The diphoton excess

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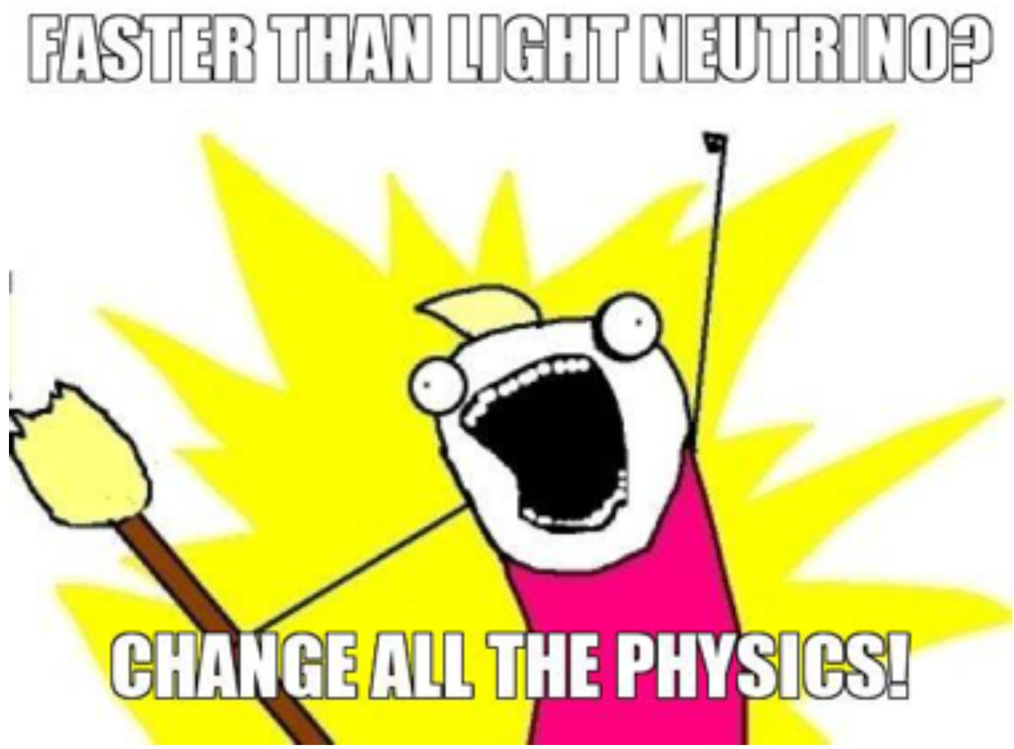
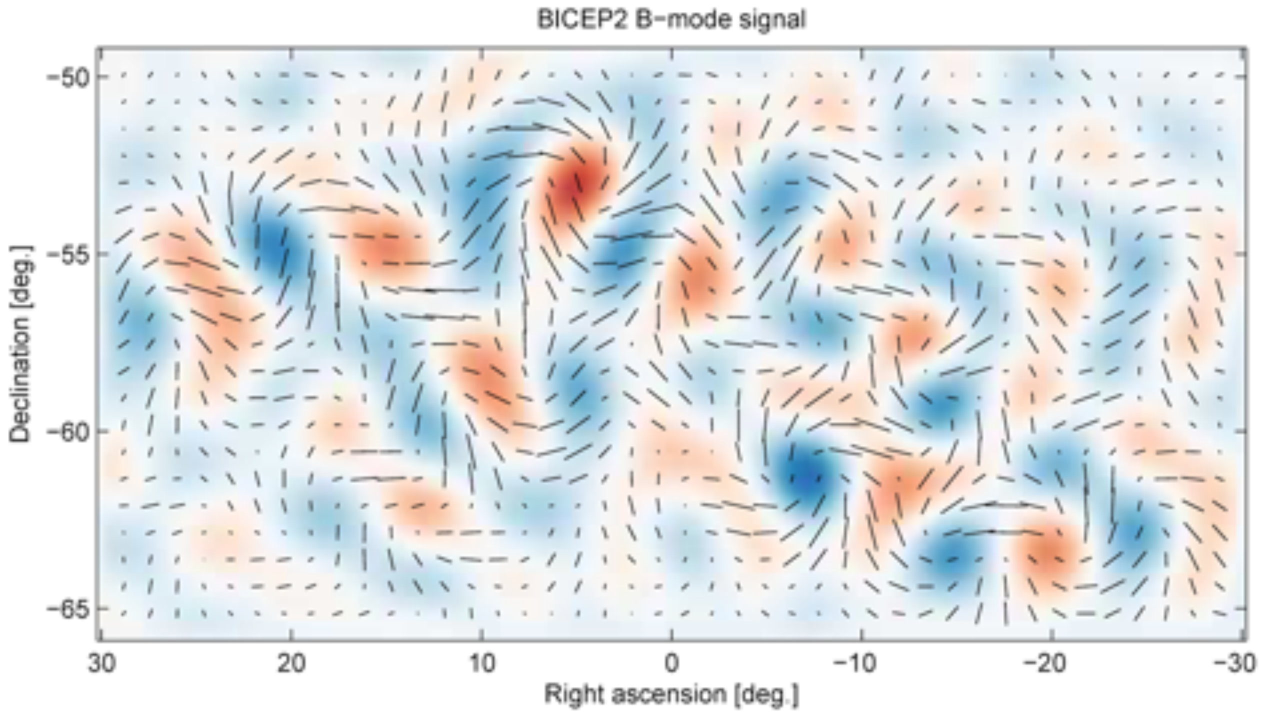
Liverpool 10/02/16

What a terrible title?!

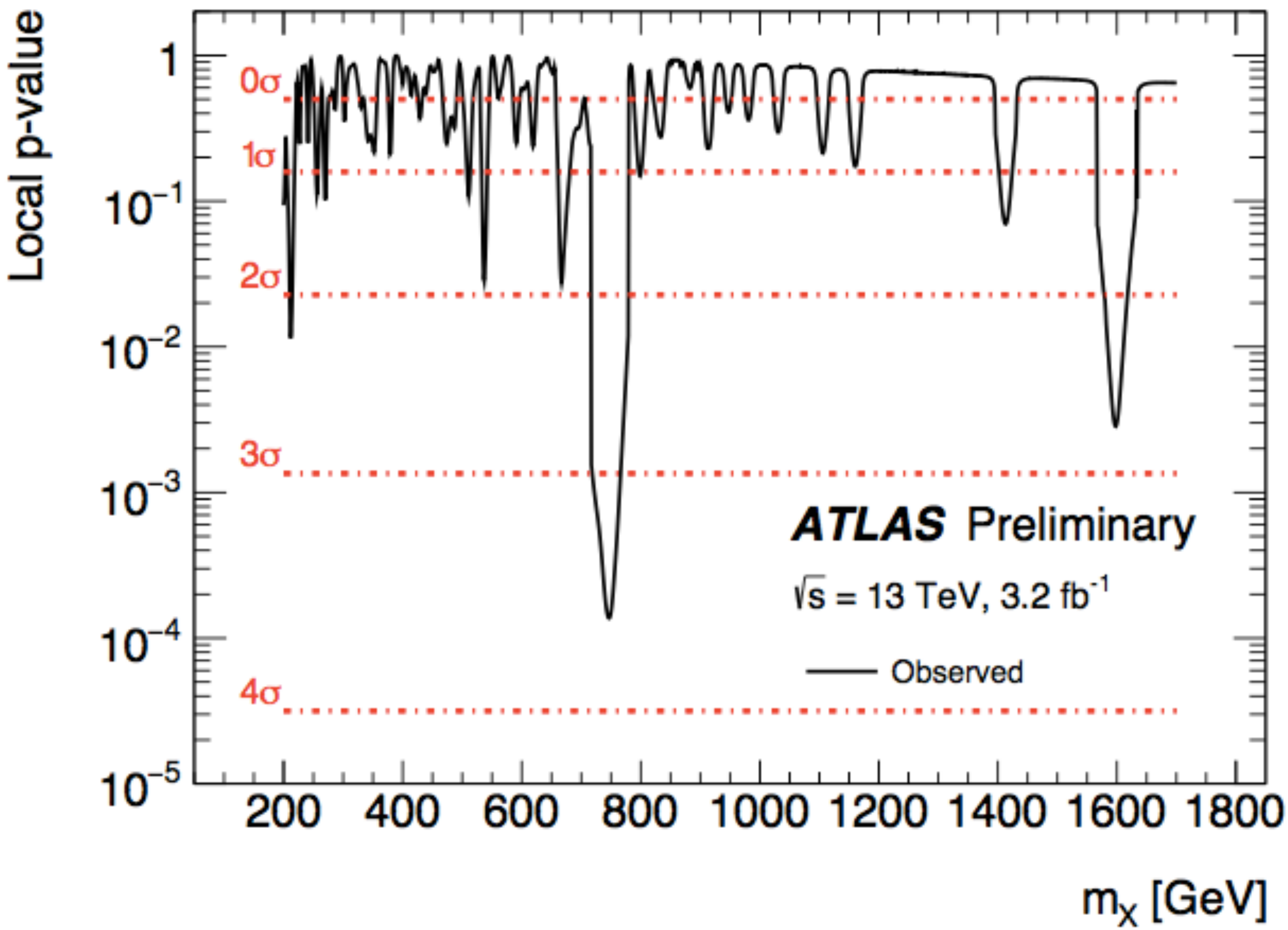
- 2011: OPERA experiment:
  "Faster-than-light neutrino anomaly".



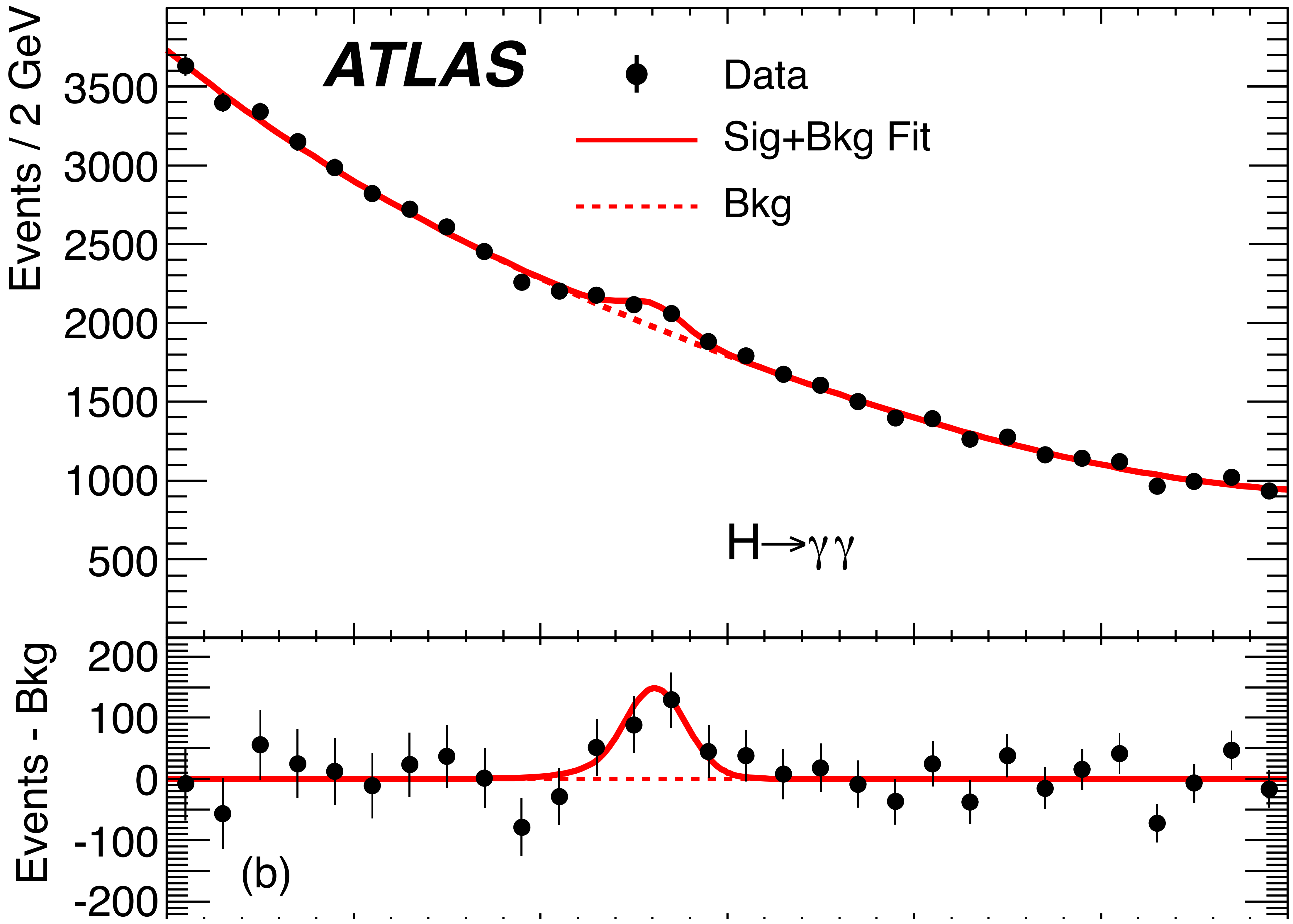
- 2014: BICAP2:
  "Gravitational Waves in the Cosmic Microwave Background".



BUT…

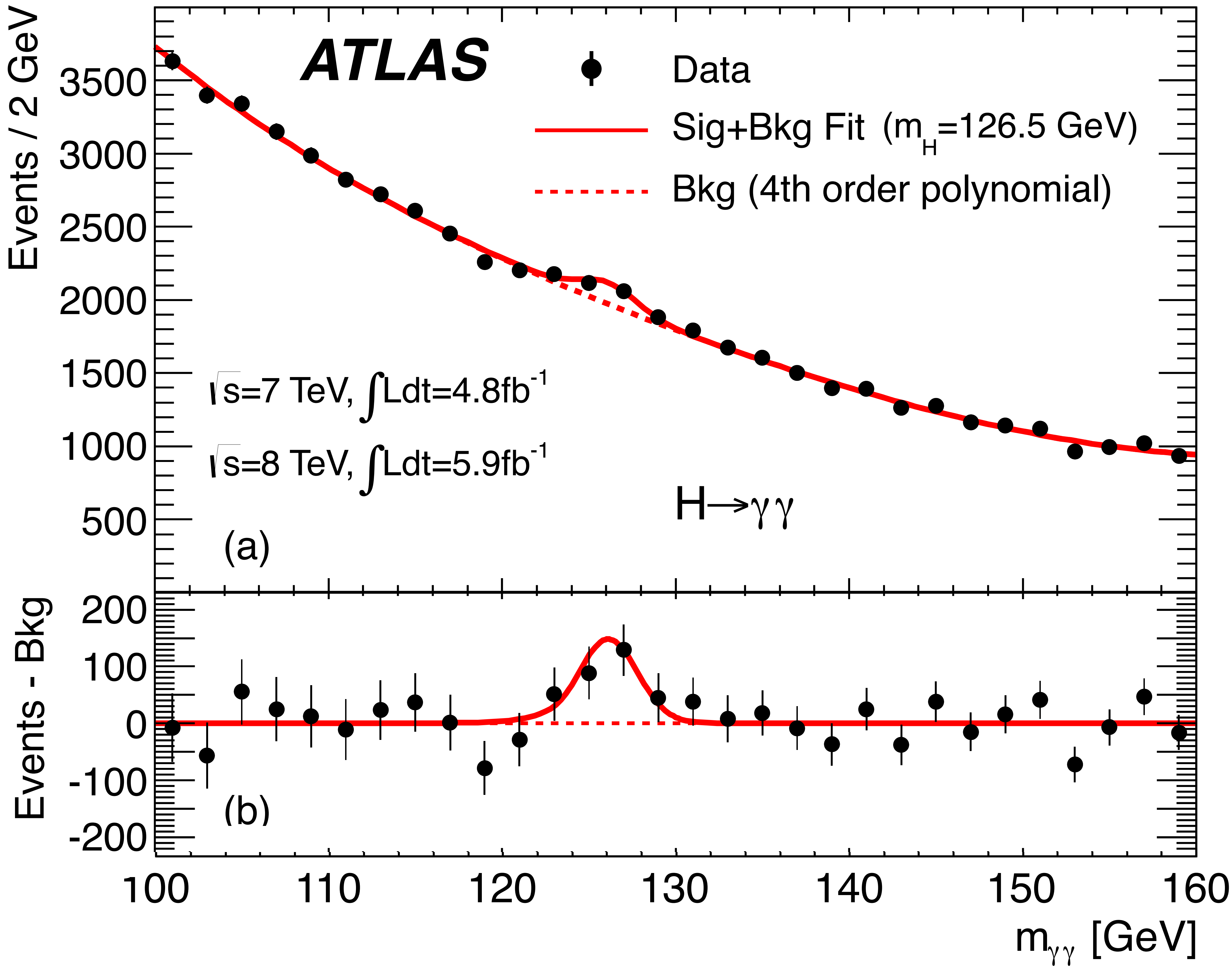

Local p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0σ
1σ
2σ
3σ
4σ
200 400 600 800 1000 1200 1400 1600 1800
m_X [GeV]
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
Observed

BUT...



ATLAS
Data
Sig+Bkg Fit
Bkg
H→γγ
Events / 2 GeV
3500
3000
2500
2000
1500
1000
500
Events - Bkg
200
100
0
-100
-200
(b)

BUT...



ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
√s=7 TeV, ∫Ldt=4.8fb^-1
√s=8 TeV, ∫Ldt=5.9fb^-1
H→γγ
(a)
(b)
Events / 2 GeV
Events - Bkg
m_γγ [GeV]
3500
3000
2500
2000
1500
1000
500
200
100
0
-100
-200
100
110
120
130
140
150
160

From http://atlas.ch

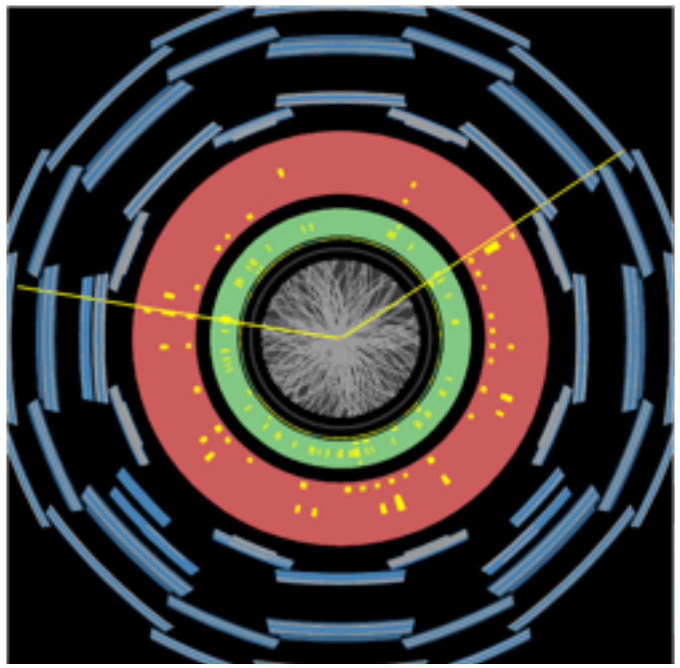
- Discovery News: LHC Has Found a Bump: Exotic Physics or Just Noise?_
- CBC News: Large Hadron Collider data hints at possible new particle discovery_
- Wired: **Cern's potential new particle discovery is 'a total game changer'_**
- Gizmodo: **Don't Get Too Excited Yet About the LHC's Hint of a New Particle _**
- Motherboard: Did the LHC Bag a Ginormous New Higgs Boson?_
- New York Times: Physicists in Europe Find Tantalizing Hints of a Mysterious New Particle_

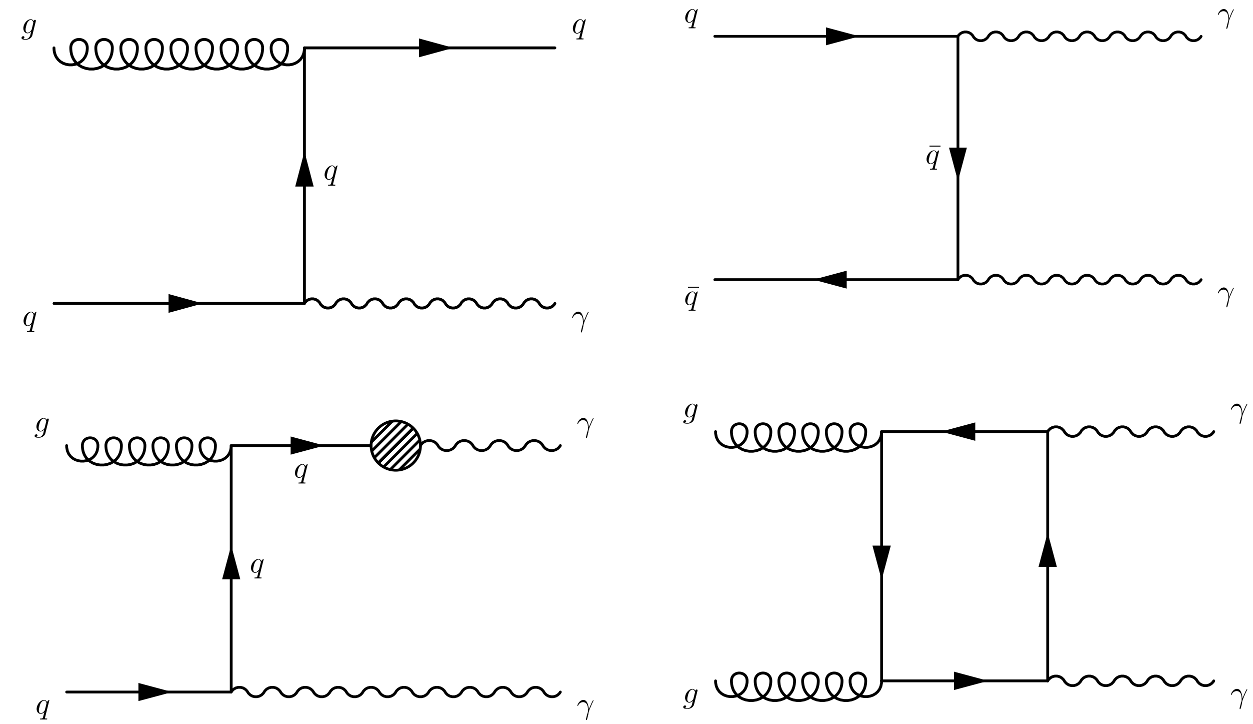

The Beginning

A Toroidal LHC ApparatuS

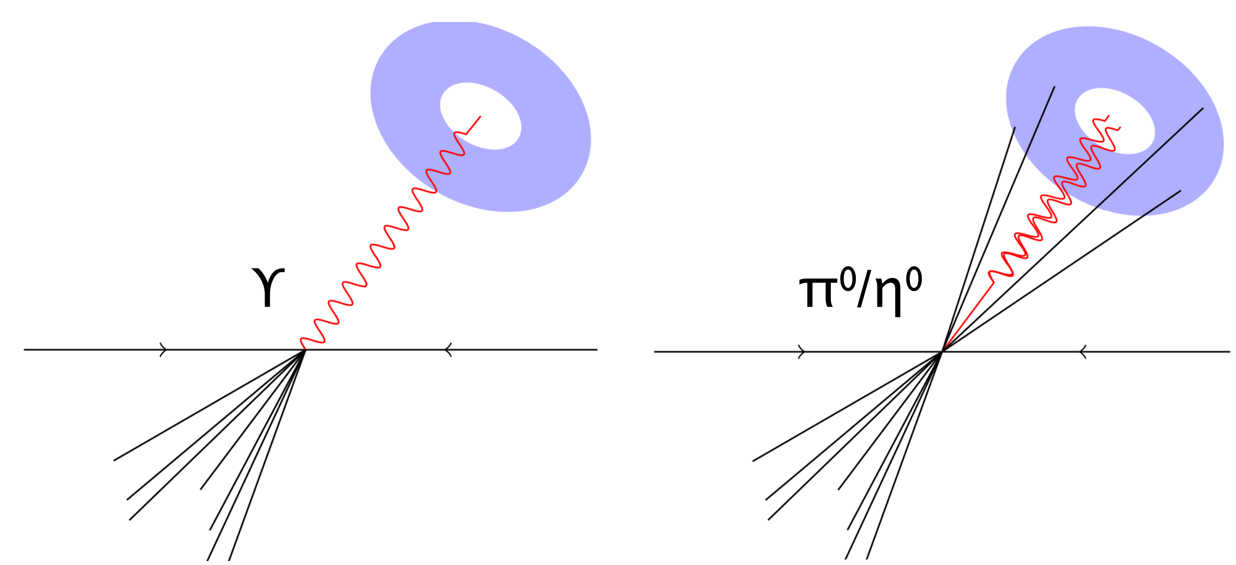
Isolated prompt photons

- Prompet
  - Direct from the hard scatter.



