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Prompt photon production with two jets in POWHEG

Tomas Jezo, Michael Klasen, Alexander Neuwirth

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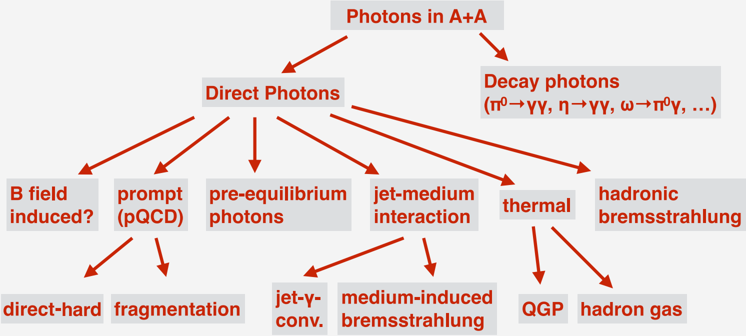
Photons

- Many sources of photons in proton-proton and heavy ion collisions:



Photons in A+A

Direct Photons

Decay photons
$(\pi^0\to\gamma\gamma, \eta\to\gamma\gamma, \omega\to\pi^0\gamma, \ldots)$

B field induced?

prompt (pQCD)

pre-equilibrium photons

jet-medium interaction

thermal

hadronic bremsstrahlung

direct-hard

fragmentation

jet-γ-conv.

medium-induced bremsstrahlung

QGP

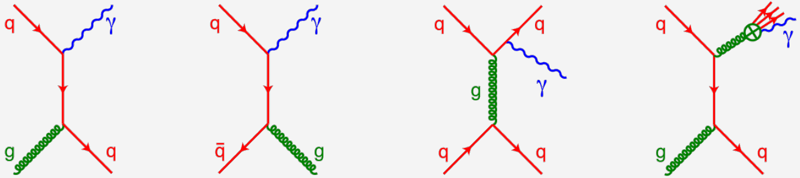
hadron gas

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

Thermal: are expected to be produced in quark gluon plasma

$$\mathrm{d}N_\gamma^{\text{thermal}} = \mathrm{d}N_\gamma^{\text{direct}} - \mathrm{d}N_\gamma^{\text{prompt}}$$

Prompt photons

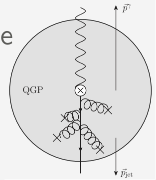


a) Compton b) annihilation c) bremsstrahlung d) fragmentation

Prompt Fragmentation

$$\mathrm{d}\sigma = \sum_{a,b,c}\int_0^1 \mathrm{d}x_a\,\mathrm{d}x_b\,\mathrm{d}z\,\underbrace{f_{a/A}(x_a,\mu_F)f_{b/B}(x_b,\mu_F)}_{\text{PDFs}}\cdot\underbrace{\mathrm{d}\hat{\sigma}_{cX}\left(x_aP_A,x_bP_B,\frac{P_\gamma}{z},\mu_F\right)}_{\text{partonic cross section}}\underbrace{D_{\gamma/c}(z,\mu_F)}_{\text{fragmentation}}$$

- Probe low-$x \sim \frac{2p_T^\gamma}{\sqrt{s}}\exp(-y)$ and $Q \sim p_T^\gamma$ region where gluon density is large
- Scale and nuclear PDF uncertainties large at low p_T
- Real photons are important probes of the QGP (e.g. $T_{eff.}$)
- p_T-distribution of inclusive photons well described > 4 GeV

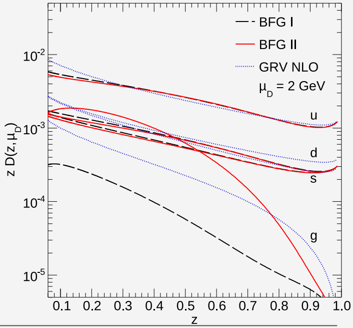


Photon Fragmentation

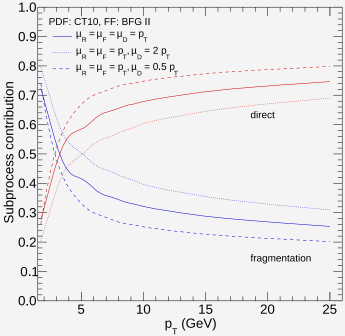
Measured:

