Prompt photon production with POWHEG

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Work done with T. Jezo, C. Klein-Bösing, F. König, and H. Poppenborg

DFG

HELMHOLTZ GEMEINSCHAFT
Allianz für Astroteilchenphysik

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

References

Recent related publications:

- MK, C. Klein-Bösing, F. König, J.P. Wessels
  How robust is a thermal photon interpretation of the ALICE low-p_T data?
  JHEP 1310 (2013) 119 [arXiv:1307.7034]
- M. Brandt, MK, F. König
  Nuclear parton density modifications from low-mass lepton pair production at the LHC
  Nucl. Phys. A 927 (2014) 78 [arXiv:1401.6817]
- MK, F. König
  New information on photon fragmentation functions
  Eur. Phys. J. C 74 (2014) 3009 [arXiv:1403.2290]
- MK, C. Klein-Bösing, K. Kovarik, G. Kramer, M. Topp, J.P. Wessels
  NLO Monte Carlo predictions for heavy-quark production at the LHC: pp collisions in ALICE
  JHEP 1408 (2014) 109 [arXiv:1405.3083]

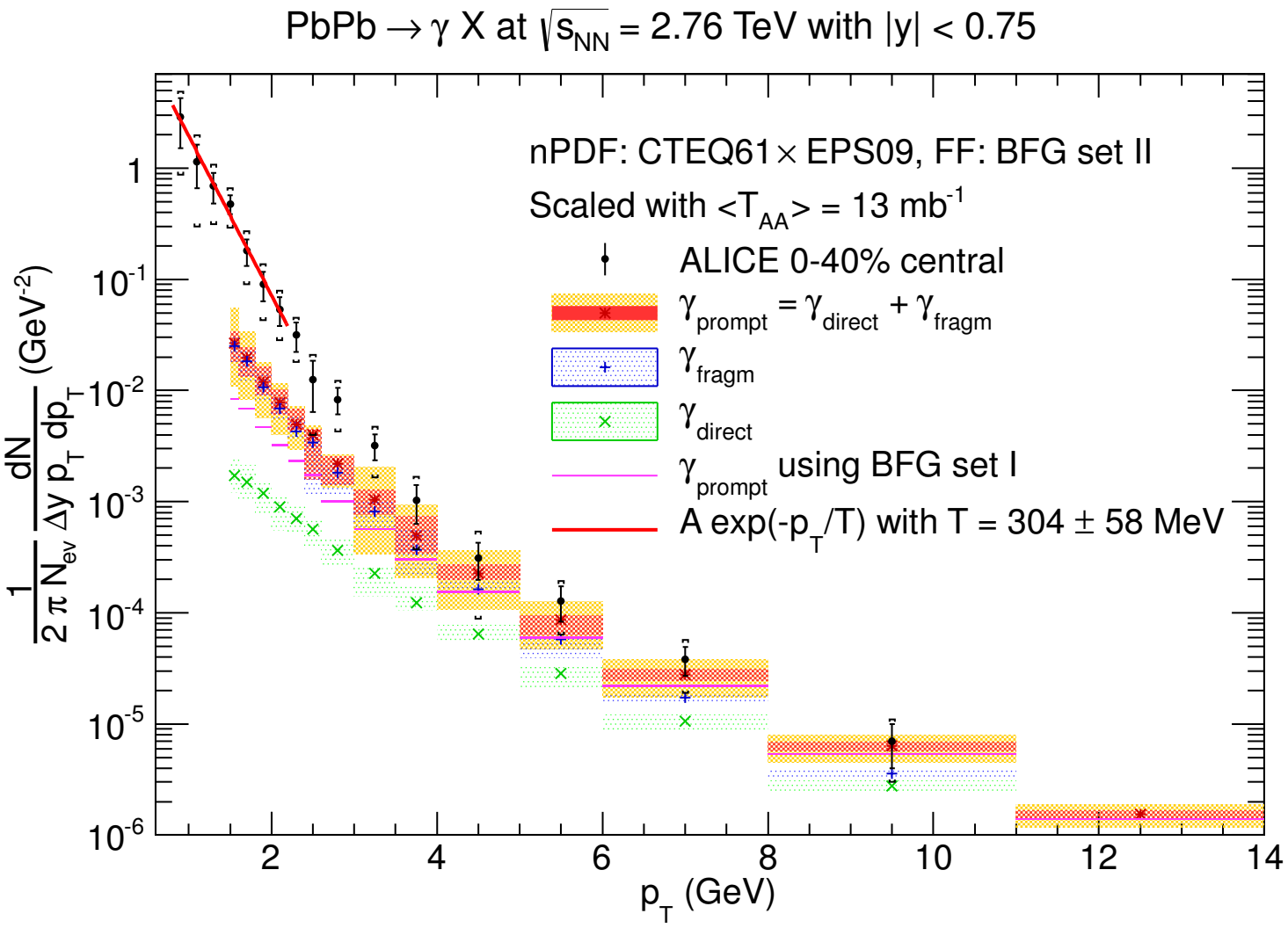
References

Other related publications:

- R. Kunnawalkam Elayavalli, K. Zapp
  Simulating V+jet processes in heavy ion collisions with JEWEL
  Eur. Phys. J. C 76 (2016) 695 [arXiv:1608.03099]
- J. Casalderey-Solana, D. Can Gulhan, J. Guilherme Milhano, D. Pablos, K. Rajagopal
  Predictions for boson-jet observables and fragmentation function ratios from a hybrid strong/weak coupling model for jet quenching
  JHEP 1603 (2016) 053 [arXiv:1508.00815]

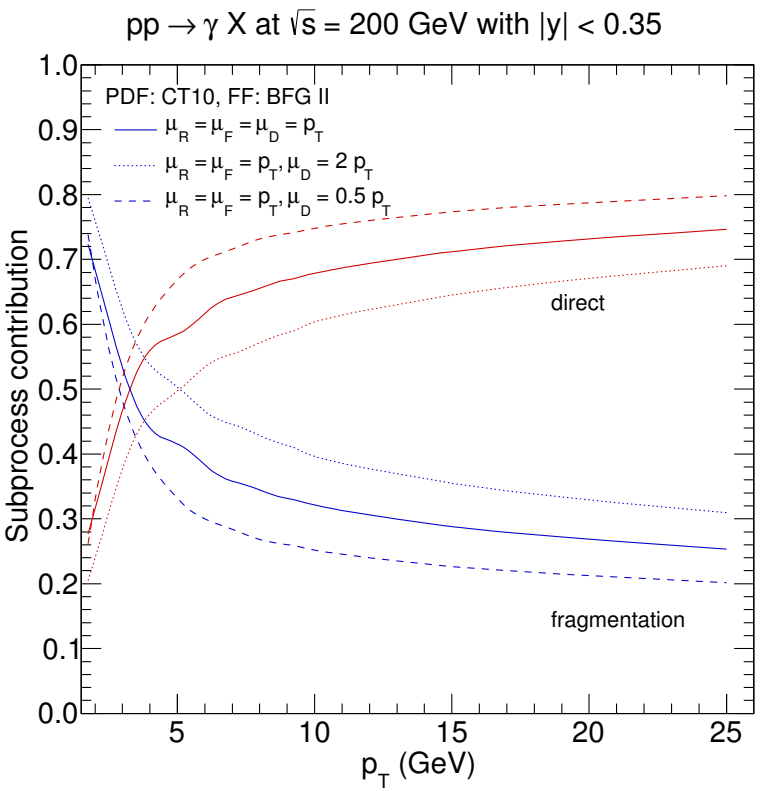
How robust is a thermal photon interpretation ...?

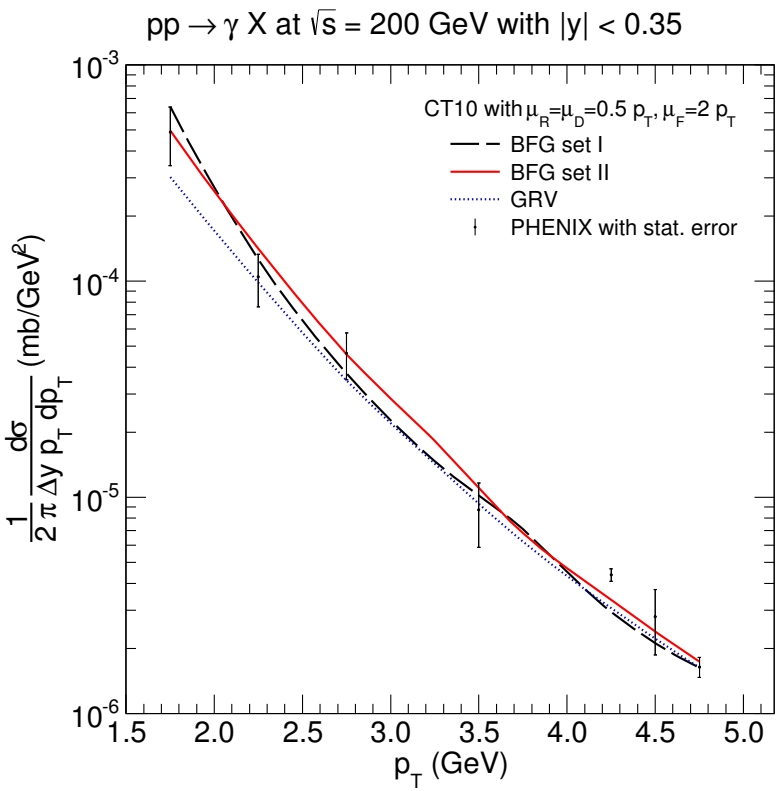
MK., C. Klein-Bösing, F. König, J.P. Wessels, JHEP 1310 (2013) 119



