

Recent work on electromagnetic probes:

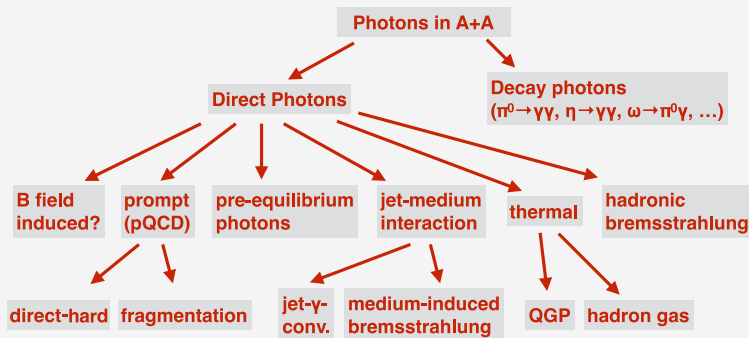
Real and virtual photon production in POWHEG

Tomas Jezo, Michael Klasen, [Alexander Puck Neuwirth](#)



Photons

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

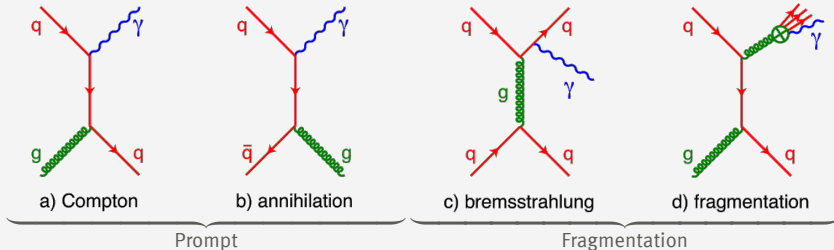


Direct-hard: directly produced in the hard collisions, computed in perturbative non-thermal QCD.

Thermal: are expected to be produced in quark gluon plasma

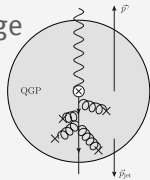
$$dN_{\gamma}^{\text{thermal}} = dN_{\gamma}^{\text{direct}} - dN_{\gamma}^{\text{prompt}}$$

Prompt photons



- ▶ Probe low- $x \sim \frac{2p_T^\gamma}{\sqrt{s}} \exp(-y)$ and $Q \sim p_T^\gamma$ region where gluon density is large
- ▶ Measure saturation effects in gluon density
- ▶ Real photons are important probes of the QGP (e.g. $T_{\text{eff.}}$)
- ▶ Scale and nuclear PDF uncertainties large at low p_T

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



Photon Fragmentation

- ▶ Fragmentation functions (FF), like PDFs, usually can not be computed in perturbative theory and must be measured at an initial scale
 - ▶ Prompt photons in e^+e^- collisions (limited data)
 - ▶ Prompt photons in hadronic collisions¹
 - ▶ In vector meson production, assuming dominating hadronic fluctuations of the photon at low scales (VMD)²
- ▶ LO Photon evolution equation, with momentum transfer z and factorization scale μ_F

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

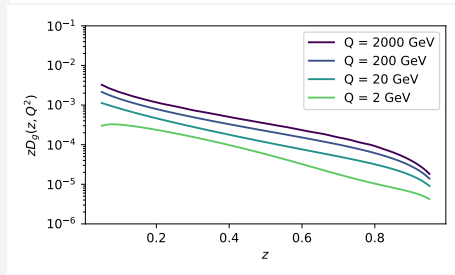
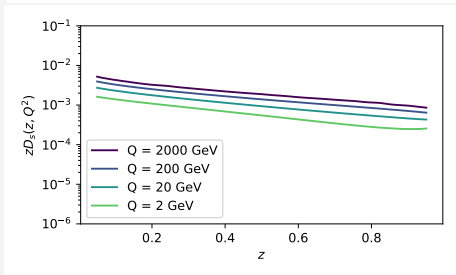
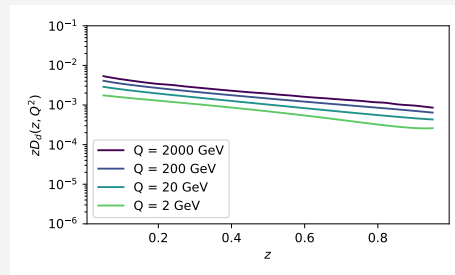
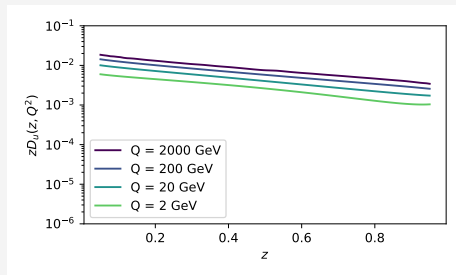
$$D_{\gamma/q}(z, \mu_F) = \frac{\alpha}{2\pi} P_{\gamma q}(z) \log \left(\frac{\mu_F^2}{\mu_s^2} \right) + D_{\gamma/q}^{\text{measured}}(z, \mu_s) \quad D_{\gamma/g}(z, \mu_F) = \text{const.}$$

