The Latest ATLAS Higgs Results

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on behalf of the ATLAS Collaboration

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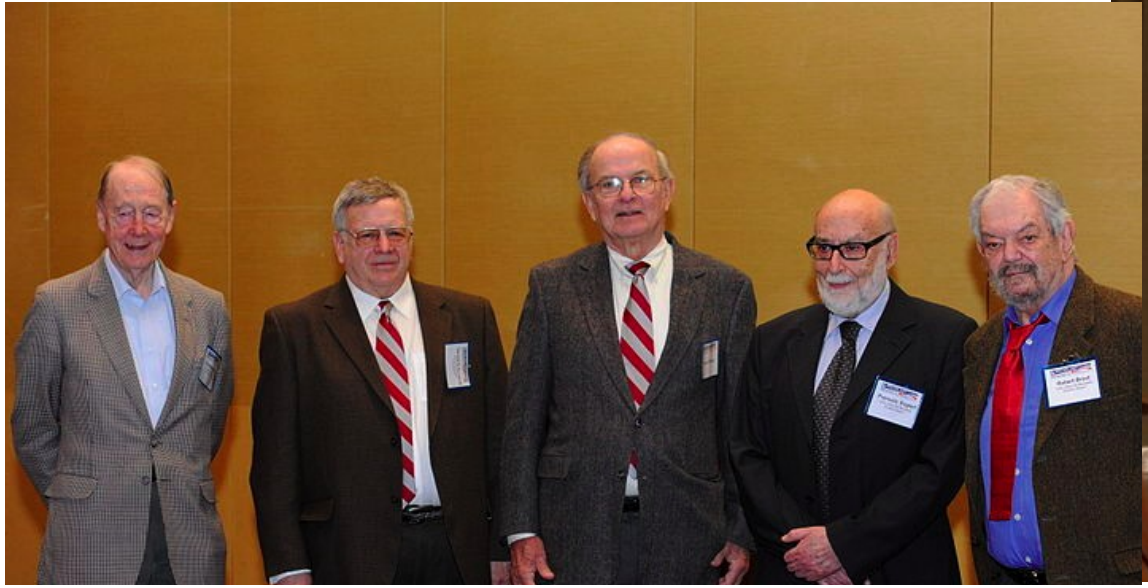
March 29, 2013

SMU | Dedman College of Humanities & Sciences

Expectations for the Higgs from the Standard Model

Philip Warren Anderson

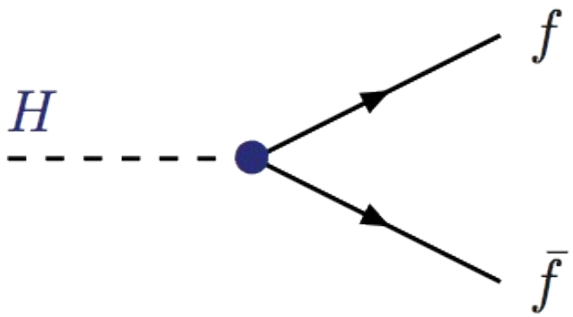


Left-to-right: Tom Kibble, Gerald Guralnik, Carl Hagen, Francois Englert, Robert Brout, and Peter Higgs.

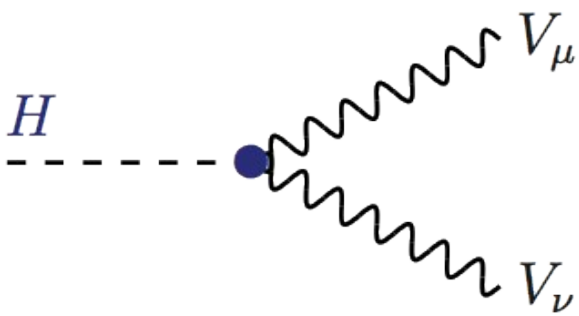
1962: *Anderson noted that spontaneous symmetry breaking has implications for mass (in response to an argument from Schwinger) → gauge transformation + local conservation law does not necessarily require zero-mass bosons.*

1964: *three separate groups – Brout and Englert; Higgs; Guralnik, Hagen, and Kibble – propose relativistic models that allow for the symmetry group of a gauge theory to be broken when it's combined with an additional field. This leads to masses for the gauge bosons in the original theory.*

The Higgs Boson

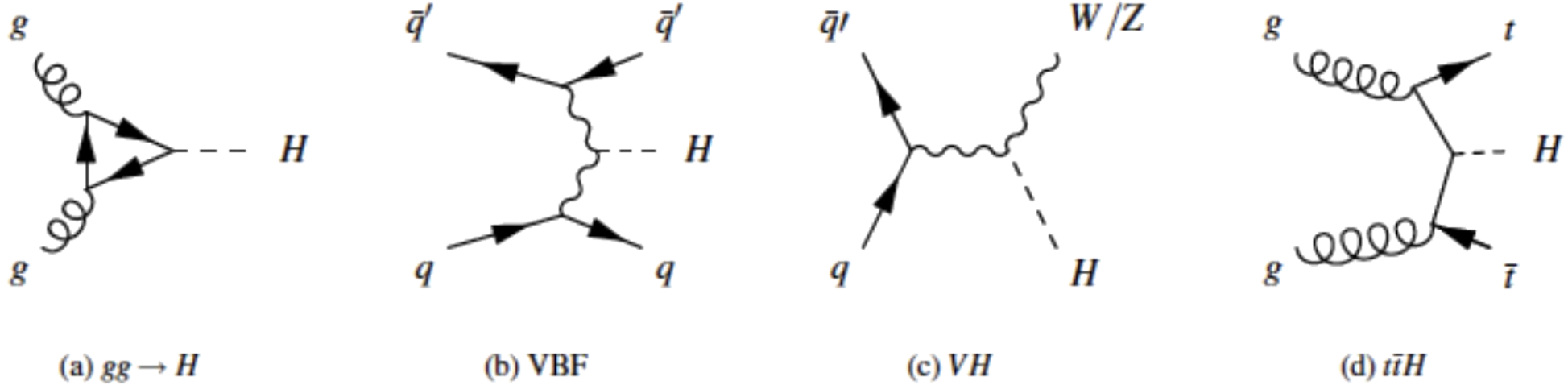


$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2}\, m_f \qquad \times\ (i)$$



$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2}\, M_V^2 \qquad \times\ (-ig_{\mu\nu})$$

The Higgs boson <u>mass</u> is a free parameter in the Standard Model (SM) and must be measured. It is a <u>spin-0, CP-even</u> boson ($J^P=0^+$). The <u>propagator</u> for the Higgs is a function of its mass. The <u>couplings</u> shown above are given entirely by the masses of the fermions and bosons.



gg → H ("ggF")

Higgs p_T spectrum calculated using POWHEG up to NLO, including QCD soft-gluon re-summation up to NNLL. Cross-section calculation is NNLO and includes NNLL soft-gluon re-summations and NLO EW corrections.

qq' → VH ("VH")

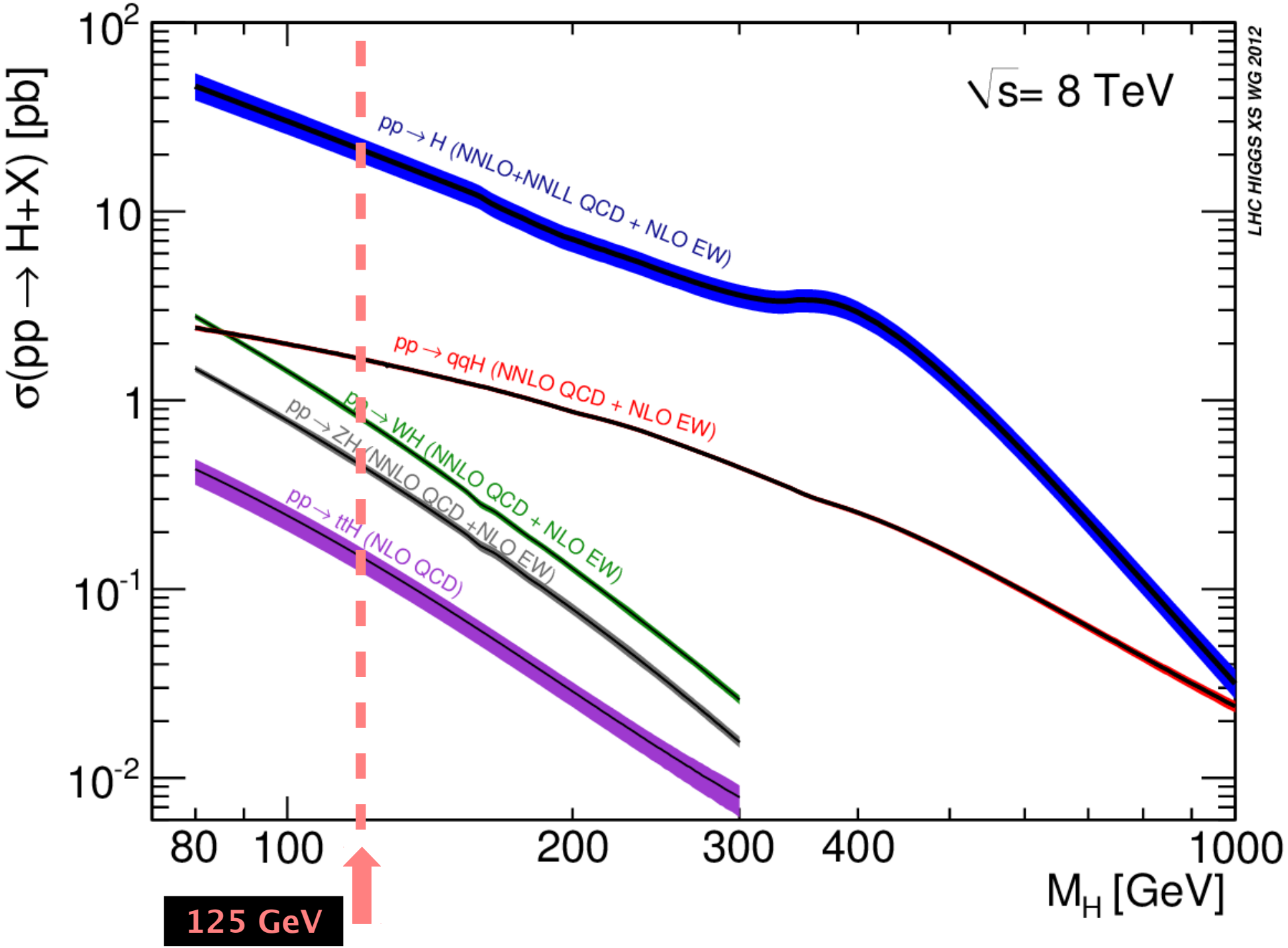
Simulated using PYTHIA. Cross-sections calculated at NLO and NNLO in QCD, and NLO EW corrections are applied.

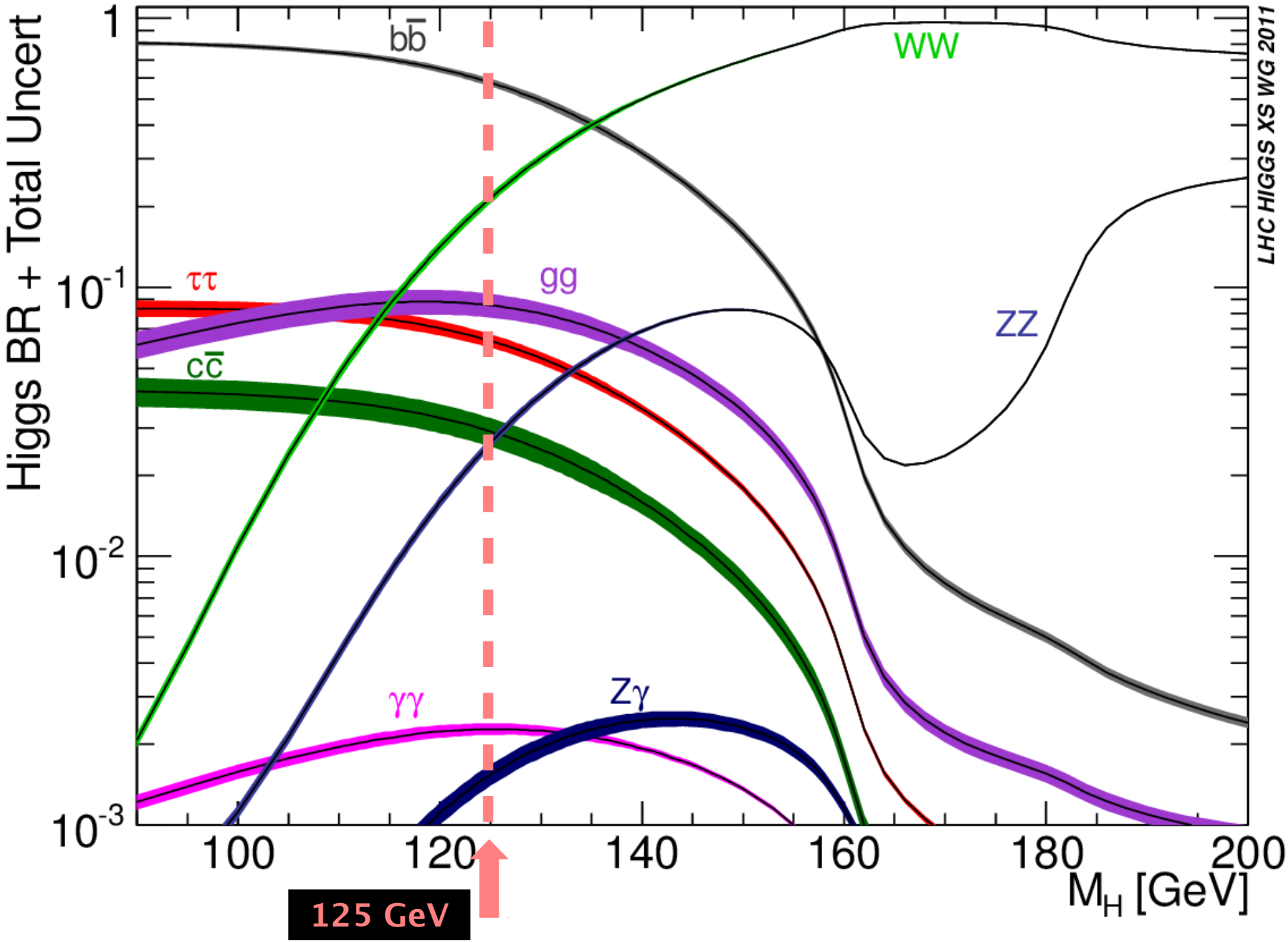
qq' → Hqq' ("VBF")

Same p_T treatment as ggF. Cross-section calculated with full NLO QCD and EW corrections.

gg → ttH ("ttH")

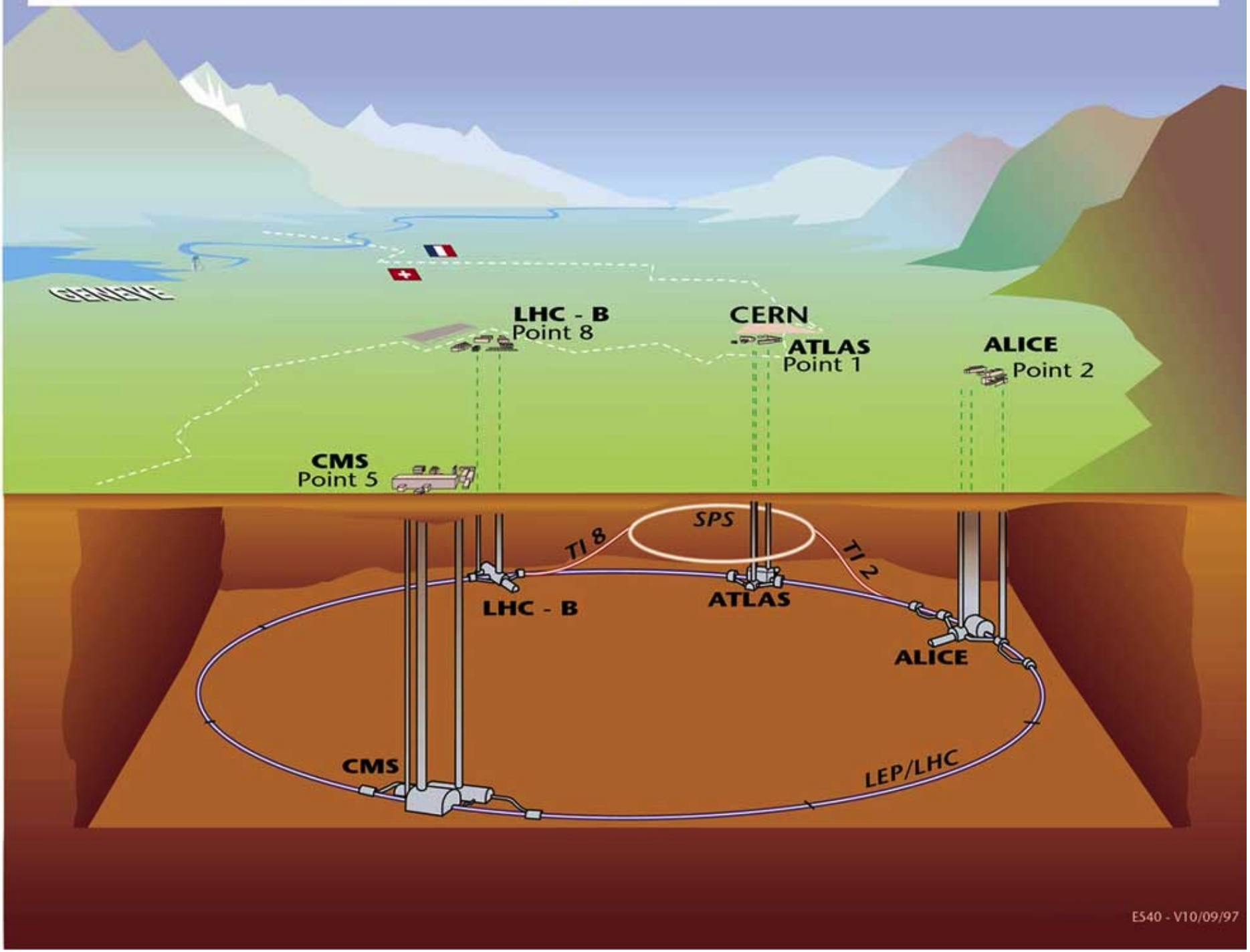
Simulated using PYTHIA. Cross-sections calculated at NLO QCD.

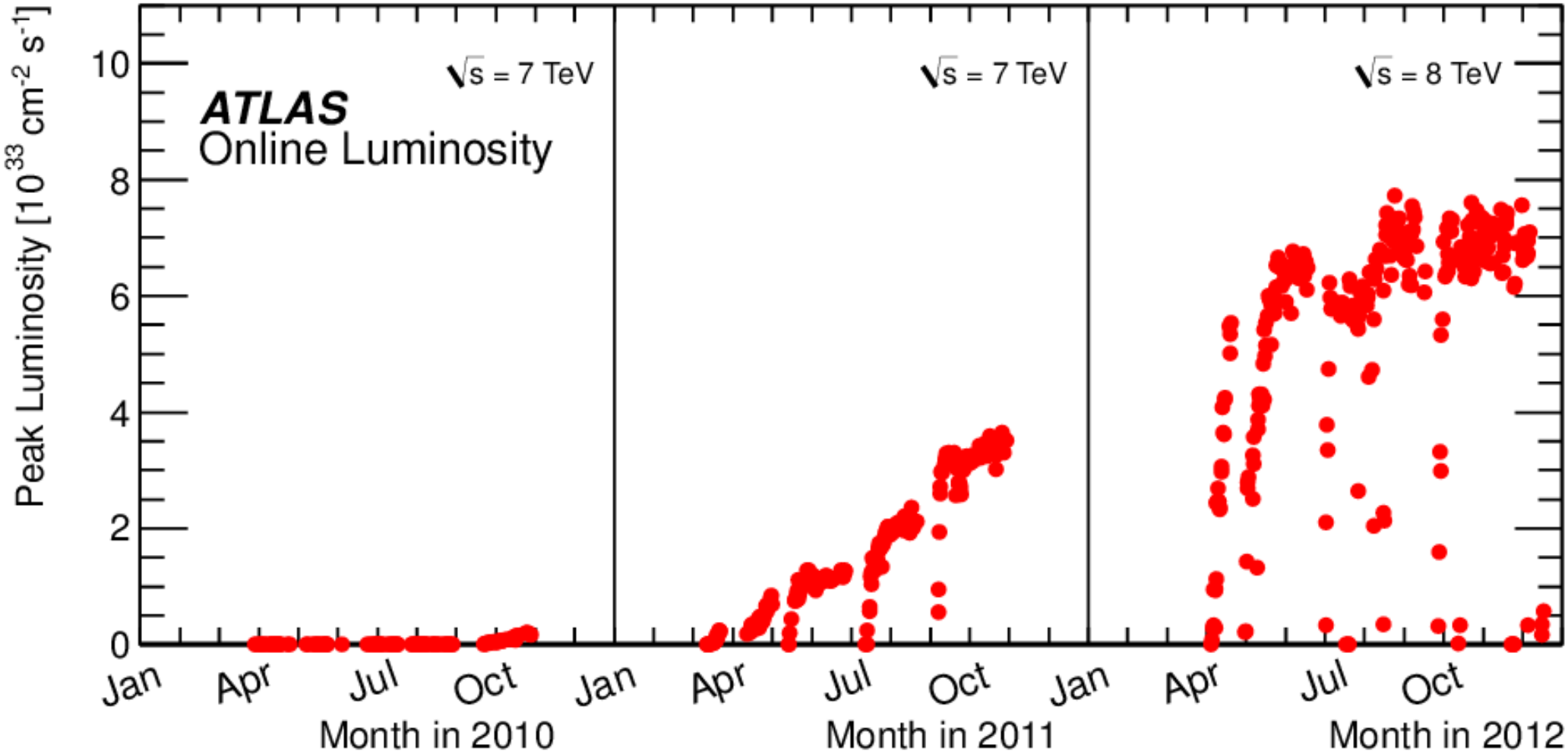

$\sqrt{s}$= 8 TeV
LHC HIGGS XS WG 2012
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
σ(pp → H+X) [pb]
M_H [GeV]
125 GeV


Higgs BR + Total Uncert
1
10^{-1}
10^{-2}
10^{-3}
$b\bar{b}$
WW
$\tau\tau$
gg
ZZ
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$
100
120
140
160
180
200
M_H [GeV]
LHC HIGGS XS WG 2011
125 GeV

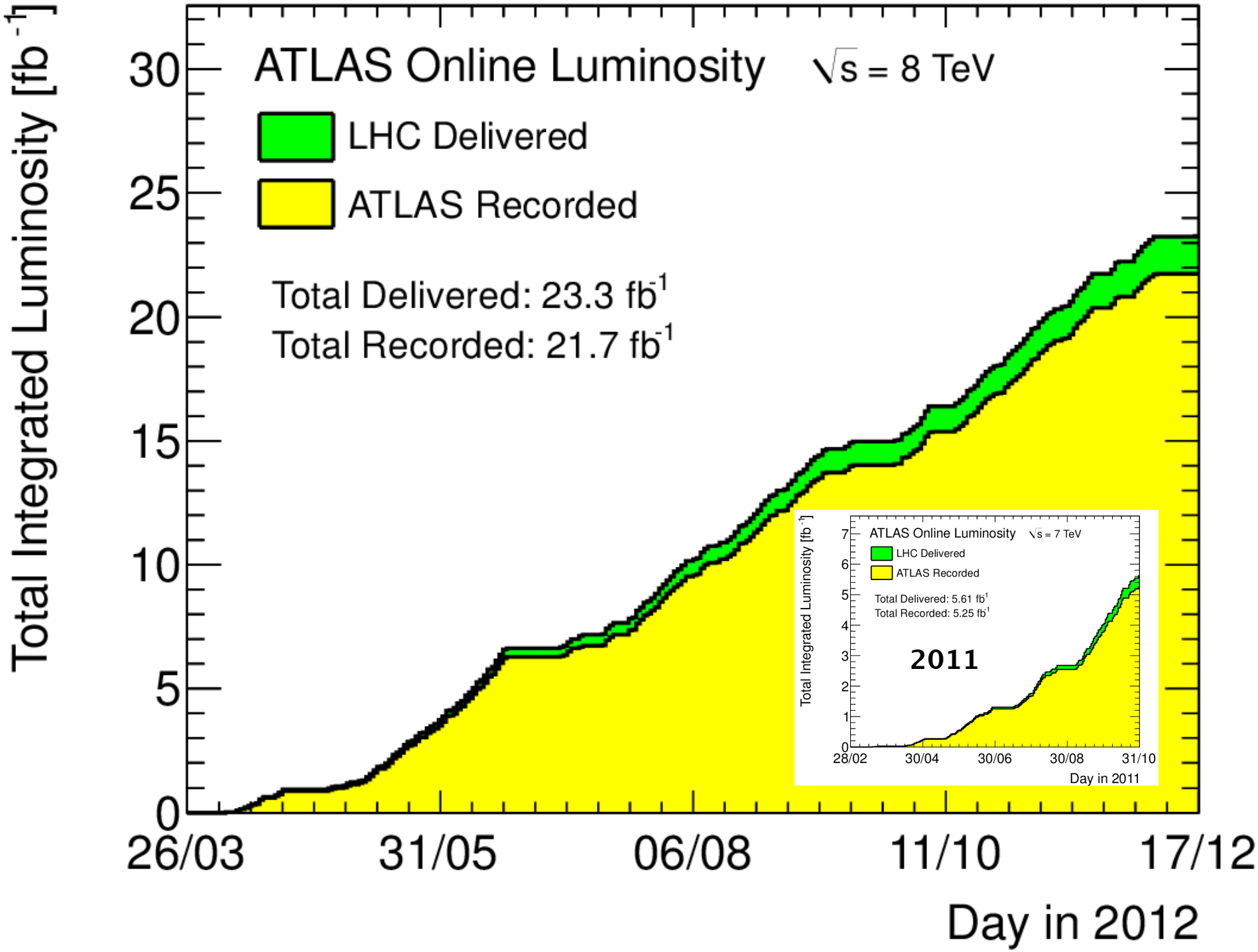
The ATLAS Experiment at the LHC

Overall view of the LHC experiments.

