

Prompt photon production with two jets in POWHEG

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Photons

Production:

Prompt:

$$N_{\gamma}^{\text{prompt}} = N_{\gamma}^{\text{direct-hard}} + N_{\gamma}^{\text{frag}}$$

Direct-hard: directly produced in the hard collisions, computed in perturbative QCD (non-thermal).

Fragmentation: originating from quark and gluon fragmentation.

Thermal: are expected to be produced in QGP

$$dN_{\gamma}^{\text{thermal}} = dN_{\gamma}^{\text{direct}} - dN_{\gamma}^{\text{prompt}}$$

Direct: all photons produced in hadron collisions except decays.

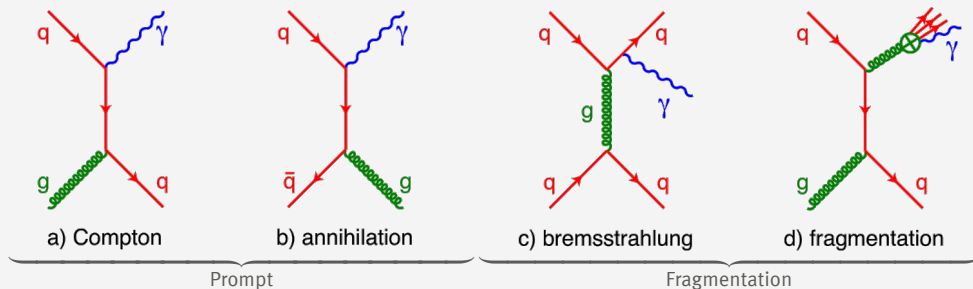
Decay: background from uncorrelated hadronic decays, eg. π^0 .

Detection:

Directly: photons are detected directly in e.g. the calorimeter.

Indirectly: via low invariant-mass e^+e^- pairs

Prompt photons

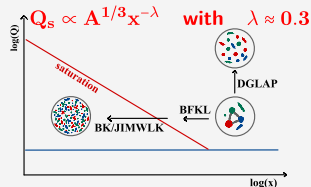


- ▶ Real photons are important probes of the QGP ($T_{eff.}$)
- ▶ NLO calculations exist (JETPHOX, NNLOJET, MCFM, Berger/Gordon/Klasen)
- ▶ p_T -distribution of inclusive photons well described > 4 GeV
- ▶ How reliable is the thermal photon interpretation?
- ▶ Scale and nuclear PDF uncertainties large at low p_T

Gluon distribution

- ▶ Gluon PDF mainly constrained by jet production and indirectly in DIS experiments
- ▶ Gluons drive significant fraction of scatterings at the LHC $\rightarrow$ precise knowledge of gluon PDFs is crucial (e.g. for $gg \rightarrow H$)
- ▶ Probe low- x and $Q \sim p_T^\gamma$ region where gluon density is large

- ▶ Gluon saturation via balanced gluon splitting and gluon-gluon fusion
 $\rightarrow$ Color Glass Condensate (CGC) model.



- ▶ Prompt photons provide an independent observable that gives direct access to gluon density and are less affected by final state effects
- ▶ At LO the gluon distribution's x -dependence is: $x \sim \frac{2p_T}{\sqrt{s}} \exp(-y)$
 $\Rightarrow$ probe small x in low $p_T^{\gamma,j}$ for large $\sqrt{s}$ and y (forward rapidity).

Photon Fragmentation

- ▶ PDFs and fragmentation functions (FF) usually can not be computed in perturbative theory.
- ▶ Operator product expansion separate short- and long distance contributions
- ▶ Factorized photon-hadron production cross section with undetected remains X

$$d\sigma_{AB \rightarrow \gamma X}(p_a, p_B, p_\gamma) = \sum_{a,b,c} \int_0^1 dx_a dx_b dz \underbrace{f_{a/A}(x_a, \mu_F) f_{b/B}(x_b, \mu_F)}_{\text{PDFs}} \cdot \underbrace{d\hat{\sigma}_{ab \rightarrow cX}(x_a P_A, x_b P_B, \frac{P_\gamma}{z}, \mu_F)}_{\text{partonic cross section}} \underbrace{D_{\gamma/c}(z, \mu_F)}_{\text{fragmentation}}$$

including photons from the partonic cross sections through

$$D_{\gamma/\gamma}(z, \mu_F) = \delta(1 - z)$$

- ▶ $\hat{\sigma}$ is not IR safe for identified partons, factorization theorems cancel these universal (collinear) divergences¹

¹Collins, J. C. et al. *Adv. Ser. Direct. High Energy Phys.* **5**, 1–91. arXiv: [hep-ph/0409313](https://arxiv.org/abs/hep-ph/0409313) (1989).

