Results from the Higgs Searches at the LHC

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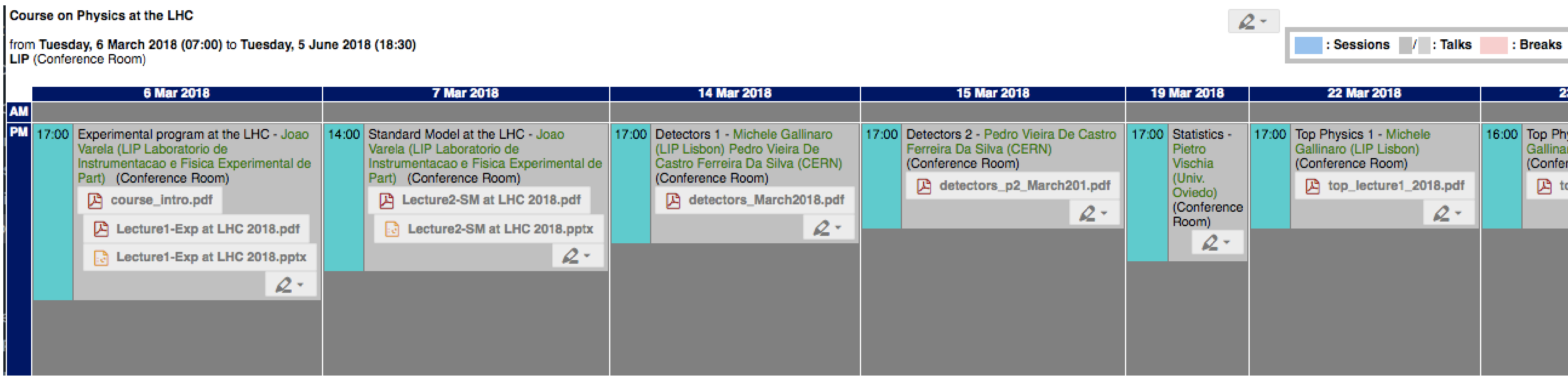
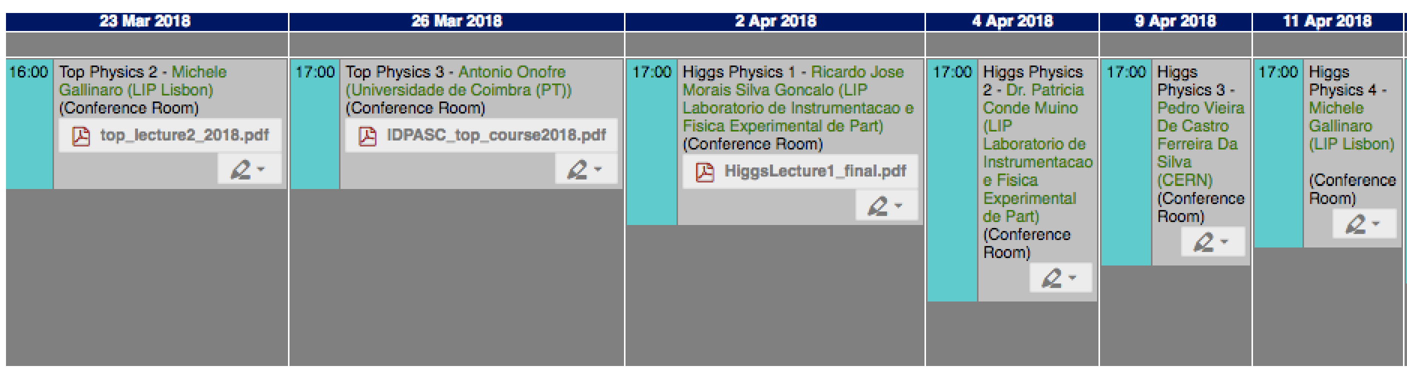
Up to now



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



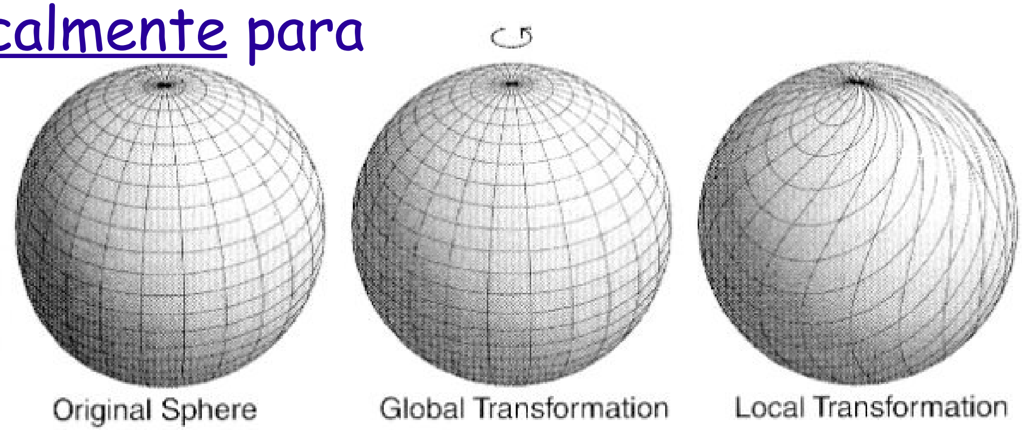
Overview

- Reminder
  - Higgs mechanism
  - 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
- The $H\to WW\to \ell\nu\ell\nu$ channel
  - Electrons, muons
  - Jets, missing transverse energy
  - Background measurement
  - Fits
  - Vector boson fusion
- Combinations

- Simetrias → Interações!

equações invariantes localmente para certas simetrias

aparecem novos campos, que descrevem as forças !!

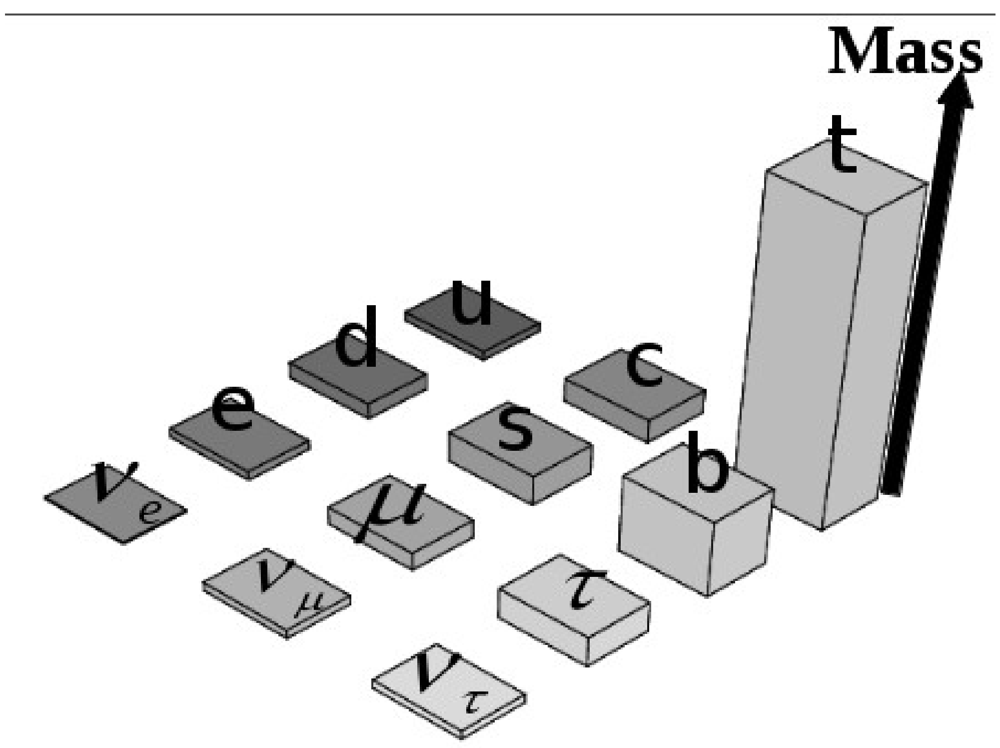


Grupo de simetrias do Modelo Padrão

mudança de fase		rotações em 3D		generalização do SU(2)
U(1)	×	SU(2)	×	SU (3)
Fotão Electromagnetismo		Interacções fracas Bosões W^+,W^-,Z		Interação forte Gluões

O problema da massa no Modelo Padrão

- Porque uma diferença tão grande nas massas das partículas fundamentais?



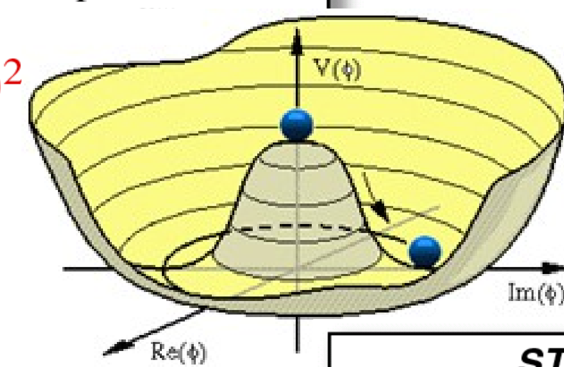
O mecanismo de Higgs

HIGGS FIELD

Complex weak isospin scalar doublet Φ with scalar potential $V[\Phi]$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad V[\Phi] = \mu^2 \Phi^\dagger \Phi + \lambda\,(\Phi^\dagger \Phi)^2$$

$$(\lambda > 0,\ \mu^2 < 0)$$



STANDARD MODEL

Yang-Mills $SU(2)_L \times U(1)_Y$

massless gauge bosons W_μ and B_μ

and *massless* fermions ψ

$$\mathcal{L} = -\frac{1}{2} W_{\mu\nu} \cdot W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$+ \left| \left(i\partial_\mu - g' \frac{Y}{2} B_\mu - g \frac{1}{2} \boldsymbol{\tau} \cdot W_\mu \right) \Phi \right|^2 - V(\Phi)$$

$$+ \bar{\psi}_L \gamma^\mu \left(i\partial_\mu - g' \frac{Y}{2} B_\mu - g \frac{1}{2} \boldsymbol{\tau} \cdot W_\mu \right) \psi_L$$

$$+ \bar{\psi}_R \gamma^\mu \left(i\partial_\mu - g' \frac{Y}{2} B_\mu \right) \psi_R$$

SPONTANEOUS SYMMETRY BREAKING

One component acquires non-zero vacuum expectation value

$$\langle 0|\Phi|0\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \longrightarrow \Phi(x) = \frac{1}{\sqrt{2}} \exp\left(i \frac{\xi \cdot \tau}{2v} \right) \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

- Prevê uma nova partícula: o Bosão de Higgs!

The SM Higgs Lagrangian after symmetry breaking

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

Couplings to EW gauge bosons

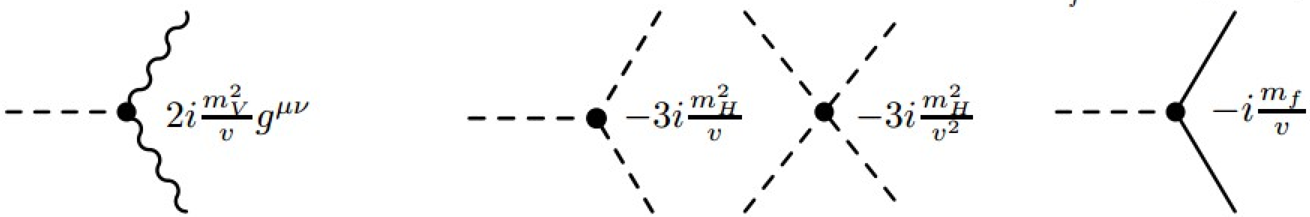
$$\left[m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \frac{h}{v}\right)^2$$

Higgs self-couplings

$$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$$

Couplings to fermions

$$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$



$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v \ (v = \text{vacuum expectation value})$$

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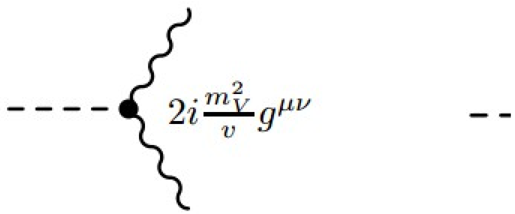

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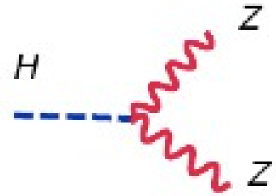
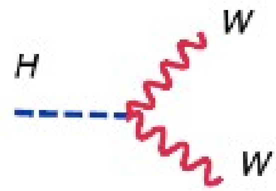


$$2i\frac{M_Z^2}{2v}g_{\mu\nu}$$



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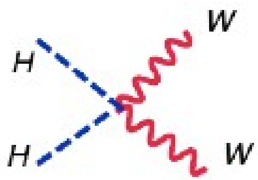

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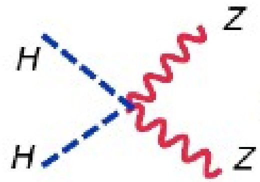
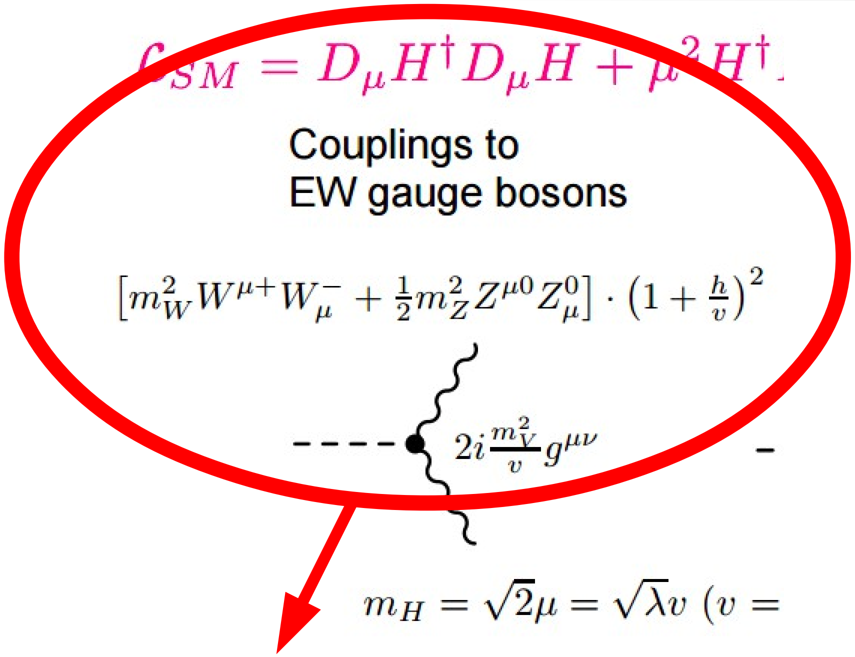
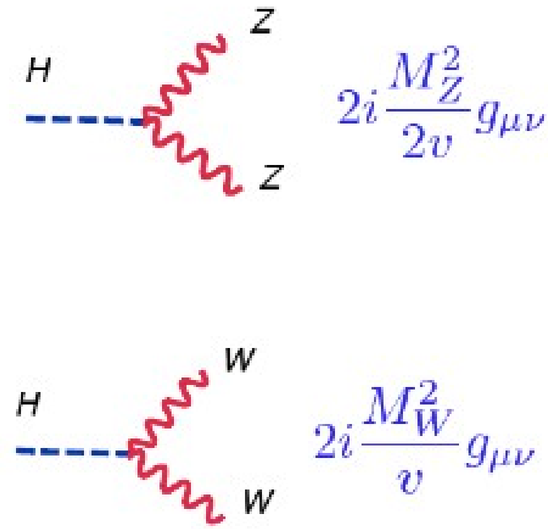


$$2i\frac{M_Z^2}{4v}g_{\mu\nu}$$





- $H \rightarrow WW$
- $H \rightarrow ZZ$

- First observation
- Cross sections at 7, 8 and 13 TeV

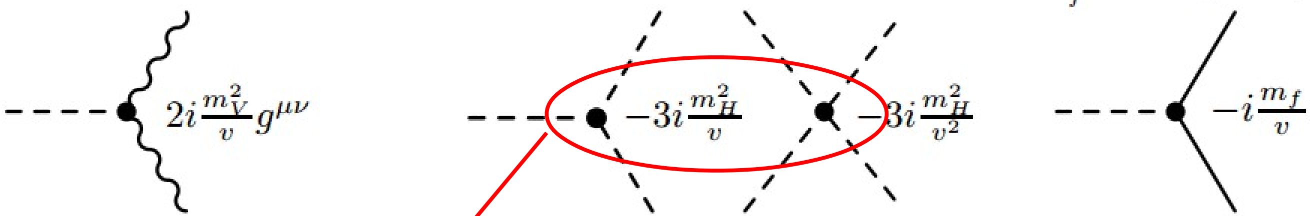
  Differential distributions

Higgs self interactions

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

Couplings to EW gauge bosons | Higgs self-couplings | Couplings to fermions

$$\left[m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \frac{h}{v}\right)^2 \qquad -\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4 \qquad -\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$



$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v \quad (v = \text{vacuum expectation value})$$

- Higgs properties: mass, self interactions, spin and parity
- Experimental measurements:
  - Mass: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ decays
  - HH production

Higgs couplings to fermions

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

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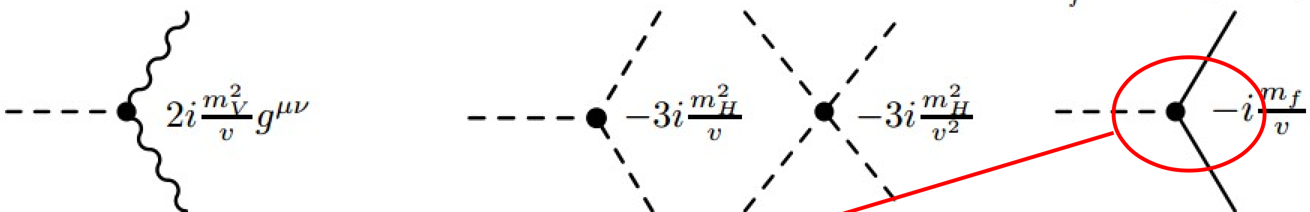

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- Couplings to fermions
- Experimental measurements:
  - Decay rates to quarks and leptons:
  - Rare decays
  - Indirect measurements: gluon-gluon fusion

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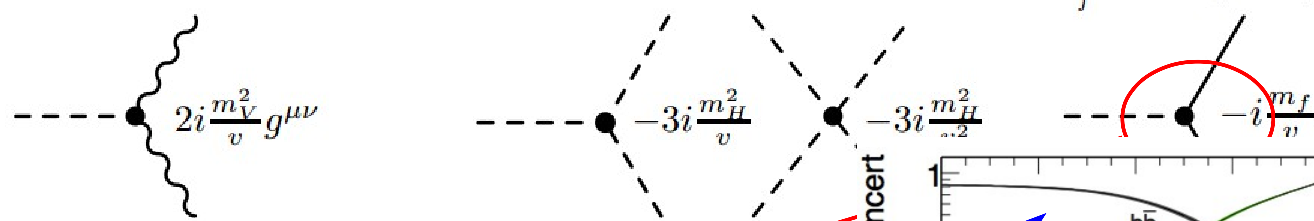

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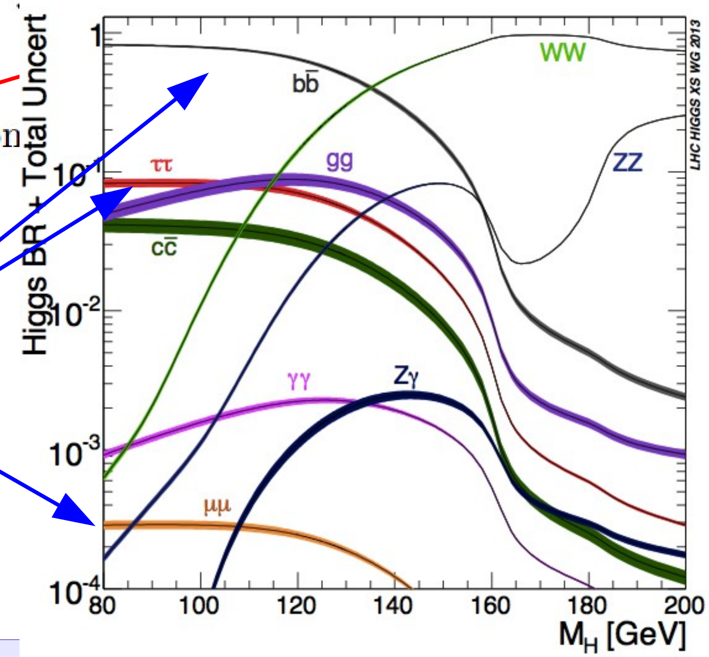

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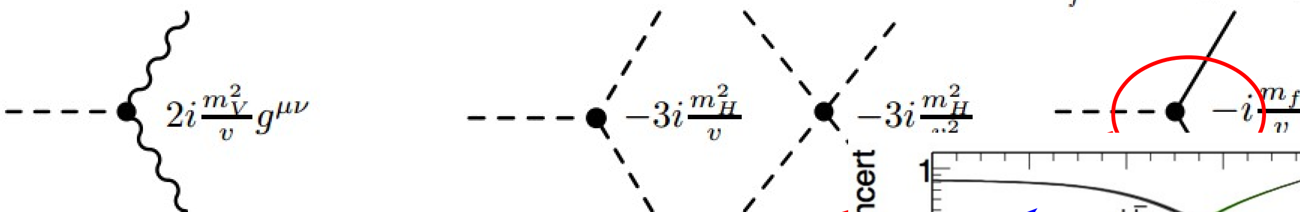

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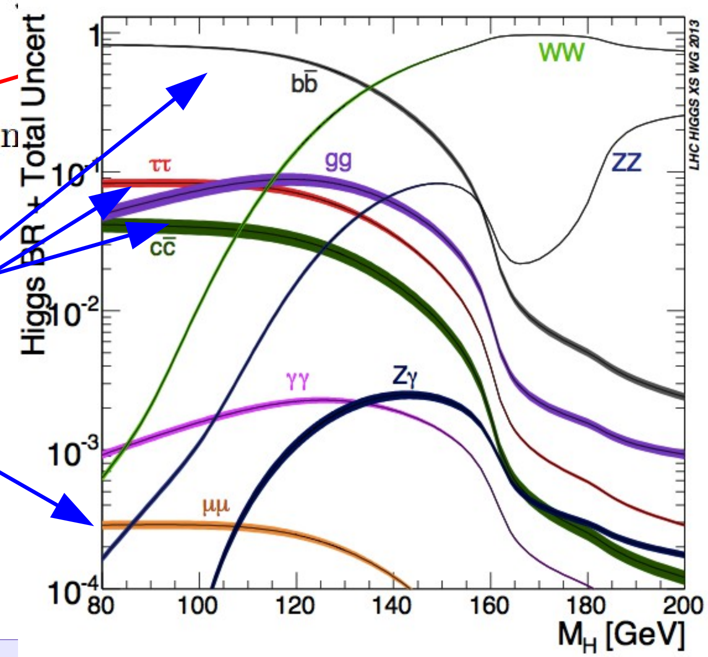

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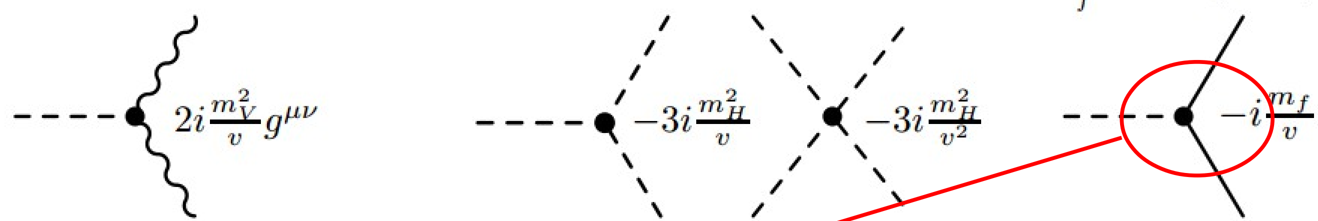

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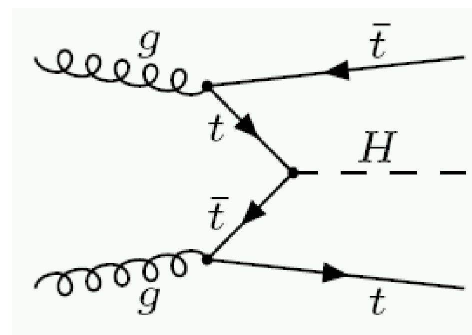
- Couplings to fermions
- Experimental measurements:
  - Decay rates to quarks and leptons:
  - Rare decays
  - Indirect measurements: gluon-gluon fusion
  - Associated production with top-quark pairs



Where to start?

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \mathrm{h.c.}\right)$$

Couplings to EW gauge bosons | Higgs self-couplings | Couplings to fermions

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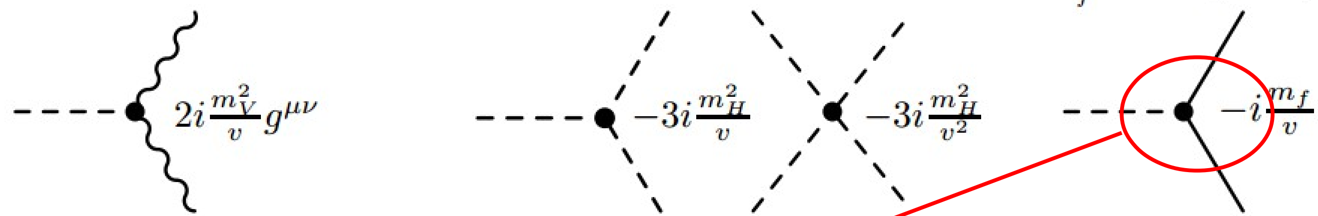


$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v \quad (v = \text{vacuum expectation value})$$

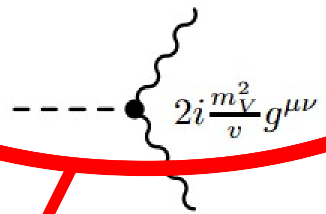
- Couplings to new particles?
- Experimental measurements:
  - Search for invisible decays
  - Total decay width:
    - Constraint from visible decays
    - Interference effects in ZZ production

Focus of this lecture

$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger$

Couplings to
EW gauge bosons

$$\left[m_W^2 W^{\mu+} W_\mu^- + \tfrac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \tfrac{h}{v}\right)^2$$



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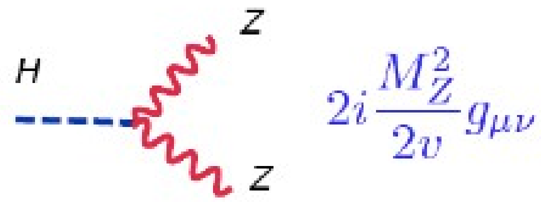
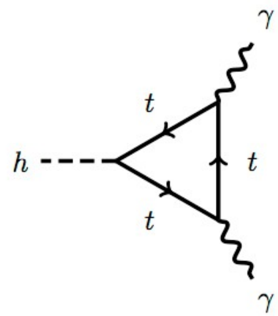
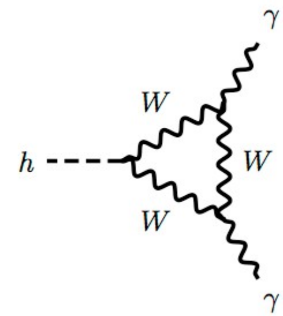


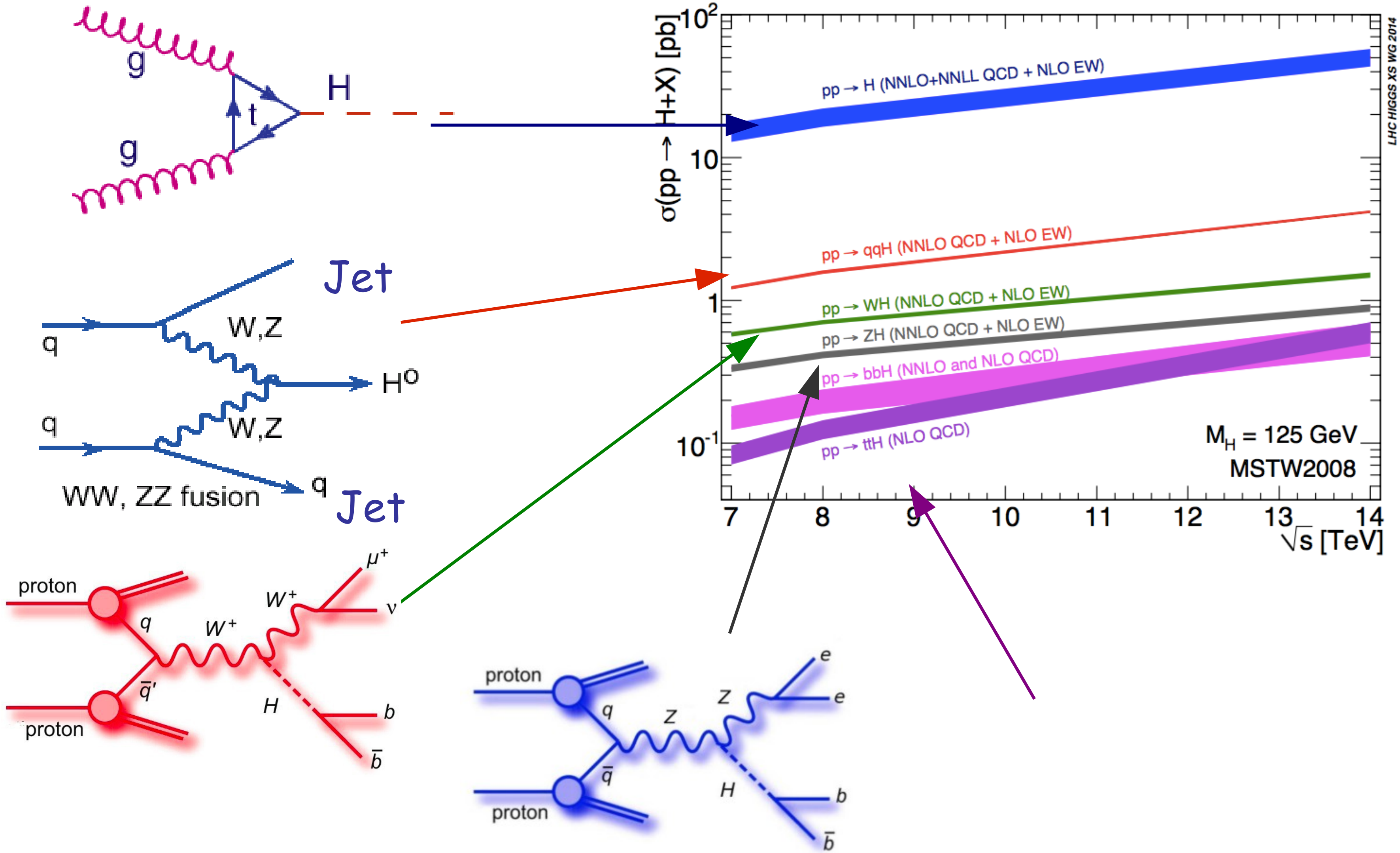




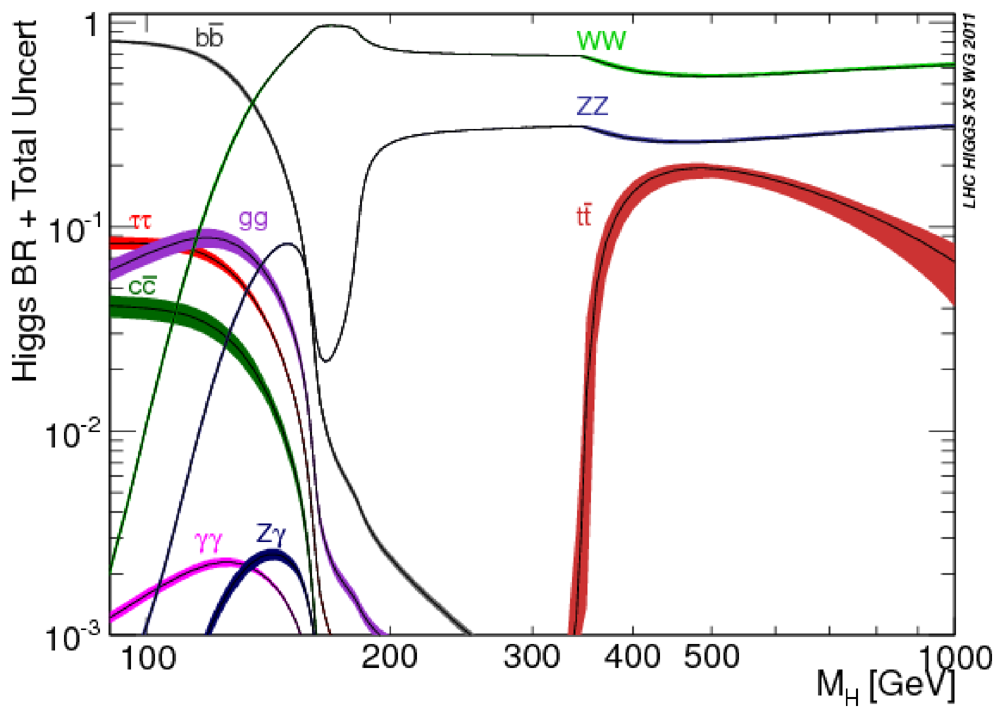
- H → WW
- H → ZZ
- H → γγ

- Discovery channels
- Cross sections at 7, 8 and 13 TeV
  - Differential distributions
- Mass
- Spin, parity

