Measurements of isolated prompt photons in *pp* collisions with the ATLAS detector

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for the ATLAS Collaboration

LHC EW workshop
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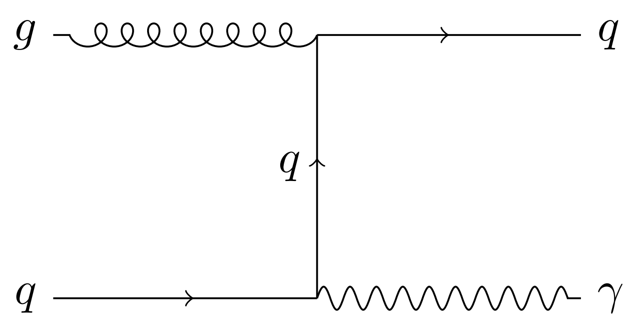
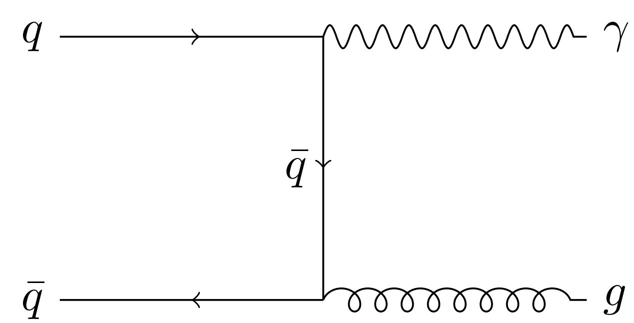
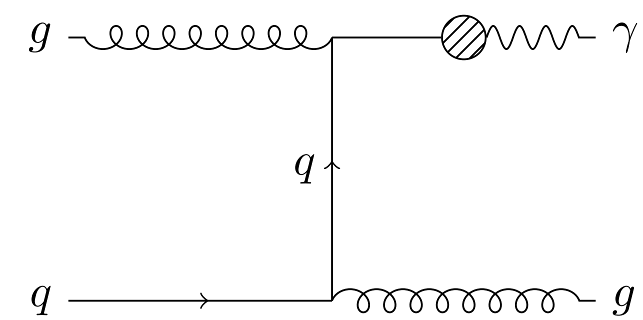
Theoretical relevance



Compton Scattering



Annihilation

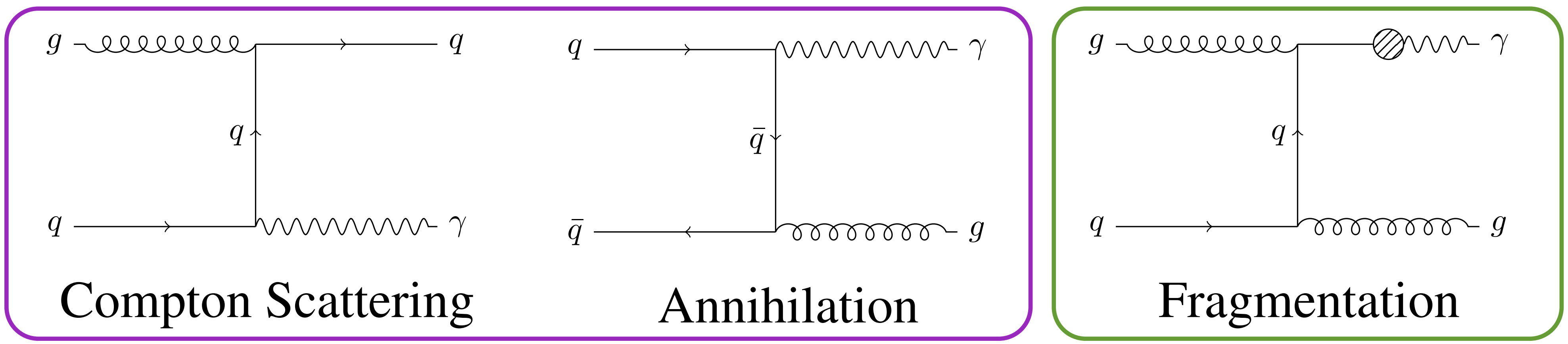


Fragmentation

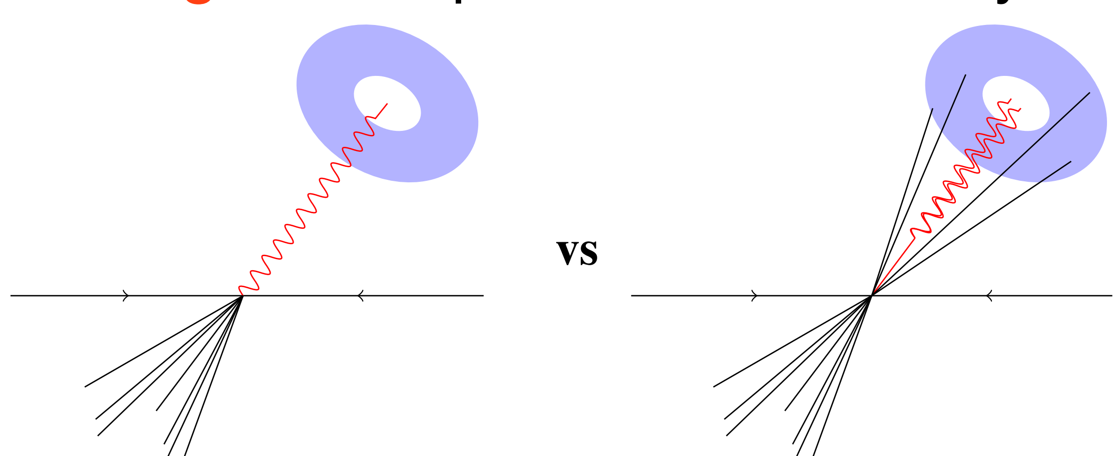
- tests of perturbative QCD predictions (prompt photons mainly produced in parton hard scattering)
- PDF fits:
  - dominant process (qg) involves gluons in the initial state ⇒ probe $g_p(x)$
  - photon + HF (c,b) jet dominated by g + c,b ⇒ probe $c_p(x)$, $b_p(x)$ (intrinsic b/c?)
- test understanding of detector performance and of QCD backgrounds to new physics (e.g. $H\rightarrow\gamma\gamma$)

Isolated prompt photons at hadron colliders

- Prompt photons: direct (from the hard scatter) + (parton) fragmentation
  - direct: dominated by Compton at LHC, photon well separated from parton
  - fragmentation: more important at low $E_T(\gamma)$; photon closer to hadrons



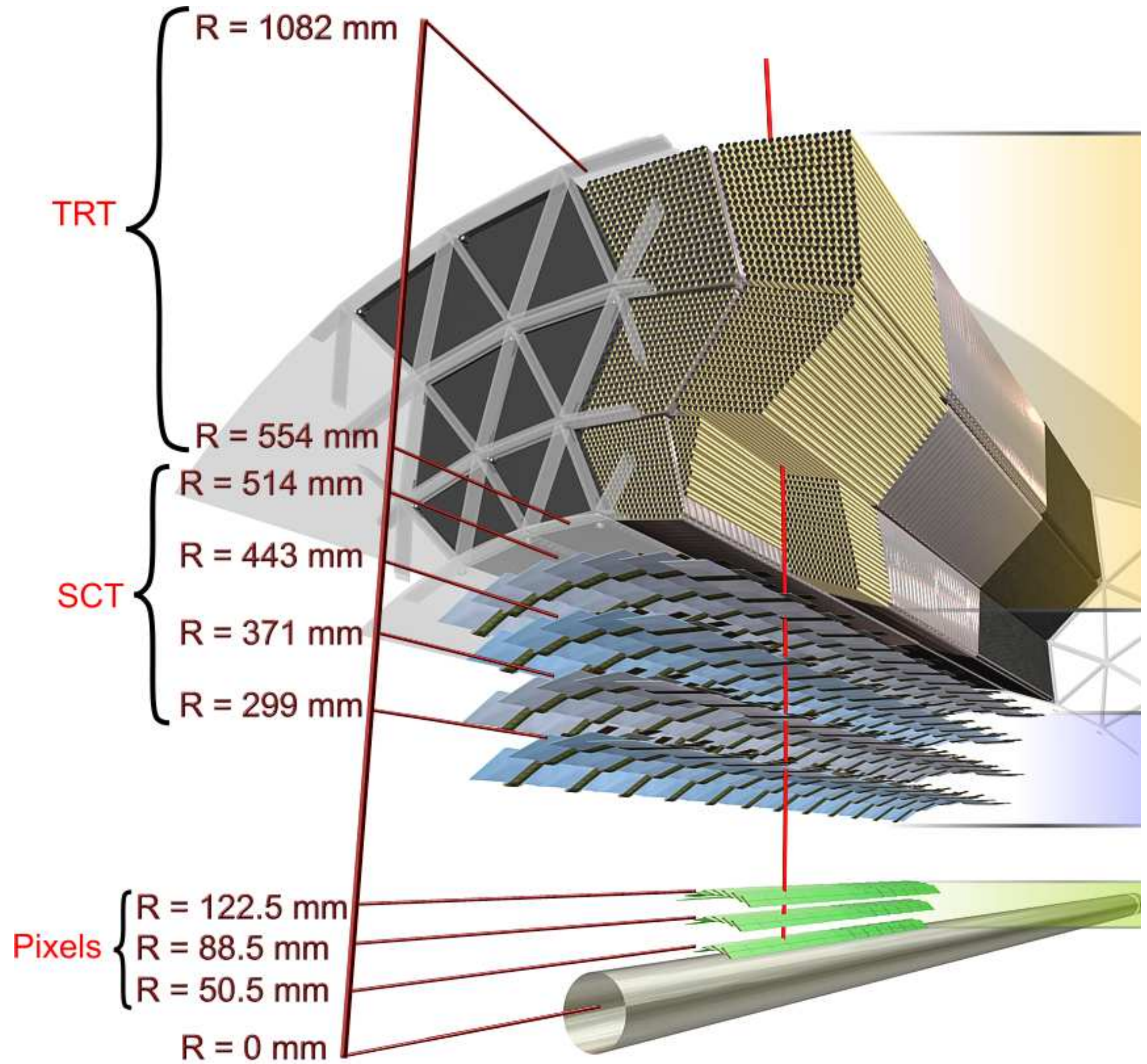
- Isolated: isolation criterion imposed from the beginning
  - isolation energy = additional hadronic transverse energy near photon axis
  - reduces fragmentation (~30% of total xsec at 15 GeV, <10% above 35 GeV)
  - reduces main QCD backgrounds: photons from decays of π^0/η in jets



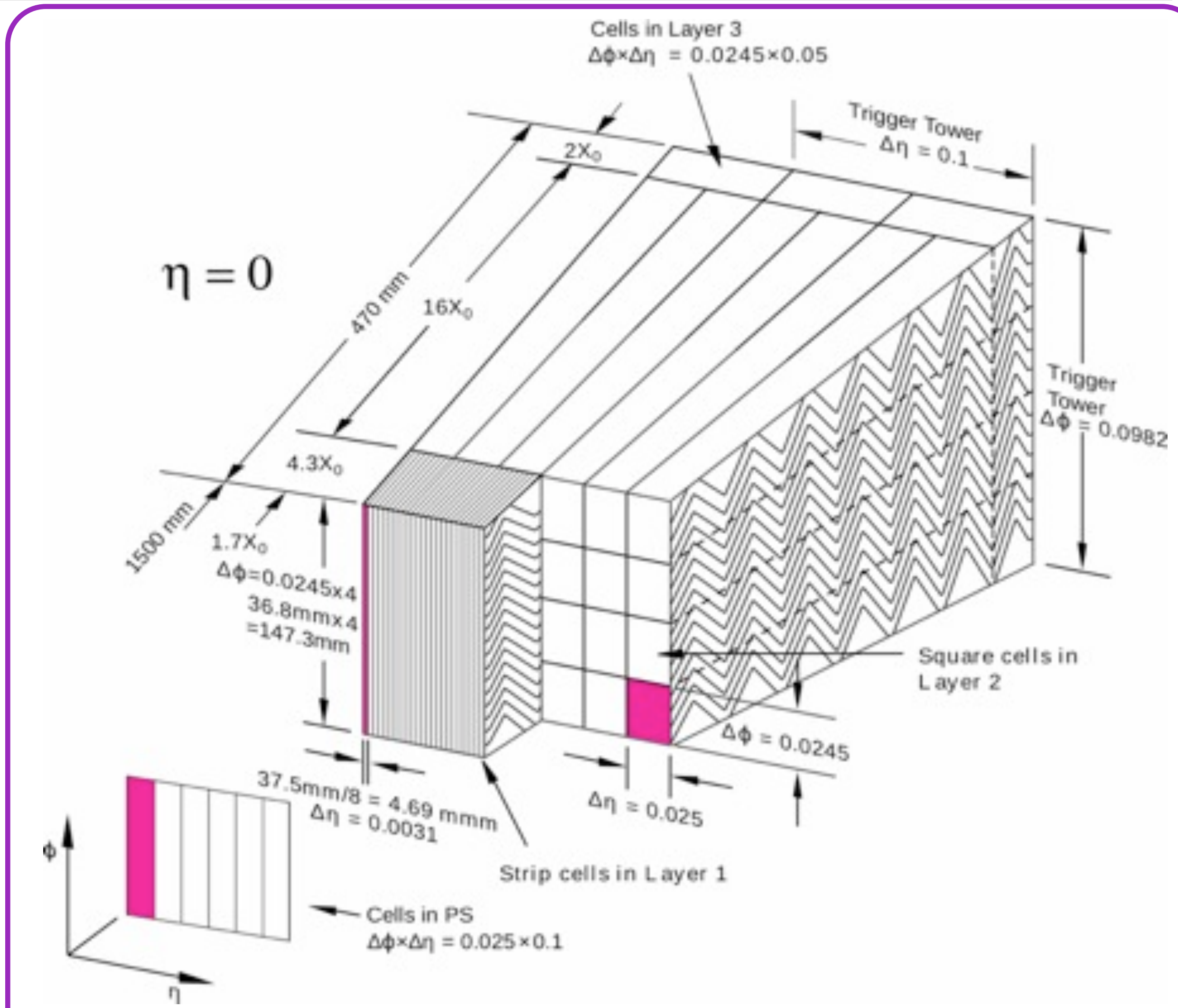
Isolated prompt photon measurements in ATLAS

- All published results based on *pp* collisions at $\sqrt{s}$ = 7 TeV, 2010 data
  - inclusive prompt photon xsection:
    - *Phys. Rev. D 83, 052005 (2011)* (0.9 pb^{-1}, $15 < E_T(\gamma) < 100$ GeV, $|\eta(\gamma)|<1.81$)
    - *Phys. Lett. B 706, 150 (2011)* (35 pb^{-1}, $45 < E_T(\gamma) < 400$ GeV, $|\eta(\gamma)|<2.37$)
  - photon+jet xsection
    - *Phys. Rev. D85, 092014 (2012)* (37 pb^{-1}, $25 < E_T(\gamma) < 400$ GeV, $|\eta(\gamma)|<1.37$)
  - inclusive diphoton xsection
    - *Phys. Rev. D85, 012003 (2012)* (37 pb^{-1}, $E_T(\gamma) > 16$ GeV, $|\eta(\gamma)|<2.37$)
- Analysis of more recent data is ongoing (new results available soon)
- Results are compared to fixed-order NLO calculations (JetPhoX, DiPhox, ResBos) and (in some cases) LO+PS generators

ATLAS: A Toroidal LHC ApparatuS



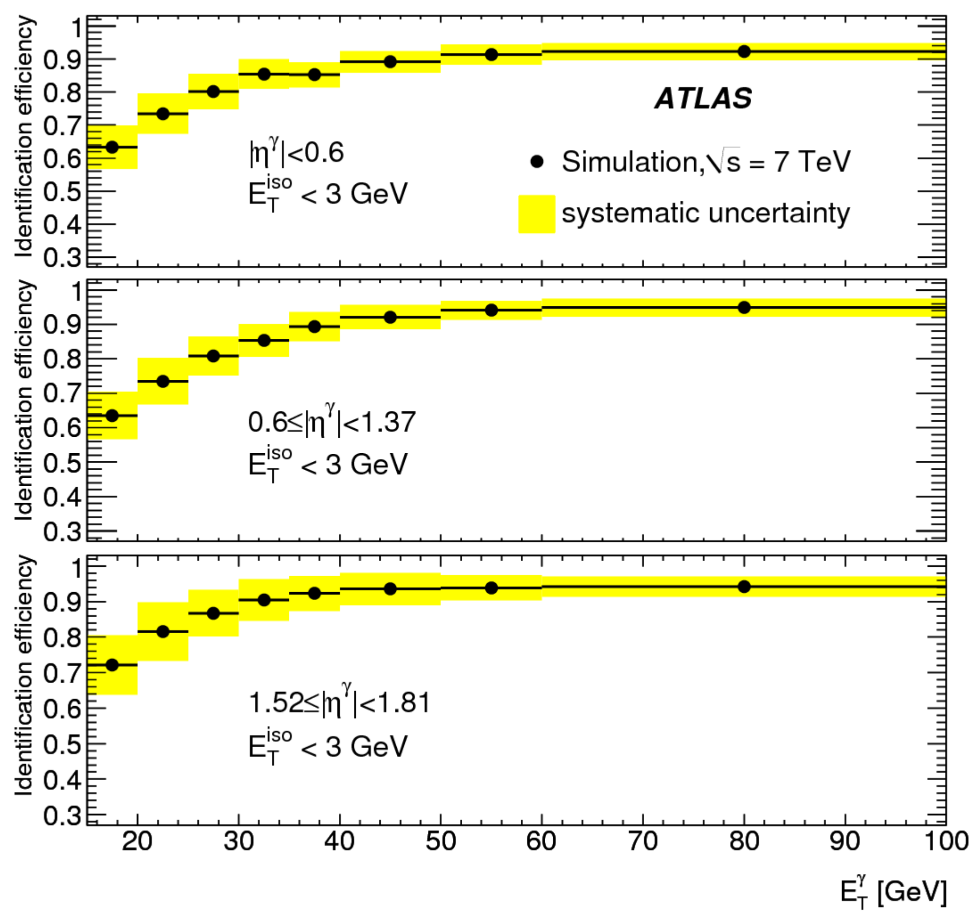
- Inner Detector (|η|<2.5)
  - track charged particles
  - measure transition radiation
  - ✓ reconstruct γ conversions
  - ✓ e/γ discrimination



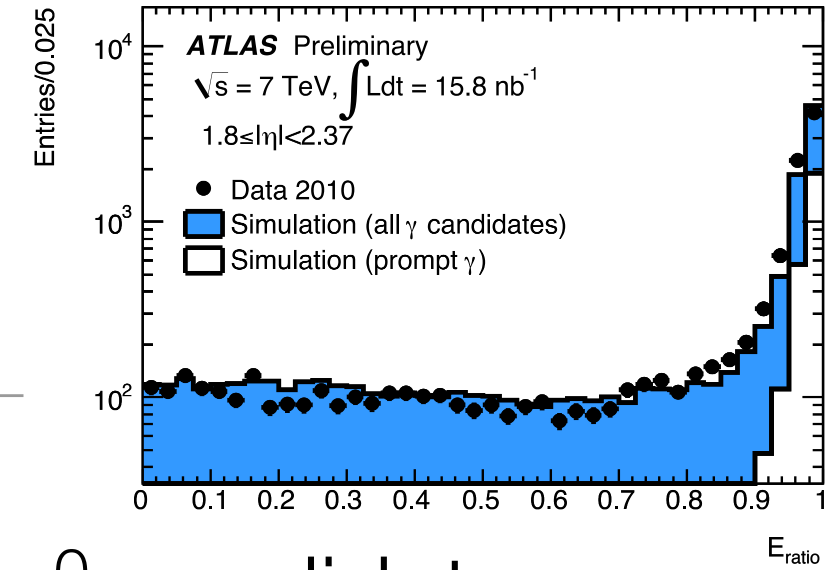
- Pb-LAr EM calorimeter
  - very fine layer1 segmentation up to |η|=2.37 (barrel/endcap crack: 1.37<|η|<1.52)
  - ✓ γ energy/direction measurement
  - ✓ π^0/γ discrimination (shower shape)
  - σ_E/E = (10-17%)(η) / √E (GeV) ⊕ (1.2%-1.8%)

Photon reconstruction and identification

- Reconstruction seeded by ECAL cluster with E>2.5 GeV in 3x5 cells (ηxφ) in layer 2
  - no matched track: unconverted γ (~2/3)
  - matched to track(s) from γ conversion in ID: converted γ (~1/3)
- Reconstruction efficiency ε_{reco} from MC: ~80-85% in barrel (|η|<1.37), ~70% in endcap (1.52<|η|<2.37)
  - Inefficiency largely due to malfunctioning connection links, fixed before 2011 run
  - Systematic uncertainties from MCs with different: generators, material, fraction of fragmentation photons (~5%). Other uncertainties from energy scale and efficiency of isolation requirement (~4%)
- Photon identification: cuts on ECAL shower shape variables (neural net also deployed for $H\rightarrow\gamma\gamma$)
  - different cuts for converted/unconverted photons
  - ε_{ID} from 60% (15 GeV) to >90% (>~50 GeV)
  - uncertainties from data/MC comparison in control samples (5-10% at low E_T in 2010; now reduced to 2-3%, see *ATLAS-CONF-2012-123*)
- Trigger efficiency: ~(99.5±0.5)% for identified photons with E_T above trigger threshold



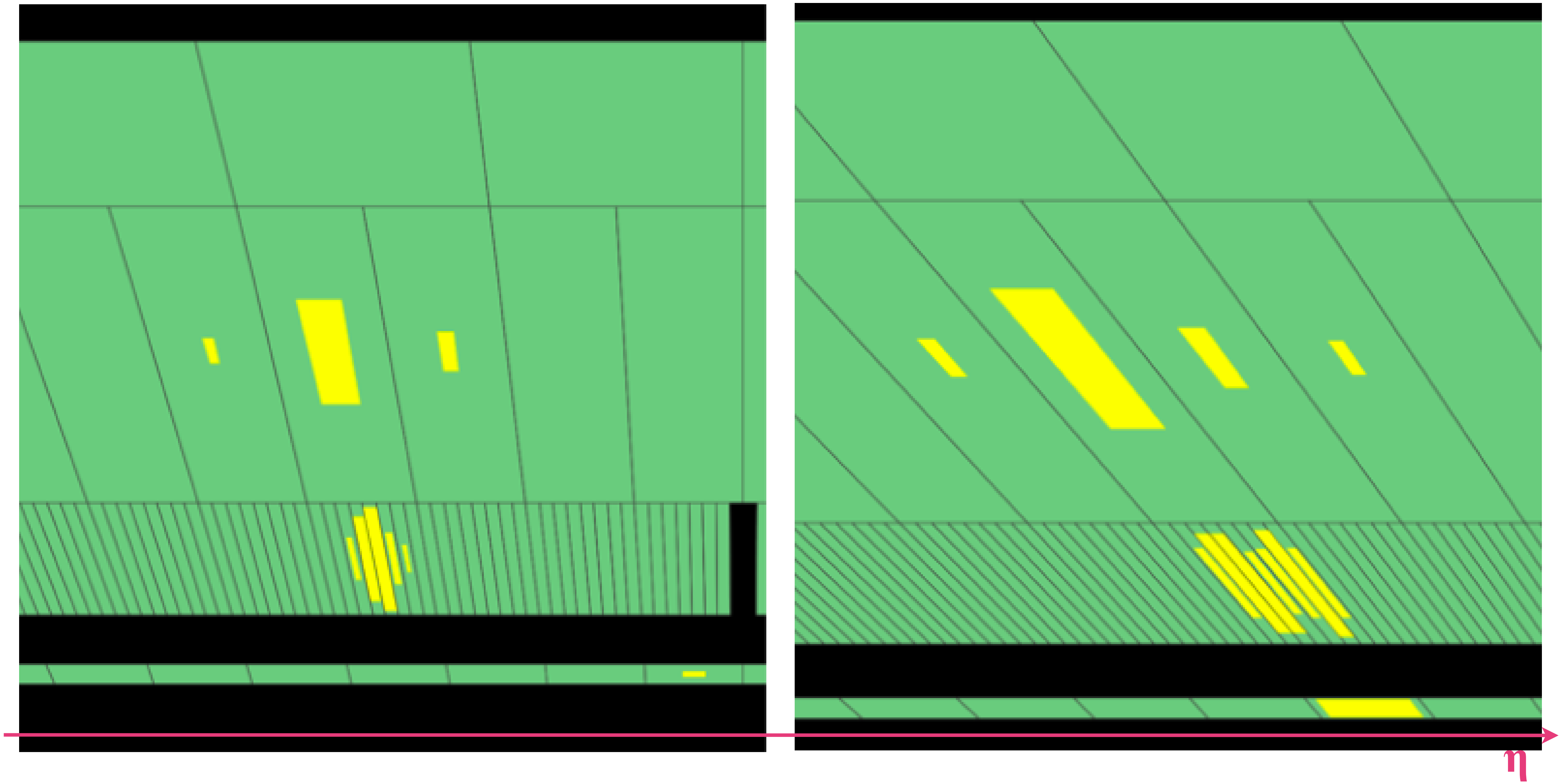
Photon/π^0 discrimination



single γ candidate

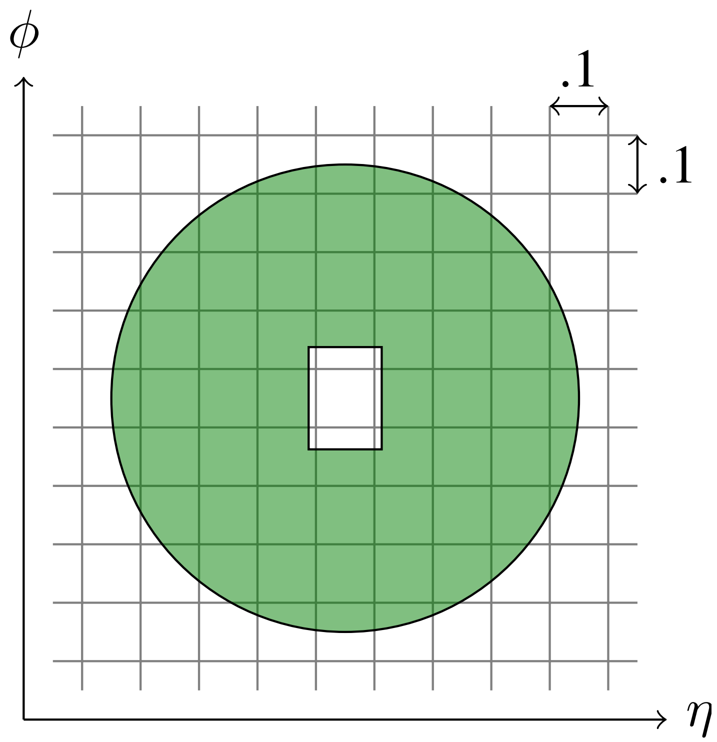
π^0 candidate

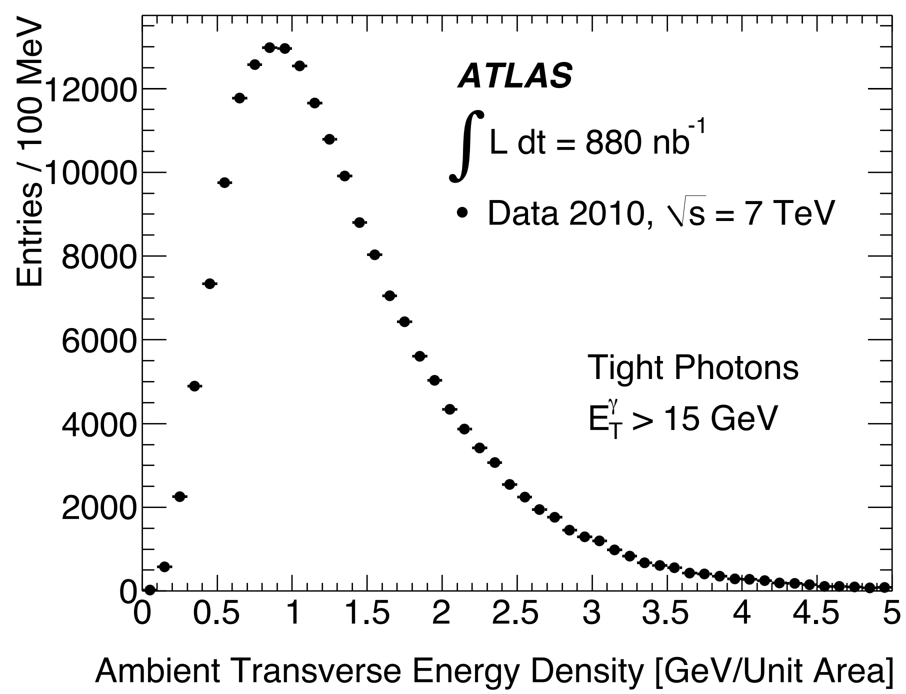
- S3
- S2 (middle)
- S1 (strips)
- Pre-sampler