Photon Fragmentation

- ▶ Altarelli-Parisi gluon splitting kernels

$$P_{gq}(z) = C_F \frac{1 + (1-z)^2}{z} \quad P_{gg}(z) = 2C_A \left[\left(\frac{1}{1-z} \right)_+ z + z(1-z) + \frac{1-z}{z} \right] \\ + \left(\frac{11}{6}C_A - \frac{1}{3}N_f \right) \delta(1-z)$$

- ▶ Similar for photon splitting kernels with $C_F \rightarrow Q_i^2$ and $C_A \rightarrow 0$ (uncharged photon)

$$P_{\gamma q}(z) = Q_q^2 \frac{1 + (1-z)^2}{z} \quad P_{\gamma g}(z) = 0 \text{ (at leading order)}$$

- ▶ Photon evolution equation

$$\mu_F^2 \frac{d}{d\mu_F^2} D_{\gamma/c}(z, \mu_F) = \frac{\alpha}{2\pi} P_{\gamma c}(z)$$

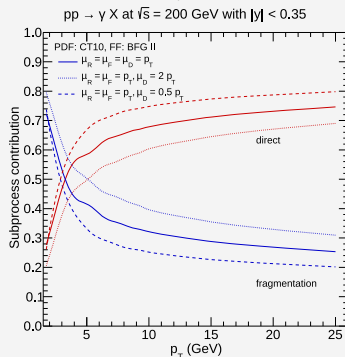
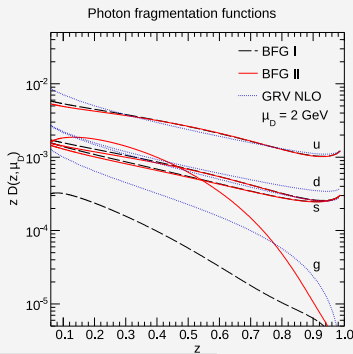
$$D_{\gamma/q}(z, \mu_F) = \frac{\alpha}{2\pi} P_{\gamma q}(z) \log \left(\frac{\mu_F^2}{\mu_s^2} \right) + D_{\gamma/q}^{\text{measured}}(z, \mu_s) \quad D_{\gamma/g}(z, \mu_F) = \text{const.}$$

- ▶ At NLO renormalization group equations couple splitting functions $P_{\gamma q}$, $P_{\gamma g}$ and $P_{\gamma\gamma}$

Photon Fragmentation

Measured:

- ▶ Prompt photons in e^+e^- collisions (limited data)
- ▶ Prompt photons in hadronic collisions²
- ▶ In vector meson production, assuming dominating hadronic fluctuations of the photon at low scales (VMD)³: $D_{\gamma,i}^{\text{had}}(z, \mu_s) = \sum_{V=\rho,\omega,\phi} \frac{4\pi\alpha}{f_V^2} D_{V/i}(z, \mu_s)$



²Adare, A. et al. *Phys. Rev. C* **87**, 054907. arXiv: 1208.1234 [nucl-ex] (2013).

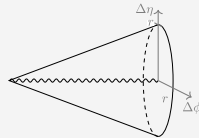
³Klasen, M. & König, F. *Eur. Phys. J. C* **74**, 3009. arXiv: 1403.2290 [hep-ph] (2014).

Photon isolation

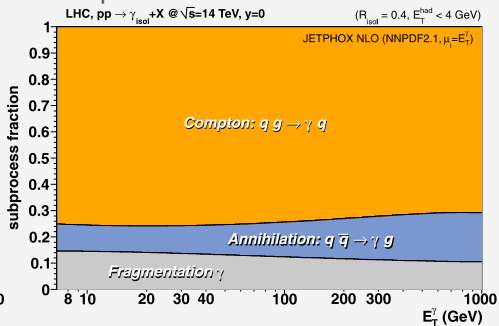
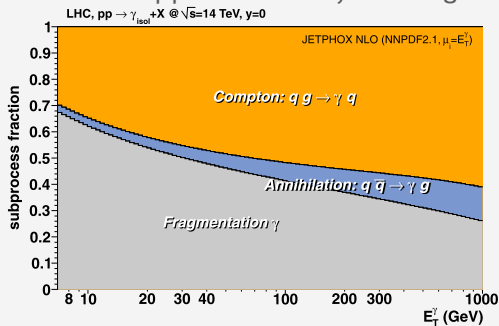
Boost invariant definition:

Cone radius: $R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

Activity in the cone: $p_T^{\text{iso}} = \sum_{i=1}^{\Delta R_i < R_{\text{max}}} p_T^i$

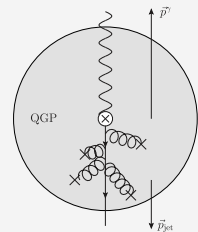
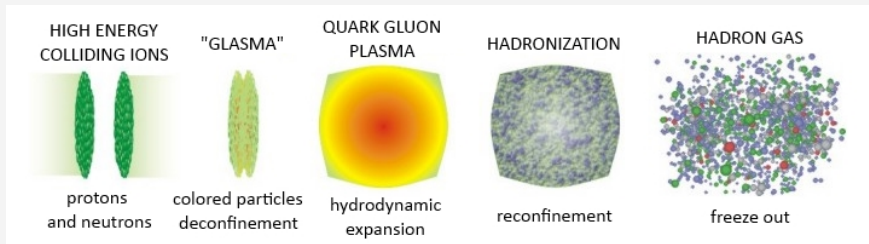


Isolation suppresses decay and fragmentation photons⁴:



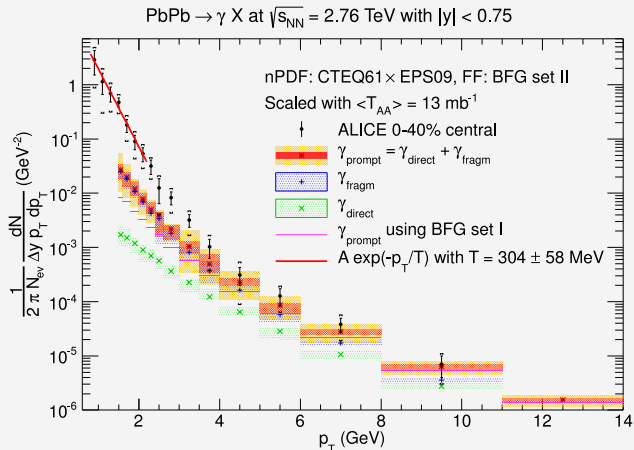
⁴d'Enterria, D. & Rojo, J. *Nucl. Phys. B* **860**, 311–338. arXiv: 1202.1762 [hep-ph] (2012).

Quark Gluon Plasma



- ▶ Thermal photons are produced by the constituents of the plasma (quarks and gluons)
- ▶ Probe properties of the QGP
- ▶ Medium decreases jet-momentum $\rightarrow$ jet quenching
- ▶ Suppressed back-to-back correlation

Prompt photon production at NLO in POWHEG



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- ▶ Good agreement in higher p_T perturbative region
- ▶ Photon probes the gluon density and QGP properties

⁵Klasen, M. et al. *JHEP* **10**, 119. [arXiv: 1307.7034 \[hep-ph\]](https://arxiv.org/abs/1307.7034) (2013).

Direct photon codes

Shower Monte Carlo Event Generators:

Code	$pp \rightarrow \gamma j$	$pp \rightarrow \gamma jj$	$pp \rightarrow \gamma\gamma$
POWHEG	NLO+PS	[NLO+PS, this project]	[NLO+PS, not public]
Sherpa	NLO+PS	NLO+PS	NLO+PS
MG5,HW7	(NLO+PS)	(NLO+PS)	(NLO+PS)
Pythia	LO	-	LO
$\vdots$			

Integrators:

Code	$pp \rightarrow \gamma j$	$pp \rightarrow \gamma jj$	$pp \rightarrow \gamma\gamma$
NNLOJET[not public]	NNLO+FF(NNLO)	[NLO]	NNLO+FF(NNLO)
JETPHOX/DIPHOX	NLO+FF(NLO)	[LO]	NLO+FF(NLO)
MCFM	NLO+FF(LO)	LO	NLO+FF(LO), NNLO
$\vdots$			

Either FF or Parton showers (PS) is needed to generate physical results.

POsitive Weight Hardest Emission Generator (POWHEG)

FKS subtraction:

- ▶ Divergence can be made explicit in dimensional regularization using δ - and plus-distributions.
- ▶ Then they get cancelled between Reals and Virtuals.
 - ▶ Soft divergences $\frac{2p_i^0}{\sqrt{s}} = \xi_i \rightarrow 0$, in Real $(p_i \cdot p_j p_i \cdot p_k)^{-1} \propto \xi_i^{-2}$
 - ▶ Collinear divergences $\cos(\theta_{ij}) = y_{ij} \rightarrow 1$, in Real $(p_i \cdot p_j)^{-1} \propto (1 - y_{ij})^{-1}$

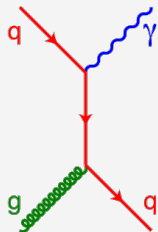
NLO Matching:

- ▶ NLO amplitude has n -particle (Born and Virtual) and $n + 1$ -particle (Real) contributions
- ▶ POWHEG attaches first emission to n -particle state with a modified Sudakov factor such that NLO accuracy is preserved.

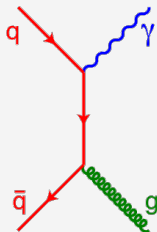
$$\Delta_R(p_T) \sim \exp \left[- \int d\Phi_R \frac{R(\Phi_B, \Phi_R)}{B(\Phi_B)} \theta(k_T(\Phi_B, \Phi_R) - p_T) \right]$$

- ▶ PS must generate radiation only from below the scale k_T ($\rightarrow$ veto algorithm).

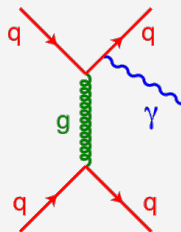
POsitive Weight Hardest Emission Generator (POWHEG)



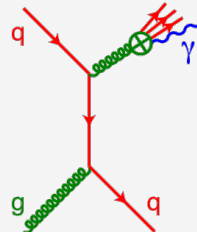
a) Compton



b) annihilation



c) bremsstrahlung



d) fragmentation

Prompt

Fragmentation

POWHEG-NLO

Pythia-Shower

► Separation between NLO and fragmentation contribution is non-trivial in NLO+PS

POsitive Weight Hardest Emission Generator (POWHEG)

Fragmentation contribution⁶:

- ▶ QED parton shower ($q \rightarrow q\gamma$), 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

Renormalization and factorization scales:

- ▶ $\mu = \mu_p = p_T^{\gamma,q,g}$ (from underlying Born process)

Born-level event generation cut:

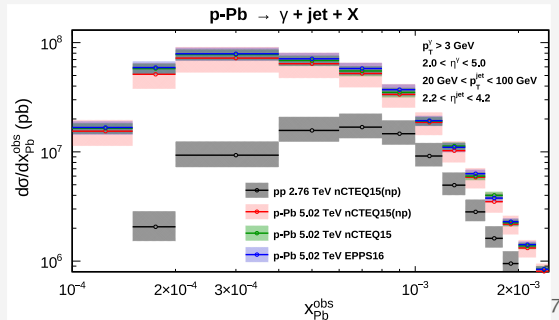
- ▶ $pp \rightarrow \gamma + X$ has coll. divergence at LO $\rightarrow$ impose $p_T > p_T^{\min}$
- ▶ Influences events at low $p_T \rightarrow$ region of interest for thermal γ

Similar spike issue as for dijets:

- ▶ Symmetrization of FS parton splitting (doublefsr = 1)

⁶Hoeche, S. et al. *Phys. Rev. D* **81**, 034026. arXiv: 0912.3501 [hep-ph] (2010), Jezo, T. et al. *JHEP* **11**, 033. arXiv: 1610.02275 [hep-ph] (2016).

Photon+jet production at NLO+PS



- ▶ Forward photon and forward jet
- ▶ Always probed at very low x
- ▶ Observation of photon+jet gives access to $x_{Pb}^{obs} = \frac{p_T^\gamma e^{-\eta^\gamma} + p_T^{jet} e^{-\eta^{jet}}}{2E_{Pb}}$.
- ▶ Important for global determination of nuclear PDFs ($\rightarrow$ nCTEQ).
- ▶ Eliminate scale uncertainties by taking ratios

⁷Klasen, M. et al. *JHEP* **03**, 081. [arXiv: 1709.04154 \[hep-ph\]](https://arxiv.org/abs/1709.04154) (2018).

Isolated photon + jet production with CMS

Proton-proton and proton-lead collisions⁸:

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

Isolated photons:

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

Jets:

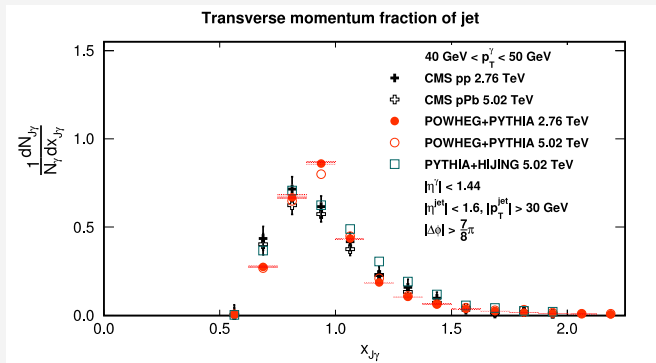
- ▶ Anti- k_T cluster algorithm with $R = 0.3$
- ▶ $p_T^{jet} > 30 \text{ GeV}$ and $|\eta^{jet}| < 1.6$

Choice of PDFs:

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

⁸Tech. rep. (CERN, Geneva, 2013). <http://cds.cern.ch/record/1631991>.

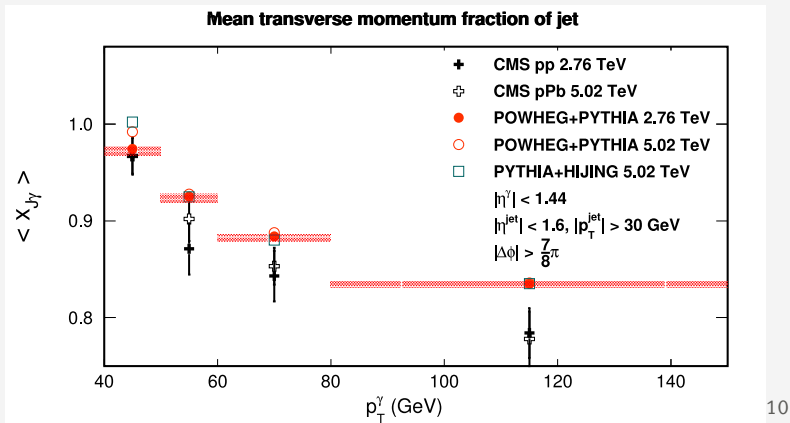
Transverse momentum ratio of jets over photons with CMS



- POWHEG peak sharper/at higher $x_{J\gamma} = \frac{p_T^j}{p_T^{\gamma}}$ than PYTHIA → CMS smear/resolution?
- At LO $x_{J\gamma} = 1$
- No significant cold nuclear effects
- Softer (and more) jets at large p_T^{γ}

⁹Klasen, M. et al. *JHEP* **03**, 081. [arXiv: 1709.04154 \[hep-ph\]](https://arxiv.org/abs/1709.04154) (2018).