- Prompt photons in e^+e^- collisions (limited data)
- Prompt photons in hadronic collisions[1]
- In vector meson production, assuming dominating hadronic fluctuations of the photon at low scales (VMD)[2]: $D^{\text{had}}_{\gamma,i}(z,\mu_s) = \sum_{V=\rho,\omega,\phi} \frac{4\pi\alpha}{f_V^2} D_{V/i}(z,\mu_s)$

Photon fragmentation functions



pp → γ X at $\sqrt{s}$ = 200 GeV with |y| < 0.35



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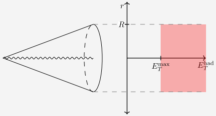
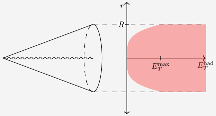
[1] Adare, A. *et al.* *Phys. Rev. C* **87,** 054907. arXiv: `1208.1234 [nucl-ex]` (2013).

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

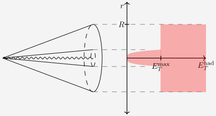
Photon isolation



(a) fixed-cone isolation



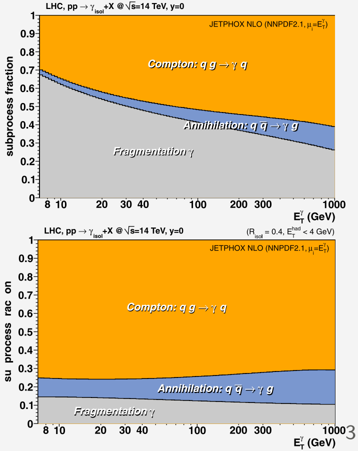
(b) smooth-cone isolation



(c) hybrid isolation

Simple boost invariant definition of a fixed-cone (a):

- Radius around the photon is defined as $R^{\text{iso}} = \sqrt{\Delta\phi^2 + \Delta\eta^2}$
- Activity in the cone is measured by the transverse momenta p_T of the particles
- Photon is isolated if the sum of the transverse momenta does not exceed a threshold $E_T^{\max} = p_T^{\text{iso}} \geq \sum_{i=1}^{\Delta R_i < R_{\max}} p_T^i$
- Isolation supresses fragmentation photons



[3]

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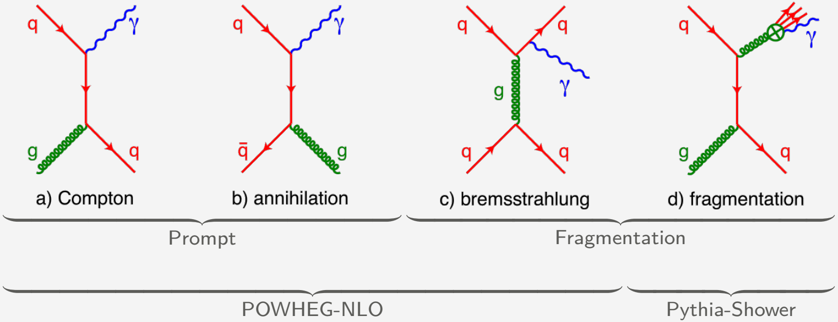
[3] d'Enterria, D. & Rojo, J. *Nucl. Phys. B* **860,** 311–338. arXiv: `1202.1762 [hep-ph]` (2012).

POsitive Weight Hardest Emission Generator (POWHEG)



- Separation between NLO and fragmentation contribution is non-trivial in NLO+PS
- In order to regulate the divergences we must include pure QCD di-/trijet production at LO

Born	$pp \to \gamma j \sim \mathcal{O}(\alpha\alpha_s)$		$pp \to jj \sim \mathcal{O}(\alpha_s^2)$	
Virtual	$\mathcal{O}(\alpha\alpha_s) \cdot \mathcal{O}(\alpha)$	$\mathcal{O}(\alpha\alpha_s) \cdot \mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha_s^2) \cdot \mathcal{O}(\alpha)$	$\mathcal{O}(\alpha_s^2) \cdot \mathcal{O}(\alpha_s)$
Real	$pp \to \gamma\gamma j \sim \mathcal{O}(\alpha^2\alpha_s)$	$pp \to \gamma jj \sim \mathcal{O}(\alpha\alpha_s^2)$		$pp \to jjj \sim \mathcal{O}(\alpha_s^3)$

