Probing perturbative QCD at the ATLAS experiment

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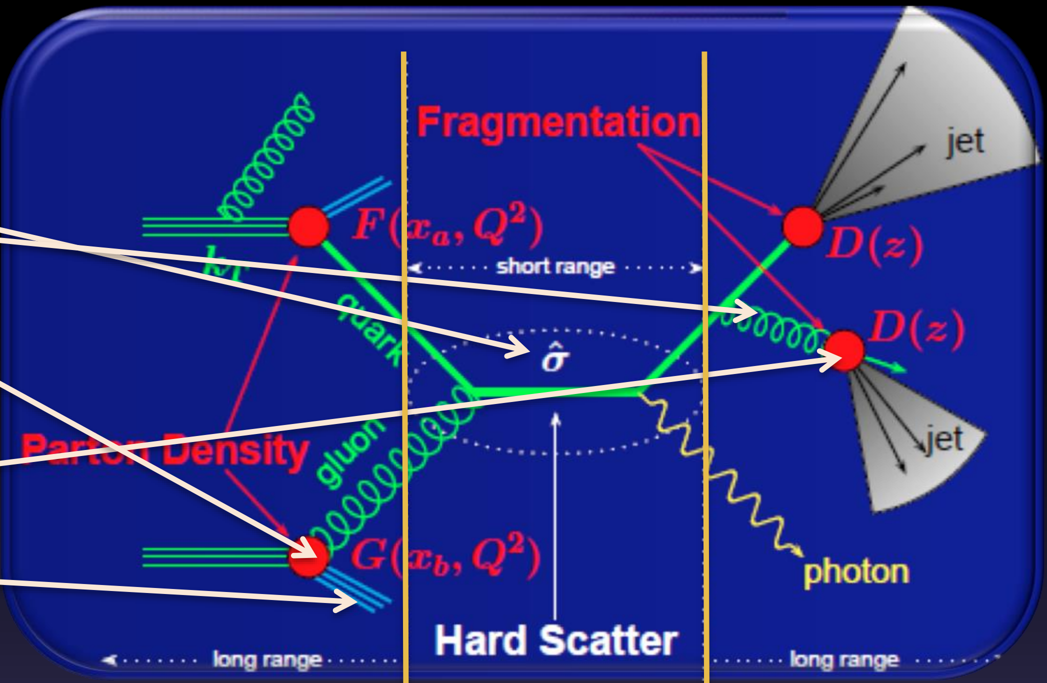
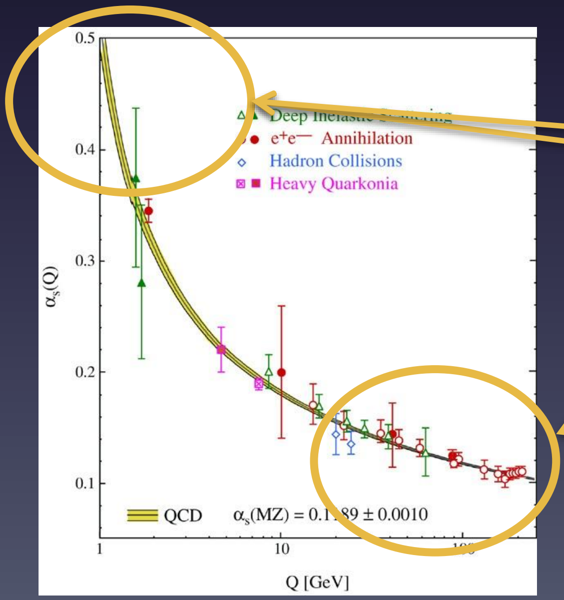
Introduction

The strong interaction intervenes in various ways and at various scales in every single event at the LHC

- Matrix element of interest $(\hat{\sigma})$
- Gluon emission (ISR/FSR)
- Proton structure (F,G)
- Fragmentation and hadronization (D(z))
- Underlying event





Long distance physics

Short distance physics

Long distance physics

We can make robust predictions!

Not covered today

ATLAS measurements: correlations and decorrelations in multijet events

- Multijet Energy-Energy Correlations: *Eur. Phys. J. 77 (2017) 872*
- Dijet Azimuthal Decorrelations: *Phys. Rev. D 98 (2018) 092004*

Motivation

- Multijet energy-energy correlations can be used to:
  - Extract a measurement of $\alpha_s(m_Z)$
  - Test α_s running (QCD β-functions) and fixed-order calculations used in Renormalization Group Equation at various (large) energy scales
  - Test NLO predictions on multijet processes
  - Test parton shower models in multijet predictions and tune generators
  - It can even be sensitive to new physics
    - New colored fermions modifying β-functions

The observables

- The TEEC observable is defined as the transverse energy-weighted angular distribution of jet pairs in a multijet event
  - It is infrared safe quantity with small 2nd order corrections
  - Precisely measured
  - Can be used to get α_s at various Q-scale: use $Q=H_T/2$

- The asymmetry between the forward and backward part of TEEC can also be measured (ATEEC).
  - Even better mitigation of scale uncertainties because scales are not asymmetric in cosϕ.

TEEC:

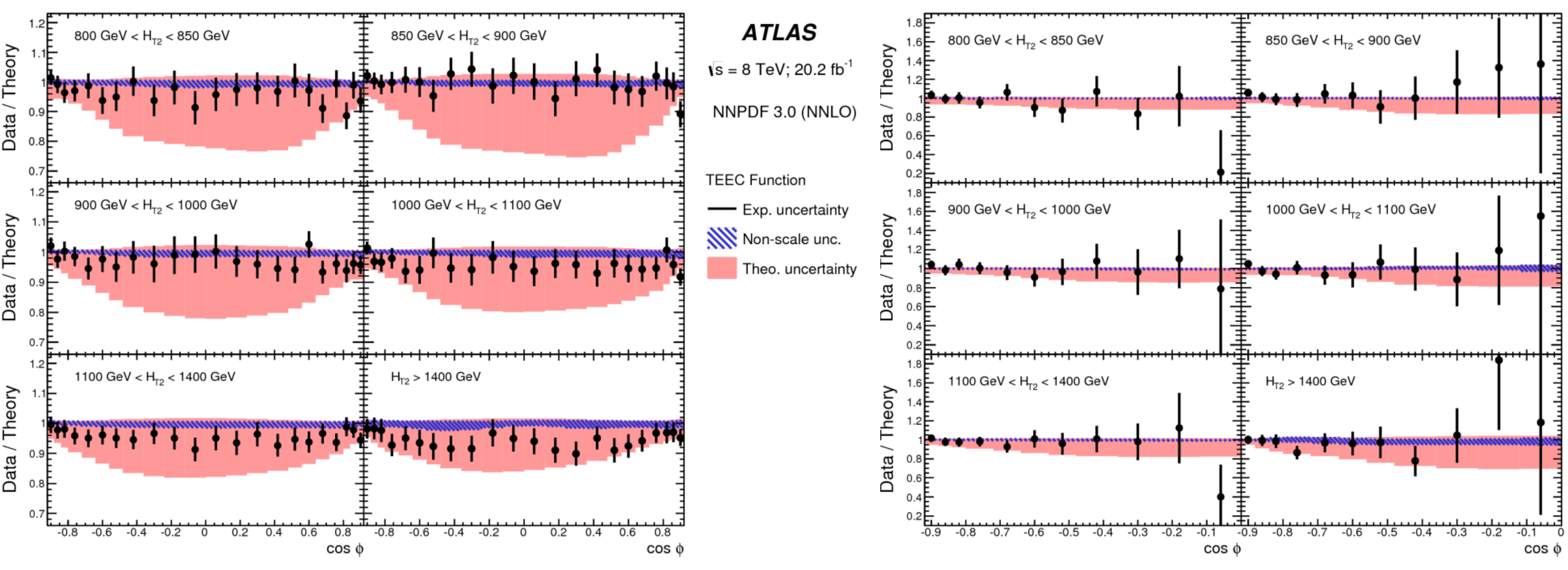
$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi} \equiv \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\mathrm{T}i}E^A_{\mathrm{T}j}}{\left(\sum_k E^A_{\mathrm{T}k}\right)^2}\delta(\cos\phi-\cos\phi_{ij})$$

ATEEC:

$$\left.\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\right|_{\phi} - \left.\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\right|_{\phi-\pi}$$

N: events in a cosϕ bin,
ij :jet pairs, ϕ_{ij} is ϕ_j-ϕ_i

- NLOJet++ provides an excellent description of both TEEC and ATEEC for most of the kinematic regions probed
  - Little disagreement for TEEC at high H_T
- Scale uncertainties are much smaller for ATEEC
  - Indicate a too large estimate of higher order effects in TEEC
- Both measurements can be used to extract α_s, with higher expected precision for $\alpha_s(Q^2)$ from ATEEC