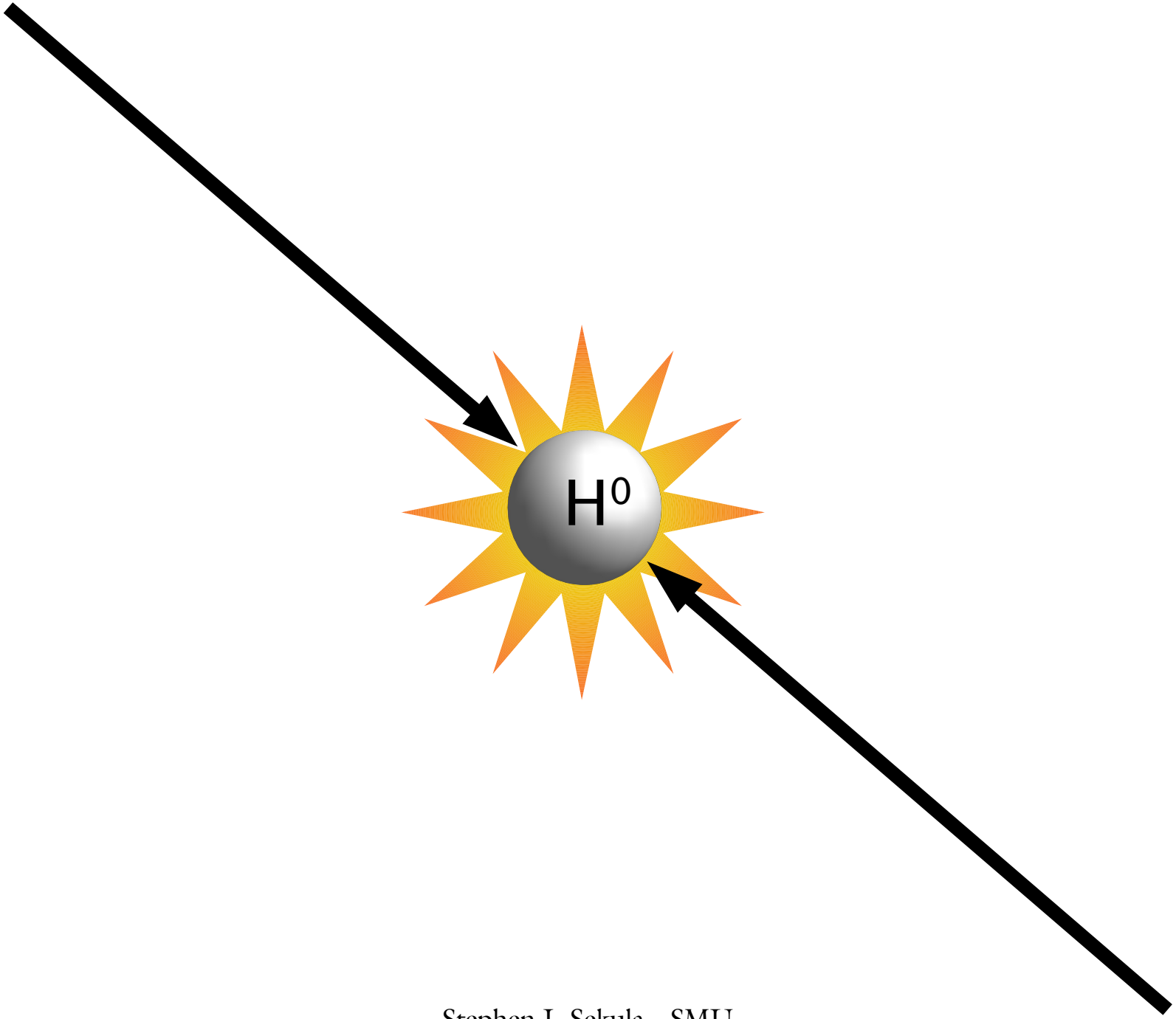




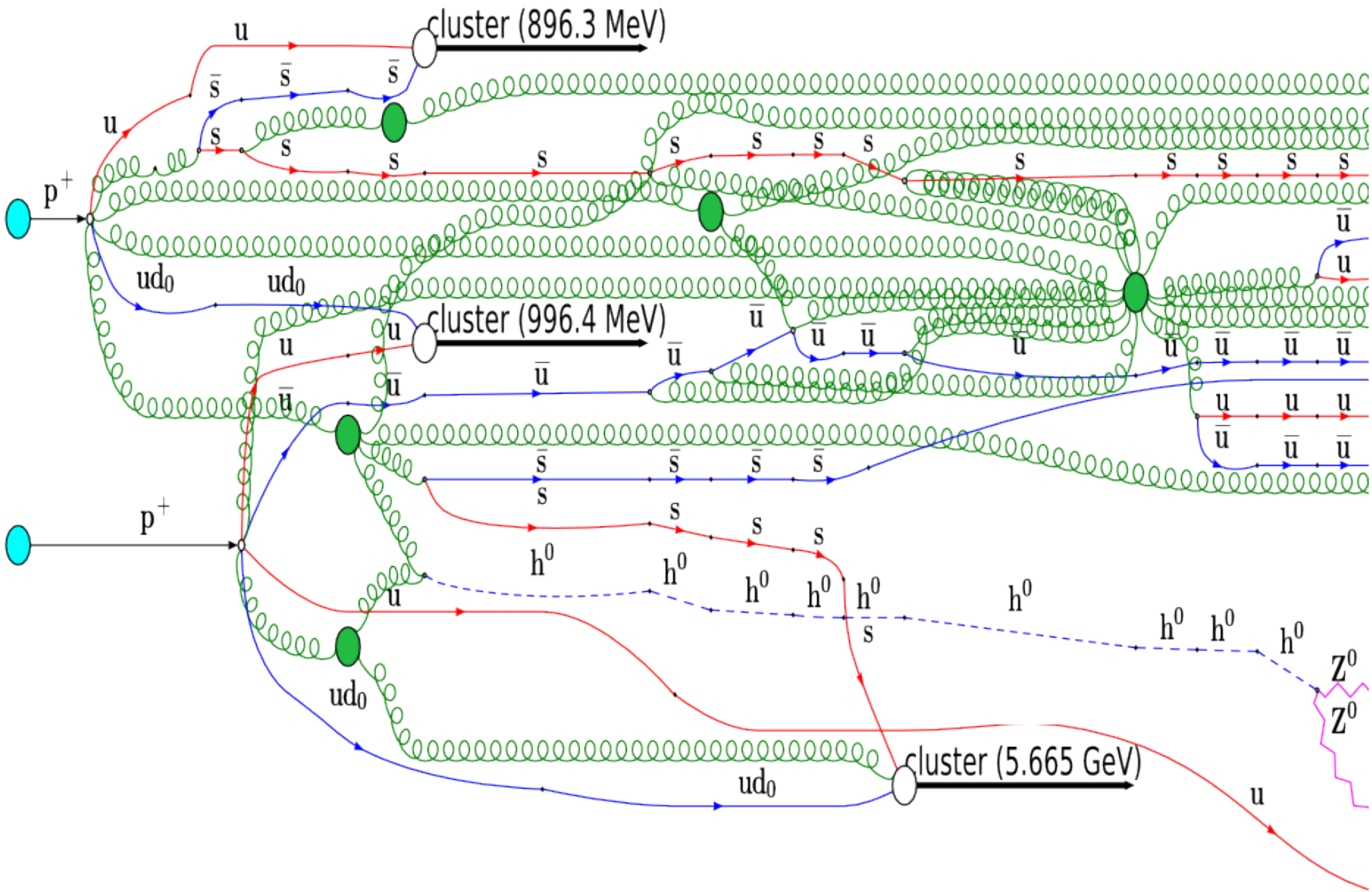
MANY THANKS TO OUR COLLEAGUES ON THE LHC FOR THEIR INCREDIBLE WORK THAT DELIVERED SUCH HIGH PERFORMANCE!


ATLAS Online Luminosity
√s = 8 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 23.3 fb-1
Total Recorded: 21.7 fb-1
Total Integrated Luminosity [fb-1]
0
5
10
15
20
25
30
26/03
31/05
06/08
11/10
17/12
Day in 2012
ATLAS Online Luminosity
√s = 7 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 5.61 fb-1
Total Recorded: 5.25 fb-1
2011
Total Integrated Luminosity [fb-1]
28/02
30/04
30/06
30/08
31/10
Day in 2011

Ideal . . .

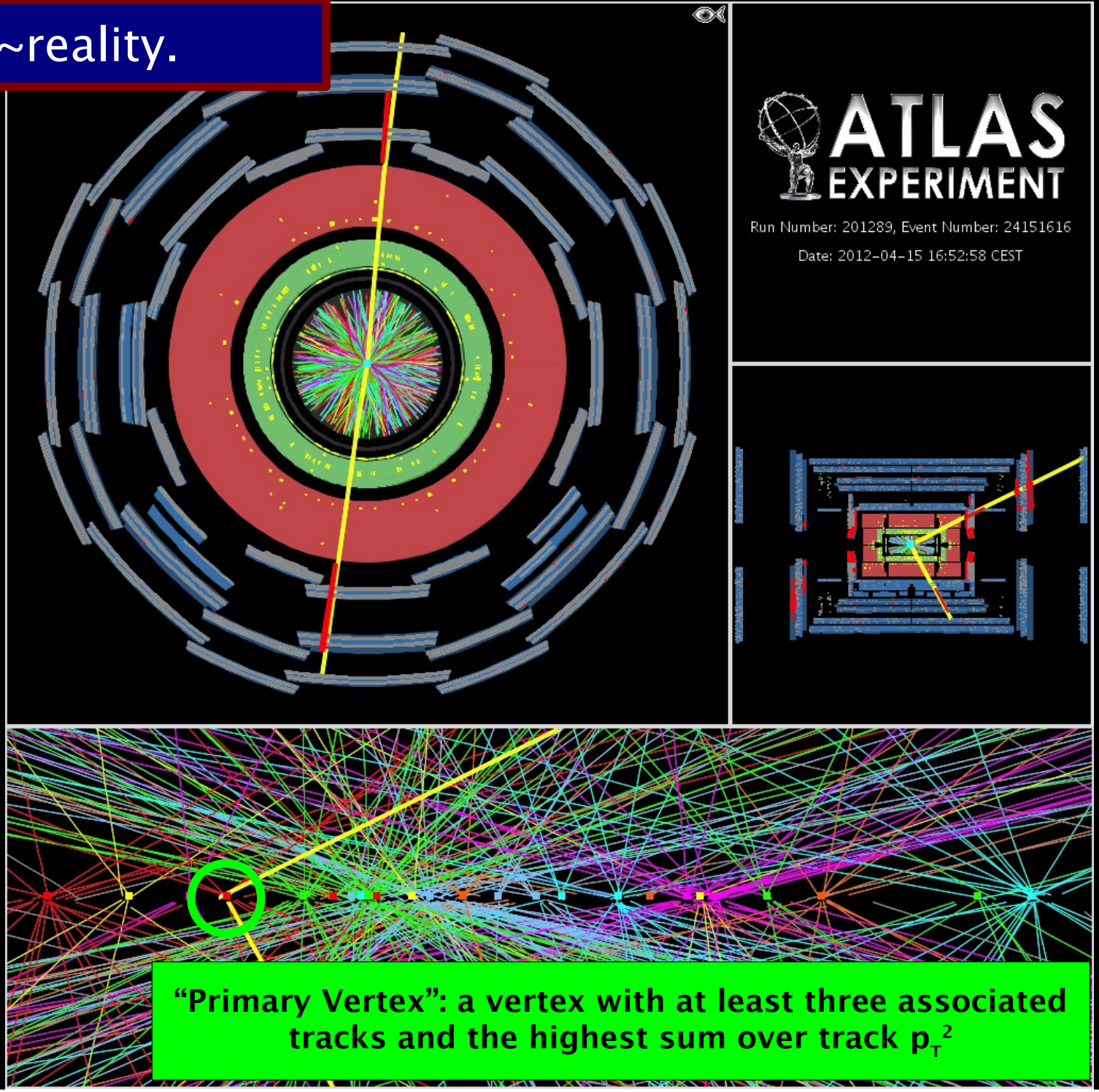


. . . more realistic . . .

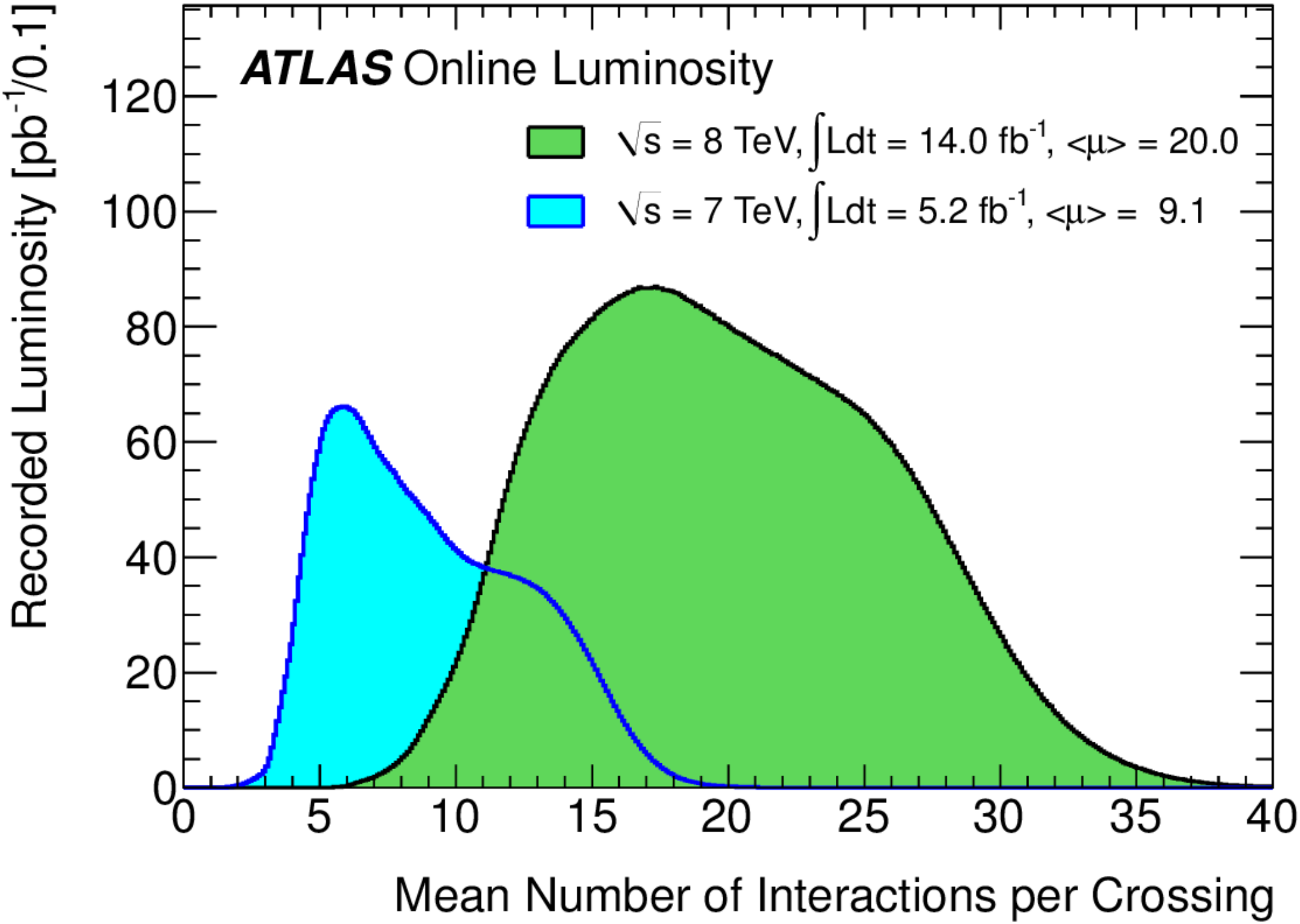


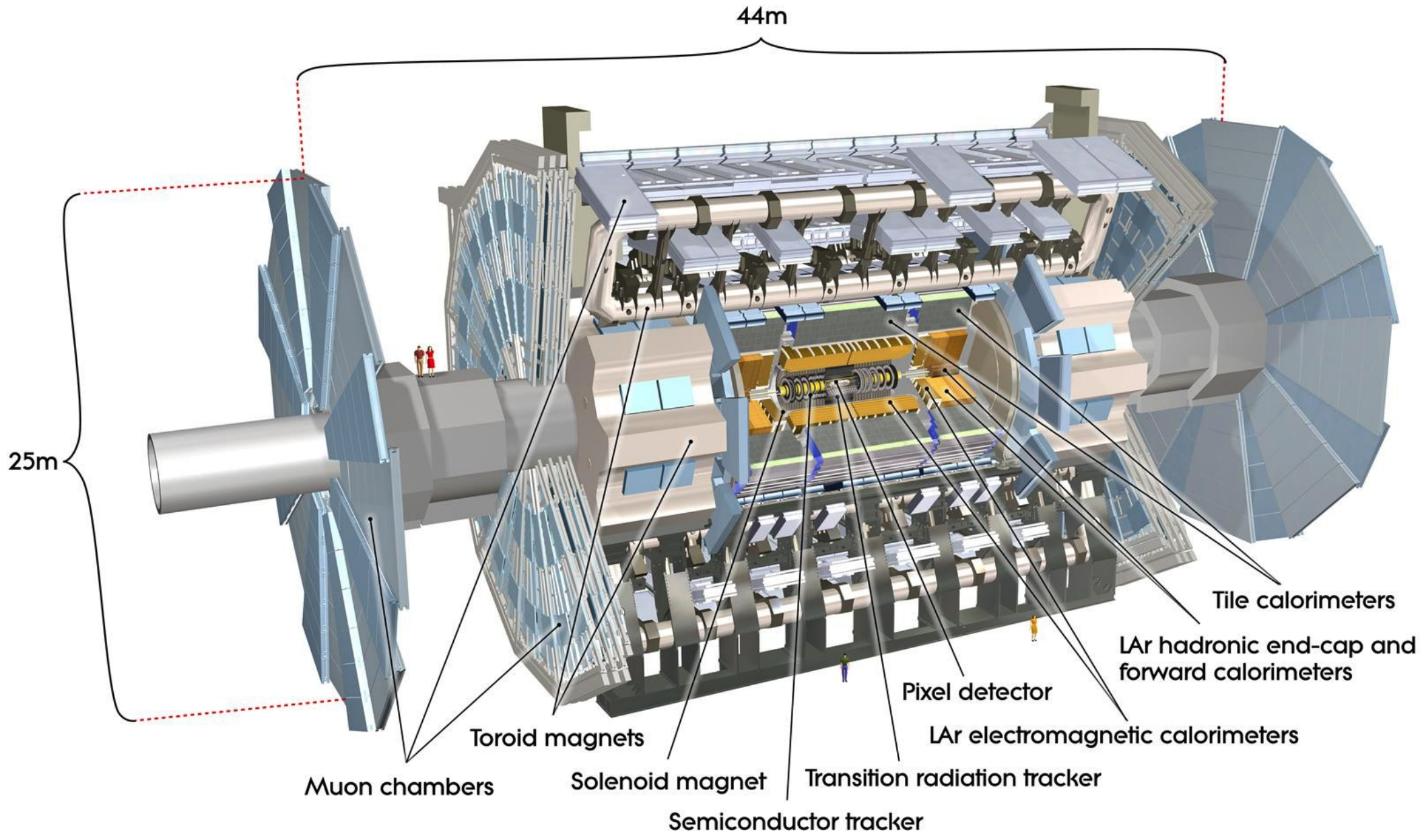
CREDIT: MCViz (mcviz.net)

. . . ~reality.



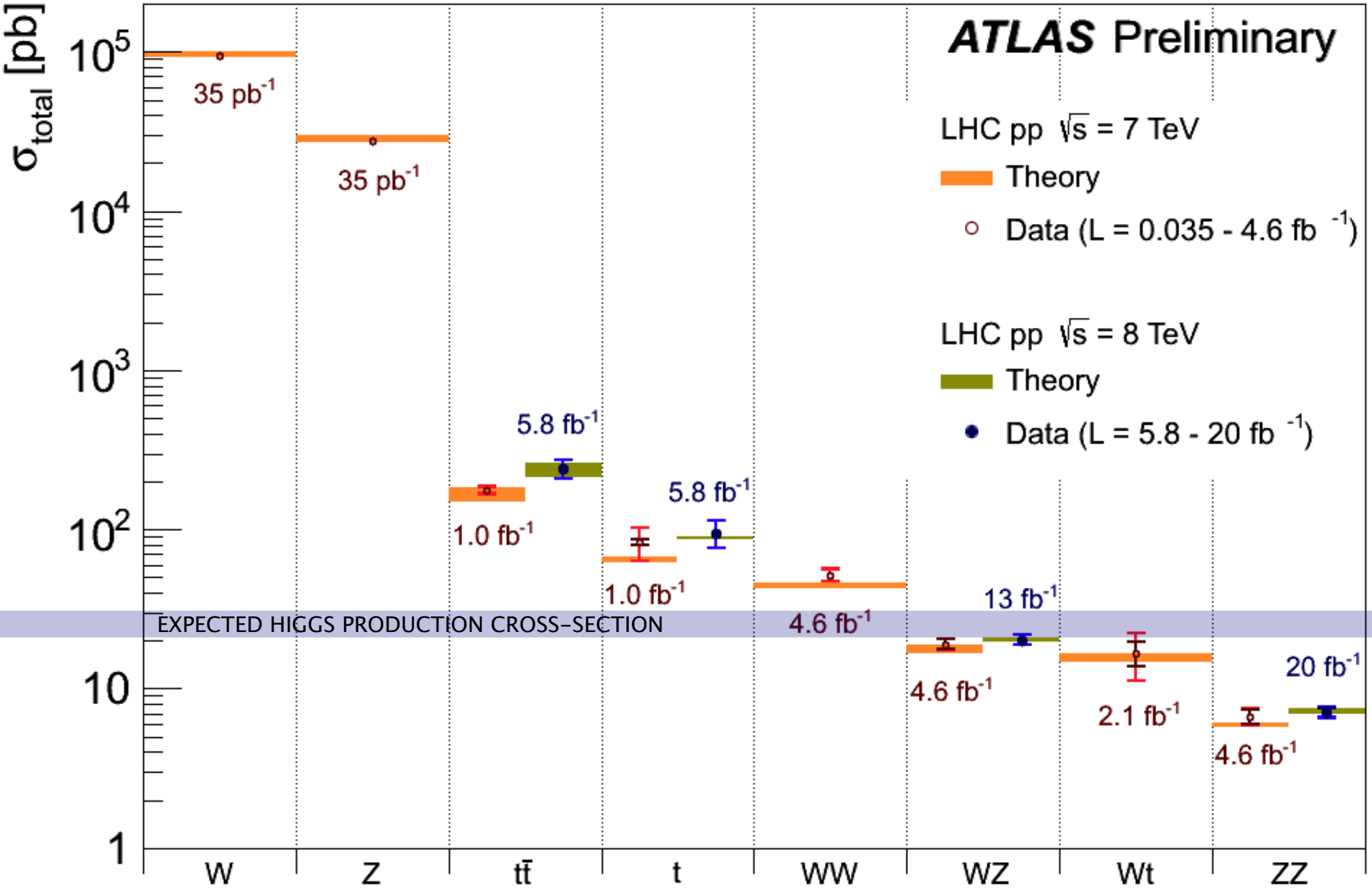
"Primary Vertex": a vertex with at least three associated tracks and the highest sum over track p_T^2


ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 14.0 fb⁻¹, <μ> = 20.0
√s = 7 TeV, ∫Ldt = 5.2 fb⁻¹, <μ> = 9.1
Recorded Luminosity [pb⁻¹/0.1]
Mean Number of Interactions per Crossing
0
20
40
60
80
100
120
0
5
10
15
20
25
30
35
40


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

The Latest ATLAS Higgs Results

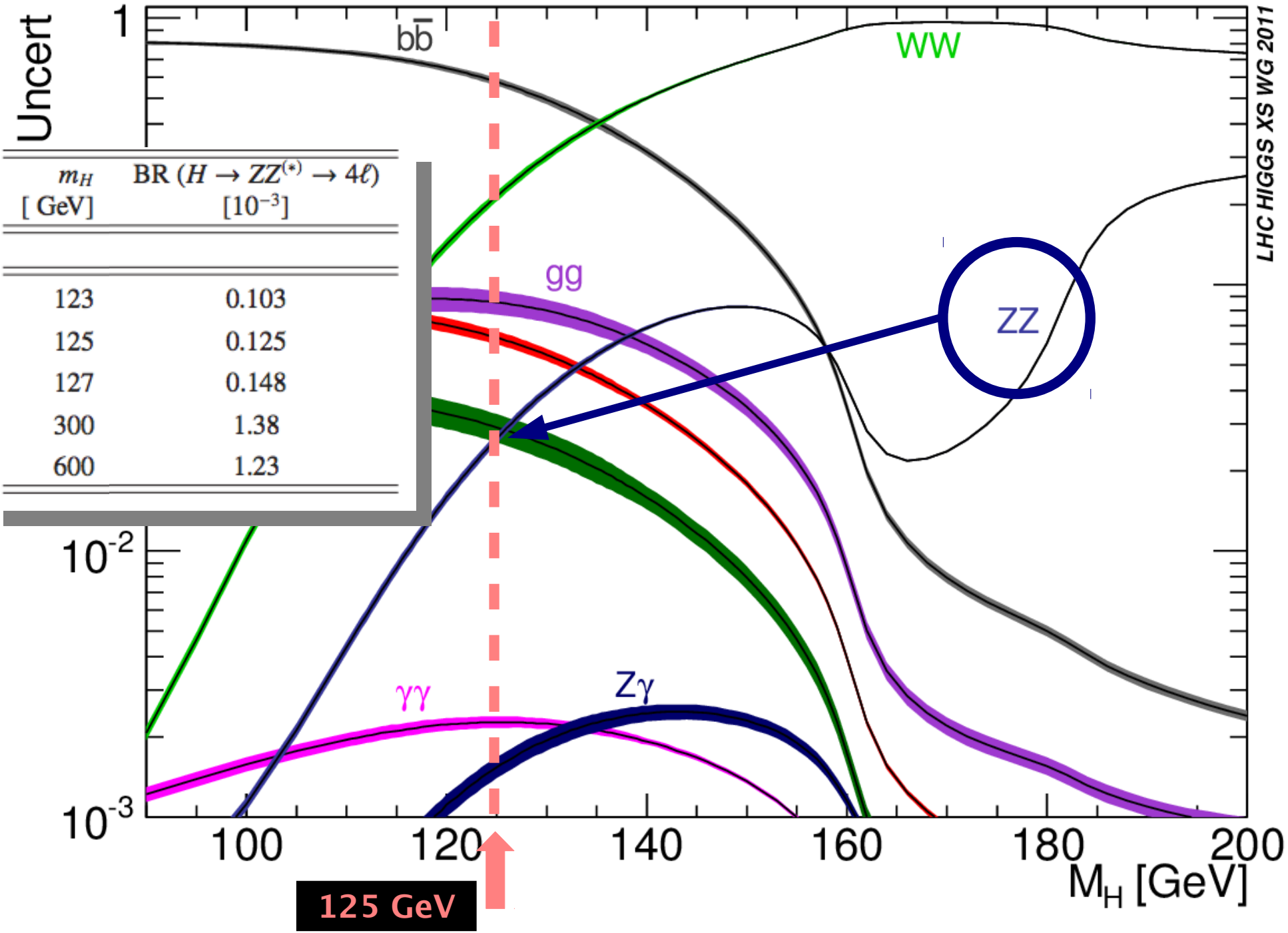
Channels and Reconstruction



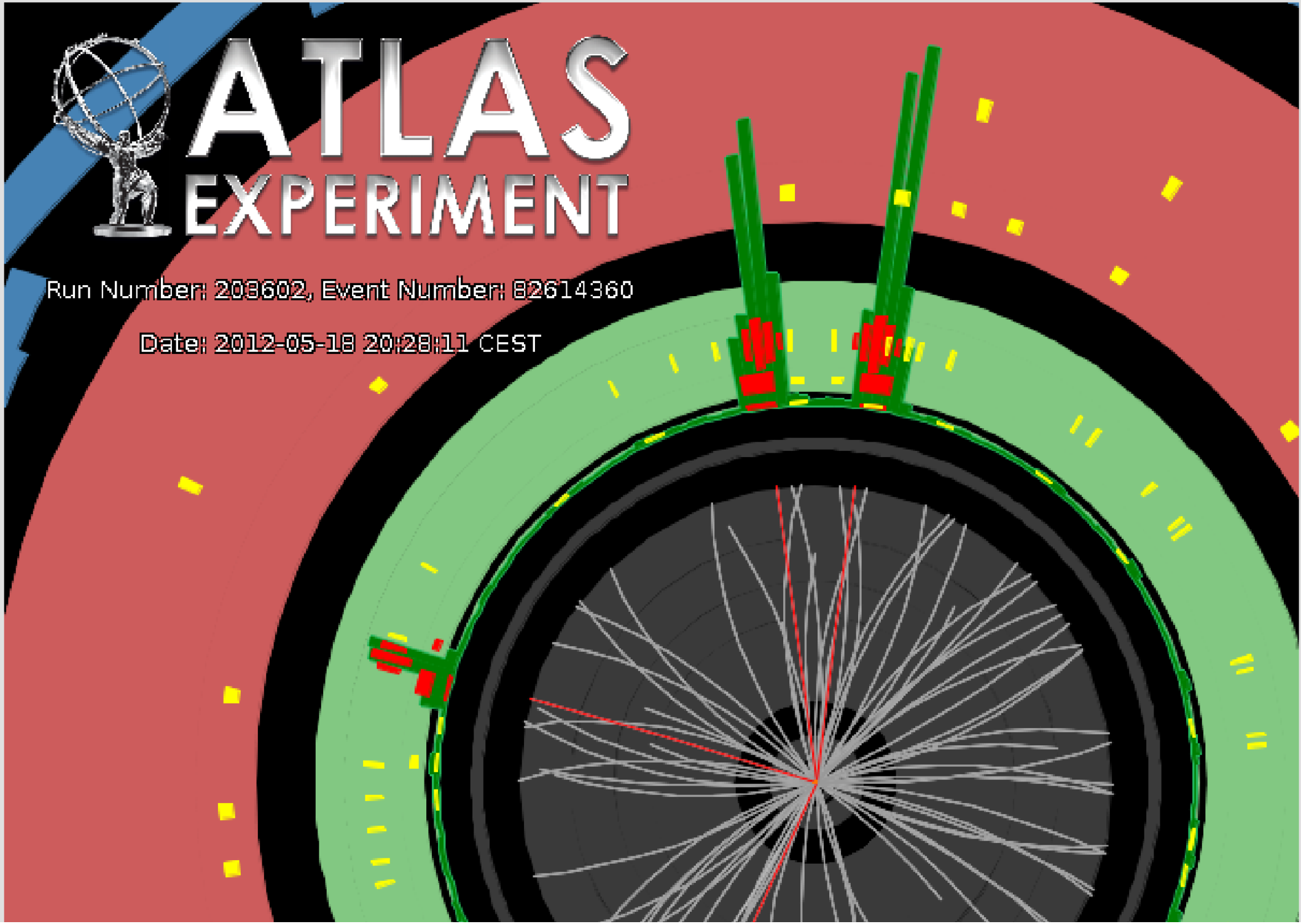
Processes like inclusive production of top, W, Z, and dibosons will of course yield background rejection challenges in Higgs searches/measurements.