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

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

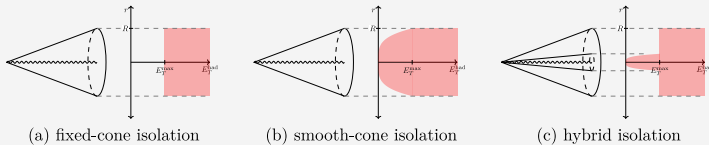
Photon Fragmentation

Fragmentation function BFG I³



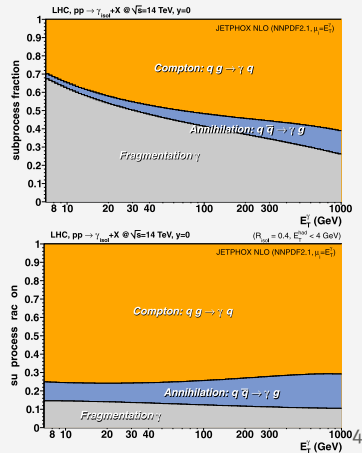
³Bourhis, L. et al. *Eur. Phys. J. J.* **2**, 529–537. arXiv: hep-ph/9704447 (1998).

Photon isolation



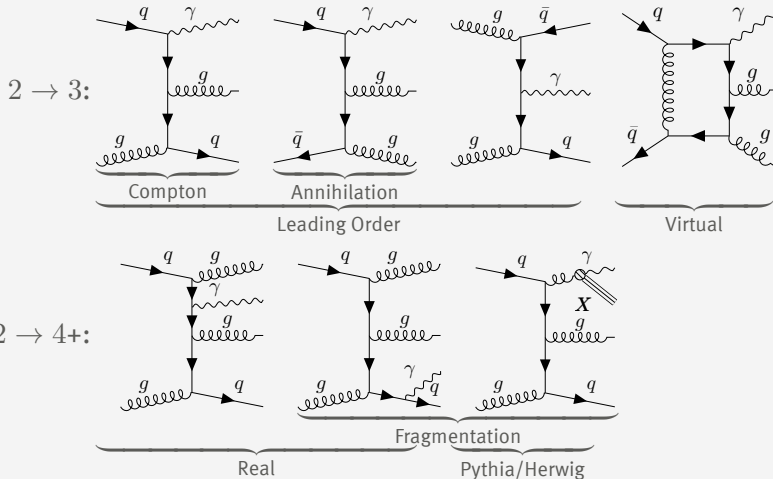
Simple boost invariant definition of a fixed-cone (a):

- ▶ 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 $E_T^{\text{max}} = p_T^{\text{iso}} \geq \sum_{i=1}^{\Delta R_i < R_{\text{max}}} p_T^i$
- ▶ Isolation suppresses fragmentation photons



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

Prompt photon production in POWHEG with two jets

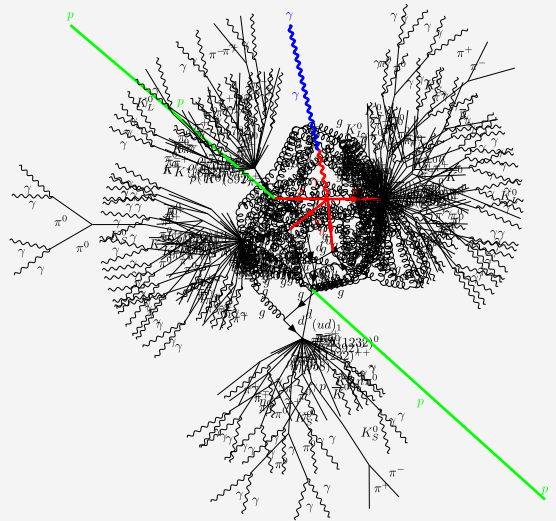


- ▶ Avoid FFs by using POWHEG method for NLO matching with parton shower
- ▶ Separation between NLO and fragmentation contribution is non-trivial in NLO+PS
- ▶ In order to regulate the divergences we must include pure QCD trijet production at LO

