LHC and ATLAS

symbiosis leading to particle discoveries

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University of Oxford, Particle Physics Seminar
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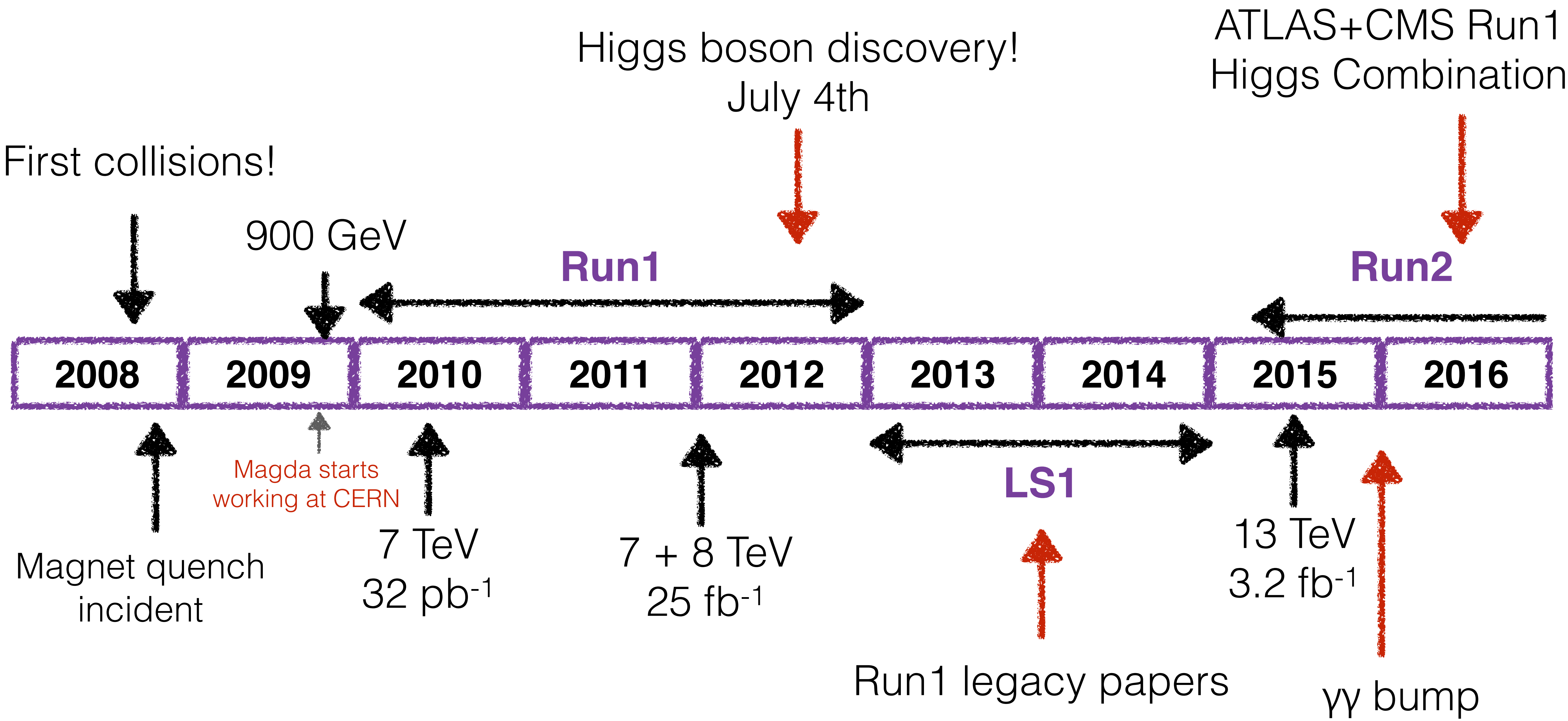
Introduction and Overview



Talk biased towards my work on **Higgs** physics on **ATLAS**…
All four experiments (ATLAS, CMS, ALICE and LHCb) did an amazing job the last few years! Lots of interesting physics results in Run1!

Large Hadron Collider

LHC is colliding two beams of protons at large energies (currently 6.5 TeV per beam)

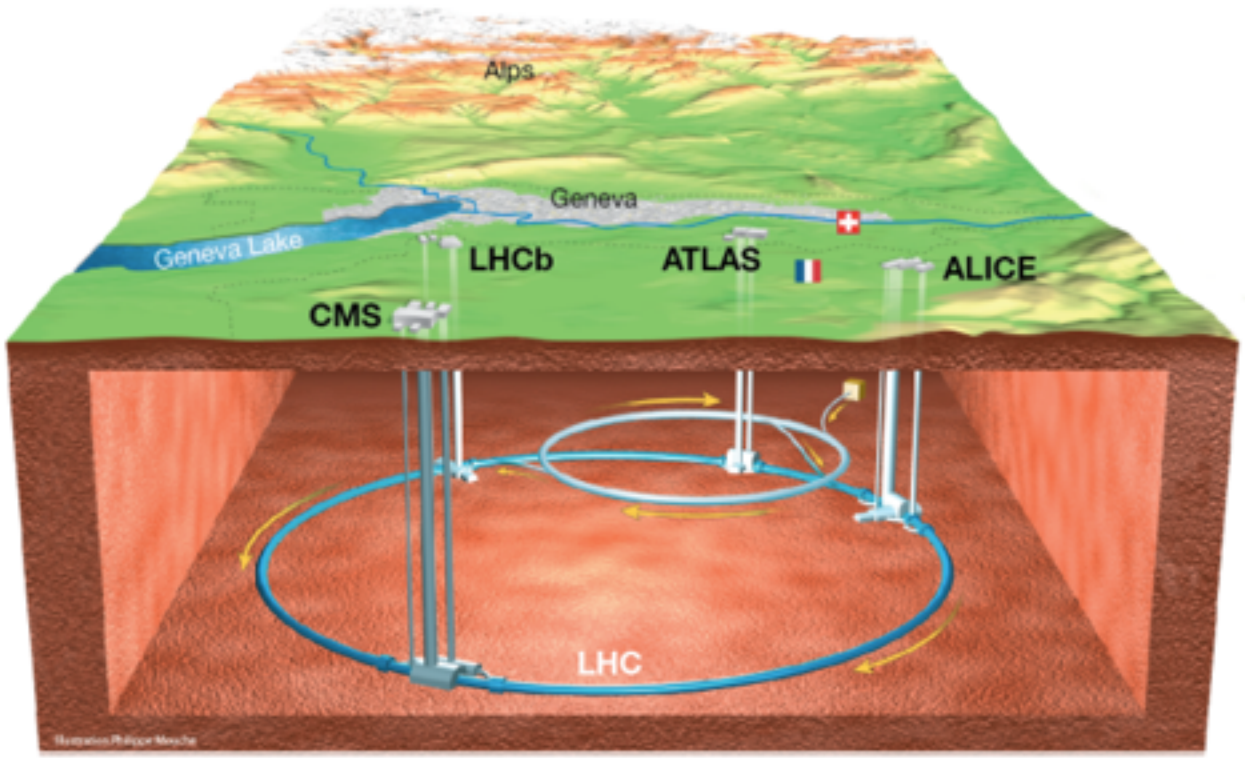
$E=mc^2$!!

large energies mean that we can produce heavy (large mass) particles and recreate the conditions shortly after the Big Bang

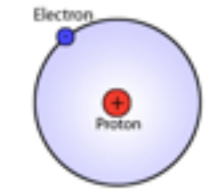
LHC is basically a giant microscope that allows us to see the universe at the smallest scales

What do we get out of the LHC? Knowledge!

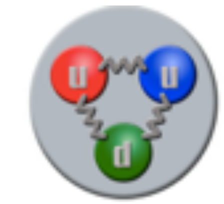
LHC Operations



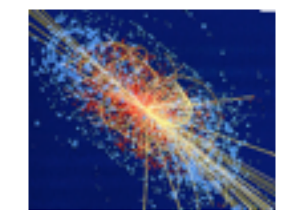
Hydrogen



Protons



Bunches

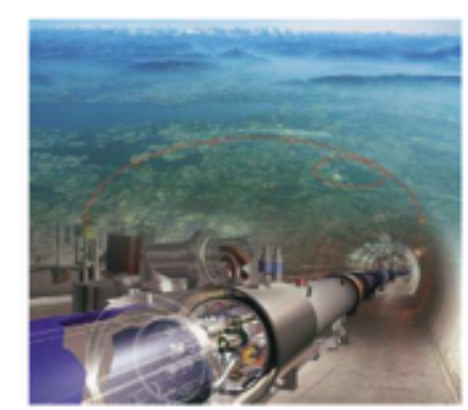


Collisions

Physics!

LHC operations:

1. Pre-accelerate protons to 450 GeV (hydrogen atoms stripped off from electrons)
2. Group protons into bunches and inject into the LHC ring (~10^{11} protons per bunch)
3. Ramp (accelerate the beams to 6.5 TeV using RF cavities)
4. Squeeze (collimate the beams to very small area - magnets)
5. Collide stable beams at 4 points along the LHC ring:
    1. **ATLAS** - general purpose detector
    2. **CMS** - cross check for ATLAS*
    3. **ALICE** - specialised detector for analysing lead ions collisions
    4. **LHCb** - aimed at b-quark studies (matter and antimattter)

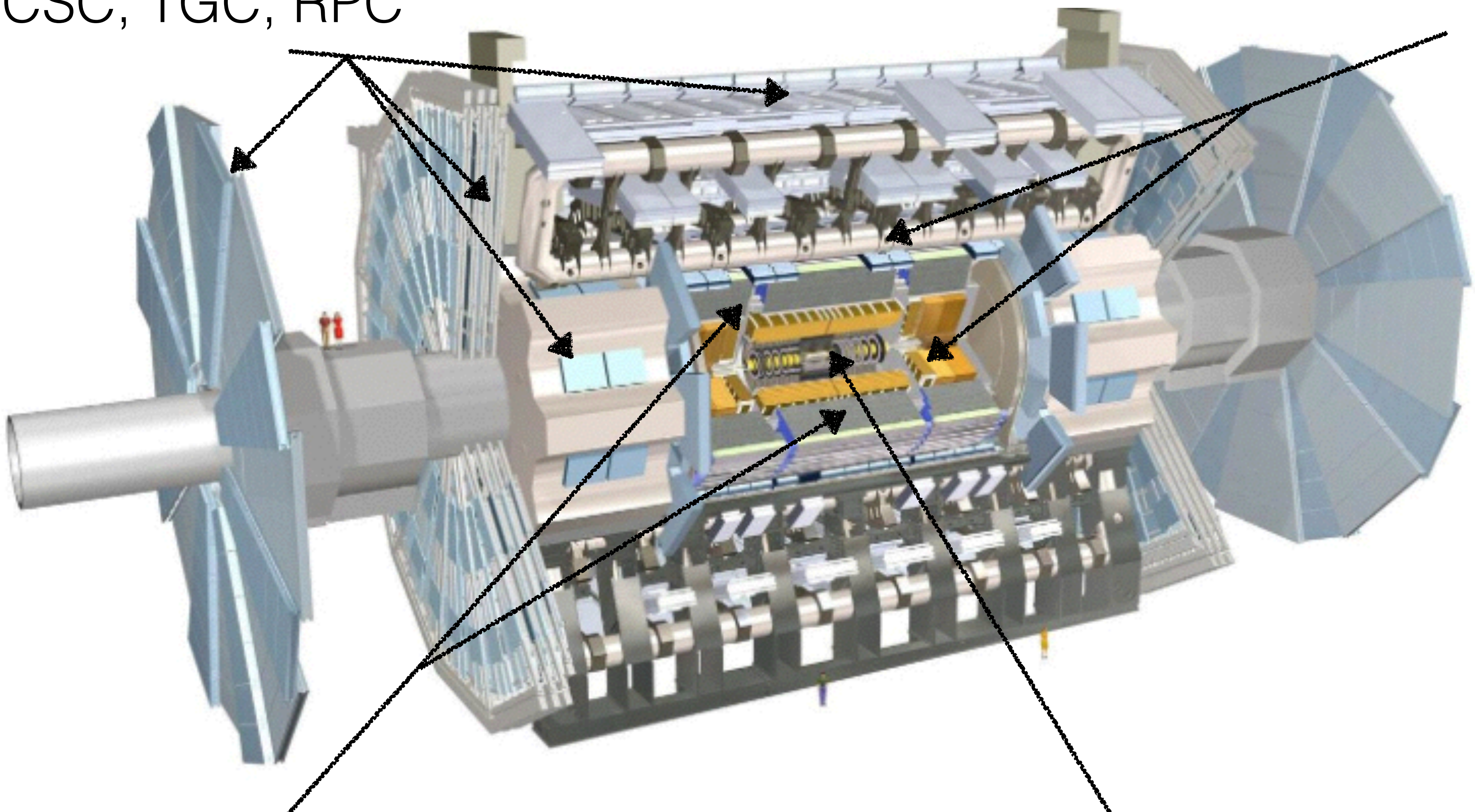


* - and vice versa :)

ATLAS Overview

Muon Spectrometer
- tracking and trigger
- muons
- MDT, CSC, TGC, RPC

Magnets
- bending
- charged particles
- Solenoid, Toroid

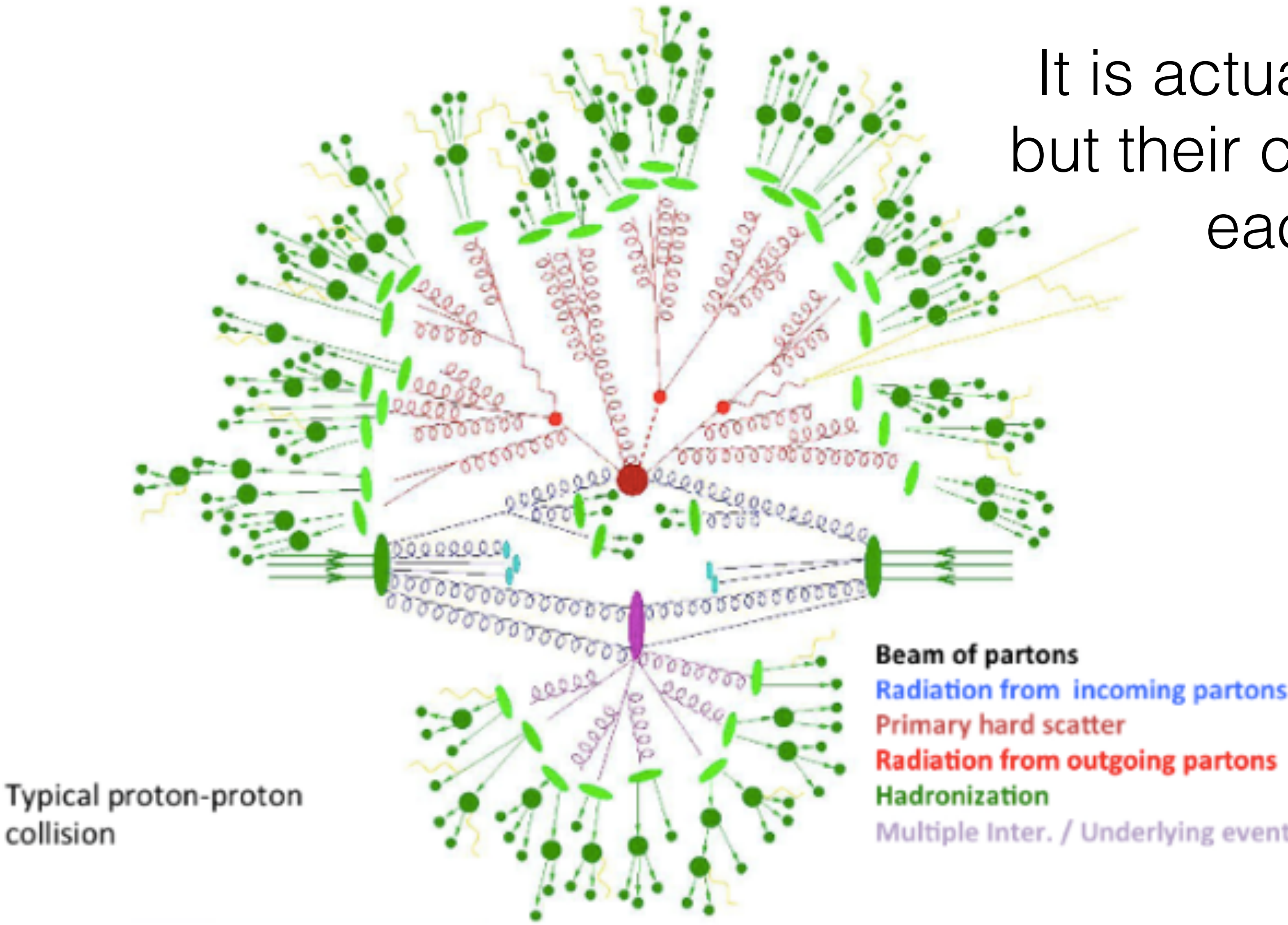


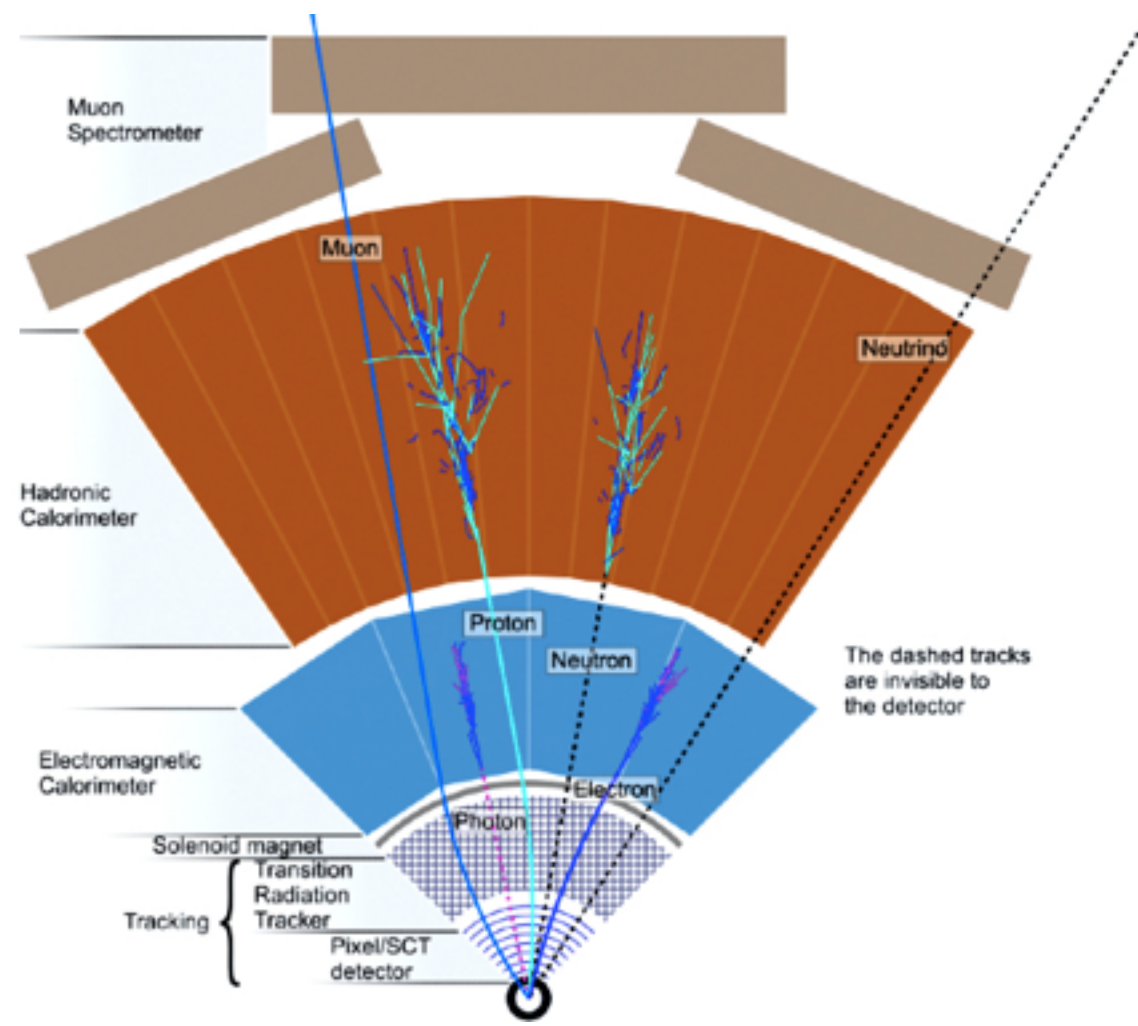
Calorimeters
- energy measurement and trigger
- e/γ and hadrons
- LAr, Tile

Inner Detector
- tracking and vertexing
- charged particles
- Pixel, SCT, TRT

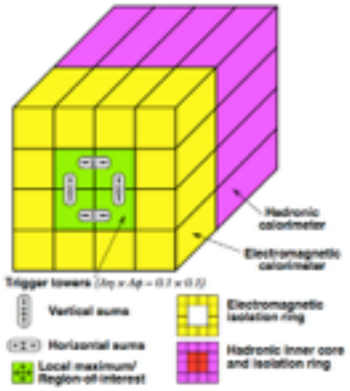
Collisions

It is actually not the protons which collide but their constituents (quarks and gluons) - each carrying a fraction of its proton's momentum (x)





Need to simulate this complex environment starting from the hard scatter process to the outgoing partons, which then hadronize and interact with the detector



Trigger

Or how do we know which collision to record?

Needs fast decision whether current "event" is interesting to keep for offline analysis - read-out system and storage do not allow for all the events to be stored (and most of them are not interesting anyway!)

LHC $\xrightarrow{\text{40MHz}}$ **L1** $\xrightarrow{\text{100kHz}}$ **HLT** $\xrightarrow{\text{1kHz}}$

40 millions collisions per second

Fast electronics finds regions of interest (RoI) based on the information from the calorimeters and muon detectors

Software algorithms reconstruct data in RoIs and make a final decision

Full information on the event is stored to disk

Reconstruction and Identification

ATLAS provides us with byte stream data.
Need to know how to interpret this RAW format.

Reconstruction

Software algorithms analyse the data and look for patterns (we know how particles interact with matter) - tracks are collections of hits in the ID, photons are energy deposits in the calorimeters, neutrinos are the missing transverse energy per event

Objects, hits, calorimeter cells

Identification

Even more sophisticated algorithms can tell us if a given track belongs to an electron or a muon, or if a photon was prompt and isolated

e, γ, μ, ν, τ …

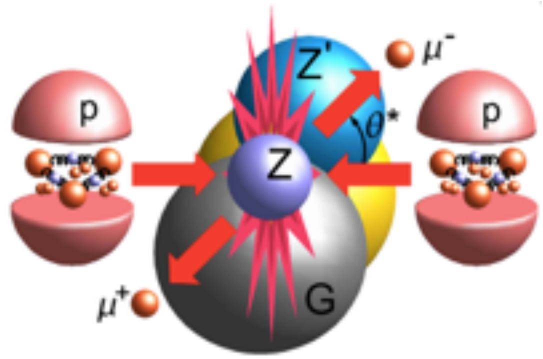
Data Analysis!

What next? Analysis of all the objects in the event in search of the signal - trace back from stable (or elementary) particles to unstable (or composite) ones

LHC+ATLAS - Summary

START

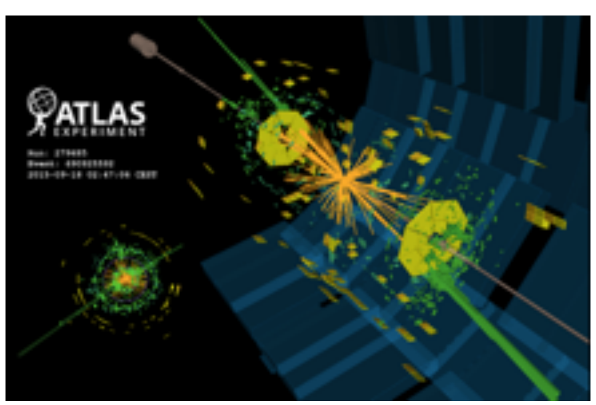
LHC



TDAQ

(trigger+data aquisition)

Long road from LHC to Physics Results - Need excellent performance and availability of all the parts!



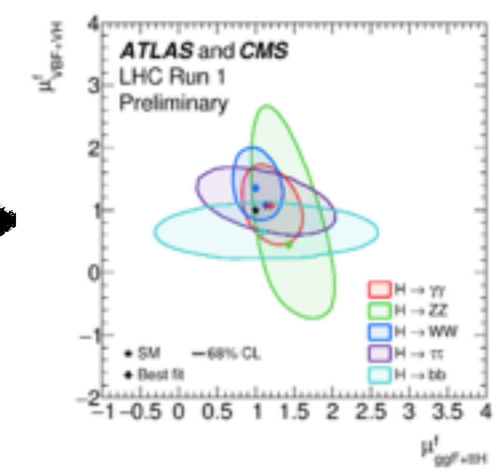
ATLAS

Data preparation

Data Quality

Combined Performance

Analysis



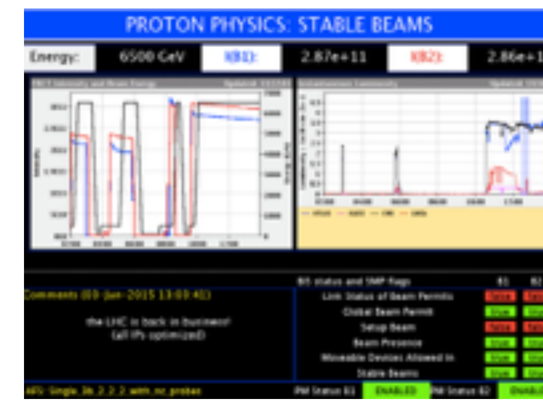
FINISH

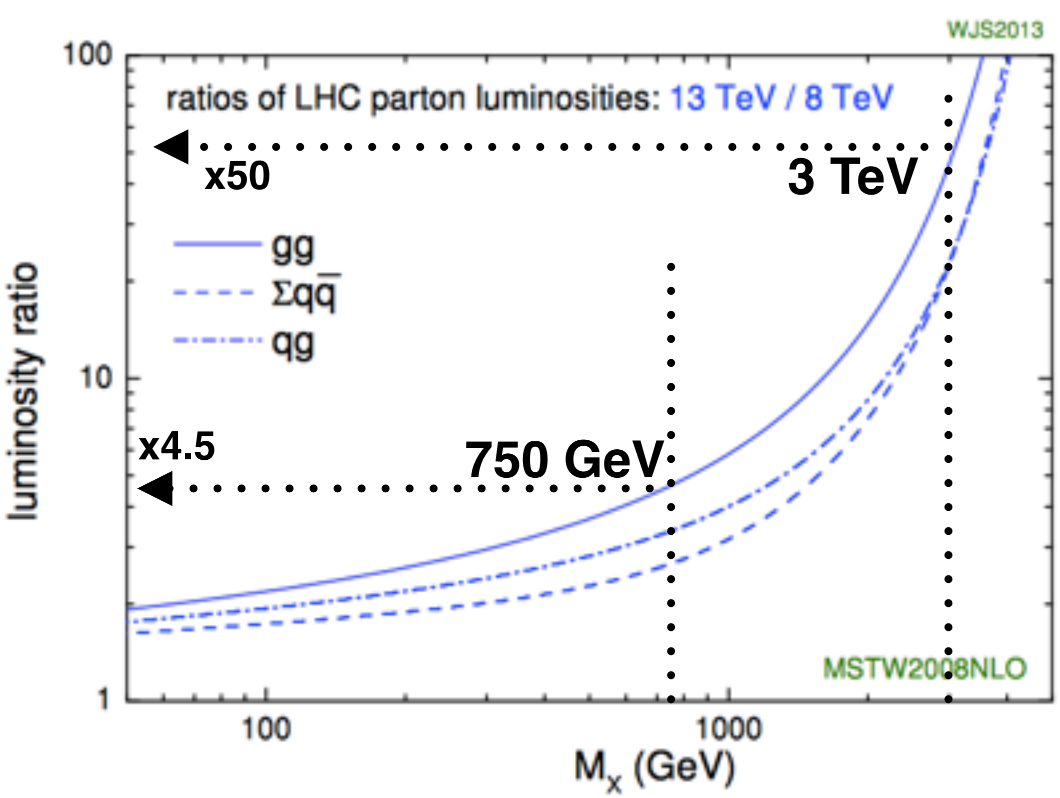
Switching gears to **Physics!**

Triumph of the **Standard Model (SM)** theory

A few points I would like to talk about:

1. **physics in Run1**
    1. Discovery of the Higgs boson
    2. Precision measurements of the SM parameters
2. **physics in Run2**
    1. New energies = new possibilities
    2. Discovery of new particles (we hope!)
    3. Precision measurements of the Higgs boson



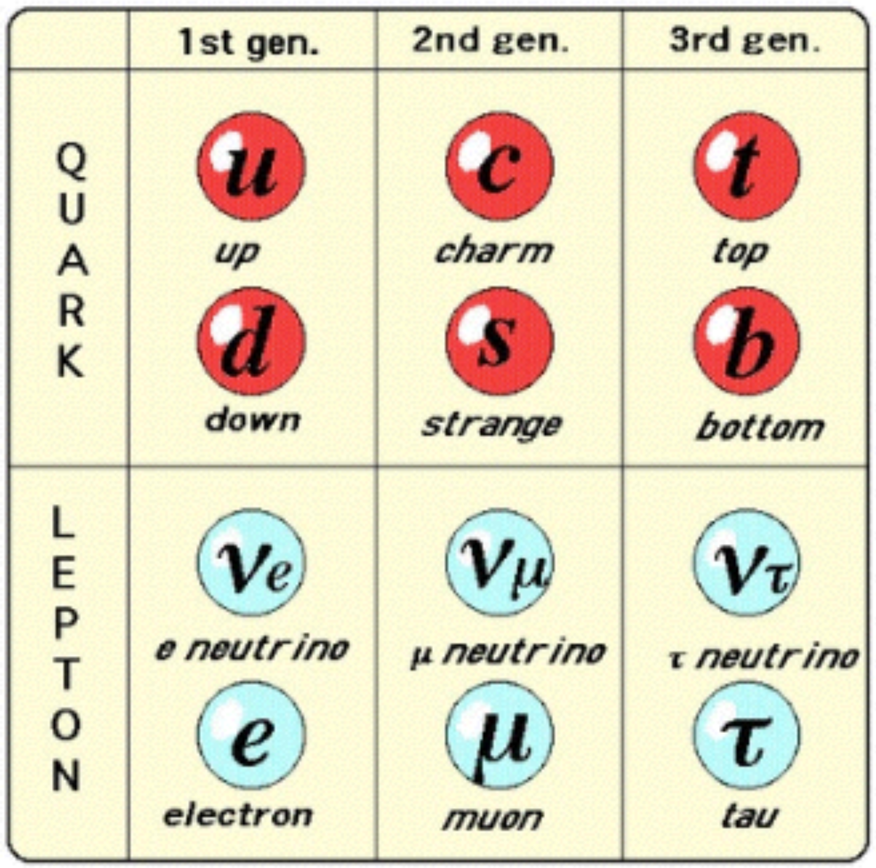


Looking for **Beyond the Standard Model (BSM)** physics

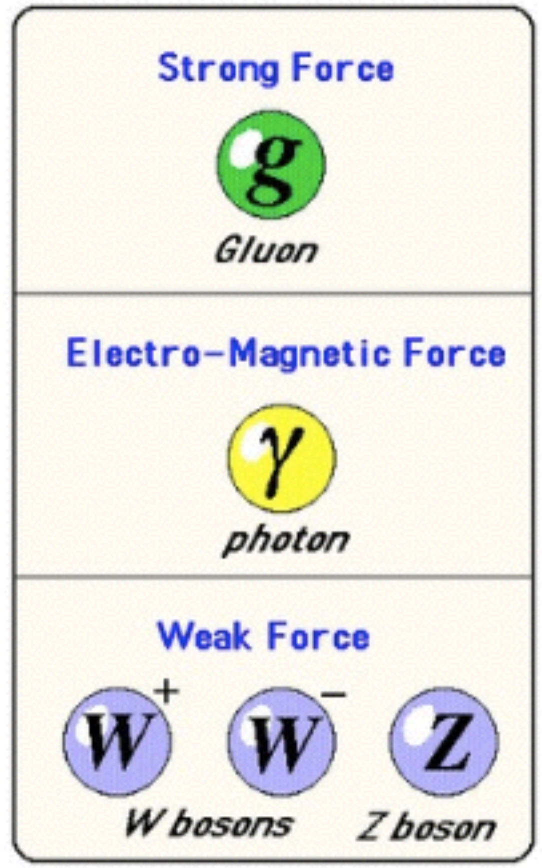
Huge increase in the luminosity ratio between 8 and 13 TeV - especially at high resonance masses!!!