Higgs production



Higgs decays

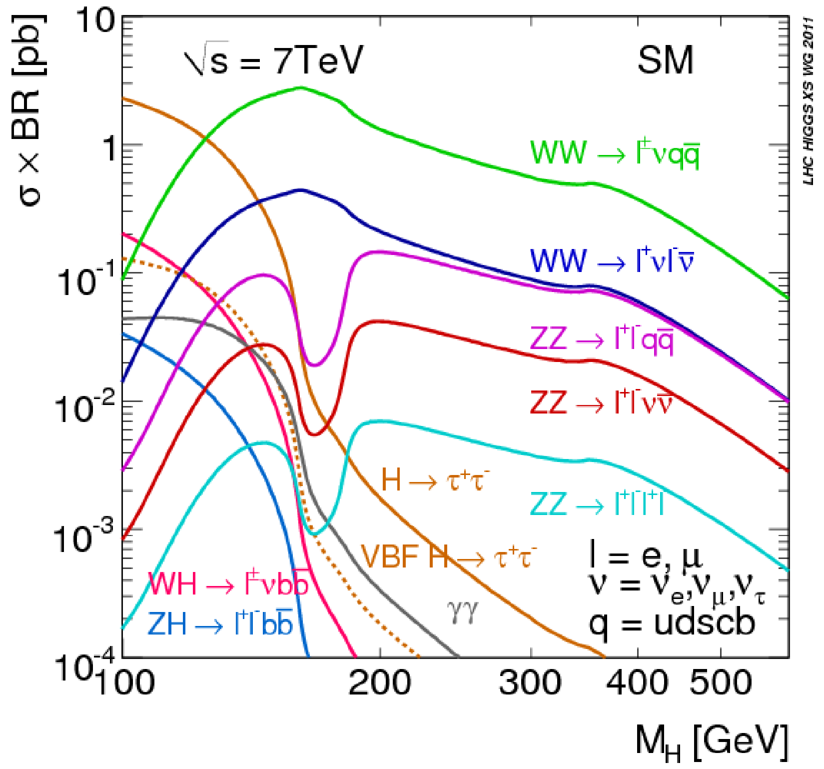


- 5 different decay modes
  - High mass: ZZ, WW
  - Low mass: bb, γγ, WW, ZZ, ττ
- Low mass very challenging
  - Large backgrounds

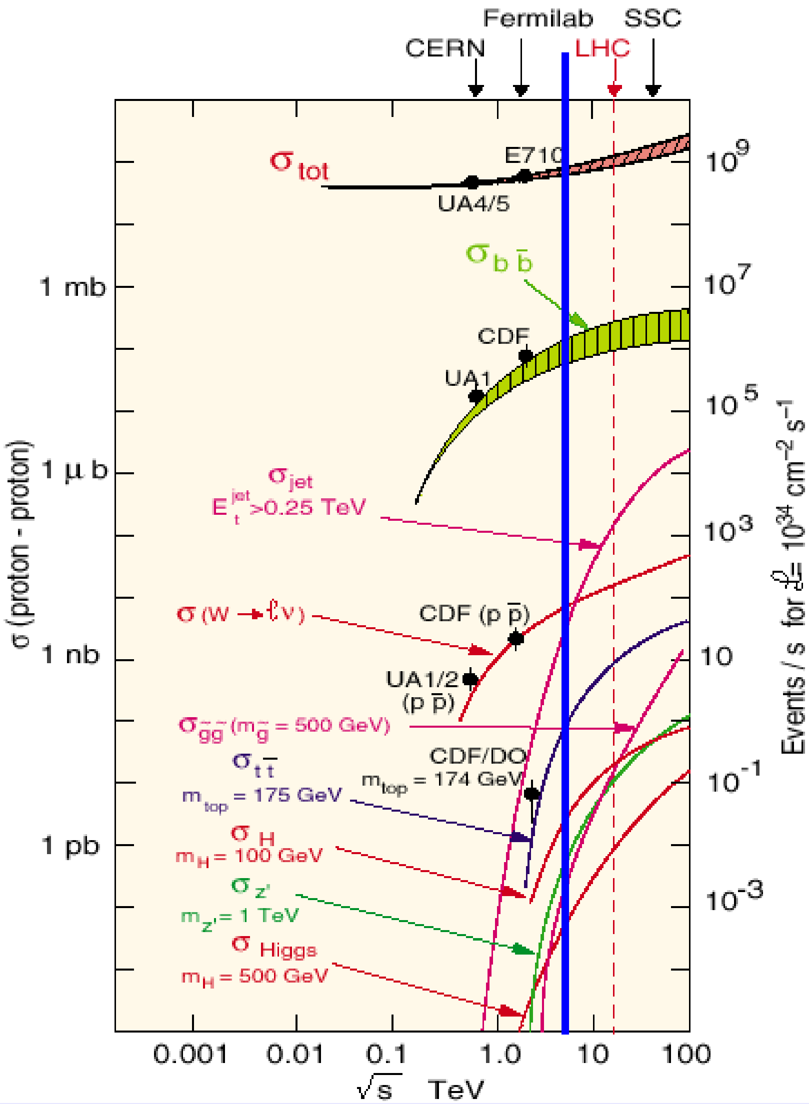
Best mass resolution: H→γγ, H→ZZ→llll

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:

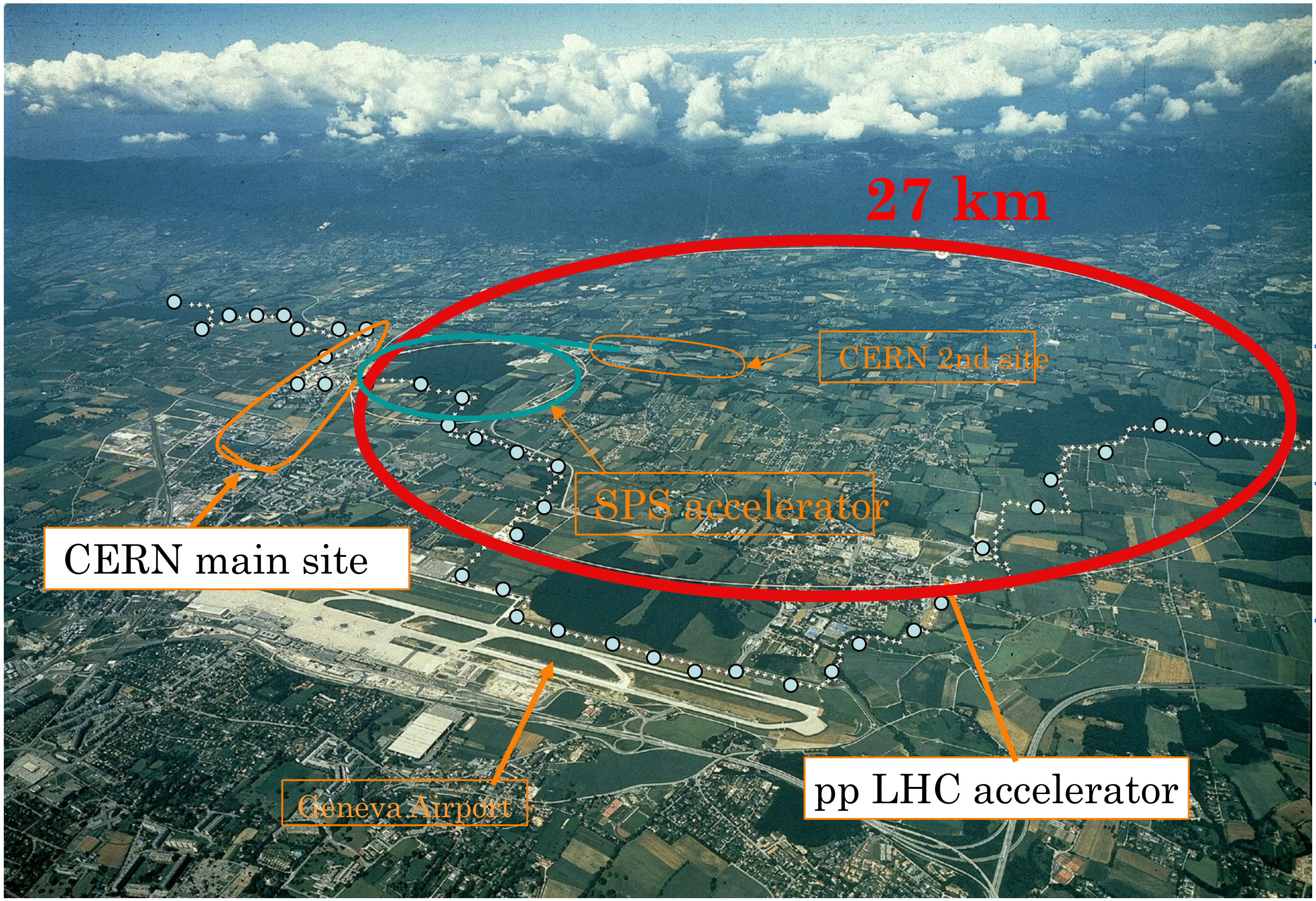
~ 10^3 x σ(bb)

- ~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)

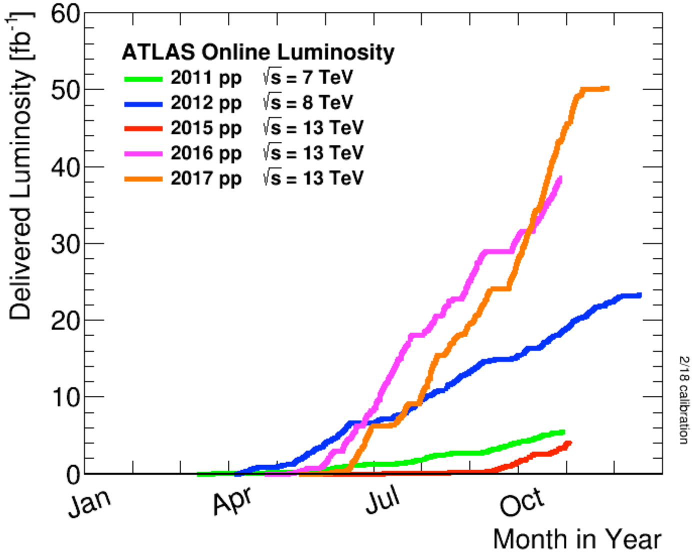
- Most interactions produce jets
  - Either quarks or gluons
- Need to identify clear signatures that distinguish the processes of interest from this background

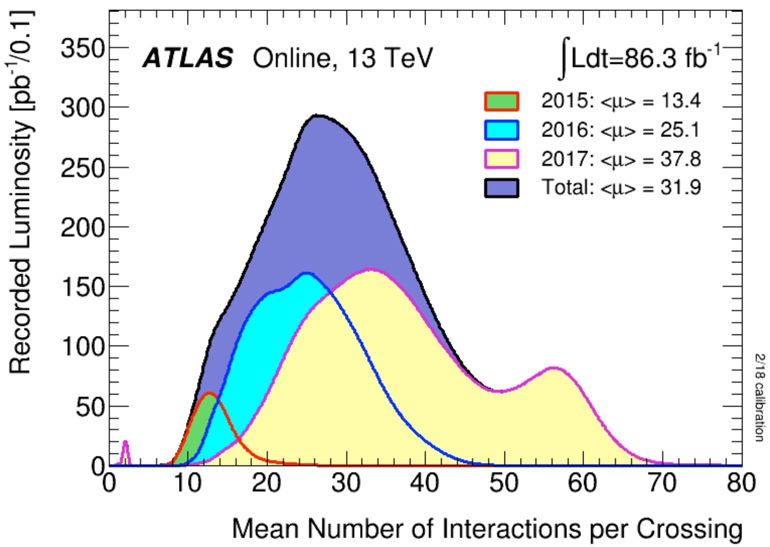
The Large Hadron Collider



- pp collisions at
  7 TeV in 2010/11
  8 TeV in 2012
  13 TeV in 2015-18
- 40 MHz p bunch crossing rate
- Up to ~60 collisions per bunch crossing!
- Four experiments: ATLAS, CMS, LHCb, ALICE

LHC delivered data





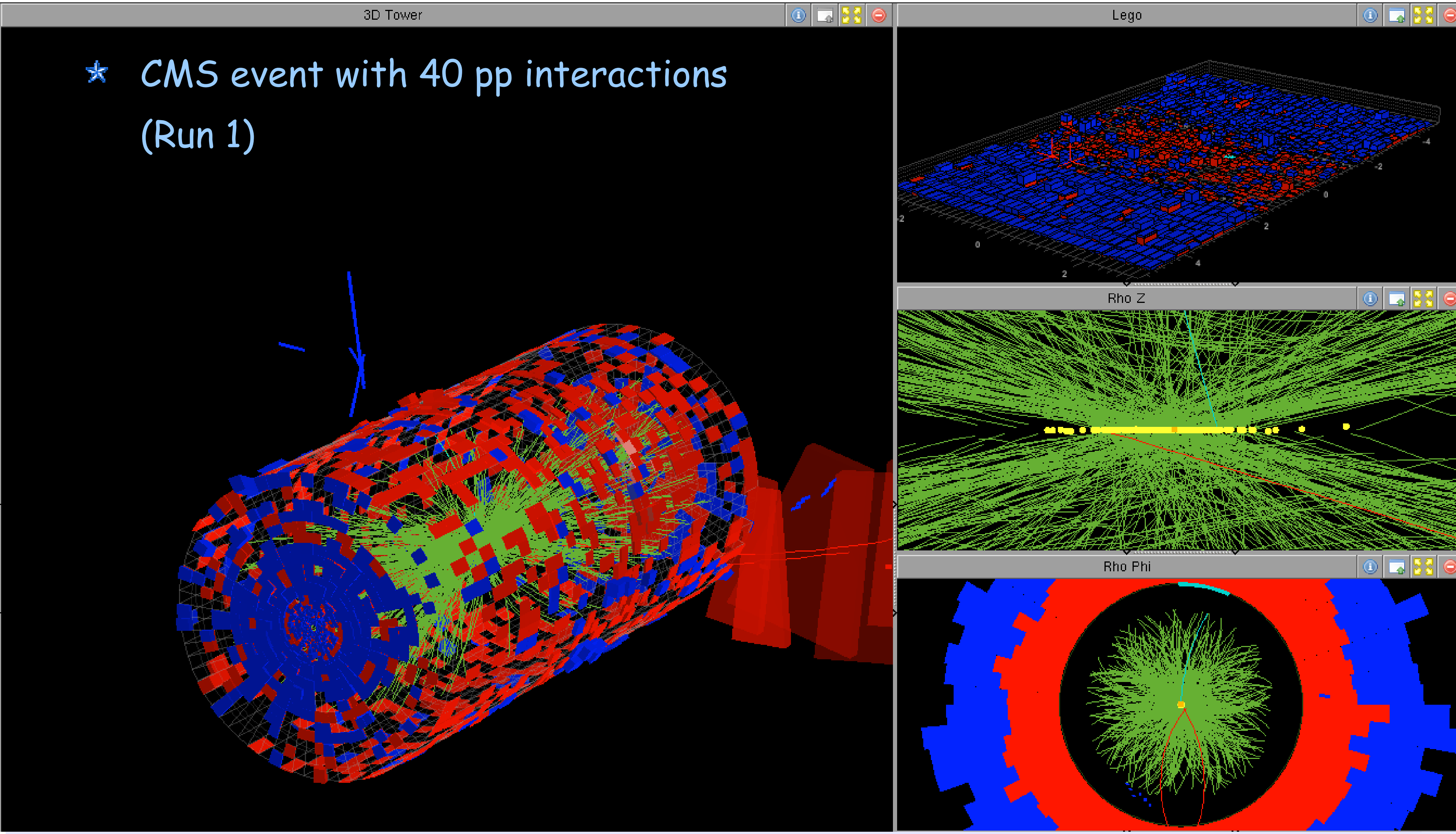
ATLAS pp 25ns run: June 5-November 10 2017										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.9	99.3	99.5	99.4	99.9	97.8	99.9	100	100	99.2
Good for physics: 93.6% (43.8 fb^{-1})										

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 June 5 – November 10 2017, corresponding to a delivered integrated luminosity of 50.4 fb^{-1} and a recorded integrated luminosity of 46.8 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.5 fb^{-1}. Analyses that don't require the toroid magnet can use these data.

- 86 fb^{-1} 13 TeV pp collisions
- 21.2 fb^{-1} 8 TeV pp collisions
- 5.2 fb^{-1} 7 TeV pp collisions
- ~94% of the delivered luminosity was good for physics!

Pile-up

- CMS event with 40 pp interactions (Run 1)



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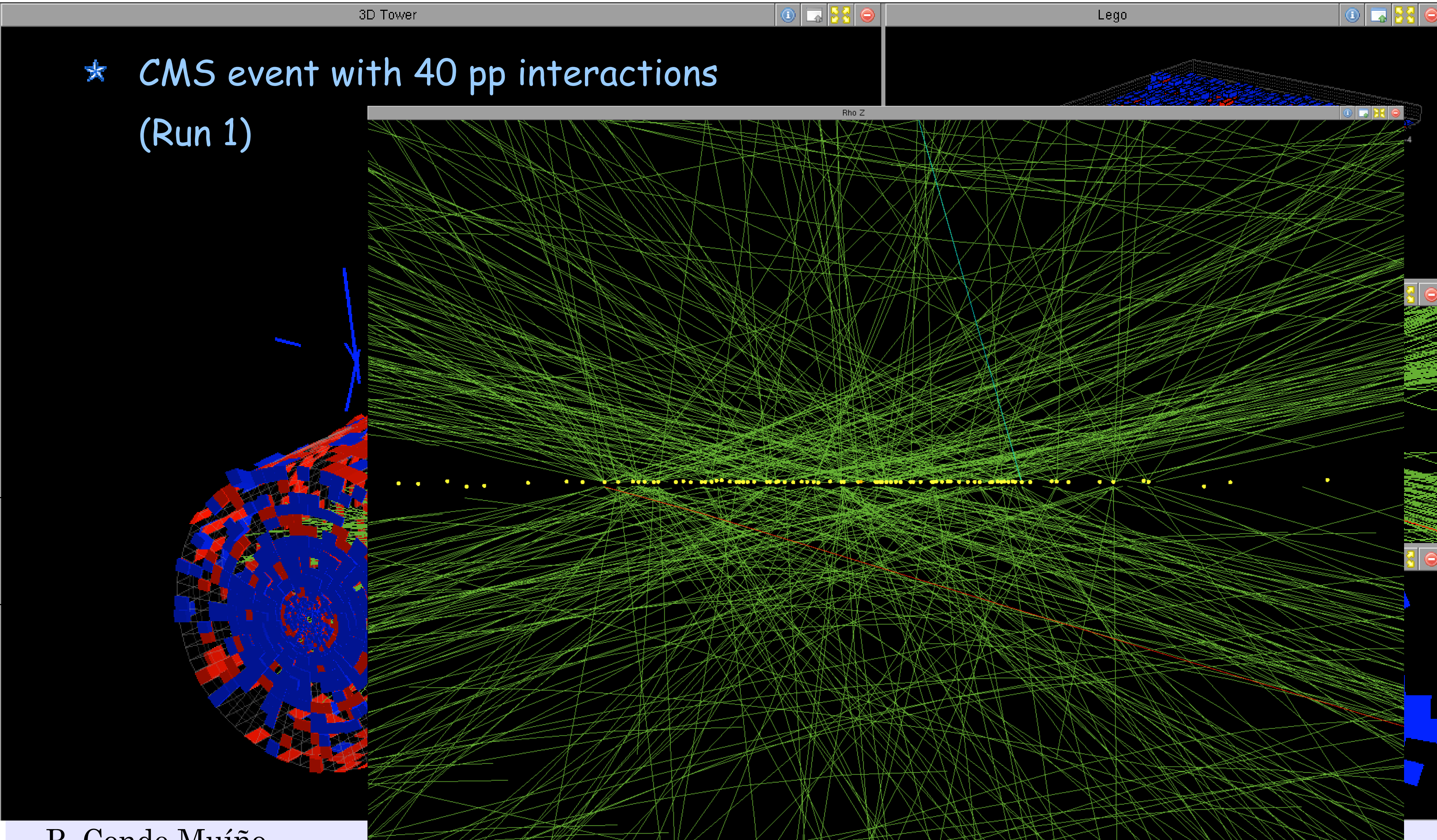
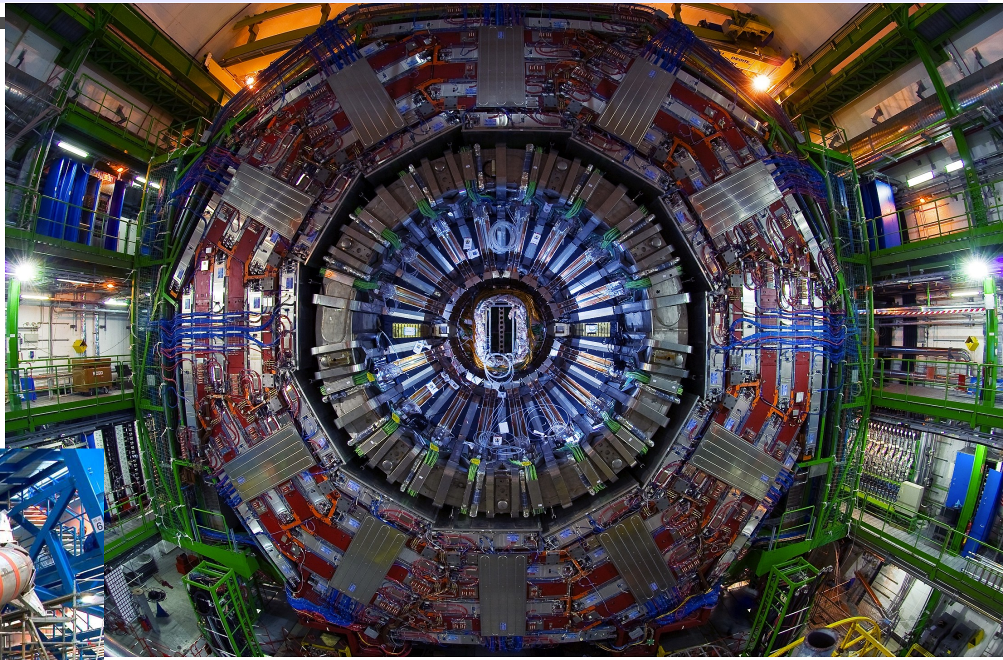
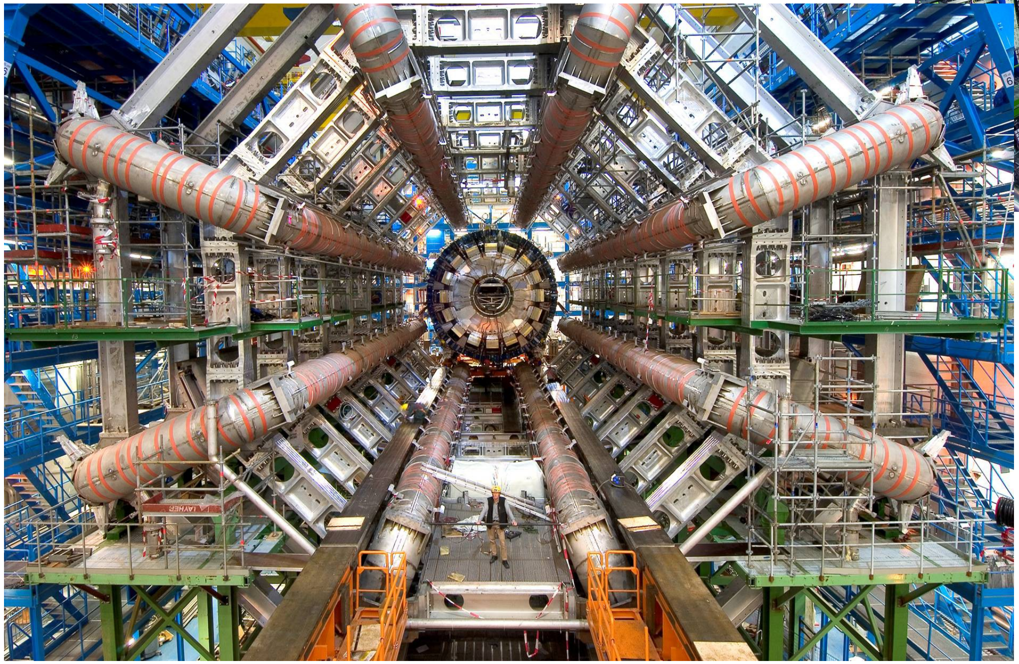


The ATLAS and CMS detectors



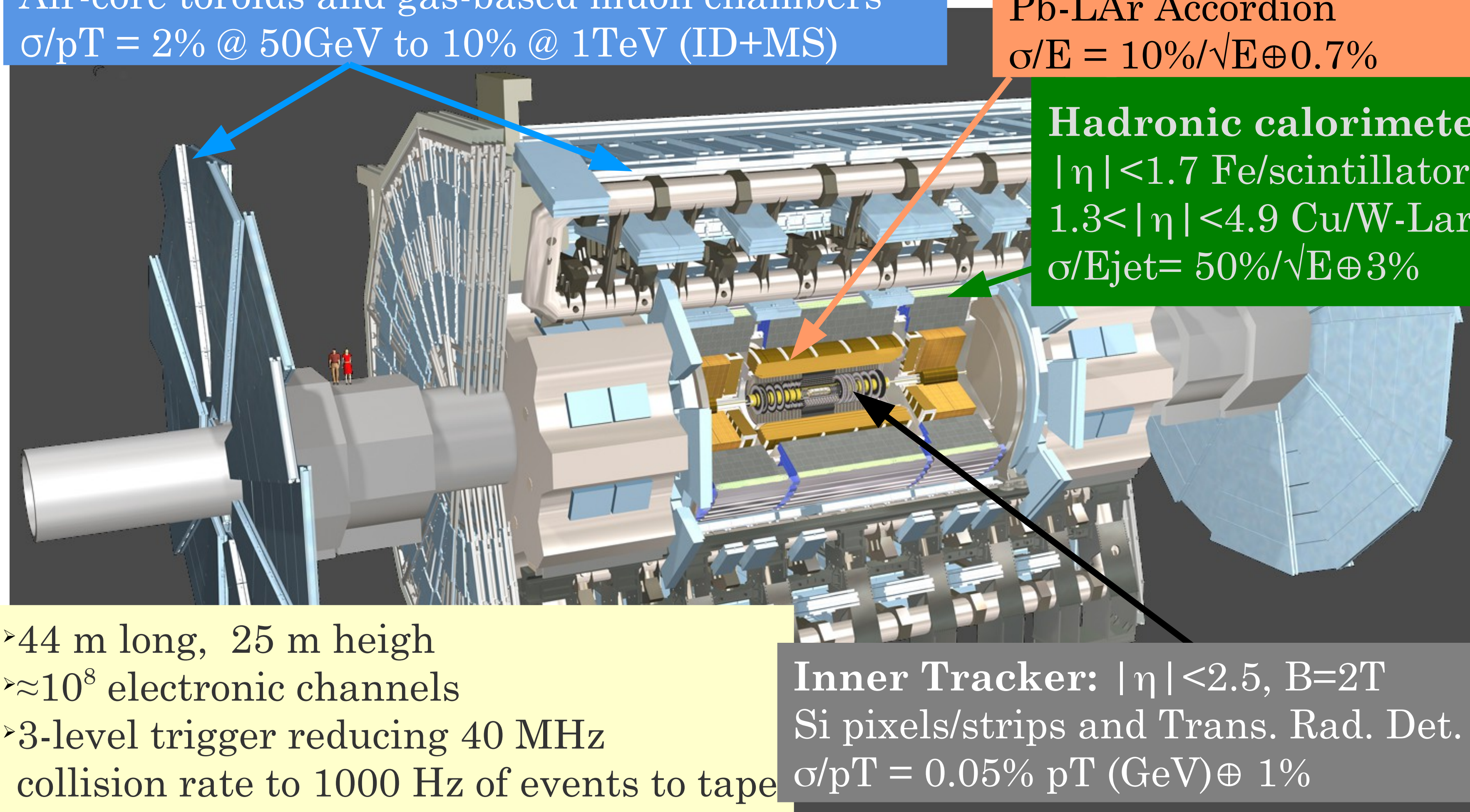


The ATLAS detector

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

EM calorimeter: $|\eta|<3.2$
Pb-LAr Accordion
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$

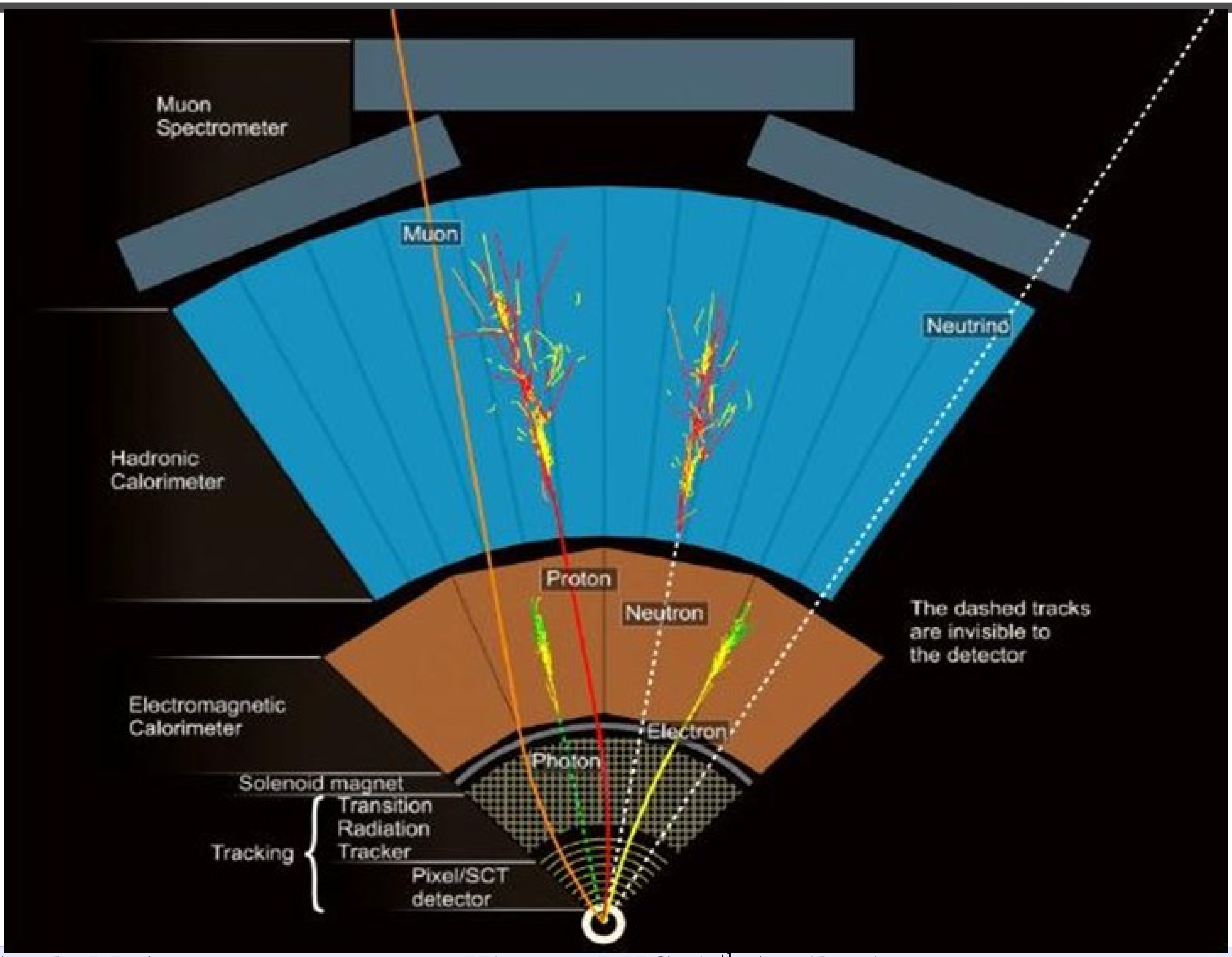
Hadronic calorimeter:
$|\eta|<1.7$ Fe/scintillator
$1.3<|\eta|<4.9$ Cu/W-Lar
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$



