Perspectives on multi-jet /photon+jet /multi-photon physics

H. Jung (DESY) (for ATLAS + CMS)

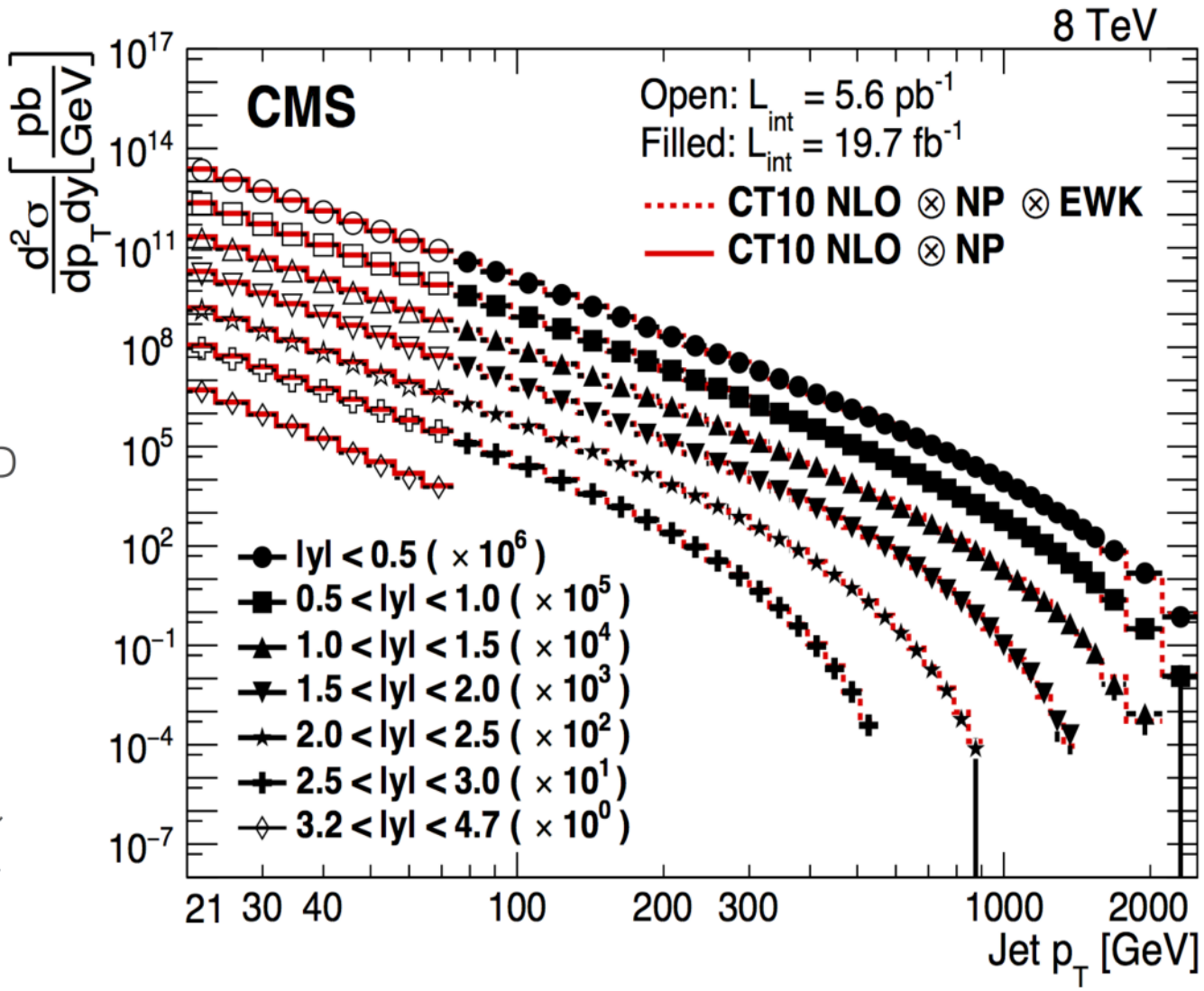
- Inclusive Jets as a benchmark for Jet physics
- Correlations in multi-jet events
  - beyond fixed order calculations
- Multi-photon measurements
  - need for parton-shower resummation
- Photon+jets

Inclusive Jet measurements

Inclusive jets at 8 TeV (CMS)

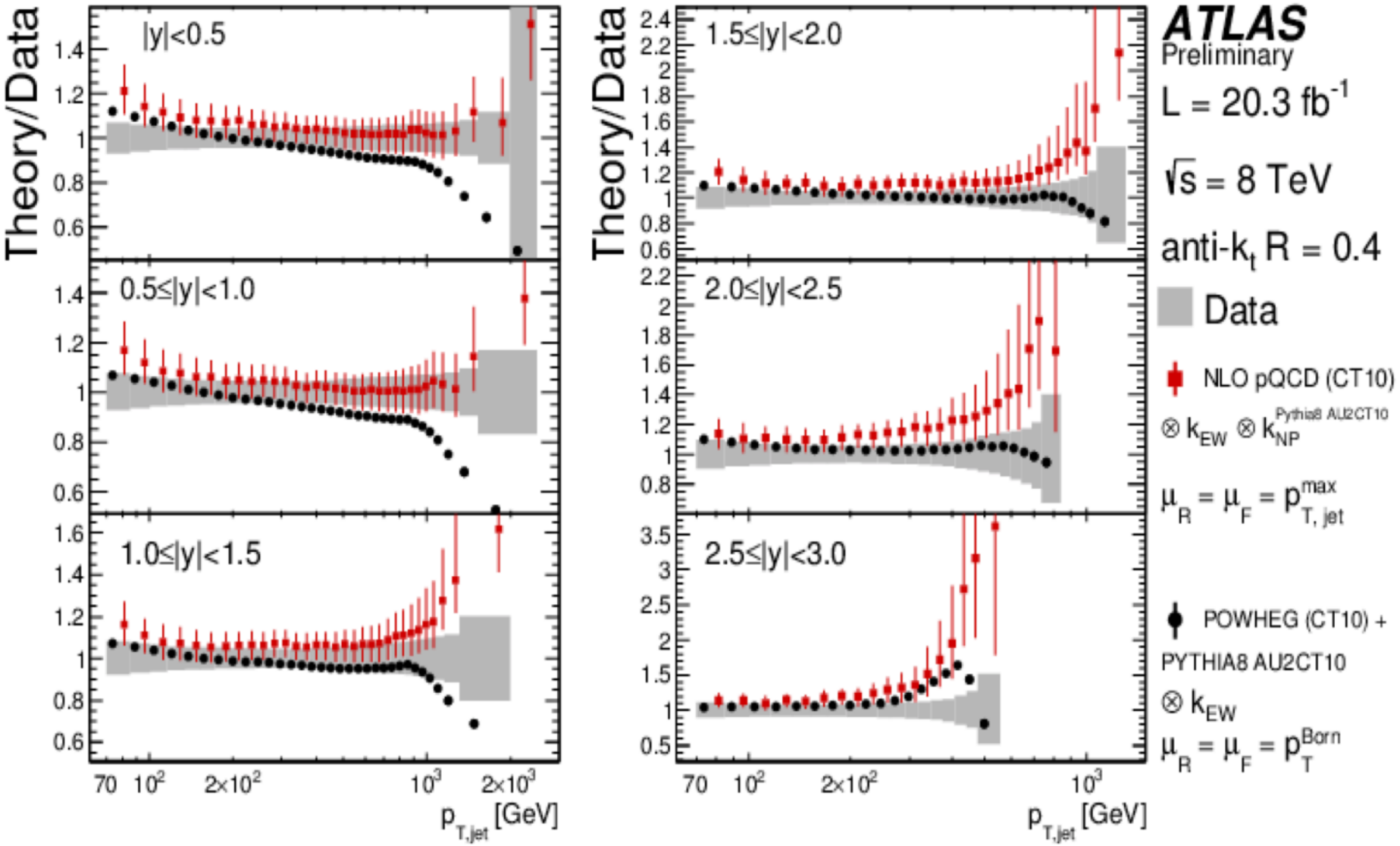
- Inclusive jets within $0 < |y| < 4.7$ and $p_T \geq 21\,GeV$
- QCD benchmark
  - used to constrain collinear PDF
  - used to measure α_s
  - benchmark for all QCD MC generators at LO and NLO !
- sets the level of experimental uncertainties
  - JES uncert. leads to ~ 2-4% at low, up to ~ 20 % at highest p_T

CMS JHEP 1703, 156 (2017)



Inclusive jets: comparison to predictions 8TeV

ATLAS STDM-2015-01

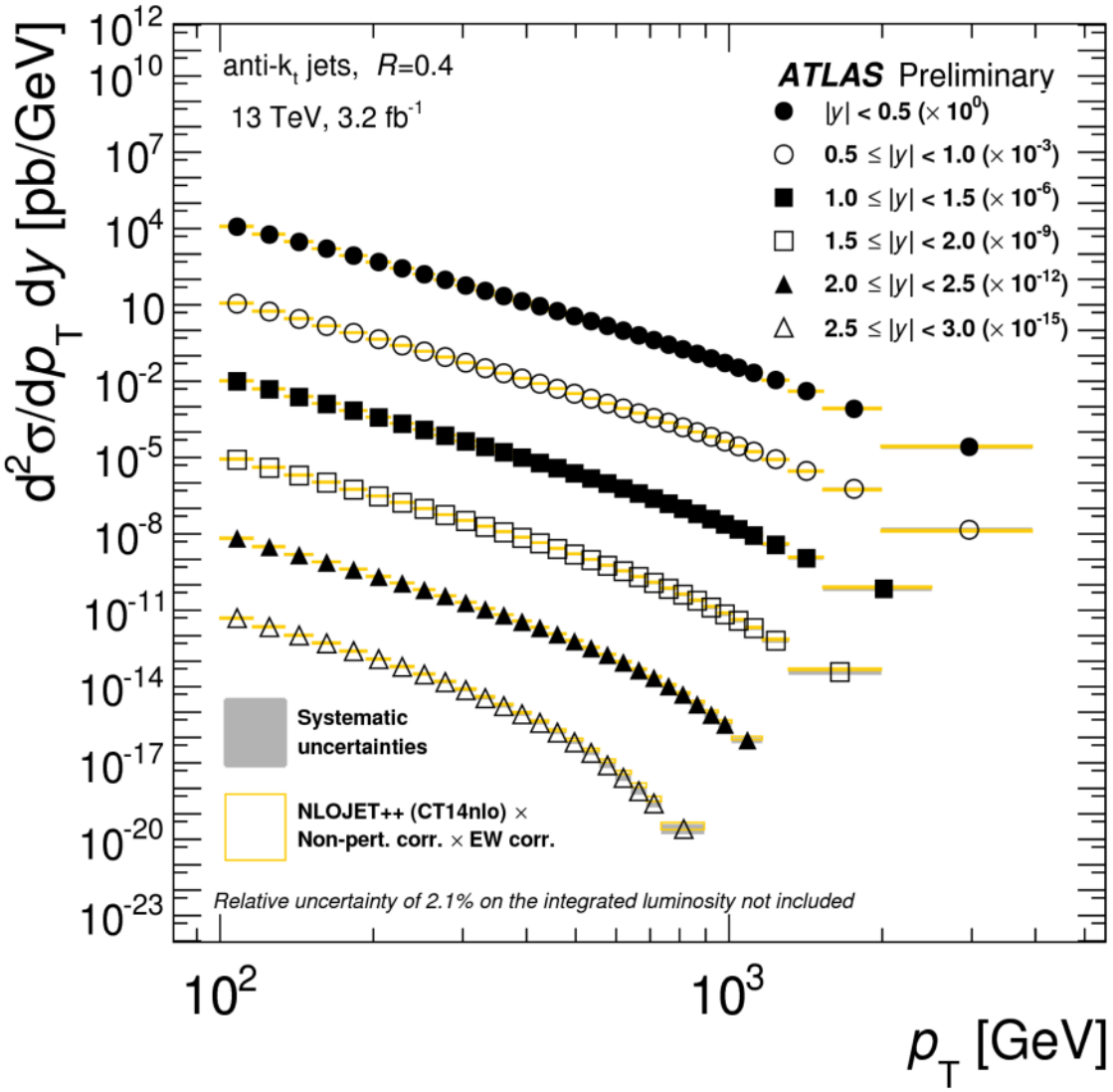


- NLO+PS smaller than NLO, but shows slope !

Inclusive jets at 13 TeV

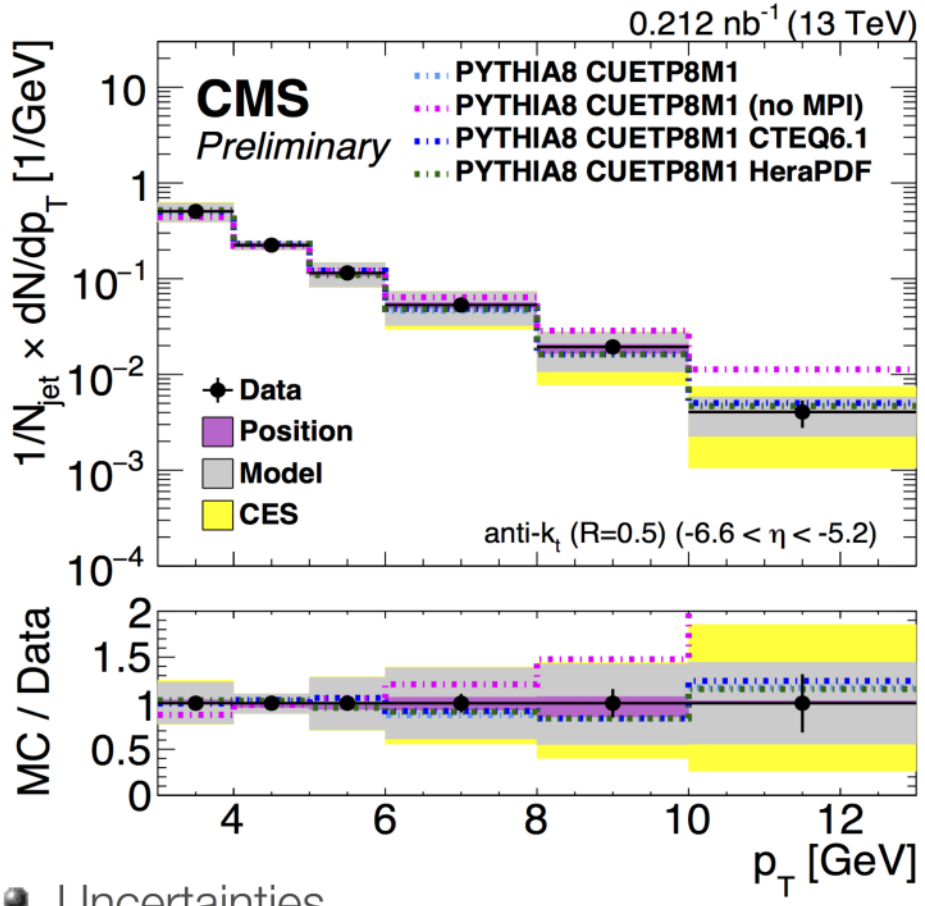
- Inclusive jets over large rapidity and p_T range
- benchmark for all QCD calculations
  - sets the level of experimental uncertainties:
  - JES uncert. leads to ~ 4% at low p_T , up to ~ 33 % for forward η

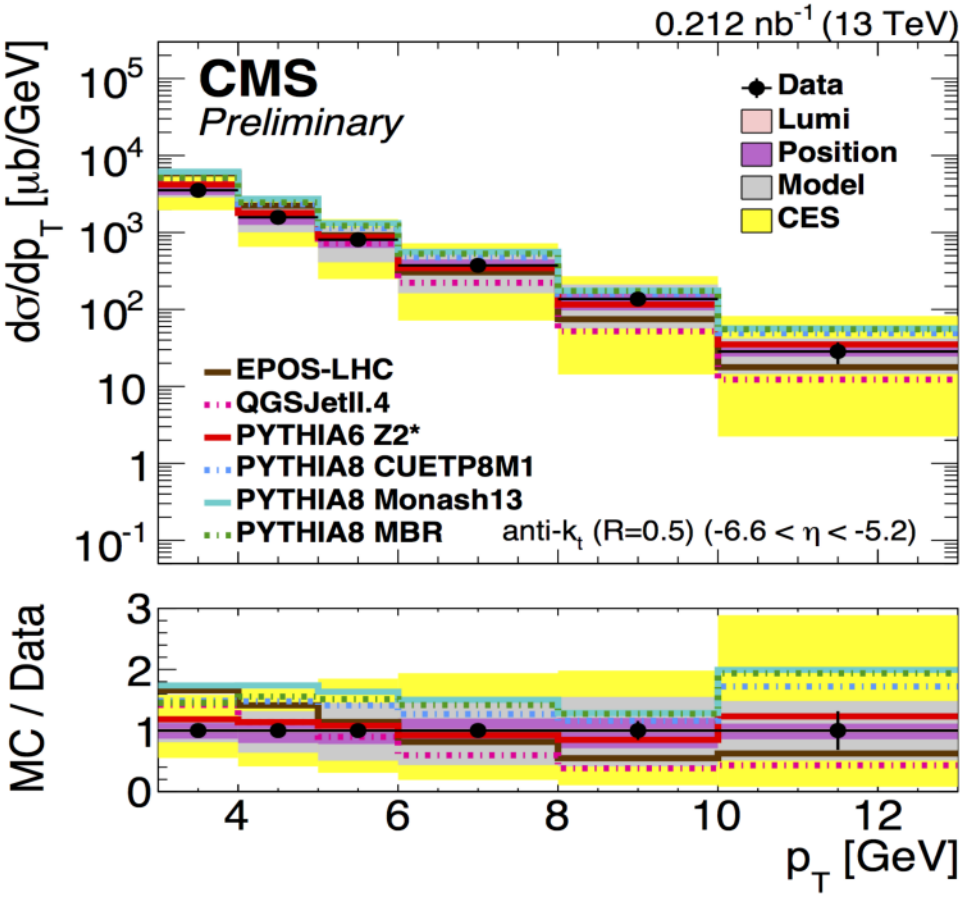
ATLAS-CONF-2016-092



Jets in the very forward region

CMS-FSQ-16-003

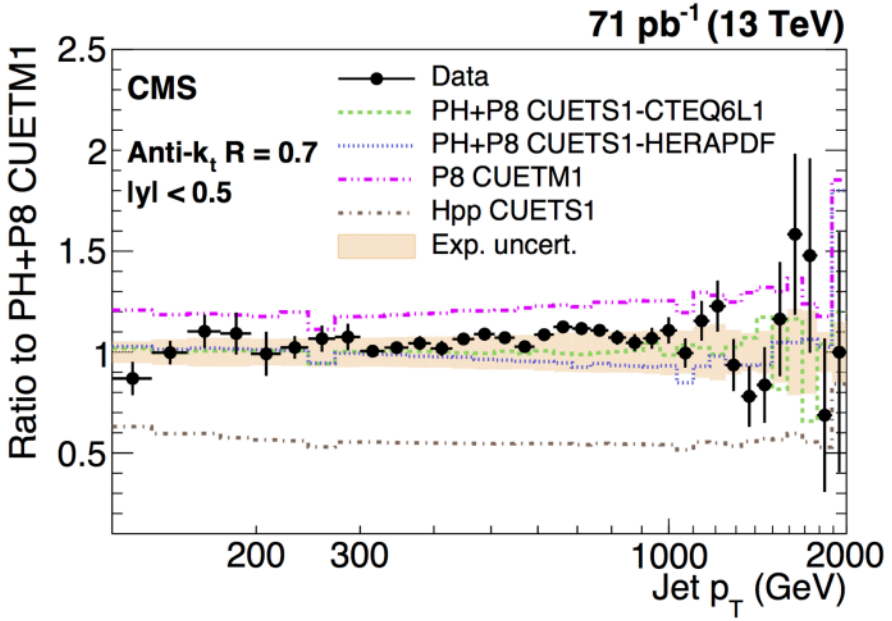




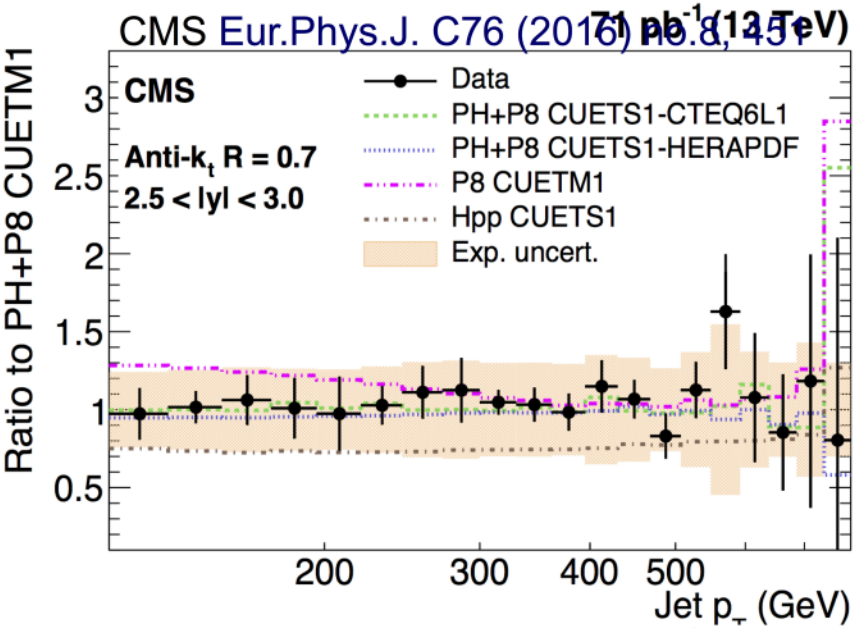
- Uncertainties
  - JES: 5-70 % for normalized distribution
    > 50 % for absolute x-section,
  - Model: 20 – 50 % (different tunes: CUET, 4C and EPOS)

