Searches for new physics with di-boson signatures with the ATLAS detector

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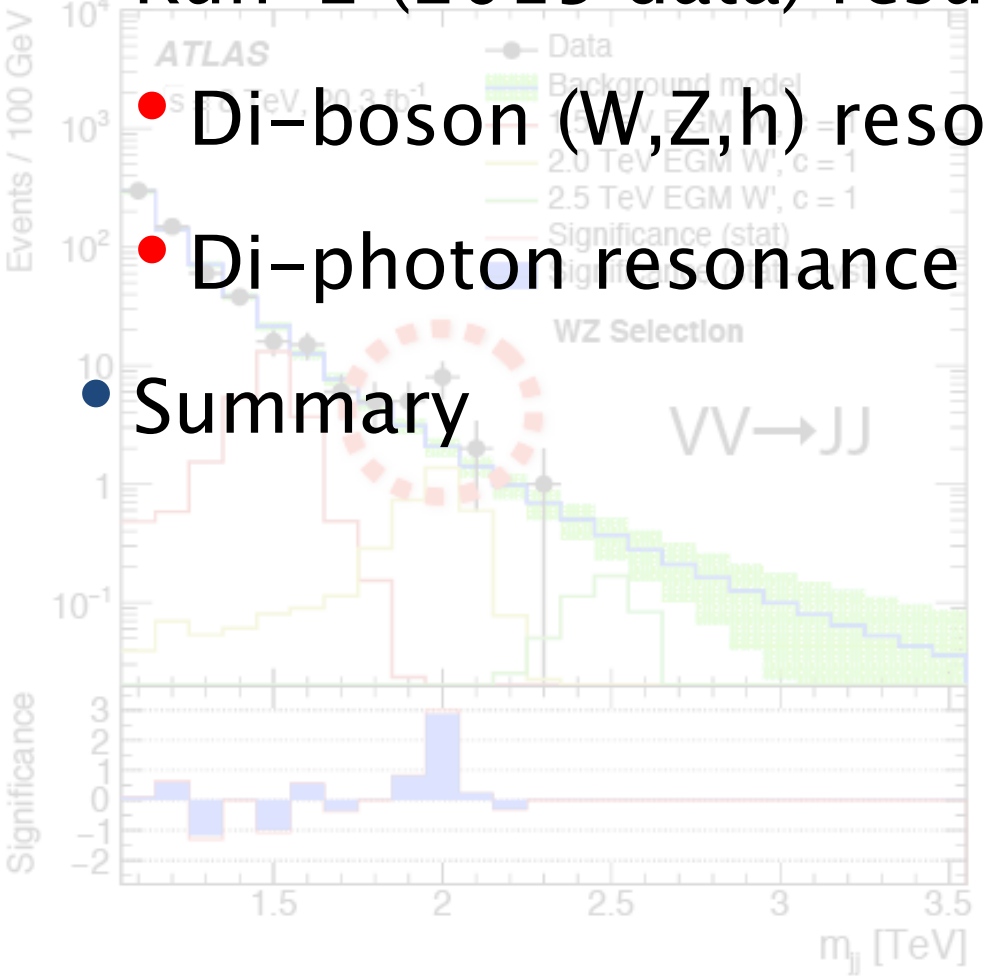
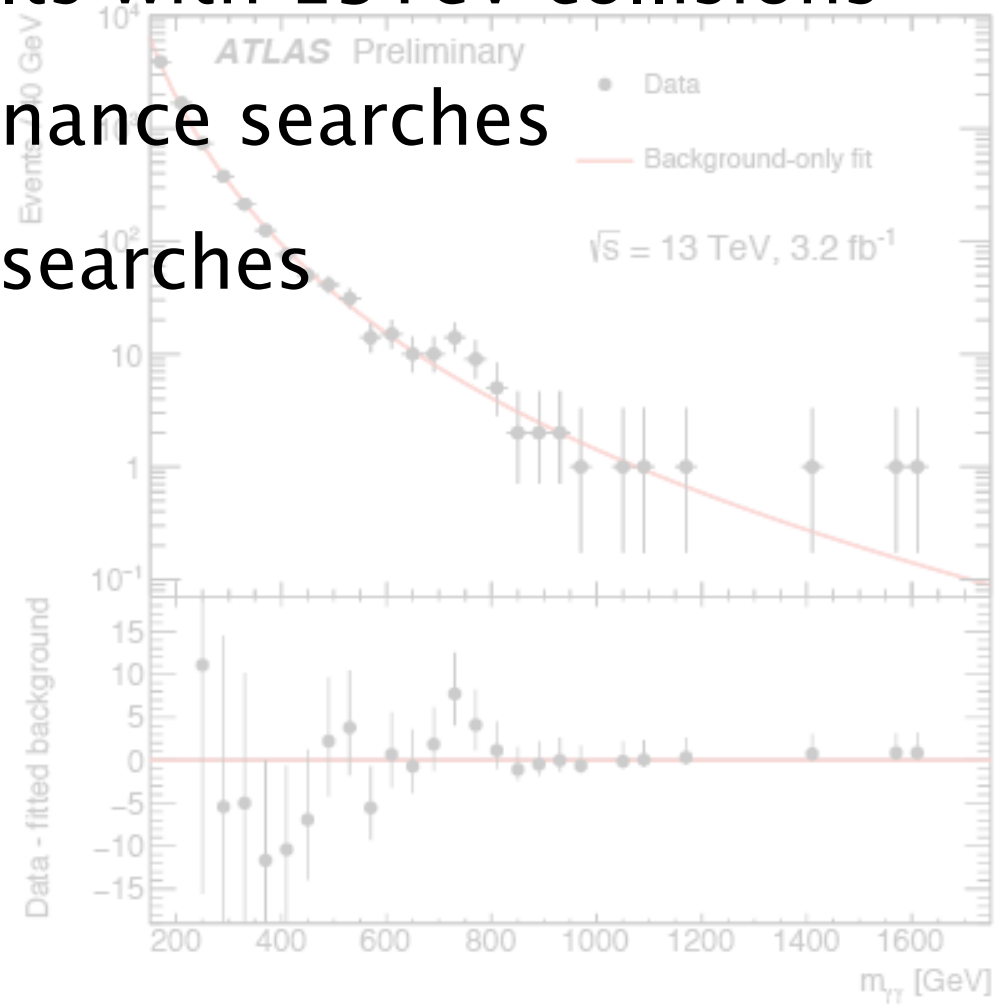
2016 Spring KPS Pioneer Symposium Program

"New resonance searches at the LHC and impacts on BSM phenomenology"

Outline

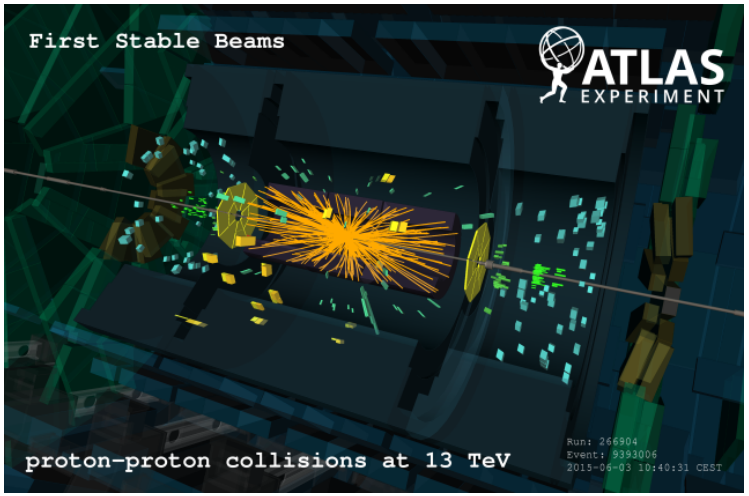
- LHC and ATLAS
- Run-2 (2015 data) results with 13TeV collisions
  - Di-boson (W,Z,h) resonance searches
  - Di-photon resonance searches
- Summary

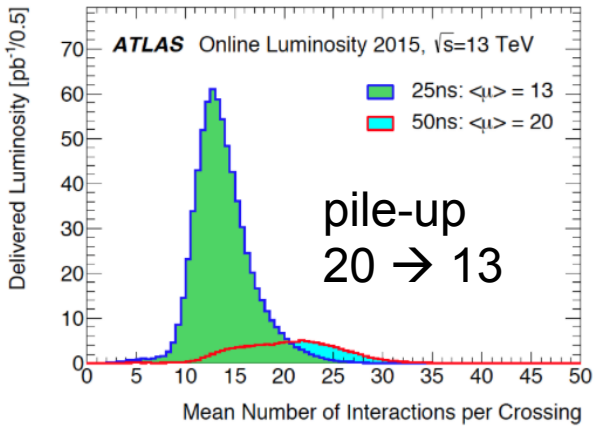


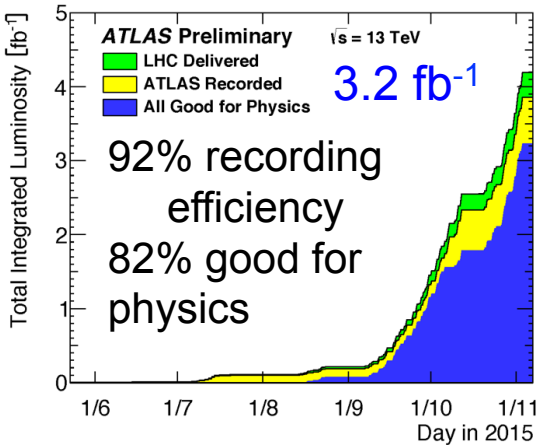


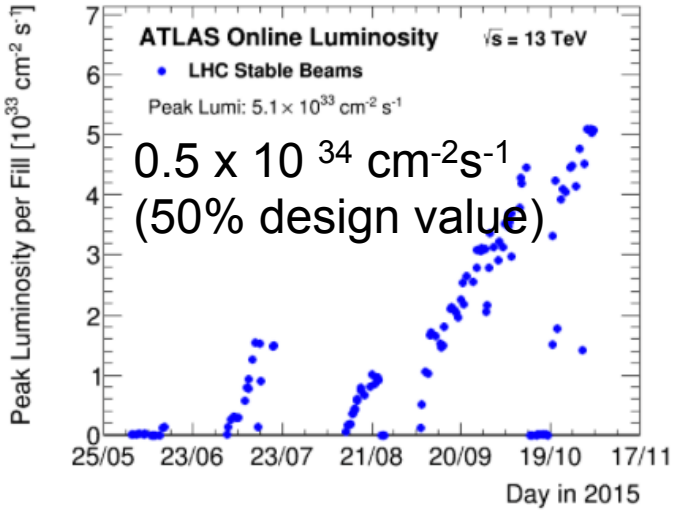
2015 LHC in back on business (Run-2)

13 TeV collisions

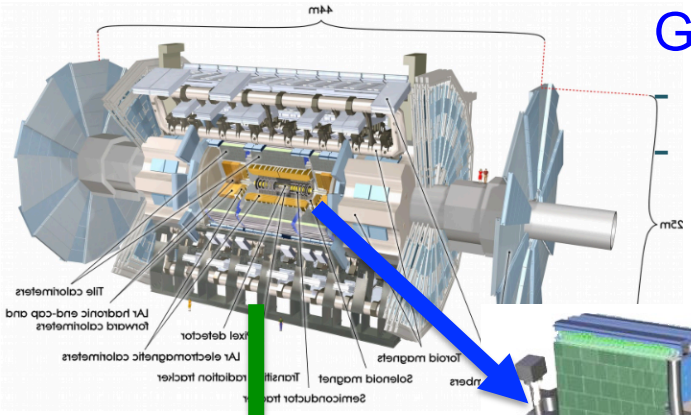






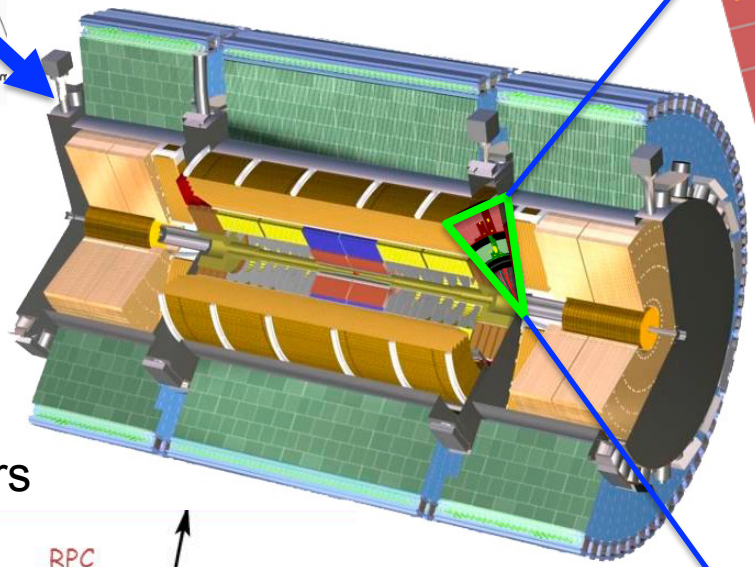


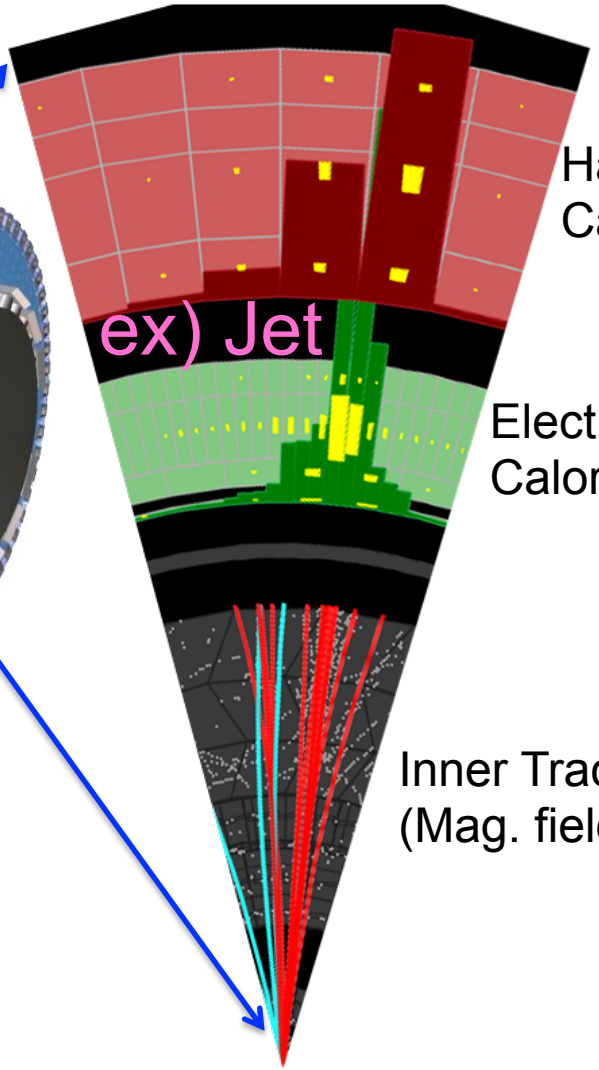
ATLAS detector



General purpose detector

- excellent tracking in central region & muon spectrometer
- good energy measurements with fine segmented calorimeters



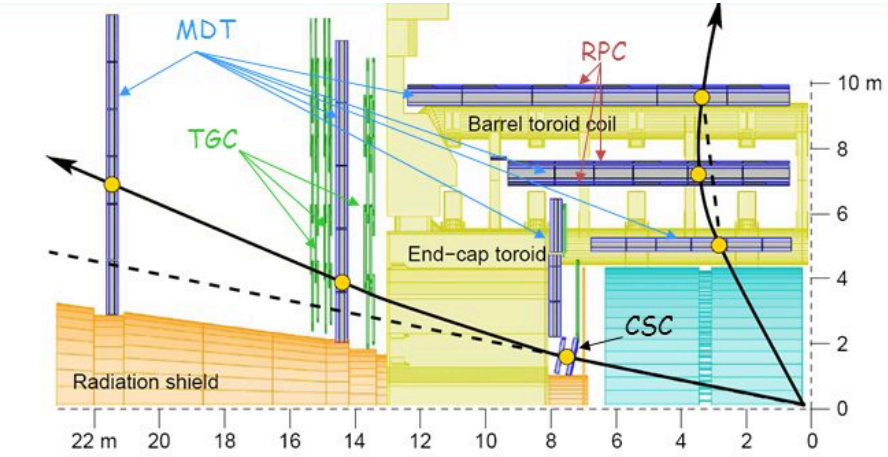


Hadron Calorimeter

Electromagnetic Calorimeter

Inner Tracker (Mag. field = 2T)

