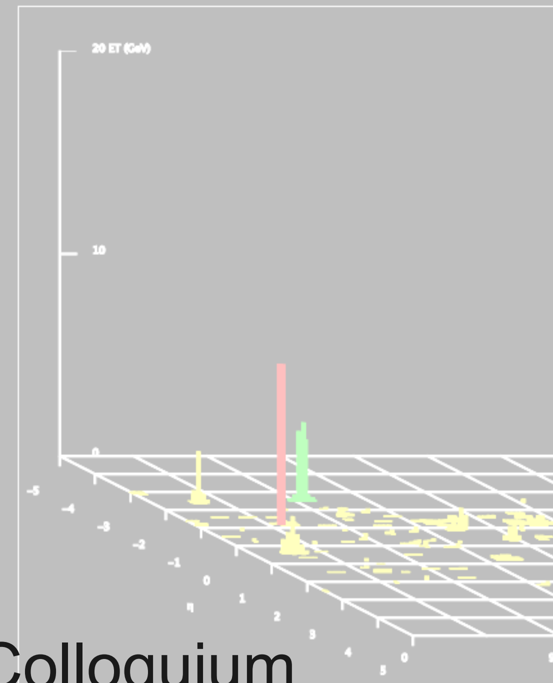
The Discovery of a New State with a Mass of 126 GeV/c^2

Stephen Sekula
Southern Methodist University
The ATLAS Collaboration



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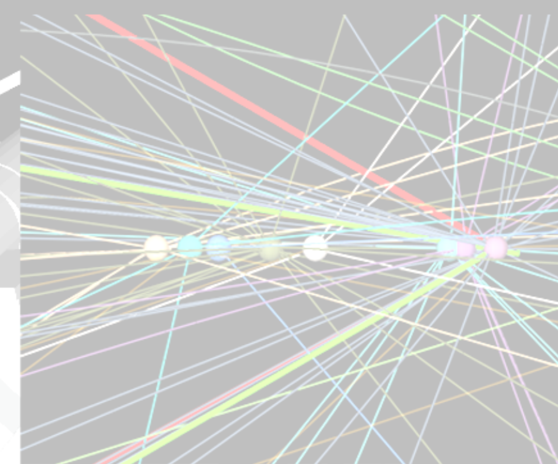
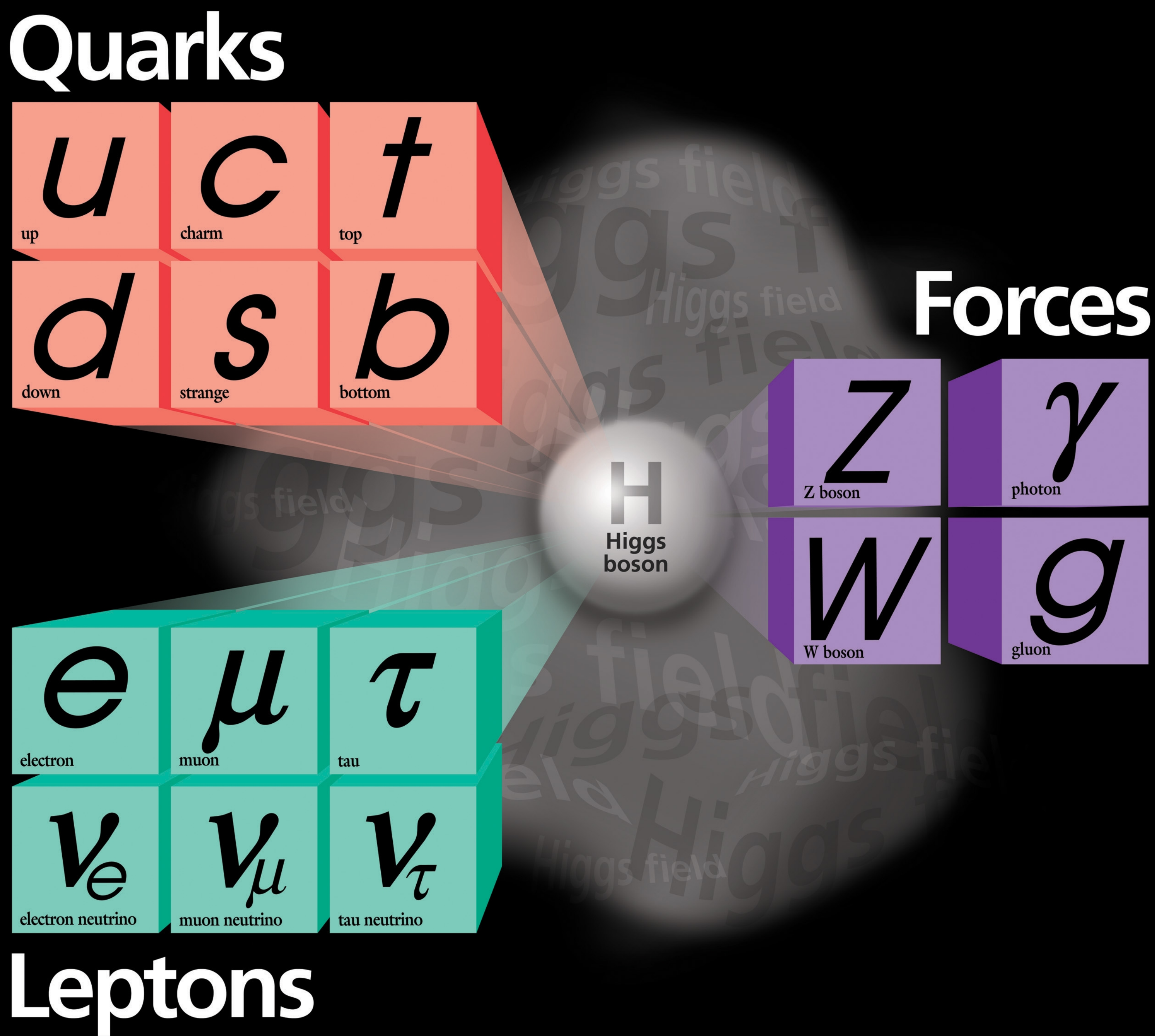
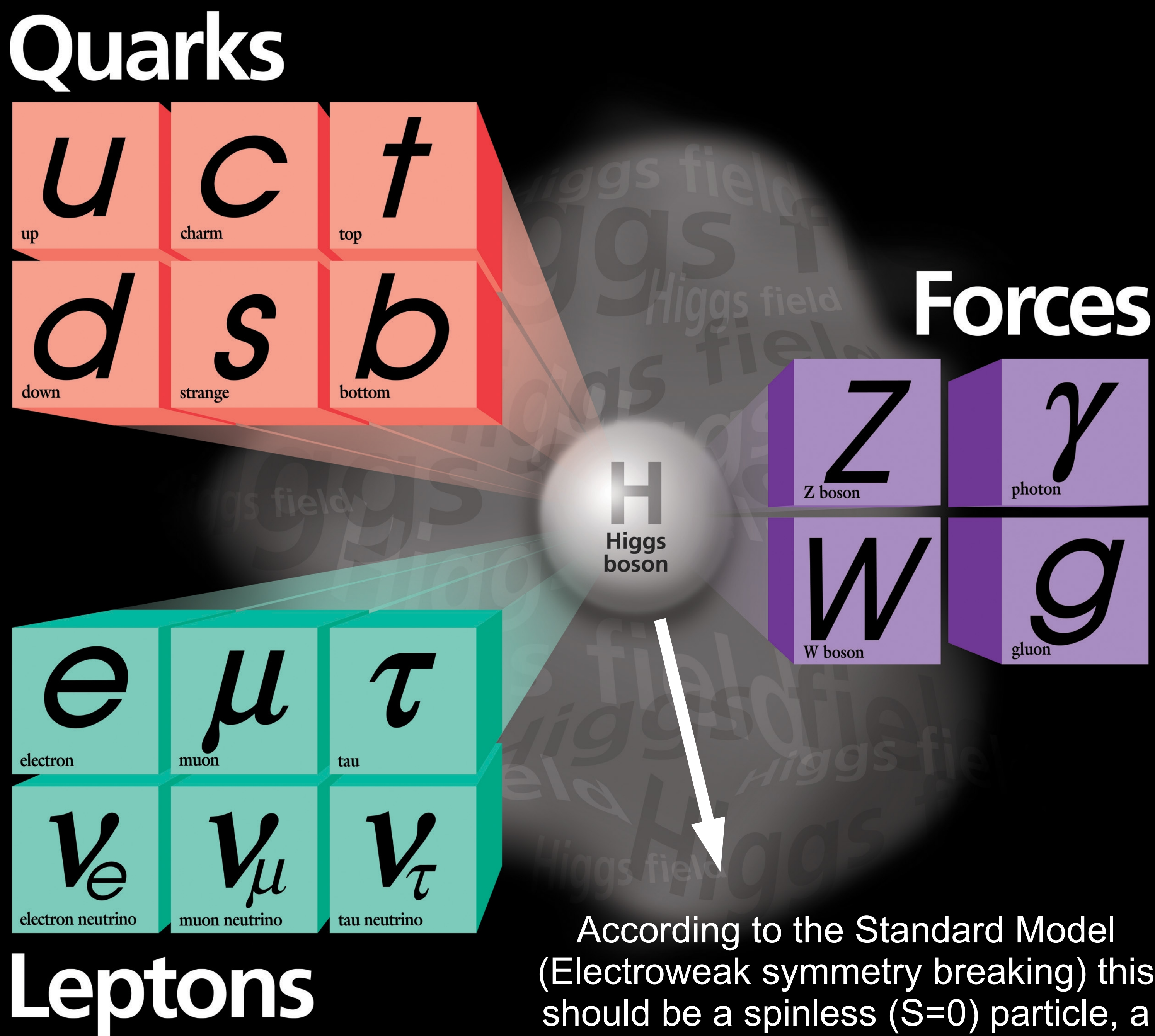
September 13, 2012




Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
Higgs field
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons



According to the Standard Model (Electroweak symmetry breaking) this should be a spinless (S=0) particle, a boson (integer spin), whose couplings to other particles determines their mass.

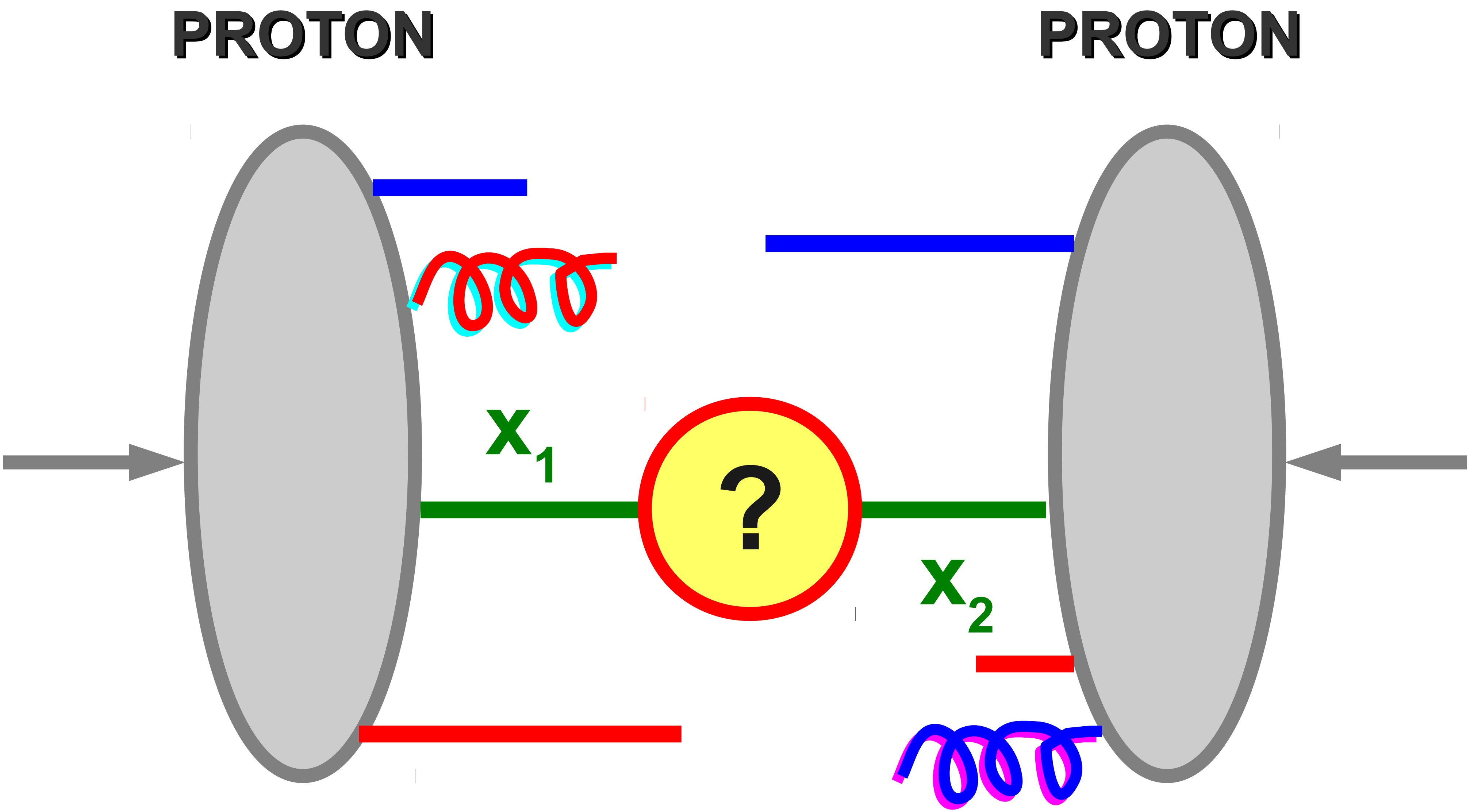
PARTICLE MASS

PARTICLE SPIN

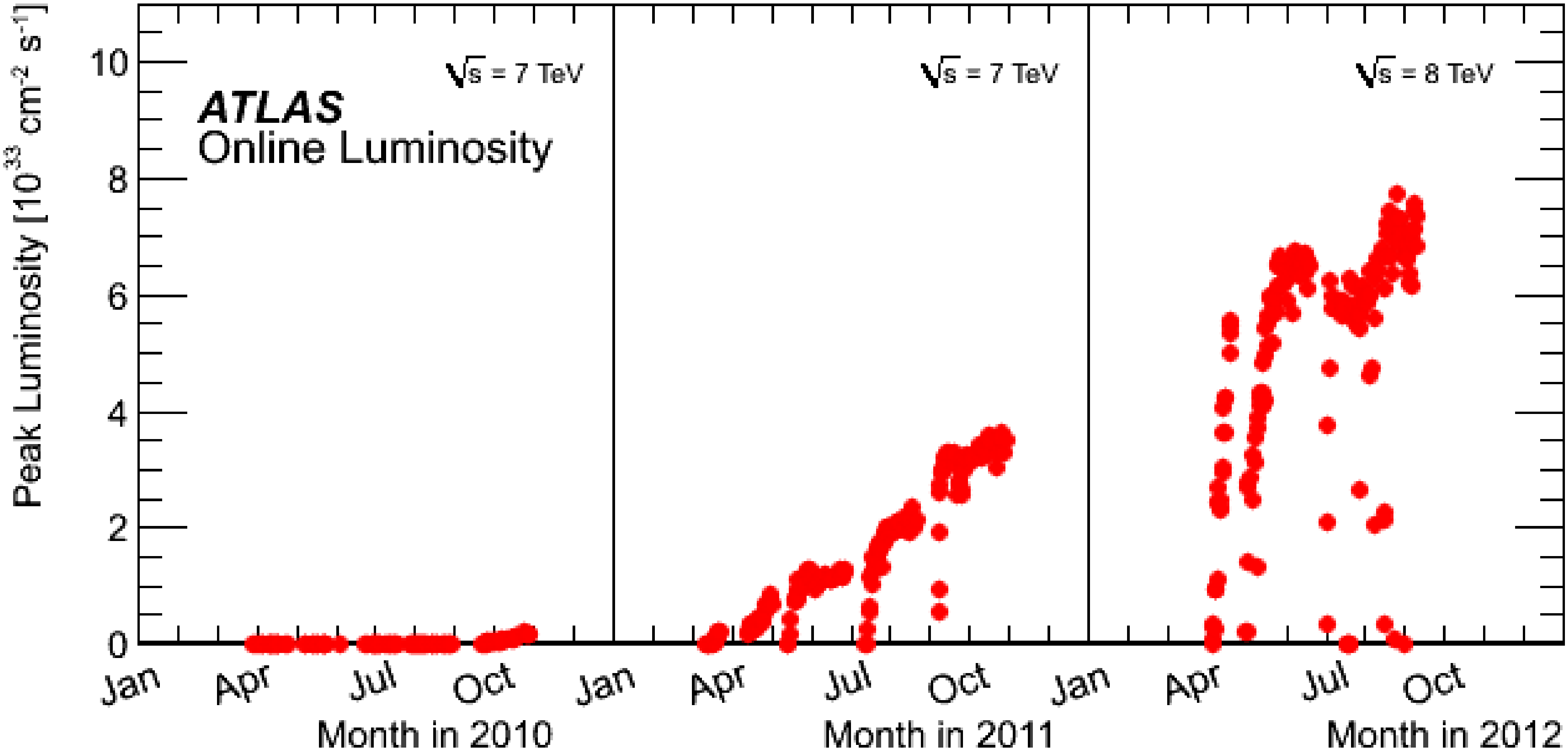
PARTICLE CP

PARTICLE COUPLINGS

[for instance:
rate of production
rate of decay]



The center-of-mass (CM) proton-proton energy is denoted by $E_{CM} = \sqrt{s}$, but the primary interaction only receives a fraction of the total energy of either proton. For a symmetric collider, the energy available for the interaction is $E_{int} = \sqrt{(x_1 x_2 s)}$



We routinely operate now at instantaneous luminosities of **(7.0-7.5)x10^{33} interactions per cm^2 per second ($cm^{-2}s^{-1}$)**.

A convenient unit of area is a "barn" (as in, "You can't hit the broad side of a barn.") - it is the typical unit of cross-sectional area in nuclear and subnuclear physics.

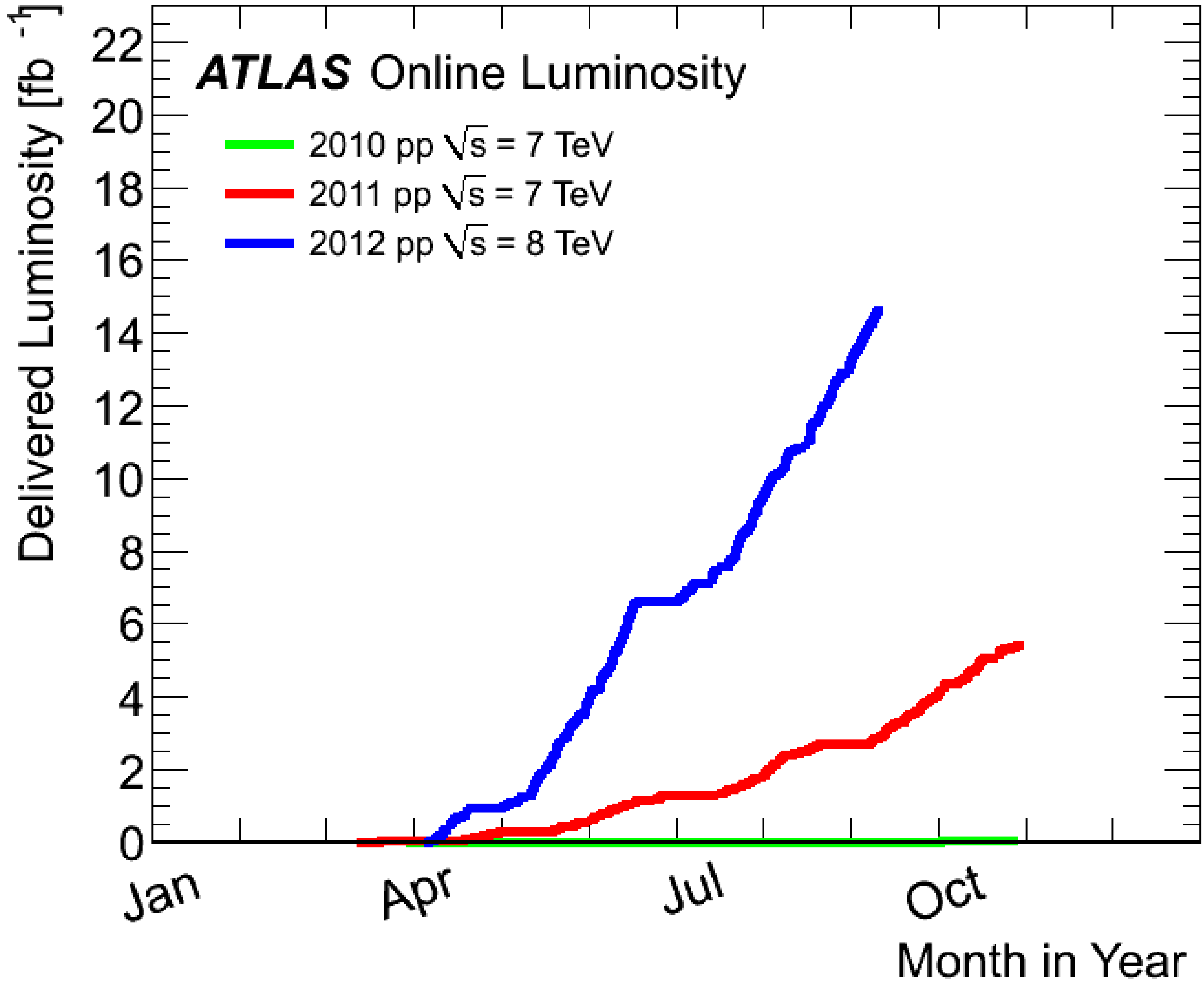
1 barn = 10^{-24} cm^2, so in these units the LHC achieves luminosities of **~7.5x10^9 b^{-1} s^{-1}**, or in units more appropriate to the scale of LHC physics, about **7.5 x 10^{-6} fb^{-1} s^{-1}**

$$\mathcal{L} = \int L \; dt$$

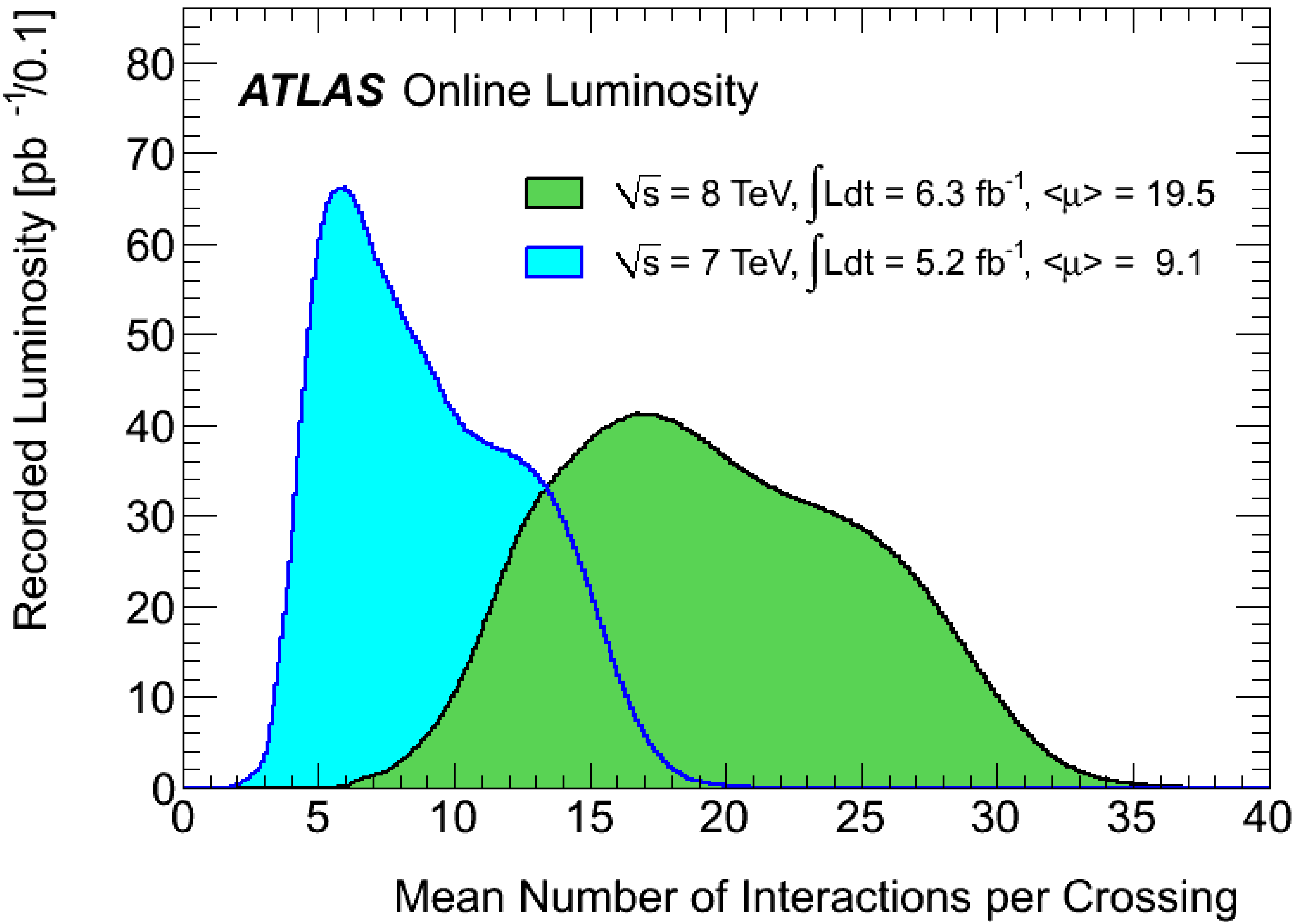
"Integrated Luminosity" measured in fb^{-1}

"Instantaneous Luminosity" measured in $fb^{-1}\ s^{-1}$

LHC data sample sizes are measured in units of **fb^{-1}** because once you know this number, and you know the cross-section (probability of producing) a specific process, you can estimate how often that process will appear in your collider.