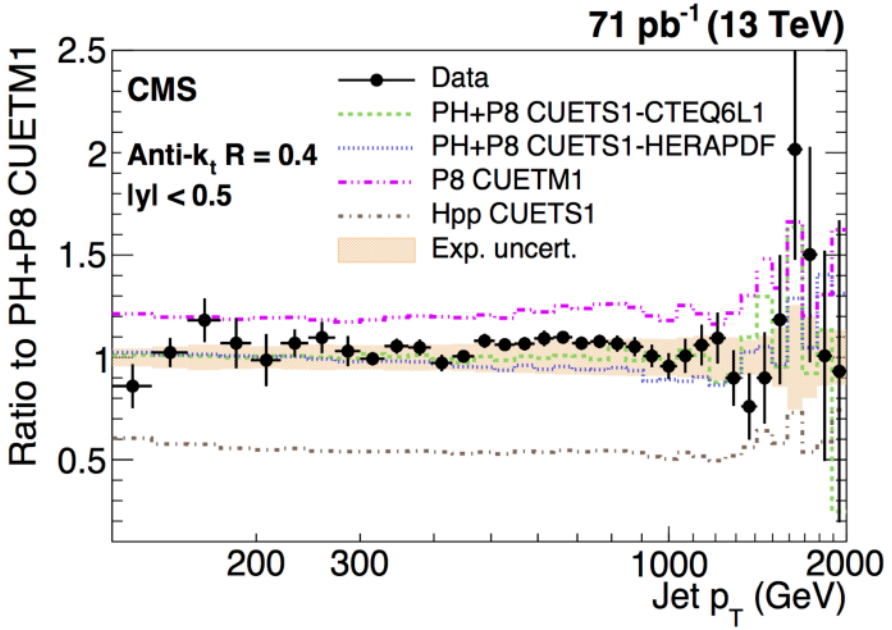
- Measurement sensitive to MPI treatment in very forward region
  - sensitivity to p-fragmentation region ?

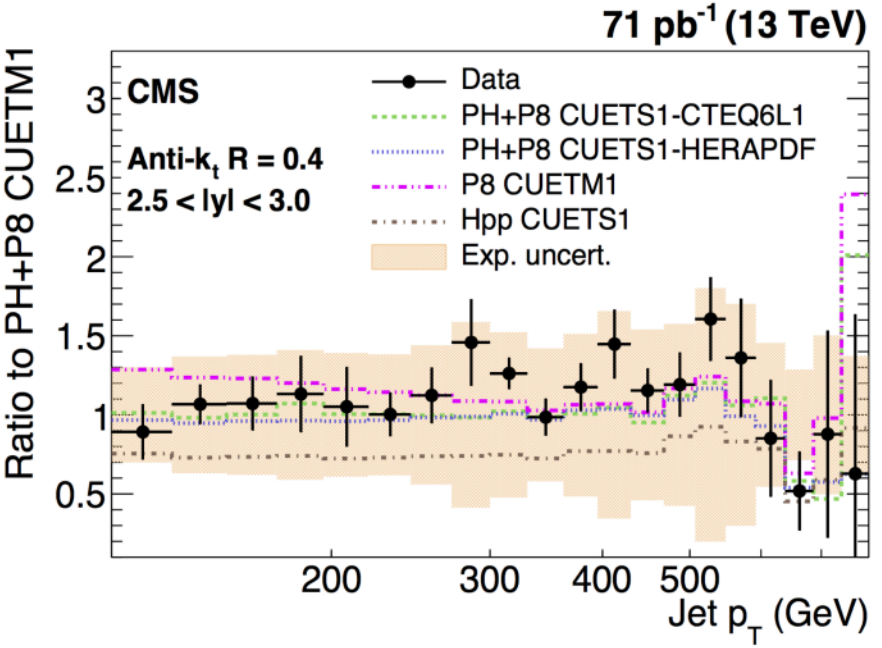
Inclusive jets: comparison to predictions 13 TeV



CMS Eur.Phys.J. C76 (2016) no.8, 451







Correction factors in Inclusive jets at 8 TeV

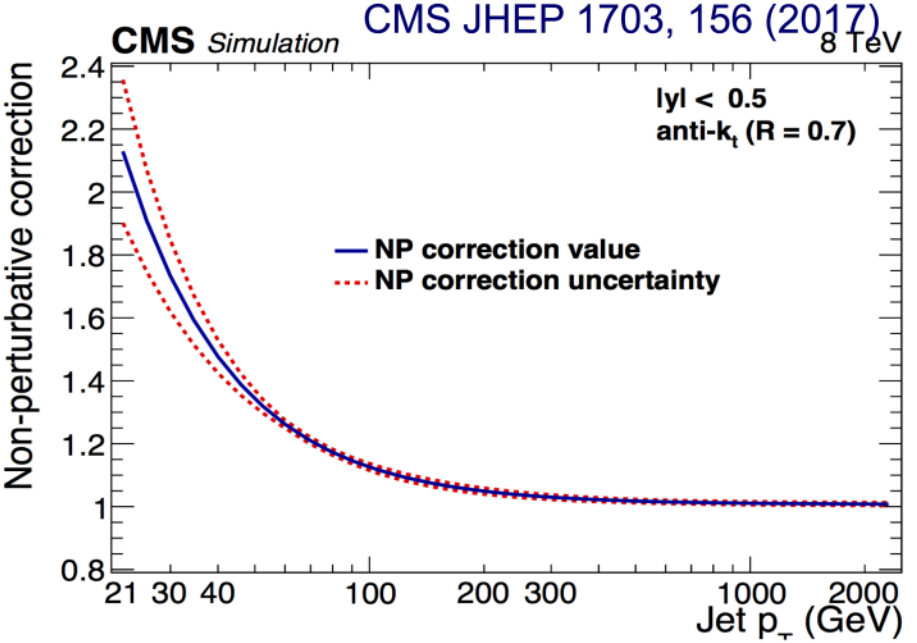
- Inclusive jets within $0 < |y| < 4.7$ and $p_T \geq 21\,GeV$
- for comparison with fixed NLO calculation, non-pert. (NP) factors needed:

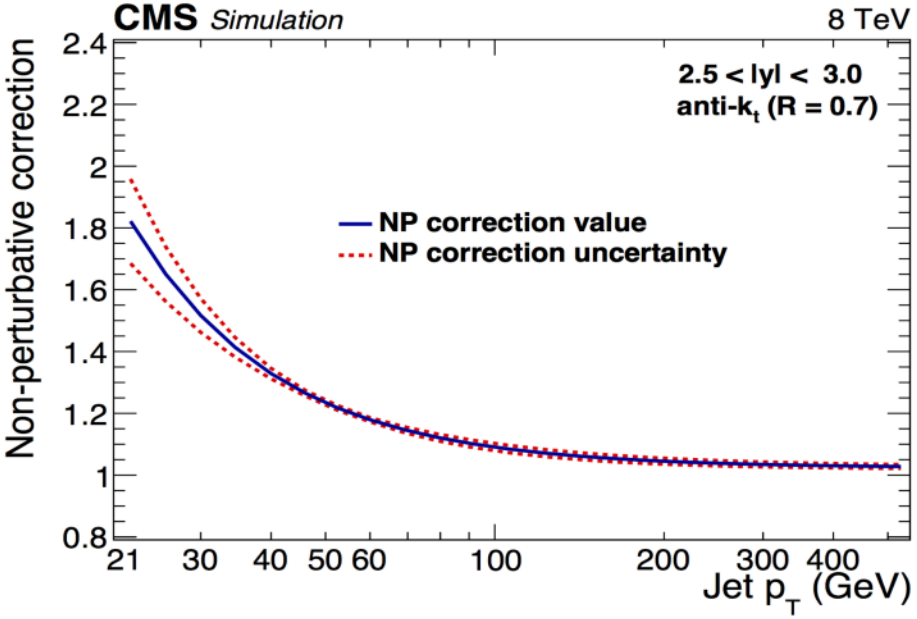
$$K^{NP} = \frac{\sigma(nominal)}{\sigma(noHAD, noMPI)}$$

here taken from PH+PS and LO+PS

- Can NP factors be obtained from LO tunes ?
- what about PS correction factors ?

CMS JHEP 1703, 156 (2017)





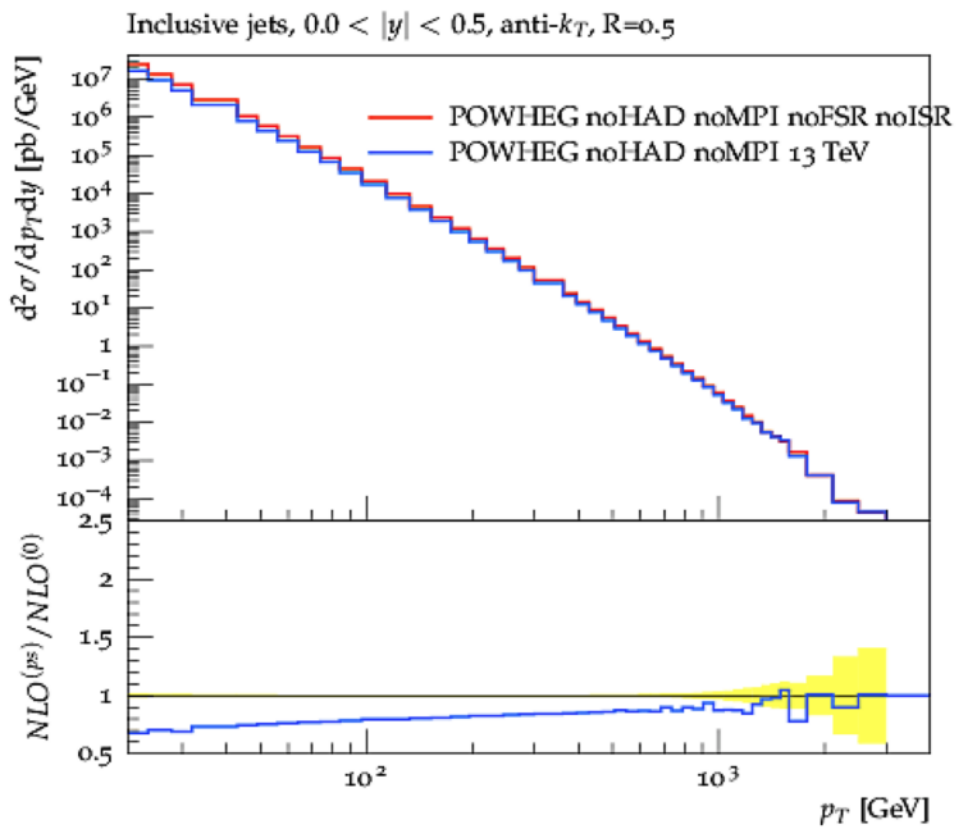
Parton shower effects in NLO +PS calcs.

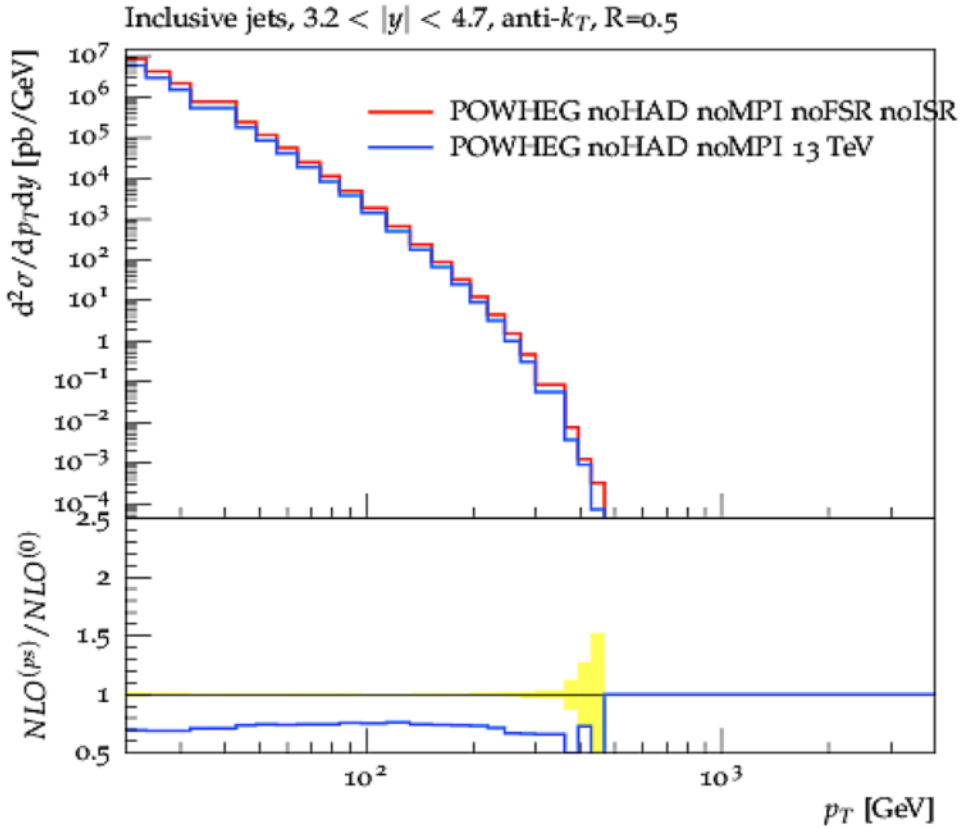
- use NLO+PS to calculate:

$$K^{PS} = \frac{N^{(ps)}_{NLO-MC}}{N^{(0)}_{NLO-MC}}$$

Approach described in:
S. Dooling et al Phys.Rev., D87:094009, 2013.

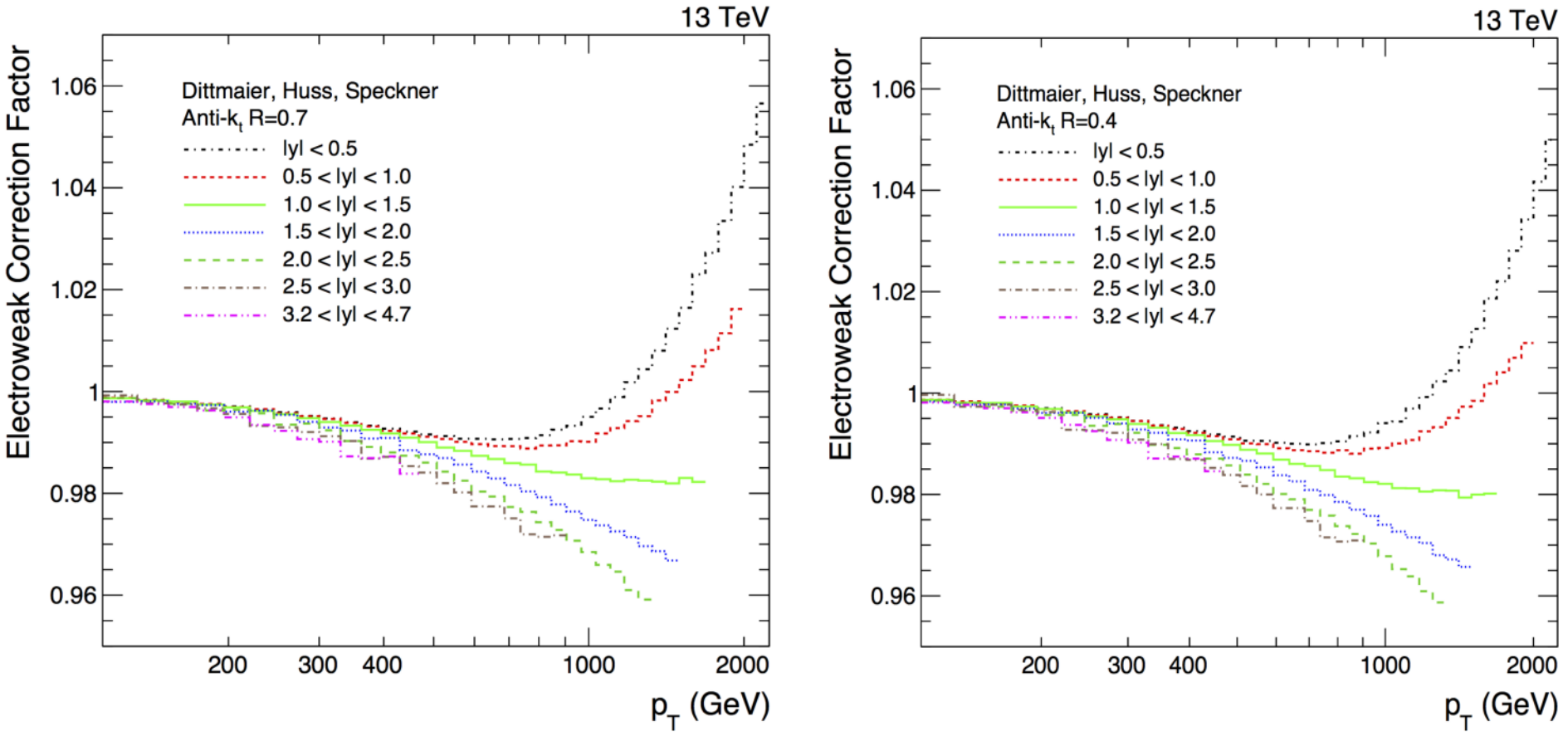
- Corrections to be applied to fixed order NLO calculations for PDF fits:
  - kinematic effects from ISR
  - radiation outside of jet-cone