Standard Model

matter particles



guage particles



Electroweak interactions

massive

these bosons are responsible for
interactions between particles

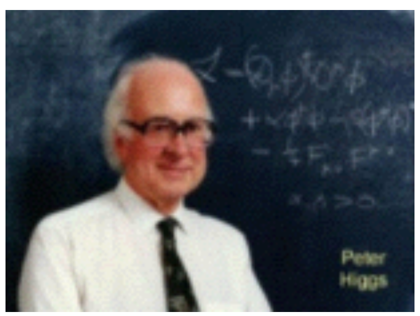
Very successful theory (tested at the LHC and other experiments) but it doesn’t explain why the particles need to have mass or how do they gain them!

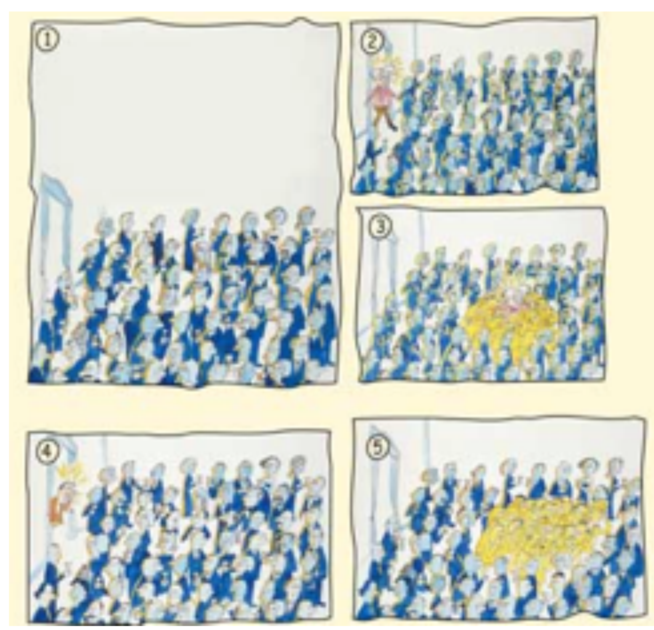
Here comes the **BEH** (**Borut-Englert-Higgs**) mechanism
- spontaneously breaking the electroweak symmetry

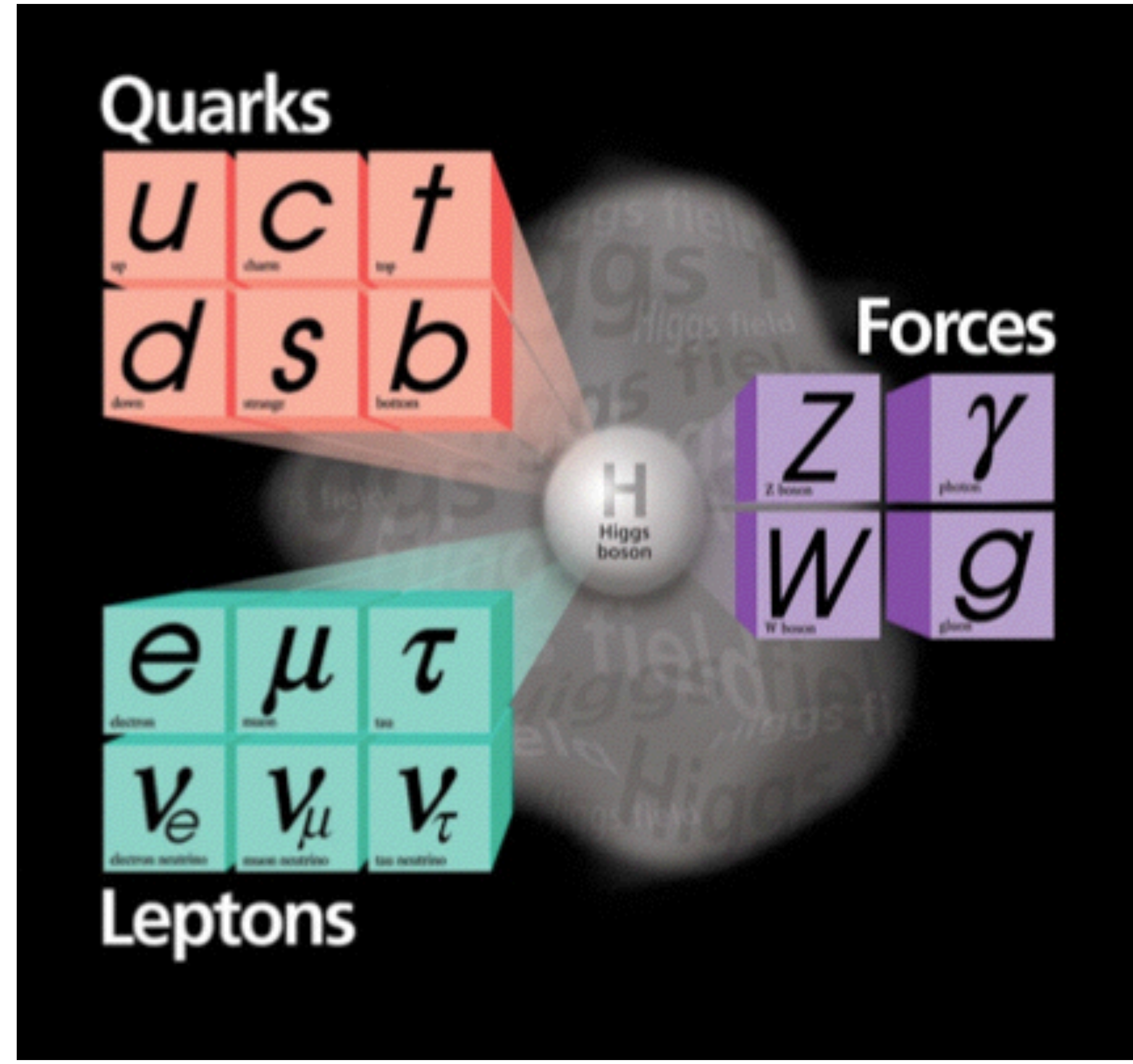
Higgs mechanism

Unification of the weak and
electromagnetic forces
electroweak interactions

previously no mechanism to add mass terms - “by hand” would break the gauge invariance and make the theory not renormalisable







Higgs mechanism - spontaneous symmetry breaking (symmetry still valid for the Lagrangian but not for the vacuum state of the system)

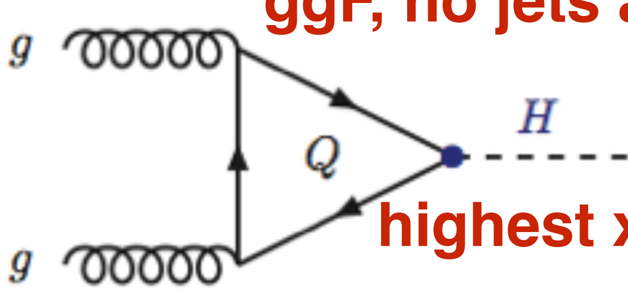
The universe is filled with a Higgs field, and by interacting with this field, gauge bosons and fermions acquire mass!

Mass of the Higgs boson (a quantum of the Higgs field) is not predicted by the theory. Higgs self-coupling is determined by m_H.

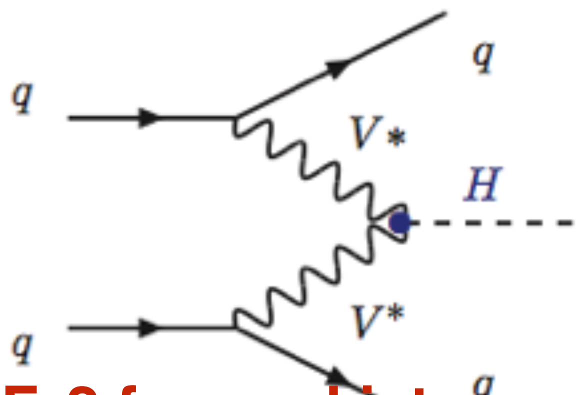
$$\lambda = \frac{m_{\mathrm{H}}^2}{2v^2}$$

Higgs boson production at the LHC

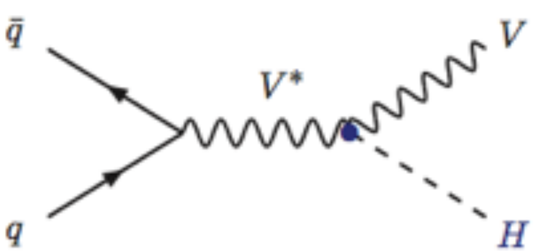
ggF, no jets at LO



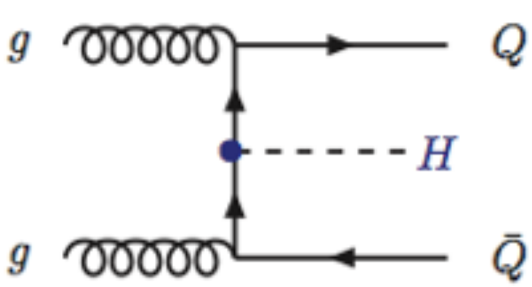
highest x-sec



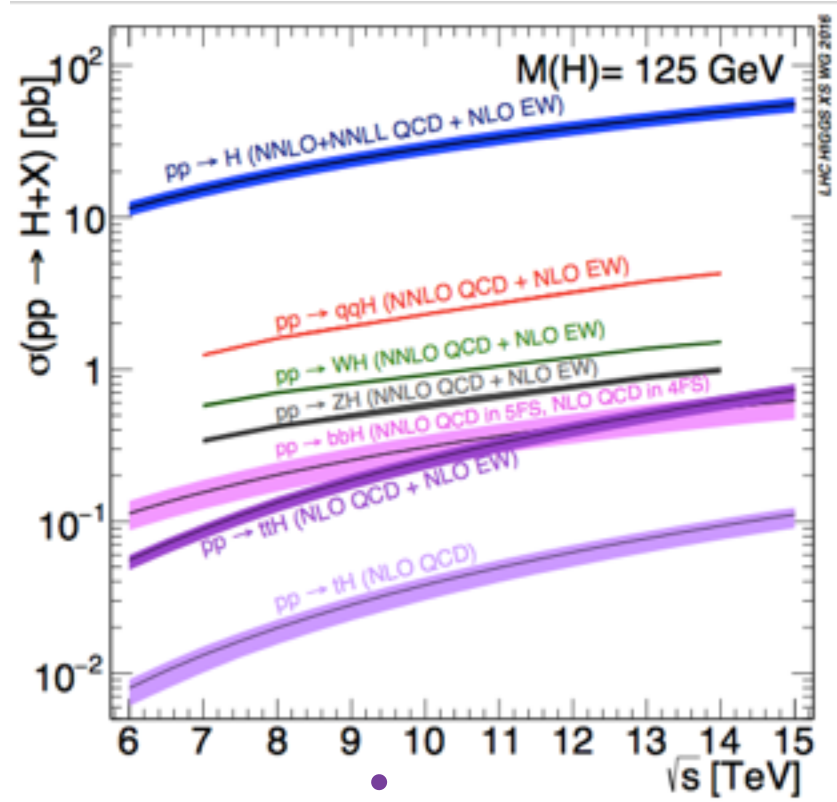
VBF, 2 forward jets

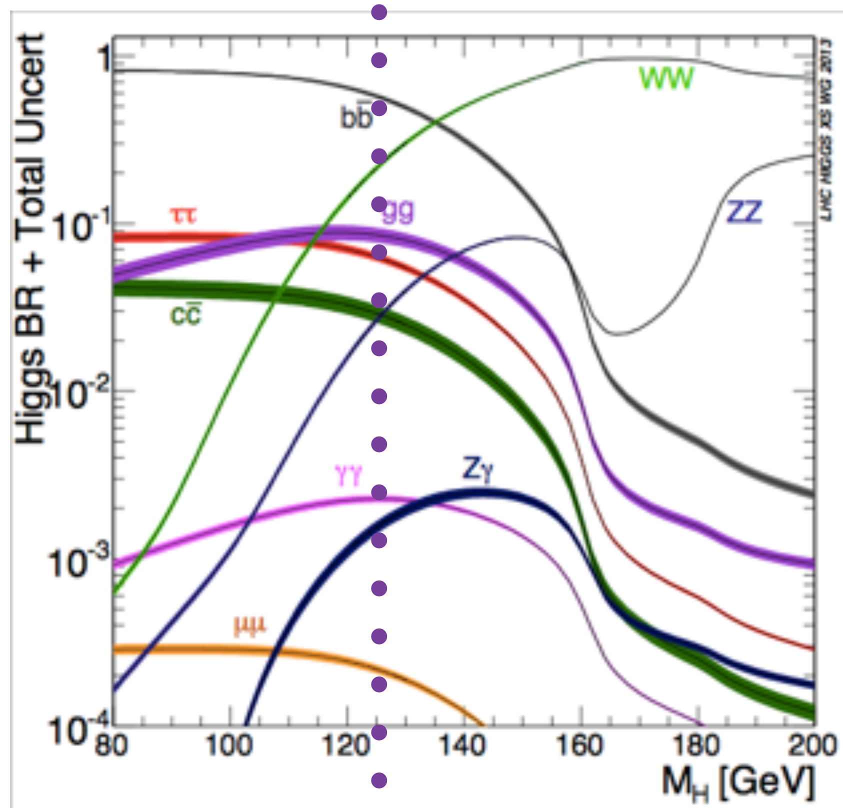


VH, associated W/Z boson



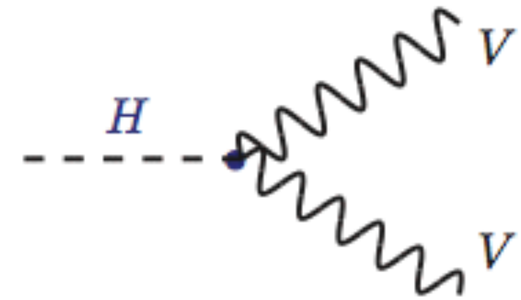
ttH, two top quarks, H-t coupling



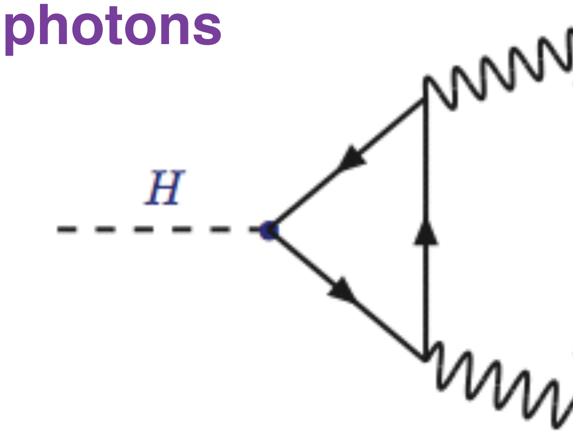


m_H = 125 GeV

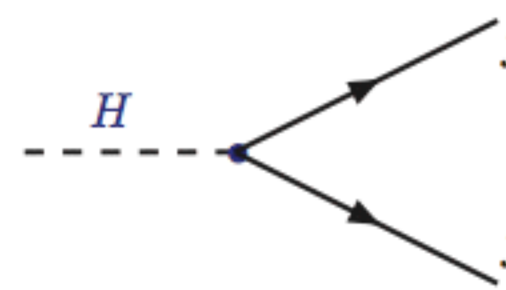
- large branching fraction
- leptons, jets, neutrino (depending on the decay mode)



- small branching fraction (0.2%)
- two photons



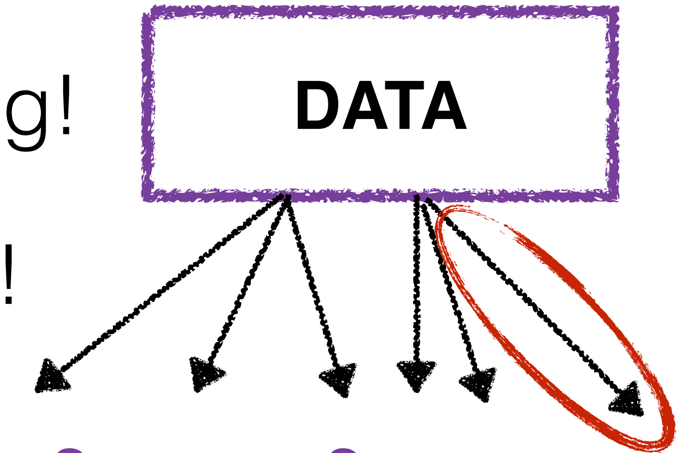
- bb - largest branching fraction but large backgrounds



Physics Analysis Strategy

A mixture of everything!

All possible triggers!



2e, 1γ, 2γγ, eμ, 2eμ,ν, τ …

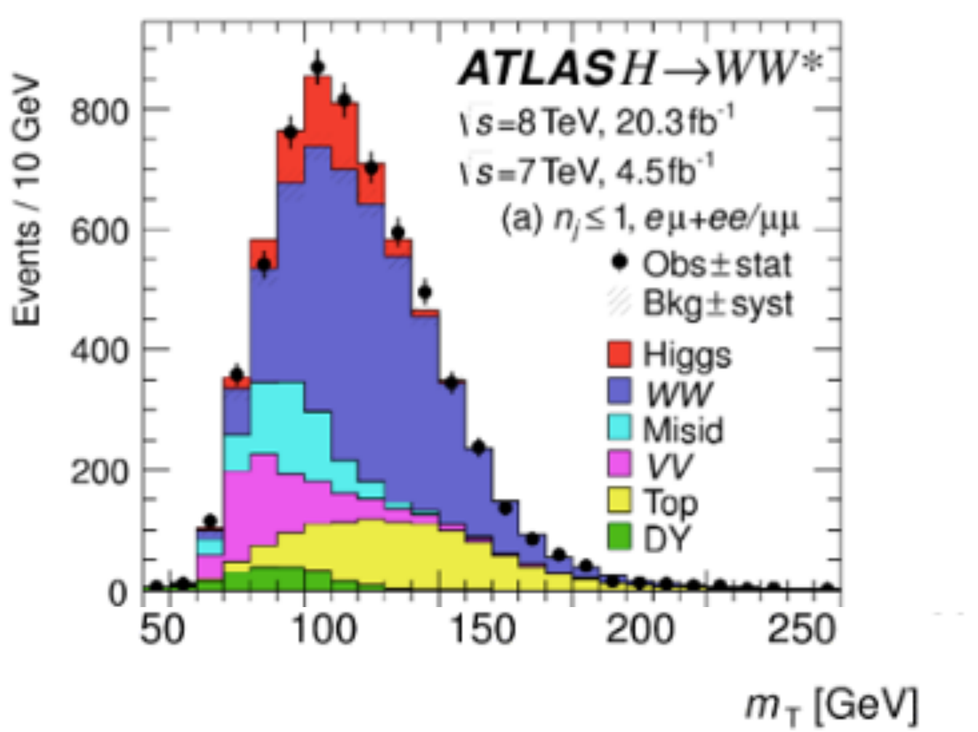
What is the final state you are looking for?

H->WW*->lνlν example

2e, 2μ and 1e1μ - di-lepton triggers

WW, top, DY, VV, fakes

SR: low m_{ll}, binned in jet multiplicity
CR: unique for each bkg



Step 1:
Select part of data with your trigger

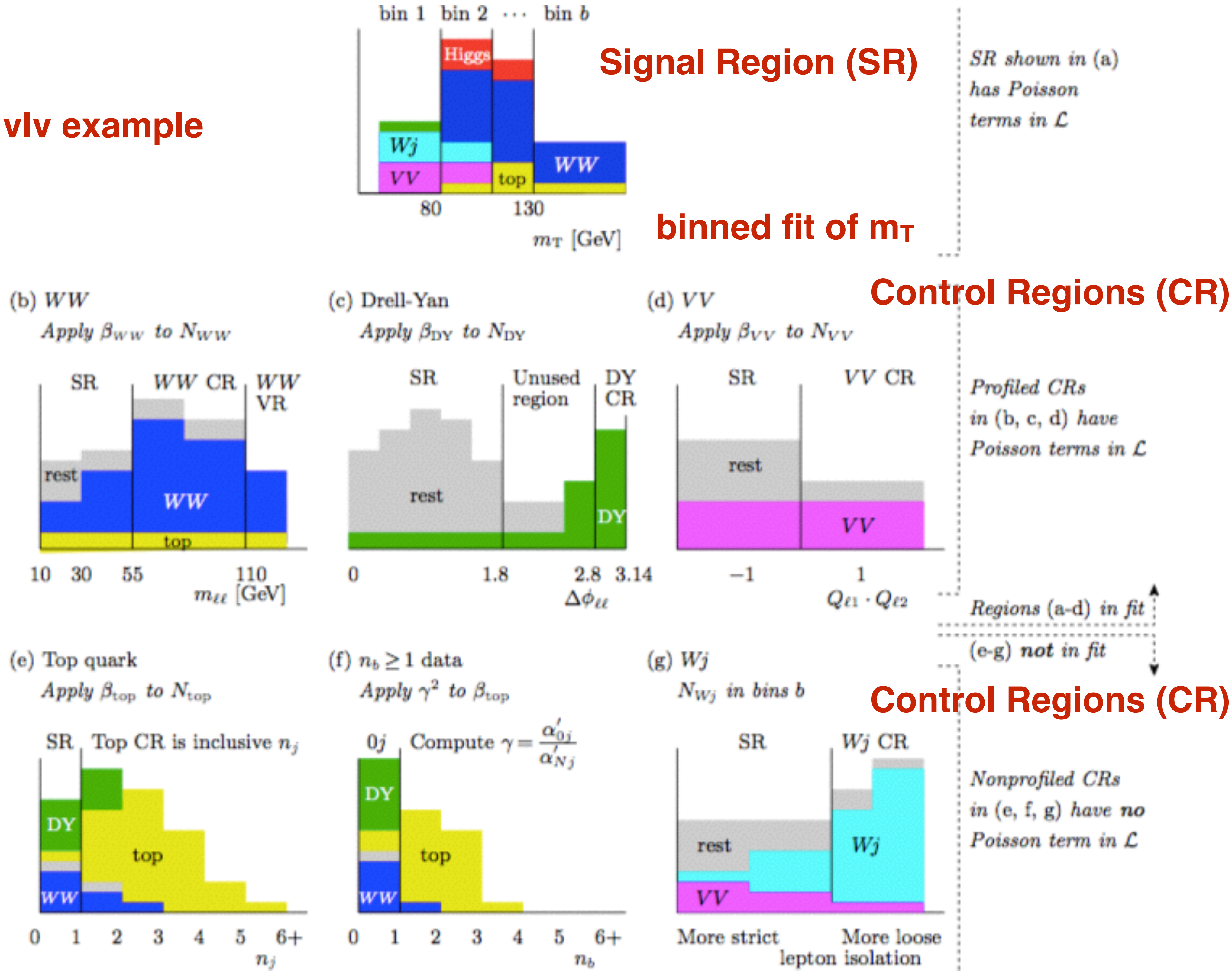
Step 2:
Identify backgrounds with the same final state as your signal (or the ones which can mimic your signal)

Step 3:
Find a signal region rich in your signal, find control regions targeting each backgrounds - estimate them!

Step 4:
Find a signal discriminant - and fit it!

Signal and Control Regions

H->WW*->lvlv example



Short Statistics Explanation

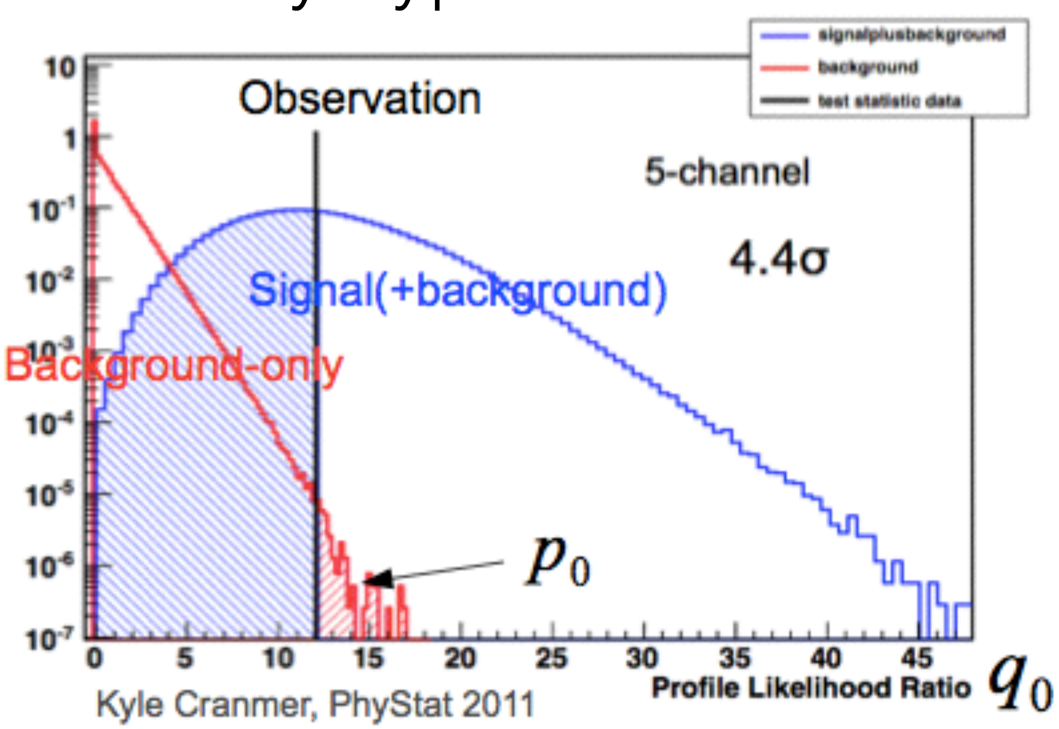
The common approach is to build a likelihood model including all the parameters of your analysis (and systematics). Maximum likelihood fit then gives you the best fit parameters describing your model given the data.

What is a p-value and why do we use it?

If we find a deviation of the data above the background-only hypothesis we need to calculate what its significance - is it a big bump or not?

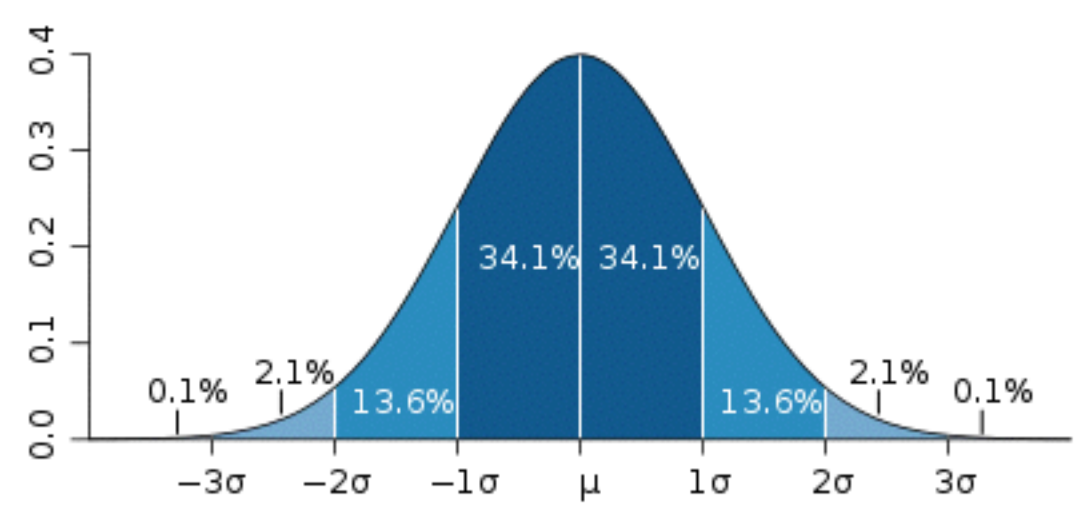
p_0-value gives us a probability that the excess in the data is a fluctuation from the background-only hypothesis.

Build test statistic that compares S+B to B-only hypothesis based on the data



p_0 gives significance of rejecting the background-only hypothesis:

- 5σ - p_0 of 1 in 3.5 million
- 3σ - p_0 of 1 in 740

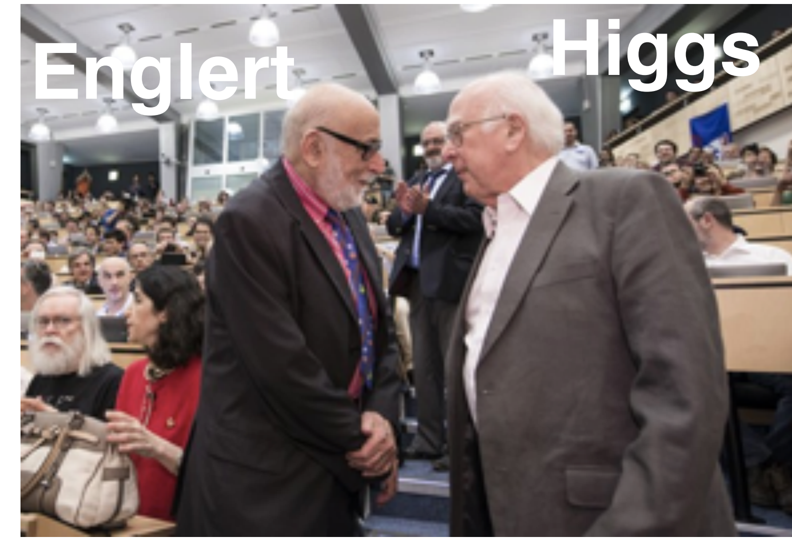


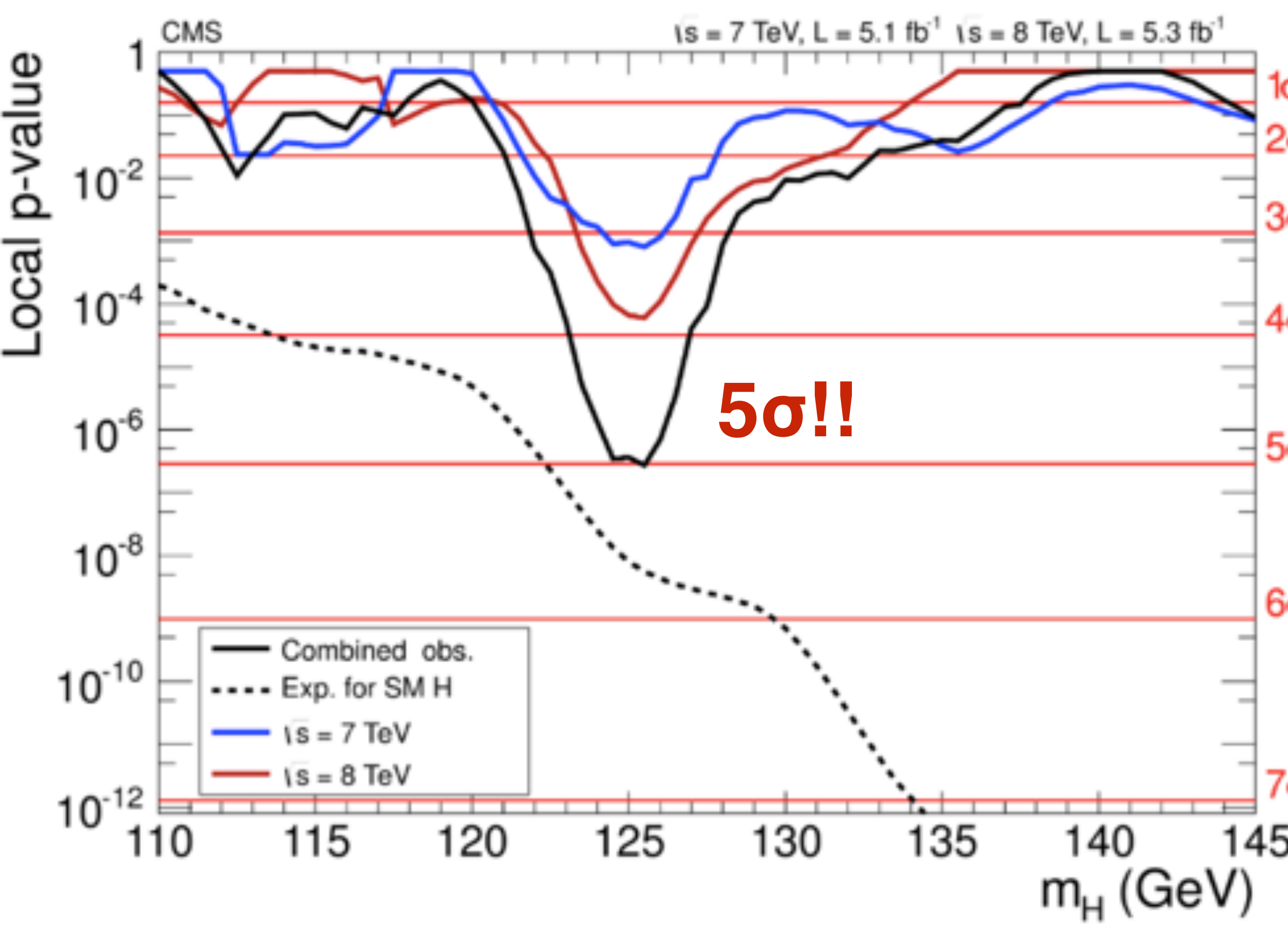
Higgs Discovery at the LHC

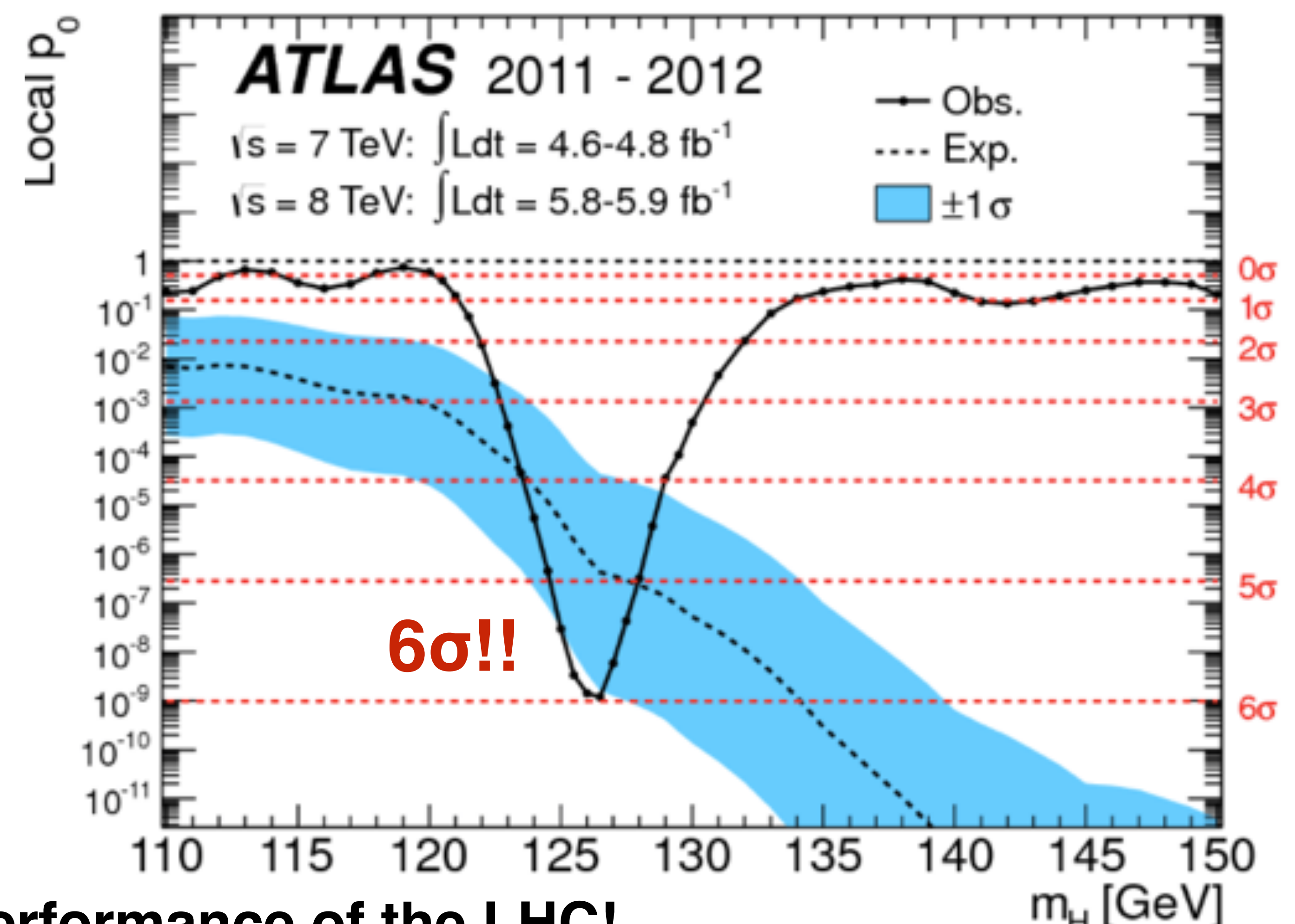
July 4th 2012

H->γγ, H->ZZ->4l and H->WW*->lνlν with 7 TeV and 5.8 fb^{-1} at 8 TeV

3σ - evidence
5σ - discovery







Wouldn't be possible without the excellent performance of the LHC!