POsitive Weight Hardest Emission Generator (POWHEG)

direct photon with 2 jets production at NLO:

<table>
<tr><td>Born</td><td colspan="2">$pp \to \gamma jj \sim \mathcal{O}(\alpha\alpha_s^2)$</td><td colspan="2">$pp \to jjj \sim \mathcal{O}(\alpha_s^3)$</td></tr>
<tr><td>Virtual</td><td>$\mathcal{O}(\alpha\alpha_s^2) \cdot \mathcal{O}(\alpha)$</td><td>$\mathcal{O}(\alpha\alpha_s^2) \cdot \mathcal{O}(\alpha_s)$</td><td>$\mathcal{O}(\alpha_s^3) \cdot \mathcal{O}(\alpha)$</td><td>$\mathcal{O}(\alpha_s^3) \cdot \mathcal{O}(\alpha_s)$</td></tr>
<tr><td>Real</td><td>$pp \to \gamma\gamma jj \sim \mathcal{O}(\alpha^2\alpha_s^2)$</td><td colspan="2">$pp \to \gamma jjj \sim \mathcal{O}(\alpha\alpha_s^3)$</td><td>$pp \to jjjj \sim \mathcal{O}(\alpha_s^4)$</td></tr>
</table>

NLO Matching:

- FKS subtraction to handle regularized divergences between Reals and Virtuals
- 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.

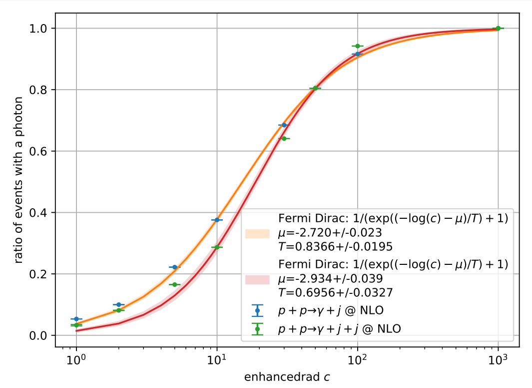
$$\Delta_R(p_T) \sim \exp\left[-\int \mathrm{d}\Phi_R \frac{R(\Phi_B, \Phi_R)}{B(\Phi_B)} \theta(k_T(\Phi_B, \Phi_R) - p_T)\right]$$

- PS must generate radiation only from below the scale k_T (→ veto algorithm).

Enhanced QED radiation

- The Born processes of different coupling strength rarely result in direct photon events $p + p \to \gamma + j(+j)$, compared to pure QCD events $p + p \to j + j(+j)$.
- If no QED emission is attached to the latter, it could still also produce a photon that is not directly produced in the hard process, but in the subsequent shower.

"enhancedrad" c feature increases the probability of attaching a QED radiation to the pure QCD Born process.



Enhanced QED radiation

Usual emission:

- solve for p_T with random $r \in (0,1)$, where U is the upper bound of the Sudakov factor $f \sim \frac{R}{B}$.
$$\log \Delta^U(p_T) = \log(r)$$
- accept event with $P_{\text{acc}} = f/U$ probability and reject with $1 - f/U$ probability.
- if rejected, repeat procedure for lower p_T until the emission is accepted or Λ_{QCD} is reached.

Enhanced QED radiation[4]:

- Introducing the parameter $c > 1$, while P_{acc} is unchanged.
$$\log \Delta^{cU}(p_T) = \log(r) \qquad \Leftrightarrow \qquad \log \Delta^U(p_T) = \frac{\log(r)}{c}$$
- Adjusted weight for n rejected emissions
$$w_n = \frac{1}{c} \prod_{i=1}^{n} \frac{1 - \frac{f_i}{cU_i}}{1 - \frac{f_i}{U_i}}$$

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[4] Hoeche, S., Schumann, S. & Siegert, F. *Phys. Rev. D* **81,** 034026. arXiv: `0912.3501 [hep-ph]` (2010).