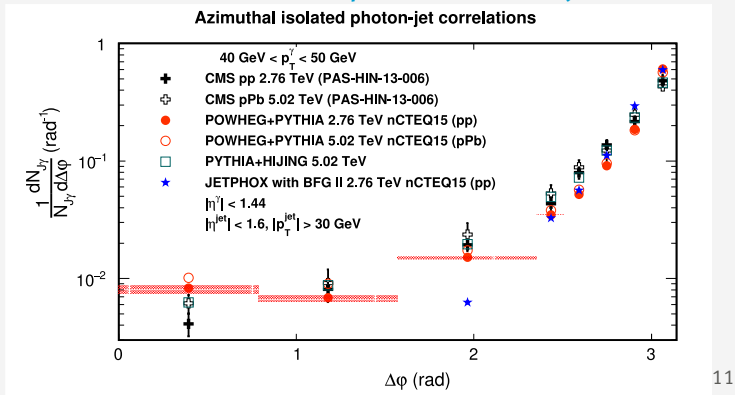
Mean jet transverse momentum fraction with CMS



- Higher $p_T^\gamma \rightarrow$ possible to produce ≥ 1 jets (e.g. “Mercedes star”) $\rightarrow$ falling $\langle x_{J\gamma} \rangle$
- No Quark-Gluon-Plasma $\rightarrow$ not a sign of rescattering in the medium!

¹⁰Klasen, M. et al. *JHEP* **03**, 081. [arXiv: 1709.04154 \[hep-ph\]](https://arxiv.org/abs/1709.04154) (2018).

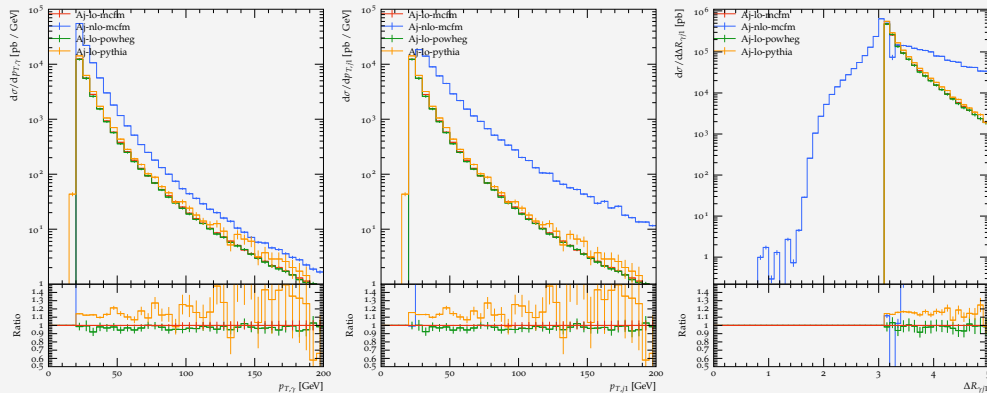
Azimuthal correlation of photons and jets with CMS



- ▶ No significant cold nuclear effects, flatter distributions at large p_T^γ
- ▶ POWHEG NLO + PYTHIA 8 PS describes data within errors
- ▶ JETPHOX does not describe the data below $\Delta\phi = 2\pi/3$, as the maximum number of jets at NLO is two

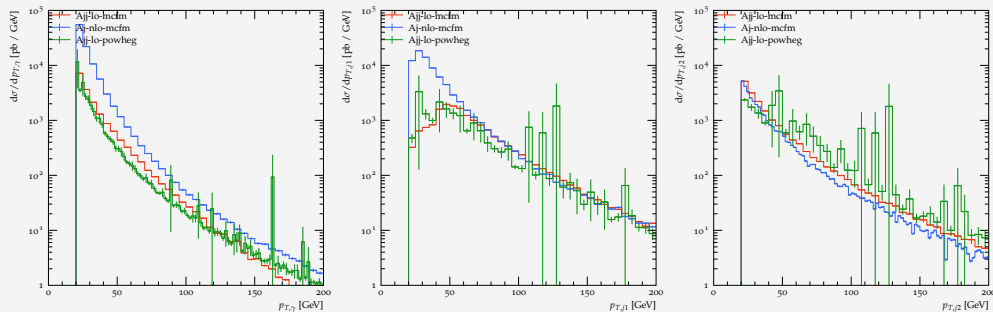
¹¹Klasen, M. et al. *JHEP* **03**, 081. [arXiv: 1709.04154 \[hep-ph\]](https://arxiv.org/abs/1709.04154) (2018).

Preliminary: Photo production with one jets



- Fixed order without PS/FF
- $p_T^{\gamma,j} > 20$ GeV cut
- Beyond LO photon and jet are no longer back to back
- Rapidity dependence visible for $R > \pi$

Preliminary: Leading order photo production with two jets



- Improved sampling and/or more statistics needed
- High $p_{T,j1}$ dependence dominated by Real correction/jet emission.

Outlook:Photons

- ▶ Virtual corrections for photon+dijets must be calculated
- ▶ Requires use of automatization (FormCalc, RECOLA, MG5_aMC@NLO)
- ▶ Comparison with ALICE [γh] data¹²
- ▶ Comparison of isolation criteria
- ▶ Comparison of QCD/QED PS (PYTHIA, HERWIG, SHERPA)
- ▶ Indispensible baseline for corresponding QGP studies

¹²Acharya, S. et al. *Phys. Rev. C* **102**, 044908. arXiv: 2005.14637 [[nuc1-ex](#)] (2020).