EW contributions at high p_T

- Electroweak effects from virtual exchange of W,Z bosons

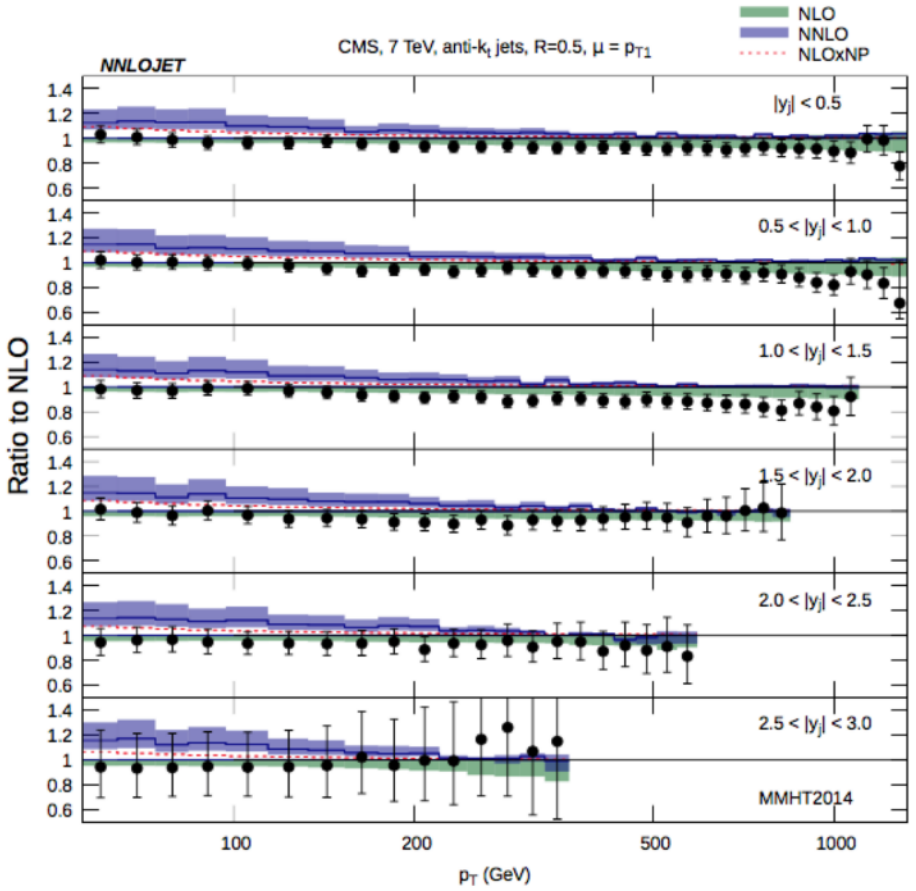


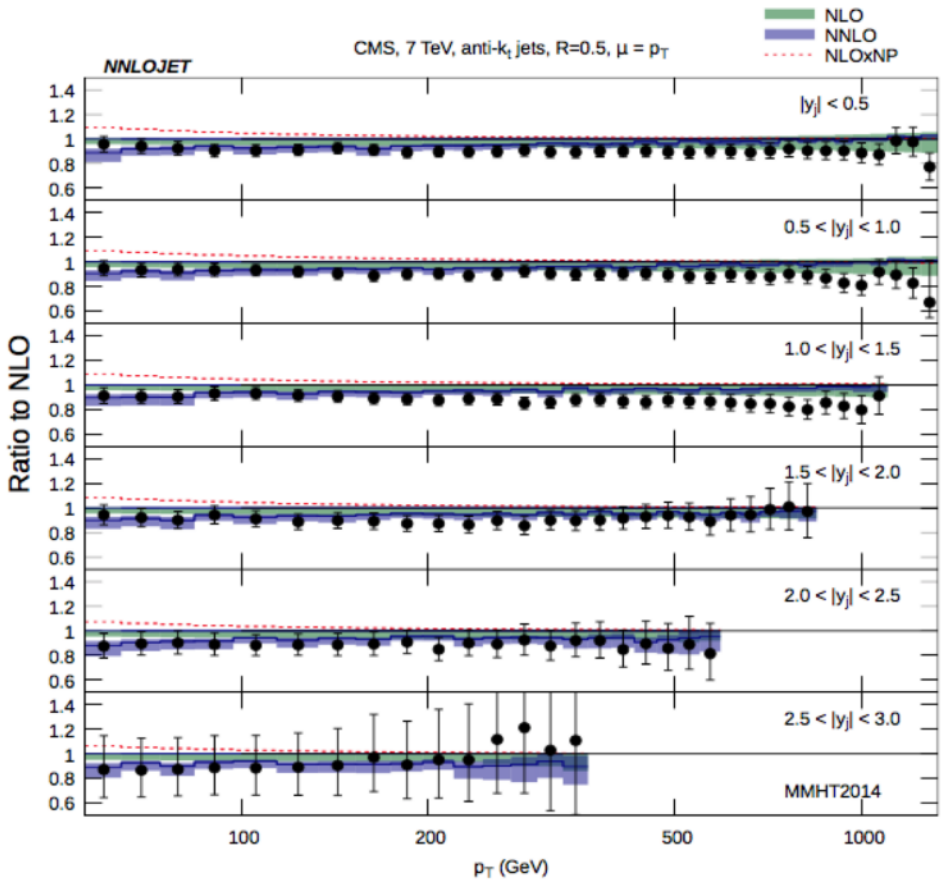
- Electroweak effects become sizable at large p_T
  - applied to fixed NLO calculation similar to NP correction

NNLO fixed order calculations for inclusive jets

- New NNLO calculation
  - issue is scale choice: leading jet p_T or average p_T

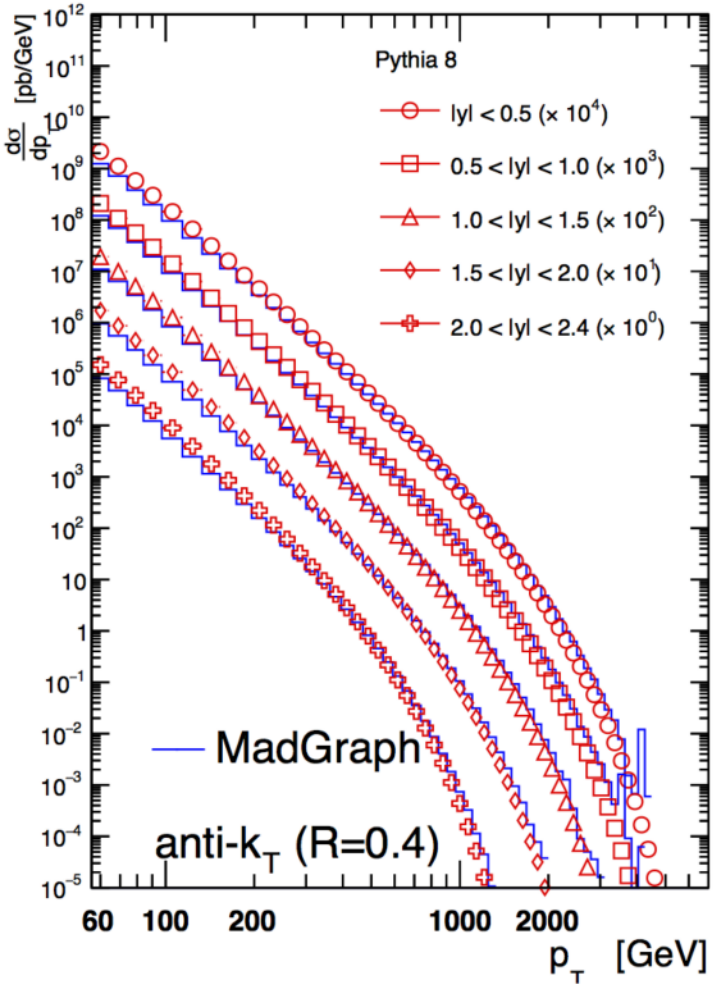
J. Currie, E. W. N. Glover, and J. Pires.
Phys. Rev. Lett., 118(7):072002, 2017.
plots from: J. Currie at SMP-J workshop

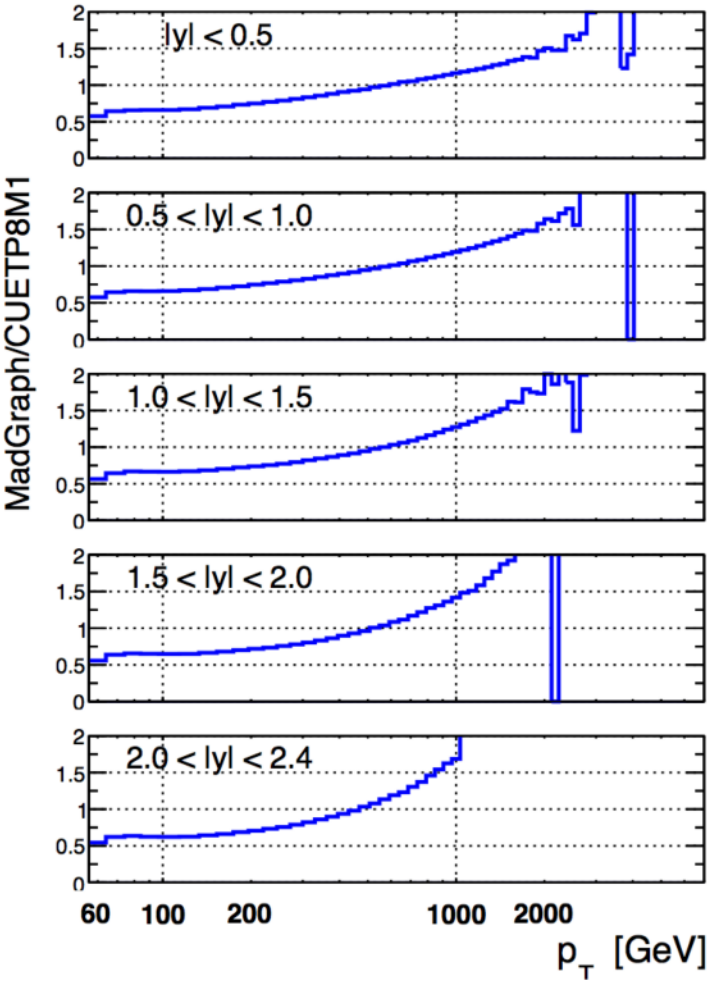




- reduced scale uncertainties compared to NLO

MADGRAPH – P8: inclusive jets





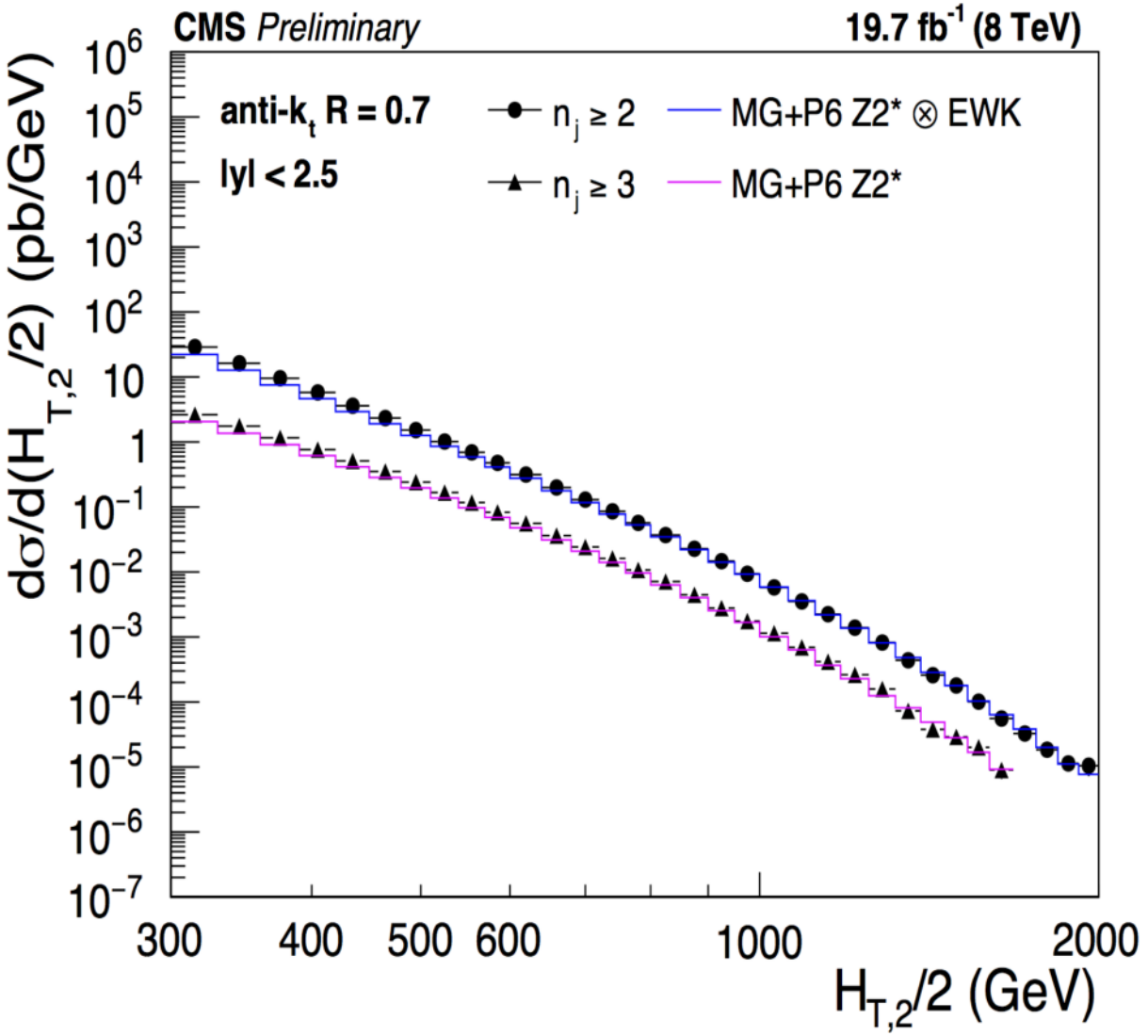
P. Connor

- P8 is close to data
- MADGRAPH (→ 4 partons) with CUET has different shape for inclusive jets
  - this a known effect … but not clear where it comes from !

Cross sections of 2 and 3 jets

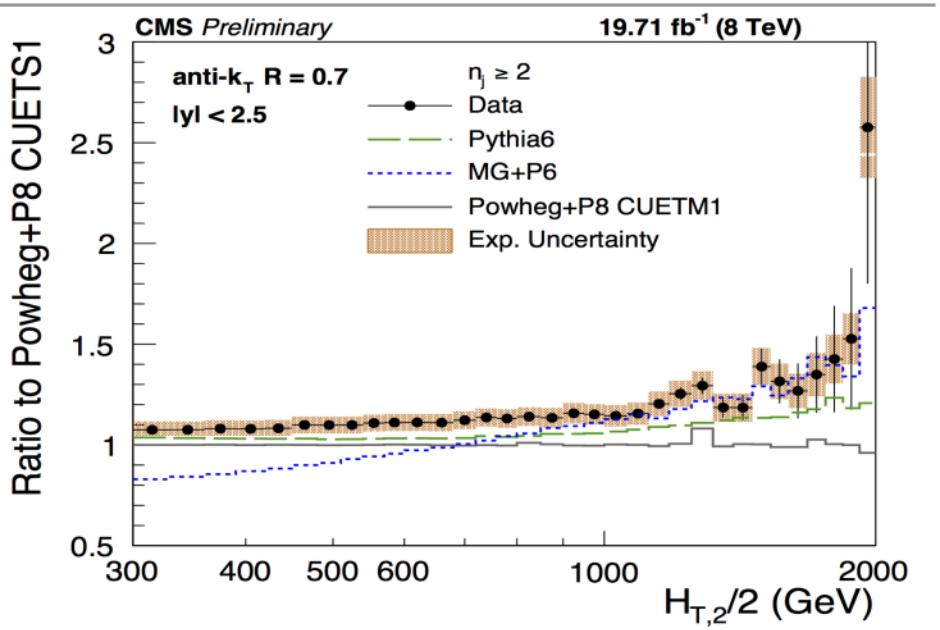
- x-section of 2, 3 jets vrs $H_{T2}/2$ (average p_T of 2 leading jets) with $p_T > 150, |y| < 2.5$
- sensitive test for higher order
  - used to determine α_s
- uncertainties:
  - JEC: 2 -10 %
- measure ratio R_{32}
  - small uncertainties ~ 1%

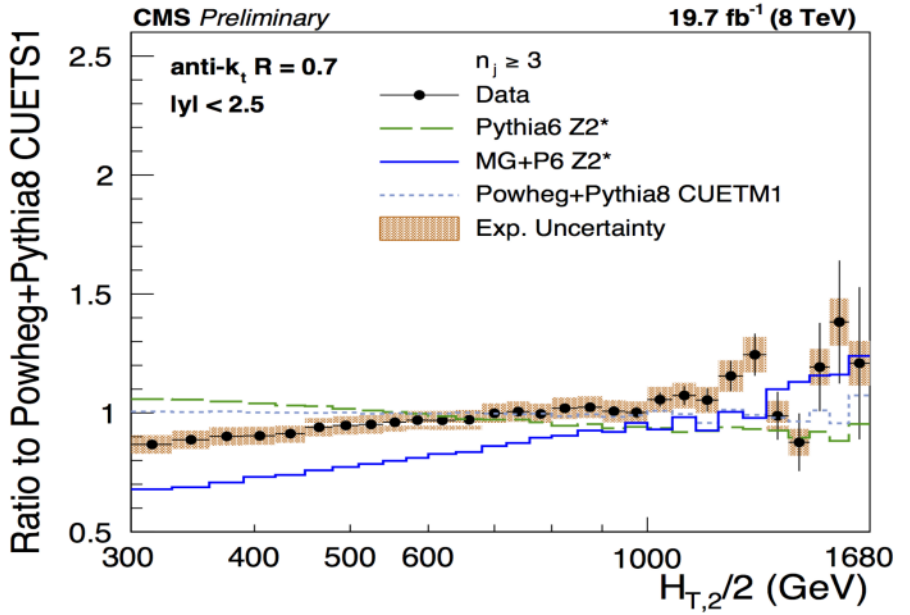
CMS-SMP-16-008



Cross sections of 2 and 3 jets

- Detailed look:
  - Powheg (2jet) and Madgraph5+P6 Z2* (up to 4 partons) show deviations !
- different shape of Powheg & MG





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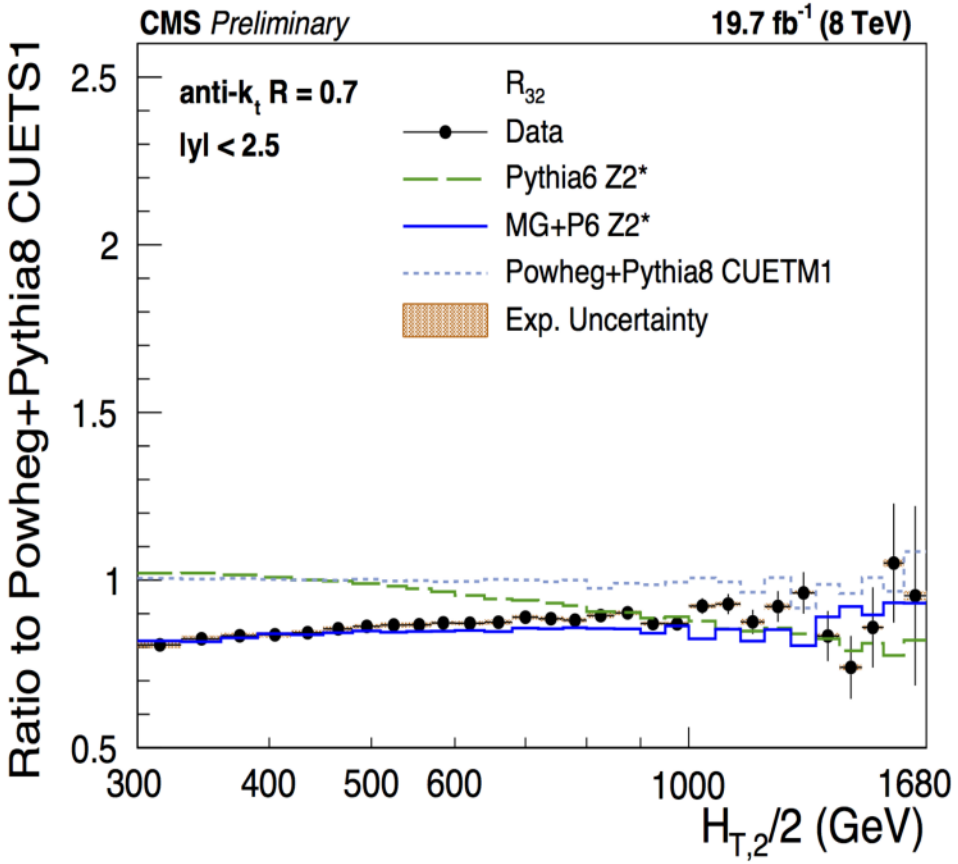