ATLAS Online Luminosity
2010 pp √s = 7 TeV
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
Delivered Luminosity [fb-1]
0
2
4
6
8
10
12
14
16
18
20
22
Jan
Apr
Jul
Oct
Month in Year



ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 6.3 fb⁻¹, <μ> = 19.5
√s = 7 TeV, ∫Ldt = 5.2 fb⁻¹, <μ> = 9.1
Recorded Luminosity [pb⁻¹/0.1]
Mean Number of Interactions per Crossing
0
10
20
30
40
50
60
70
80
0
5
10
15
20
25
30
35
40

$$N_X = \mathcal{L} \cdot \sigma(pp \to X)$$

Example:

- Let's say that the cross-section for producing the Higgs with a certain mass at a certain center-of-mass collision energy is **1pb**
- Let's say that the total integrated luminosity of the collider is **5 fb^{-1} = 5,000 pb^{-1}**
- Then the total number of collisions that produce a Higgs is **N = 5,000**
- This DOESN'T take into account detector acceptance, trigger efficiency, selection efficiency, etc.

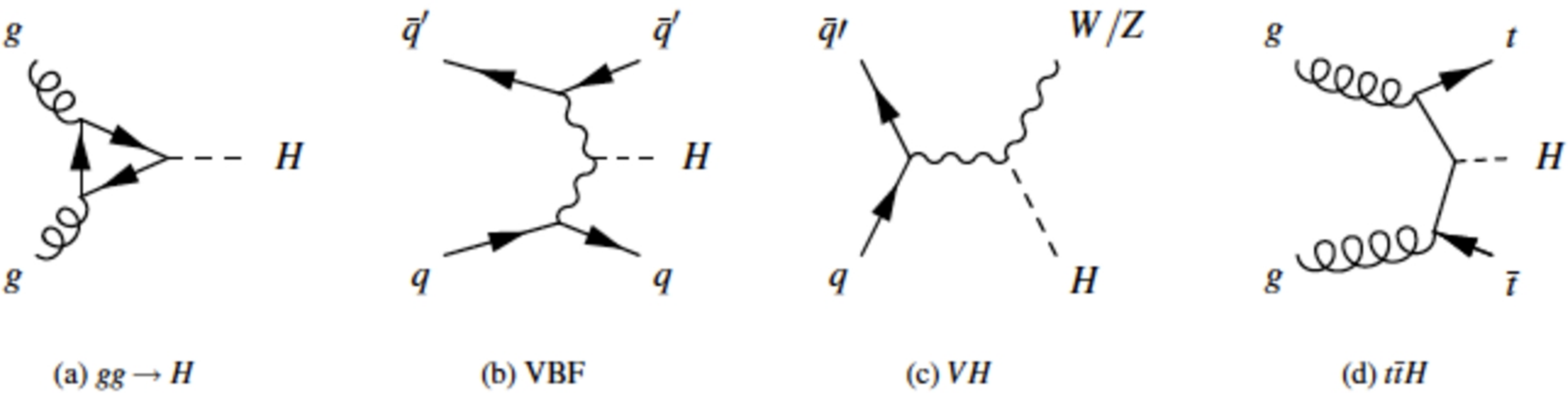
Theoretical Particle Physics

Accelerator/Collider Physics

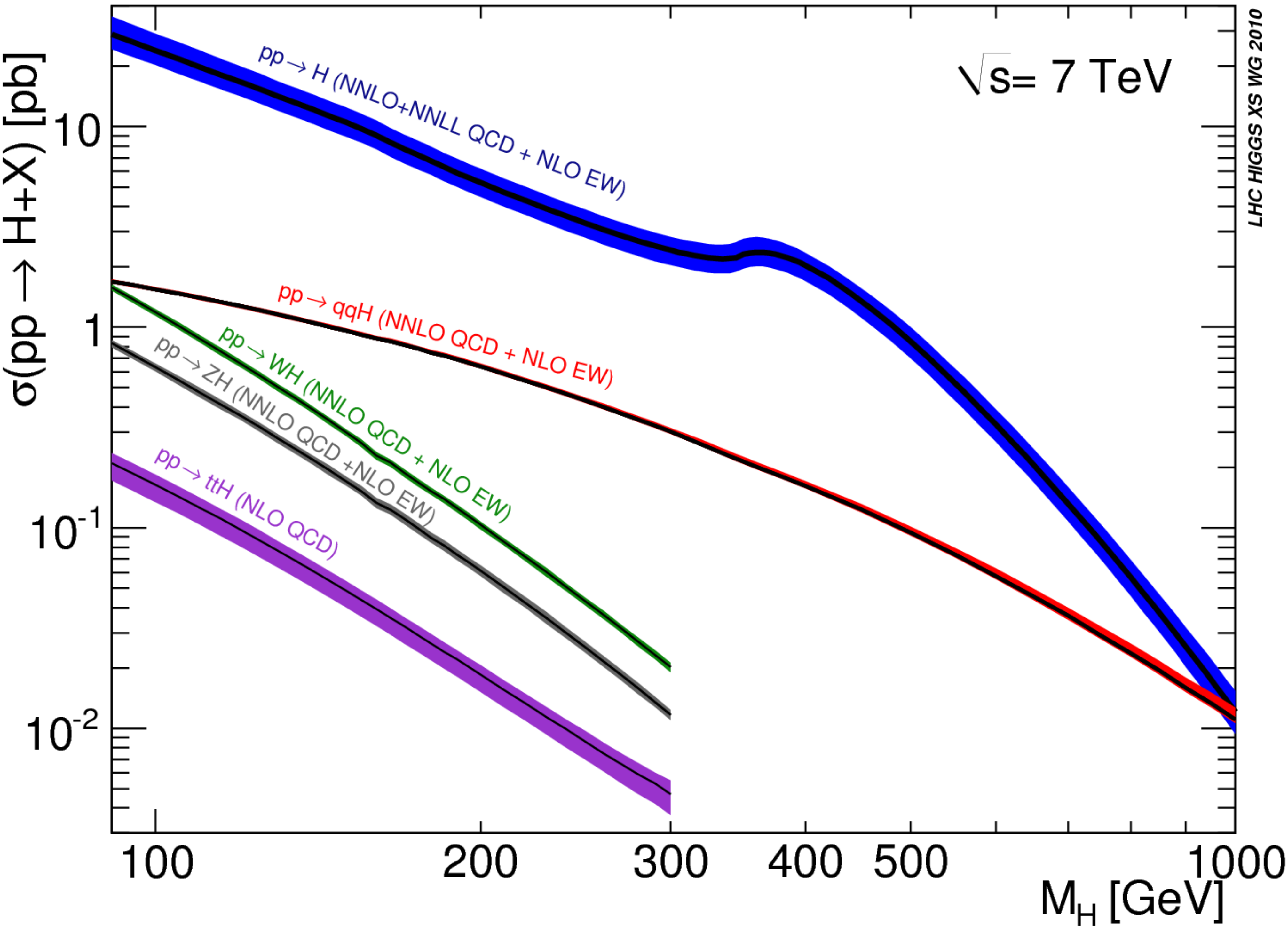
$$N_X = \mathscr{L} \cdot \sigma(pp \rightarrow X)$$

Experimental Particle Physics

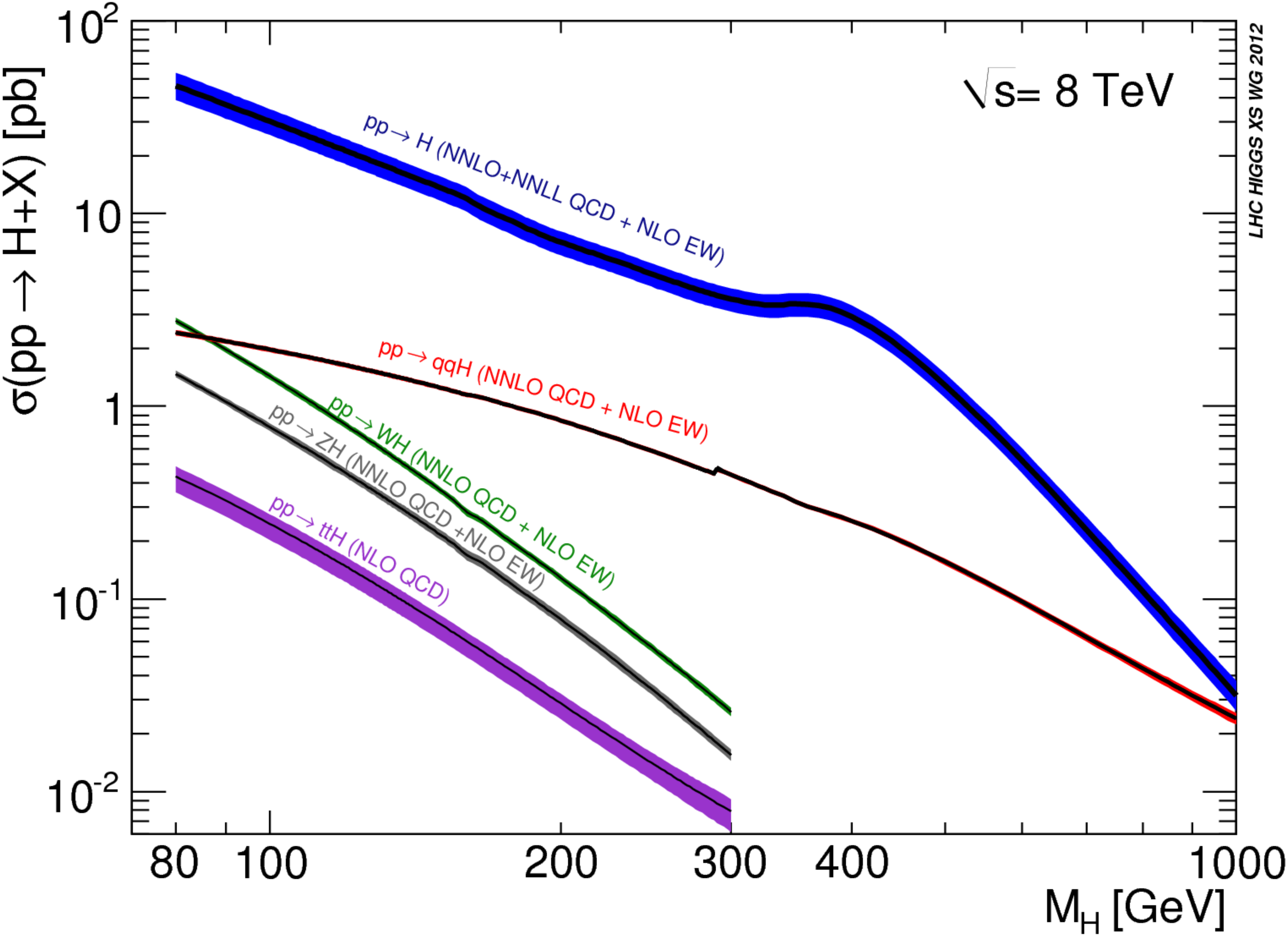
How should the Higgs be produced?



These are “leading order” diagrams – there are many higher-order diagrams that can also contribute for each of these processes.

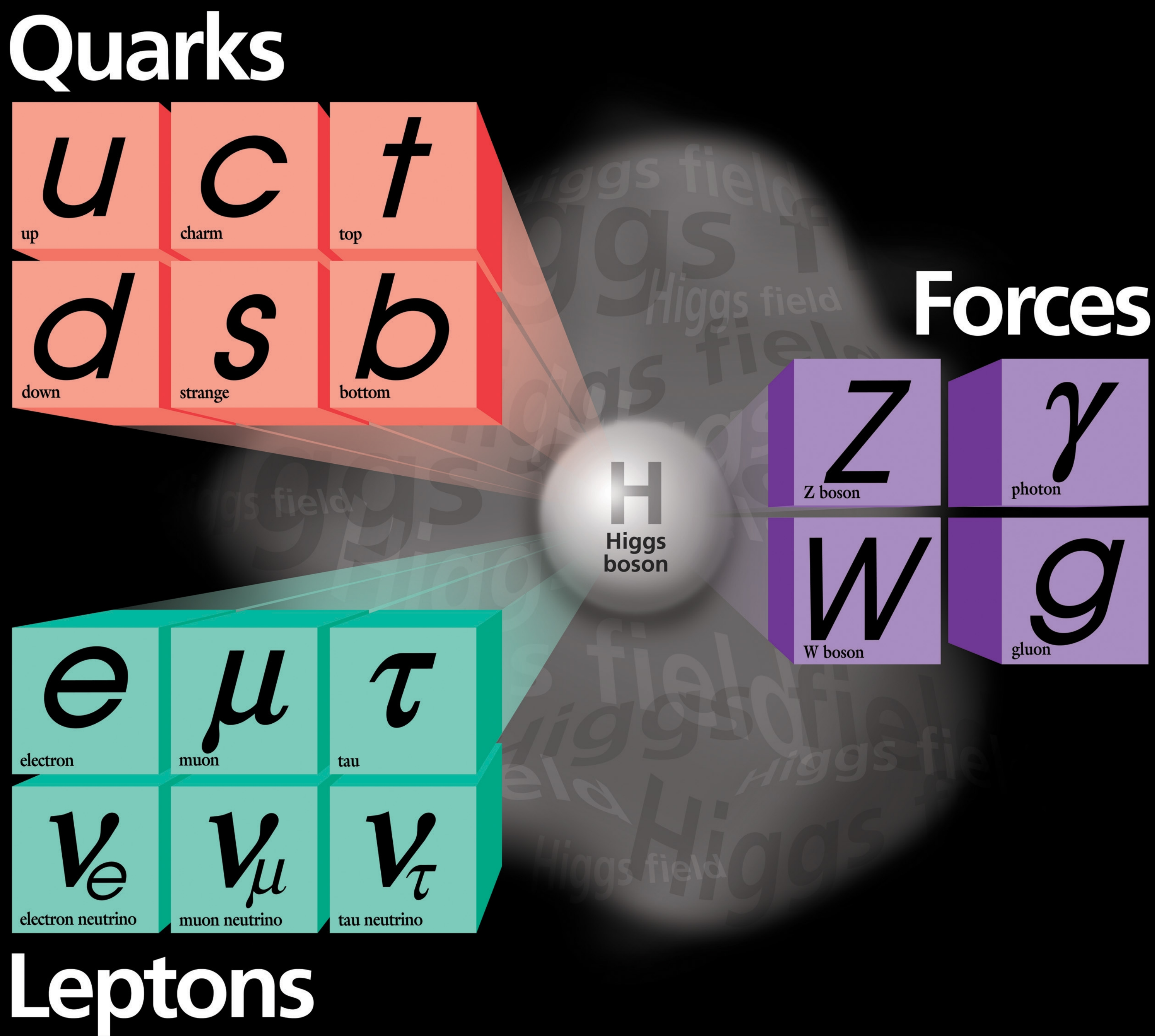


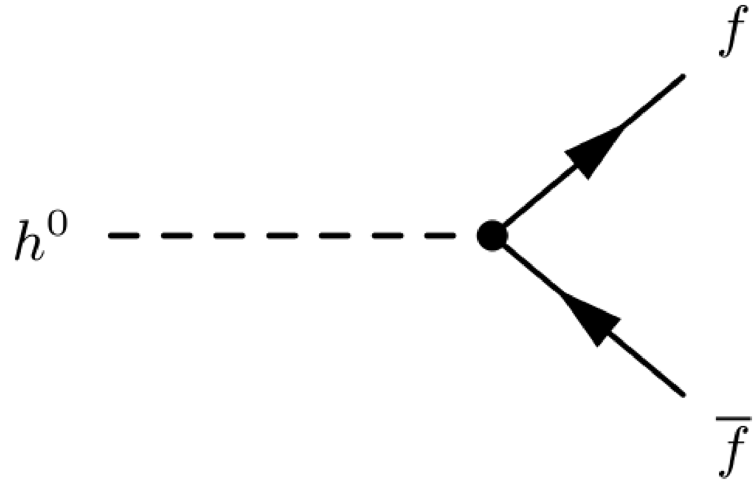
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
√s= 7 TeV
LHC HIGGS XS WG 2010
σ(pp → H+X) [pb]
M_H [GeV]
10
1
10^-1
10^-2
100
200
300
400
500
1000



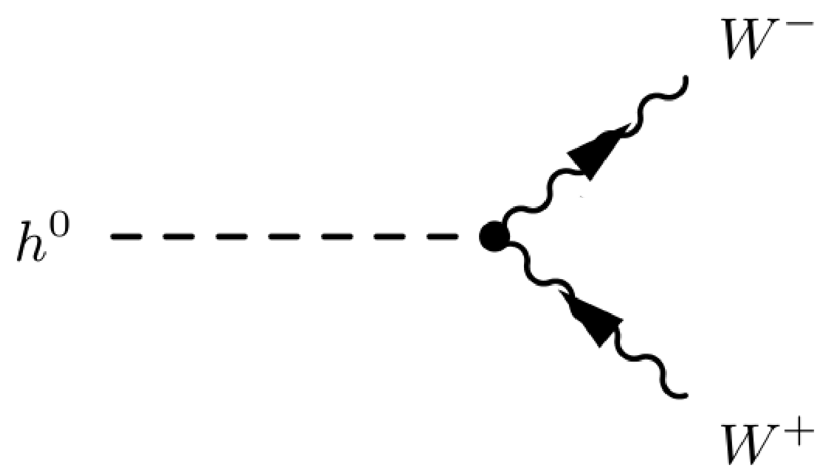
$\sqrt{s}$= 8 TeV
LHC HIGGS XS WG 2012
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
σ(pp → H+X) [pb]
10^2
10
1
10^{-1}
10^{-2}
80
100
200
300
400
1000
M_H [GeV]

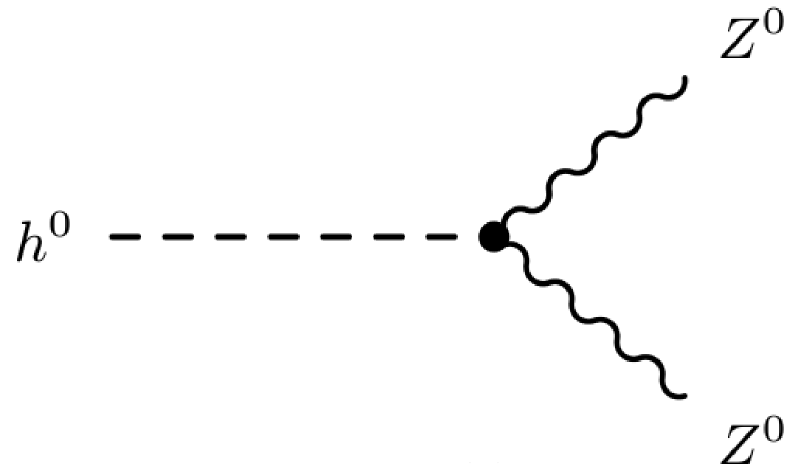
How should the Higgs boson decay?

