Diphoton searches *in ATLAS*

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Les Rencontres de Moriond EW 2016

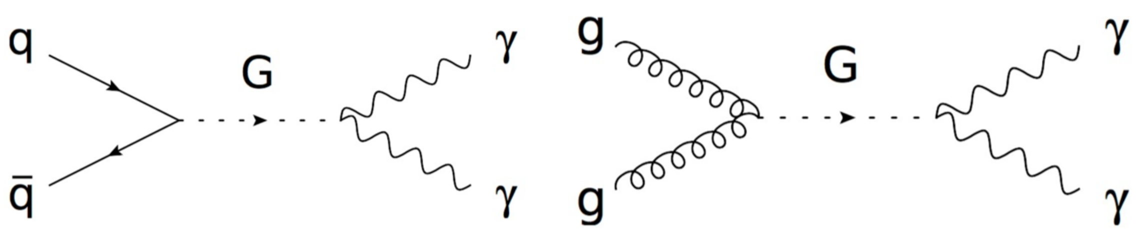
Why diphoton searches?

- Clean signal over smooth and well known background (e.g. $H(125)\rightarrow\gamma\gamma$)
- Several extensions of the Standard Model predict high-mass states decaying to two photons
- Benchmark models…

Spin-0 analysis *e.g. extended Higgs sector*	Spin-2 analysis *e.g. Randall-Sundrum graviton*

- 2HDM
  - ✓ 5 physical states $h^0, H^0, A^0, H^{\pm}$
  - ✓ Under certain conditions, scalar and/or pseudo-scalar states can have sizable branching ratio to diphoton

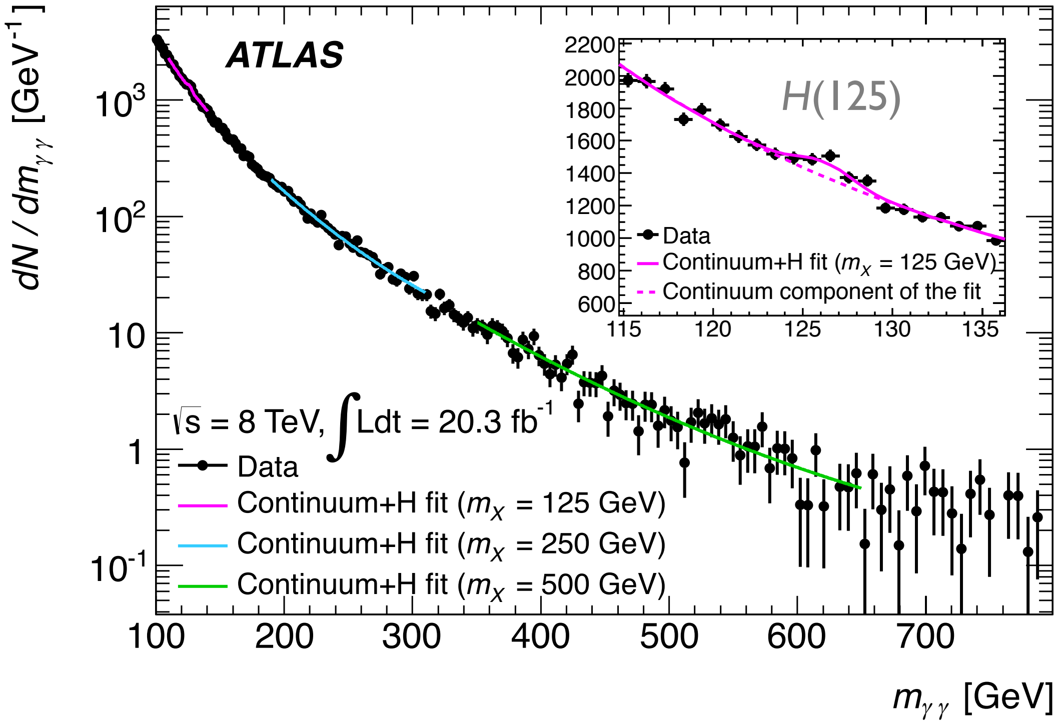
- Model predicts tower of Kaluza-Klein graviton states with TeV mass scale
- Phenomenology
  - ✓ m_{G*} = mass of lightest KK excitation
  - ✓ κ/M_{Pl} = dimensionless coupling to SM fields



Recap of latest Run 1 results

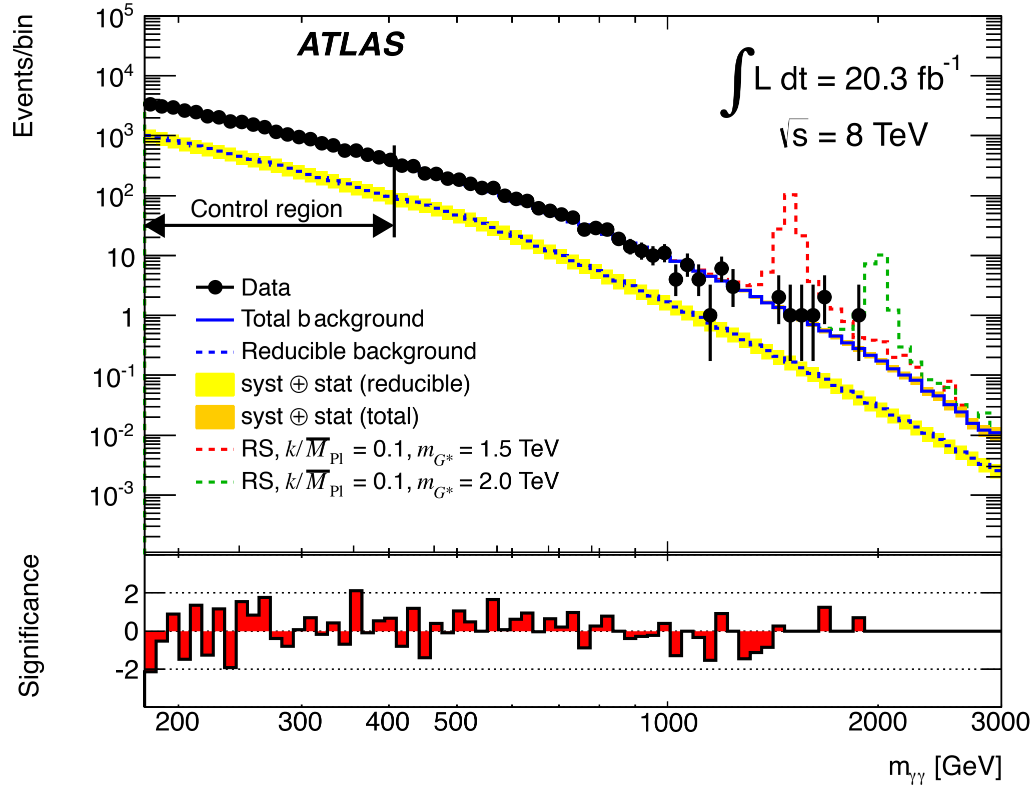
Search for scalar diphoton resonances in the mass range 65-600 GeV with the ATLAS detector in pp collision data at $\sqrt{s}$ = 8 TeV

Phys. Rev. Lett. 113, 171801



Search for high-mass diphoton resonances in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector

Phys. Rev. D 92, 032004 (2015)



Overview of ATLAS 13 TeV analyses

- **Common pre-selections & photon identification**
  - ✓ $E_T^{\gamma 1} > 40$ GeV, $E_T^{\gamma 2} > 30$ GeV
  - ✓ Precision region of EM calorimeter: $|\eta| < 2.37$, 1.37-1.52 excluded
  - ✓ Tight photon identification based on shower moments in EM calorimeter
  - ✓ Photon isolation (calorimeter cone + track isolation)

SPIN-0 ANALYSIS

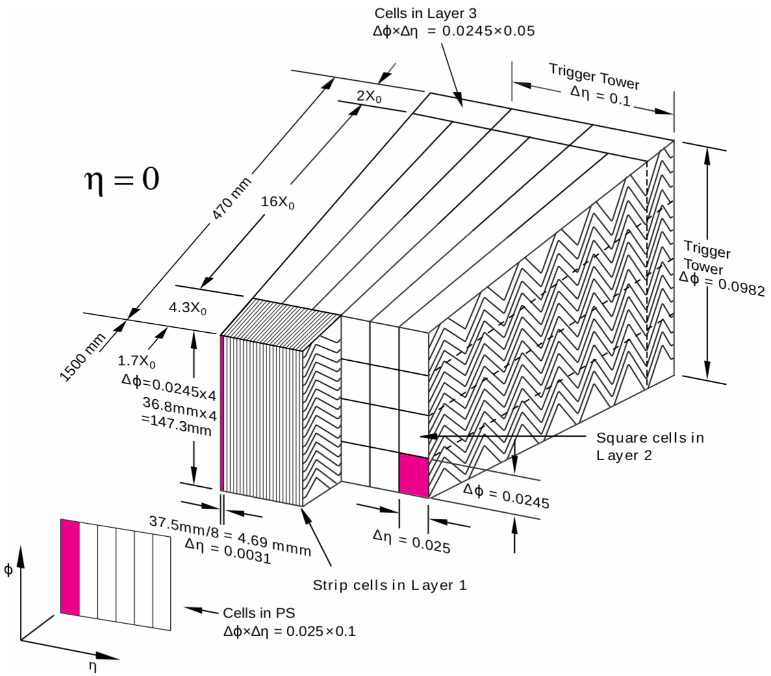
- **Optimized for Higgs-like signal**
  - ✓ $E_T^{\gamma 1} > 0.4\ m_{\gamma\gamma}$, $E_T^{\gamma 2} > 0.3\ m_{\gamma\gamma}$
    - +20% significance for $m_X > 600$ GeV
    - Effectively deplete forward regions
- **As model-independent as possible**
  - ✓ Limit on fiducial cross section
- **Search range**
  - ✓ m_X = [200 GeV – 2 TeV]
  - ✓ Γ_X/m_X = [0% - 10%]

SPIN-2 ANALYSIS

- **Loose selection**
  - ✓ $E_T^{\gamma 1} > 55$ GeV, $E_T^{\gamma 2} > 55$ GeV
    - Preserve acceptance at high mass
- **Use RS graviton as (kinematic) benchmark**
- **Search range**
  - ✓ m_G = [500 GeV – 3 TeV]
  - ✓ κ/M_{Pl} = [0.01-0.3]
  - ✓ $\Gamma_G/m_G \sim$ [0.01% - 11%]
    - $\Gamma_G \sim 1.44\ (\kappa/M_{Pl})^2$

Photon energy calibration

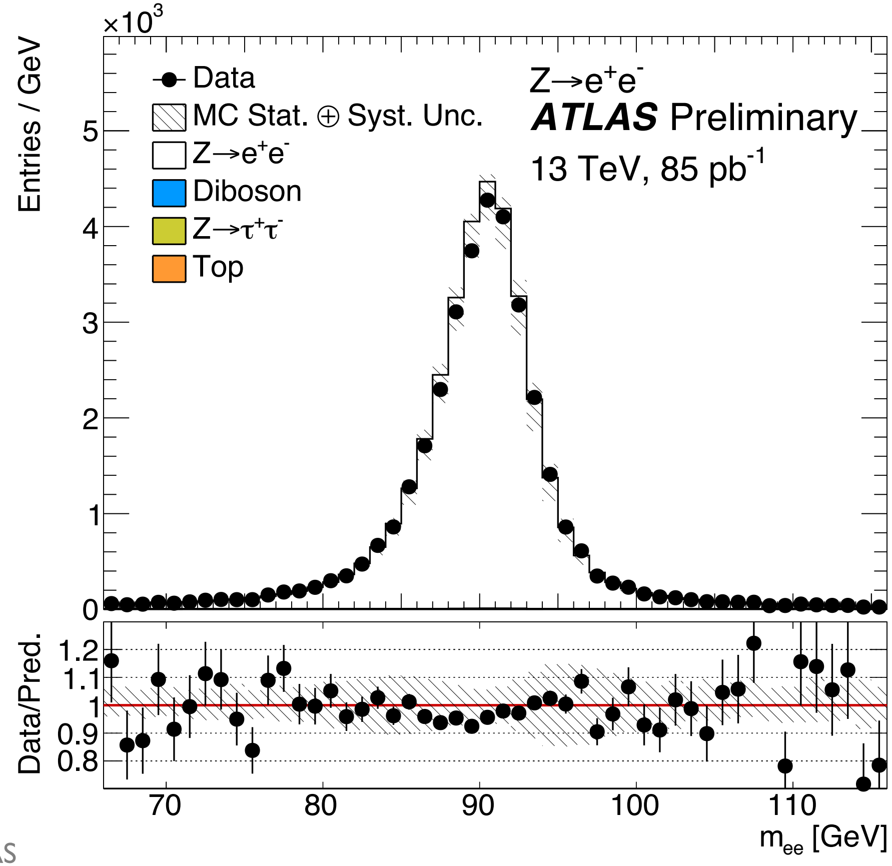
- **MV regression to calibrate photon cluster energy, optimized on MC**
  - ✓ i.e. Eur.Phys.J. C74 (2014) 3071
  - ✓ EMC longitudinal layers inter-calibration from from 2012 data + additional uncertainty
    - Mostly affecting constant term
  - ✓ Energy scale and resolution corrections validated with 13 TeV $Z \rightarrow ee$ events



- **At E_T^γ > 100-200 GeV, resolution dominated by constant term…**
  - ✓ c = 0.6% - 1.5%

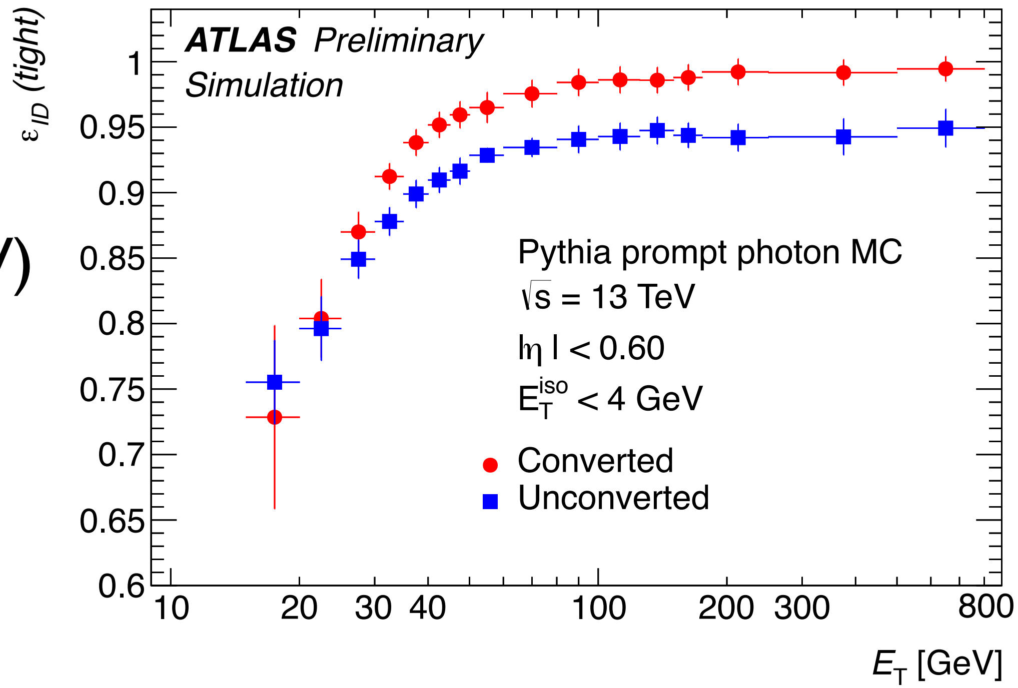
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- **Uncertainties**
  - ✓ Energy scale: ±(0.4%-2%)
  - ✓ Energy resolution (E_T^γ=300 GeV): ±(80%-100%)

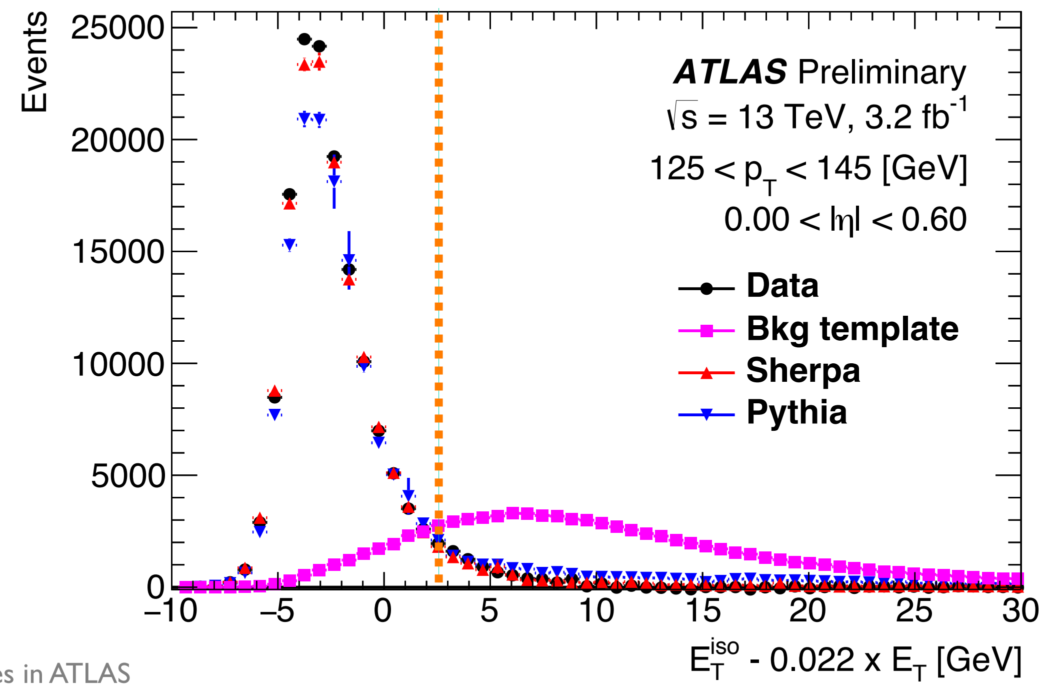


Photon identification and isolation

- **Identification**
  - ✓ 85% (E_T~50 GeV) -95% (E_T~200 GeV)
  - ✓ Uncertainty: full data/MC difference
    - ±1% - ±5% for E_T > 50 GeV
    - η dependent



- **Isolation**
  - ✓ Calorimeter (ΔR=0.4)
    - $E_T^{iso} < 0.022\ E_T^{\gamma} + 2.45$ GeV
  - ✓ Track p_T^{iso} (ΔR=0.2)
    - $p_T^{iso} < 0.05\ E_T^{\gamma}$
  - ✓ Uncertainty: full data/MC difference

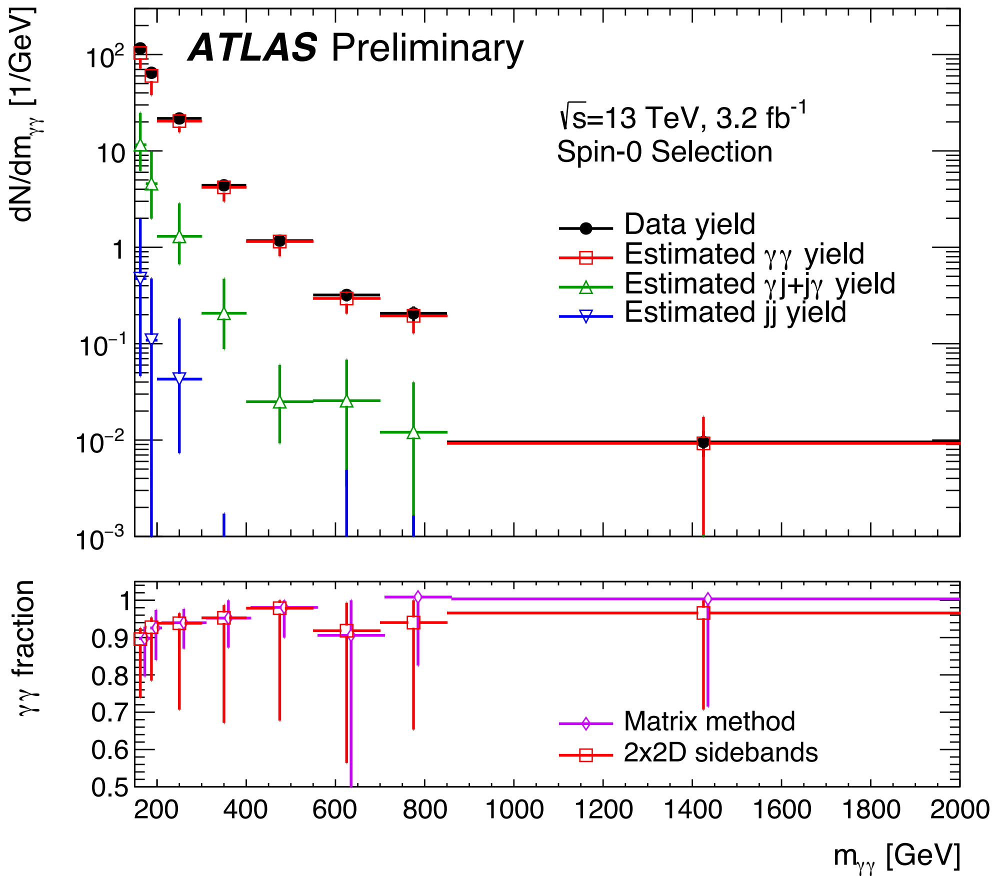


Sample composition

- Estimated for both selections using "2x2D-Sideband" and "Matrix Method"
  - ✓ As in SM diphoton cross section measurements (e.g. New J. Phys. 15 (2013) 043007)

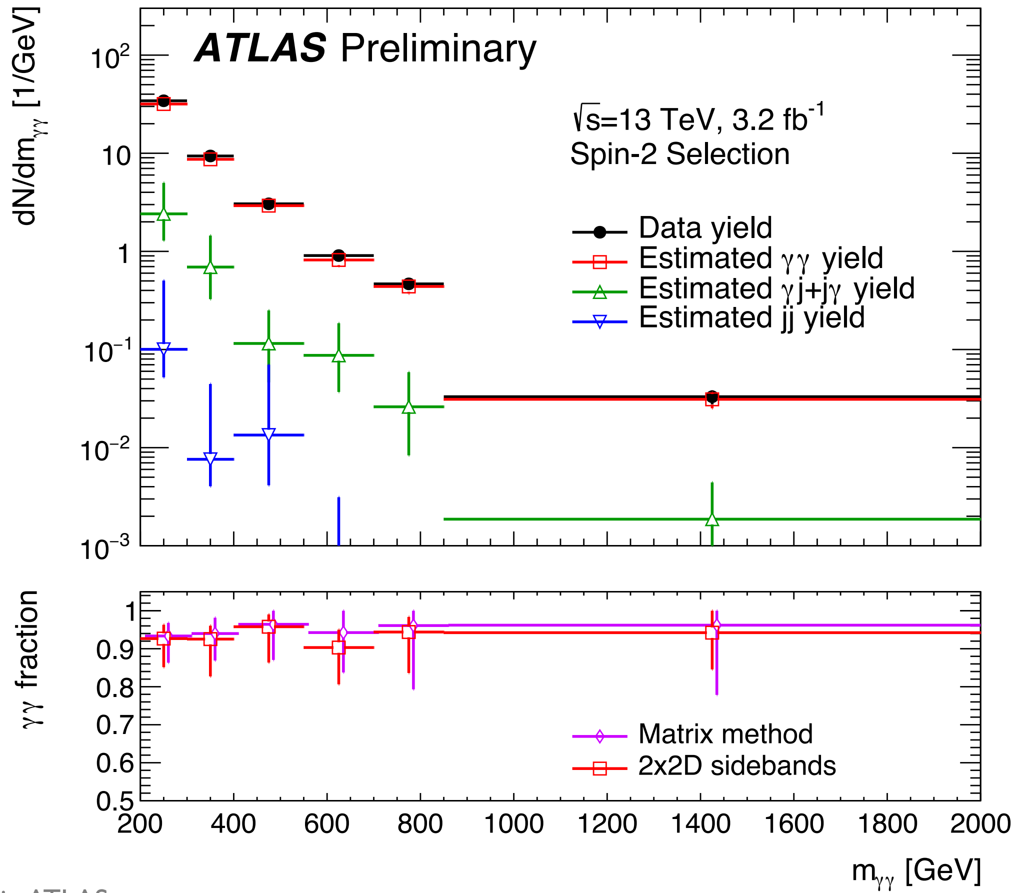
SPIN-0 ANALYSIS

$$P_{\gamma\gamma} = 93^{+3}_{-8}\ \%$$



SPIN-2 ANALYSIS

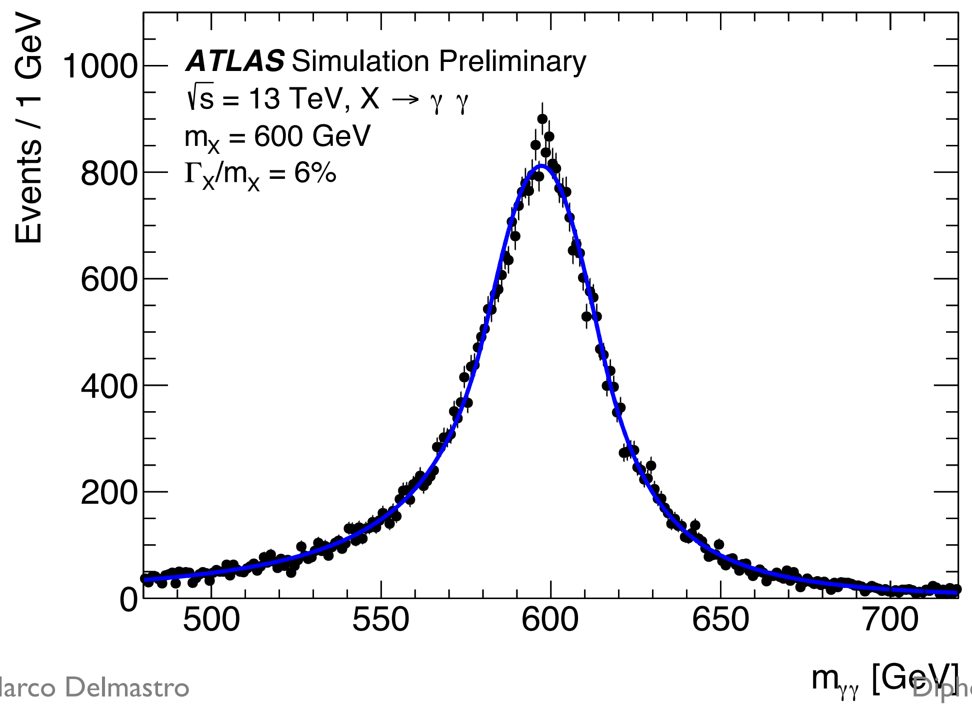
$$P_{\gamma\gamma} = 94^{+3}_{-7}\ \%$$



Signal modeling

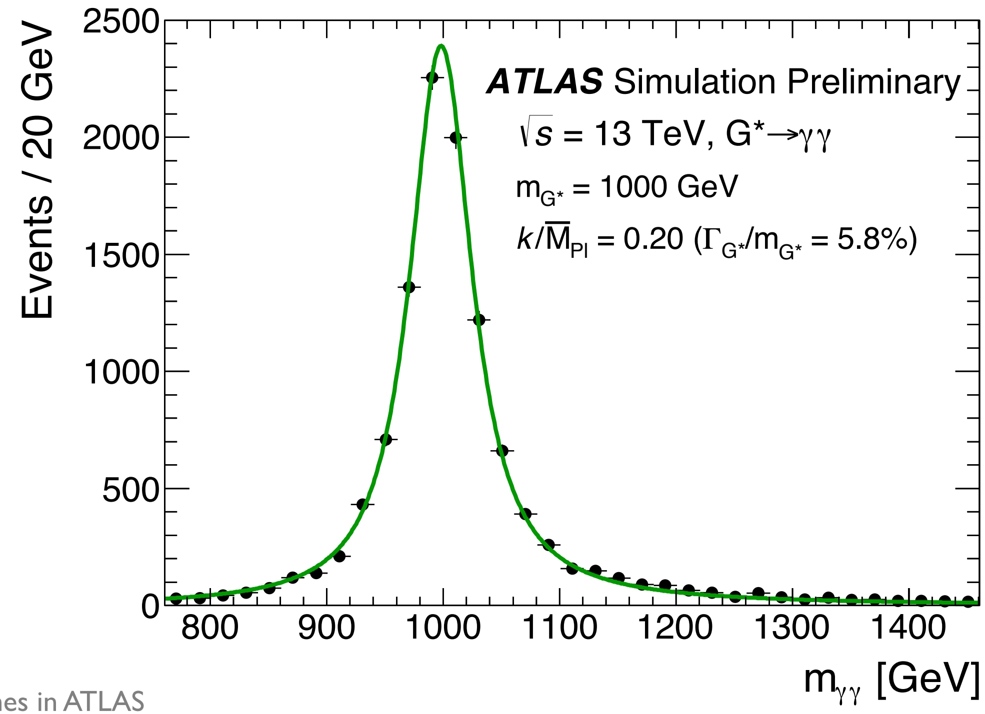
SPIN-0 ANALYSIS

- Heavy Higgs-like model
  - ✓ Narrow-width (Γ_X = 4 MeV)
  - ✓ Large-width ($\Gamma_X \lesssim$10% m_X)
    - Powheg line-shape assuming SM couplings convoluted to detector response (ggF)
    - $m_X \pm 2\Gamma_X$
- Double-Sided Crystal Ball