New information on photon fragmentation functions

MK., F. König, Eur. Phys. J. C 74 (2014) 3009





Recalculation of direct processes at NLO

T. Jezo, MK, F. König, JHEP 1611 (2016) 033

Leading order:

- Tree-level processes: $q\bar{q} \to \gamma g$, $qg \to \gamma q$
- Also with color and spin correlations (needed for POWHEG)
- Traces with FormCalc 8.4, checked against literature and MG5

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- Traces with FormCalc 8.4, checked against literature and MG5

Virtual corrections:

- One-loop processes: $q\bar{q} \to \gamma g$, $qg \to \gamma q$
- Tensor reduction w/ Form, scalar functions w/ LoopTools 2.13
- Renormalization in $\overline{\mathrm{MS}}$, checked against MG5_aMC@NLO

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Real corrections:

- Tree-level processes: $q\bar{q} \to \gamma gg(q\bar{q})$, $qg \to \gamma qg$, $gg \to \gamma q\bar{q}$
- Traces with FormCalc 8.4, checked against MG5
- Dipole subtraction, QCD checked against AutoDipole 1.2.3
- Integrated QED dipole reproduces fragmentation function

Reference calculation and choice of input parameters

NLO calculation: [P. Aurenche et al., Phys. Rev. D 73 (2006) 094007]

- JETPHOX
- Direct and fragmentation contributions

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Renormalization and factorization scales:

- $\mu = \mu_p = \mu_\gamma = p_T^\gamma$
- Variations by relative factors of two, but not four

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Photon fragmentation function: [L. Bourhis et al., Eur. Phys. J. C 2 (1998) 529]

- BFG set II

The POWHEG method

P. Nason et al., JHEP 0411 (2004) 040; 0711 (2007) 070; 1101 (2011) 095

NLO calculations:

- Increase normalization, reduce scale dependence $(\mu, \mu_{\boldsymbol{p}}, \mu_\gamma)$
- Include only one additional parton, no hadronization

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Parton shower Monte Carlos:

- Leading-order normalization, large scale dependence
- Many additional partons, different hadronization models

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NLO+PS with POWHEG:

- Subtract overlap with FKS [Frixione, Kunszt, Signer., Nucl. Phys. B 467 (1996) 399]
- Generate hardest radiation first, only positive weights
- Match to any PS (PYTHIA, HERWIG, ...) with p_T veto

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Required ingredients:

- Color- and spin-correlated squared Born amplitudes
- Finite (UV-renormalized and IR-subtracted) loop amplitudes
- Real emission squared amplitudes

Specific issues for photons

T. Jezo, MK, F. König, JHEP 1611 (2016) 033

"Fragmentation" contribution: [S. Höche et al., Phys. Rev. D 81 (2010) 034026]

- QED parton shower ($q \to q\gamma$), matched to NLO direct cont.
- Suppressed wrt. to QCD by α/α_s, color factors, multiplicities
- Globally only 2% photons in total QCD+QED event samples
- Reweight QED radiation by $C{=}50\,(100)$, check independence

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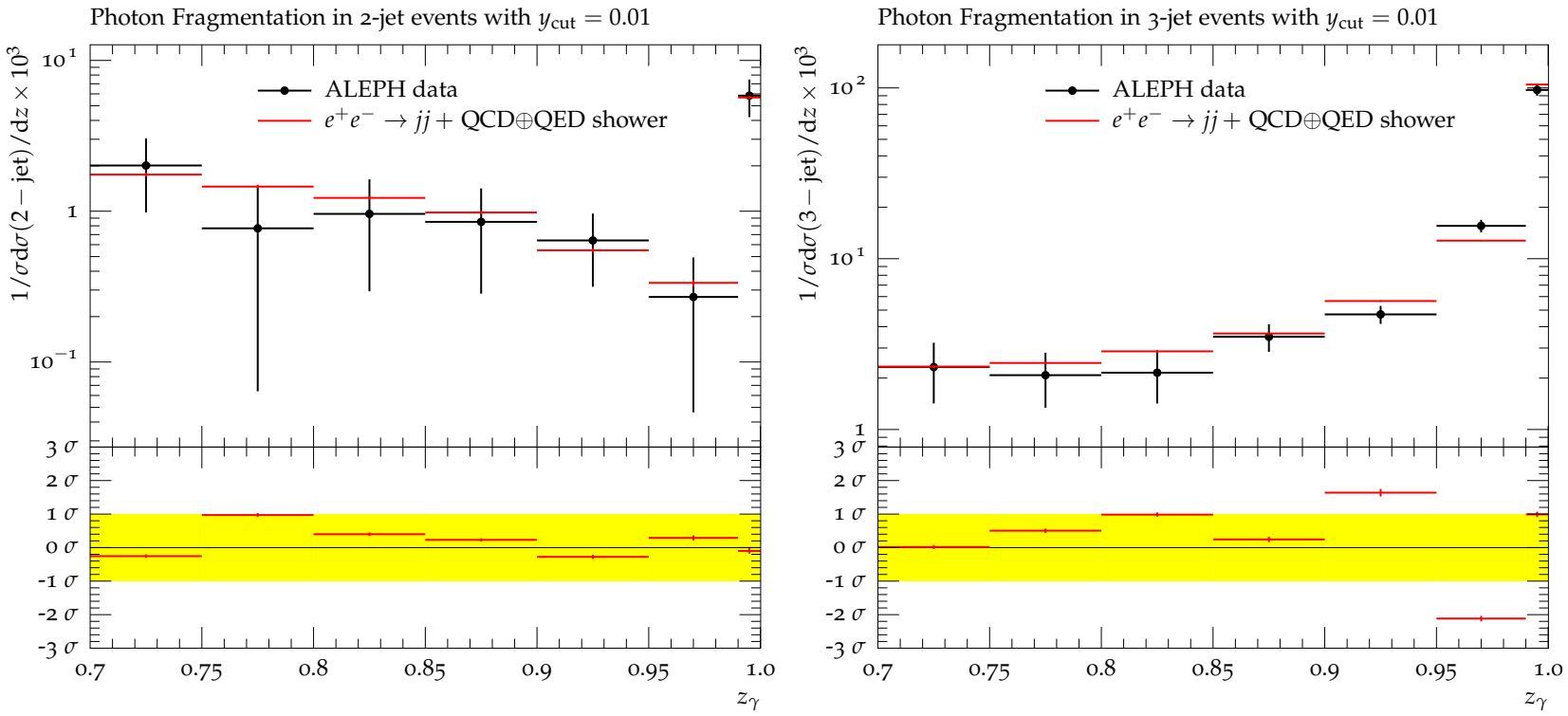
Symmetrization of parton splitting in the final state:

- `doublefsr=1`
- Reduces POWHEG cross section by 10%

Photon fragmentation function in 2- and 3-jet events

S. Höche et al., Phys. Rev. D 81 (2010) 034026 (Fig. 1)



Excellent description of ALEPH data [ALEPH Coll., Z. Phys. C 69 (1996) 365]

Works also for other jet resolution parameters $y_{\rm cut} \geq \min\left(\frac{E_i}{E_j}, \frac{E_j}{E_i}\right) \cdot \frac{s_{ij}}{s}$

Born suppression factor

P. Nason, C. Oleari, arXiv:1303.3922

Born-level event generation cut:

- $pp \to \gamma + X$ has coll. divergence at LO $\to$ impose $p_T > p_T^{\min}$
- Influences events at low $p_T \to$ region of interest for thermal γ
- Not applicable for studies of QGP

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Analytic Born suppression factor:

- Multiplies Born cross section
  - POWHEG ($p_{T,\mathrm{peak}} = 10$ GeV, power $i = 3$):

$$f_{\mathrm{sup.}} = \left(\frac{p_T^2}{p_T^2 + p_{T,\mathrm{peak}}^2} \right)^i$$

  - Approximation of $\Theta(p_T - p_T^{\min})$ (e.g. with $p_T^{\min} = 1$ GeV):

$$f_{\mathrm{sup.}} = \frac{1}{\pi} \left[\arctan[(p_T - p_T^{\min}) \cdot 10^4] + \frac{\pi}{2} \right]$$

- Events then reweighted by $1/f_{\mathrm{sup.}}$, checked independence

Experimental conditions at RHIC

PHENIX Collaboration at RHIC

Center-of-mass energy: $\sqrt{s}_{\mathrm{pp}} = 200$ GeV

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Inclusive photons: [Phys. Rev. C 87 (2013) 054907 and D 86 (2012) 072008]

