Tests of Perturbative QCD with Photon Final States using the ATLAS Experiment

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Motivation

Studies of the production of photons in proton-proton collisions at the LHC provide…

- testing ground for wide range of Standard Model predictions in new kinematic regimes.
  - Unique colourless probe to test pQCD predictions.
- constraints on the content of the proton.
- description of background event kinematics for different searches for new physics.
  - Identify regions of phase space that require improved MC modelling.
  - Study impact of treatment of heavy quarks in ME and PS computations.

What we measure?

Cross-sections in fiducial volume

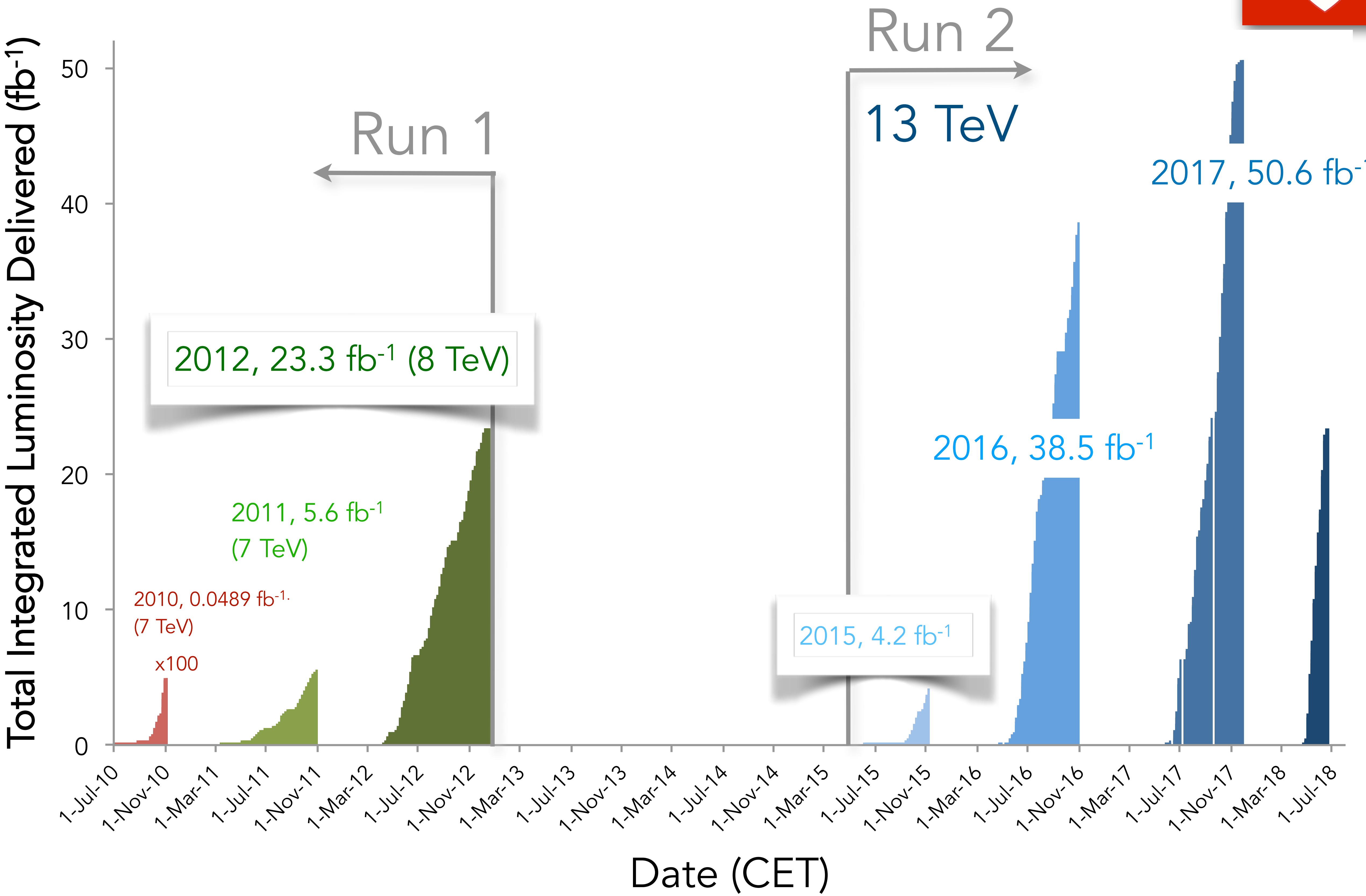
Number of background-subtracted data events

$$\frac{d\sigma}{dX}(i) = \frac{N_{\mathrm{sig}}^{(i)}}{\Delta X^{(i)} \; \mathscr{L} \; \epsilon_{\mathrm{trigger}} \; C_{\mathrm{unfolding}}^{(i)}}$$

Width of bin i

Corrections for detector resolution, reconstruction and selection efficiencies

ATLAS data samples



Outline

- Inclusive prompt photon (13 TeV)
  [PLB 770 (2017) 473, arXiv:1701.06882]
- Di-photon (8 TeV) [PRD 95 (2017) 112005, arXiv:1704.03839]
- Tri-photon (13 TeV) [PLB 781 (2018) 55, arXiv:1712.07291] New
- Photon+jets (13 TeV) [PLB 780 (2018) 578, arXiv:1801.00112] New
- Photon+b/c (8 TeV) [PLB 776 (2018) 295, arXiv:1710.09560] New

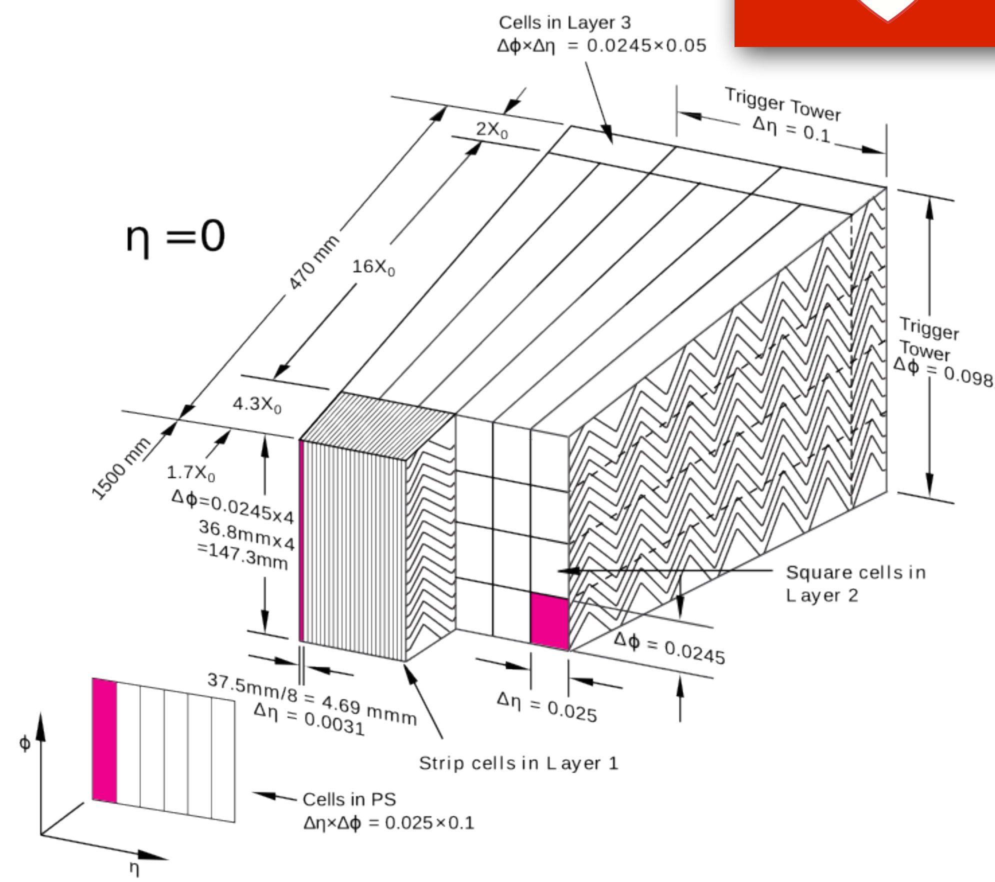
Photon reconstruction

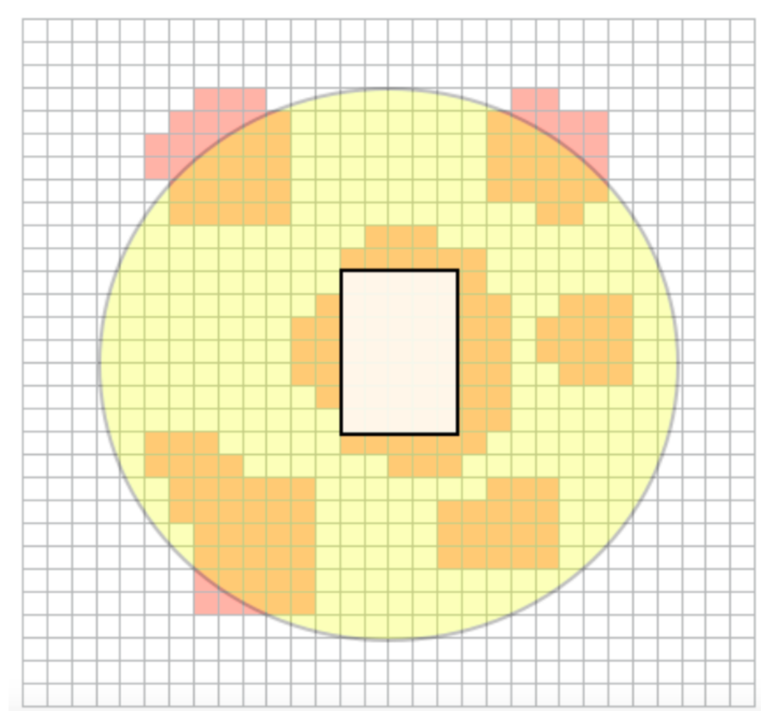
- *"Prompt"* photons: Photons that are not secondaries from hadron decays.

