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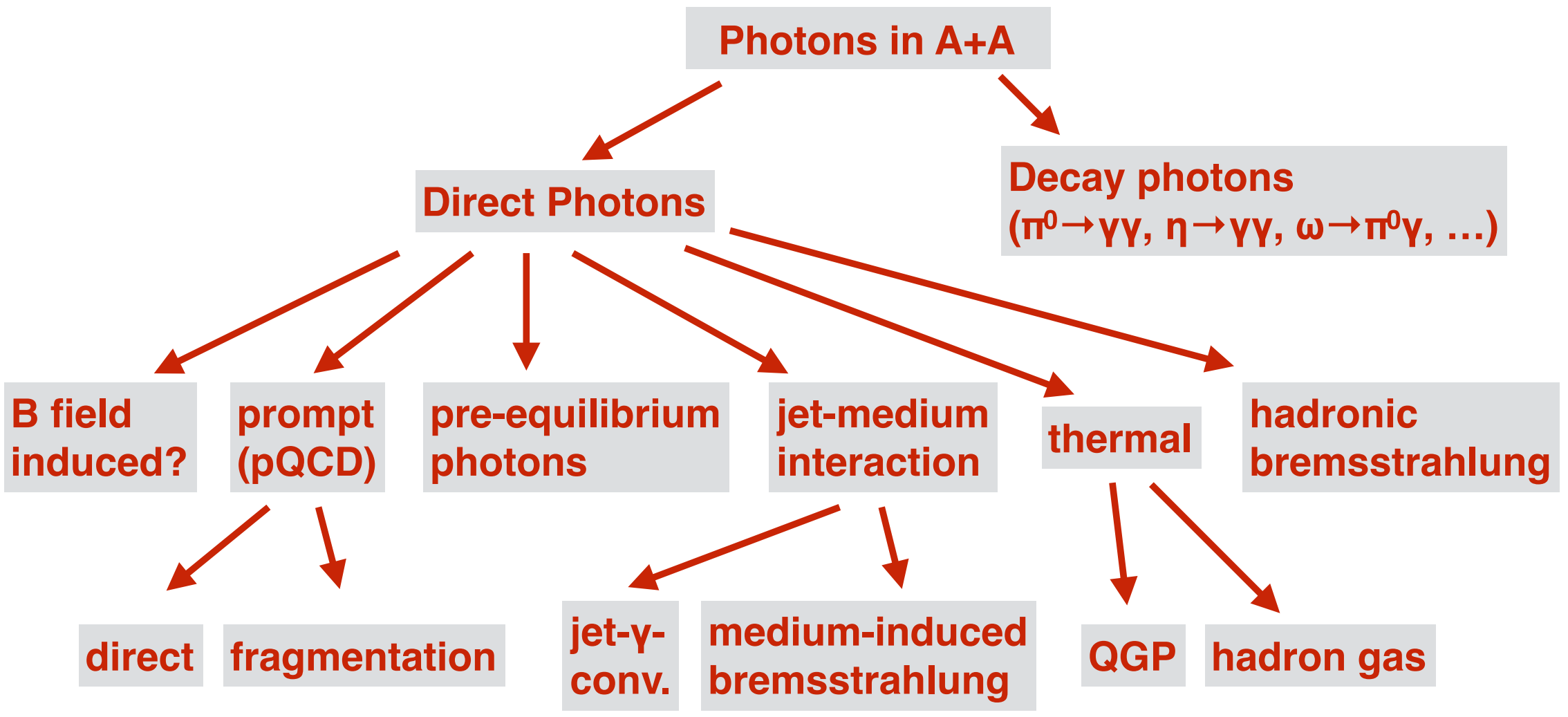
Prompt photon production with up to three jets in POWHEG

Photons

There are many sources of photons in proton-proton and heavy ion collisions. The figure below shows how they can be grouped [1].