Everything in this section is publicly available in:
ATLAS-CONF-2013-013

$H^0 \rightarrow Z^0 Z^{0(*)}$

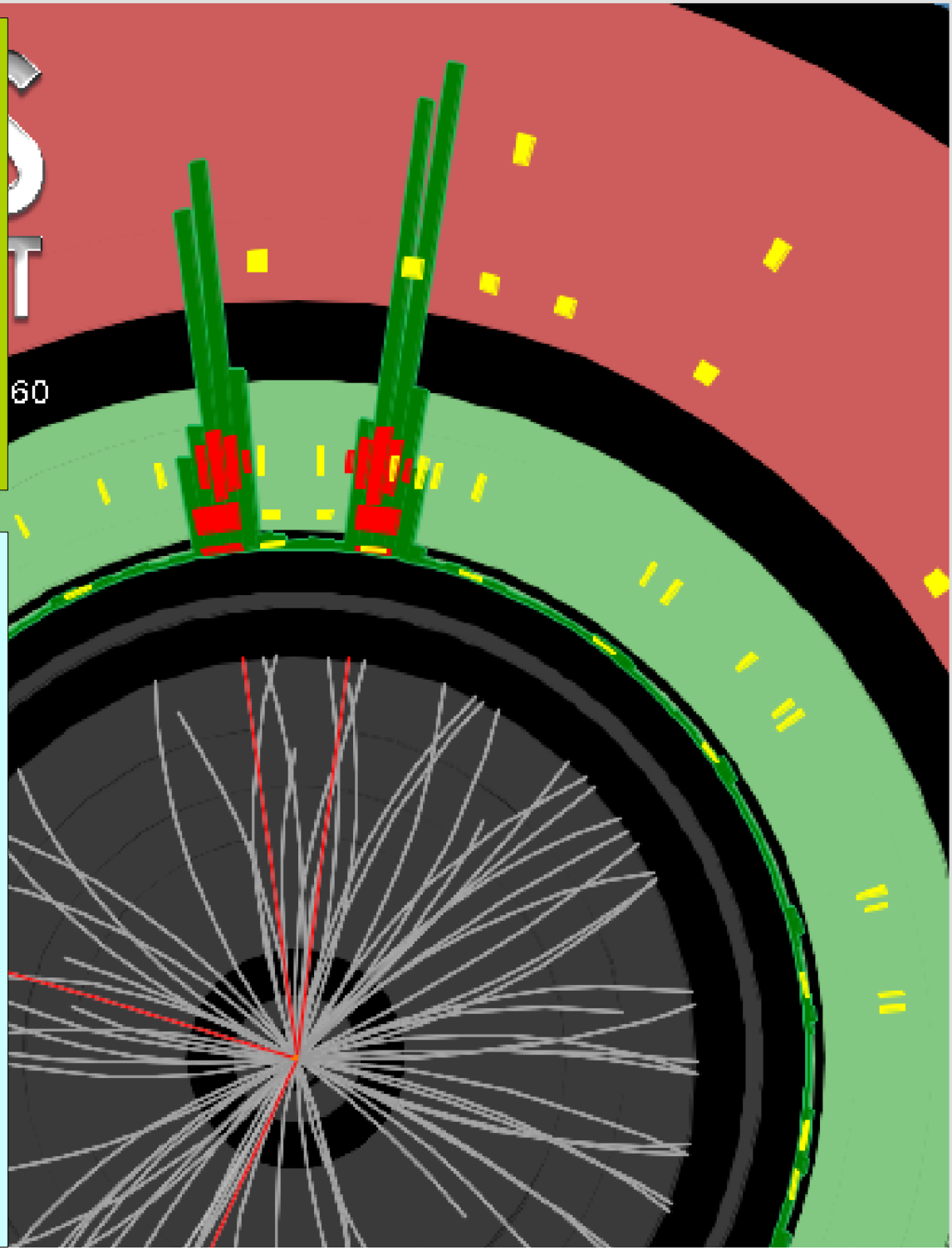


m_H [GeV]	BR $(H \to ZZ^{(*)} \to 4\ell)$ $[10^{-3}]$
123	0.103
125	0.125
127	0.148
300	1.38
600	1.23


ATLAS
EXPERIMENT
Run Number: 208602, Event Number: 82614360
Date: 2012-05-18 20:28:11 CEST

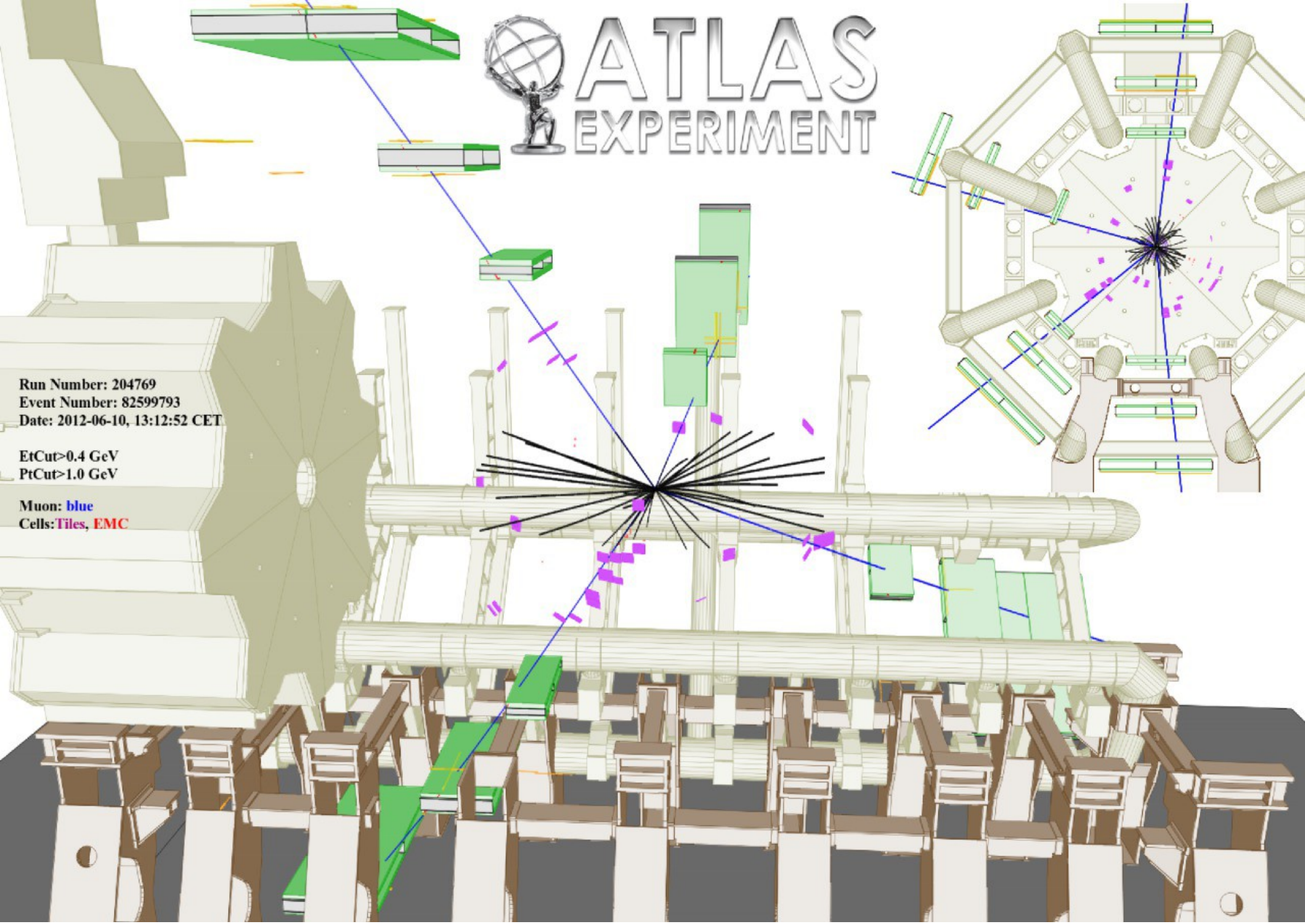
Trigger p_T [GeV] thresholds (involving electrons)

	2011	2012
single-e	20-22	25
di-elec.	12	12
e+mu	10	12 or 24



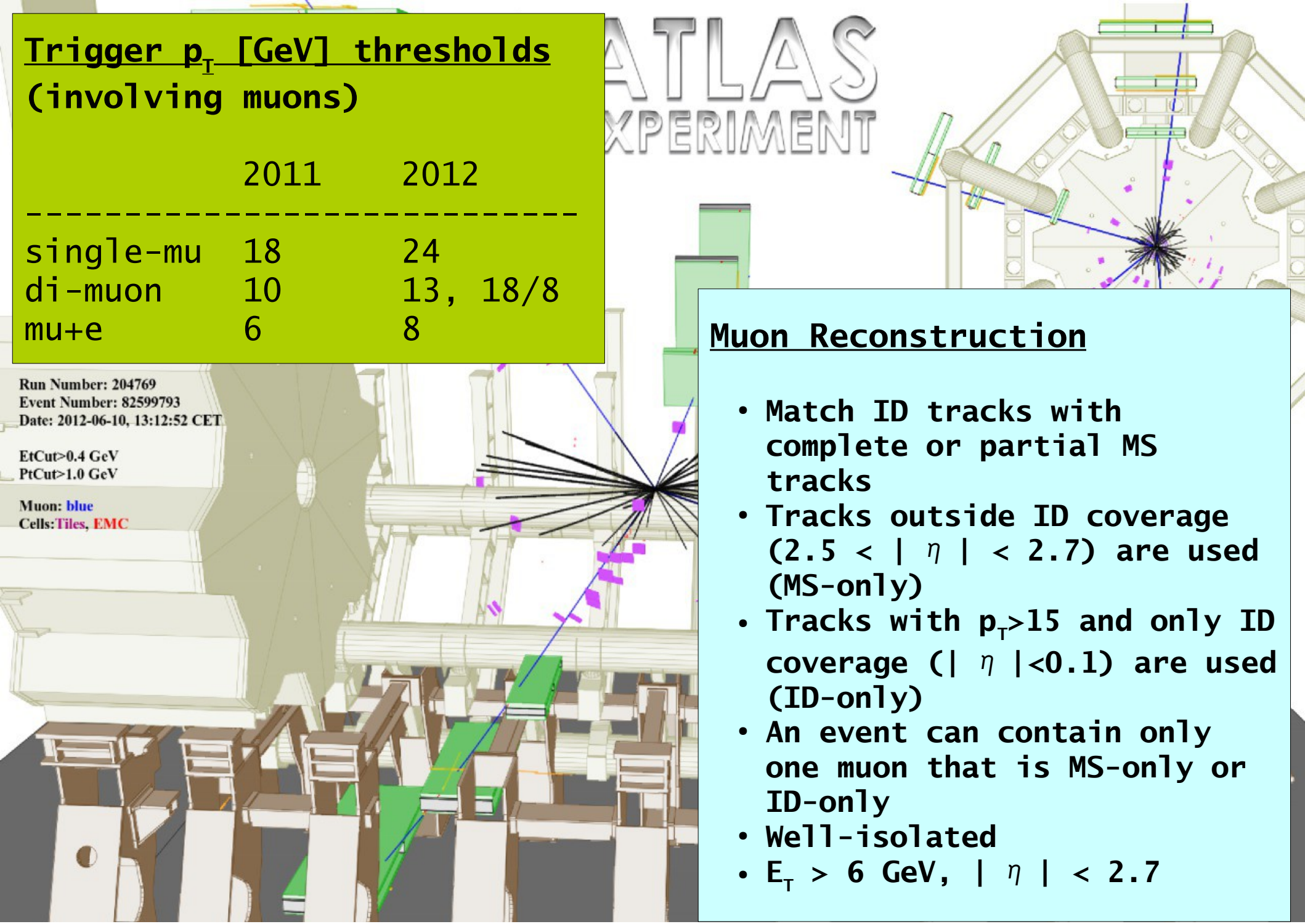
Electron Reconstruction

- EM cluster associated with ID track
- Bremsstrahlung-recovered
- Calorimeter shower consistent with electron interaction.
- Passes identification requirements (tighter in endcap regions)
- Well-isolated
- $E_T > 7$ GeV, $|\eta| < 2.47$


ATLAS
EXPERIMENT
Run Number: 204769
Event Number: 82599793
Date: 2012-06-10, 13:12:52 CET
EtCut>0.4 GeV
PtCut>1.0 GeV
Muon: blue
Cells:Tiles, EMC

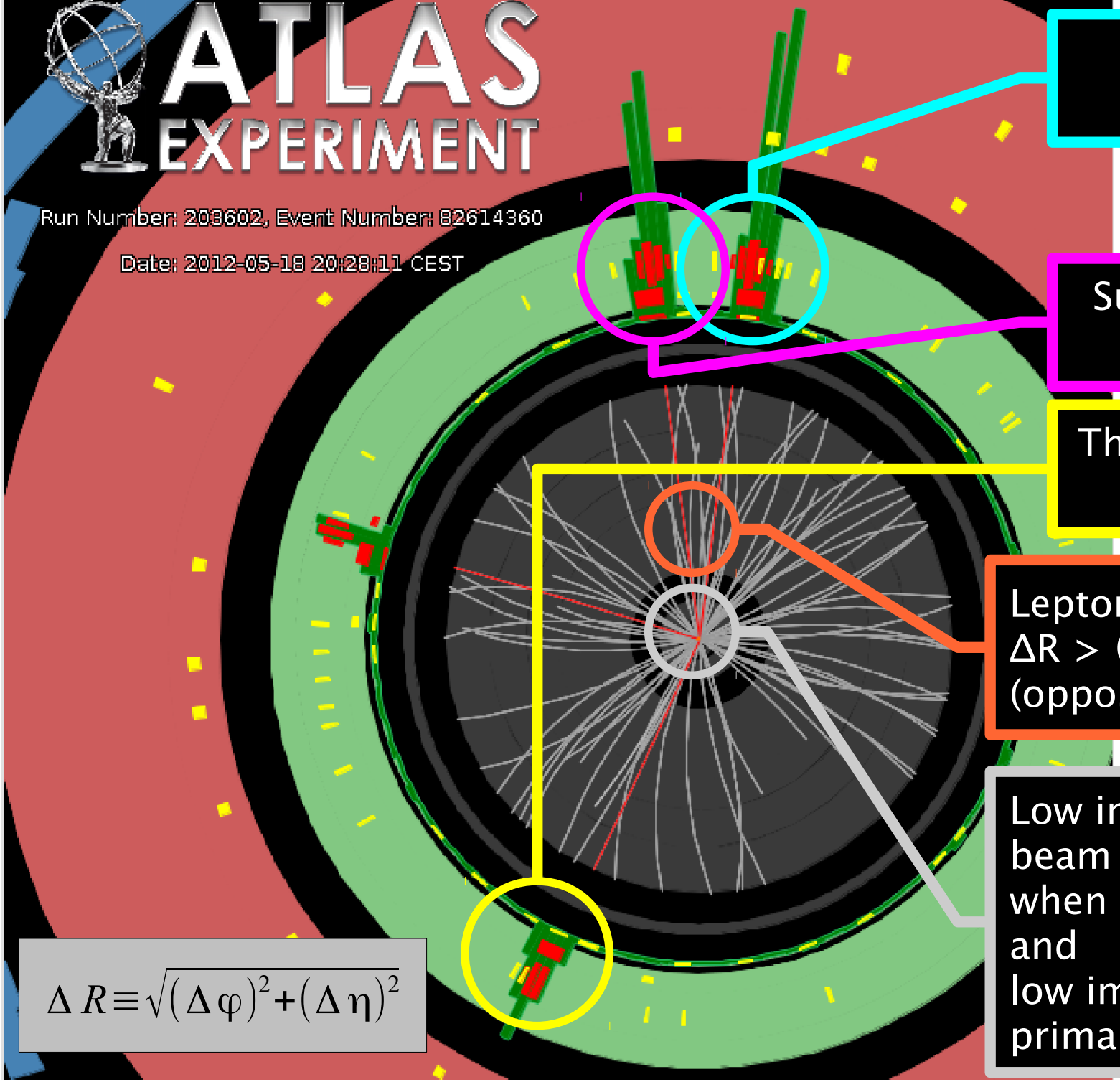
Trigger p_T [GeV] thresholds (involving muons)

	2011	2012
single-mu	18	24
di-muon	10	13, 18/8
mu+e	6	8



Muon Reconstruction

- Match ID tracks with complete or partial MS tracks
- Tracks outside ID coverage ($2.5 < |\eta| < 2.7$) are used (MS-only)
- Tracks with p_T>15 and only ID coverage ($|\eta|$<0.1) are used (ID-only)
- An event can contain only one muon that is MS-only or ID-only
- Well-isolated
- $E_T > 6$ GeV, $|\eta| < 2.7$



Leading lepton:
$p_T > 20$ GeV

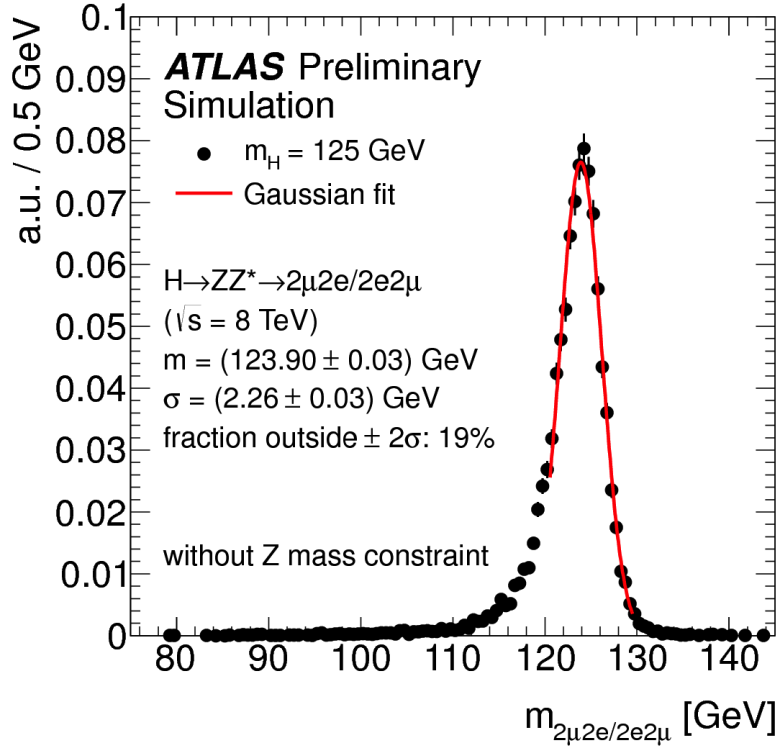
Sub-leading lepton:
$p_T > 15$ GeV

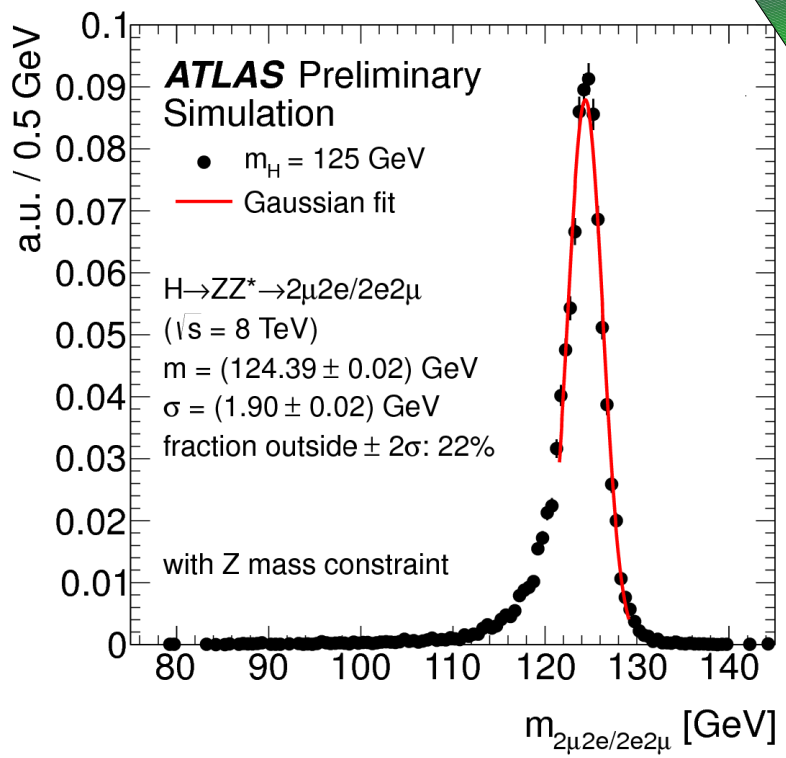
Third-leading lepton:
$p_T > 10$ GeV

Leptons well-separated,
$\Delta R > 0.1$ (0.2) for same (opposite) flavor leptons.