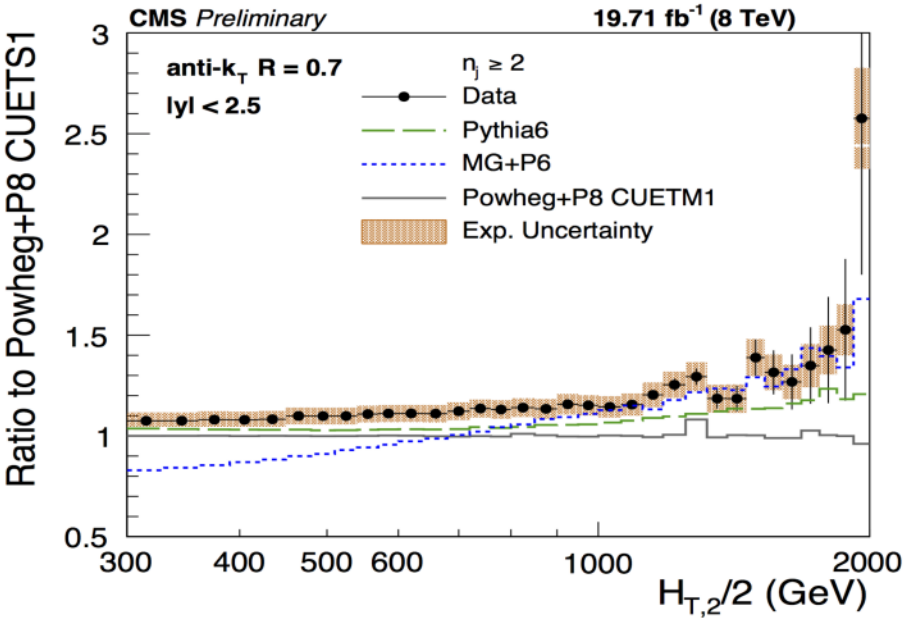

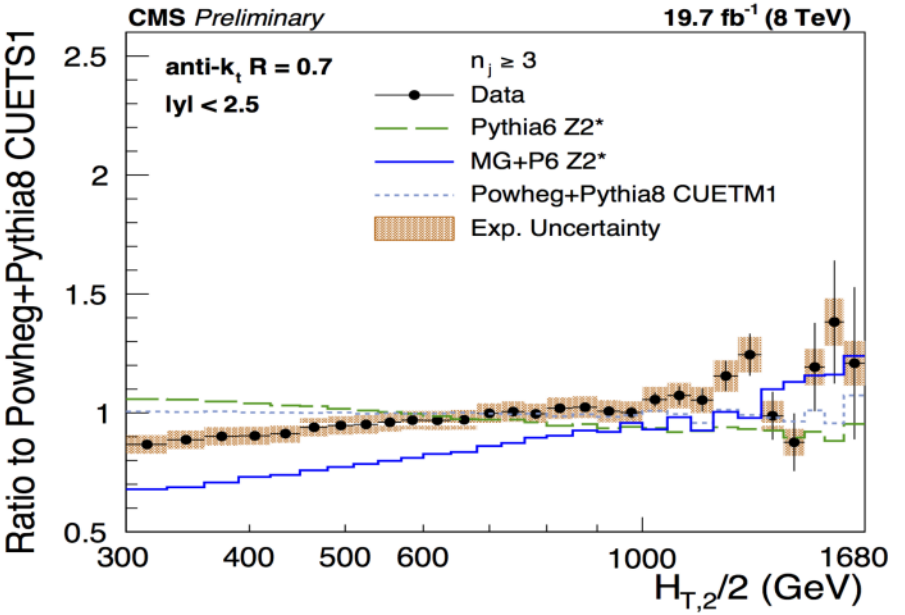

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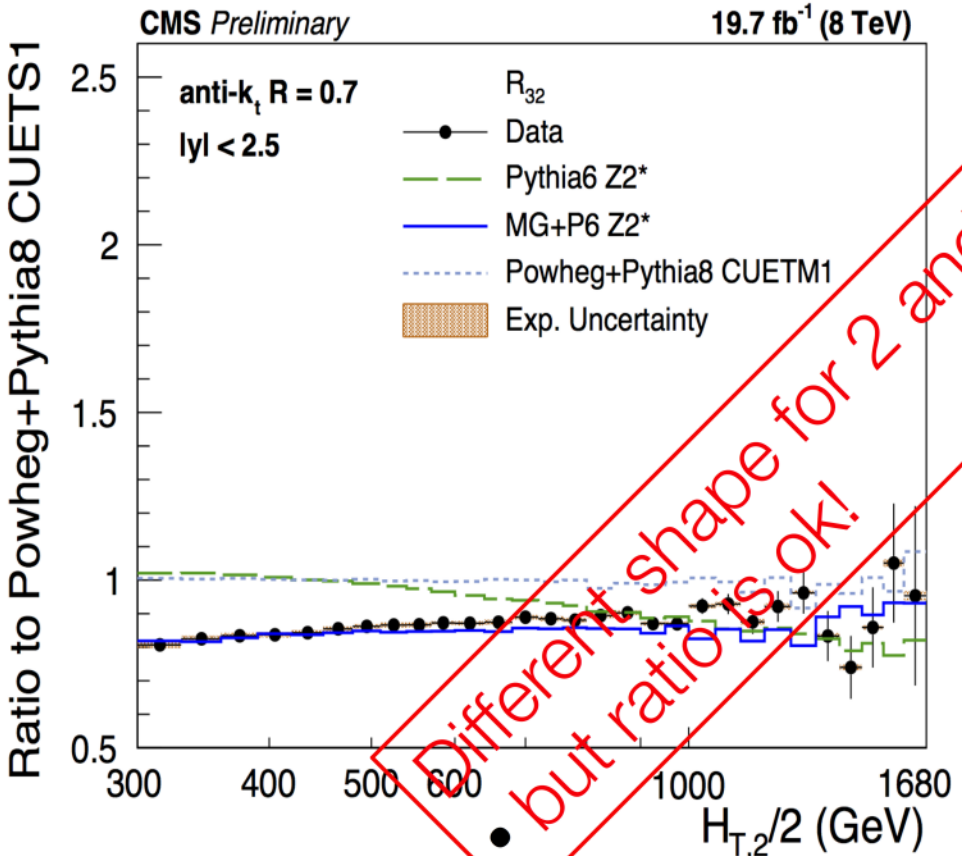
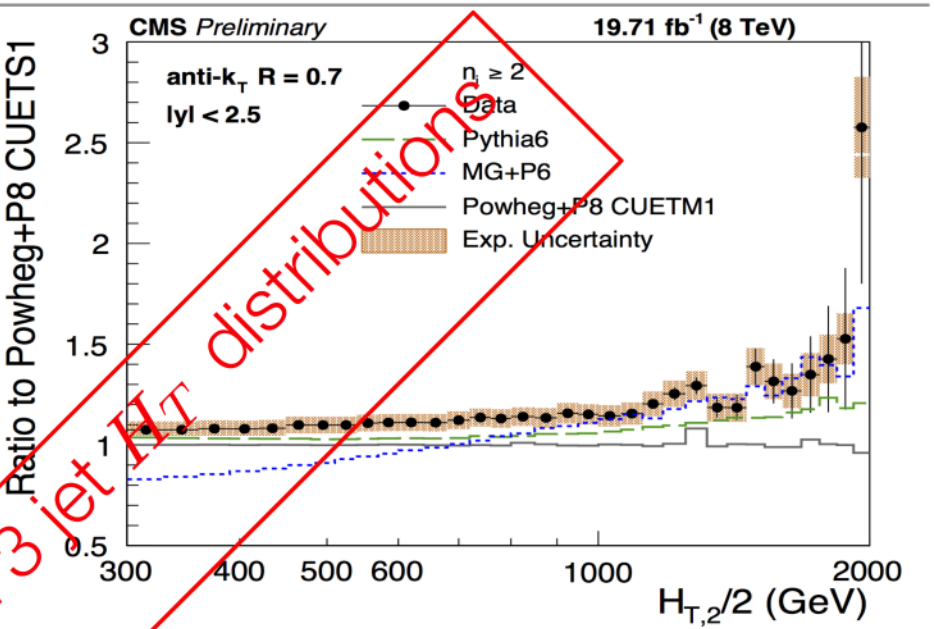
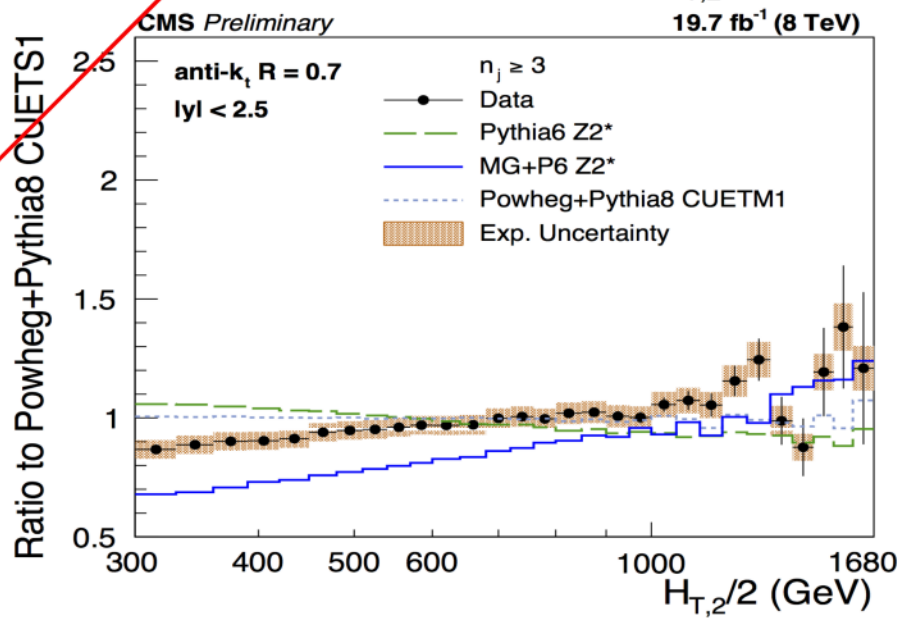




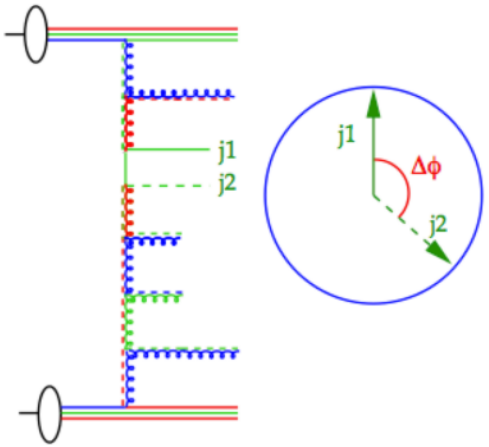


Different shape for 2 and 3 jet H_T distributions but ratio's ok!

Looking beyond hardest jets

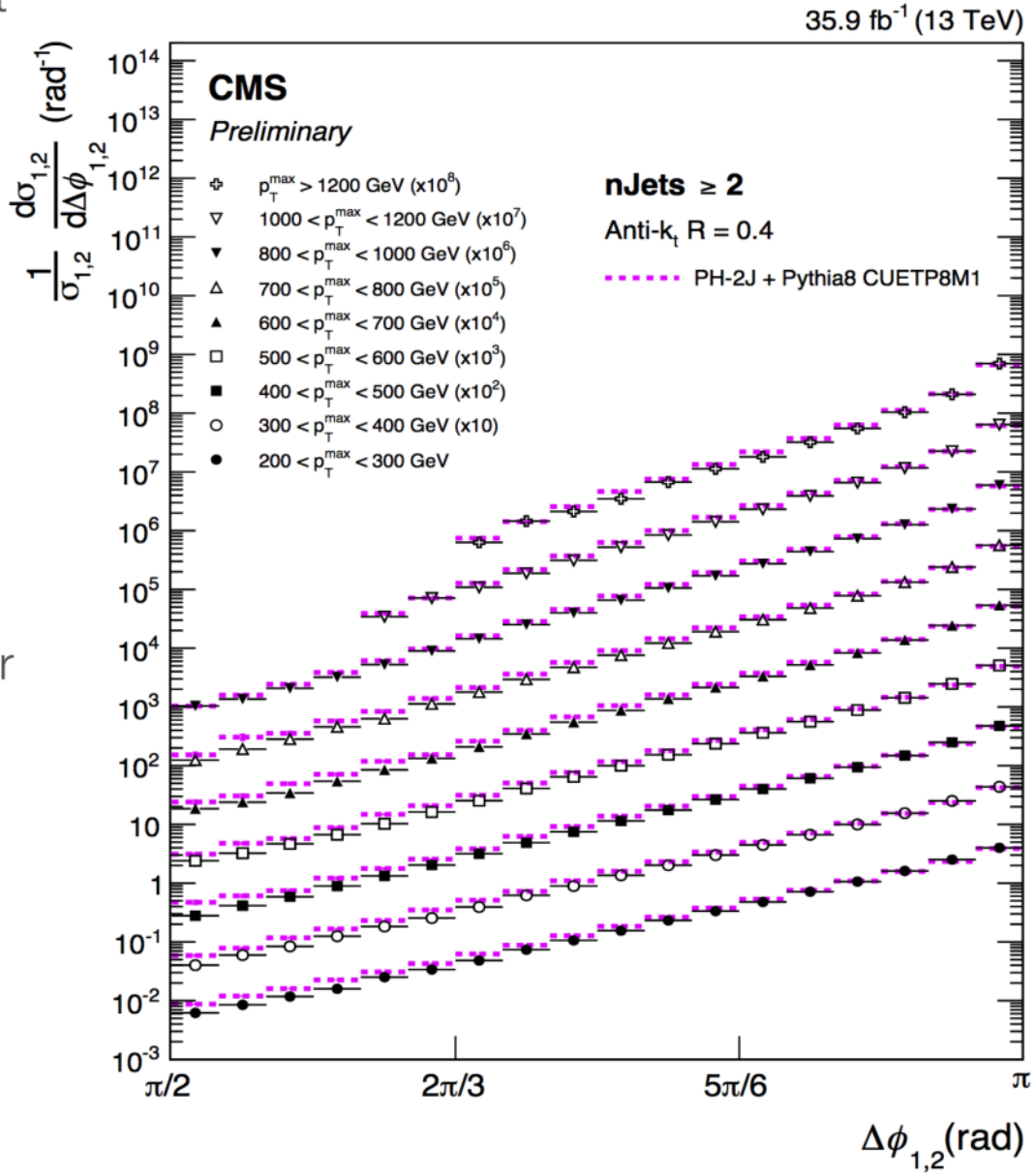
Azimuthal correlations in multi-jet events

- Azimuthal correlations in multijets at 13 TeV

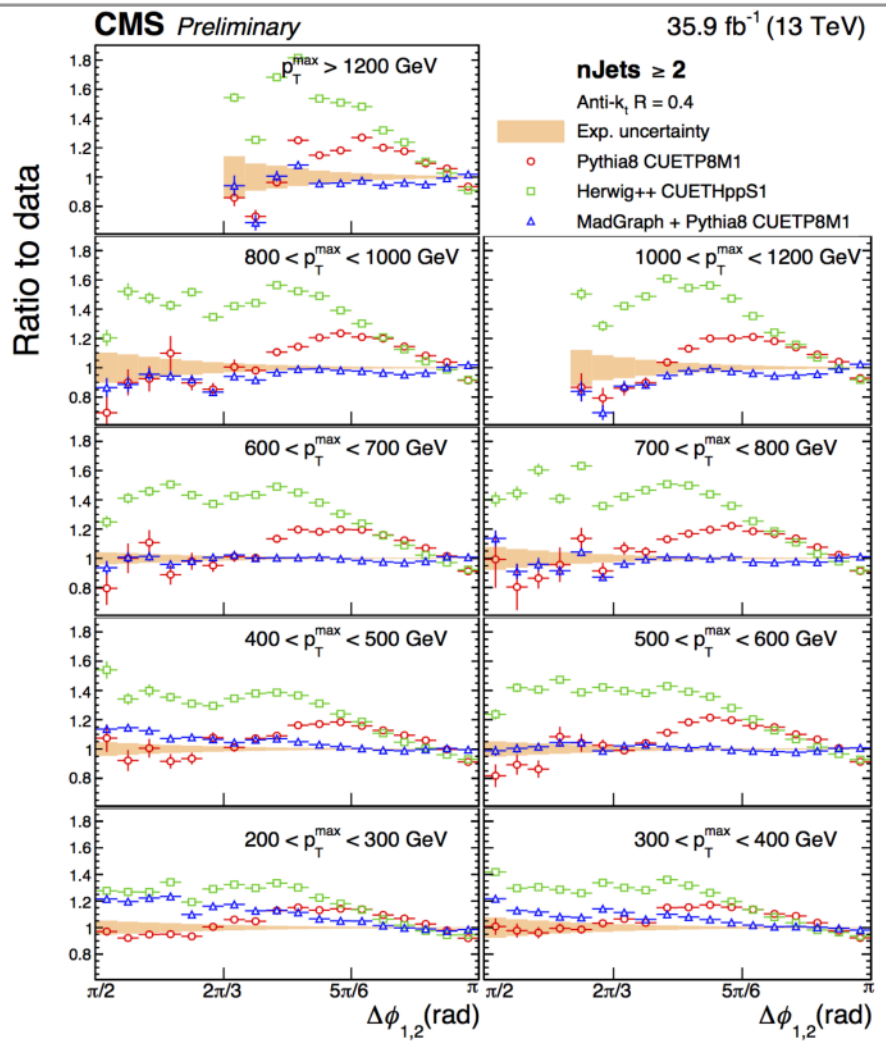


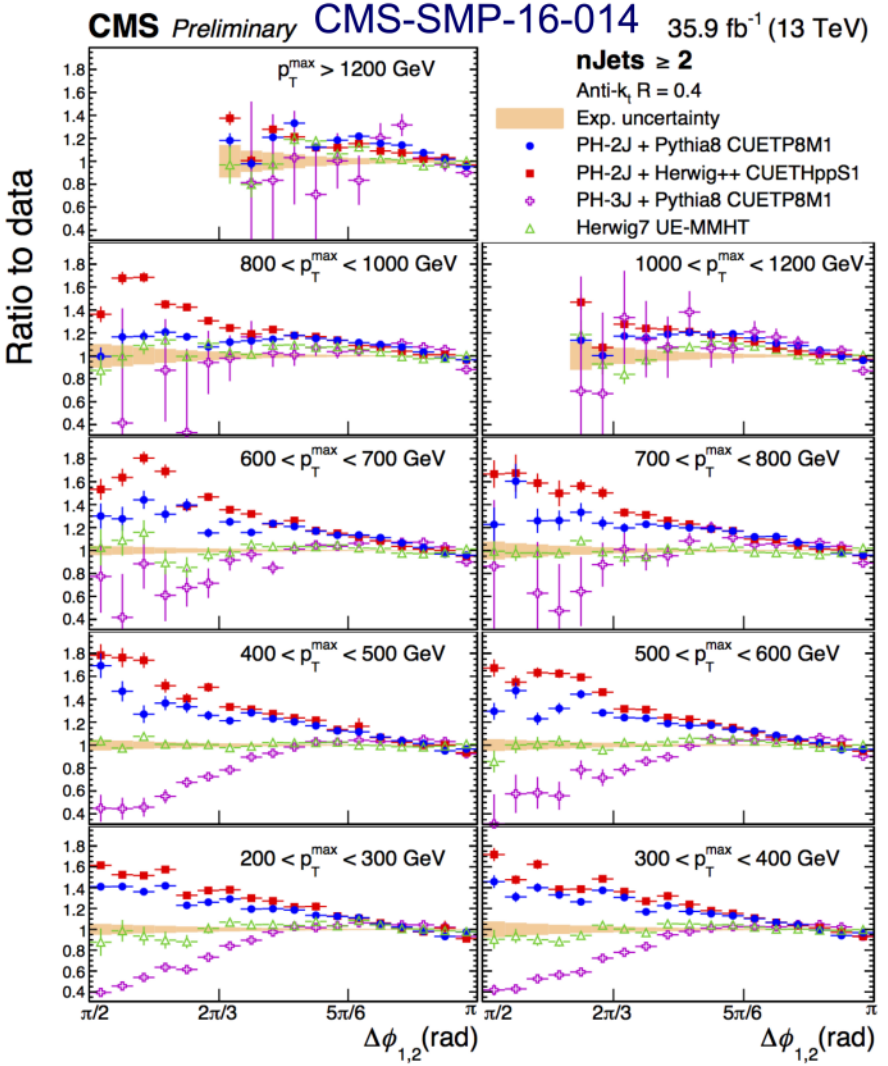
  - measurement sensitive to higher order QCD radiation: 3 (or 4 or 5 or …Jets)
  - measure: $\Delta\ \phi_{12}$ but also ϕ correlations in multijets
- $p_T > 100\ GeV, |y| < 2.5$
  - very small uncertainties from JEC: 0.1% at π to 3 % at $\pi/2$