- Photon reconstruction:
  - EM calorimeter cell cluster.
  - Consider both unconverted and converted candidates.

- Photon identification:
  - Nine variables quantifying the shower shape.
  - Fine granularity of first calorimeter layer suppresses π^0 background.
  - "Tight" identification efficiency > 90% for E_T > 40 GeV.

- Photon isolation:
  - Require low amount of energy around photon.
  - Suppresses jets mis-identified as photons.



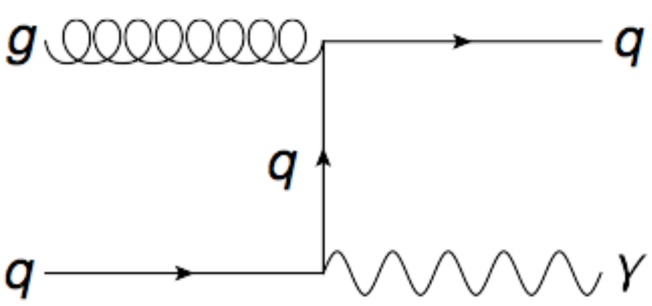


See talks:
- N. Proklova, *"Electron and photon identification with the ATLAS detector"*.
- S. Morgenstern, *"Electron and photon energy measurement calibration with the ATLAS detector"*
- P. Podberezko, *"The ATLAS Electron and Photon Trigger "*.

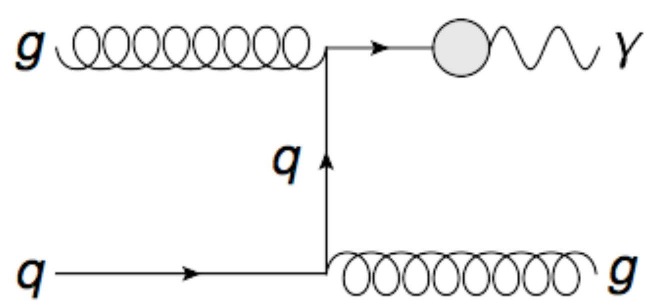
Inclusive photon

PLB 770 (2017) 473 [arXiv:1701.06882]

$pp \rightarrow \gamma + X$

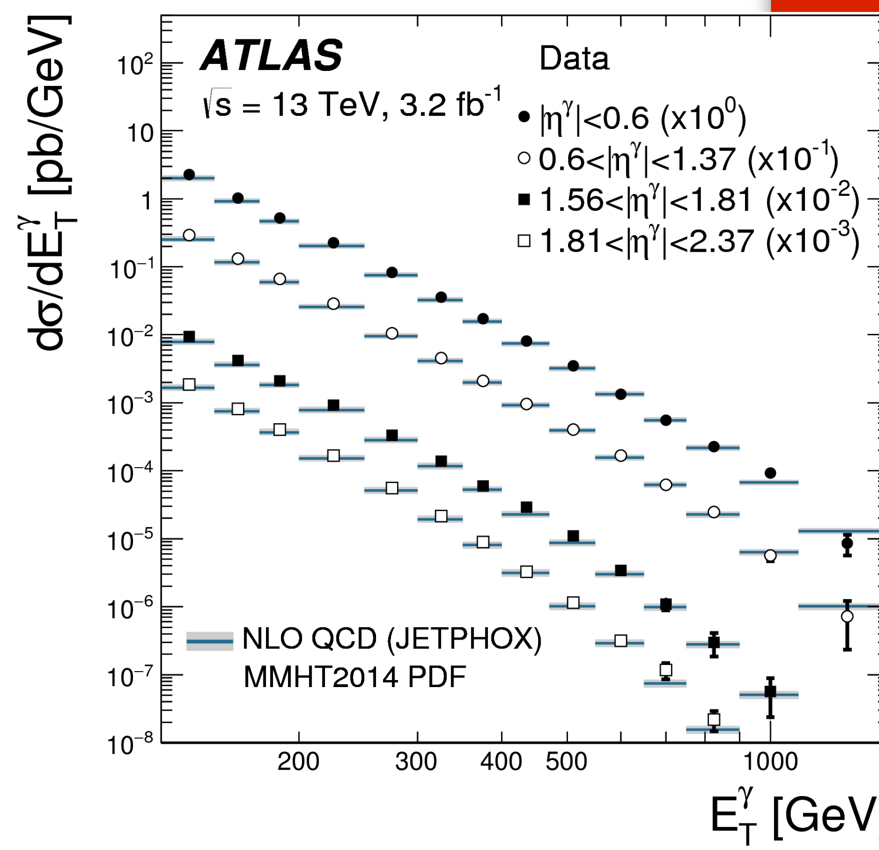


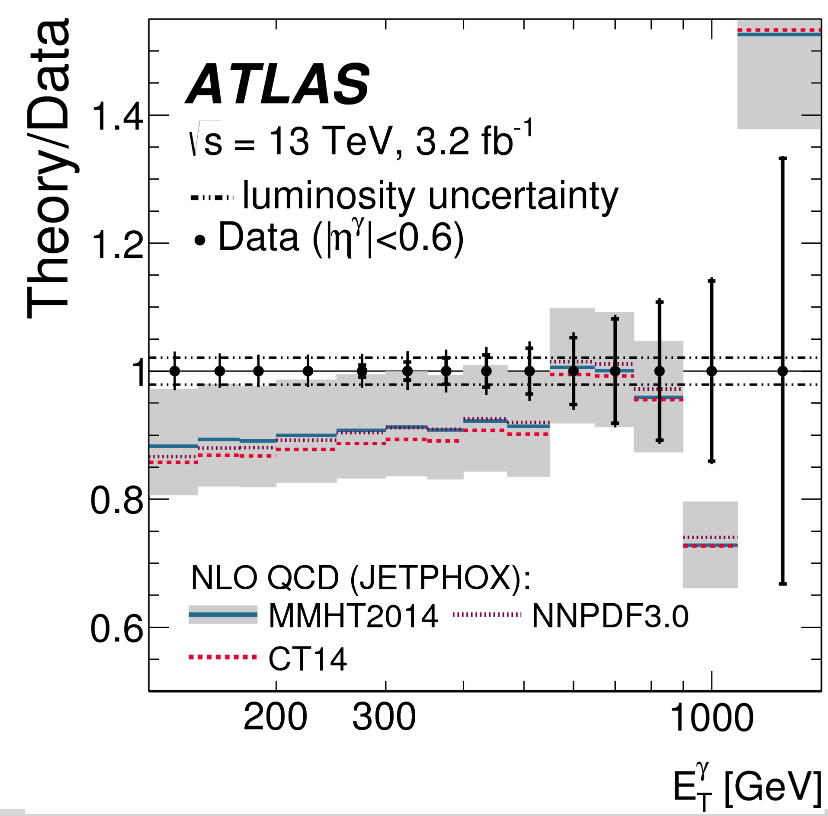
Direct



Fragmentation

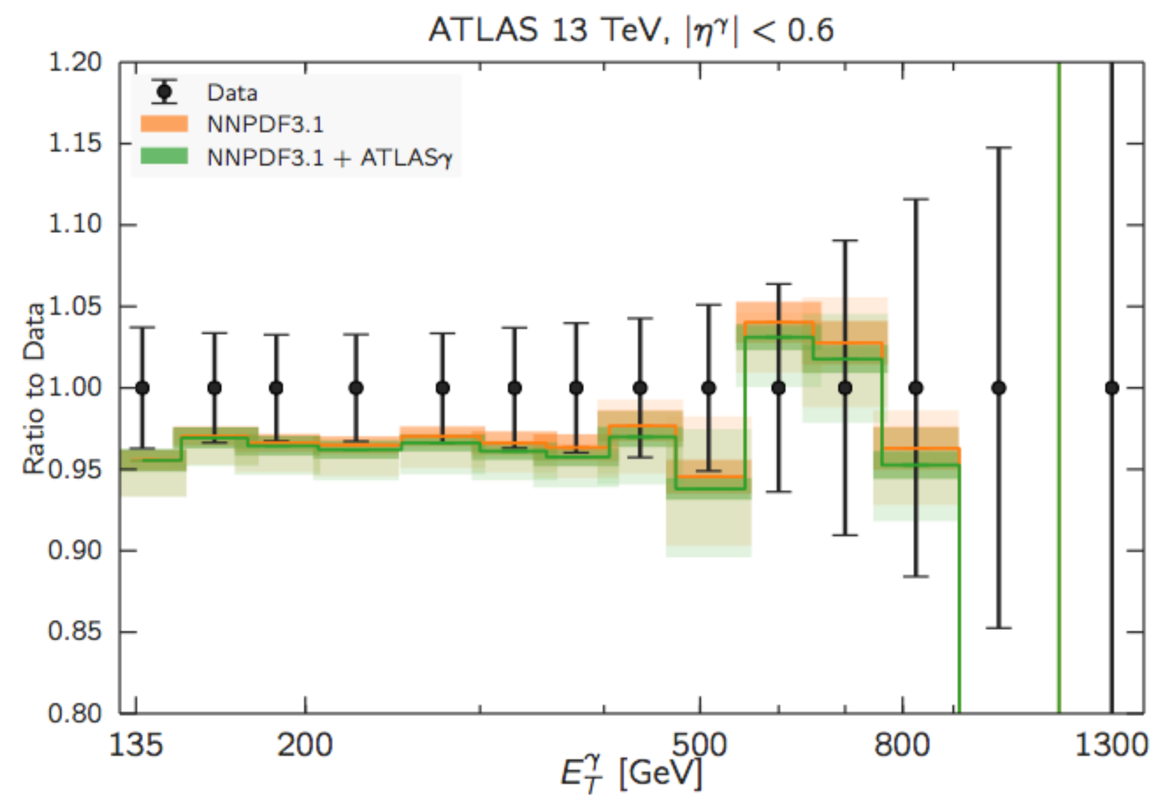
- Sensitivity at LO to gluon density in proton.
- NLO pQCD calculations provide adequate description of measurements; however, test sensitivity limited by theoretical uncertainties associated with missing higher-order terms in pQCD.