Outlook:Photons

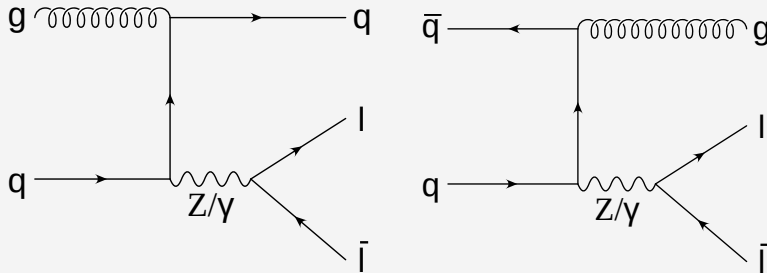
Simulations for FOward CALorimeter in ALICE (after LS3):

- ▶ Access to nPDFs at very small x
- ▶ Search for saturation and transition to QGP
- ▶ Ultraperipheral collisions and long-range correlations
- ▶ Fraction of events where Photon in FoCal, but Jets in ALICE?

Simulations for ALICE3:

- ▶ Focus will be on soft photons
- ▶ Observed cross sections much larger than predicted at low p_T
- ▶ However, non-perturbative region ...

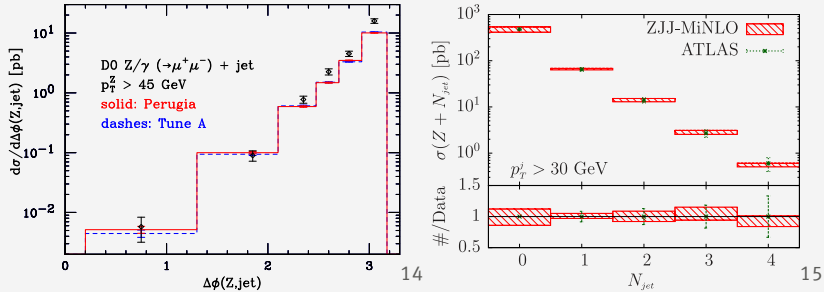
Outlook:Dileptons



- ▶ Application to low-mass dileptons in pp and pPb collisions
- ▶ Comparison with ALICE data¹³
- ▶ Dominated by light- and heavy-meson decays
- ▶ Analysis of multijet events in ALICE containing a dilepton
- ▶ Obtain new information on jet formation

¹³Acharya, S. et al. *Phys. Rev. C* **102**, 055204. arXiv: 2005.11995 [nucl-ex] (2020).

Z-boson + jet production: Multi-scale improved NLO (MiNLO)



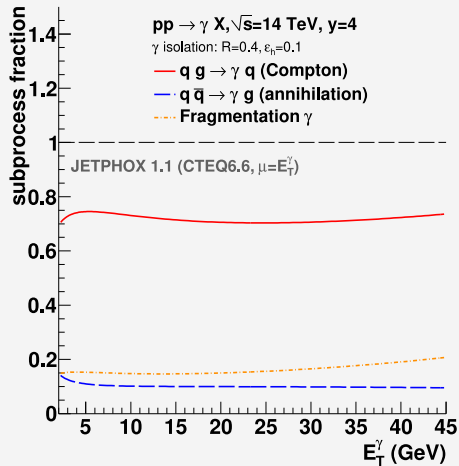
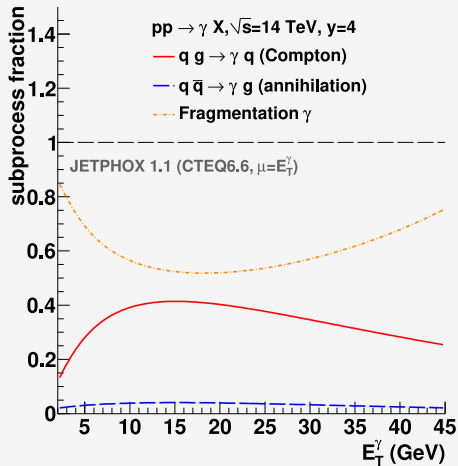
- ▶ NLO extension of the matrix element reweighting procedure employed in tree level matrix element-parton shower merging algorithms.
- ▶ Resums to all orders the large logarithms that arise from kinematic configurations involving disparate scales.
- ▶ MiNLO for prompt photon production in POWHEG requires implementation of analytic resummed parts

¹⁴Alioli, S. et al. *JHEP* **01**, 095. arXiv: 1009.5594 [hep-ph] (2011).

¹⁵Campbell, J. M. et al. *JHEP* **08**, 005. arXiv: 1303.5447 [hep-ph] (2013).

Thank you!

Forward/Focal isolation



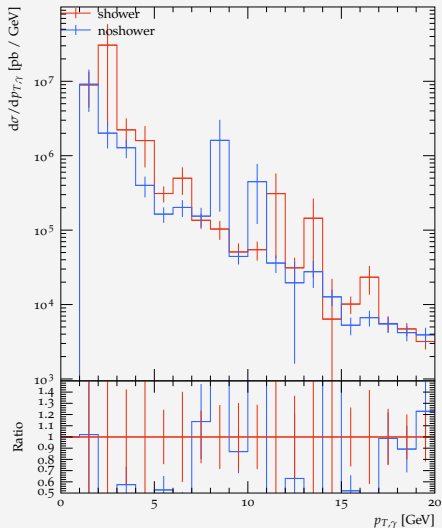
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¹⁶ALICE Collaboration, C. Tech. rep. (CERN, Geneva, 2020). <https://cds.cern.ch/record/2719928>.