CMS-SMP-16-014



Azimuthal correlations in multi-jet events





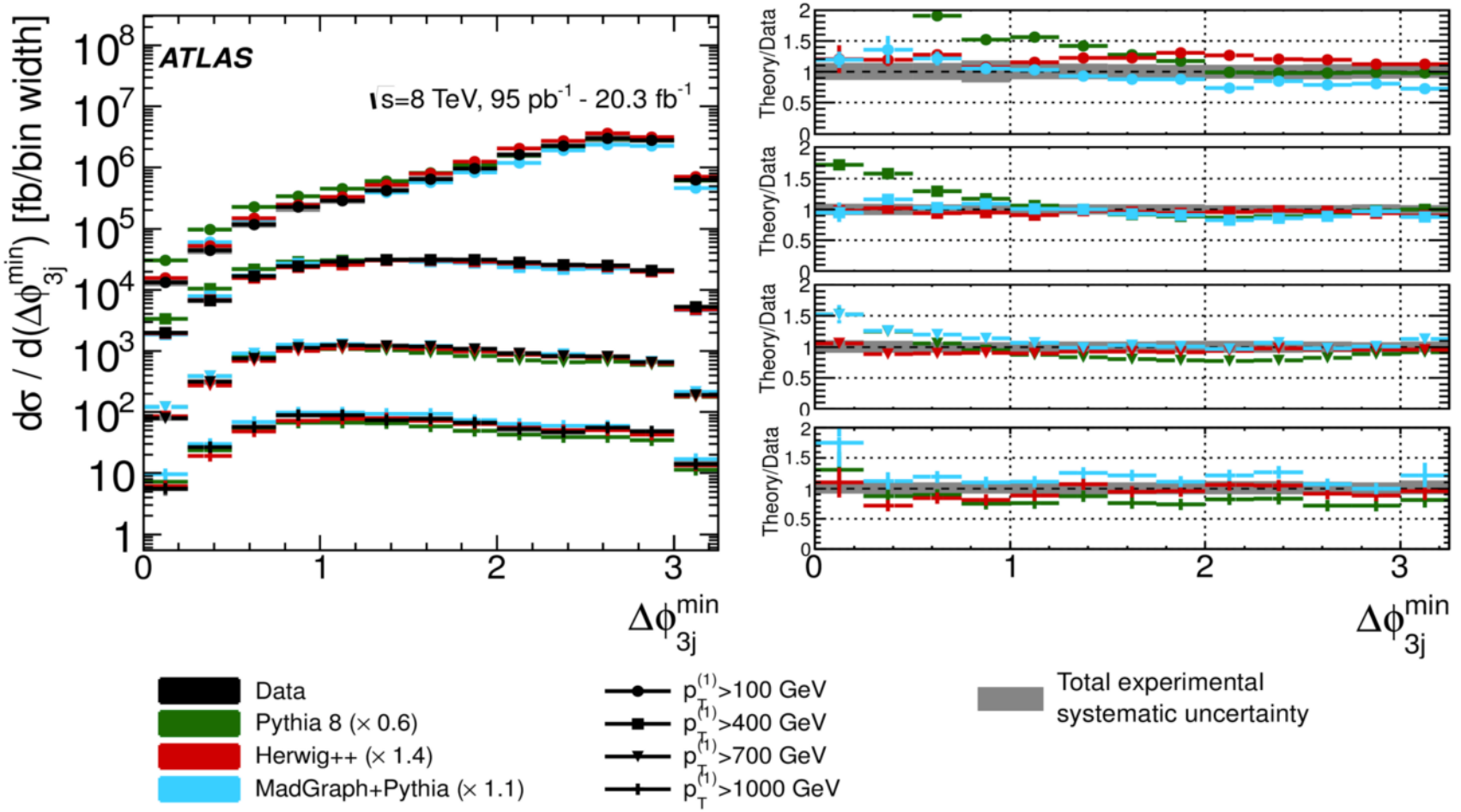
- Madgraph5+P8 (up to 4 partons) is best
  - deviations of LO 2 → 2 MCs in region sensitive to hard 3rd jet

- Powheg (2jet)+P8 shows deviations
- Powheg (3jet)+P8 is off
- H7 (MC2NLO) best

Azimuthal correlations in multi-jet events at 8TeV

ATLAS JHEP 11 (2016) 110

- $\Delta\phi_{3j}^{min}$ minimum ϕ separation between any of 3 jets in 4jet events

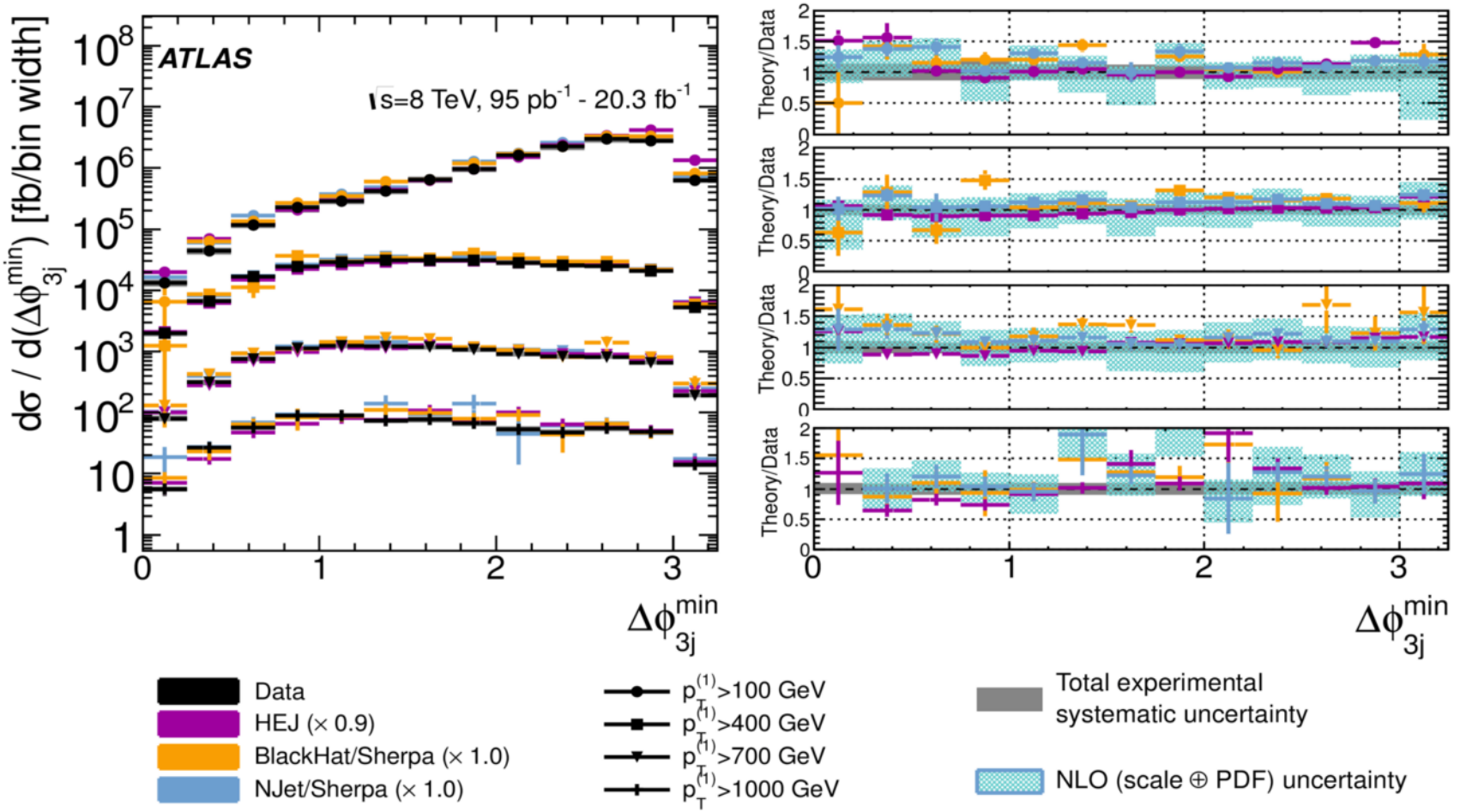


- P8 shows deviations (jets from PS)
- H++ is good (still jets from PS)
- Madgraph5+P8 (up to 4 partons) best

Azimuthal correlations in multi-jet events

ATLAS JHEP 11 (2016) 110

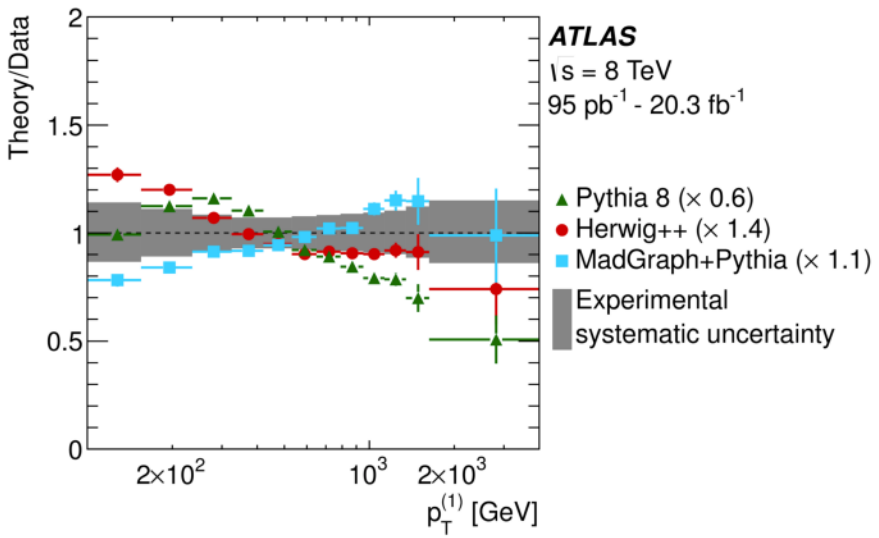
- $\Delta\phi_{3j}^{min}$ minimum ϕ separation between any of 3 jets in 4jet events

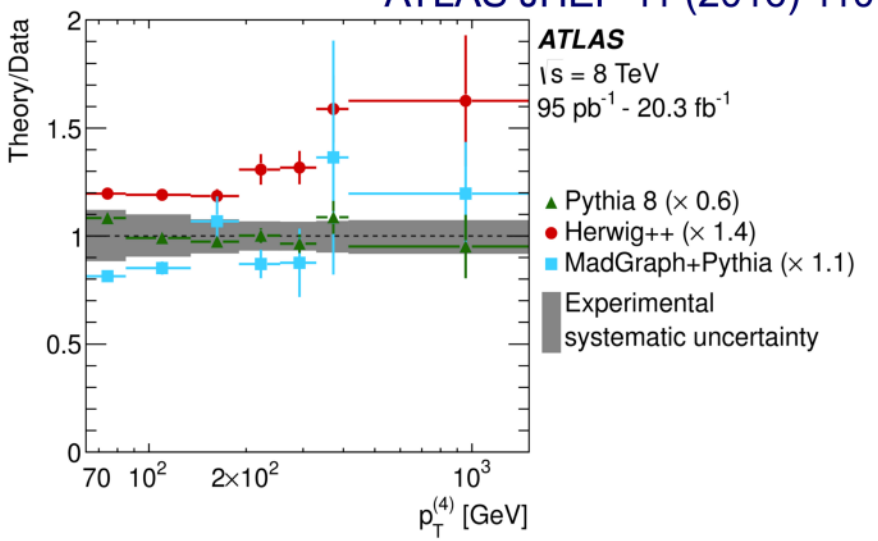


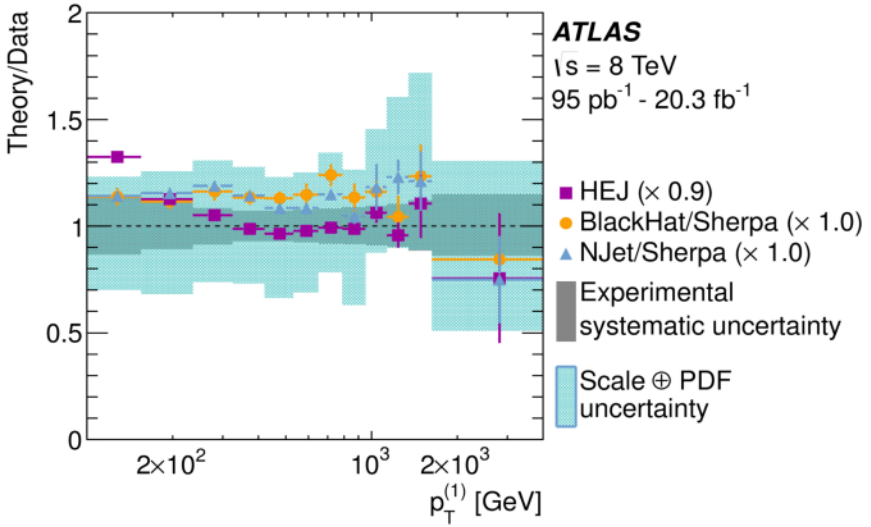
- fixed order NLO 4jet without PS describes data well within scale uncertainty !
- HEJ also good (has multi-partons in high energy approximation)

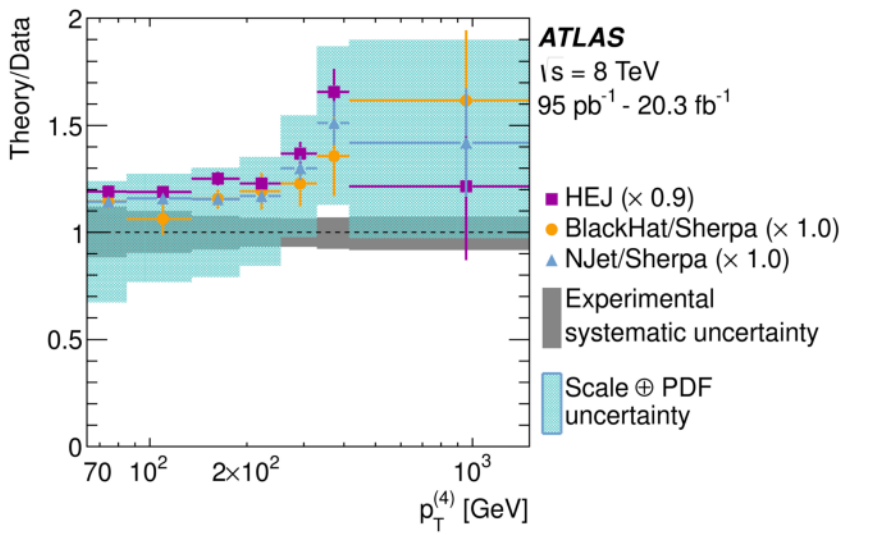
P_T spectra in multi-jet events

ATLAS JHEP 11 (2016) 110









- NLO calculations not necessarily better than LO, even $2 \rightarrow 2$ +PS

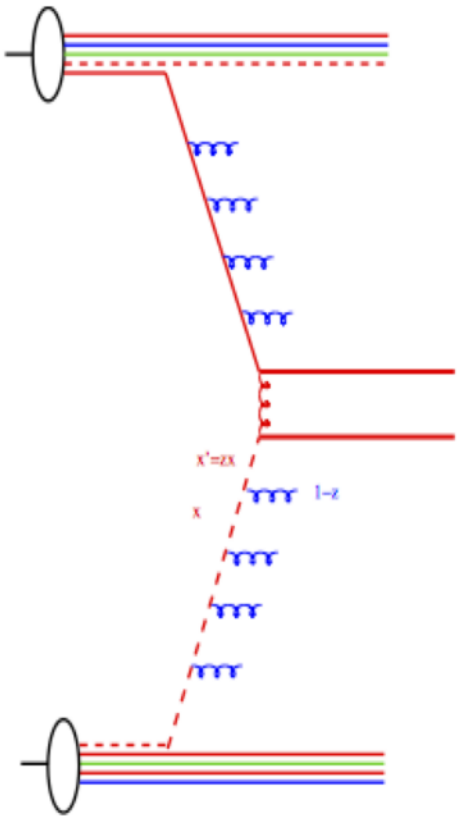
Multi Jets prospects: $\Delta\phi$ at highest p_T

high p_T dijet production in the back-to-back region

- soft parton radiation contributes (NLO parton level x-section unphysical)

soft partons contribute to $pT^{soft}/pT^{hard} \to 0$

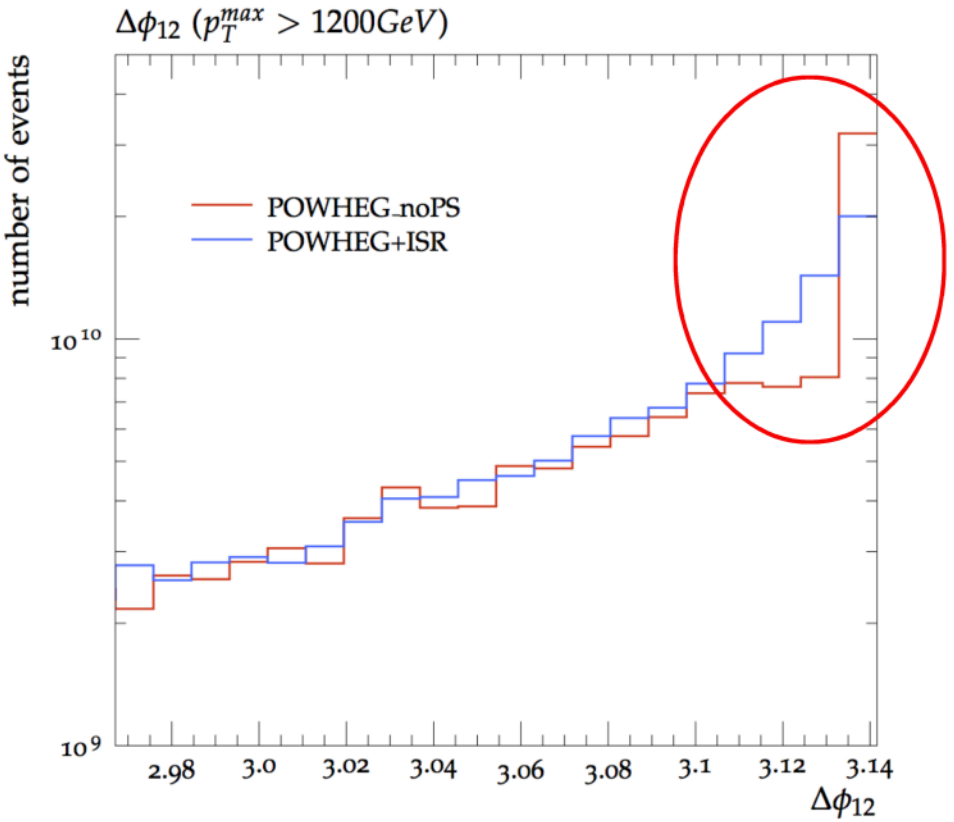
- soft gluon resummation
  - TMD resummation
  - soft gluons
  - for $pT^{\mathbf{hard}}$ **~ 100** GeV**,** pT^{soft} **~ 1 *GeV***
    - soft jets are not measurable
  - for $pT^{\mathbf{hard}}$ **~ 3** TeV**,** pT^{soft} **~ 30 *GeV***
    - soft jet are detectable



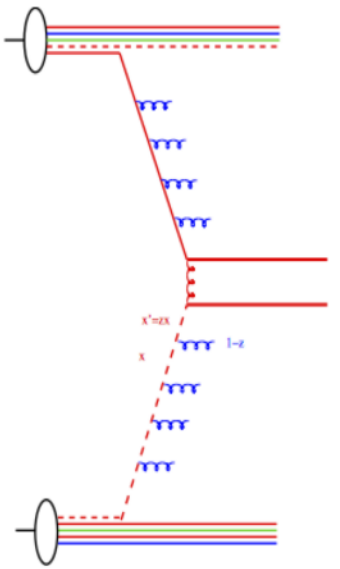
Multi Jets prospects: $\Delta\phi$ at highest p_T

high p_T dijet production in the back-to-back region

- tricky interplay between real and virtual emissions
  - resummation needed – like in p_T of Z ?



A. Bermudez-Martinez



- How well is PS working in this region ?
- can we see initial-final state (factorization breaking) effects ?

- initial state radiation plays important role for decorrelation

Issues in jet measurements

- General PS MC event generators with 2 → 2 ME perform very well
  - for details often higher order ME are necessary
  - parton shower is needed everywhere
- PS corrections for fixed higher order calculations
  - how to determine ?
  - how to estimate uncertainties ?
- Different parton showers
  - measurements become sensitive to details of PS
  - how to tell the differences ?
- multi-leg – PS merging
  - clearly separate what is calculable and where modeling/tuning starts
  - what is tuning freedom ?