ATLAS+CMS Run1 Combination

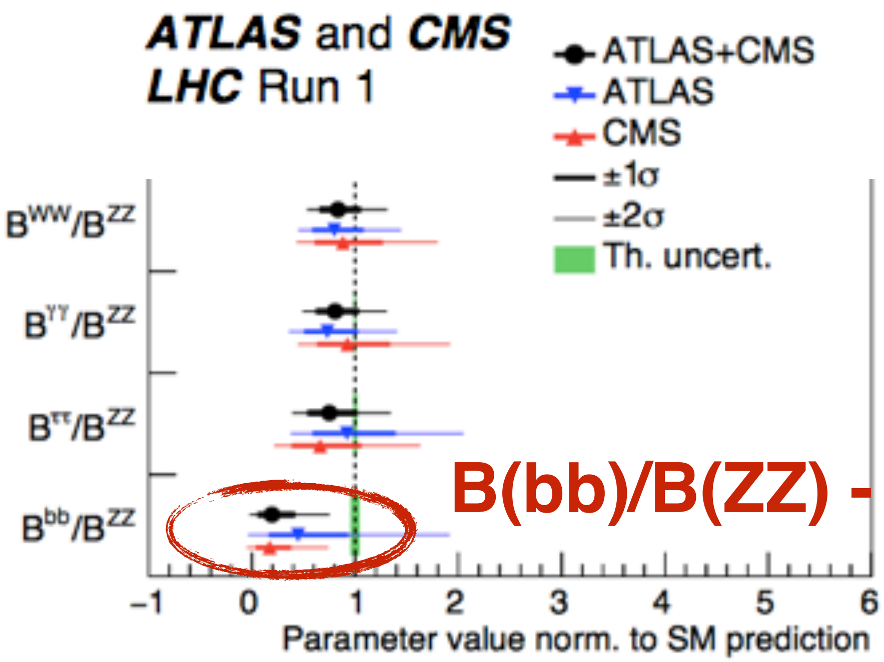
Public since June 8th 2016! CERN-EP-2016-100 arXiv 1606.02266

$$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})\ \text{GeV}$$

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[91]	[92]	$1.14^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.11^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ$	[93]	[94]	$1.52^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$	$1.04^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$	7.6 (5.6)	7.0 (6.8)
$H \to WW$	[95,96]	[97]	$1.22^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.90^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[98]	[99]	$1.41^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$	$0.88^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[100]	[101]	$0.62^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[102]	[103]	$-0.6^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$		
ttH production	[77,104,105]	[107]	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$	2.7 (1.6)	3.6 (1.3)

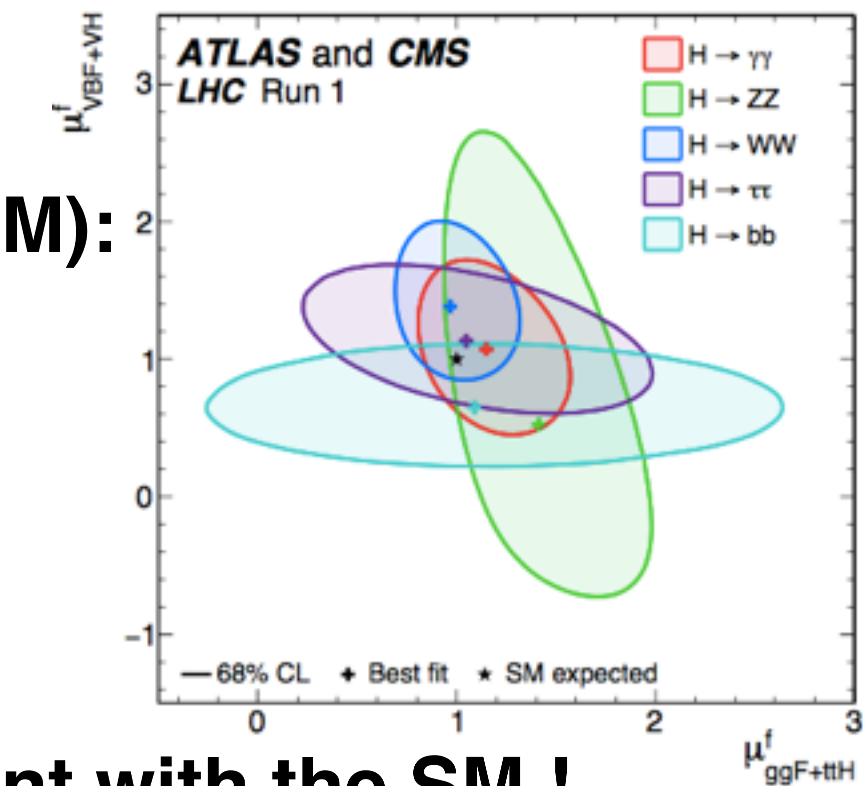
Input channels to the combination with their individual results

ATLAS+CMS Run1 Combination

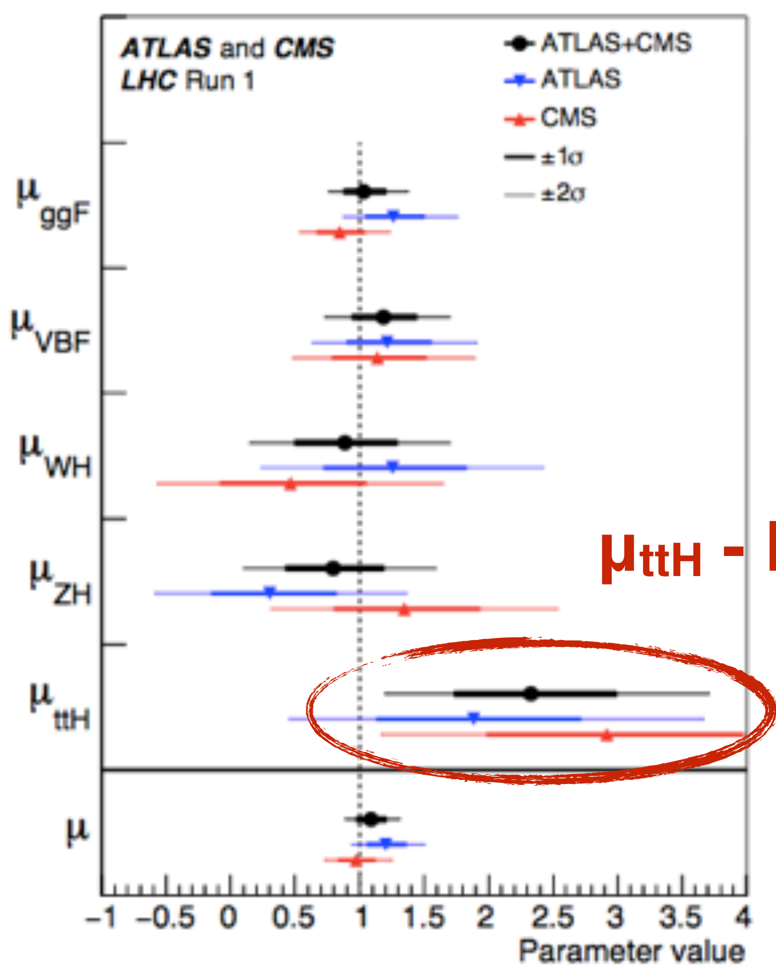


B(bb)/B(ZZ) - low?

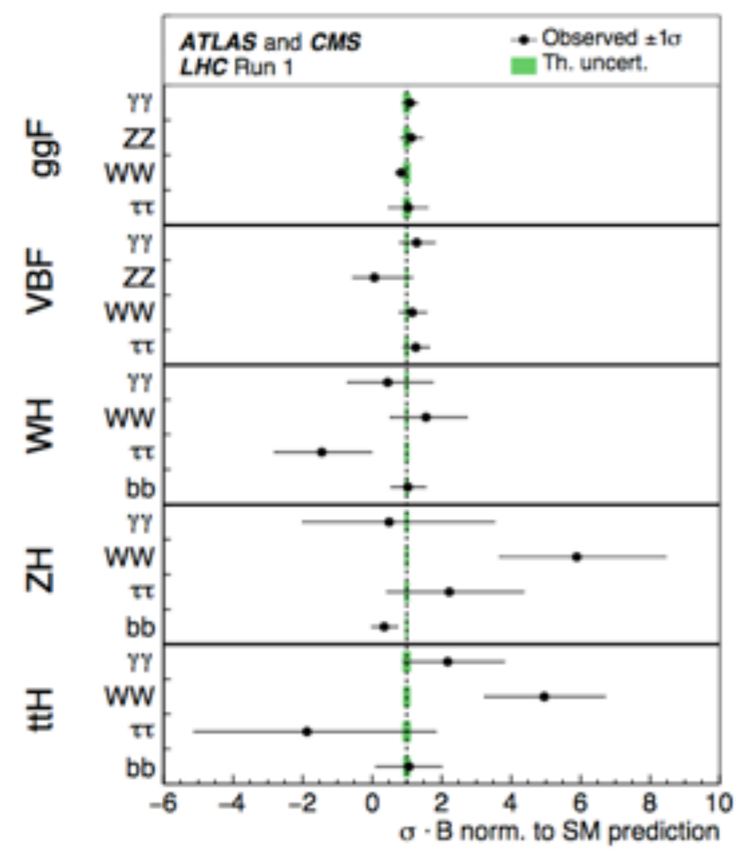
Measurements (wrt SM): x-sec, Br, couplings

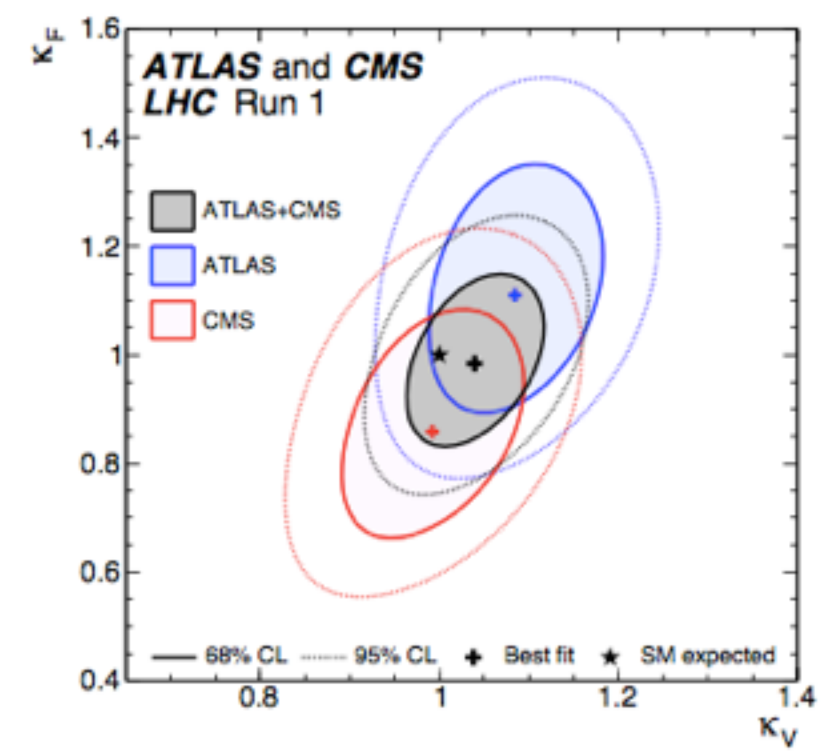


Remarkable agreement with the SM !



μ_{ttH} - high?





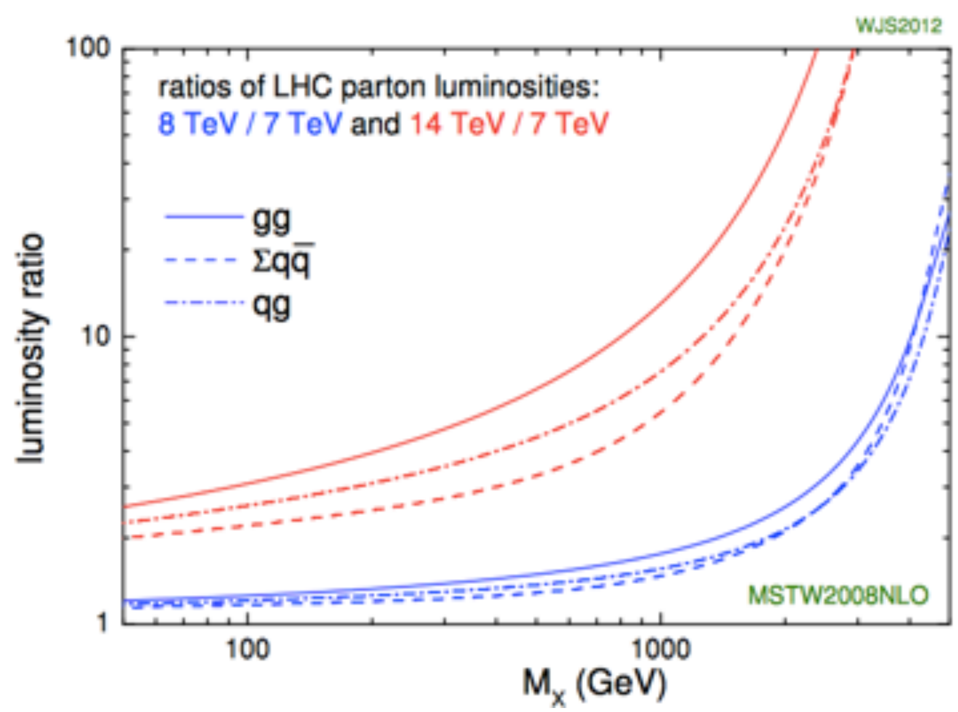
What to do in Run2?

Rediscovery of 125 GeV Higgs and more precise properties measurements

There is something beyond the Standard Model (BSM) but we don't know what… SM does an incredible job in describing the data in the regime we are currently probing.

Some questions which SM is not able to explain:

- **neutrino masses and mixing**
- **presence of dark matter**
- **abundance of matter over anti-matter**
- **hierarchy problem**
- **strong CP problem**



Also a jump from 8 TeV to 13 TeV provides unique opportunity to look at higher masses - new particles which could be part of BSM theories!

X->γγ analysis

Why diphotons?

- clean signature and easy to trigger
  - ggF - nothing more than 2γ (at LO)
- excellent invariant mass resolution
- moderate level of backgrounds

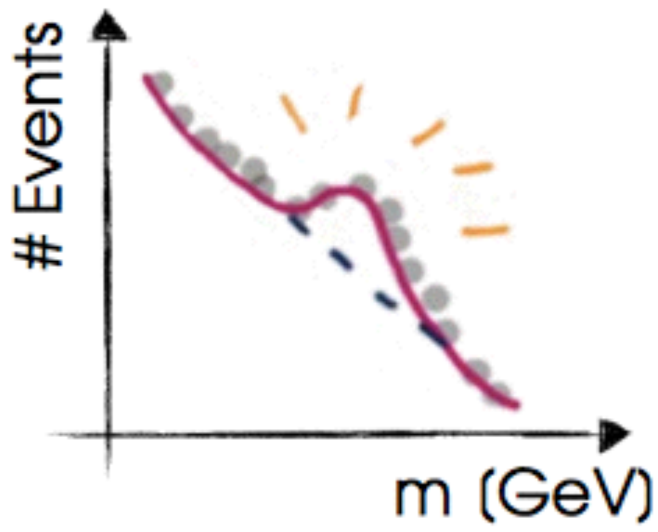
Backgrounds:

- γγ - continuum production, dominant, same final state - irreducible
- γj - one jet fakes a photon - reducible
- jj - two jets fake photons - reducible
- other backgrounds with electrons faking photons are negligible

Run1 - focus on SM Higgs search, and 125 GeV Higgs properties
Run2 - go higher in mass and search for a resonance! **Focus of this talk**

Analysis strategy:

- fit to $m_{\gamma\gamma}$



Benchmark Models

Search for **spin-0** and **spin-2** high mass $\gamma\gamma$ resonances

spin-0 model:

- Higgs-like high mass resonance (ggF production only)
- Powheg-Box interfaced with Pythia8, and CT10 PDF with Pythia8 AZNLO UE tune

spin-2 model:

- Randall-Sundrum (RS) graviton model which entails a lightest Kaluza-Klein graviton excitation (G*) with a dimensionless coupling k/M_{Pl} (k - curvature of the extra dimension, M_{Pl} - reduced Planck scale)
- lightest excitation is expected to be narrow for $k/M_{Pl} < 0.3$; $\Gamma_{G^*}=1.44(k/M_{Pl})^2 m_{G^*}$
- Pythia8 with NNPDF23LO with A14 UE tune

	Benchmark model	Mass range	Range
Spin-2	RS graviton	0.5-5 TeV	$k/M_{Pl} = 0.01\text{-}0.3$
Spin-0	Higgs-like	0.2-2 TeV	$\Gamma_X/m_X < 0.1$

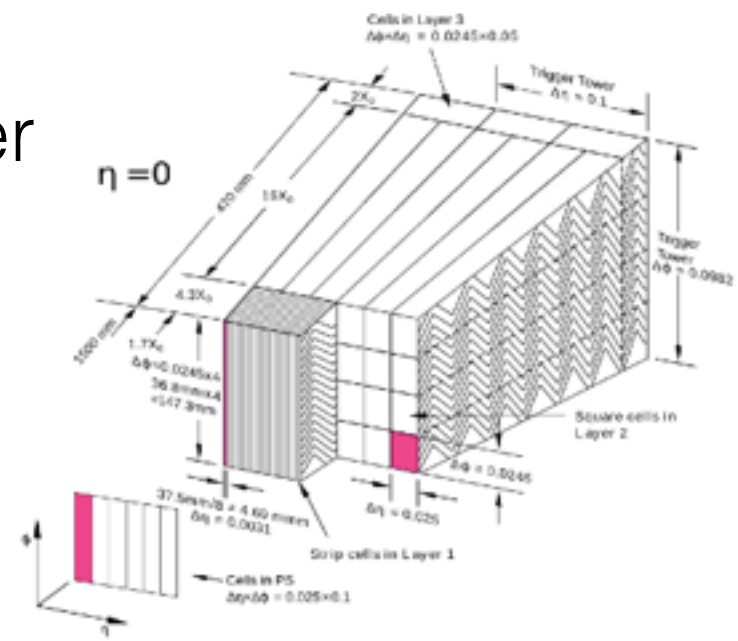
Public since June 14th 2016!

CERN-EP-2016-120
arXiv 1606.03833

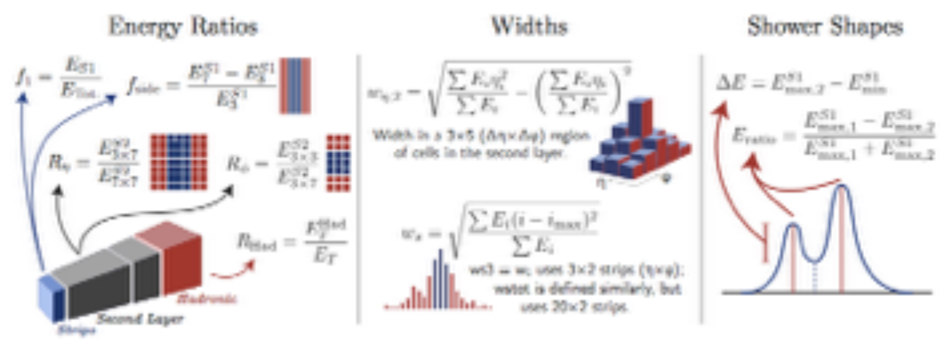
3.2 fb^{-1} 13 TeV, 2015 data

Photon reconstruction, identification and isolation

Reconstruction:
- clusters of energy in the electromagnetic calorimeter
- matching track and/or conversion vertex
  - separation into converted and unconverted

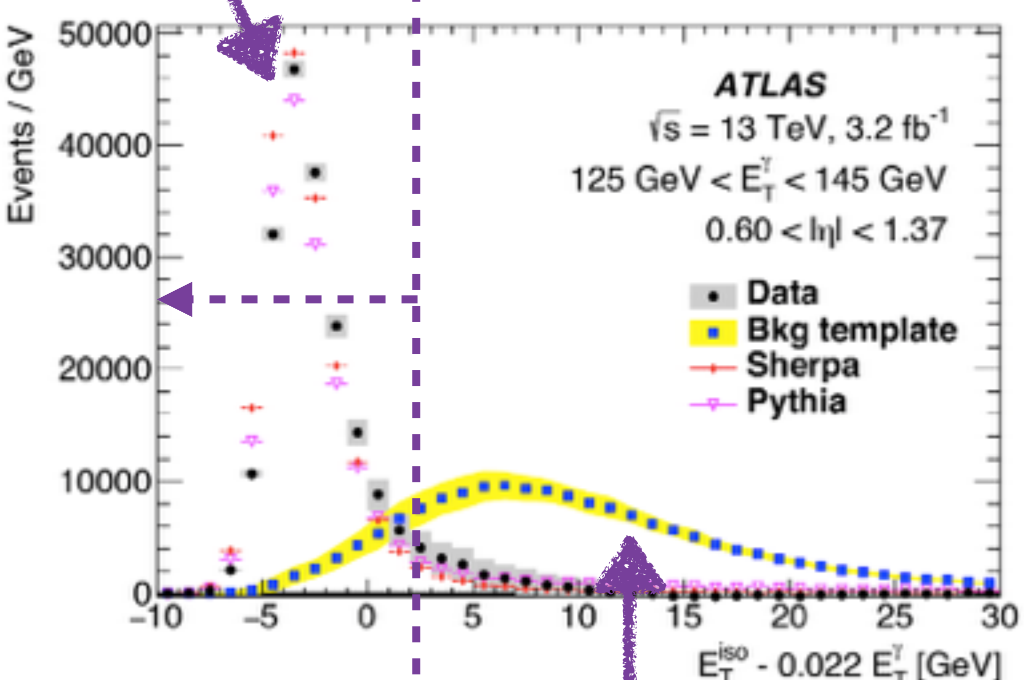


Identification:
- shower shapes in the calorimeters



$$\frac{\sigma_E}{E} = \frac{10\,\%}{\sqrt{E}} \oplus 0.7\,\%$$

real γ

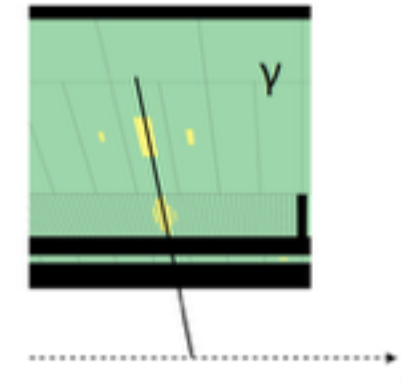


Isolation:
- calorimeter - sum of the energy clusters in ΔR=0.4 cone - E_T^{iso}
  - leakage correction and pileup subtraction
- track - scalar sum of the transverse momenta of the tracks in ΔR=0.2 cone - p_T^{iso}

calorimeter isolation

fake γ

Event Selection



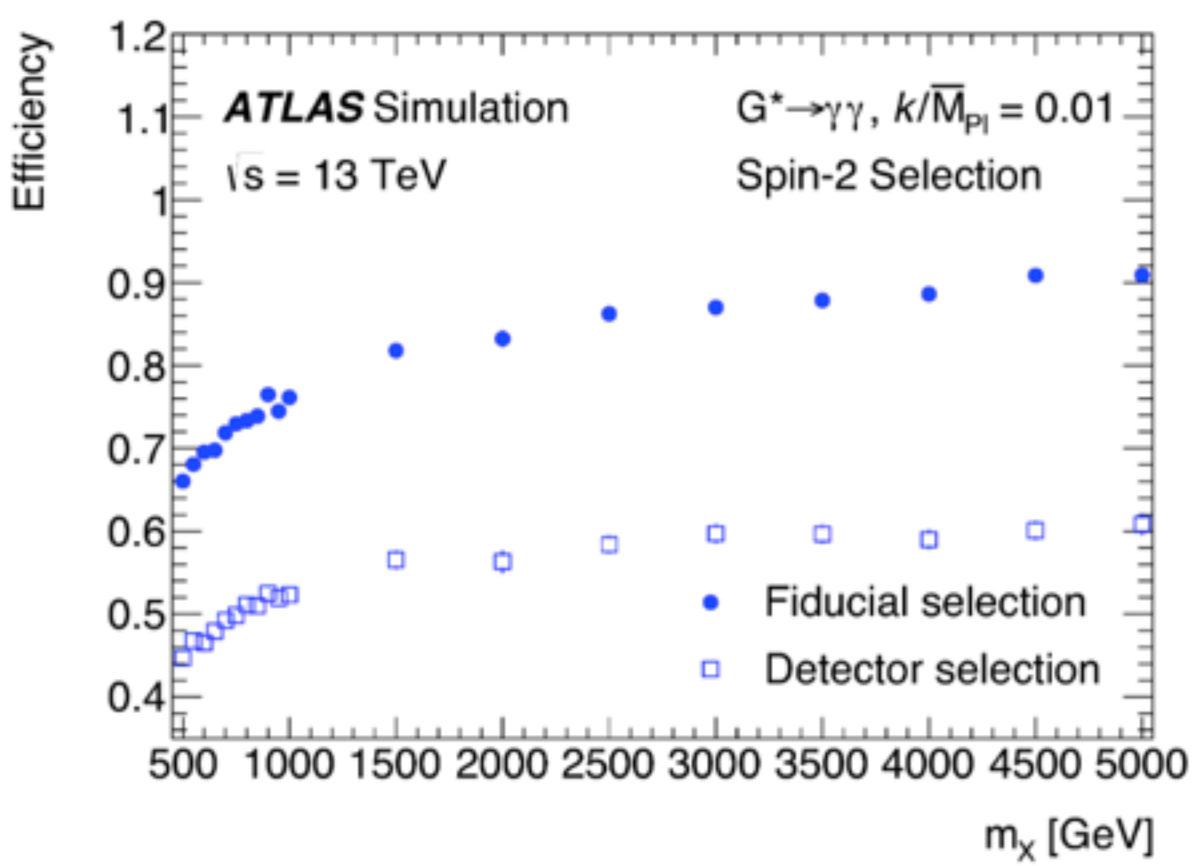
Simple selection:

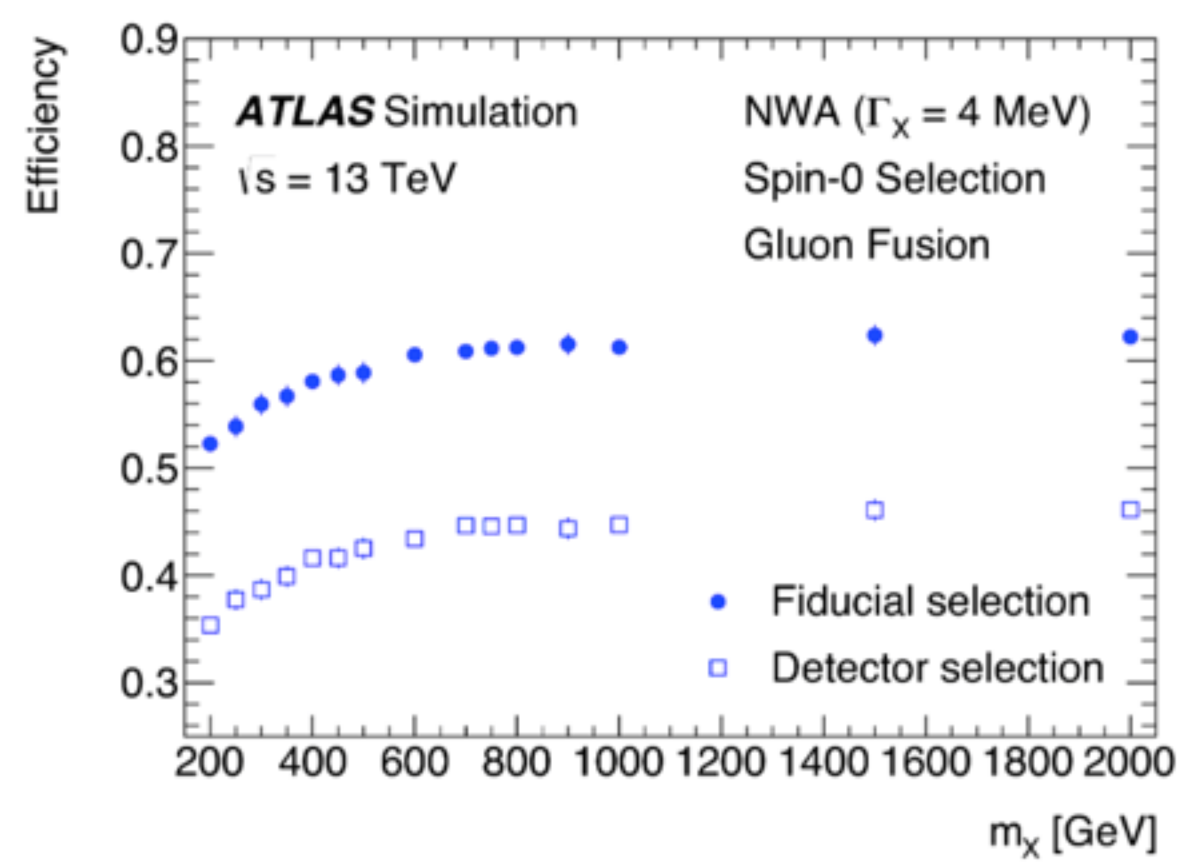
1. Diphoton trigger (35/25 GeV E_T thresholds)
2. Primary vertex selected using NN based on photon pointing
3. Two well identified and isolated photons with $|\eta|<2.37$ (excl. crack region):
    1. E_T > 55 GeV for spin-2
    2. $E_T > 0.4(0.3)*m_{\gamma\gamma}$ for spin-0 leading (subleading) γ

Expected signal yield

A - acceptance of the kinematic requirements

C - reconstruction and identification efficiency



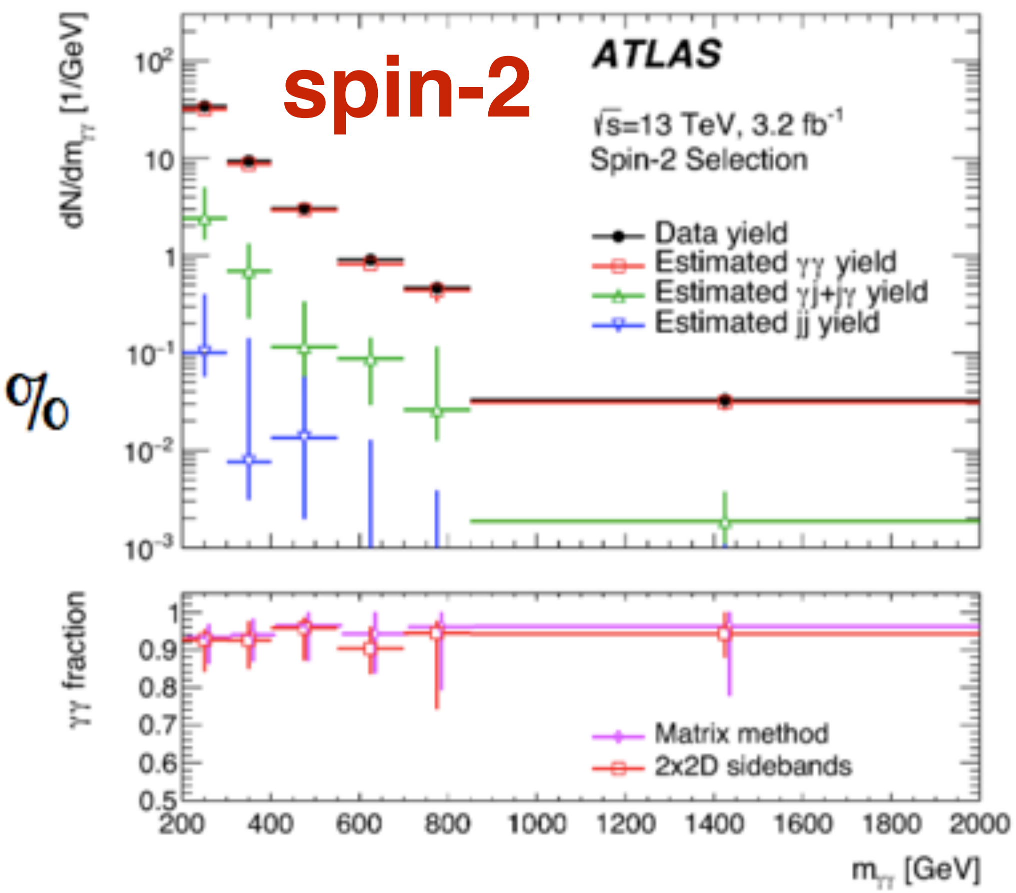


Sample Composition

γγ is the dominant background!