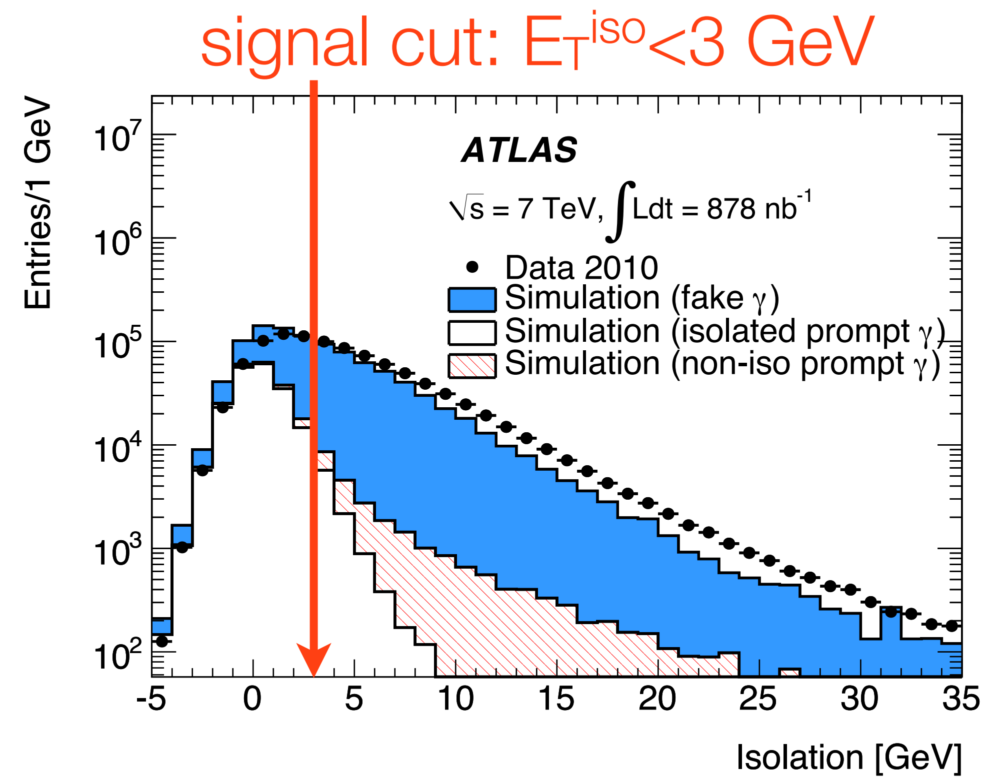


✓ *loose* and *tight* photon ID criteria based on shower shapes in calorimeters

Photon calorimeter isolation



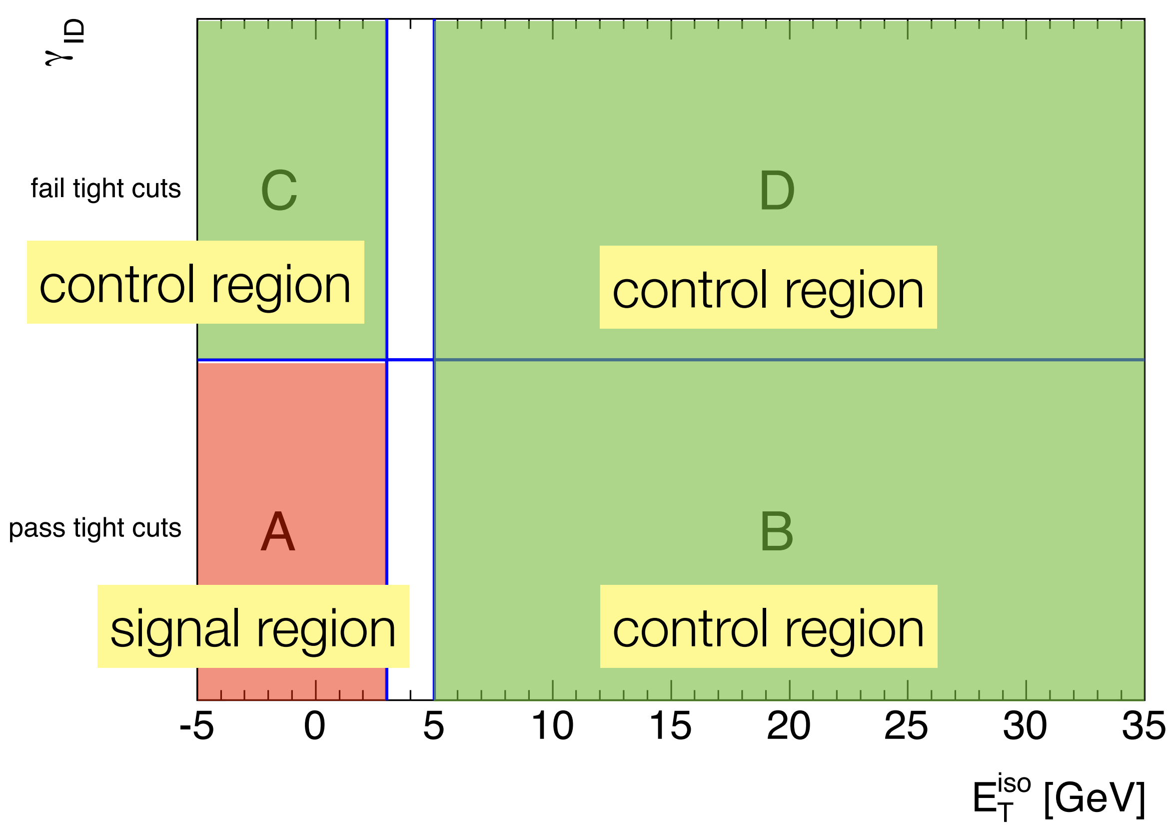


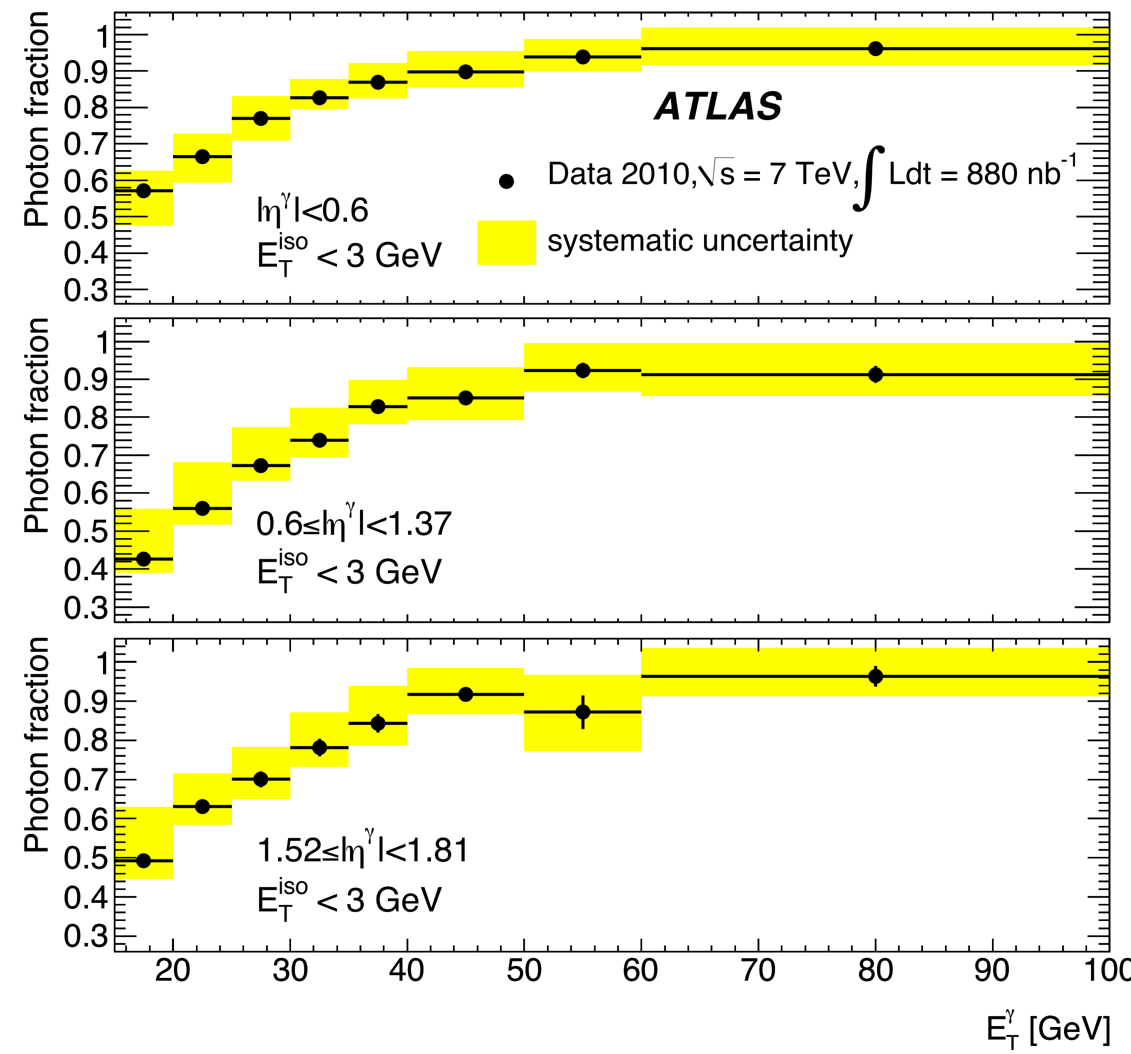


- E_T^{iso}= Σ(calo cells) in cone $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < .4$, not in core cluster (5x7 cells)
- Subtract out-of-core leakage
- Subtract soft-jet activity from pileup and underlying event (*Cacciari, Salam and Sapeta, JHEP 04 (2010) 065*)
  - for events with 1 primary vertex: PYTHIA: 440 MeV, HERWIG: 550 MeV, DATA: 540 MeV
  - correction increases linearly with # of primary vertices
- O(0.5 GeV) shift observed between data and MC ⟹ use data-driven isolation templates if possible
- slightly different isolation variable used in 2011/2012 analyses; data-MC shift ~100 MeV

Signal extraction

$$N_{\mathbf{A}}^{\mathrm{sig}} = N_{\mathbf{A}}^{\mathrm{obs}} - N_{\mathbf{A}}^{\mathrm{bkg}} = N_{\mathbf{A}}^{\mathrm{obs}} - R^{\mathrm{bkg}} \frac{(N_{\mathbf{B}}^{\mathrm{obs}} - N_{\mathbf{B}}^{\mathrm{sig}})(N_{\mathbf{C}}^{\mathrm{obs}} - N_{\mathbf{C}}^{\mathrm{sig}})}{N_{\mathbf{D}}^{\mathrm{obs}} - N_{\mathbf{D}}^{\mathrm{sig}}}$$



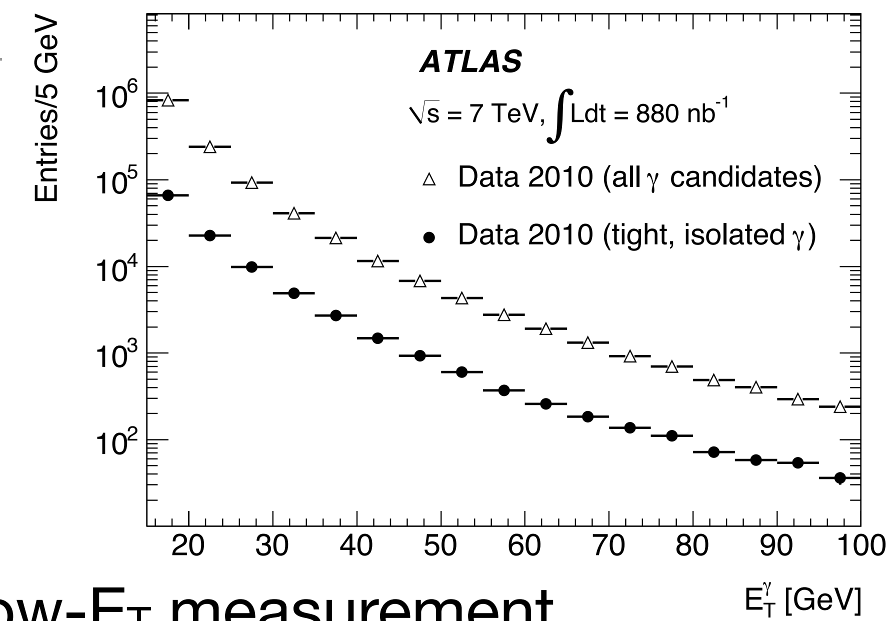


$N_{\mathbf{K}}^{\mathrm{sig}} = c_{\mathbf{K}} N_{\mathbf{A}}^{\mathrm{sig}} \quad (\mathbf{K} = \mathbf{B}, \mathbf{C}, \mathbf{D})$ c_K from MC (c_B,c_C ~few%)

$R^{\mathrm{bkg}} = \frac{N_{\mathbf{A}}^{\mathrm{bkg}} N_{\mathbf{D}}^{\mathrm{bkg}}}{N_{\mathbf{B}}^{\mathrm{bkg}} N_{\mathbf{C}}^{\mathrm{bkg}}}$ consistent with 1 in bkg MC

- Purity rapidly increases from 50% (15 GeV) to >95% (>100 GeV)
- Main systematic uncertainties from: MC inputs (up to ~10%); bkg control regions (up to 6%)
- Results cross-checked with isolation template fit (signal template: e from W/Z in data; bkg template: photons failing the tight ID criteria). Results agree within few %
- Isolated electron contamination estimated from data and MC control samples

Inclusive isolated prompt photon cross section



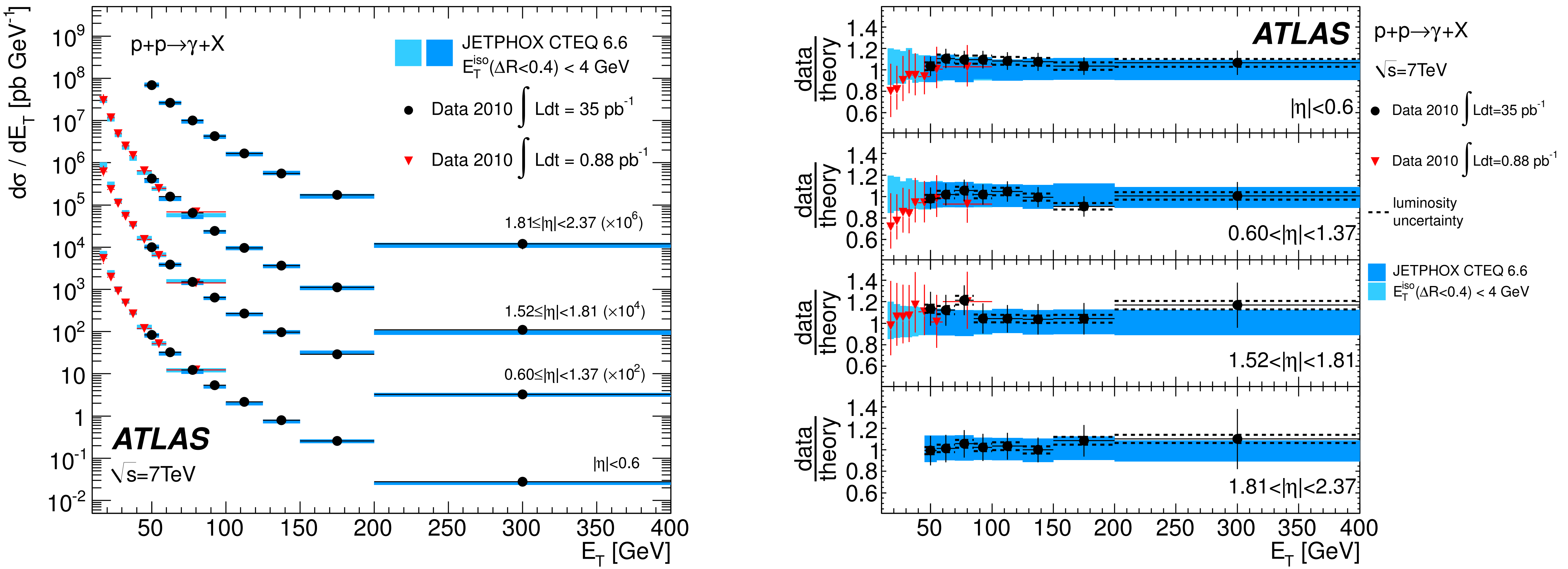
- Two analyses with different luminosities
  - 0.88 pb^{-1} analysis: $15 < E_T(\gamma) < 100$ GeV, $|\eta(\gamma)|$ in: [0,0.6) [0.6,1.37) [1.52, 1.81)
  - 35 pb^{-1} analysis: $45 < E_T(\gamma) < 400$ GeV, $|\eta(\gamma)|$ in: [0,0.6) [0.6,1.37) [1.52, 1.81) [1.81, 2.37)
- Complementary $E_T(\gamma)$ ranges, fragmentation only affects low-E_T measurement
- Very similar analysis techniques
- Additional cross section systematic uncertainties:
  - unfolding: bin-by-bin vs SVD or iterative (Bayesian): <2% difference, within non-closure error
  - luminosity: uncertainty down from 11% to 3.5% (3.9% in 2011)
- NLO pQCD predictions by JetPhoX 1.2.2 *(Eur. Phys. J. C21 (2001) 303)* with CTEQ 6.6 PDFs [MSTW 2008: 3-5% difference] and scales set to $E_T(\gamma)$
  - parton isolation energy < 4 GeV in cone $\Delta R = 0.4$
  - uncertainties: vary PDF eigenvalues (4% → 2%), scales between .5 and 2 $E_T(\gamma)$ (20% → 8%), isolation cut between 2 and 6 GeV: ±2%

Inclusive photon cross section

[Phys. Rev. D 83, 052005 (2011)](#)

[Phys. Lett. B 706, 150 (2011)](#)

[ATL-PHYS-PUB-2011-013](#)



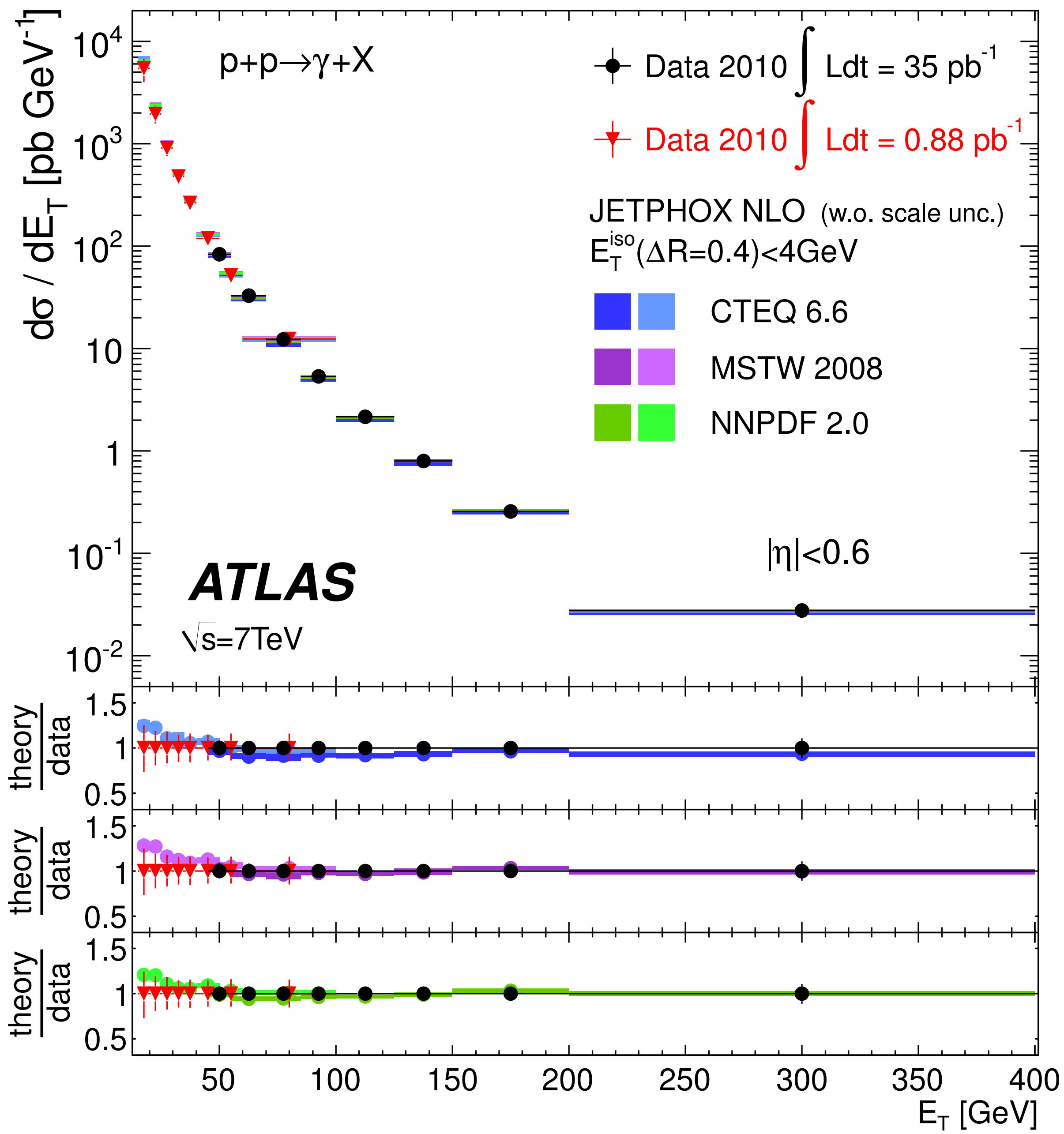
- Results systematically limited across full E_T range
- The two measurements are consistent in the overlapping E_T, η bins
- Data/(NLO pQCD) comparison:
  - experimental uncertainty comparable to theoretical one
  - disagreement (ratio data/theory<1) below 35 GeV, good agreement above
  - similar trend with other PDF sets (MSTW2008, NNPDF 2.0)

