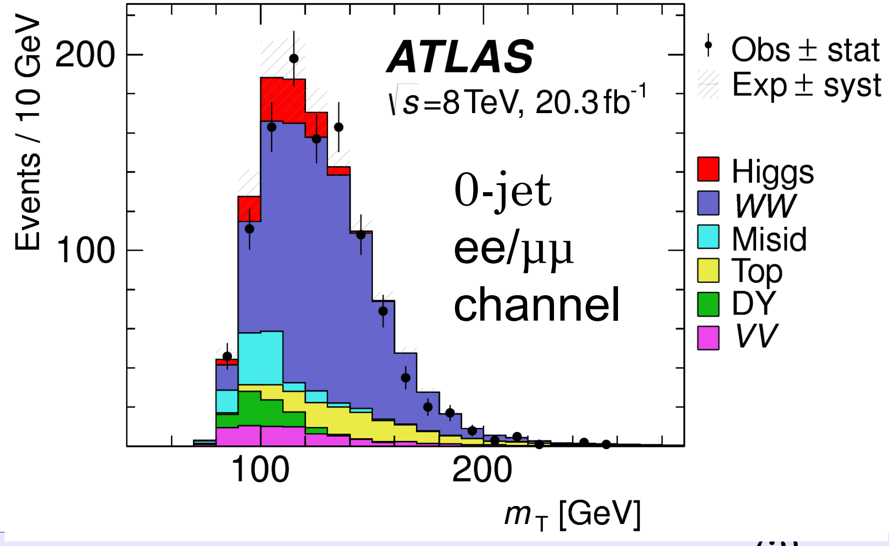
- Fit the transverse mass

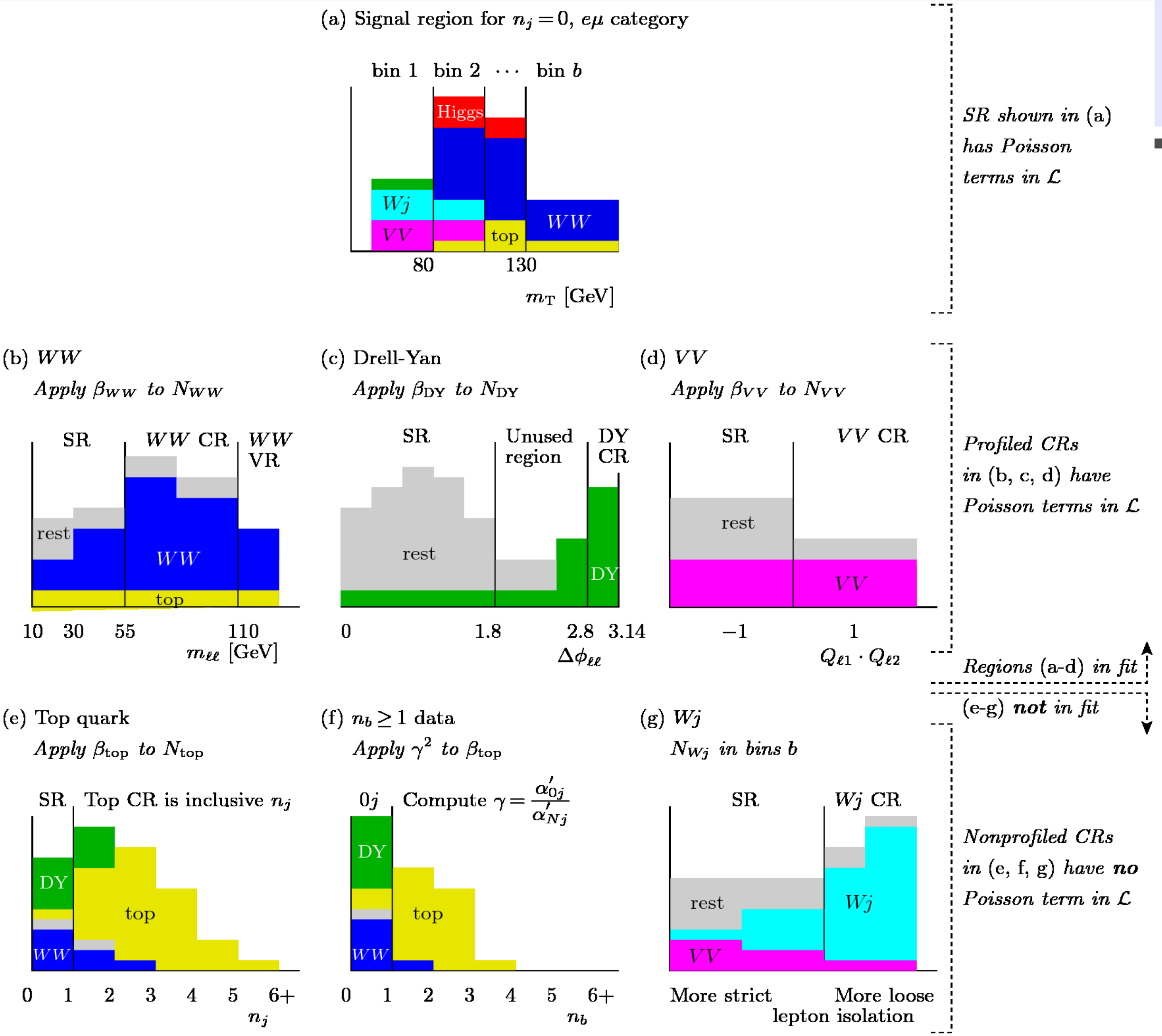
$$m_T = \sqrt{(E_T^{\ell\ell} + |\vec{p}_T^{miss}|)^2 - (\vec{p}_T^{\ell\ell} + \vec{p}_T^{miss})^2}$$

- Separate different analysis categories:

  0-, 1-, 2-jets

- Split signal region at m_{ll}= 30 GeV





SR shown in (a) *has Poisson terms in $\mathcal{L}$*

Profiled CRs in (b, c, d) *have Poisson terms in $\mathcal{L}$*

Regions (a-d) *in fit*

(e-g) ***not*** *in fit*

Nonprofiled CRs in (e, f, g) *have* ***no*** *Poisson term in $\mathcal{L}$*

Signal extraction

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

- Global fit for all signal and background regions
- μ = signal strength
- Signal region: Poisson term

$$f(N\,|\,\lambda) = e^{-\lambda}\lambda^{N}/N!$$

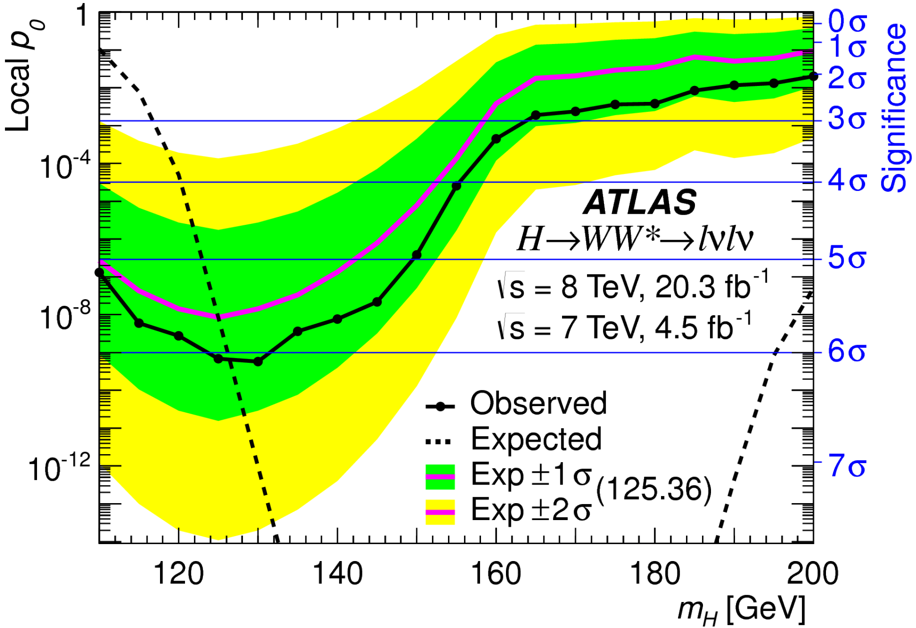
$$\lambda = \mu\cdot S + \Sigma_k\, B_k$$

- Poisson terms for background regions (normalization)
- Constraints of the systematic uncertainties

(a) Signal region categories

SR category i				Fit var.
n_j, flavor	$\otimes\, m_{\ell\ell}$	$\otimes\, p_{\mathrm{T}}^{\ell 2}$	$\otimes\, \ell_2$	
$n_j = 0$				
$e\mu$	$\otimes\,[10, 30, 55]$	$\otimes\,[10, 15, 20, \infty]$	$\otimes\,[e, \mu]$	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

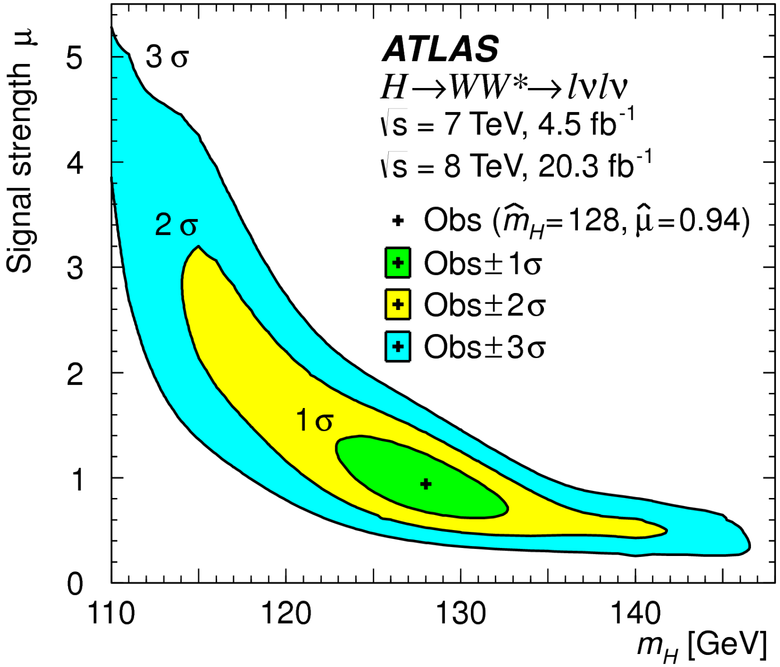


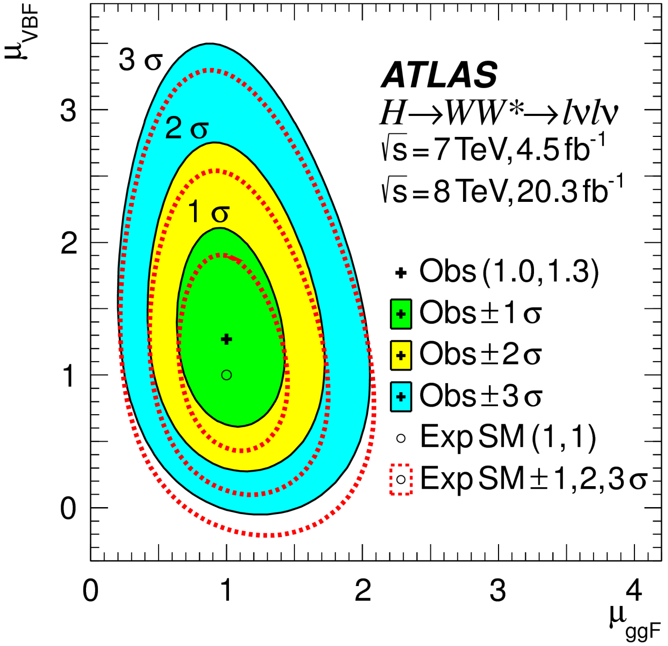
- p_0 = probability that the observed excess of events is due to a background fluctuation
- Minimum p_0 at 130 GeV (6.1σ)
- Same p_0 at 125.36 GeV

