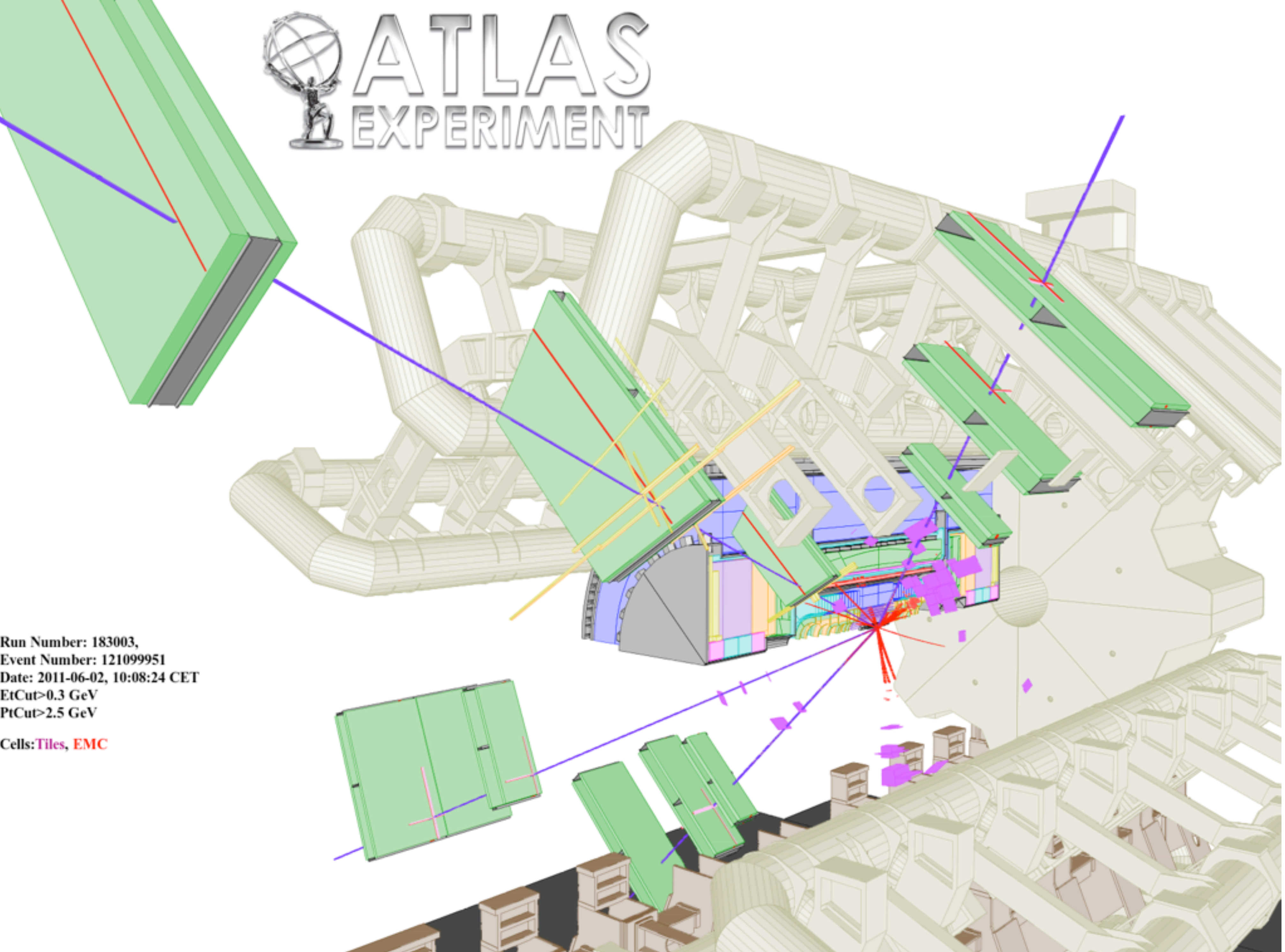


PP7 - Higgs Boson Physics

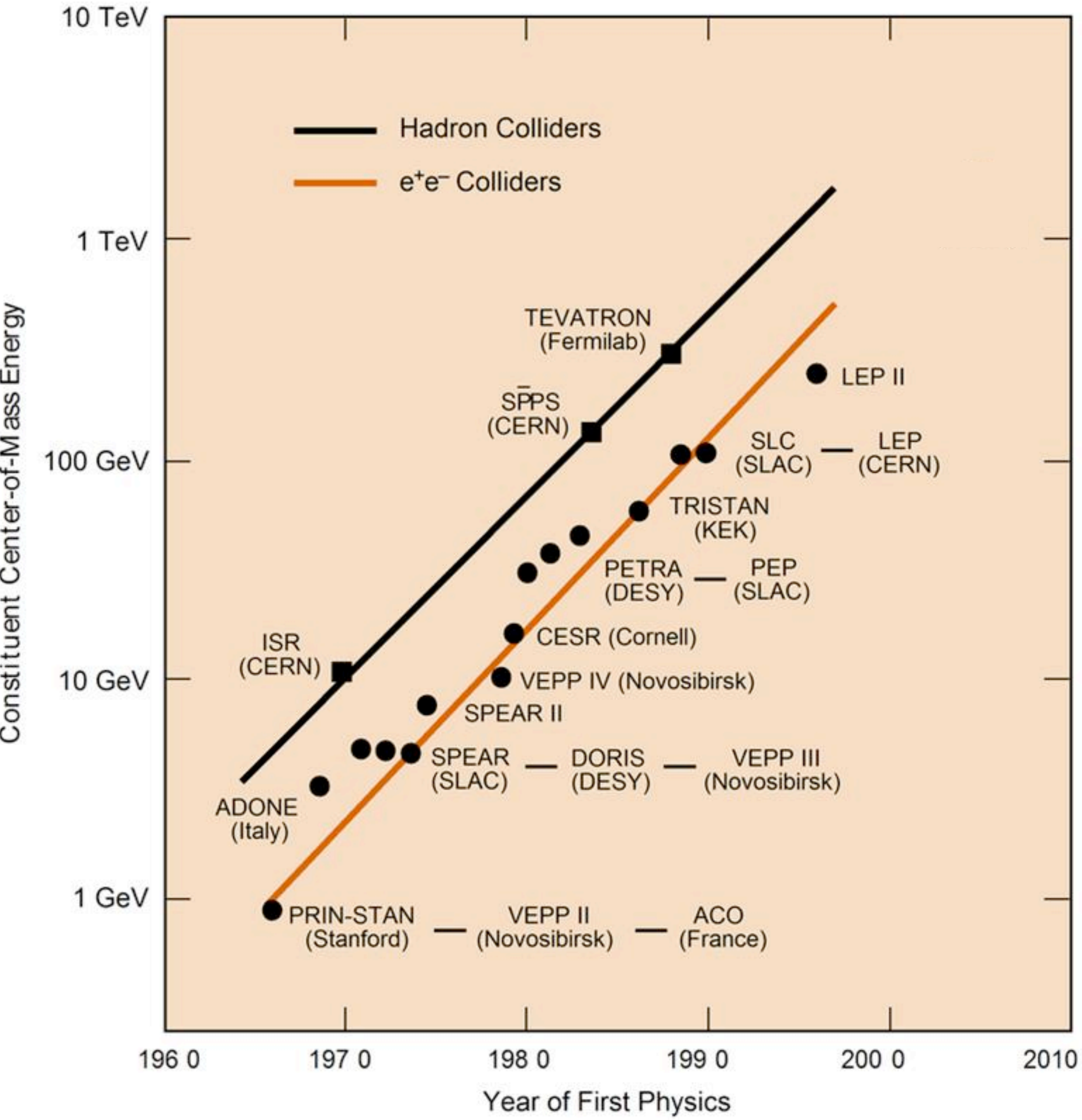
The discovery of a SM-like Higgs boson at the LHC

K. Nikolopoulos
University of Birmingham

MPAGS
January, 2014

UNIVERSITY OF BIRMINGHAM

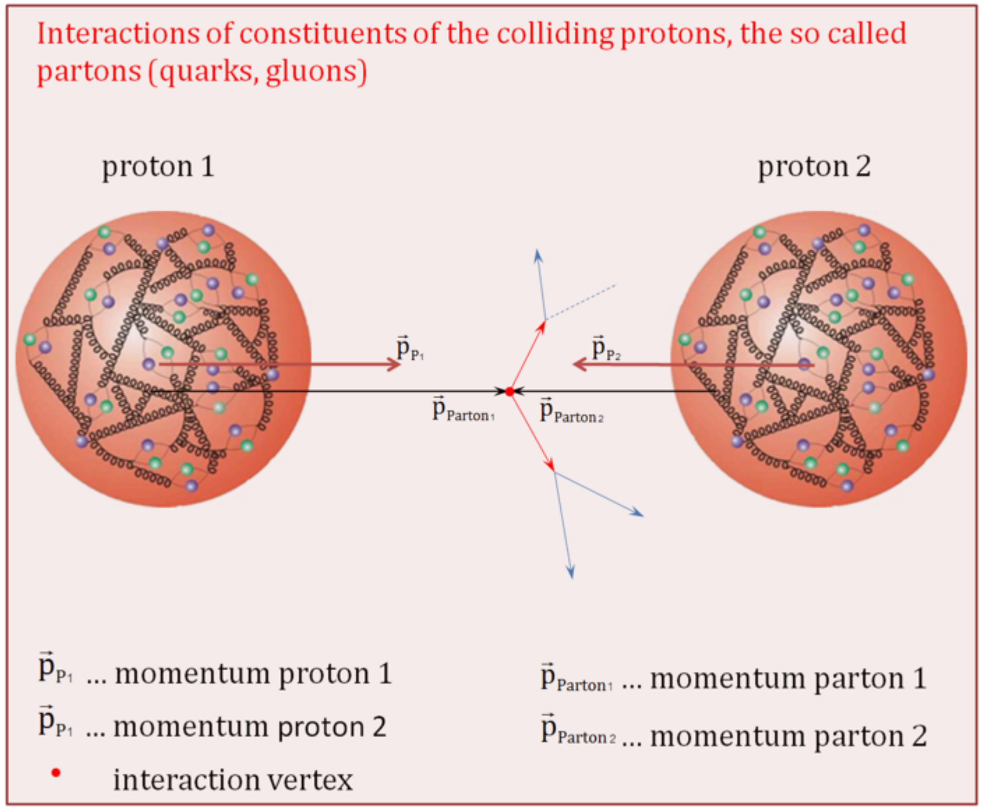
But we know how to do this!



Experimental particle physics is all about colliding particles and observing the result!

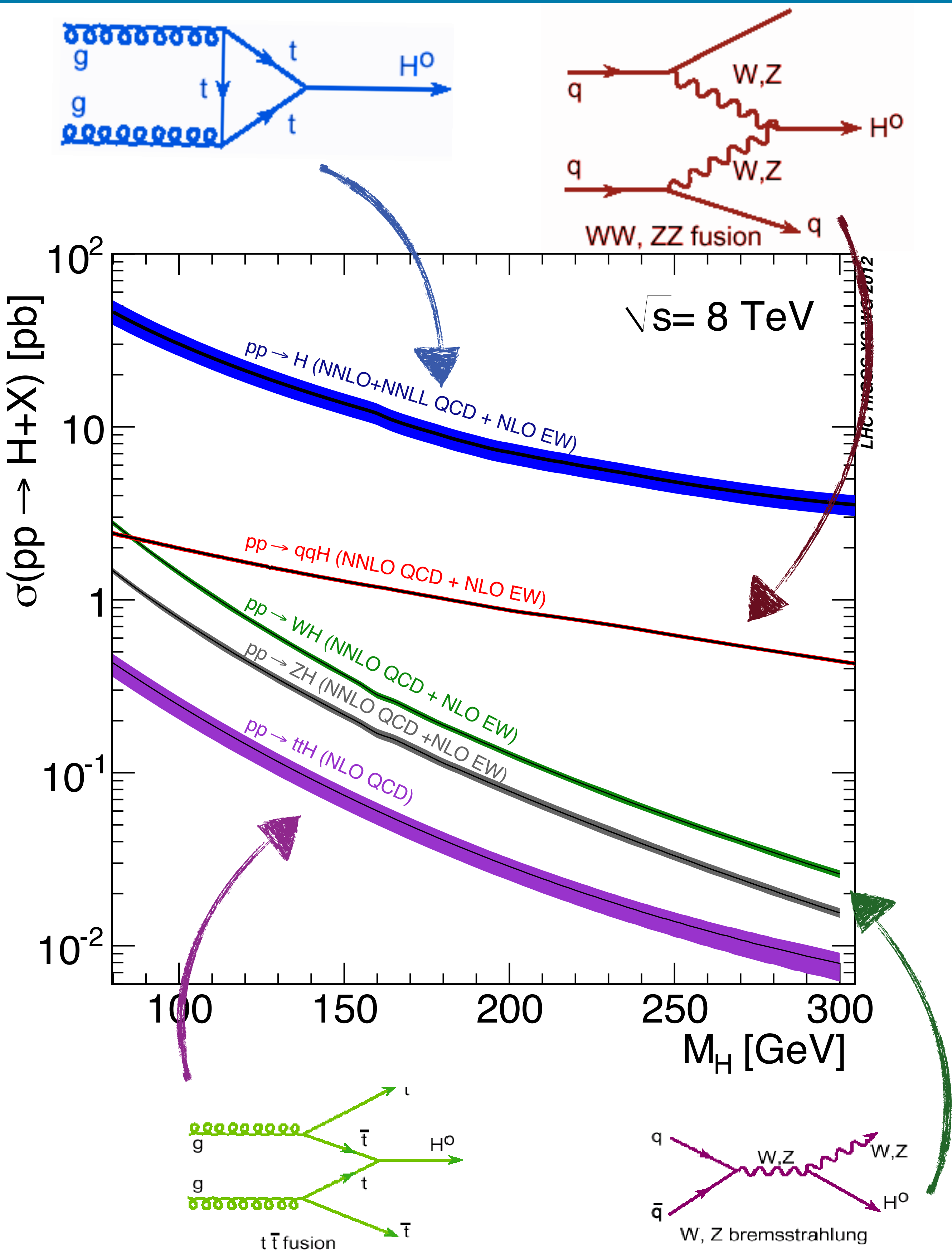
smaller distances ↔ higher collision energies

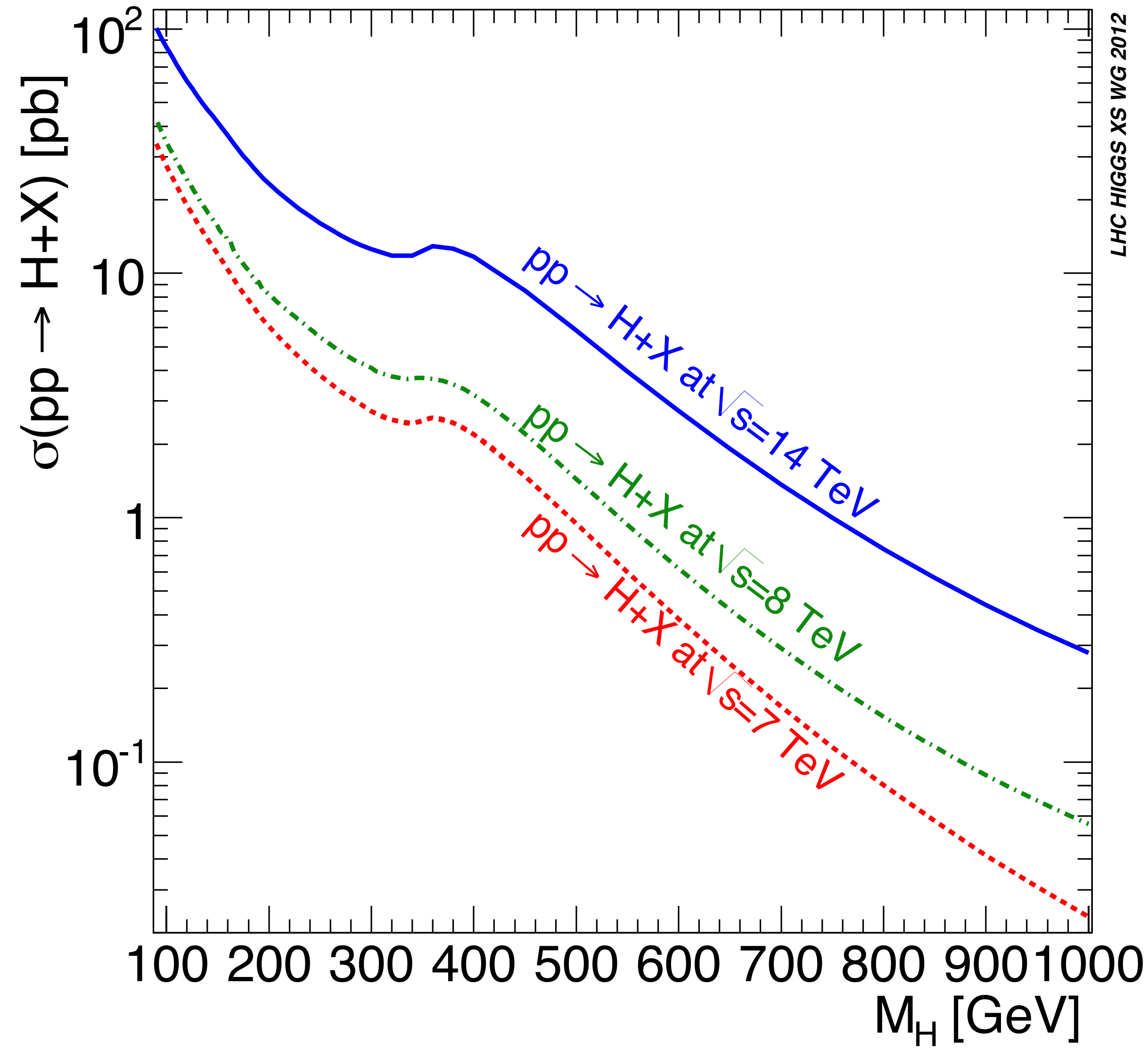
Easier with Hadron Colliders
e^+e^- Colliders better for precision measurements



Interactions between constituents of the protons, carrying fraction of nominal Centre-of-Mass Energy

Higgs boson production



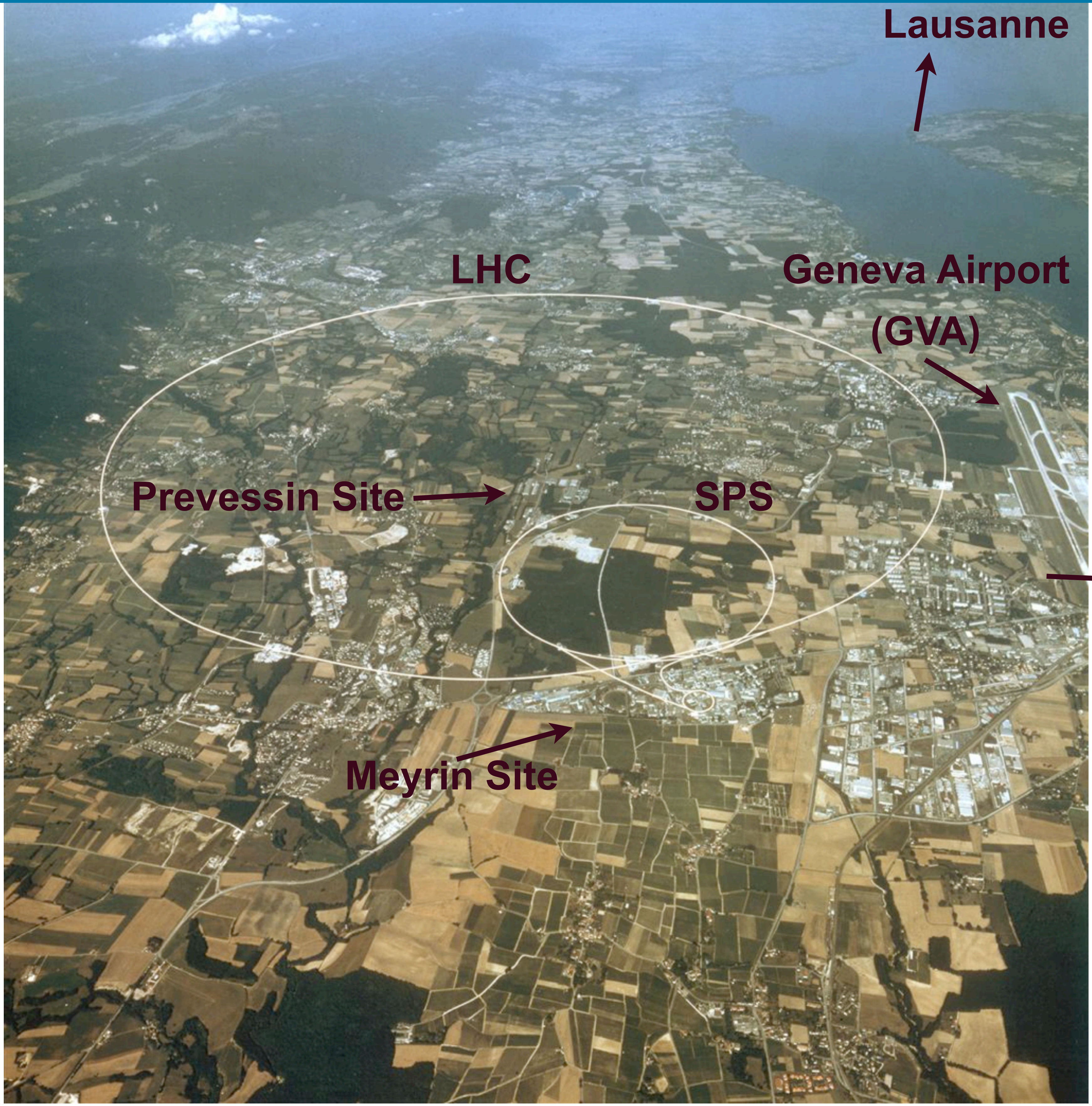


For m_H = 125 GeV cross-section increases

by ~1.3 when going from 7 to 8 TeV

by ~3.3 when going from 7 to 14 TeV

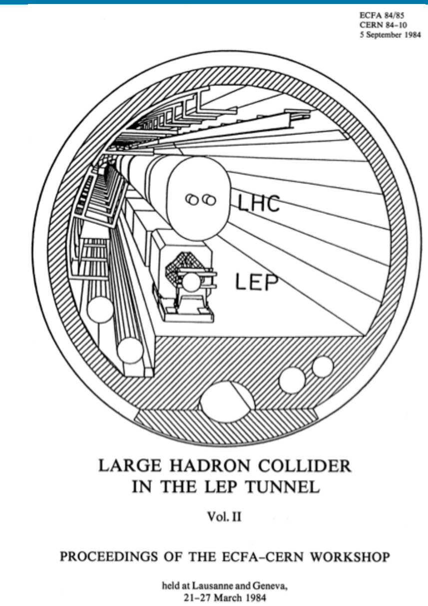
Aerial view of CERN site

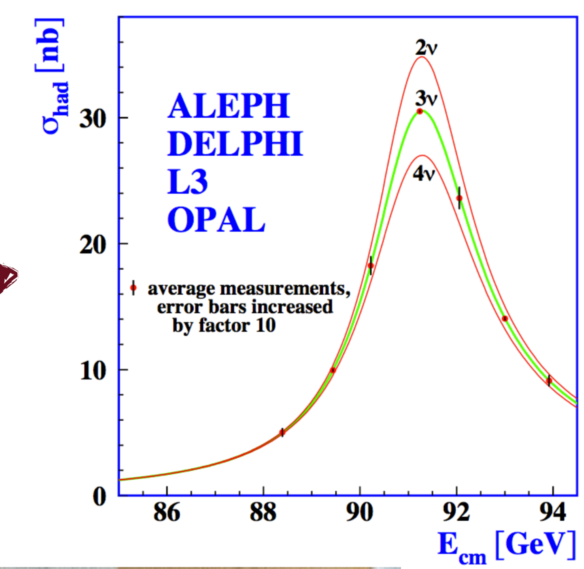


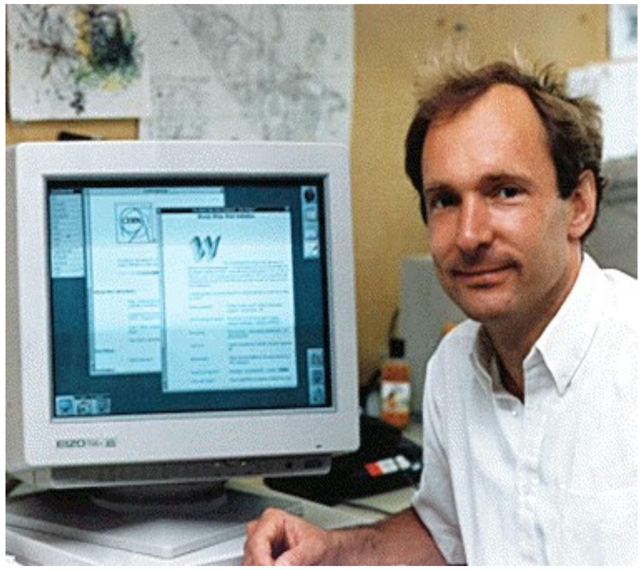
Geneva

CERN Timeline: A versatile fundamental research program

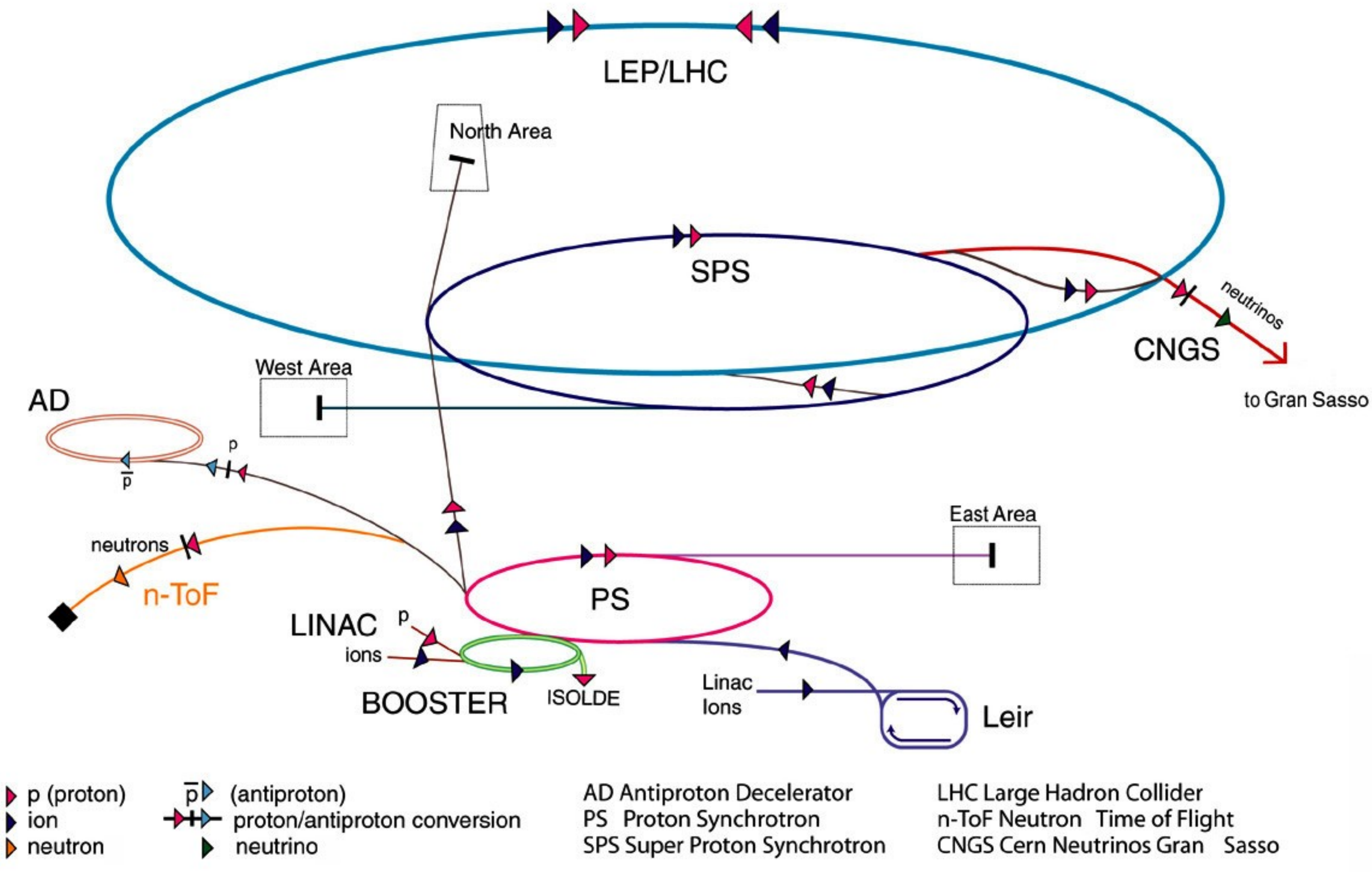
1954 CERN was founded
1957 Synchrocyclotron (SC), first accelerator, begins operation
1959 Proton Synchrotron (PS) begins operation
1968 Georges Charpak invents multiwire proportional chamber (Nobel Prize 1992)
1971 Intersecting Storage Rings (ISR) starts operation (first pp collider)
1973 Discovery of Neutral Currents - first confirmation of electroweak theory (today known as the Standard Model)
1976 Super Proton Synchrotron (SPS) begins operation
1983 Discovery of W and Z particles
1984 Nobel Prize: C. Rubbia and S. v. der Meer for W and Z
1984 First ideas on LHC
1989 Large Electron Positron collider (LEP) begins operation; confirms existence of only 3 neutrino families
1989 Tim Berners-Lee invents the World Wide Web
1993 Precise results on CP violation; difference between matter and antimatter
1995 First observation of antihydrogen
1999 Construction of Large Hadron Collider (LHC) begins
2000 Creation of quark-gluon plasma, new state of matter
2002 First results on antihydrogen atoms
2008 The LHC start-up
2010 The real LHC start-up...
2012 Discovery of a Higgs-like boson







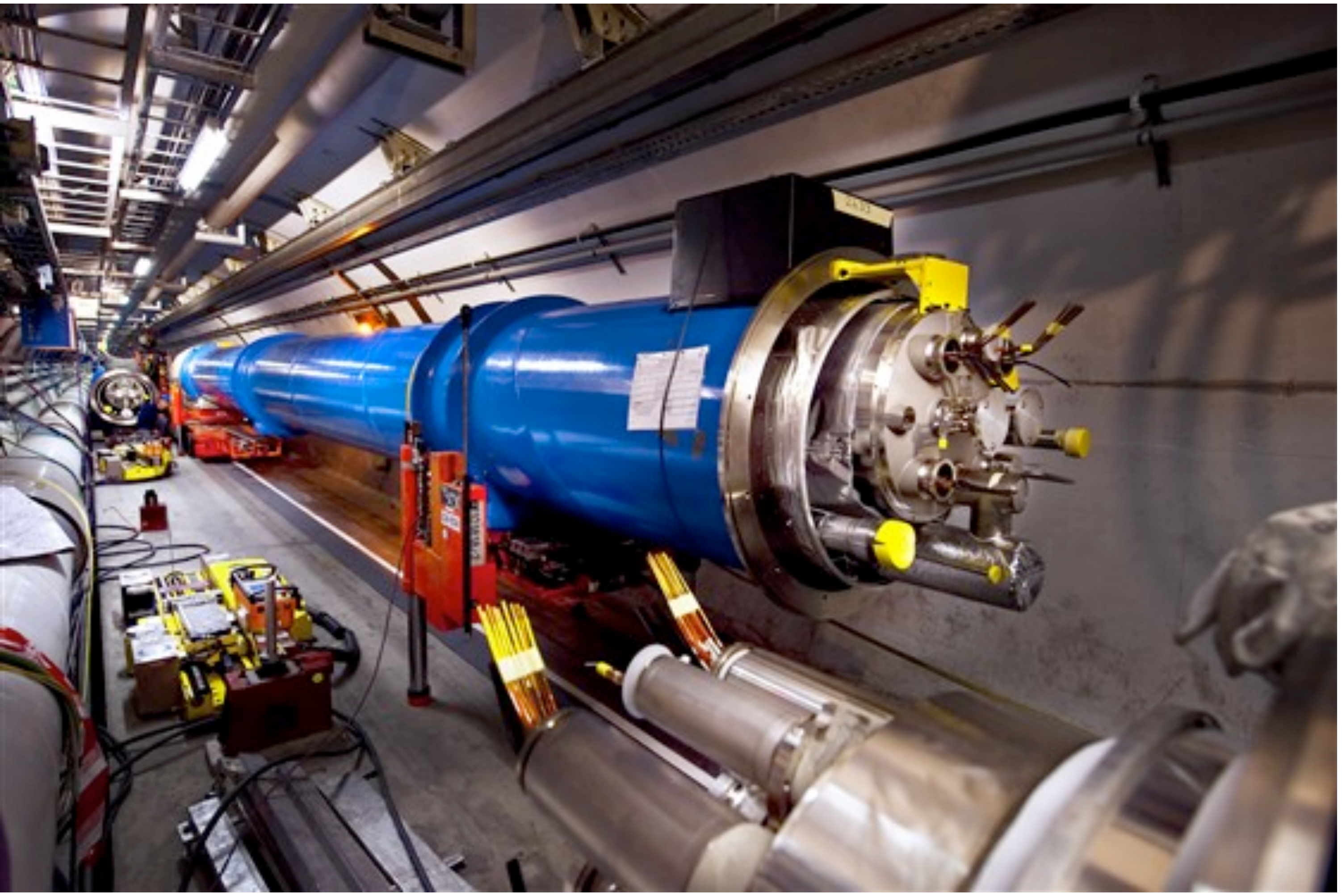
CERN accelerator complex



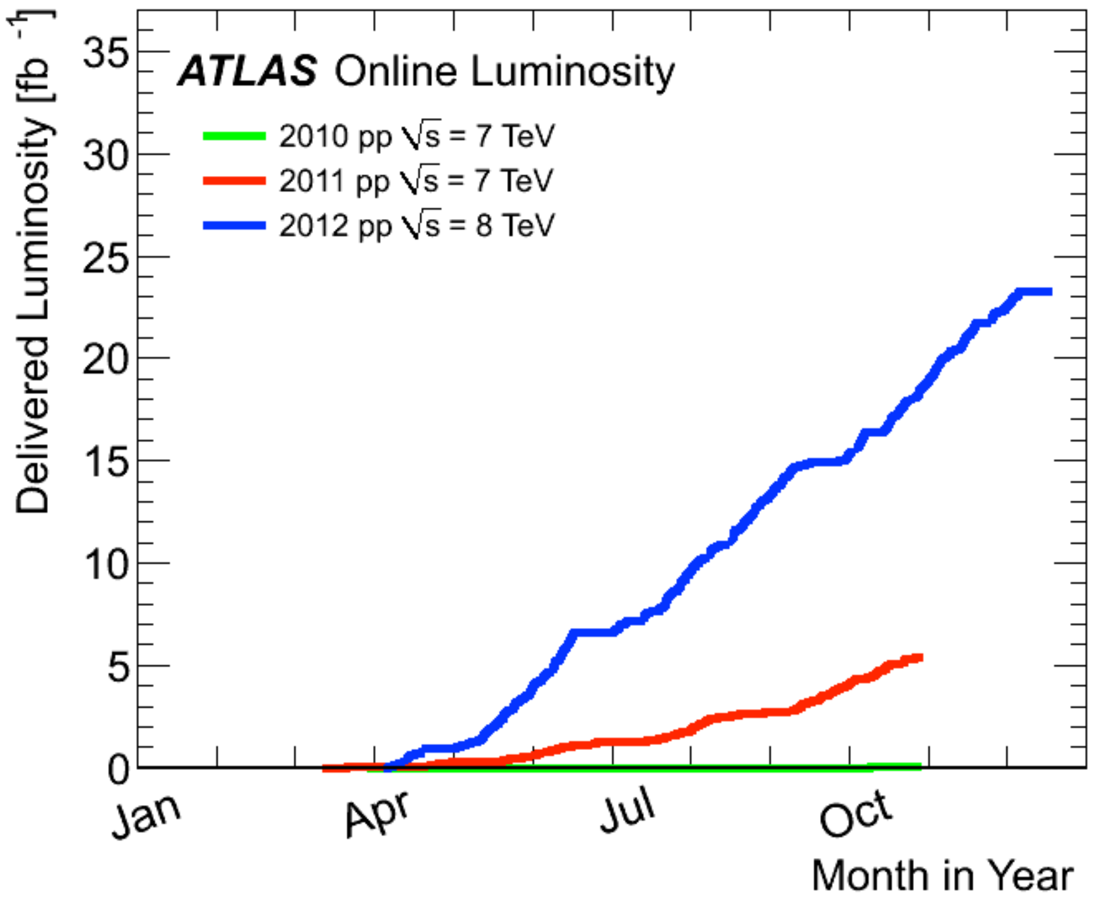
Maximizing the return of the investment by exploiting already existing infrastructure as much as possible!

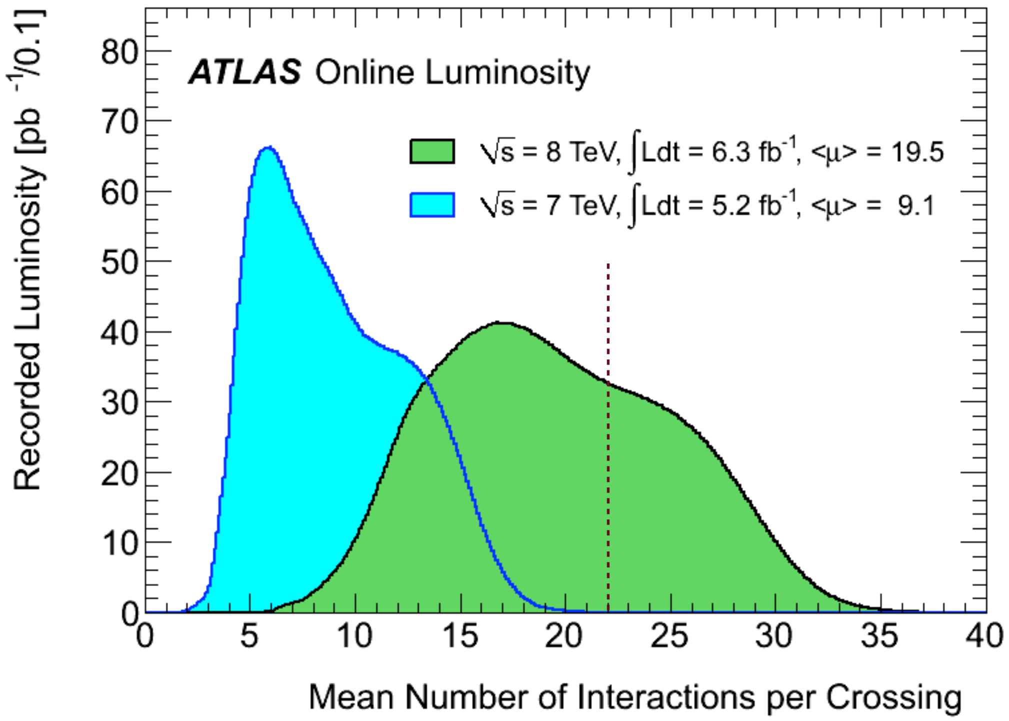
The Large Hadron Collider

1232 superconducting dipoles with a field of 8.3T
1.9K → the coolest place in the universe!

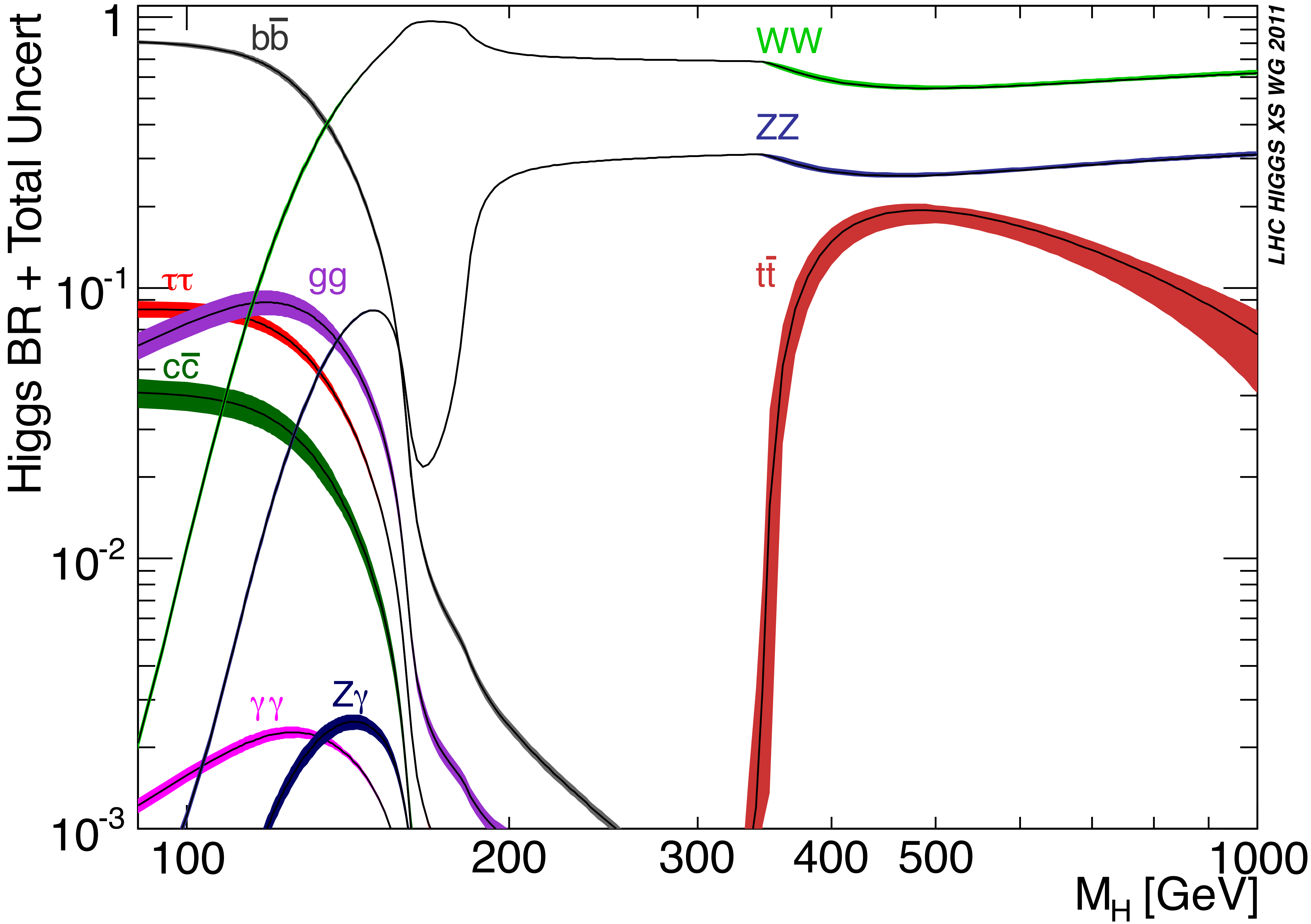


Parameter (Design)	LHC
Centre-of-mass Energy	7/8 (14) TeV
Bunches/Beam	1854/1380(2808)
Luminosity	$3.65\cdot10^{33}/7.7\cdot10^{33}(1\cdot10^{34})$ $cm^{-2}m^{-1}$
Bunch Spacing	50 (25) ns



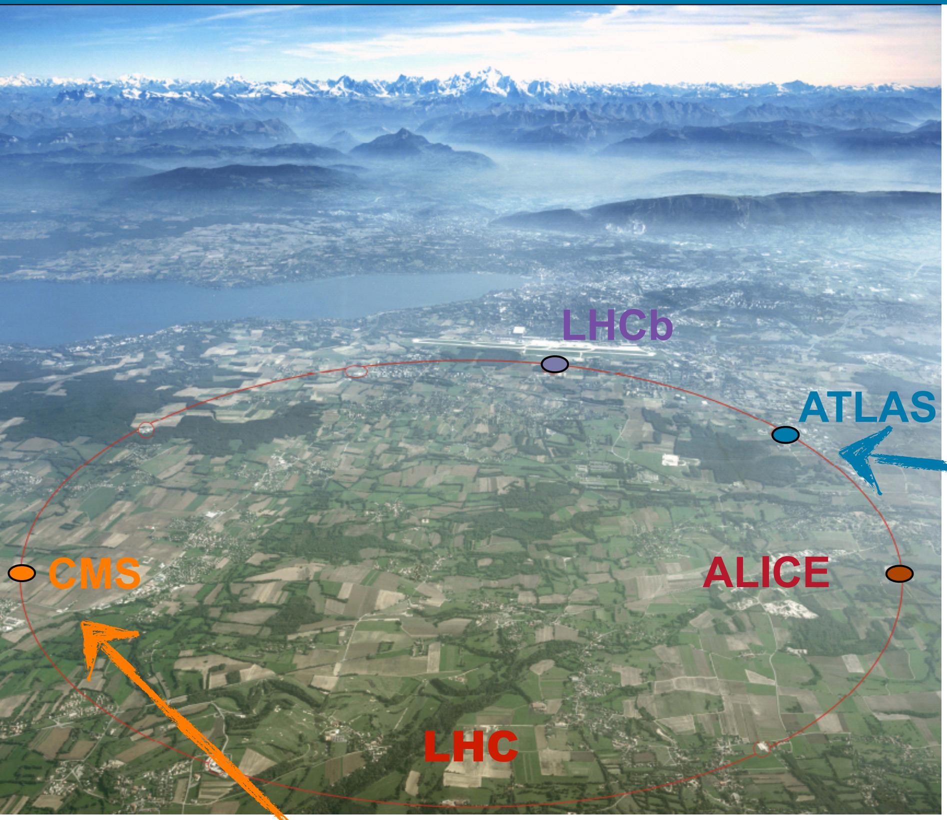


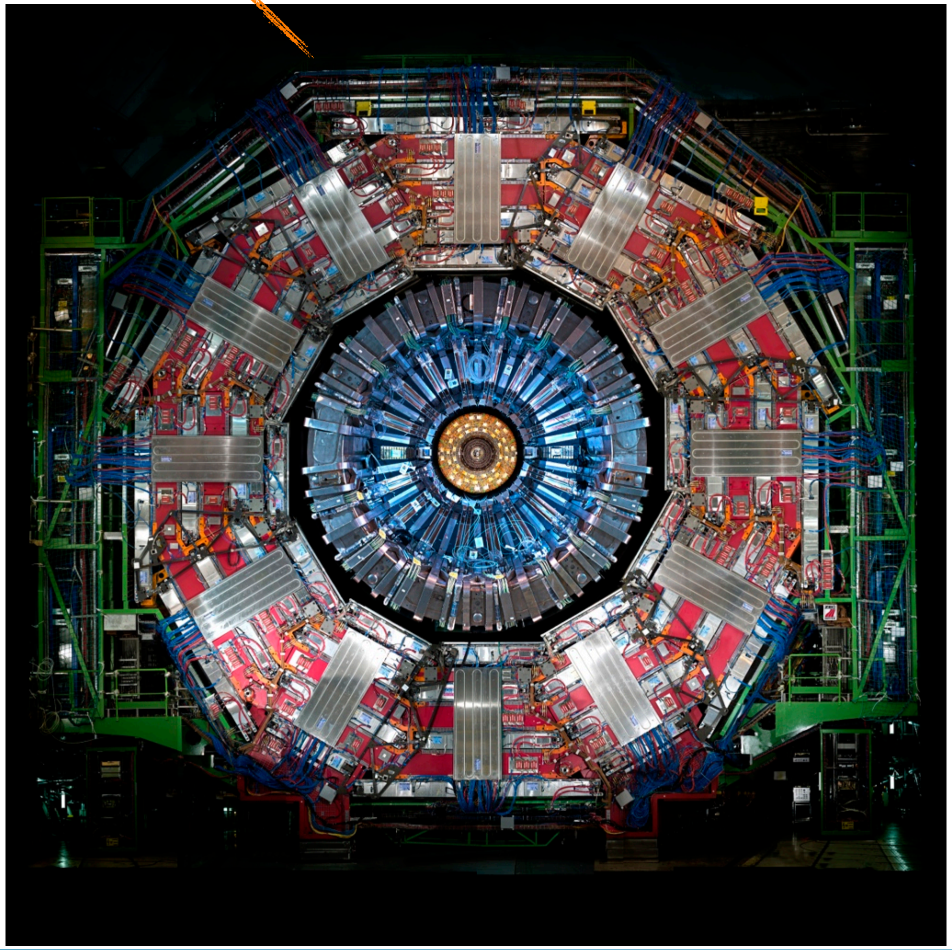
Higgs boson decays

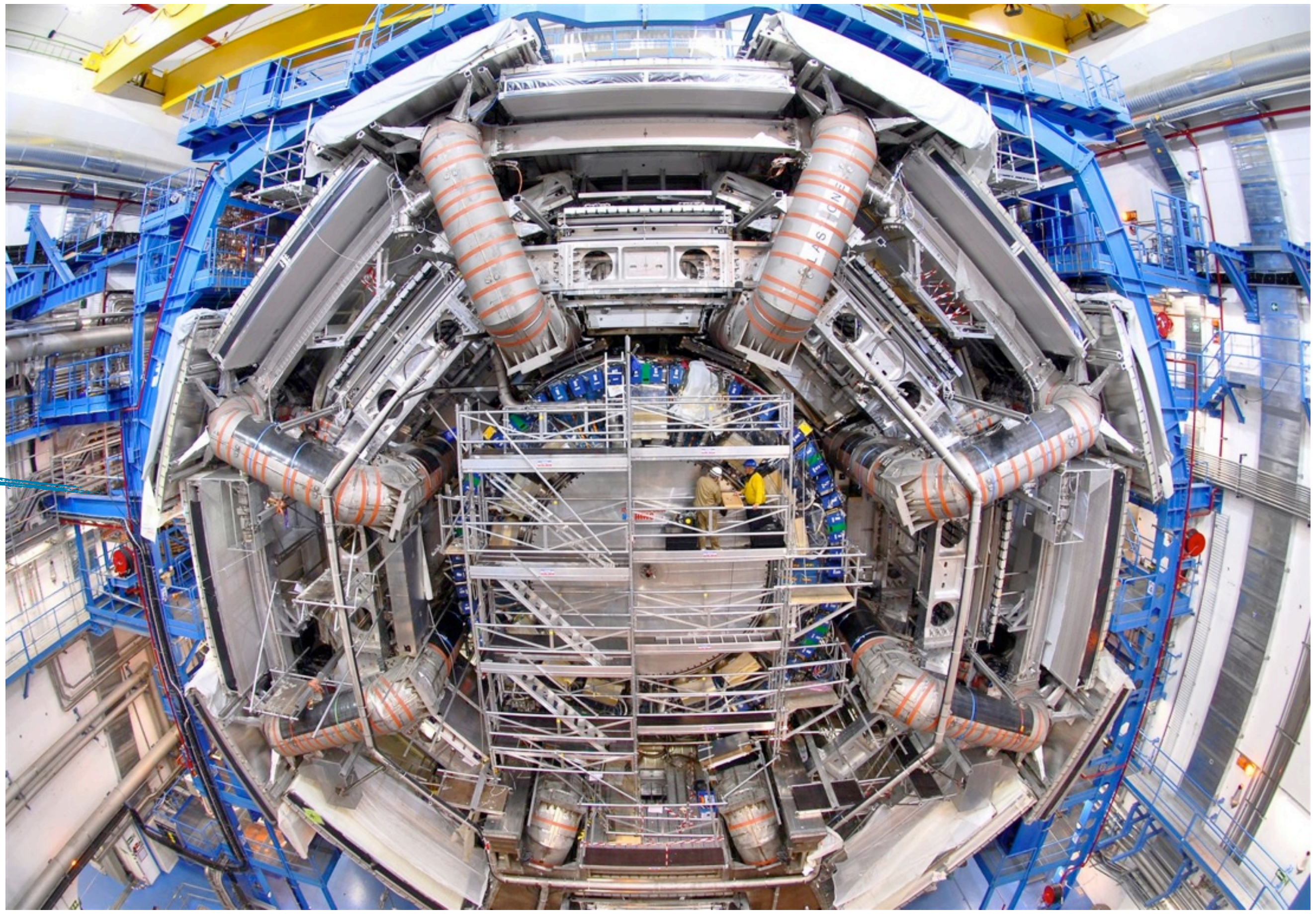


Higgs boson is rather short-lived, decaying through different channels!

ATLAS and CMS Detectors



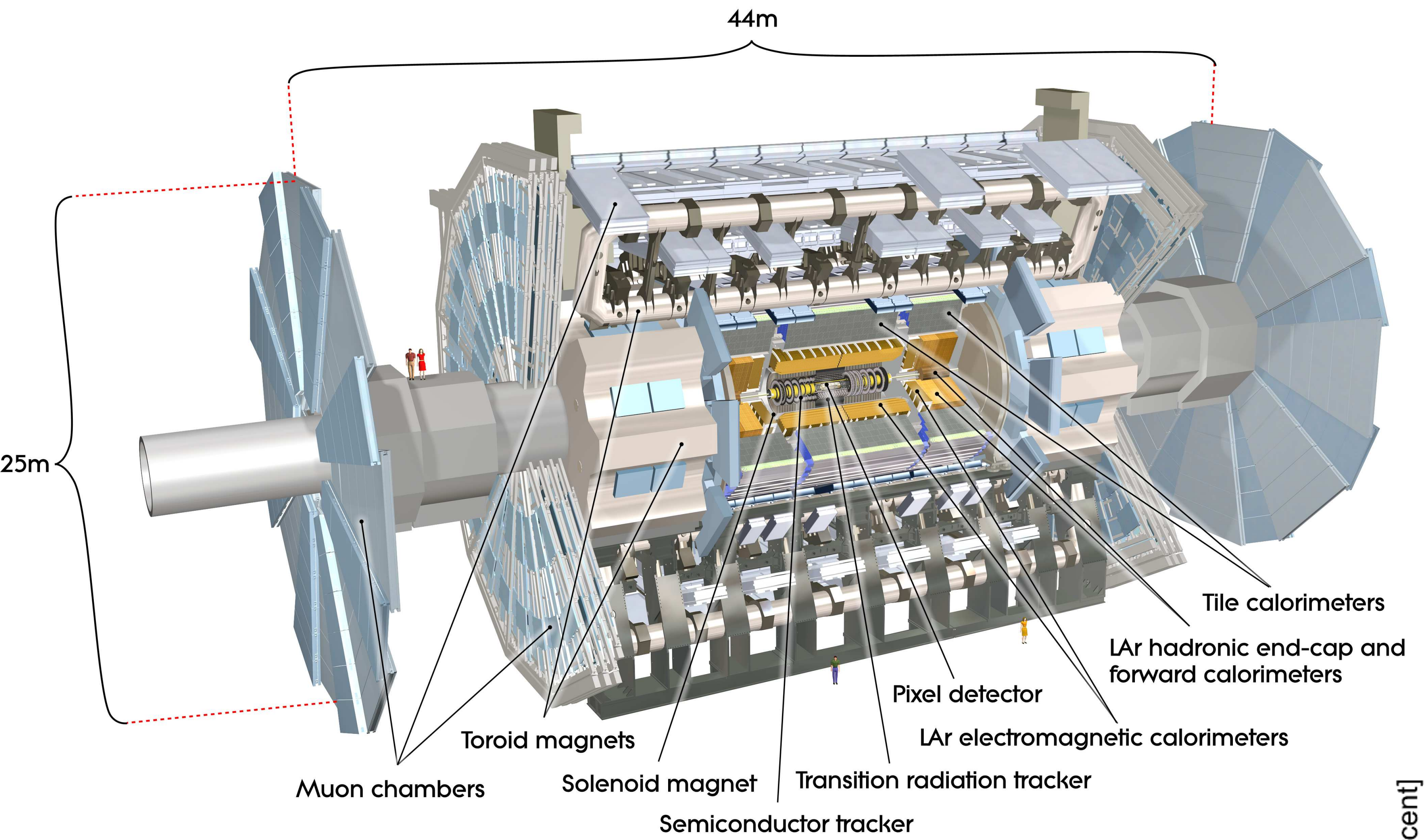




ATLAS Collaboration: 38 countries, 177 institutions, ~2900 scientific authors

A Toroidal LHC ApparatuS

⇒ General purpose detector designed for the harsh LHC environment

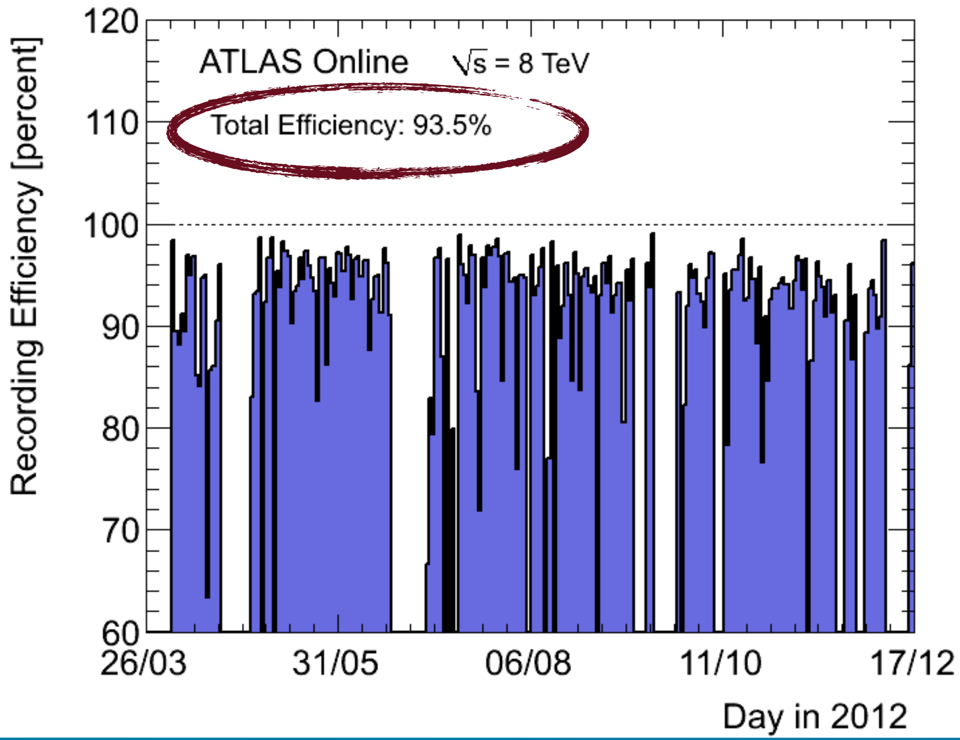


	ATLAS
Magnets	2T solenoid, 3 air-core toroids
Tracking	silicon + transition radiation tracker
EM Calorimetry	sampling LAr technology
Hadron Calorimetry	plastic scintillator (barrel) LAr technology (endcap)
Muon	independent system with trigger capabilities
Trigger	3 Level Implementation from 40 MHz to 400 Hz

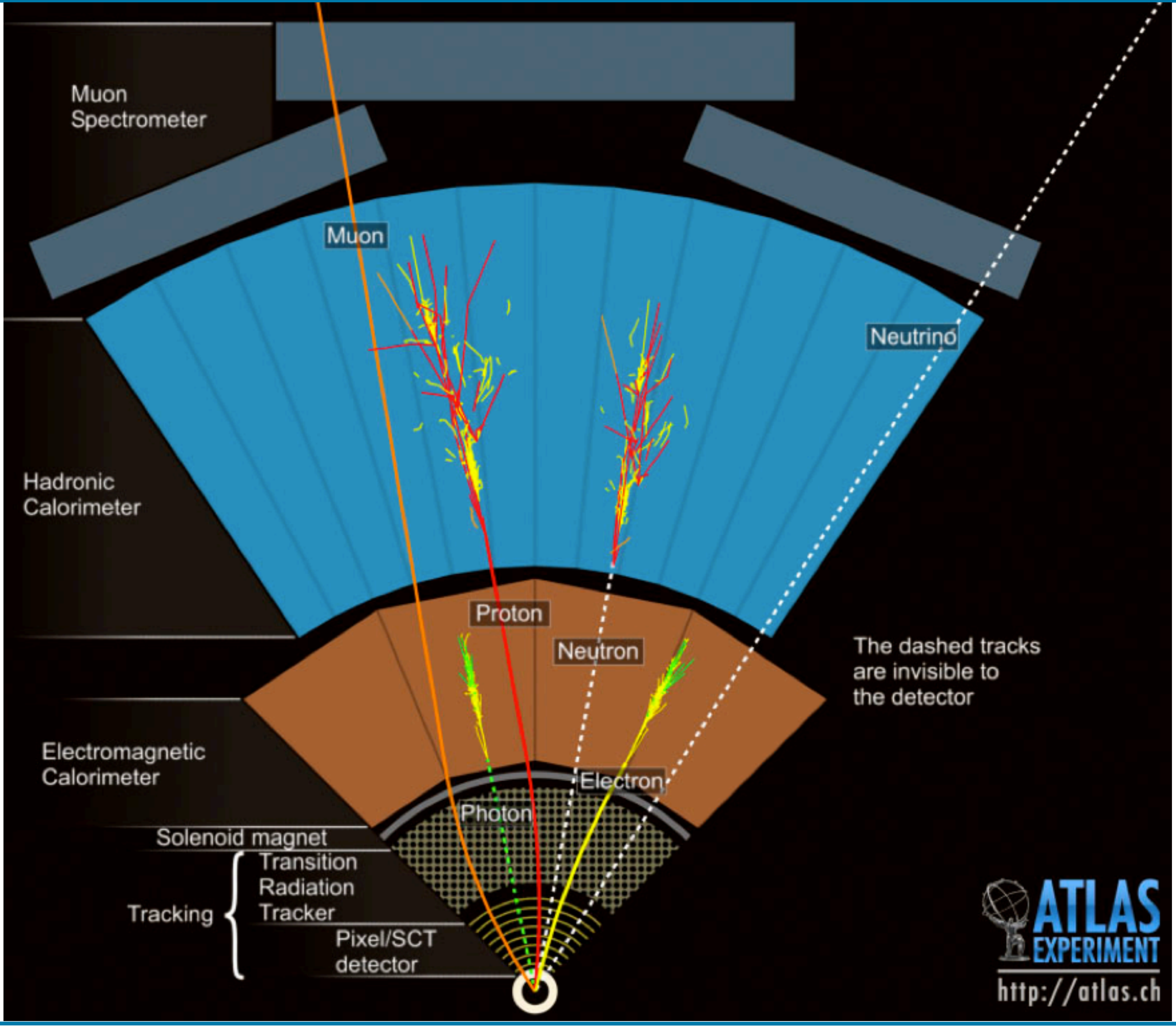
⇒ Very important to ensure high data-taking efficiency/quality

ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.4	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.8%										

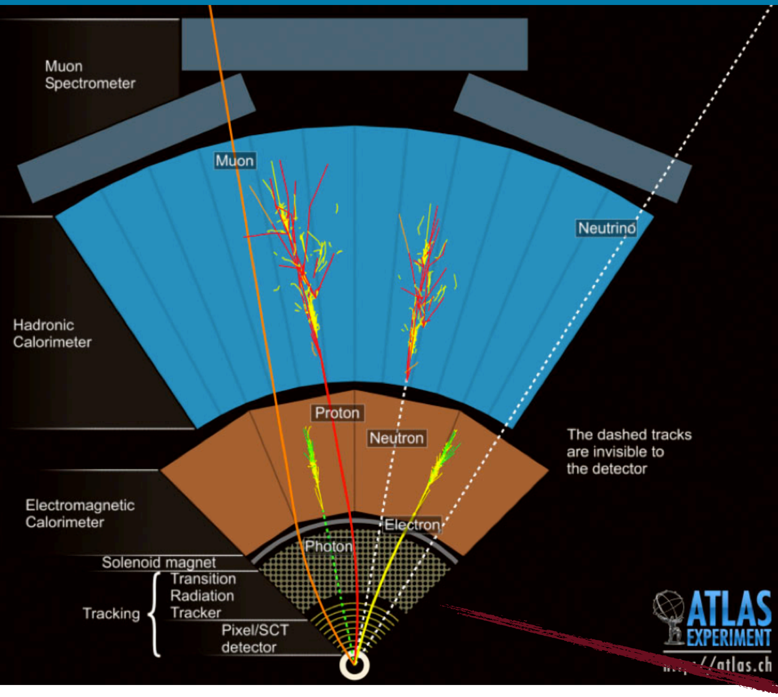
Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb^{-1} of recorded data.

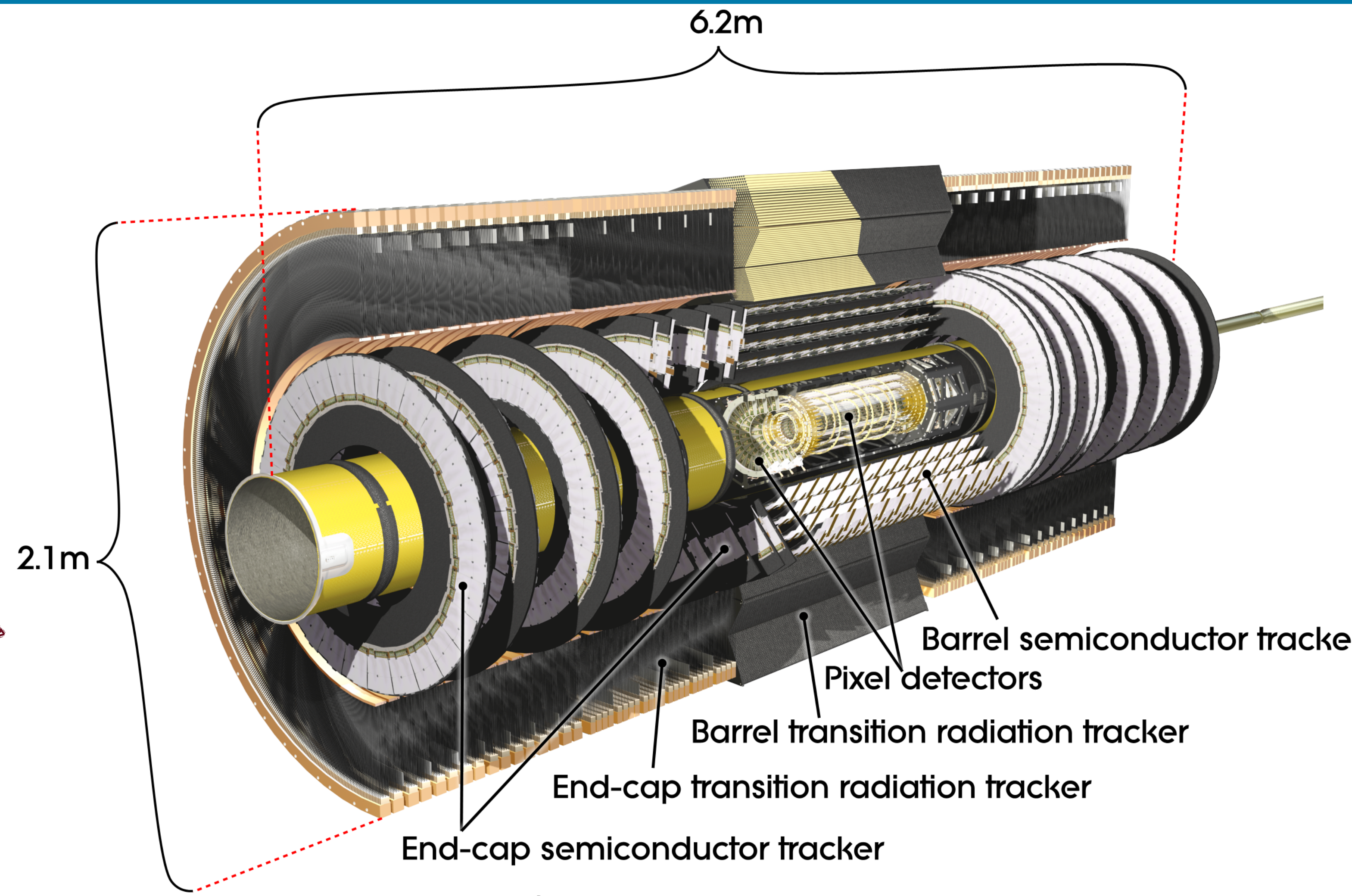


High Energy Physics Particle detectors

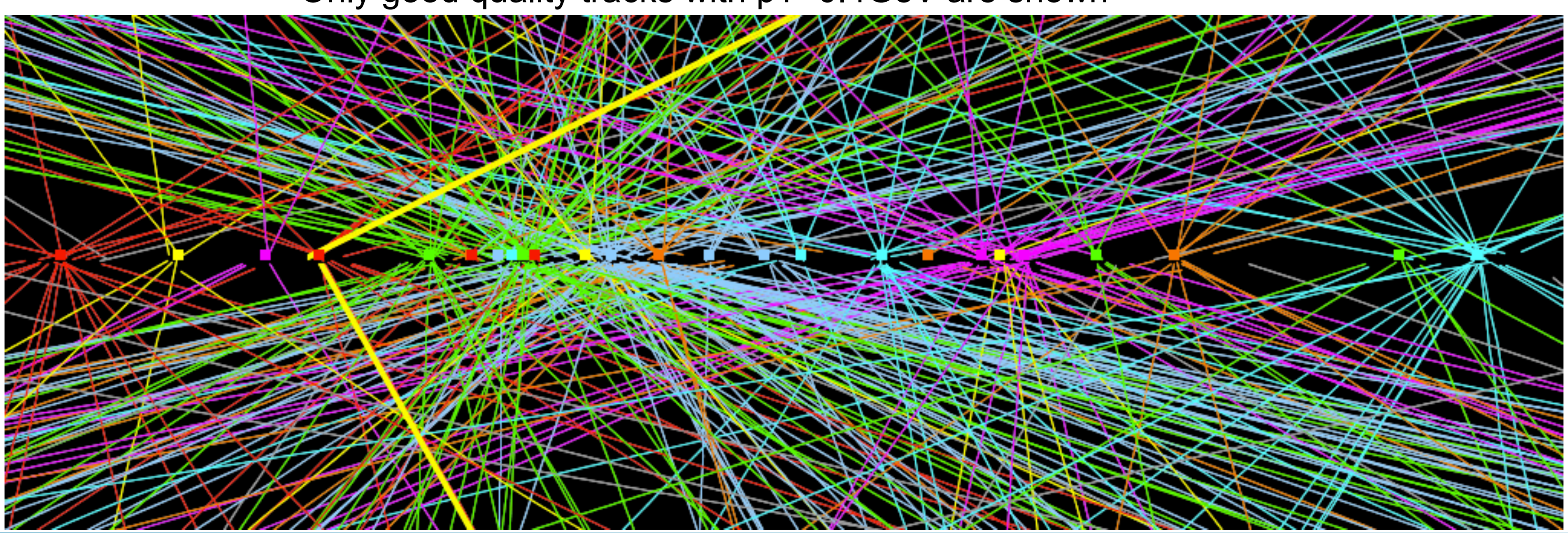


Inner Detector

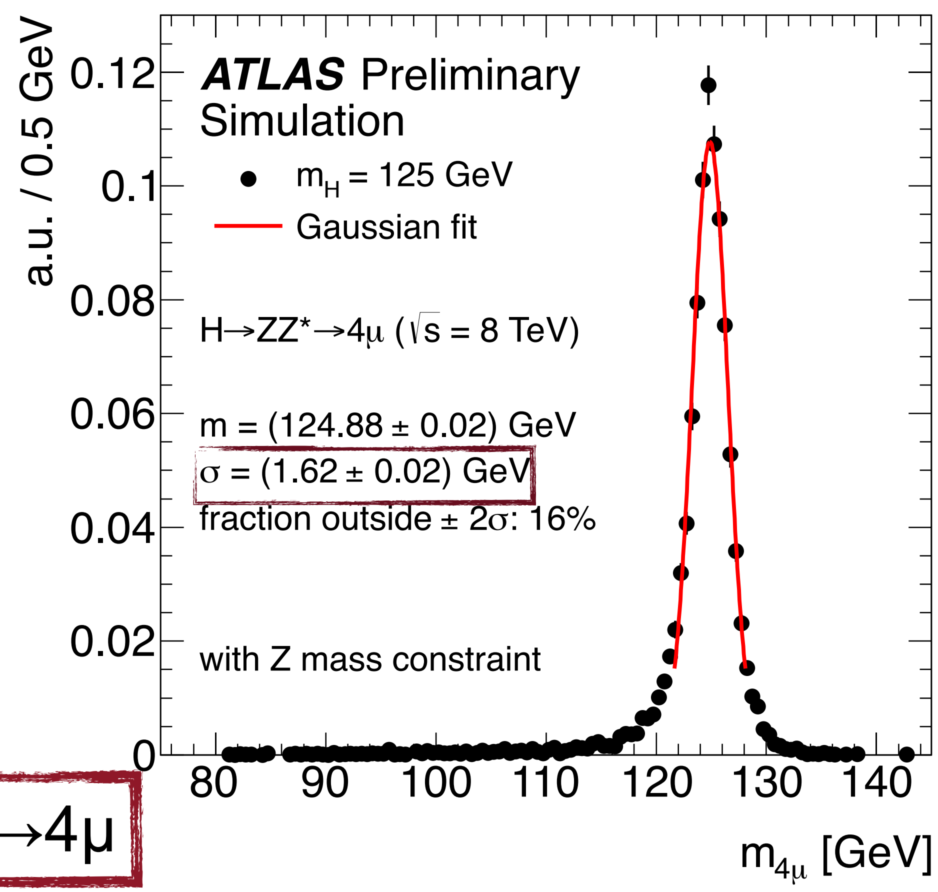




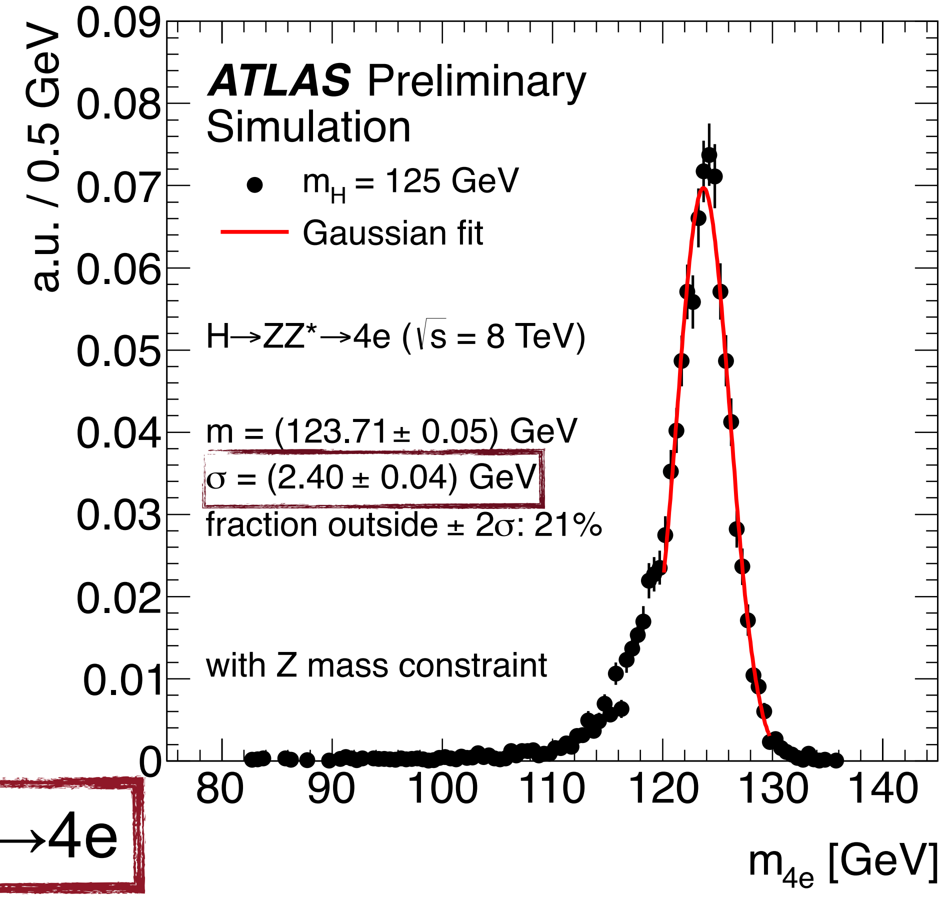
Z→μμ candidate with 25 reconstructed vertices from the 2012 run.
Only good quality tracks with pT>0.4GeV are shown



Muons and Electrons

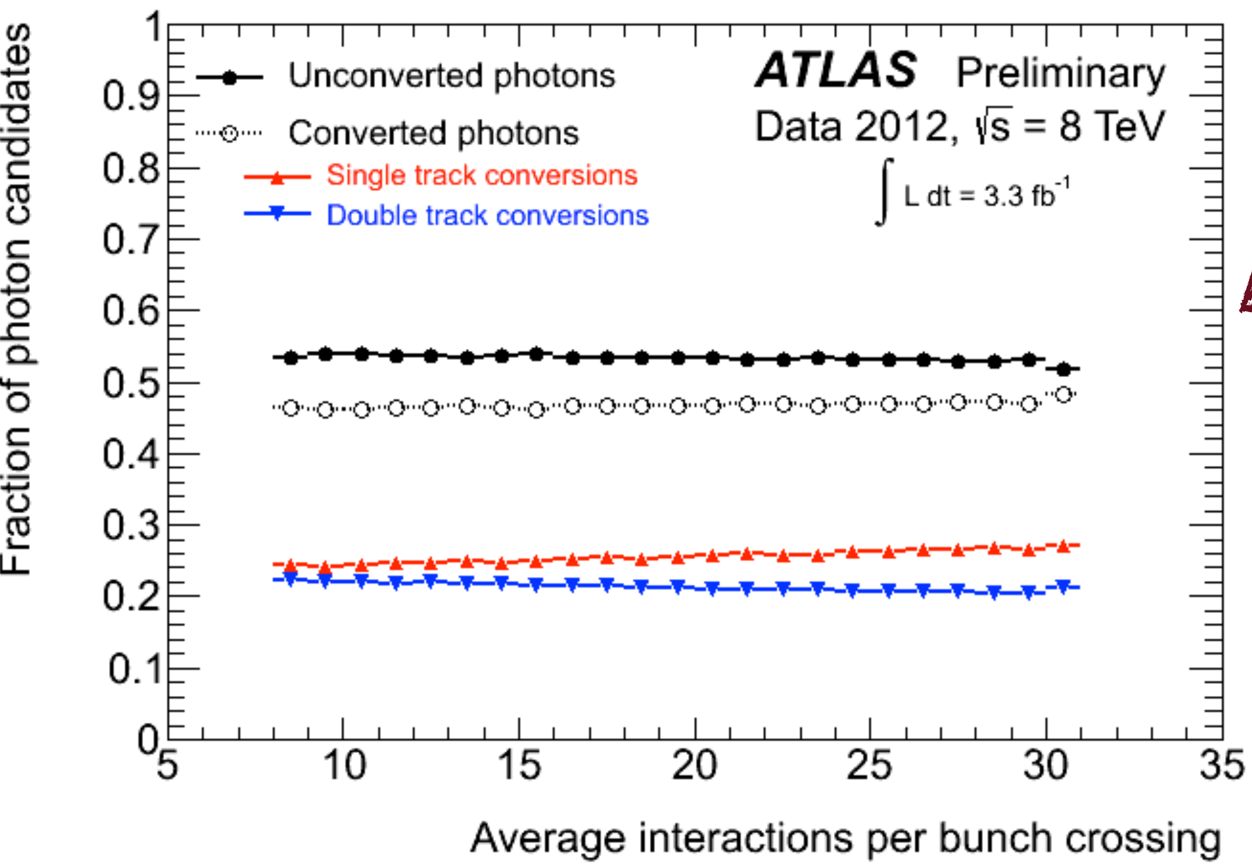


H→ZZ*→4μ



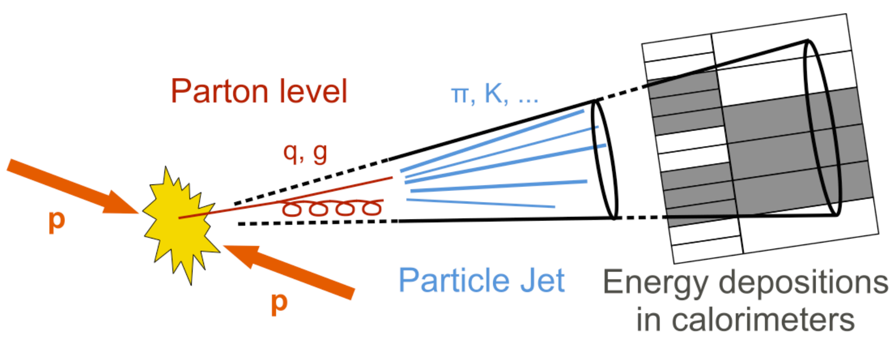
H→ZZ*→4e

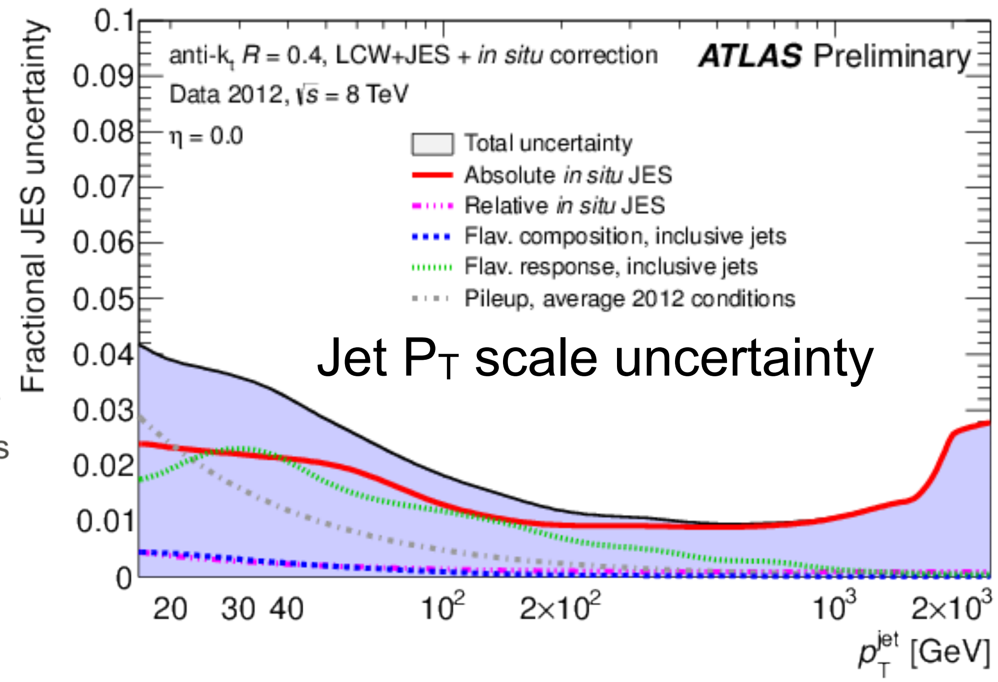
Photons

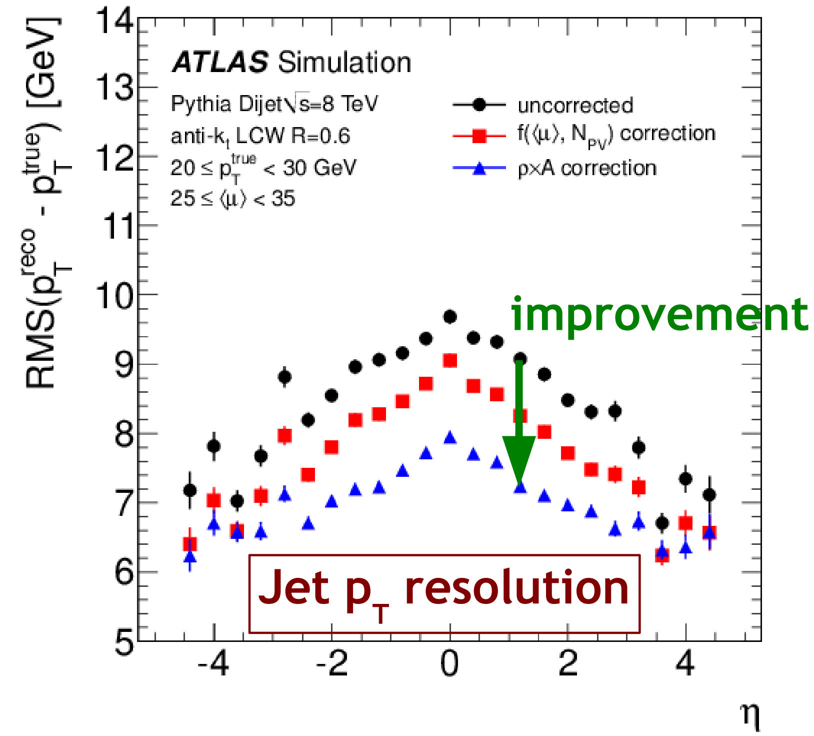


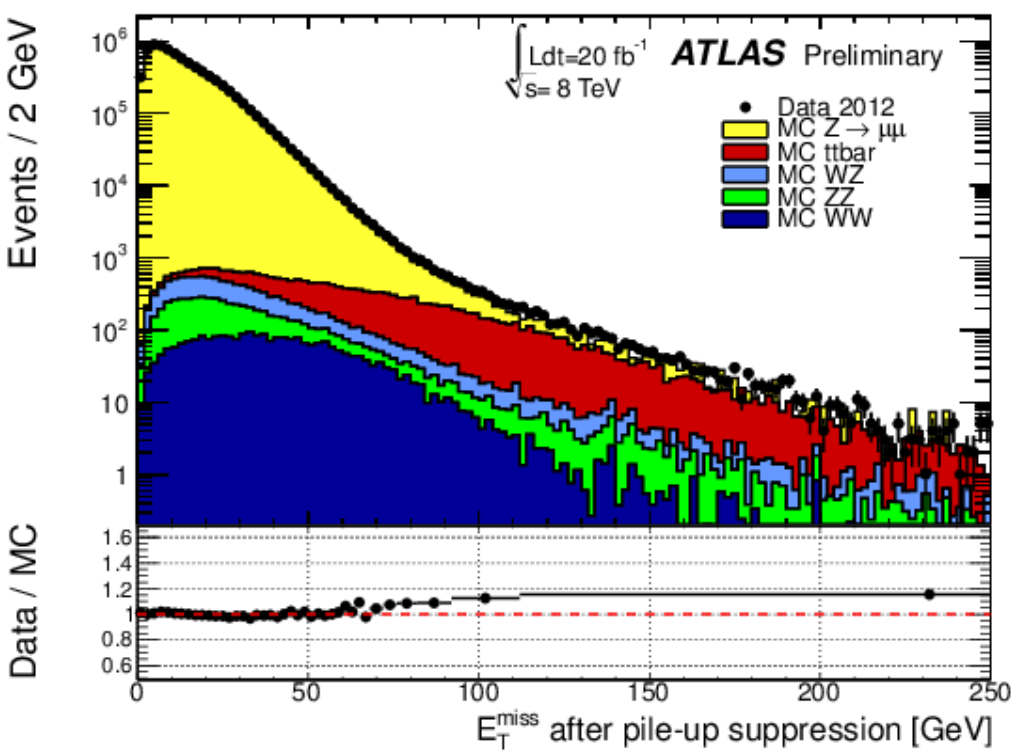
Stable photon reconstruction vs pile-up (within 1%)

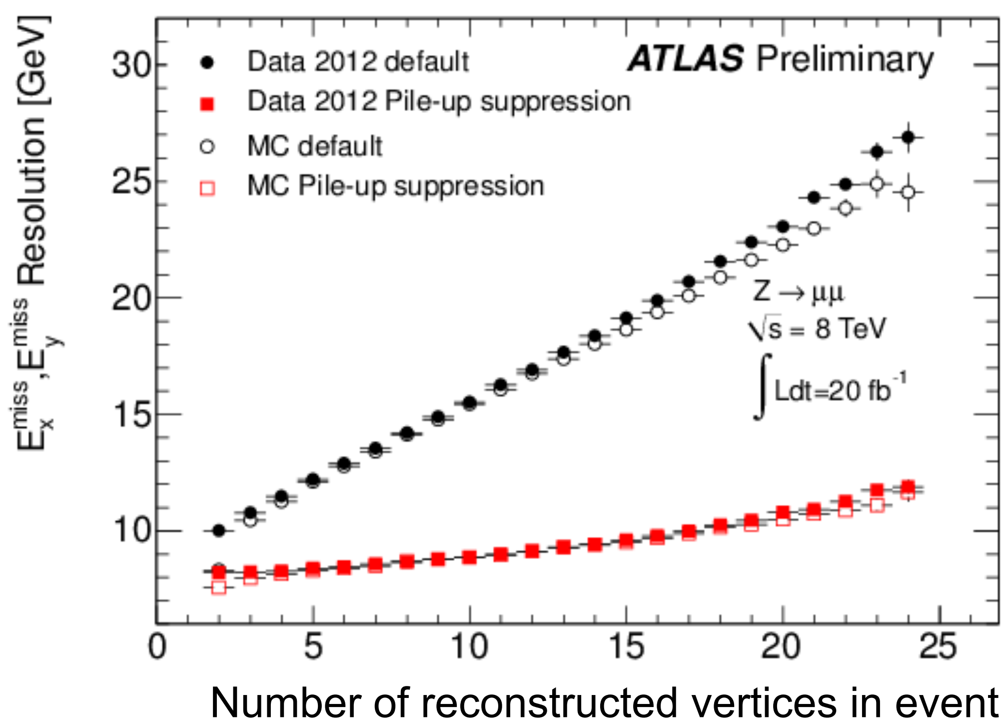
Jets and Missing E_T

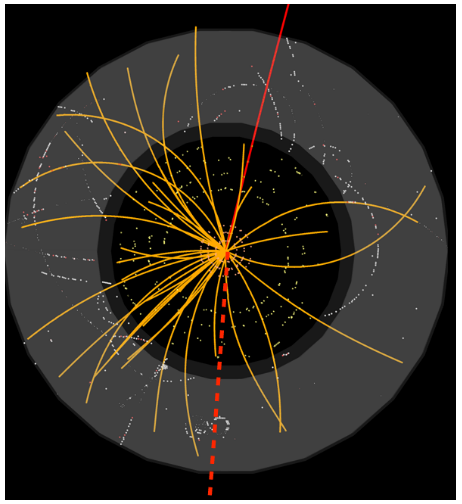












W→μν candidate

τ-leptons and b-jets

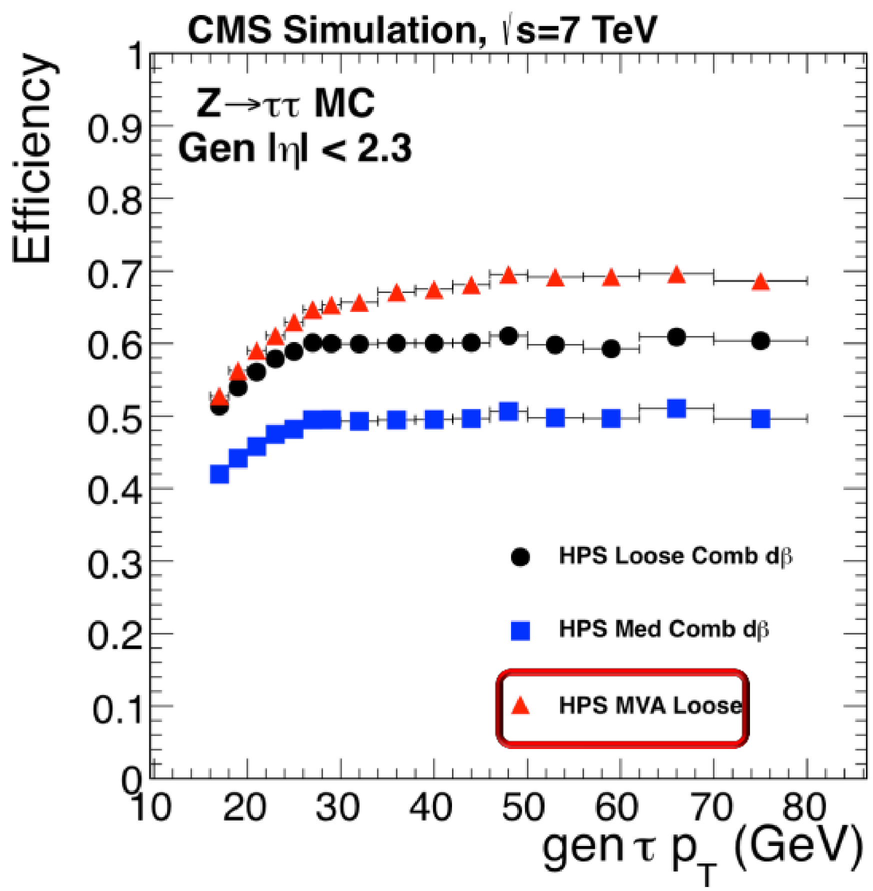
The τ-lepton is special!