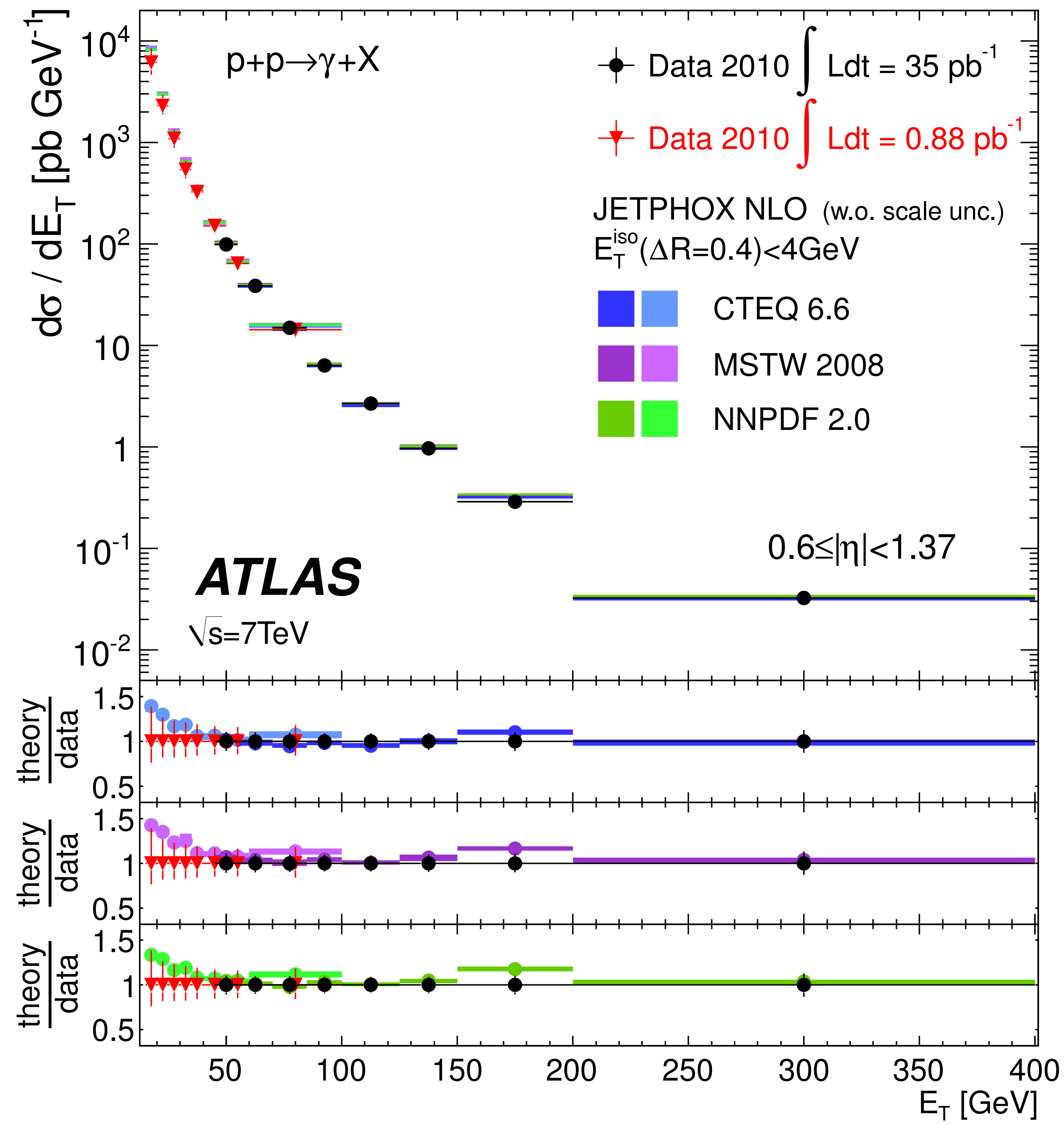
Inclusive photon cross section

Phys. Rev. D 83, 052005 (2011)

Phys. Lett. B 706, 150 (2011)

ATL-PHYS-PUB-2011-013

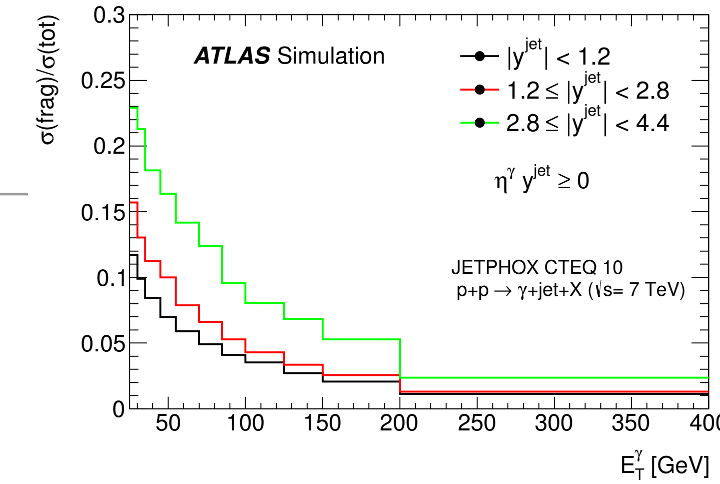


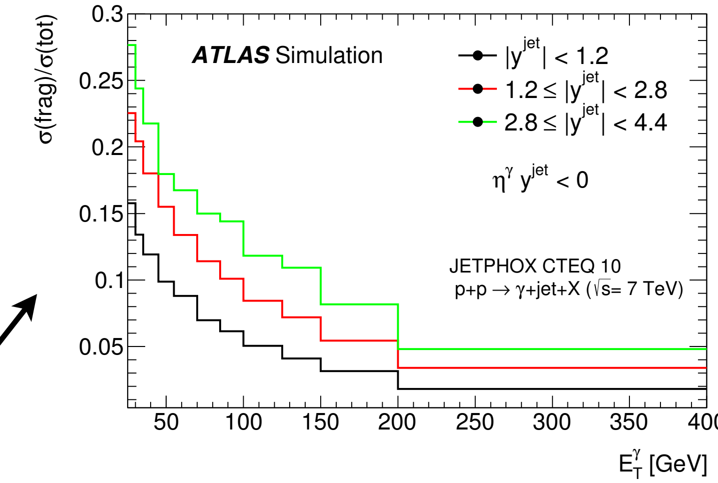


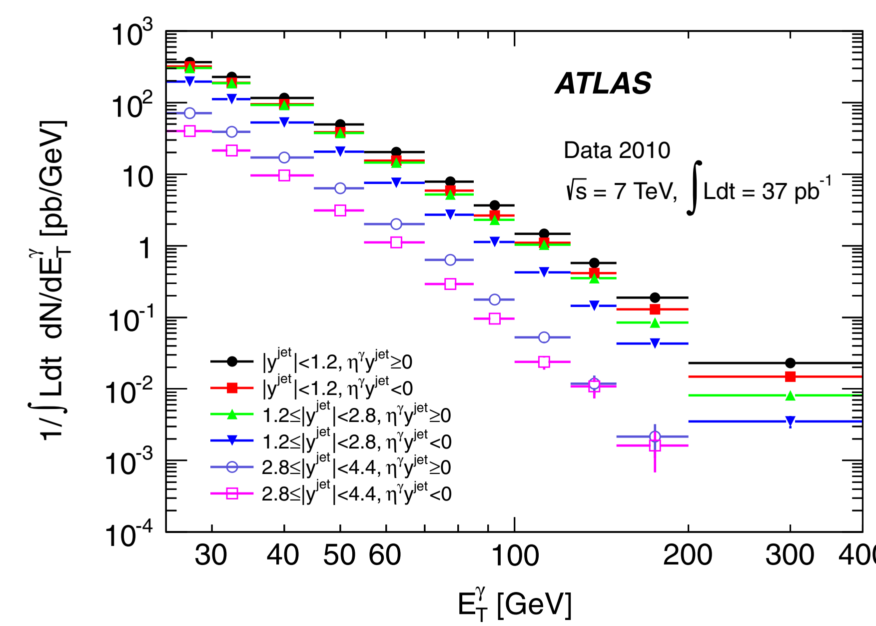
Phys. Rev. D85, 092014 (2012)

Photon+jet cross section

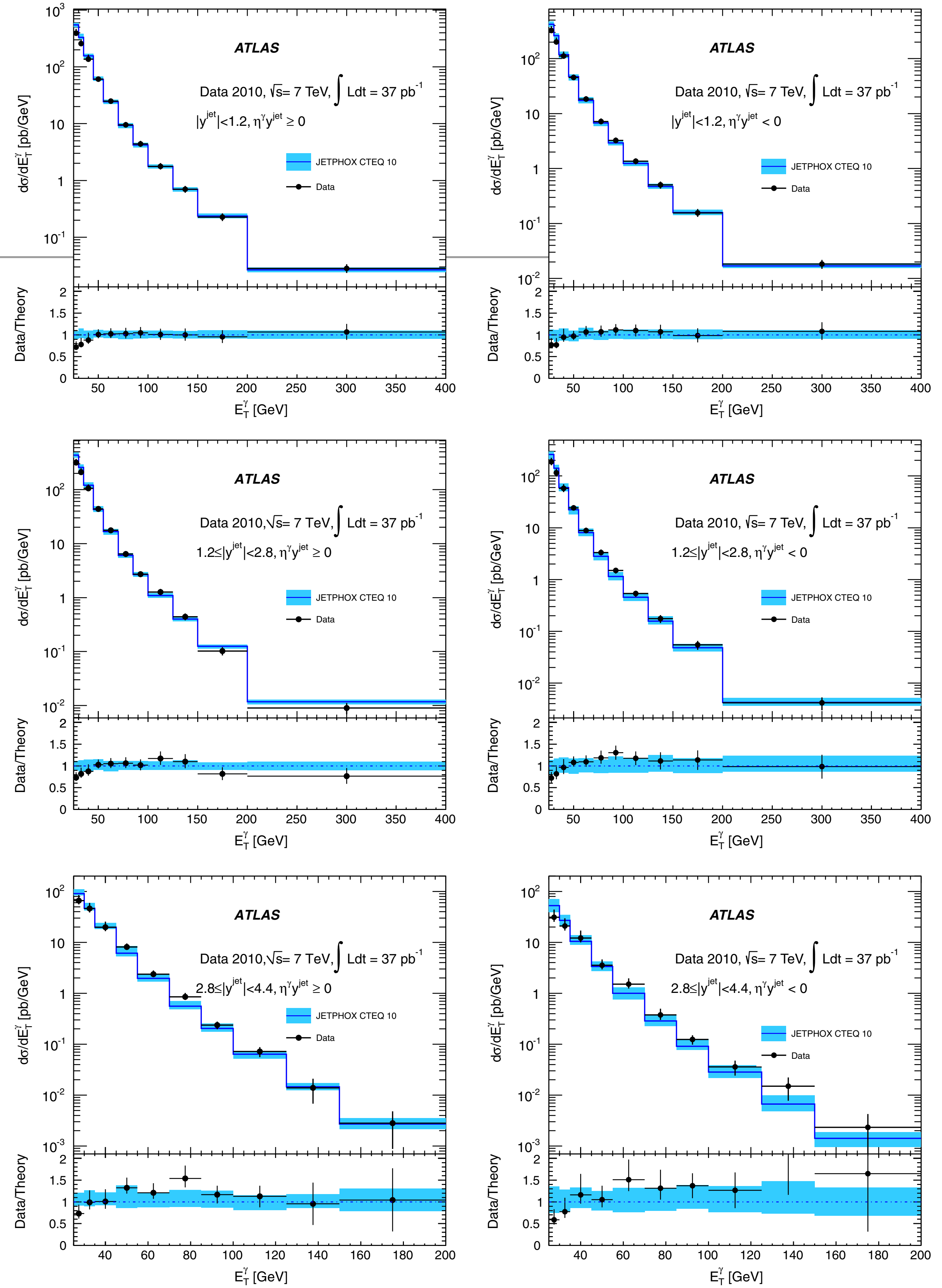
- Similar dataset (2010 data, 37 pb^{-1}) and ingredients as for inclusive analysis, but:
  - consider only photons in barrel ($|\eta_\gamma|<1.37$), $25<E_T^\gamma<400$ GeV
  - require one jet ($\Delta R_{\gamma j}>1.0$): $|y_j|<1.2$ (central), $1.2<|y_j|<2.8$ (forward) or $2.8<|y_j|<4.4$ (very forward)
- same-sign ($\eta_\gamma y_j>0$) and opposite-sign ($\eta_\gamma y_j<0$) cross sections measured separately vs E_T^γ (similar to D0, Phys, Lett. B666, 435 (2008)) ⇒ explore configurations with different contribution from fragmentation photons
- use anti-kT (R=0.4) jets with $p_T^j>20$ GeV
- Experimental systematic uncertainty:
  - 15%- 8% in central jet, same-sign configuration
  - 40% to 22% in very forward jet, opposite-sign case
  - significant contribution from photon simulation (PYTHIA vs HERWIG, varying frag./direct between 0 and 100%)







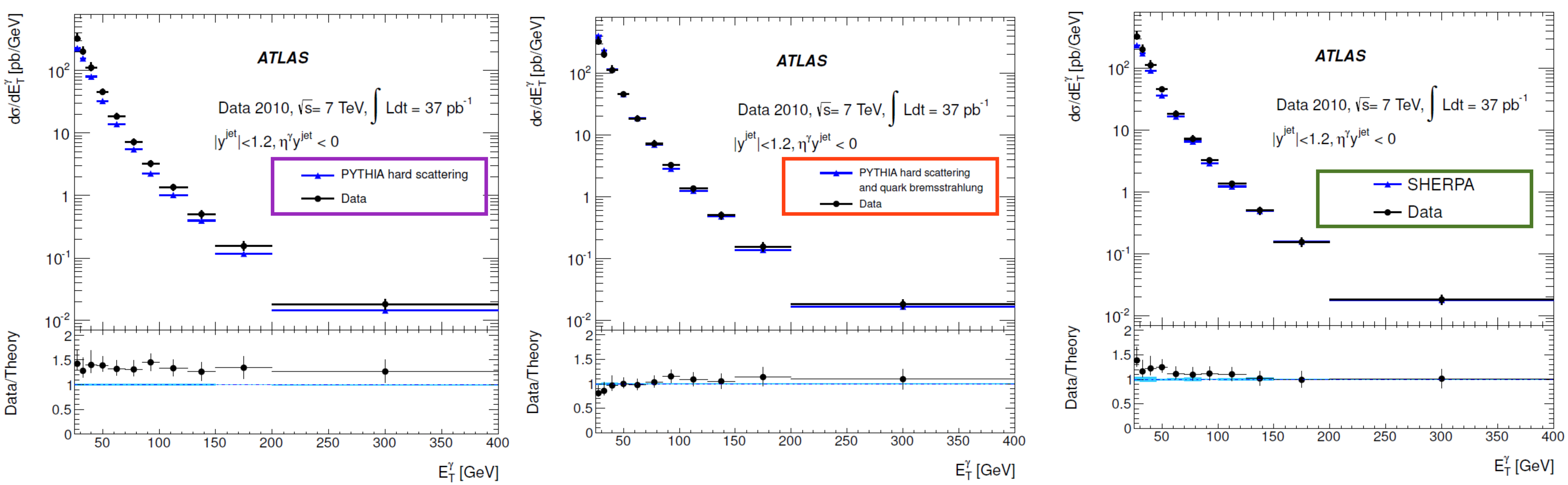
Photon+jet xsection



- Theoretical predictions with JetPhoX 1.3 with CT10 PDFs
  - (parton) isolation<4 GeV in cone R=0.4, scales set to E_T^γ
  - corrected for hadronization/UE (using Pythia and Herwig, various tunes): corrections ~1 (0.9 at very low E_T^γ)
- Systematic uncertainties
  - scales ($E_T^\gamma/2 \leftrightarrow 2E_T^\gamma$): 10%-40%
  - PDF eigenvalues: 5%-10%
  - parton isolation cut (2%-10%)
  - non perturbative corrections (3%-20%)
  - largest uncertainties for very forward jets
- MSTW2008/NNPDF2.1: similar results, within the total uncertainty
- Data vs theory: agreement for all configurations, same trend (theory>data) at low E_T^γ as for inclusive cross section

Photon+jet xsection: testing LO+PS generators

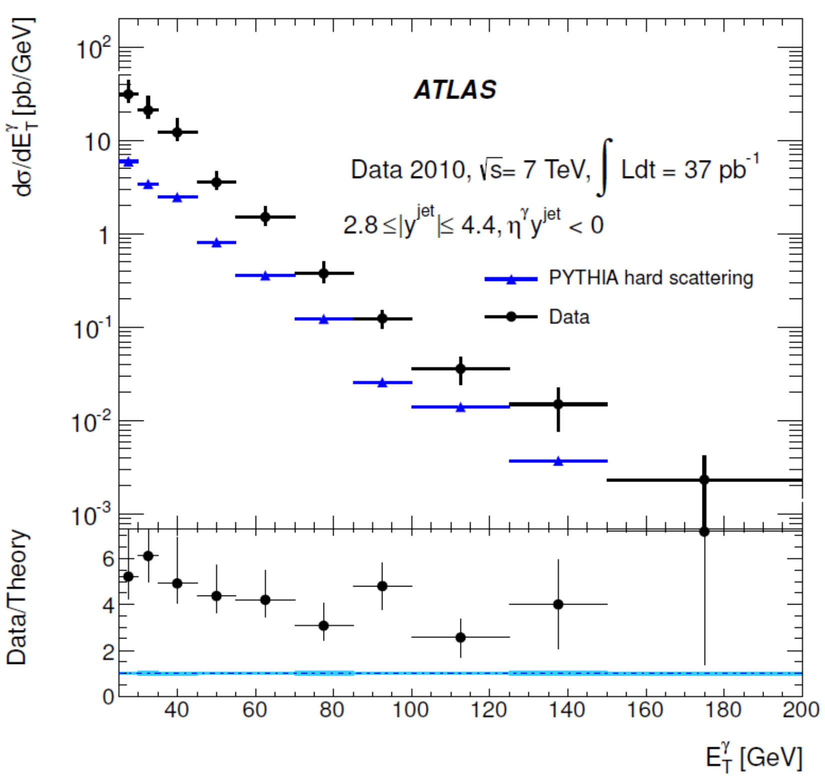
- The measurement has been used to test the main full event generators used in ATLAS (with the corresponding ATLAS tune - errors are stat. only)
  - PYTHIA6, only hard scattering photons (qg→qγ + qqbar→gγ)
  - PYTHIA6, hard-scattering + brem photons (QCD 2→2 + photon emission in PS)
  - Sherpa (ME for photon + emission of up to 4 real partons)

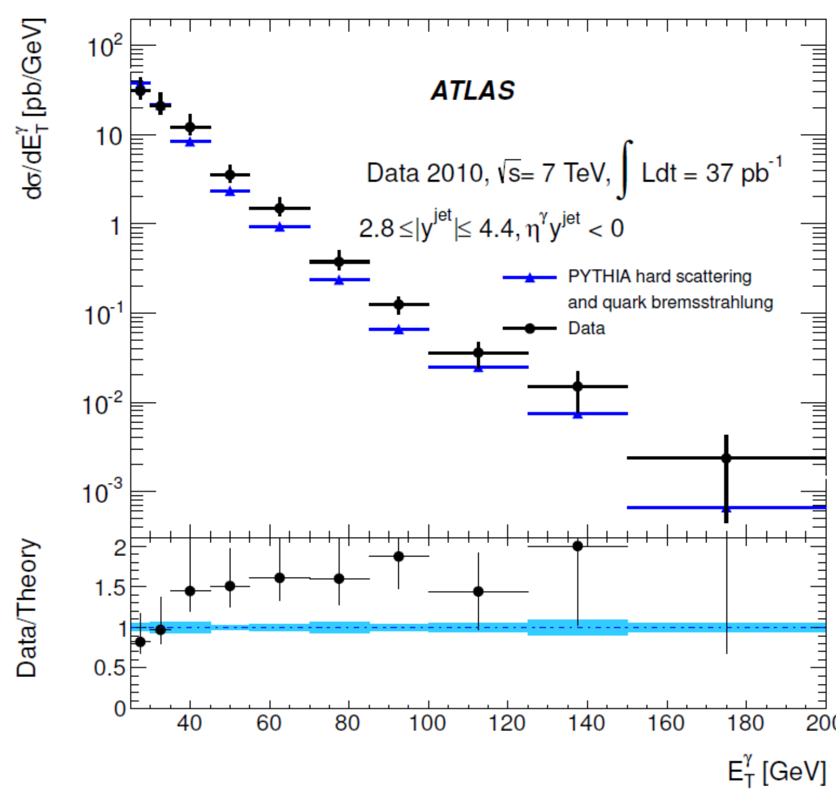


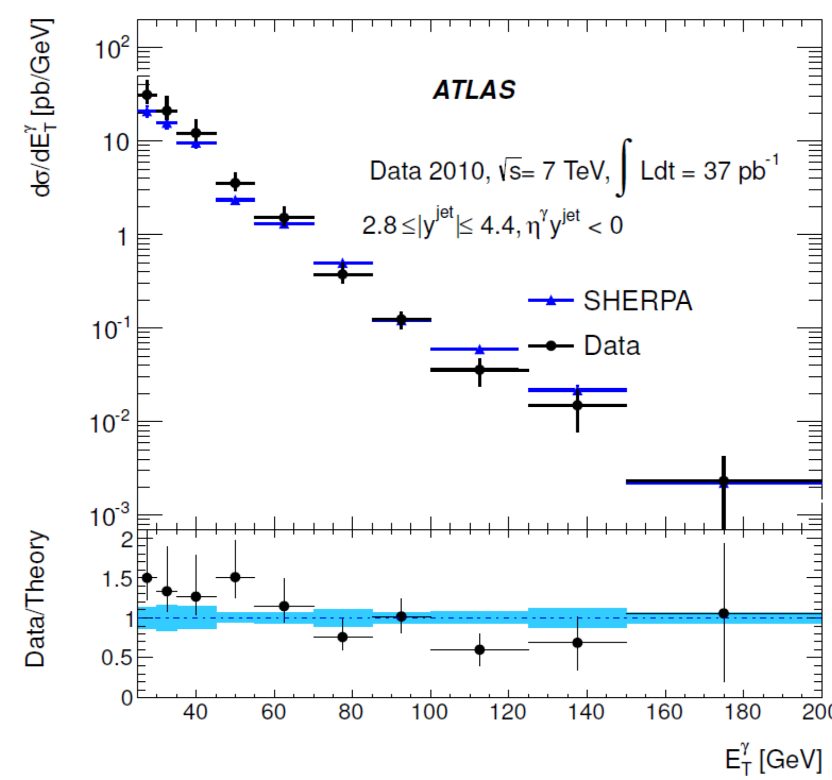
- Pure hard scattering sample clearly lacks the fragmentation component
- Good agreement with PYTHIA6 hard+brem photons and Sherpa (central jets, opposite-sign)

Photon+jet xsection: testing LO+PS generators

- Moving to configurations with larger contribution from fragmentation
  - disagreement with PYTHIA6 gets worse
  - agreement with Sherpa remains even in the other 5 cases



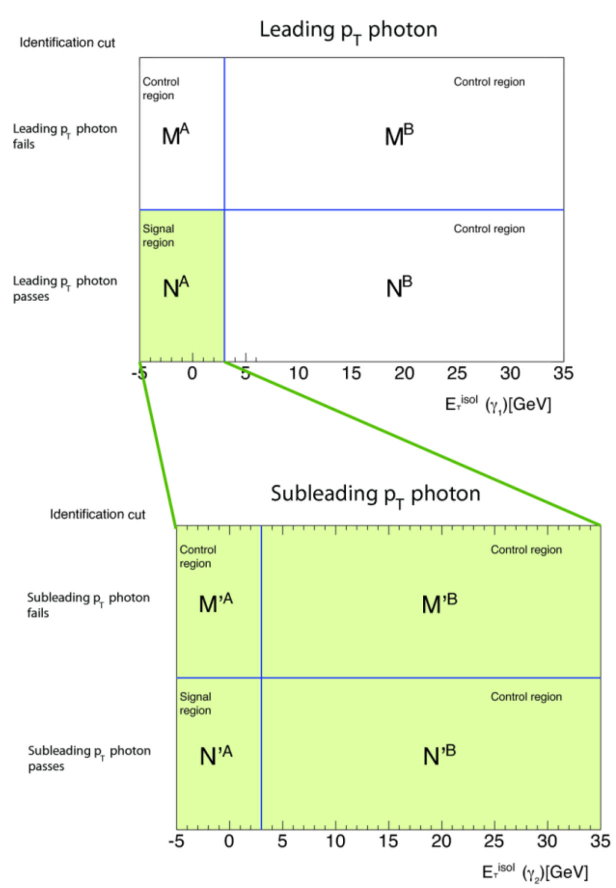




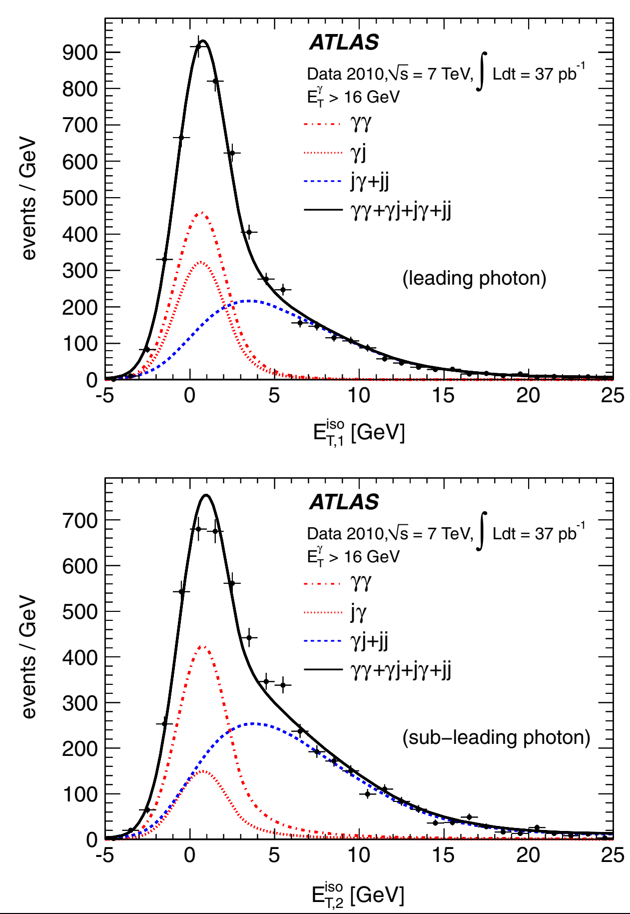
Di-photon cross section: background subtraction