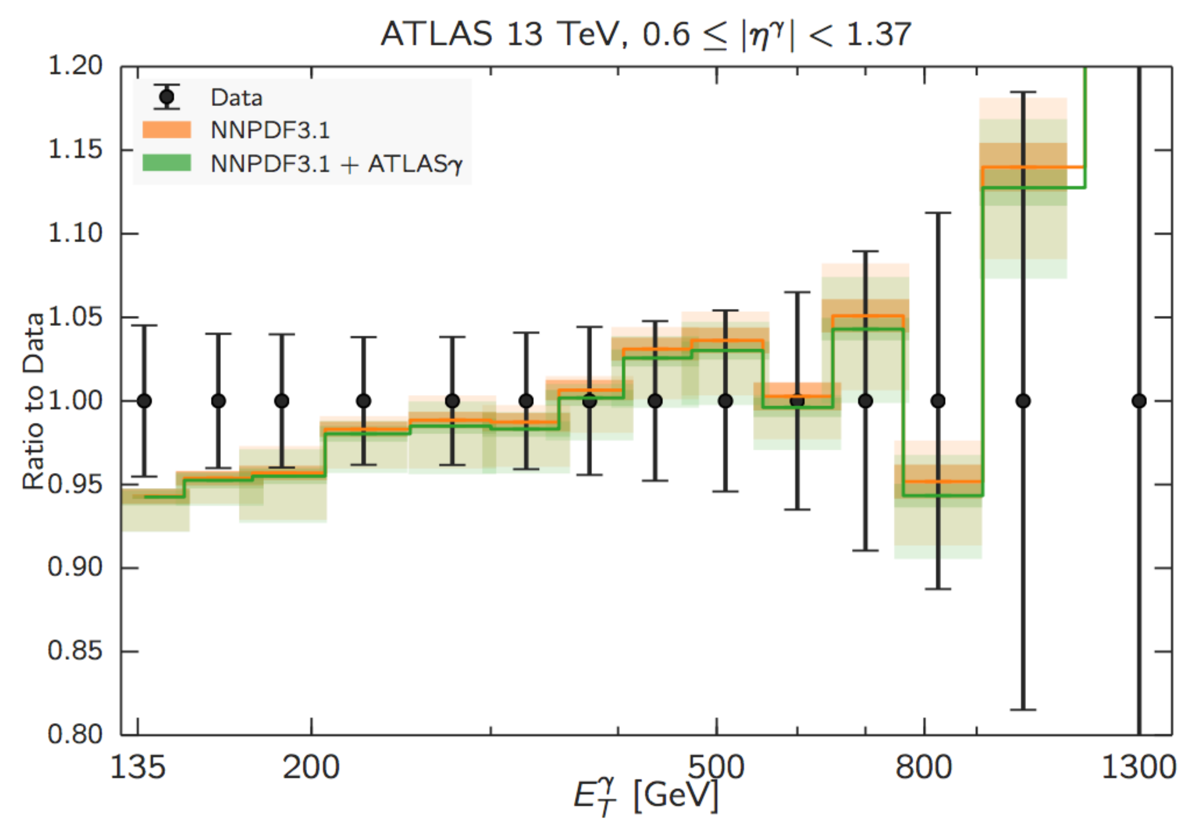




Inclusive photon

- NNLO pQCD calculations now available.
- Theoretical uncertainties reduced by a factor of ~ 2, and now of the same order as experimental uncertainties.
- This opens up a new opportunity for precision QCD at LHC and inclusion of prompt photon data into PDF fits.





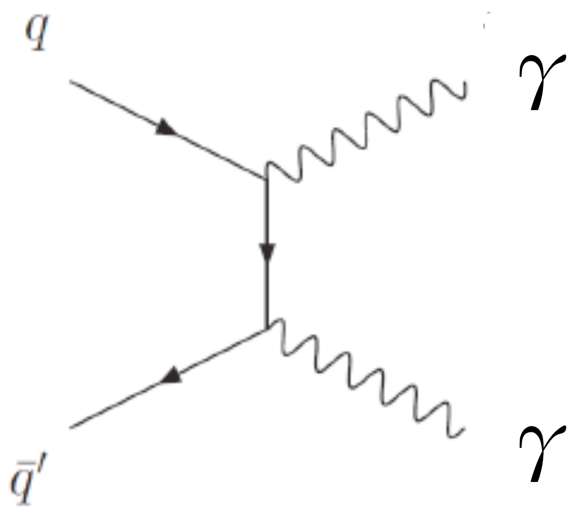
Campbell, Ellis and Williams, Phys. Rev. Lett. 118 (2017) 222001 [arXiv:1612.04333]

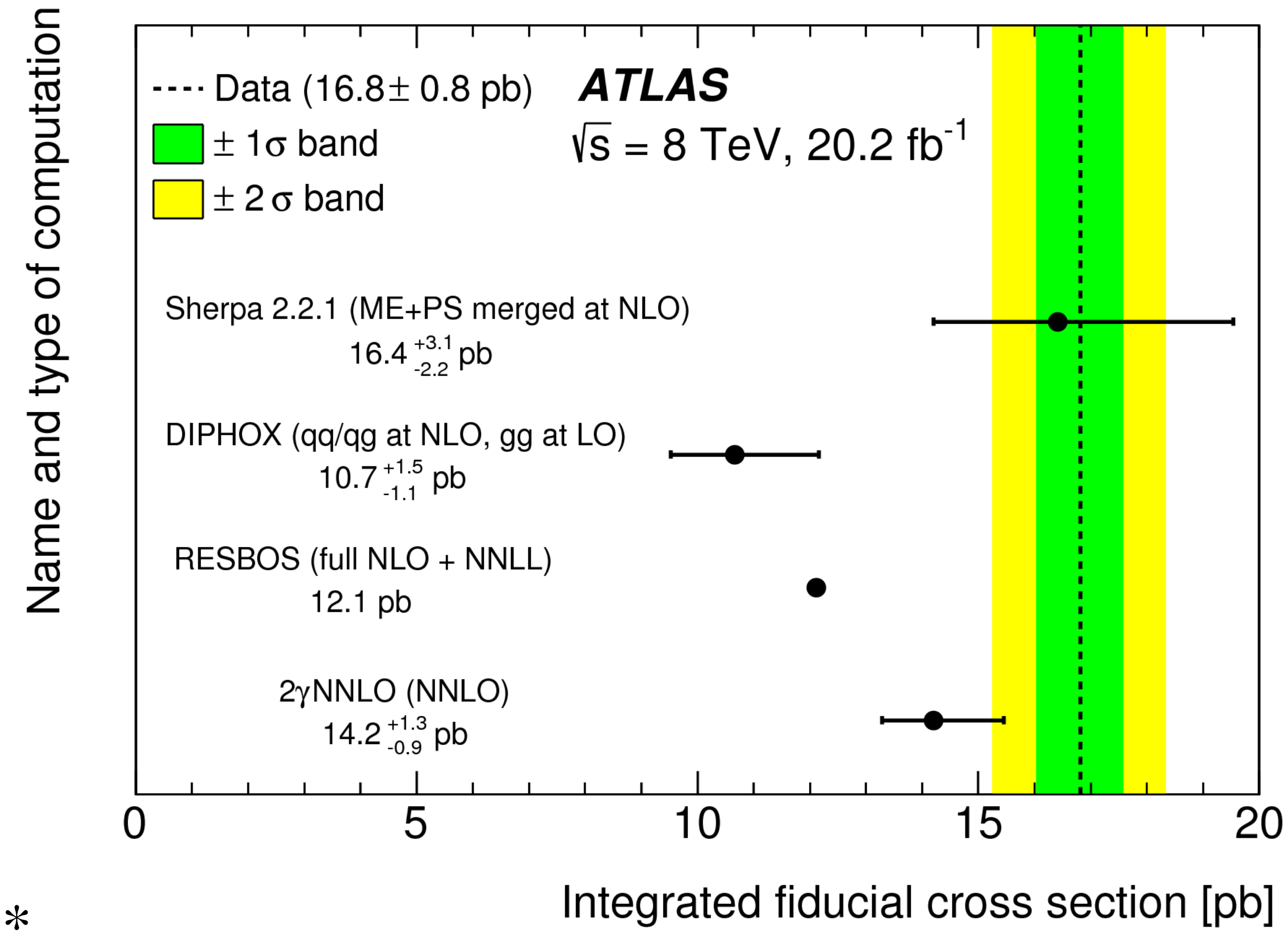
Campbell, Rojo, Slade and Williams, EPJC 786 (2018) 470 [arXiv: 1802.03021]