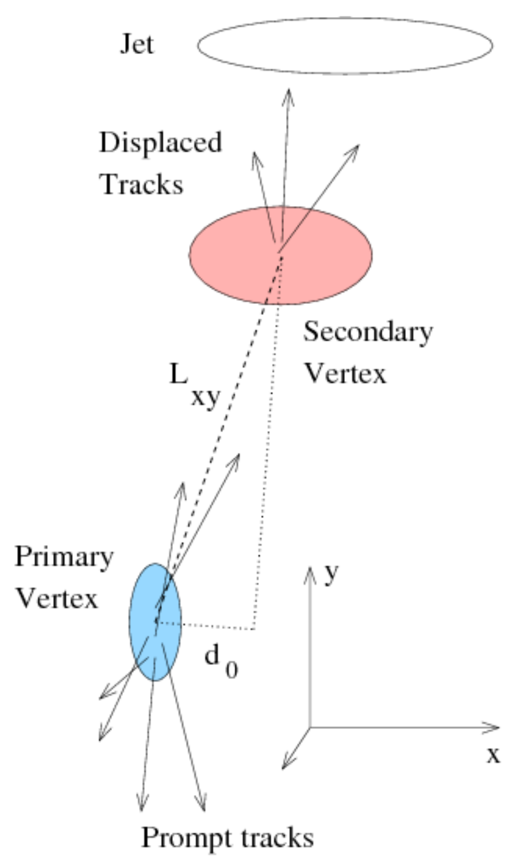
Mass of 1.78 GeV and cτ = 87.1 μm,

the only lepton that decays in our detector, in various ways...

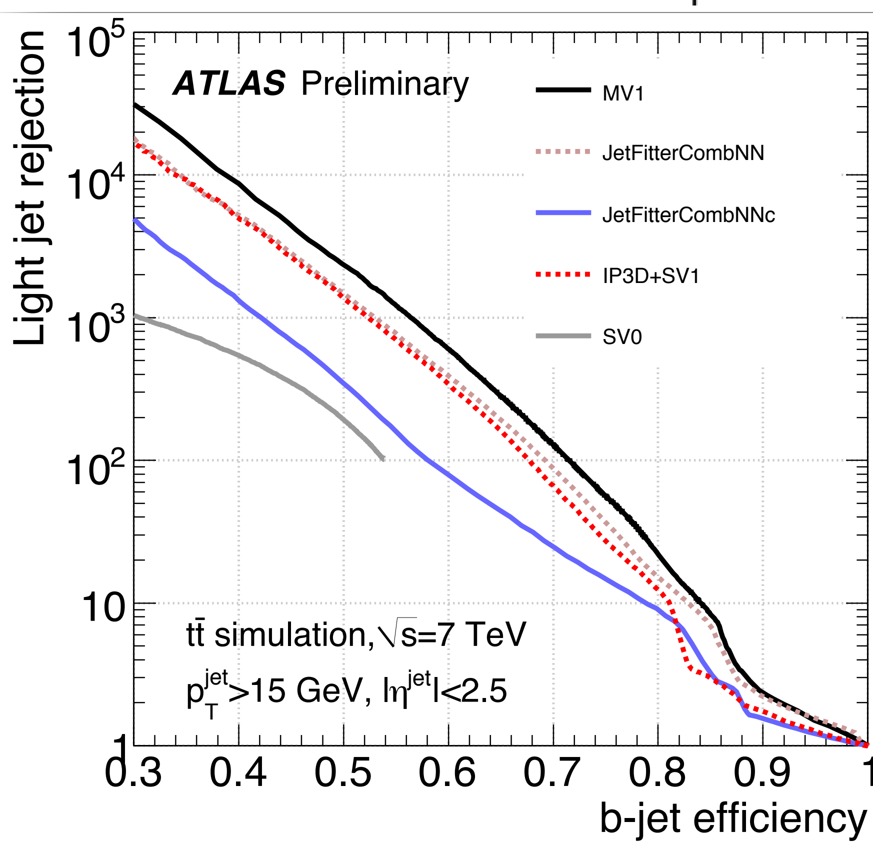
τ → lνν ~35%

τ → hadrons ~ 65%





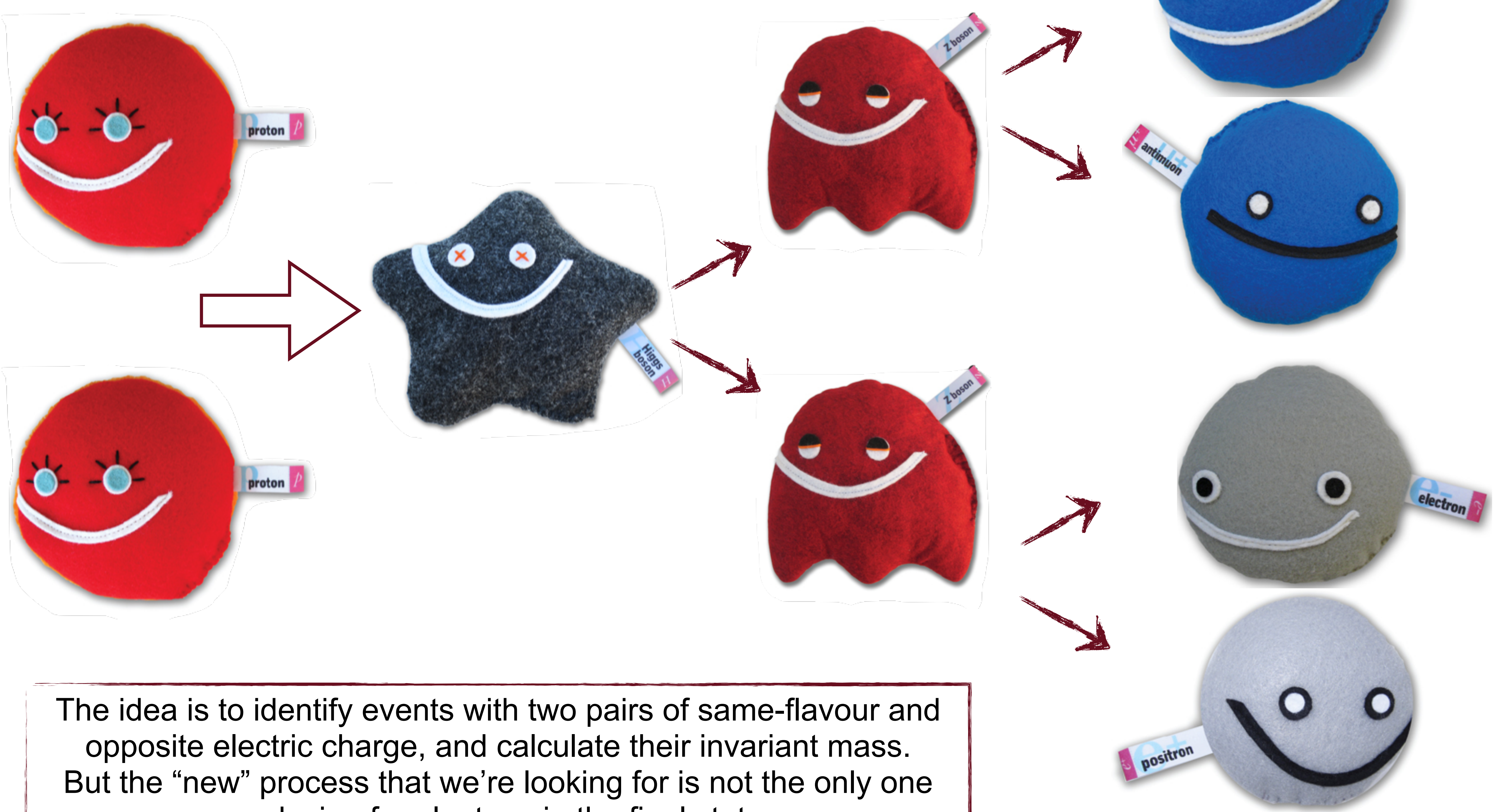
cτ = 492 μm



The
H→ZZ→4l
as an example analysis

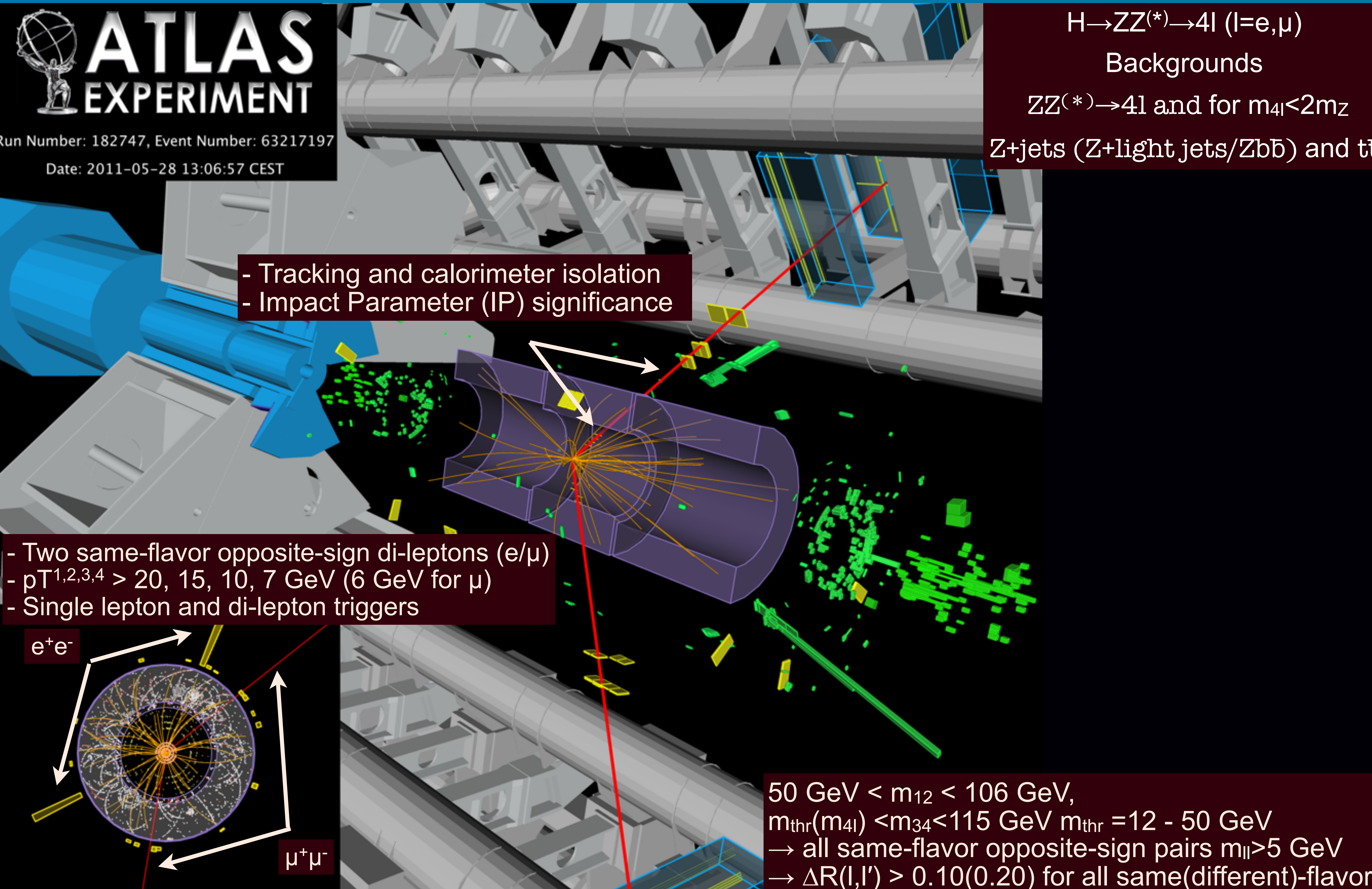
pp→H→ZZ→$\mu^+\mu^-e^+e^-$

Invariant mass of the system:
$m^2 = E^2 - \mathbf{p}^2$



The idea is to identify events with two pairs of same-flavour and opposite electric charge, and calculate their invariant mass. But the “new” process that we’re looking for is not the only one producing four leptons in the final state.

$H \to ZZ^{(*)} \to 4l$: Event Selection



$H \to ZZ^{(*)} \to 4l$ (l=e,μ)

Backgrounds

$ZZ^{(*)} \to 4l$ and for $m_{4l} < 2m_Z$

Z+jets (Z+light jets/$Zb\bar{b}$) and $t\bar{t}$

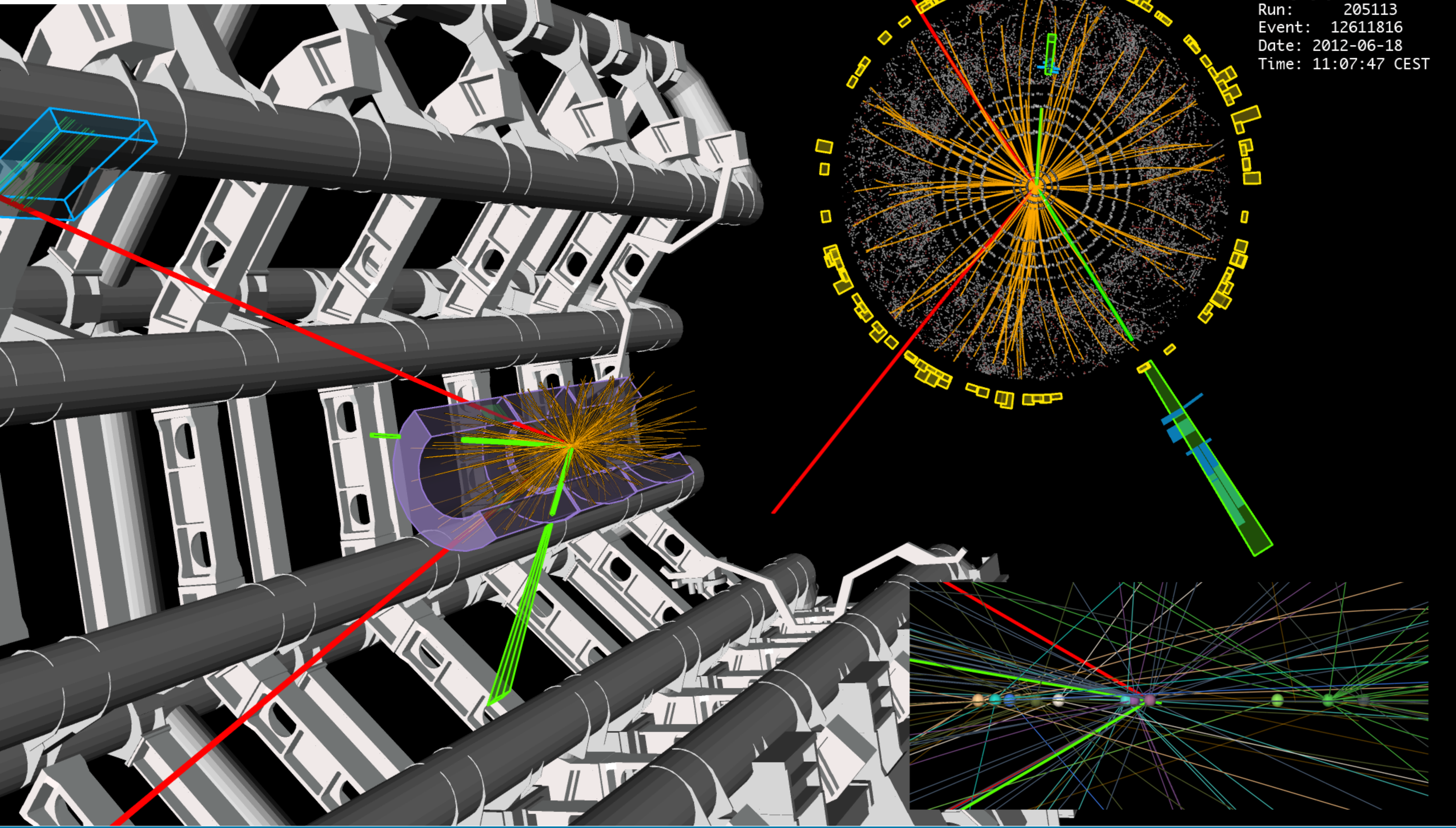
- Tracking and calorimeter isolation
- Impact Parameter (IP) significance

- Two same-flavor opposite-sign di-leptons (e/μ)
- $p_T^{1,2,3,4}$ > 20, 15, 10, 7 GeV (6 GeV for μ)
- Single lepton and di-lepton triggers

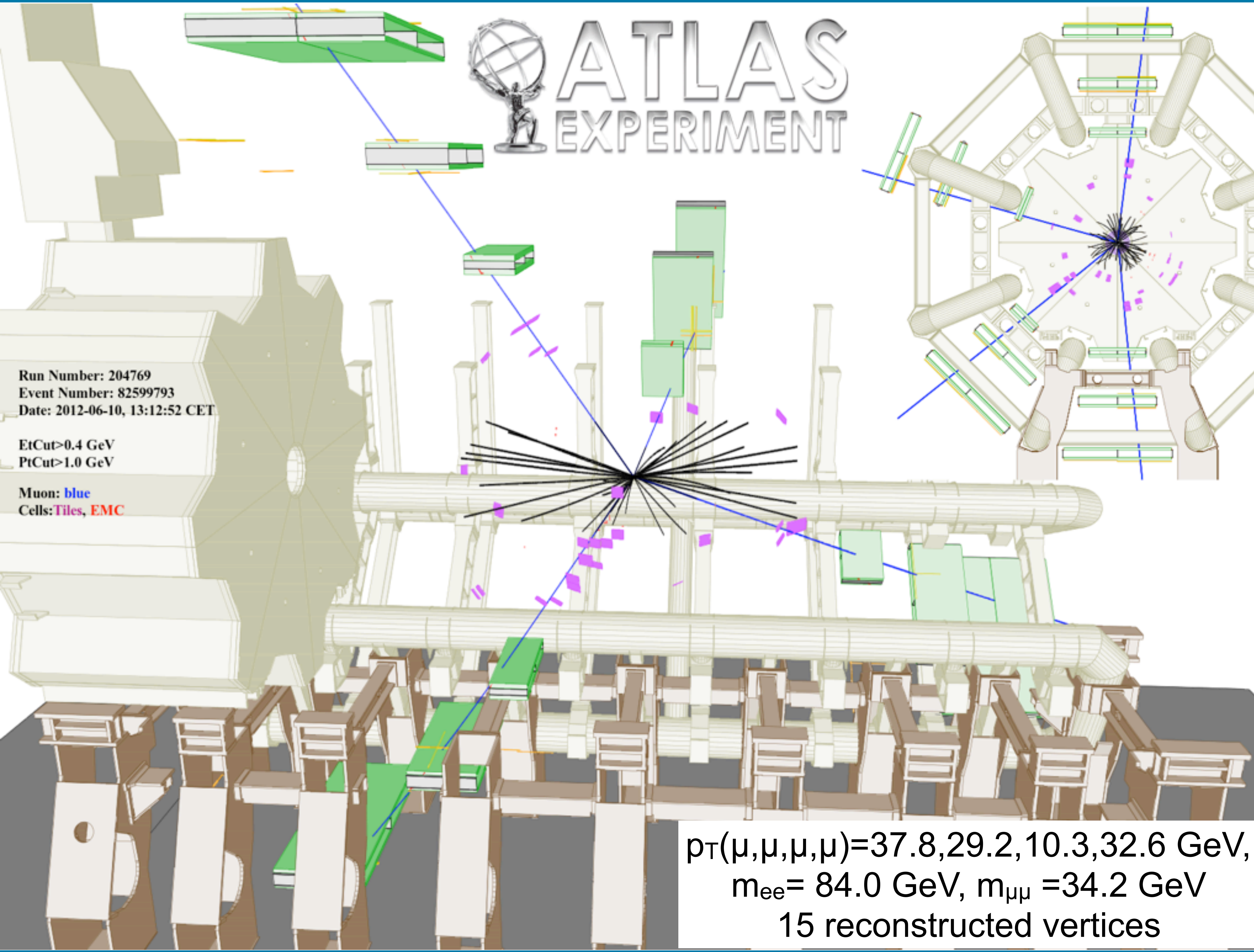
50 GeV < m_{12} < 106 GeV,
$m_{thr}(m_{4l})$ < m_{34} < 115 GeV m_{thr} = 12 - 50 GeV
→ all same-flavor opposite-sign pairs m_{ll} > 5 GeV
→ $\Delta R(l,l')$ > 0.10(0.20) for all same(different)-flavor

eeμμ candidate with m_{4l} = 123.9 GeV

$p_T(e,e,\mu,\mu)$=18.7,76.0,19.6,7.9 GeV,
m_{ee}= 87.9 GeV, $m_{\mu\mu}$ =19.6 GeV
12 reconstructed vertices

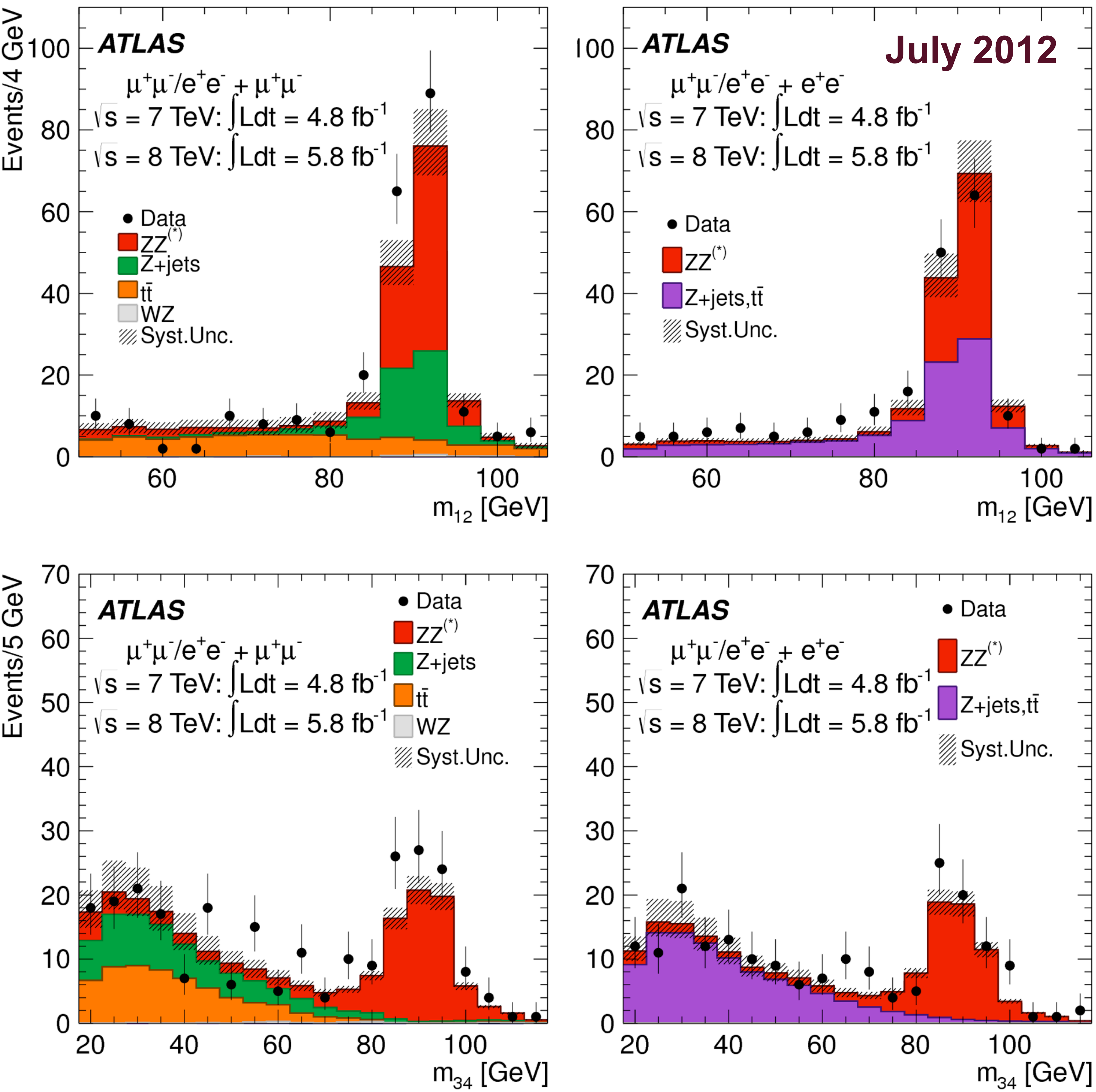


μμμμ candidate with m_{4l} = 123.5 GeV



$p_T(\mu,\mu,\mu,\mu)$=37.8,29.2,10.3,32.6 GeV,
m_{ee}= 84.0 GeV, $m_{\mu\mu}$ =34.2 GeV
15 reconstructed vertices

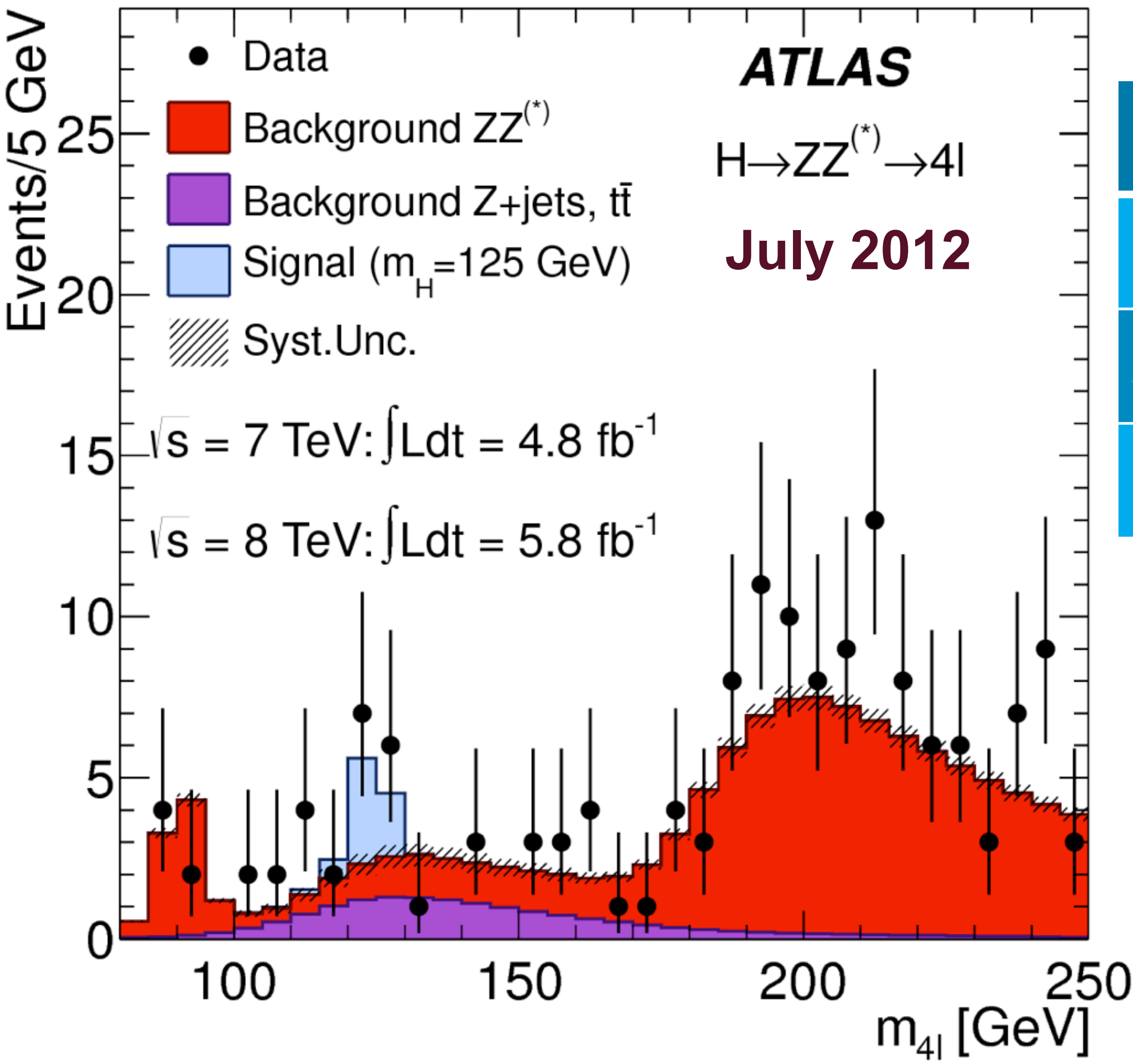
H→ZZ(*)→4l: Backgrounds



Background-dominated Control Region

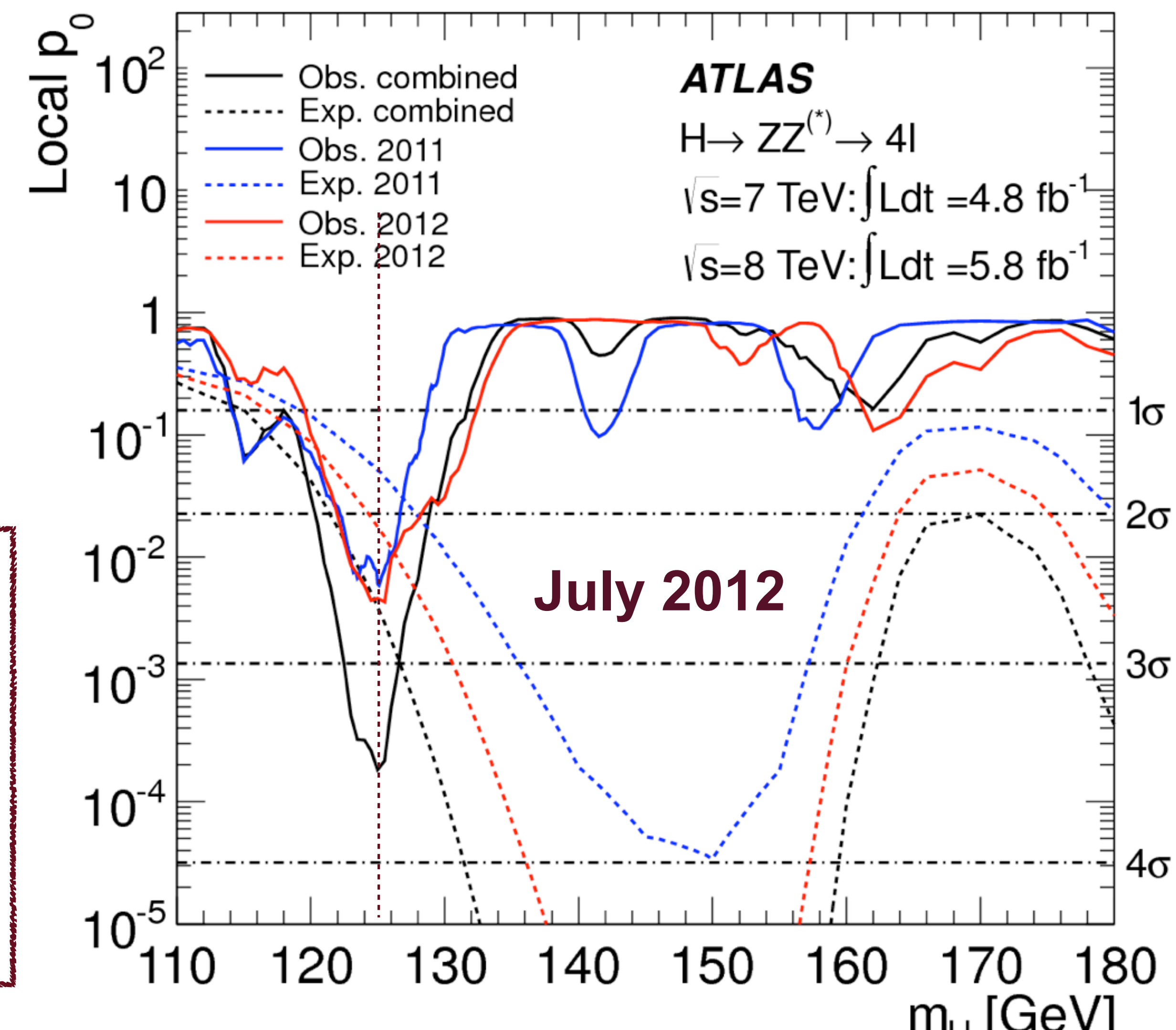
[Remove isolation/impact parameter requirements on sub-leading di-lepton]

$H \to ZZ^{(*)} \to 4l$: Results



for m_{4l} region with 125±5GeV

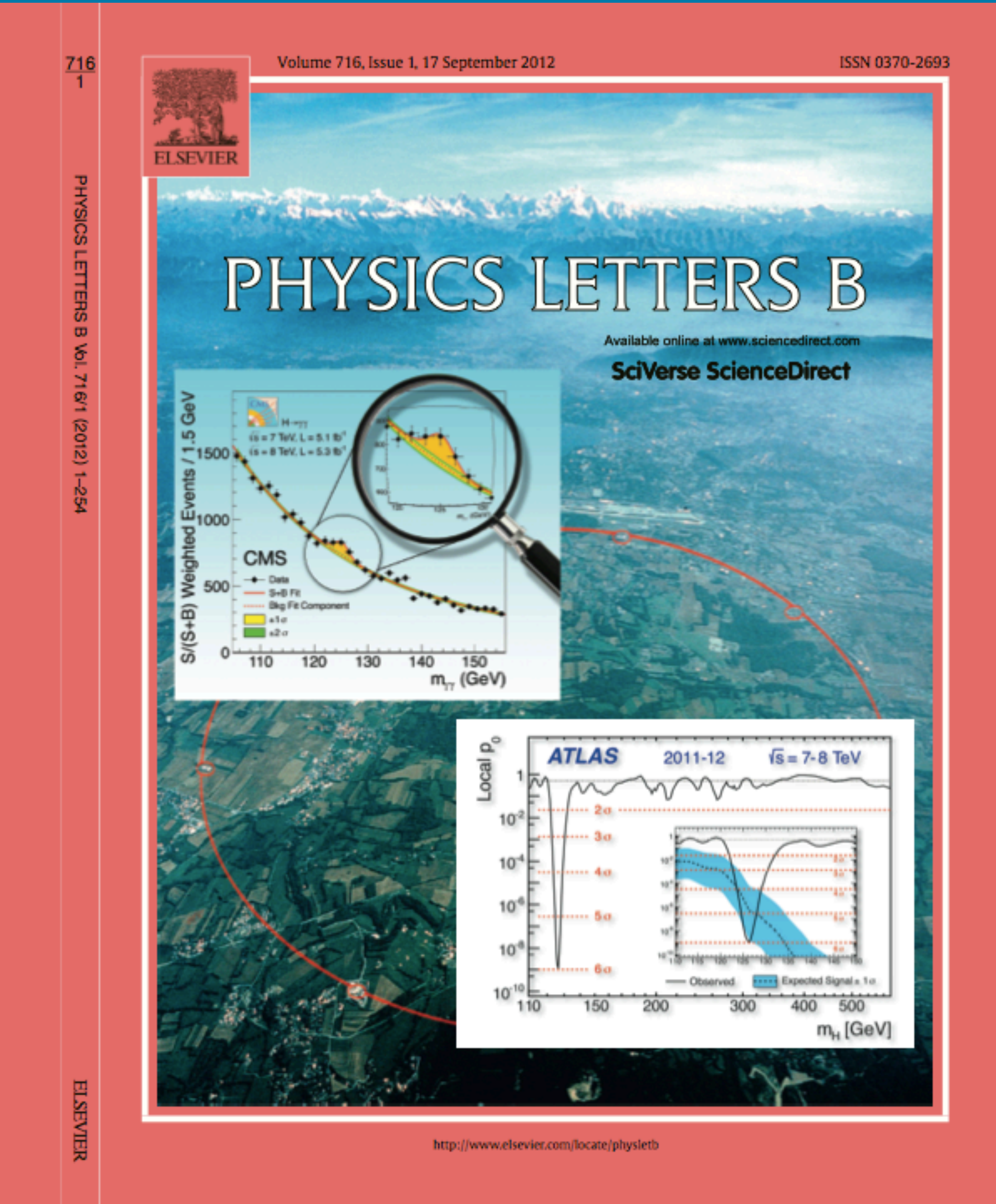
	Signal	$ZZ^{(*)}$	Other Backgrounds	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
2μ2e/2e2μ	2.29±0.33	0.80±0.05	1.27±0.19	5
4e	0.90±0.14	0.44±0.04	1.09±0.20	2

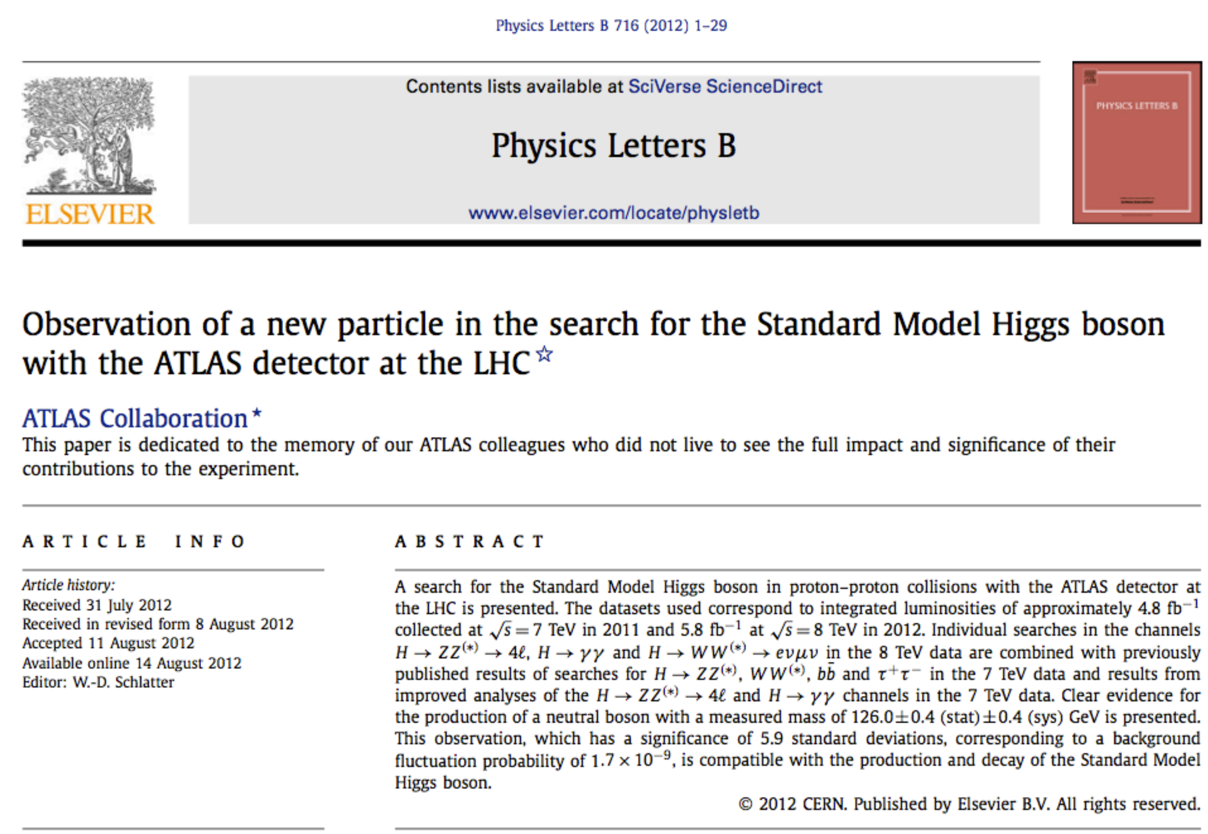


Significance of excesses

- 8 TeV (2012): 2.6σ at 125.5 GeV, expected 2.1σ
- 7 TeV (2011): 2.5σ at 125 GeV, expected 1.6σ
- Combined: **3.6σ** at m_H=125 GeV, expected 2.7σ
- ~2.5σ after look-elsewhere effect (110-141 GeV)

The discovery papers!





Physics Letters B 716 (2012) 1–29

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

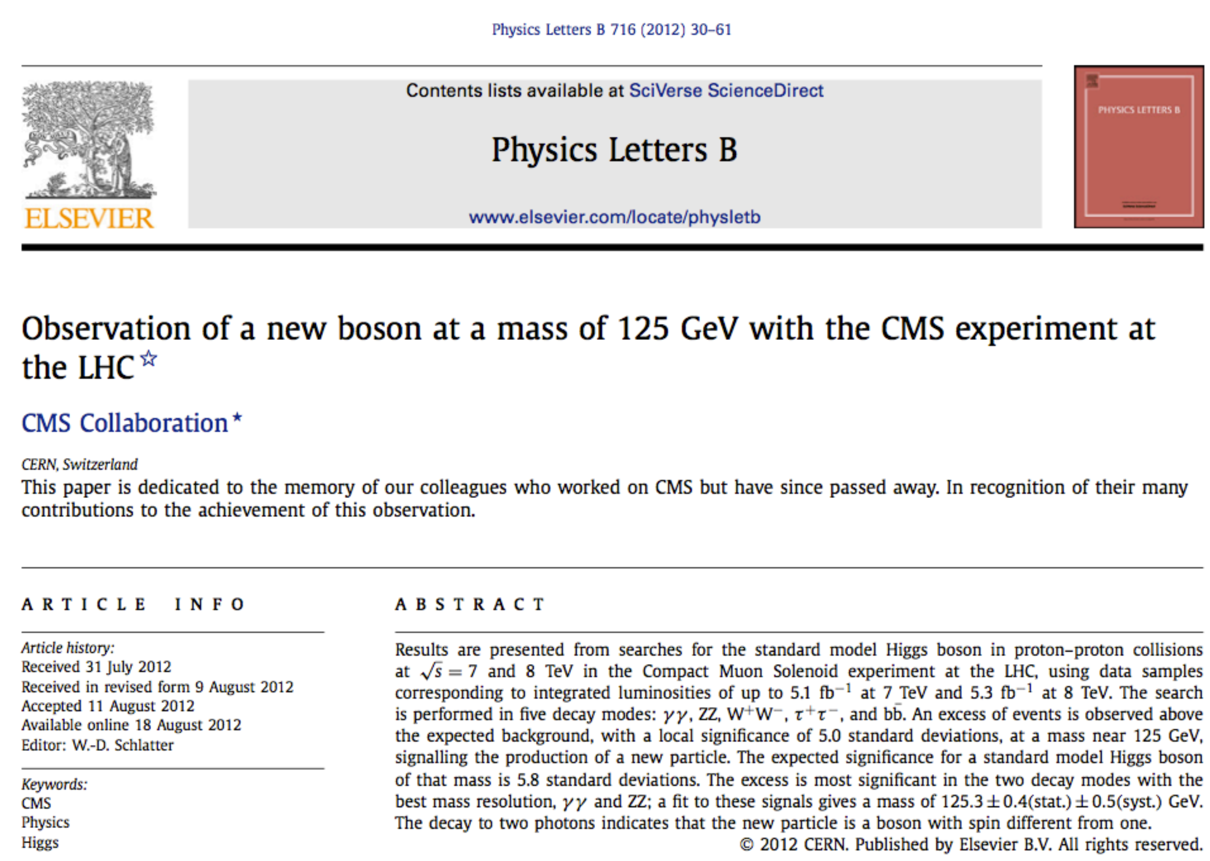
This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

ARTICLE INFO

Article history:
Received 31 July 2012
Received in revised form 8 August 2012
Accepted 11 August 2012
Available online 14 August 2012
Editor: W.-D. Schlatter

ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s}=7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s}=8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.



Physics Letters B 716 (2012) 30–61

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

ARTICLE INFO

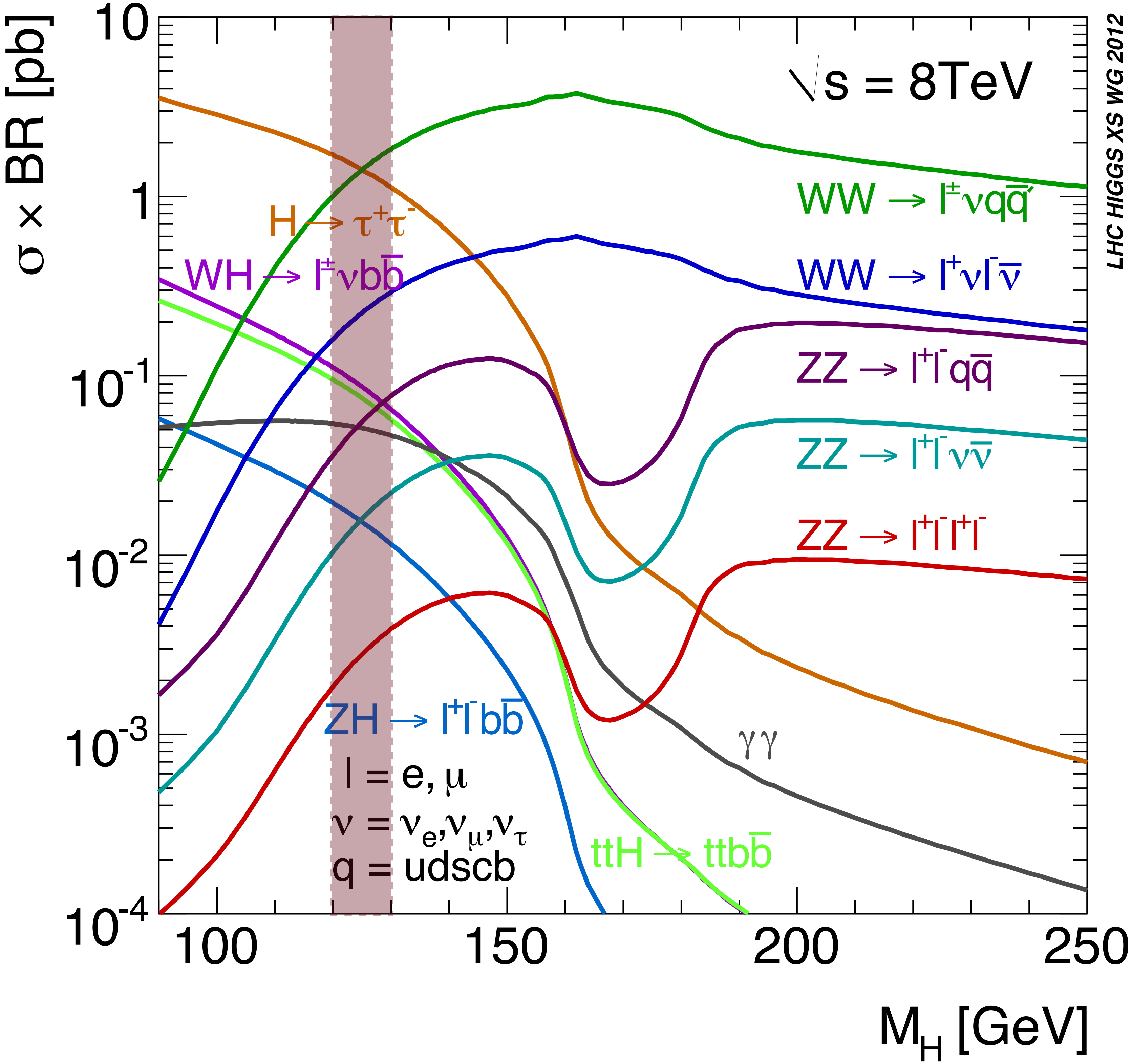
Article history:
Received 31 July 2012
Received in revised form 9 August 2012
Accepted 11 August 2012
Available online 18 August 2012
Editor: W.-D. Schlatter

Keywords:
CMS
Physics
Higgs

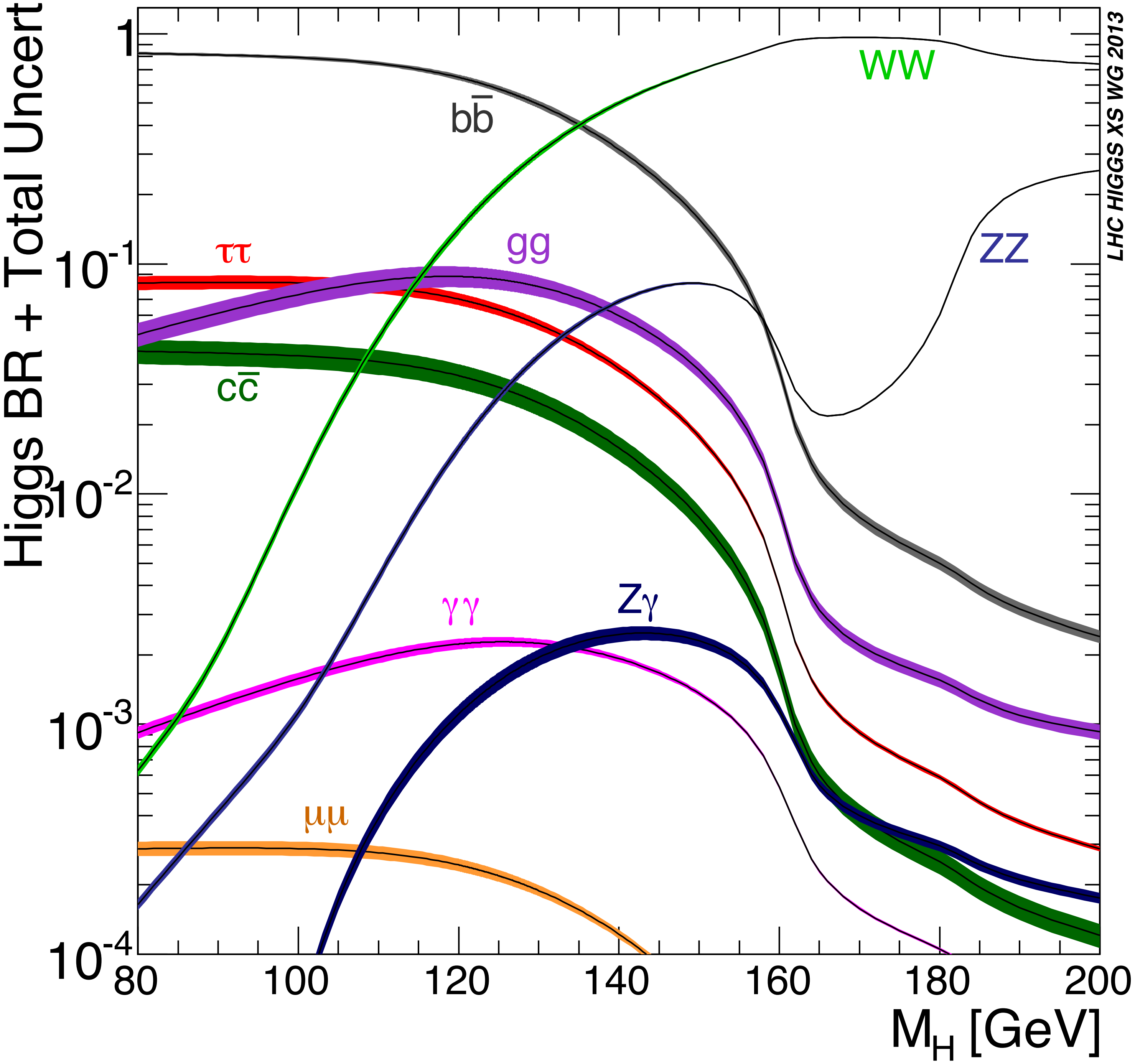
ABSTRACT

Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s}=7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and bb. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

Higgs boson decays



As many as possible of the potential final states of the newly found particle should be studied!

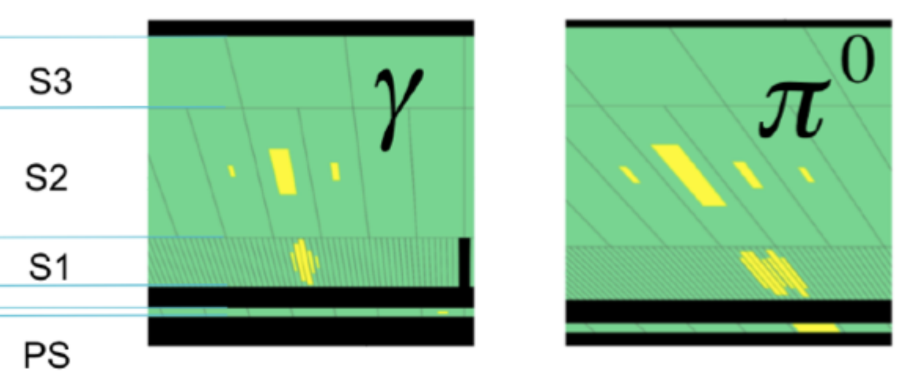


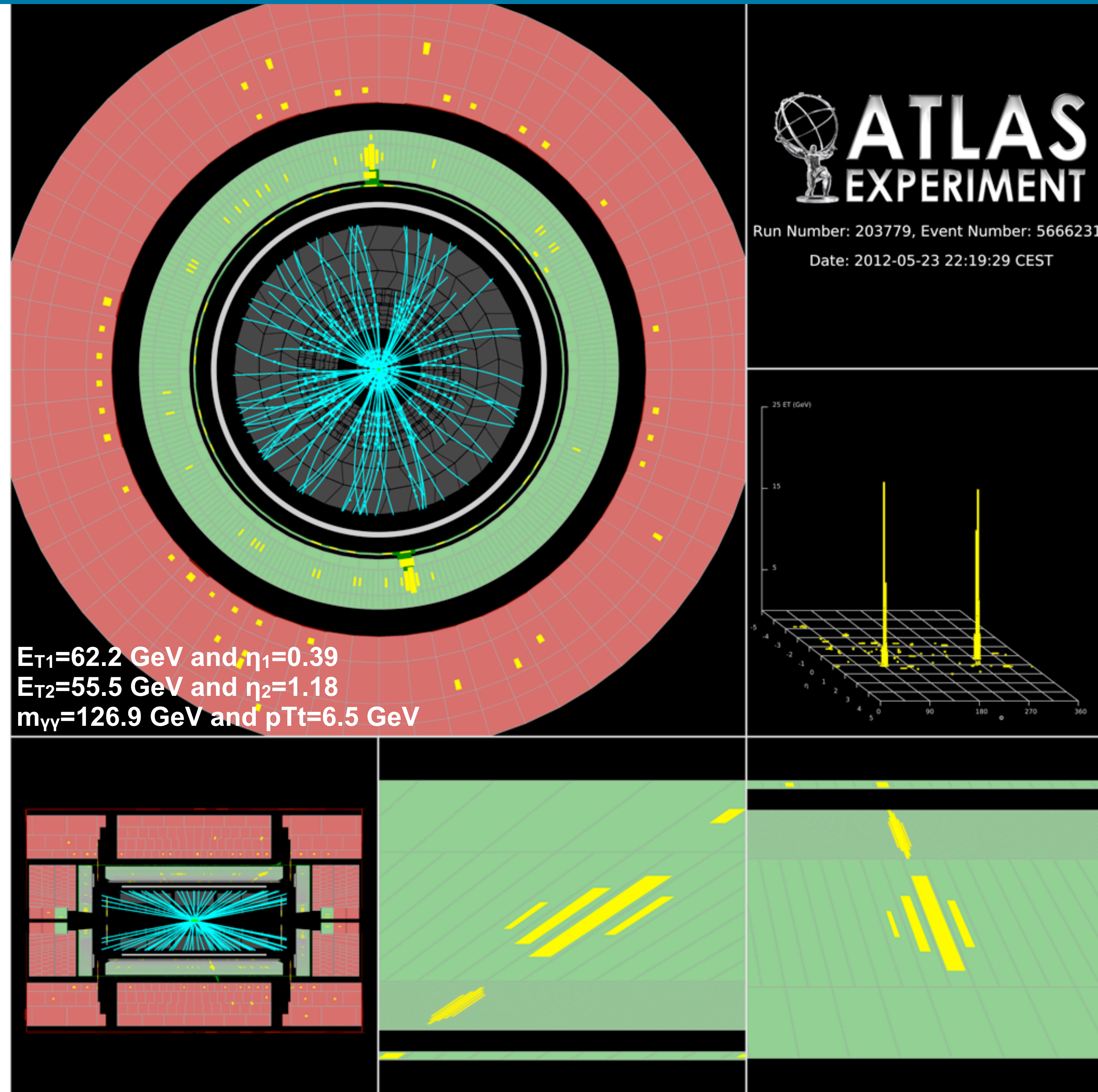
$H \rightarrow \gamma\gamma$

H→γγ

- Sensitive for low m_H (110 - 150 GeV)
- Search for narrow peak in $m_{\gamma\gamma}$
  - Background from data
  - Categorize wrt S/B and resolution
- Main Backgrounds:
  - → di-photon ➛ $m_{\gamma\gamma}$ resolution
  - → jj and γj ➛ photon-ID

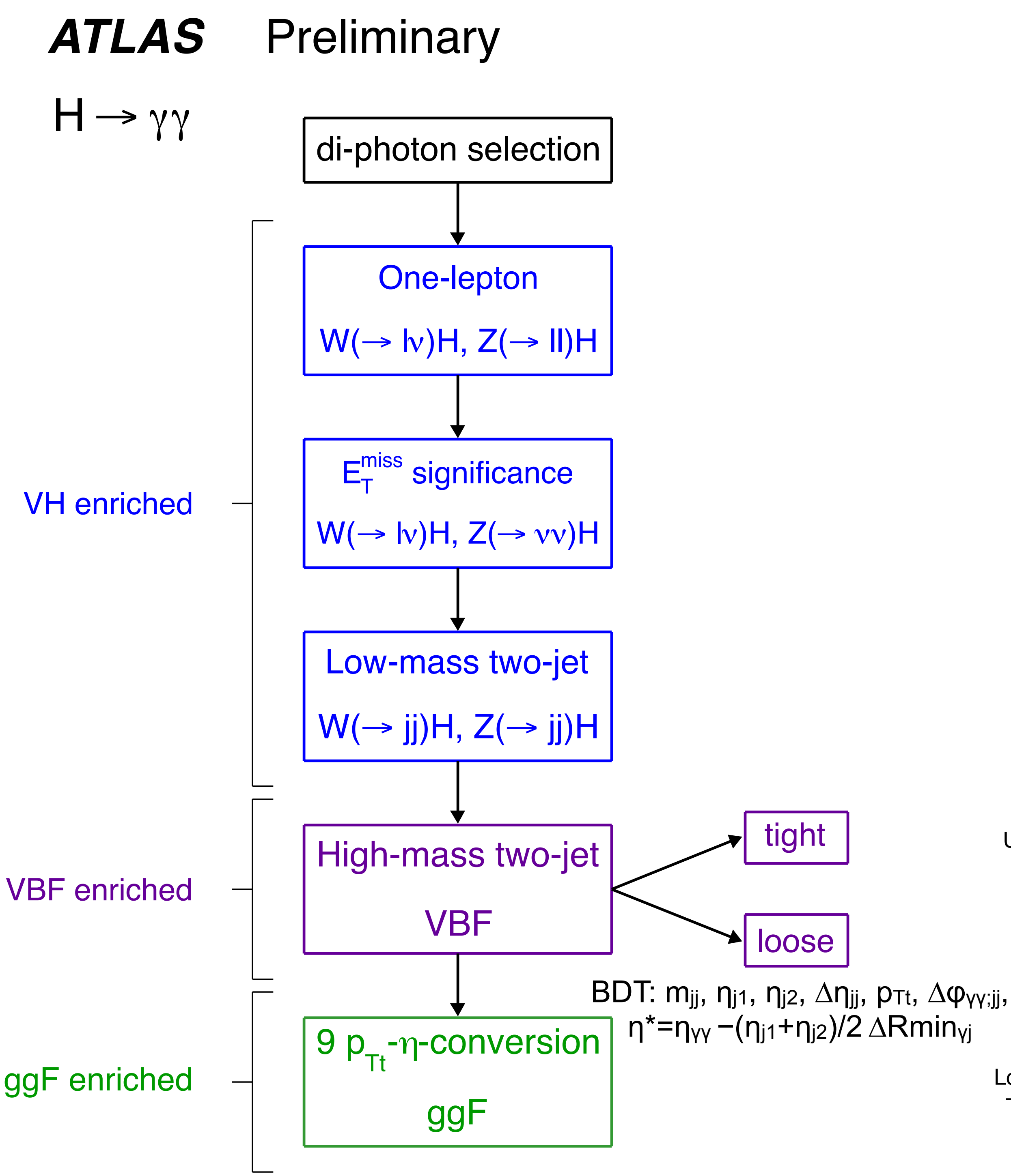
π^0-γ Rejection





H→γγ: Event Categories

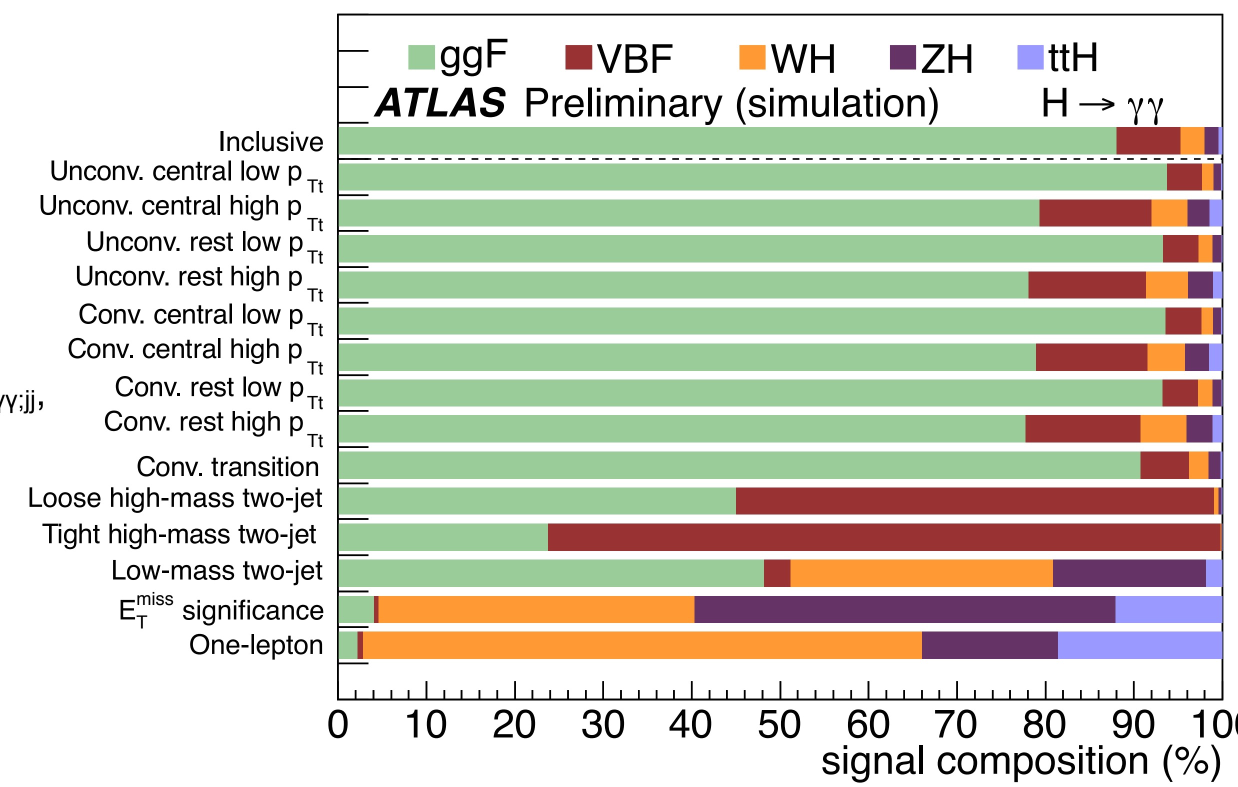
Improve the overall S/B of the analysis, and enhance particular signal contributions for properties studies



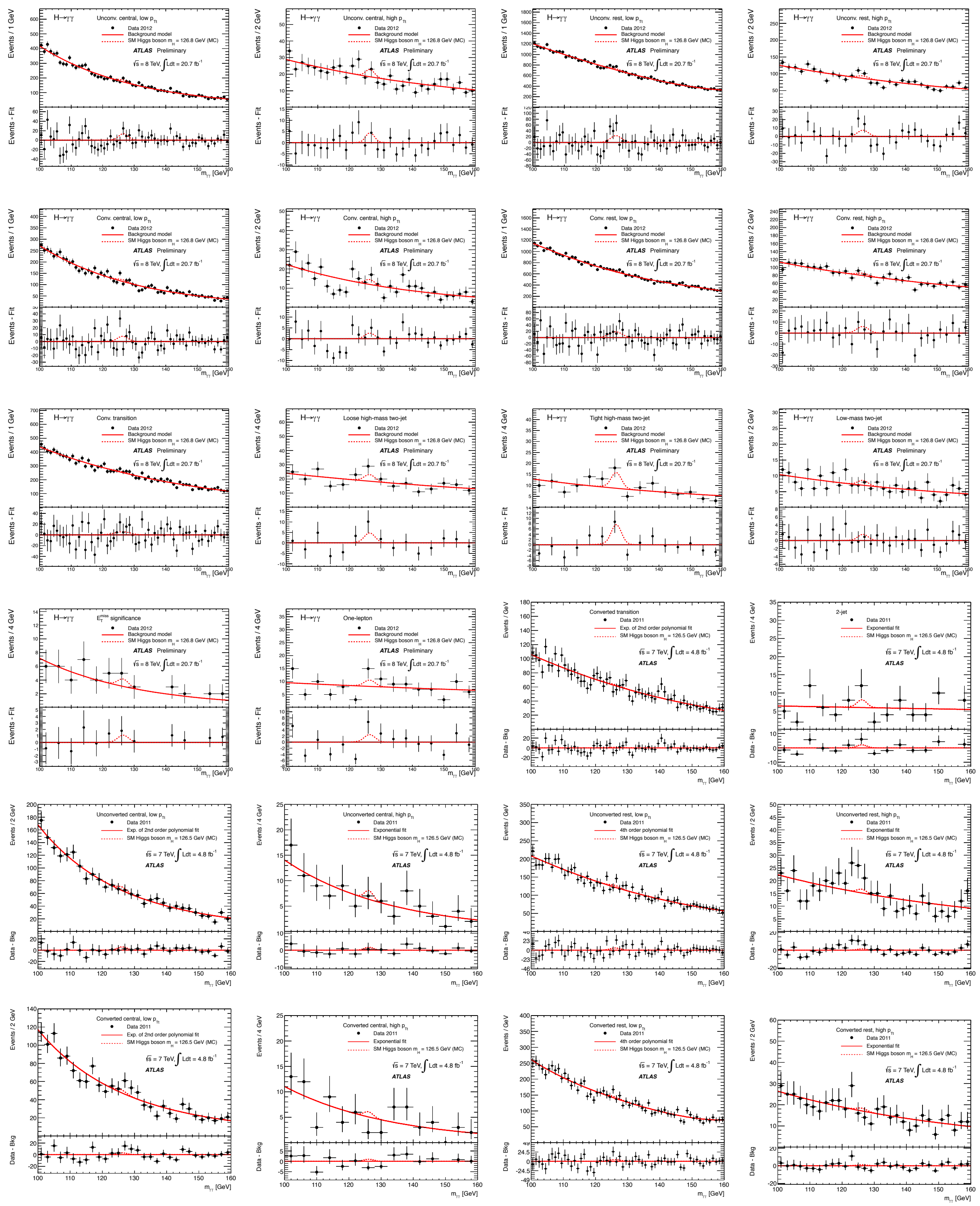
14 exclusive categories

8 TeV (90% signal window)

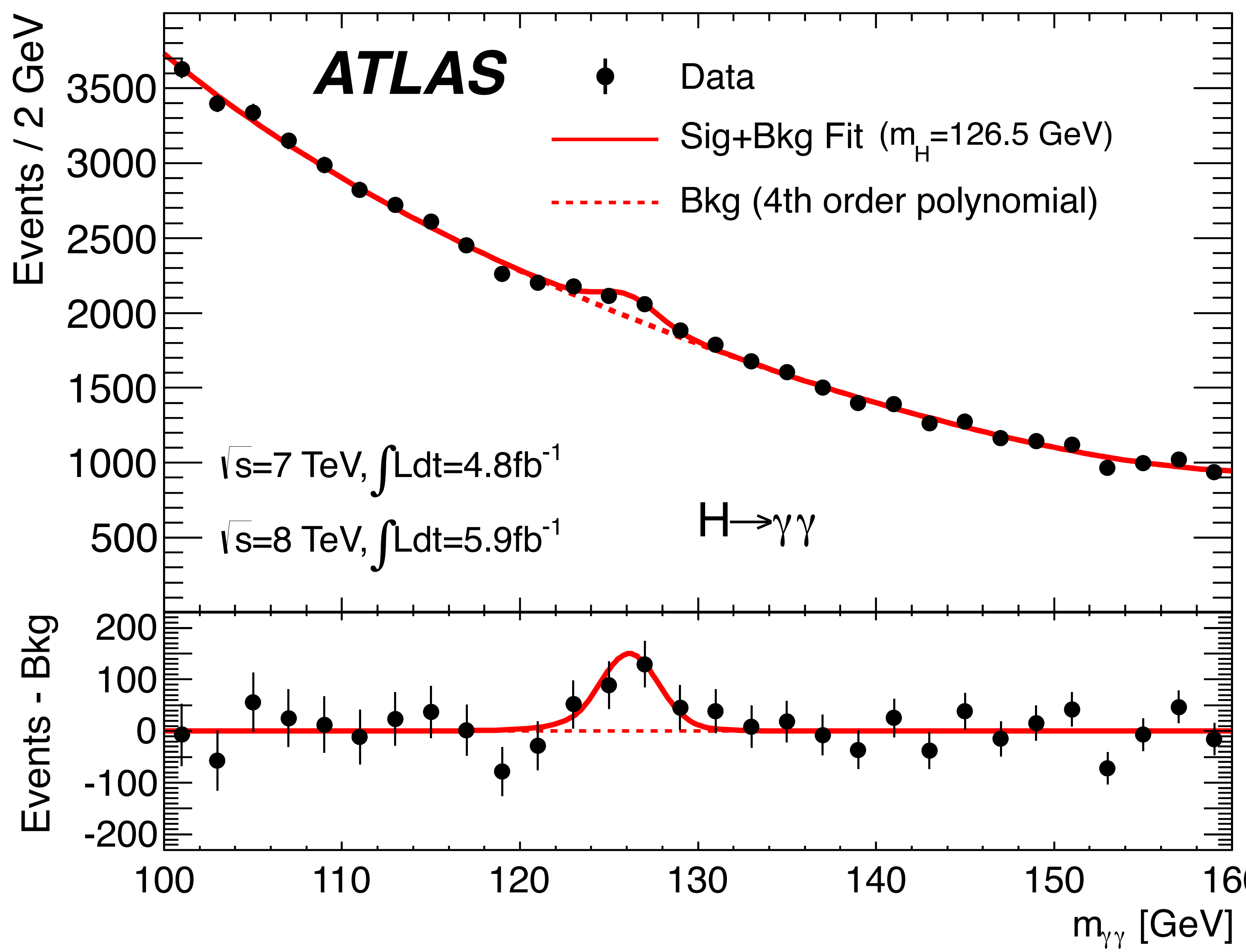
$\sqrt{s}$	8 TeV				
Category	σ_{CB}(GeV)	Observed	N_S	N_B	N_S/N_B
Unconv. central, low p_{Tt}	1.50	911	46.6	881	0.05
Unconv. central, high p_{Tt}	1.40	49	7.1	44	0.16
Unconv. rest, low p_{Tt}	1.74	4611	97.1	4347	0.02
Unconv. rest, high p_{Tt}	1.69	292	14.4	247	0.06
Conv. central, low p_{Tt}	1.68	722	29.8	687	0.04
Conv. central, high p_{Tt}	1.54	39	4.6	31	0.15
Conv. rest, low p_{Tt}	2.01	4865	88.0	4657	0.02
Conv. rest, high p_{Tt}	1.87	276	12.9	266	0.05
Conv. transition	2.52	2554	36.1	2499	0.01
Loose High-mass two-jet	1.71	40	4.8	28	0.17
Tight High-mass two-jet	1.64	24	7.3	13	0.57
Low-mass two-jet	1.62	21	3.0	21	0.14
E_T^{miss} significance	1.74	8	1.1	4	0.24
One-lepton	1.75	19	2.6	12	0.20
Inclusive	1.77	14025	355.5	13280	0.03



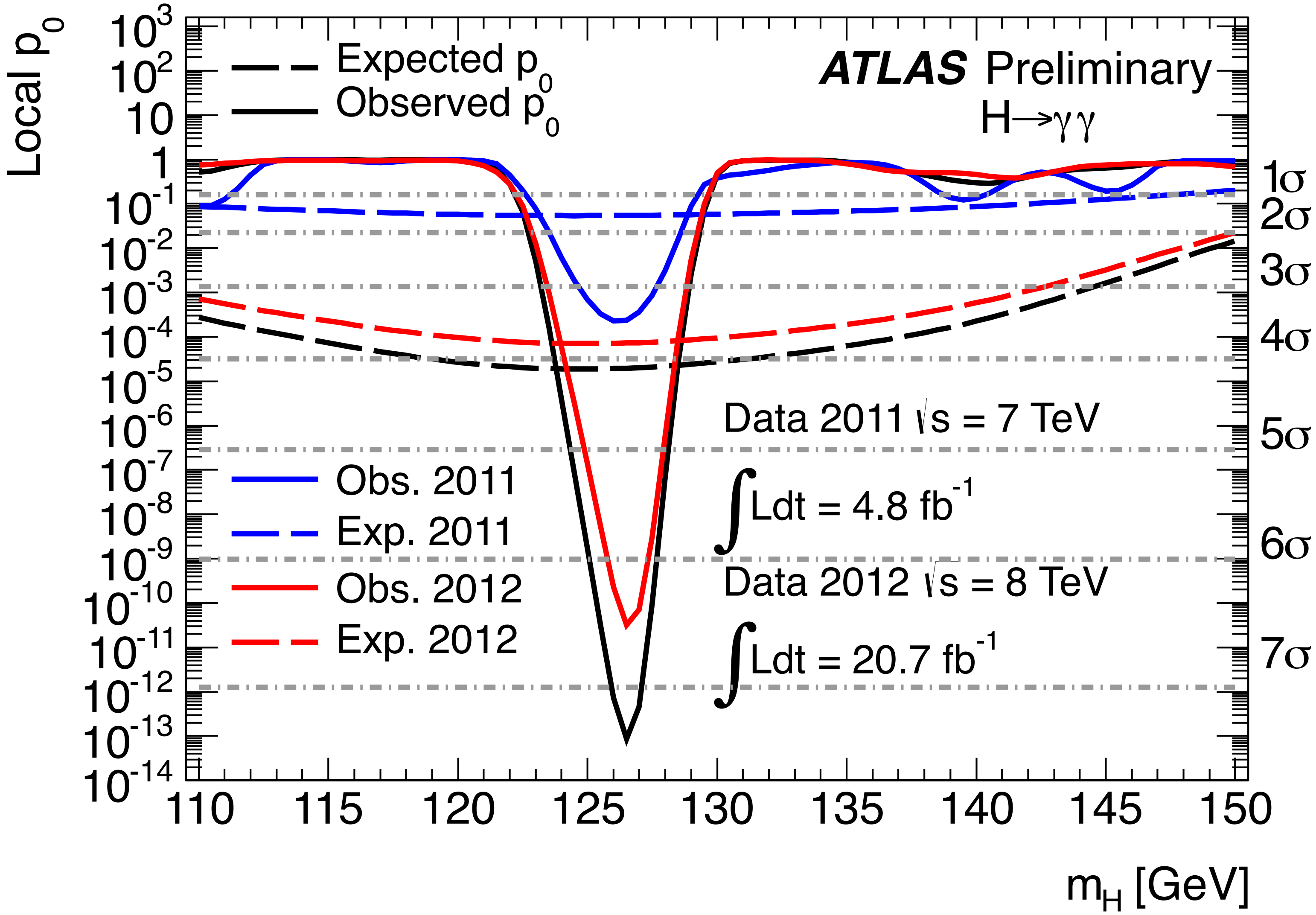
H→γγ: $m_{\gamma\gamma}$ spectra



all categories

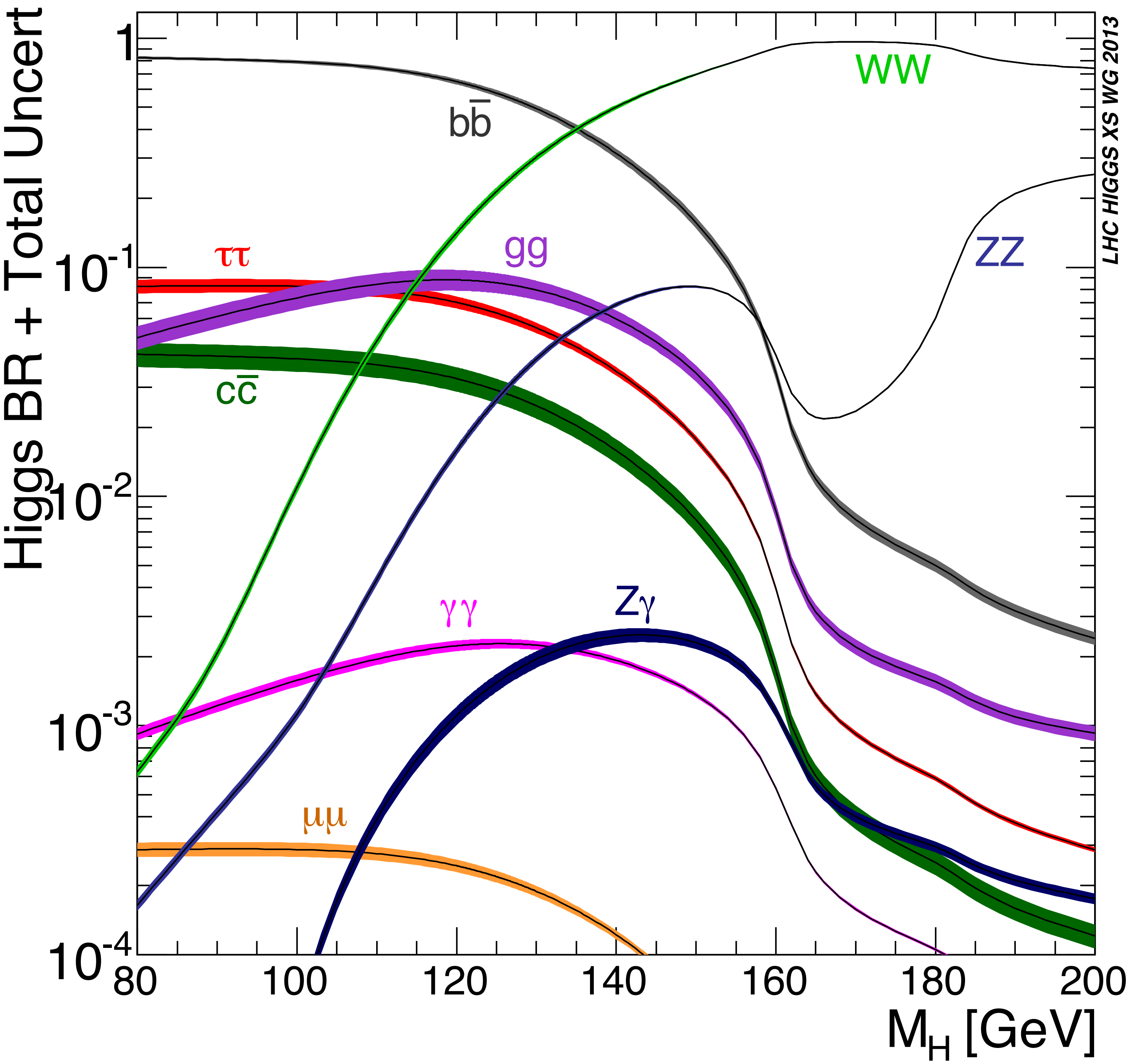


H→γγ: Results



Most significant deviation from background only hypothesis at m_H =126.5 GeV:

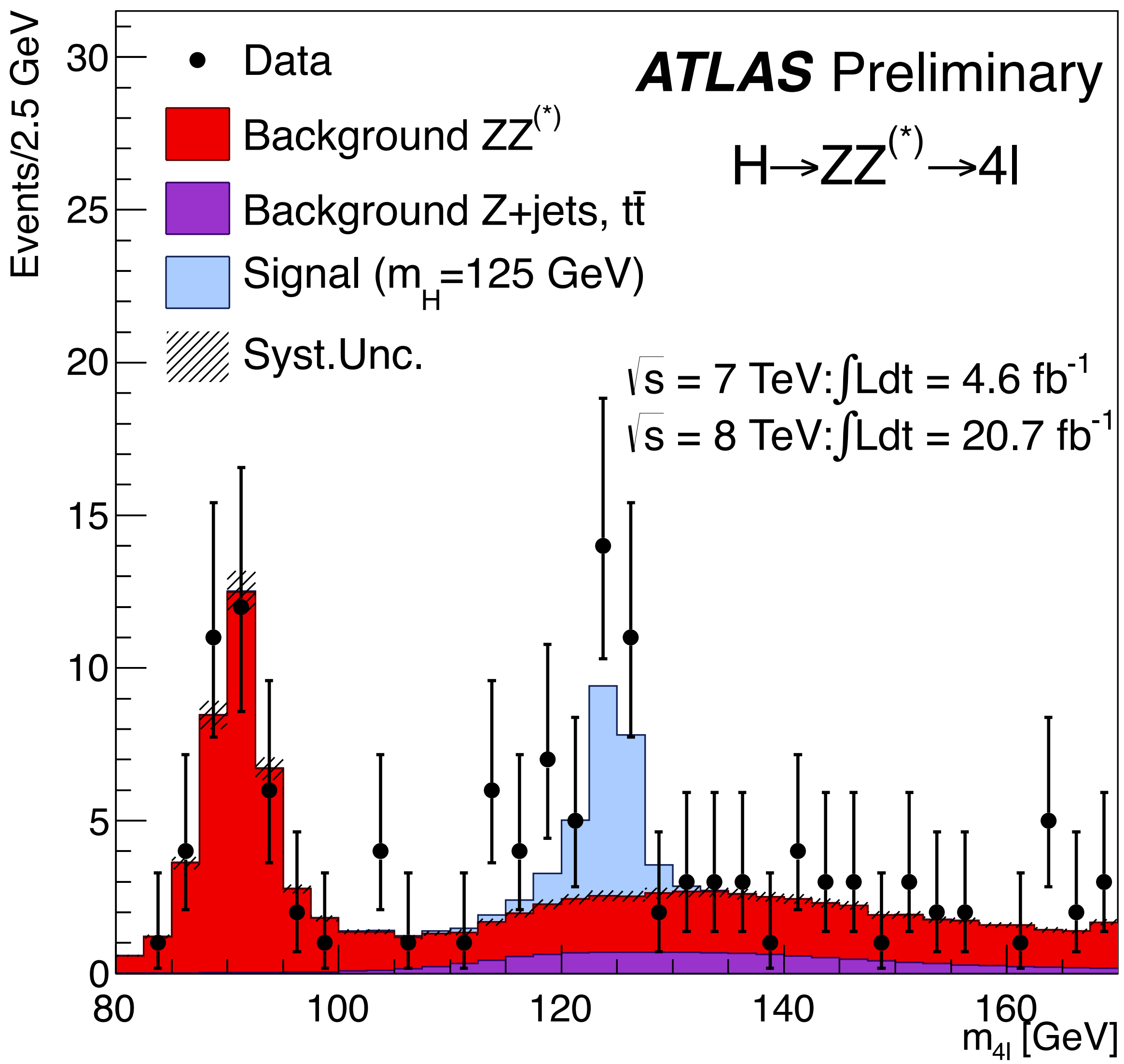
- Local significance: **7.4σ** (with 4.1σ expected) @ m_H=126.5 GeV
  - Inclusive analysis: 6.1σ (with 2.9σ expected)
- Mass measurement: **126.8 ± 0.2 (stat) ± 0.7 (syst) GeV**
  - Main systematics: γ energy scale from Z→ee, material modeling and presampler energy scale → 0.6 GeV
- Rate with respect to Standard Model: **$1.65 \pm 0.24\ (stat)^{+0.25}_{-0.85}$**
  - 2.3σ deviation from the Standard Model

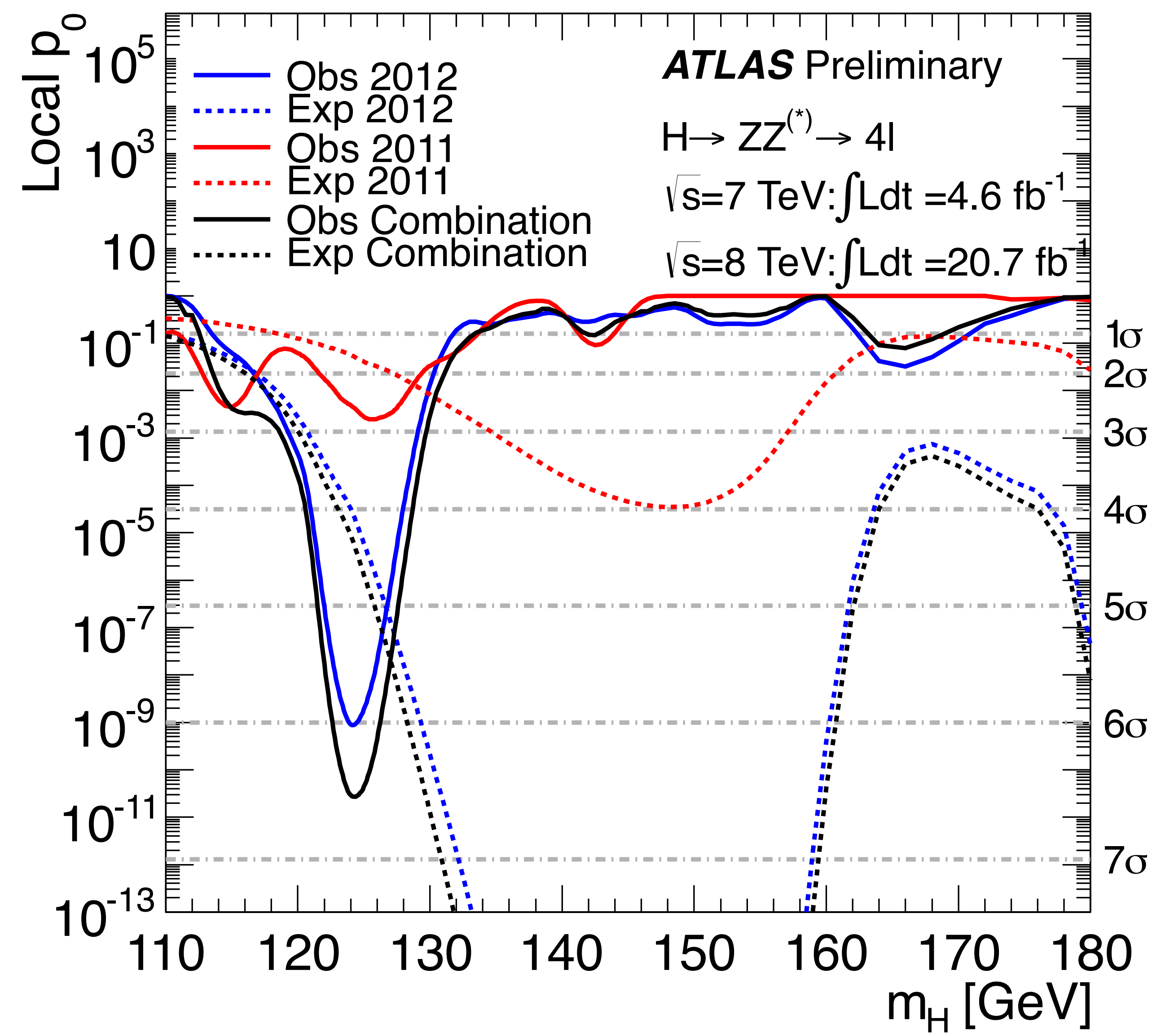


Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200
M_H [GeV]
$b\bar{b}$
WW
$\tau\tau$
gg
ZZ
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$
$\mu\mu$

H→ZZ→4l

$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Results of Event Selection





for m_{4l} region with 125±5GeV

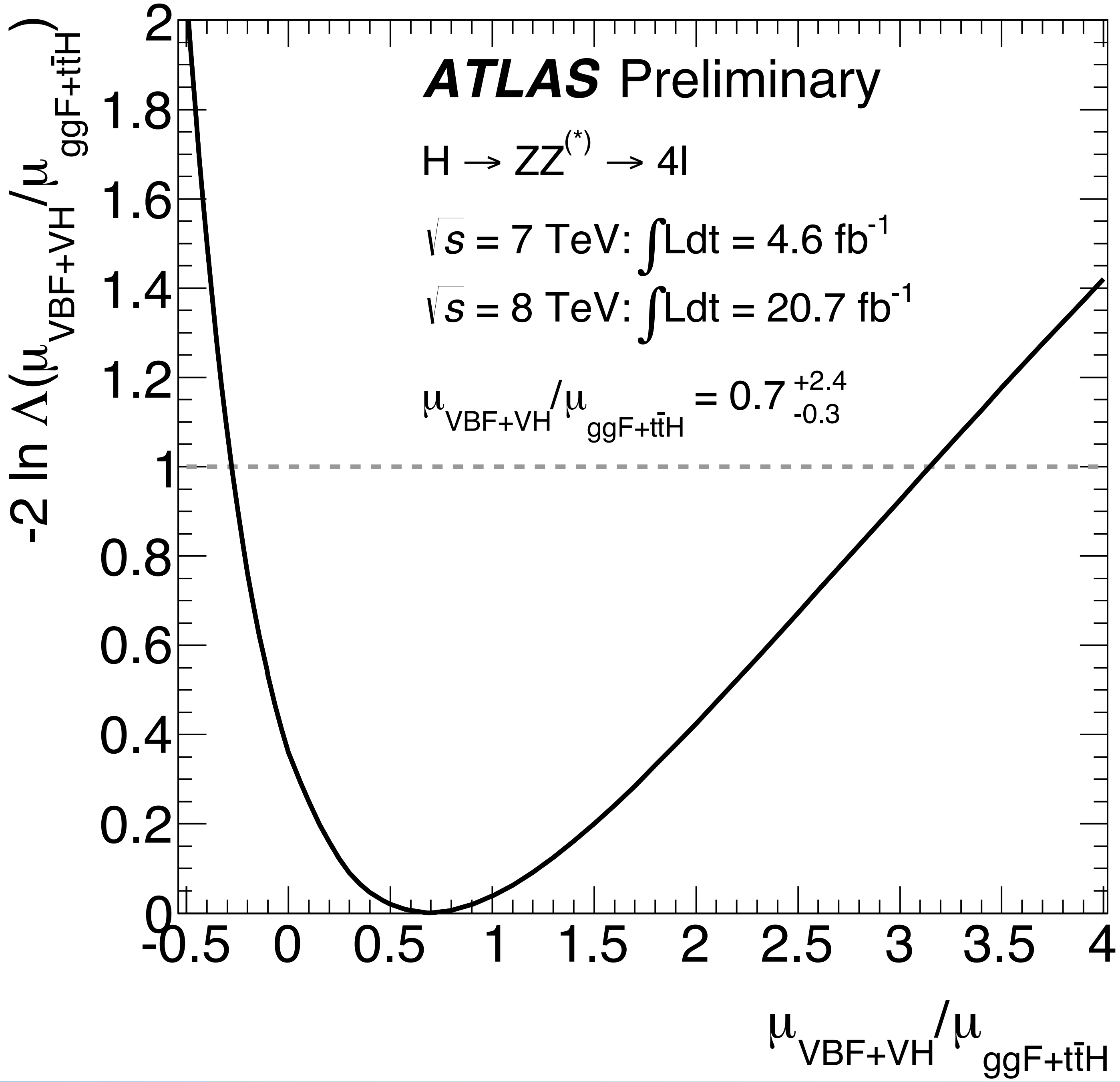
	Signal	$ZZ^{(*)}$	Other Background	Observed	S/B
4μ	6.3±0.8	2.8±0.1	0.55±0.15	13	~1.9
2μ2e	3.0±0.4	1.4±0.1	1.56±0.33	5	~1.0
2e2μ	4.0±0.5	2.1±0.1	0.55±0.17	7	~1.5
4e	2.6±0.4	1.2±0.1	1.11±0.28	6	~1.1

- Local significance: **6.6σ** (4.4σ)@m_H=124.3GeV
- Mass: **$124.3^{+0.6}_{-0.5}$(stat)$^{+0.5}_{-0.3}$(syst) GeV**
  - Main systematics: electron/muon energy/ momentum scale uncertainties
- Rate with respect to SM: $1.7^{+0.5}_{-0.4}$
  - **1.5 ± 0.4 @ m_H=125.5 GeV**

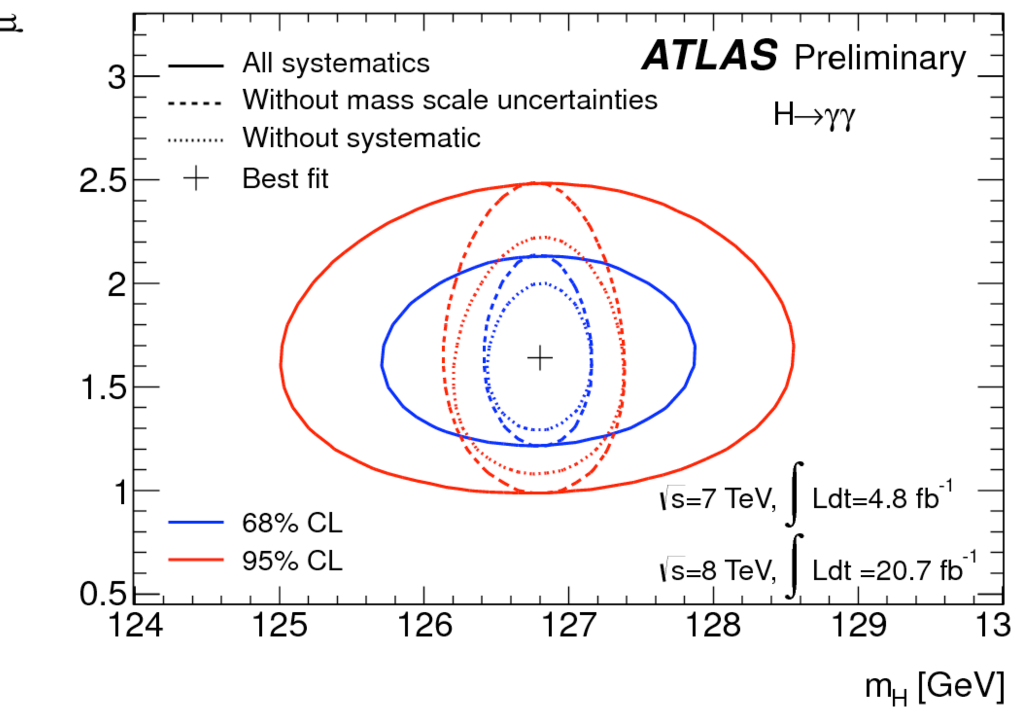
H→ZZ$^{(*)}$→4l: Couplings

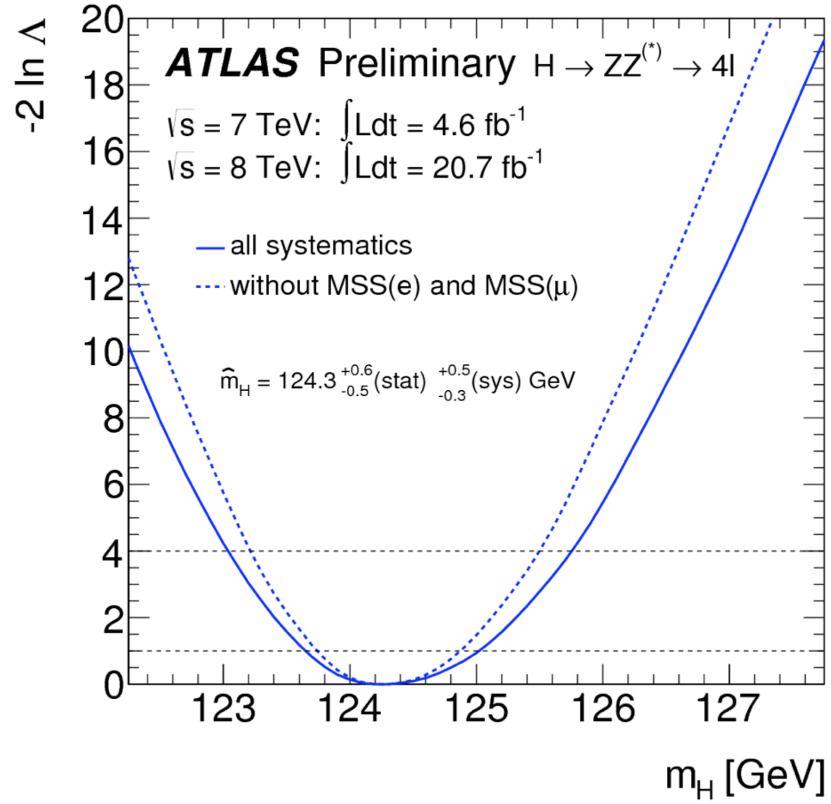
The couplings of the Higgs boson are probed by further categorizing the observed events.

