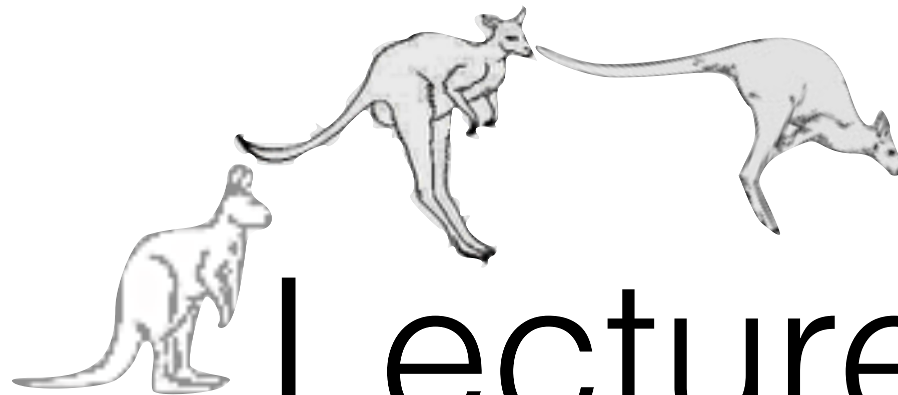


Lecture 1:

The Rise and Fall of the 750 DiPhoton

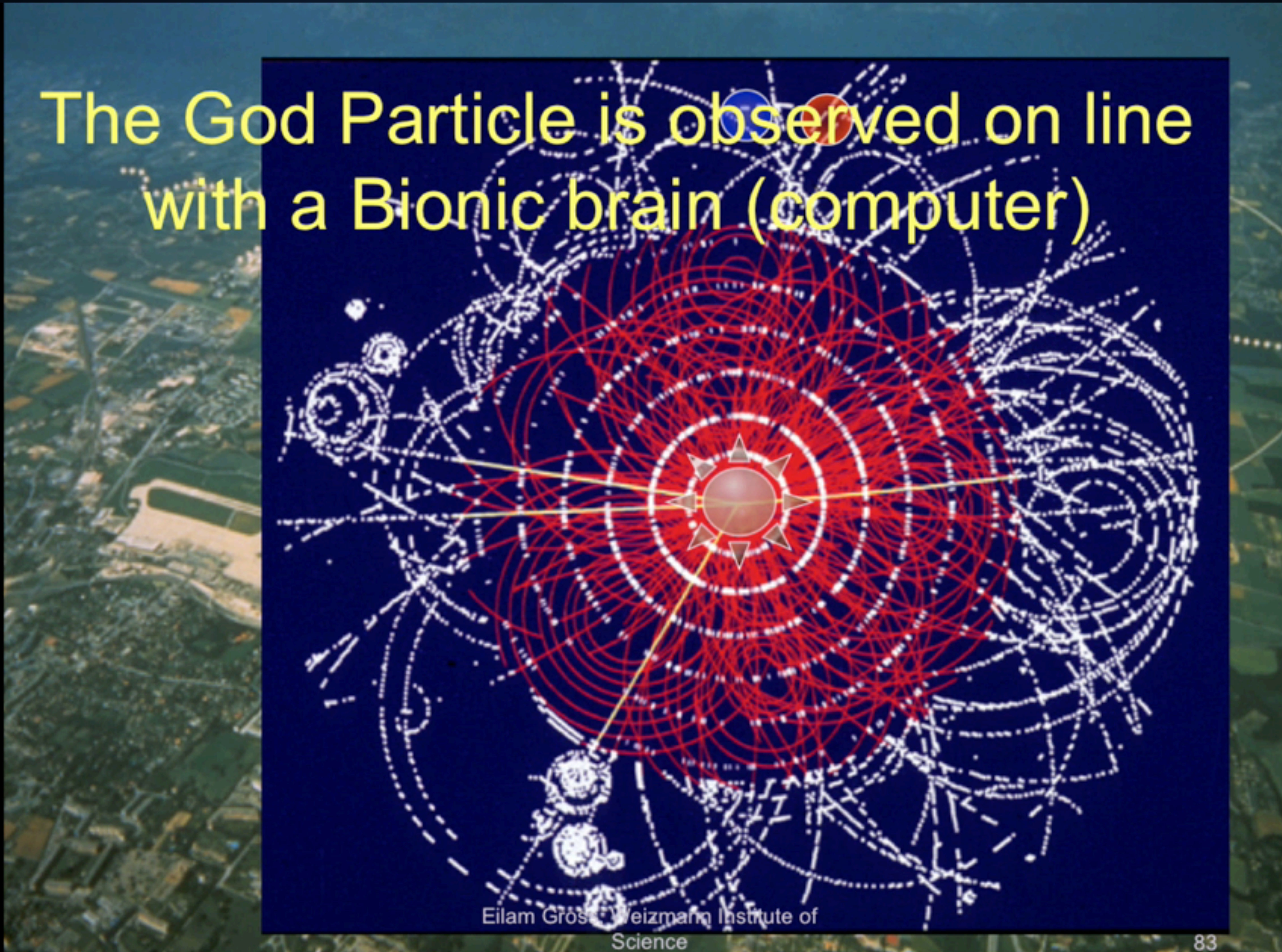
A case study of the LEE

Eilam Gross

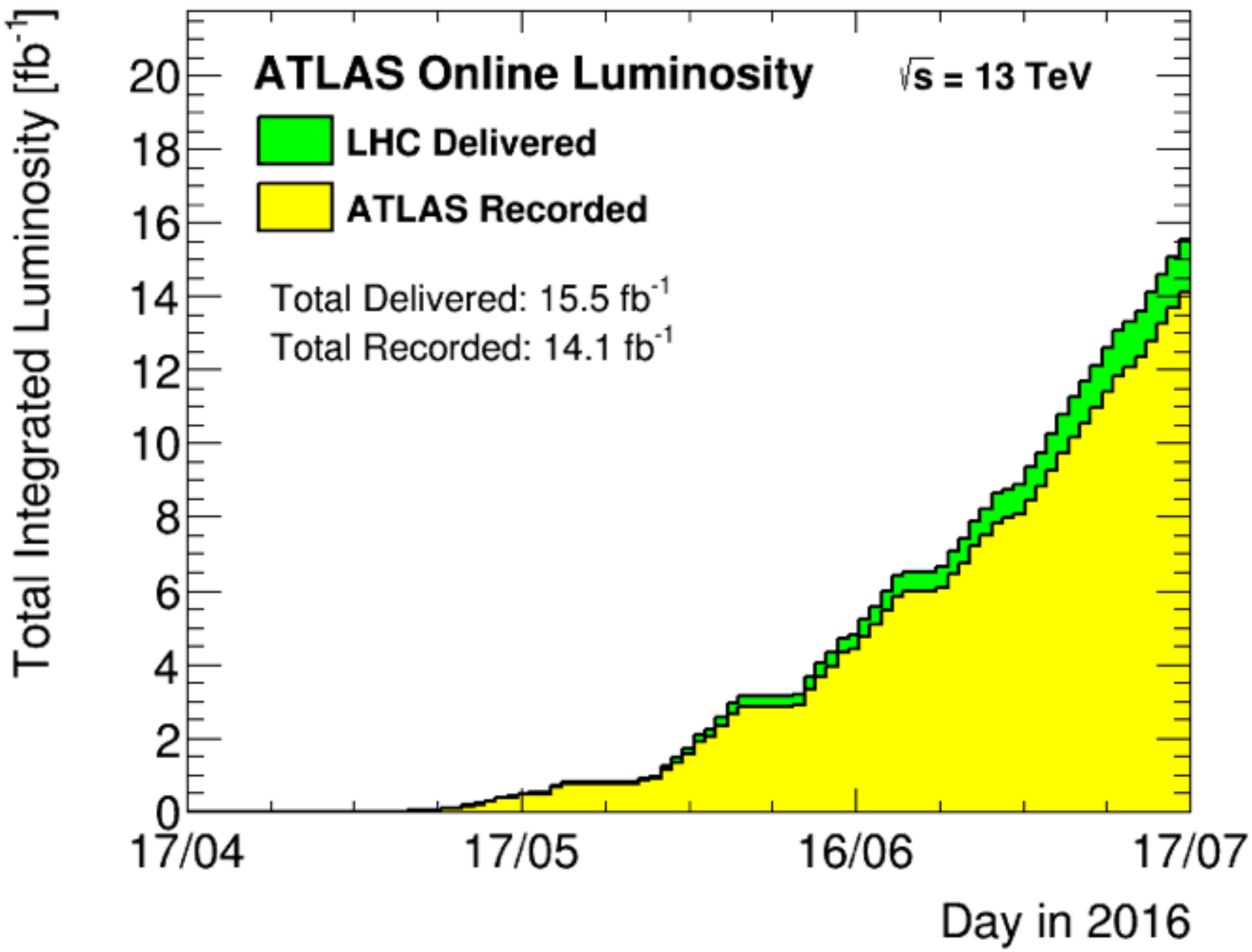
About your Lecturer

- Eilam Gross, eilam.work@gmail.com
- Prof of Particle Physics @ the Weizmann Institute of Science, Rehovot, Israel
- Member of the ATLAS collaboration @ CERN
- Main Interests :
  - DATA Analysis (statistics of HEP)
  - Higgs Physics (Standard Model and Beyond the Standard Model)

- Lecture 1:
  The rise and fall of the 750 GeV DiPhoton.
  - The LHC accelerator and ATLAS detector in a nut shell
  - Nano statistical introduction (Profile Likelihood, p-values and CLs)
- Lecture 2:
  Higgs properties (Mass, Spin, Couplings, Width)

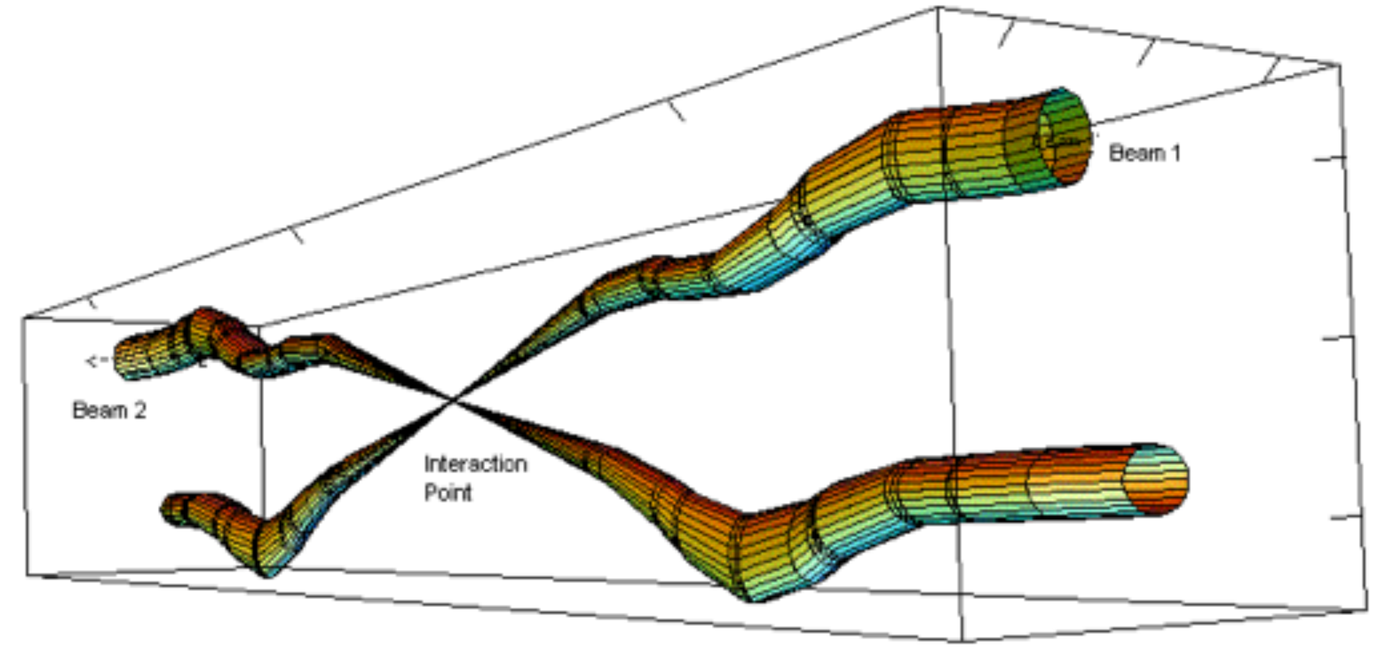

The God Particle is observed on line
with a Bionic brain (computer)
Eilam Gross, Weizmann Institute of
Science
83

$$N = L \cdot \sigma = \int \frac{dL}{dt} dt$$



LHC

- We aim to squeeze the beam size down as much as possible at the collision point to increase the chances of a collision.
- Even so… protons are very small things.
- So even though we squeeze our 100,000 million protons per bunch down to 64 microns (about the width of a human hair) at the interaction point, we get only around 20 collisions per crossing with nominal beam currents.
- The bunches cross (every 25 ns.)
- Most protons miss each other and carry on around the ring time after time. The beams are kept circulating for hours
- Total beam energy at top energy, nominal beam,2808 bunches * 1.15*1011 protons @ 13TeV each. =2808*1.15*1011*13*1012*1.602*10^{-19} Joules ~ 640 MJ per beam (eq 140 Kg TNT)



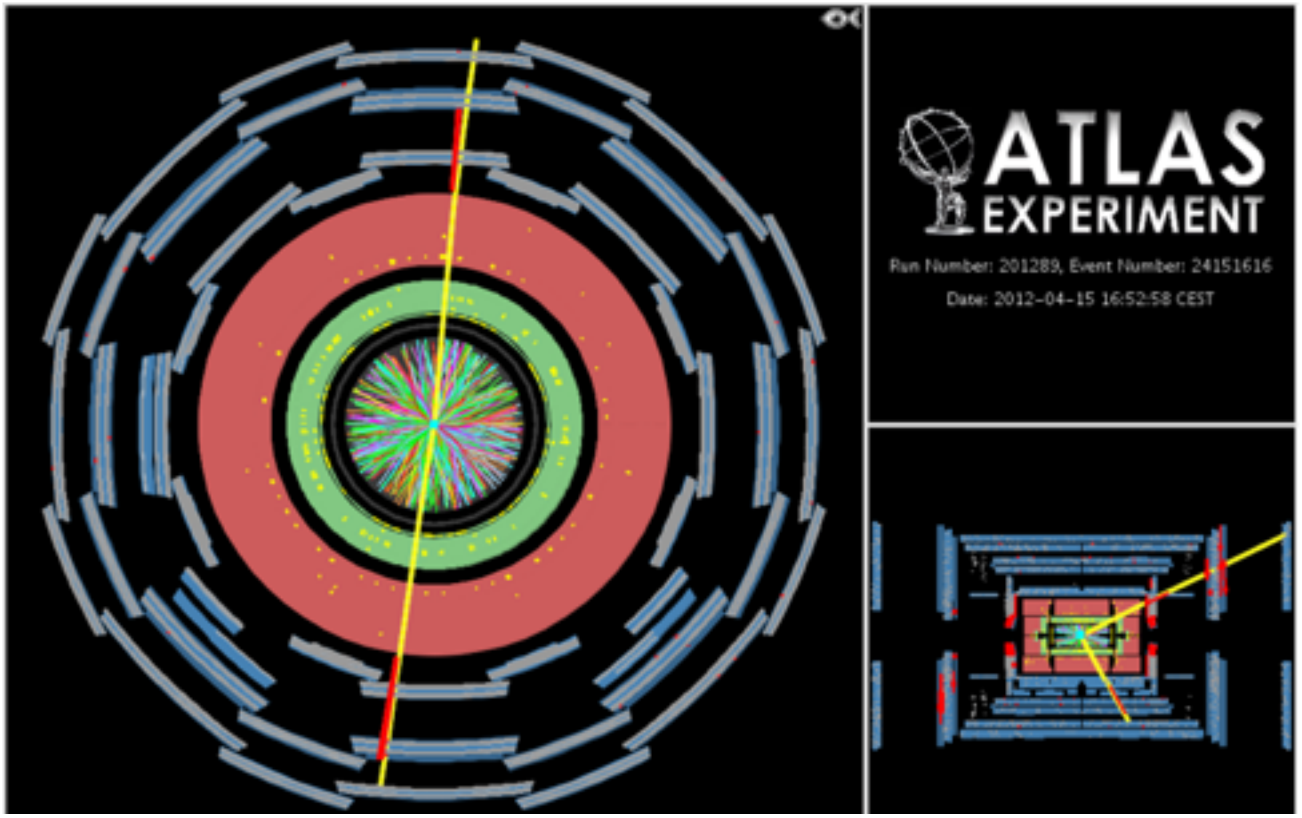
Relative beam sizes around IP1 (Atlas) in collision

- Number of event at a nominal luminosity is

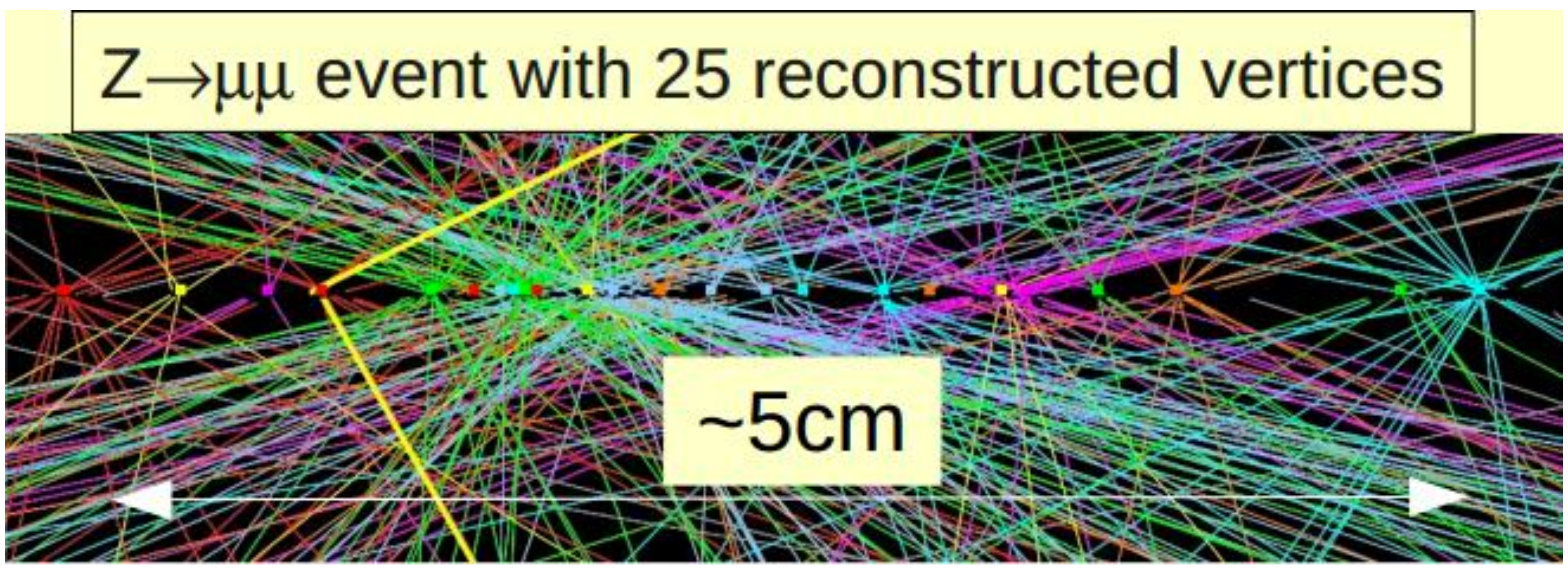
$$N_{total} = \frac{L \cdot \sigma_{inel}}{f_{revol}} = \frac{10nb^{-1}sec^{-1} \cdot 80mb}{11245\,\sec^{-1}} = 71{,}142$$

Pileup

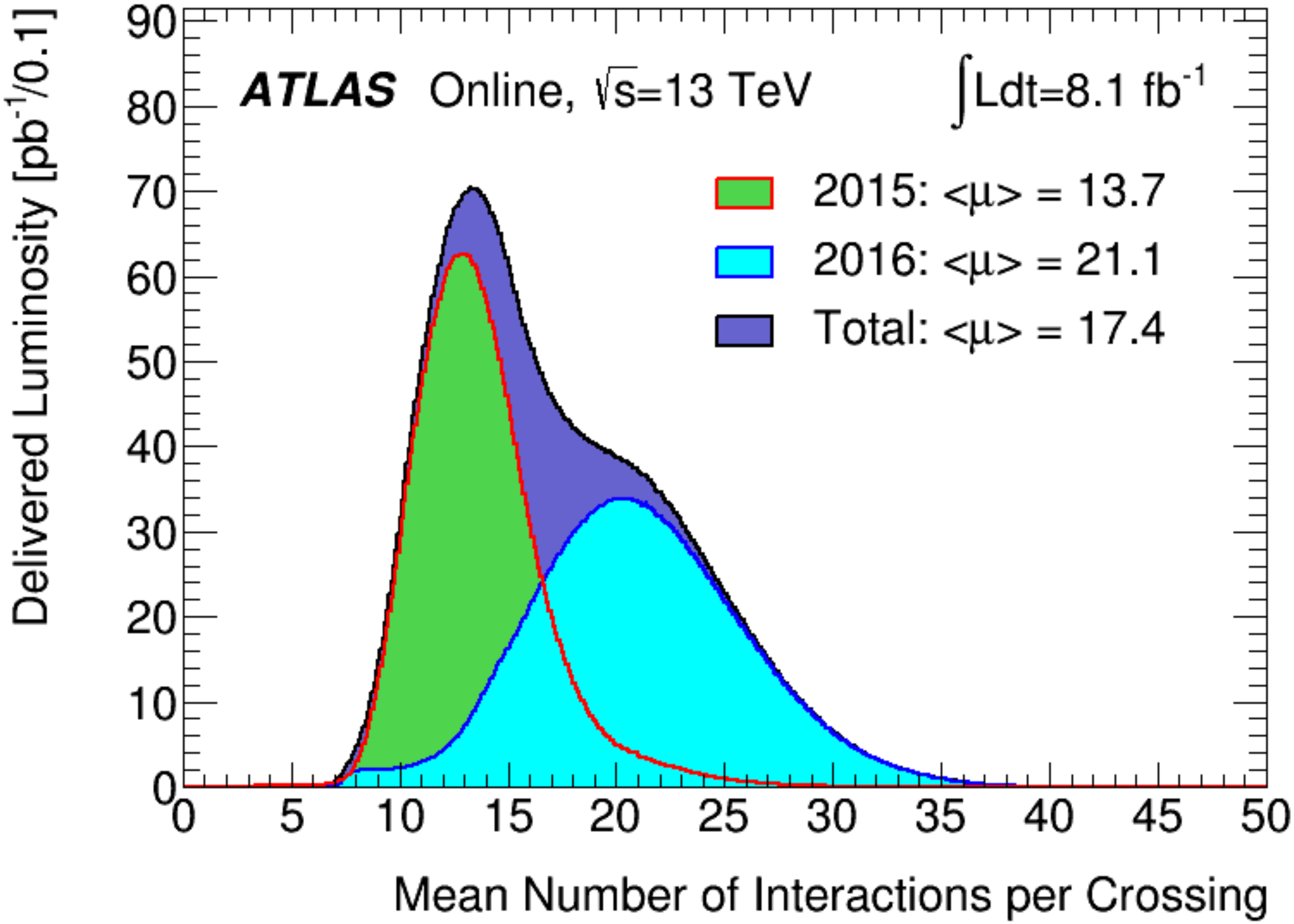
$$\mu = \frac{N_{total}}{n_{bunches}} = \frac{71142}{2808} = 25$$



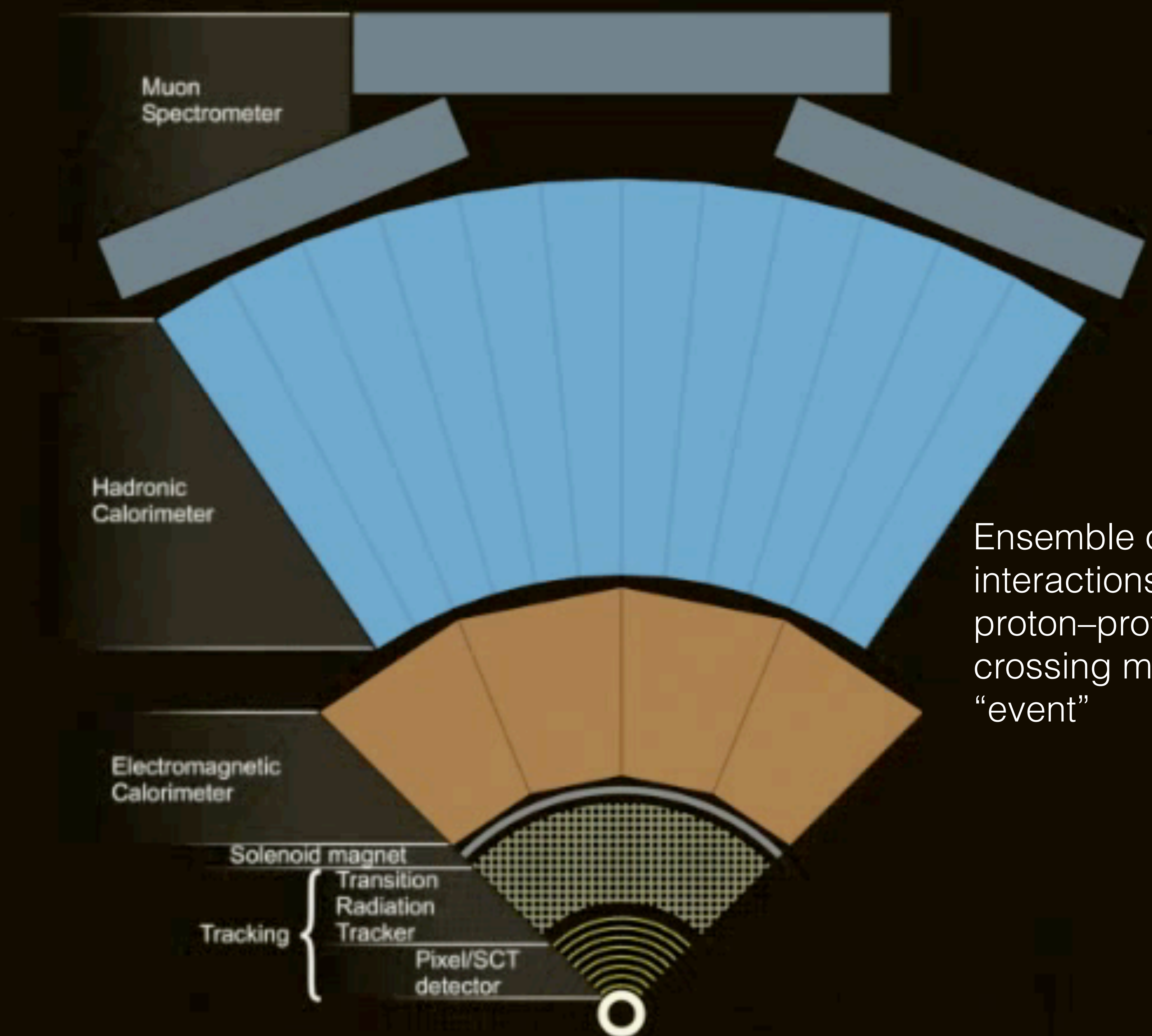
- Pileup is the average number of pp interactions in an event
- It depends on the instantaneous luminosity & the number of bunches
  - Average of 21 (peak: 40) interactions per crossing in 2012. Similar in 2016. LHC design value:



- Most analyses quite insensitive to pileup at this rate, several mitigation methods used
- However: higher trigger thresholds → low-p_T physics suffers

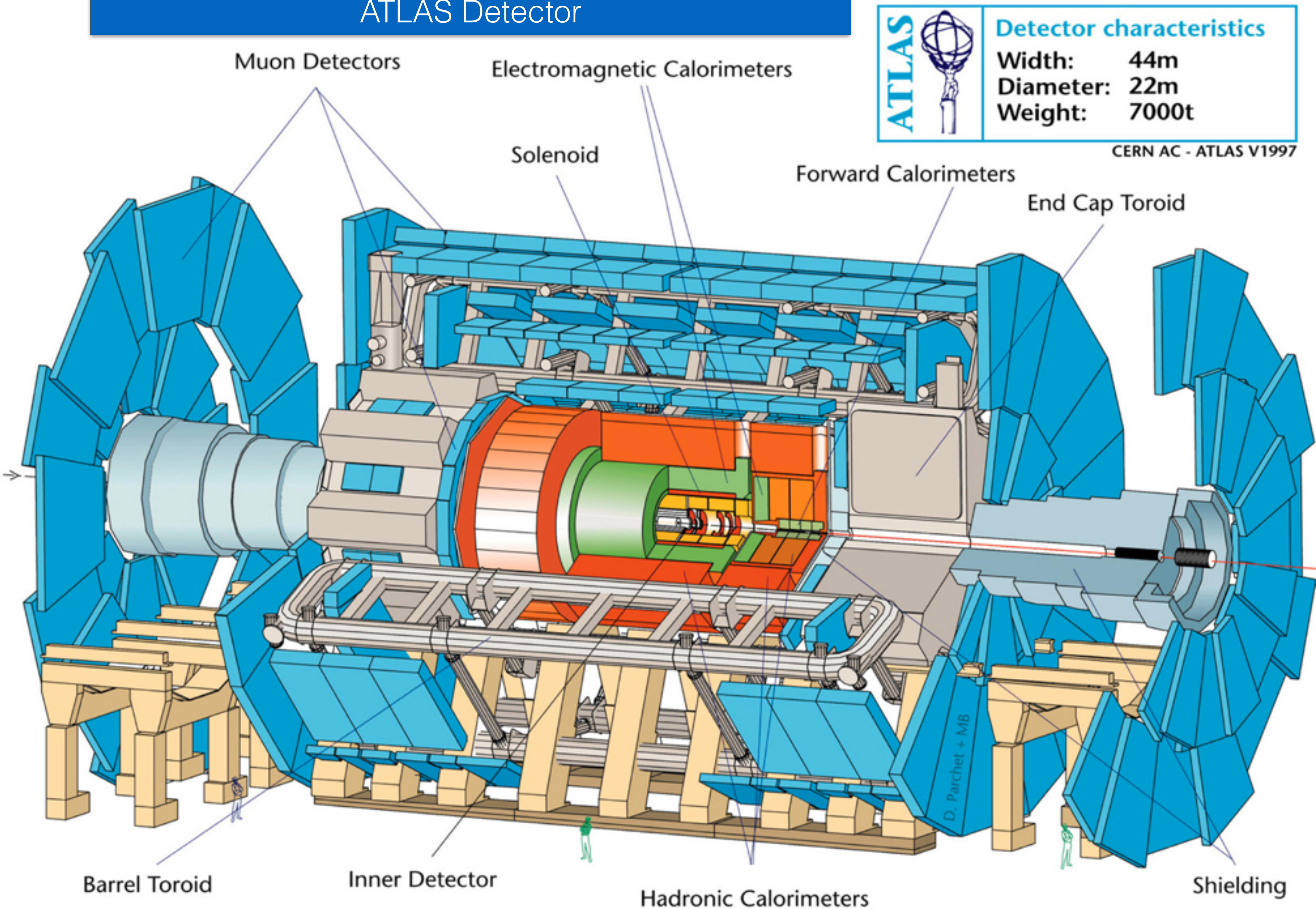

ATLAS Online, $\sqrt{s}$=13 TeV
$\int$Ldt=8.1 fb^{-1}
2015: <μ> = 13.7
2016: <μ> = 21.1
Total: <μ> = 17.4
Delivered Luminosity [pb^{-1}/0.1]
Mean Number of Interactions per Crossing
0
10
20
30
40
50
60
70
80
90
0
5
10
15
20
25
30
35
40
45
50

Generic Detector



Ensemble of measured interactions in a given proton–proton bunch crossing makes up an "event"

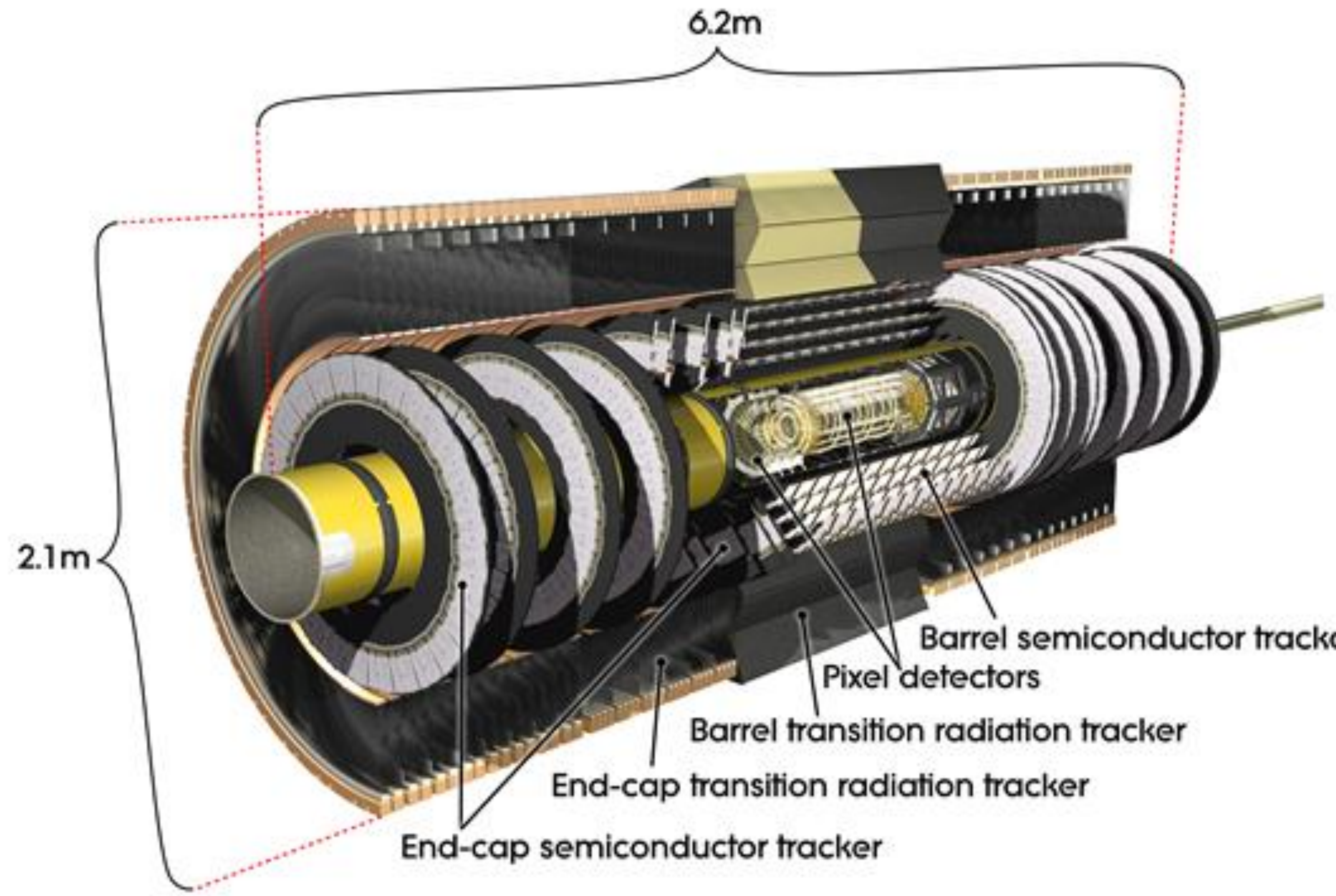
ATLAS Detector



Inner Detector

- The inner detector is the first part of ATLAS to see the decay products of the collisions

- The Inner Detector measures the direction, momentum, and charge of electrically-charged particles produced in each proton-proton collision.