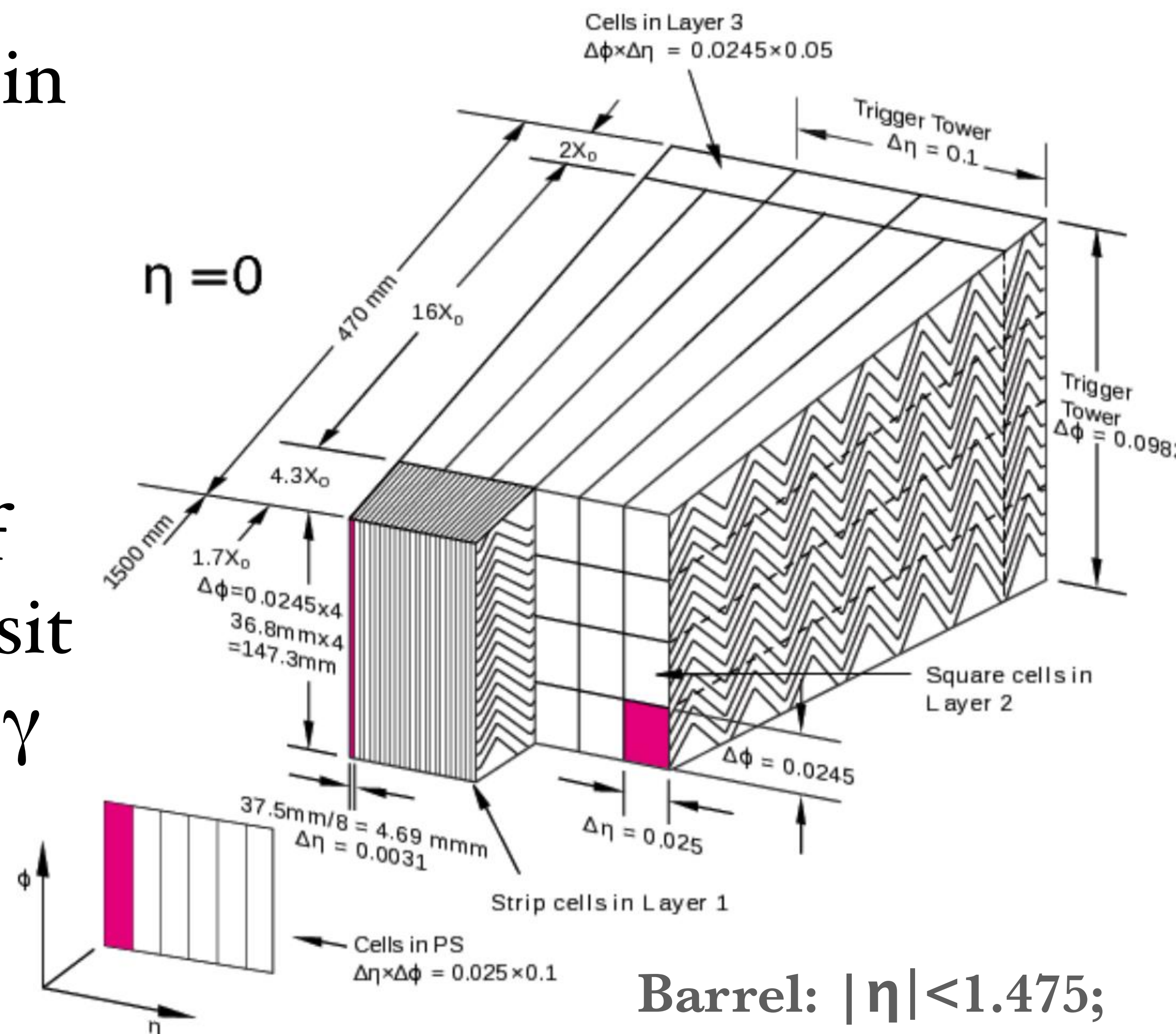


- Isolated
  - Isolation criterion imposed to reduce QCD BG.
    - Photons from neutral meson decays in jets.



Measuring photons in ATLAS

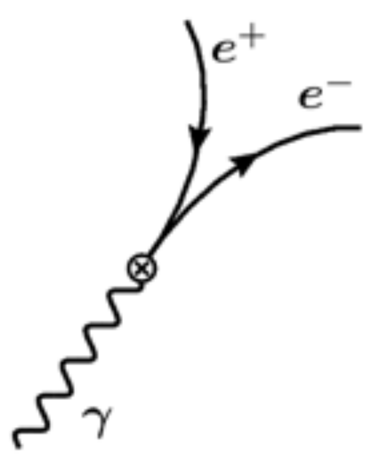
- LAr EM calorimeter:
  - 1st layer: high granularity in η up to 2.37 -> γ/π° separation (EM shower moments)..
  - 2nd layer: collects most of the energy... energy deposit in the EM calorimeter ->γ energy.
  - 3rd layer: used to correct for leakage.

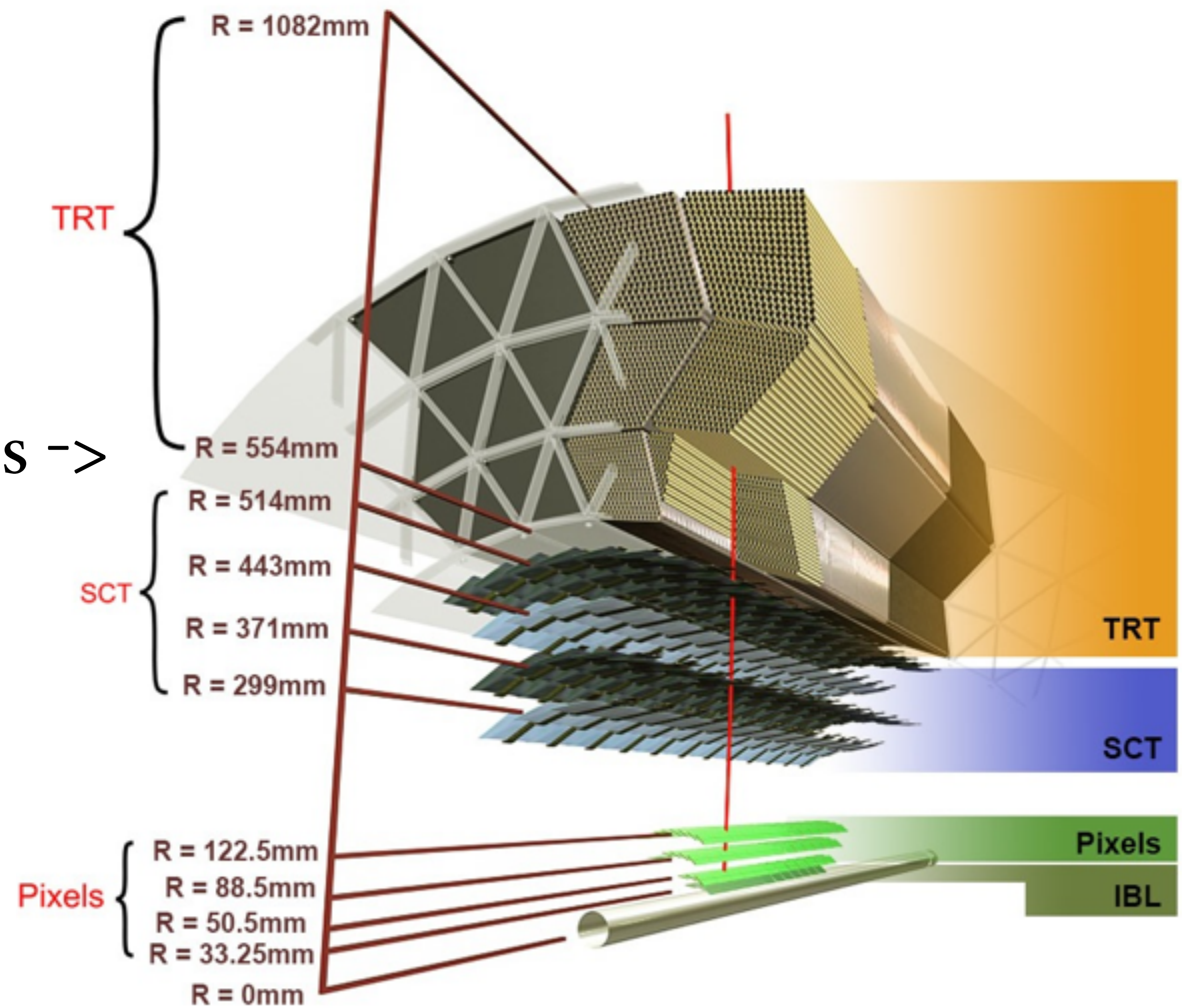


Barrel: |η|<1.475;
Endcap: 1.375<|η|<3.2

Measuring photons in ATLAS

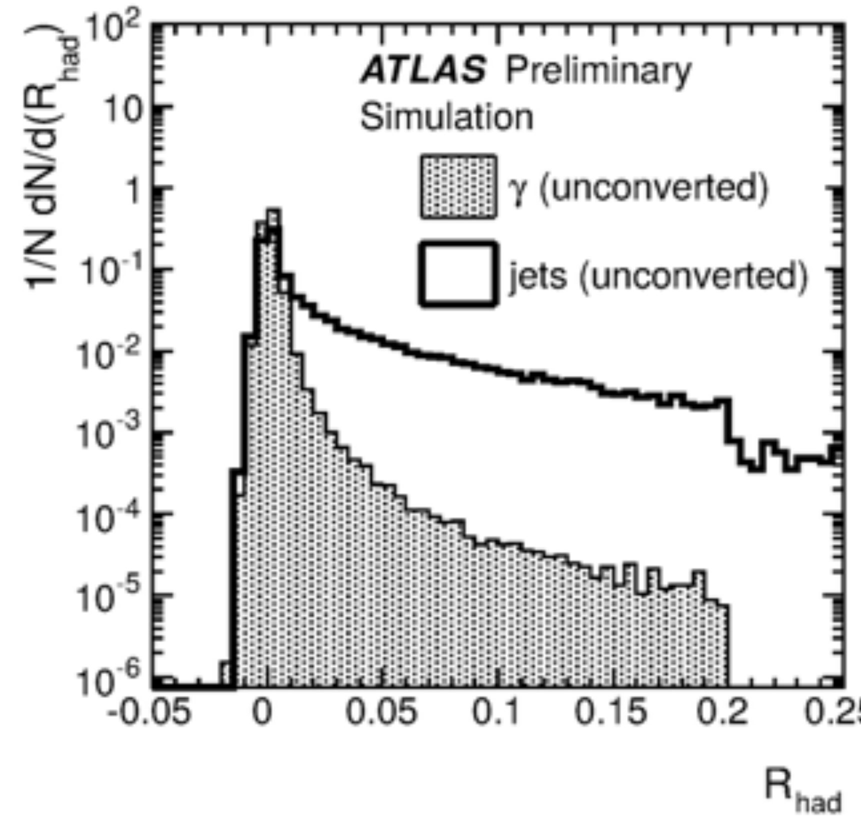
* Inner detector (ID)
  * Measure transition radiation -> e/γ discrimination.
  * Track charged particles -> γ conversion reconstruction.

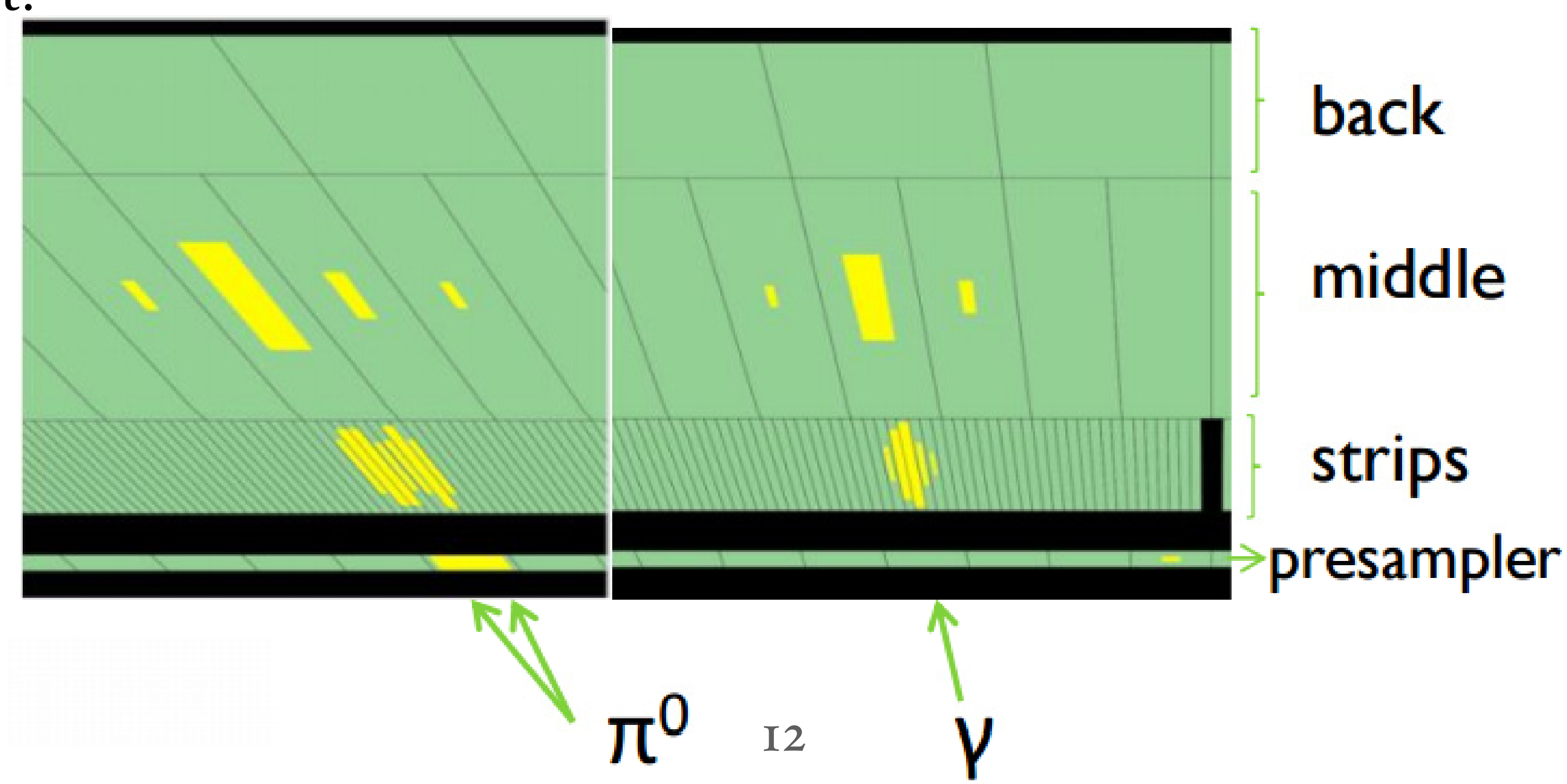




Photon identification

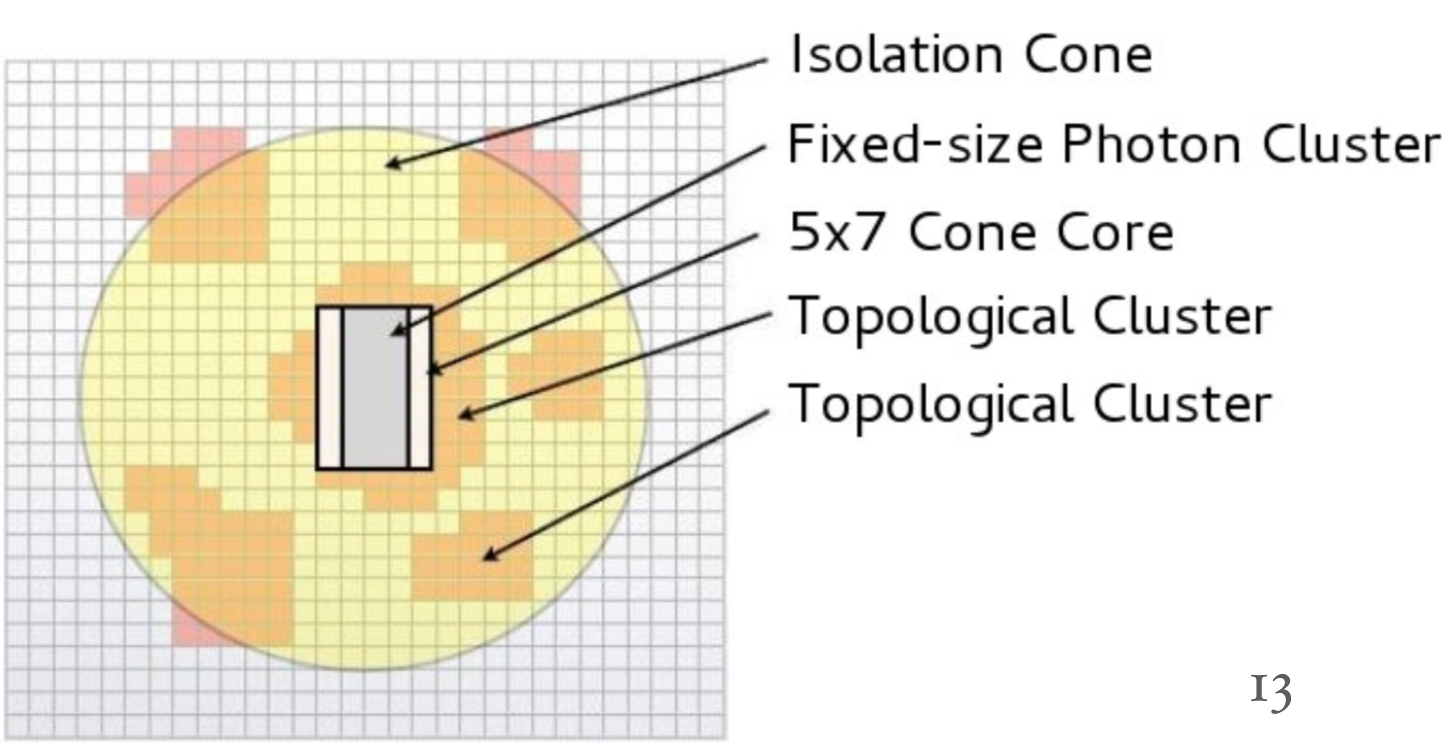
- Loose vs Tight:
  - Identification performed by applying cuts over discriminating variables (shower shapes) from the calorimeter layers.
  - Shower shapes: variables that describe the shape of the electromagnetic shower in the calorimeter, and the fraction of energy deposited in the hadronic calorimeter.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





Photon isolation

- Computed from topological clusters in ΔR cone:
  - Sum over all particles (except the photon!) inside a cone of radius R centered on the photon in the η-ϕ plane.
- Isolation is applied independently of the identification, varying isolation has little impact on ID efficiency.
- Isolation energy corrected event-by-event for leakage (of the photon), pileup and underlying event contributions (average correction for 1 Primary vertex: ~540MeV).



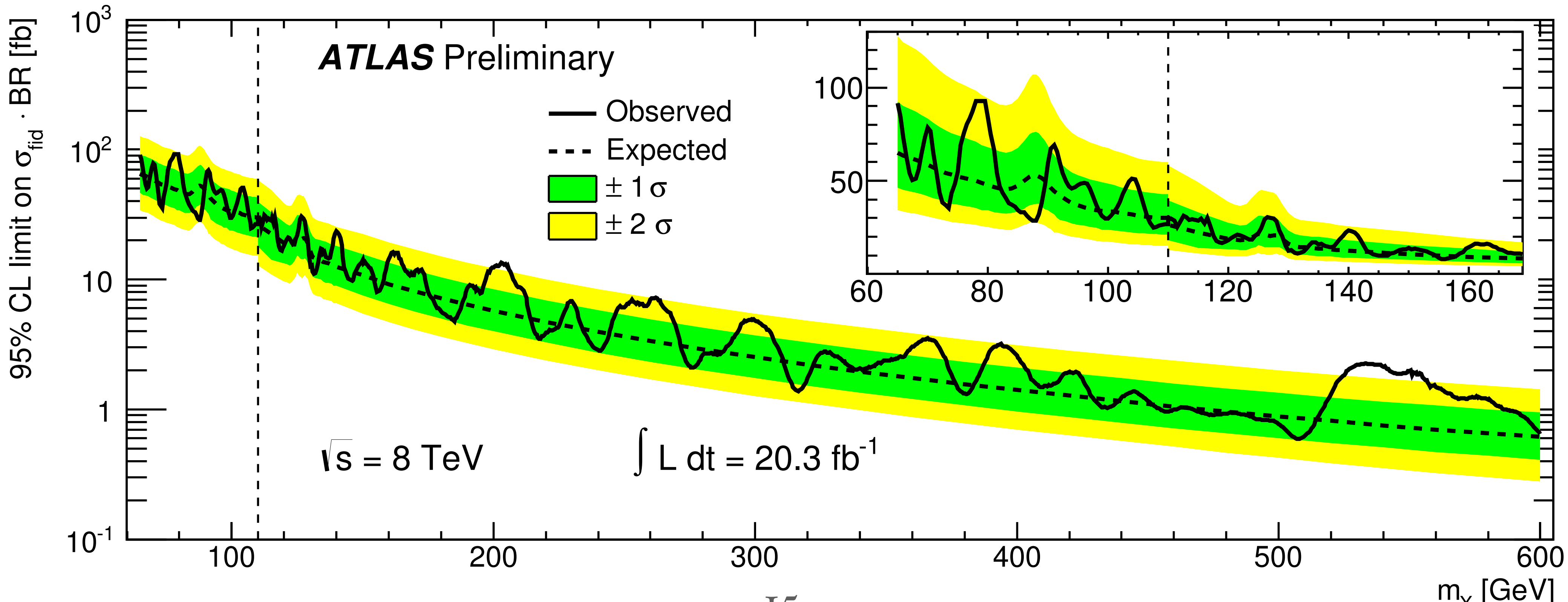
- Track isolation:
  Scalar sum of the pT of the tracks from the primary vertex with pT > 1 GeV in a cone around the photon candidate.