- $\mathcal{L}$ (Run 2006) $= 4.0$ and 8.0 pb^{-1}
- $p_T^\gamma \in [1; 5]$ and $[5; 25]$ GeV
- $|\eta^\gamma| < 0.35$

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Isolated photons: [Phys. Rev. D 86 (2012) 072008]

- $E^{\mathrm{had.}}/E^\gamma \leq 0.1$
- $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq 0.5$

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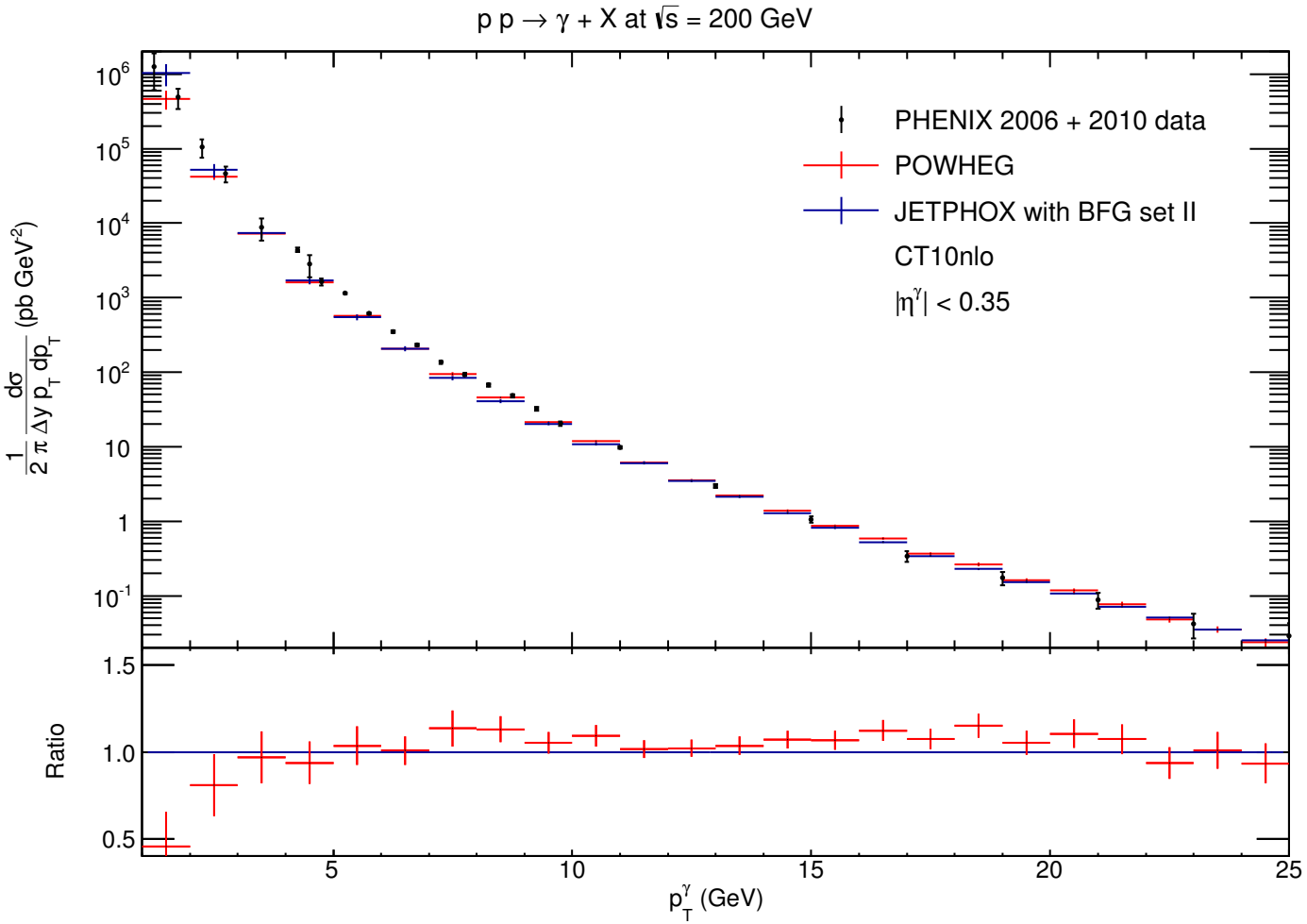
Photons + jets: [Phys. Rev. C 80 (2009) 024908]

- $\mathcal{L}$ (Runs 2005 + 2006) $= 3.0 + 10.7$ pb^{-1}
- Anti-k_T cluster algorithm with $R = 0.4$

Comparison of NLO and POWHEG with PHENIX data

T. Jezo, MK, F. König, JHEP 1611 (2016) 033

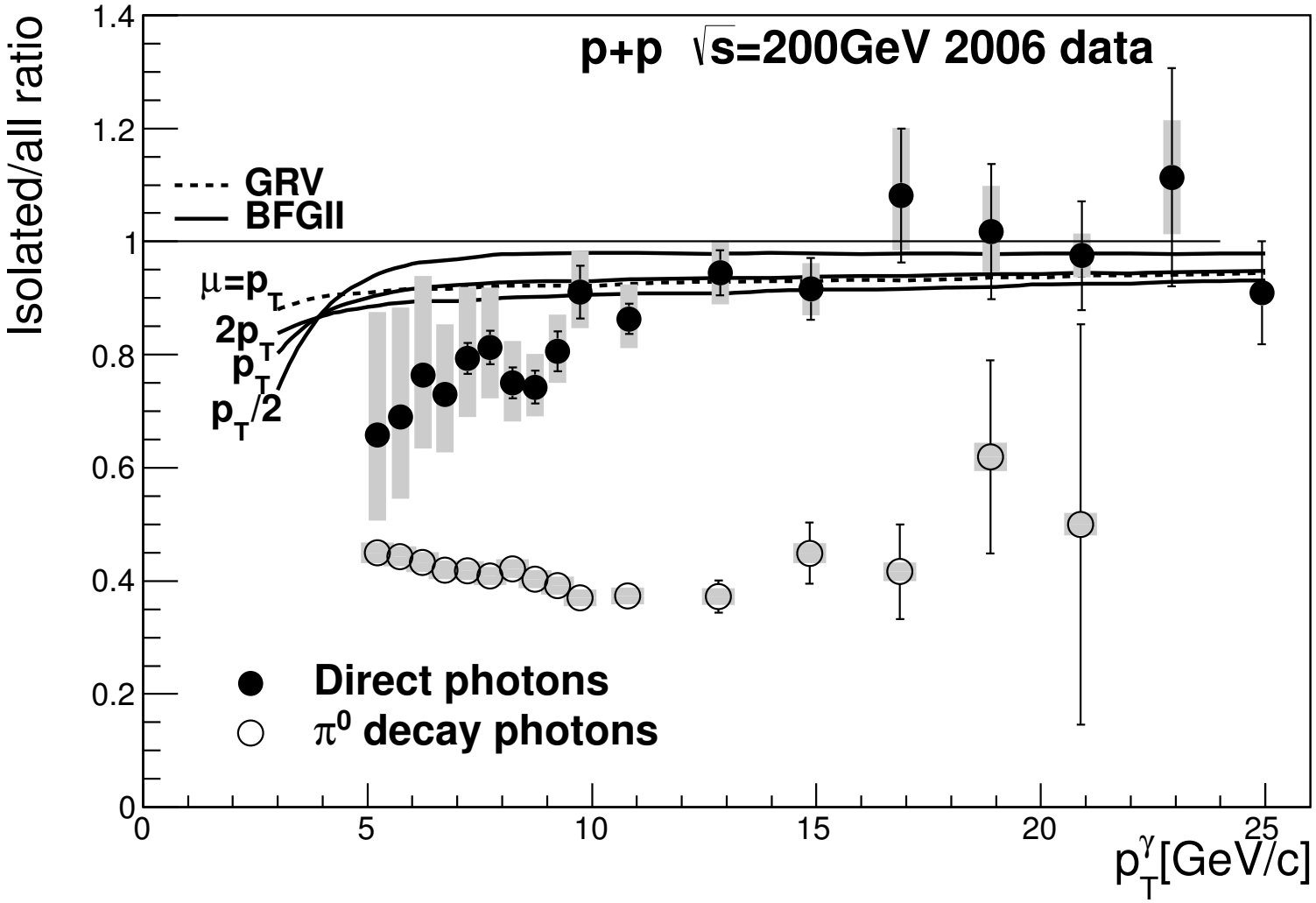


JETPHOX ($\mu = \mu_p = \mu_\gamma = p_T$) too large at low p_T → fragmentation cont.