- Pixel Detector
  80 Million pixels

- Semiconductor Tracker (SCT)
  A silicon microstrip tracker , 6 Million channels

- Transition Radiation Tracker (TRT).
  Can help in ID of pions vs electrons vs photons

  Made of gas tubes with straws.
  350,000 read-out channels.

Electromagnetic Calorimeter

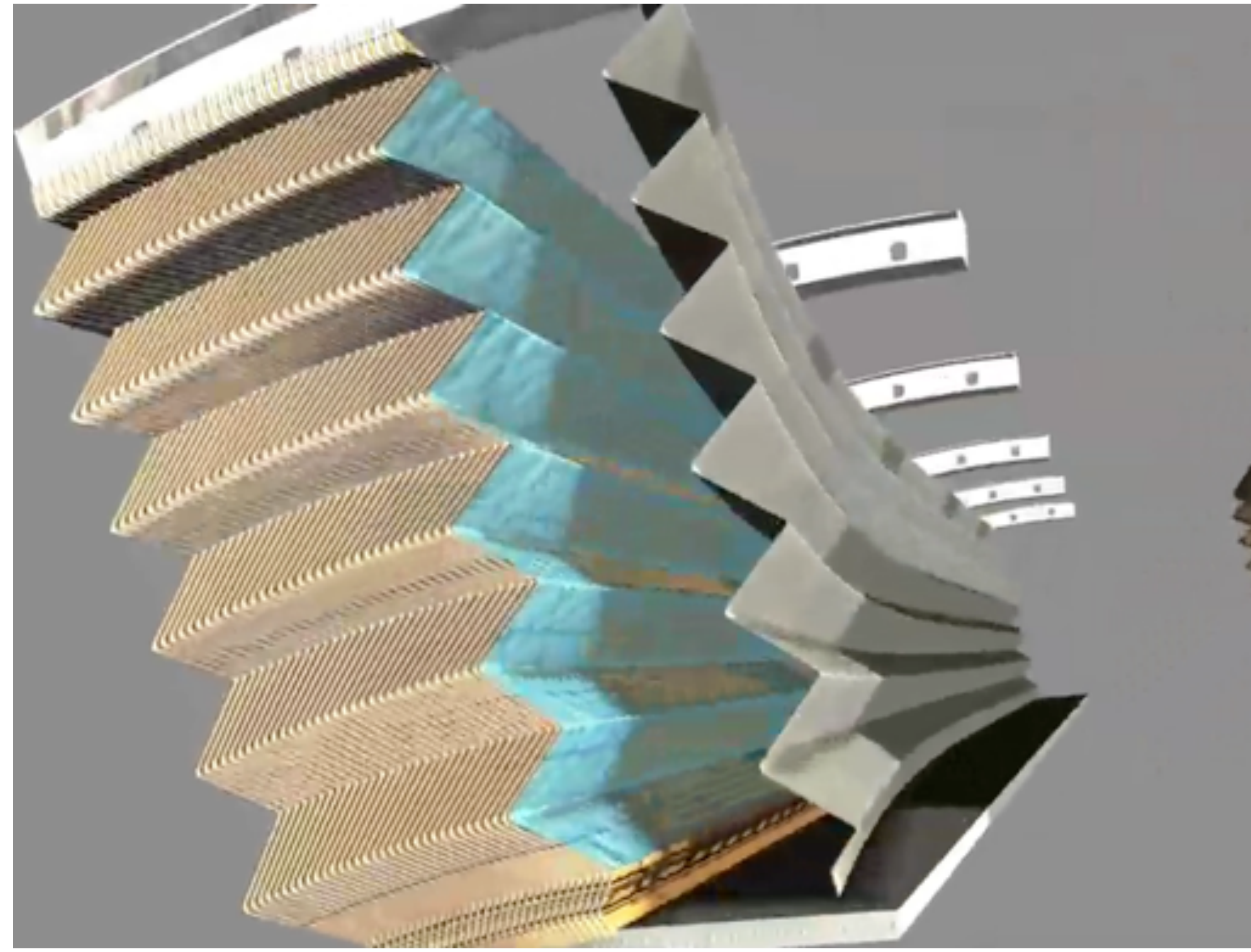
- Calorimeters measure the energy a particle loses as it passes through the detector. It is usually designed to stop entire or “absorb” most of the particles coming from a collision, forcing them to deposit all of their energy within the detector.

- Accordion shaped layers made of layers of lead and stainless steel (particle absorbers)

- Between LAr,
  -172 centigrade

- The electrons (phtons) build up showers proportional to their energy

- Calorimeters can stop most known particles except muons and neutrinos.



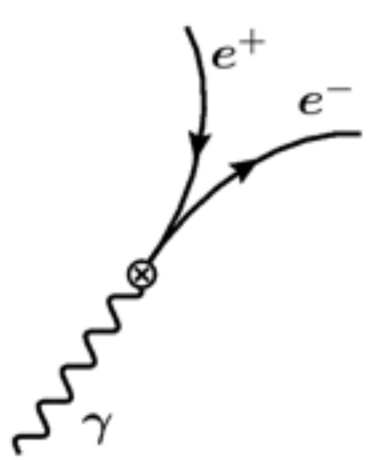
- Barrel 6.4m long, 110,000 channels.

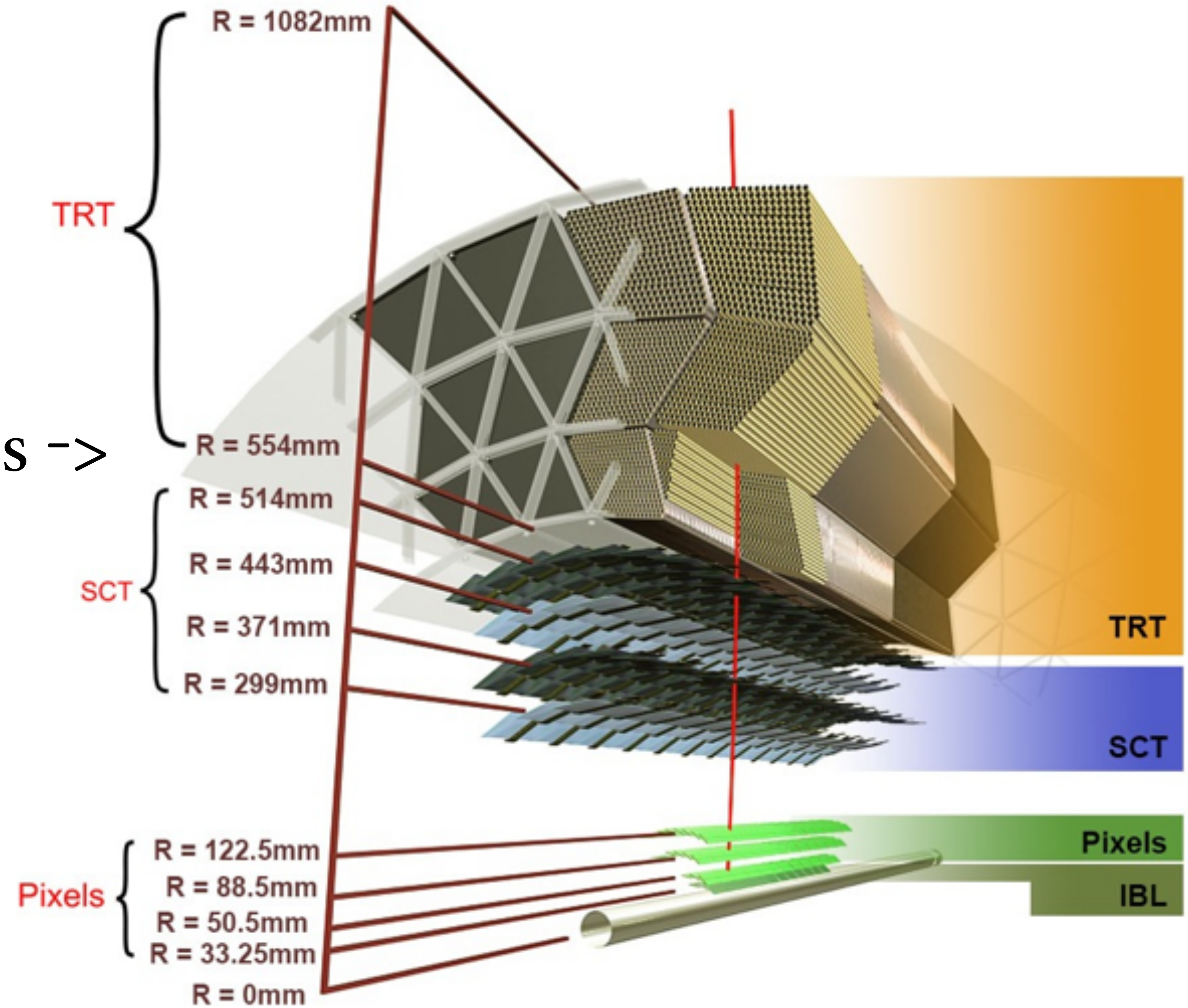
- Works with Liquid Argon at -183°C

- LAr endcap consists of the forward calorimeter, electromagnetic (EM) and hadronic endcaps

Measuring Photons in ATLAS

- Inner detector (ID)
  - Measure transition radiation -> e/γ discrimination.
  - Track charged particles -> γ conversion reconstruction.





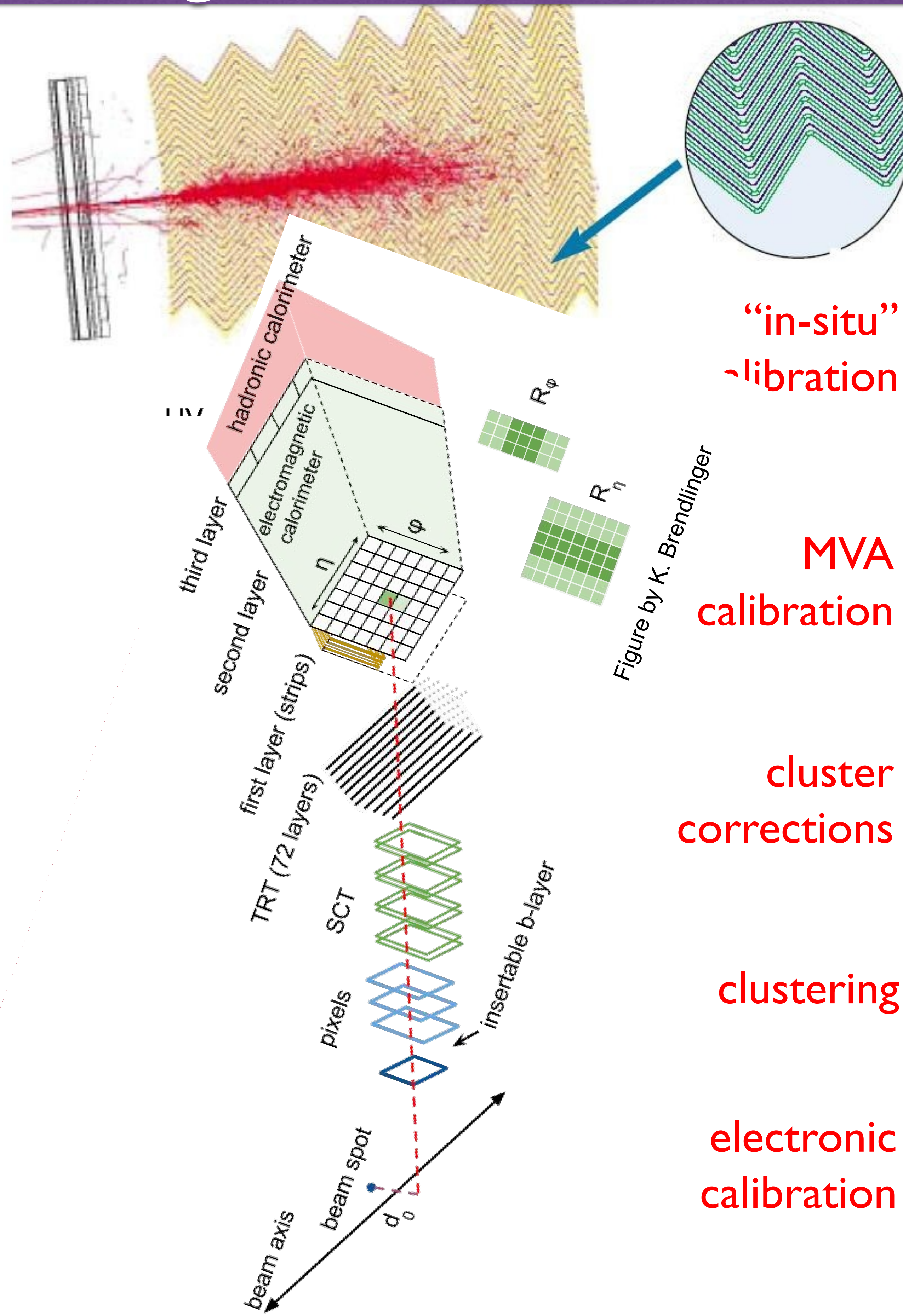
Measuring Photons in ATLAS

A photon showers in the EMC. Most of its energy is lost in Pb

Electrons in EM shower ionize LAr

Ionization electrons produce current

Current is collected, amplified, shaped, sampled and digitized for each EMC cell



“in-situ” calibration

Photon energy scale is adjusted to EM scale from Z→ee events

MVA calibration

Cluster energy is corrected for loss to get photon energy

cluster corrections

Cluster energies are corrected for detectors effects

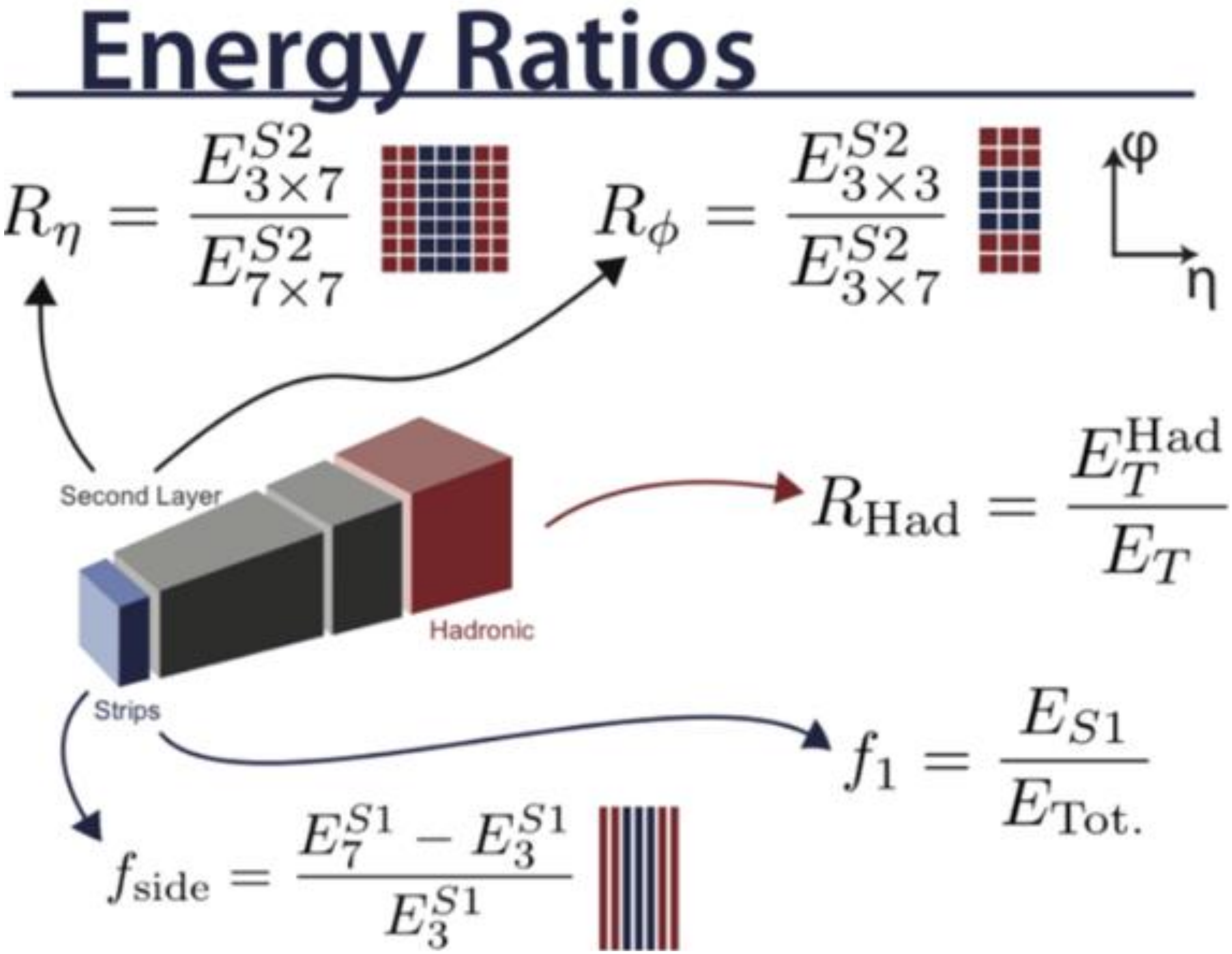
clustering

Cells are grouped in clusters

electronic calibration

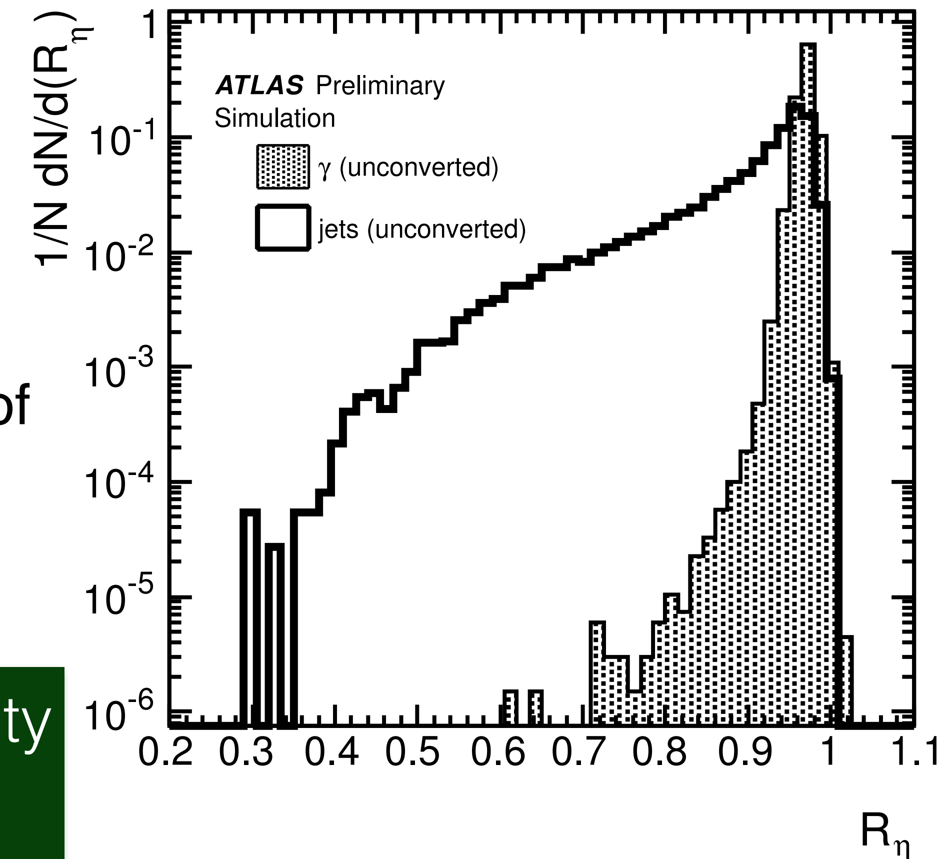
Energy in a cell is reconstructed from signal samples

Shower Shapes



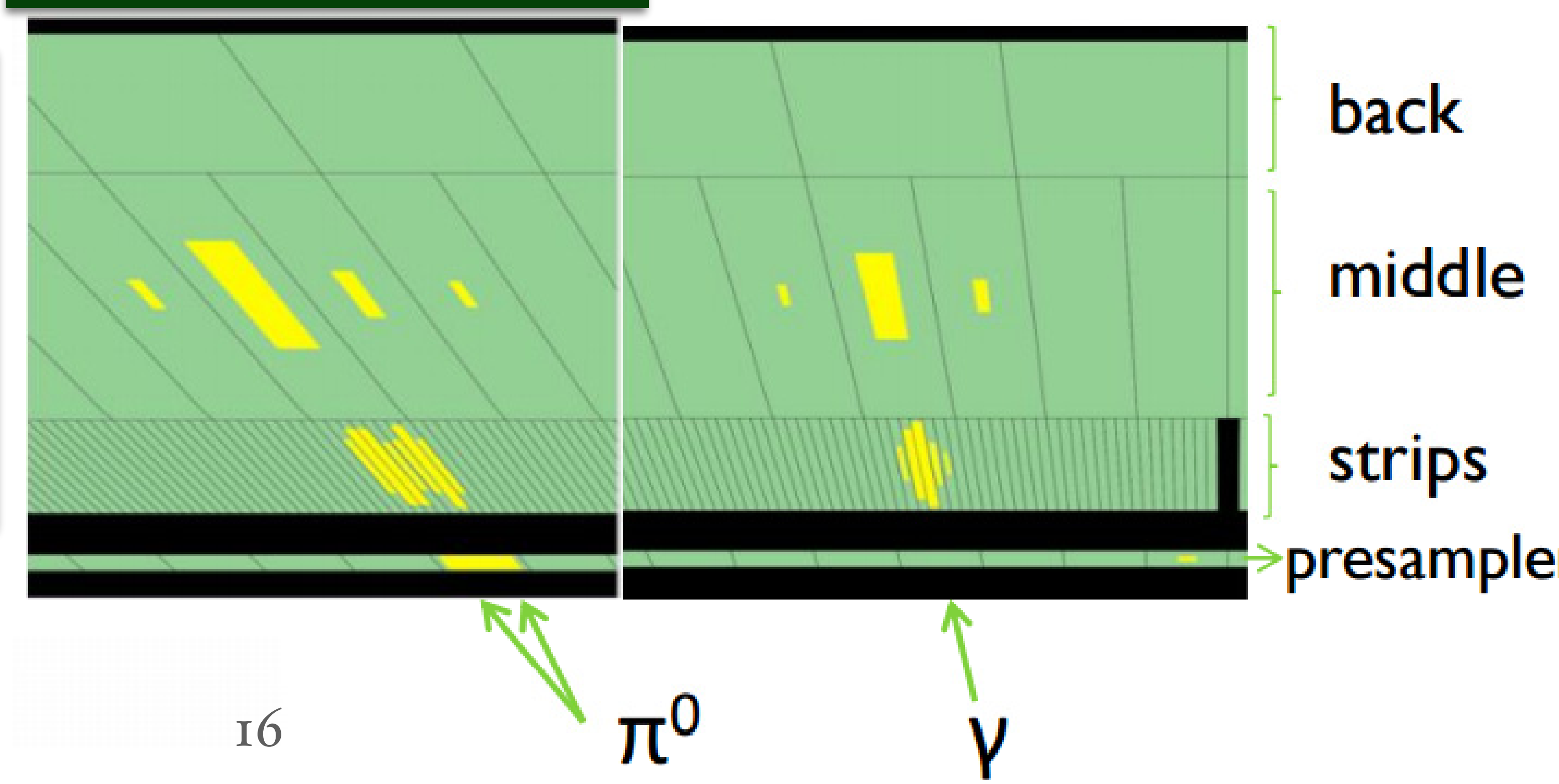
Photon Identification

- Shower Shapes
  - Identification performed by applying cuts over discriminating variables (shower shapes) from the calorimeter layers.
  - Shower shapes: variables that describe the shape of the electromagnetic shower in the calorimeter, and the fraction of energy deposited in the hadronic calorimeter.
  - Cuts are binned in η, and by converted/unconverted photons.
  - Pileup robust.



Calorimeter granularity allows to separate photons from pions

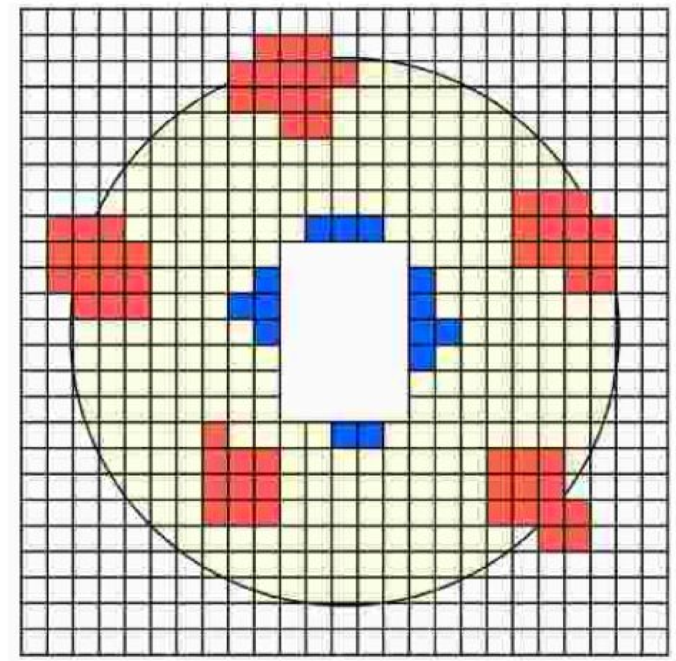
Efficiency:
85% (E_T=50GeV)-95%(E_T=200GeV)
Uncertainty:
±1% - ±5% for E_T >50GeV
η & E_T dependent
(uncertainty measured MC vs DATA)

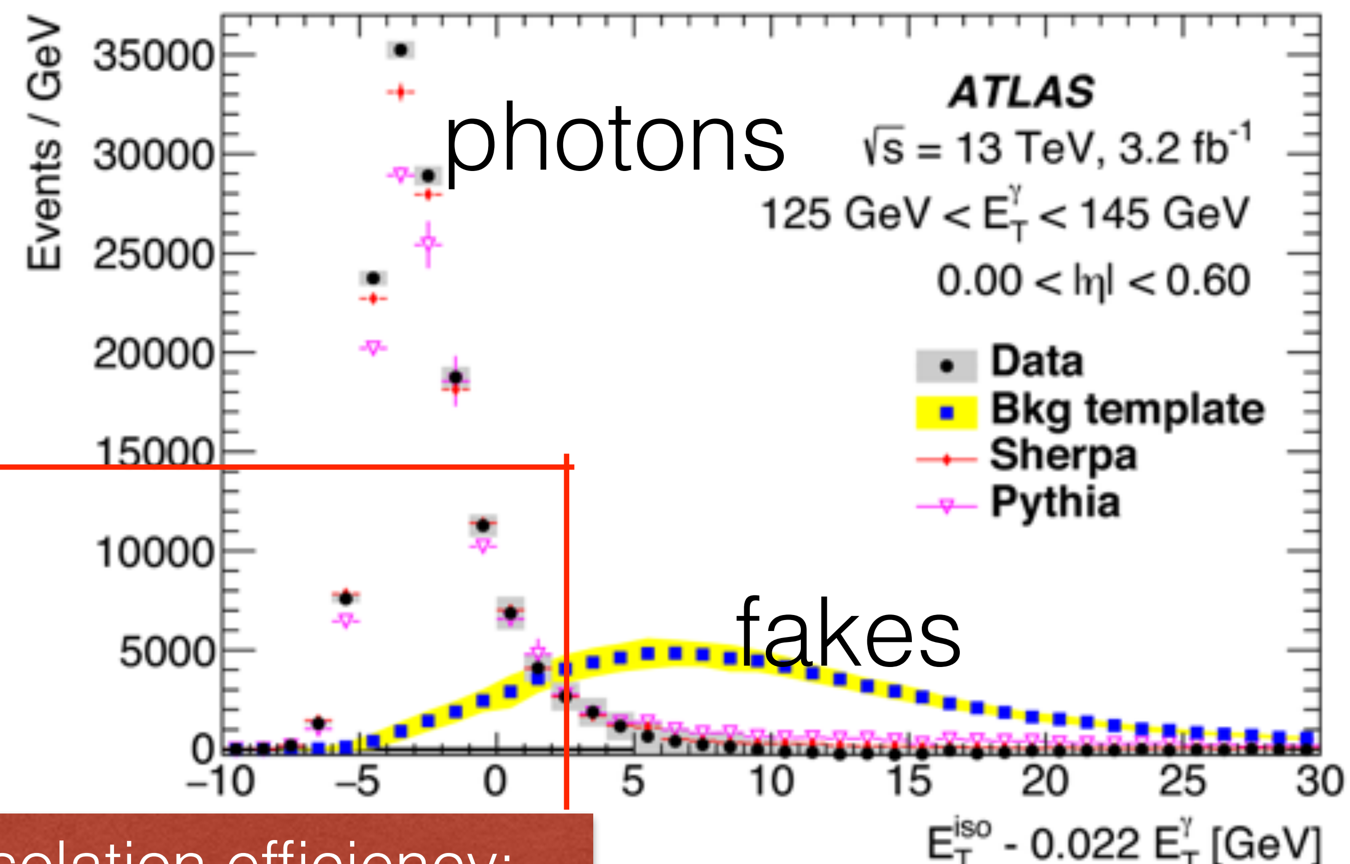


PHOTON ISOLATION

- Tight Isolation is used for reducible BG rejection (fake photons)

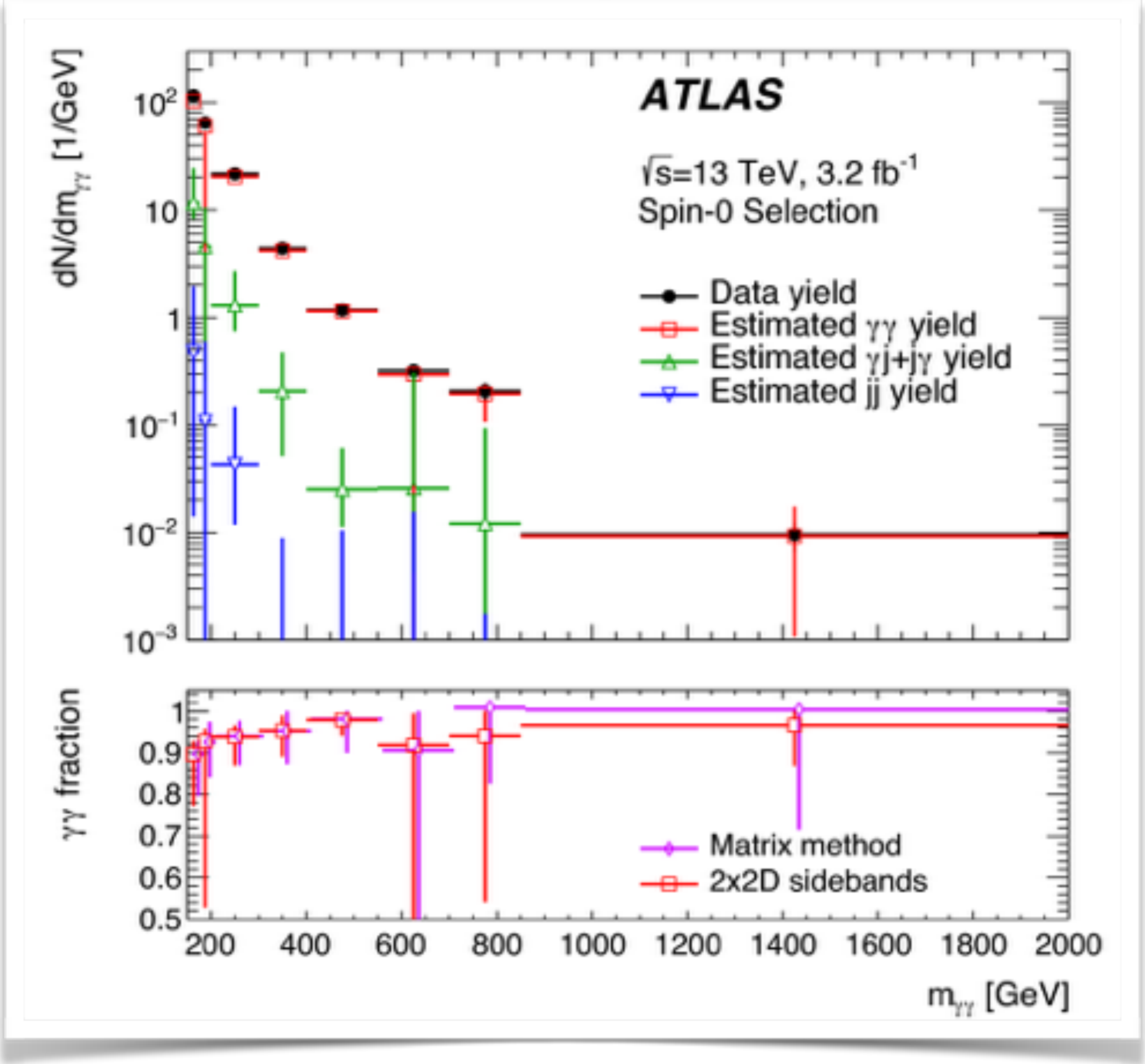
- Both **calorimeter isolation** and **track isolation** ARE **required.**
  - Calo isolation $\mathbf{E_T^{ISO}}$ → sum of E_T of energy clusters within $\Delta R = 0.4$
    - Ignore $\Delta\eta\times\Delta\phi = 0.125\times0.125$ centered on photon
    - Subtract out-of-cone energy from isolation
  - $E_{T,iso} - 0.022\, E_T < 2.45$ GeV
  - Track isolation → scalar sum of track p_T (p_T>1GeV) within $\Delta R = 0.2$ & consistent with selected primary vertex $p_{T,iso} < 0.05\, E_T$