  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



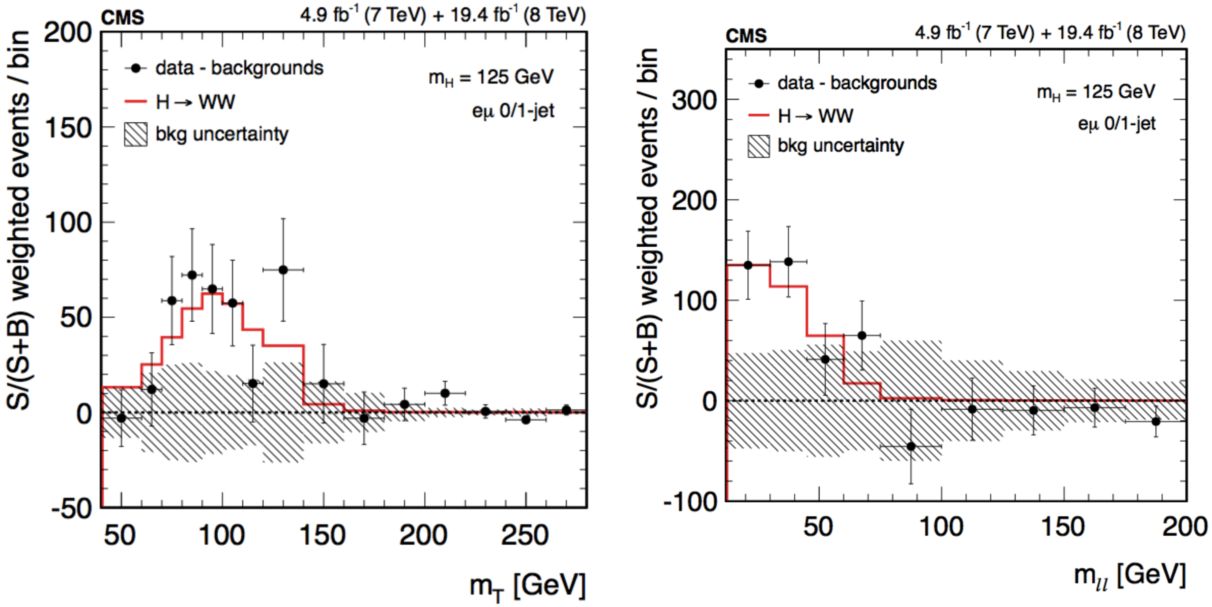


- Signal strength compatible with SM expectations

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

CMS H→WW results

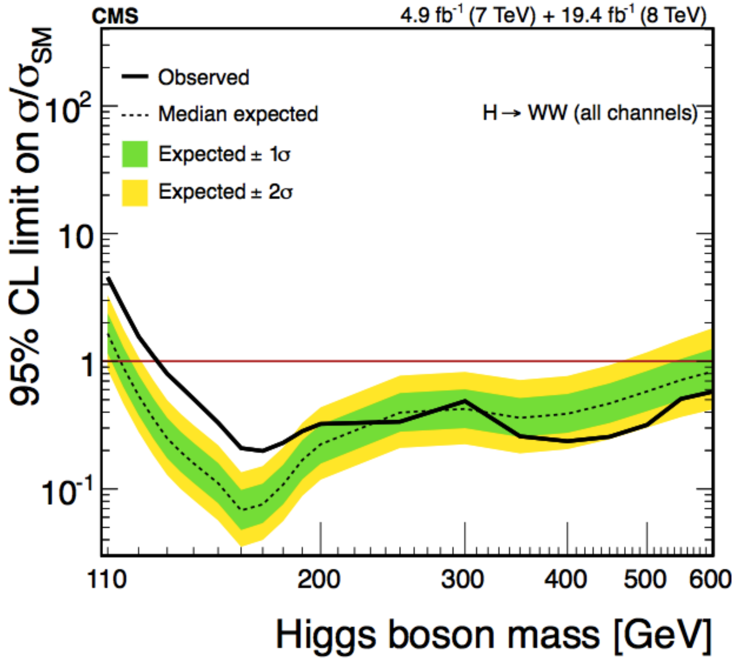
- m_T and m_{ll} after the final selection:

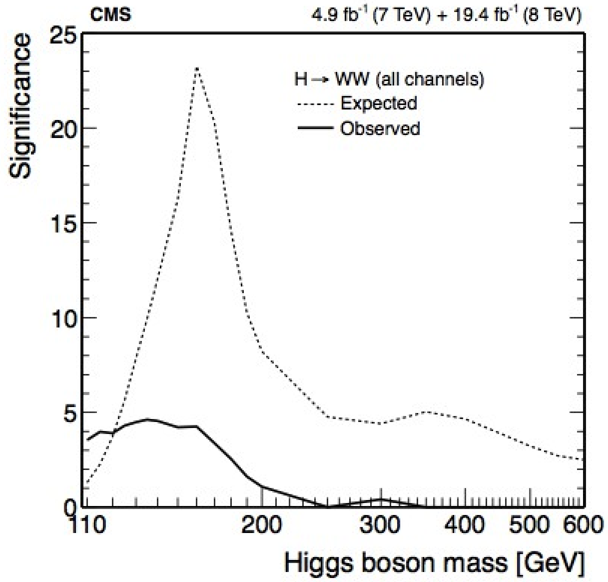


- In addition, they consider also a 3-lepton category (VH associated production)

CMS H→WW results

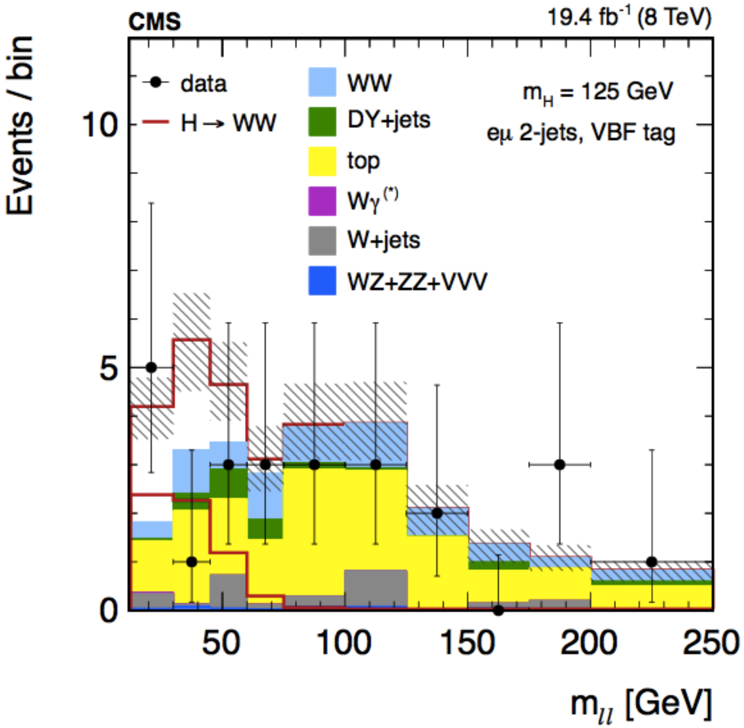
- Combined results

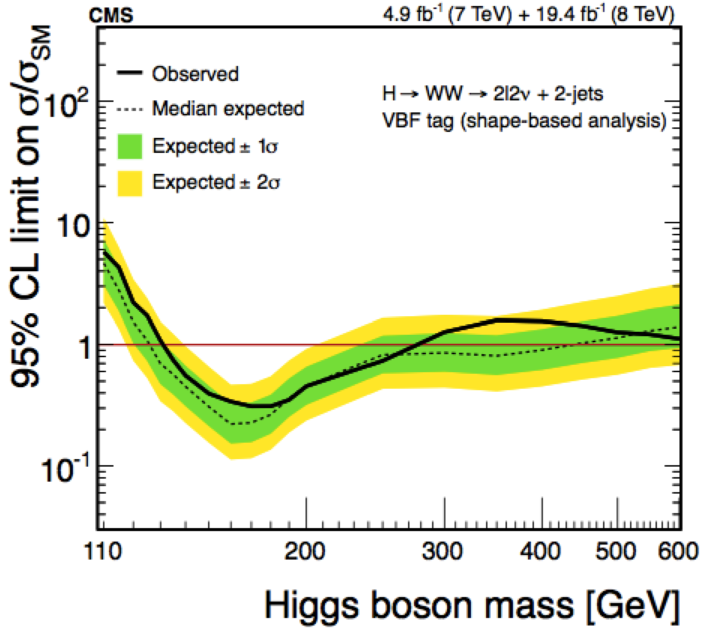




0/1-jet analysis $m_H = 125\,\text{GeV}$	95% CL limits on σ/σ_{SM} expected / observed	Significance expected / observed	σ/σ_{SM} observed
$(m_T, m_{\ell\ell})$ template fit (default)	0.4 / 1.2	5.2 / 4.0 sd	0.76 ± 0.21
$(m_R, \Delta\phi_R)$ parametric fit	0.5 / 1.4	5.0 / 4.0 sd	0.88 ± 0.25
Counting analysis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