Need to know the fraction of γγ, γj and jj
- background estimation!

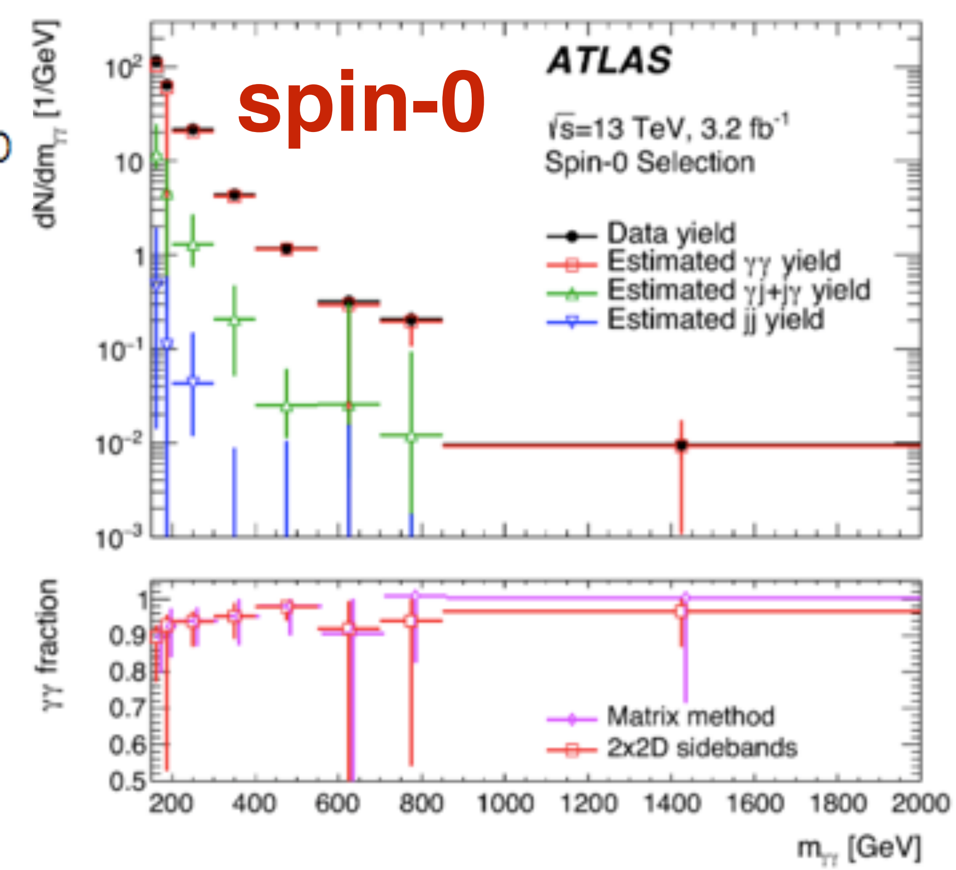
$(94^{+3}_{-7})\%$



Two methods based on control regions built from events failing the isolation requirements and/or tight identification criteria:

1. 2x2 sideband method
2. matrix method

$(93^{+3}_{-8})\%$



Both methods can be applied over the full kinematic range or in bins of $m_{\gamma\gamma}$ - inclusive and differential background composition!

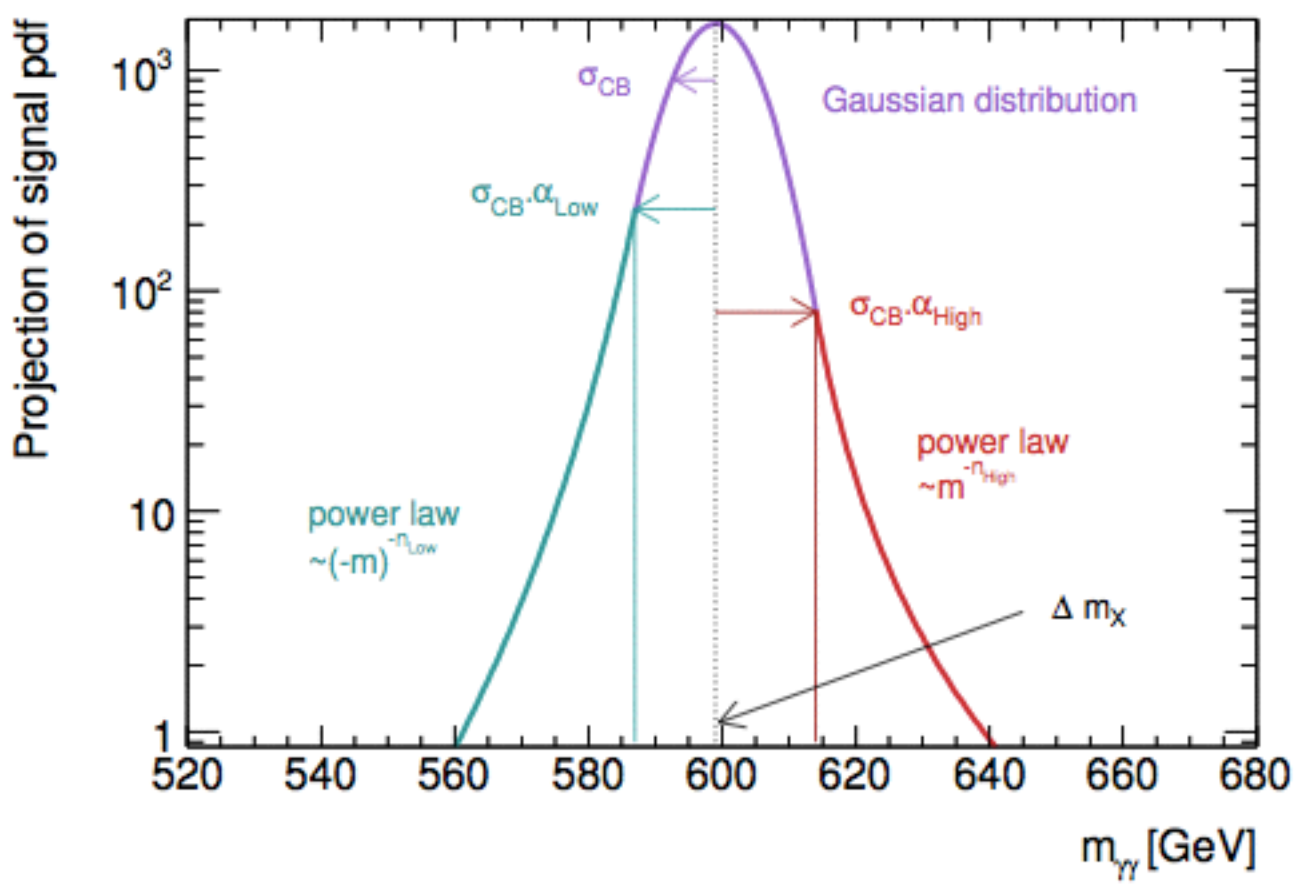
Signal Modelling

$m_{\gamma\gamma}$ spread = intrinsic decay width convoluted with the experimental resolution

Photon energy resolution effects lead to a $m_{\gamma\gamma}$ distribution that is both non-Gaussian and asymmetric (even for NW signal)

Experimental resolution can be described by a double sided Crystal-Ball (**DSCB**)

$$N \cdot \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{\text{low}} \leq t \leq \alpha_{\text{high}} \\ \dfrac{e^{-0.5\alpha_{\text{low}}^2}}{\left[\frac{\alpha_{\text{low}}}{n_{\text{low}}}\left(\frac{n_{\text{low}}}{\alpha_{\text{low}}} - \alpha_{\text{low}} - t\right)\right]^{n_{\text{low}}}} & \text{if } t < -\alpha_{\text{low}} \\ \dfrac{e^{-0.5\alpha_{\text{high}}^2}}{\left[\frac{\alpha_{\text{high}}}{n_{\text{high}}}\left(\frac{n_{\text{high}}}{\alpha_{\text{high}}} - \alpha_{\text{high}} + t\right)\right]^{n_{\text{high}}}} & \text{if } t > \alpha_{\text{high}}, \end{cases}$$

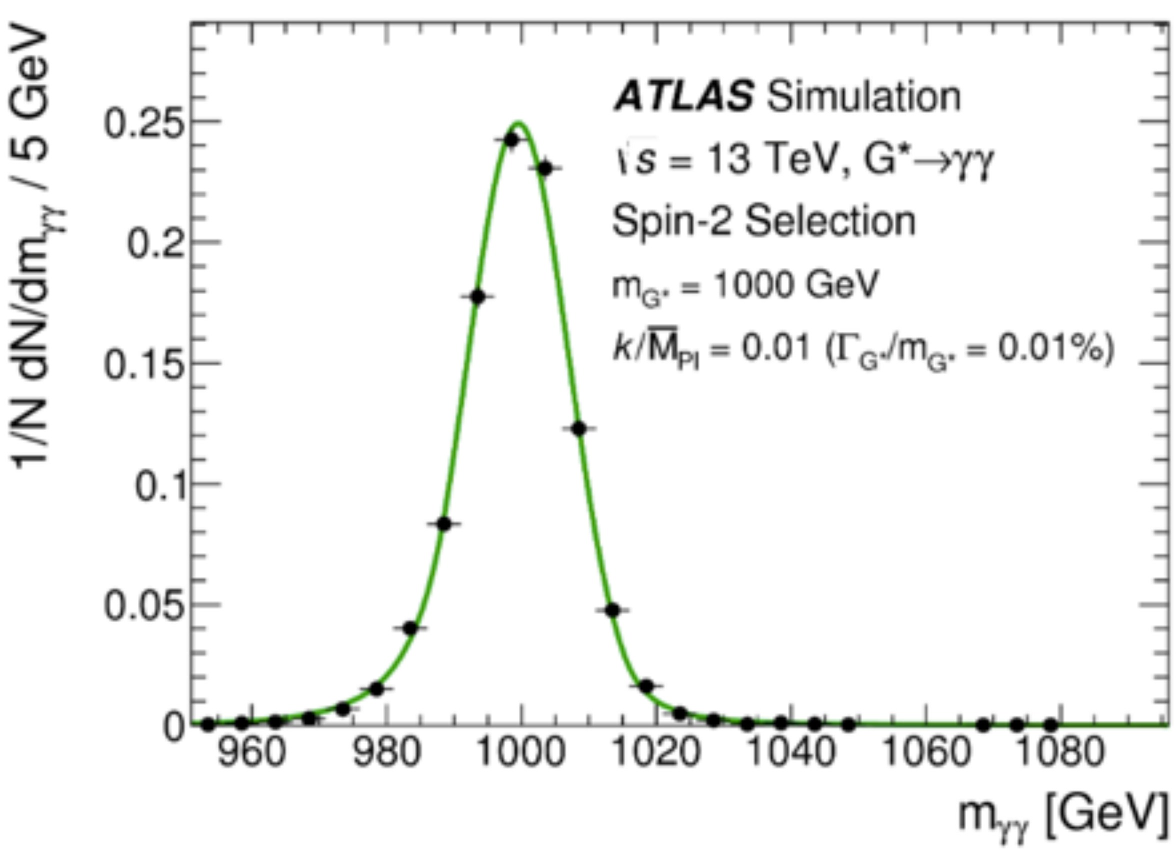


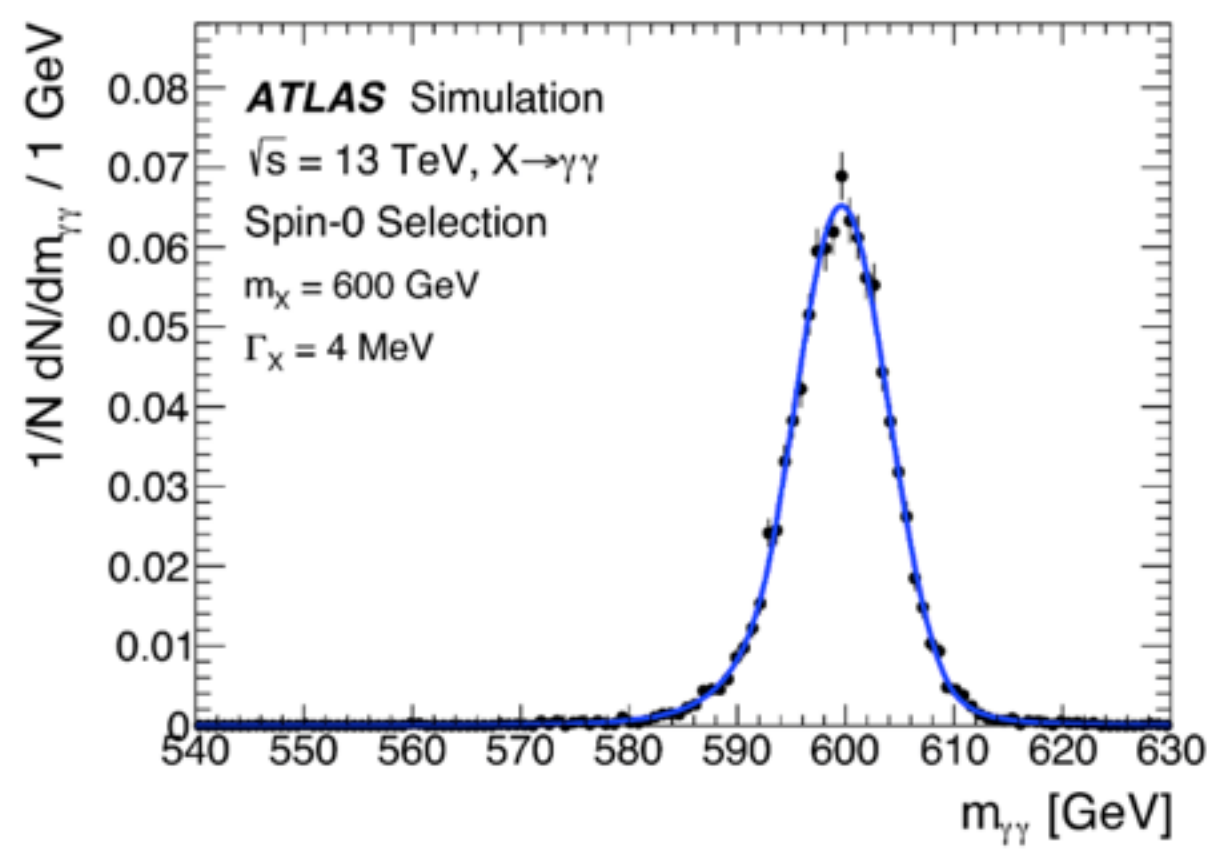
Gaussian core extended by power-law tails above and below the peak

Signal Modelling - NWA

NWA - $m_{\gamma\gamma}$ resolution is 2 GeV at m_X=200 GeV and 13 GeV at m_X=2 TeV
- uncertainty on the mass resolution driven by the uncertainty on the constant term of the energy resolution (+30%/-20% to +60%/-40% between m_X=200 GeV and m_X=1 TeV)

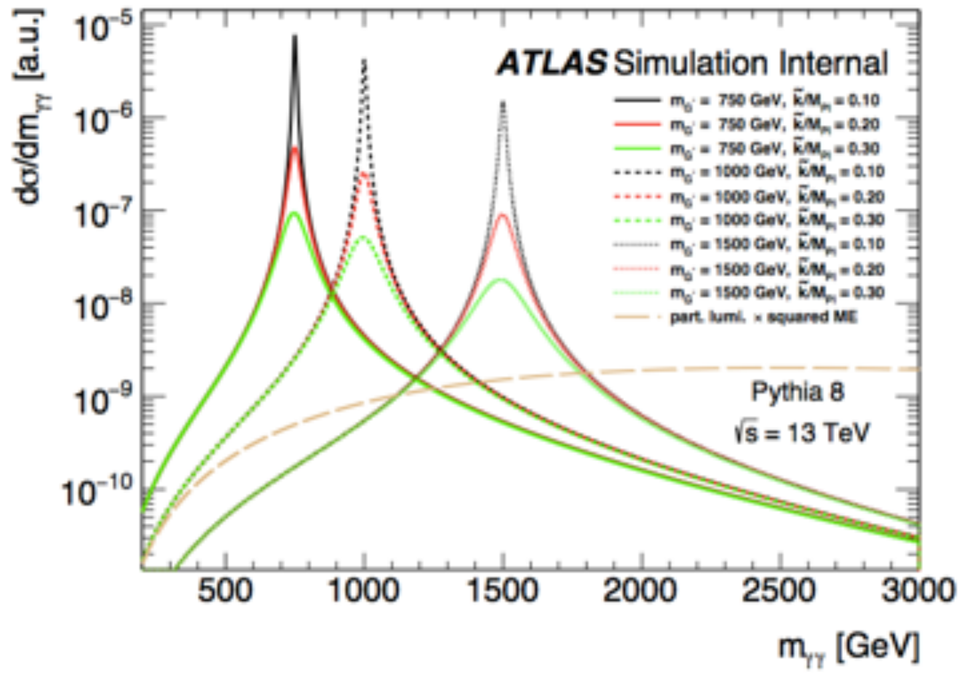
Parametrization based on DSCB



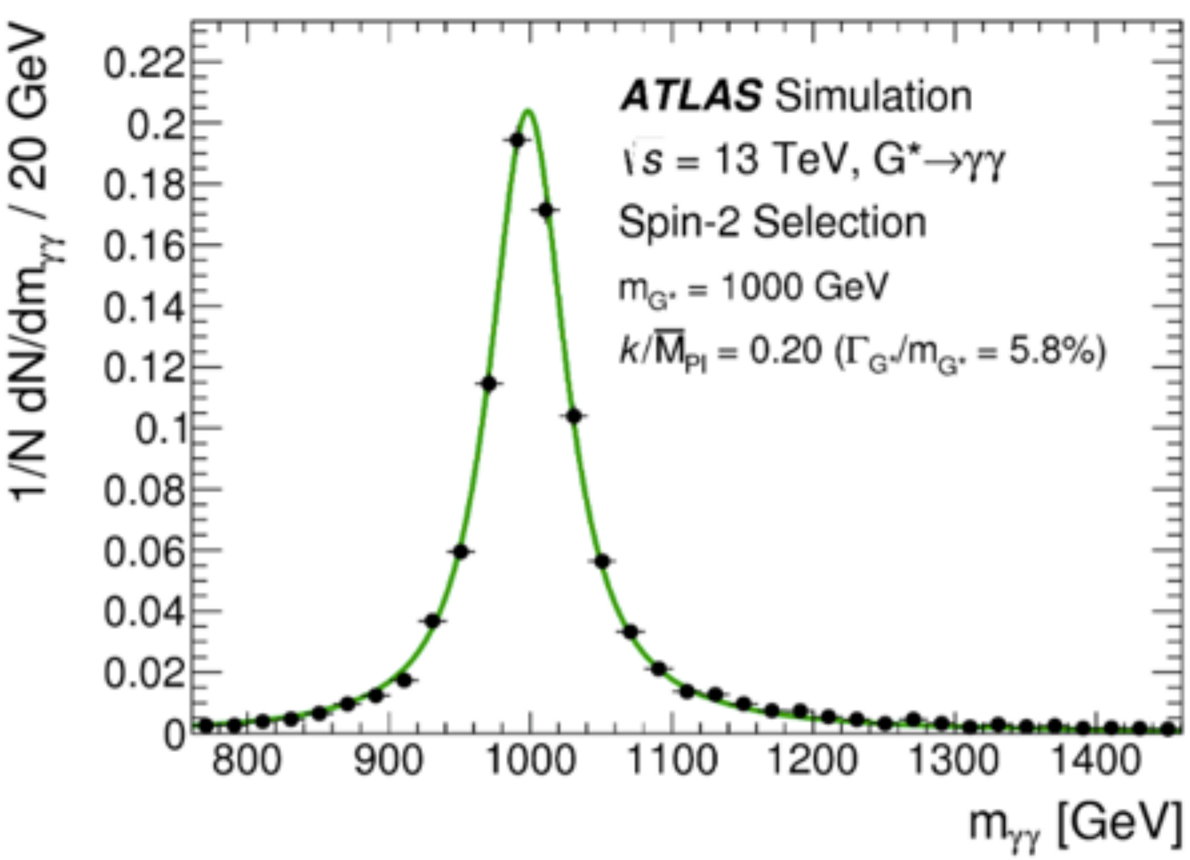


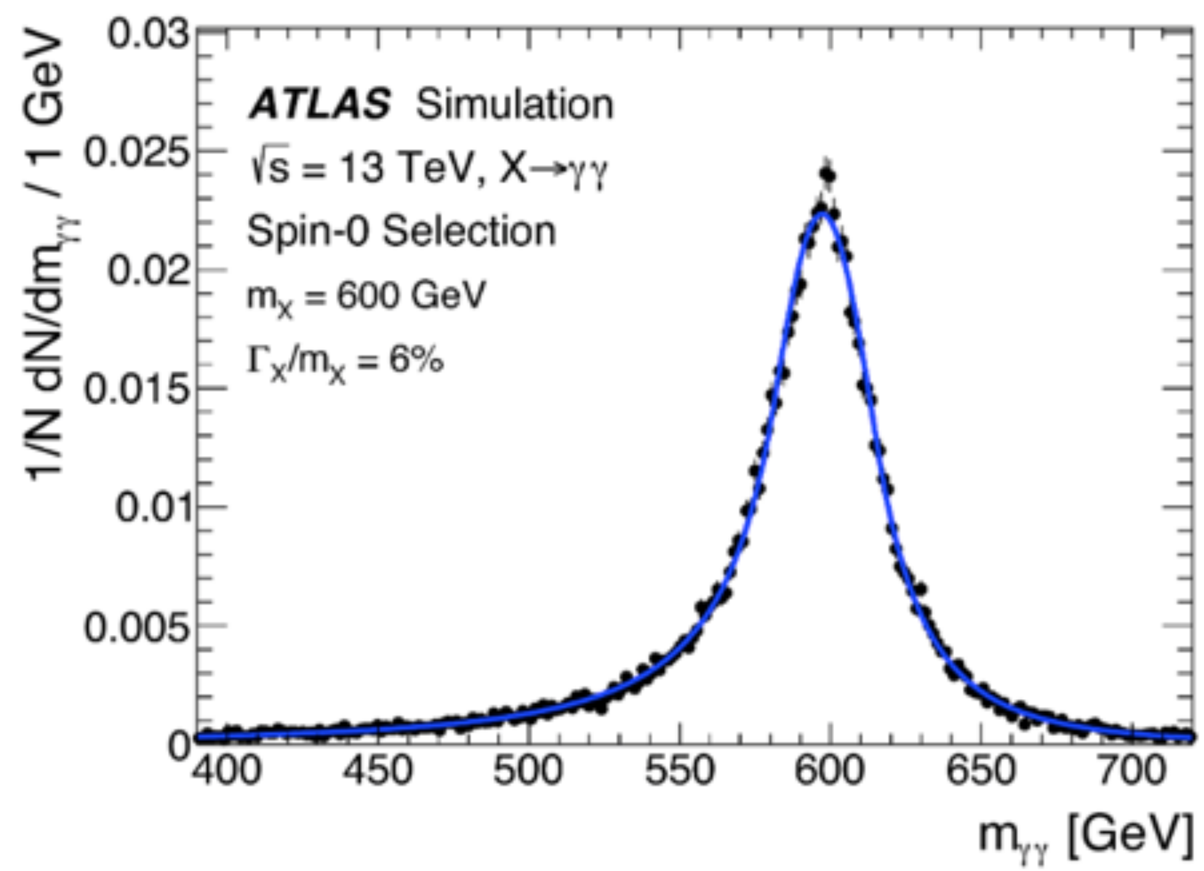
Signal modelling - LWA

spin-2 - theoretical line shape from a product of Breit-Wigner distribution, parton luminosity term and ME term, and convoluted with DSCB - Pythia



spin-0 - theoretical line shape, and detector resolution predicted from DSCB - Powheg-Box





Background Modelling - spin-2

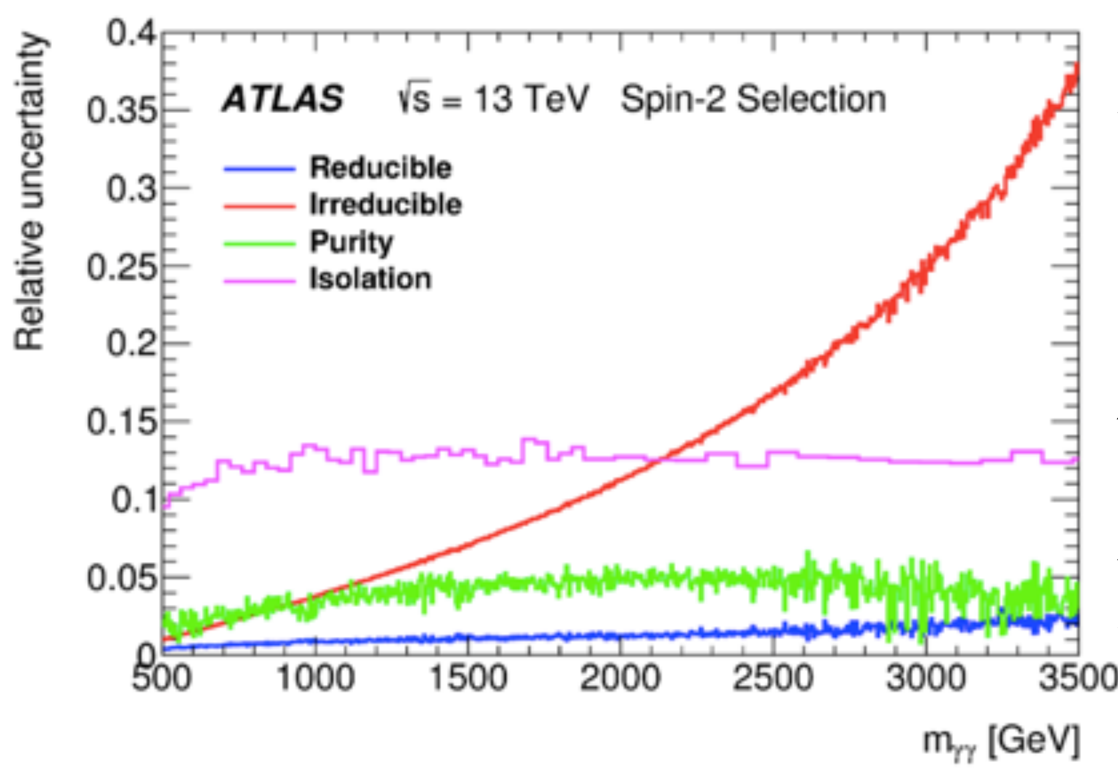
spin-2 - MC extrapolation (not enough data events at high mass)

irreducible γγ - $m_{\gamma\gamma}$ shape from NLO DIPHOX at parton level; ratio of DIPHOX and Sherpa (as a function of $m_{\gamma\gamma}$ - variations up to 20%) is used to reweight fully simulated NLO Sherpa MC

reducible γj/jj - control sample with non-tight ID and loose isolation; $m_{\gamma\gamma}$ shape from functional form; shape uncertainties from varying ID requirements

$m_{\gamma\gamma}$ shape uncertainties:

- PDF eigenvector variations (up to 140% at 5 TeV)
- PDF choice (up to 5%)
- photon isolation (up to 10%)
- QCD scale (up to 5%)



Pre-fit $m_{\gamma\gamma}$ shape uncertainties:

- **irreducible** - NLO γγ computations (dominated by PDFs)
- **isolation** - choice of parton-level isolation cut in DIPHOX
- **purity** - relative normalization between γγ and γj/jj
- **reducible** - $m_{\gamma\gamma}$ shape

Background Modelling

spin-0 - functional form adapted from di-jet searches

$m_{\gamma\gamma}$ shape - family of functions: $$f_{(k)}(x; b, \{a_k\}) = N(1 - x^{1/3})^b x^{\sum_{j=0}^{k} a_j (\log x)^j} \qquad x = \frac{m_{\gamma\gamma}}{\sqrt{s}}$$

k+2 free parameters - choice of k=0 was made based on the constraints on spurious signal (< 20% of the statistical uncertainty on the fitted signal yield) - using γγ pseudo-data from DIPHOX and γj/jj from data in a control sample (smoothen with a fit function); F-test was performed to ensure that a more complex (larger value of k) function is not necessary

uncertainties - 7 to 0.006 events from 0.2 to 2 TeV (NWA), 20 to 0.04 events from 0.2 to 2 TeV (Γ/m=6%)