JETPHOX ($\mu = \mu_p = 0.5\, p_T$, $\mu_\gamma = 2\, p_T$) better [MK, F. König, EPJC 74 (2014) 3009]

Fraction of isolated photons at NLO

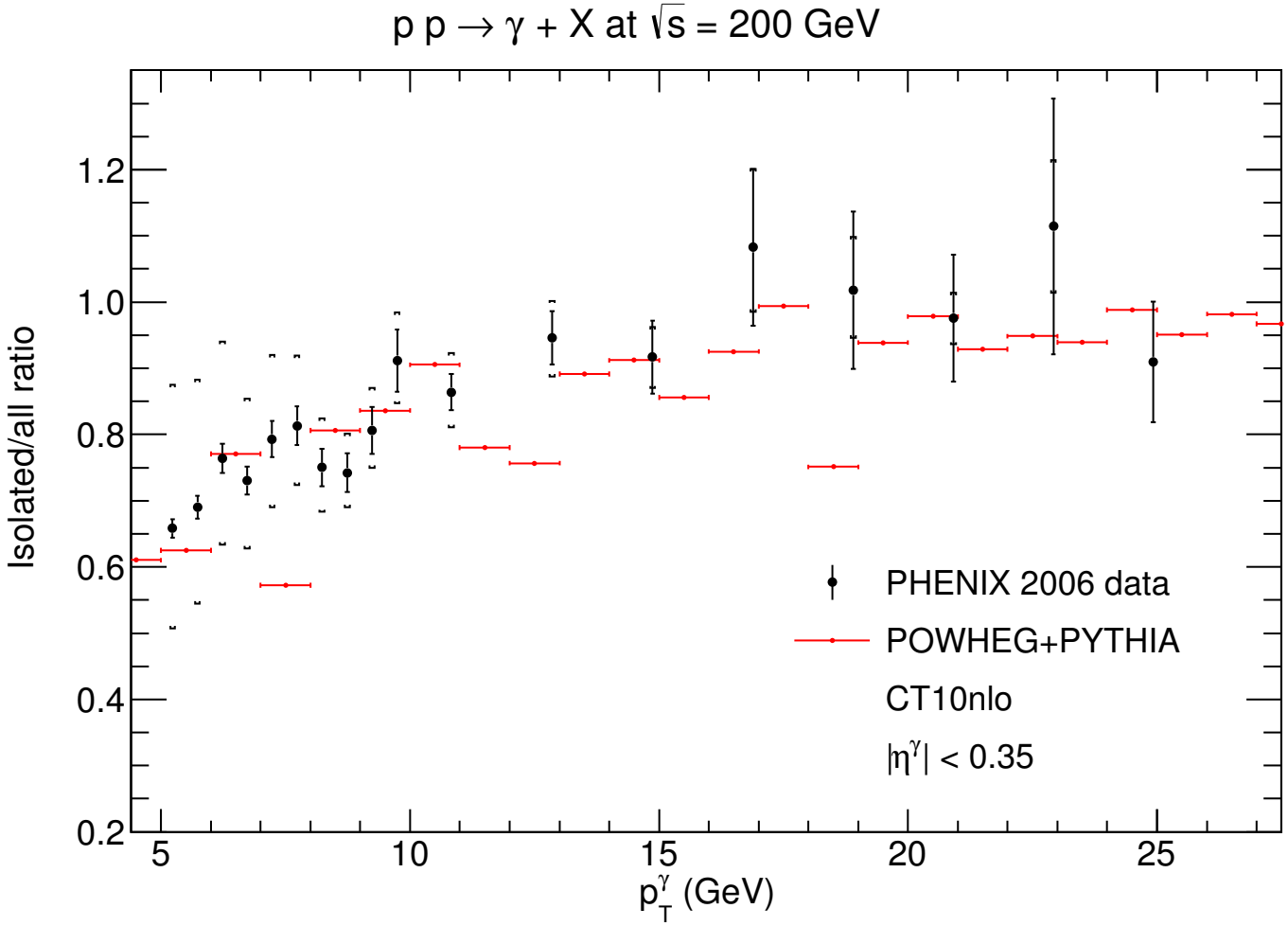
PHENIX Coll., Phys. Rev. D 86 (2012) 072008 (Fig. 13)



NLO too high at small and intermediate p_T for all scale choices

Fraction of isolated photons with POWHEG

T. Jezo, MK, F. König, JHEP 1611 (2016) 033

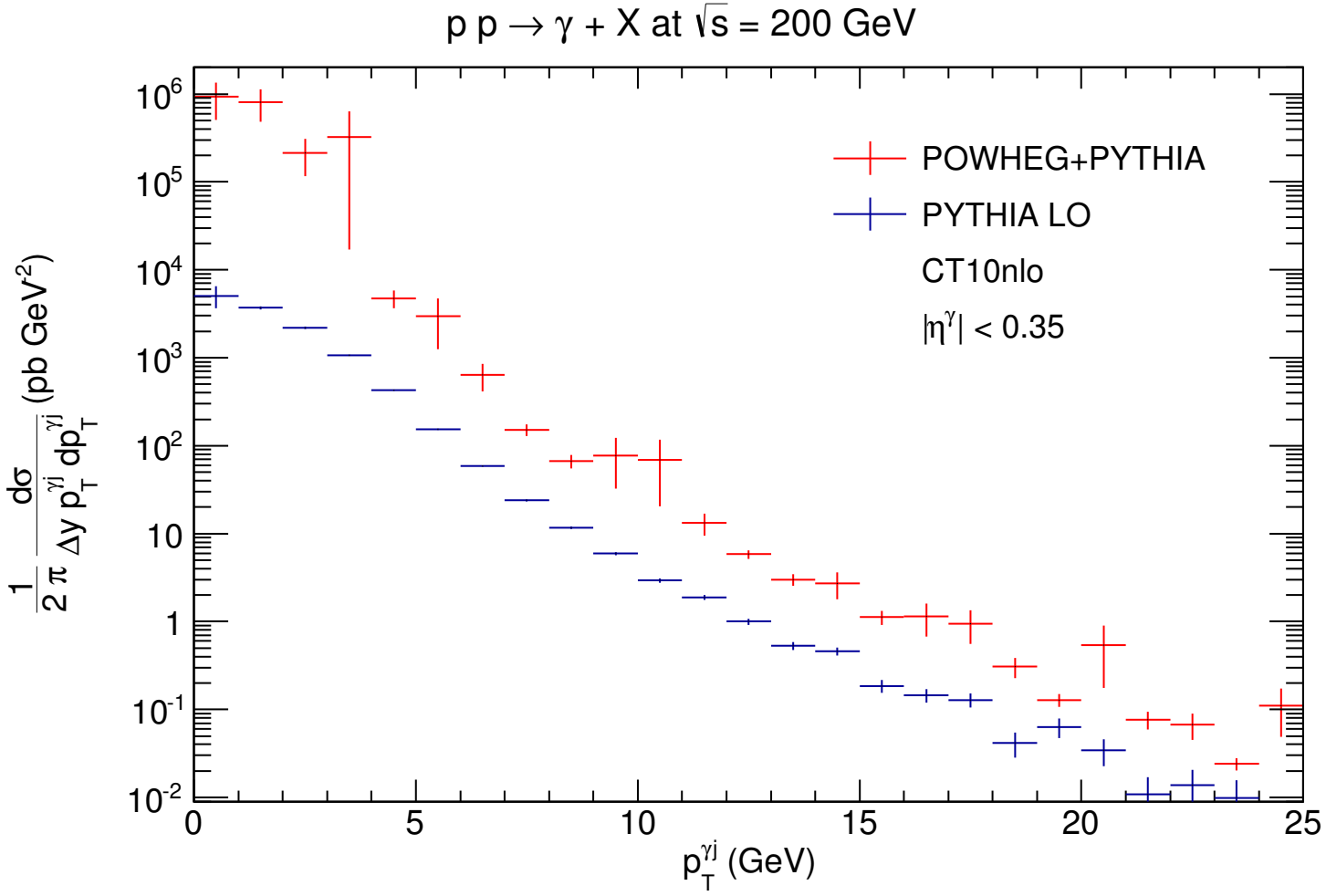


POWHEG gives first correct description

Scale uncertainty cancels completely (no fragmentation cont.)