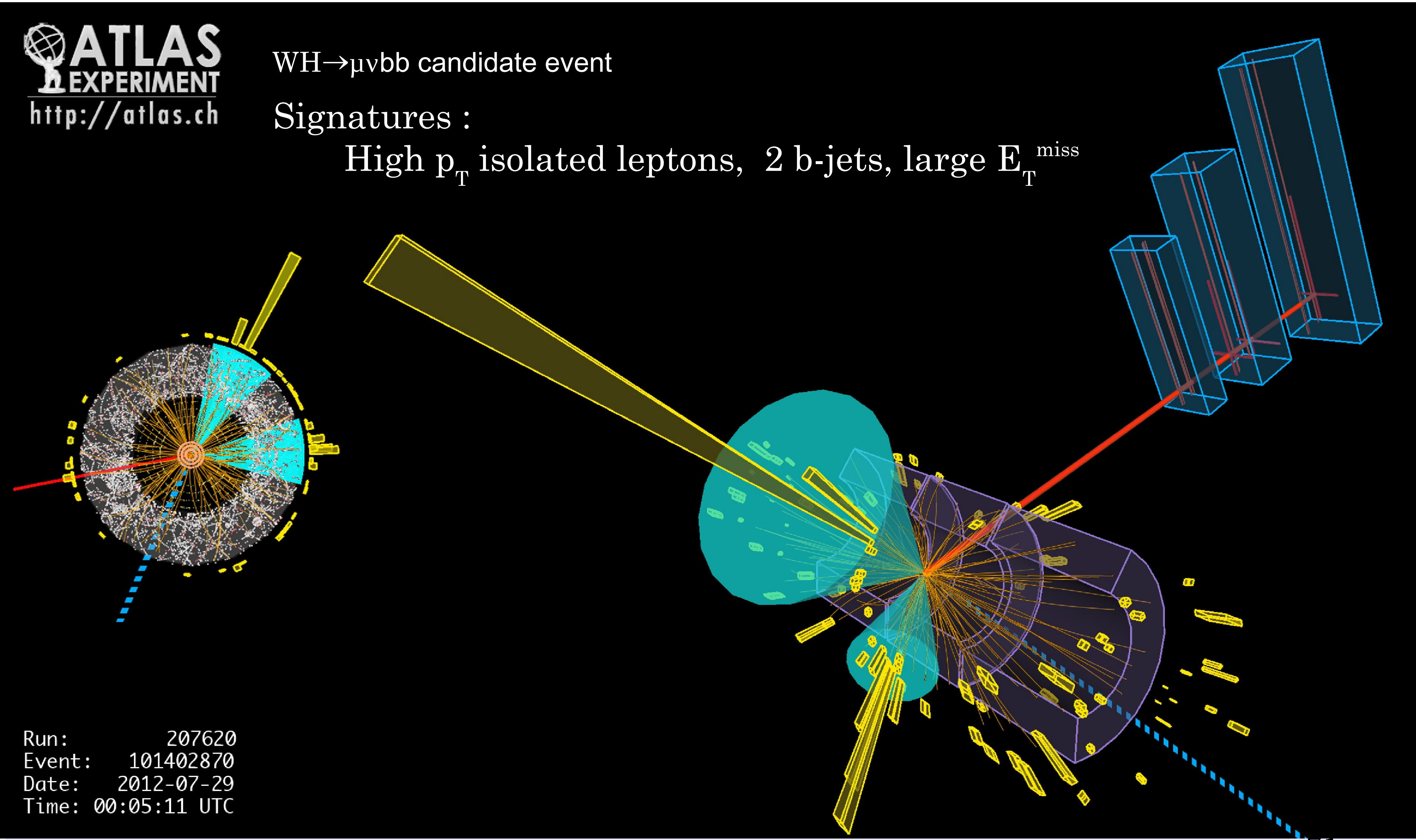
CMS H→WW VBF results





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

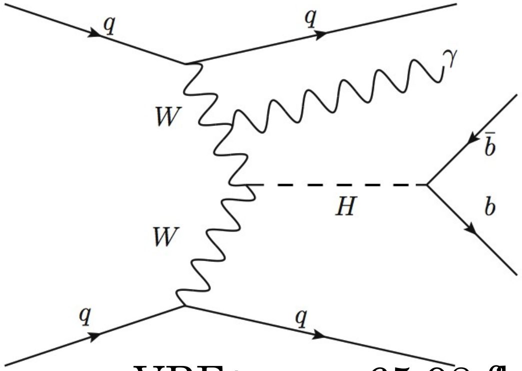


Signatures :

High p_T isolated leptons, 2 b-jets, large E_T^{miss}

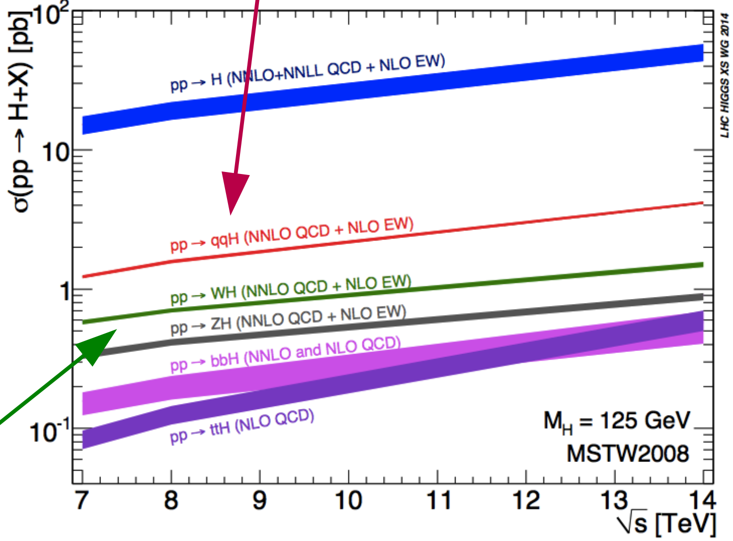
H → bb: how?

- Explore non-dominant production modes
- Vector boson fusion + photon (VBF search)
  - Use photon to trigger
  - bbγjj non-resonant bckg. suppressed by ~10×

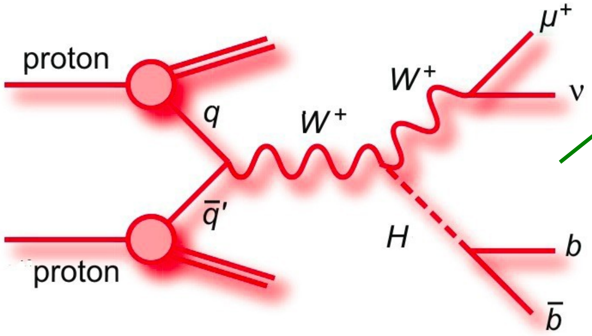


VBF+γ: σ = 65.98 fb

- Previous inclusive VBF (H→bb) limits:
  - **ATLAS:** obs/expect. upper limit : 4.4/5.4 × SM
  - CMS Run 1 obs/expect. upper limit: 5.5/2.5 × SM
  - CMS Run 2 (2015)
    - obs/expect. upper limit: 3.0/5.0 × SM

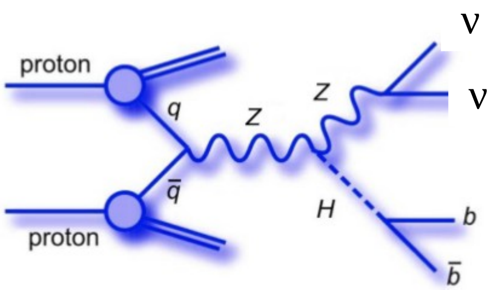


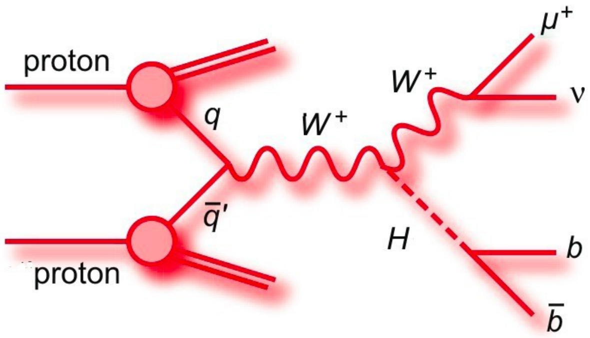
- Associated production with W or Z (VH search)
  - Trigger on e/μ from W/Z decay

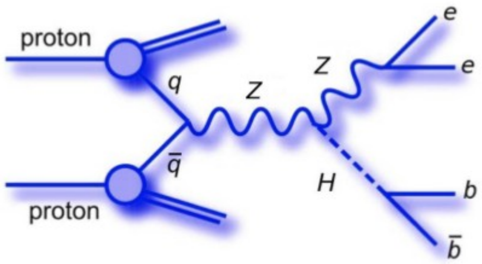


WH: σ = 1.373 pb
ZH: σ = 0.884 pb

VH searches: 3 channels





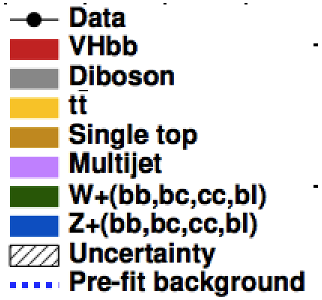


- 0-lepton:
  - $E_T^{miss} > 150$ GeV
- 1-lepton:
  - e/μ, p_T>25 GeV
  - Tight isolation
  - Missing E_T
  - $p_T^V > 150$ GeV
- 2-leptons:
  - Isolated ee, μμ
  - p_T^1>25 GeV, p_T^2>7 GeV
  - No missing E_T,
  - $m_{\ell\ell}$ compatible with m_Z

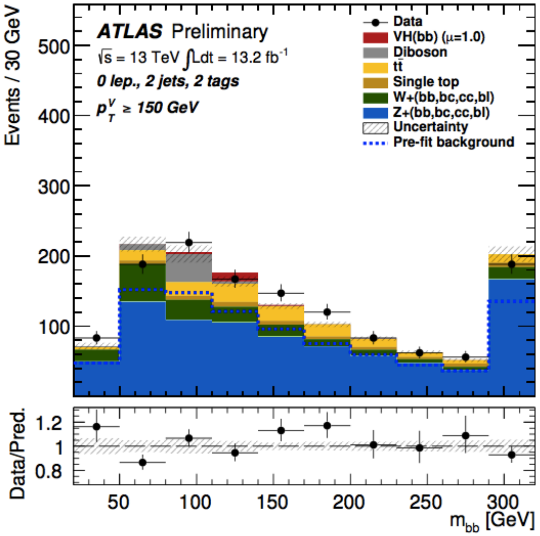
- Two jets
  - anti-kT with R=0.4
  - P_T^{j1}>45 GeV
  - p_T^{j2}>20 GeV
- Improved b-tagging with respect to Run 1:
  - Eff: 70%, light jet rejection: 380, charm rejection: 12
- Analysis categories:
  - 2/3 jets (0/1lepton)
  - 2/≥3jets (2lept.)
  - P_T^V </> 150 GeV (2lept)