SPIN-2 ANALYSIS

- RS-graviton-like model
  - ✓ κ/M_{Pl} = 0.01 (Γ_G = 0.01% m_G) to measure and parameterize detector response (DSCB)
- Analytical convolution of theoretical line-shape with detector response



Background modeling

SPIN-0 ANALYSIS

- **Functional form → sidebands**
  - ✓ **Family of nested functions with increasing d.o.f.**

$$f_{(k)}(x; b, \{a_k\}) = N(1 - x^{1/3})^b x^{\sum_{j=0}^{k} a_j (\log x)^j}$$

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

  - ✓ Validated on MC+data template
  - ✓ All function parameters free
- **"Spurious signal" uncertainty**
  - ✓ S+B fits on MC+data template
- **F-test on binned data**
  - ✓ Validate need of additional d.o.f. (k=0 chosen)

$$F = \frac{\dfrac{\sum_i (y_i - f_1(x_i))^2 - \sum_i (y_i - f_2(x_i))^2}{p_2 - p_1}}{\dfrac{\sum_i (y_i - f_2(x_i))^2}{n - p_2}}$$

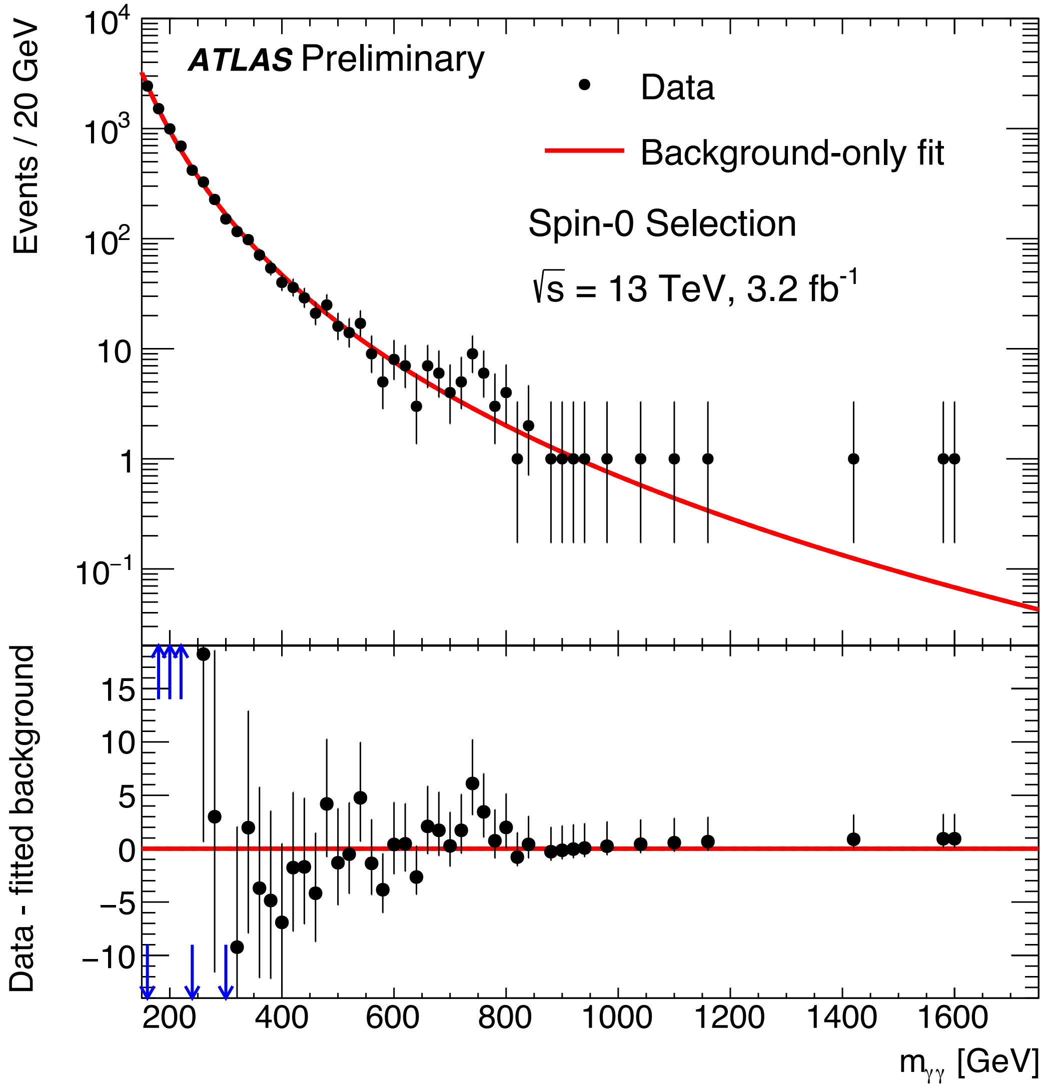
SPIN-2 ANALYSIS

- **MC+data template → high mass**
  - ✓ **Irreducible (γγ) → MC**
    - DIPHOX NLO parton level
    - SHERPA γγ including detector simulation, reweighted to DIPHOX $m_{\gamma\gamma}$
  - ✓ **Reducible (γj, jγ, jj) → data**
    - Inverting tight shower shape criteria
    - Varying loose criteria
- **Mixed according to data-driven purities**

Results

SPIN-0 ANALYSIS

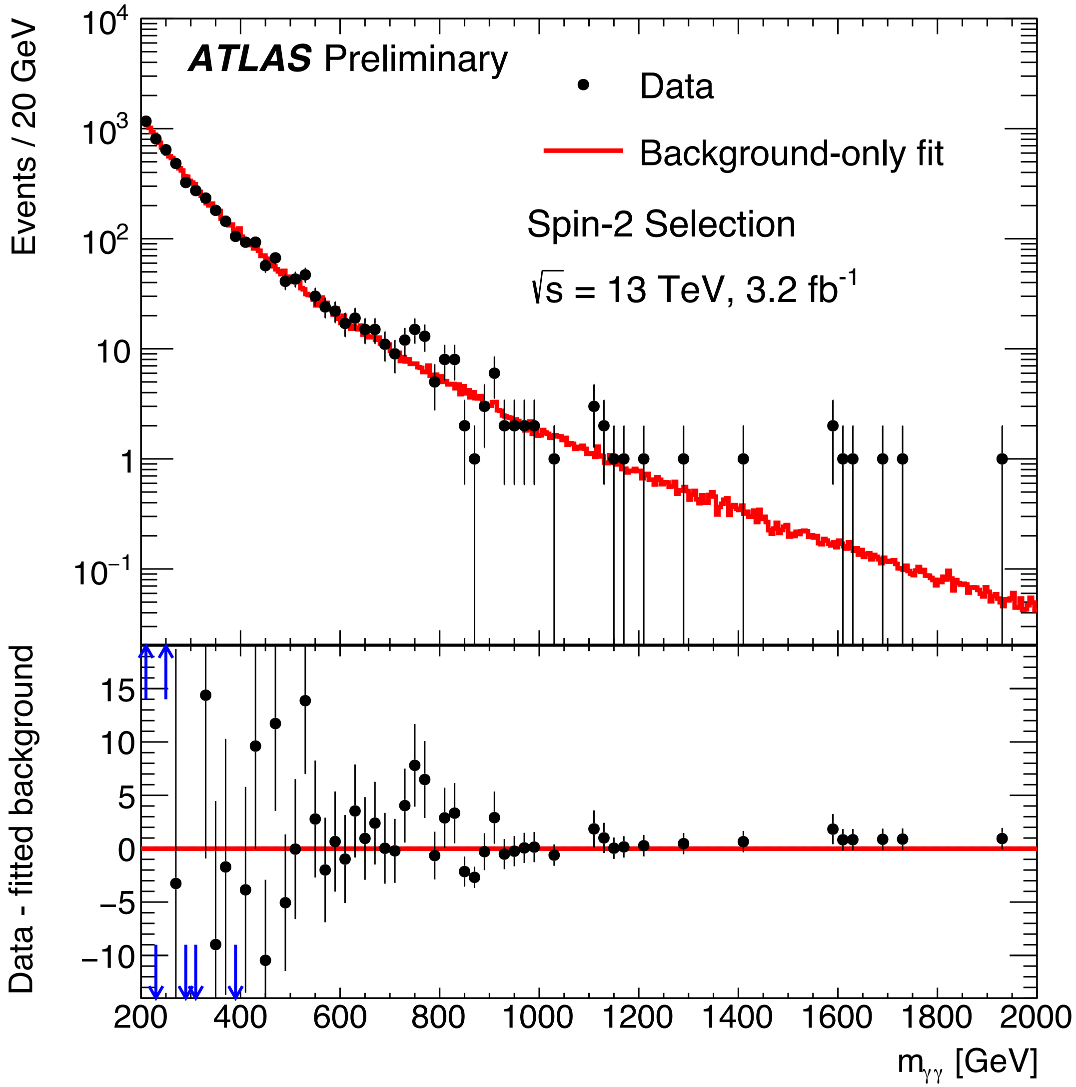
background-only fit



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

SPIN-2 ANALYSIS

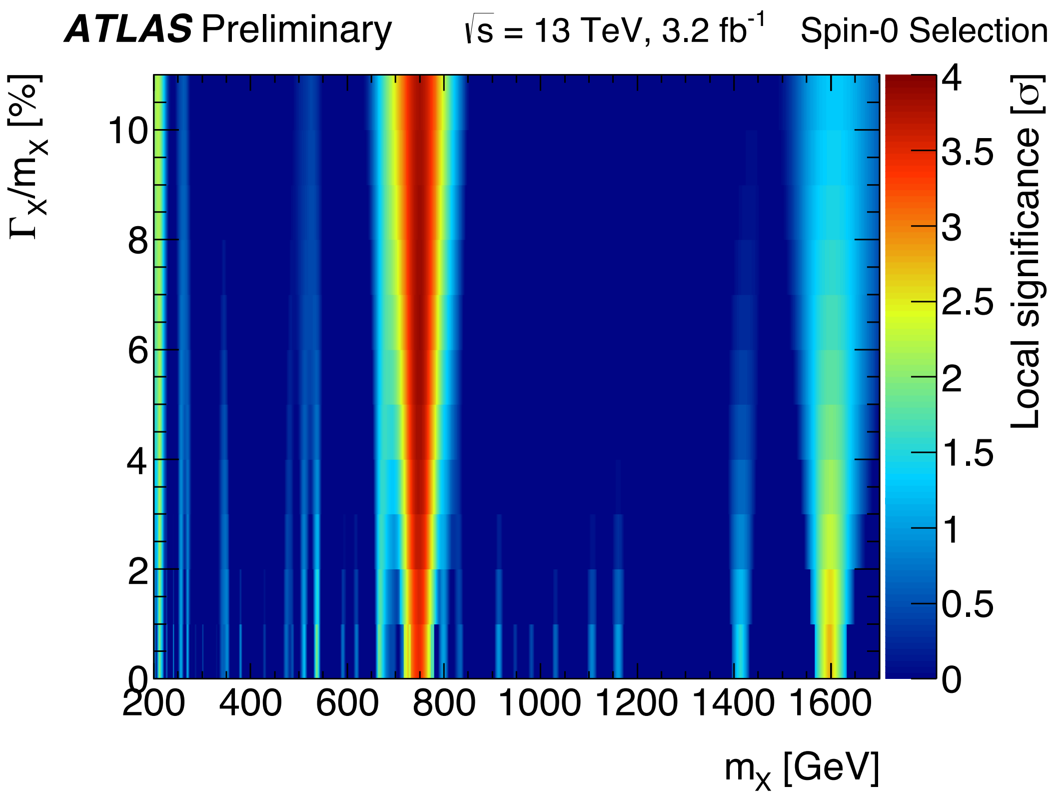
background-only fit



5066 events ($m_{\gamma\gamma}$ > 200 GeV)

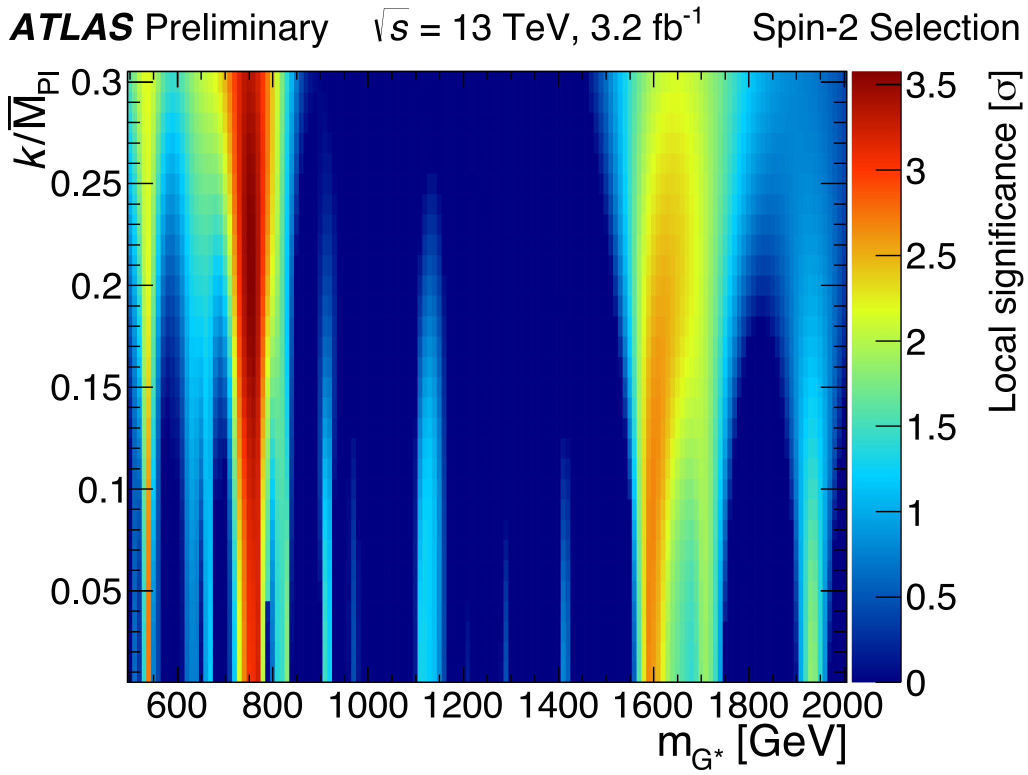
Results

SPIN-0 ANALYSIS



- Largest deviation from B-only hypothesis
  - ✓ m_X ~ 750 GeV, Γ_X ~ 45 GeV (6%)
  - ✓ Local Z = **3.9 σ**
  - ✓ Global Z = **2.0 σ**
    - m_X = [200 GeV - 2 TeV]
    - Γ_X/m_X = [1% - 10%]

SPIN-2 ANALYSIS



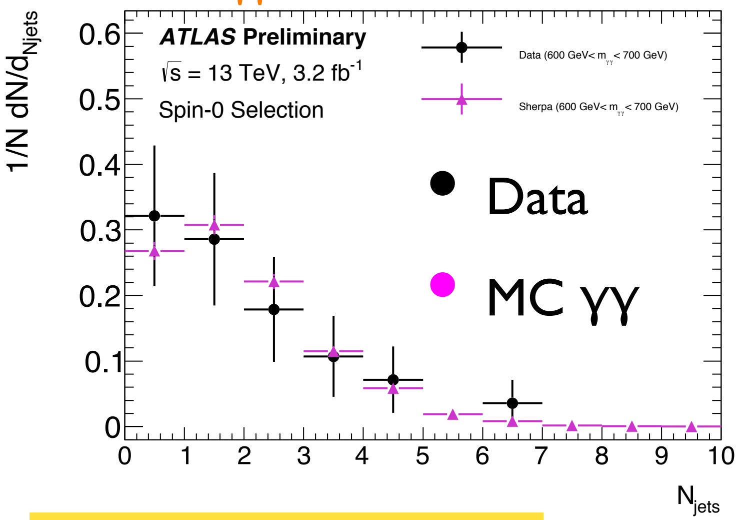
- Largest deviation from B-only hypothesis
  - ✓ m_G ~ 750 GeV, κ/M_{Pl} ~ 0.2 (Γ_G ~ 6% m_G)
  - ✓ Local Z = **3.6 σ**
  - ✓ Global Z = **1.8 σ**
    - m_X = [500 GeV – 3.5 TeV]
    - κ/M_{Pl} = [0.01 – 0.3]

Properties of sideband and excess regions

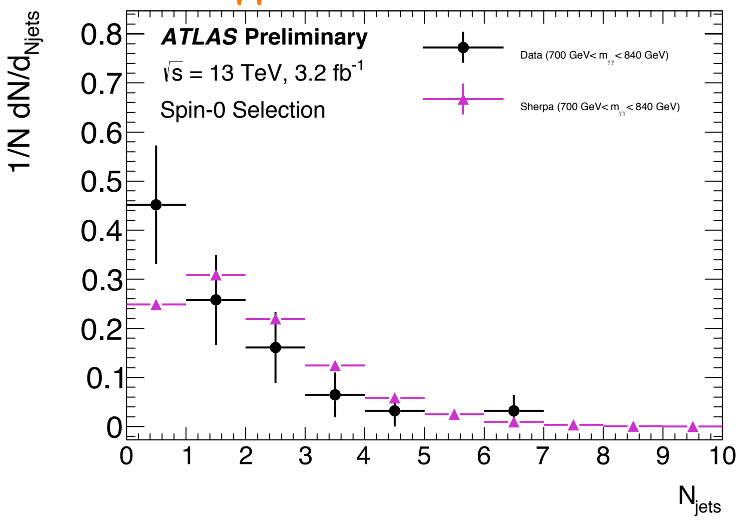
N_{jets}

SPIN-0 ANALYSIS

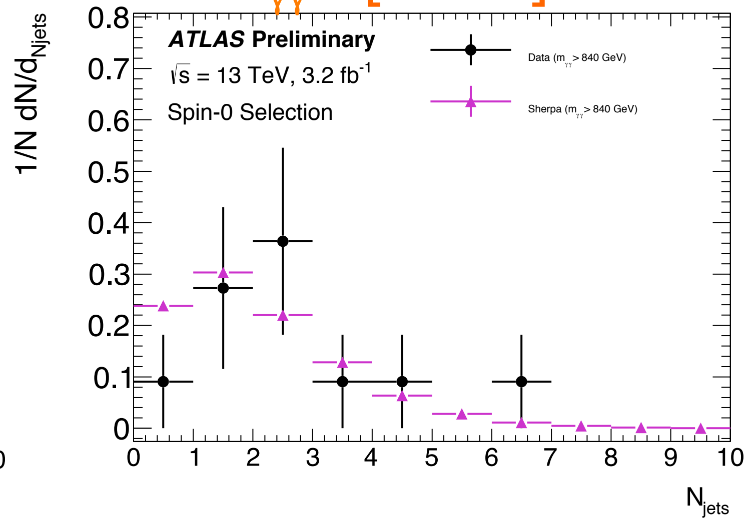
$m_{\gamma\gamma}$ = [600-700] GeV



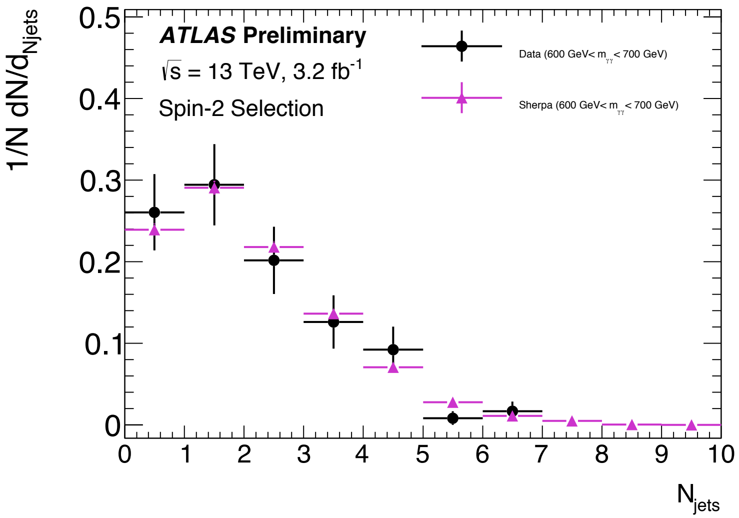
$m_{\gamma\gamma}$ = [700-840] GeV

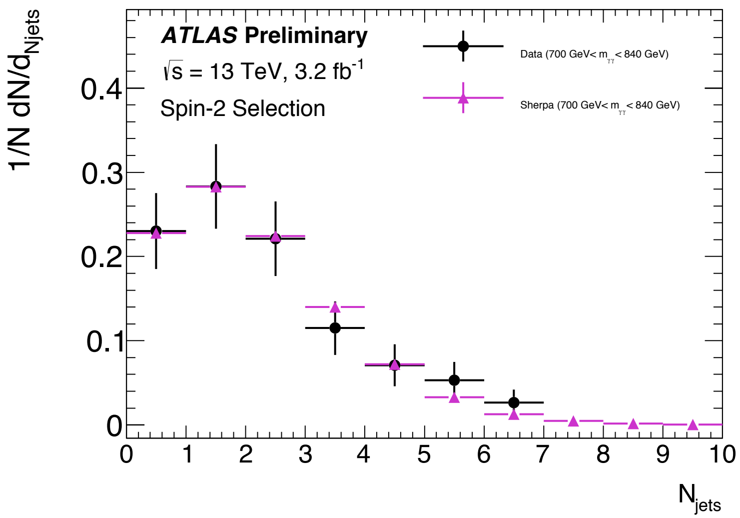


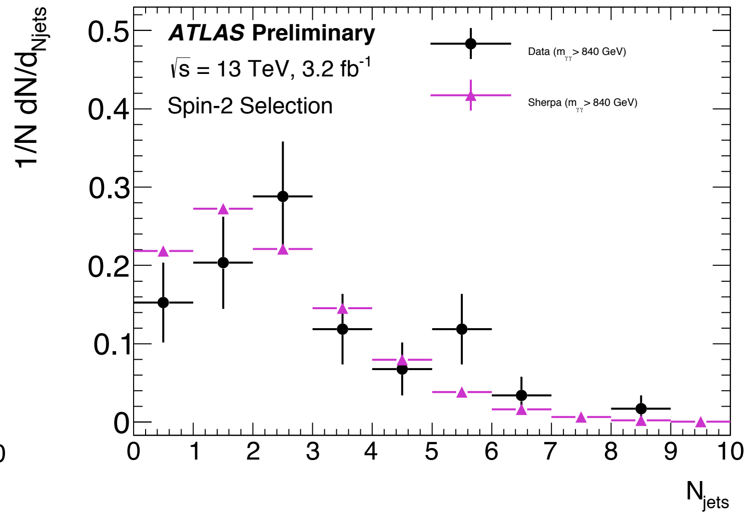
$m_{\gamma\gamma}$ =[840-∞] GeV



SPIN-2 ANALYSIS







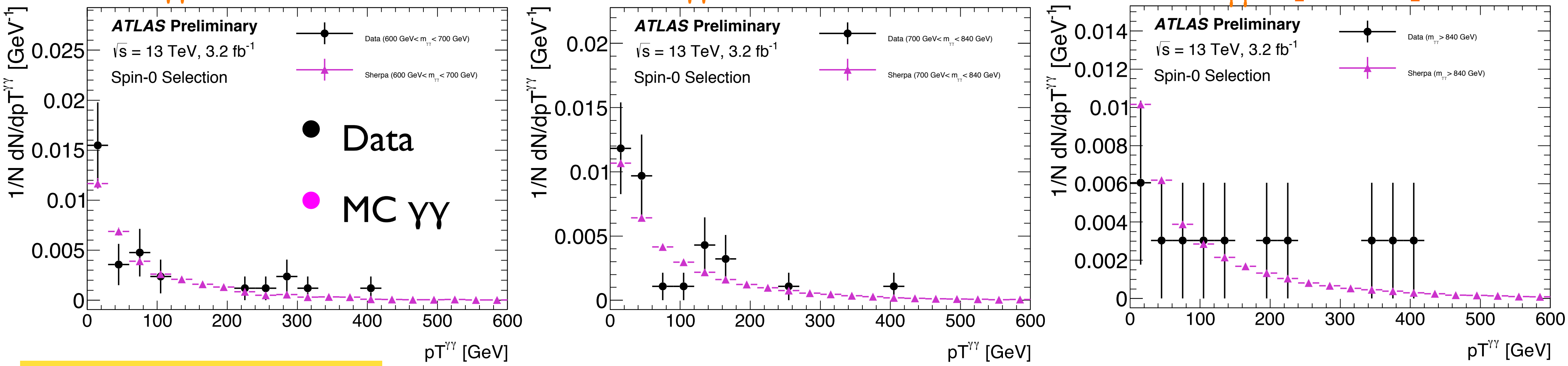
anti-k_t R-0.4 | $y_j < 2.4 \rightarrow p_T^j > 25$ GeV + JVT < 0.64 | $2.4 < y_j < 4.4 \rightarrow p_T^j > 50$ GeV