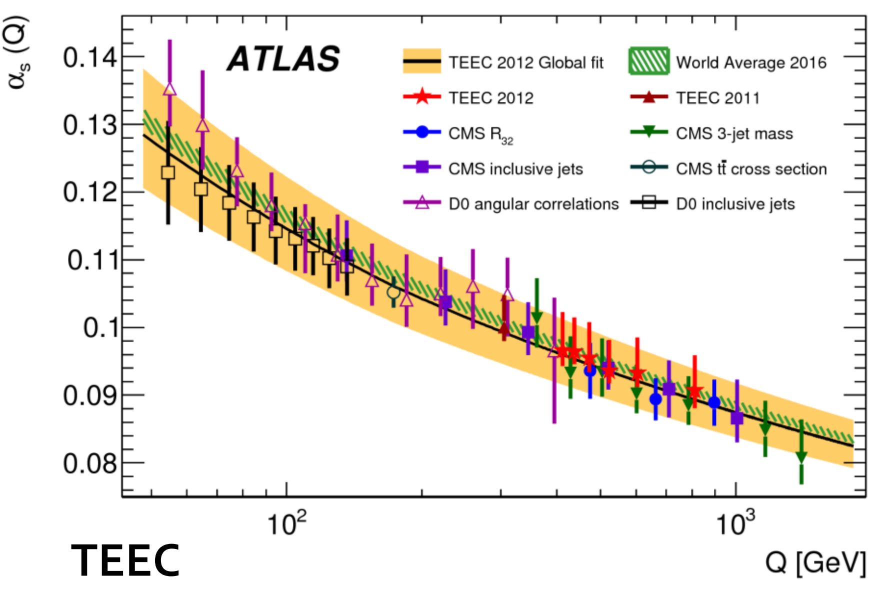


- $\alpha_s(m_Z)$ is obtained from a χ^2 minimization in each bin of H_T with the various sources of systematics as nuisance parameters
  - Assuming RGE, $\alpha_s(m_Z)$ measured in each H_T bin are evolved to $Q=H_T/2$ to get $\alpha_s(Q)$

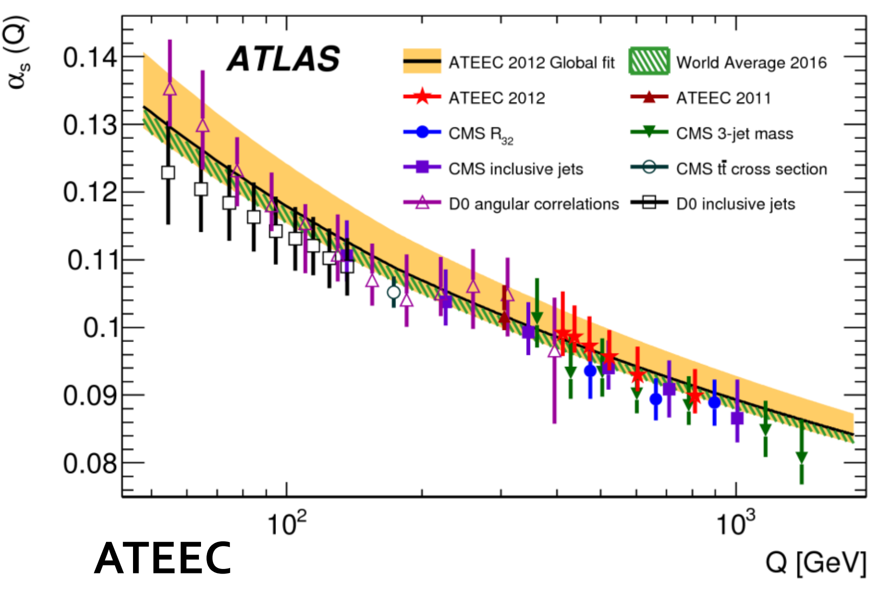
- Results are:
  - Consistent with world average
  - More precise than other hadron collider results

TEEC: $$\alpha_S(m_Z) = 0.1162 \pm 0.0011\,(\mathrm{exp})\,{}^{+0.0076}_{-0.0061}\,(scl) \pm 0.0018\,(pdf) \pm 0.0003\,(np)$$

ATEEC: $$\alpha_S(m_Z) = 0.1196 \pm 0.0013\,(\mathrm{exp})\,{}^{+0.0061}_{-0.0013}\,(scl) \pm 0.0017\,(pdf) \pm 0.0004\,(np)$$



TEEC



ATEEC

Dijet Azimuthal Decorrelations:

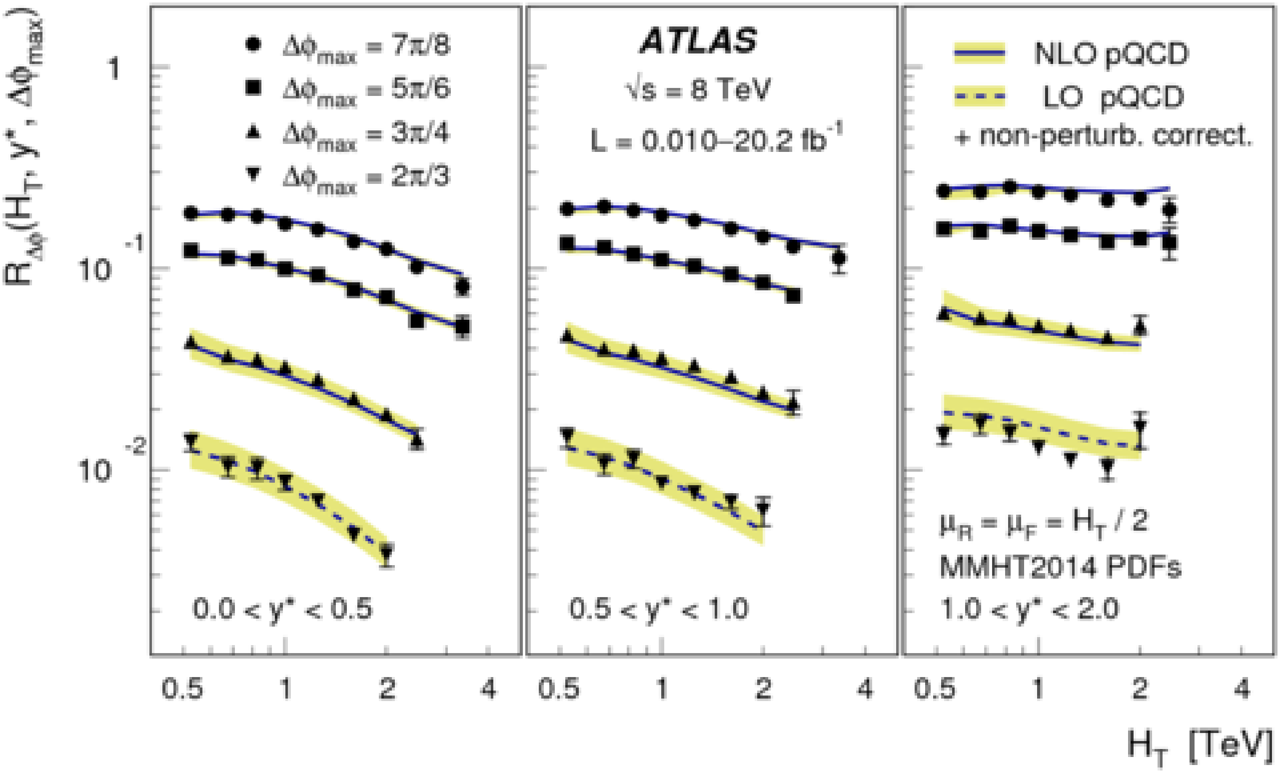
- Difference in the azimuthal angle between the two leading jets in multijet events is sensitive to higher order corrections
  - If $N_{jets} = 2$: $\Delta\phi_{dijet} = |\phi_{j1} - \phi_{j2}| = \pi - \varepsilon$ (LO predictions)
  - If $N_{jets} = 3$: $\pi > \Delta\phi_{dijet} > 2\pi/3$ (1st radiation corr.)
  - For $\Delta\phi_{dijet} < 2\pi/3$, $N_{jets} \geq 4$ (higher order corr. and PS)

- The ratio of 2 of the above measurements can be used as a precise alternative to extract α_s
  - To be measured as a function of $Q = H_T$, y^*, and $\Delta\phi_{max}$

$$R_{\Delta\phi}(H_T, y^*, \Delta\phi_{\max}) = \frac{\dfrac{d^2\sigma}{dH_T dy^*}(\Delta\phi_{dijet} < \Delta\phi_{\max})}{\dfrac{d^2\sigma}{dH_T dy^*}(\Delta\phi_{dijet} < \pi)}$$

- NLO predictions describe very well the data for all H_T and y^* when the event topology is dominated by 3-jets events
  - Stringent pQCD test

- The 4-jets dominated region ($\Delta\phi_{max} < 2\pi/3$) can only be obtained at LO, but $R_{\Delta\phi}$ is well-describes