Main backgrounds

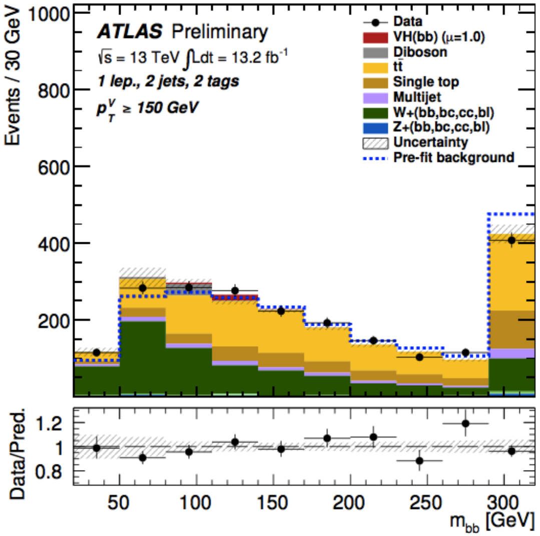
- Dominant backgrounds dependent on channel
  - Z+bjets dominates in 0, 2 lepton channels
  - Top quark and W+jets in 1 lepton channel
  - Multi-jet:
    - negligible in 0/2 lepton channels after anti-QCD cuts
    - Data-driven in 1 lepton channel



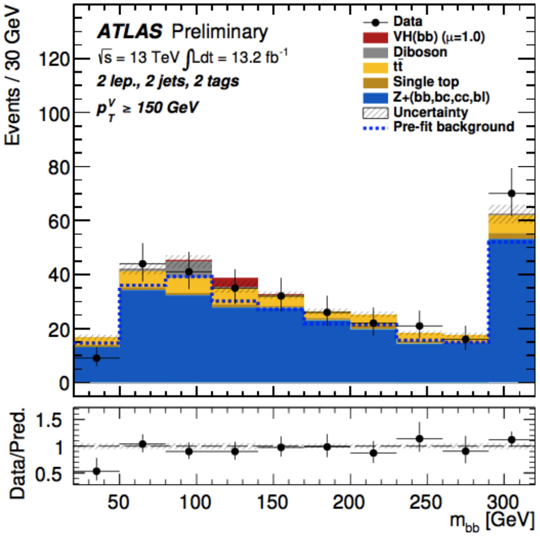
0 lepton



1 lepton

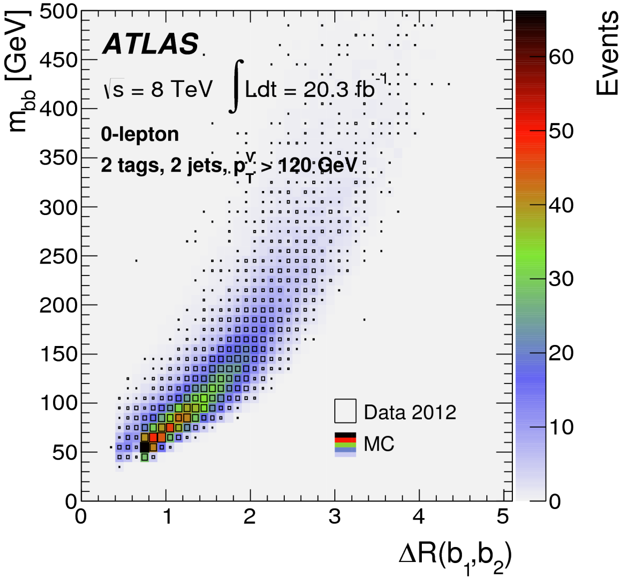


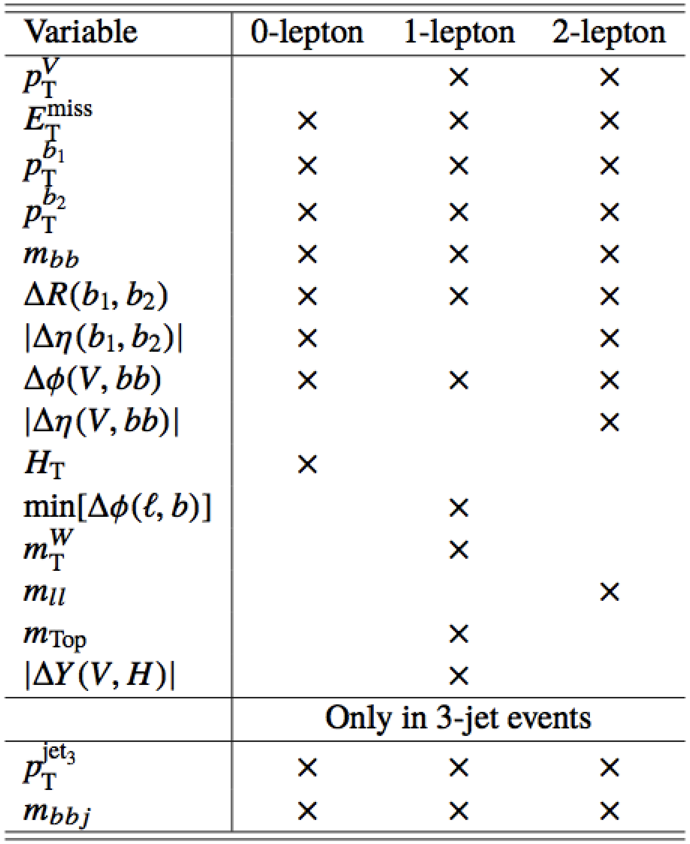
2 leptons



Multi-variate analysis

- Boosted decision tree (BDT)
  - Combine many different variables
  - Trained in 8 categories: 3 lepton, 2/3 jets, low/high p_T^V bin (2 lepton channel)
- Most discrimination from m_{bb} and $\Delta R(b_1,b_2)$





Variable	0-lepton	1-lepton	2-lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\|\Delta\eta(b_1, b_2)\|$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\|\Delta\eta(V, bb)\|$			×
H_T	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
m_{ll}			×
m_{Top}		×	
$\|\Delta Y(V, H)\|$		×	
	Only in 3-jet events		
$p_T^{\text{jet}_3}$	×	×	×
m_{bbj}	×	×	×

- New in run 2: m_{Top}, $|\Delta Y(V,H)|$ → +7% in sensitivity

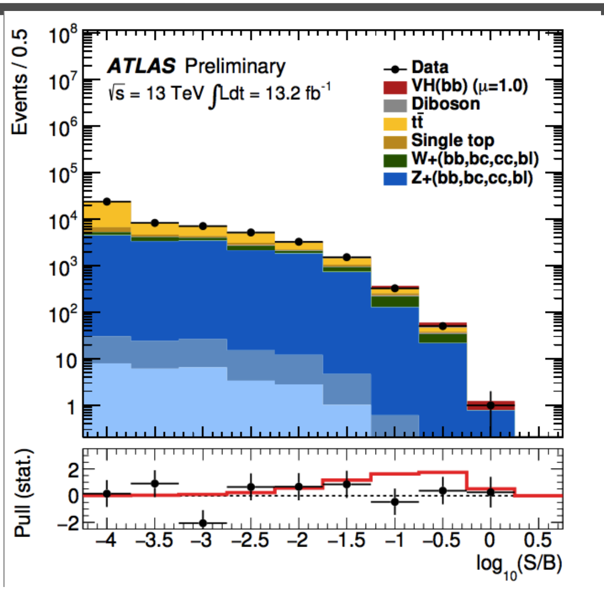
Combined fit

- Profiled likelihood fit to measure the signal strength

  Take into account all event categories

- Use BDT discriminant as input

- Post-fit distributions:

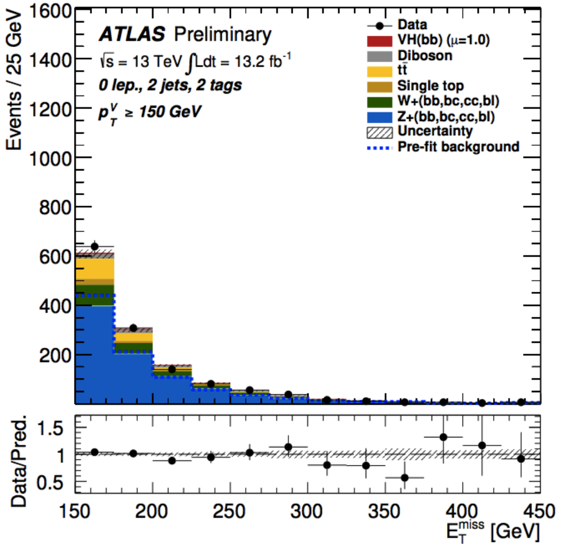


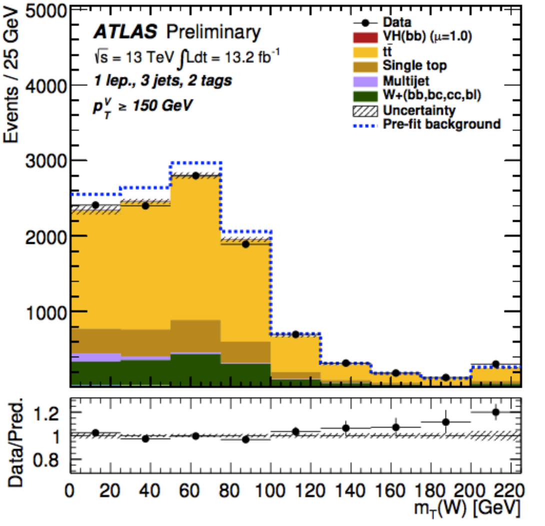
E_T^{miss}

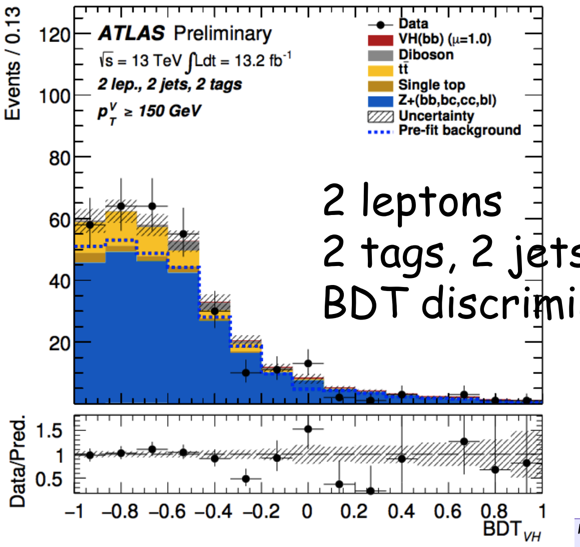
0 lep, 2jets, 2btags

W transverse mass

1 lep., 3jets, 2 btags







2 leptons

2 tags, 2 jets

BDT discriminant

Results H→bb in association with a W or Z

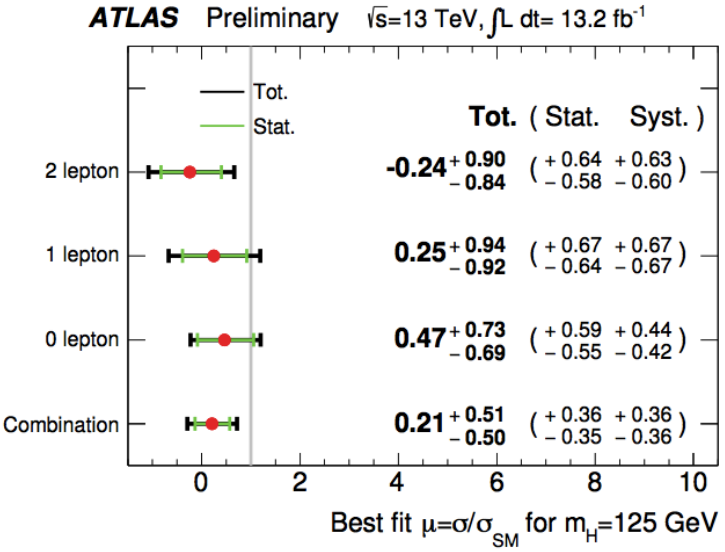
ATLAS-CONF-2016-091

- Combined signal strength with 13.2 fb^{-1} of pp collisions at √s= 13 TeV

$$\mu_{VH,H\rightarrow bb}=0.21^{+0.51}_{-0.50}$$

Systematic and statistical uncertainties of the same size

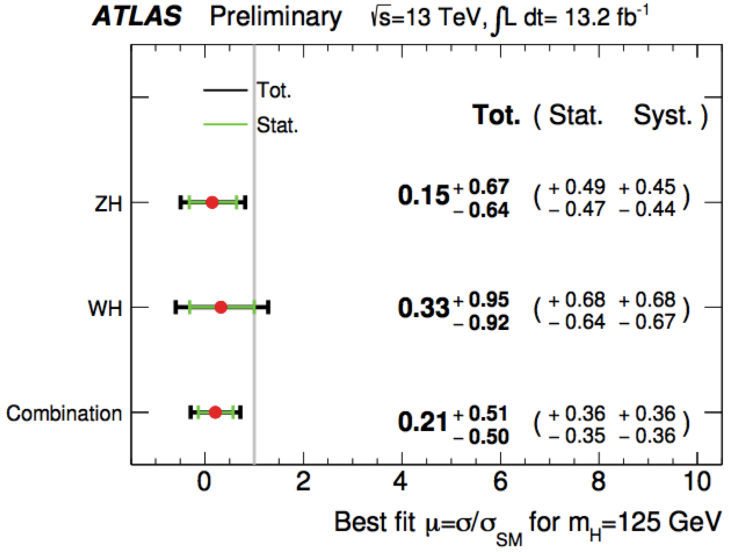
Dominant systematics from b-tagging and background normalization & modelling (W+jets, Z+jets, top)



- Fit cross checked with di-boson signal (WZ+ZZ with Z→bb)

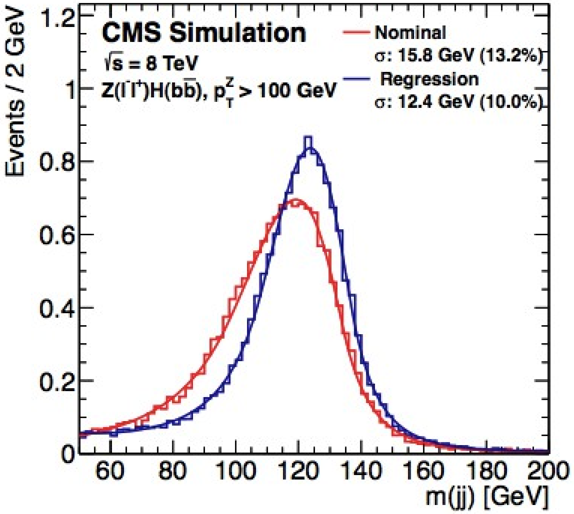
Observed significance: 3.2σ

$$\mu_{VZ}=0.91\pm0.17(stat)^{+0.32}_{-0.23}(sys)$$

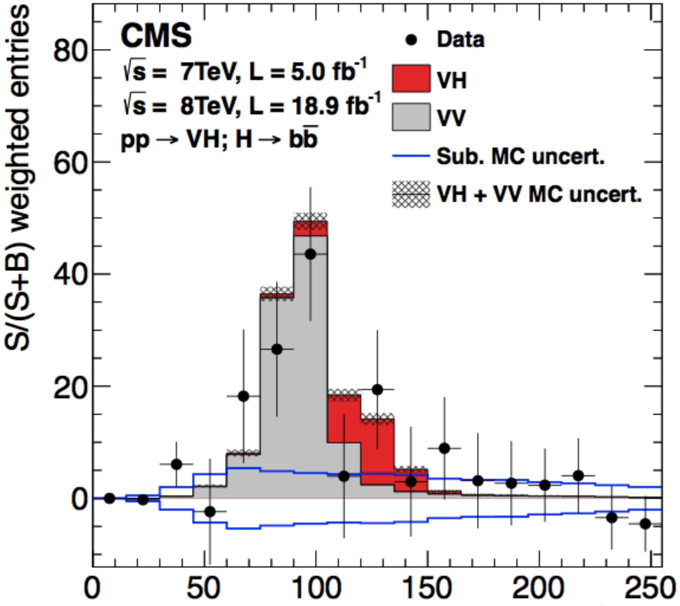


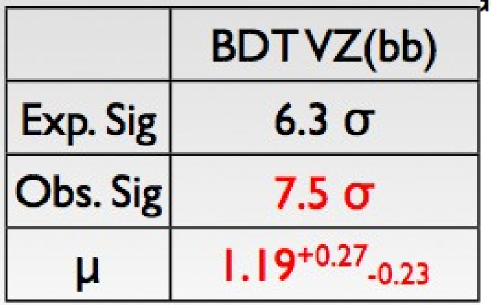
CMS VH→bb

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



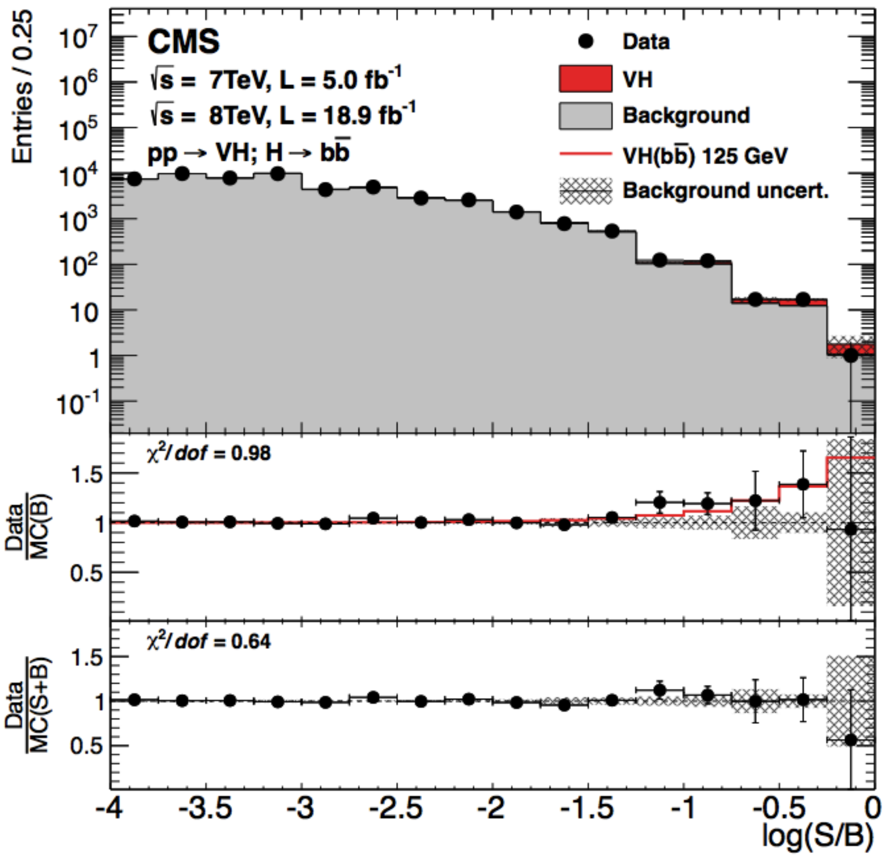
- VZ, with Z→bb, analysis:

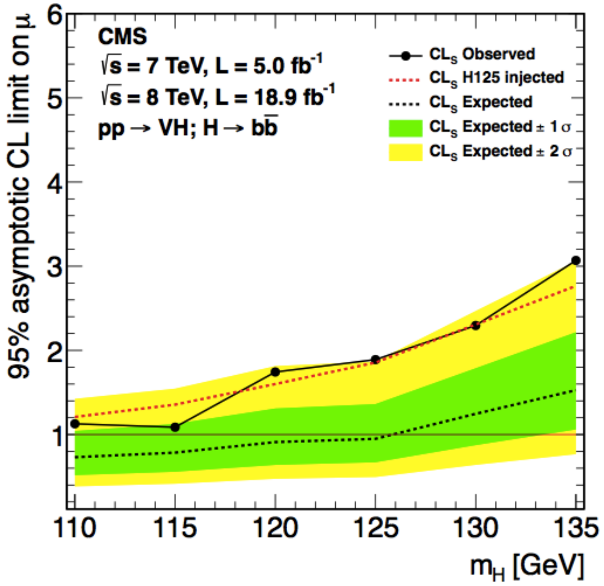




	BDT VZ(bb)
Exp. Sig	6.3 σ
Obs. Sig	7.5 σ
μ	$1.19^{+0.27}_{-0.23}$

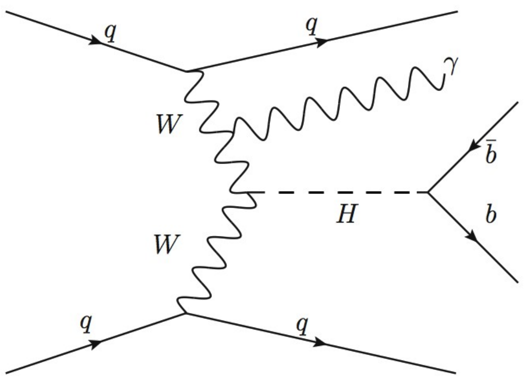
CMS VH→bb results





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

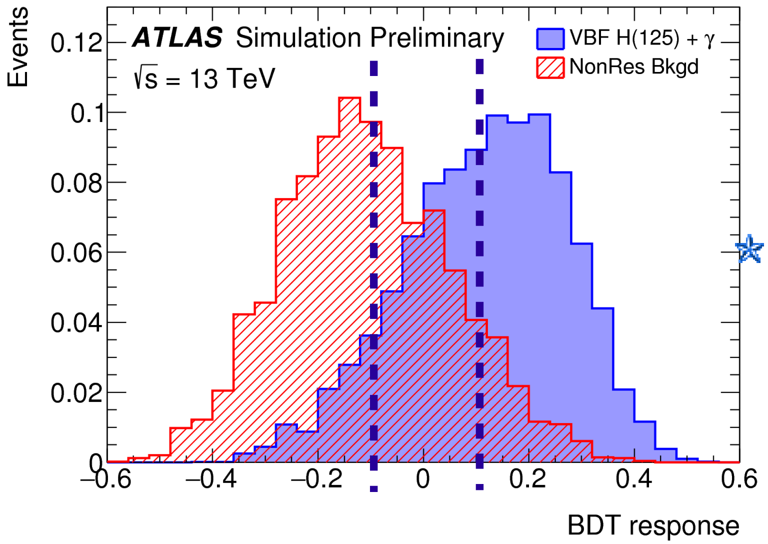
VBF+γ search



- Trigger:
  - L1 trigger: single photon (p_T > 25 GeV)
  - High level trigger: 4 jets p_T > 35 GeV, m_{jj} > 700 GeV
- Selection:
  - Tight ID photon, p_T > 30 GeV
  - 4 jets with p_T> 40 GeV
    - 2 central (|η|<2.5) b-tagged jets
    - p_T(bb system) > 80 GeV
    - Non b-tagged jets: m_{jj}> 800 GeV
- BDT discriminant
  - Built with variables uncorrelated to m_{bb}

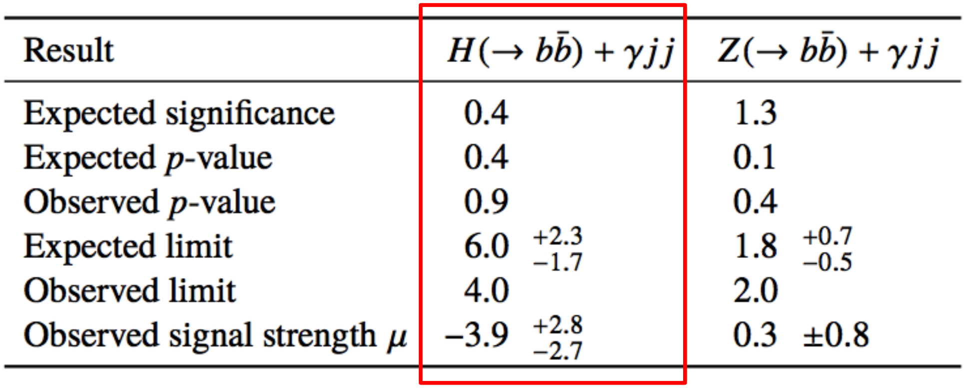
$$\Delta R(jet,\gamma), m_{jj}, \Delta\eta_{jj}, H_T^{soft}, jet\ width, \gamma\ centrality, p_T^{balance}$$

  - Define 3 regions with different S/B
  - Fit m_{bb} in these 3 regions



VBF+γ results

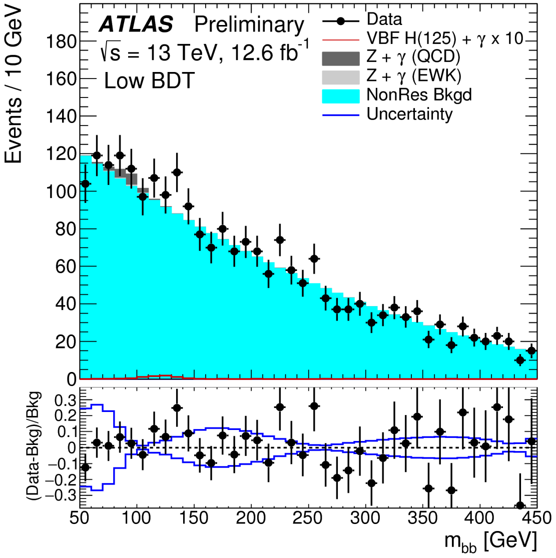
- Use a profile likelihood fit
- Non resonant background estimated with 2nd order polinomial fit in m_{bb} sideband
- Fit tested searching for Z→bb + γ production:
  - Expected 95% CL limit: $1.8^{+0.7}_{-0.5}$
  - Observed: 2.0



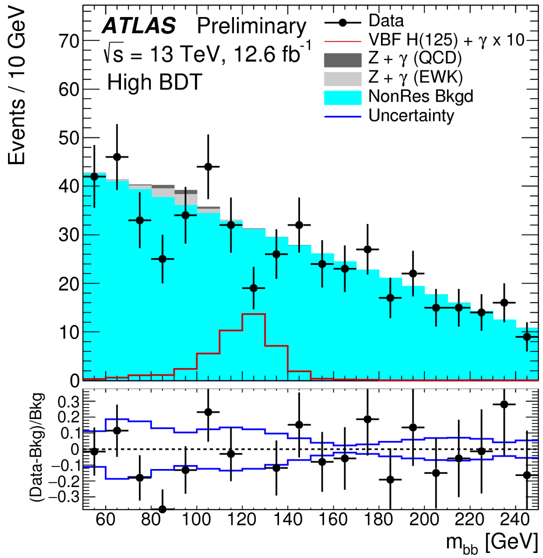
Result	$H(\rightarrow b\bar{b})+\gamma jj$	$Z(\rightarrow b\bar{b})+\gamma jj$
Expected significance	0.4	1.3
Expected *p*-value	0.4	0.1
Observed *p*-value	0.9	0.4
Expected limit	$6.0^{+2.3}_{-1.7}$	$1.8^{+0.7}_{-0.5}$
Observed limit	4.0	2.0
Observed signal strength μ	$-3.9^{+2.8}_{-2.7}$	0.3 ± 0.8

- Observed signal strength in the Higgs search:
  $$\mu_{H,VBF+\gamma}=-3.9^{+2.8}_{-2.7}$$
- Expected 95% CL limit:
  $$6.0^{+2.3}_{-1.7}$$
- Observed 95% CL limit:
  $$4\times(\sigma\times BR)^{SM}$$

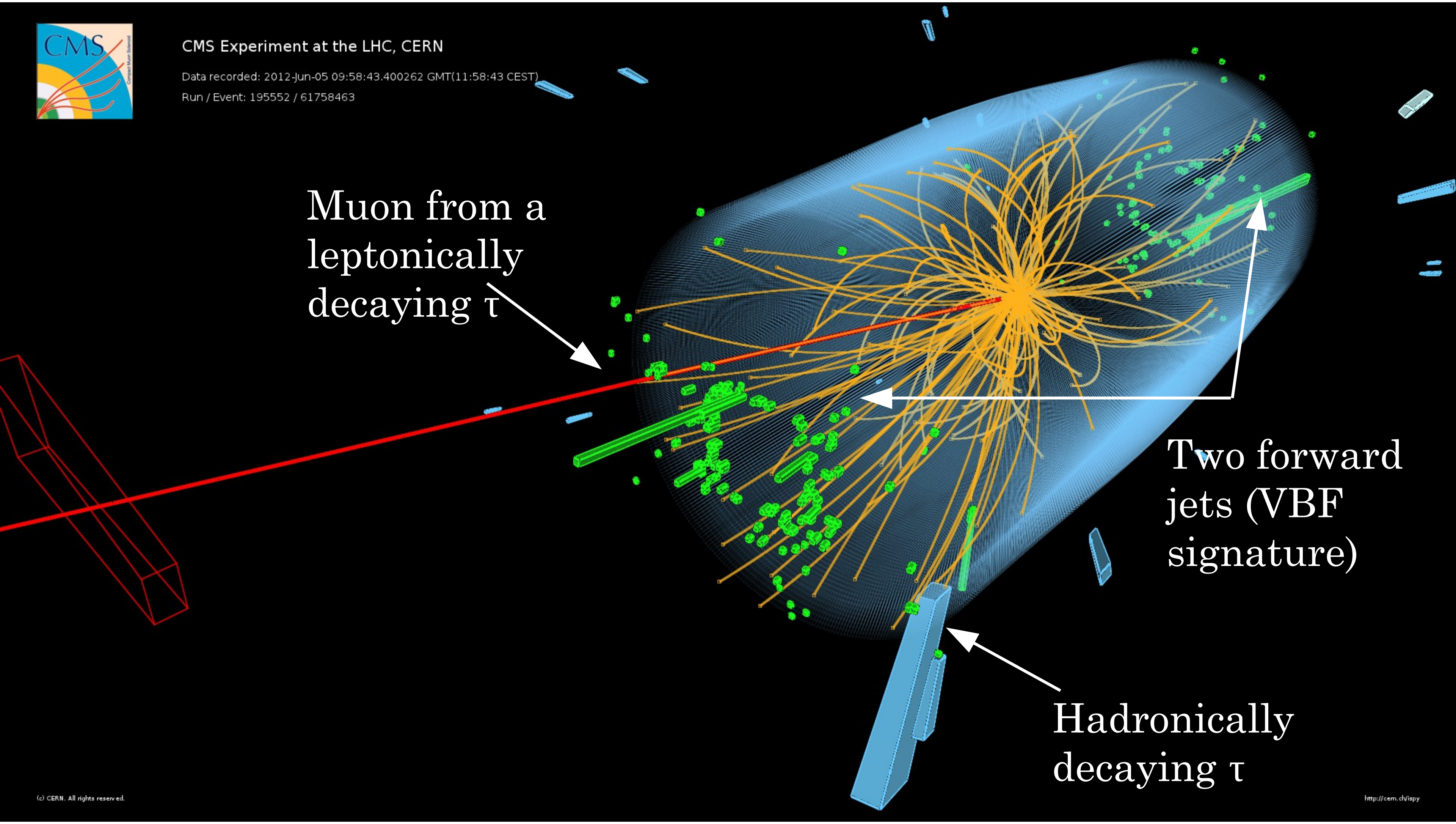
- Low BDT score region:



- High BDT score region



H→ττ



Muon from a leptonically decaying τ

Two forward jets (VBF signature)

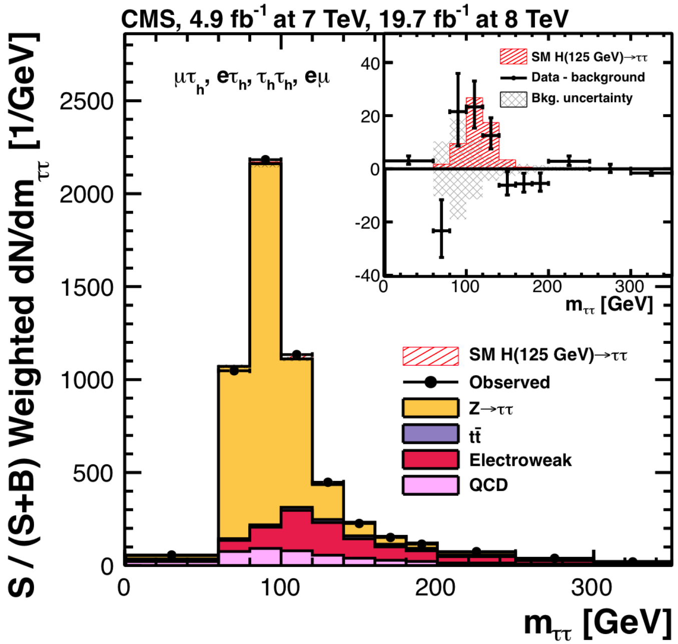
Hadronically decaying τ

CMS-HIG-13-004
ATLAS-CONF-2013-108

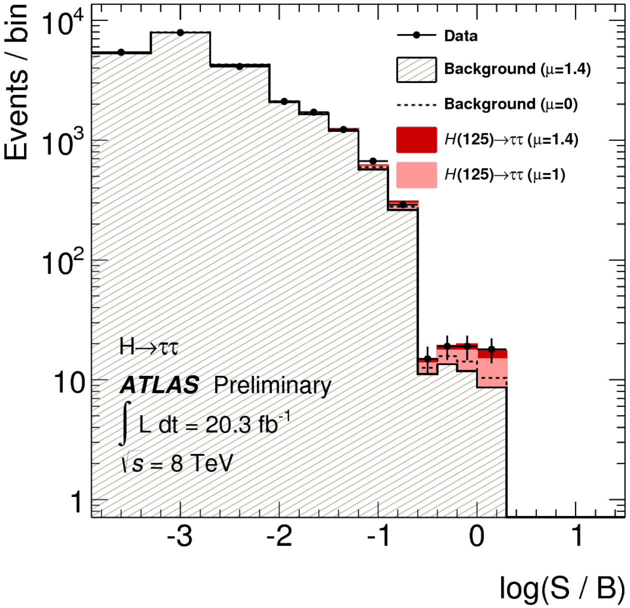
H→ττ results

- Using MVA to better disentangle signal from background

CMS ττ mass



Combined BDT score for all the search channels

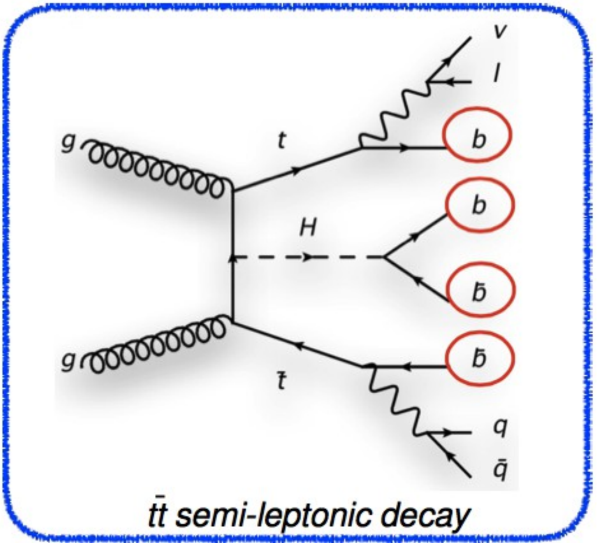


- Evidence for the Higgs decaying to ττ pairs in both experiments
- Signal strength: $\mu = \sigma/\sigma_{SM} = 1.4^{+0.5}_{-0.4}$ at ATLAS and 0.78±0.27 in CMS

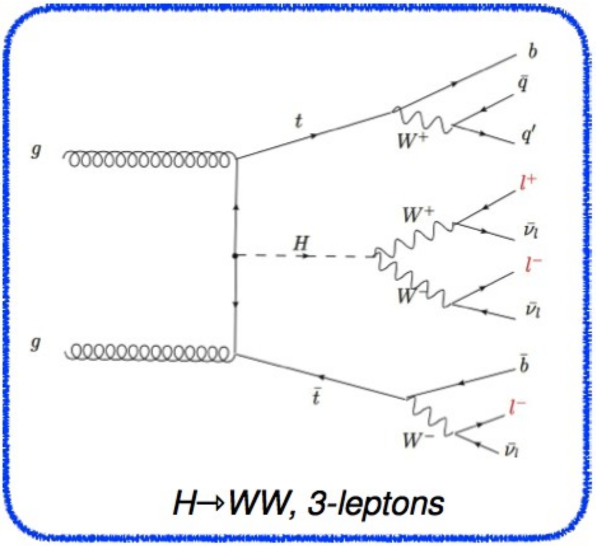
Search for Higgs boson in ttH production

- Many possible final states

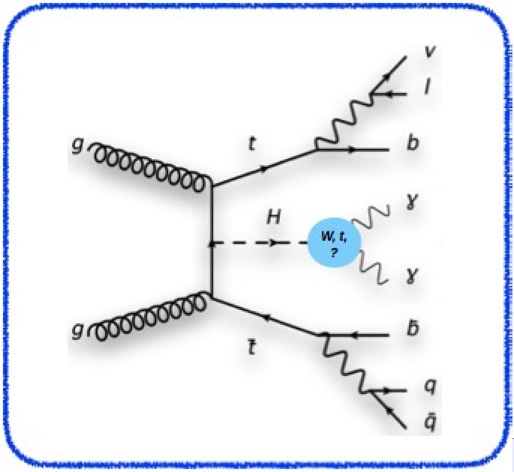
Higgs decay mode	Branching ratio [%]
H→ bb	58.1
H→ WW	21.5
H→ ττ	6.3
H→ ZZ	2.6
H→ γγ	0.23



$t\bar{t}$ semi-leptonic decay

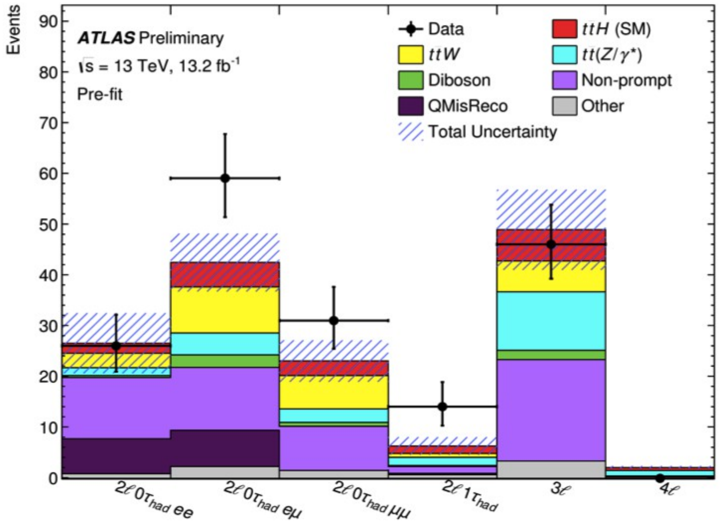


H→WW, 3-leptons

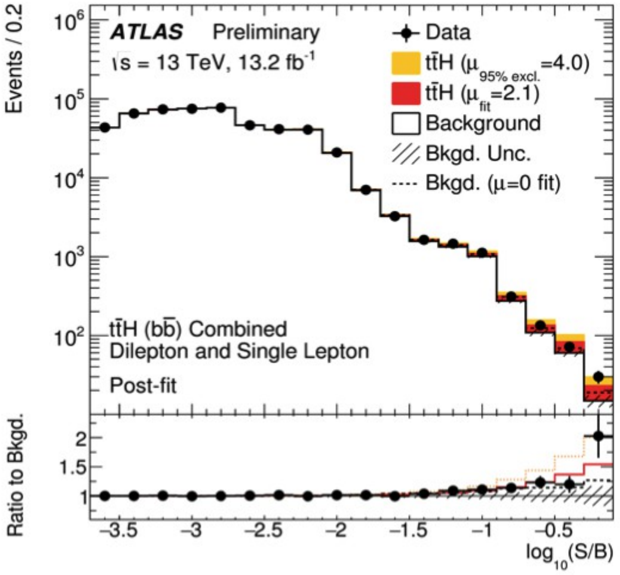


Search for Higgs boson in ttH production

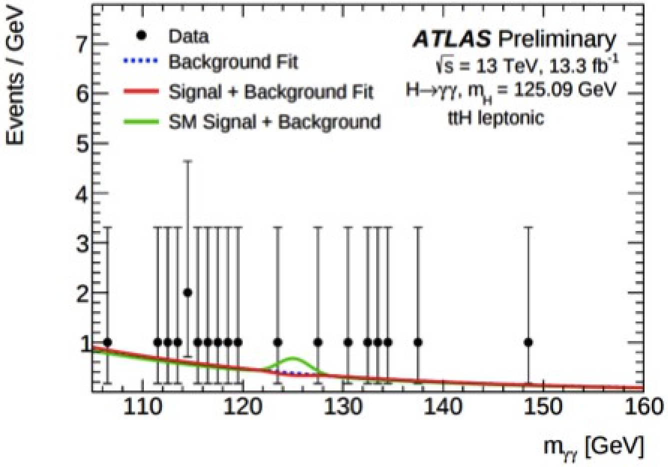
- Multi-leptons: cut and count in different event categories



- BDT discriminant in ttH (H→bb)