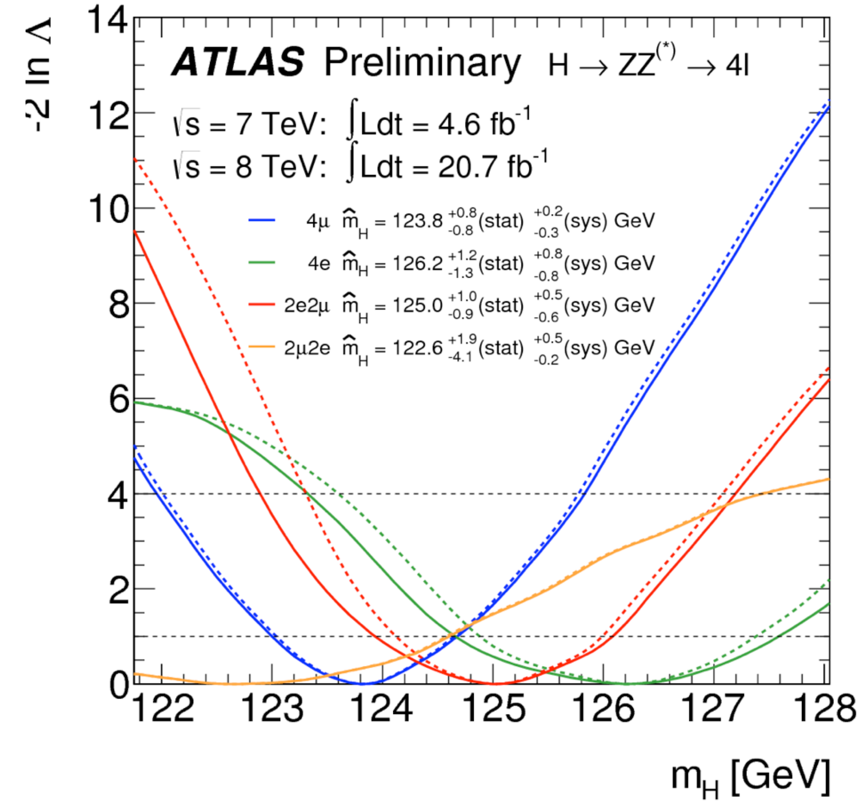
- VBF-like events : Events with at least two jets in VBF topology
- VH-like events : Events with additional leptons in the final state
- ggF-like events: All remaining events

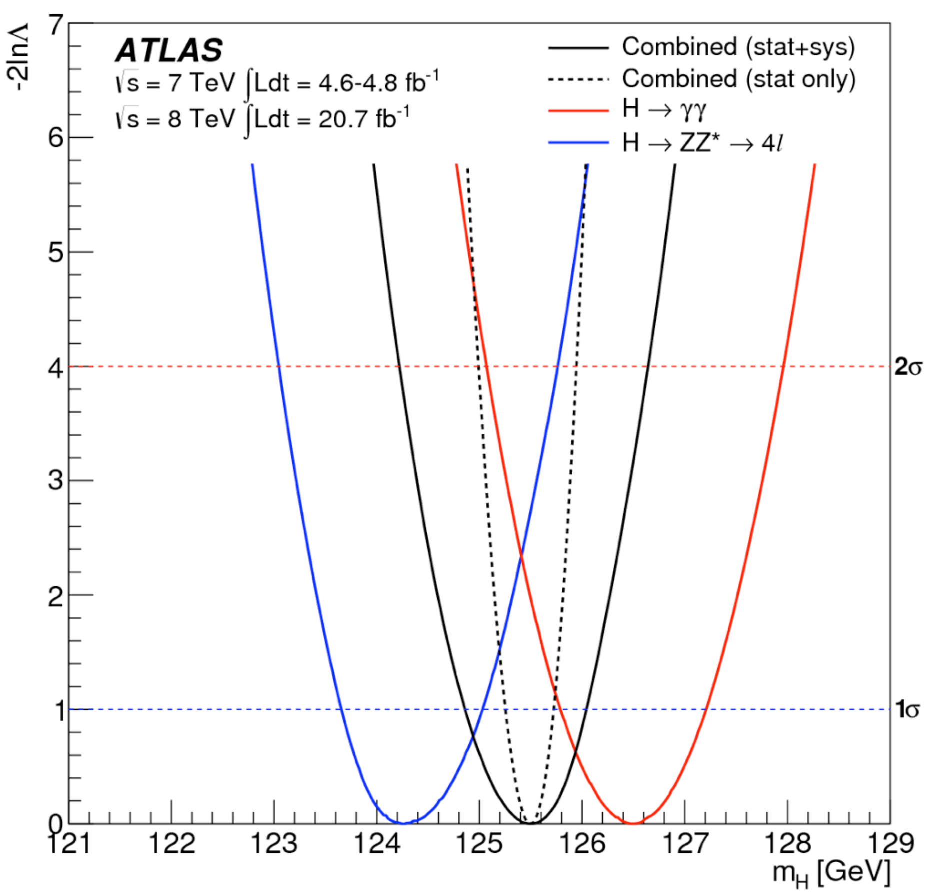


The Higgs boson mass









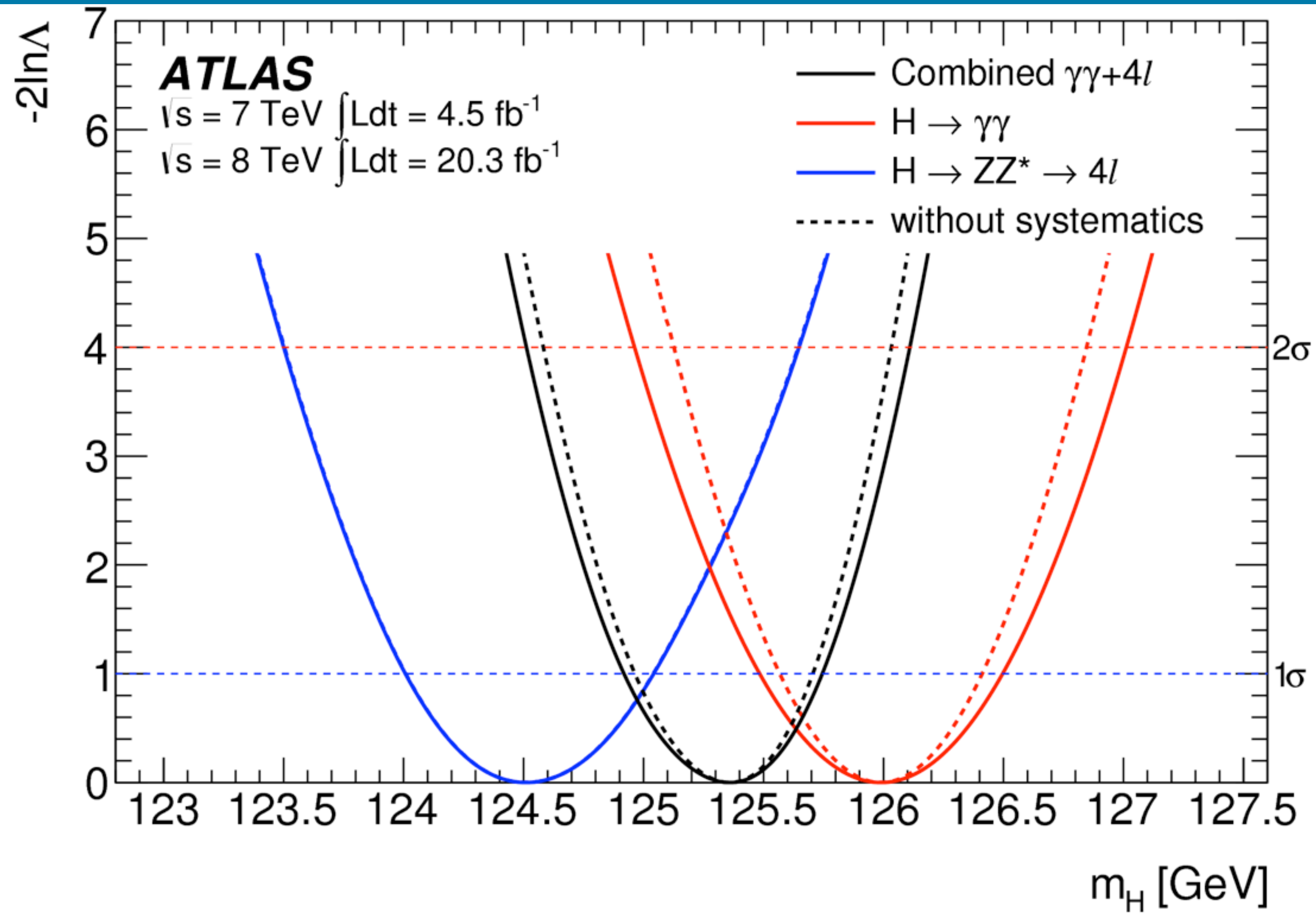
Higgs boson mass measurement using:

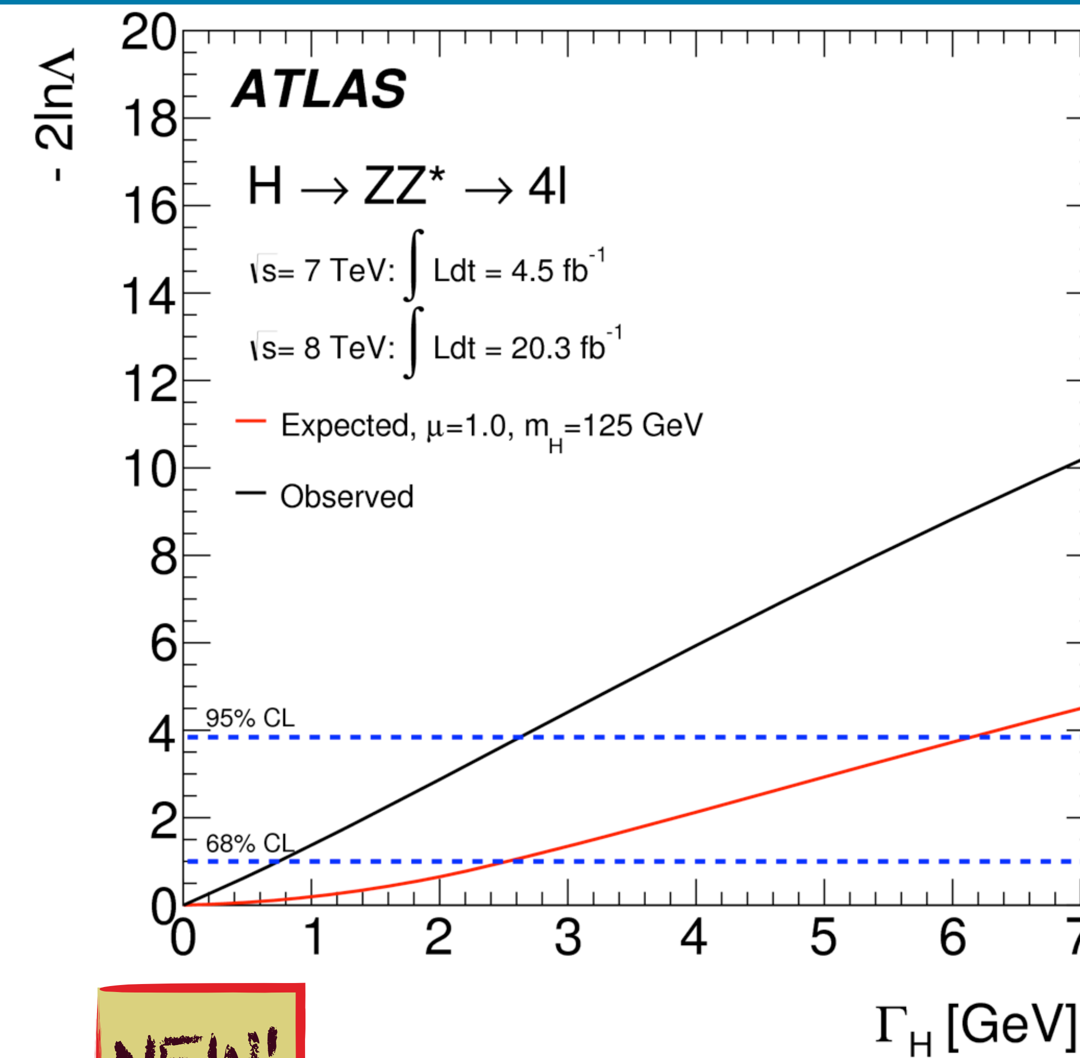
- H→γγ : **126.8 ± 0.2 (stat) ± 0.7 (syst) GeV**
- H→ZZ→4l : **$124.3^{+0.6}_{-0.5}$(stat)$^{+0.5}_{-0.3}$(syst) GeV**

Combined m_H:**125.5 ± 0.2 (stat)$^{+0.5}_{-0.6}$ (syst) GeV**

- single particle to give as much/more discrepant result 1.5% (2.4σ)
- by moving ±1σ the main systematics (calibration, upstream material, pre-samples energy scale) consistency increases up to 8%
- H→4l consistency leads to -0.8σ adjustment of e/γ energy scale
  - shift -350 MeV for H→γγ mass
- CMS : m_H = **125.7 ± 0.3 (stat) ± 0.3 (syst) GeV**

H→ZZ(*)→4l/H→γγ: m_H and Γ_H measurement





Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZ^* \to 4\ell$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

NEW!

H→ZZ→4l
- Event-by-event (detector response)⊗(H line-shape)
- Γ_H<2.6 (6.2@SM rate) GeV @ 95% CLs

H→γγ
- Non-relativistic Breit-Wigner ⊗ detector resolution
- Γ_H<5.0 (6.2@SM rate) GeV @ 95% CLs

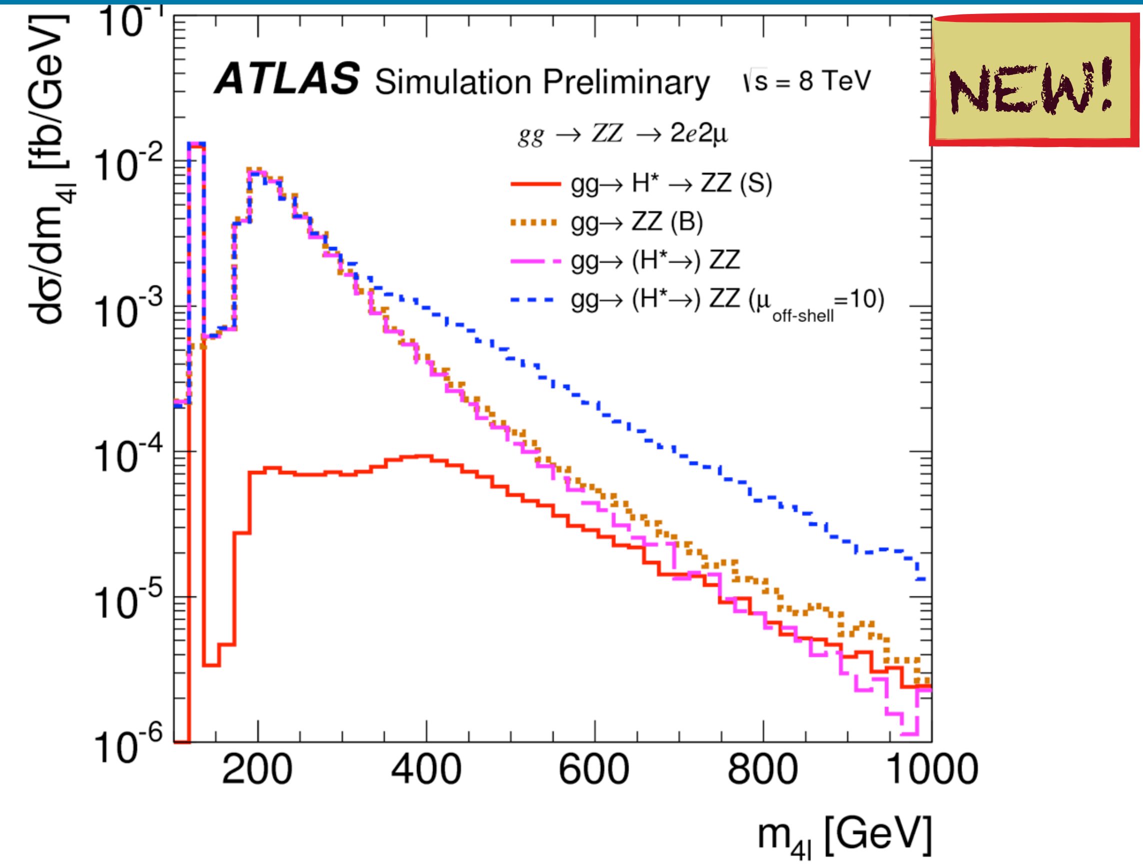
H→4l/H→γγ compatibility: **1.97σ**
- fixing rates to SM expectation →1.6σ
- γ systematics as box →1.8σ

Indirect Γ_H measurement: Introduction

Off-shell production of Higgs boson provides indirect constraint to Γ_H

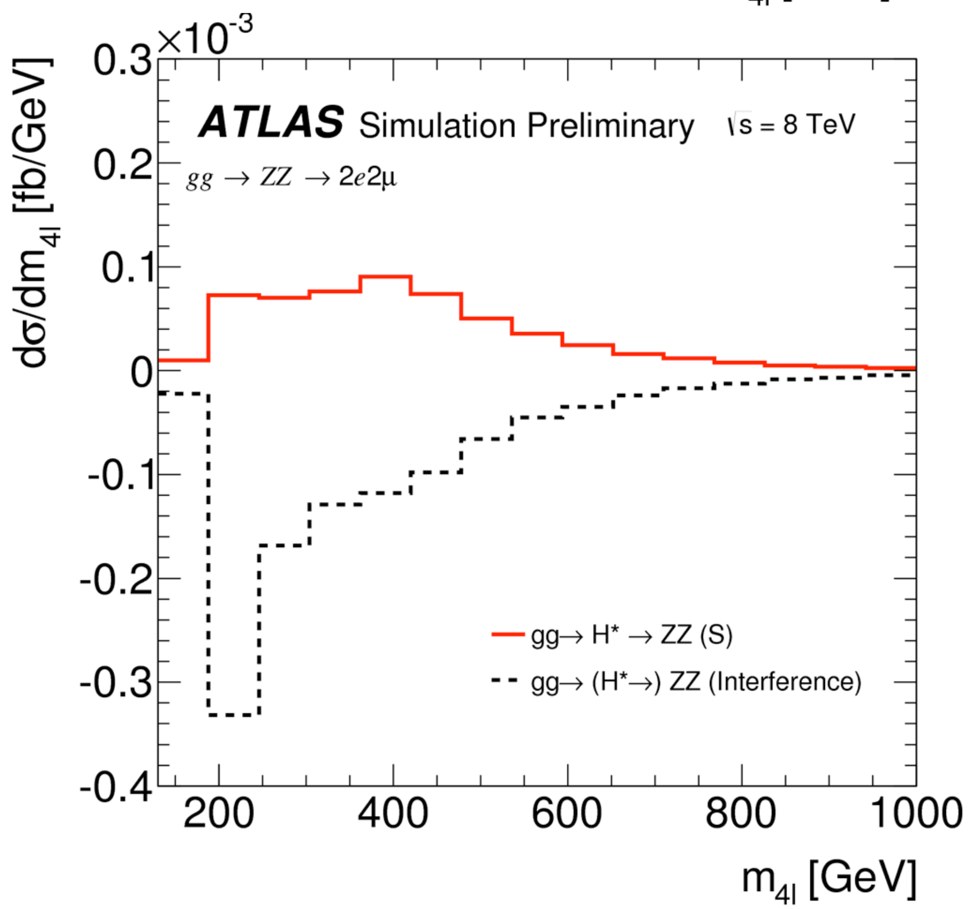
$$\frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}}\cdot\kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

$$\frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell, SM}}} = \mu_{\text{off-shell}} = \kappa^2_{g,\text{off-shell}}\cdot\kappa^2_{V,\text{off-shell}}$$



Implemented with H→ZZ with the following assumptions:

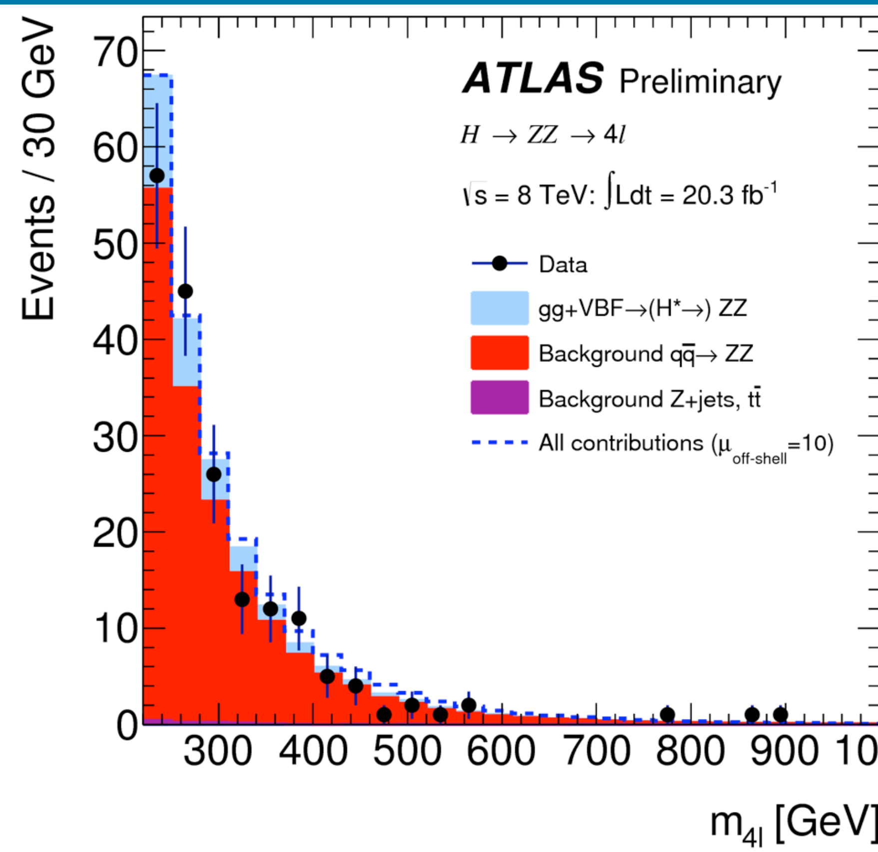
→ Backgrounds insensitive to new physics modifying off-shell couplings
→ Running of couplings similar for on-shell/off-shell region
→ Use inclusive selections [where HO corrections available]
→ gg→ZZ K-factors in off-shell region unknown
[for signal known to NNLO, gg→WW at NLO indicates that K-factors may be of similar magnitude, see later]

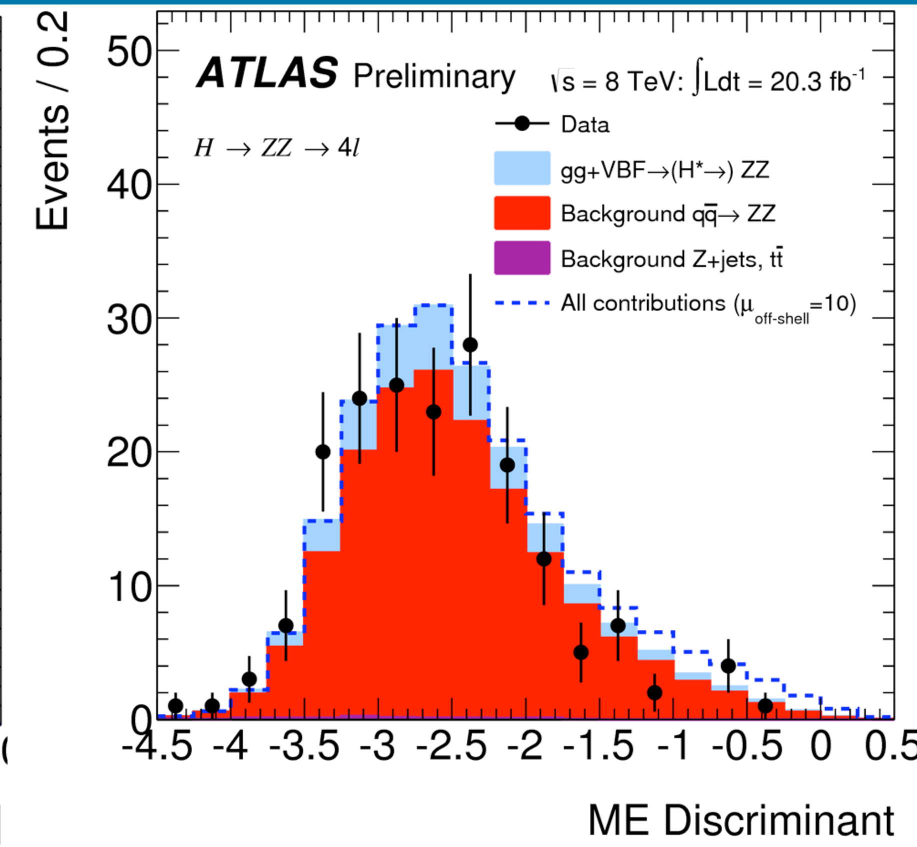


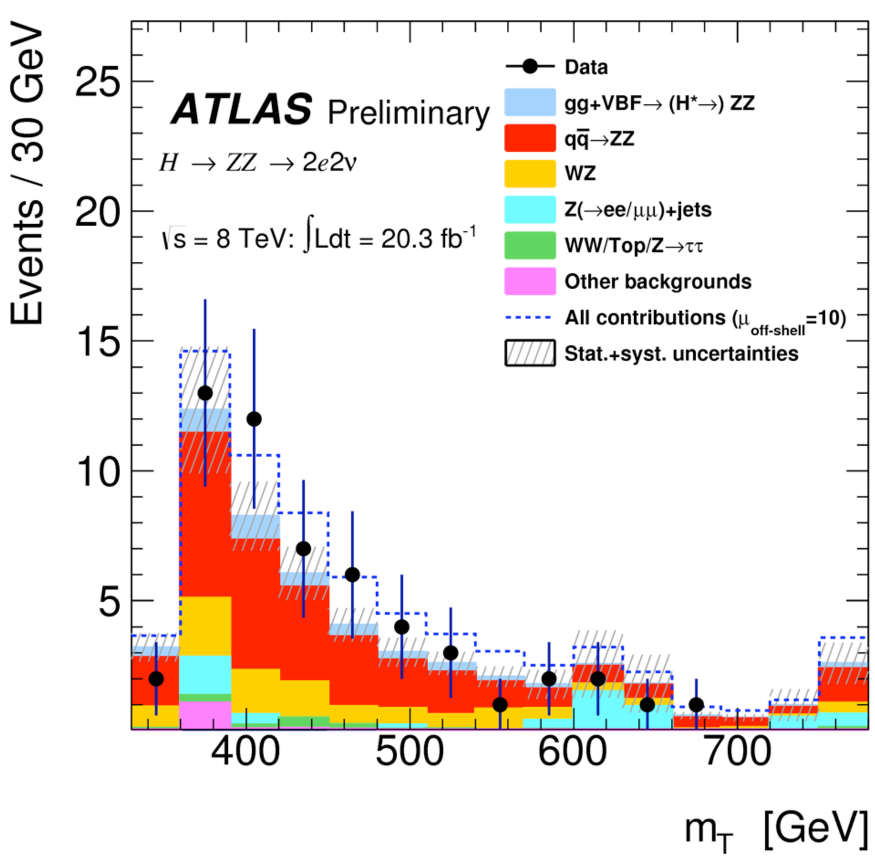
Similar assumptions to the one used for the coupling studies with the κ-factor framework

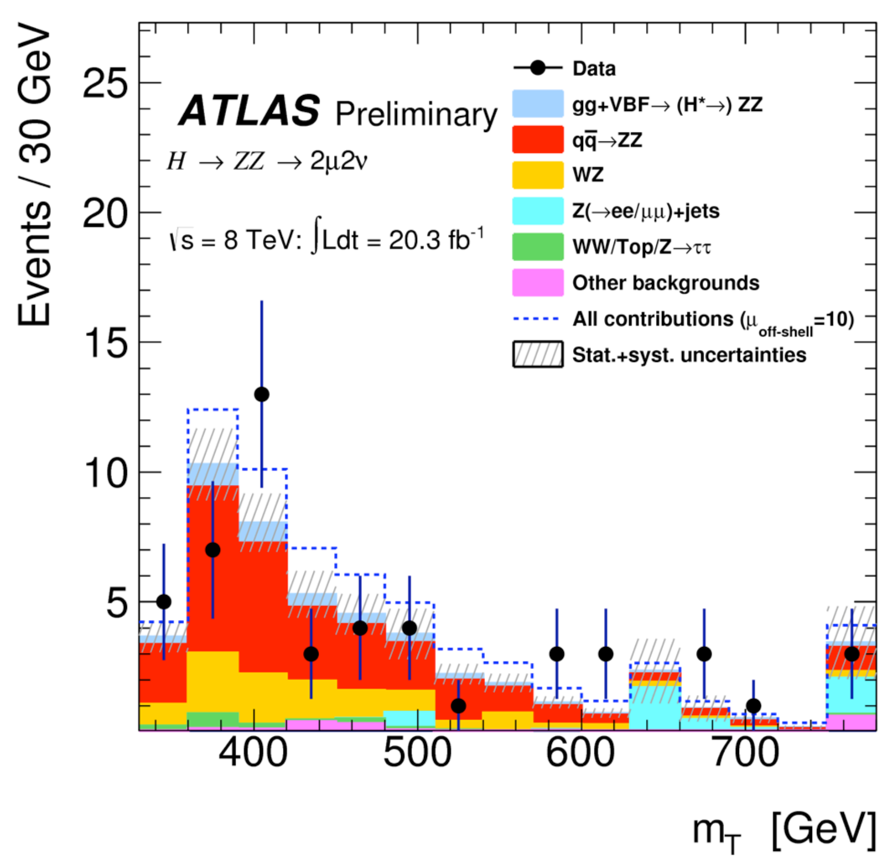
Indirect Γ_H measurement: Analysis

ZZ→4l
- Off-peak region [220 GeV, 1TeV]
- Matrix Element Kinematic Discriminant to separate gg→H*→ZZ→4l from qq→ZZ→4l/ gg→(H*)→ZZ→4l
- Limit on off-shell rate based on fit on MEKD shape



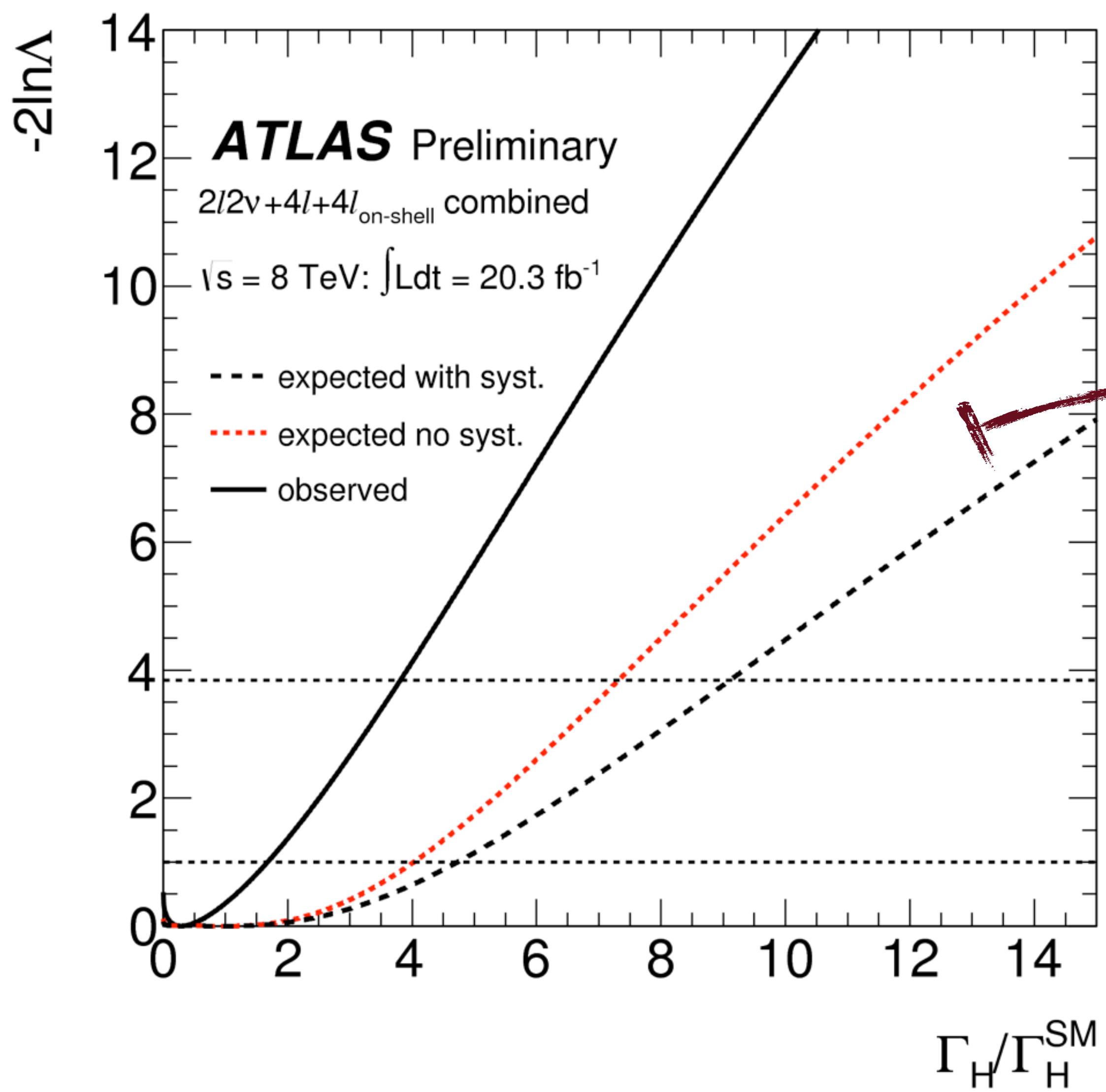


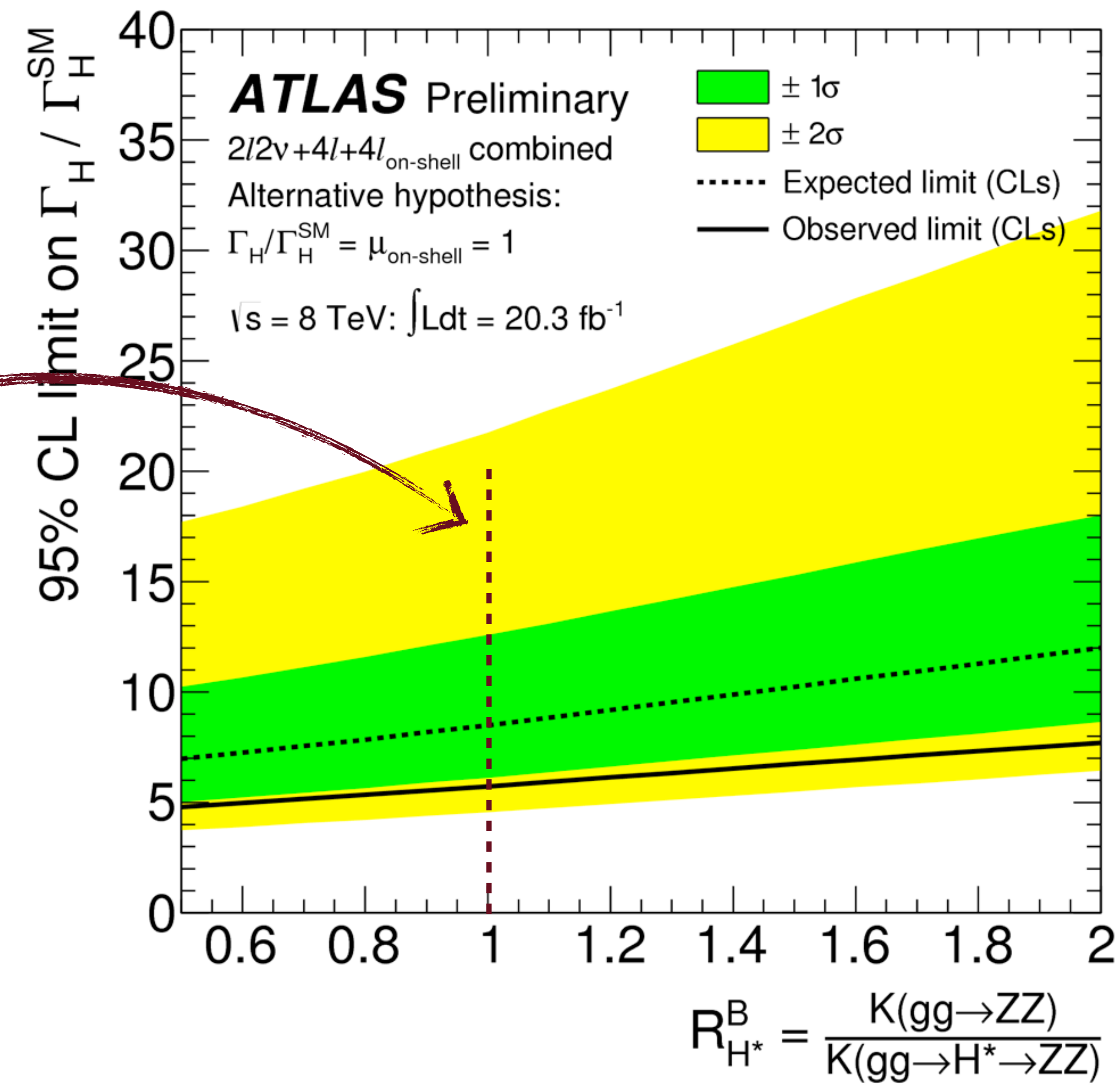




ZZ→llνν
- ETmiss>150 GeV and 76 GeV<m_{ll}<106
- Main backgrounds: qq→ZZ and WZ/WW, Z+jets and top
- Off-peak region m_{TZZ}>350 GeV
- Limit on off-shell rate based on event counting

Indirect Γ_H measurement: Results

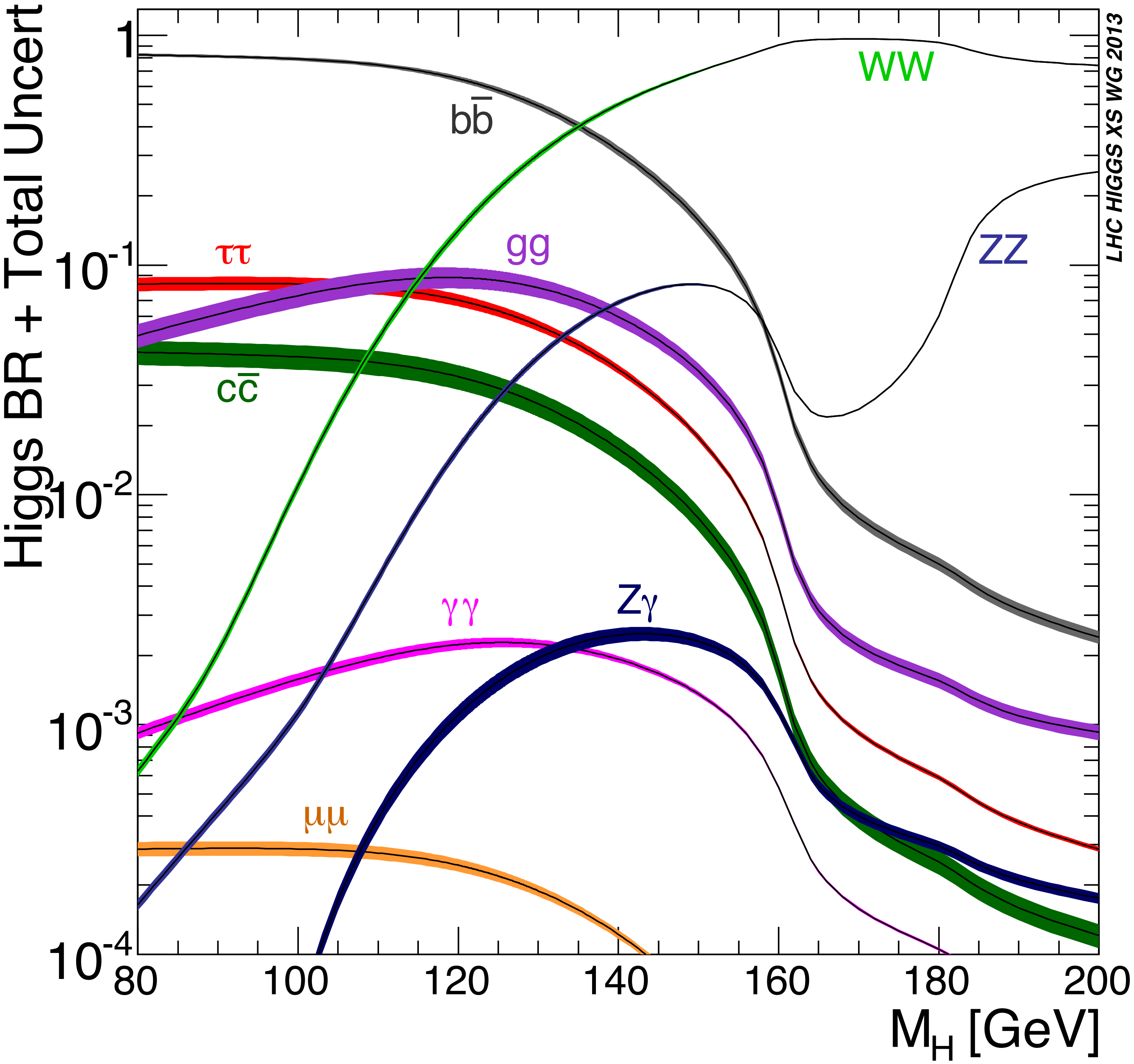




Results are expressed as a function of the unknown K-factor for the gg→ZZ background.

Assuming background K-factors same as for signal:

- Γ_H/Γ_{SM} < 4.8 (5.8) at 95% CLs with alternative hypothesis $R^B_{H^*}=1$, $\Gamma_H/\Gamma_{SM}=1$ and $\mu_{on\text{-}shell}=1.51$
- Γ_H/Γ_{SM} < 5.7 (8.5) at 95% CLs with alternative hypothesis $R^B_{H^*}=1$, $\Gamma_H/\Gamma_{SM}=1$ and $\mu_{on\text{-}shell}=1.00$

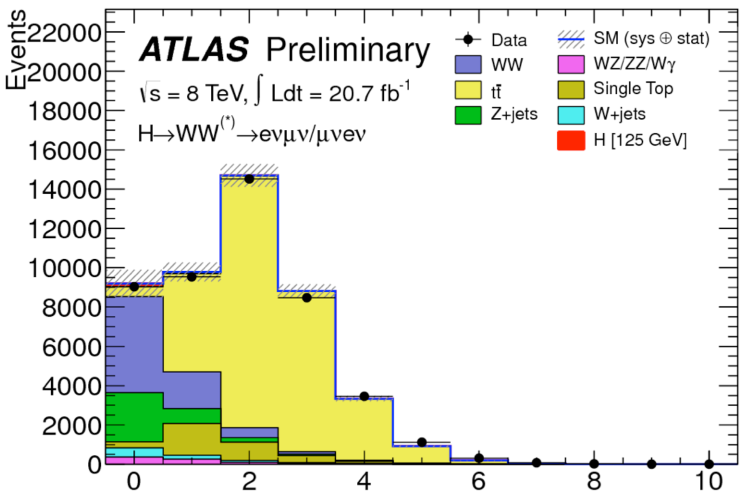


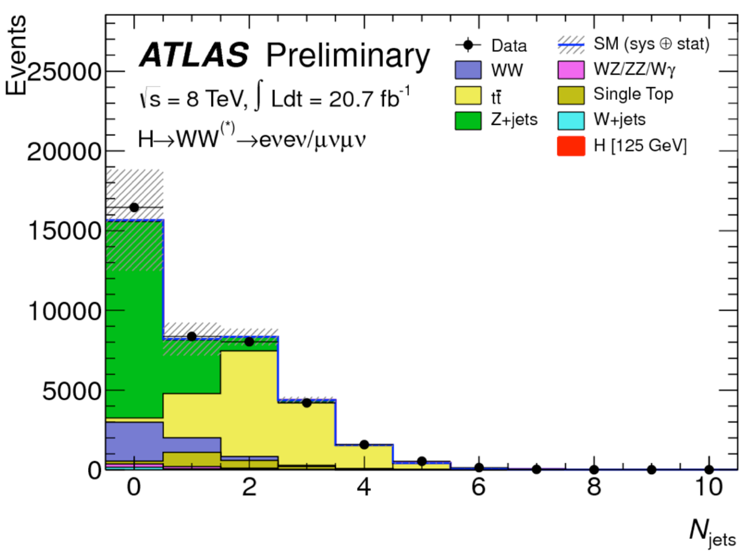
Higgs BR + Total Uncert
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200
M_H [GeV]
LHC HIGGS XS WG 2013
$b\bar{b}$
WW
ZZ
ττ
gg
$c\bar{c}$
γγ
Zγ
μμ

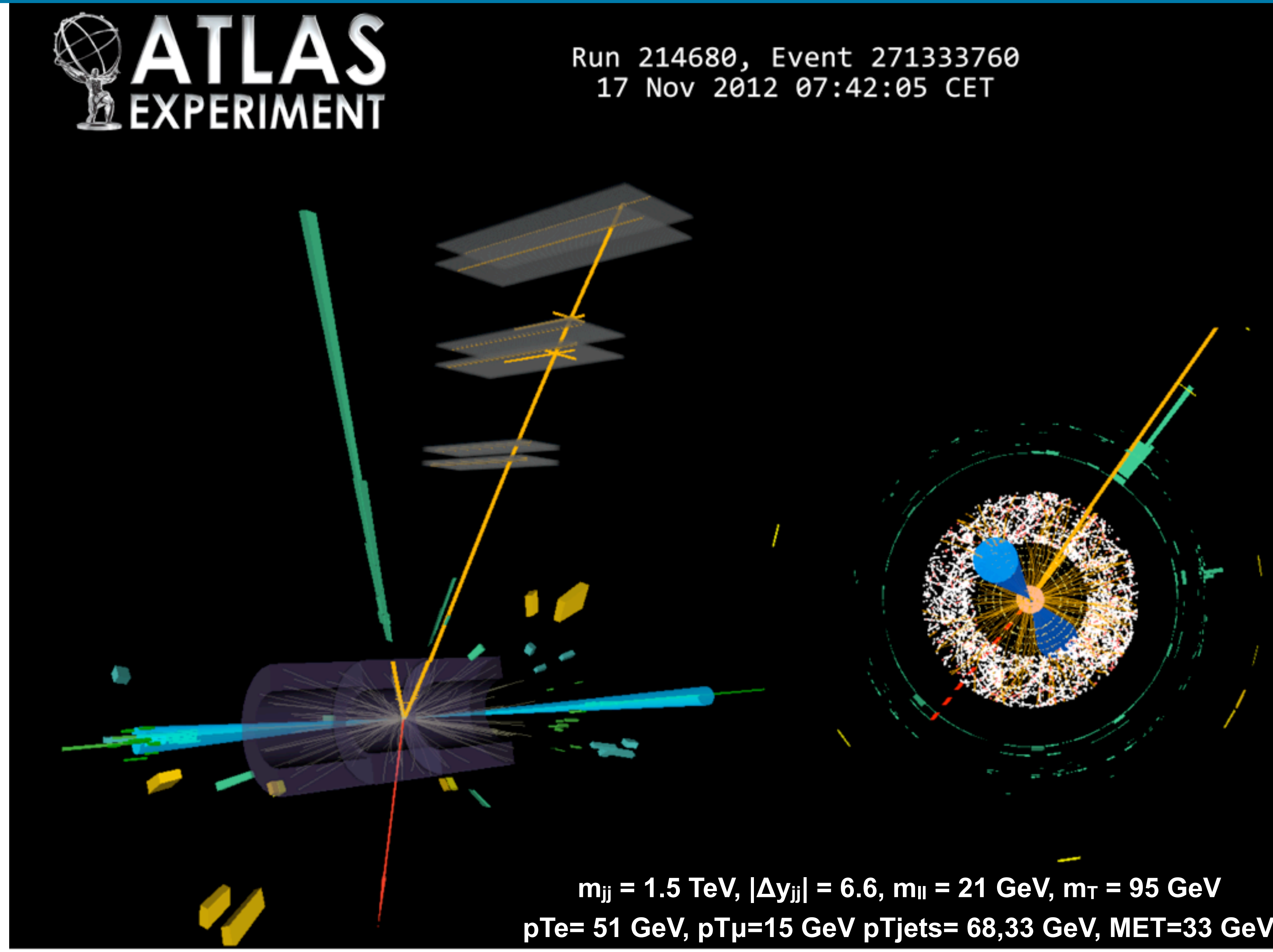
H→WW→lνlν

$H \to WW^{(*)} \to l\nu l\nu$

- Sensitive in wide mass range
- Also very complicated
  - no mass peak
  - uses all ATLAS components!
- Signature is ll + MET
- Observables: m_{ll} and m_T
- Backgrounds: WW, top, W/Z+jets
- Separate final states:
  - lepton flavors: μe, eμ, μμ, ee
  - jet multiplicities: 0, 1, ≥2

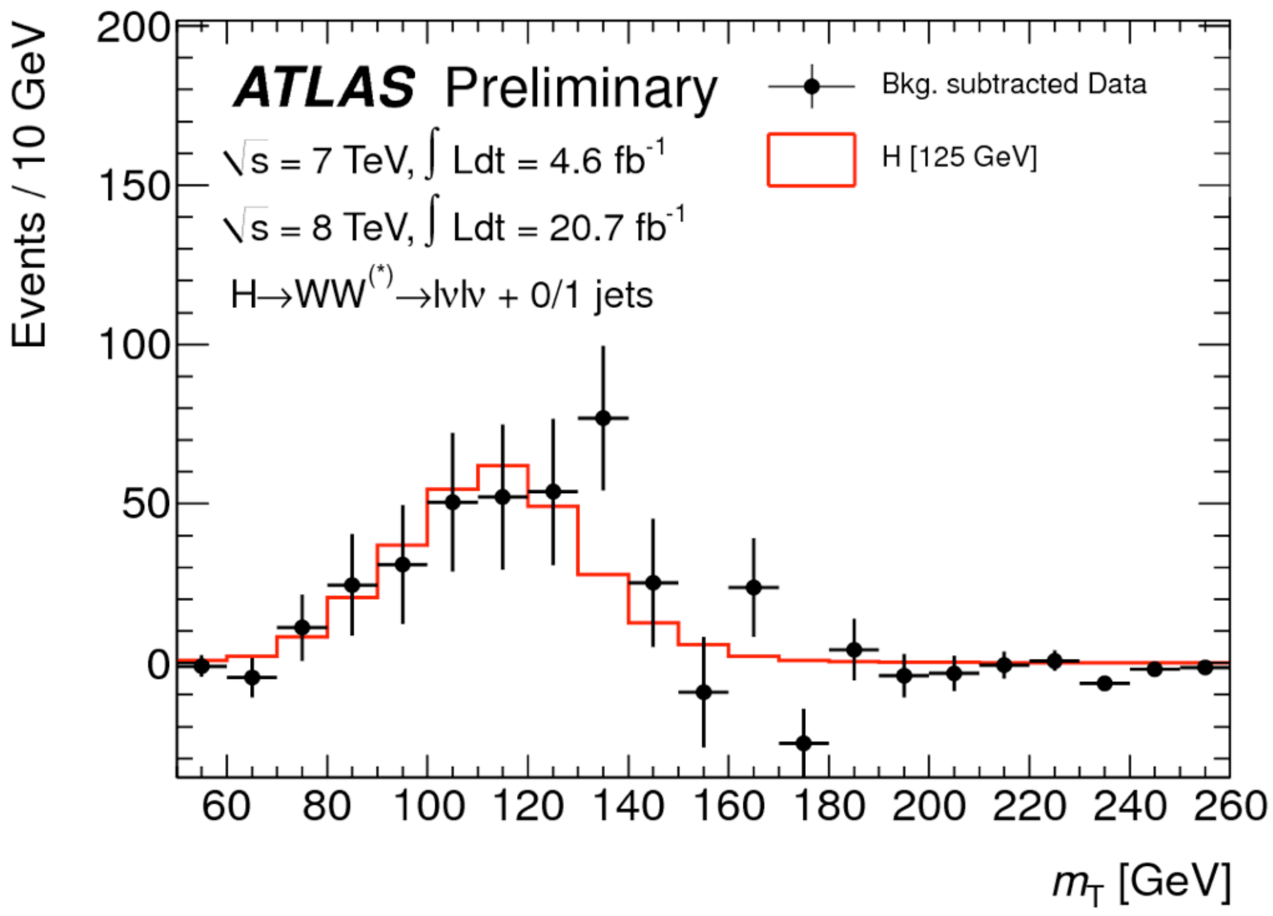


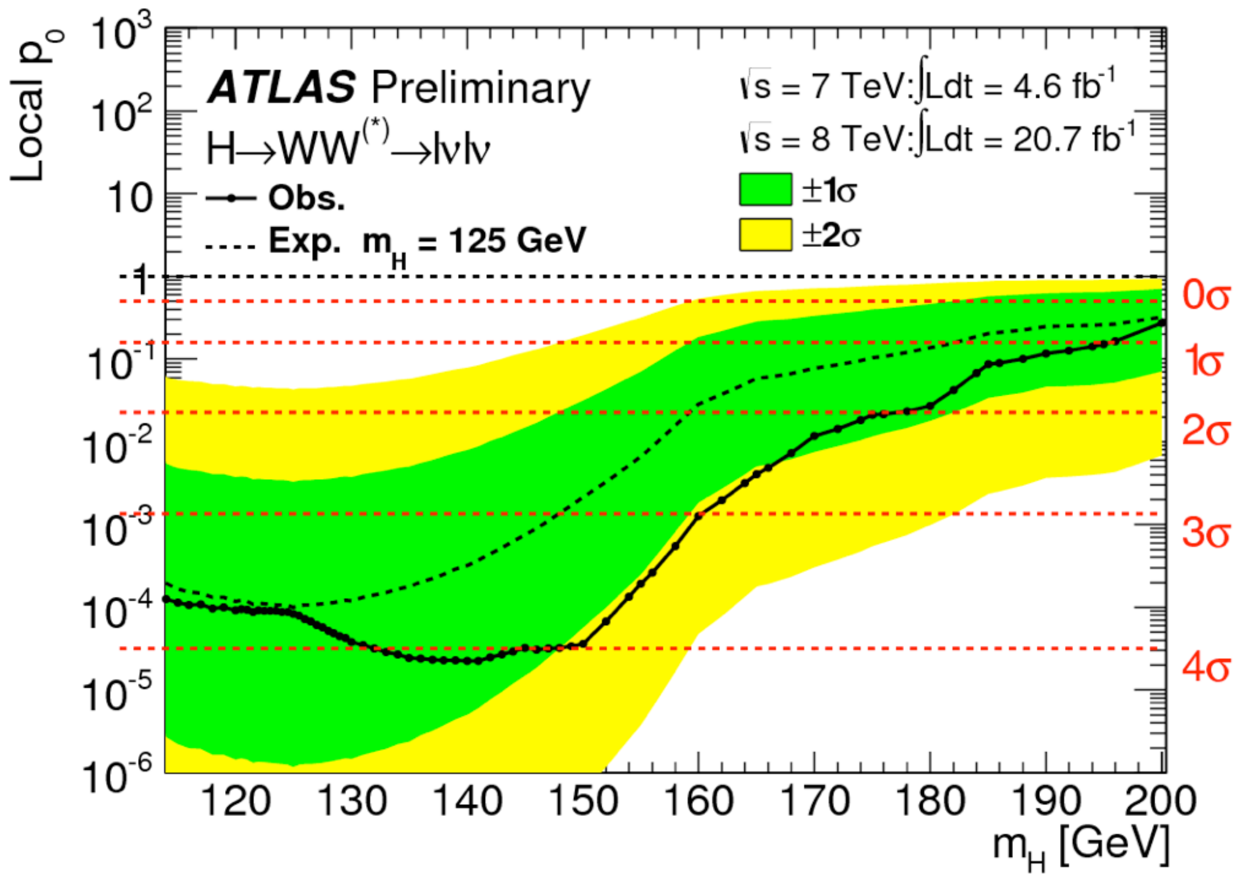




$$m_T = ((E_T^{\ell\ell} + E_T^{miss})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{miss}|^2)^{1/2} \text{ with } E_T^{\ell\ell} = (|\mathbf{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2)^{1/2}$$

H→WW$^{(*)}$→lνlν: Results 2011+2012

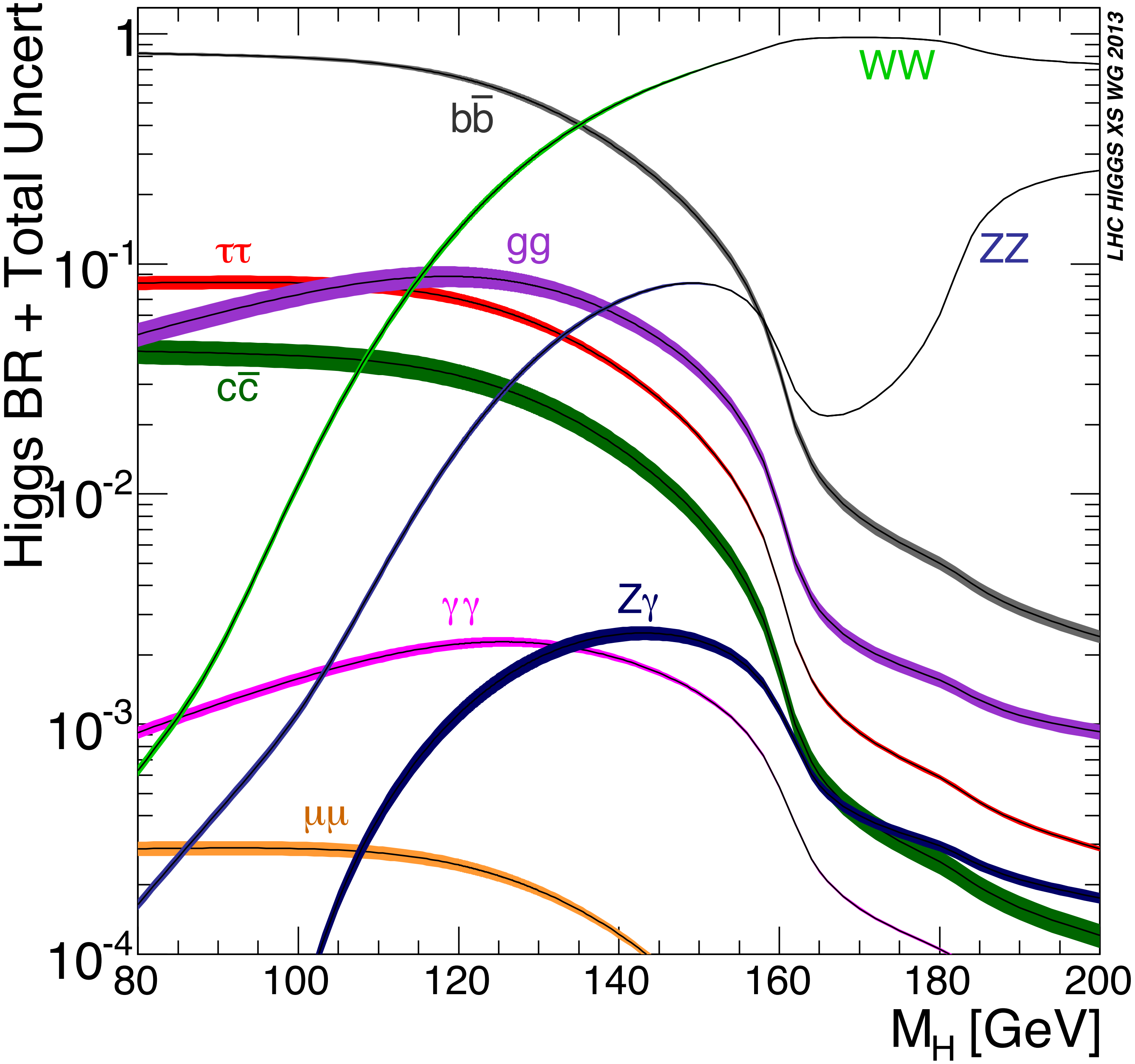




Local significance at m_H=140GeV is 4.1σ

Local significance at m_H=125GeV is 3.8σ

Rate with respect to SM: 1.01 ± 0.31 @ m_H=125 GeV

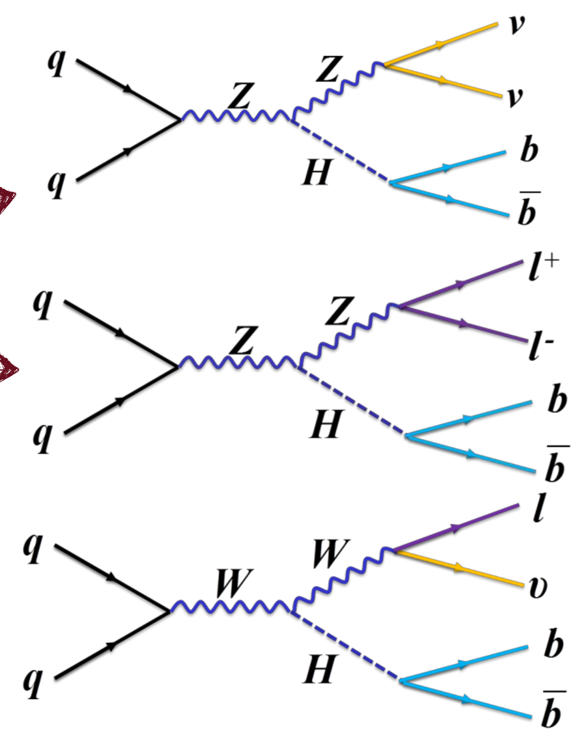


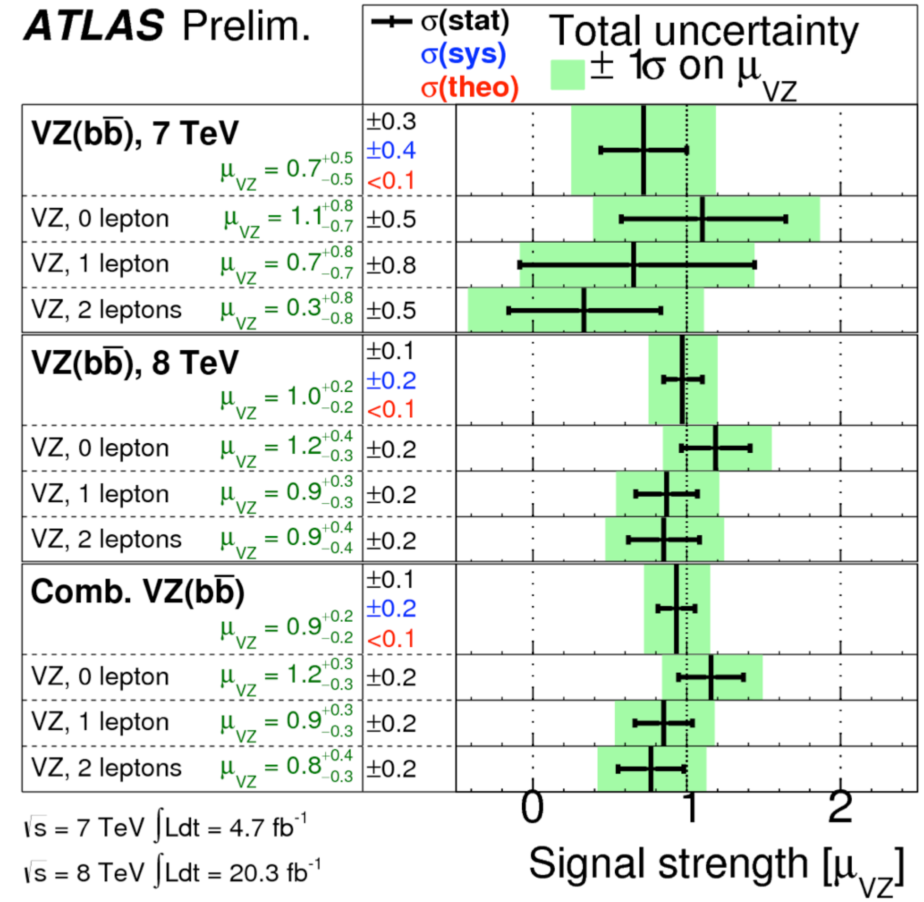
$H \rightarrow bb$

H→bb

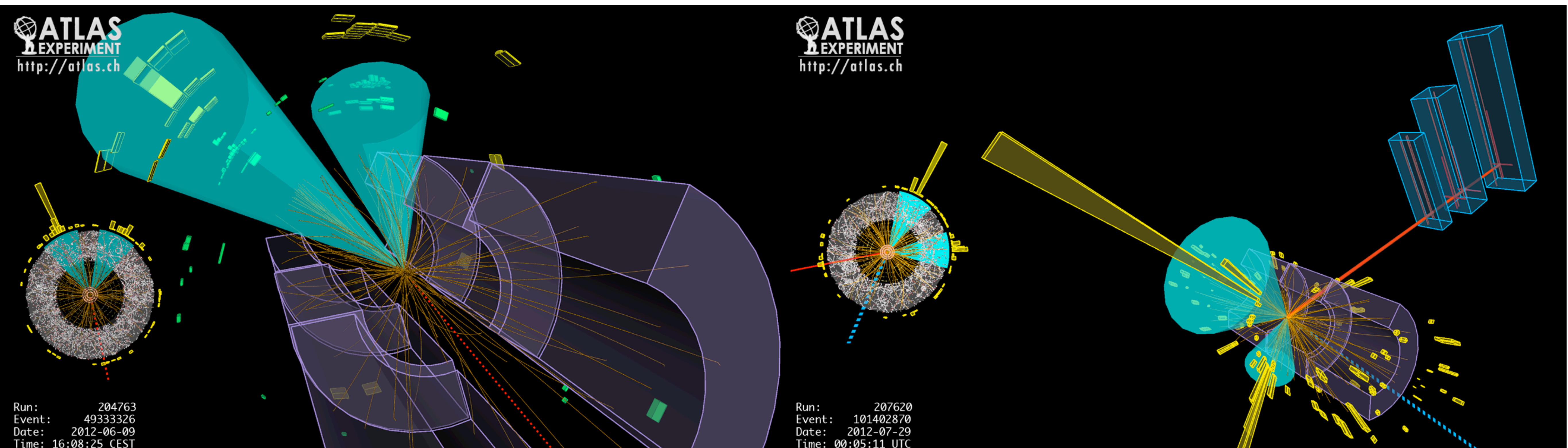
ATLAS-CONF-2013-079

- Largest BR but very high background
- Exploit associated production with W or Z
  - Final states with leptons, MET and b-jets
- Backgrounds: W/Z+jets and top
- Final discriminant m_{bb}
- Separate final states:
  - number of leptons: 0, 1, 2
  - $P_T(V)$ or MET
  - number of jets
  - 26 signal bins in total
    - + 27 control regions

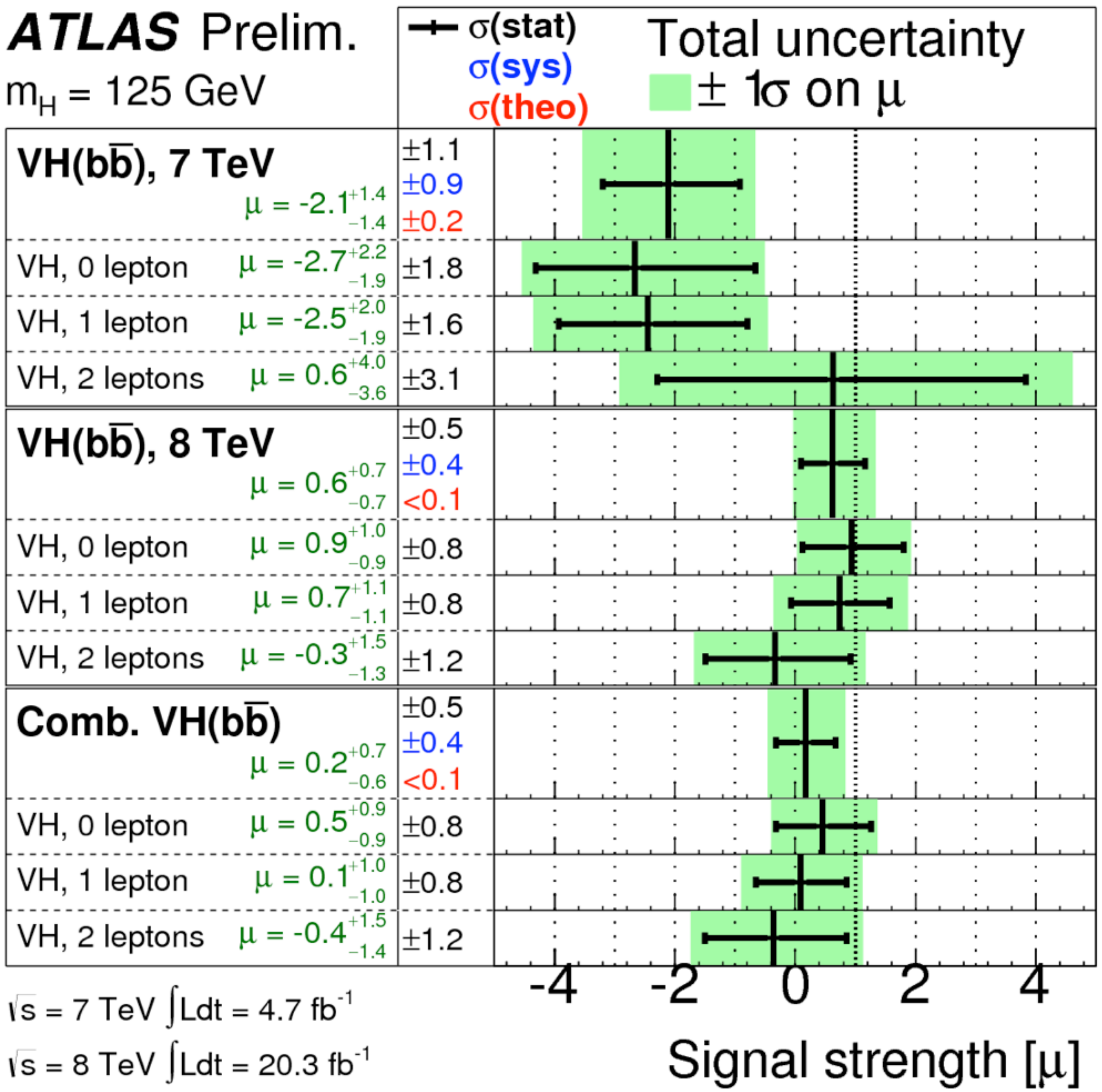


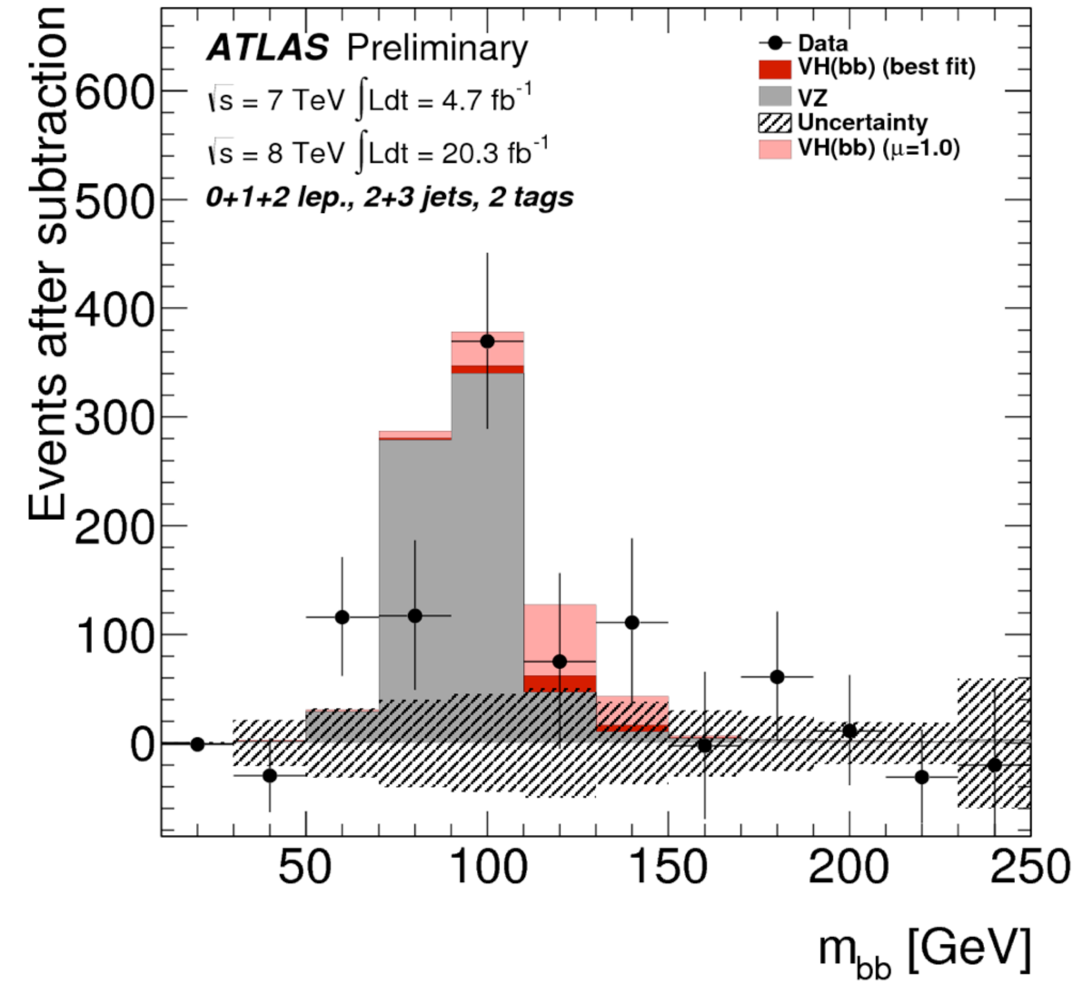


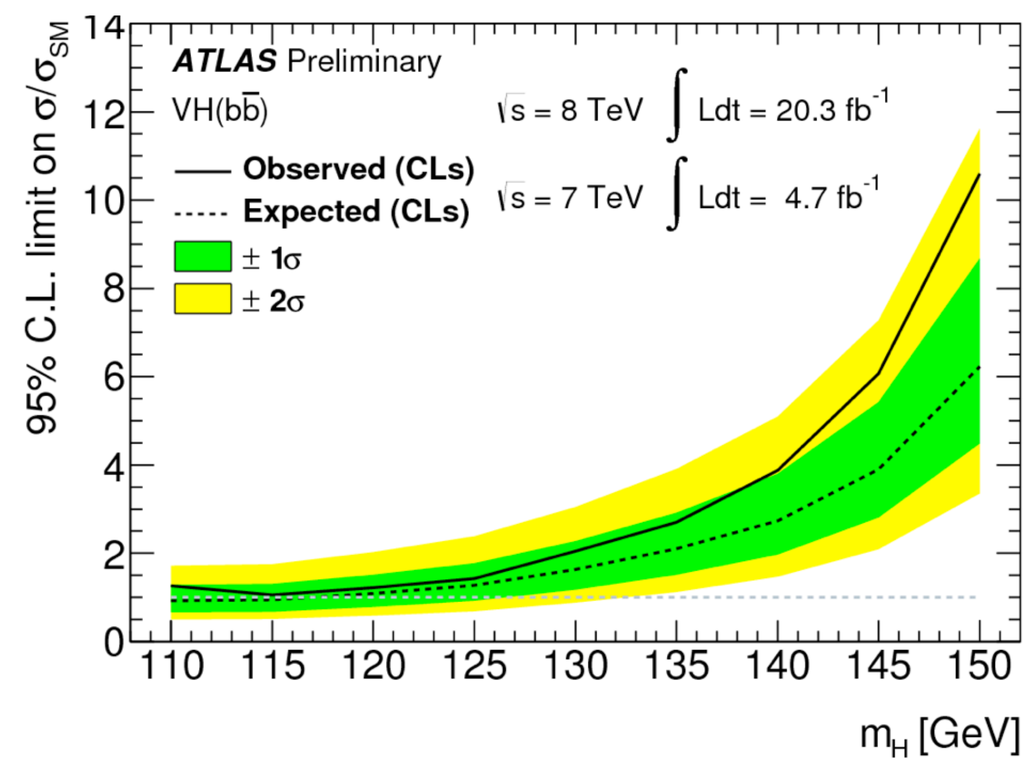
observation at 4.8σ(5.1σ) of VZ(→bb) production



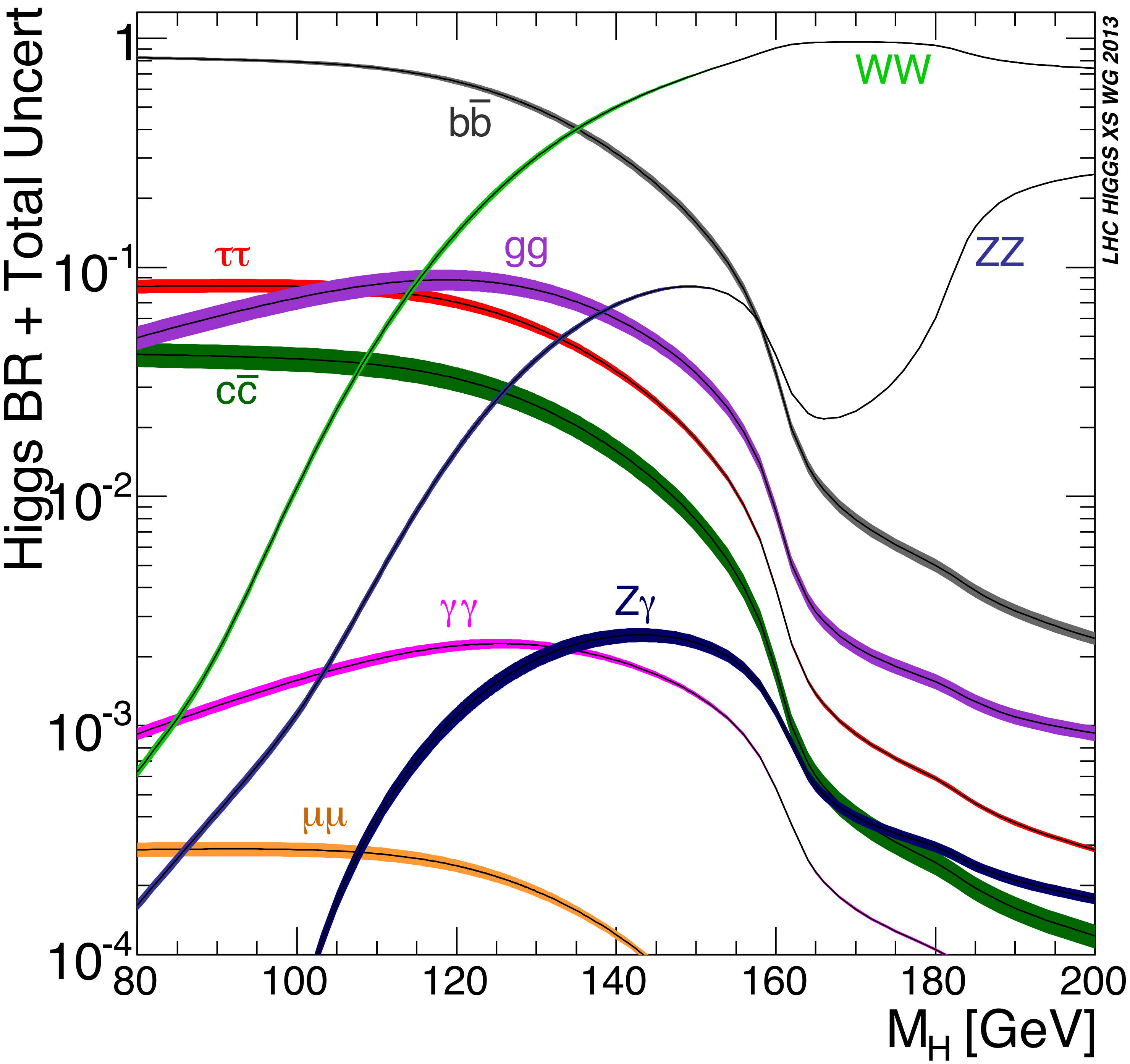
H→bb







m_H=125 GeV
95% CL exclusion limit 1.4 (1.3) x SM
μ = 0.2 ± 0.5 (stat) ± 0.4 (syst)
CMS : significance 2.1(2.1)σ for m_H=125 GeV



Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
bb̄
WW
ττ
gg
ZZ
cc̄
γγ
Zγ
μμ
1
10-1
10-2
10-3
10-4
80
100
120
140
160
180
200
M_H [GeV]