Transverse momentum balance of photons and jets

T. Jezo, MK, F. König, JHEP 1611 (2016) 033



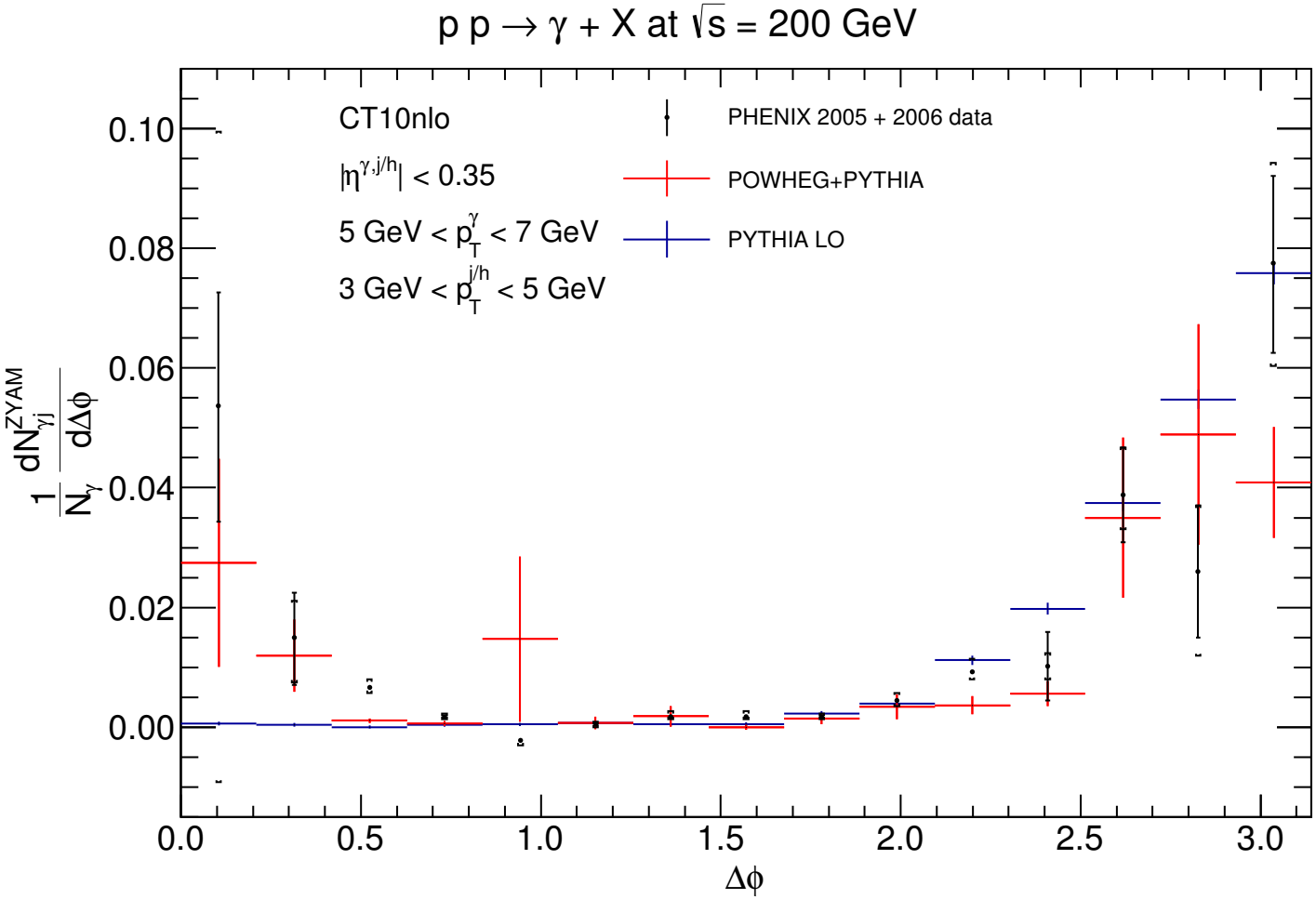
Individual cuts on $p_T^\gamma > 1$ GeV and $p_T^j > 1$ GeV

At $p_T^{\gamma j} \to 0$ NLO diverges, PYTHIA/POWHEG have finite turnover

PYTHIA underestimates absolute cross section in particular at low p_T

Azimuthal correlation of photons and jets

T. Jezo, MK, F. König, JHEP 1611 (2016) 033

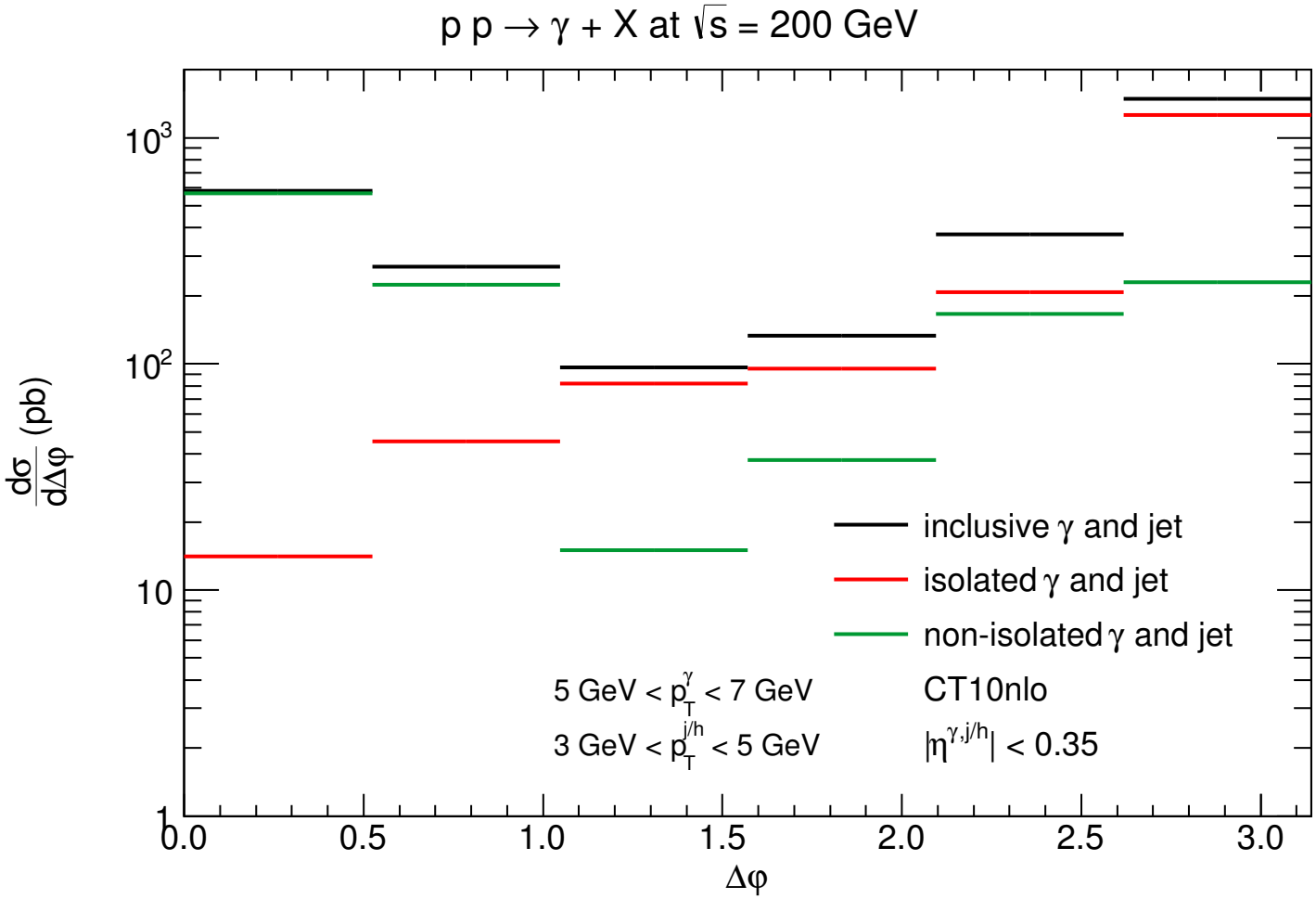


At $\Delta\phi \to \{0, \pi\}$ NLO diverges, PYTHIA/POWHEG have finite turnover

PYTHIA has no "fragmentation" and wrong normalization (not shown)

Contributions of isolated and "fragmentation" photons

T. Jezo, MK, F. König, JHEP 1611 (2016) 033



"Fragmentation" processes mostly collinear ($\Delta\phi \simeq 0$, but also π)

Experimental conditions at LHC

ATLAS Coll., arXiv:1701.06882, Phys. Lett. B (in press)

Proton-proton collisions:

- $\sqrt{s}_{\mathrm{pp}} = 13$ TeV
- $\mathcal{L}\ (\mathrm{Run}\ 2015) = 3.2\ \mathrm{fb}^{-1}$

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Isolated photons:

- In $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$, $E_T^{\rm iso} \leq 4.8 + 4.2 \cdot 10^{-3} \cdot E_T^{\gamma}$
- $p_T^{\gamma} > 125$ GeV and $|\eta^{\gamma}| < 0.6$ up to $1.81 < |\eta^{\gamma}| < 2.37$