- three alternative methods based on photon isolation (and photon identification)
  - 2x2D sideband: extension of 2D sidebands method to the case of 2 photons: for events with leading candidate in signal region, a second 2D plane is used for subleading candidate
  - 2D fit to isolation energies of both photon candidates
  - 4x4 matrix (method exploited by CDF and D0)
- in all methods, isolation templates or efficiencies are measured on data (isolated electrons from W/Z and non-tight control sample)

2x2D sidebands



2D fit



4x4 matrix

observed number of diphoton candidates passing/failing E_T^{iso}<3 GeV cut

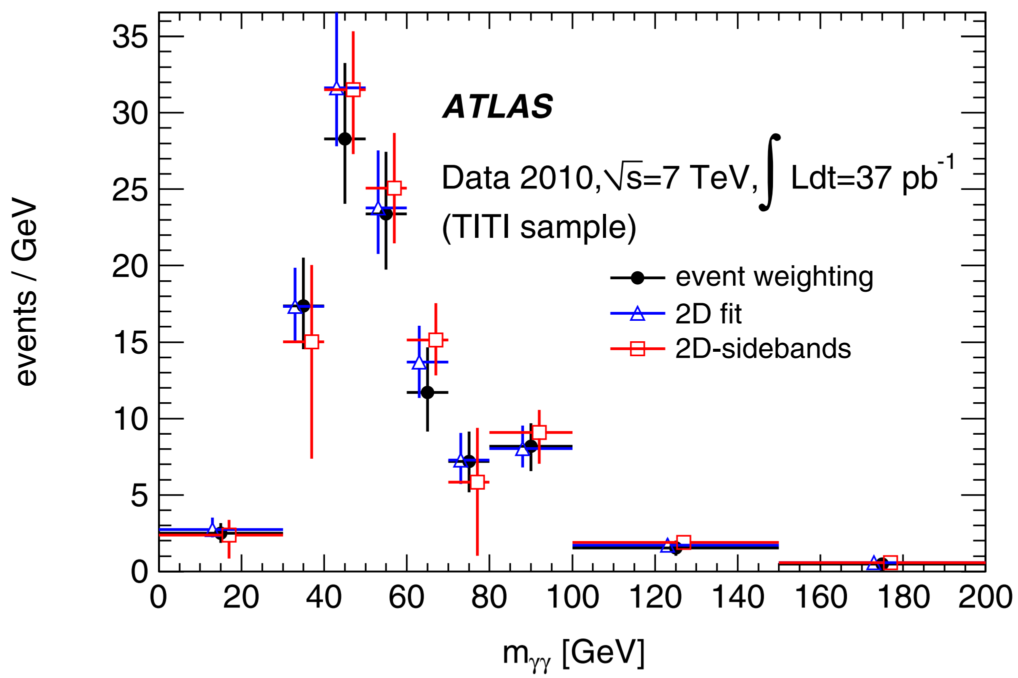
$$\begin{pmatrix} S_{PP} \\ S_{PF} \\ S_{FP} \\ S_{FF} \end{pmatrix} = \mathbf{E} \begin{pmatrix} W_{\gamma\gamma} \\ W_{\gamma j} \\ W_{j\gamma} \\ W_{jj} \end{pmatrix}$$

true yields

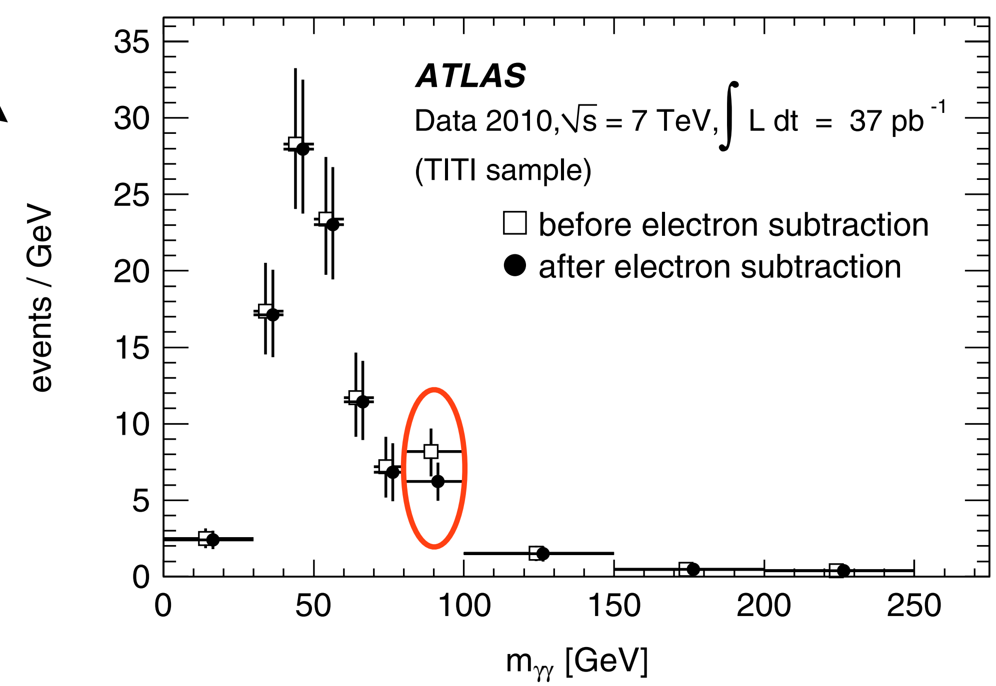
E = efficiency matrix

Di-photon signal yield

- Select events with two photons in pseudorapidity acceptance ($|\eta^{\gamma}|<2.37$), $E_T^{\gamma}>16$ GeV (trigger: 15 GeV), passing tight ID, isolated ($E_T^{iso}<3$ GeV), $\Delta R_{\gamma\gamma}>0.4$
- Three methods give consistent results with comparable syst. uncertainty (~15%)

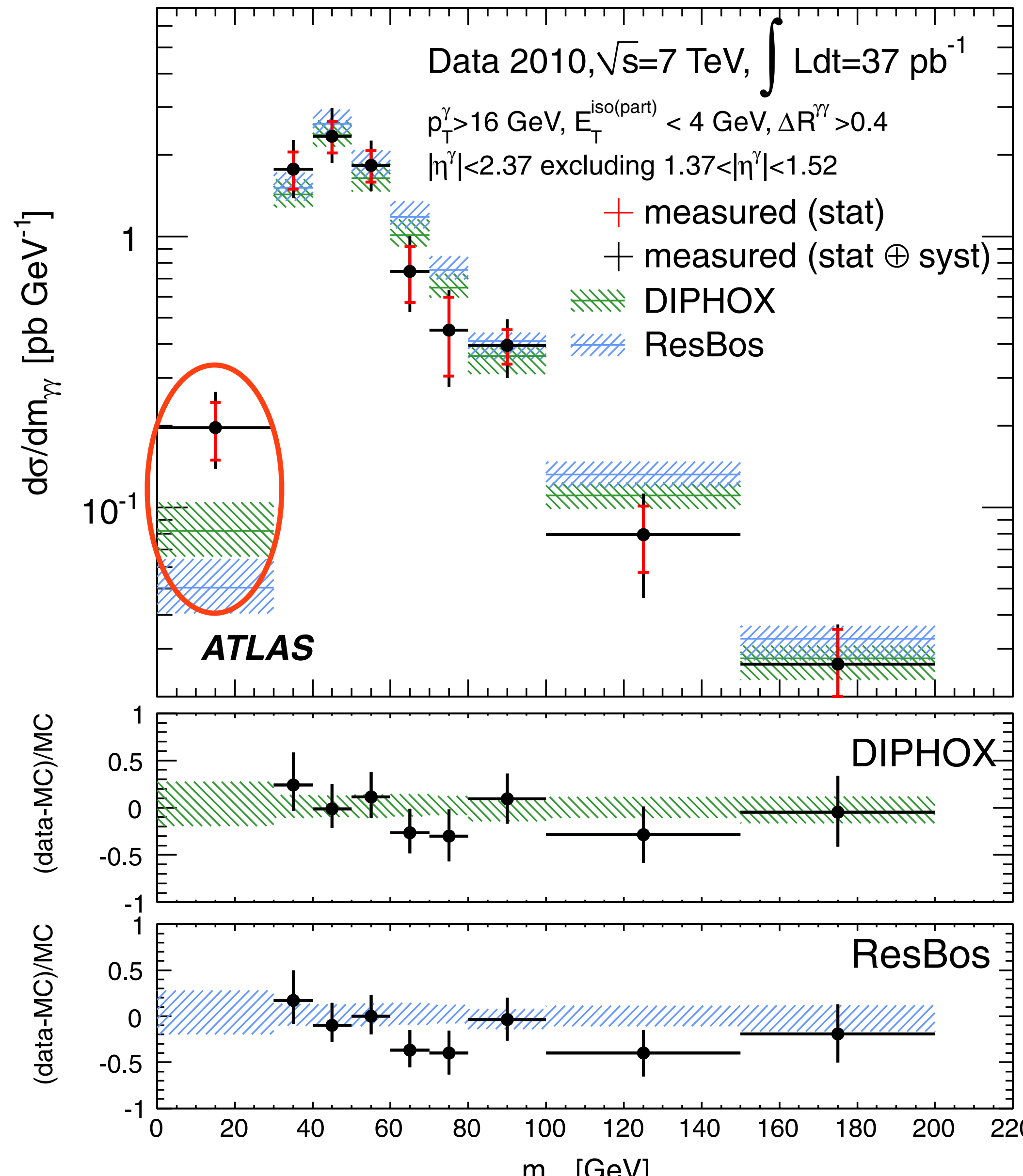


- Isolated electron bkg (W/Z, DY, ..) subtracted solving a matrix equation using measured e⟷γ fake rates



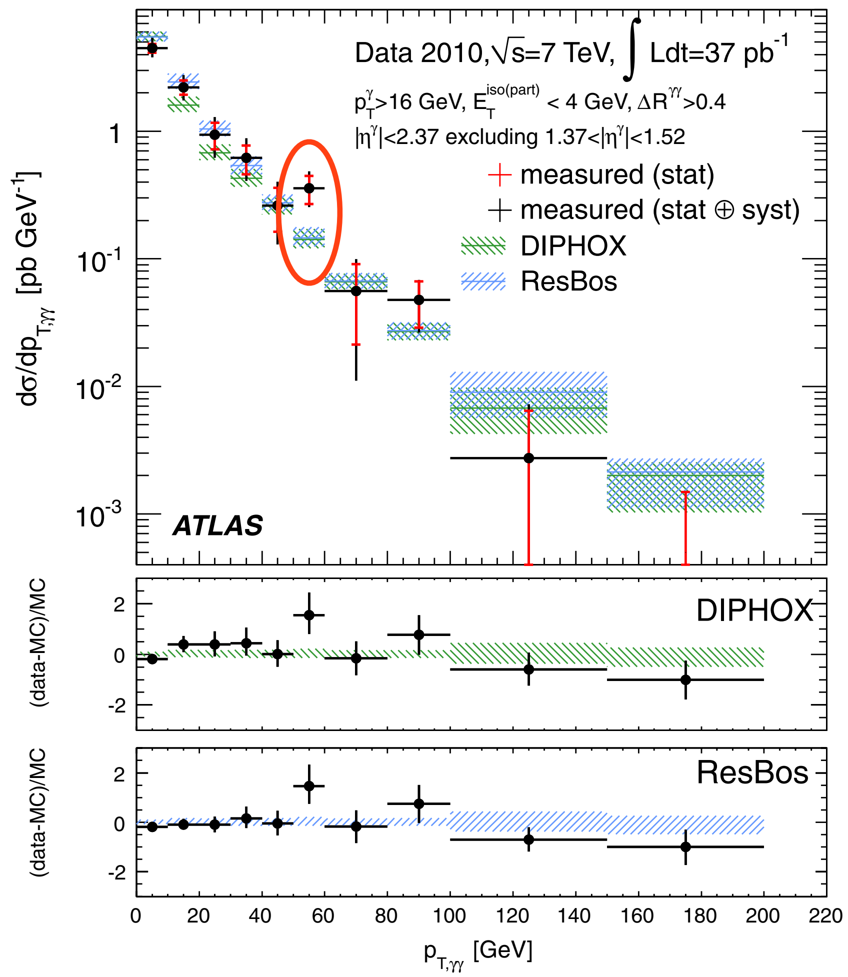
Isolated di-photon xsection

- Theoretical predictions obtained with
  - DIPHOX: fully NLO (including fragmentation) + LO box (technically, NNLO, but large gluon flux..)
  - ResBos: NLO + fragmentation@LO + NNLL resummation of soft gluon ISR
  - Scales set to $M_{\gamma\gamma}$, PDFs = CTEQ6.6
  - (parton) isolation cut = 4 GeV in dR=0.4
- Systematic uncertainties on theory:
  - scale variations (50-200%)
  - PDF eigenvalues
  - isolation cut (2-6 GeV): 5%
- MSTW2008: increase by 10%, within CTEQ errors
- Data/theory: fair agreement (with some exceptions), but rather large uncertainties ⇒ need more data (not yet systematically limited)

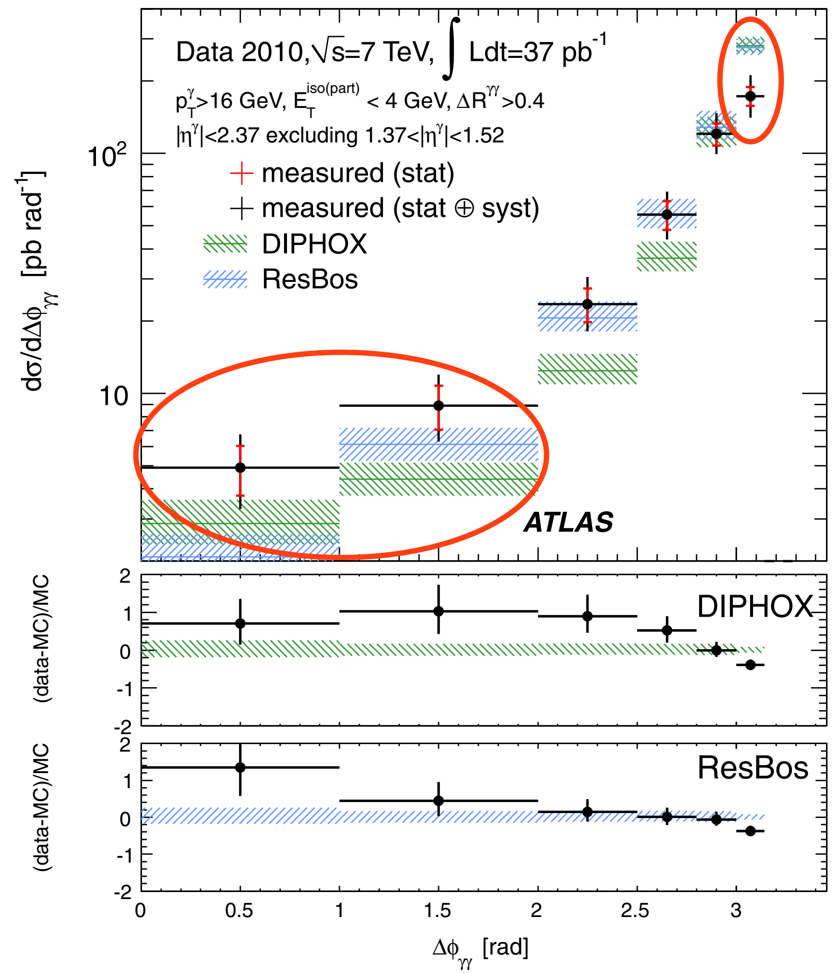


- scale uncertainty: 10-28%
- PDF uncertainty: 2-15%

Isolated di-photon xsection



- scale uncertainty: ~10-40%
- PDF uncertainty: ~1-40%

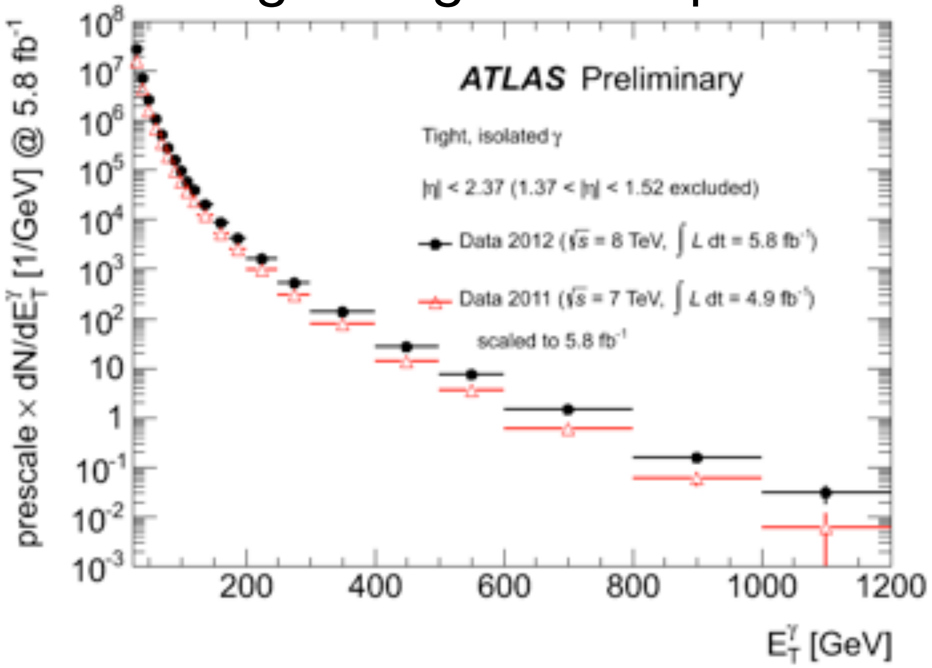


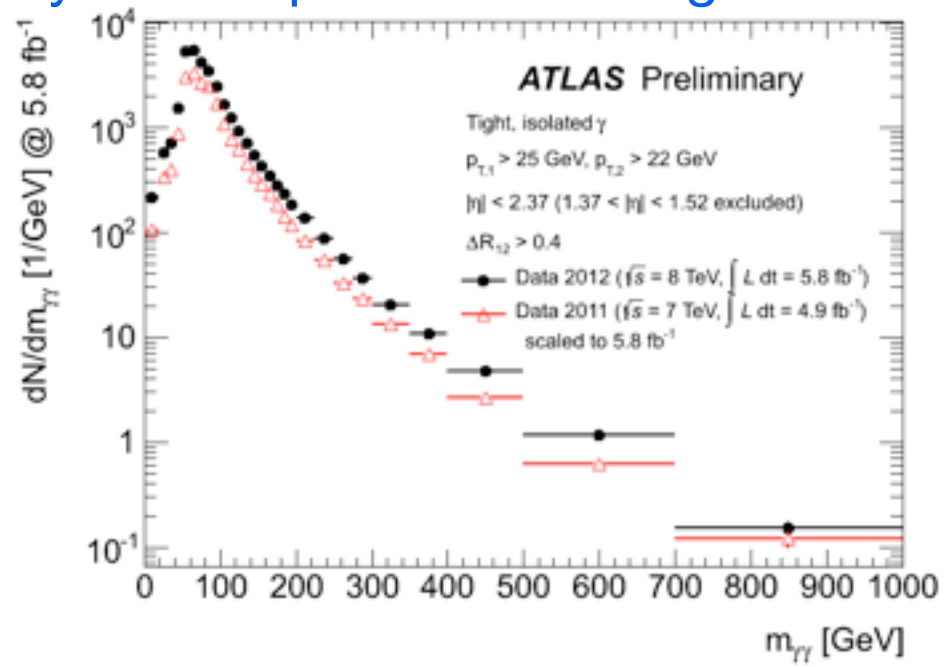
- scale uncertainty: ~6-25%
- PDF uncertainty: ~1-7%

- Hints of disagreement at low $\Delta\varphi$ (in addition to low $m_{\gamma\gamma}$) as well as $\Delta\varphi\sim\pi$ (expected limitation of fixed order calculation)
- Qualitative agreement with results by CMS and Tevatron
- Recent NNLO calculation (2γNNLO) should reduce disagreement at low $\Delta\varphi$ (2011/2012 data will tell...)

2011 (7 TeV) and 2012 (8 TeV) data analysis

- much larger data samples provided by LHC in 2011 and 2012
  - much larger single and diphoton statistics ⇒ theory can be probed over larger E_T range





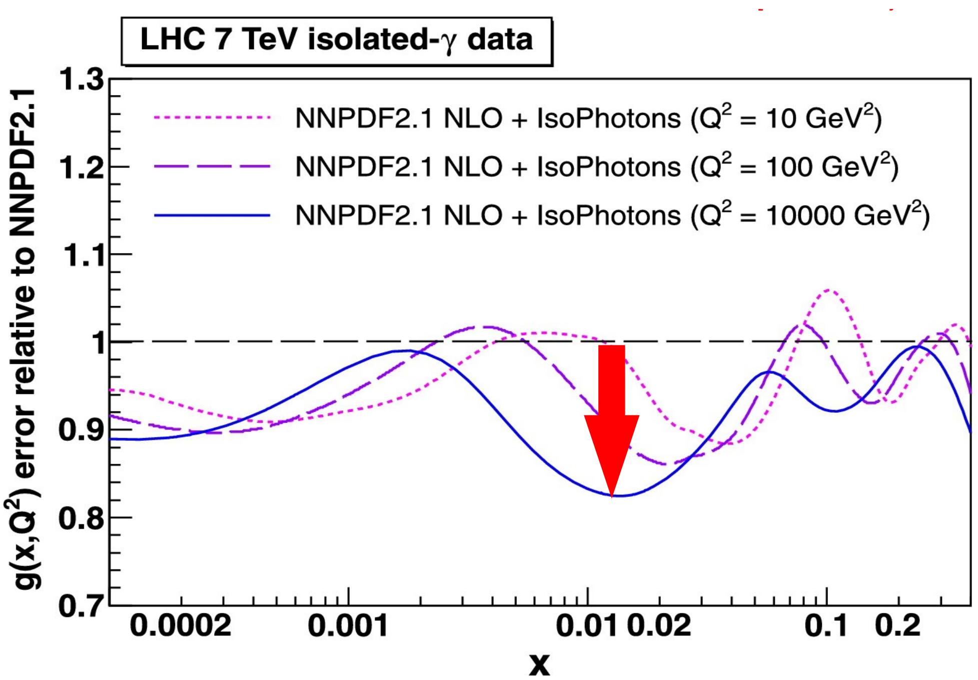
- improved detector/accelerator understanding
  - lumi uncertainty down from 11% to ~2%
  - EM scale uncertainty down from 3% to 1%
  - photon ID uncertainty down from 5-10% to 2-3% (several data-driven measurements from $Z \to ll\gamma$, electrons from $Z \to ee$ and photon-enriched samples of known purity)

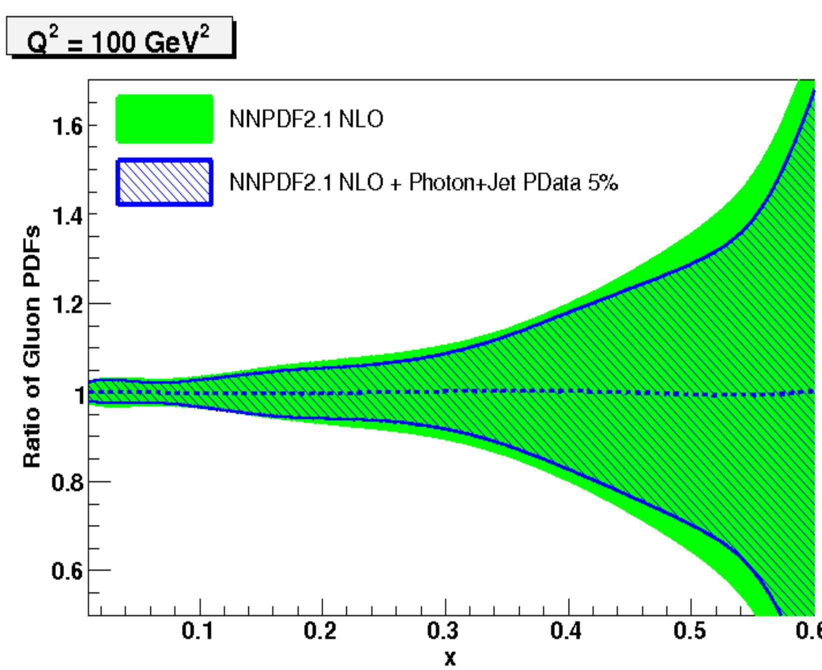
➡ more precise data/theory comparison (limited by theory? need for NNLO calculations?)