Prompt photon production in POWHEG with two jets

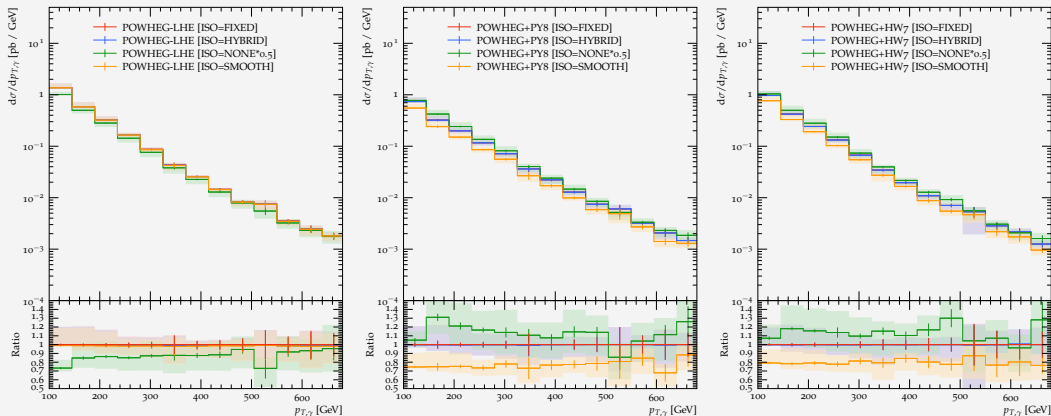
Example event

- ▶ Diagram shows a complete generated proton-proton event with parton shower effects and hadron decays.
- ▶ Colliding protons 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.



Prompt photon production in POWHEG with two jets

Transverse momentum distribution of the photon for different isolation schemes with no Parton Shower (left), PYTHIA (center) and HERWIG (right) parton showers

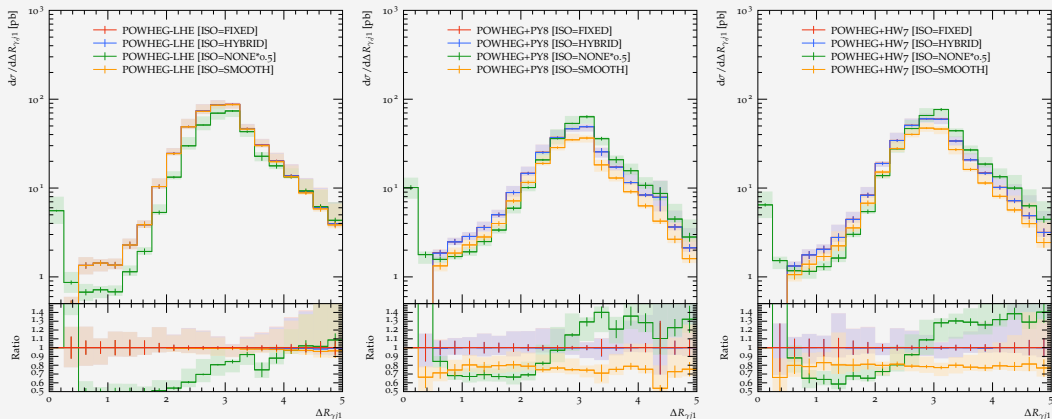


► Isolation insignificant without PS

► Isolation reduces cross section, especially towards low p_T and for smooth isolation

Prompt photon production in POWHEG with two jets

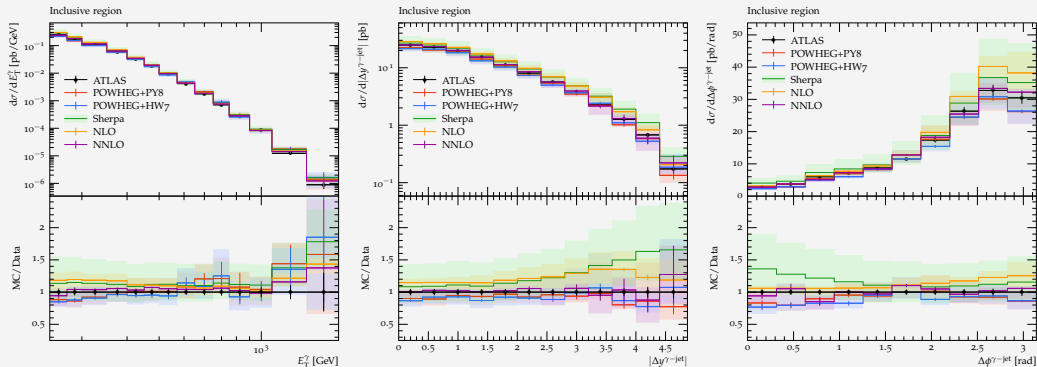
$\Delta R_{\gamma j_1}$ distribution of the photon for different isolation schemes