Multi-channel phasespace construction

Same algorithm as in trijet[5]:

- Start from $2 \to 2$ massless phase space
- With 3 massless final state particles there are 6 FSR and 3 ISR divergent regions $(i, j \geq 3)$

$$S_{0j}^{\text{ISR}} = S_{1j} + S_{2j} = \frac{1}{E_j^2(1-\cos^2\theta_{1j})}, \qquad S_{ij}^{\text{FSR}} = \frac{E_i^2+E_j^2}{2E_i^2E_j^2(1-\cos\theta_{ij})} \tag{1}$$

- POWHEG provides routines to construct $N+1$ phase space corresponding to either FSR/ISR divergent regions with good importance sampling $(\Phi_{2\to 3,kj})$
- Pick region randomly and surpress other regions

$$\tilde{S}_{0j} = \frac{S_{ij}}{\sum_j(S_{0j}+\sum_i S_{ij})}, \qquad \tilde{S}_{ij} = \frac{S_{ij}}{\sum_j(S_{0j}+\sum_i S_{ij})}\frac{E_j}{E_i+E_j} \tag{2}$$

$$\mathrm{d}\Phi_B = \sum_{kj}\tilde{S}_{kj}\mathrm{d}\Phi_{2\to 3,kj} \qquad \tilde{S}_{0j,ij} \to \begin{cases} 1 & \text{as } E_j \to 0 \text{ or } \theta_{ij} \to 0 \\ 0 & \text{else} \end{cases} \tag{3}$$

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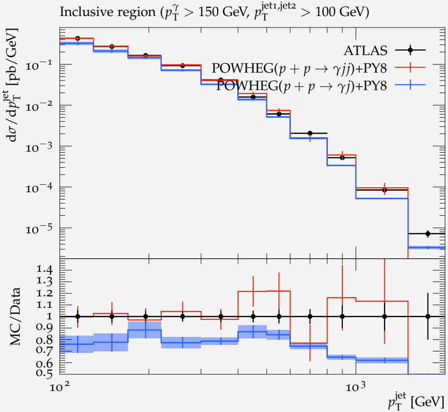
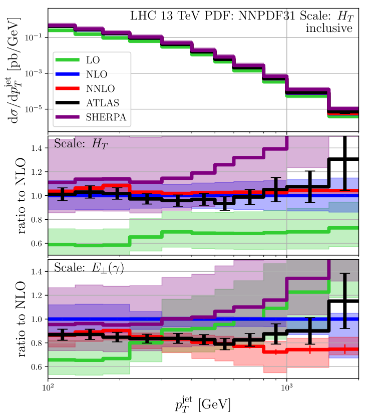
[5] Kardos, A., Nason, P. & Oleari, C. *JHEP* **04,** 043. arXiv: `1402.4001 [hep-ph]` (2014).

Preliminary: Photon and jets observables

- Isolated-photon plus two-jet production in pp collisions at $\sqrt{s} = 13$ TeV and POWHEG $(pp \to \gamma j)$ + Pythia8 and POWHEG $(pp \to \gamma jj)$ + Pythia8 predictions ($\Delta R = 0.4$ and $E^{\text{iso}}_{\text{T,cut}} \equiv 0.0042 \cdot E_T^{\gamma} + 4.8$ GeV)[6].





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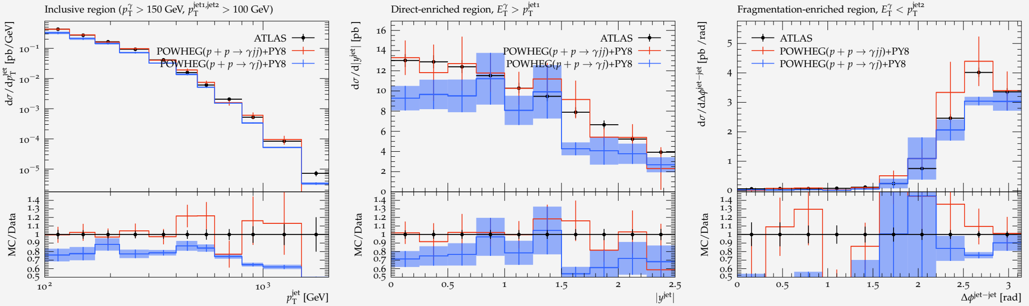
[6] Aad, G. *et al.* *JHEP* **03,** 179. arXiv: `1912.09866 [hep-ex]` (2020), Badger, S. *et al.* arXiv: `2304.06682 [hep-ph]` (Apr. 2023).