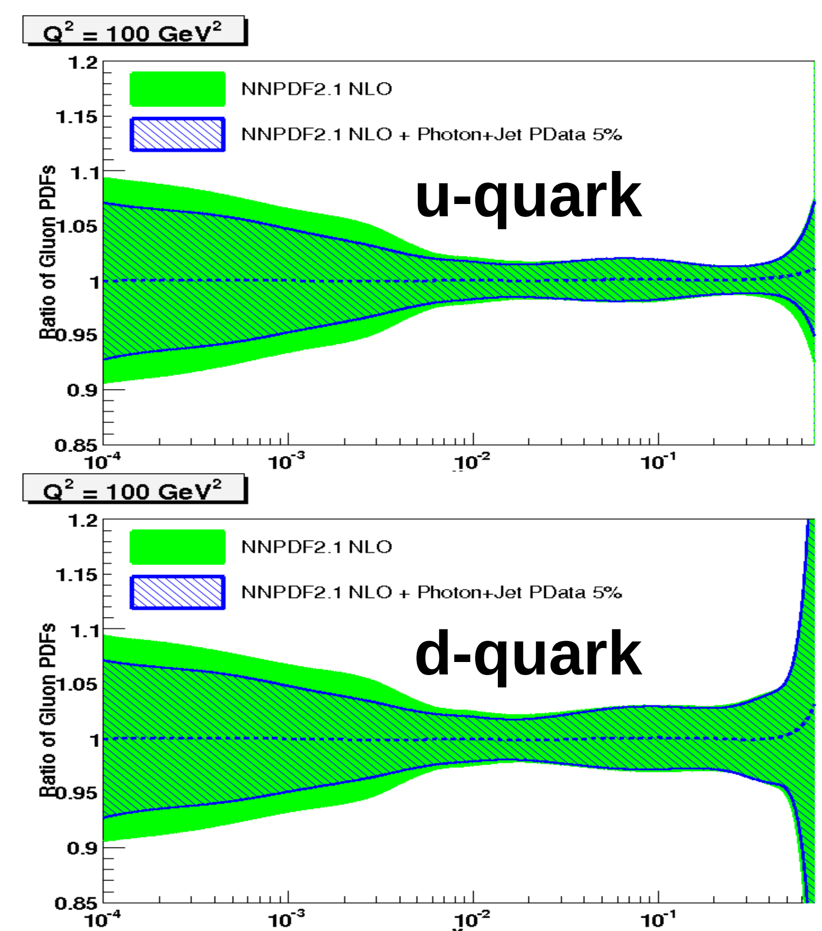
- diphoton and inclusive photon xsections w/ full 2011 statistics in the pipeline

Using single photon data in PDF fits

- Rojo, D'Enterria, Nucl. Phys. B 860, 311 (2012) + following studies
  - includes ATLAS single photon and photon+jet measurements
  - isolated photon data reduces error on g PDF up to 15%
  - using current photon+jet xsection, g PDF uncertainty reduced by <~5%
    - with 5% experimental uncertainties could reduce g PDF uncertainty by about ~15% at high x and u,d PDF uncertainty by up to ~25% at low x







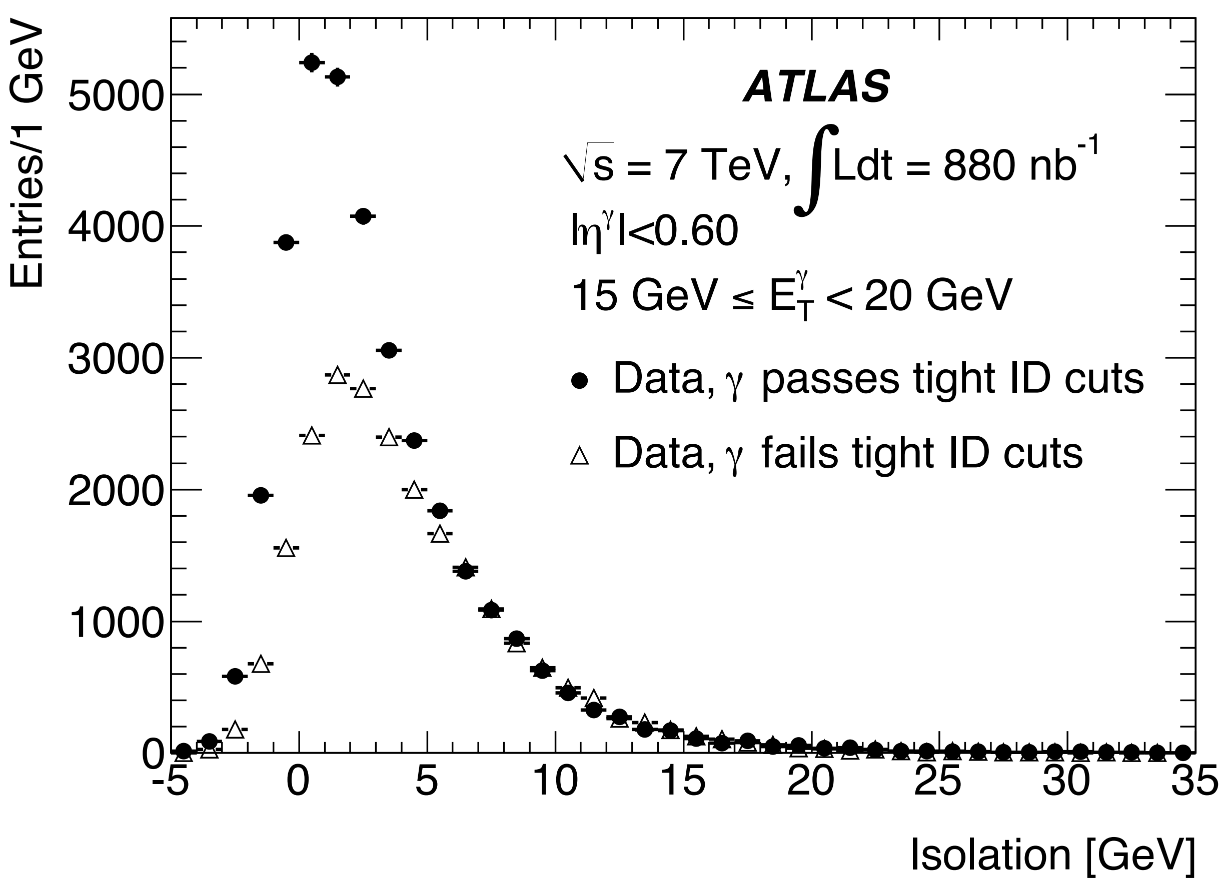
Conclusion

- 2010 data collected by ATLAS has been used to provide a first set of basic photon measurements (single photon, photon+jet and di-photon xsection)
    - photon reconstruction and identification have been commissioned
    - good efficiency (reco ~85%, ID ~95%), high purity (>95%) above 100 GeV
        - reconstruction inefficiencies recovered in winter 2011 shutdown
    - tools developed for SM photon xsections have been successfully applied also to searches (Higgs, exotics..)
- In general, fair/good agreement is observed between measured cross sections and NLO predictions
    - still rather large uncertainties, both theory and experiment
    - some tensions at low E_T in inclusive photon and photon+jet xsection
    - hints of possibly large discrepancies in di-photon xsection in some phase-space regions
- Among the full event generators used in ATLAS, Sherpa is the one currently giving the best agreement with photon xsections
- 2011 data analyses are being finalized, with improved systematic uncertainties
- A corresponding reduction of theoretical uncertainties (NNLO?) is desirable to obtain more precise comparisons

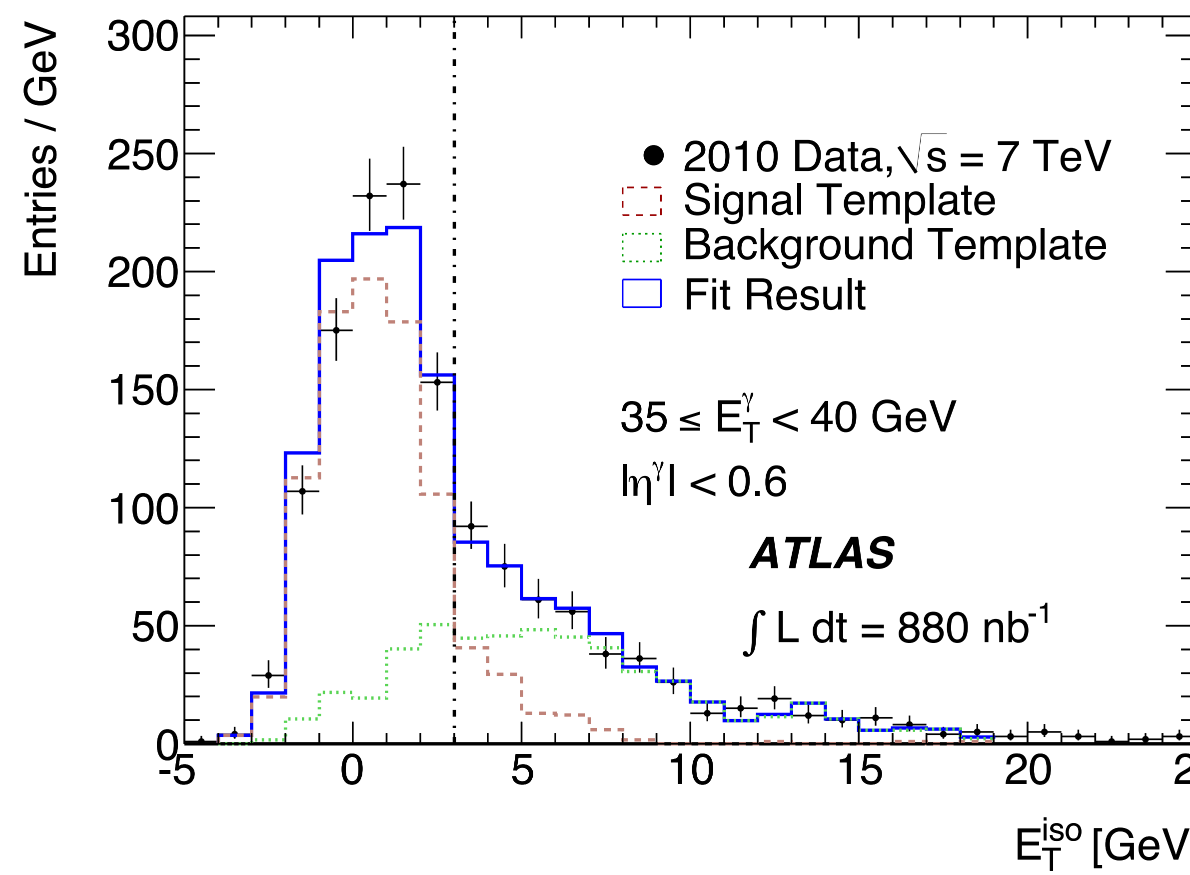
More slides

Isolation template fit

- Fit isolation distribution in data with sum of signal and background templates

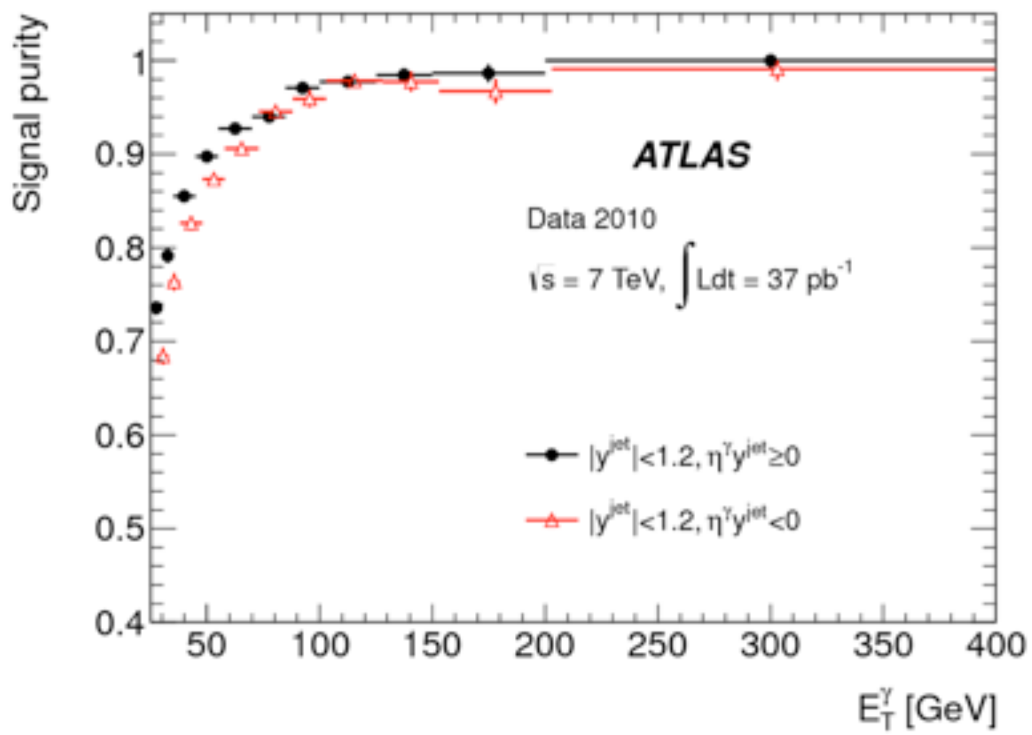


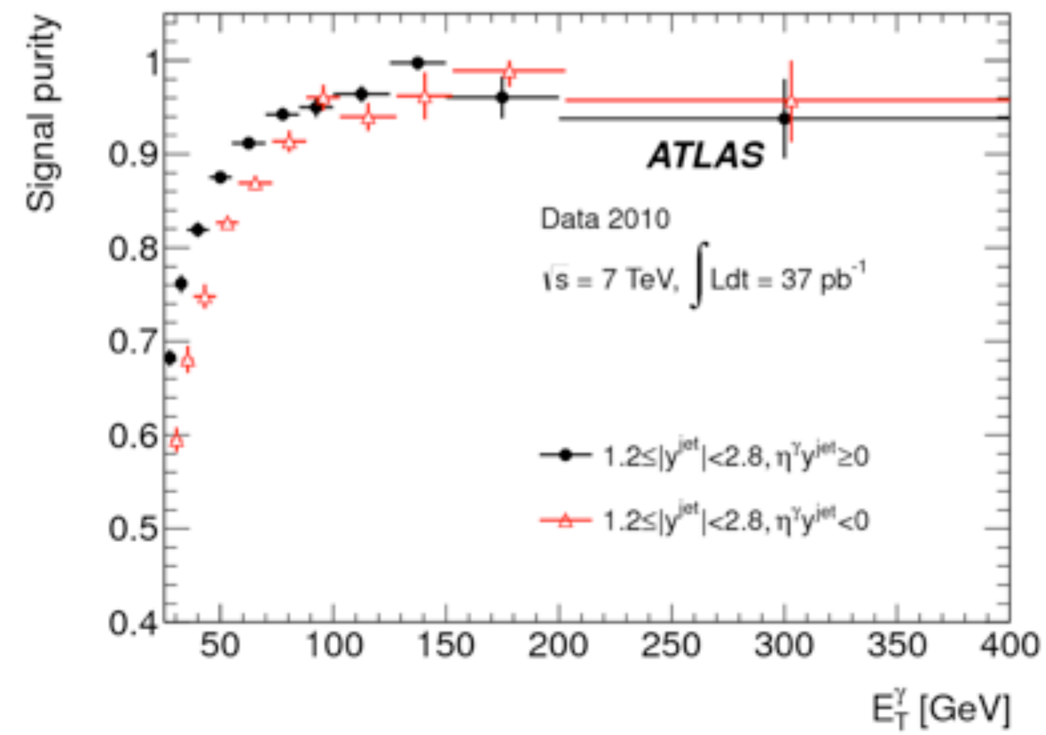
bkg template: data driven, from photon candidates failing a few strip shape variables (weakly correlated with E_T^{iso})