Multi-Photon measurements

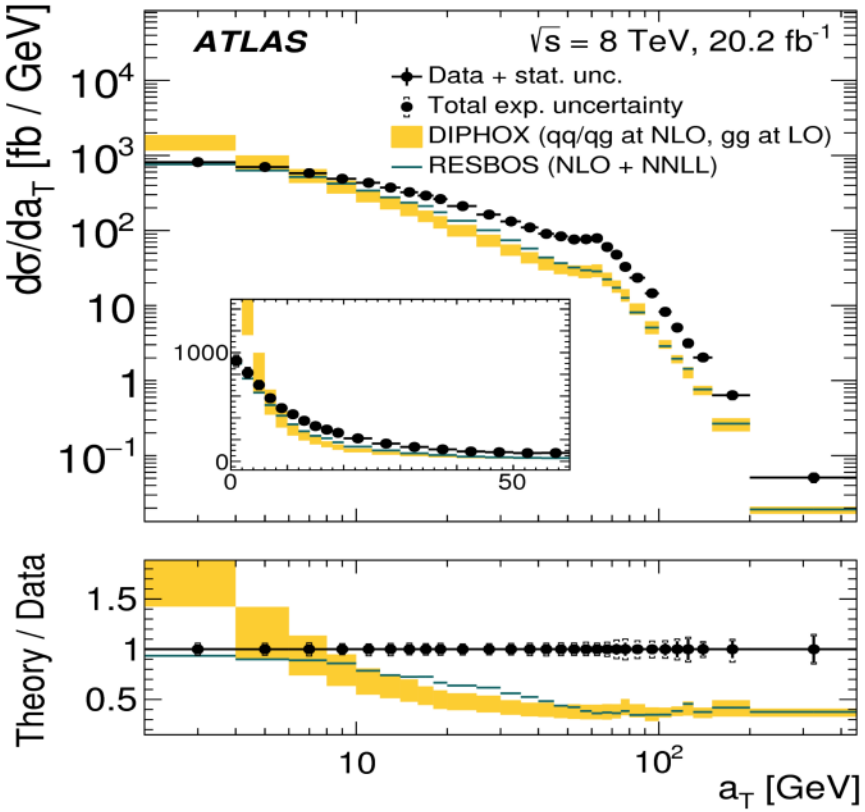
Photon pair production

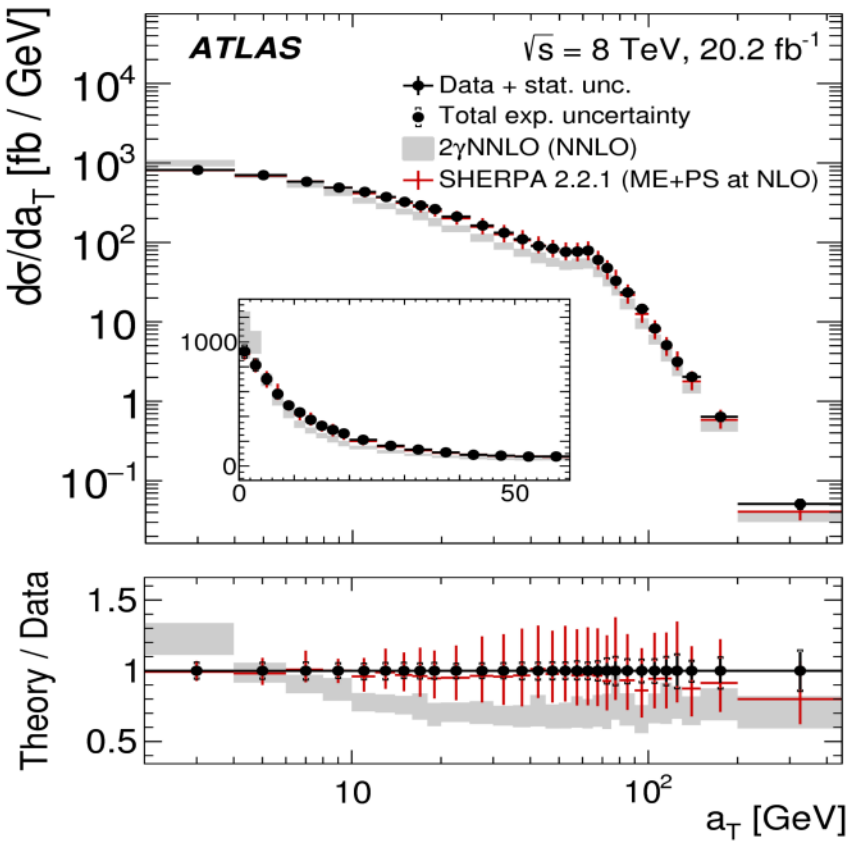
- 2 isolated γ's in $|\eta^{\gamma}| < 1.37$ *or* $1.56 < |\eta^{\gamma}| < 2.36$

  $E_{T1}^{\gamma} > 40\ GeV,\ E_{T1}^{\gamma} > 30\ GeV$

  - a_T : p_T wrt thrust axis
  - sensitive to higher order QCD and soft gluon resummation

ATLAS arXiv:1704.03839





- soft gluon resummation very essential for description !
- NNLO parton level not enough !

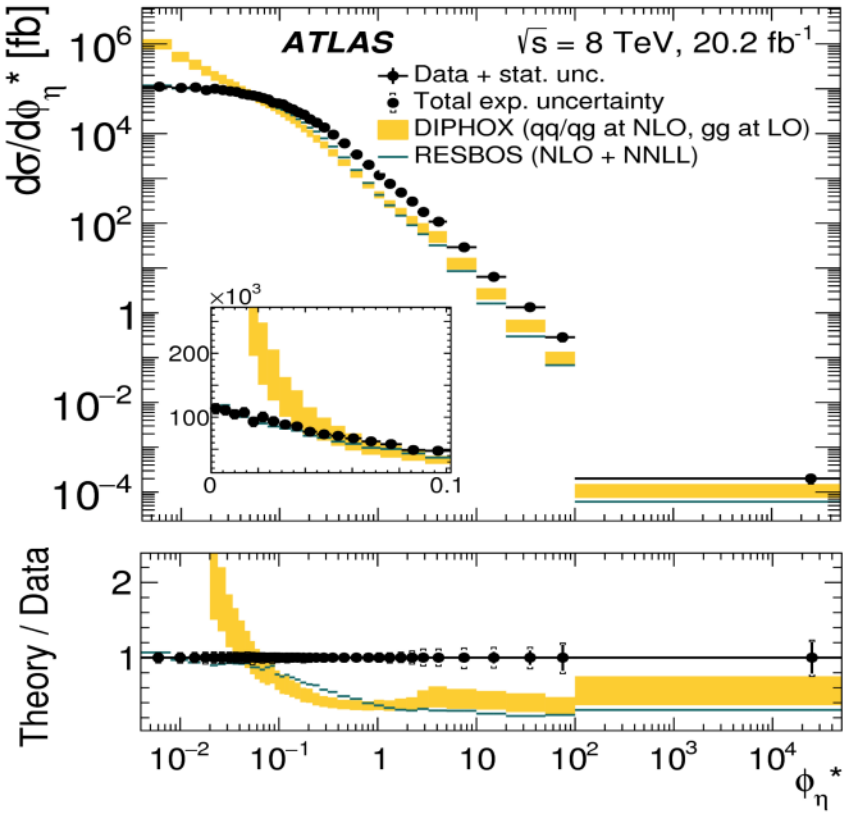
Photon pair production

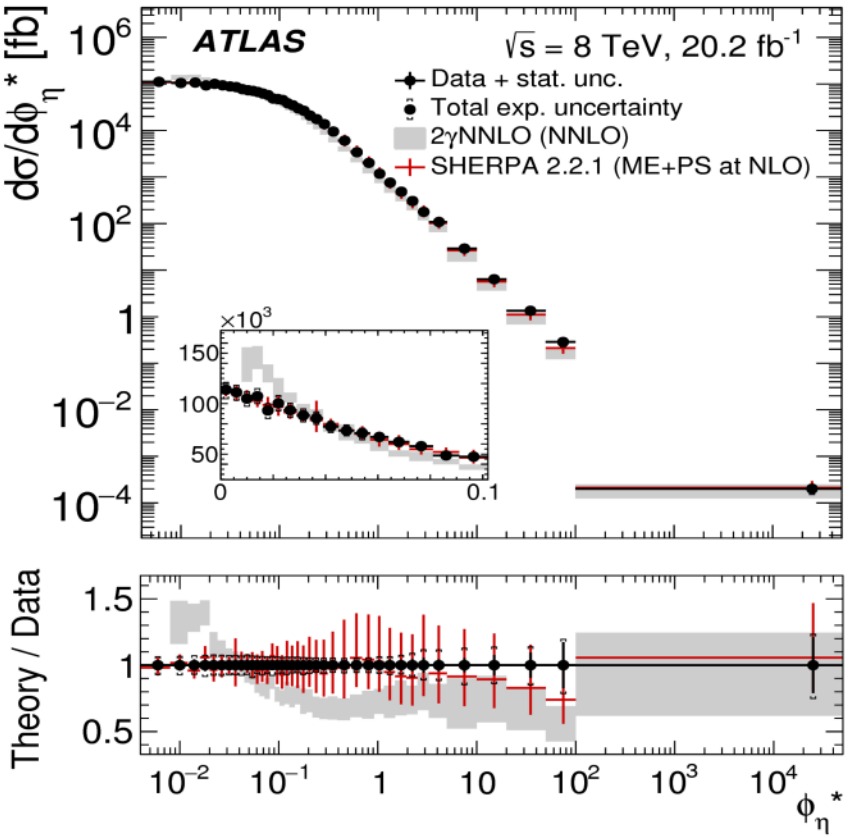
- 2 isolated γ's (new observable, similar pT)

$$\phi^* = \tan\left(\frac{\pi - \Delta\phi_{\gamma\gamma}}{2}\right)$$

  - sensitive to higher order QCD and soft gluon resummation

ATLAS arXiv:1704.03839





- soft gluon resummation, as in parton shower very essential for description !

Photon + jet measurements

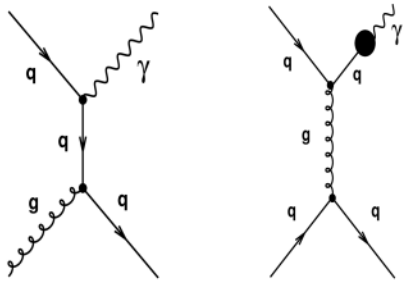
Photon+ 1 jet

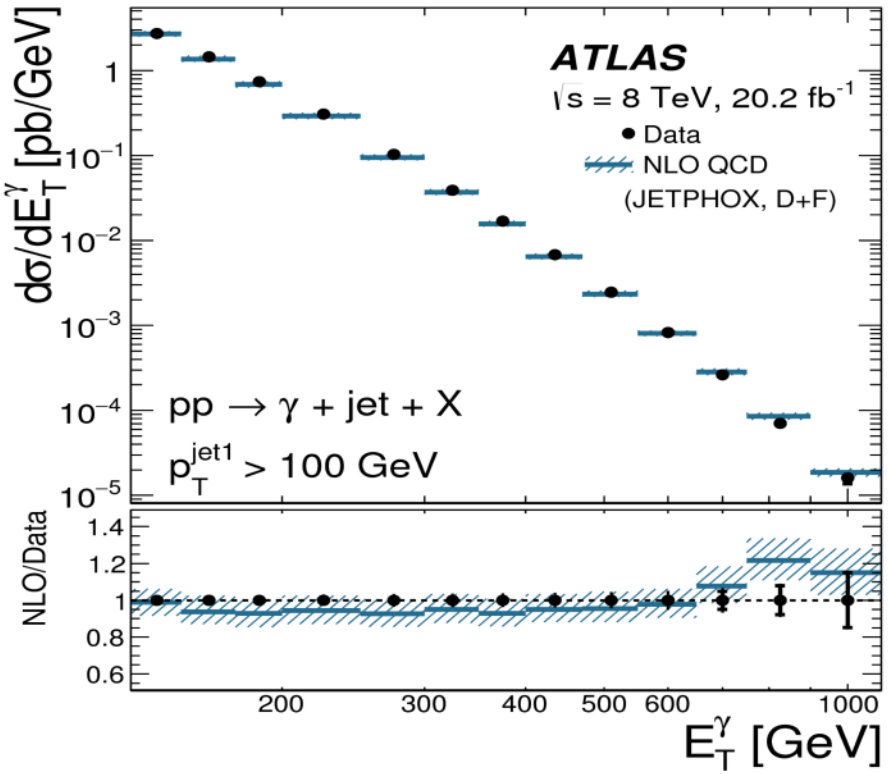
ATLAS Nucl.Phys. B918 (2017) 257

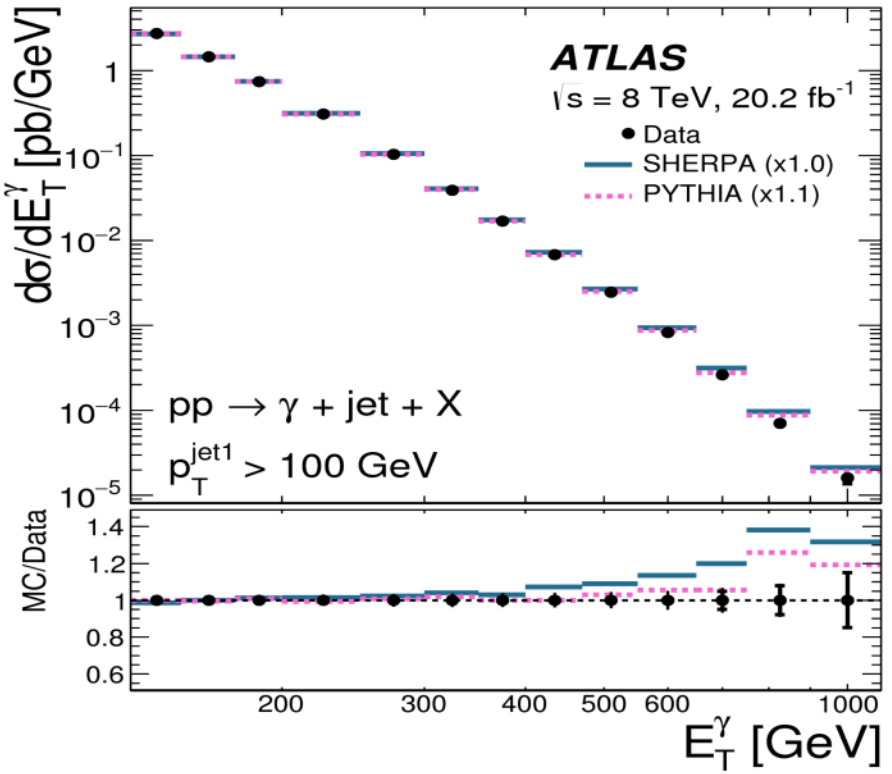
- isolated γ and jets in

$$|\eta^{\gamma}| < 2.37 \quad E_T^{\gamma} > 130\ GeV$$

PYTHIA: 2 → 2 +PS, Cteq6L1
SHERPA: → 5 partons, CT10nlo
JETPHOX (dir+res) CT10nlo + $\gamma\ frag.fct$







- NLO, and LO+PS work well !

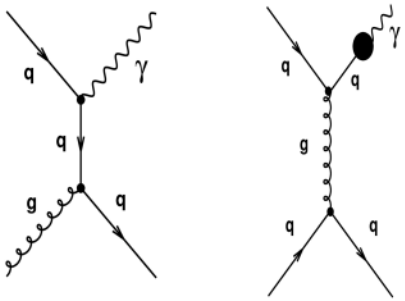
Photon+ 1 jet

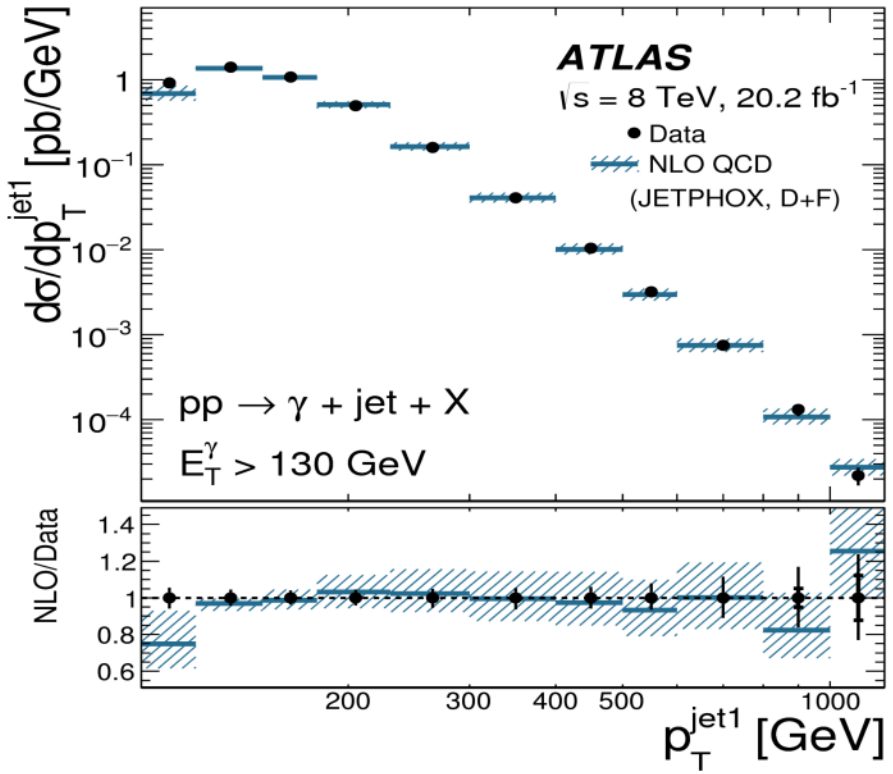
ATLAS Nucl.Phys. B918 (2017) 257

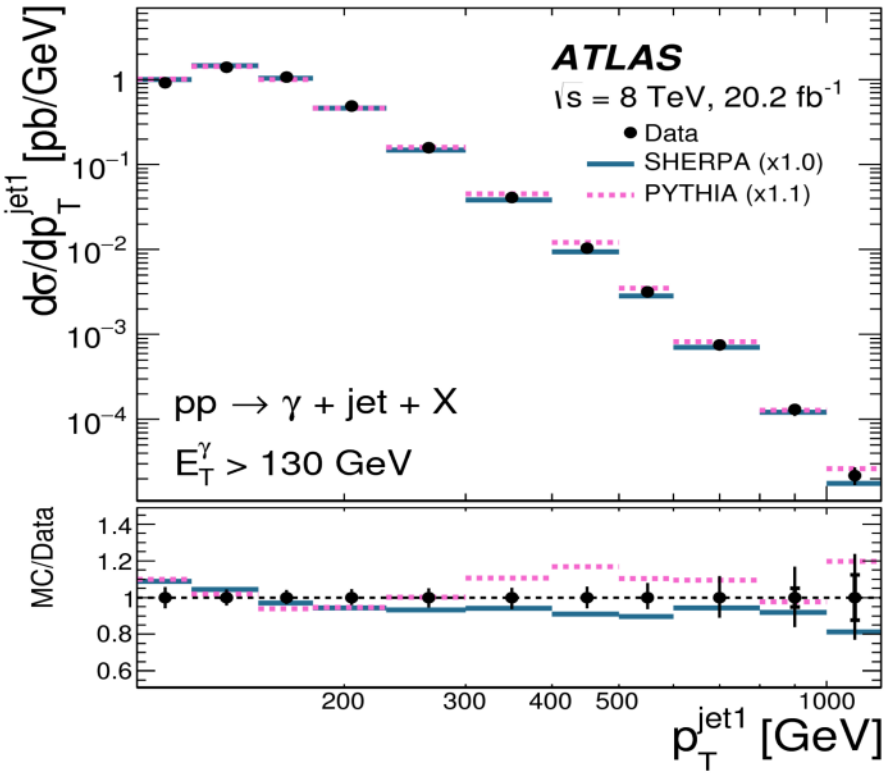
- isolated γ and jets in

  $|\eta^{\gamma}| < 2.37 \quad E_T^{\gamma} > 130\ GeV$

  PYTHIA: 2 → 2 +PS, Cteq6L1
  SHERPA: → 5 partons, CT10nlo
  BLACKHAT: direct → 3 partons CT10nlo







- NLO, and LO+PS work well !