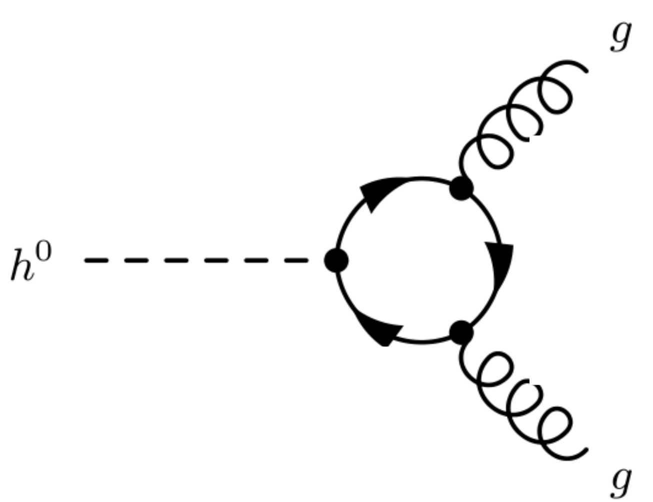

Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Higgs field
H
Higgs boson
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons

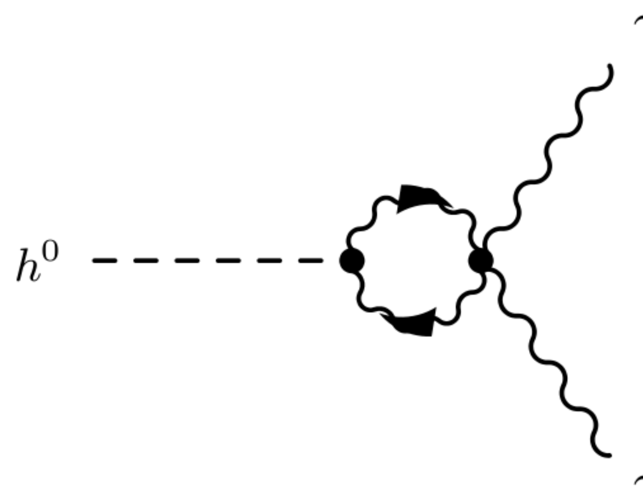


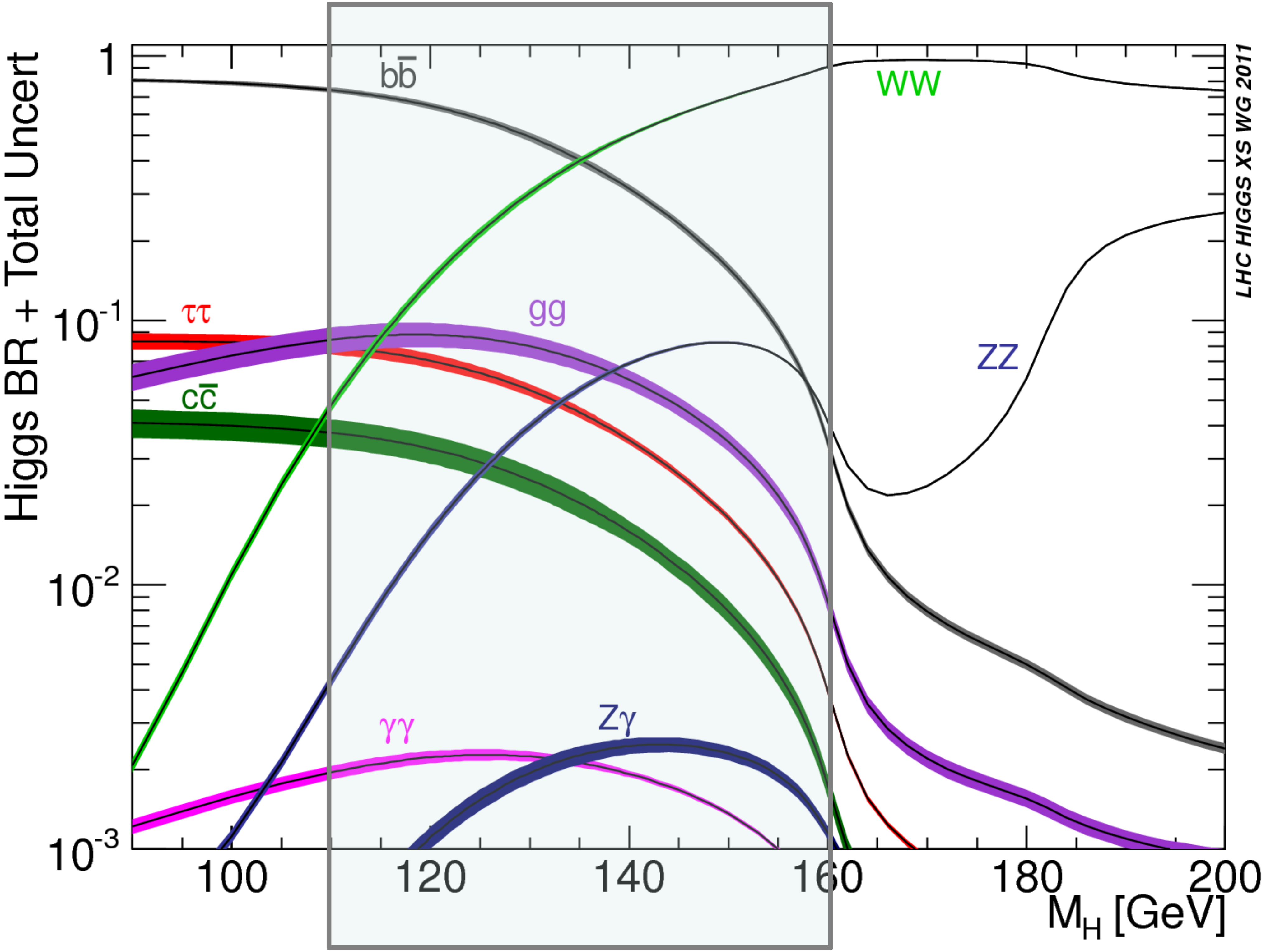
Most likely fermions (based on mass):
τ lepton and b-quark











Higgs BR + Total Uncert
1
10-1
10-2
10-3
100
120
140
160
180
200
M_H [GeV]
LHC HIGGS XS WG 2011
bb̄
WW
ττ
gg
cc̄
ZZ
γγ
Zγ

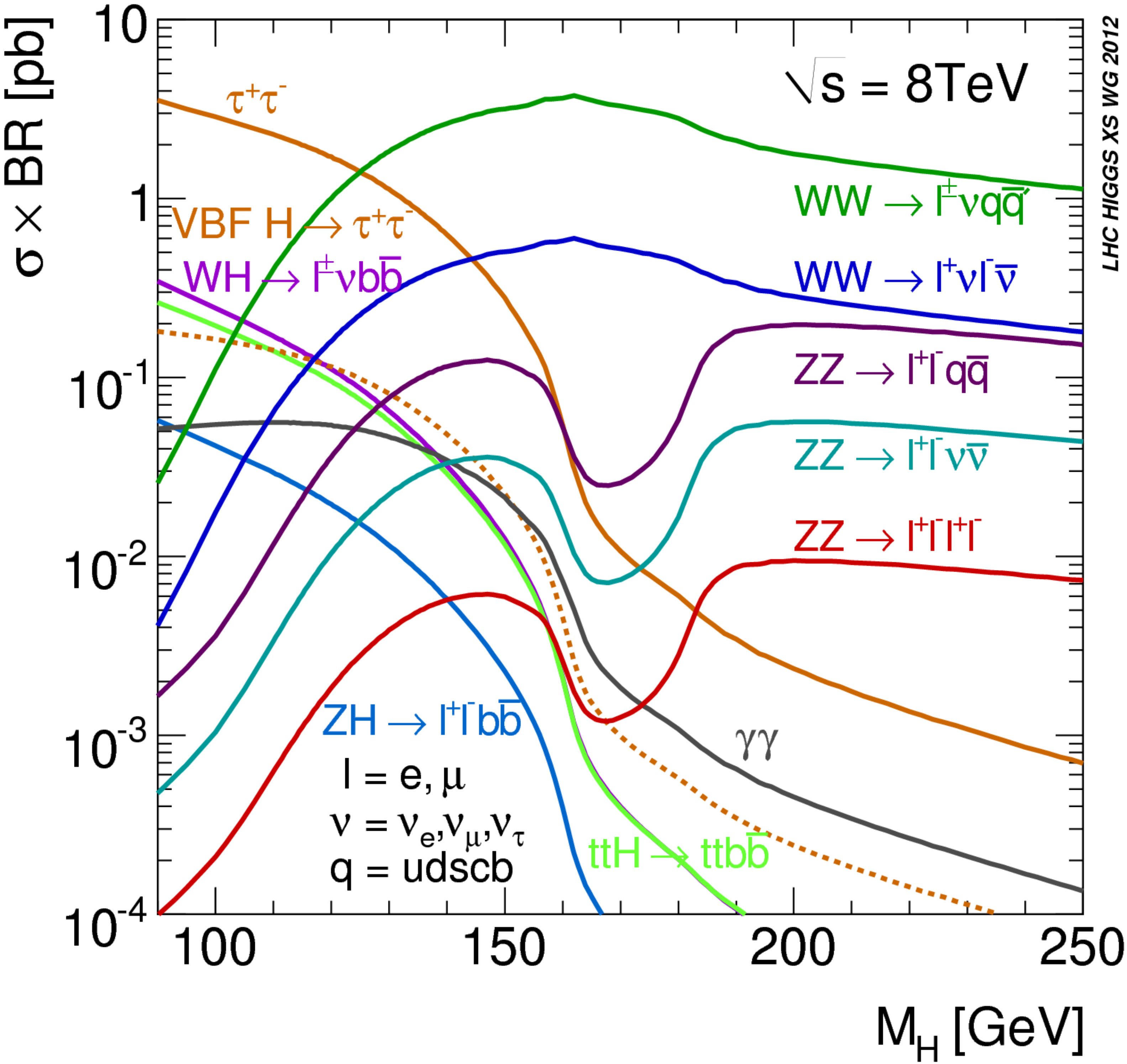
What, then, are the best ways to look for the Higgs boson?

Final states involving only quarks or gluons are experimentally extremely challenging

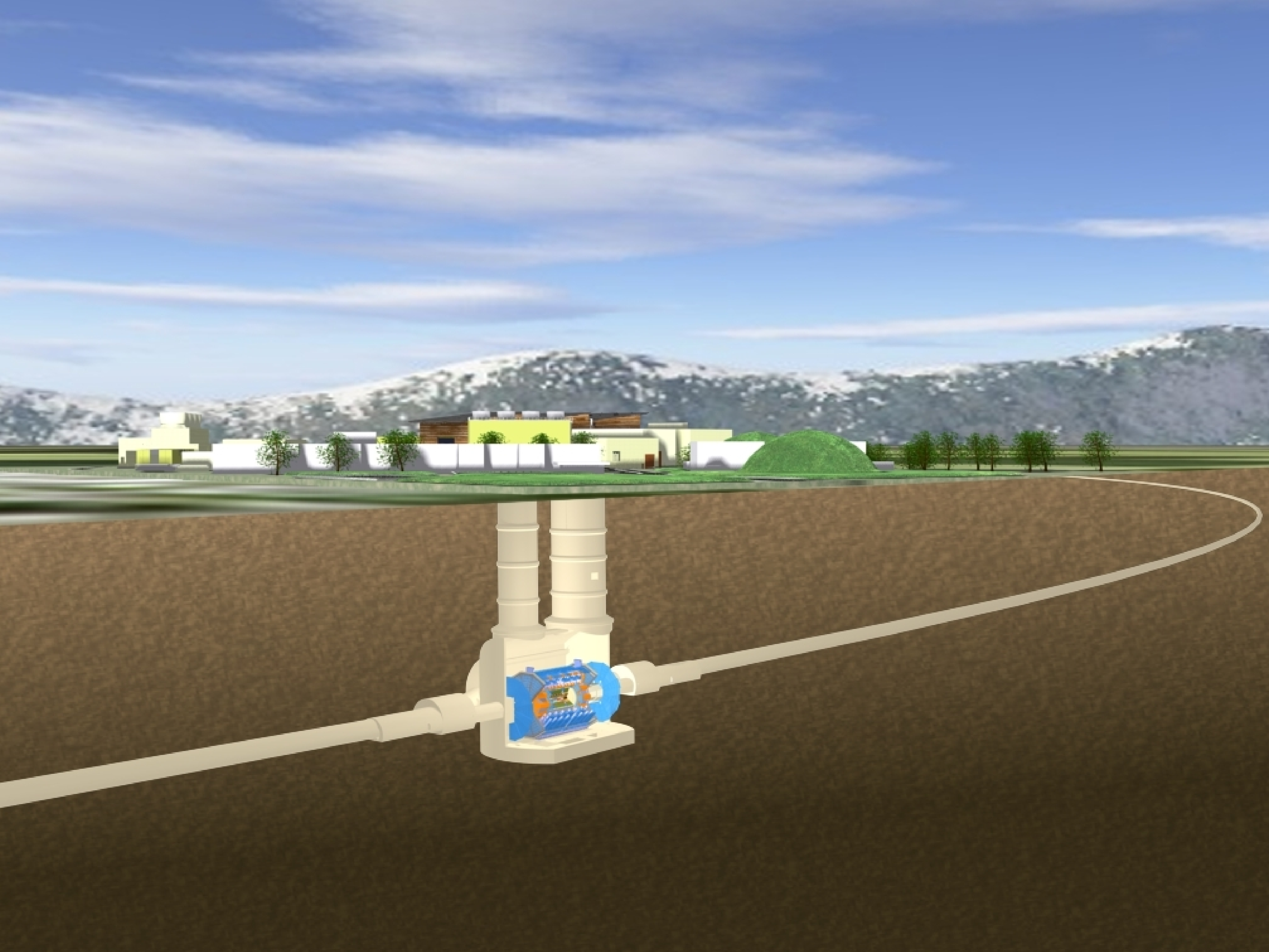
[in a hadron collider, nearly everything produced is gluons and quarks → JETS]

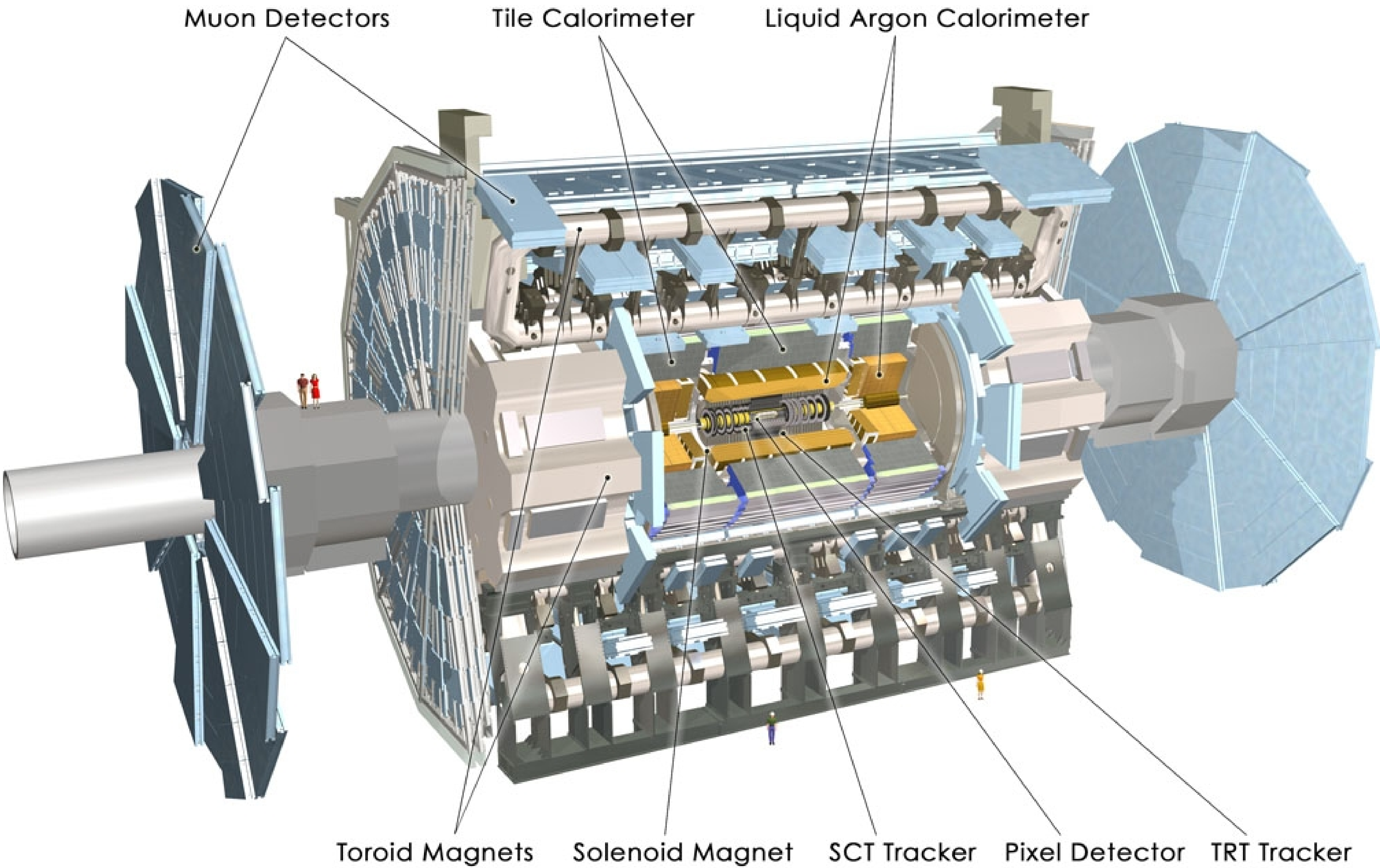
Final states involving tau leptons are challenging because $\tau \rightarrow X + \nu$ ($X = e, \mu$, quarks)

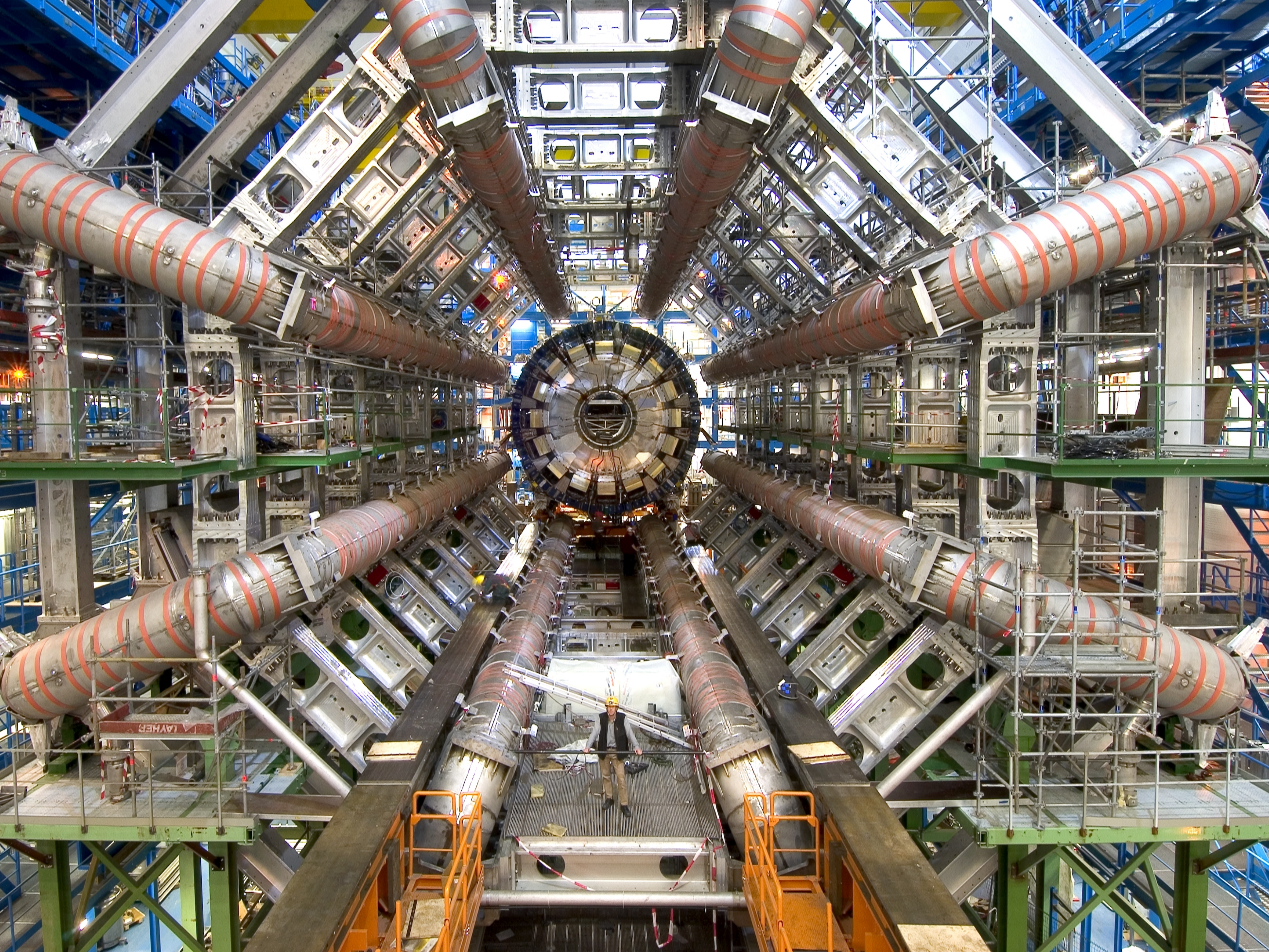
Final states involving only photons, electrons, or muons are experimentally very accessible, but happen at lower rates overall.

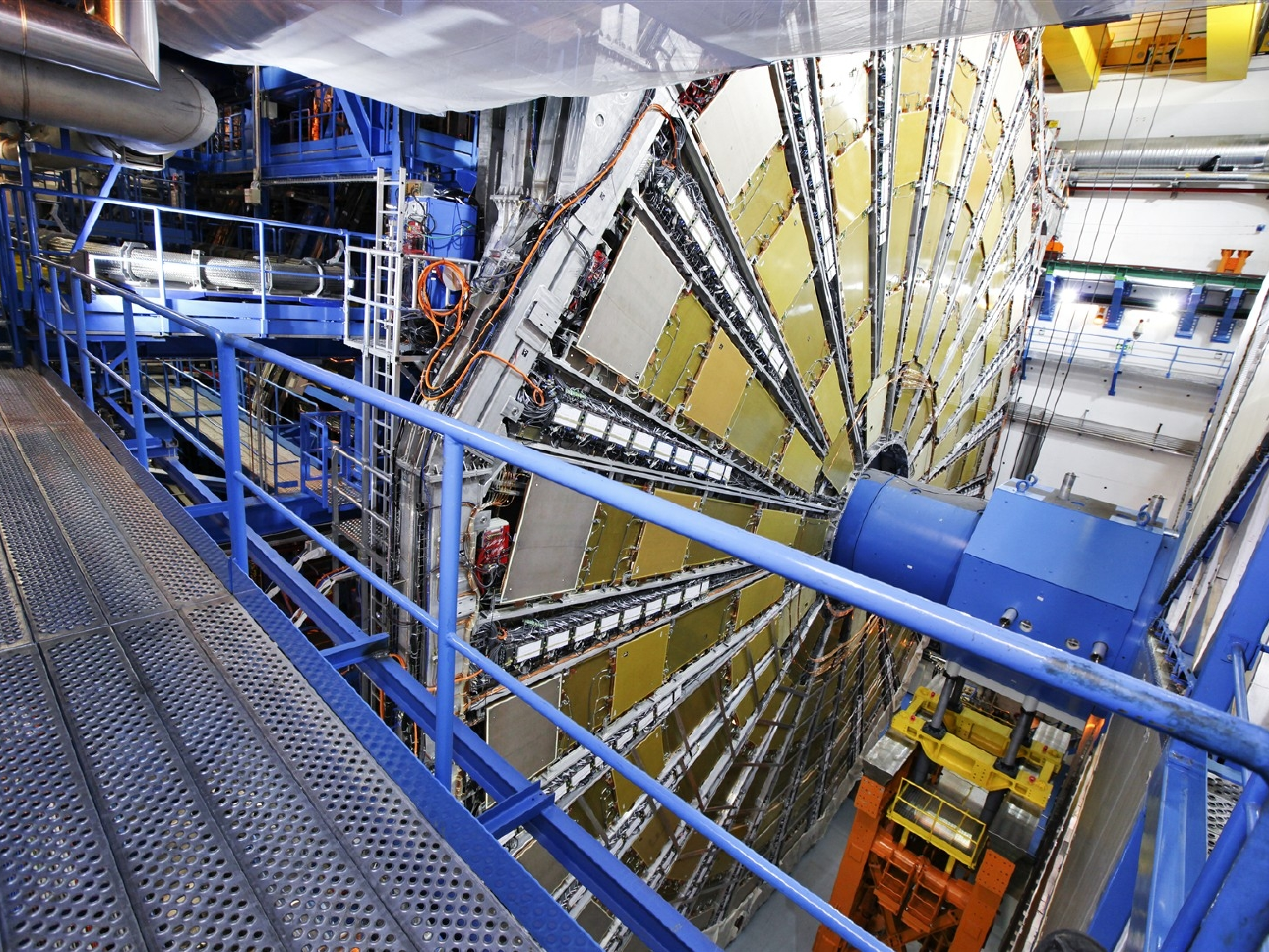


$\sigma \times BR$ [pb]
$\sqrt{s}$ = 8TeV
LHC HIGGS XS WG 2012
$\tau^+\tau^-$
VBF $H \rightarrow \tau^+\tau^-$
$WH \rightarrow l^{\pm}\nu b\bar{b}$
$WW \rightarrow l^{\pm}\nu q\bar{q}'$
$WW \rightarrow l^+\nu l^-\bar{\nu}$
$ZZ \rightarrow l^+l^-q\bar{q}$
$ZZ \rightarrow l^+l^-\nu\bar{\nu}$
$ZZ \rightarrow l^+l^-l^+l^-$
$ZH \rightarrow l^+l^-b\bar{b}$
$\gamma\gamma$
$l = e, \mu$
$\nu = \nu_e, \nu_\mu, \nu_\tau$
q = udscb
$ttH \rightarrow tt b\bar{b}$
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
100
150
200
250
M_H [GeV]