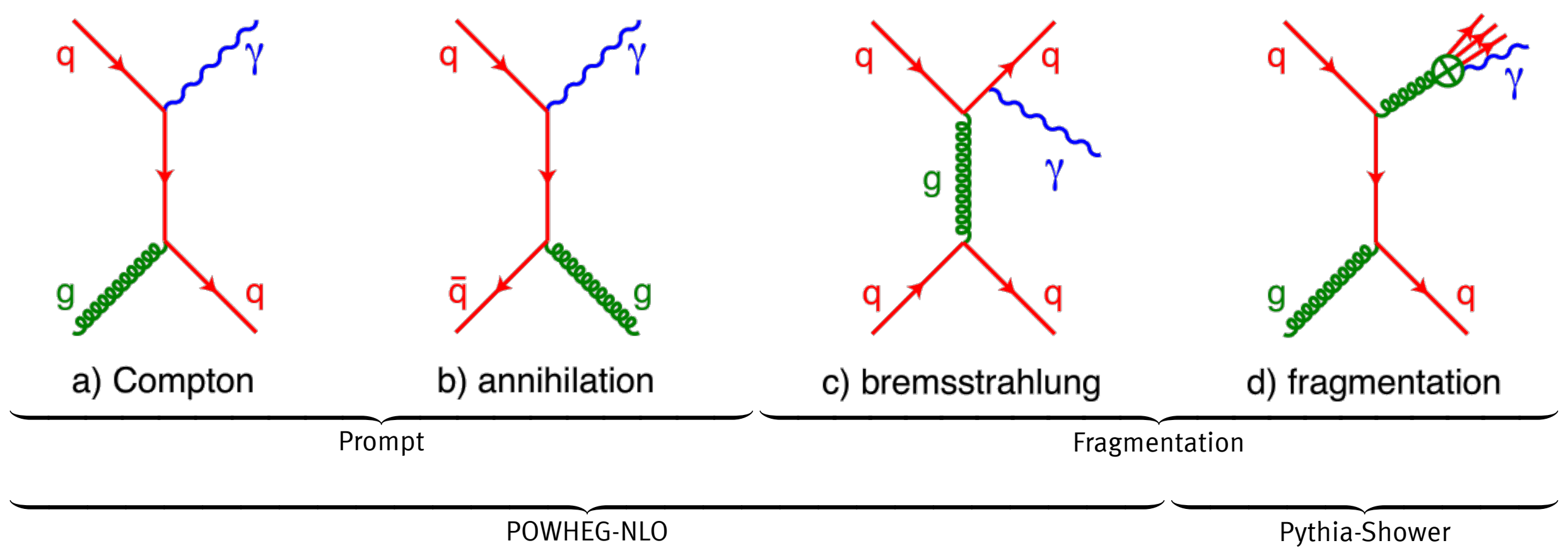
Photons in A+A
- **Direct Photons**
  - **B field induced?**
  - **prompt (pQCD)**
    - **direct**
    - **fragmentation**
  - **pre-equilibrium photons**
  - **jet-medium interaction**
    - **jet-γ-conv.**
    - **medium-induced bremsstrahlung**
  - **thermal**
    - **QGP**
    - **hadron gas**
  - **hadronic bremsstrahlung**
- **Decay photons (π⁰→γγ, η→γγ, ω→π⁰γ, …)**

We focus on prompt photon production, meaning photons that are prompt-direct, produced in the hard collisions, computed in perturbative non-thermal QCD, as well as fragmentation photons originating from quark and gluon fragmentation. The production rate of thermal photons in QGP can be obtained by subtracting the rate of prompt photons from the rate of direct photons. Photons are either detected directly, e.g. in an electromagnetic calorimeter or by conversion via e^+e^- pairs of low invariant-mass.

Prompt photons

Prompt photons probe the low-x and $Q \sim p_T^\gamma$ region where the gluon density is high. Thus, they provide an independent observable that gives direct access to the gluon density in protons and nuclei and is less affected by final state effects than jets. The real photons are important probes of the QGP and its effective temperature ($T_{eff.}$) as they do not interact strongly and experience no jet-quenching effects.

Prompt photons are typically separated into Compton, annihilation, bremsstrahlung and fragmentation processes. While this is reasonable at leading order going to next-to-leading order plus parton shower, this separation becomes non-trivial, as [2] shows below.



POWHEG - POsitive Weight Hardest Emission Generator

Since the NLO amplitude has n-particle (Born and Virtual) and $n+1$-particle (Real) contributions, they must be matched. POWHEG attaches the first emission to the n-particle state with a modified Sudakov factor $\Delta_R(p_T)$ so that the NLO accuracy is preserved.