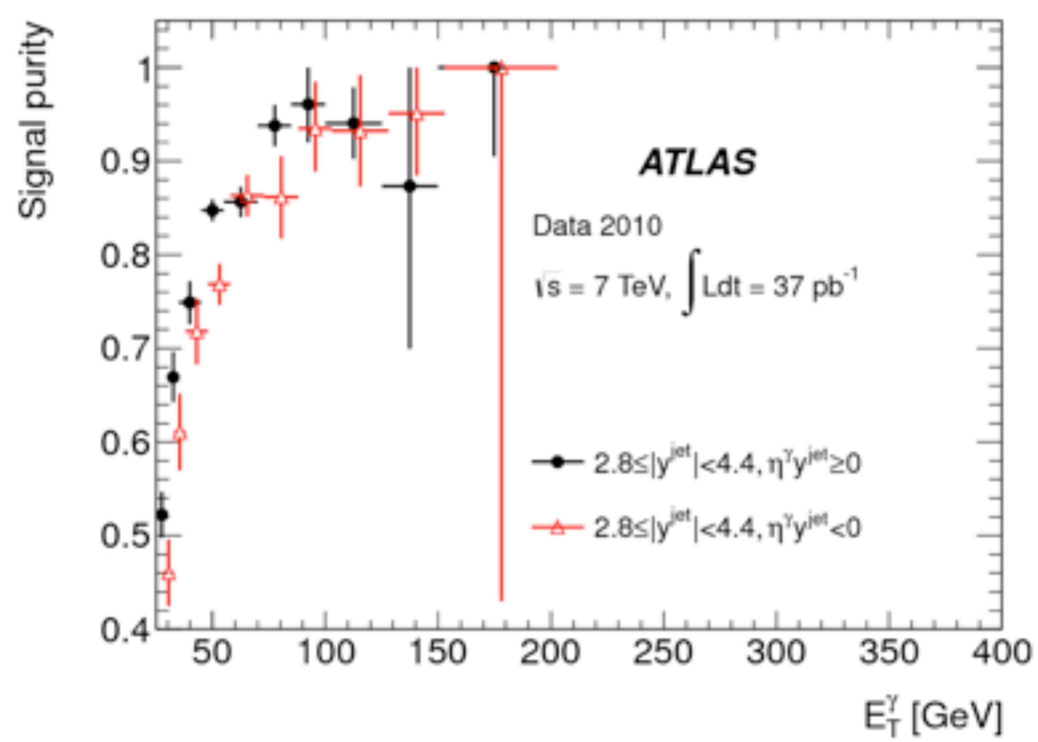


signal template: data driven, from electrons from W→eν and Z→ee

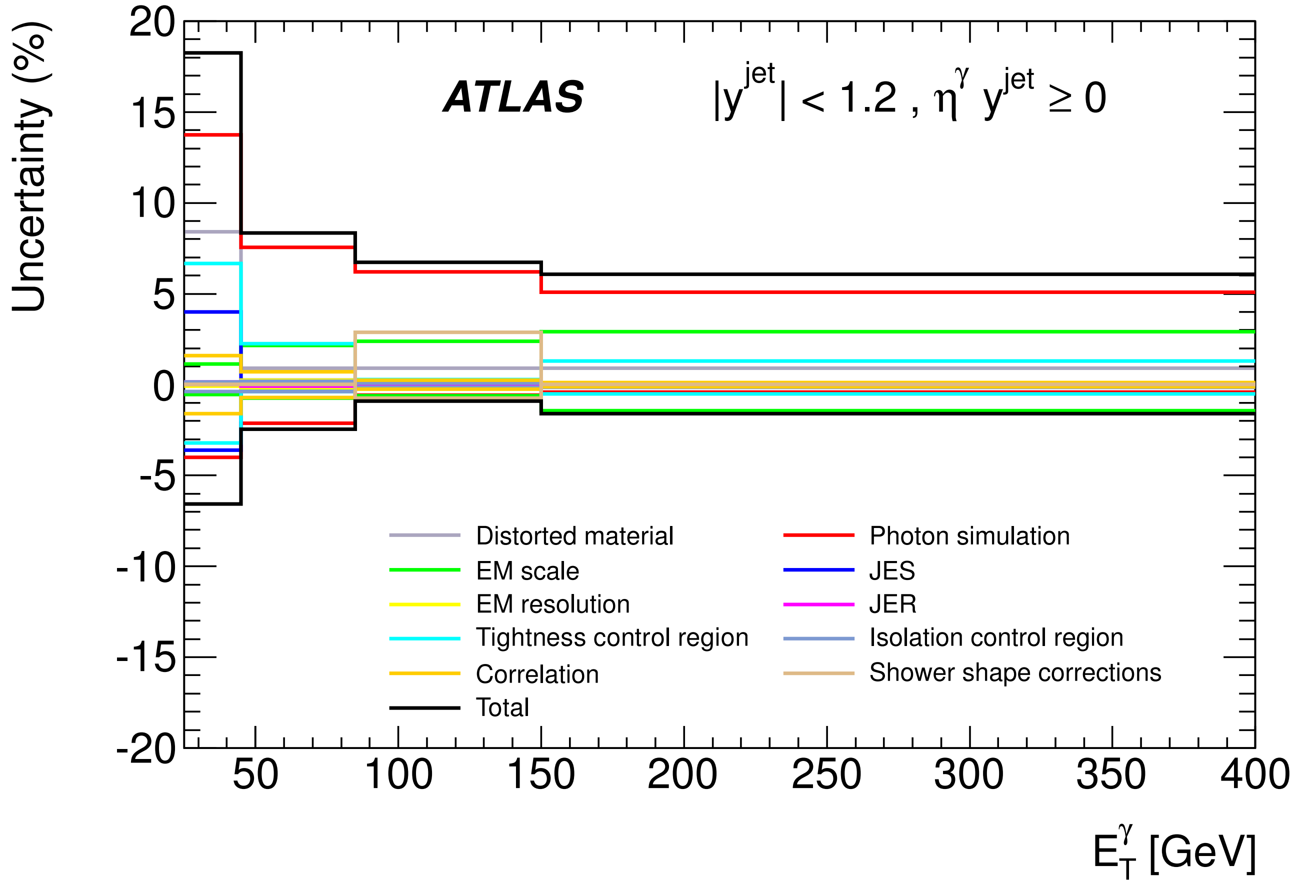
Photon+jet purity

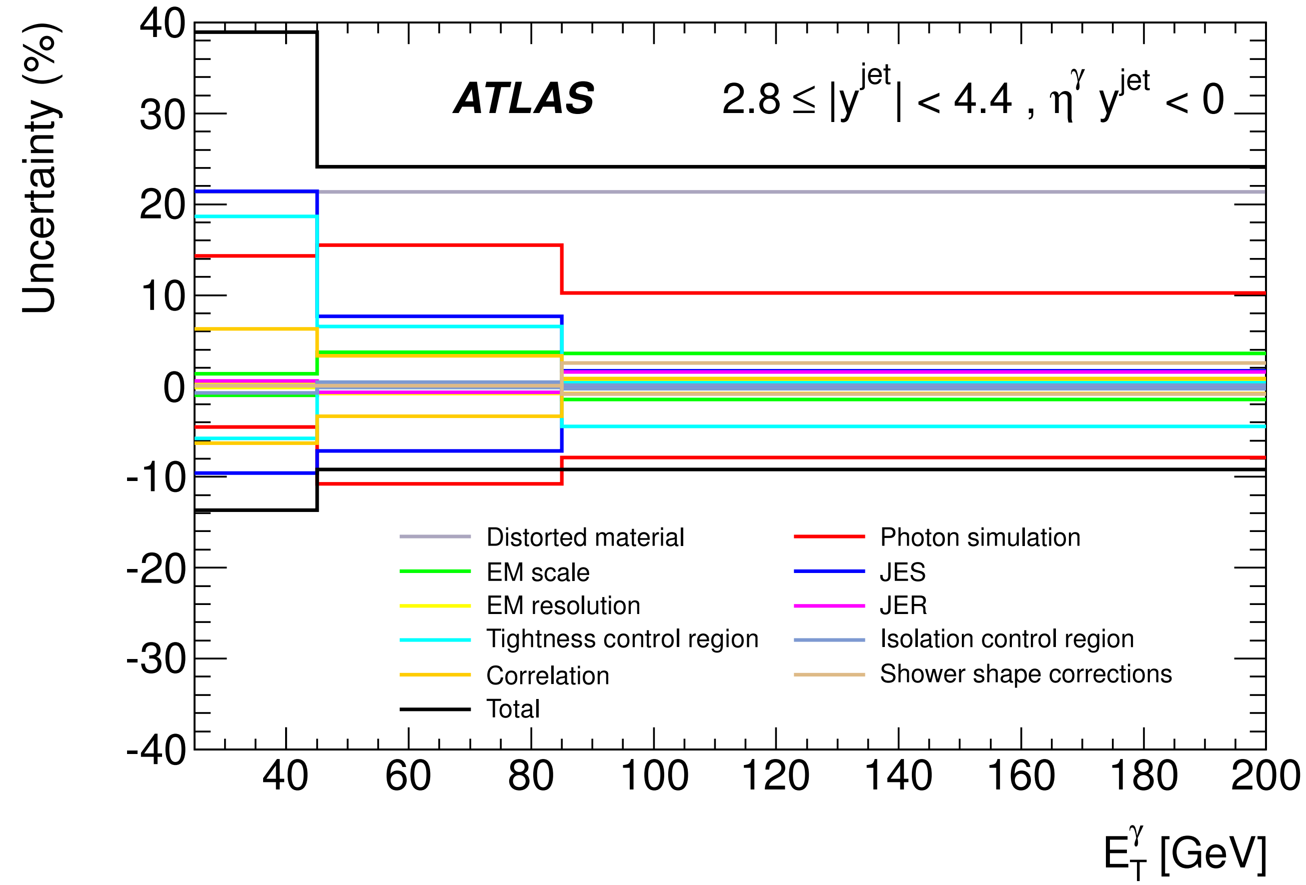




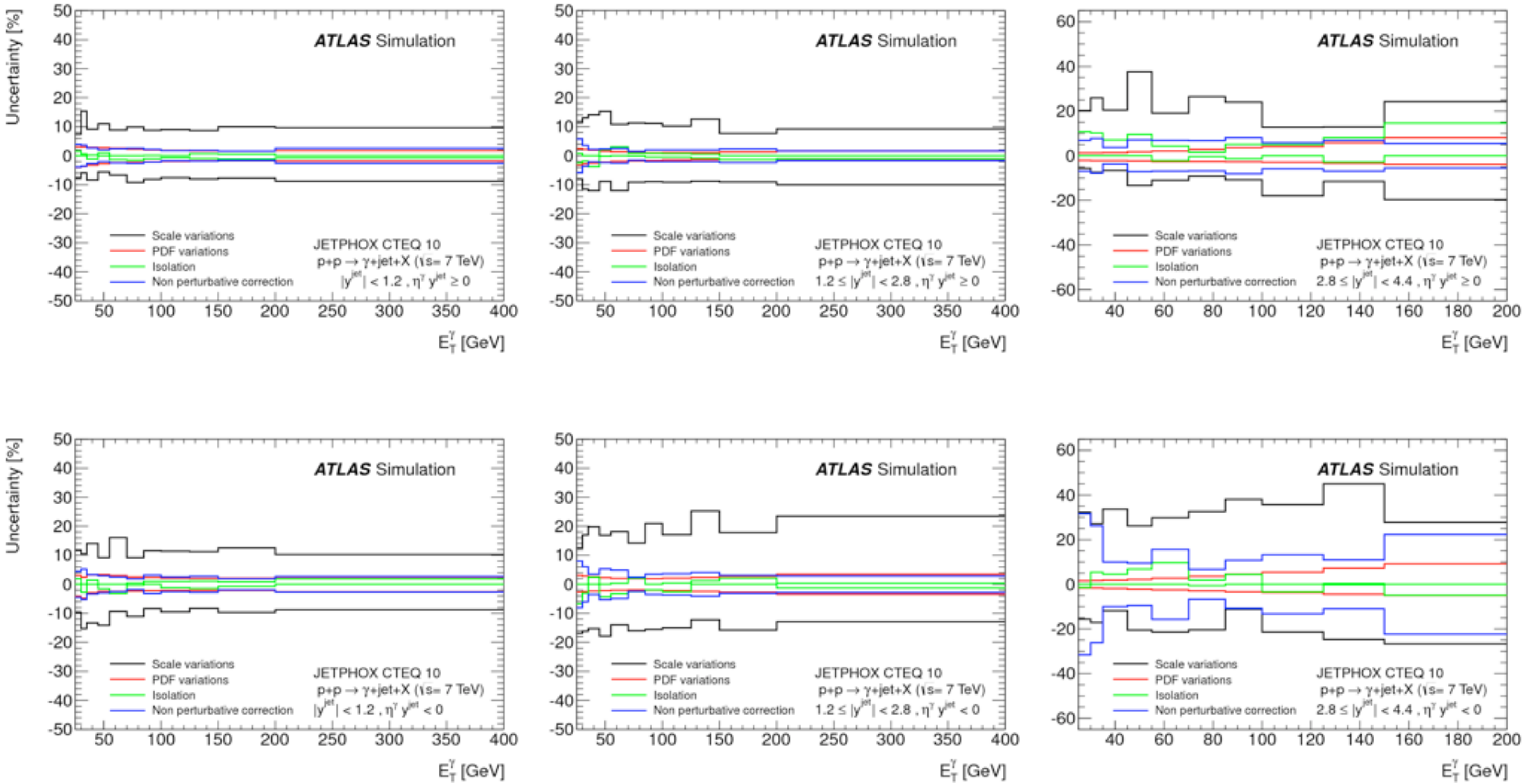


Photon+jet systematic uncertainties (examples)

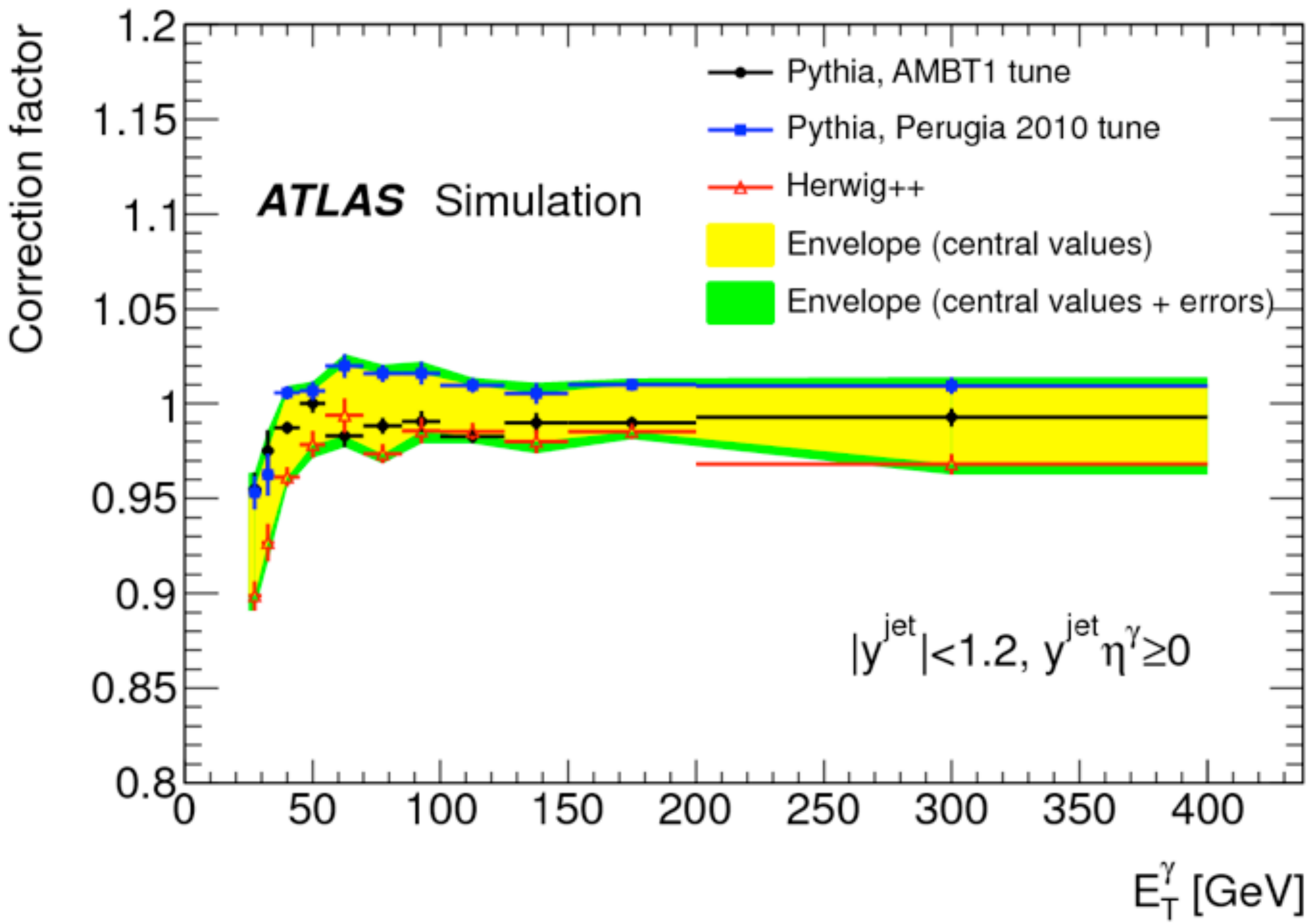




Photon+jet: theory xsection uncertainties



Photon+jet: NP corrections (example)



Diphoton xsection uncertainties

- stat and syst comparable
- main systematic uncertainties:
    - bkg control sample (non-tight photons)
    - ID efficiency
    - reco efficiency (material uncertainty)

$m_{\gamma\gamma}$ [GeV]	$d\sigma/dm_{\gamma\gamma}$ [pb/GeV]	
0–30	0.20 ± 0.05	$^{+0.05}_{-0.03}$
30–40	1.8 ± 0.3	$^{+0.4}_{-0.3}$
40–50	2.3 ± 0.3	$^{+0.6}_{-0.4}$
50–60	1.83 ± 0.24	$^{+0.36}_{-0.28}$
60–70	0.74 ± 0.17	$^{+0.19}_{-0.13}$
70–80	0.45 ± 0.15	$^{+0.11}_{-0.09}$
80–100	0.40 ± 0.06	$^{+0.08}_{-0.08}$
100–150	0.079 ± 0.022	$^{+0.025}_{-0.025}$
150 − 200	0.026 ± 0.009	$^{+0.006}_{-0.004}$
$p_{T,\gamma\gamma}$ [GeV]	$d\sigma/dp_{T,\gamma\gamma}$ [pb/GeV]	
0–10	4.5 ± 0.4	$^{+0.9}_{-0.6}$
10–20	2.2 ± 0.3	$^{+0.5}_{-0.4}$
20–30	0.94 ± 0.22	$^{+0.28}_{-0.24}$
30–40	0.62 ± 0.16	$^{+0.21}_{-0.14}$
40–50	0.26 ± 0.10	$^{+0.10}_{-0.09}$
50–60	0.36 ± 0.09	$^{+0.09}_{-0.05}$
60–80	0.06 ± 0.03	$^{+0.03}_{-0.03}$
80–100	0.048 ± 0.019	$^{+0.009}_{-0.010}$
100–150	0.003 ± 0.004	$^{+0.003}_{-0.002}$
150–200	0.000 ± 0.002	$^{+0.000}_{-0.000}$
$\Delta\phi_{\gamma\gamma}$ [rad]	$d\sigma/d\Delta\phi_{\gamma\gamma}$ [pb/rad]	
0.00–1.00	4.9 ± 1.1	$^{+1.5}_{-1.1}$
1.00–2.00	8.9 ± 1.8	$^{+2.5}_{-1.9}$
2.00–2.50	24 ± 4	$^{+6}_{-4}$
2.50–2.80	56 ± 8	$^{+12}_{-9}$
2.80–3.00	121 ± 13	$^{+24}_{-17}$
3.00–3.14	173 ± 16	$^{+36}_{-29}$

Measured xsection (15-100 GeV, |η|<0.6)

TABLE III. The measured isolated prompt photon production cross section, for $0.00 \leq |\eta^{\gamma}| < 0.60$. The systematic uncertainties originating from the purity measurement, the photon selection, the photon energy scale, the unfolding procedure and the luminosity are shown. The total uncertainty includes both the statistical and all systematic uncertainties, except for the uncertainty on the luminosity.

	Measured								JETPHOX	
E_T^{γ} [GeV]	$\frac{d\sigma}{dE_T^{\gamma}}$ [nb/ GeV]	stat [nb/ GeV]	syst (purity) [nb/ GeV]	syst (efficiency) [nb/ GeV]	syst (en. scale) [nb/ GeV]	syst (unfolding) [nb/ GeV]	syst (luminosity) [nb/ GeV]	total uncertainty [nb/ GeV]	$\frac{d\sigma}{dE_T^{\gamma}}$ [nb/ GeV]	total uncertainty [nb/ GeV]
[15, 20)	5.24	±0.11	$^{+0.52}_{-0.88}$	±0.81	$^{+0.51}_{-0.46}$	±0.11	±0.58	$^{+1.3}_{-1.4}$	6.8	$^{+1.4}_{-0.9}$
[20, 25)	1.88	±0.05	$^{+0.18}_{-0.20}$	±0.21	$^{+0.14}_{-0.14}$	±0.04	±0.21	±0.36	2.38	$^{+0.45}_{-0.30}$
[25, 30)	0.88	±0.03	±0.07	±0.08	$^{+0.09}_{-0.08}$	±0.02	±0.10	$^{+0.16}_{-0.15}$	1.01	$^{+0.17}_{-0.13}$
[30, 35)	0.461	±0.016	$^{+0.029}_{-0.019}$	±0.035	$^{+0.045}_{-0.046}$	±0.009	±0.05	±0.07	0.50	$^{+0.10}_{-0.04}$
[35, 40)	0.254	±0.011	$^{+0.017}_{-0.015}$	±0.019	$^{+0.027}_{-0.025}$	±0.005	±0.028	±0.04	0.28	$^{+0.04}_{-0.03}$
[40, 50)	0.115	±0.005	$^{+0.008}_{-0.006}$	±0.007	$^{+0.009}_{-0.009}$	±0.0023	±0.013	$^{+0.017}_{-0.016}$	0.127	$^{+0.018}_{-0.014}$
[50, 60)	0.050	±0.003	$^{+0.003}_{-0.002}$	±0.003	$^{+0.006}_{-0.005}$	±0.001	±0.005	$^{+0.008}_{-0.007}$	0.052	$^{+0.007}_{-0.006}$
[60, 100)	0.0120	±0.0007	$^{+0.0007}_{-0.0005}$	±0.0006	$^{+0.0013}_{-0.0012}$	±0.0002	±0.0013	$^{+0.0019}_{-0.0018}$	0.0121	$^{+0.0014}_{-0.0012}$

Measured xsection (15-100 GeV, 0.6≤|η|<1.37)

TABLE IV. The measured isolated prompt photon production cross section, for $0.60 \leq |\eta^{\gamma}| < 1.37$. The systematic uncertainties originating from the purity measurement, the photon selection, the photon energy scale, the unfolding procedure and the luminosity are shown. The total uncertainty includes both the statistical and all systematic uncertainties, except for the uncertainty on the luminosity.

	Measured								JETPHOX	
E_T^{γ} [GeV]	$\frac{d\sigma}{dE_T^{\gamma}}$ [nb/ GeV]	stat [nb/ GeV]	syst (purity) [nb/ GeV]	syst (efficiency) [nb/ GeV]	syst (en. scale) [nb/ GeV]	syst (unfolding) [nb/ GeV]	syst (luminosity) [nb/ GeV]	total uncertainty [nb/ GeV]	$\frac{d\sigma}{dE_T^{\gamma}}$ [nb/ GeV]	total uncertainty [nb/ GeV]
[15, 20)	5.9	±0.2	$^{+1.8}_{-0.5}$	±1.0	$^{+0.6}_{-0.5}$	±0.1	±0.6	$^{+2.3}_{-1.4}$	8.5	$^{+1.7}_{-1.3}$
[20, 25)	2.23	±0.07	$^{+0.49}_{-0.18}$	±0.28	$^{+0.16}_{-0.16}$	±0.04	±0.24	$^{+0.6}_{-0.4}$	3.0	$^{+0.5}_{-0.4}$
[25, 30)	1.05	±0.03	$^{+0.16}_{-0.06}$	±0.10	$^{+0.10}_{-0.10}$	±0.021	±0.12	$^{+0.24}_{-0.19}$	1.28	$^{+0.18}_{-0.16}$
[30, 35)	0.52	±0.02	$^{+0.06}_{-0.03}$	±0.04	$^{+0.05}_{-0.05}$	±0.011	±0.06	$^{+0.11}_{-0.09}$	0.64	$^{+0.11}_{-0.09}$
[35, 40)	0.313	±0.014	$^{+0.029}_{-0.021}$	±0.024	$^{+0.035}_{-0.032}$	±0.006	±0.034	$^{+0.06}_{-0.05}$	0.344	$^{+0.052}_{-0.039}$
[40, 50)	0.146	±0.006	$^{+0.014}_{-0.011}$	±0.009	$^{+0.013}_{-0.013}$	±0.003	±0.016	$^{+0.025}_{-0.022}$	0.161	$^{+0.022}_{-0.019}$
[50, 60)	0.062	±0.004	$^{+0.005}_{-0.004}$	±0.003	$^{+0.006}_{-0.006}$	±0.001	±0.007	$^{+0.010}_{-0.009}$	0.065	$^{+0.009}_{-0.007}$
[60, 100)	0.0138	±0.0008	$^{+0.0013}_{-0.0009}$	±0.0007	$^{+0.0016}_{-0.0014}$	±0.0003	±0.0015	$^{+0.0025}_{-0.0022}$	0.0154	$^{+0.0019}_{-0.0015}$

Measured xsection (15-100 GeV, 1.52≤|η|<1.81)

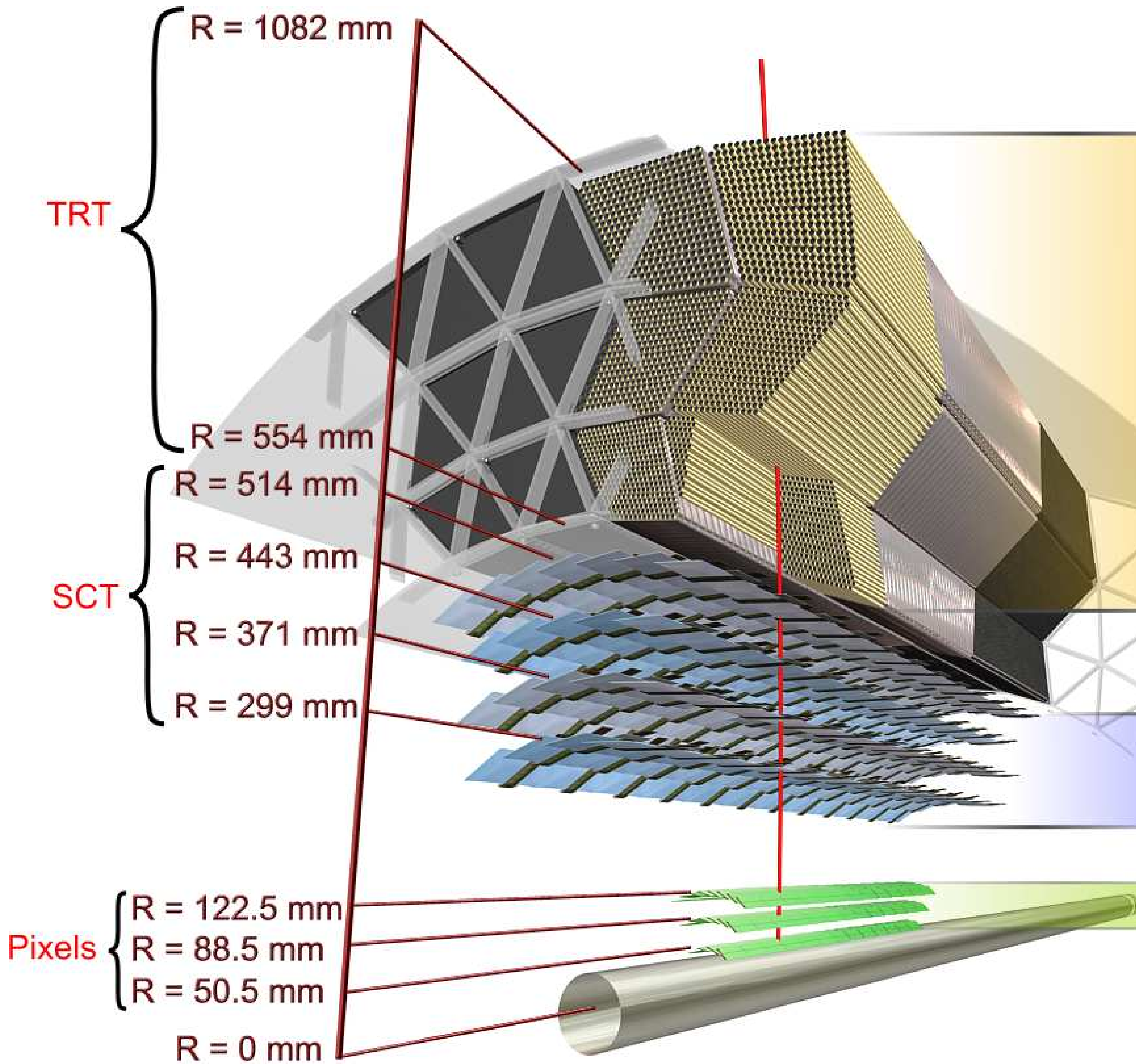
TABLE V. The measured isolated prompt photon production cross section, for $1.52 \leq |\eta^\gamma| < 1.81$. The systematic uncertainties originating from the purity measurement, the photon selection, the photon energy scale, the unfolding procedure and the luminosity are shown. The total uncertainty includes both the statistical and all systematic uncertainties, except for the uncertainty on the luminosity.

	Measured								JETPHOX	
E_T^γ	$\frac{d\sigma}{dE_T^\gamma}$	stat	syst (purity)	syst (efficiency)	syst (en. scale)	syst (unfolding)	syst (luminosity)	total uncertainty	$\frac{d\sigma}{dE_T^\gamma}$	total uncertainty
[GeV]	[nb/ GeV]	[nb/ GeV]	[nb/ GeV]	[nb/ GeV]	[nb/ GeV]	[nb/ GeV]	[nb/ GeV]	[nb/ GeV]	[nb/ GeV]	[nb/ GeV]
[15, 20)	2.9	±0.1	$^{+0.8}_{-0.3}$	±0.5	$^{+0.3}_{-0.3}$	±0.1	±0.3	$^{+1.1}_{-0.7}$	3.1	$^{+0.6}_{-0.5}$
[20, 25)	1.12	±0.04	$^{+0.15}_{-0.08}$	±0.16	$^{+0.08}_{-0.08}$	±0.02	±0.12	$^{+0.27}_{-0.24}$	1.10	$^{+0.20}_{-0.15}$
[25, 30)	0.47	±0.02	$^{+0.06}_{-0.04}$	±0.05	$^{+0.05}_{-0.04}$	±0.01	±0.05	$^{+0.11}_{-0.09}$	0.46	$^{+0.07}_{-0.06}$
[30, 35)	0.240	±0.013	$^{+0.028}_{-0.016}$	±0.023	$^{+0.025}_{-0.026}$	±0.005	±0.026	$^{+0.052}_{-0.045}$	0.233	$^{+0.037}_{-0.030}$
[35, 40)	0.142	±0.009	$^{+0.018}_{-0.010}$	±0.012	$^{+0.014}_{-0.013}$	±0.0032	±0.016	$^{+0.030}_{-0.026}$	0.126	$^{+0.020}_{-0.015}$
[40, 50)	0.062	±0.004	$^{+0.005}_{-0.004}$	±0.005	$^{+0.006}_{-0.006}$	±0.0013	±0.007	$^{+0.011}_{-0.010}$	0.058	$^{+0.008}_{-0.007}$
[50, 60)	0.0237	±0.0025	$^{+0.0026}_{-0.0028}$	±0.0019	$^{+0.0024}_{-0.0022}$	±0.0005	±0.003	±0.005	0.0243	$^{+0.0033}_{-0.0027}$
[60, 100)	0.0066	±0.0005	$^{+0.0005}_{-0.0003}$	±0.0005	$^{+0.0008}_{-0.0007}$	±0.0002	±0.0007	$^{+0.0013}_{-0.0012}$	0.0057	$^{+0.0007}_{-0.0006}$

Systematic uncertainties (45-400 GeV analysis)

Systematic	Reco. Eff.	ID Eff.	Yield	Unfolding	Theory
Finite Statistics per bin				$< 2\%$	
Generator	1%	$< 1\%$	$\sim 1\%$	3%	
E_T Resolution				$< 1\%$	
Photon ID			$< 5\%$		
Photon Isolation			$< 1\%$		
Signal Leakage			$2\% - 8\%$		
Background Correlations			$< 4\%$		
Energy Scale			$2\% - 8\%$		
Material	$1\% - 4\%$	$1\% - 2\%$	$< 1\%$		
Soft-jet Energy Density			$3\% - 7\%$		
Transverse Energy Leakage			$1\% - 4\%$		
Hard/Brem Composition	1%	$< 1\%$	$1\% - 7\%$		
OTX	0.2%				
Photon Isolation Cut	$3\% - 4\%$				
Intrinsic Precision		$1\% - 3\%$			
Photon Sample Selection		0.5%			
Conv/Unconv. Photon Ratio		$< 1\%$			
Scale uncertainty					$10\% - 20\%$
PDFs					$2\% - 5\%$
Parton level Isolation					$< 2\%$