Small tension with at larger y^*

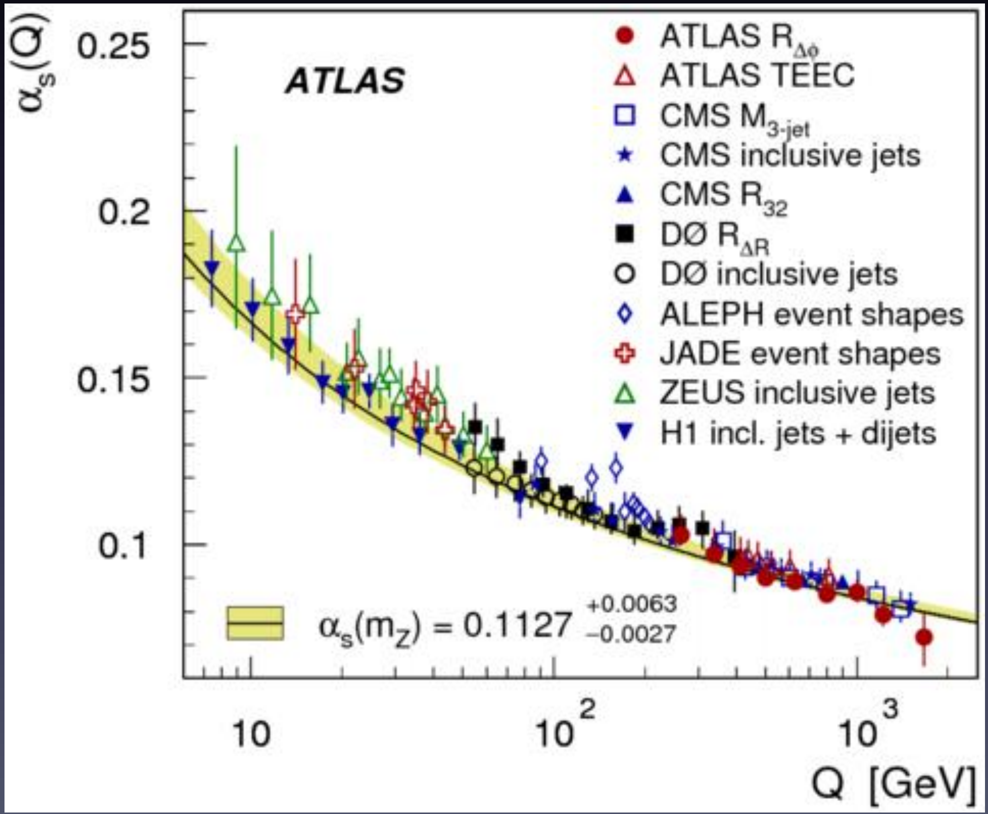
- Large scale uncertainties
- Impact of non-resummed large logs?

- Strategy to extract $\alpha_s(Q)$ similar to what was used in (A)TEEC.

$$\alpha_S^{R_{\Delta\phi}} = 0.1127 \pm 0.0005\,(stat)\,{}^{+0.0018}_{-0.0017}\,(\mathrm{exp}) \pm {}^{+0.0060}_{-0.0020}\,(theo)$$

$$\alpha_S^{World} = 0.1181 \pm 0.0011$$

- Results:
  - Extend test of RGE up to Q = 1.6 TeV
  - Consistent with world average at $Q=M_Z$
  - Small tension in the running (shape)
    - Disappear if Q=262.5 GeV is ignored



ATLAS measurements: prompt photon cross sections

- Isolated photon plus jets: *Phys. Lett. B 780 (2018) 578*
- Isolated photon plus heavy-flavor jets: *Phys. Lett. B 776 (2018) 295*

Note: Results of a triphoton cross section measurement and an inclusive isolated photon cross section ratio measurement are presented in back-up slides. You can also ask me questions about these…

γ+jets: Motivation

- Studying prompt* photon production allows to test:
  - Hard scatter ME calculations and their dynamic
  - QED emission from high-p_T jets (fragmentation)
  - Tune MC

- Compare LO and NLO predictions to measured observables *O*
  - If X = jets, then $O = E_T^{\gamma}$, P_T^{jet}, $m^{\gamma\text{-}jet}$, $\Delta\phi_{\gamma\text{-}jet}$ and $|\cos\theta^*|$

*Prompt photons = all photons not coming from hadron decay

γ+jets: Different contributions

- $|\cos\theta^*|$ indicates, at LO, the relative contribution from hard scatter and softer quark fragmentation effects
  - t-channel quark exchange -> hard scatter

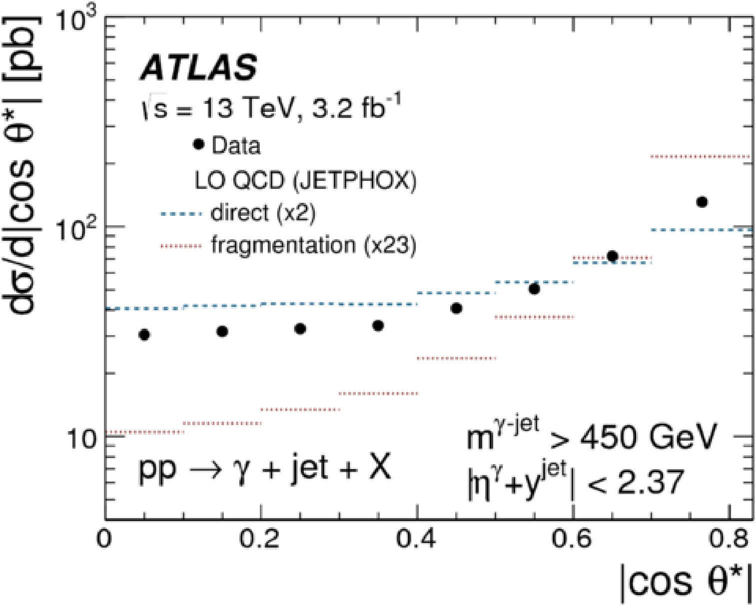
$$qg \to q\gamma \Rightarrow \quad \frac{d\sigma}{d\cos\theta^*} \xrightarrow{|\cos\theta^* \to 1|} (1-|\cos\theta^*|)^{-1}$$

  - t-channel gluon exchange ->dijet + frag.

$$q\bar{q} \to q\bar{q}[\gamma] \Rightarrow \quad \frac{d\sigma}{d\cos\theta^*} \xrightarrow{|\cos\theta^* \to 1|} (1-|\cos\theta^*|)^{-2}$$

  - s-channel: both effects are non-singular

$$\cos\theta^* = \tanh(\frac{\Delta y}{2}), \qquad \Delta y = |y_\gamma - y_{jet}|$$



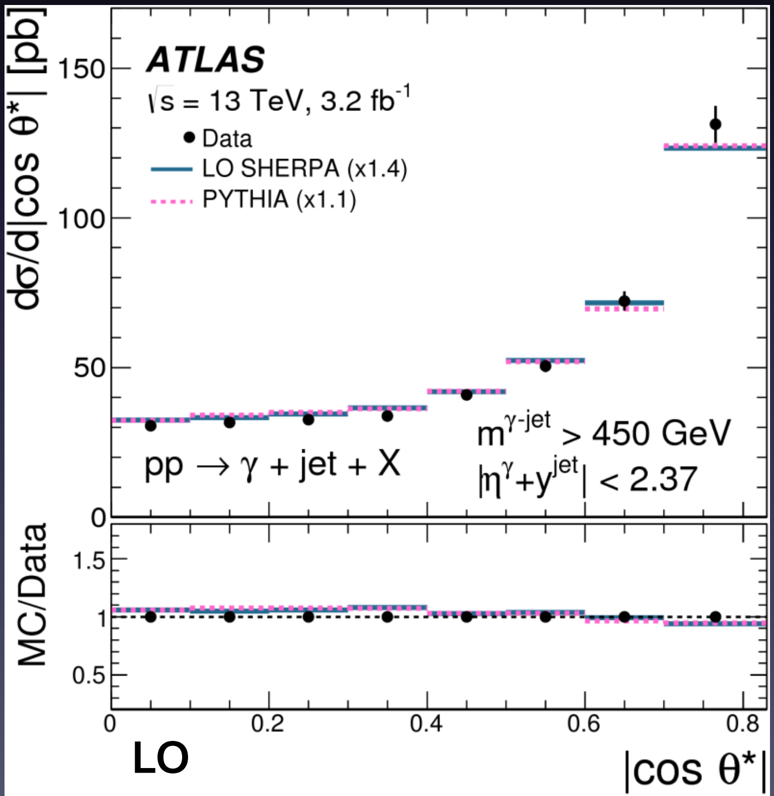
Frixione Isolation on γ:

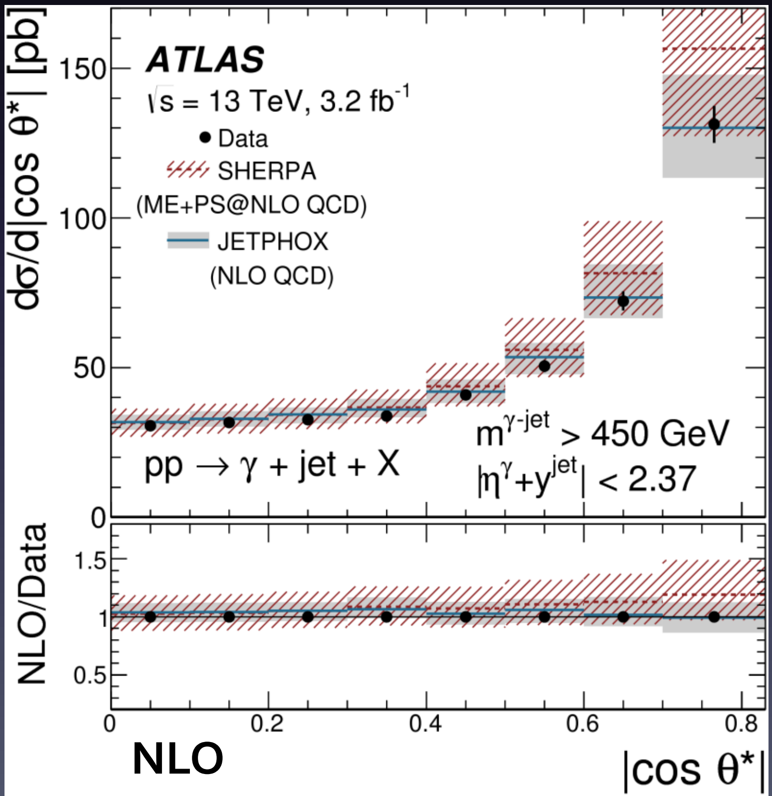
To regularize collinear divergences in ME, and constraints fragmentation :

$$E_T^{\max}(R) = \varepsilon E_T^\gamma \left[\frac{(1-\cos R)}{1-\cos R_0}\right]^n \qquad R < R_0 = 0.3$$

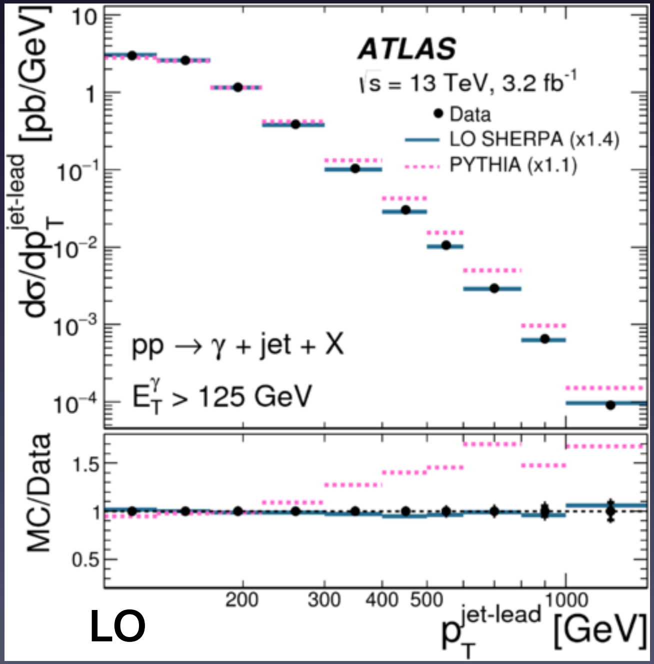
Also help suppressing π^0, η bkg.

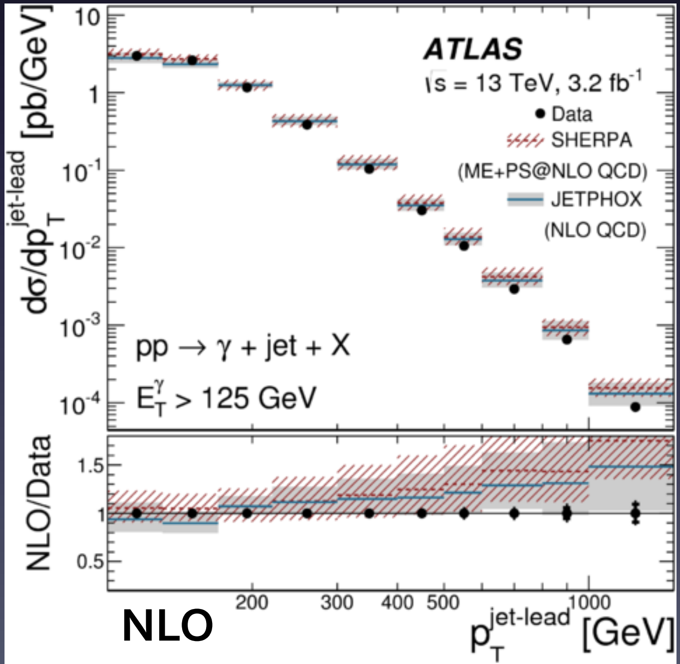
- Both LO and NLO describe well the composition of γ+jets in terms of hard scatters and softer QED emission
  - Good description of photon bremsstrahlung both from QED FSR and from ME calculation
    - LO predictions are normalized to the measured cross section value
    - Scale uncertainties only included for NLO (dominant systematic)





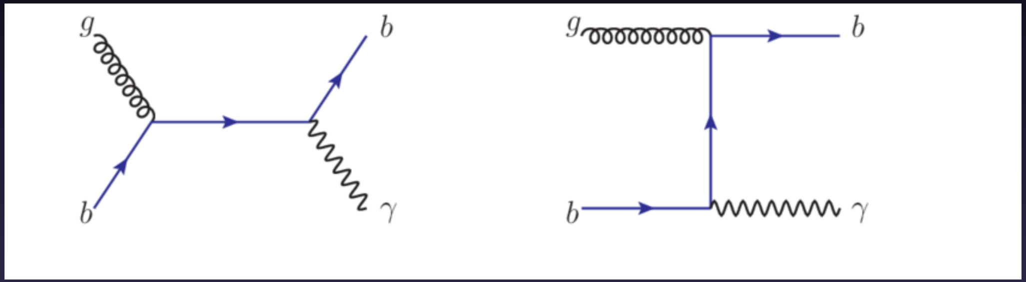
- Excellent shape description from LO SHERPA but agreement spoiled at large p_T^{jet} when higher order corrections are added.
  - NNLO corrections?
    - E_T^{γ} is well described at both LO and NLO so it is a QCD issue…
    - JETPHOX has no PS correction and agrees a little bit better
- Pythia has too large γ-brem from tune for harder jets





γ+HF-jets: Motivation

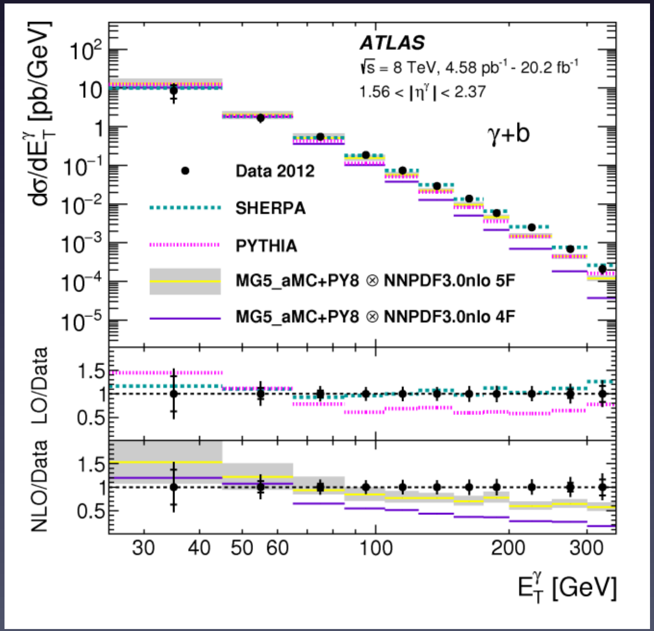
- Study the heavy flavor (HF) content of the proton
- Treatment of massive quarks in ME calculations
  - 5 flavor scheme: $m_{c,b} = 0$ in ME, initial b-line from PDF
    - Large log resummed in DGLAP



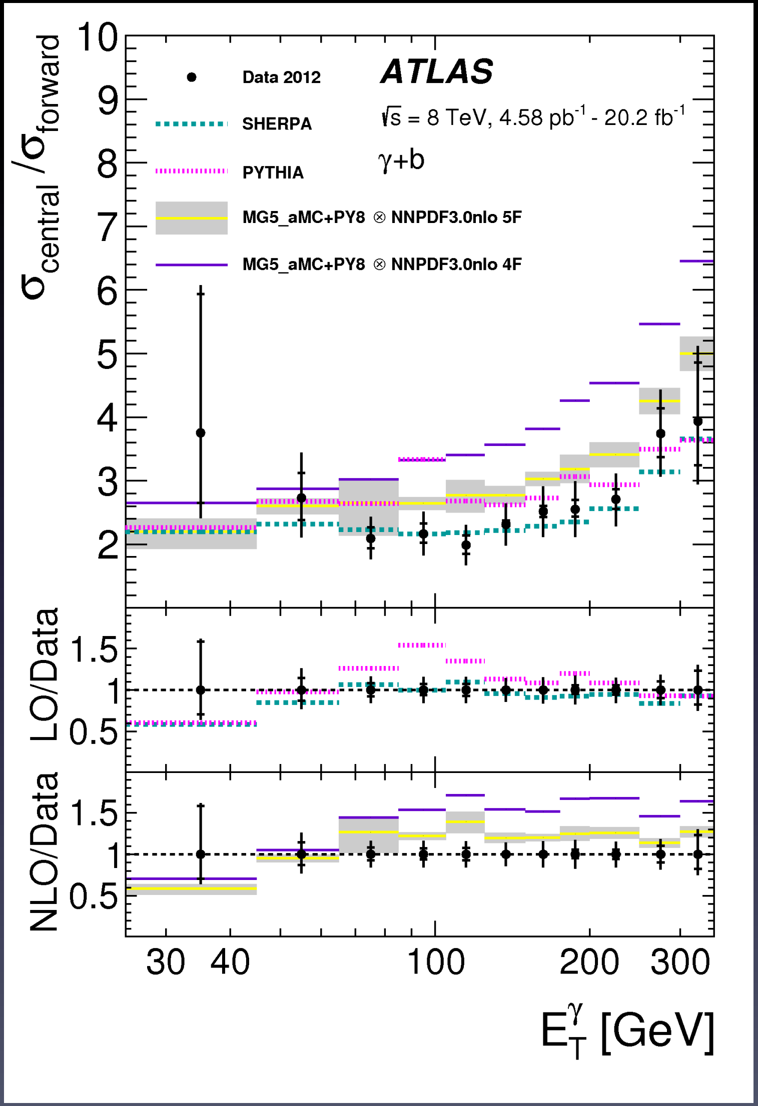
  - 4 flavor scheme: $m_b \neq 0$ in ME so only 4 flavors in PDF, b-quark obtained from gluon-splitting in ME
    - Introduces non-resummed large $\log(Q^2/m_b^2)$ when Q is large
- Mass of c- and b- quarks in PS spoils "resummation"?