Di-photon

PRD 95 (2017) 112005 [arXiv:1704.03839]

$$pp \rightarrow \gamma\gamma + X$$





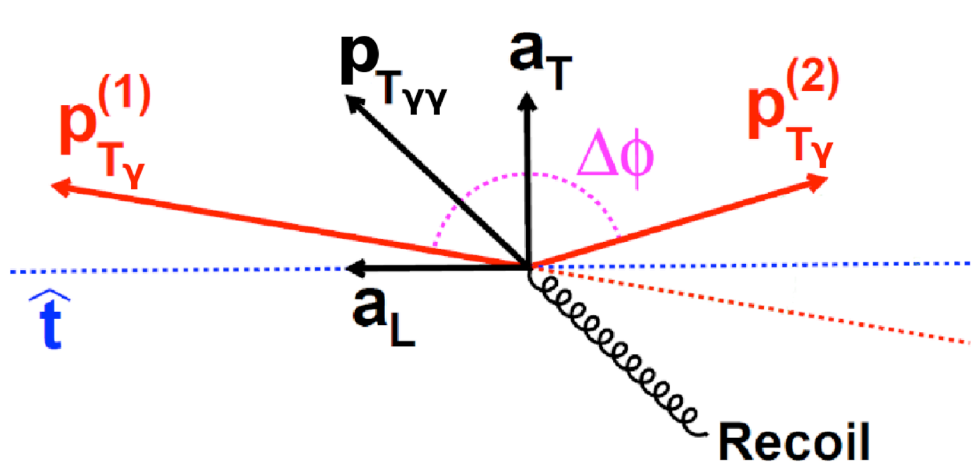
- Cross-section at 8 TeV measured differentially as function of 6 kinematic observables: $m_{\gamma\gamma}$, $|\cos\theta^*_\eta|$, $\Delta\phi_{\gamma\gamma}$, $p_{T,\gamma\gamma}$, a_T, ϕ^*_η .
- Systematic uncertainties reduced by up to x2 compared to measurements at 7 TeV, due to improvements in background estimation.
  - Despite higher pile-up conditions

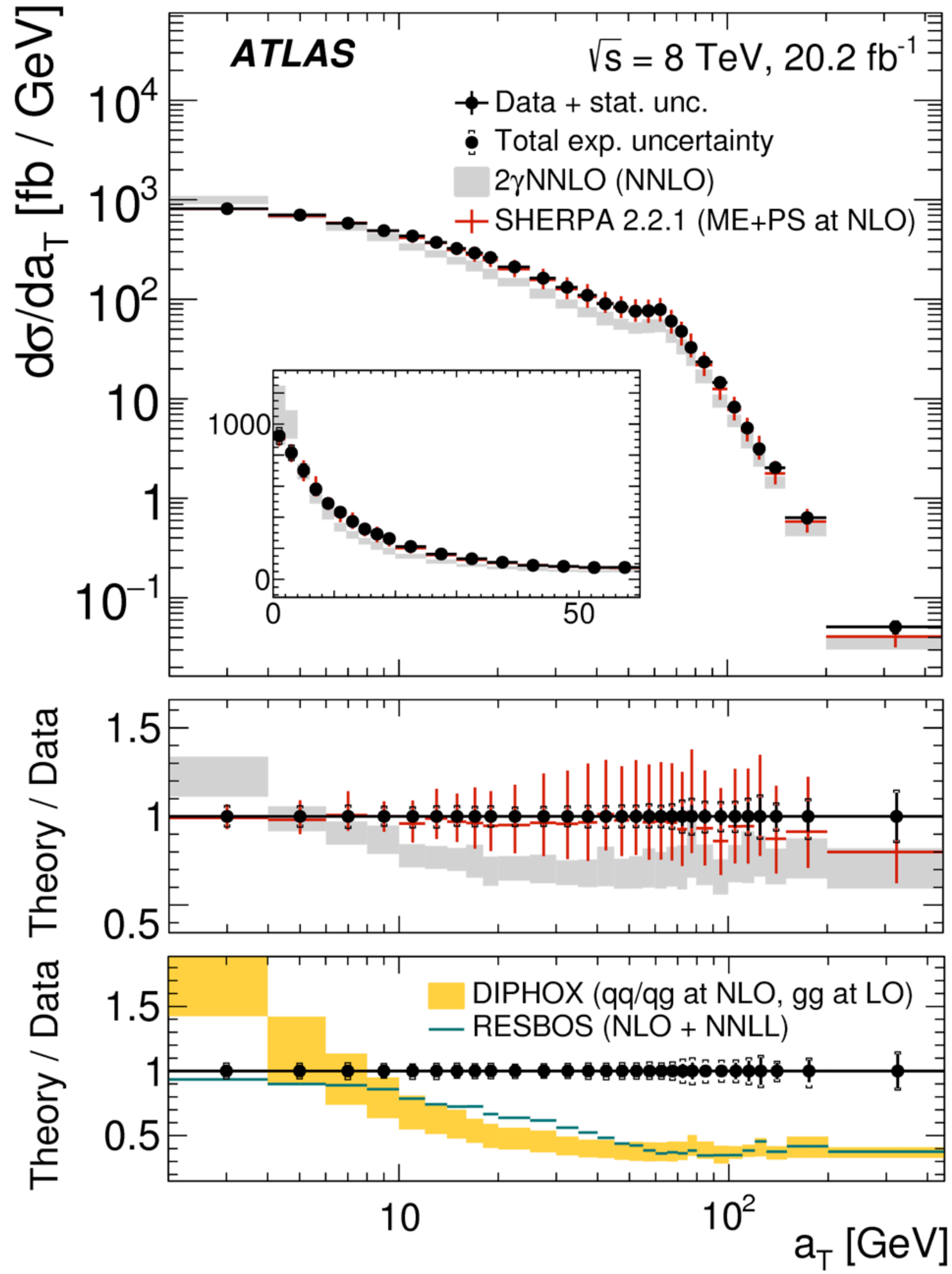
Prediction from ME+PS at NLO (Sherpa) is in agreement with measurement.

Di-photon

PRD 95 (2017) 112005 [arXiv:1704.03839]

- Measurements are well-described by SHERPA (ME+PS at NLO).
- Specific regions of phase space particularly sensitive to soft gluons emissions.
  - Low a_T region well described by parton shower (SHERPA) or inclusion of soft-gluon resummation (RESBOS)
- In some regions, disagreements of up to x2 between NLO and data.
  - Inclusion of NNLO corrections not sufficient to reproduce the measurements.





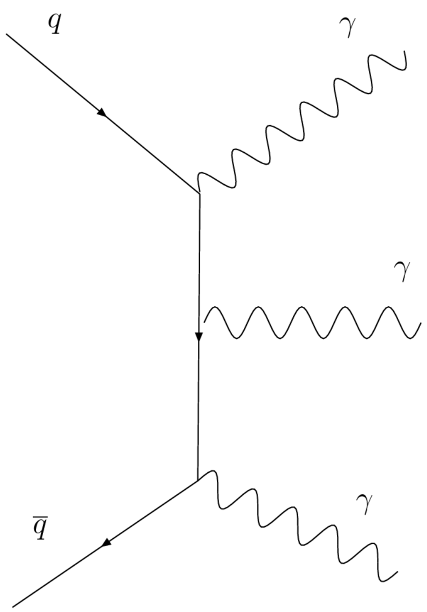
Tri-photon

New

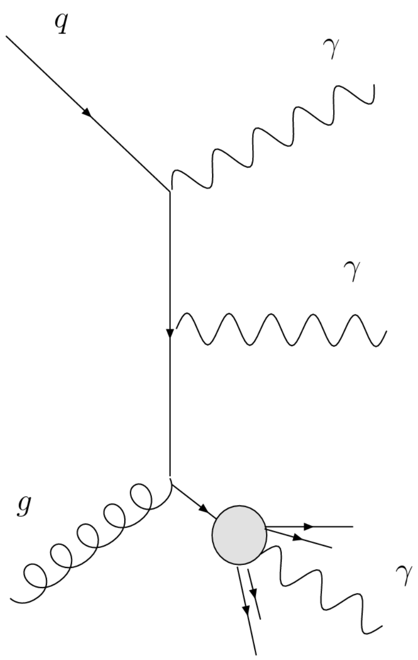
PLB 781 (2018) 55 [arXiv:1712.07291]

$$pp \rightarrow \gamma\gamma\gamma + X$$

- Rare process: At LO contribution is order α_{EM}^3.
- Complementary phase space to inclusive photon and di-photon production.
- Study topology and kinematics of individual photons, pairs of photons and three-photon system (13 kinematic variables).



Direct



Fragmentation

- Main background: electron and jet mis-identification.
  - Electron mis-identified as a photon
    - Estimated from $ee\gamma$, $ee\gamma\gamma$, $e\nu\gamma\gamma$ MC events (LO Sherpa).
    - Mis-ID rate corrected to match measurement in Z→ee data.
  - Jet mis-identified as a photon
    - 2D sideband applied to account for all combinations of photons meeting or failing to meet the tight identification or isolation criteria.