Photon+ 2 jet

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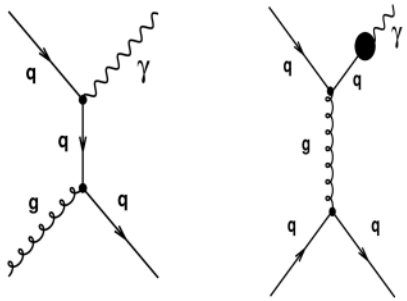
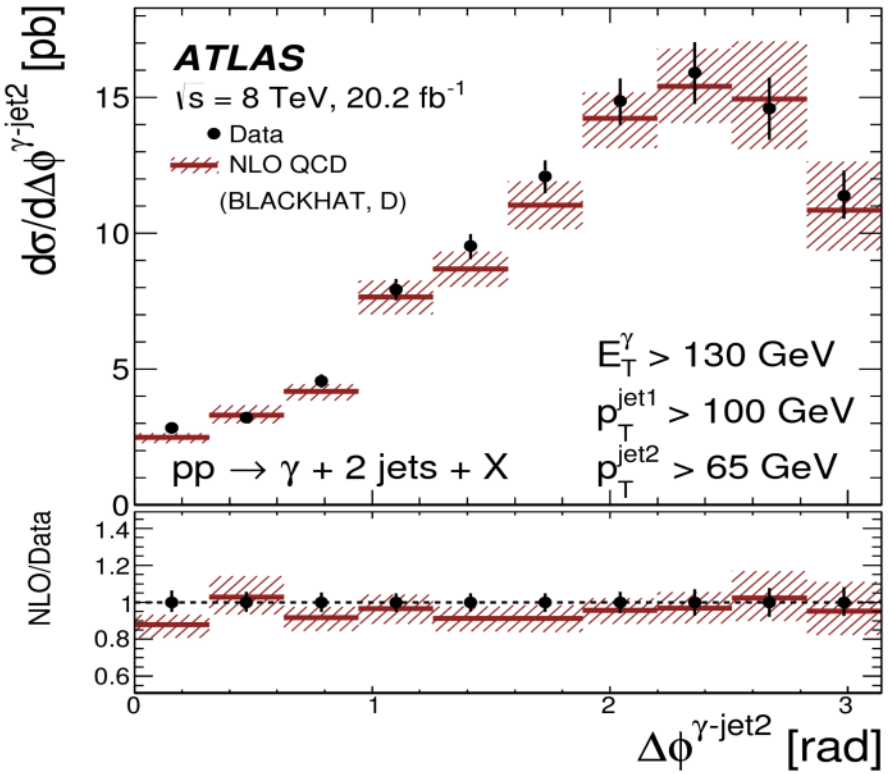
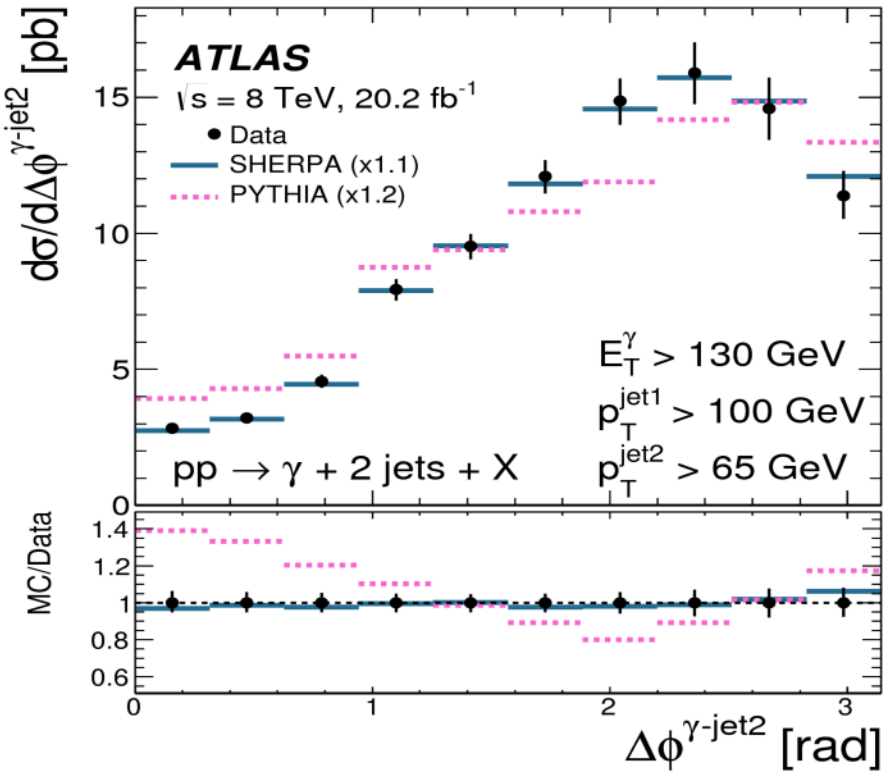
- isolated γ and jets in
  $|\eta^{\gamma}| < 2.37 \quad E_T^{\gamma} > 130\ GeV$

  PYTHIA: 2 → 2 +PS, Cteq6L1
  SHERPA: → 5 partons, CT10nlo
  BLACKHAT: direct → 3 partons CT10nlo





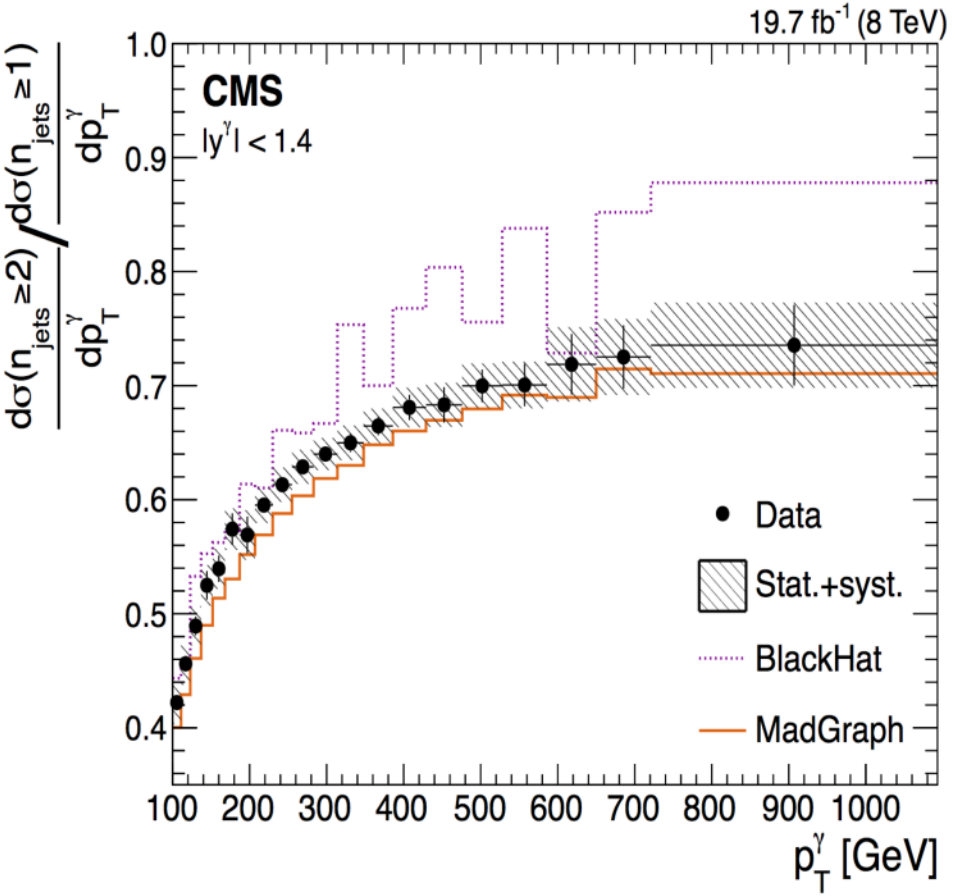


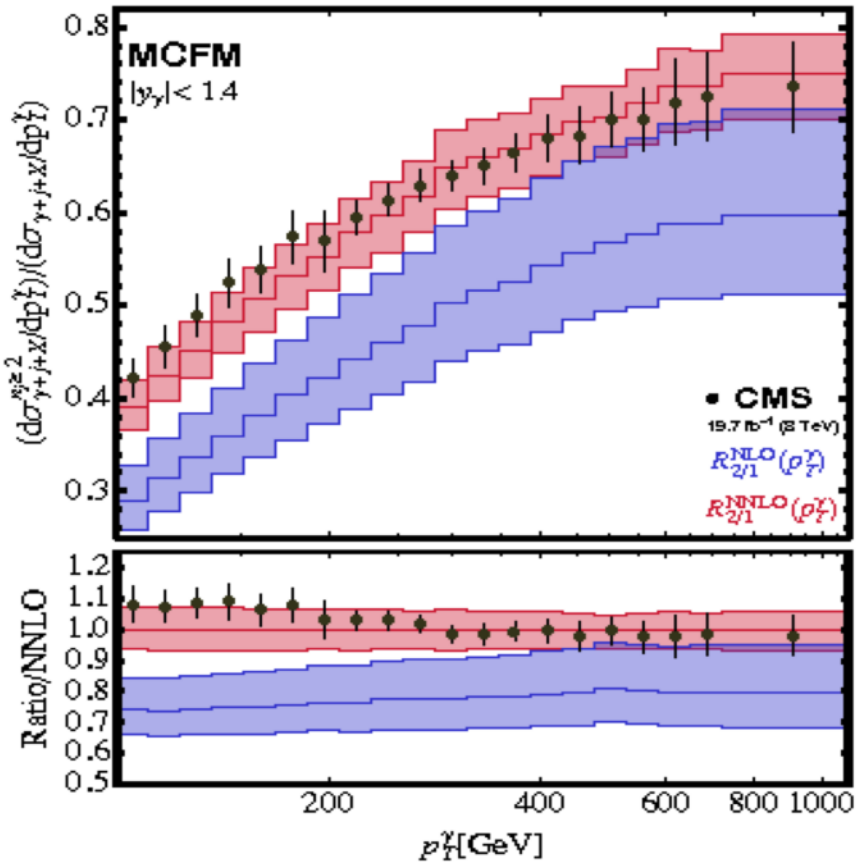
- deviations for 2→2 + PS (jet2 from PS)
- NLO and multi-leg LO work well

Photon+ 1/2 jet – NNLO calculation

CMS JHEP 1510 (2015) 128
Campbell, Ellis, Williams 1703.10109

- isolated γ with $E_T \geq 40\ GeV$ and jets (R=0.5) with $p_T > 30\ GeV, |\eta| < 2.4$
- measure $\gamma+2jet\ /\ \gamma+1jet$



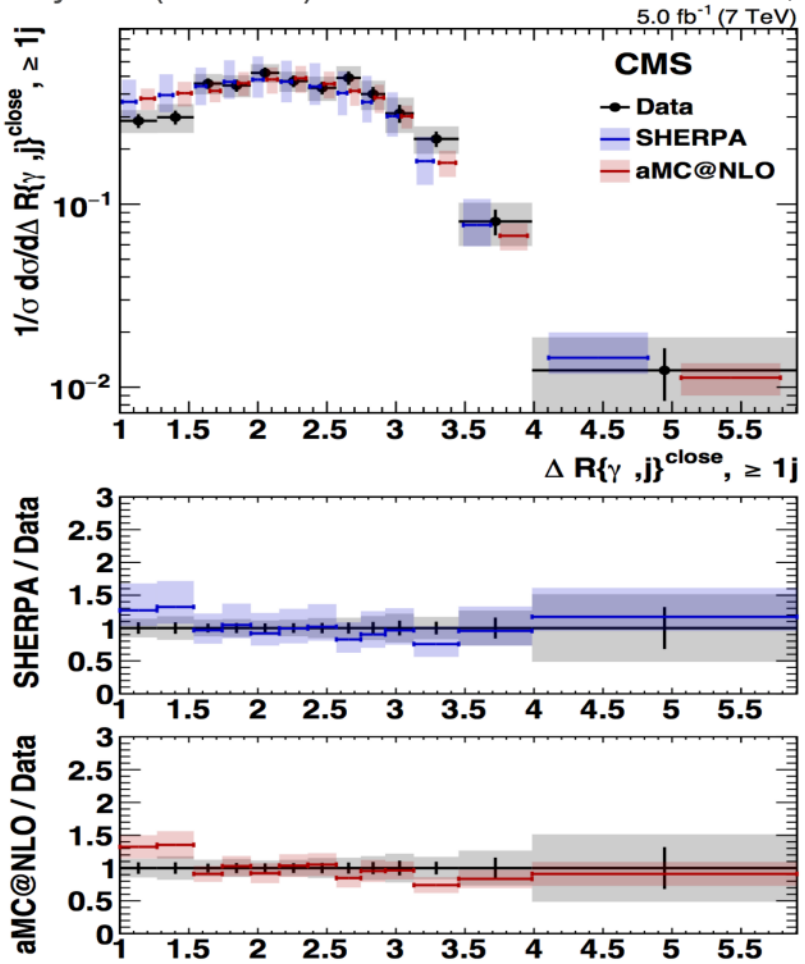


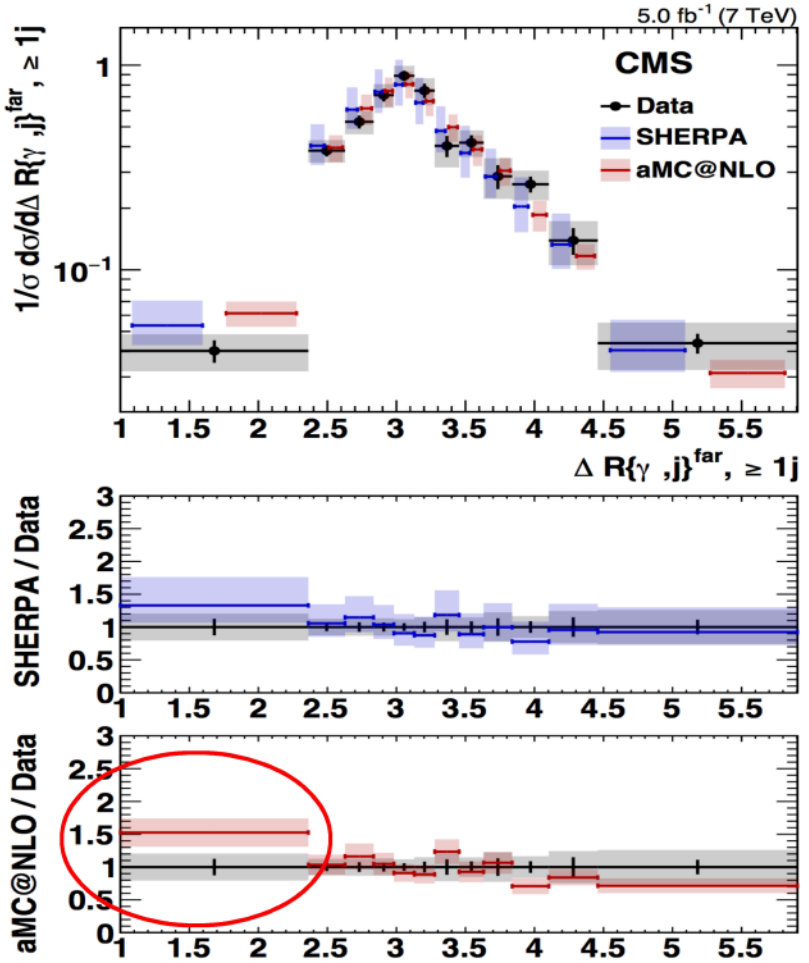
- recent NNLO calculation improves (compared to NLO) agreement with measurement

Photon pair + jets

- 2 isolated γ's with $E_T \geq 40\,(25)\ GeV$ and $|\eta| < 2.5$
- jets (R=0.5) with $p_T > 25\ GeV, |\eta| < 4.7$

CMS-PAS-SMP-14-021





- SHERPA (LO → 3partons), aMC@NLO (NLO ->2 partons) well. except small $\Delta\ R$

Issues in photon measurements

- $\gamma + jet(s)$
  - fixed higher order-and PS merged calculations able to describe measurements, even for correlations
- $\gamma\gamma + X$
  - even NNLO fixed order calculations are not enough in certain regions
  - new NNLO calculation for $\gamma\gamma + jets$ improves description
  - resummation of soft gluons (parton shower) is needed
    - sensitive to details of parton showers ?

Wishlist for boson + X measurements

- $\gamma + X$
  - NNLO prediction of differential cross section on various variables in addition to $p_T{}^{\gamma}$?
  - differential cross section at NNLO ?
  - calculations made available for experiments to run with our own selections ?
- $\gamma\gamma$ +X
  - differential NNLO cross sections?
- $W\gamma$ +X and $Z\gamma$ +X EWK
  - NLO EWK differential cross sections as function of different variables ?
- $W\gamma\gamma$ +X and $Z\gamma\gamma$+X
  - exclusive and inclusive NNLO cross sections?
  - differential NNLO cross sections?

Conclusions

- Inclusive jet cross section – benchmark for jet physics
  - measurements have small uncertainties, so higher order contributions – parton shower become important
- Multi-jet correlations
  - some distributions are not well described
  - sensitivity to differences in parton showering
- Photon Pair production
  - all order resummation in addition to fixed higher order contributions needed (as in DY)
- Photon + jet
  - higher order predictions and LO+PS describe most of distributions

- Measurements in jet area become sensitive to details of all order resummation (parton shower) and allow for detailed studies of color structure !

Many thanks to

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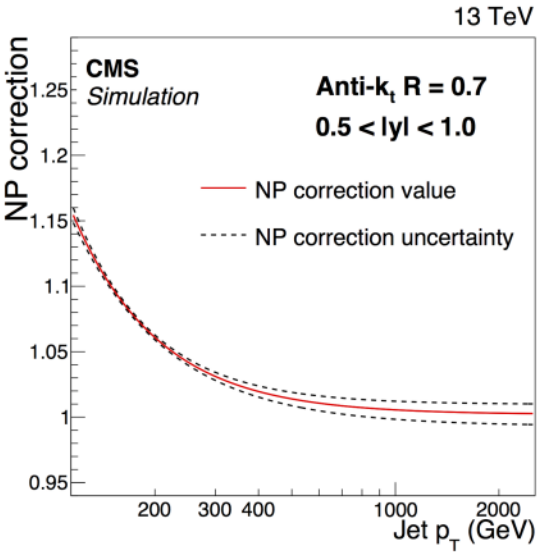
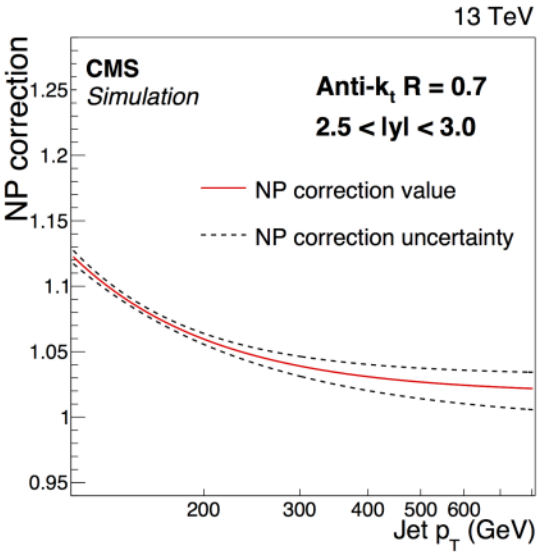
Kostas Theofilatos, Mayda Velasco
Mikko Voutilainen,
Patrick Connor, Armando Bermudez-Martinez,
Hyunyong Kim, Paolo Gunnellini

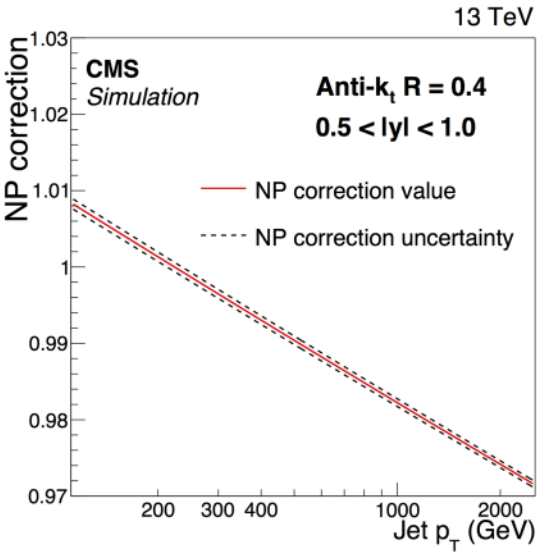
Appendix

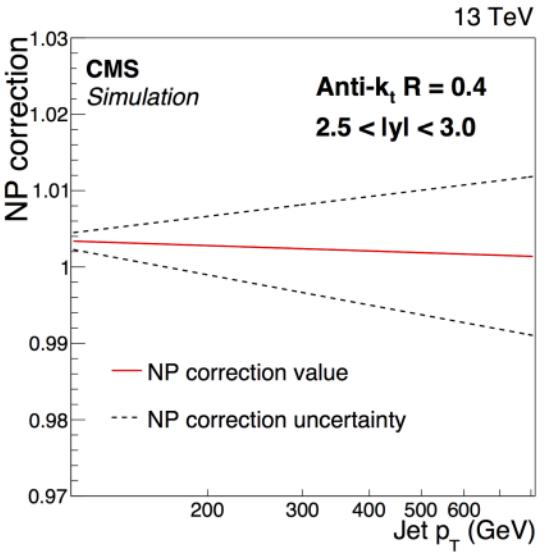
Non-pert correction factors for inclusive jets at 13 TeV