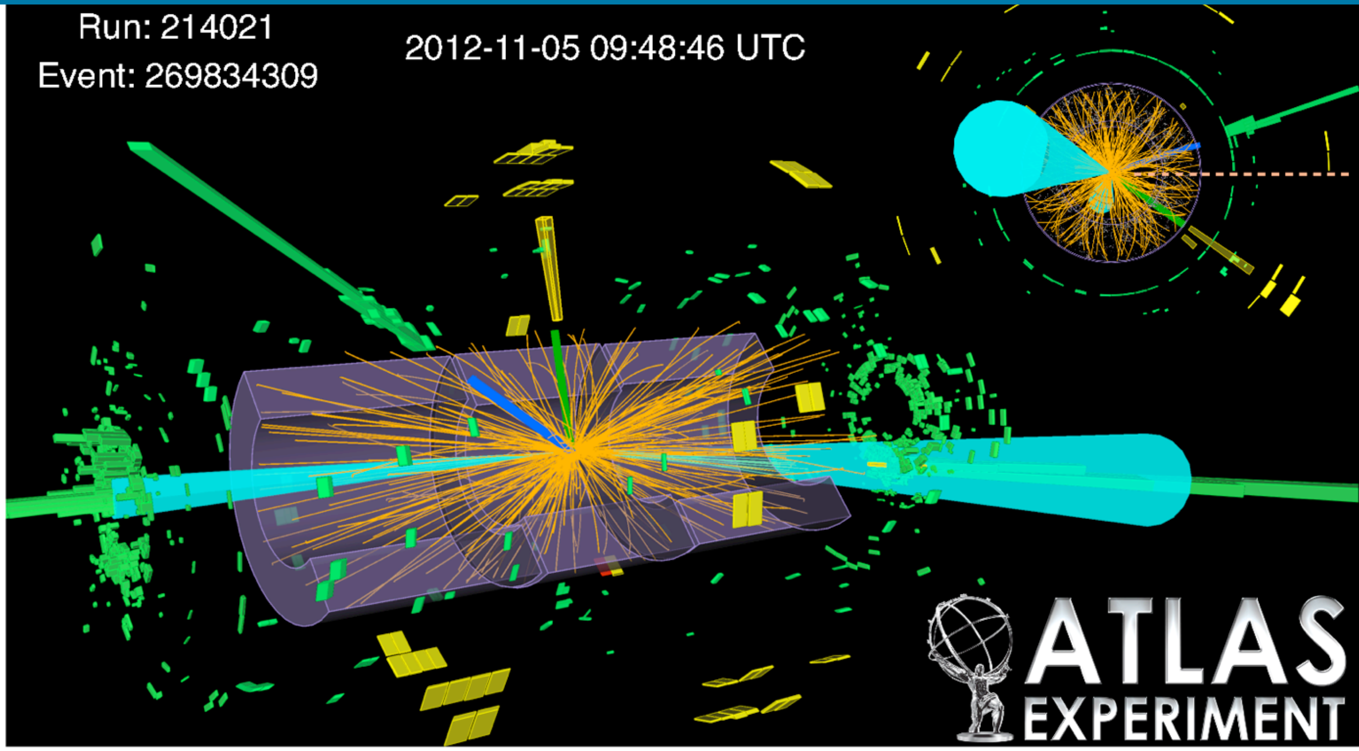
H→ττ

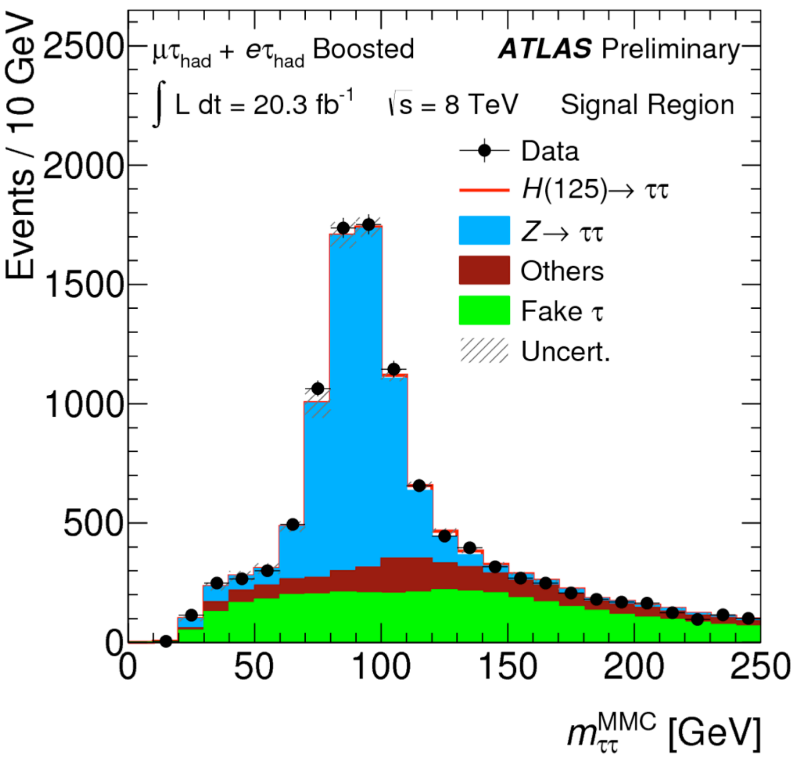
H→ττ

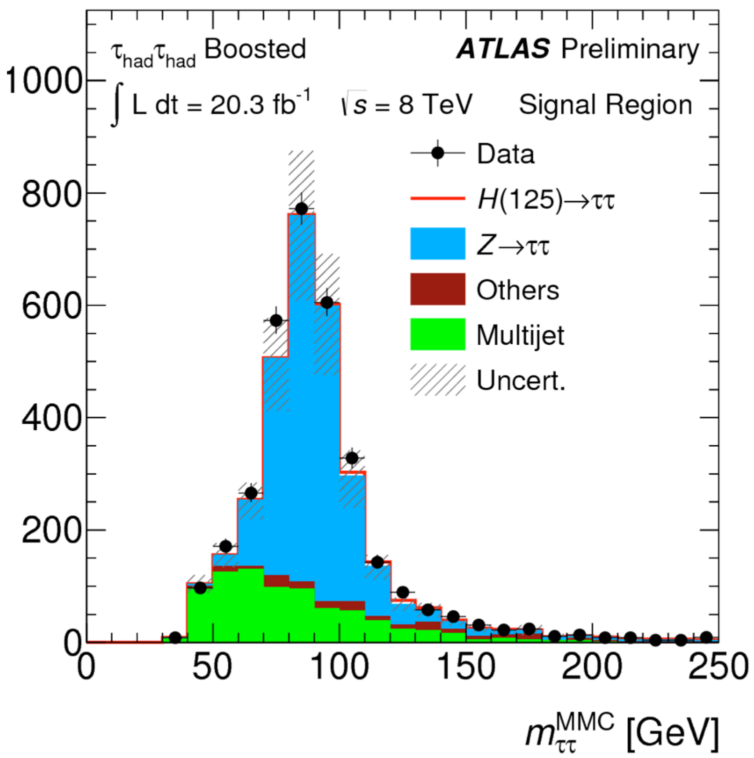
- This channel is directly sensitive to the τ Yukawa coupling
- Expected to be the first channel to give direct evidence for coupling to leptons.
- Search in three sub-channels
  - τlepτlep BR~12% -> 2lepton
  - τlepτhad BR ~46% -> 1lepton
  - τhadτhad BR~42%->0lepton
- Background

  - Z->ττ dominant estimated from data using the embedding technique

"Fakes": Multijet, W+jets, top from dta
"Other": Diboson produciton and H->WW* from MC





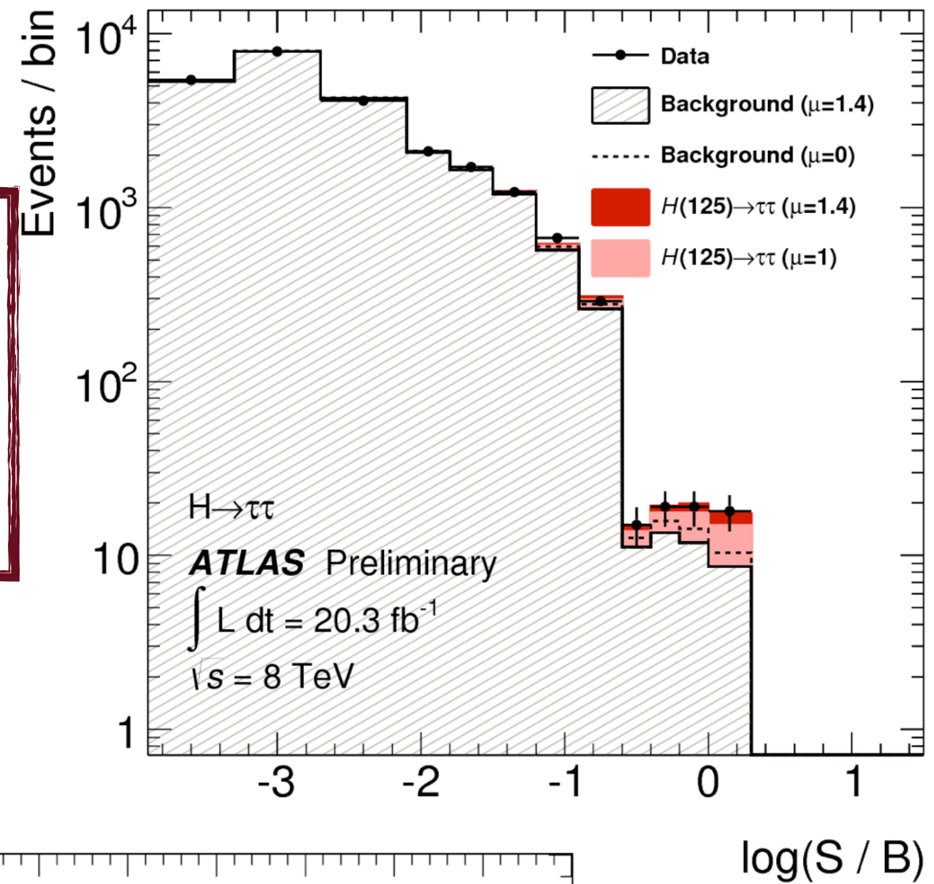


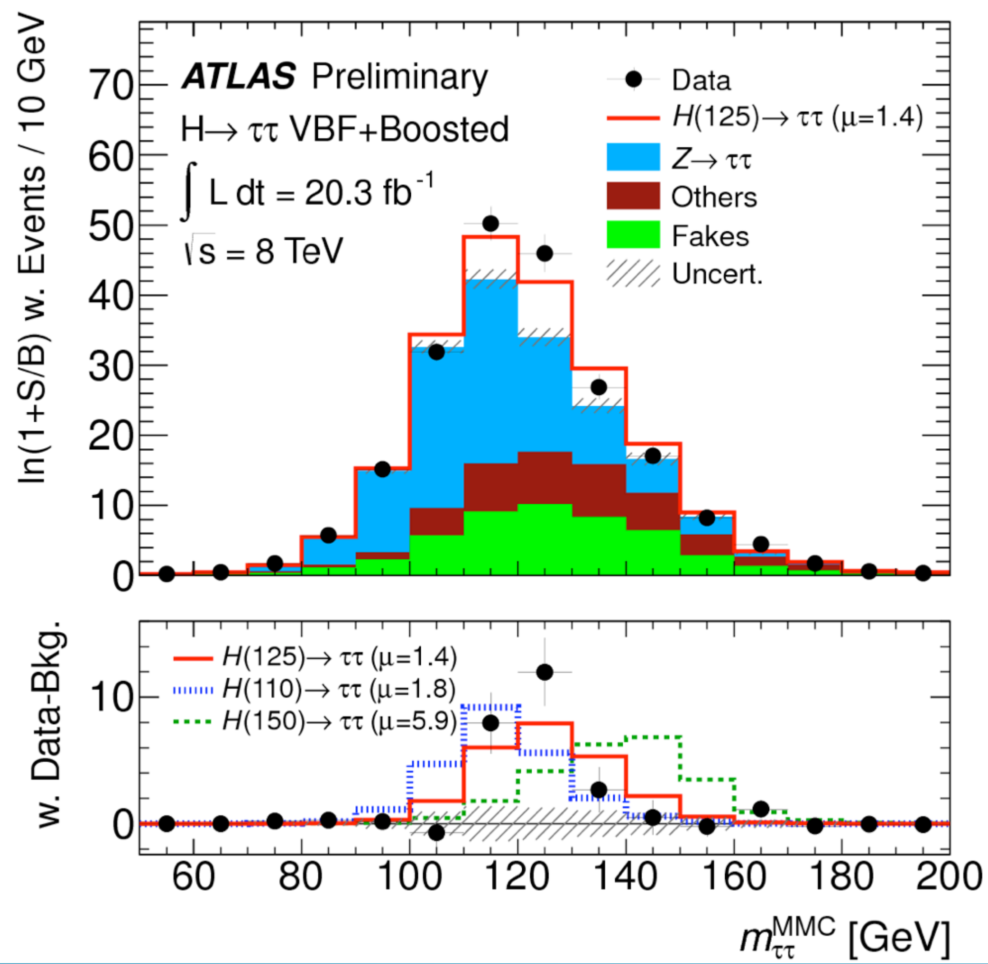
Analysis performed using Boosted Decision Tree
Variables, include properties of the di-tau system, jet topology, and event activity
Two categories:
VBF : 2 jets with large pseudorapidity separation
Boosted: events failing the VBF category, bith with large di-tau pT

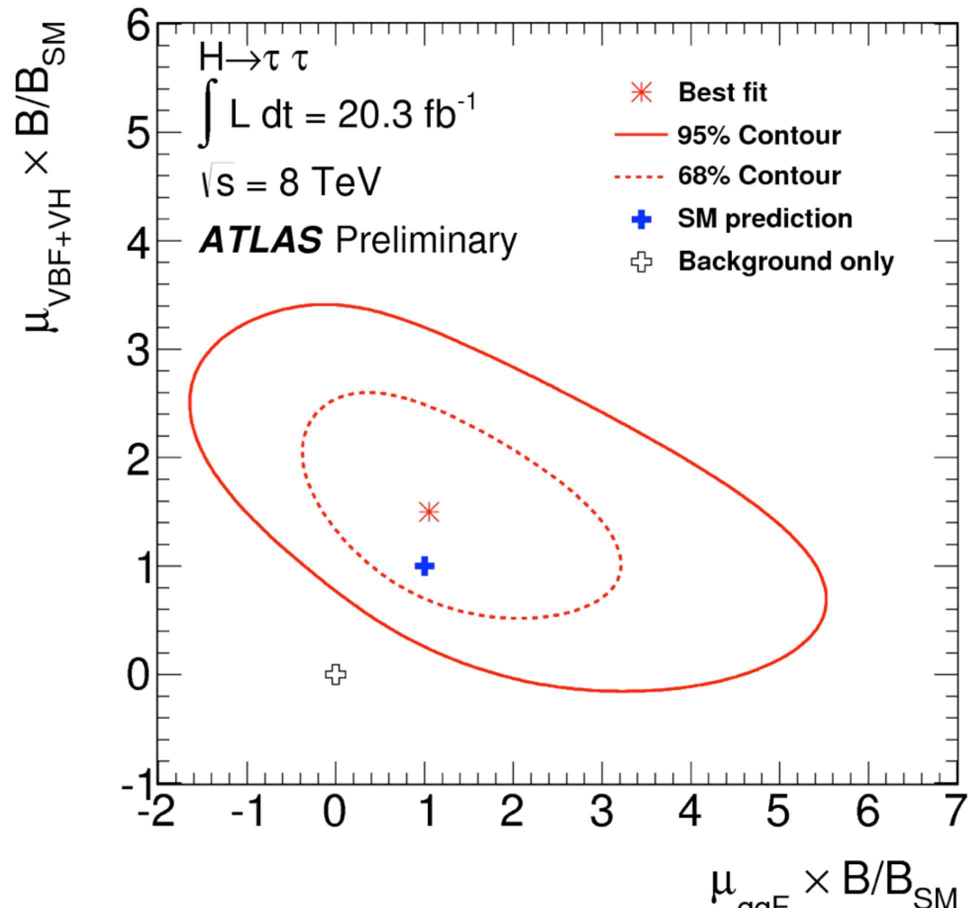
H→ττ

Using an MVA observe evidence for Higgs boson decays to τ-leptons, with signficance of 4.1σ (3.2σ expected)

- Signal Strength for mH=125GeV: μ= 1.43+0.31-0.29(stat) +0.41-0.30(syst)
- In agreement with SM expectation



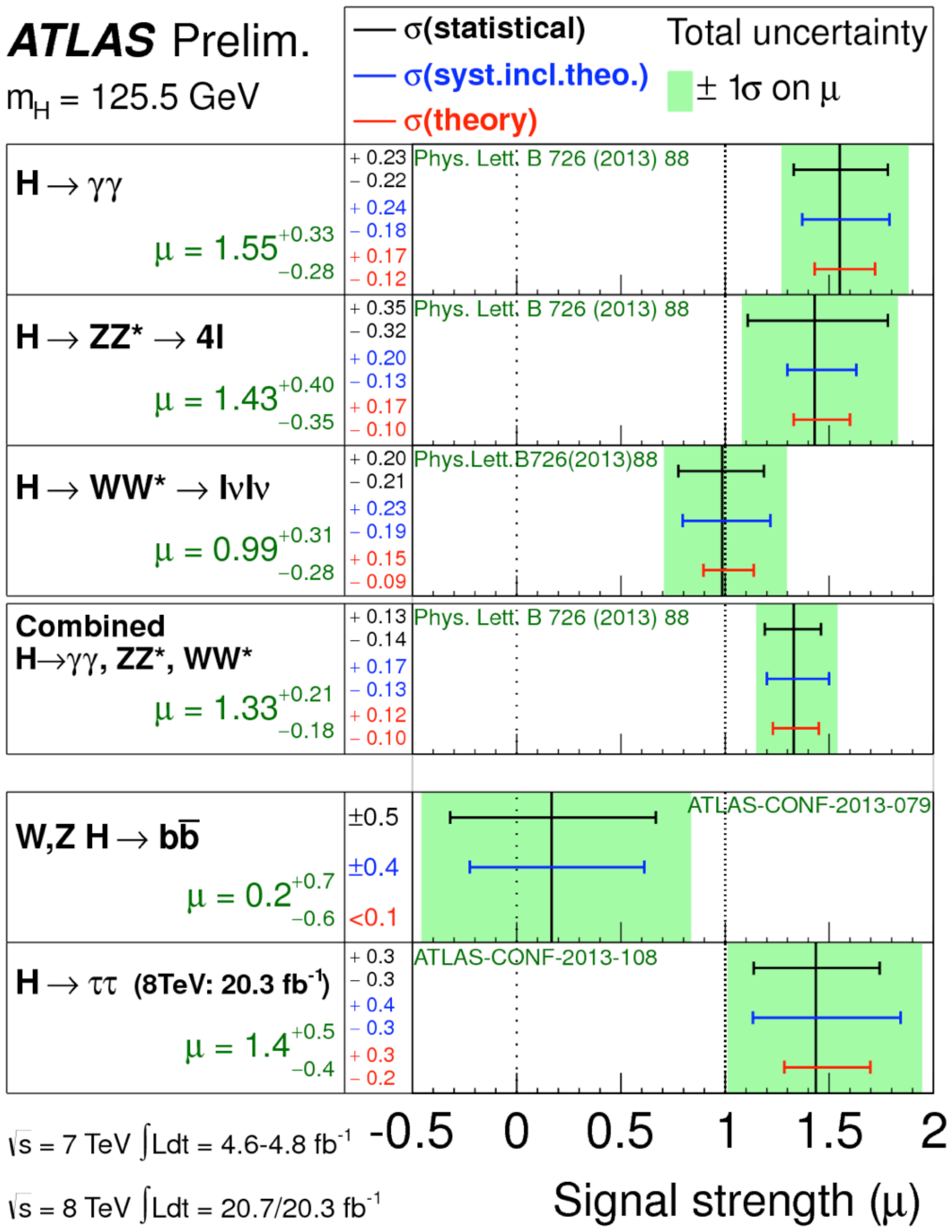


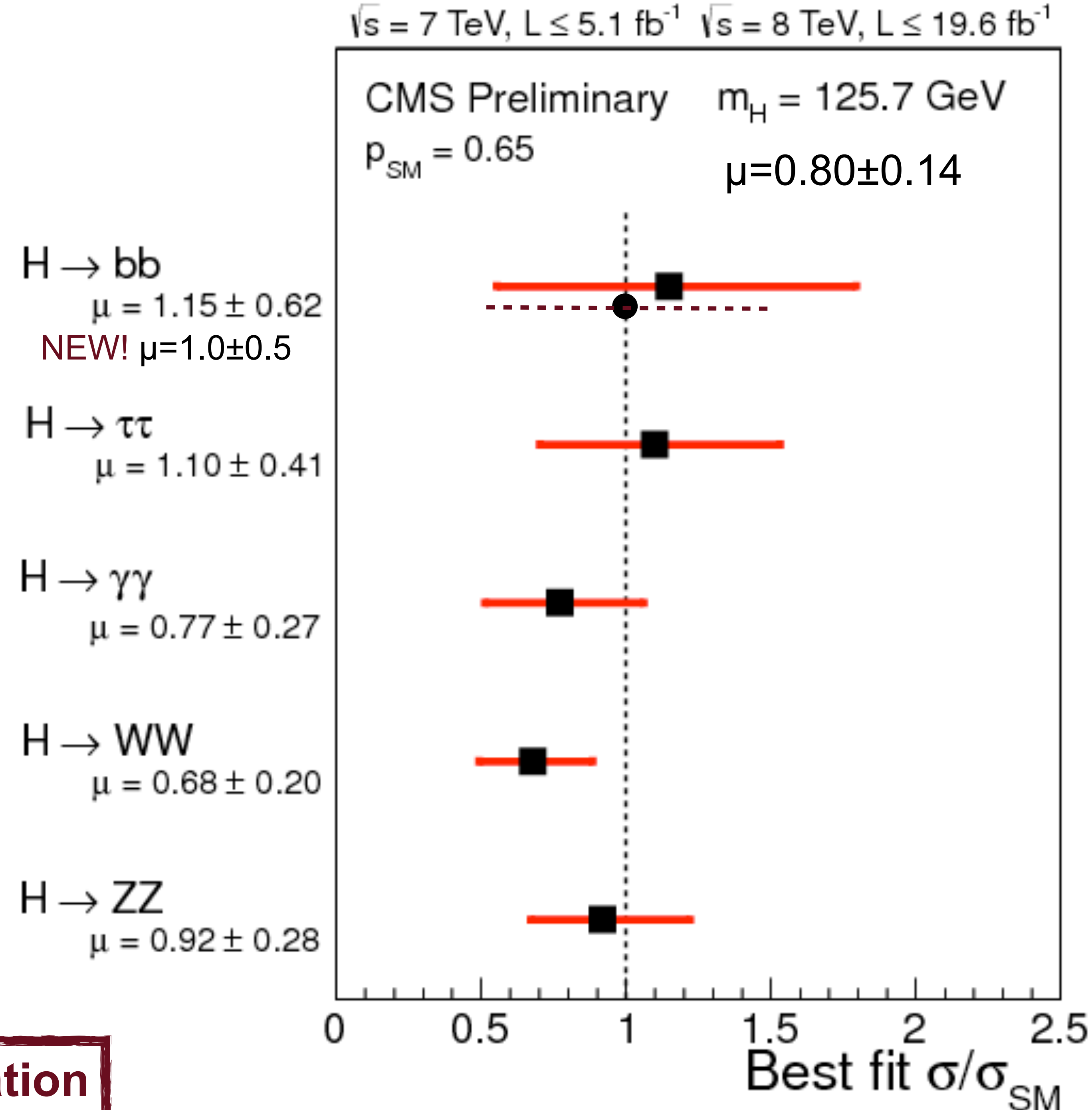


Rates/Couplings

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

Overview: Rate/Mass measurements





Rates in overall agreement with SM expectation

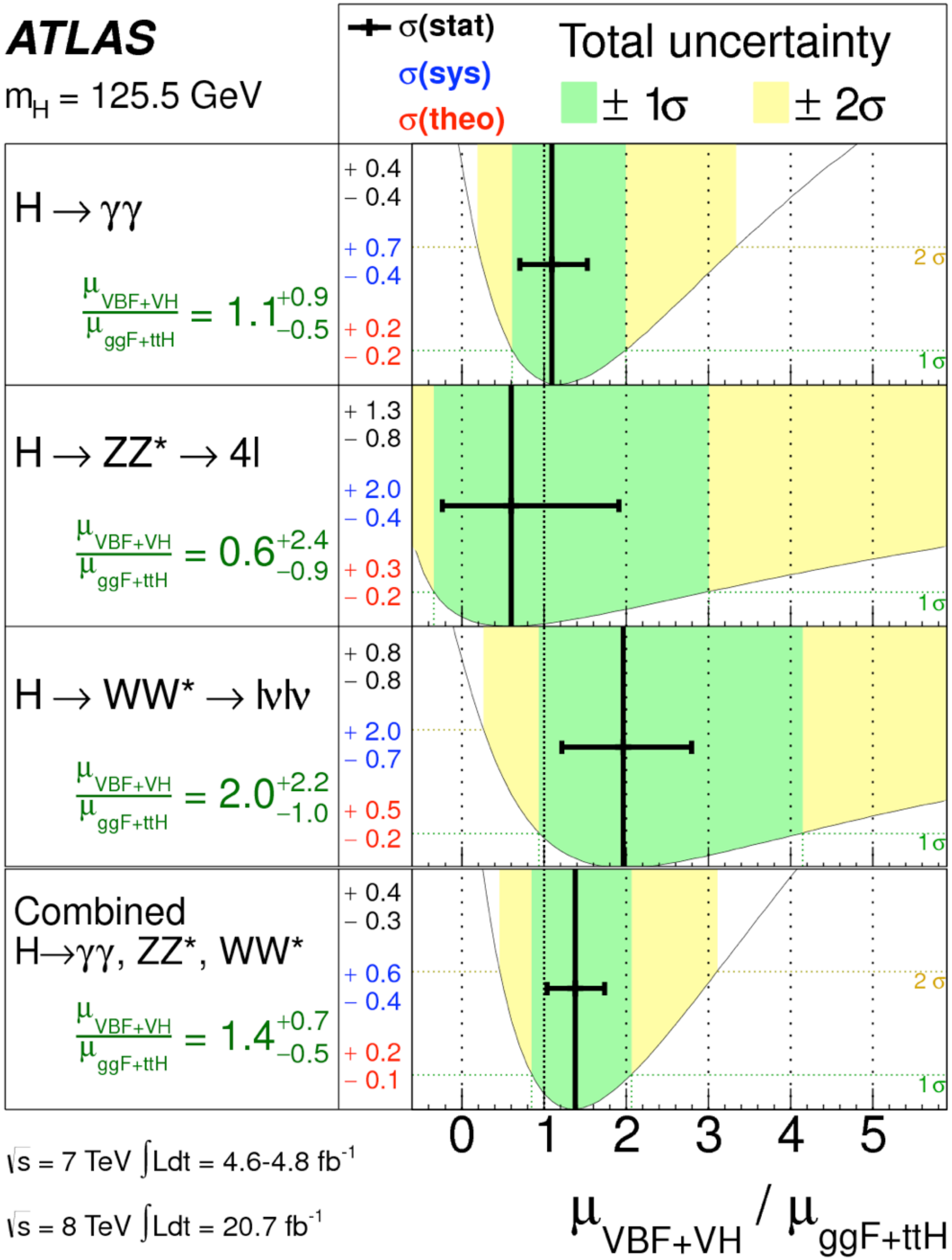
Results from the two experiments fluctuating around the SM expectations.

The ATLAS and CMS **mass combinations in good agreement**

ATLAS : $m_H = 125.5 \pm 0.2\ (stat)^{+0.5}_{-0.6}\ (syst)$ GeV

CMS : $m_H = 125.7 \pm 0.3\ (stat) \pm 0.3\ (syst)$ GeV

Signal strength for production mechanisms

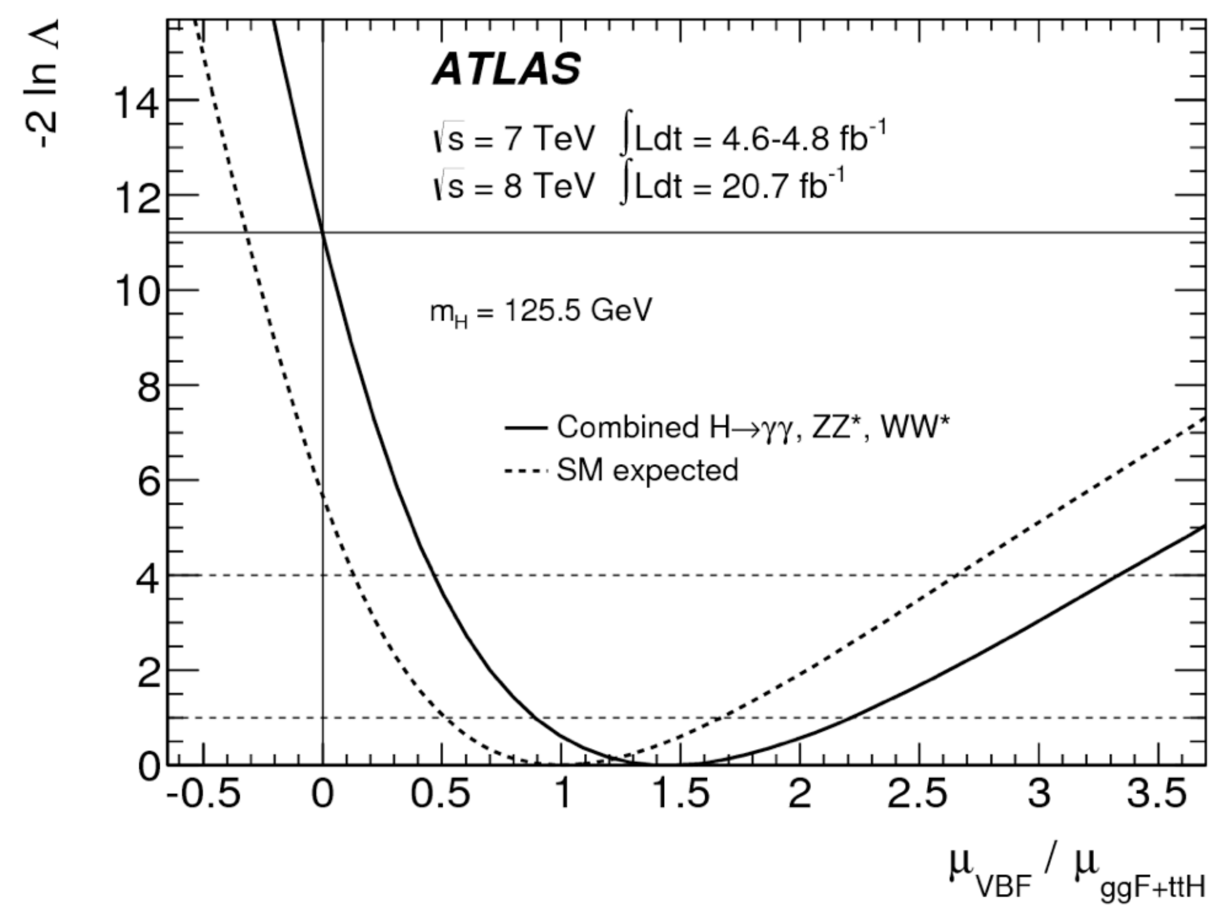


Overall Higgs boson signal strength measurement:

- no information on different production mechanisms
- assuming SM ratio of production cross-section

Separate vector-boson/gluon mediated processes:

- use two signal strengths μ_{VBF+VH} and $\mu_{ggF+ttH}$
- $\mu_{VBF+VH} / \mu_{ggF+ttH} = 1.4^{+0.4}_{-0.3}\text{(stat)}^{+0.6}_{-0.4}\text{(sys)}$
  - model independent (no assumption on branching ratios)
- 3.3σ evidence for VBF Higgs boson production



Effective Lagrangian

J. R. Espinosa et al. Higgs Hunting 2012 (arXiv:1207.1717[hep-ph])

$\mathcal{L}$ valid at $E \sim M_t$.

Field content : SM + scalar h (no extra light states)

$$\mathcal{L} = \mathcal{L}[h] - \left(M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu\right)\left[1 + 2a\frac{h}{v} + O(h^2)\right]$$
$$- m_{\psi_i} \bar{\psi}_i \psi_i \left[1 + c\frac{h}{v} + O(h^2)\right] + \ldots$$

Contino et al '10 '12

Incorporates $SU(2)_L \times U(1)_Y \to U(1)_{em}$ breaking

$$\mathcal{L} = \mathcal{L}[h] - \left(M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu\right)\left[1 + 2\underset{\downarrow \kappa_V}{a}\frac{h}{v} + O(h^2)\right]$$
$$- m_{\psi_i} \bar{\psi}_i \psi_i \left[1 + \underset{\swarrow \kappa_F}{c}\frac{h}{v} + O(h^2)\right] + \ldots$$

Contino et al '10 '12

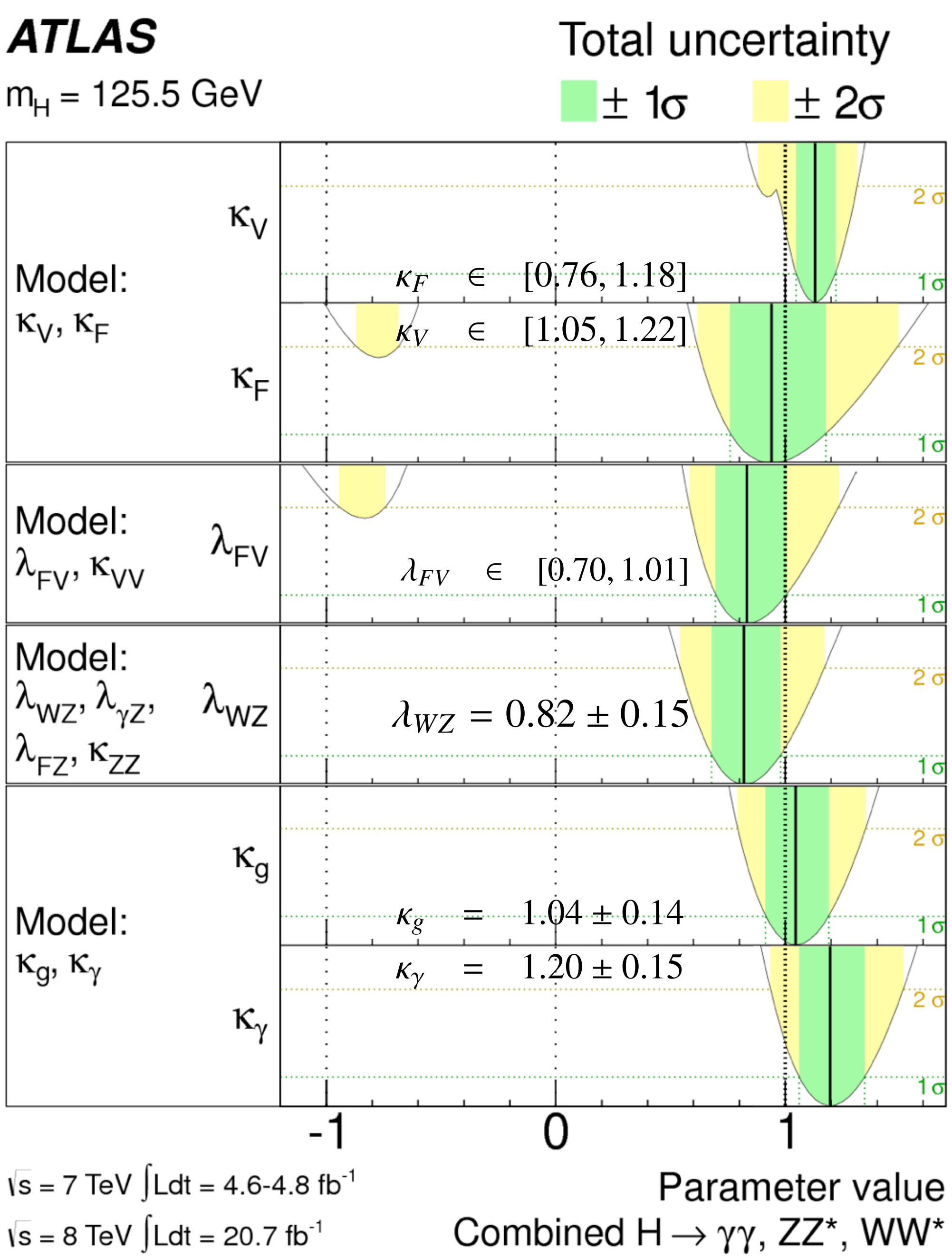
Higgs boson couplings

Table 10: Summary of the coupling benchmark models discussed in this paper, where $\lambda_{ij} = \kappa_i/\kappa_j$, $\kappa_{ii} = \kappa_i\kappa_i/\kappa_H$, and the functional dependence assumptions are: $\kappa_V = \kappa_W = \kappa_Z$, $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$ (and similarly for the other fermions), $\kappa_g = \kappa_g(\kappa_b, \kappa_t)$, $\kappa_\gamma = \kappa_\gamma(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W)$, and $\kappa_H = \kappa_H(\kappa_i)$.

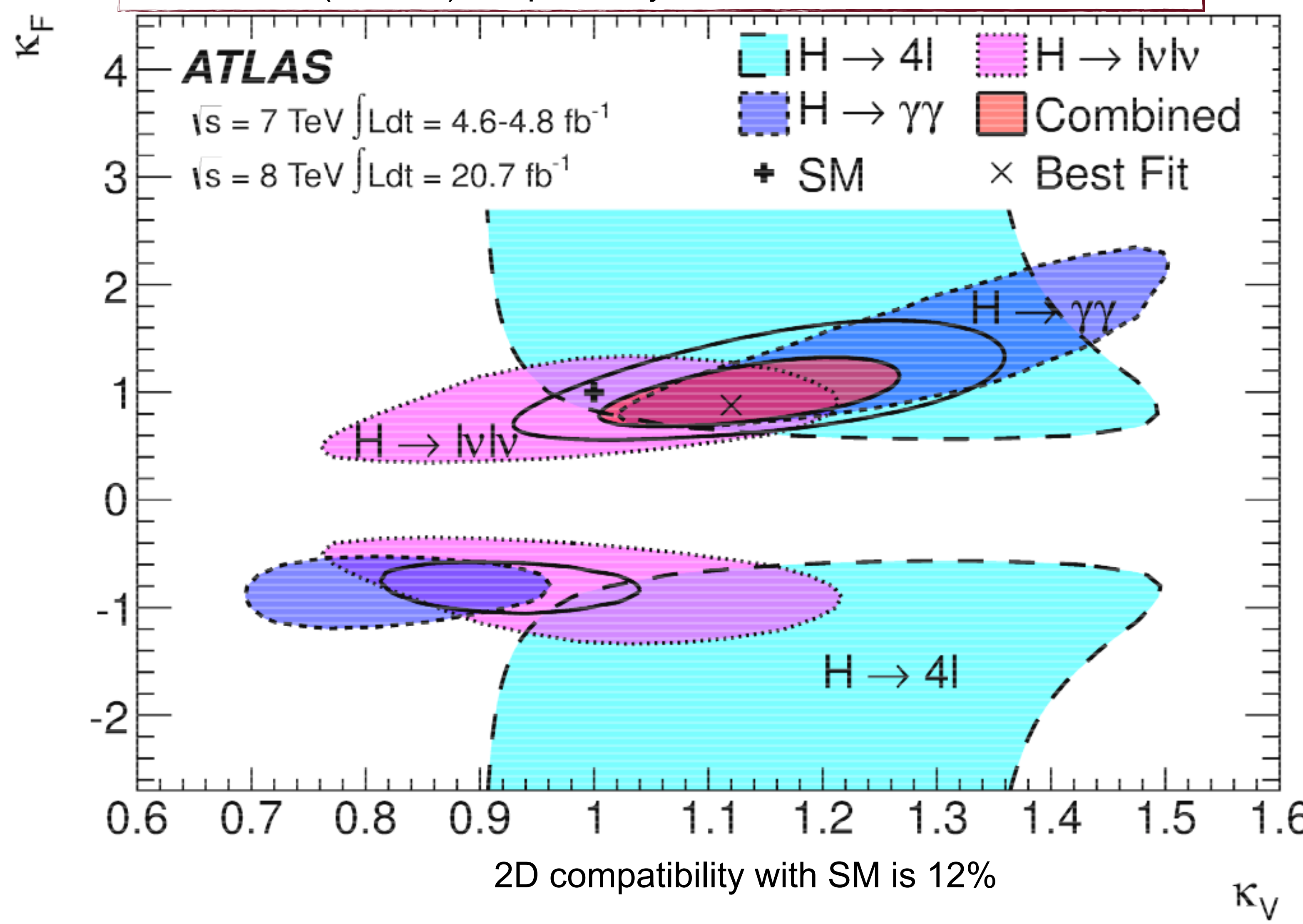
Model	Probed couplings	Parameters of interest	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-
3	Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	√	√	√	-
4		$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$	-	√	√	-	-
5	Vertex loops	κ_g, κ_γ	=1	=1	-	-	√

Higgs boson signal strength measurement following formalism of arXiv:1209.0040

- single resonance of 125.5 GeV
- narrow width approximation
- only modifications of the coupling strengths



Deviations described by overall scales kF (kV) for fermions (bosons), respectively, no BSM contribution



Spin/CP

ATLAS Spin/CP studies: The channels

Channel	$H \to ZZ^{(*)} \to 4\ell$	$H \to WW^{(*)} \to \ell\nu\ell\nu$	$H \to \gamma\gamma$
Dataset	20.7 fb^{-1} @ 8 TeV 4.8 fb^{-1} @ 7 TeV	20.7 fb^{-1} @ 8 TeV	20.7 fb^{-1} @ 8 TeV
Reference	ATLAS-CONF-2013-013	ATLAS-CONF-2013-031	ATLAS-CONF-2013-029
Signal	JHU⊕PYTHIA	PowHeg/JHU⊕PYTHIA	PowHeg/JHU⊕PYTHIA
Tested Hypotheses			
0^-	✓	-	-
1^+	✓	✓	-
1^-	✓	✓	-
2^+	✓	✓	✓

- **Spin Combination**
  - ZZ+WW+γγ
  - ATLAS-CONF-2013-040
  - Phys. Lett. B 726 (2013), pp. 120-144

Production modes

spin-0 : ggF (qqbar annihilation negligible)

spin-1 : qqbar annihilation

spin-2 : ggF & qqbar annihilation

For the Graviton inspired tensor with minimal couplings to SM, ggF dominates with qqbar ~4%, but higher order QCD corrections may significantly modify this → scan f_{qqbar}

VBF and VH production modes:

γγ : included in the analysis

4l : VBF production does not modify kinematics

lvlv: negligible contribution

Statistical Treatment

$$\mathcal{L}\left(J^P,\mu,\theta\right) = \prod_j^{N_{channel}} \prod_i^{N_{bins}} P\left(N_{i,j}|\mu_j S_{i,j}^{(J^P)}(\theta) + B_{i,j}(\theta)\right) \times \mathcal{A}_j(\theta)$$

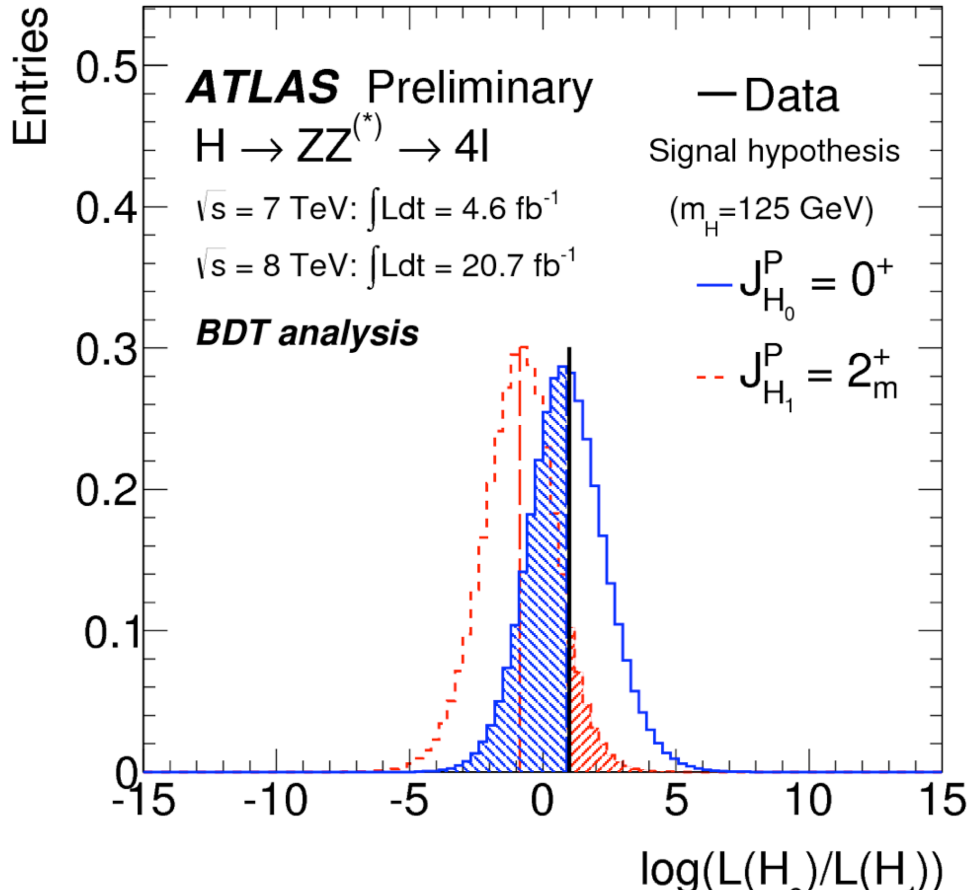
The test statistic is the ratio of profiled likelihoods (LLR) between the two hypotheses, nuisance parameters profiled separately for each hypothesis

$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\rm alt}, \hat{\hat{\mu}}_{J^P_{\rm alt}}, \hat{\hat{\theta}}_{J^P_{\rm alt}})}$$

The test statistic distribution for each hypothesis is extracted from ensemble tests (pseudo-experiments using the profiled values for nuisance parameters) and the CLs is built

$$\mathrm{CL_s}(J^P_{\rm alt}) = \frac{p_0(J^P_{\rm alt})}{1 - p_0(0^+)}$$

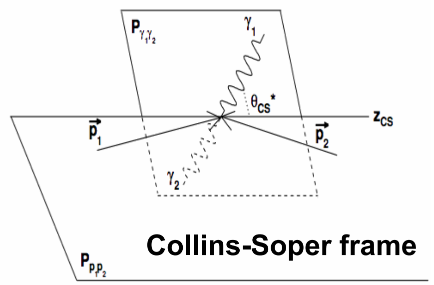
Note: μ_{SM} and μ_{JP} profiled independently
(ie no assumptions on production rates)



H→γγ : Introduction

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

Discriminating variable: polar angle of the photons with respect to the z-axis of the Collins-Soper frame (minimize effect of ISR)

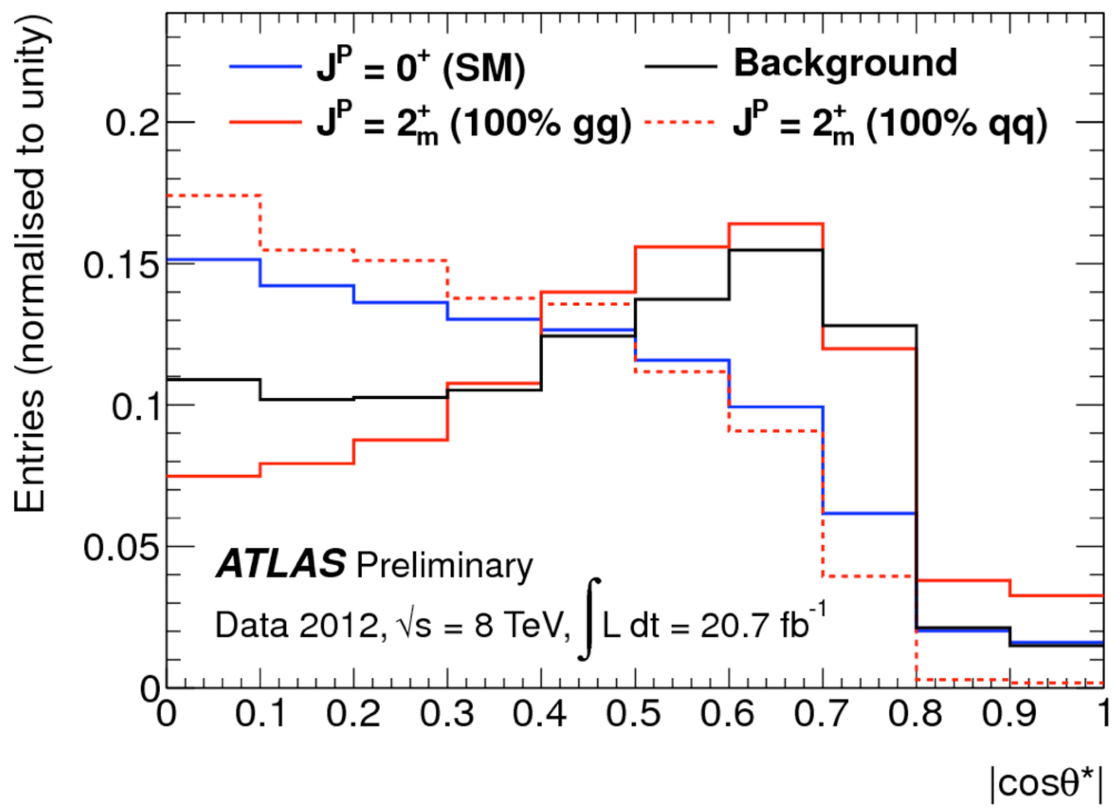


Before acceptance requirements:
- spin 0 : isotropic decay
- spin 2 : distribution depends on the qq/gg fractions:

$$100\%\ gg : \frac{dN}{d\cos\theta*} = 1 - 6\cos^2\theta^* + \cos^4\theta^*$$

$$100\%\ q\bar{q} : \frac{dN}{d\cos\theta*} = 1 - \cos^4\theta^*$$

- Background : peaking in the forward-backward direction

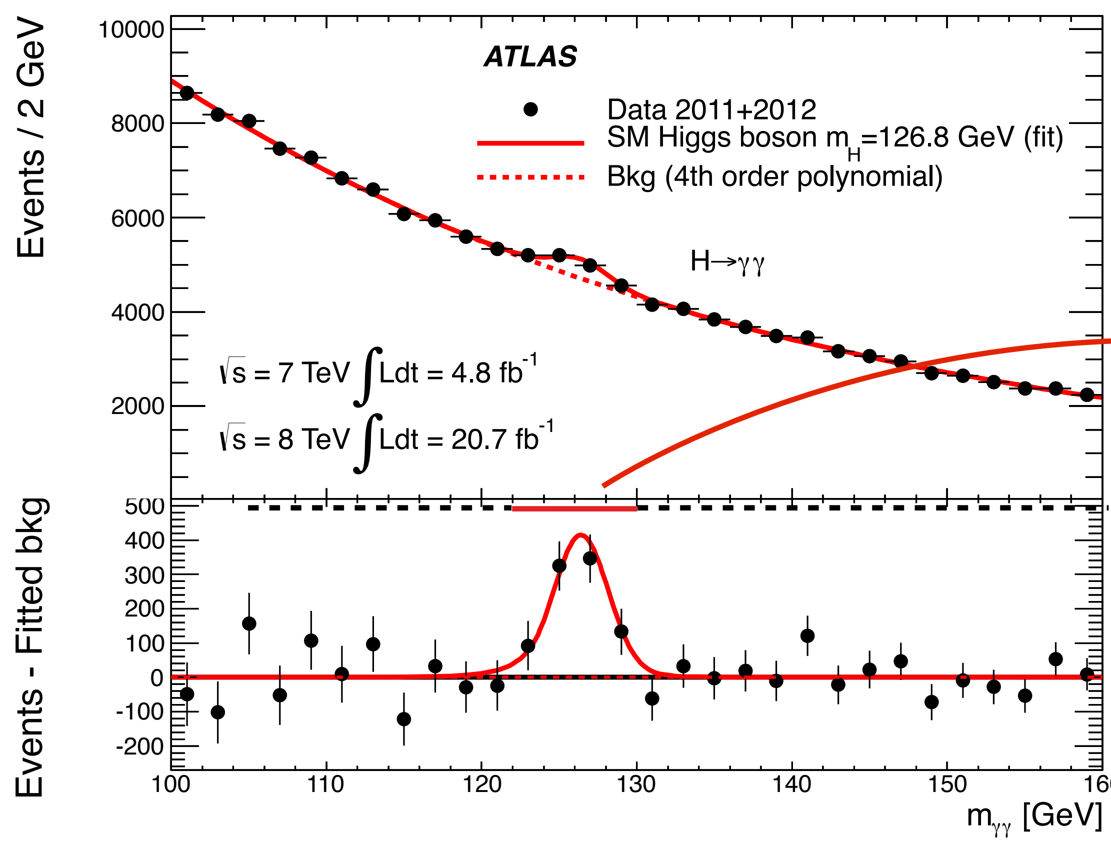


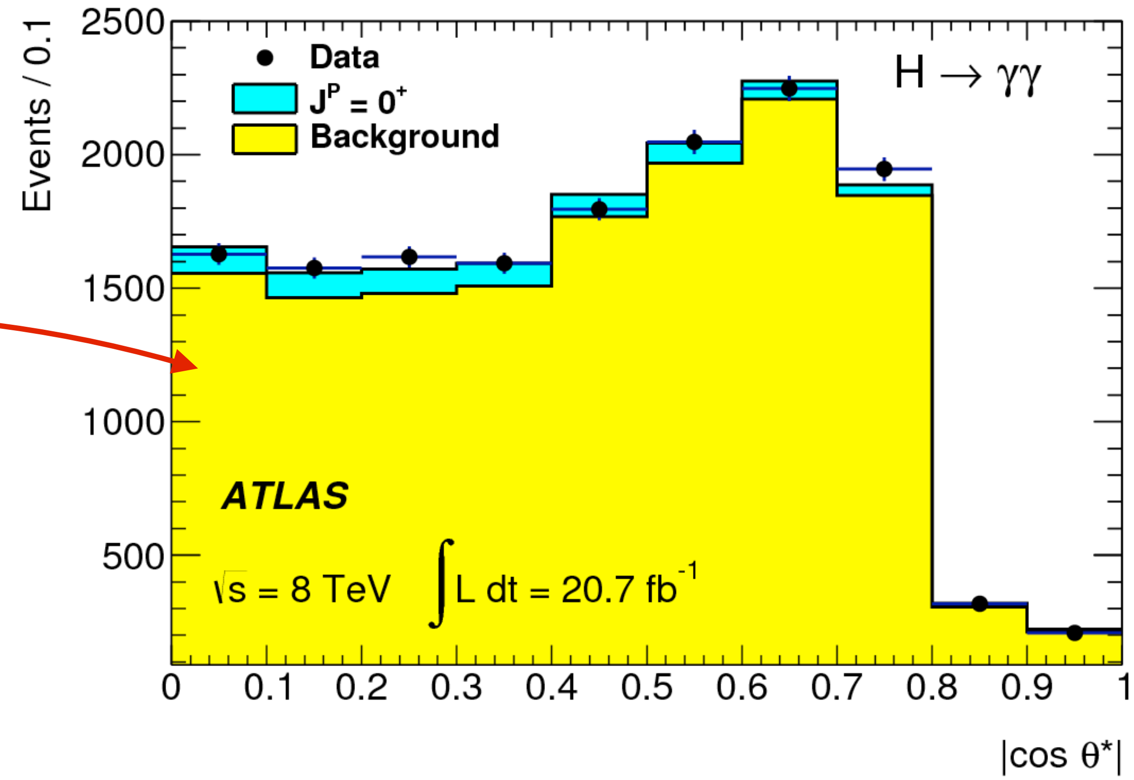
- Analysis similar to "rate/mass" analysis but optimized selection:
  - $p_{T\gamma 1}>0.35\ m_{\gamma\gamma}$ and $p_{T\gamma 2}>0.25\ m_{\gamma\gamma}$

  [Minimize $m_{\gamma\gamma}$ and cosθ* correlations for background]

$H\rightarrow\gamma\gamma$: Fit Procedure

$H\rightarrow\gamma\gamma$ is a low S/B final state (inclusive ~3%)
- Simultaneous fit to $m_{\gamma\gamma}$ and |cosθ*| in signal region
- $m_{\gamma\gamma}$ in side-bands



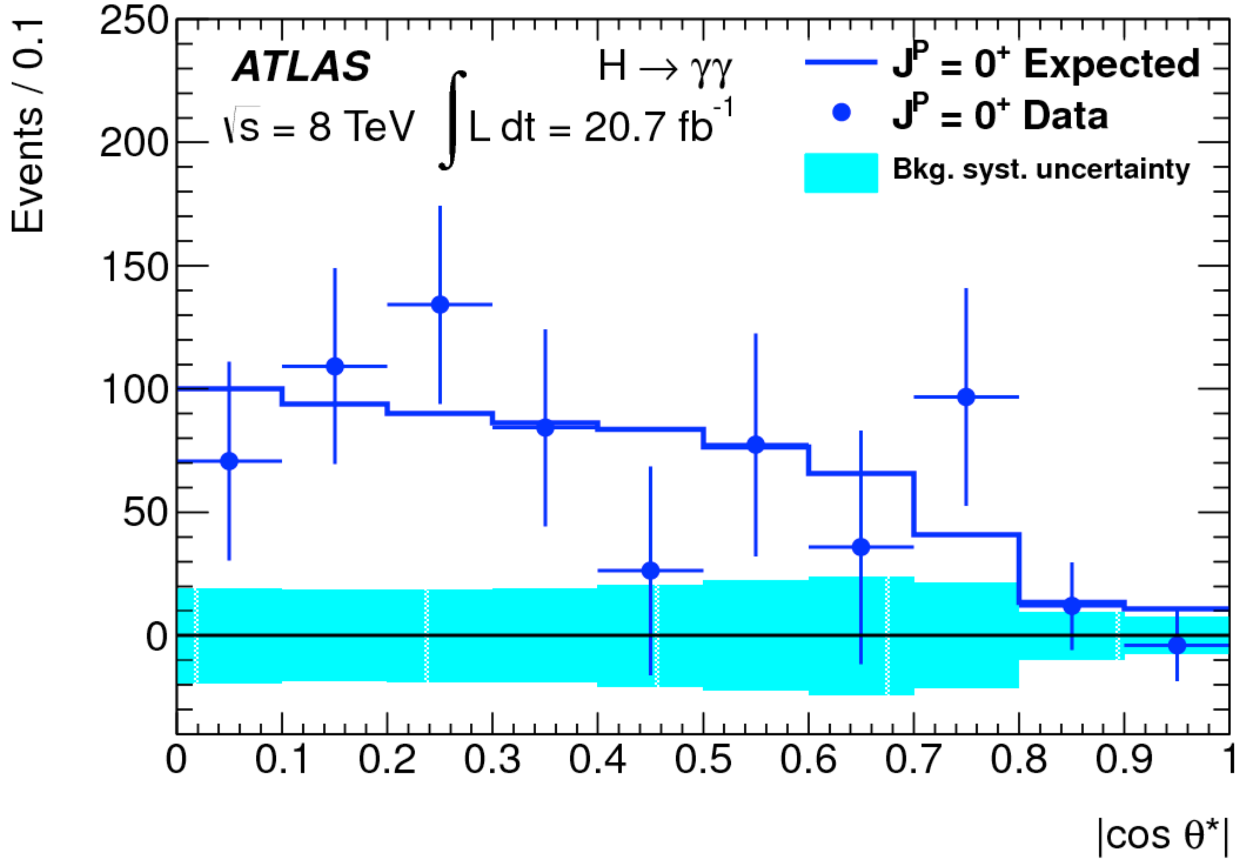


For 105 GeV < m_{4l} < 160 GeV
14977 candidate events
~14300 background events
~370 SM Higgs boson signal

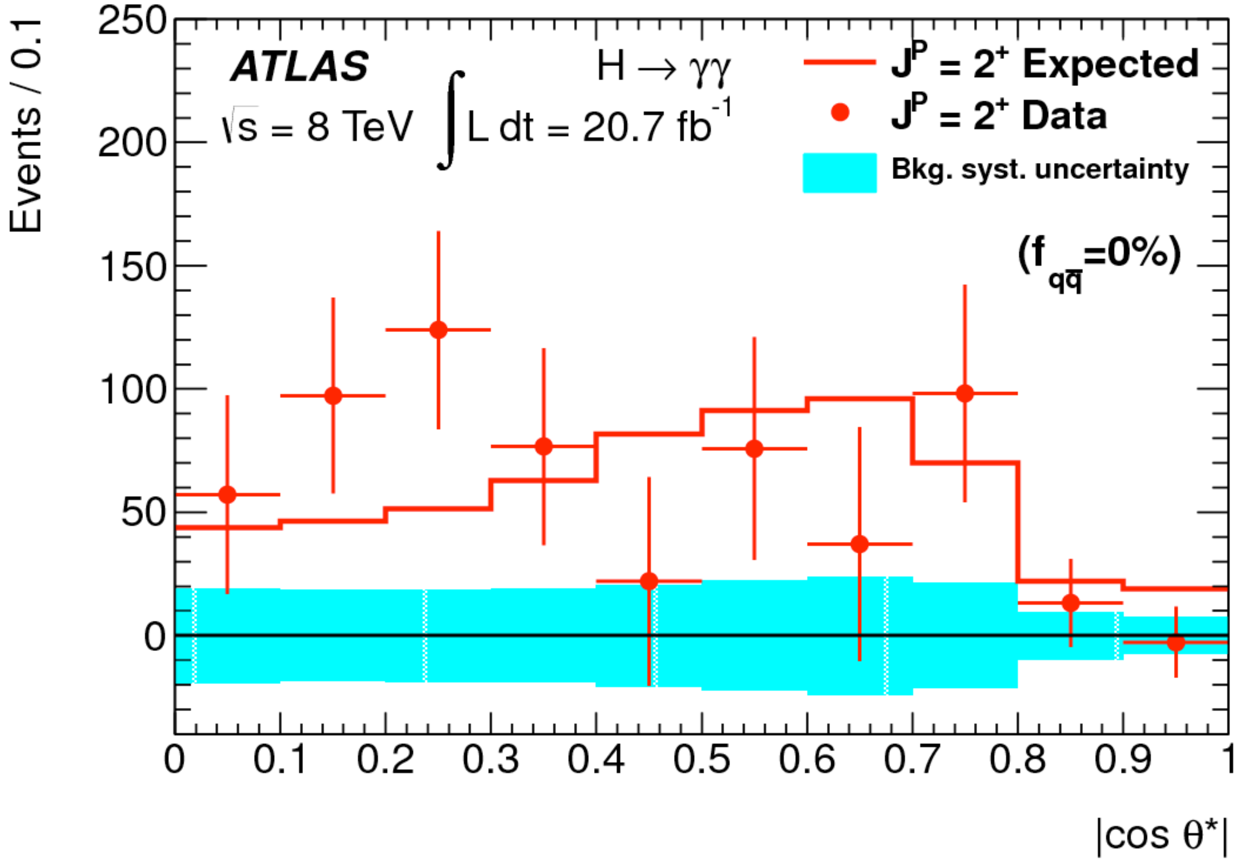
H→γγ : Fit results 0^+ vs 2^+

Background subtracted distributions

Fit assuming 0^+

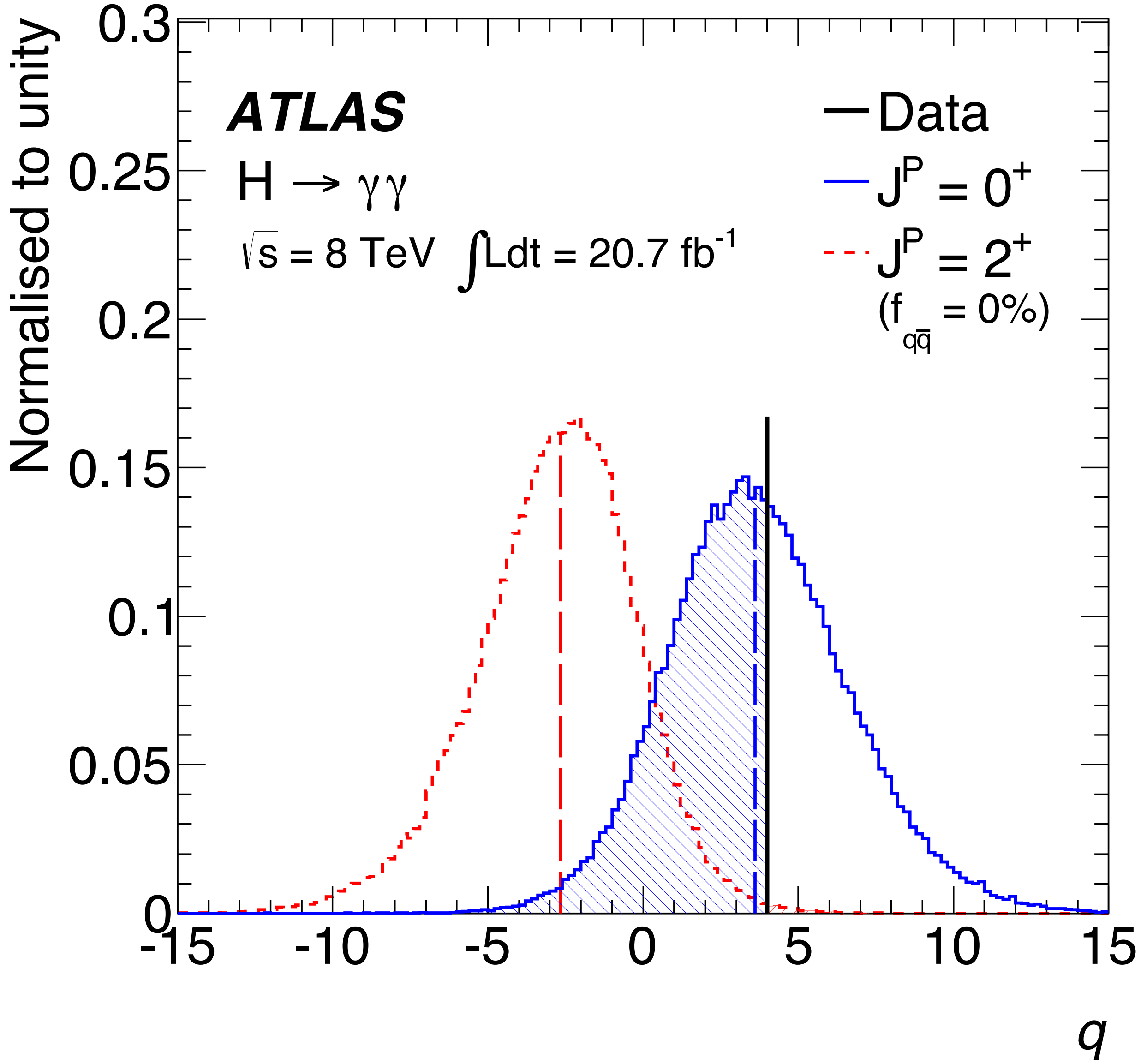


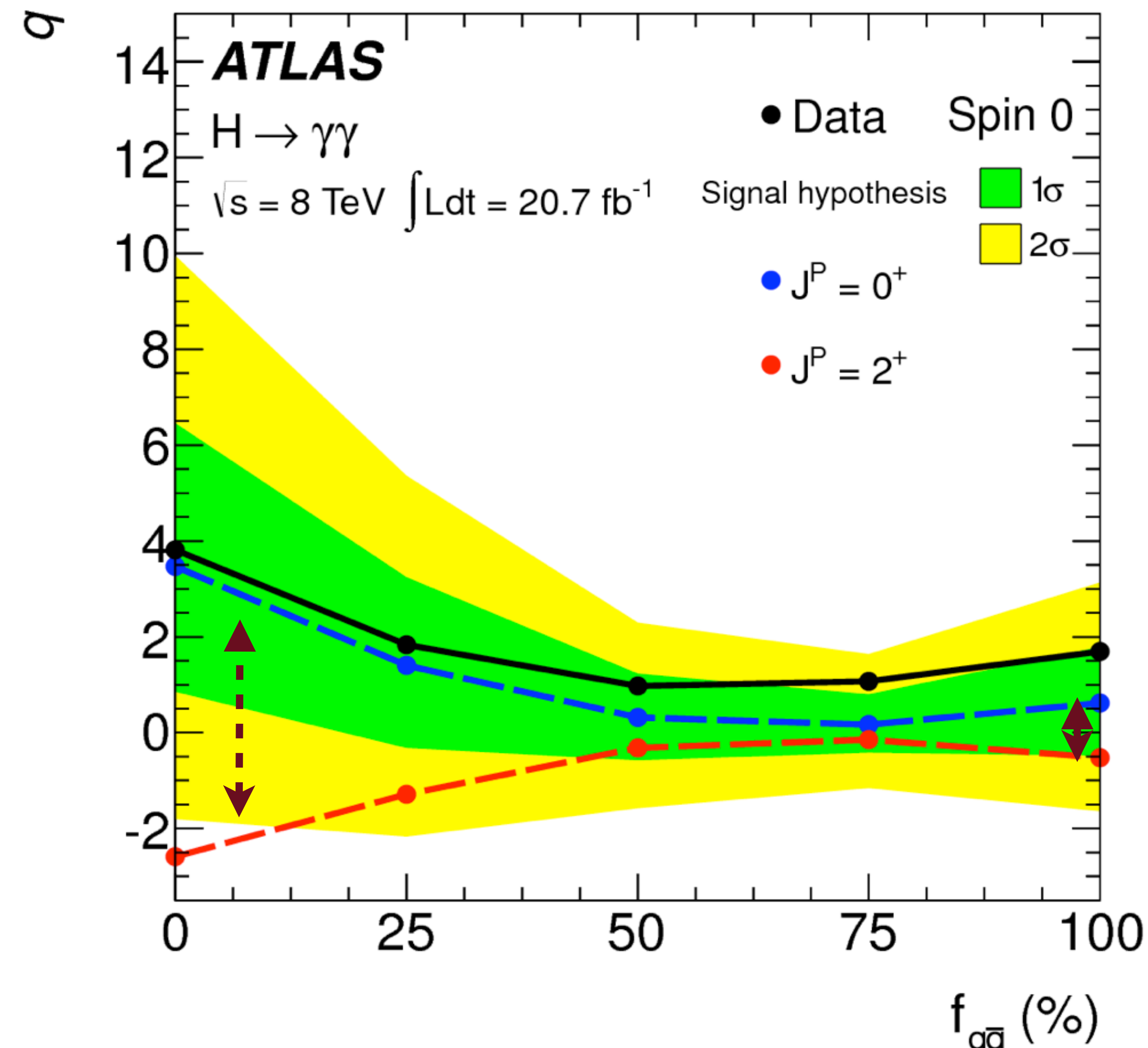
Fit assuming 2^+ (100% gg)



Data differ slightly, owing to the background being determined separately for each spin hypothesis

H→γγ: LLR 0+ vs 2+



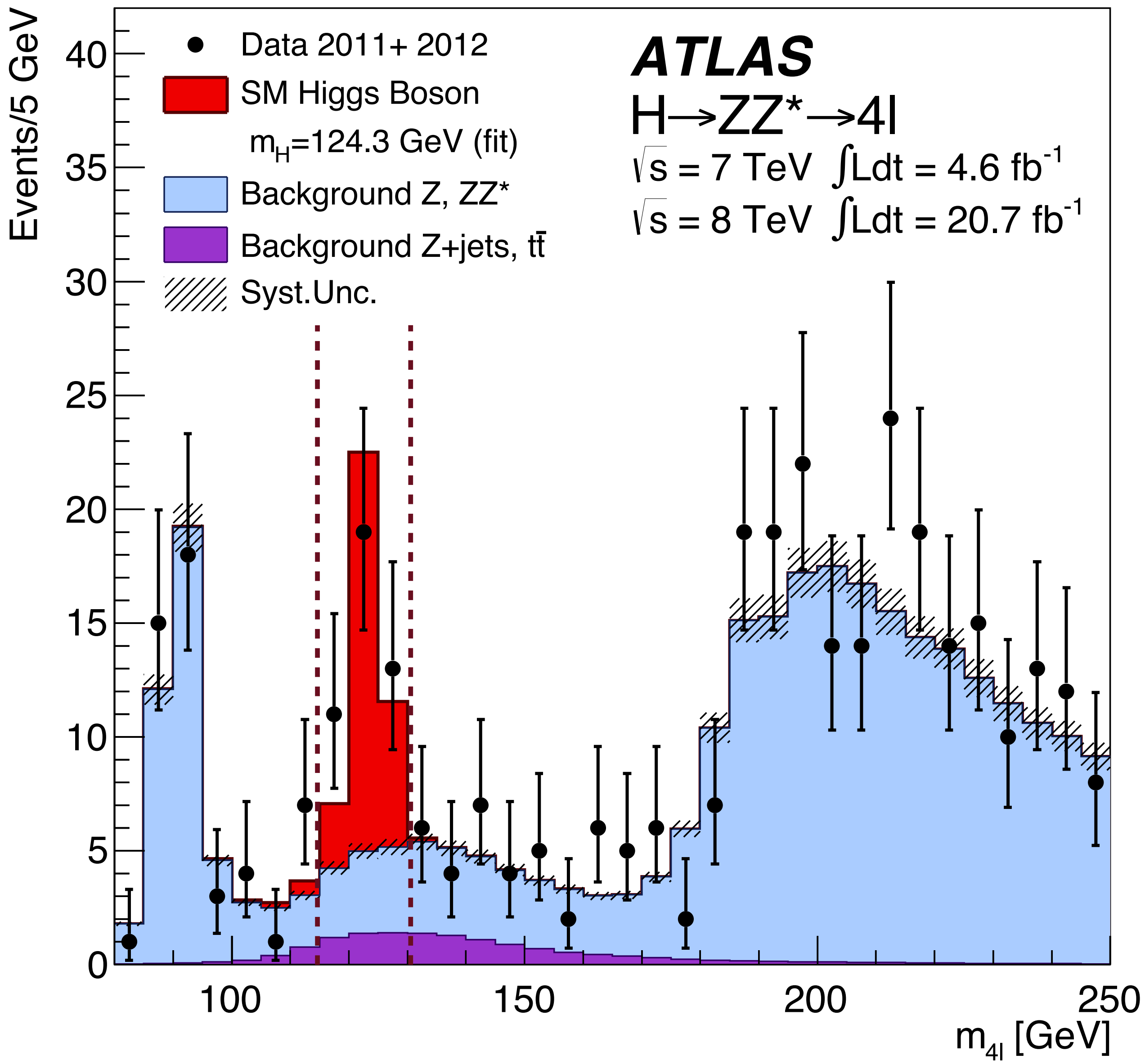


$H \to \gamma\gamma$

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$	
100%	0.148	0.135	0.798	0.025	0.124	87.6%
75%	0.319	0.305	0.902	0.033	0.337	66.3%
50%	0.198	0.187	0.708	0.076	0.260	74.0%
25%	0.052	0.039	0.609	0.021	0.054	94.6%
0%	0.012	0.005	0.588	0.003	0.007	99.3%

The 2^+ hypothesis is disfavored with respect to the 0^+ hypothesis.

H→ZZ→4l: Introduction



Ideal channel for spin/CP studies

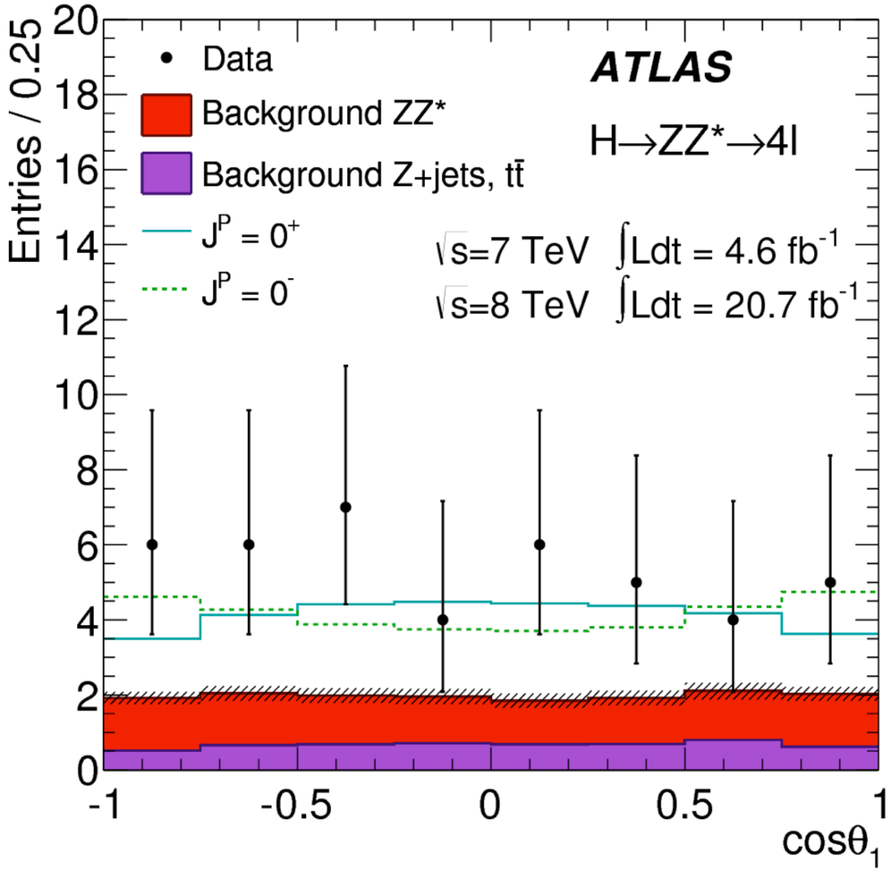
- Complete reconstruction of the event topology
- Clean (S/B ~1 to 2 depending on final state)
- Several observable depending on spin/CP available

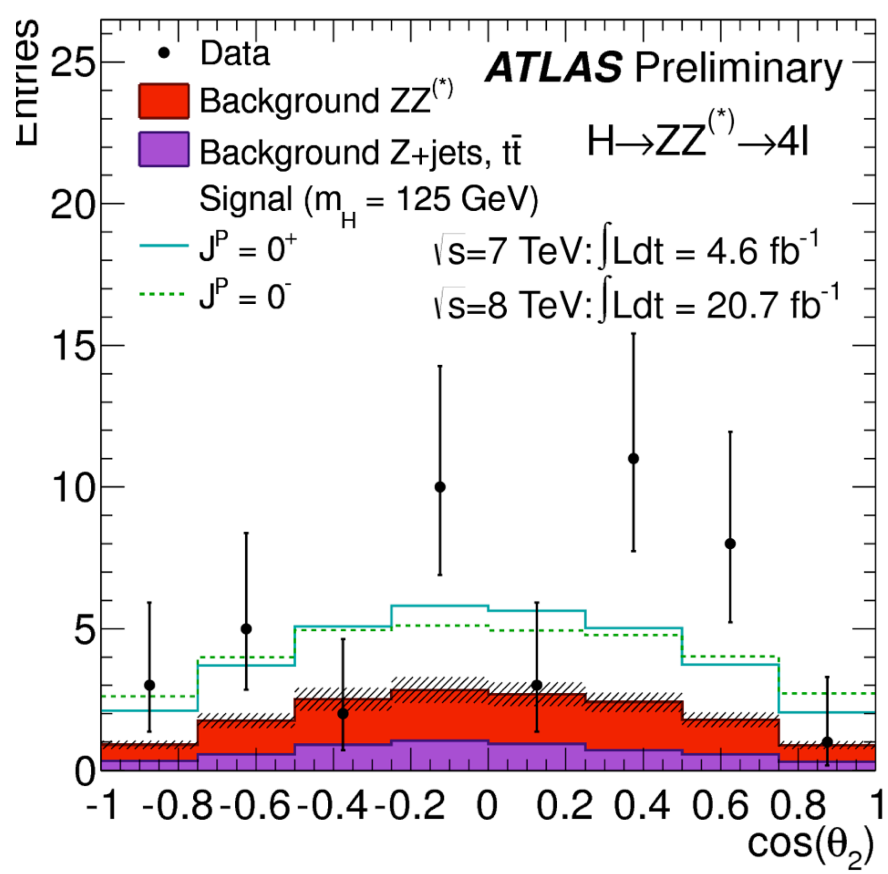
For 115 GeV < m_{4l} < 130 GeV
43 candidate events
16 background events
18 SM Higgs boson events expected

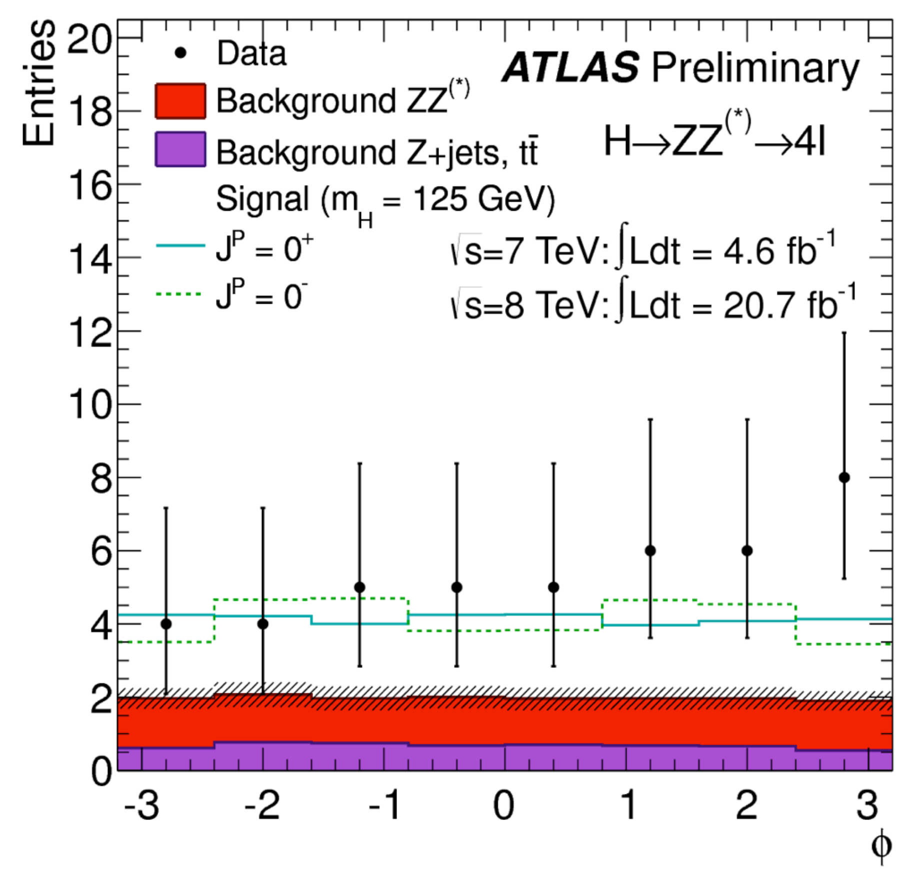
Split signal region [in GeV] → 6% sensitivity improvement:
- High S/B [121,127]
- Low S/B (115,121) ∪ (127,130)

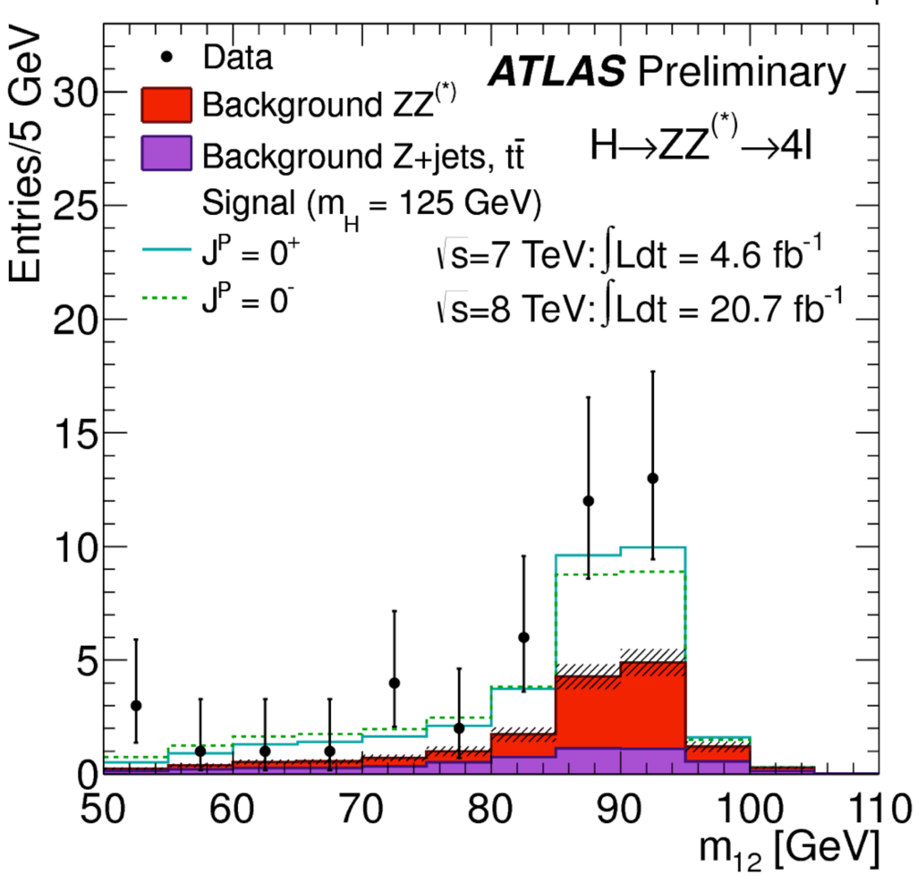
Two approaches:
- Train BDT separately for each hypothesis
- Use ME corrected for acceptance and pairing effects