Focal Powheg Setup

- ▶ generate 100×10000 Events (already 100GB with shower)
- ▶ bornktmin 1
- ▶ bornsup 10

Transverse photon momentum dependence



► $\sqrt{S} = 13\text{TeV}$

Photon-Cuts:

► $3.4 < \eta^\gamma < 5.8$

► $1 < p_T^\gamma/\text{GeV} < 40$

Photon-Isolation:

► $R^{\text{iso}} = 0.4$

► $E_T^{\text{iso}}/\text{GeV} = 5$

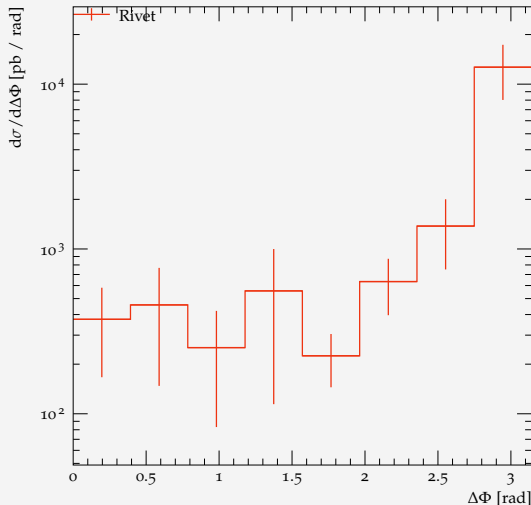
Jet:

► $-1.6 < \eta^j < 1.6$ (to be changed to FoCal/ALICE acceptance)

► $30 < p_T^j/\text{GeV}$

► AntiKt with $R^j = 0.3$

Azimuthal angle difference of photon and jet



► $\sqrt{S} = 13\text{TeV}$

Photon-Cuts:

► $3.4 < \eta^\gamma < 5.8$

► $10 < p_T^\gamma/\text{GeV} < 40$

Photon-Isolation:

► $R^{\text{iso}} = 0.4$

► $E_T^{\text{iso}}/\text{GeV} = 5$

Jet:

► $-1.6 < \eta^j < 1.6$ (to be changed to FoCal/ALICE acceptance)

► $30 < p_T^j/\text{GeV}$

► AntiKt with $R^j = 0.3$



Isolation

Effect of the isolation ($R^{\text{iso}} = 0.4$, $E^{\text{iso}}/\text{GeV} = 2$) on $\Delta\phi$ distribution:

$$5 < p_T^\gamma/\text{GeV} < 20$$

$$5 < p_T^\gamma/\text{GeV} < 20$$

$$20 < p_T^\gamma/\text{GeV} < 40$$

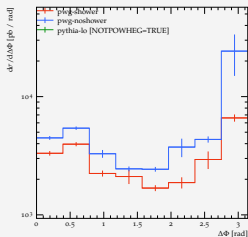
$$20 < p_T^\gamma/\text{GeV} < 40$$

$$30 < p_T^j/\text{GeV} < 60$$

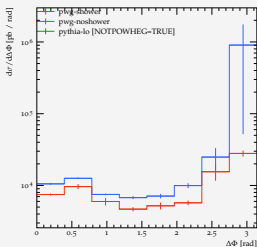
$$20 < p_T^j/\text{GeV} < 30$$

$$30 < p_T^j/\text{GeV} < 60$$

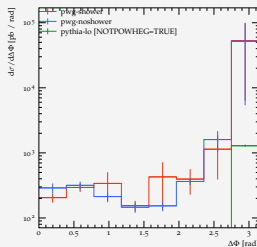
$$20 < p_T^j/\text{GeV} < 30$$



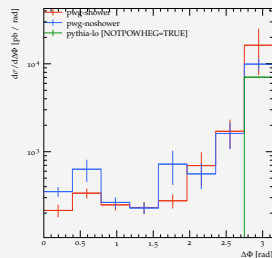
↓ isolated



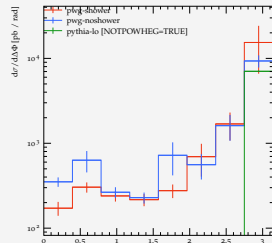
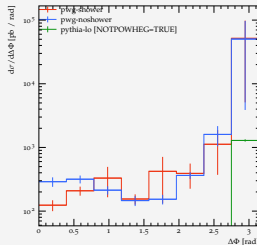
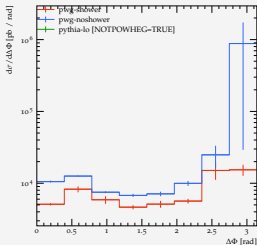
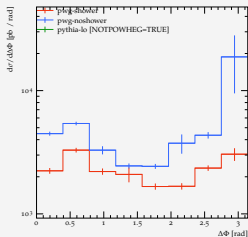
↓ isolated