CMS Eur.Phys.J. C76 (2016) no.8, 451

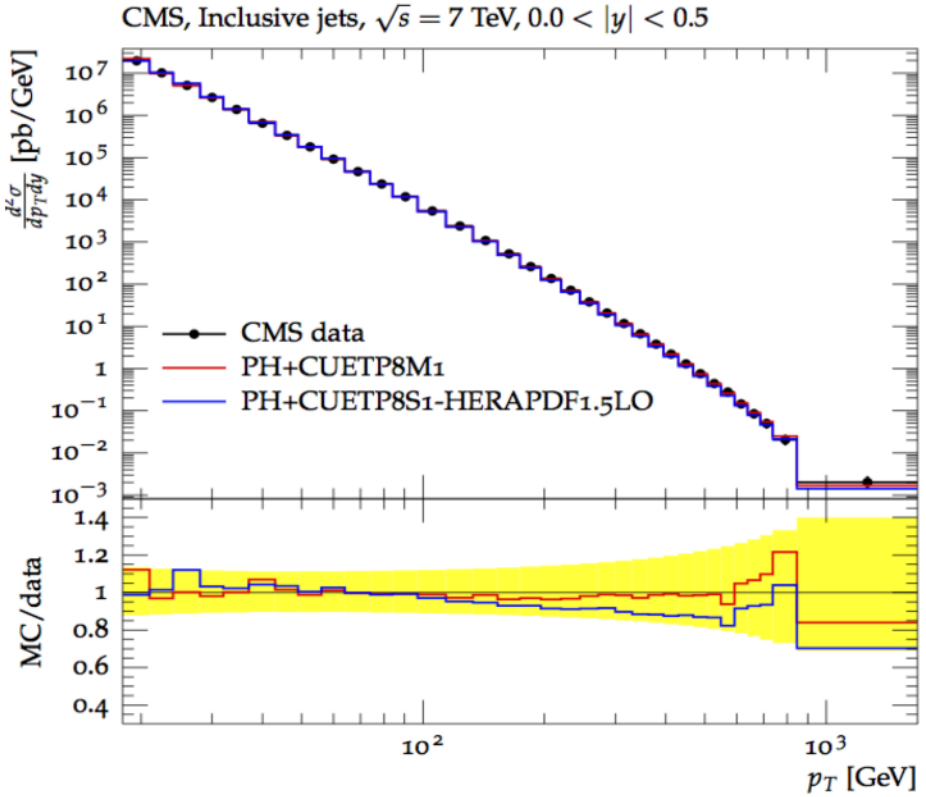


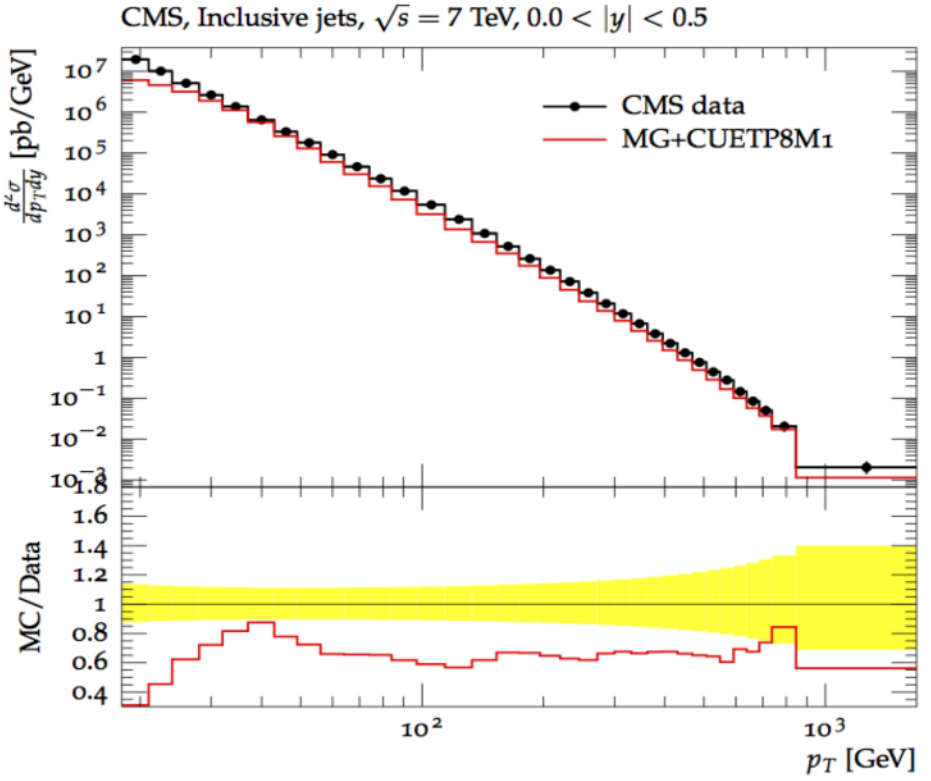






MADGRAPH – POWHEG: inclusive jets





- POWHEG with CUET tune works fine for inclusive jets
- MADGRAPH with CUET has different shape for inclusive jets
  - this a known effect … but not clear where it comes from !

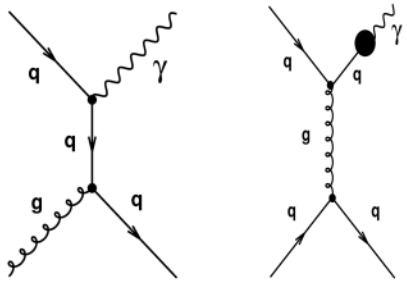
Photon+ 3 jets

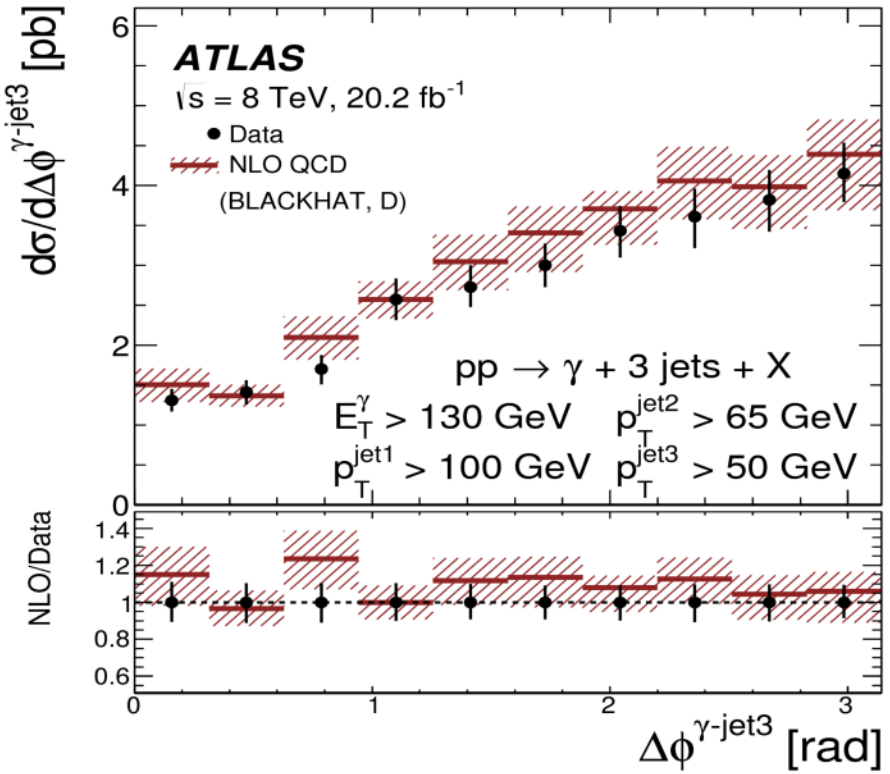
ATLAS Nucl.Phys. B918 (2017) 257

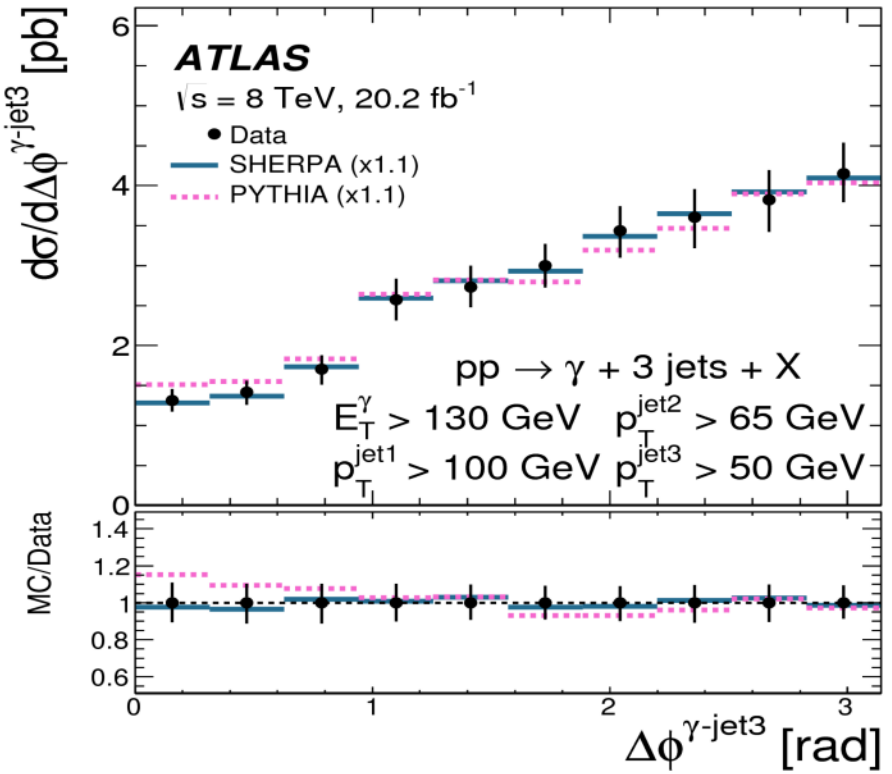
- isolated γ and 3 jets in

$$|\eta^{\gamma}| < 2.37 \quad E_T^{\gamma} > 130\ GeV$$

PYTHIA: 2 → 2 +PS, Cteq6L1
SHERPA: → 5 partons, CT10nlo
BLACKHAT: direct → 3 partons CT10nlo







- NLO, and LO+PS work well !

Photon pair production

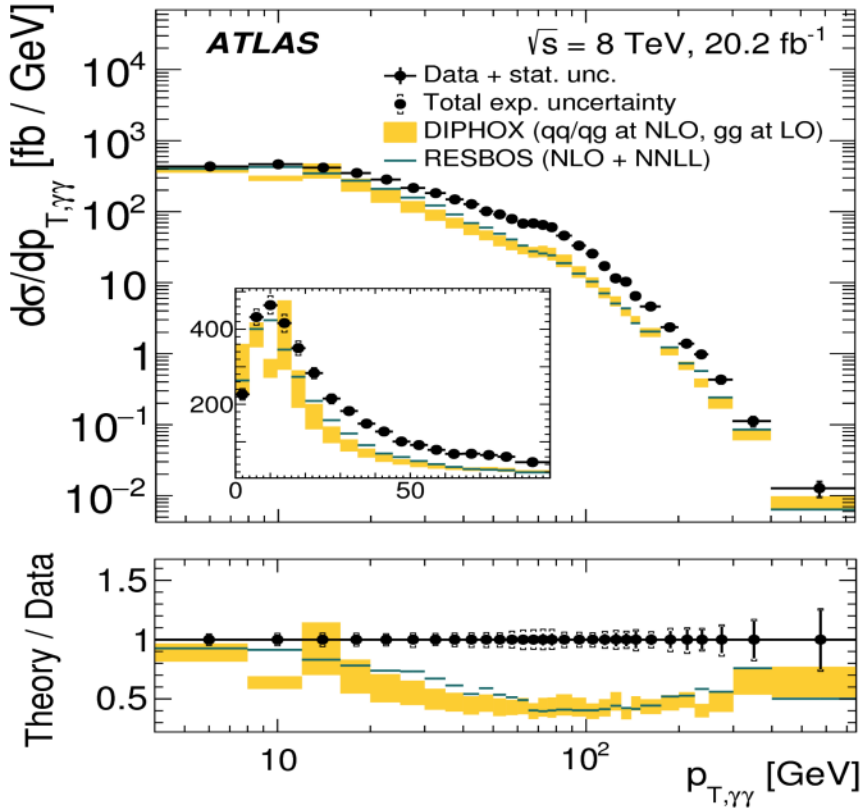
- 2 isolated γ's in

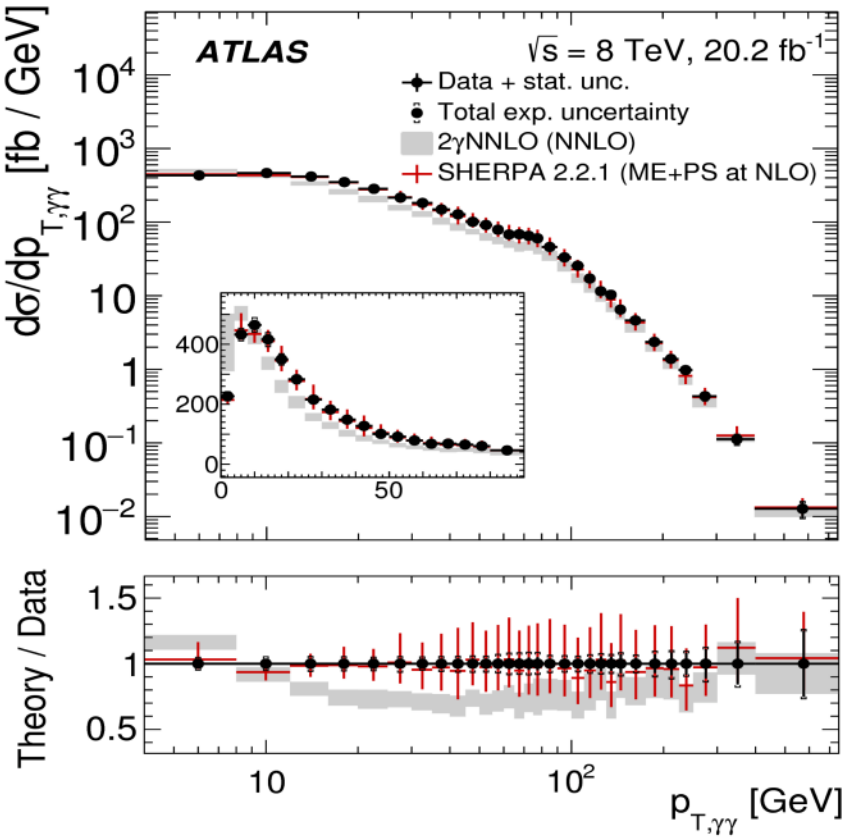
  $|\eta^{\gamma}| < 1.37$ *or* $1.56 < |\eta^{\gamma}| < 2.36$

  $E_{T1}^{\gamma} > 40\ GeV,\ E_{T1}^{\gamma} > 30\ GeV$

  - sensitive to higher order QCD and soft gluon resummation

ATLAS arXiv:1704.03839





- soft gluon resummation, as in parton shower very essential for description !

Photon pair production

- 2 isolated γ's in

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  $E_{T1}^{\gamma} > 40\ GeV,\ E_{T1}^{\gamma} > 30\ GeV$

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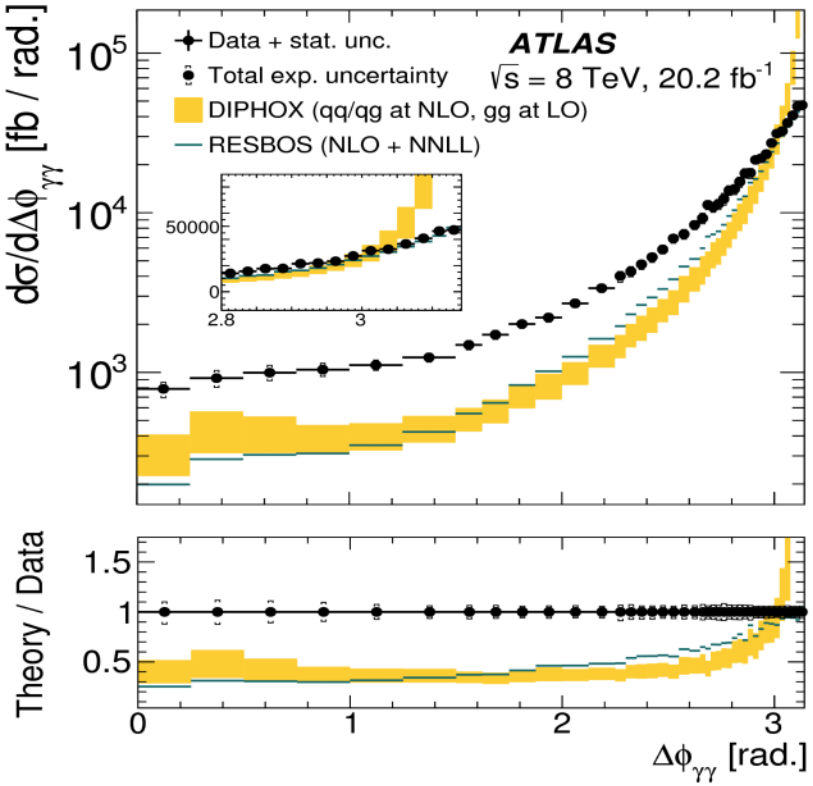

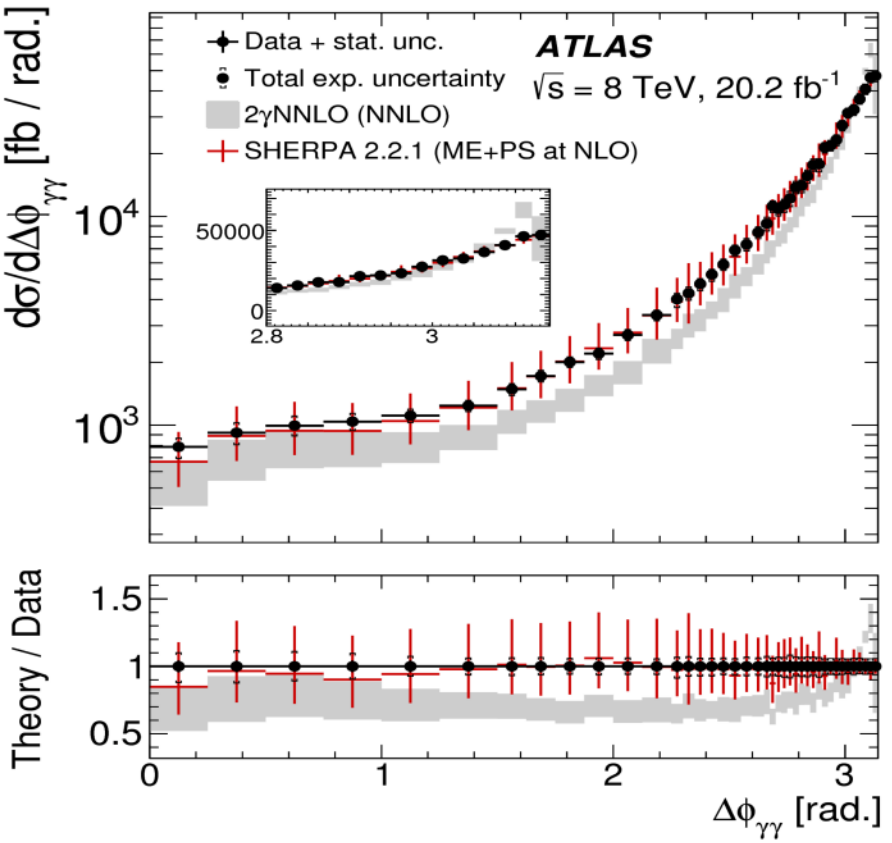

- soft gluon resummation very essential for description !
- NNLO parton level not enough !