- ▶ When the hardest jet is close to the isolation cone around the photon $\Delta R_{\gamma j_1} < 0.5$ the isolation eliminates most of the cross section
- ▶ Parton shower shifts contributions to low $\Delta R_{\gamma j_1} < 0.5$

Prompt photon production in POWHEG with two jets

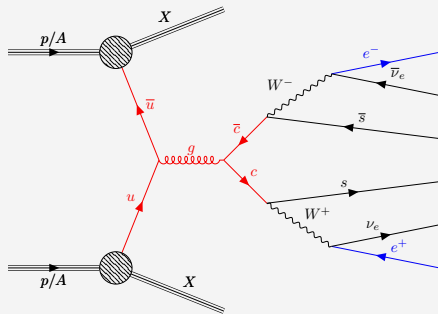
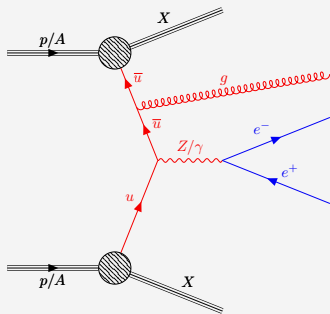
- Isolated-photon plus two-jet production in pp collisions at $\sqrt{s} = 13$ TeV and POWHEG ($pp \rightarrow \gamma j$) + Pythia8 and POWHEG ($pp \rightarrow \gamma jj$) + Pythia8 predictions ($\Delta R = 0.4$ and $E_{T,\text{cut}}^{\text{iso}} \equiv 0.0042 \cdot E_T^\gamma + 4.8 \text{ GeV}$)⁵.



⁵Aad, G. et al. JHEP **03**, 179. arXiv: 1912.09866 [hep-ex] (2020), Badger, S. et al. JHEP **10**, 071. arXiv: 2304.06682 [hep-ph] (2023), Ježo, T. et al. arXiv: 2409.01424 [hep-ph] (Sept. 2024).

Virtual photons

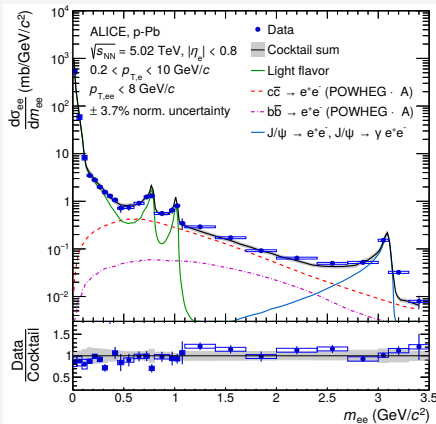
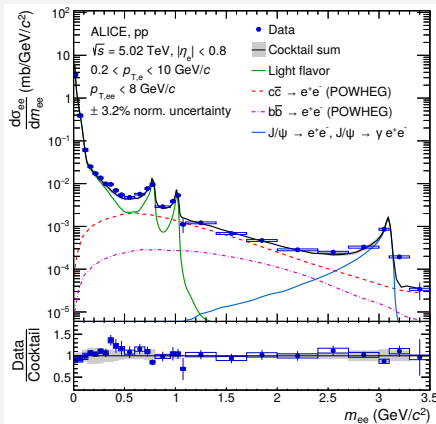
- ▶ Exactly same Feynman diagrams as real photons, but the photon is off-shell and branches into a **lepton pair (ee)**, with possible Z -interference
- ▶ Kroll-Wada theorem relates low invariant mass dileptons to on-shell photons⁶
- ▶ Huge background from light flavour decays in low invariant electron pair mass region
- ▶ Huge background from heavy flavour decays in the intermediate mass region



⁶Kroll, N. M. & Wada, W. *Phys. Rev.* **98**, 1355–1359 (1955).

Dielectron studies

ALICE dilepton analysis⁷



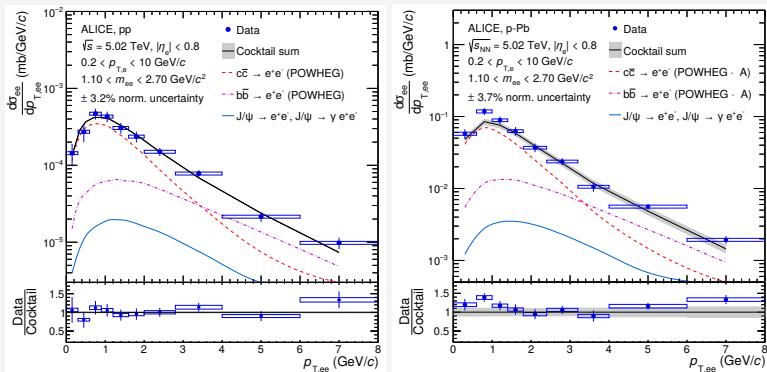
Dilepton as a clock in nuclear collisions:

- ▶ Pre-equilibrium effects around $m_{ee} \gtrsim 2$ GeV
- ▶ Expected formation of the QGP in the range $1 \text{ GeV} \lesssim m_{ee} \lesssim 2 \text{ GeV}$
- ▶ Hadronic phase at later emission stages with $m_{ee} \lesssim 1 \text{ GeV}$

⁷Acharya, S. et al. *Phys. Rev. C* **102**, 055204. arXiv: 2005.11995 [nucl-ex] (2020).