Preliminary: Photon and jets observables

- NLO Process with an additional jet catches characteristics of the distributions better than the LO+PS process, especially fragmentation-enriched region.
- Needs more statistics!



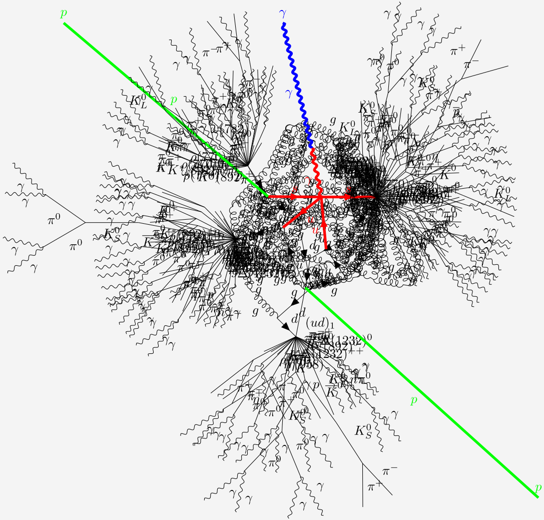
Inclusive region ($p_T^\gamma > 150$ GeV, $p_T^{\mathrm{jet1,jet2}} > 100$ GeV)

Direct-enriched region, $E_T^\gamma > p_T^{\mathrm{jet1}}$

Fragmentation-enriched region, $E_T^\gamma < p_T^{\mathrm{jet2}}$

Example event

- Diagram shows a complete generated proton-proton event with parton shower effects and hadron decays.
- Colliding partons in green.
- Hard process is colored in red and compressed into one vertex.
- Real photon is colored in blue.
- Many π^0 decays from jets into even more photons.



Outlook

- $pp \to \gamma j(j)$ is an important baseline for corresponding (N)PDF+QGP studies
- Parton shower valid instead of fragmentation functions
- Release $pp \to \gamma jj$ as POWHEG process
- Comparison with existing ALICE data $[\gamma h]$ data[7]
- Comparison of the different isolation criteria
- Comparison of QCD/QED PS (PYTHIA, HERWIG, ...)
- Soft photons in FOrward CALorimeter in ALICE (after LS3) and ALICE3
- Ingredient for MiNLO(') photon+jets in POWHEG

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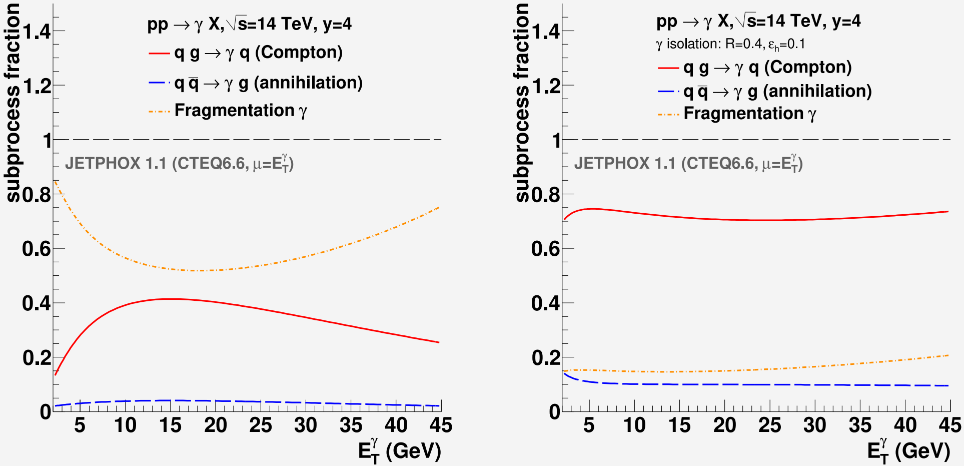
[7] Acharya, S. *et al.* *Phys. Rev. C* **102,** 044908. arXiv: 2005.14637 `[nucl-ex]` (2020).