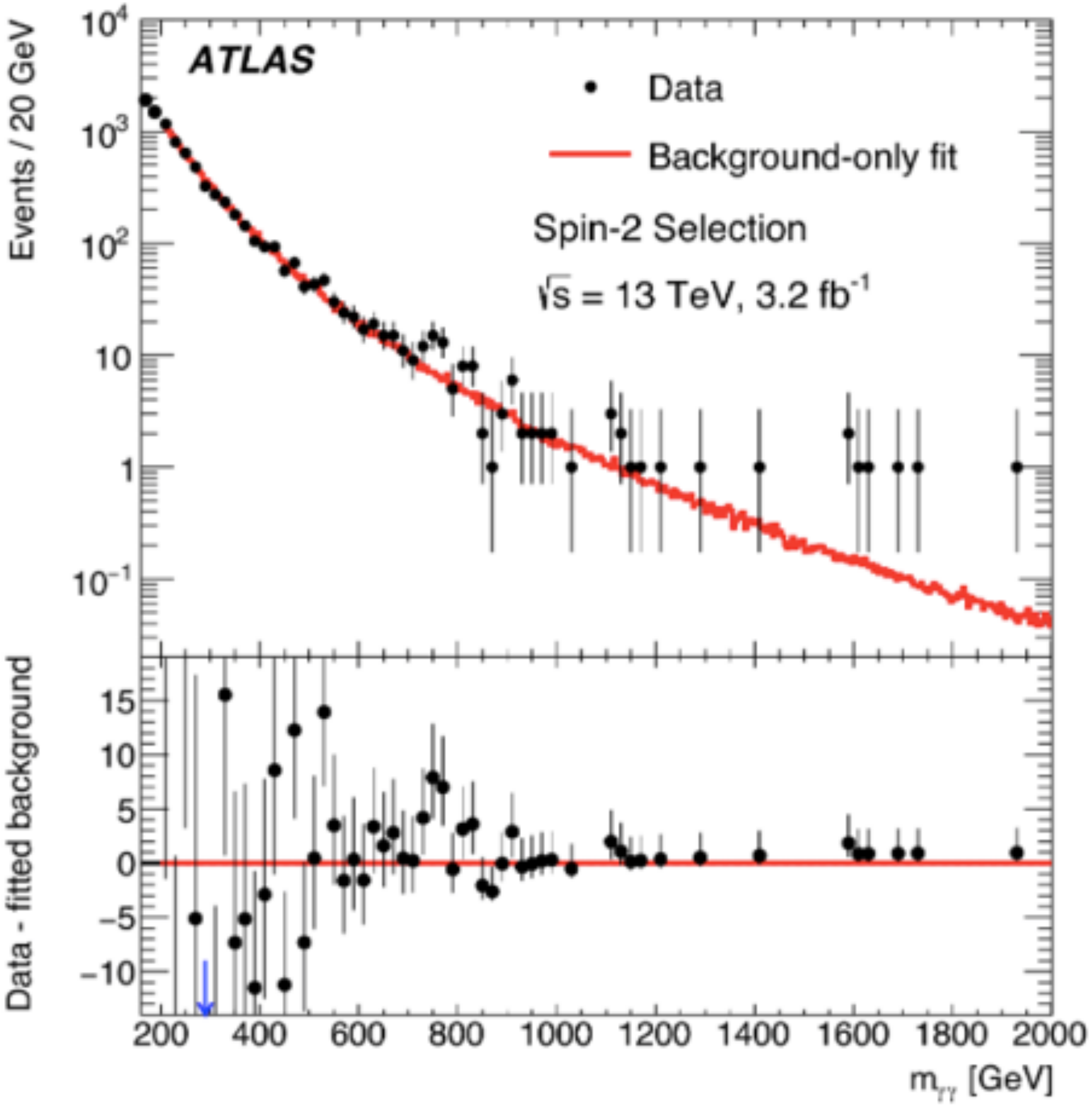
spin-0/2 - comparison of two bkg estimation methods in the regions where they are used

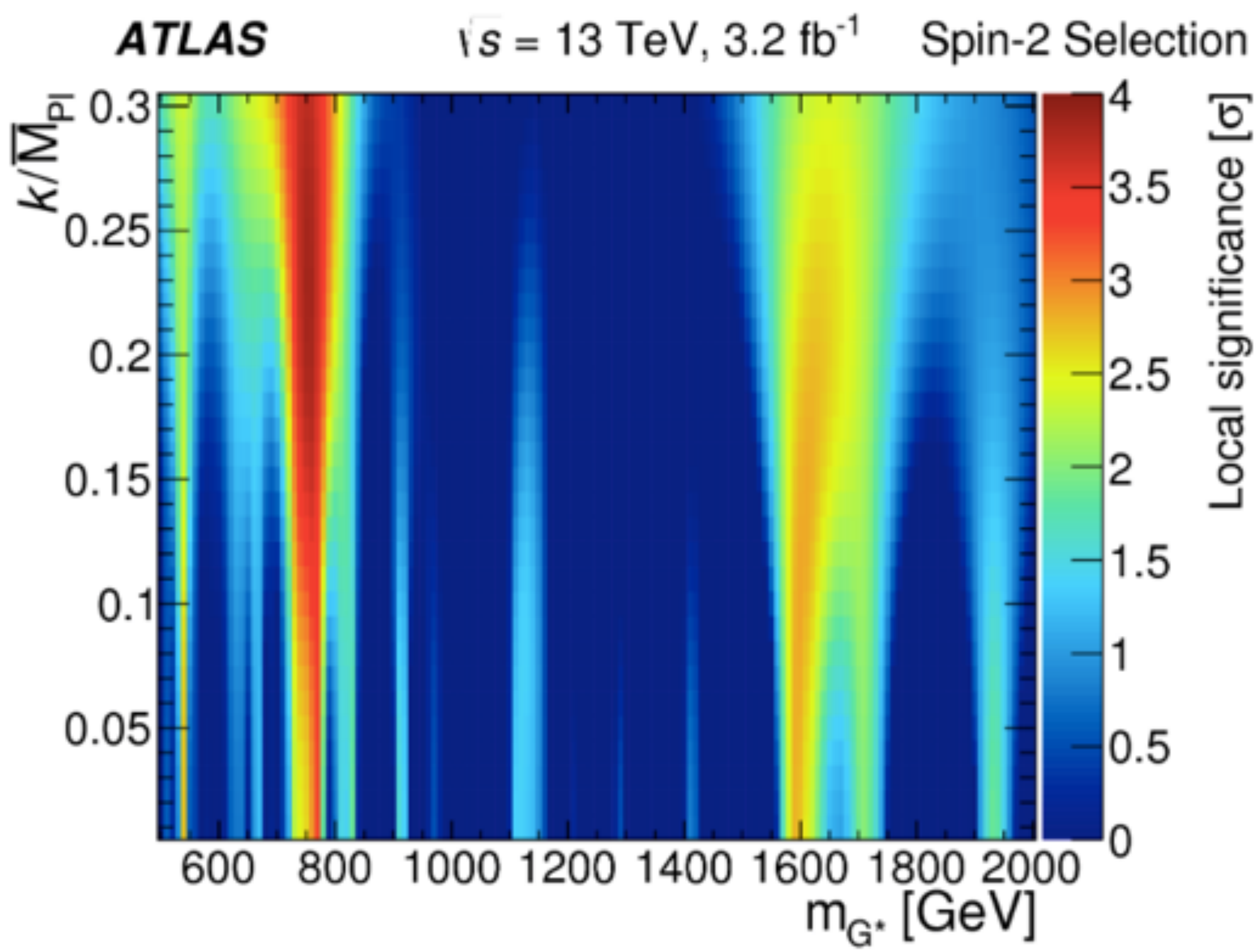
Investigated signal region	Background from MC extrapolation	Background from functional form
m = 750 GeV, Γ/m = 6%		
720-780 GeV, spin-2 selection	$\boxed{20.1\pm0.3\pm0.7}$	21.9±1.2±0.4
720-780 GeV, spin-0 selection	6.7±0.1±0.4	$\boxed{6.8\pm0.7\pm0.3}$
m = 1500 GeV, Γ/m = 6%		
1440-1560 GeV, spin-2 selection	$\boxed{1.14\pm0.02\pm0.09}$	1.51±0.27±0.08
1440-1560 GeV, spin-0 selection	0.32±0.01±0.04	$\boxed{0.33\pm0.11\pm0.04}$

$\boxed{}$ default background estimate

Results for spin-2

5066 events with $m_{\gamma\gamma}$ > 200 GeV



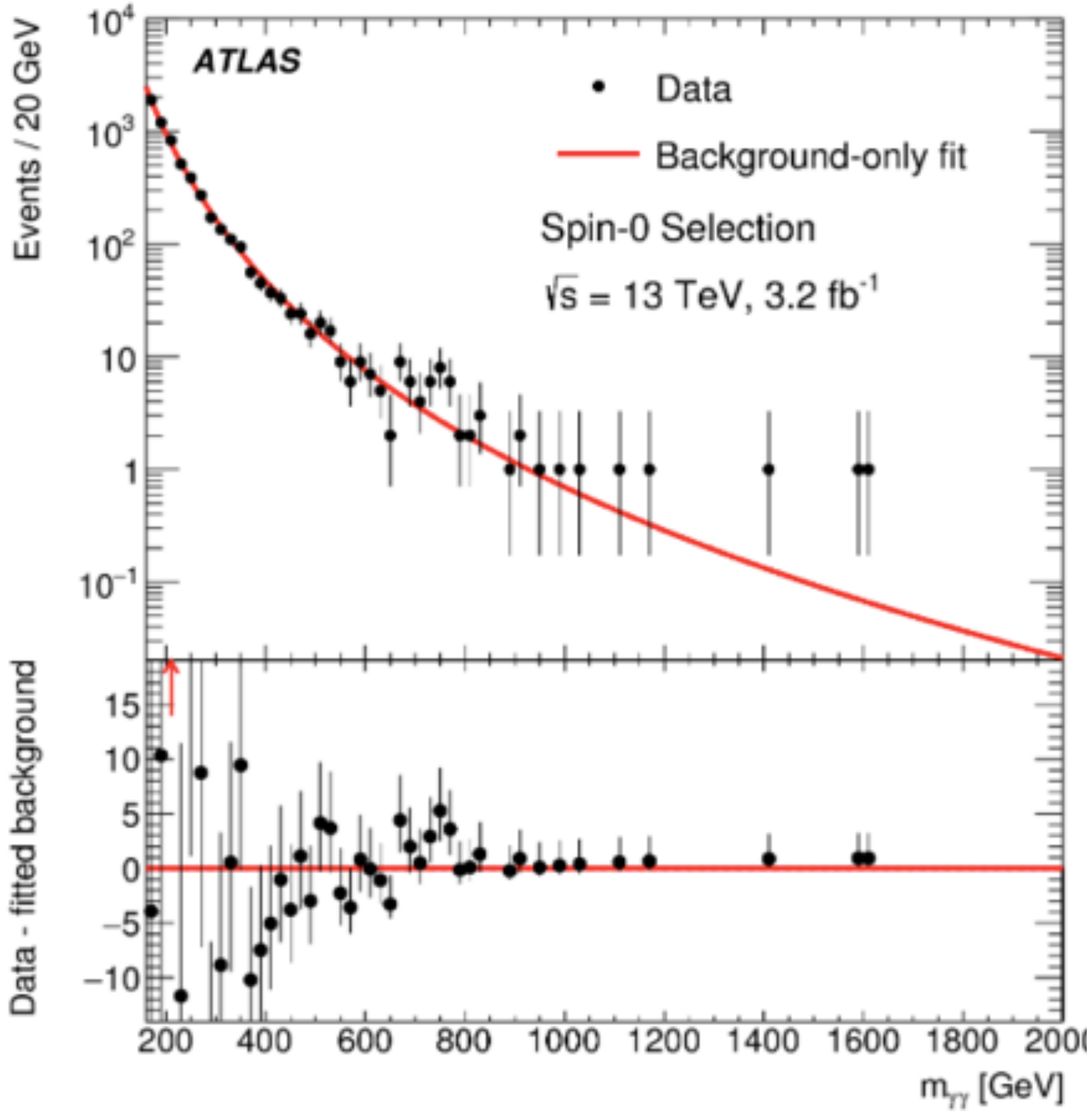


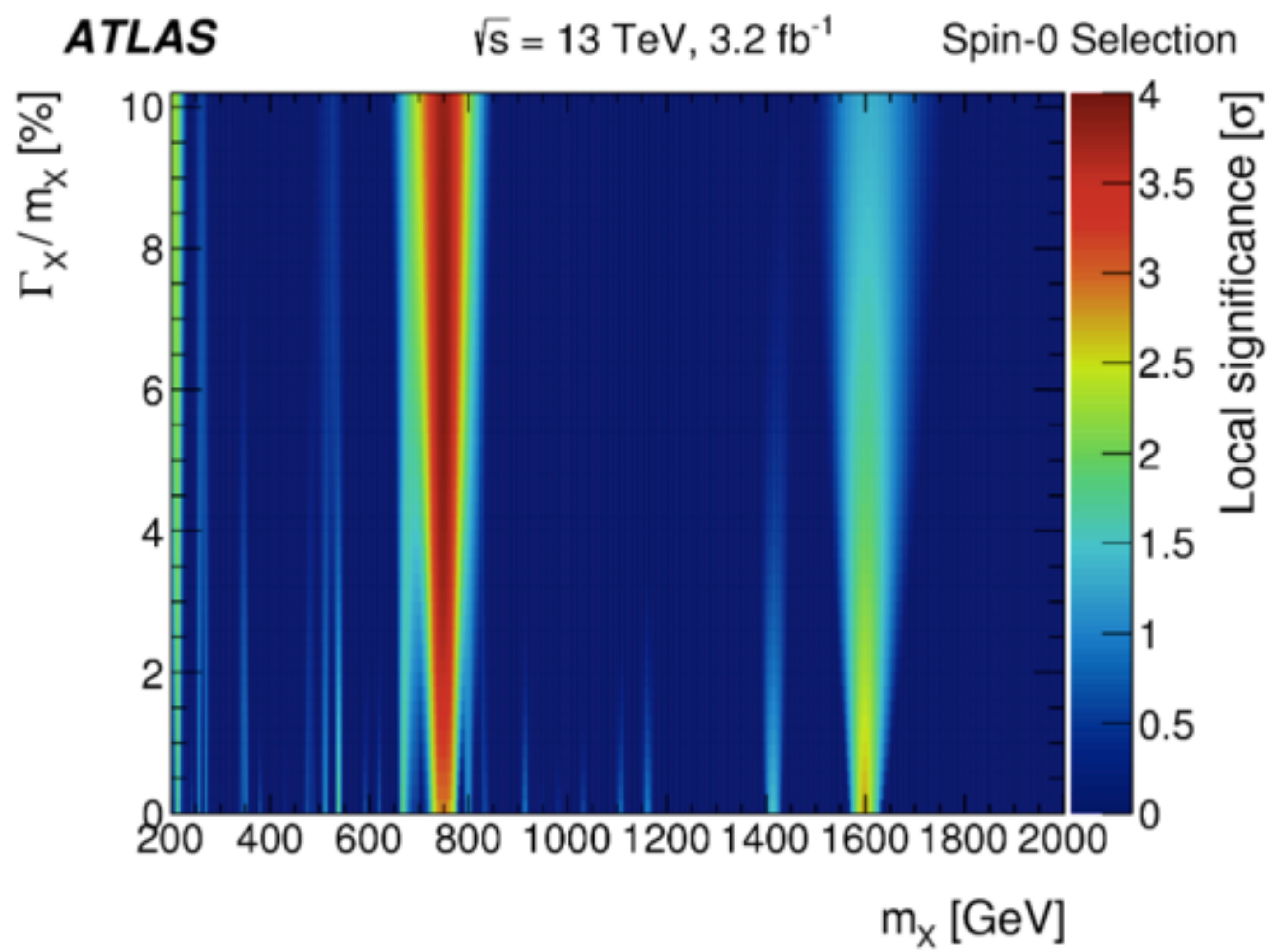
Best-fit @ 750 GeV and k/M_{Pl}=0.23 (57 GeV): local **3.8σ** and global **2.1σ**

Best-fit for NWA @ 770 GeV: local **3.3σ**

Results for spin-0

2878 events with $m_{\gamma\gamma}$ > 200 GeV





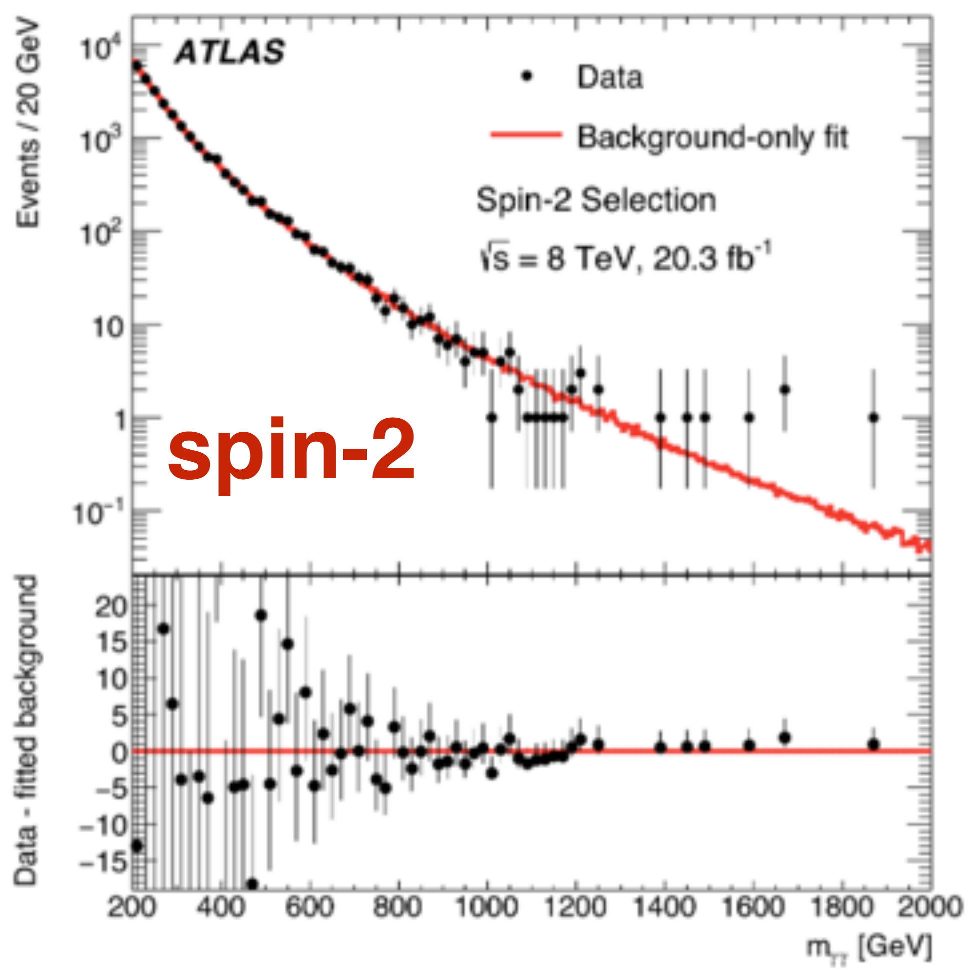
Best-fit @ 750 GeV and Γ_X/m_X=6% (45 GeV): local **3.9σ** and global **2.1σ**

Best-fit for NWA @ 750 GeV: local **2.9σ**

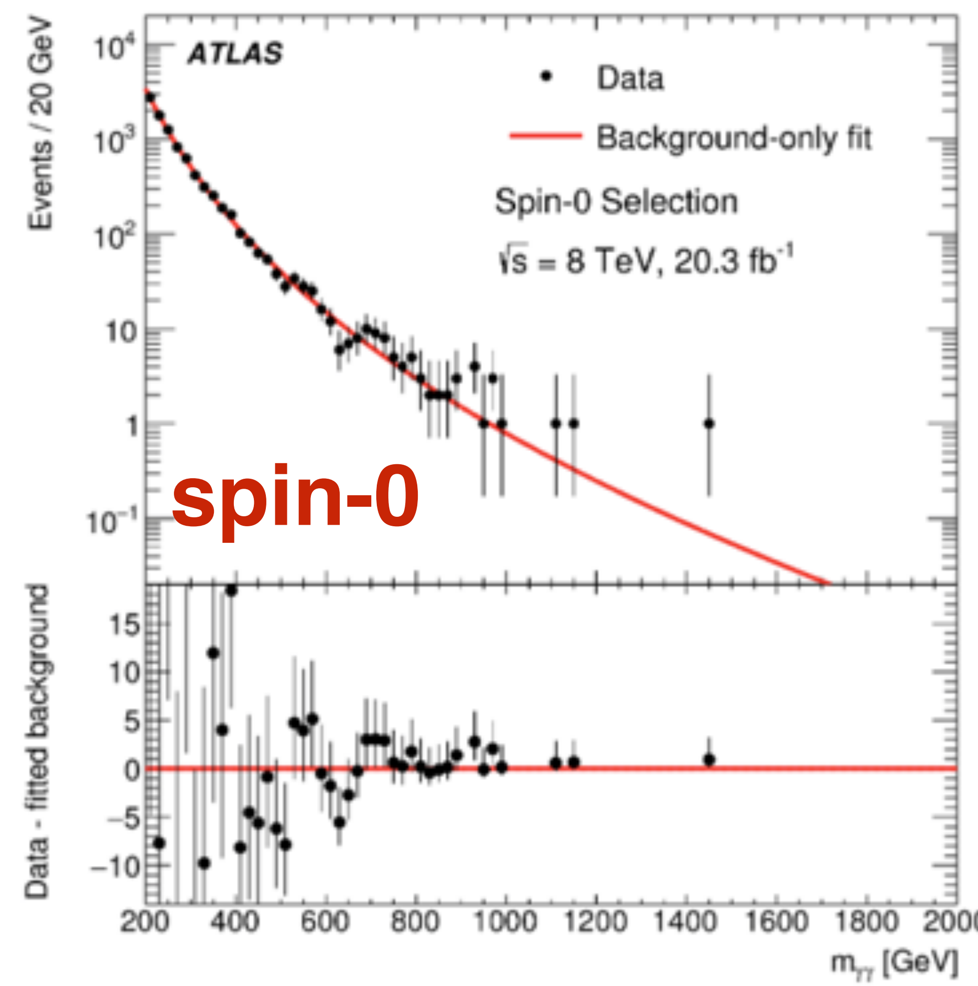
What about 8 TeV?

8 TeV data (20.3 fb^{-1}) was re-analysed using updated photon energy calibration; all the selection was kept the same as in Run 1 publications - signal/background modelling follows 13 TeV analysis

spin-2 - no **excess** over background-only hypothesis



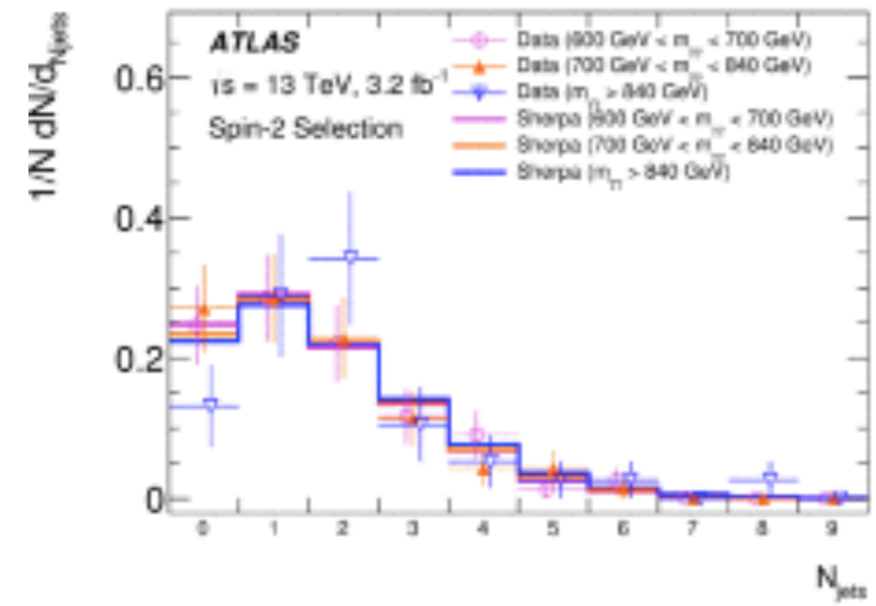
spin-0 - 750 GeV and Γ_X/m_X=6%, small excess with local significance of **1.9σ**

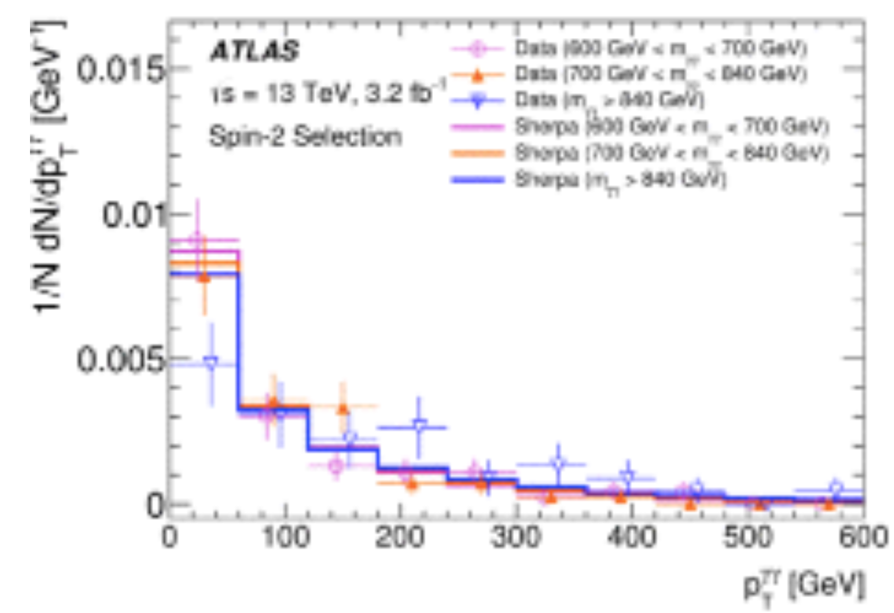


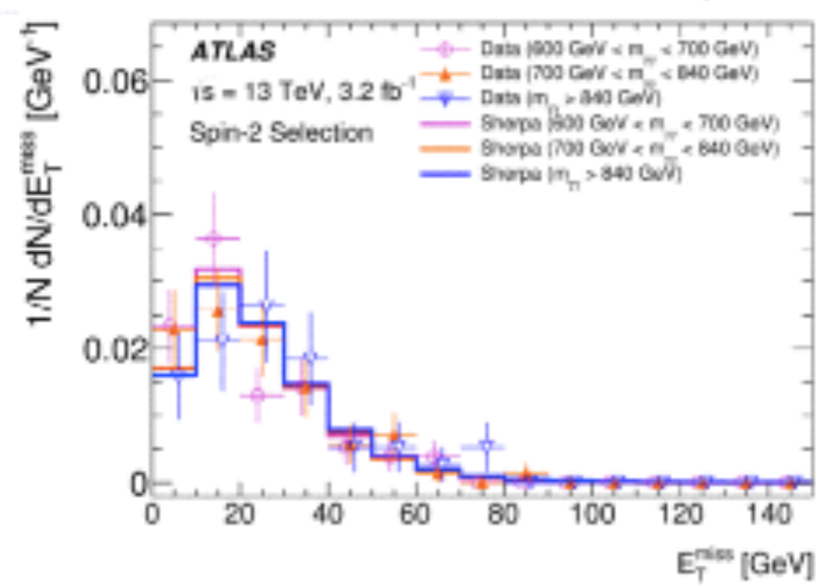
8TeV vs 13 TeV and summary

	Spin-2 Selection		Spin-0 Selection	
	Free width	Narrow width	Free width	Narrow width
	13 TeV			
Mass for the largest excess	750 GeV	770 GeV	750 GeV	750 GeV
Width over mass for the largest excess	8%	-	6%	-
Local significance	3.8	3.3	3.9	2.9
Global significance	2.1		2.1	
	8 TeV			
Local significance (at 13 TeV best-fit)	-		1.9	
	8 TeV - 13 TeV Compatibility			
gluon-gluon scaling (4.7)	2.7	2.2	1.2	1.5
quark-antiquark scaling (2.7)	3.3	2.4	2.1	2.0

Compatibility (in σ) between 8/13 TeV assuming gluon or quark initiated process







Properties of events with $m_{\gamma\gamma}$ > 600 GeV:

- no electrons or muons
- 8% of jets are b-tagged (85% eff.)

Theory Speculations

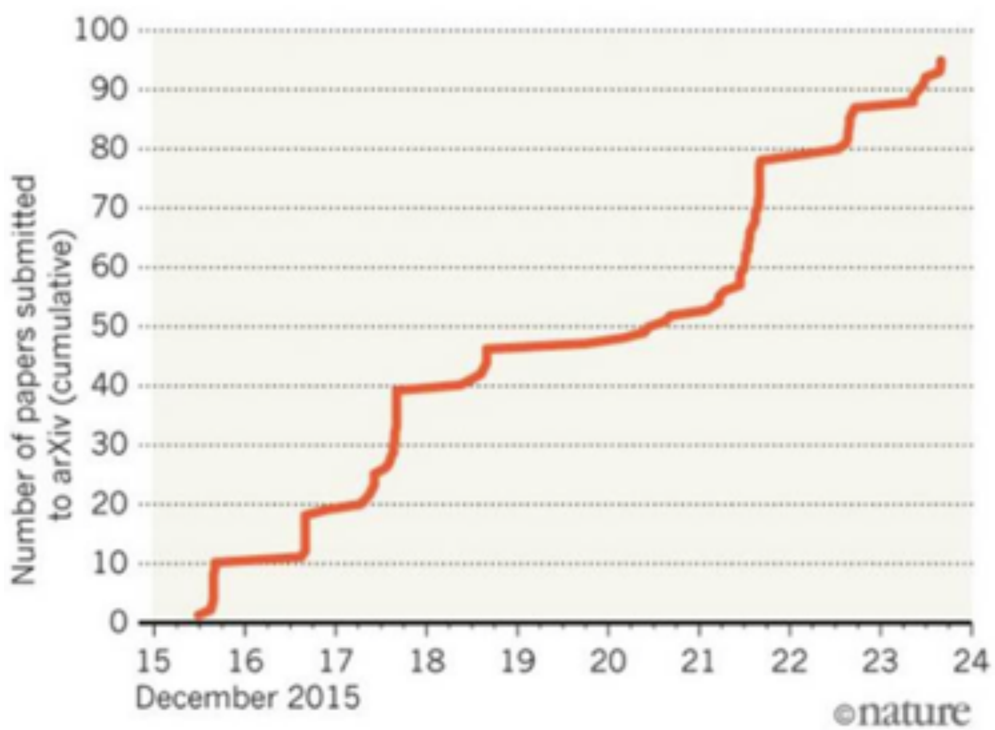
What do we know now:

- a bump in $m_{\gamma\gamma}$ around 750 GeV (14 events in ATLAS, 10 events in CMS)
- 3.9σ in ATLAS and 2.3σ in CMS (local significance)
- width of around 6% so 45 GeV
- no excess in other channels like jj, WW, ZZ

neutral scalar?