- SHERPA gives a near perfect description of the E_T^γ at all y^γ
  - Significant tensions with (2->2) LO PYTHIA (5FS m_b=0 in ME)

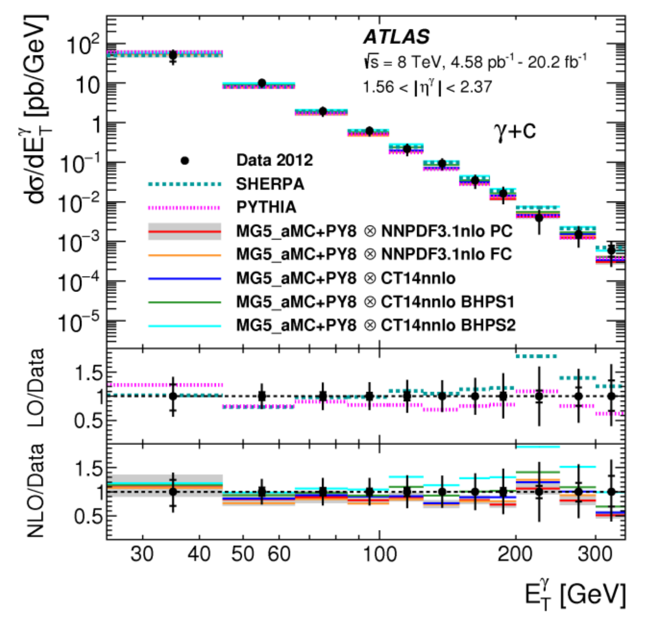
- NLO+PS don't describe high E_T^γ, but 5 FS agrees better than 4 FS
  - Fails where $\log(Q^2/m_b^2)$ are large
  - Gluon-splitting, modeled at LO, dominates over Compton at high E_T^γ due to steeply falling PDF.



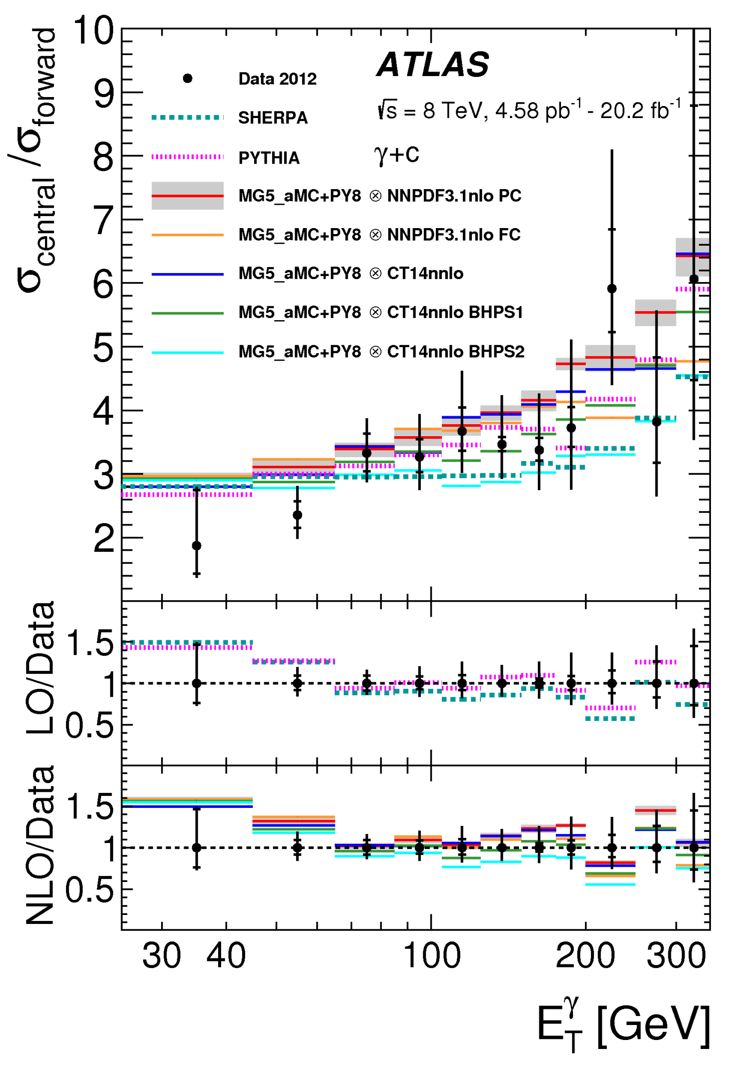
γ+b



- Agreement between data and NLO+PS predictions much better than for γ+b because gluon-splitting process is relatively less important at probed E_T^γ
  - Larger PDF and electric charge
  - Gluon-splitting comparable to γ+b for E_T^γ>~ 700 GeV
- Even if not enough precision to infirm intrinsic-charm, tensions with BHPS2 indicate that IC<2.1%



γ+c



Conclusion

- ATLAS performed comprehensive studies of pQCD effects in multijets and prompt photon events
  - Sensitive to NLO ME, FSR, photon fragmentation

- Precise measurements of α_s have been obtained
  - Extend the range of Q^2 at which it is observed
  - Most precise hadron collider measurement: ATTEC
  - Good agreement with world average

- From multijet measurements
  - NLO 3-jets well described, but PS must be tuned on these data

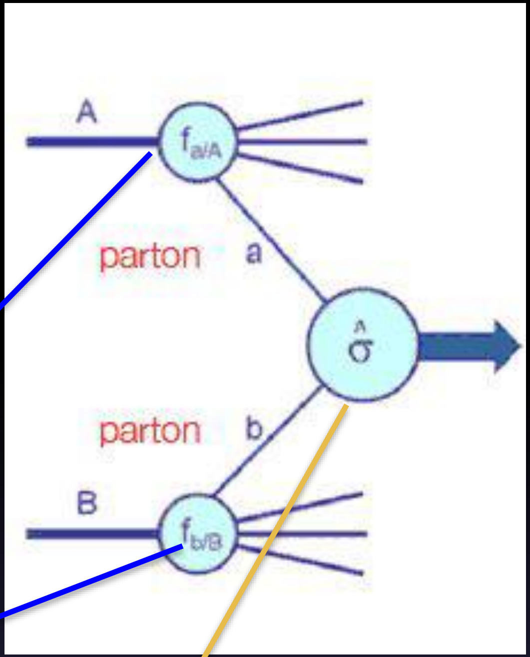
- From γ+(b)-jets:
  - Understand the interplay of hard scatter and fragmentation
  - Gluon-splitting mismodeling, worse in 4 FS than 5 FS
  - Some tensions with high intrinsic charm contribution to proton

Back-up slides

Factorization theorem:

The probabilities for short-distance and long-distance processes factorize

The long-distance factors are universal and can be empirically obtained from ancillary measurements.



$$d\sigma(P_1,P_2)=\sum_{i,j,k}\int dx_1\,dx_2\,dz\,f_i(x_1,\mu_F)f_j(x_2,\mu_F)D_{k\to H}(z,\mu_F)$$
$$\times\, d\tilde{\sigma}_{ij\to k+X}(p_1=x_1P_1,p_2=x_2P_2,p_k=P/z,\alpha_S(\mu_R),Q^2,\mu_R,\mu_F)$$

Evolution equations (e.g. DGLAP), analogous to β-functions for α_S, account for transition from one scale to the other

These QCD predictions involve assumptions, approximations, and phenomenological modeling impacting final state selections and differential cross section predictions

Parton shower accounting for the effect of evolution on final states:

- Soft and collinear approximations (where QCD radiation is enhanced)
- Leading order kernel functions
- Choice of ordering parameter

Parton distribution function (PDF):