Thank you!

Forward/Focal isolation



[8]

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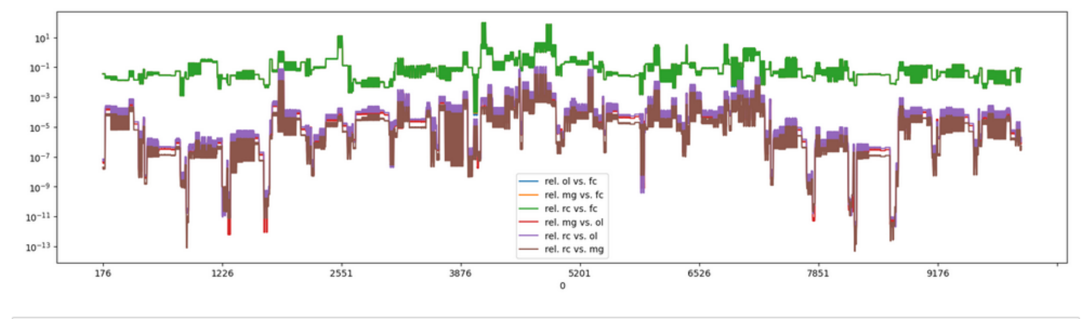
[8] ALICE Collaboration, C. Tech. rep. (CERN, Geneva, 2020). https://cds.cern.ch/record/2719928.

Virtual comparision

Comparison of the virtuals from FormCalc, RECOLA2, OpenLoops2 and MG5_aMC@NLO:

- x-axis random phase space point × flavour structure



Going to low scale

Using $Q = p_T^\gamma$ becomes problematic at low p_T, some solutions are:

- Look at ratios since the scale uncertainties are correlated and therefore cancel out
- Fix the scale to some value $Q \geq 1.2$ GeV
- Compute a ratio between $f^1 = F(Q = Q_0)$ and $f^2 = F(Q = 2Q_0)$ in a reliable region $(Q_0 > 2GeV)$ and use $F(Q)\frac{f^1}{f^2}$
- Theoretically motivated powerlaw fit[9]:

$$\frac{\mathrm{d}\sigma^{\mathsf{pp}}}{\mathrm{d}p_T\,\mathrm{d}y} = A_{\mathsf{pp}}(1 + \frac{p_T^2}{P_0})^{-n} \tag{4}$$

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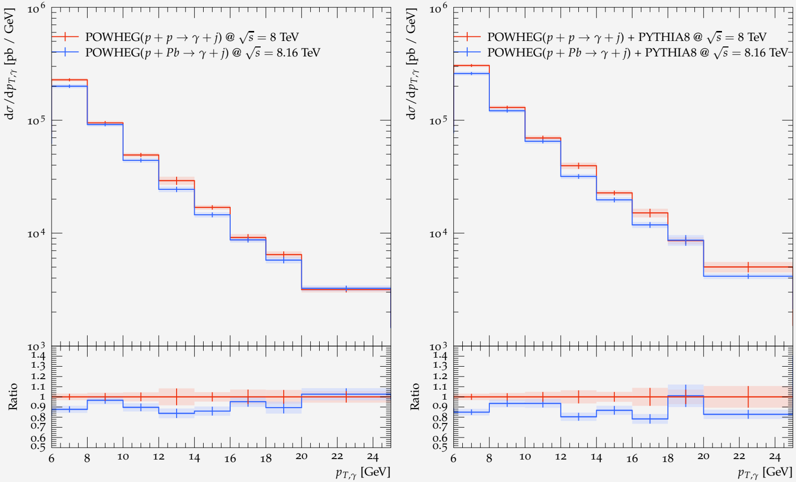
[9] Garcia-Montero, O., Löher, N., Mazeliauskas, A., Berges, J. & Reygers, K. *Phys. Rev. C* **102,** 024915. arXiv: `1909.12246 [hep-ph]` (2020), Adare, A. *et al. Phys. Rev. C* **91,** 064904. arXiv: `1405.3940 [nucl-ex]` (2015).