Virtual photons

Uses template PYTHIA/POWHEG cc/bb distribution normalization in the hadronic cocktail.

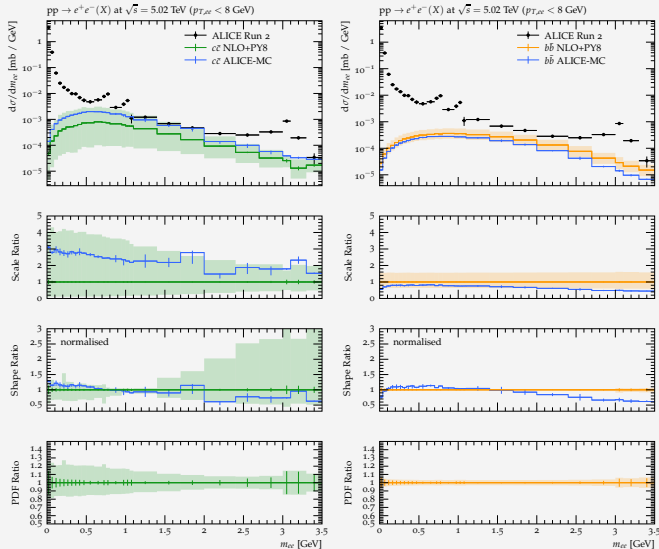


But:

- ▶ Theory uncertainties are underestimated (<4% normalization uncertainty)
- ▶ DY/virtual photon not included/considered

Virtual photons

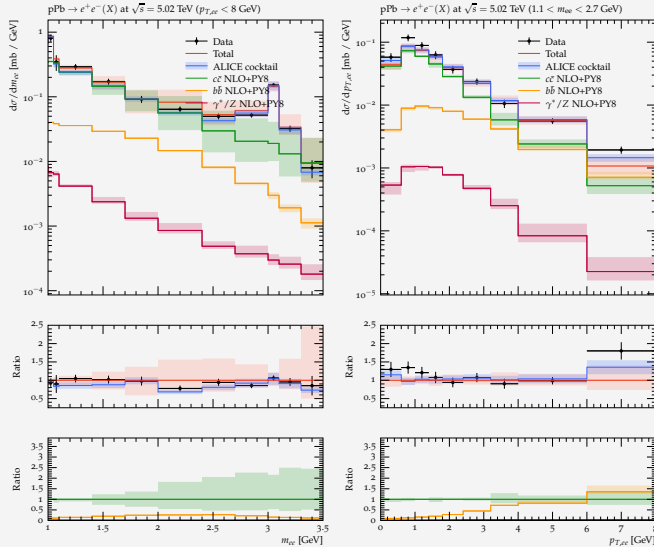
Full PDF and scale uncertainty of open heavy quark production via POWHEG.⁸



⁸Andronic, A. et al. [arXiv: 2401.12875 \[hep-ph\]](https://arxiv.org/abs/2401.12875) (Jan. 2024).

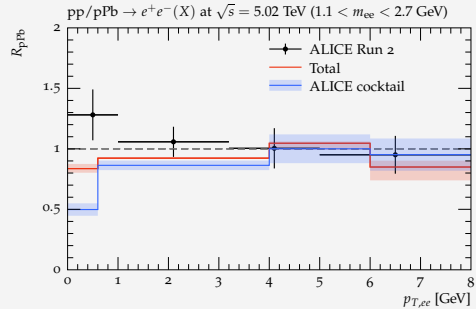
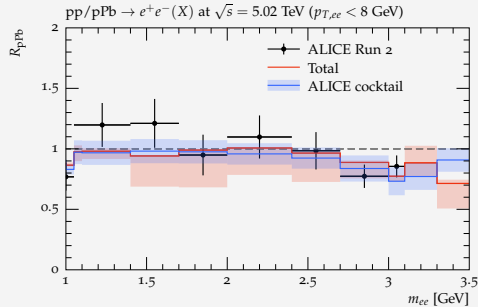
Virtual photons

More realistic normalized uncertainties, recent MSHT20 and nCTEQ15HQ PDFs and added Drell-Yan contribution improve the fitted cocktail.