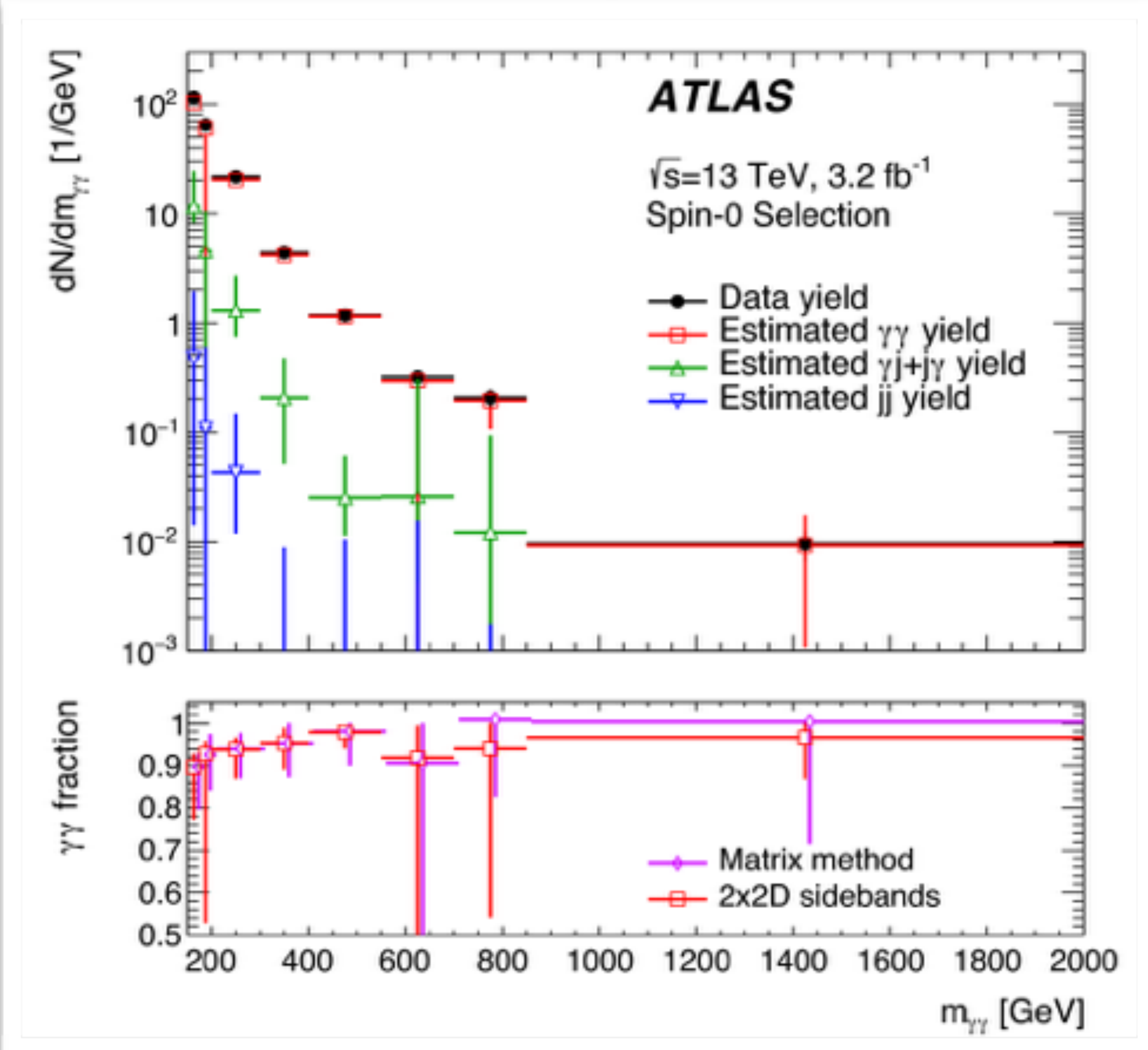
Isolation efficiency:
90 - 96% (E_T=100-500)
Isolation uncertainty:
1-2%

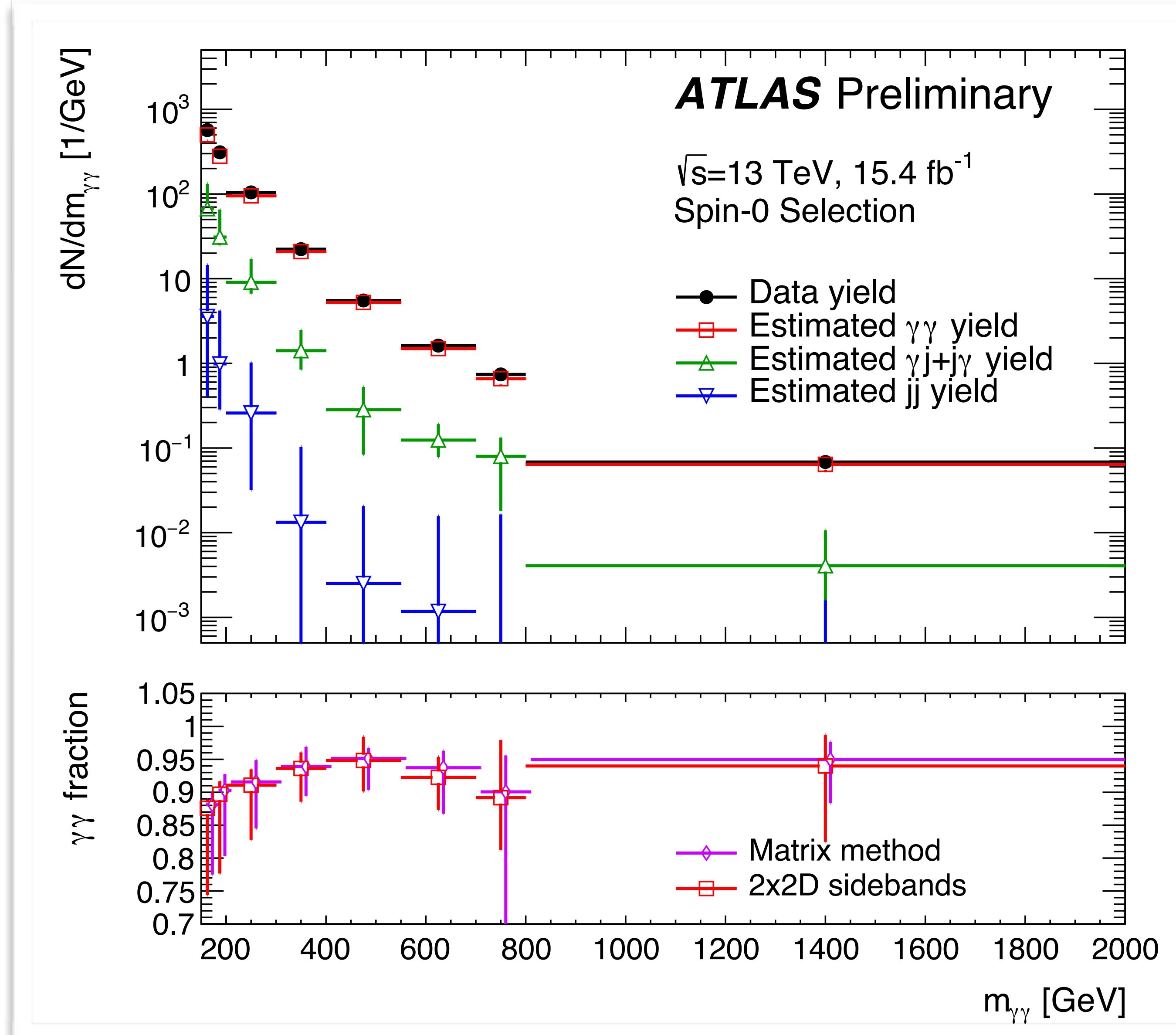
Decomposition of BG



- Using sophisticated methods (Matrix & Sidebands) we estimate the BG composition (γj,jγ,jj)
- The resulting **inclusive purity** is $Purity_{\gamma\gamma} = 93^{+3}_{-8}\%$

Decomposition of BG





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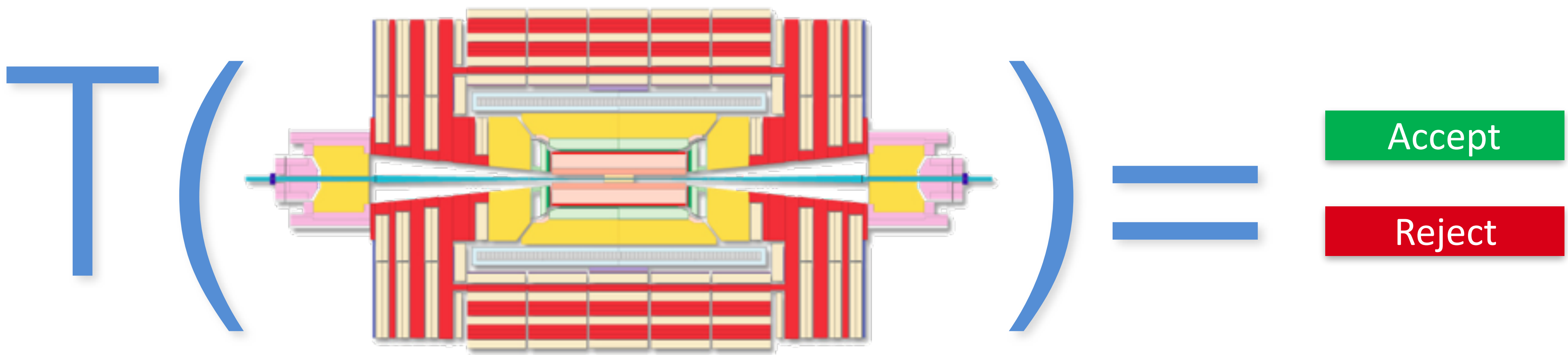
- The resulting **inclusive purity** is $Purity_{\gamma\gamma} = 93^{+3}_{-8}\%$

Trigger

First selection filter: reduce initial event rate by factor of one million for recording.

For each **event** the Trigger is a function of the event data, the apparatus, physics channel and parameters



Look at (almost) all bunch crossings, select most interesting one, collect all detector information and store it for offline analysis (do this with a reasonable amount of resources)

Slide from A. Höcker

Trigger and Data Acquisition System (DAQ)

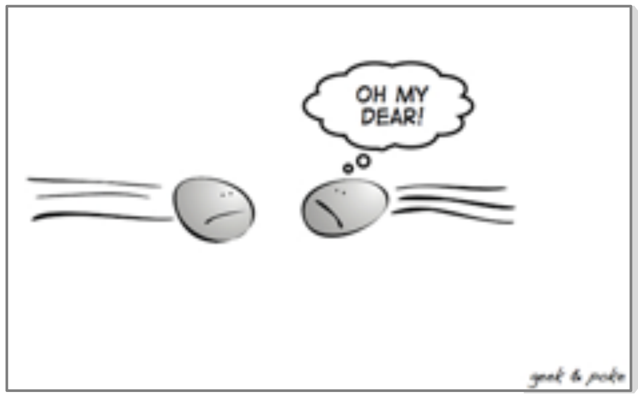
The trigger system selects 100 interesting events per second out of 1000 million total. The data acquisition system channels the data from the detectors to storage.

- Level 1. Of 40 million bunch crossings per second, less than 100,000 are kept
- Level 2. A few thousand events per second pass Level-2, and have their data passed on to Level-3.
- Level 3. About 200 events per second are left after the Level-3 analysis, and these are passed on to a data storage system for offline analysis.

Slide from A. Höcker

The data path in a nutshell
(example ATLAS)

Large Hadron Collider

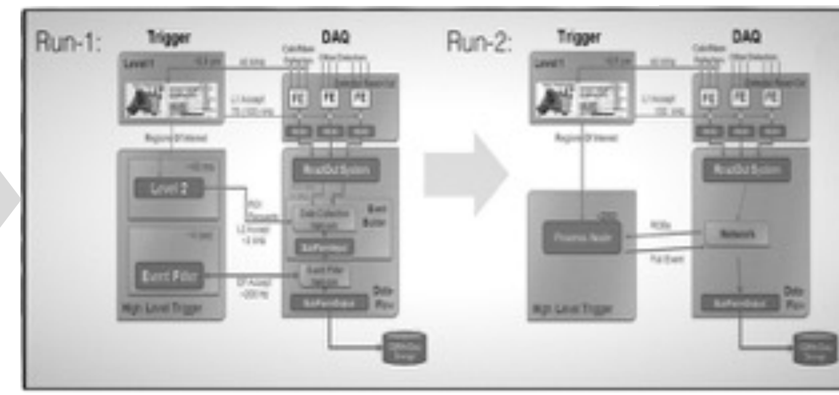


25/50 ns bunch distance

$L_{max} \sim 1 \times 10^{34}$ cm^{-2} s^{-1}

LHC Detector

Trigger & Online monitoring



L1 (HW, up to 100 kHz) + HLT (SW, 1 kHz)

Low-threshold single lepton triggers, single MET and jet triggers, and low-threshold di-object & topological triggers

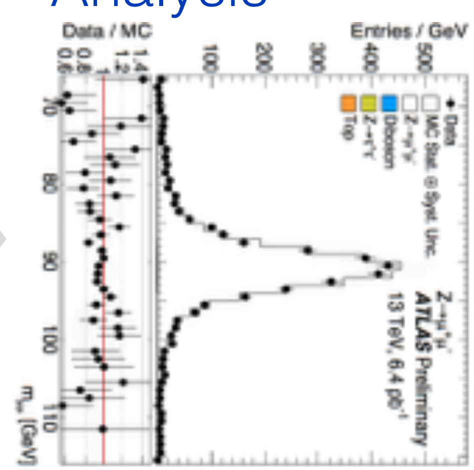
Calibration & Reconstruction

48h calibration & data quality processing, then prompt reconstruction of data in Tier-0

Distributed computing

Production of standardised derived datasets for physics and performance analysis

Analysis



Performance groups provide standard physics objects with calibrations and uncertainties, unified in analysis release

Analysis groups build physics analyses upon this ground work

Also: MC production — *O*(4 billion) 13 TeV events produced per experiment

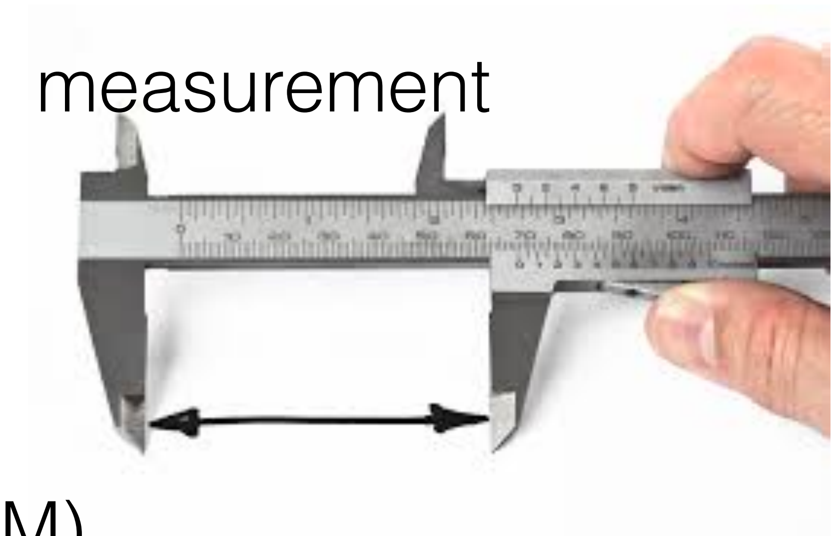
Slide from A. Höcker

Analysis

- What are we up to?
  - Search

OR

- measurement



- Explore the underlying theory (SM, BSM) (understand the Signal)
- Define the Signal and the Background (Predefined signal is based on a phenomenological Model)
- Understand the background (DATA driven or MC simulation)
- Define and understand the Nuisance Parameters (systematics)
- Design and optimise an analysis
- Analyse the (statistics of the) results

Statistics in a nut Shell

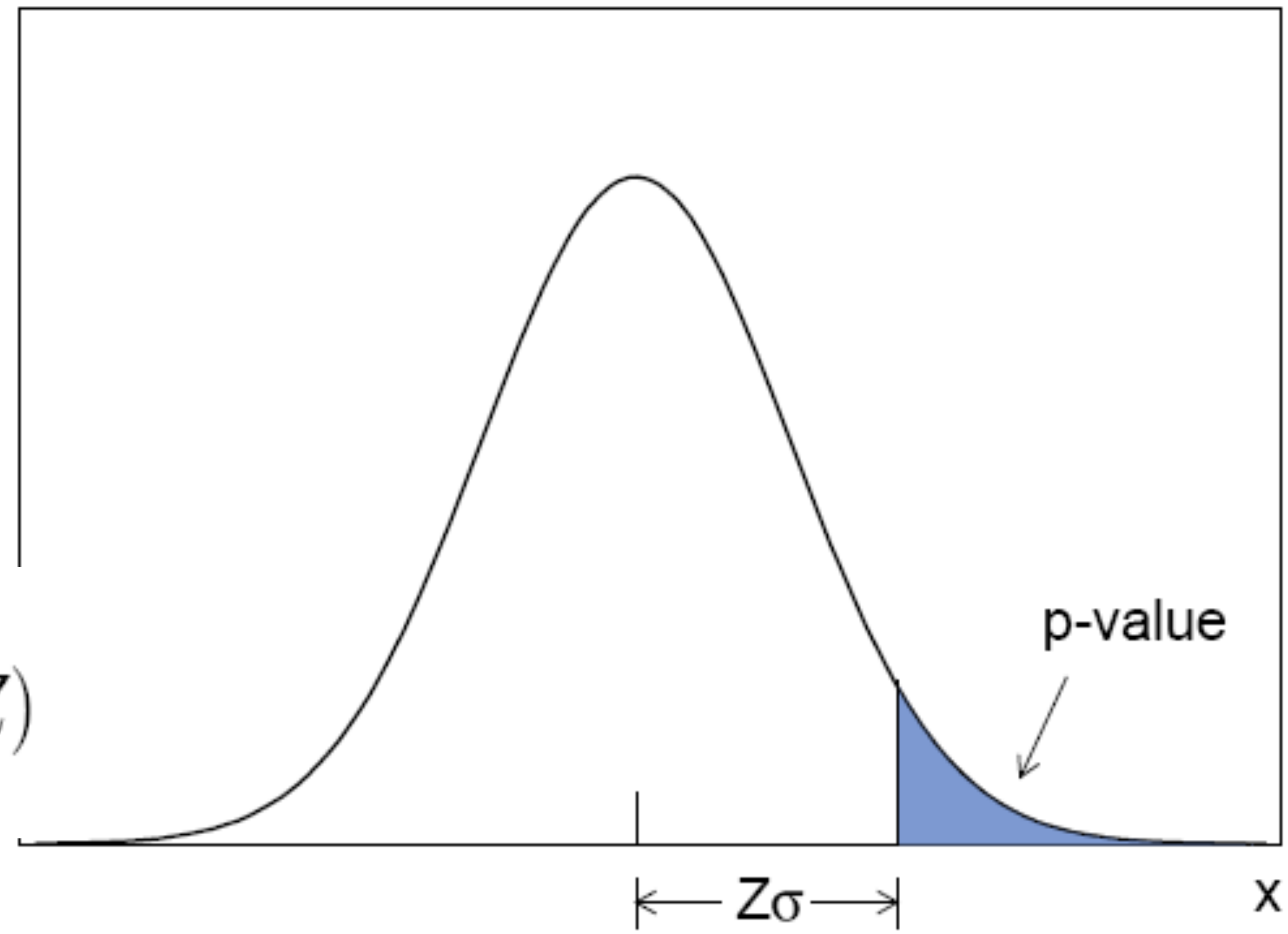
- The first step in any hypothesis test is to state the relevant **null,** H_{null} and **alternative hypotheses,** say, H_{alt}
- *The next step is to define a test statistic, q, under the null hypothesis*
- Compute from the observations the observed value q_{obs} *of the test statistic* q.
- *Based on* q_{obs} *find the p-value which is a measure of the compatibility of the data with null hypothesis*
- Decide (based on *the p-value*) to either
  fail to reject the null hypothesis or
  reject it in favor of an alternative hypothesis (if p-value is small)
- It is a custom in High Energy Physics to use

Discovey $\quad H_{null} = BG \quad p_{bg} = 2.9 \cdot 10^{-7} \sim 5\sigma$

Exclusion $\quad H_{null} = s + b \quad p_s = 0.05 = 5\% \sim 2\sigma$

From p-values to Gaussian significance

It is a custom to express the p-value as the significance associated to it, had the pdf were Gaussians



$$p = \int_Z^{\infty} \frac{1}{\sqrt{2\pi}} e^{-x^2/2}\, dx = 1 - \Phi(Z)$$

$$Z = \Phi^{-1}(1-p)$$

$\boxed{\text{A significance of } Z = 5 \text{ corresponds to } p = 2.87 \times 10^{-7}.}$

Beware of 1 vs 2-sided definitions!

WILKS THEOREM

$$q(\alpha_i) \equiv -2\ln\frac{L(\alpha_i,\hat{\hat{\theta}}_j)}{L(\hat{\alpha}_i,\hat{\theta}_j)} = -2\ln\frac{\max_\theta L(\alpha_i,\theta_j)}{\max_{\alpha,\theta} L(\alpha_i,\theta_j)}$$

$$q(\alpha_i) \equiv -2\log\frac{L(\alpha_i,\hat{\hat{\theta}}_j)}{L(\hat{\alpha}_i,\hat{\theta}_j)} \sim \chi_n^2$$

Test Statistics	Purpose	Experession	LR
q_0	discovery of positive signal	$q_0 = \begin{cases} -2\ln\lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$	$\lambda(0) = \dfrac{L(0,\hat{\hat{\theta}}_0)}{L(\hat{\mu},\hat{\theta})}$
t_μ	2-sided measurement	$t_\mu = -2\ln\lambda(\mu)$	$\lambda(\mu) = \dfrac{L(\mu,\hat{\hat{\theta}}_\mu)}{L(\hat{\mu},\hat{\theta})}$
$\tilde{t}_\mu$	avoid negative signal (FC)	$\tilde{t}_\mu = -2\ln\tilde{\lambda}(\mu)$	$\tilde{\lambda}(\mu) = \begin{cases} \dfrac{L(\mu,\hat{\hat{\theta}}_\mu)}{L(\hat{\mu},\hat{\theta})} & \hat{\mu} \geq 0 \\ \dfrac{L(\mu,\hat{\hat{\theta}}_\mu)}{L(0,\hat{\hat{\theta}}_0)} & \hat{\mu} < 0 \end{cases}$
q_μ	exclusion	$q_\mu = \begin{cases} -2\ln\lambda(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$	
$\tilde{q}_\mu$	exclusion of positive signal	$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$	

q_{null}

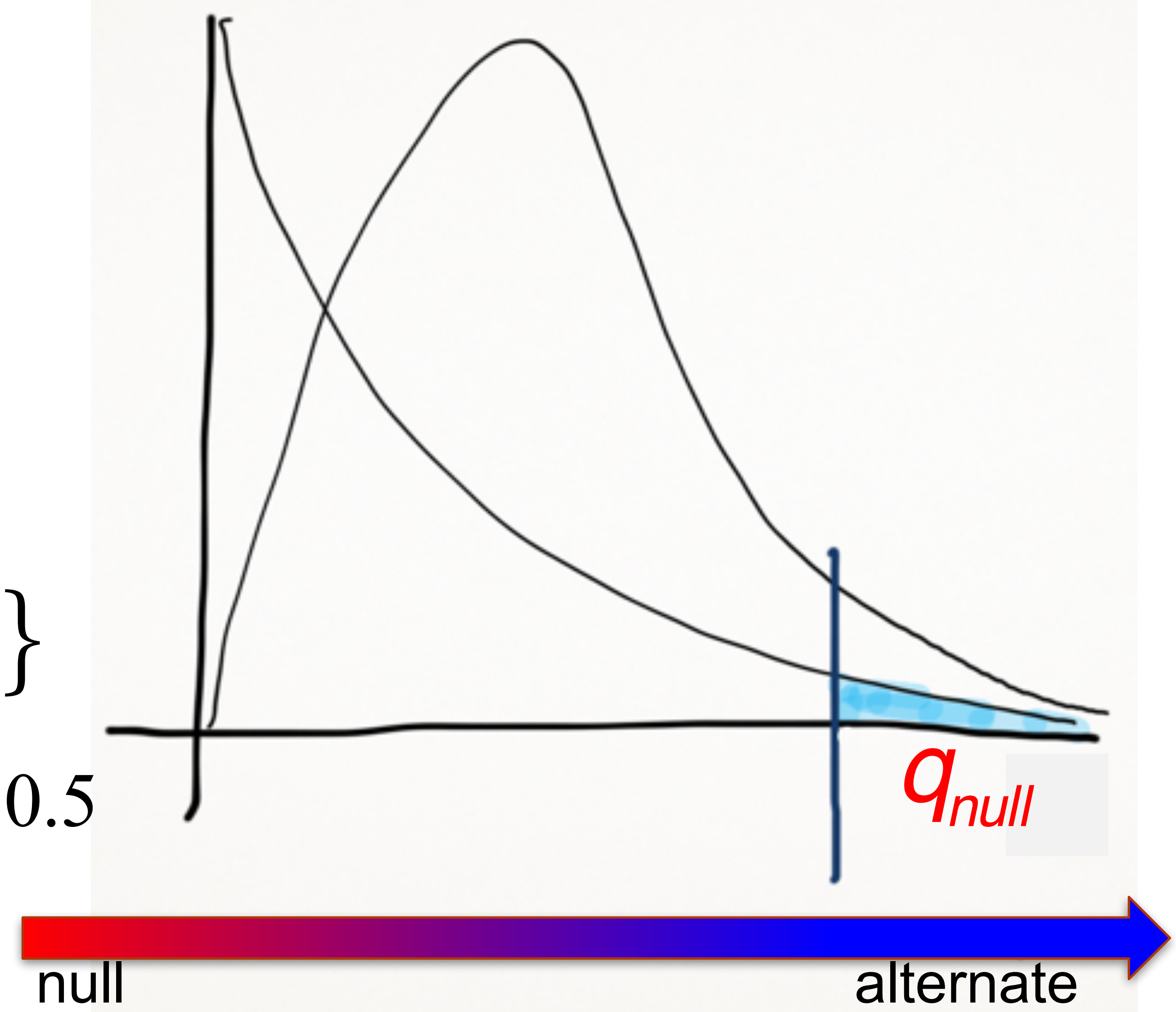
$f(q_{null} \mid H_{null})$

$q_{obs} \equiv q_{null,obs}$

$$p = \int_{q_{obs}}^{\infty} f(q_{null} \mid H_{null}) dq_{null}$$

$f(q_{null} \mid H_{alt})$

$$q_A \equiv q_{null,A} = \begin{array}{c} \{ q \mid med\{ f(q_{null} \mid H_{alt}) \} \} \\ \int_{q_{null,A}}^{\infty} f(q_{null} \mid H_{null}) dq_{null} = 0.5 \end{array}$$



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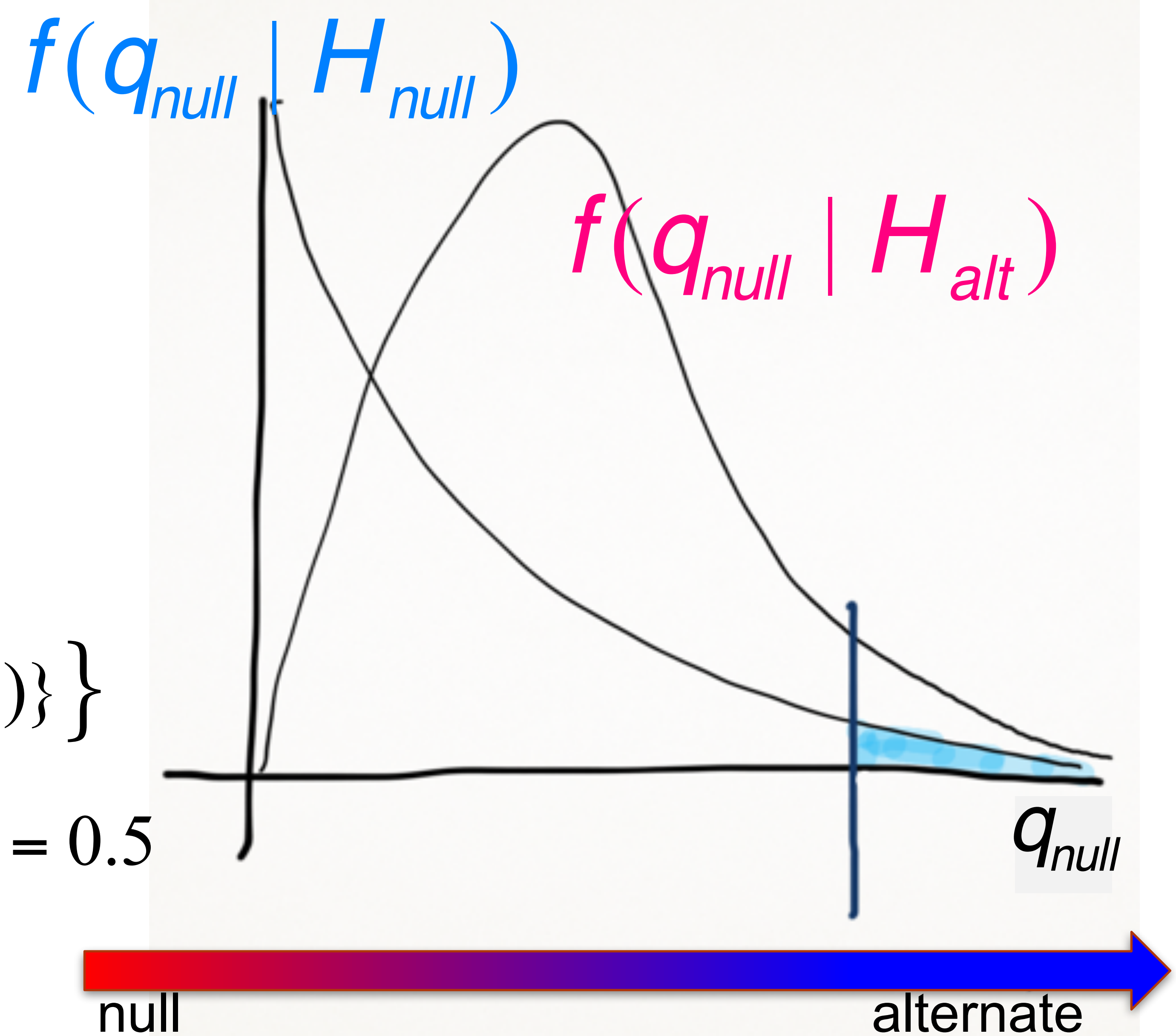