Nuclear effects

- Photon is confined to $|y| < 0.8$ with an isolation cone of $R^{\text{iso}} = 0.4$ and an isolation energy of $p_T^{\text{iso}} = 2$ GeV



Direct photon codes

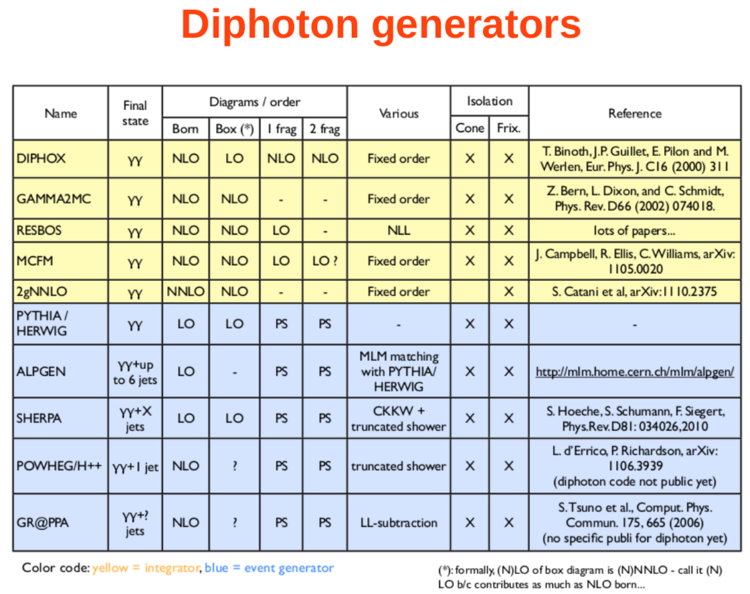
Shower Monte Carlo Event Generators:

Code	$pp \to \gamma j$	$pp \to \gamma jj$	$pp \to \gamma\gamma$
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	$pp \to \gamma j$	$pp \to \gamma jj$	$pp \to \gamma\gamma$
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.



Diphoton generators

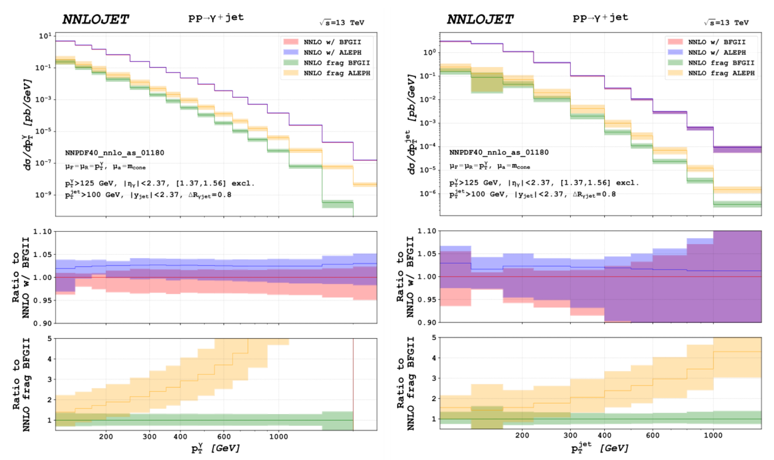
Name	Final state	Diagrams / order				Various	Isolation		Reference
		Born	Box (*)	1 frag	2 frag		Cone	Frix.	
DIPHOX	γγ	NLO	LO	NLO	NLO	Fixed order	X	X	T. Binoth, J.P. Guillet, E. Pilon and M. Werlen, Eur. Phys. J. C16 (2000) 311
GAMMA2MC	γγ	NLO	NLO	-	-	Fixed order	X	X	Z. Bern, L. Dixon, and C. Schmidt, Phys. Rev. D66 (2002) 074018.
RESBOS	γγ	NLO	NLO	LO	-	NLL	X	X	lots of papers...
MCFM	γγ	NLO	NLO	LO	LO ?	Fixed order	X	X	J. Campbell, R. Ellis, C. Williams, arXiv: 1105.0020
2gNNLO	γγ	NNLO	NLO	-	-	Fixed order		X	S. Catani et al, arXiv:1110.2375
PYTHIA / HERWIG	γγ	LO	LO	PS	PS	-	X	X	-
ALPGEN	γγ+up to 6 jets	LO	-	PS	PS	MLM matching with PYTHIA/ HERWIG	X	X	http://mlm.home.cern.ch/mlm/alpgen/
SHERPA	γγ+X jets	LO	LO	PS	PS	CKKW + truncated shower	X	X	S. Hoeche, S. Schumann, F. Siegert, Phys.Rev.D81: 034026,2010
POWHEG/H++	γγ+1 jet	NLO	?	PS	PS	truncated shower	X	X	L. d'Errico, P. Richardson, arXiv: 1106.3939 (diphoton code not public yet)
GR@PPA	γγ+? 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