Properties of sideband and excess regions

$p_T^{\gamma\gamma}$

SPIN-0 ANALYSIS

$m_{\gamma\gamma}$ = [600-700] GeV $m_{\gamma\gamma}$ = [700-840] GeV $m_{\gamma\gamma}$ =[840-∞] GeV



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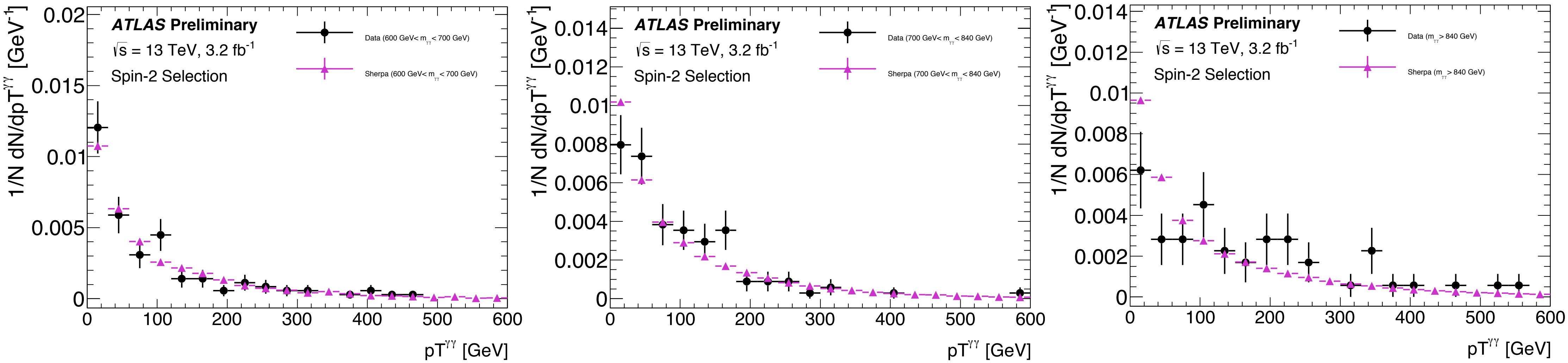
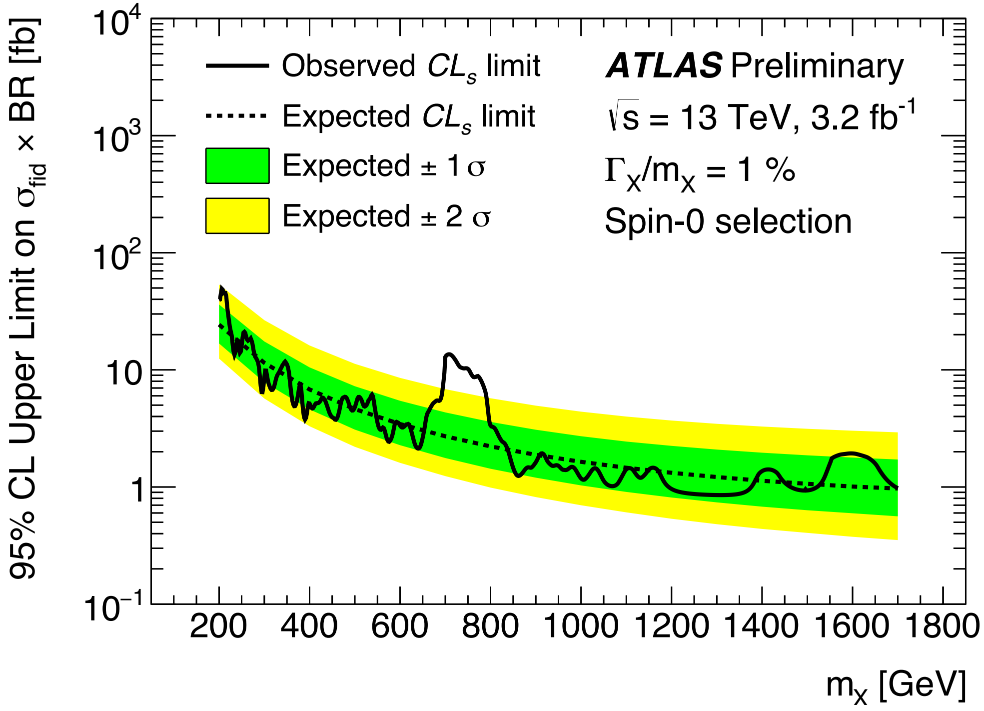
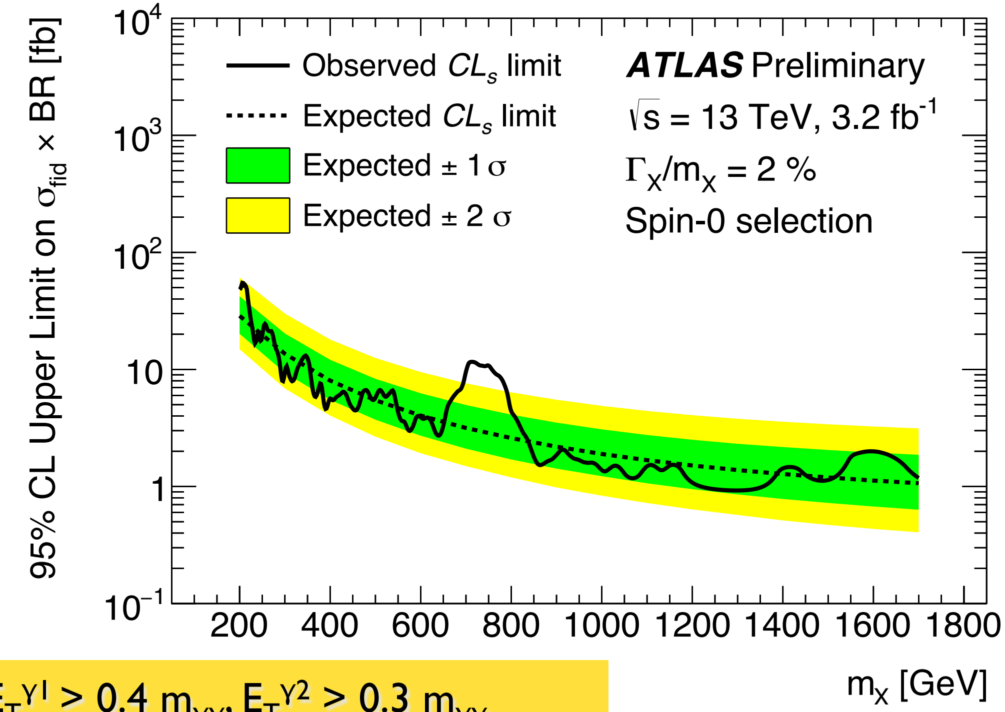


Limit on fiducial cross-section

SPIN-0 ANALYSIS

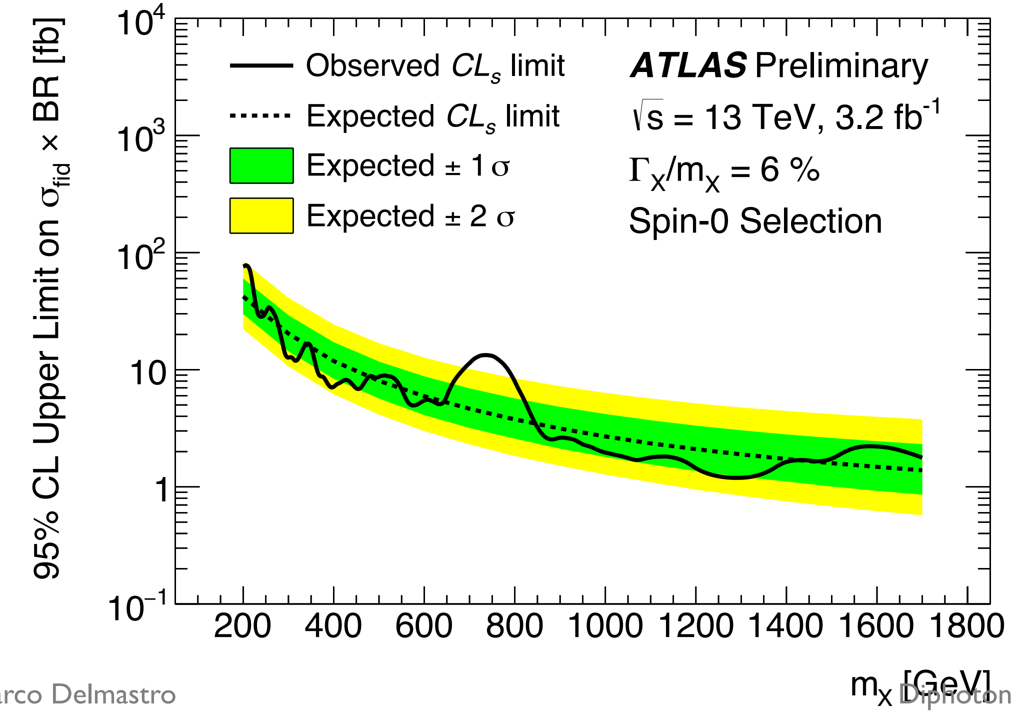


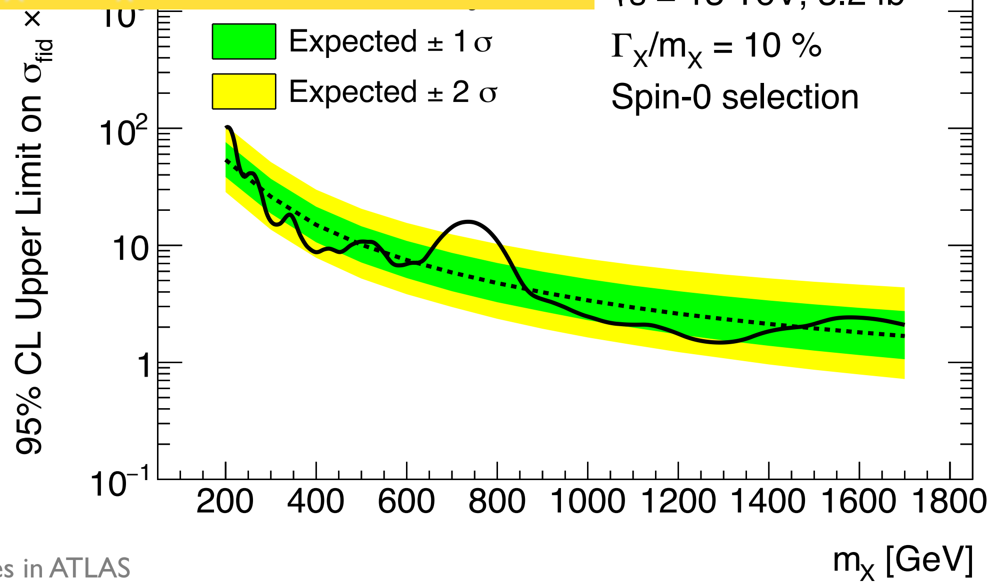


$E_T^{\gamma 1} > 0.4\ m_{\gamma\gamma}$, $E_T^{\gamma 2} > 0.3\ m_{\gamma\gamma}$

E_T^{iso} (ΔR=0.4) < 0.05 E_T^{γ} + 6 GeV

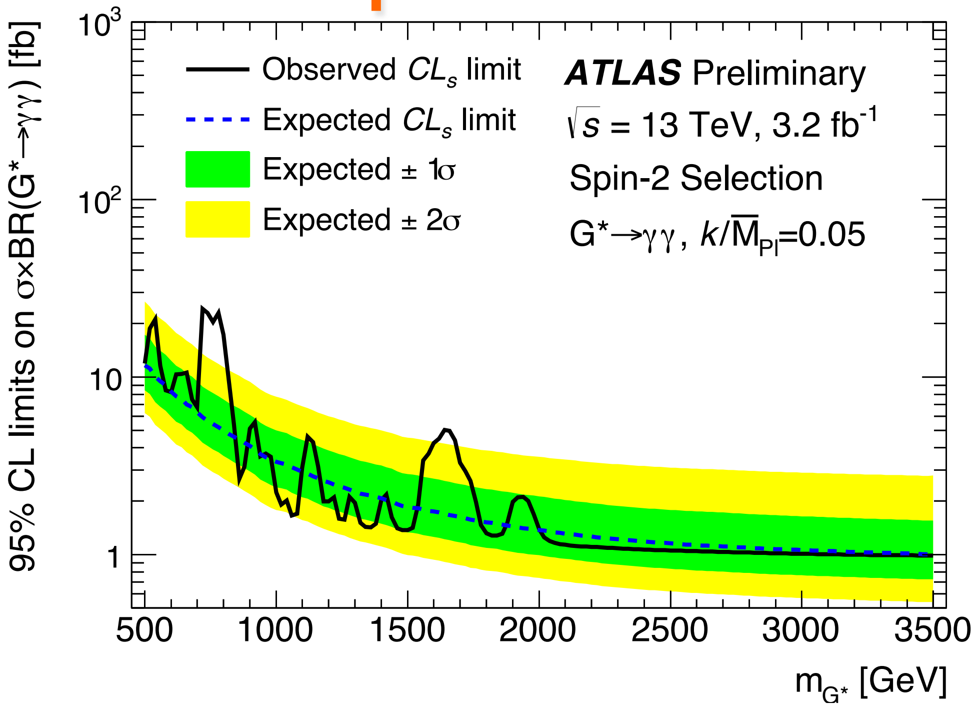
$m_X \pm 2\Gamma_X$

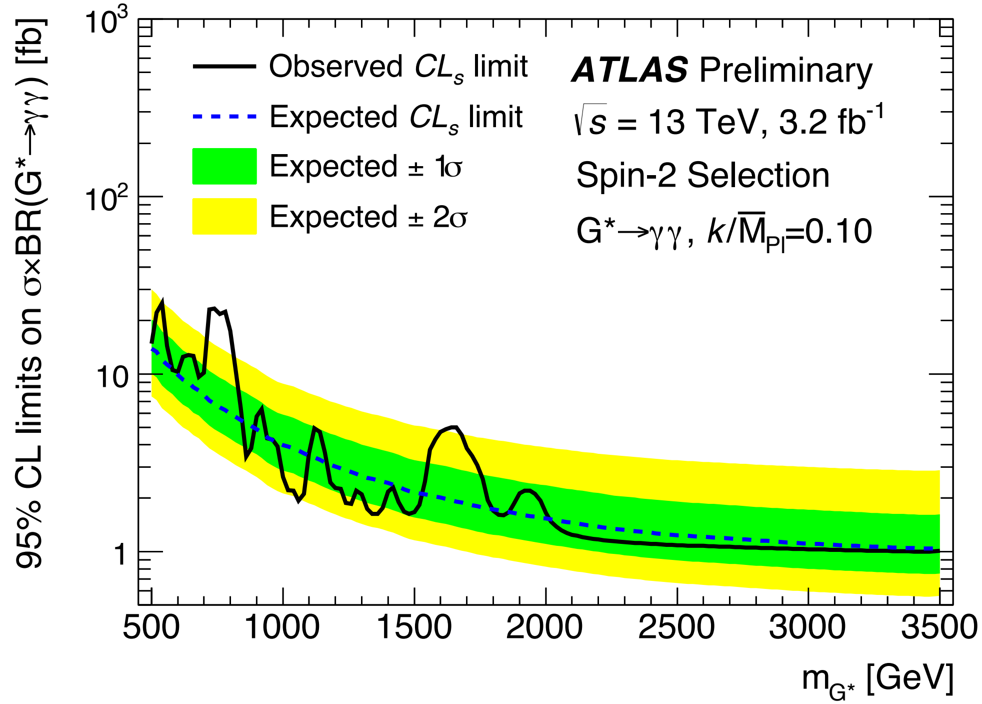


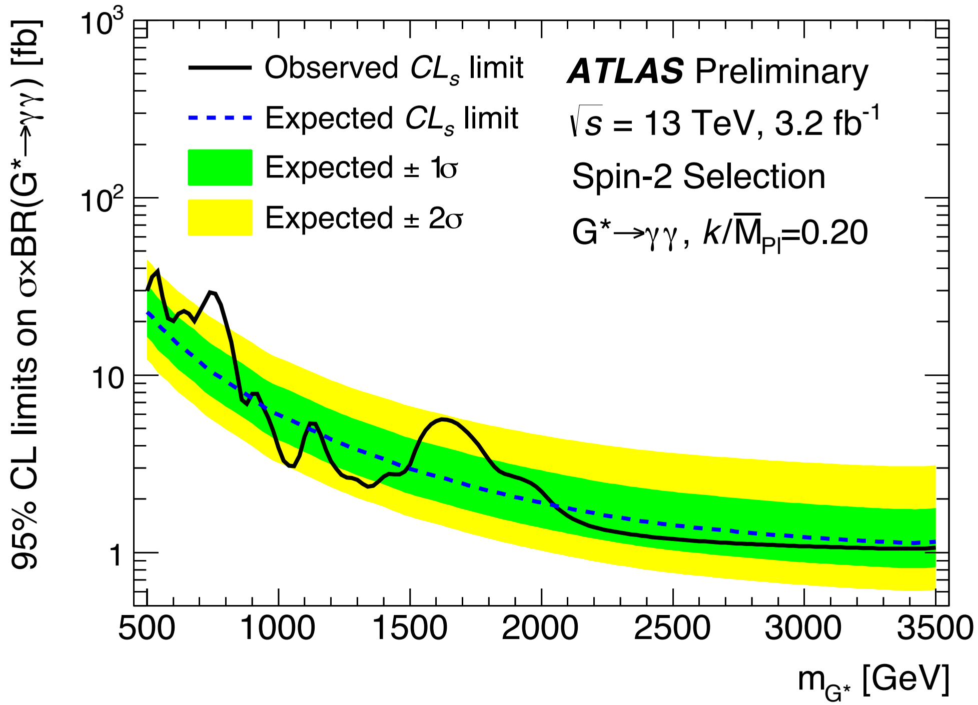


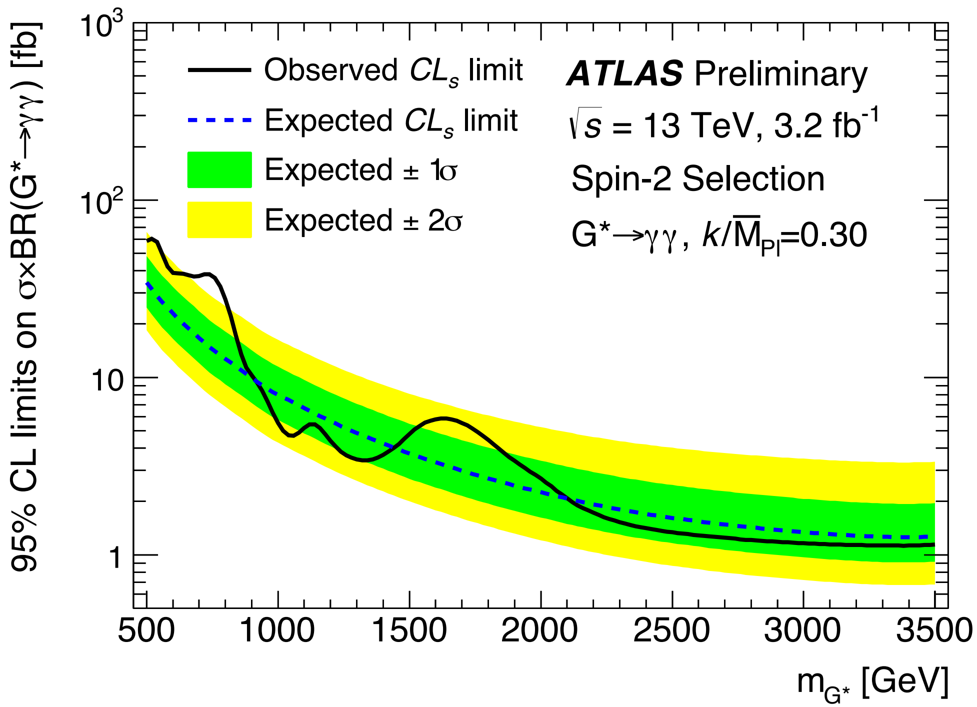
Limit on production cross section

SPIN-2 ANALYSIS





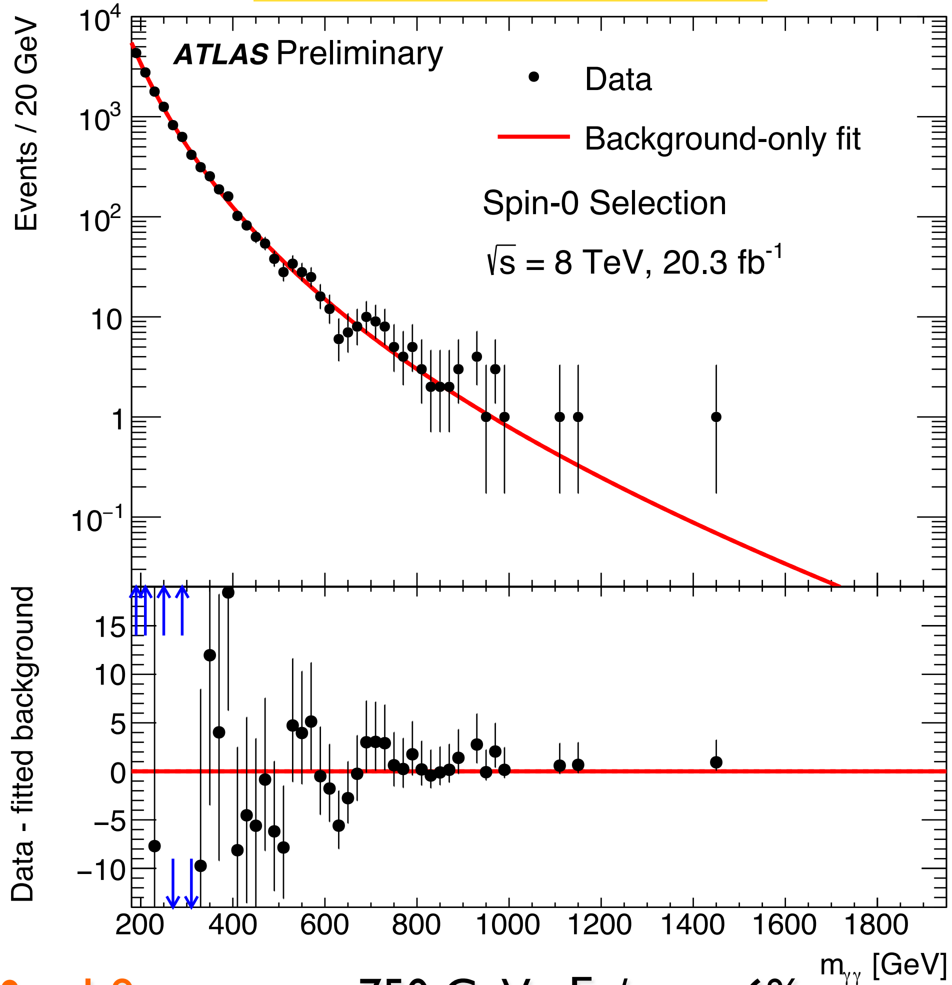




Compatibility with 8 TeV data

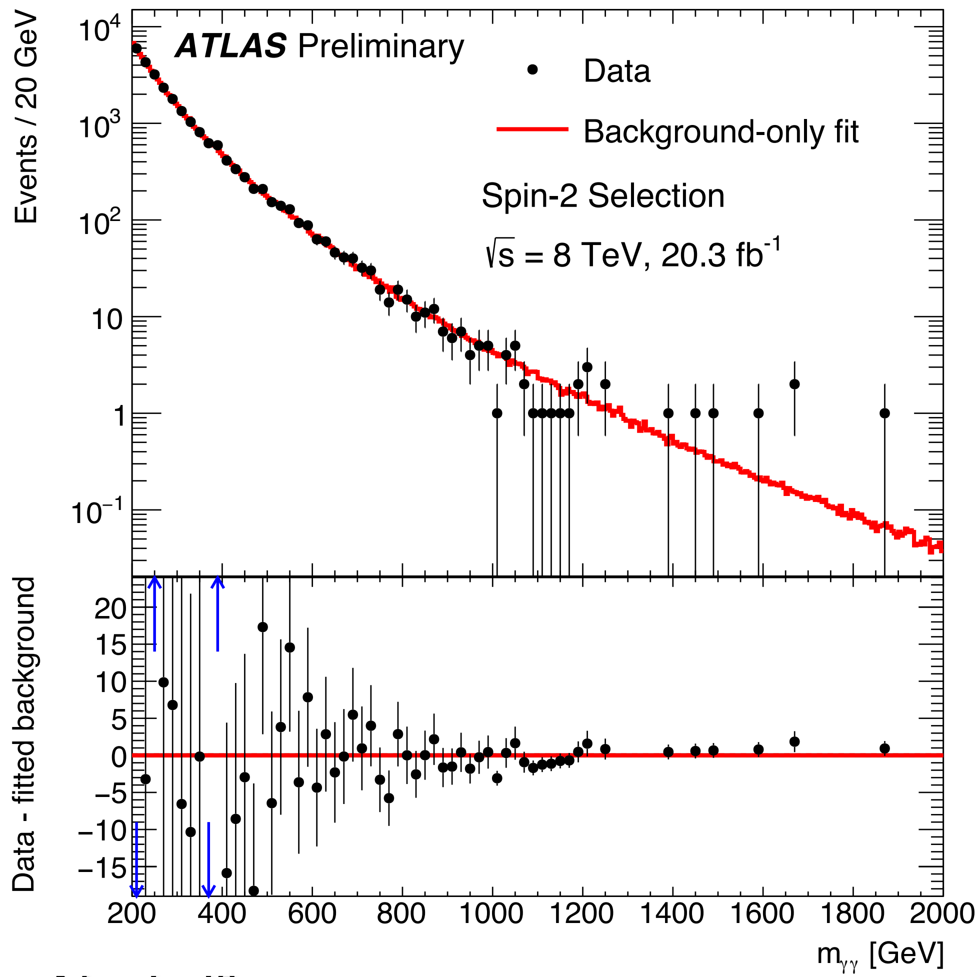
- 8 TeV data re-analyzed: latest Run 1 γ calibration + same Run 1 selections + 13 TeV analysis methods