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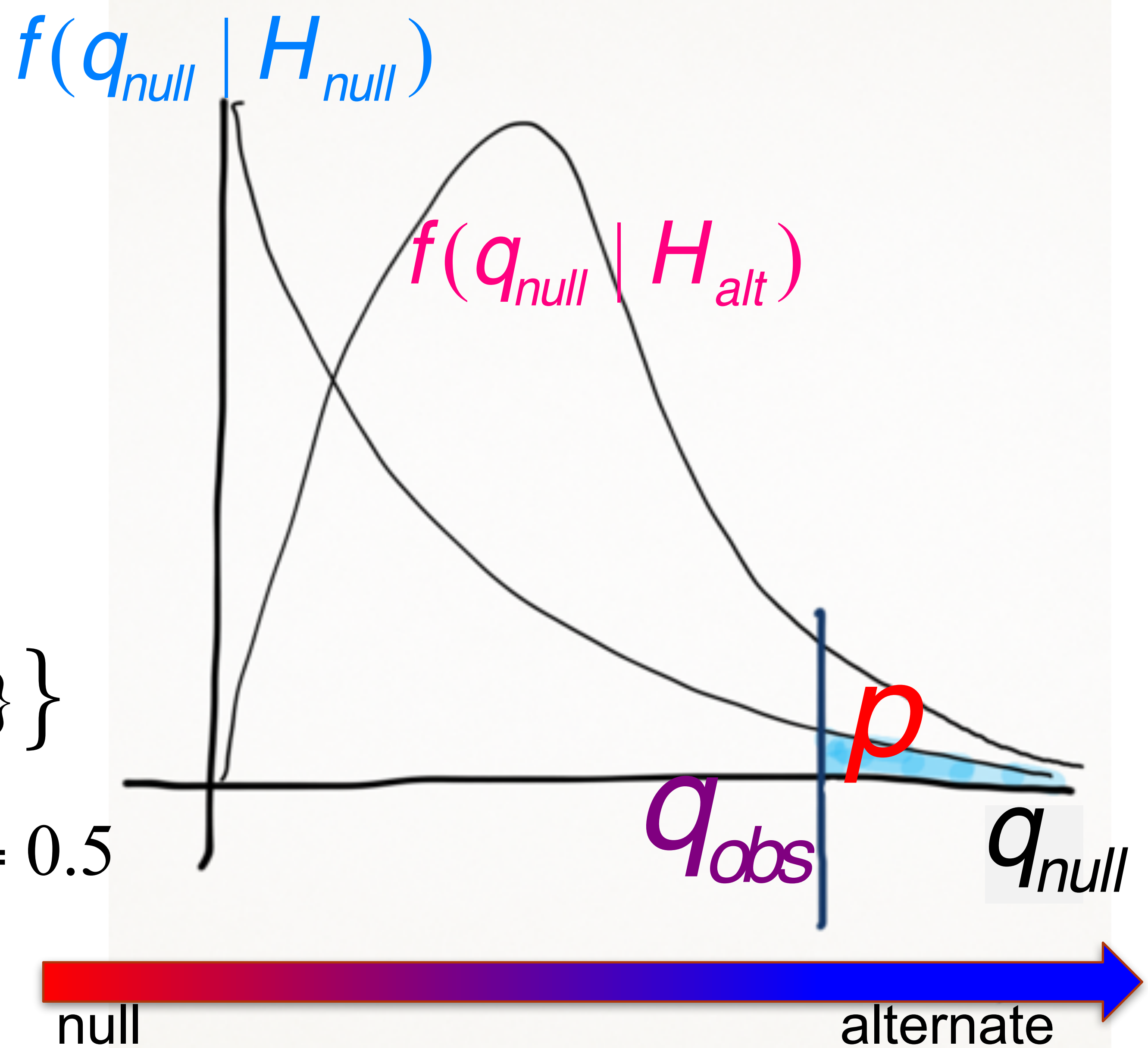


q_{null}

$f(q_{null} \mid H_{null}) \sim \chi^2$

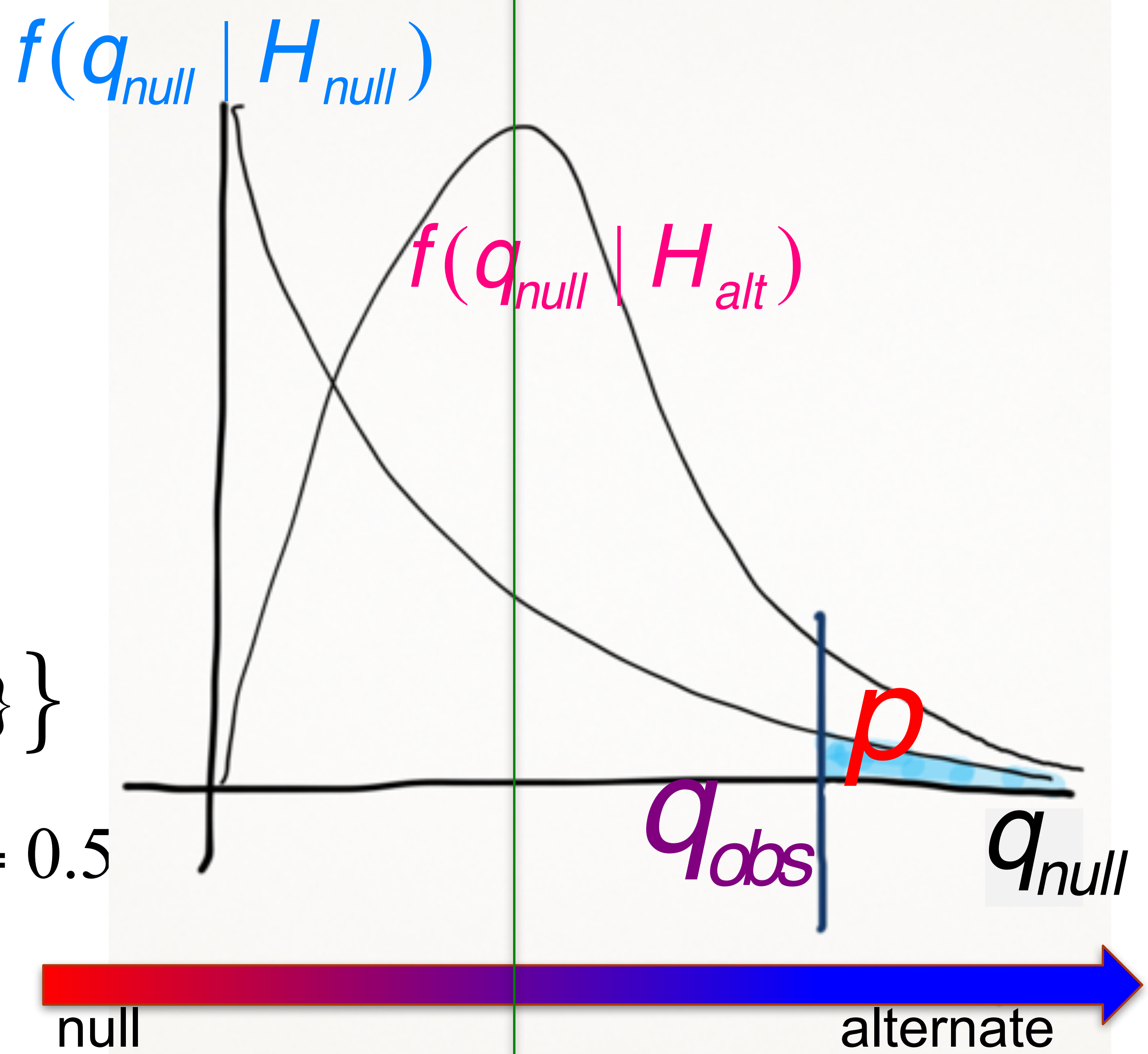
$q_{obs} \equiv q_{null,obs}$

$p = \int_{q_{obs}}^{\infty} f(q_{null} \mid H_{null}) dq_{null}$

$f(q_{null} \mid H_{alt})$

$$q_A \equiv q_{null,A} = \{q \mid med\{f(q_{null} \mid H_{alt})\}\}$$

$$\int_{q_{null,A}}^{\infty} f(q_{null} \mid H_{null}) dq_{null} = 0.5$$

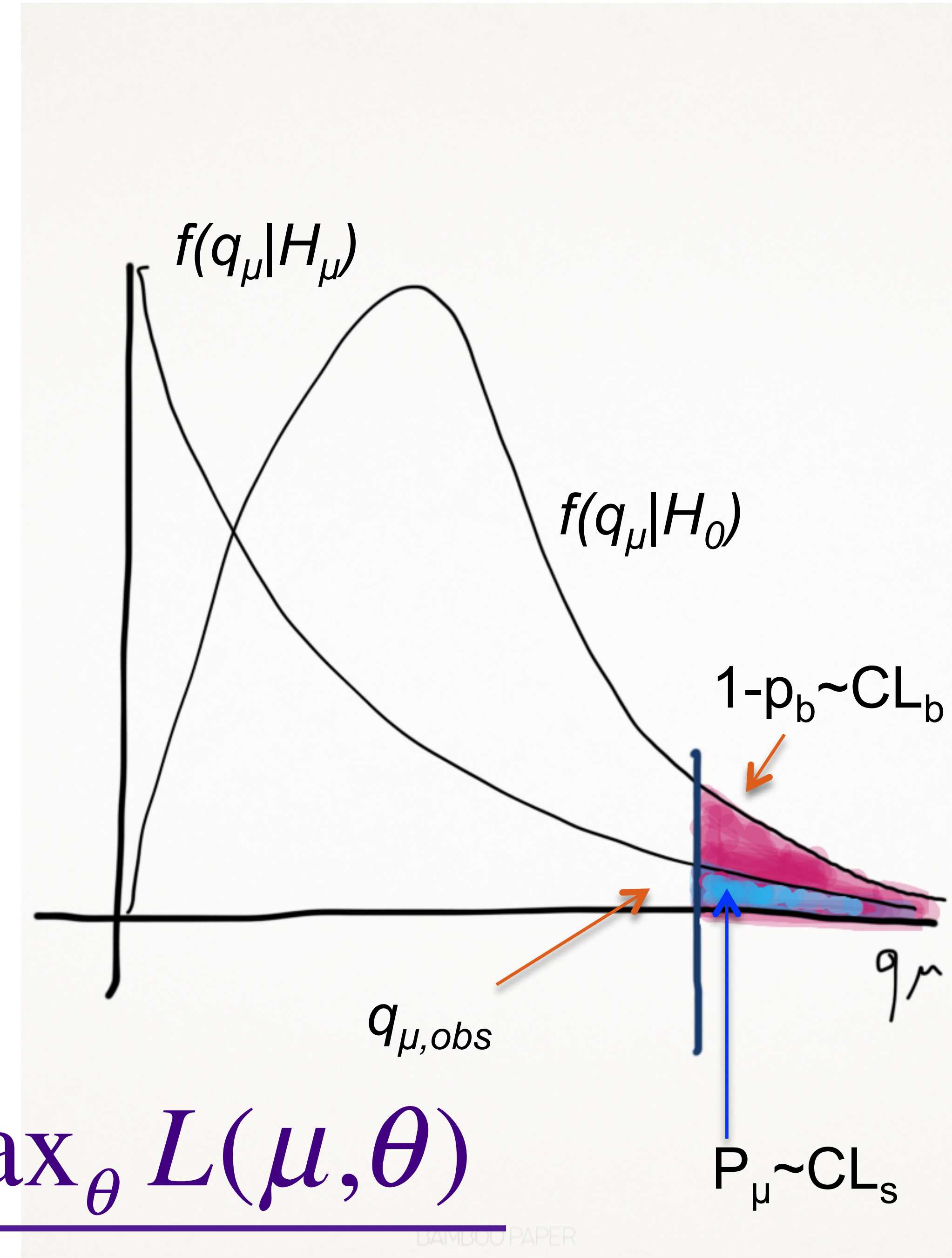


$$Z_{expected} = \sqrt{q_{null,A}}$$

$q_A \equiv q_{null,A}$

- The CLs method modifies the p-value to prevent rejecting the s+b hypothesis due to downward fluctuations of the background (which prevents the exclusion of a signal, to which you might not be sensitive)

$$p'_{\mu}(m) = \frac{p_{\mu}(m)}{1 - p_b}$$



$$q_{\mu} \equiv -2\ln\frac{L(\mu,\hat{\hat{\theta}})}{L(\hat{\mu},\hat{\theta})} = -2\ln\frac{\max_{\theta} L(\mu,\theta)}{\max_{\mu,\theta} L(\mu,\theta)}$$

Fix m, scan μ until you find $\mu_{up}(m) = \left\{ \mu \middle| p'_{\mu}(m) = 5\% \right\}$

Understanding The Yellow and Green Bands

excess=>worse limit perhaps, on the way to discovery

deficit=>better limit

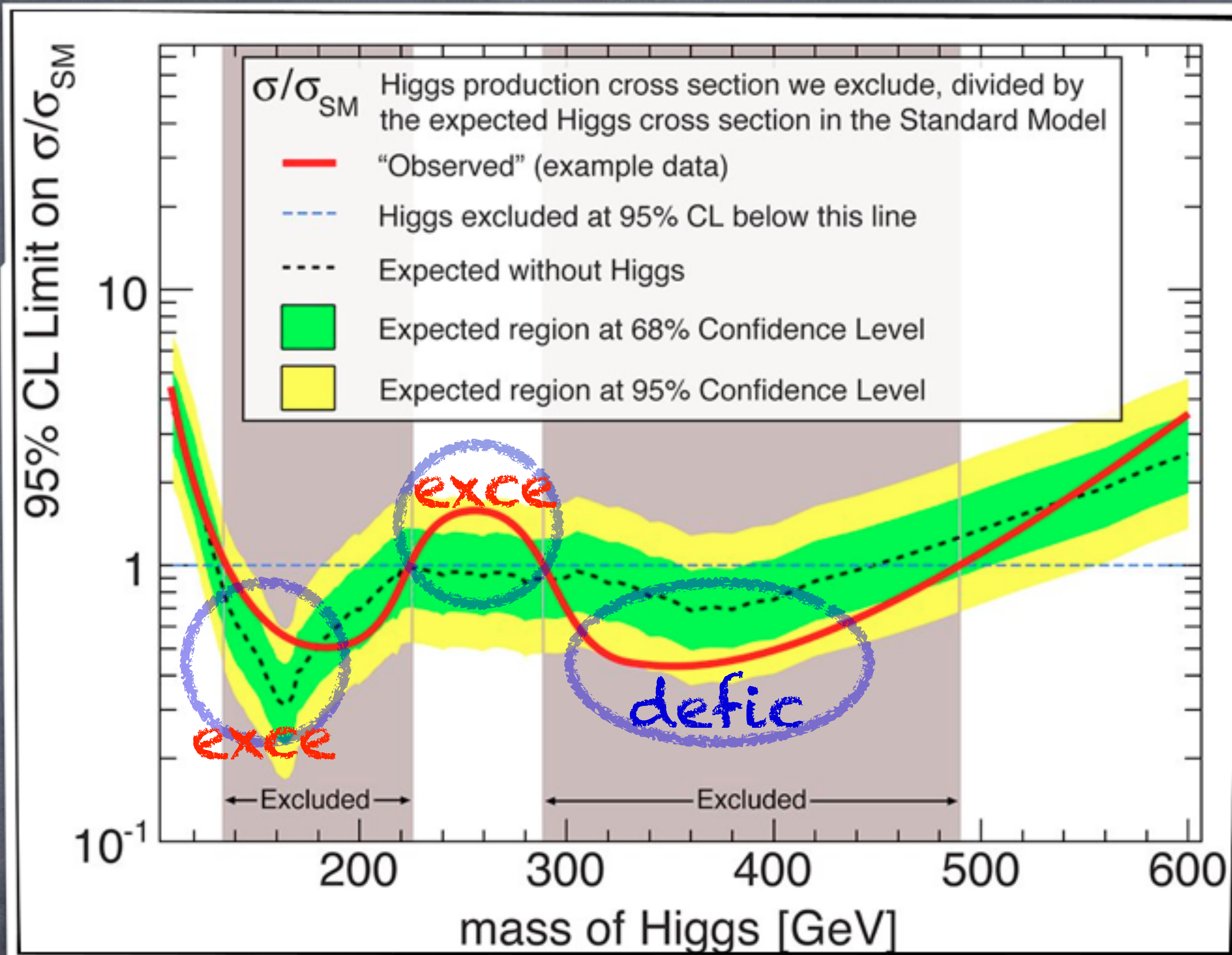
$$\mu = \frac{\sigma}{\sigma_{Model}}$$

$$\mu_{up}(m) = \left\{ \mu \middle| p'_{\mu}(m) = 5\% \right\}$$

$$\mu_{up}(m) < 1 --> $$

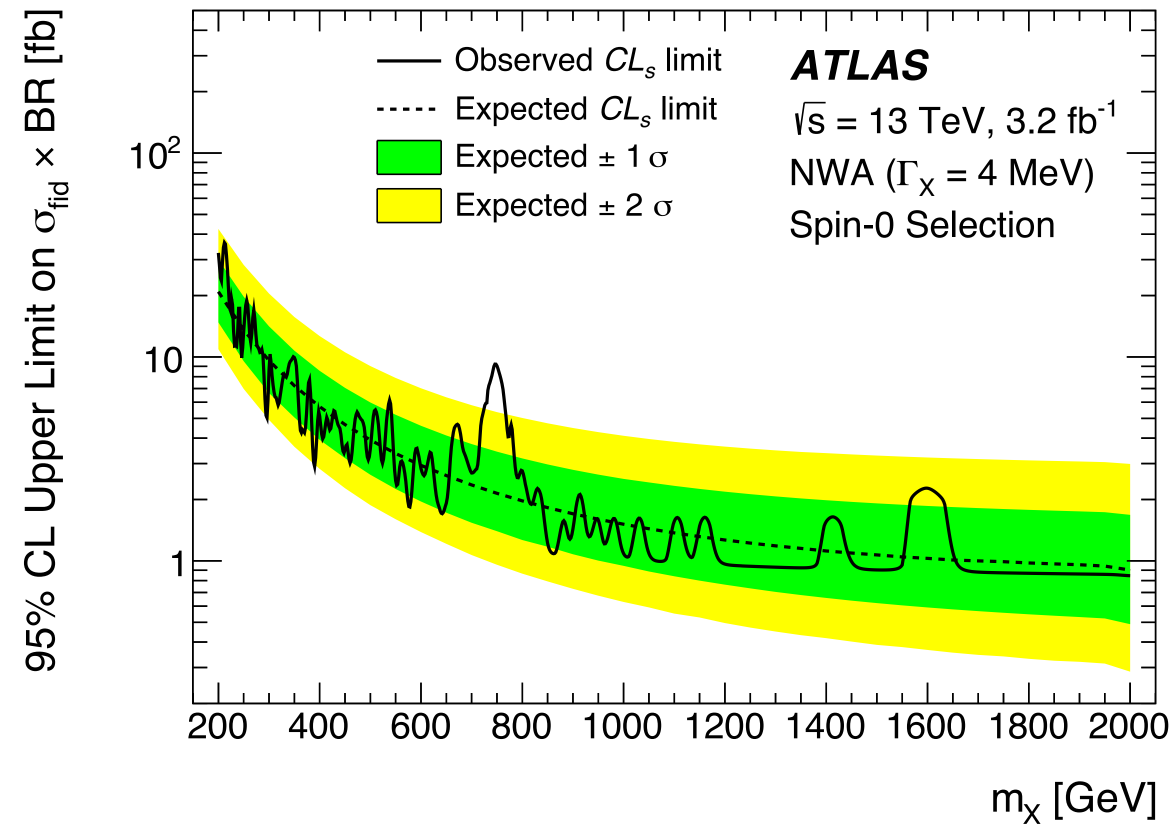
$$\sigma < \sigma_{model}(m) --> $$

$$excl \quad m \quad @95\%CL$$

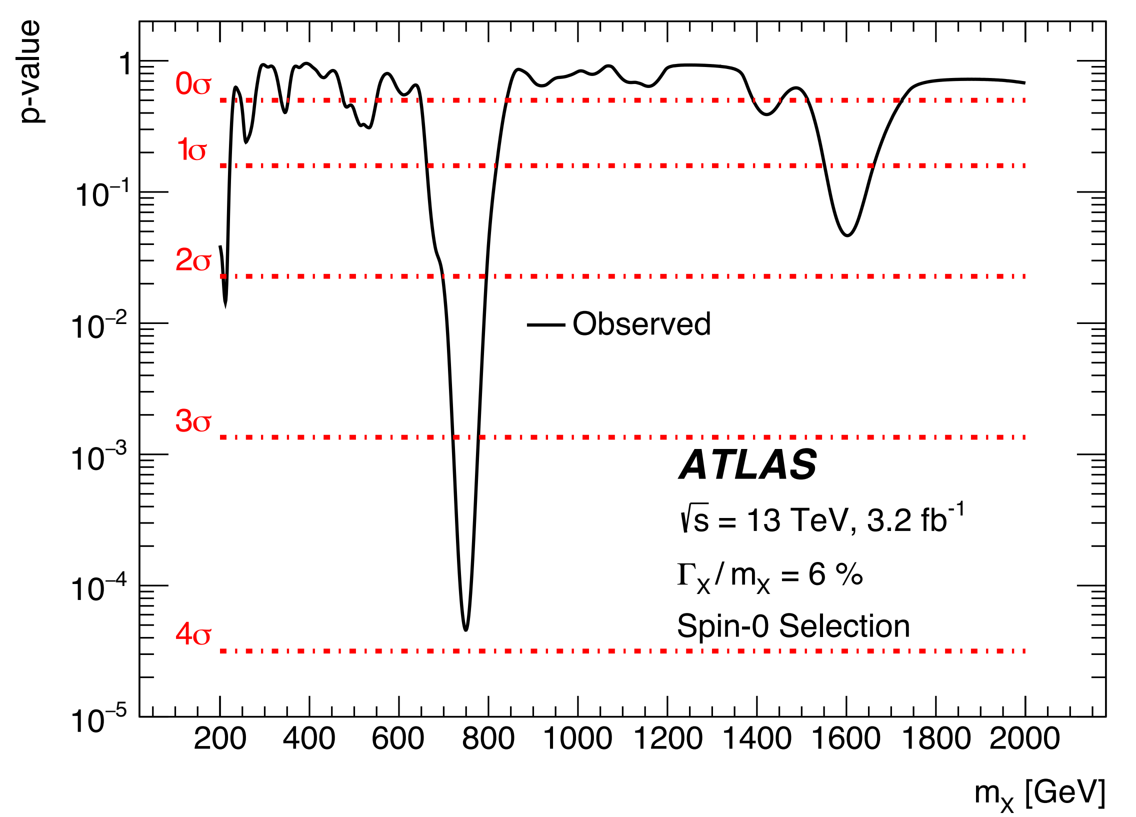


L=L(Data)
Expected is with the alternative Asimov Data
i.e. find μ_{up} with the expected BG data set

- Reject the Background hypothesis —> Discovery
- Reject the Signal (s+b) hypothesis —> Exclusion of the signal



- A failed search ends up with exclusion plots



- A successful search ends up with a p-value plot, international fame, and a job (or an offer of a better one).

End of Statistical Introduction
More on the
Look Elsewhere Effect
LEE
to come


HAPPY
2015

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

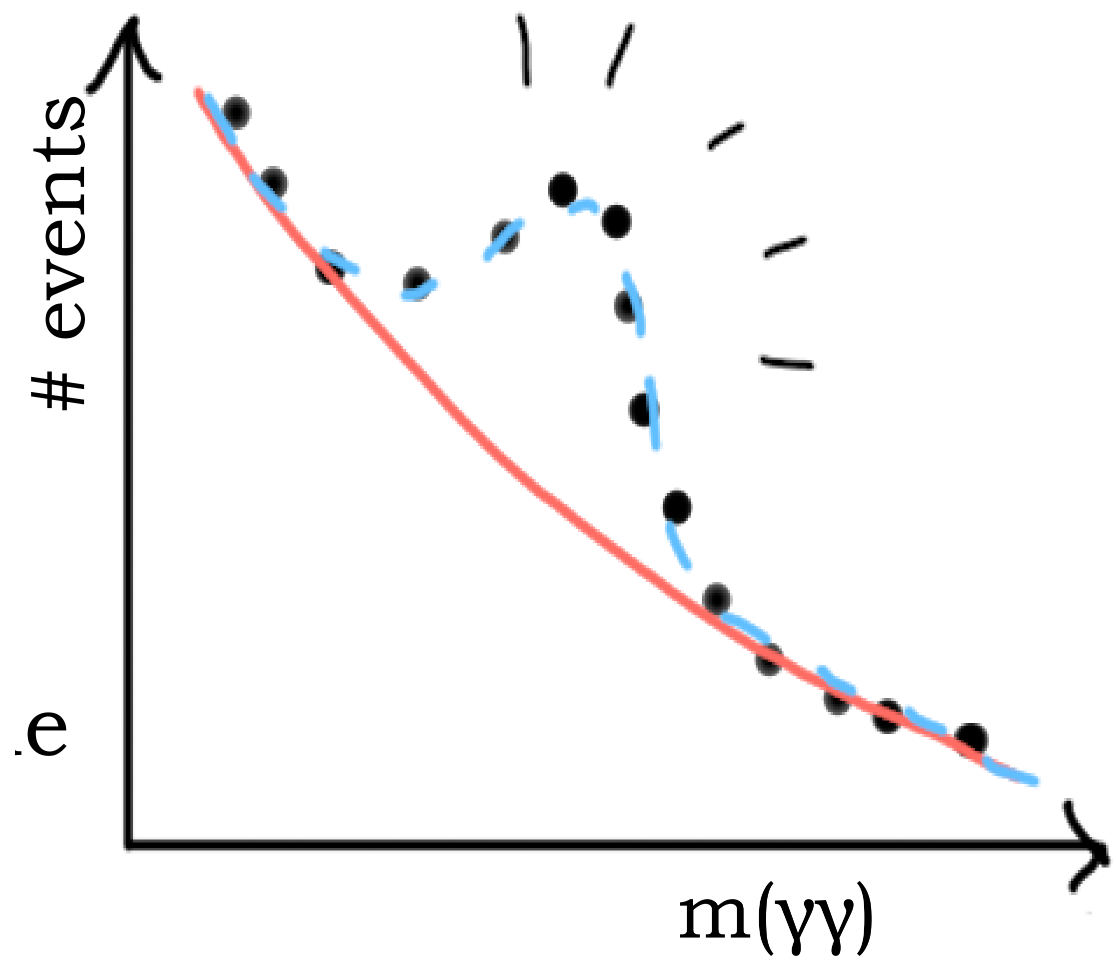
Submitted to: JHEP

CERN-EP-2016-120
14th June 2016

Search for resonances in diphoton events at $\sqrt{s}$=13 TeV with the ATLAS detector

The ATLAS Collaboration

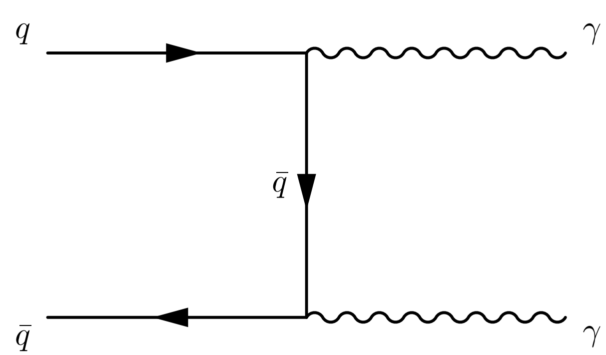
- The Higgs group of ATLAS did not need a motivating model…. Scalars are always interesting particles to search for.
- Here the signature dictates the search and not a specific model.
- Scan the diphoton spectrum above the Higgs mass and look for a bump. Its a classic search of a bump on a top of continuous falling BG
- Understanding and being able to predict the background is **essential** for the analysis



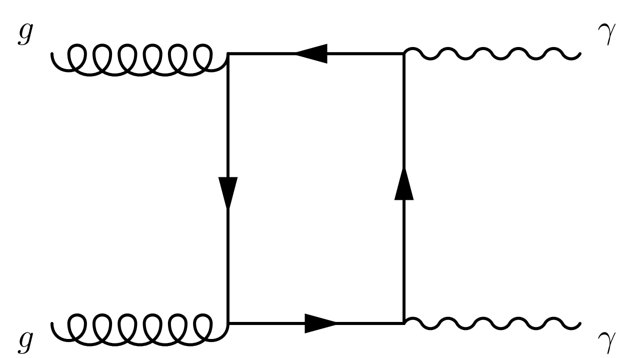
Background

- The background is essentially the Standard Model

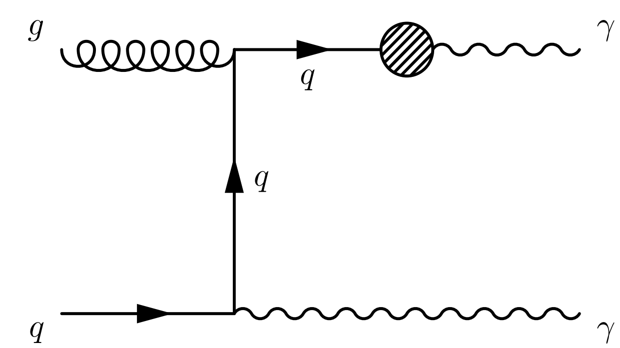
born



box



parton fragmentation



- How well do we know the process?
  Diphox (NLO) MC
  https://arxiv.org/abs/hep-ph/9911340

Higher orders

$q\bar{q} \to \gamma\gamma$

LO

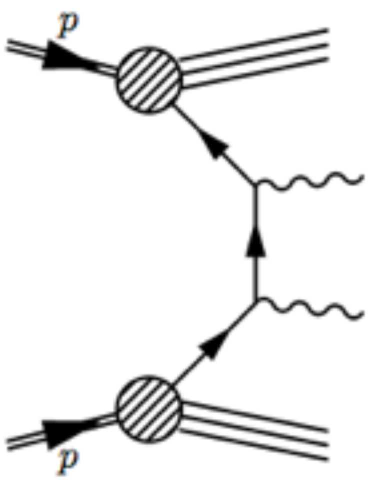


Diagram a

$+ \cdots +$

NLO

up to $O(\alpha_s)$

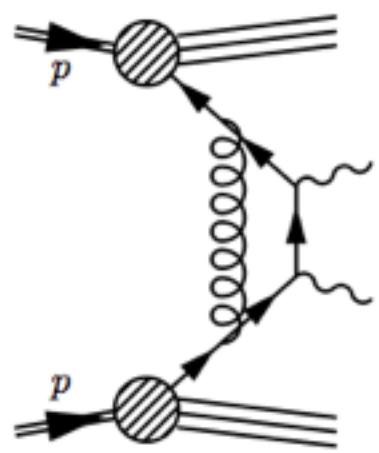
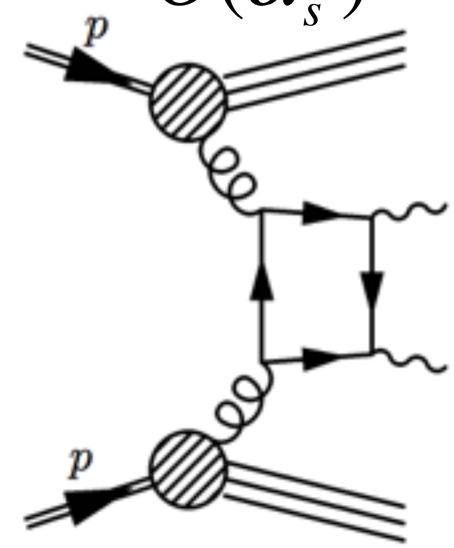


Diagram b

$+ \cdots$

NNLO

$O(\alpha_s^2)$



$+ \cdots$

$+$

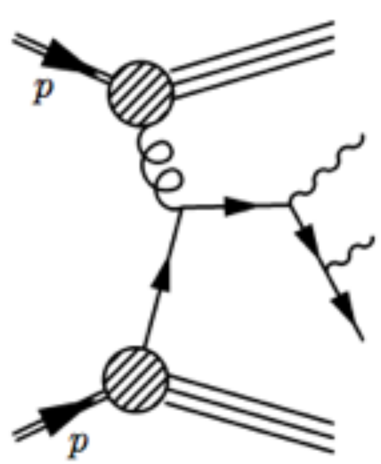


Diagram c

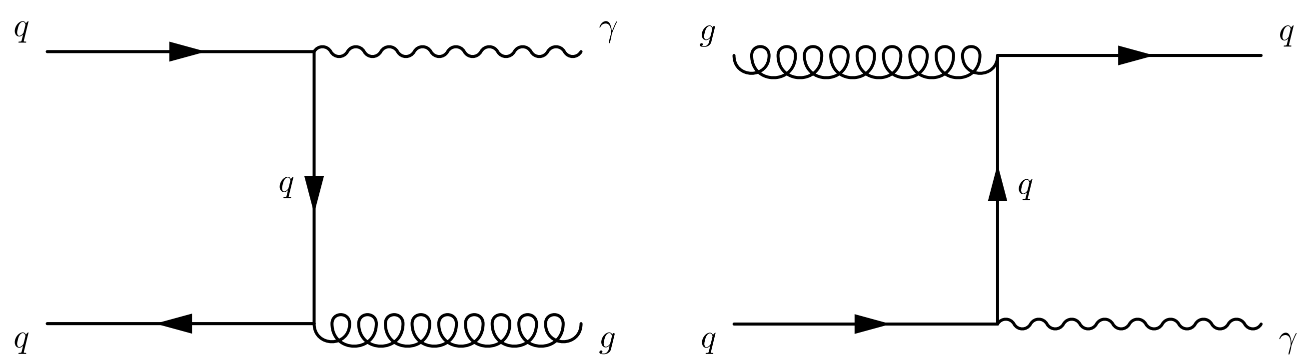
NLO

$gq \to \gamma\gamma q$

$+ \cdots$

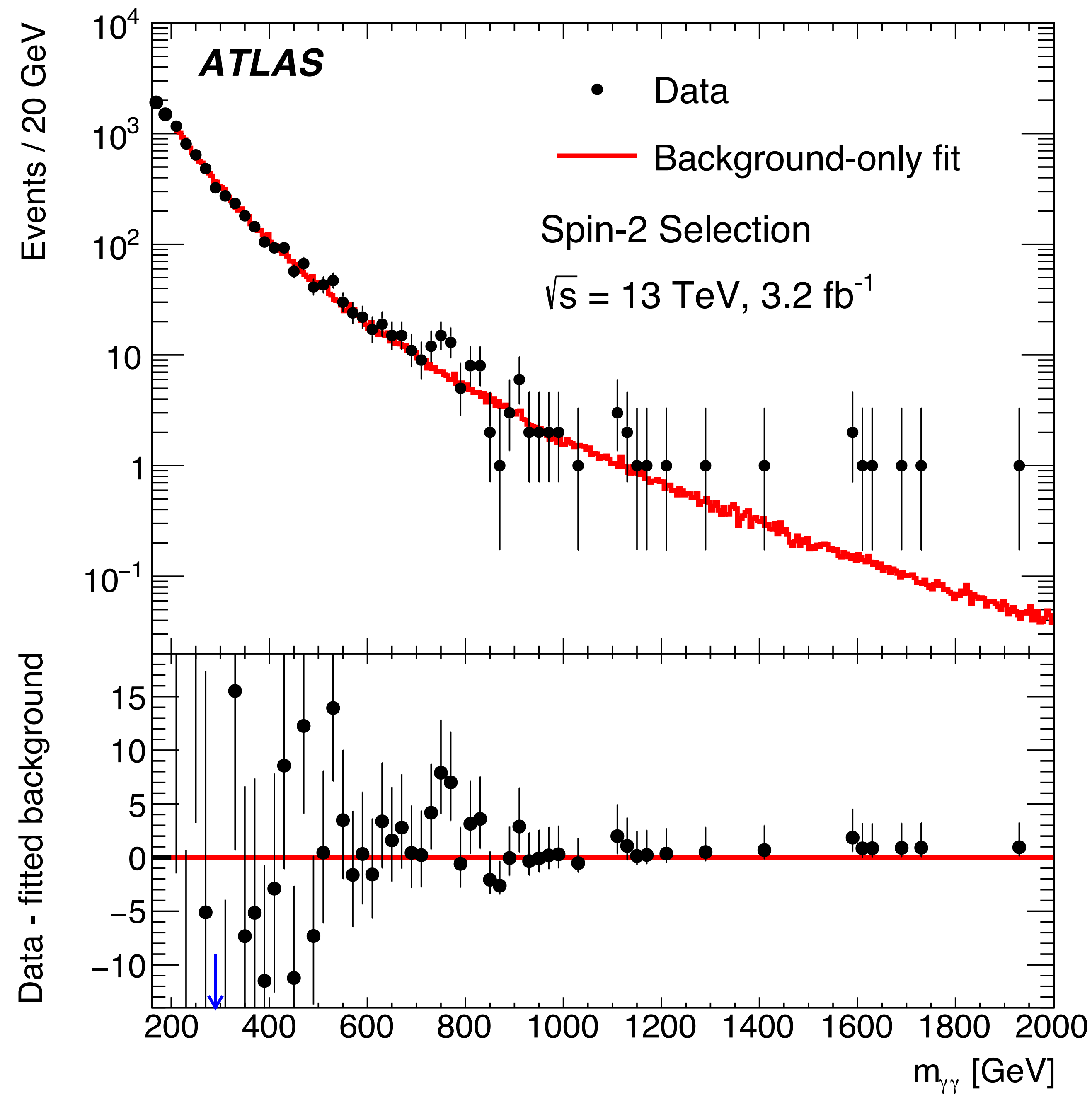
FAKES

- Life is not pure Feynman diagrams
- A photon should be identified
- Jets (quarks and gluons) might be misidentified as photons, introducing contamination to our diphoton sample
- qγ with quark jets identified as photons are referred to as **reducible background**

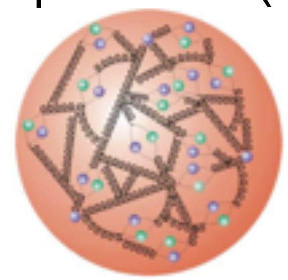


- How much reducible, depends on the performance of the experimental photon isolation and photon identification
- Photon isolation/identification are a derivative of the detector performance
- No Monte Carlo can reliably describe the fake rate with a limited amount of computing time…
- Nevertheless,
  fakes can be measured from the data with highly sophisticated methods