- 44 m long, 25 m heigh
- $\approx 10^8$ electronic channels
- 3-level trigger reducing 40 MHz collision rate to 1000 Hz of events to tape

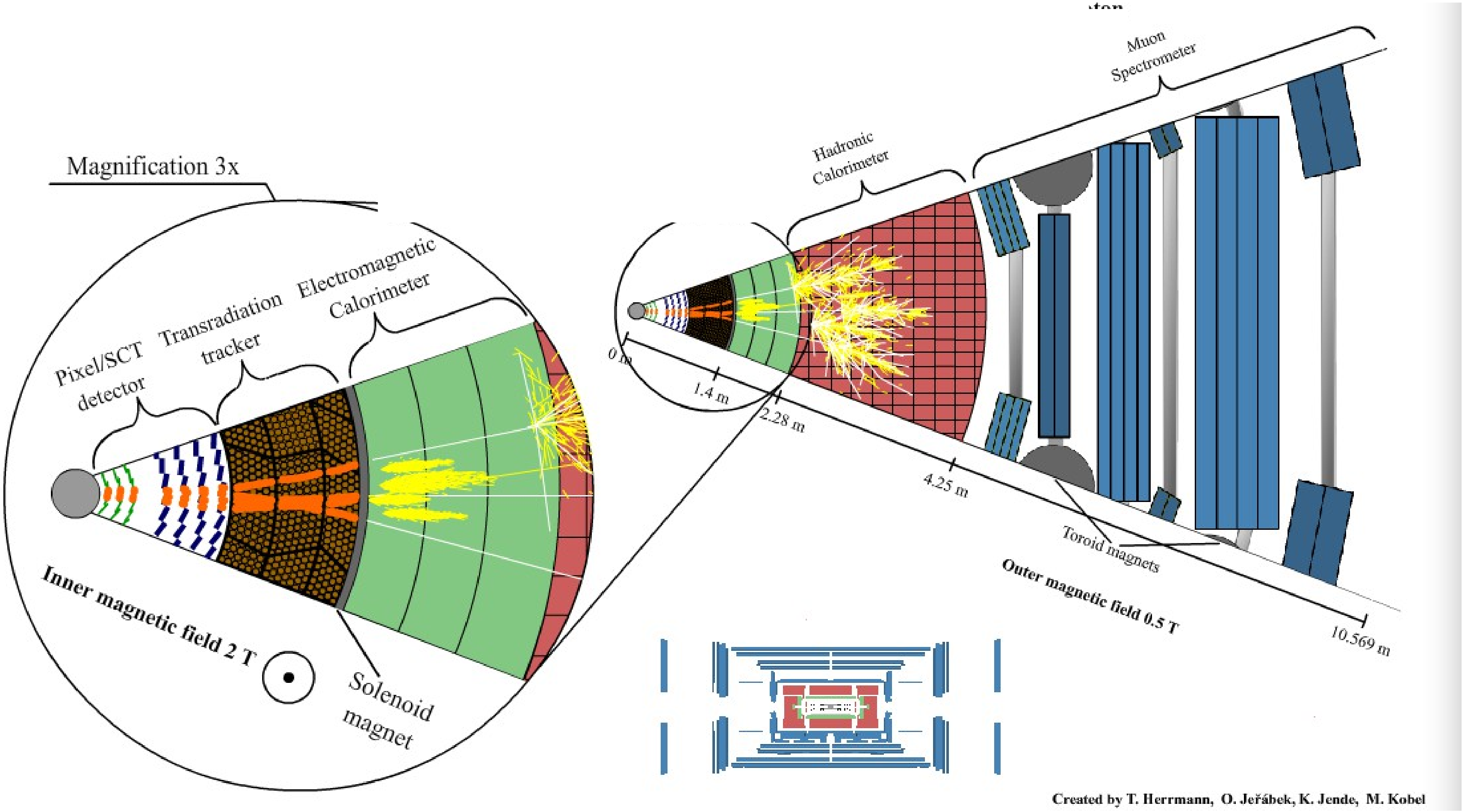
Inner Tracker: $|\eta|<2.5$, B=2T
Si pixels/strips and Trans. Rad. Det.
$\sigma/pT = 0.05\%\ pT\ (GeV) \oplus 1\%$

Particle identification

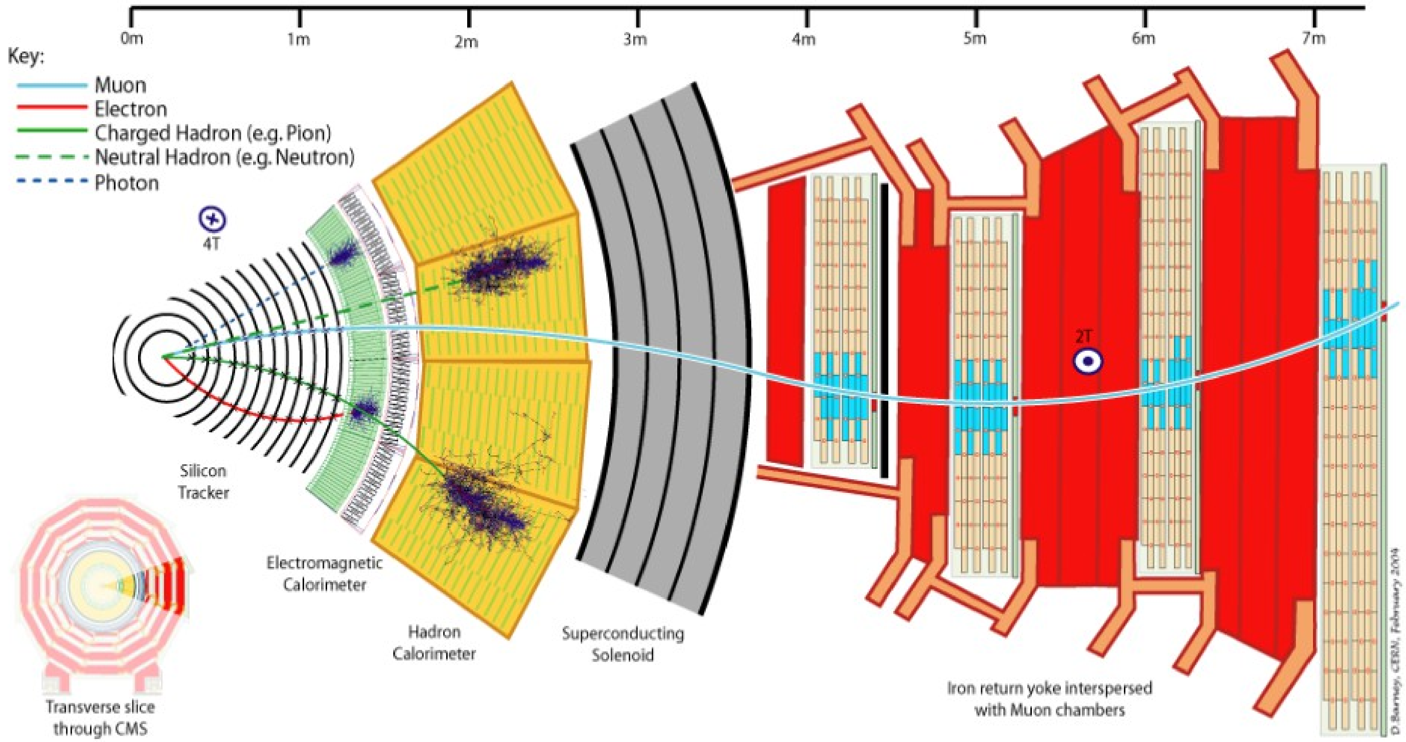


Jets

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



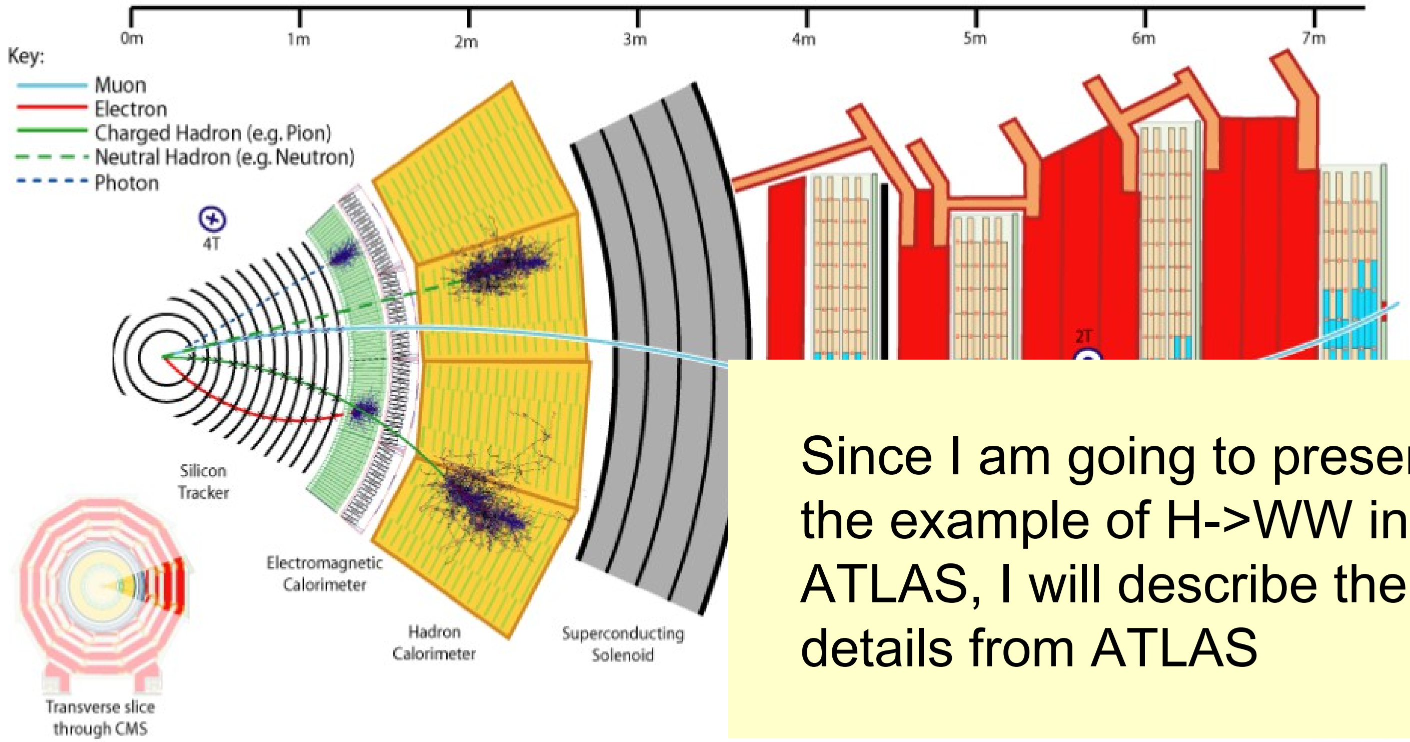
Particle identification @CMS



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)

From the detector to physics

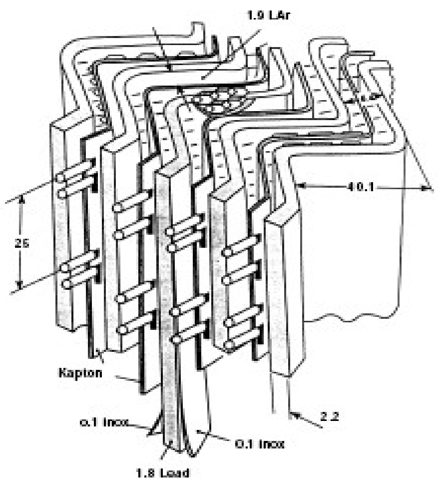
- The detector gives us a list of bites that contain the electronic record of the bunch crossing

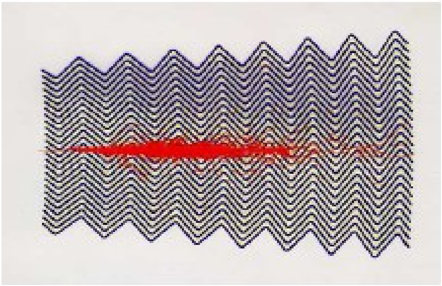

```
0x01e84c10:  0x01e8 0x8848 0x01e8 0x83d8 0x6c73 0x6f72 0x7400 0x0000
0x01e84c20:  0x0000 0x0019 0x0000 0x0000 0x01e8 0x4d08 0x01e8 0x5b7c
0x01e84c30:  0x01e8 0x87e8 0x01e8 0x8458 0x7061 0x636b 0x6167 0x6500
0x01e84c40:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c50:  0x01e8 0x8788 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
0x01e84cd0:  0x01e8 0x8798 0x01e8 0x8598 0x7265 0x7475 0x726e 0x0000
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
0x01e84d20:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
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
```

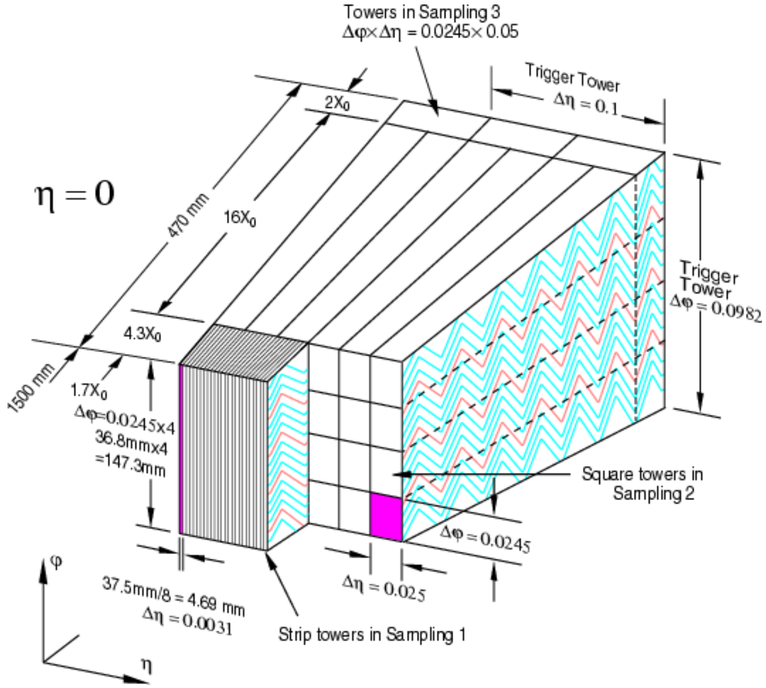

- How to get useful information from there?
- How to identify particles and measure its properties?
- How can we “see” a Higgs boson with this?

How to reconstruct e/γ:ATLAS example

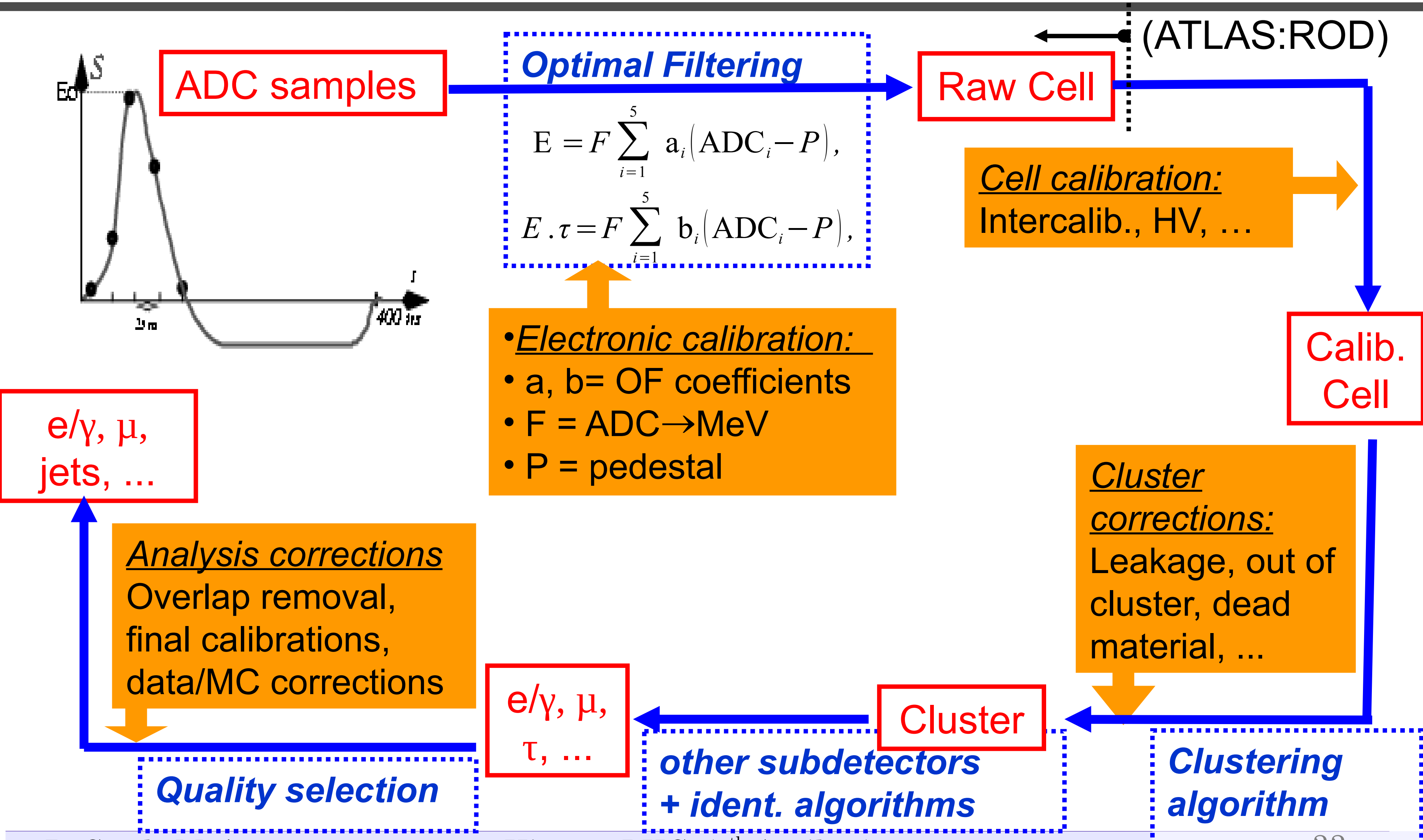
- LAr read out system: from the detector to the deposited energy
- Clustering algorithms
- Calibrations
- Photon/e identification algorithms







Reconstructing energy (calorimeter)

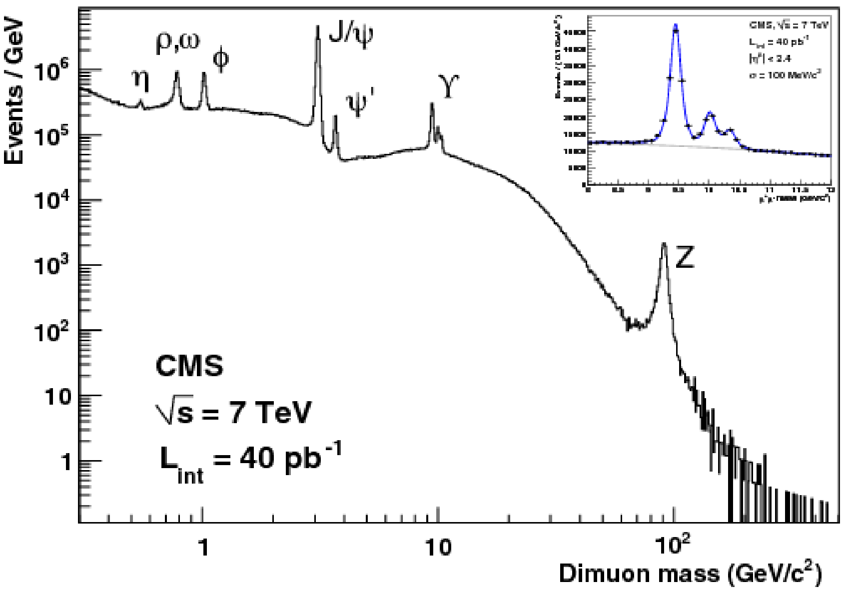


Particle reconstruction

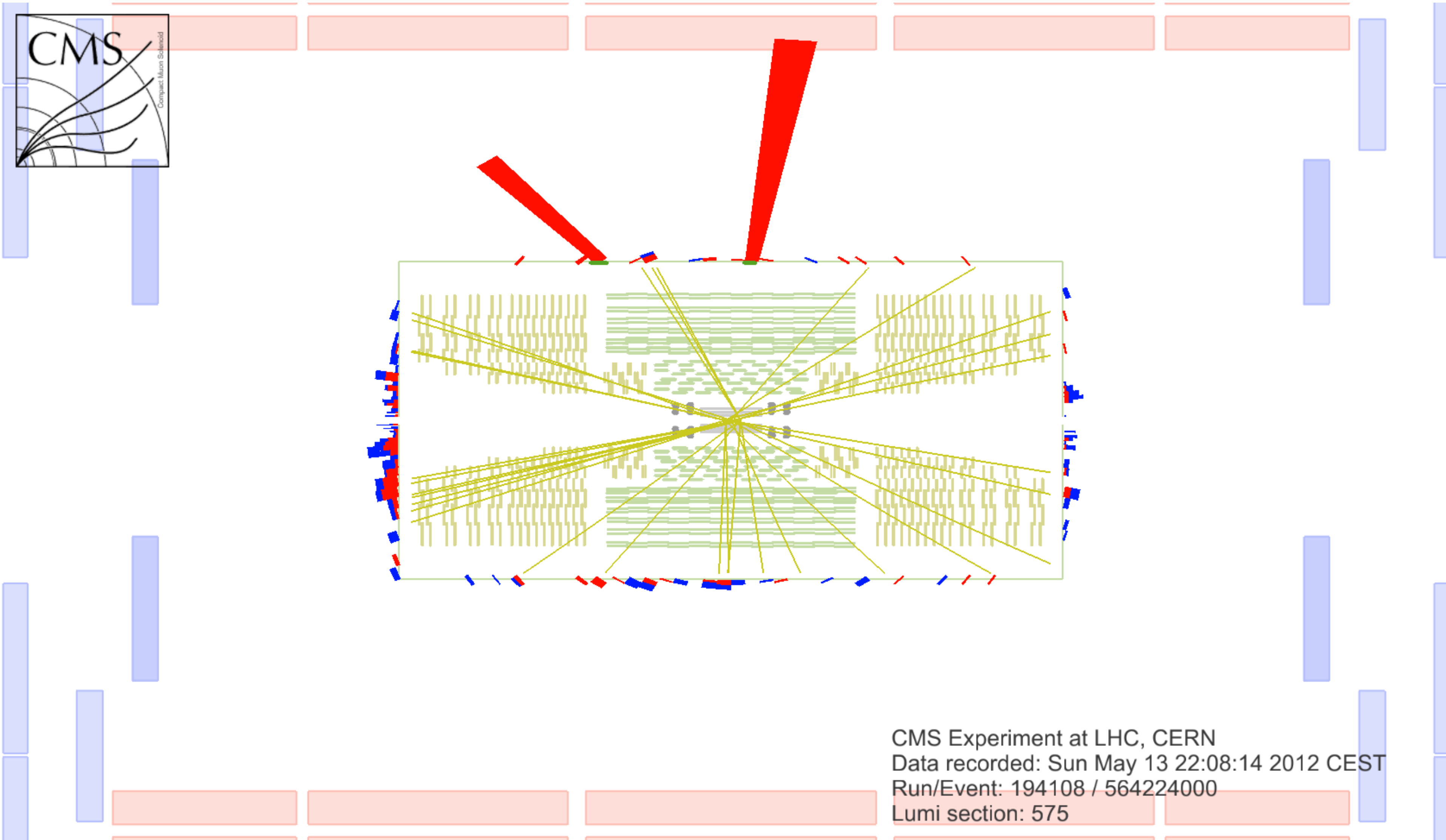
- From the properties of the particles produced in its decay we can infer the properties of the Higgs boson

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

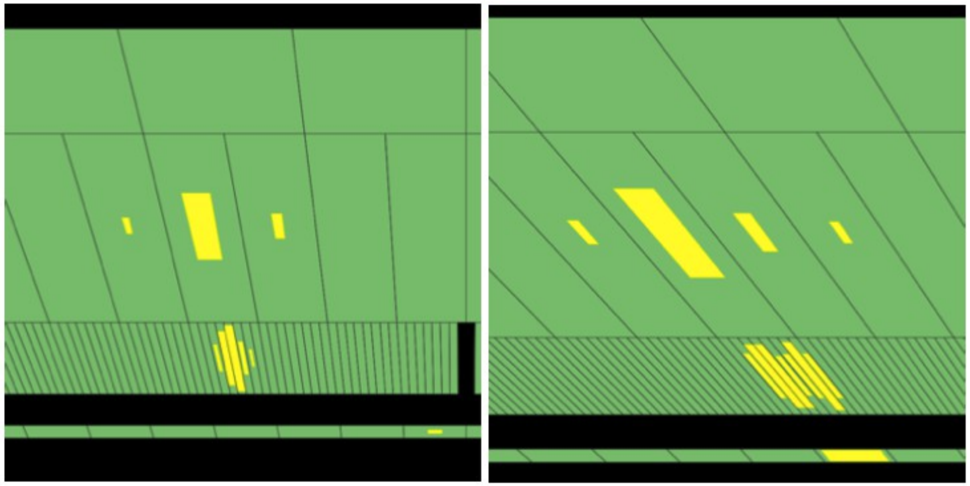
- 20 years of particle physics in one single plot



Run 1 analysis: H→γγ



e/γ identification



Photon π^0

Definitions

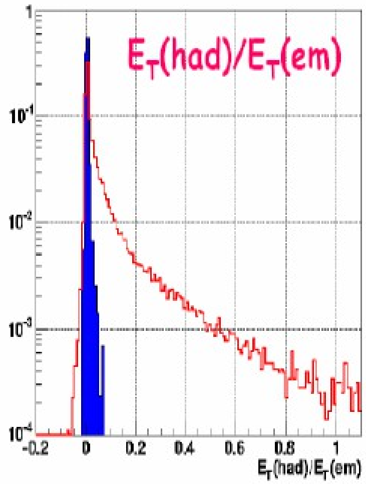
- Identification performed by applying cuts over discriminating variables (shower shapes) from the calorimeter layers.
- There is a 'loose' and 'tight' selection of cuts.
- Cuts are binned in η, and by converted/unconverted photons.