SPIN-0 ANALYSIS



- $1.9\ \sigma$ at m_X = 750 GeV , Γ_X/m_X = 6%
- Compatibility with 13 TeV scalar
  - ✓ gg (scaling: 4.7) → compatibility: $1.2\ \sigma$
  - ✓ qq (scaling: 2.7) → compatibility: $2.1\ \sigma$

SPIN-2 ANALYSIS



- No significant excess
- Compatibility with 13 TeV graviton
  - ✓ gg → compatibility: $2.7\ \sigma$
  - ✓ qq → compatibility: $3.3\ \sigma$

Summary

- Search for new resonances decaying to diphotons performed with 3.2 fb^{-1} 13 TeV data, with two analyses targeting "spin-0" and "spin-2" scenarios

- Most of the $\gamma\gamma$ spectrum consistent with B-only hypothesis

- Largest deviation from background-only hypothesis observed in broad region around 750 GeV, with global significance 2.0 (1.8) σ for the spin-0 (spin-2) analysis

- Numerous cross-checks of events with masses ~ 750 GeV performed

- 8 TeV data re-analyzed using latest Run1 calibration, compatibility with 13 TeV results assessed
  - ✓ Scalar 1.2 σ (gg) – 2.1 σ (qq)
  - ✓ Graviton 2.7 σ (gg) – 3.3 σ (qq)

- More data needed to verify excess origin: looking forward to 2016 LHC run!

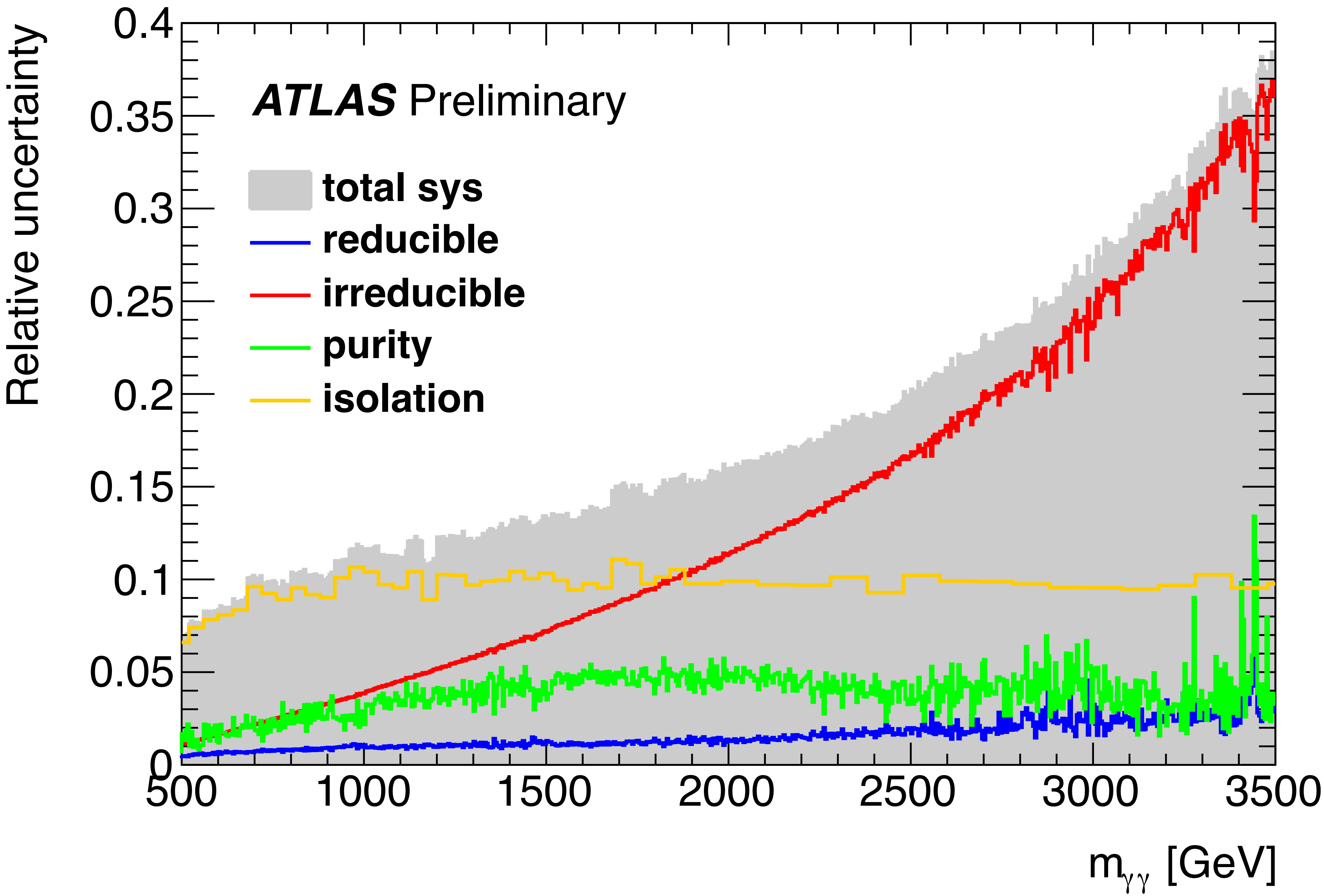
Additional information

Systematic uncertainties

Source of uncertainty	Uncertainty for spin-0 analysis	Uncertainty for spin-2 analysis	
Background modelling (mass dependent)	spurious signal $2 - 10^{-3}$ events for NWA $20 - 5.10^{-3}$ events for Γ / M=7%	± 7% to ± 35% on predicted shape	p_0 and limit
Signal mass resolution (mass dependent)	$^{+55-110\%}_{-20-40\%}$		p_0 and limit
Signal photon identification (mass dependent)	±(3 – 2)%		limit
Signal photon isolation (mass dependent)	±(4-1)%	±(3-1)%	limit
Signal production process dependence	± 3% for NWA	N/A	limit
	± 6% for larger decay width	N/A	limit
Trigger efficiency	±0.6%		limit
Luminosity	±5.0%		limit

Background modeling

SPIN-2 ANALYSIS



Acceptance

SPIN-0 ANALYSIS

- **Fiducial region**
  - ✓ $E_T^{\gamma 1\,(truth)} > 0.4\ m_{\gamma\gamma}$, $E_T^{\gamma 2 (truth)} > 0.3\ m_{\gamma\gamma}$
  - ✓ $E_T^{iso\,(truth)}\,(R=0.4) < 0.05\ E_T^{\gamma\,(truth)}) + 6$ GeV
  - ✓ $m_X \pm 2\Gamma_X$
- **ggF as baseline**
  - ✓ Difference to alternative production modes as systematics (ggF, VBF, WH, ZH, ttH)
- **As model-independent as possible**
- C_X = 55%-70% for m_X= 200-700 GeV

SPIN-2 ANALYSIS

- **Total selection efficiency**
- **RS graviton as benchmark**
- $A_G \times C_G$= 45%-60% for m_G= 500-3000 GeV

Source of uncertanty	Scalar	Common	Graviton
Signal photon identification (mass dependent)		$\pm(3-2)\%$	
Signal photon isolation (mass dependent)	$\pm$(4-1)%		$\pm$(3-1)%
Signal production process dependence	$\pm$ 3% for NWA		N/A
	$\pm$ 6% for larger decay width		N/A
Trigger efficiency		$\pm$0.6%	
Luminosity		$\pm$5.0%	
Photon energy scale and resolution		negligible	

Compatibility between spin-0 and spin-2 analyses

- Events in spin-0 analysis are subset of events in spin-2 analysis for $m_{\gamma\gamma}$ > 185 GeV, so two analyses are not independent
  - ✓ Resampling techniques (bootstrap)
    - *Union dataset is sliced into N blocks with 10 events in each block.*
    - *N blocks are randomly picked without considering possible duplication (i.e. the same block could be selected for more than one time).*
    - *Resampled dataset will then pass spin-0 and spin-2 selections, outcome spectra are fed into max LL S+B fit assuming same signal hypothesis*
    - *Procedure is repeated many times until decent statistics are accumulated for compatibility check*

- Assuming spin-0 signal: 0.02 σ
- Assuming spin-2 signal: 0.9 σ

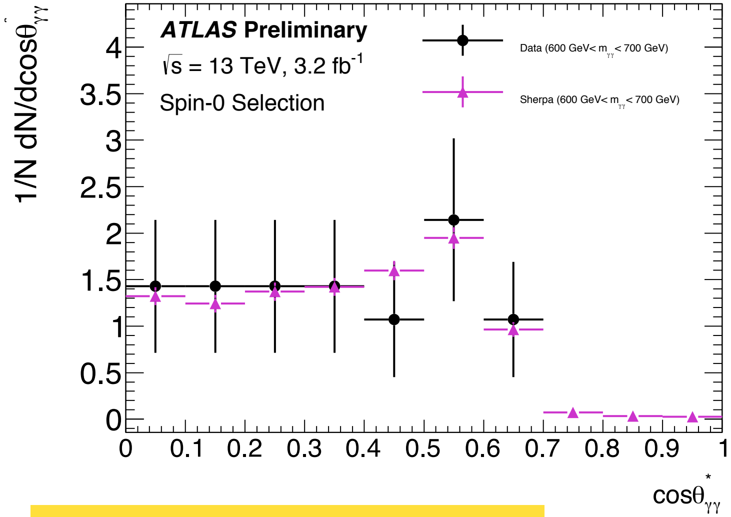
8 TeV analysis selections

Criteria	Scalar analysis	Graviton analysis
Trigger	`EF_g35_loose_g25_loose`	
GRL	v61-pro14-02_DQDefects-00-01-00_PHYS_StandardGRL_All_Good	
LAr	LArError, TileError, event corruption	
vertex	At least one PV with 3 associated tracks or more	
Presel.	At least two photons passing loose ID, OQ, photon cleaning with $\lvert\eta_{S2}\rvert$ <1.37 or 1.56< $\lvert\eta_{S2}\rvert$ <2.37	
E_T cuts	$E_{T,1} > 0.4 \times m_{\gamma\gamma}$ and $E_{T,2} > 0.3 \times m_{\gamma\gamma}$	$E_{T,1} > 50\,\text{GeV}$ and $E_{T,2} > 50\,\text{GeV}$
Photon ID	Require both candidates to pass `tight` photon ID	
Isolation	$\begin{cases} E_{\mathrm{T}}^{\text{iso,calo}} < 6\text{ GeV} & \text{if}\quad E_{\mathrm{T}} < 80\text{ GeV} \\ E_{\mathrm{T}}^{\text{iso,calo}} < 6\text{ GeV} + 0.7\%(E_{\mathrm{T}} - 80\text{ GeV}) & \text{if}\quad E_{\mathrm{T}} > 80\text{ GeV} \end{cases}$ and $E_{\mathrm{T}}^{\text{iso,track}} < 2.6$ GeV	$E_{\mathrm{T}}^{\text{iso,calo}} < 8\text{ GeV}$ $-0.07\text{ GeV} + 4.8\cdot 10^{-4} E_{\mathrm{T}} + 2.6\cdot 10^{-6}\frac{1}{\text{GeV}} E_{\mathrm{T}}^2$
$m_{\gamma\gamma}$	$m_{\gamma\gamma} > 150\,\text{GeV}$	

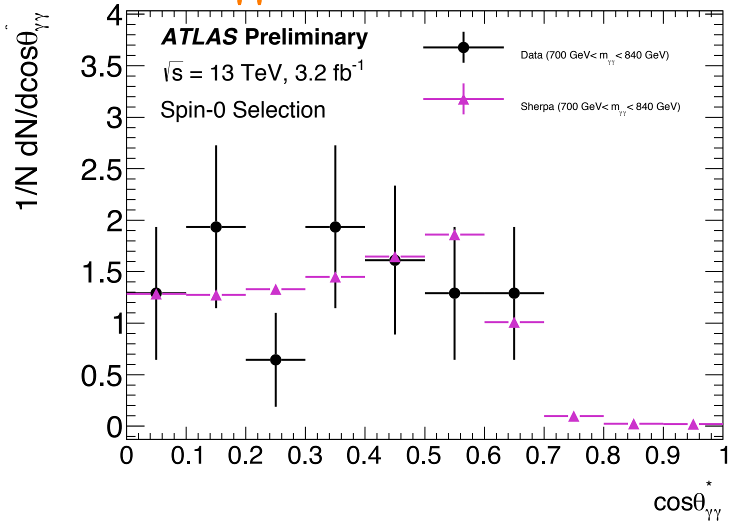
Properties of sideband and excess regions $\cos\theta^*_{\gamma\gamma}$

SPIN-0 ANALYSIS

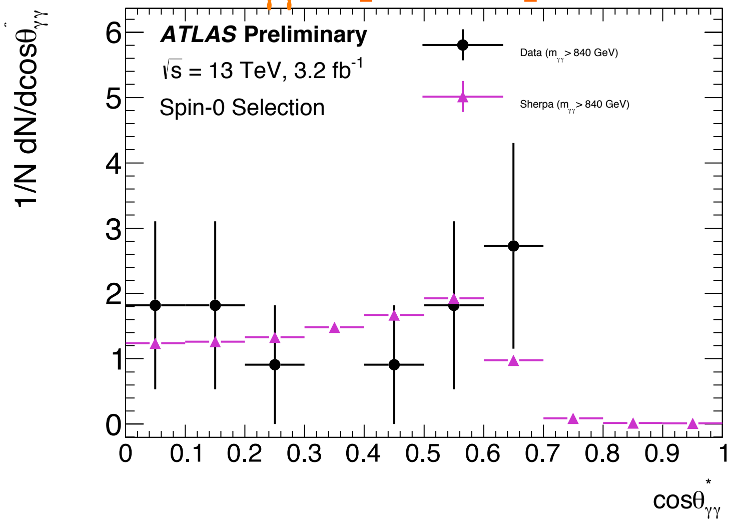
$m_{\gamma\gamma}$ = [600-700] GeV



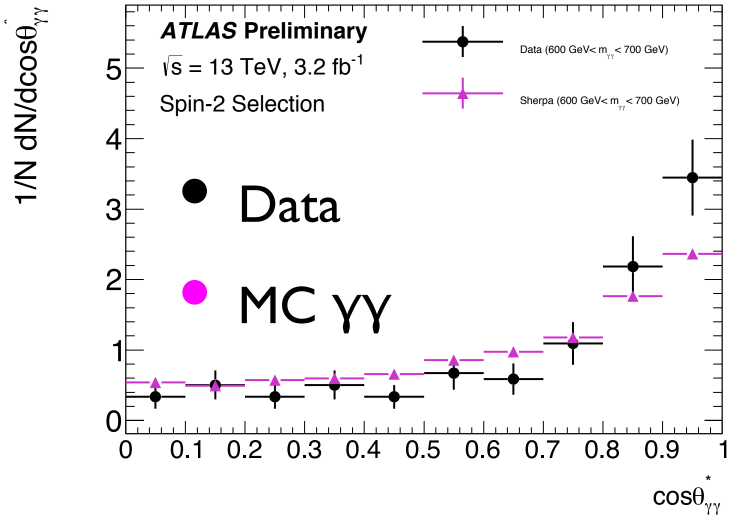
$m_{\gamma\gamma}$ = [700-840] GeV

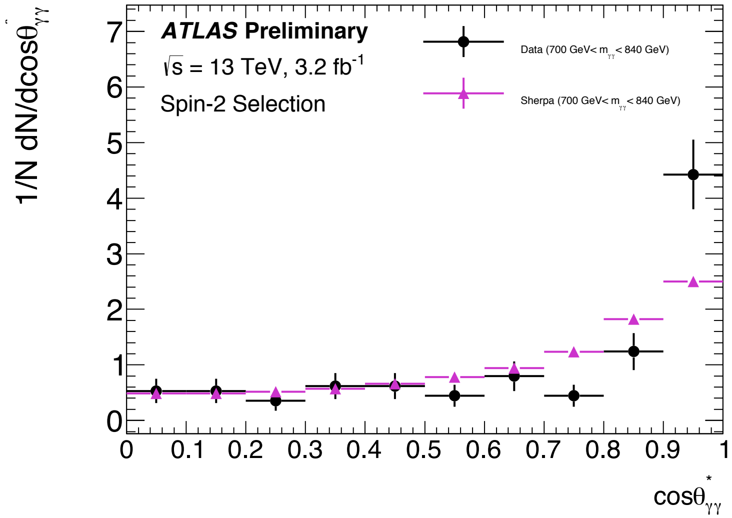


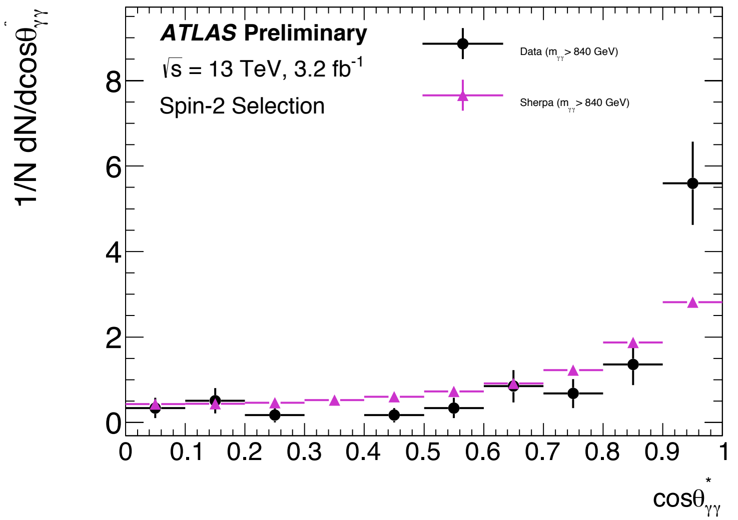
$m_{\gamma\gamma}$ =[840-∞] GeV



SPIN-2 ANALYSIS



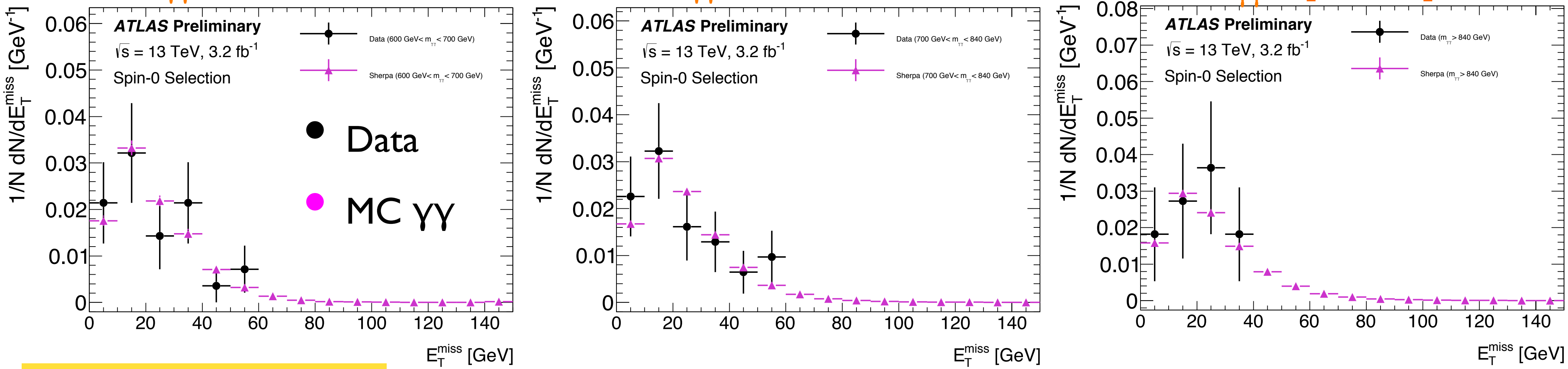




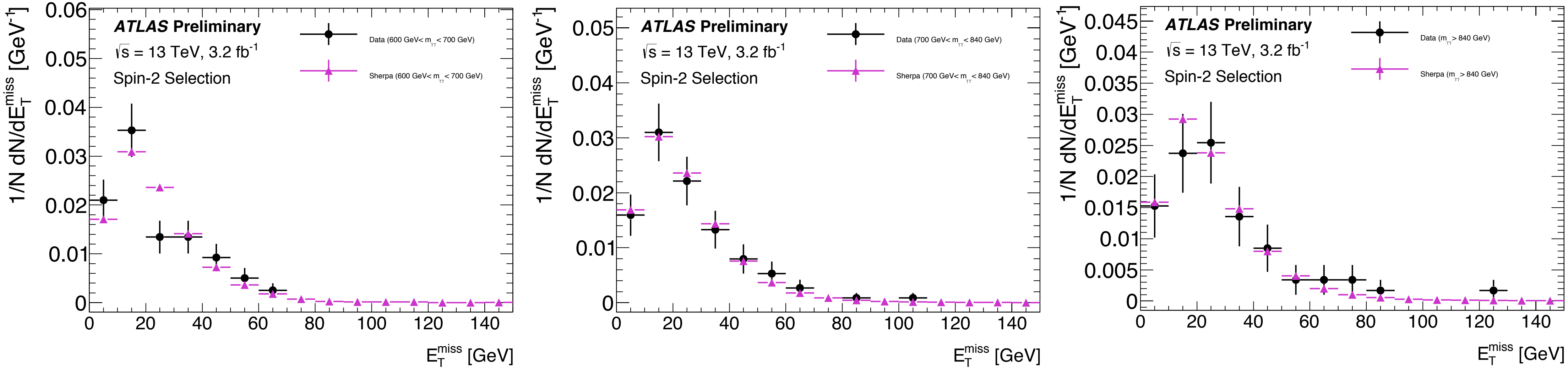
Properties of sideband and excess regions E_T^{miss}