Low impact parameter to beam axis (<10 mm) for when ID track present; and
low impact parameter to primary vertex (<1mm).

$$\Delta R \equiv \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2}$$

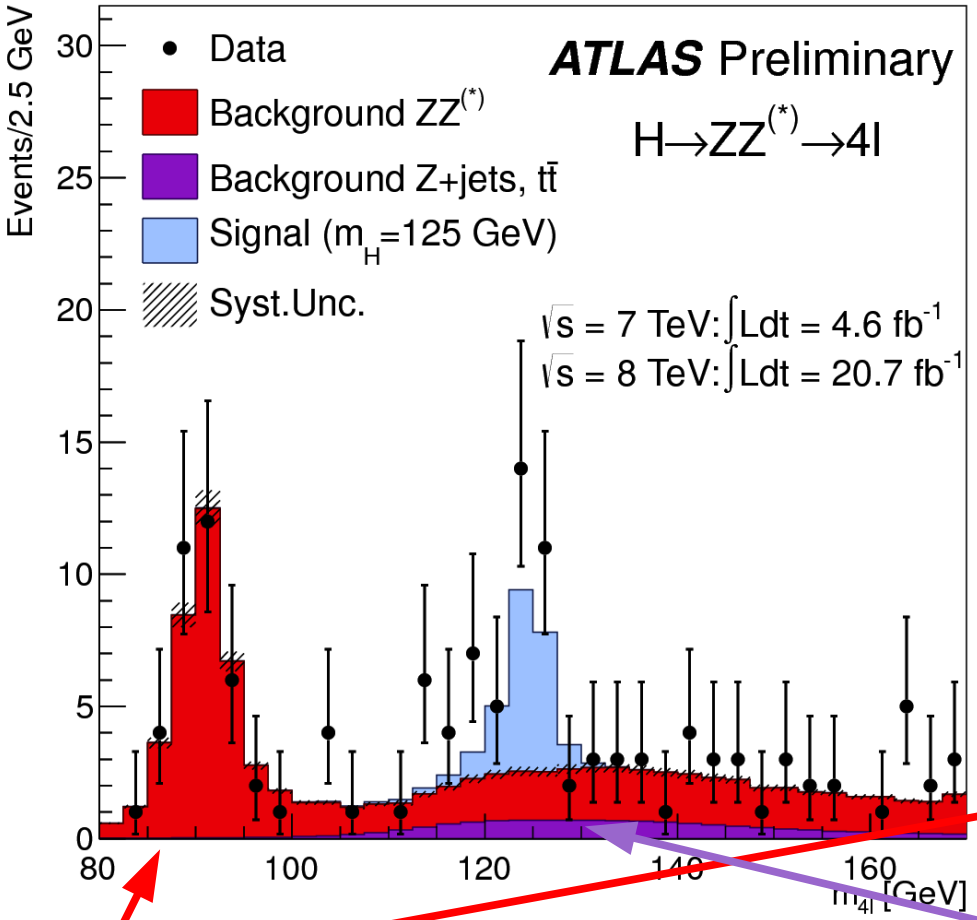


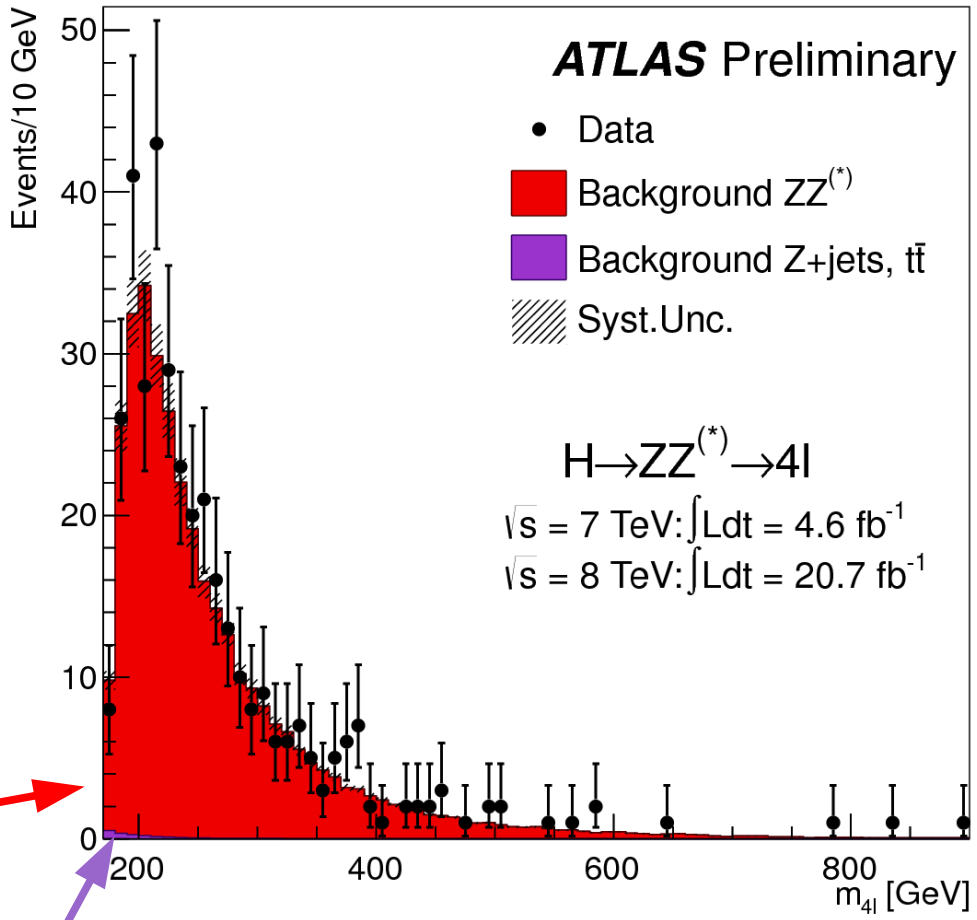


Employ Z-mass constraint

Higgs Candidate Reconstruction

- Of all possible quadruplets, only those with the same-flavor, opp.-sign pair with mass closest to the Z are kept → **this is the "leading pair", m_{12} = [50, 106] GeV**
- m_{34} = [m_{min}, 115] GeV, where m_{min} = 12 for m_{4l} < 140 GeV and rises linearly to 50 GeV at m_{4l} = 190 GeV, where it plateaus.
- **m_{4l} is the final discriminant, with a Z-mass constraint on m_{12}**
  - the Z lineshape and experimental di-lepton mass uncertainty are accounted in this constraint





<u>pp → ZZ(*) background</u>
"Irreducible" in that it contains exactly the same final state with real leptons. Estimated from MC with cross-section fixed from prediction (MCFM)

<u>pp → Z+jets, tt background</u>
"Reducible" in that there are not two real Z bosons and the leptons are a mixture of real and fake. Estimated using data-driven means.

	4μ		$2\mu 2e/2e2\mu$		$4e$	
	low mass	high mass	low mass	high mass	low mass	high mass
$\sqrt{s} = 8$ TeV integrated luminosity 20.7 fb^{-1}						
$ZZ^{(*)}$	12.4 ± 0.6	92.6 ± 6.7	14.7 ± 0.9	144 ± 11	5.4 ± 0.5	55.9 ± 4.5
Z, $Zb\bar{b}$, and $t\bar{t}$	1.9 ± 0.6	0.5 ± 0.2	6.1 ± 1.5	1.5 ± 0.4	2.5 ± 0.6	0.6 ± 0.2
total background	14.3 ± 0.8	93.1 ± 6.7	20.8 ± 1.8	145 ± 11	8.0 ± 0.8	56.5 ± 4.5
data	27	93	28	169	13	55
$m_H = 123$ GeV	4.4 ± 0.6		5.4 ± 0.8		2.2 ± 0.4	
$m_H = 125$ GeV	5.8 ± 0.7		7.0 ± 0.9		2.9 ± 0.4	
$m_H = 127$ GeV	6.7 ± 0.9		8.4 ± 1.2		3.4 ± 0.5	
$\sqrt{s} = 7$ TeV integrated luminosity 4.6 fb^{-1}						
$ZZ^{(*)}$	2.2 ± 0.1	16.8 ± 1.2	2.5 ± 0.2	26.6 ± 2.0	0.8 ± 0.1	9.4 ± 0.8
Z, $Zb\bar{b}$, and $t\bar{t}$	0.2 ± 0.1	0.05 ± 0.02	2.4 ± 0.5	0.6 ± 0.1	2.0 ± 0.5	0.48 ± 0.1
total background	2.4 ± 0.1	16.9 ± 1.2	4.9 ± 0.6	27.1 ± 2.0	2.8 ± 0.5	9.8 ± 0.8
data	8	23	5	23	2	13
$m_H = 123$ GeV	0.7 ± 0.1		0.8 ± 0.1		0.3 ± 0.1	
$m_H = 125$ GeV	1.0 ± 0.1		1.1 ± 0.2		0.4 ± 0.1	
$m_H = 127$ GeV	1.0 ± 0.2		1.2 ± 0.2		0.4 ± 0.1	

Low mass = [100, 160] GeV, high mass = >160 GeV

Systematics – Rate and Mass

Lepton Reconstruction and ID Efficiency

	4mu	2mu2e	2e2mu	4e
Muons: (uniform across mass range)	0.8%	0.4%	0.4%	-
Elec.: (@125 GeV)	-	8.7%	2.4%	9.4%

Affecting the mass measurement:

Elec. Energy Scale (ES) from Z->ee:
- 0.4% (0.2%) on 4e (2e2mu)

ES for low-pT muons (J/psi):
- <1%

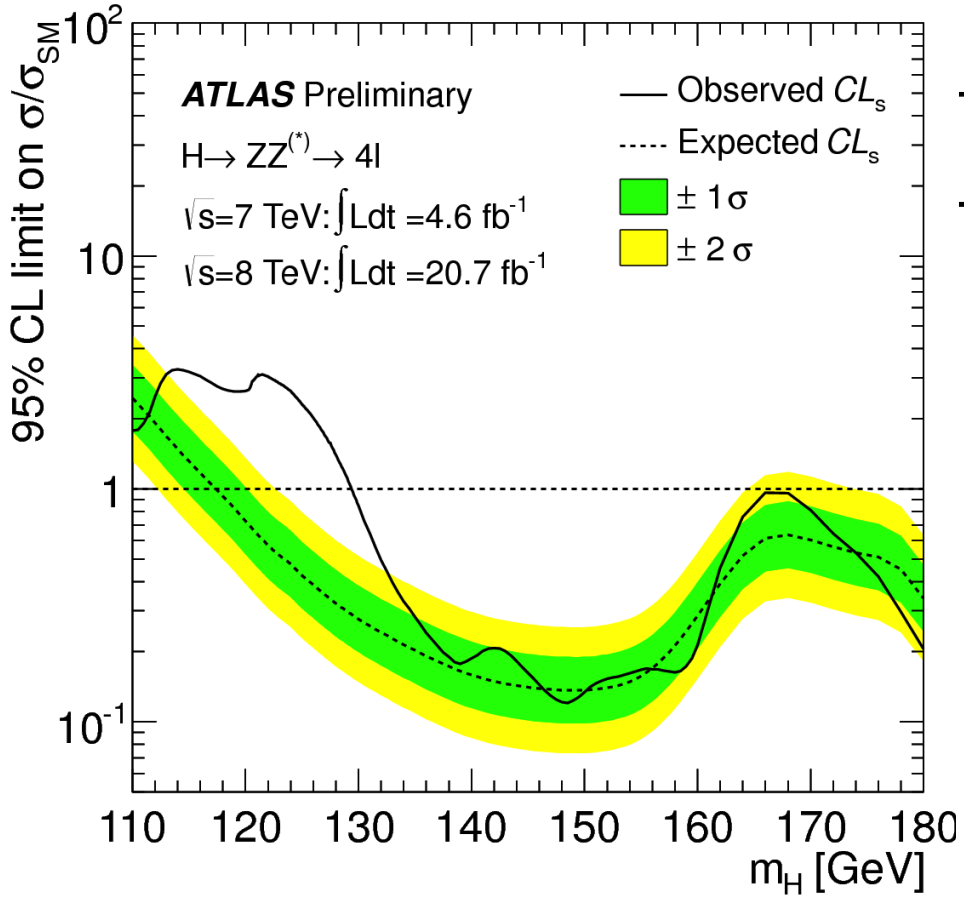
Final-state QED radiation modeling:
- <0.1%

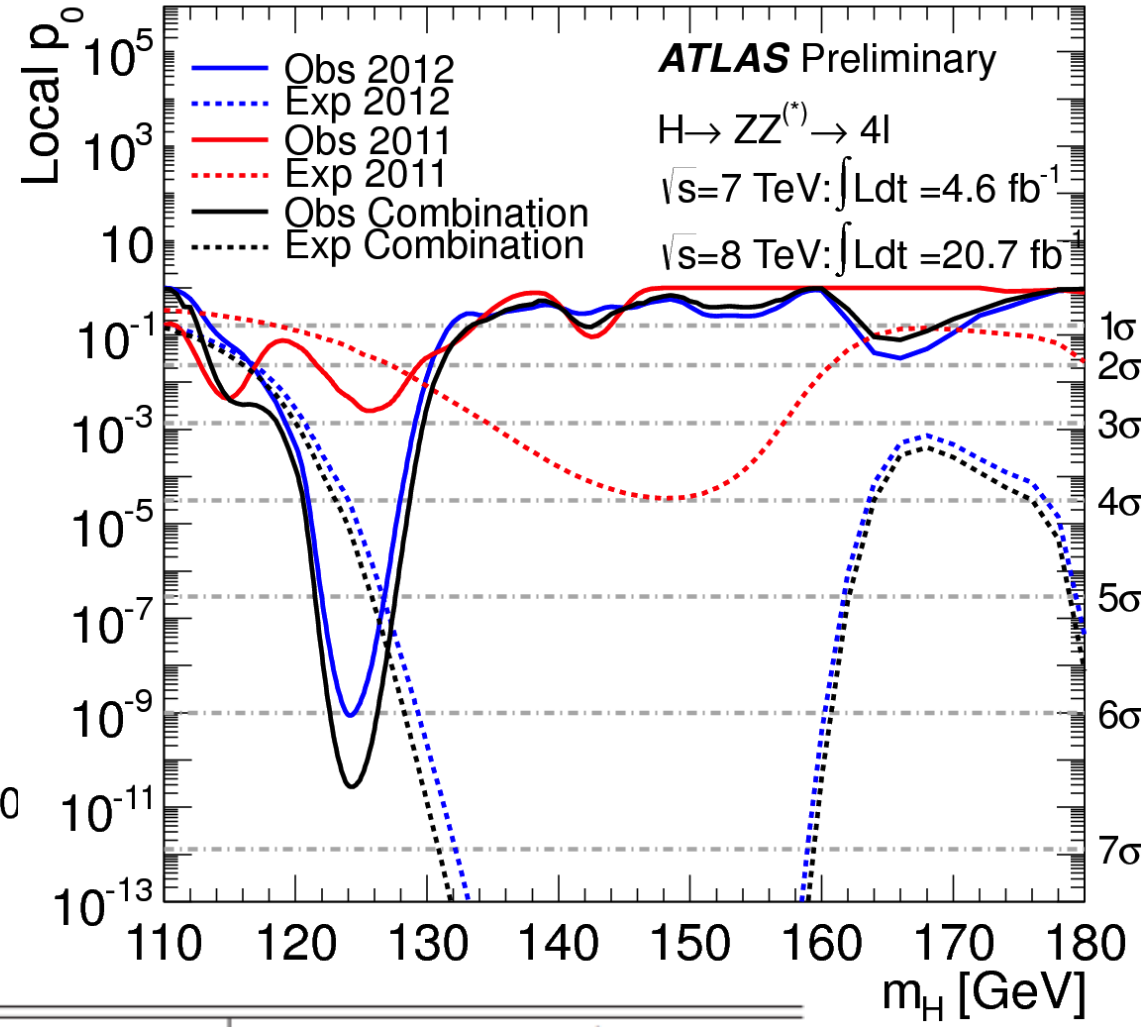
Higgs pT:
- 1%: evaluated by varying pT spectrum in ggF according to the PDF and QCD scale uncertainties.

Background estimates:
- see previous slide

Luminosity Measurement:

2011	2012
1.8%	3.6%

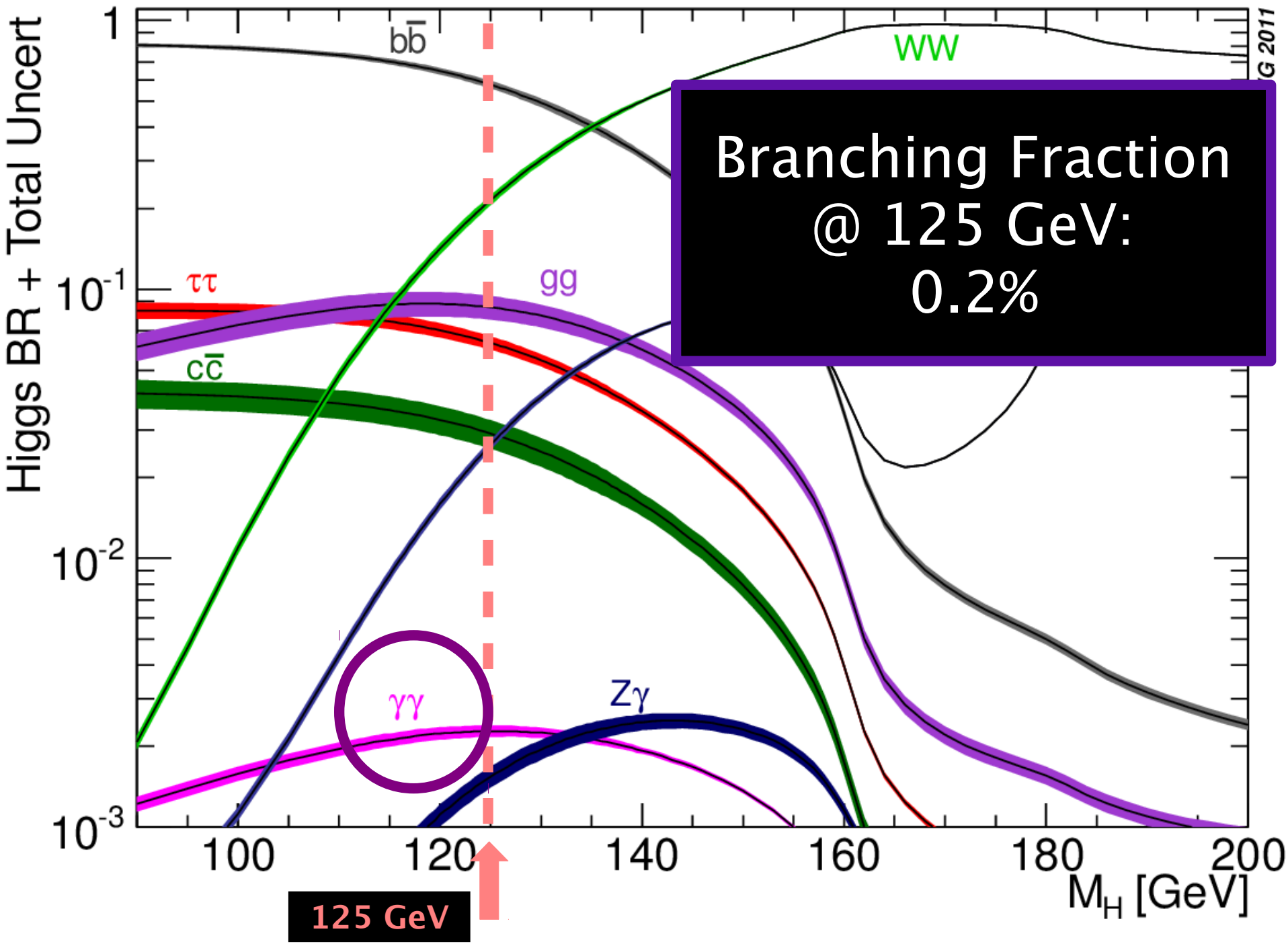


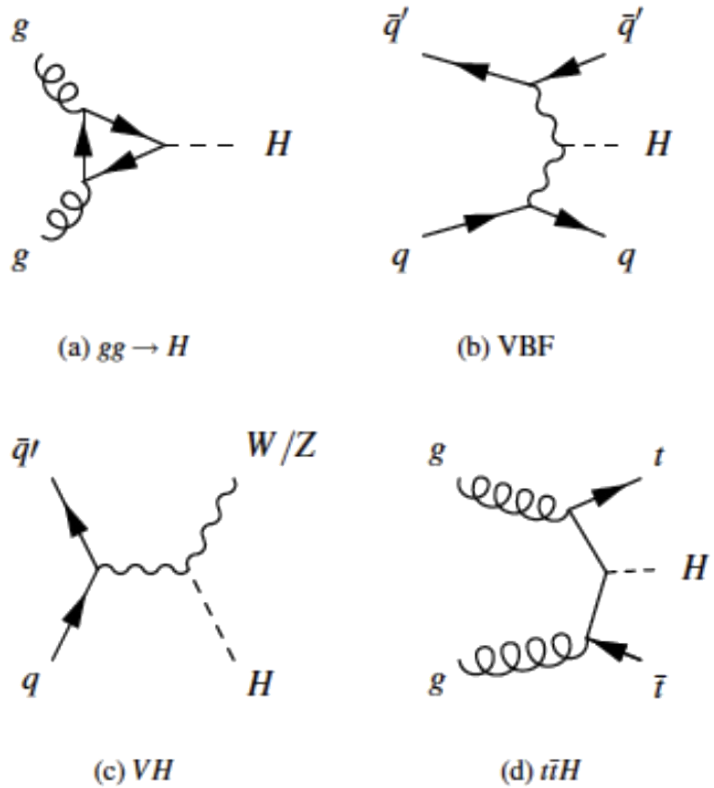


	observed			expected	
data set	min p_0	significance [σ]	$m_H(p_0)$	min $p_0(m_H)$	significance [σ]
$\sqrt{s} = 7$ TeV	2.5×10^{-3}	2.8	125.6 GeV	3.5×10^{-2}	1.8
$\sqrt{s} = 8$ TeV	8.8×10^{-10}	6.0	124.1 GeV	2.8×10^{-5}	4.0
combined	2.7×10^{-11}	6.6	124.3 GeV	5.7×10^{-6}	4.4

Everything in this section is publicly available in:
ATLAS-CONF-2013-012

$H^0 \rightarrow \gamma\gamma$

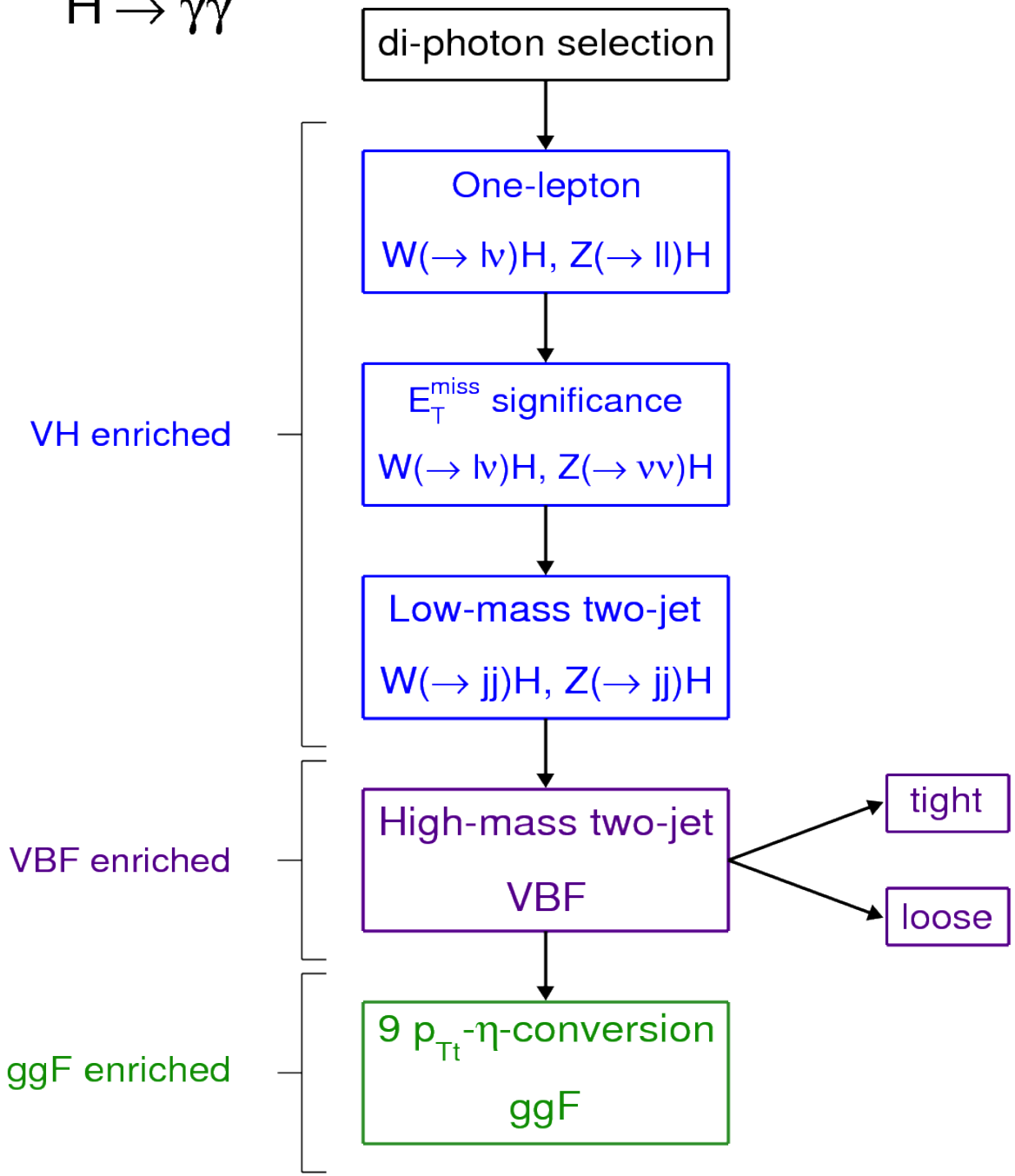

Higgs BR + Total Uncert
1
10^{-1}
10^{-2}
10^{-3}
$b\bar{b}$
WW
$\tau\tau$
gg
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$
100
120
140
160
180
200
M_H [GeV]
125 GeV
Branching Fraction
@ 125 GeV:
0.2%



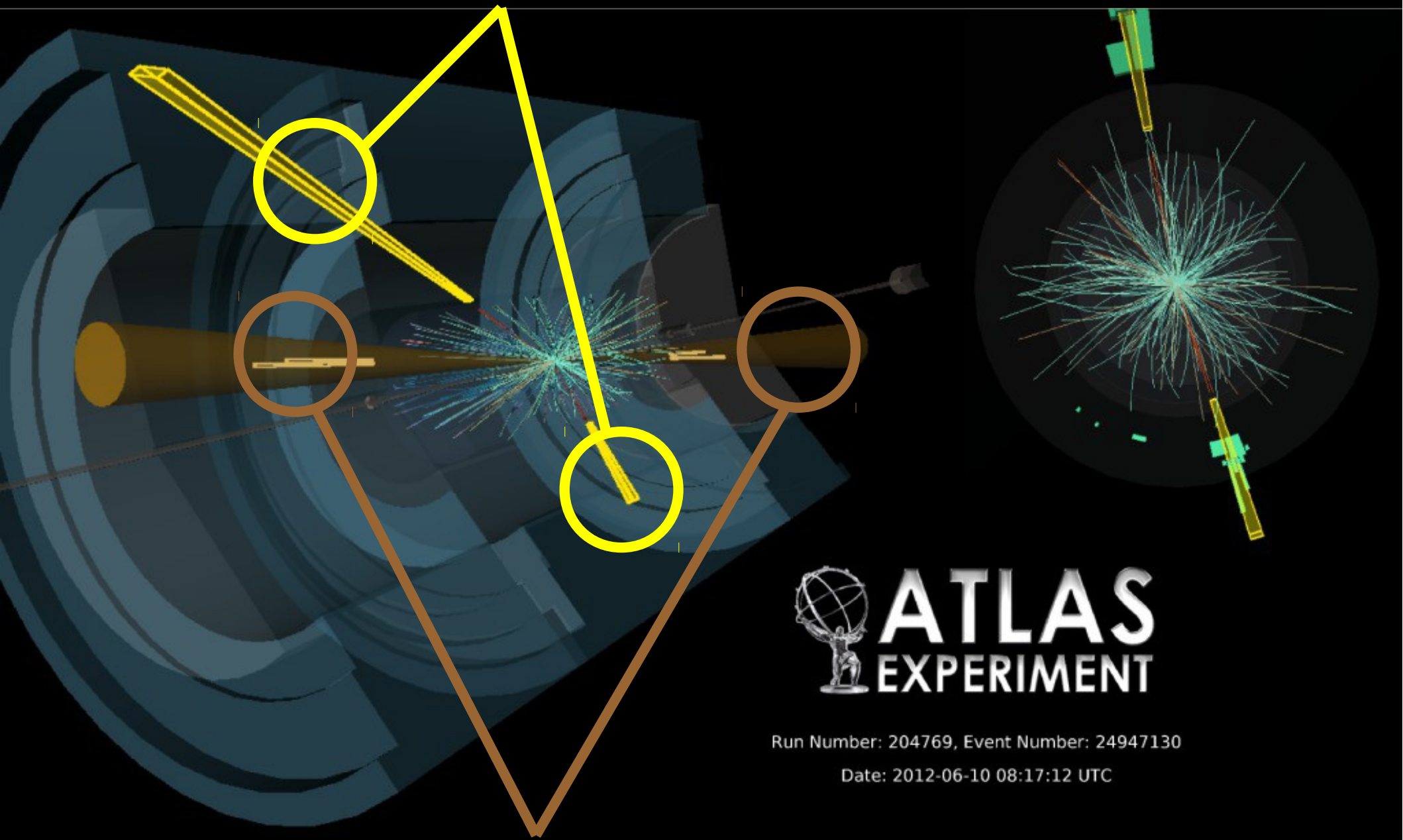
Categorization allows for events with different signal-to-background ratios to be treated separately, and finally for the couplings of the Higgs to be assessed.