Tri-photon

New

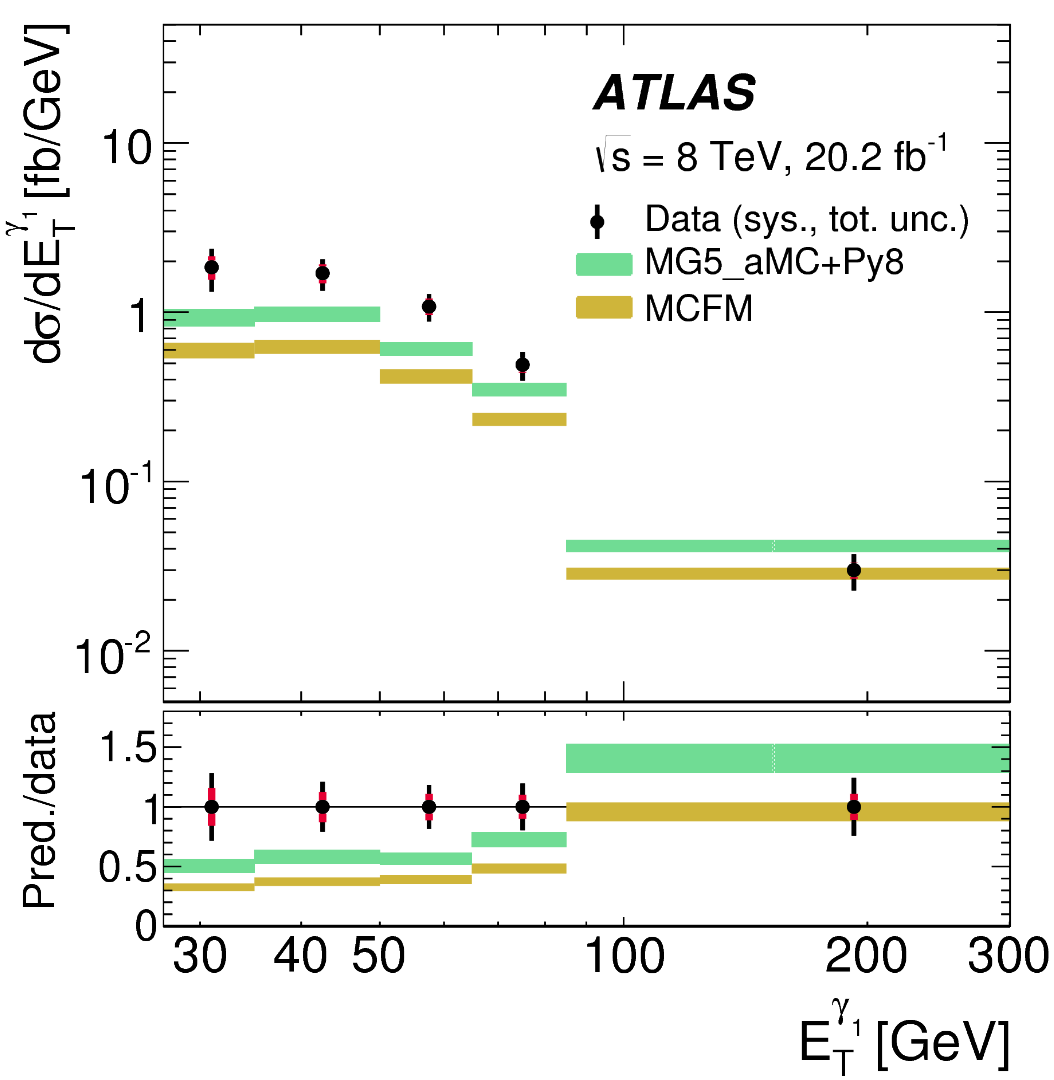
PLB 781 (2018) 55 [arXiv:1712.07291]

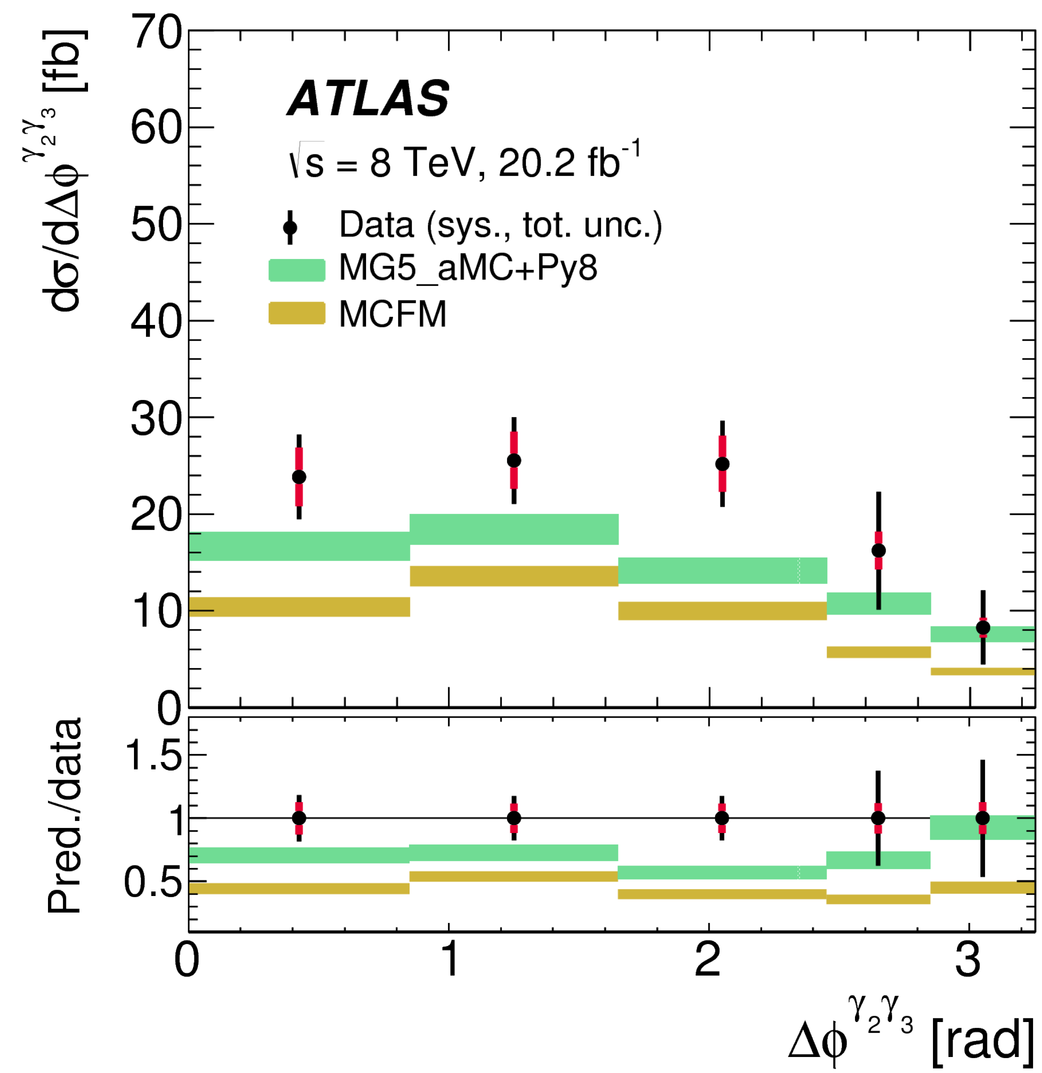
- NLO predictions underestimate measured cross-section by ~ x1.5-2.
- NLO fails to describe regions of low E_T.
- Addition of PS to NLO improves agreement.
- Need improved MC modelling of this process.

$$\sigma_{\text{meas}} = 72.6 \pm 6.5\,(\text{stat.}) \pm 9.2\,(\text{syst.})\ \text{fb}$$

$$\sigma_{\text{NLO}} = 31.5\,^{+3.2}_{-2.5}\ \text{fb}\,(\text{MCFM})$$

$$\sigma_{\text{NLO+PS}} = 46.6\,^{+5.7}_{-3.6}\ \text{fb}\,(\text{MadGraph5}_a\text{MC@NLO})$$