SPIN-0 ANALYSIS

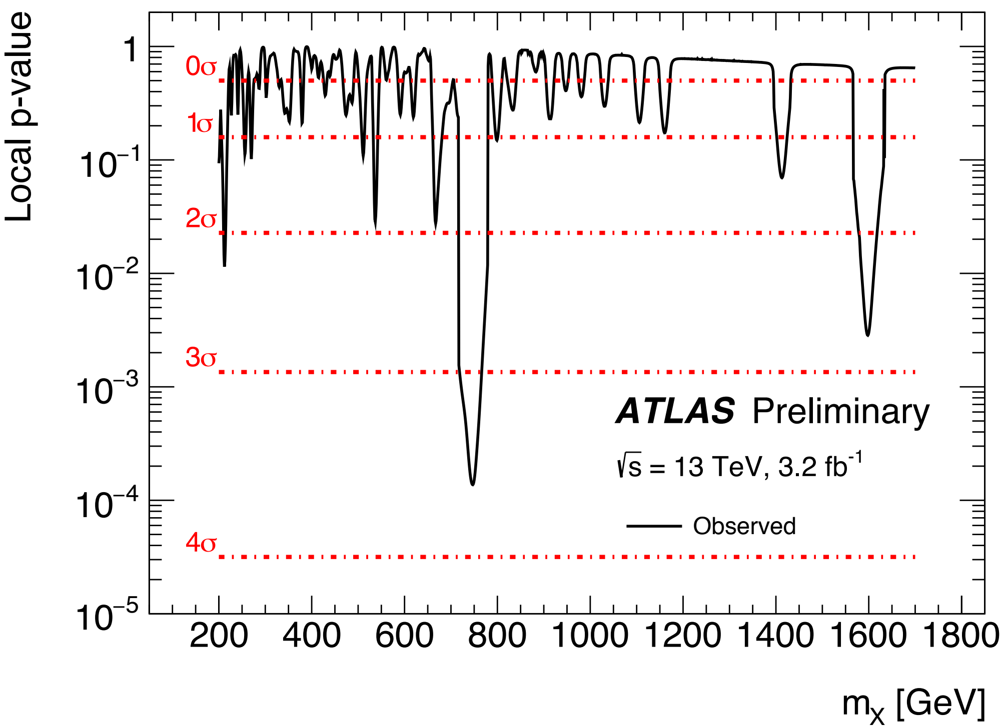
$m_{\gamma\gamma}$ = [600-700] GeV $m_{\gamma\gamma}$ = [700-840] GeV $m_{\gamma\gamma}$ =[840-∞] GeV

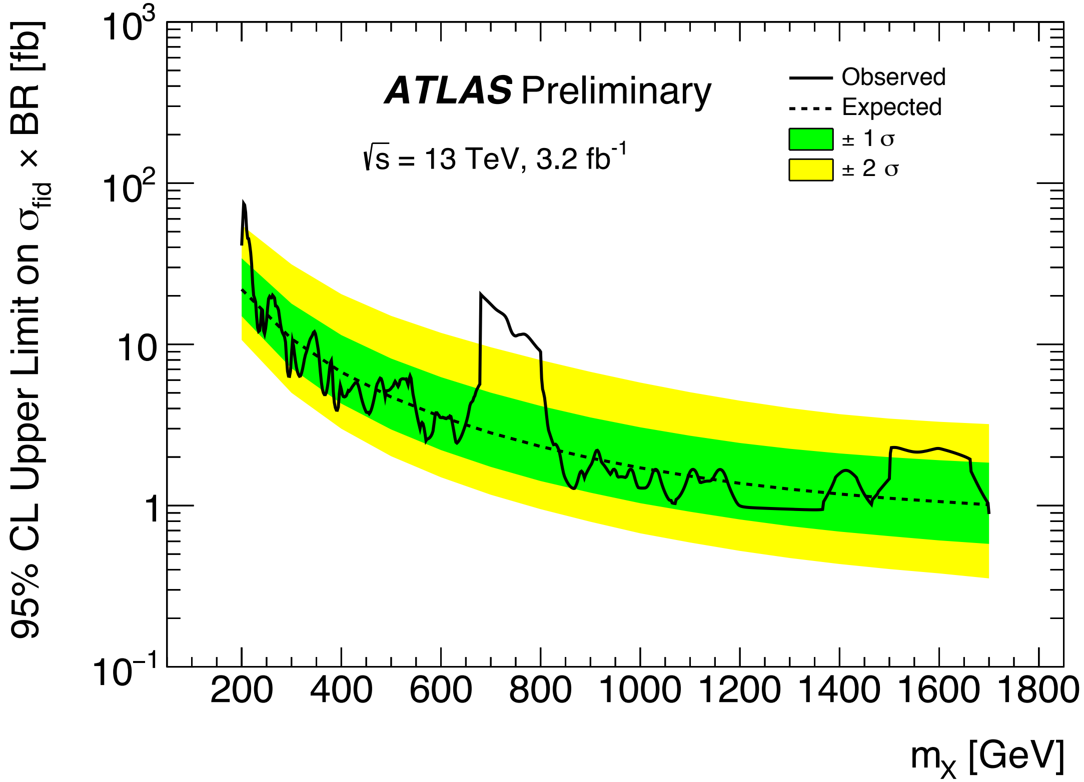


SPIN-2 ANALYSIS



EOYE NW results



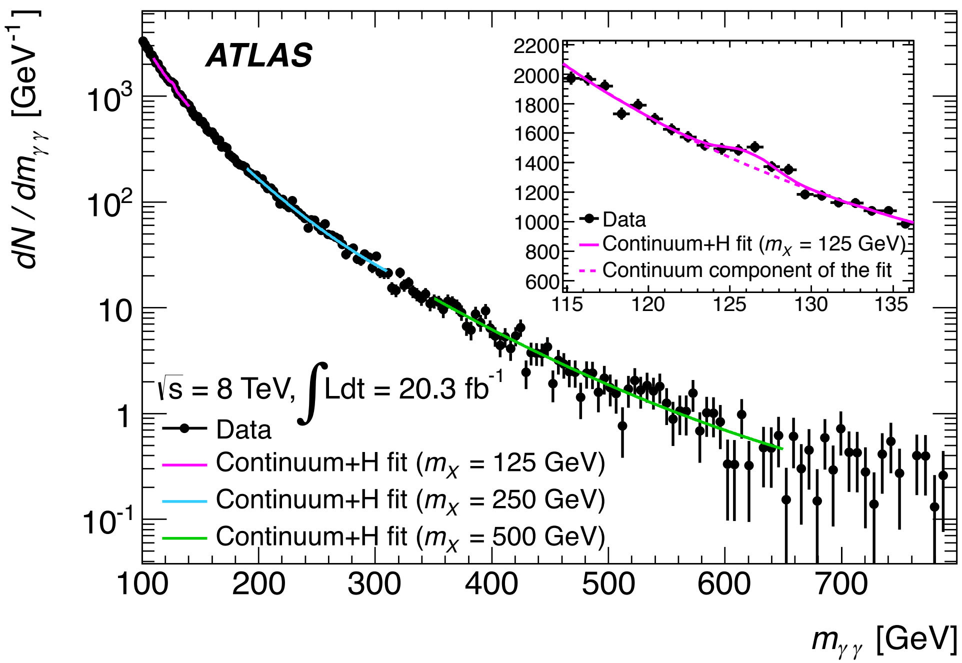


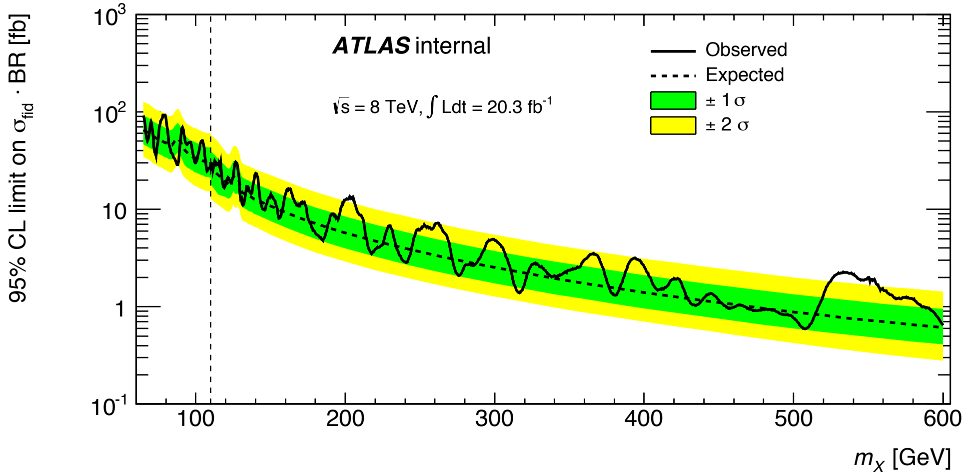
- Largest deviation from B-only hypothesis
  - ✓ m_X ~ 750 GeV
  - ✓ Local Z = 3.6 σ
  - ✓ Global Z = 2.0 σ
    - m_X = [200 GeV - 2 TeV]

Recap of latest Run 1 results

Search for scalar diphoton resonances in the mass range 65-600 GeV with the ATLAS detector in pp collision data at $\sqrt{s}$ = 8 TeV

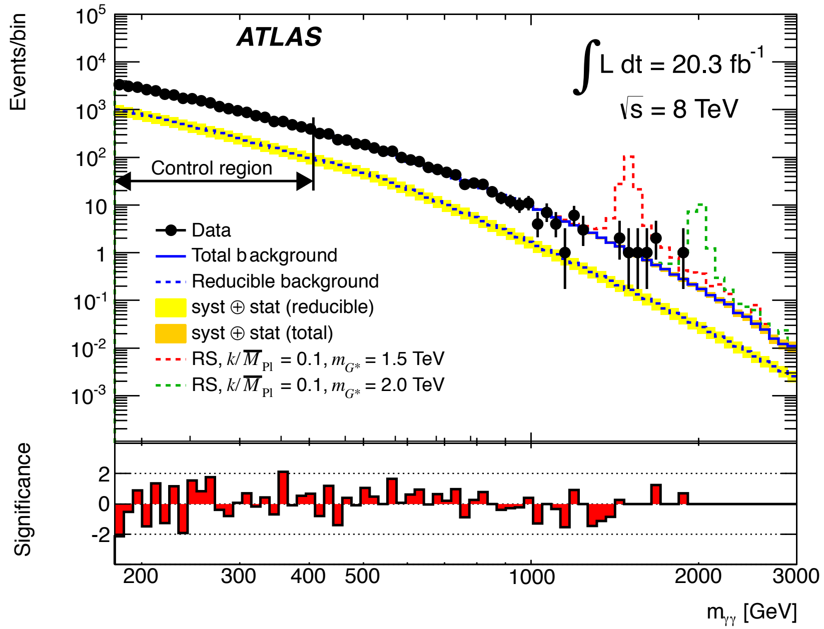
Phys. Rev. Lett. 113, 171801

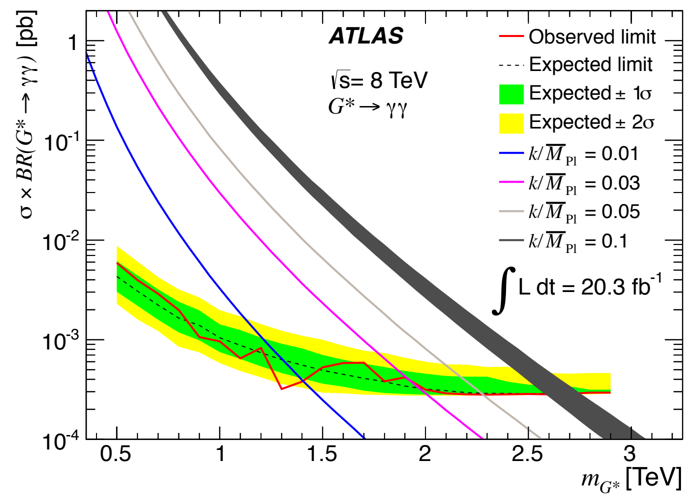




Search for high-mass diphoton resonances in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector

Phys. Rev. D 92, 032004 (2015)

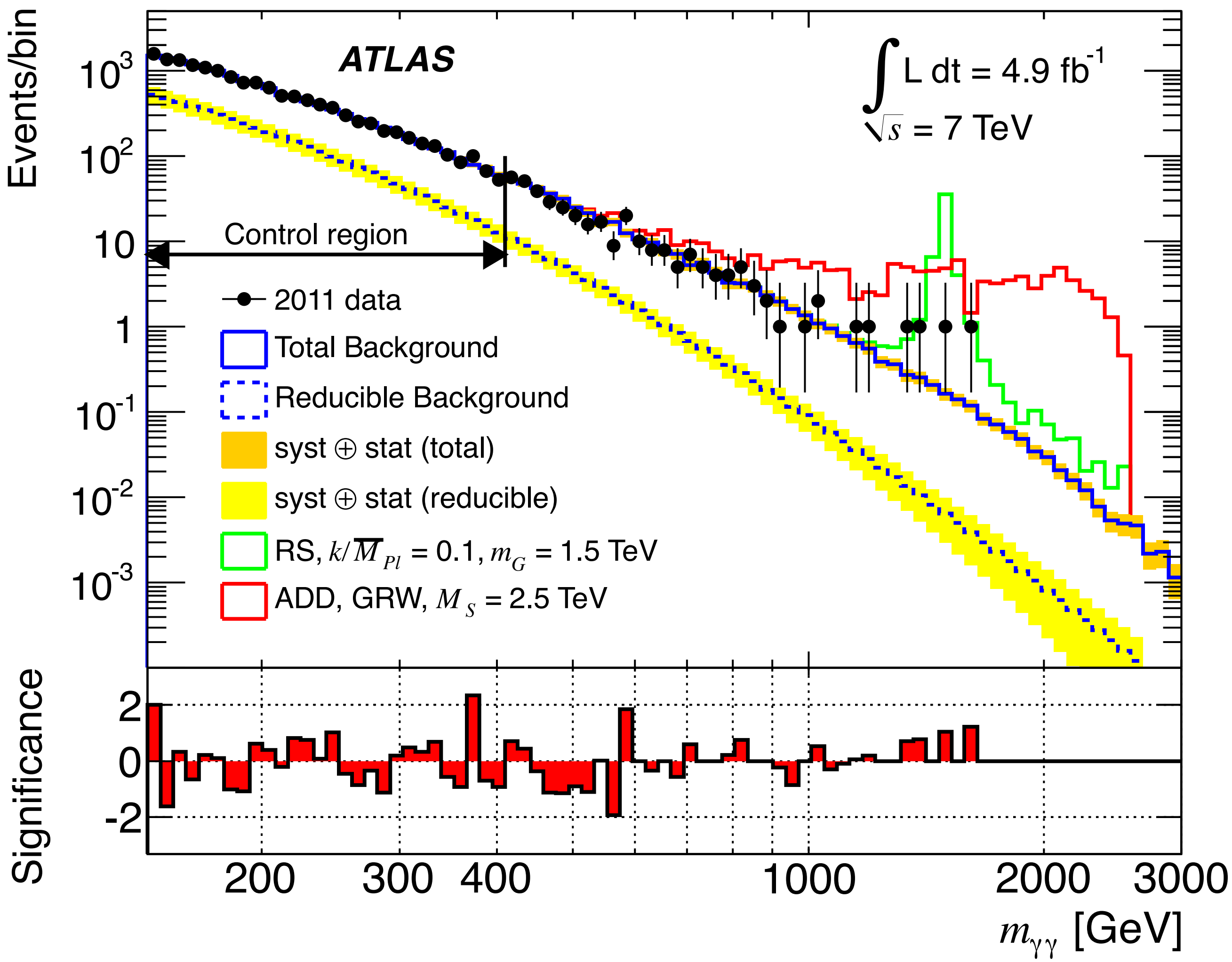




Recap of latest Run 1 results

Search for Extra Dimensions in diphoton events using proton-proton collisions recorded at $\sqrt{s}$ = 7 TeV with the ATLAS detector at the LHC

New J. Phys. 15 (2013) 043007



Data sample & Selections

- **Luminosity & Trigger**
  - ✓ Trigger: $E_T^{\gamma 1}$ 35 GeV, $E_T^{\gamma 2} > 25$ GeV + loose EM shower identification
    - ~99% efficient w.r.t. final selections
  - ✓ **3.2 fb^{-1} ± 5%**

SCALAR

- $E_T^{\gamma 1} > 0.4\ m_{\gamma\gamma}$, $E_T^{\gamma 2} > 0.3\ m_{\gamma\gamma}$
- 7391 events ($m_{\gamma\gamma} > 150$ GeV)
- **2878 events ($m_{\gamma\gamma} > 200$ GeV)**

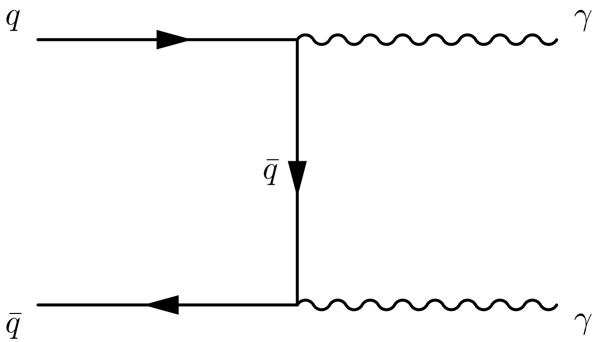
GRAVITON

- $E_T^{\gamma 1} > 55$ GeV, $E_T^{\gamma 2} > 55$ GeV
- **5066 events ($m_{\gamma\gamma} > 200$ GeV)**

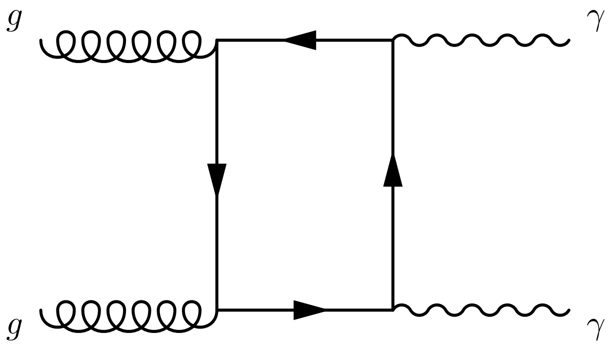
Background modeling

IRREDUCIBLE

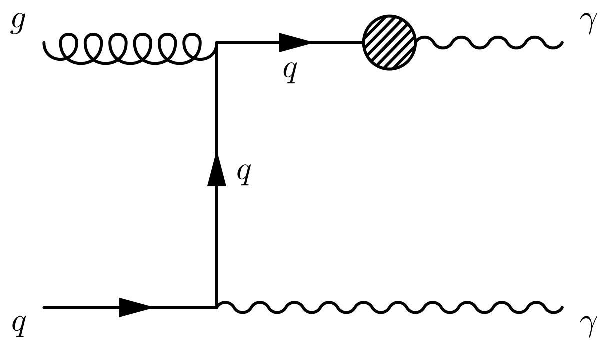
born



box

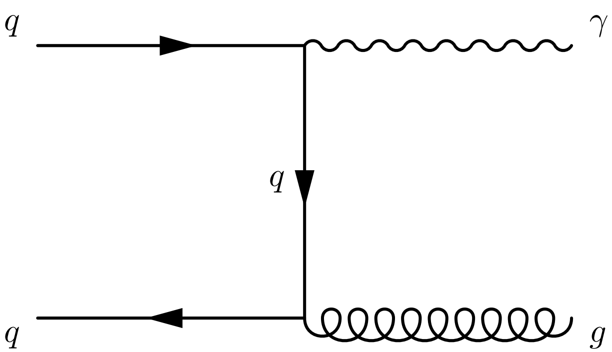


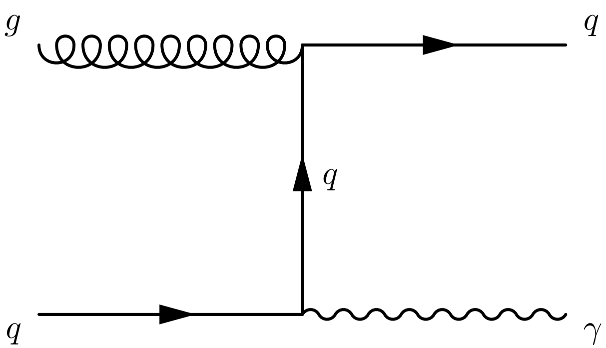
parton fragmentation

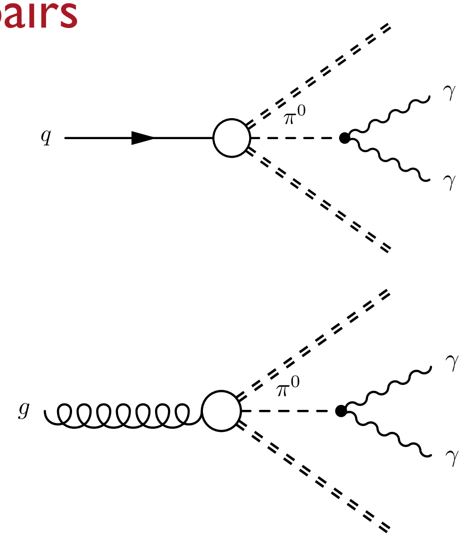


REDUCIBLE

jets in γj and jj events with a neutral meson decaying in collimated photon pairs





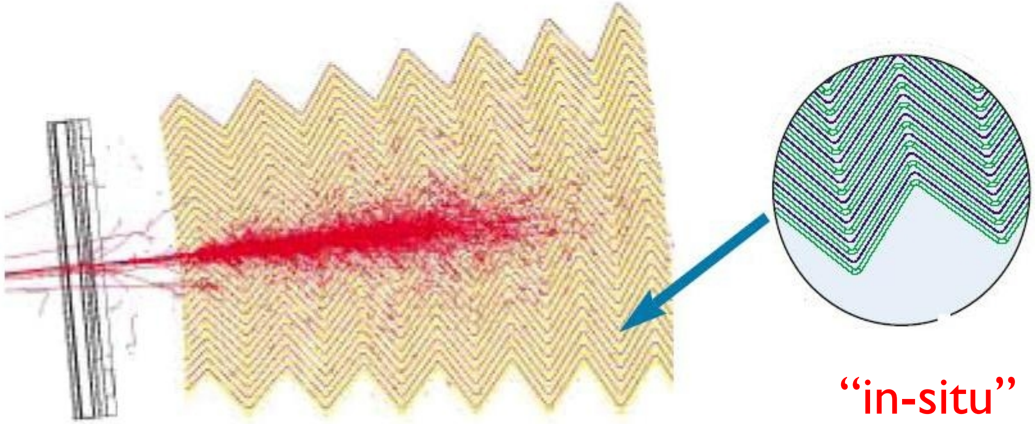


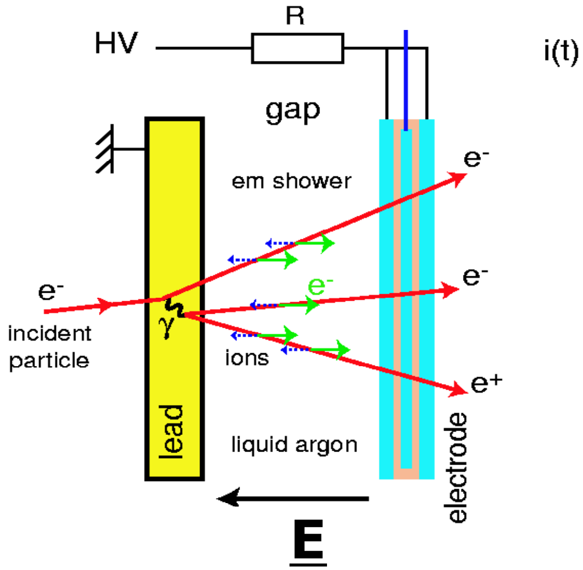
A photon showers in the EMC. Most of its energy is lost in Pb