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

The following parton shower should only generate radiation only from below the k_T scale ($\rightarrow$ veto algorithm). In contrast to MC@NLO, this method avoids negatively weighted events. Renormalization and factorization scales are chosen by the $p_T^{\gamma,q,g} = \mu$ of the underlying Born process. Since $pp \rightarrow \gamma + X$ has a collinear divergence at LO a cut must be imposed on $p_T > p_T^{\mathrm{min}}$, affecting events in the region of interest at low p_T. In POWHEG, the fragmentation contribution, i.e. QED parton shower ($q \rightarrow q\gamma$), is matched to the NLO direct computation [3, 4]. However, it is expected to be suppressed with respect to QCD by a/a_s, color factors and multiplicities.

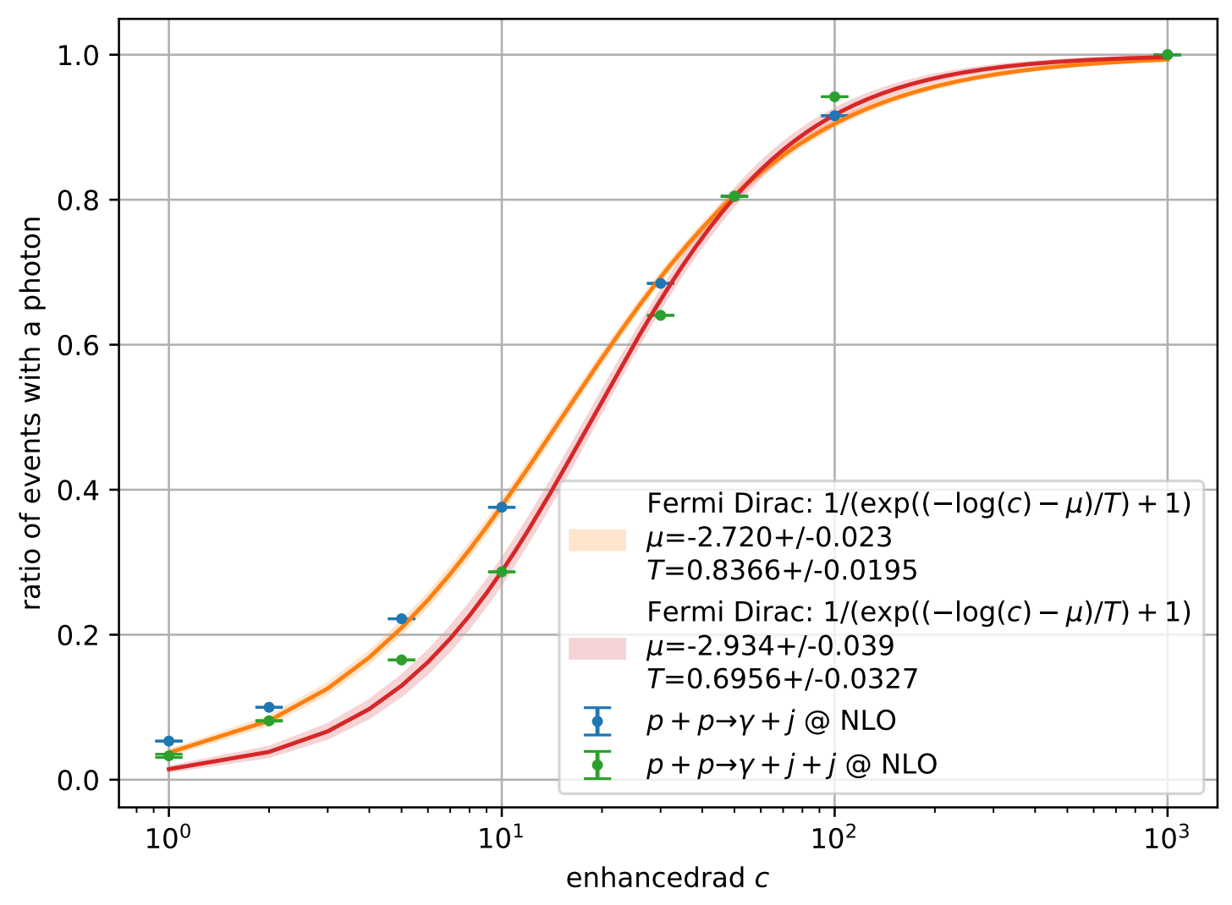
Enhanced QED radiation

Because of the different coupling strengths, direct photon events $p+p \rightarrow \gamma + j(+j)$ are rarely generated, compared to pure QCD events $pp \rightarrow j+j$. 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.