[10][11]

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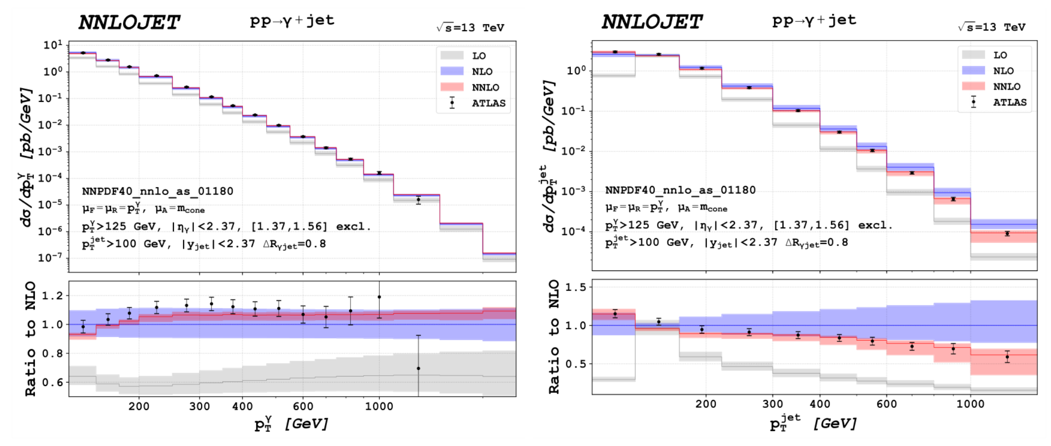
[10] Chen, X., Gehrmann, T., Glover, N., Höfer, M. & Huss, A. *JHEP* **04,** 166. arXiv: `1904.01044 [hep-ph]` (2020).

[11] Chen, 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]`.

NNLOJET



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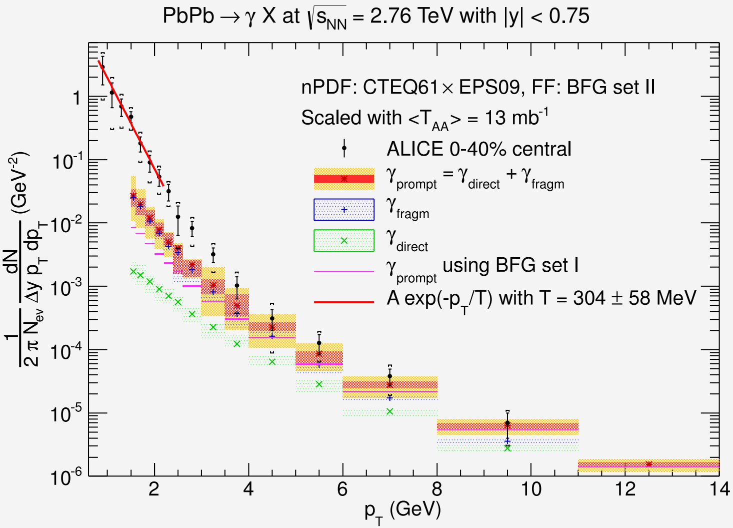
[12] Chen, X., Gehrmann, T., Glover, N., Höfer, M. & Huss, A. *JHEP* **04,** 166. arXiv: 1904.01044 [hep-ph] (2020).

[13] Chen, 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].

QGP temperature



[14]

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[14] Klasen, M., Klein-Bösing, C., König, F. & Wessels, J. P. *JHEP* **10,** 119. arXiv: `1307.7034 [hep-ph]` (2013).