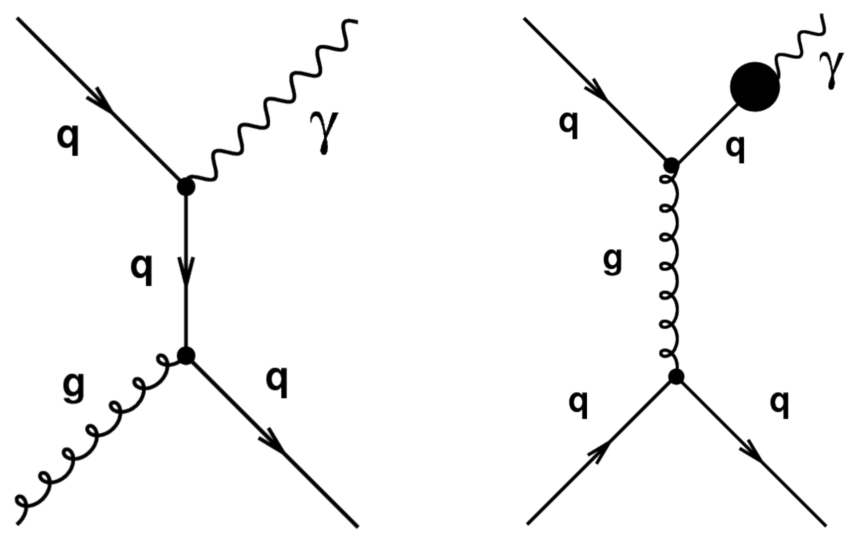


Photon + jets

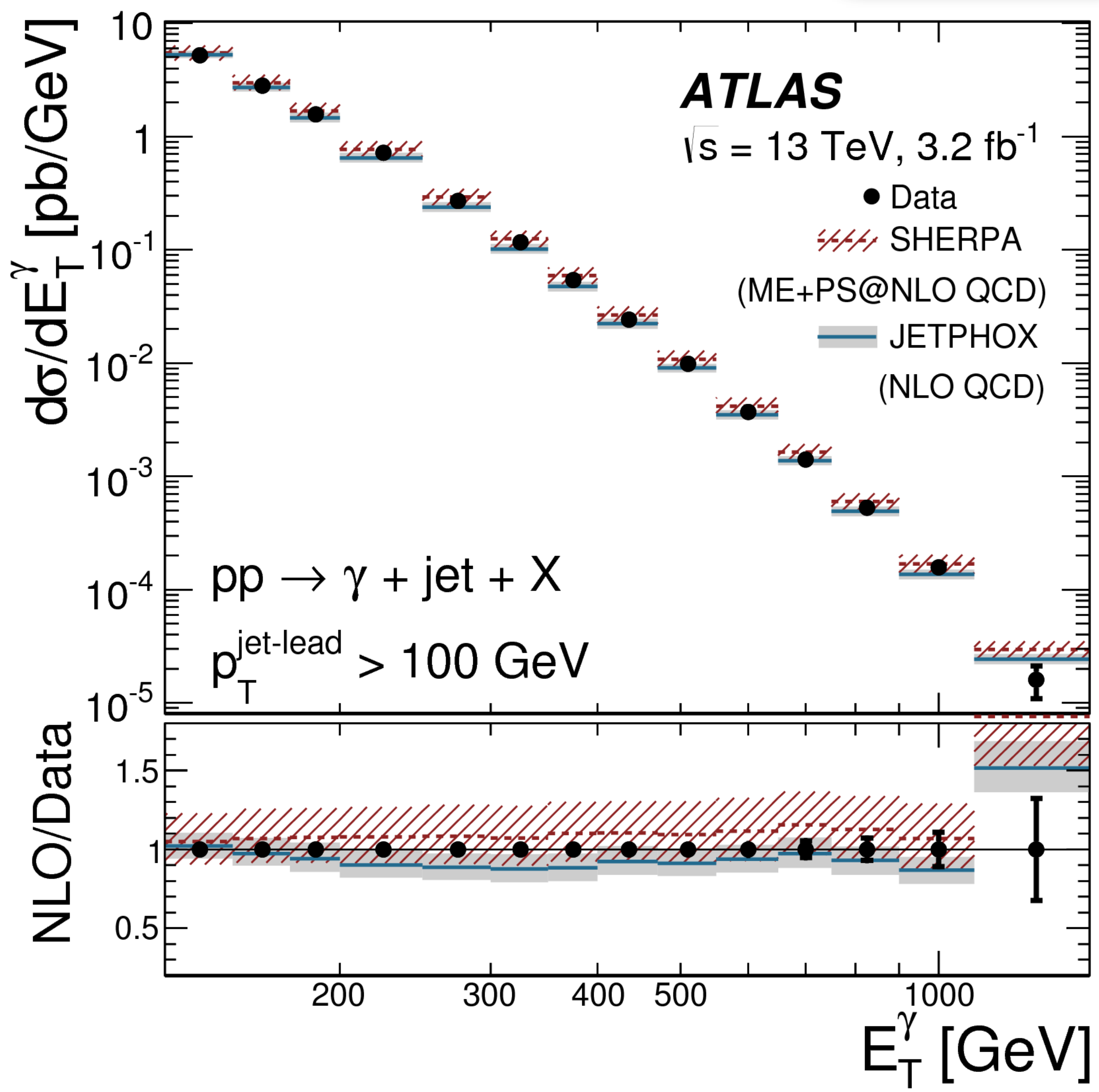
New

PLB 780 (2018) 578 [arXiv:1801.00112]

$$pp \to \gamma + \text{jets}$$



- Study dynamics of γ + jets production.
- Differential cross-sections measured as function of E_T^{γ}, $p_T^{\text{jet-lead}}$, $\Delta\phi^{\gamma-\text{jet}}$, $m^{\gamma-\text{jet}}$, $|\cos\theta^*|$.
- NLO calculations provide good description of measurements.
- For most of the phase space studied, theoretical uncertainties are larger than experimental uncertainties.



Photon + jets

New

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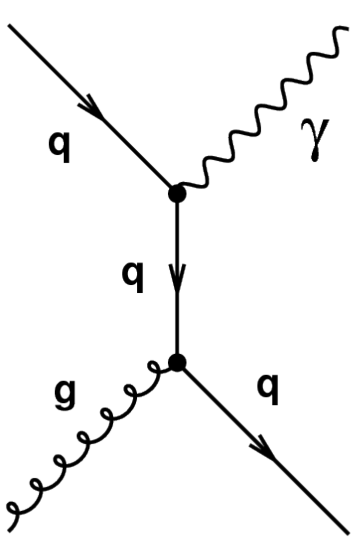
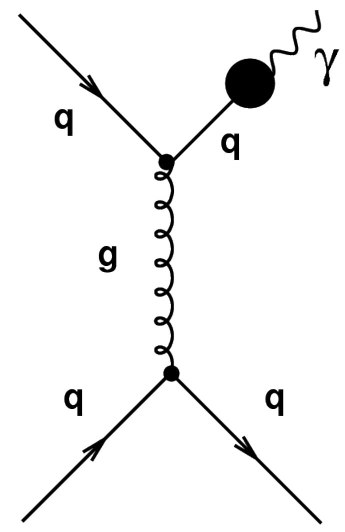
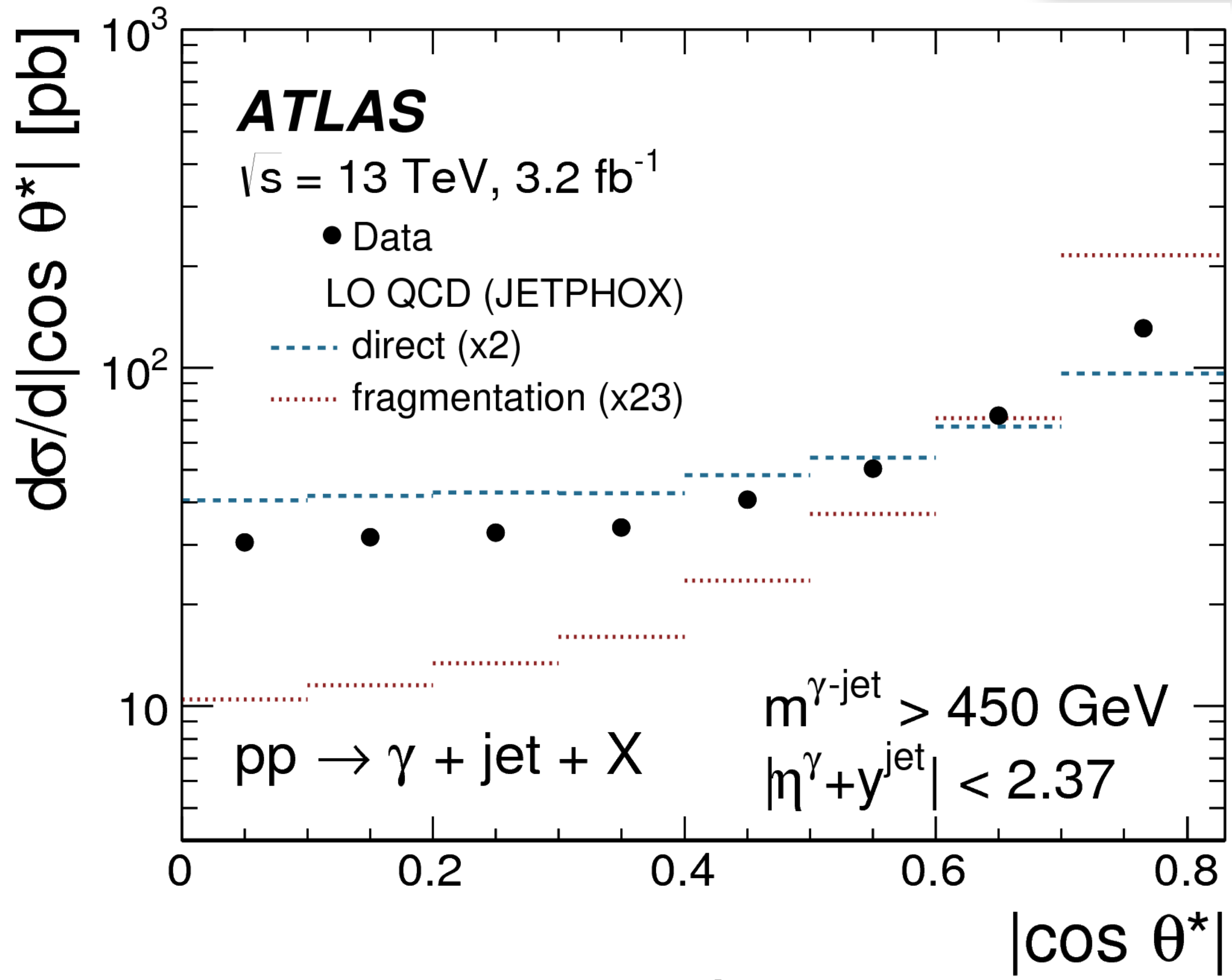


$(1-|\cos\theta^*|)^{-1}$



$(1-|\cos\theta^*|)^{-2}$



Cross-section as function of θ^* provides insight into relative contributions of direct vs fragmentation components, as well as possibility of testing dominance of t-channel quark exchange.

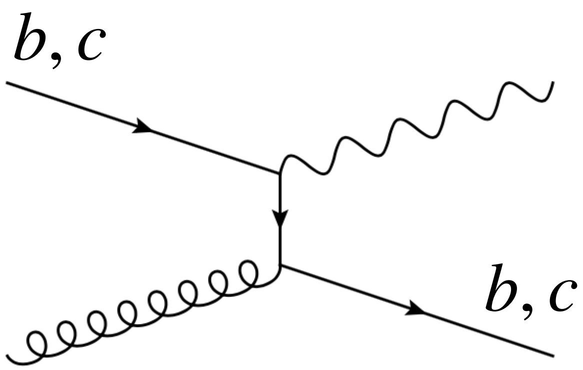
Quark exchange diagrams observed to dominate.