Virtual photons

Looking at ratios R_{pPb} between pp and pPb collisions



- ▶ most scale uncertainties cancel out in the ratio
- ▶ larger uncertainties due to open charm production remain in the intermediate invariant mass spectrum

Conclusion

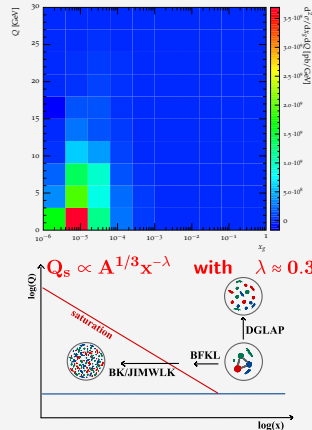
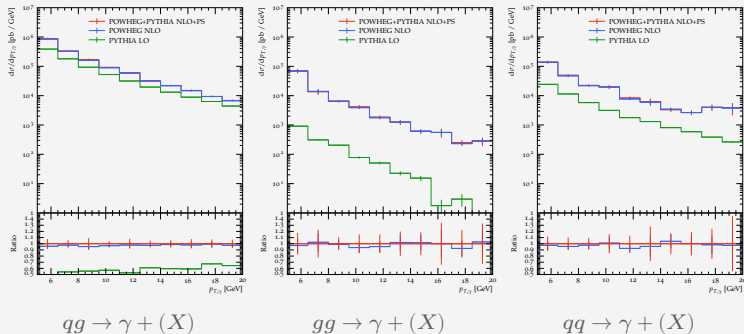
Summary:

- ▶ Parton shower can be a substitute for fragmentation functions
- ▶ New $pp \rightarrow \gamma jj$ NLO process in POWHEG-BOX-V2
- ▶ Despite similar topologies processes involving a single photon are phenomenologically different
- ▶ Large scale uncertainties can be reduced/shifted by normalizing to shape uncertainty
- ▶ Drell-Yan virtual photon contribution is small in given kinematic range, but can improve the fit
- ▶ HEPData and Rivet analyses simplify comparison of theory and data

Thank you!

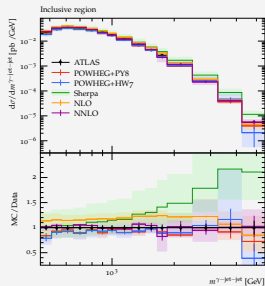
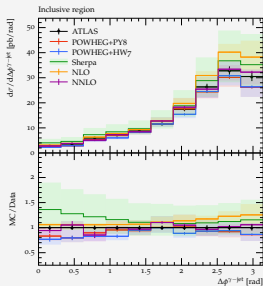
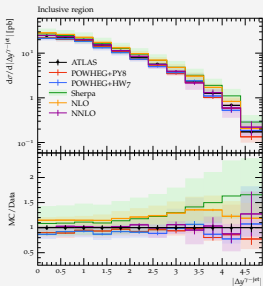
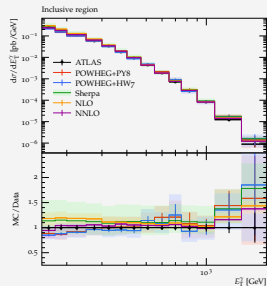
Preliminary: FOCAL studies

Predictions for isolated prompt photons in the FOCAL experiment at $\sqrt{s} = 14$ TeV are shown. The cuts applied on the photon are $3.4 < \eta^\gamma < 5.8$ with a fixed isolation cone of $R_{\text{iso}} = 0.4$ and $E_T^{\text{iso}} = 5$ GeV.



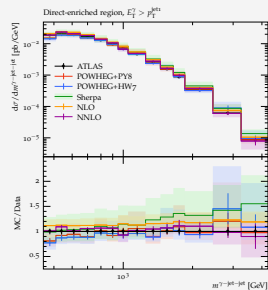
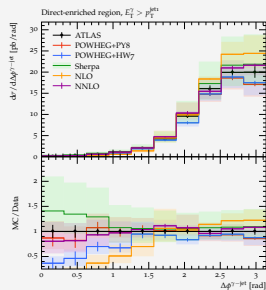
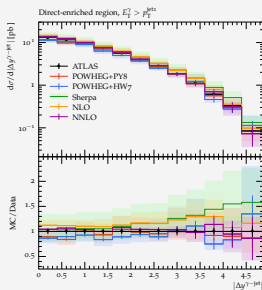
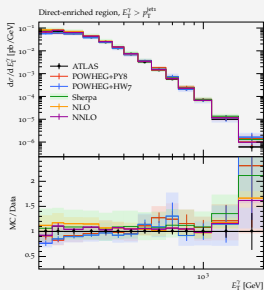
Real photon