What is the real problem?

Desperate junkies search for an alleged "needle in the haystack."

Recap

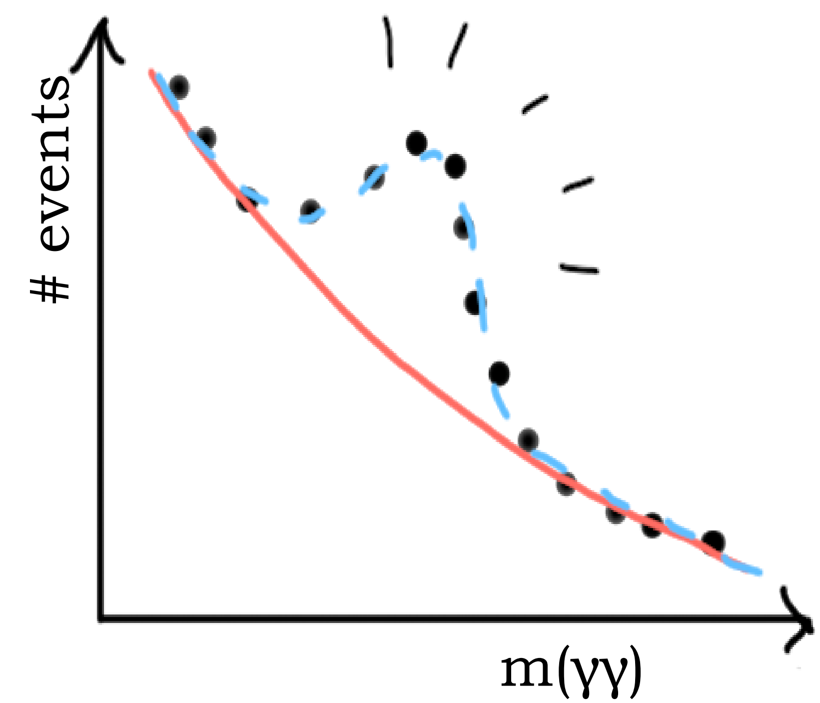
* Run1 (65-600GeV):
    * Two regions: low mass (65-110GeV) and high (110-600GeV). Extending the SM Higgs search that was done form 100-160GeV.
    * The analysis was done assuming NWA (?).



?

Event Selection

- Trigger: 35 (25) GeV for leading (subleading) photon.
- Pre-selections:
  - $E_T^{\gamma 1} > 40$ GeV, $E_T^{\gamma 2} > 30$ GeV ("baseline")
  - Relative cuts: "High mass" -> $E_T^{\gamma 1} > 0.4\, m_{\gamma\gamma}$, $E_T^{\gamma 2} > 0.3\, m_{\gamma\gamma}$
  - Isolation: "High mass" working point -> topoetcone40 < 0.022* E_T + 2.45 GeV ptcone20 < 0.05* p_T



Relative Cuts Optimization

- Optimization of relative E_T cuts performed by maximizing ratio of significance obtained when applying relative cuts to significance with the "baseline" cuts.

- Independent from number of signal events:

$$Z = \frac{S}{\sqrt{B}} \qquad Z_{\text{relative cuts}} / Z_{\text{default cuts}} = \frac{\epsilon_S}{\sqrt{\epsilon_B}}$$

- 0.4/0.3 relative cuts chosen.

- Typical gain in significance for ggH samples:
  - ~10% at 200GeV.
  - >20% at 1TeV.

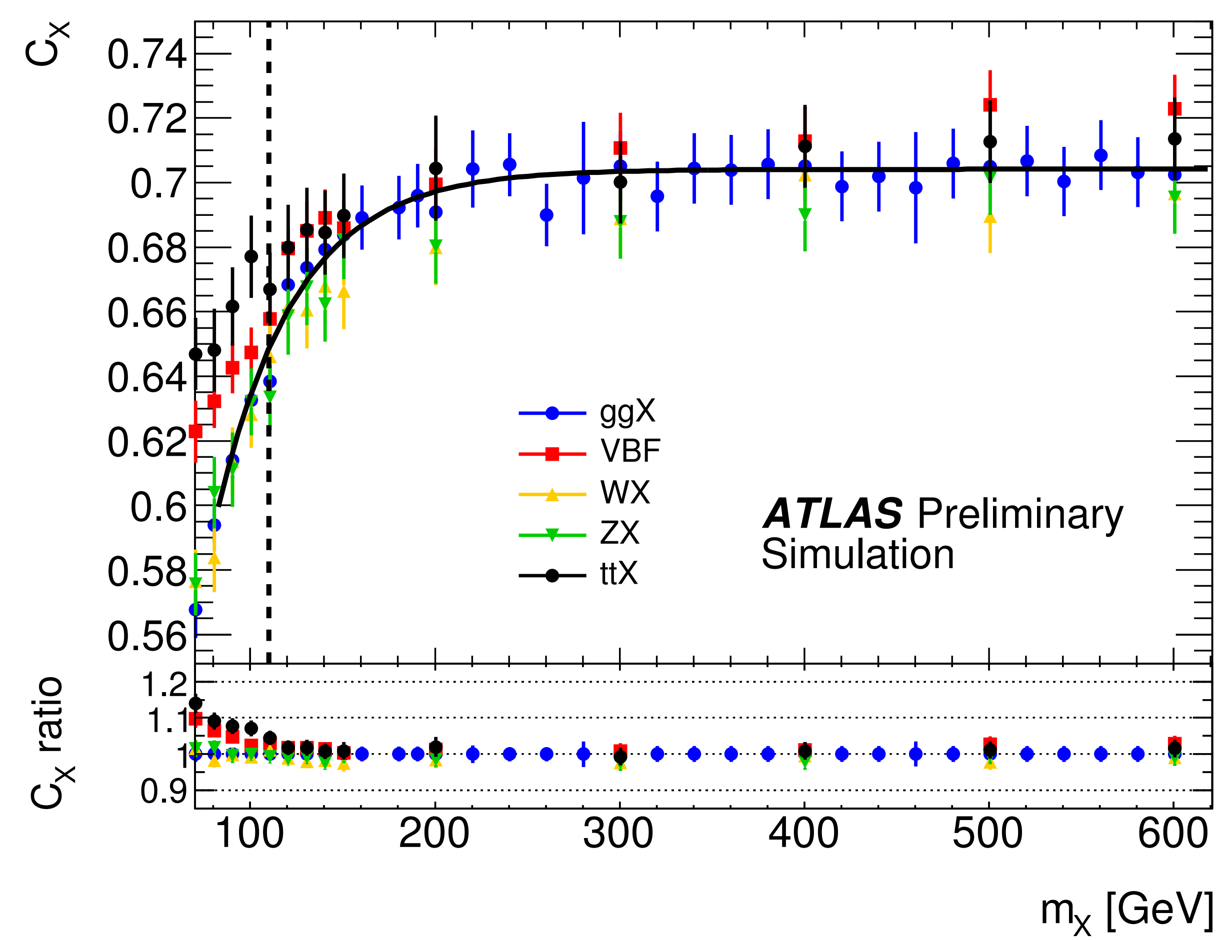
Isolation Optimization

- Optimization done maximizing relative significance with re $Z = \frac{S}{\sqrt{B}}$ to γγ + γj.
  - topoetcone40 < 0.022* E_T + 2.45 GeV
  - ptcone20 < 0.05* p_T
- The relative significance improvement is >20% from 600GeV.
- The typical efficiency range from 80% at 200GeV to 90% at 800GeV.
- Total efficiency:
  - ggF: 30%->40%.
  - Higher for VBF and lower for ttH.

Fiducial Volume

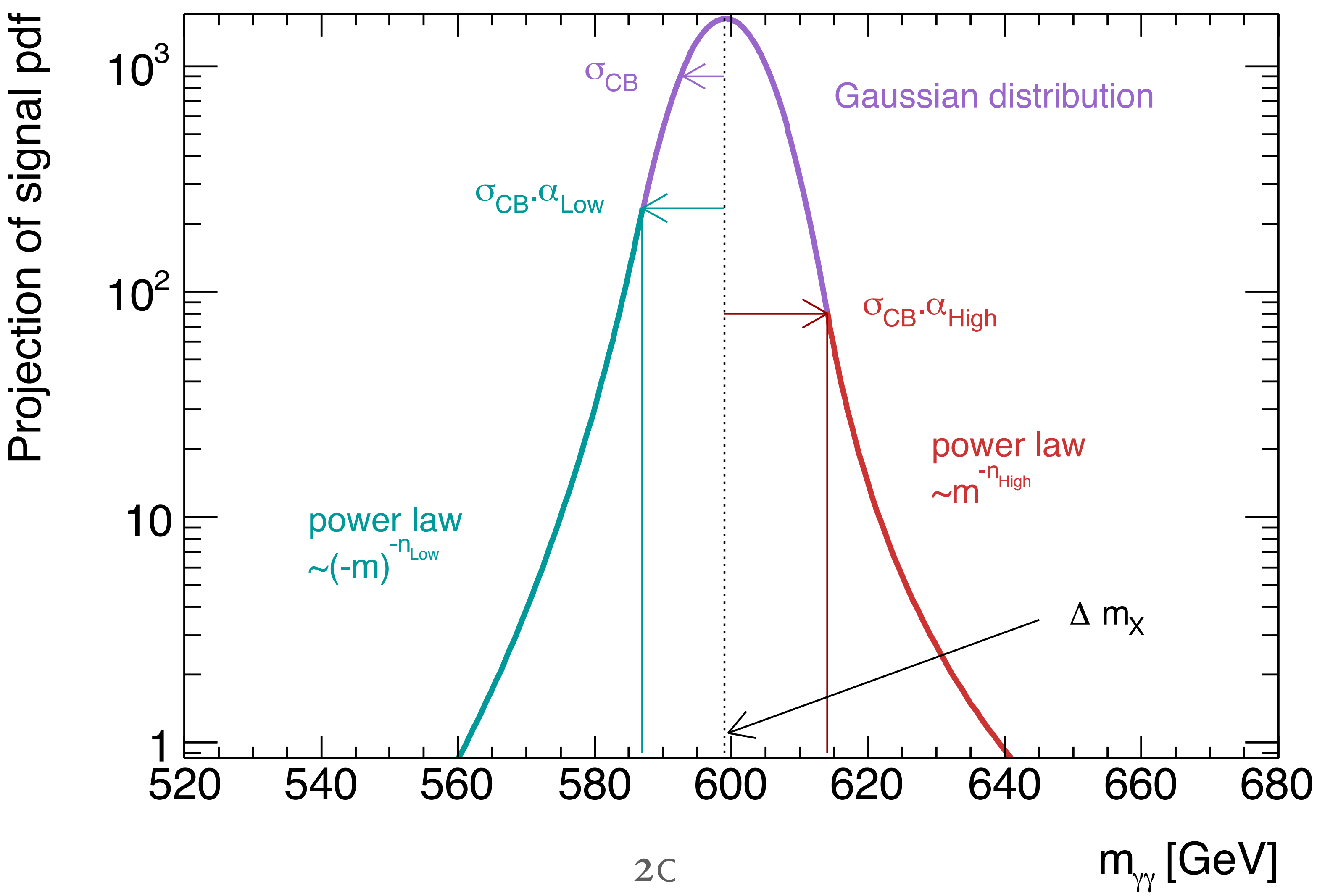
- Limits on fiducial cross section!
- Fiducial cross section: $\sigma_{fid} = \frac{N^{signal}}{C_X \cdot L}$
- C_X = correction factor in fiducial volume. $C_X = \frac{N_{\text{selection}}}{N_{\text{acceptance}}}$
  - Computed for several Higgs-like production modes.
  - Difference as systematics.

- Truth isolation choice driven both by **model independence** (similar C_X factor for different production mode) and by matching with **experimental isolation requirement.**
- Best choice is "VarCone40Loose" -> $E_T^{iso}(R=0.4)/(E_T^{\gamma true} + 120) < 0.05$.
  - $E_T^{iso}(R=40)$ = etcone40
  - Model dependence: 3%



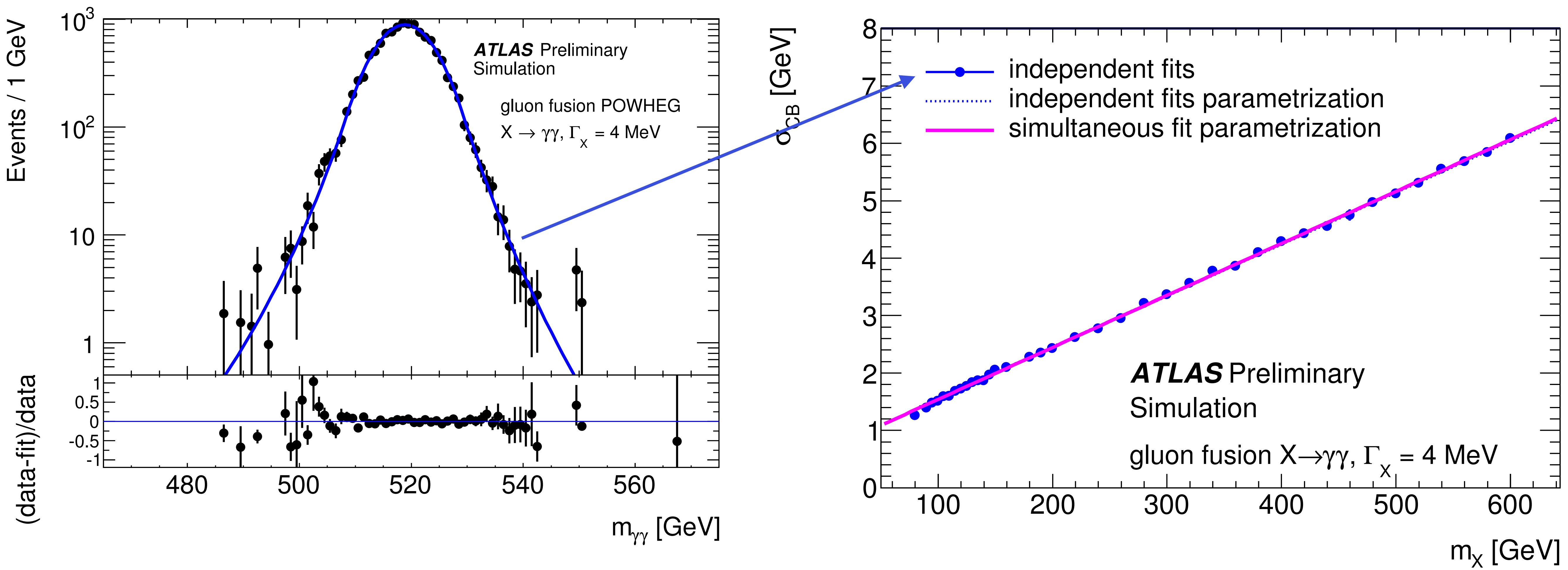
Signal Modelling

- Following approach used in Run 1 analysis.
- Simultaneous fit of Double-Sided Crystal Ball (DSCB) function to all signal samples with parameter parameterization vs $m_{X.}$



Signal Parametrization

* Comparison of the multiple mass fit parametrisation to the output parameters of the single mass point fits and to the parametrization of the single mass point fit parameters.



Background Modeling

* Aim: Finding a function that can **simultaneously fit the largest possible background range** (ideally 150 GeV – infinite) will allow to **extend search to highest possible mass hypothesis.**
* Procedure
  * Fit mass distribution with a signal-plus-background function on background MC sample for given mass hypothesis in 1GeV step.
  * Extract (fake) signal yield for corresponding hypothesis = spurious signal (SS) -> use the maximum over all variations.
  * Validate function that doesn't produce spurious signal for given mass hypothesis larger than 20% of expected background fluctuations assuming $4fb^{-1}$.
  * Also request that **SS associated to function does not saturate to constant values.**
    * Even if small! It would be a sign of a systematic deviation from data, hidden by large statistical uncertainty.
    * The SS of a good function should "oscillate" around zero.
* Important: the SM background is estimated using data only! MC is used only to validate the function but not to estimate the background.

Background Modeling Function

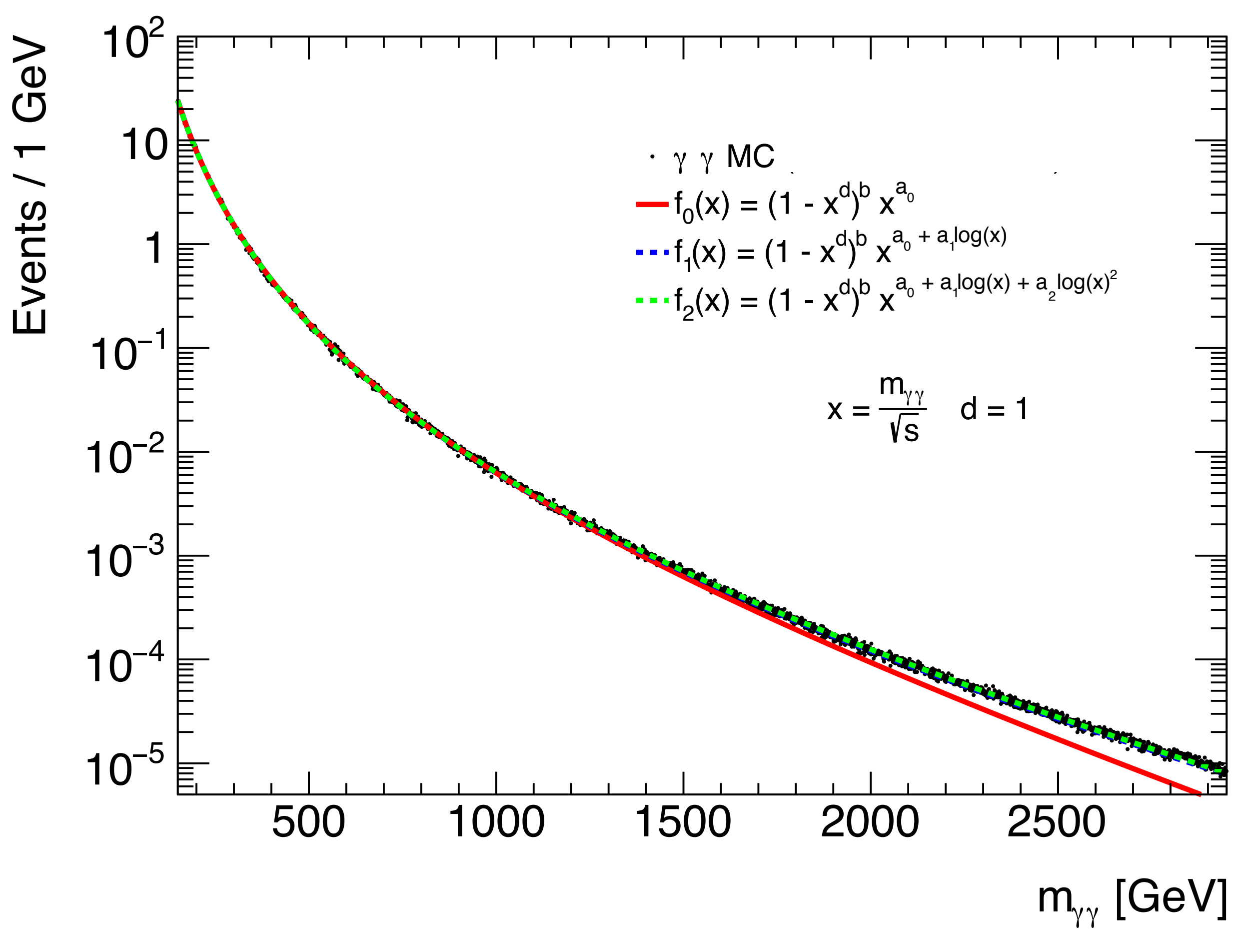
- Several functions are tested to model the background in the mass range [150-2950] GeV.

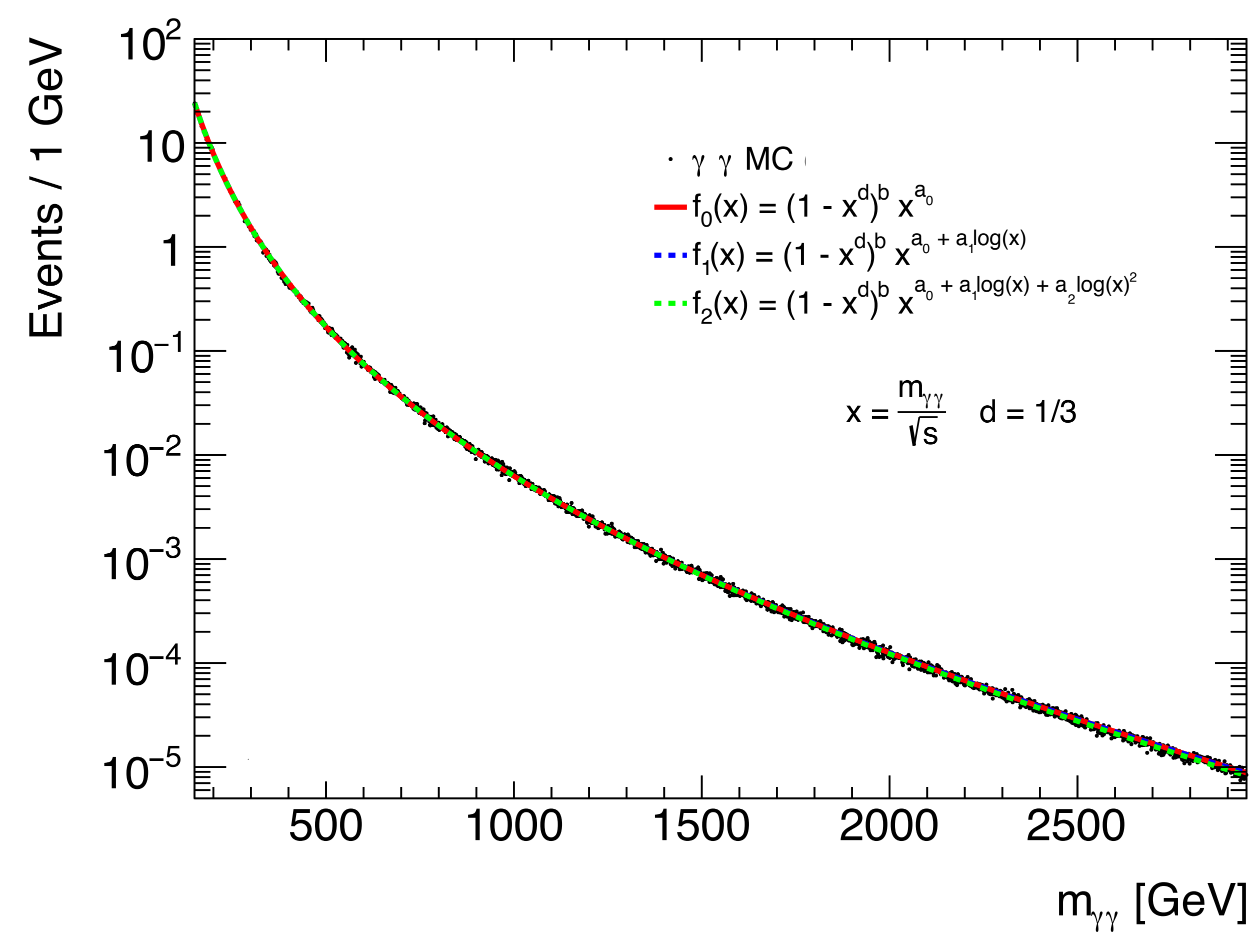
- The $m_{\gamma\gamma}$ continuous spectrum is fit by smooth functional forms of the form:

$$f_{k;d}(x; b, \{a_k\}) = (1 - x^d)^b x^{\sum_{j=0}^{k} a_j \log(x)^j} \qquad x = \frac{m_{\gamma\gamma}}{\sqrt{s}}$$

- Starting from the simplest functional form (k=0) -> data prefers d=1/3 to best describe the whole mass range.