- Uncertainties on measurements used to extract structure functions
- Modeling of structure functions at Q_0

$$F(x,Q_0) = A_1 x^{A_1}(1-x)^{A_2} P(x;A_3)$$

Fragmentation function:

- Gaussian modeling of D(x,s) at small x
- Supplemented by hadronization model

$$D(x,s) \propto \exp\left[-\tfrac{1}{2\sigma^2}\left(\xi-\xi_p\right)\right]$$

$$\xi \equiv \ln\left(\tfrac{1}{x}\right), \quad \xi_p \cong \tfrac{1}{4}\ln\left(\tfrac{s}{\Lambda^2}\right),$$

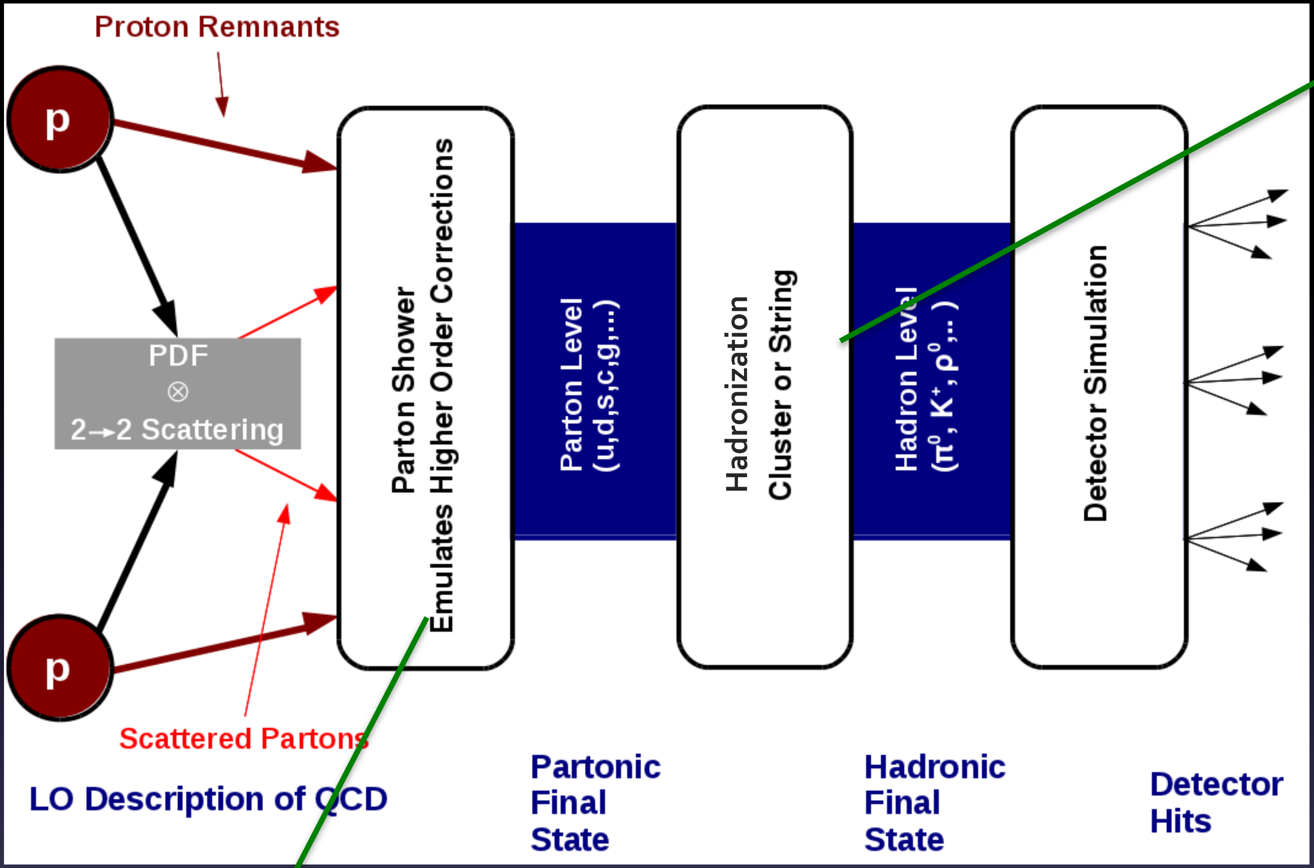
$$\sigma \propto \left[\ln\left(\tfrac{s}{\Lambda^2}\right)\right]^{3/4}$$

Various QCD effects are often modeled differently by theorists, and are implemented in their generator. Measurements test the accuracy of modeling choices. There are also overlaps.

Generator	Features	Comments
SHERPA 1.4	ME up to 5 partons, with C-S dipole shower,CKKW matching, cluster frag., 5FS (with $m_b \neq 0$)	CT10 PDF, NLO norm.
PYTHIA	LO 2->2 ME, PT-order dipole shower, 5FS, Lund string frag., AU2 and A14 tunes	PHOTOS, LO PDF (CT10)
Herwig++	LO 2->2, angular-order shower, cluster frag., UE-EE tunes	LO PDF (CTEQ6L1)
Sherpa 2.2	NLO up to 2 partons, LO up to 3 add. Partons, MEPS@NLO merging,	YFS QED resum., features of 1.4.
MadGraph	Pythia 8.2 , NNPDF23NLO	4-jet tree-level +PS or 2-jet NLO+PS, CKKWL matching/FxFx merging, A14 PS tune
NLOJET++	NLO 2->3, no npQCD effects, no PS (inf.-red sing. Removed with C-S dipole,) and no resum.	NNLO PDF with same as in ME, corrections from Pythia 6
JetPhox	Full NLO pp->γ+jet+X (direct + frag.), n_f=5, NLO frag from BFG module, no PS, no npQCD corr.	NNLO PDF, npQCD corr from Pythia 6, photon iso.

Non exhaustive list of features and options

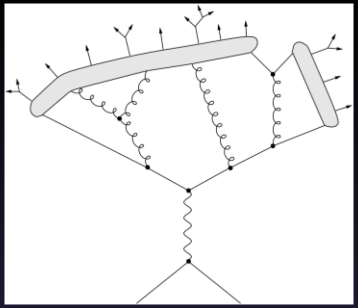
Pythia (8.175) vs Herwig++ (2.63)



Hadronization:

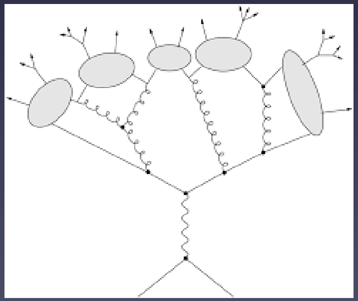
Lund string

(linear confinement)



Cluster

(preconfinement)



Showers ordering:

(nLL resummation)