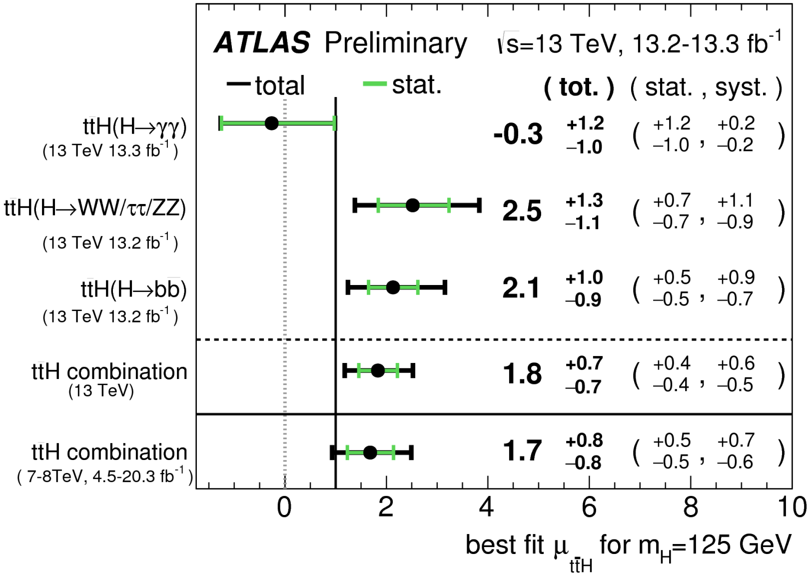


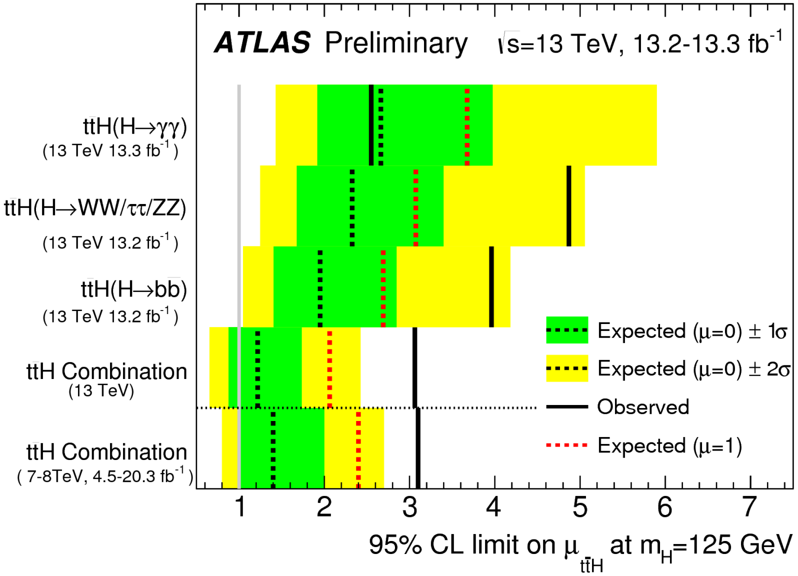
- $m_{\gamma\gamma}$ in ttH (H→γγ) leptonic events



Results on ttH Higgs searches

- Combined signal strength: $\mu = 1.7^{+0.5}_{-0.5}(stat)^{+0.7}_{-0.6}(sys)$





- Expected and observed significance:

Channel	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H, H \to \gamma\gamma$	−0.2	0.9
$t\bar{t}H, H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H, H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8

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
    - $H \to \tau\tau$, $H \to bb$
- Work continues now to understand the properties of this Higgs boson
  - Cross sections: inclusive, differential
  - Measure all its properties accurately (production and decay rates, spin, C and P, …)
  - Search for new physics in the Higgs sector

Backup

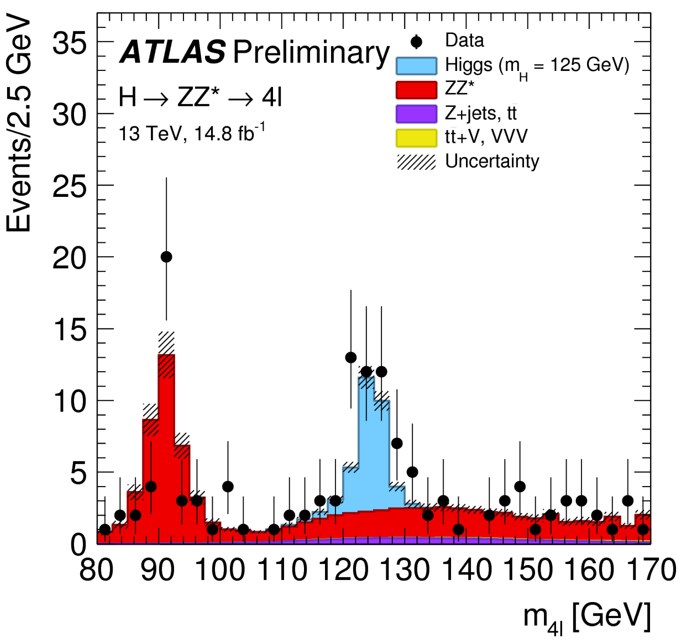
Higgs re-discovery at 13 TeV

ATLAS-CONF-2016-079

ATLAS-CONF-2016-067

- $H \rightarrow ZZ \rightarrow 4\ell$

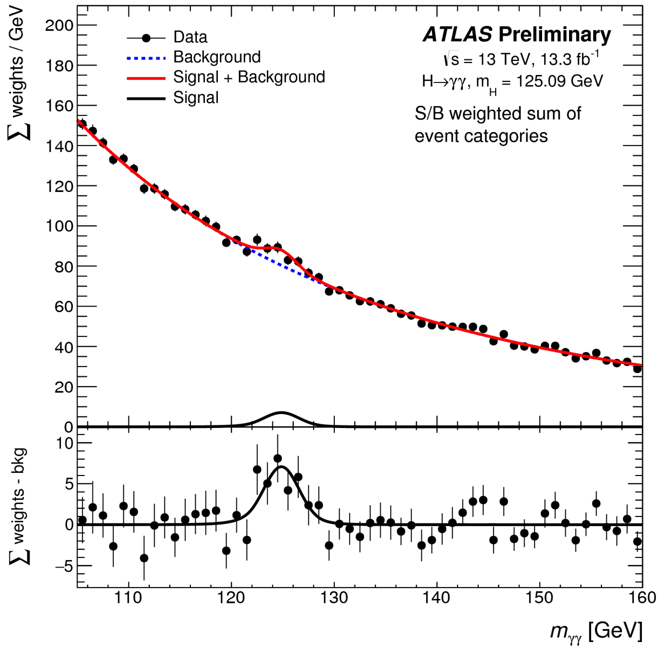
14.8 fb^{-1} pp collisions @ 13



$$\sigma_{\text{tot,SM}} = 55.5^{+3.8}_{-4.4} \text{ pb.}$$
$$\sigma_{\text{tot}} = 81^{+18}_{-16} \text{ pb}$$

- $H \rightarrow \gamma\gamma$

13.3 fb^{-1} pp collisions @ 13 TeV



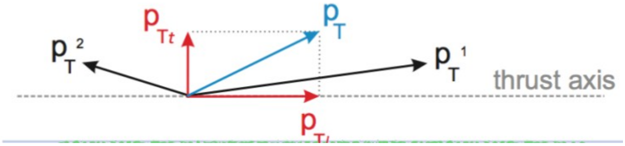
$$\sigma_{\text{fid}} = 47.0 \pm 13.9\,(\text{stat.}) \pm 5.4\,(\text{syst.})\text{ fb}$$

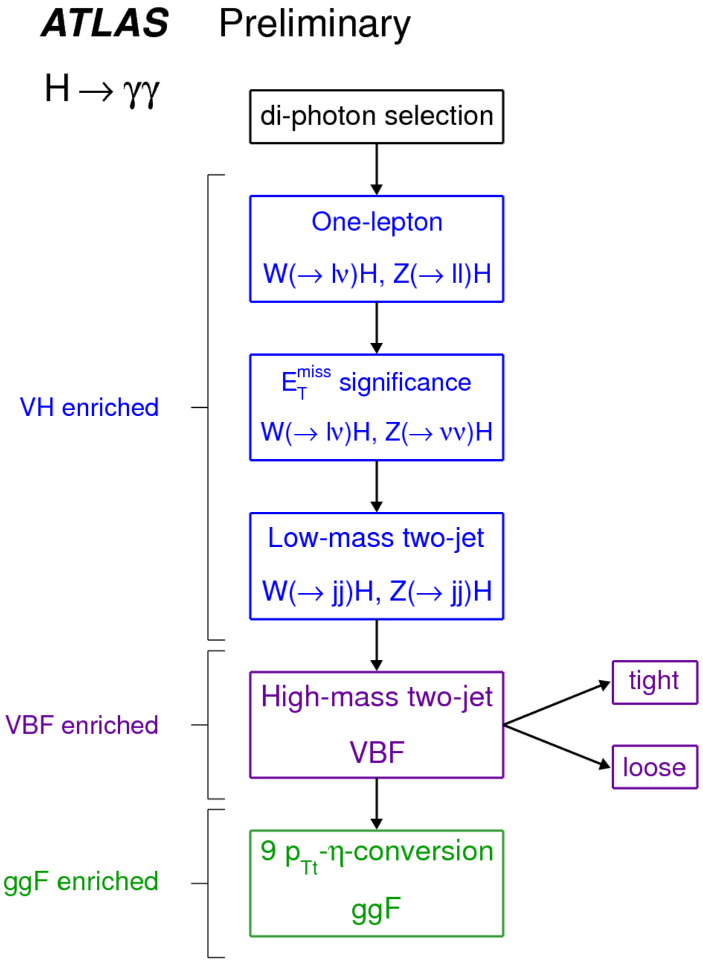
SM prediction $62.8^{+3.4}_{-4.4}$ fb

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




ATLAS Preliminary

$H \rightarrow \gamma\gamma$

di-photon selection

VH enriched

One-lepton
W(→ lν)H, Z(→ ll)H

E_T^{miss} significance
W(→ lν)H, Z(→ νν)H

Low-mass two-jet
W(→ jj)H, Z(→ jj)H

VBF enriched

High-mass two-jet
VBF
→ tight
→ loose

ggF enriched

9 p_{Tt}-η-conversion
ggF

Pacman method - systematic uncertainties and advantages

- Assign systematic uncertainties on ϵ by computing difference between measured efficiencies and true efficiencies:
  - different flavour → same flavour extrapolation for $\epsilon^{\text{non-}Z/\gamma^*}$
  - Z peak → 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.