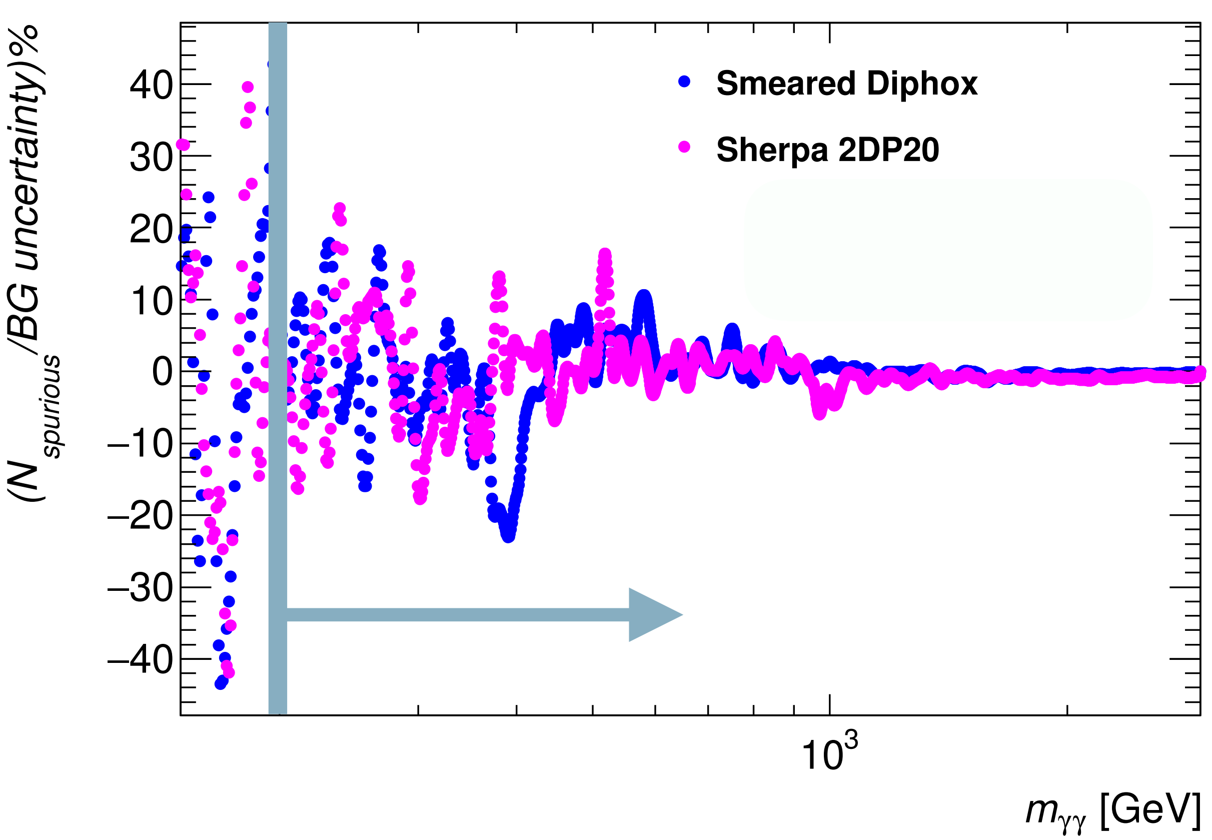
$$f_0(x; b, a_0) = (1 - x^{1/3})^b x^{a_0}$$

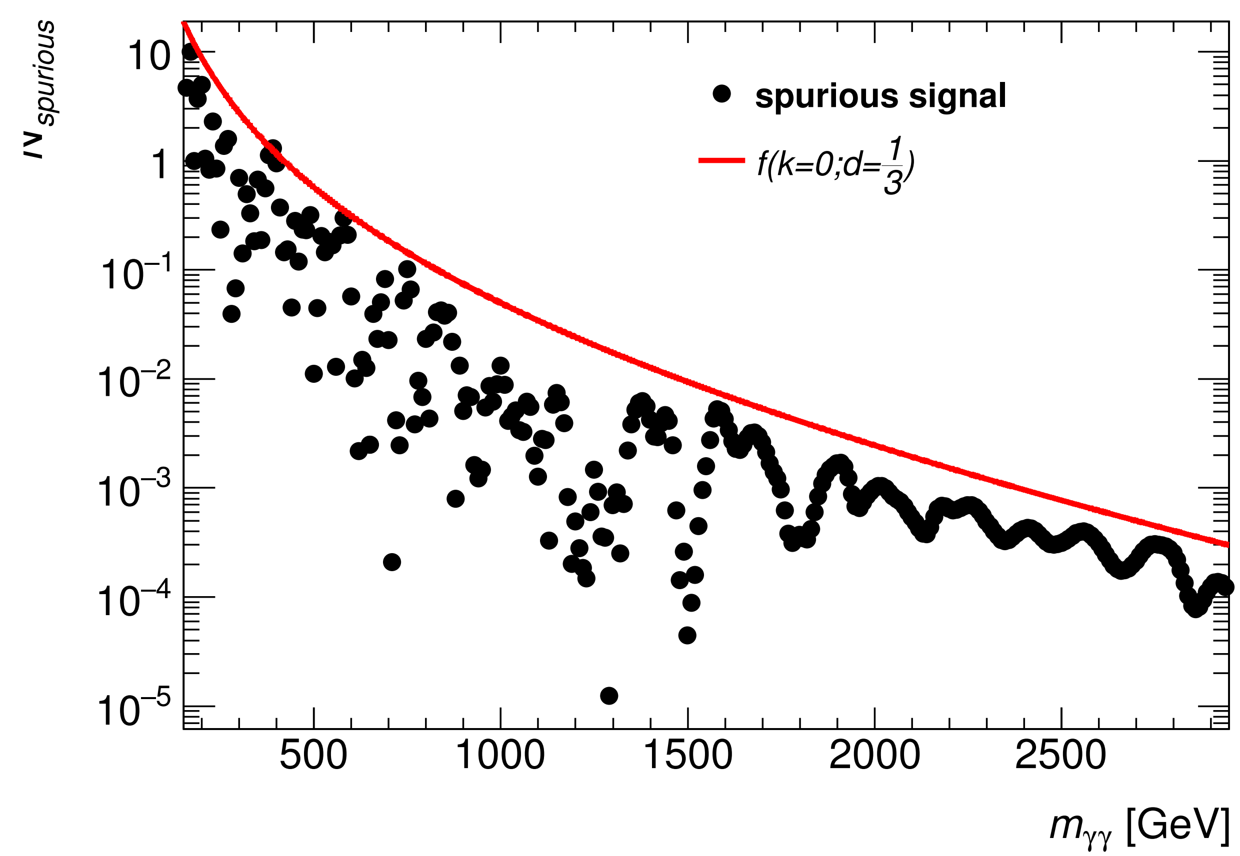




Spurious Signal

- All functions considered for that search, passed the criteria defined before for the SS test! Relative spurious signal distribution for the simplest function shown on the LHS.
- However, larger values of relative spurious signal, reaching > 50% levels, are observed for all functions in the mass range between 150 GeV and 200 GeV.
  - Therefore, until a more reliable validation can be performed (e.g. with larger MC samples), we propose to start fitting the diphoton data from $m_{\gamma\gamma}$ = 200 GeV.
- The amount of spurious signal parameterized as a function of m_X using $(1-x^{1/3})^b x^{a_0}$ can be seen o the RHS (conservative estimate).



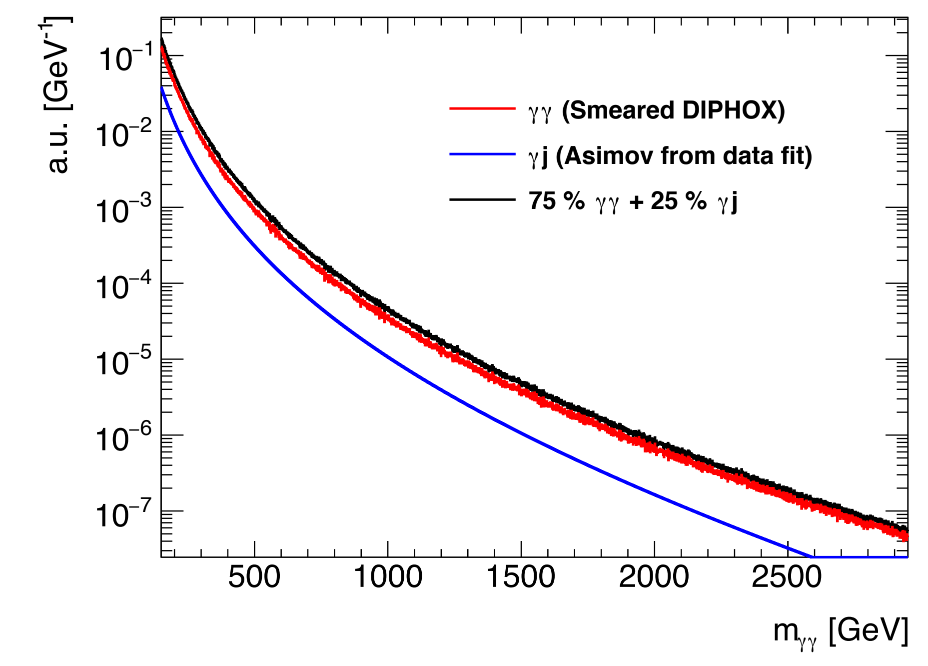


PDF Variations

- Generate DIPHOX PDF variations on “small” sample (25 M events).

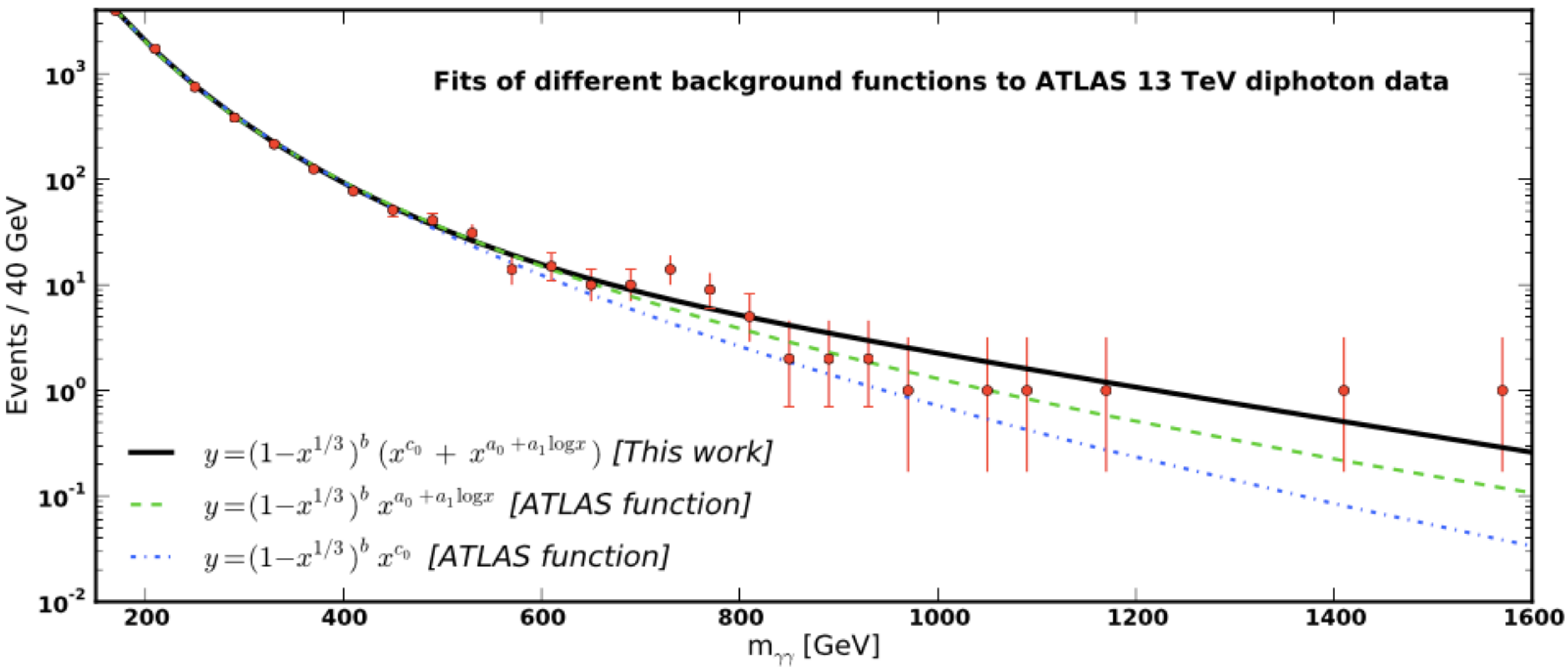
γj-Enriched Data

- “Orthogonal” control sample from data (~1.7 fb^{-1}).
  - The sample contains a fraction of genuine γγ (potentially large at high $m_{\gamma\gamma}$).
- What will we use this sample for?
  - Directly test the fitting functions (LHS) -> would represent an extreme case of γj contamination.
  - Mix 15-25% Asimov dataset representing that background contribution (nominal and uncertainties) with γγ MC 85-75% (RHS top) to make additional SS tests (using central fit result in RHS bottom).



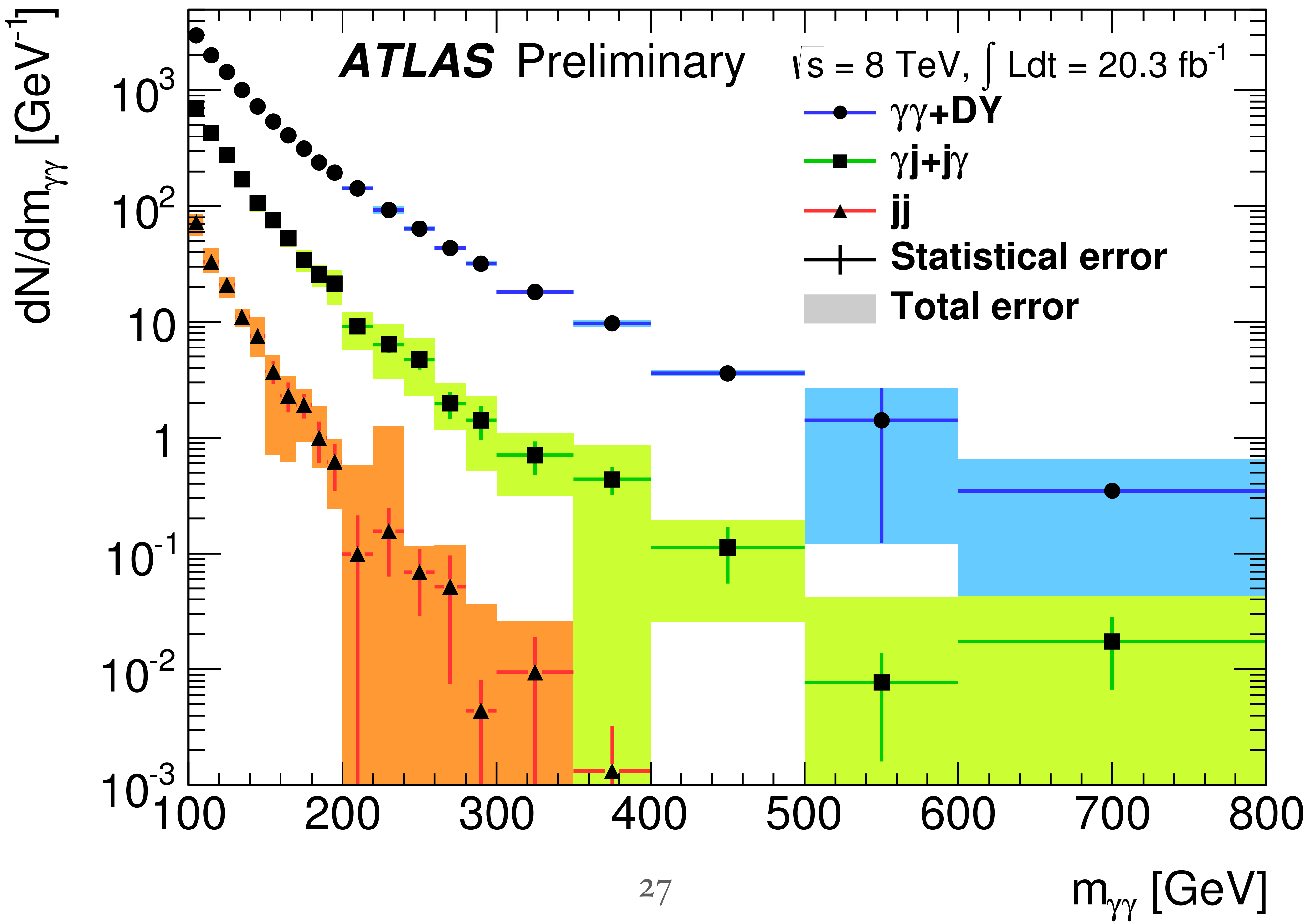
Do we need additional free parameter?

* One might be tempted to use a more complex function to fit the data.



Purity

- Higher than 90% at run2!



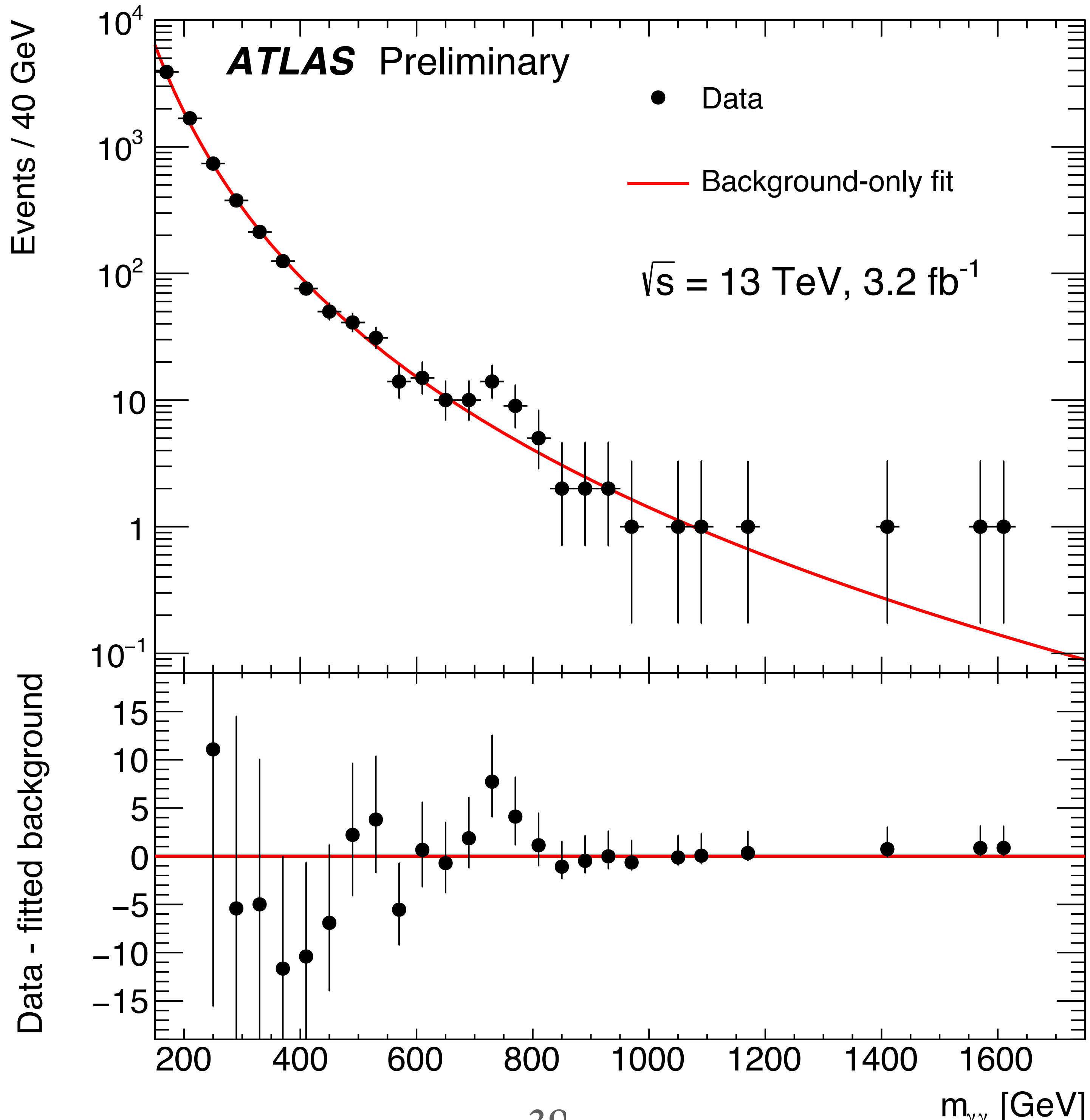
Uncertainties

Source	Uncertainty
	Background modeling ∘•
Spurious signal	$2-10^{-3}$ events, mass-dependent
Background fit	$\leq 50\%$–$\leq 20\%$ of the total signal yield uncertainty, mass- and signal-dependent
	Signal modeling ∘•
Photon energy resolution	$^{+[55-110]\%}_{-[20-40]\%}$, mass-dependent
	Signal yield •
Luminosity	±5%
Trigger	±0.63%
	C_X factors •
Photon identification	±(3–2)%, mass-dependent
Photon isolation	±(4.1–1)%, mass-dependent
Production process	±3.1%

Table 1: Summary of the systematic uncertainties in the signal-plus-background likelihood fit when considering the NWA signal model. The ∘ symbol denotes categories of uncertainties that affect the local p-value for the background-only hypothesis, while the • symbol denotes uncertainties that impact the limit on $\sigma_{\text{fiducial}} \times \text{BR}(X \to \gamma\gamma)$.