ATLAS Preliminary

$H \rightarrow \gamma\gamma$



Well-isolated calorimeter deposits



High-mass, high-η (non-central) jets

Trigger p_T [GeV] thresholds

2012

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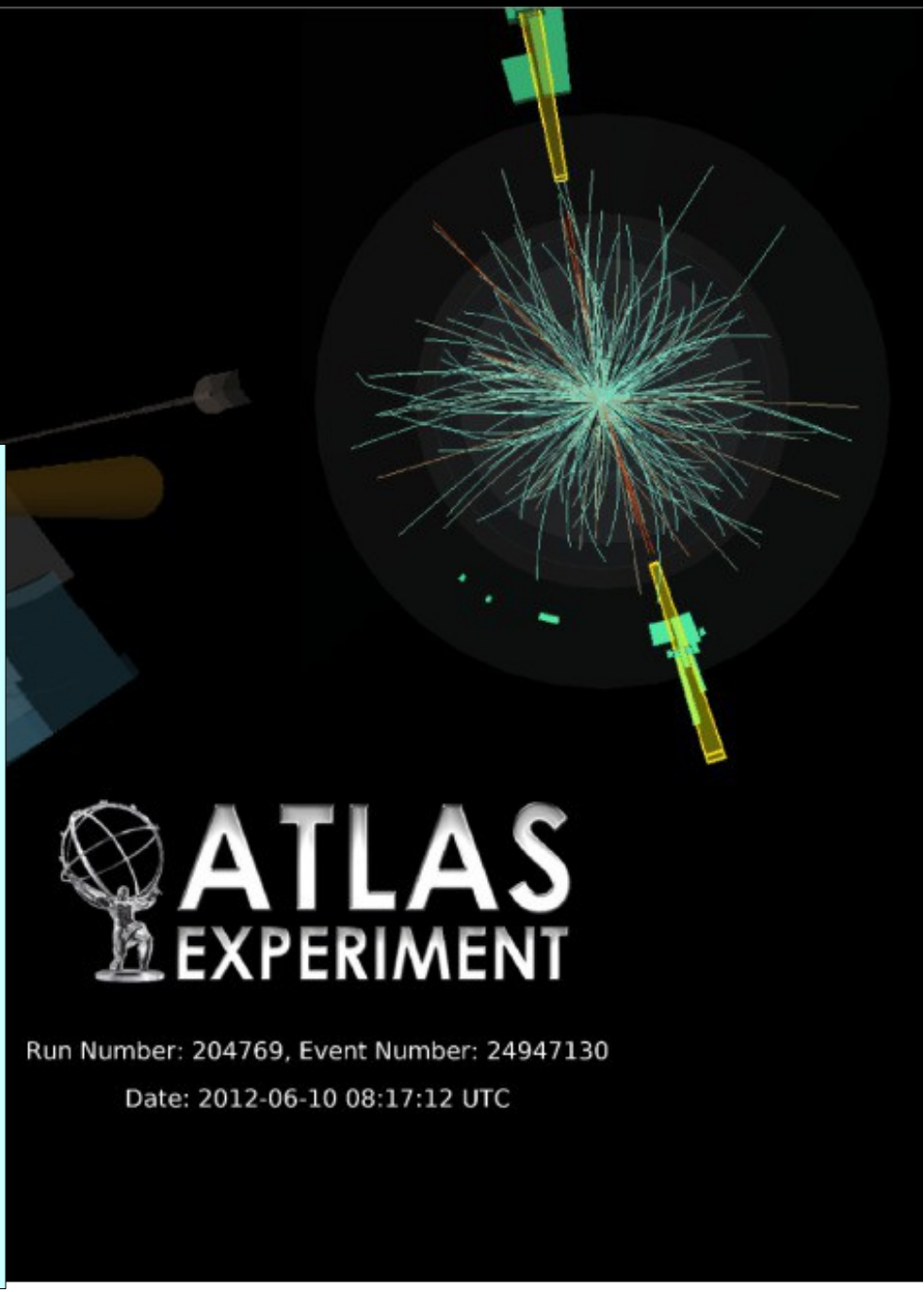
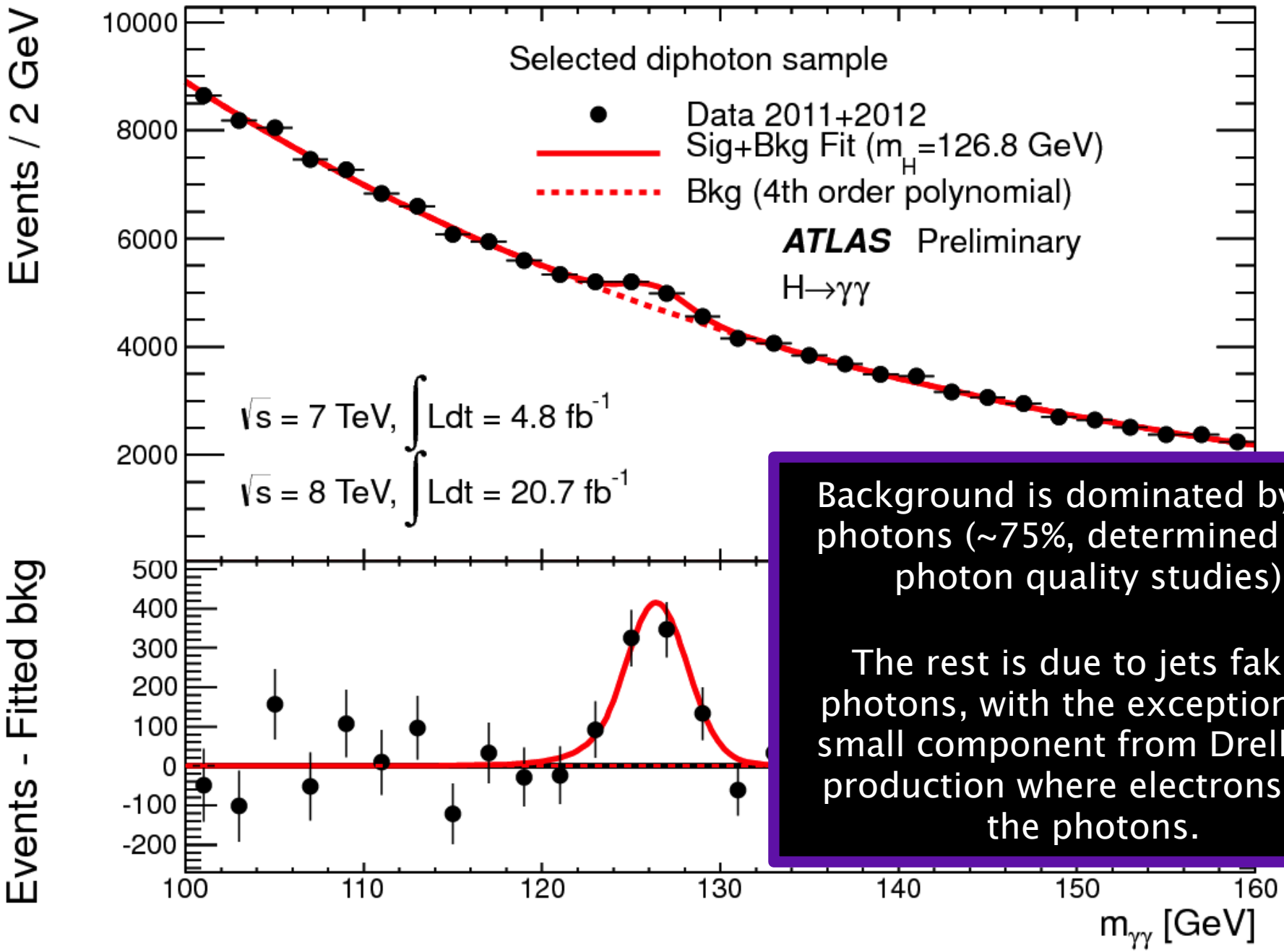
di-photon 25 and 35

(99% efficient on signal passing final selection)

Photon Reconstruction

- EM cluster without associated ID track ("unconverted") or associated with tracks consistent with in-material conversion ("converted")
- pT(1) > 40 and pT(2) > 30
- $|\eta| < 2.37$ excluding [1.37,1.56]
- Well-isolated
- Longitudinal calorimeter segmentation (and conversion vertex, for converted photons) used to determine primary vertex that yielded the photon





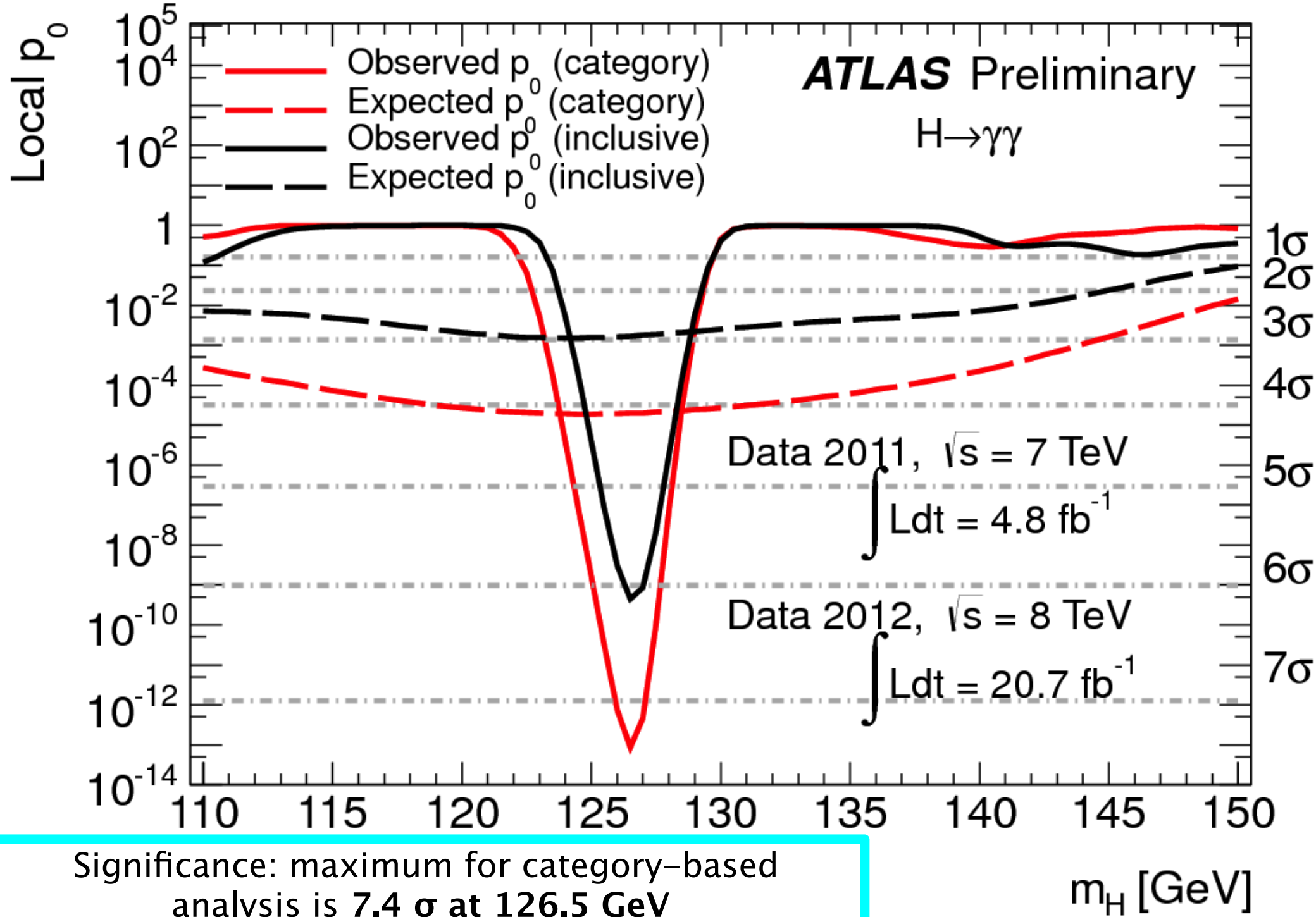
Background is dominated by real photons (~75%, determined from photon quality studies).

The rest is due to jets faking photons, with the exception of a small component from Drell-Yan production where electrons fake the photons.

Systematics – Rate and Mass

Systematic uncertainties	Value(%)			Constraint
Luminosity	±3.6			
Trigger	±0.5			
Photon Identification	±2.4			Log-normal
Isolation	±1.0			
Photon Energy Scale	±0.25			
Branching ratio	±5.9% – ±2.1% (m_H = 110 - 150 GeV)			Asymmetric Log-normal
Scale	ggF: $^{+7.2}_{-7.8}$	VBF: $^{+0.2}_{-0.2}$	WH: $^{+0.2}_{-0.6}$	Asymmetric
	ZH: $^{+1.6}_{-1.5}$	ttH: $^{+3.8}_{-9.3}$		Log-normal
PDF+α_s	ggF: $^{+7.5}_{-6.9}$	VBF: $^{+2.6}_{-2.7}$	WH: ±3.5	Asymmetric
	ZH: ±3.6	ttH: ±7.8		Log-normal
Theory cross section on ggF	Tight high-mass two-jet:		±48	Log-normal
	Loose high-mass two-jet:		±28	
	Low-mass two-jet:		±30	

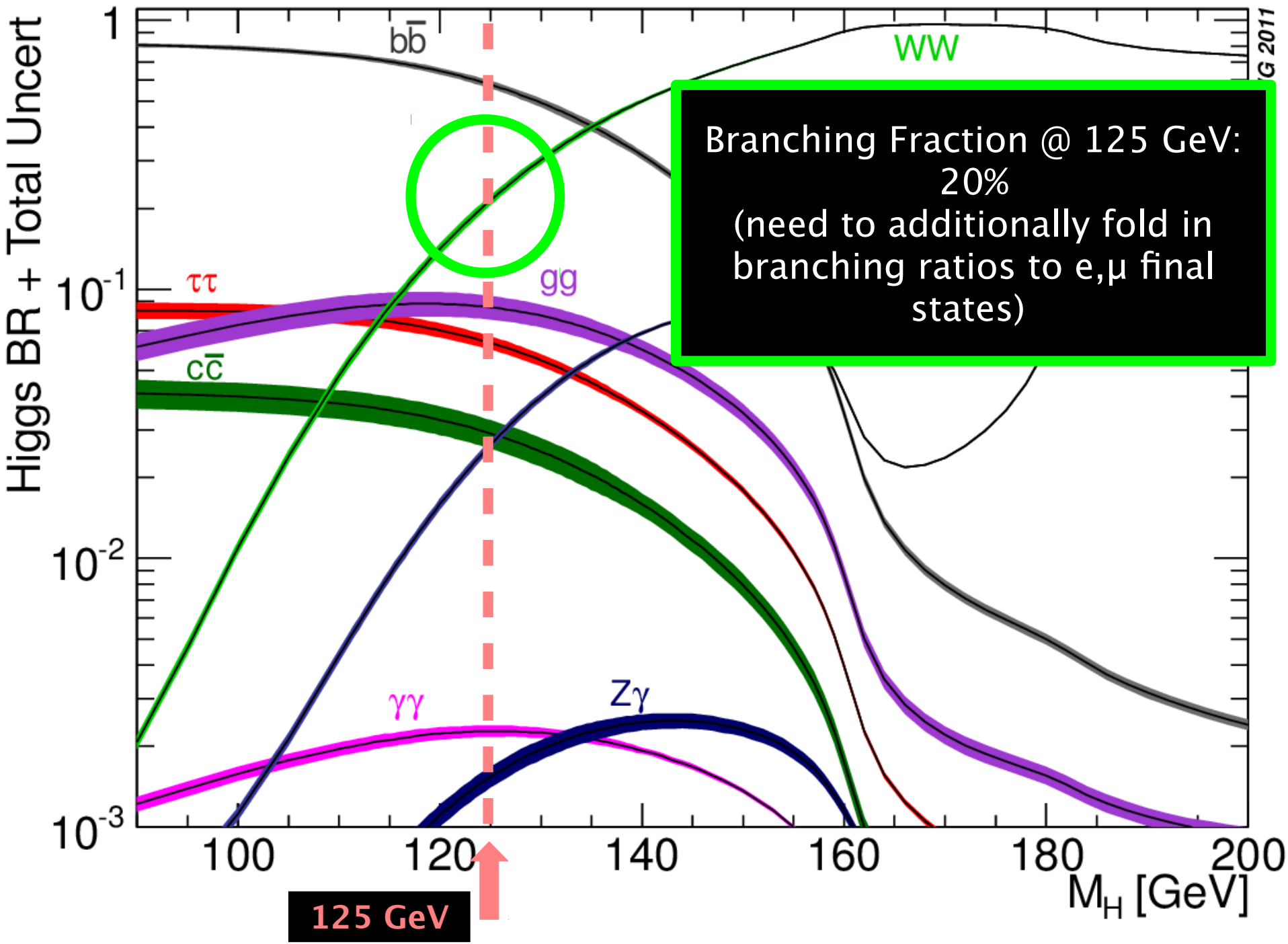
There are also systematics associated with category migration that I don't discuss here.

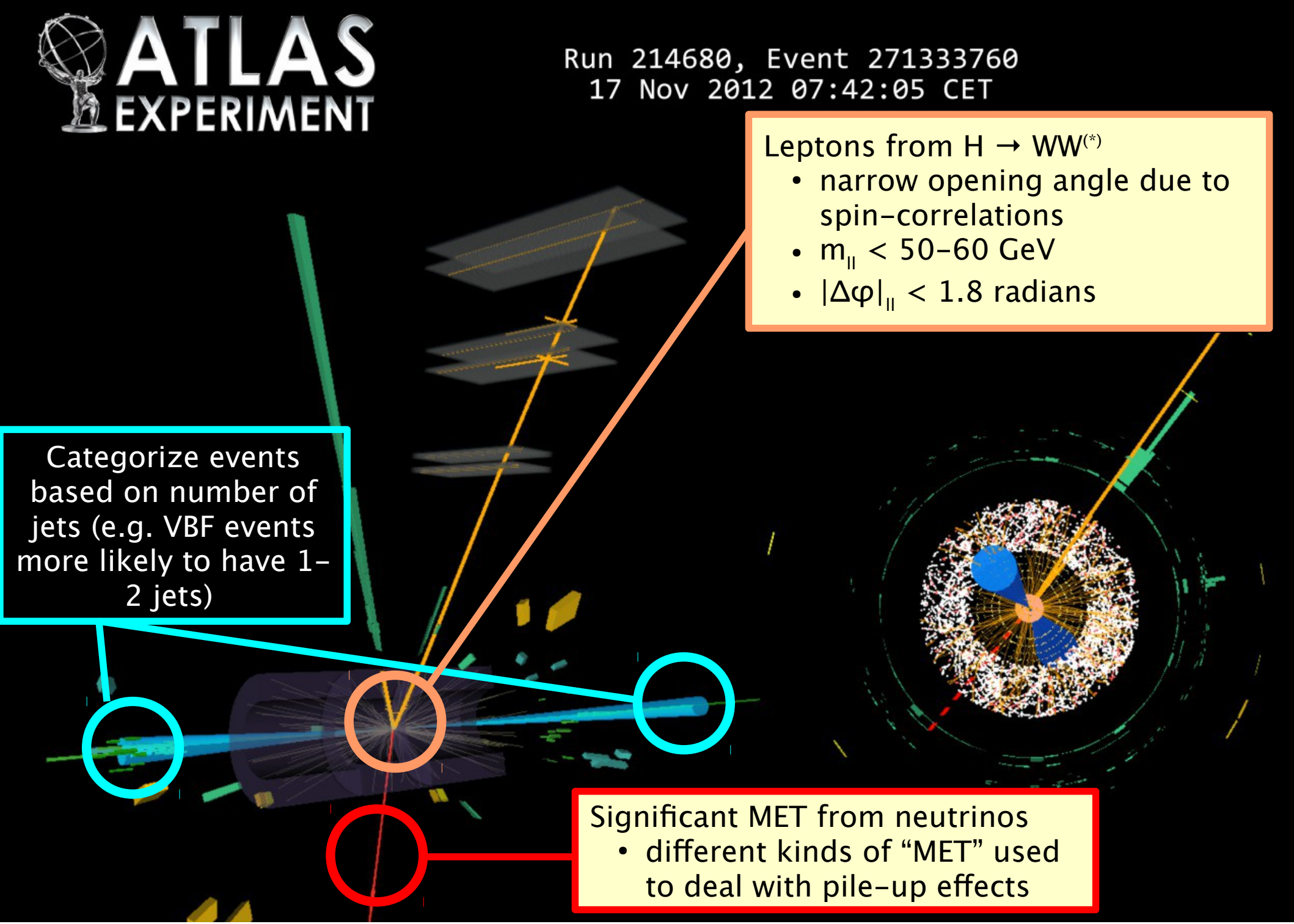


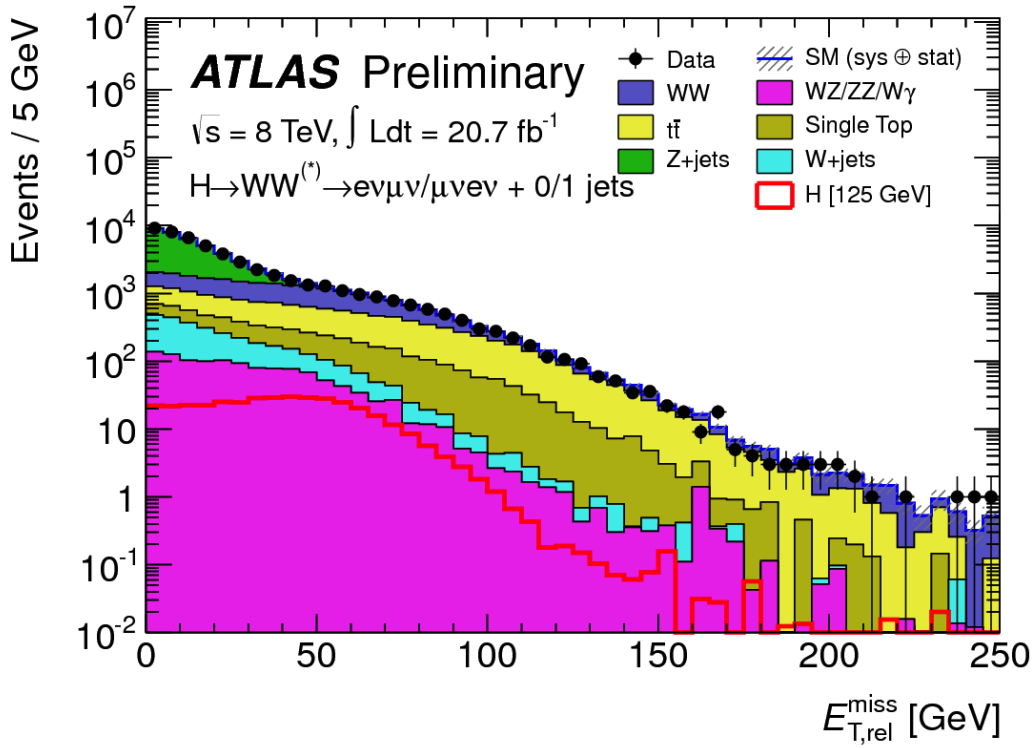
Significance: maximum for category-based analysis is **7.4 σ at 126.5 GeV**

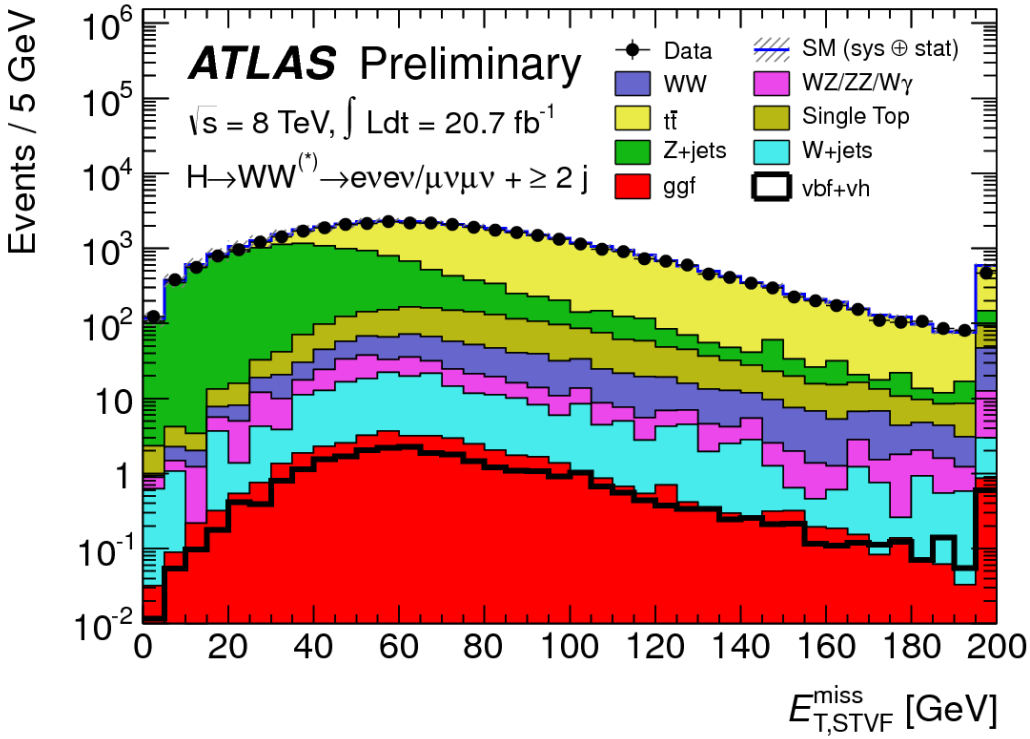
Everything in this section is publicly available in:
ATLAS-CONF-2013-030

$H^0 \rightarrow W^{\pm}W^{\mp(*)}$


Higgs BR + Total Uncert
1
10^{-1}
10^{-2}
10^{-3}
$b\bar{b}$
WW
ττ
gg
$c\bar{c}$
γγ
Zγ
100
120
140
160
180
200
M_H [GeV]
125 GeV
Branching Fraction @ 125 GeV: 20%
(need to additionally fold in branching ratios to e,μ final states)