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

Electrons

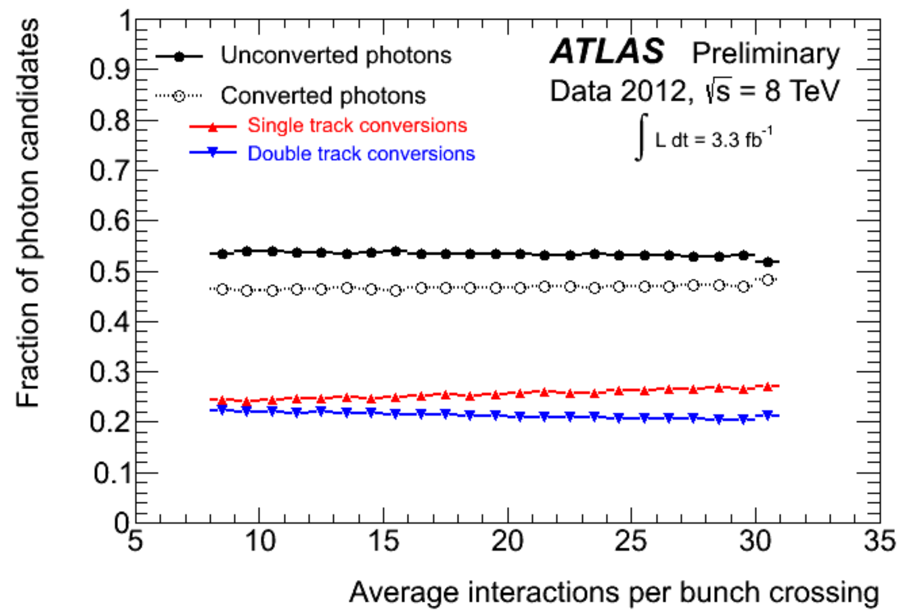
Jets

Hadronic leakage



γ identification

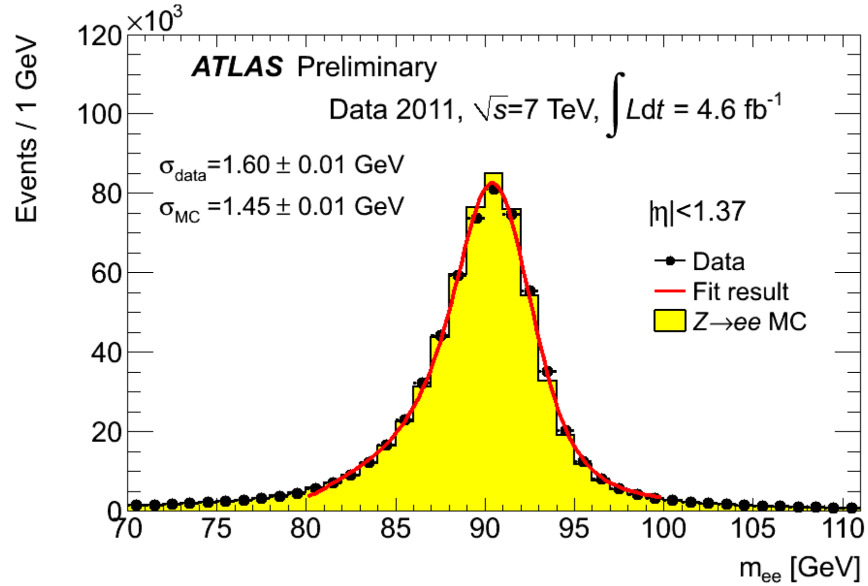
- Normal photons → unconverted
- Converted photons: γ →e+e-
  - After interaction with material in front of the calorimeter
  - Can have one or two tracks.
- Pileup can lead to misreconstructing unconverted photons as converted γ
  - 3% migration of 2-track to 1-track conversions.
  - Fraction of converted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

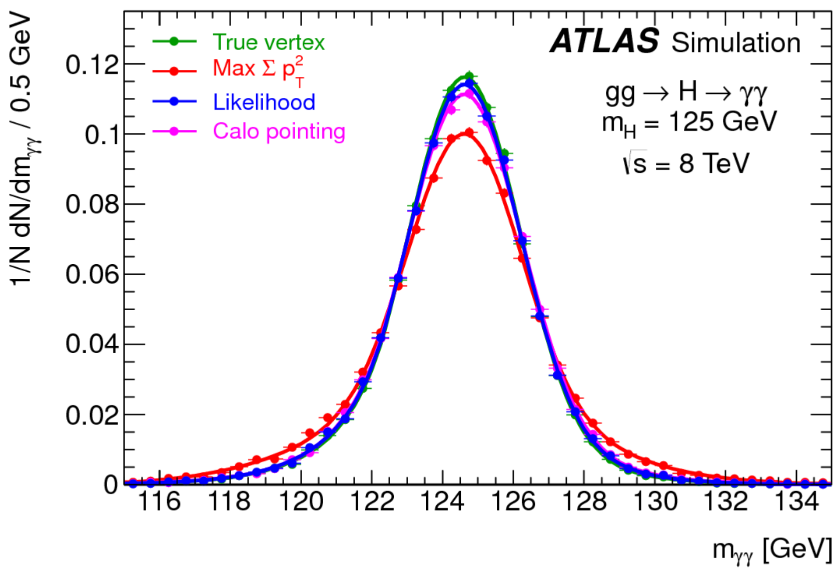


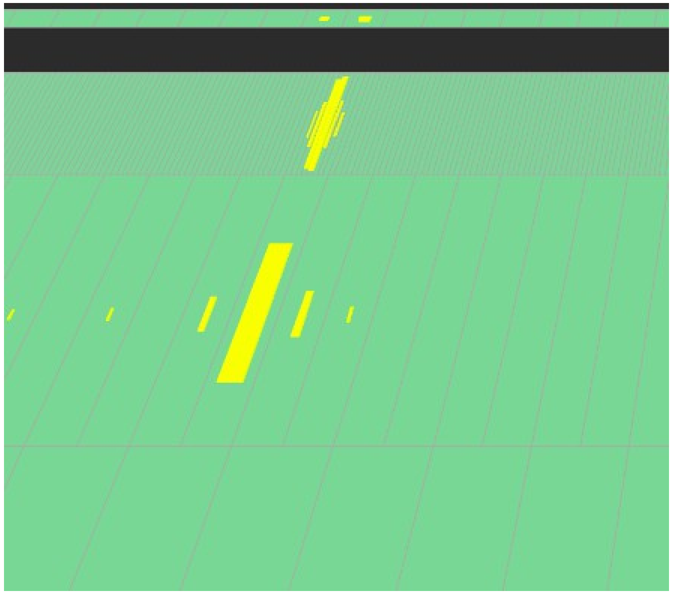
- Energy scale at m_Z known to ~ 0.5%
- Excellent mass resolution
  - 1.6-3.1 GeV
- Linearity better than 1%

γ association to primary vertex

- Use calorimeter segmentation to associate γ to primary vertex

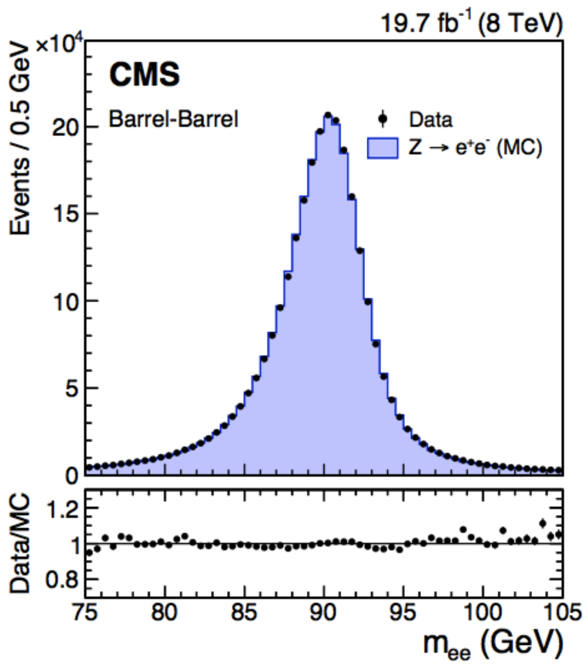
$\sigma_z \sim 15$ mm

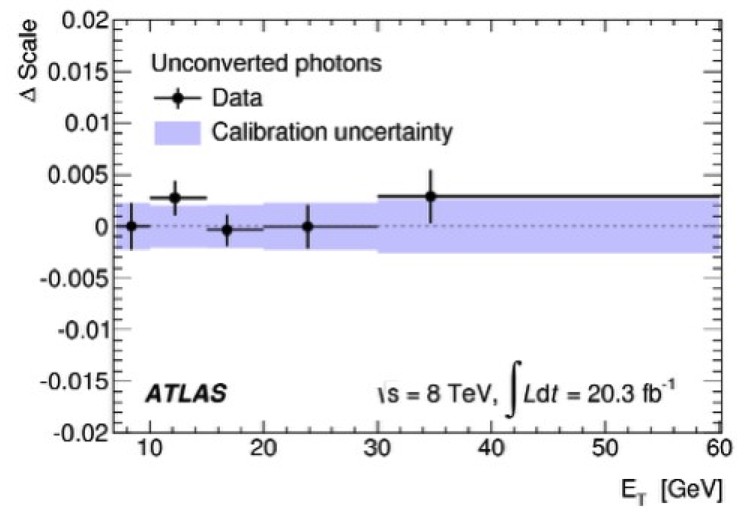




Improved γ identification & calibration

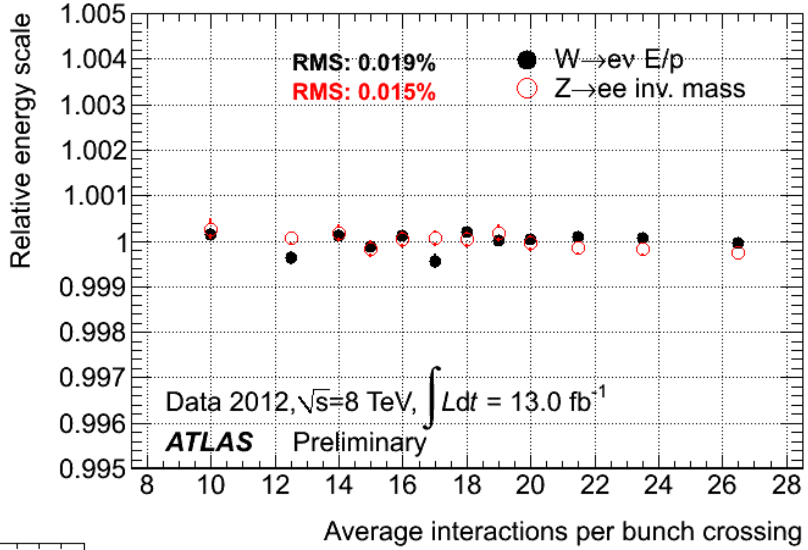
- Both, ATLAS and CMS, improved their photon energy measurement and identification procedures
- Validated the energy scale and systematics with data

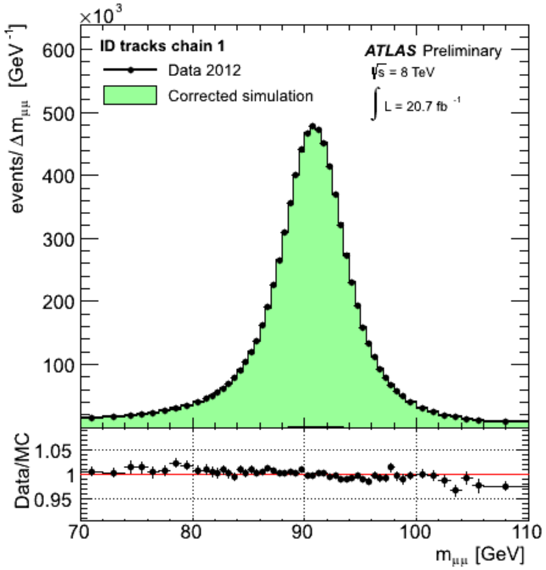


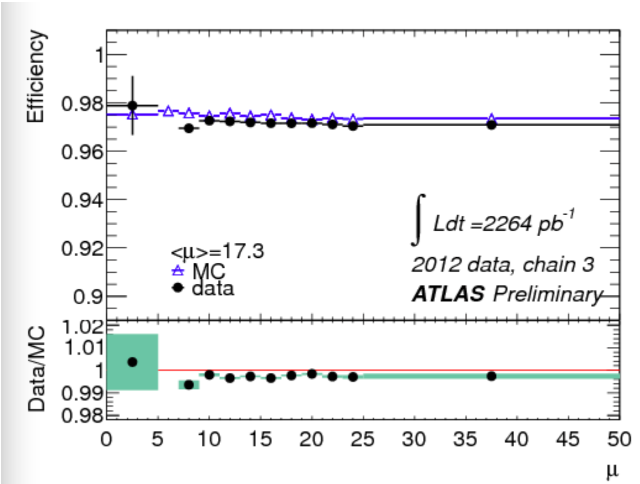


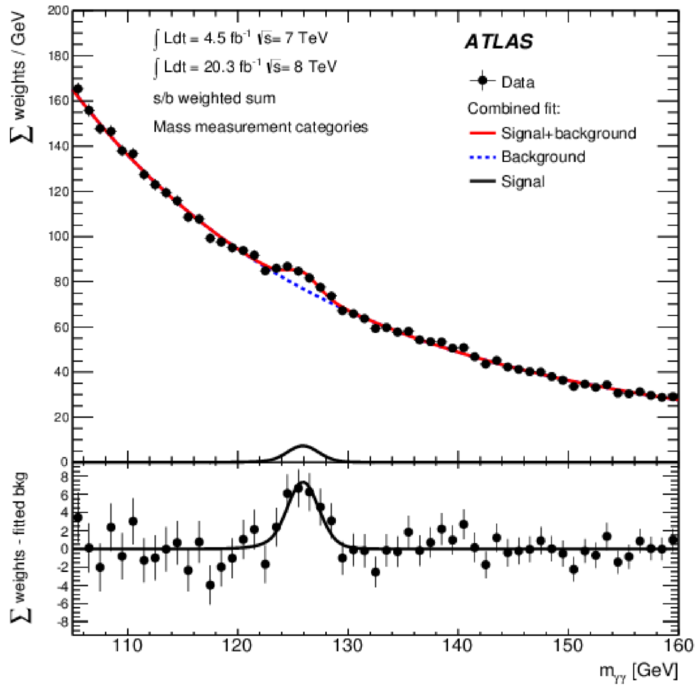
e and μ reconstruction

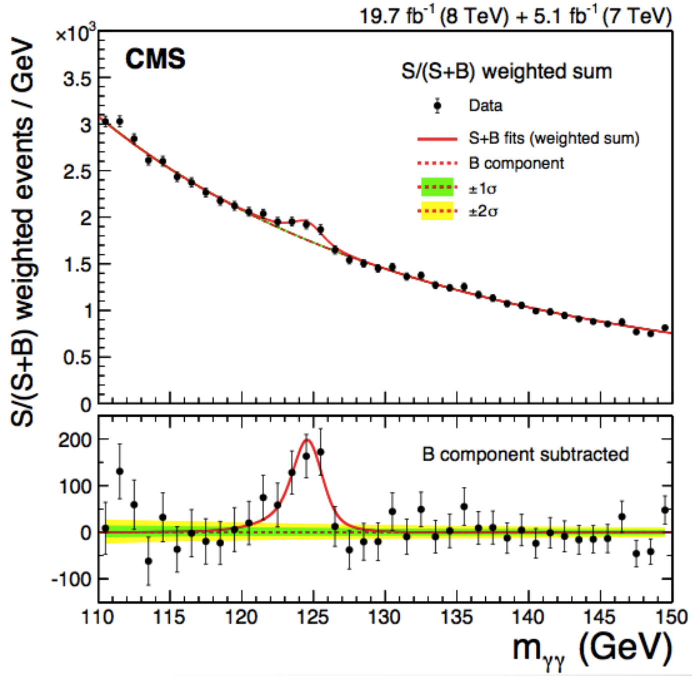
- Electrons: combine shower shape information from calorimeter with tracking information (including transition-radiation in TRT)
- Muons: combined tracks in inner detector and muon chambers
- MC simulation corrected to reproduce the detector resolution, energy scale and efficiency precisely











- 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

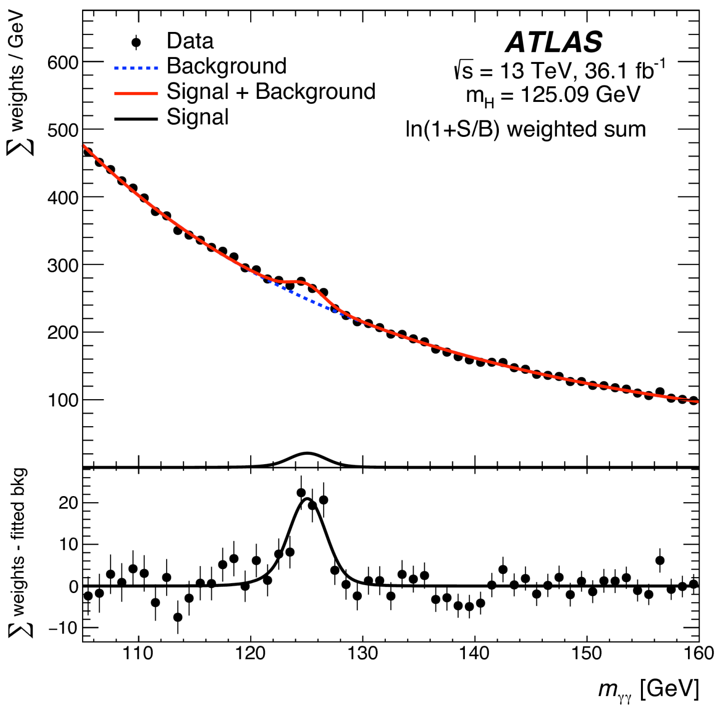
$\mu = \sigma/\sigma_{SM} = 1.14^{+0.26}_{-0.23}$

- Background fluctuation probability ~ 10^{-8}

Higgs re-discovery at 13 TeV

- $H \to \gamma\gamma$ arXiv:1802.04146

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



- Signal strength

$$\mu = 0.99\,^{+0.15}_{-0.14} = 0.99\ \pm 0.12\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{exp.})\,^{+0.07}_{-0.05}\,(\text{theo.})\,,$$

Factor of two more precise than Run 1!!

- Fiducial cross section

$$\sigma_{\text{fid}} = 55 \pm 9\,(\text{stat.}) \pm 4\,(\text{exp.}) \pm 0.1\,(\text{theo.})\,\text{fb}\,,$$

Theoretical prediction

64 ± 2 fb

Table from M. Duehrssen Moriond 2018

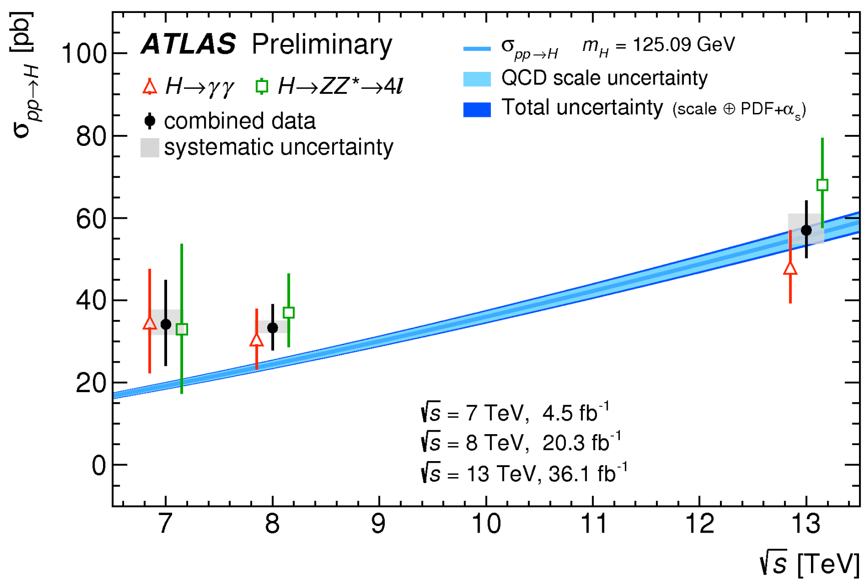
σ_{fid} [fb]	$h \to \gamma\gamma$	$h \to 4l$
ATLAS SM	55 ±9(stat) ±4(exp) ±0.1(th) 64 ± 2 1802.04146	3.62 ±0.5(stat) $^{+0.25}_{-0.20}$(sys) 2.91 ± 0.13 JHEP 10 (2017) 132
CMS SM	84 ±11(stat) ±7(syst) 75 ± 4 CMS-PAS-HIG-16-040	2.92 $^{+0.48}_{-0.44}$(stat) $^{+0.28}_{-0.24}$(syst) 2.76 ± 0.14 JHEP 11 (2017) 047

Differential cross sections in H → γγ

ATLAS-CONF-2017-047

arXiv:1802.04146

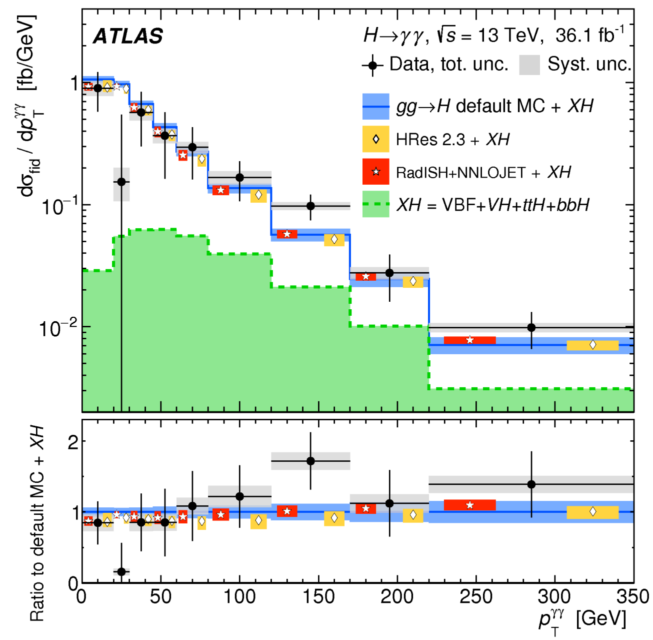
- Cross section as a function of the pp center of mass energy



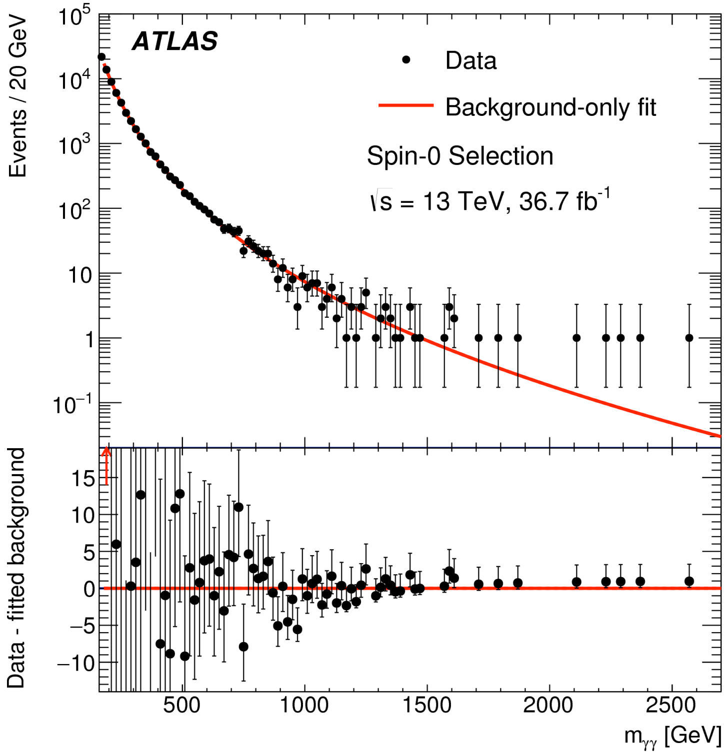
- H → γγ differential cross section as a funtion of $p_T^{\gamma\gamma}$

Agreement with theory

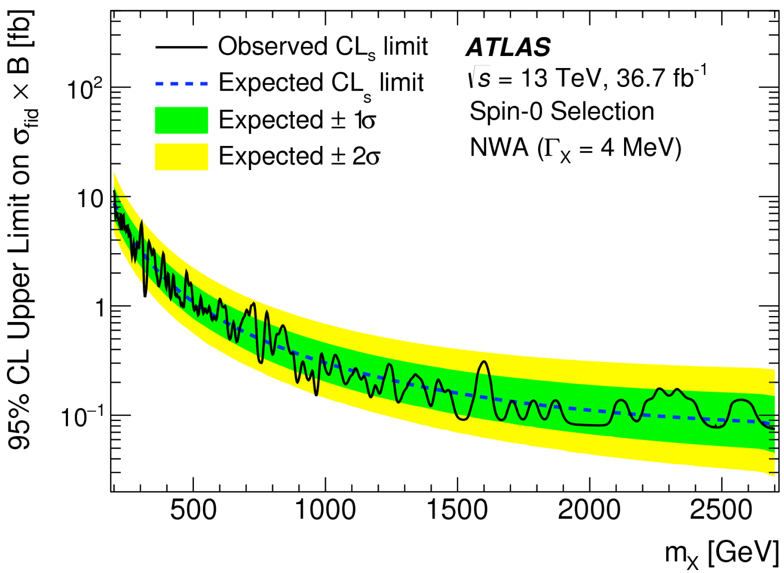
Slightly harder pT in data?



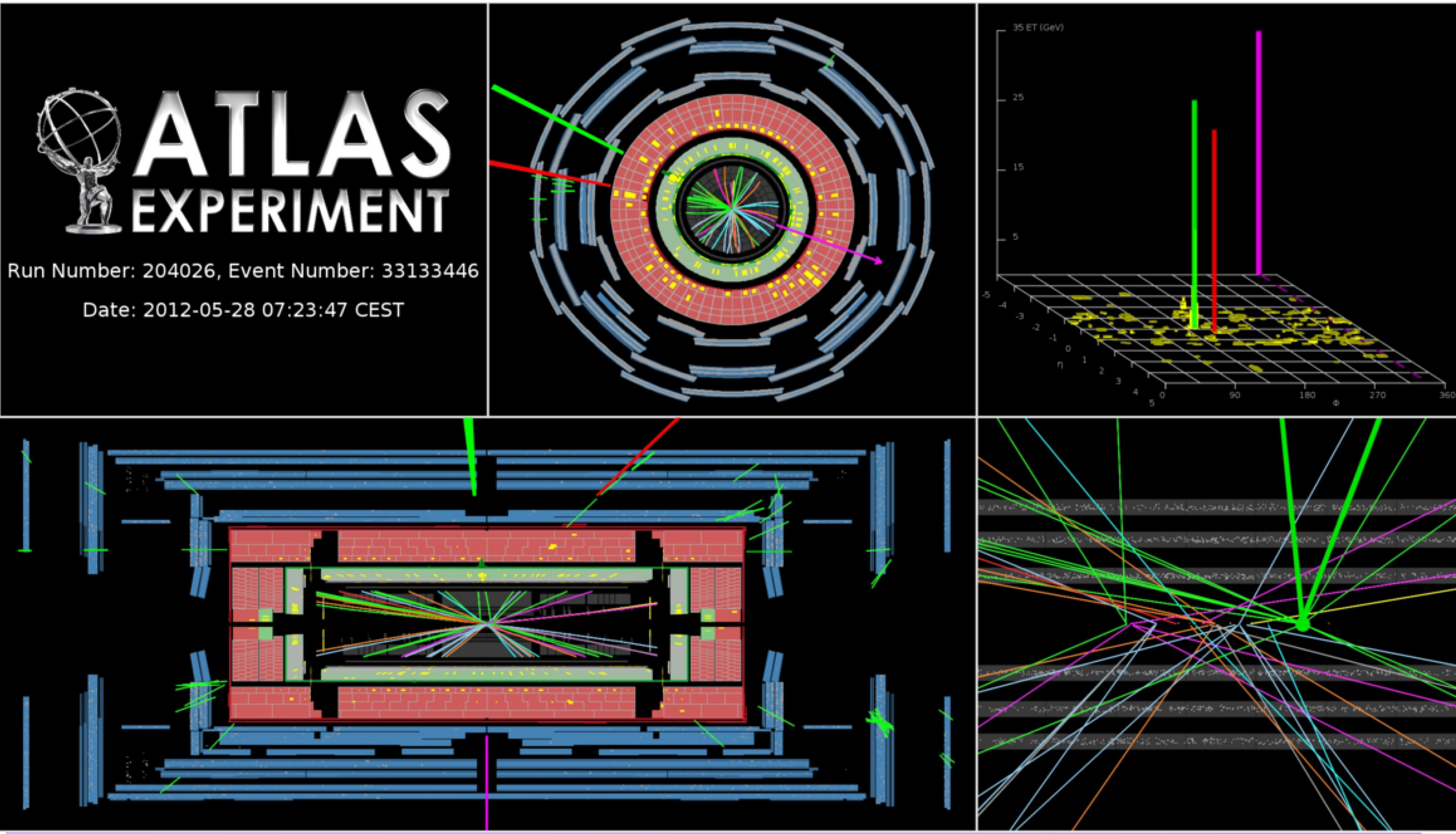
Di-γ high mass searches



- No signal seen → limits



H→WW→lνlν



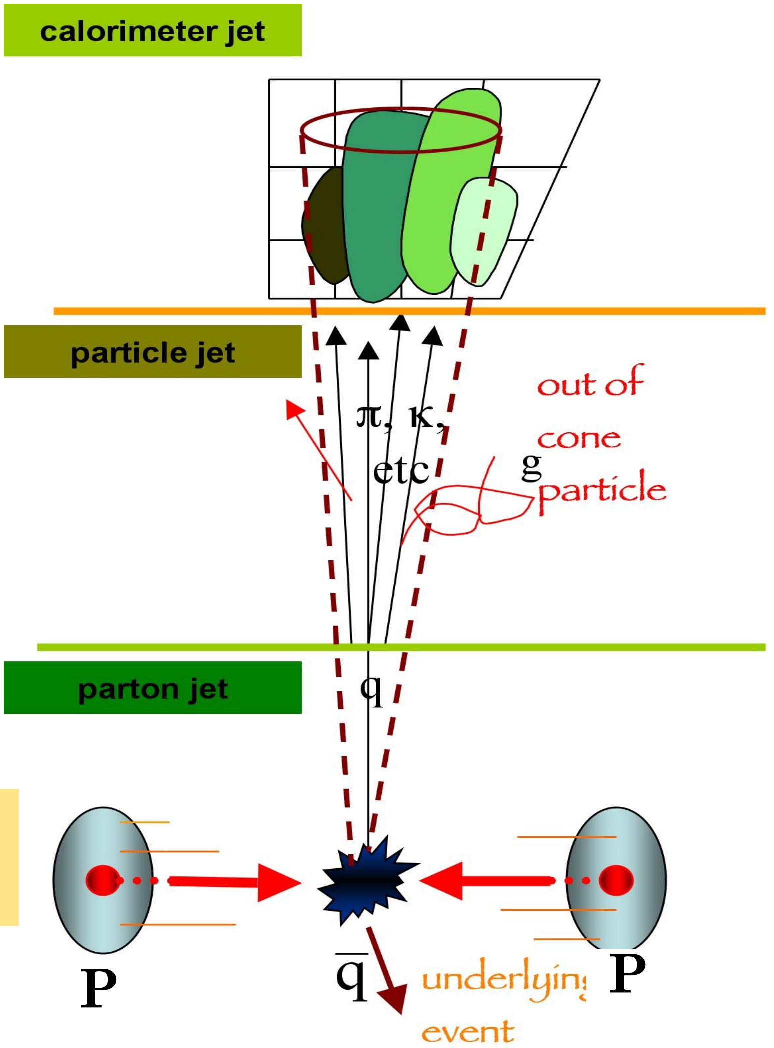
ATLAS
EXPERIMENT
Run Number: 204026, Event Number: 33133446
Date: 2012-05-28 07:23:47 CEST

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/…

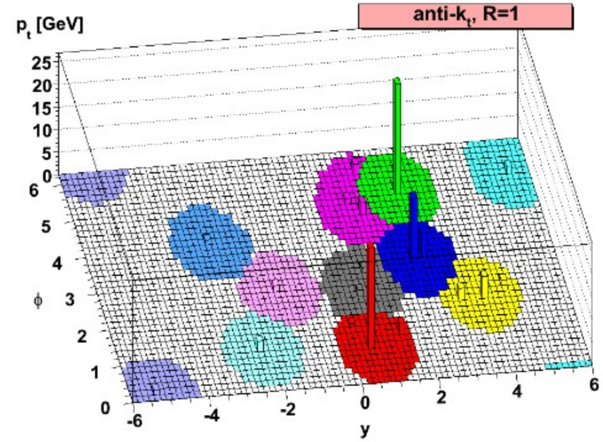
- Complex detector properties:
  - non-linear energy response
  - non-instrumented regions, dead material
  - invisible energy

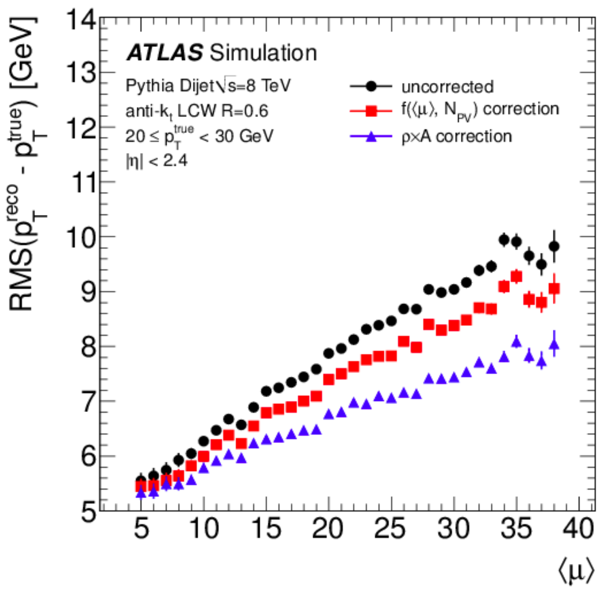
- Algorithm effects:
  - Out of cone radiation, infrared safeness

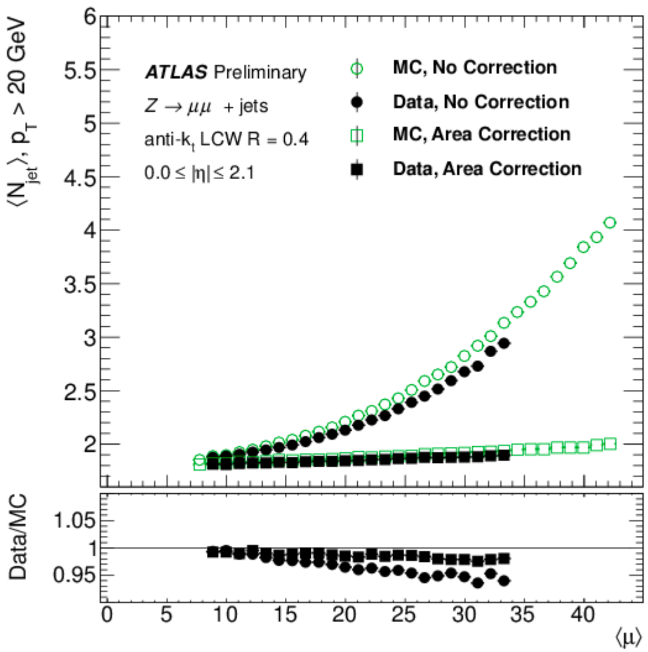


Jet Reconstruction

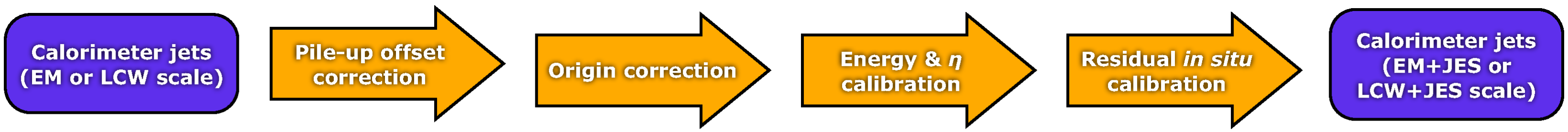
- Use Anti-kT with R = 0.4
  - Constituents: 3D clusters in calorimeter
- Calibrate to hadronic scale
- Sensitive to pile-up
  - Apply pile-up corrections





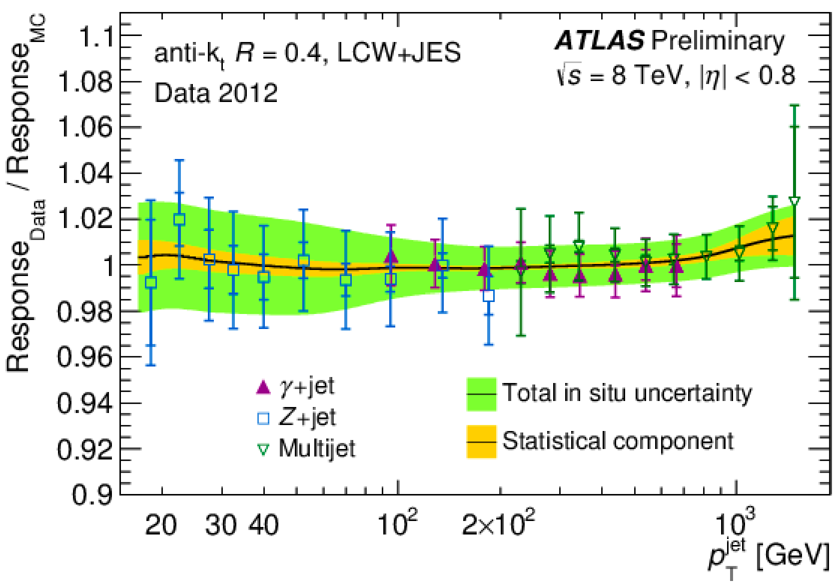


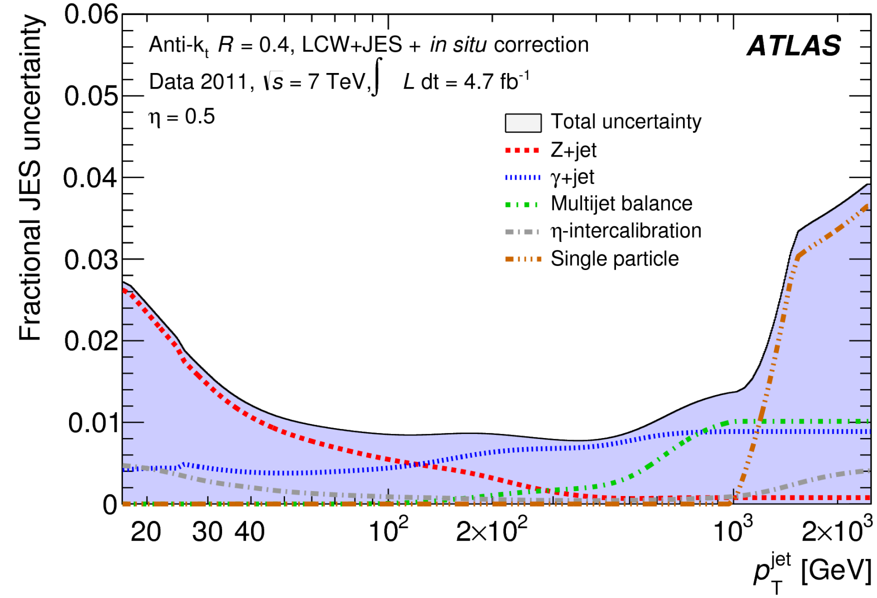
Jet energy scale uncertainty



- 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.