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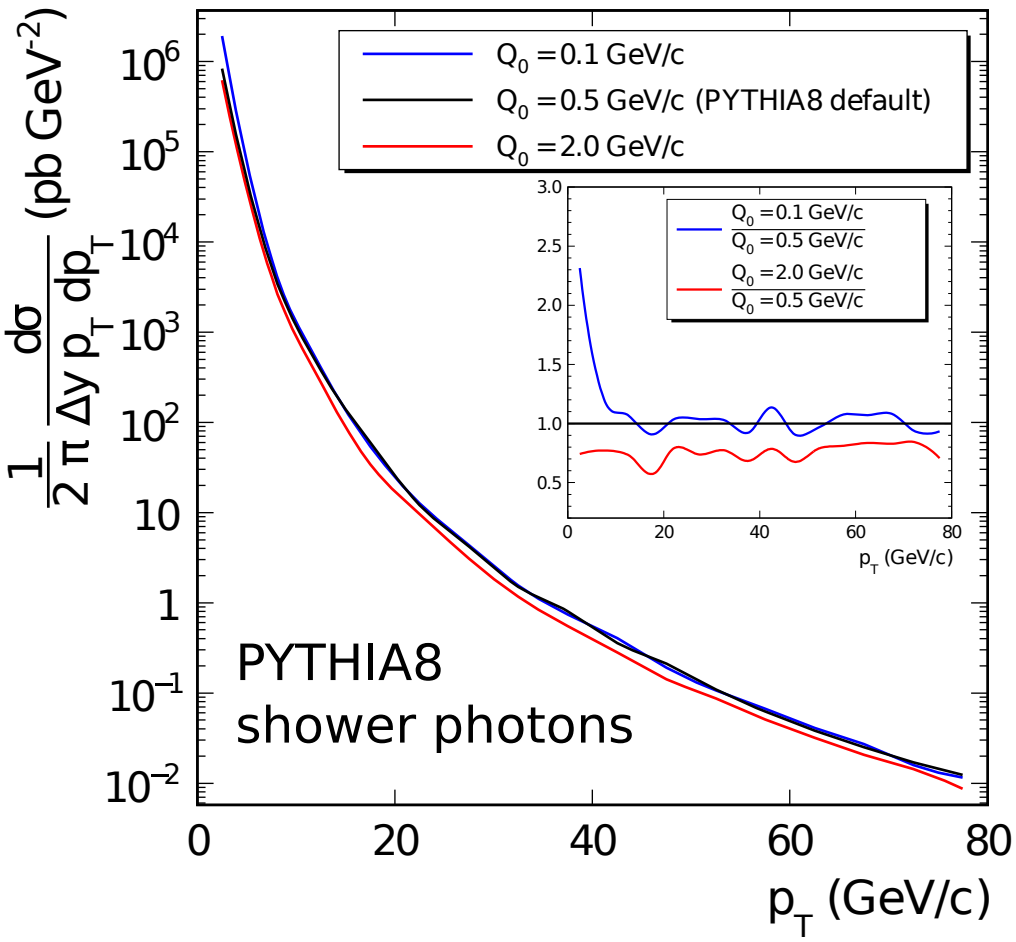
- $p_T^\gamma > 125$ GeV and $|\eta^\gamma| < 0.6$ up to $1.81 < |\eta^\gamma| < 2.37$

Choice of scales and PDFs:

- $\mu = \mu_f = p_T^\gamma$, variations by relative factors of two (not four)
- No variations of Q_0 for QED final state shower and μ_γ
- NNPDF2.3QED LO/NLO (cf. Monash 2013, similar to CT14)

Sensitivity to QED shower cutoff scale Q_0

MK, C. Klein-Bösing, H. Poppenborg, to be published

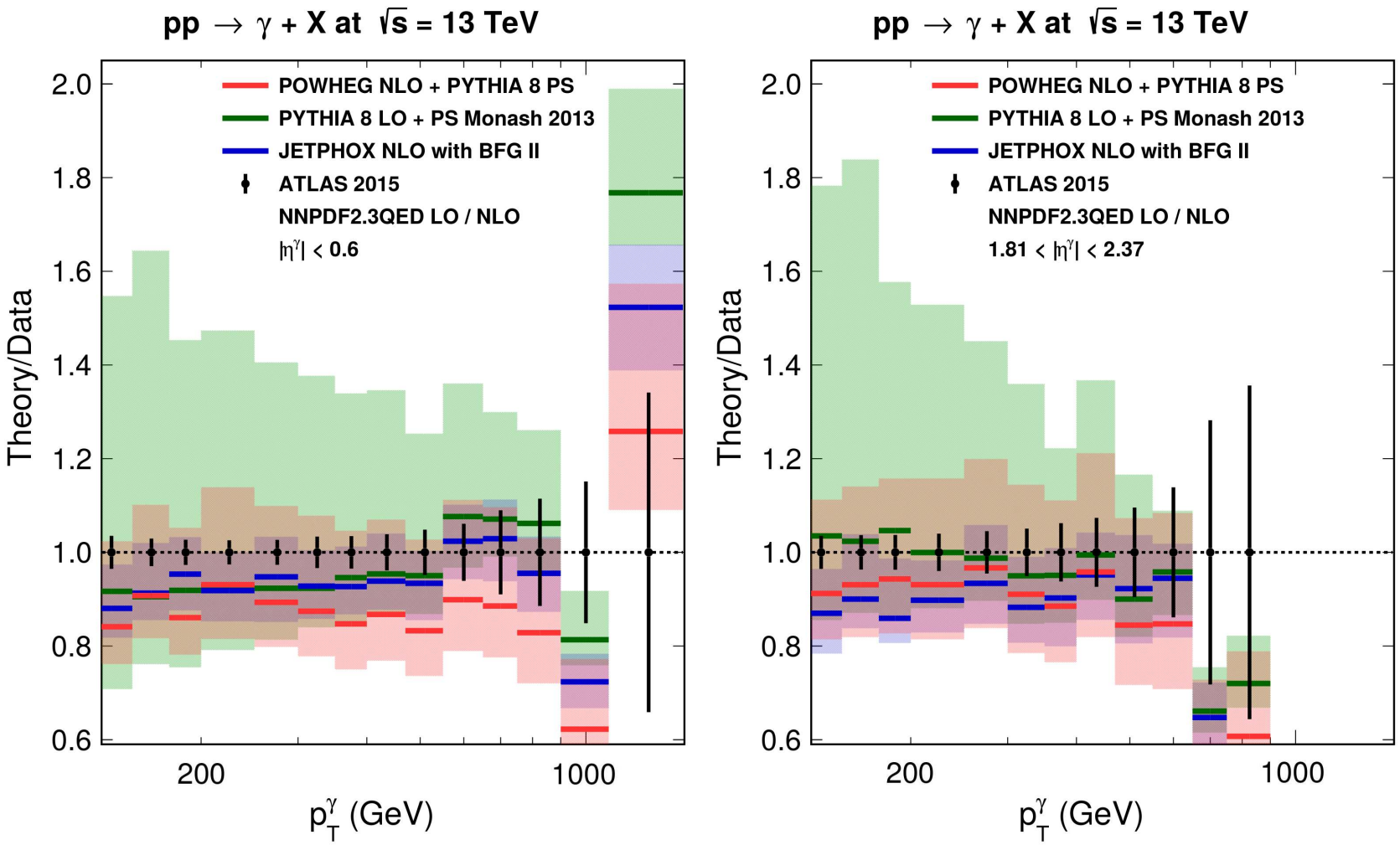


PYTHIA 8 LO very sensitive to infrared cutoff Q_0 at low p_T^γ

POWHEG NLO has cancellation of virtual and soft divergences

Transverse momentum of isolated photons with ATLAS

MK, C. Klein-Bösing, H. Poppenborg, to be published



Inclusive photons → no significant differences

PYTHIA 8 LO + PS is tuned (Monash 2013) → large uncertainties

Experimental conditions at LHC (2)

CMS Coll., CMS PAS HIN-13-006

Proton-proton and proton-lead collisions:

- $\sqrt{s}_{\mathrm{pp}} = 2.76$ TeV, $\mathcal{L}$ (Run 2013) $=$ 5.3 pb^{-1}
- $\sqrt{s}_{\mathrm{pPb}} = 5.02$ TeV, $\mathcal{L}$ (Run 2013) $= 30.4$ nb^{-1}

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Isolated photons:

- In $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$, $E_T^{\mathrm{iso}} \leq 5$ GeV
- No photons with $|\eta^\gamma - \eta^{\mathrm{track}}| < 0.02$, $|\phi^\gamma - \phi^{\mathrm{track}}| < 0.15$
- $p_T^\gamma > 40$ GeV and $|\eta^\gamma| < 1.44$

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- $p_T^\gamma > 40$ GeV and $|\eta^\gamma| < 1.44$

Jets:

- Anti-k_T cluster algorithm with $R = 0.3$
- $p_T^{\mathrm{jet}} > 30$ GeV and $|\eta^{\mathrm{jet}}| < 1.6$