Muon Spectrometers

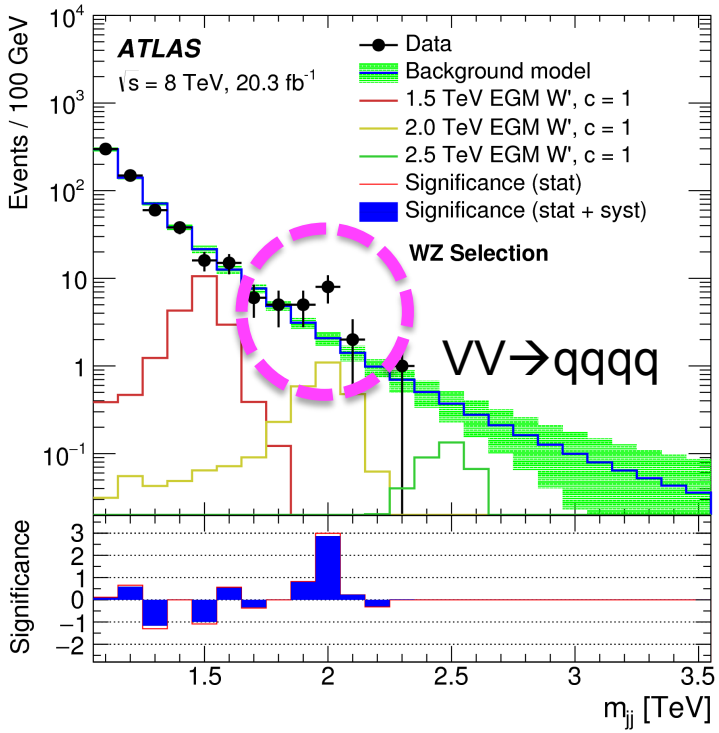


PART 1
Di-boson resonance searches

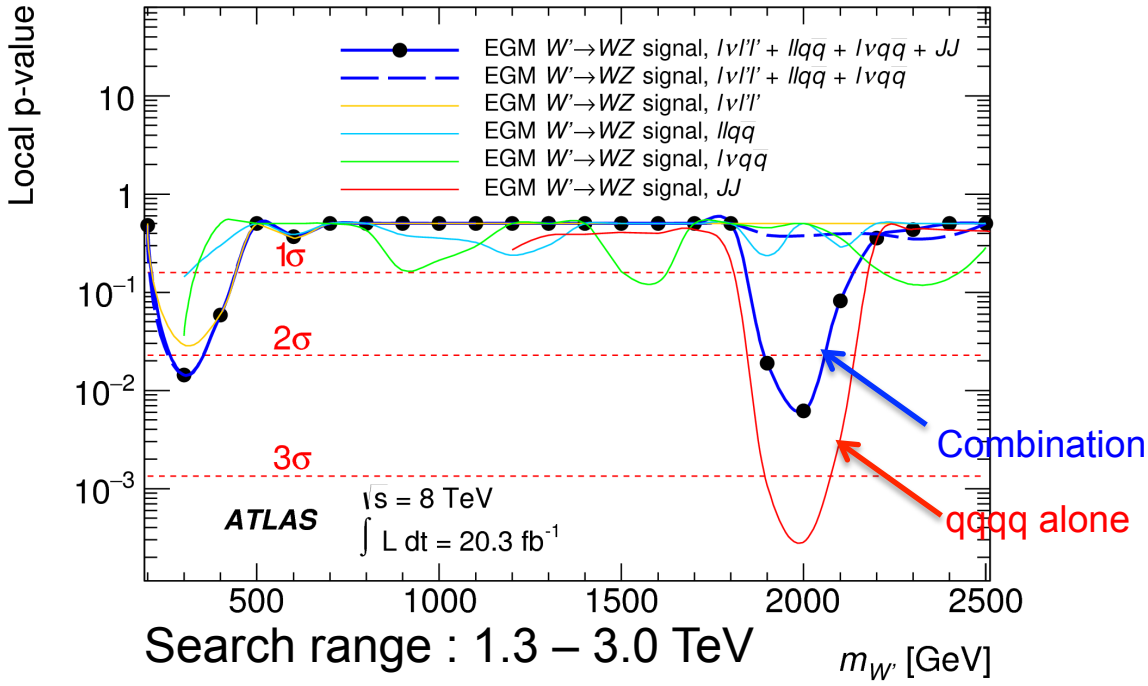
New Physics? Stat fluctuation? 8TeV Run-1

- Searches made in several final states
  - VV→qqqq (JHEP12(2015)55)
  - WV→lvqq (EPJC75(2015)209)
  - ZV→llqq (EPJC75(2015)209)
  - WZ→lvll (PLB737(2014)223)

Non ignorable excess observed in qqqq channel
Local (global) significant : 3.4σ (2.5σ) at 2TeV
Local significance reduces to 2.5σ in combination



Combination (PLB755(2016)285)



Search range : 1.3 – 3.0 TeV

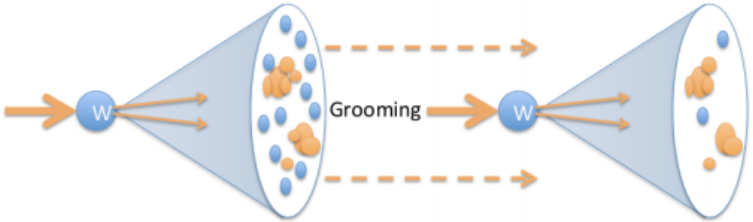
need to confirm this in Run-2

Boosted boson tagging

- Heavy 'object' decays into diboson:
  results in boosted bosons, large BR in hadronic decays

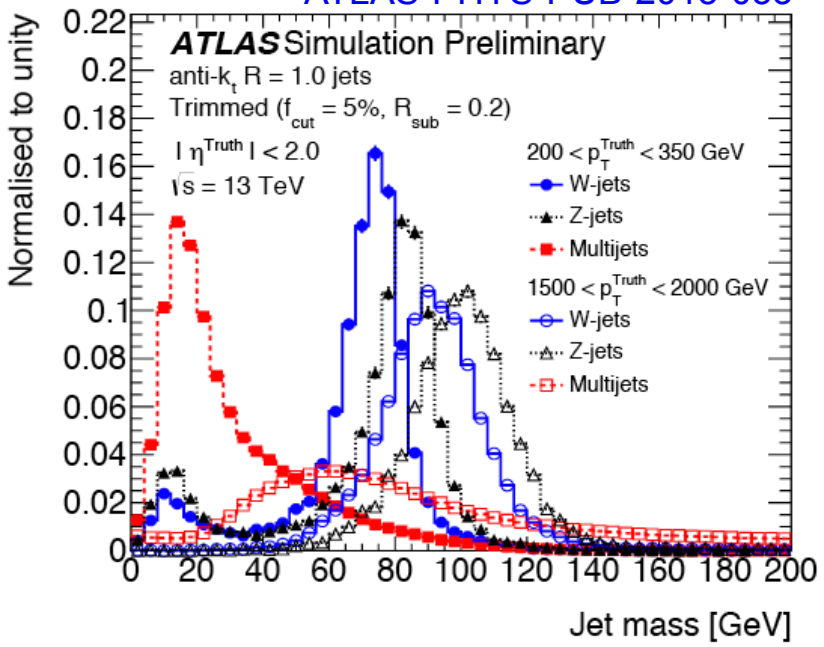
boosted V→qq tagging became important

boosted W/Z → qq = J



- removing soft component
- identifing two sub-jets

ATLAS-PHYS-PUB-2015-033

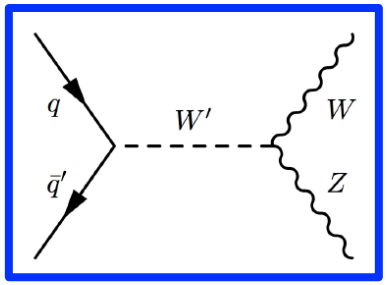


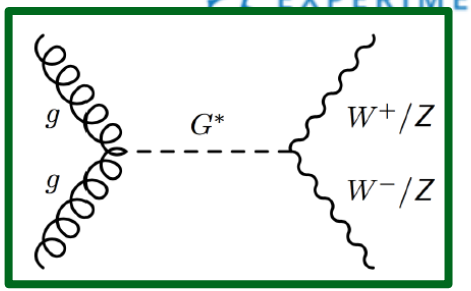
Large radius Jet R = 1.0
Jet mass : ±15 GeV around W/Z mass peak
2-prong likeliness (D_2)

50% efficiency
~50 BG rejection factor (p_T>200GeV)

ATLAS searches in Run-2 (2015)

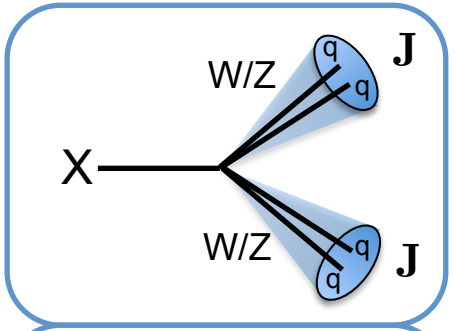
- Theoretical interpretations
  - Heavy Vector Triplet (HVT)
  - Randall-Sundrum Graviton (RSG)





- VV → qqqq (= **JJ**) ATLAS-CONF-2015-073

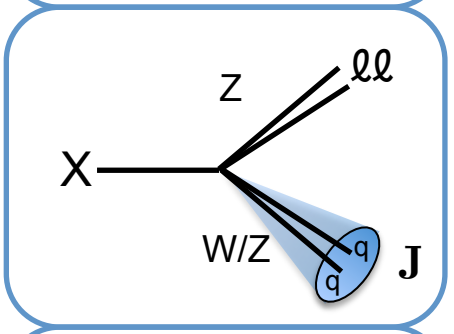
  (full-hadronic)



- VV → ℓνqq / ℓℓqq (=ℓν **J** / ℓℓ **J**, ℓℓ+2jets)

  (1-lepton, 2-lepton)

  ATLAS-CONF-2015-075
  ATLAS-CONF-2015-071
  ATLAS-CONF-2016-016

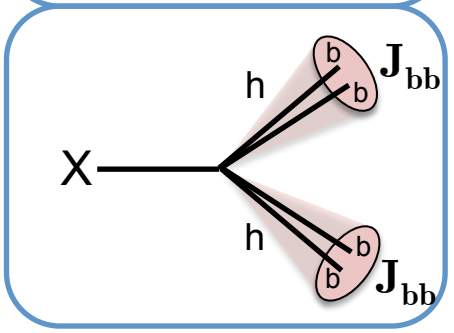


- VV → νvqq (νν **J**) ATLAS-CONF-2015-068

  (0-lepton)

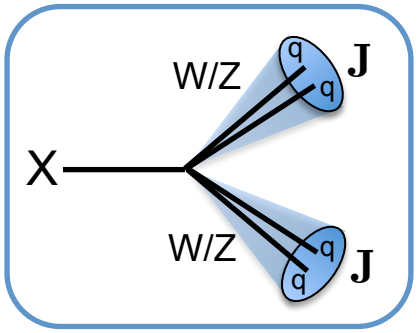
- hh → bbbb ($\mathbf{J}_{bb}\mathbf{J}_{bb}$) ATLAS-CONF-2016-014

  (full-hadronic with b-tagging)



DiBoson→ JJ(all hadronic) (13TeV)

- Based on the Run-1 substructure analysis
- V→qq tagging (D_2, mJ, N_{tracks}) cut applied for strong BG suppression
- BG fit with empirical function
- Main uncertainties from J energy/mass scale



2 Boson Jets

$p_T^{J1} > 450\,\mathrm{GeV}$

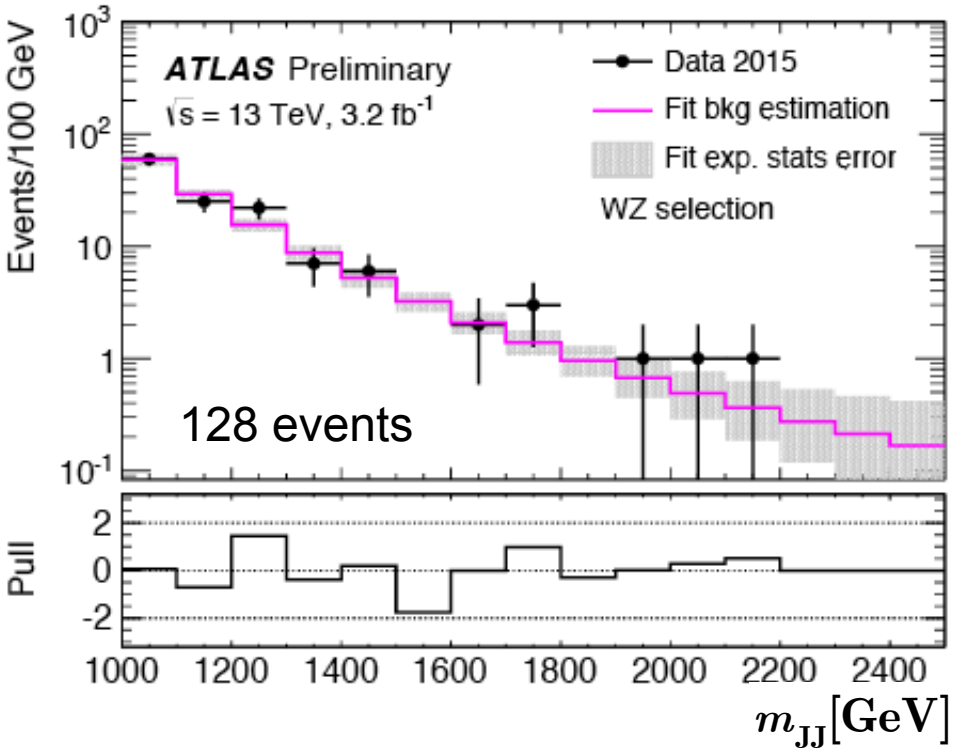
$p_T^{J2} > 200\,\mathrm{GeV}$

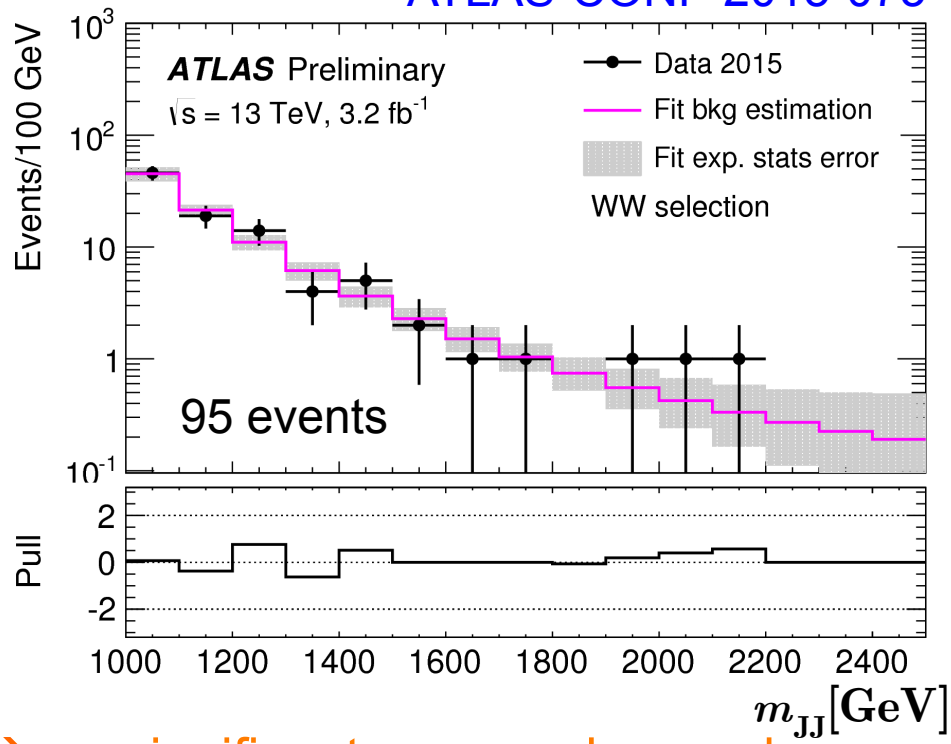
$n_{track} < 30$

$|y_1 - y_2| < 1.2$

p_T symmetry

ATLAS-CONF-2015-073





38 events pass all (WW,ZZ,WZ) selections

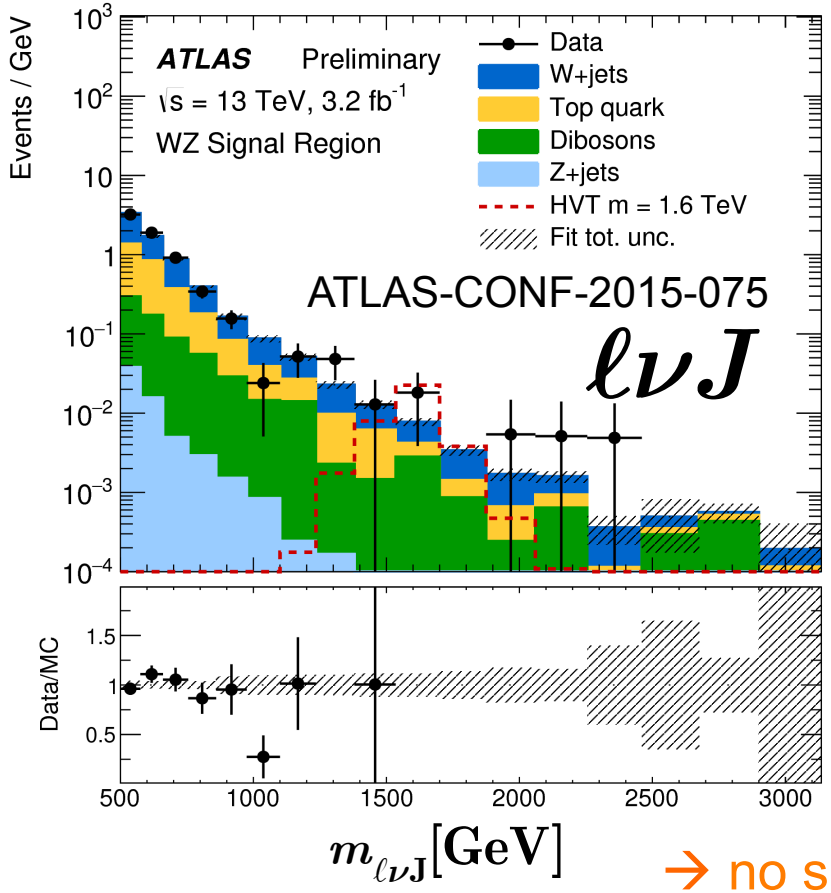
→ no significant excess observed

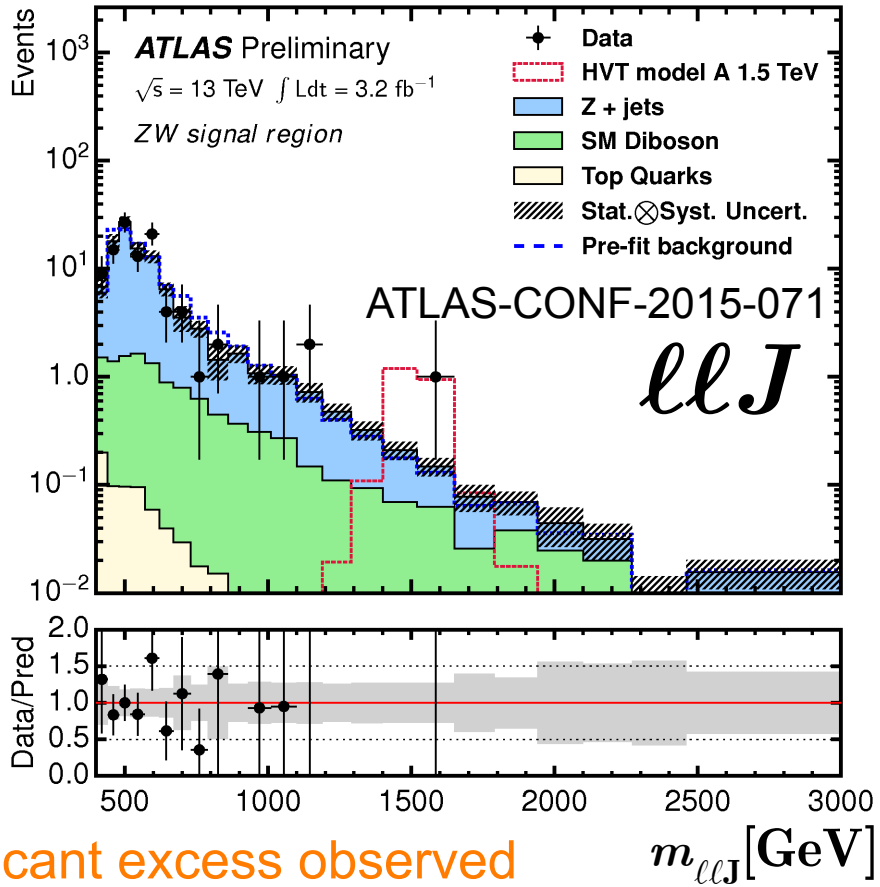
DiBoson→ℓνJ / ℓℓJ

- same analysis cut applied as Run1
- main BG from W/Z+jets, ttbar estimated in control region and extrapolated to signal region
- look for high-mass range (700-3000GeV)

W→lν + boson jet
- $p_T^V > 0.4\, m_{l\nu J}$
- $E_T^{miss} > 100$ GeV
- b-jet veto

Z→ll + boson jet
- $p_T^V > 0.4\, m_{llJ}$
- $m_{ll} = m_Z$



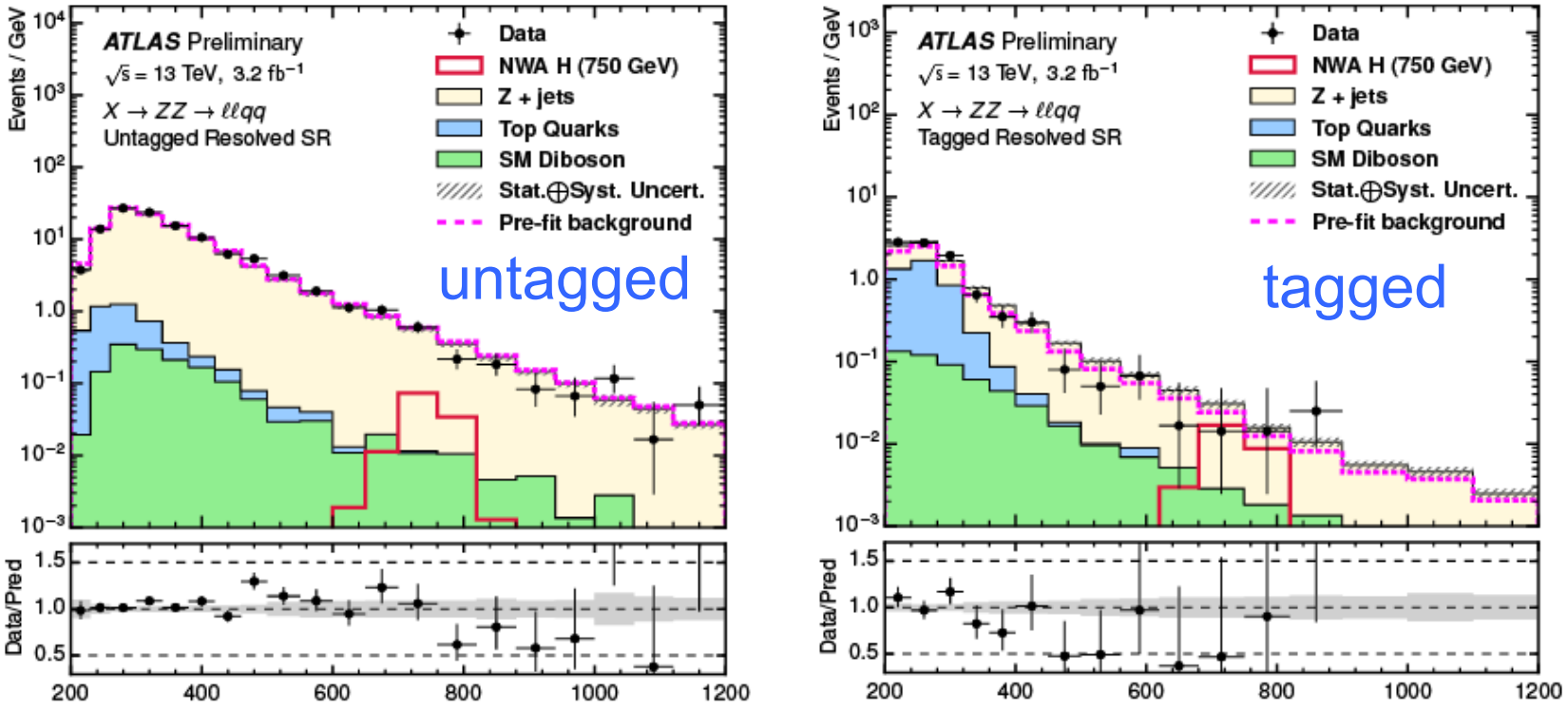


→ no significant excess observed

DiBoson→ℓνjj / ℓℓjj

new

- Aim also for intermediate mass range (300–1000 GeV: heavy Higgs, bulk RS graviton)
- Lower mass → resolved 2-jets
- Categorize based on b-tag (n_b=2→ tagged, n_b<2→ untagged)
  Z→ bb (21% among qq) can suppress the Z(→ℓℓ)+jets

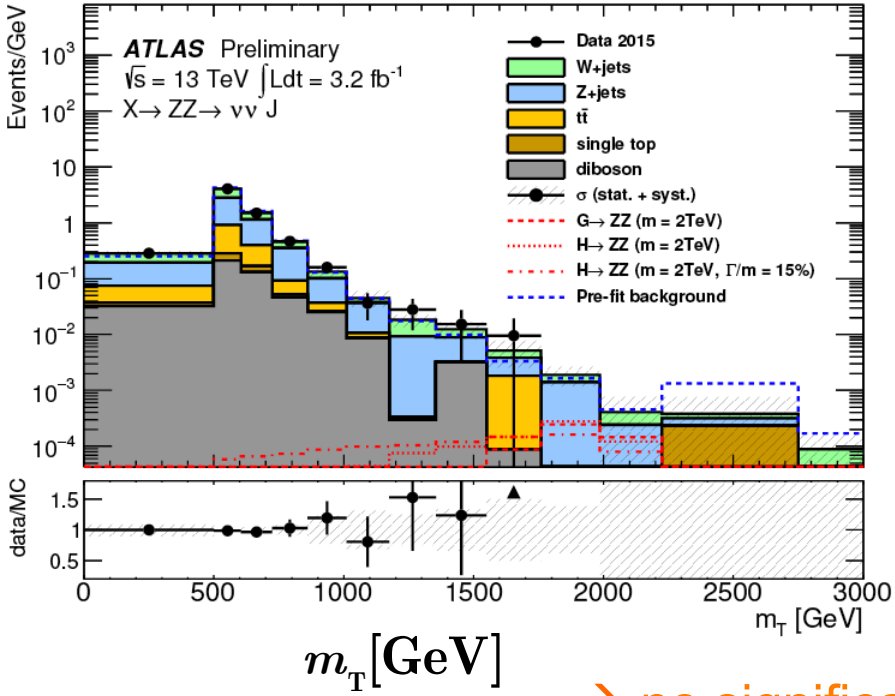


→ no significant excess observed

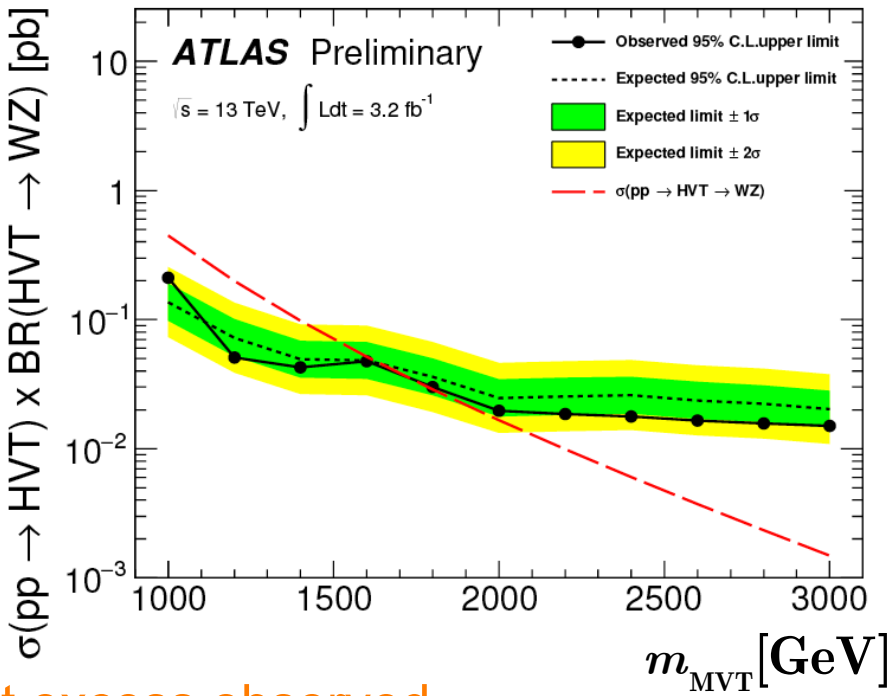
DiBoson→νν J

- Events selected with p_{TJ}>200 GeV, E^{T}_{miss}>250 GeV
- large radius jet tagging
- BG (V+jets, ttbar) estimated in CR
- main uncertainties in large-R Jet energy scale, D_2, MET modeling

ATLAS-CONF-2015-068



95% CL m_{HVT}<1600GeV

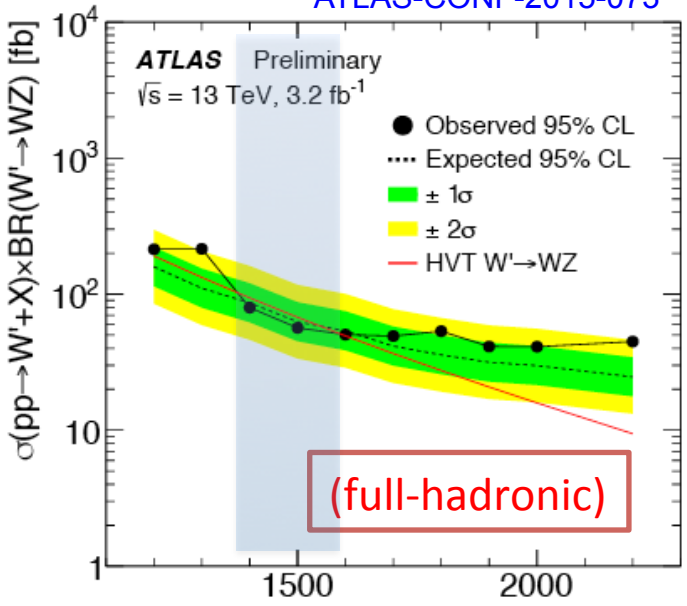


→ no significant excess observed

13TeV Limits summary (HVT→VV)

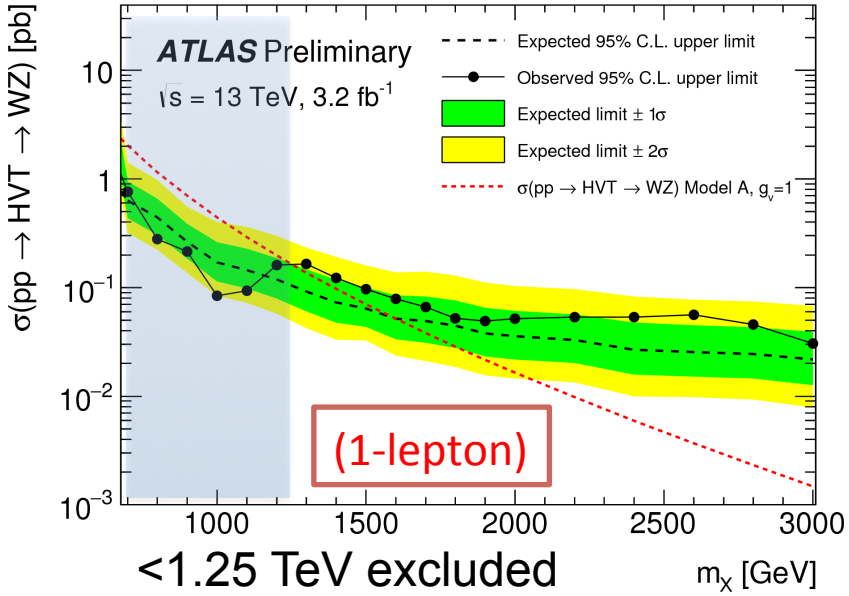
ATLAS EXPERIMENT

ATLAS-CONF-2015-073



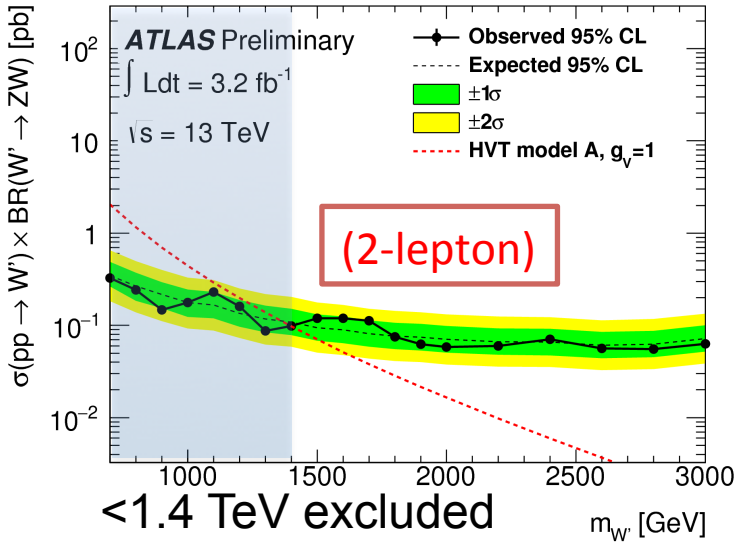
1.36 < m < 1.6 TeV excluded $m_{W'}$ [GeV]

ATLAS-CONF-2015-075



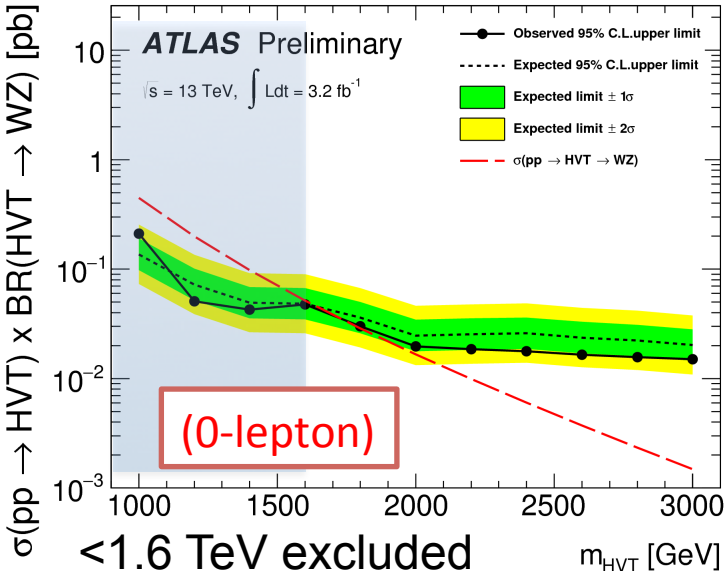
<1.25 TeV excluded

ATLAS-CONF-2015-071



<1.4 TeV excluded

ATLAS-CONF-2015-068

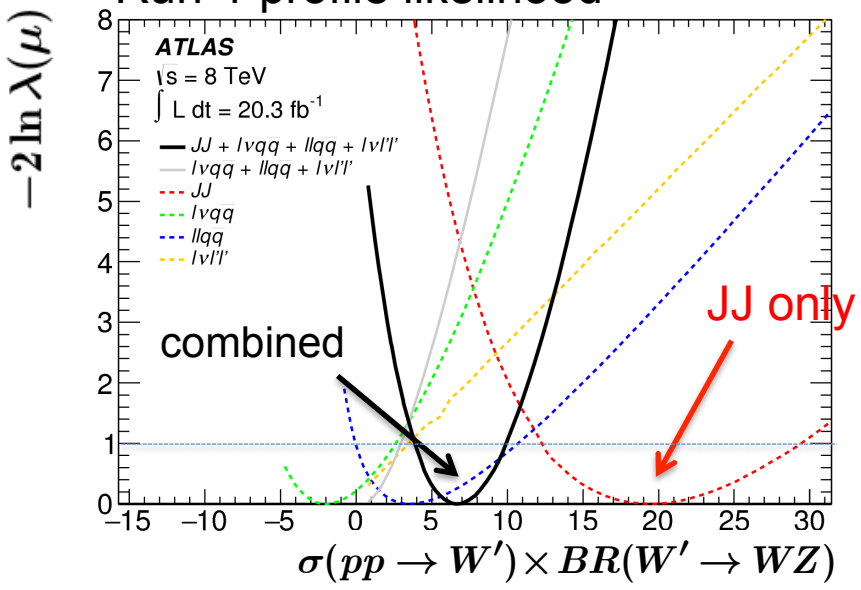


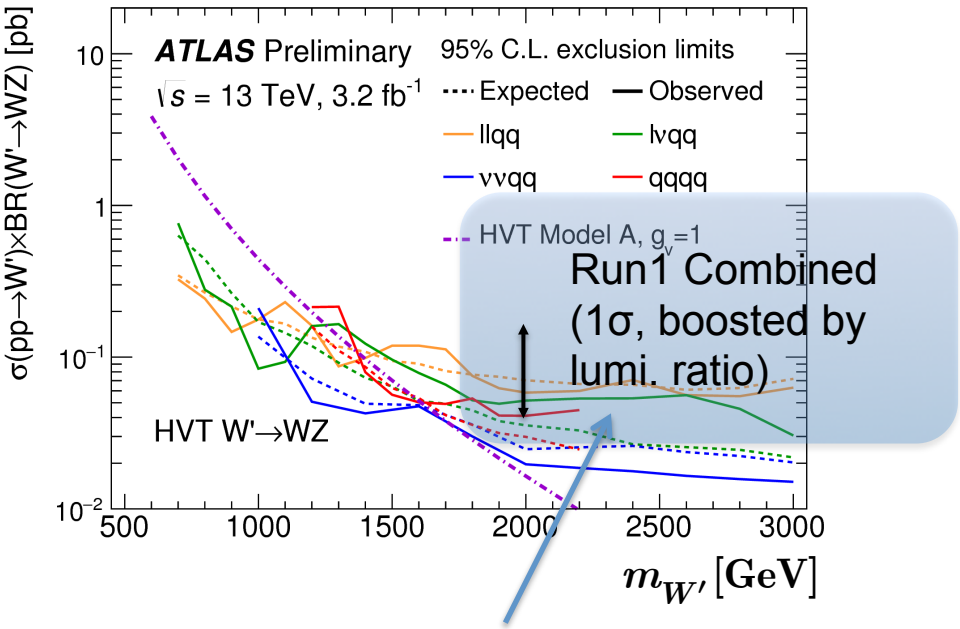
<1.6 TeV excluded

13TeV Limits summary vs. 8TeV

- Important to check the compatibility with Run-1
- Did Run-2 (2015) already contradict with Run-1 excess?

Run-1 profile likelihood





best fit value for combined (JJ) is 7 (20) fb

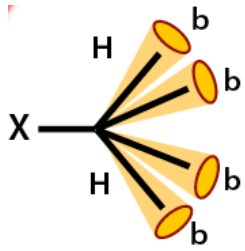
luminosity ratio 13TeV/8TeV is ~7 (15) for qq (gg) process at 2TeV

warning: This is not an ATLAS official statement

Compatibility is marginal

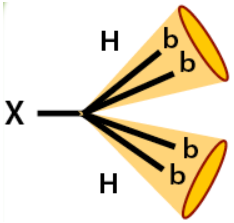
DiHiggs→$J_{bb}J_{bb}$ (or 4b)

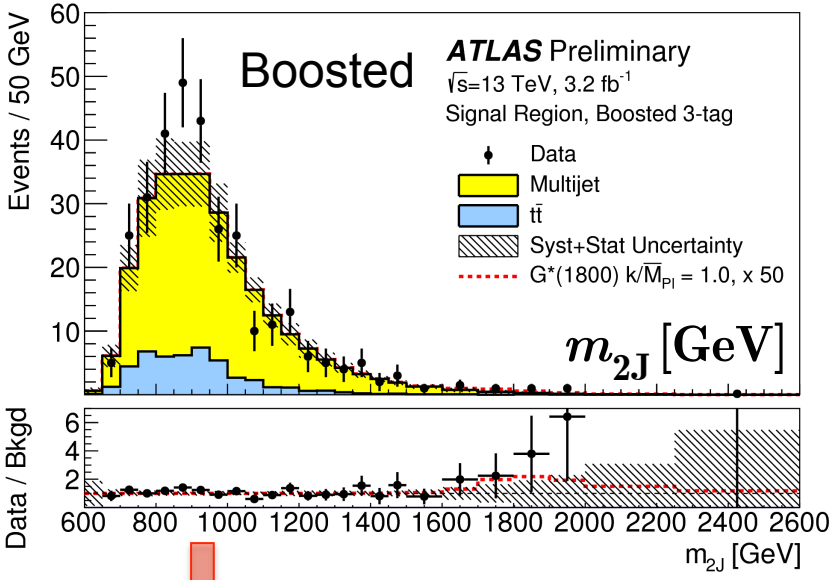
Resolved analysis
(low mass)
4x (R=0.4 b-tagged jets)
m_{bb} = Higgs mass cut

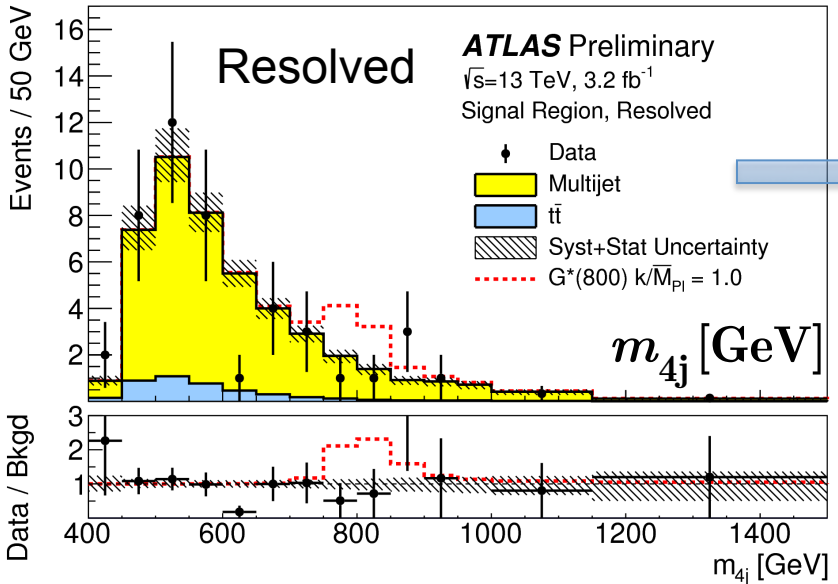


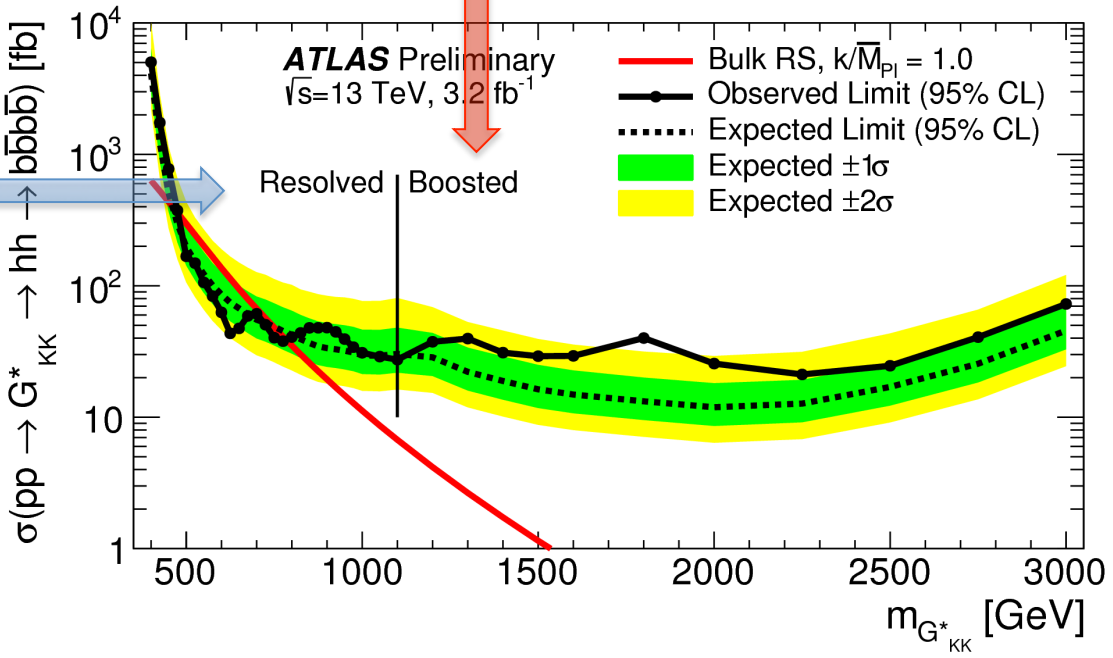
m_{4b} dependent kinematic cut

Boosted analysis
(high mass)
2x (R=1.0 jets p_T>250GeV)
4x (R=0.2 track-jets)
m_J = Higgs mass
3 or 4 b-tag









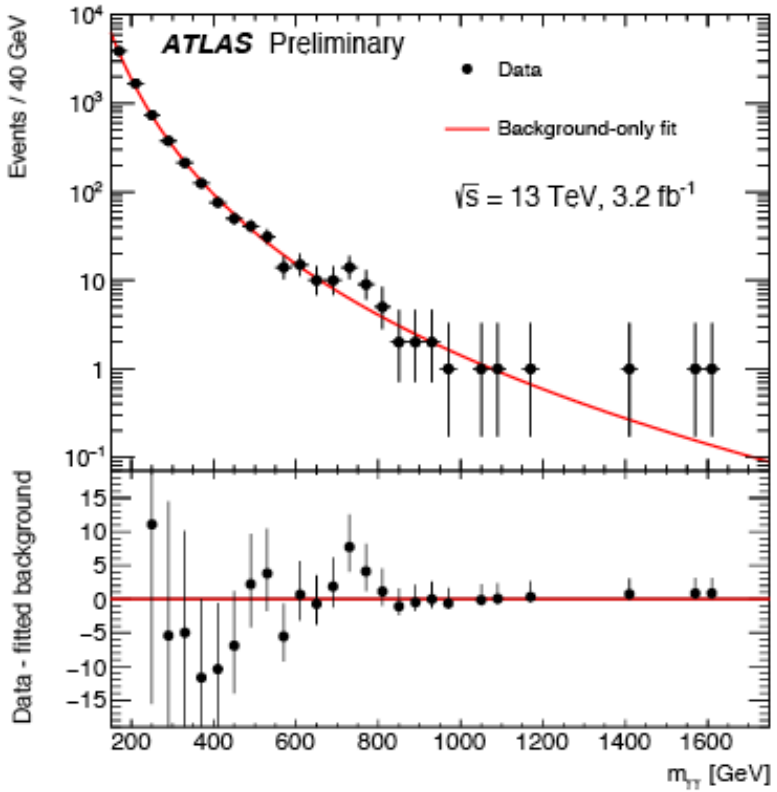
multi-jet background is predominant

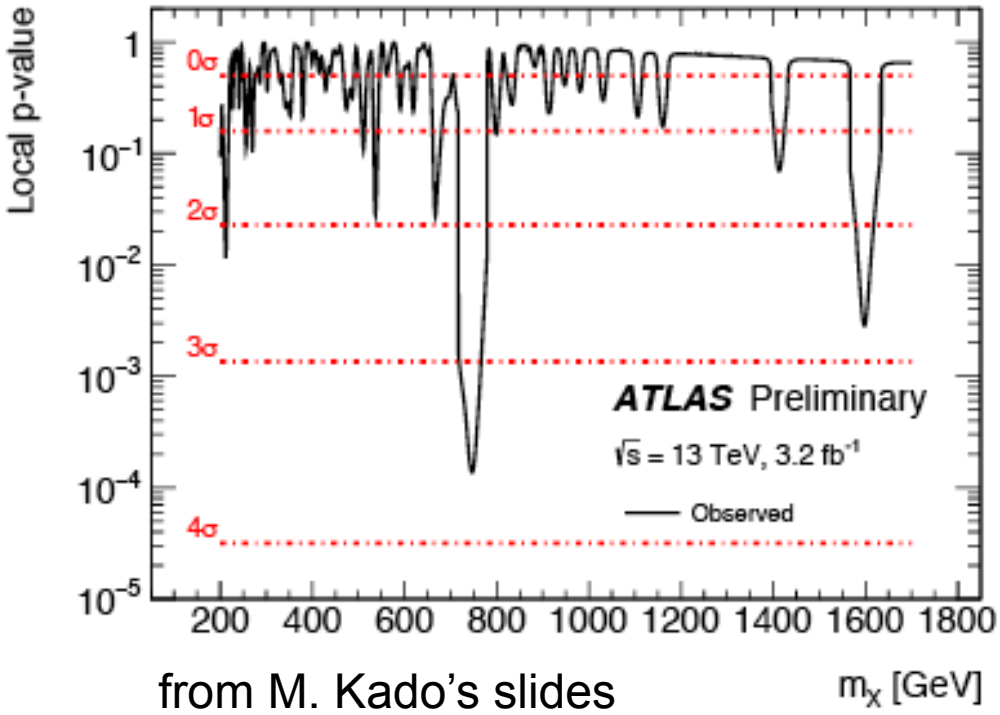
[part 1] Diboson searches summary

- Boosted (and non-boosted) di-boson resonance searches at 13TeV with 3.2/fb performed
- Excesses (2.5-3.4σ) seen at m~2TeV in Run-1 is not confirmed in Run-2
- Compatibility 13 vs. 8 TeV is marginal
- More statistics needed in 2016 data to update the statement

PART 2
Di-photon resonance searches

2015.12 CERN End-of-Year Event





from M. Kado's slides

- Based on **"SM Higgs like"** resonance (spin=0) model
- With NWA hypo., 3.6σ local significance is observed at 750 GeV
  2.0σ global significance, taking a LEE effect (0.2–2.0 TeV)
- With LWA hypo., 3.9σ local (2.3σ global)

Updates since 2015.12

- Introduction of Spin-2 (Graviton) model
- Event selection optimization
- Improvement of signal/background modeling
- Data driven fake background (jj, jγ, $\gamma\gamma$) estimations

Physics models and analysis

Common pre-selections & photon IDs

- $E_T^{\gamma 1} > 40\,\mathrm{GeV}$, $E_T^{\gamma 2} > 30\,\mathrm{GeV}$
- Tight photon ID (shower moments in EM calorimeter) 95% @ E_T~200GeV
- Isolations – Calo cone ΔR=0.4 : $E_T^{\mathrm{iso}} < 0.022\ E_T^{\gamma} + 2.45\,\mathrm{GeV}$
  – Track cone ΔR=0.2 : $p_{\mathrm{T}}^{\mathrm{iso}} < 0.05\ E_{\mathrm{T}}^{\gamma}$

Bench mark models:

new

SPin-0 analysis (extended Higgs sector)

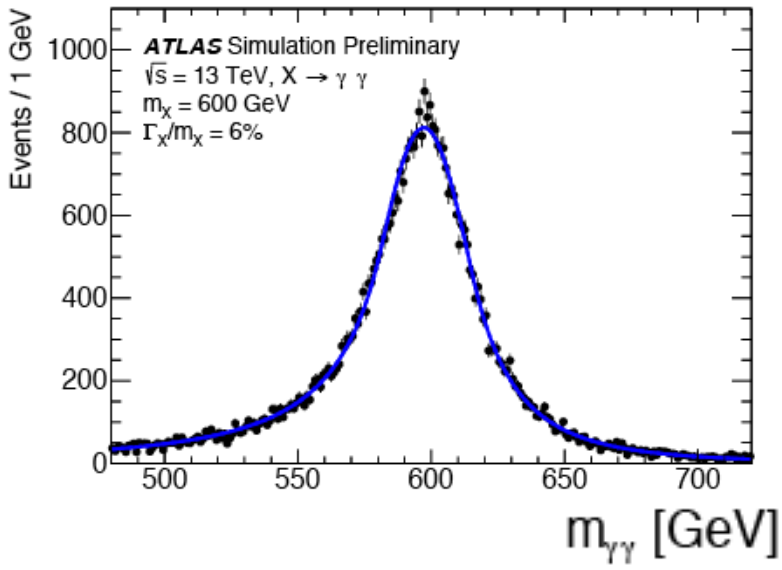
- 2HDM model : H^0 scalar
- emphasis on the barrel region
  $E_T^{\gamma 1} > 0.4\,m_{\gamma\gamma}$, $E_T^{\gamma 2} > 0.3\,m_{\gamma\gamma}$
- search region
  - m_X=[200,2000] GeV
  - Γ_X/m_X=[0–10] %

SPin-2 analysis (Randall-Sundrum graviton)

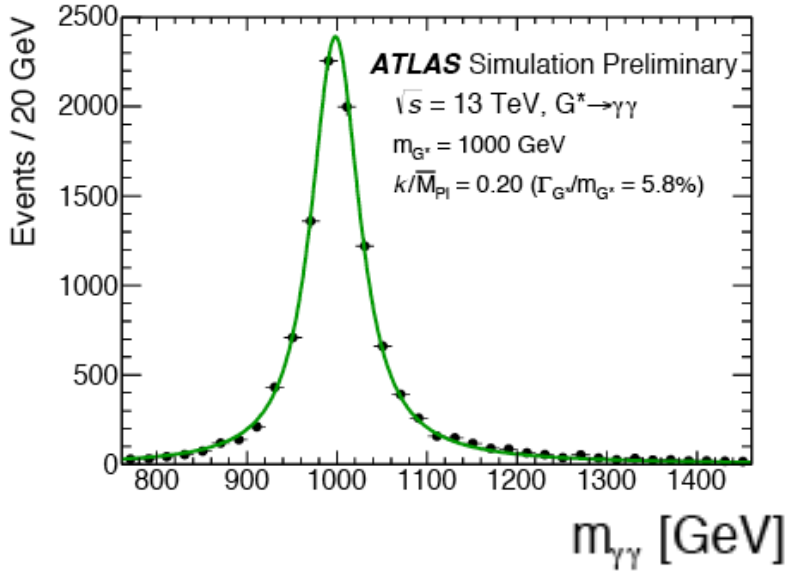
- KK-graviton states in TeV scale
- retain acceptance in forward region looser selection
  $E_T^{\gamma 1}$, $E_T^{\gamma 2} > 55\,\mathrm{GeV}$
- search region
  - m_X=[500,3000] GeV
  - κ/M_{PL}: = [0.01,0.3]
    (Γ_{G^*}/m_{G^*}=[0.014, 11]%)

Signal modeling for two scenarios

SPin-0 analysis



SPin-2 analysis



Heavy Higgs like model

- Narrow-width approx. (Γ_X=4 MeV)
- Large-width approx. (Γ_X/m_X <10%)
- Detector resolution modeling
  Double-sided Crystal ball function
  (DSCB: Gaussian + Power-law tail)
  convoluted with line shape

RS-graviton like model

- Pythia Graviton MC
  Narrow-width approx. (κ/M_{PL}=0.01)
  Wide-width approx. (κ/M_{PL}<0.3)
- Detector response (DSCB) convoluted with line shape

Background modeling for two scenarios

SPin-0 analysis

Optimized for the middle range where there are enough data events

- using a smooth functional form, fully data-driven to model the total background (sidebands)

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

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

- k=0 (lowest D.O.F) is selected
- validated with MC, data

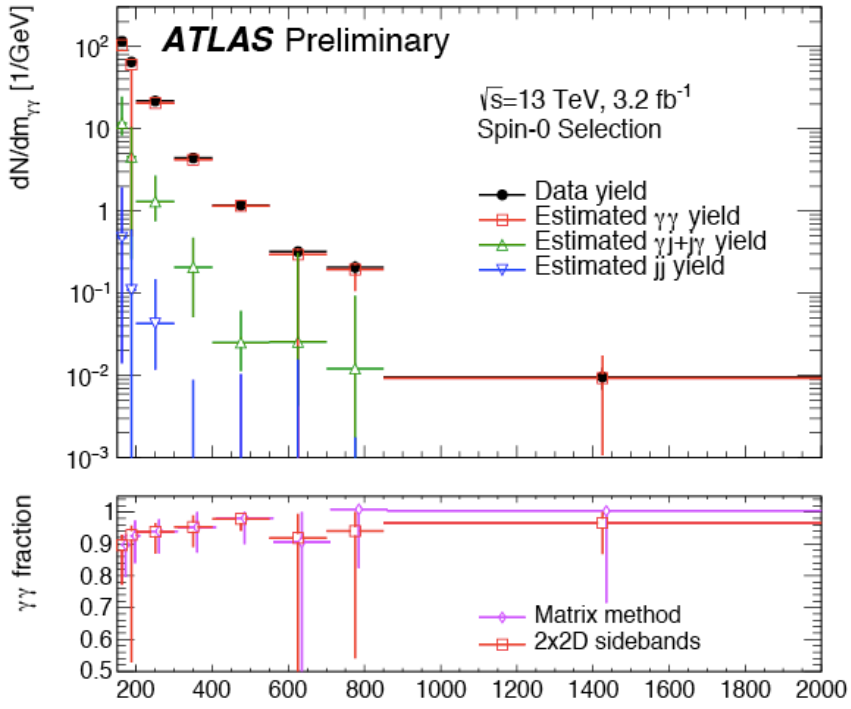
SPin-2 analysis

- Optimized at searching for high mass range (not enough events)
- Diphoton (irreducible) : MC
  - DIPHOX NLO shape/XS
  - Sherpa event level
- γj, jγ, jj (reducible) : data
  - control region : inverting tight shower shape criteria

Background composition

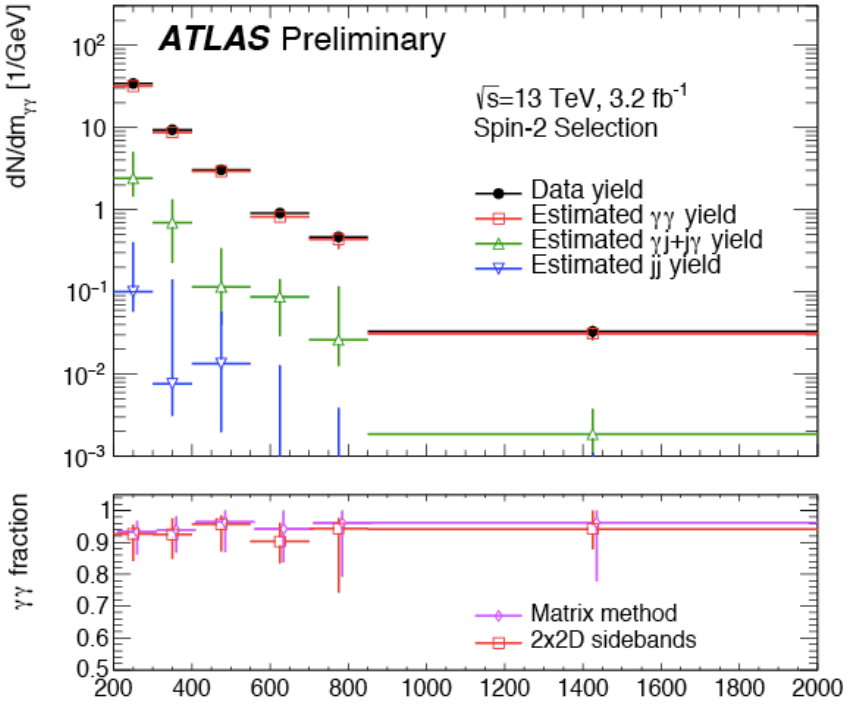
- Predominantly constituted by di-photon events
- Quantitative understanding needed for both analyses
- Compositions ($\gamma\gamma, \gamma j, jj$) estimated with control regions
- Good agreement btw. data and the prediction

SPin-0 analysis



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

SPin-2 analysis

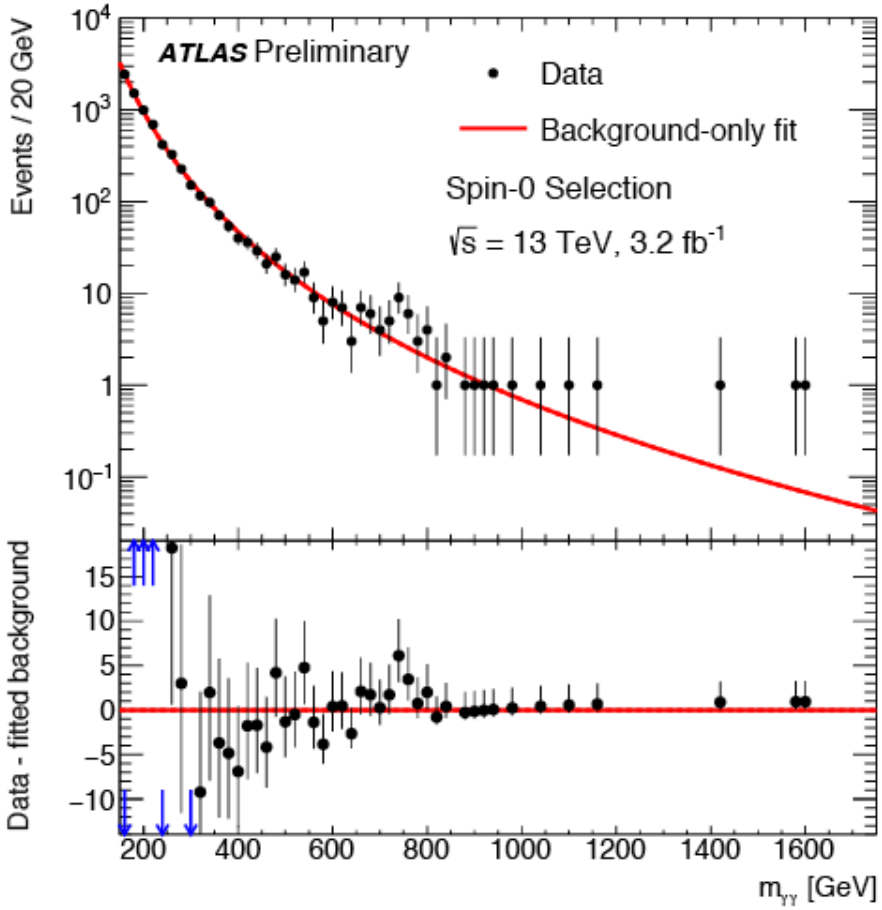


$P_{\gamma\gamma} = 94^{+3}_{-7}\,\%$

Diphoton Results

SPin-0 analysis

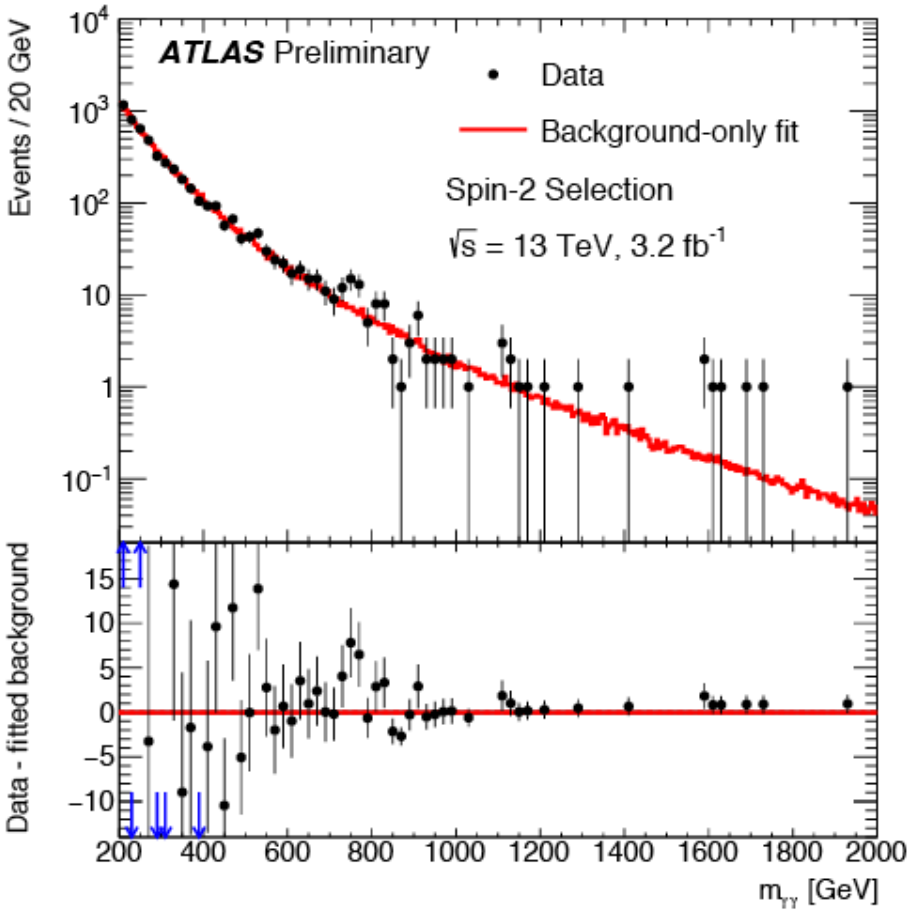
background-only fit



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

SPin-2 analysis

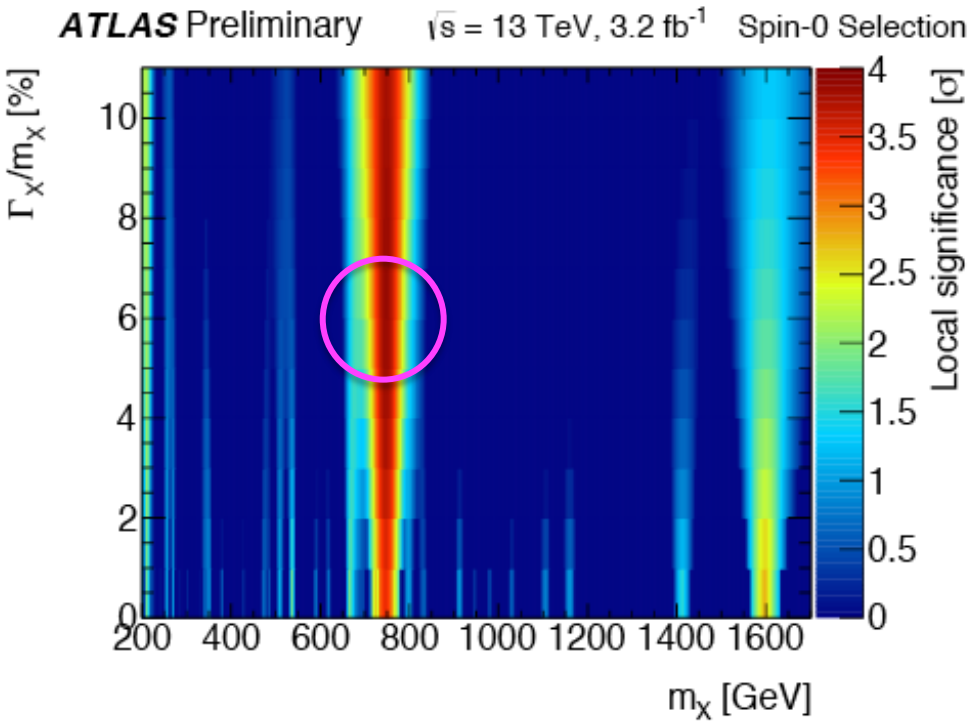
background-only fit



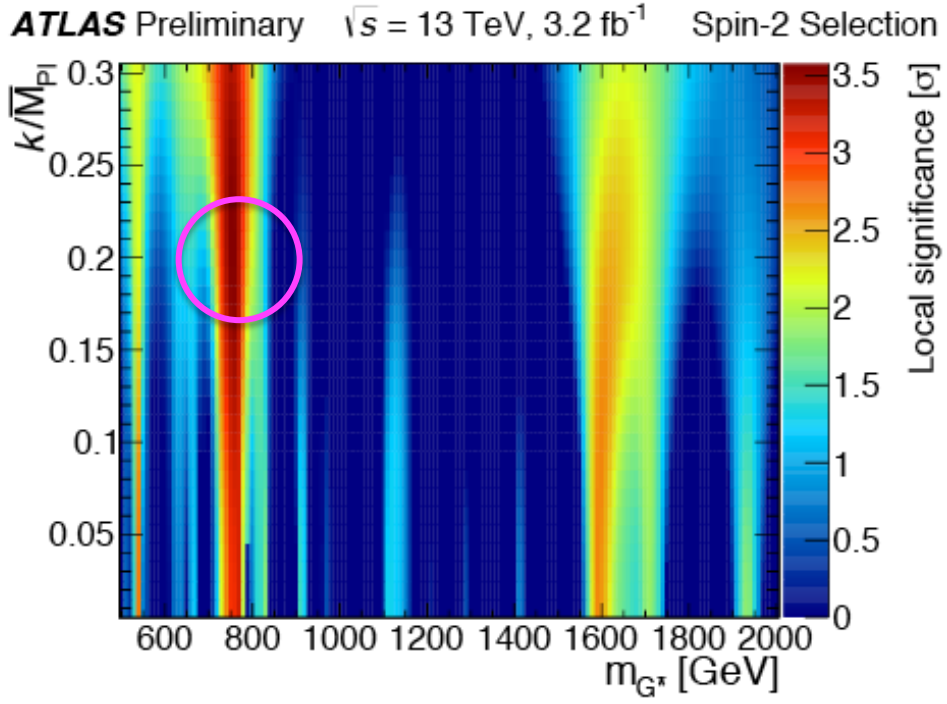
5066 events ($m_{\gamma\gamma}$ > 200 GeV)

Significance

SPin-0 analysis



SPin-2 analysis



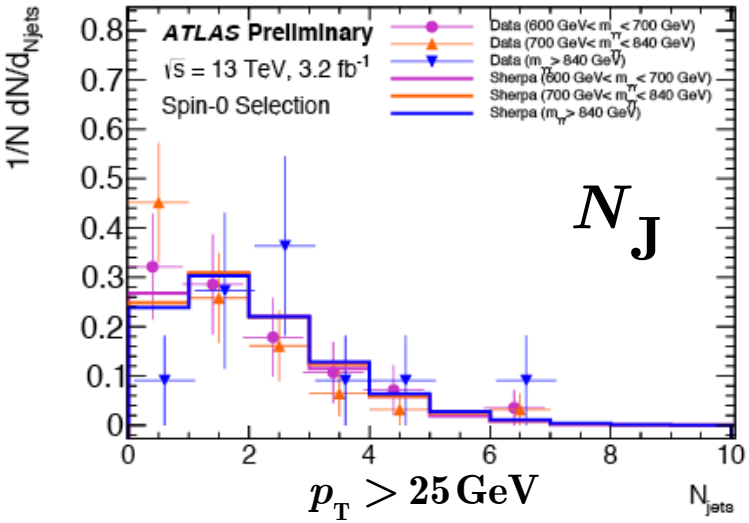
Strongest deviation from B-only hypothesis around 750GeV

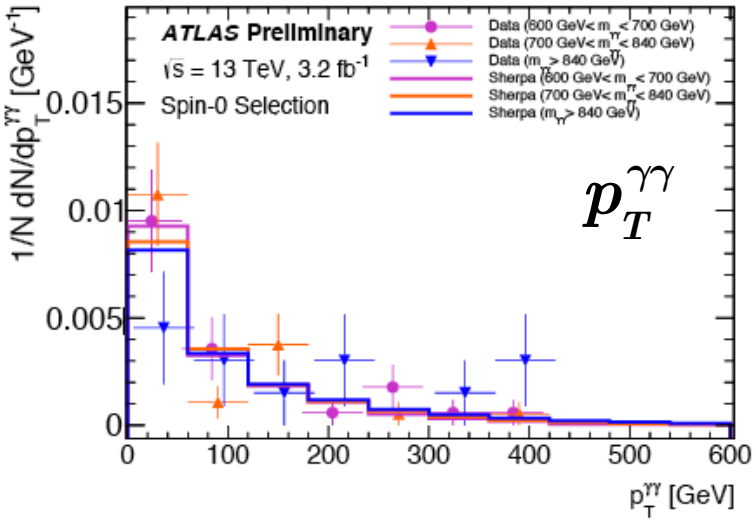
- Local (Global) Z=3.9(2.0)σ
- 6% width Γ_X~45GeV

- Local (Global) Z =3.6(1.8)σ
- 6% width κ /M_{PL}~0.2

characteristics around 750 GeV

SPin-0 analysis



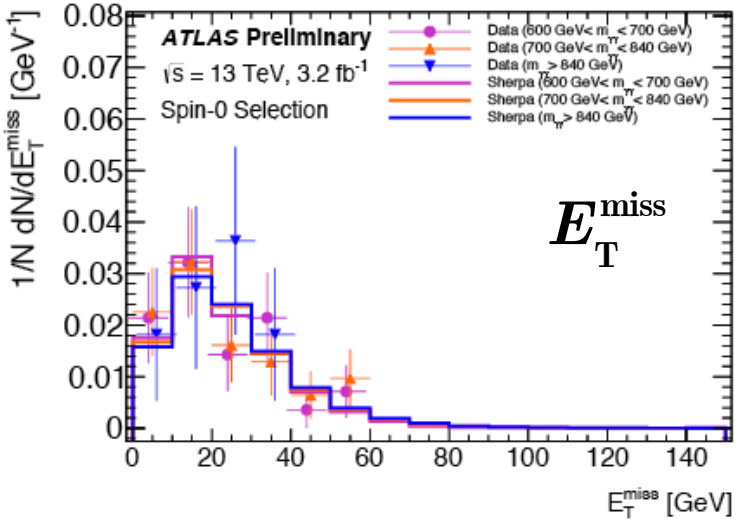


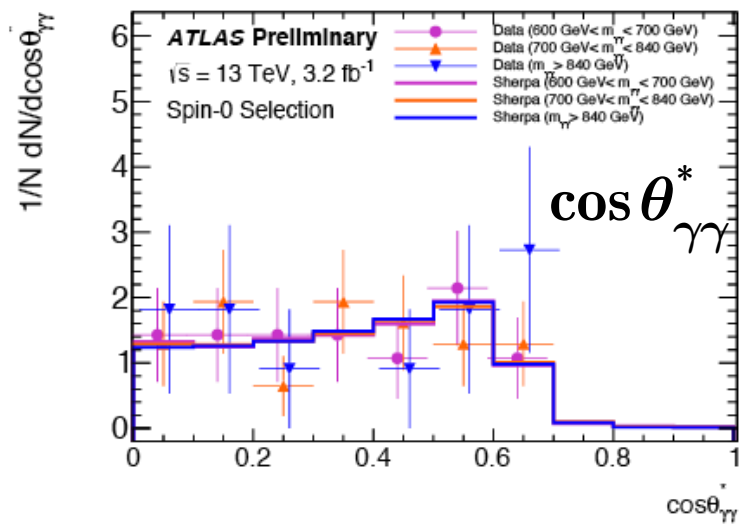
data
MC

$600 < m_{\gamma\gamma} < 700\,\mathrm{GeV}$

$700 < m_{\gamma\gamma} < 840\,\mathrm{GeV}$

$840 < m_{\gamma\gamma}$



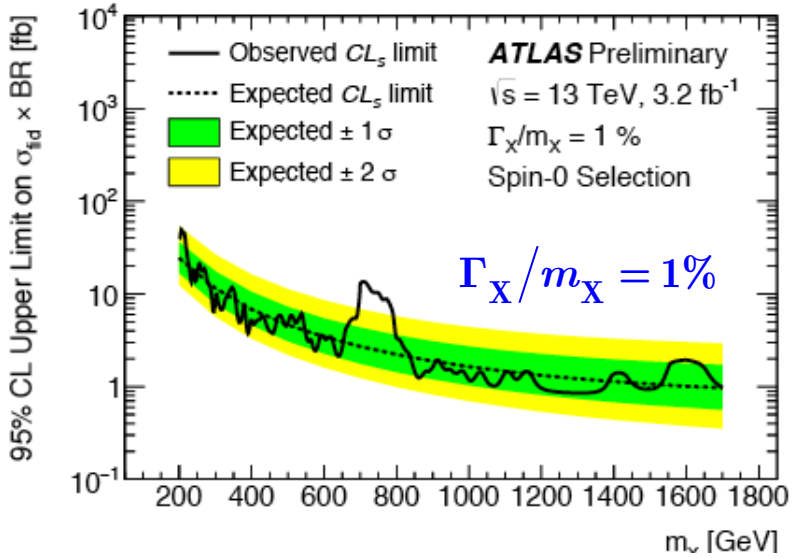


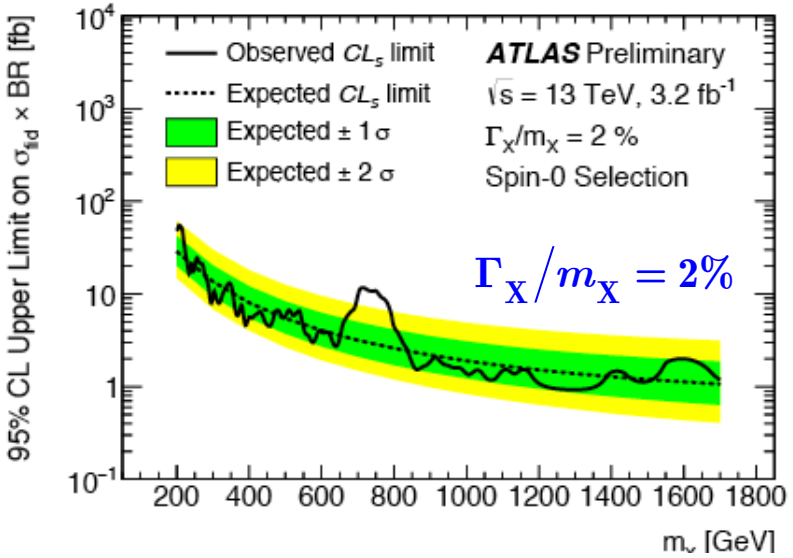
no significant difference is observed

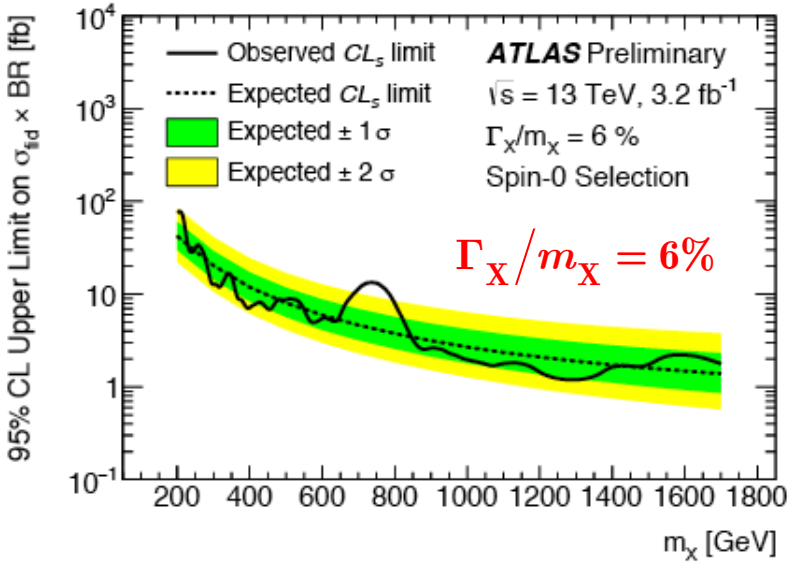
limit on production cross section

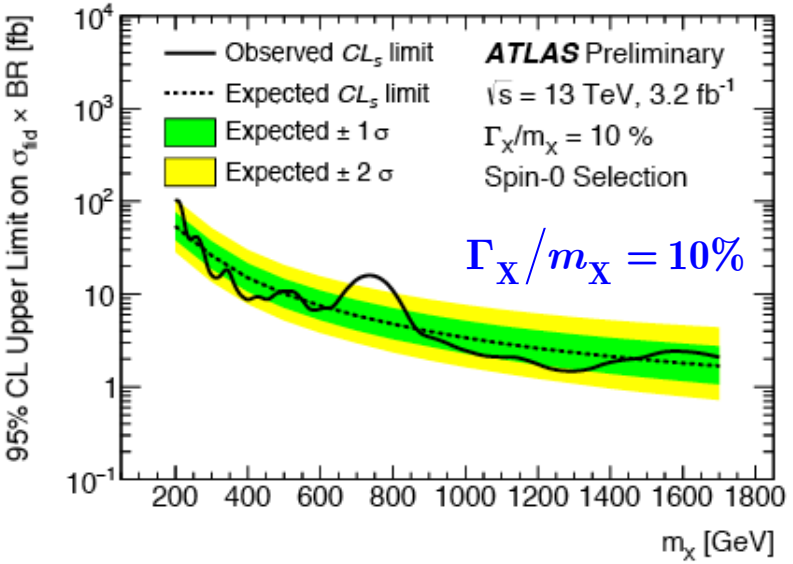
SPin-0 analysis

varying the width





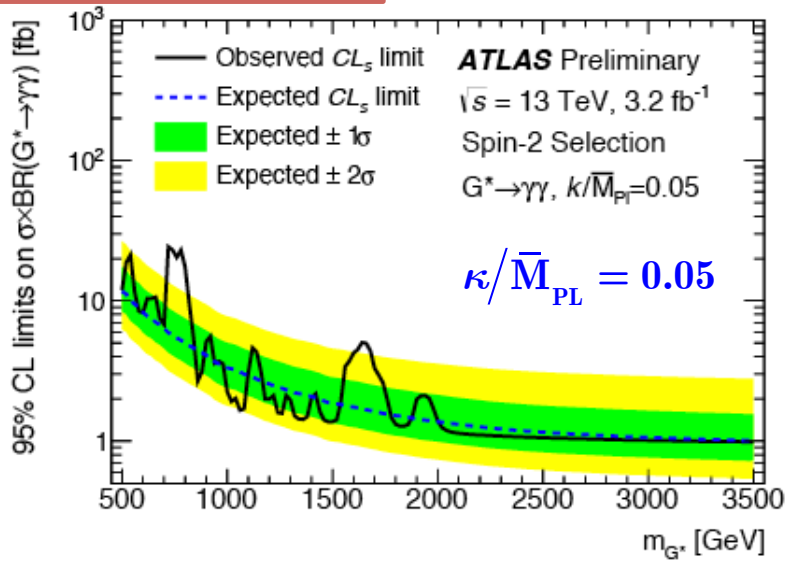


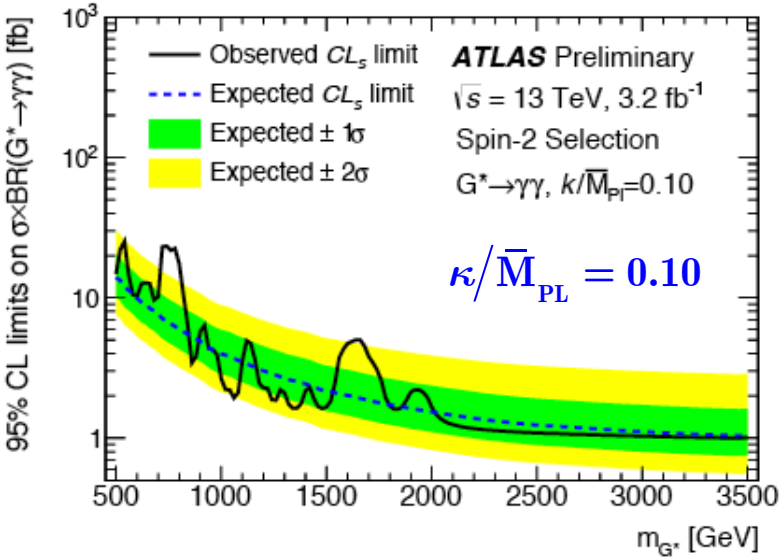


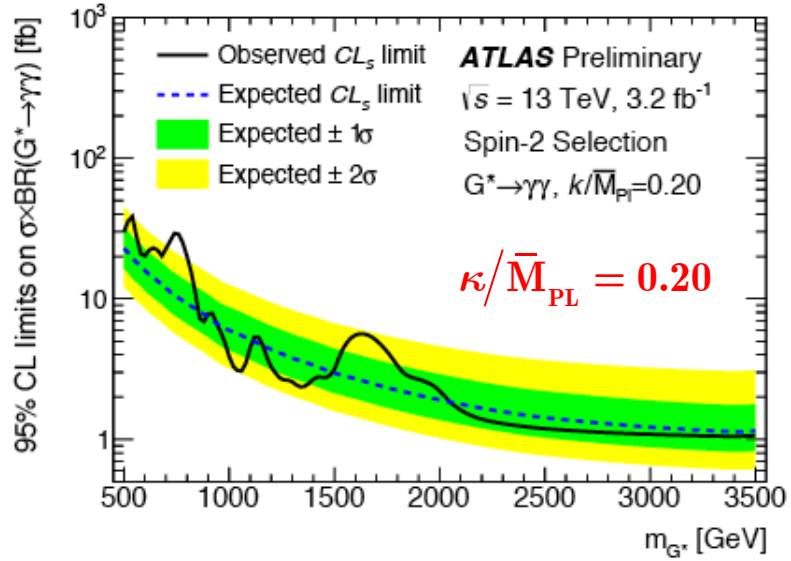
limit on production cross section

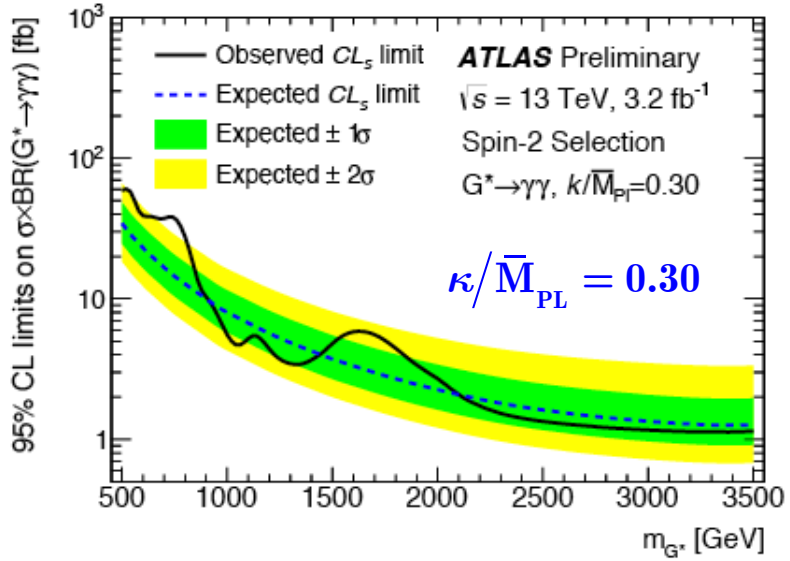
SPin-2 analysis

varying the width









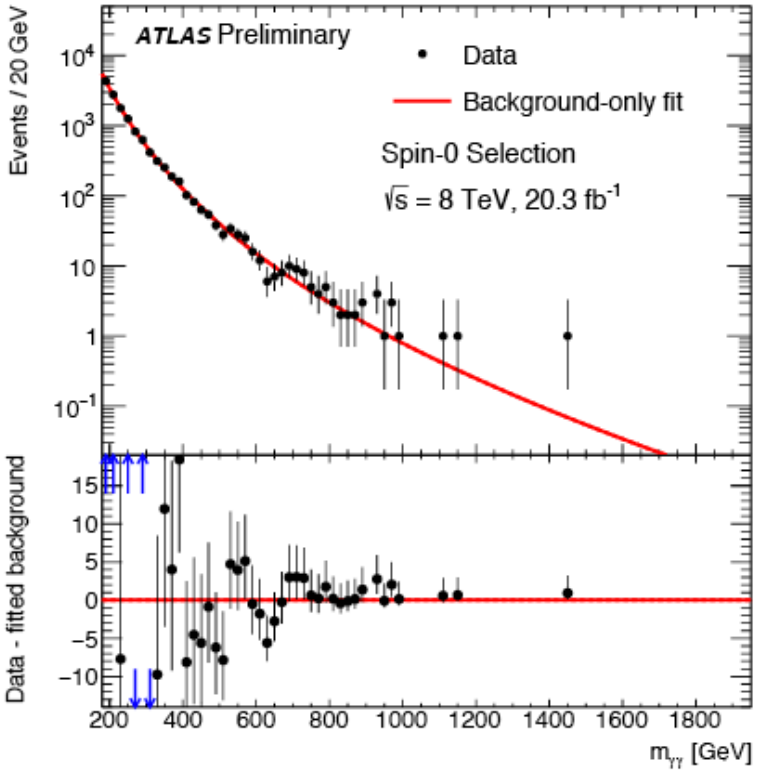
Compatibility with 8TeV data

8TeV pp collision data (2012) are re-analyzed:

latest Run 1 calibration, the Run 1 selections & ID, covering higher mass range (spin-0)

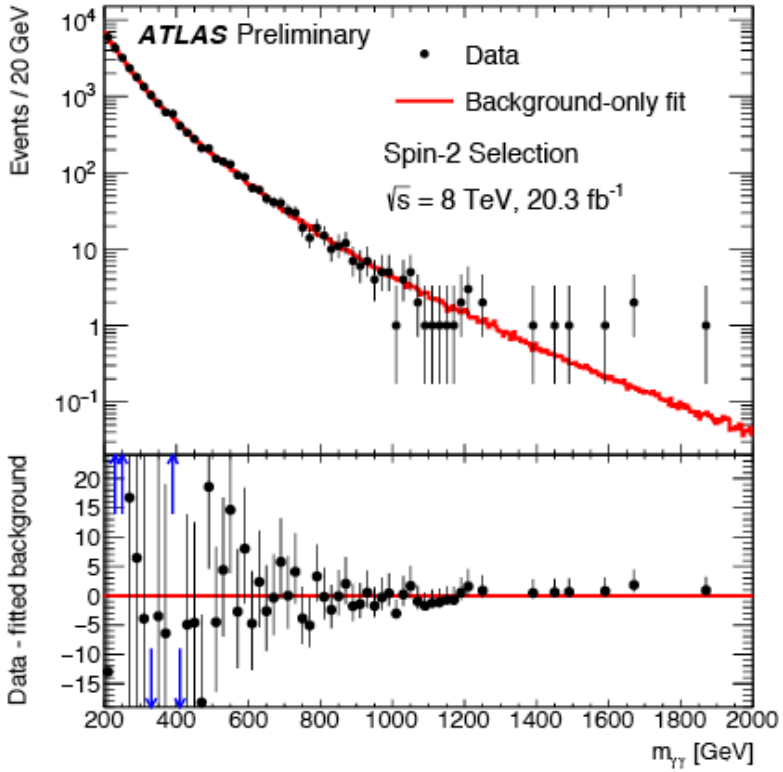
signal and background modeling a la 13 TeV style

SPin-0 analysis



- 1.9σ @750GeV (with 6% width)
- the consistency to 13TeV
  - gg (scaling: 4.7) 1.2σ
  - qq (scaling: 2.7) 2.1σ

SPin-2 analysis



- no excess over BG only hypo
- the consistency to 13TeV
  - gg 2.7σ
  - qq 3.3σ

luminosity ratio
s-channel
production

[part 2] diphoton searches summary

- **Updated the analysis for diphoton resonance search at 13TeV with 3.2/fb, based on the two scenarios (spin-0 and spin-2)**

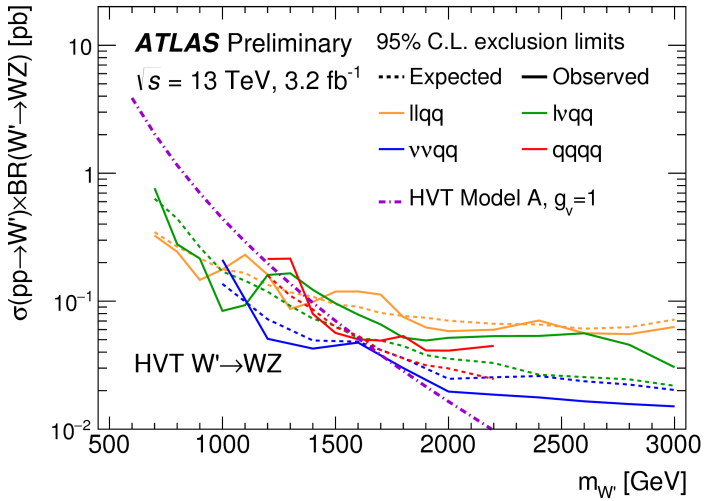
- Strongest deviation from BG only hypothesis around 750GeV is observed
  - **local** (global) significance of **3.9** (2.0) σ for spin-0
  - **local** (global) significance of **3.6** (1.8) σ for spin-2

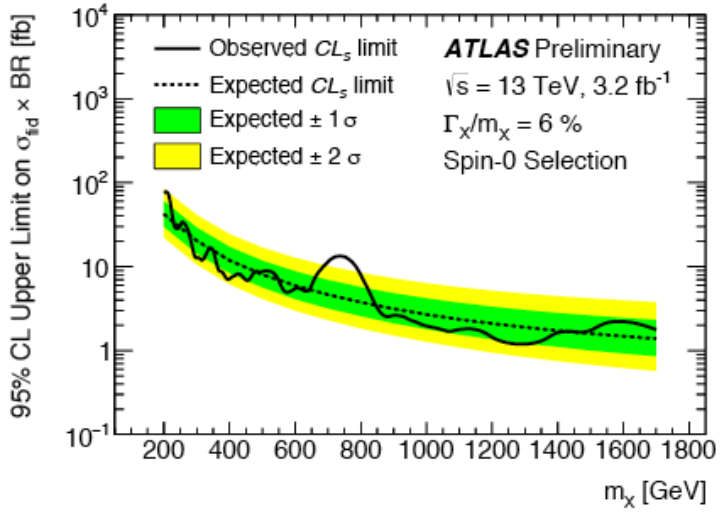
- Event properties are checked around 750 GeV, no significant differences are confirmed

- Consistency with 8TeV results (re-analysis) are checked
  - spin-0 : 1.2σ (gg), 2.1σ (qq)
  - spin-2 : 2.7σ (gg), 3.3σ (qq)

ATLAS Resonance Searches Summary

- Sensitivity to new physics is boosted with 13 TeV
  (in many analyses, the sensitivities already surpassed 8TeV results)
- So far, tantalizing results from 2015 data
  - The di-boson excess (~2.0TeV) seen in Run-1 not confirmed?
  - The diphoton excess (~750GeV) not evident in Run-1 shows up in Run-2?
- ATLAS is ready for 2016 (collision) data taking, and expecting higher integrated luminosity this year (~25/fb)
  (LHC starts collisions from next week)
- will have more solid clues by the end of summer, stay tuned



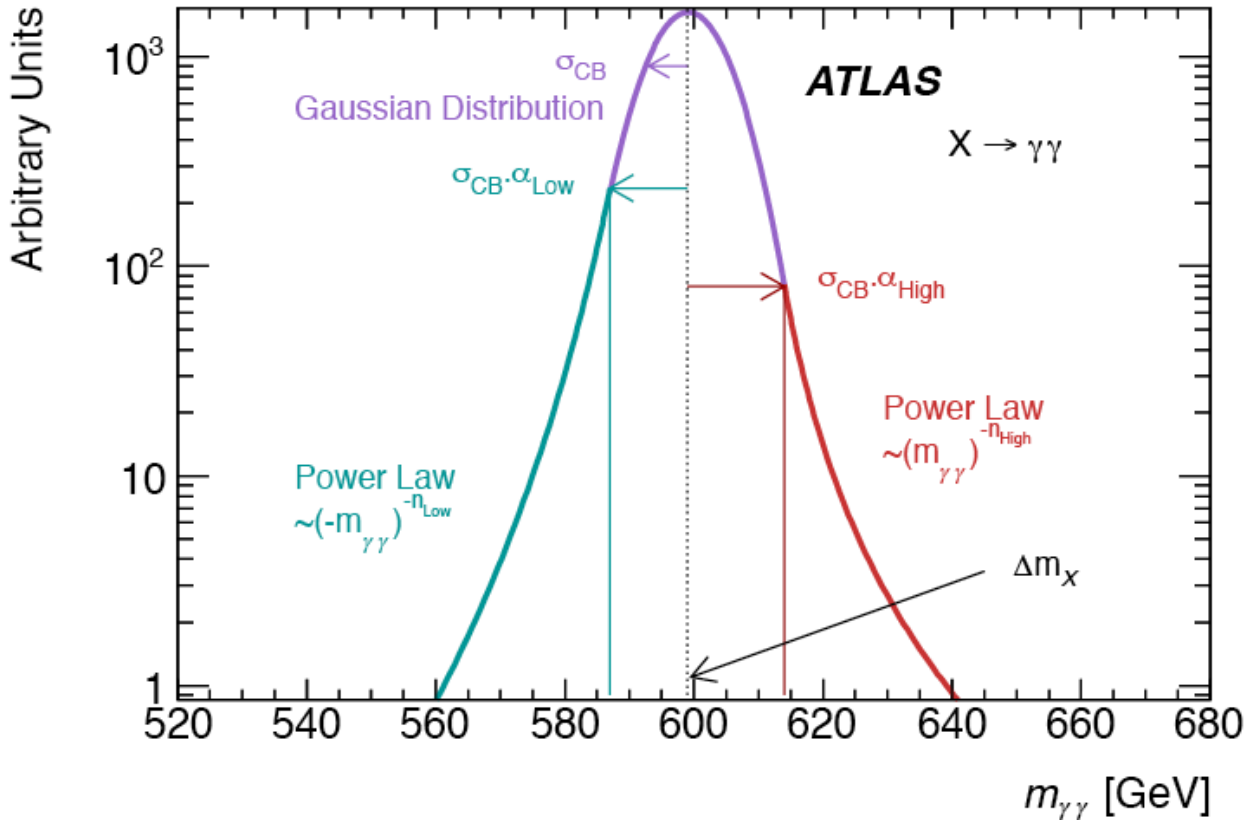


EXTRA SLIDES

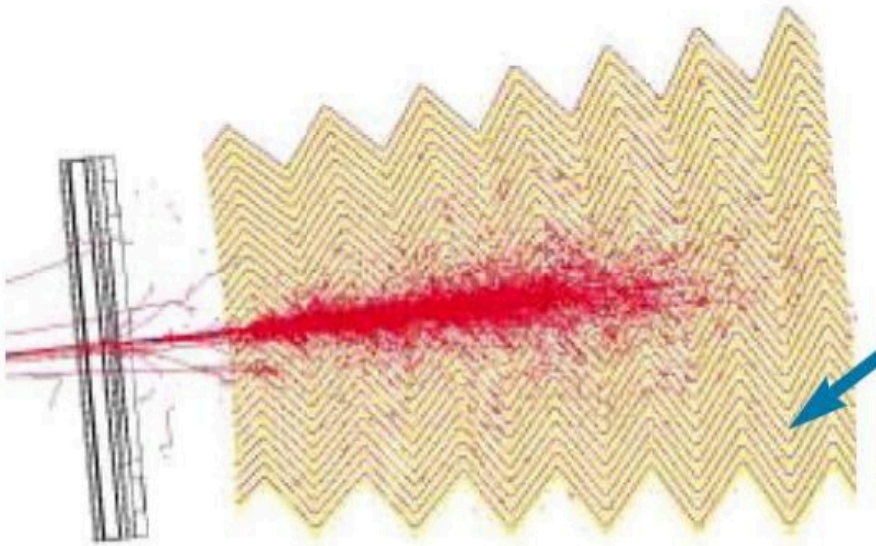
Double Sided Crystal Ball function

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

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



ATLAS liquid argon electromagnetic calorimeters

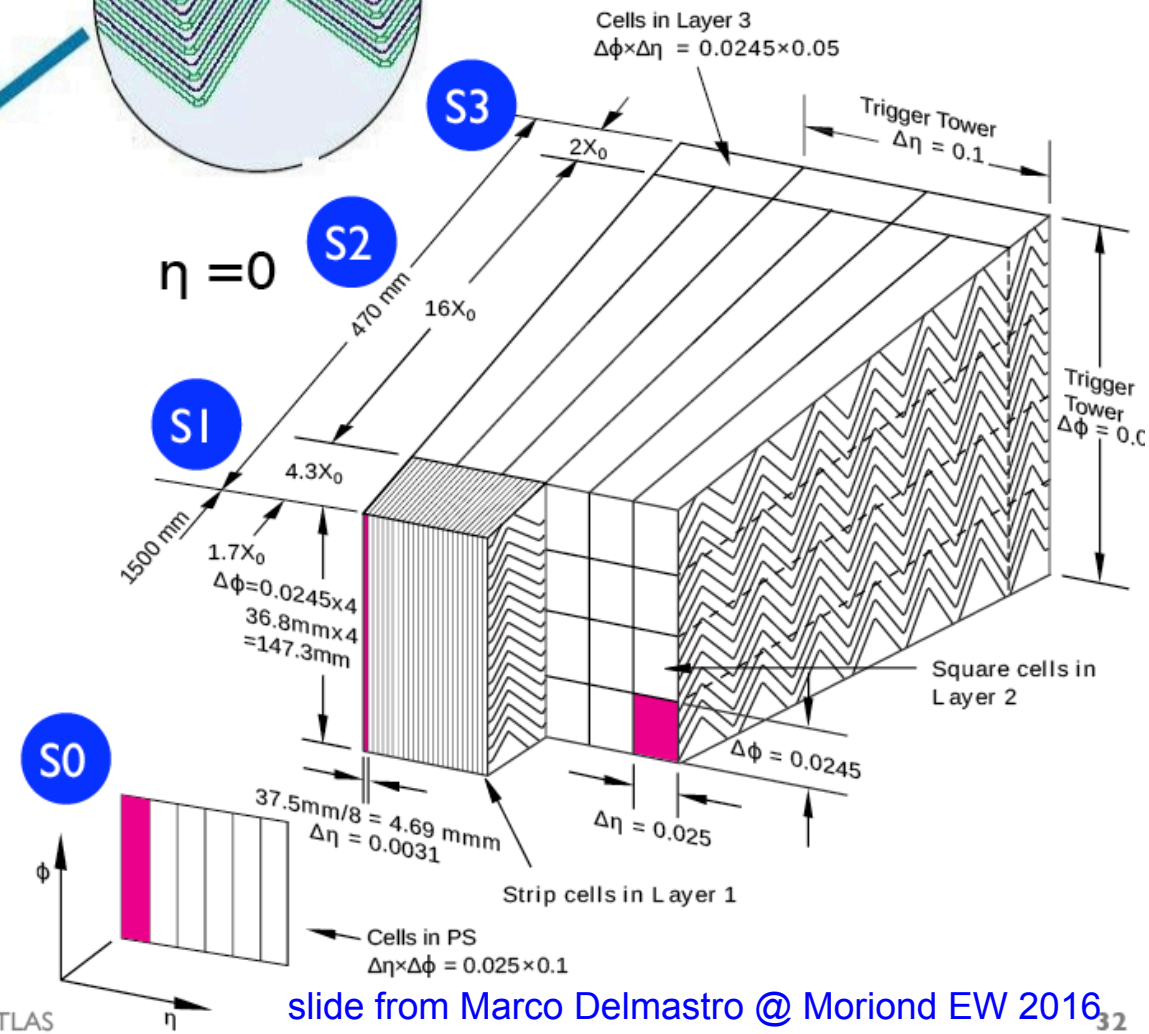


sampling calorimeter
Pb-LAr

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



slide from Marco Delmastro @ Moriond EW 2016

Variables and Position

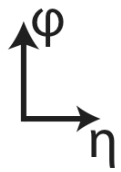
	Strips	2nd	Had.
Ratios	f_1, f_{side}	R_η*, R_ϕ	$R_{Had.}$*
Widths	$w_{s,3}$, $w_{s,tot}$	$w_{\eta,2}$*	-
Shapes	ΔE, E_{ratio}		

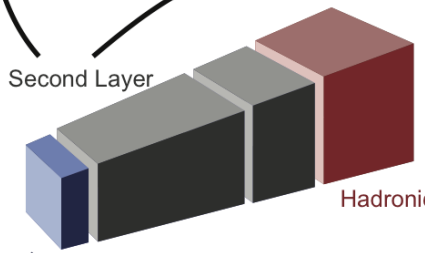
* Used in PhotonLoose.

Energy Ratios

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

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





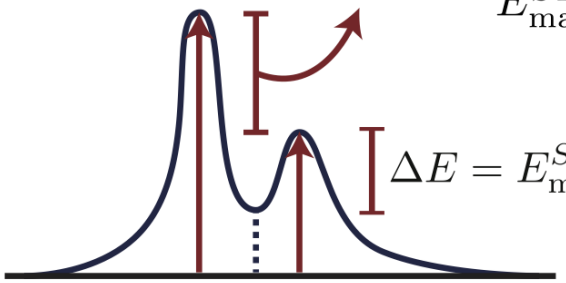
$$R_{\mathrm{Had}} = \frac{E^{\mathrm{Had}}_T}{E_T}$$

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

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

Shower Shapes

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

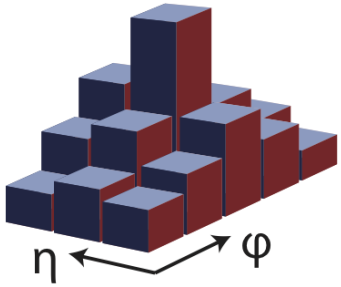


$$\Delta E = E^{S1}_{\mathrm{max},2} - E^{S1}_{\mathrm{min}}$$

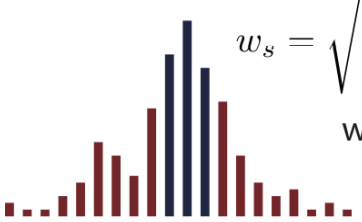
Widths

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

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



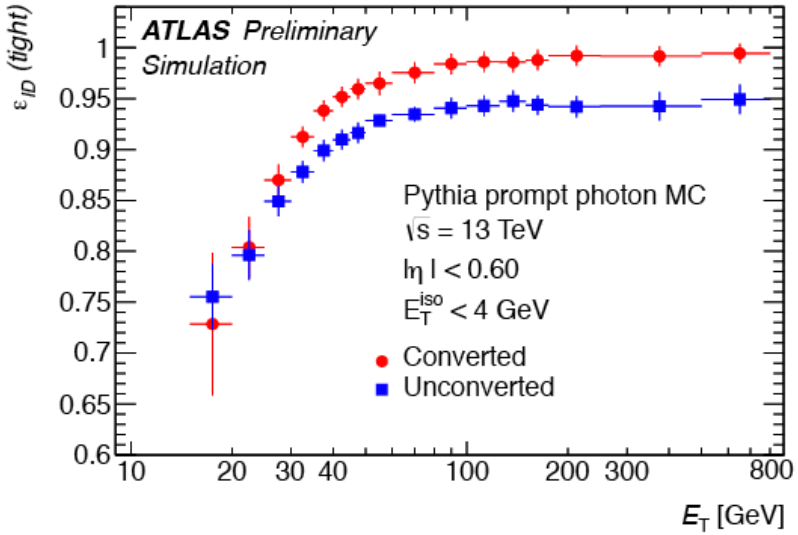
$$w_s = \sqrt{\frac{\sum E_i (i - i_{\mathrm{max}})^2}{\sum E_i}}$$

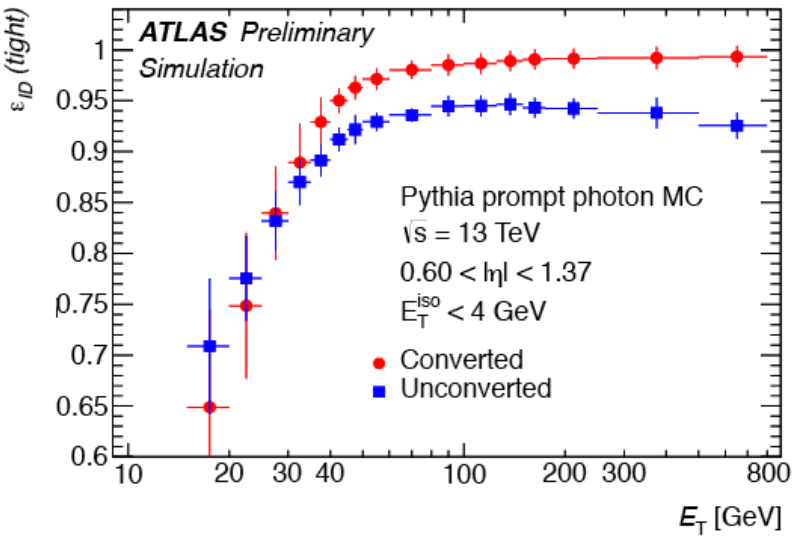


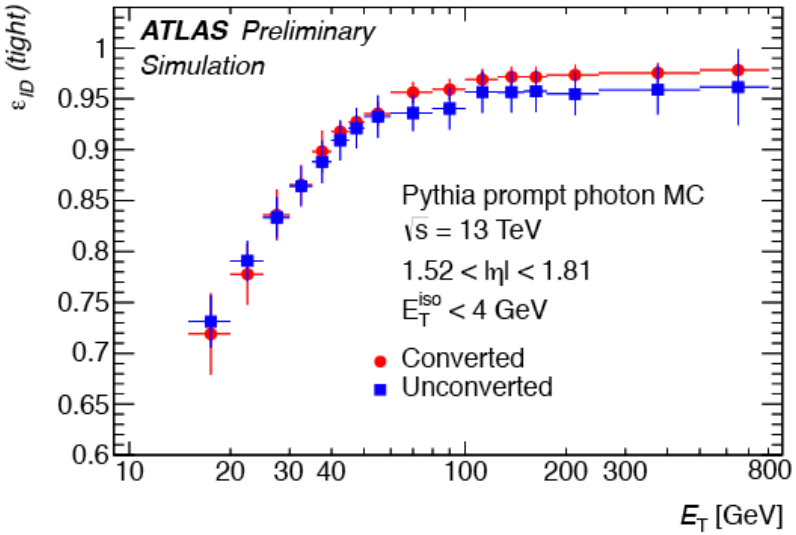
ws3 = w_1 uses ±1 strips (three total); wstot is defined similarly, but uses 20×2 strips.

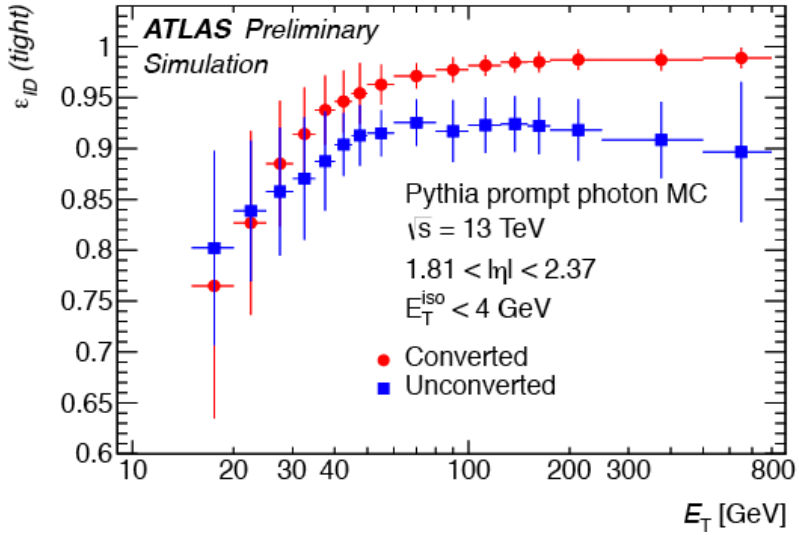
Photon ID

- 85% (E_T~50GeV)-95%(E_T~200GeV)
- Uncertainty : estimated from data vs. MC
  - ±1%- 5% for E_T>50 GeV
  - η dependent





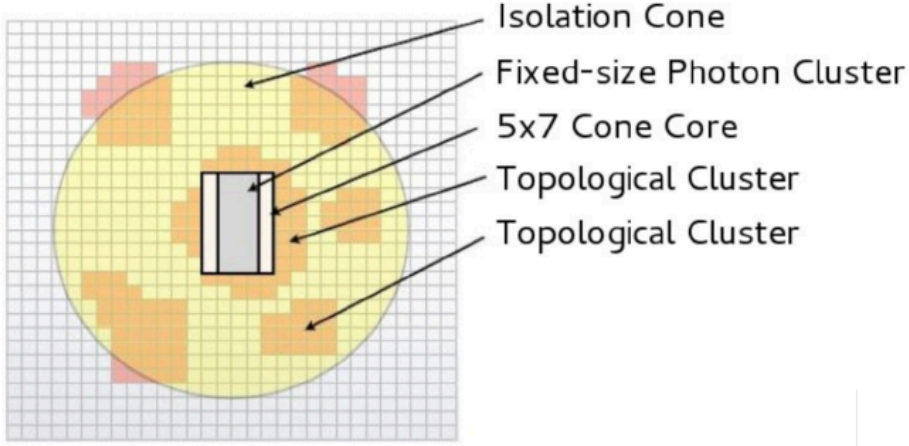


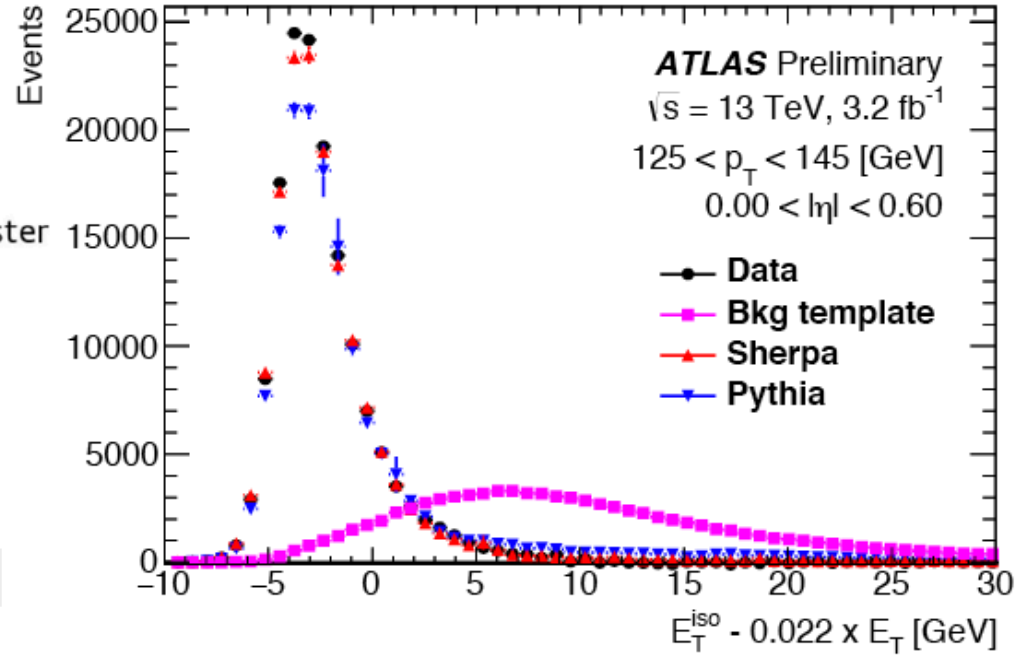


Photon Isolation

- Calorimetric isolation
  - energy clusters deposited in a cone of 0.4
  - excluding the area $\Delta\eta\times\Delta\phi=0.125\times0.175$ (center)

  corrected event-by-event
  - leakage of photon clusters
  - pileup contributions

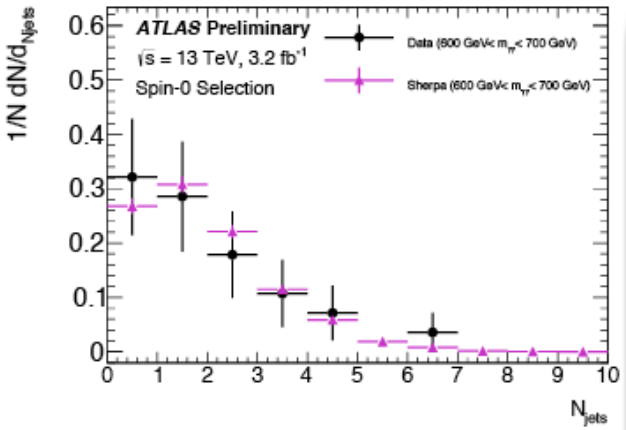




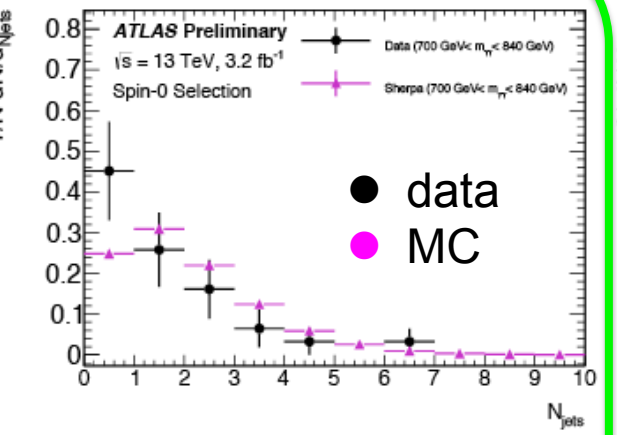
characteristics around 750 GeV

N_J Number of Jets (pT>25GeV, |η|<4.4, pileup rejection with track for pT>50GeV, |η|<2.4)

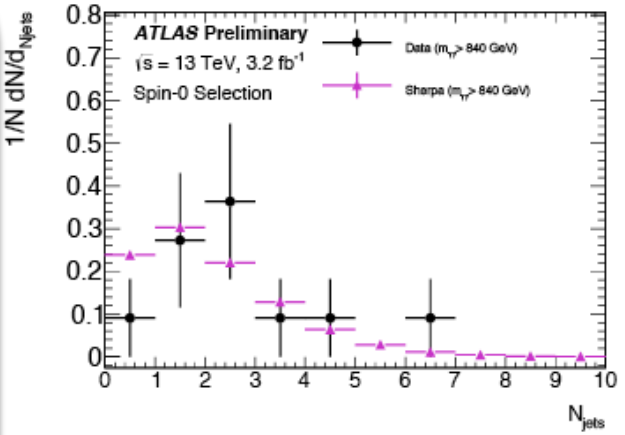
SPin-0 analysis



$600 < m_{\gamma\gamma} < 700\,\mathrm{GeV}$

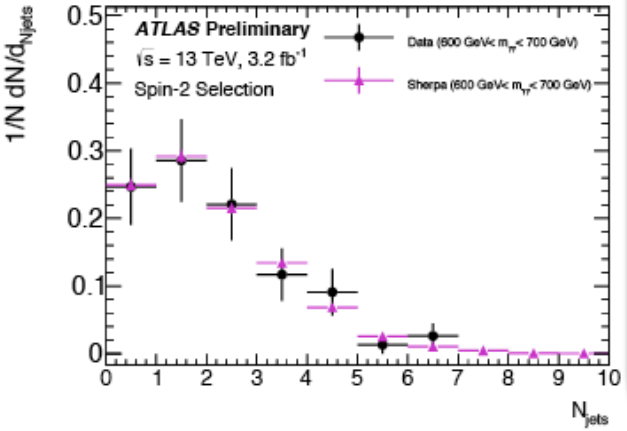


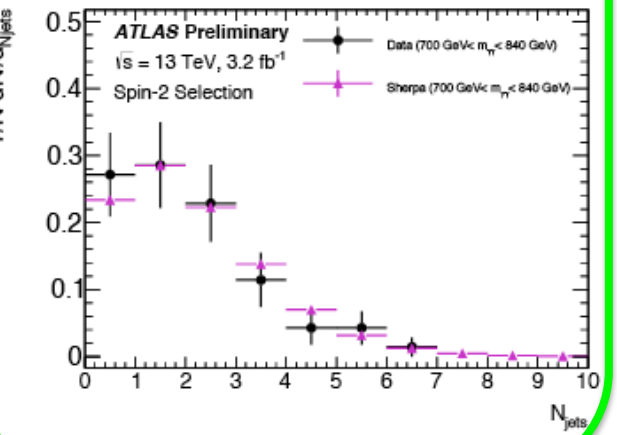
$700 < m_{\gamma\gamma} < 840\,\mathrm{GeV}$

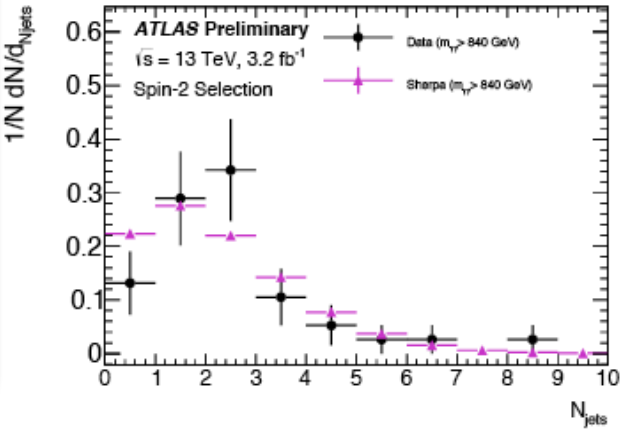


$840\,\mathrm{GeV} < m_{\gamma\gamma}$

SPin-2 analysis

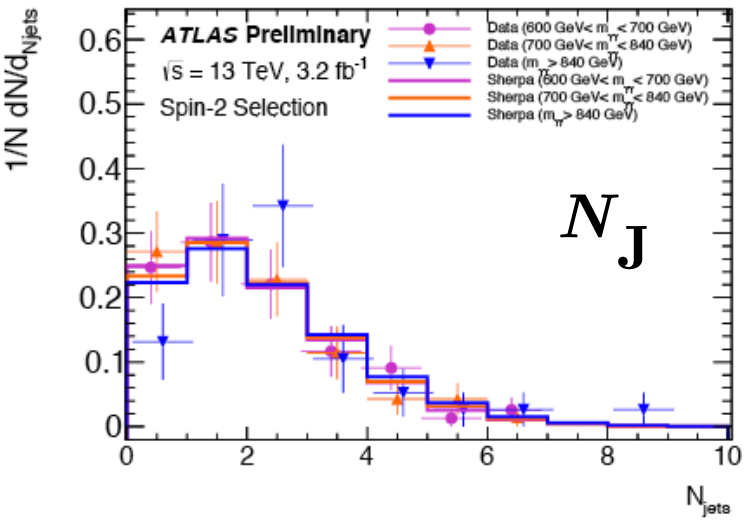


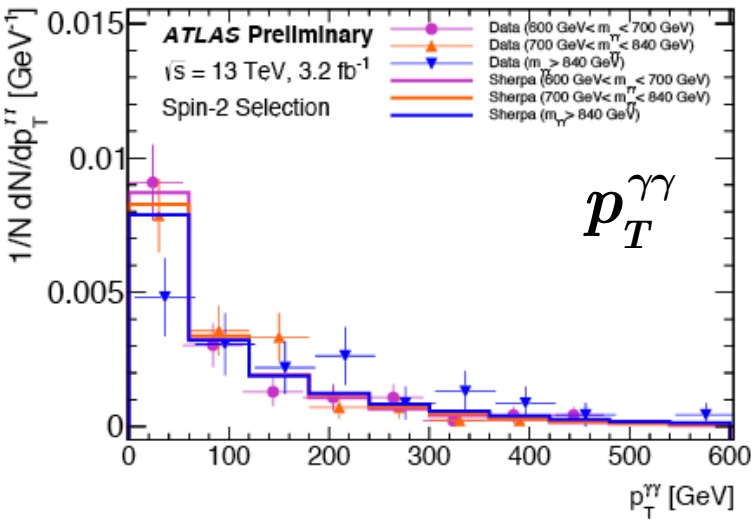




characteristics around 750 GeV

SPin-2 analysis





data
MC

$600 < m_{\gamma\gamma} < 700\,\mathrm{GeV}$

$700 < m_{\gamma\gamma} < 840\,\mathrm{GeV}$

$840 < m_{\gamma\gamma}$