↓ isolated



↓ isolated



Diphoton generators

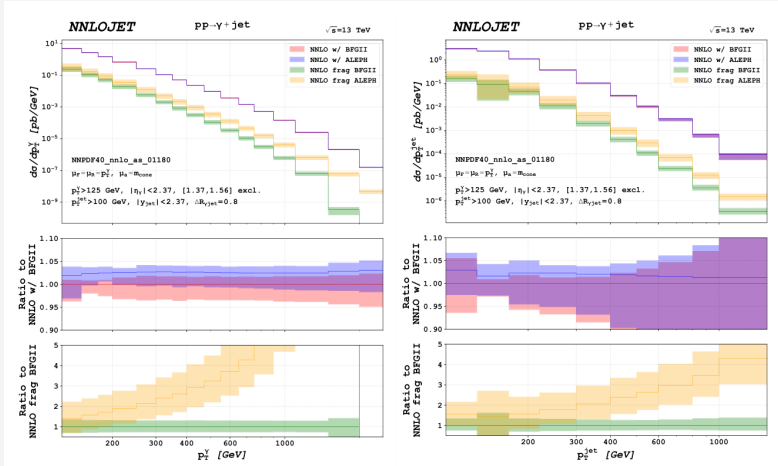
Name	Final state	Diagrams / order				Various	Isolation		Reference
		Born	Box (*)	1 frag	2 frag		Cone	Frix.	
DIPHOS	YY	NLO	LO	NLO	NLO	Fixed order	X	X	T. Binoth, J.P. Guillet, E. Pilon and M. Werlen, Eur. Phys. J. C16 (2000) 311
GAMMA2MC	YY	NLO	NLO	-	-	Fixed order	X	X	Z. Bern, L. Dixon, and C. Schmidt, Phys. Rev. D66 (2002) 074018.
RESBOS	YY	NLO	NLO	LO	-	NLL	X	X	lots of papers...
MCFM	YY	NLO	NLO	LO	LO ?	Fixed order	X	X	J. Campbell, R. Ellis, C. Williams, arXiv: 1105.0020
2gNNLO	YY	NNLO	NLO	-	-	Fixed order		X	S. Catani et al, arXiv: 1110.2375
PYTHIA / HERWIG	YY	LO	LO	PS	PS	-	X	X	-
ALPGEN	YY+up to 6 jets	LO	-	PS	PS	MLM matching with PYTHIA/HERWIG	X	X	http://mlm.home.cern.ch/mlm/alpger/
SHERPA	YY+X jets	LO	LO	PS	PS	CKKW + truncated shower	X	X	S. Hoeche, S. Schumann, F. Siegert, Phys.Rev.D81: 034026,2010
POWHEG/H++	YY+1 jet	NLO	?	PS	PS	truncated shower	X	X	L. d'Errico, P. Richardson, arXiv: 1106.3939 (diphoton code not public yet)
GR@PPA	YY+? jets	NLO	?	PS	PS	LL-subtraction	X	X	S. Tsuno et al., Comput. Phys. Commun. 175, 665 (2006) (no specific publi for diphoton yet)

Color code: yellow = integrator; blue = event generator

(*) formally, (N)LO of box diagram is (N)NNLO - call it (N) LO b/c contributes as much as NLO born...

https://indico.cern.ch/event/242419/contribution/19/attachments/412185/572744/LHC_France_SCHWOERER.pdf

NNLOJET

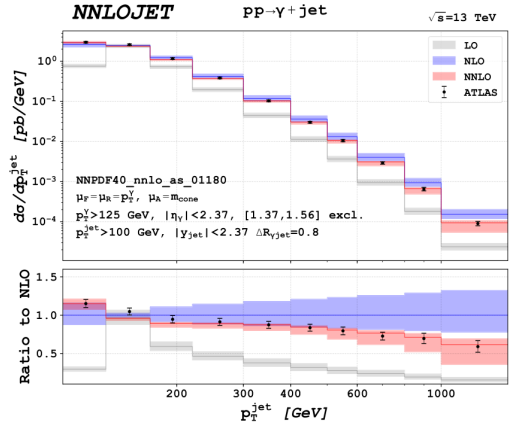
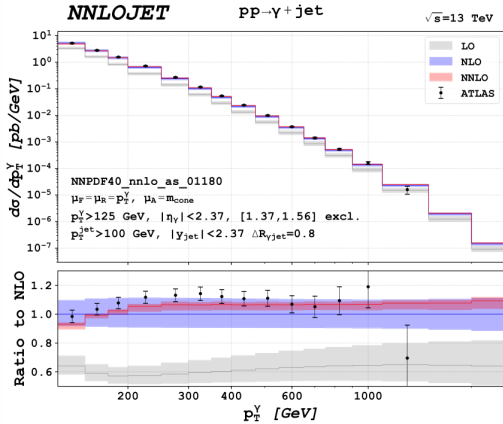


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¹⁷Chen, X. et al. *JHEP* **04**, 166. arXiv: 1904.01044 [hep-ph] (2020).

¹⁸Chen, X. et al. in 16th DESY Workshop on Elementary Particle Physics: Loops and Legs in Quantum Field Theory 2022 (Aug. 2022). arXiv: 2208.02669 [hep-ph].

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¹⁹Chen, X. et al. *JHEP* **04**, 166. arXiv: 1904.01044 [hep-ph] (2020).

²⁰Chen, X. et al. in 16th DESY Workshop on Elementary Particle Physics: Loops and Legs in Quantum Field Theory 2022 (Aug. 2022). arXiv: 2208.02669 [hep-ph].