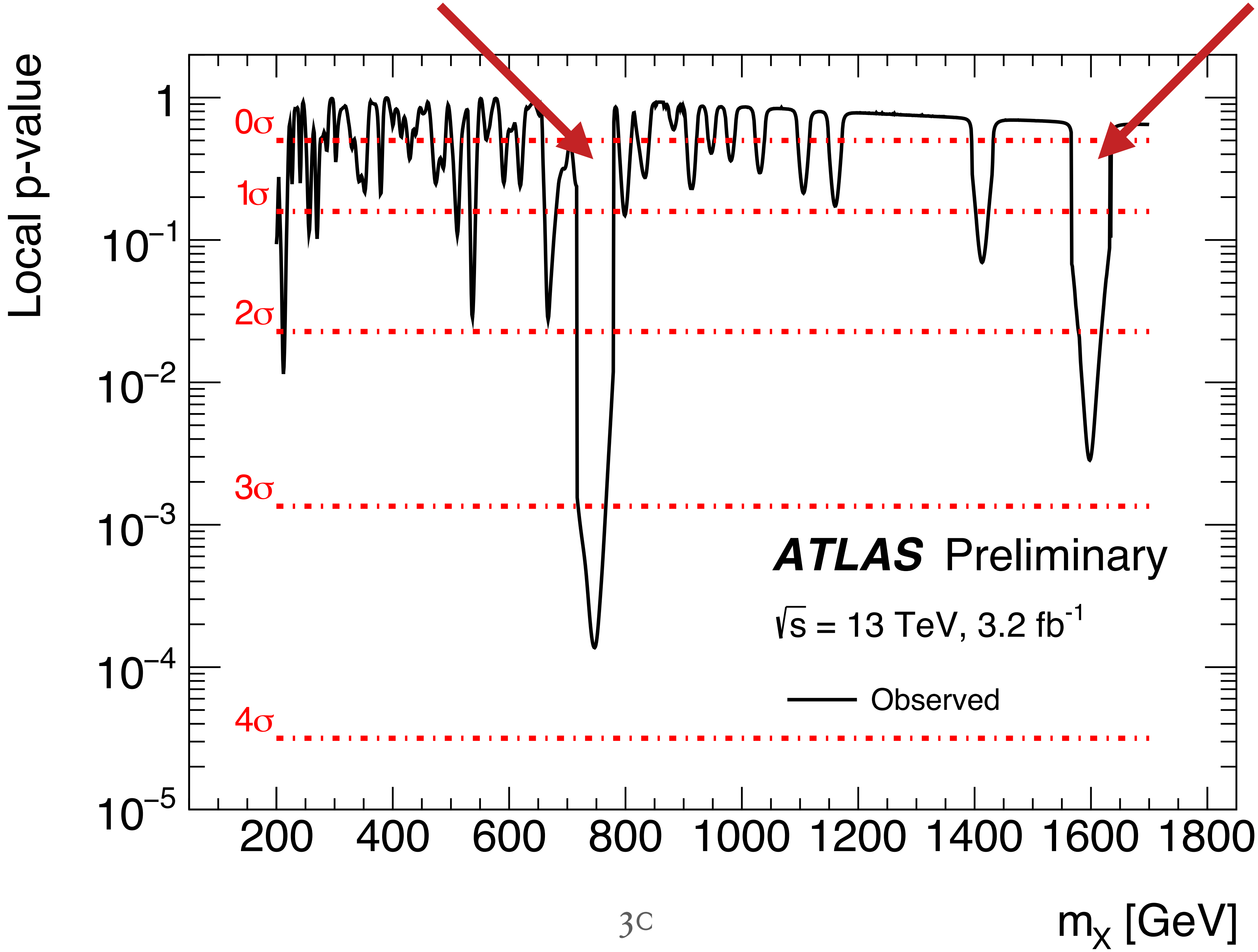
BG only fit

- The red curve (BG only fit) is the outcome of "unbinned fit"!



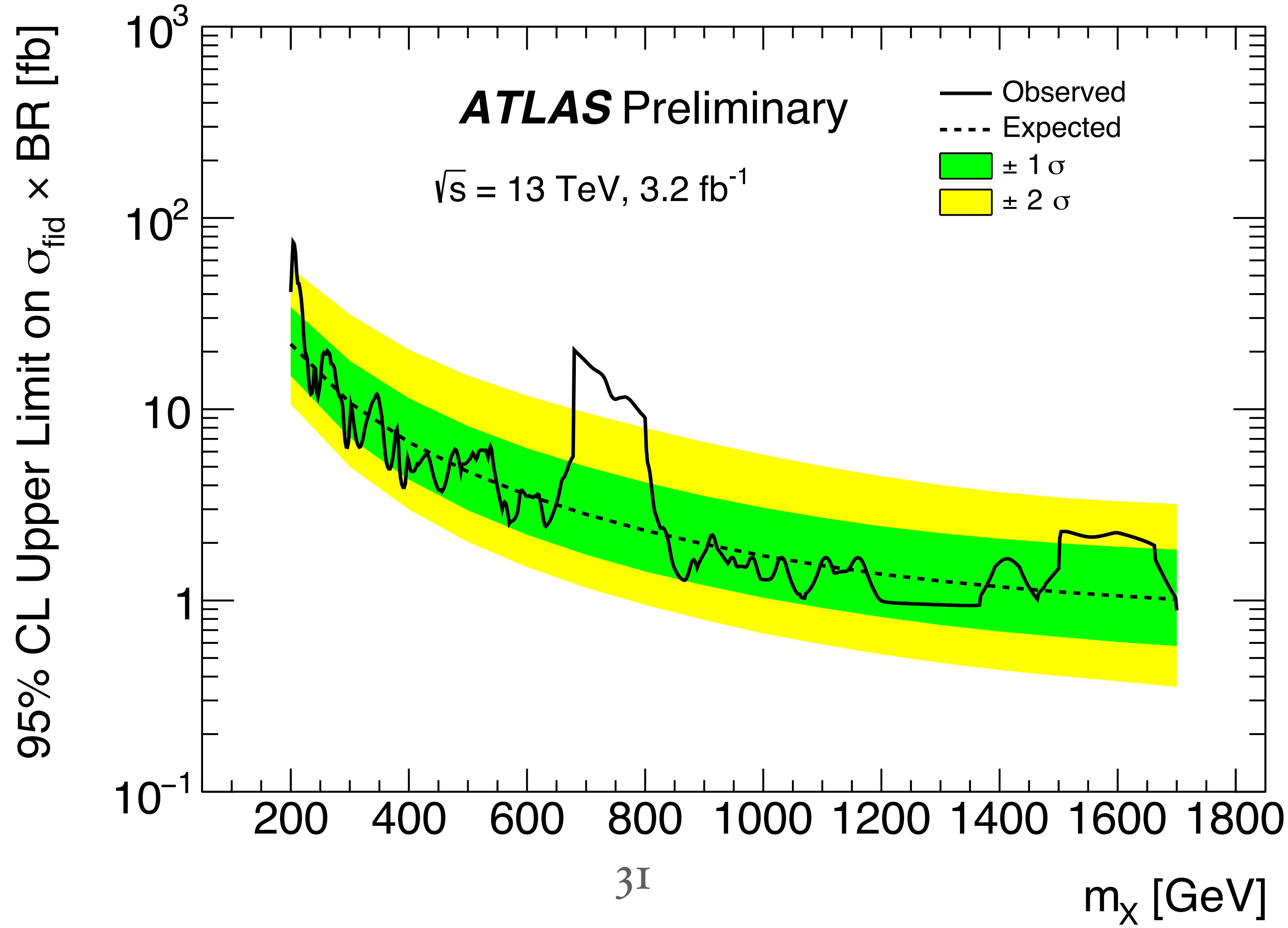
Signal + BG fit

- NWA: local - 3.6σ; global - 2.0σ.
- Under 6%: local - 3.9σ; global (2D LEE) - 2.3σ.
- NWA: local - 2.8σ;



Results

* Validity for resonances with non-negligible natural width:
  * Bias evaluation (injecting large width signal events).
  * The bias is smaller than 10% (20%) for a natural width given by width/mass = 0.4% (width/mass = 1.4%).

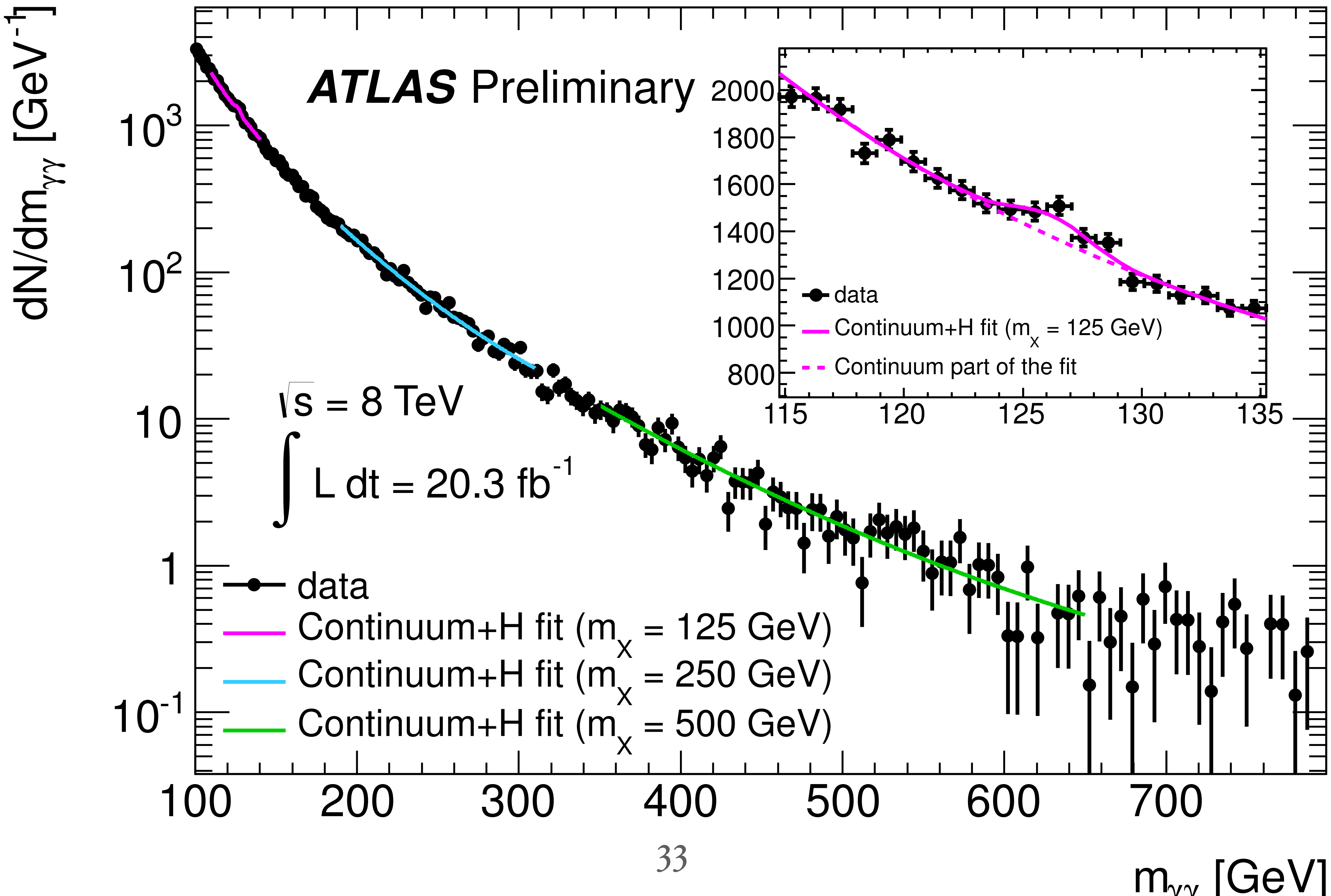


Peak region

* Not many events...
* The events in this region are scrutinized.
* No detector or reconstruction effect that could explain the larger rate is found, nor any indication of anomalous background contamination.
* The kinematic properties of these events are studied with respect to those of events populating the invariant mass regions above and below the excess, and no significant difference is observed.

Run1

- Assuming *s*-channel gluon-initiated process -> the two results are compatible within 2.2 and 1.4 standard deviation assuming NWA and 6% respectively.

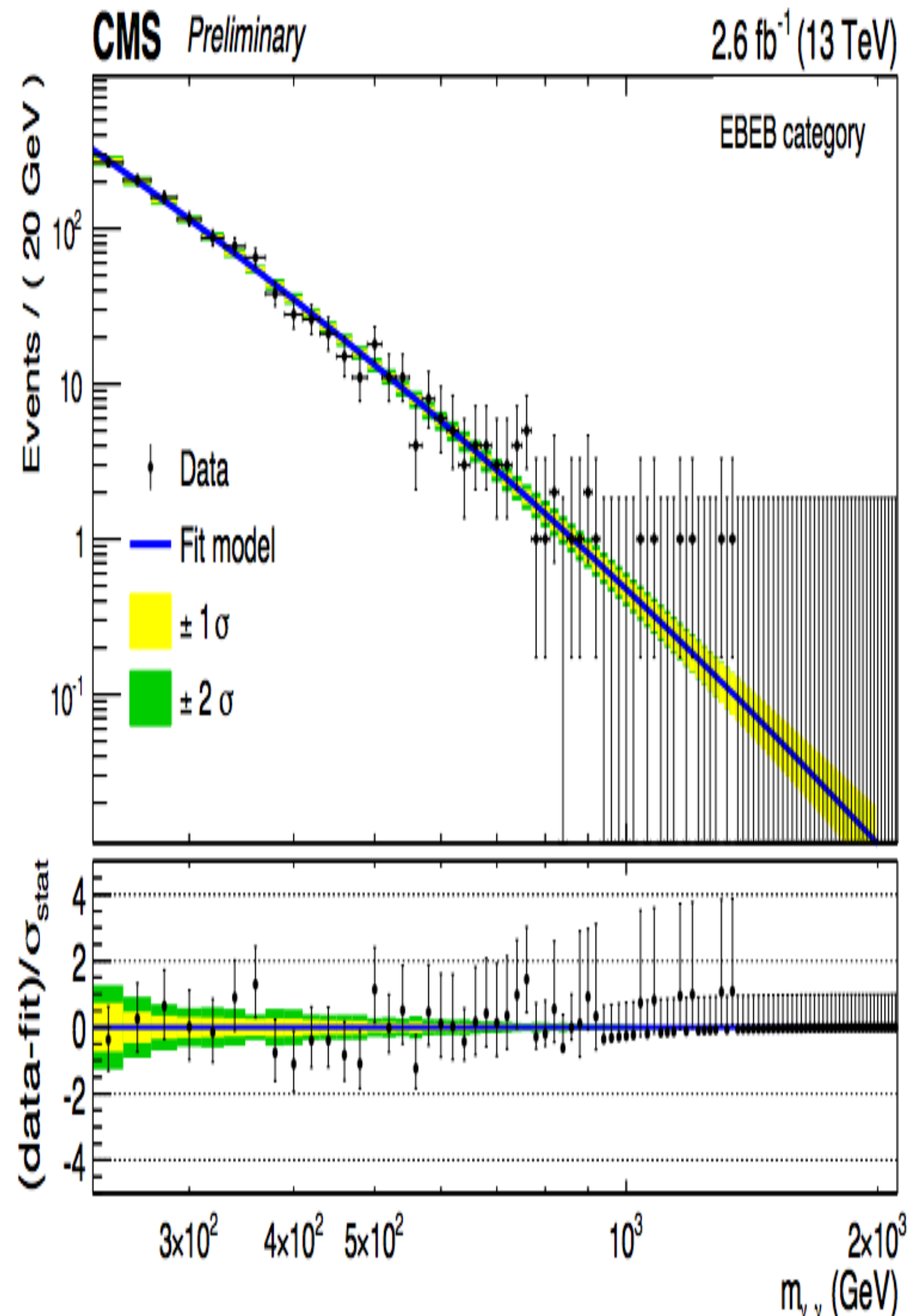


What's Next?

- Extending the mass range:
  - Low mass - <100GeV -> more work is needed due to the Z peak (converted photons, fakes etc).
  - Closing the gap - 150-200GeV -> need more statistics of MC to validate our method.
  - High mass - >3TeV -> determination of uncertainties associated to the extrapolation of the background function.
- Validating the analysis for spin 2 hypothesis (any other missing idea?).
- Validity of the limit for larger resonance widths -> plan to have 2D plot of width vas mass.
- Adding interference effects.... always ignored ;(

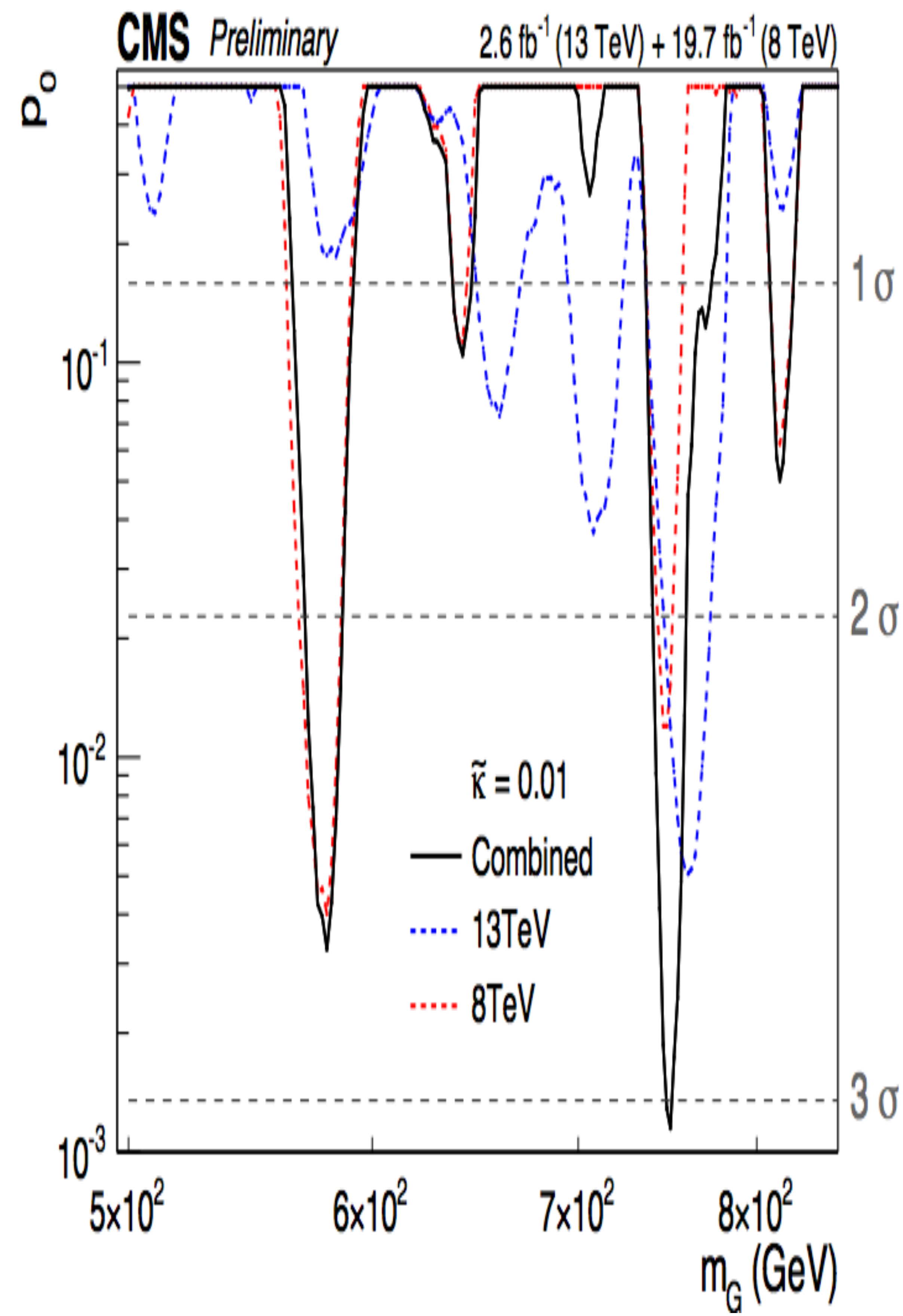
CMS

- Using 2.6 fb^{-1} and optimising for spin 2 particle, CMS see a moderate excess as well.
- Major differences with respect to ATLAS:
  - Cuts:
    - Fixed pT > 75GeV.
    - Barrel/endcap categories (no EE).
  - Signal modelling:
    - RS graviton theoretical line shape.
    - Coupling: 0.01-0.2 → ΓG/mG = 0%-6%.
    - Morphing.
  - BG modelling:
    - 80% purity for BE category.
    - Functional form: $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot\log(m_{\gamma\gamma})}$
    - Possible mis-modelling: <1/2 of bg stat uncertainty.
  - Uncertainties: Different set than ATLAS…



CMS

* Results:
  * local - 2.6σ @760GeV.
  * global - 1.2σ.
* Combined with run1:
  * local - 3.0σ @750GeV.
  * global - <1.7σ.