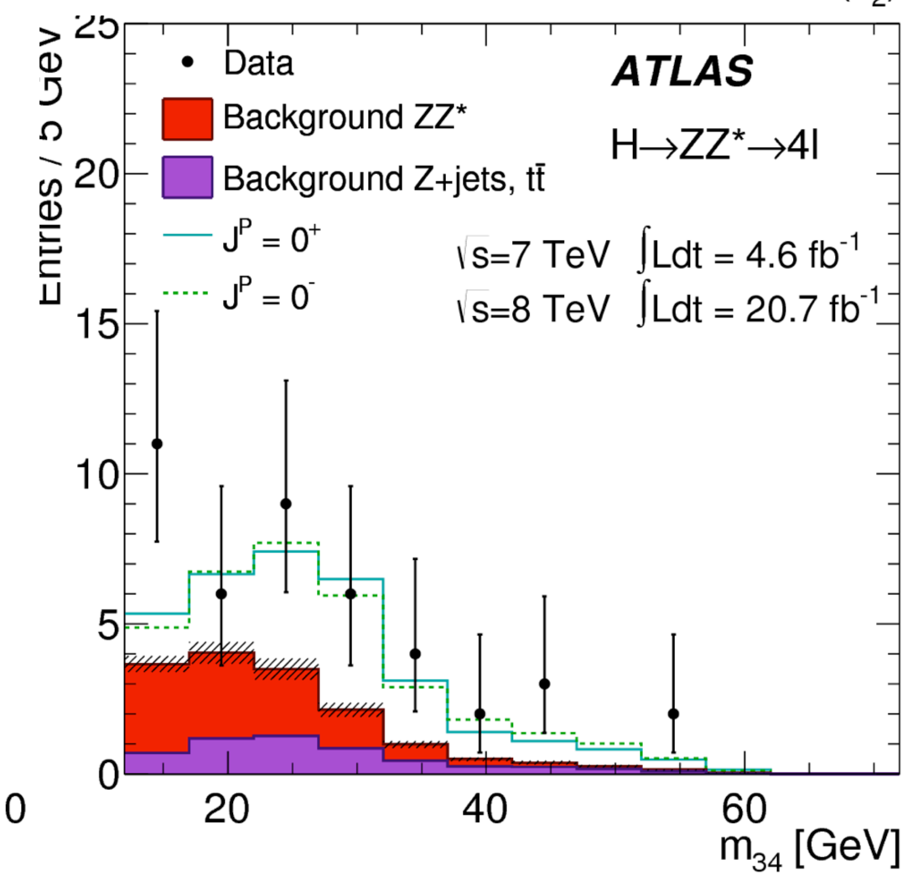
H→ZZ→4l: Input Variables





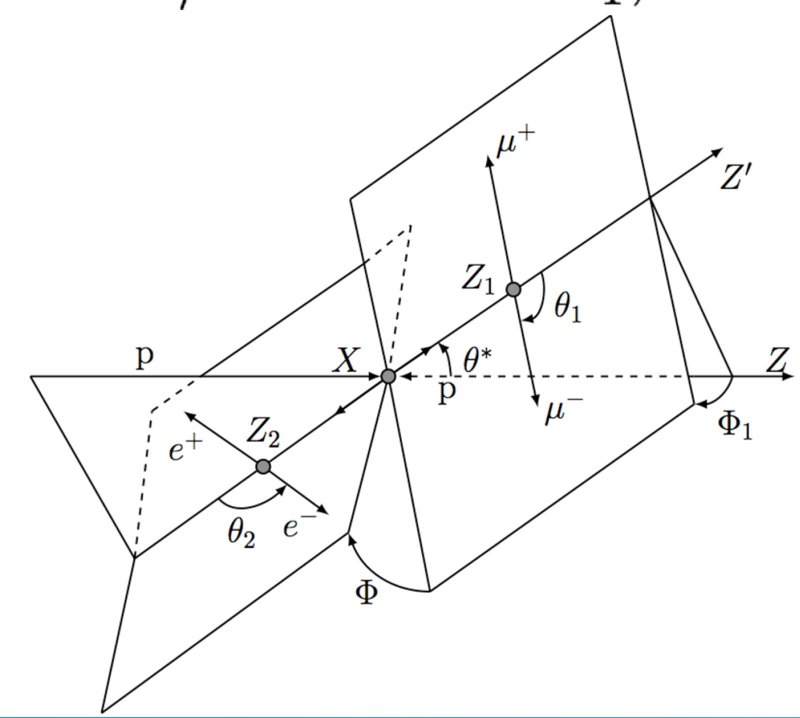




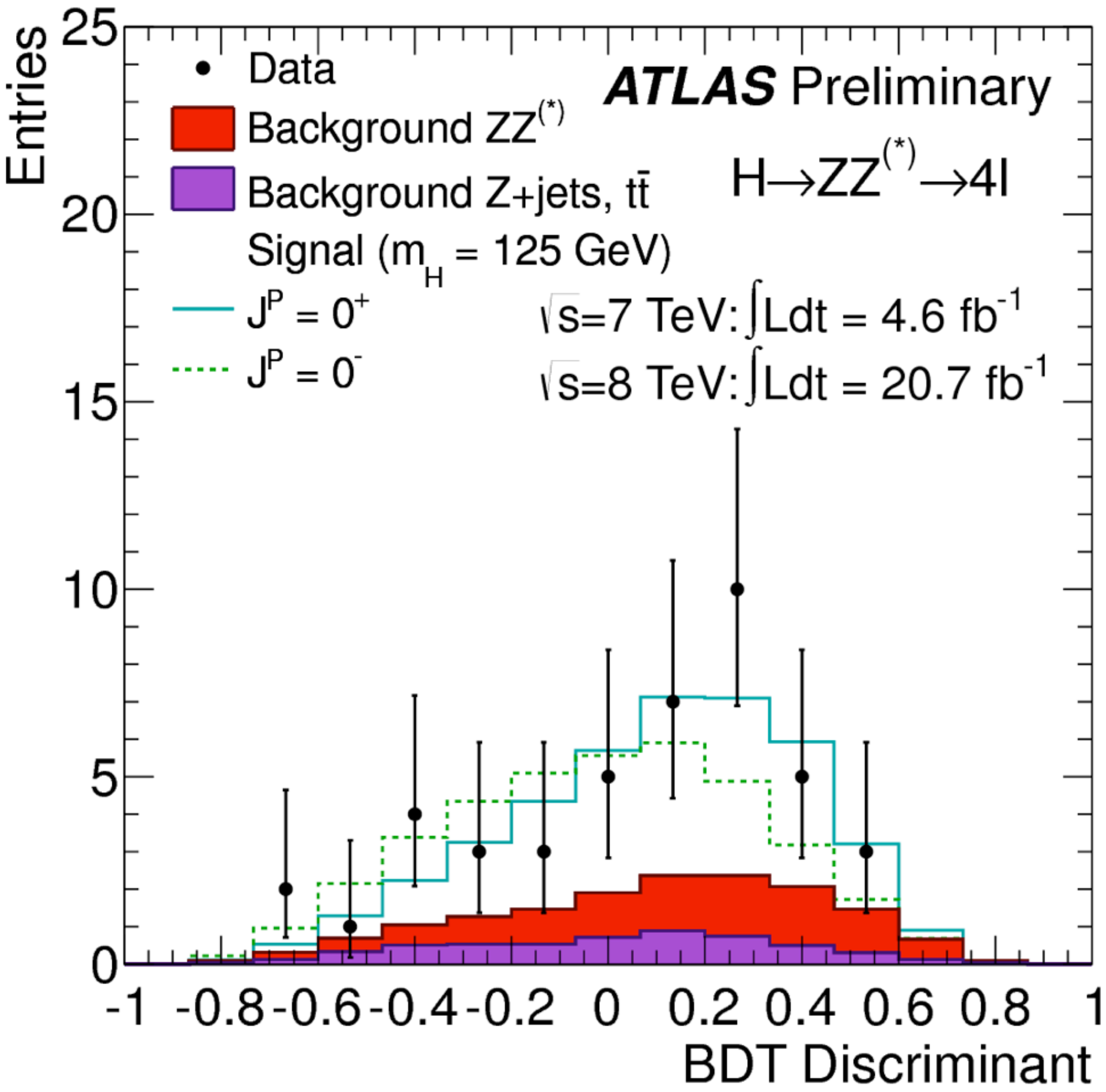


For $0^+/0^-$: $\Phi, \theta_1, \theta_2, m_{12}, m_{34}$

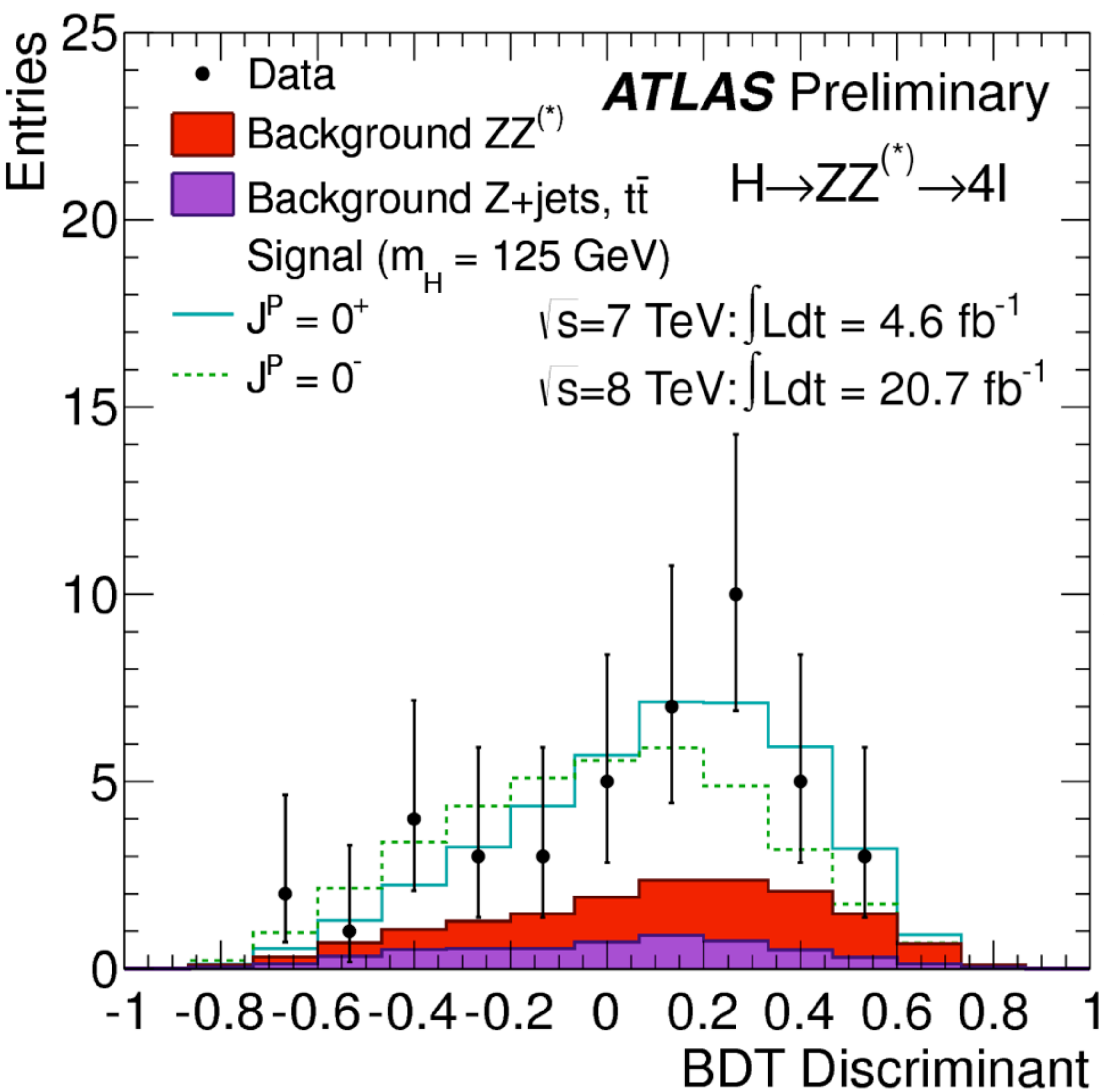
For 0^+/other add : Φ_1, θ^*

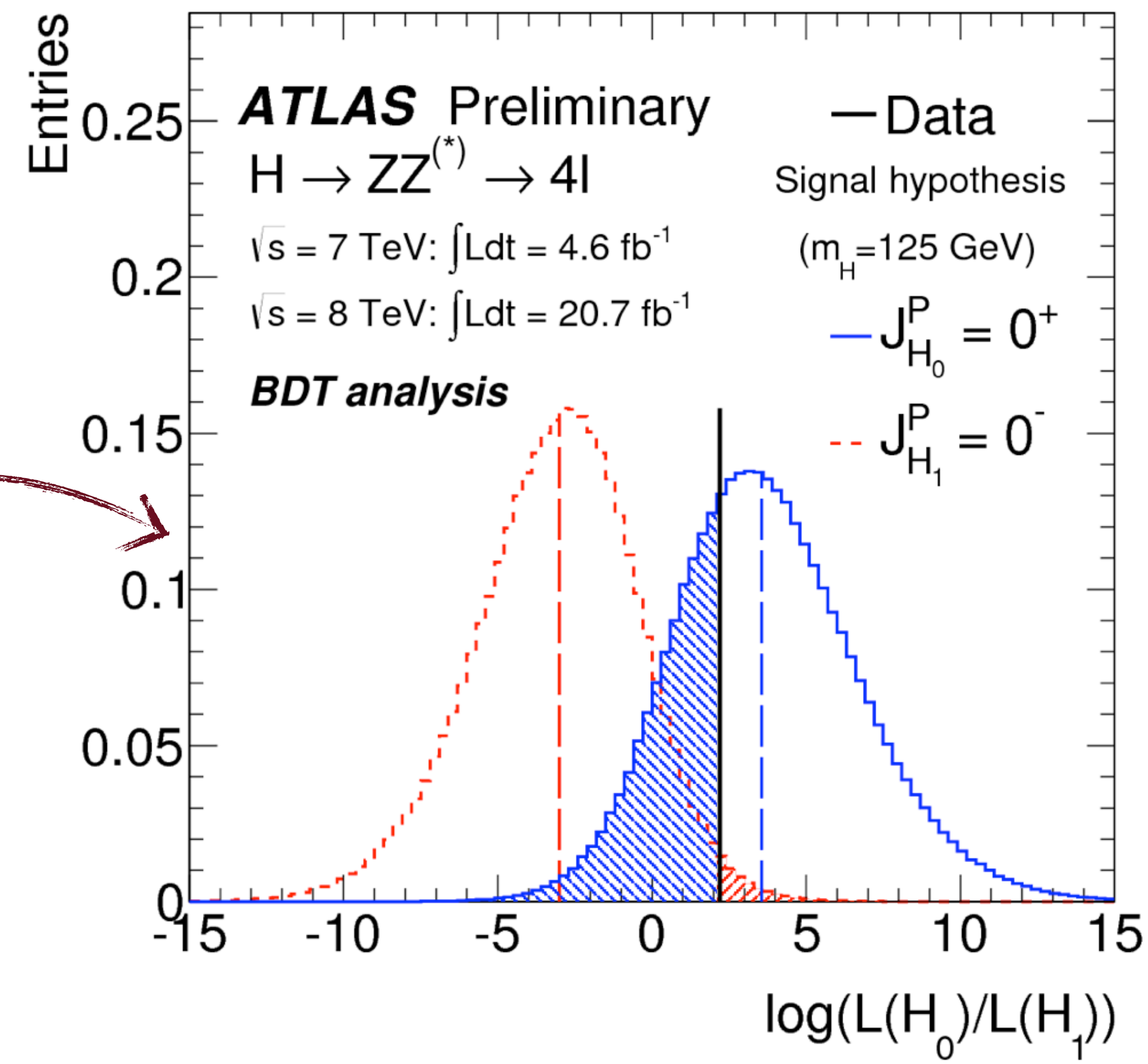


H→ZZ→4l : Distribution of discriminant



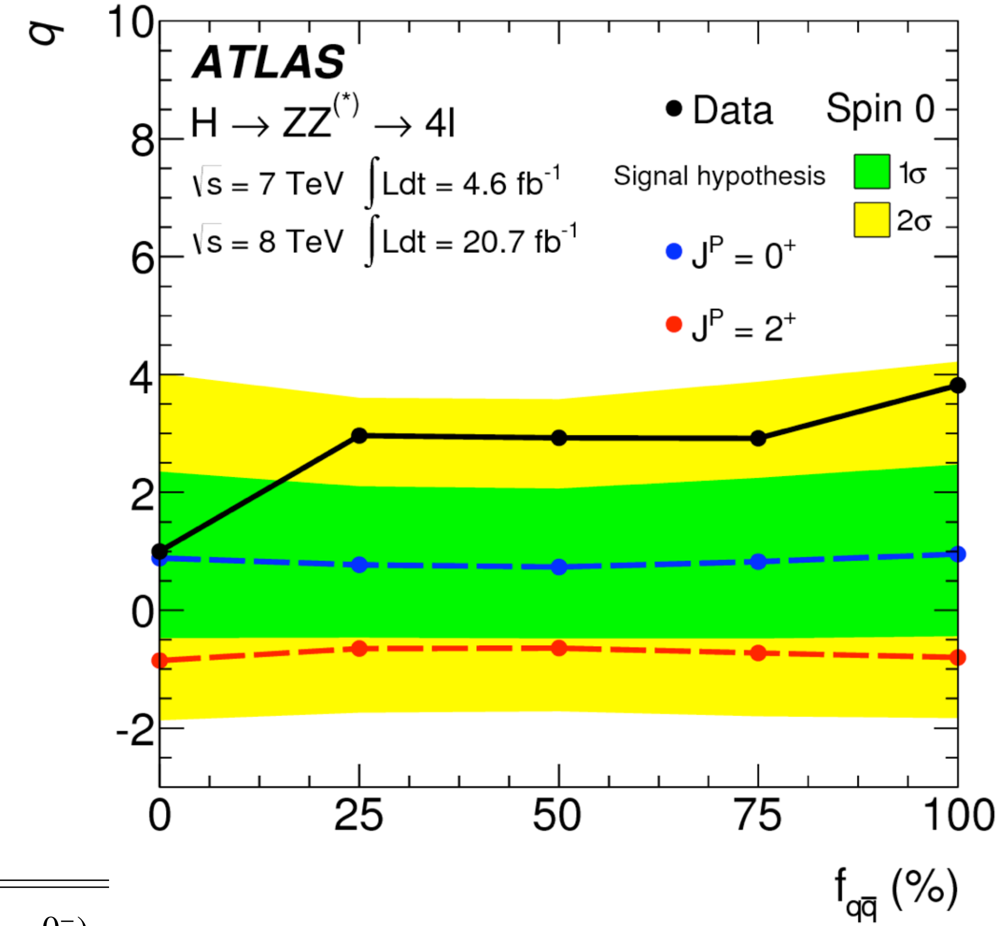
H→ZZ→4l : LLR 0^+ vs 0^-





H→ZZ→4l : Results Overview

Main Systematic:
- High S/B vs Low S/B regions normalization (~10%) owing to the uncertainty on m_H



Channel	0^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 0^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 0^-)$	$CL_s(J^P = 0^-)$	
$H \rightarrow ZZ^*$	$1.5 \cdot 10^{-3}$	$3.7 \cdot 10^{-3}$	0.31	0.015	0.022	97.8%

Channel	1^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^-)$	$CL_s(J^P = 1^-)$	
$H \rightarrow ZZ^*$	$0.9 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$	0.15	0.051	0.060	94.0%

Channel	1^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^+)$	$CL_s(J^P = 1^+)$	
$H \rightarrow ZZ^*$	$4.6 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	0.55	$1.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$	99.8%

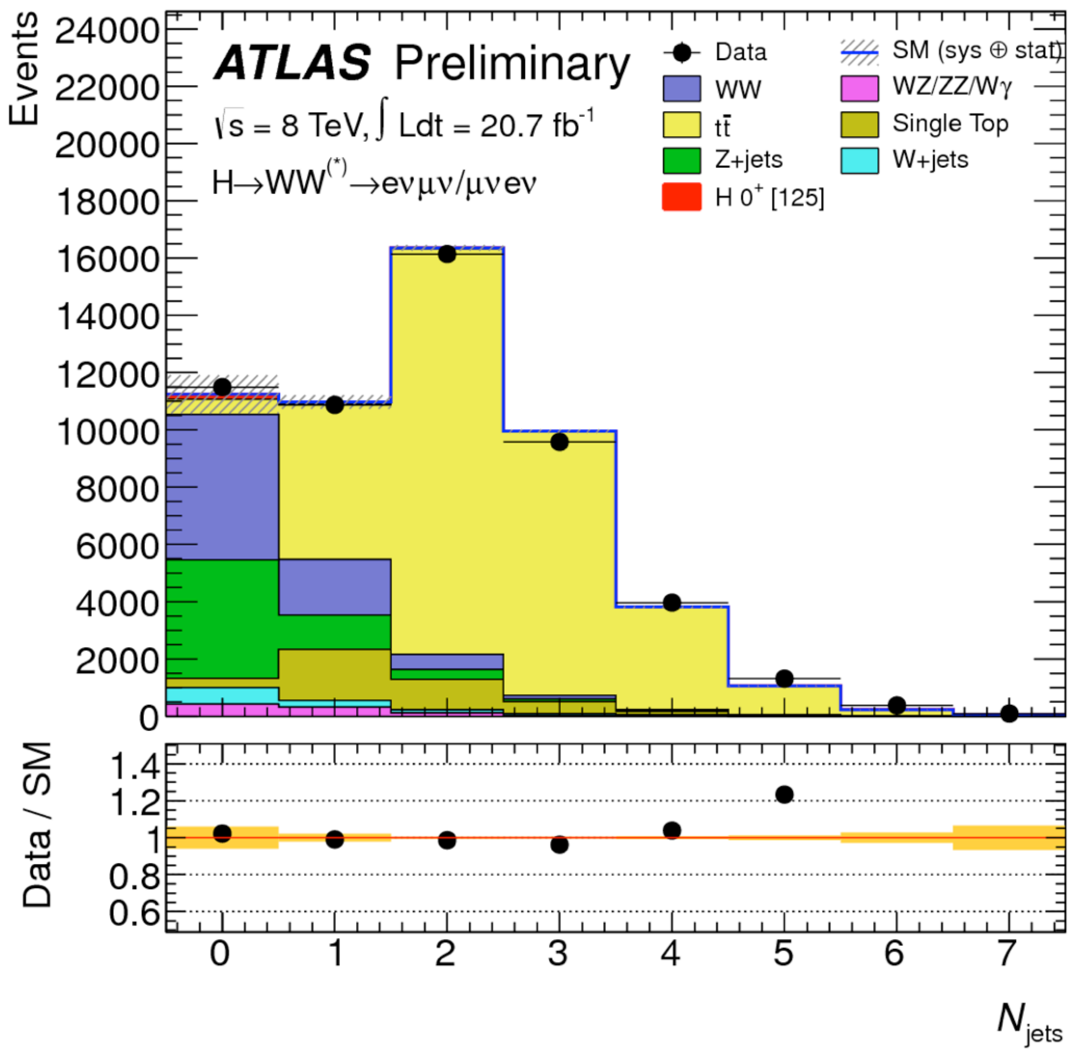
$H \rightarrow ZZ^*$

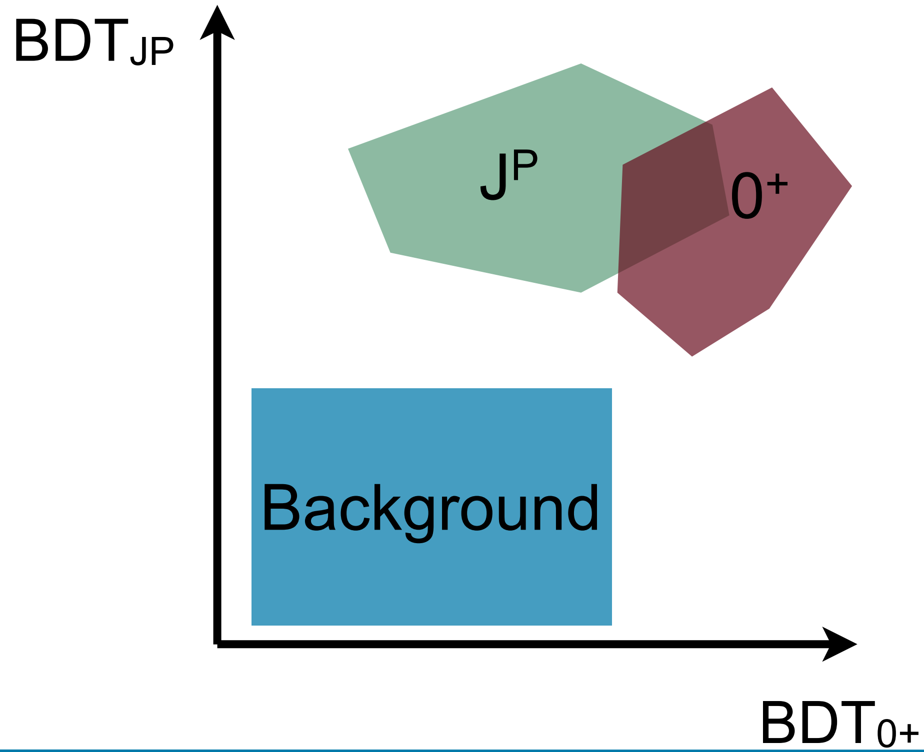
$f_{q\bar{q}}$	2^+ assumed assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$	
100%	0.102	0.082	0.962	0.001	0.026	97.4%
75%	0.117	0.099	0.923	0.003	0.039	96.1%
50%	0.129	0.113	0.943	0.002	0.035	96.5%
25%	0.125	0.107	0.944	0.002	0.036	96.4%
0%	0.099	0.092	0.532	0.079	0.169	83.1%

All alternative hypotheses are disfavored with respect to the 0^+ hypothesis.

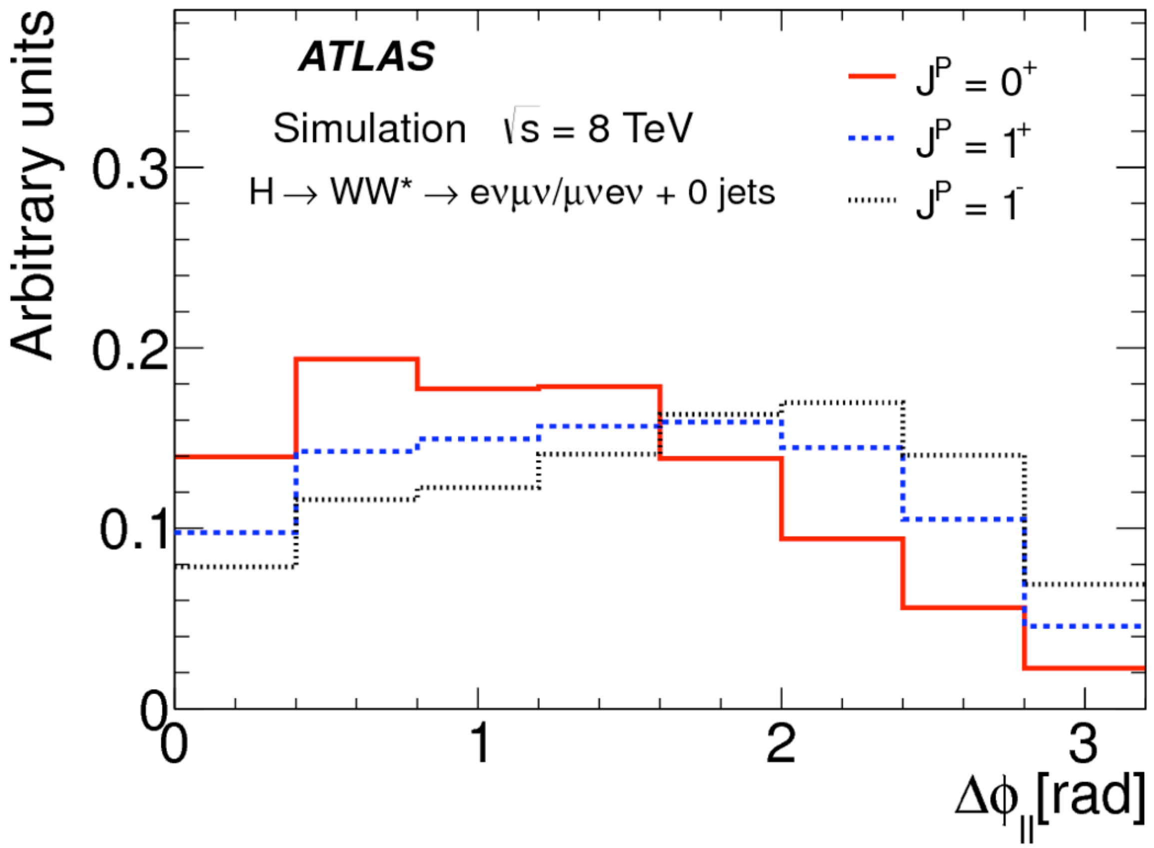
H→WW→lνlν: Introduction

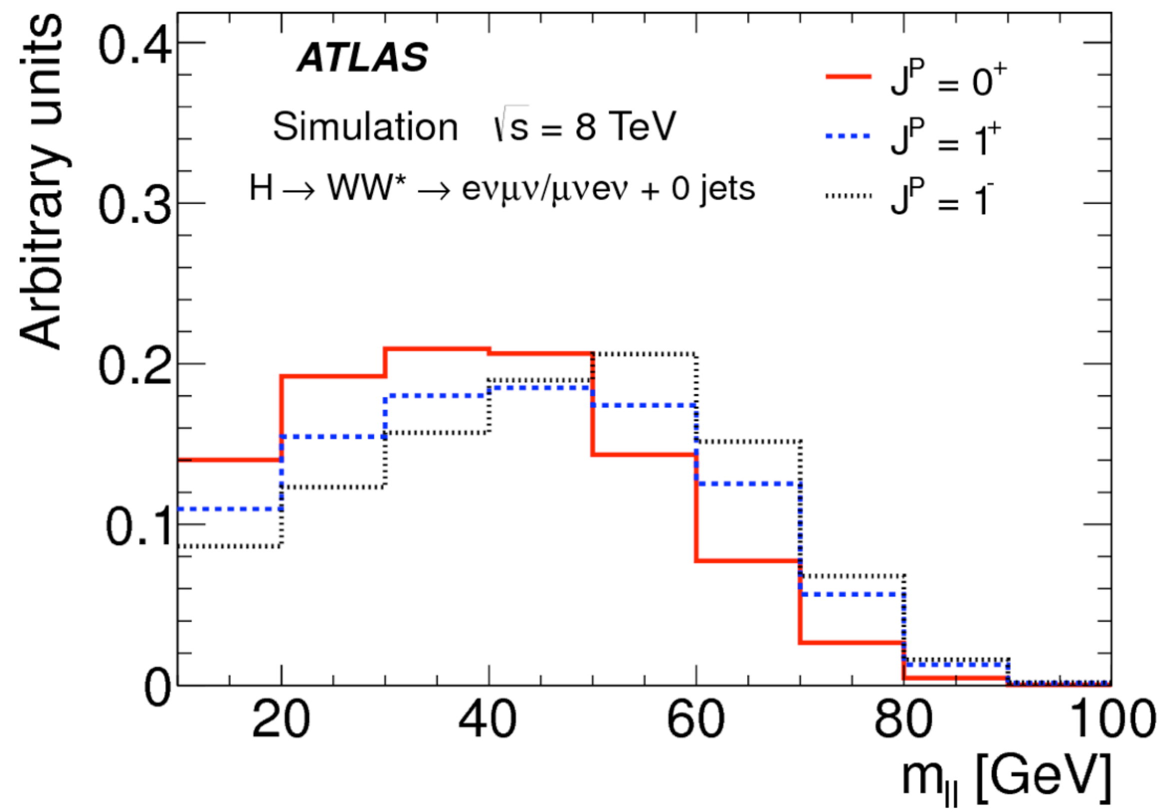
- Restricted to "different flavour" (eμ) events and no jets
  - $p_{Tl1}>25$ GeV and $p_{Tl2}>15$ GeV
  - $p_{Tj}>25$ GeV for $|\eta|<2.5$ ($p_{Tj}>30$ GeV for $2.5<|\eta|<4.5$)
- Rate analysis already exploits spin-0 nature of SM Higgs boson
  - Relax spin-sensitive requirements
  (allow spin study while keeping backgrounds under control)
  - E_TMissRel > 20 GeV
  - m_{ll} < 80 GeV
  - p_{Tll} > 20 GeV
  - $\Delta\varphi_{ll}$ < 2.8
- m_{ll}, $\Delta\varphi_{ll}$, p_{Tll}, m_T sensitive to spin
- Two BDT classifiers are used:
  - BDT_{0+}: SM Higgs signal against the sum of all backgrounds
  - BDT_{JP}: J^P signal against the sum of all backgrounds
  - Perform 2D-fit in (BDT_{0+},BDT_{JP})
- pT spectrum uncertainties found to have small effect

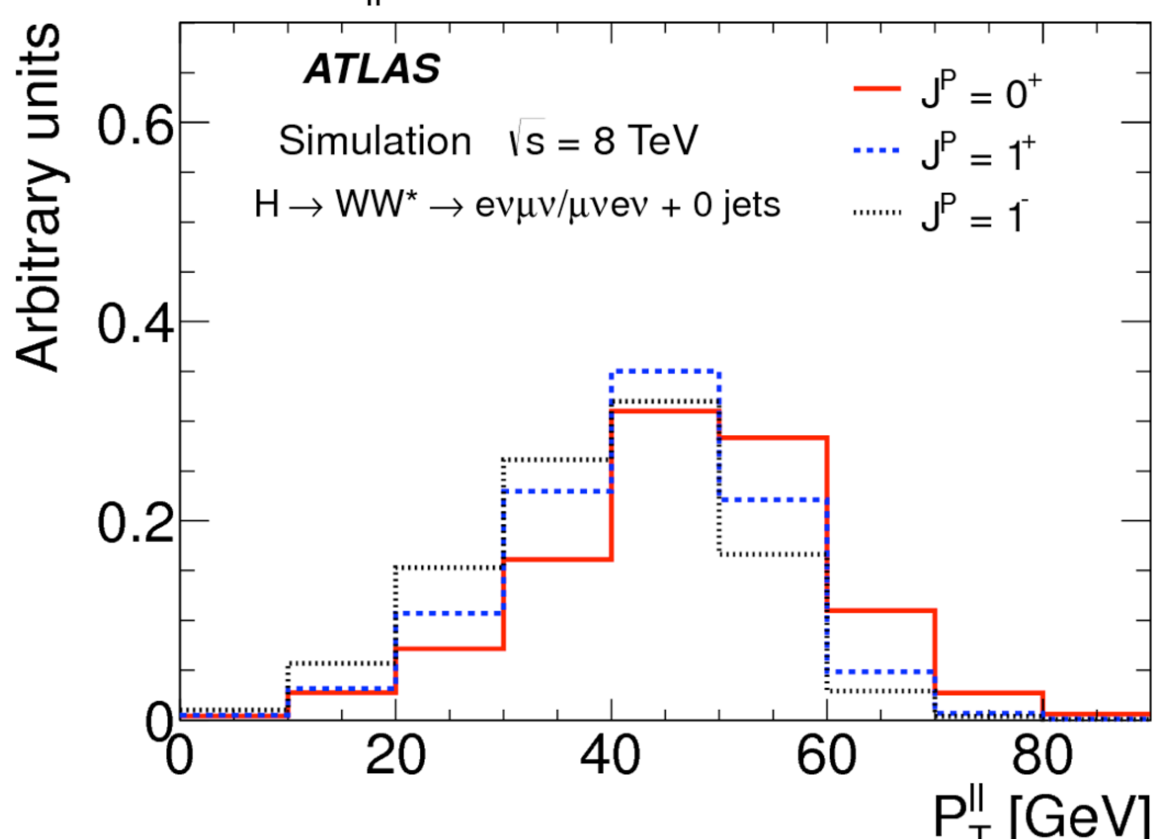




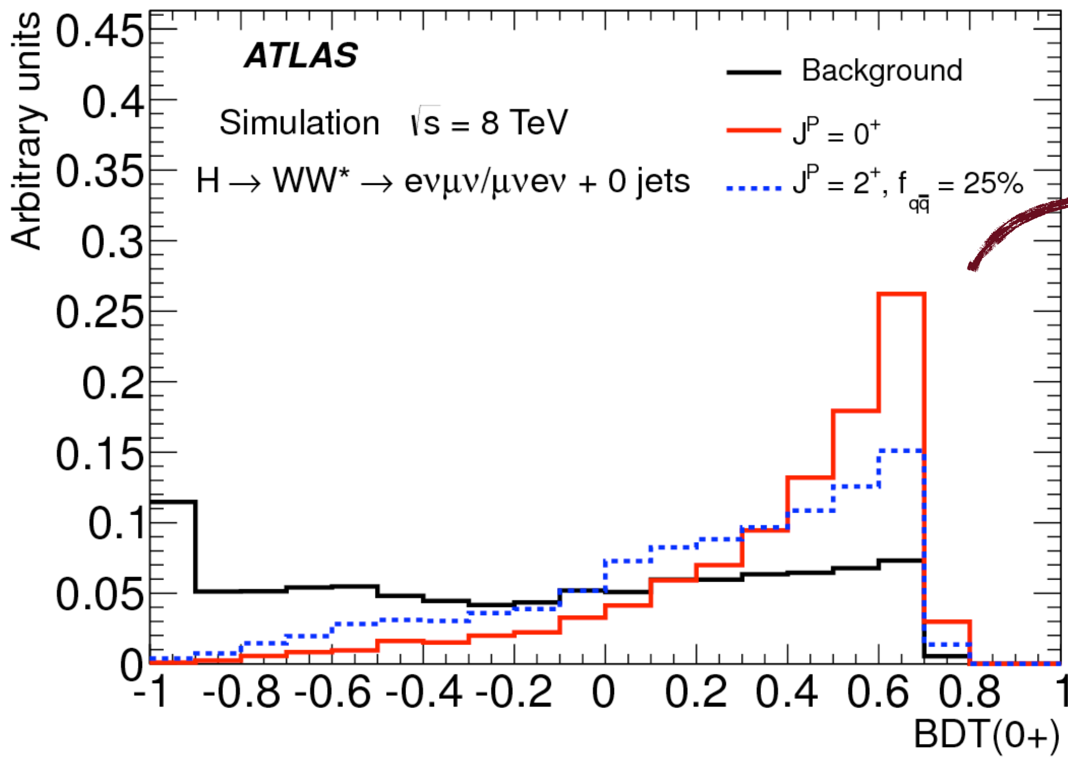
H→WW→lνlν: Spin/CP sensitive variables

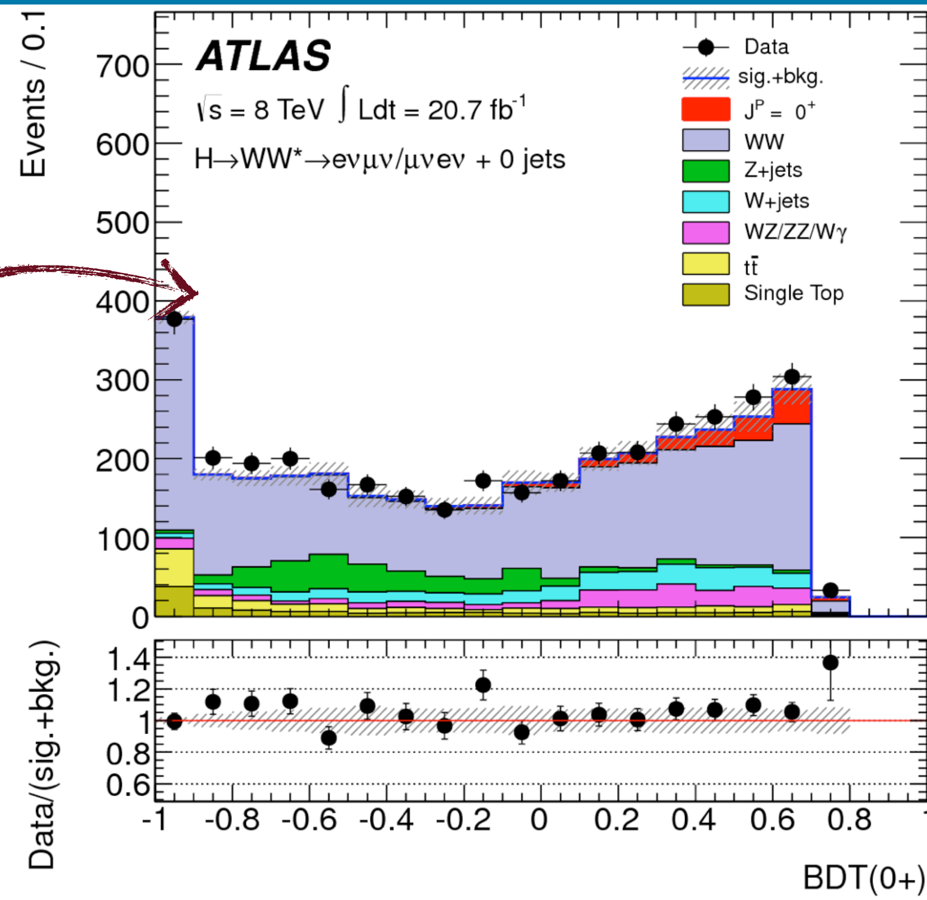




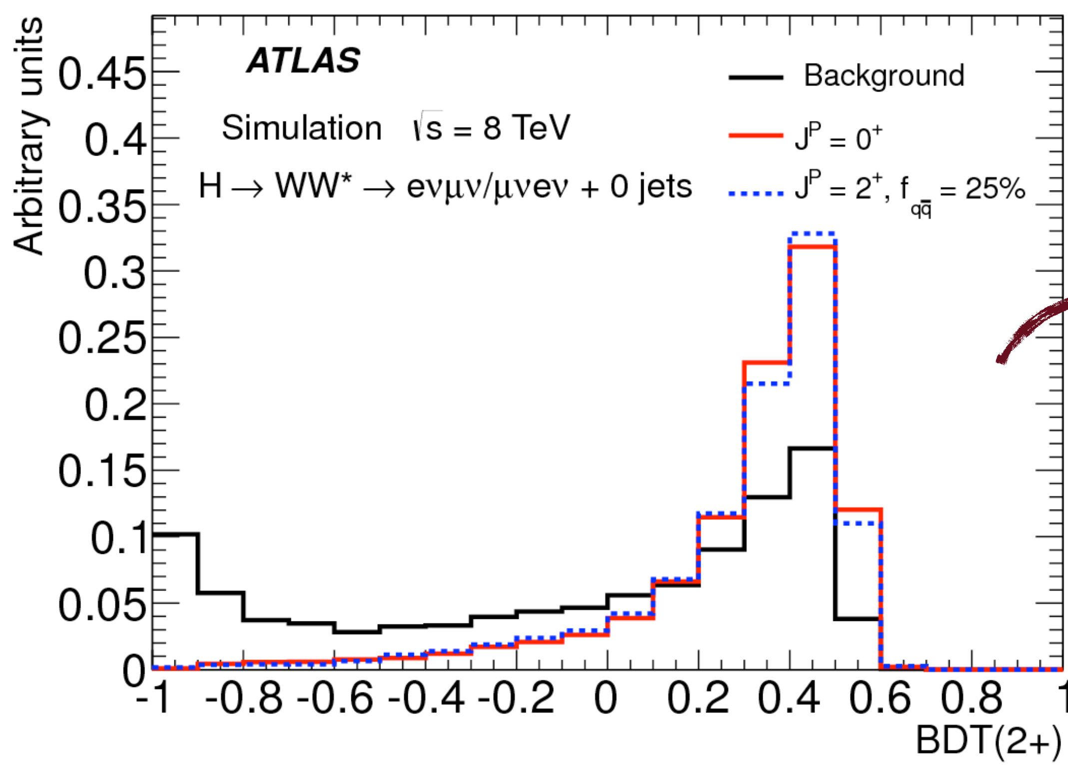


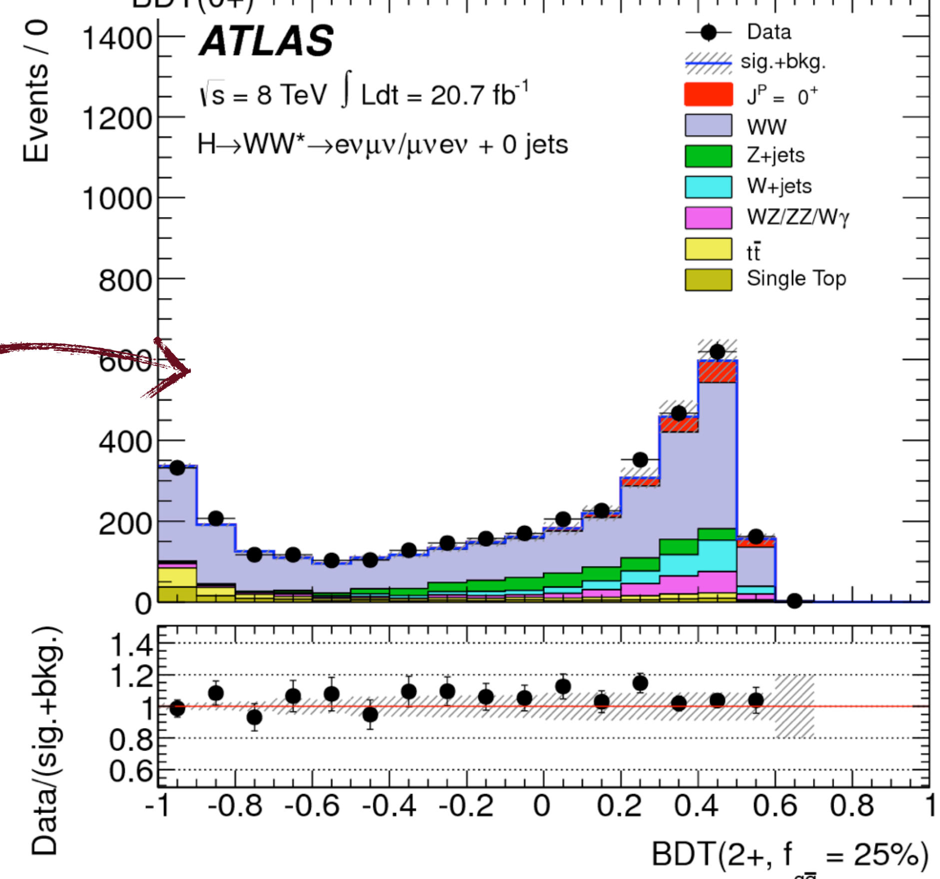
H→WW→lνlν: BDT output



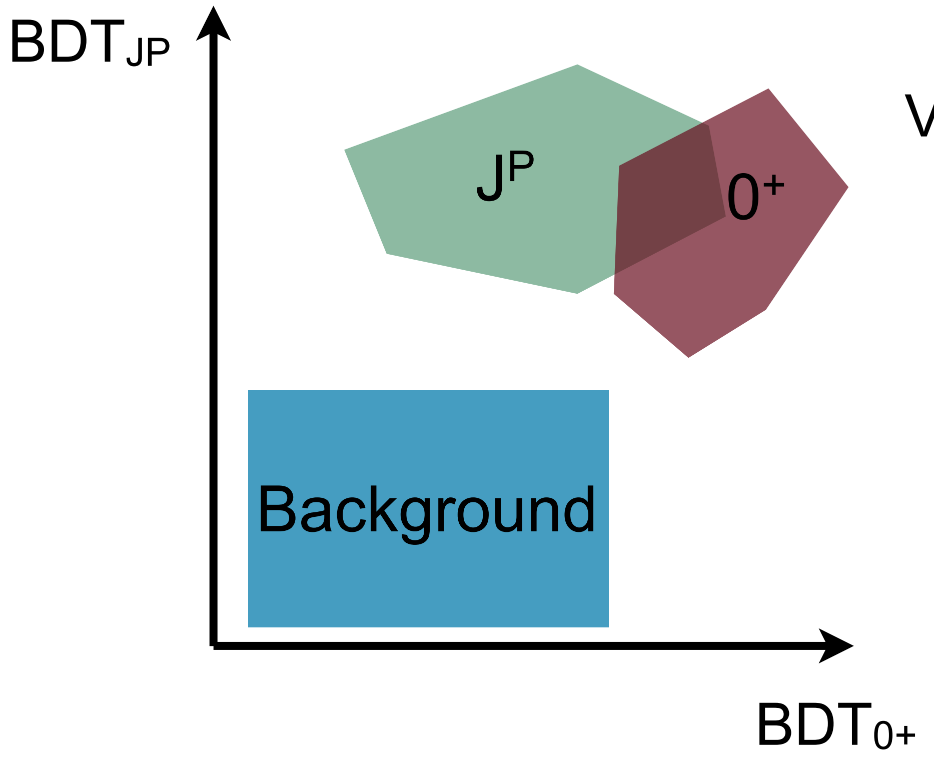


After full selection
3615 candidate events
3300 exp. background
170 exp. SM Higgs boson





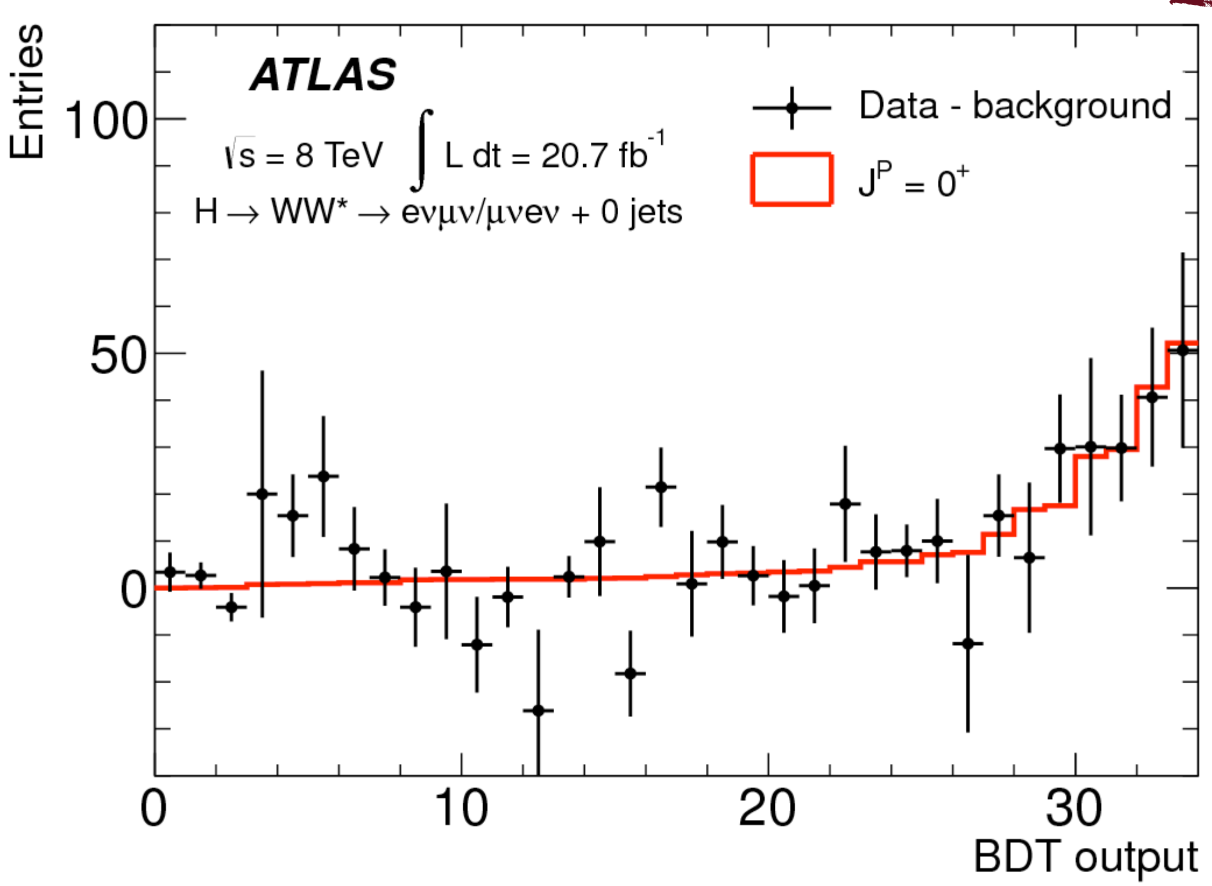
H→WW→lνlν : Post-fit output

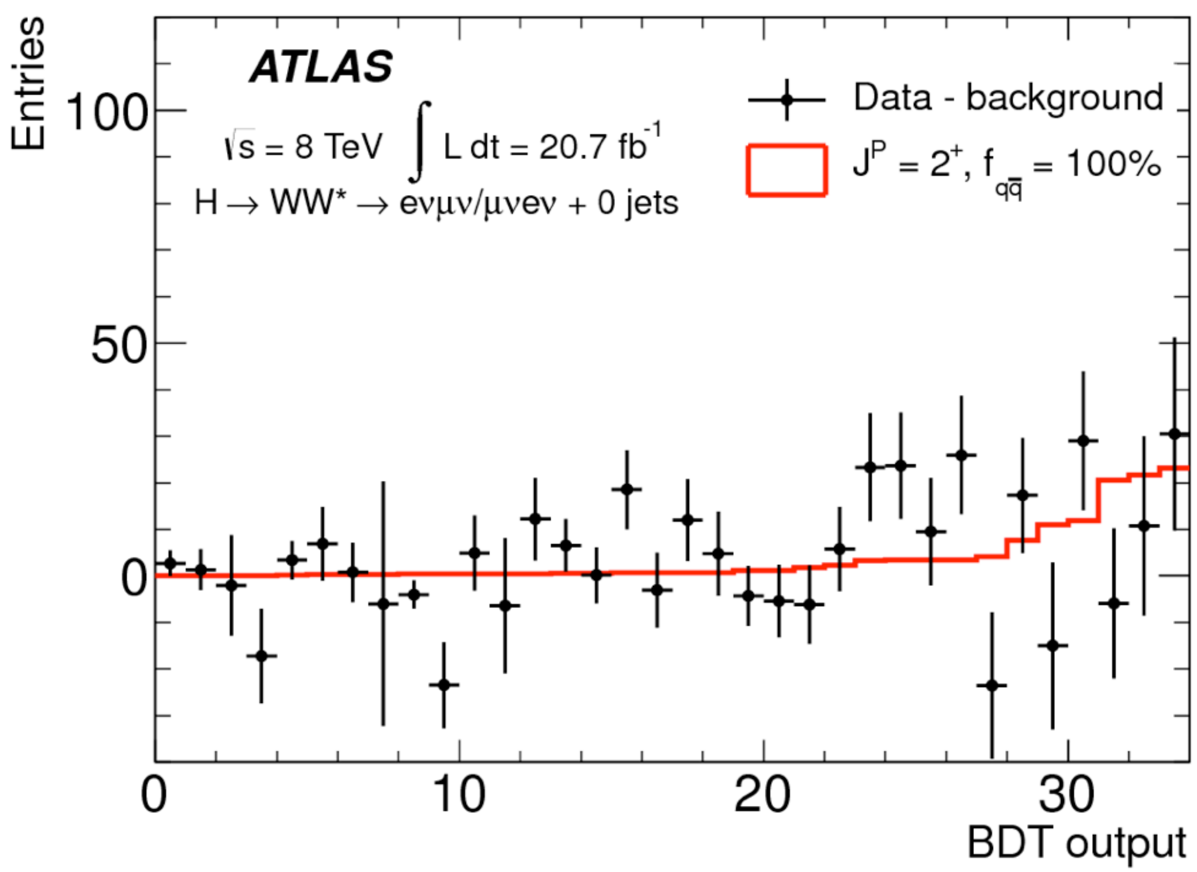


Visualization of the results in the post-fit background-subtracted plots

Data more consistent with spin-0 with respect to spin-2

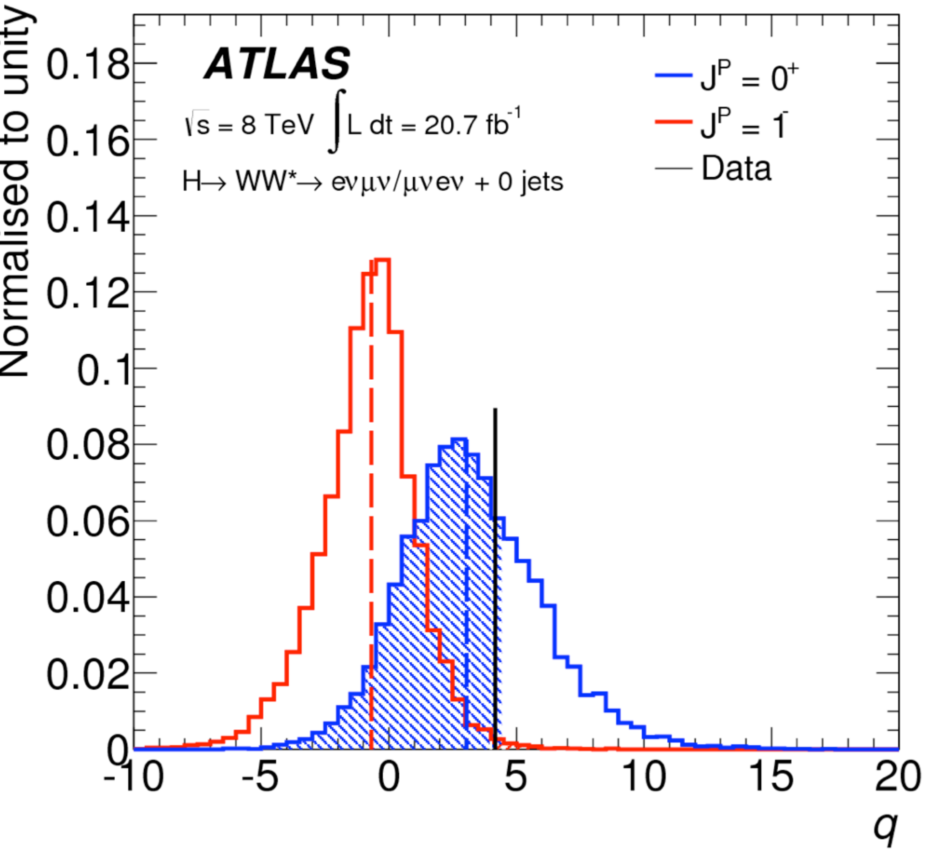
The (BDT_0,BDT_{JP}) distribution is remapped into an 1D distribution by ordering the bins by increasing expected signal. Empty bins (expected content <0.1) are removed.

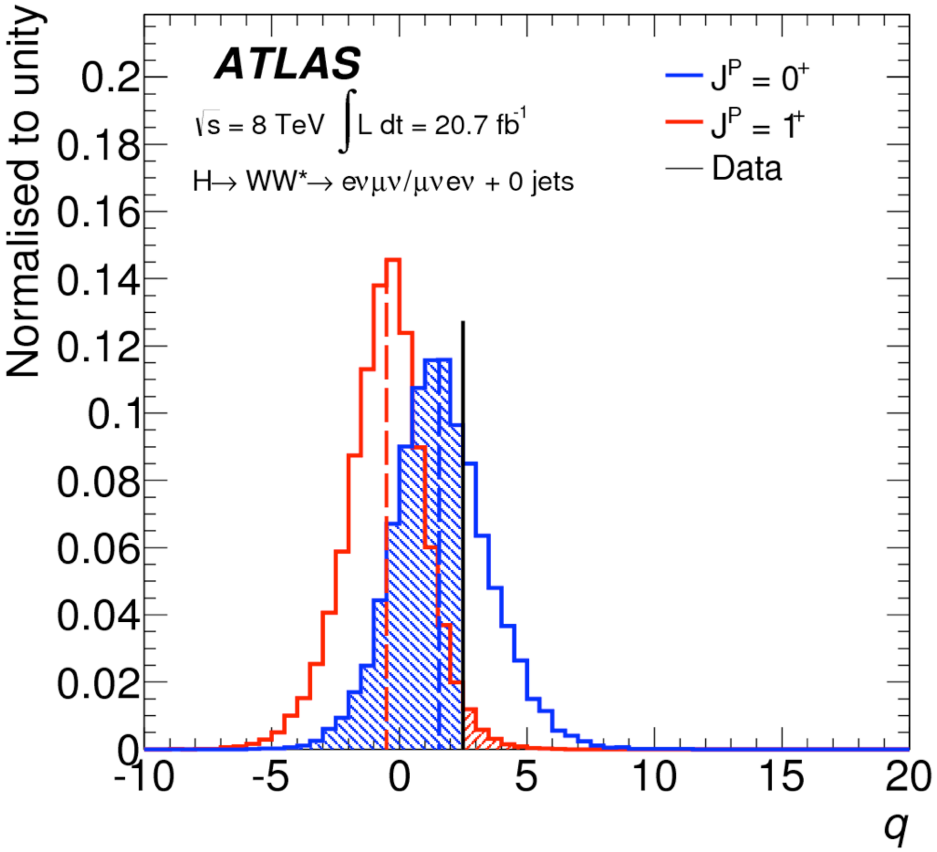


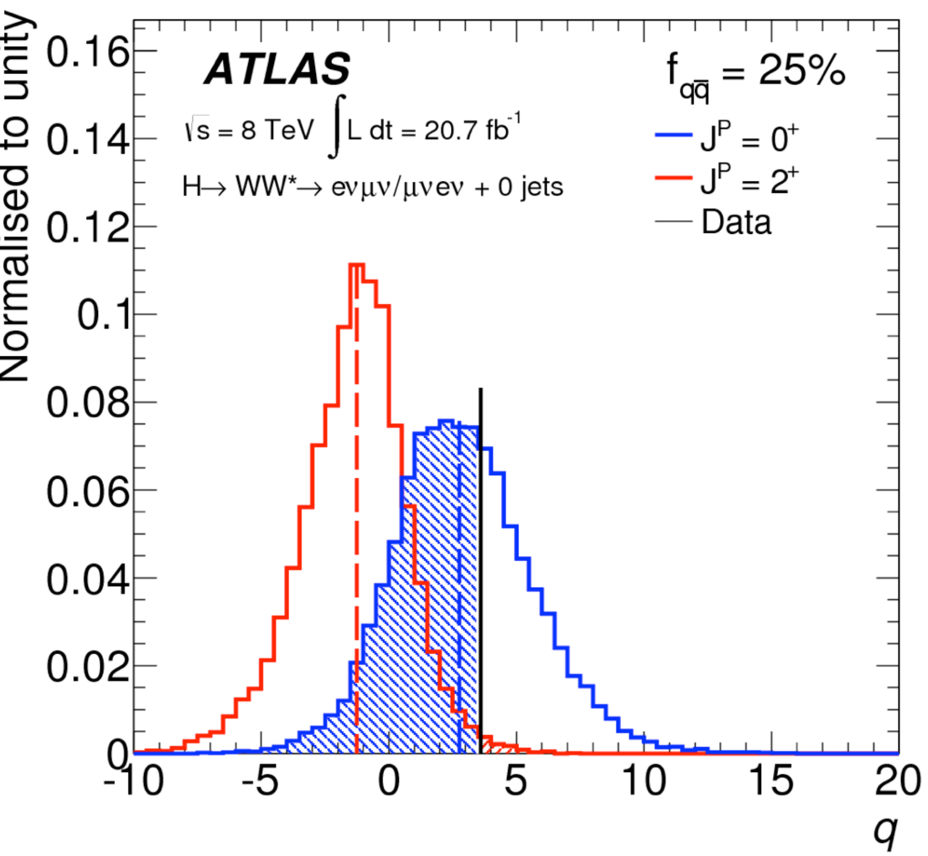


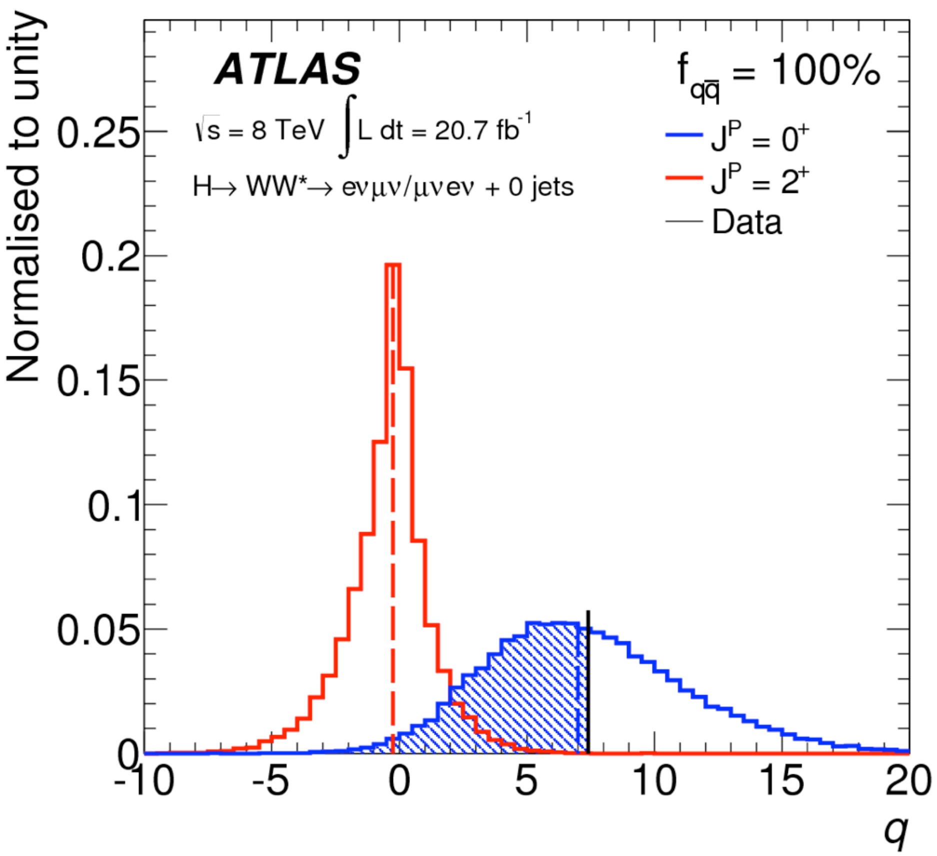
Data described better by spin-0 with respect to spin-2 (100% qqbar)

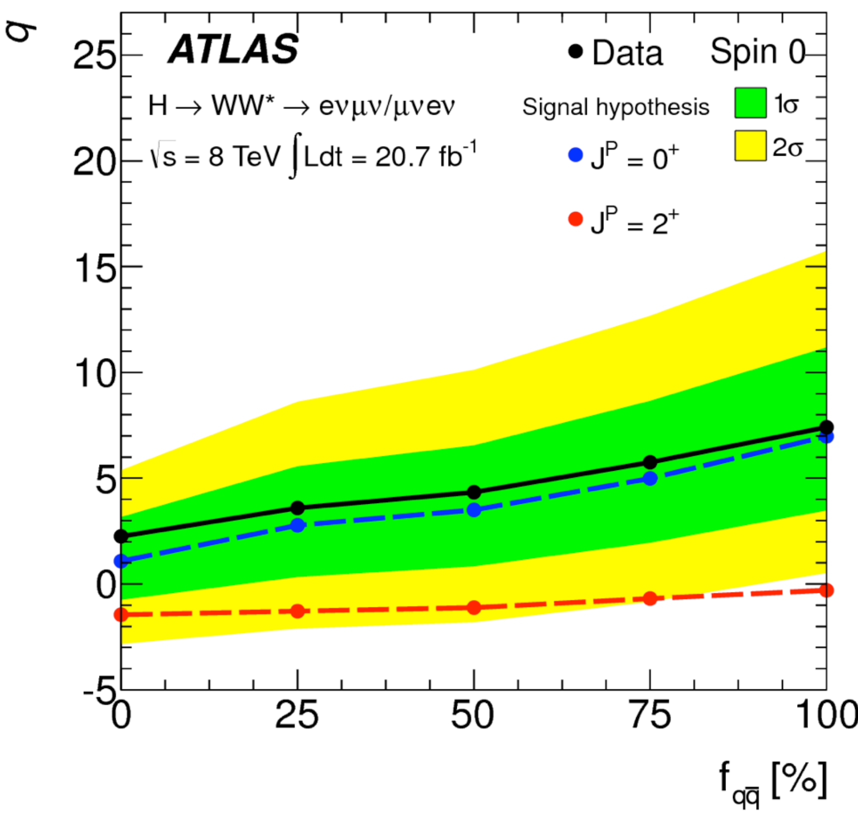
$H \to WW \to l\nu l\nu$: LLR 0^+ vs $1^\pm$ and 2^+











H→WW→lνlν: Results Overview

Channel	1^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^+)$	$\mathrm{CL_s}(J^P = 1^+)$	
$H \to WW^*$	0.11	0.08	0.70	0.02	0.08	92%
Channel	1^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^-)$	$\mathrm{CL_s}(J^P = 1^-)$	
$H \to WW^*$	0.06	0.02	0.66	0.006	0.017	98.3%

$H \to WW^*$

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$\mathrm{CL_s}(J^P = 2^+)$	
100%	0.013	$3.6 \cdot 10^{-4}$	0.541	$1.7 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$	>99.9%
75%	0.028	0.003	0.586	0.001	0.003	99.7%
50%	0.042	0.009	0.616	0.003	0.008	99.2%
25%	0.048	0.019	0.622	0.008	0.020	98.0%
0%	0.086	0.054	0.731	0.013	0.048	95.2%

All alternative hypotheses are disfavored with respect to the 0^+ hypothesis.

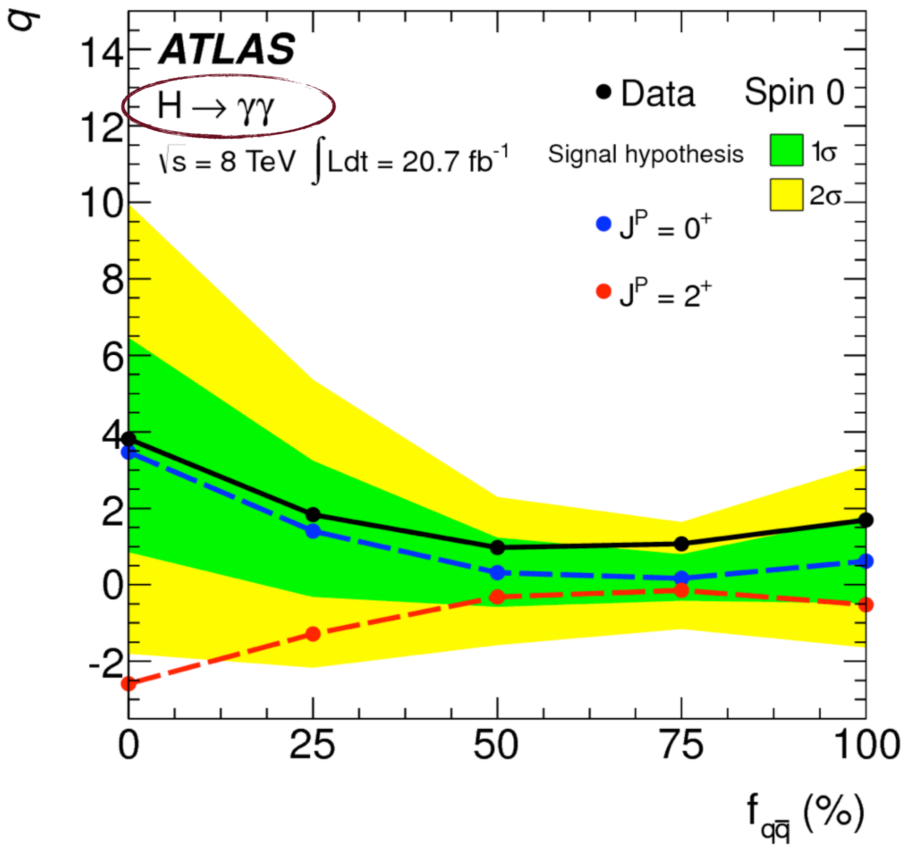
Combination

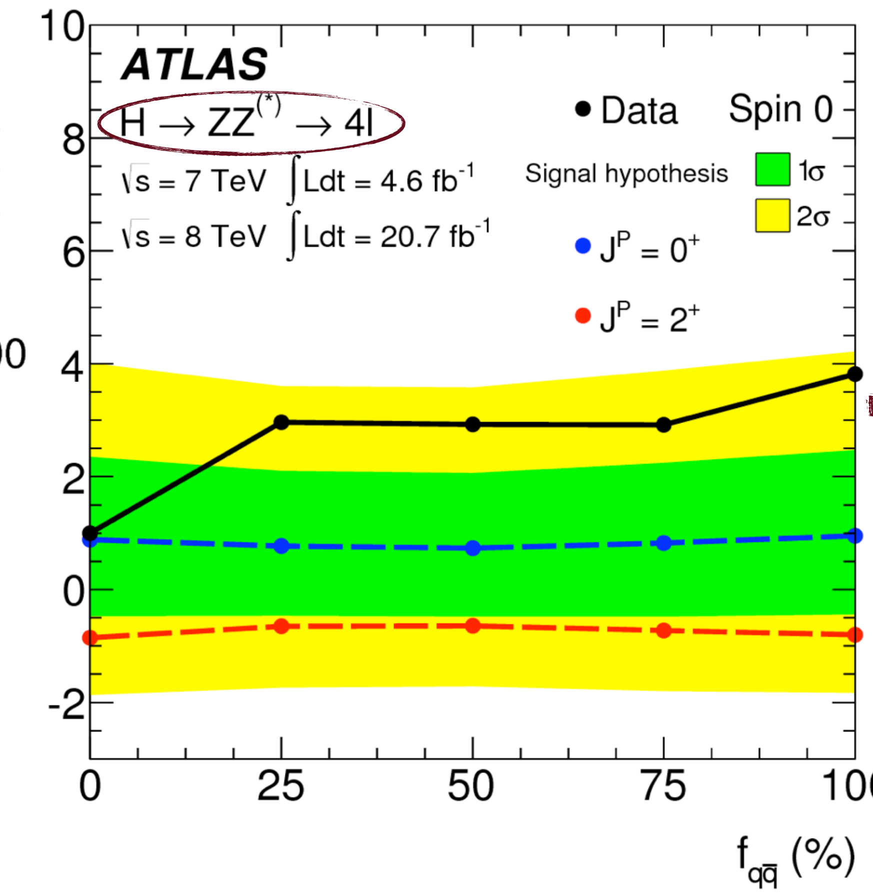
Channel	$H \to ZZ^{(*)} \to 4\ell$	$H \to WW^{(*)} \to \ell\nu\ell\nu$	$H \to \gamma\gamma$
Dataset	$20.7\ \mathrm{fb}^{-1}$ @ 8 TeV $4.8\ \mathrm{fb}^{-1}$ @ 7 TeV	$20.7\ \mathrm{fb}^{-1}$ @ 8 TeV	$20.7\ \mathrm{fb}^{-1}$ @ 8 TeV
Reference	ATLAS-CONF-2013-013	ATLAS-CONF-2013-031	ATLAS-CONF-2013-029
Signal	JHU⊕PYTHIA	PowHeg/JHU⊕PYTHIA	PowHeg/JHU⊕PYTHIA
0^-	✓	-	-
1^+	✓	✓	-
1^-	✓	✓	-
2^+	✓	✓	✓

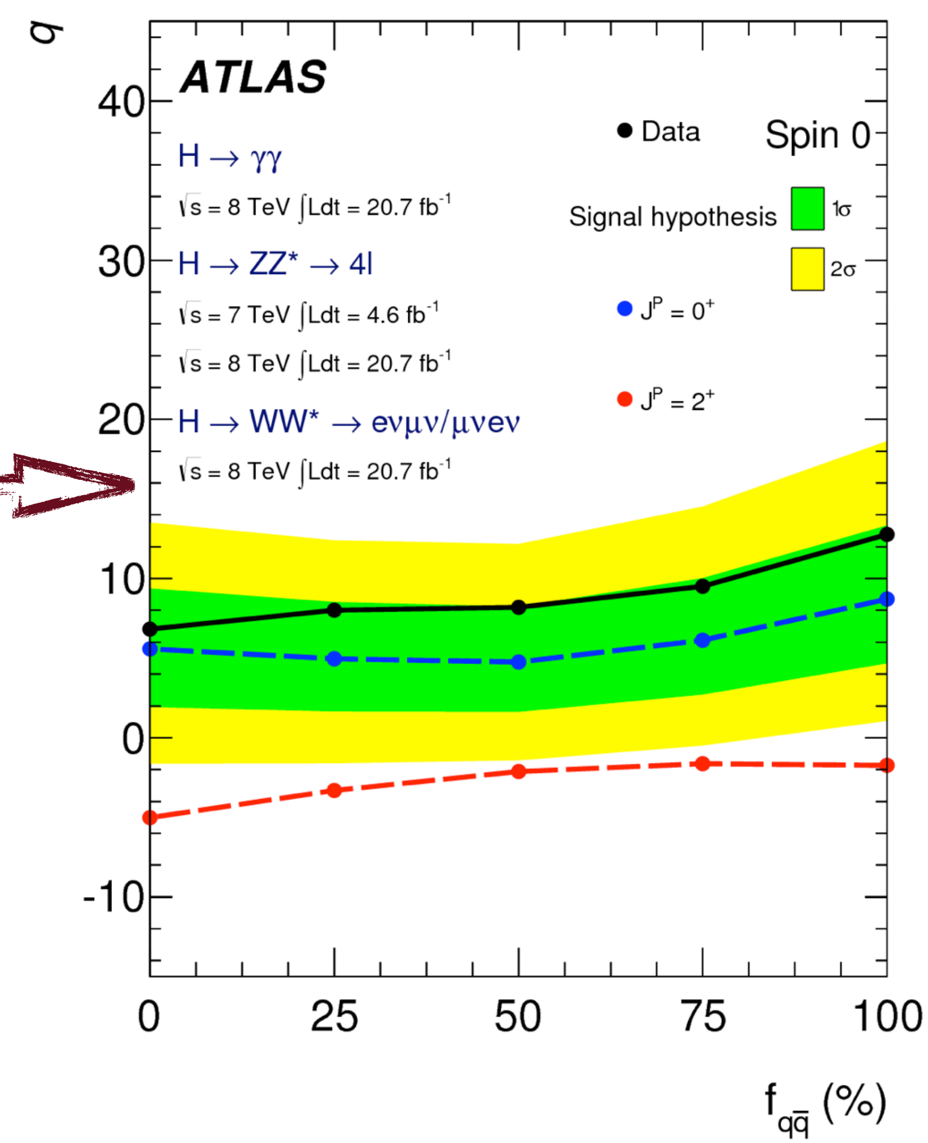
A note on systematic uncertainties:

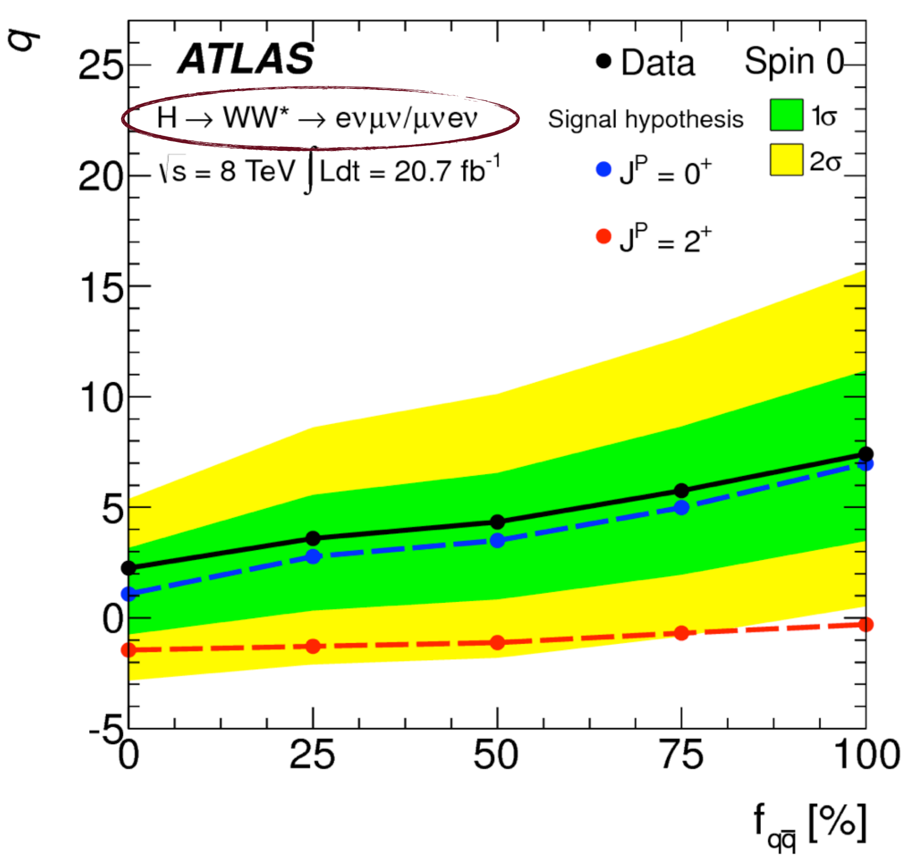
- e/μ reconstruction,identification and trigger efficiencies and energy/momentum resolution uncertainties correlated between $H \to ZZ^* \to 4l$ and $H \to WW^* \to l\nu l\nu$
- e/γ energy scale correlated across all channels
- effect of mass measurement uncertainty negligible
- overall impact (by comparing results w/ and w/o profiling) estimated to be <0.3σ
- Higgs boson p_T spectrum small effect <0.1σ

Combination: The case of 0^+ vs 2^+



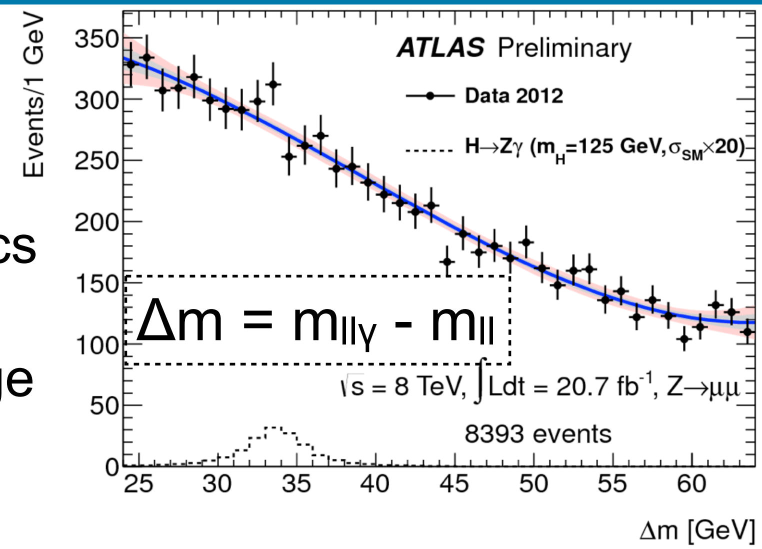


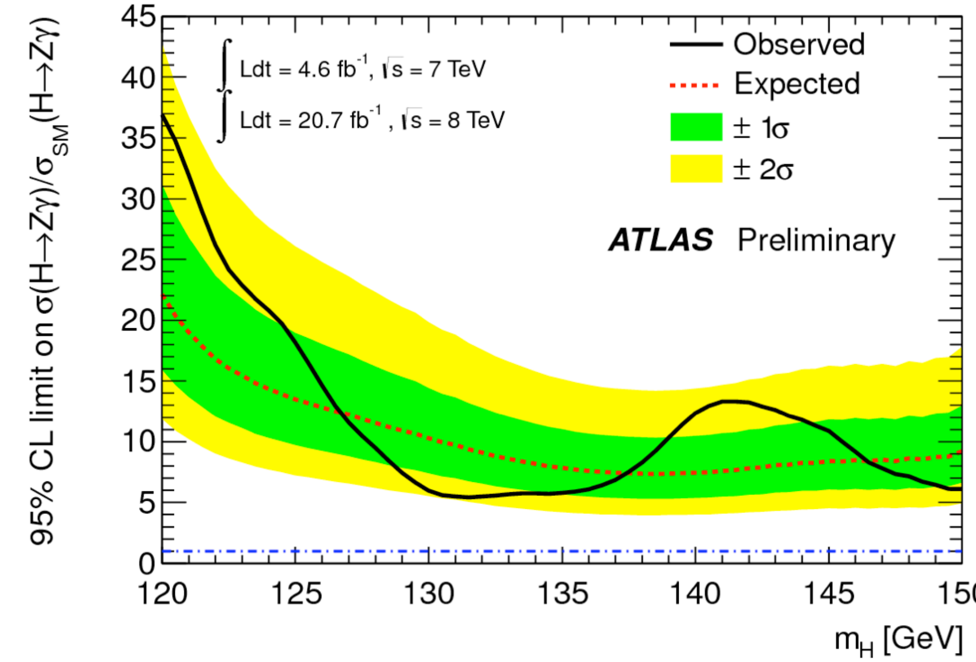




“Rare” Higgs boson decays

H→Zγ

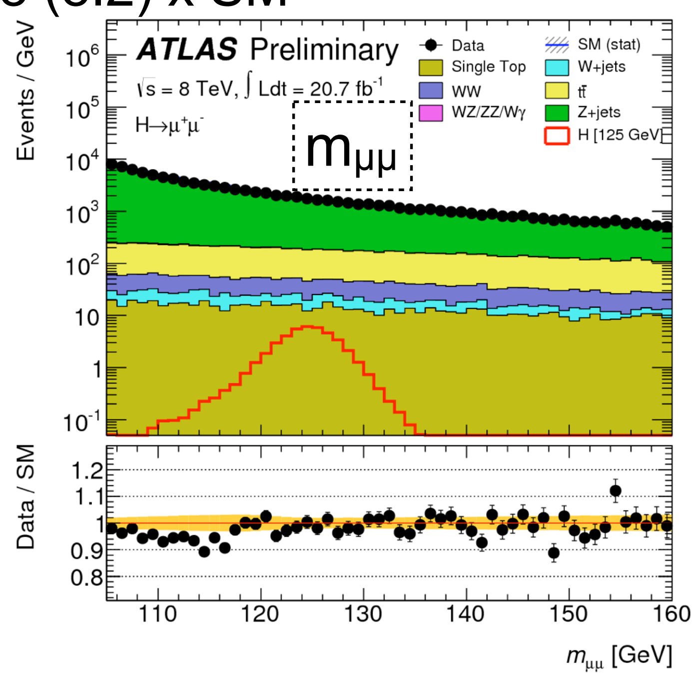


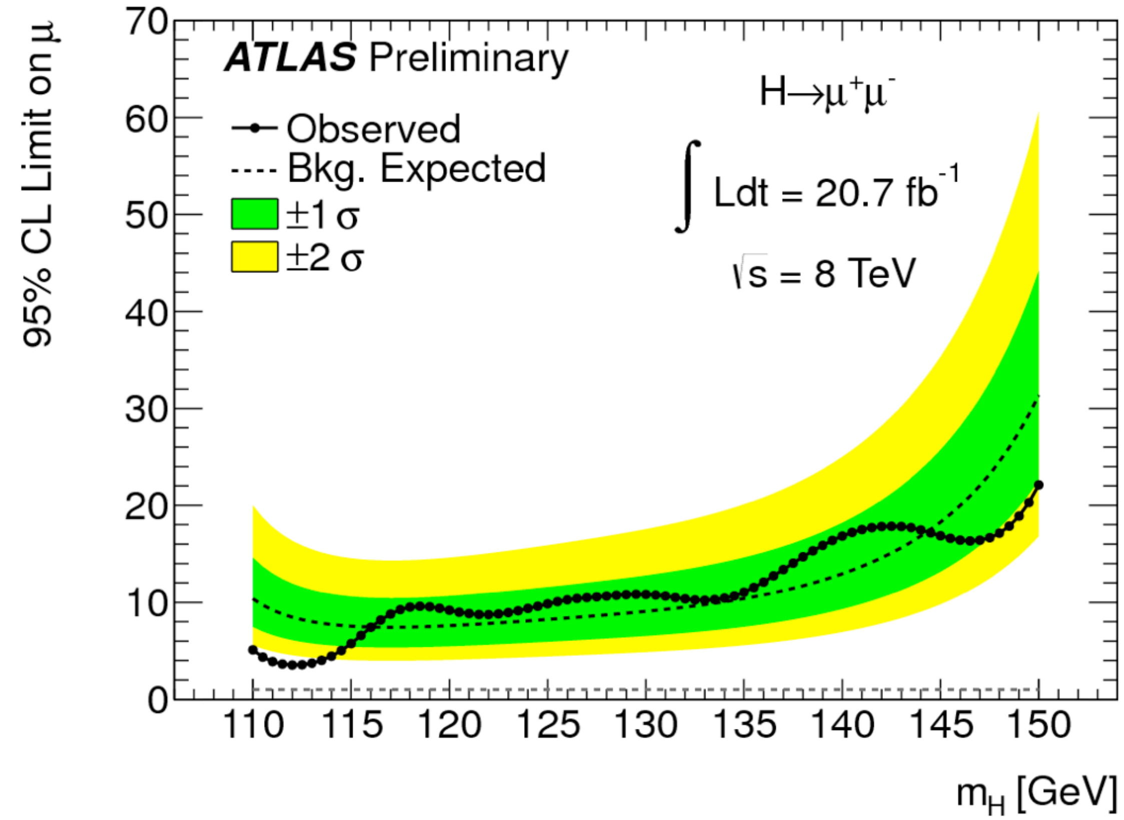


-loop induced → sensitive to new physics
-small BR; S/B~0.01
-signature: same-flavour opposite-charge isolated leptons + photon
-m_H=125 GeV:
95% CL upper limit 18.5 (13.5) x SM

H→μμ

-probe directly the coupling to muons
-small BR; S/B ~ 0.002
-select two opposite-charge muons (pT>25,15 GeV, $pT_{\mu\mu}$>15 GeV)
-backgrounds: Z/γ*→μμ, top, dibosons
-m_H=125 GeV: 95% CL upper limit 9.8 (8.2) x SM

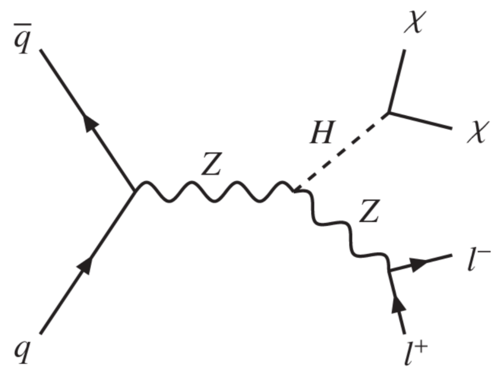




more channels being looked at:
ttH, with H→bb, H→γγ,
VBF H→bb, etc

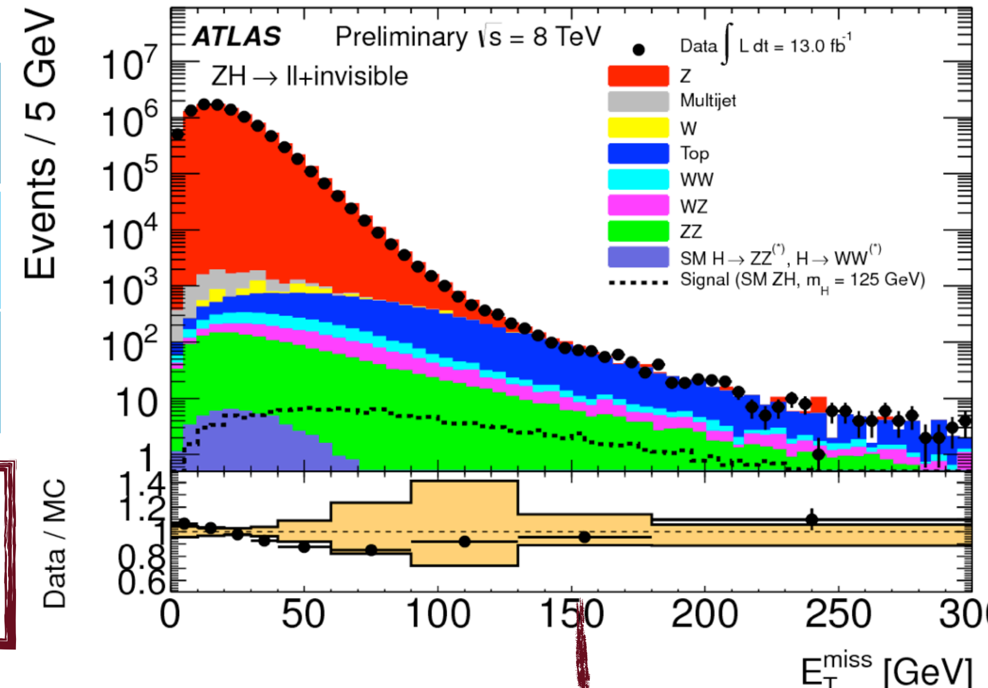
"Invisible" Higgs boson decays

"Invisible" decays are suppressed in SM → Observation would be direct indication of New Physics!

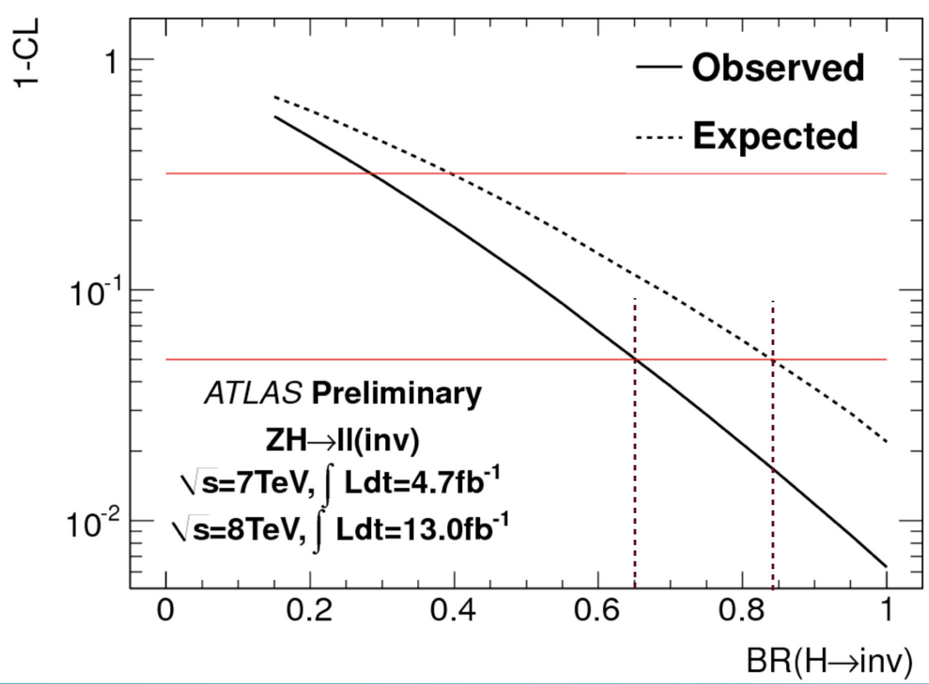


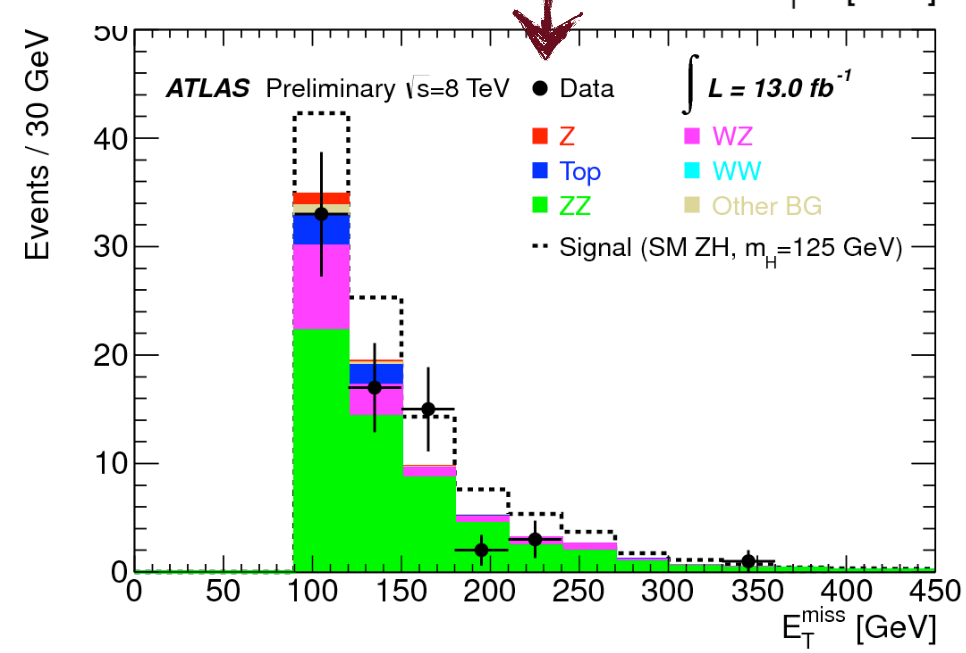
- Signature : Z→ee/μμ + large MET
- Main Backgrounds: ZZ→llνν, WZ→lνll, WW→lνlν
- Require MET > 90 GeV and optimize selection for ZH-like events

	Expected SM Backgrounds	Observed
7 TeV/4.7 fb^{-1}	32.7 ± 1.0 (stat) ± 2.6 (syst)	27
8 TeV/13.0 fb^{-1}	78.0 ± 2.0 (stat) ± 6.5 (syst)	71



95% CL Upper Limit on the BR(H→invisible) for m_H=125 GeV: is <65% with <84% expected





Summary

Convinced, beyond reasonable doubt, of the observation of a boson with m_H~125.5 GeV

Production rates in channels involving vector bosons in good agreement with Standard Model expectation.