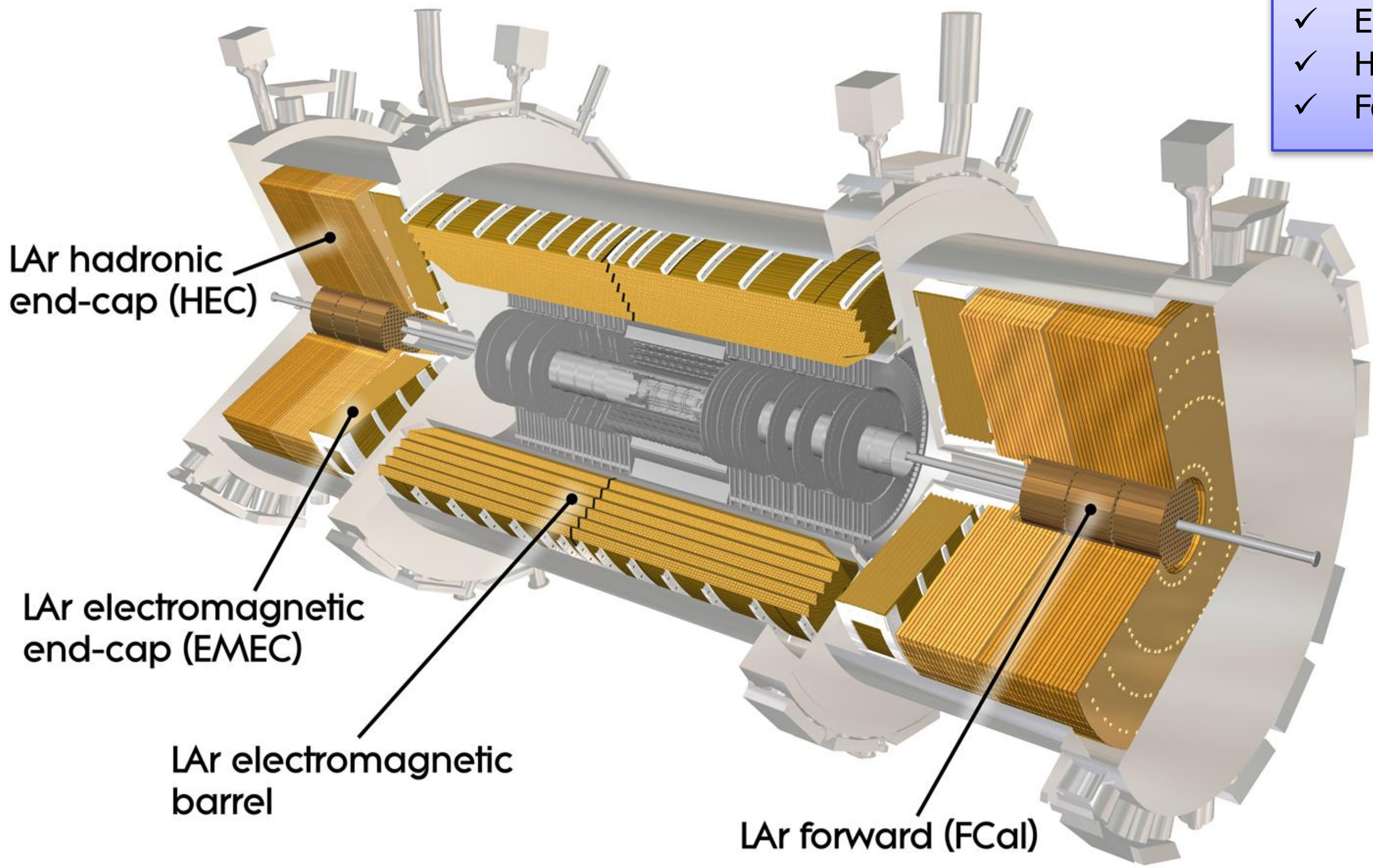
Inner detector (charged particle tracking)



- Transition Radiation Tracker
  - 350k channels
  - 4mm (diameter) straws
  - TR ⇒ e/π discrimination
  - ≈36 hits/track
  - ≈130 μm resolution
- Semi-Conductor Tracker
  - 6.3M channels
  - 4 cylinders, 8 hits/track
  - ≈17μm resolution
- Pixel Tracker
  - 80M channels, 3 layers
  - ≈10 μm resolution

✓Converted γ reconstruction
✓e/γ discrimination

ATLAS liquid argon calorimeters



- ✓ EM Barrel : ($|\eta|<1.475$) [Pb-LAr]
- ✓ EM End-caps : $1.4<|\eta|<3.2$ [Pb-LAr]
- ✓ Hadronic End-cap: $1.5<|\eta|<3.2$ [Cu-LAr]
- ✓ Forward Calorimeter: $3.2<|\eta|<4.9$ [Cu,W-Lar]

EM Calorimeter

- PB-LAr Accordion
- $\Delta E/E = \left(10\%/\sqrt{E}\right) \oplus .7\%$
- $.025\times.025$ cells ($\eta \times \phi$)
- Angular res.: 50 mrad / $\sqrt{E}$

Hadronic Calorimeter

- Fe-scintillator for $|\eta| < 1.7$
  - $\Delta E/E = \left(50\%/\sqrt{E}\right) \oplus 6\%$
- Cu-LAr for $1.5 < |\eta| < 3.2$
  - $\Delta E/E = \left(50\%/\sqrt{E}\right) \oplus 3\%$

✓ Reject fake photons (mostly from π^0 in jets) based on shower shape

Discriminating variables for photon ID

Hadronic leakage

$$R_{\mathrm{had}_1} = \frac{E_T^{\mathrm{had\,1}}}{E_T}$$

$E_t^{\mathrm{had\ I}}$ is the energy in the first layer of the hadronic calorimeter behind EM cluster

Middle layer (S2) variables

containment in η

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

containment in ϕ

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

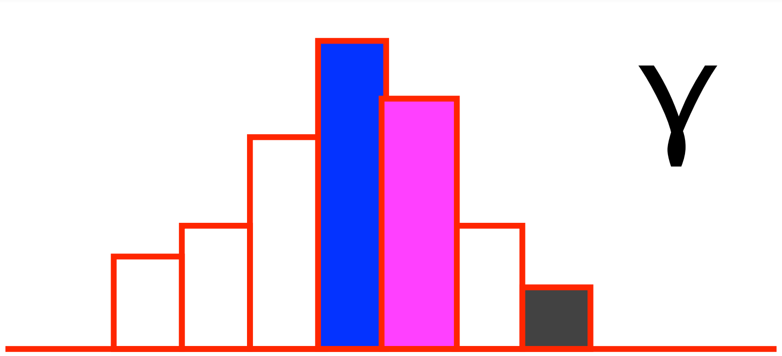
E^{S2}_{XY} is the summed energy of S2 cells in a window of size X×Y ($\eta \times \phi$ units)

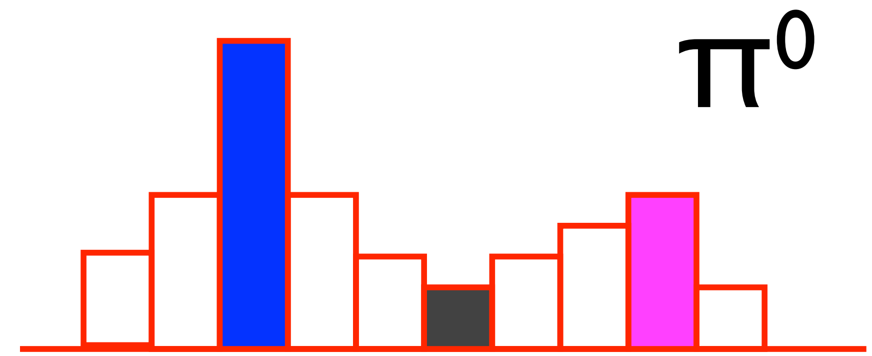
$$w_2 = \sqrt{\frac{\sum E_i \eta_i^2}{\sum E_i} - \left(\frac{\sum E_i \eta_i}{\sum E_i}\right)^2}$$

Lateral width (physical units) calculated in a window of size 3×5 ($\eta \times \phi$ units)

Discriminating variables for photon ID

Front Layer (Strip, S1) Variables





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

Containment in η
E(±n) is the sum of E in ±n strips about max

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

Asymmetry between 1st and 2nd maxima

$$\Delta E = \left[E^{S1}_{2^{\text{nd}}\text{max}} - E^{S1}_{\text{min}}\right] / \text{ MeV}$$

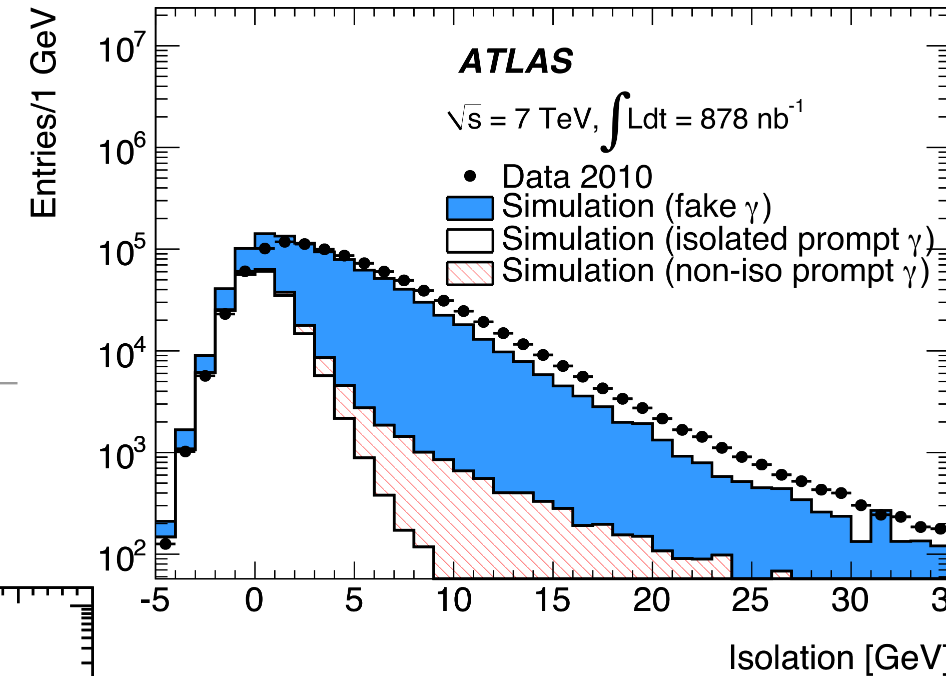
E^{S1}_{min} is the energy of the strip cell with least energy between the 1st and and 2nd maxima

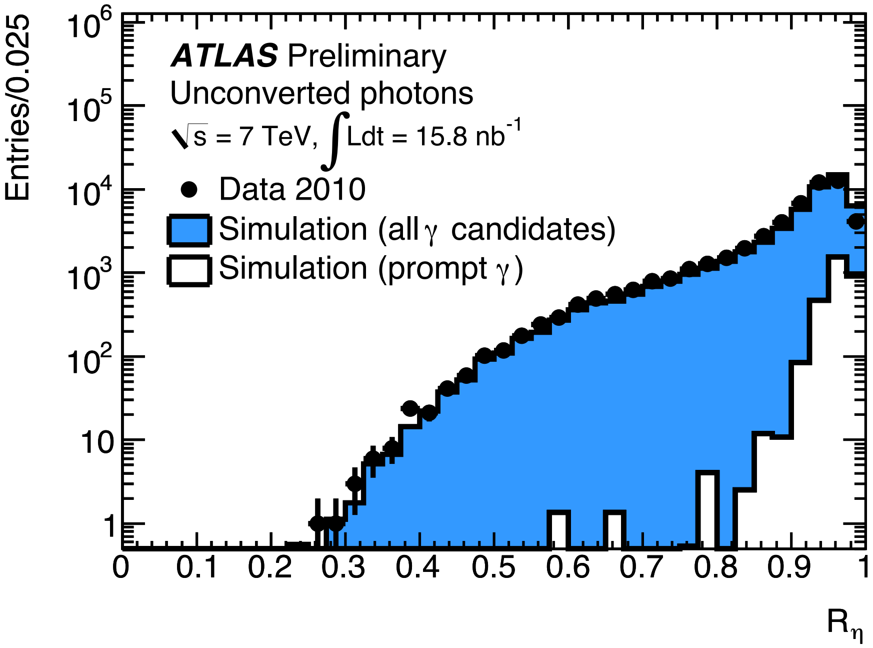
$$w_{s\,3} = \sqrt{\frac{\sum E_i (i - i_{\text{max}})^2}{\sum E_i}}$$

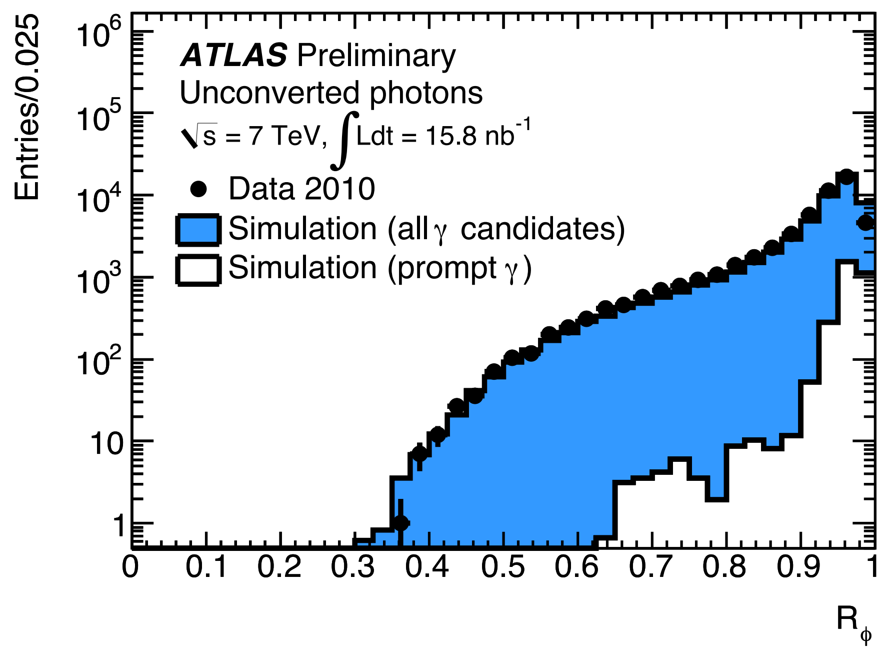
Width (cell units) using 2 strips about max.

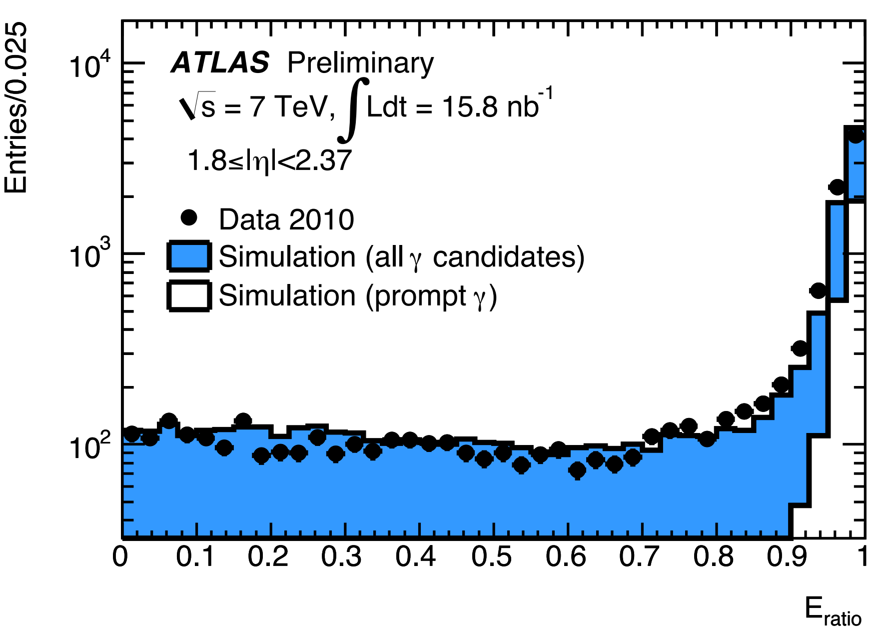
$w_{s\,\text{tot}}$ Width (cell units) using ~ 40 strip cells, 20 in η and 2 in ϕ.

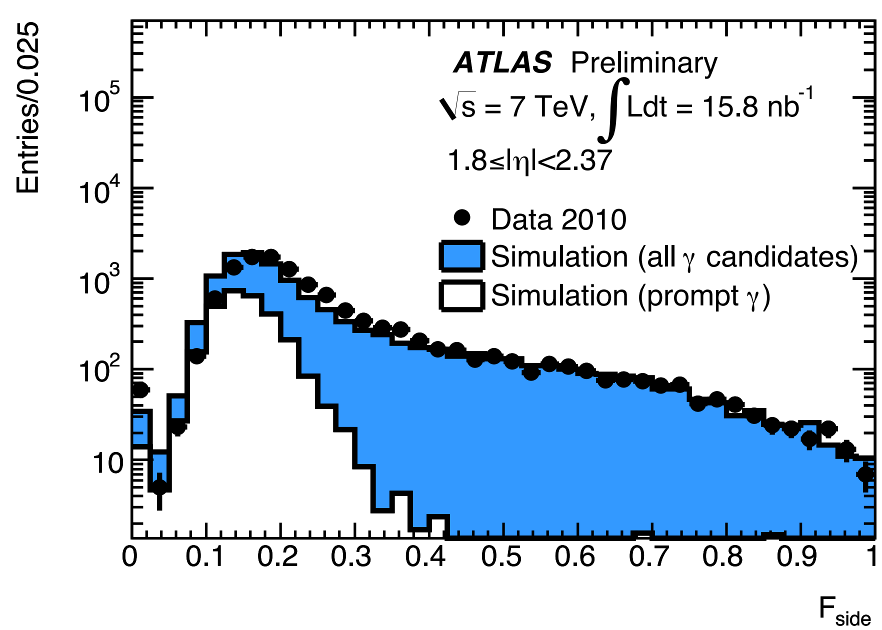
Selected data/MC comparison





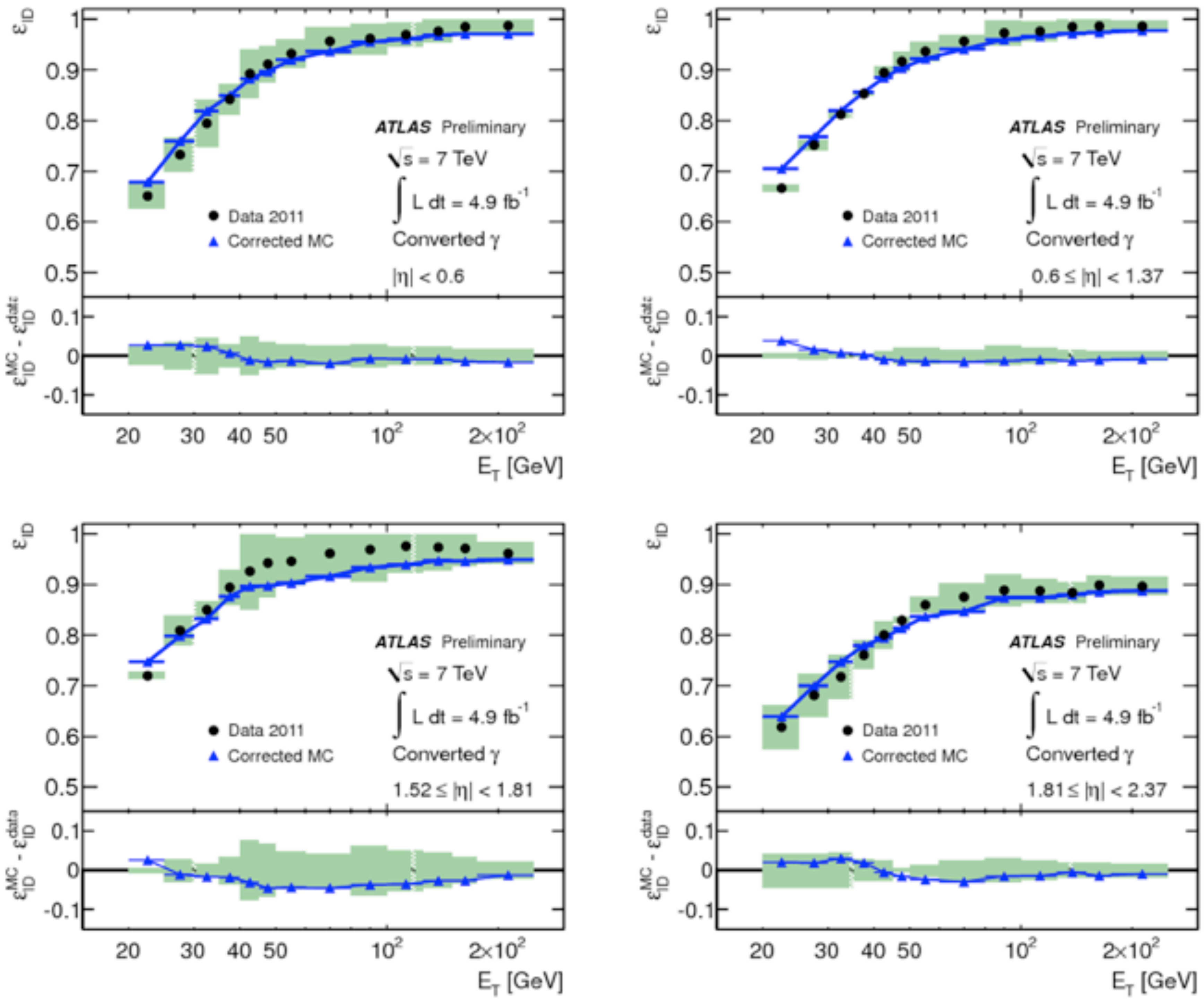






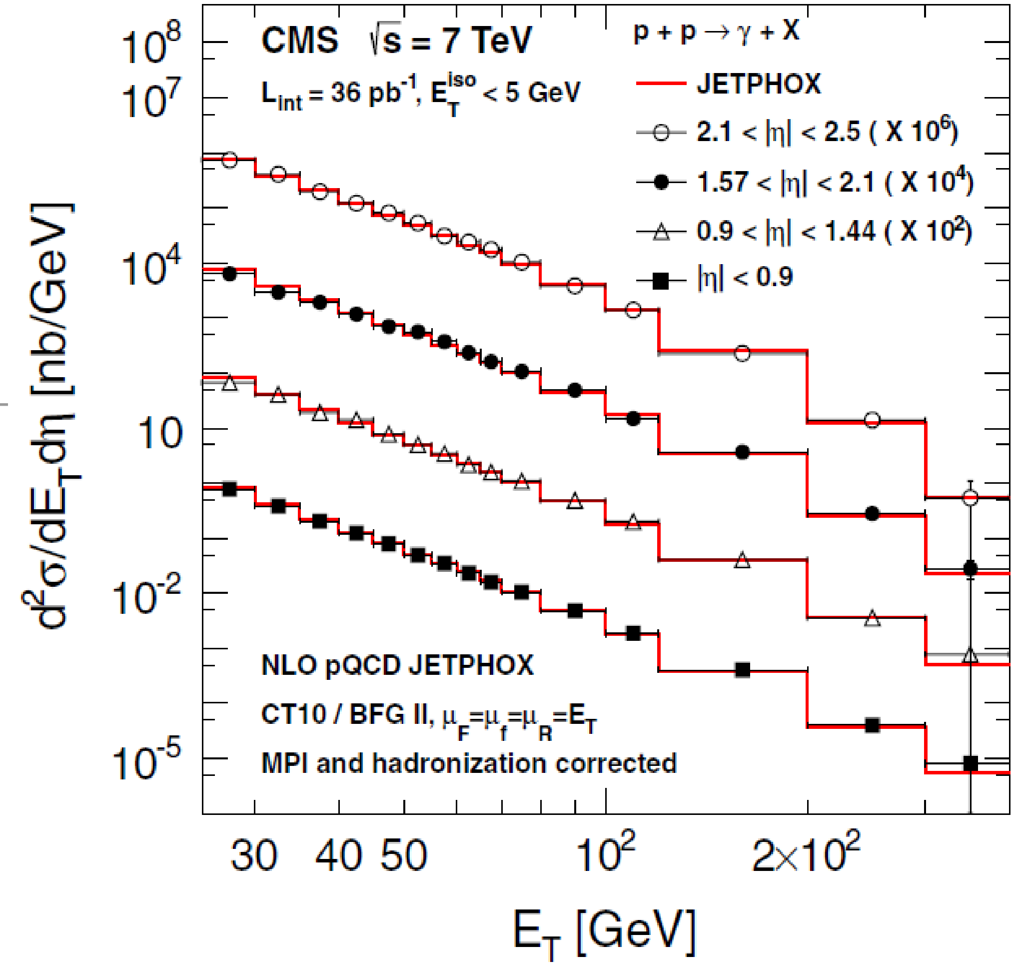
Photon ID efficiency in 2011

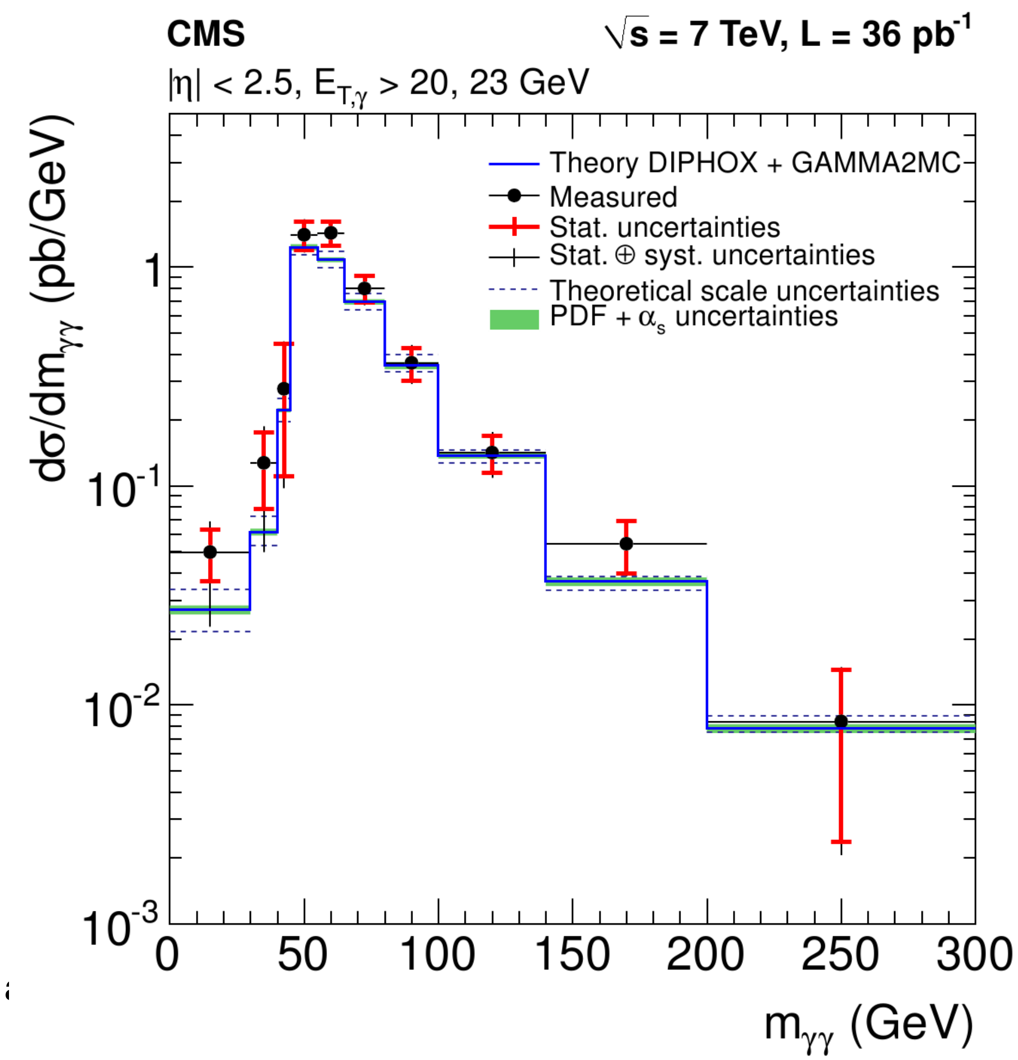
- Much better data/MC agreement in 2011 after MC corrections