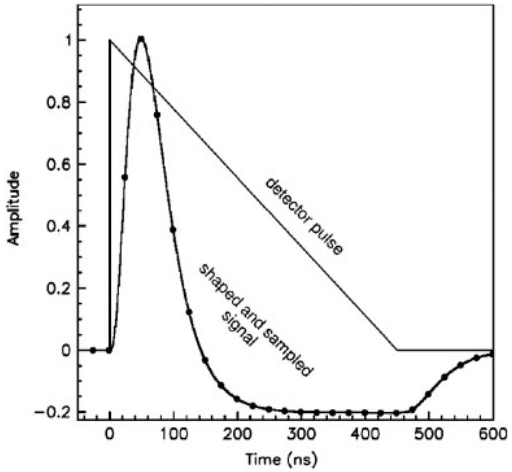
Electrons in EM shower ionize LAr

Ionization electrons produce current

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







"in-situ" intercalibration

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

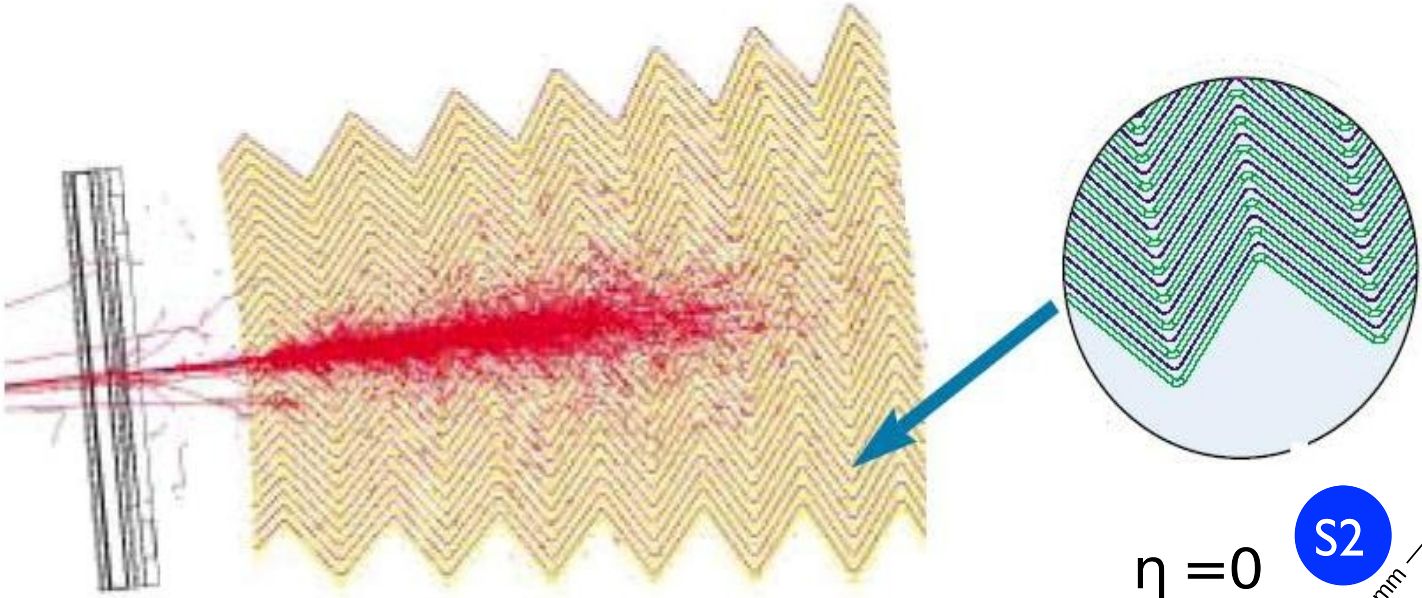
clustering

Cells are grouped in clusters

electronic calibration

Energy in a cell is reconstructed from signal samples

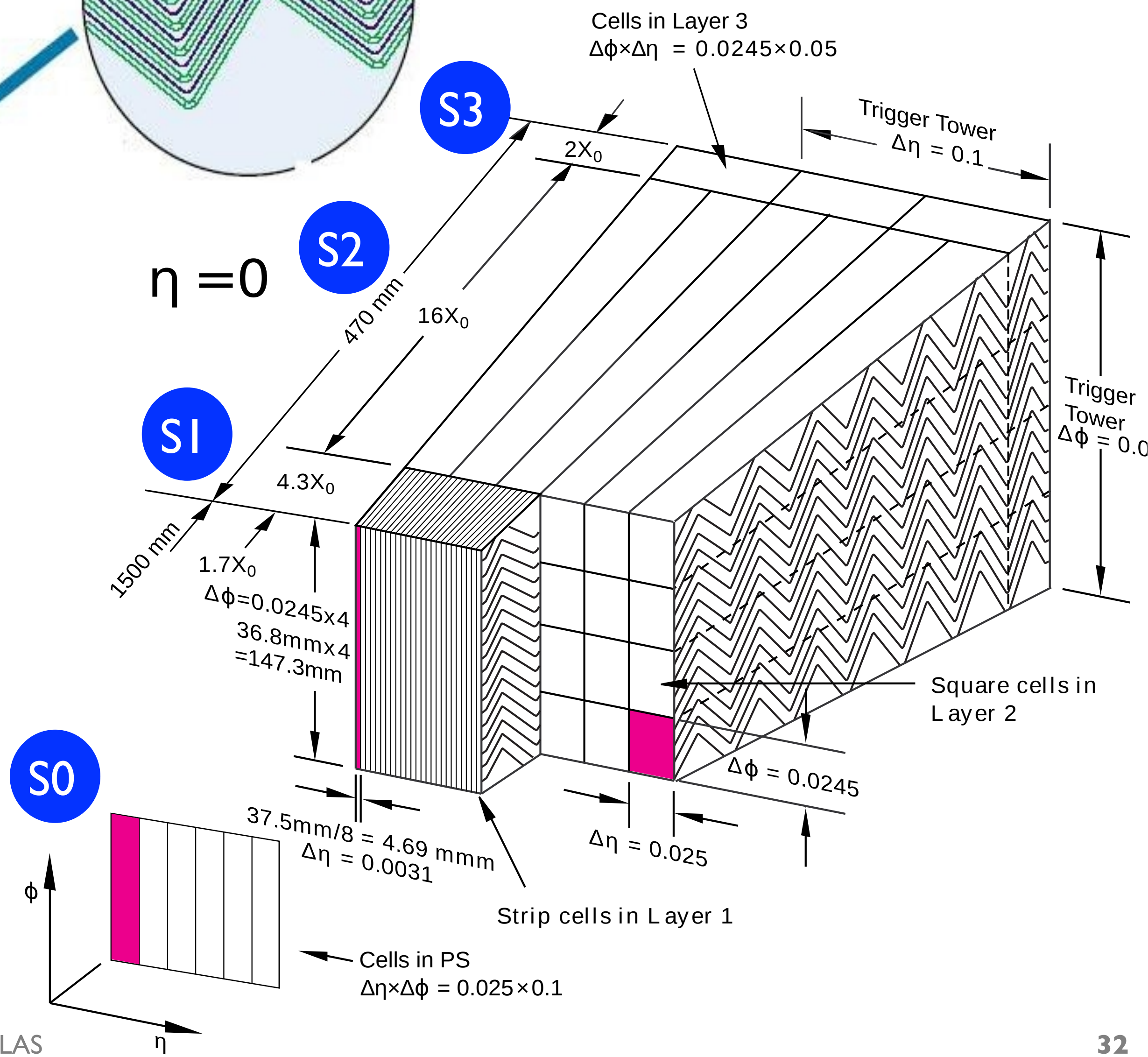
ATLAS liquid argon electromagnetic calorimeters



sampling calorimeter
Pb-LAr

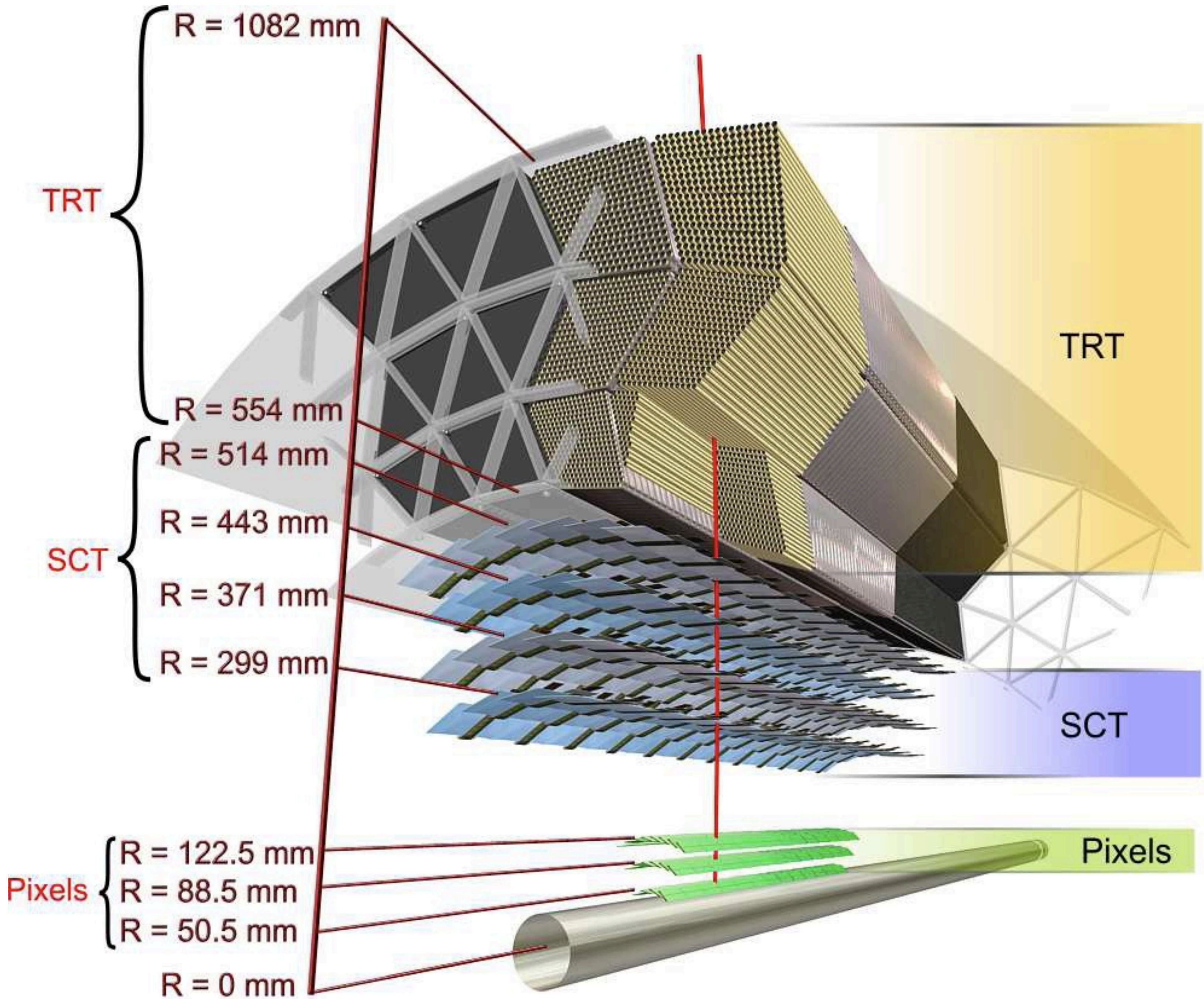
10 % 250 MeV 0.7%

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$



• S0 (Presampler)	Energy loss correction	
• S1 (Strips)	γ/π^0 separation	4.3 X_0
• S2 (Middle)	Main energy deposit	16 X_0
• S3 (Back)	High energy showers	2 X_0

ATLAS Inner Detector



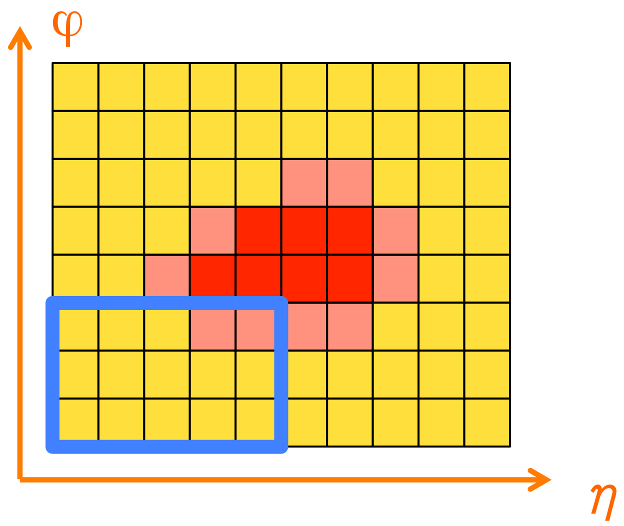
- **+ IBL !**
- **Properties of track from charged particles**
  - ✓ momentum
  - ✓ charge
- **Transition Radiation**
  - ✓ e/pi discrimination

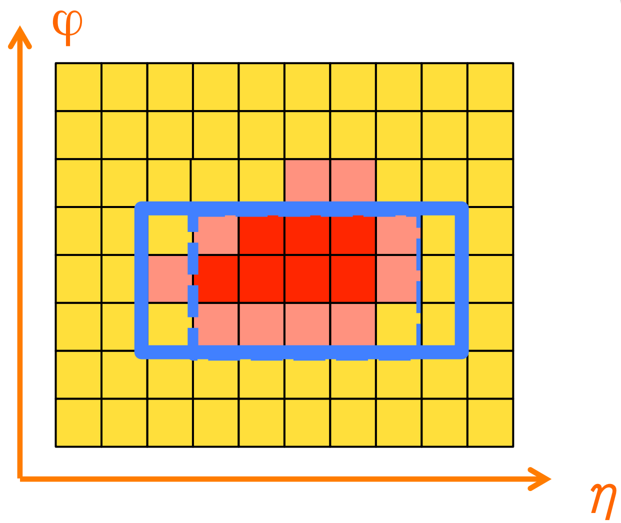
- e/γ discrimination
- γ conversion reconstruction

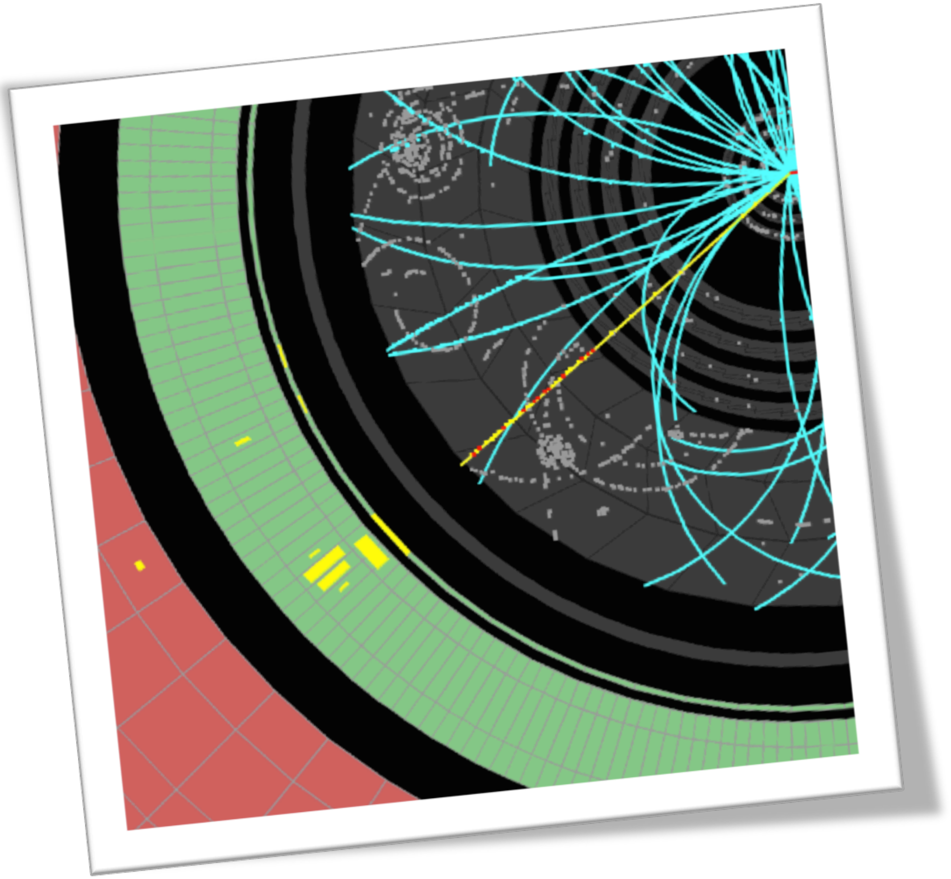
Electrons and photons in ATLAS

Electron and photon candidates in ATLAS are built from EM "sliding window" fixed-size rectangular clusters, that can be associated to tracks

- ✓ $\Delta\eta \times \Delta\phi$ = 0.075 × 0.175 (Barrel), 0.125 × 0.125 (Endcap)
- ✓ Unifed between electrons and photons in 2015
- ✓ Size is trade-off between energy leakage and noise pickup



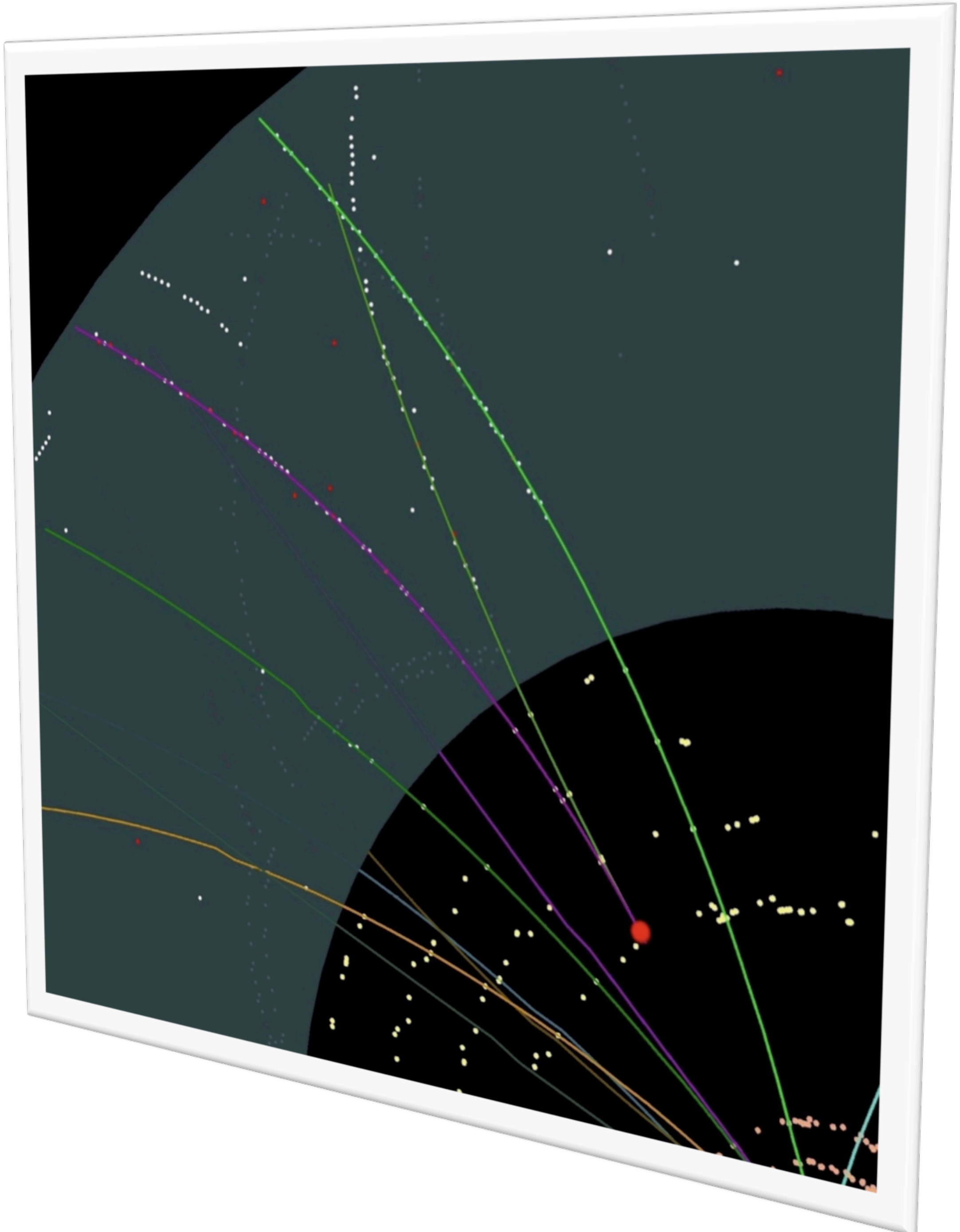




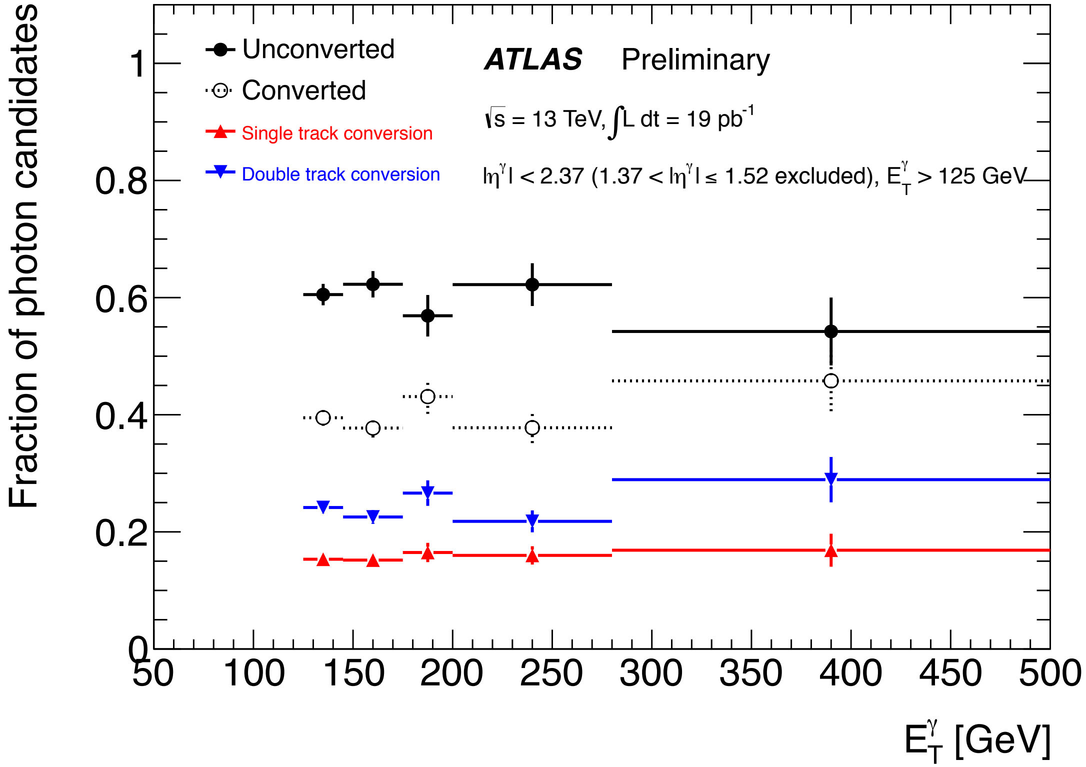
- **Cells in EM clusters are calibrated to "EM scale"**
  - ✓ Including expected average sampling fraction, from simulated electron at 100 GeV
- **Several corrections needed for e and γ, mostly based on simulation**
  - ✓ e.g. energy losses outside cluster, losses in upstream material, variable sampling fraction…

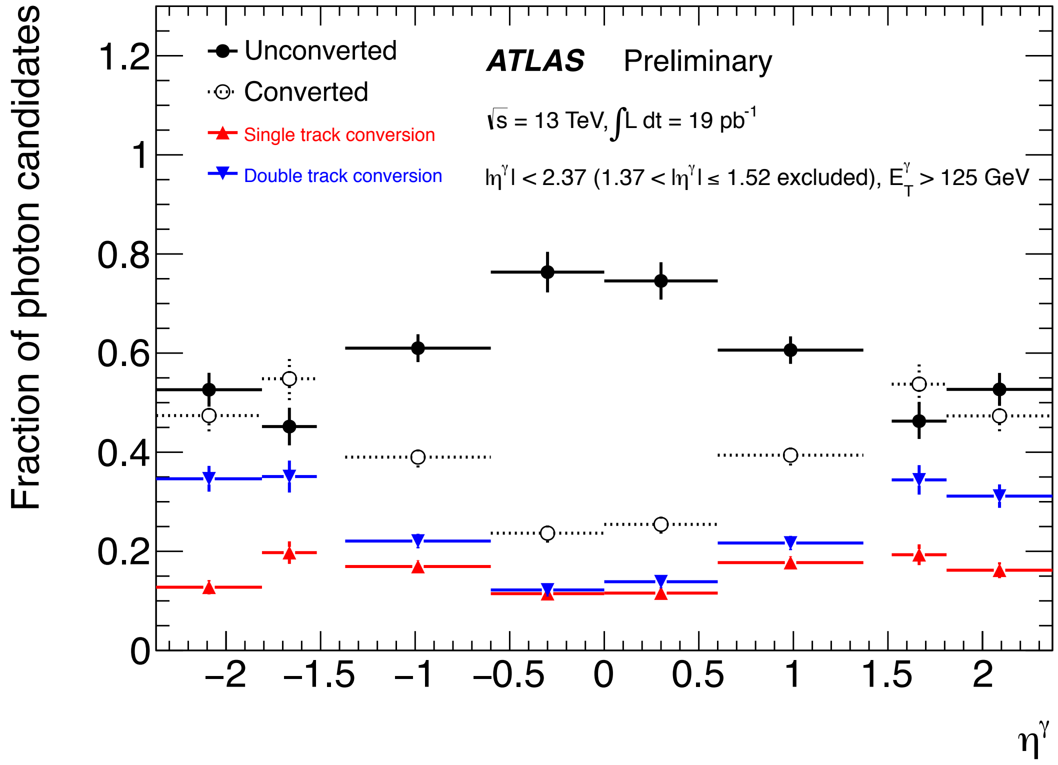
Photon conversion reconstruction

- **Candidate photon conversion vertices reconstructed from tracks pre-selected as loosely matching EMC clusters**
  - ✓ 1 or 2 tracks
  - ✓ 1-track conversions from tracks that missing the hit in innermost ID layer
- Photon reconstruction expected efficiency
  - ✓ ~ 98% for photons E_T > 25 GeV
  - ✓ > 99% for unconverted photons
  - ✓ ~ 95% for converted (R < 80 cm)
- **Expected fraction of converted photons**
  - ✓ ~ 20% at | η | ~ 0 - ~ 45% | η | ~ 1.6
- Relative fraction of reconstructed photon conversion depends on:
  - ✓ Material upstream EMC
  - ✓ In MC, on conversion model…