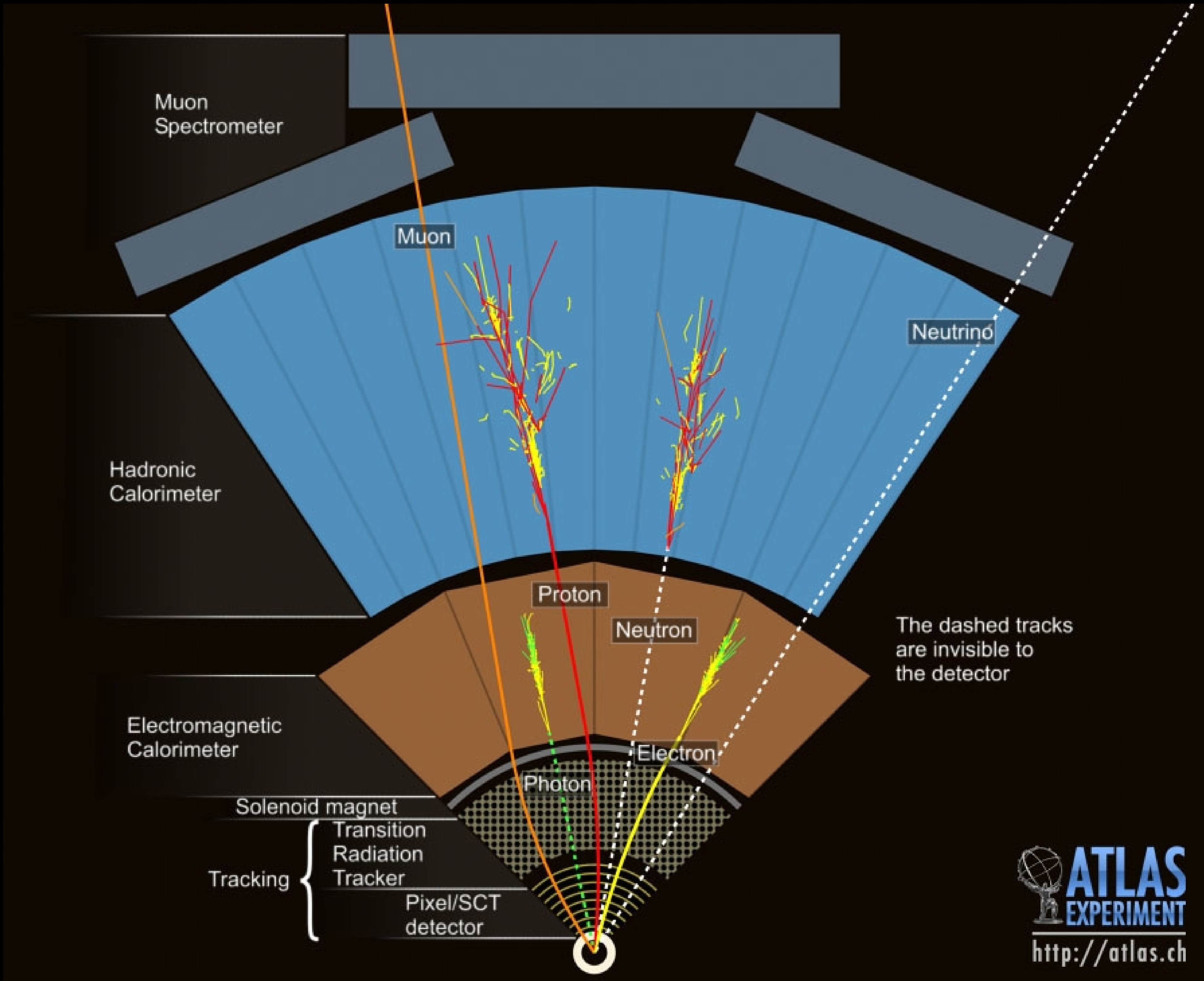



Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

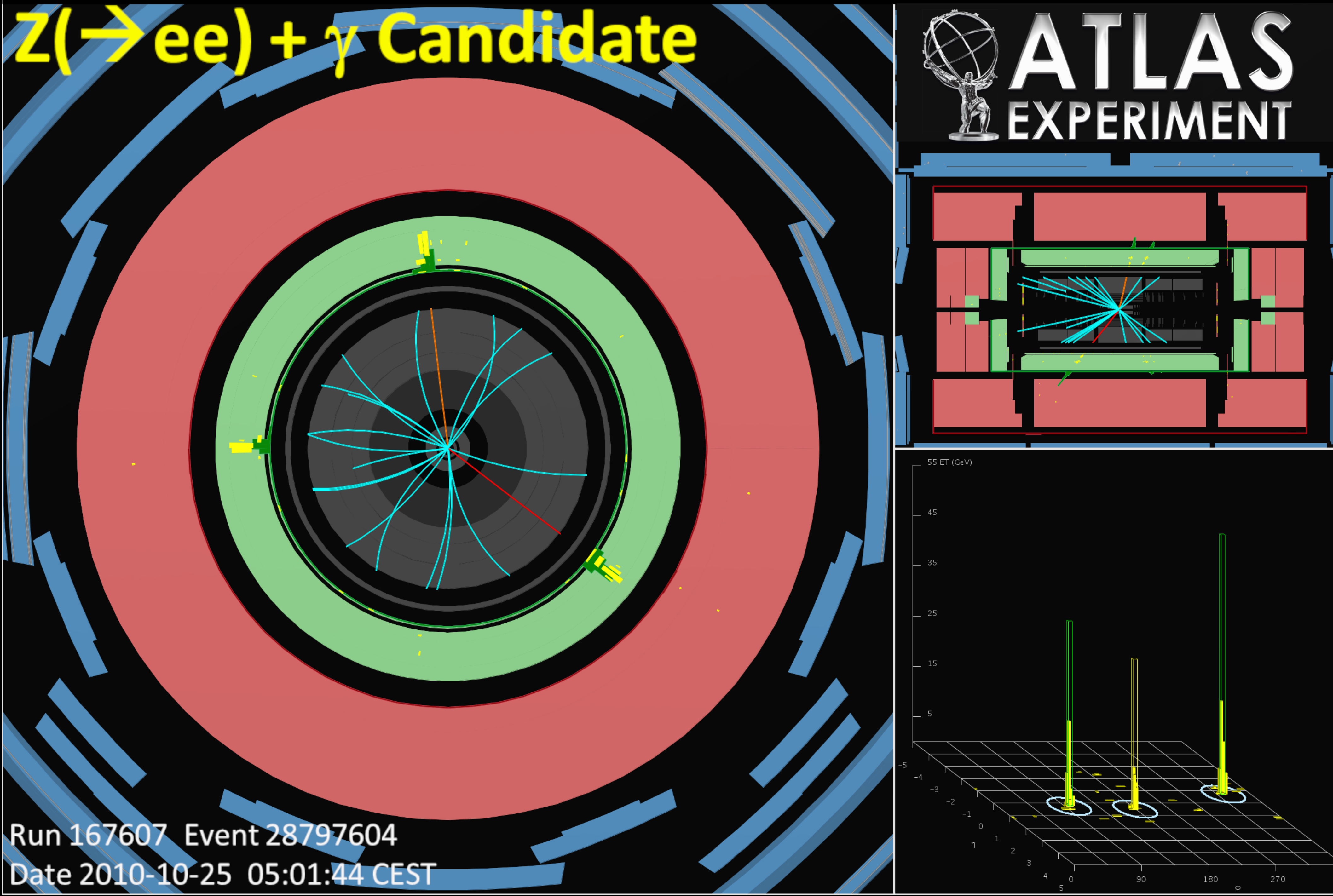




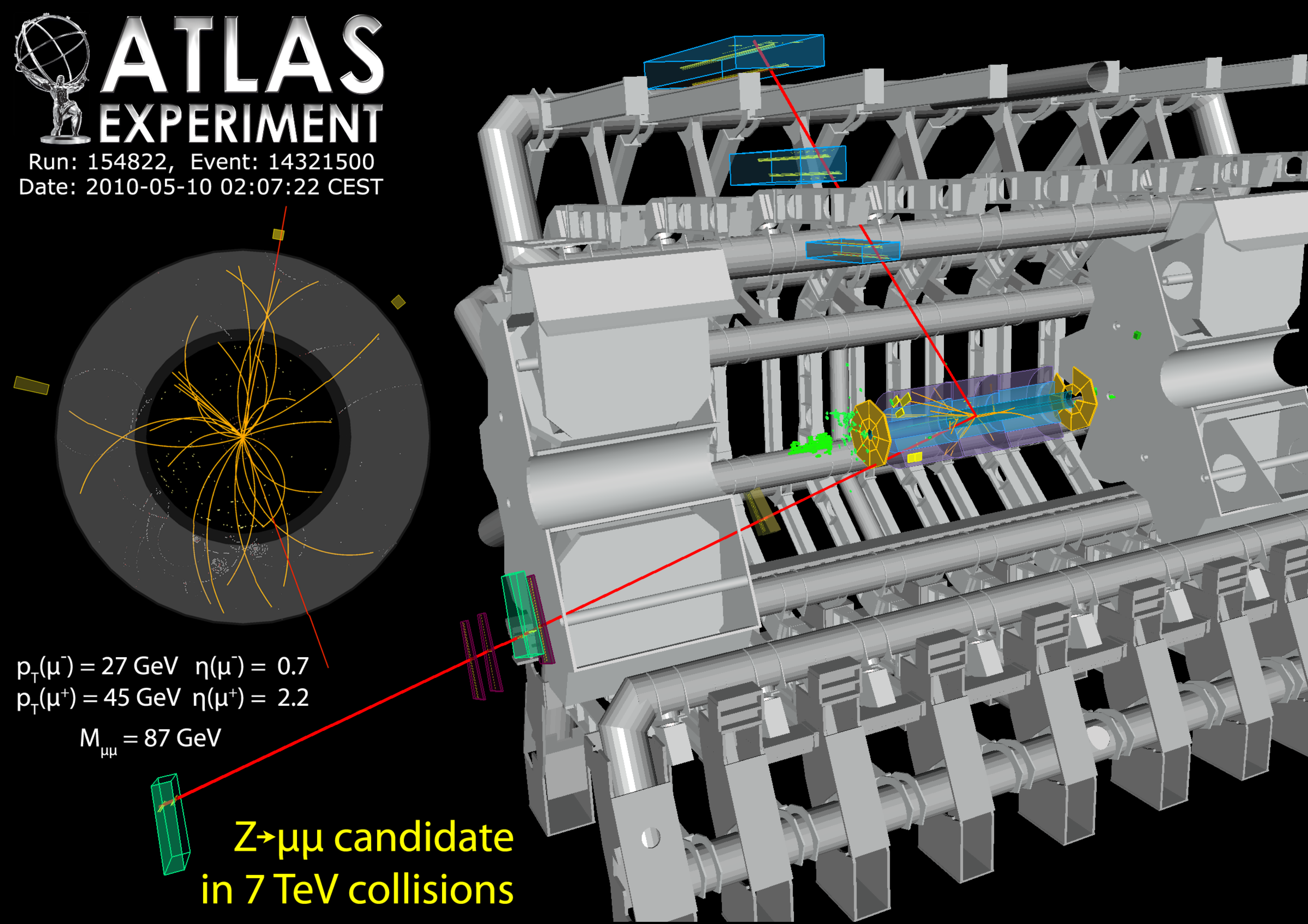

C
D



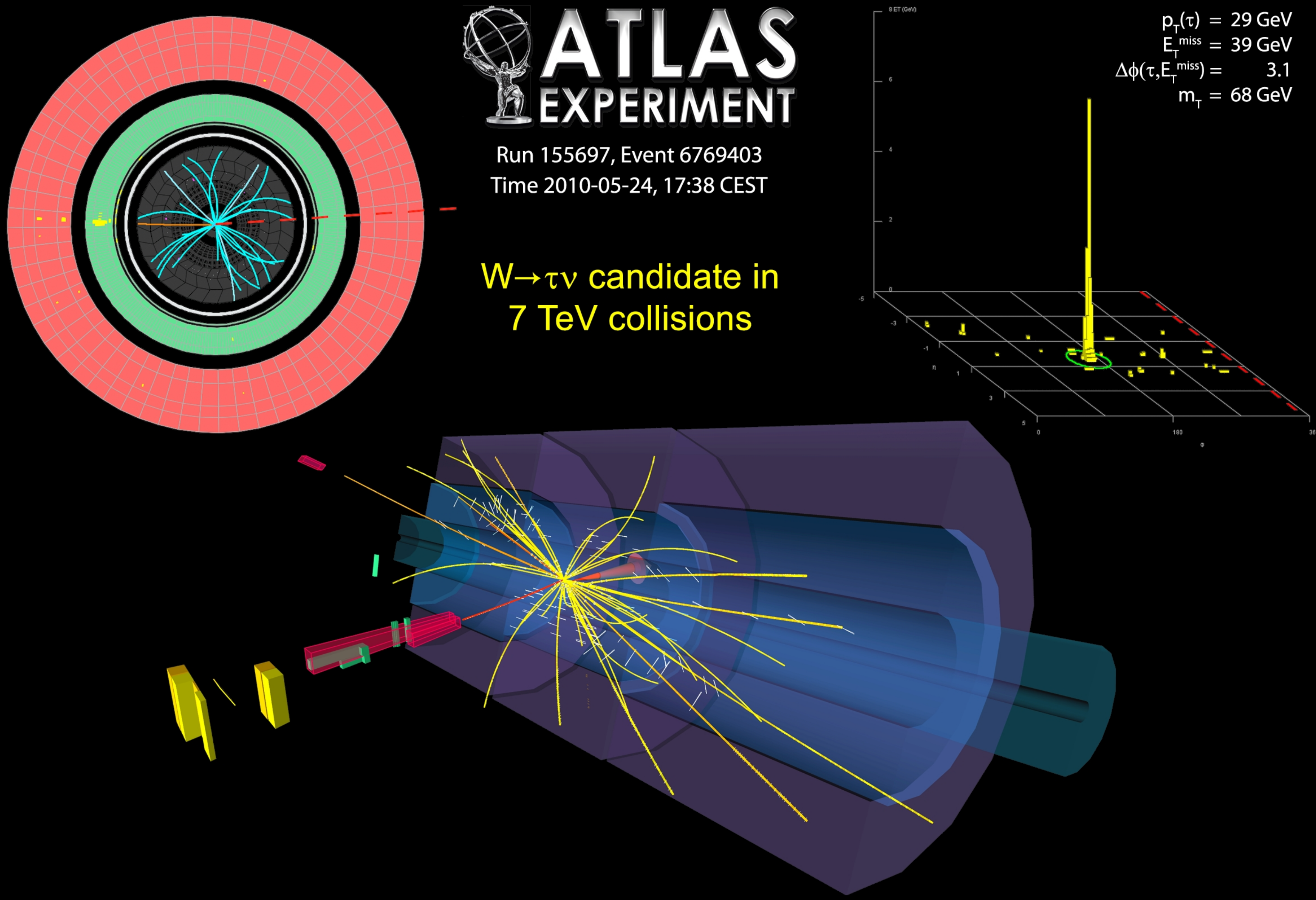
Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Proton
Neutron
Electron
Photon
Neutrino
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch



Electron and Photon reconstruction and identification



Muon reconstruction and identification



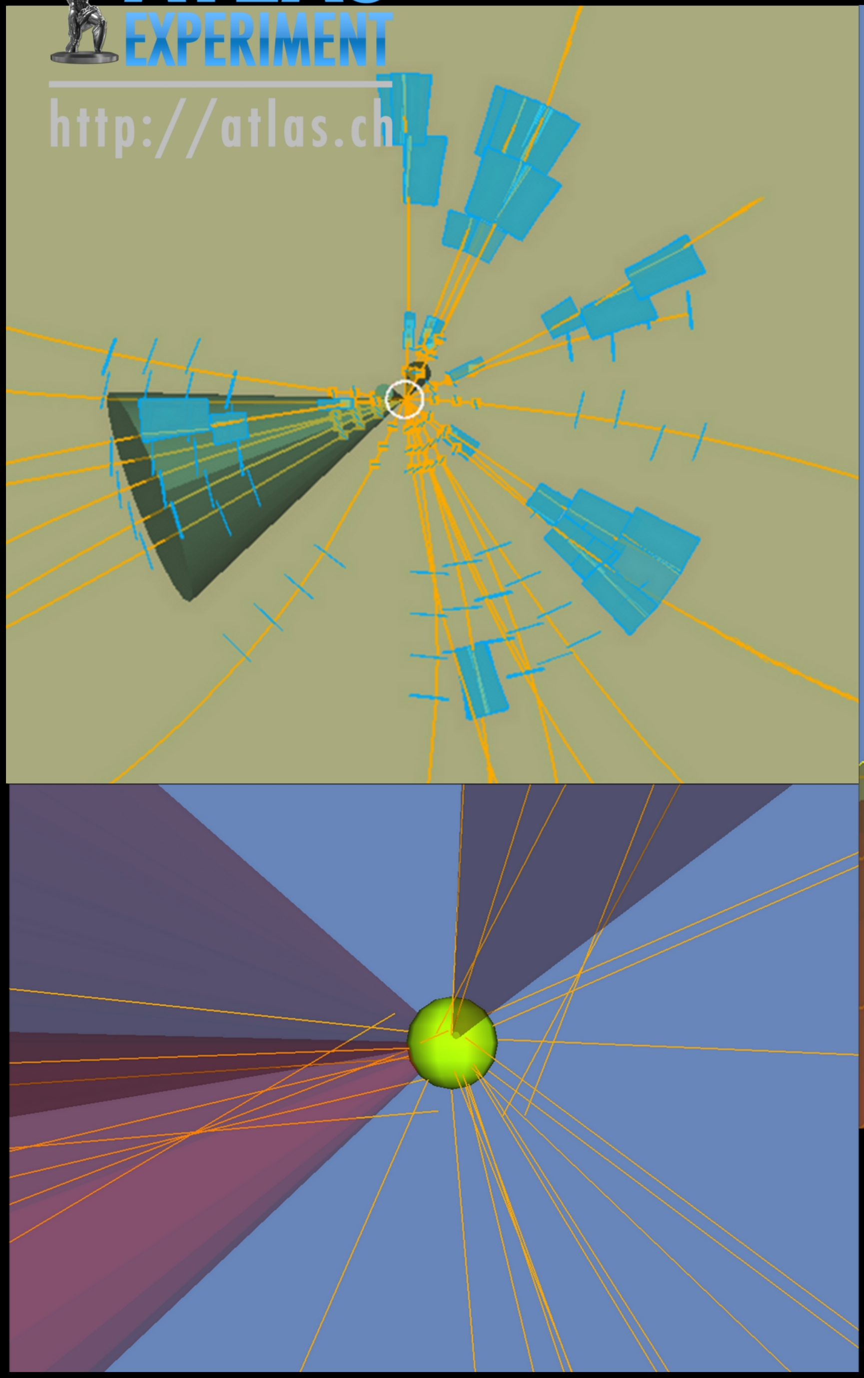
Tau lepton reconstruction and identification

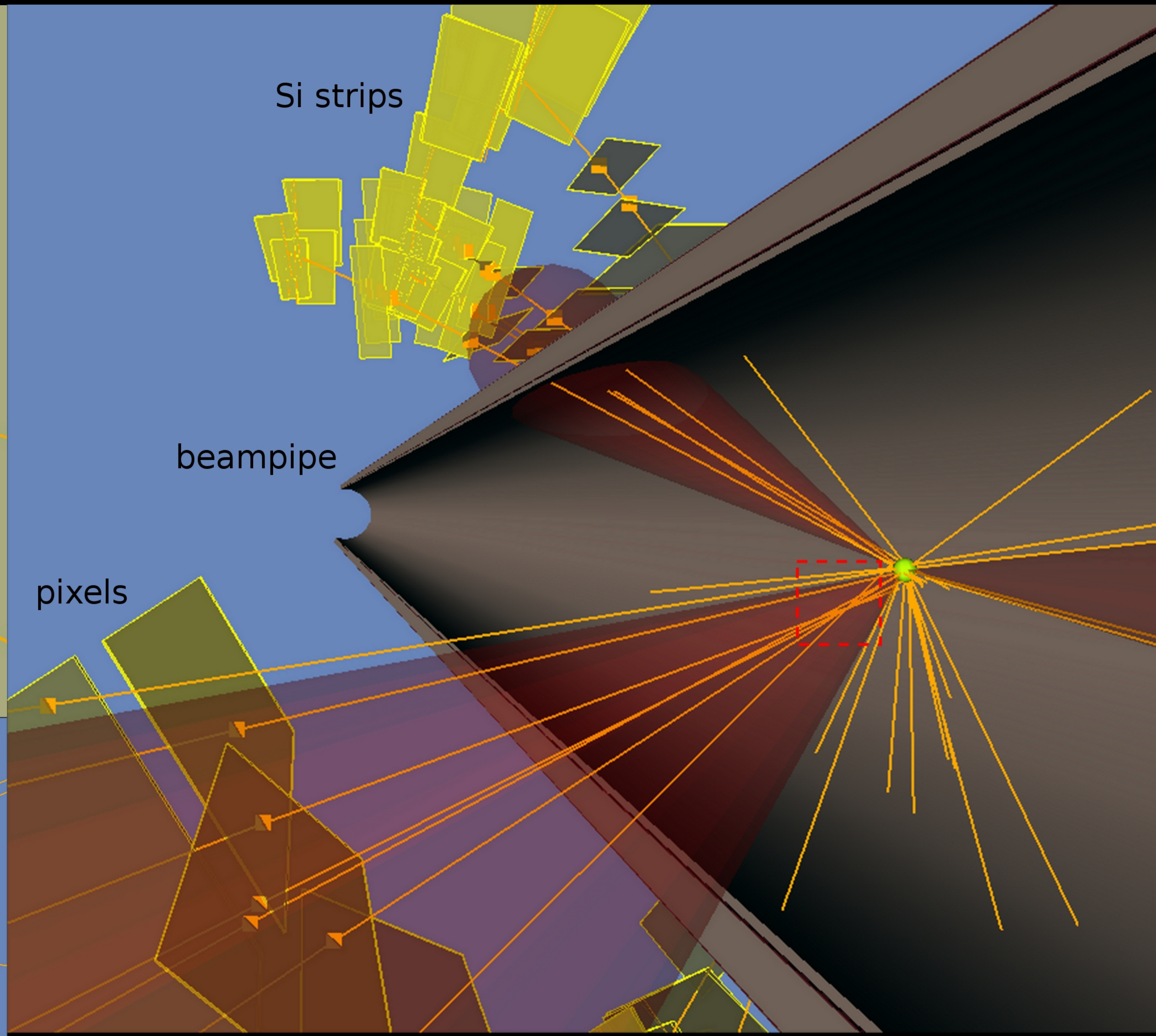
ATLAS EXPERIMENT

http://atlas.ch

Run 152166
Event 817271

b-tagged jet in 7 TeV collisions

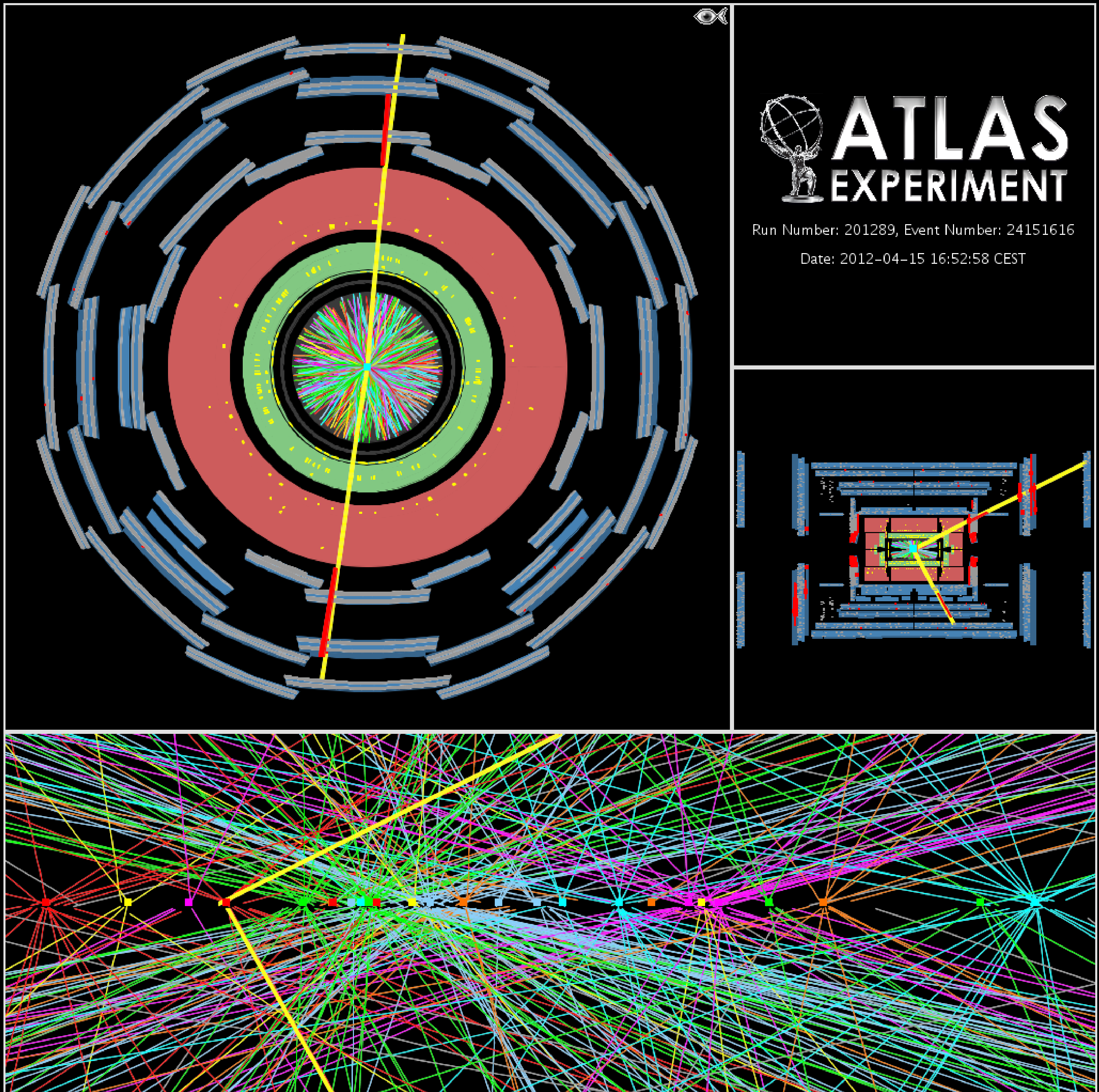




p_T^{jet} =19 GeV (measured at electromagnetic scale)

4 b-tagging quality tracks in the jet

Bottom quark jet (b-jet) reconstruction and identification


ATLAS
EXPERIMENT
Run Number: 201289, Event Number: 24151616
Date: 2012-04-15 16:52:58 CEST

Experimental Sidenote:
How to avoid fooling yourself or being fooled by nature

Imagine you want to choose a coin to use in making binary decisions (e.g. which of two restaurants to eat at), but you want a BIASED coin so that your favorite comes up more often.