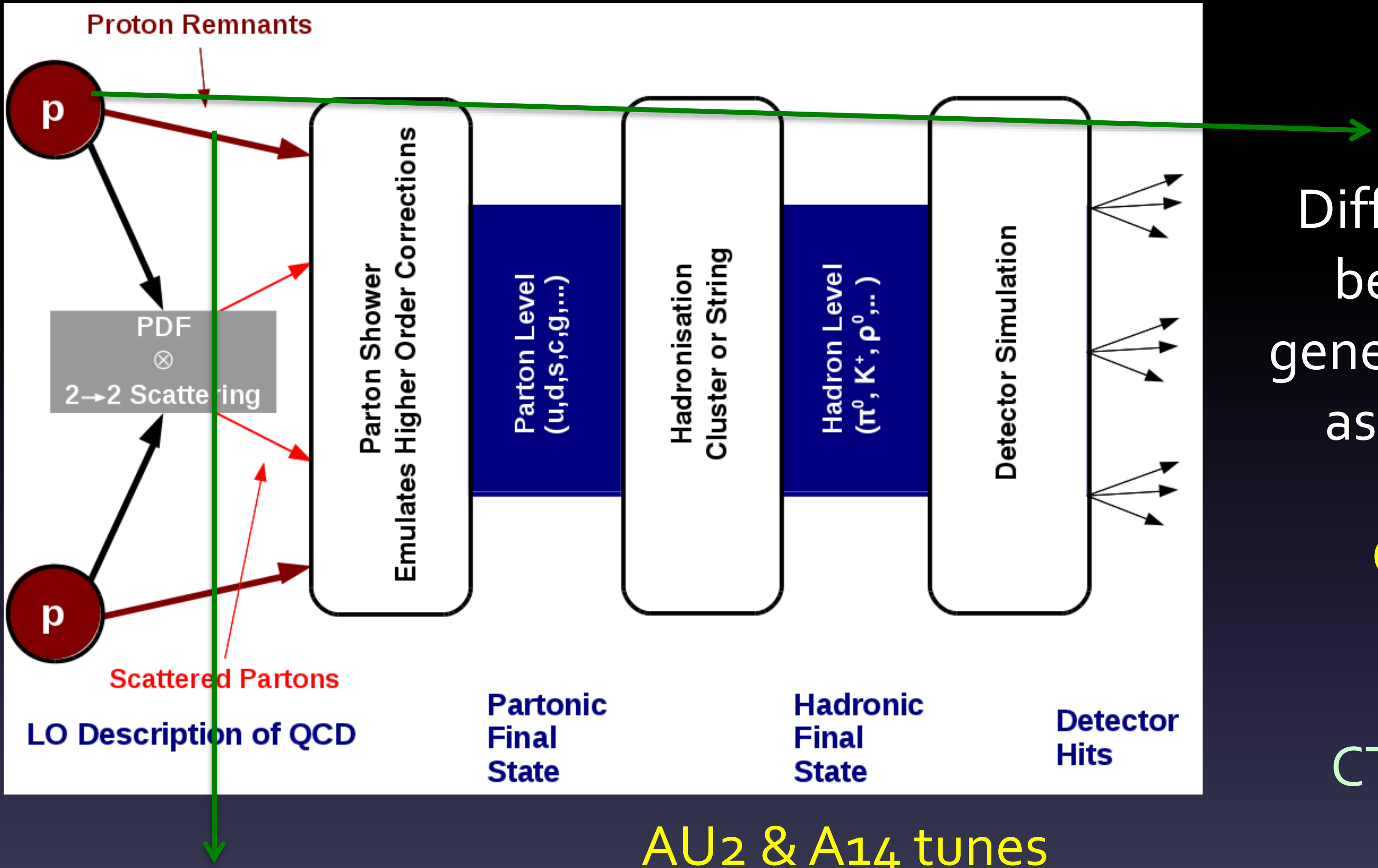
pT-ordered showers

(natural for a shower partly based on dipole approach)

angular-ordered showers

(deal with quantum interference)

Pythia (8.175) vs Herwig++ (2.63)



PDF:
Different can be used in generators, but as **default**:

CT10
(NLO)

CTEQ6L1
(LO)

Multiple interactions:
(Each generator is tuned for different PDF on Run-1 ATLAS data)

AU2 & A14 tunes
(Many parameters)

EE3-EE5 tunes
(Fewer parameters)

Measuring observables sensitive to these effects allows to:

- Determine best model/calculations for predictions
- Tune fragmentation and FSR parameters or PDF fit.

It is however important to keep in mind that many of these different QCD effects are intertwined with each others

- Hard to disentangle them in a measurement, to know exactly which effect is mismodeled in a prediction and why.
- Accuracy (validity) of the modeling of each effect can vary with event topology, kinematic observable, and phase space selection

Efforts are made to measure quantities that minimizes the impact of some of these effects, while enhancing the sensitivity to some others.

Measuring α_s

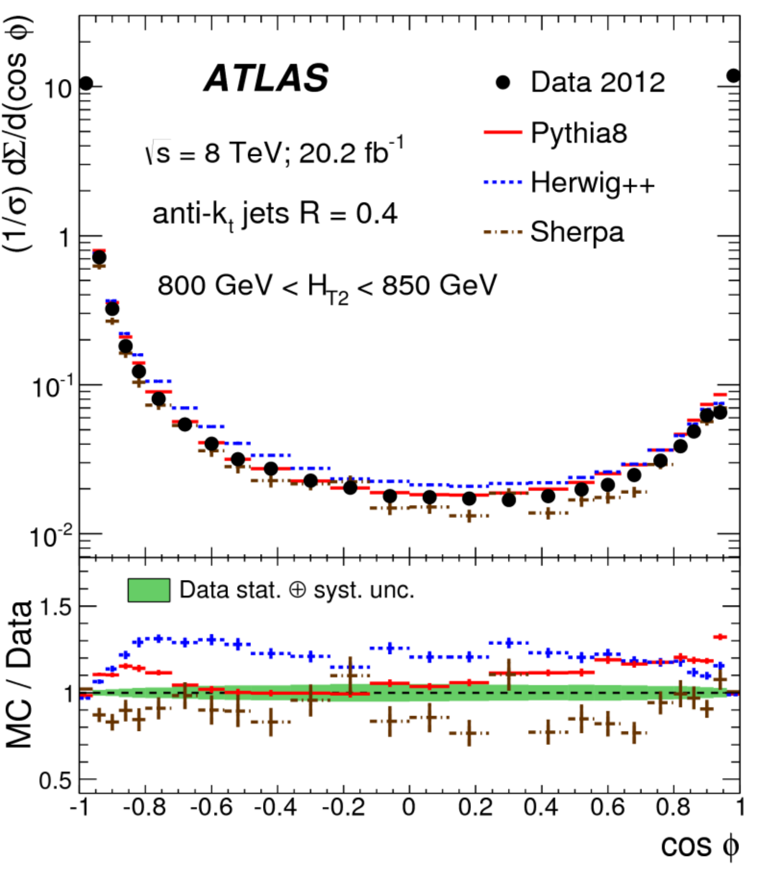
- Precision on α_s impacts all pQCD predictions because ME, PS and PDF all depend on α_s
  - PDF also depends on RGE

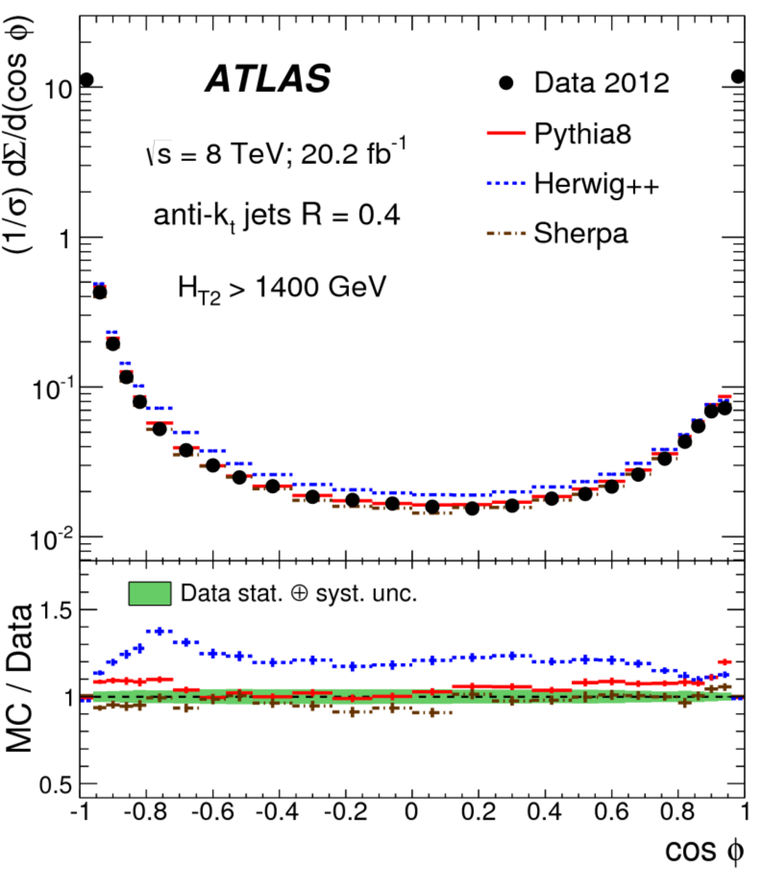
- However, a value of α_s extracted from $d\sigma/dX$ measurements depend on ME, PS, and PDF, used at different scales
  - α_s and the RGE are assumed in the input of the measurement
  - results in larger uncertainties (smaller sensitivity) to pQCD.
  - Precision on α_s is also limited by large scale uncertainties

- Cannot get α_s in a fully model independent way, but PS and PDF dependence can be suppress by using ratios to extract α_s
  - e.g. Can use $R_{3/2}$ the ratio of trijet to dijet cross sections

Comparing TEEC measurement results to tree-level predictions

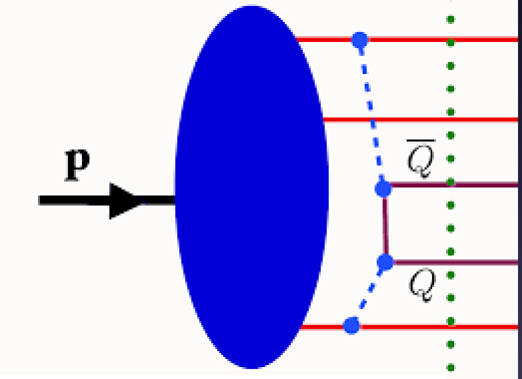
- LO 2->2 ME are sufficient to provide a good description of the data
  - Pythia describe the data as well if not better than Sherpa 1.4
- Dipole showers provide a much better model of TEEC than the angular-ordered Herwig++ shower





γ+B-jets: Motivation

- Study the heavy flavor (HF) content of the proton
  - Extrinsic component where HF follows from PDF evolution
  - Intrinsic component which would consist on a non-pQCD HF contribution to PDF
    - Has never been observed before but was hypothesized by Brodsky et al. (1980)
    - A model (BHPS) with various level of intrinsic charm (IC) contribution (0.6% and 2.1%) is available through LHAPDF
    - Larger effect expected at large Bjorken-x, so intrinsic HF contribution is enhanced when selecting high η^{γ} and E_T^{γ}
    - Since $m_b >> m_c \sim \Lambda_{QCD}$, b-quark can more accurately be perturbatively included in PDF, so IC is expected to be larger.