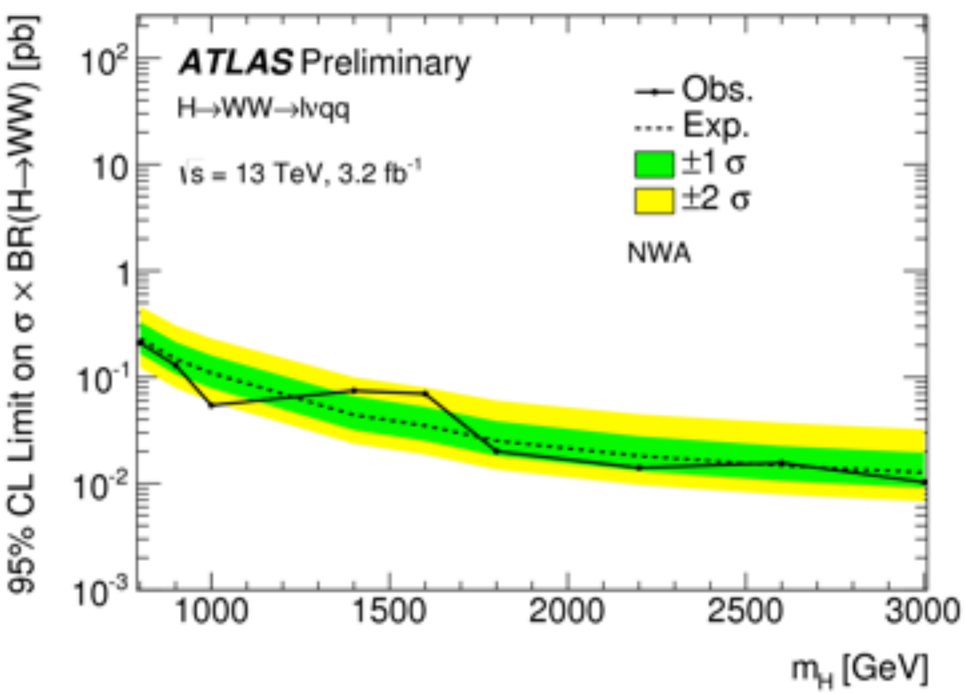


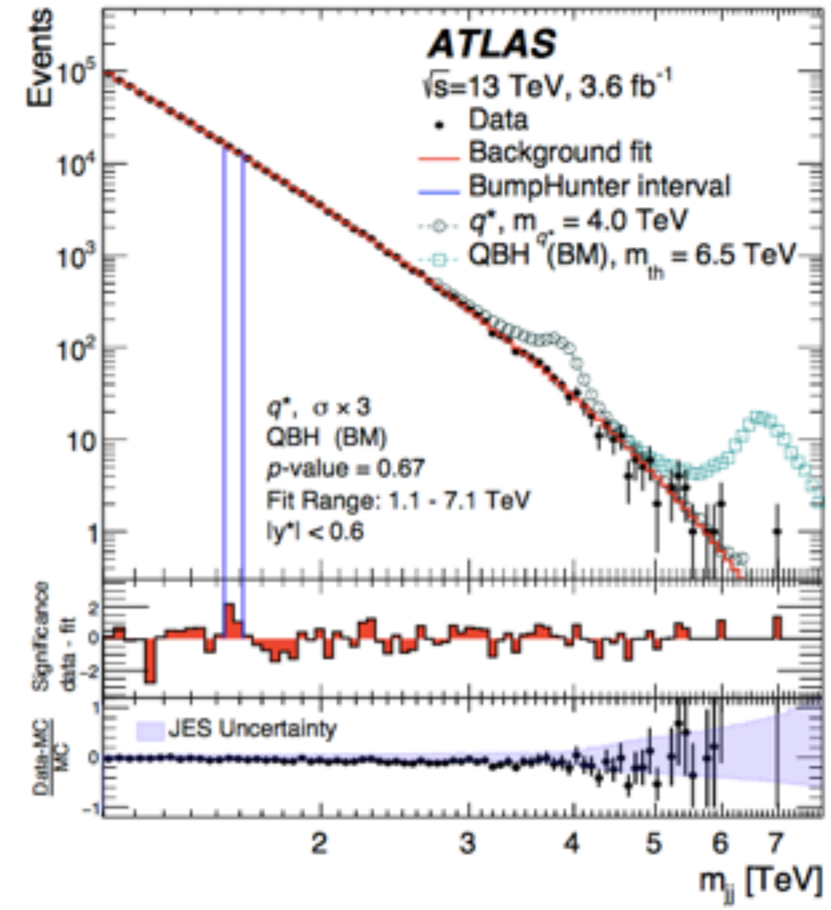
Questions

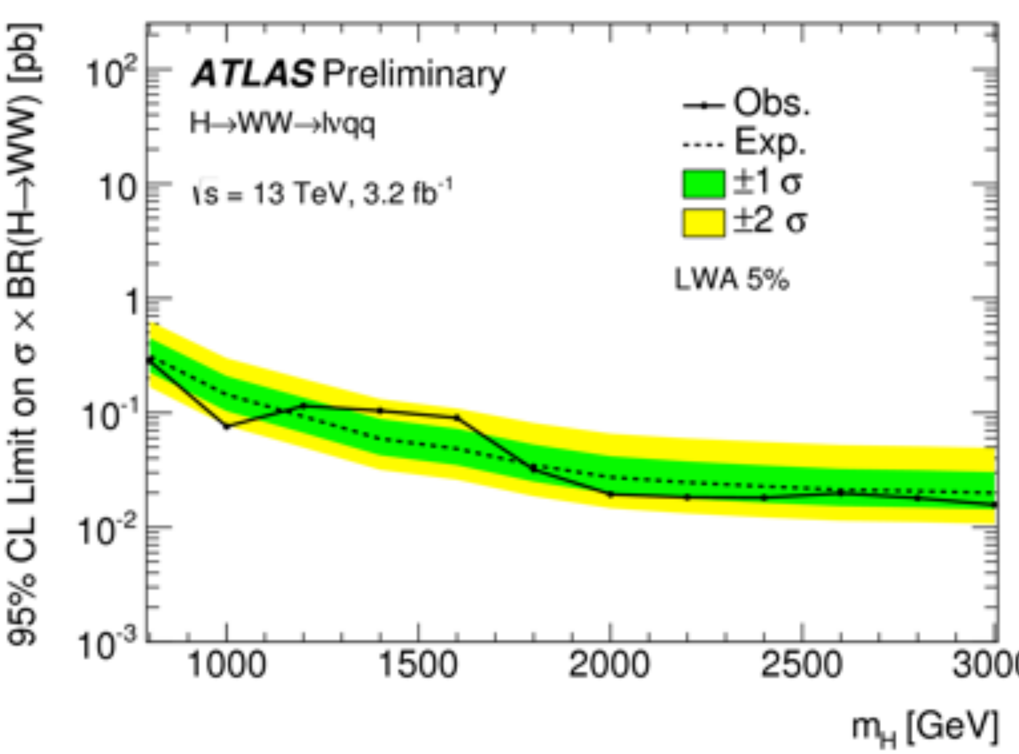
* Can it be two -degenerate states? Too soon to know...
* Can it be S -> aa -> 4 photons? S -> ay -> 3 photons? “The high-granularity first layer is used to further discriminate single photons from overlapping photon pairs originating from the decays of neutral mesons in jet fragmentation”.

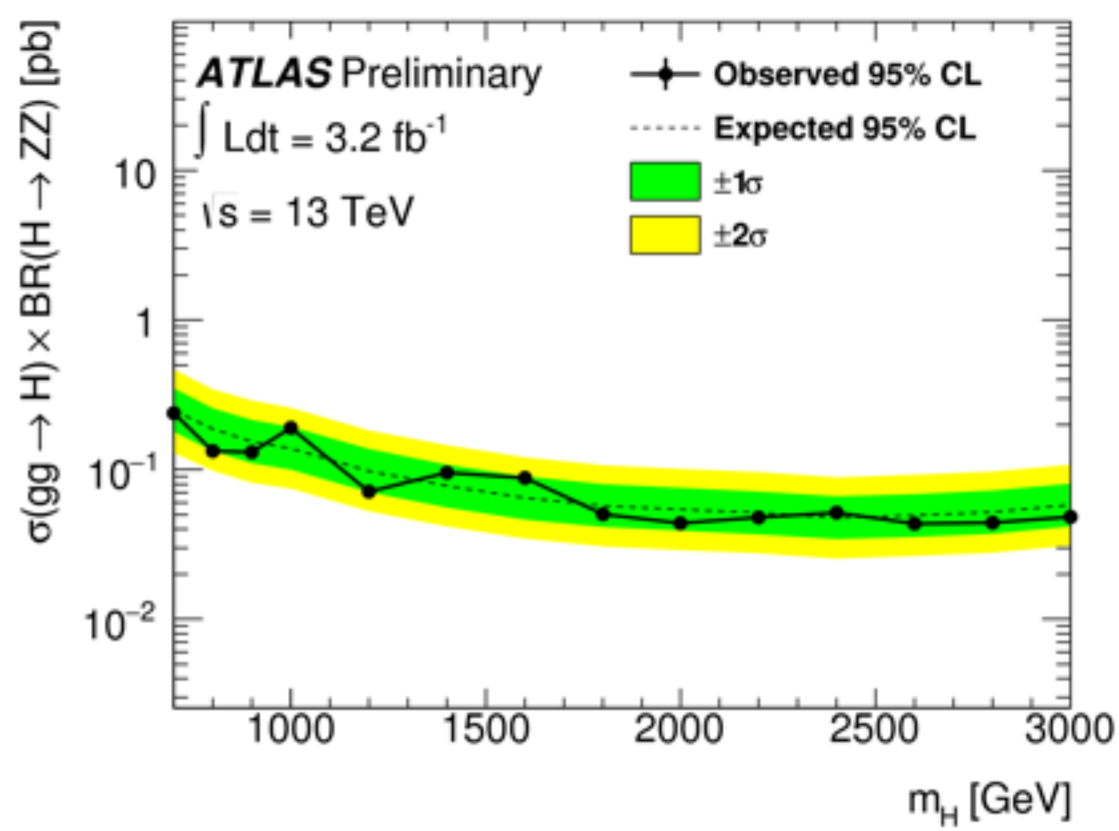
Questions

- What about other channels? Not at 750GeV but…



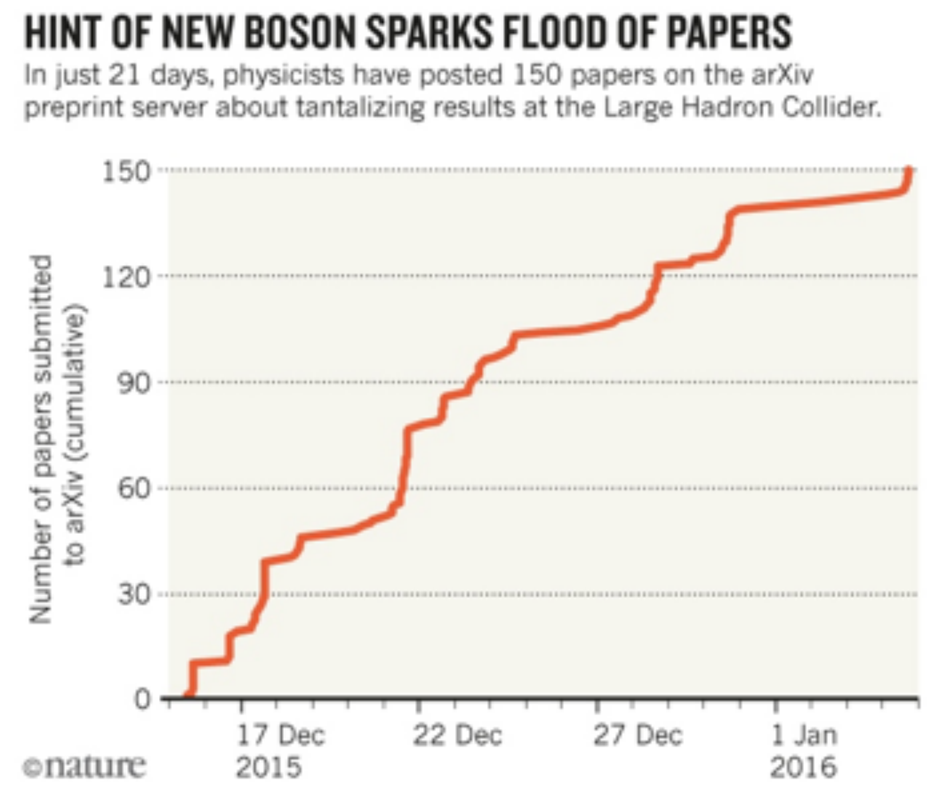


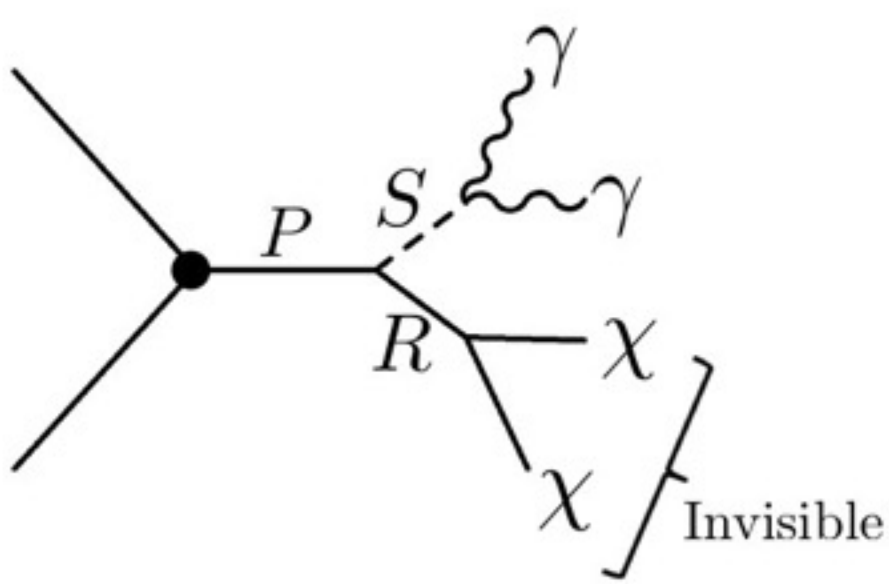


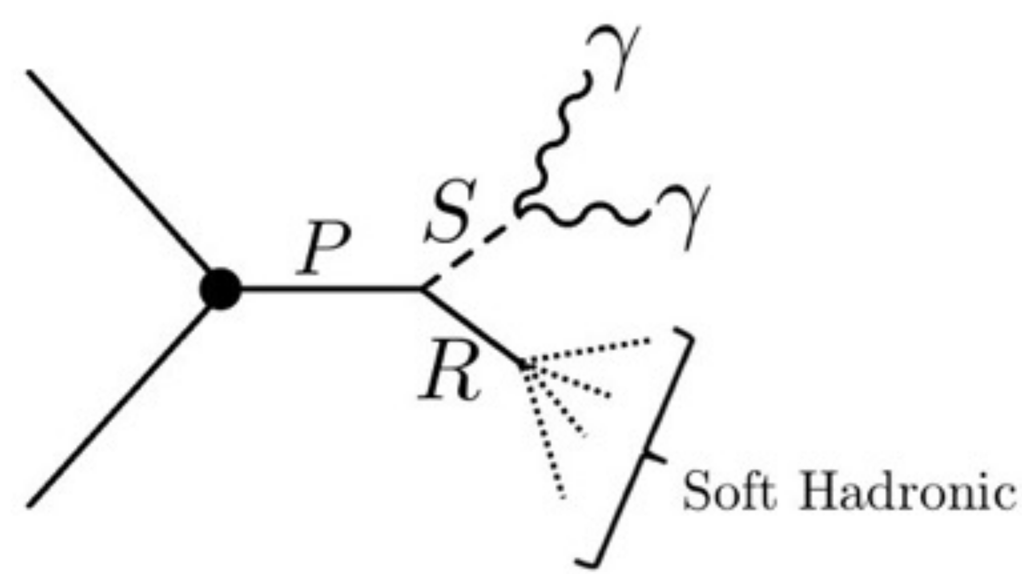


Interpretation

- Many papers:
  - ~165 spin-0 resonance
  - ~5 spin-2 resonance
  - ~5 parent resonance/kinematic edge







Problems

* Biggest problem: too large width for such high rate!
* Additional:
  * no activity in the peak region.
  * no peaks in other channels (mainly old dijet -> make both ggF and qq production hard to believe).

Killing beloved theories

* 2HDM with CP conserving and no additional particles.
* EWS with no additional particles.
* Dilaton.
* MSSM but not SUSY :)
* Adding either singlet or doublet ->
  must add other BSM particles as well (w, top - can't explain the rate in ggF)...
  tree level coupling can't explain what we see!

What if?!

- What if we confirm it is new physics at summer?
  - First:

  - Start to answers all the questions -> association, two degenerate states, 4 photons etc.
  - Crucial point -> do we see it in other channels? Dijet? ttbar? VV? ZGamma? etc.

What if?!

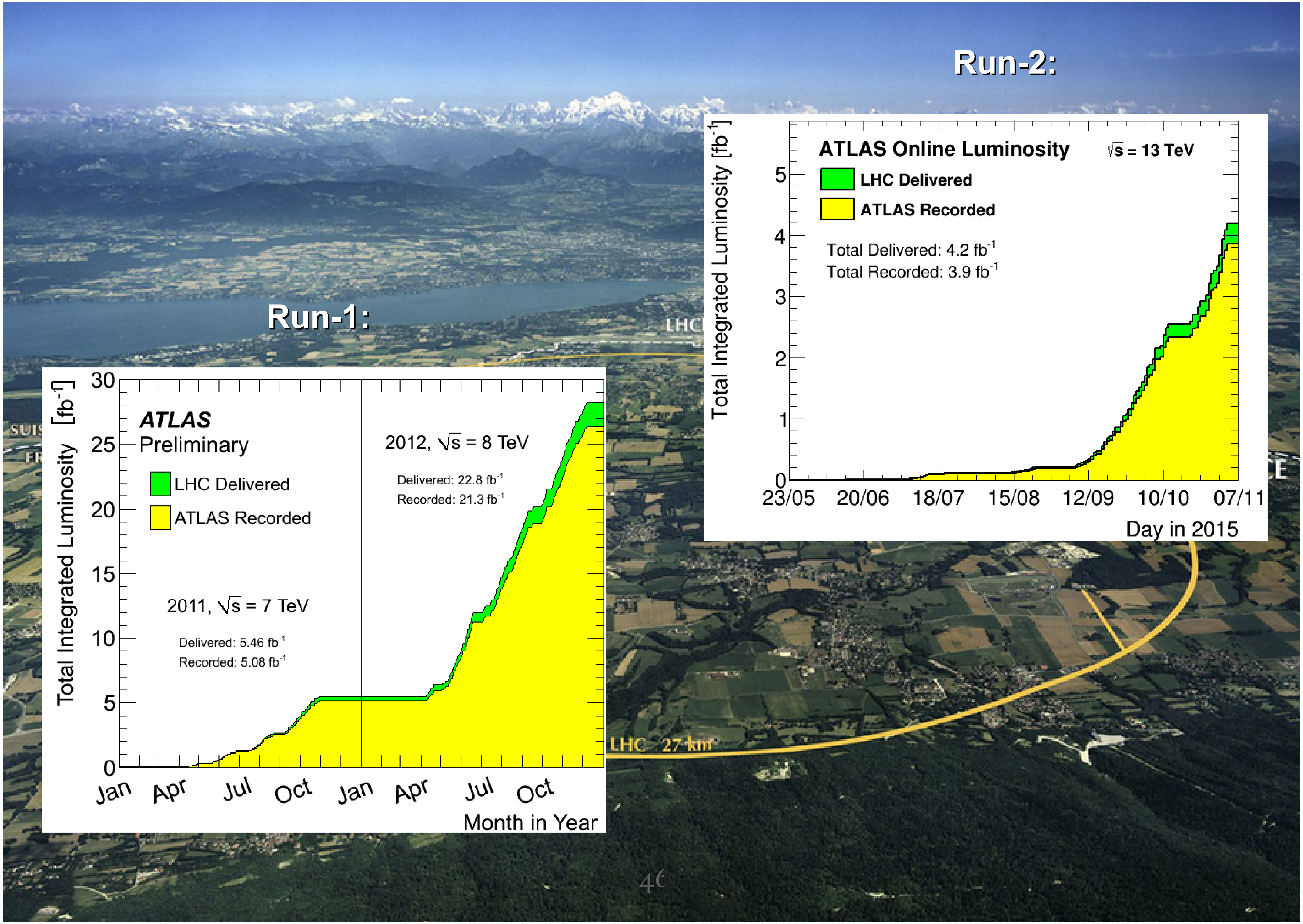
- What if it is all gone???
  - Still:

  - ATLAS -> we learnt a lot during the process of understanding and scrutinizing!
  - HEP -> >150 papers predicting theories that explain such anomaly :)

Thank you for listening

Backup

Integrated luminosity



Reconstruction strategy

- Search for energy clusters within the second layer of the EM calorimeter.
- Create ‘preclusters’ with energy > 2.5 GeV.
- Form clusters in $\Delta\eta \times \Delta\phi$ -> 3x7 clusters in the barrel and 5x5 in the endcap.
- Clusters matched to tracks:
  - Matched based on position.
  - Use track information to classify particles:
    electron, converted photon, or unconverted photon.
- Rebuild clusters, where the cluster size depends on the particle type and location in the calorimeter.