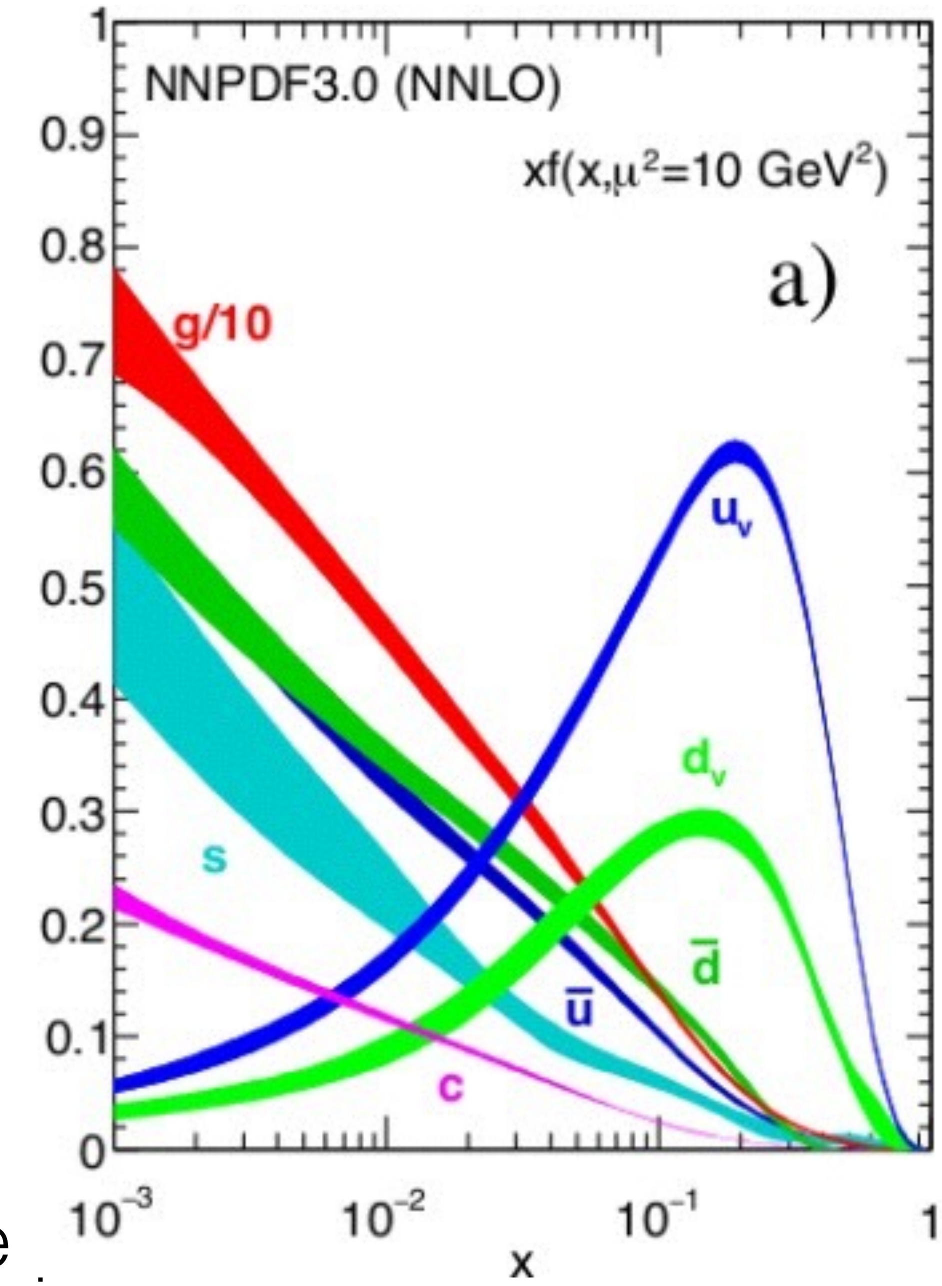
- Atlas spin 2 analysis is using a Monte Carlo (SHERPA corrected with DIPHOX)
- Fakes are estimated from data.
- The drawback (spin 2) is the systematics introduced by MC uncertainties which do not exist when estimating background from data (spin 0)
- An example is Parton Distribution Functions (PDF) which describe the structure of the proton



- Protons are not just up and down quarks (uud)
- We assume two partons interact



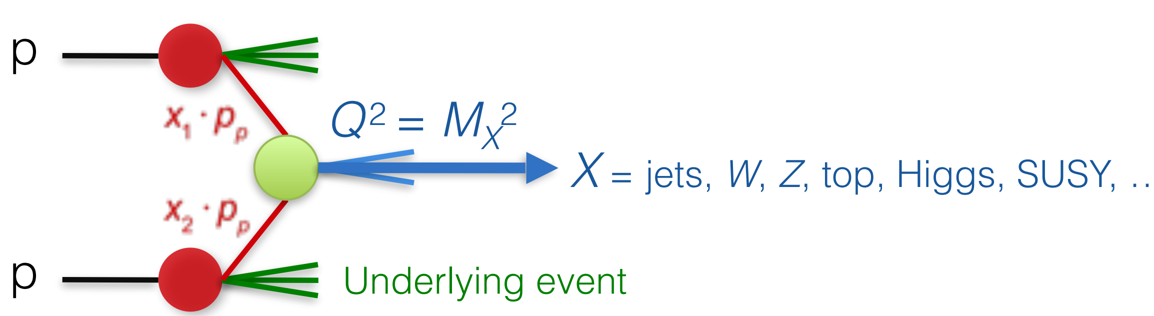
- Each has momentum fraction x1, x2 of hadron
  Given by parton distribution function (PDFs)
- Either valence (u,d) or gluons & sea quarks
- Cross section given by a convolution of PDF with parton parton cross section



$$\sigma = \sum_{\substack{partons\ i \\ colour\ j}} C_{ij} \int_0^1 d\tau \int_\tau^1 \frac{dx_1}{\tau} \left[f_1(x_1) f_2(\tau / x_1) \right] \sigma'(\tau s)$$

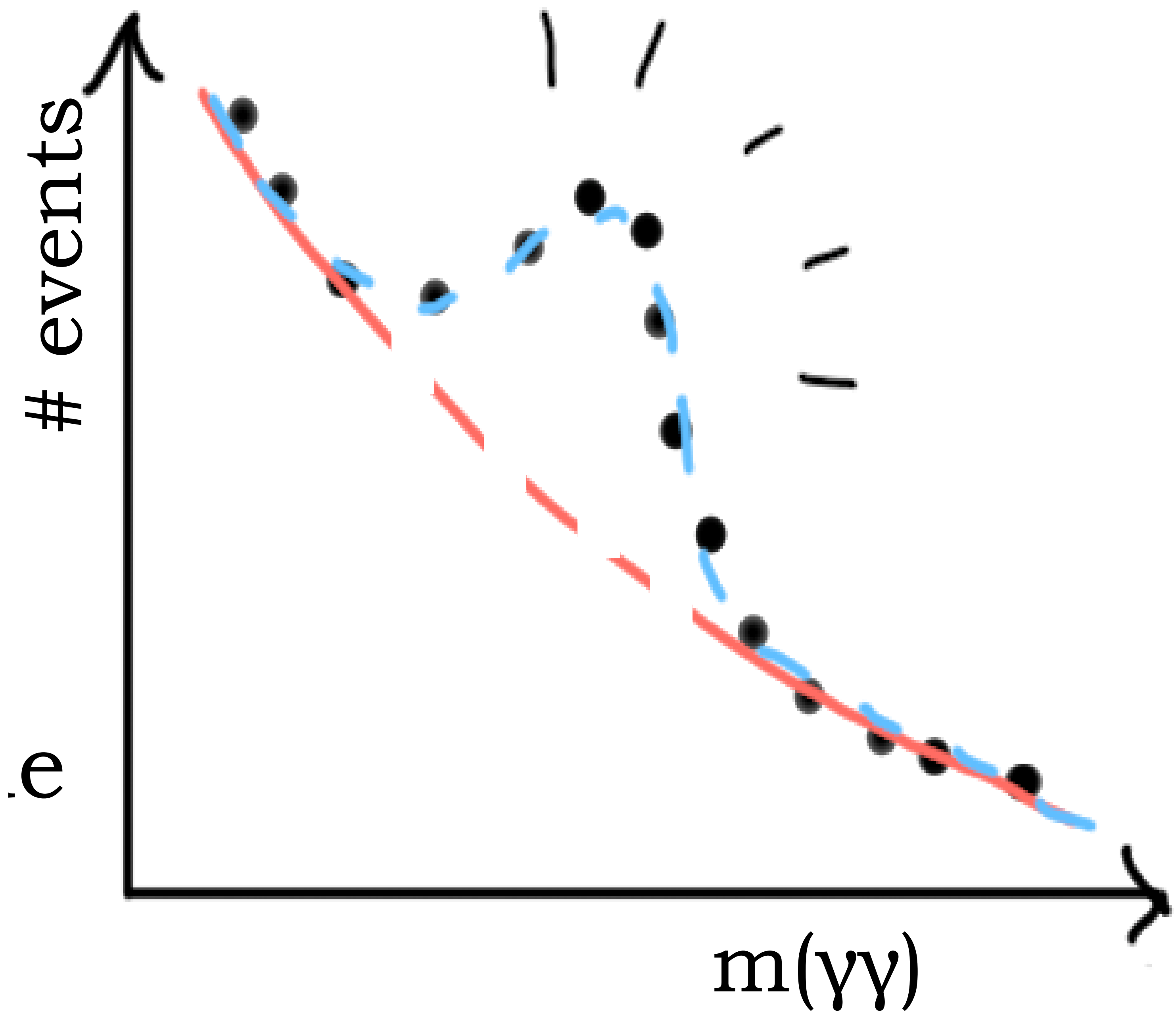
σ' *is partonic cross section*

$\tau = x_1 x_2$



The parton density functions rise dramatically towards low x:Low-*x* regime (eg, Higgs production) dominated by gluon−gluon collisions: “gluon collider”

- To avoid the need for MC to describe background, one can try to use DATA to estimate the background in the signal region
- Side band is a classical method:
  It requires statistics around the signal region

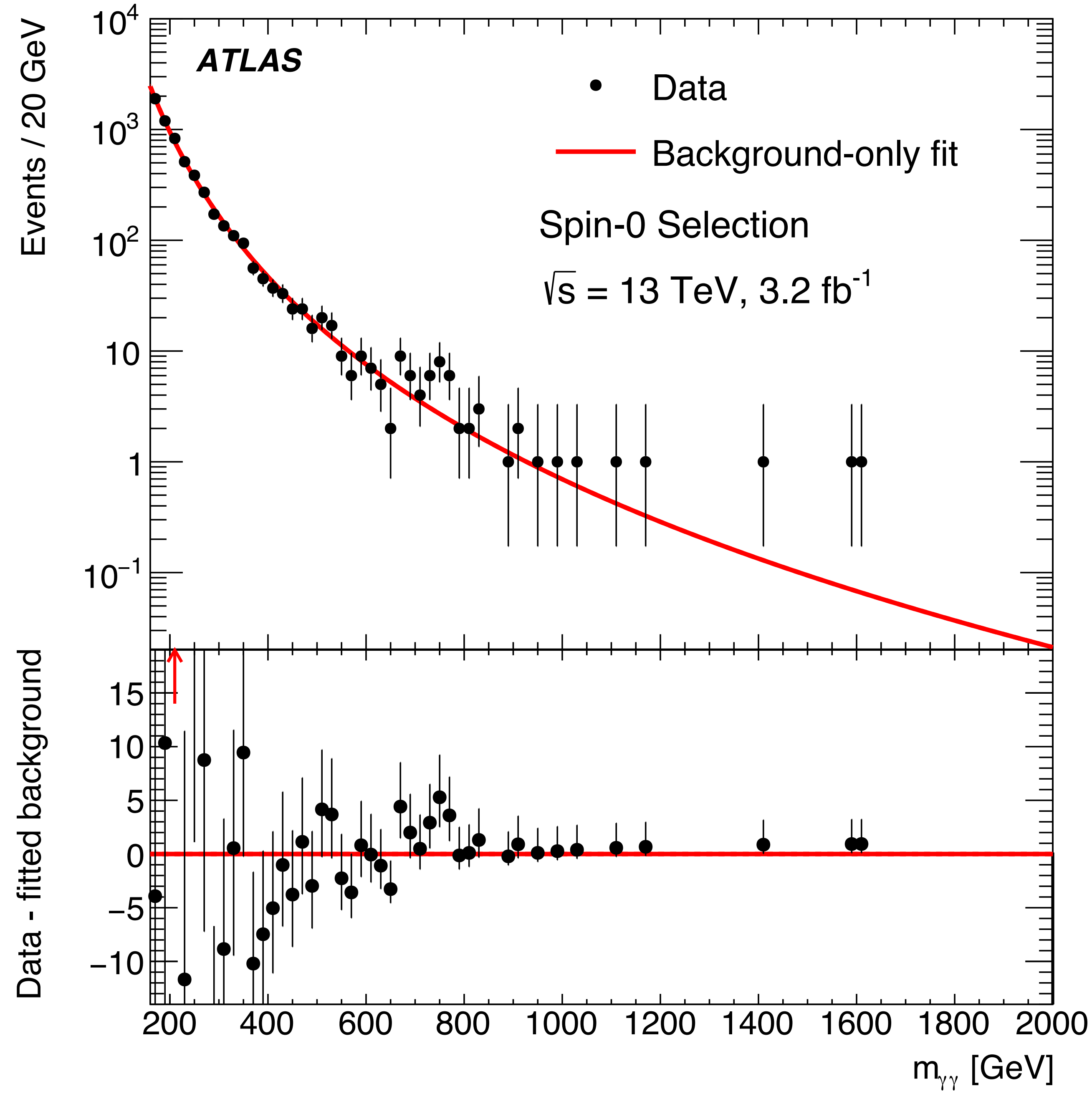


Functional Fit

- Allas, there is no statistics in the upper side of the signal region

- Fit is an alternative way

- Drawback of the fit, its empirical and is driven by one side of the mass region



Determining the BG (spin 0 functional form)

- Use the following functional form:

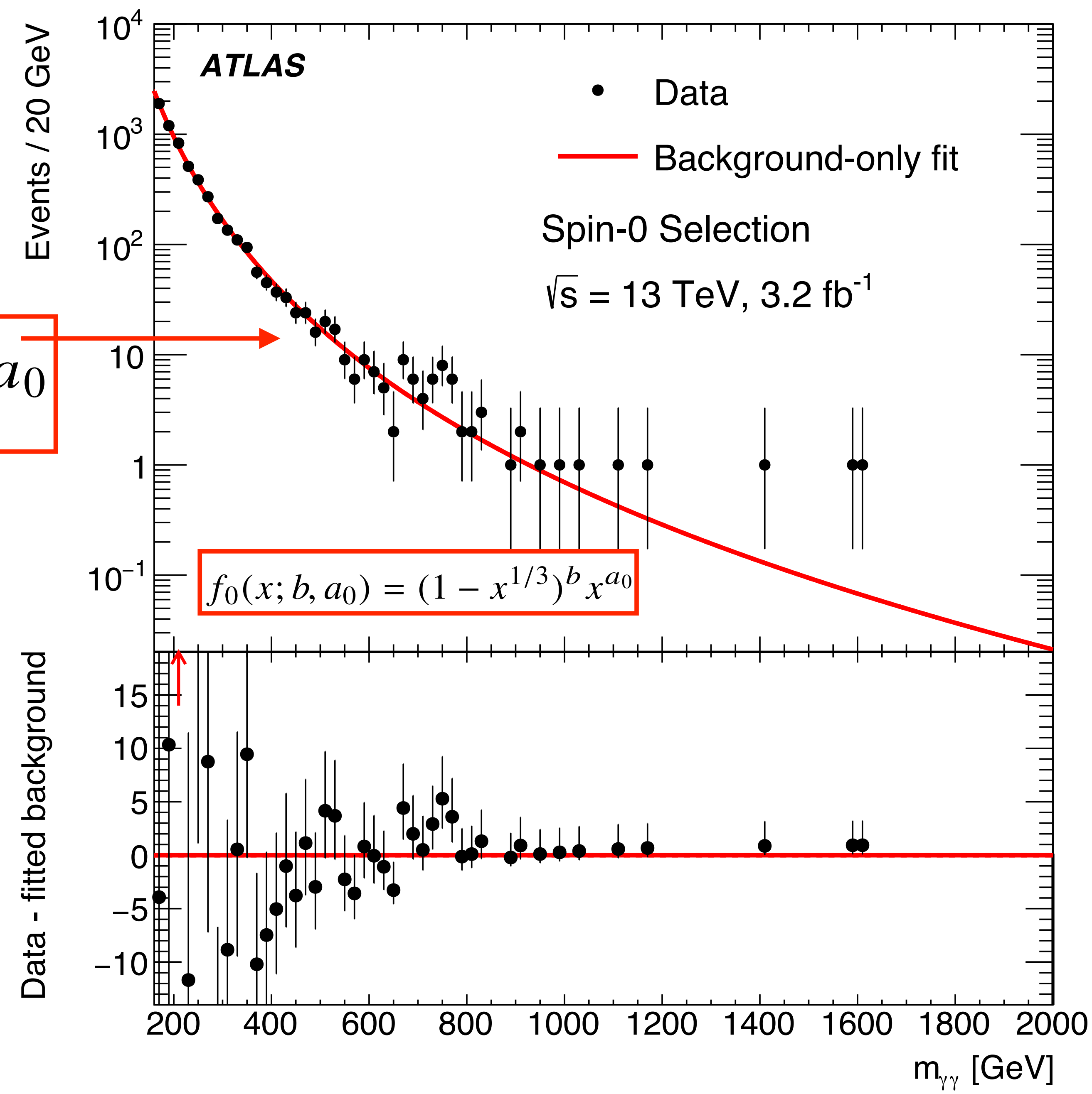
$$f_{k;d}(x; b, \{a_k\}) = (1 - x^d)^b x^{\sum_{j=0}^{k} a_j \log(x)^j}$$

$$x = m_{\gamma\gamma} / \sqrt{s}$$

- Use statistical chi^2 based test to determine the number of d.o.f-> k=0

$$\boxed{f_0(x; b, a_0) = (1 - x^{1/3})^b x^{a_0}}$$

  - 2 shape d.o.f. (+Normalization)



- Validate with MC (Sherpa based + reducible BG template)

- Fit s+b with b-only template. The resulting "signal" is considered spurious. We require spurious signal<20% b-uncertainty

Analysis

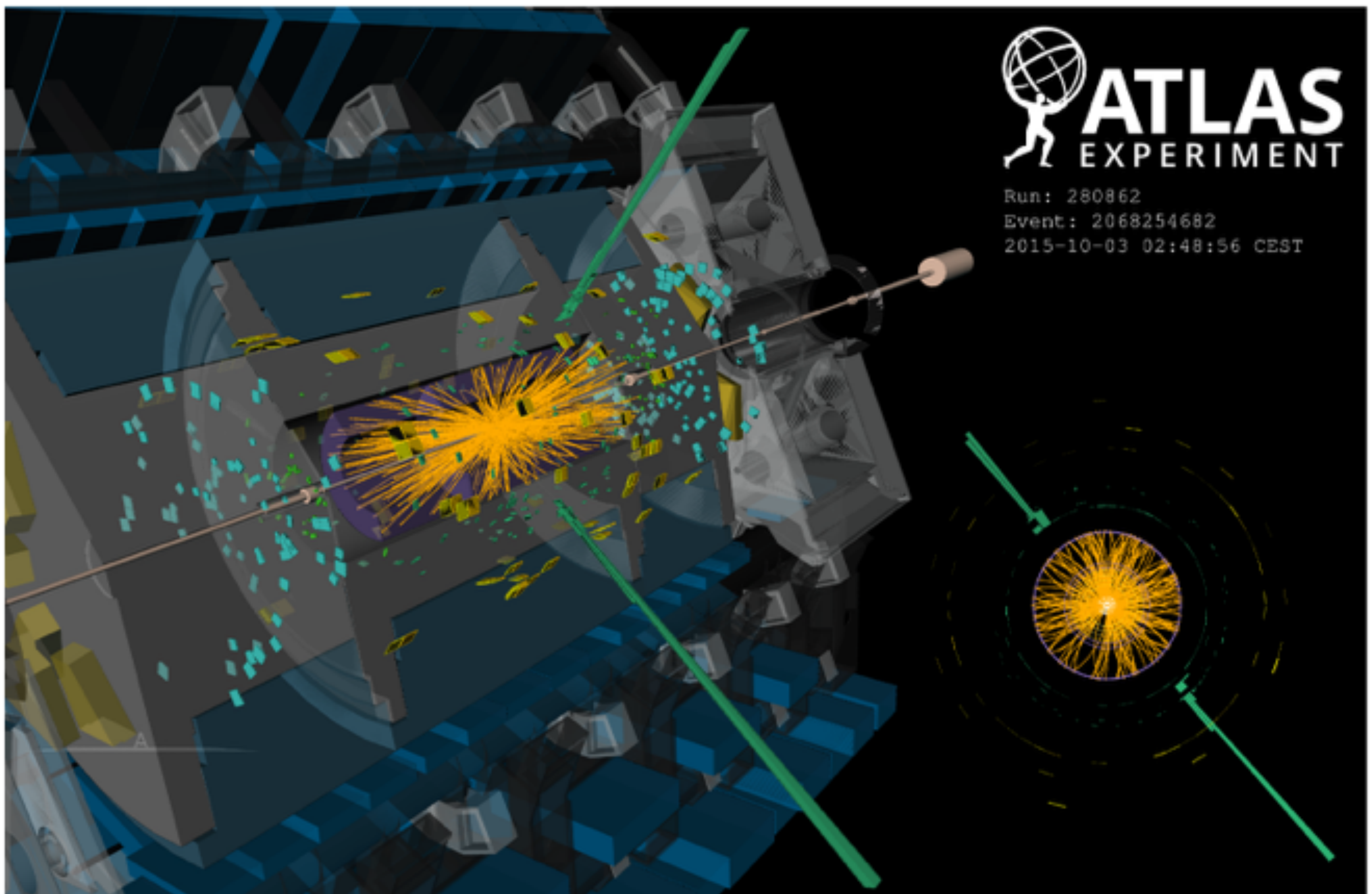
Trigger & Pre-Cuts

Trigger: p_T>35 (25) GeV for leading (subleading) photon.

Tight photon ID with

$E_T^{\gamma 1} > 40$ GeV, $E_T^{\gamma 2} > 30$ GeV ("baseline")

2 Isolated Photons



Trigger & Pre-Cuts

Spin 2 vs **Spin 0**

$E_T^{\gamma 1} > 55\text{GeV}, E_T^{\gamma 2} > 55\text{GeV}$.
Preserve acceptance at high mass.

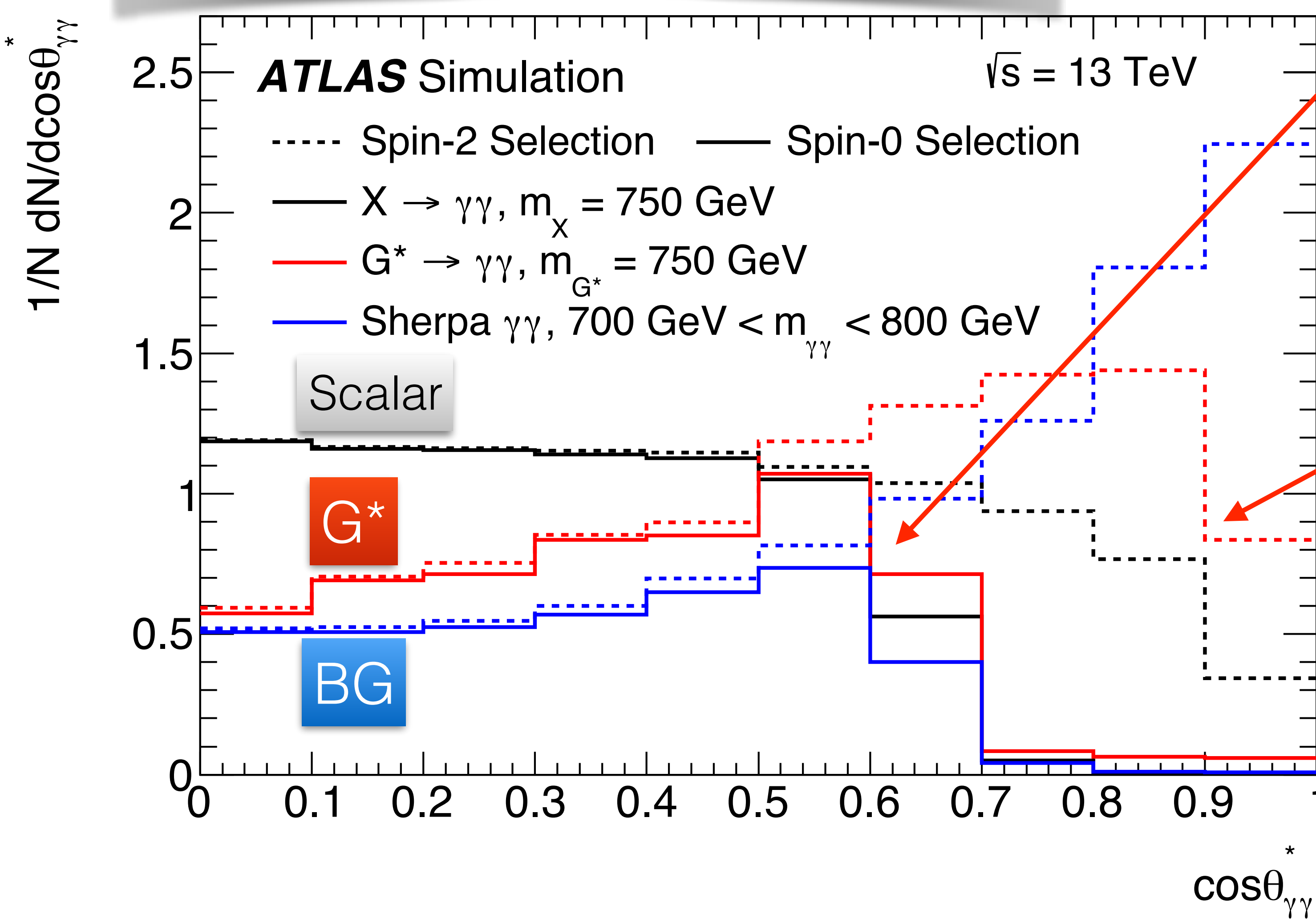
Optimized for Higgs-like signal:
$E_T^{\gamma 1} > 0.4 m_{\gamma\gamma}, E_T^{\gamma 2} > 0.3 m_{\gamma\gamma}$.
+20% significance for m_X > 600 GeV.

Collins Sopper

$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

Spin 0 cuts will reduce the sensitivity to the Graviton signal

Spin 2 Selection



Determining the Background

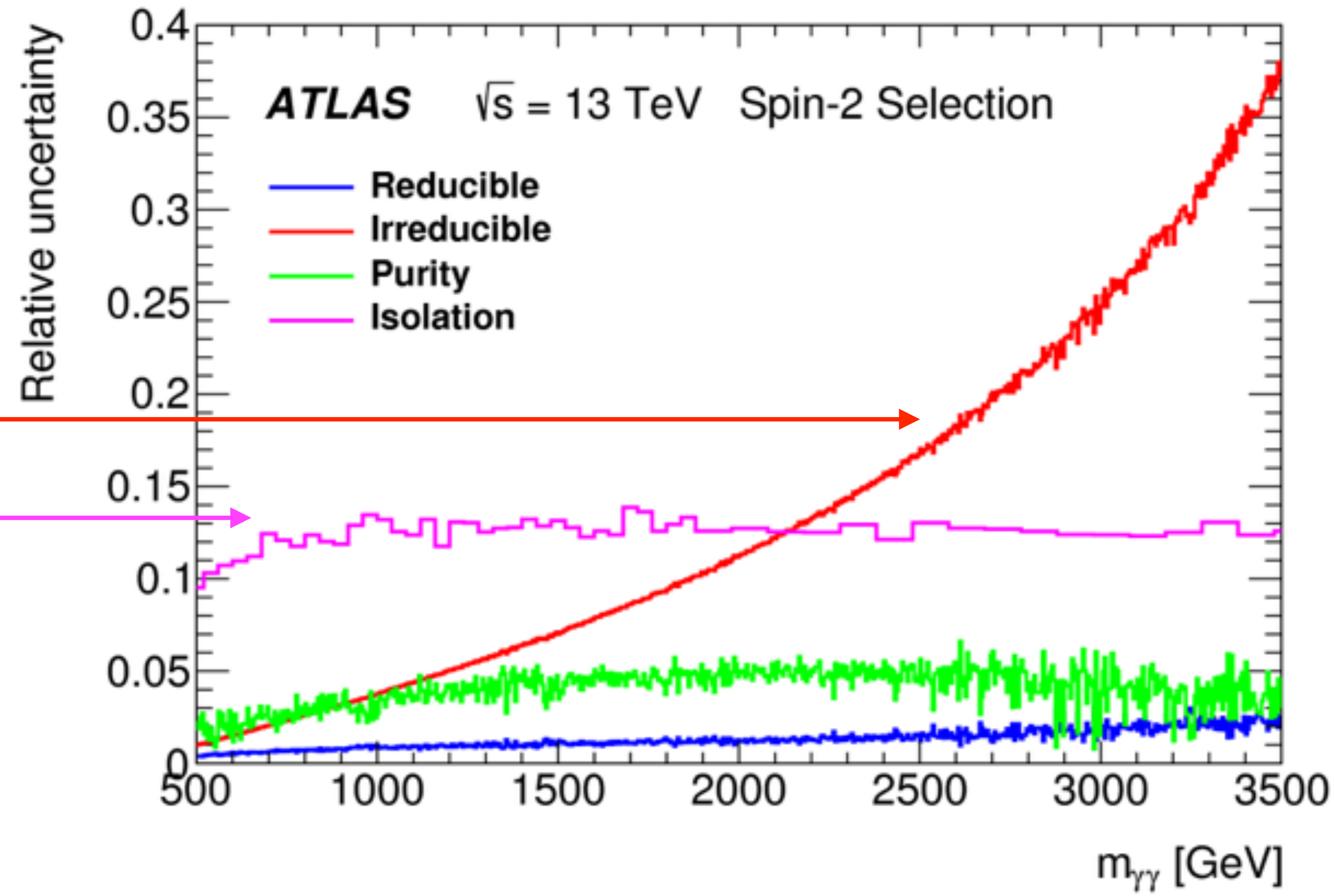
Monte Carlo simulation (Spin 2) VS **Functional Form (Spin 0)**

- **Correct LO SHERPA (fully simulated) with NLO Diphox**
- Search goes up to 5000 GeV-> **Shape from MC, Normalisation from Data**
- Reducible BG determined from DATA, extrapolated with function to high $m\gamma\gamma$

- Use LO SHERPA to obtain and validate the functional form
- Function is then fitted and constrained by DATA all over the relevant mass range (150-2000 GeV)
- Use smooth functional form

Monte Carlo simulation (Spin 2)

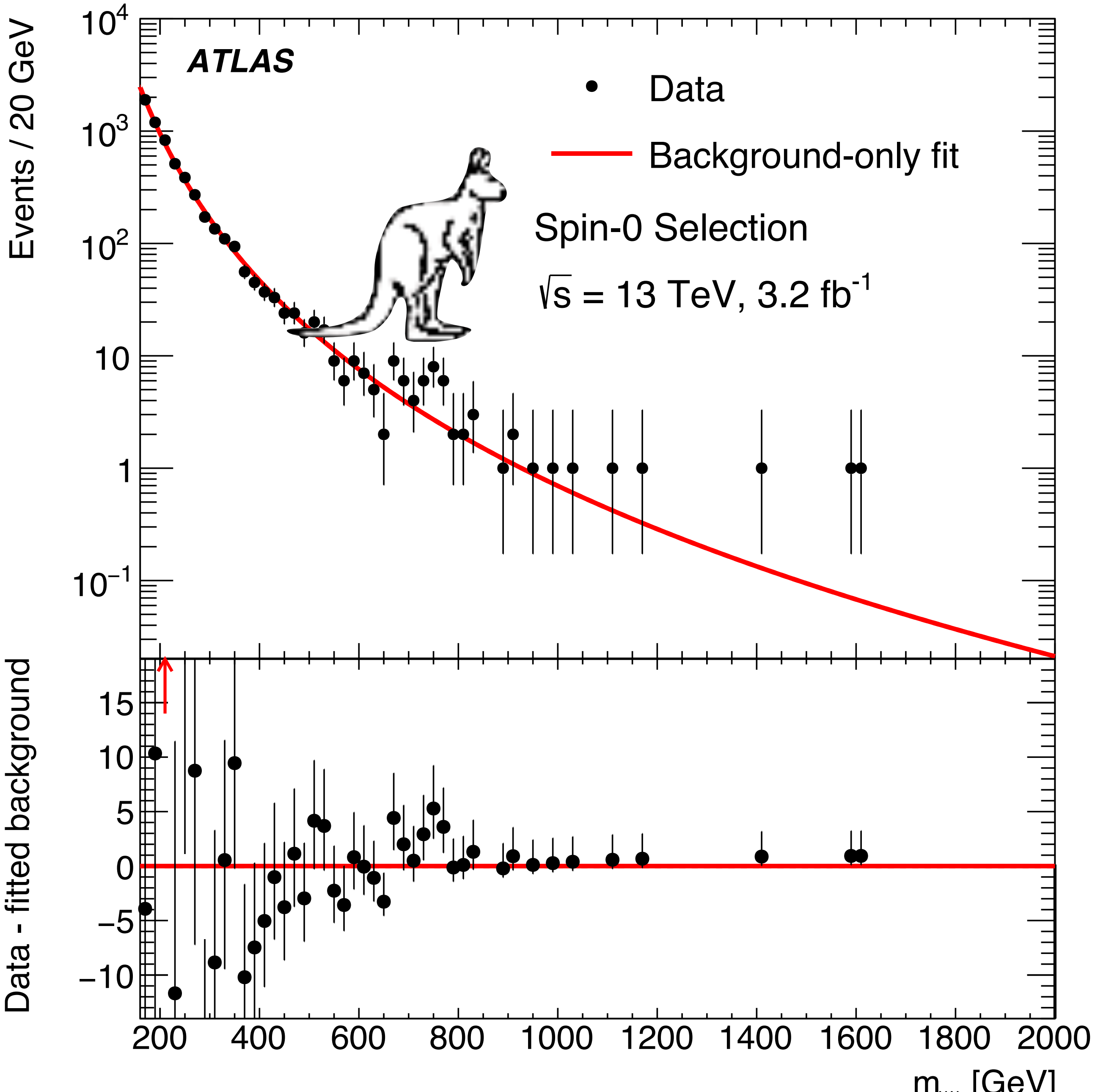
- Price of MC in uncertainties
- PDF and Renormalisation Scale QCD (Irred) takes off to 35% @ 3500 GeV
- Isolation uncertainty (due to parton level matching with full simulation)