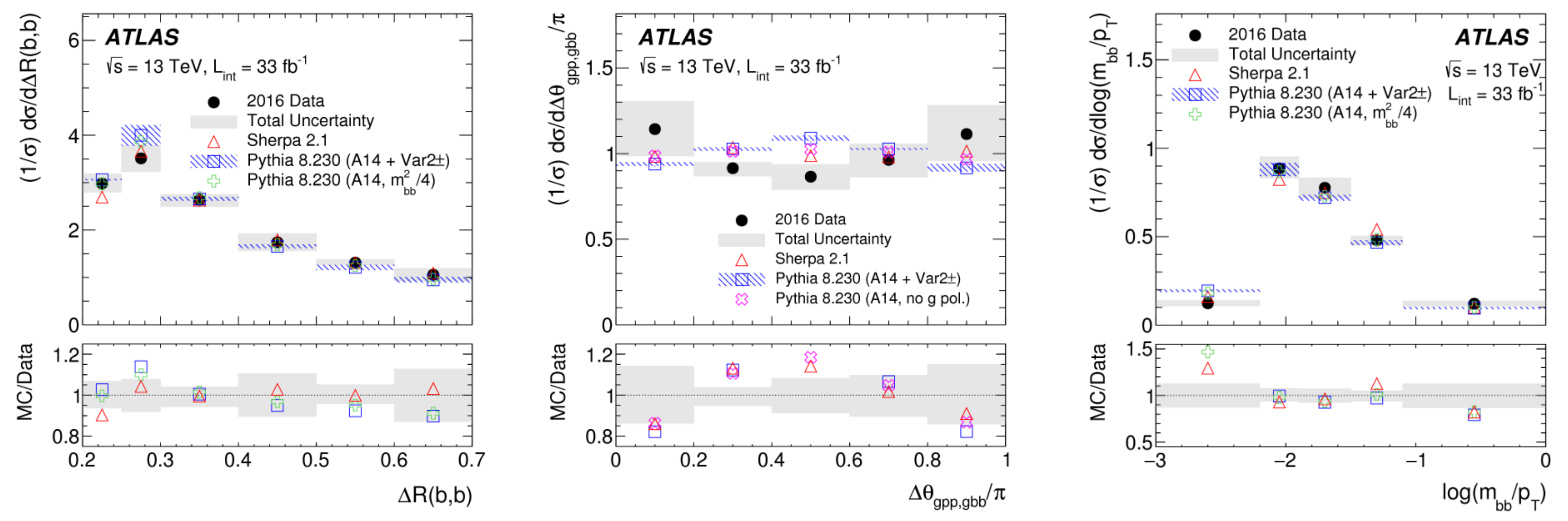


Five-quark Fock state |uudQQ> of the proton at the origin of IC .

Adv.High Energy Phys. 2015 (2015) 231547

Gluon splitting (g→bb)

- Gluon splitting to b-quarks in PS is mismodeled because $m_b \neq 0$ removes singularities of QCD splitting functions
- A dedicated ATLAS measurement tested small-angle gluon splitting to b-jets
  - R=1.0 groomed jets selects gluons-jets while R=0.2 b-tagged track-jets are used for b-jets

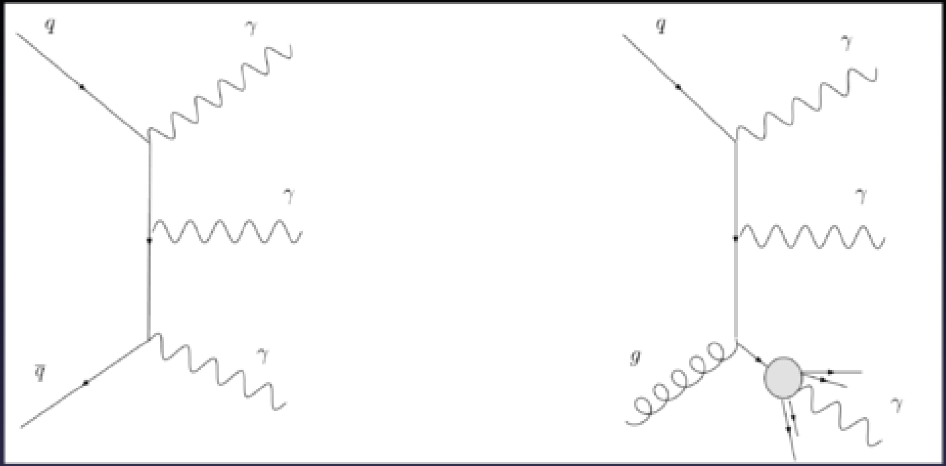


Further ATLAS photon + X measurements

- Three isolated photons: *Phys. Lett. B 781 (2018) 55*
- Inclusive isolated photon ratios **arXiv:1901.10075 [hep-ex]**

Triphoton: Motivation

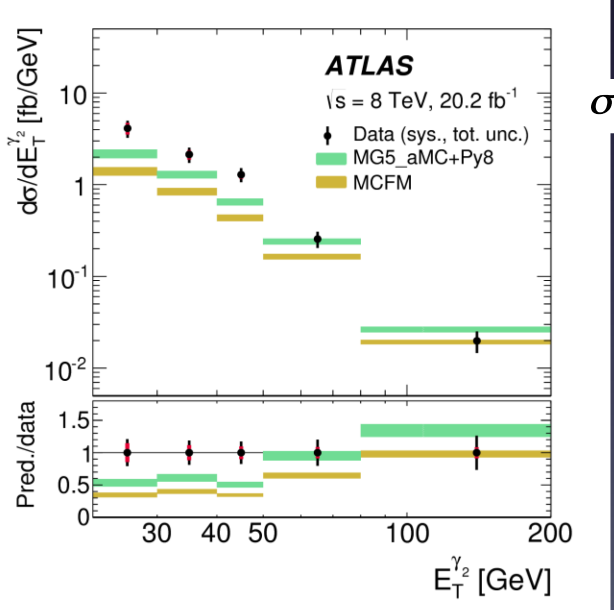
- Similar motivation as γ+jets measurements, but in more extreme final states
  - Hard process: qqbar->$\gamma\gamma\gamma$.
  - Frag: qg->$\gamma\gamma$q[γ] (QED ISR and/or FSR from PS)



- Used in BSM searches
  - X_0+γ where X_0 could be a KK-graviton, or a pseudoscalar decaying to a pair of photons

Triphoton: Results

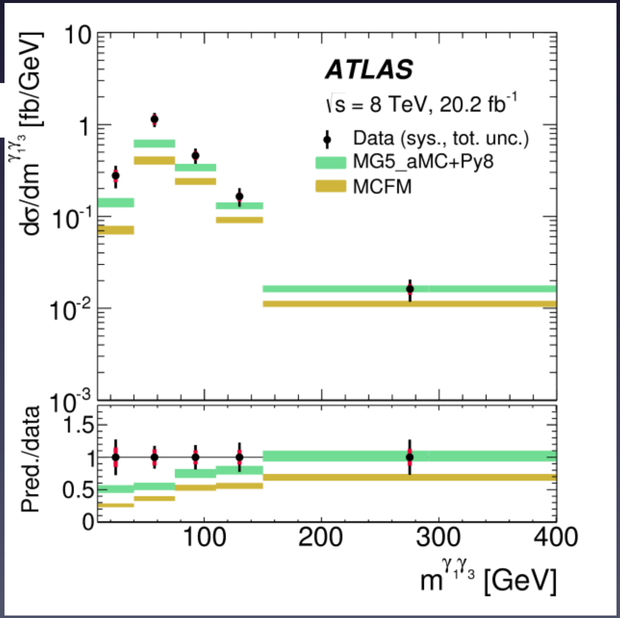
- Total cross section in large disagreement with predictions, but some shape discrepancies too
  - MadGraph and MCFM don't agree but have similar shape
    - Likely not a PS effect because MCFM has no PS, but shapes are similar.
  - NLO EWK corrections are small and don't explain the discrepancy
  - Similar issues observed in $\gamma\gamma$, $W\gamma\gamma$ and $Z\gamma\gamma$, but NNLO corrections significantly improved the data-prediction agreement in $\gamma\gamma$.



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

$$\sigma_{MCFM} = 31.5^{+3.2}_{-2.5}\ fb$$

$$\sigma_{MG5} = 46.6^{+5.7}_{-3.6}\ fb$$



Inclusive γ cross section ratios

- Important lost of sensitivity to pQCD effects in photon production measurements due to scale uncertainties

➡ Measure $R^{\gamma}_{13/8}$ as a function of different observables

  - Predictions available at NLO

- The distribution of this ratio can further be normalized on the $R^{Z}_{13/8}$ measured value obtained by ATLAS
  - $R^{Z}_{13/8}$ (meas.) = 1.537 ± 0.001 (stat.) ± 0.010 (syst.) ± 0.044 (lumi.)
    - Agreed with predictions calculated at NNLO

Inclusive γ cross section ratios

- Generally good description of data by NLO predictions
  - Some hint of tensions for high and low (~125 GeV) E_T^γ
    - Not very consistent between η^γ regions, and need more stats.
  - Near perfect agreement for forward photon
- Normalizing on $R^Z_{13/8}$ doesn't change the results