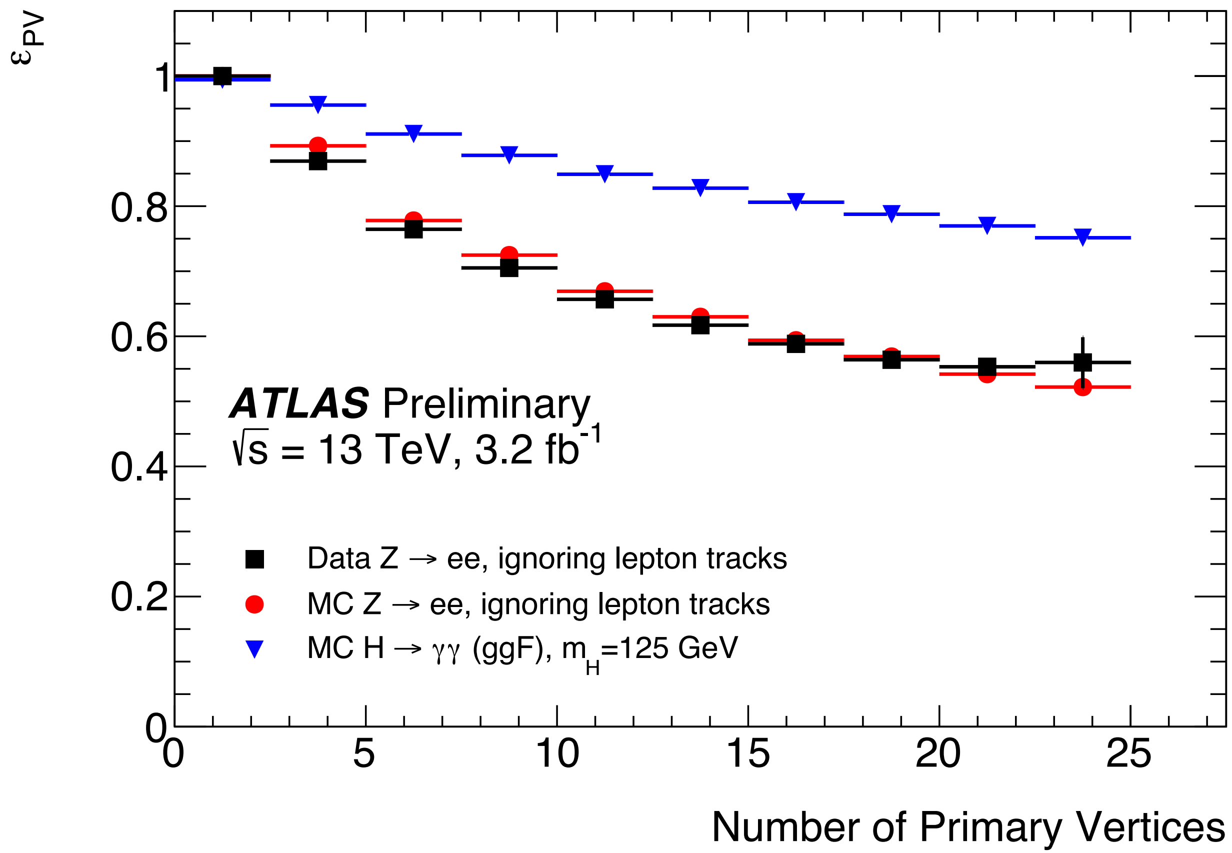
Photon conversion reconstruction



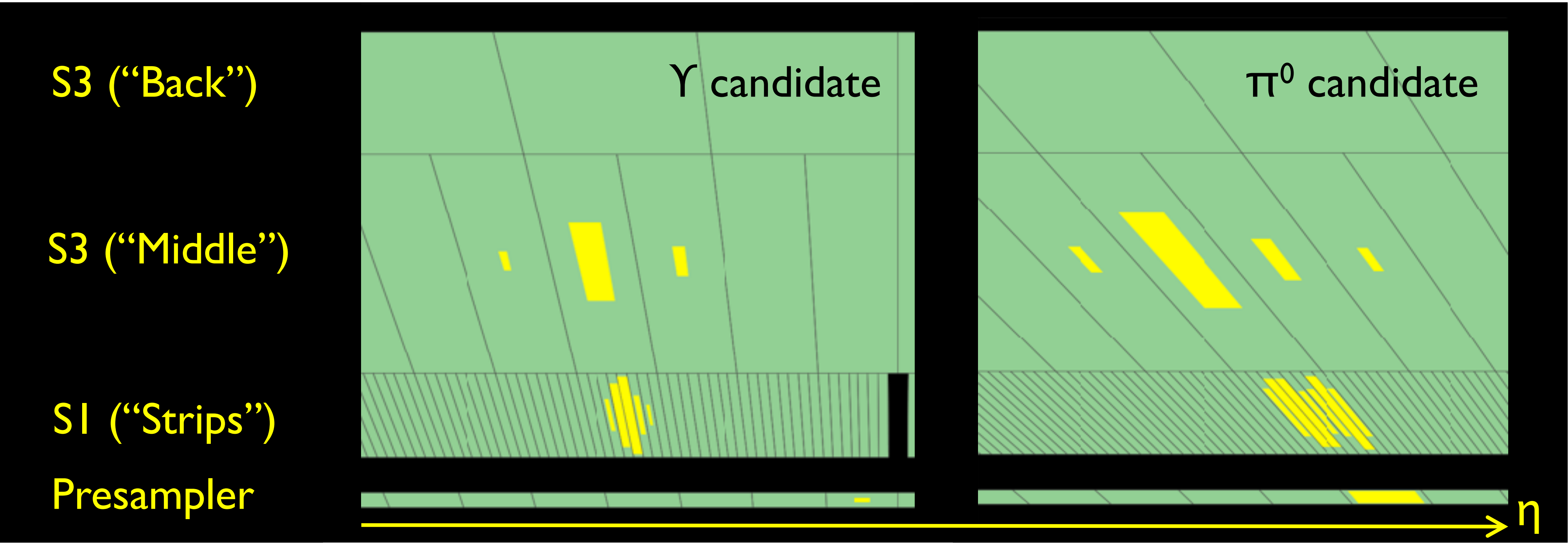


Photon pointing

- z position of diphoton primary vertex obtained by combining average beam-spot position with photon pointing, enhanced by using tracks from photon conversions with conversion radii in Si volume
  - ✓ Resolution ~15 mm in z direction
- NN discriminant with $\Sigma p_T, \Sigma p_T^2$, diphoton balancing with vertex tracks, trajectory from calorimeter segmentation (z pointing) to choose best vertex candidate
  - ✓ After this procedure contribution of the opening angle resolution to the mass resolution is negligible.
  - ✓ Efficiency to reconstruct the correct primary vertex within ±0.3 mm is about 88%.



Photon identification



Photon identification

Variables and Position

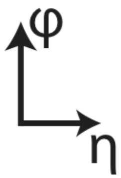
	Strips	2nd	Had.
Ratios	$f_1,\ f_{\mathrm{side}}$	R_η*, R_ϕ	$R_{\mathrm{Had.}}$*
Widths	$w_{s,3},\ w_{s,tot}$	$w_{\eta,2}$*	-
Shapes	$\Delta E,\ E_{\mathrm{ratio}}$		

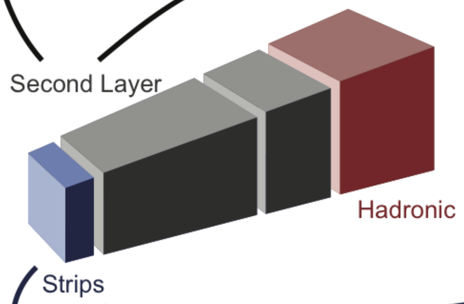
* Used in PhotonLoose.

Energy Ratios

$$R_\eta = \frac{E^{S2}_{3\times7}}{E^{S2}_{7\times7}}$$

$$R_\phi = \frac{E^{S2}_{3\times3}}{E^{S2}_{3\times7}}$$





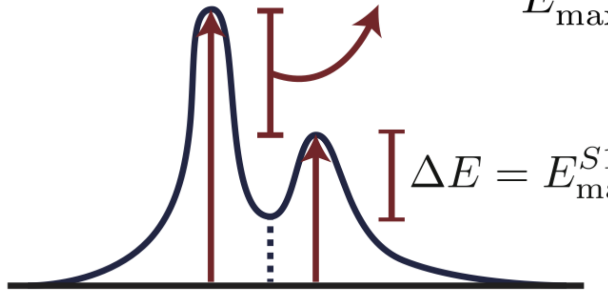
$$R_{\mathrm{Had}} = \frac{E_T^{\mathrm{Had}}}{E_T}$$

$$f_1 = \frac{E_{S1}}{E_{\mathrm{Tot.}}}$$

$$f_{\mathrm{side}} = \frac{E^{S1}_{7\times1} - E^{S1}_{3\times1}}{E^{S1}_{3\times1}}$$

Shower Shapes

$$E_{\mathrm{ratio}} = \frac{E^{S1}_{\mathrm{max},1} - E^{S1}_{\mathrm{max},2}}{E^{S1}_{\mathrm{max},1} + E^{S1}_{\mathrm{max},2}}$$

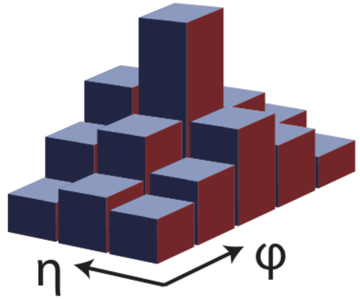


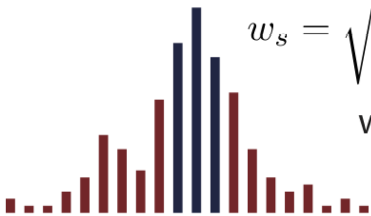
$$\Delta E = E^{S1}_{\mathrm{max},2} - E^{S1}_{\mathrm{min}}$$

Widths

$$w_{\eta,2} = \sqrt{\frac{\sum E_i \eta_i^2}{\sum E_i} - \left(\frac{\sum E_i \eta_i}{\sum E_i}\right)^2}$$

Width in a 3×5 (Δη×Δφ) region of cells in the second layer.

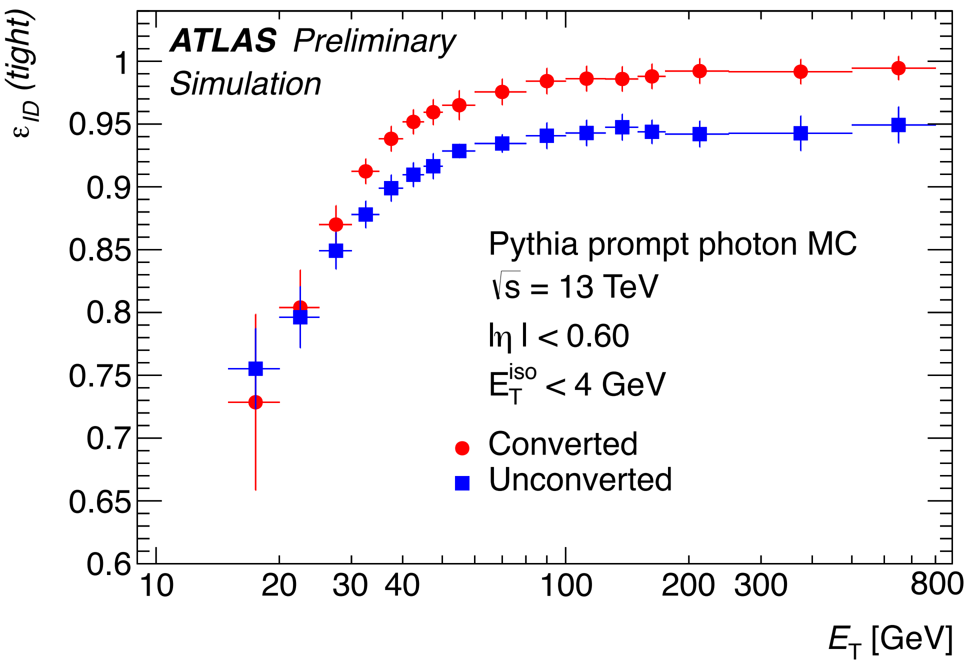


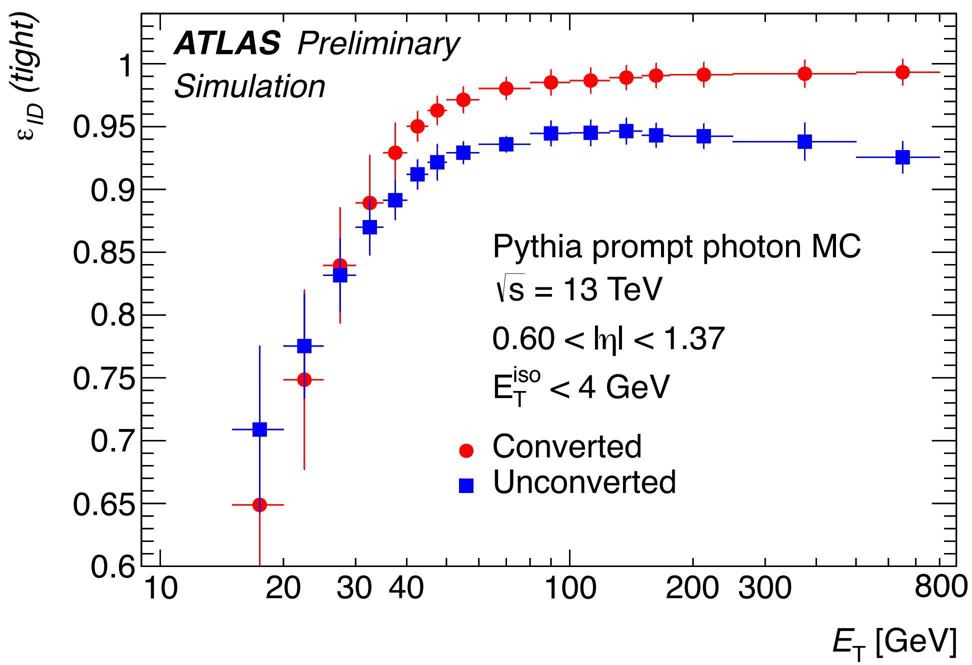


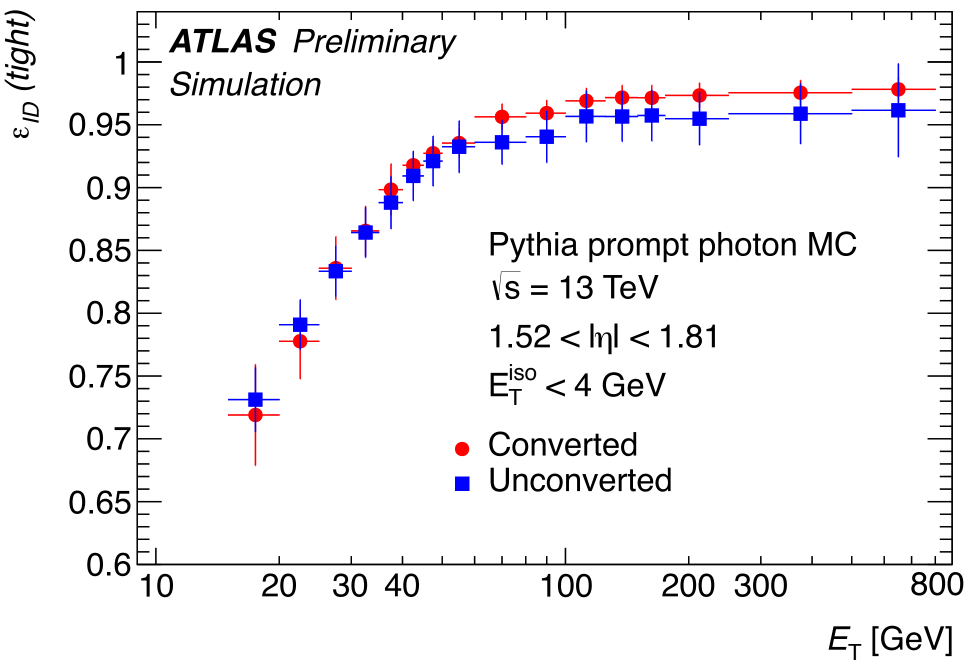
$$w_s = \sqrt{\frac{\sum E_i (i - i_{\mathrm{max}})^2}{\sum E_i}}$$

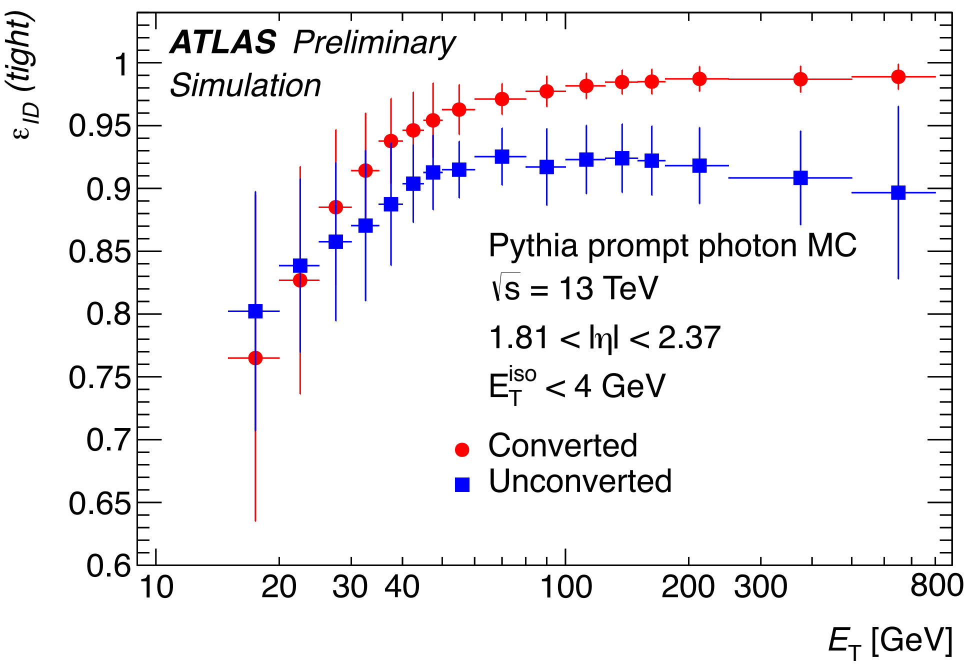
ws3 = w_1 uses ±1 strips (three total); wstot is defined similarly, but uses 20×2 strips.

Photon identification 2015





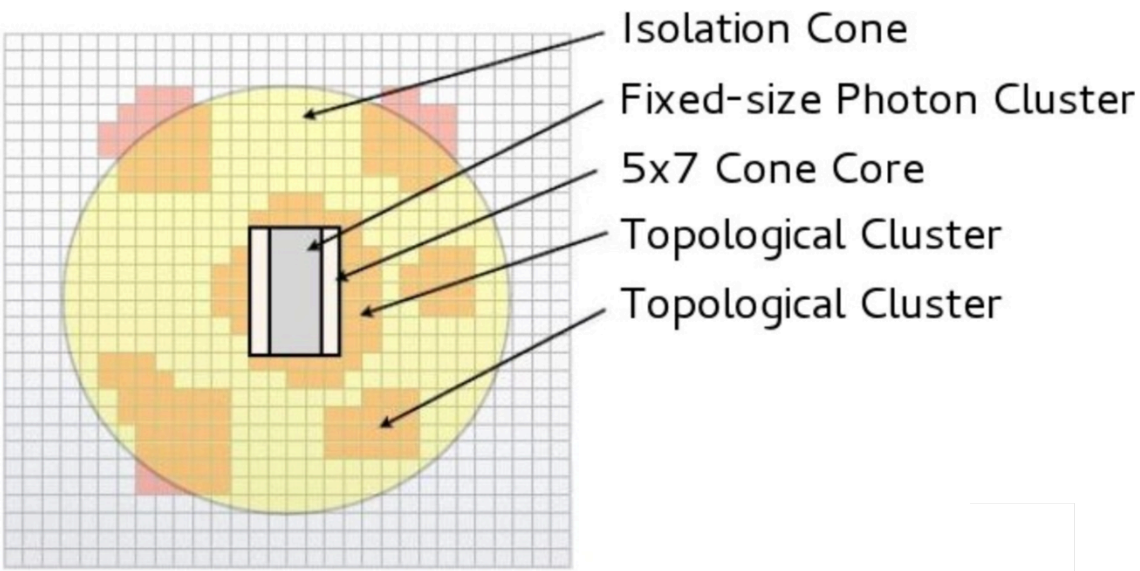


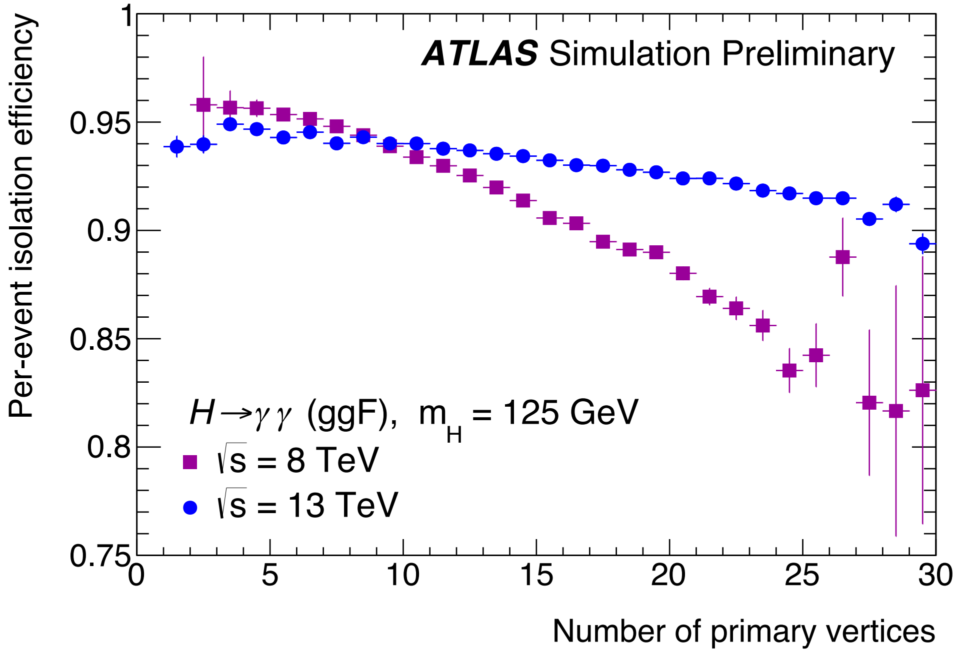


Photon isolation

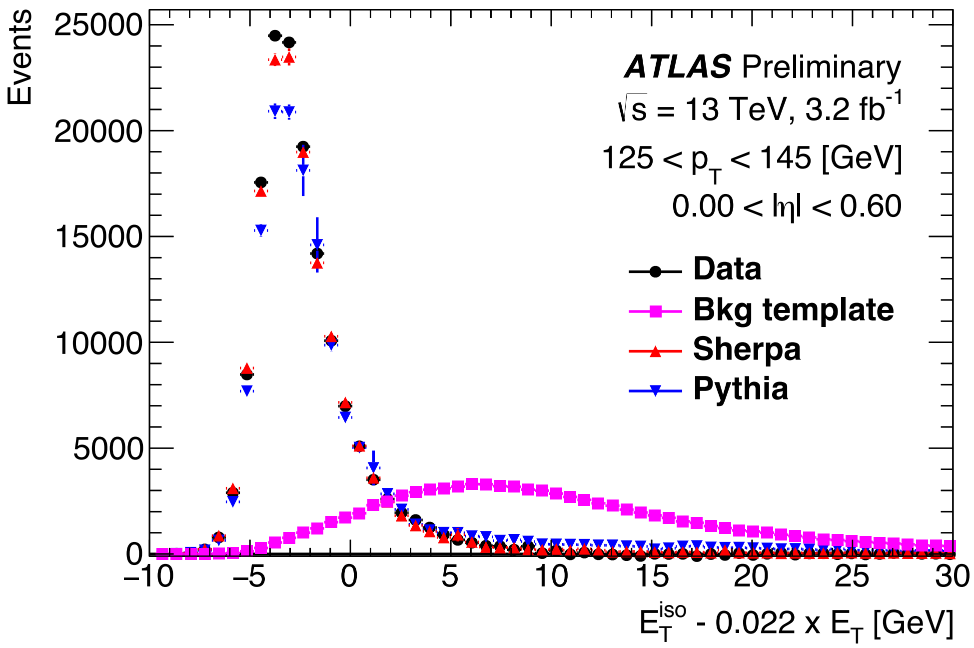
- Calorimetric isolation energy corrected event-by-event
  - ✓ Leakage of photon cluster
  - ✓ Underlying event and pileup contributions
    - Average correction for 1 PV ~540MeV

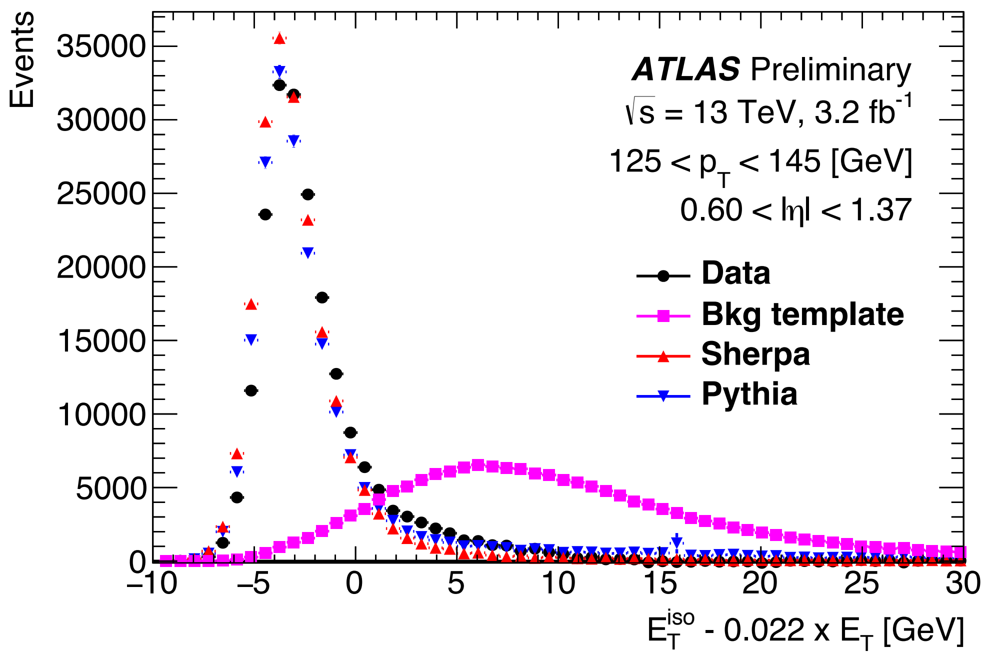
Cacciari, Salam and Soyez, JHEP 04, 005 (2008)
Cacciari, Salam and Sapeta, JHEP 04, 065 (2010)