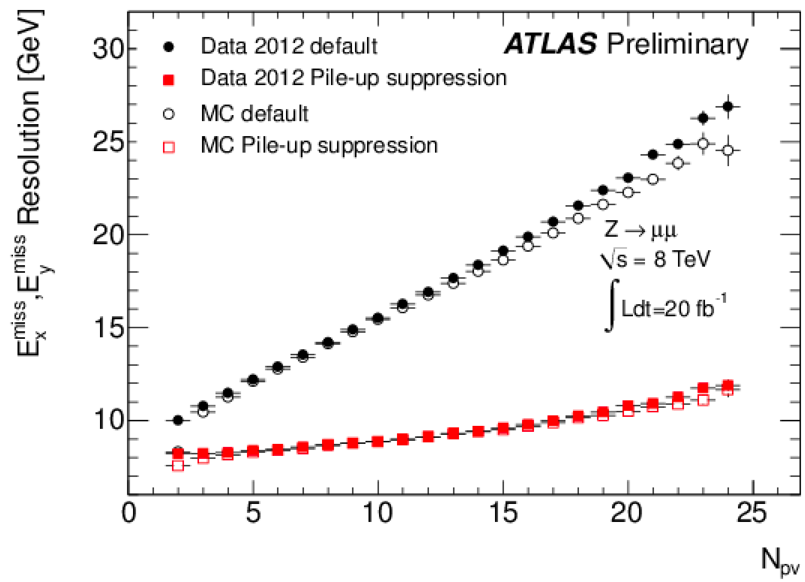
- JES uncertainty dominated by in-situ uncertainties

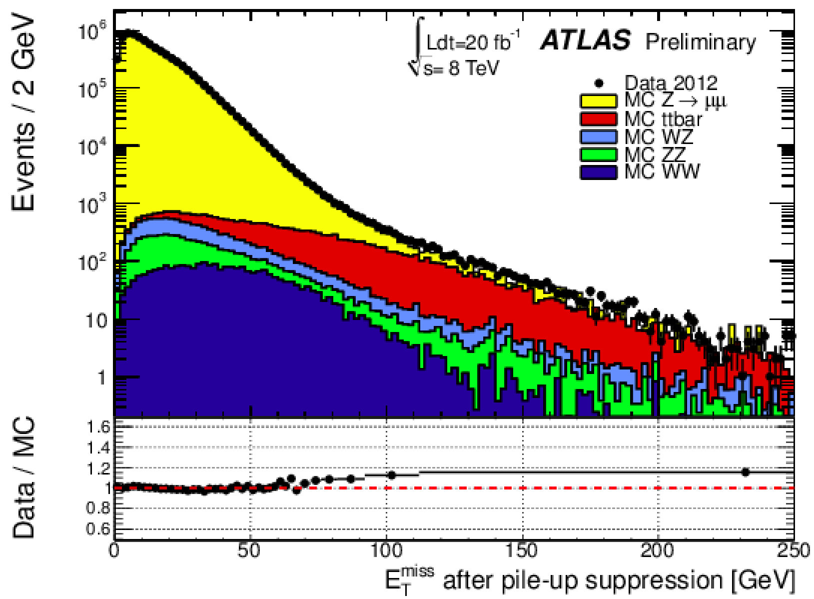




Missing E_T performance

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





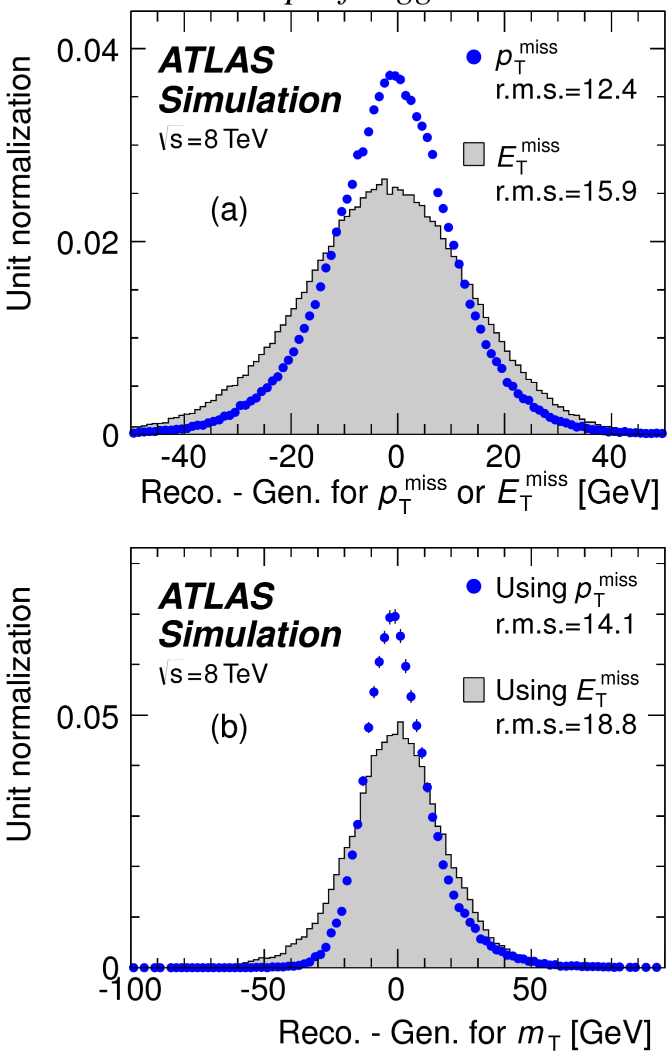
- ETmiss resolution worsens significantly with increasing pile-up
  - Correct it using tracking information
- Good data-MC agreement

E_T^{miss} on the H→WW→lνlν search

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

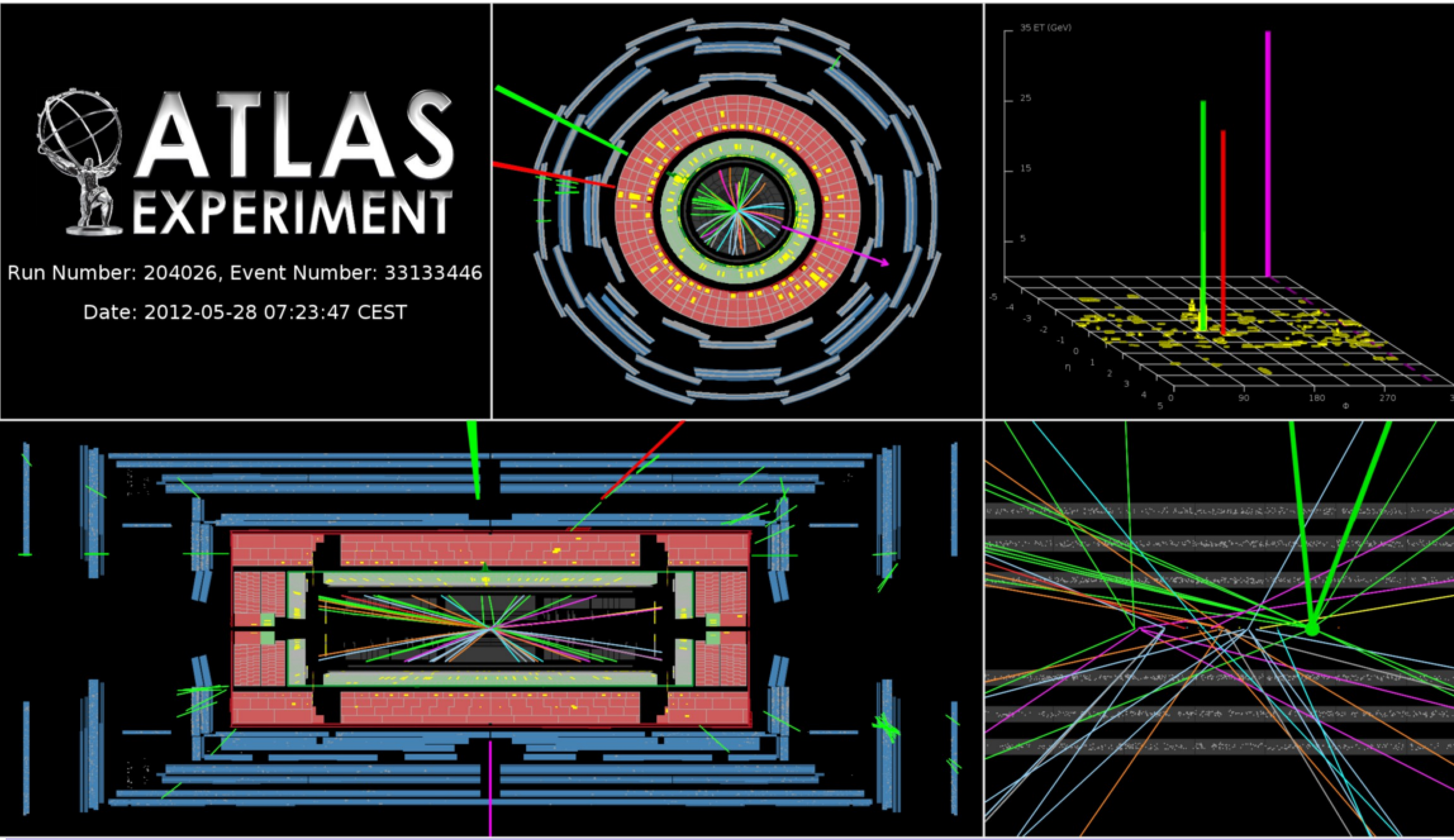
- Calorimeter based E_T^{miss}
  - Large rapidity coverage, sensitive to neutral particles
  - Soft term: calibrated calorimeter clusters
- p_T^{miss}:
  - Soft term calculated using tracking
  - Improves resolution by ~20%
- $p_T^{miss,track}$: $$p_{\mathrm{T}}^{\mathrm{miss,track}} = -\sum p_{\mathrm{T}}^{\mathrm{tracks}}$$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

MC sample for ggF H → WW*



H→WW→lνlν

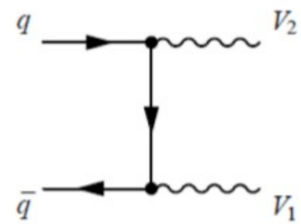
Phys. Lett. B 726 (2013), pp. 88-119



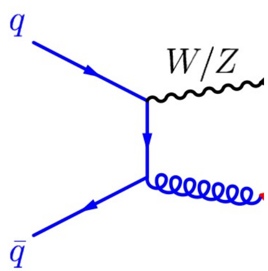
Main backgrounds

- Di-boson production

  WW, WZ, ZZ



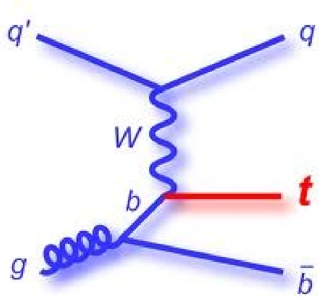
- Others: W+jets, Wγ, Drell-Yan

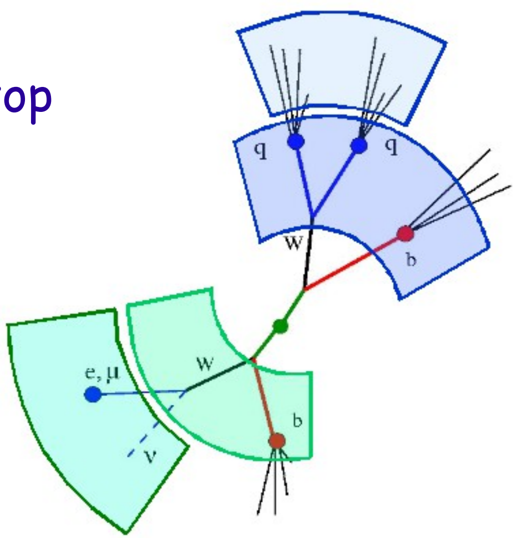


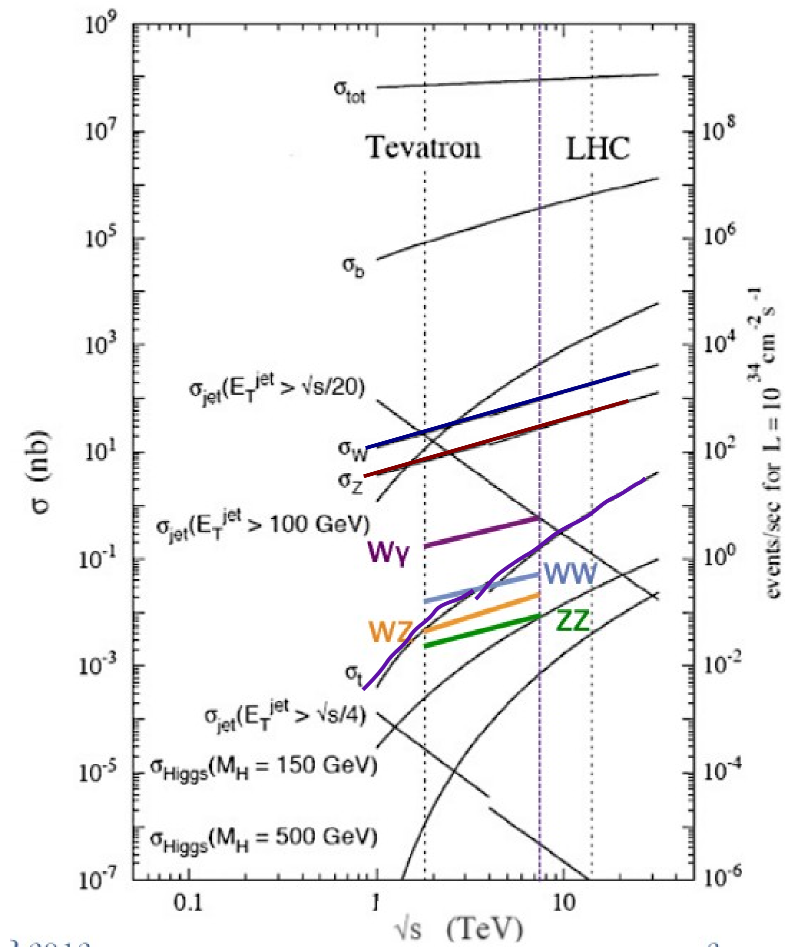
- Top production:

  t-tbar

  Single top

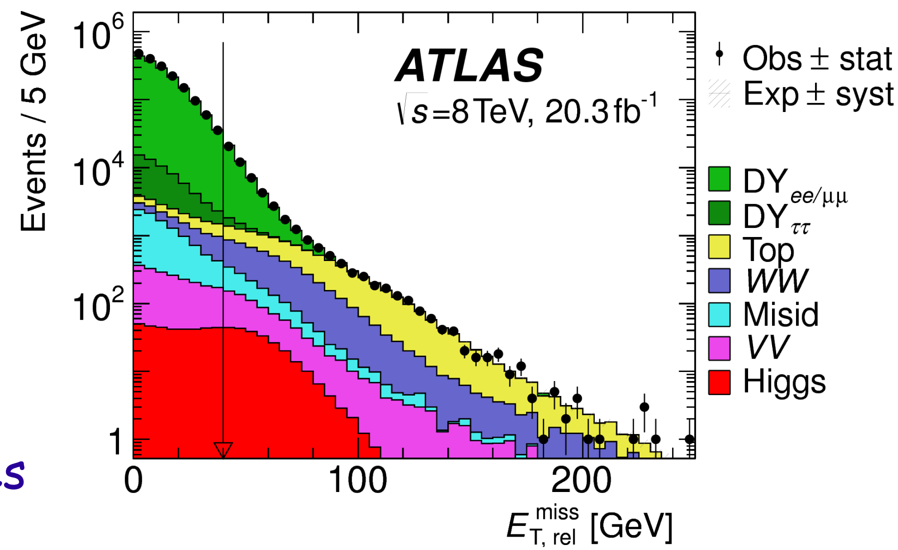


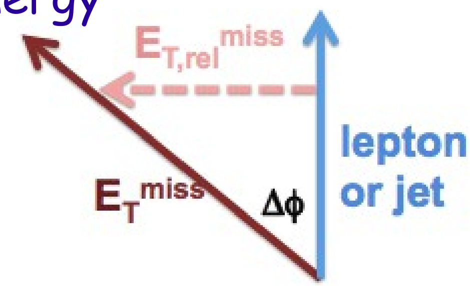


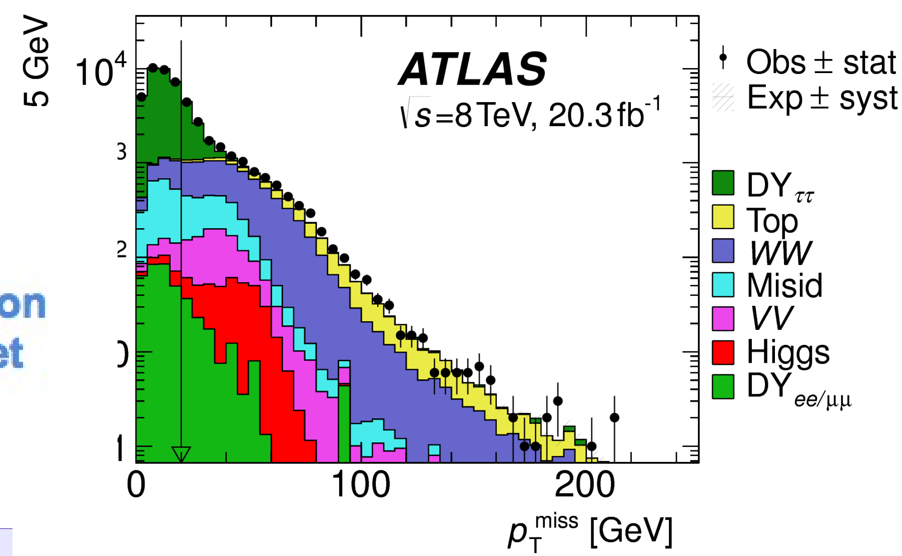


Event selection

- 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



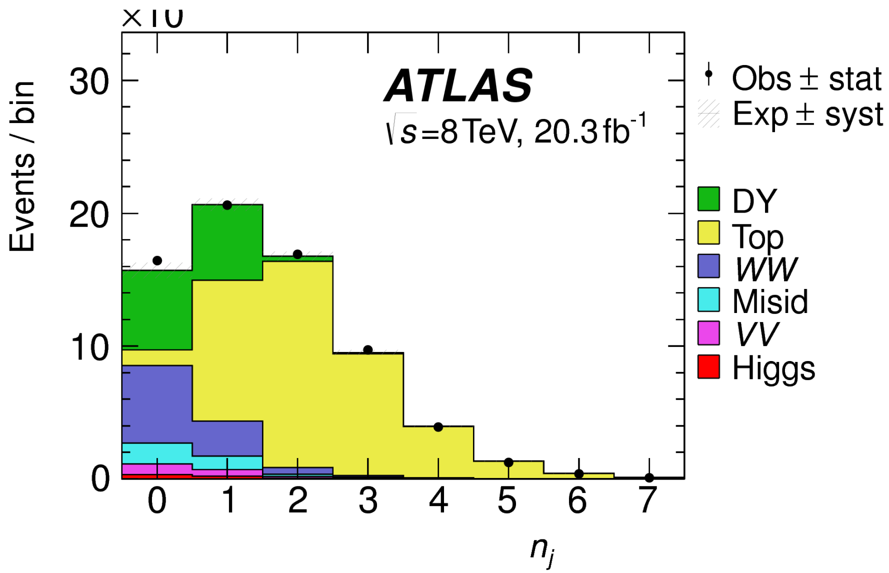




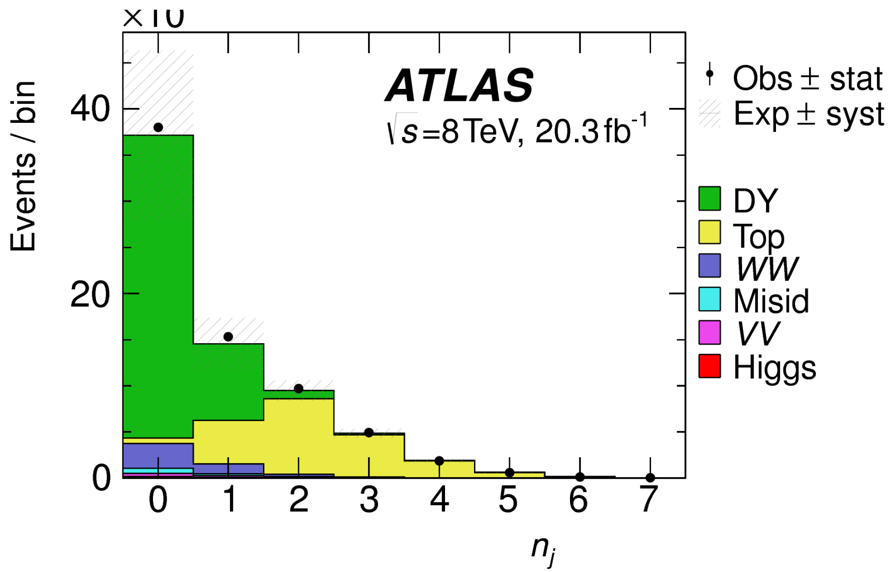
Use calorimeter and tracking systems

Analysis categories

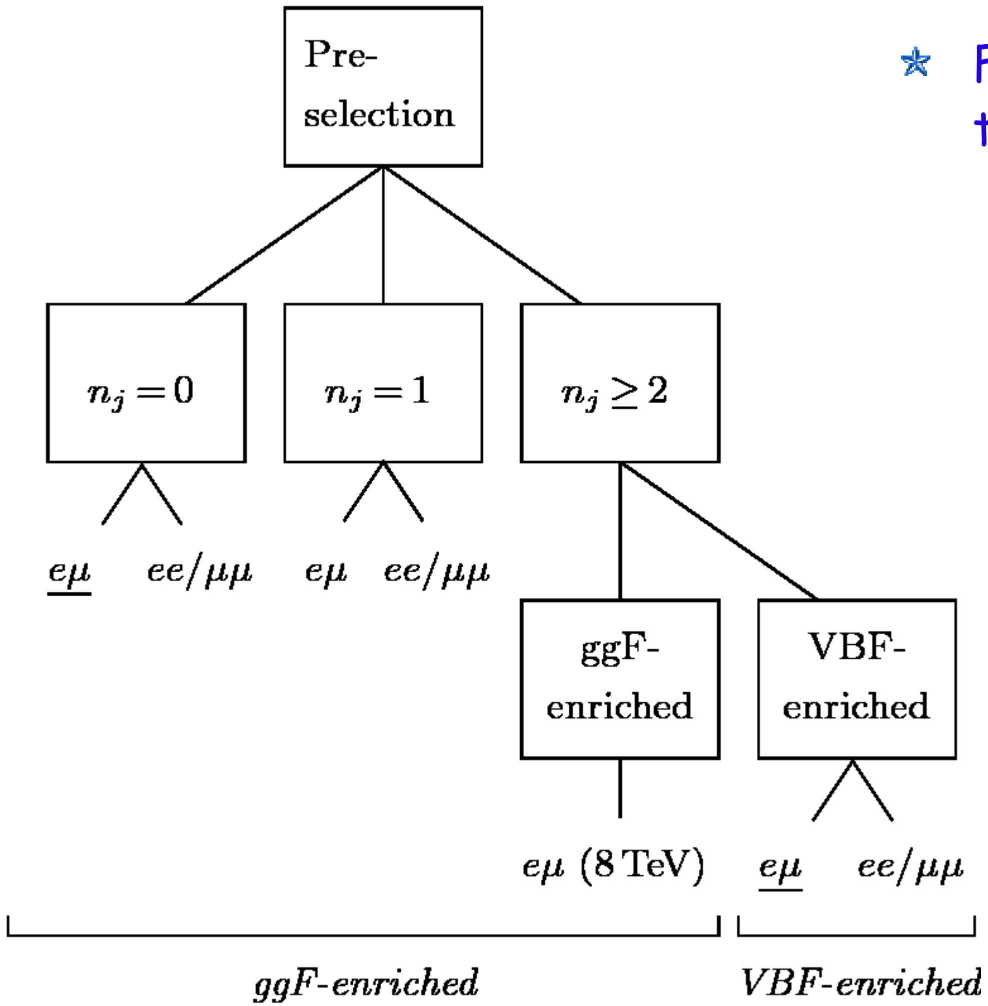
- Different flavour final state



- Same flavour final state

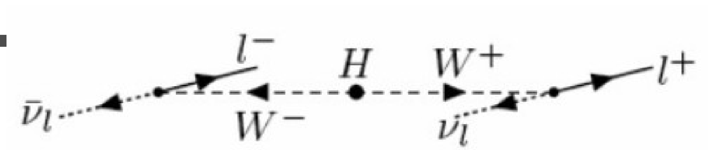


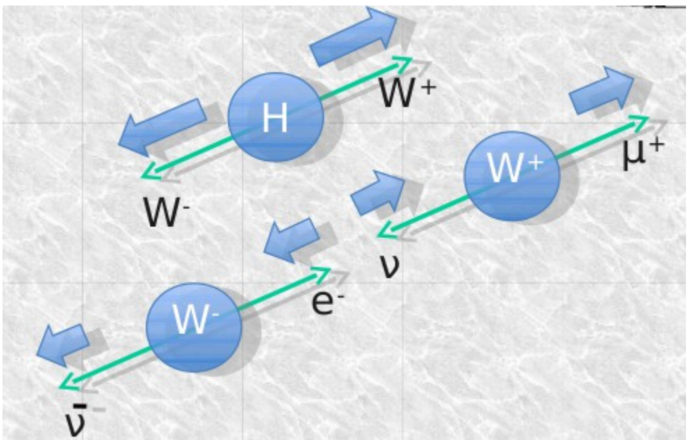
- Consider separately different categories: 0, 1, 2 jets
  - Sensitive to different production mechanisms
    - Gluon gluon fusion dominates the 0-jet category
    - VBF dominate the 2-jet category
  - Affected by different backgrounds

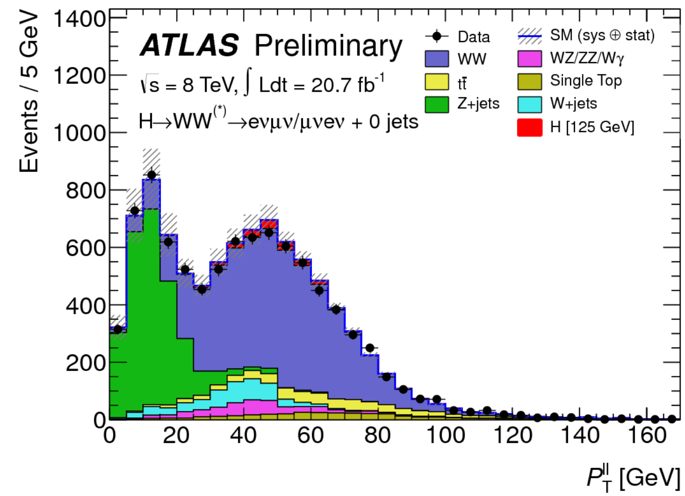


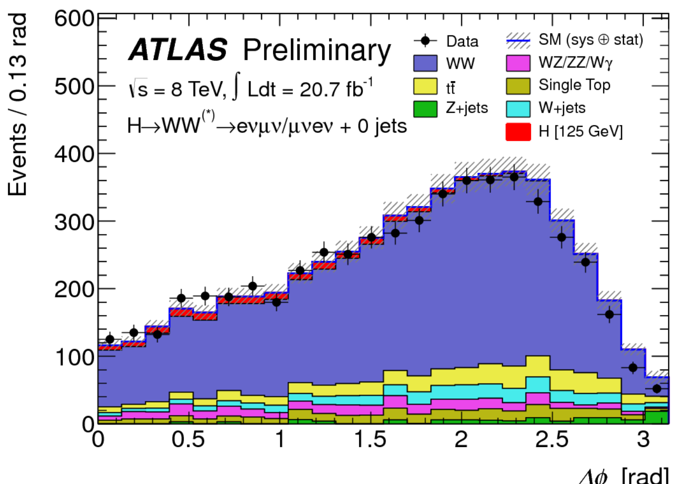
- Further selection will depend on the analysis category