ATLAS EXPERIMENT
Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET
Leptons from H → WW(*)
• narrow opening angle due to spin-correlations
• m_{ll} < 50-60 GeV
• $|\Delta\varphi|_{ll}$ < 1.8 radians
Categorize events based on number of jets (e.g. VBF events more likely to have 1-2 jets)
Significant MET from neutrinos
• different kinds of "MET" used to deal with pile-up effects



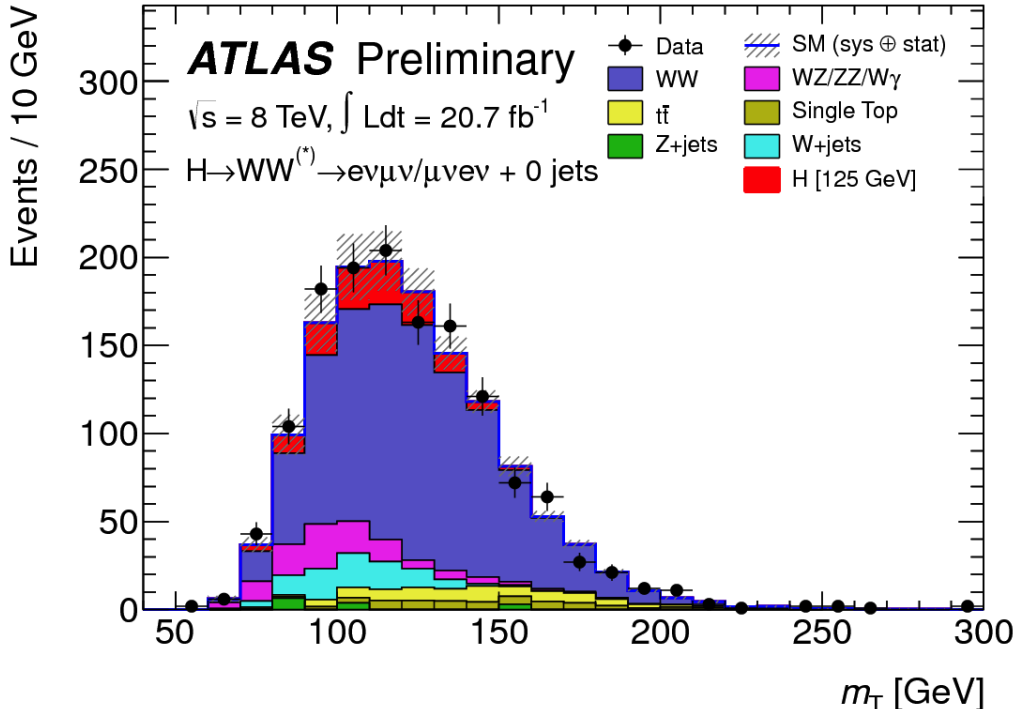


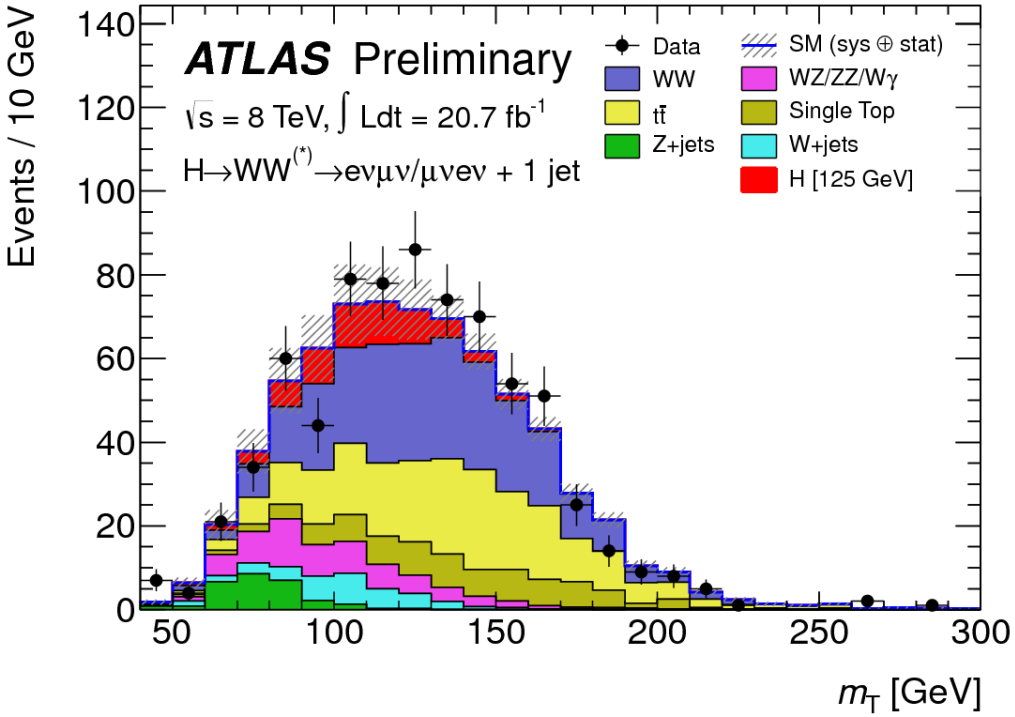
Major backgrounds are:

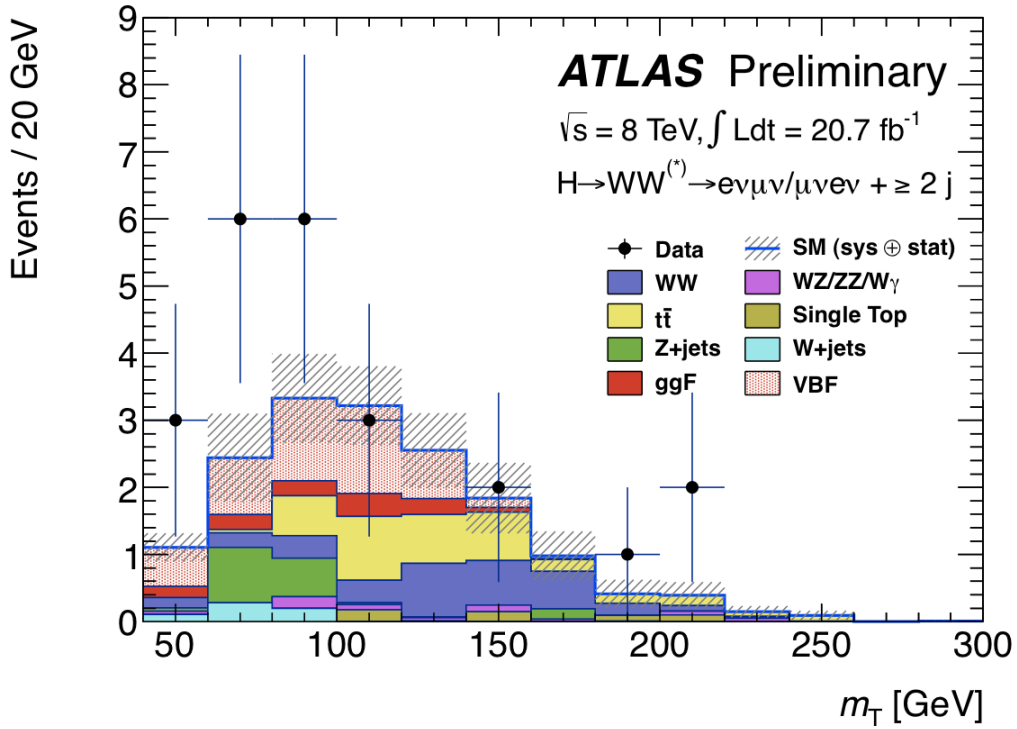
- Z+jets, WW, top, diboson

Strategy:

- Define Control Regions (CR) rich in specific sources
- Constrain the amount in the Signal Region based on CR studies

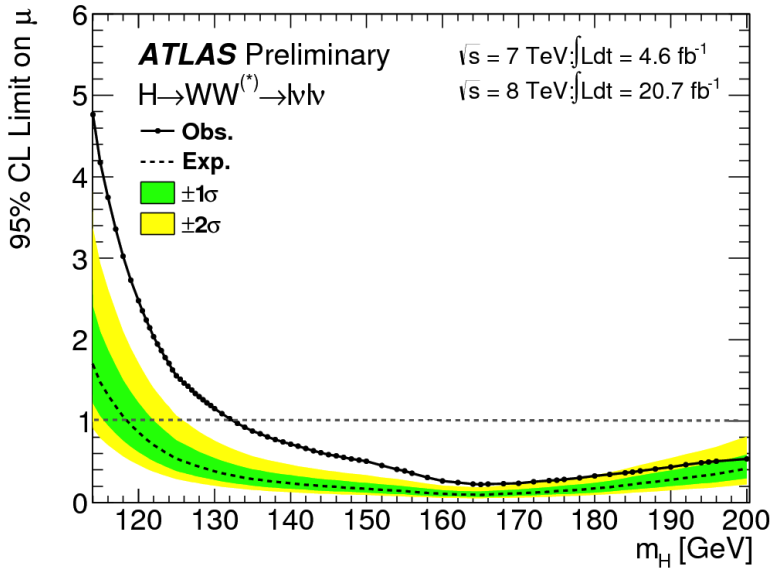


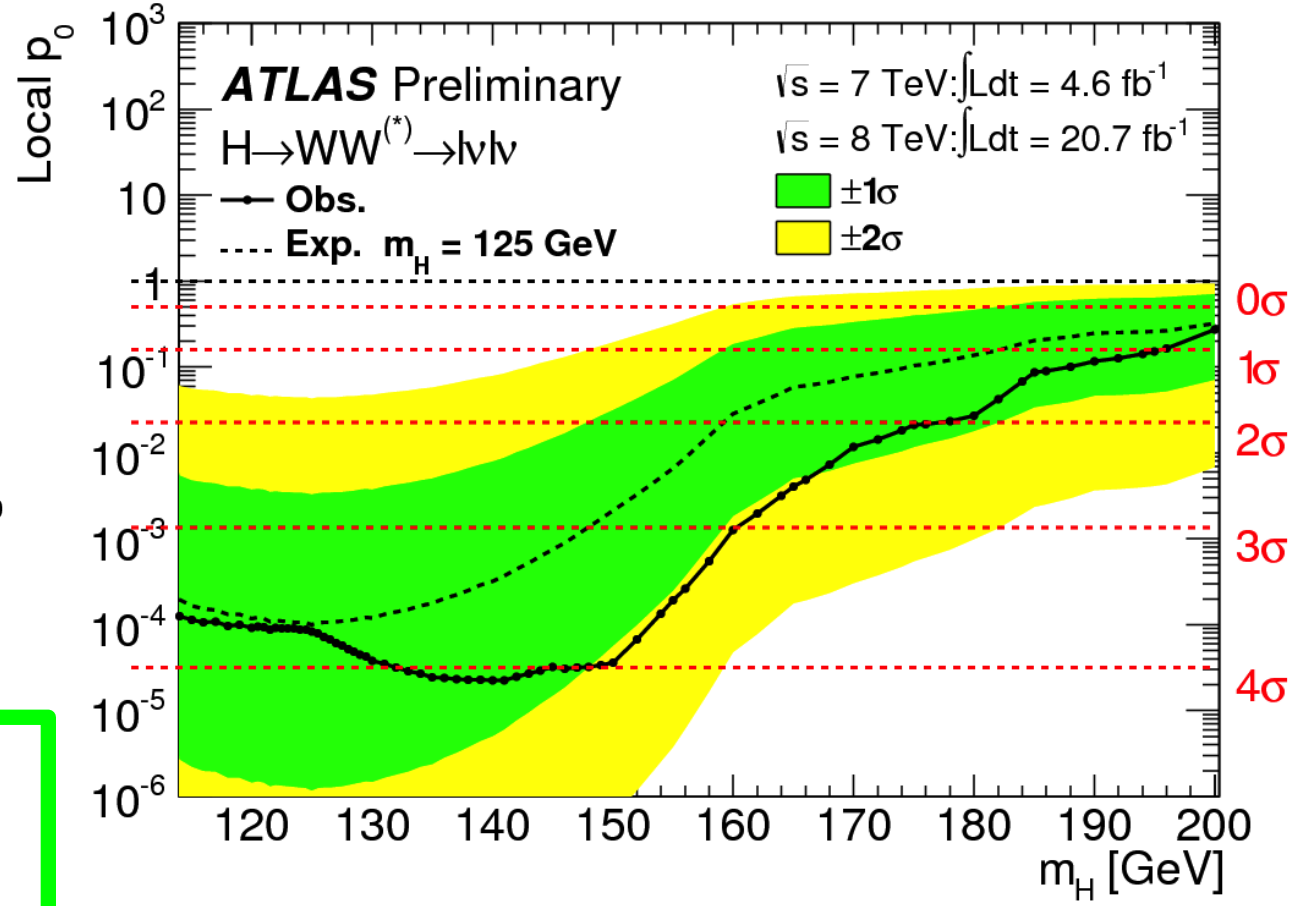




Signal Region in 8 TeV Data

Taking into account background estimates, the data clearly support the presence of a contribution in addition to the projected non-Higgs backgrounds.





Significance:

Combined Categories:

@125 GeV: 3.7σ

(p-value = 1×10^{-4})

VBF Only:

@125 GeV: 2.5σ

(p-value = 0.006)

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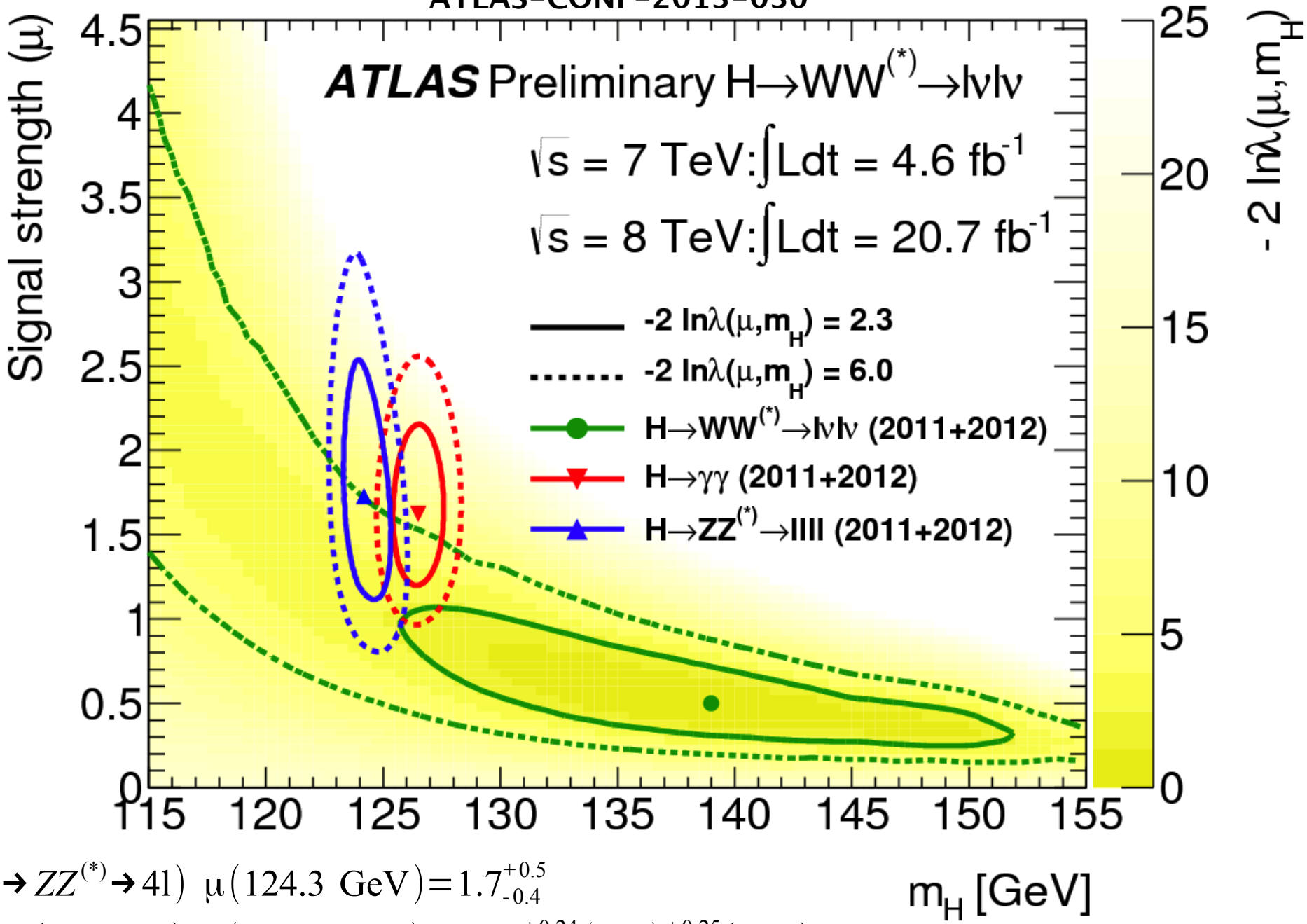
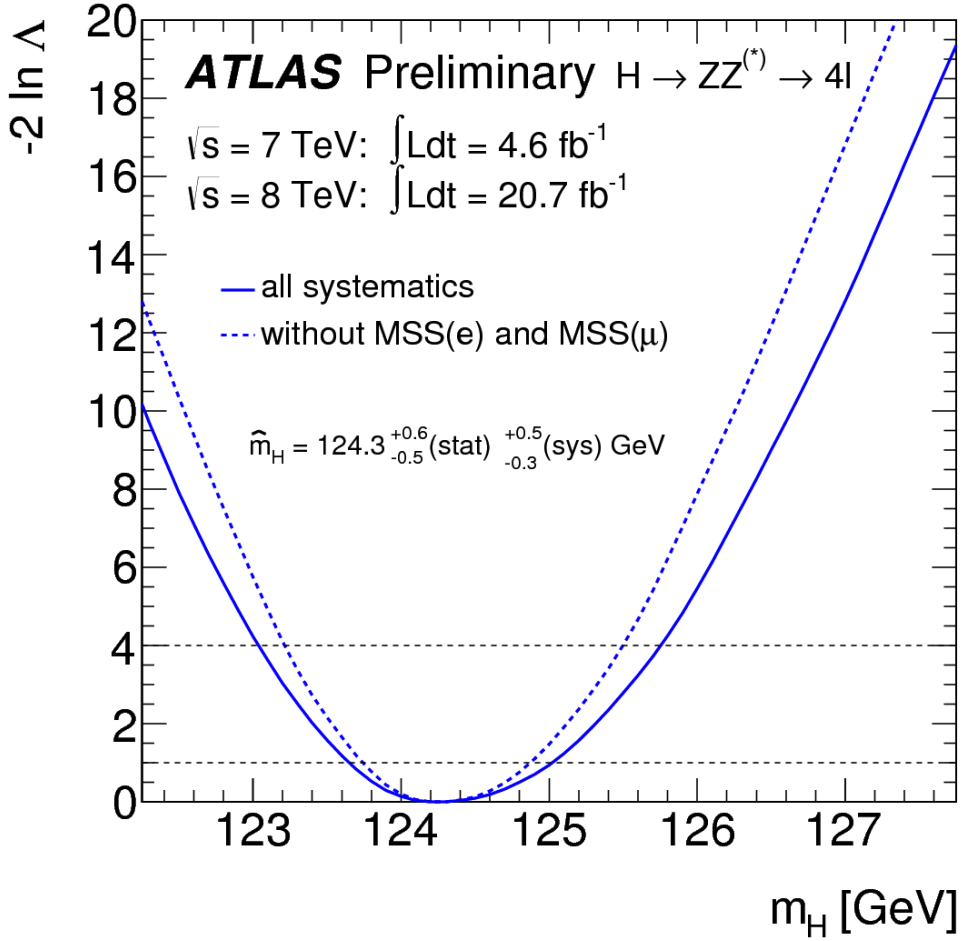


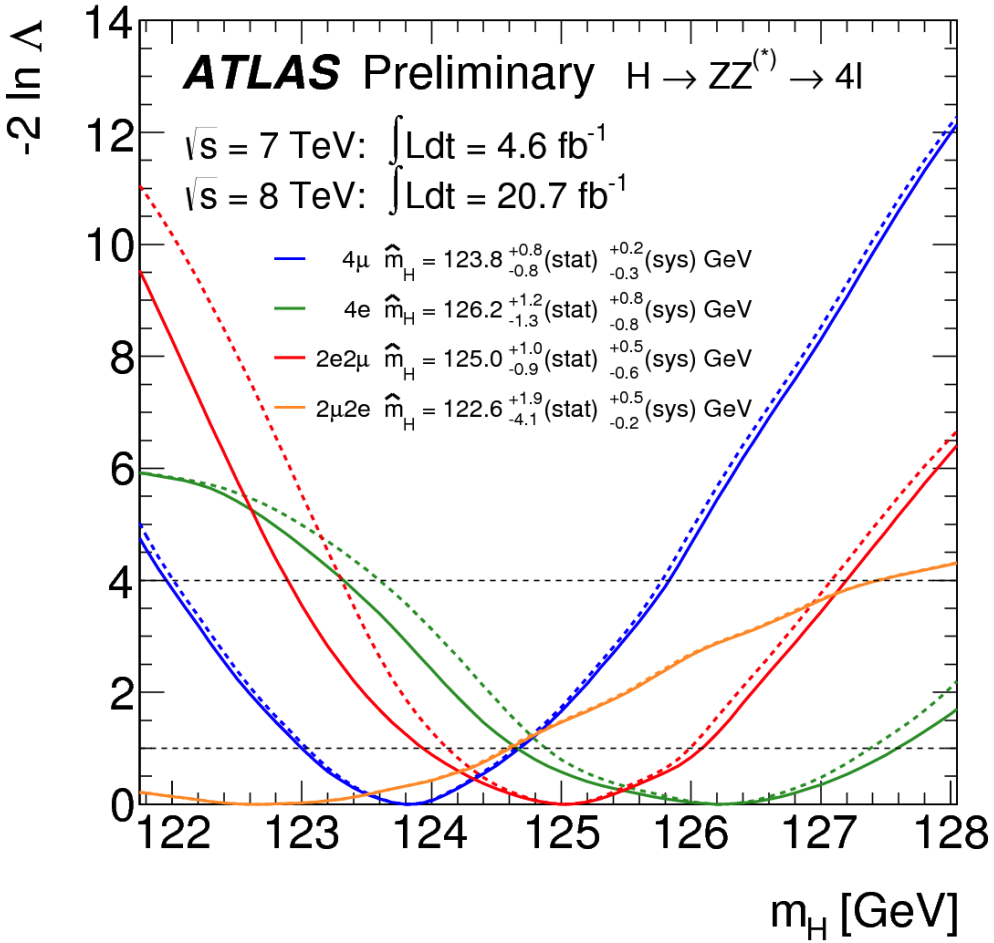
$(H \to ZZ^{(*)} \to 4l)$ $\mu(124.3\ \text{GeV}) = 1.7^{+0.5}_{-0.4}$

$(H \to \gamma\gamma)$ $\mu(126.8\ \text{GeV}) = 1.65^{+0.24}_{-0.24}(\text{stat})^{+0.25}_{-0.18}(\text{syst})$

$(H \to WW)$ $\mu(125) = 1.01 \pm 0.21(\text{stat}) \pm 0.19(\text{theory}) \pm 0.12(\text{syst}) \pm 0.04(\text{lumi})$

Mass

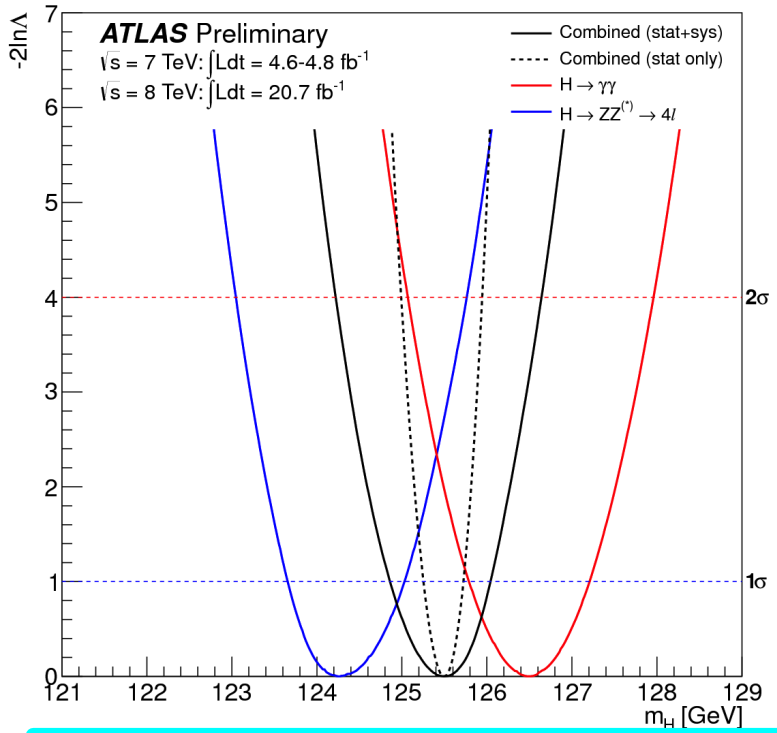


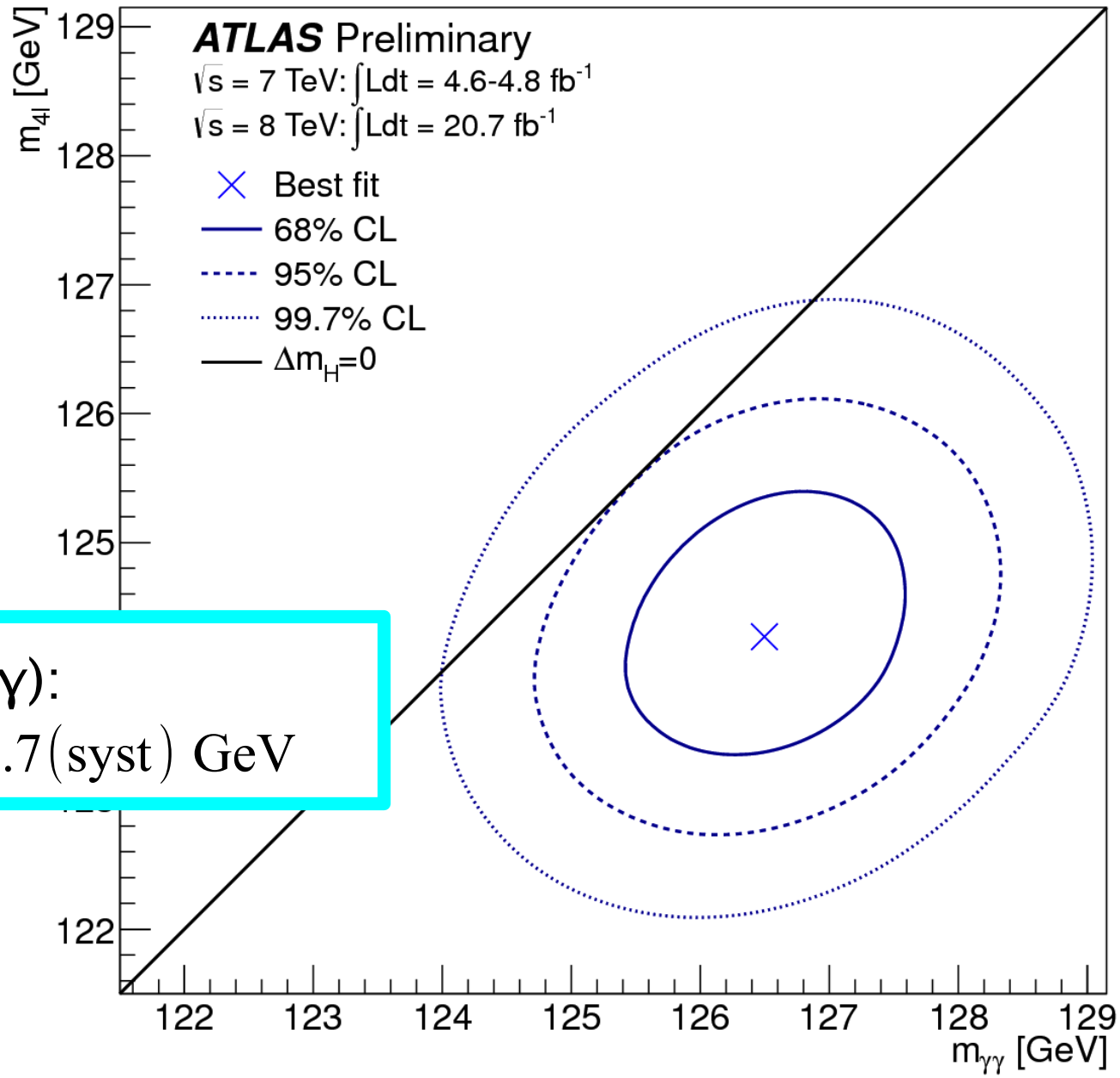


Describe the mass distributions using smooth, non-parametric unbinned estimates of prob. density functions for signal from simulation, and vary the background shapes within uncertainties to obtain shape systematics