RESULTS

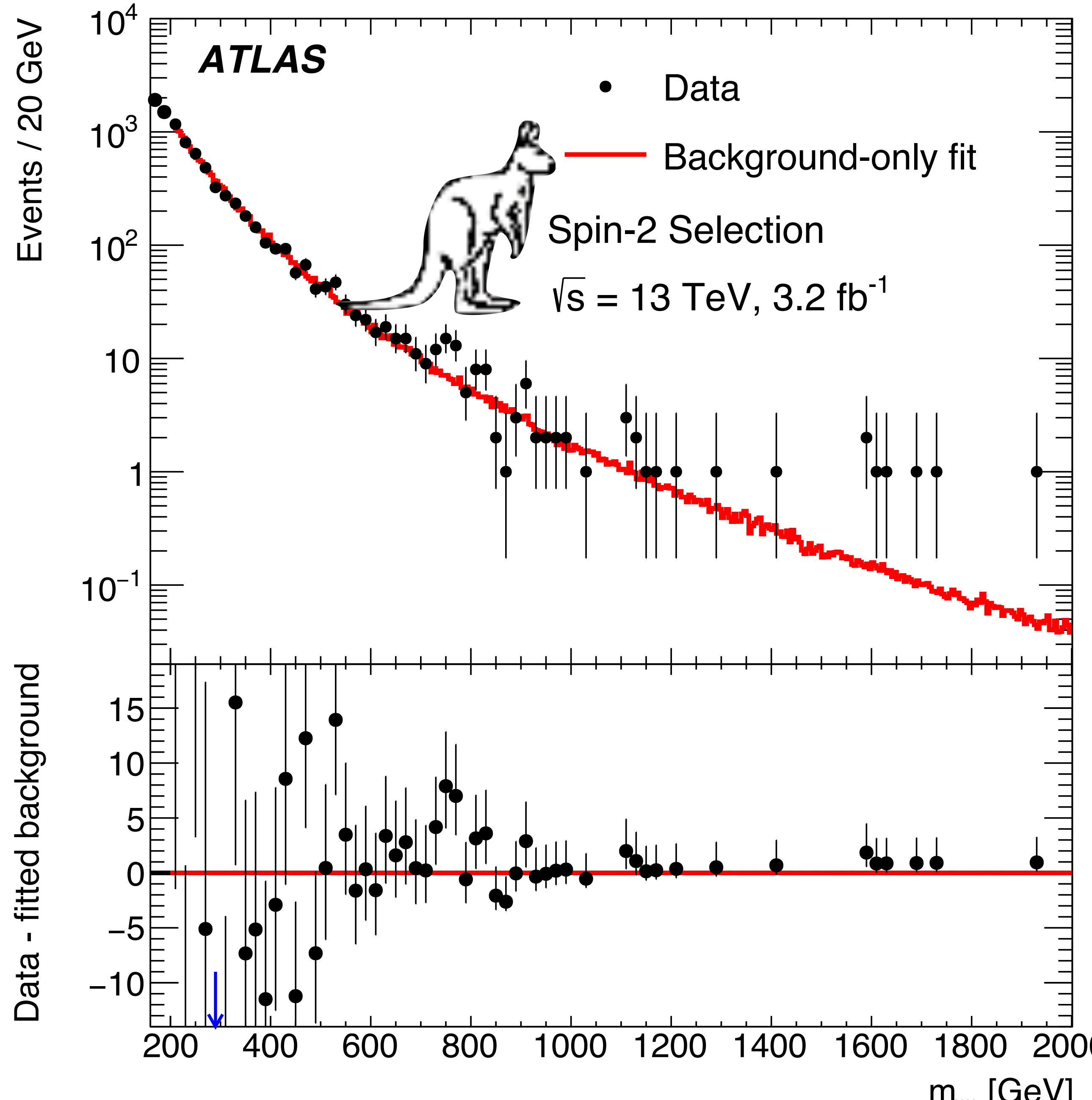
Spin 0

7391 (2878) events for $m_{\gamma\gamma}$ > 150 (200) GeV



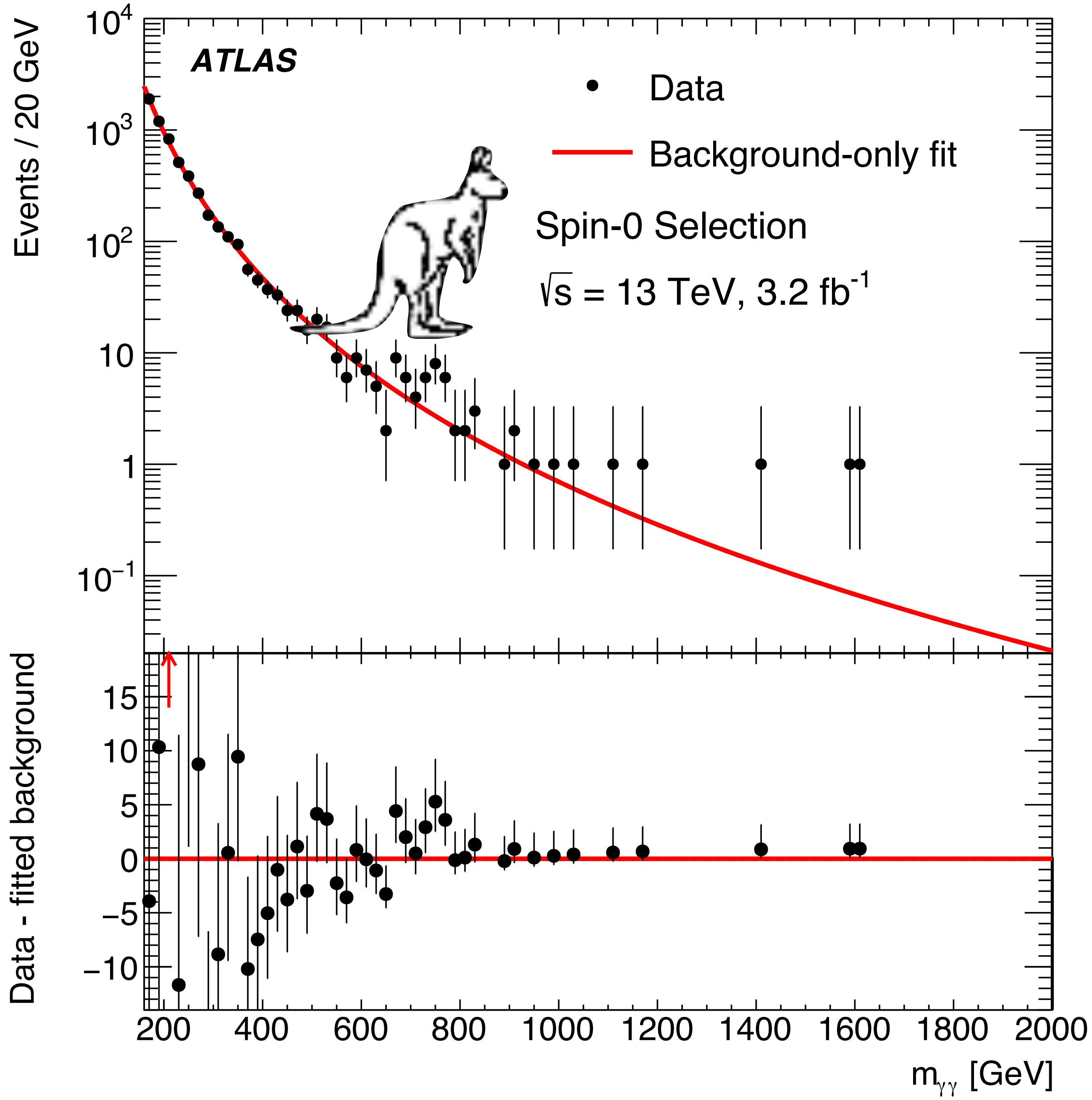
Spin 2

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



Spin 0

7391 (2878) events for $m_{\gamma\gamma} > 150$ (200) GeV



p-value
is the probability of the background with the data.

$2\sigma \sim 5\% \sim 1:20$

$3\sigma \sim 0.003 \sim 1:330$

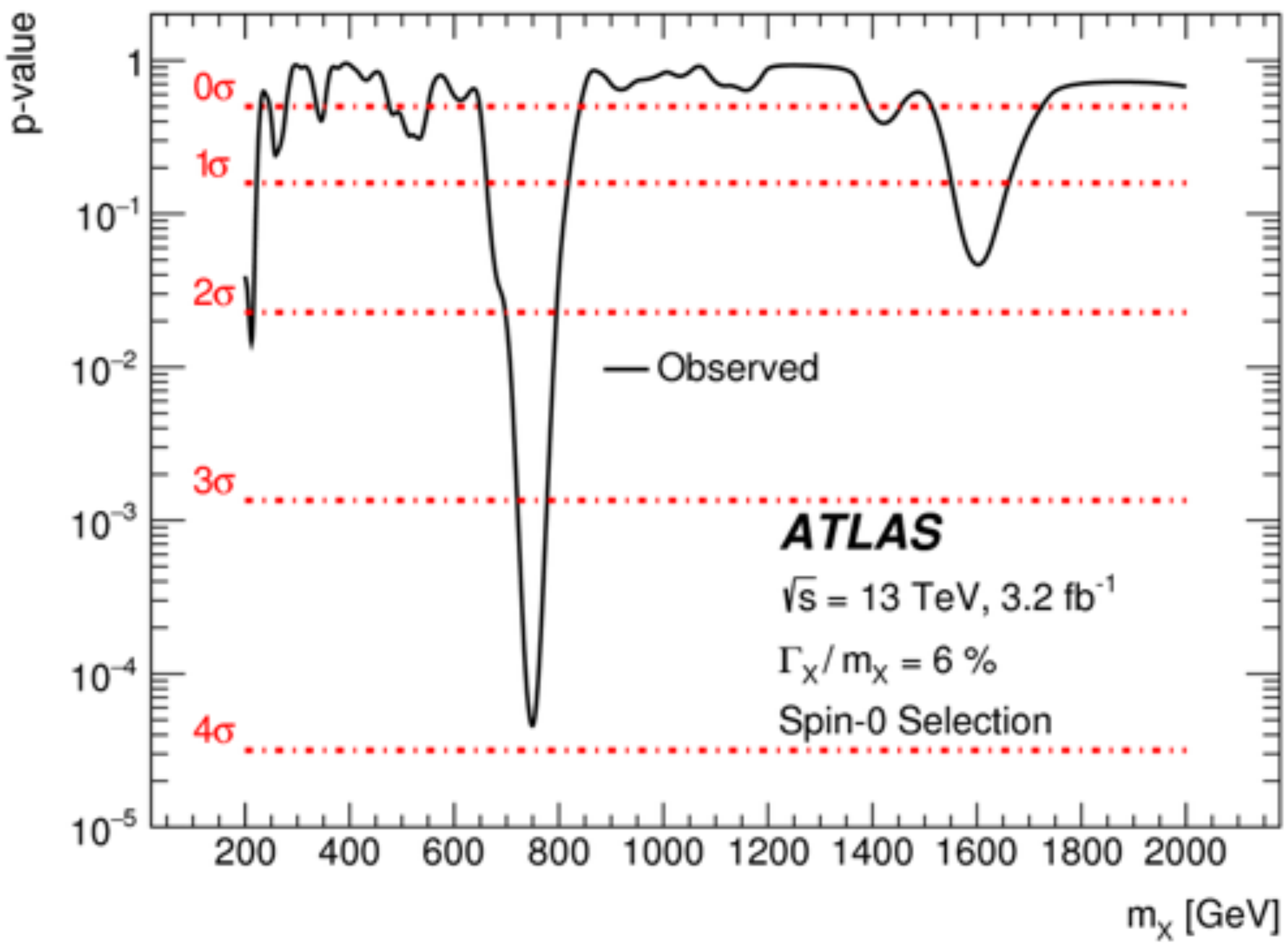
$5\sigma \sim 3 \cdot 10^{-7} \sim 1:3.3\text{ M}$

Spin 0

Largest significance

$m_X \sim 750\text{GeV}, \Gamma_X \sim 45\text{GeV}(6\%)$

Local Z = **3.9σ**



Spin 0

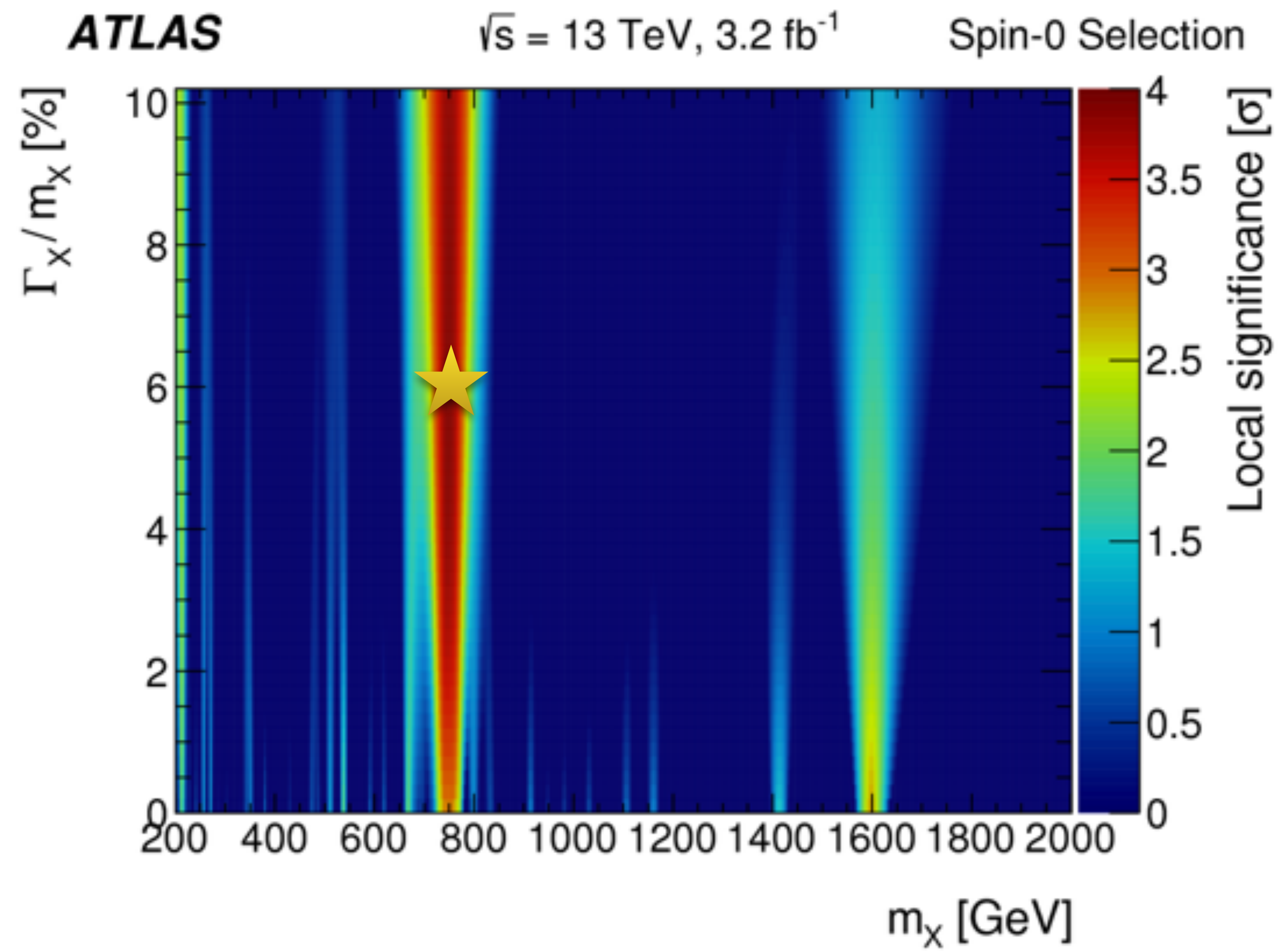
2D Scan

Largest significance

$m_X \sim 750$GeV, $\Gamma_X \sim 45$GeV(6%)

Local Z = **3.9σ**

m=200-2000 GeV
Γ_X/m_X=0-10%

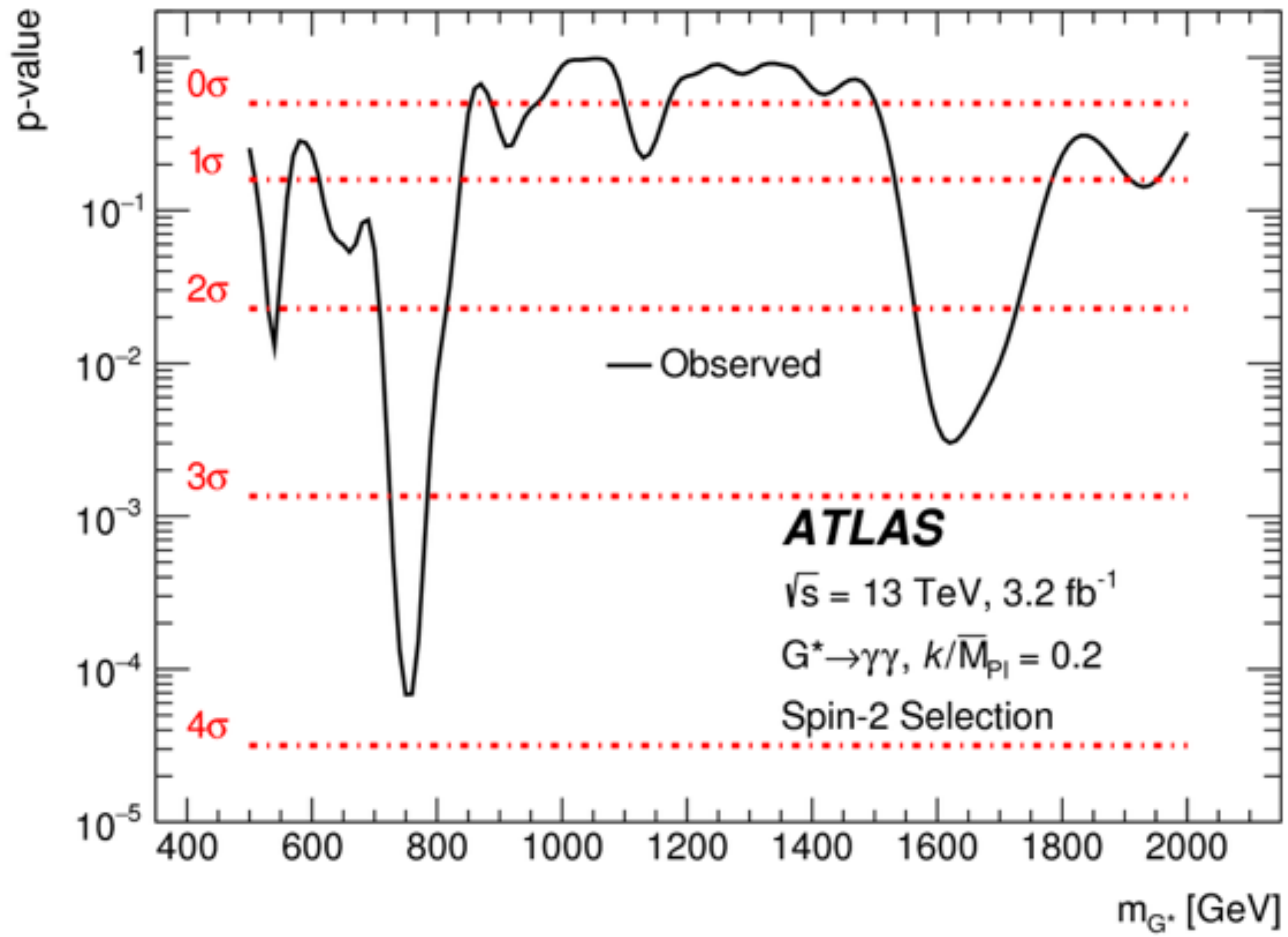


Spin 2

Largest significance

$m_G \sim 750GeV, \kappa/M_{Pl} \sim 0.23$
$(\Gamma_G \sim 57$ Gev$\sim 7\% m_G)$

Local Z = **3.8σ**



Spin 2

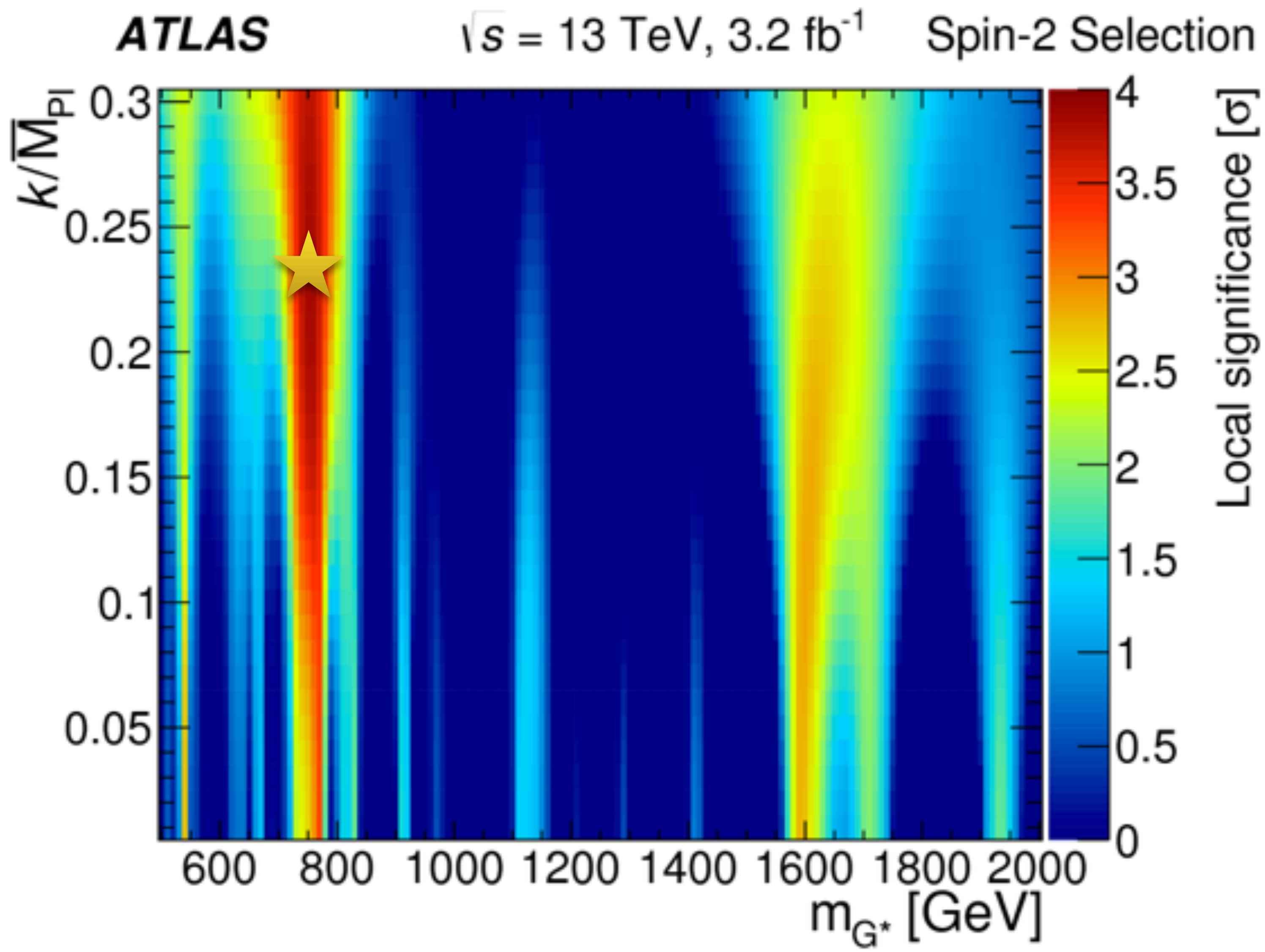
2D Scan

Largest significance

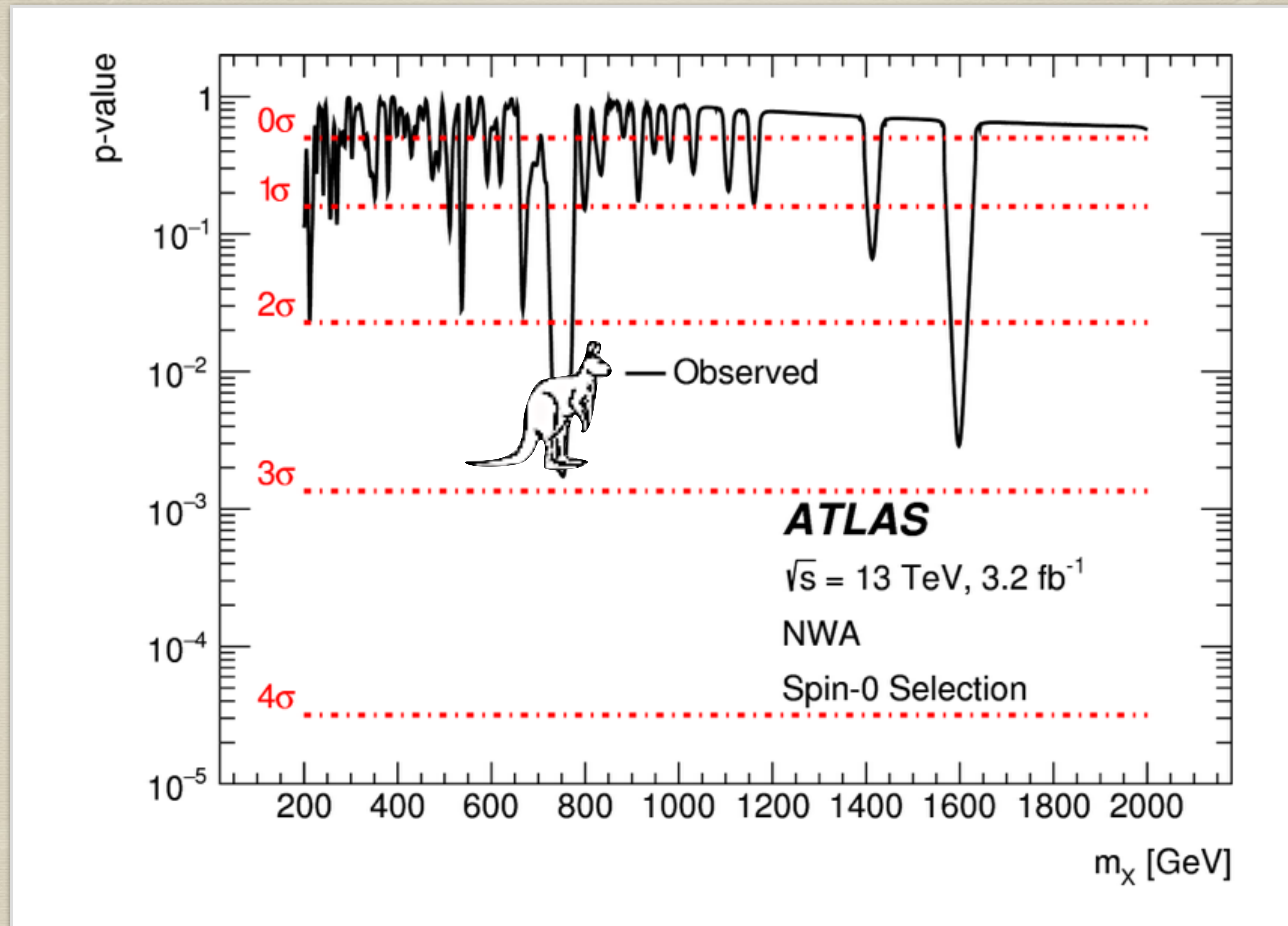
$m_G \sim 750$GeV, $\kappa/M_{Pl} \sim 0.23$

($\Gamma_G \sim 57$ Gev~7%m_G)

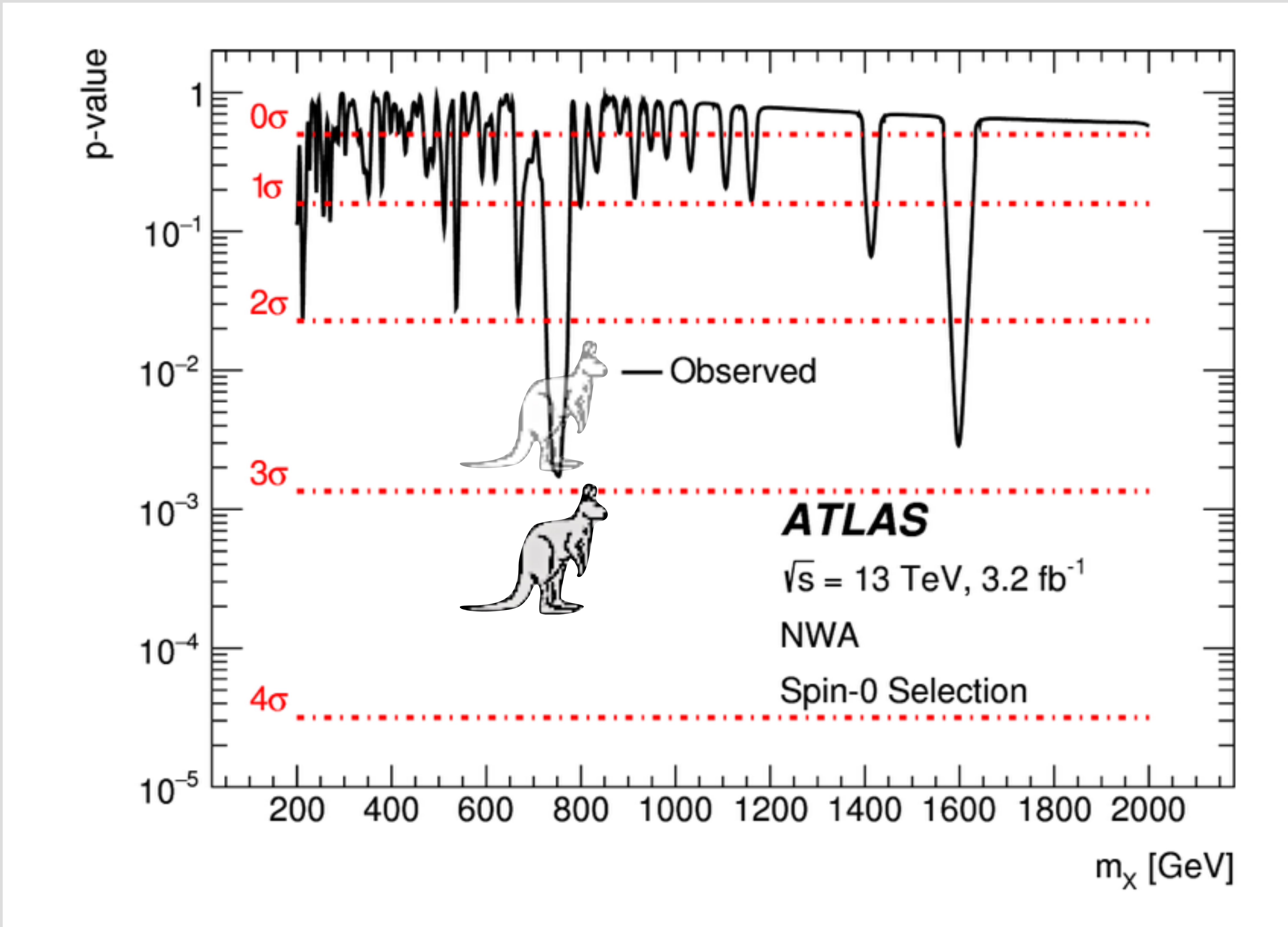
Local Z = **3.8σ**



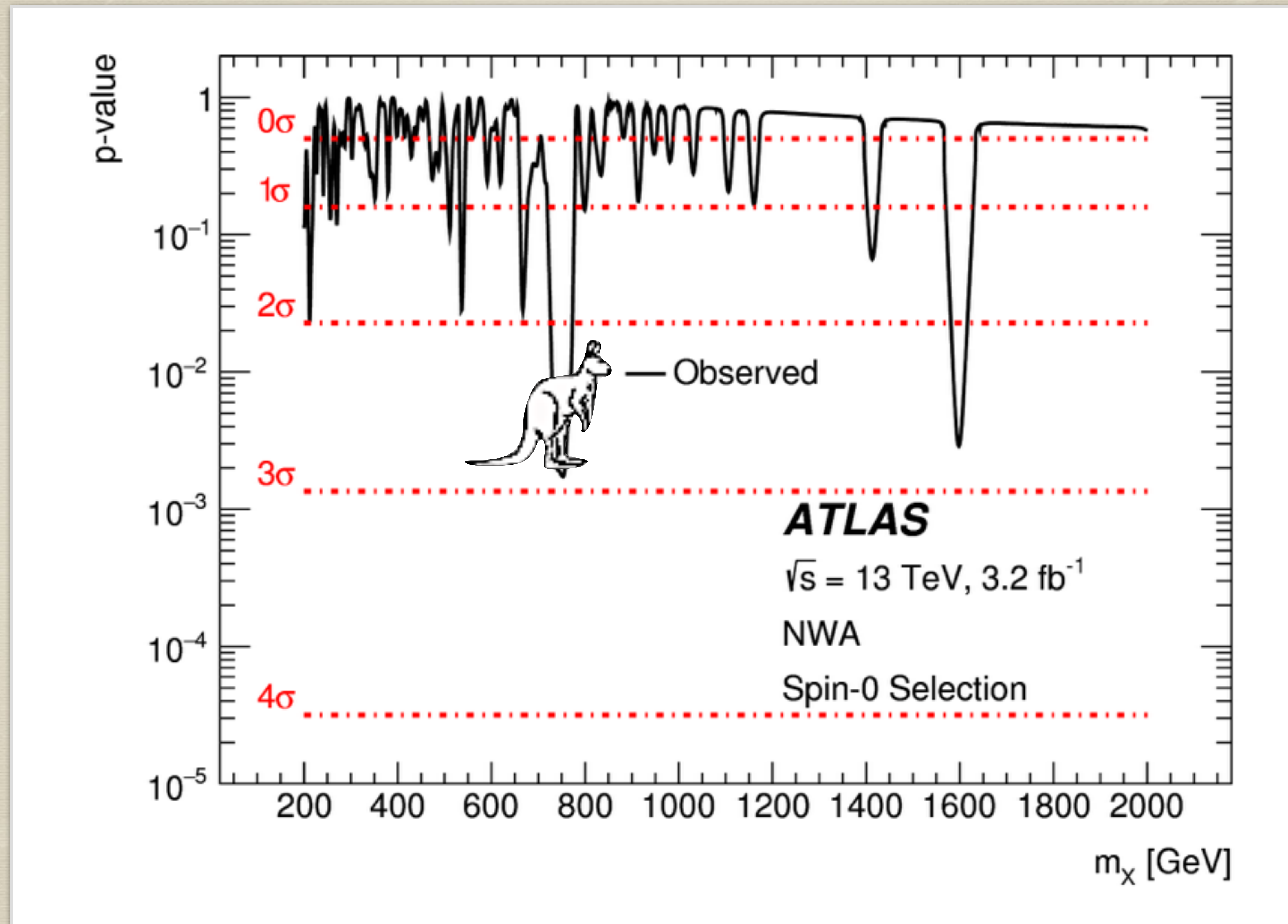
SUMMARY 2015: Where do we go from here?



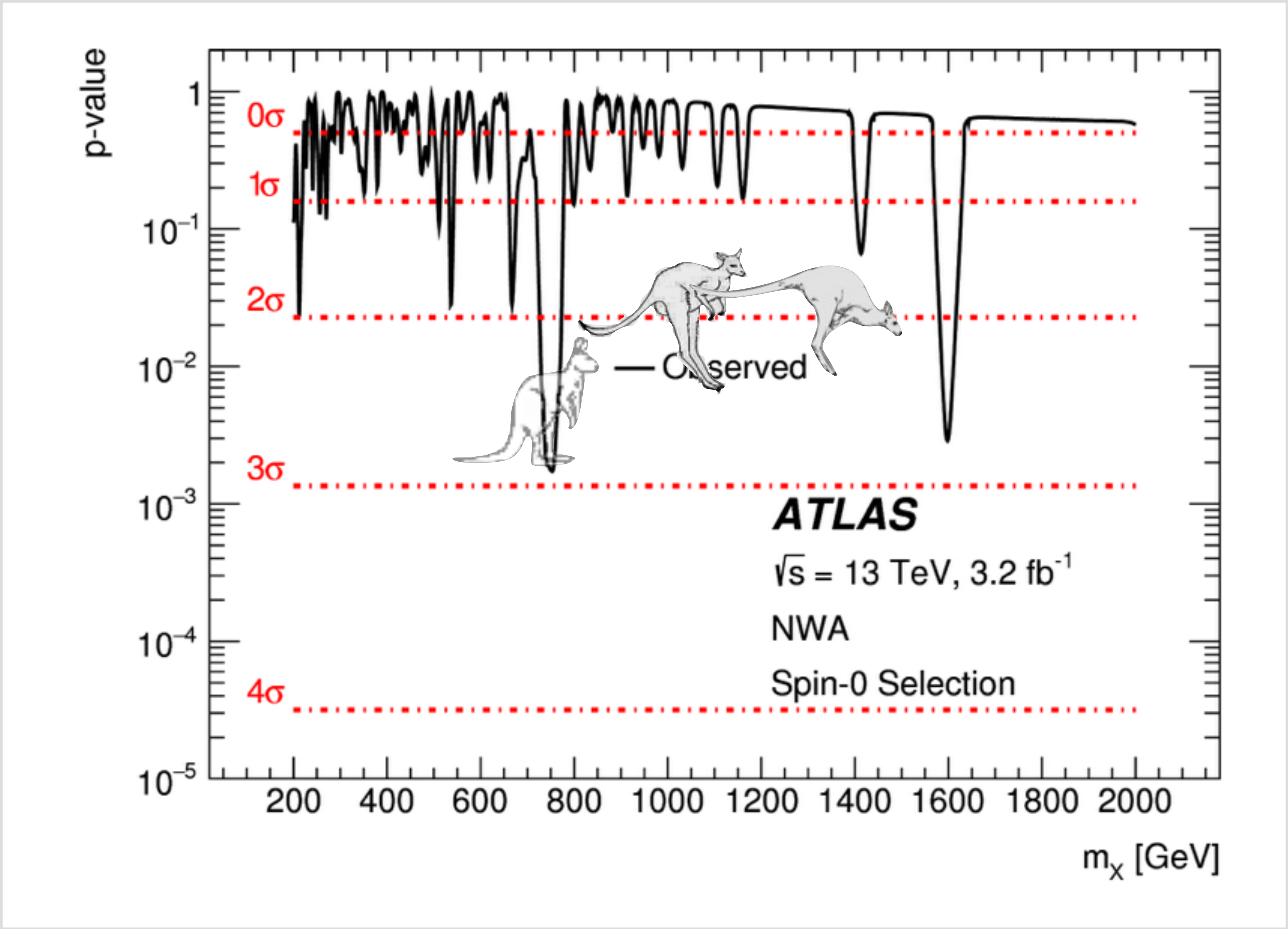
SUMMARY 2015: Here? (establishing a signal!)