Further selection

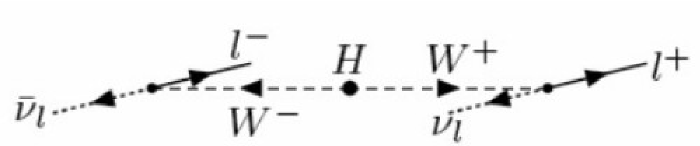


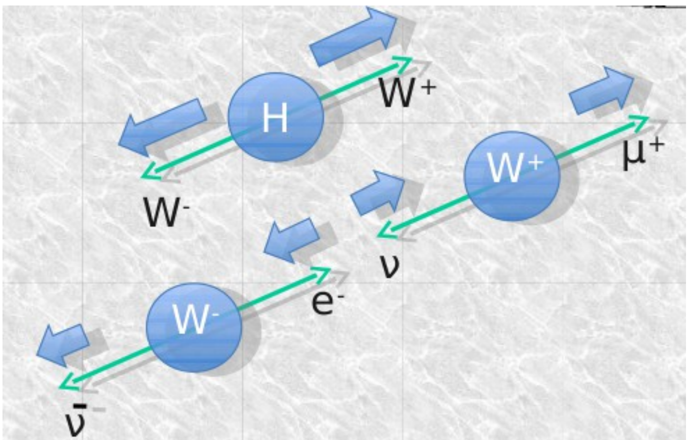


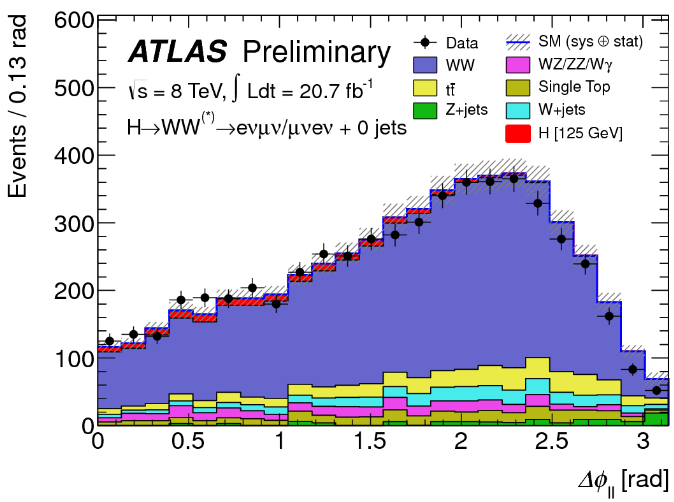


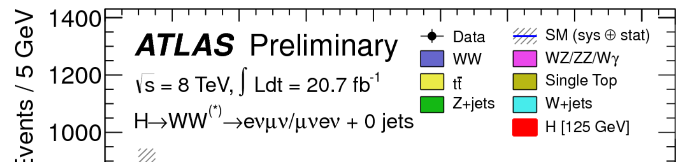


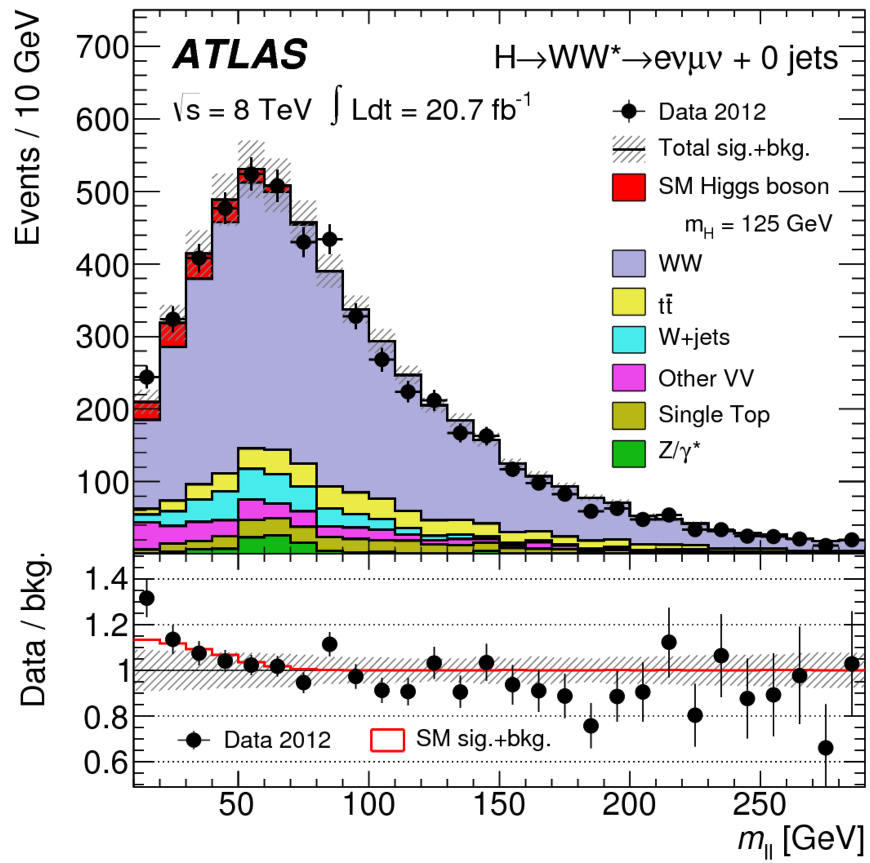
Further selection





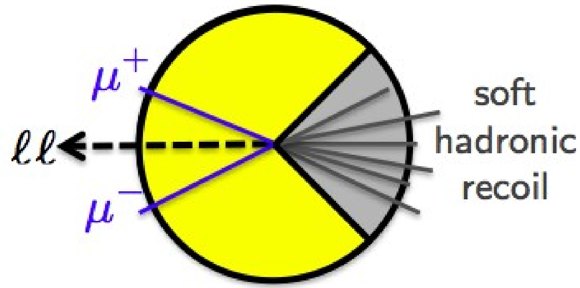


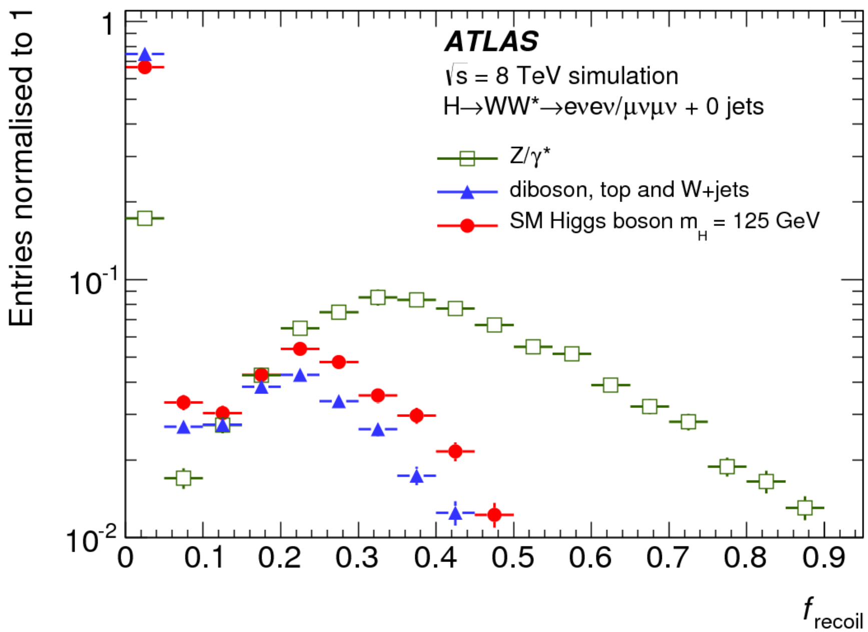




Further selection (II)

- 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



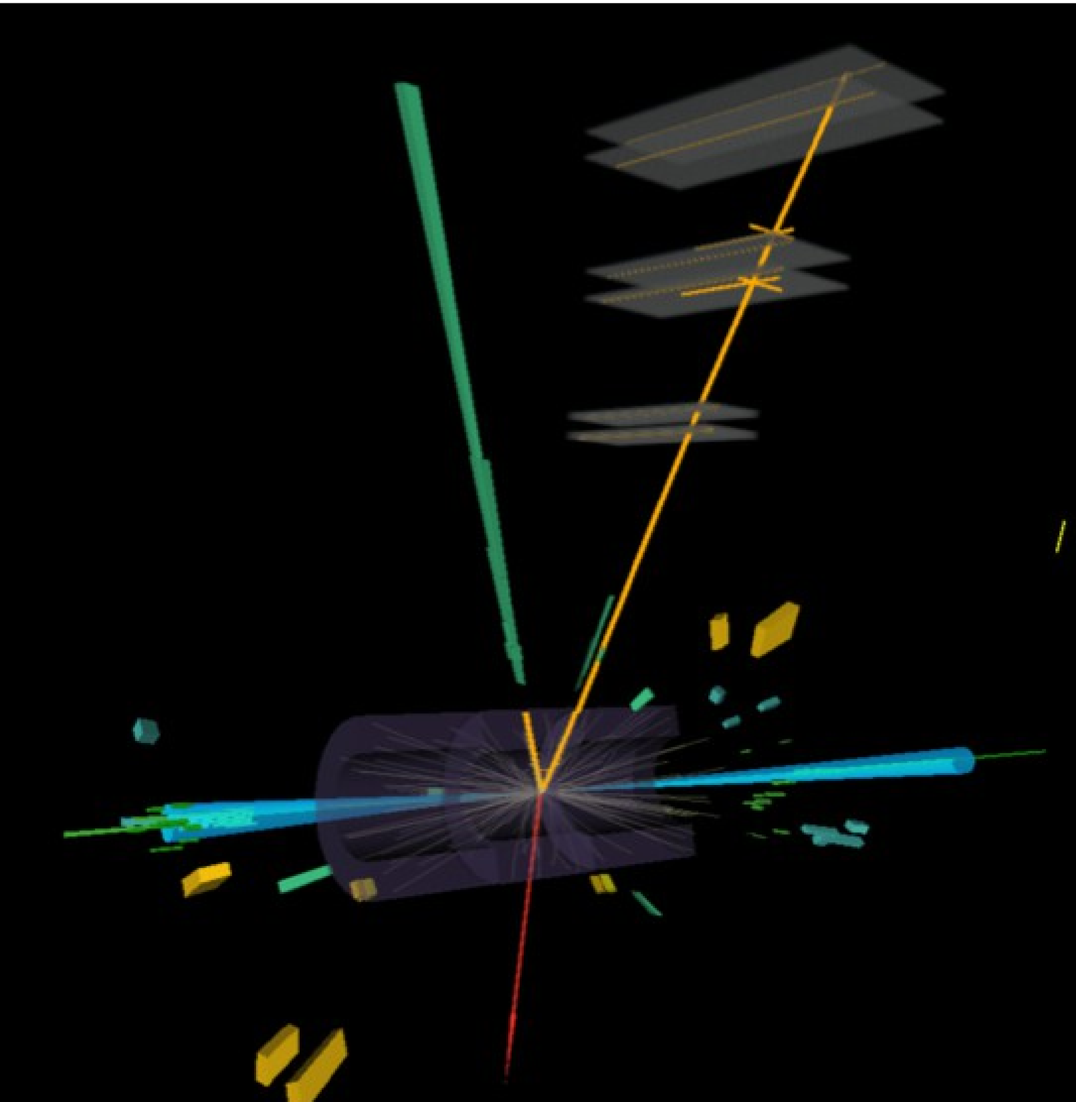


$$f_{recoil} = \frac{\left|\sum |JVF| \times \vec{p_T}\right|}{p_T^{\ell\ell}}$$

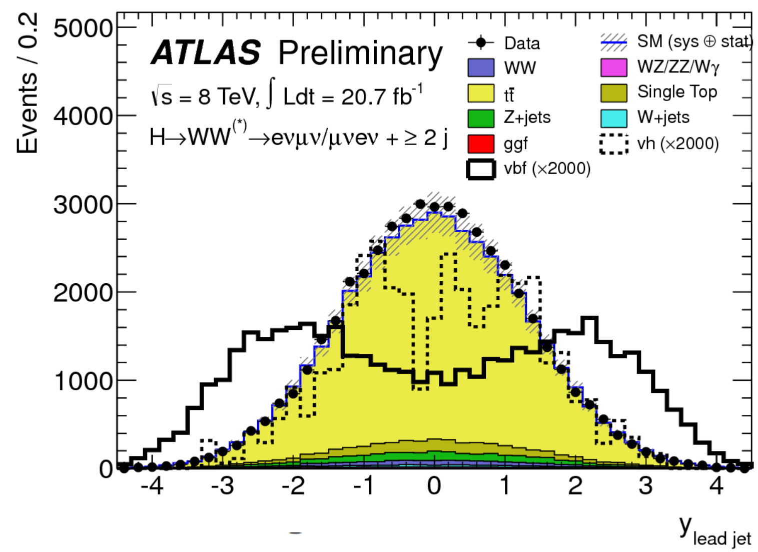
- Require

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

2-jet analysis



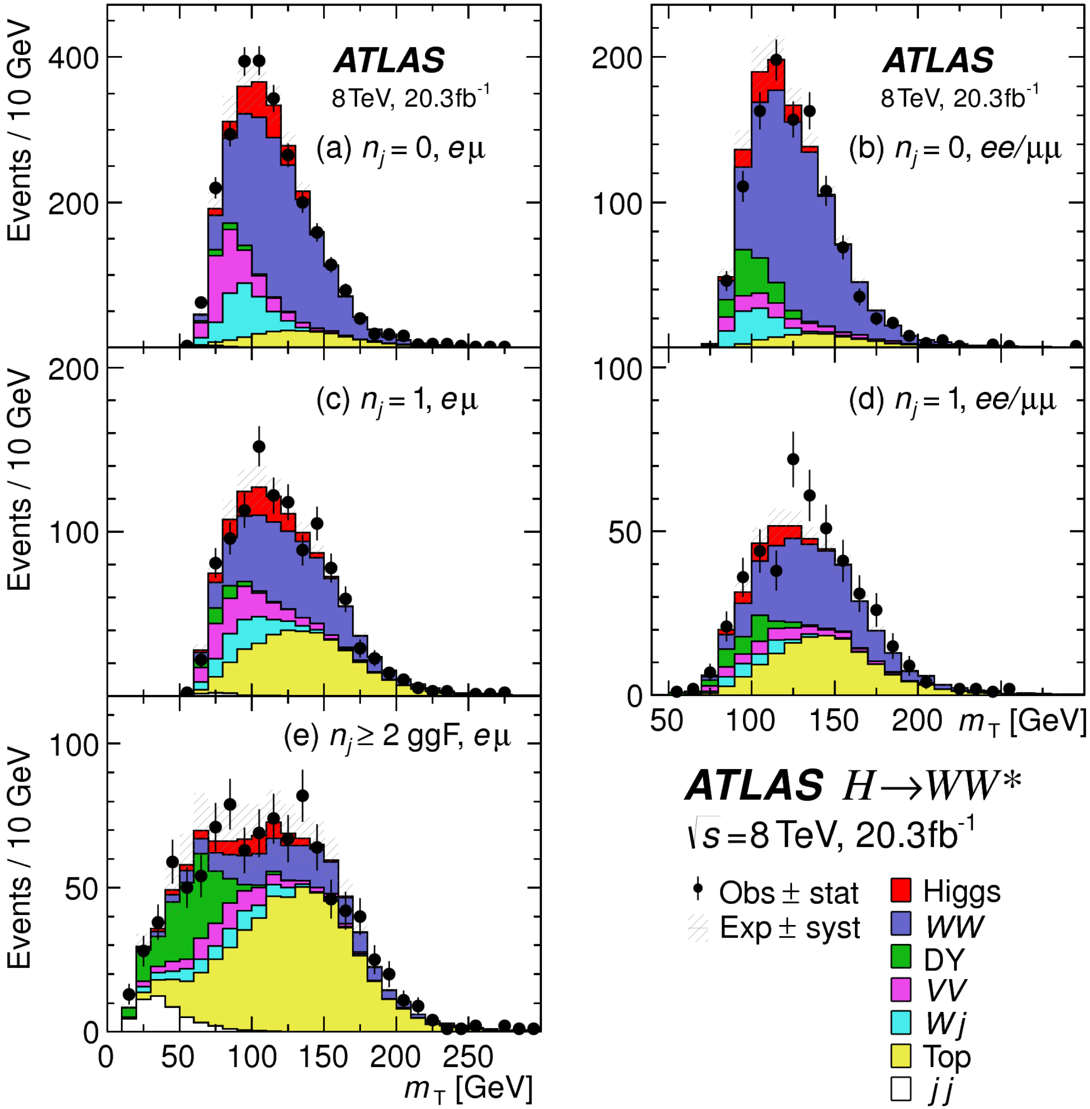
- Dominated by VBF
- Large rapidity gap between jets



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

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

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!

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

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 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

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

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

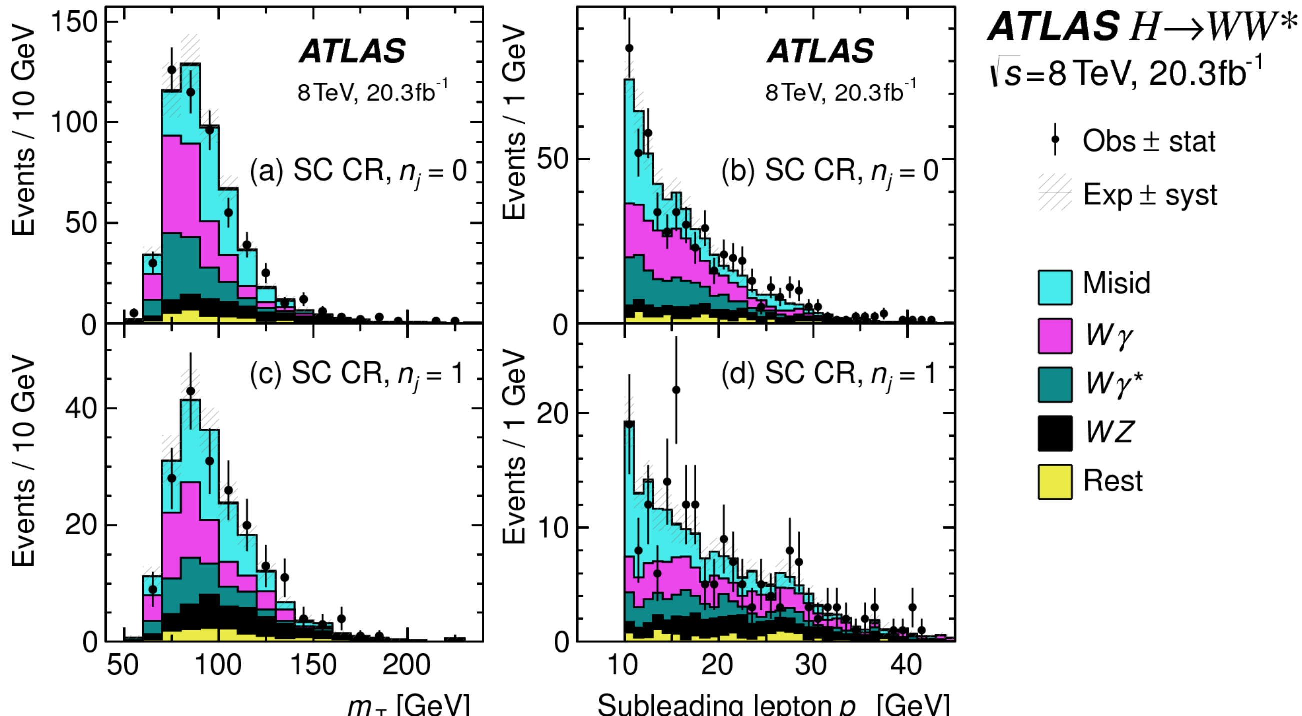
Diboson background composition and modelling from MC

Uncertainty dominated by jet scale (jet bin classification)

- Same flavour: use MC for normalization

  Validated with the same sign region

Same sign control region



Top quark background estimation

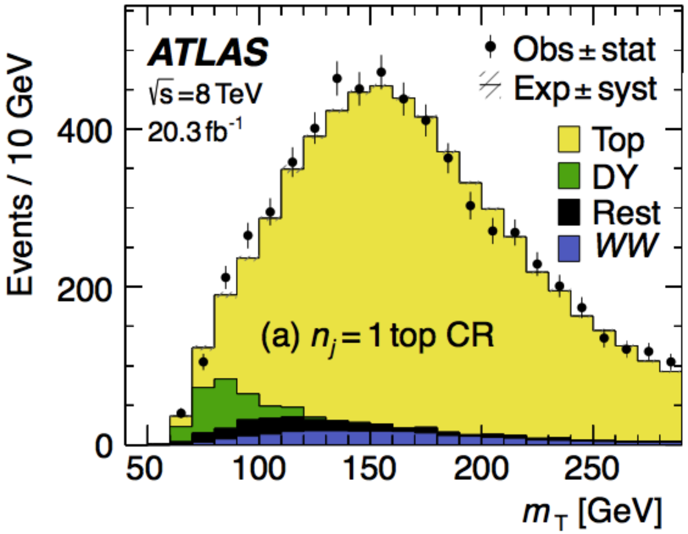
Top:

- 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

Top control region



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

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

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

- 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

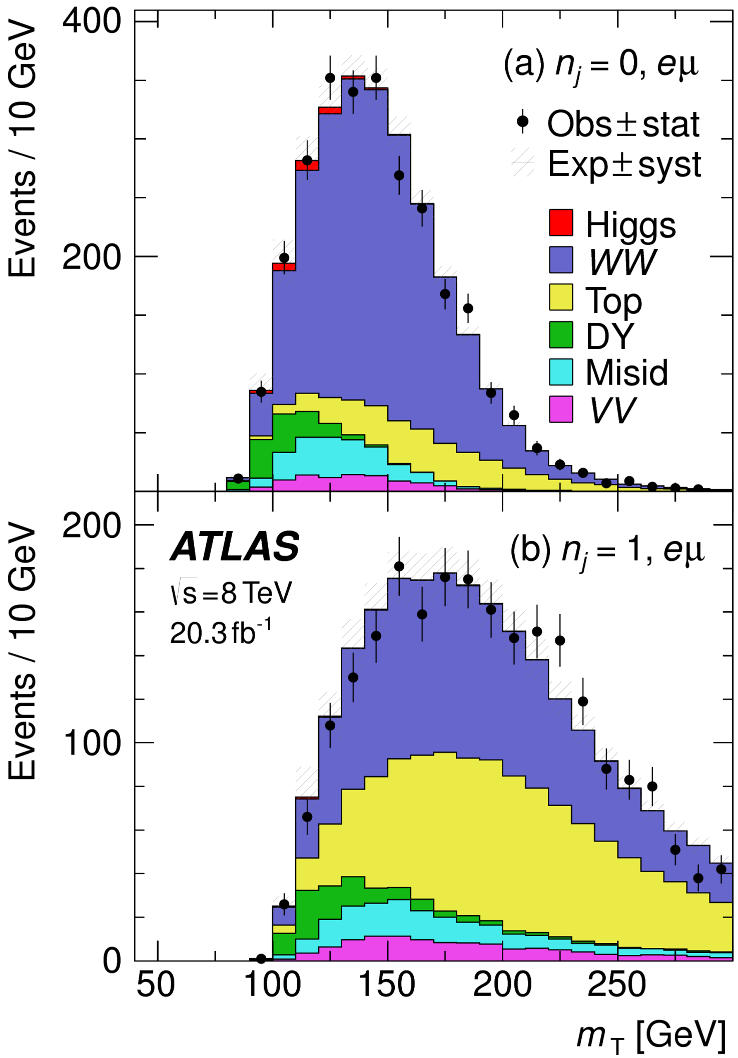
WW:

- 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, ...)

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

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



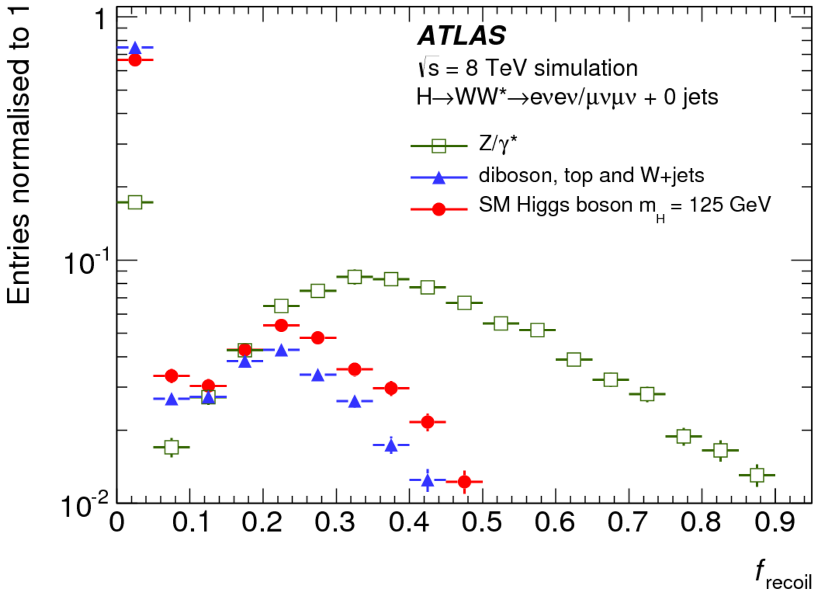
Z/γ* background

- 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 $N_{\rm sig}$ (in %)

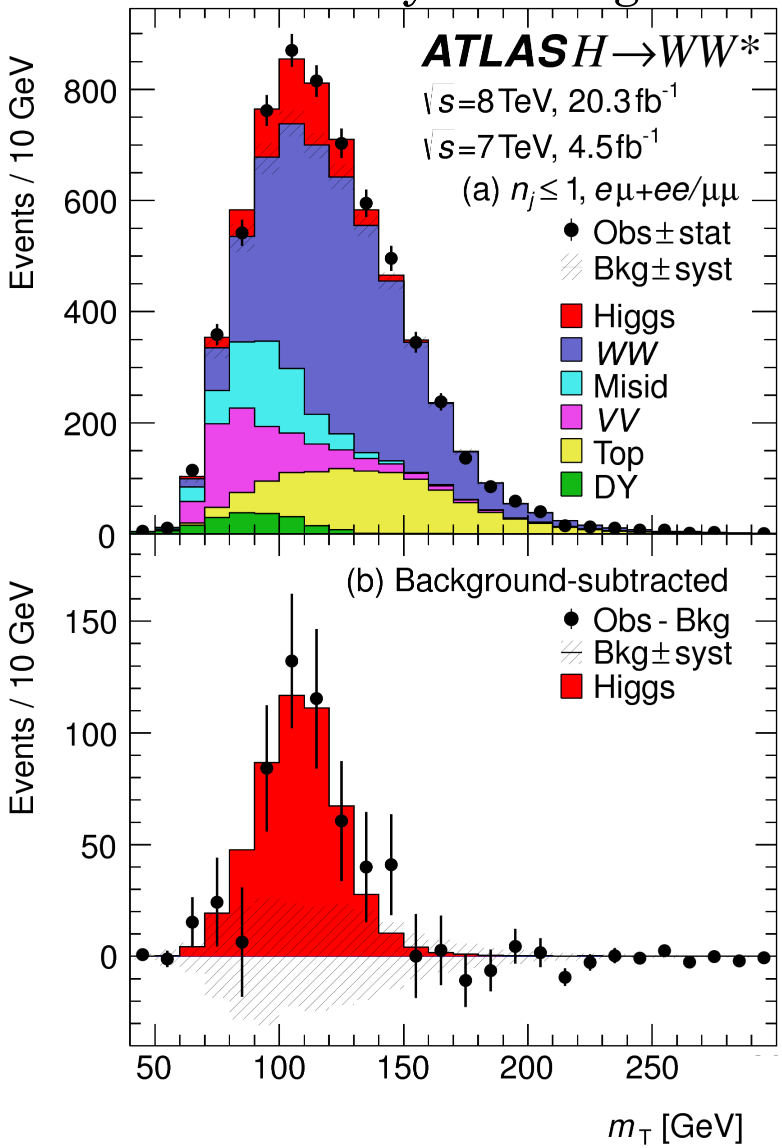
	$n_j=0$	$n_j=1$	$n_j \geq 2$ ggF	$n_j \geq 2$ VBF
ggF H, jet veto for $n_j=0$, ϵ_0	8.1	14	12	-
ggF H, jet veto for $n_j=1$, ϵ_1	-	12	15	-
ggF H, $n_j \geq 2$ cross section	-	-	-	6.9
ggF H, $n_j \geq 3$ cross section	-	-	-	3.1
ggF H, total cross section	10	9.1	7.9	2.0
ggF H acceptance model	4.8	4.5	4.2	4.0
VBF H, total cross section	-	0.4	0.8	2.9
VBF H acceptance model	-	0.3	0.6	5.5
$H \rightarrow WW^*$ 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
$p_{\rm T}^{\rm miss}$ scale & resolution	0.6	1.4	0.1	1.2
$f_{\rm recoil}$ 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 $N_{\rm bkg}$ (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
$Z/\gamma^* \rightarrow \tau\tau$ estimate	0.6	0.3	1.6	1.6
$Z/\gamma^* \rightarrow ee$, $\mu\mu$ 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
$p_{\rm T}^{\rm miss}$ 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
$f_{\rm recoil}$ 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