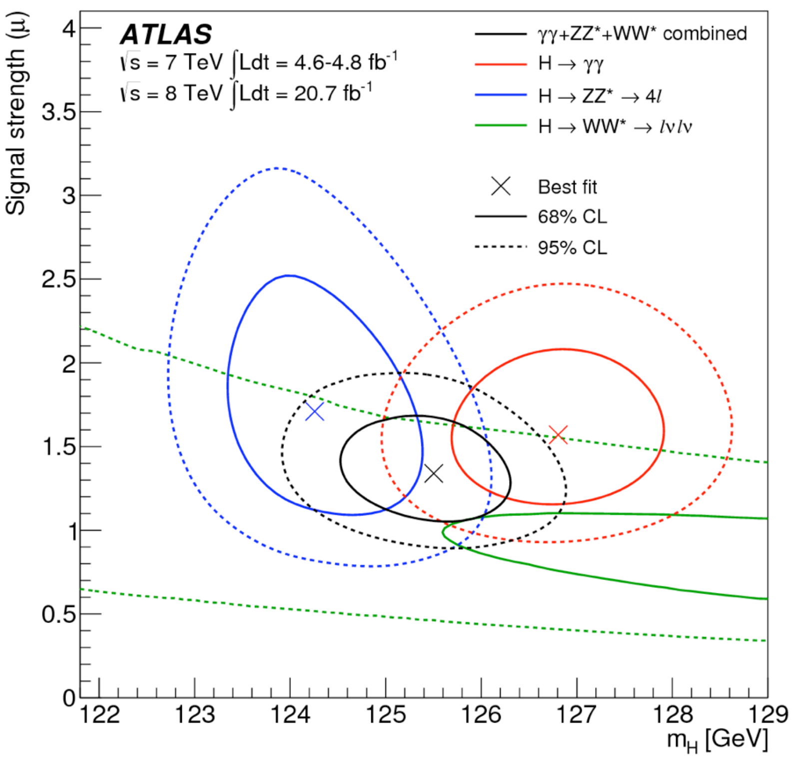
[Large couplings with $W^{\pm}$ and Z^0, coupling through loops to the photon]

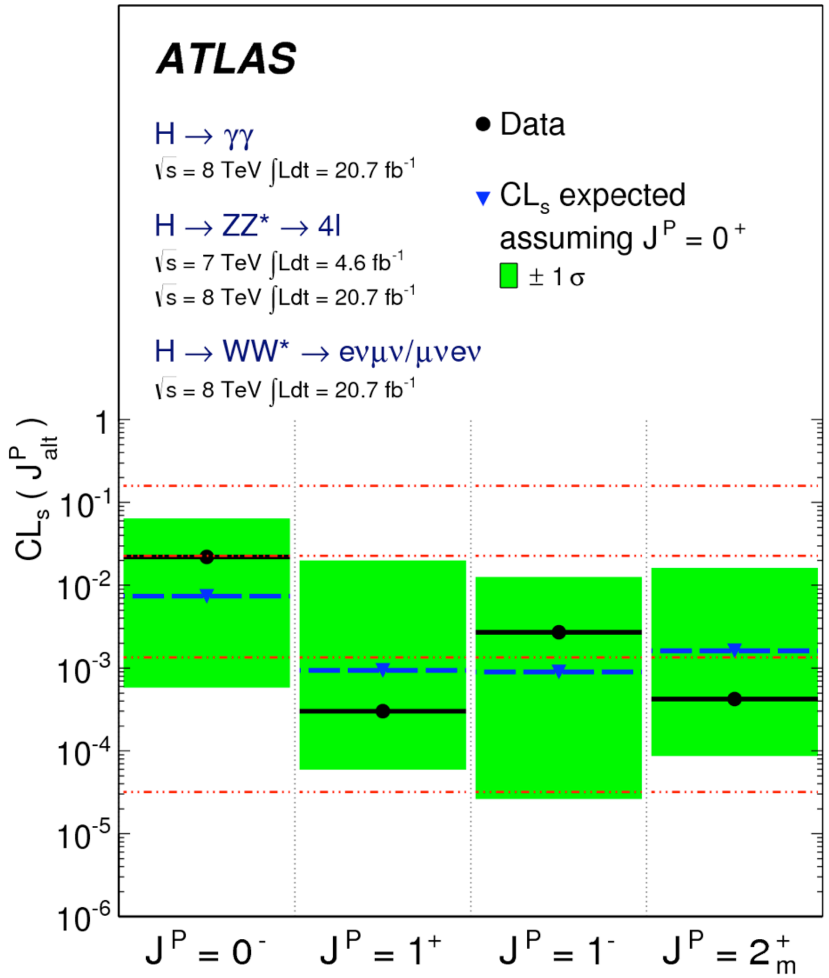
Studies of its spins strongly disfavor the hypothesis of non 0^+ pure state

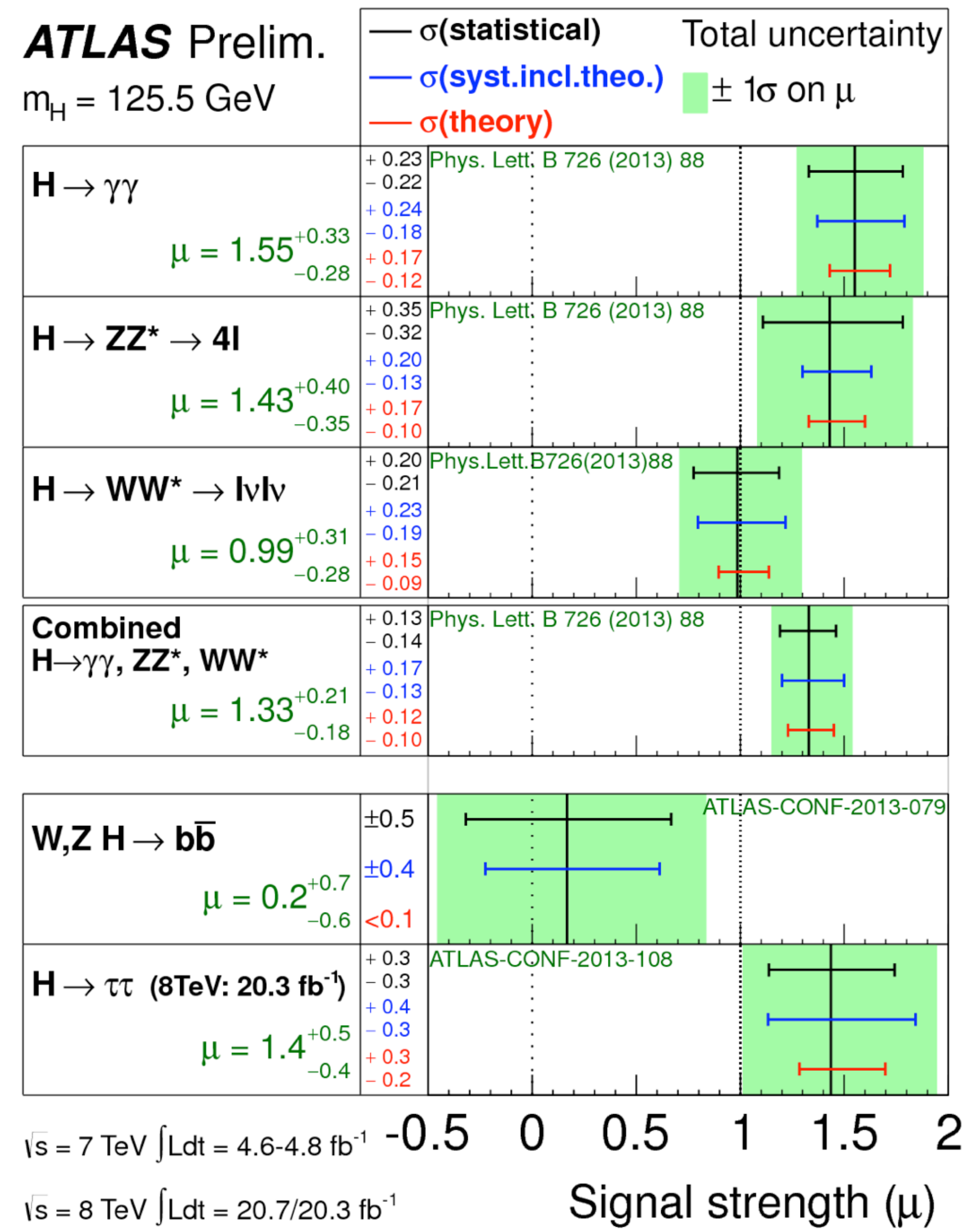
The new particle is a Higgs boson

τ-leptons coupling direct evidence, b-quarks coupling indications and top-quark coupling indirect evidence

It's a Standard Model-like Higgs boson







The new particle is a SM-like Higgs boson

[Not the end of the story... just a new window to understand Nature!]

Do its properties deviate from SM predictions? At which level?

The only Higgs boson? Does it couple to dark matter?

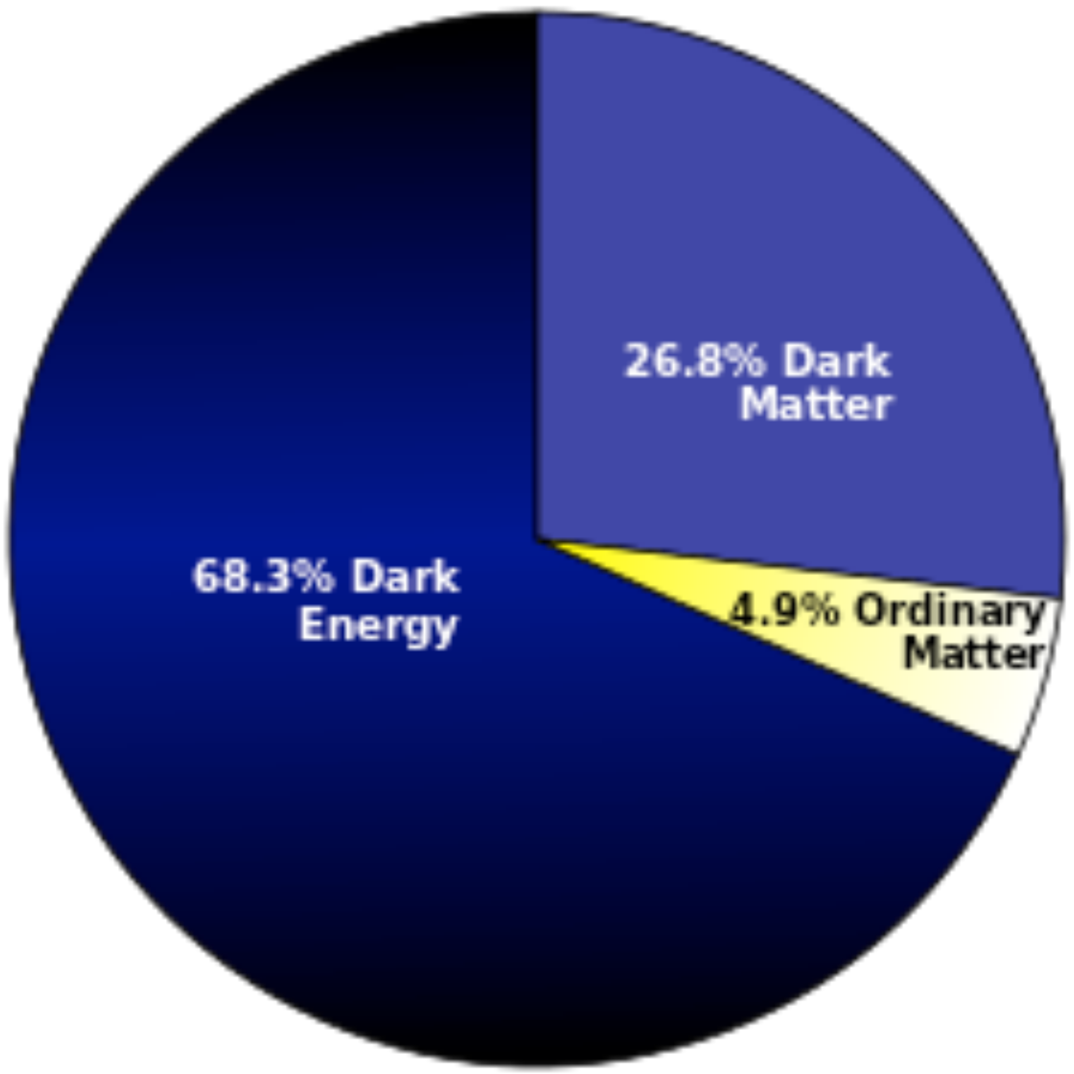
Future LHC (Run 2/3, HL) could provide answers!

Summary

Even further!

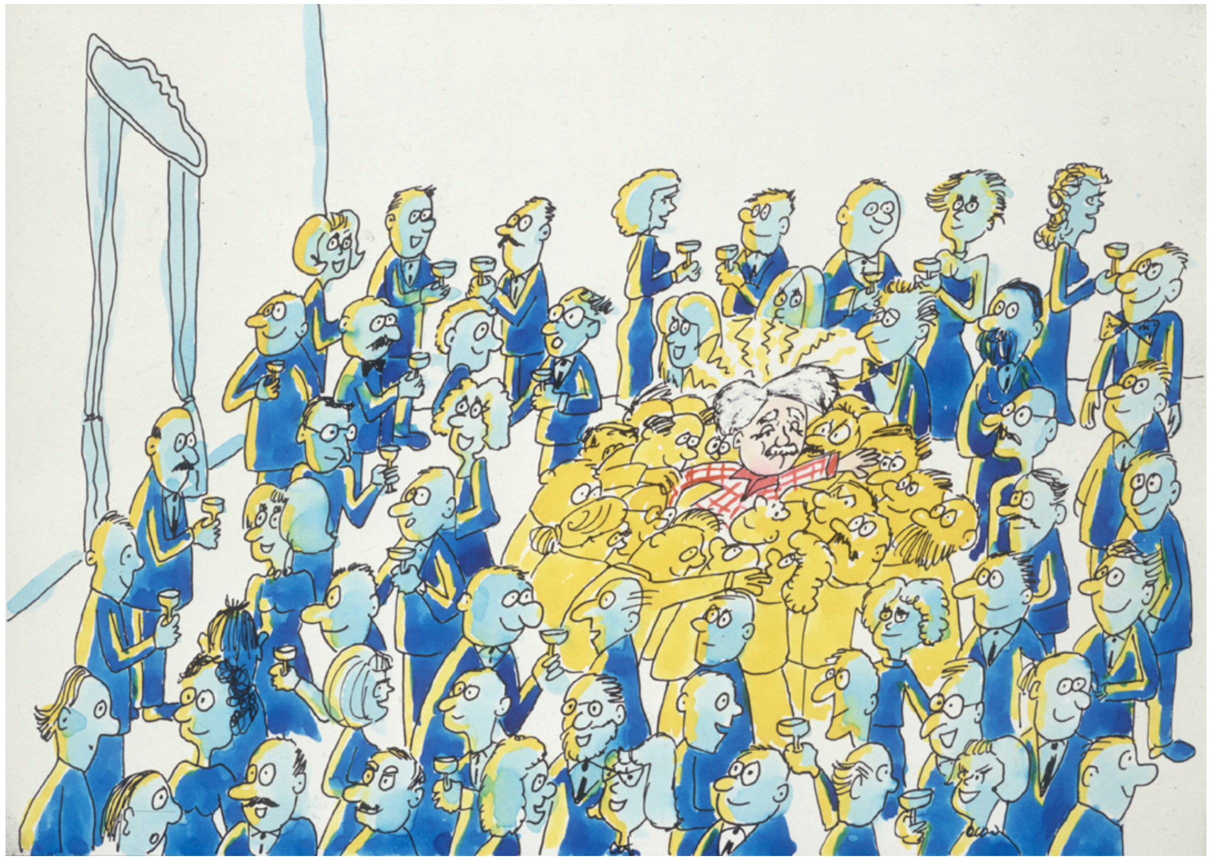
The now-completed Standard Model is not the “final theory”.

- Does not incorporate gravity
- There is no explanation for the Higgs field Vacuum Expectation Value or the Higgs boson mass
- Why the masses of the fermions are so different?
- What is dark matter composed of? Dark energy?



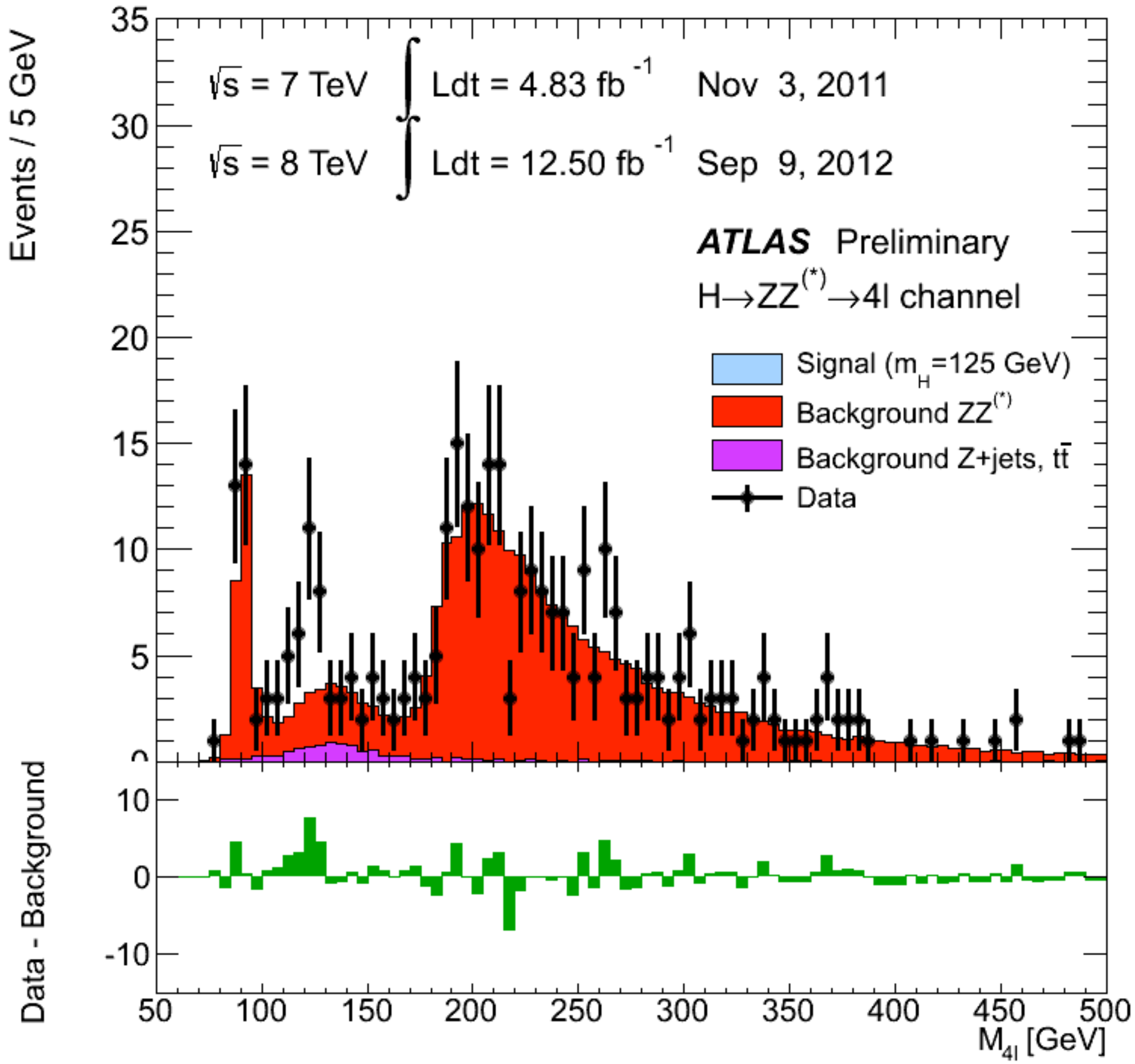
Additional Slides

An analogy

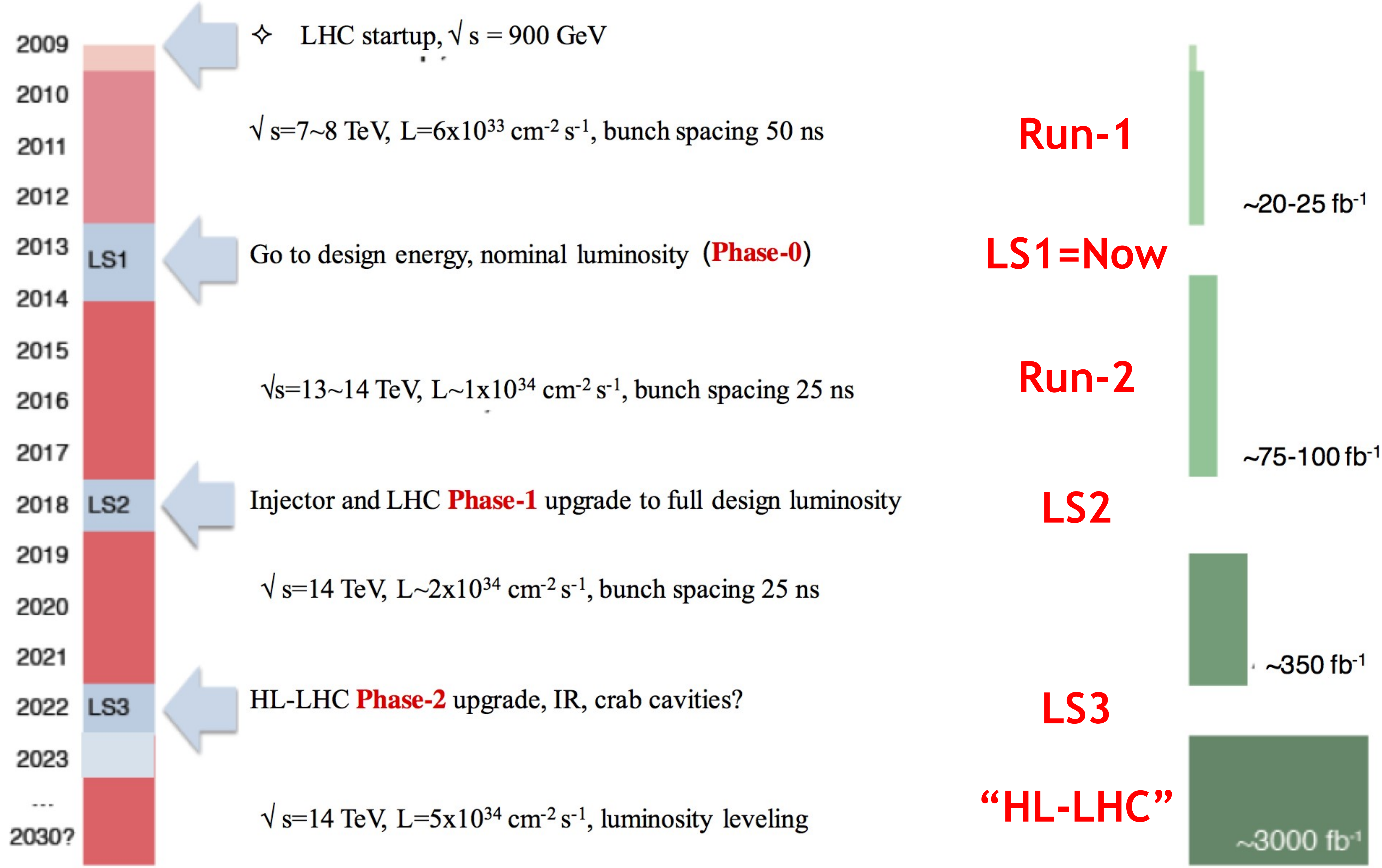


The Higgs boson has been the holy grail of particle physics for the last four decades!

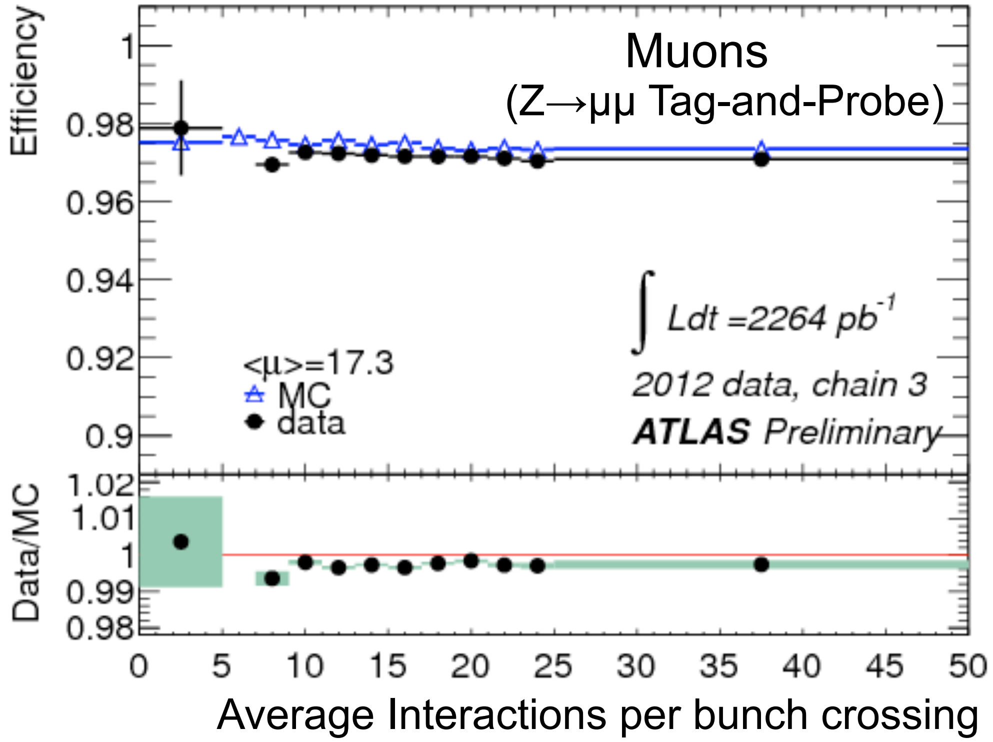
Evolution of the H→ZZ(*)→4l excess

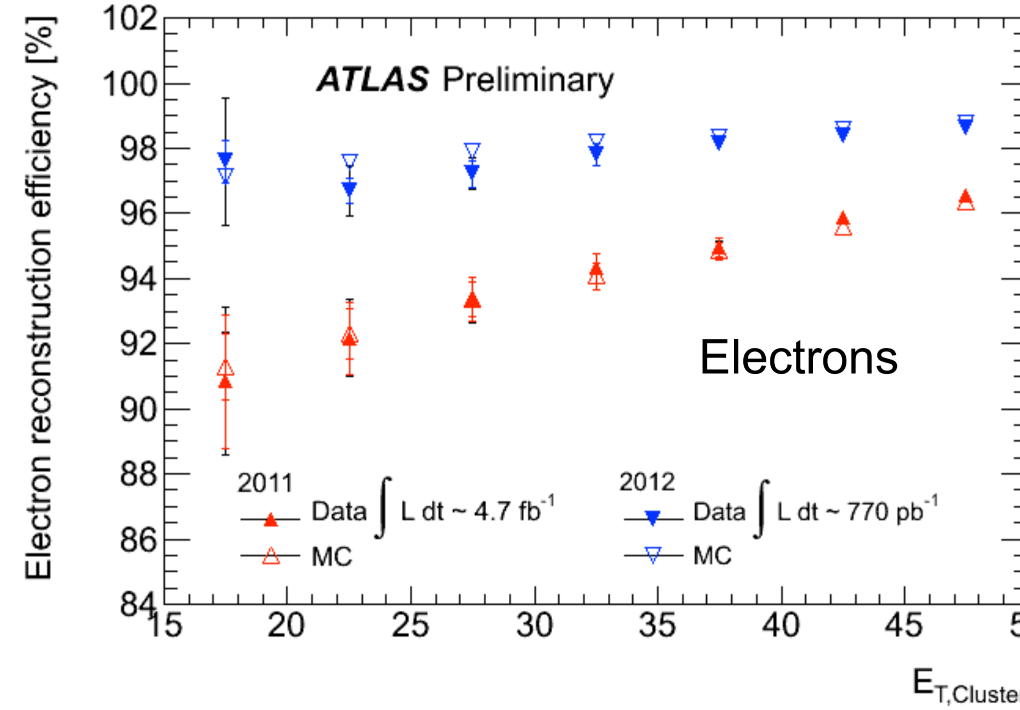


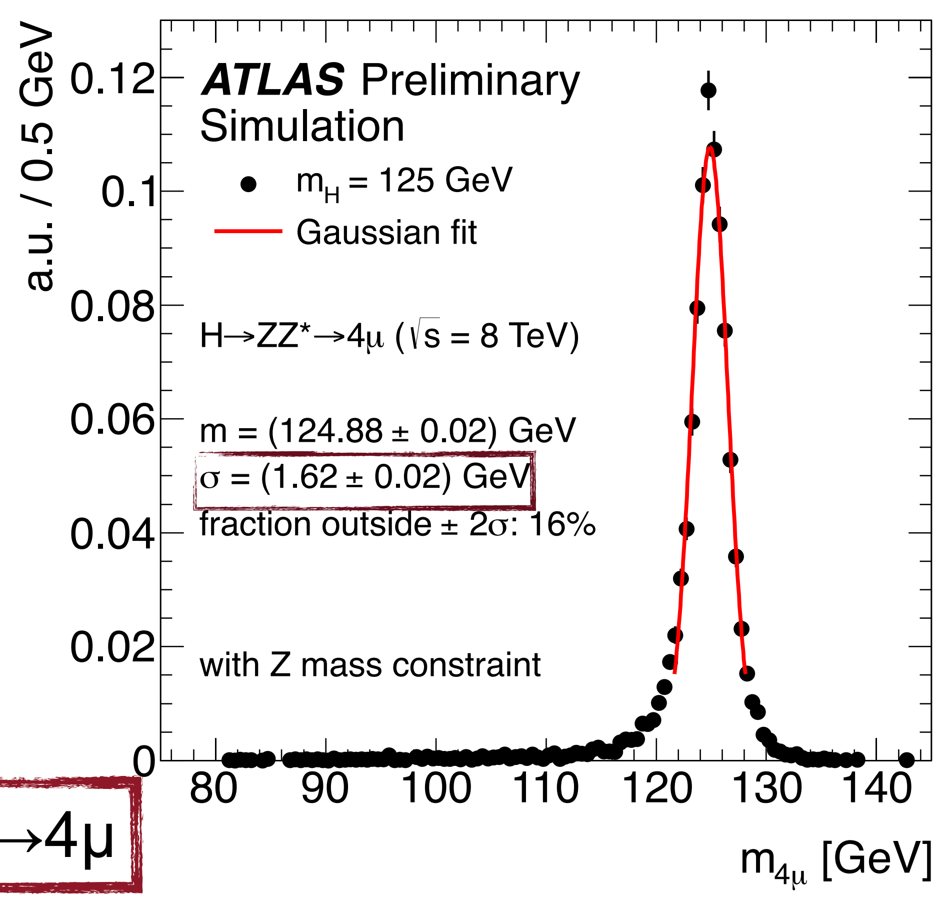
Future of LHC



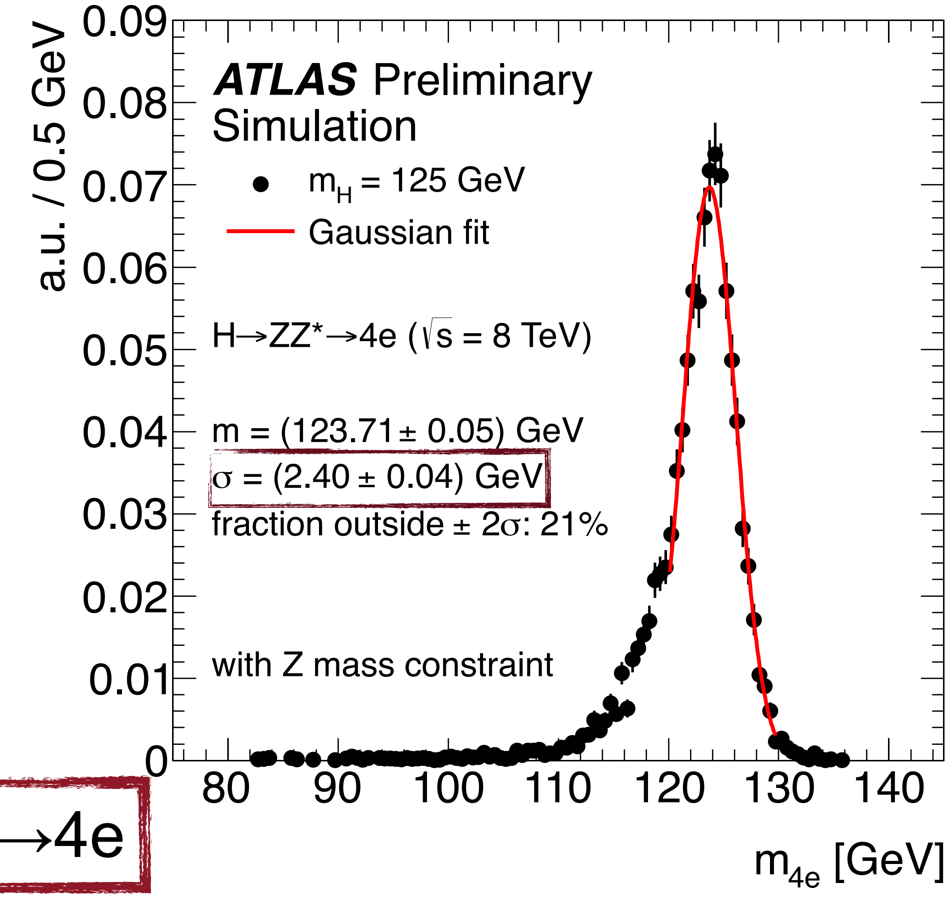
Muons and Electrons





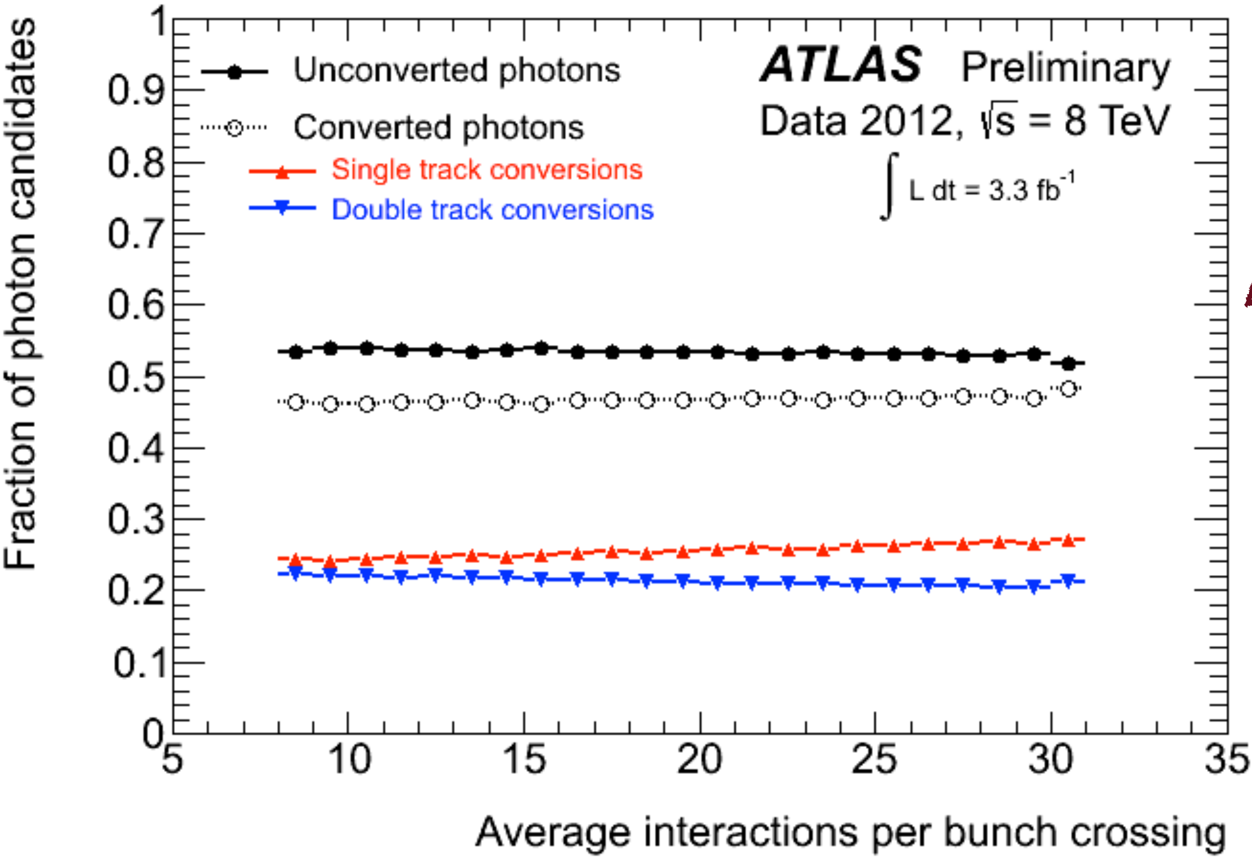


H→ZZ*→4μ

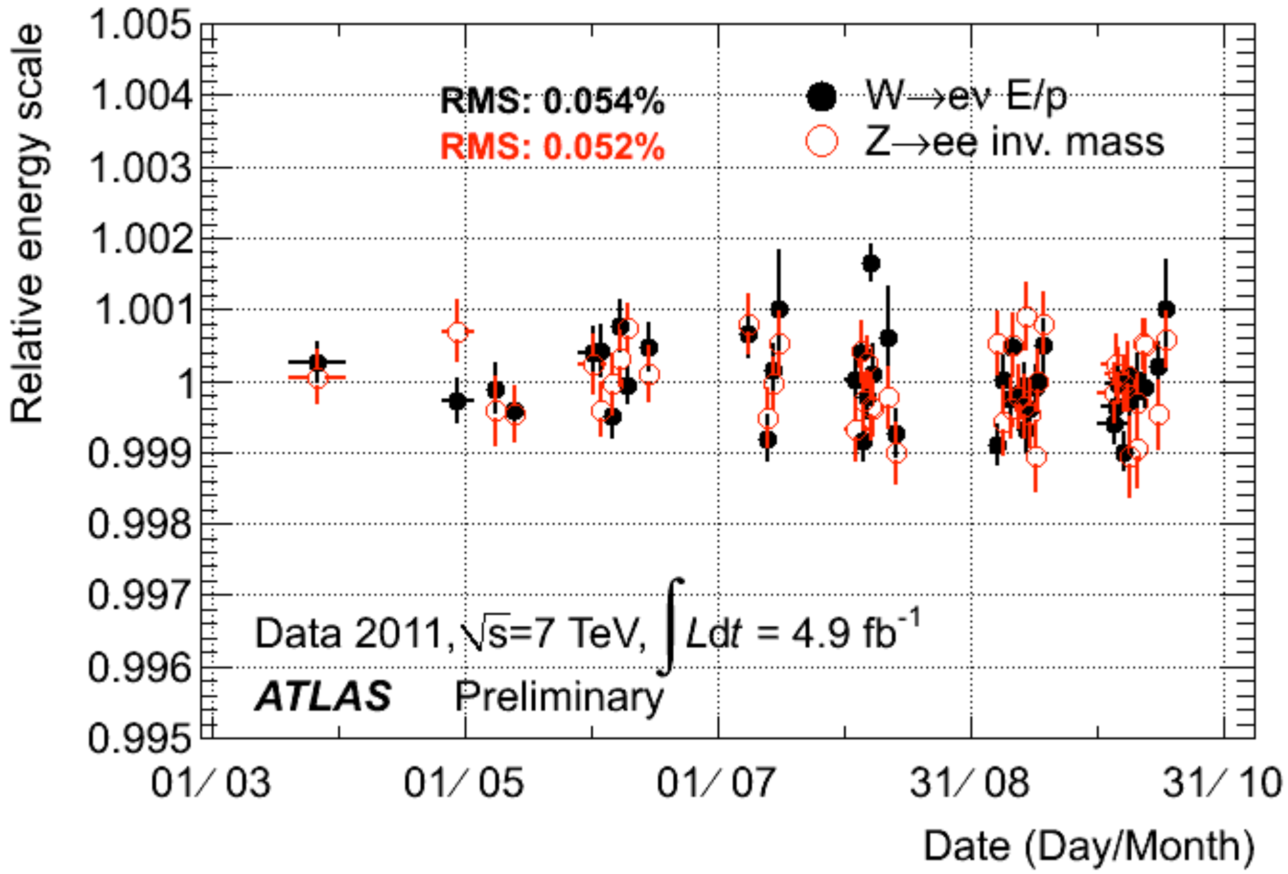


H→ZZ*→4e

Photons

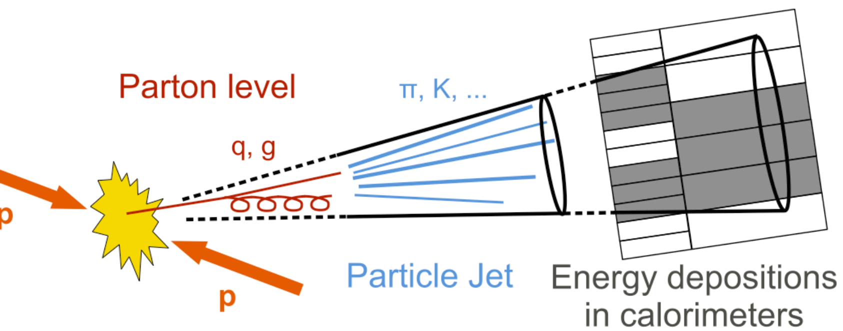


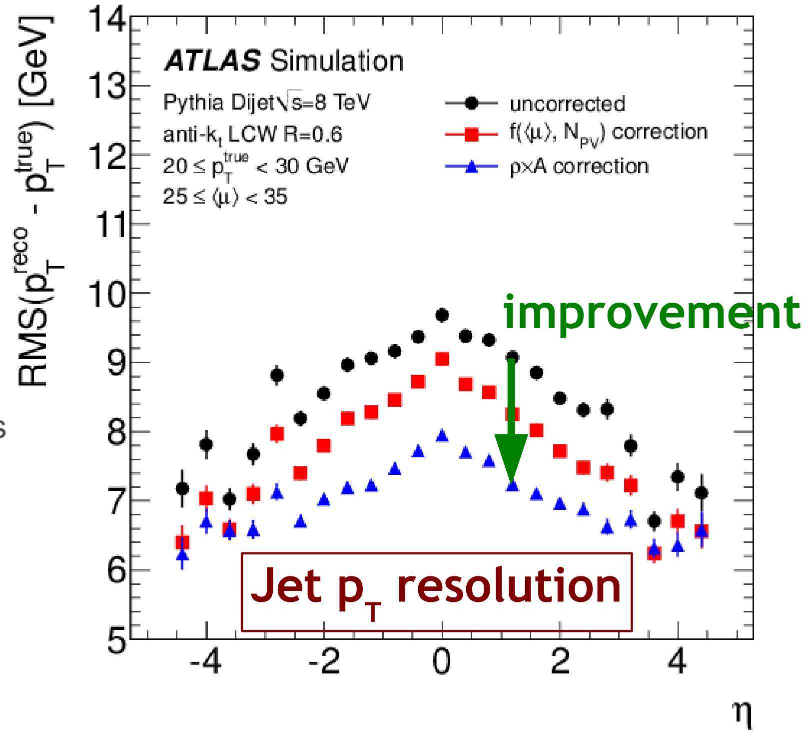
Stable photon reconstruction vs pile-up (within 1%)

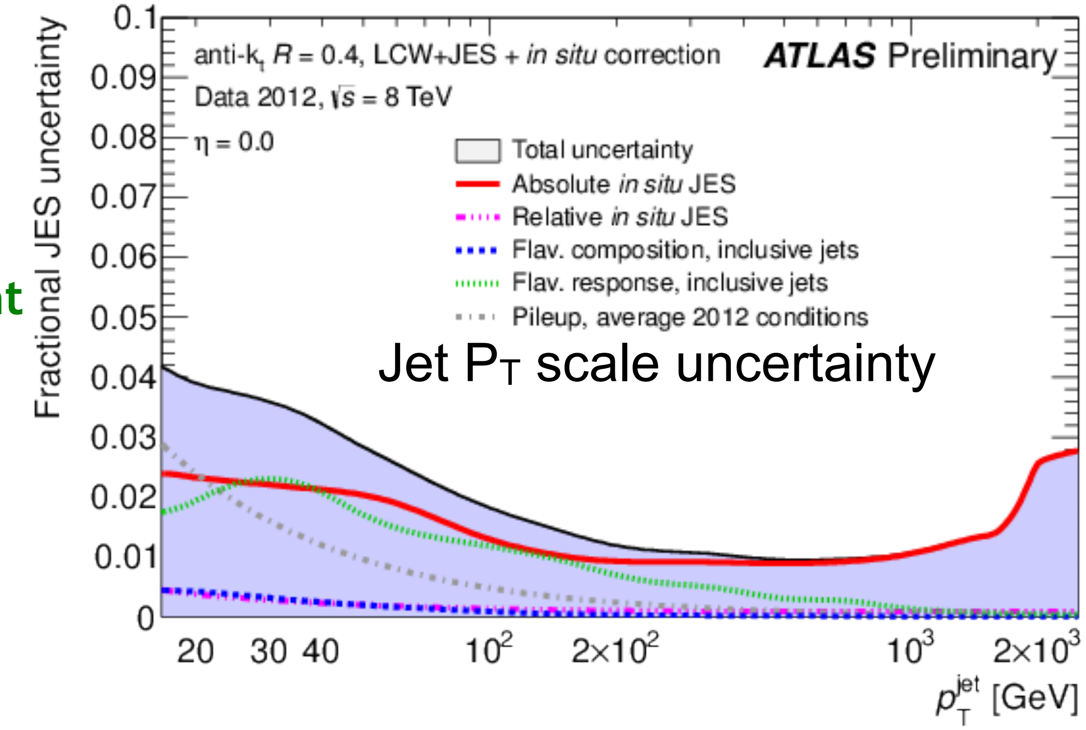


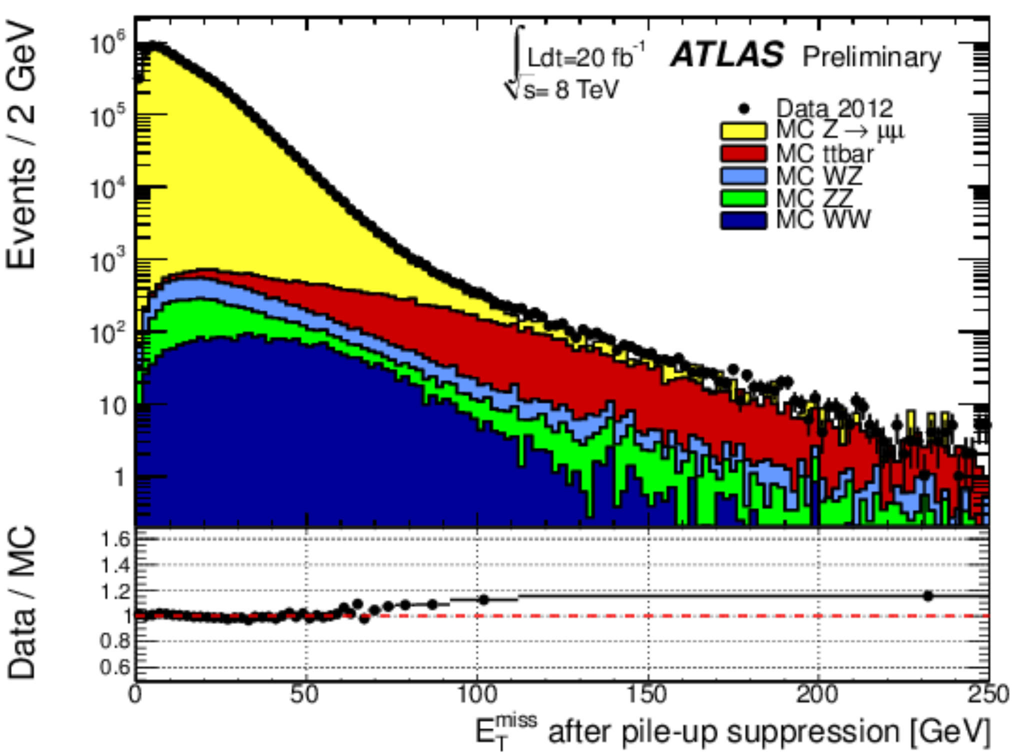
- Excellent stability of the EM calorimeter response!
  - Studied with Z,J/ψ→ee and W→eν events
  - Energy scale at m_Z known to ~0.3%
  - Uniformity ~1% (2.5% for 1.37< |η|<1.8)

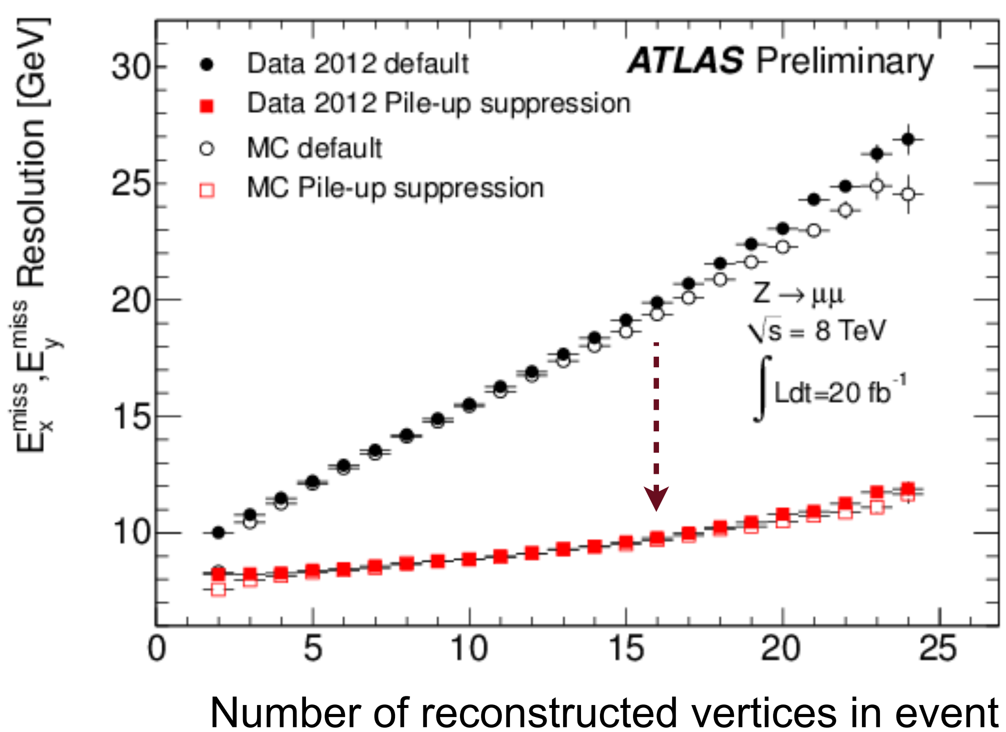
Jets and Missing E_T

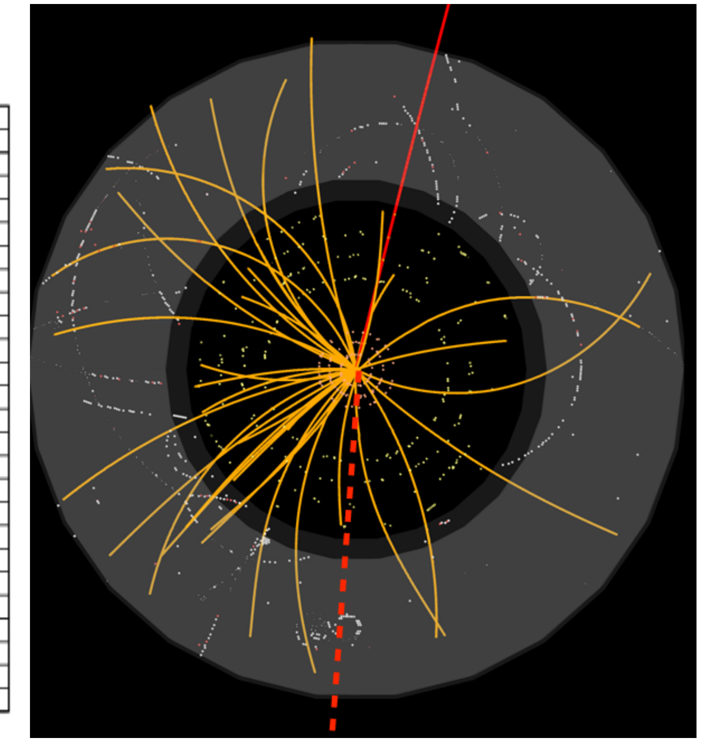












W→μν candidate

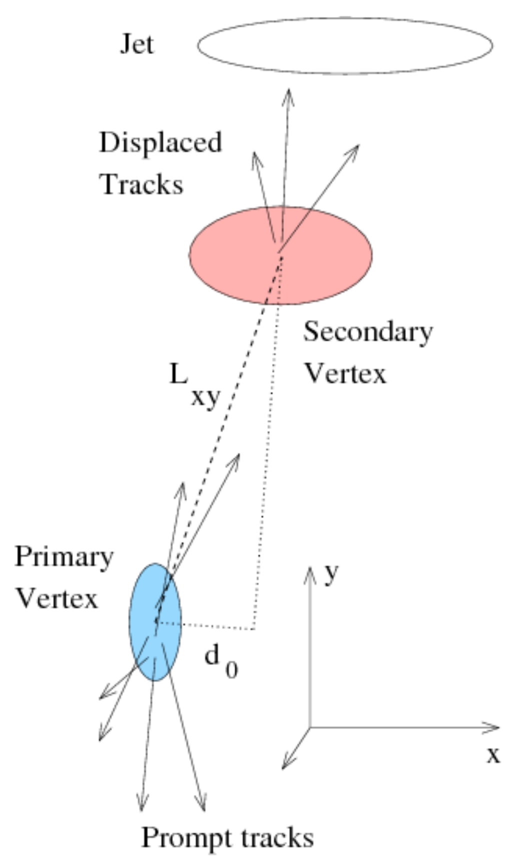
The τ-lepton is special!

Mass of 1.78 GeV and cτ = 87.1 μm,

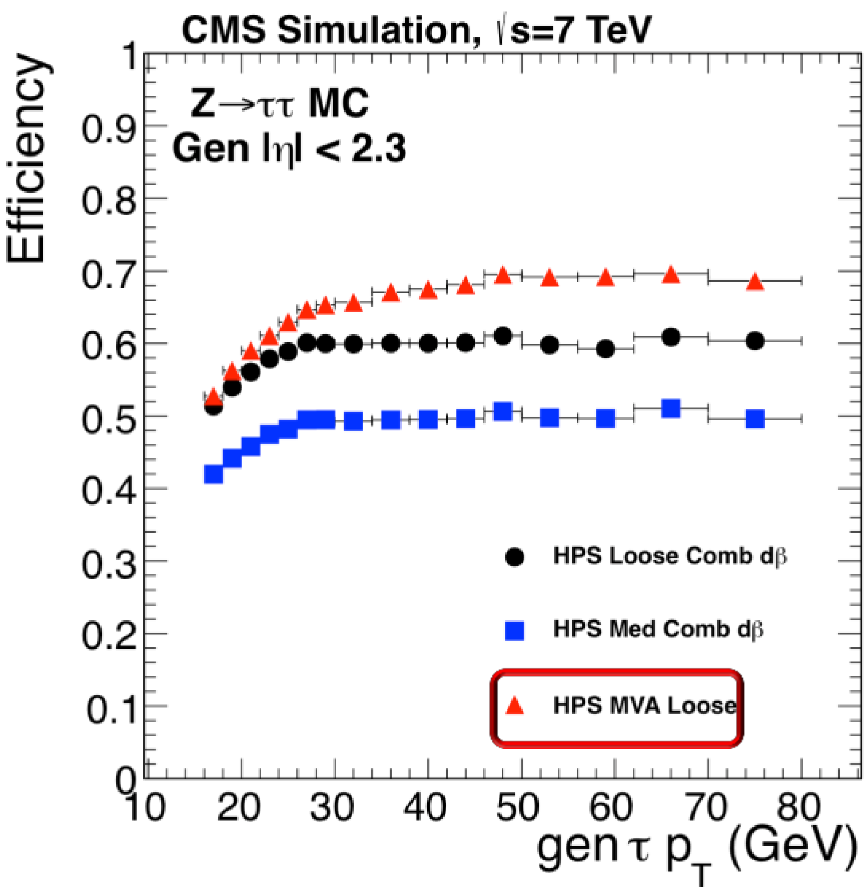
the only lepton that decays in our detector, in various ways...

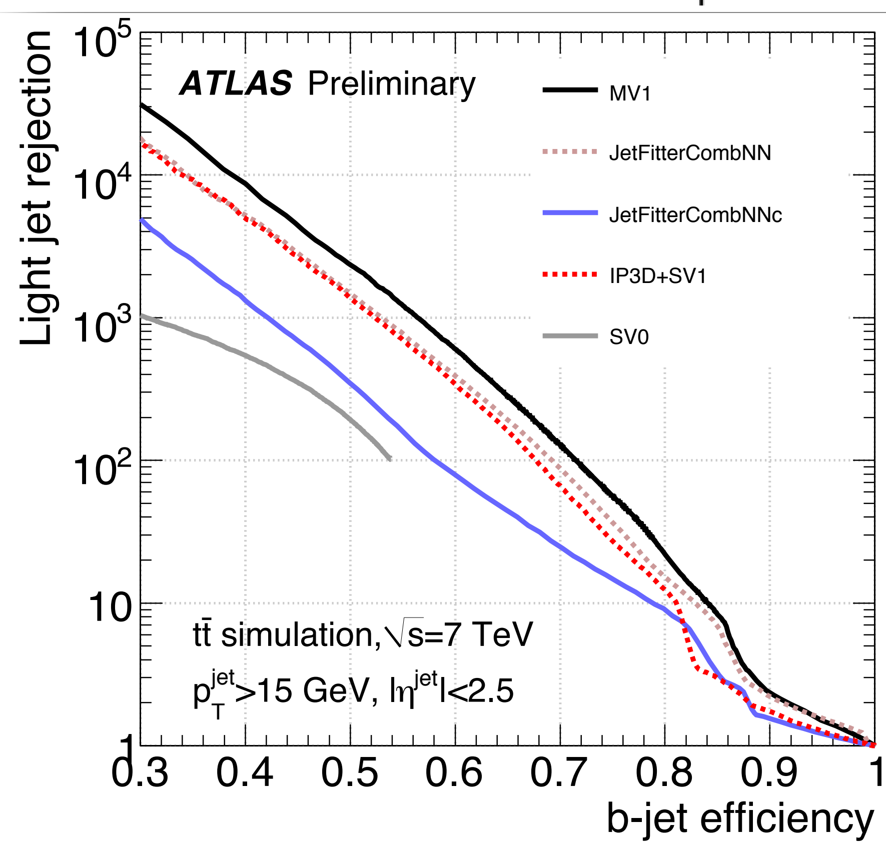
$\tau \rightarrow l\nu\nu$ ~35%

$\tau \rightarrow$ hadrons ~ 65%

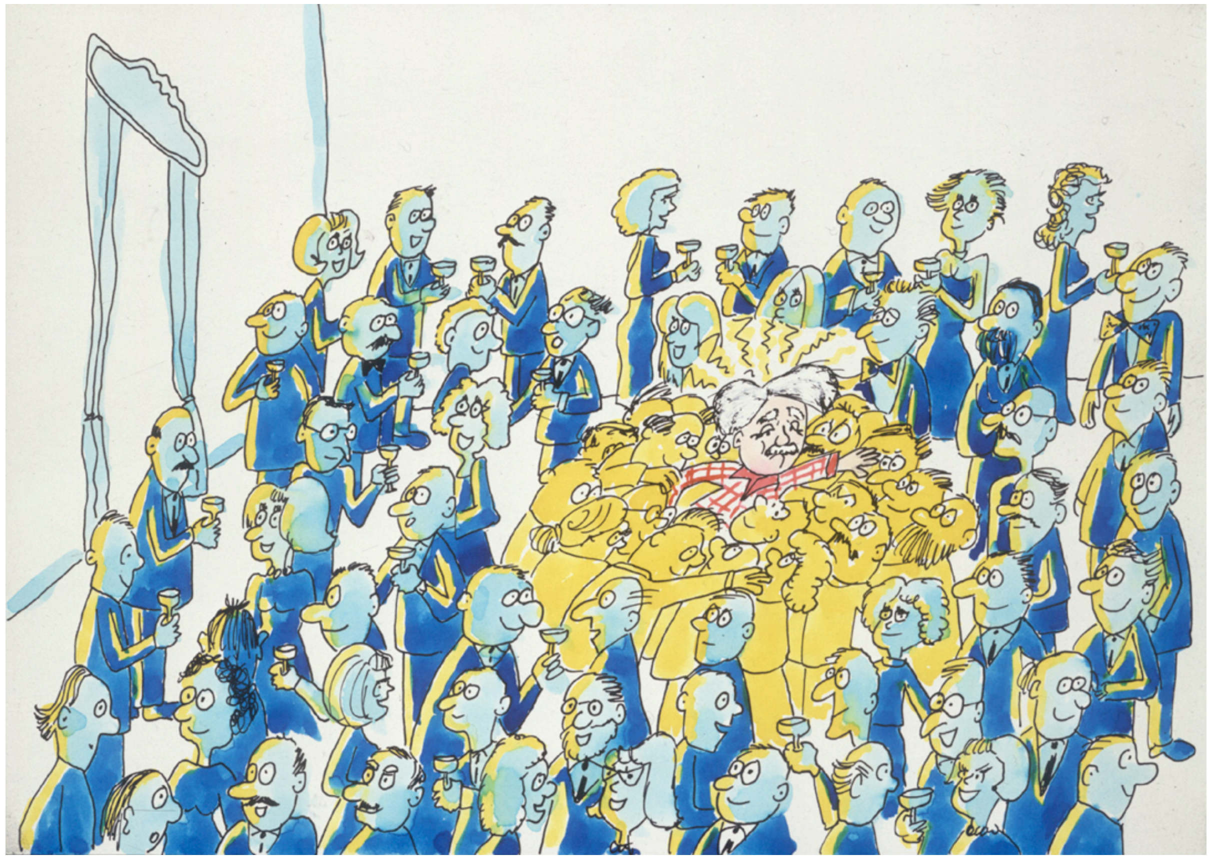


cτ = 492 μm





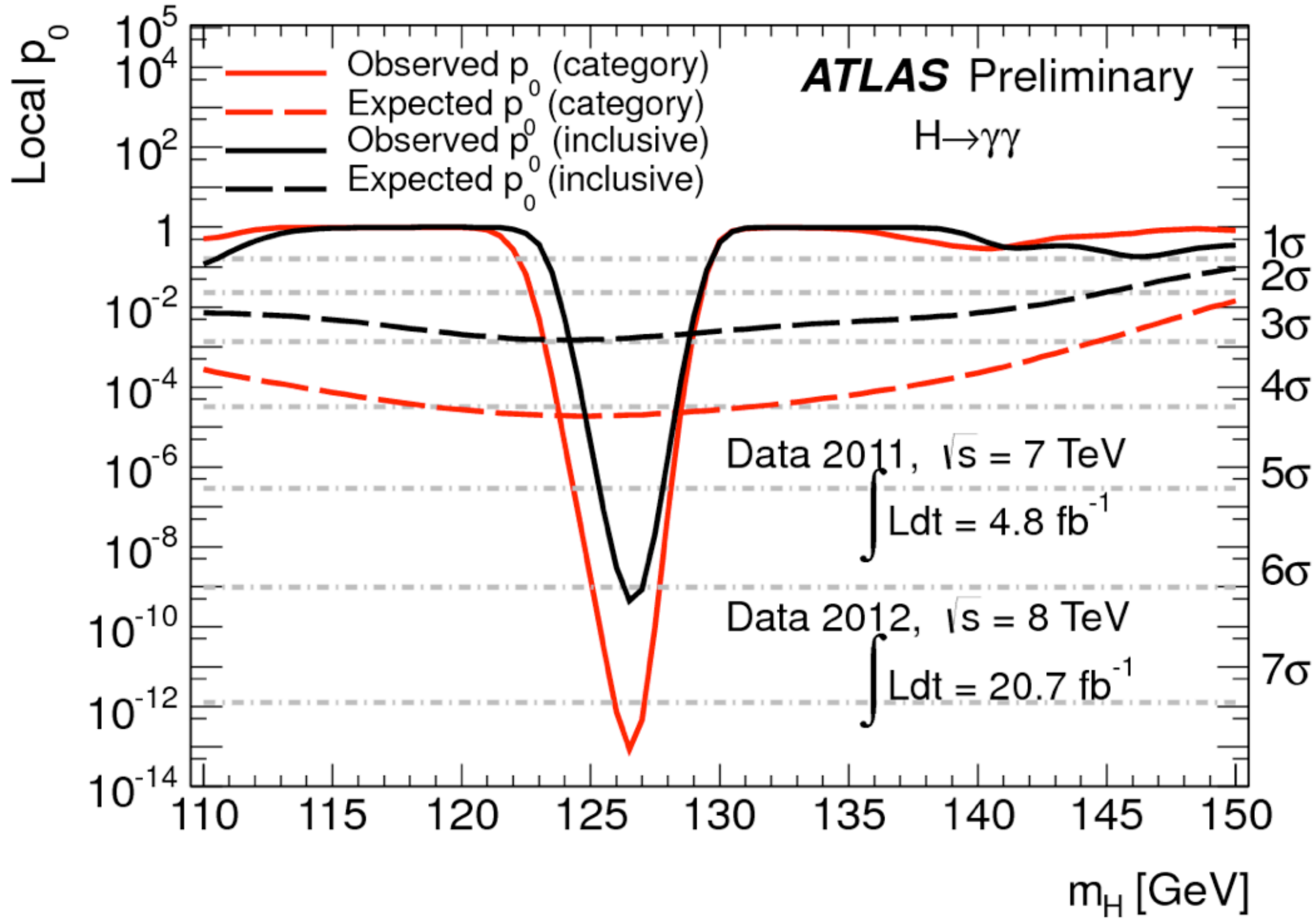
An analogy



In the SM electromagnetic and weak interactions unified through $SU(2)_L \otimes U(1)_Y$, with massless carriers
Symmetry spontaneously broken through the non-vanishing vacuum expectation value of the Higgs field.
Three of the four degrees of freedom of the Higgs field are becoming the longitudinal polarizations of the vector bosons, the fourth is the Higgs boson → excitation of the vacuum needs energy, it's a massive particle.
The fermions couple to Higgs boson proportionally to their mass through Yukawa couplings.

The Higgs boson has been the holy grail of particle physics for quite the last three decades!

H→γγ: Results

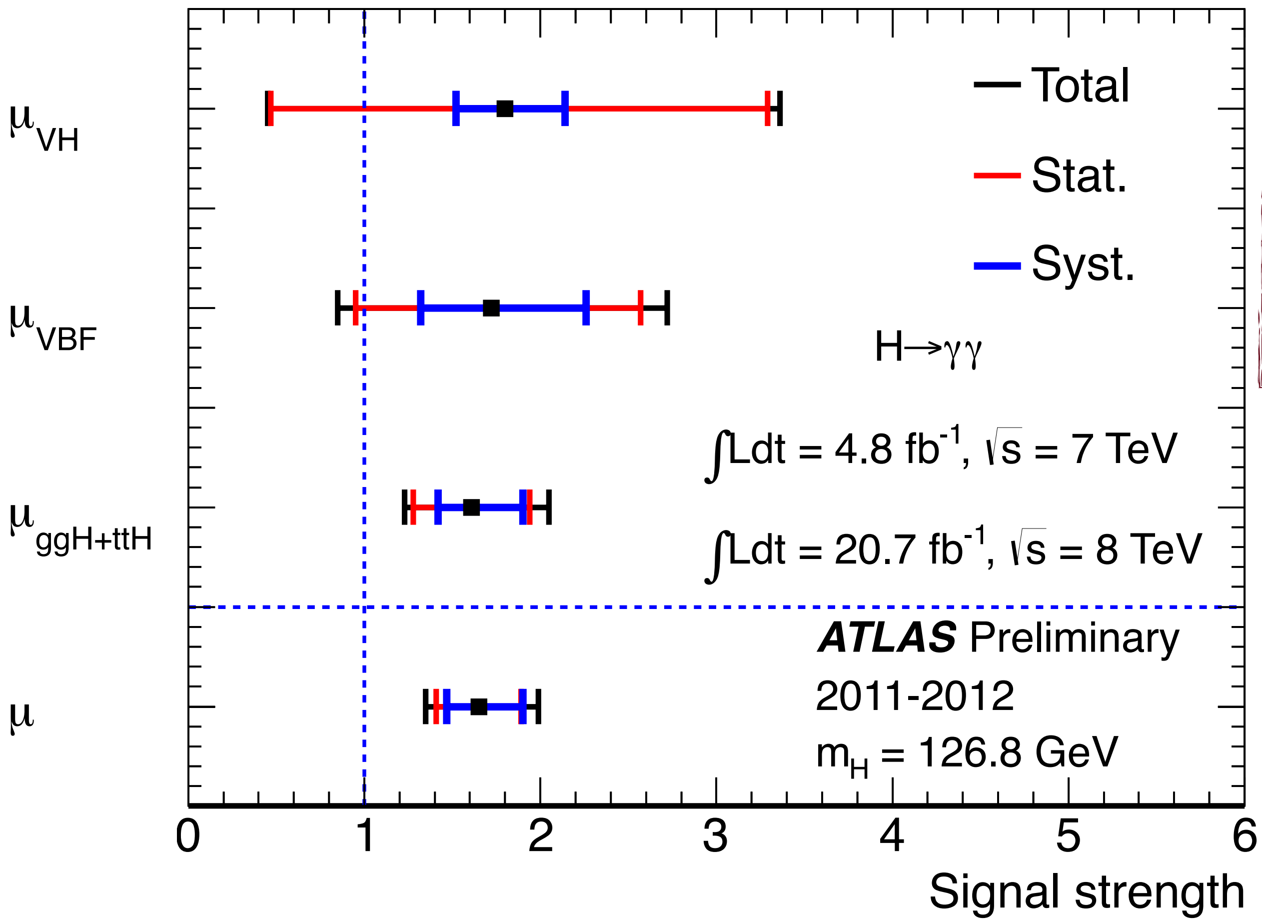


<u>Most significant deviation from background only hypothesis at m_H =126.5 GeV:</u>

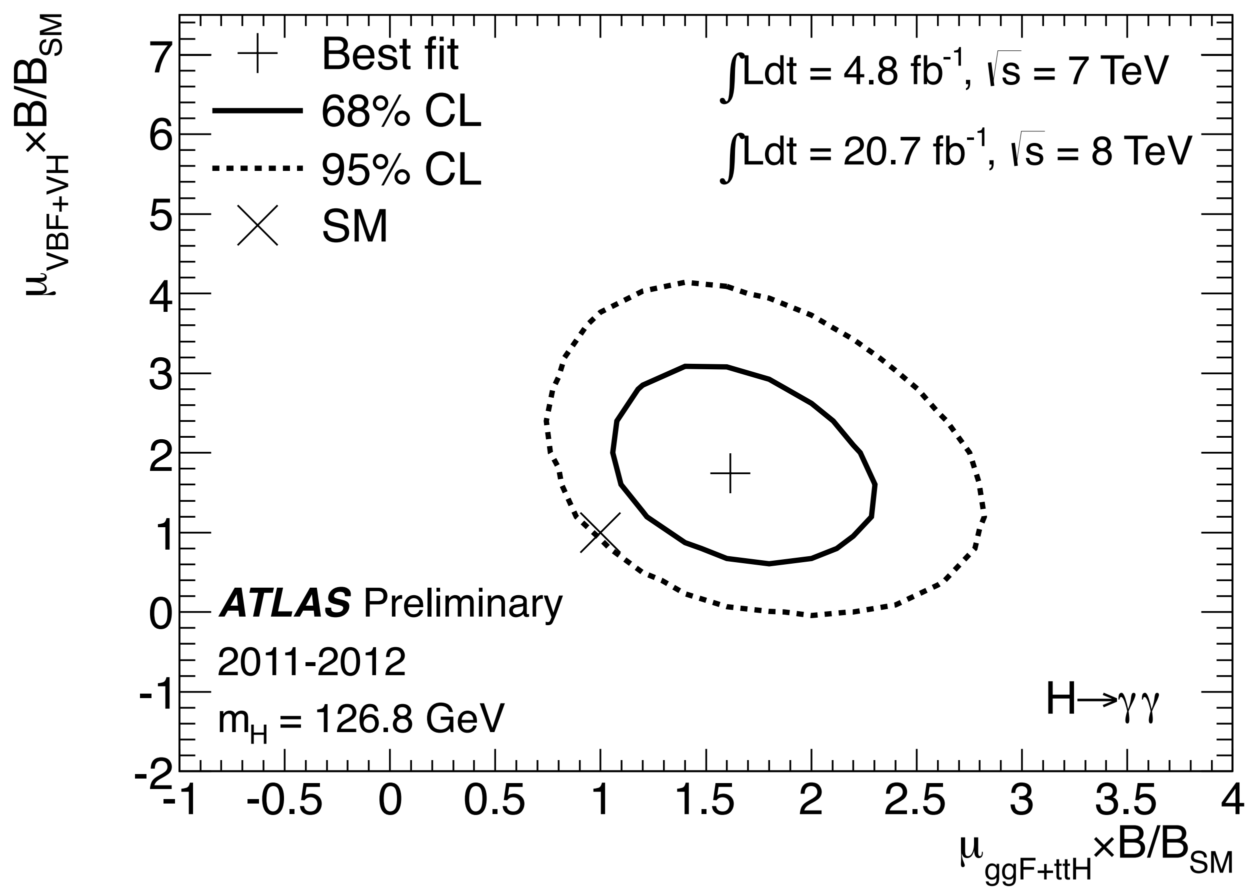
- Local significance: 7.4σ (with 4.1σ expected) @ m_H=126.5 GeV
  - Inclusive analysis: 6.1σ (with 2.9σ expected)
- Mass measurement: 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV
  - Main systematics: γ energy scale from Z→ee, material modeling and presampler energy scale → 0.6 GeV
- Rate with respect to Standard Model: 1.65 ± 0.24 (stat)$^{+0.25}_{-0.85}$

H→γγ: Signal Strength

Signal strength (μ) = (signal rate from data) / (expected SM signal rate at m_H)



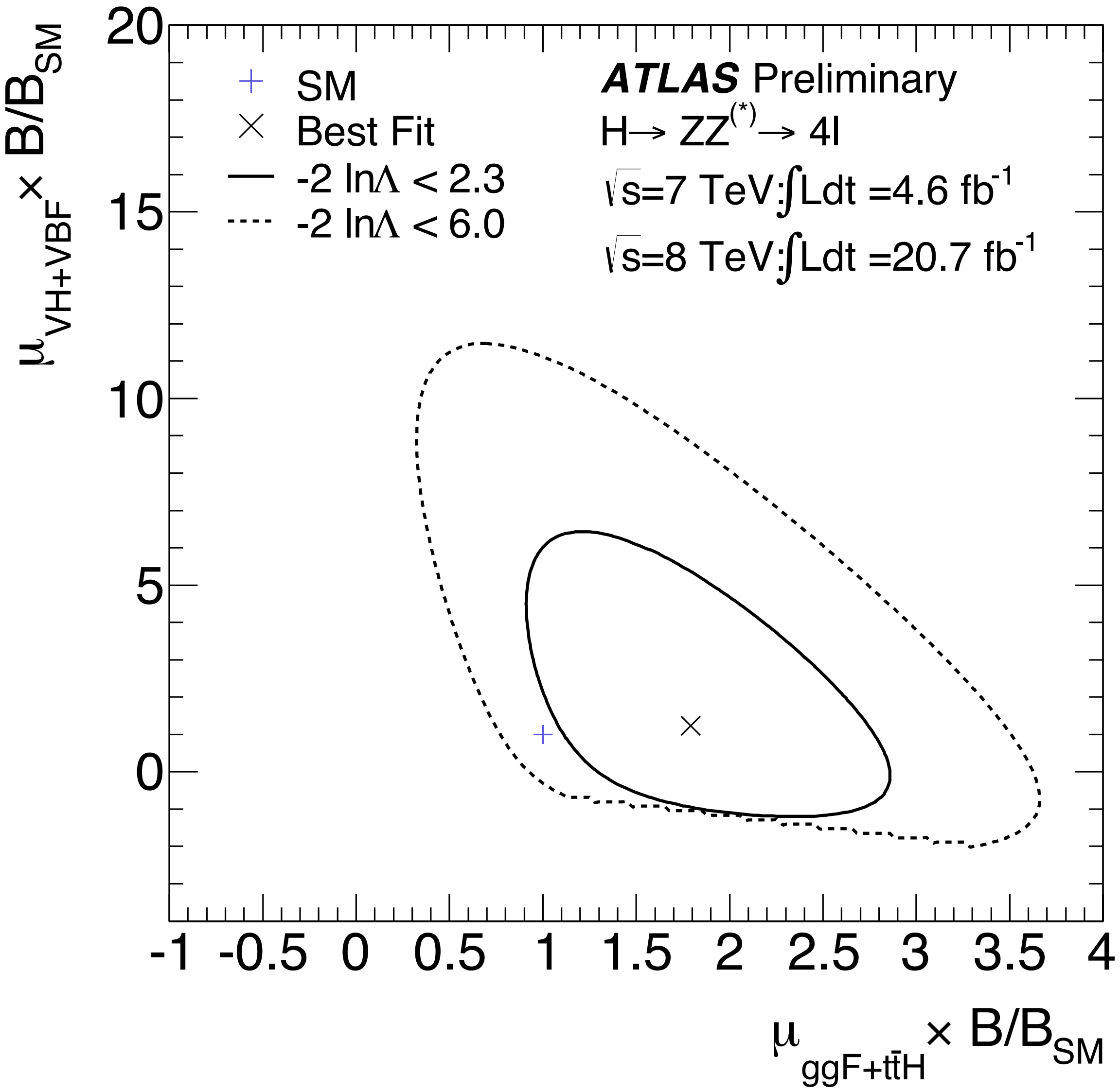
- Best-fit value for m_H =126.8 GeV: **$\mu=1.65^{+0.34}_{-0.30}$**
- 2.3σ deviation from the Standard Model

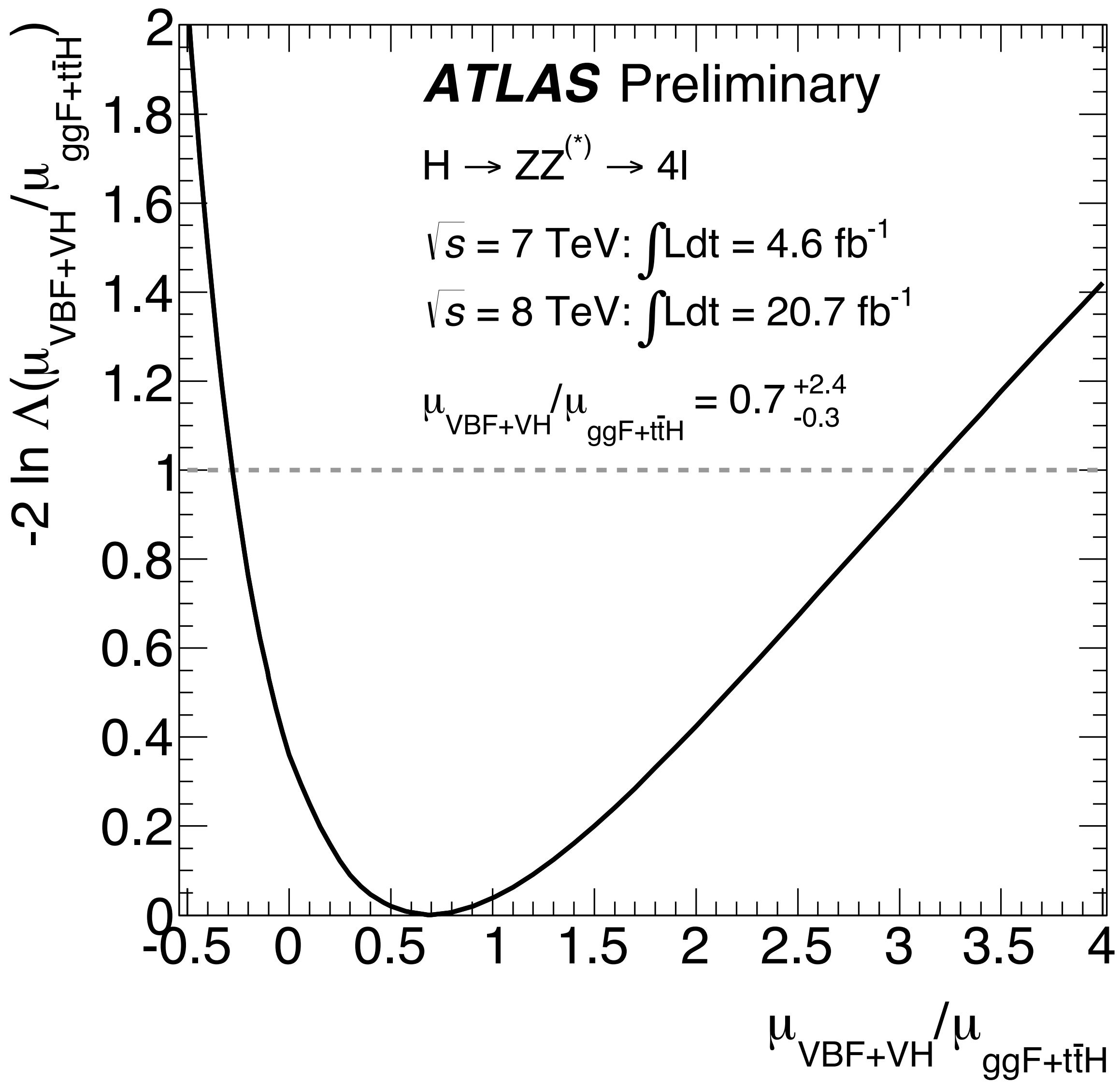


Fiducial cross-section defined for the kinematic range $E^{\gamma 1}_T > 40$ GeV, $E^{\gamma 2}_T > 30$ GeV, $|\eta^\gamma| < 2.37$, measured using 20.7 fb^{-1} of data at $\sqrt{s}$ = 8 TeV, is 56.2 ± 10.5(stat) ± 6.5(syst) ± 2.0(lumi) fb.