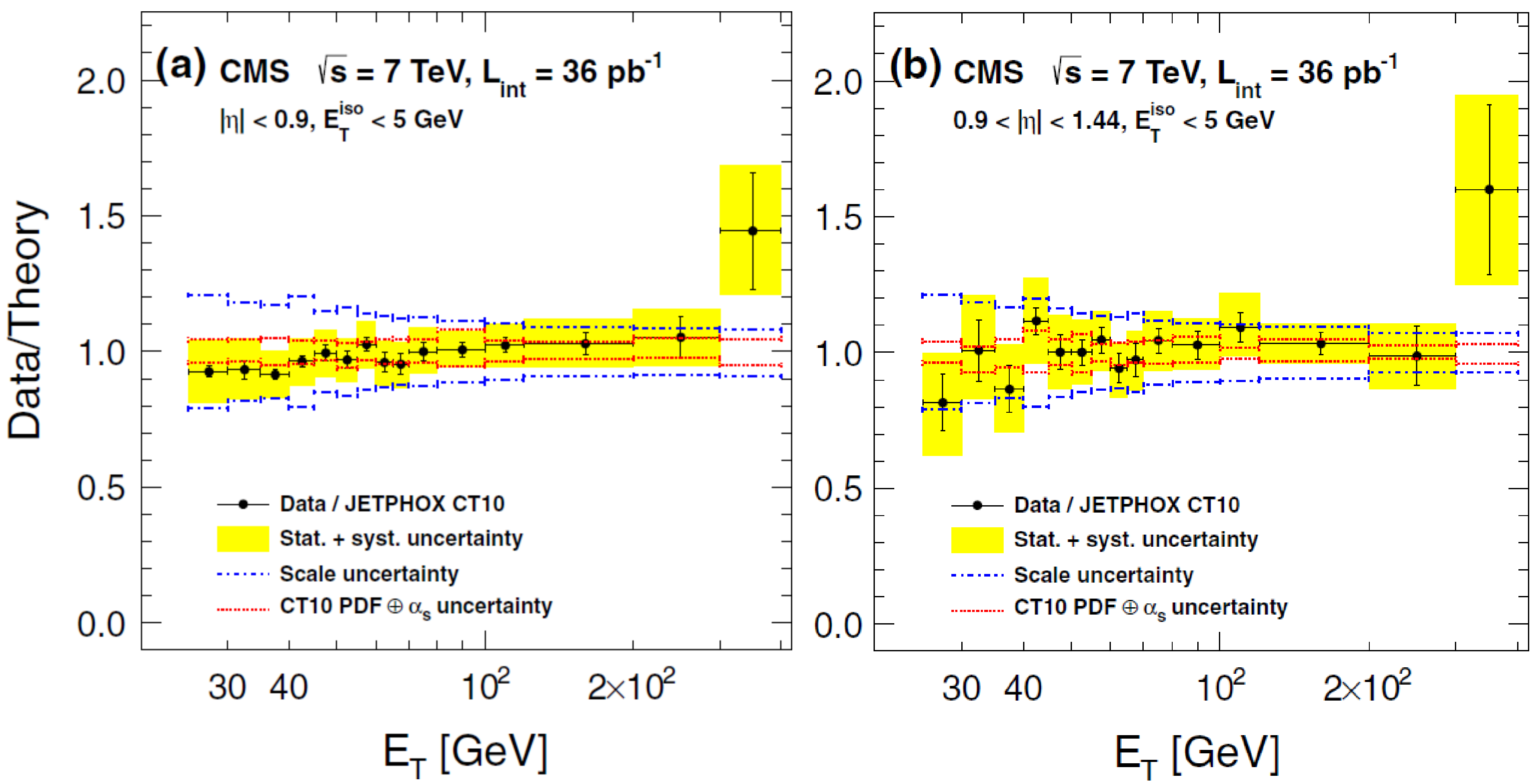
CMS measurements

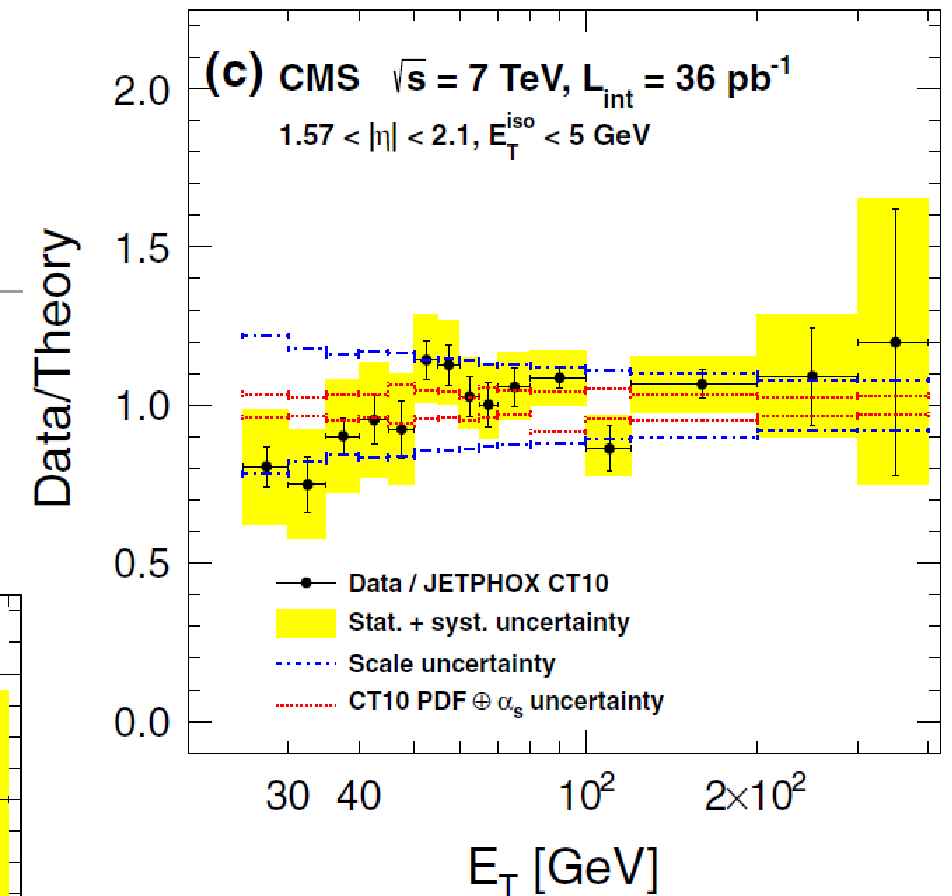
- Inclusive photon cross section (Phys. Rev. D84 052011 (2011))
  - $E_T(\gamma)$ > 25 GeV
  - $|\eta(\gamma)|$ in: [0,0.9) [0.9,1.44) [1.57, 2.1) [2.1, 2.5)
  - particle-level isolation of 5 GeV
- Di-photon cross section (JHEP 1201 (2012) 133)
  - $E_T(\gamma)$ > 23, 20 GeV
  - $|\eta(\gamma)|<1.44$ or $1.56<|\eta(\gamma)|<2.5$
  - particle-level isolation of 5 GeV
  - $dR_{\gamma\gamma}>0.45$

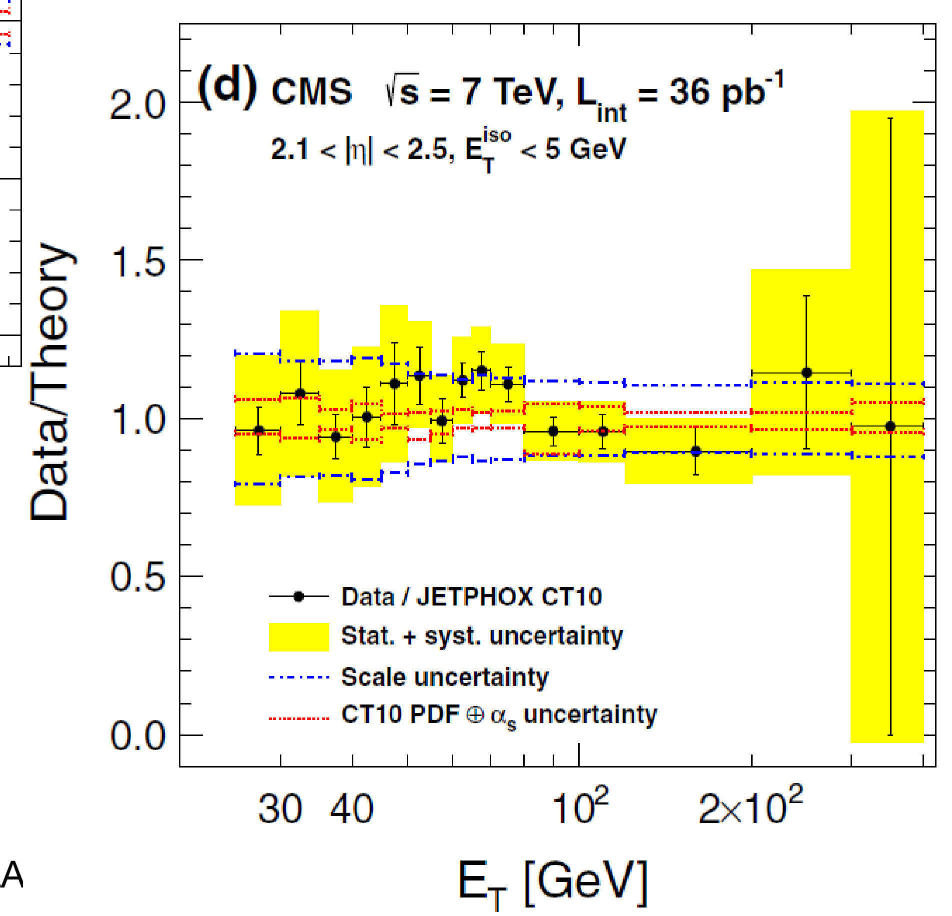




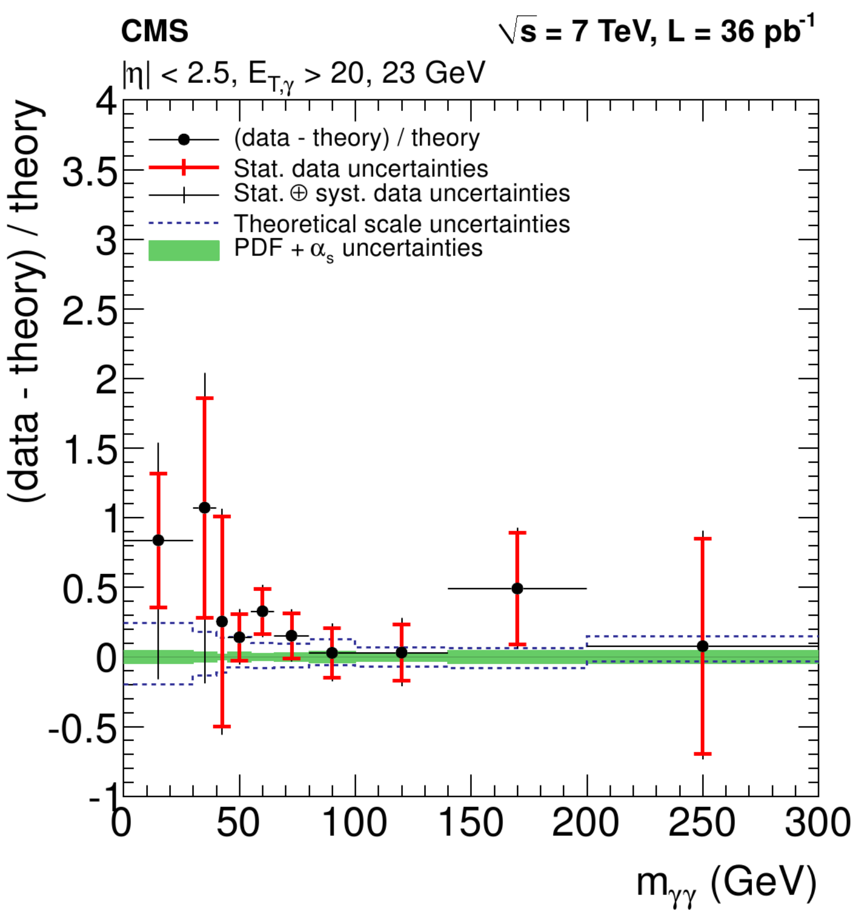
CMS single photon

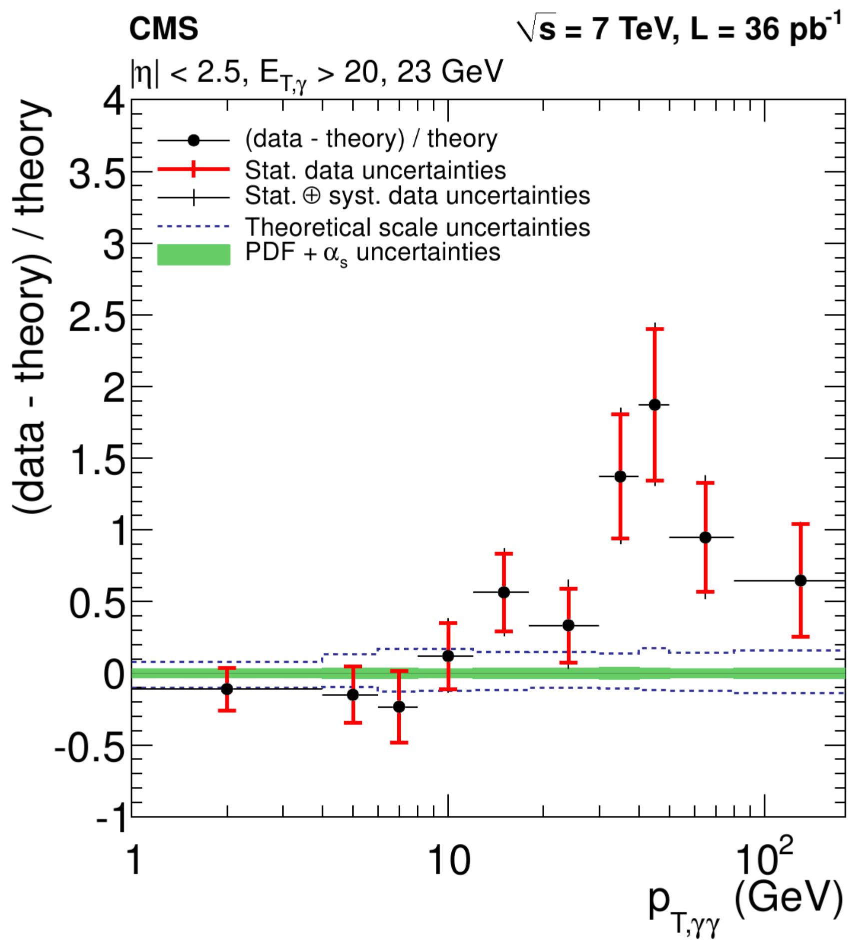


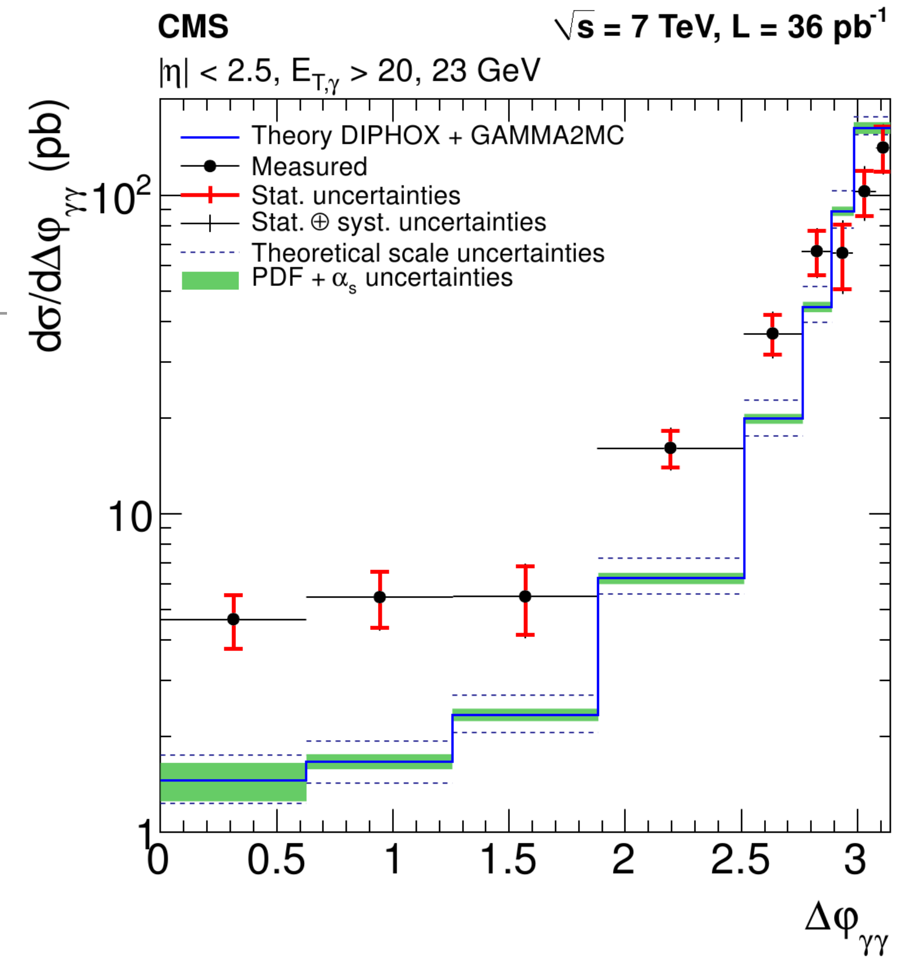


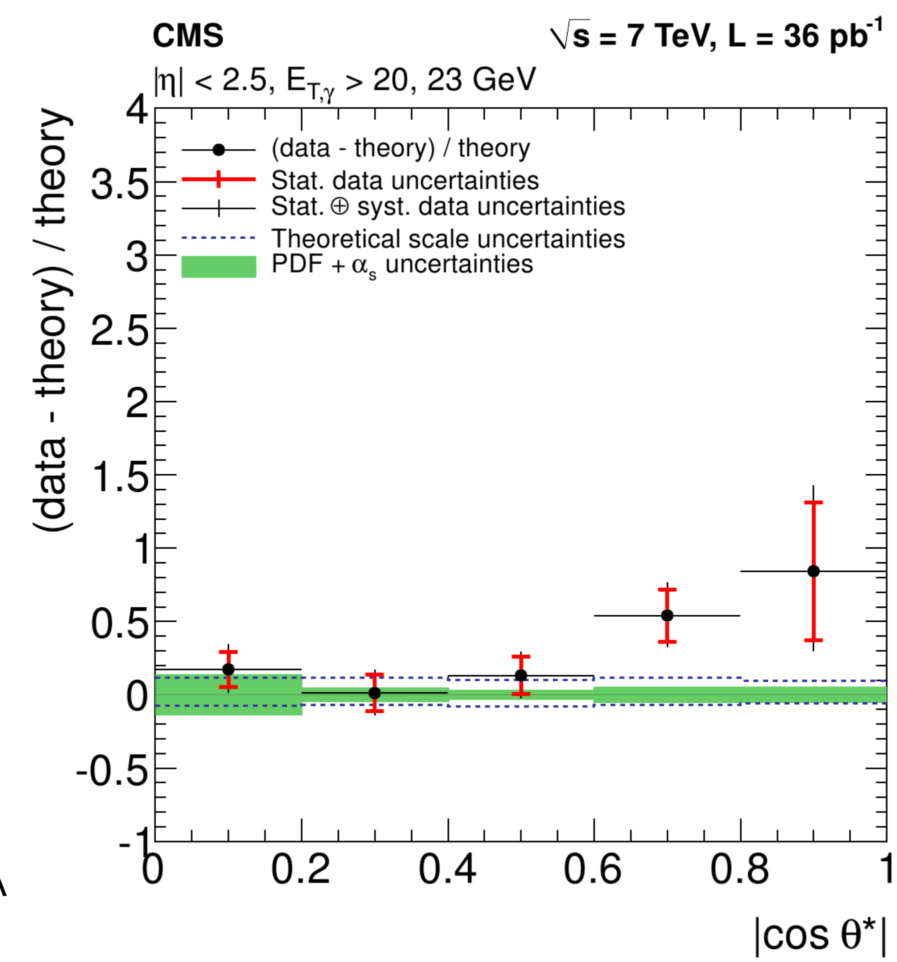


CMS diphotons









PDF reweighting (JETPHOX + NNPDF)

- JETPHOX 1.3.0 NLO pQCD code.
- NNPDF21_100.LHgrid (100 replicas) interfaced via LHAPDF5.8.5
- BFG-II parton-to-photon FFs (but suppressed by isolation cuts).
- All scales set to default: $\mu_R = \mu_F = \mu_{FF} = E_T^\gamma$
- Exp. kinematics+isolation cuts & p_T binnings for 30+ systems:

  100 replicas direct-γ NLO: ~ 7h CPU / 1M evts (~5 days for 20 Mevts !)

  100 replicas frag-γ NLO: ~10h CPU / 1M evts (~1 week for 20 Mevts !)

  ×30 !

- NNPDF2.1 reweighting technique: **[R.D.Ball et al. NPB 849 (2011) 112]**

(1) Compute $d\sigma_{NLO}/dp_T$ for 100 replicas, compare to $d\sigma_{exp}/dp_T$

(2) χ^2 (syst.⊕stat. uncert., no err. matrices) per replica: $$\chi^2_k = \frac{1}{N_{\rm dat}} \sum_{i=1}^{N_{\rm dat}} \frac{(\sigma_i^{({\rm th}),(k)} - \sigma_i^{({\rm exp})})^2}{\Delta^2_{\rm tot}}$$

(3) Obtain associated "weight" for each replica: $$w_k = \frac{(\chi^2_k)^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi^2_k}}{\frac{1}{N}\sum_{k=1}^{N} (\chi^2_k)^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi^2_k}}$$

(4) Obtain new effective number of replicas: $$N_{\rm eff} \equiv \exp\left\{\frac{1}{N}\sum_{k=1}^{N} w_k \ln(N/w_k)\right\}$$

(5) Obtain reweighted PDF replicas: $$\langle \mathcal{O} \rangle_{\rm new} = \frac{1}{N}\sum_{k=1}^{N} w_k \mathcal{O}[f_k]$$