You find a coin that yields a HEADS result 14/20 coin flips. Is it biased? How would you assess its possible level of preference for HEADS?

First, you need to establish the question you are trying to answer:

"What is the chance that a fair coin, one which is not preferential to either heads or tails, can yield 14 or more HEADS results in 20 flips?"

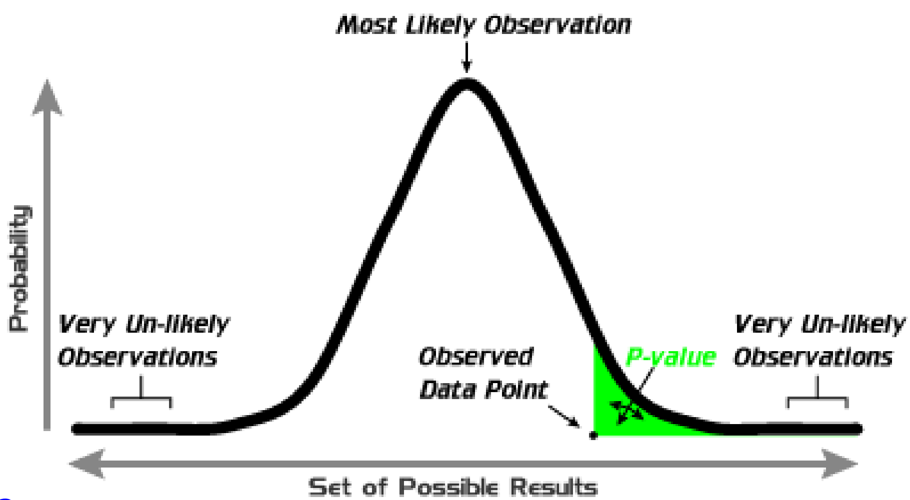
Analogy in the Higgs search: "If I see an excess in data over what is expected from the Standard Model, how probable is it for the Standard Model to have produced that many or more events in data?"

Use binomial probabilities to estimate the chance that a fair coin can yield 14 or more HEADS in 20 coin flips:

$$\text{Prob}(14\text{ heads}) + \text{Prob}(15\text{ heads}) + \cdots + \text{Prob}(20\text{ heads})$$
$$= \frac{1}{2^{20}}\left[\binom{20}{14} + \binom{20}{15} + \cdots + \binom{20}{20}\right] = \frac{60{,}460}{1{,}048{,}576} \approx 0.058$$

Here, binomial probability theory is the analogy to the Standard Model and how it's used to predict outcomes in an experiment.

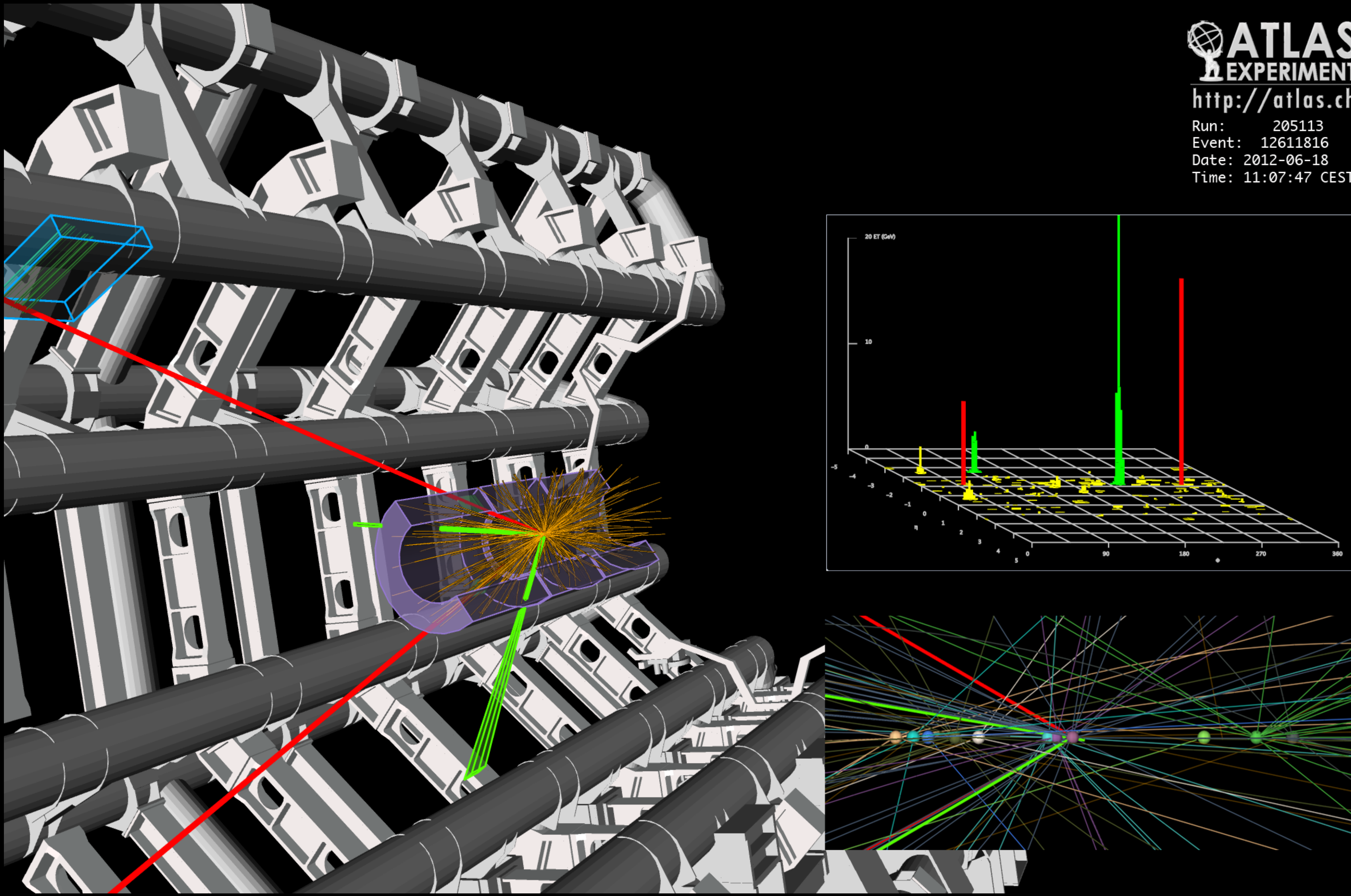
This number, 0.058, is called the "p-value" - the probability that random chance alone, not the presence of an unfair coin, could yield 14 or more HEADS from 20 flips of a coin.

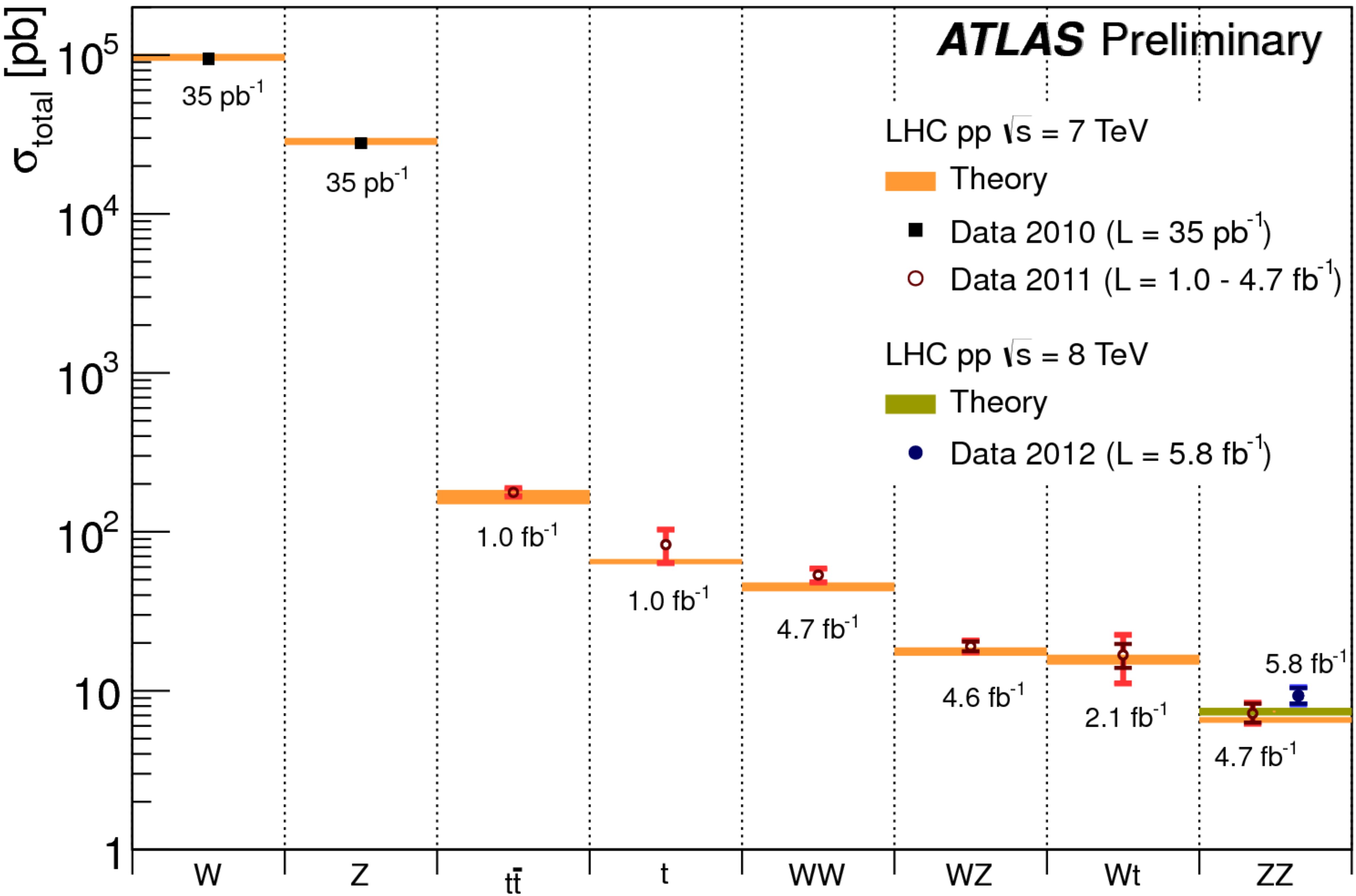


A p-value (shaded green area) is the probability of an observed (or more extreme) result arising by chance

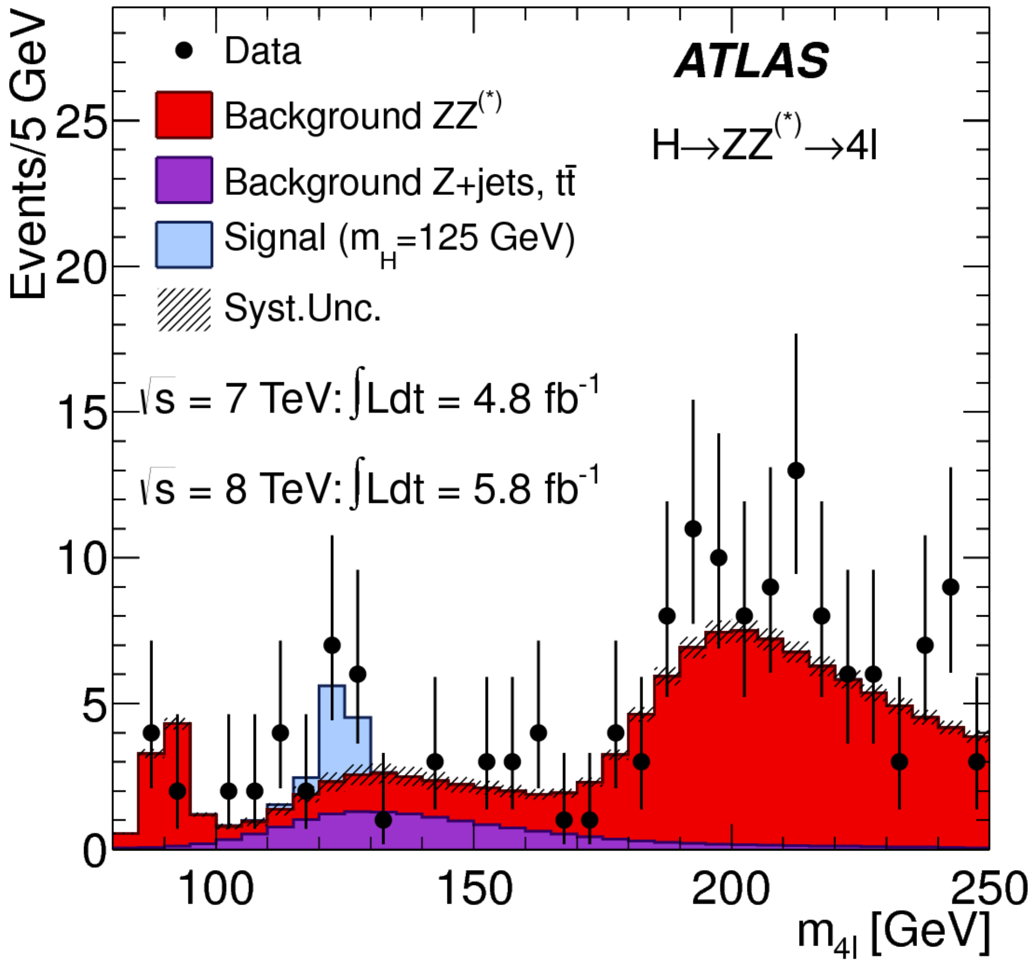
Experimental Results in the Search for a Higgs Boson Candidate

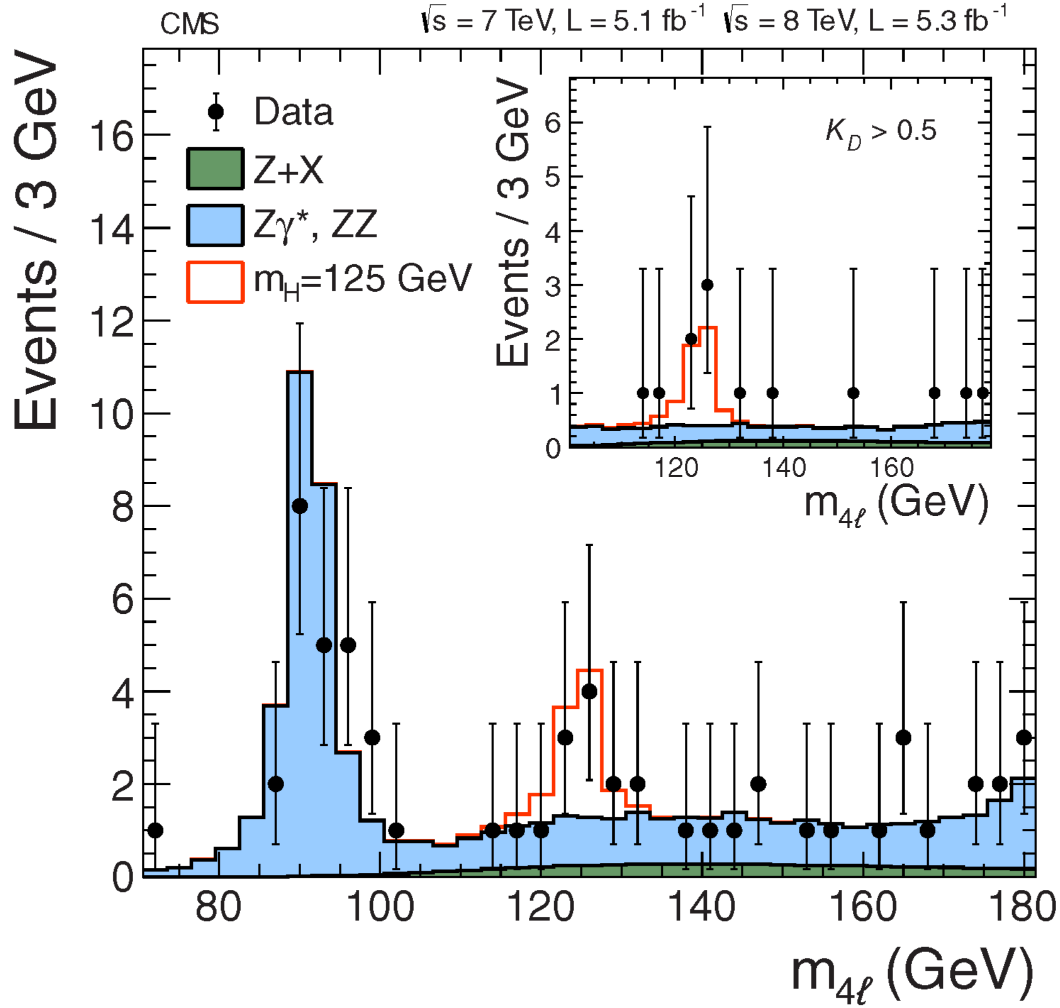
$H \rightarrow ZZ^{(*)} \rightarrow 4l$
The "Golden Mode"


ATLAS
EXPERIMENT
http://atlas.ch
Run: 205113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST

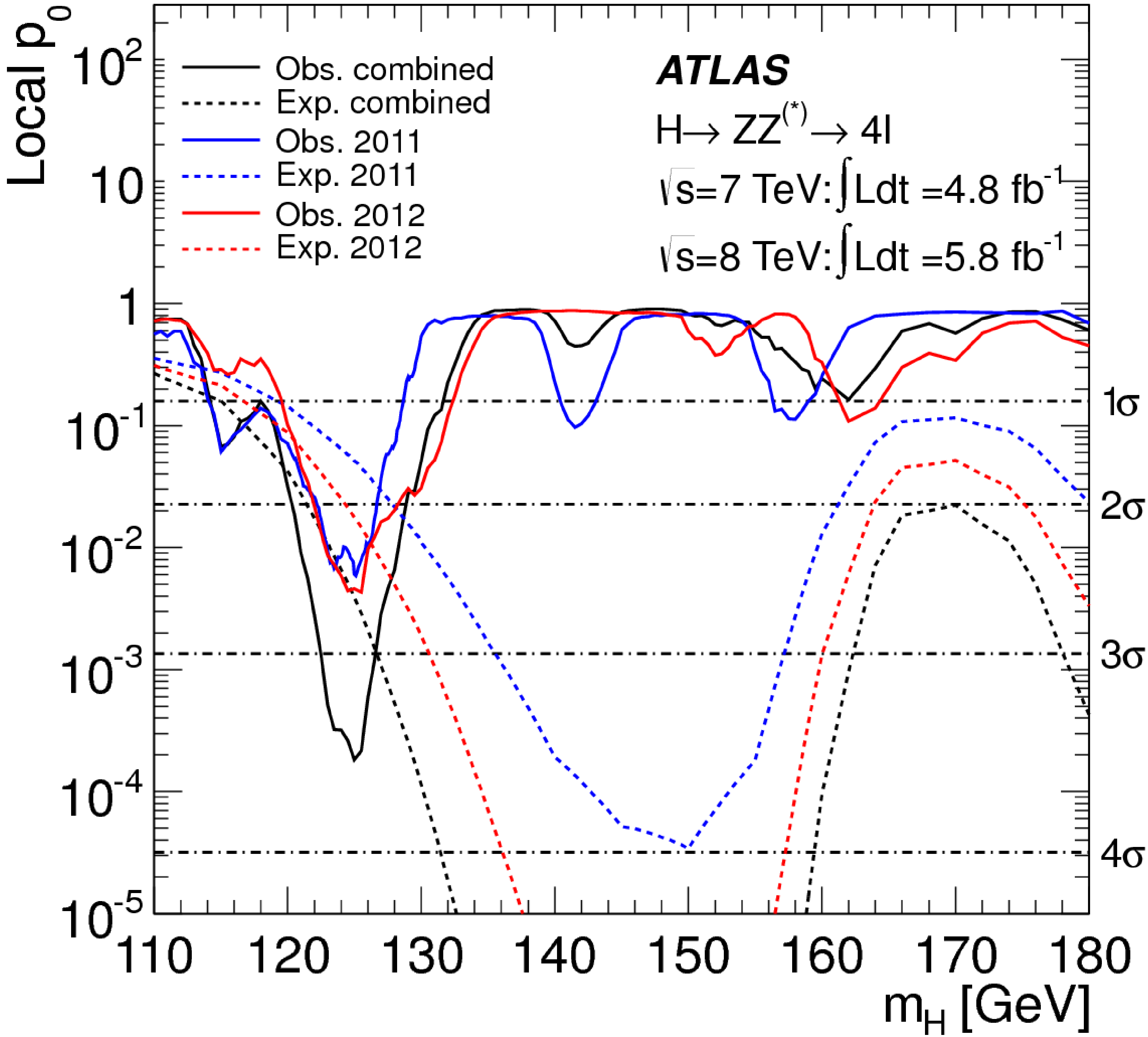


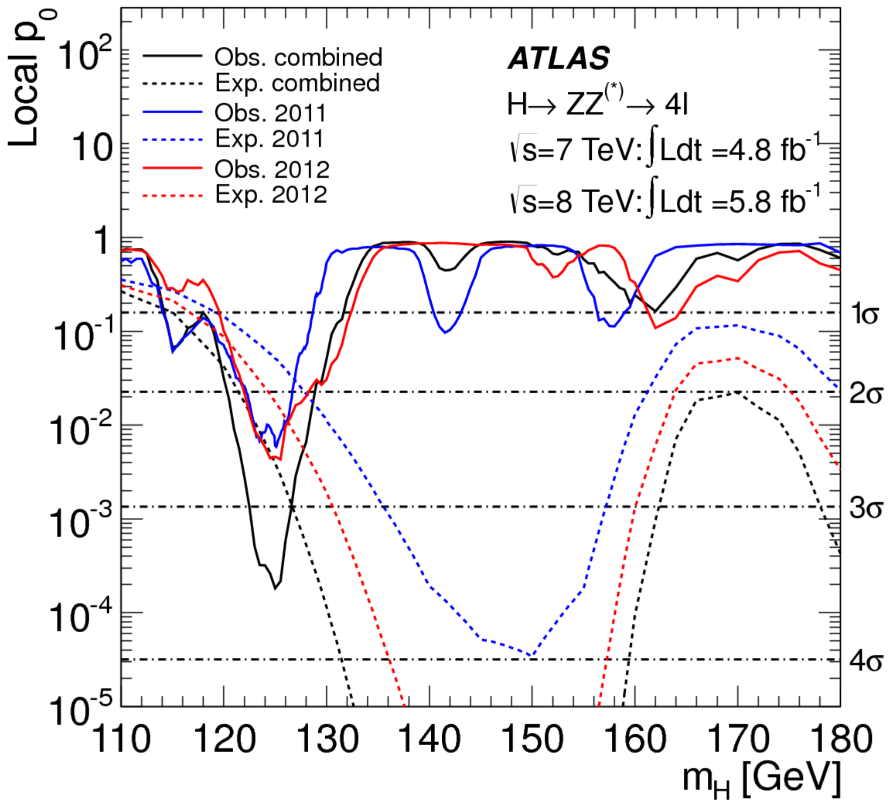
For comparison, the product of Higgs production cross-section and the branching fraction to ZZ(*) and then to four leptons is between $2x10^{-4}$ pb and $6x10^{-3}$ pb for Higgs masses between 100-200 GeV/c2