Photon + b/c

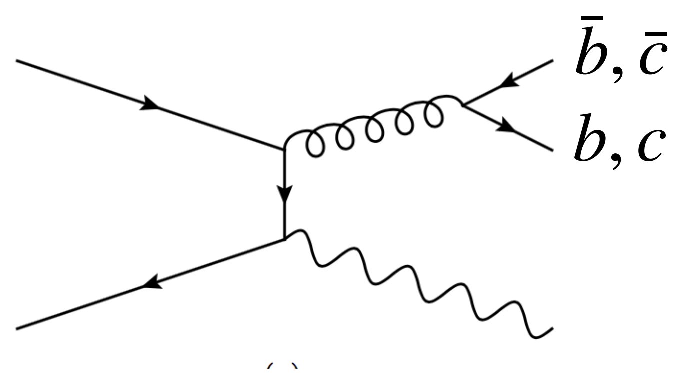
New

PLB 776 (2018) 295 [arXiv:1710.09560]

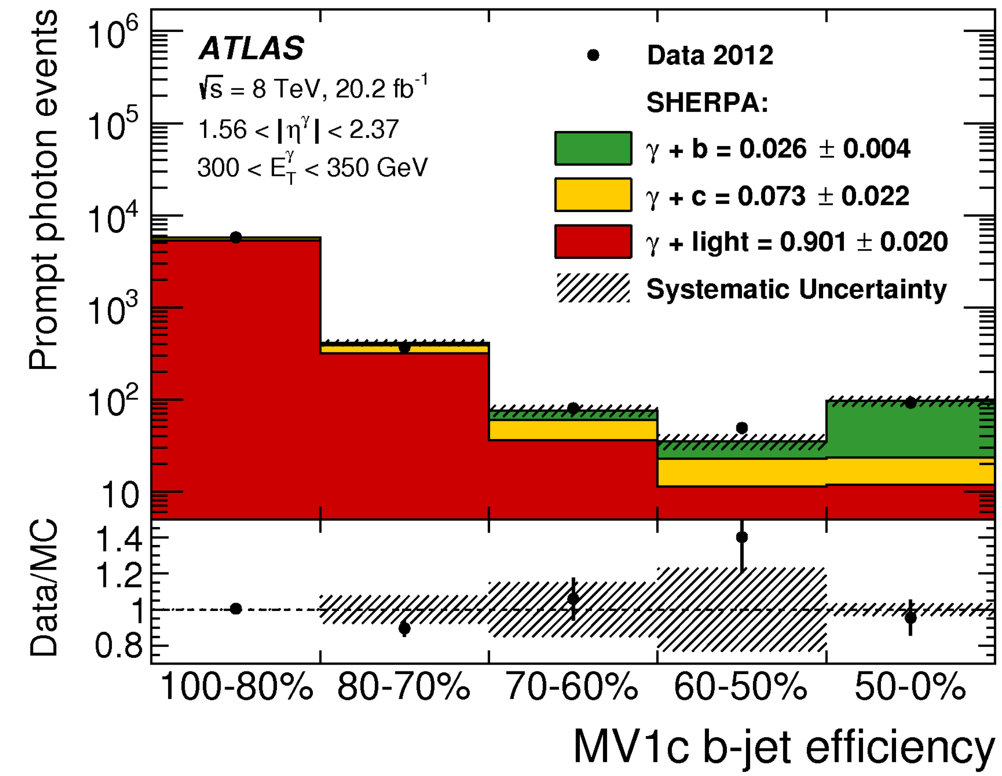
$$pp \rightarrow \gamma + \mathrm{b/c}$$

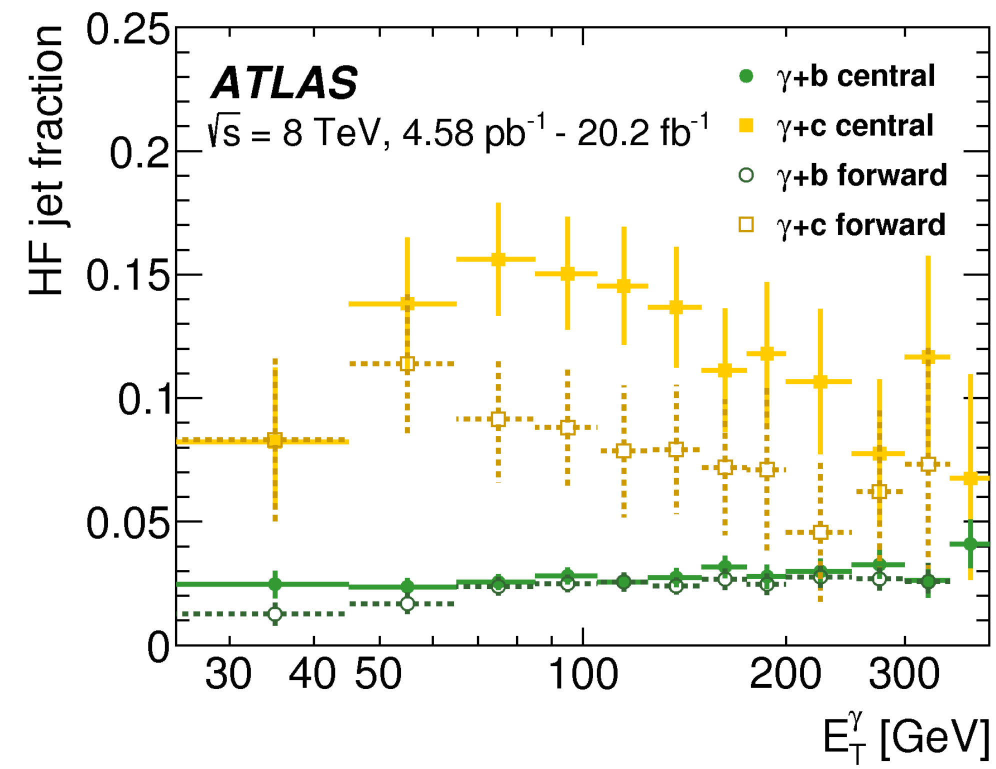


Compton



Gluon splitting





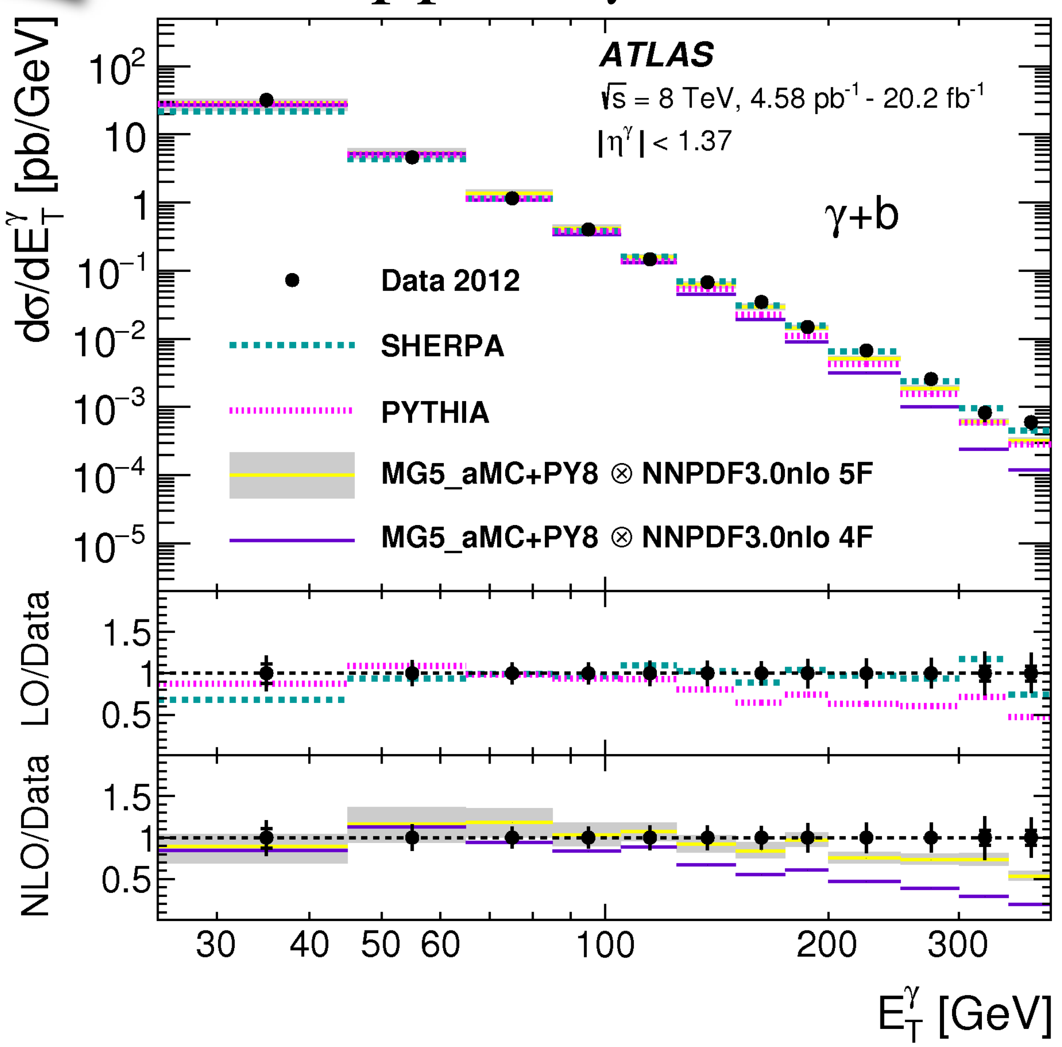
- Sensitive to b/c-quark content of proton.
  - Sensitive to intrinsic charm hypothesis.
- Test modelling of b-quark in MC generators
  - Test flavour number scheme: 4F vs 5F.
- Analysis overview:
  - Select photon + jets events.
  - Photon purity estimated using data-driven 2D sideband method.
  - Use template fit method to extract b and c fractions.