Inclusive regime



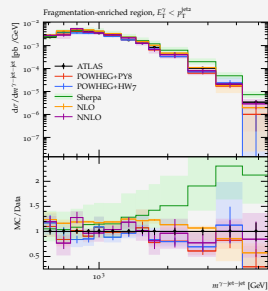
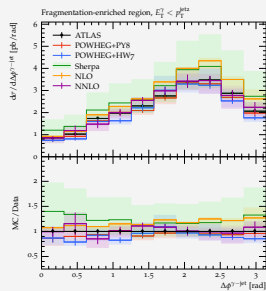
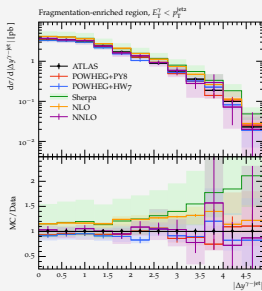
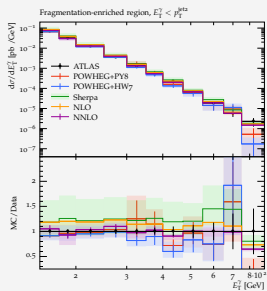
Real photon

Direct-enriched regime, $E_T^\gamma > p_T^{\text{jet1}}$



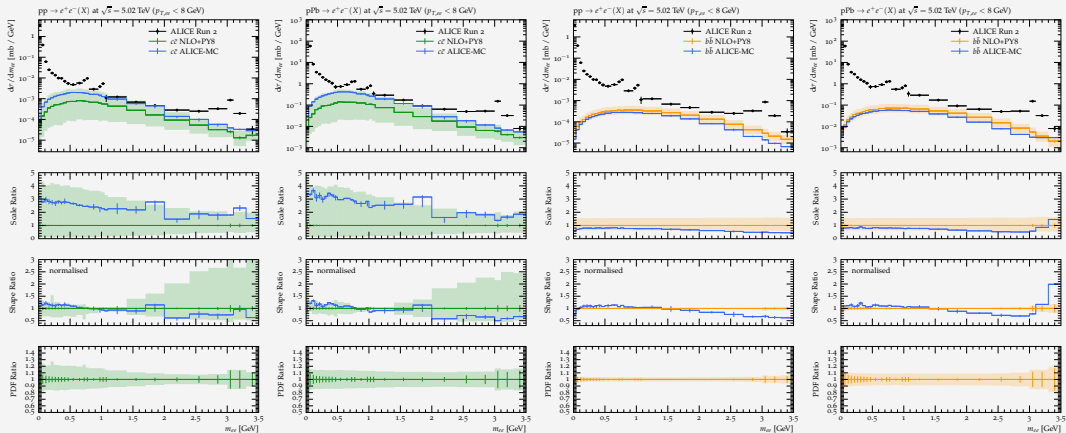
Real photon

Fragmentation-enriched regime, $E_T^\gamma < p_T^{\text{jet2}}$



Virtual photon

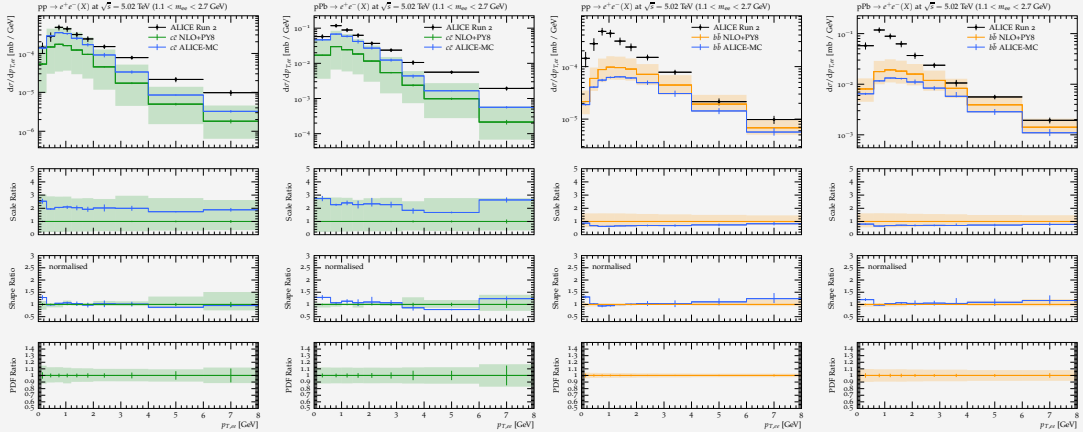
Full PDF and scale uncertainty of open heavy quark production via POWHEG⁹.



⁹Andronic, A. et al. [arXiv: 2401.12875 \[hep-ph\]](https://arxiv.org/abs/2401.12875) (Jan. 2024).