Speculations about the new resonance:

- must decay to γγ (other decays might be suppressed or limited by the available data statistics)
- must be electrically neutral and spin 0 or 2 (1 is forbidden by Landau-Yang theorem) - spin 2 less plausible since spin-2 Kaluza-Klein graviton excitations have universal couplings and there was no excess found in any other channel
- not part of the SM since Higgs was the last missing particle

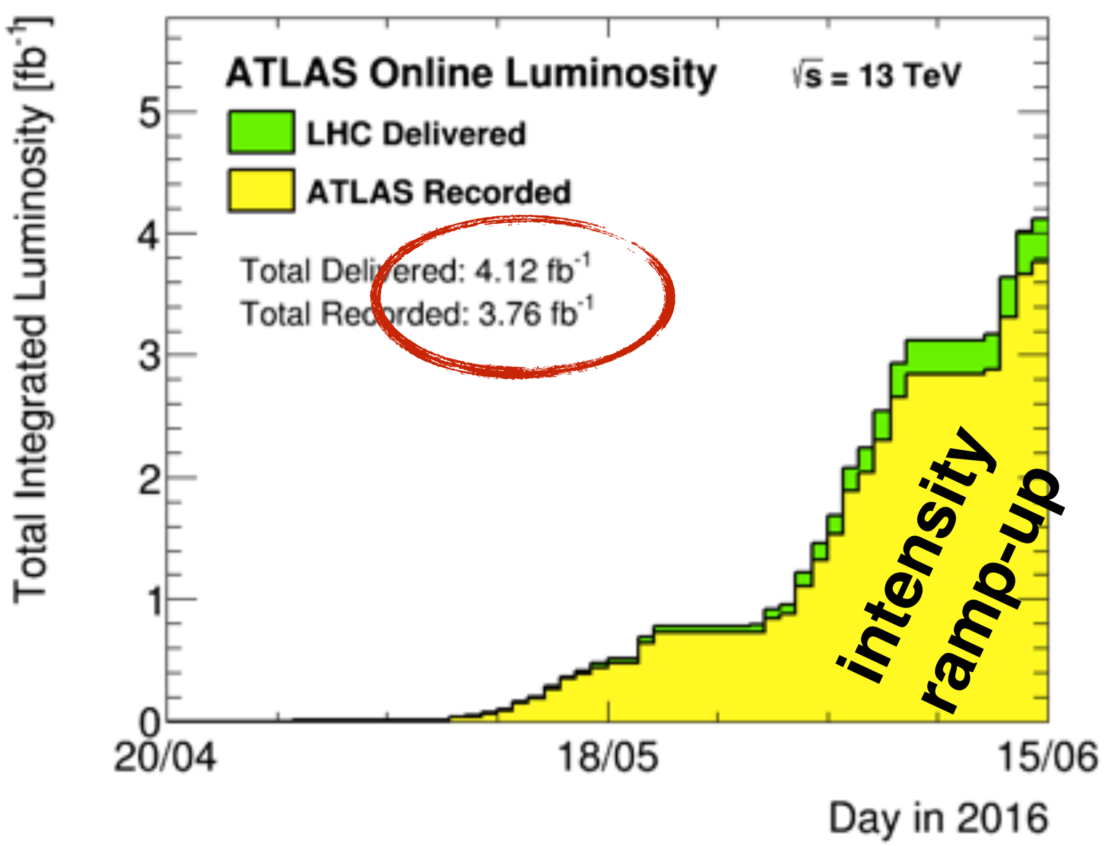


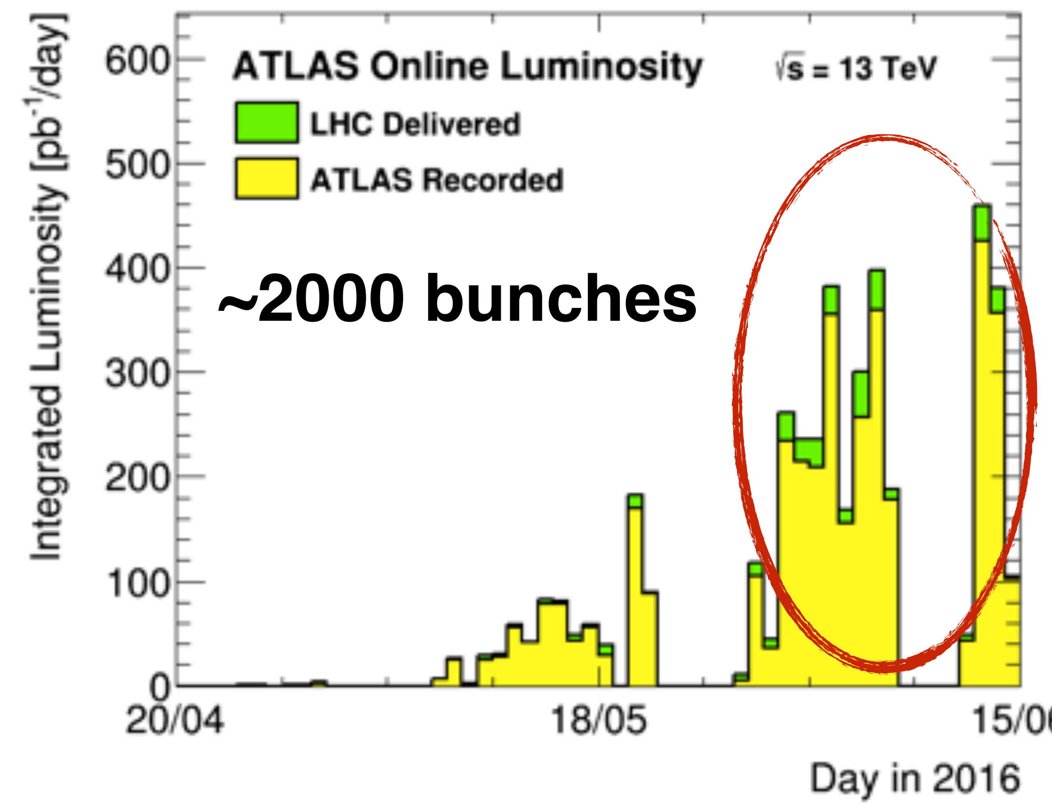
Possibilities??

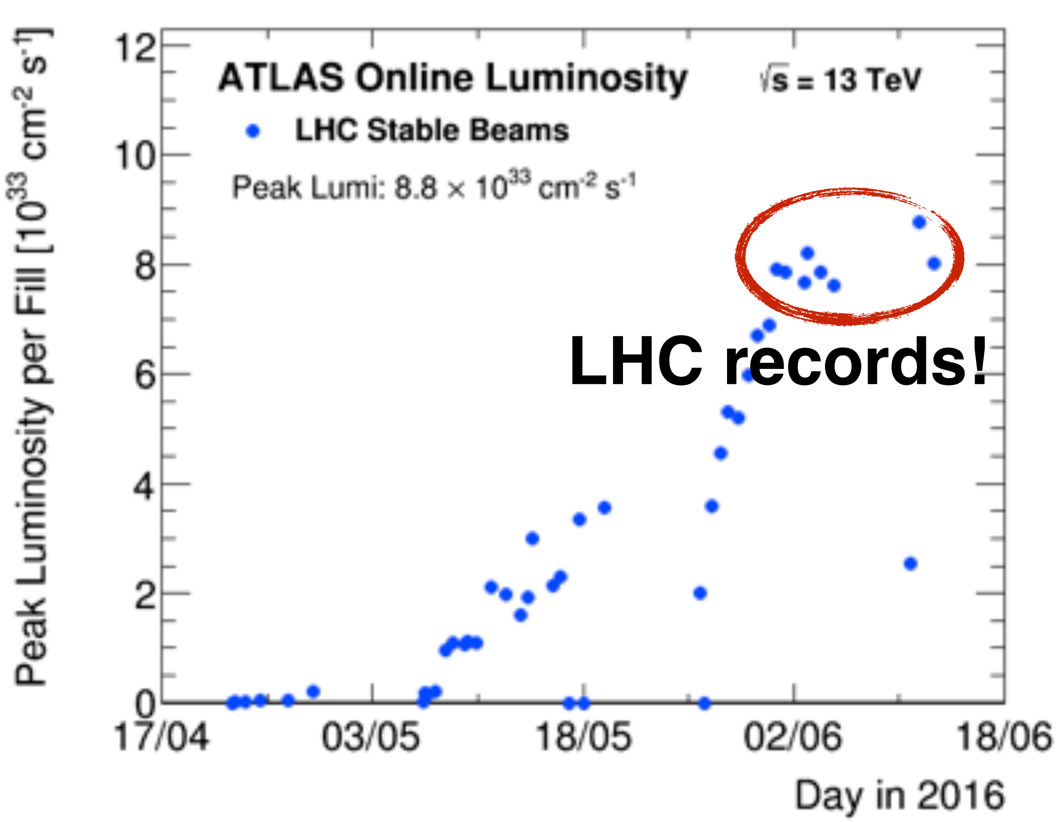
- models with additional vector-like fermions
- generic singlet scalar or pseudoscalar
- composite scalar
- dark matter models with scalar mediator
- …..

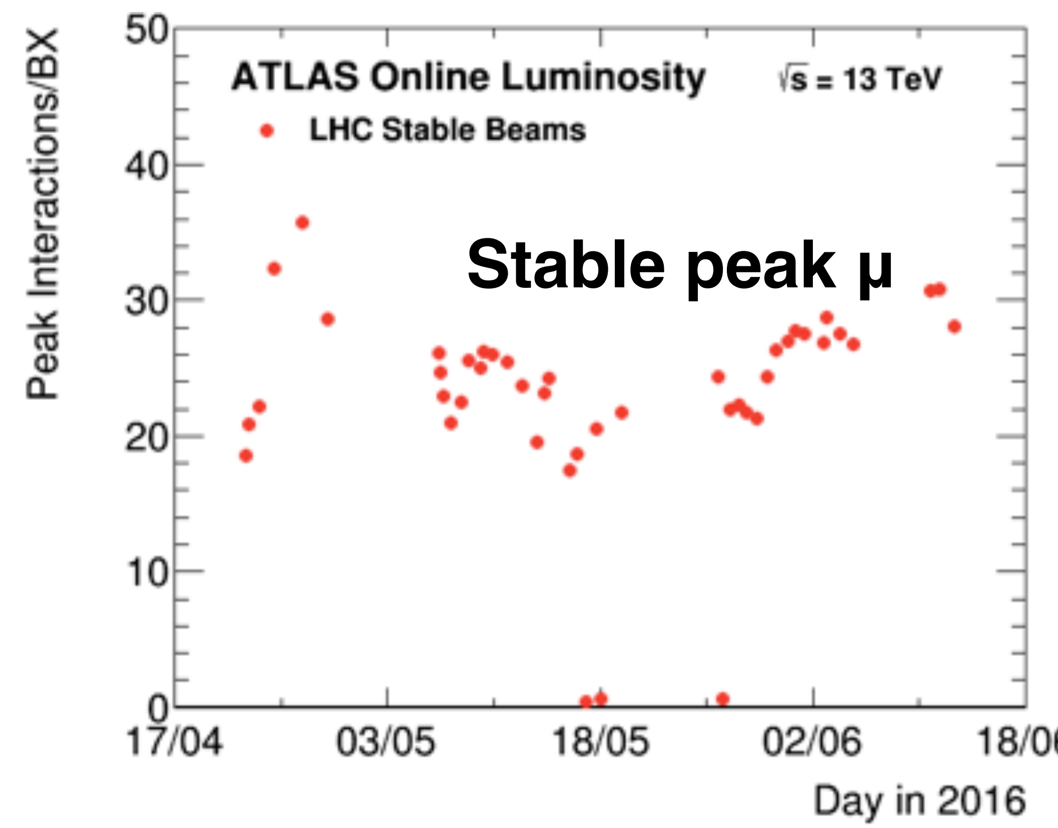
Need more DATA!

LHC Performance in 2016









Summary and Outlook

LHC is performing remarkably well (recovered after the weasel incident) and has already delivered the same amount of data as in 2015!!!

ATLAS detector is also performing remarkably well, collecting the data and recording it for physics.

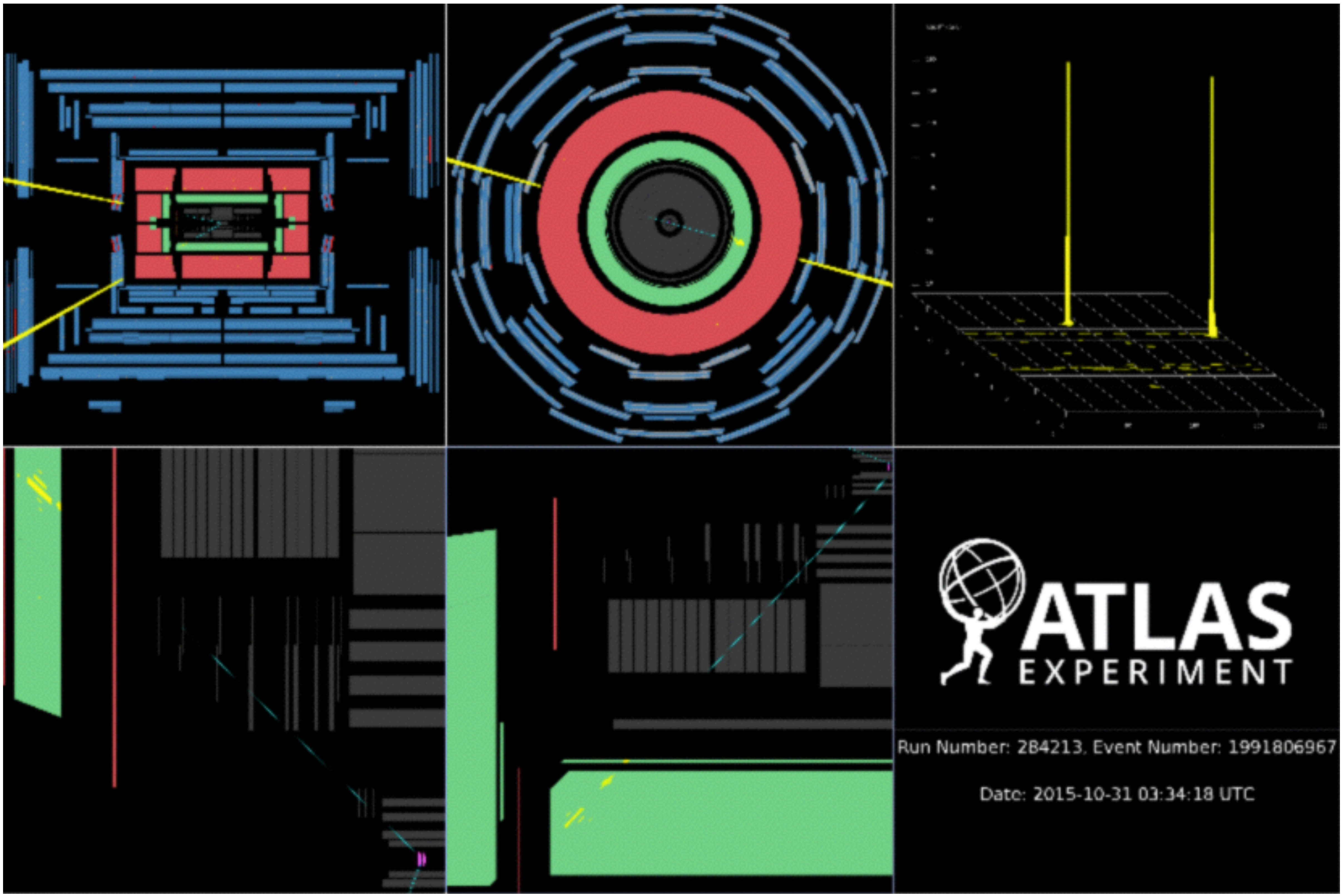
One of the most exciting results of last year is a bump in $m_{\gamma\gamma}$ around **750 GeV** - seen both by ATLAS and CMS.

Data collected this year will be crucial to understand this excess (if it persists).

Stay tuned! New results coming out for ICHEP (August, Chicago).

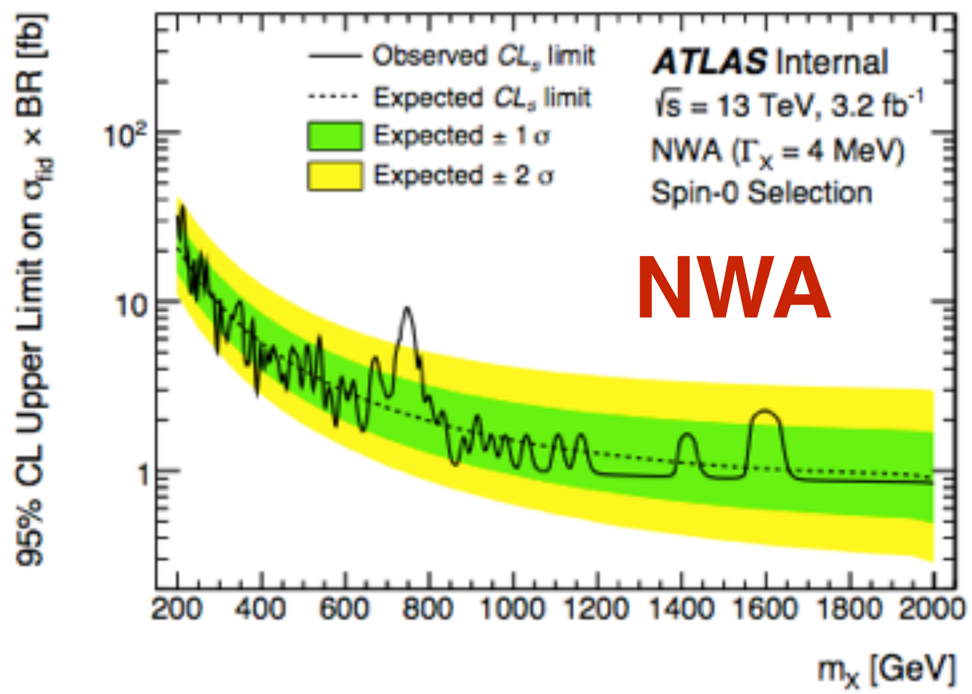
BACKUP

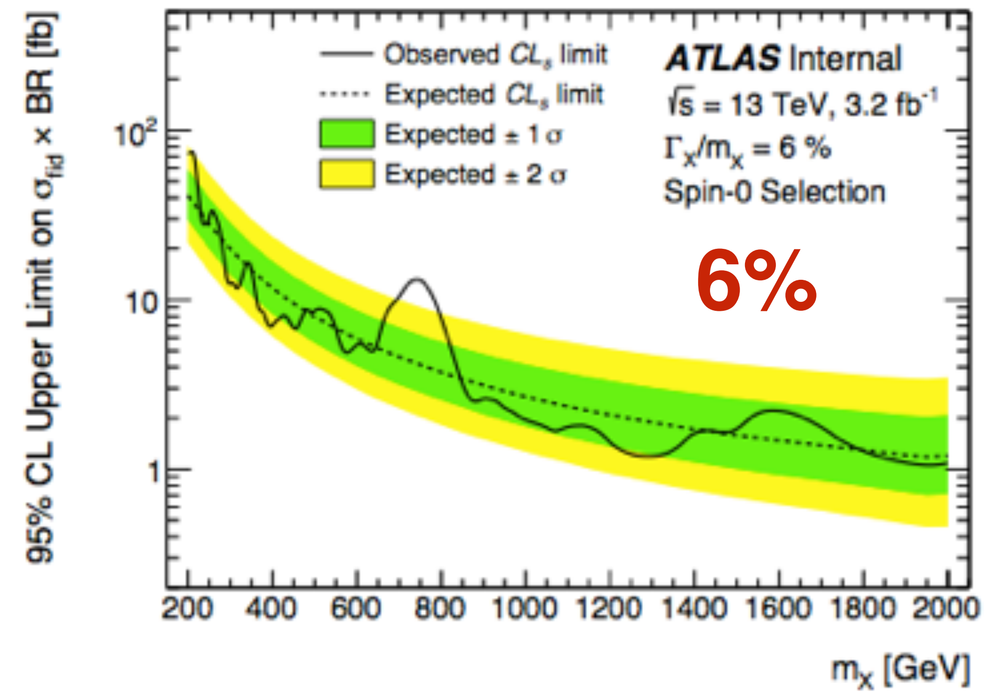
Two converted photons. E_T, η, phi, iso: 322 GeV, -1.33, -0.27, 0.86 GeV (leading) and 316 GeV, -2.32, 2.86, -0.21 GeV (subleading)



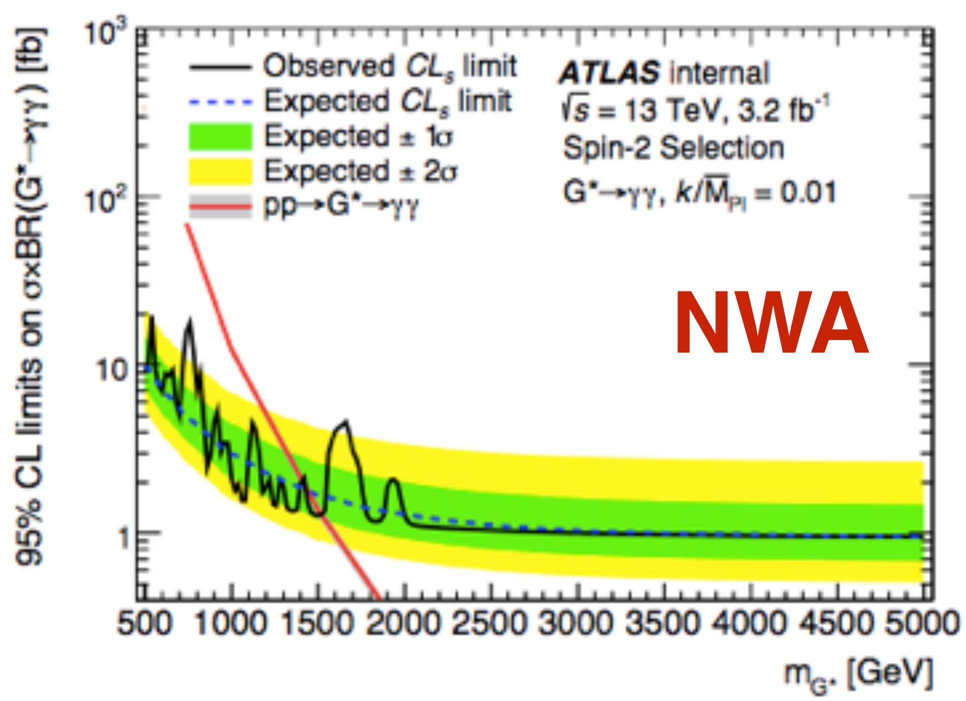
Limits on x-sec

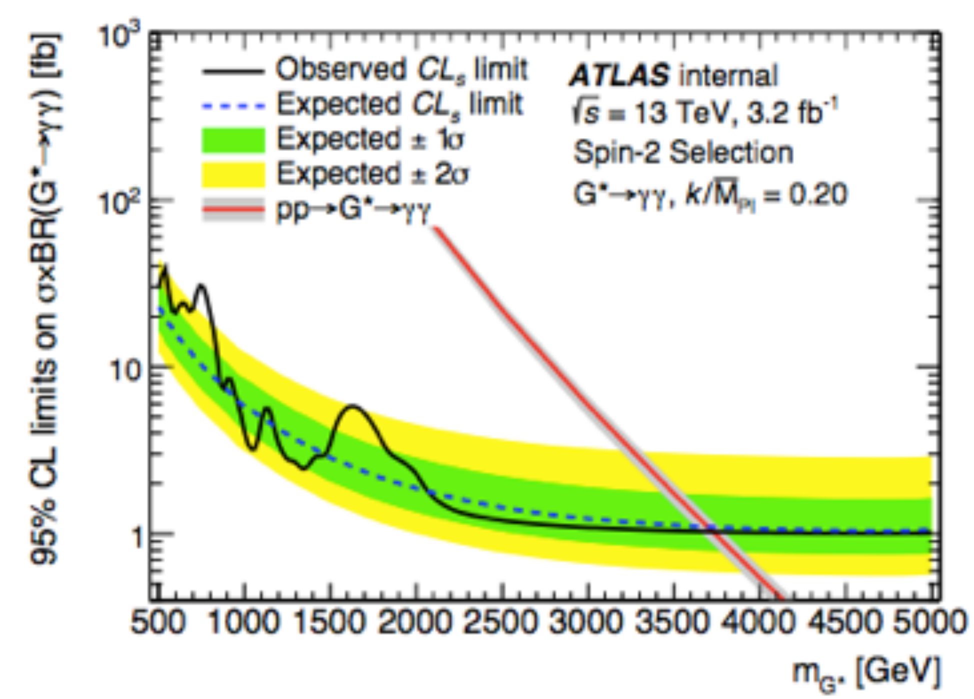
spin-0 - limits on the fiducial x-sec are given in a model independent way (fiducial acceptance - selection follows the cuts applied at the reconstruction level)

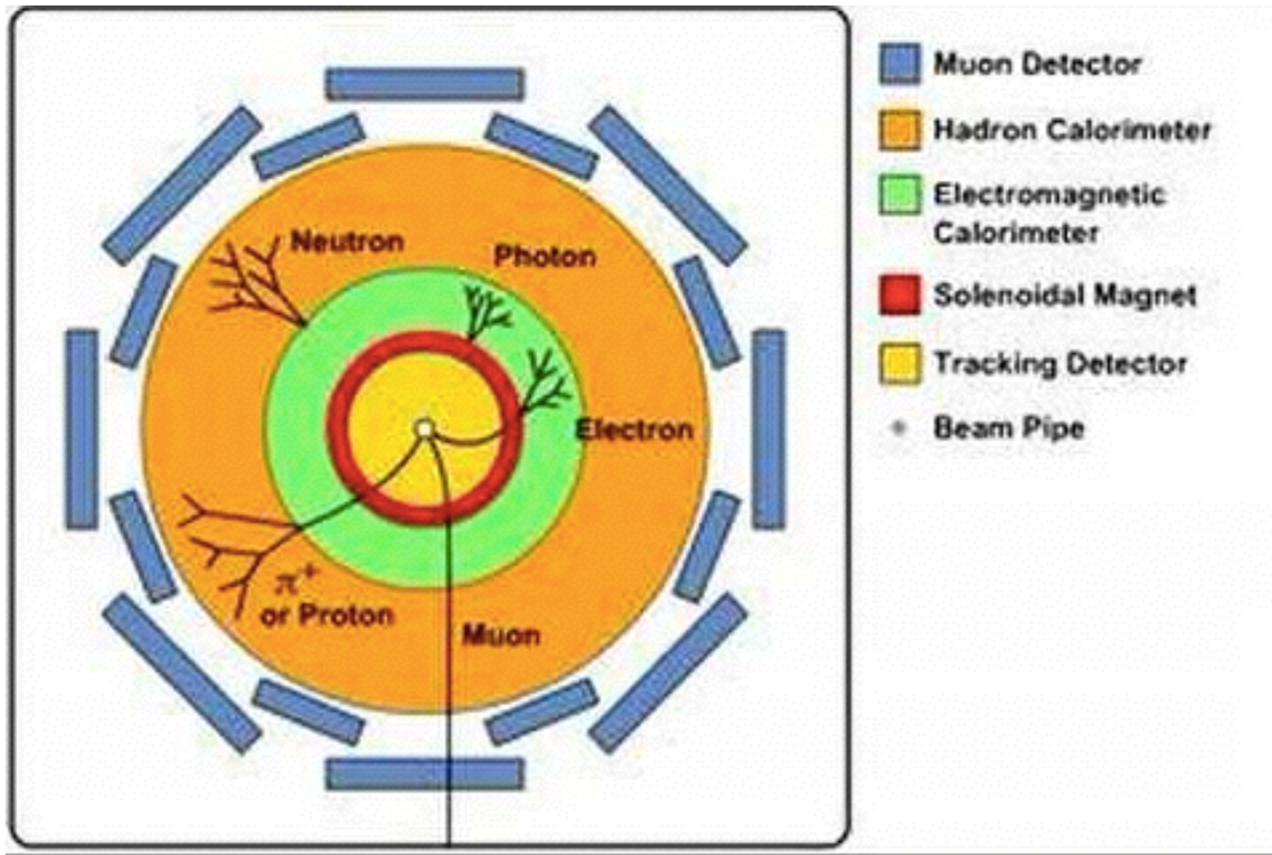


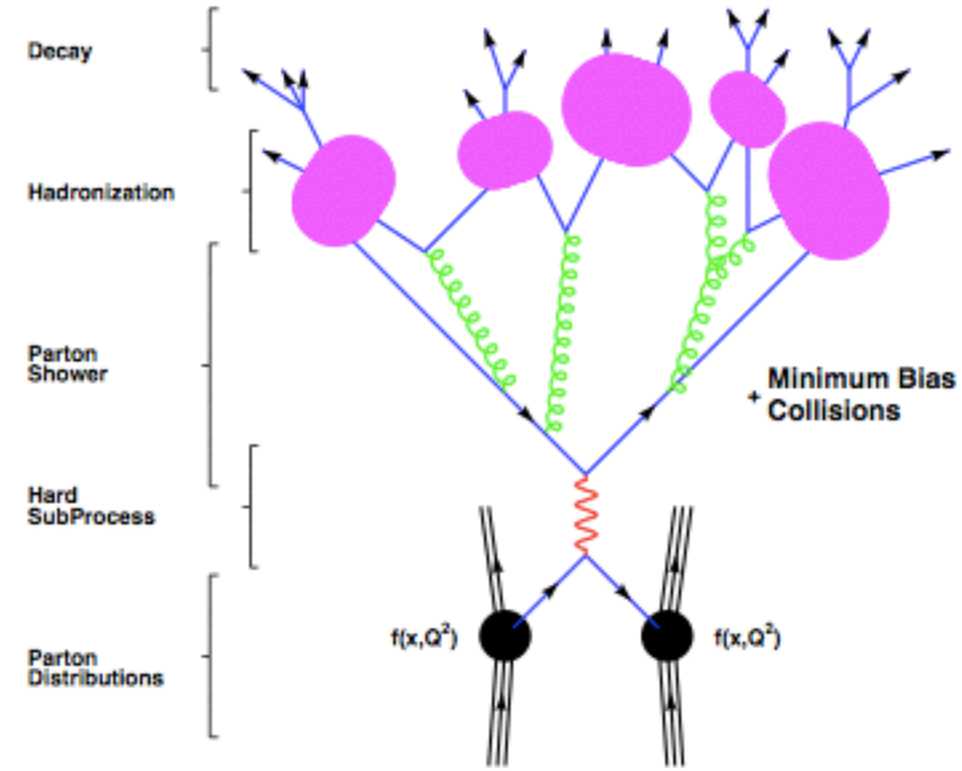


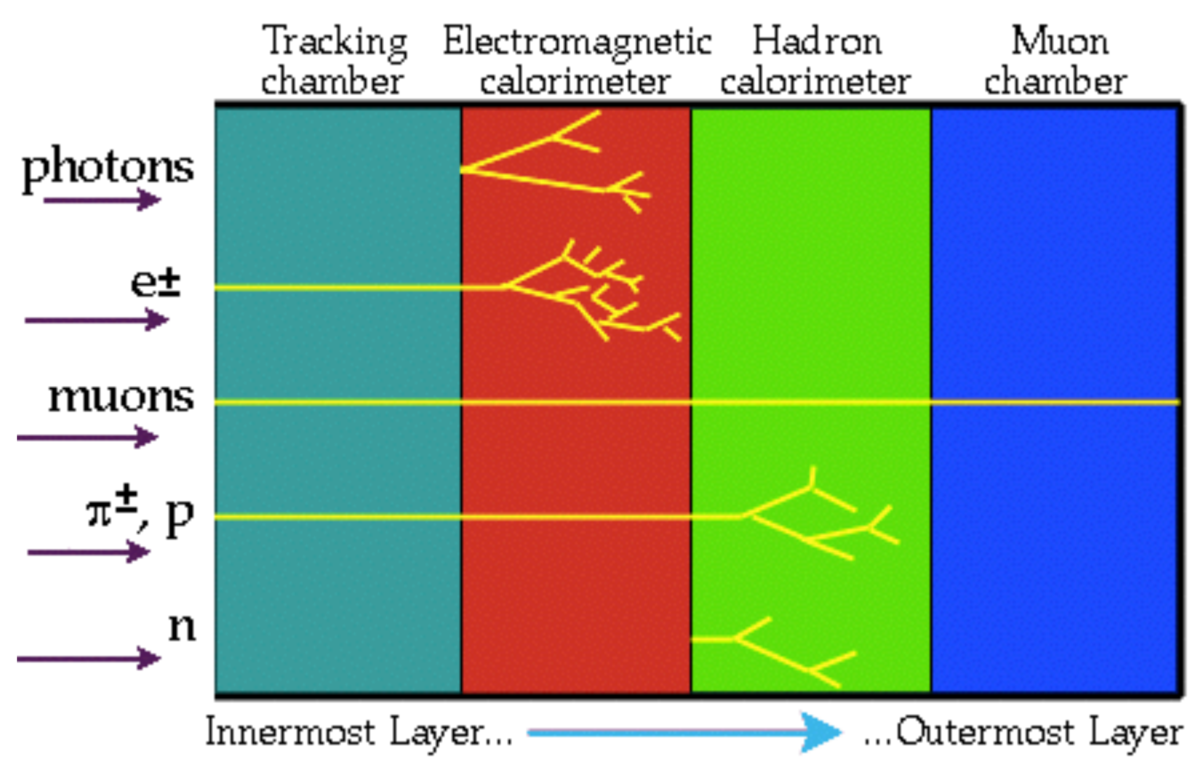
spin-2 - limits on the x-sec are given assuming specific benchmark models