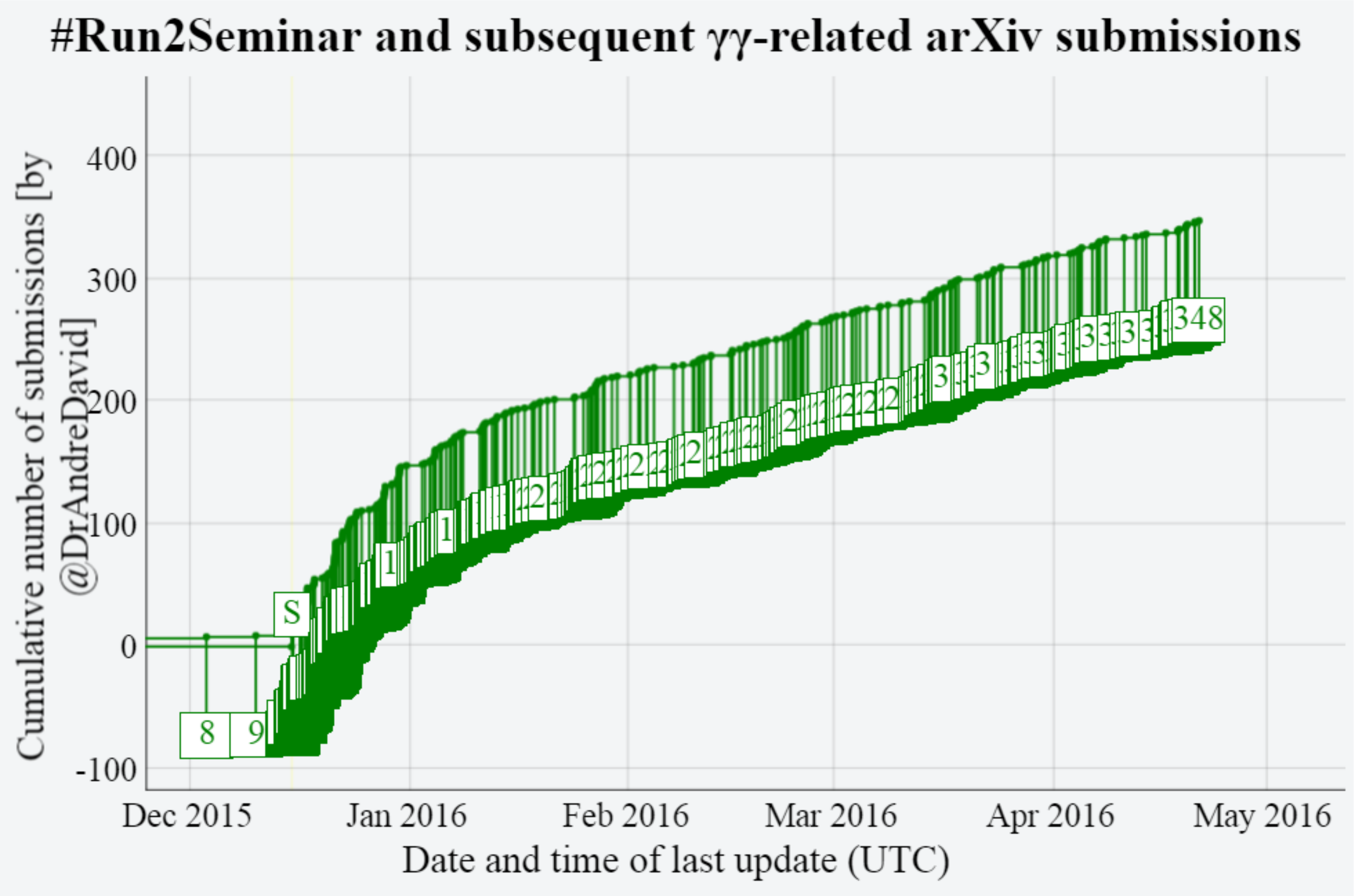


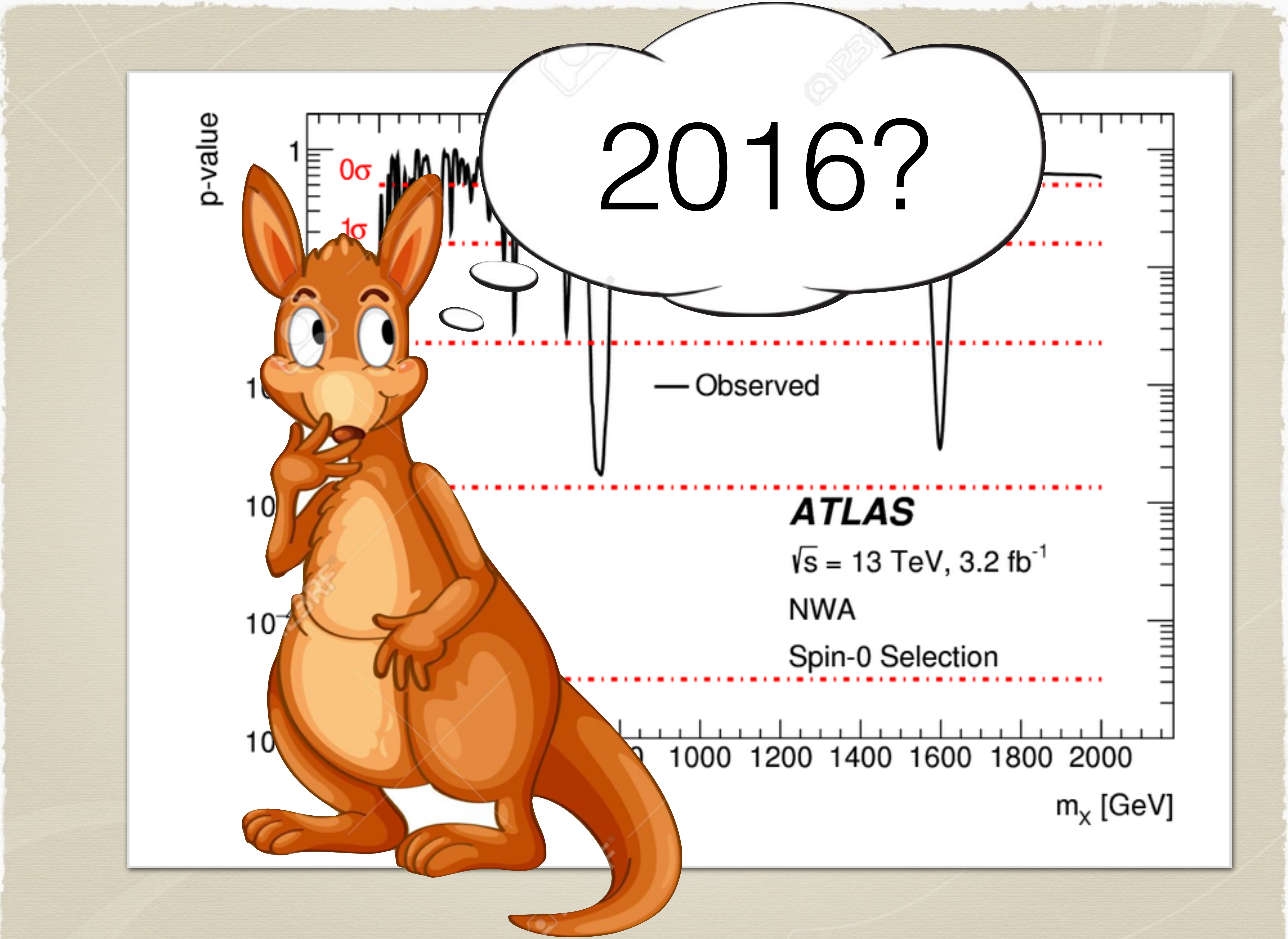
SUMMARY 2015: OR



SUMMARY 2015: THERE

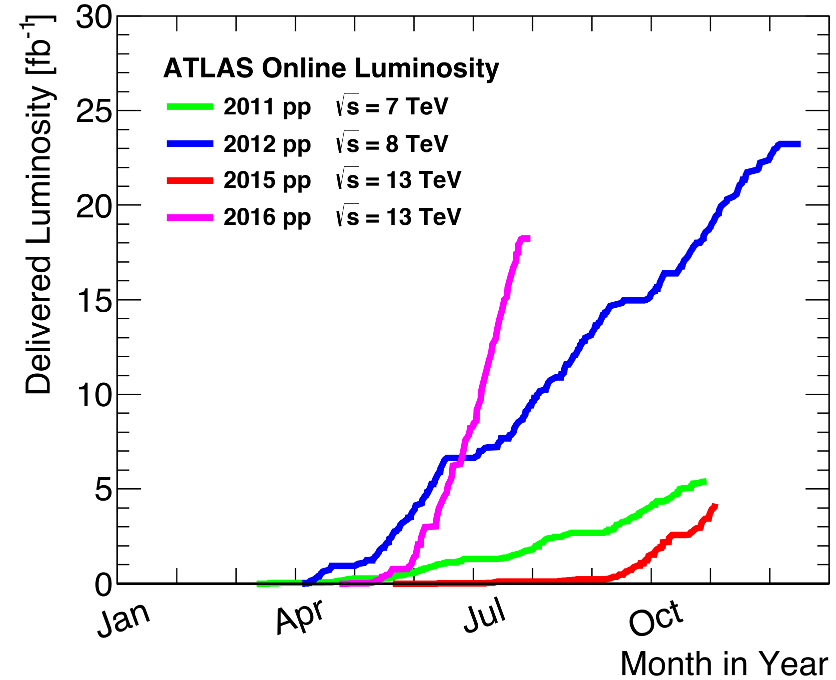



#Run2Seminar and subsequent γγ-related arXiv submissions
Cumulative number of submissions [by @DrAndreDavid]
400
300
200
100
0
-100
Dec 2015
Jan 2016
Feb 2016
Mar 2016
Apr 2016
May 2016
Date and time of last update (UTC)
S
8
9
348

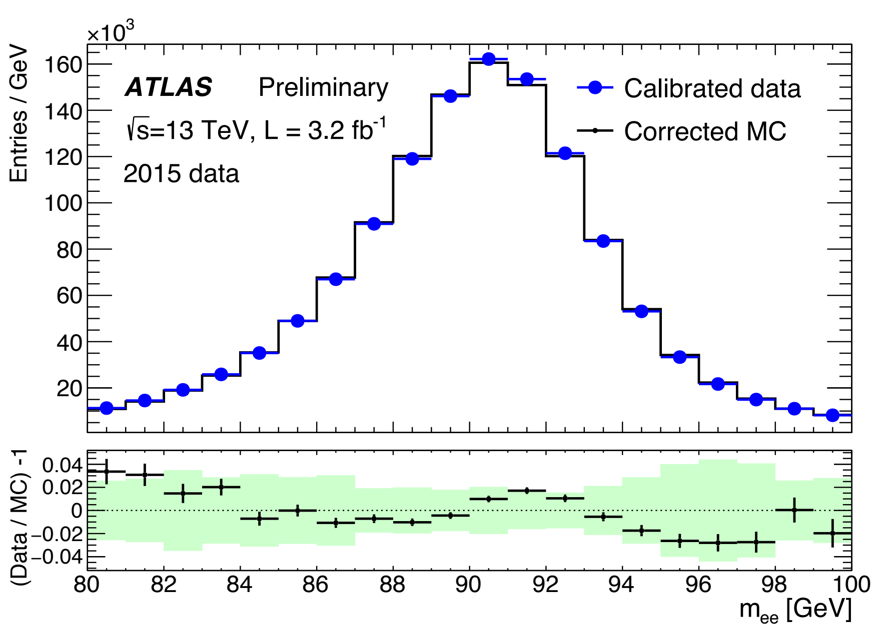

2016?
p-value
1
0σ
1σ
— Observed
ATLAS
√s = 13 TeV, 3.2 fb-1
NWA
Spin-0 Selection
1000
1200
1400
1600
1800
2000
m_X [GeV]

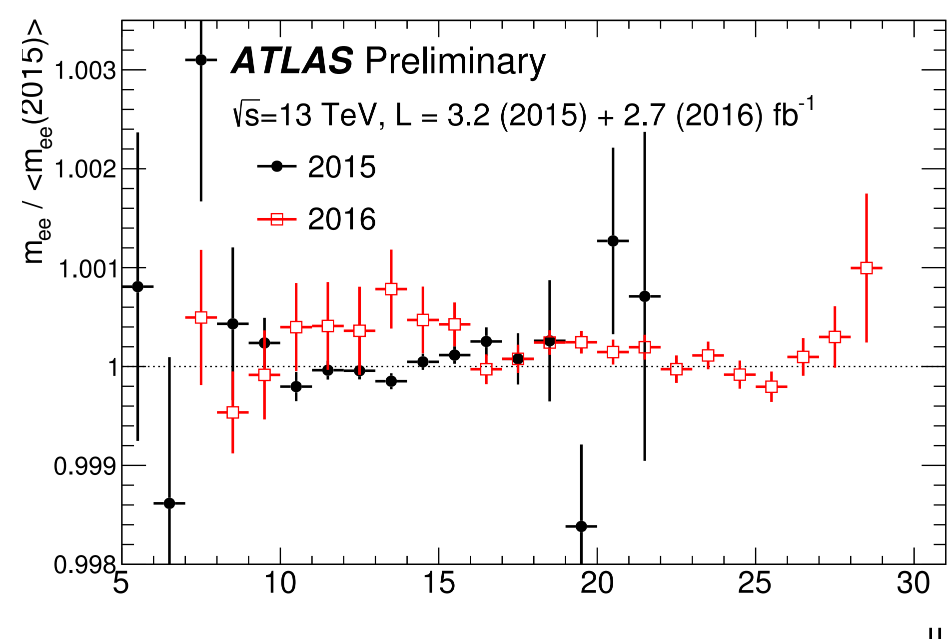
2016 DATA Taking

- Impressive performance of the LHC
  - Peak luminosity beyond design
  - ATLAS data-taking efficiency > 90%
  - 12.2 fb^{-1} of 2016 data analysed
    - Data taken until July 16 (~ 4 weeks ago!)

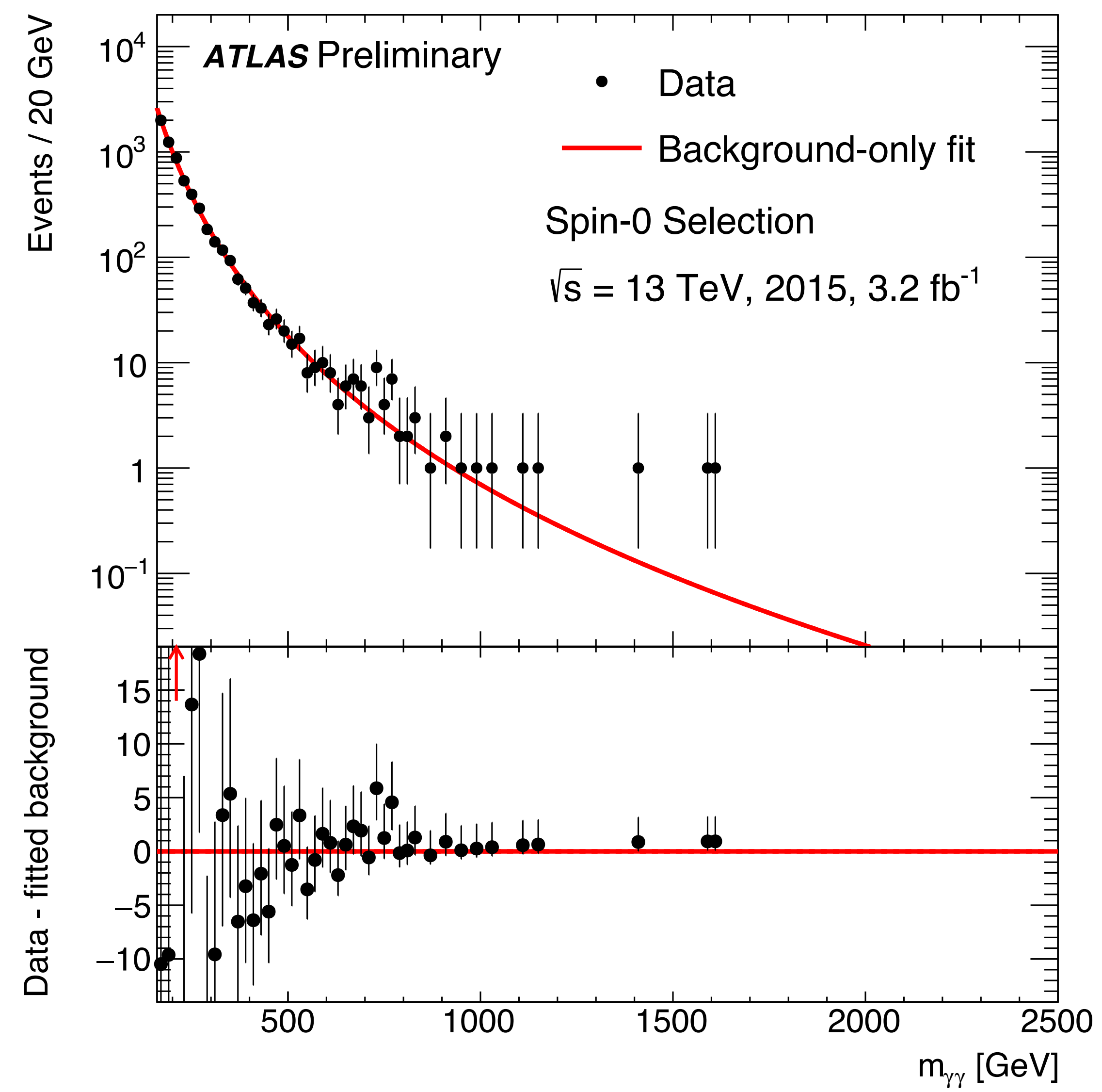


- Improved reconstruction and energy calibration, based on experience with 13 TeV data



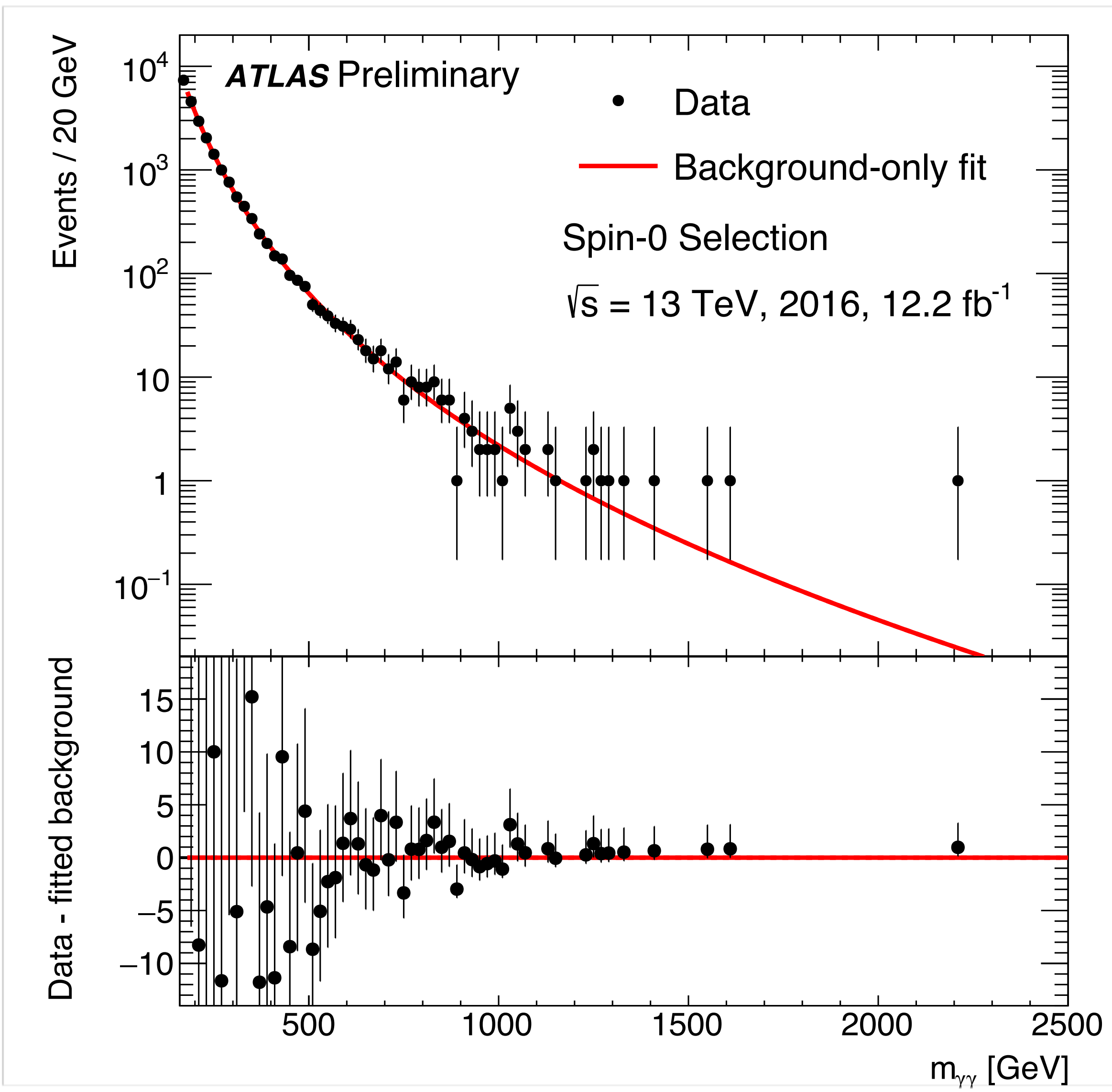


- 2015 reprocessed and reanalysed
  - Excess @ 750 GeV → 730 GeV
  - 3.9σ → 3.4σ local significance
    - Basically 2 events affected by new reconstruction and calibration



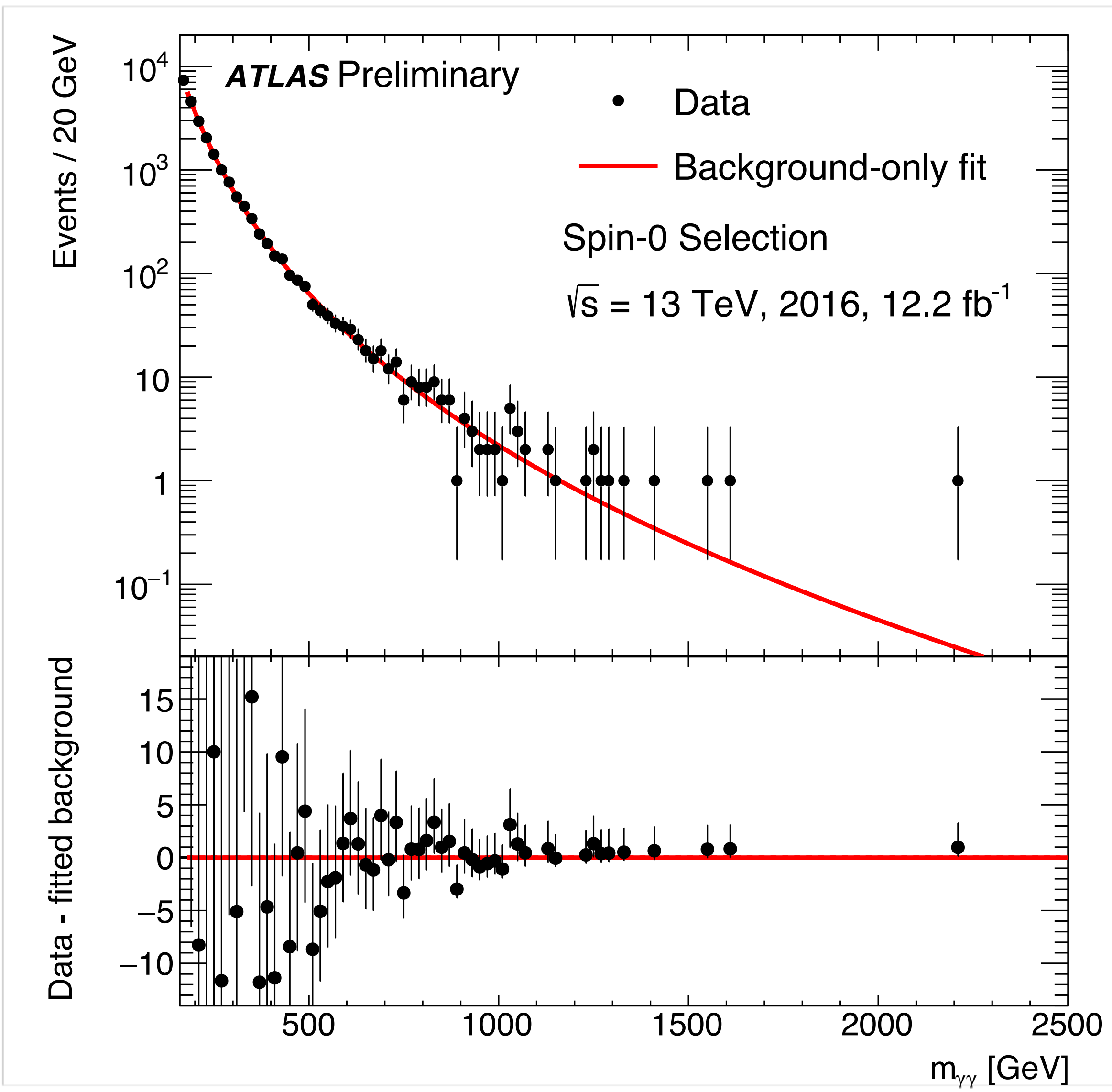
With the higher pileup conditions of the 2016 data, more work is needed to complete the analysis in the extended acceptance of the spin-2 selection

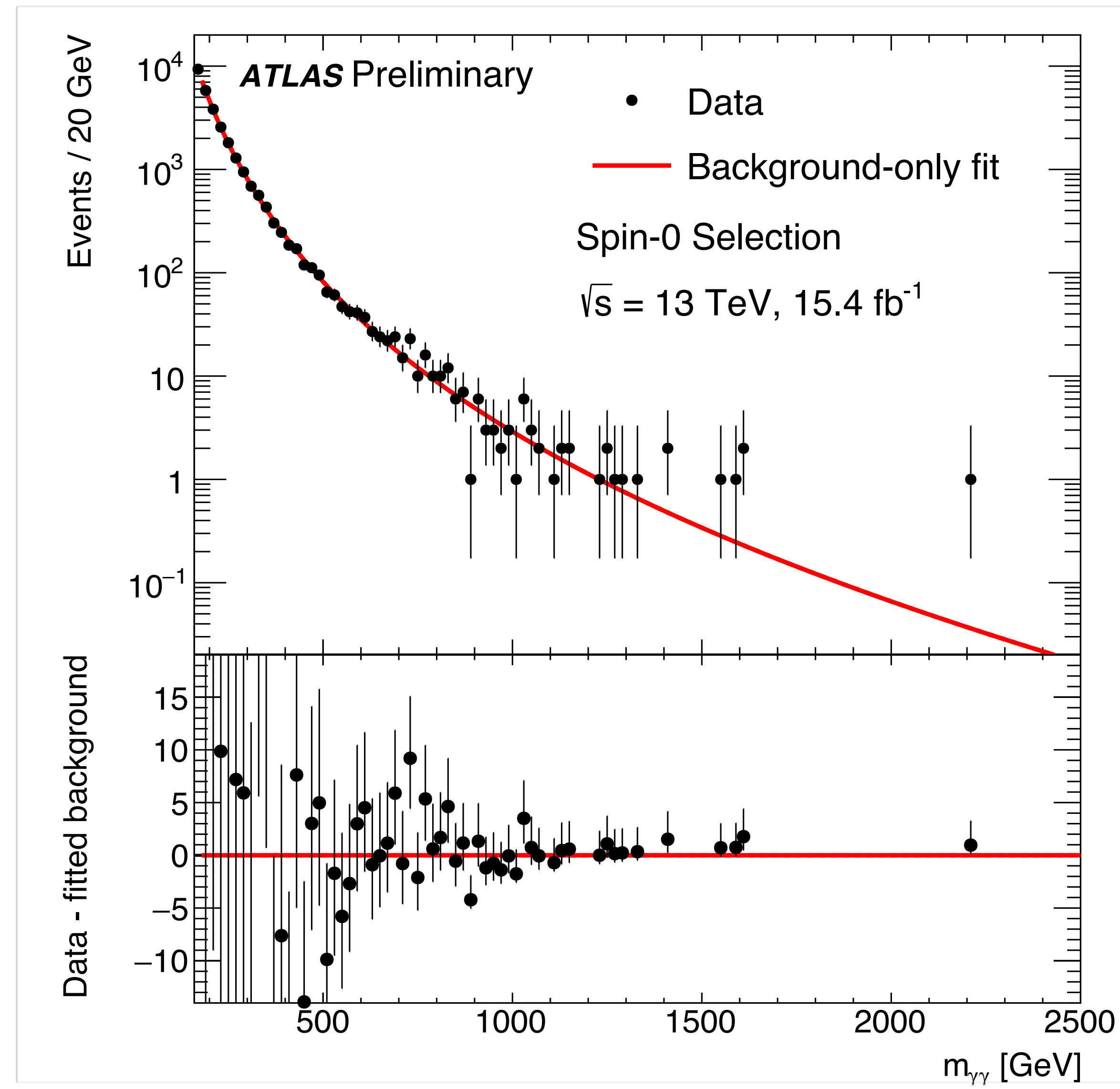
2016 Alone



No significant excess in 2016 data,

Combined 2015+2016

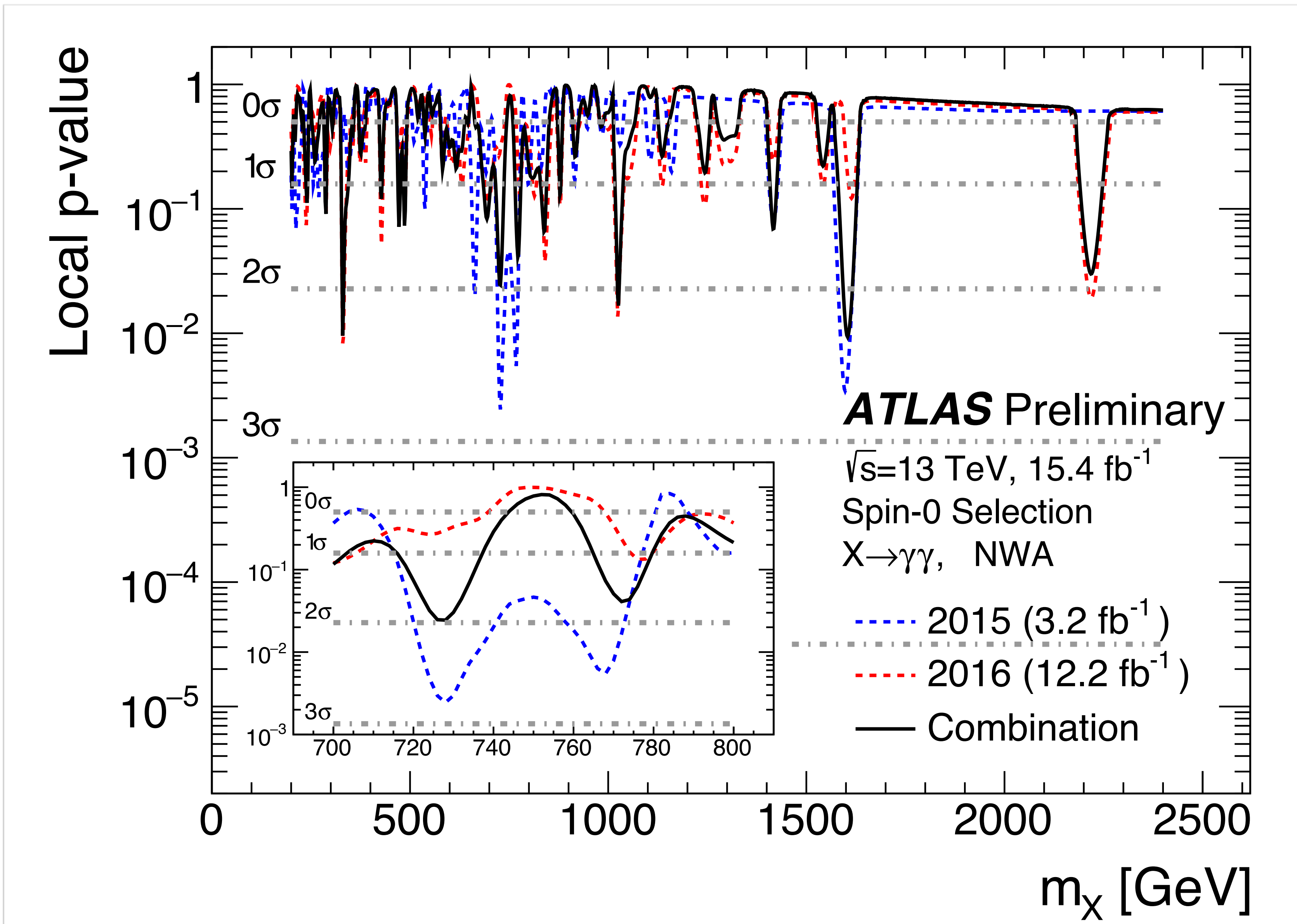




No significant excess in 2016 data, compatibility between 2015 and 2016 datasets for signal cross-section @ 730 GeV: 2.7σ