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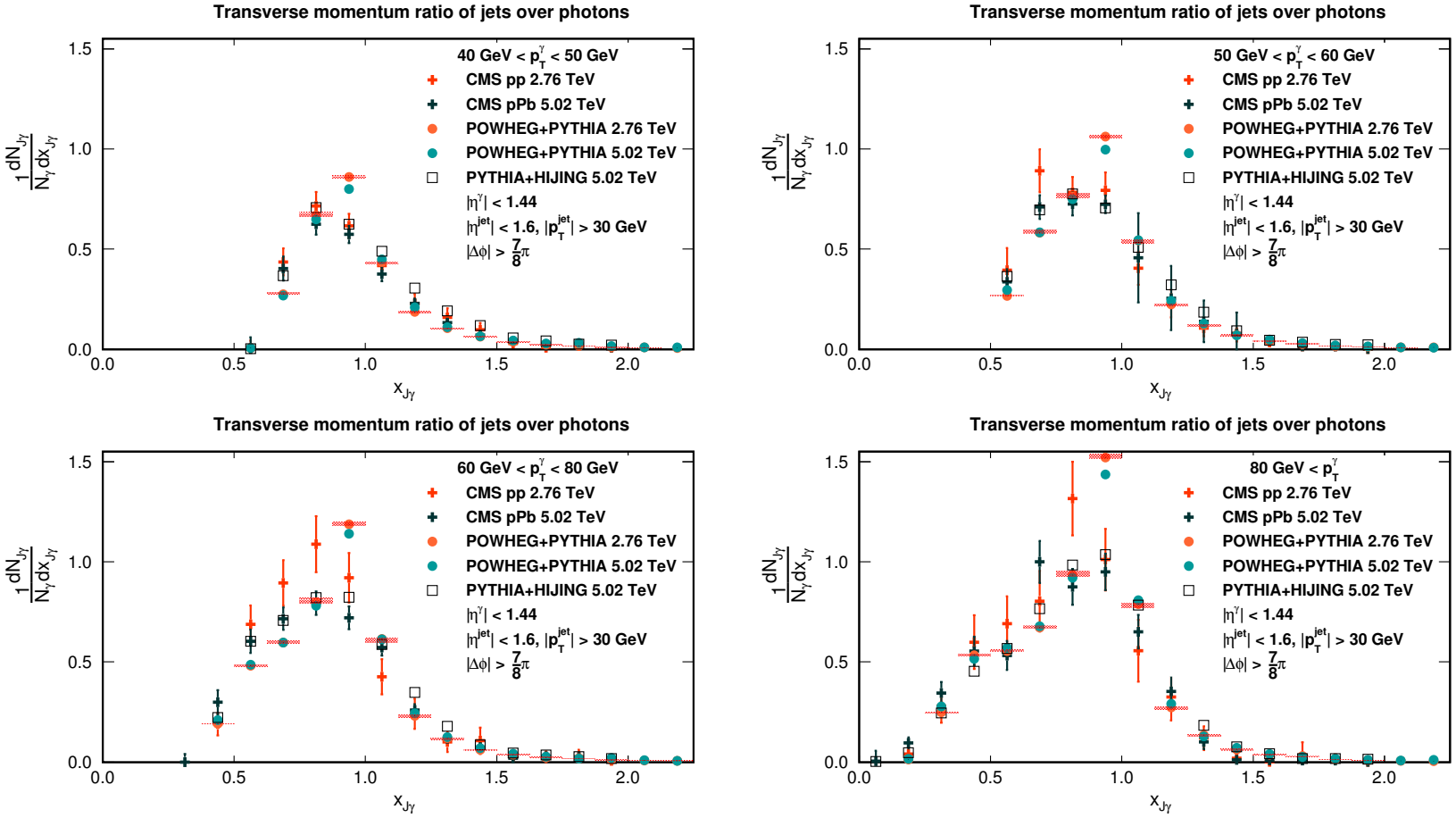
Choice of PDFs:

- CTEQ 6.1 $\overline{\rm MS}$ (p) and nCTEQ15-np (Pb, no pion data)

Transverse momentum ratio of jets over photons with CMS

MK, C. Klein-Bösing, H. Poppenborg, to be published

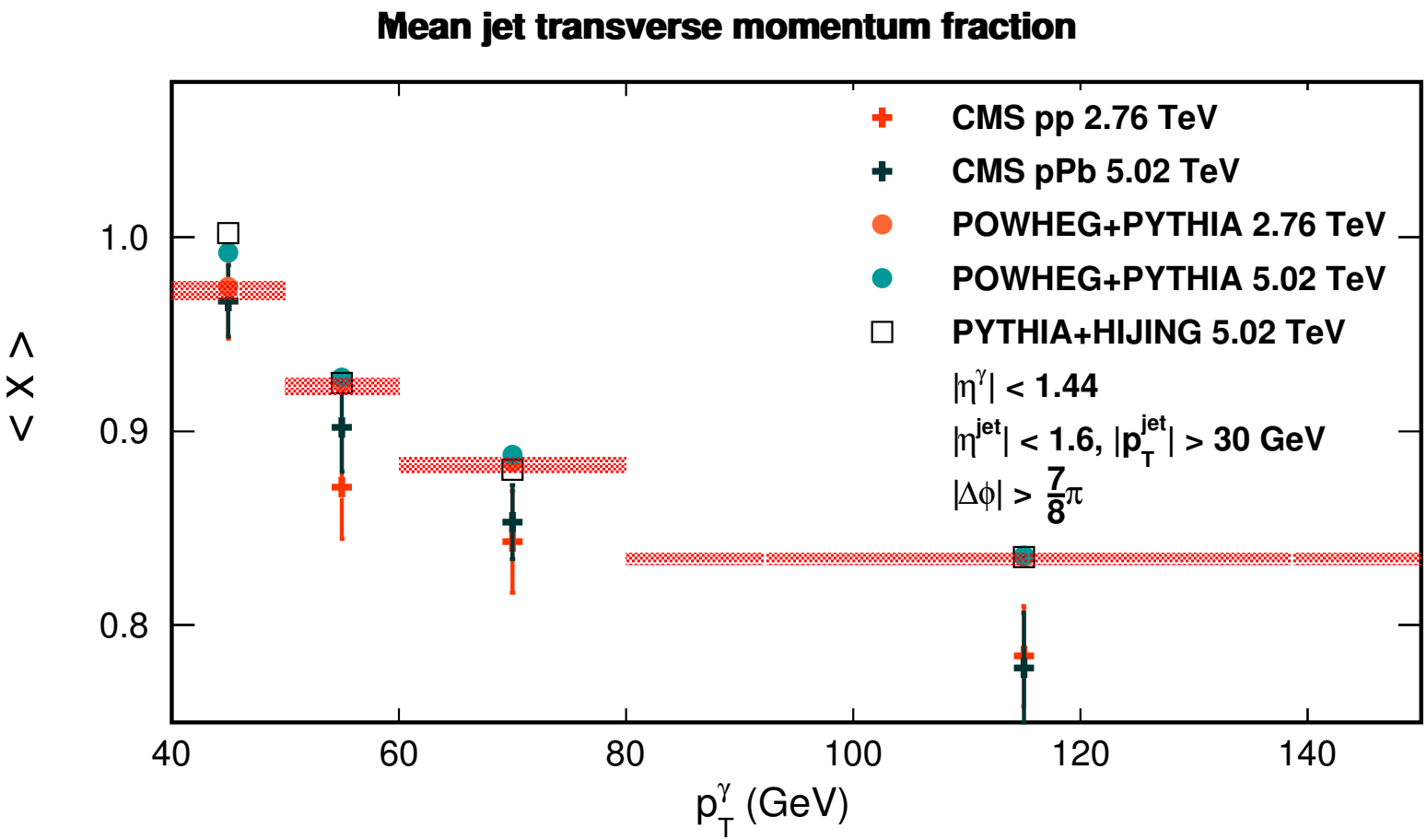


No significant cold nuclear effects, softer (and more) jets at large p_T^γ

POWHEG peak sharper/at higher $x_{J\gamma}$ than PYTHIA $\rightarrow$ CMS resolution?