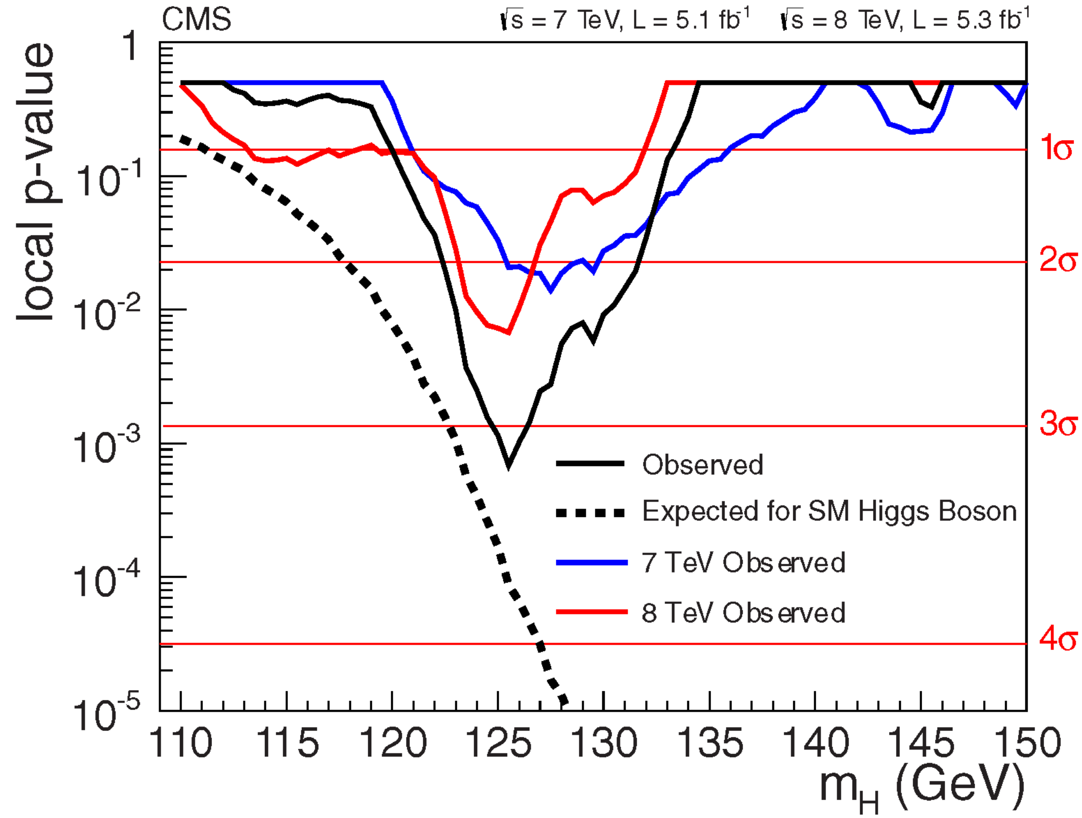




Both experiments independently observe an excess above the expected contributions from non-Higgs “background” events. The regions with the largest excesses are consistent and centered in the region around 125 GeV/c^2.

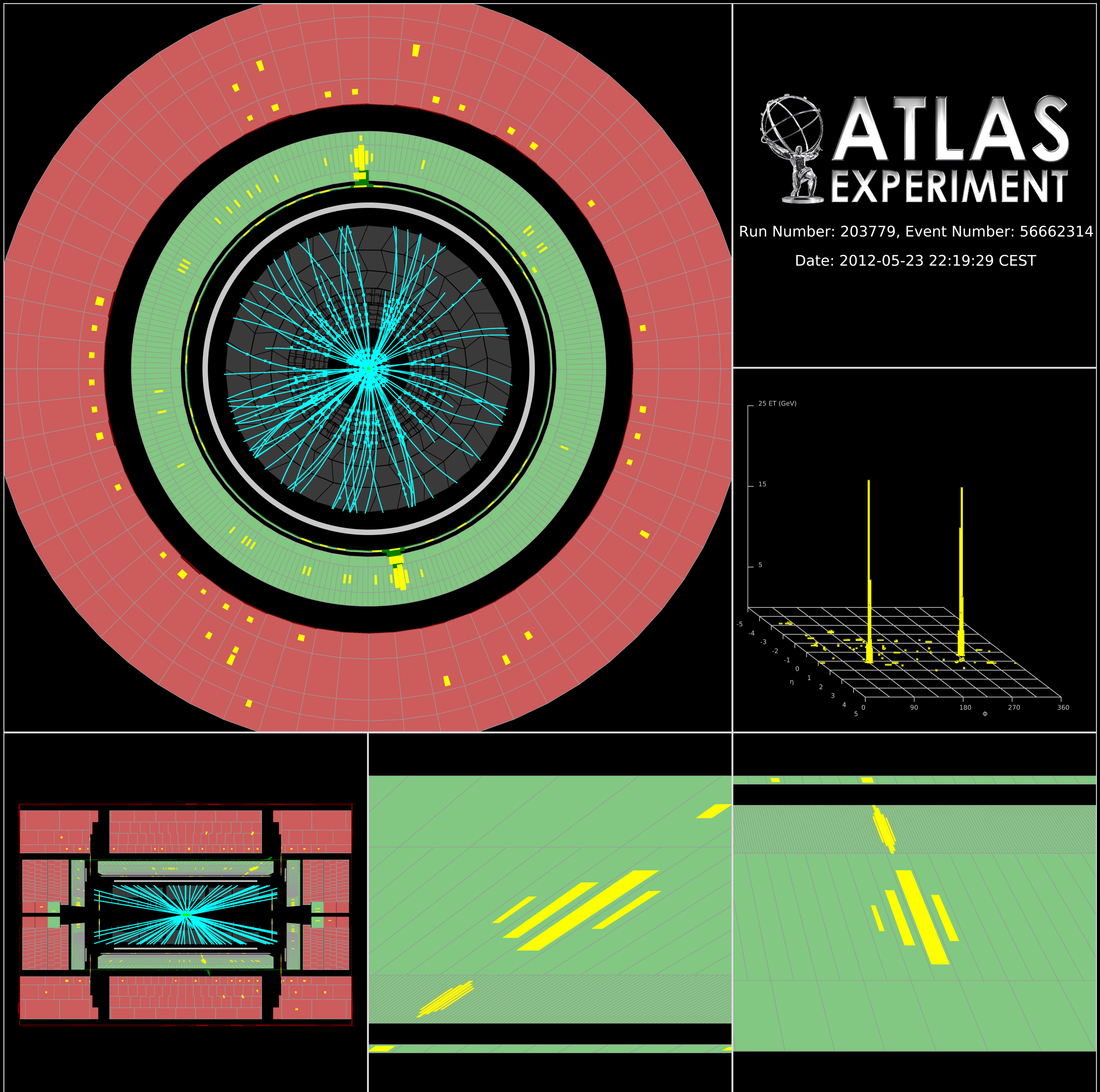

Local p_0
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Obs. combined
Exp. combined
Obs. 2011
Exp. 2011
Obs. 2012
Exp. 2012
ATLAS
$H \rightarrow ZZ^{(*)} \rightarrow 4l$
$\sqrt{s}$=7 TeV: $\int Ldt$ =4.8 fb^{-1}
$\sqrt{s}$=8 TeV: $\int Ldt$ =5.8 fb^{-1}
1σ
2σ
3σ
4σ
110
120
130
140
150
160
170
180
m_H [GeV]

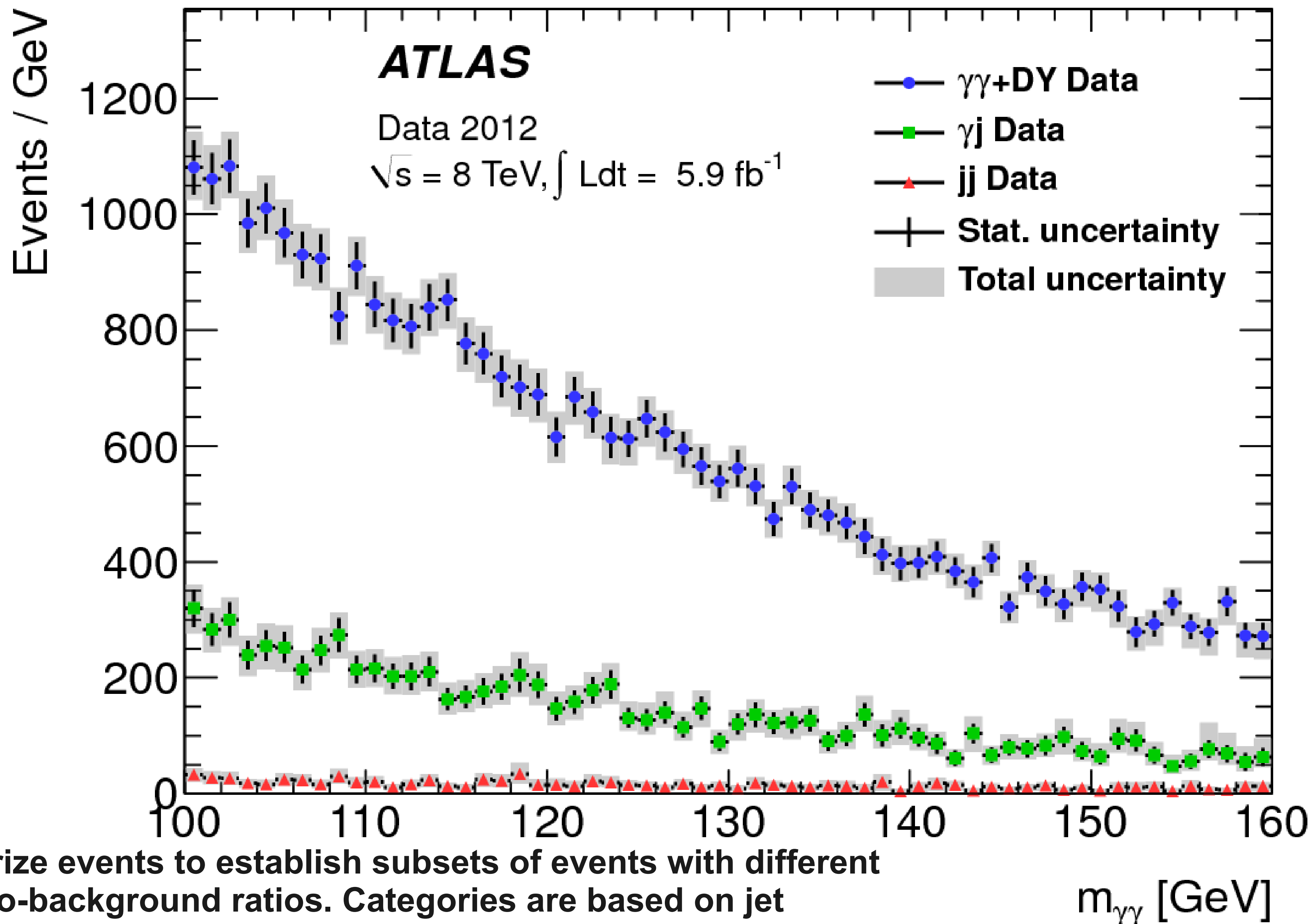




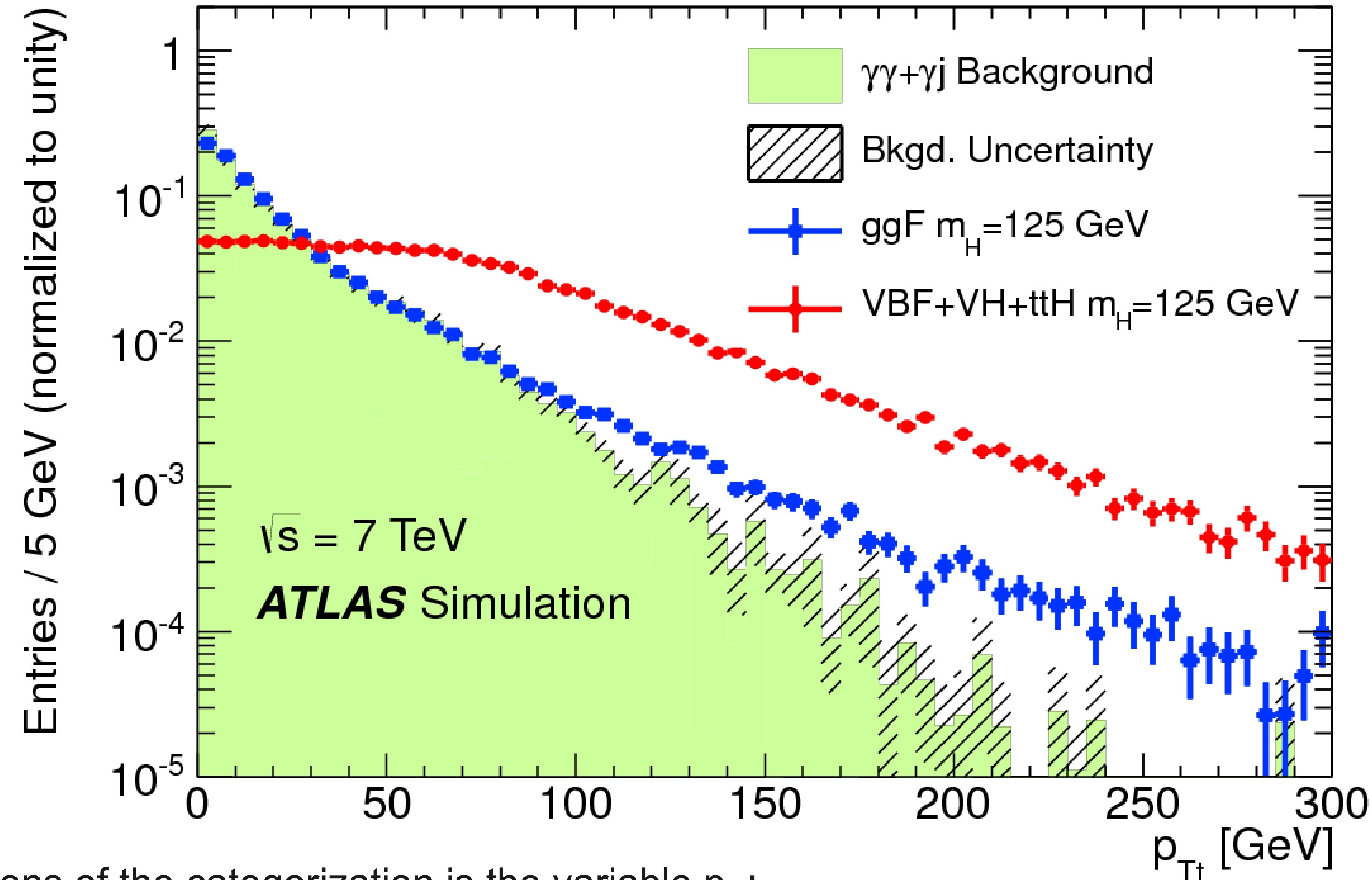
From the perspective of a detailed statistical analysis, both experiments independently observe an excess above the expected contributions from non-Higgs "background" events. The regions with the largest excesses are fairly consistent and centered in the region around 124-126 GeV/c^2.

$H \rightarrow \gamma\gamma$

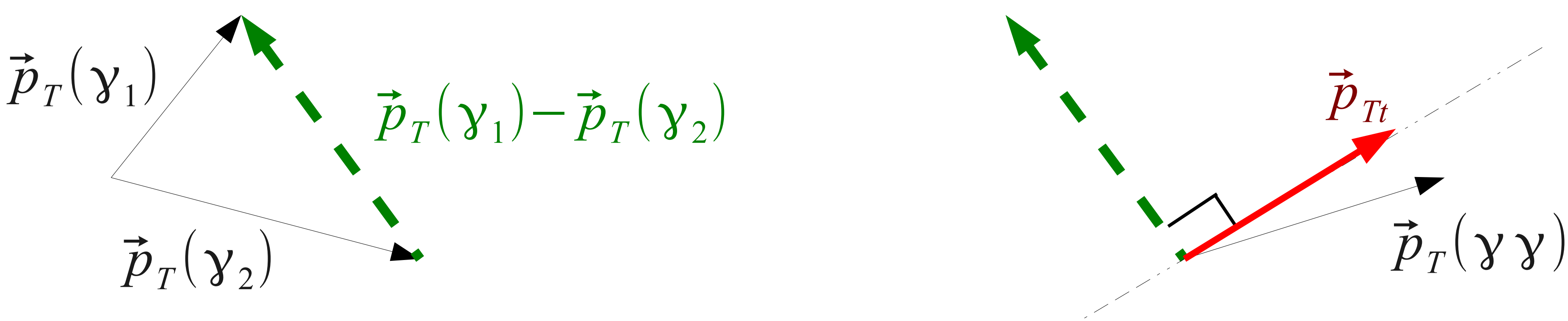

ATLAS EXPERIMENT
Run Number: 203779, Event Number: 56662314
Date: 2012-05-23 22:19:29 CEST
25 ET (GeV)
15
5
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
360
Φ

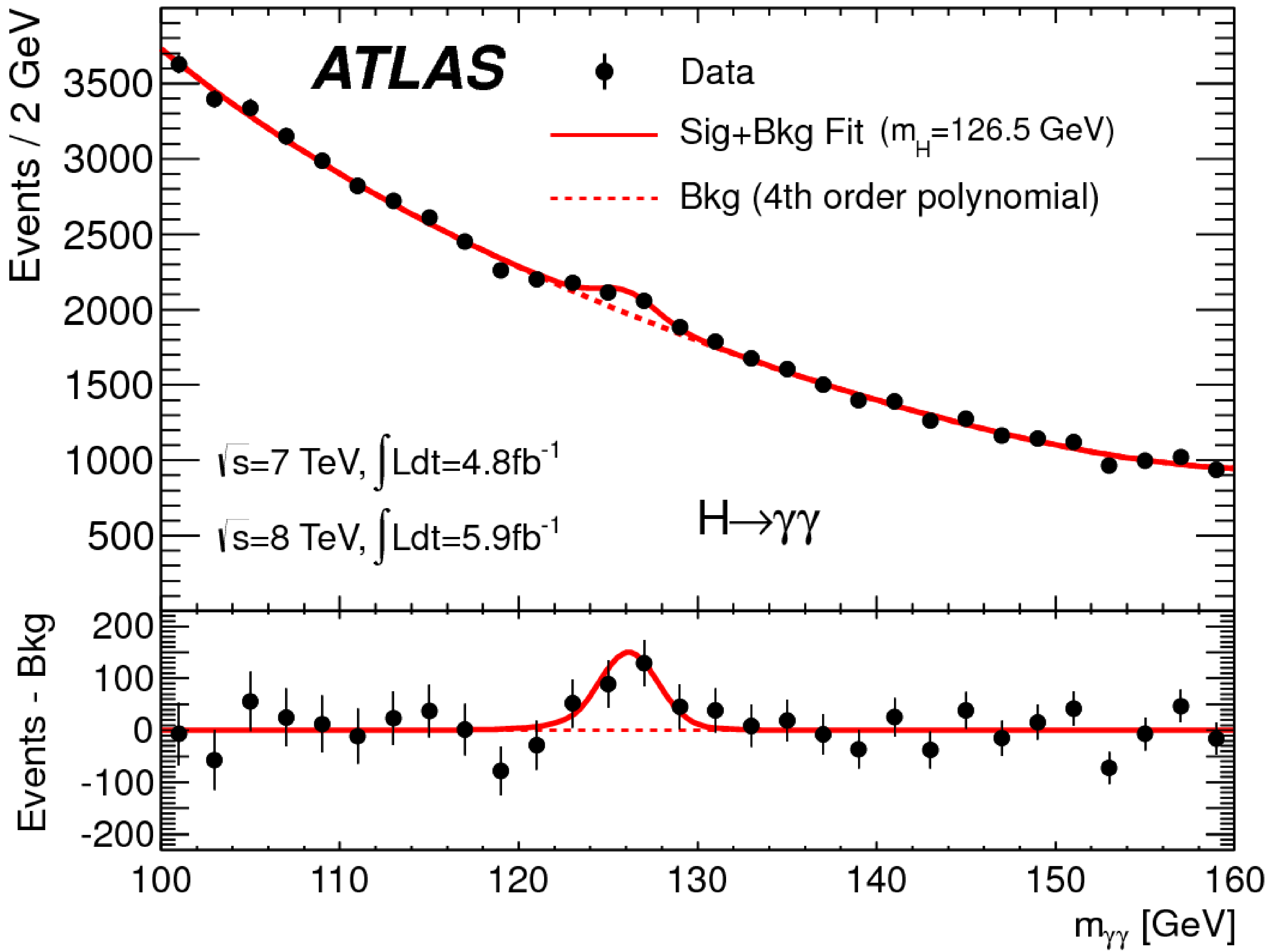


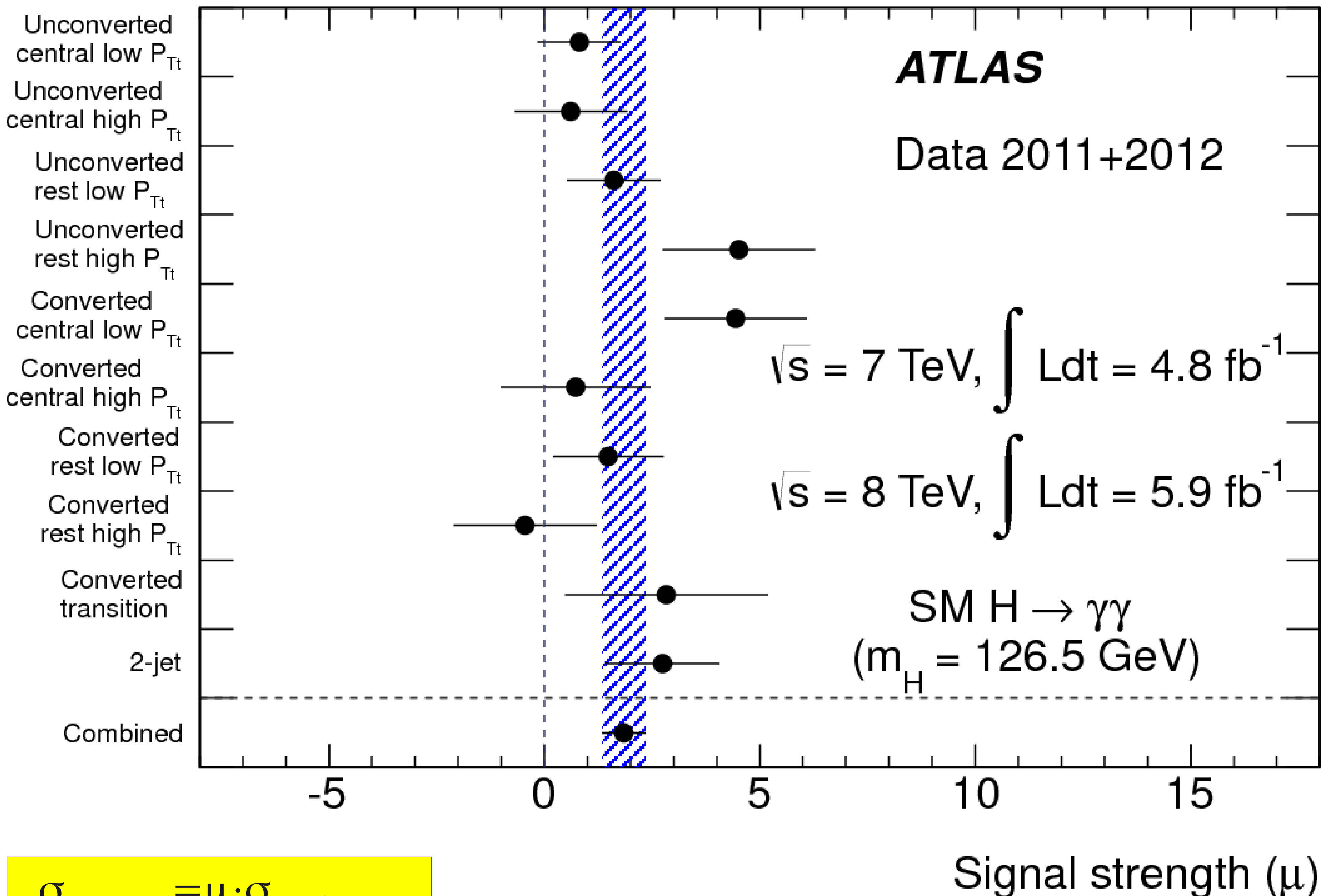
Categorize events to establish subsets of events with different signal-to-background ratios. Categories are based on jet multiplicity (0-1, 2), whether or not there is a converted photon, the polar angle of the photons, and the angular relationships of the photons . . .