Combining all channels:

$$m_H = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})\ \text{GeV}$$





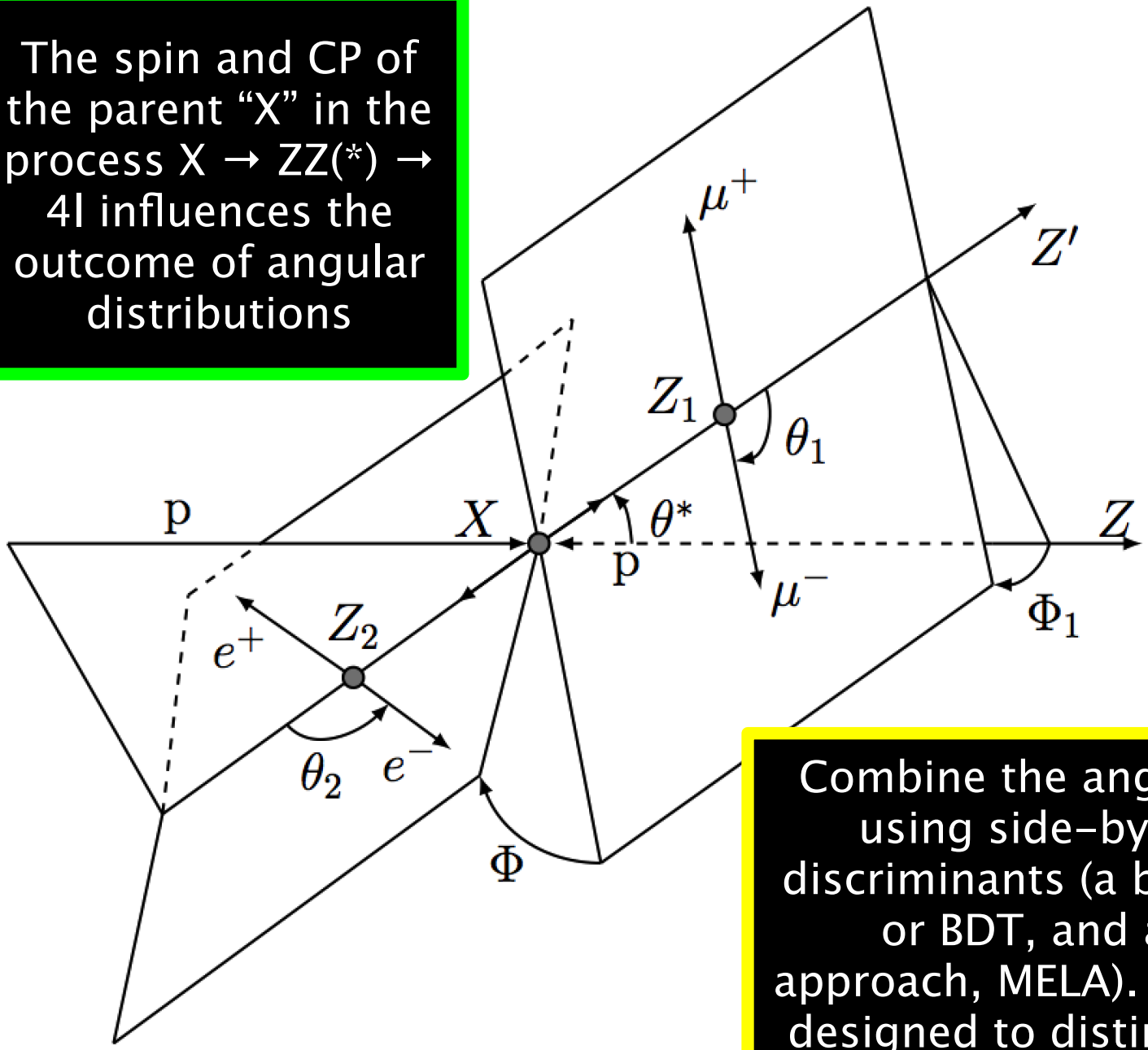
Mass (H → γγ):

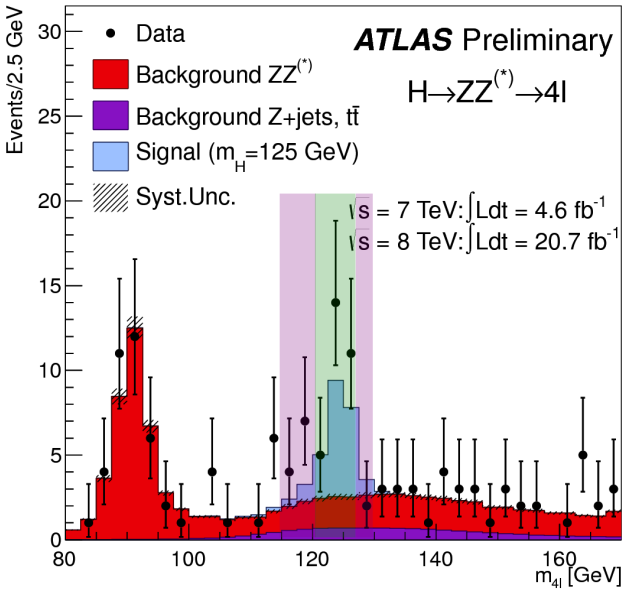
$$m_H = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})\ \text{GeV}$$

$$m_H^{combined} = 125.5 \pm 0.2(\text{stat}) \pm {}^{+0.5}_{-0.6}(\text{syst})$$

Spin and Parity Quantum Numbers

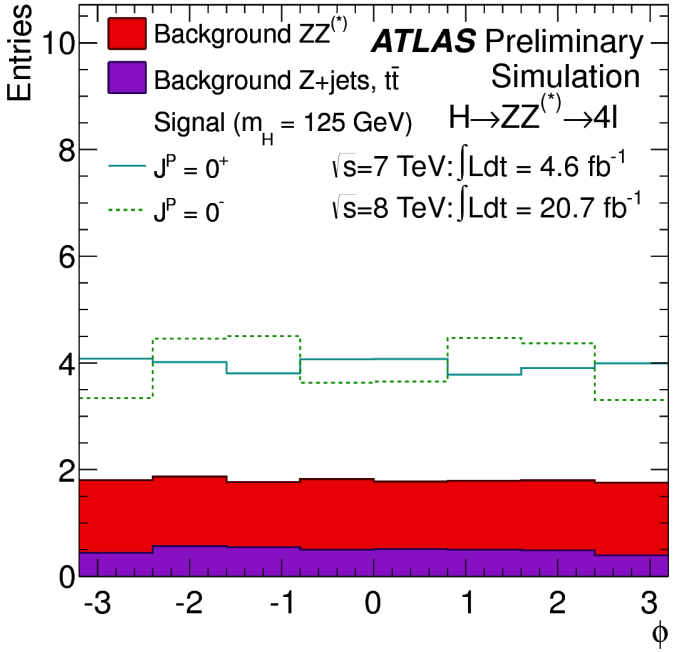
The spin and CP of the parent "X" in the process X → ZZ(*) → 4l influences the outcome of angular distributions



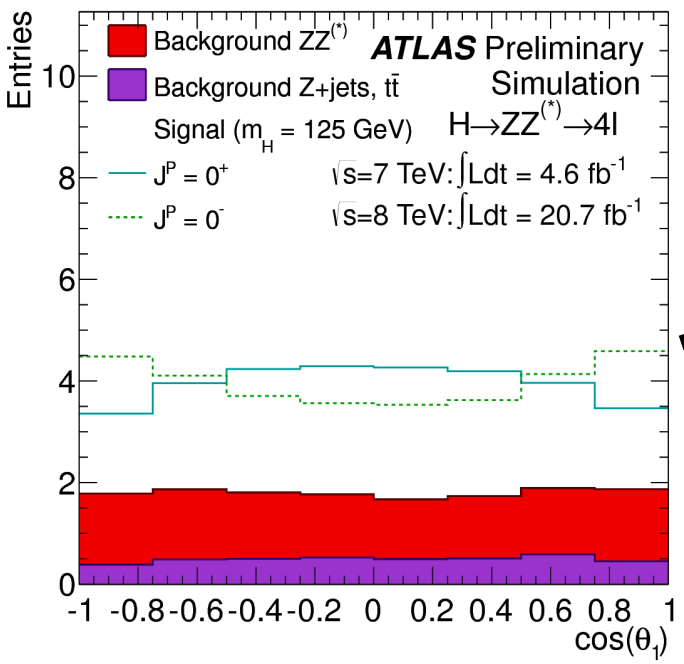


Use data only from [115-130], split into **low-signal** and **high-signal** regions

Combine the angles illustrated above using side-by-side multivariate discriminants (a boosted decision tree, or BDT, and a matrix element approach, MELA). The discriminants are designed to distinguish different pairs of spin-CP hypotheses: 0^+, 0^-, 1^+, 1^-, 2^+_m, and 2^-



Angle between Z_1, Z_2 decay planes



Angle between l_1l_2 decay plane and the plane defined by Z_2,z-axis

etc.

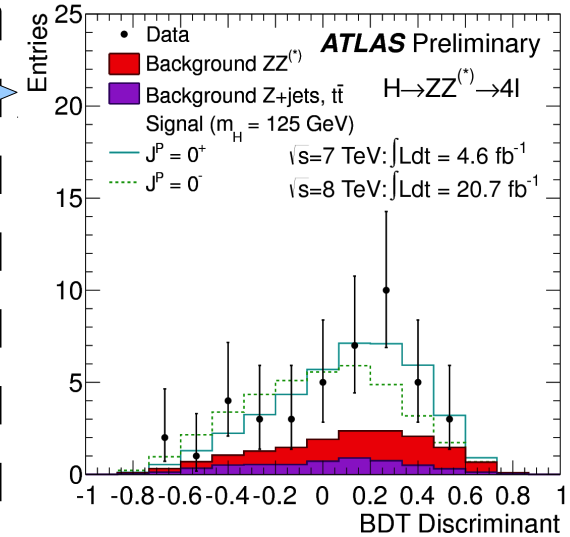
BDT

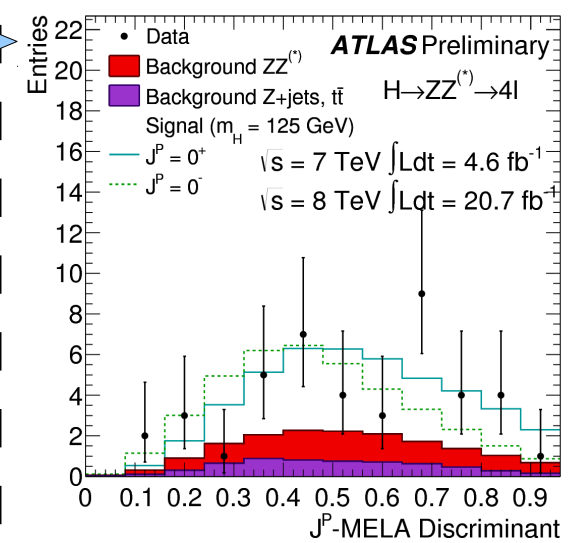
Trained on signal events in mass window using Φ, θ_1, θ_2, m_{12}, m_{34} for 0^+ vs. 0^-; add θ^* and Φ_1 for the spin-1 and spin-2 training.

or

MELA

Compute exact probability for a spin-CP state for each event, corrected for acceptance and selection





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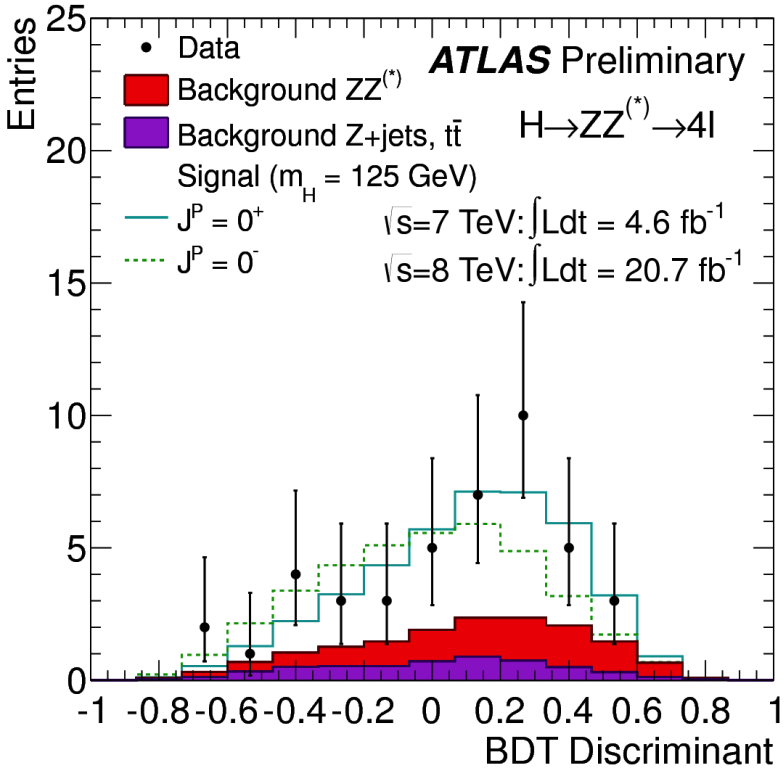
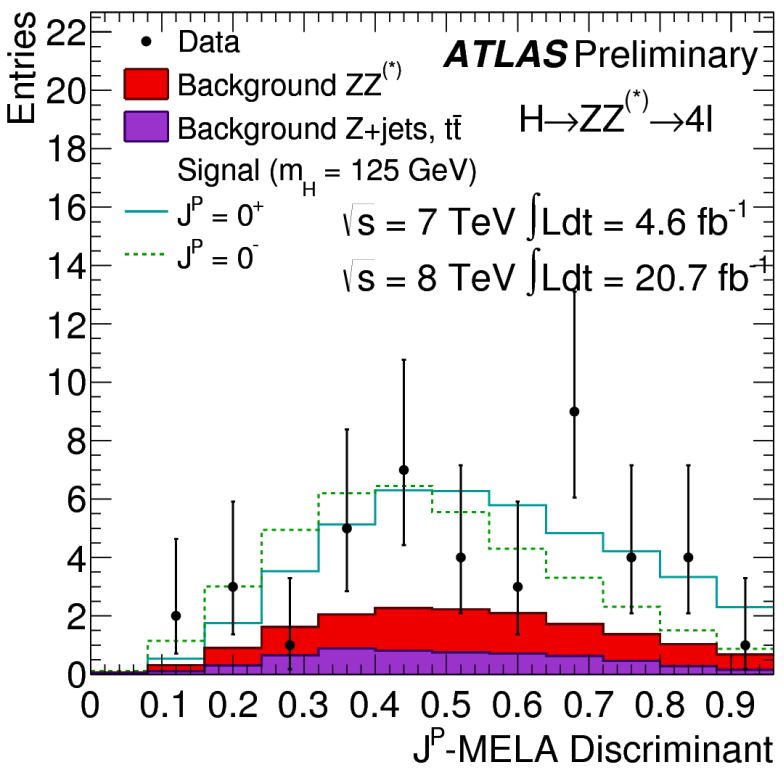
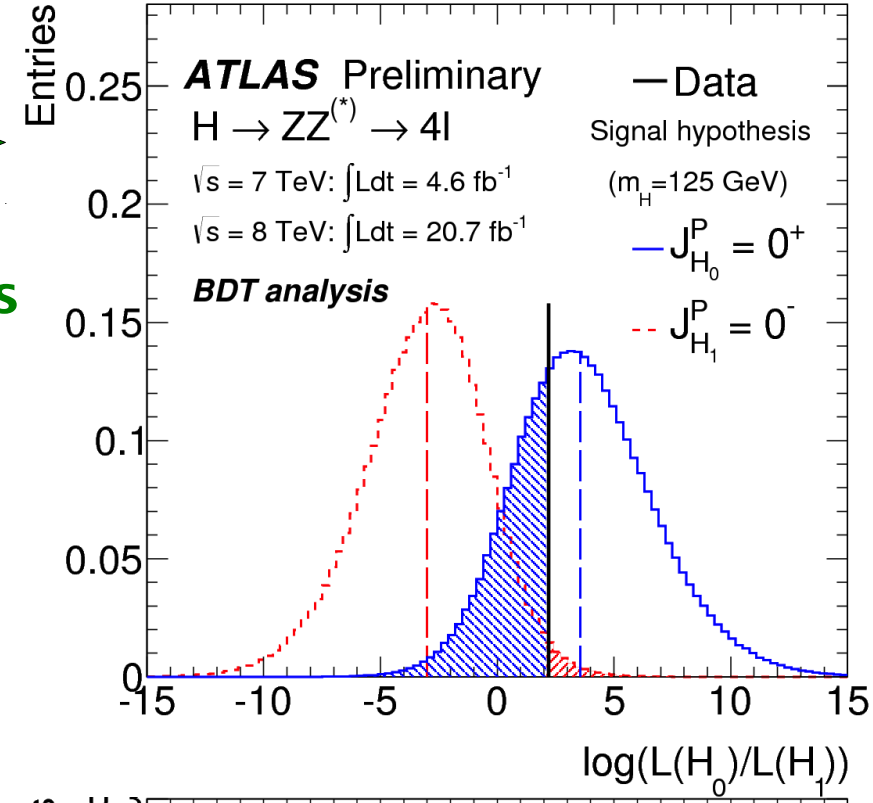
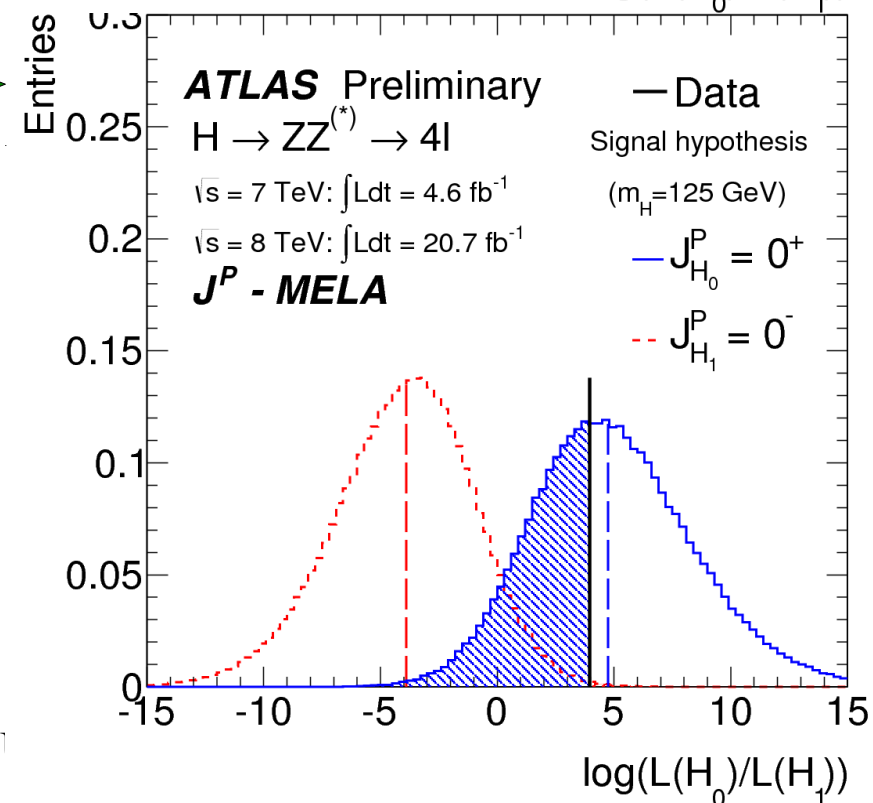
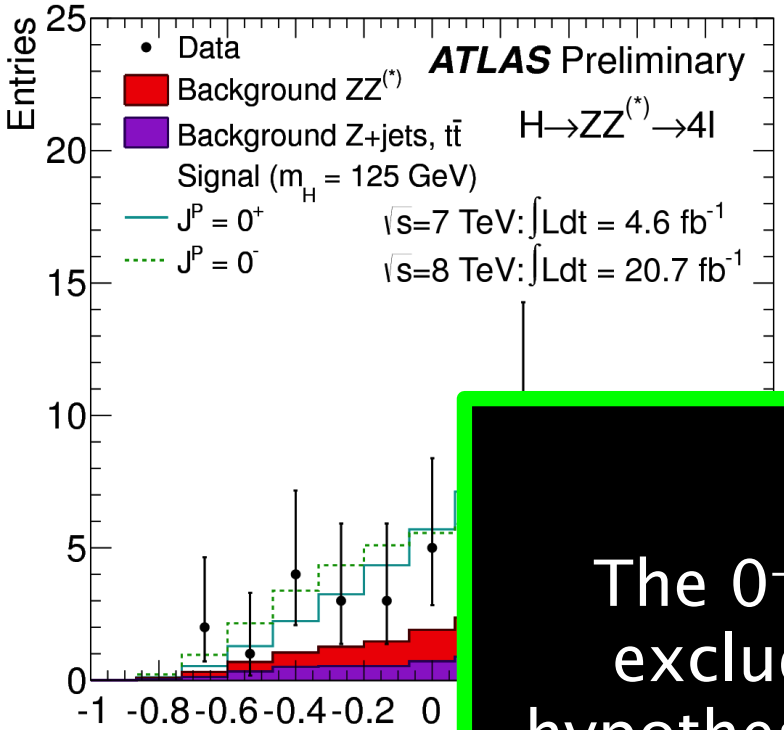


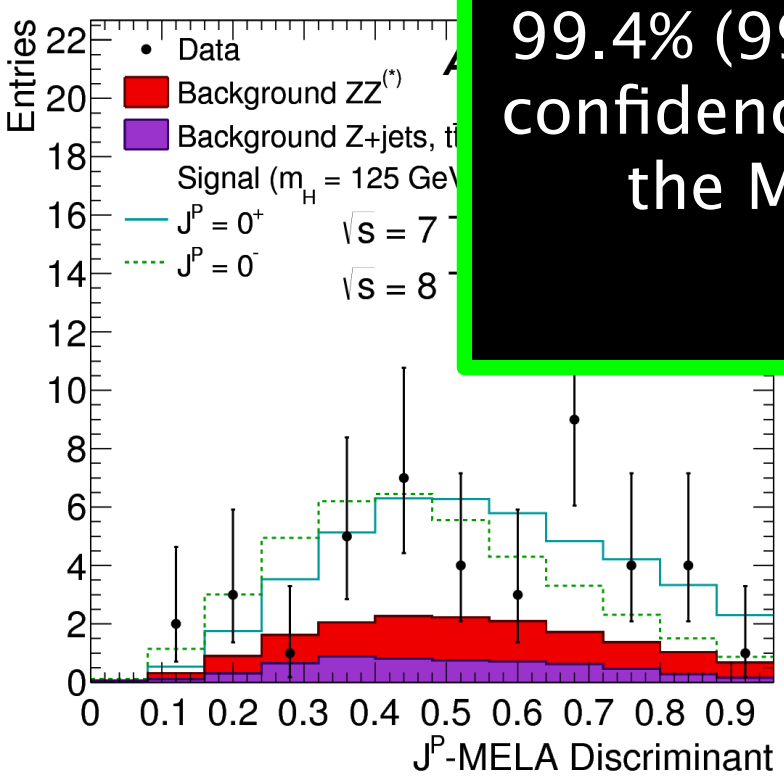


Use ensembles of 500,000 pseudo-experiments to assess separation of the two hypotheses