Photon + b/c

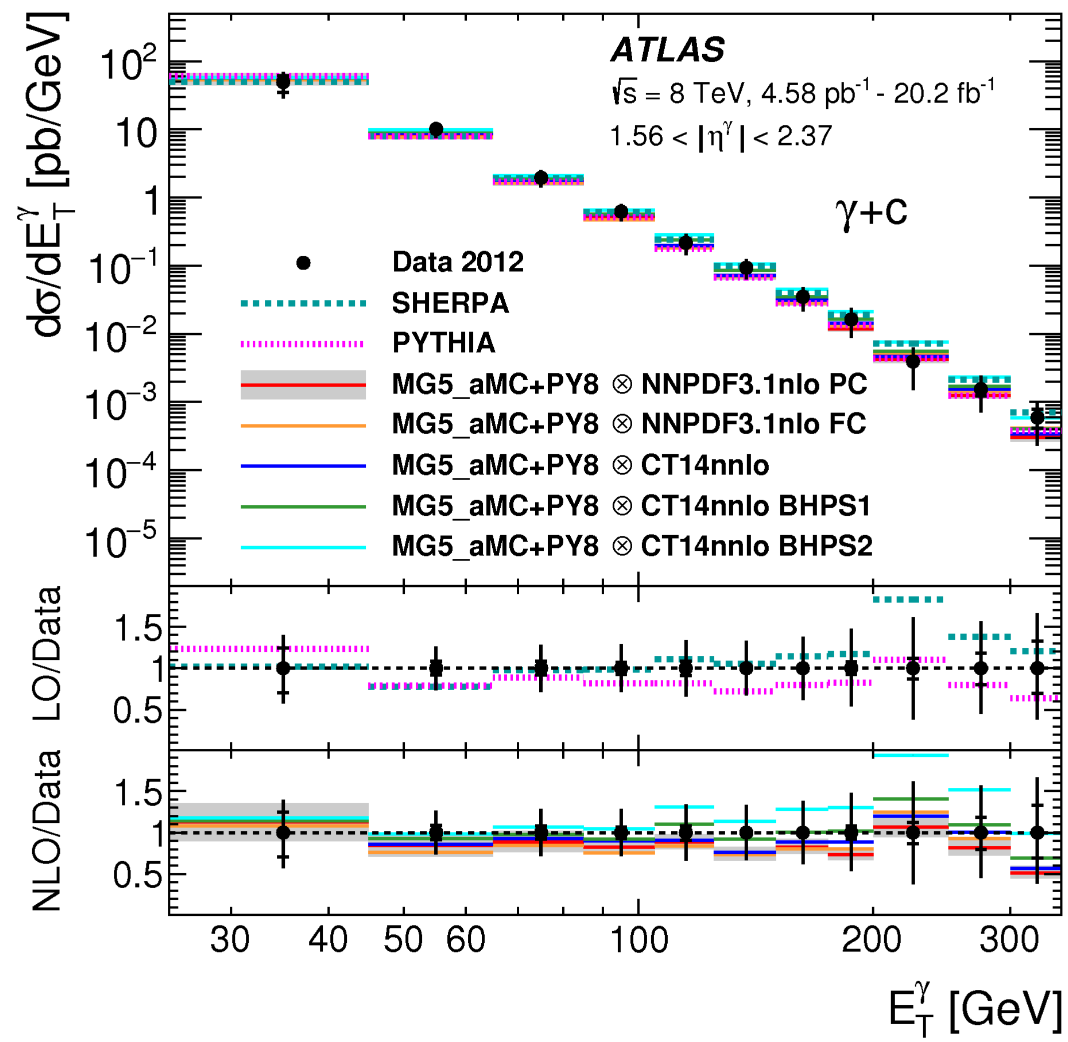
New

PLB 776 (2018) 295 [arXiv:1710.09560]

$pp \rightarrow \gamma + \mathrm{b}$



$pp \rightarrow \gamma + \mathrm{c}$



- LO: Sherpa provides good description of data.
- NLO: 5F scheme provides better description of data up to 200 GeV.
  - Higher-order calculations expected to improve modelling at higher E_T.

- Within uncertainties, LO and NLO provide good description of data.
- Predictions with IC predict higher cross-section at high x.

Summary

- Large data samples, well-understood detector performance and effective pile-up mitigation techniques make it possible to perform precision measurements of known Standard Model processes.

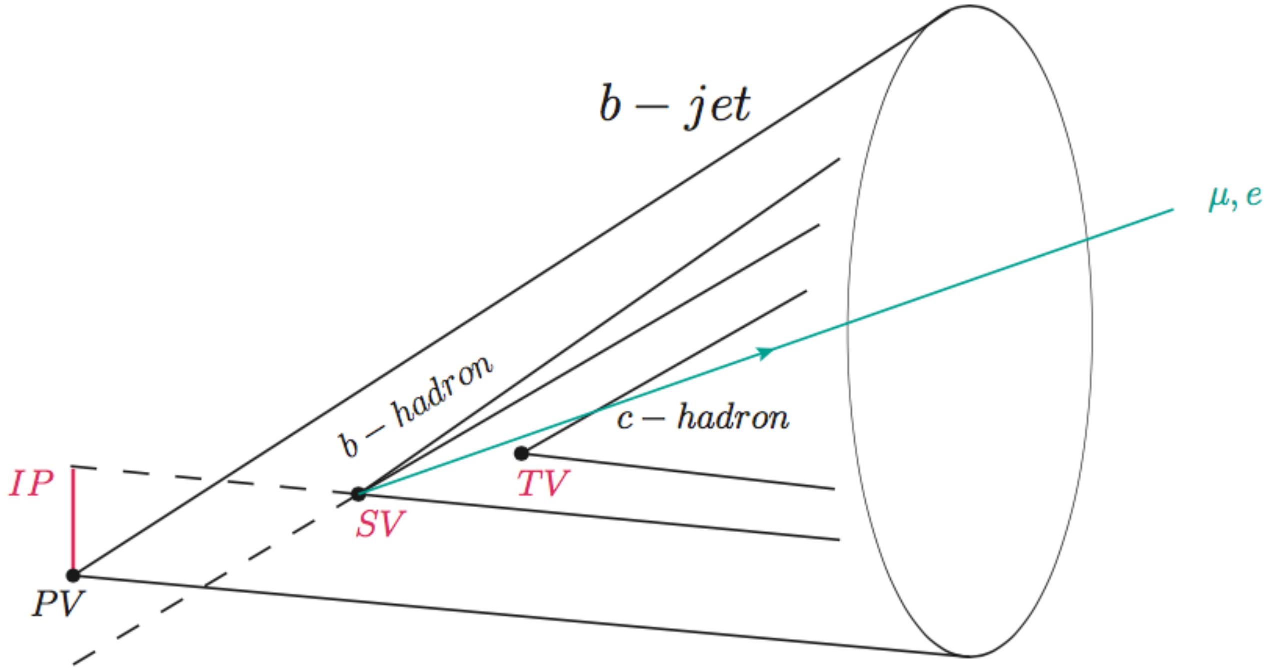
- Study of photon production in *pp* collisions provides stringent tests of QCD.
  - Calculations beyond NLO needed to reduce theoretical uncertainties and improve modelling.

- Measurements can be used to set constraints on proton PDFs.

Backup

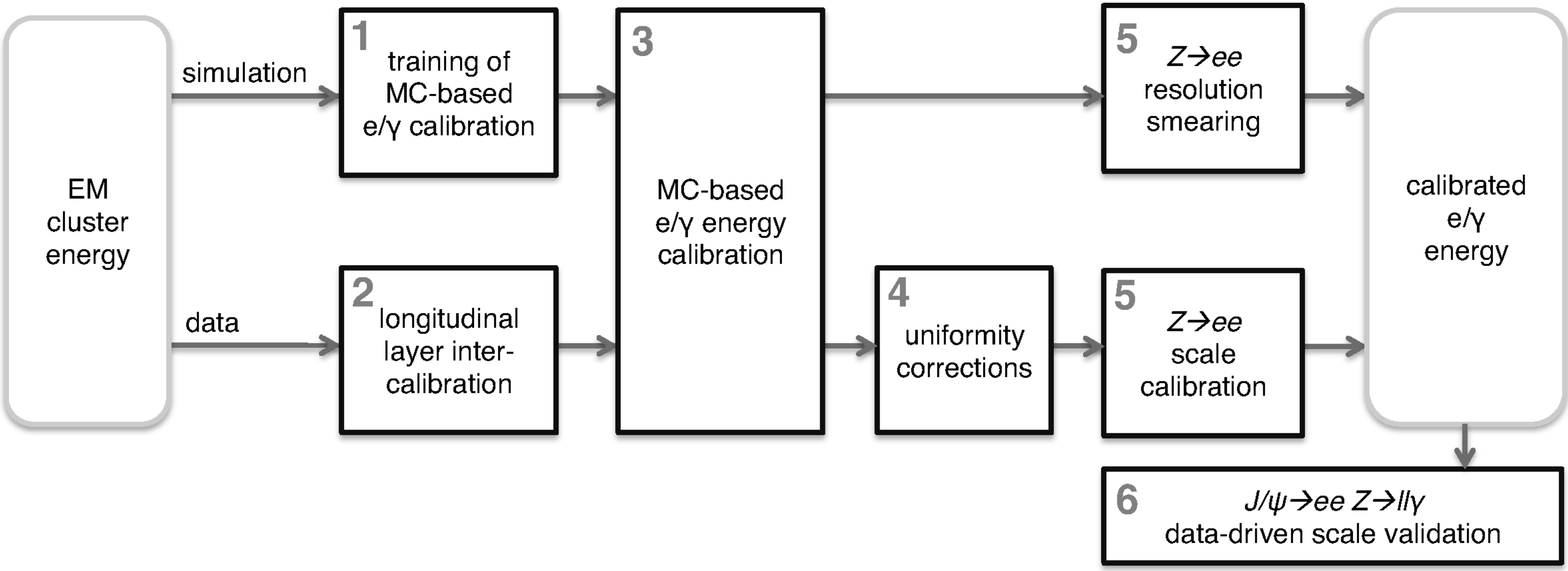
b/c-jet identification

- MV1c neural network trained to differentiate b-jets from c-jet and light jets
  - Takes as input three types of parameters
    - **Impact parameter** information
    - **Secondary vertex** information
    - **Decay chain path** information, up to tertiary vertex
- Efficiency calibrated in independent analyses for the three flavours of jets



Electron/photon energy calibration

Schematic overview of the procedure used to calibrate the energy response of electrons and photons in ATLAS.



- S. Morgenstern, "*Electron and photon energy measurement calibration with the ATLAS detector*"