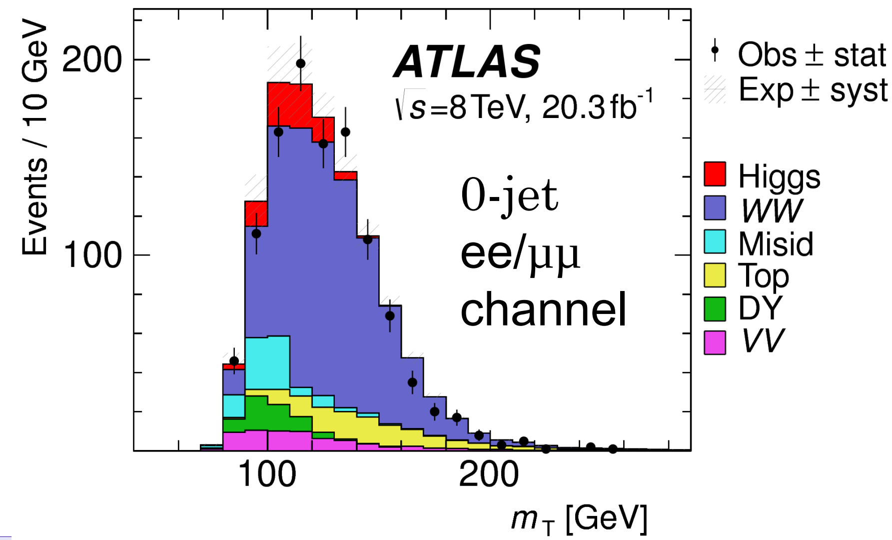
- Fit the transverse mass

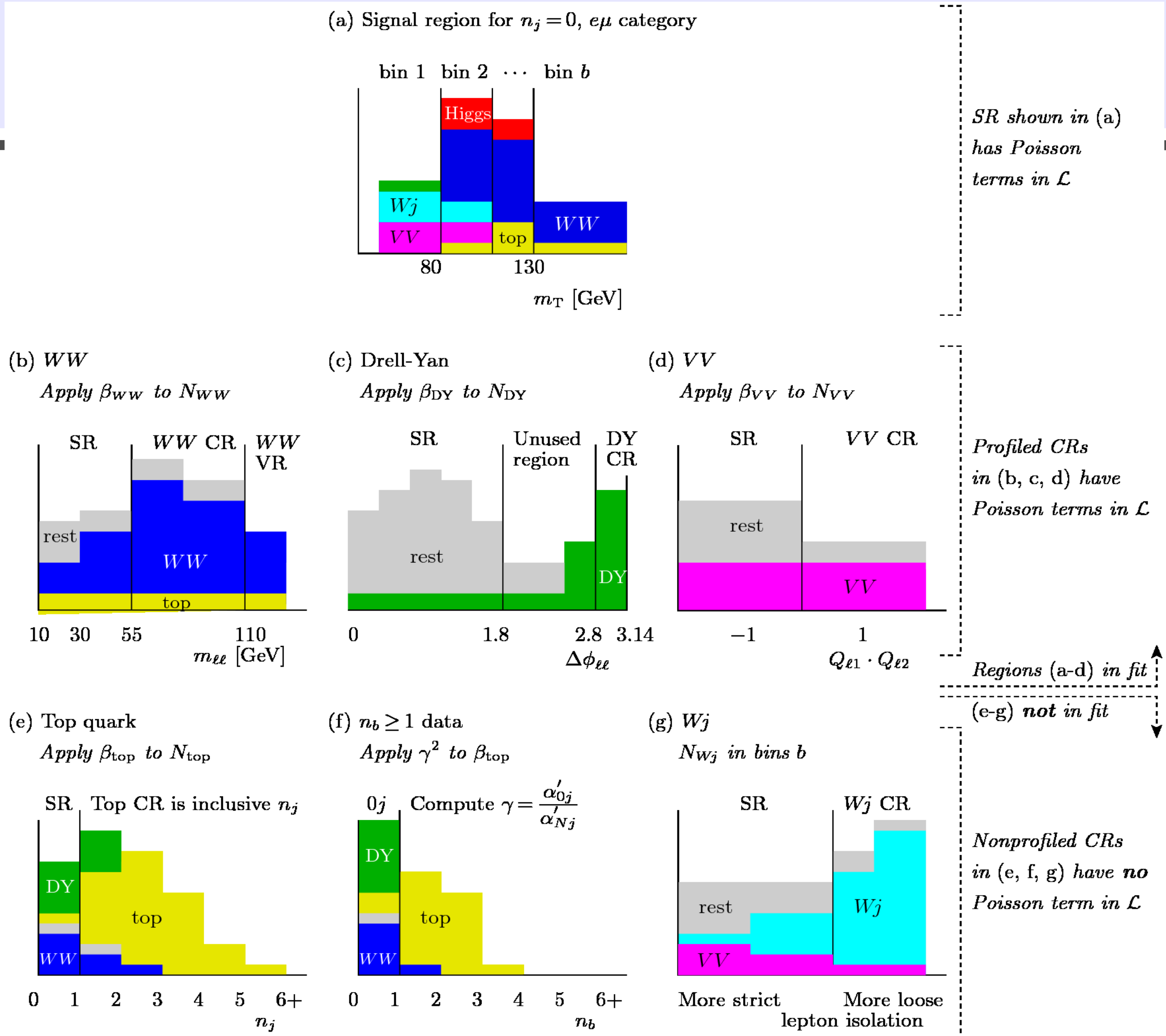
$$m_T = \sqrt{(E_T^{\ell\ell} + |\vec{p}_T^{miss}|)^2 - (\vec{p}_T^{\ell\ell} + \vec{p}_T^{miss})^2}$$

- 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

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

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

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

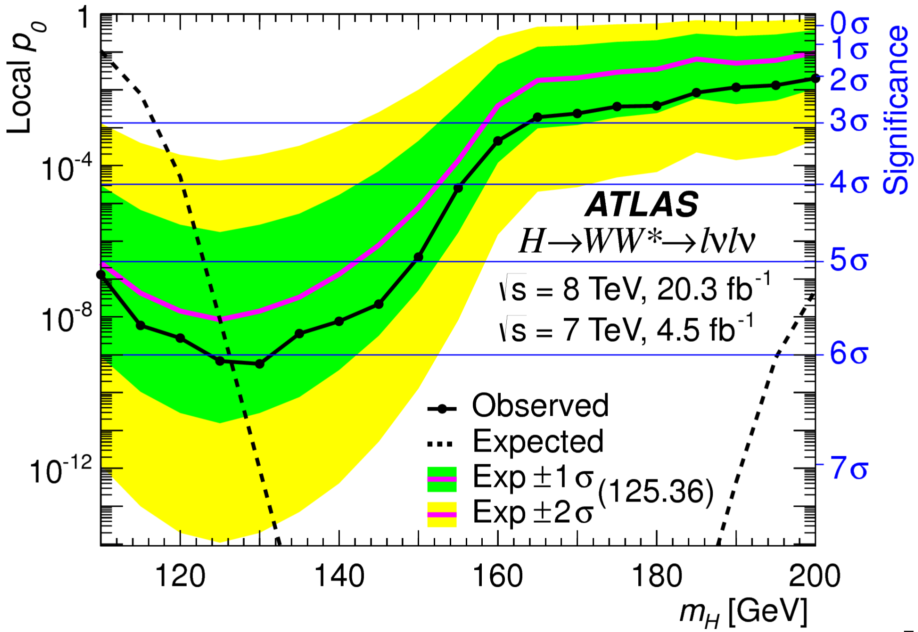
$$\lambda=\mu\cdot S+\Sigma_k B_k$$

- 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}

Run 1 H→WW results

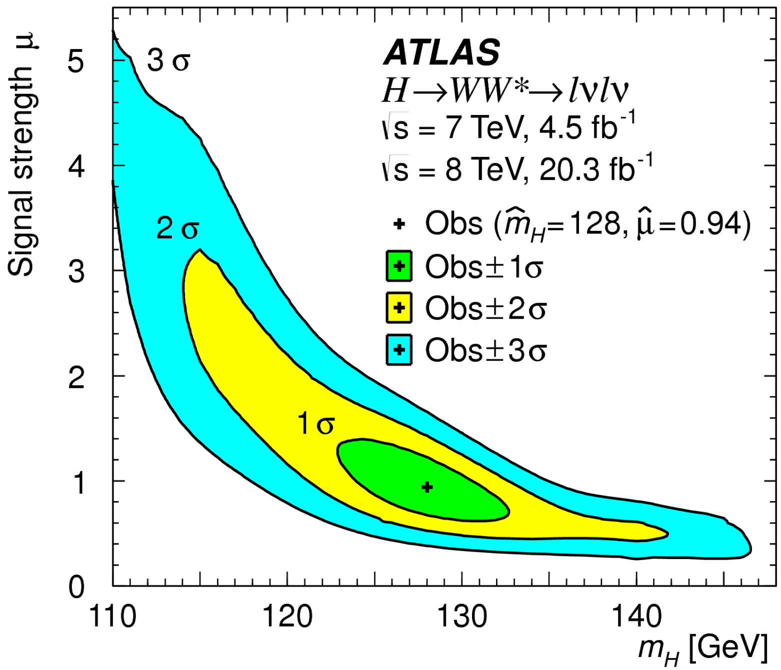


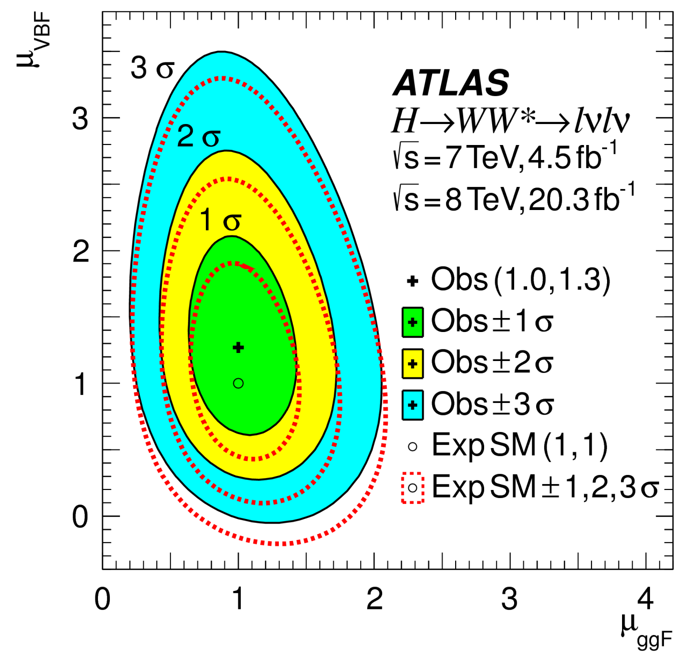
- p_0 = probability that the observed excess of events is due to a background fluctuation
- Minimum p_0 at 130 GeV (6.1σ)
- Same p_0 at 125.36 GeV

  Expected 5.8σ
- Signal strength at 125.36 GeV:

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

Run 1 signal strength

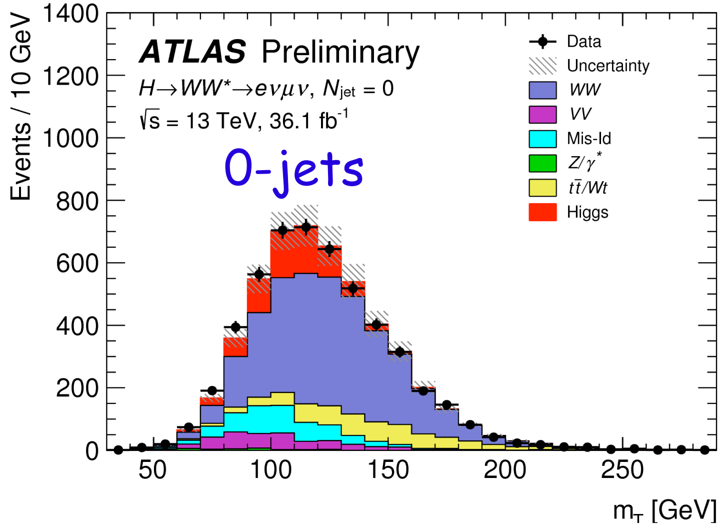


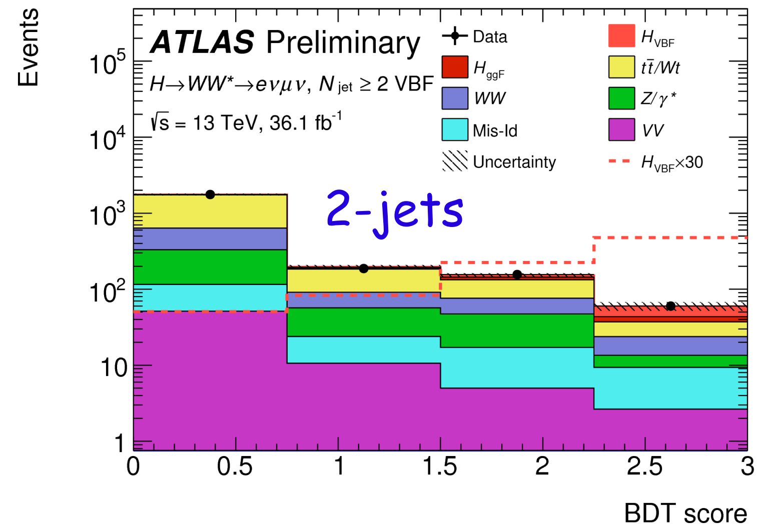


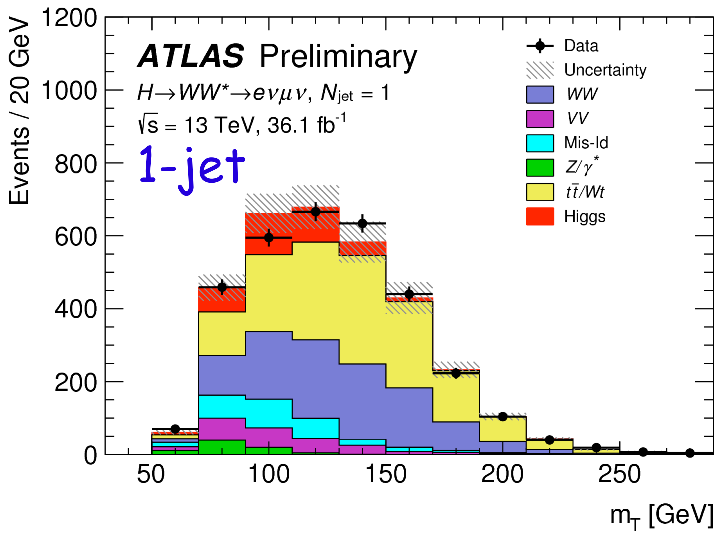
- Signal strength compatible with SM expectations

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

Run 2 H→WW→lνlν Results







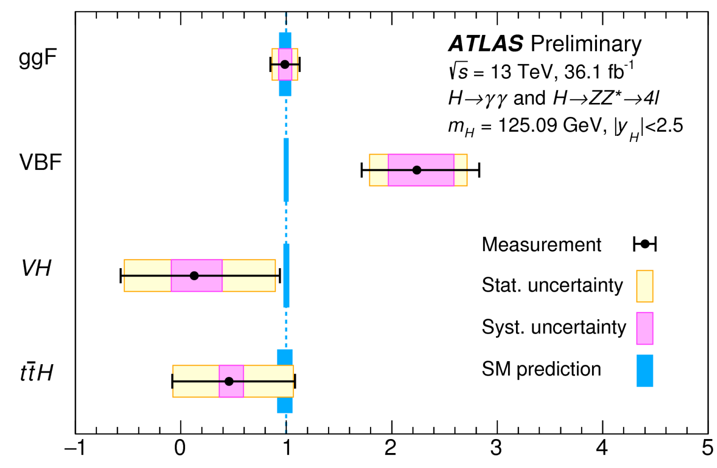
- Signal strength for different production modes
  - Precision getting better than Run 1 ATLAS+CMS combination!

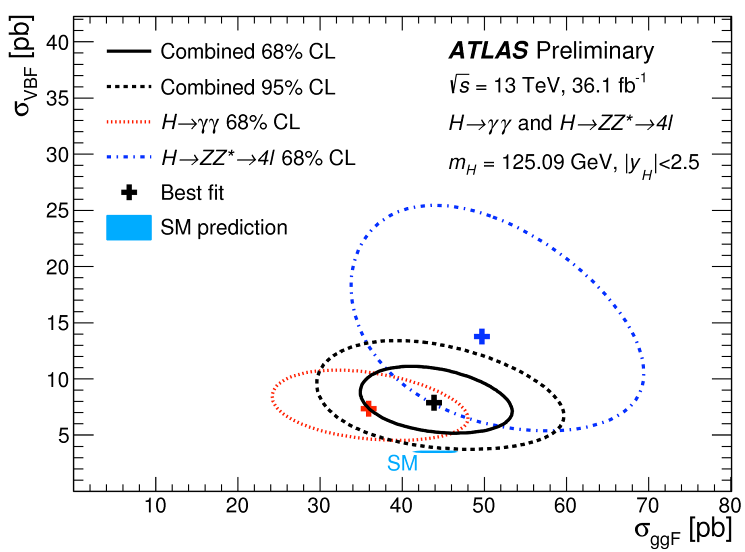
$$\mu_{ggF} = 1.21^{+0.12}_{-0.11}(\text{stat.})^{+0.18}_{-0.17}(\text{sys.}) = 1.21^{+0.22}_{-0.21}$$

$$\mu_{VBF} = 0.62^{+0.30}_{-0.28}(\text{stat.}) \pm 0.22(\text{sys.}) = 0.62^{+0.37}_{-0.36}$$

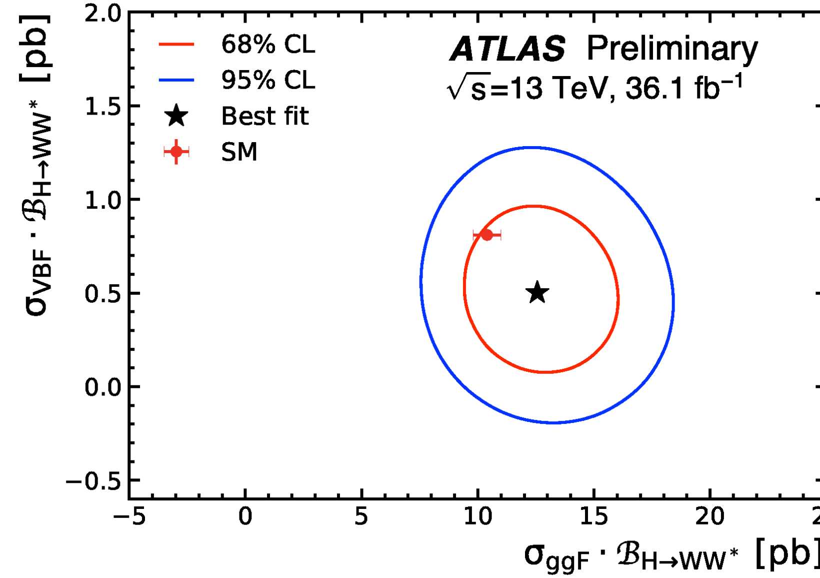
Run 2 VBF vs ggF in di-boson channels

- $H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$

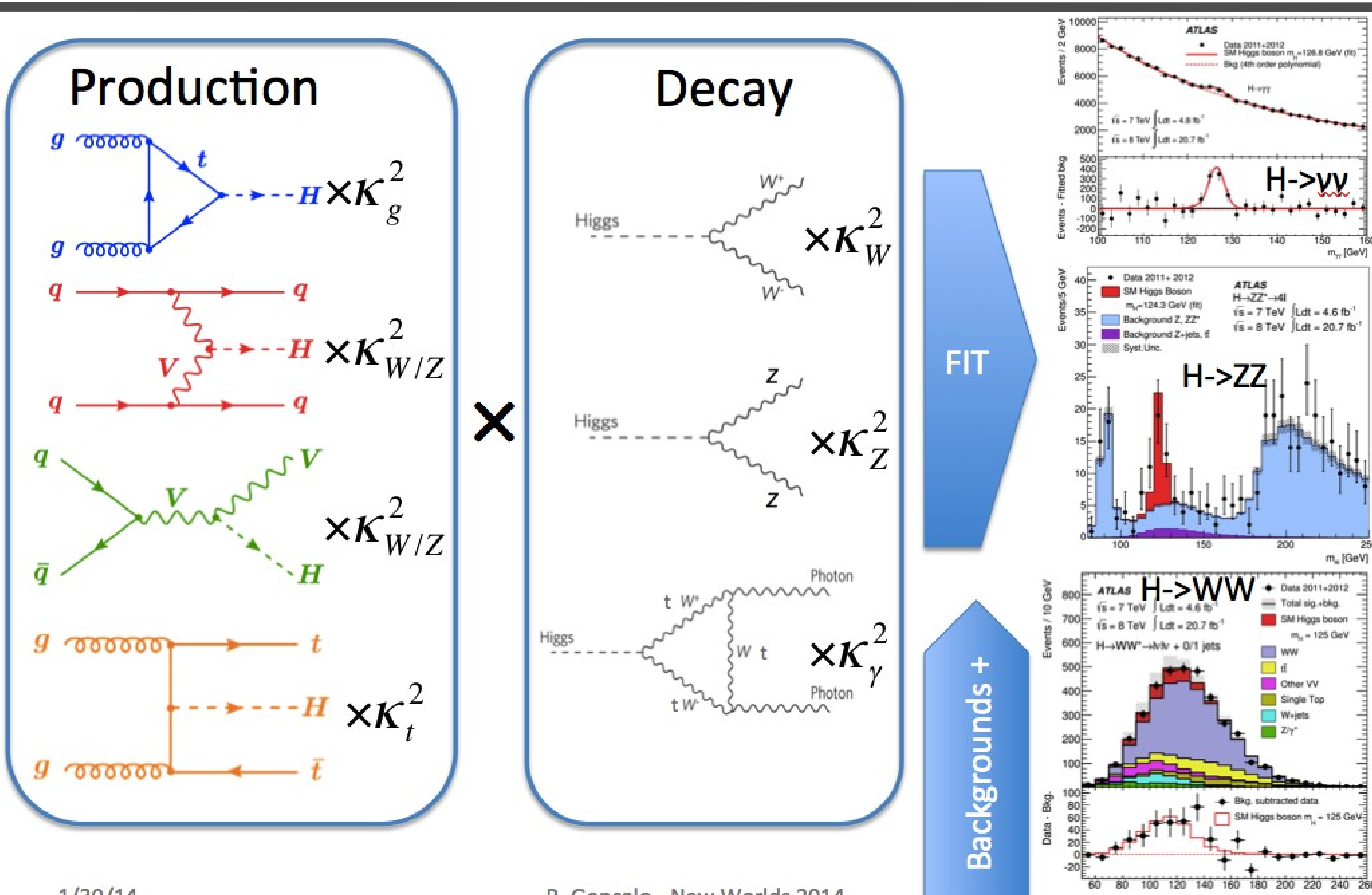




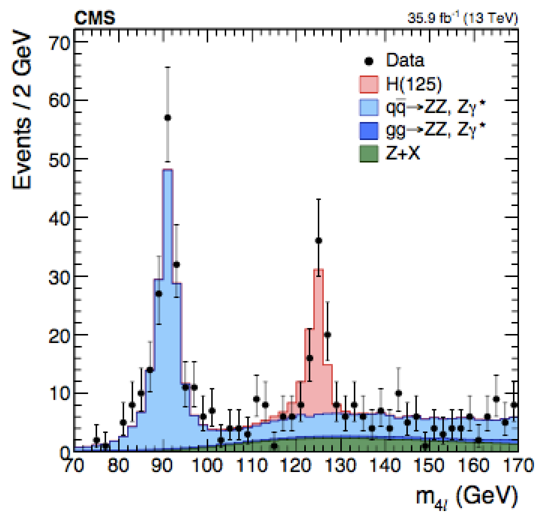
- $H \rightarrow WW \rightarrow l\nu l\nu$

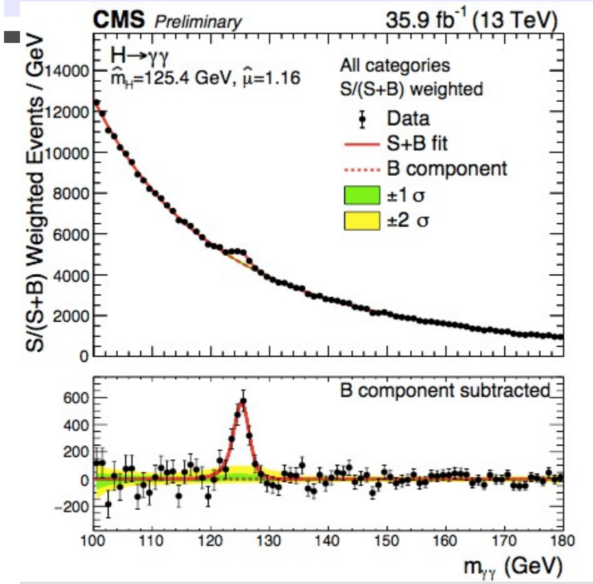


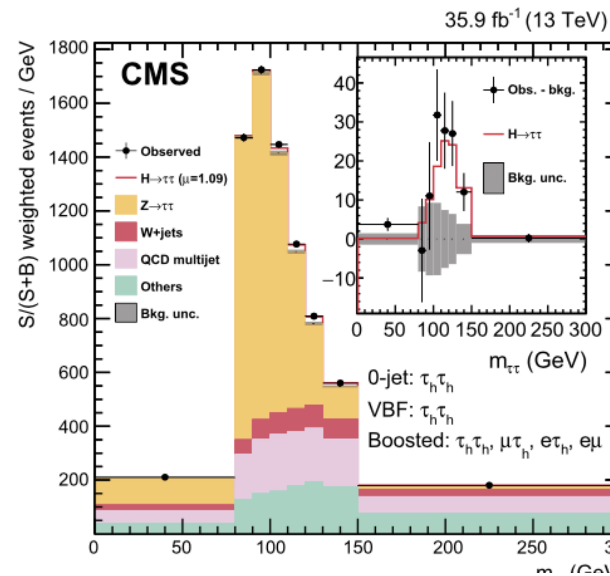
Couplings combination

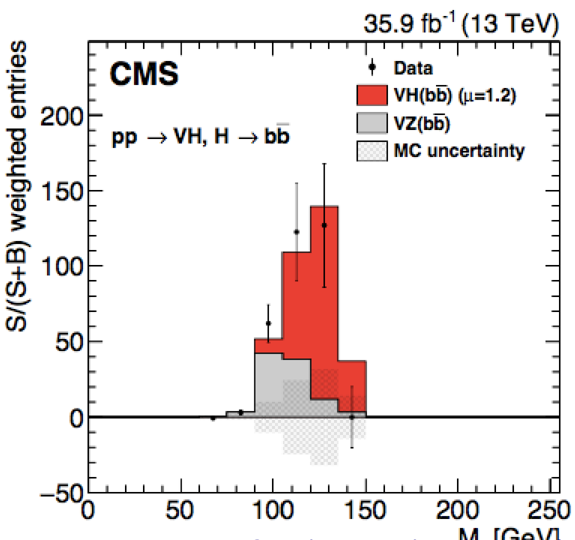


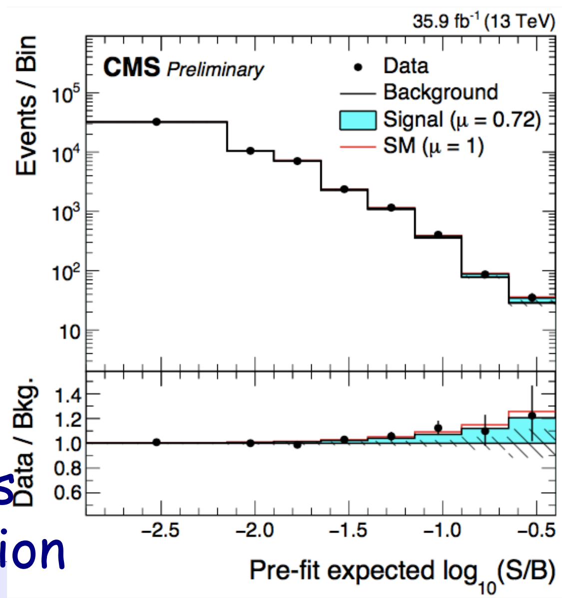
CMS combination @ 13 TeV

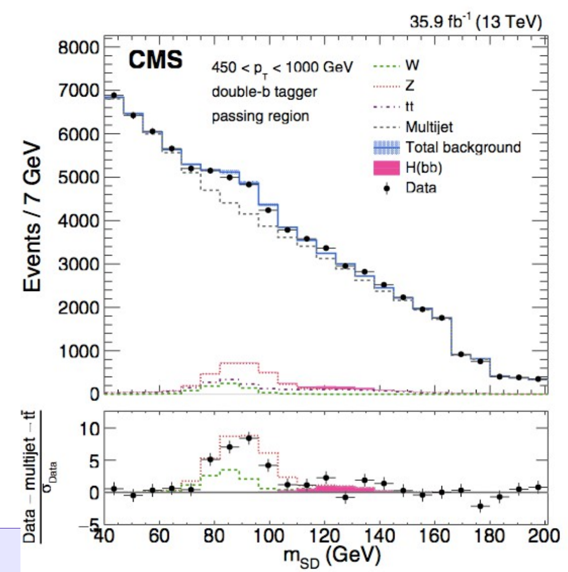








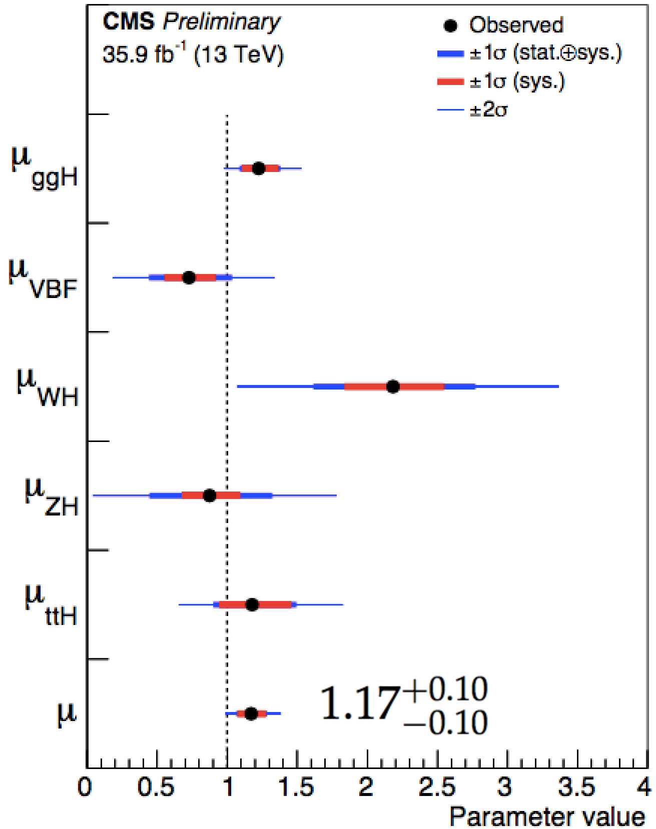




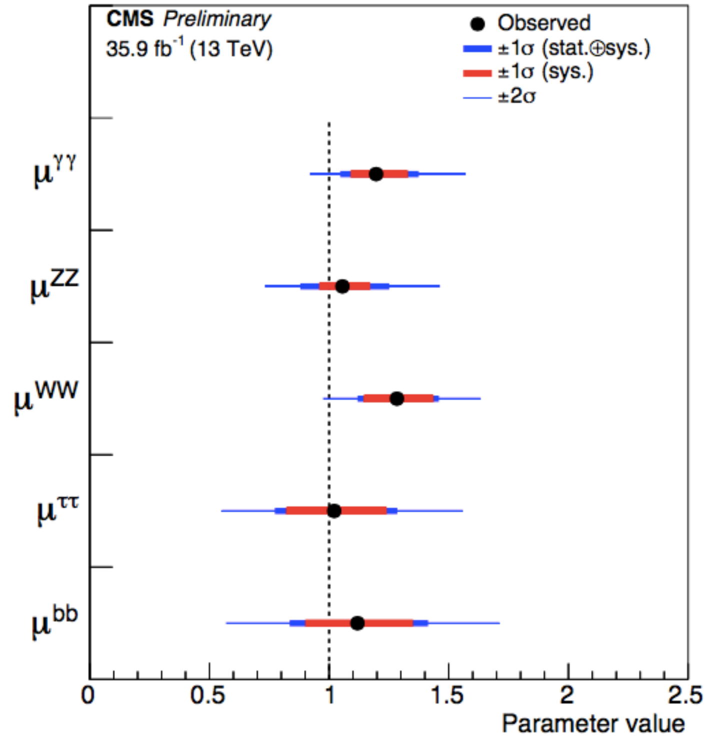
Some of the channels used in the combination

CMS combination results

- Production rates with respect to SM



- Decay rates with respect to SM

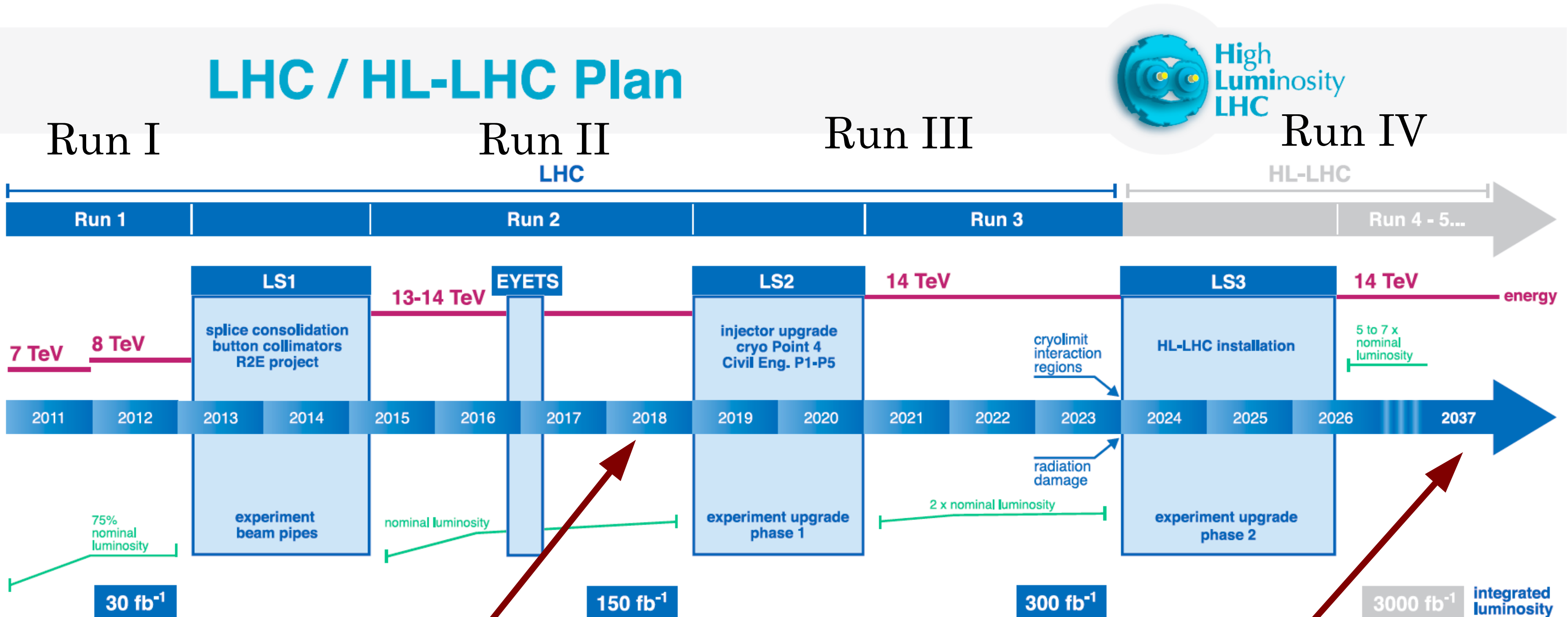


Invisible decay BR < 22% @ 95% CL

What next?