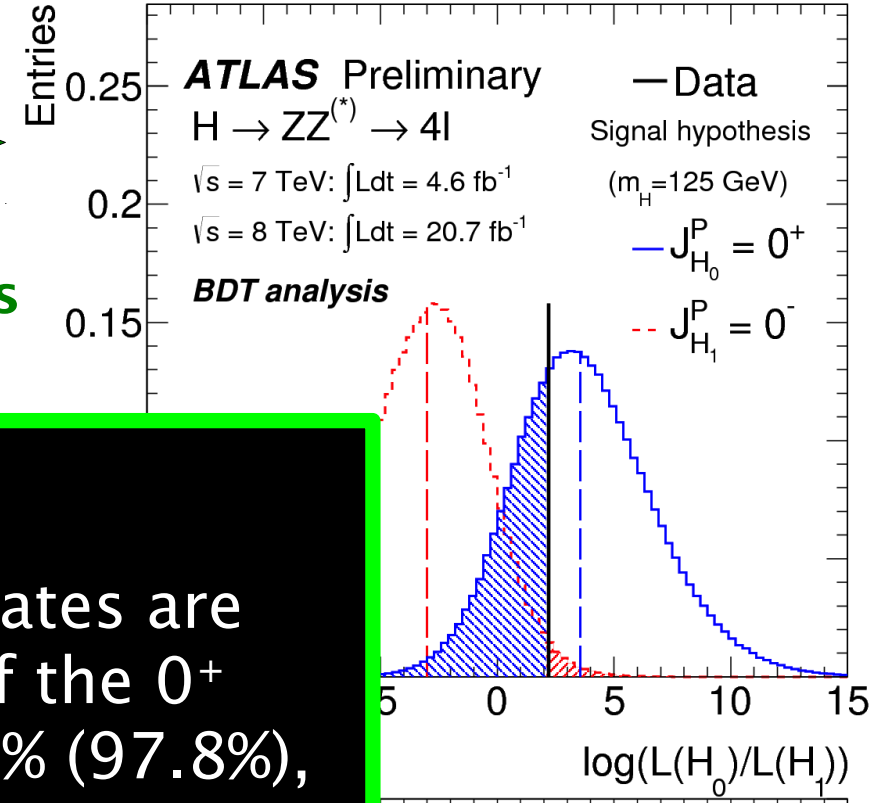


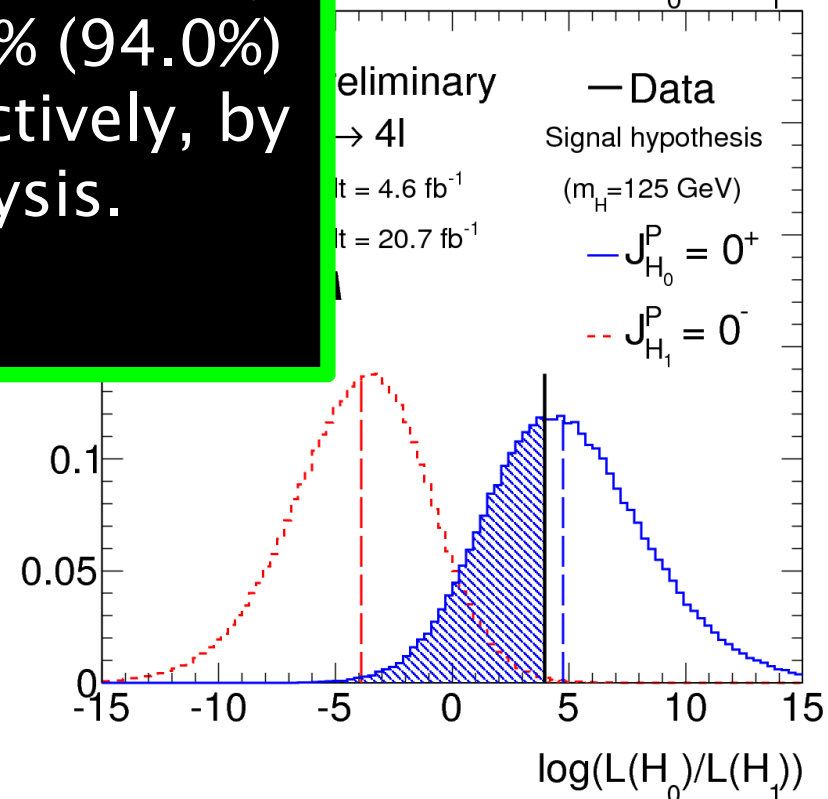




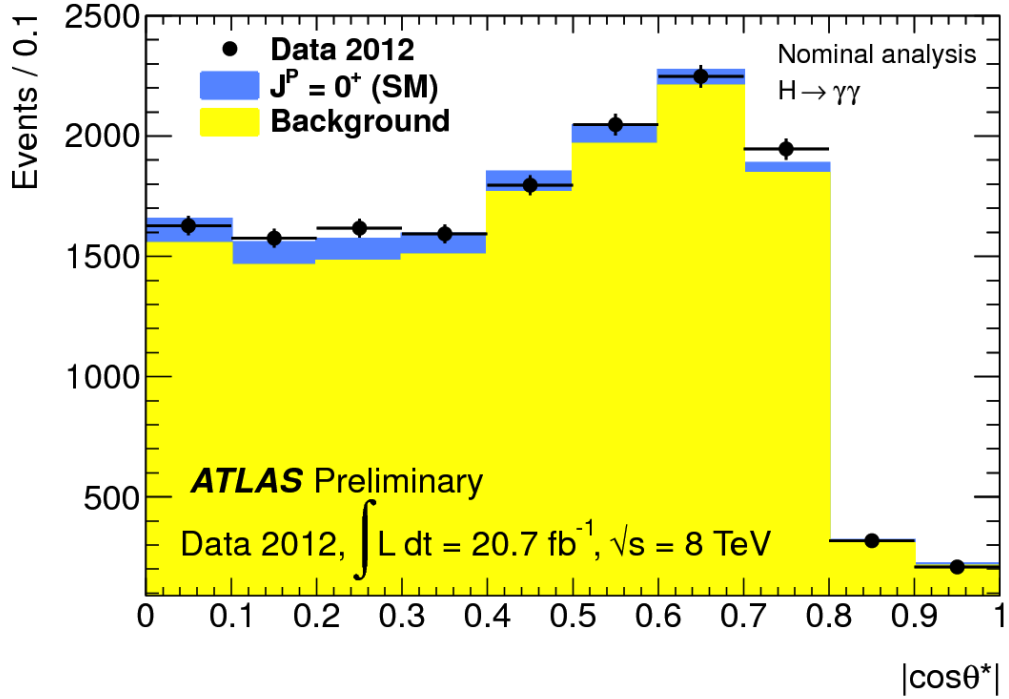


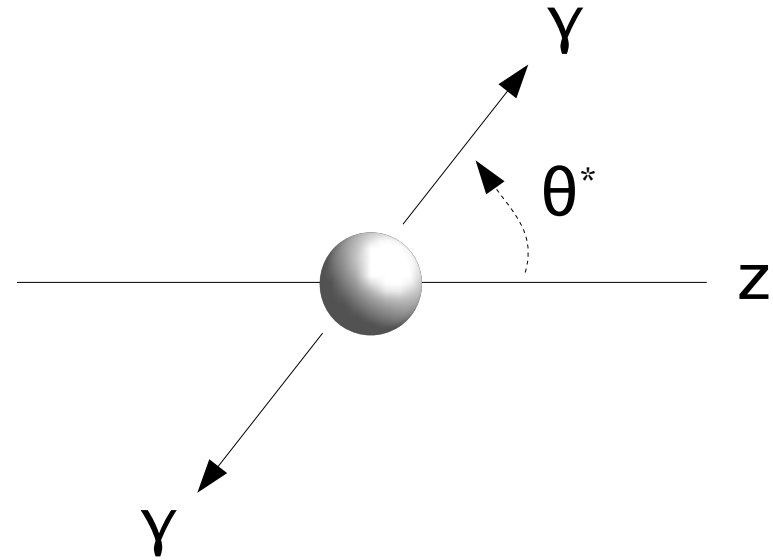
Use ensembles of 500,000 pseudo

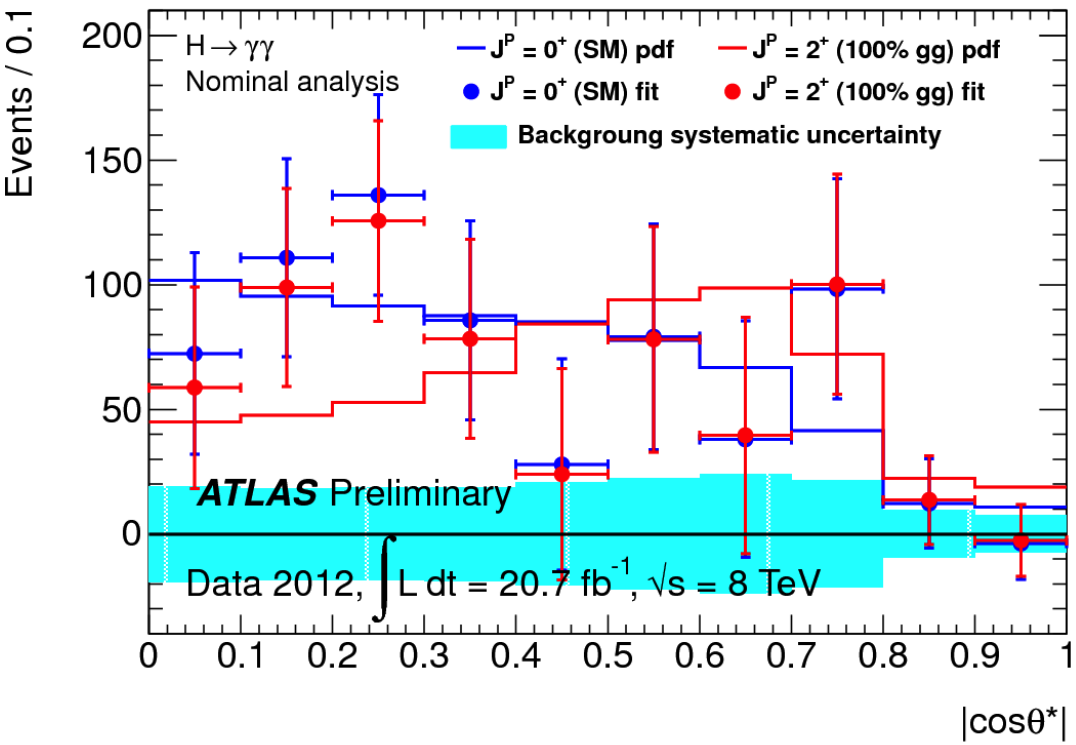


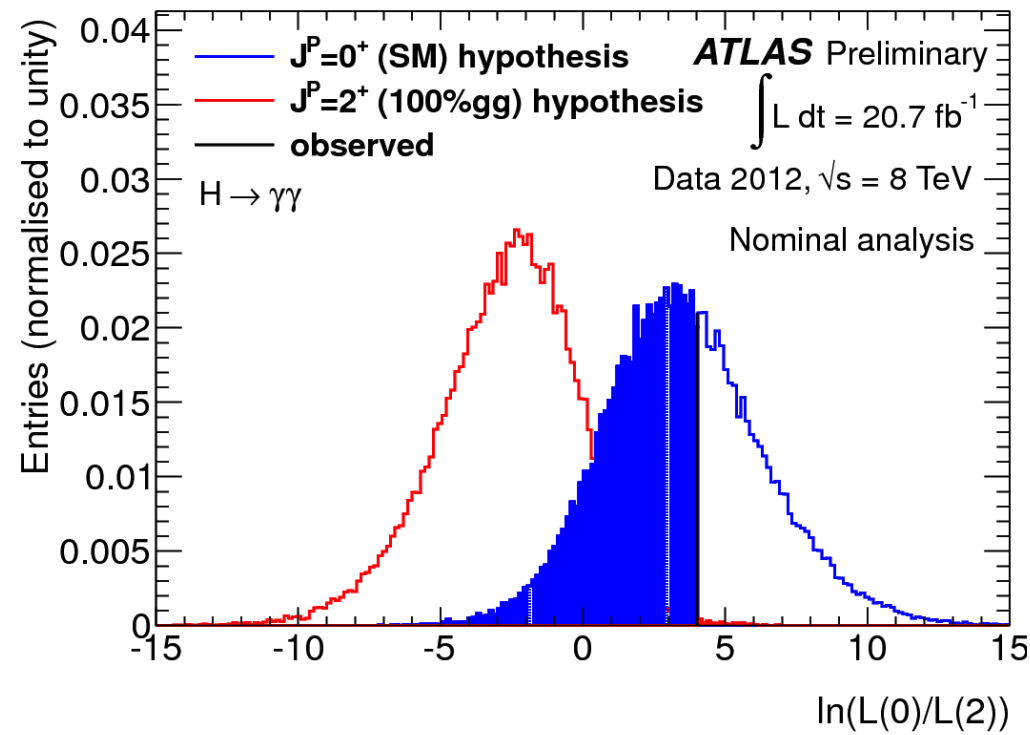


The 0^-, 1^+, and 1^- states are excluded in favor of the 0^+ hypothesis at the 99.6% (97.8%), 99.4% (99.8%), and 96.9% (94.0%) confidence levels, respectively, by the MELA (BDT) analysis.









Spin-2^+ excluded at 99% C.L. with respect to Spin-0^+

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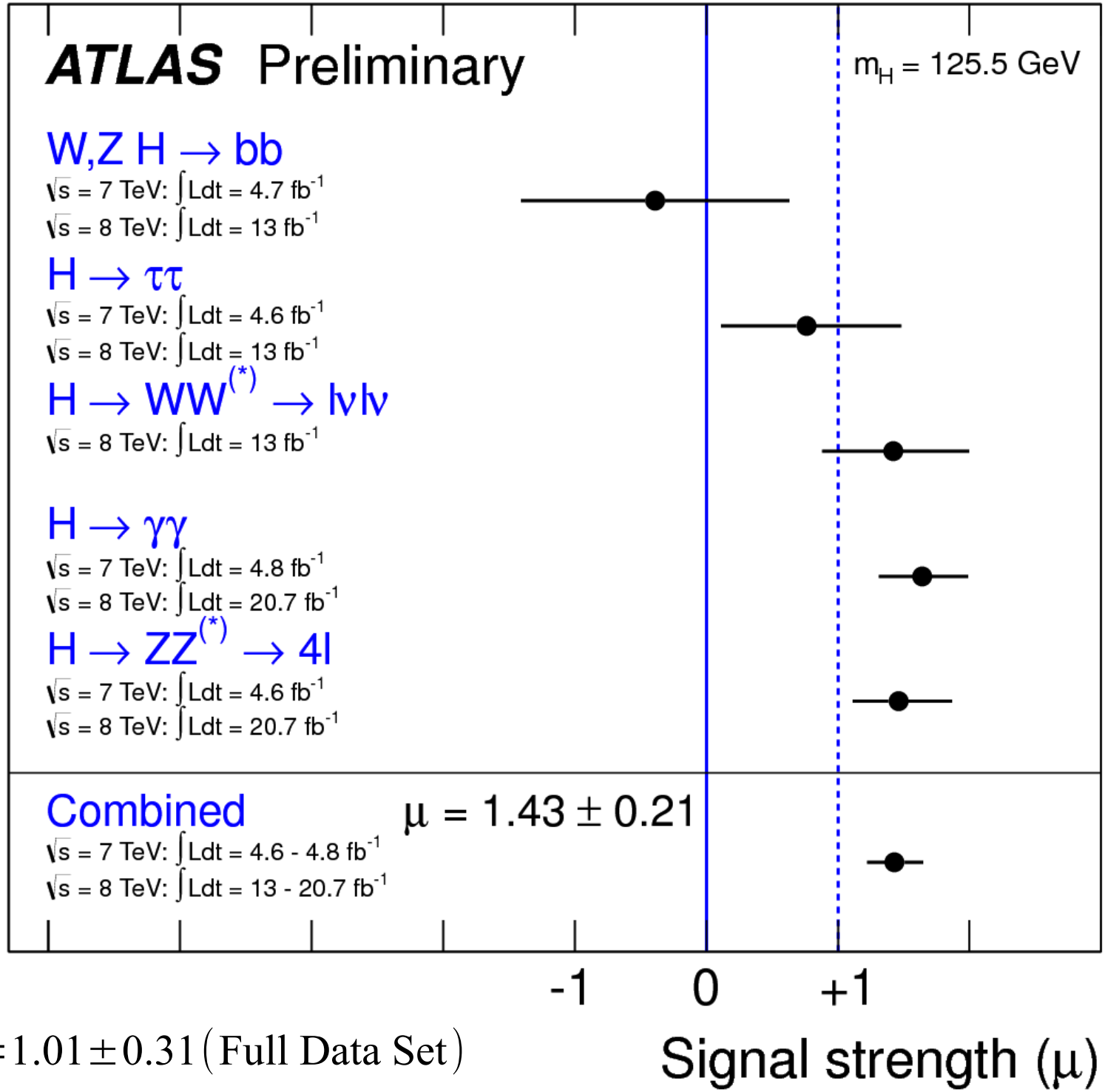
Couplings

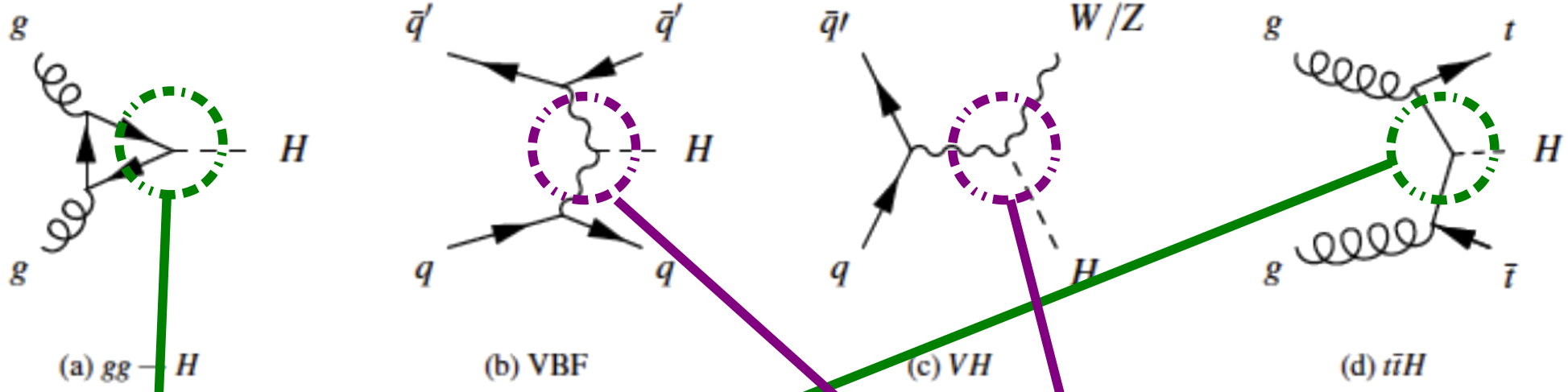


NOTE!

Plot still contains Fall 2012 WW result

$$\mu_{WW}(125) = 1.01 \pm 0.31 \,(\text{Full Data Set})$$

ATLAS-CONF-2013-034

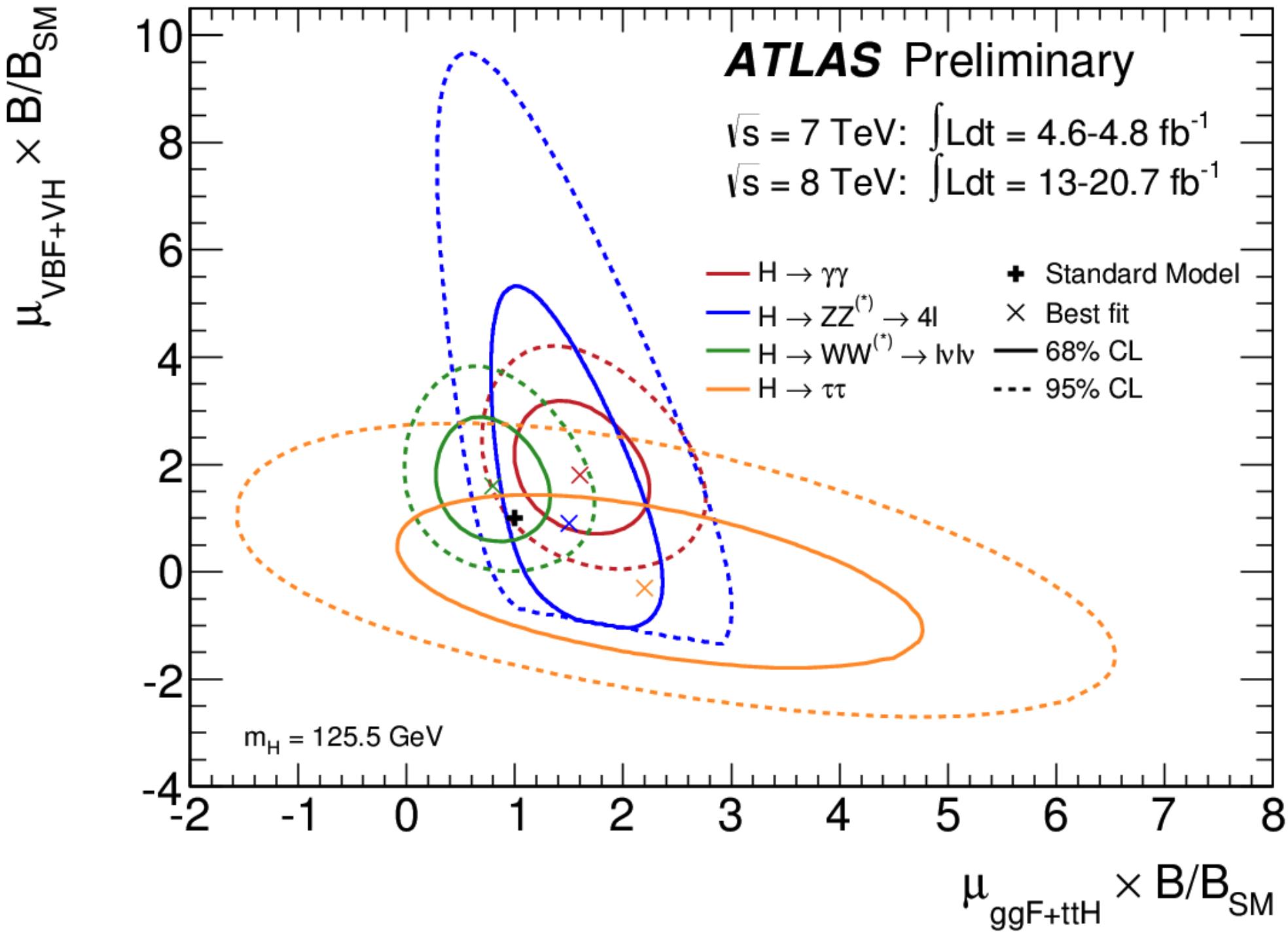


Proceed dominantly through top in SM, probe the coupling to fermions, and are combined into a single scale factor $\mu_{ggH+ttH}$

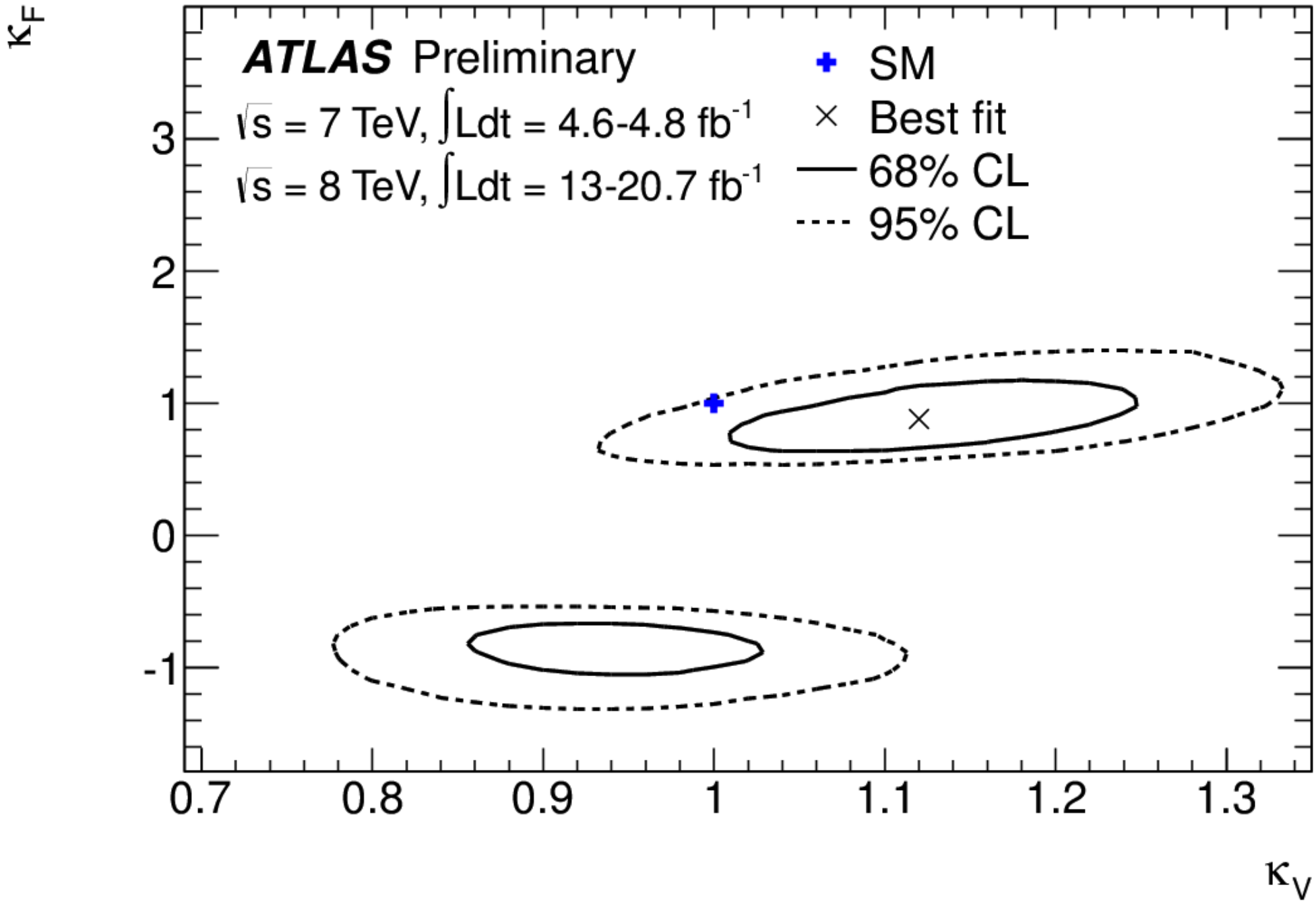
Probe the coupling to bosons, and are combined into a single scale factor μ_{VBF+VH}

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]
		2011 $\sqrt{s}$ =7 TeV	
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu$, 2-jet VBF, ℓ-tag$\}$	4.6
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\}$	4.8
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{$0-jet, 1-jet, 2-jet VBF$\}$	4.6
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{$0-jet$\} \oplus \{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, $VH\}$	4.6
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{$0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet$\}$	4.6
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{$1-jet, 2-jet$\}$	4.6
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	4.6
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7
		2012 $\sqrt{s}$ =8 TeV	
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu$, 2-jet VBF, ℓ-tag$\}\}$	20.7
$H \to \gamma\gamma$	–	14 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\} \oplus \{\ell$-tag, $E_{\mathrm{T}}^{\mathrm{miss}}$-tag, 2-jet VH$\}$	20.7
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{$0-jet, 1-jet, 2-jet VBF$\}$	20.7
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, $VH\}$	13
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{$0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet$\}$	13
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{$1-jet, 2-jet$\}$	13
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	13
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13

ATLAS-CONF-2013-034



ATLAS-CONF-2013-034



ATLAS-CONF-2013-034

Conclusions

Conclusions

- ATLAS reports clear observations of a Higgs-like boson in multiple channels

$$m_H^{combined} = 125.5 \pm 0.2\,(\text{stat}) \pm {}^{+0.5}_{-0.6}\,(\text{syst})$$

$$\mu^{combined} = 1.43 \pm 0.21$$

Couplings so-far consistent with SM within uncertainties

- I've only been able to show a little today (!)
  - please read the recent conference notes!
  - looking forward to final public results and publications on the 2011+2012 data samples in all channels.