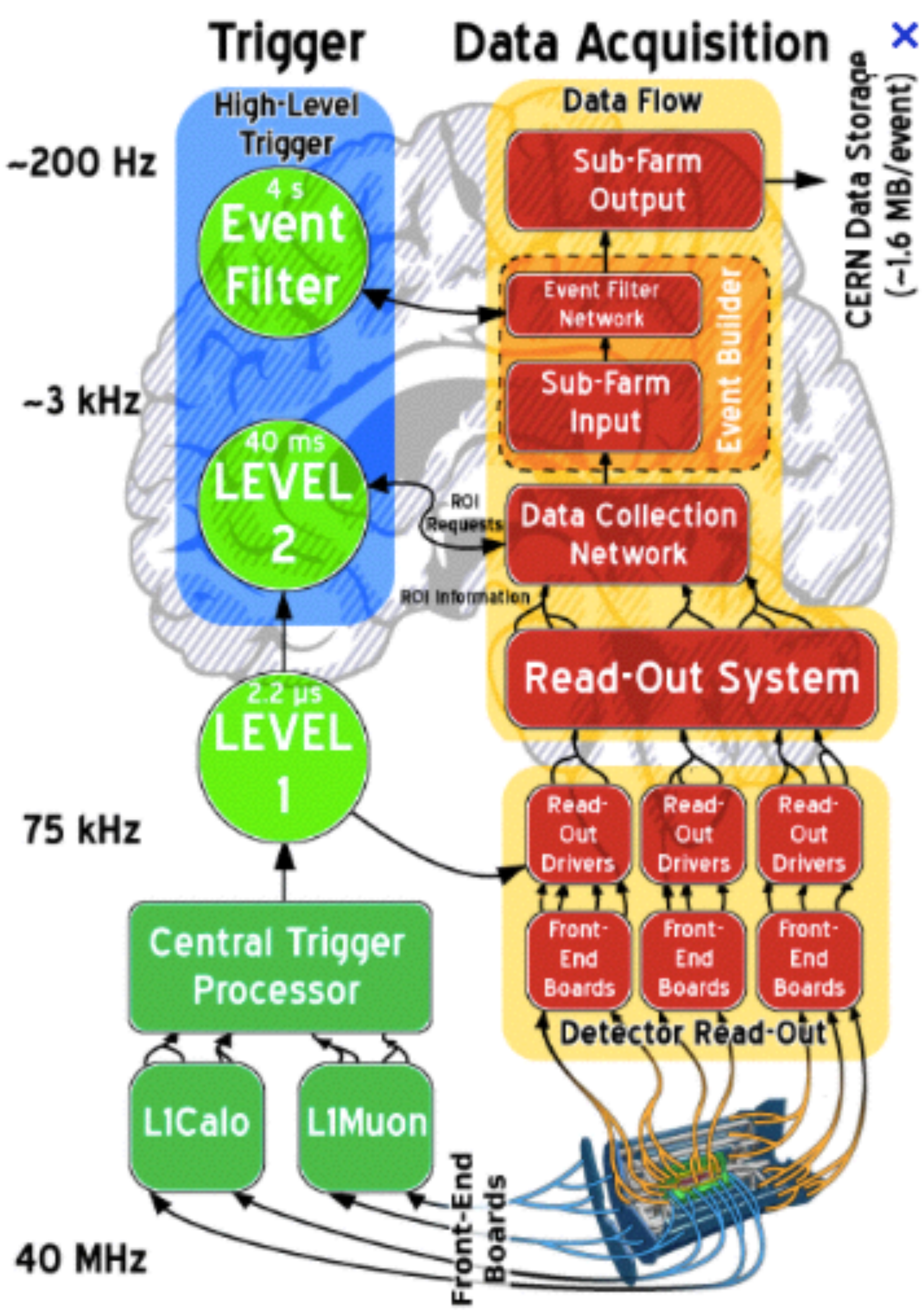




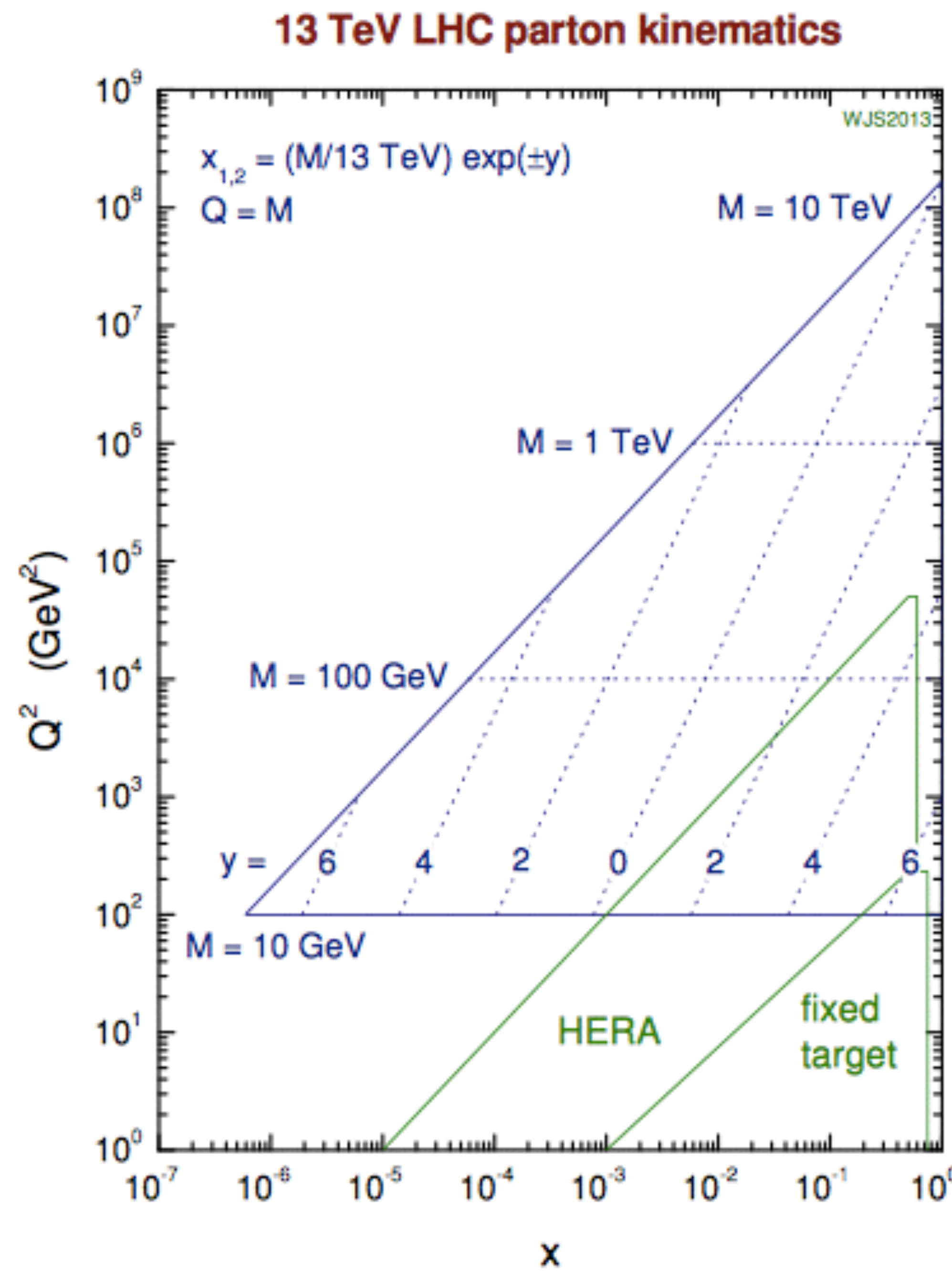

Muon Detector
Hadron Calorimeter
Electromagnetic Calorimeter
Solenoidal Magnet
Tracking Detector
Beam Pipe
Neutron
Photon
Electron
π^+ or Proton
Muon


Decay
Hadronization
Parton Shower
Hard SubProcess
Parton Distributions
Minimum Bias Collisions
$f(x,Q^2)$
$f(x,Q^2)$

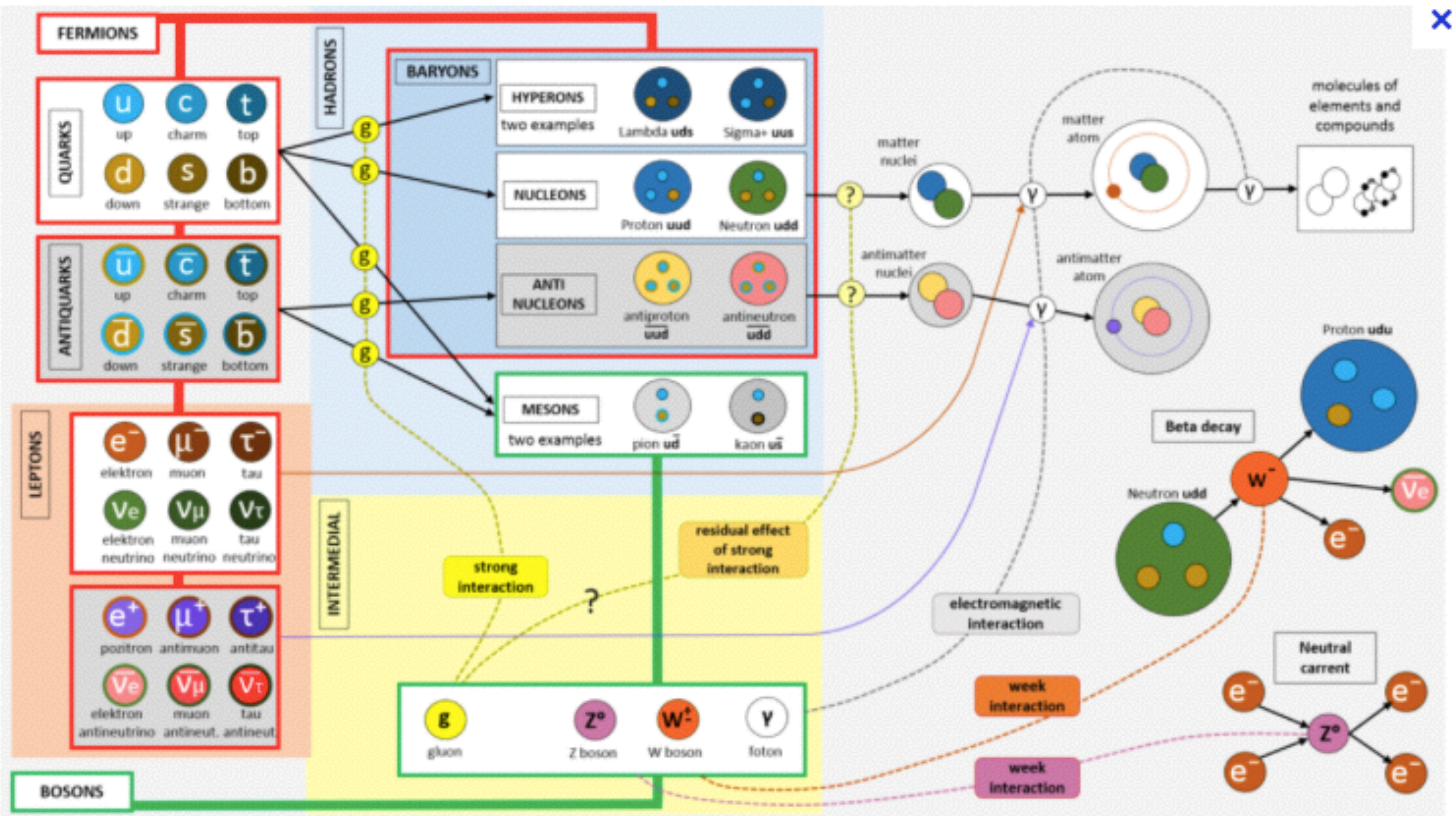

Tracking chamber
Electromagnetic calorimeter
Hadron calorimeter
Muon chamber
photons
e±
muons
$\pi^\pm$, p
n
Innermost Layer...
...Outermost Layer



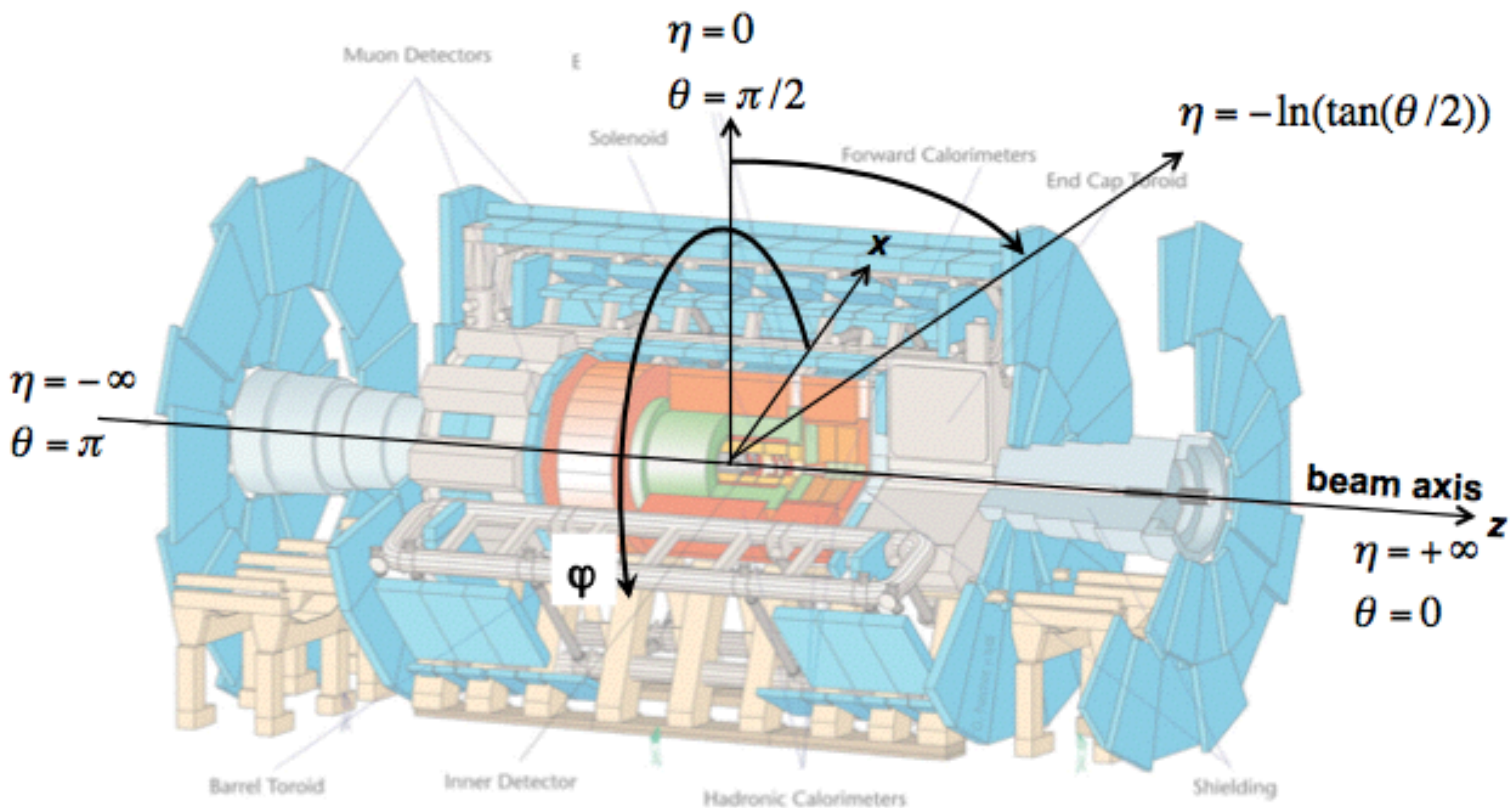
Trigger
Data Acquisition
High-Level Trigger
~200 Hz
4 s
Event Filter
~3 kHz
40 ms
LEVEL 2
2.2 μs
LEVEL 1
75 kHz
Central Trigger Processor
L1Calo
L1Muon
40 MHz
Data Flow
Sub-Farm Output
Event Filter Network
Sub-Farm Input
Event Builder
ROI Requests
ROI Information
Data Collection Network
Read-Out System
Read-Out Drivers
Front-End Boards
Detector Read-Out
Front-End Boards
CERN Data Storage
(~1.6 MB/event)



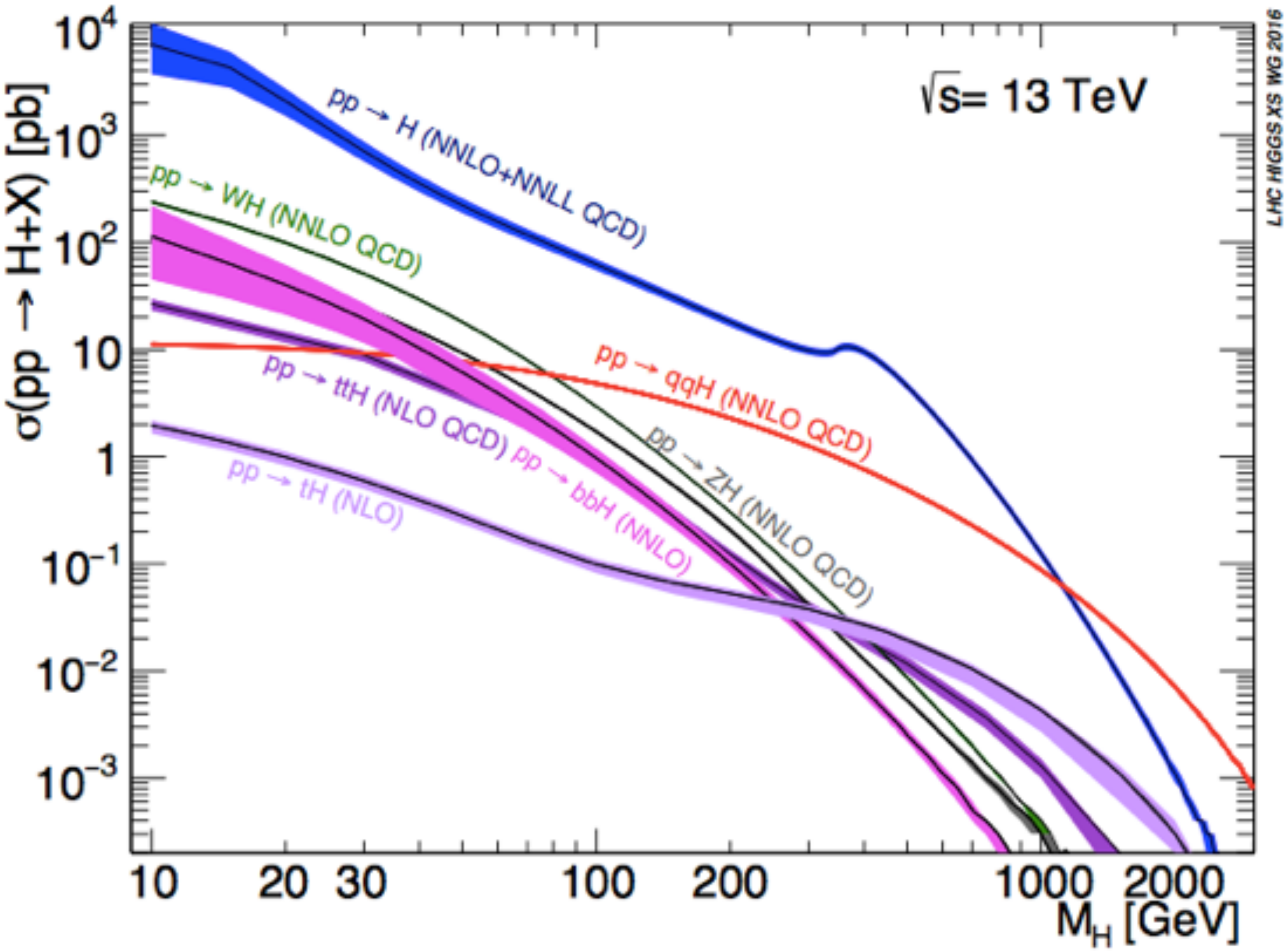
13 TeV LHC parton kinematics
WJS2013
$x_{1,2} = (M/13\ \text{TeV})\ \exp(\pm y)$
Q = M
M = 10 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = 6 4 2 0 2 4 6
HERA
fixed target
Q^2 (GeV^2)
x



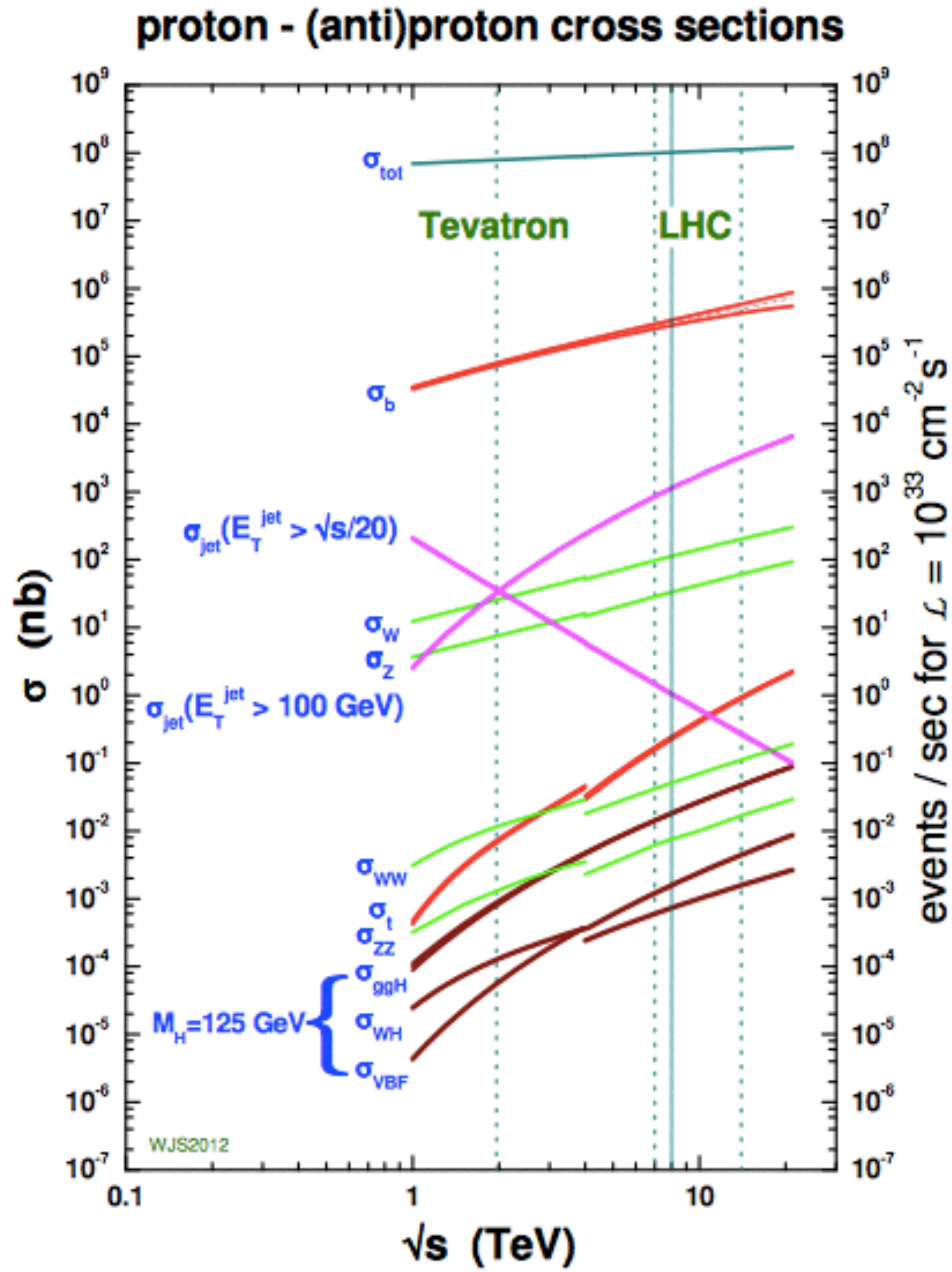
FERMIONS
QUARKS
up
charm
top
down
strange
bottom
ANTIQUARKS
up
charm
top
down
strange
bottom
LEPTONS
elektron
muon
tau
elektron neutrino
muon neutrino
tau neutrino
pozitron
antimuon
antitau
elektron antineutrino
muon antineut.
tau antineut.
BOSONS
HADRONS
BARYONS
HYPERONS
two examples
Lambda uds
Sigma+ uus
NUCLEONS
Proton uud
Neutron udd
ANTI NUCLEONS
antiproton
antineutron
MESONS
two examples
pion
kaon
INTERMEDIAL
strong interaction
residual effect of strong interaction
?
gluon
Z boson
W boson
foton
matter nuclei
antimatter nuclei
matter atom
antimatter atom
molecules of elements and compounds
Proton udu
Beta decay
Neutron udd
electromagnetic interaction
week interaction
week interaction
Neutral current



$$\vec{p}_T = (p_x, p_y) \qquad p_T = p\sin\theta, \quad E_T = E\sin\theta \qquad \vec{E}_T^{miss} = -\sum_{\text{clusters}\, i} E_i \hat{n}_i$$

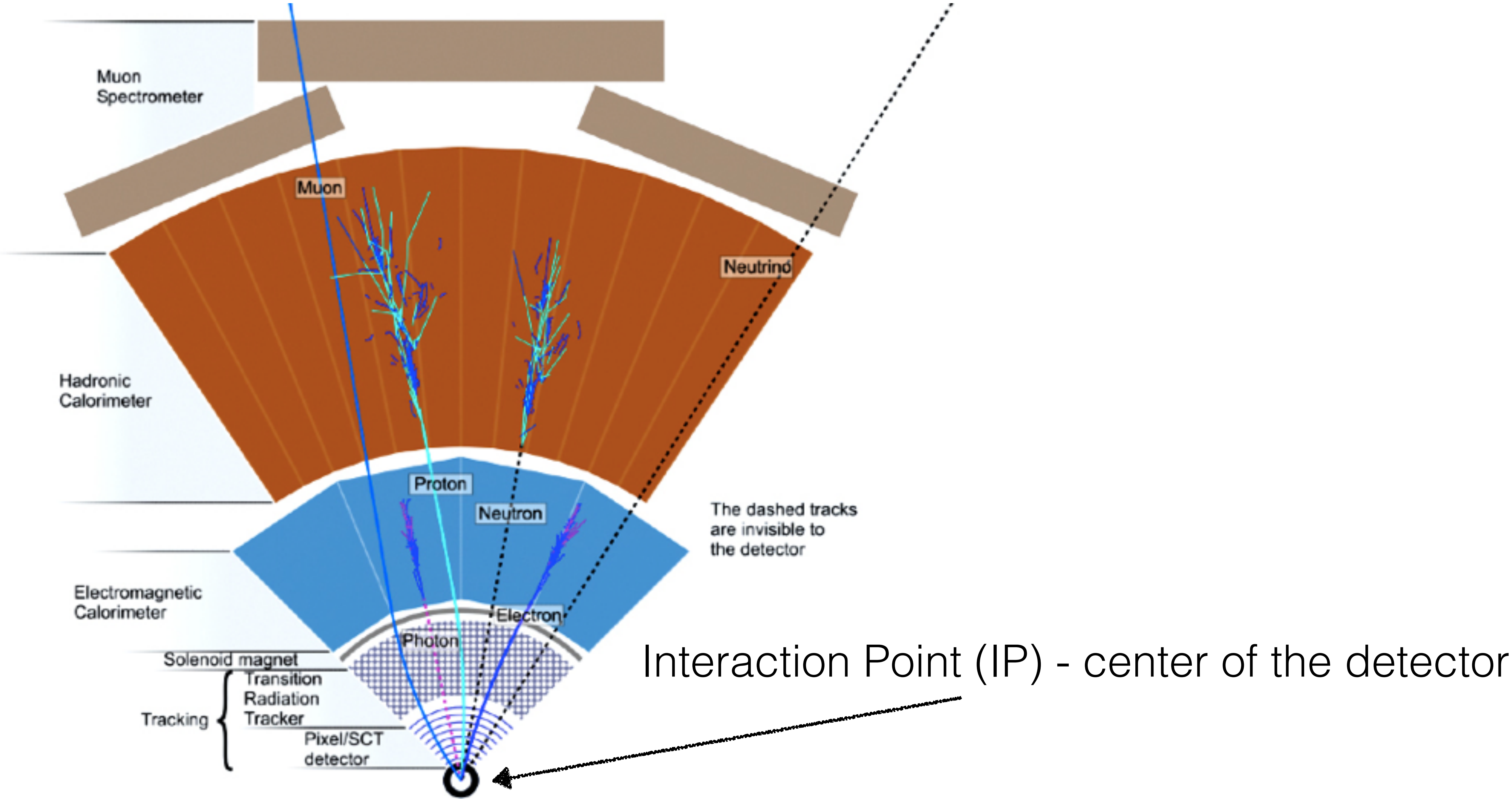


$\sqrt{s}$= 13 TeV
LHC HIGGS XS WG 2016
pp → H (NNLO+NNLL QCD)
pp → WH (NNLO QCD)
pp → qqH (NNLO QCD)
pp → ttH (NLO QCD)
pp → bbH (NNLO)
pp → ZH (NNLO QCD)
pp → tH (NLO)
σ(pp → H+X) [pb]
M_H [GeV]



proton - (anti)proton cross sections
Tevatron
LHC
σ_{tot}
σ_b
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/20)$
σ_W
σ_Z
$\sigma_{jet}(E_T^{jet} > 100$ GeV)
σ_{WW}
σ_t
σ_{ZZ}
M_H=125 GeV
σ_{ggH}
σ_{WH}
σ_{VBF}
WJS2012
σ (nb)
$\sqrt{s}$ (TeV)
events / sec for $\mathcal{L} = 10^{33}$ $cm^{-2}s^{-1}$

ATLAS Overview



Each detector has a different role and all of the detectors are required to be fully operational to ensure the highest performance (e.g. having no readout from the electromagnetic calorimeter will prevent us from studying electrons and photons)

Signal uncertainties and statistical procedure

Uncertainties related to the modelling of the signal component in the fit

Uncertainty	Spin-2 search	Spin-0 search
Signal mass resolution (mass dependent)	${}^{+(30-60)}_{-(20-40)}\%$	${}^{+(40-60)}_{-(30-45)}\%$
Signal photon identification (mass dependent)	$\pm(2$–$3)\%$	
Signal photon isolation (mass dependent)	$\pm(2$–$1)\%$	$\pm(4$–$1)\%$
Signal production process	N/A	$\pm(3$–$6)\%$ depending on Γ
Trigger efficiency	$\pm0.6\%$	
Luminosity	$\pm5.0\%$	

mass dependent:

- 0.5-5 TeV for spin-2
- 0.2-2 TeV for spin-0

Maximum likelihood fits of $m_{\gamma\gamma}$ distributions for:

- **(m_X,k/M_{Pl})** for spin-2
- **(m_X,α)** for spin-0 where α is Γ/m_X

Function to describe the data:

$$N_S f_S(m_{\gamma\gamma}) + N_B f_B(m_{\gamma\gamma})$$

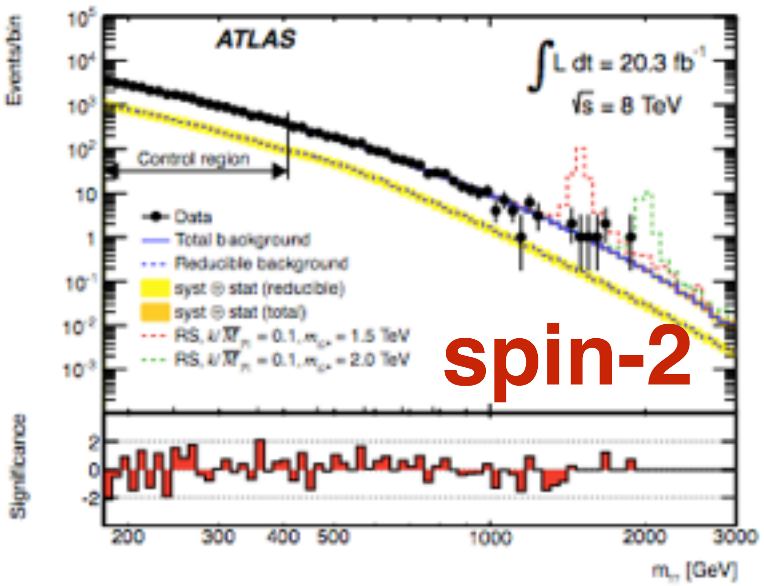
fitted number of signal and background events and normalized invariant mass distributions

p_0 for compatibility with a background-only hypothesis is calculated based on profile likelihood ratio test statistic and using asymptotic approximation

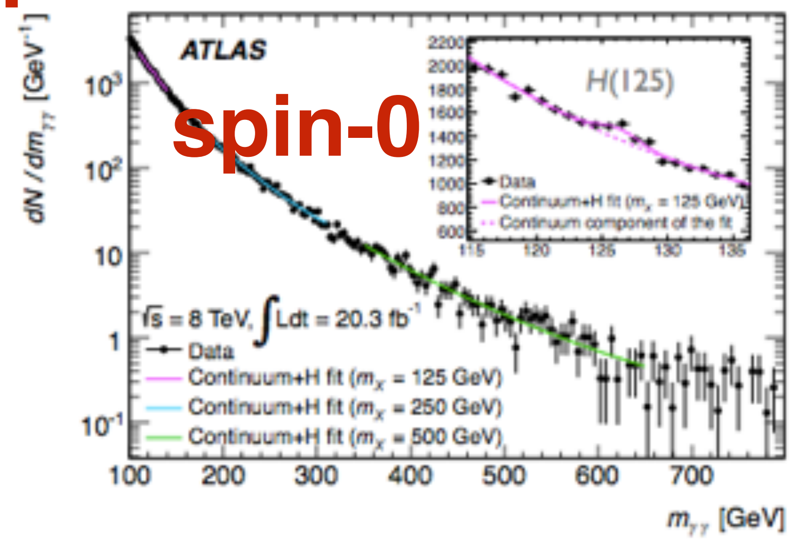
What about 8 TeV?