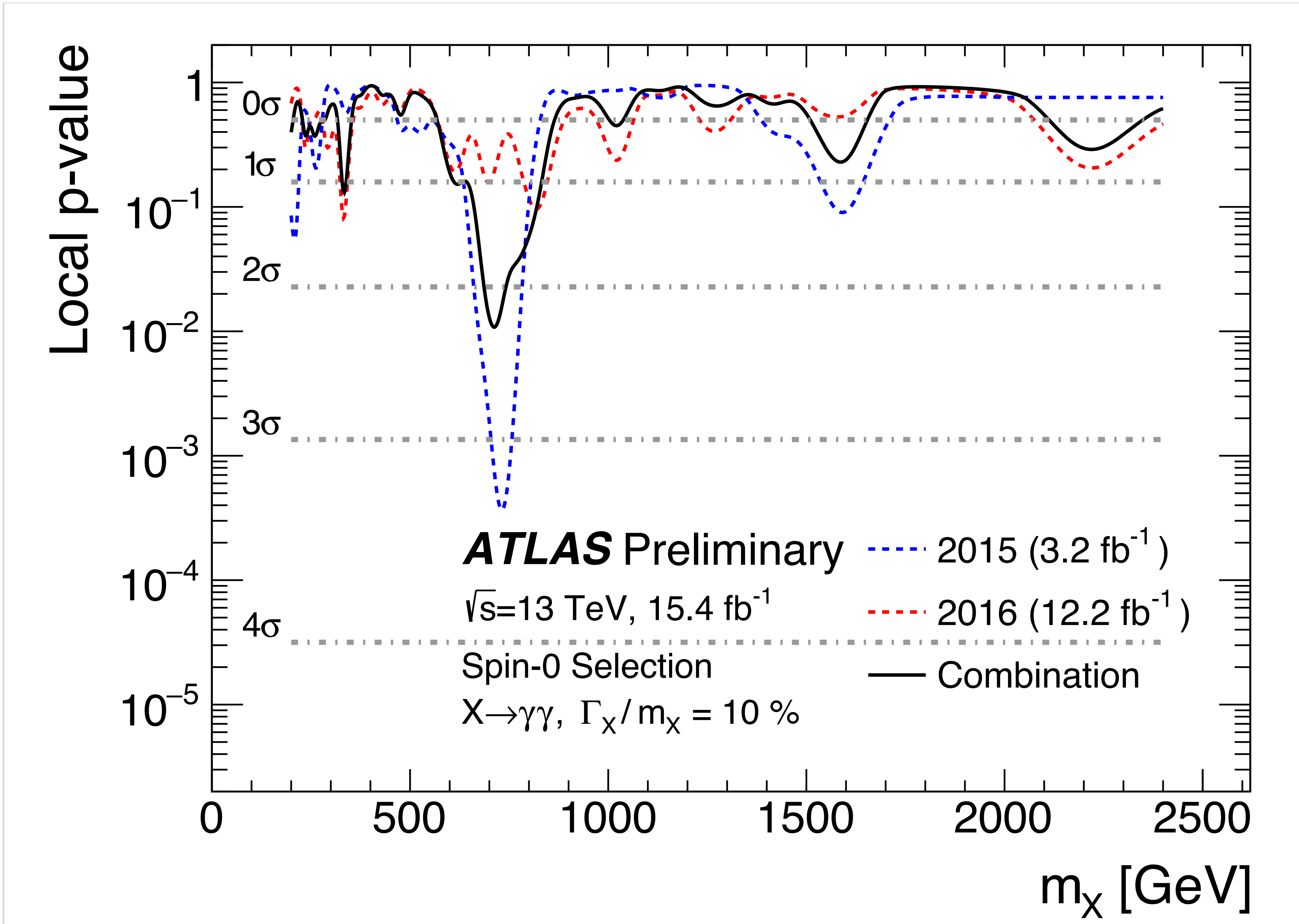
2015 vs 2016 p-values

Largest significance for combined dataset @ 1.6 TeV (2.4σ local)

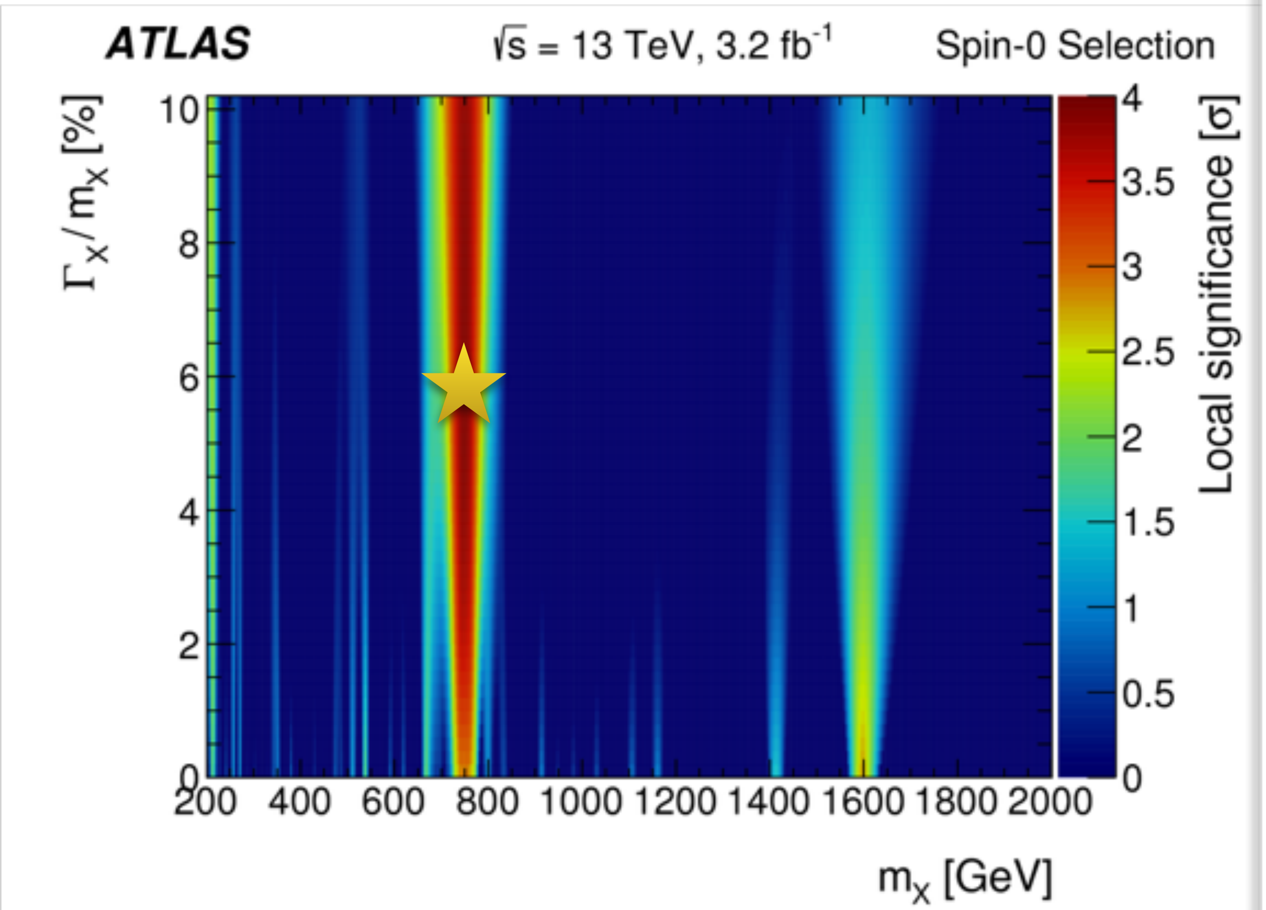


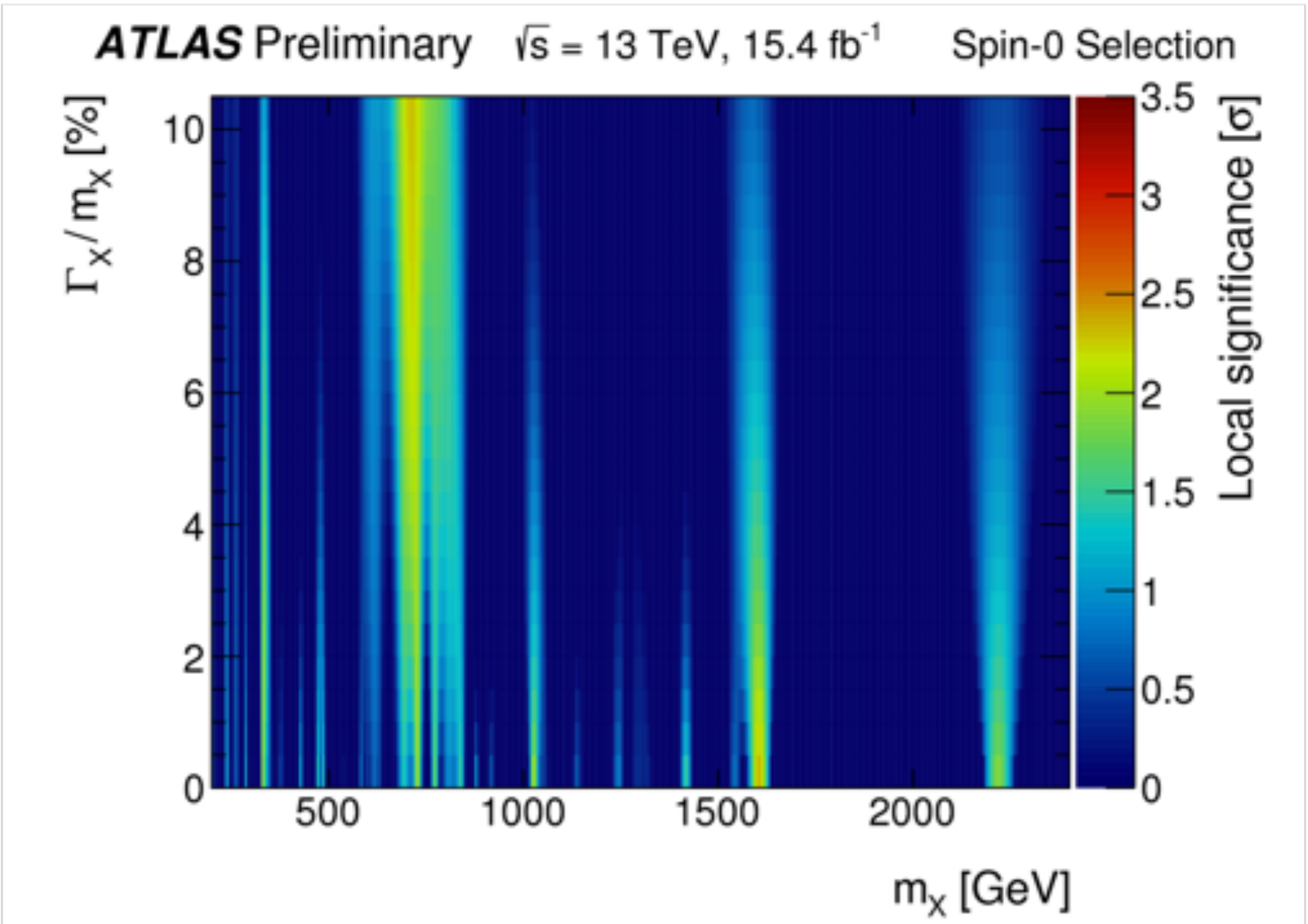
10% Width

Around 700-800 GeV: 2.3σ local significance @ 710 GeV for combined dataset



2015 vs 2016, which is which?





What Happened?

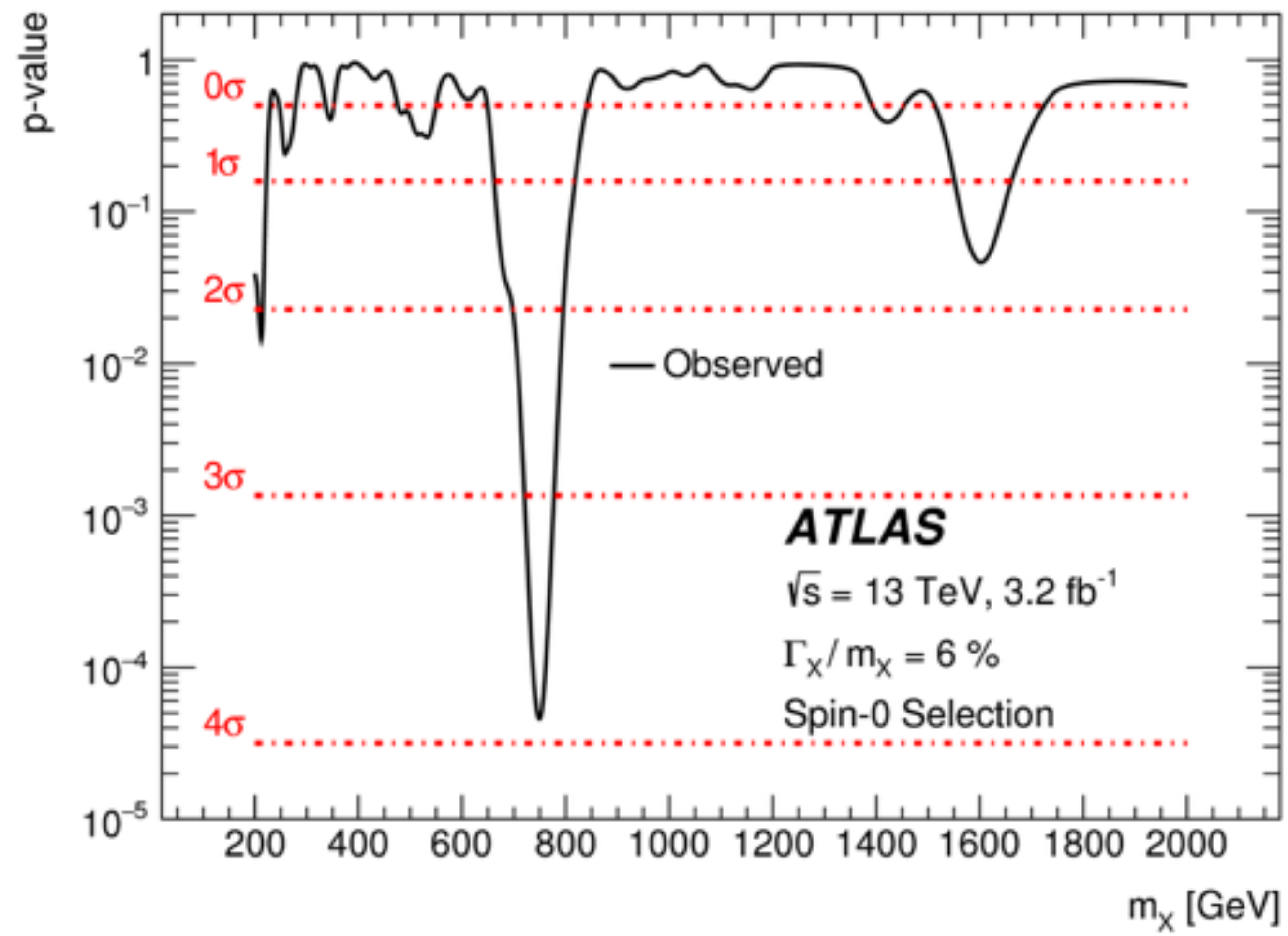
Spin 0

2015

Largest significance

$m_X \sim 750 GeV, \Gamma_X \sim 45 GeV (6\%)$

Local Z = **3.9σ**



Any peak with Z>3.9σ
with m=200-2000 will draw our attention

$$P_{global}(u) \approx p_{local}(u) + E(n_{u_0})e^{\frac{u_0-u}{2}}$$

$$p_{local} = 5\cdot 10^{-5}$$
$$u_0 = 0$$
$$n_{u_0} = 7 \pm 2.6$$
$$u = Z^2 = 3.9^2 = 15.2$$
$$p_{global} = 5\cdot 10^{-5} + (7\pm 2.6)e^{-15.2/2} = (2.2-4.8)10^{-3}$$
$$Z_{global} \sim 2.7 \pm 0.1\sigma$$

The LEE is even stronger when you consider another dimension
(the width range (0-10%m) should also be taken into account)

Spin 2

2015

2D Scan

Largest significance

$m_X \sim 750\mathrm{GeV}, \Gamma_X \sim 45\mathrm{GeV}(6\%)$

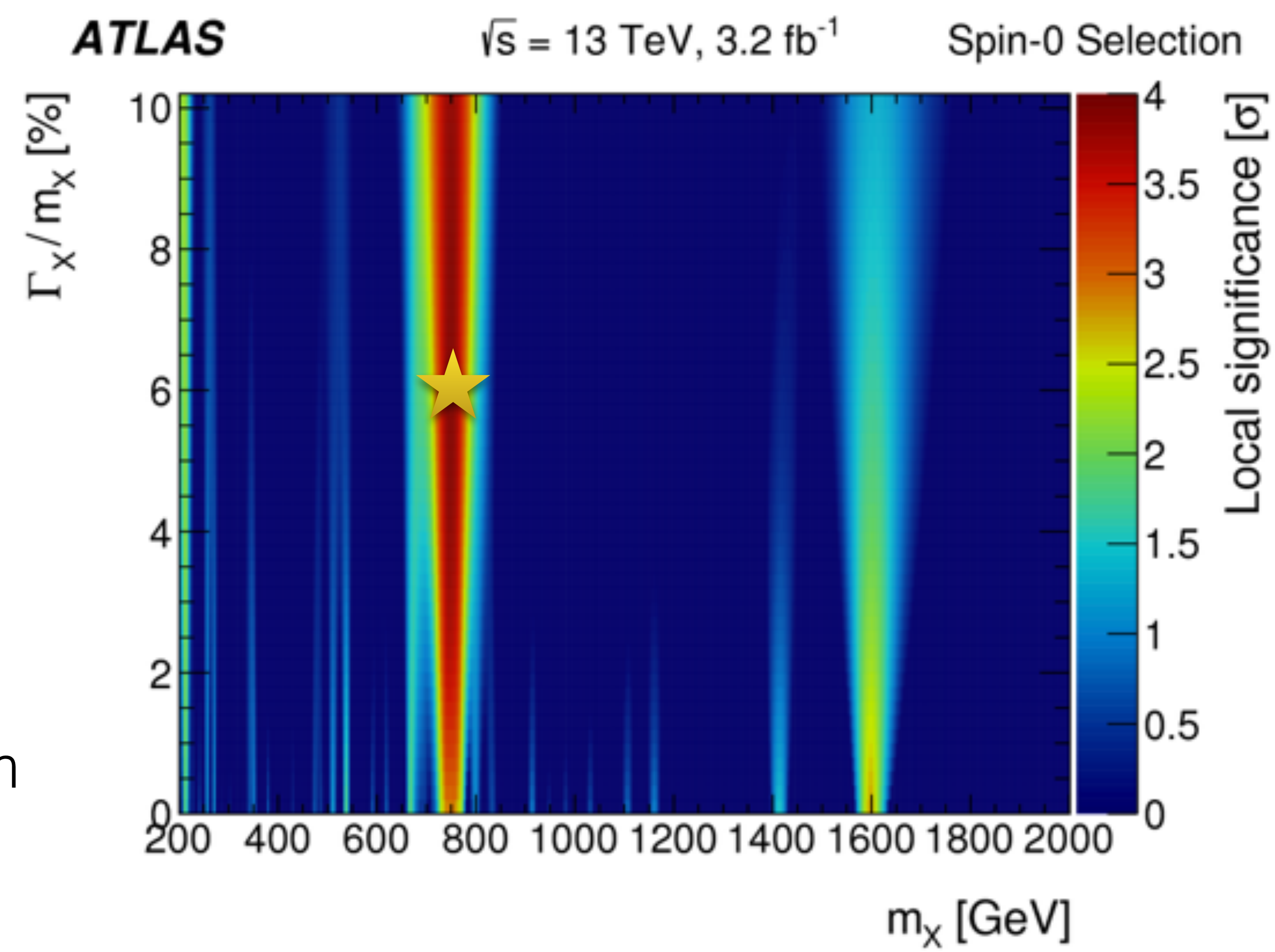
Local Z = **3.9σ**

m=200-2000 GeV
Γ_X/m_X=0-10%

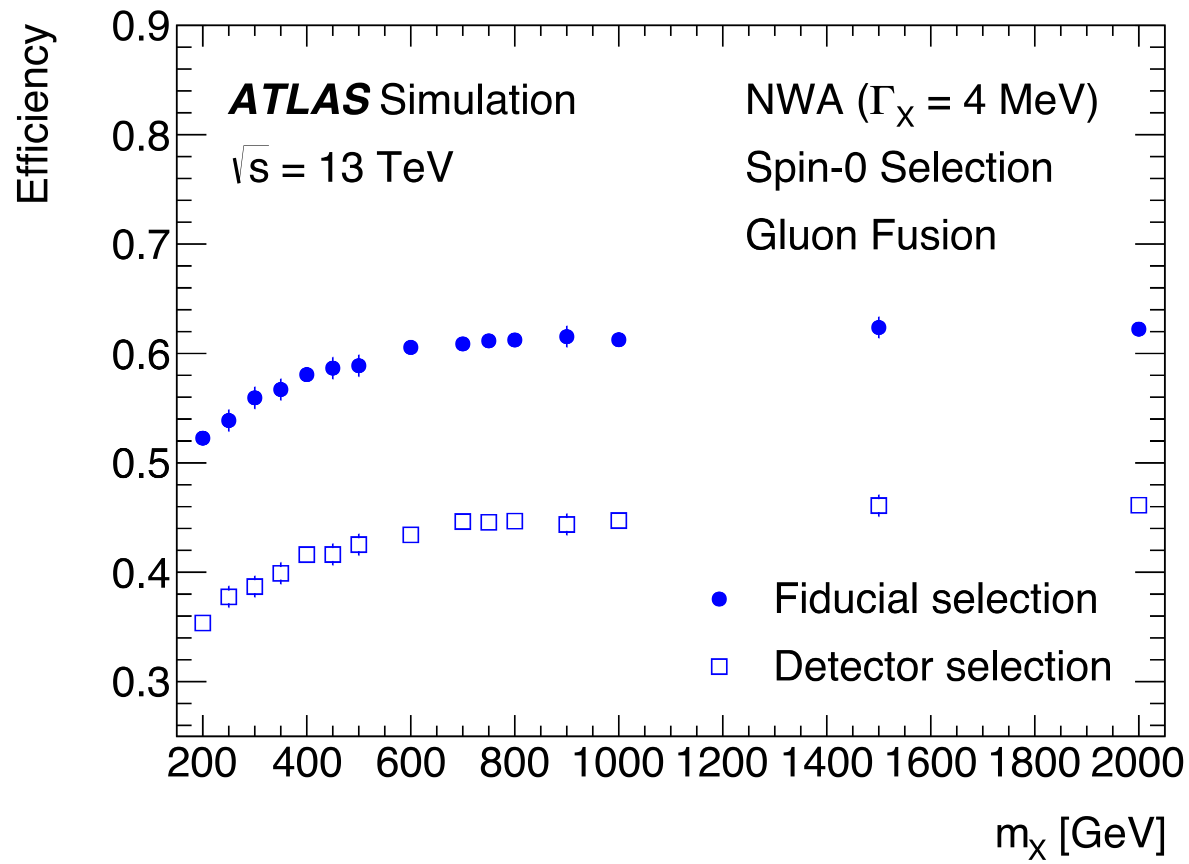
Use toys or asymptotic formula from
O. Vitells et. al. Astropart. Phys. 35 (2011) 230–234, arXiv:1105.4355

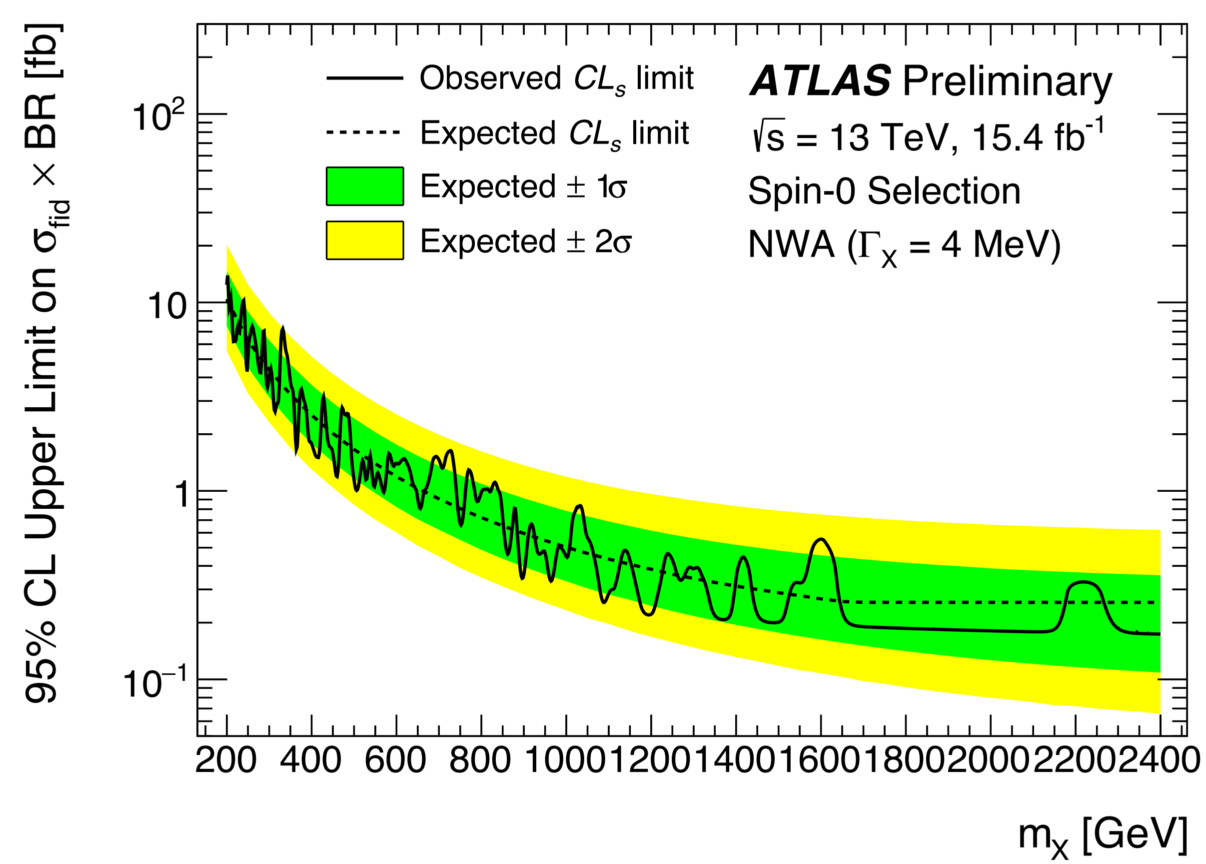
$$Z_{local} = 3.9\sigma$$
$$Z_{global} = 2.1\sigma$$

2.1σ is not something to write home about

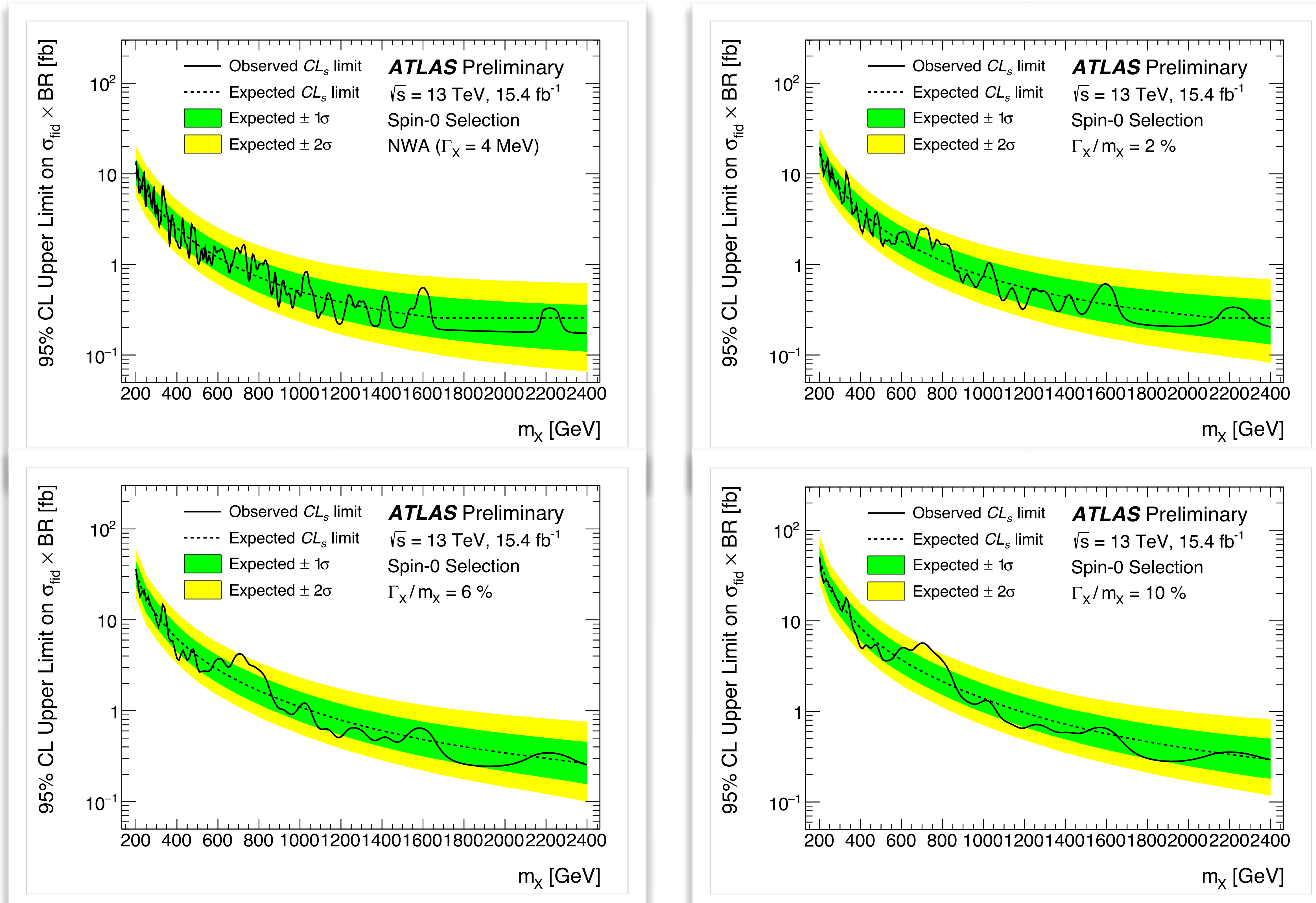


- In the absence of signal derived limits conclude the search
- Limit setting based on fiducial cross-section to minimise model dependence
  - Fiducial volume: ~same kinematic selection, isolation at particle level
  - Limits extended from 2 to 2.4 TeV with 2016 data





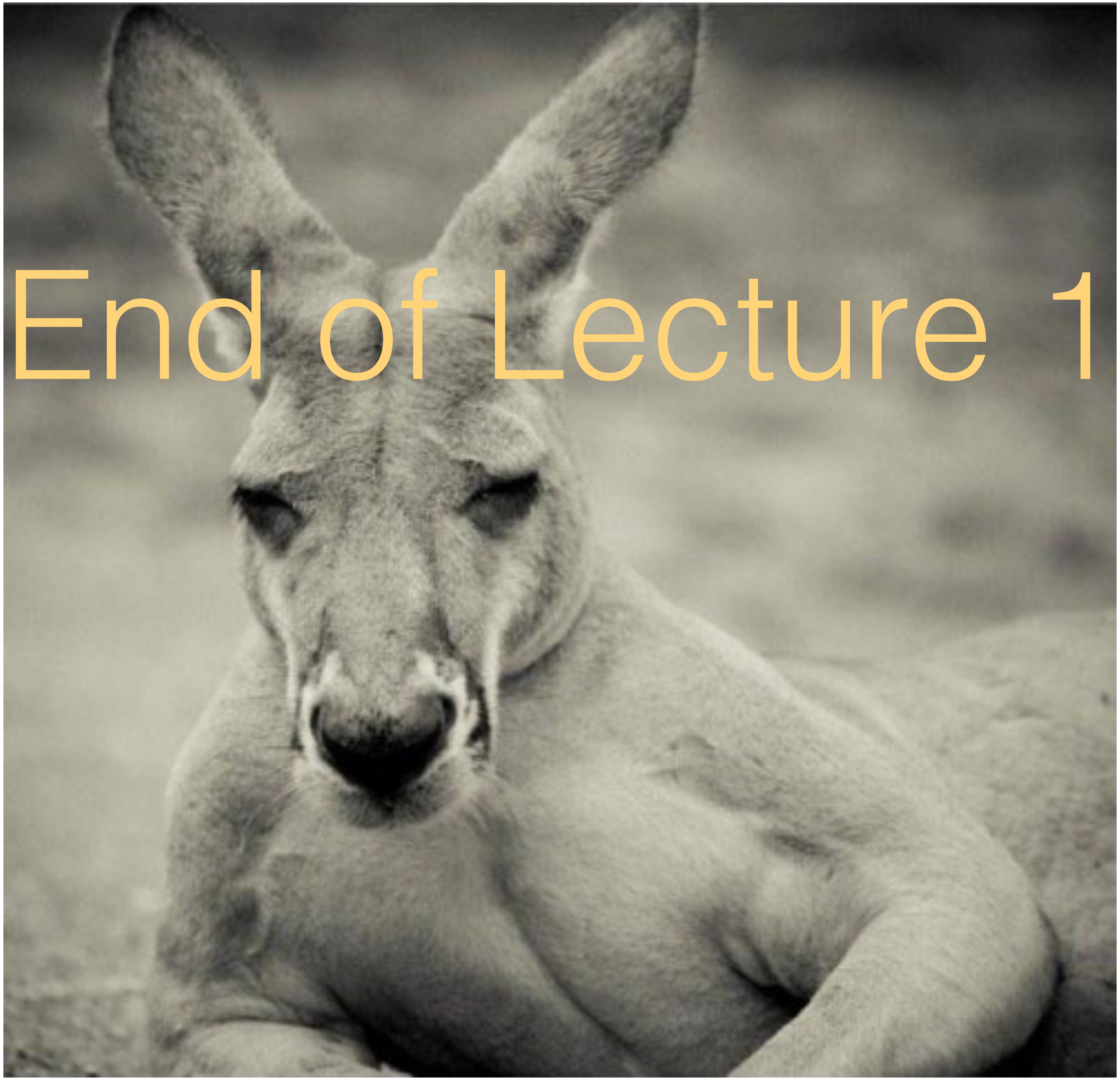
Limits



Observed CL_s limit
Expected CL_s limit
Expected ± 1σ
Expected ± 2σ
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 15.4 fb^{-1}
Spin-0 Selection
NWA (Γ_X = 4 MeV)
Γ_X / m_X = 2 %
Γ_X / m_X = 6 %
Γ_X / m_X = 10 %
95% CL Upper Limit on $\sigma_{fid} \times$ BR [fb]
m_X [GeV]
10^{-1}
1
10
10^2
200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400

What Happened?

Beware of LOCAL significance!


End of Lecture 1