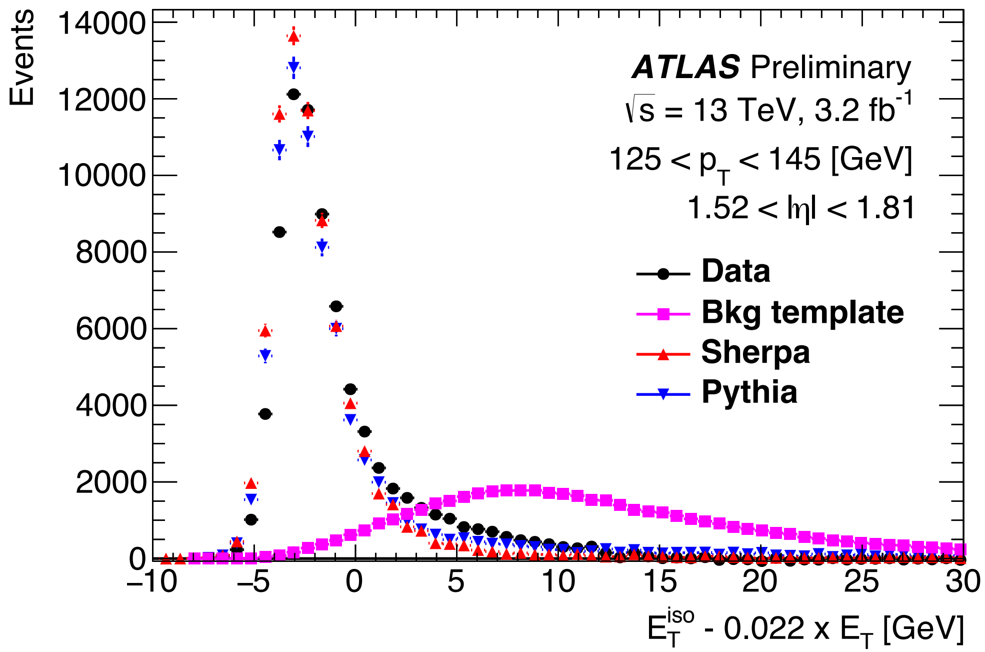


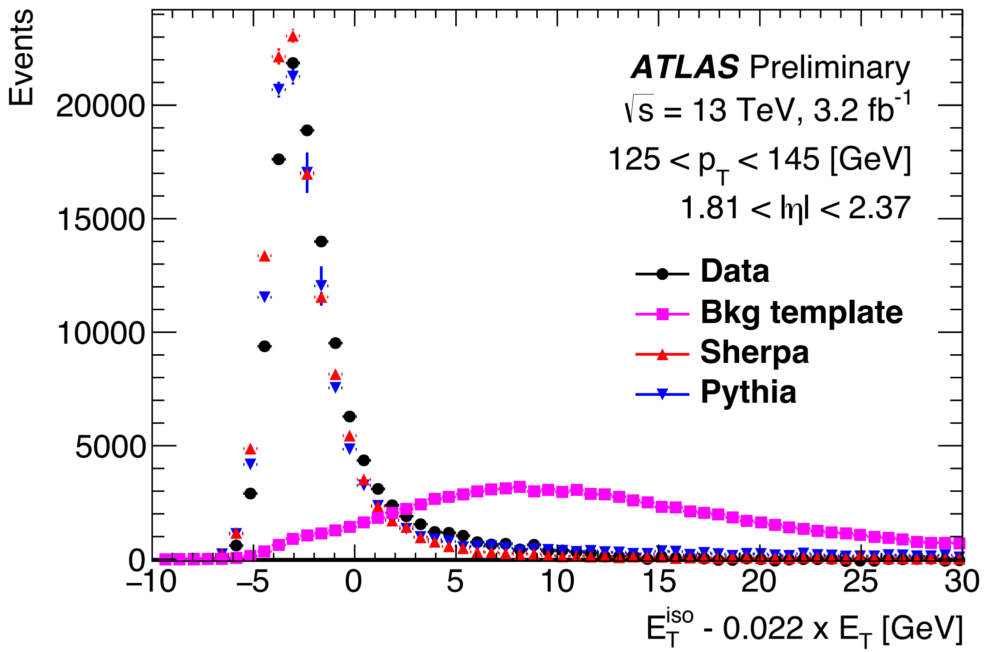


Photon isolation 2015



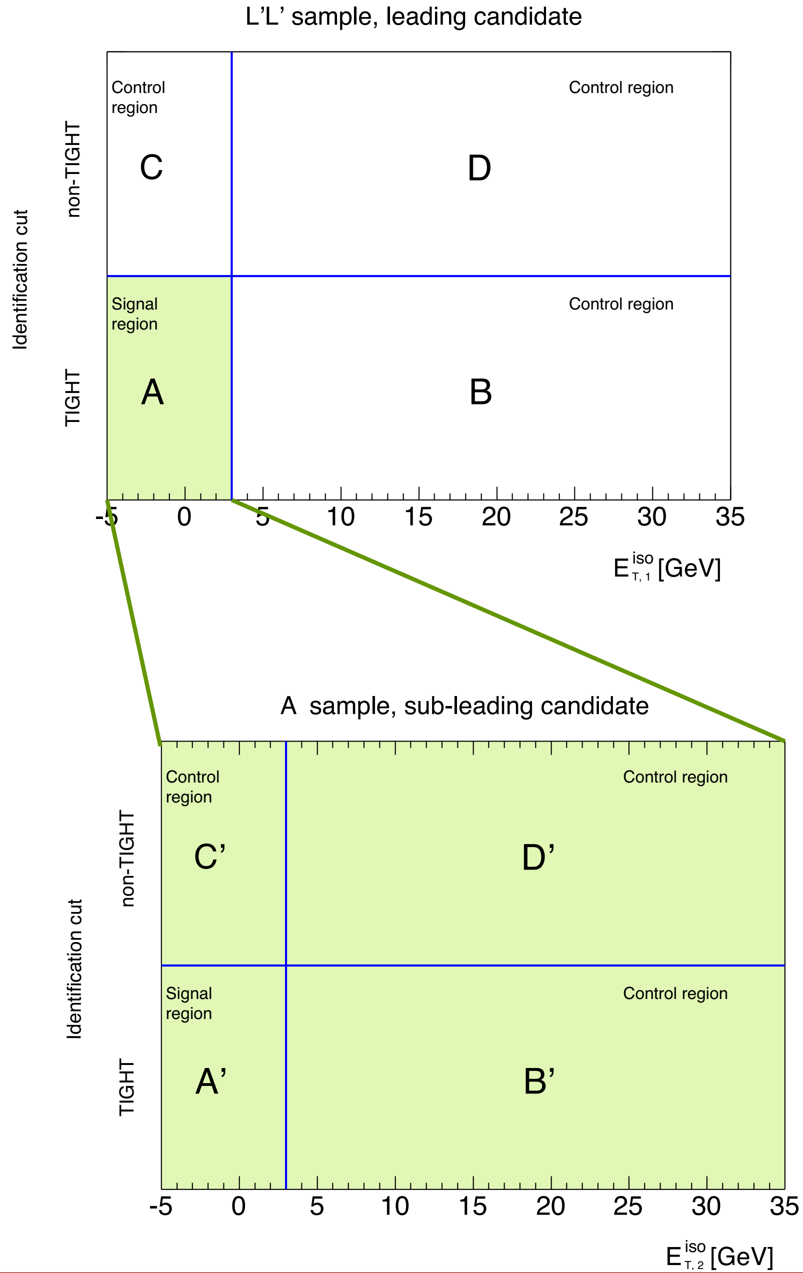




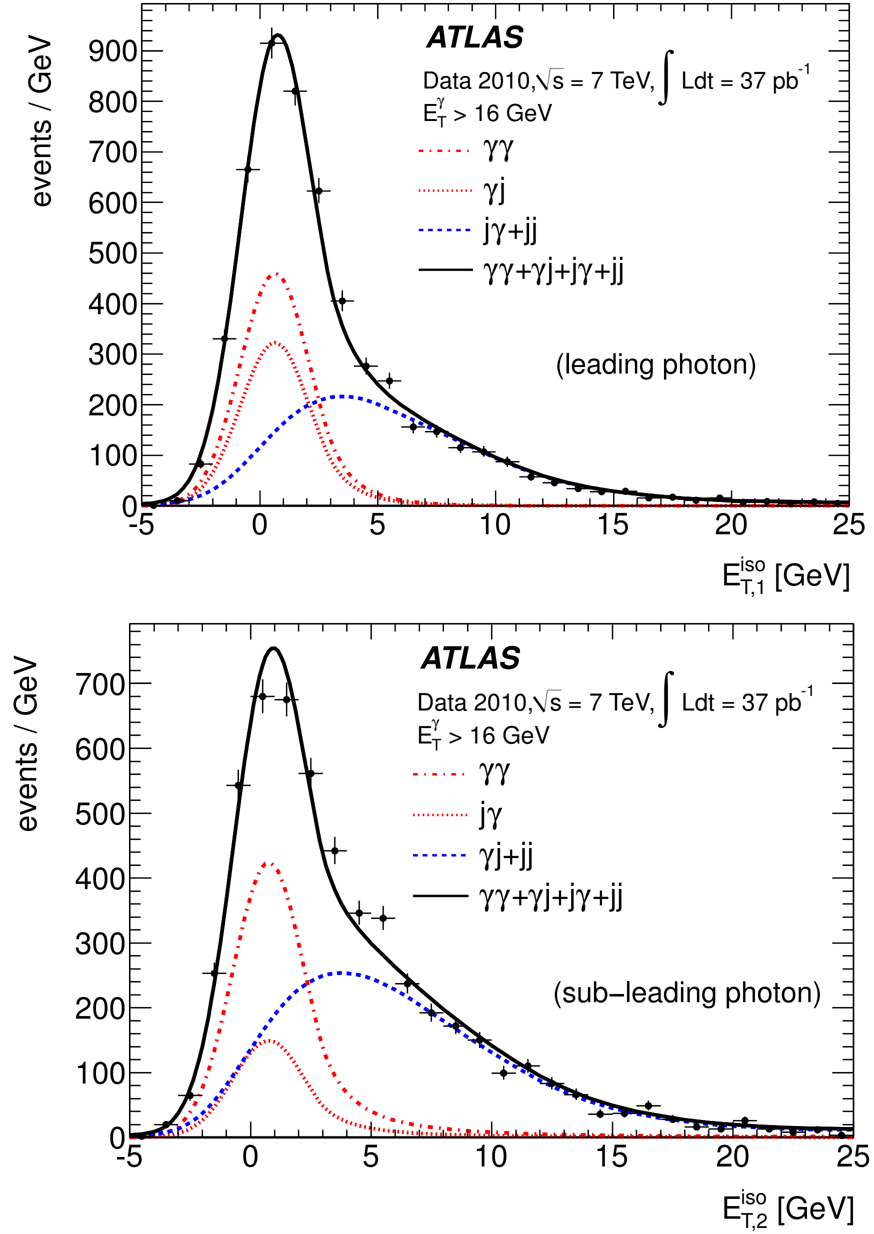


Background estimates

2x2D-sidebands



2D isolation template fit



Background estimates

Matrix Method

$$\begin{pmatrix} \mathrm{PP} \\ \mathrm{PF} \\ \mathrm{FP} \\ \mathrm{FF} \end{pmatrix} = \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1(1-\epsilon_2) & \epsilon_1(1-f_2) & f_1(1-\epsilon_2) & f_1(1-f_2) \\ (1-\epsilon_1)\epsilon_2 & (1-\epsilon_1)f_2 & (1-f_1)\epsilon_2 & (1-f_1)f_2 \\ (1-\epsilon_1)(1-\epsilon_2) & (1-\epsilon_1)(1-f_2) & (1-f_1)(1-\epsilon_2) & (1-f_1)(1-f_2) \end{pmatrix} \begin{pmatrix} W_{\gamma\gamma} \\ W_{\gamma j} \\ W_{j\gamma} \\ W_{jj} \end{pmatrix}$$

Passes or Fails isolation cut

ε_i = probability for a γ to pass isolation cut (data-driven)

f_i = probability for a jet to pass isolation cut (data-driven)

Event weights

accounting for the correlation of the isolation energy of the 2 γ candidates

Do we need an additional free parameter?

- One might be tempted to use a more complex function to fit the data
  - ✓ If a"more complex" function $f_b(x; \{p_b\})$ embeds the simpler one $f_a(x; \{p_a\})$ (e.g. there exist a choice of $\{p_b\}$ such that $f_b(x; \{p_b\})$ = one $f_a(x; \{p_a\})$, then the function with more degrees of freedom will have a smaller χ^2
- The problem is to decide whether f_b is more motivated than f_a
  - ✓ Eyes are not good judges…
  - ✓ **F-test → the function *F* has Fisher distribution *f(F; p*$_1$*, p*$_2$*)* if the added parameter is not improving the model**

$$F = \frac{\dfrac{\sum_i (y_i - f_1(x_i))^2 - \sum_i (y_i - f_2(x_i))^2}{p_2 - p_1}}{\dfrac{\sum_i (y_i - f_2(x_i))^2}{n - p_2}}$$

One rejects the hypothesis that the additional parameter if useless if **P < 0.05**, where P is the probability of observing a *F* value at least as extreme as the one in data, if drawn from a Fisher distribution with the same degrees of freedom

Statistical procedure

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

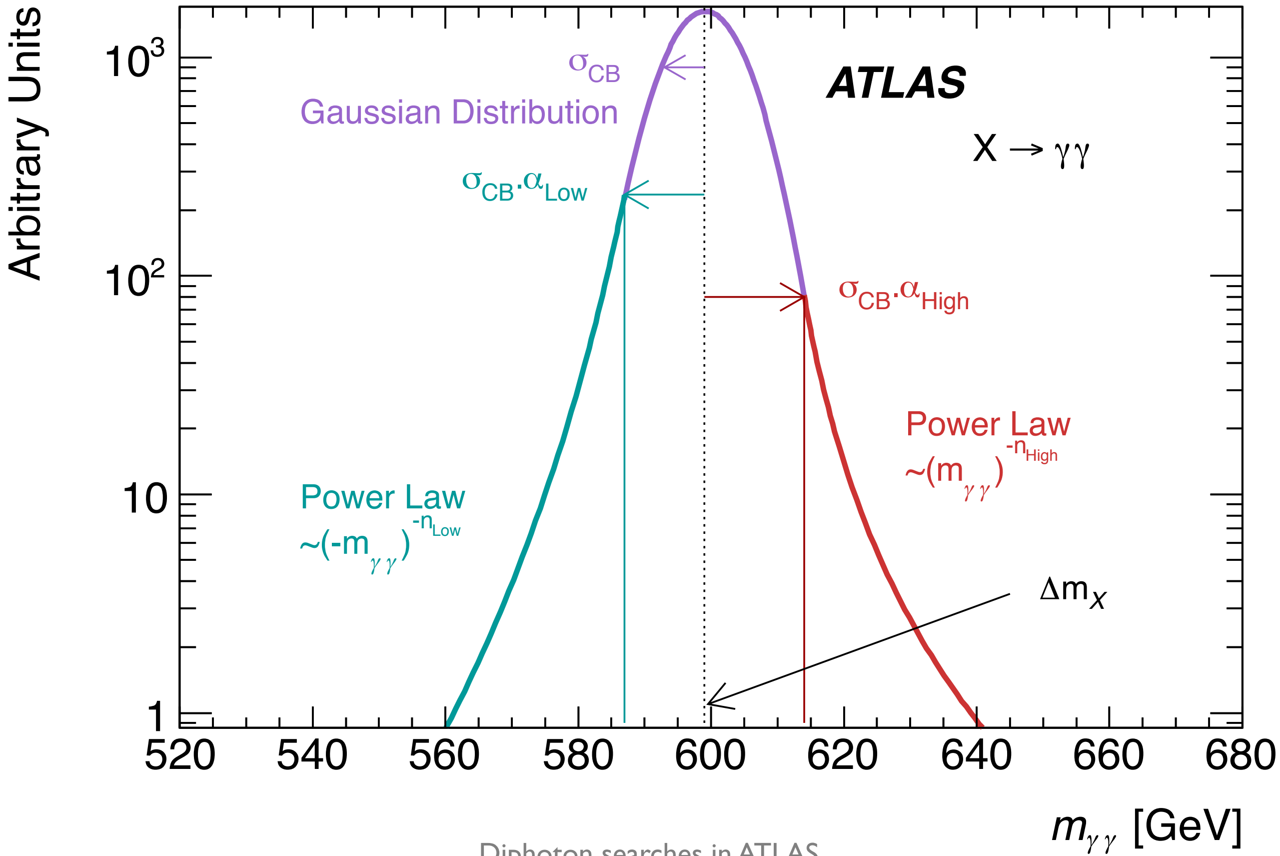
$$q_0(m_X, \alpha) = -2 \log \frac{L(0, m_X, \alpha, \hat{\hat{\nu}})}{L(\hat{\sigma}, m_X, \alpha, \hat{\nu})}$$

$$p_{\text{global}} \approx E[\phi(A_u)] = p_0 + e^{-u/2}(N_1 + \sqrt{u} N_2)$$

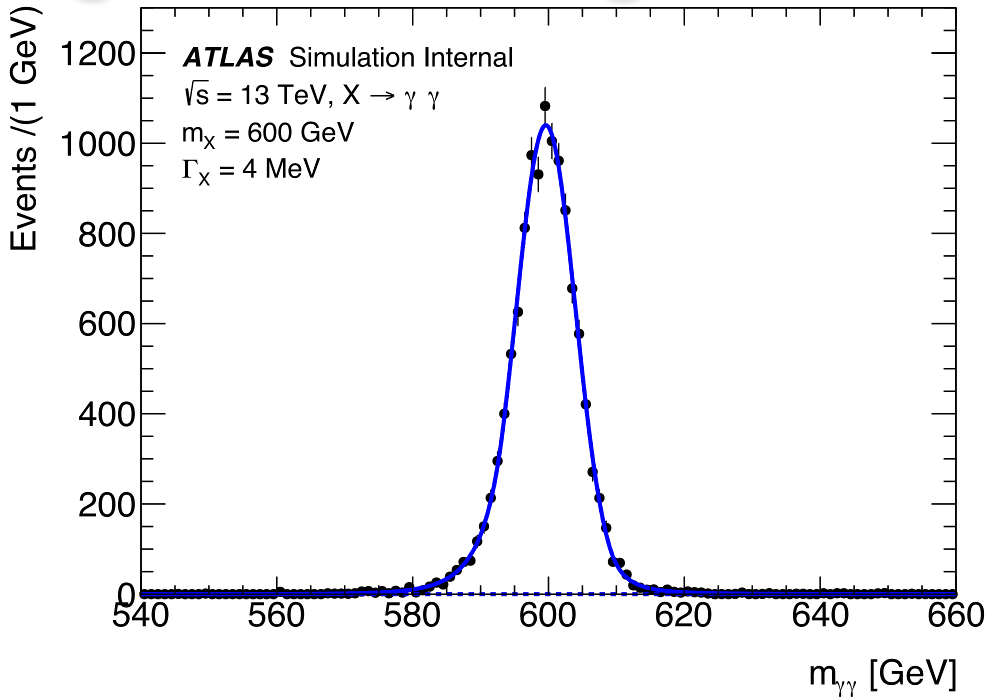
Double-Sided Crystal Ball function

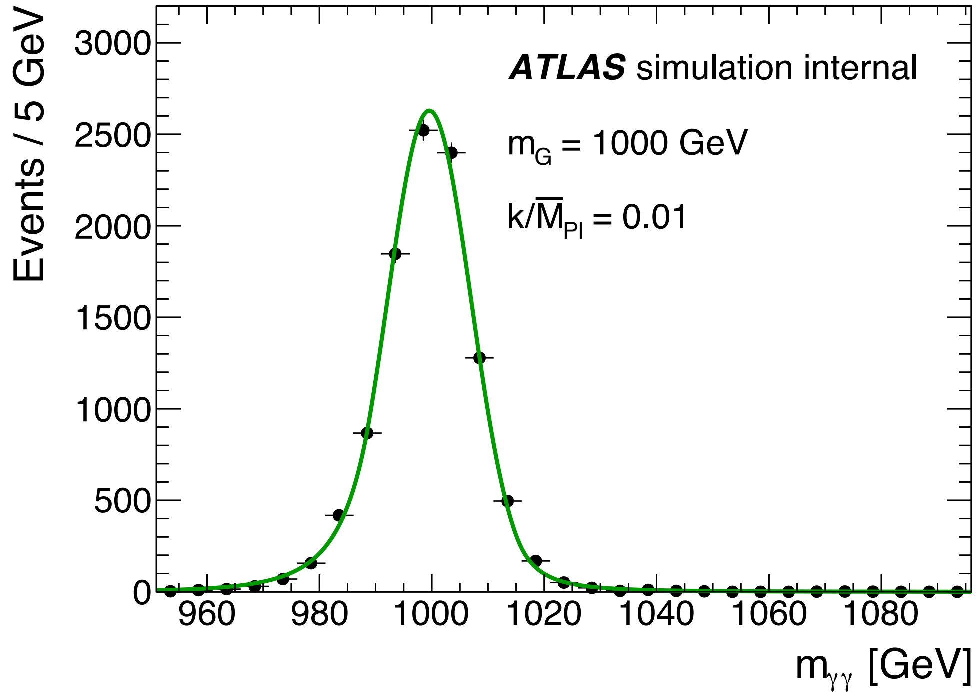
$$N \cdot \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{\text{low}} \geq t \geq \alpha_{\text{high}} \\ \dfrac{e^{-0.5\alpha_{\text{low}}^2}}{\left[\frac{\alpha_{\text{low}}}{n_{\text{low}}}\left(\frac{n_{\text{low}}}{\alpha_{\text{low}}} - \alpha_{\text{low}} - t\right)\right]^{n_{\text{low}}}} & \text{if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

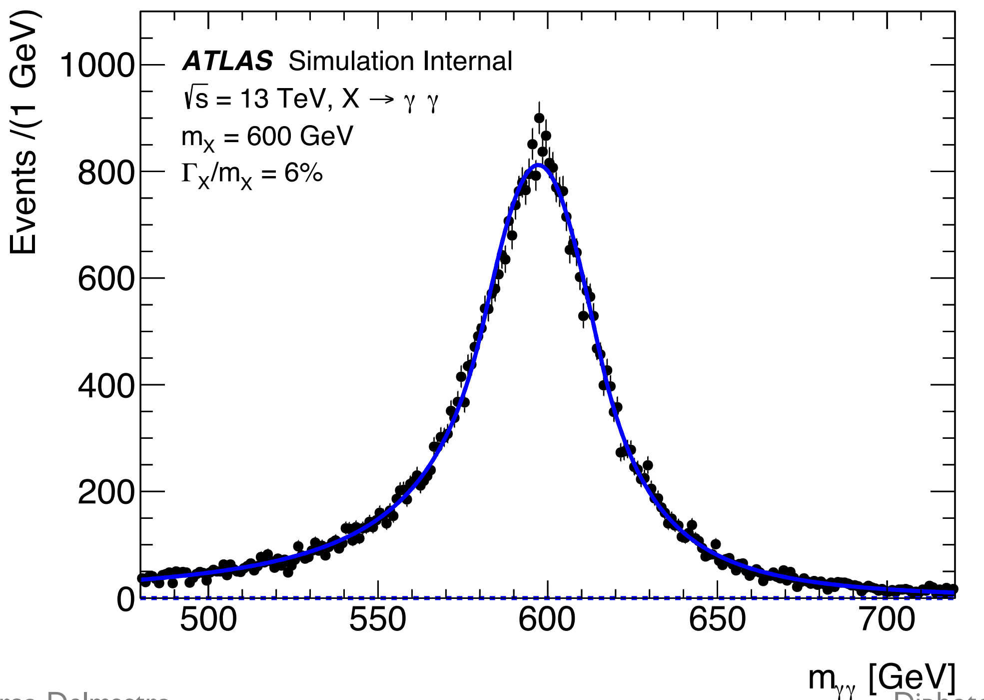
$$t = \Delta m_X / \sigma_{CB}, \Delta m_X = m_X - \mu_{CB}$$

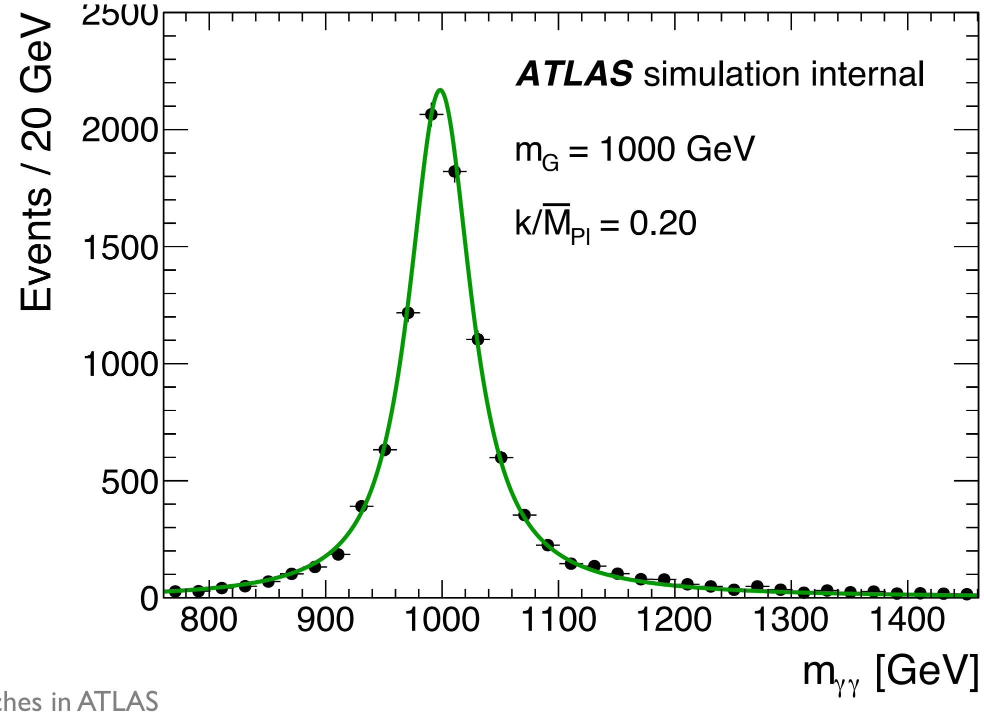


Signal modeling









JVF

- Jet Vertex Fraction

$$\mathrm{JVF}(jet, vtx_j) = \frac{\sum_k p_{\mathrm{T}}(trk_k^{jet}, vtx_j)}{\sum_n \sum_l p_{\mathrm{T}}(trk_l^{jet}, vtx_n)}$$