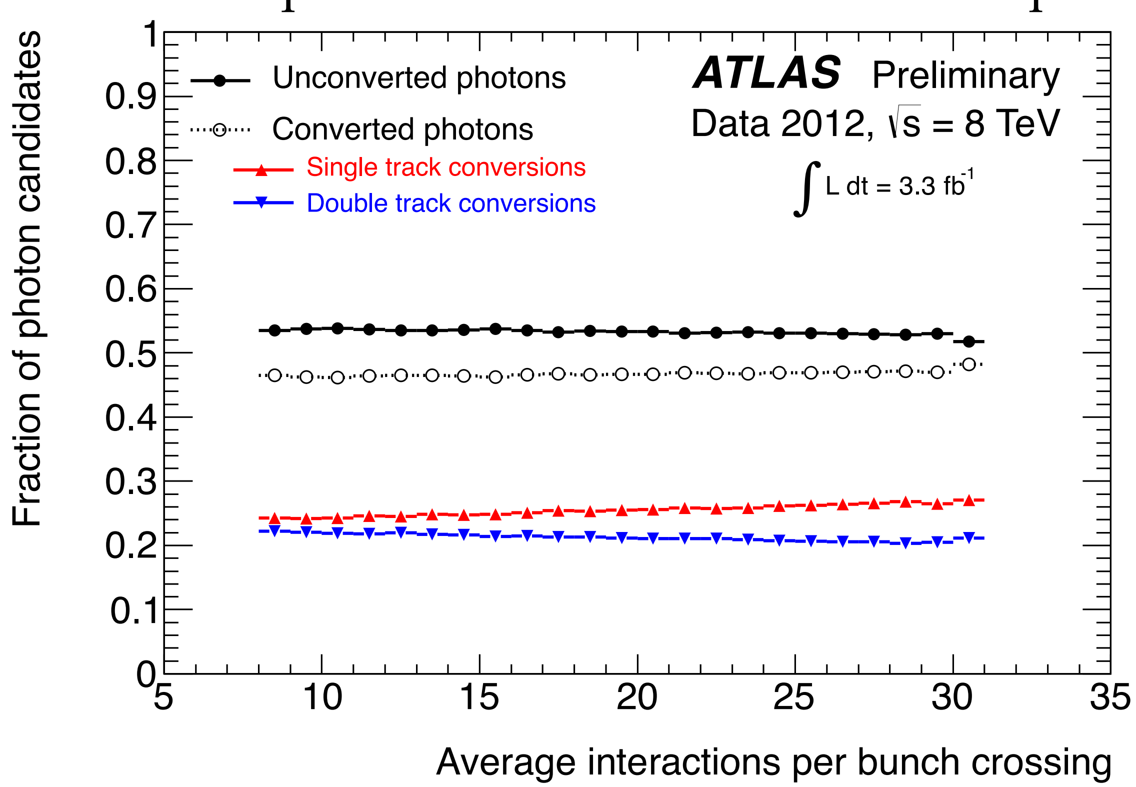
Particle type	Barrel	Endcap
Electron	0.075×0.175	0.125×0.125
Converted photon	0.075×0.175	0.125×0.125
Unconverted photon	0.075×0.125	0.125×0.125

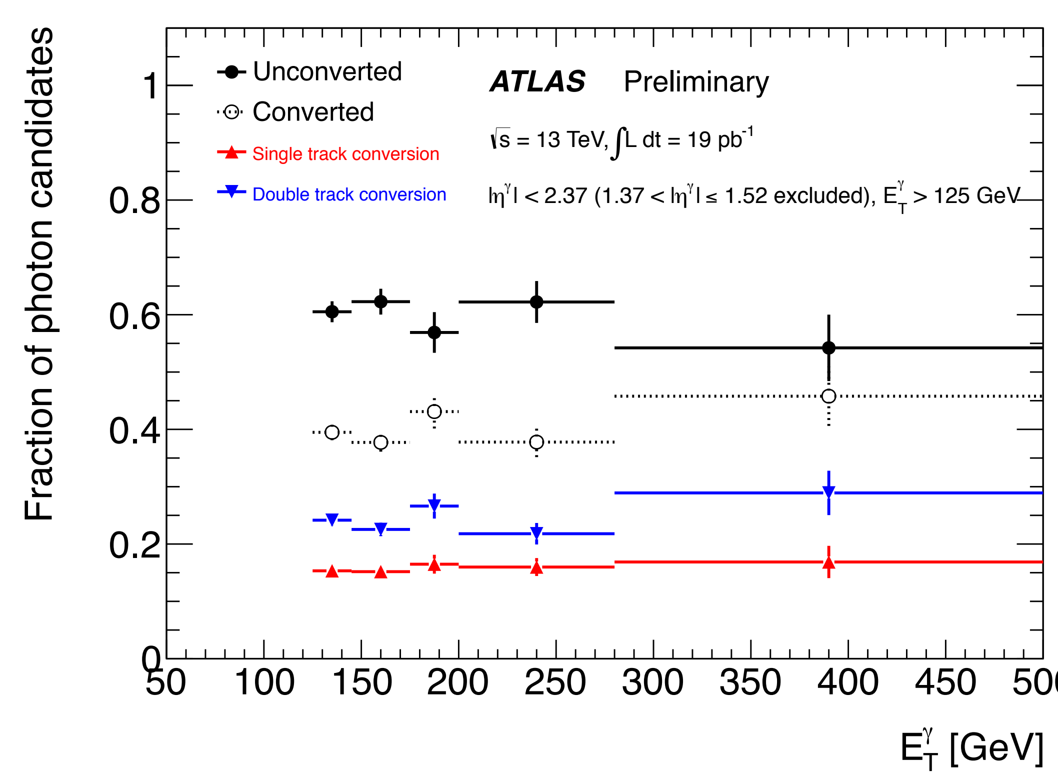
Cluster size in η and ϕ for different particle in Run 1.

Photon conversion

- Photons often interact with material before the calorimeter, and convert into an electron/positron pair -> converted photons.
- Relative fraction of photon conversion is flat with respect to transverse energy but vary with η, due to different amounts of material in different η regions.
- Converted photons can be categorised as having one or two tracks.
- Photons which convert after R =0.8 m are not defined as converted.

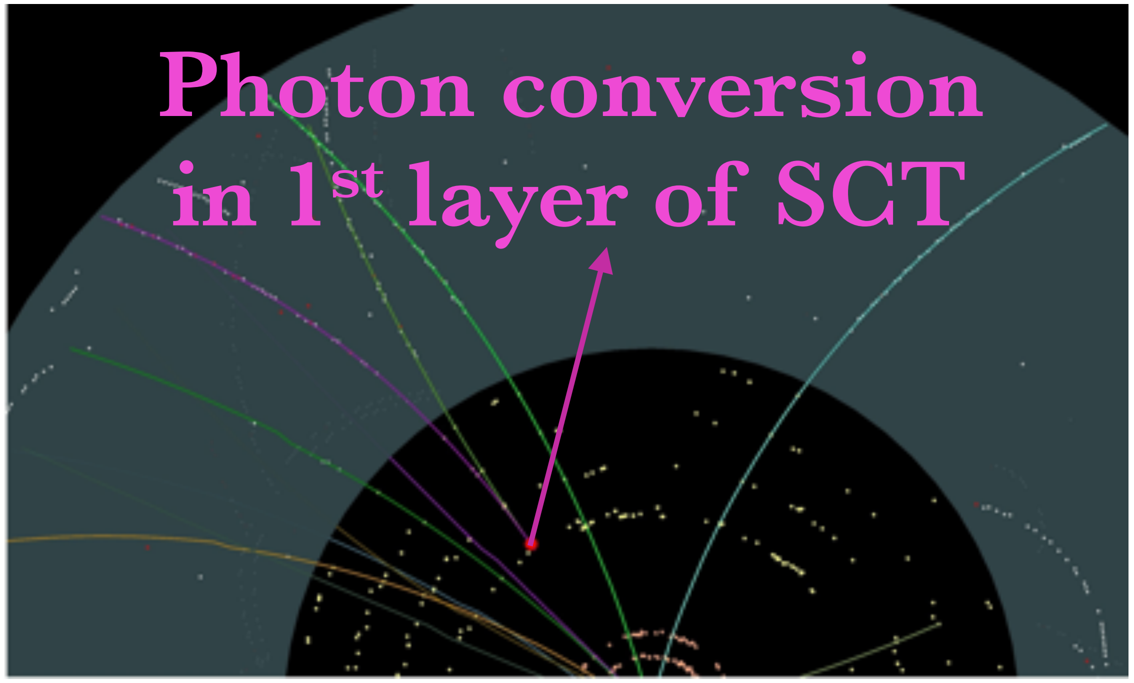
Stable photon reconstruction vs Pileup

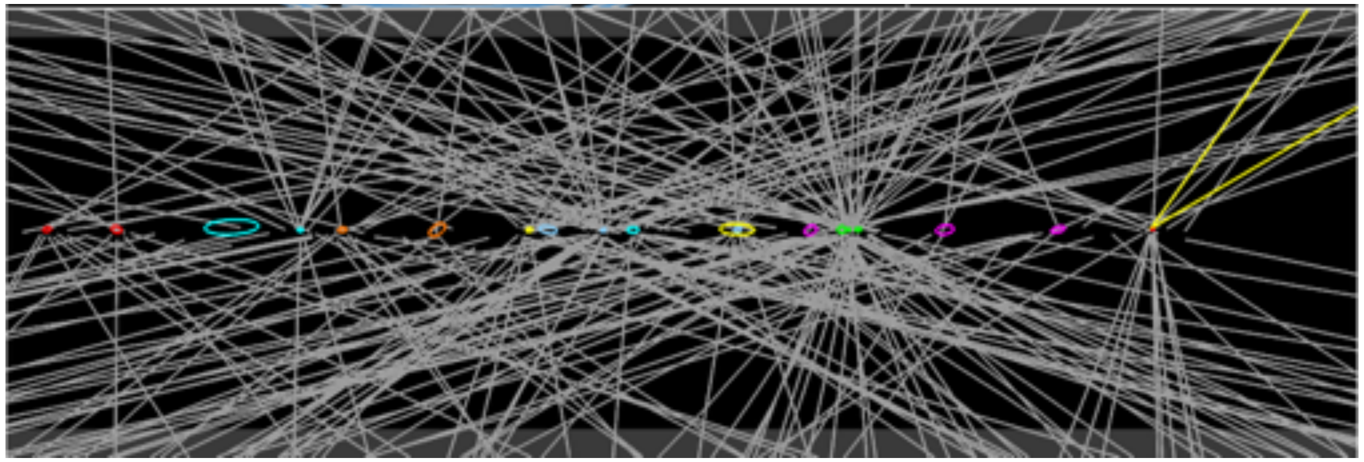




Photon conversion

- Pileup can lead to mis-reconstructing unconverted photons as converted photons.
- More tracks increases the likelihood of any one track matching an unconverted or single track converted photon.
- This is under control:
  - 3 % migration of 2-track conversions to 1-track conversions.
    → 1-track conversion is when either the two tracks are highly collimated or one track is too soft to be reconstructed.
  - Fraction of converted vs unconverted photon candidates is stable to 1 % between extreme pileup values.



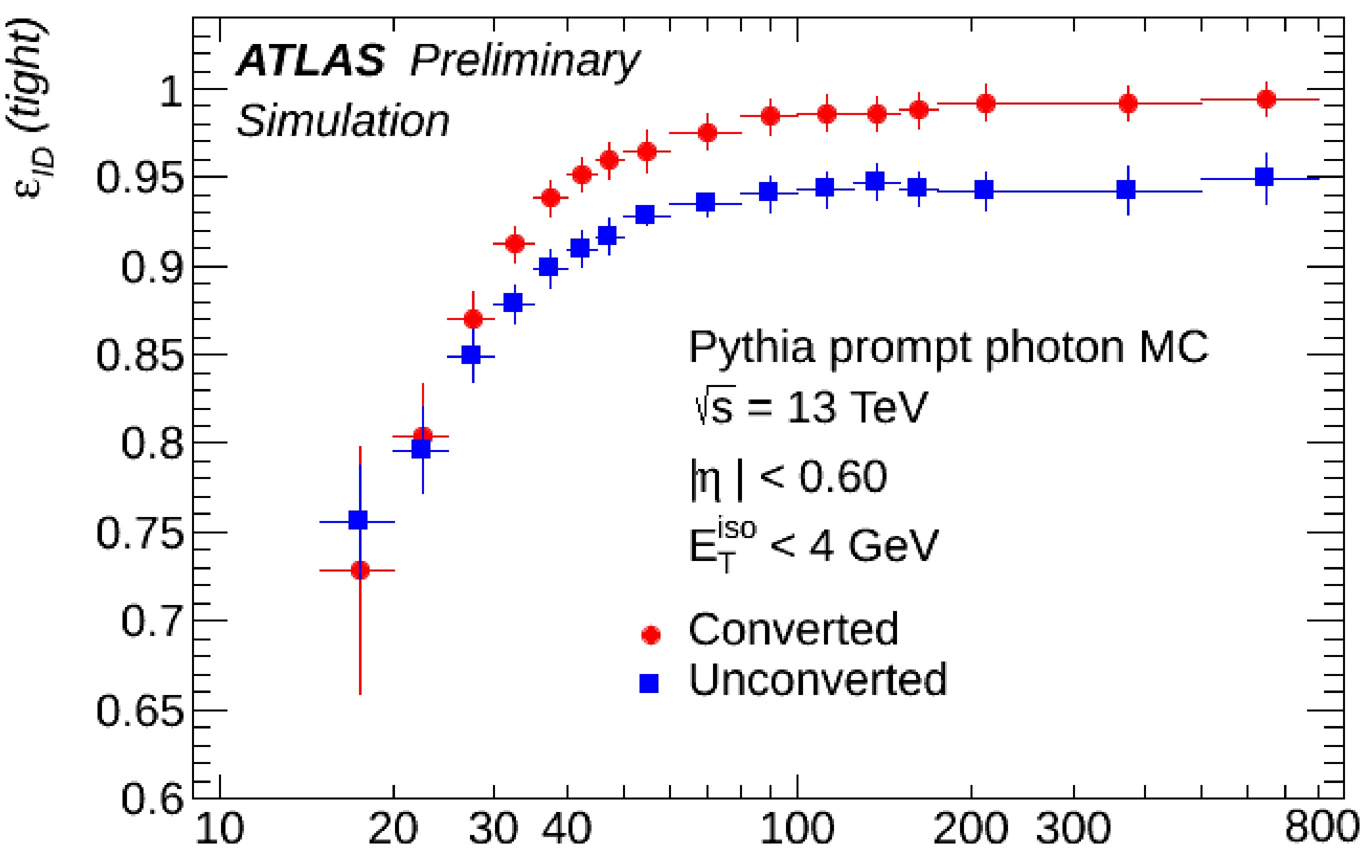


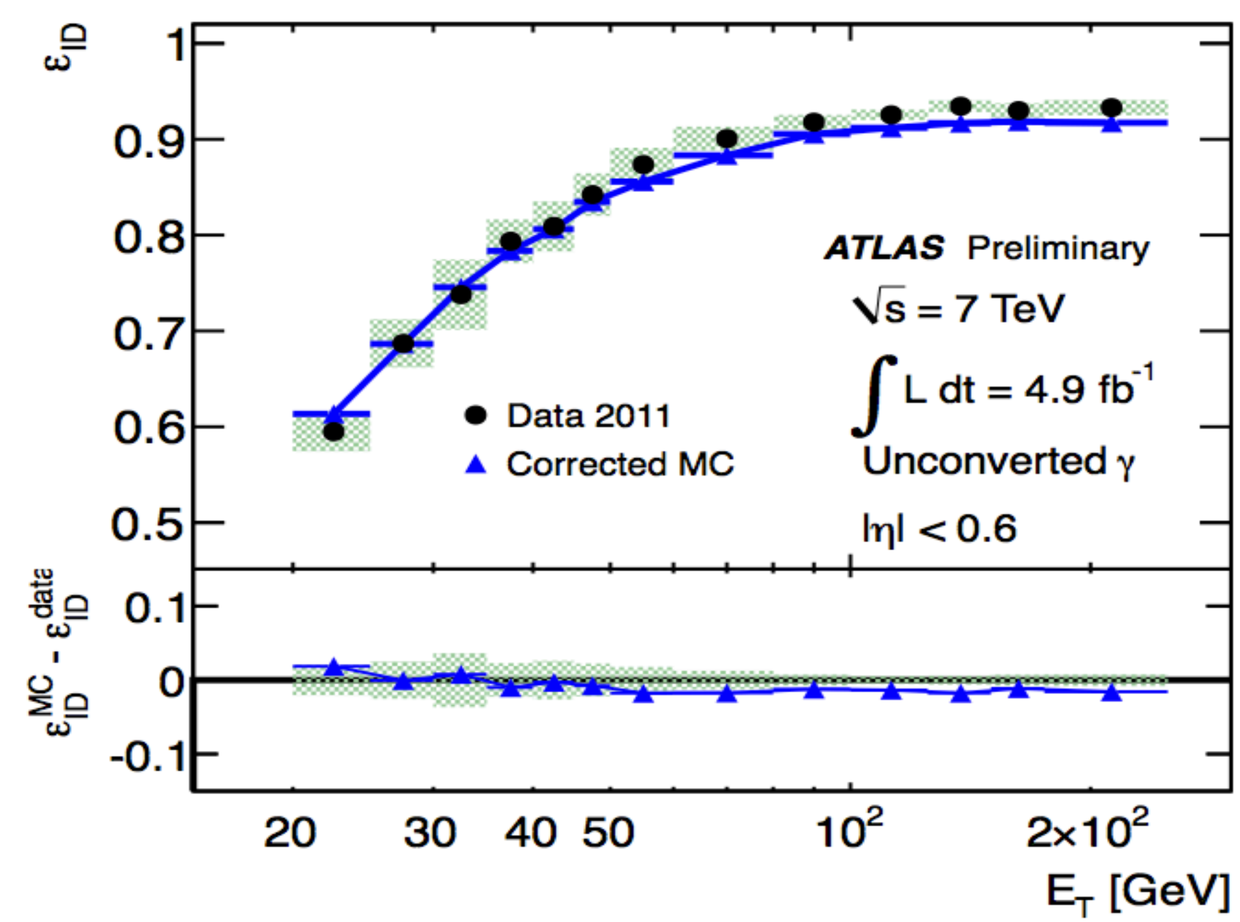
Conversion

* Main culprit for fakes is the TRT due to the poor resolution in eta.
* For that we play with:
  * Cuts on the PID probability (most of the pileup tracks come from hadrons and not electrons).
  * Hit quality (the so called tube hits that indicate shared or badly measured drift circles) associated with a robust definition for that (the drift circle errors did not scale well with pileup).

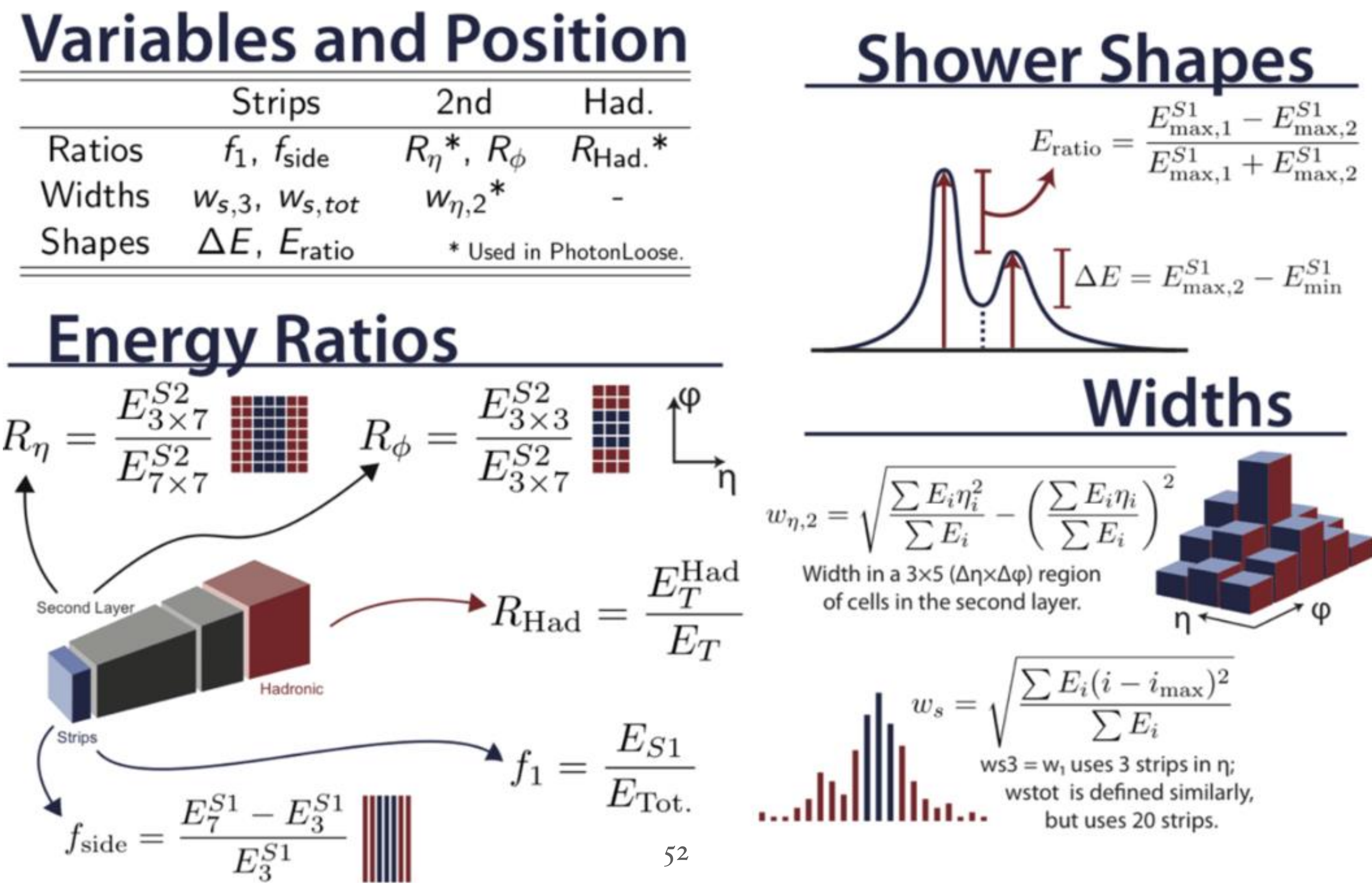
Photon identification efficiency

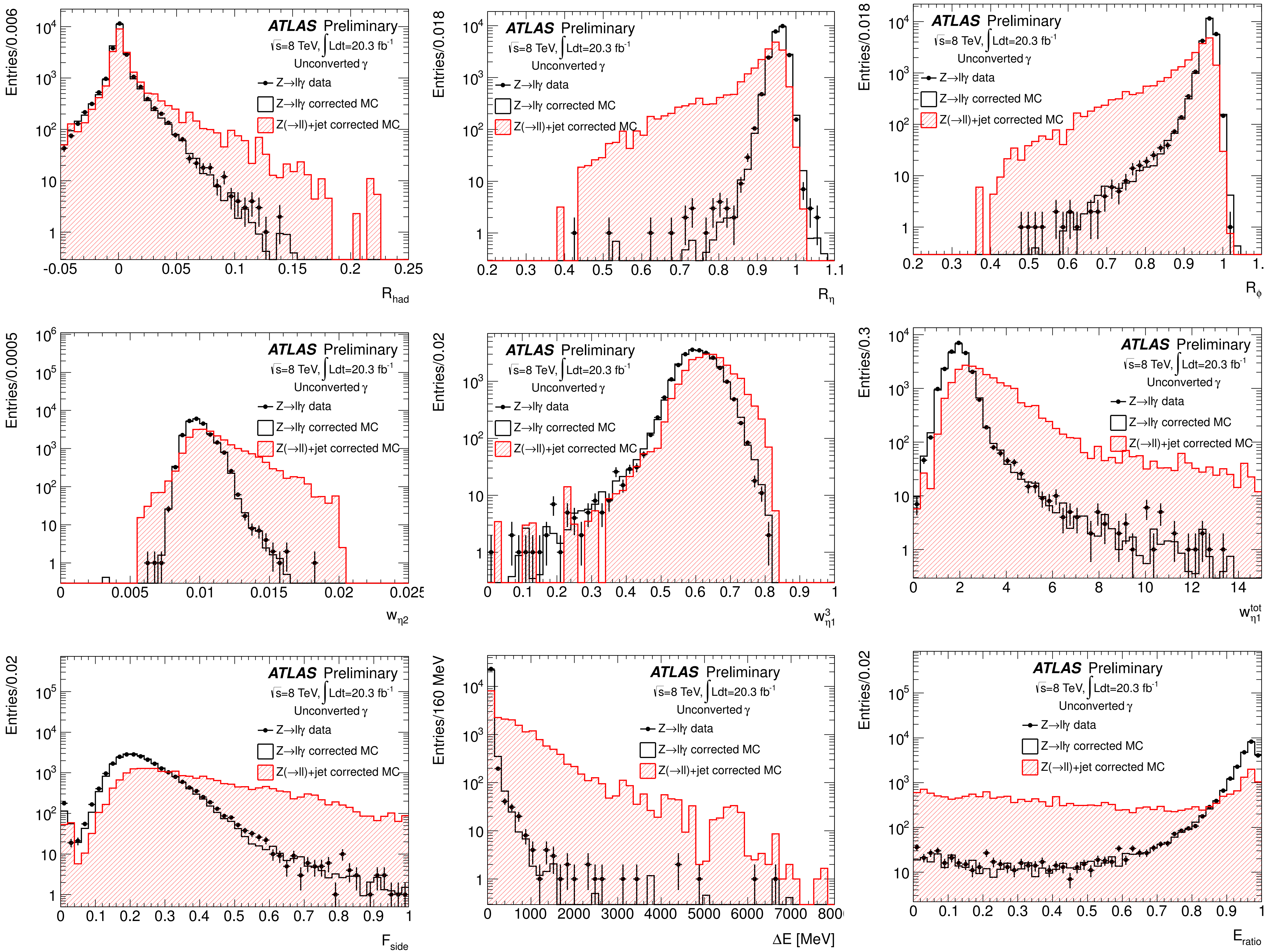
- From MC, corrected for Data/MC discrepancies (EM shower moments).
- Separately for converted and unconverted γ.