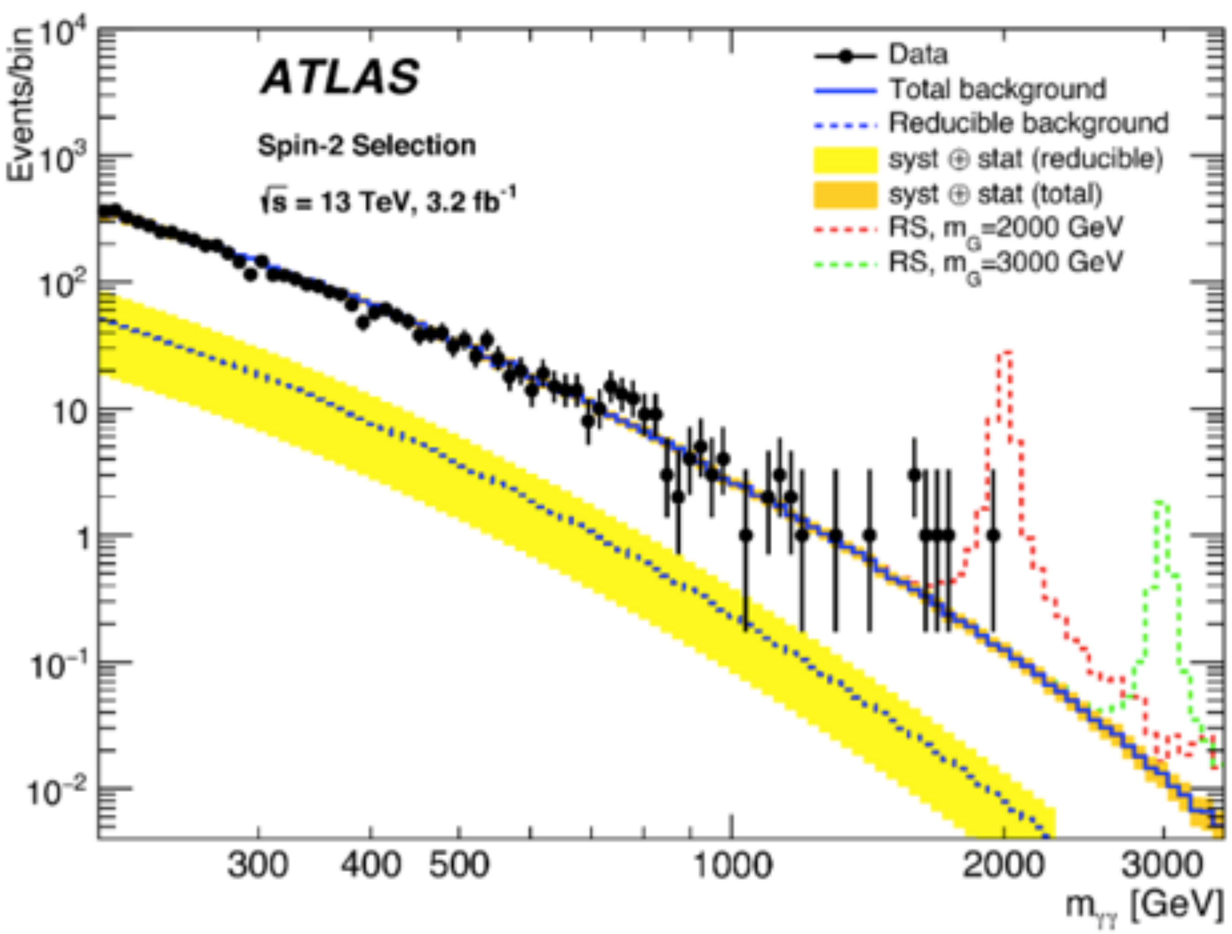
Run1

Phys. Rev. D 92, 032004 (2015)

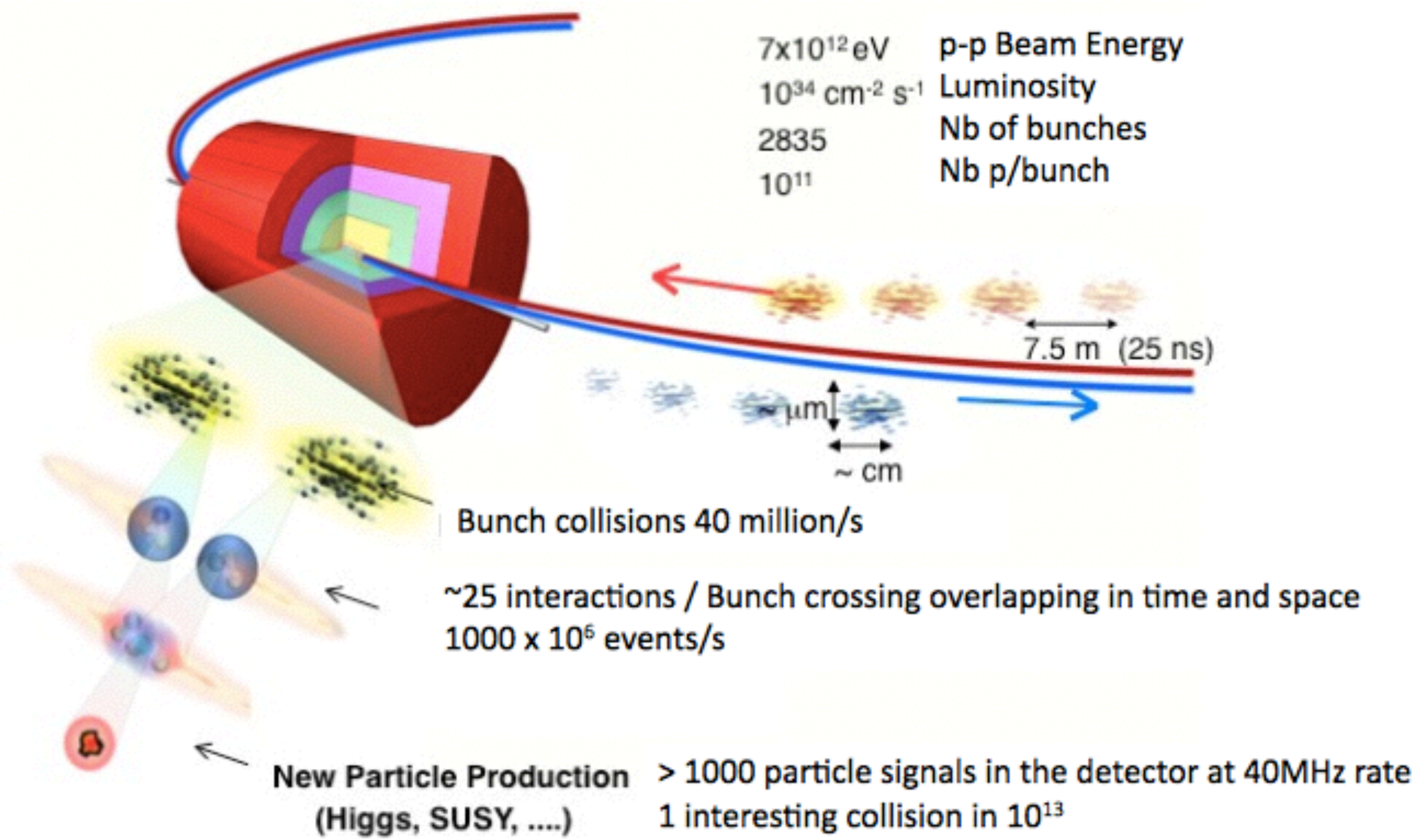


Phys. Rev. Lett. 113, 171801





LHC



7x10^12 eV p-p Beam Energy
10^34 cm-2 s-1 Luminosity
2835 Nb of bunches
10^11 Nb p/bunch
7.5 m (25 ns)
~ μm
~ cm
Bunch collisions 40 million/s
~25 interactions / Bunch crossing overlapping in time and space
1000 x 10^6 events/s
New Particle Production
(Higgs, SUSY, ...)
> 1000 particle signals in the detector at 40MHz rate
1 interesting collision in 10^13

Short Statistics Explanation

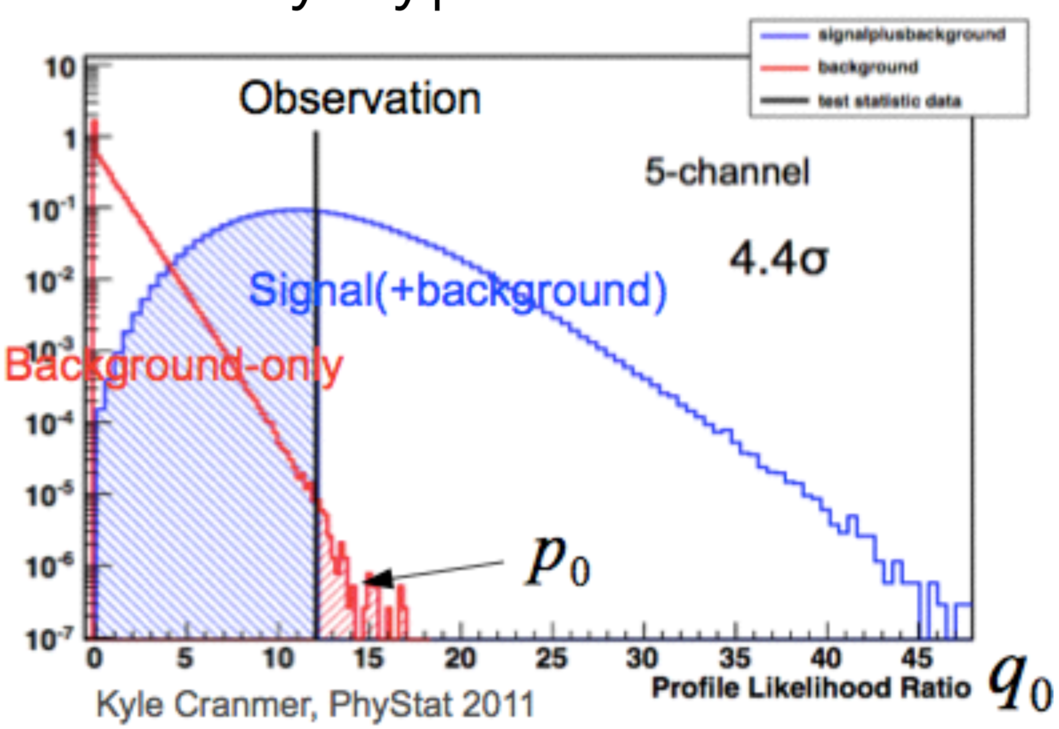
The common approach is to build a likelihood model including all the parameters of your analysis (and systematics). Maximum likelihood fit then gives you the best fit parameters describing your model given the data.

What is a p-value and why do we use it?

If we find a deviation of the data above the background-only hypothesis we need to calculate what its significance - is it a big bump or not?

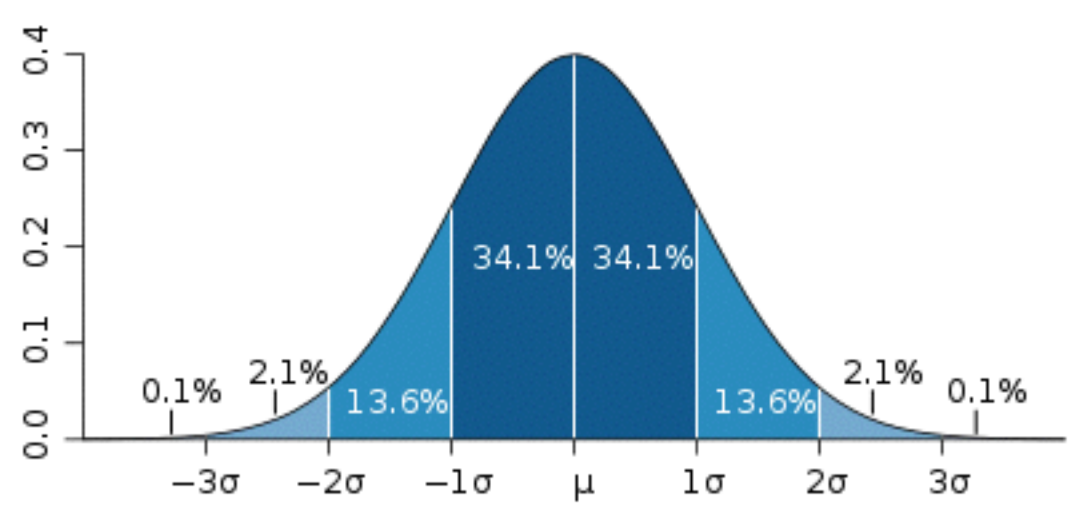
p_0-value gives us a probability that the excess in the data is a fluctuation from the background-only hypothesis.

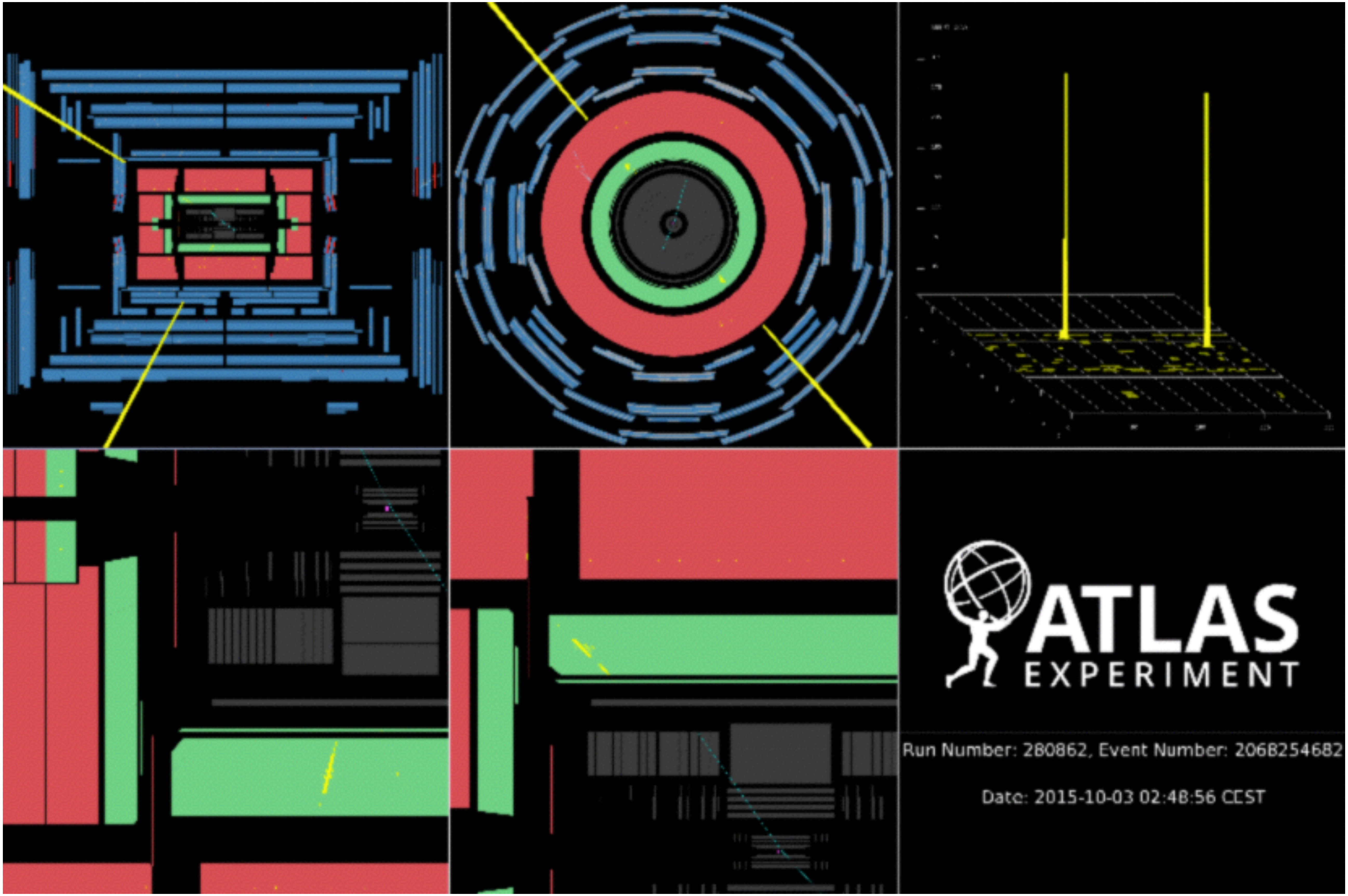
Build test statistic that compares S+B to B-only hypothesis based on the data

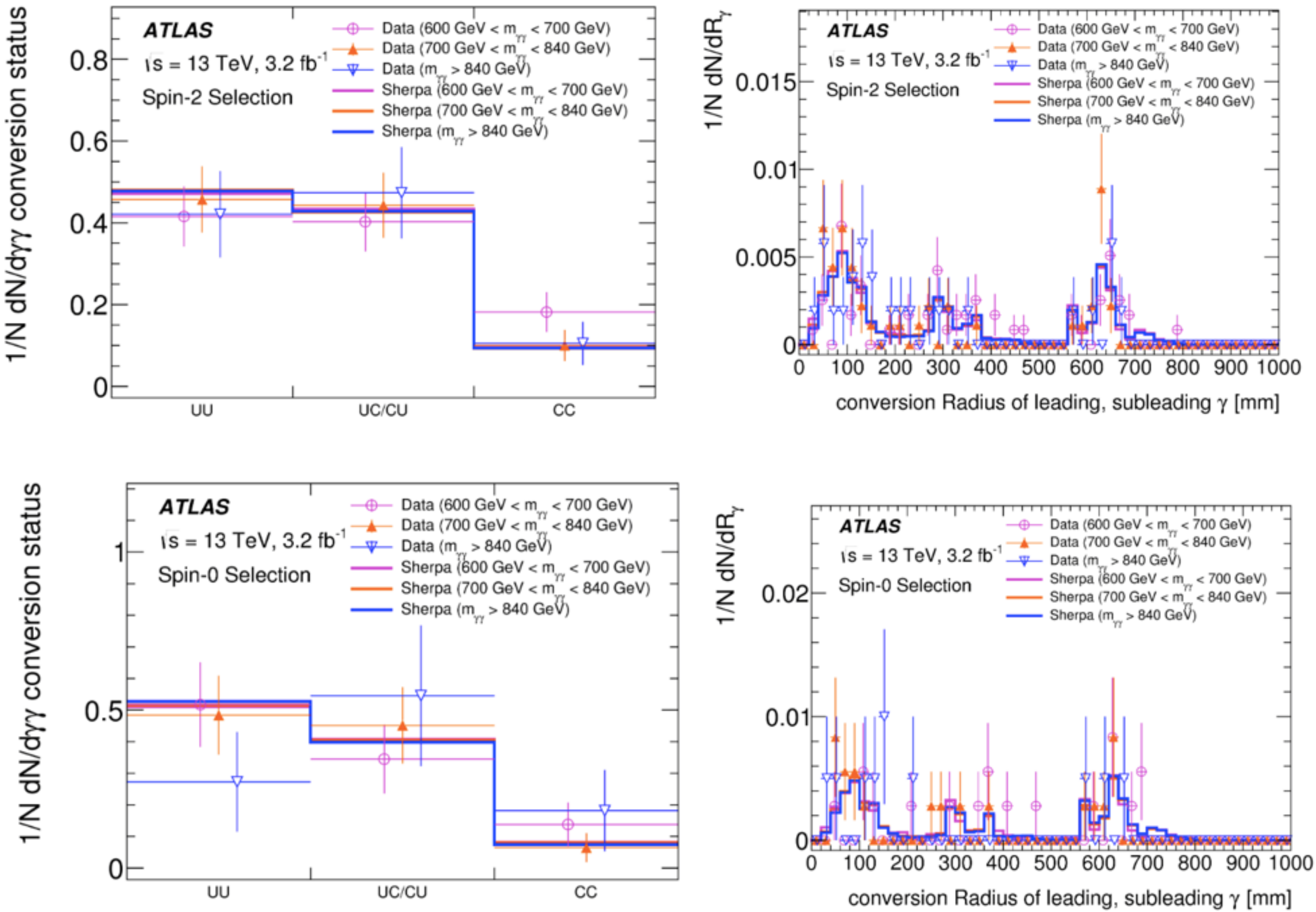


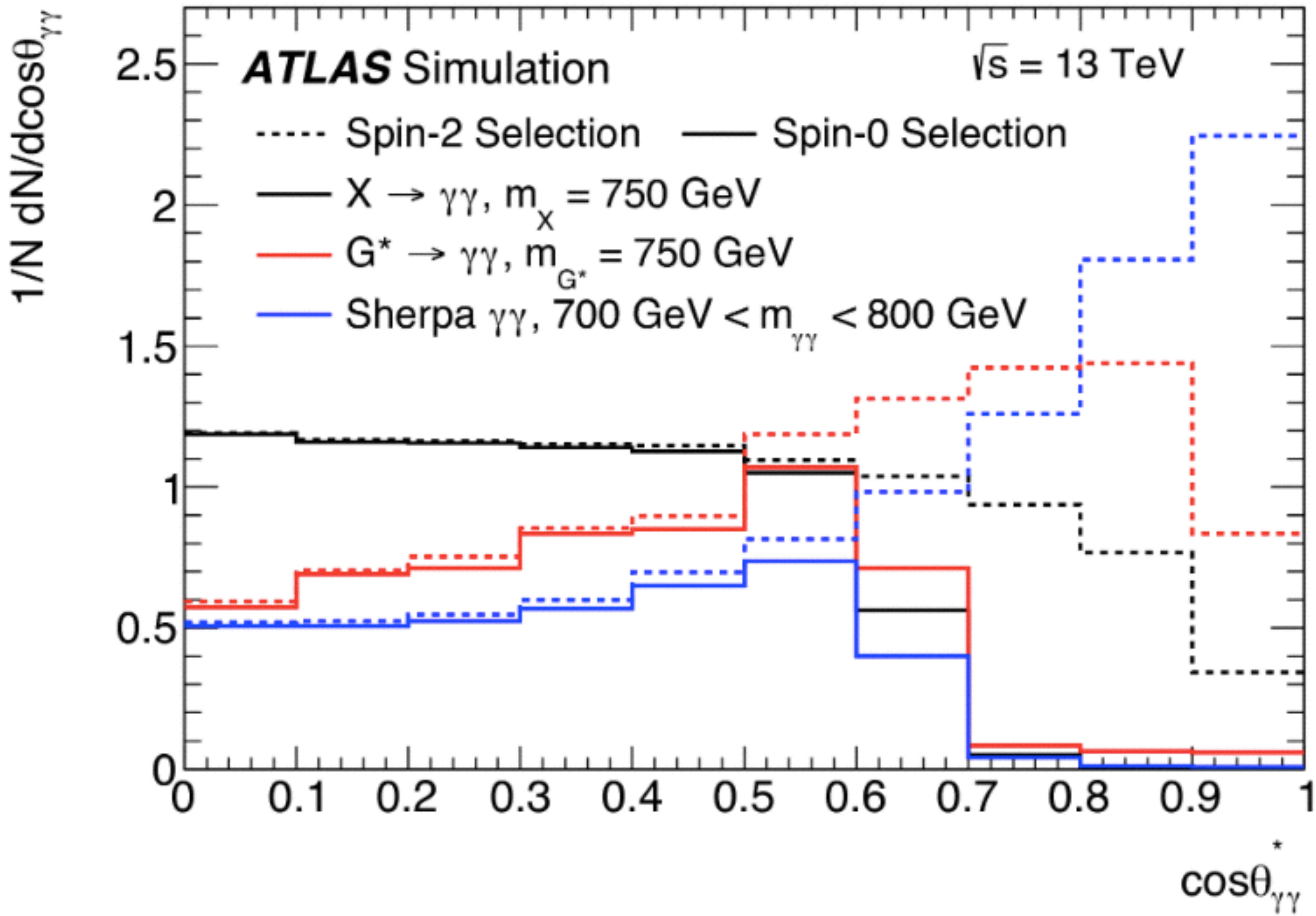
p_0 gives significance of rejecting the background-only hypothesis:

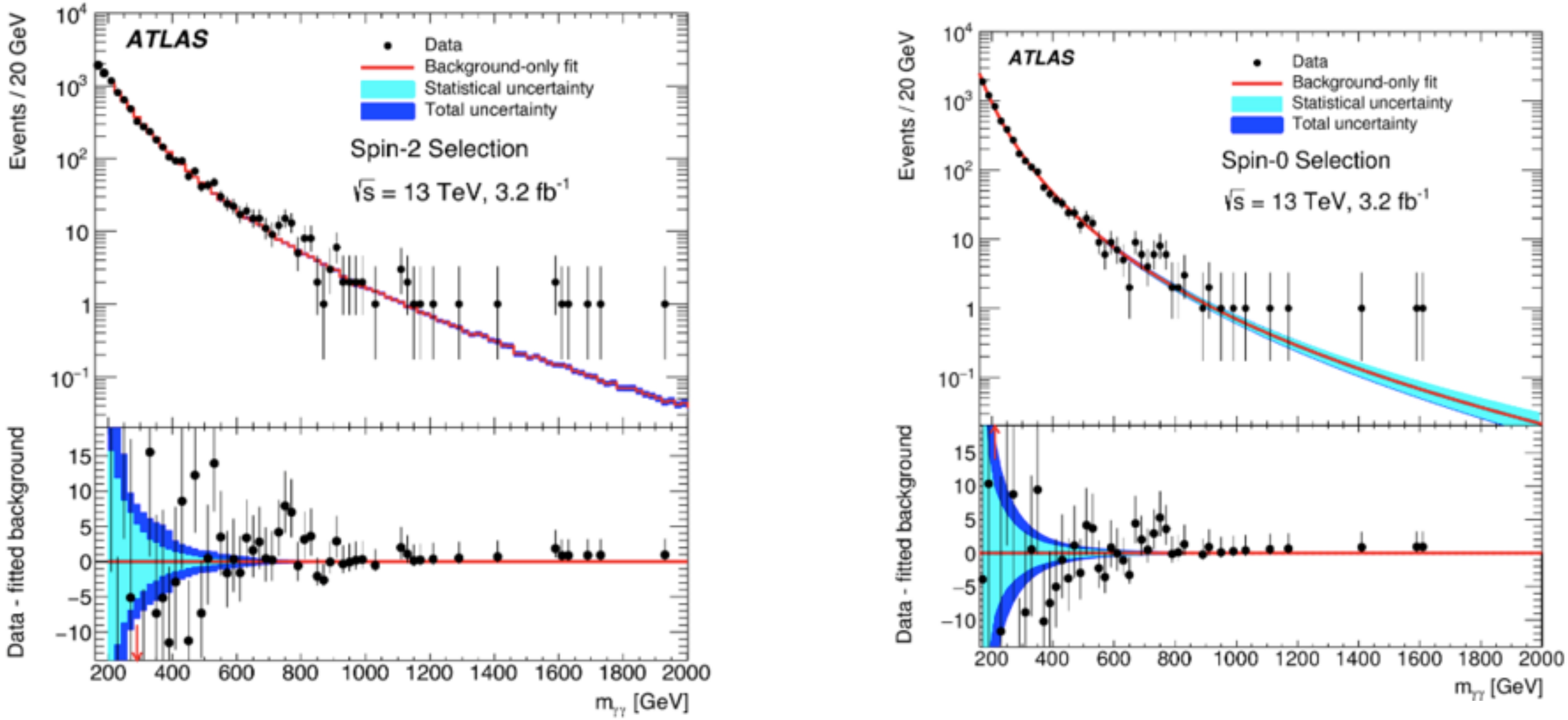
- 5σ - p_0 of 2.9×10^{-7} -1 in 3.5 million
- 3σ - p_0 of 1.3×10^{-3} -1 in 740

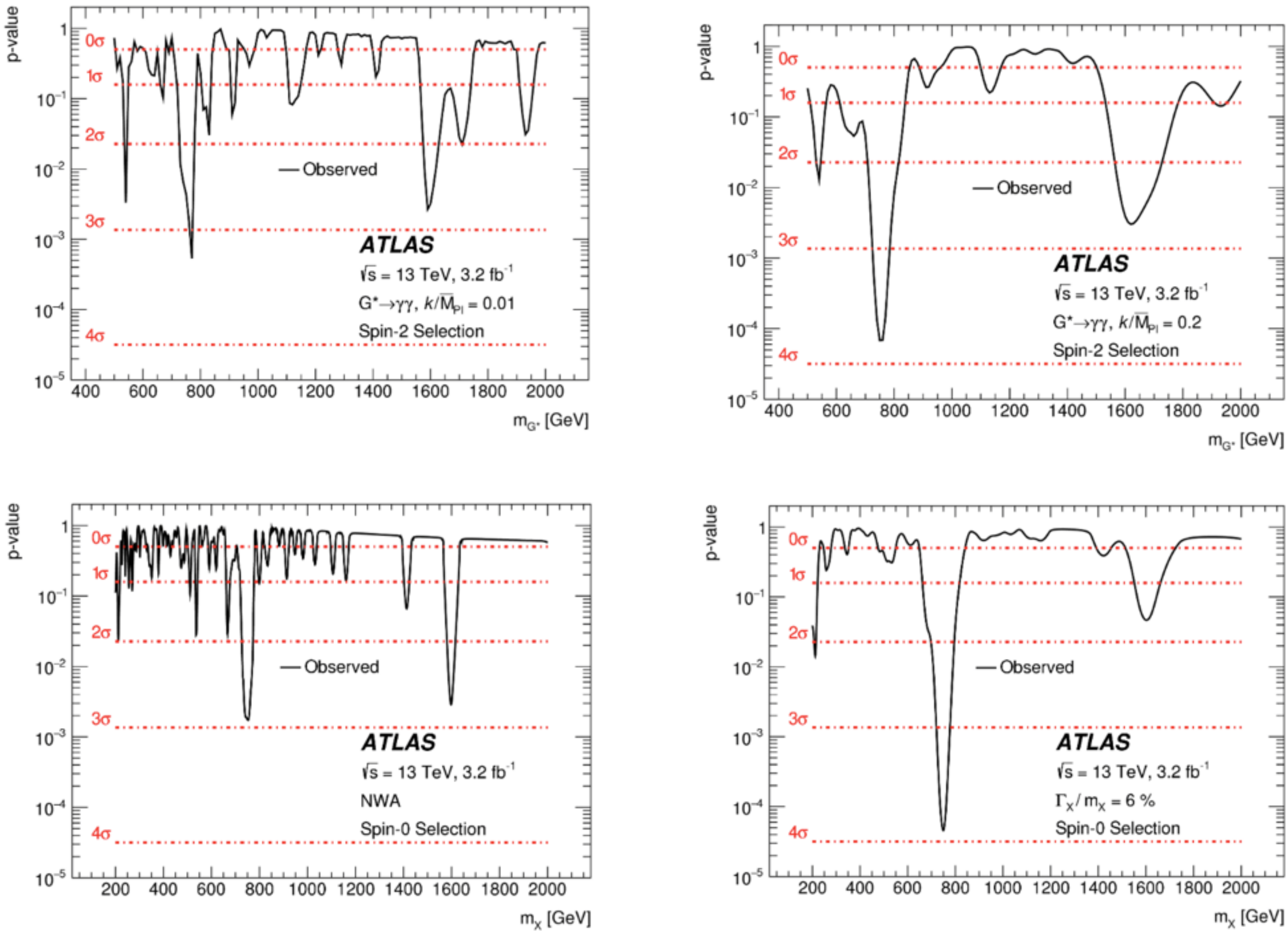



ATLAS
EXPERIMENT
Run Number: 280862, Event Number: 2068254682
Date: 2015-10-03 02:48:56 CEST


ATLAS
√s = 13 TeV, 3.2 fb-1
Spin-2 Selection
Data (600 GeV < mγγ < 700 GeV)
Data (700 GeV < mγγ < 840 GeV)
Data (mγγ > 840 GeV)
Sherpa (600 GeV < mγγ < 700 GeV)
Sherpa (700 GeV < mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dγγ conversion status
UU
UC/CU
CC
1/N dN/dRγ
conversion Radius of leading, subleading γ [mm]
Spin-0 Selection


ATLAS Simulation
$\sqrt{s}$ = 13 TeV
Spin-2 Selection
Spin-0 Selection
$X \rightarrow \gamma\gamma$, m_X = 750 GeV
$G^* \rightarrow \gamma\gamma$, m_{G^*} = 750 GeV
Sherpa $\gamma\gamma$, 700 GeV < $m_{\gamma\gamma}$ < 800 GeV
$1/N\, dN/d\cos\theta^*_{\gamma\gamma}$
$\cos\theta^*_{\gamma\gamma}$
0
0.5
1
1.5
2
2.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


ATLAS
Data
Background-only fit
Statistical uncertainty
Total uncertainty
Spin-2 Selection
√s = 13 TeV, 3.2 fb-1
Events / 20 GeV
Data - fitted background
m γγ [GeV]
ATLAS
Data
Background-only fit
Statistical uncertainty
Total uncertainty
Spin-0 Selection
√s = 13 TeV, 3.2 fb-1
Events / 20 GeV
Data - fitted background
m γγ [GeV]


p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0σ
1σ
2σ
3σ
4σ
Observed
ATLAS
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
$G^* \to \gamma\gamma$, $k/\overline{M}_{Pl}$ = 0.01
Spin-2 Selection
400 600 800 1000 1200 1400 1600 1800 2000
m_{G^*} [GeV]
p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0σ
1σ
2σ
3σ
4σ
Observed
ATLAS
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
$G^* \to \gamma\gamma$, $k/\overline{M}_{Pl}$ = 0.2
Spin-2 Selection
400 600 800 1000 1200 1400 1600 1800 2000
m_{G^*} [GeV]
p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0σ
1σ
2σ
3σ
4σ
Observed
ATLAS
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
NWA
Spin-0 Selection
200 400 600 800 1000 1200 1400 1600 1800 2000
m_X [GeV]
p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0σ
1σ
2σ
3σ
4σ
Observed
ATLAS
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
Γ_X / m_X = 6 %
Spin-0 Selection
200 400 600 800 1000 1200 1400 1600 1800 2000
m_X [GeV]