Futuro do LHC e de ATLAS

Run I Run II Run III Run IV

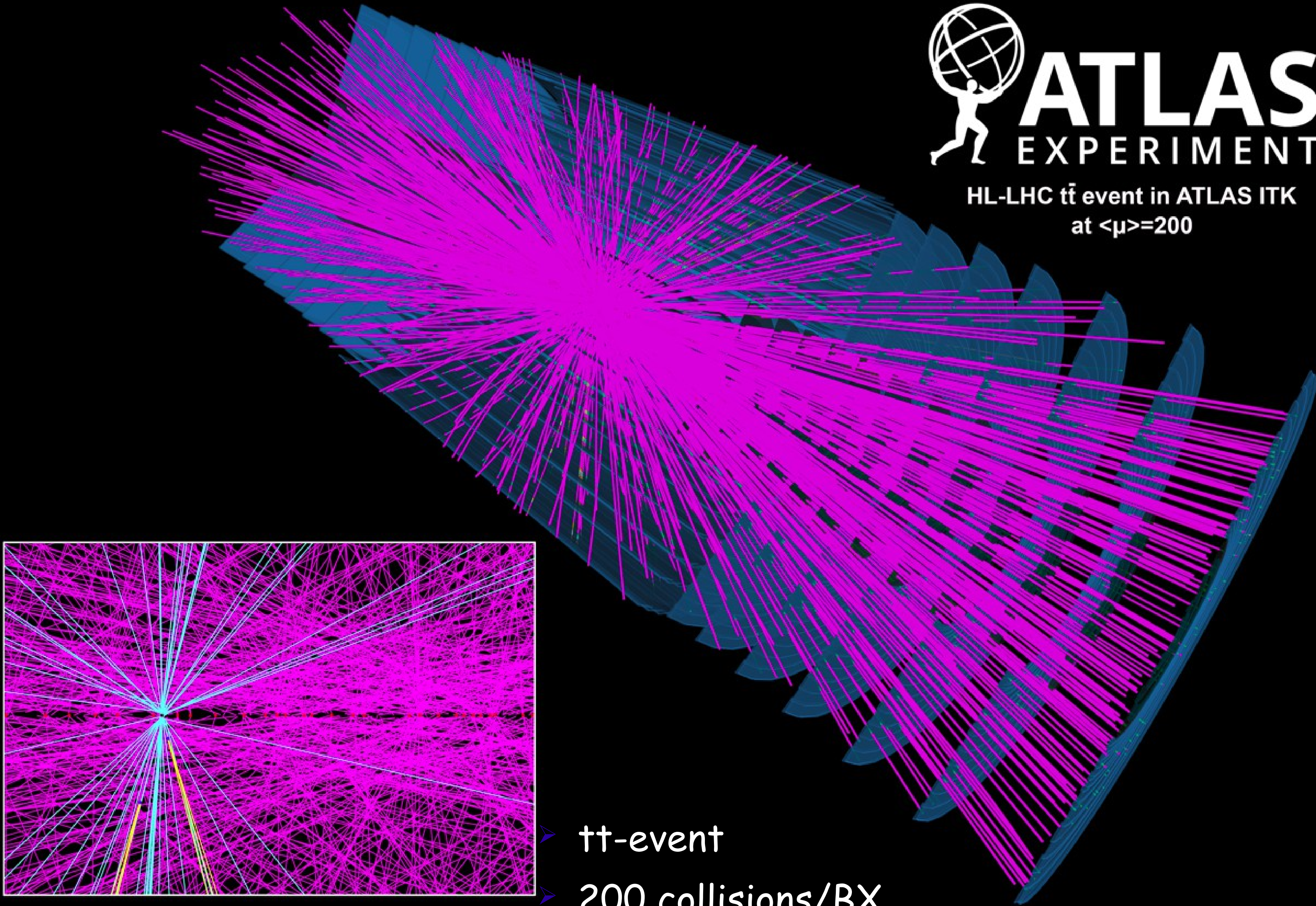


$L = 10^{34}\ cm^{-2}s^{-1}$ $L = 2\times10^{34}\ cm^{-2}s^{-1}$ $L = 5\times10^{34}\ cm^{-2}s^{-1}$

$\mu = 27$ $\mu = 55$ $\mu = 140$

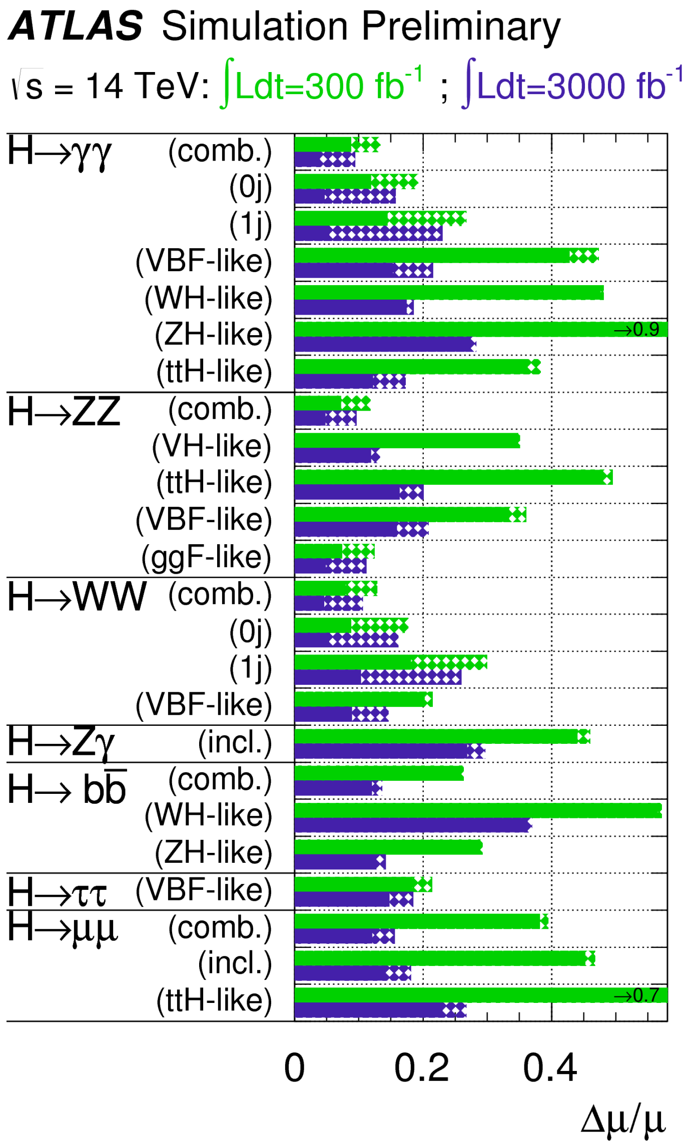
Aqui estamos

2037!!!



- tt-event
- 200 collisions/BX

Future perspectives



- Future LHC and detector upgrades will allow to improve significantly the precision of the Higgs boson signal strengths
  - Uncertainty below 10% for most of the channels!
- Continue to probe the SM predictions
- Or discover new physics!!

	$\delta\kappa_V$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet	<6%	<6%	<6%
2HDM (large t_β)	~1%	~10%	~1%
MSSM	~.001%	~1.6%	~-.4%
Composite	~-3%	~-(3-9)%	~-9%
Top Partner	~-2%	~-2%	~1%

Rare Higgs boson decays

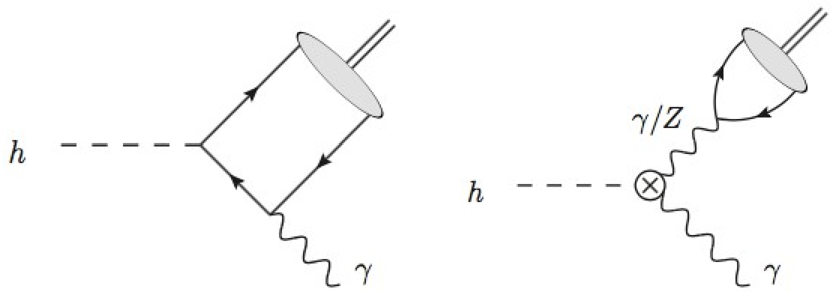
Higgs decays to mesons + γ

- $H \to J/\Psi\,\gamma$: sensitive to Hcc coupling
- $H \to \phi\gamma$, $H \to \rho\gamma$: sensitive to couplings to light quarks
- $H \to \Upsilon\gamma$: sensitive to beyond SM signals in the Hbb coupling

- Very small branching ratios:

  ~10^{-5} to 10^{-10}

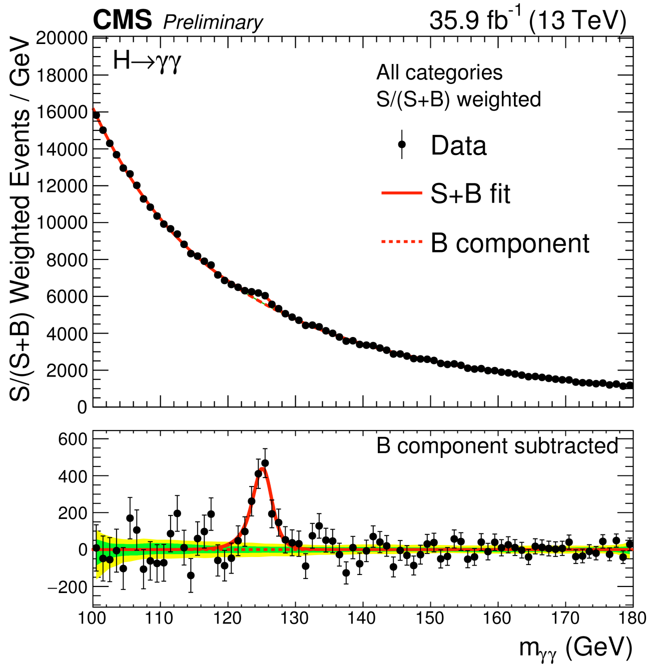
  need very high luminosity



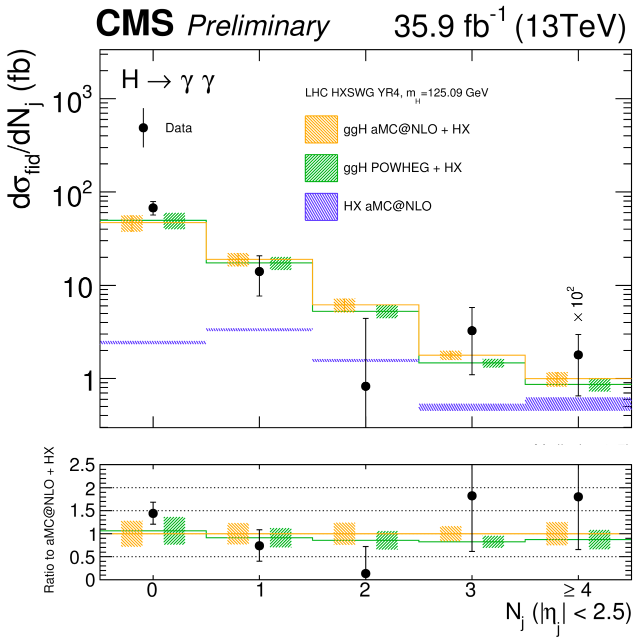
Process	σ/σ_{SM} (95% CL)
H→J/Ψγ (ATLAS) Run1	<540
H→J/Ψγ (CMS) Run1	<540
H→ργ (ATLAS) 36 fb-1 @ 13 TeV	<52
H→ϕγ (ATLAS) 36 fb-1 @ 13 TeV	<208

Run1 (yellow)
Run2: 36 fb^{-1} (red)

Backup

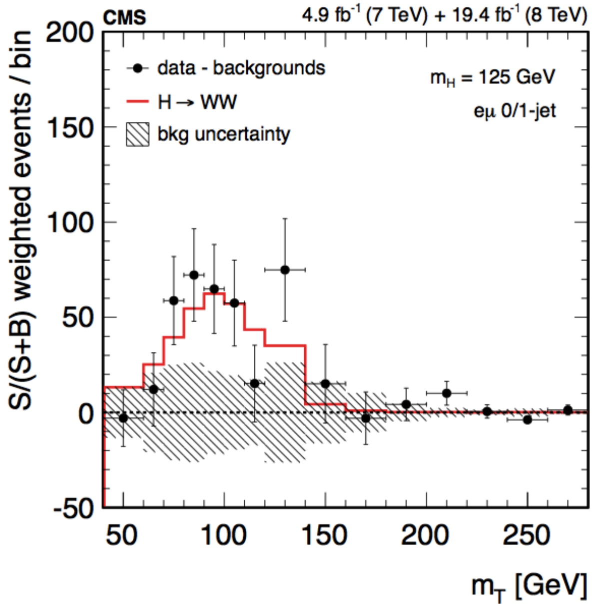


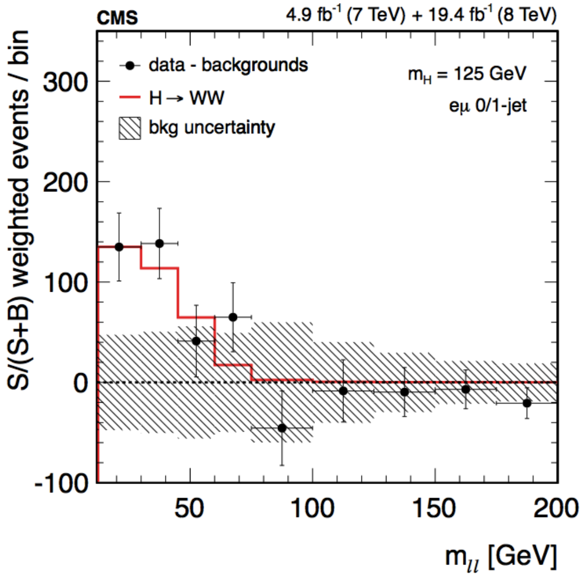
- Results compatible with expectations



CMS H→WW results

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

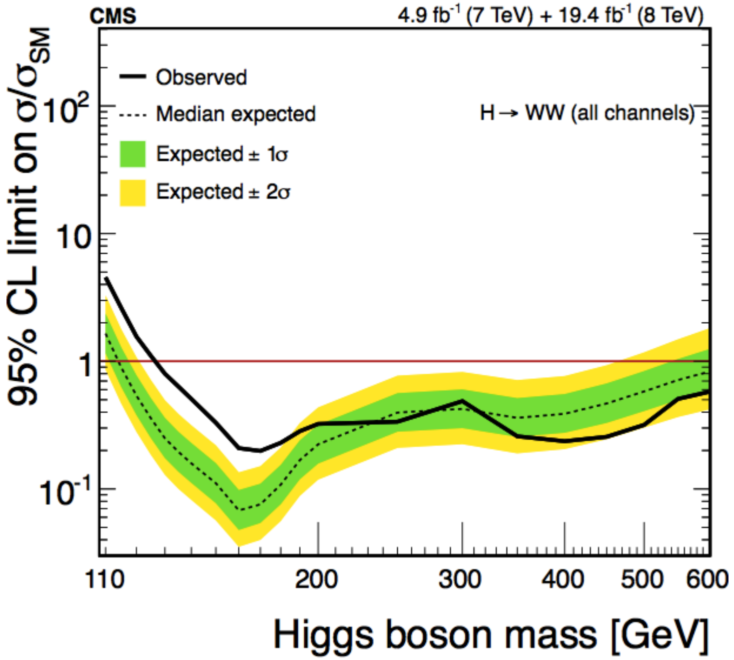


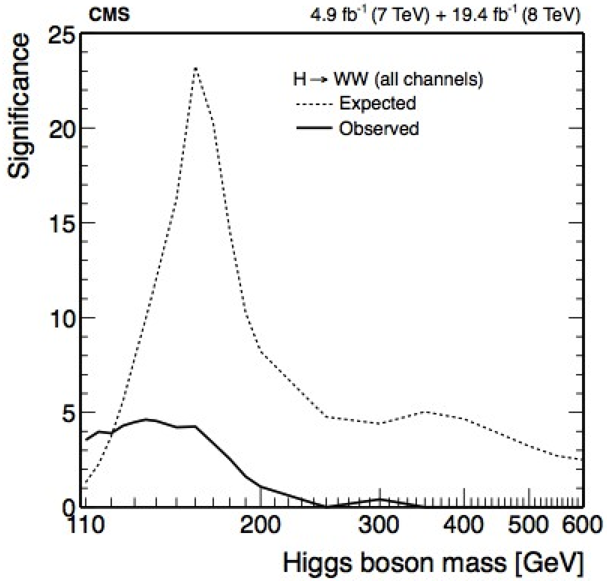


- In addition, they consider also a 3-lepton category (VH associated production)

CMS H→WW results

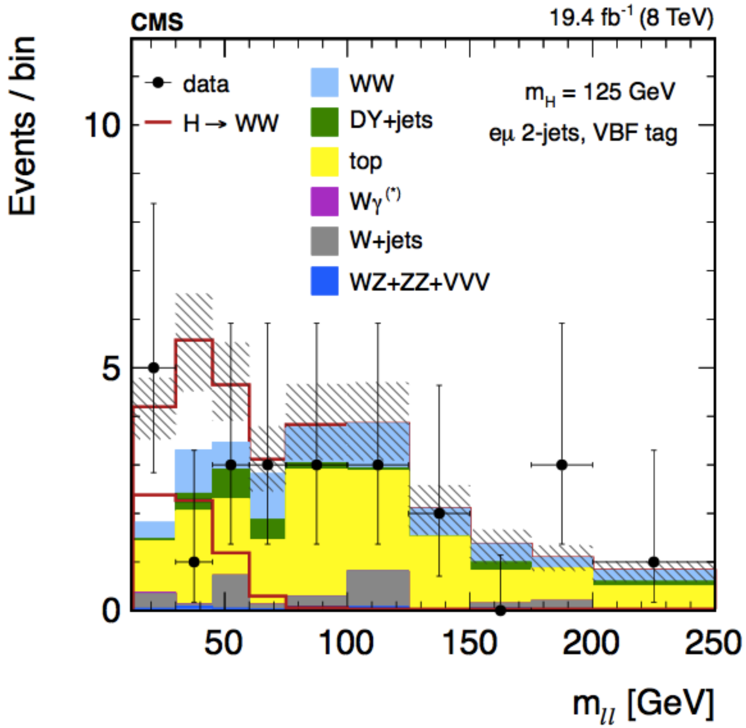
- Combined results

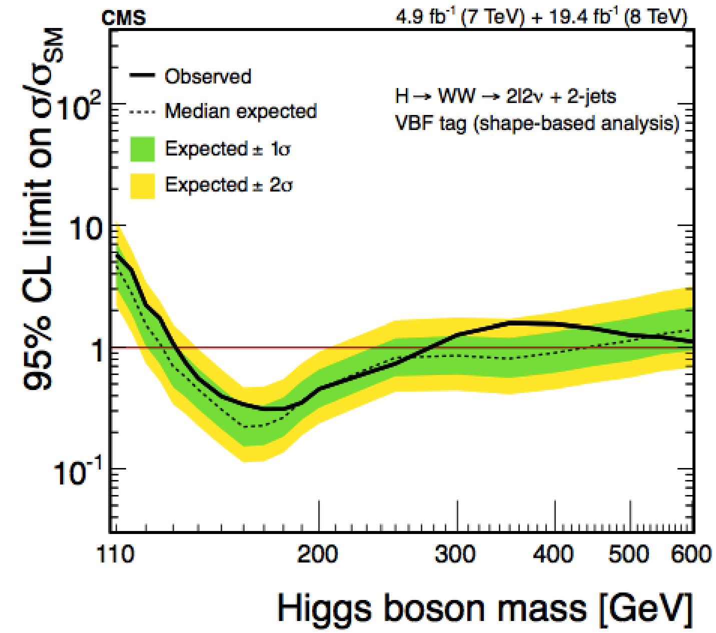




0/1-jet analysis $m_H = 125$ GeV	95% CL limits on σ/σ_{SM} expected / observed	Significance expected / observed	σ/σ_{SM} observed
$(m_T, m_{\ell\ell})$ template fit (default)	0.4 / 1.2	5.2 / 4.0 sd	0.76 ± 0.21
$(m_R, \Delta\phi_R)$ parametric fit	0.5 / 1.4	5.0 / 4.0 sd	0.88 ± 0.25
Counting analysis	0.7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

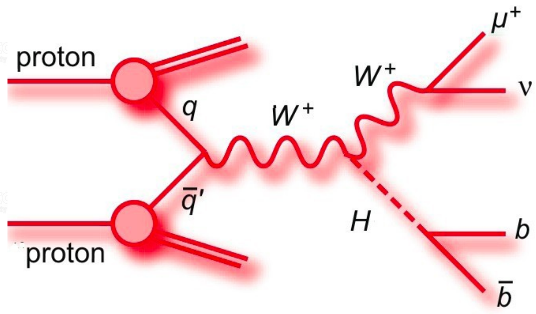
CMS H→WW VBF results

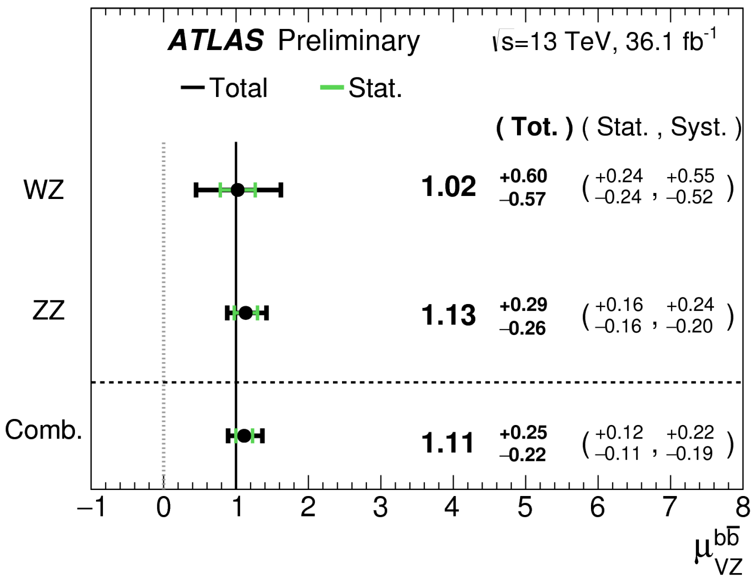


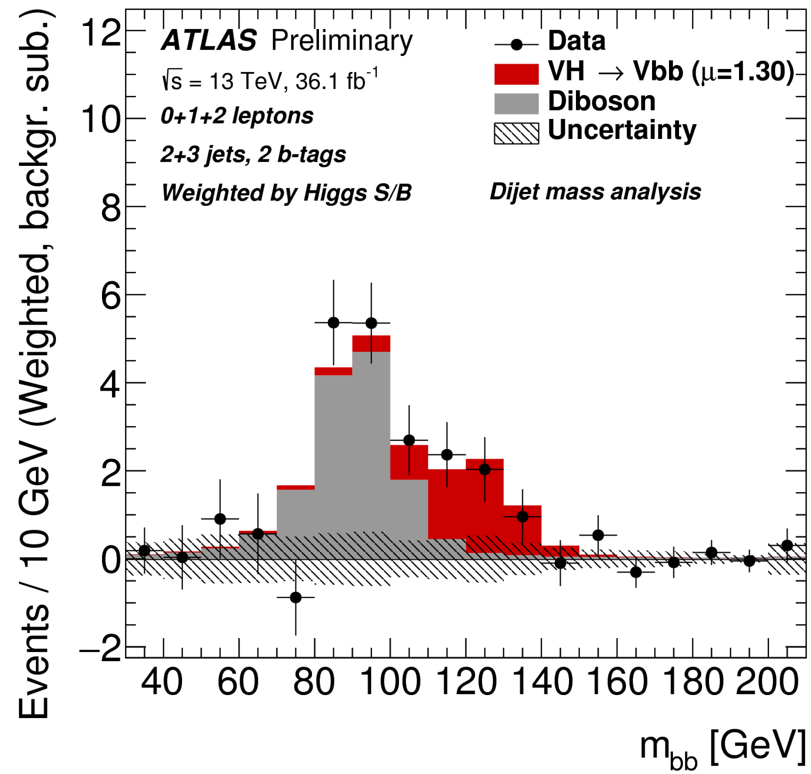


VBF analysis $m_H = 125\,\text{GeV}$	95% CL limits on σ/σ_{SM} expected / observed	Significance expected / observed	σ/σ_{SM} observed
Shape-based (default)	1.1 / 1.7	2.1 / 1.3 sd	$0.62^{+0.58}_{-0.47}$
Counting analysis	1.1 / 0.9	2.0 / —	$-0.35^{+0.43}_{-0.45}$

Evidence of Higgs decaying to b-quarks



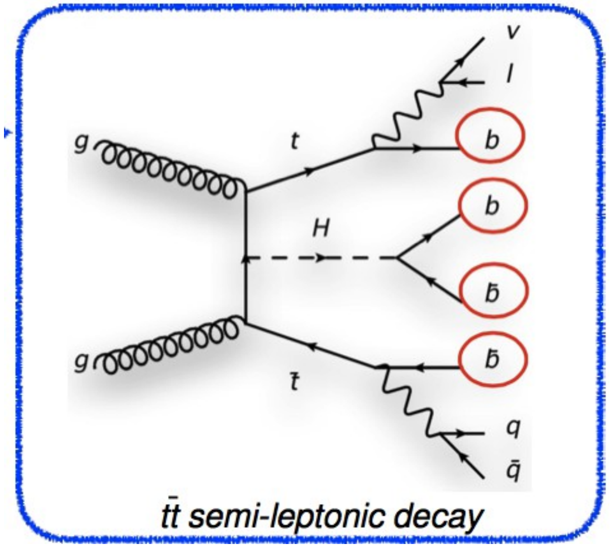




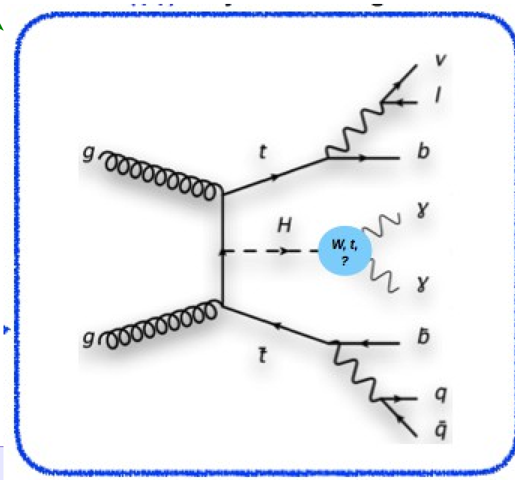
Search for Higgs boson in ttH production

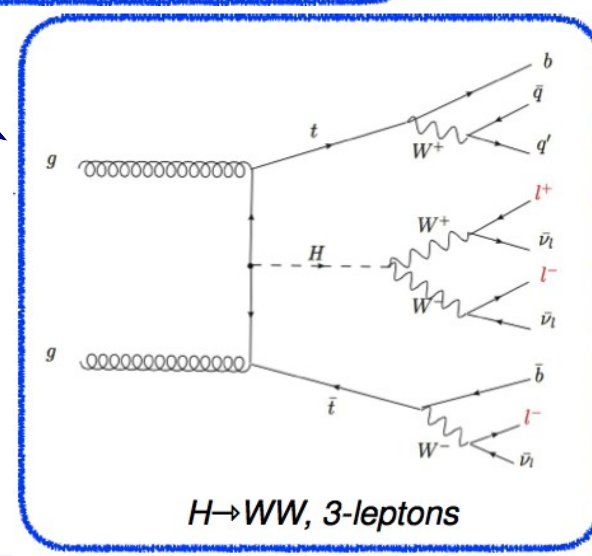
- Many possible final states

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

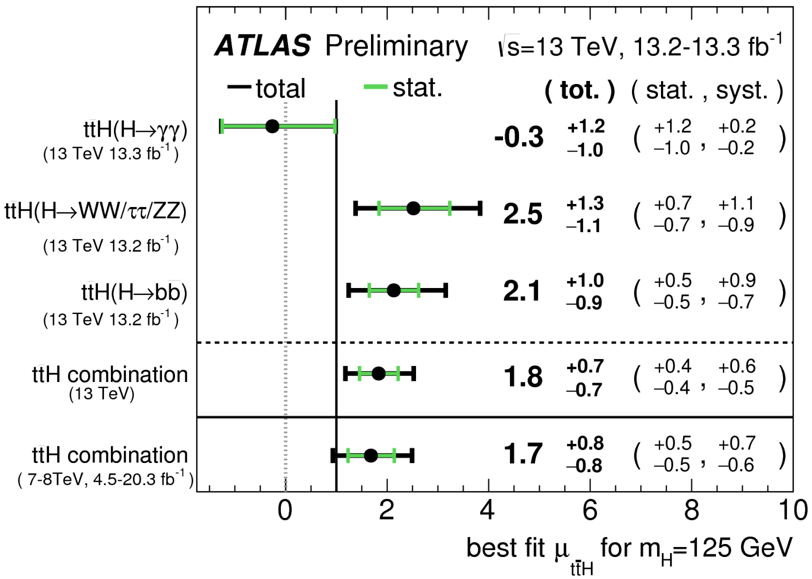


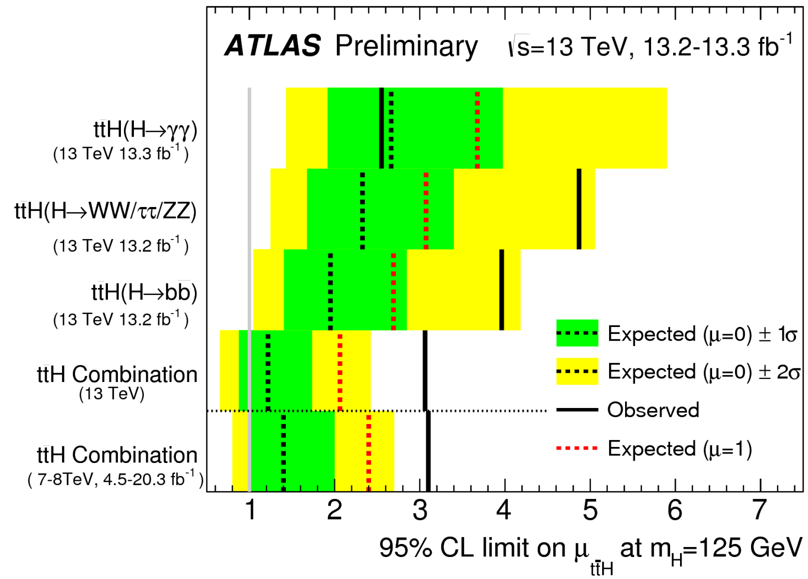


H→WW, 3-leptons

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