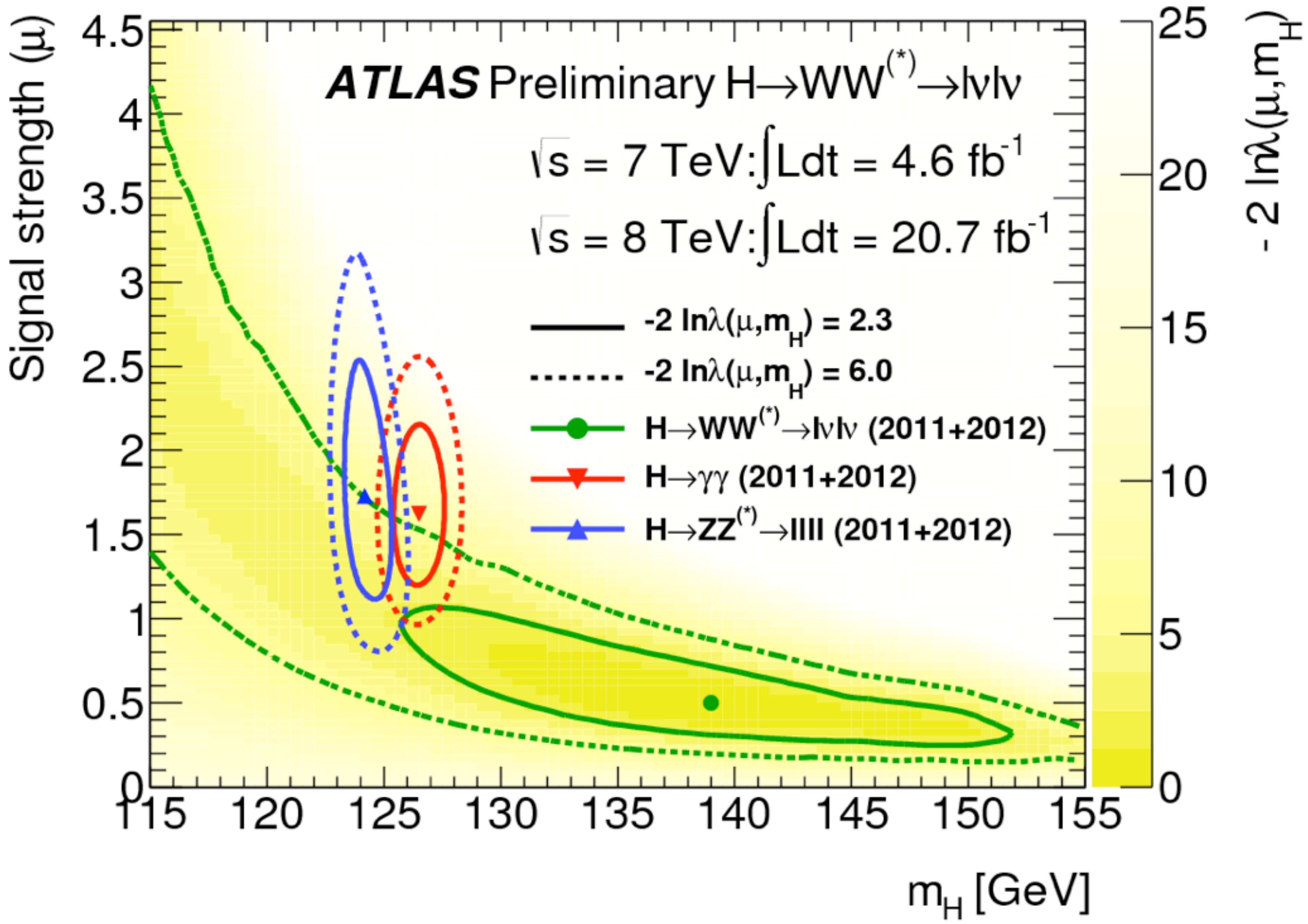
$H \to ZZ^{(*)} \to 4l$: Couplings

- The couplings of the Higgs boson can be probed by further categorising the observed events.
  - VBF-like events : Events with at least two jets in VBF topologyTwo jets with
  - VH-like events : Events with additional leptons in the final state
  - ggF-like events: All remaining events





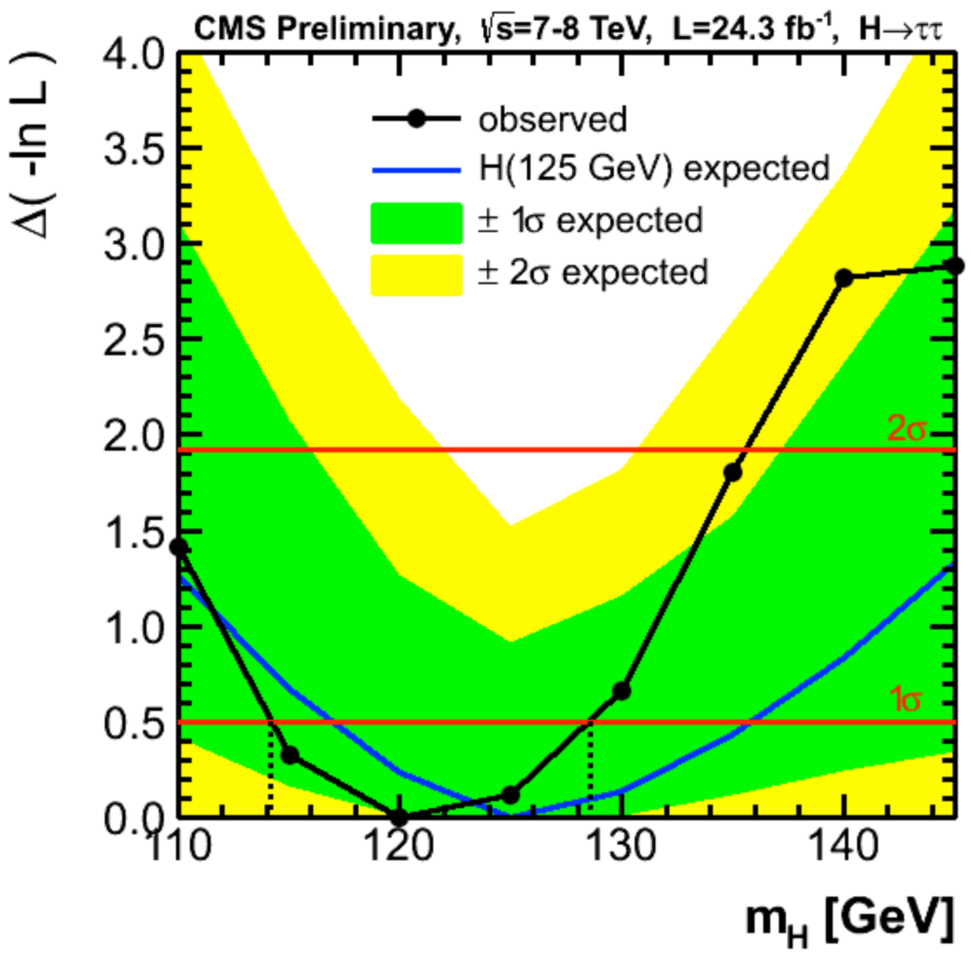
Higgs boson mass: H→WW*→lνlν and H→ττ



H→WW*→lνlν

Very poor sensitivity to the Higgs boson mass

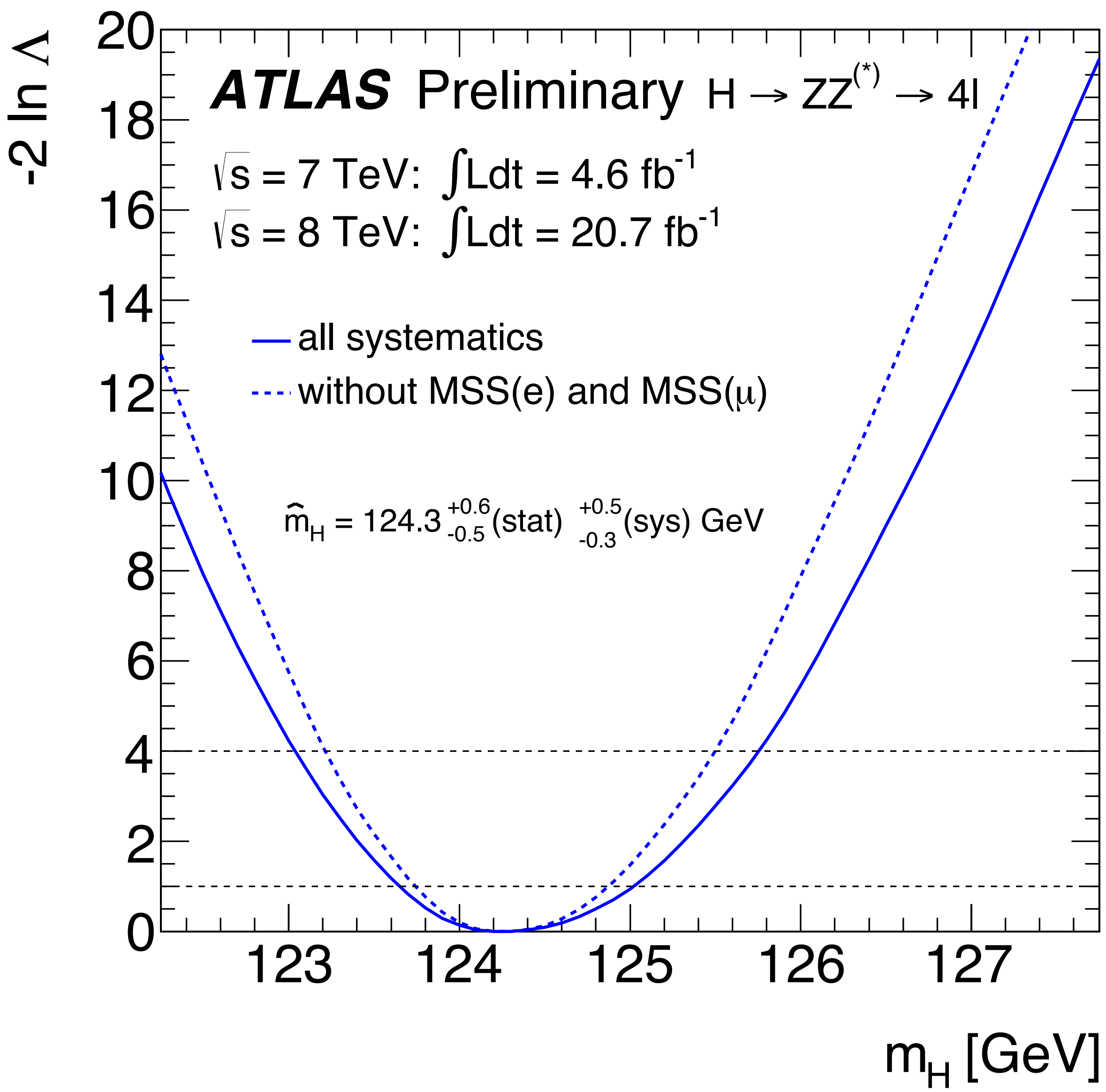
Mass 120^{+9}_{-7} GeV

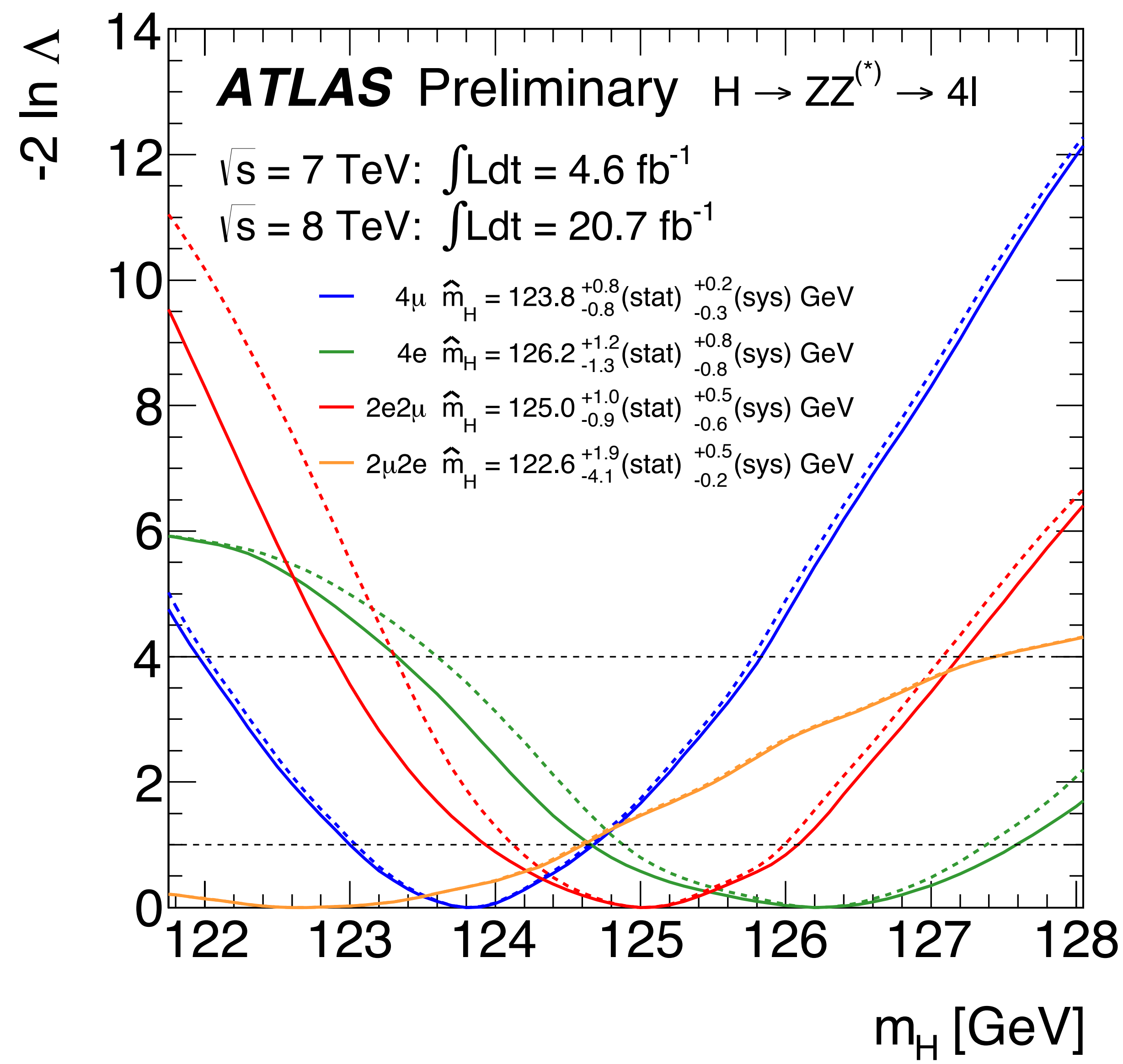


H→ ττ

Small sensitivity to the Higgs boson mass

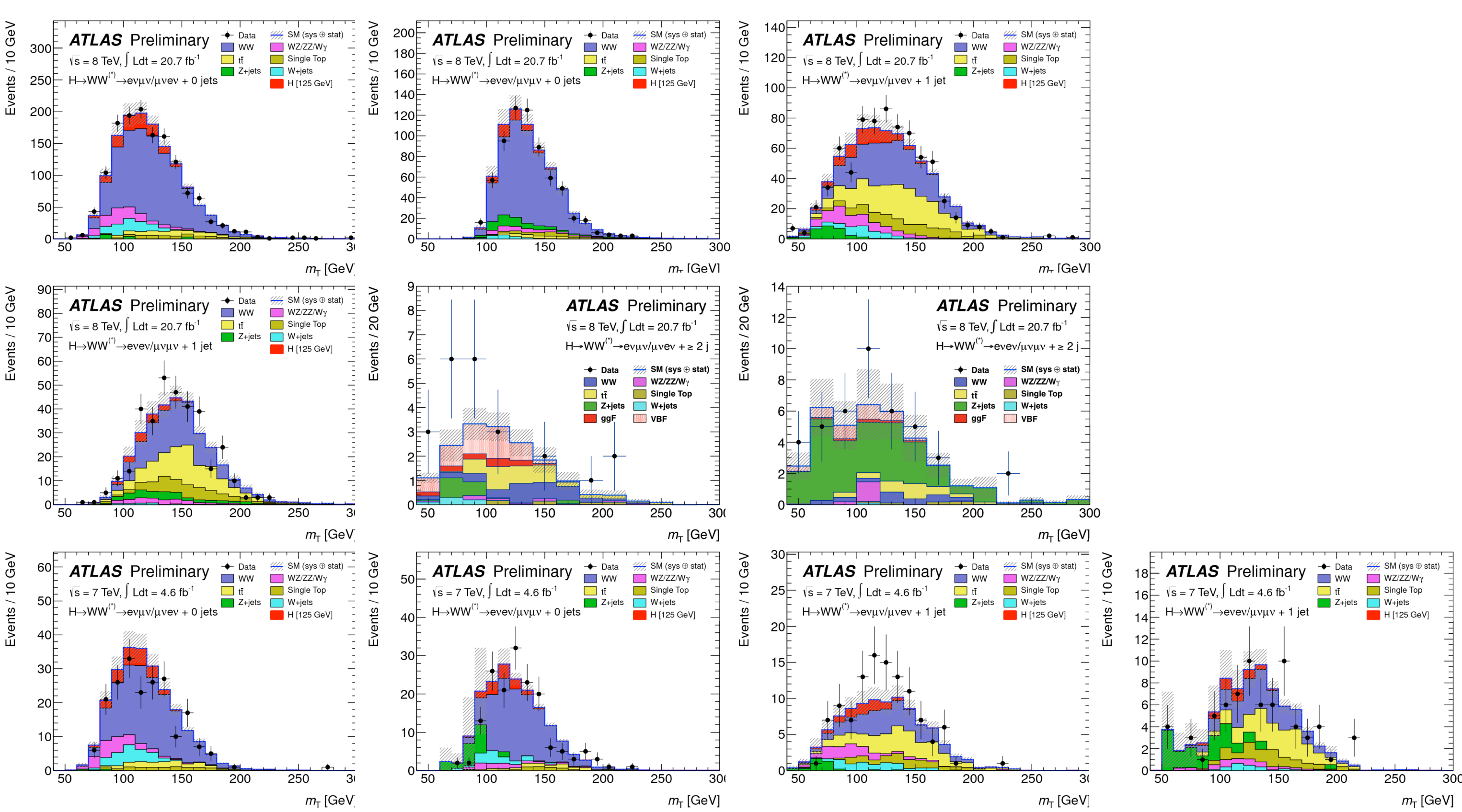
$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Mass Measurement

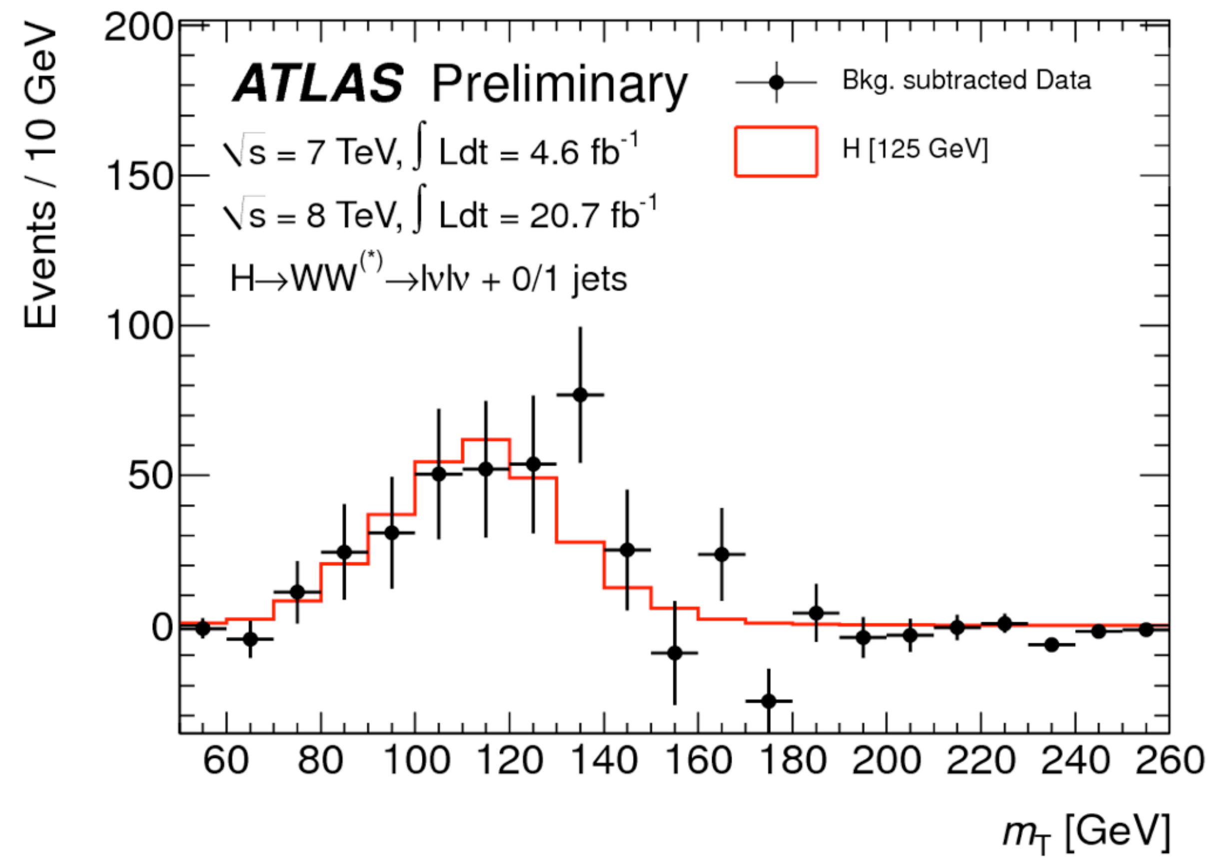




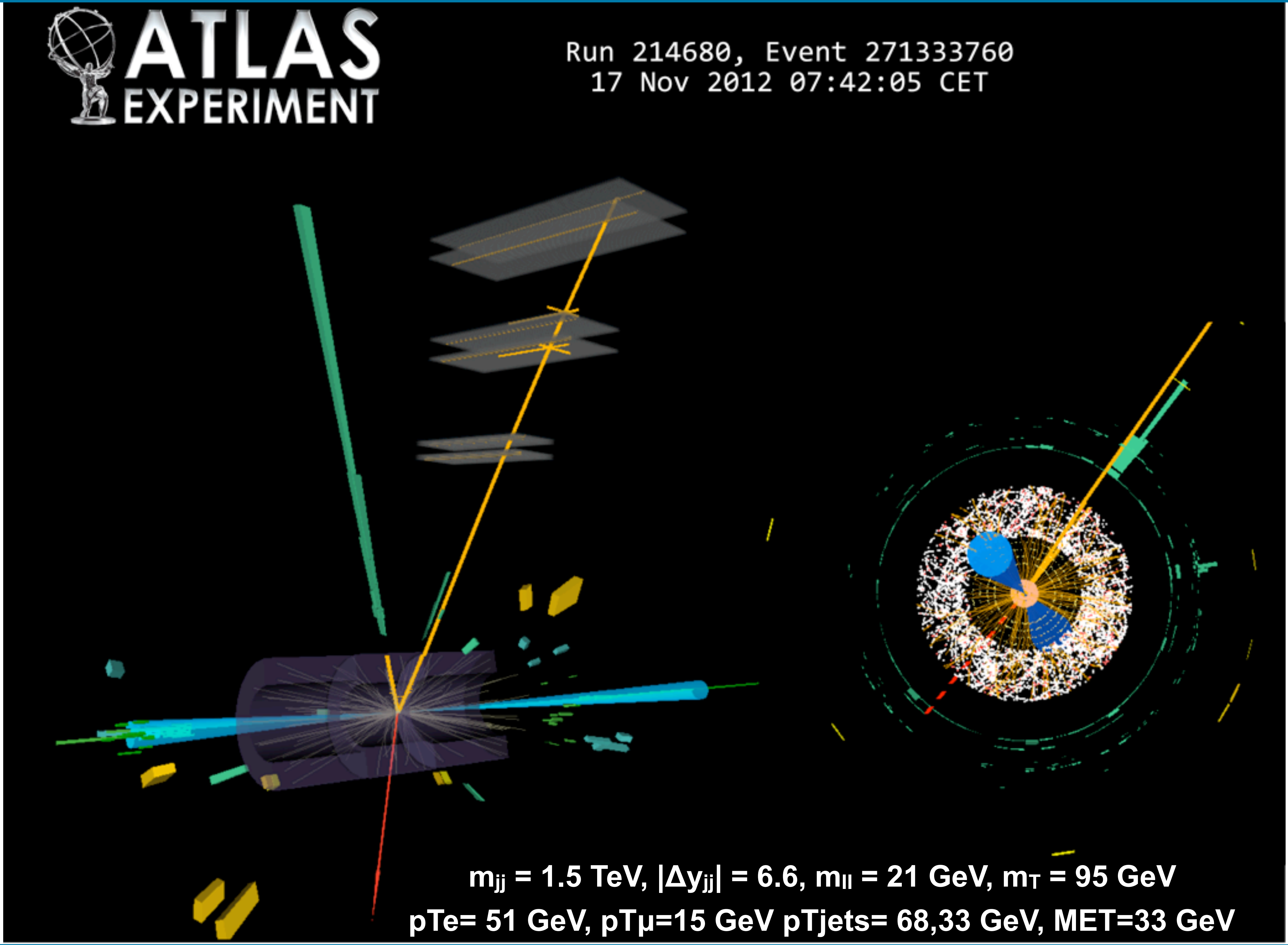
- Mass: $124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})$ GeV
  - Main systematics: electron/muon energy/momentum scale uncertainties
- Muon and electron dominated final states in agreement within the (large) statistical uncertainties

$H \to WW^{(*)} \to l\nu l\nu$

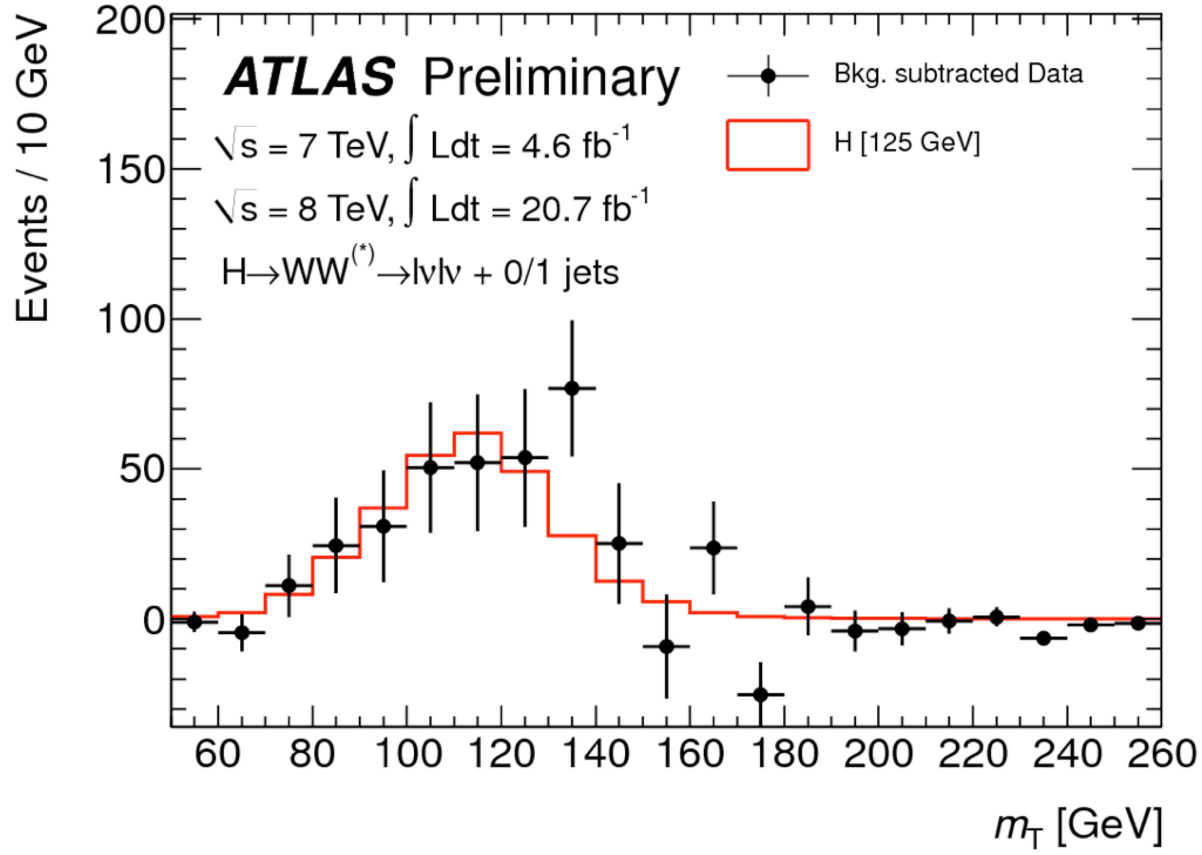


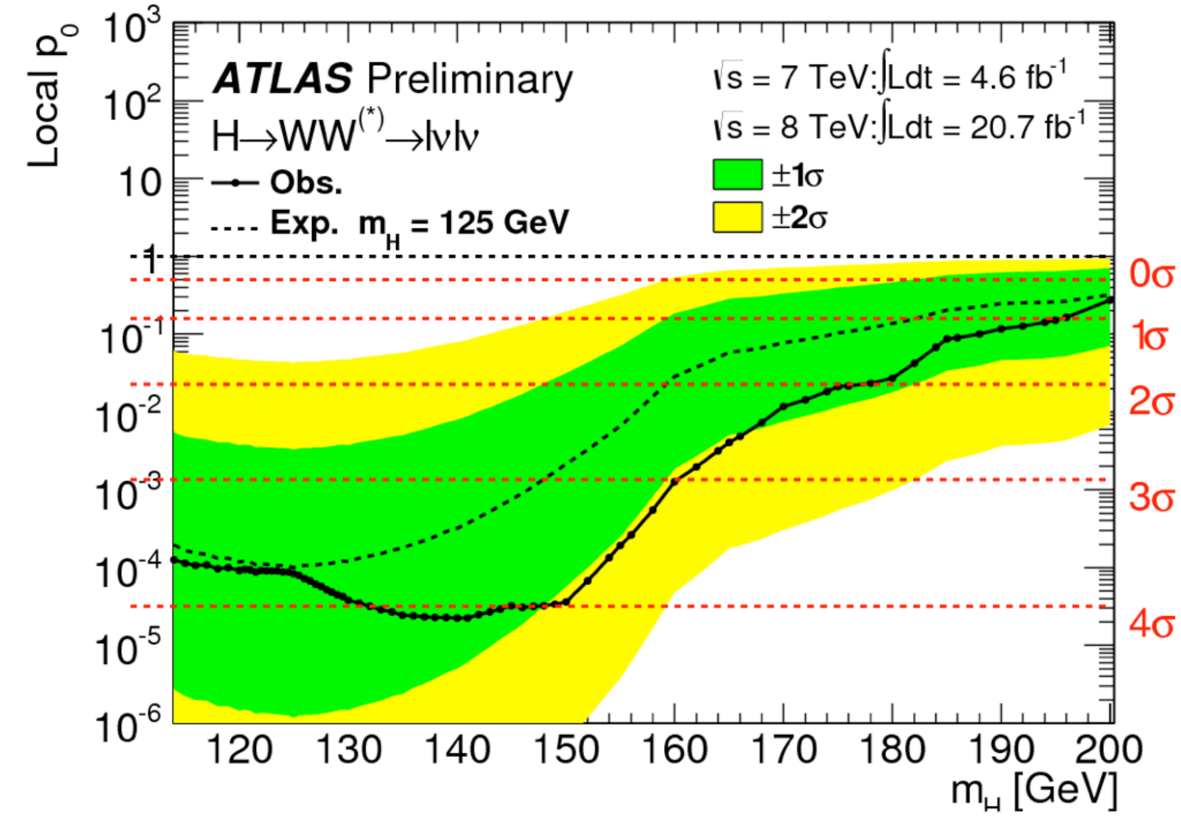


$H \to WW^{(*)} \to e\nu\mu\nu$ +2 jet Event Display

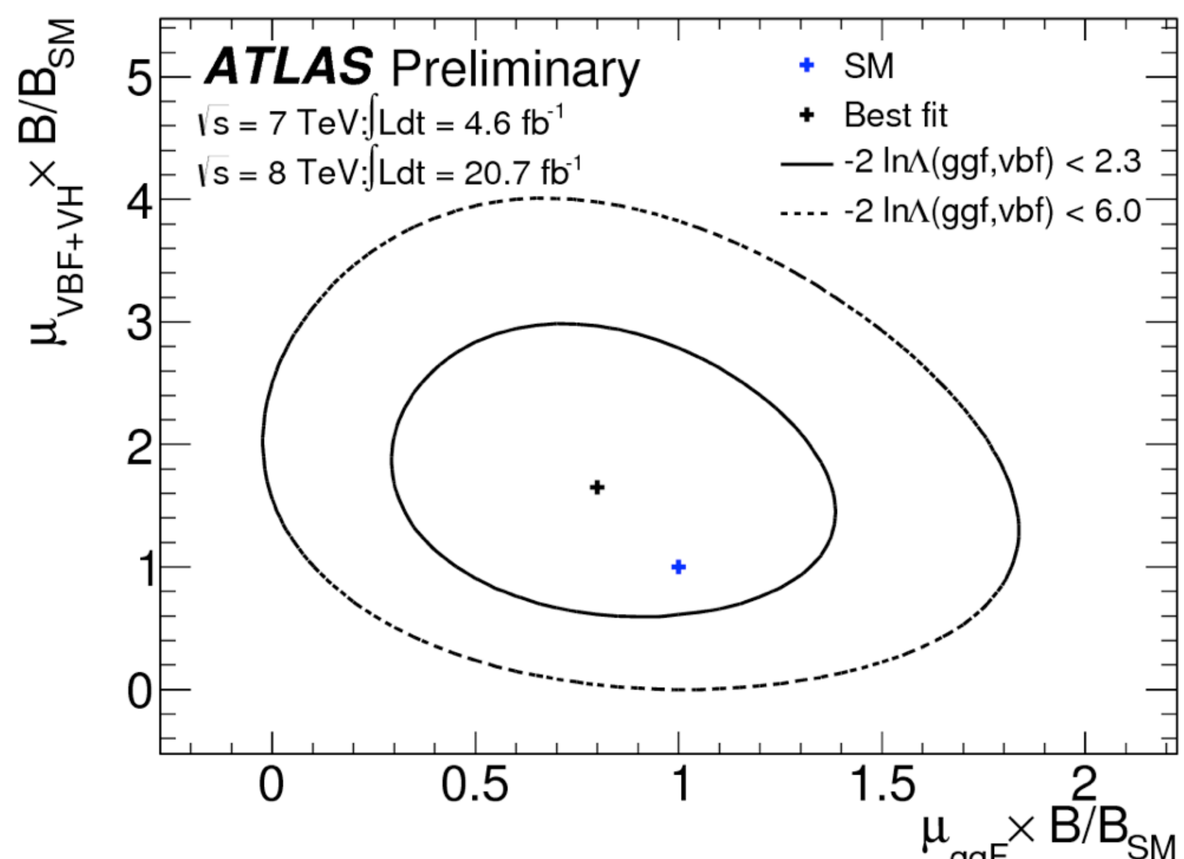


H→WW(*)→lνlν: Results 2011+2012





- Local significance at m_H=140GeV is 4.1σ
- Local significance at m_H=125GeV is 3.8σ
- Rate with respect to SM: 1.01 ± 0.31 @ m_H=125 GeV

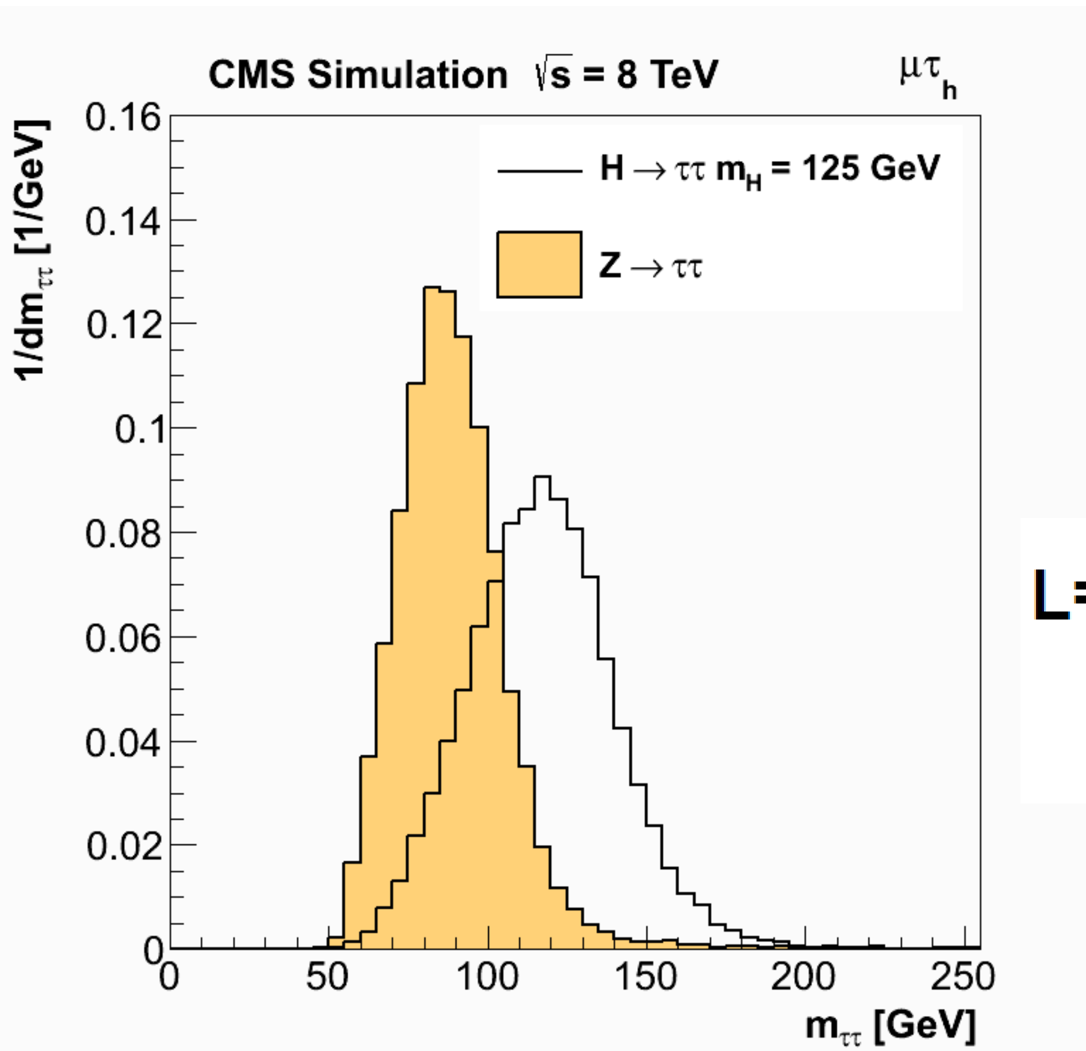


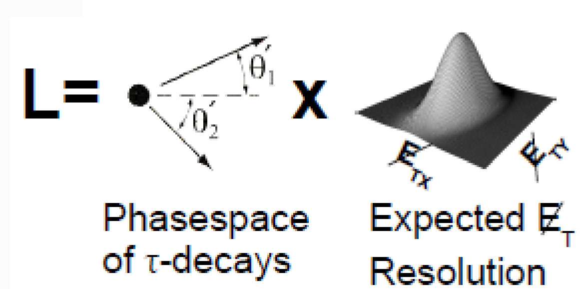
$H \to \tau\tau$

- Most promising channel to directly probe Higgs boson coupling to leptons
- Observables: $m_{\tau\tau}$
- Backgrounds: $Z \to \tau\tau$, top
- Separate final states:
  - τ-decays: μe, μμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
  - jet multiplicities: 1, 2
- Relatively poor mass resolution due to the neutrinos

number of jets → ($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$); τ p_T ↓

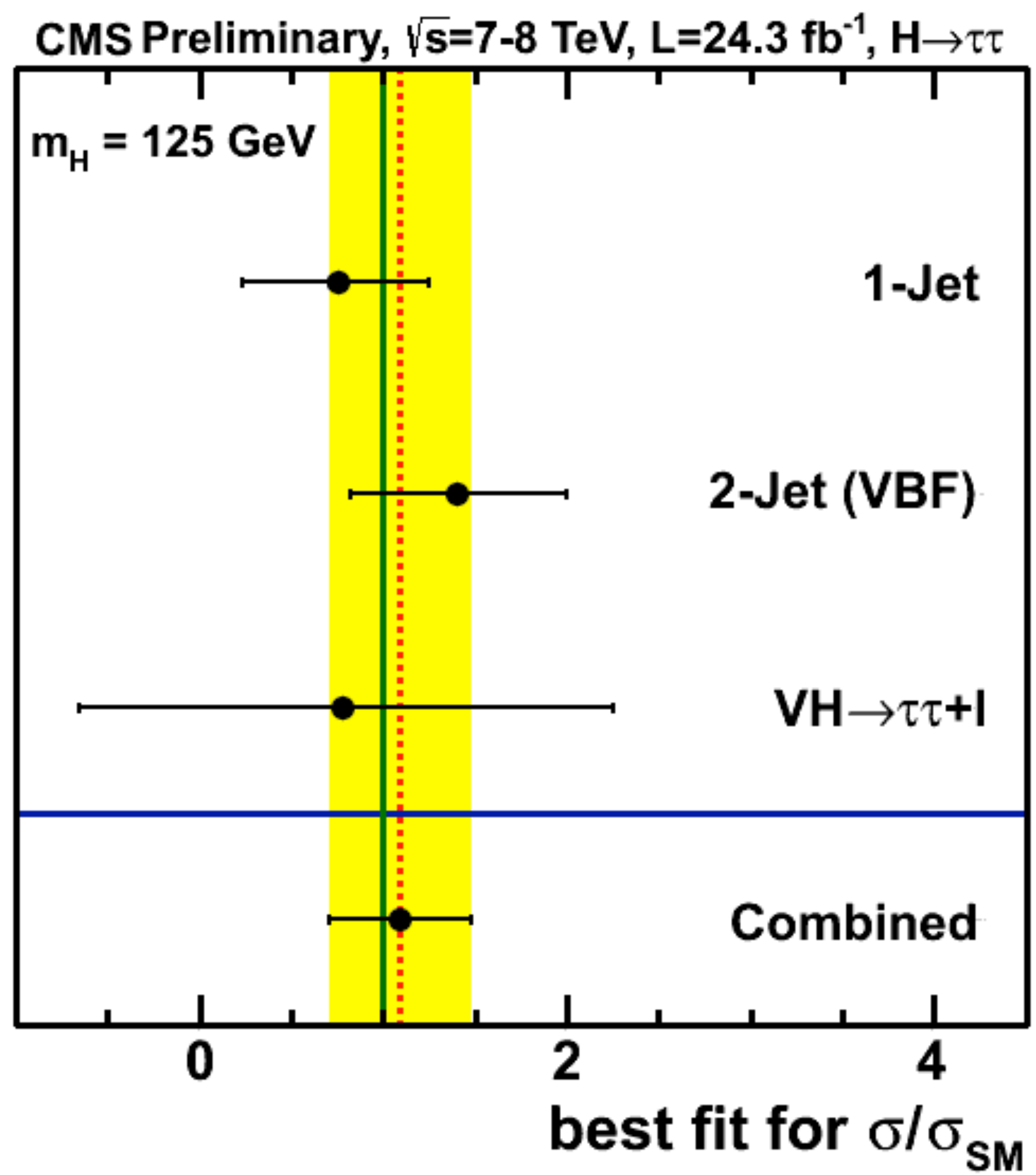
0-jet, low p_T ▪ High background, constrains nuisance parameters ▪ No fit for signal	**1-jet, low p_T** ▪ Enhancement from jet requirement	**2-jet (VBF)** ▪ ≥2 jets, no jet in rapidity gap ▪ $m(jj) > 500$ GeV, $\lvert\Delta\eta(jj)\rvert > 3.5$
0-jet, high p_T ▪ High background, constrains nuisance parameters ▪ No fit for signal	**1-jet, high p_T** ▪ Enhancement from jet and p_T requirement	
	$\tau_h\tau_h$ 1-jet 1 jet, high $p_T(H)$ requirement	**$\tau_h\tau_h$ 2-jet (VBF)** 2 jets, high $p_T(H)$ requirement, $m(jj) >$ 250 GeV, $\lvert\Delta\eta(jj)\rvert > 2.5$





- Maximum likelihood method used to improve resolution
  - Using on event-by-event basis the four-momenta of the visible decay products, MET, and expected MET resolution
  - Integrating over unconstrained d.o.f.
- Obtain 15-20% resolution on $m_{\tau\tau}$

H→ττ: Results



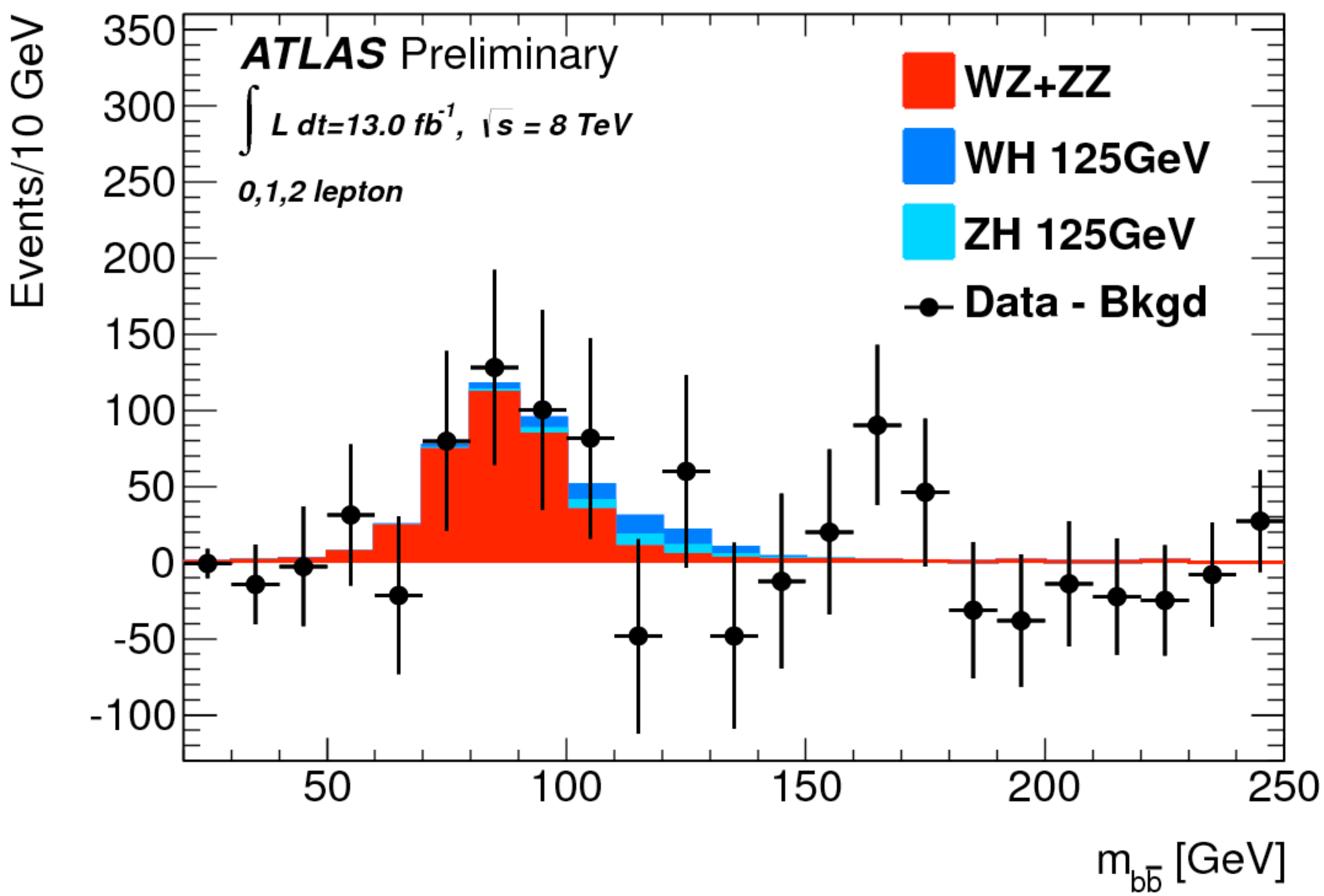
Local significance at m_H=120GeV is 2.93σ (2.65σ)

Local significance at m_H=125GeV is 2.85σ (2.62σ)

Consistent picture across different channels

Rate with respect to SM: 1.1 ± 0.4 @ m_H=125 GeV

H→bb

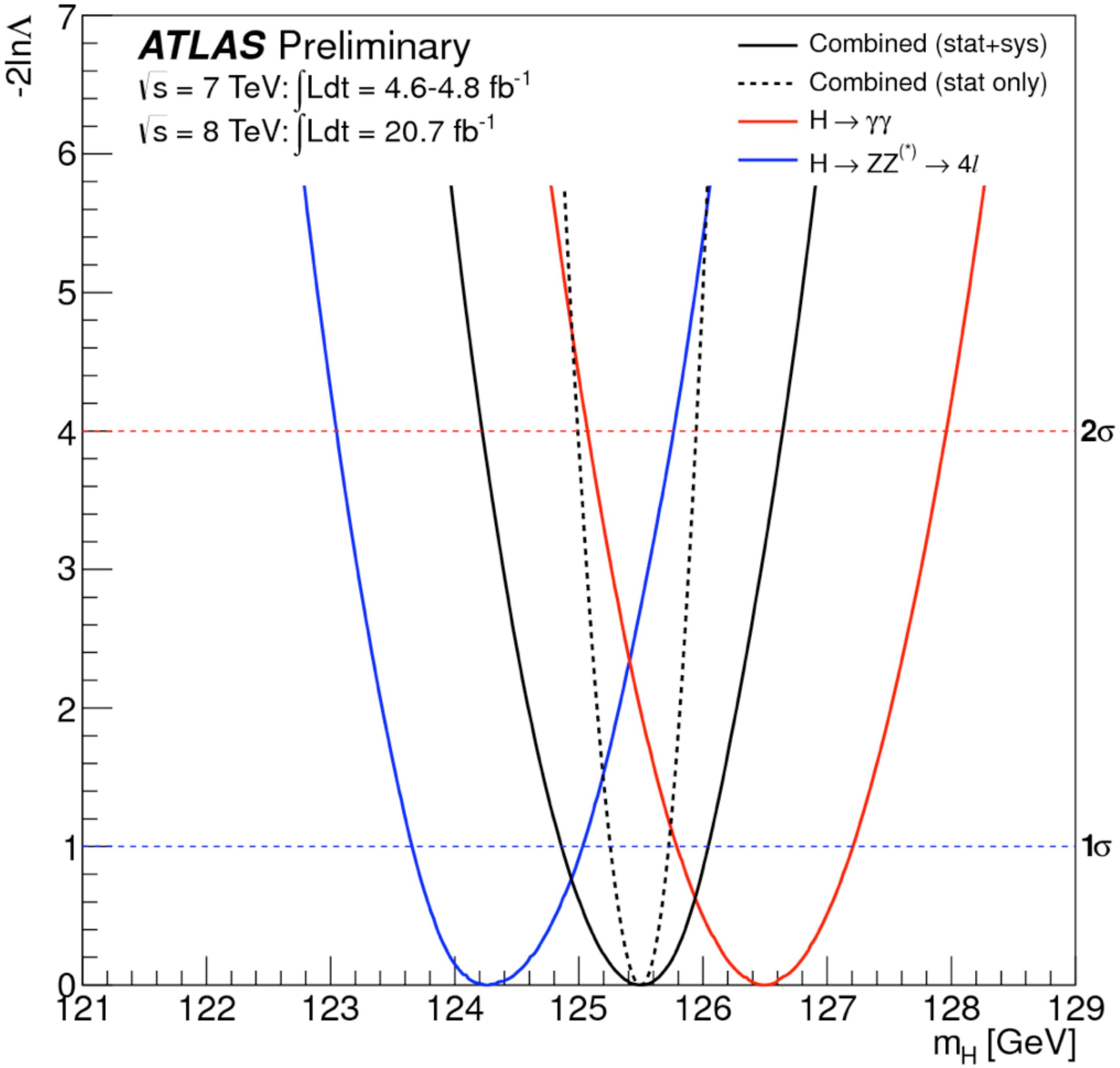


Similar to VH but with x5 in cross-section

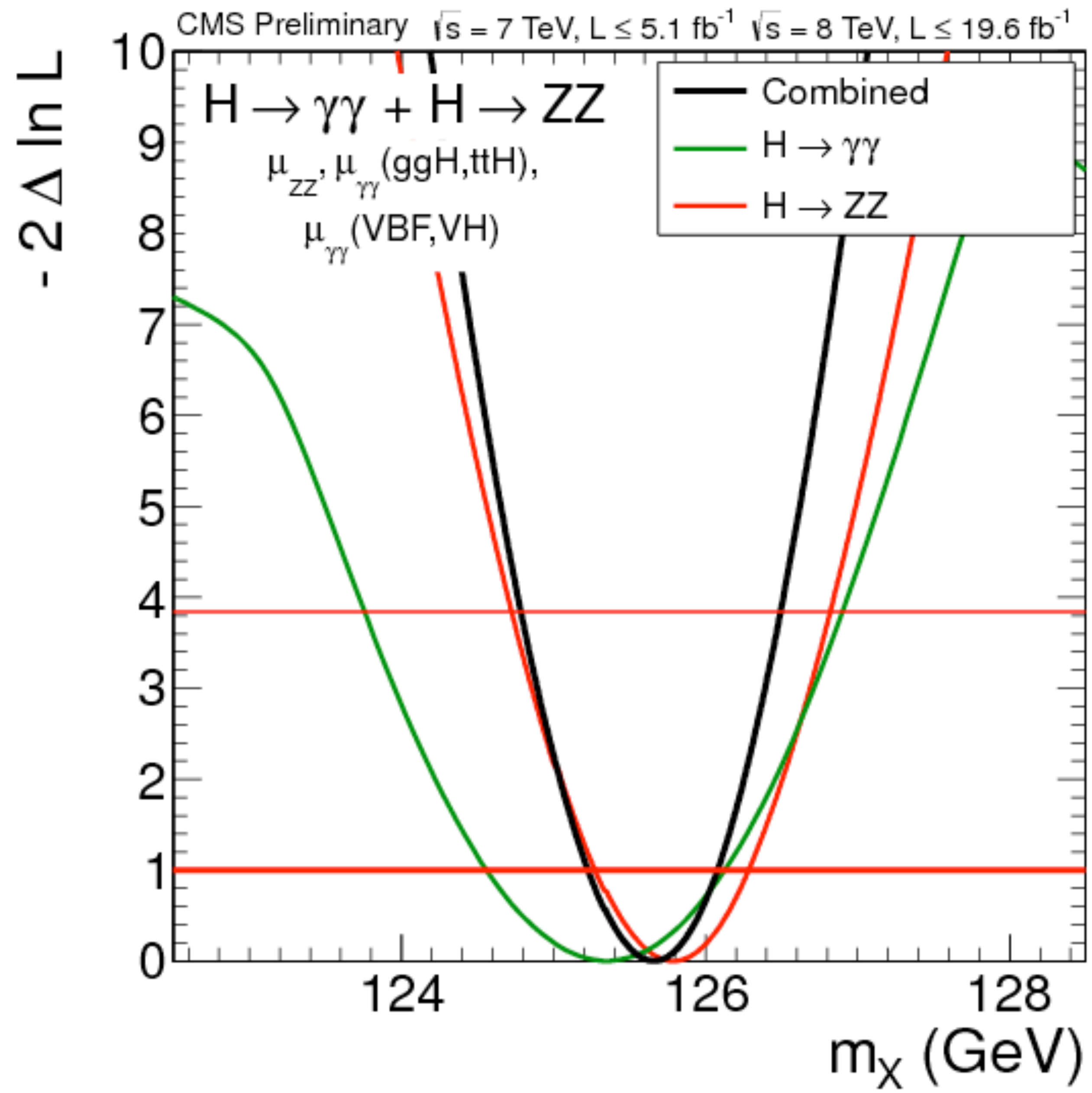
(W/Z)(Z→bb) observation significance : 4.0σ

μ_D = 1.09 ± 0.20 (stat) ± 0.22 (syst)

Overview: Mass measurement



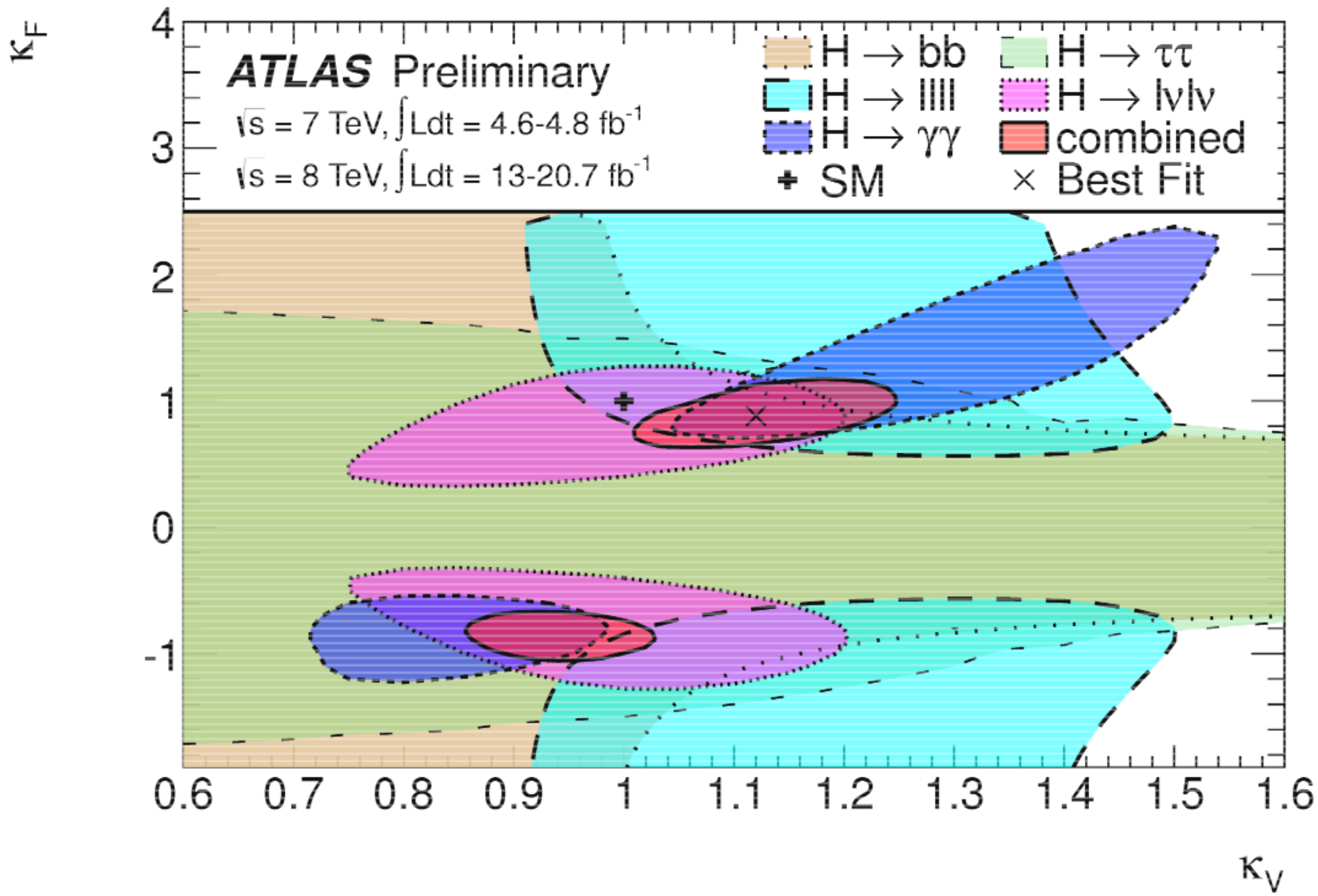
m_H = 125.5 ± 0.2 (stat)$^{+0.5}_{-0.6}$ (syst) GeV



m_H = 125.7 ± 0.3 (stat) ± 0.3 (syst) GeV

Using the high resolution channels only
The ATLAS and CMS mass combinations are in good agreement

Overview: Coupling studies



Assumptions

- the resonance corresponds to a CP-even boson

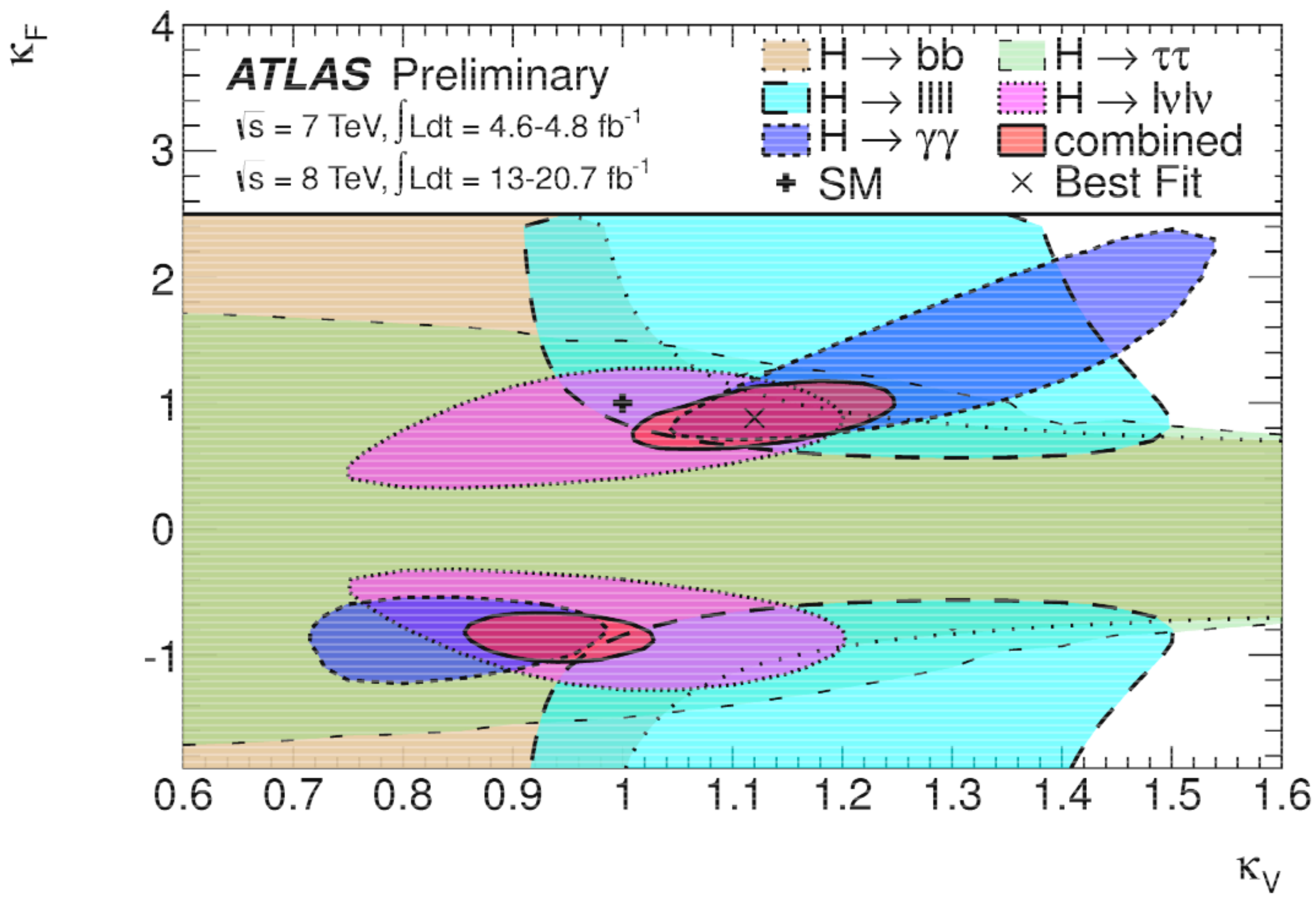
- no contributions beyond the Standard Model

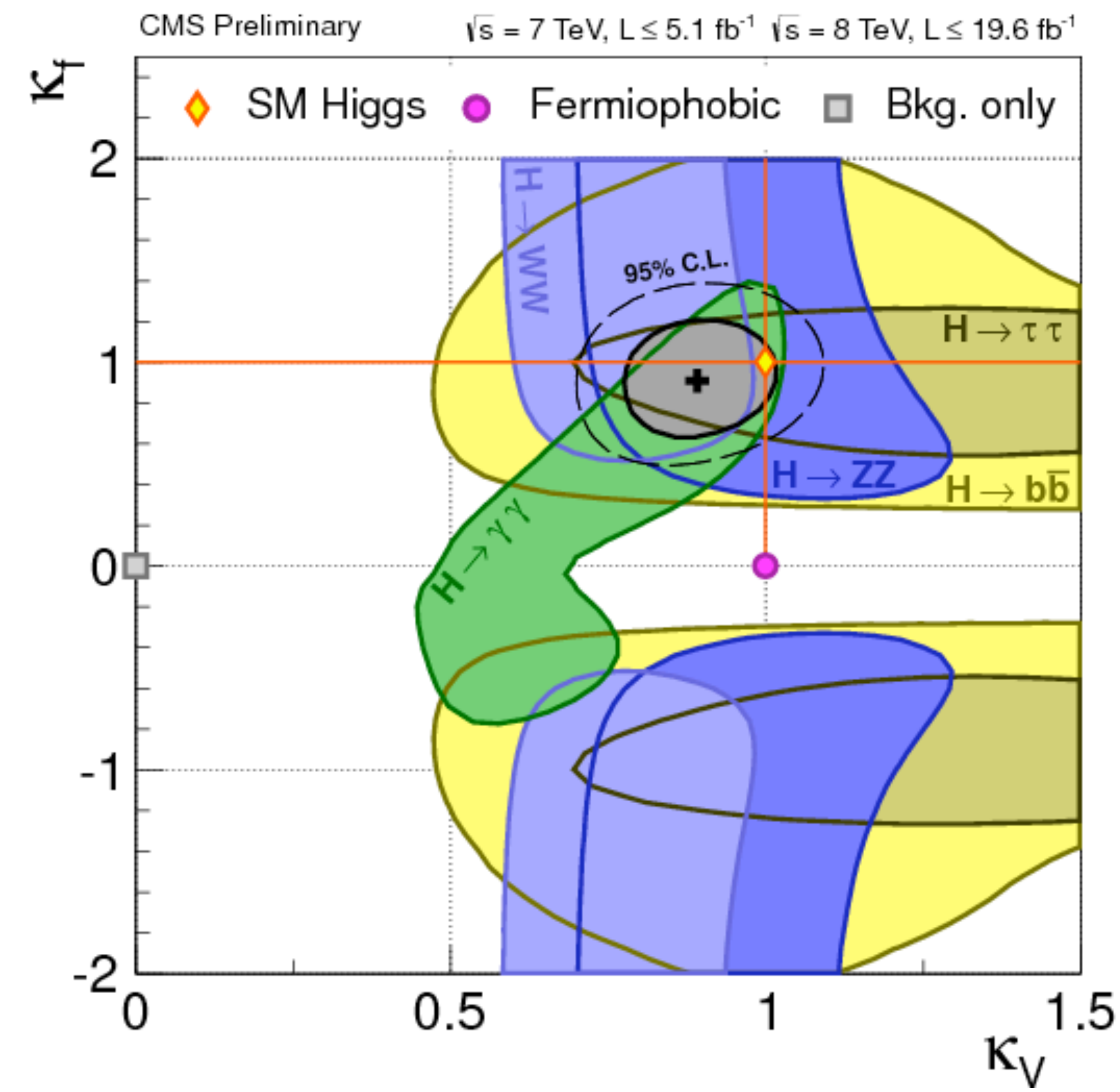
- deviations of vector boson couplings to the Higgs described by one overall scaling (κ_V)

- deviations of fermion couplings to the Higgs described by one overall scaling (κ_F)

Data compatible with the Standard Model expectation for both experiments

Overview: Coupling studies





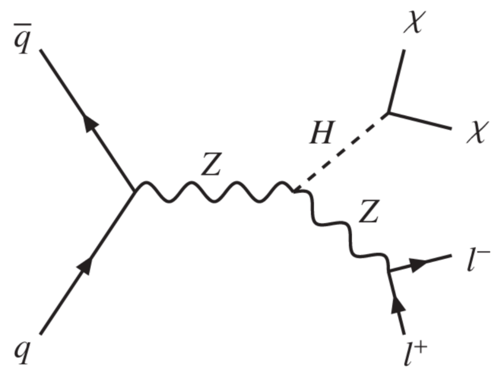
Assuming that:

- the resonance corresponds to a CP-even boson
- no contributions beyond the Standard Model
- deviations of vector boson couplings to the Higgs described by one overall scaling (κ_V)
- deviations of fermion couplings to the Higgs described by one overall scaling (κ_F)

Data compatible with the Standard Model expectation for both experiments

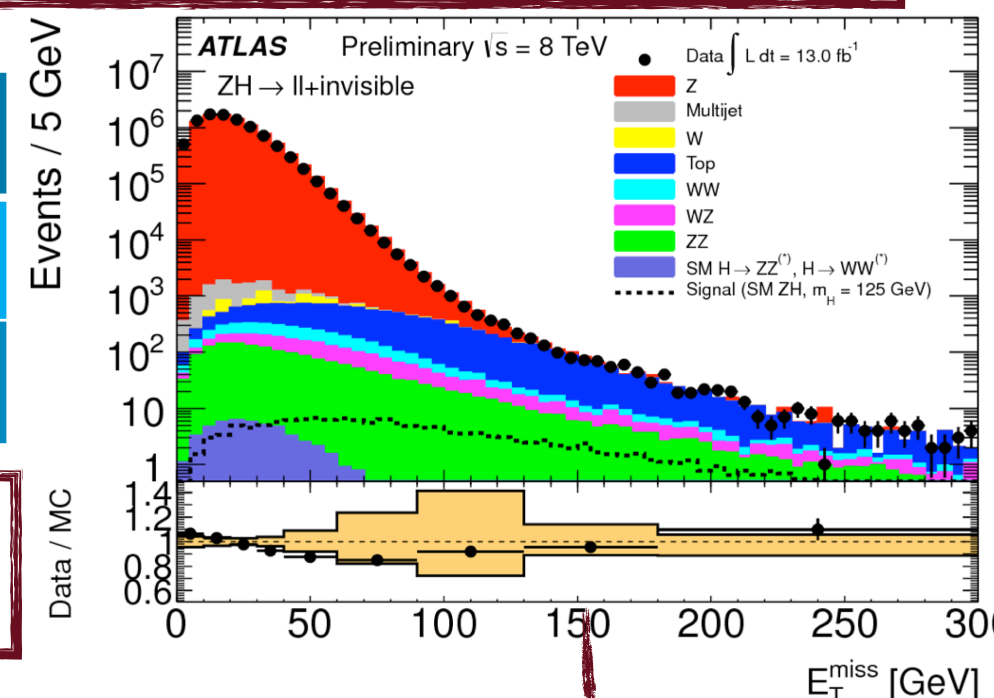
“Invisible” Higgs boson decays

“Invisible” decays are suppressed in SM → Observation would be direct indication of New Physics!

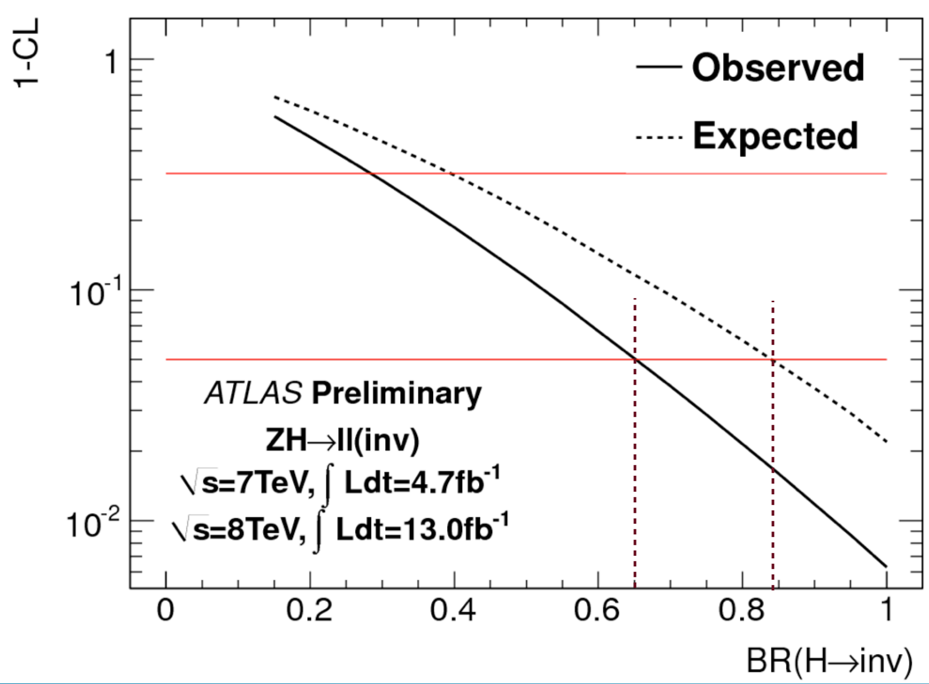


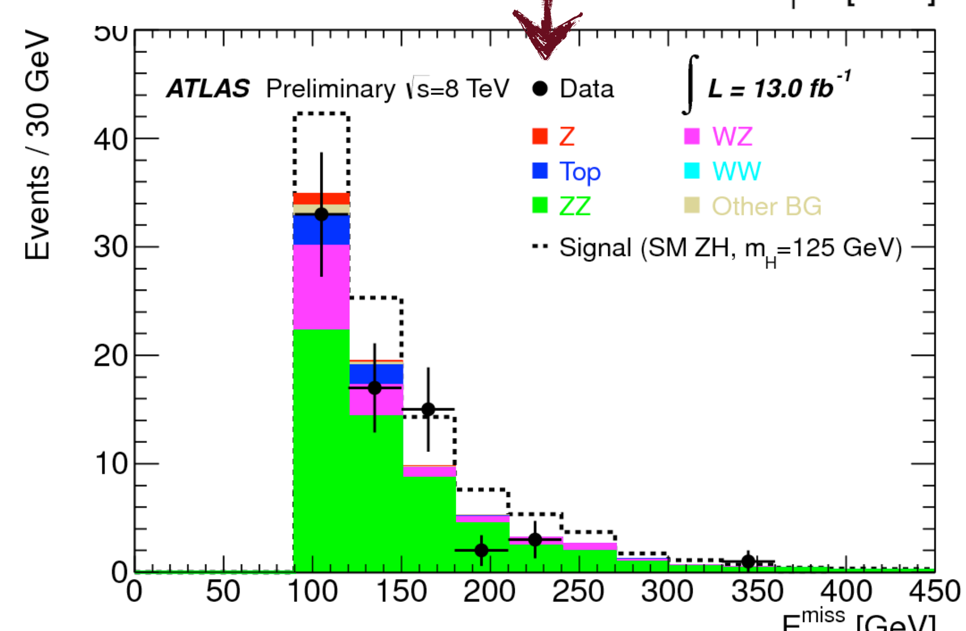
- Signature : Z→ee/μμ + large MET
- Main Backgrounds: ZZ→llνν, WZ→lνll, WW→lνlν
- Require MET > 90 GeV and optimize selection for ZH-like events

	Expected SM Backgrounds	Observed
7 TeV/4.7 fb^{-1}	32.7 ± 1.0 (stat) ± 2.6 (syst)	27
8 TeV/13.0 fb^{-1}	78.0 ± 2.0 (stat) ± 6.5 (syst)	71

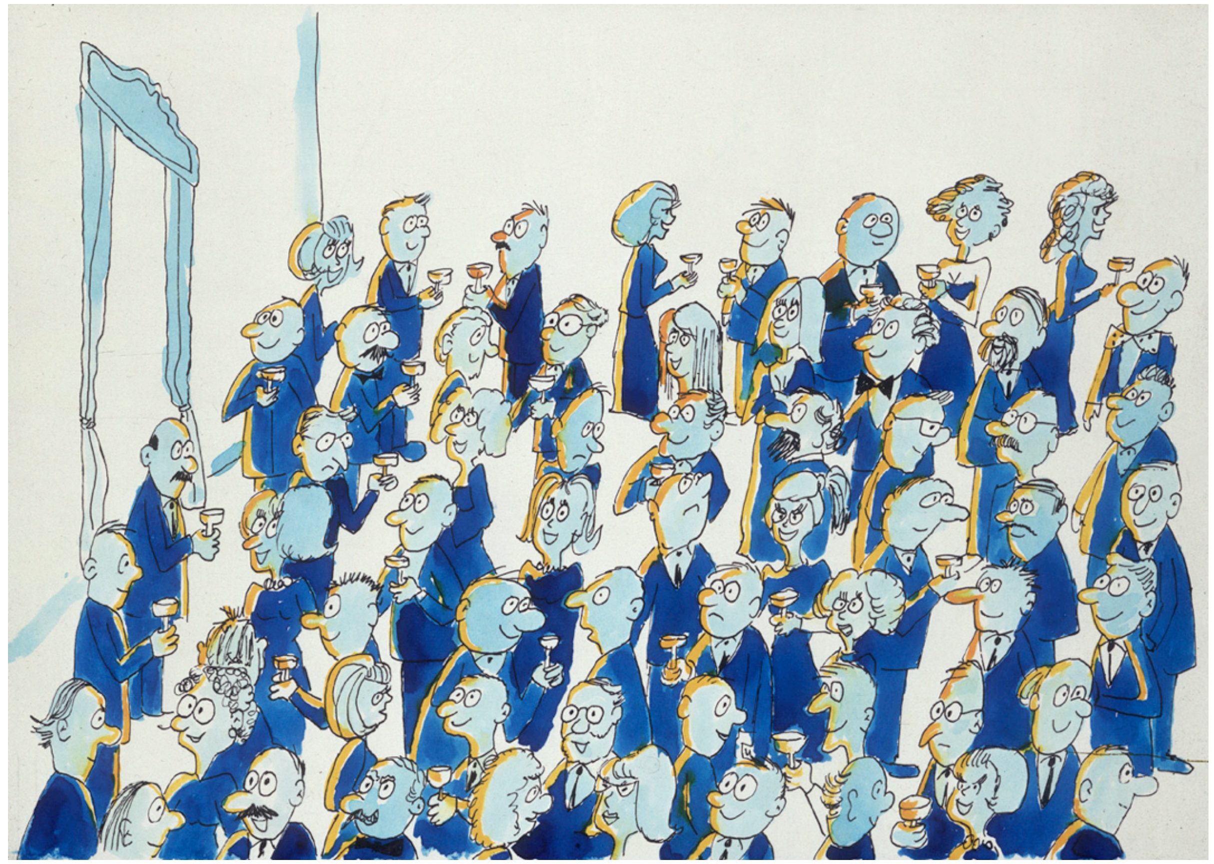


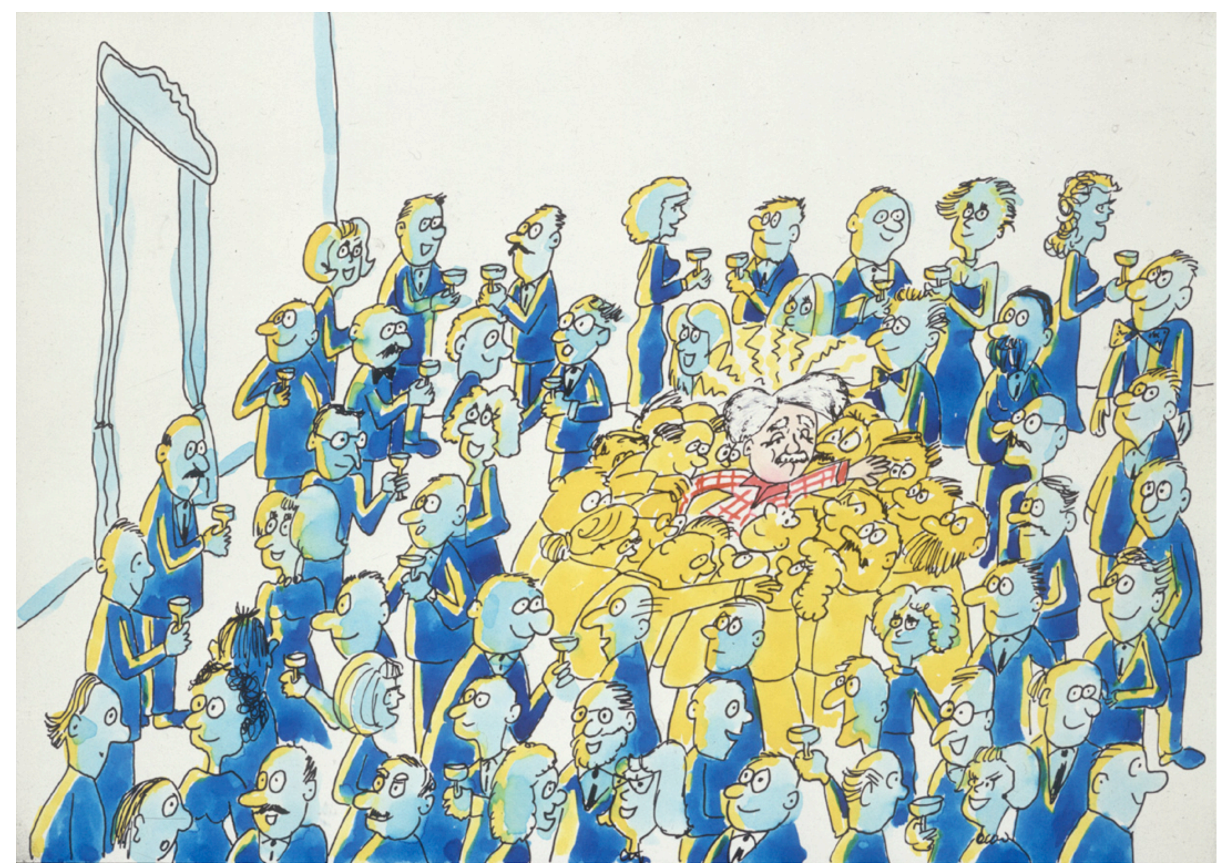
95% CL Upper Limit on the BR(H→invisible) for m_H=125 GeV: is <65% with <84% expected



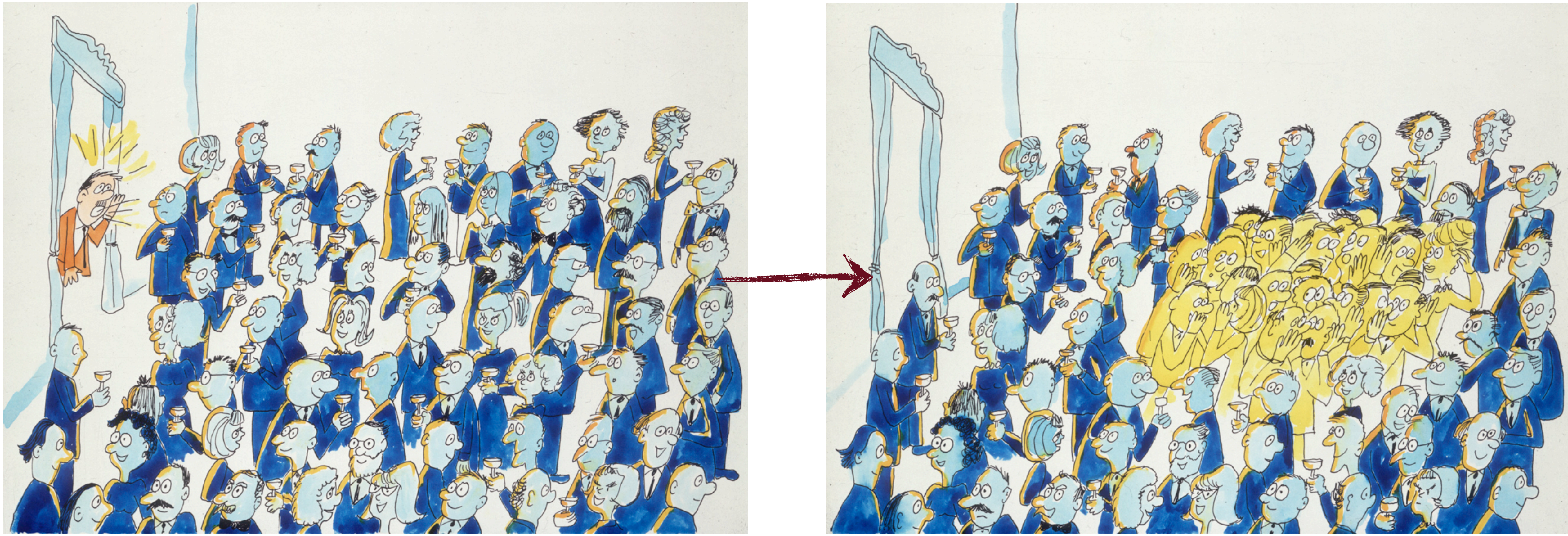


An analogy for the Higgs mechanism





An analogy for the Higgs mechanism



In the SM the electromagnetic and weak interactions are unified through the symmetry $SU(2)_L \otimes U(1)_Y$, where the carriers are massless.

This symmetry is spontaneously broken through the non-vanishing vacuum expectation value of the Higgs field.

Three of the four degrees of freedom of the Higgs field are becoming the longitudinal polarizations of the vector bosons, the fourth is the Higgs boson → excitation of the vacuum needs energy.

The fermions couple to the Higgs boson proportionally to their mass through Yukawa couplings.

The Higgs boson has been the holy grail of particle physics for quite the last three decades!

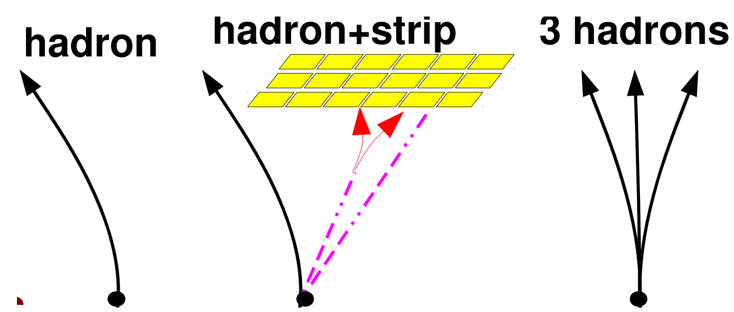
τ-leptons and b-jets

The τ-lepton is special!

Mass of 1.78 GeV and cτ = 87.1 μm, **the only lepton that decays in our detector**, in various ways...