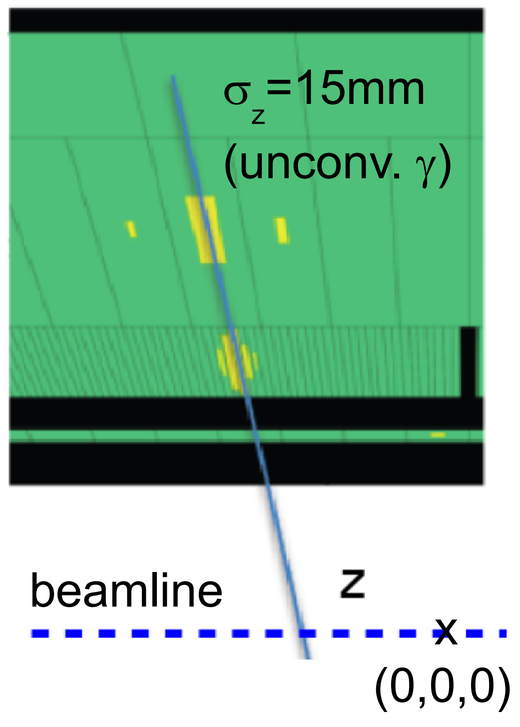
Shower shapes




ATLAS Preliminary
√s=8 TeV, ∫Ldt=20.3 fb⁻¹
Unconverted γ
Z→llγ data
Z→llγ corrected MC
Z(→ll)+jet corrected MC
Entries/0.006
R_had
Entries/0.018
R_η
Entries/0.018
R_φ
Entries/0.0005
w_η2
Entries/0.02
w^3_η1
Entries/0.3
w^tot_η1
Entries/0.02
F_side
Entries/160 MeV
ΔE [MeV]
Entries/0.02
E_ratio

DiPhoton vertex selection

- Determination of correct primary vertex important for several reasons:
    - For the invariant mass the photon kinematics are corrected using the z of the chosen vertex → resolution is improved.
    - Needed for calculation of track isolation variables.
    - Method is very robust against pile-up.
- Diphoton vertex selection algorithm using neural networks trained with following input:
    - Combined *z*-position of the intersections of the extrapolated photon trajectories with the beam axis.
    - Σp_T and Σp_T^2 of tracks from associated vertex.
    - $\Delta\varphi(\gamma\gamma,$ vertex), azimuthal distance between diphoton system and vertex.

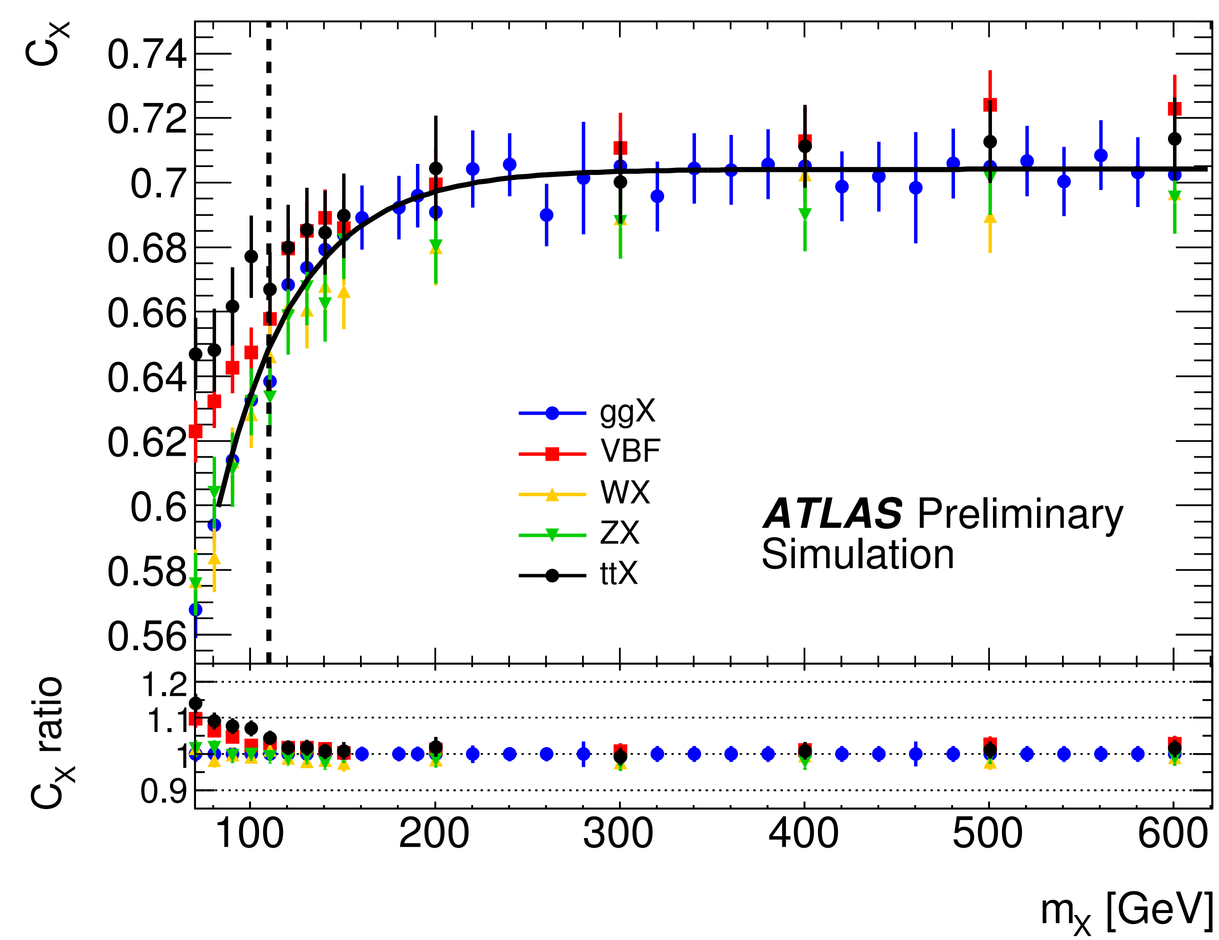


Fiducial Volume

- To extract the fiducial cross-section the number of fitted signal events in data must be corrected for detector effects.
- The kinematic cuts applied on the truth photon variables to define the fiducial volume are chosen to mimic the ones used at the reconstruction level.
- Large model dependence when **no truth isolation** requirement in fiducial volume.
  - ttH far below other C_X factors (larger jet activity results in lower efficiency of experimental isolation selection).
  - All production modes / mass values within ~10% of each other.

$$C_X = \frac{N_{\text{selection}}}{N_{\text{acceptance}}}$$

- Truth isolation choice driven both by **model independence** (similar C_X factor for different production mode) and by matching with **experimental isolation requirement.**
- Best choice is "VarCone40Loose" -> $E_T^{iso}(R{=}0.4)/(E_T^{\gamma true} + 120) < 0.05$.
  - $E_T^{iso}(R{=}40)$ = etcone40
  - Model dependence: 3%



Isolation

- Truth:
  - The particle isolation is defined as the transverse energy of the vector sum of all stable particles (except muons and neutrinos) found within the ΔR = 0.4 cone around the photon.
- Reco:
  - Track isolation: scalar sum of the transverse momenta of all tracks with $p_T >$ 1 GeV in a cone of size ΔR = 0.2.
    Only tracks consistent with originating from the diphoton production vertex are used, and the tracks associated to converted photon candidates are excluded.
  - Calorimetric isolation: sum of the transverse energy of the topological clusters with positive energy reconstructed in the calorimeter around each photon candidate in a cone of radius ΔR = 0.4, after subtracting the contributions from the photon itself, and correcting for the leakage of the photon energy and the effects of underlying event and pileup .

Statistical Treatment

* Use same model as in RunI, implemented in HFitter.

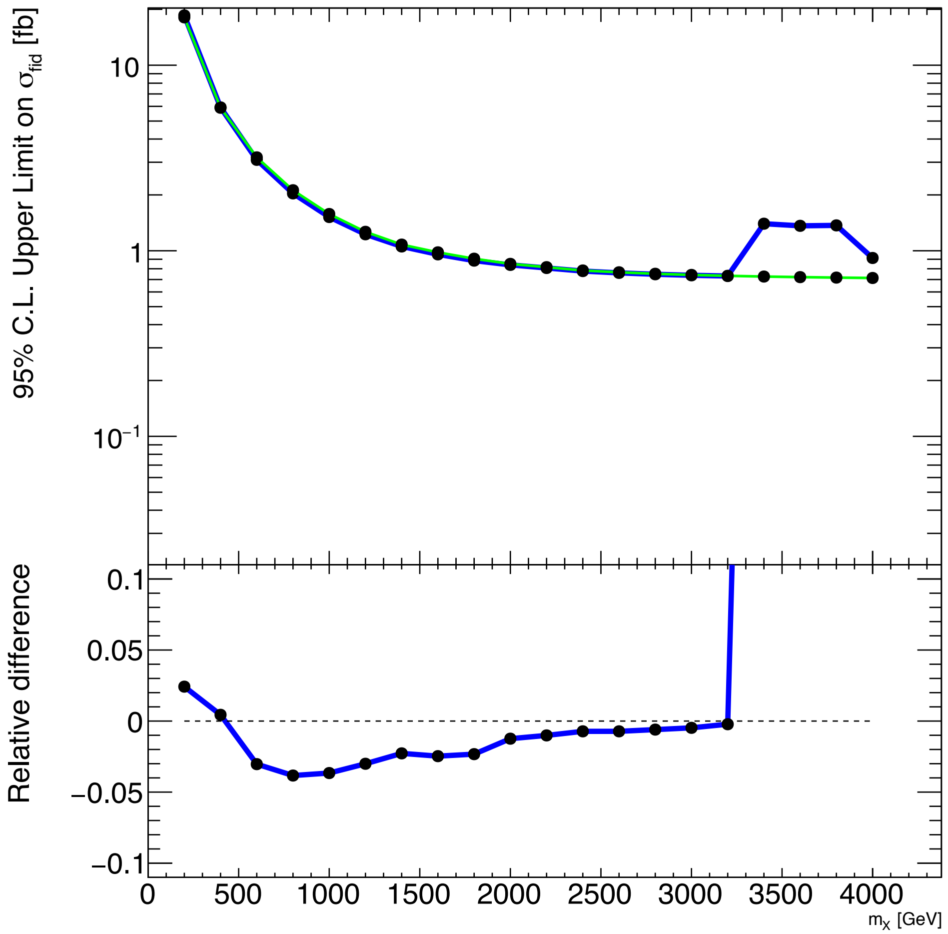
$$\mathcal{L}(m_{\gamma\gamma};\sigma_{fid},m_X,\mu,m_H,N_{bkg},\xi,\boldsymbol{\theta}) = N_X(\sigma_{fid},m_X,\boldsymbol{\theta}_{N_X},\theta_{SS})f_X(m_{\gamma\gamma},m_X,\boldsymbol{x}_X(m_X),\theta_\sigma) + N_{bkg}f_{bkg}(m_{\gamma\gamma},a,b)$$

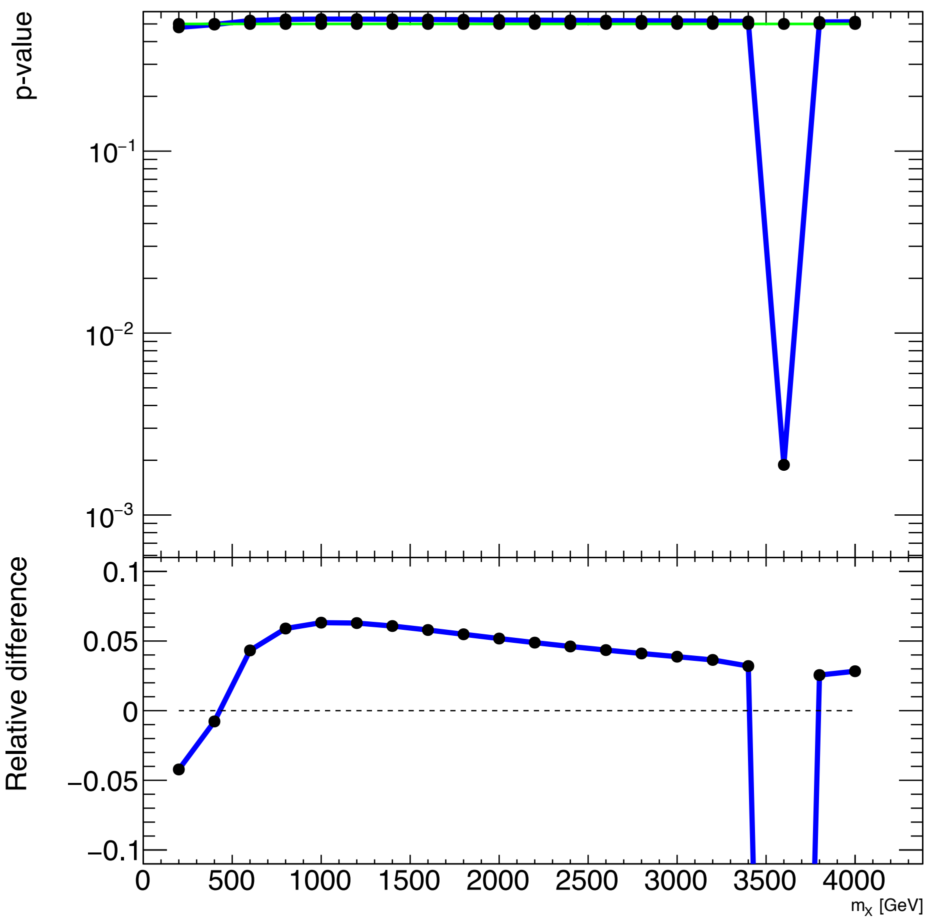
* Systematics uncertainties treated as NPs:

- θ_{lumi}: uncertainty on the integrated luminosity of the data sample;
- $\theta_{eff,X}$, $\theta_{isol,X}$:photon efficiency and isolation systematics on the new resonance;
- θ_{SS}: spurious signal systematic;
- θ_{ES}: photon energy resolution systematics;
- θ_{ER}: photon energy scale systematics.

Expected Limit

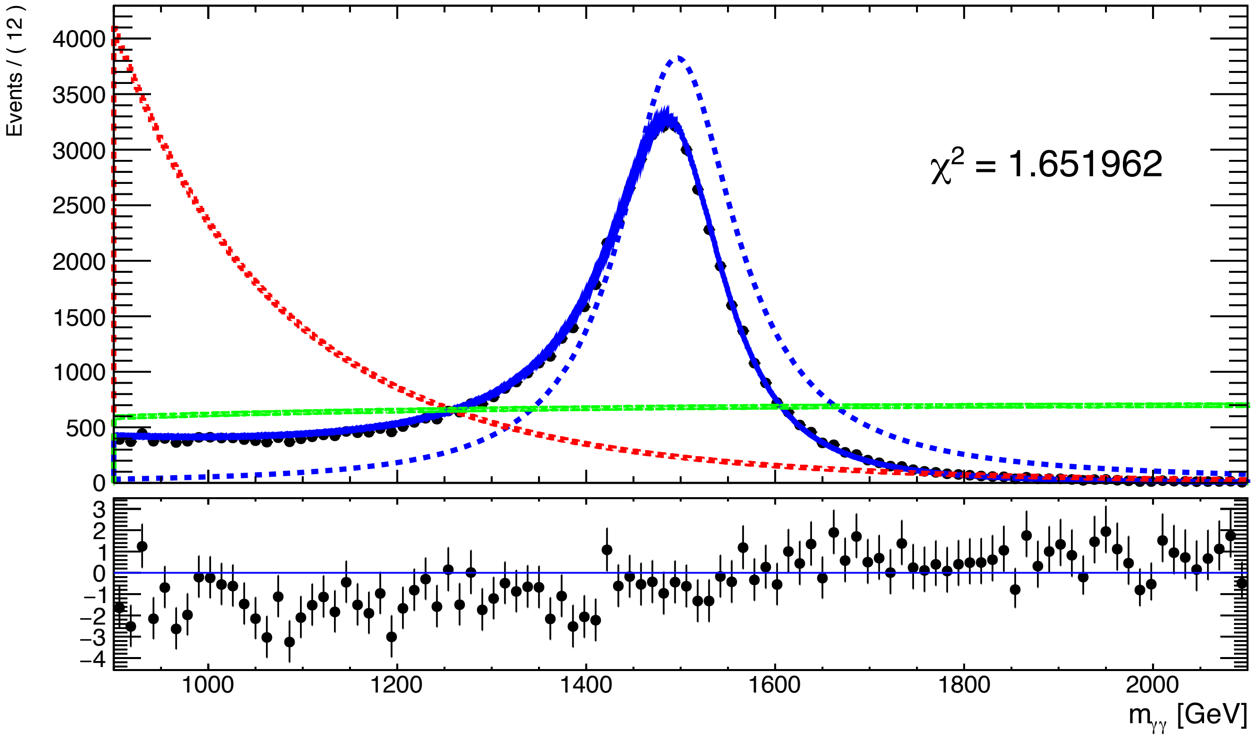
- Limit "saturates" to constant value, background at high mass becomes negligible.
- Expected limit does not significantly changed elsewhere when 1 event injected at $m_{\gamma\gamma}$ = 3.6 TeV (LHS).
  - Largest limit distortion ~ 4%
  - Background fit does not get significantly distorted/pulled by presence of injected event.
- P0 plot ...(RHS).

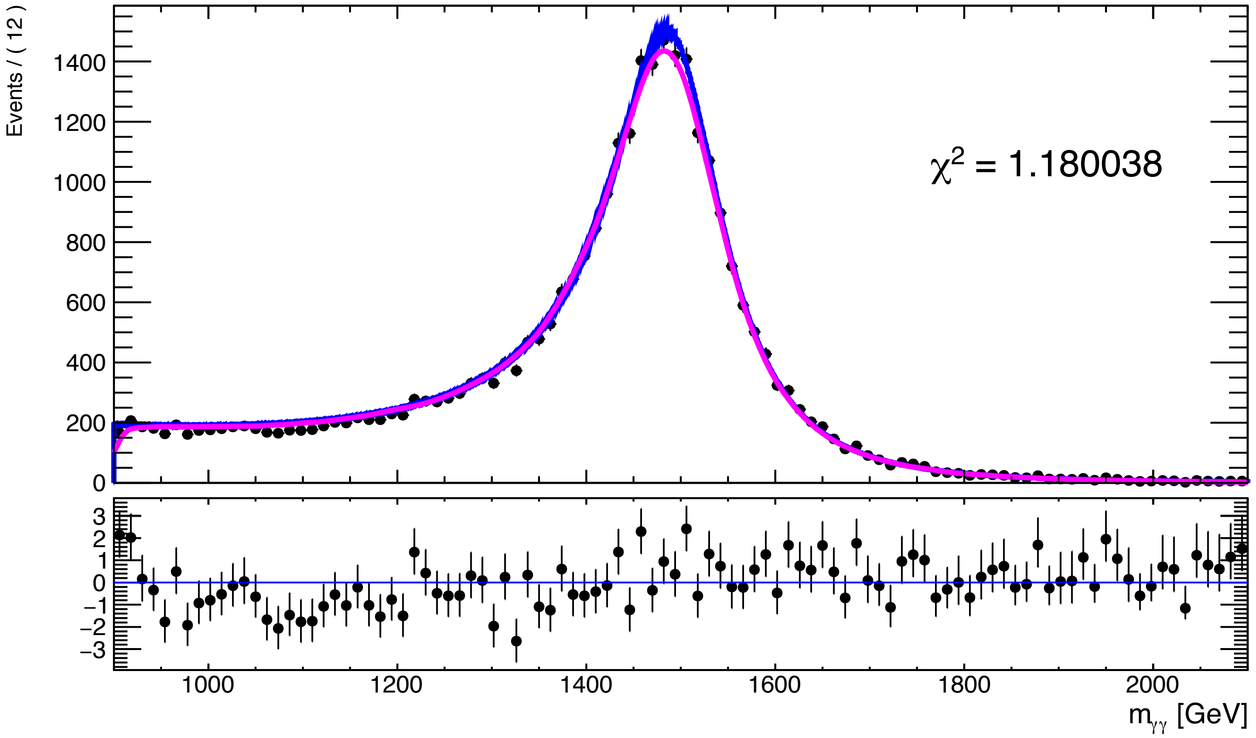




Large Width Signal

- Results were obtained using signal samples under the assumption of "Narrow Width Approximation" (NWA).
- In order to check the validity of the results on large width signal, the resolution function used in that analysis (DSCB) need to be convoluted with function that will describe the natural width of the new particle.
    - Breit-Wigner (BW) function was used in run1, but careful study found it to be insufficient to model the line shape.
    - The true line shape is modelled by a BW multiplied by contributions from parton luminosity and squared matrix element of the production process.
        - Only the gluon-gluon luminosity and the squared matrix element of the Higgs-like resonance production via gluon-gluon fusion at Born level are taken into account in modeling the line shape.
    - Its convolution with the resolution function describes the resonance shape well. This is found to be true for all the nine mass and width values where MC samples are available.
    - Results are shown for m_X=1500GeV and width=10% of m_X.
- Results are being finalized.





Uncertainties

ATLAS

(not given by CMS)

(crucial to decode NWA ATLAS result!)

Source	Uncertainty
	Background modeling °•
Spurious signal	$2-10^{-3}$ events, mass-dependent
Background fit	≤ 50%–≤ 20% of the total signal yield uncertainty, mass- and signal-dependent
	Signal modeling °•
Photon energy resolution	$^{+[55-110]\%}_{-[20-40]\%}$, mass-dependent
	Signal yield •
Luminosity	±5%
Trigger	±0.63%
	C_X factors •
Photon identification	±(3–2)%, mass-dependent
Photon isolation	±(4.1–1)%, mass-dependent
Production process	±3.1%

CMS

- ✓ Bias term on parametric background model (no size given)
- ✓ Luminosity : 4.6%
- ✓ Trigger and photon ID : 10%
- ✓ Signal PDF : 6% *(not in ATLAS, several production processes)*
- ✓ Photon energy scale : 1% *(negligible in ATLAS)*