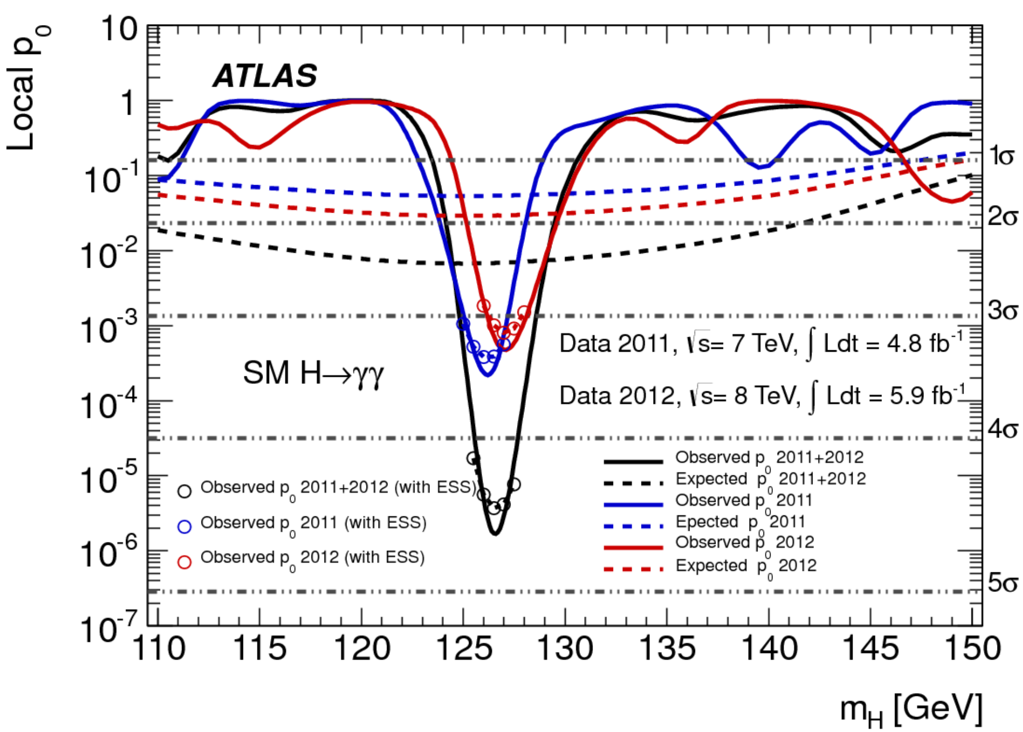
One of the dimensions of the categorization is the variable p_{tT}:

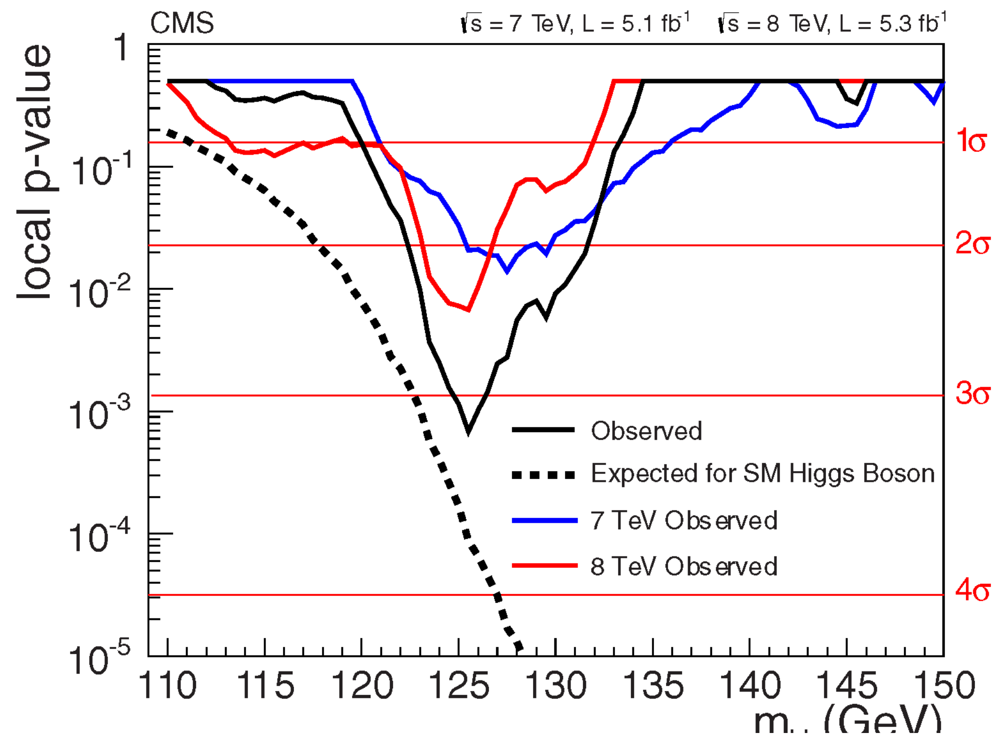


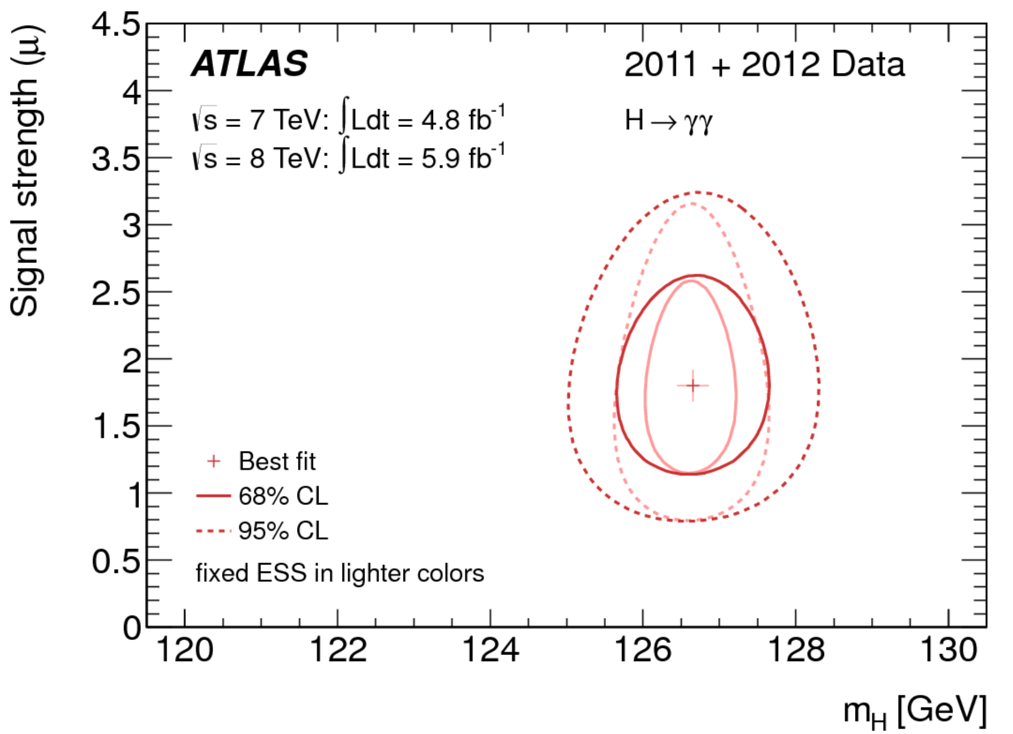

ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
$\sqrt{s}$=7 TeV, $\int Ldt$=4.8fb^{-1}
$\sqrt{s}$=8 TeV, $\int Ldt$=5.9fb^{-1}
$H \rightarrow \gamma\gamma$
Events / 2 GeV
Events - Bkg
$m_{\gamma\gamma}$ [GeV]

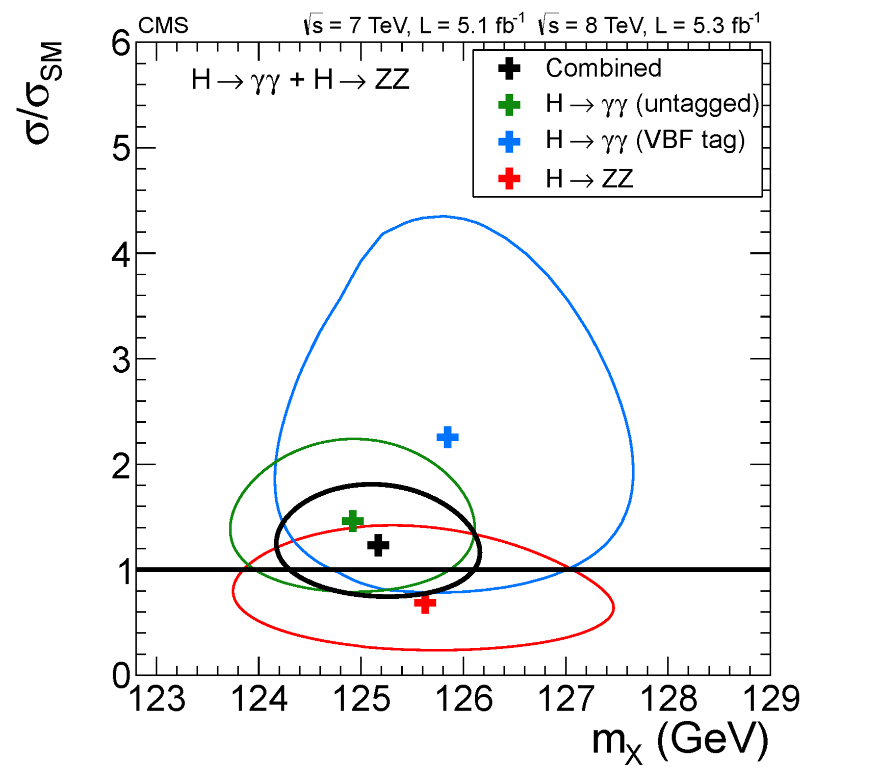


$$\sigma_{measured} = \mu \cdot \sigma_{predicted}$$

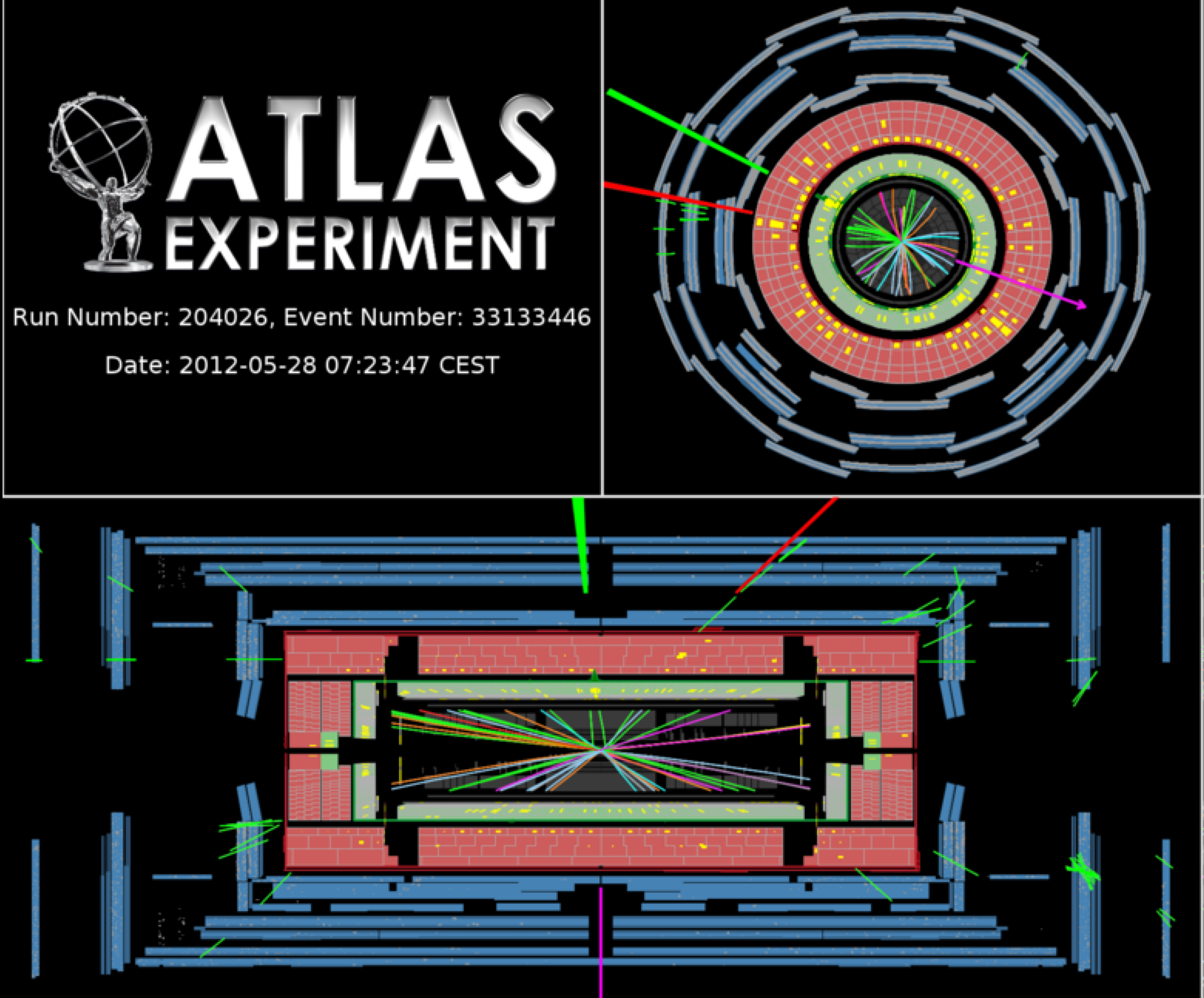

ATLAS
Local p0
SM H→γγ
Data 2011, √s= 7 TeV, ∫ Ldt = 4.8 fb-1
Data 2012, √s= 8 TeV, ∫ Ldt = 5.9 fb-1
Observed p0 2011+2012 (with ESS)
Observed p0 2011 (with ESS)
Observed p0 2012 (with ESS)
Observed p0 2011+2012
Expected p0 2011+2012
Observed p0 2011
Epected p0 2011
Observed p0 2012
Expected p0 2012
1σ
2σ
3σ
4σ
5σ
mH [GeV]

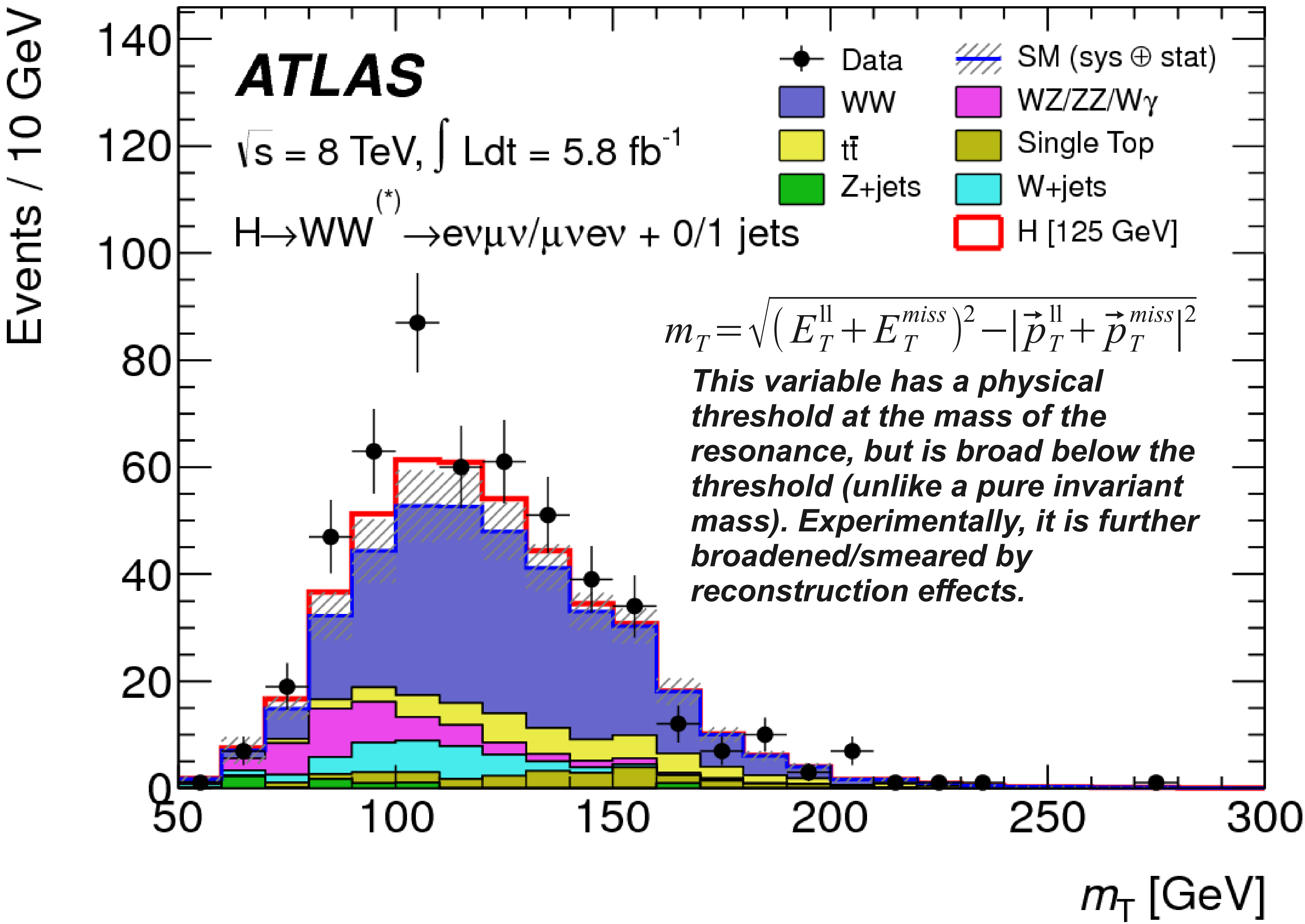

CMS
√s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
local p-value
Observed
Expected for SM Higgs Boson
7 TeV Observed
8 TeV Observed
1σ
2σ
3σ
4σ

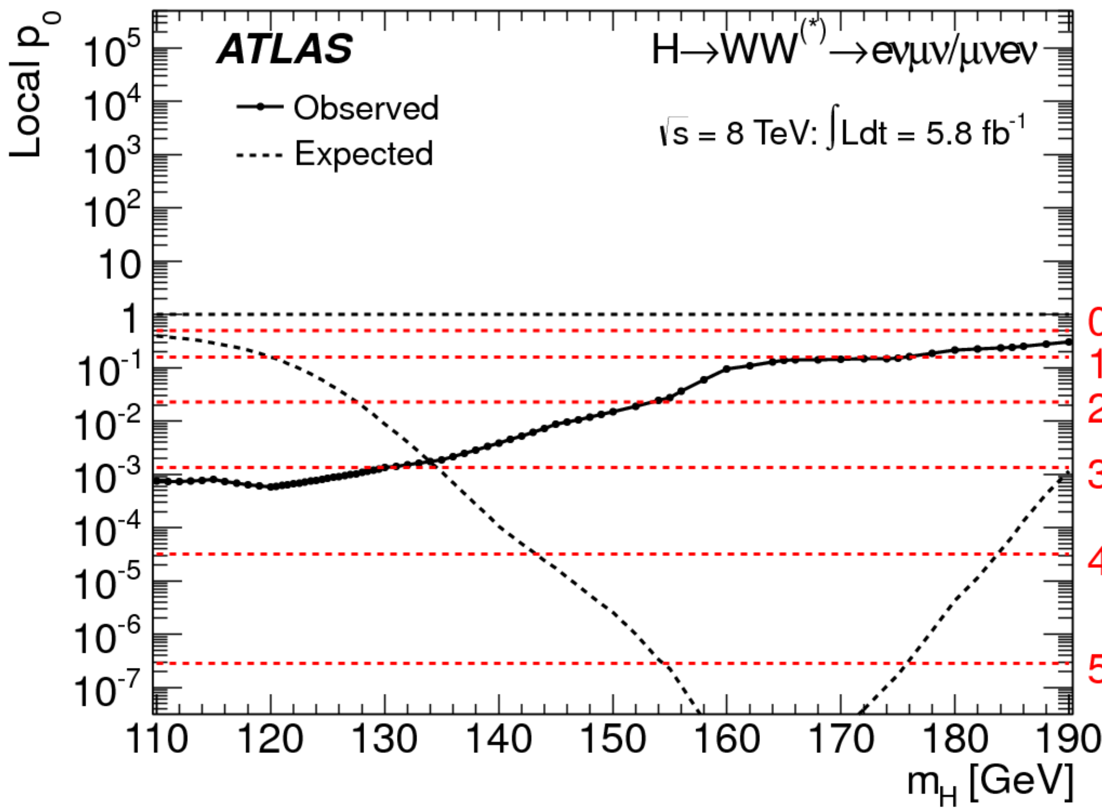

ATLAS
2011 + 2012 Data
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.9 fb-1
H→γγ
Signal strength (μ)
Best fit
68% CL
95% CL
fixed ESS in lighter colors
mH [GeV]