Virtual photon

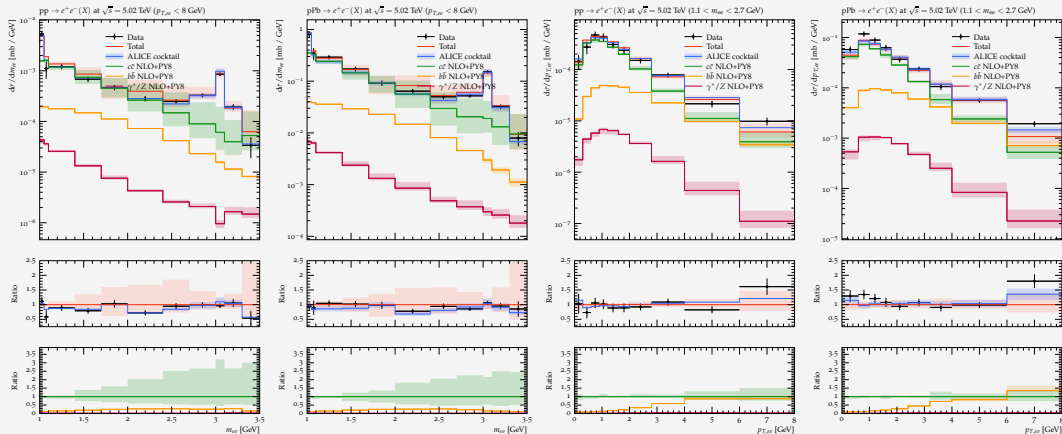
Full PDF and scale uncertainty of open heavy quark production via POWHEG¹⁰.



¹⁰Andronic, A. et al. [arXiv: 2401.12875 \[hep-ph\]](https://arxiv.org/abs/2401.12875) (Jan. 2024).

Virtual photon

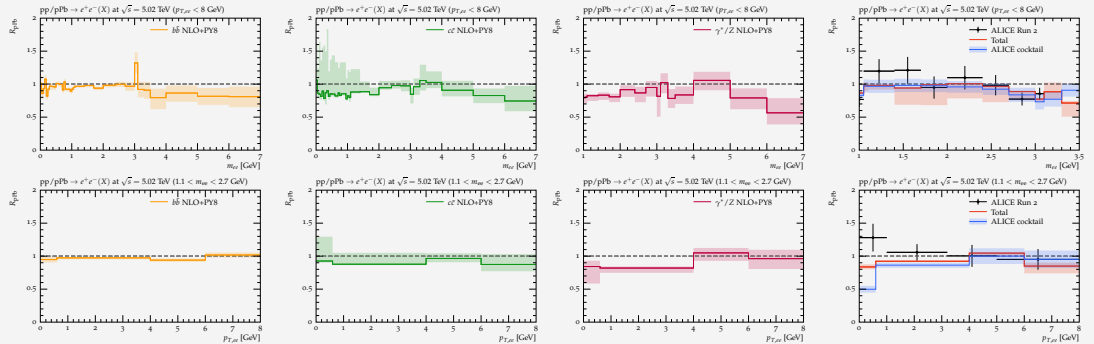
More realistic normalized uncertainties and added Drell-Yan contribution improve the fitted cocktail.



Virtual photon

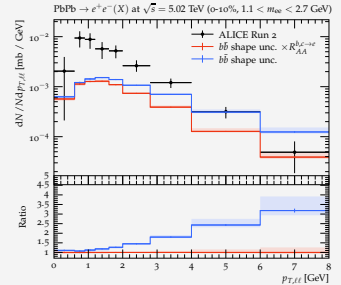
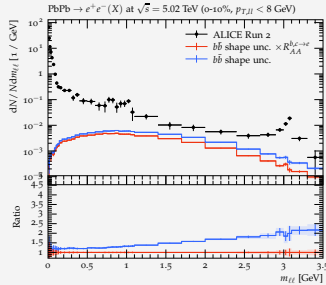
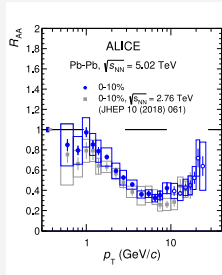
R_{pPb}

Full PDF and scale uncertainty of open heavy quark production via POWHEG.



Virtual photon

Open bottom production $\text{PbPb} \rightarrow b\bar{b}(X)$ with and without including a $R_{AA}^{b,c \rightarrow e}$ factor¹¹.



¹¹Acharya, S. et al. Phys. Lett. B **804**, 135377. arXiv: 1910.09110 [nucl-ex] (2020), Acharya, S. et al. arXiv: 2308.16704 [nucl-ex] (Aug. 2023).