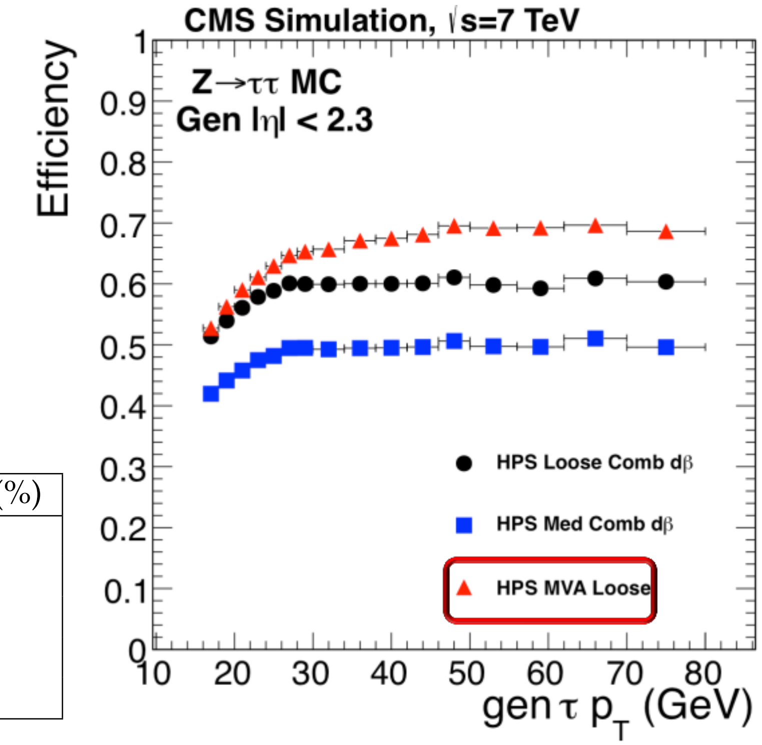
τ → lνν ~35%

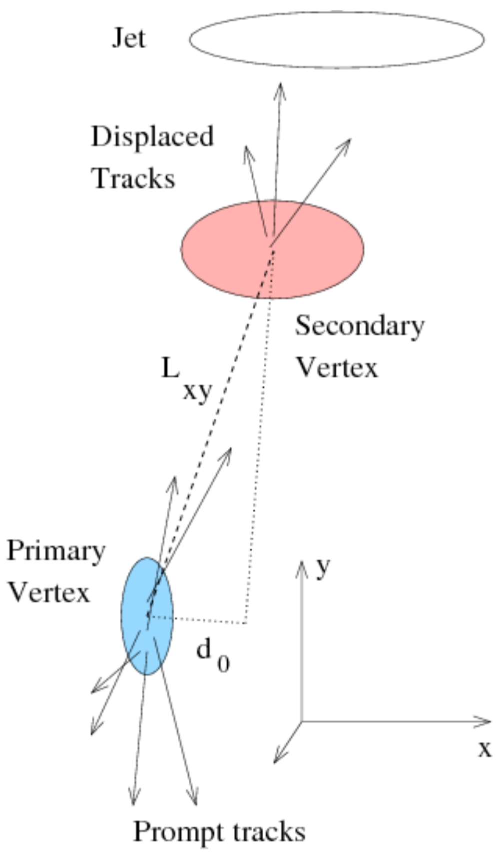
τ → hadrons ~ 65%



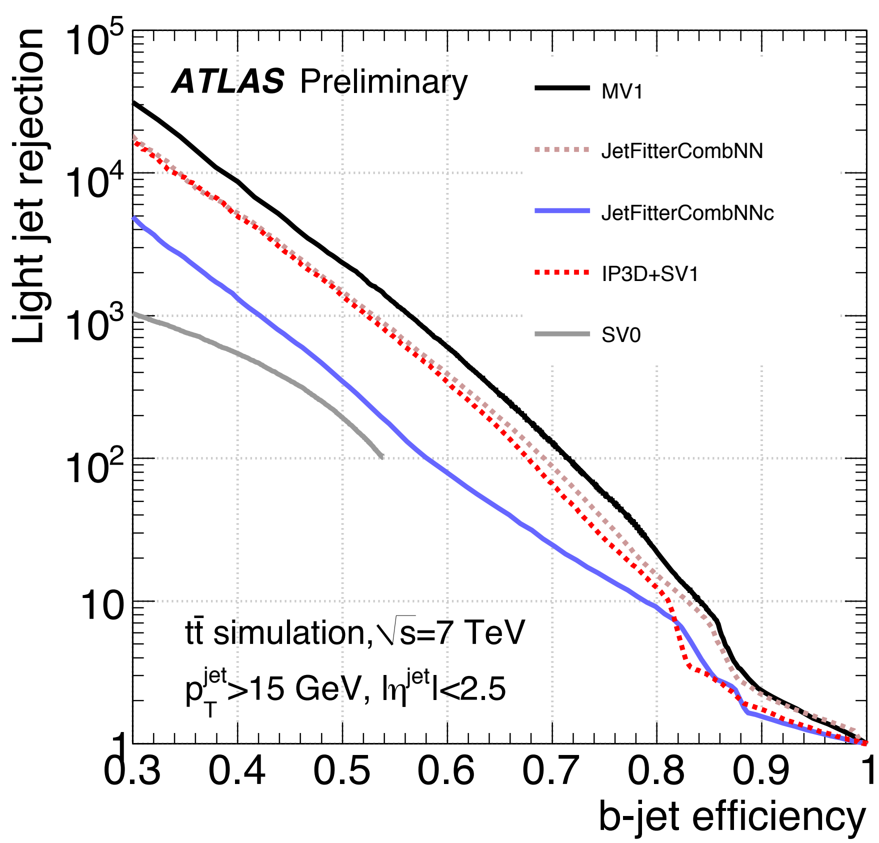
dominant hadronic decay modes

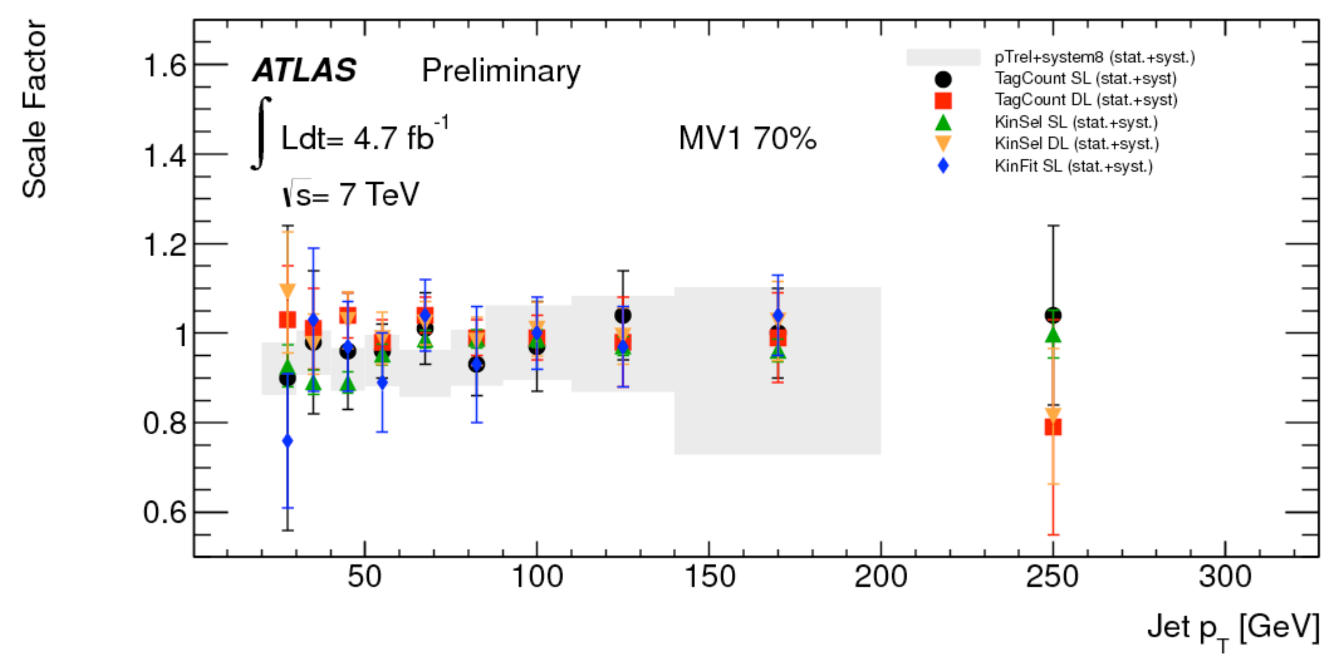
Decay mode	Resonance	Mass (MeV/c^2)	Branching fraction (%)
$\tau^- \to h^- \nu_\tau$			11.6%
$\tau^- \to h^- \pi^0 \nu_\tau$	ρ^-	770	26.0%
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	a_1^-	1200	9.5%
$\tau^- \to h^- h^+ h^- \nu_\tau$	a_1^-	1200	9.8%
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$			4.8%



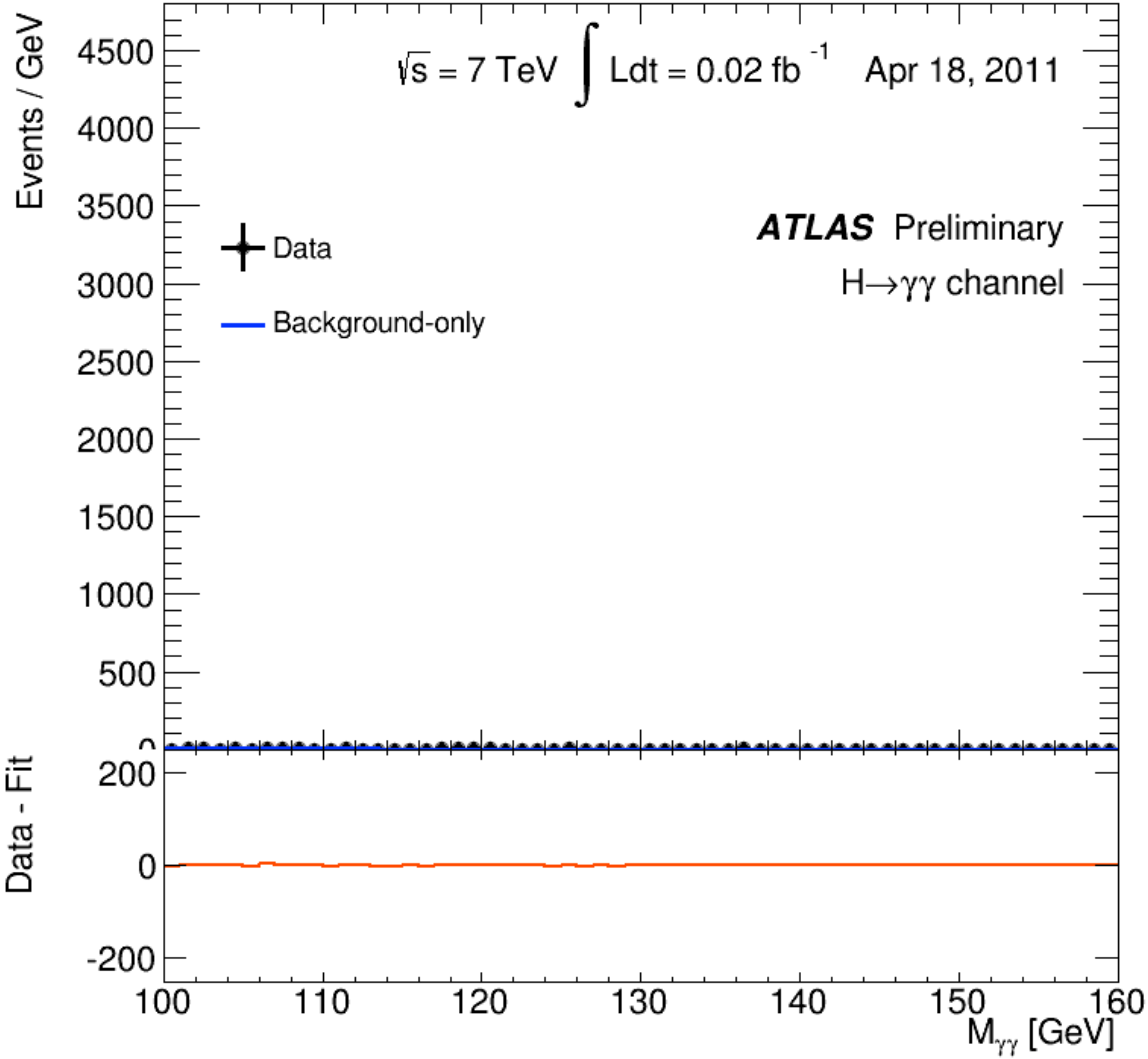


cτ = 492 μm



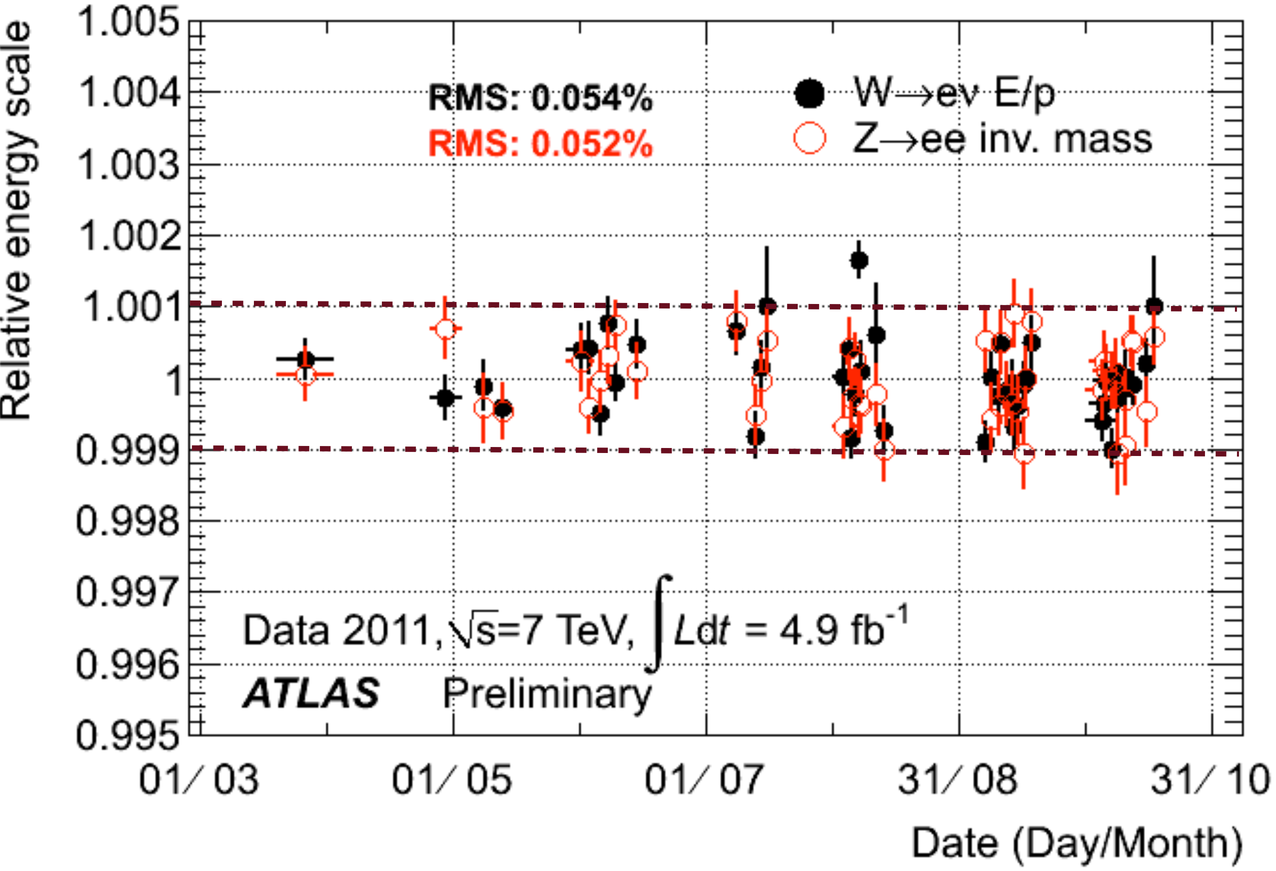


Text



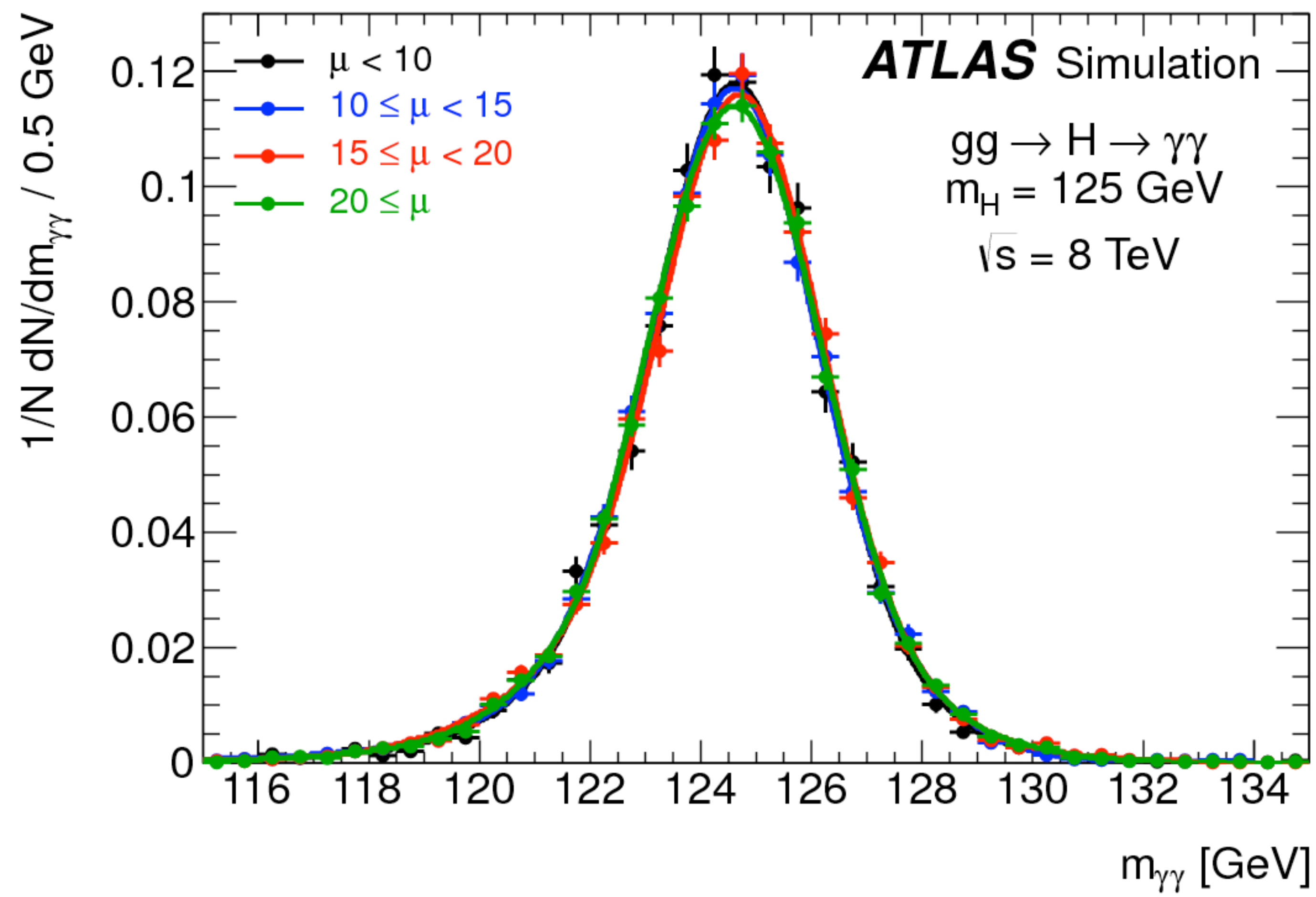
$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.02 fb^{-1} Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
Data - Fit
$M_{\gamma\gamma}$ [GeV]
4500
4000
3500
3000
2500
2000
1500
1000
500
0
200
-200
100
110
120
130
140
150
160

H→γγ: $m_{\gamma\gamma}$ resolution



$$m^2_{\gamma\gamma}=2E_1E_2(1-\cos\alpha)$$

- Excellent stability of the EM calorimeter response!
  - Studied with Z,J/ψ→ee and W→eν events
  - Energy scale at m_Z known to ~0.3%
  - Uniformity ~1% (2.5% for 1.37< |η|<1.8)
- Resolution of inclusive sample ~1.6 GeV
  - ~90% of events within ±2σ
- Mass resolution immune to pile-up



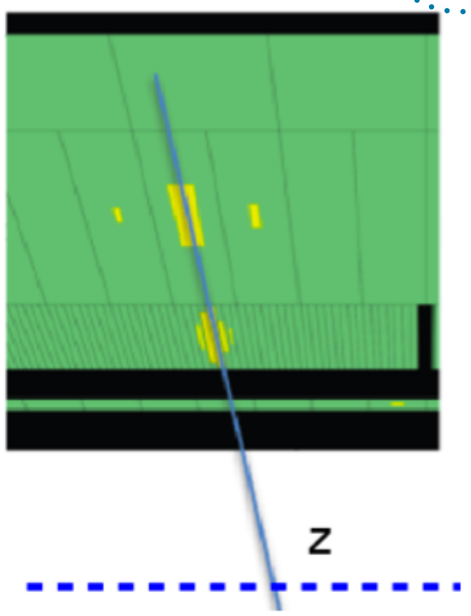
H→γγ: $m_{\gamma\gamma}$ resolution

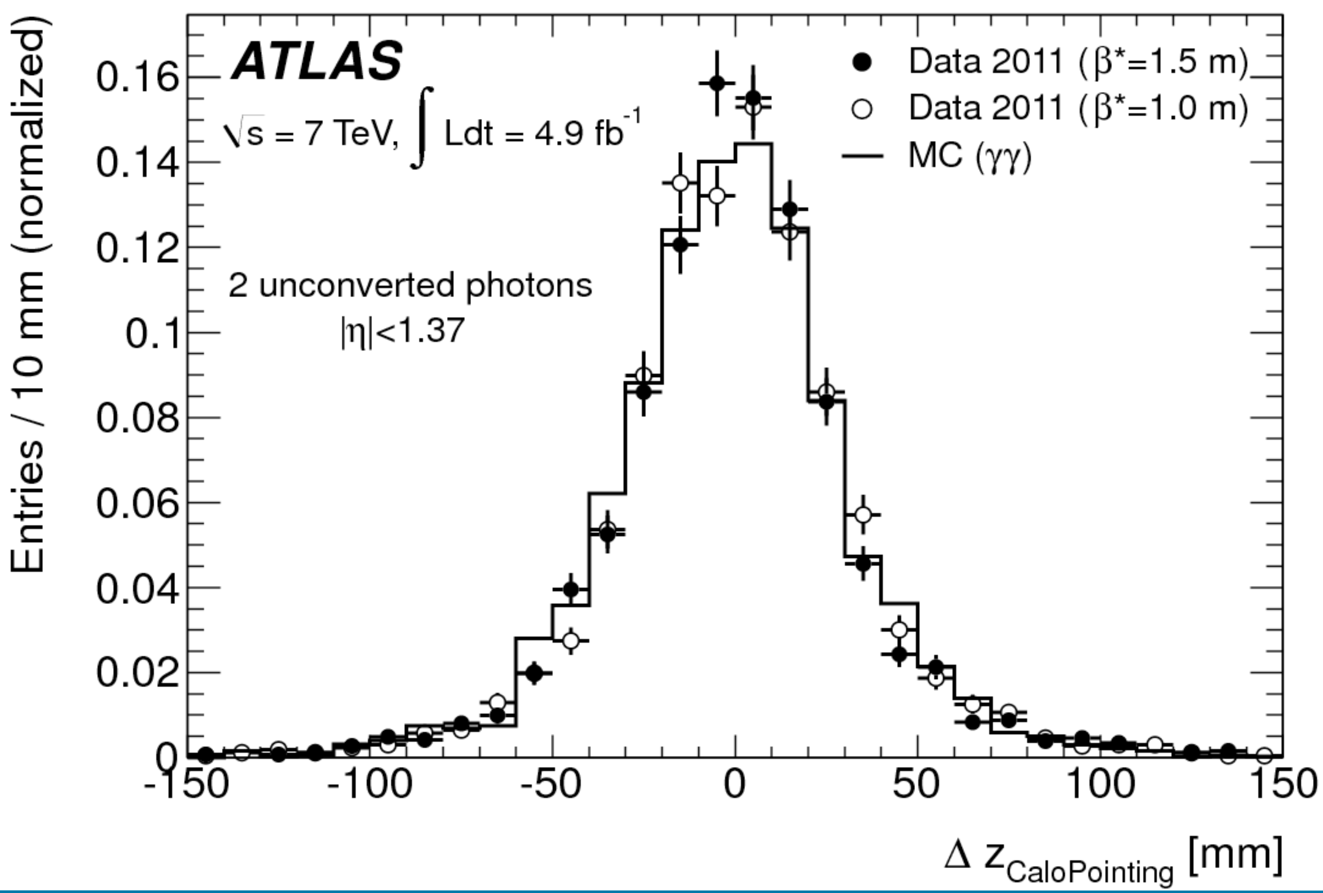
$$m^2_{\gamma\gamma}=2E_1E_2(1-\cos\alpha)$$

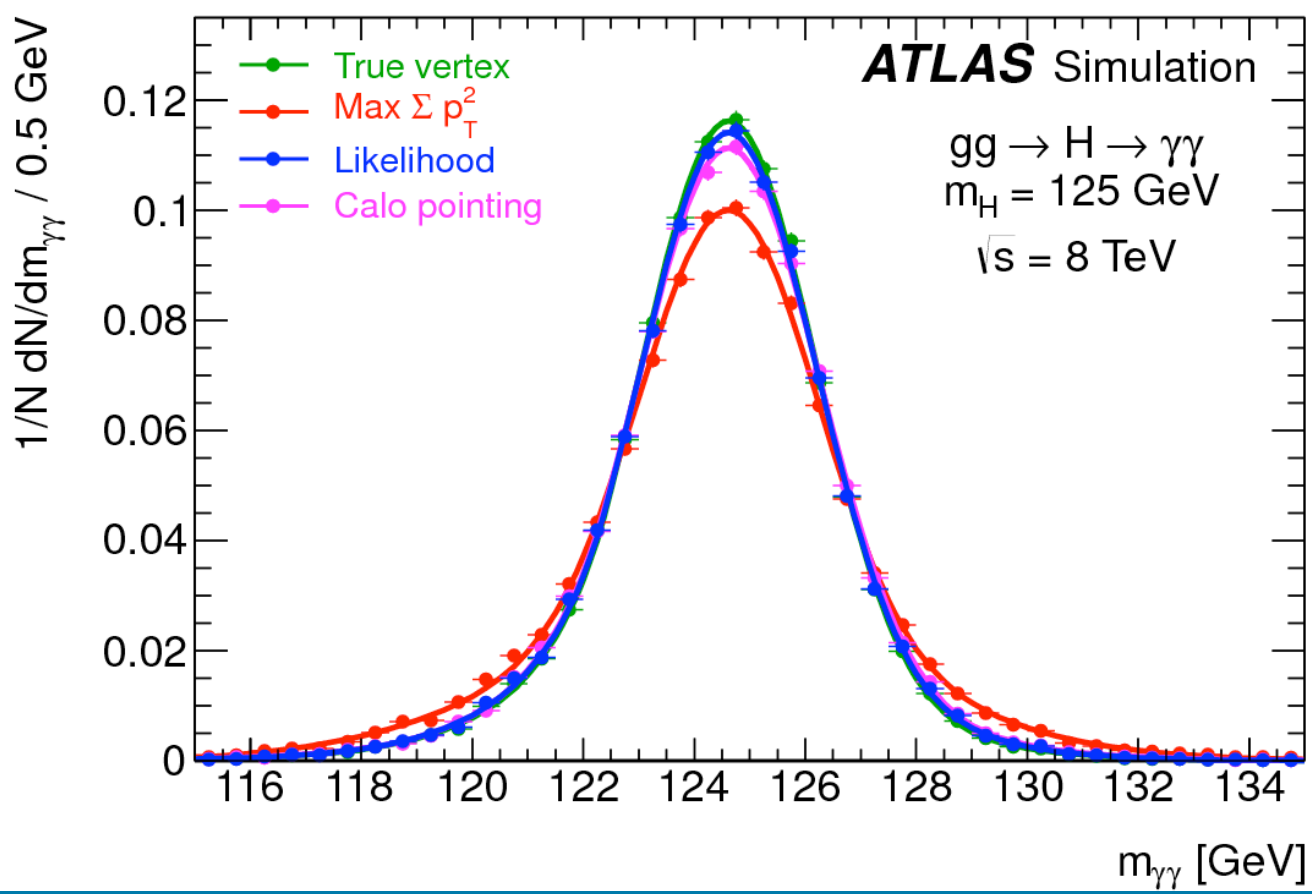
- LHC beam spot σ_z~5-6 cm and O(20) vertices → identify "primary" vertex challenging

Use the strengths of the detector!

- Build likelihood to identify the primary vertex using
  - longitudinal/lateral segmentation of EM calorimeter (photon pointing) → **σ_z~1.5 cm**
  - use beam-spot constraint/converted photon tracks
  - reconstructed vertex $\Sigma(pT)^2$
- pile-up robust
- contribution of angular term to $m_{\gamma\gamma}$ resolution negligible





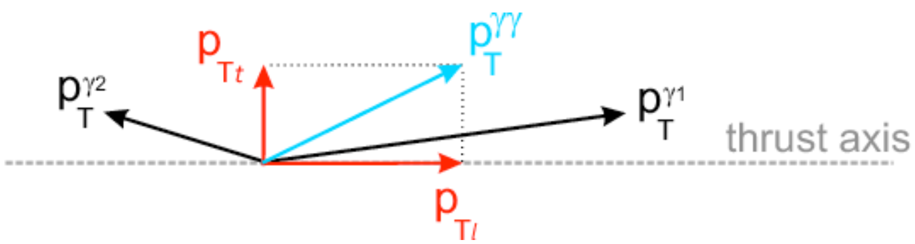


Statistics Treatment

Statistics Treatment:

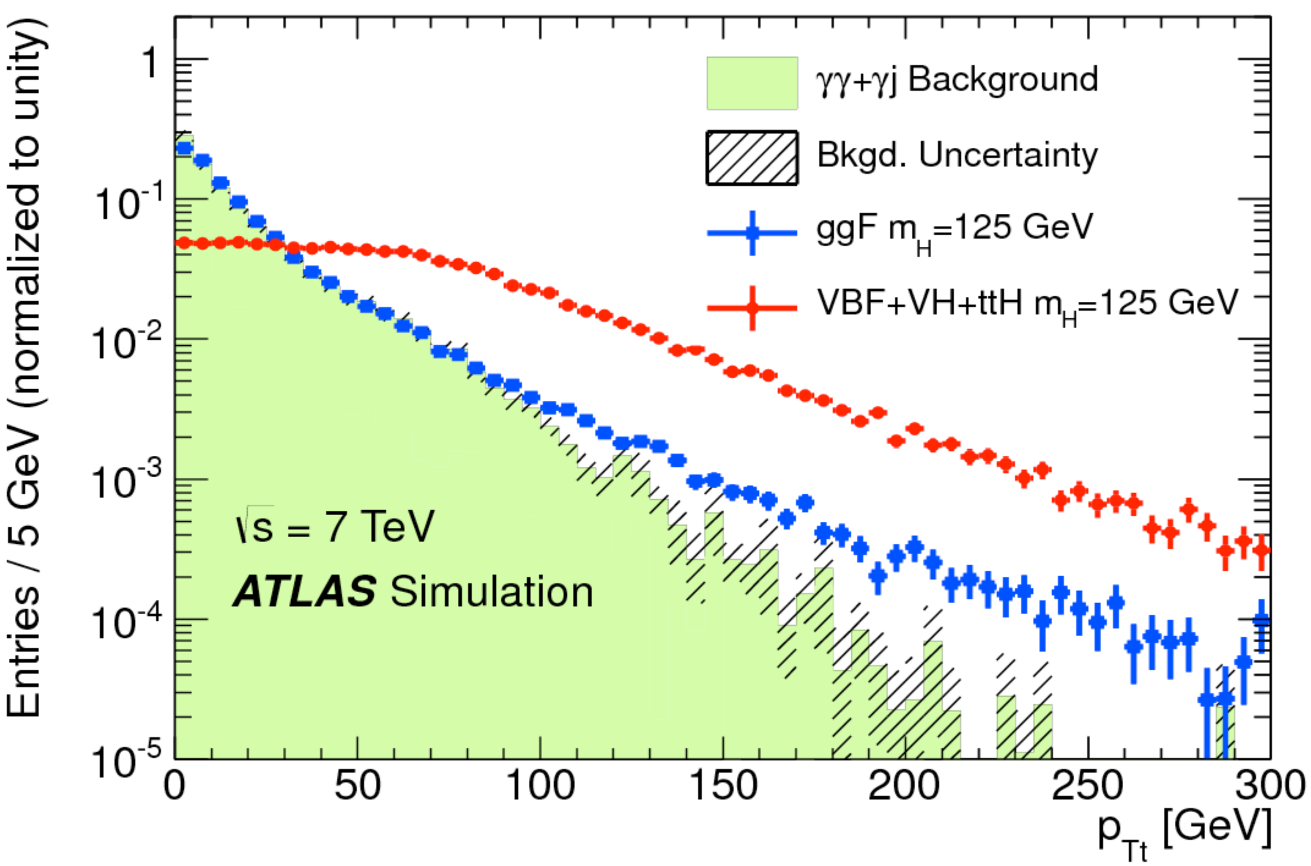
- profile likelihood ratio [Eur.Phys.J.C71:1554,2011]
  - → nuisance parameters for systematic uncertainties
- exclusion limits using CL_S [J. Phys. G 28 (2002) 2693-2704]

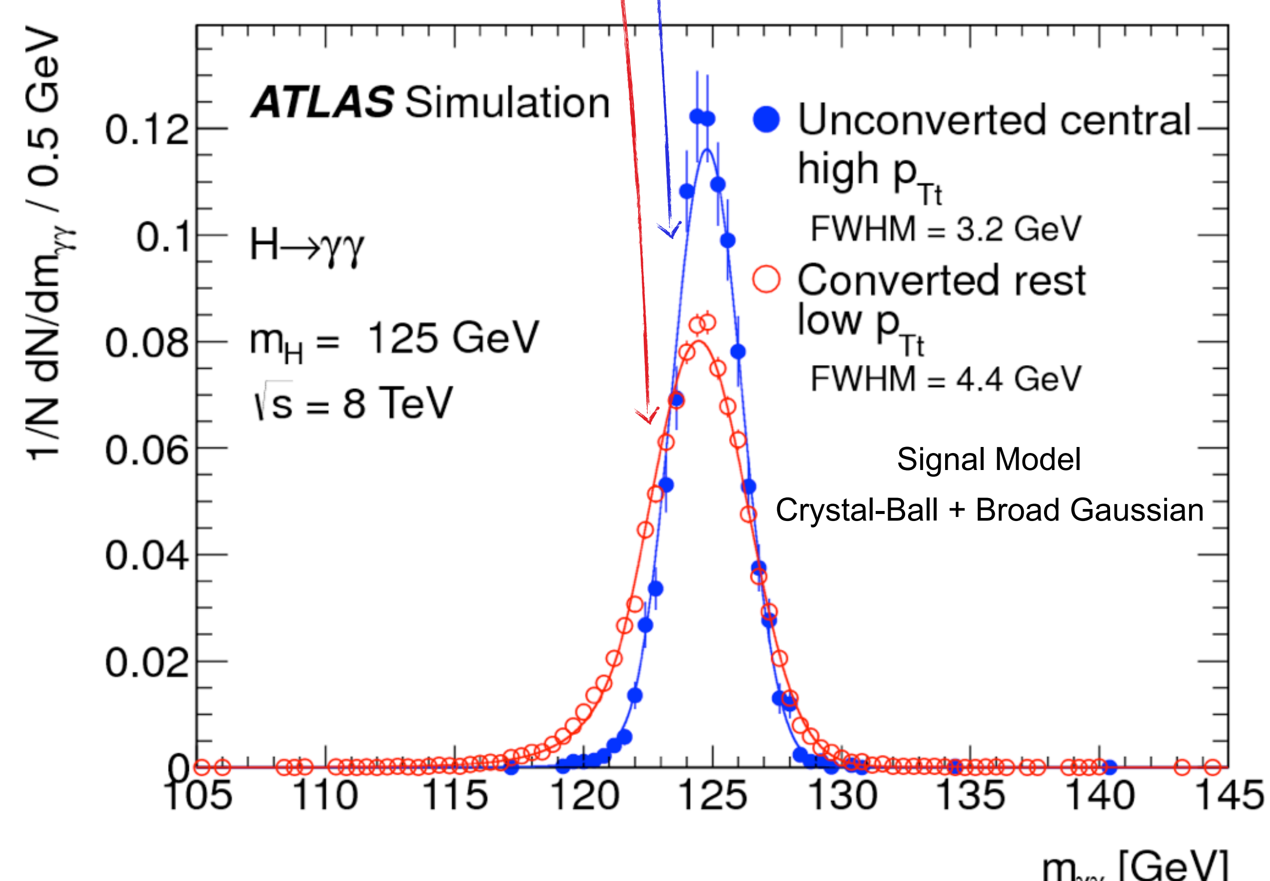
H→γγ: Event Categories



8 TeV (90% signal window)

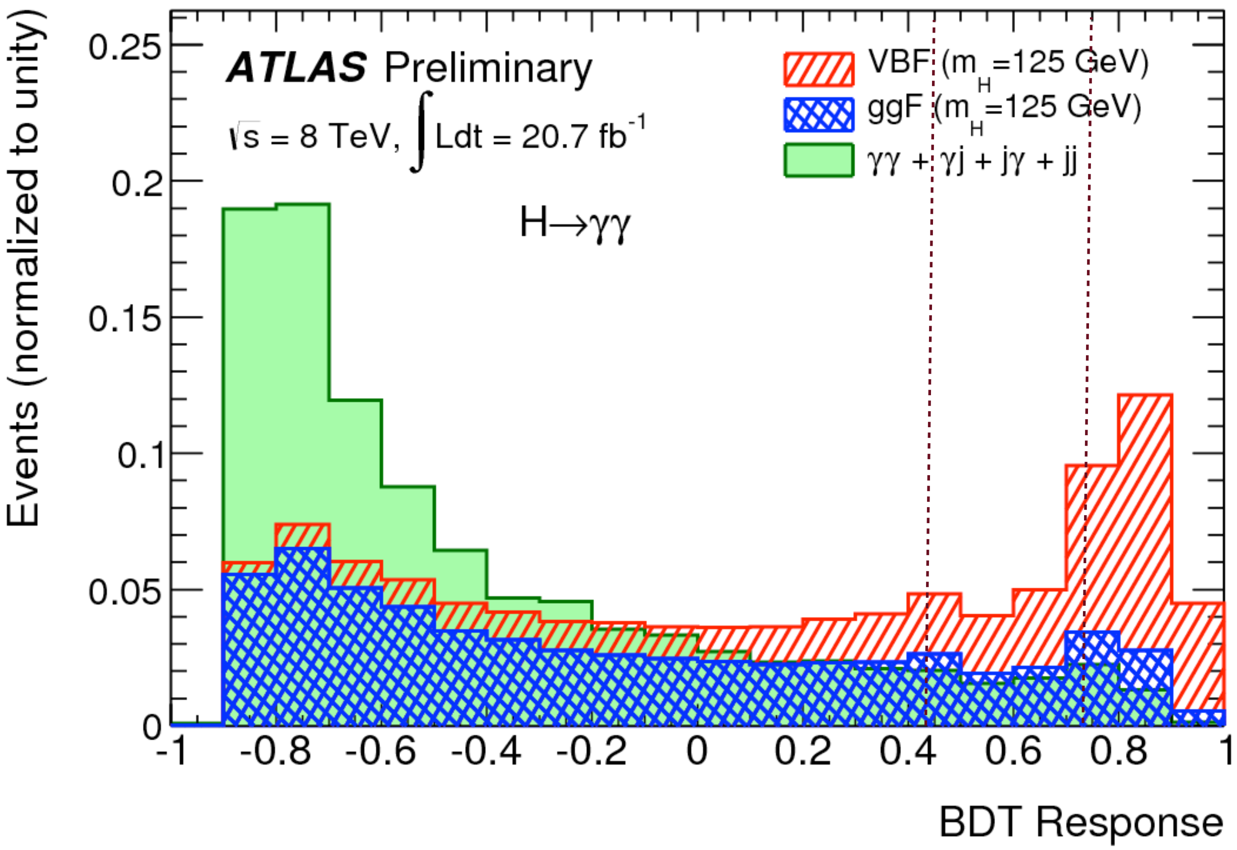
$\sqrt{s}$	8 TeV				
Category	σ_{CB}(GeV)	Observed	N_S	N_B	N_S/N_B
Unconv. central, low p_{Tt}	1.50	911	46.6	881	0.05
Unconv. central, high p_{Tt}	1.40	49	7.1	44	0.16
Unconv. rest, low p_{Tt}	1.74	4611	97.1	4347	0.02
Unconv. rest, high p_{Tt}	1.69	292	14.4	247	0.06
Conv. central, low p_{Tt}	1.68	722	29.8	687	0.04
Conv. central, high p_{Tt}	1.54	39	4.6	31	0.15
Conv. rest, low p_{Tt}	2.01	4865	88.0	4657	0.02
Conv. rest, high p_{Tt}	1.87	276	12.9	266	0.05
Conv. transition	2.52	2554	36.1	2499	0.01
Loose High-mass two-jet	1.71	40	4.8	28	0.17
Tight High-mass two-jet	1.64	24	7.3	13	0.57
Low-mass two-jet	1.62	21	3.0	21	0.14
E_T^{miss} significance	1.74	8	1.1	4	0.24
One-lepton	1.75	19	2.6	12	0.20
Inclusive	1.77	14025	355.5	13280	0.03

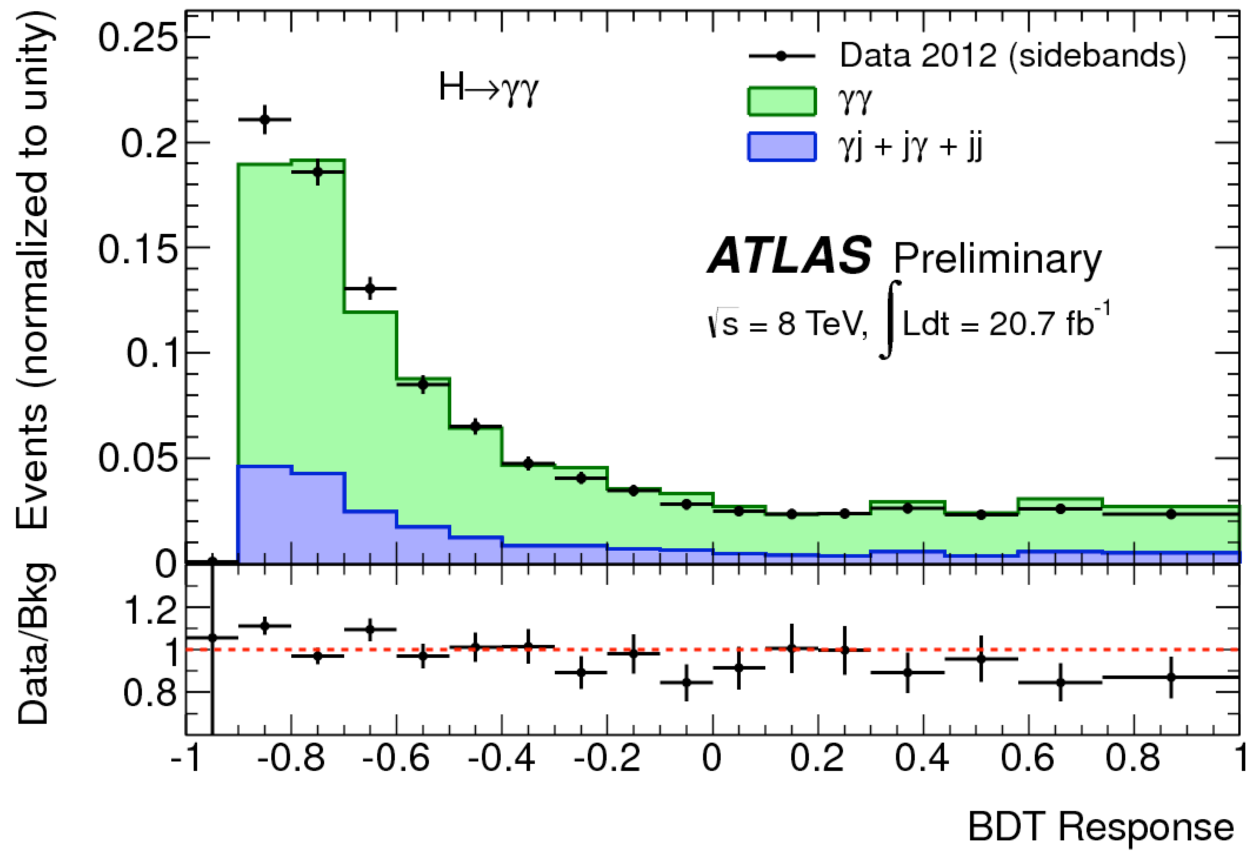




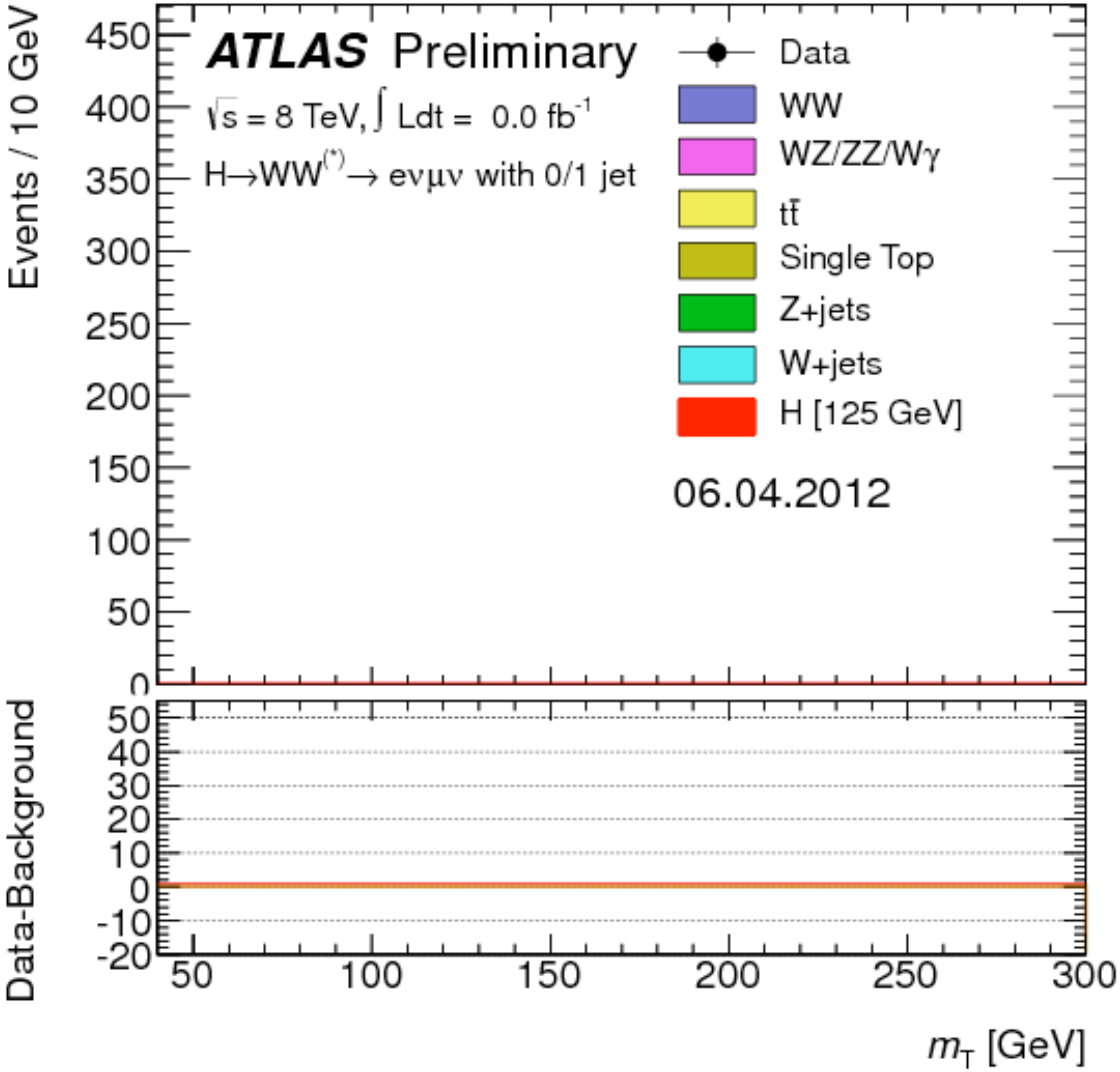
H→γγ: BDT Response

BDT: m_{jj}, η_{j1}, η_{j2}, $\Delta\eta_{jj}$, p_{Tt}, $\Delta\varphi_{\gamma\gamma;jj}$, $\eta^{*}=\eta_{\gamma\gamma}-(\eta_{j1}+\eta_{j2})/2$ $\Delta R\min_{\gamma j}$

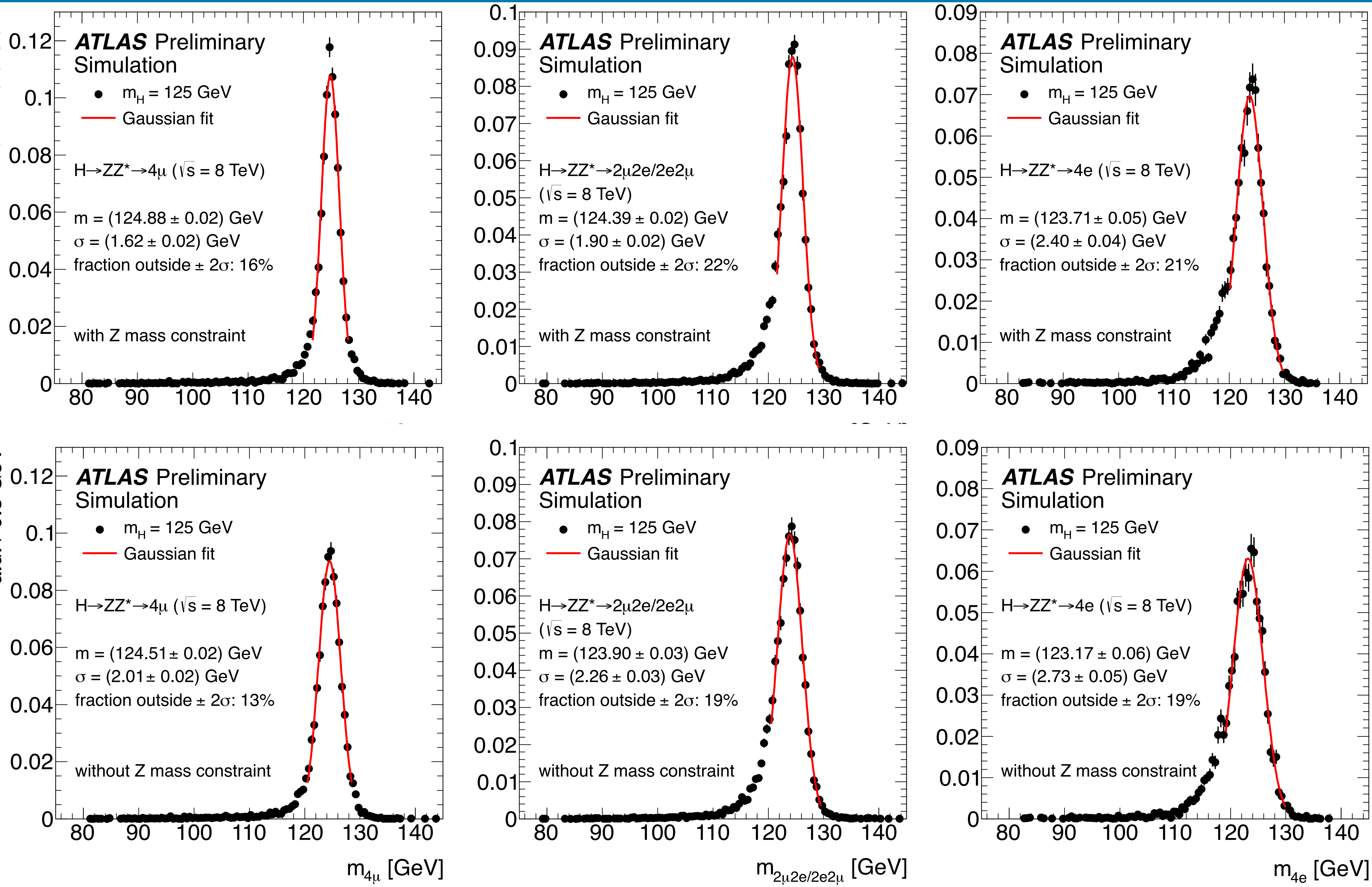




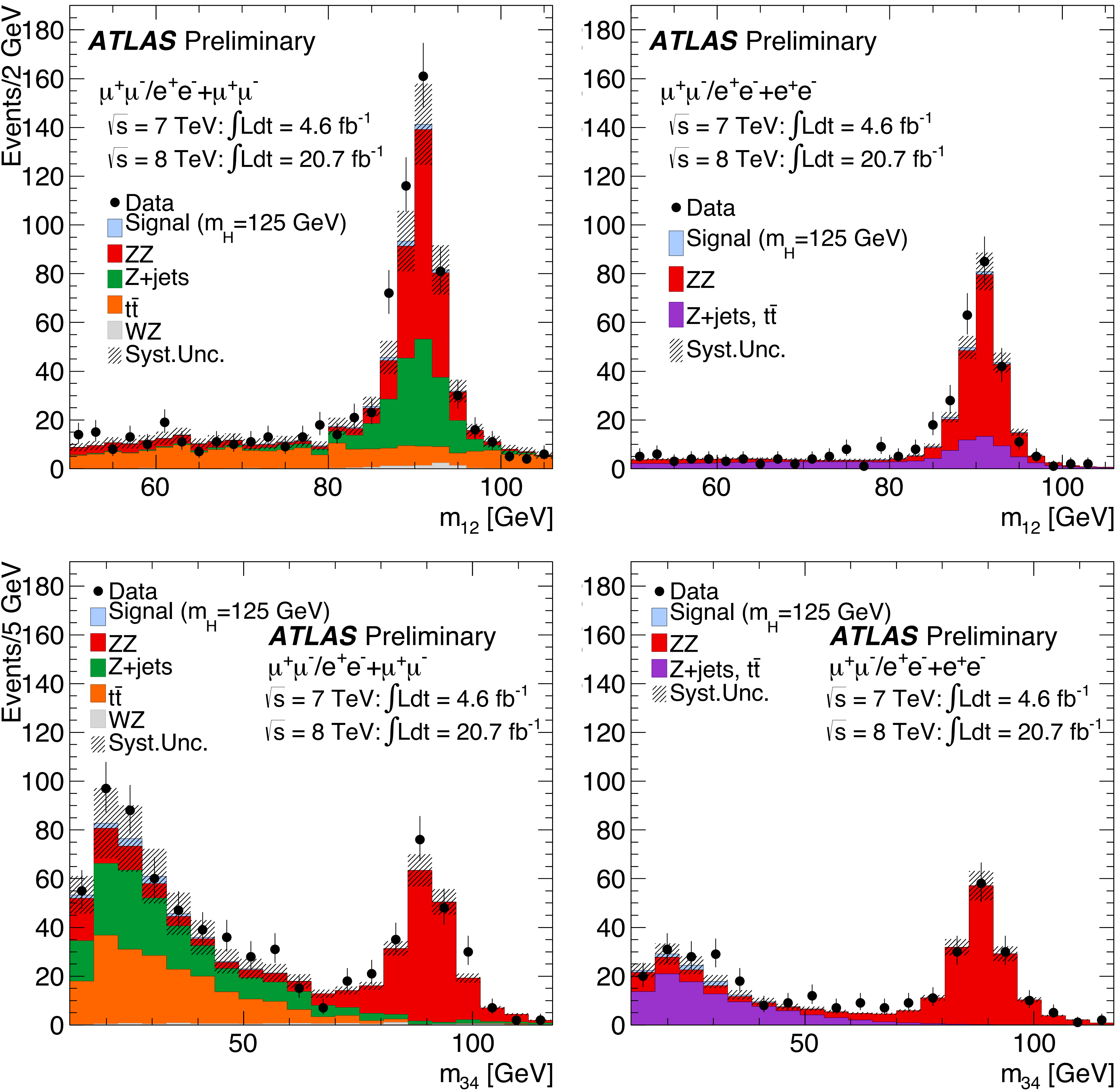
Text


ATLAS Preliminary
$\sqrt{s}$ = 8 TeV, $\int$ Ldt = 0.0 fb^{-1}
H→WW$^{(*)}$→ eνμν with 0/1 jet
Data
WW
WZ/ZZ/Wγ
$t\bar{t}$
Single Top
Z+jets
W+jets
H [125 GeV]
06.04.2012
Events / 10 GeV
Data-Background
m_T [GeV]
0
50
100
150
200
250
300
350
400
450
-20
-10
0
10
20
30
40
50
50
100
150
200
250
300

H→ZZ(*)→4l: Mass resolution



H→ZZ(*)→4l Background Estimates: Control Regions



Background-dominated Control Region

→ Remove isolation/impact parameter requirements on sub-leading di-lepton

→ Normalize to data-driven estimates

→ Normalization/shape of reducible backgrounds well described

H→WW(*)→lνlν: Event Selection

Table 2: Selection listing for 8 TeV data. The criteria specific to $e\mu + \mu e$ and $ee + \mu\mu$ are noted as such; otherwise, they apply to both. Pre-selection applies to all N_{jet} modes. The rapidity gap is the y range spanned by the two leading jets. The $m_{\ell\ell}$ split is at 30 GeV. The modifications for the 7 TeV analysis are given in Section 6 and are not listed here. Energies, masses, and momenta are in units of GeV.

Category	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 1$	$N_{\text{jet}} \geq 2$
Pre-selection	Two isolated leptons ($\ell = e, \mu$) with opposite charge Leptons with $p_{\text{T}}^{\text{lead}} > 25$ and $p_{\text{T}}^{\text{sublead}} > 15$ $e\mu + \mu e$: $m_{\ell\ell} > 10$ $ee + \mu\mu$: $m_{\ell\ell} > 12$, $\lvert m_{\ell\ell} - m_Z \rvert > 15$		
Missing transverse momentum and hadronic recoil	$e\mu + \mu e$: $E_{\text{T,rel}}^{\text{miss}} > 25$ $ee + \mu\mu$: $E_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $p_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $f_{\text{recoil}} < 0.05$	$e\mu + \mu e$: $E_{\text{T,rel}}^{\text{miss}} > 25$ $ee + \mu\mu$: $E_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $p_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $f_{\text{recoil}} < 0.2$	$e\mu + \mu e$: $E_{\text{T}}^{\text{miss}} > 20$ $ee + \mu\mu$: $E_{\text{T}}^{\text{miss}} > 45$ $ee + \mu\mu$: $E_{\text{T,STVF}}^{\text{miss}} > 35$ -
General selection	- $\lvert \Delta\phi_{\ell\ell,MET} \rvert > \pi/2$ $p_{\text{T}}^{\ell\ell} > 30$	$N_{b\text{-jet}} = 0$ - $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto	$N_{b\text{-jet}} = 0$ $p_{\text{T}}^{\text{tot}} < 45$ $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto
VBF topology	- - - -	- - - -	$m_{jj} > 500$ $\lvert \Delta y_{jj} \rvert > 2.8$ No jets ($p_{\text{T}} > 20$) in rapidity gap Require both ℓ in rapidity gap
$H \to WW^{(*)} \to \ell\nu\ell\nu$ topology	$m_{\ell\ell} < 50$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_{T}	$m_{\ell\ell} < 50$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_{T}	$m_{\ell\ell} < 60$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ - Fit m_{T}

H→bb: Event Selection

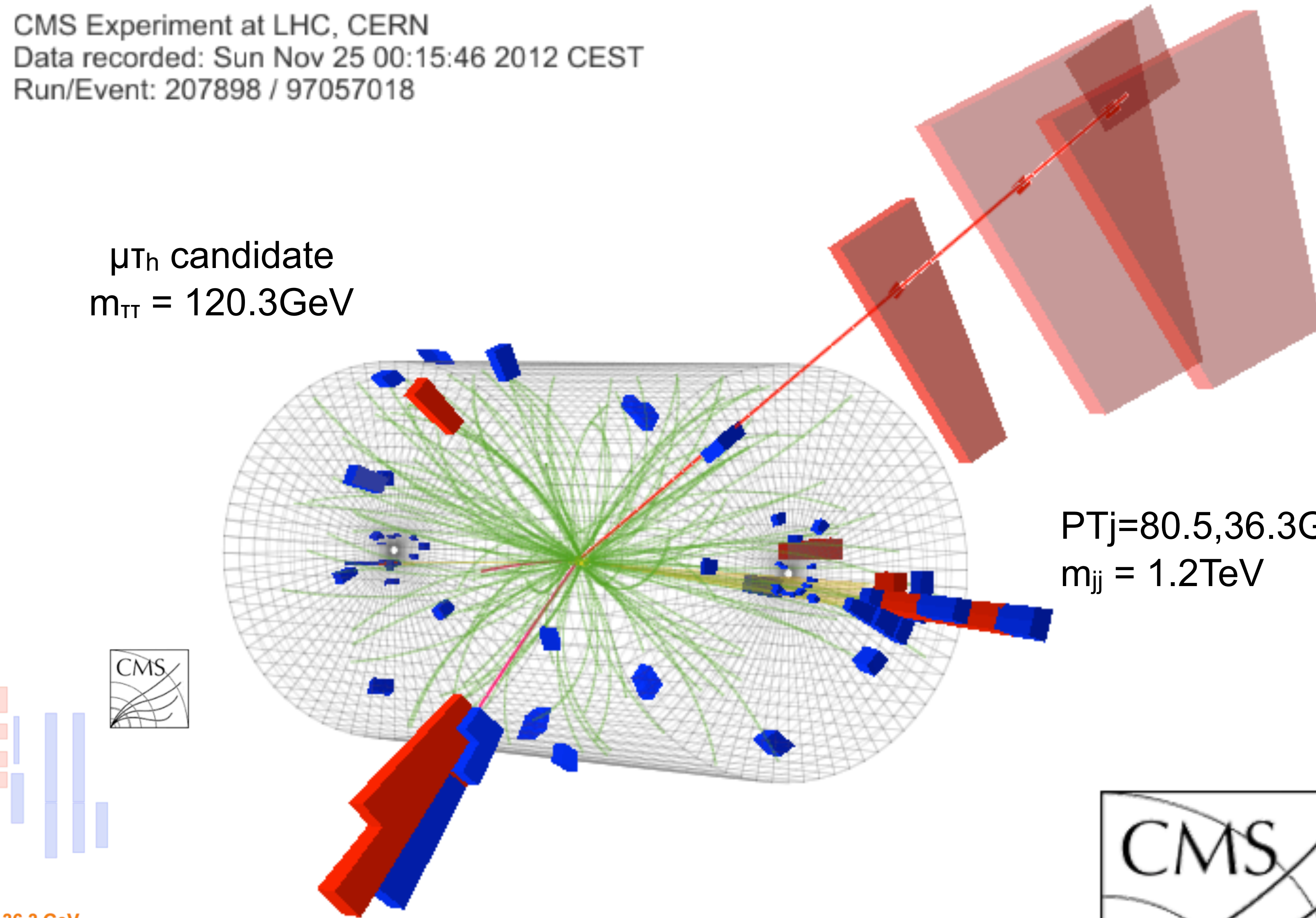
Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV + ≤ 1 extra jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV + 0 extra jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV -
Missing E_T	$E_T^{miss} > 120$ GeV $p_T^{miss} > 30$ GeV $\Delta\phi(E_T^{miss}, p_T^{miss}) < \pi/2$ $\mathrm{Min}[\Delta\phi(E_T^{miss}, \mathrm{jet})] > 1.5$ $\Delta\phi(E_T^{miss}, b\bar{b}) > 2.8$	-	$E_T^{miss} < 60$ GeV
Vector Boson	-	$m_T^W < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

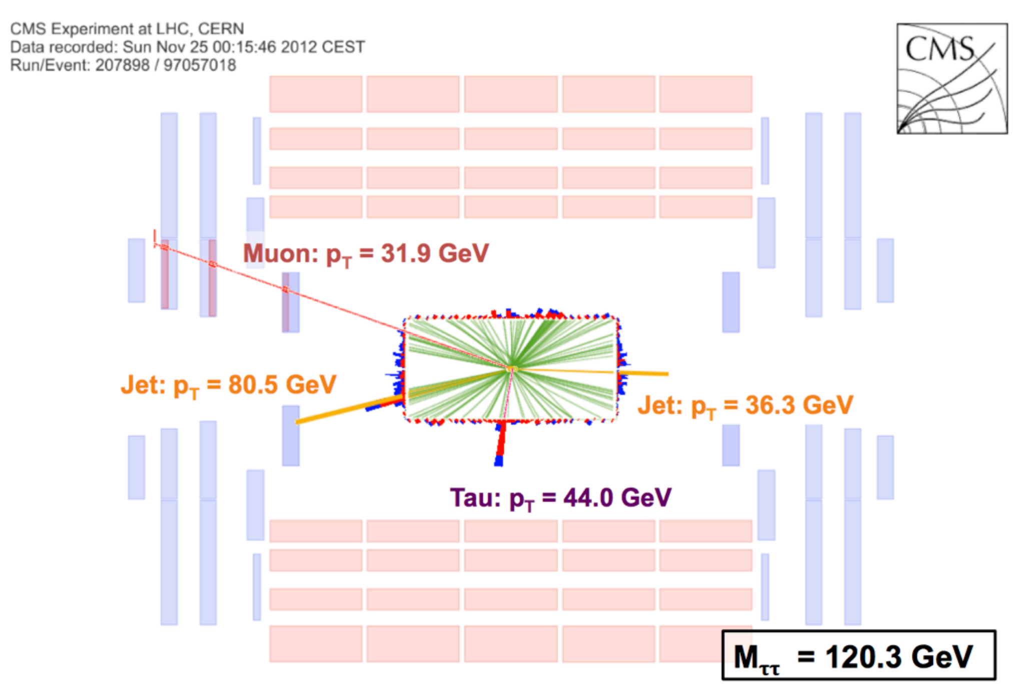
0-lepton channel			
E_T^{miss} (GeV)	120-160	160-200	>200
$\Delta R(b, \bar{b})$	0.7-1.9	0.7-1.7	<1.5

1-lepton channel					
p_T^W (GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b, \bar{b})$	>0.7			0.7-1.6	<1.4
E_T^{miss} (GeV)	> 25				> 50
m_T^W (GeV)	> 40			-	

2-lepton channel					
p_T^Z(GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b, \bar{b})$	>0.7			0.7-1.8	<1.6

H→ττ: Event Display VBF-like candidate





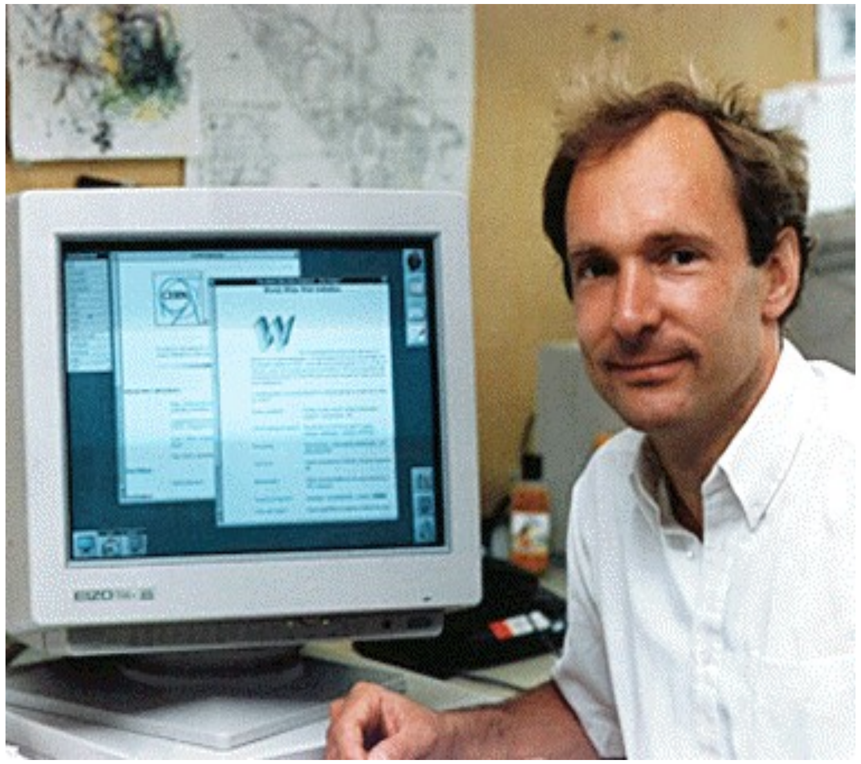
A small deviation: The World Wide Web

The **World Wide Web**, invented in 1989 and implemented in 1990, by Tim Berners-Lee, was an effort to facilitate the communication of physicists.

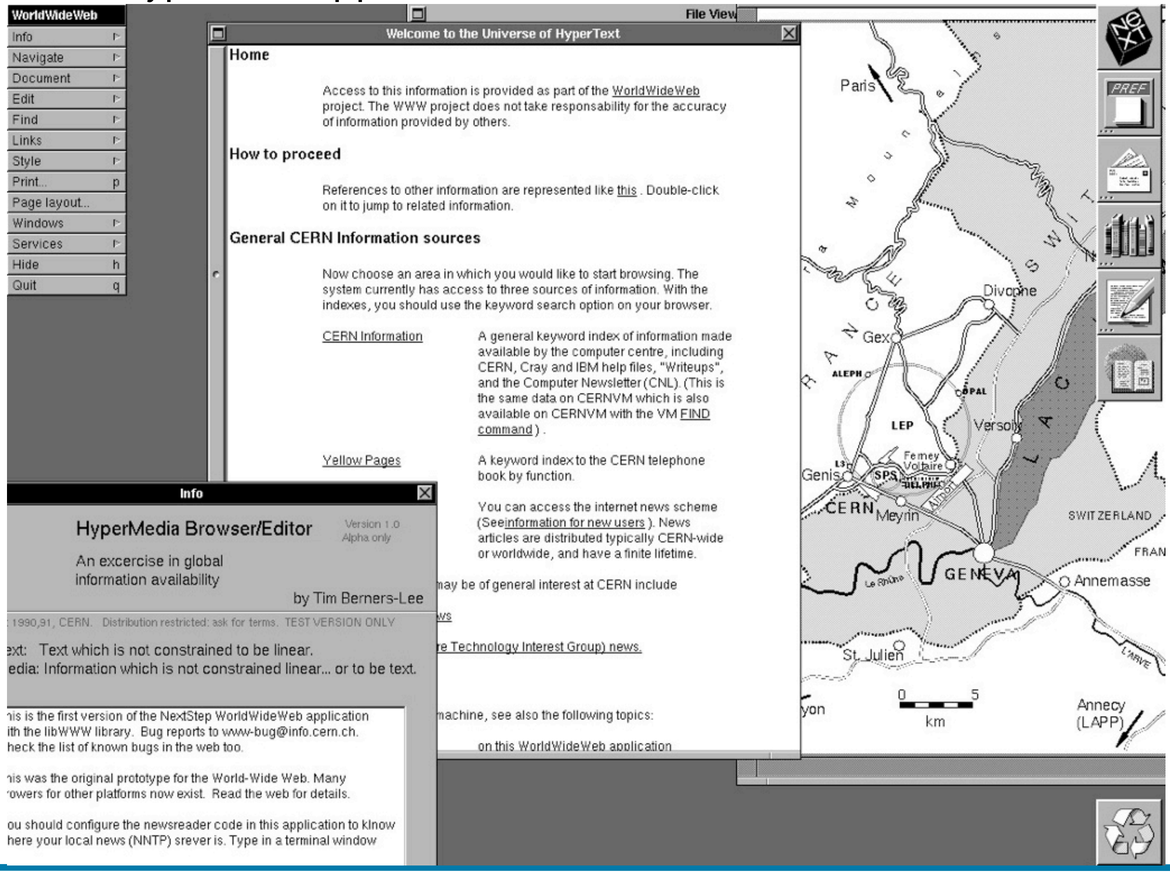
Today, as we all know, it's way beyond that!

The first web-page to come on-line:

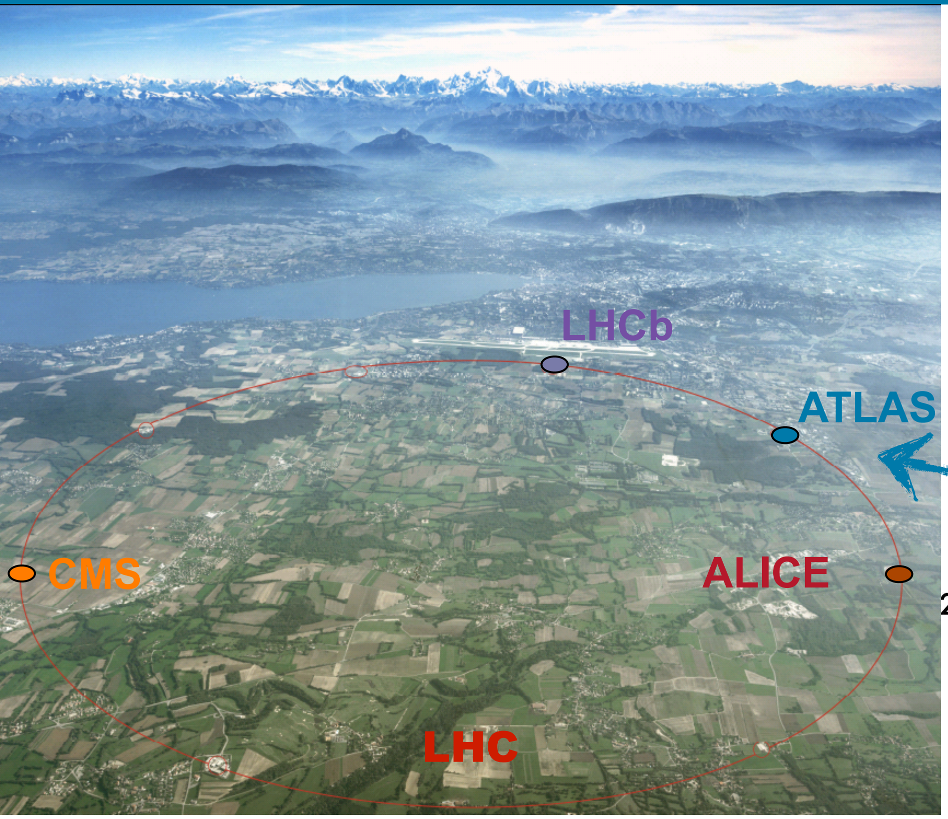
http://info.cern.ch/

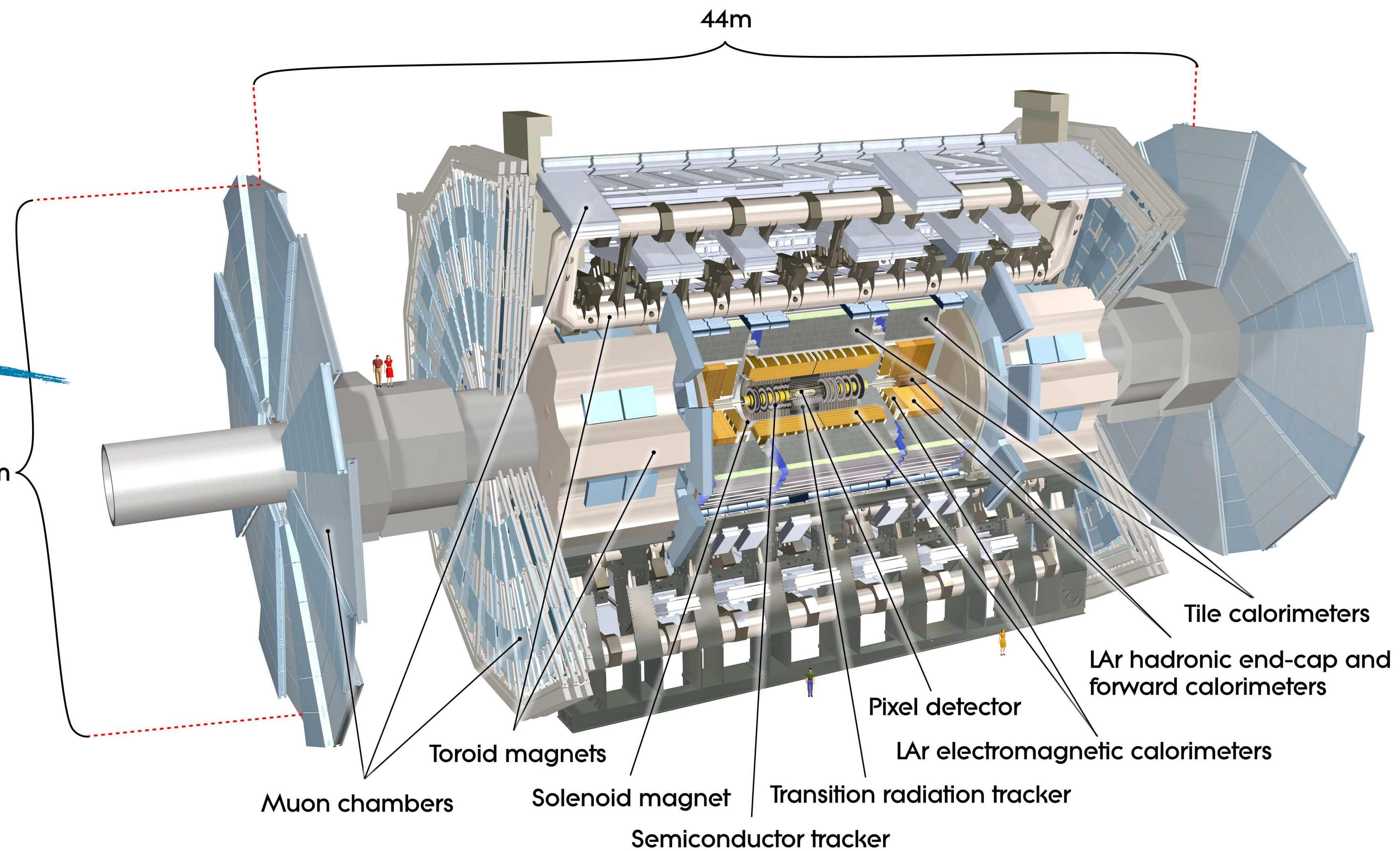


A screen shot on the NeXT screen, the computer of Tim Berners-Lee with HyperText application used to browse the WWW in 1990.



A Toroidal LHC ApparatuS

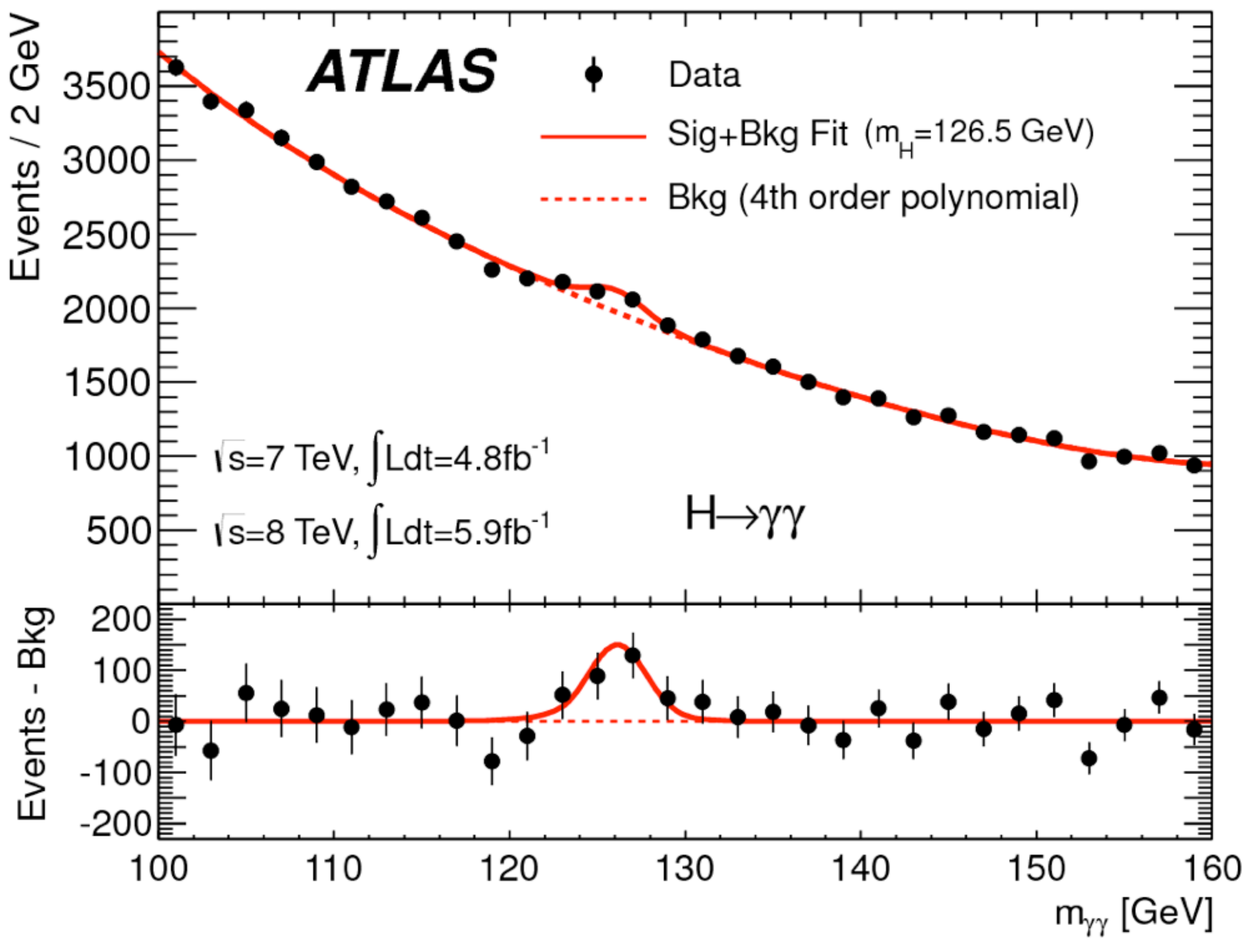




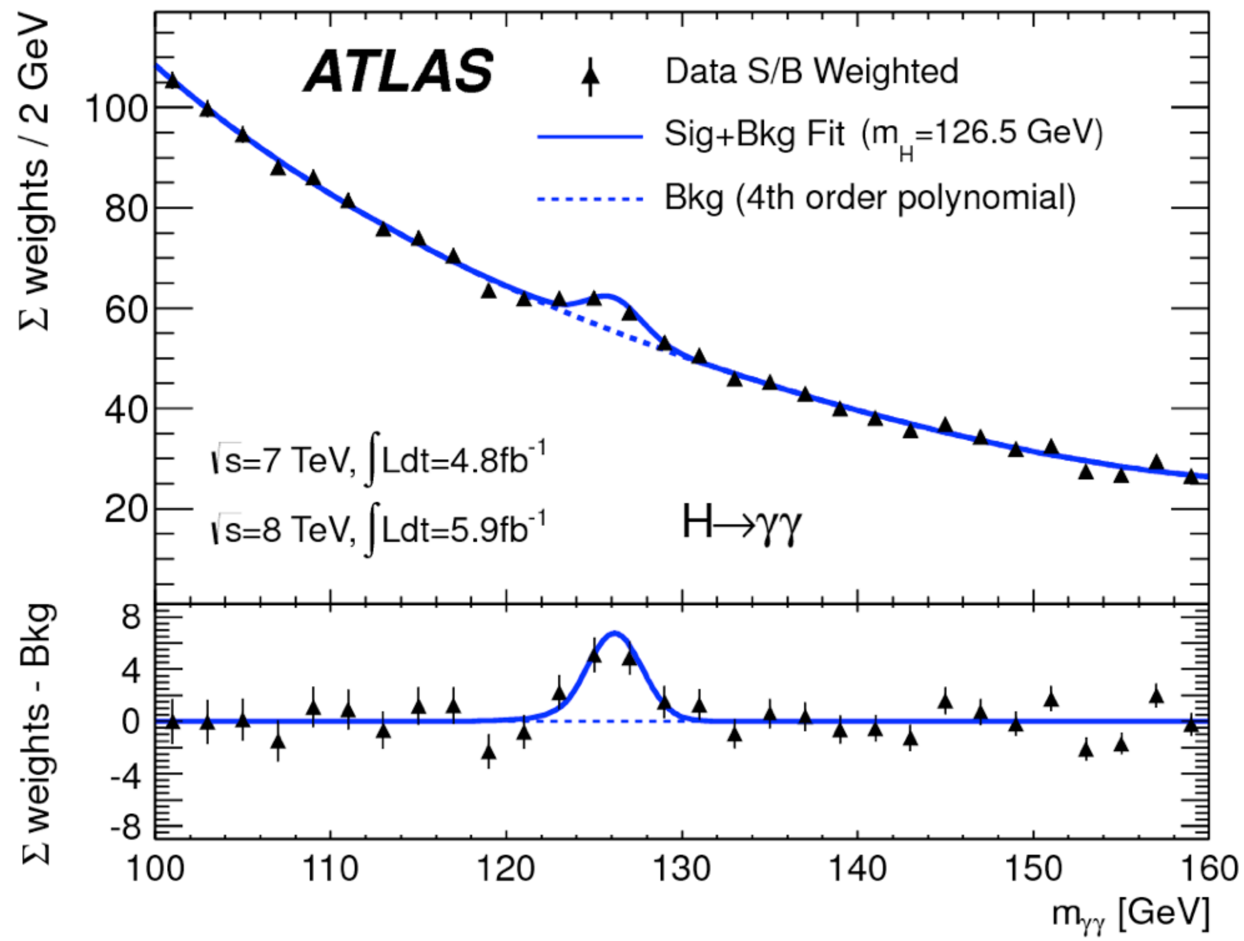
⇒ General purpose detector designed for the harsh LHC environment

	ATLAS
Magnets	2T solenoid, 3 air-core toroids
Tracking	silicon + transition radiation tracker
EM Calorimetry	sampling LAr technology
Hadron Calorimetry	plastic scintillator (barrel) LAr technology (endcap)
Muon	independent system with trigger capabilities

H→γγ

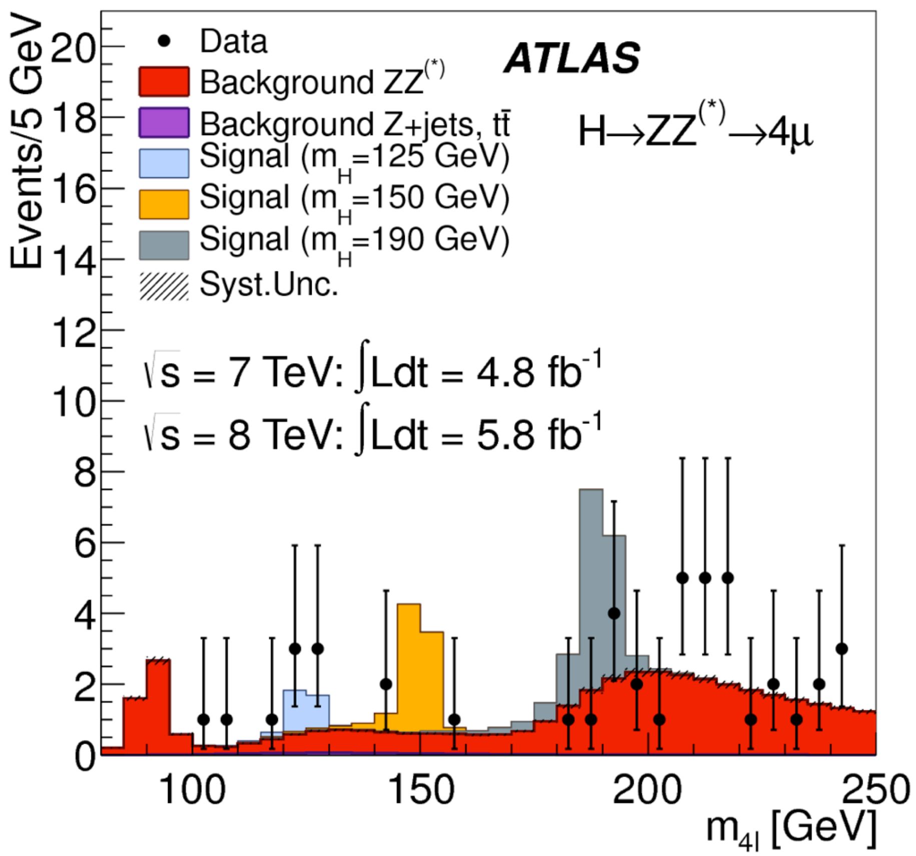


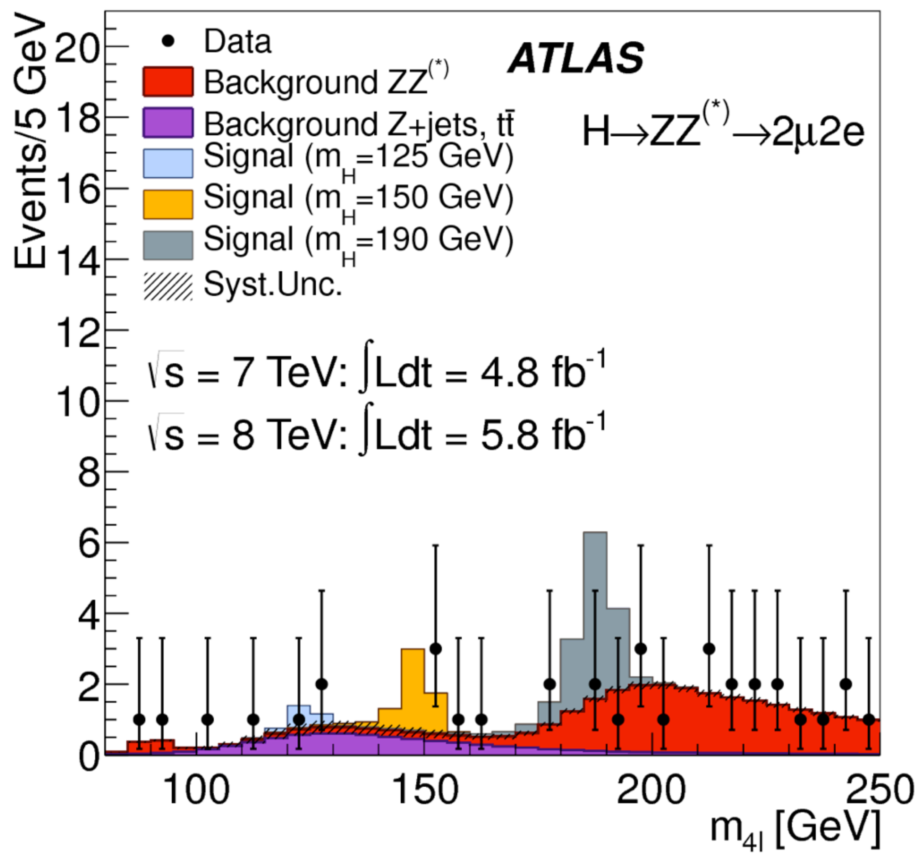
ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
$\sqrt{s}$=7 TeV, $\int Ldt$=4.8fb^{-1}
$\sqrt{s}$=8 TeV, $\int Ldt$=5.9fb^{-1}
H→γγ
Events / 2 GeV
Events - Bkg
$m_{\gamma\gamma}$ [GeV]

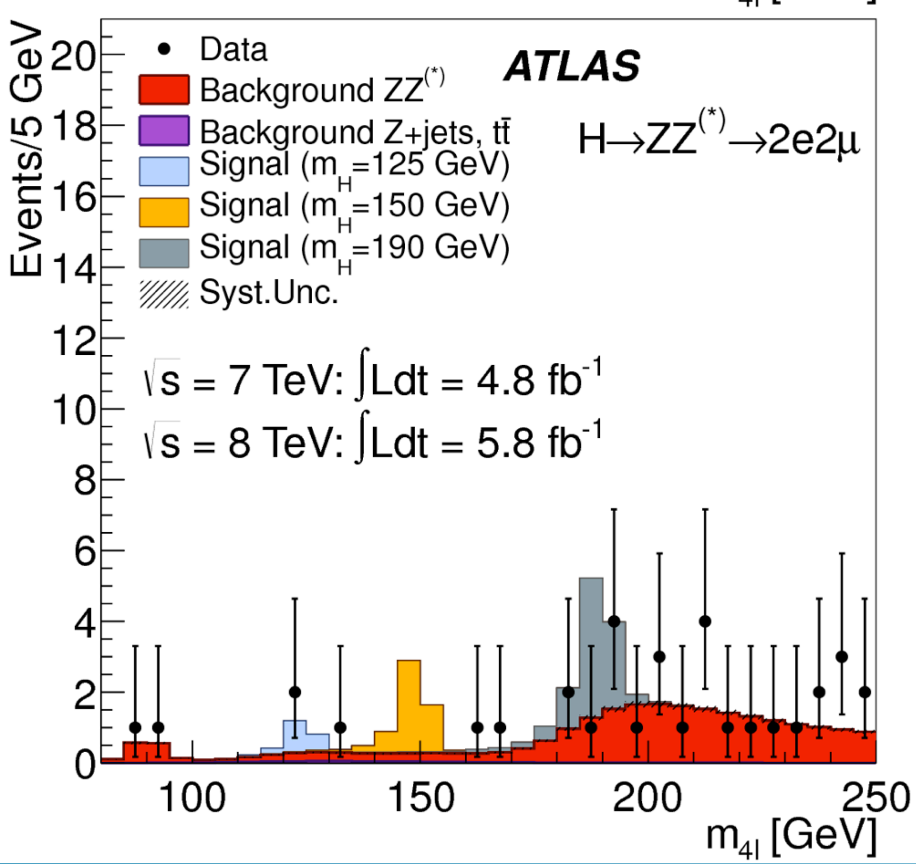


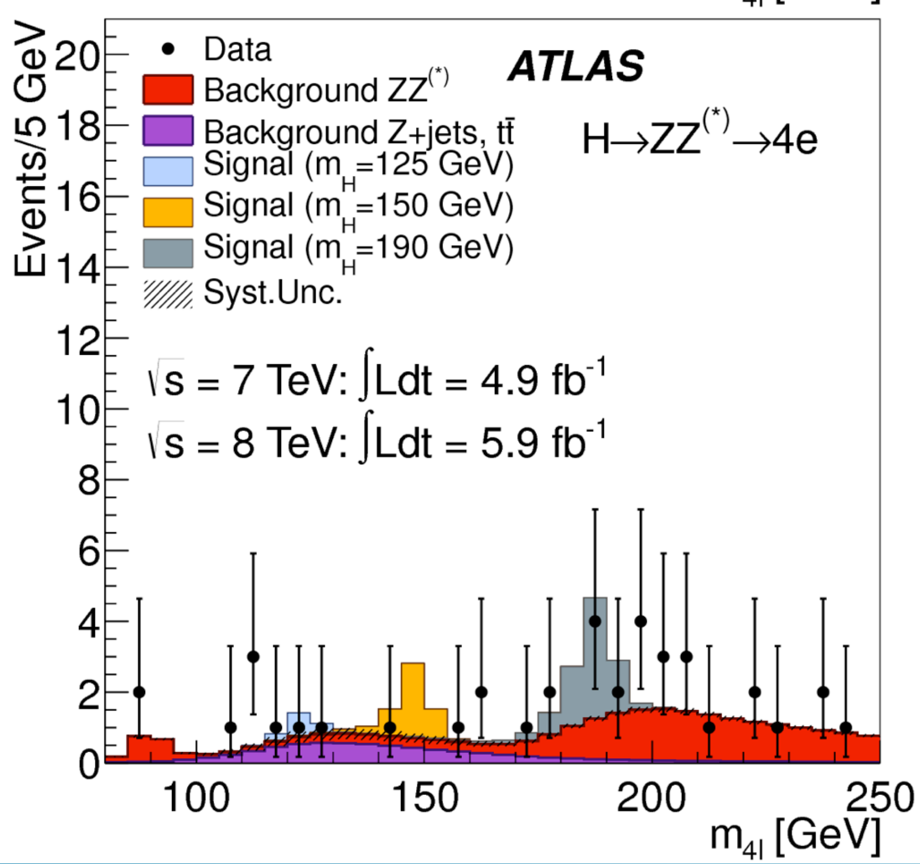
ATLAS
Data S/B Weighted
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
$\sqrt{s}$=7 TeV, $\int Ldt$=4.8fb^{-1}
$\sqrt{s}$=8 TeV, $\int Ldt$=5.9fb^{-1}
H→γγ
Σ weights / 2 GeV
Σ weights - Bkg
$m_{\gamma\gamma}$ [GeV]

Results per final state









Signal Efficiency

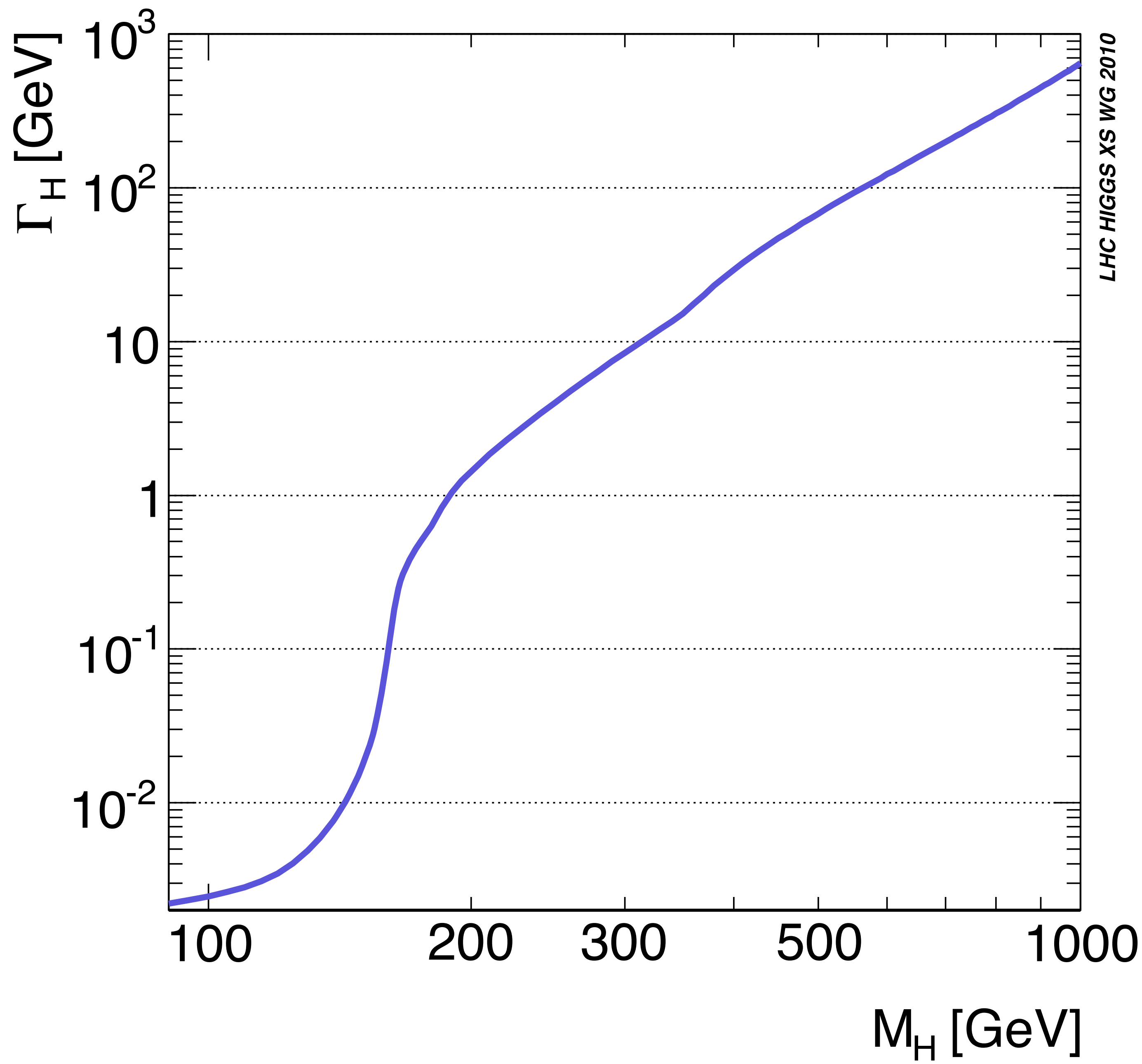
for m_H=125 GeV (8 TeV)

4μ ~36%

2e2μ/2μ2e ~22%

4e ~20%

Higgs Boson Width



The limits presented in this search assume cross sections based on on-shell Higgs boson production and decay and use Monte Carlo generators with an ad-hoc Breit-Wigner Higgs line shape. Recently potentially important effects related to off-shell Higgs boson production and interference effects between the Higgs boson signal and backgrounds have been discussed [arXiv:1107.0683]. The inclusion of such effect may affect limits at very high Higgs masses (m_H > 400 GeV).

Effective Lagrangian

J. R. Espinosa et al. Higgs Hunting 2012 (arXiv:1207.1717[hep-ph])

$\mathcal{L}$ valid at $E \sim M_t$.

Field content : SM + scalar h (no extra light states)

$$\mathcal{L} = \mathcal{L}[h] - \left(M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu\right)\left[1 + 2a\frac{h}{v} + O(h^2)\right]$$

$$- m_{\psi_i} \bar{\psi}_i \psi_i \left[1 + c\frac{h}{v} + O(h^2)\right] + \ldots$$

Contino et al '10 '12

In

$$\mathcal{L} = \mathcal{L}[h] - \left(M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu\right)\left[1 + 2\underbrace{a}_{\kappa_V}\frac{h}{v} + O(h^2)\right]$$

$$- m_{\psi_i} \bar{\psi}_i \psi_i \left[1 + \underbrace{c}_{\kappa_F}\frac{h}{v} + O(h^2)\right] + \ldots$$

Contino et al '10 '12