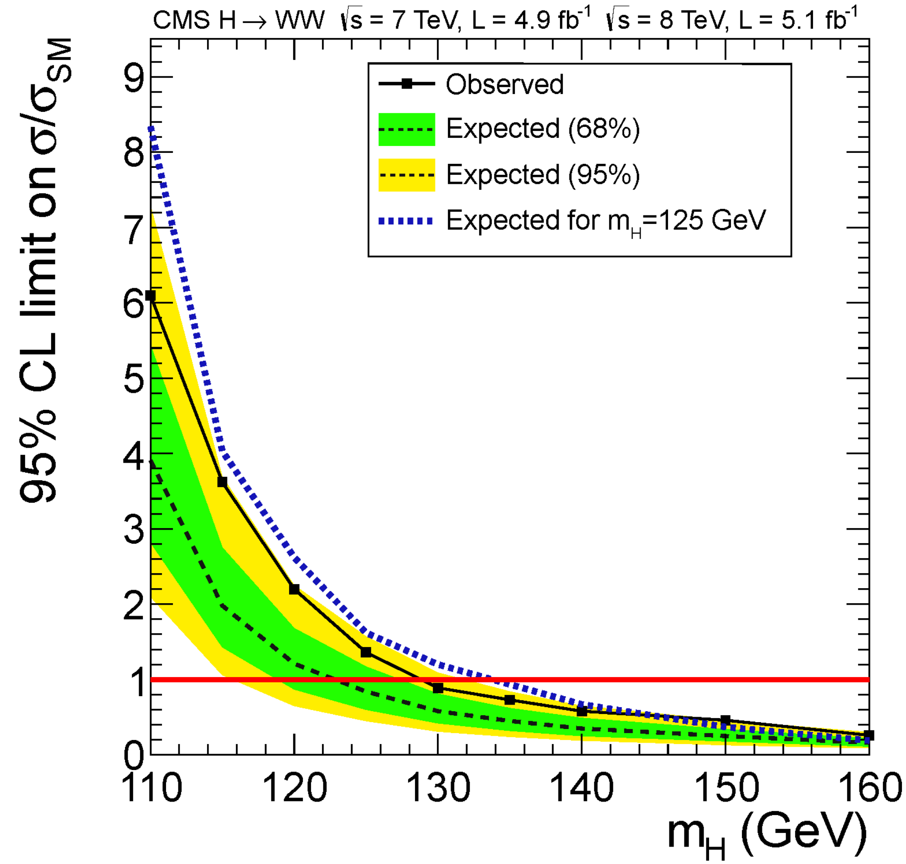

CMS
√s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
σ/σSM
H→γγ + H→ZZ
Combined
H→γγ (untagged)
H→γγ (VBF tag)
H→ZZ
mX (GeV)

$$H \rightarrow W^{+}W^{-}$$


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


ATLAS
$\sqrt{s}$ = 8 TeV, $\int$ Ldt = 5.8 fb^{-1}
$H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu/\mu\nu e\nu$ + 0/1 jets
Data
SM (sys ⊕ stat)
WW
WZ/ZZ/Wγ
$t\bar{t}$
Single Top
Z+jets
W+jets
H [125 GeV]
$m_T = \sqrt{\left(E_T^{ll} + E_T^{miss}\right)^2 - \left|\vec{p}_T^{\,ll} + \vec{p}_T^{\,miss}\right|^2}$
This variable has a physical threshold at the mass of the resonance, but is broad below the threshold (unlike a pure invariant mass). Experimentally, it is further broadened/smeared by reconstruction effects.
Events / 10 GeV
0
20
40
60
80
100
120
140
50
100
150
200
250
300
m_T [GeV]



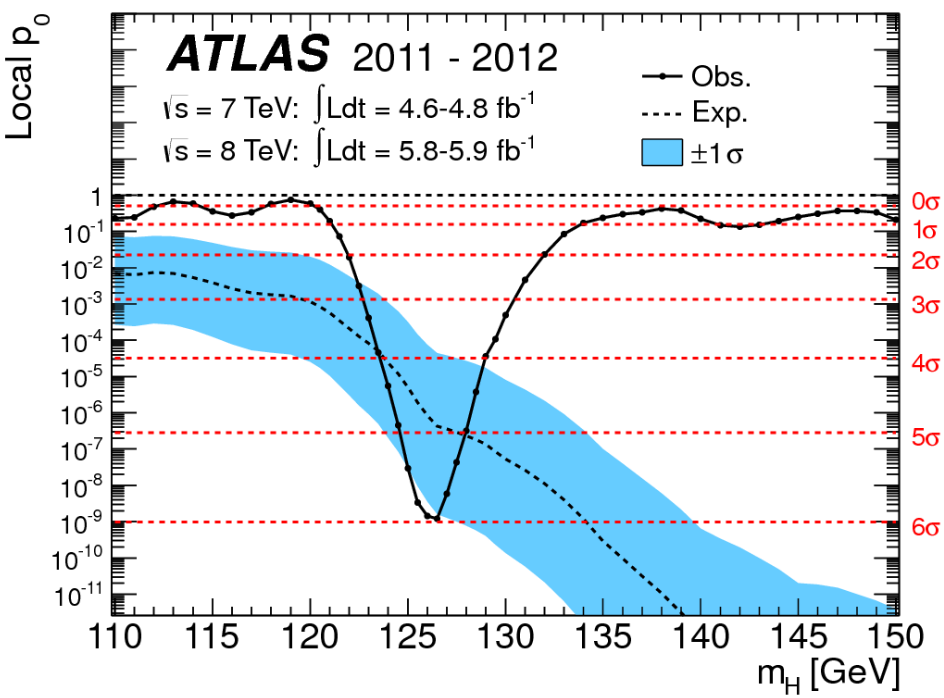


The excesses observed by both ATLAS and CMS are "broad," as expected from this channel. But both experiments independently observe such an excess in their data.

Experimental Summary

ATLAS Publication:
Phys. Lett. B 716 (2012) 1-29

CMS Publication:
Phys. Lett. B 716 (2012) 30-61



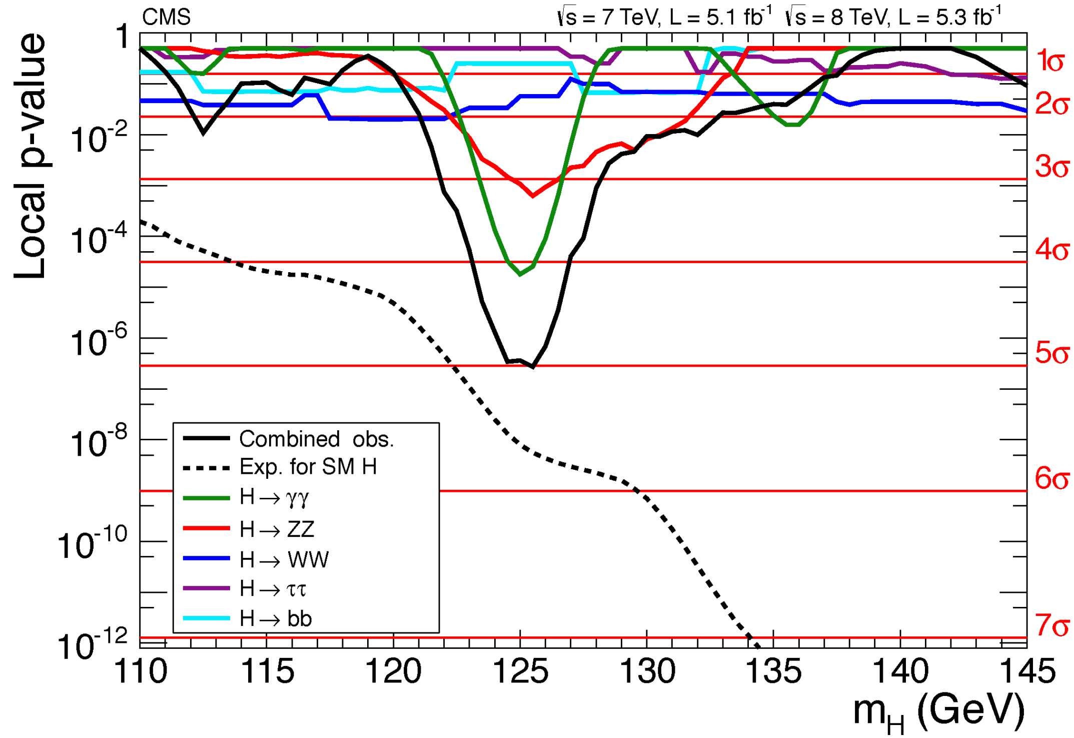
Strength of the ATLAS excess

The maximum value of the local significance is 6.0σ.

Taking into account systematic effects from energy measurement resolution, that maximum reduces to 5.9σ.

Taking into account the fact that the search actually looks over a wide range of masses (and fluctuations can occur when you look in more places), the global significance is:

5.1σ (global significance)

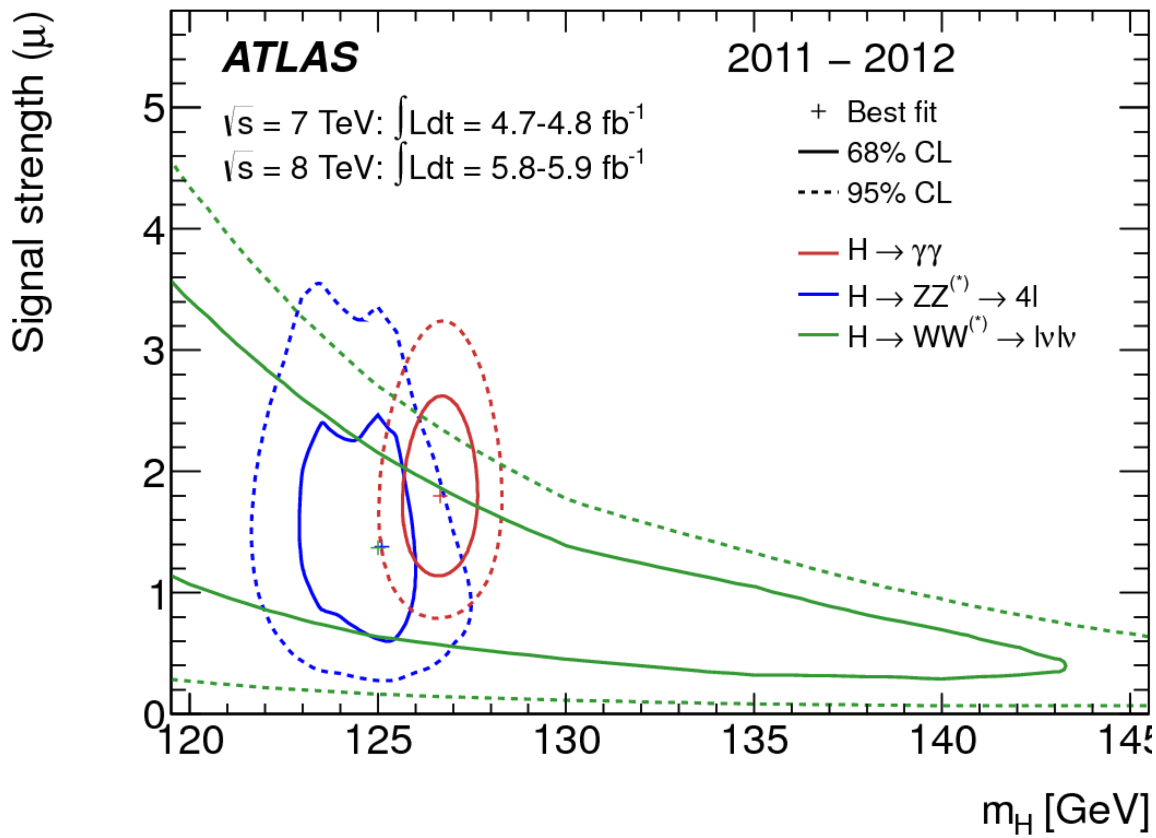


Strength of the CMS excess

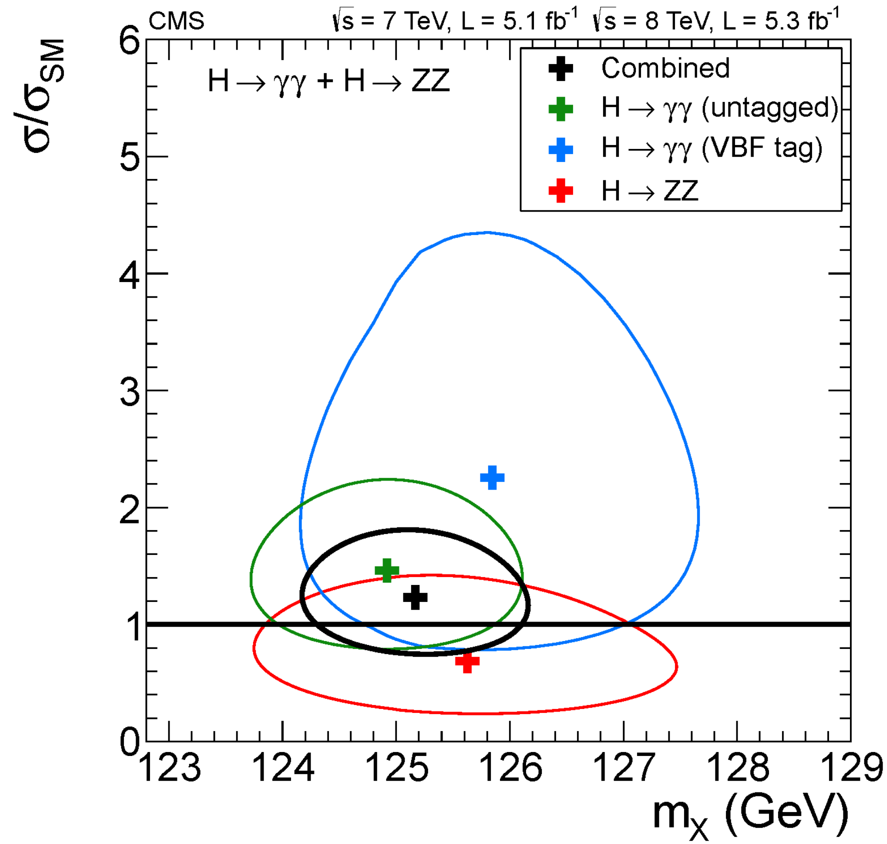
The maximum value of the local significance is 5.0σ.

Taking into account the fact that the search actually looks over a wide range of masses (and fluctuations can occur when you look in more places), the global significance is:

4.5σ (global significance)



ATLAS Mass Measurement

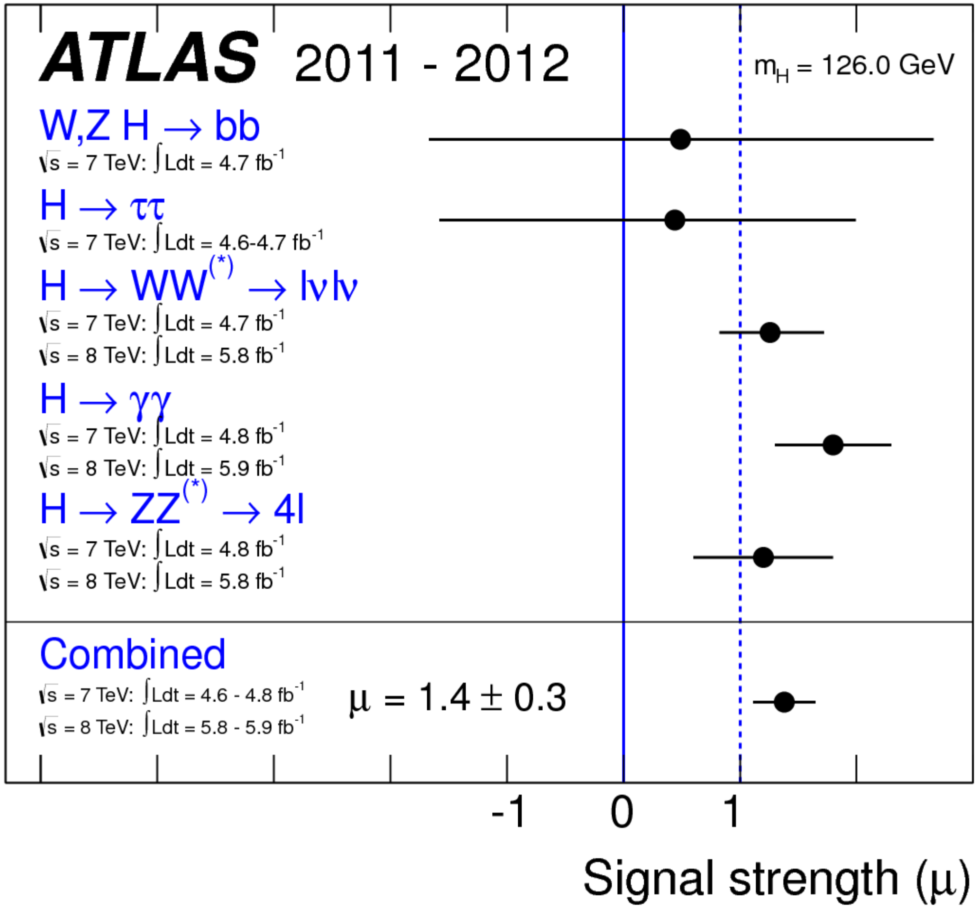


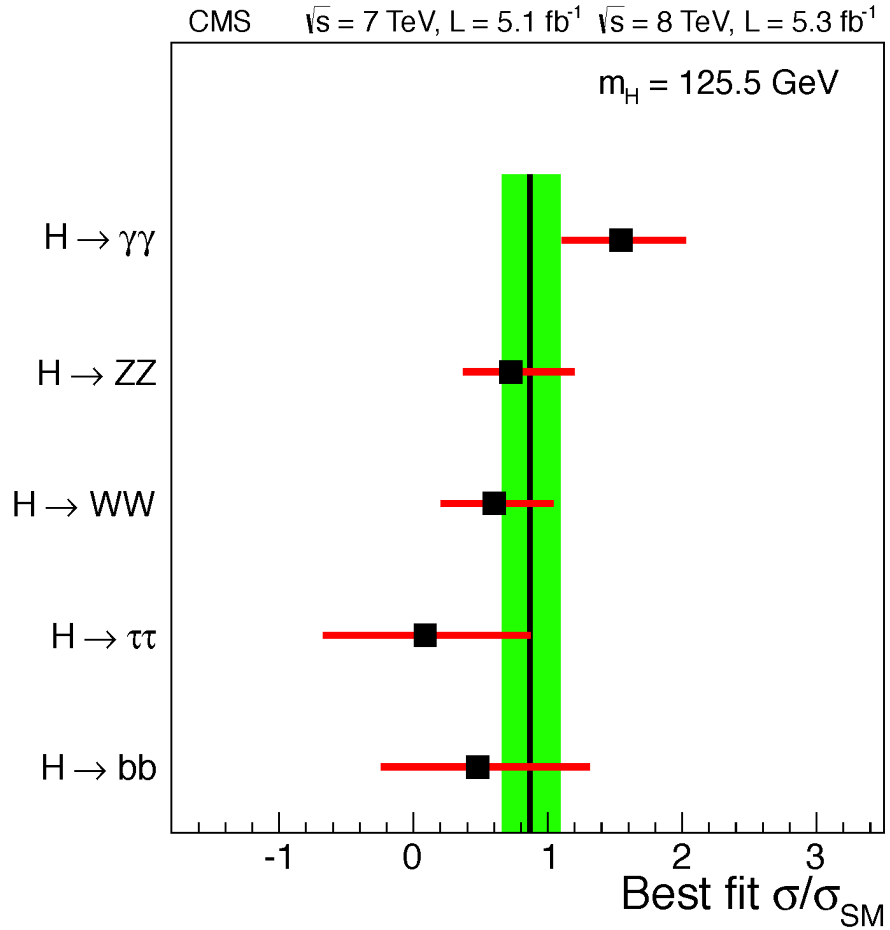
CMS Mass Measurement

$$M_H = 126.0 \pm 0.4\,(\text{stat.}) \pm 0.4\,(\text{syst.})\,\text{GeV/c}^2$$

$$M_H = 125.3 \pm 0.4\,(\text{stat.}) \pm 0.5\,(\text{syst.})\,\text{GeV/c}^2$$

The mass is consistent between the two experiments.





Within currently published statistics, this particle is so-far consistent with the Higgs boson hypothesis. But we want to reduce the uncertainties here (more statistics, better experimental techniques, better theoretical modeling) to see if that H → γ γ "excess" holds up.

PARTICLE MASS

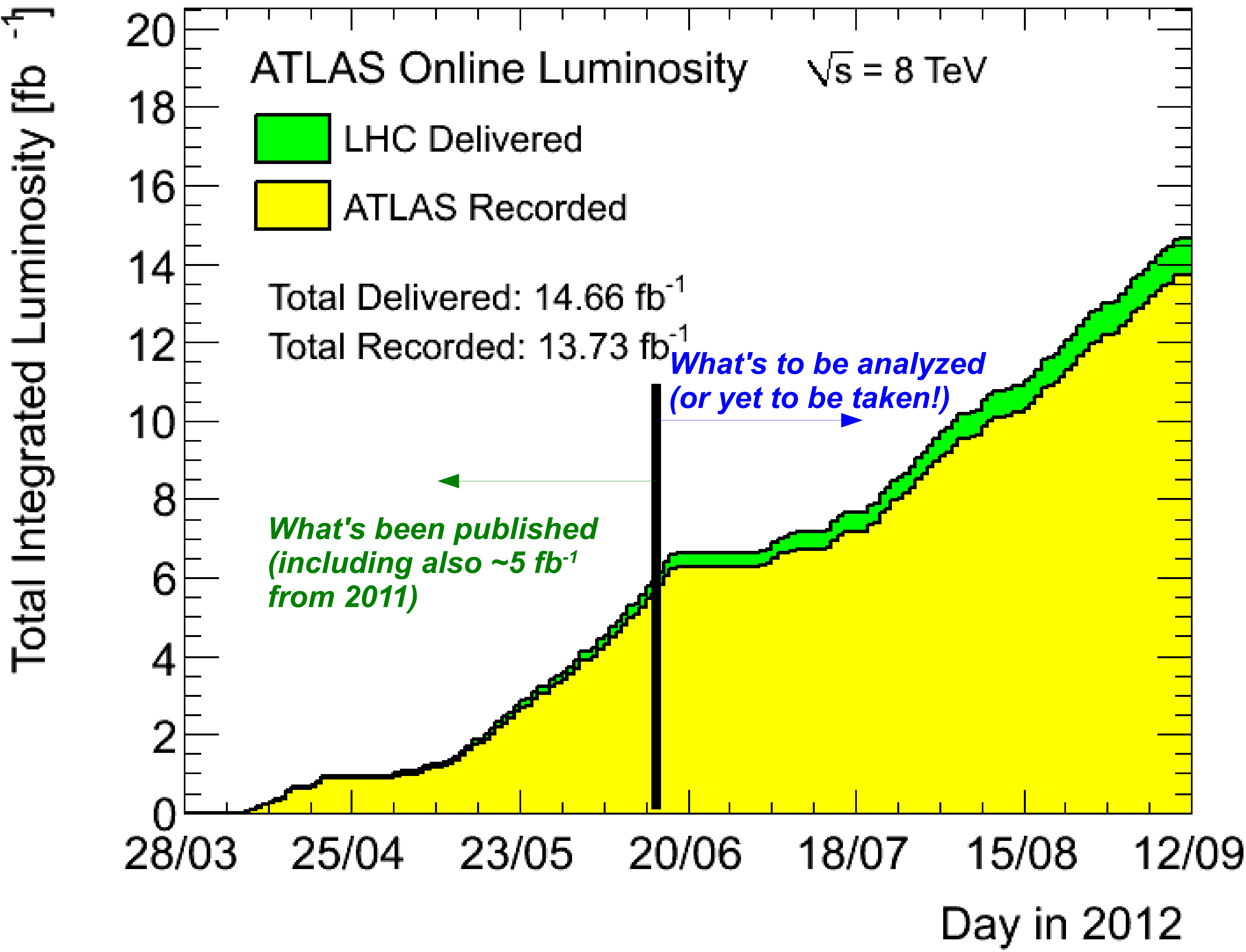
PARTICLE SPIN

PARTICLE CP

PARTICLE COUPLINGS

[for instance:
rate of production
rate of decay]

The Next Steps



ATLAS Online Luminosity
√s = 8 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 14.66 fb-1
Total Recorded: 13.73 fb-1
What's to be analyzed
(or yet to be taken!)
What's been published
(including also ~5 fb-1
from 2011)
Total Integrated Luminosity [fb-1]
0
2
4
6
8
10
12
14
16
18
20
28/03
25/04
23/05
20/06
18/07
15/08
12/09
Day in 2012

Outlook

- Properties of the Higgs
  - Efforts underway to determine spin and CP quantum numbers of this new particle
  - Efforts continue to look at existing and new decay modes of the new particle
- Beyond the Higgs
  - Efforts are expanding to look for cousins of this new particle (e.g. additional Higgs particles that might gives mass to things like dark matter or neutrinos - "Godzilla Particles")
  - Efforts continue to generally look for signs of physics not predicted in the Standard Model (extra dimensions of space, supersymmetric partners of the Standard Model particles, a connection between gravity and the Standard Model, etc.)

All figures and numbers in this talk were obtained from public ATLAS and CMS repositories. For copies, or more plots and numbers than are dreamed of in your philosophy, check out these links:

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2012-27/
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12028TWiki

Event Displays, etc.:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic