Results on isolated photon, photon+jet and diphoton production in ATLAS (p-p, Pb-Pb collisions)

Photon 2015, BINP, Novosibirsk

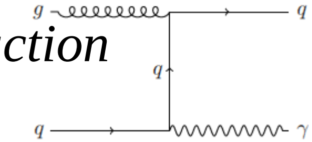
Marc Escalier, LAL

Isolated photons : a rich probe with various goals

Photons in pp environment

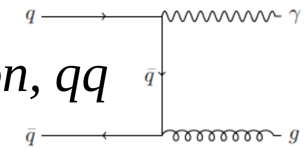
-sensitive to gluon content

Compton production (dominant)

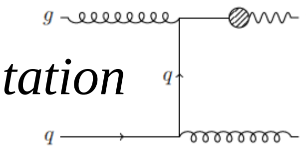


- test of perturbative QCD

annihilation, qq



fragmentation



-final state in search for resonance

γj
-generic gauss shape signal
-non-thermal Quantum Black Holes (QBH)
-excited quark ($q^* \rightarrow q\gamma$)

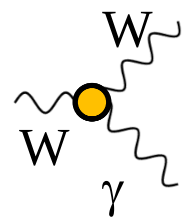
γ+MET
-LED (ADD), G+γ
-dark matter (WIMP χ), qqχχ + γ
-squarks + γ
$q \rightarrow q + \tilde{\chi}_1^0$

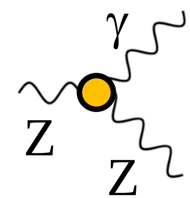
γγ+MET
-GMSB : NLSP : case of lightest neutralino $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$
LSP : gravitino $\tilde{G} \rightarrow G\gamma$
-UED: production pair KK of quarks/gluons
decay cascade until lightest KK particle :
KK photon $\gamma^* \rightarrow \gamma + G$

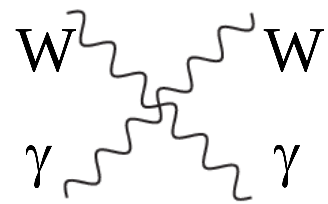
γγ : XD
-RD : KK $G^* \rightarrow \gamma\gamma$

$H \rightarrow \gamma\gamma$
(dedicated talk by **Yohei Yamaguchi)**

-probe aTGC & aQGC







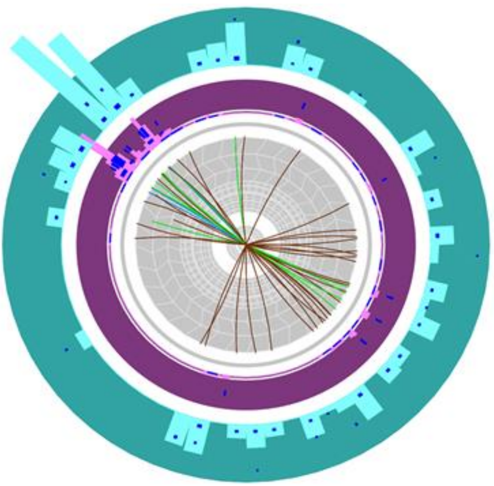
Photons in Pb Pb environment

photon…

- colorless : transparent to evolution of matter :

  → probe very initial state of collision
- sensitive to nuclear modifications (nPDFs)
- helps understanding jet quenching (di-jet asym) in hot/dense medium :

  proper energy calibration of initial (before quenching) jets



example of jet quenching, ATLAS : Phys. Rev. Lett. 105, 252303 (2010)

Struggling against background

Main background for photons object : photons from hadronic jets :
mostly light neutral mesons : π^0, η
'fake photons'

Main background for : -prompt photon production γj : jj
-$\gamma\gamma$ production : γj, jj

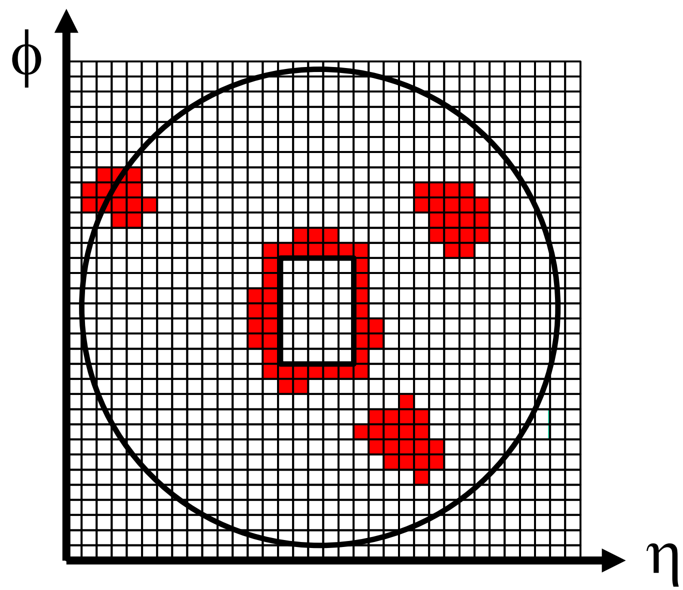
Struggling against fake photons, fakes leptons :

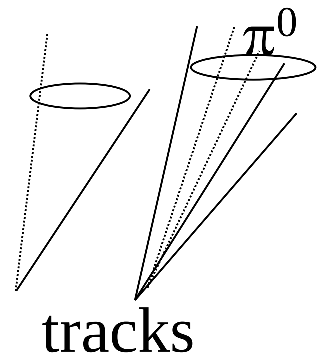
-shower-shape identification

-calorimeter isolation

-track isolation

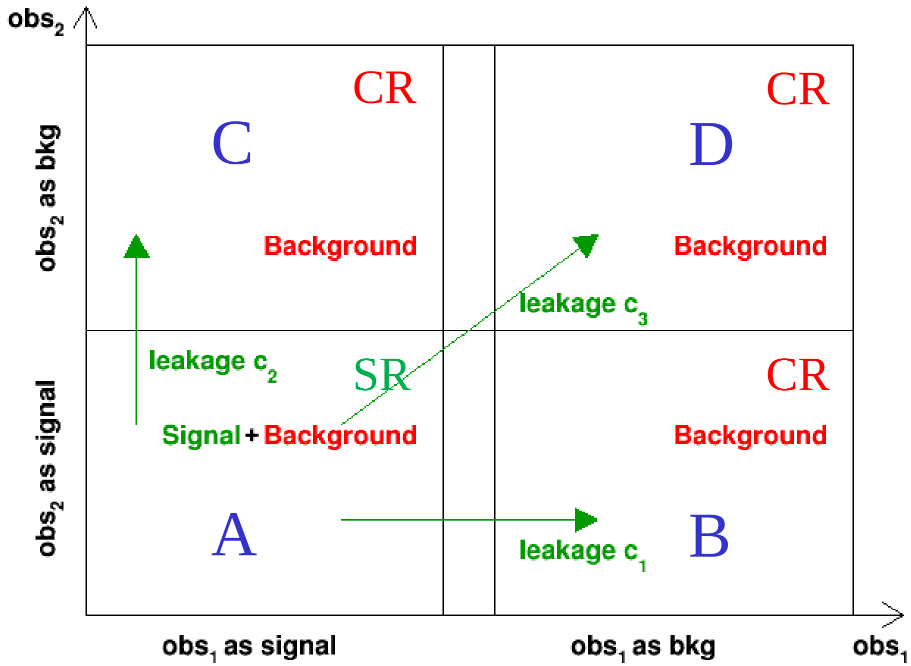
-photons
-electrons





Measuring bkg (X+j) wrt signal (X+γ)

1. Split phase space w/ two observables
   - Signal Region (SR) : 'A' : contains signal+bkg
   - Control Regions (CR's) : 'B', 'C', 'D' : dominated by bkg



Applicable to various processes :

Signal	vs	bkg	obs$_1$	obs$_2$
γj		jj	photon isol ;	quality
γγ		γj, jj	photon isol ;	quality
W(lν)γ		W(lν)j	photon isol ;	quality
W(lν)γ		γj	lepton isol ;	MET

2. Bkg in SR : deduced from CR's
   ABCD method : $N_{bkg}^{A} = N^{B} \times \frac{N^{C}}{N^{D}}$
   (purity : $N_{sig}^{A} / N_{obs}^{A}$)

3. consider signal leakage (c_i=O(5 %))

$$N_{bkg}^{A} = (N_B - c_1 N_{sig}^{A}) \frac{(N_C - c_2 N_{sig}^{A})}{(N_D - c_3 N_{sig}^{A})}$$

4. phase space properties C, D may slightly differ from A, B
   → introduce : correction factor

$$R = \frac{N_{bkg}^{A} \times N_{bkg}^{D}}{N_{bkg}^{B} \times N_{bkg}^{C}}$$

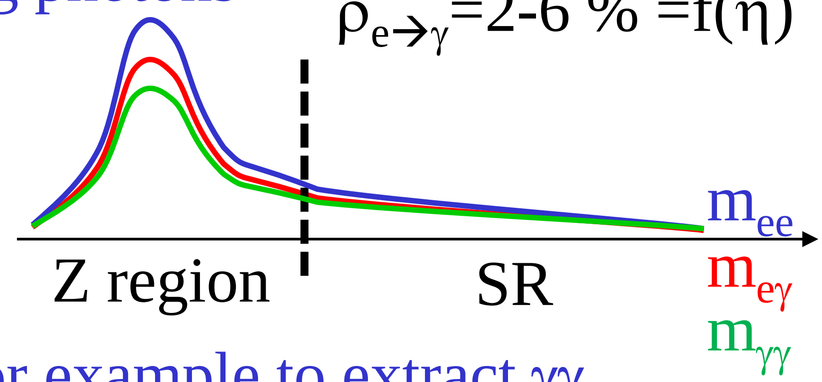
Measuring bkg (X+j) wrt signal (X+γ)

Some other methods to discriminate signal vs bkg, and evaluate bkg

- Calorimeter isolation template, in 2D
- Drell-Yan and sources w/ electrons faking photons

computes $\rho_{e\rightarrow\gamma}$ fake rate from Z→ee resonance
exploits ratio of $N_{e\gamma}$; N_{ee} from data
eg : evaluation of $N^{DY}_{\gamma\gamma}$ (SR) :
applies $\rho_{e\rightarrow\gamma}$ on N_{ee} in SR

$\rho_{e\rightarrow\gamma}$=2-6 % =f($\eta$)

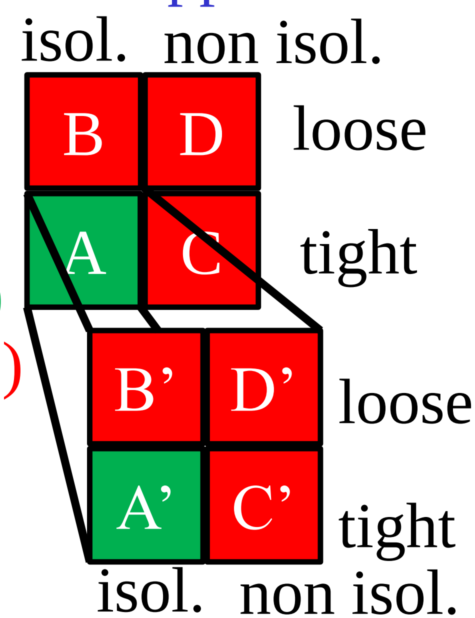


- ABCD method could be applied twice, for example to extract $\gamma\gamma$

leading γ candidate
(highest p_T)

signal region : O(γ)
control region : O(j)

sub-leading γ



connection of each region with bkg processes : $\gamma\gamma$, γj, jj

$p\,p \rightarrow \gamma X$

$\sqrt{s}$=7 TeV ; L=4.6 fb^{-1}

- Selection

$100 \leq E_T^{\gamma} \leq 1000$ GeV, barrel : $|\eta|_{\gamma} < 1.37$; end-cap : $1.52 \leq |\eta|_{\gamma} < 2.37$

- Bkg estimation

-jets faking photons (dominant)

ABCD : calo isolation threshold : 7 GeV

-electrons faking photons (<0.5 %) estimated from Z region

- Integrated cross-section

barrel

$$\sigma(\gamma + X) = 236 \pm 2\ (\text{stat})^{+13}_{-9}(\text{syst}) \pm 4\ (\text{lumi})\ \text{pb}$$

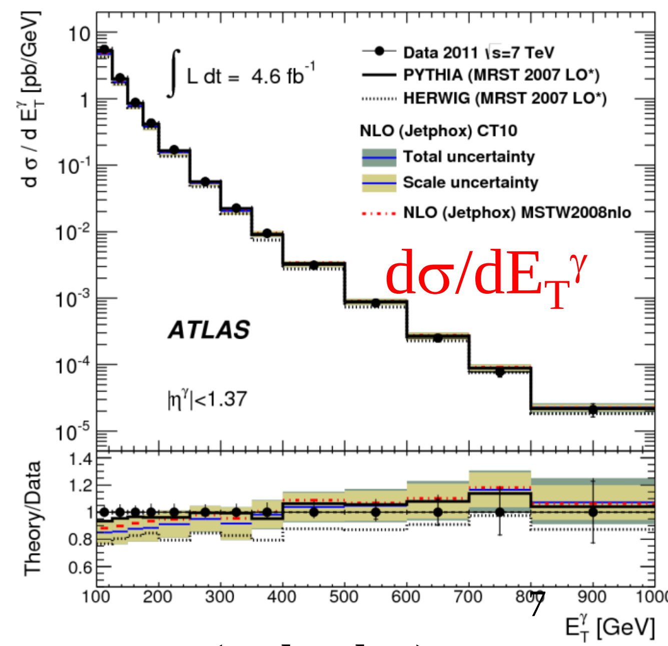
σ_{th}=203 ± 25 (th) pb (NLO : jetphox, CT10)

end-cap

$$\sigma(\gamma + X) = 123 \pm 1\ (\text{stat})^{+9}_{-7}(\text{syst}) \pm 2\ (\text{lumi})\ \text{pb},$$

σ_{th}=105 ± 15 (th) pb (NLO : jetphox, CT10)

- Differential cross-section



(+ dσ/dη$^\gamma$)

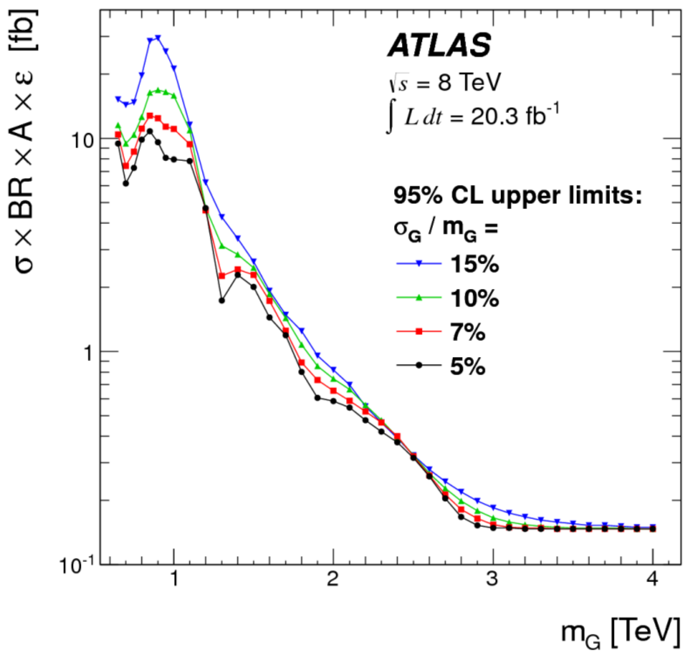
Good agreement w/ NLO QCD calculation

resonances w/ γ+j

$\sqrt{s}$=8 TeV ; L=20.3 fb^{-1}

- 95 % CL limits

-generic gauss shape signal

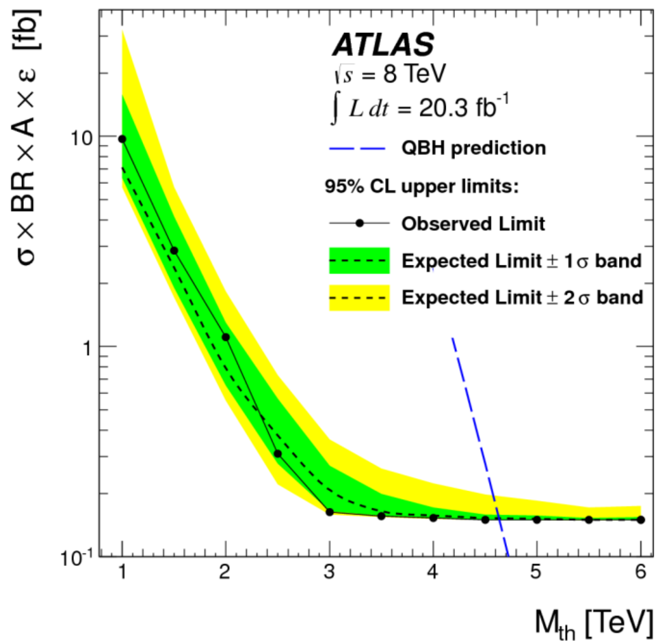


excluded 4 TeV

resonance w/ σ_{eff}=0.1 fb

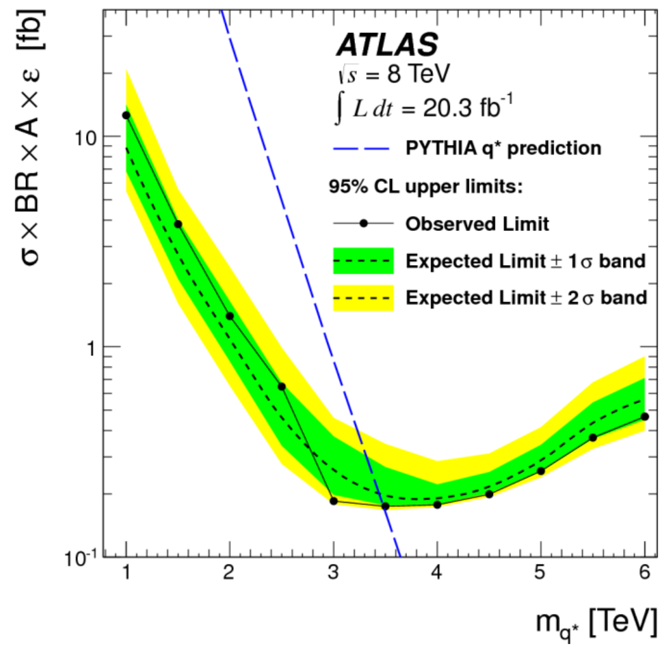
(σ_{eff}=σ x BR x A x ε)

-QBH



excluded up to 4.6 TeV

-excited quark q*



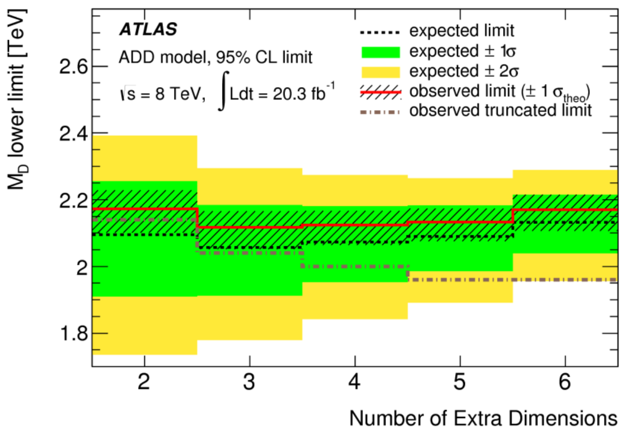
excluded up to 3.5 TeV

γ+MET : BSM $\sqrt{s}$=8 TeV ; L=20.3 fb^{-1}

- 95 % CL limits

σ_{fid} (γ+MET)=5.3 fb

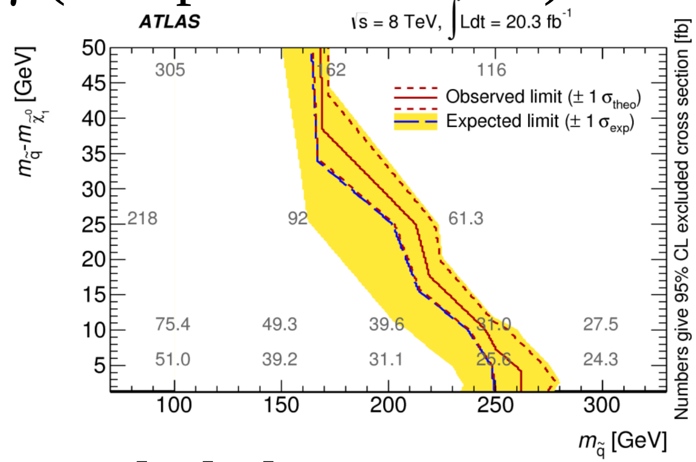
-LED : G+γ



exclude m_D=2.17 TeV

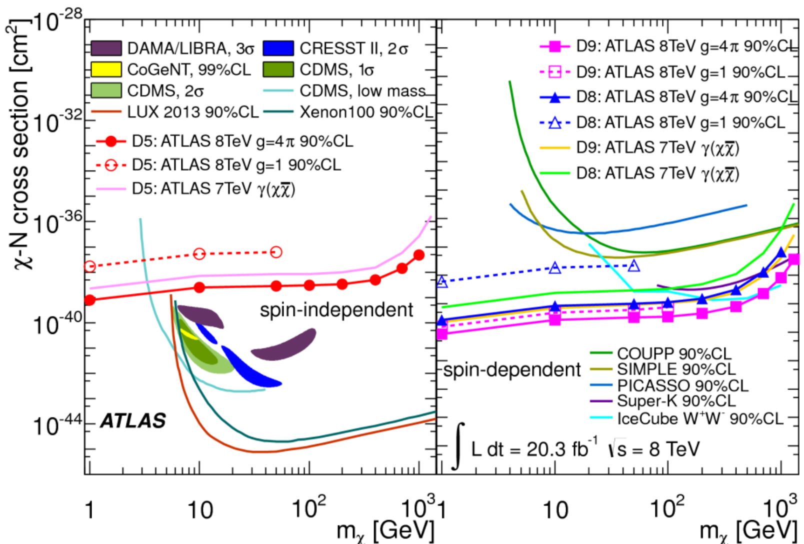
-squarks + γ (compressed model)

$\tilde{q} \rightarrow q+\chi_1^0$



excluded up to 250 GeV

-Dark matter



EFT operators for WIMP :
D5 (V), D8 (A), D9 (T)

$pp \rightarrow \tilde{q}\tilde{q}^{*}\gamma+X$

extends results to m_χ<10 GeV

p p → γγ

√s=7 TeV ; L=4.9 fb^{-1}

- Selection

$E_{T\gamma}^{L,\,S}$>25 GeV ; 22 GeV

$|\eta|_\gamma<1.37$; $1.52\leq|\eta|_\gamma<2.37$

- Bkg estimation :

-2D template likelihood fit : calorimeter isolation

-2 ABCD sidebands

- Integrated cross-section (σ_{integ})

Measured : $=44.0^{+3.2}_{-4.2}$ pb

Predicted : 44^{+6}_{-5} pb

2γNNLO : NNLO QCD direct part γγ, no fragmentation (some lower order tested also)

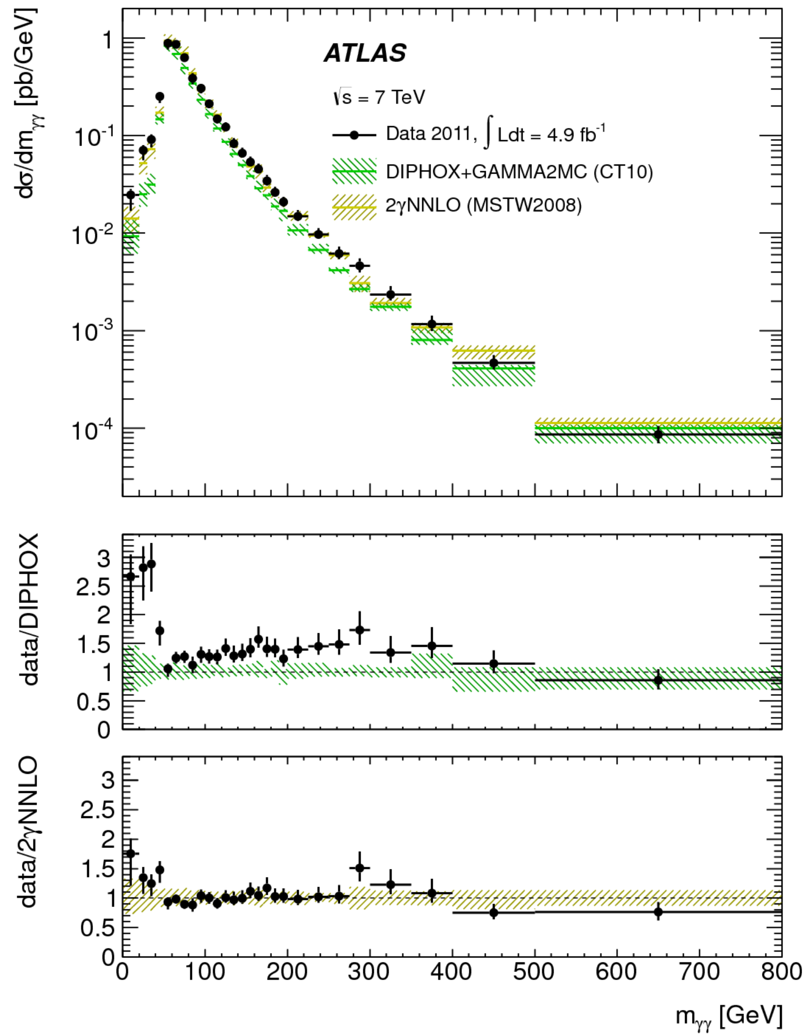
- Differential cross-section

$m_{\gamma\gamma}$: resonance search

$p_{T\gamma\gamma}$: probe HO QCD pertub. effects, fragm.

$\Delta\phi_{\gamma\gamma}$, : probe specific regions of phase space

$\cos\theta^*_{\gamma\gamma}(\gamma)$: probe spin of diphotons resonance



excellent agreement data/prediction

$\gamma\gamma$: XD

$\sqrt{s}$=8 TeV ; L=20.3 fb^{-1}

- Randall-Sundrum model

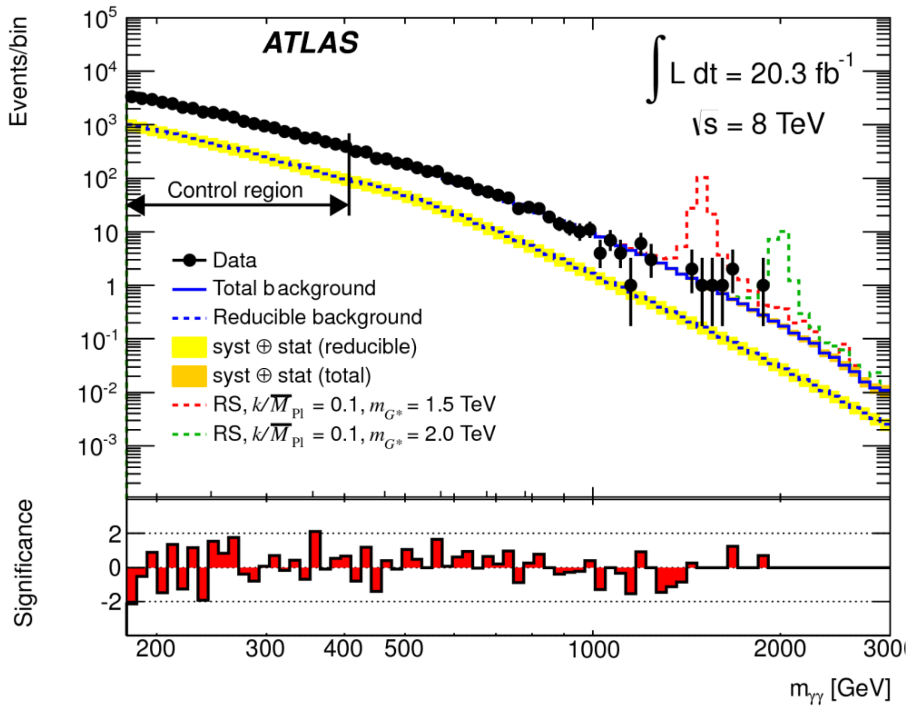
Compactification of XD→KK graviton excitation G^*

Phenomenology=f(m_{G^*} ; dimensionless coupling to SM : for $k/\overline{M}_{Pl}$=0.1

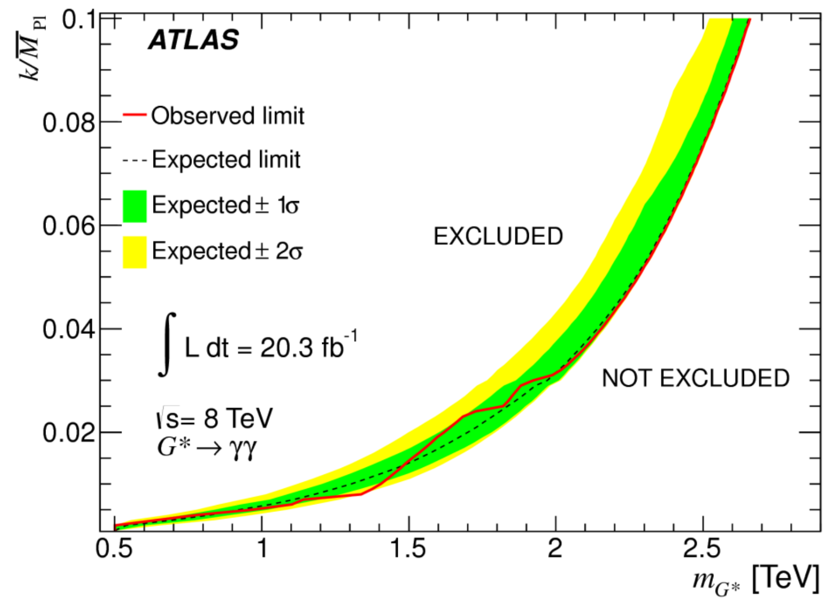
($\overline{M}_{Pl}=M_{Pl}/\sqrt{8\pi}$)

- Selection

photons : E_T>50 GeV, isolated (calo isol<8 GeV)



- 95 % CL limits



lightest graviton m_G>2.66 TeV for $k/\overline{M}_{Pl}$=0.1

$\gamma\gamma$ + MET

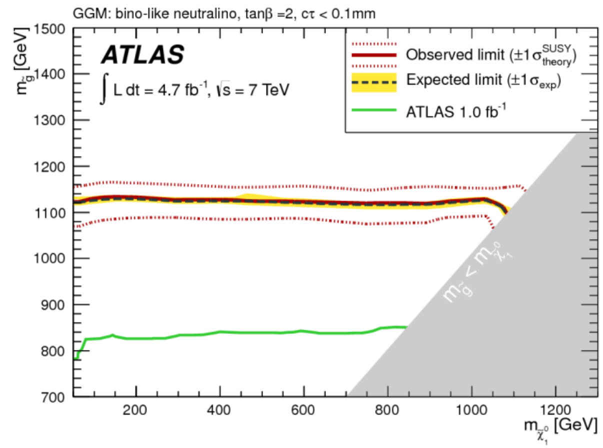
$\sqrt{s}$=7 TeV ; L=4.8 fb^{-1}

- Selection

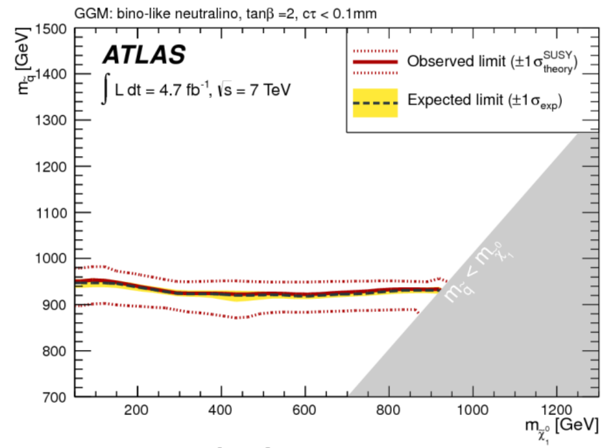
≥2 photons, p_T>50 GeV

- 95 % CL limits

  -GMSB

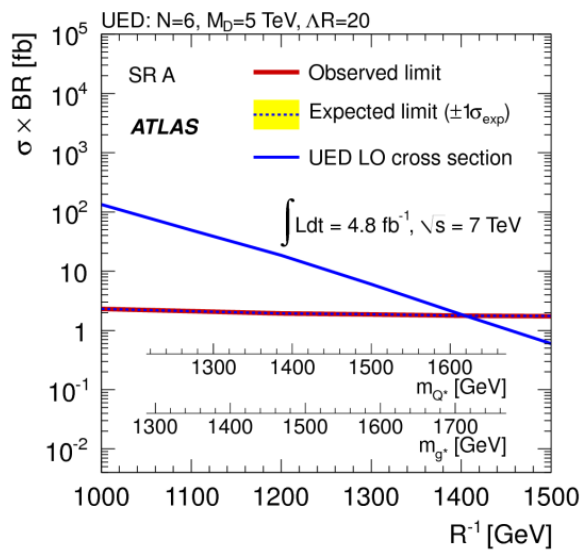


$m_{\tilde{g}}$>1.07 TeV



$m_{\tilde{q}}$>0.87 TeV

  -UED 1-D : 1/R>1.40 TeV



(W/Z)γ √s=7 TeV

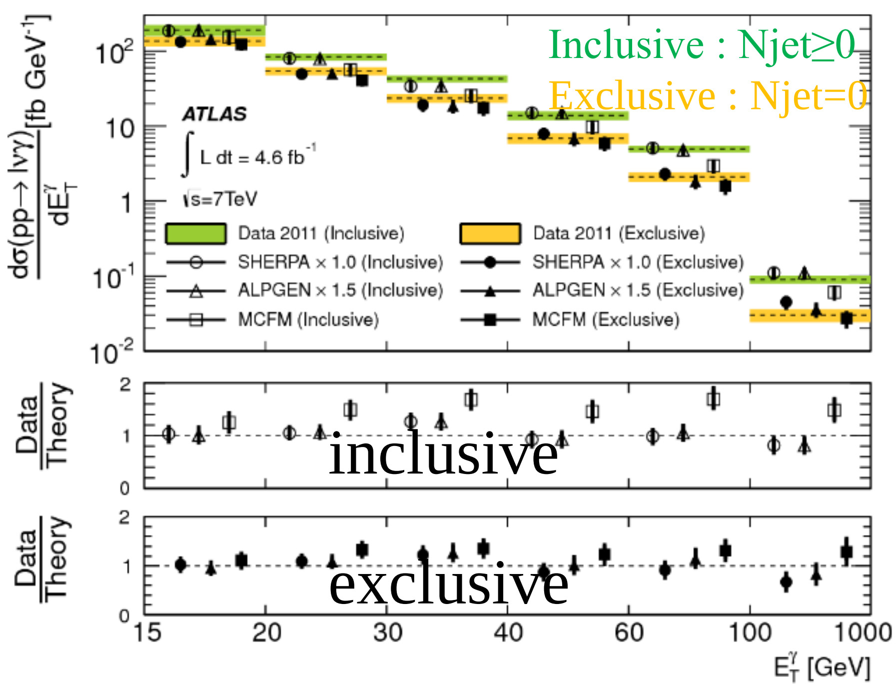
√s=7 TeV ; L=4.6 fb^{-1}

- final states : W(lν)γ, Z(ll)γ, Z(νν)γ
- Data driven estimation of bkg
- Fiducial cross-section

	$\sigma^{\text{ext-fid}}$[pb] Measurement	$\sigma^{\text{ext-fid}}$[pb] MCFM Prediction
	$N_{\text{jet}} \geq 0$	
$e\nu\gamma$	2.74 ± 0.05 (stat) ± 0.32 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\mu\nu\gamma$	2.80 ± 0.05 (stat) ± 0.37 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\ell\nu\gamma$	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$e^+e^-\gamma$	1.30 ± 0.03 (stat) ± 0.13 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\mu^+\mu^-\gamma$	1.32 ± 0.03 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\ell^+\ell^-\gamma$	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\nu\bar{\nu}\gamma$	0.133 ± 0.013 (stat) ± 0.020 (syst) ± 0.005 (lumi)	0.156 ± 0.012
	$N_{\text{jet}} = 0$	
$e\nu\gamma$	1.77 ± 0.04 (stat) ± 0.24 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$\mu\nu\gamma$	1.74 ± 0.04 (stat) ± 0.22 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$\ell\nu\gamma$	1.76 ± 0.03 (stat) ± 0.21 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$e^+e^-\gamma$	1.07 ± 0.03 (stat) ± 0.12 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\mu^+\mu^-\gamma$	1.04 ± 0.03 (stat) ± 0.10 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\ell^+\ell^-\gamma$	1.05 ± 0.02 (stat) ± 0.10 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\nu\bar{\nu}\gamma$	0.116 ± 0.010 (stat) ± 0.013 (syst) ± 0.004 (lumi)	0.115 ± 0.009

Measurement : ≈2 σ higher wrt NLO
→NNLO solves agreement
(arXiv:1504.01330)

eg : W(lν)γ f=(E_T^γ)



- Differential cross-sections

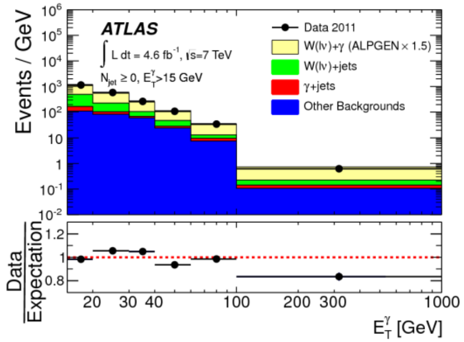
Few disagreement for W(lν)γ at high E_T^γ
NNLO solves disagreement

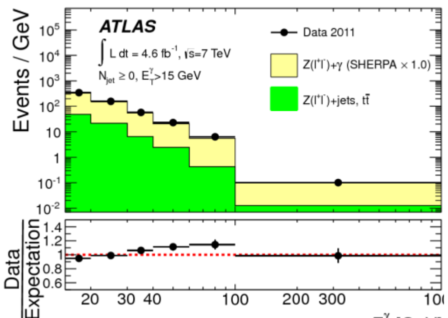
$(W/Z)\gamma$ $\sqrt{s}$=7 TeV

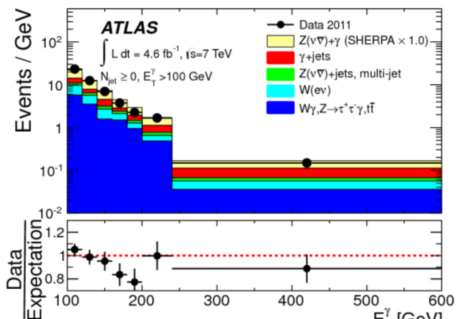
$\sqrt{s}$=7 TeV ; L=4.6 fb^{-1}

anomalous TGC enhance Vγ production w/ high E_T photon (E_T^{γ}>100 GeV)

- Limits on aTGC parameters (CP-conserving Lagrangian considered)







Charged coupling ($\Delta\kappa_\gamma=\kappa_\gamma-1$) — WW$\gamma$

Neutral coupling — ZZγ

	Measured	Expected
processes	$pp \to \ell\nu\gamma$	
Λ	∞	∞
$\Delta\kappa_\gamma$	$(-0.41, 0.46)$	$(-0.38, 0.43)$
λ_γ	$(-0.065, 0.061)$	$(-0.060, 0.056)$
Λ	6 TeV	6 TeV
$\Delta\kappa_\gamma$	$(-0.41, 0.47)$	$(-0.38, 0.43)$
λ_γ	$(-0.068, 0.063)$	$(-0.063, 0.059)$
processes	$pp \to \nu\nu\gamma$ and $pp \to \ell^+\ell^-\gamma$	
Λ	∞	∞
h_3^γ	$(-0.015, 0.016)$	$(-0.017, 0.018)$
h_3^Z	$(-0.013, 0.014)$	$(-0.015, 0.016)$
h_4^γ	$(-0.000094, 0.000092)$	$(-0.00010, 0.00010)$
h_4^Z	$(-0.000087, 0.000087)$	$(-0.000097, 0.000097)$
Λ	3 TeV	3 TeV
h_3^γ	$(-0.023, 0.024)$	$(-0.027, 0.028)$
h_3^Z	$(-0.018, 0.020)$	$(-0.022, 0.024)$
h_4^γ	$(-0.00037, 0.00036)$	$(-0.00043, 0.00042)$
h_4^Z	$(-0.00031, 0.00031)$	$(-0.00037, 0.00036)$

- No evidence for BSM physics

see also talk by Ulrike Schnoor

- Search for narrow resonances (example : Technicolor) : spin-1 mesons

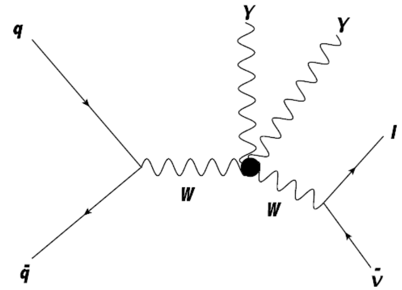
'techni-mesons' : decaying to Wγ, Zγ, using $\sqrt{s}$=8 TeV ; L=20.3 fb^{-1}

$a_T \to W\gamma$: exclude [275 ; 960] GeV $\omega_T \to Z\gamma$: exclude [200 ; 700] U [750 ; 890] GeV

Wγγ evidence, limits aQGC $\sqrt{s}$=8 TeV ; L=20.3 fb^{-1}

- inclusive selection ($N_{jet} \geq 0$)
- Bkg : data-driven estimation

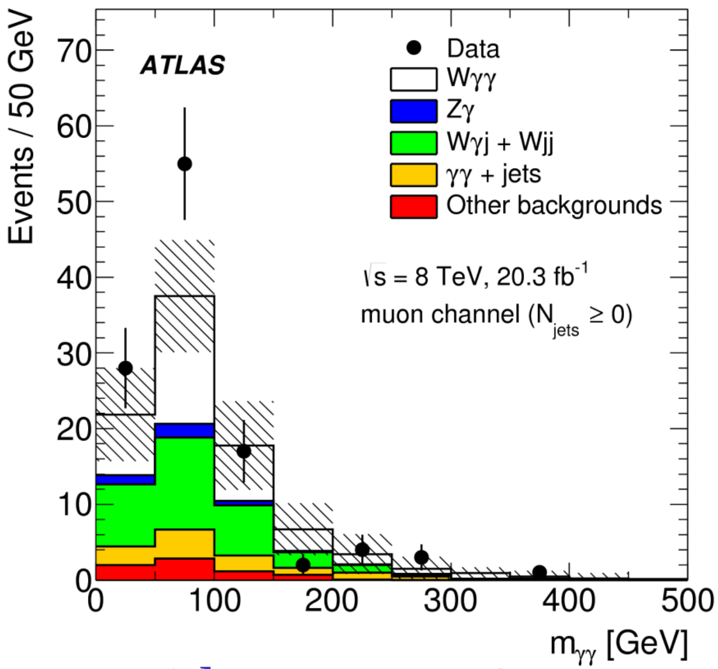
Dominant bkg : jets faking photon or lepton

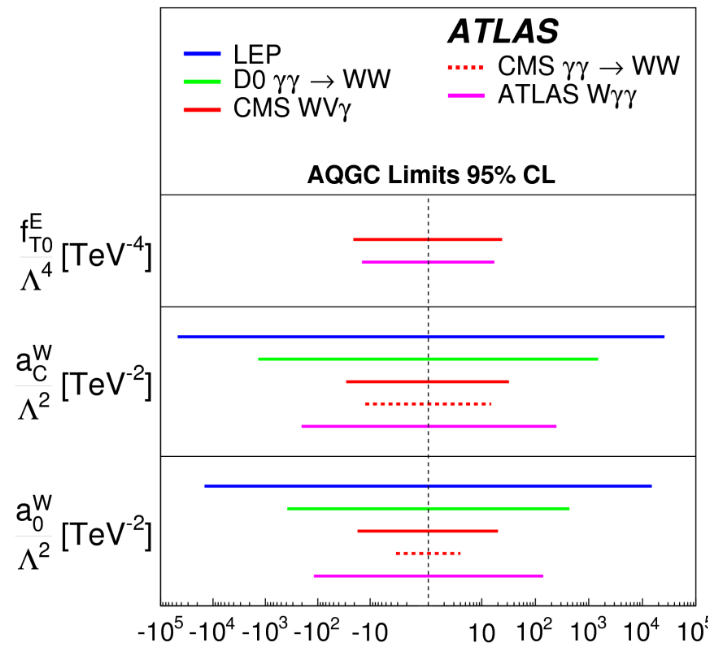


- Likelihood fit

σ=f(aQGC parameters)

- aQGC limits {N_{jet}=0 ; $m_{\gamma\gamma}$>300 GeV}





Λ : scale NP
f : coupling operator

Wγγ evidence ; p_0> 3 σ
measurement : 2 σ higher than NLO
(similar to Wγ : NNLO would help)

better or similar to LEP and D0

Pb Pb

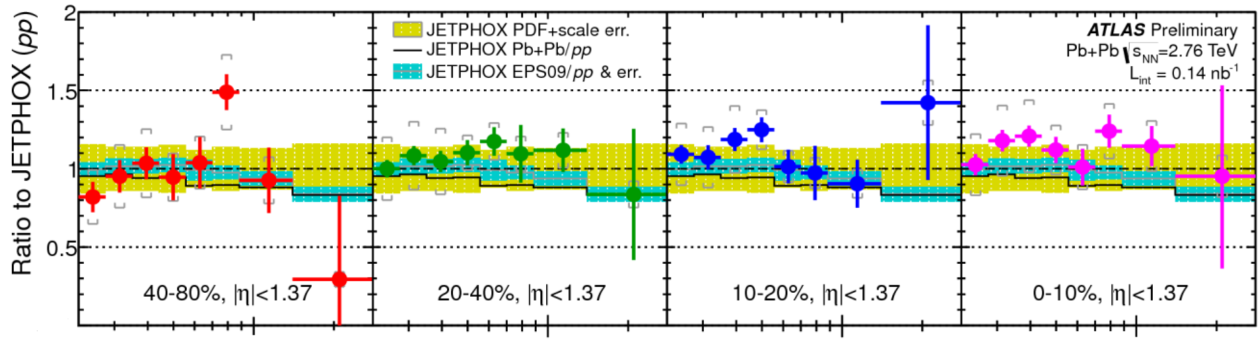
$\sqrt{s}$=2.76 TeV, L=0.14 nb^{-1}

- Estimation of signal ; bkg : 2-ABCD method
- Shower shape tight quality in Pb-Pb environment : small changes wrt pp's
- Isolation : energy deposit around cluster R=0.3

  Isolated : < 6 GeV Non Isolated : >8 GeV
- Purity : 50 % (low p_T) - 90 % (high p_T)

Total uncertainties : 10-38 %

- yields γ+X



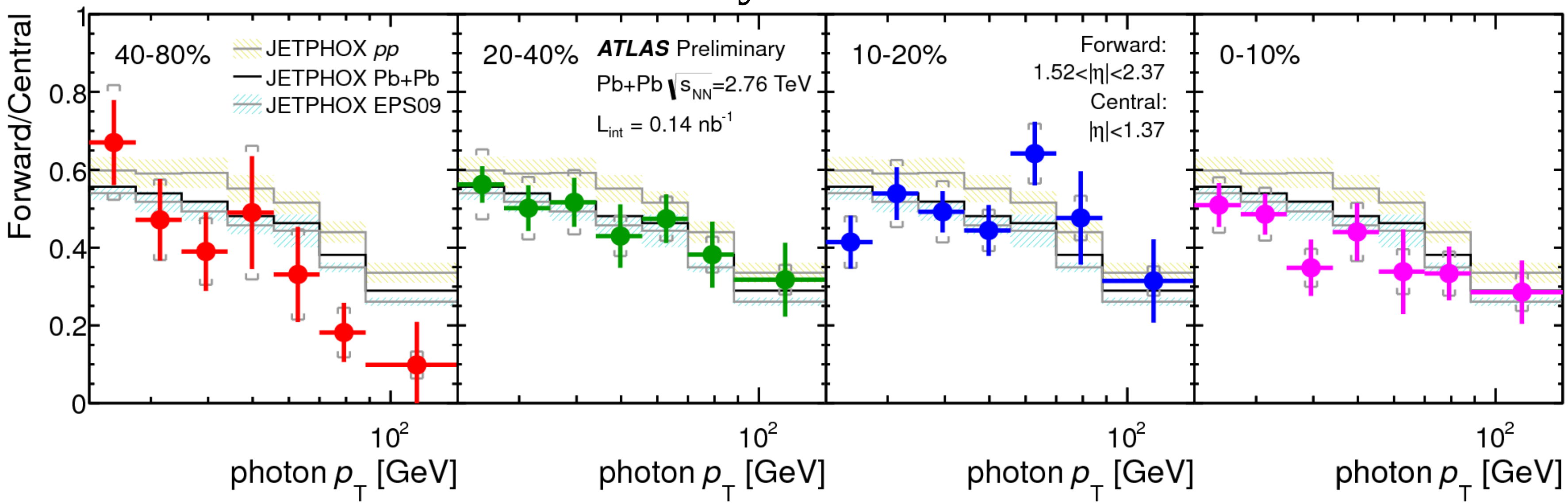
compared w/ Jetphox
w/ various Pdfs :
pp ; Pb Pb, nPDF EPS09
('isospin') (nuclear modifications to proton)

f(centrality) (done also for end-cap)

Results

$\sqrt{s}$=2.76 TeV, L=0.14 nb^{-1}

- ratio Fwd/Central : reduces systematics effects



data unable to distinguish btw scenarios ; slight preference for isospin effects

Conclusion

p p

- Single photon
  - Measured int., diff. cross-section
  - Good agreement w/ prediction
  - prospective on parton density functions
- Diphotons
  - Measured int., diff. cross-section
  - Good agreement w/ prediction
- (W/Z)γ
  - Measured int., diff. cross-section
  - Good agreement w/ prediction
  - Limits on anomalous TGC
  - search narrow resonances
  - no evidence for BSM physics
- W$\gamma\gamma$
  - Evidence for this process
  - Good agreement w/ prediction
  - Limits on aQGC in high $m_{\gamma\gamma}$

measured σ : some tensions w/ NLO computation

NNLO helps

Pb Pb : photon production

f(Centrality, pseudo-rapidity, pT)

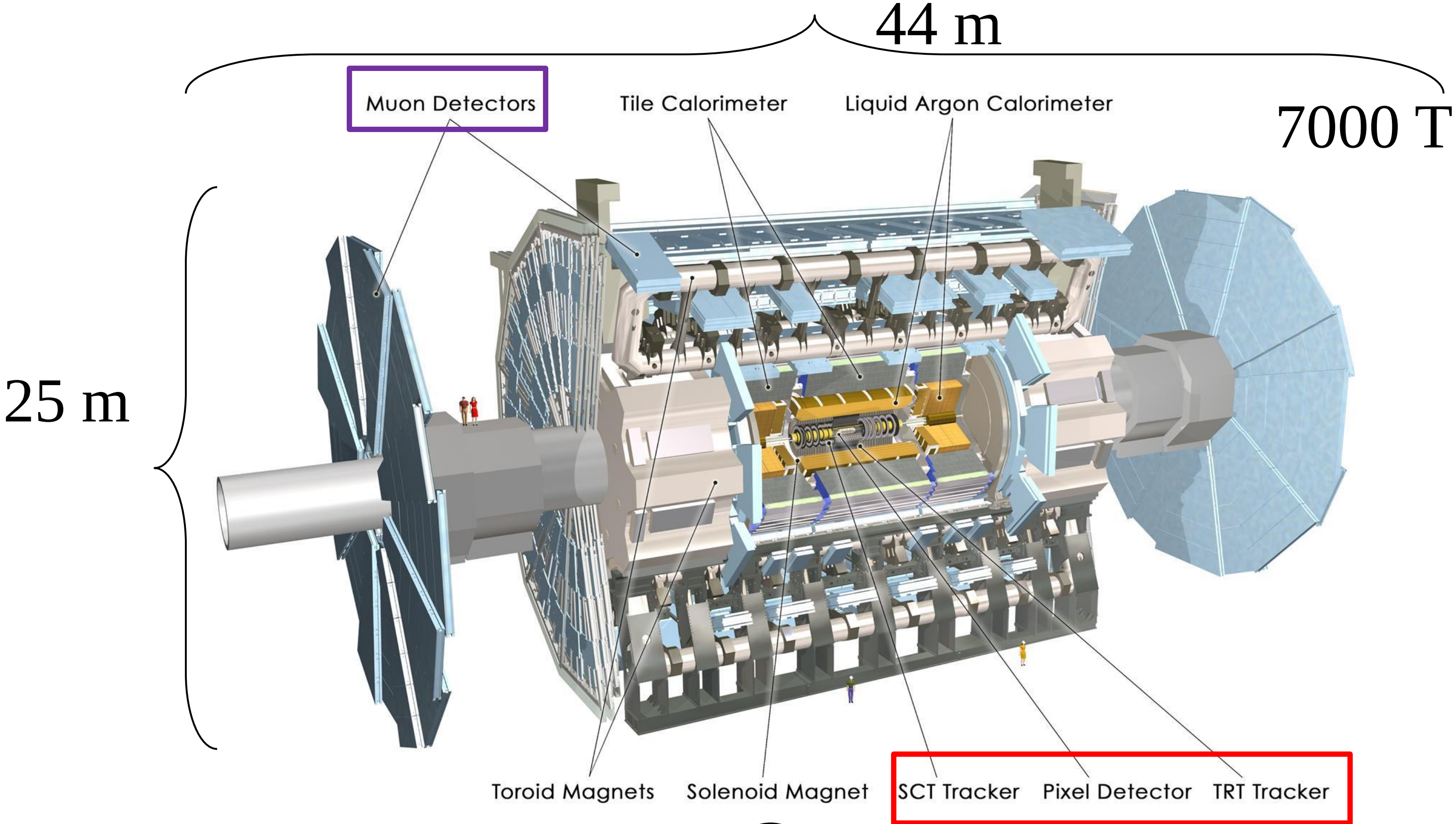
Good agreement w/ prediction

Appendix

The experimental apparatus : ATLAS

1 Inner Detector ($|\eta|<2.5$, B=2 T)
Si pixels, strips, Transition Radiation Tracker
Tracking, vertexing, e/π separation
$\sigma(p_T)/p_T < 3.8.10^{-4}$ pT [GeV] $\oplus$ 0.015

2 EM Calorimeter ($|\eta|<3.2$)
Pb-LAr accordion, longitudinal segmentation
e/γ separation
$\sigma(E)/E \approx 10\,\%/\sqrt{E} \oplus 0.7\,\%$



3 Hadronic Calorimeter
Fe-scint. ($|\eta|<1.7$) ; Cu-LAr $1.5<|\eta|<3.2$
Cu/W -LAr (fwd : $3.1<|\eta|<4.9$)
Trigger, jet, MET ; $\sigma(E)/E \approx 50\,\%/\sqrt{E} \oplus 3\,\%$

4 Muon Spectrometer ($|\eta|<2.7$)
Air core toroid magnets (0.5-1 T), gas chambers
μ trigger and momentum measurement
$\sigma(p_T)/p_T = 2\%$ at 50 GeV ; 10 % at 1 TeV

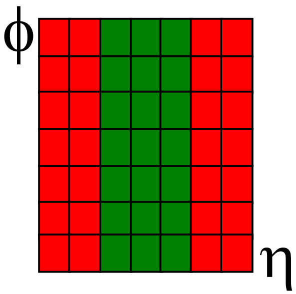
Identification photons vs jets (π^0)

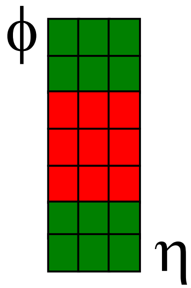
Track/cluster matching & exploits various quantities of shower shape. Ex :

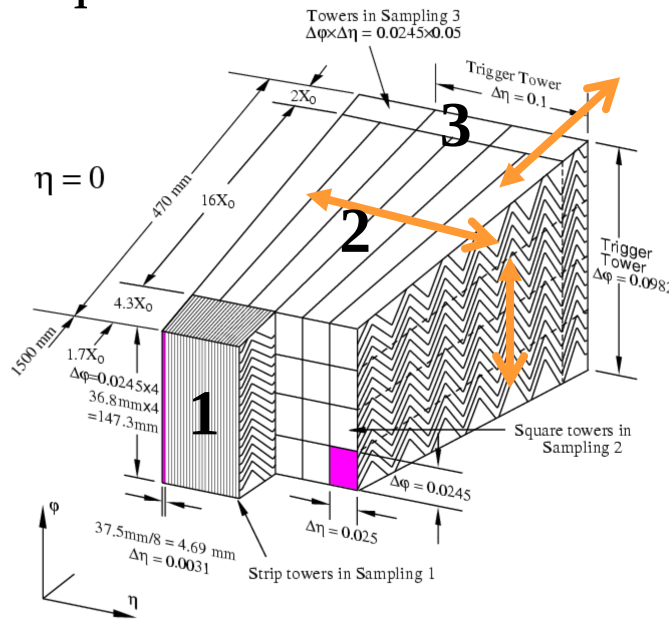
- Energy ratios

$-R_{had} = E_t^{had}/E_T$

$-R_\eta = E^{S2}_{3x7}/E^{S2}_{7x7}$ $\quad -R_\phi = E^{S2}_{3x3}/E^{S2}_{3x7}$







$-F_{side} = \dfrac{E(\pm 3)-E(\pm 1)}{E(\pm 1)}$

$-E_{ratio}$: asym. {1st ; 2nd} max

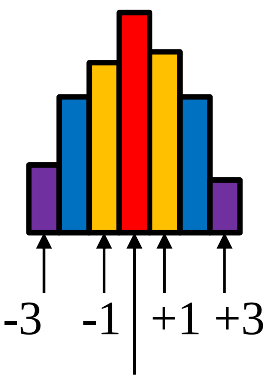
$-\Delta E = E^{S1}_{max,2} - E^{S1}_{min}$

- Widths

Σ weighted E

in 2nd or 1st sampling

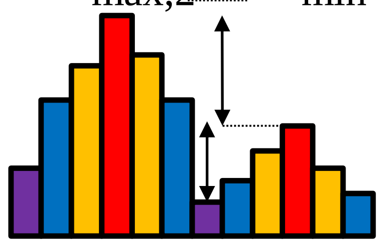
etc.



(strips)

high for fake photon

low for low photon

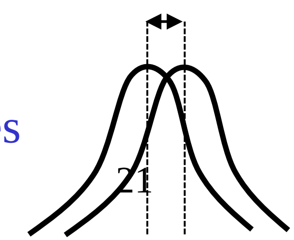


(strips)

•Data/MC disagreement in shower shapes

$\langle DV^i_{MC}\rangle - \langle DV^i_{data}\rangle$ =Fudge Factor (FF)

Later : Scale Factor



References

p p

- γ+X : production

$\sqrt{s}$=7 TeV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-16/
Phys. Rev. D 89, 052004 (2014)
http://arxiv.org/abs/1311.1440

- γ+X : constraint proton pdf w/ γ+X production

$\sqrt{s}$=7 TeV

http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2013-018/
ATL-PHYS-PUB-2013-018

- γ+j : resonances (generic gauss signal, QBH, q^*)

$\sqrt{s}$=7 TeV

http://arxiv.org/abs/1112.3580
PRL 108, 211802 (2012)
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2011-04/

$\sqrt{s}$=8 TeV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2012-22/
Phys. Lett. B 728C (2014) 562-578
http://arxiv.org/abs/1309.3230

- γ+MET : LED, squarks, DM

$\sqrt{s}$=7 TeV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2014-06/
Phys. Rev. Lett 110, 011802 (2013)
http://arxiv.org/abs/1209.4625

$\sqrt{s}$=8 TeV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2014-06/
Phys. Rev. D 91, 012008 (2015)
http://arxiv.org/abs/1411.1559

References

p p

- γγ : production
  $\sqrt{s}$=7 TeV
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-05/
  JHEP01(2013)086 http://arxiv.org/abs/1211.1913
- γγ : XD
  $\sqrt{s}$=7 TeV
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2012-06/
  new J. Phys. 15 (2013) 043007 http://arxiv.org/abs/1210.8389

  $\sqrt{s}$=8 TeV
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2012-19/
  submitted to Phys. Rev. D http://arxiv.org/abs/1504.05511
- γγ +MET
  $\sqrt{s}$=7 TeV
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2011-24/
  Phys. Lett. B 718 (2012) 411-430 http://arxiv.org/abs/1209.0753
- Wγ, Zγ production, anomalous TGC, narrow resonances
  $\sqrt{s}$=7 TeV
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-07/
  Phys. Rev. D 87, 112003 (2013) http://arxiv.org/abs/1302.1283

  $\sqrt{s}$=8 TeV
  narrow resonances
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2013-09/
  PLB 738 (2014) 428-447 http://arxiv.org/abs/1407.8150
- Wγγ production
  $\sqrt{s}$=8 TeV
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2013-05/
  sub. to PRL http://arxiv.org/abs/1503.03243
  th. explanations : http://feynrules.irmp.ucl.ac.be/wiki/AnomalousGaugeCoupling

References

- Pb Pb

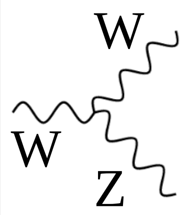
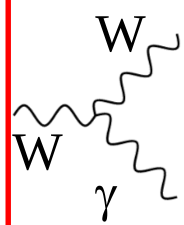
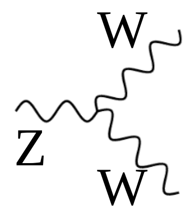
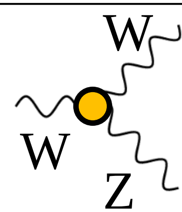
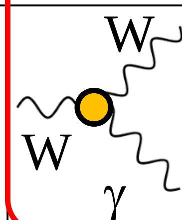
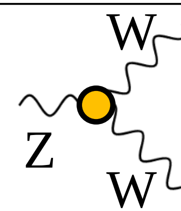
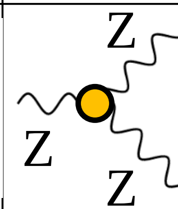
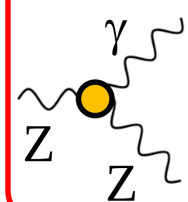
γ+X production

2011 data

First results :
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-051/
Jet-photon correlations :
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-121/
Last results :
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2014-026/

anomalous gauge couplings

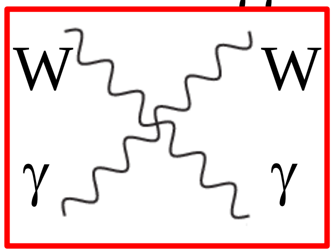
- Isolated photons : a probe for anomalous TGC

final state	WZ	Wγ	WW	ZZ	Zγ
SM				forbidden	forbidden
aTGC					

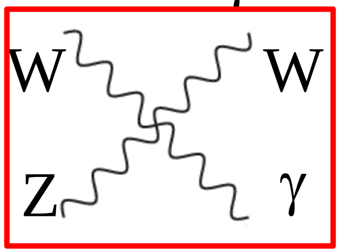
EW sector ; aTGC enhance diboson prod. rate, especially ~high p_T of photon
→Search for Wγ, Zγ (bonus : search for BSM physics w/ Wγ, Zγ final state)

- Isolated photons : a probe for anomalous QGC

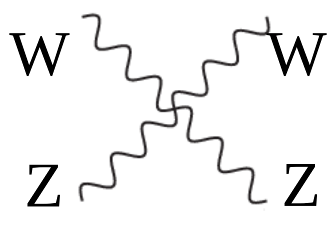
WWγγ



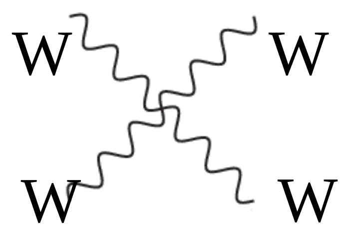
WWZγ



WWZZ



WWWW

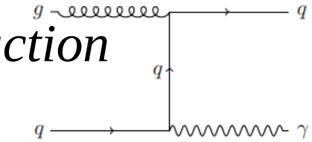


→Search for Wγγ

γ+X, $\gamma\gamma$ in pp environment

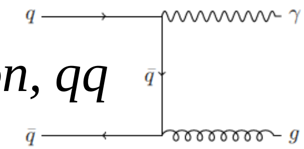
-sensitive to gluon content

Compton production (dominant)

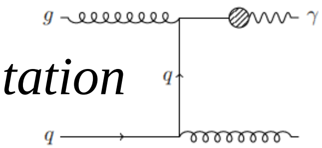


- test of perturbative QCD

annihilation, qq



fragmentation



-final state in search for resonance

γj

- -generic gauss shape signal
- -non-thermal Quantum Black Holes (QBH)
- -excited quark ($q^* \rightarrow q\gamma$)

γ+MET

- -LED (ADD), G+γ
- -dark matter (WIMP χ), $qq\chi\chi + \gamma$
- -squarks + γ
  $q \rightarrow q + \tilde{\chi}_1^0$

$\gamma\gamma$+MET

- -GMSB : NLSP : case of lightest neutralino $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$
  LSP : gravitino $\tilde{G} \rightarrow G\gamma$
- -UED: production pair KK of quarks/gluons
  decay cascade until lightest KK particle :
  KK photon $\gamma^* \rightarrow \gamma + G$

$\gamma\gamma$: XD

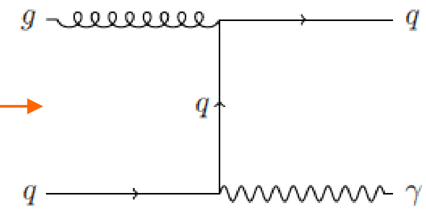
- -RD : KK $G^* \rightarrow \gamma\gamma$

$H \rightarrow \gamma\gamma$ (dedicated talk by **Yohei Yamaguchi)**

- **p p environnement**

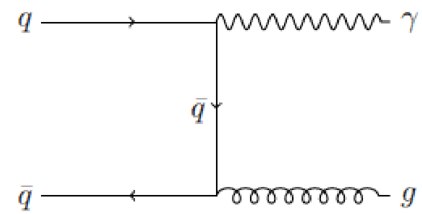
-sensitive to gluon content

Compton production (dominant process)

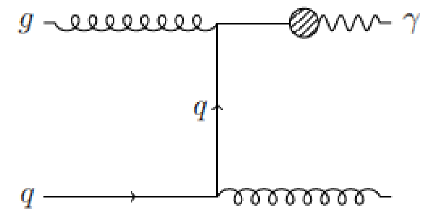


- test of perturbative QCD

annihilation, qq



fragmentation



Isolated photons : a rich probe with various goals

-final state in search for resonance

-generic gauss shape signal -non-thermal Quantum Black Holes (QBH) (evaporate faster than thermalization)	γj final state
-excited quark (q^*) -LED (ADD), G+γ -dark matter (WIMP χ), qq$\chi\chi$ + γ -squarks + γ $\tilde{q} \rightarrow q+\chi_1^0$	γ+MET
-GMSB : LSP : gravitino $\tilde{G}$ NLSP : case of lightest neutralino $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ -UED: production pair KK of quarks/gluons decay cascade until lightest KK particle : KK photon $\gamma^* \rightarrow \gamma$+G	$\gamma\gamma$+MET
-RD : KK $G^* \rightarrow \gamma\gamma$	$\gamma\gamma$: XD
-H$\rightarrow\gamma\gamma$ (dedicated talk by **Yohei Yamaguchi)**	

$\rightarrow$probe γX, $\gamma\gamma$

Misc

Systematics :

-Photon selection cuts (shower shape, isolation)

-Variations on objects treatment and definition of CR

removal of shower shape correction, changes in isolation cuts, etc

-modeling of signal in MC ; leakage corrections

-Removing fragmentation photons from MC

-Energy scale/resolution uncertainties

-Functional forms to describe bkg isolation template

- Detector performance : unfolding resolution and energy scale effects
- Integrated cross-section $\sigma^{\rm ext-fid}_{pp\to\ell\nu\gamma(\ell^+\ell^-\gamma/\nu\bar{\nu}\gamma)} = \frac{N^{\rm sig}_{W\gamma(Z\gamma)}}{A_{W\gamma(Z\gamma)}\cdot C_{W\gamma(Z\gamma)}\cdot\int\mathcal{L}dt}$

  in a defined fiducial region

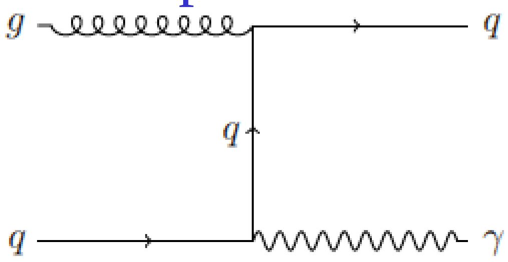
  C : reco vs generated at particle level

  A : acceptance generated at particle level
- Differential cross-section $\frac{d\sigma_i}{dx} = \frac{N_i^{\rm unfold}}{\int\mathcal{L}dt\cdot dx}$

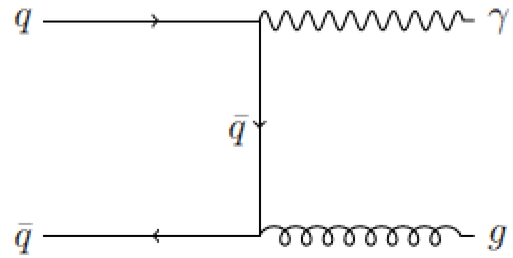
$p\,p \rightarrow \gamma X$

LO

Compton

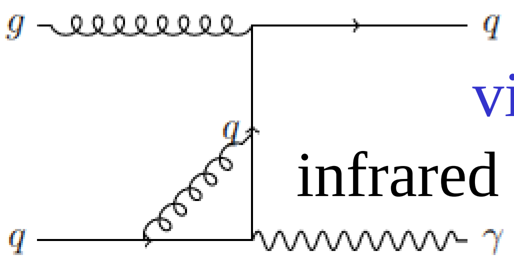


annihilation



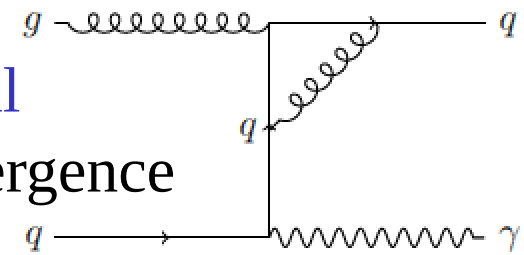
Hard scattering

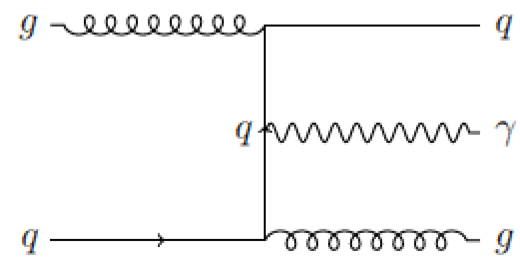
NLO Weaker $P_T\ \gamma$, higher rate



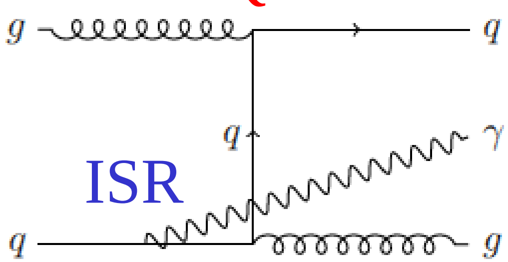
virtual

infrared divergence

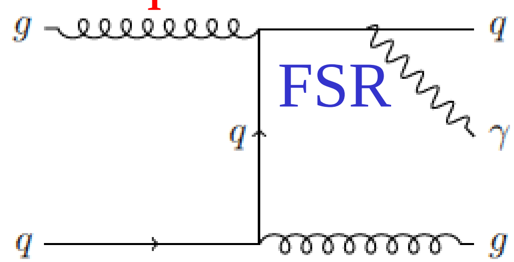




QED radiation from quark

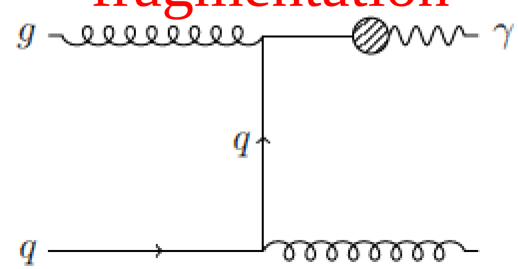


ISR



FSR

fragmentation

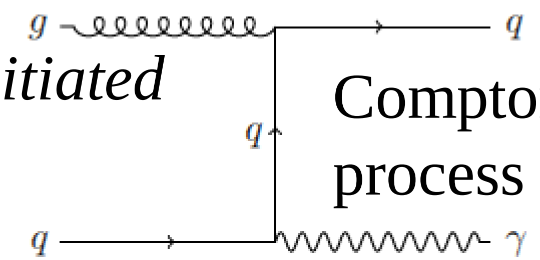


P_T<20 GeV : NLO dominant, P_T >20 GeV : LO dominant

pdf from p p → γX

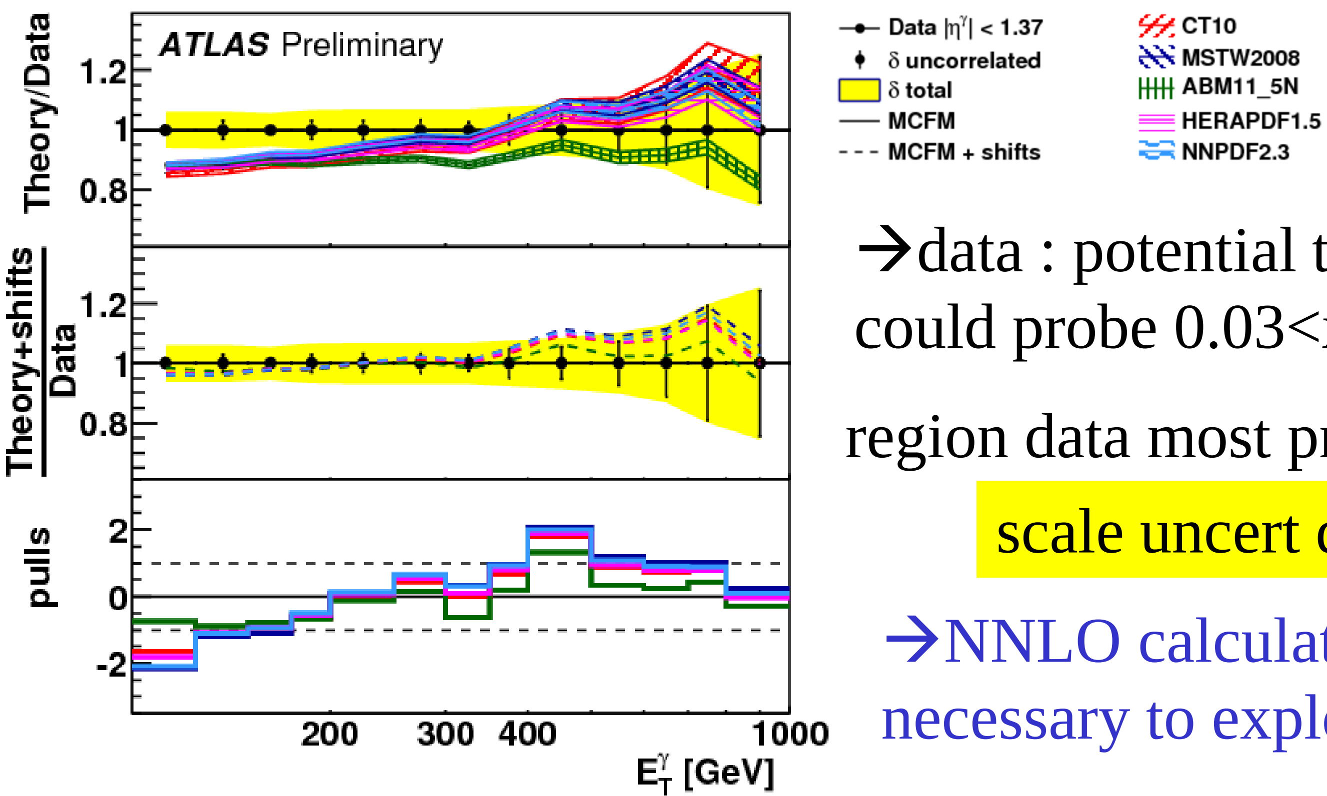
ug initiated production dominates
(q(u) ; gluon prevalence)

g initiated



Compton process

- Comparison data vs prediction for various pdf, quantifing w/ χ^2
  Tensions btw measured data and predictions



→data : potential to constrain gluon pdf could probe $0.03<x<0.3$; $x\sim 2E_T^{\gamma}/\sqrt{s}$

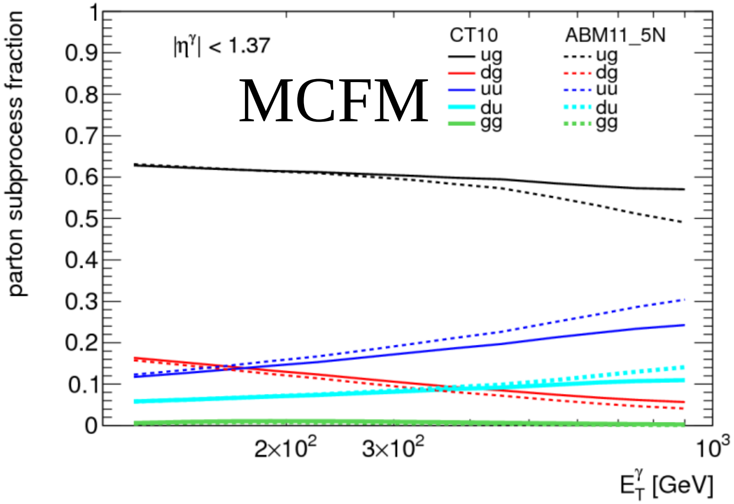
region data most precise ($200<E_T^{\gamma}<600$ GeV) :

scale uncert dominant

→NNLO calculation would be necessary to exploit fully the potential

pdf from p p → γX

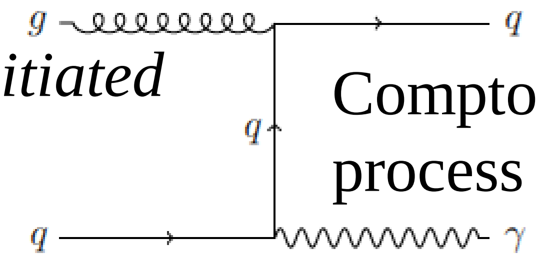
Isolated photon production



ug initiated production dominates

q(u) ; gluon prevalence

g initiated



Compton process

- Comparison data vs prediction for various pdf, quantifing w/ χ^2

  Tensions btw measured data and predictions

→data have potential to constrain shape and uncertainty on gluon distribution

could probe $0.03<x<0.3$; $x\sim 2E_T^\gamma/\sqrt{s}$

- region data most precise ($200<E_T^\gamma<600$ GeV) : scale uncert dominant

→NNLO calculation would be necessary to exploit fully the potential

γ+j : resonances $\sqrt{s}$=7 TeV ; L=2.11 fb^{-1}

- Bkg

γ+j prod
n-jets prod : radiation, fragmentation

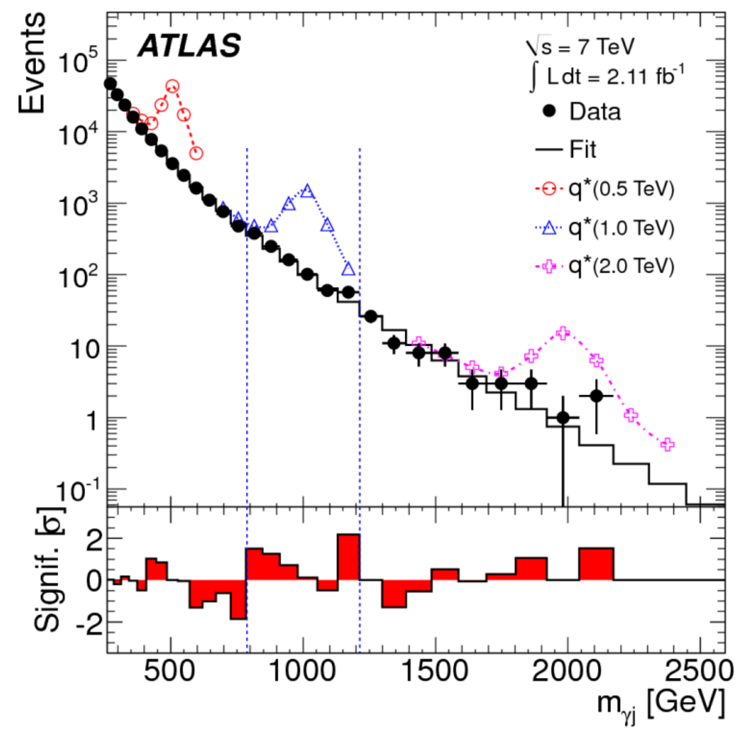
- Selection

-photons : p_T>85 GeV, $|\eta|$<1.37 (suppr. di-jet : rate ↑ w/ η)
(avoid kin. bias $m_{\gamma j}$ regions w/ lower eff.)
tight, (calo isol<7 GeV)
-jets p_T>30 GeV, $|\eta|$<2.8
$\Delta R(\gamma,j)$>0.6 (suppr. photons from fragm.)

$|\eta_\gamma - \gamma_j|$<1.4 (optimisation)

- Final DV : $m_{\gamma j}$

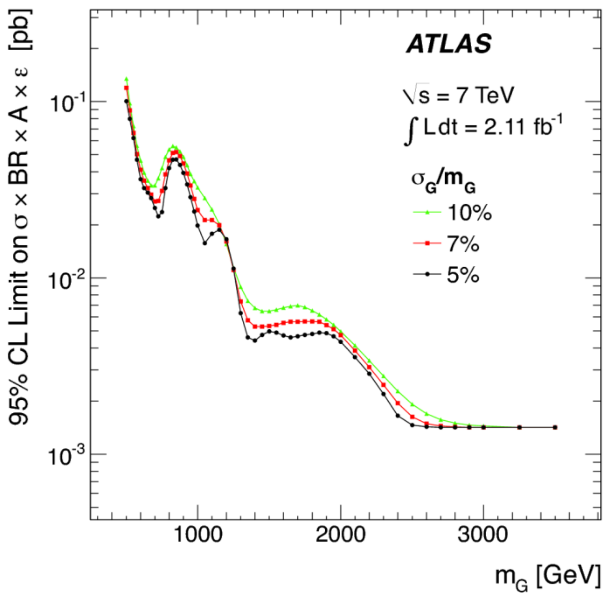
-smooth, rapidly falling
-fit smooth function



γ+j : resonances $\sqrt{s}$=7 TeV ; L=2.11 fb^{-1}

- 95 % CL limits

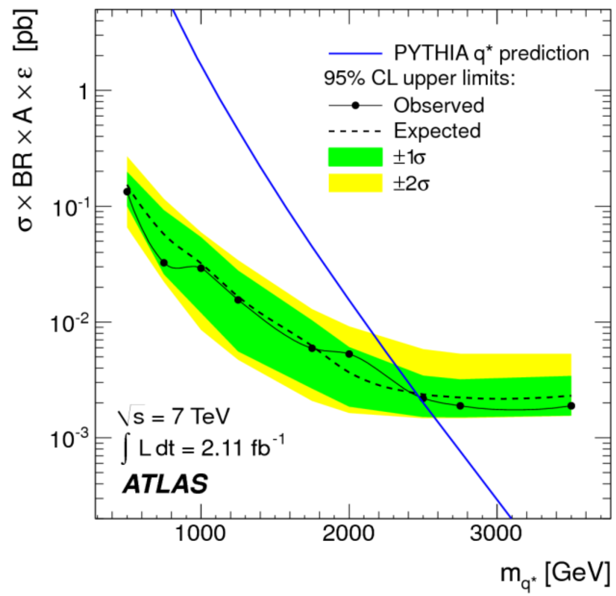
-generic gauss shape signal



2 TeV resonance excluded w/ σ_{eff}=5 fb

(σ_{eff}=σ x BR x A x ε)

-excited quark q*



excluded up to 2.46 TeV

γ+j : resonances $\sqrt{s}$=8 TeV ; L=20.3 fb^{-1}

- Bkg

γ+j prod
n-jets prod : radiation, fragmentation

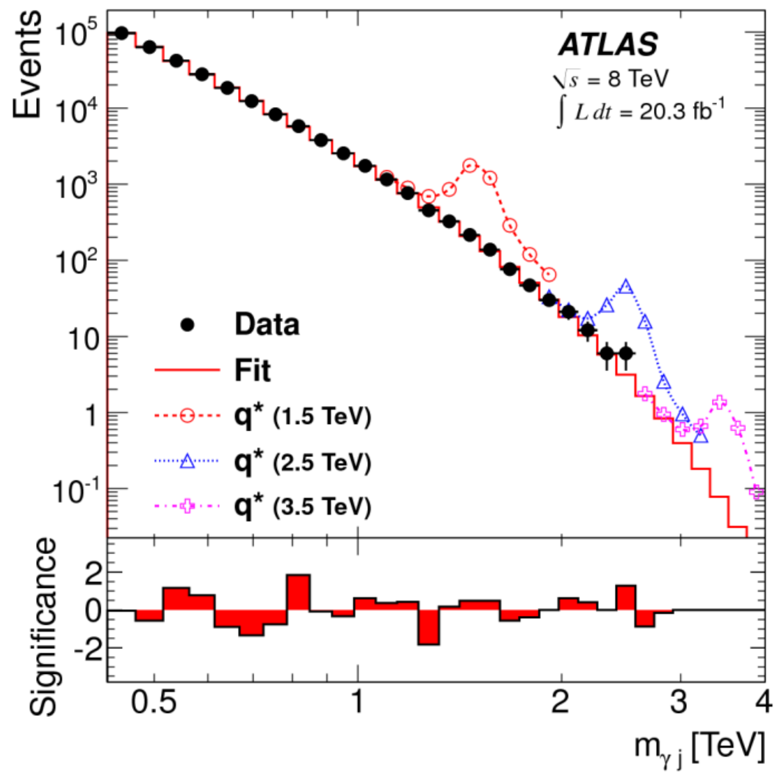
- Selection

-photons : p_T>125 GeV, $|\eta|$<1.37 (suppr. di-jet : rate ↑ w/ η)
(avoid kin. bias $m_{\gamma j}$ regions w/ lower eff.)
tight, isolated (calo isol<3.65+0.011 p_T^{γ})
-jets : p_T>125 GeV, $|\eta|$<2.8

$\Delta R(\gamma,j)$>1.0 for jets w/ p_T>30 GeV(suppr. fragm.)
$|\eta_\gamma-\gamma_j|$<1.6 (optimisation)
$m_{\gamma j}$>426 GeV : SR

- Final DV : $m_{\gamma j}$

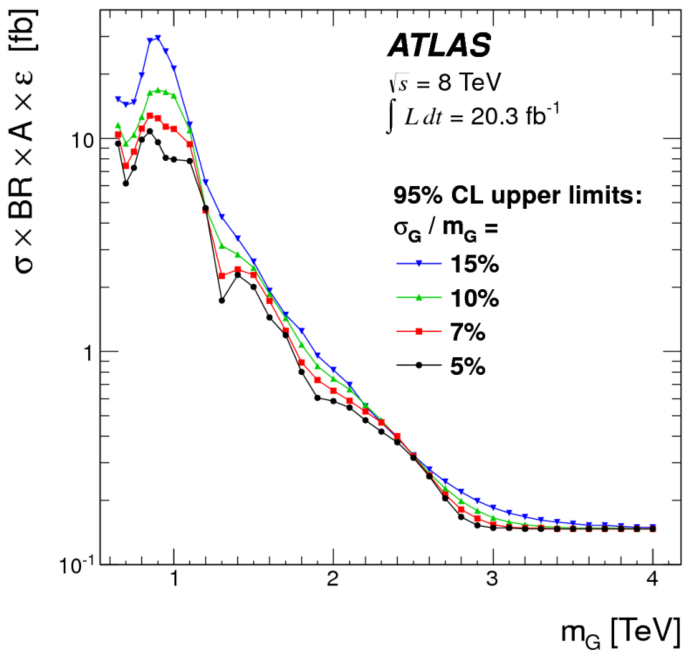
-smooth, rapidly falling
-fit smooth function



γ+j : resonances $\sqrt{s}$=8 TeV ; L=20.3 fb^{-1}

- 95 % CL limits

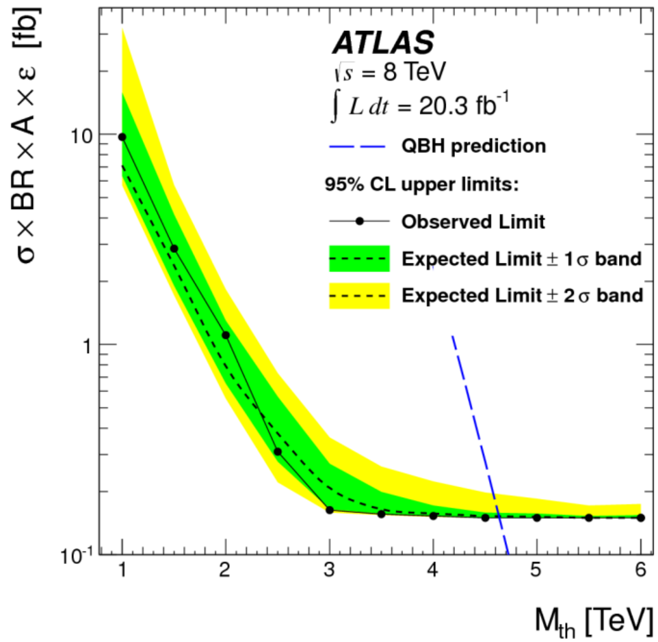
-generic gauss shape signal



4 TeV resonance excluded w/ σ_{eff}=0.1 fb

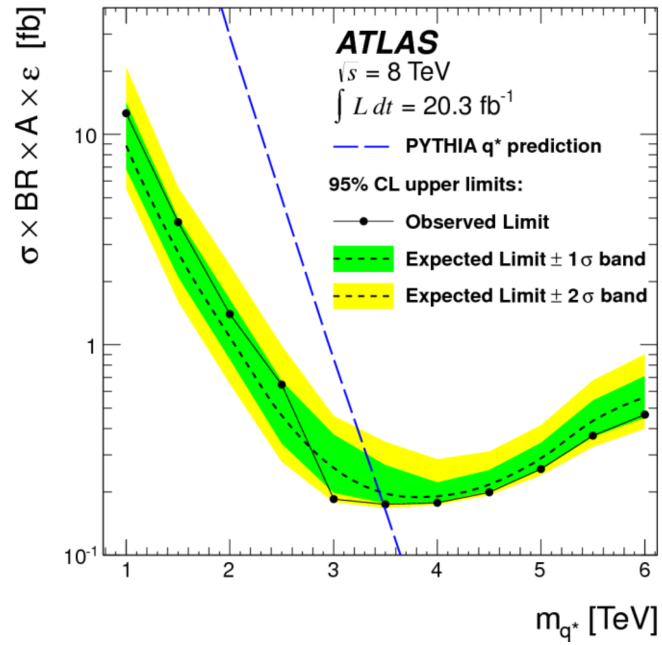
(σ_{eff}=σ x BR x A x ε)

-QBH



excluded up to 4.6 TeV

-excited quark q*



excluded up to 3.5 TeV

γ+MET : BSM

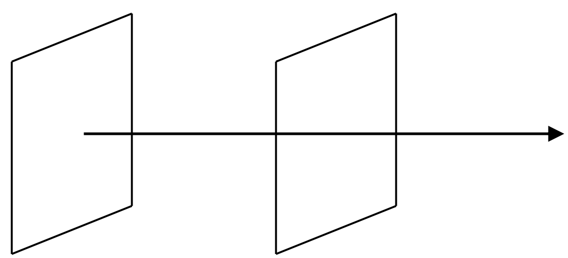
- Large extra dimensions : ADD

$m^2_{Planck} \approx m_D^{2+n} R^n$

N. Arkani-Hamed, S. Dimopoulos, G. Dvali: The Hierarchy Problem and New Dimensions at a Millimeter, Phys. Lett. B429, 263(1998), hep-ph/9803315

- Curvature space-time : Randall-Sundrum

L. Randall, R. Sundrum: A large Mass Hierarchy from a Small Extra Dimension, Phys. Rev. Lett. 83, 3370(1999), hep-ph/9905221



extra dimension : gravitation only

y

Brane Planck

0

πR_c

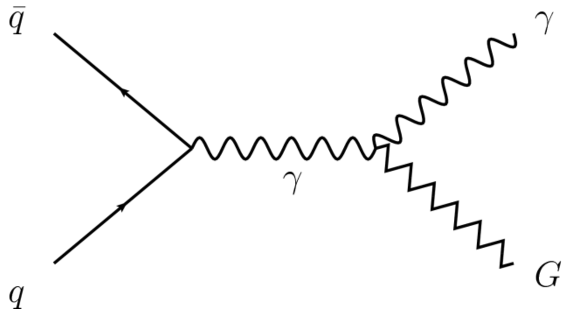
Brane TeV (SM)

$M_D = \overline{M}_{pl} e^{-k\pi Rc}$

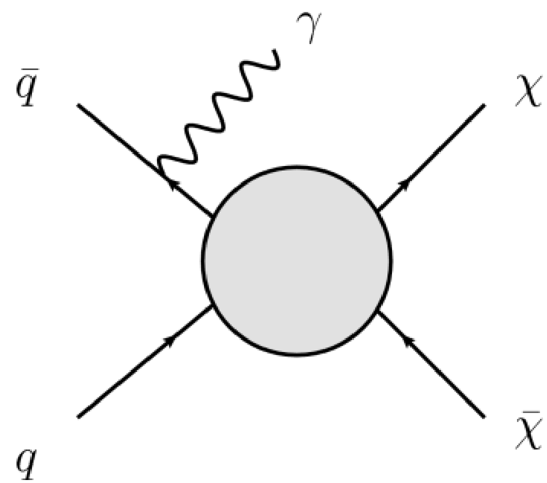
$\overline{M}_{Pl} = M_{Pl}/\sqrt{(8\pi)}$

γ+MET : BSM

-LED (ADD), G+γ

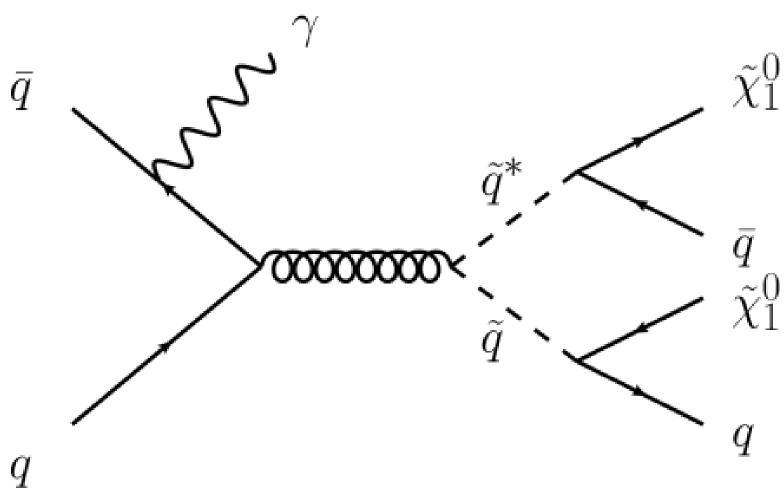


-dark matter (WIMP χ)
qq$\chi\chi$ w/ radiations



-squarks

$q \rightarrow q+\chi_1^0$



γ+MET : BSM

$\sqrt{s}$=7 TeV ; L=4.6 fb^{-1}

- Background

Z($\nu\nu$)+γ (ISR)

Wγ, Zγ, unidentified lepton

W/Z, l/j identified as photon

Top, dibosons, γ+j, multijets

- Selection

-photon p_T>150 GeV, $|\eta|<2.37$

-MET>150 GeV

$\Delta\phi(\gamma, MET)>0.4$

Veto > 1 jet

Veto electron/muon p_T>20/10 GeV (suppr. W/Z)

γ+MET : BSM

$\sqrt{s}$=8 TeV ; L=20.3 fb^{-1}

- Background

Z($\nu\nu$)+γ (ISR)
Wγ, Zγ, unidentified lepton
W/Z, l/j identified as photon
Top, dibosons, γ+j, multijets

- Selection

-photon p_T>125 GeV, $|\eta|$<1.37
-MET>150 GeV
$\Delta\phi(\gamma$, MET)>0.4
Veto > 1 jet
Veto electron/muon p_T>7/6 GeV (suppr. W/Z)

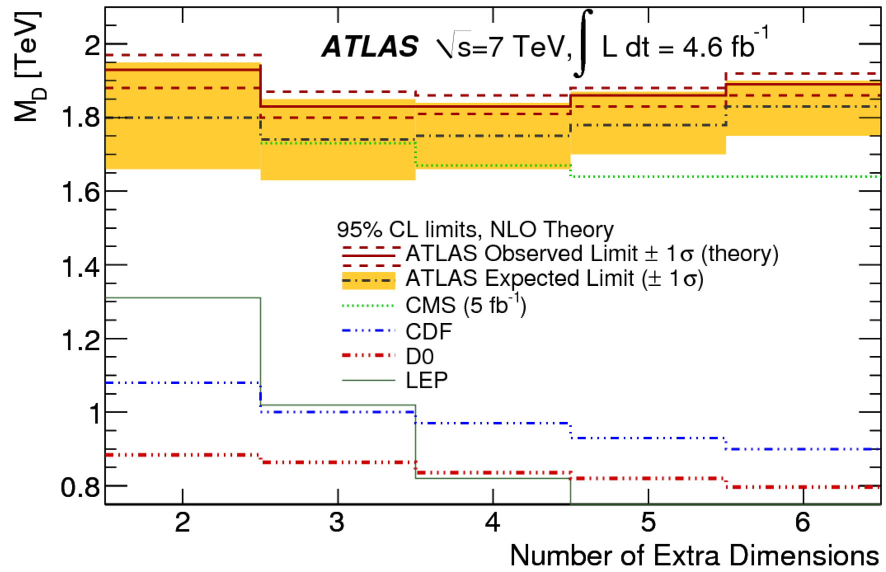
γ+MET : BSM

$\sqrt{s}$=7 TeV ; L=4.6 fb^{-1}

- 95 % CL limits

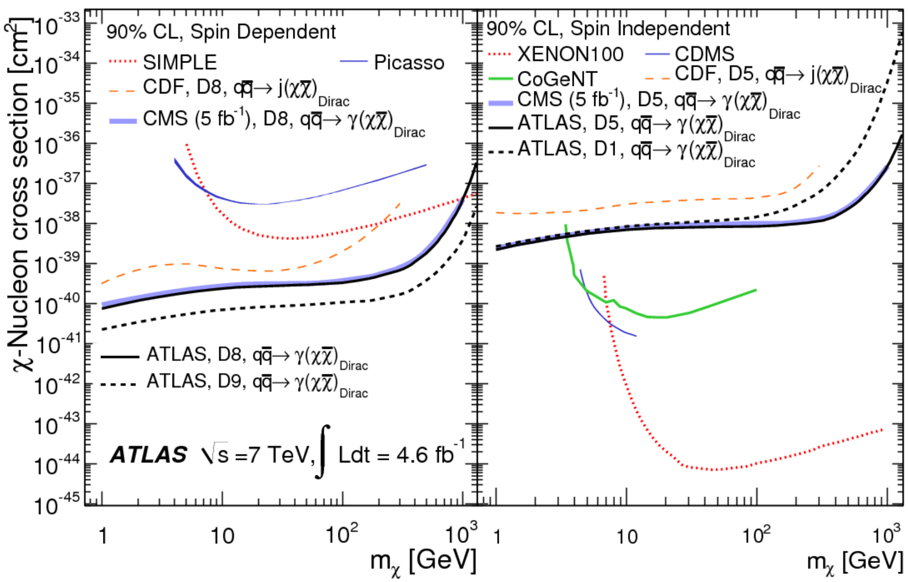
σ_{fid} =6.8 fb

-LED



exclude m_D=1.93 TeV (n=2)

-Dark matter



EFT operators for Wimp :

D5 (V), D8 (A), D9 (T)

γ+MET : BSM

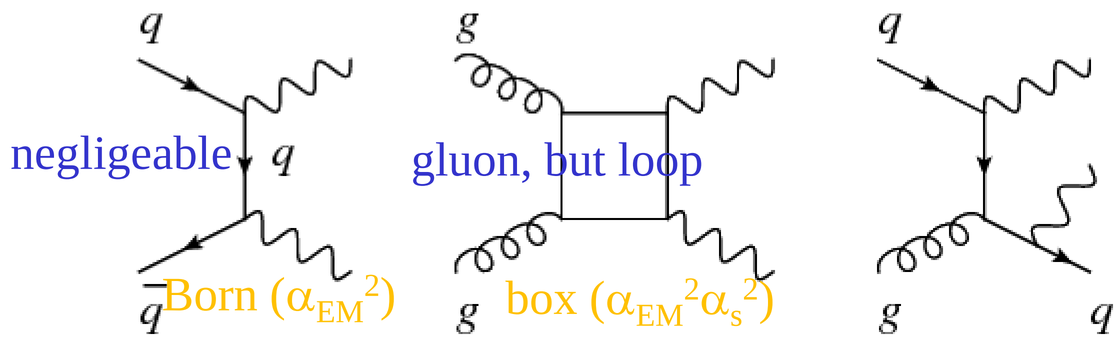
Interaction WIMP-SM description : contact interaction using EFT
Effective interactions coupling WIMP to SM particles

http://arxiv.org/abs/1502.01518

Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

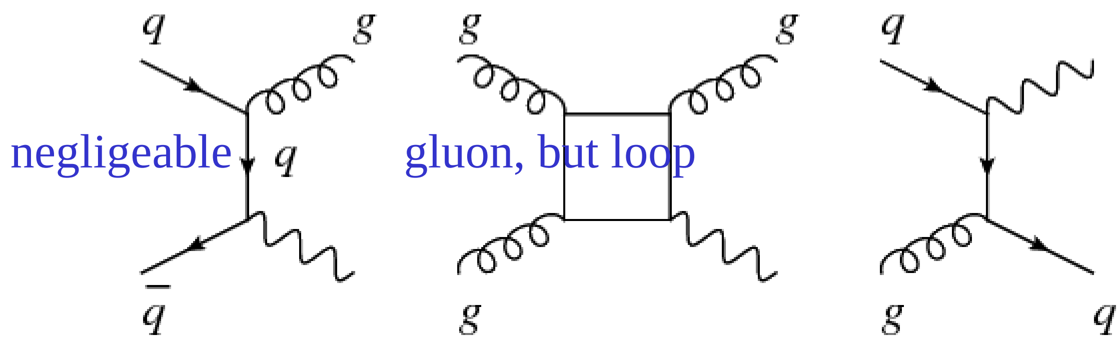
γγ, γj, jj production

γγ

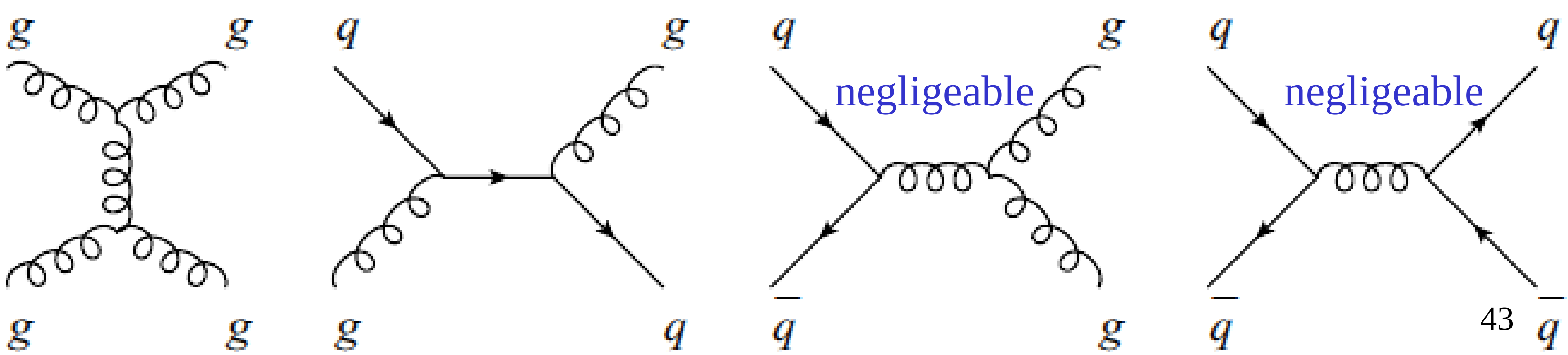


bremsstrahlung
($\alpha_{EM}^2\alpha_s$) (correction to Born)
Infrared and collinear divergence

γj



jj



p p → $\gamma\gamma$

Template fit : made in signal region : $-4<E_T^{iso}<4$ GeV
Correlations between E_T^{iso} : negligeable
→product of two for three species : γγ, γj, jj
binned distributions
Signal leakage corrections considered

signal γγ : distribution transverse isolation/efficiency : sherpa
bkg jγ : extracted from data w/ one non-tight candidate, other tight isolated
jj : data : two non tight candidates
correlation : O(8 %)

electron bkg : DY Z→ee, WW→eνeν, γW→γeν, γZ→γee

$$N_{\gamma\gamma}^{\text{sig}} = \frac{N_{\gamma\gamma} - \left[f_{e\to\gamma} N_{\gamma e} - (f_{e\to\gamma})^2 N_{ee}\right]}{(1 - f_{e\to\gamma} f_{\gamma\to e})^2}$$

H→γγ 'bkg' : neglected : 1 % of signal in $120<m_{\gamma\gamma}<130$ GeV

$pp \rightarrow \gamma\gamma$

- Integrated cross-section (σ_{integ})

Measured : $=44.0^{+3.2}_{-4.2}$ pb

Predicted :

-Pythia : LO $\gamma\gamma$, models HO through production γj, jj and ISR/FSR

-Sherpa : same features as Pythia + HO ME for real ME

36 pb (underestimates σ by 20 %)

-Diphox : NLO QCD direct and fragmentation $\gamma\gamma$; box gg$\rightarrow\gamma\gamma$ LO

-gamma2MC : HO box

39^{+7}_{-6} pb

-2γNNLO : NNLO QCD direct part $\gamma\gamma$, no fragmentation

44^{+6}_{-5} pb

- Differential cross-section

$m_{\gamma\gamma}$: resonance search

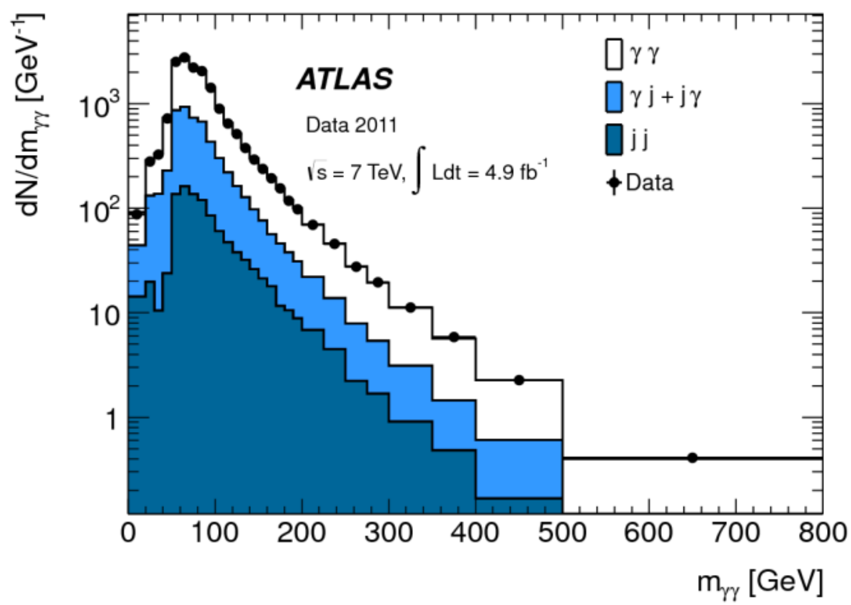
$p_{T\gamma\gamma}$: probe HO QCD pertub. effects, fragm.

$\Delta\phi_{\gamma\gamma}$, : probe specific regions of phase space

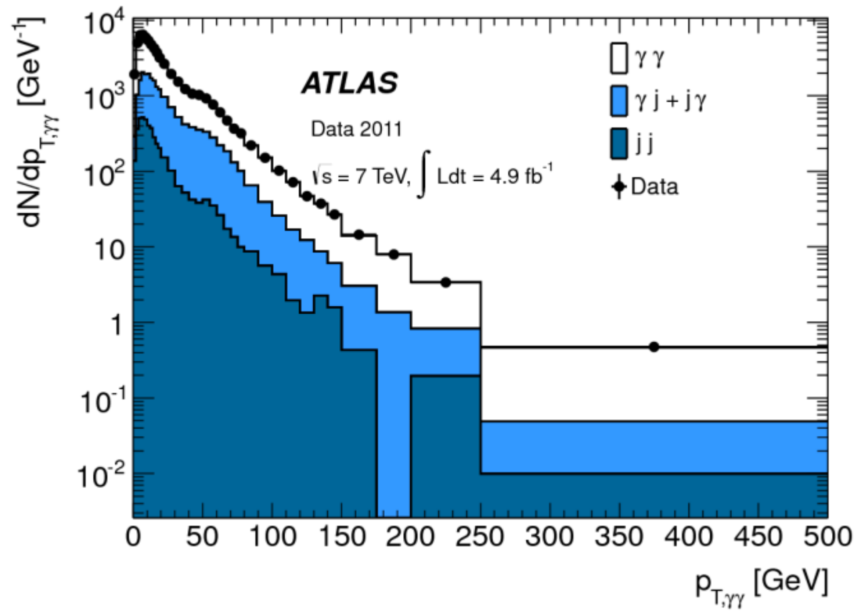
cos $\theta^*_{\gamma\gamma}(\gamma)$: probe spin of diphotons resonance

- excellent agreement data/prediction

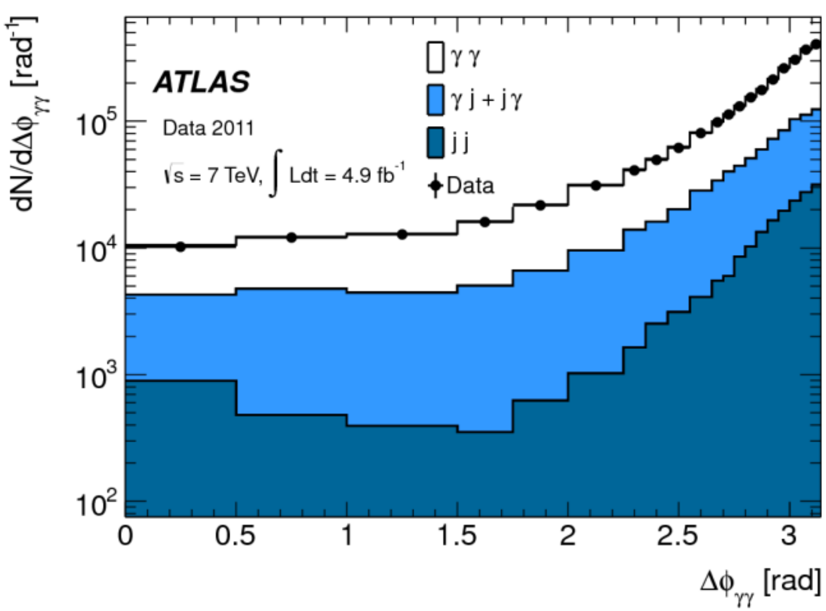
p p → γγ



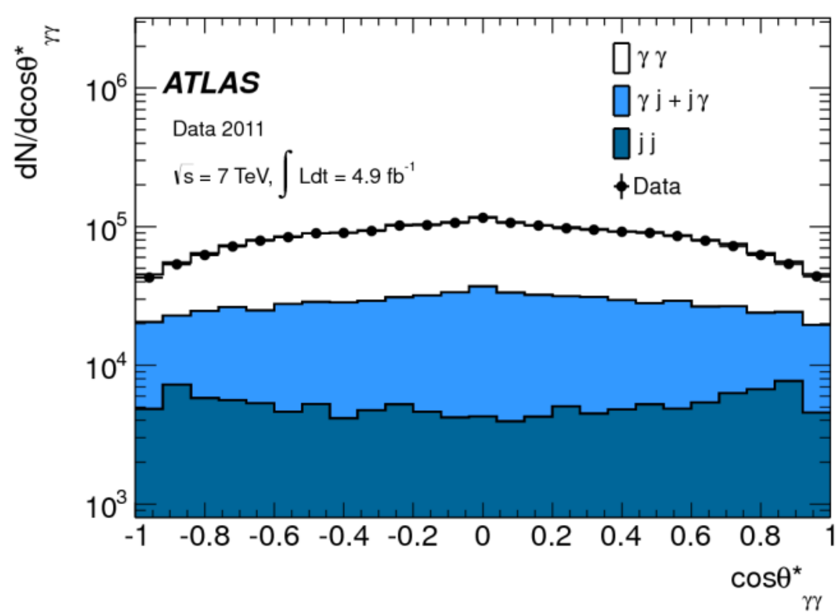
ATLAS
Data 2011
√s = 7 TeV, ∫ Ldt = 4.9 fb⁻¹
γ γ
γ j + j γ
j j
Data
dN/dm_γγ [GeV⁻¹]
m_γγ [GeV]



ATLAS
Data 2011
√s = 7 TeV, ∫ Ldt = 4.9 fb⁻¹
γ γ
γ j + j γ
j j
Data
dN/dp_T,γγ [GeV⁻¹]
p_T,γγ [GeV]



ATLAS
Data 2011
√s = 7 TeV, ∫ Ldt = 4.9 fb⁻¹
γ γ
γ j + j γ
j j
Data
dN/dΔφ_γγ [rad⁻¹]
Δφ_γγ [rad]



ATLAS
Data 2011
√s = 7 TeV, ∫ Ldt = 4.9 fb⁻¹
γ γ
γ j + j γ
j j
Data
dN/dcosθ*_γγ
cosθ*_γγ

$p\,p \rightarrow \gamma\gamma$

- Selection

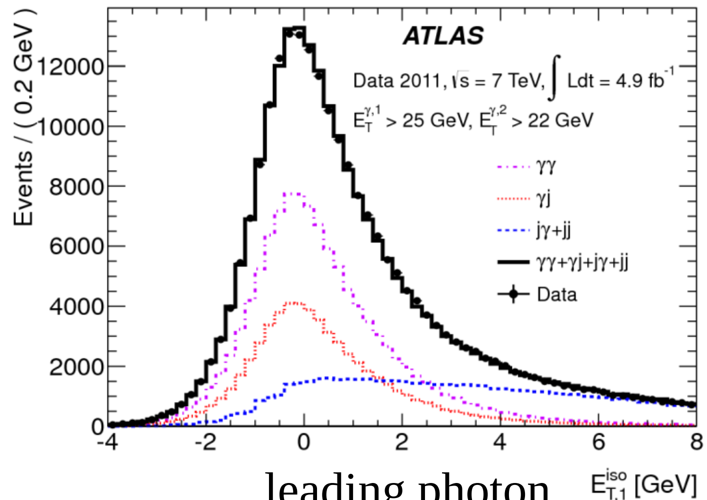
$E_{T\gamma}^{L,\,S}$>25 GeV ; 22 GeV

$|\eta|_\gamma$<1.37 ; 1.52≤$|\eta|_\gamma$<2.37

- Bkg estimation :

-2D template likelihood fit : calorimeter isolation

-2 ABCD sidebands



leading photon

signal : -4<E_T^{iso}<4 GeV

bkg : 4<E_T^{iso}<8 GeV

- Results

Yield	two-dimensional sidebands results			two-dimensional fit results		
$N_{\gamma\gamma}$	113 200	±600 (stat.)	$^{+5000}_{-8000}$ (syst.)	111 700	±500 (stat.)	$^{+4500}_{-7600}$ (syst.)
$N_{\gamma j}$	31 500	±400 (stat.)	$^{+3900}_{-3100}$ (syst.)	31 500	±300 (stat.)	$^{+4800}_{-3600}$ (syst.)
$N_{j\gamma}$	13 000	±300 (stat.)	$^{+2500}_{-\ 800}$ (syst.)	13 900	$^{+300}_{-200}$ (stat.)	$^{+3400}_{-2100}$ (syst.)
N_{jj}	8 100	±100 (stat.)	$^{+1900}_{-1400}$ (syst.)	8 300	±100 (stat.)	$^{+\ 300}_{-2100}$ (syst.)

$pp \rightarrow \gamma\gamma$

$\sqrt{s}$=7 TeV ; L=4.9 fb^{-1}

- Integrated cross-section (σ_{integ})

Measured : $=44.0^{+3.2}_{-4.2}$ pb

Predicted : 44^{+6}_{-5} pb

2γNNLO : NNLO QCD direct part γγ, no fragmentation
(some lower order tested also)

- Differential cross-section

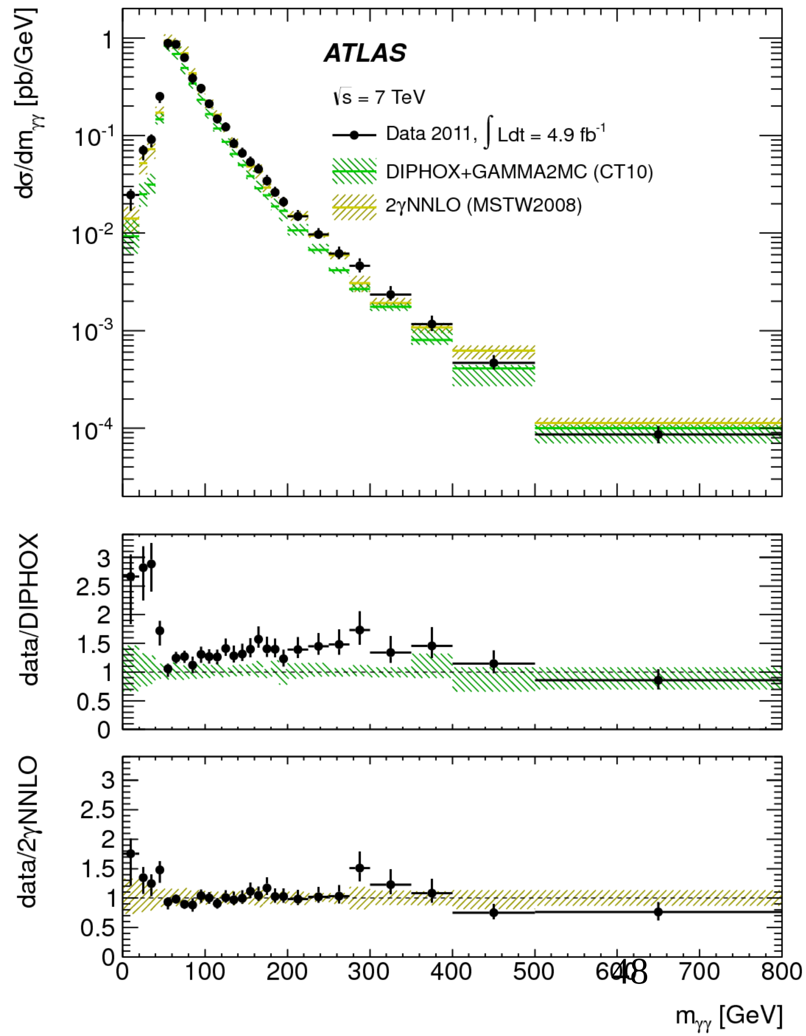
$m_{\gamma\gamma}$: resonance search

$p_{T\gamma\gamma}$: probe HO QCD pertub. effects, fragm.

$\Delta\phi_{\gamma\gamma}$, : probe specific regions of phase space

$\cos\theta^{*}_{\gamma\gamma}(\gamma)$: probe spin of diphotons resonance

excellent agreement data/prediction



$\gamma\gamma$: XD

$\sqrt{s}$=7 TeV ; L=4.9 fb^{-1}

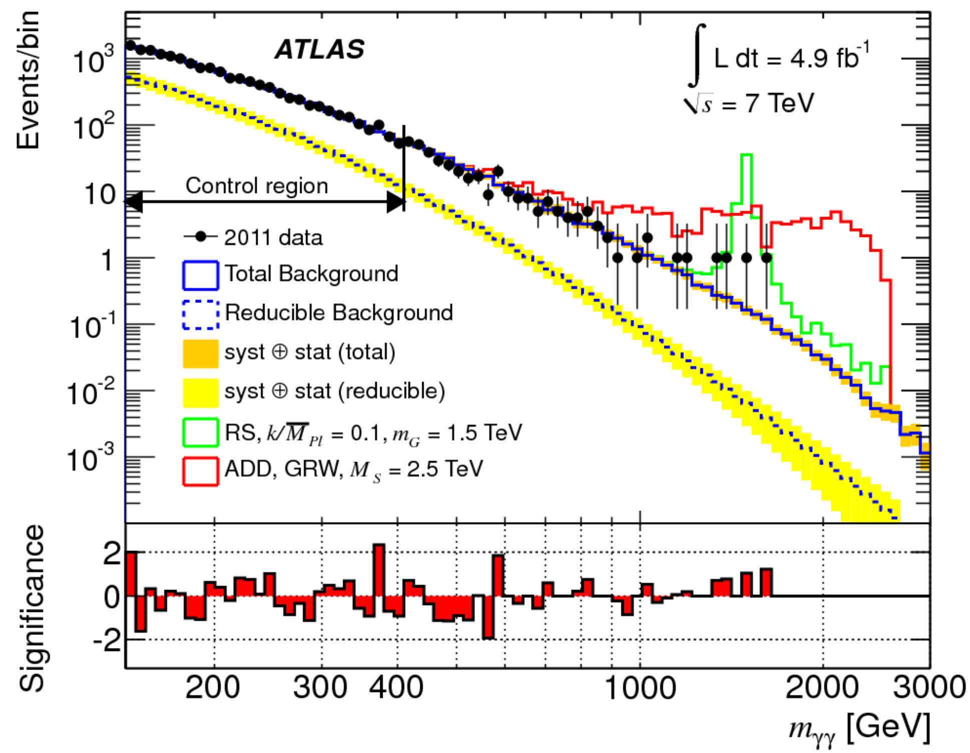
- Selection

photons : E_T>25 GeV, isolated (calo isol<5 GeV)

- bkg

shape : data-driven, for each bkg component

Normalisation : from low-mass CR

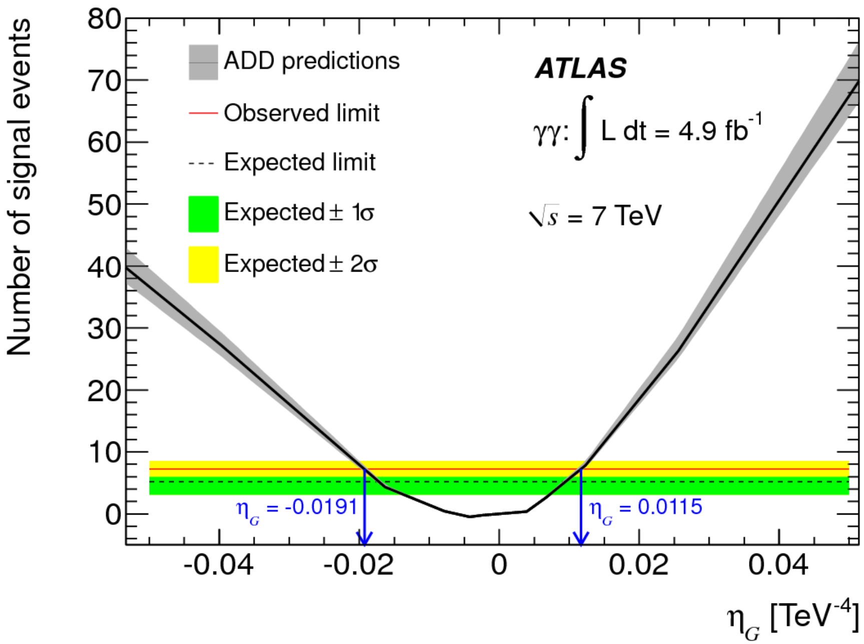


$\gamma\gamma$: XD

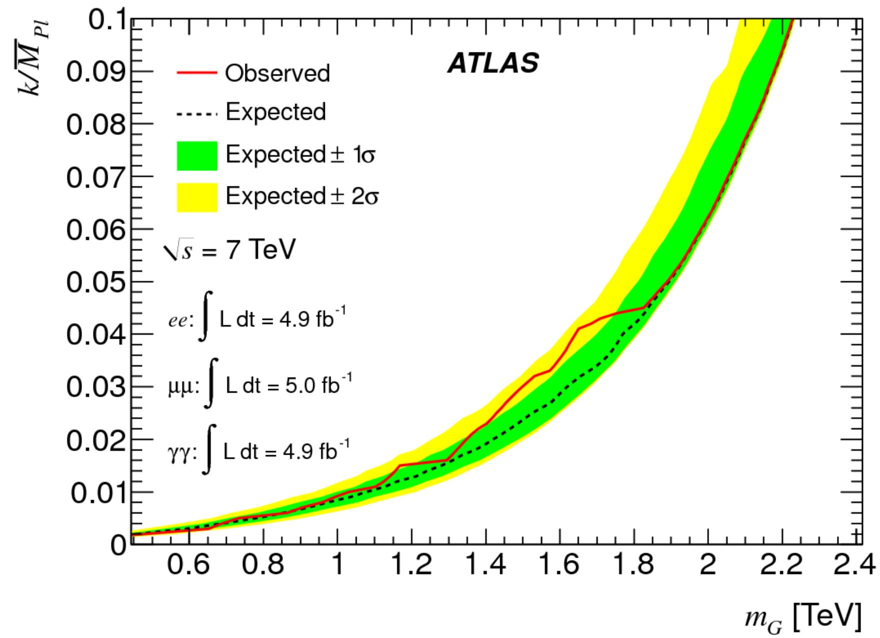
$\sqrt{s}$=7 TeV ; L=4.9 fb^{-1}

- 95 % CL limits

-ADD



-RS



m_S>2.52-3.92 TeV=f(n)

m_G>2.06 TeV for $k/\overline{M}_{Pl}$=0.1

$\gamma\gamma$: XD

$\sqrt{s}$=8 TeV ; L=20.3 fb^{-1}

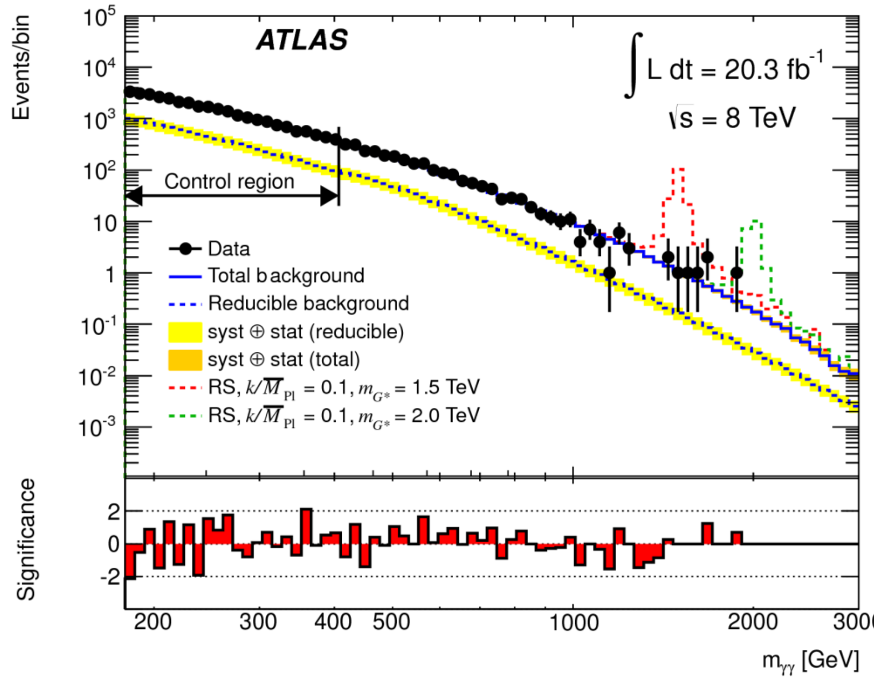
- Selection

photons : E_T>50 GeV, isolated (calo isol<8 GeV)

- bkg

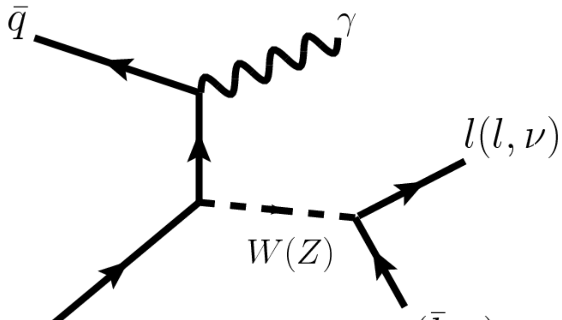
shape : data-driven, for each bkg component

Normalisation : from low-mass CR

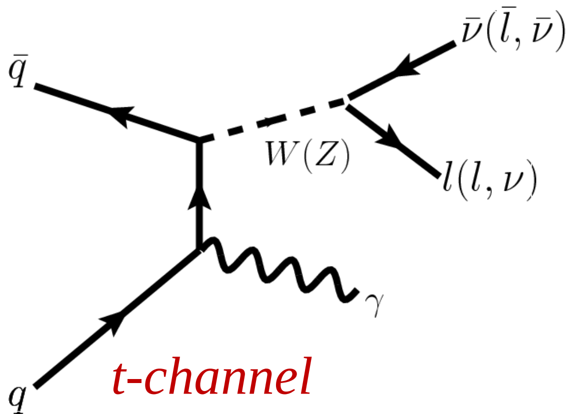


(W/Z)γ diagrams

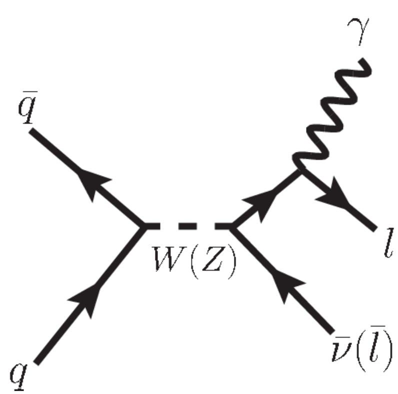
(W/Z)γ



u-channel

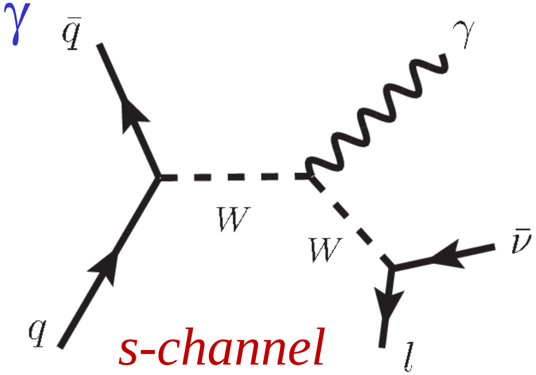


t-channel

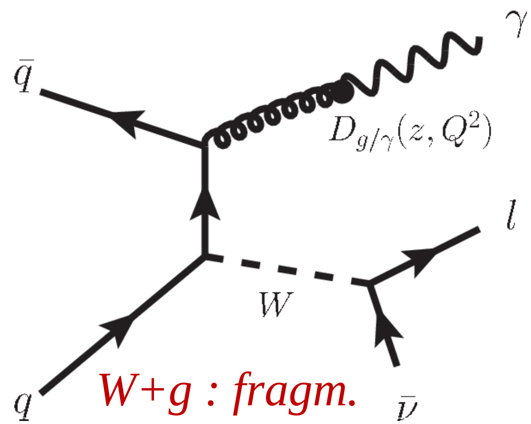


FSR

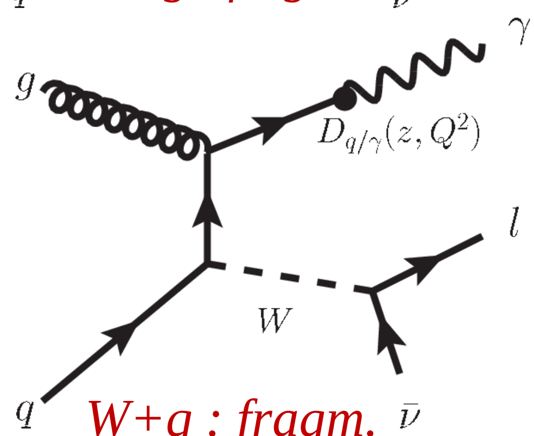
Wγ



s-channel



W+g : fragm.



W+q : fragm.

(W/Z)γ : bkg estimation

- Background estimation

W(lν)γ W+j : jet fragmentation ($\pi^0 \rightarrow \gamma\gamma$)
ABCD : photon id and isol
Z(ll) : lepton misidentified as photon, lepton lost in acceptance
MET modelling (well modeled) : Zγ CR : llγ selection
Z(ee)j CR : eνγ selection but revert Z veto
γj : -mostly jet faked as electron
(lepton from HF, charged hadrons, e from photon conversions : misidentified as prompt e)
-MET : ν from HV decays and jet mis-measurement
ABCD : lepton isol, MET (lower correlation, better discrimin. than lepton id/isol)
tt, Z(ττ), Z(ll)γ, di-bosons : small : MC

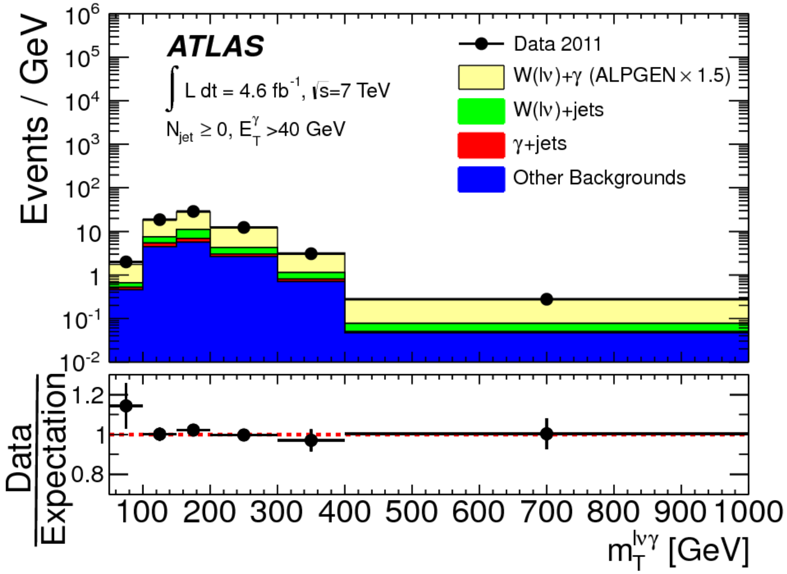
Z(ll)γ Z+j, j→γ (99 %) : ABCD : photon id and isol

Z(νν)γ W(eν) : e faked as photon : $\rho_{e\rightarrow\gamma}$ fake rate
Z(νν)j, multi-jets, jet faked as photon : ABCD method
Wγ : lepton too soft or fails id
γ+j : SR apart reverting Δϕ : Δϕ(MET ; j)<0.4 (⇔dominated by γj)
scaling to SR from MC
Other bkg : tt, 1-t, WW, Z(ττ), W(τν) : MC

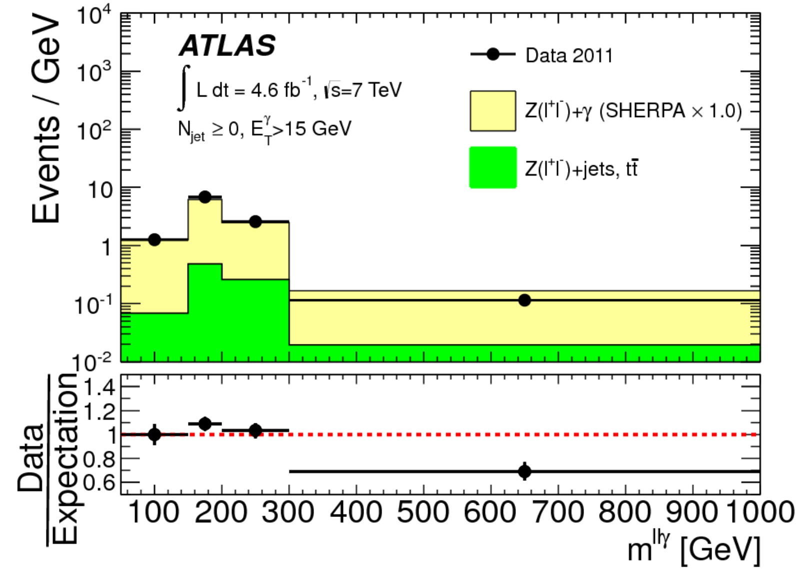
(W/Z)γ √s=7 TeV

- Data driven estimation of background

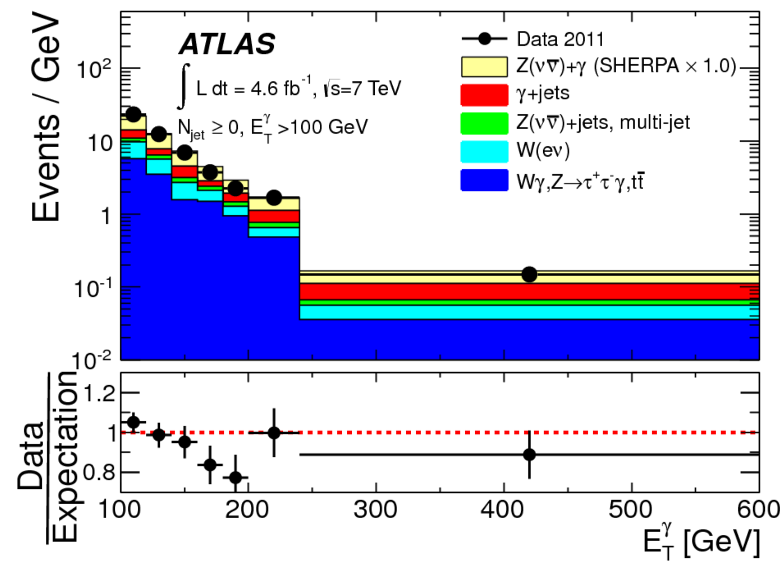
W(lν)γ



Z(ll)γ



Z(νν)γ

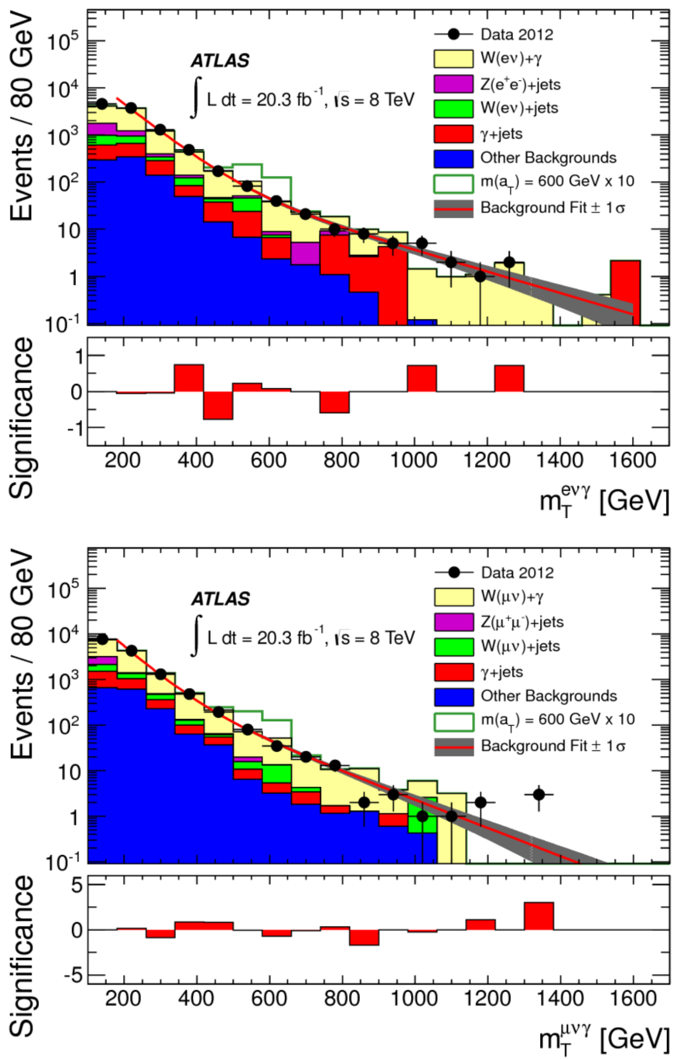


Ratio : comparison of shape btw data and prediction (normalization to data-driven extraction)

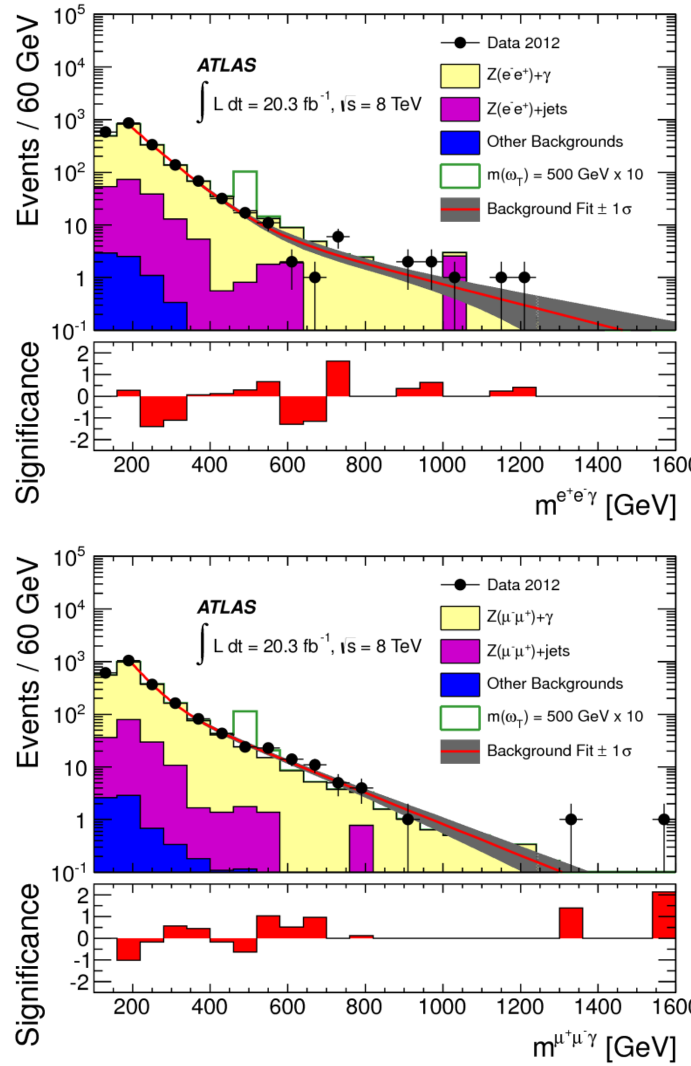
(W/Z)γ √s=8 TeV

- Data driven estimation of background

W(lν)γ



Z(ll)γ



Ratio : comparison of shape btw data and prediction
(normalization to data-driven extraction)

(W/Z)γ √s=7 TeV

√s=7 TeV ; L=4.6 fb^{-1}

- W(lν)γ

=1 l, p_T>25 GeV
MET>35 GeV
m_T(l ; MET)>40 GeV
≥1 isolated photon E_T>15 GeV
Z veto for e channel : $|m_{e\gamma}-m_Z|$>15 GeV
(suppr. Z→ee w/ one fake e→γ)

- Z(ll)γ

=2 OS same flavor l m_{ll}>40 GeV (65-115 GeV 8 TeV)
=1 isolated photon E_T>15 GeV (40 GeV 8 TeV)

- Z(νν)γ

MET>90 GeV
=1 isol photon E_T>100 GeV
Δϕ(MET ; γ)>2.6, Δϕ(MET ; j)>0.4 (suppr. γj)
veto e, μ (suppr. Wj, Wγ)

ΔR(l ; γ)>0.7 (suppr. FSR γ in W, Z decays)

- Data driven estimation of bkg
- Fiducial cross-section →

	$\sigma^{ext-fid}$[pb] Measurement	$\sigma^{ext-fid}$[pb] MCFM Prediction
	$N_{jet} \geq 0$	
$e\nu\gamma$	2.74 ± 0.05 (stat) ± 0.32 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\mu\nu\gamma$	2.80 ± 0.05 (stat) ± 0.37 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\ell\nu\gamma$	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$e^+e^-\gamma$	1.30 ± 0.03 (stat) ± 0.13 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\mu^+\mu^-\gamma$	1.32 ± 0.03 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\ell^+\ell^-\gamma$	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\nu\bar{\nu}\gamma$	0.133 ± 0.013 (stat) ± 0.020 (syst) ± 0.005 (lumi)	0.156 ± 0.012
	$N_{jet} = 0$	
$e\nu\gamma$	1.77 ± 0.04 (stat) ± 0.24 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$\mu\nu\gamma$	1.74 ± 0.04 (stat) ± 0.22 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$\ell\nu\gamma$	1.76 ± 0.03 (stat) ± 0.21 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$e^+e^-\gamma$	1.07 ± 0.03 (stat) ± 0.12 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\mu^+\mu^-\gamma$	1.04 ± 0.03 (stat) ± 0.10 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\ell^+\ell^-\gamma$	1.05 ± 0.02 (stat) ± 0.10 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\nu\bar{\nu}\gamma$	0.116 ± 0.010 (stat) ± 0.013 (syst) ± 0.004 (lumi)	0.115 ± 0.009

Measured cross-section :
≈2 σ higher than NLO prediction
→NNLO would improve agreement

$(W/Z)\gamma$ $\sqrt{s}$=7 TeV

$\sqrt{s}$=7 TeV ; L=4.6 fb^{-1}

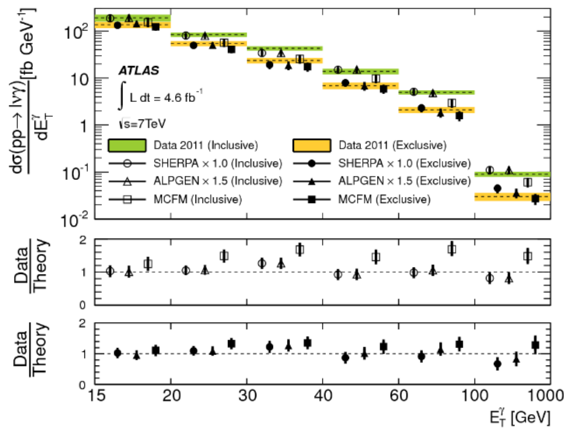
Inclusive : Njet≥0

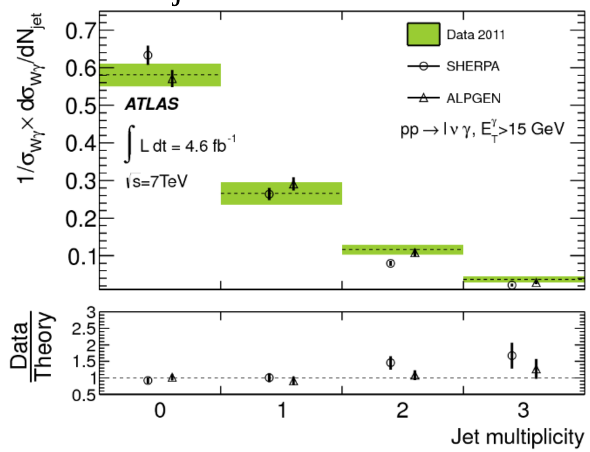
Exclusive : Njet=0

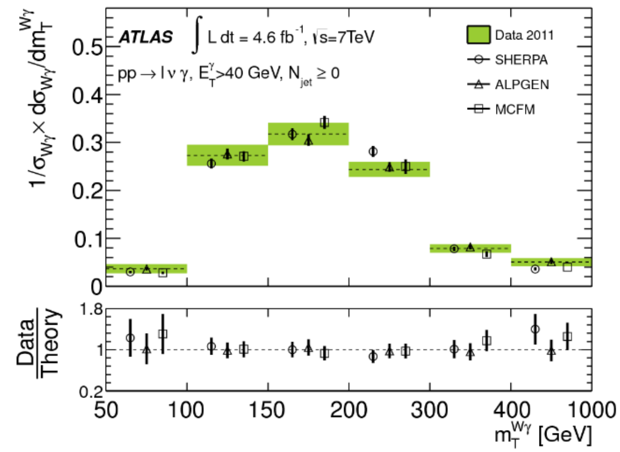
- Differential cross-sections

$f=(E_T^{\gamma})$ | $f(N_{jets})$ [normalized] | $f(m_T^W)$ [normalized]

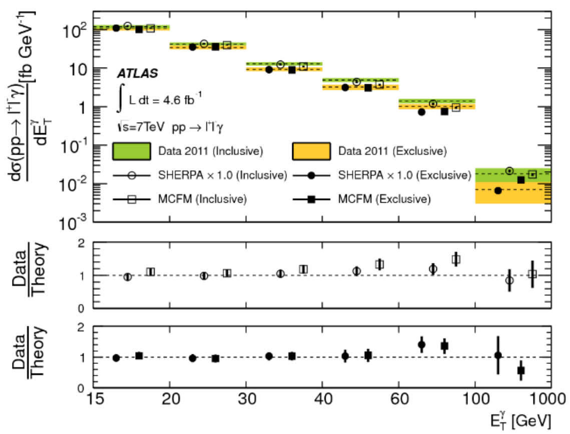
W(lν)γ

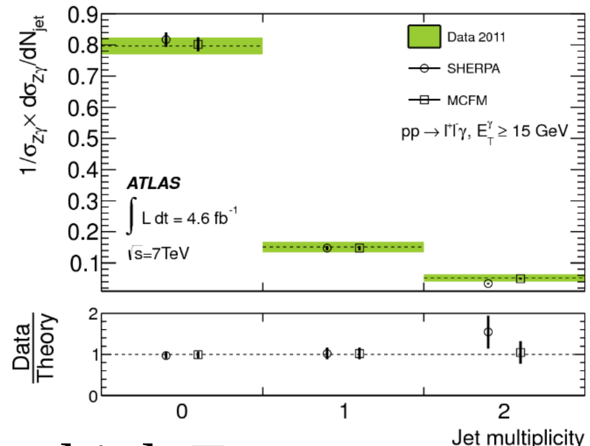


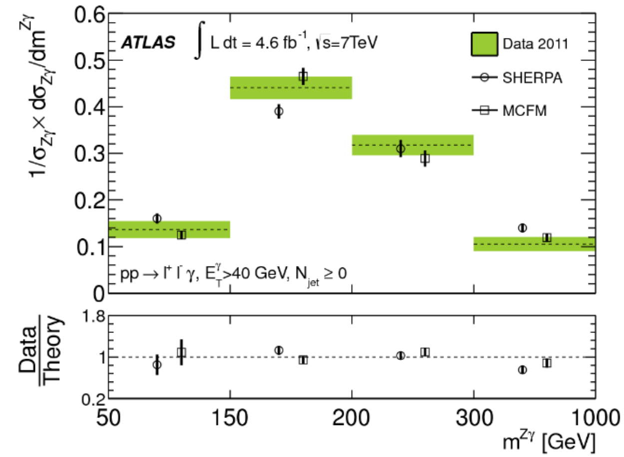




Z(ll)γ







Few disagreement for W(lν)γ at high E_T^{γ}

NNLO computation solves the disagreement (arXiv:1504.01330)

(W/Z)γ √s=7 TeV

Inclusive : Njet≥0

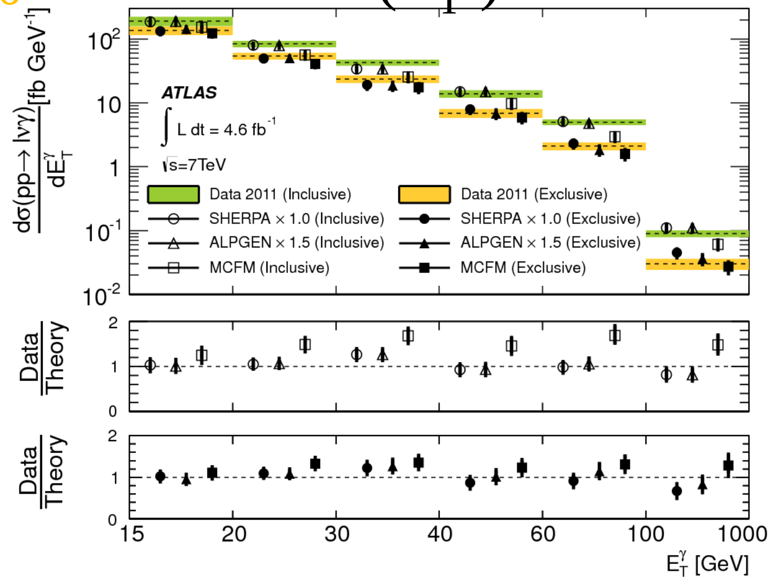
Exclusive : Njet=0

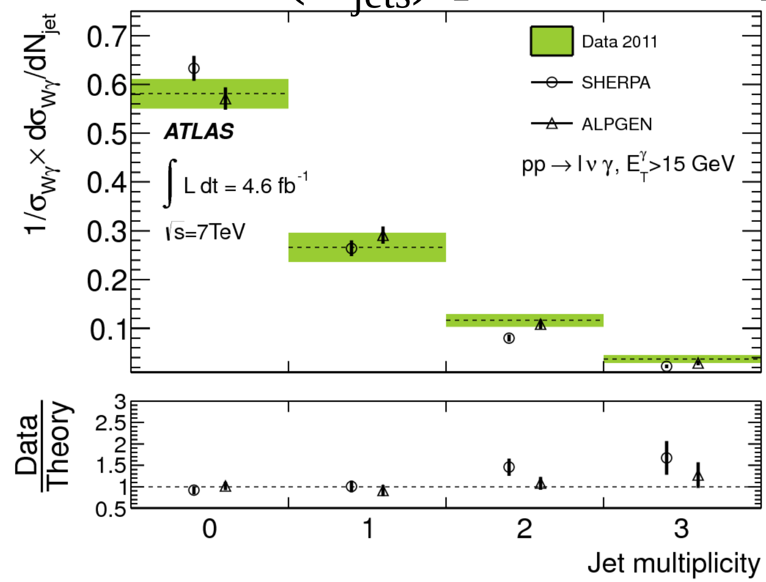
dσ/dX results

$f=(E_T^{\gamma})$

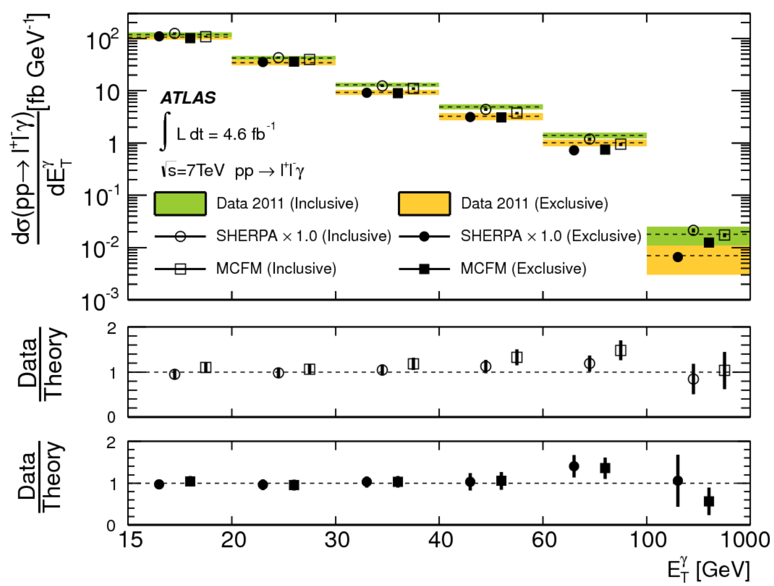
$f(N_{jets})$ [normalized]

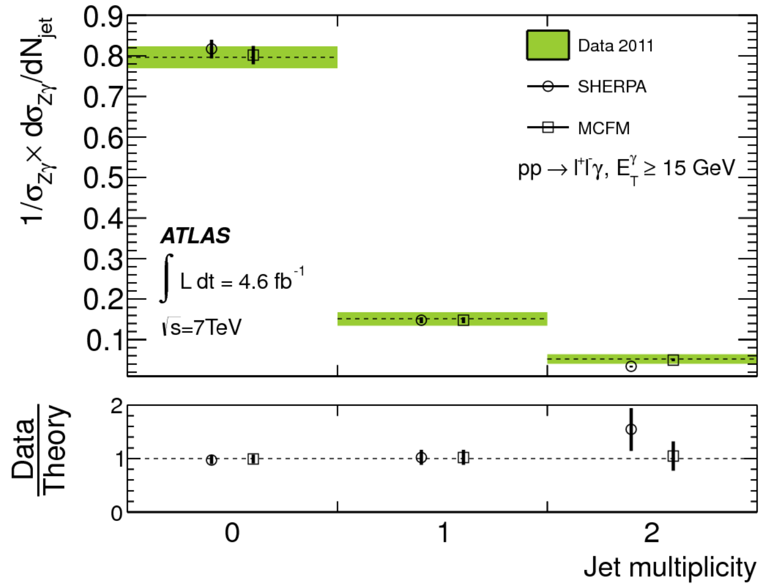
W(lν)γ





Z(ll)γ





(W/Z)γ $\sqrt{s}$=7 TeV

Inclusive : Njet≥0

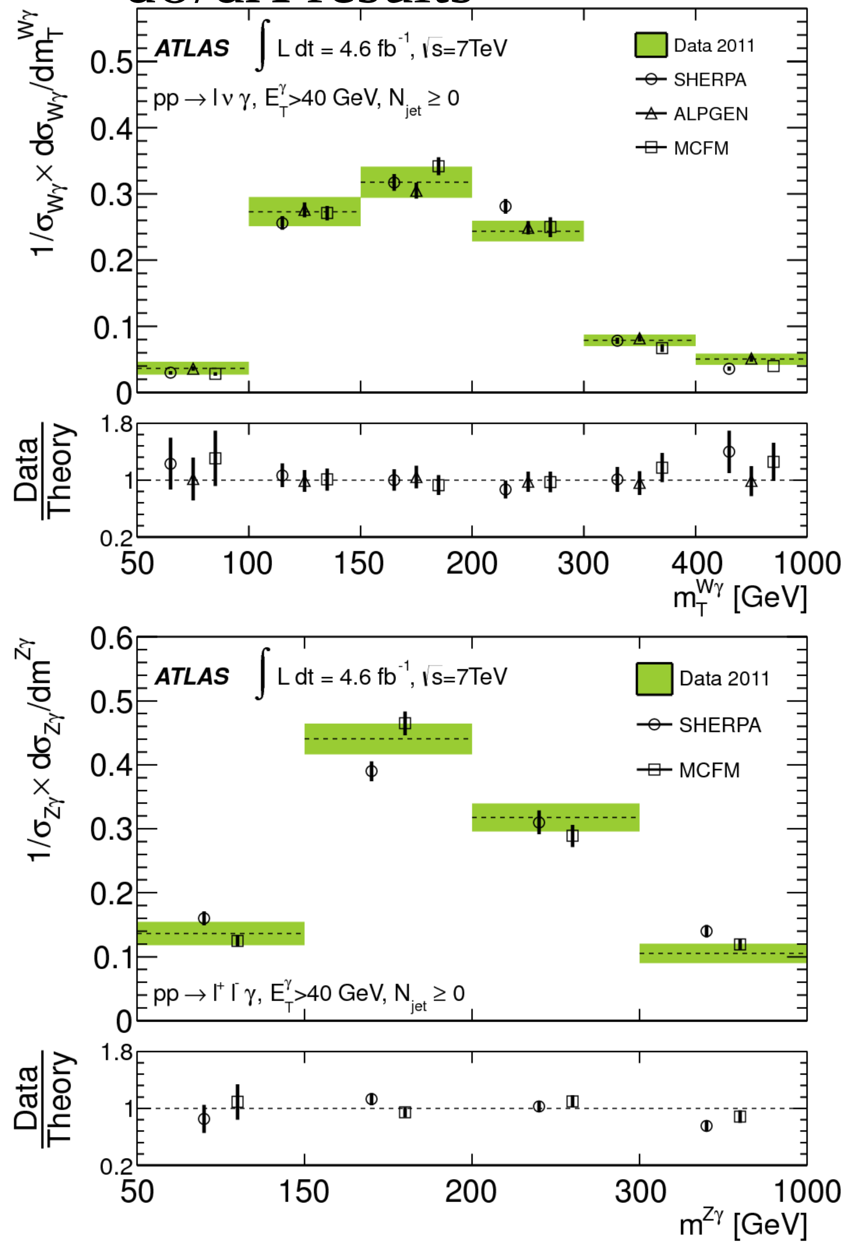
Exclusive : Njet=0

dσ/dX results

f(m_T^W) [normalized]

W(lν)γ

Z(ll)γ

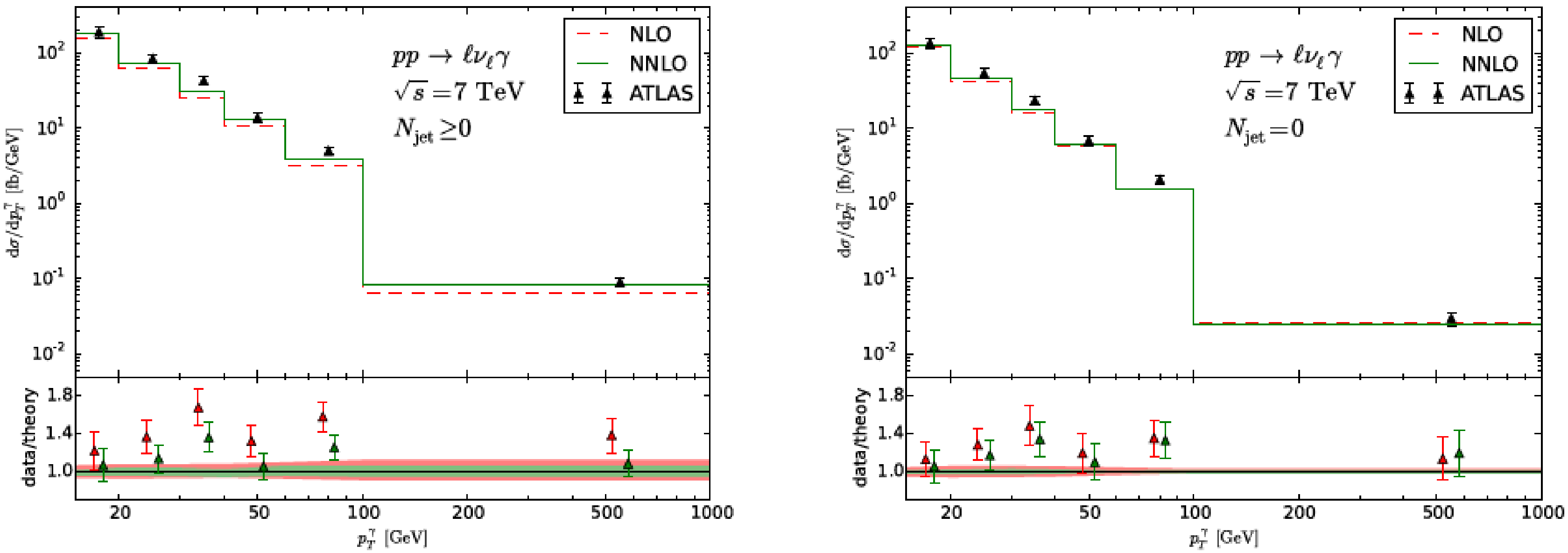


(W/Z)γ

Wγ : NNLO agreement

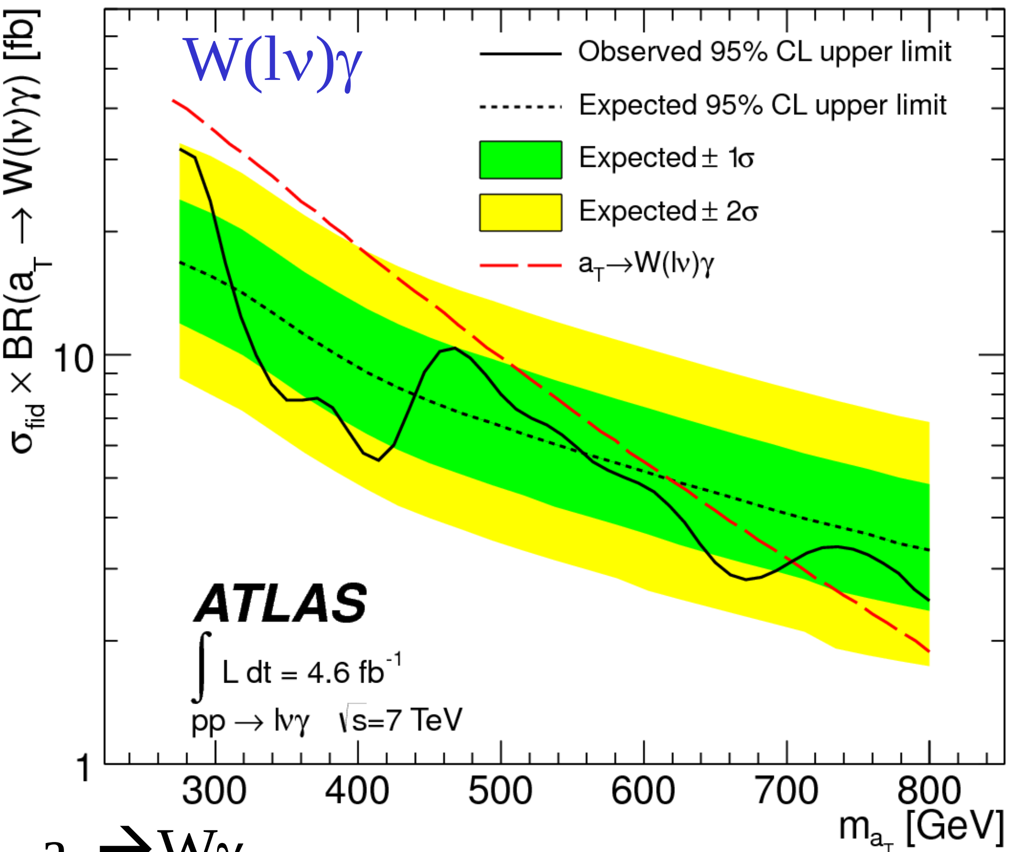
http://xxx.tau.ac.il/pdf/1504.01330.pdf

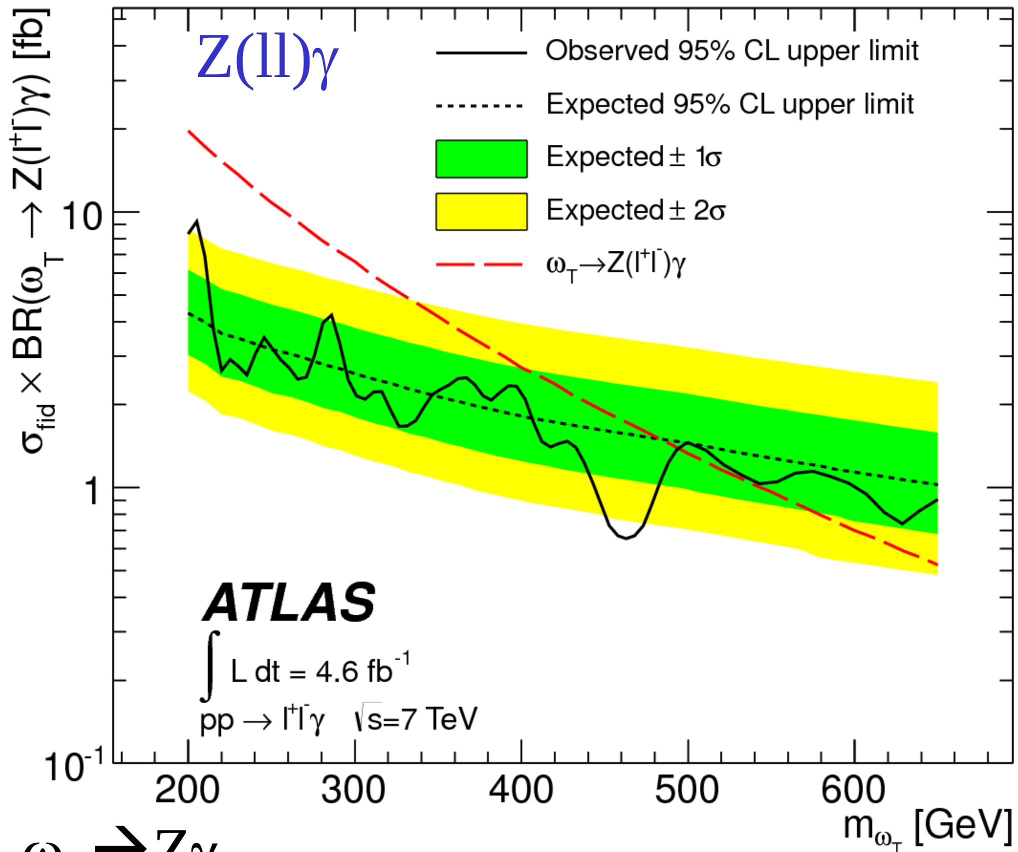
$\sqrt{s}$ [TeV]		$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]	$\sigma_{\rm NNLO}$ [pb]	$\sigma_{\rm ATLAS}$ [pb]
7	$N_{\rm jet} \geq 0$	$0.8726^{+6.8\%}_{-8.1\%}$	$2.058^{+6.8\%}_{-6.8\%}$	$2.453^{+4.1\%}_{-4.1\%}$	2.77 ±0.03 (stat) ±0.33 (syst) ±0.14 (lumi)
	$N_{\rm jet} = 0$		$1.395^{+5.2\%}_{-5.8\%}$	$1.493^{+1.7\%}_{-2.7\%}$	1.76 ±0.03 (stat) ±0.21 (syst) ±0.08 (lumi)
8	$N_{\rm jet} \geq 0$	$0.9893^{+7.7\%}_{-9.1\%}$	$2.401^{+7.4\%}_{-7.4\%}$	$2.884^{+4.1\%}_{-4.3\%}$	
	$N_{\rm jet} = 0$		$1.587^{+5.5\%}_{-6.3\%}$	$1.691^{+1.8\%}_{-2.9\%}$	



$(W/Z)\gamma$ $\sqrt{s}$=7 TeV

Search for narrow resonances (example : Technicolor) : spin-1 mesons ‘techni-mesons’ : decaying to Wγ, Zγ





$a_T \rightarrow W\gamma$

$\omega_T \rightarrow Z\gamma$

Limit : observed : 703 GeV
expected : 619 GeV

Limit : observed : 494 GeV ;
expected : 483 GeV

(W/Z)γ √s=7 TeV

TGC

PRD 47, 4889 (1993)

$$\mathcal{L}_{WW\gamma} = -ie\left[W^{\dagger}_{\mu\nu}W^{\mu}A^{\nu} - W^{\dagger}_{\mu}A_{\nu}W^{\mu\nu} + \kappa W^{\dagger}_{\mu}W_{\nu}F^{\mu\nu} + \frac{\lambda}{M_W^2}W^{\dagger}_{\lambda\mu}W^{\mu}_{\nu}F^{\nu\lambda}\right]$$

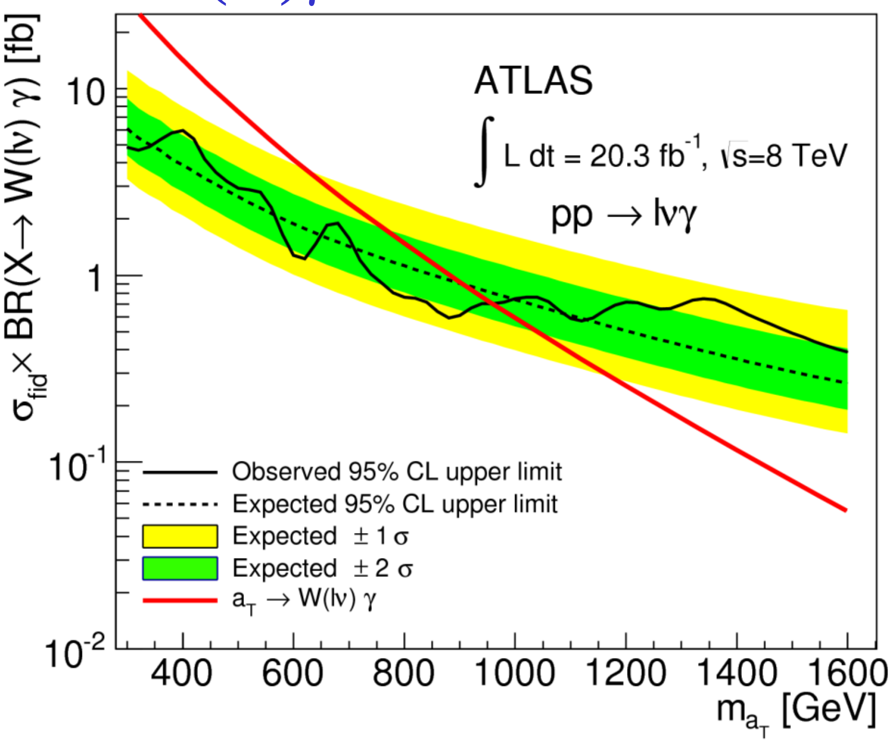
PRD 48, 5140 (1993)

$$\Gamma^{\alpha\beta\mu}_{Z\gamma Z}(q_1,q_2,P)=\frac{P^2-q_1^2}{m_Z^2}\left\{h_1^Z(q_2^{\mu}g^{\alpha\beta}-q_2^{\alpha}g^{\mu\beta})+\frac{h_2^Z}{m_Z^2}P^{\alpha}[(P\cdot q_2)g^{\mu\beta}-q_2^{\mu}P^{\beta}]+h_3^Z\epsilon^{\mu\alpha\beta\rho}q_{2\rho}+\frac{h_4^Z}{m_Z^2}P^{\alpha}\epsilon^{\mu\beta\rho\sigma}P_{\rho}q_{2\sigma}\right\}$$

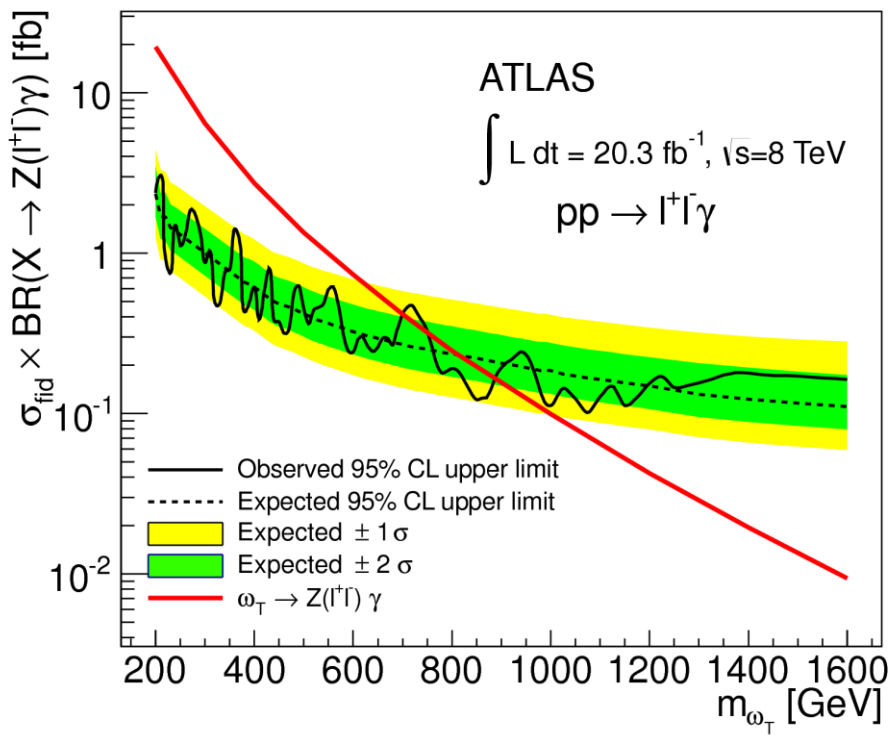
(W/Z)γ √s=8 TeV
√s=8 TeV ; L=20.3 fb^{-1}

Search for narrow resonances (example : Technicolor) : spin-1 mesons ‘techni-mesons’ : decaying to Wγ, Zγ

W(lν)γ



Z(ll)γ



a_T→Wγ
exclude [275 ; 960] GeV

ω_T→Zγ
exclude [200 ; 700] U [750 ; 890] GeV

Limit singlet scalar resonance ϕ : >1180 GeV

W(lν)γγ

Restricted to f_{T0}, f_{M2}, f_{M3}

$$\mathcal{L}_{quartic} = F_{S0}\ \mathcal{L}_{S,0} + F_{S1}\ \mathcal{L}_{S,1}$$

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

modify WWWW, WWZZ, WWZZ

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

Dimension 8 effective operators
→anomalous WWWW, WWZZ, WWAZ, WWAA, AAZZ, AZZZ, ZZZZ

$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$

f(momentum vector bosons)

$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$

$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$

$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

W(lν)γγ

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$

Dimension 8 effective operators
→anomalous WWWW, WWZZ, WWAZ, WWAA, AAAA, AAAZ, AAZZ, AZZZ, ZZZZ

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

Dimension 8 effective operators
→anomalous AAAA, AAAZ, AAZZ, AZZZ, ZZZZ

W(lν)γγ

We concentrate on anomalous quartic interaction among the electroweak gauge bosons that do not have a triple vertex associated to it. We describe these interactions using dimension eight effective operators assuming that the recently observed Higgs boson belongs to a $SU(2)_L$ doublet; see the file quartic.pdf for further details. This model is an extension of the Standard Model (SM) implemented at http://feynrules.irmp.ucl.ac.be/wiki/StandardModel; for further details see this link.

The model labeled SM_LS0_LS1 contains the standard model interactions supplemented by the dimension eight operators $L_{S,0}$ and $L_{S,1}$ defined in the file quartic.pdf. These dimension eight effective operators modify the vertices WWWW, WWZZ, and WWZZ that can be a simple re-scaling of the SM quartic interaction for a suitable choice of couplings.

The model labeled SM_LT012 contains the standard model interactions supplemented by the dimension eight operators $L_{T,0}$, $L_{T,1}$ and $L_{T,2}$ defined in the file quartic.pdf. These dimension eight effective operators give rise to anomalous WWWW, WWZZ, WWAZ, WWAA, AAAA, AAAZ, AAZZ, AZZZ, and ZZZZ vertices.

The model labeled SM_LM0123 contains the standard model interactions supplemented by the dimension eight operators $L_{M,0}$, $L_{M,1}$, $L_{M,2}$ and $L_{M,3}$ defined in the file quartic.pdf These dimension eight effective operators give rise to anomalous WWWW, WWZZ, WWAZ, WWAA, AAZZ, AZZZ, and ZZZZ vertices.

The model labeled SM_LT8_LT9 contains the standard model interactions supplemented by the dimension eight operators $L_{T,8}$ and $L_{T,9}$ defined in the file quartic.pdf. These dimension eight effective operators give rise to anomalous AAAA, AAAZ, AAZZ, AZZZ, and ZZZZ vertices.

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$,$\mathcal{L}_{M,6}$,$\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$,$\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$,$\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$,$\mathcal{L}_{T,1}$,$\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$,$\mathcal{L}_{T,6}$,$\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$,$\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

W(lν)γγ

- Background estimation

  Wγj+Wjj : jet faked as photon ($\pi^0 \rightarrow \gamma\gamma$)

  2D template fit isolation two photons

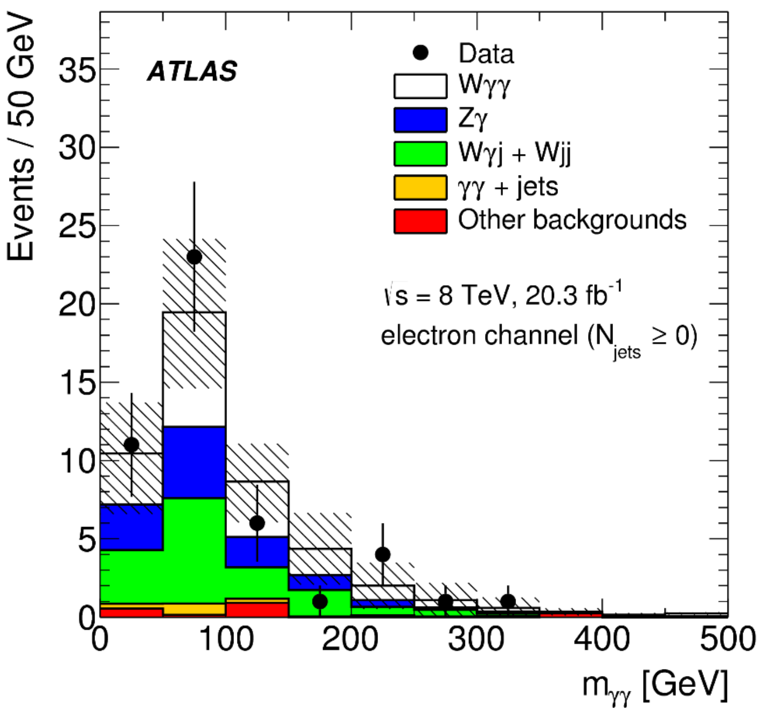
  bkg template : revert some of shower shape photon id requirements

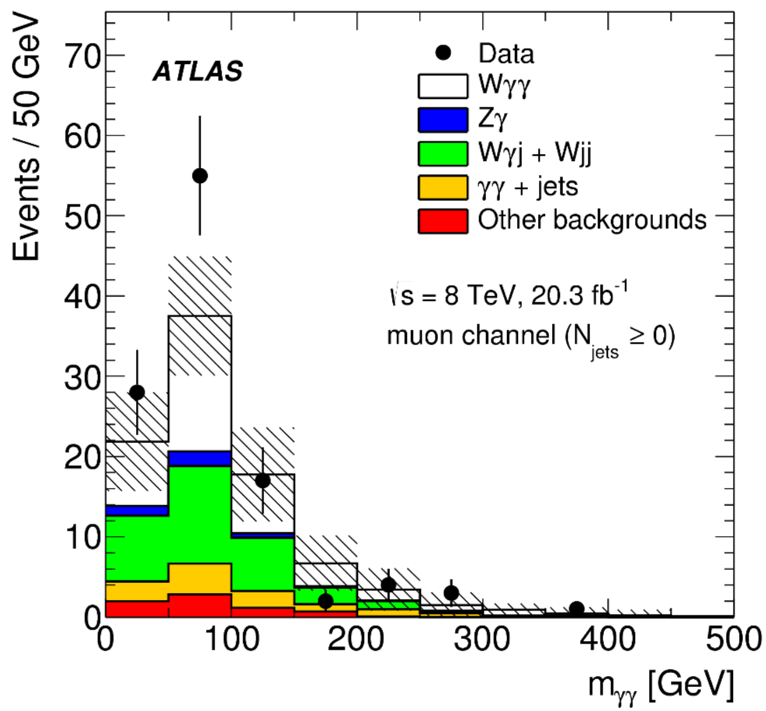
  signal template : MC

  γγj : j faked as e ; HF→μ :

  ABCD : lepton isol, MET

  lower correlation, better discrimin. than lepton id/isol





$W(l\nu)\gamma\gamma$

$\sqrt{s}$=8 TeV ; L=20.3 fb^{-1}

- Selection

=1 isolated lepton p_T>20 GeV

e : calo (trk) isolation : <0.2 (0.15) x p_T

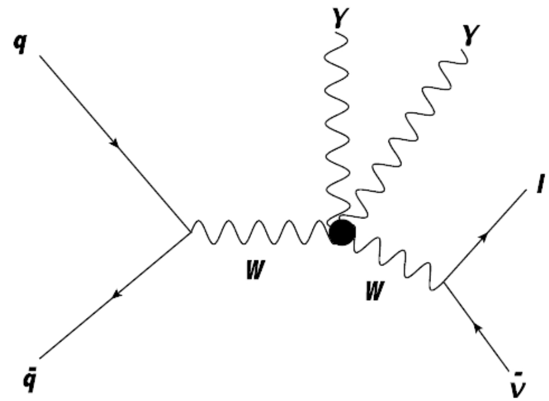
μ : track isolation < 0.15 p_T

veto 2 lepton (suppr. DY)

=2 isolated photons, p_T>20 GeV

calo isolation<4 GeV

MET>40 GeV



$\Delta R(l,\gamma)$>0.7 (suppr. FSR)

e-channel :

$p_T(e\gamma\gamma)$>30 GeV (suppr. Zγ)

veto $m_{e\gamma}^L$, $m_{e\gamma}^S$, $m_{e\gamma\gamma}$ close to m_Z (suppr. DY)

- Background estimation : data driven

$W(l\nu)\gamma\gamma$

$\sqrt{s}$=8 TeV ; L=20.3 fb^{-1}

- Fiducial region

Definition of the fiducial region
$p_T^\ell > 20\,GeV$, $p_T^\nu > 25\,GeV$, $\lvert\eta_\ell\rvert < 2.5$
$m_T > 40\,GeV$
$E_T^\gamma > 20\,GeV$, $\lvert\eta^\gamma\rvert < 2.37$, iso. fraction $\epsilon_h^p < 0.5$
$\Delta R(\ell,\gamma) > 0.7$, $\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\ell/\gamma, \text{jet}) > 0.3$
Exclusive: no anti-k_t jets with $p_T^{\text{jet}} > 30\,GeV$, $\lvert\eta^{\text{jet}}\rvert < 4.4$

- results

	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ±1.5 (syst.) ±0.2 (lumi.)	NLO QCD, CT10 pdf 2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ±0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ±1.2 (syst.) ±0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ±0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ±0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ±0.1 (lumi.)	

Evidence of $W\gamma\gamma$; $p_0 > 3\ \sigma$

Measured cross-section : 2 σ higher than NLO prediction

(similar to $W\gamma$: NNLO would help)

$W(l\nu)\gamma\gamma$

$\sqrt{s}$=8 TeV ; L=20.3 fb^{-1}

- σ=f(aQGC parameters)
- aQGC⇔excess events w/ high $m_{\gamma\gamma}$ (>300 GeV)

  →no events observed in high high $m_{\gamma\gamma}$ region

95 % limits

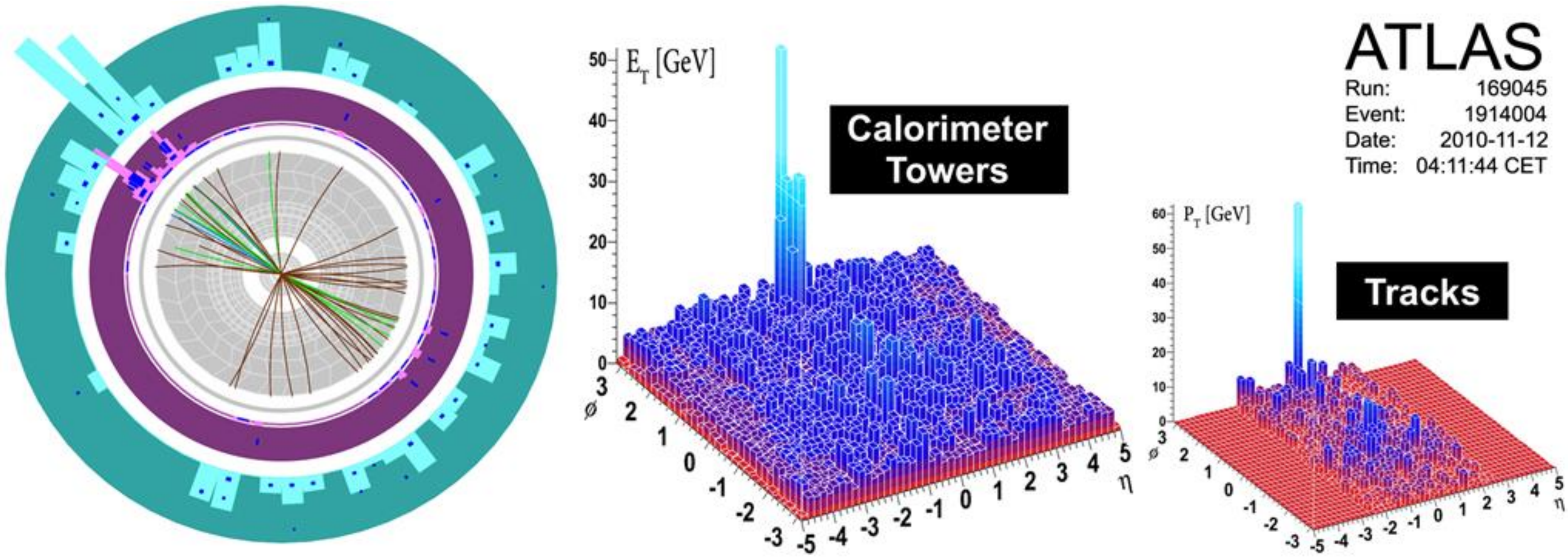
		Observed [TeV^{-4}]	Expected [TeV^{-4}]
$n=0$	f_{T0}/Λ^4	$[-0.9, 0.9] \times 10^2$	$[-1.2, 1.2] \times 10^2$
	f_{M2}/Λ^4	$[-0.8, 0.8] \times 10^4$	$[-1.1, 1.1] \times 10^4$
	f_{M3}/Λ^4	$[-1.5, 1.4] \times 10^4$	$[-1.9, 1.8] \times 10^4$
$n=1$	f_{T0}/Λ^4	$[-7.6, 7.3] \times 10^2$	$[-9.6, 9.5] \times 10^2$
	f_{M2}/Λ^4	$[-4.4, 4.6] \times 10^4$	$[-5.7, 5.9] \times 10^4$
	f_{M3}/Λ^4	$[-8.9, 8.0] \times 10^4$	$[-11.0, 10.0] \times 10^4$
$n=2$	f_{T0}/Λ^4	$[-2.7, 2.6] \times 10^3$	$[-3.5, 3.4] \times 10^3$
	f_{M2}/Λ^4	$[-1.3, 1.3] \times 10^5$	$[-1.6, 1.7] \times 10^5$
	f_{M3}/Λ^4	$[-2.9, 2.5] \times 10^5$	$[-3.7, 3.3] \times 10^5$

n : exponential choices of form factor

Λ=600 GeV for f_{T0}/Λ^4, 500 GeV for other parameters

No deviation from SM

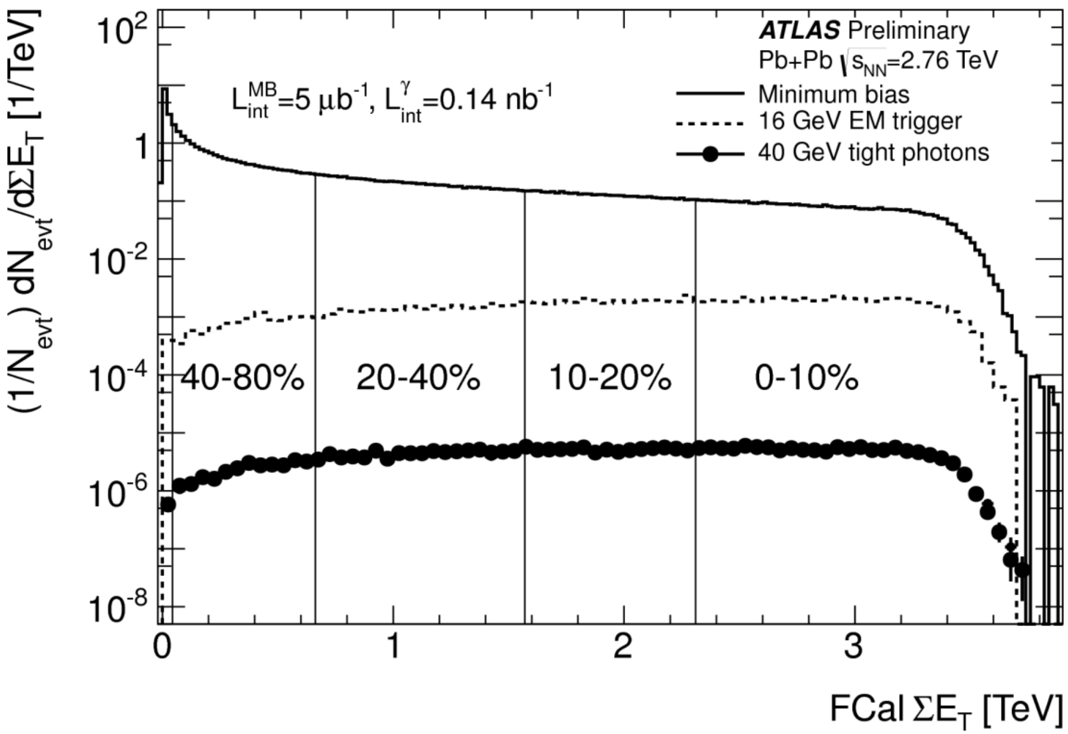
Pb Pb



Jet quenching, ATLAS, Phys. Rev. Lett. 105, 252303 (2010)

Pb Pb

Determination centrality of events : uses ΣE_T in FCal ($3.1<|\eta|<4.9$)



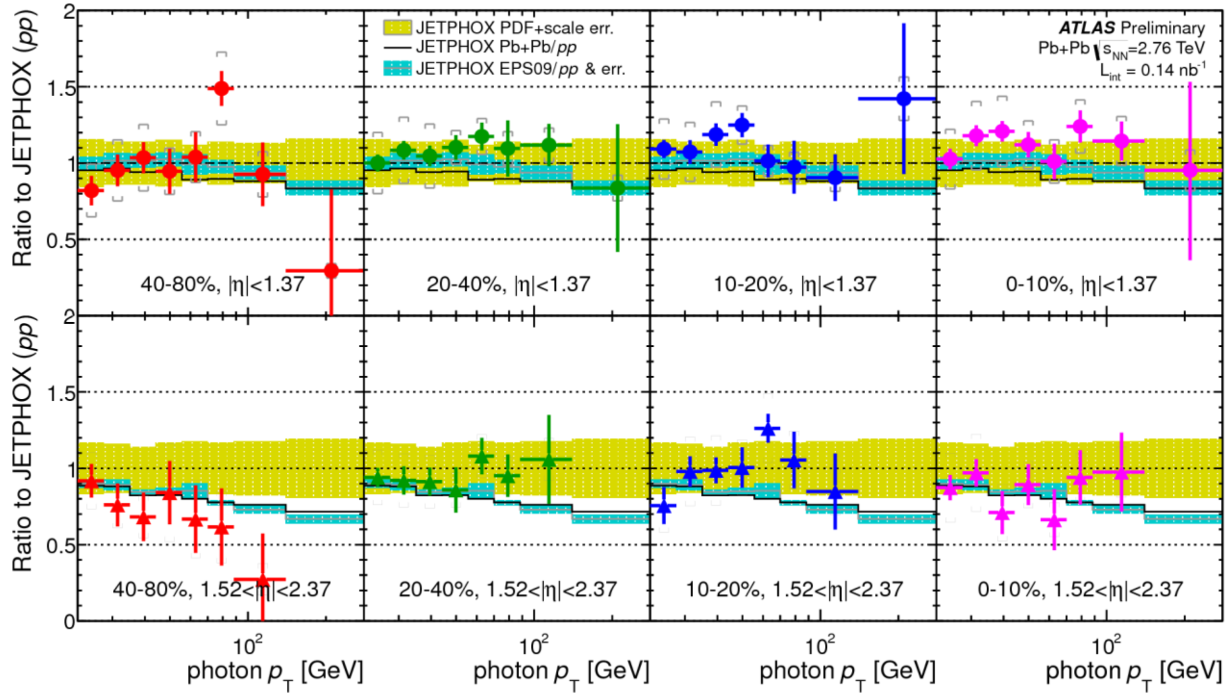
4 intervals in centrality : 40-80 % ; 20-40 % ; 10-20 % ; 0-10 %

2 intervals in pseudo-rapidité : central : $|\eta|<1.37$; forward : $1.52<|\eta|<2.37$

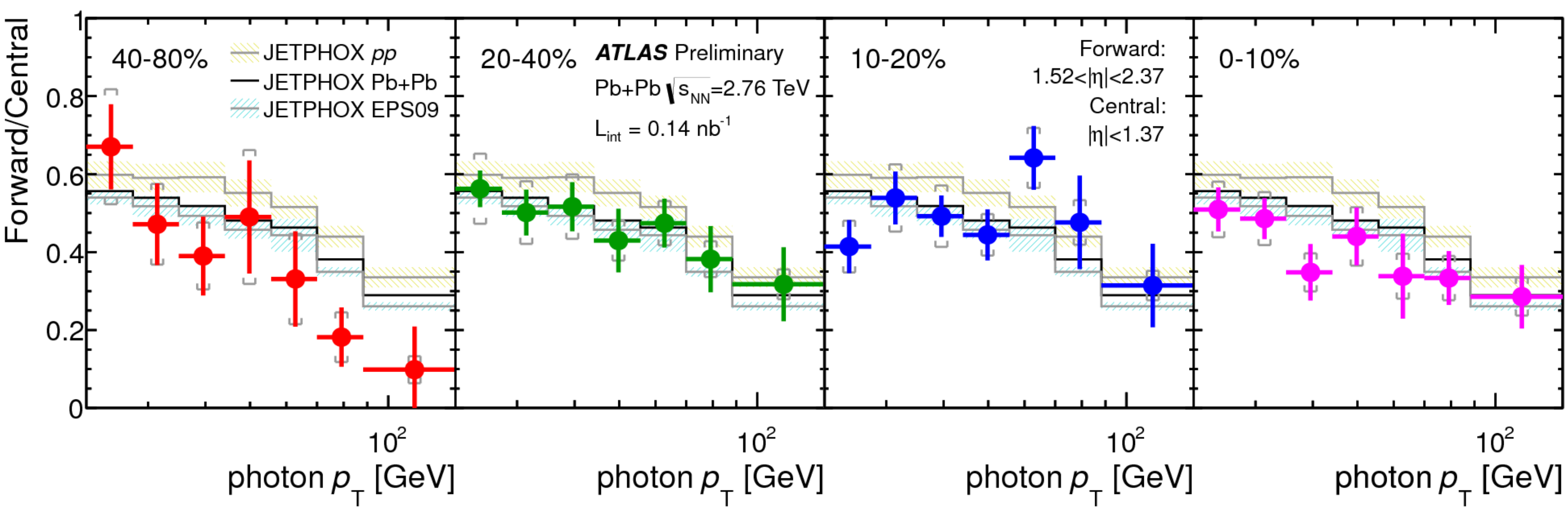
11 intervals in p_T (22.1-280 GeV)

Results

compared w/ Jetphox
Tested several PDFs :
pp ; isospin, nPDF EPS09
(nuclear modifications)

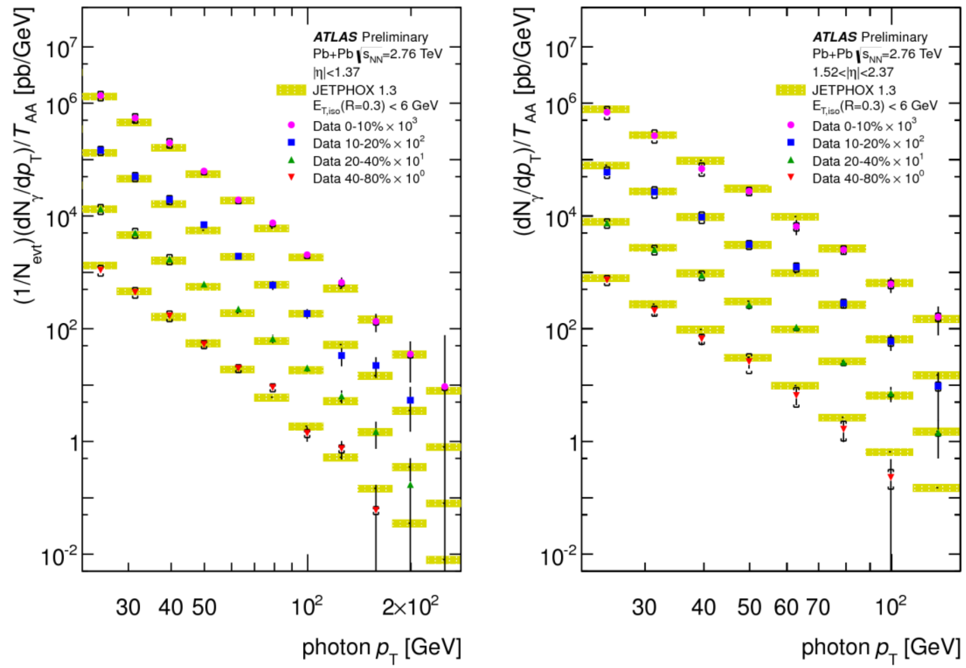


At present : data unable to distinguish between three scenarios



Pb Pb

Photons yields



Correlations jet with high-pT isolated prompt photons

Correlations jet with high-pT isolated prompt photons ATLAS-CONF-2012-121/

Same threshold for isolation

$L=0.13\ nb^{-1}$ Pb-Pb

Observable : fractional energy carried by jet ($x_{J\gamma}$)=f(centrality) : $x_{J\gamma}=p_T^{jet}/p_T^{\gamma}$

$d\Delta\phi_{J\gamma}=|\phi_{jet}-\phi_{\gamma}|$

$R_{j\gamma}$=integral of $(1/N_{\gamma})dN_{J\gamma}/dx_{J\gamma}$ over measured region,

w/ $x_{J\gamma}>p_{T,minjet}/p_{T,min}^{\gamma}$

$60<p_T^{\gamma}<90$ GeV, $|\eta|_{\gamma}<1.3$ → to limit range for recoil jet energies

$p_T^{jet}>25$ GeV, $|\eta|_j<2.1$

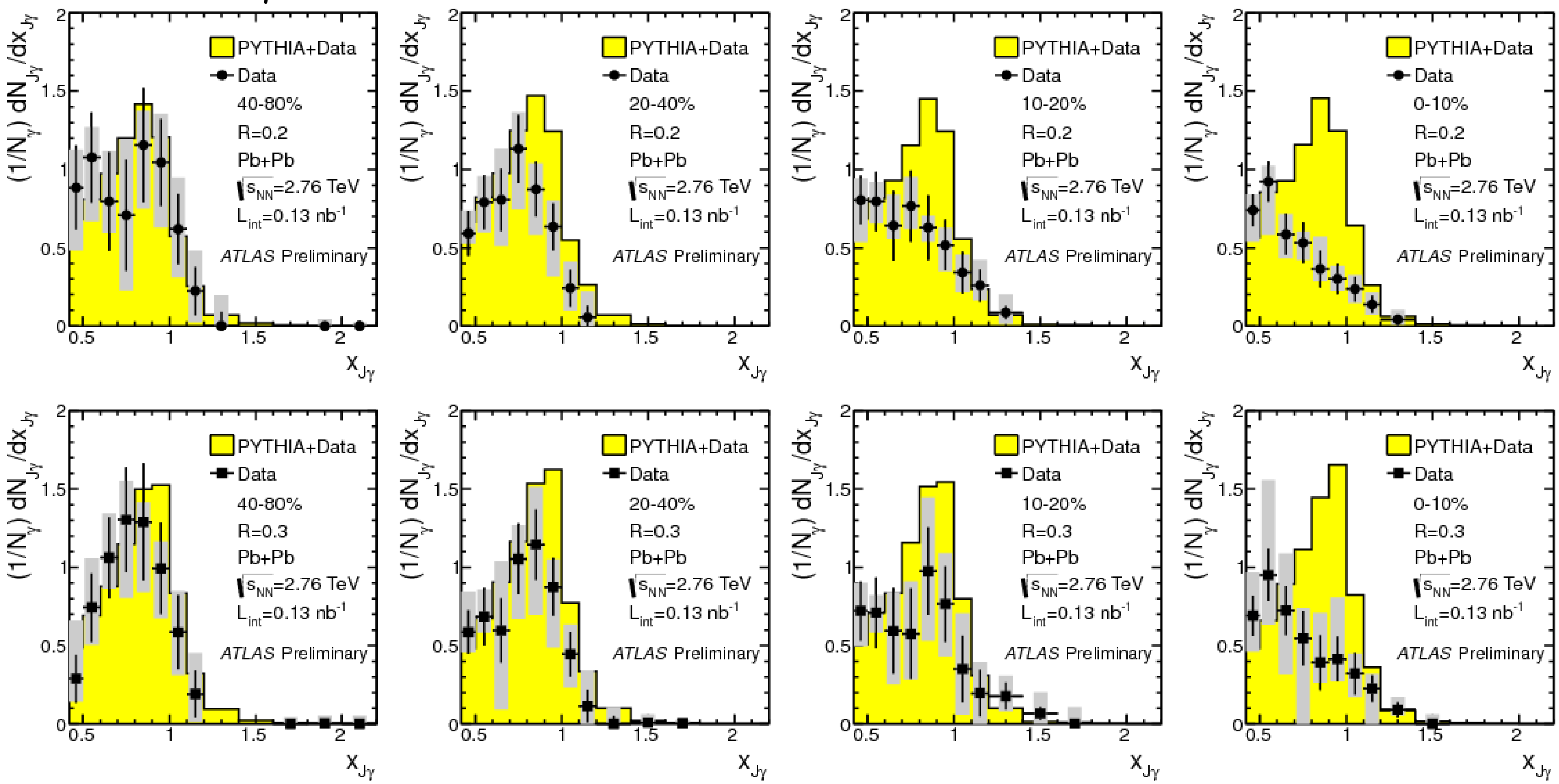
$\Delta\phi_{J\gamma}>7\pi/8$ → restrict to back-to-back topologies

Background determination : ABCD method

Results

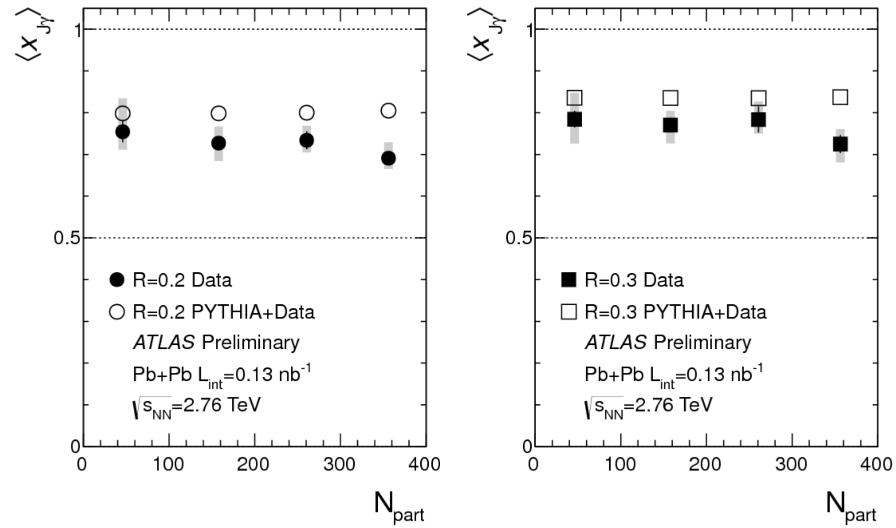
Normalized distribution of $x_{J\gamma}$ per photon : $(1/N_\gamma)dN_{J\gamma}/dx_{J\gamma}$

Shift of $x_{J\gamma}$ towards smaller values for increasing centrality

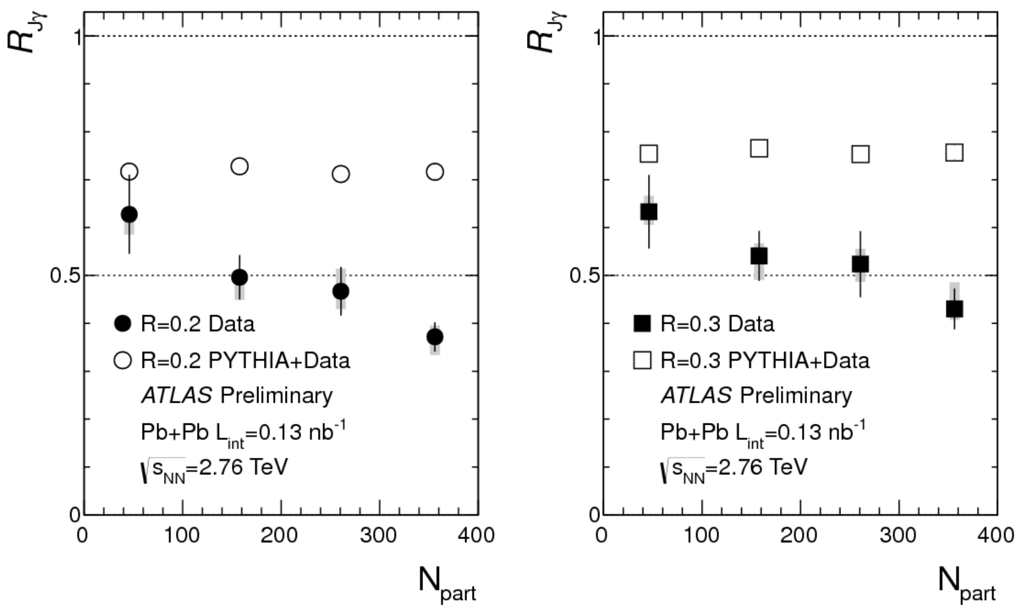


Results

mean distributions of $x_{J\gamma}$



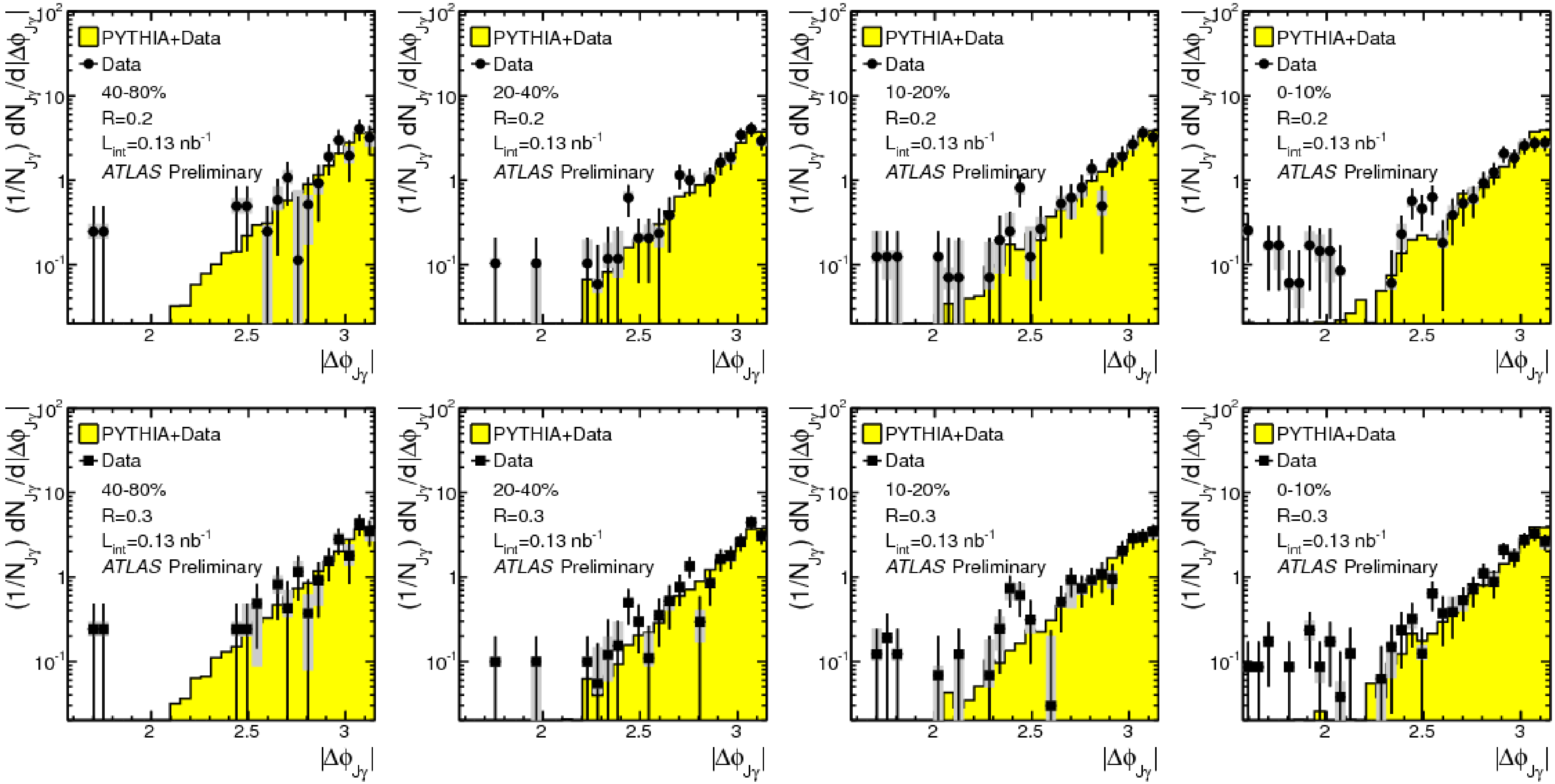
$R_{j\gamma}$=integral of $(1/N_\gamma)dN_{J\gamma}/dx_{J\gamma}$:
Measures yield of associated leading jets per photon



More central events show marked decrease w/ increasing N_{part}

Results

$\Delta\phi_{J\gamma}=|\phi_{jet}-\phi_{\gamma}|$



No modification to the in-medium parton shower

Results

Correlations jet-photon : starting point for more detailed studies of energy loss of jets in hot/dense medium

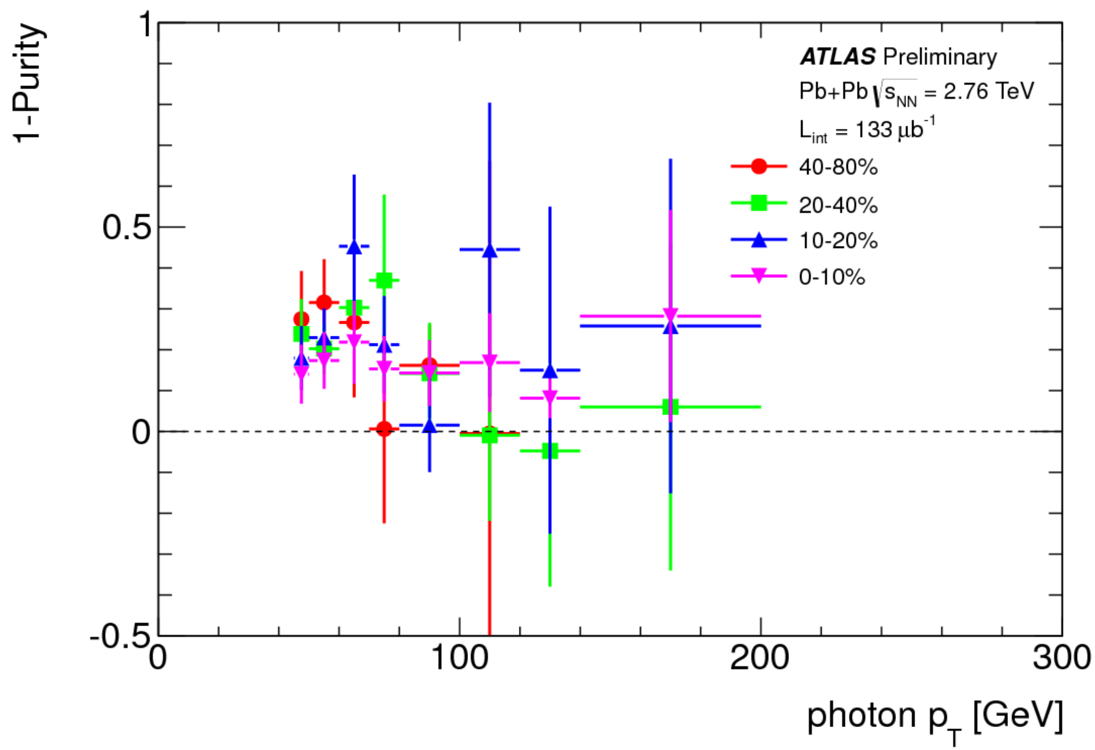
First ATLAS results on gam+jet with Pb Pb : ATLAS-CONF-2012-051

L=133 μb^{-1}

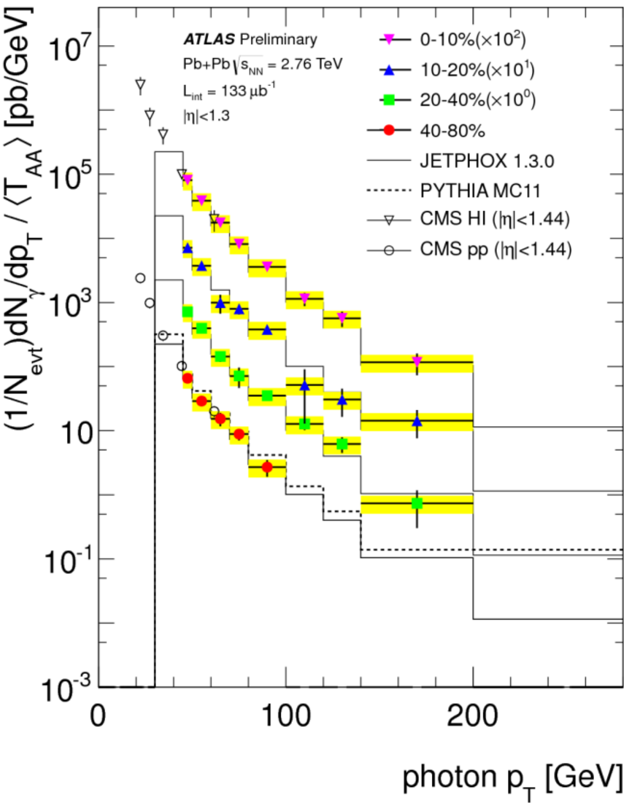
First results on gam+jet with Pb Pb

p_T : 45-200 GeV, $|\eta|<1.3$

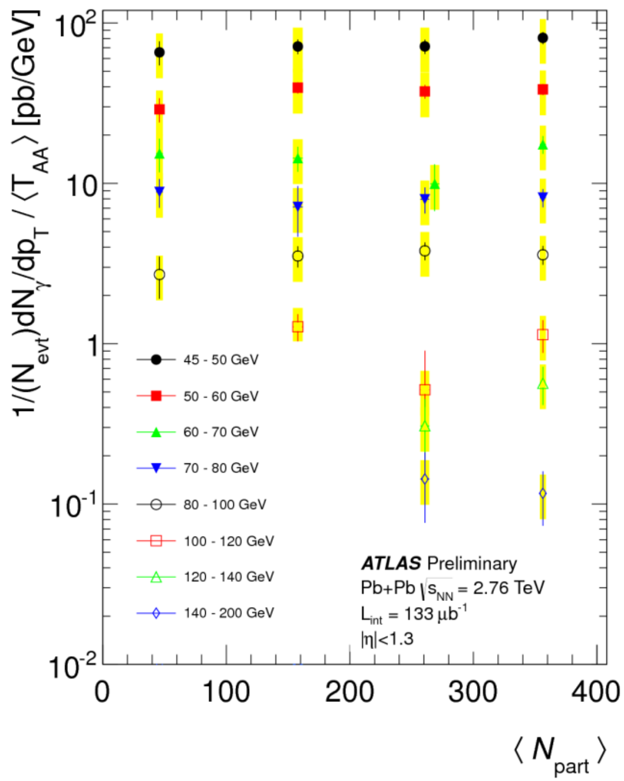
ABCD : thresholds : 6 and 8 GeV



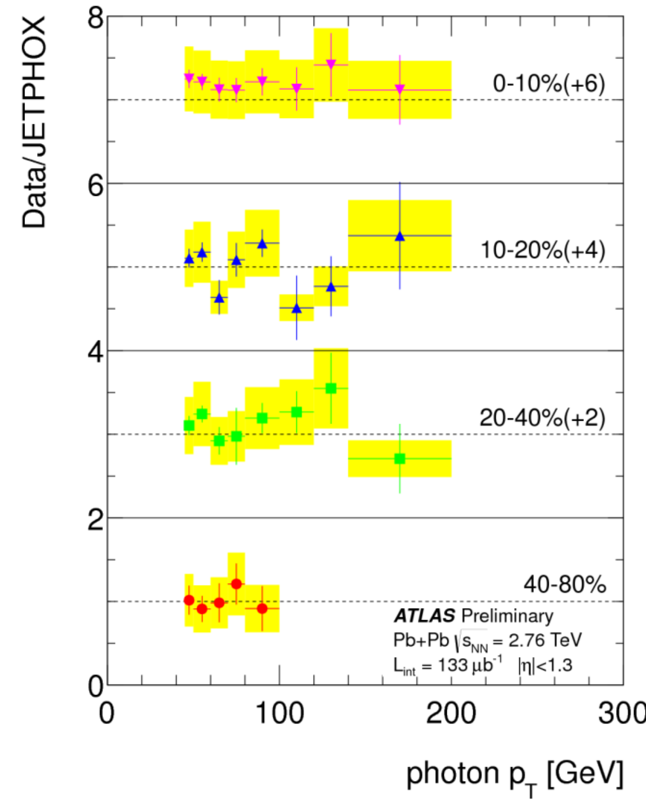
Yields prompt photons



Centrality dependence



Data/MC agreement



Good agreement

$$\frac{1}{N_{\mathrm{evt}}(C)}\frac{dN_{\gamma}}{dp_{T}}(p_{\mathrm{T}},\eta,C) = \frac{N_{A}^{\mathrm{sig}}\mathcal{U}(p_{\mathrm{T}},\eta,C)}{N_{\mathrm{evt}}(C)\epsilon_{\mathrm{tot}}(p_{\mathrm{T}},\eta,C)\Delta p_{\mathrm{T}}}$$

U : bins migration due to finite photon energy resolution

Pb Pb

$\sqrt{s}$=2.76 TeV Pb+Pb, 2011, L=0.14 nb^{-1}

- Characterize modification of hard process rate in nuclear environment

$$R_{AA} = \frac{(N_X/N_{evt})}{T_{AA}\sigma_X^{pp}}$$

N_X : #nb objects X
N_{evt} : #nb MB events
T_{AA} : mean nuclear thickness func (#binary collisions / $\sigma^{inelastic}_{NN}$)
σ^{pp}_X : cross-section process X in pp collisions

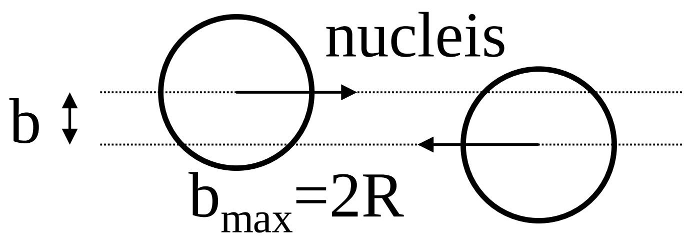
Allows comparison of yields normalized by flux incoming partons to those measured in pp collisions

- Study dependence w/ centrality

Centrality :

$$\frac{\sigma(b)}{\sigma(b_{max})} = \frac{b^2}{4R^2}$$

Connected to impact parameter



Type of collision :
-small centrality / b : central
large participation zone : hot/dense ; fireball
large number of participating/wounded nucleis
-large centrality / b : peripheral
large spectators : cold, flying away undisturbed