Mean jet transverse momentum fraction with CMS

MK, C. Klein-Bösing, H. Poppenborg, to be published

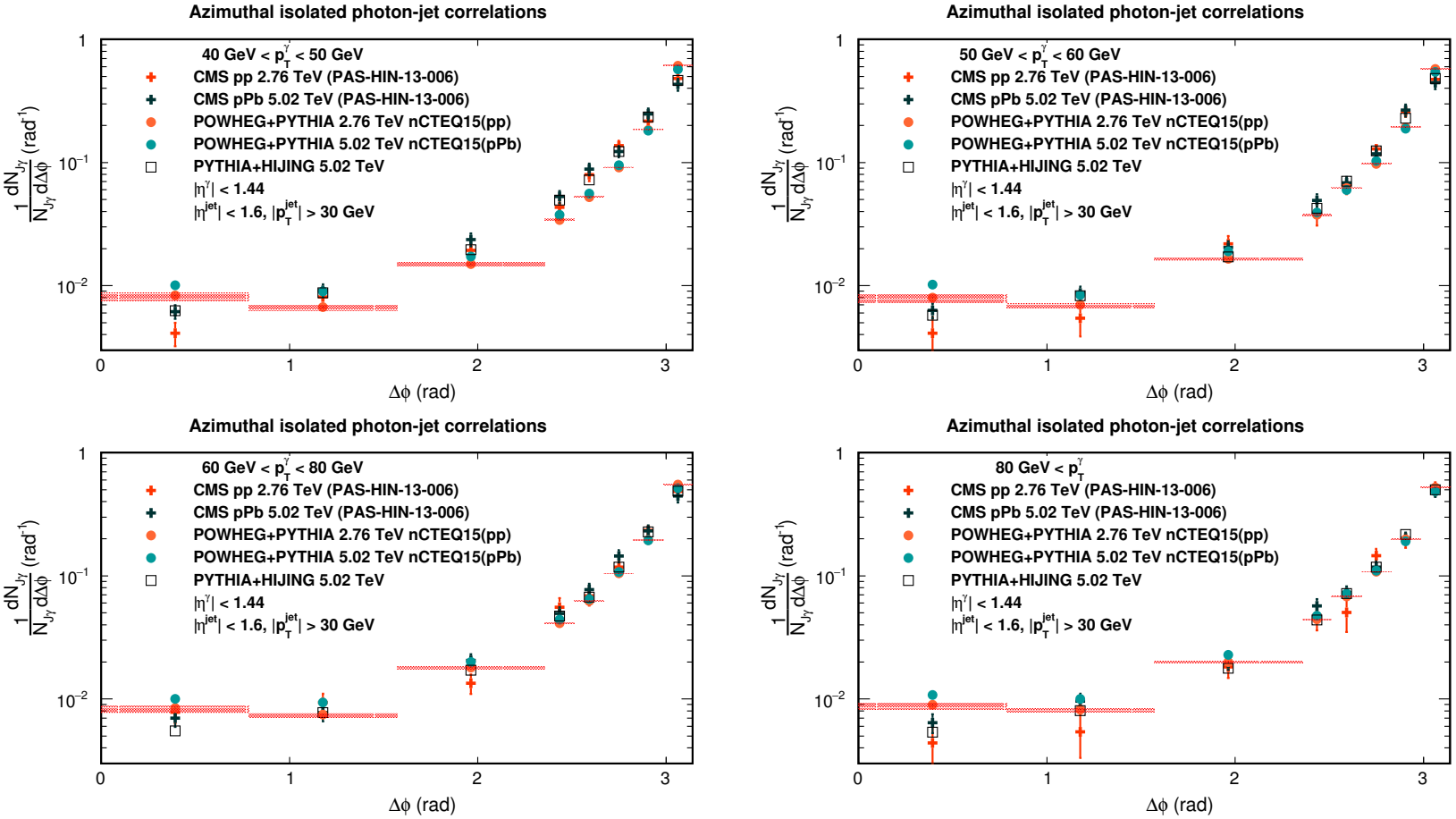


Higher $p_T^\gamma \rightarrow$ possible to produce ≥ 1 jets (e.g. "Mercedes star")

No Quark-Gluon-Plasma $\rightarrow$ not a sign of rescattering in the medium!

Azimuthal correlation of photons and jets with CMS

MK, C. Klein-Bösing, H. Poppenborg, to be published



No significant cold nuclear effects, flatter distributions at large p_T^γ

POWHEG NLO + PYTHIA 8 PS describes data within errors

Experimental conditions at LHC (3)

ALICE Collaboration at LHC

Proton-proton collisions: [ALICE Coll., Eur. Phys. J. C 75 (2015) 146]

- $\sqrt{s}_{\mathrm{pp}} = (0.9, 2.76, 7)\,\mathrm{TeV}, \mathcal{N}(\mathrm{Runs}\ 2010, 2011) = (2, 8, 9)\cdot 10^9$
- Baseline for thermal photons $\rightarrow$ no isolation cut
- Dominated by decay photons (from $\pi^0, \eta, \omega, ...$)
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Lead-lead collisions: [ALICE Coll., Phys. Lett. B 754 (2016) 235]

- $\sqrt{s}_{\rm PbPb} = 2.76$ TeV, $\mathcal{N}$ (Run 2010) $= (13.6 + 17.7) \cdot 10^6$
- 0.9 GeV $< p_T^\gamma <$ 14 GeV and $|\eta^\gamma| < 0.9$
- Subtraction of decay photons using $R_\gamma = \frac{\gamma_{\rm incl.}}{\pi^0_{\rm param.}} / \frac{\gamma_{\rm decay}}{\pi^0_{\rm param.}}$
- Direct p_T spectra with 0-20%, 20-40% and 40-80% centrality

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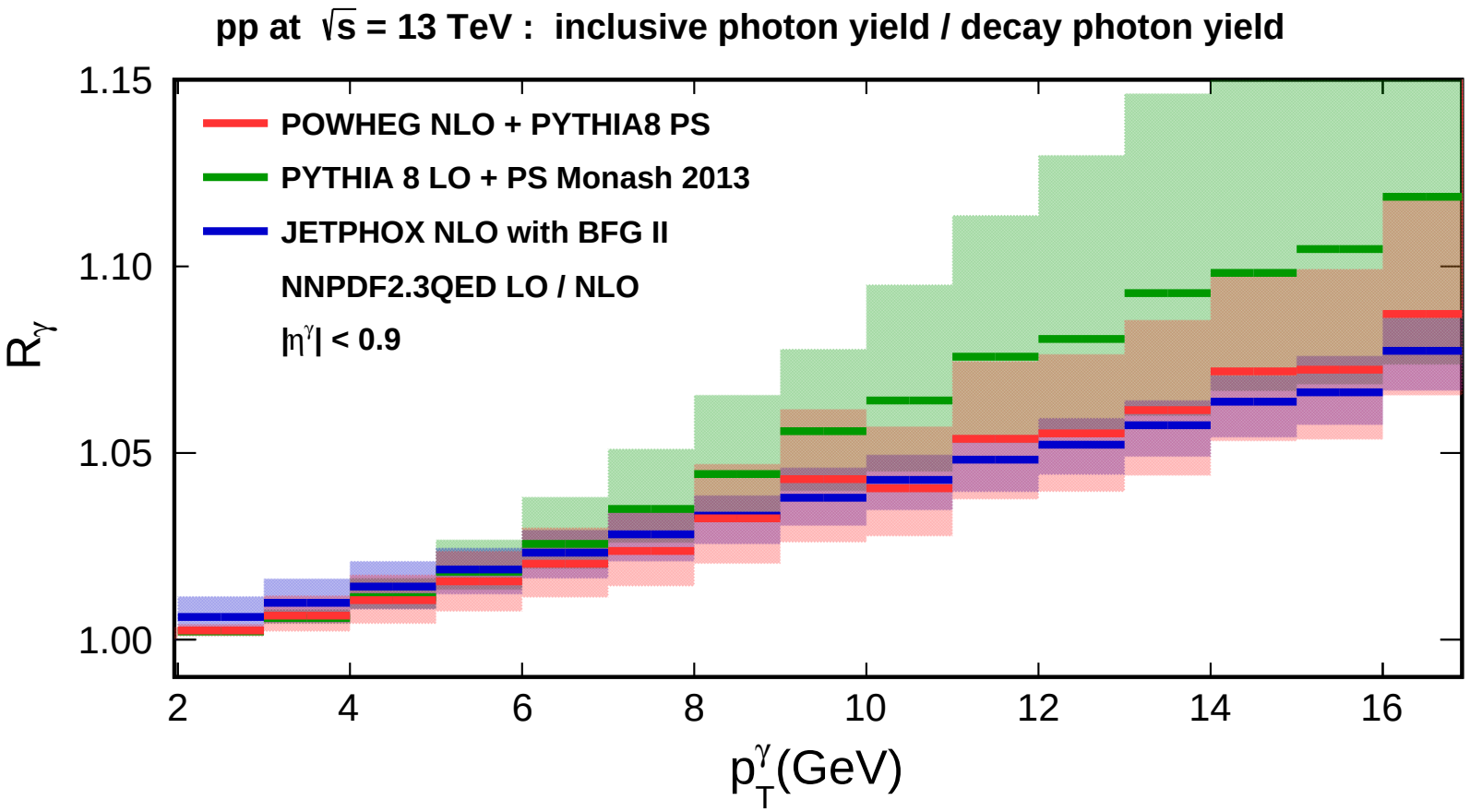
Proton-proton collisions: [ALICE Coll., to be published]

- $\sqrt{s}_{\mathrm{pp}} = 13$ TeV, $p_T^\gamma > 2$ GeV and $|\eta^\gamma < 0.9|$
- NNPDF2.3QED LO/NLO (cf. Monash 2013, similar to CT14)

Ratio of inclusive over decay photons with ALICE

MK, C. Klein-Bösing, H. Poppenborg, to be published



POWHEG NLO + PYTHIA 8 PS agrees with JETPHOX NLO

PYTHIA 8 LO + PS is significantly steeper

Conclusion

Motivation:

- Prompt photons are an important probe of the QGP
- Photon-jet correlations important for jet quenching

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Results:

- Improved agreement with p_T spectrum of inclusive photons
- First correct description of isolated photon fraction
- Reliable prediction for photon-jet p_T-balance
- First correct description of photon-jet azimuthal correlation
- Decomposition into isolated and "fragmentation" photons

Outlook

What remains to be done:

- Application to AA collisions
- Application to forward kinematics in LHCb
- Study cold nuclear effects with nPDFs
- Implement medium effects (energy loss, hydrodynamics, ...)