Prompt photon production with POWHEG

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

DFG

Graduiertenkolleg 2149
Research Training Group

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

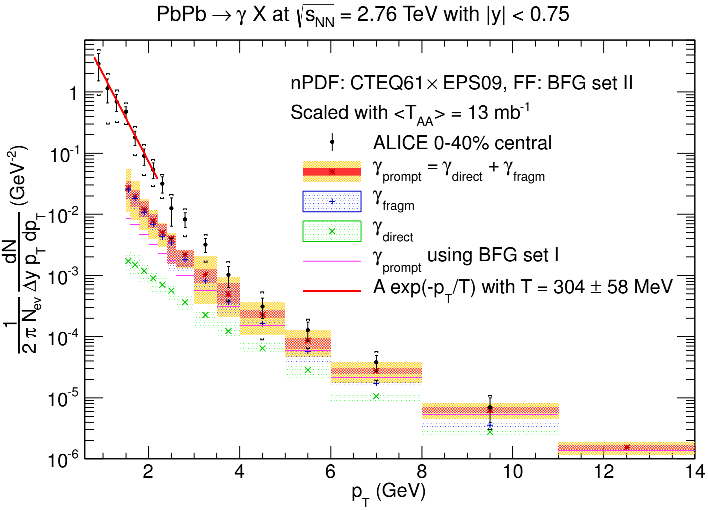
References

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]

How robust is a thermal photon interpretation ...?

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



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

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 $\overline{\rm MS}$, checked against MG5_aMC@NLO

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

Renormalization and factorization scales:

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

Parton densities in the proton: [H. Lai et al., Phys. Rev. D 82 (2010) 074024]

- CT10nlo

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 (μ, μ_p, μ_γ)
- Include only one additional parton, no hadronization

Parton shower Monte Carlos:

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

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

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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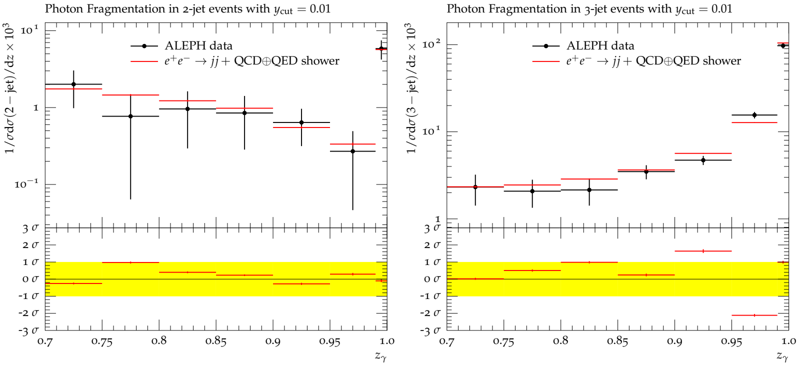
Symmetrization of parton splitting in the final state:

- `doublefsr=1`

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 $y_{\text{cut}} \geq \min\left(\frac{E_i}{E_j}, \frac{E_j}{E_i}\right) \cdot \frac{s_{ij}}{s}$

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 $p_T > p_T^{\text{min}}$
- 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 $\Theta(p_T - p_T^{\mathrm{min}})$ (e.g. with $p_T^{\mathrm{min}} = 1$ GeV):

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

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

Experimental conditions at LHC

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

Proton-proton collisions:

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

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Isolated photons:

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

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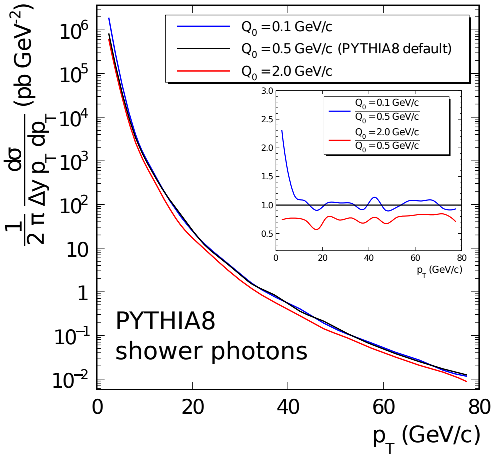
- $p_T^\gamma > 125$ GeV and $|\eta^\gamma| < 0.6$ up to $1.81 < |\eta^\gamma| < 2.37$

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

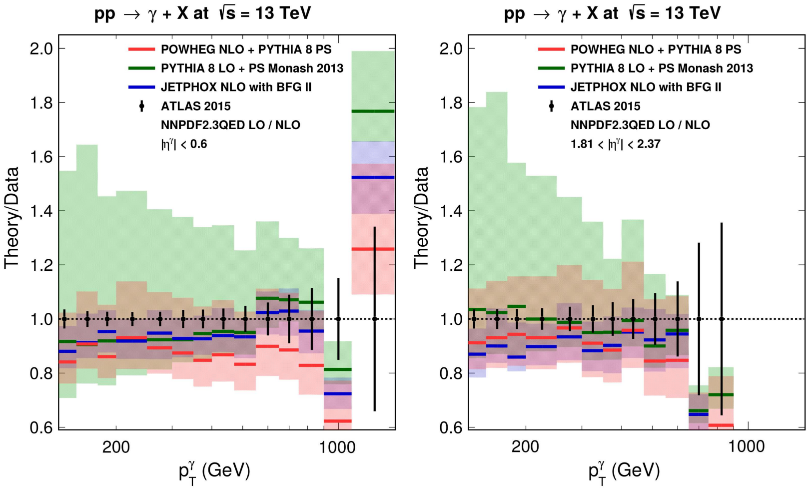


PYTHIA 8 LO very sensitive to infrared cutoff Q_0 at low p_T^γ

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

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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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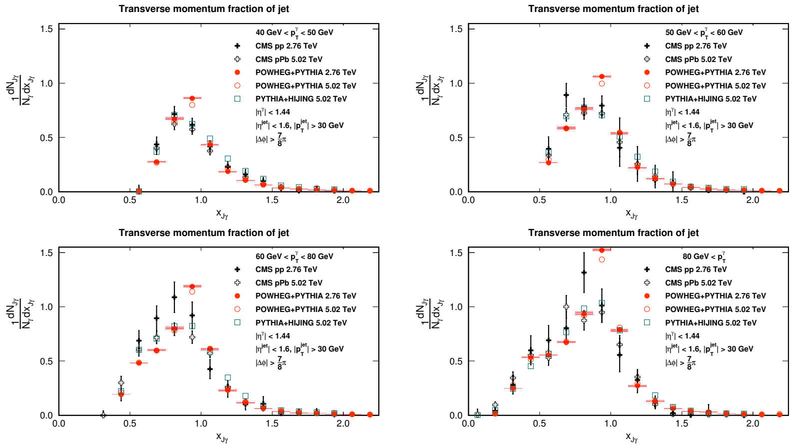
Choice of PDFs:

- CTEQ 6.1 $\overline{\mathrm{MS}}$ (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

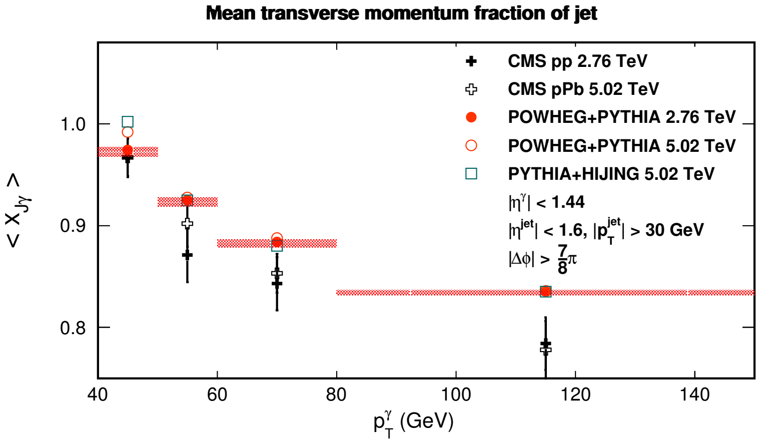


No significant cold nuclear effects, softer (and more) jets at large p_T^γ

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

Mean jet transverse momentum fraction with CMS

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

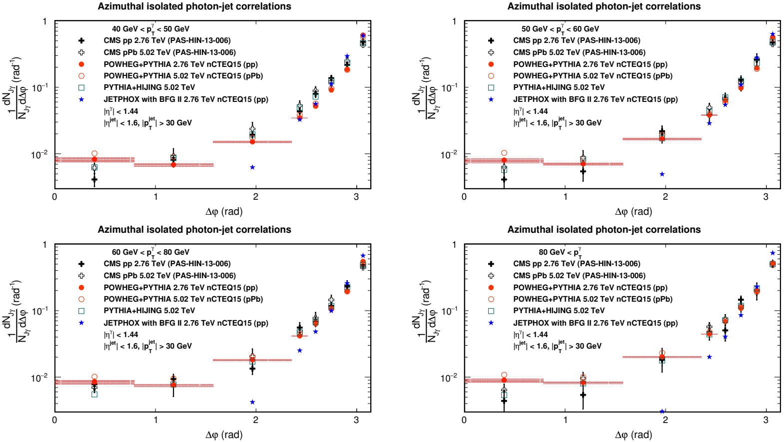


Higher p_T^{γ} $\rightarrow$ possible to produce ≥ 1 jets (e.g. "Mercedes star")

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

Conclusion

Motivation:

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

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- Recalculation of direct photon production at NLO
- POWHEG implementation: QED PS, Born suppression
- Experiments: PHENIX at RHIC, ATLAS/CMS/ALICE at LHC.

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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