With the `enhancedrad` feature the probability of attaching a QED radiation to the pure QCD Born process is increased. The p_T of an emission is determined by solving the equation

$$\log \Delta^{cU}(p_T) = \frac{\log(r)}{c}$$

where $\Delta^{cU}(p_T)$ is a lower bound of the modified Sudakov factor $\Delta_R(p_T)$, r is a randomly chosen number and c is the `enhancedrad` parameter. The emission of a particle at solved p_T is accepted with $\log \Delta_R(p_T) / \log \Delta^{cU}(p_T)$ or is vetoed otherwise. If the emission is rejected, the procedure is repeated for lower p_T until the emission is accepted or Λ_{QCD} is reached. No enhanced radiation would mean a parameter $c = 1$ in the equation.



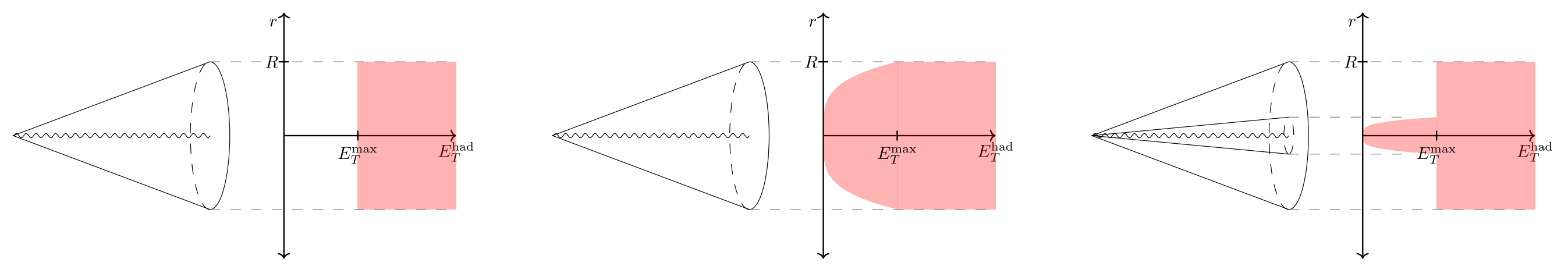
We observe that the number of photons produced before the shower scales as a Fermi Dirac statistic with the `enhancedrad` parameter c. Note, however, that depending on the analysis, more reweighed photons do not necessarily reduce uncertainties.

References

1. Reygers, K. *Direct photon measurements* `https://indico.cern.ch/event/1174824/contributions/5066277/`. Accessed: 2023–03-17. 2022.
2. A Forward Calorimeter (FoCal) in the ALICE experiment. `https://cds.cern.ch/record/2696471` (2019).
3. Hoeche, S., Schumann, S. & Siegert, F. Hard photon production and matrix-element parton-shower merging. *Phys. Rev. D* **81,** 034026. arXiv: `0912.3501 [hep-ph]` (2010).
4. Jezo, T., Klasen, M. & König, F. Prompt photon production and photon-hadron jet correlations with POWHEG. *JHEP* **11,** 033. arXiv: `1610.02275 [hep-ph]` (2016).
5. Amoroso, S. *et al. Les Houches 2019: Physics at TeV Colliders: Standard Model Working Group Report* in *11th Les Houches Workshop on Physics at TeV Colliders: PhysTeV Les Houches* (Mar. 2020). arXiv: `2003.01700 [hep-ph]`.
6. Aad, G. *et al.* Measurement of isolated-photon plus two-jet production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. *JHEP* **03,** 179. arXiv: `1912.09866 [hep-ex]` (2020).

Photon isolation

There are several ways to isolate the photon. Below, a photon is isolated as long as the red region is unpopulated [5].

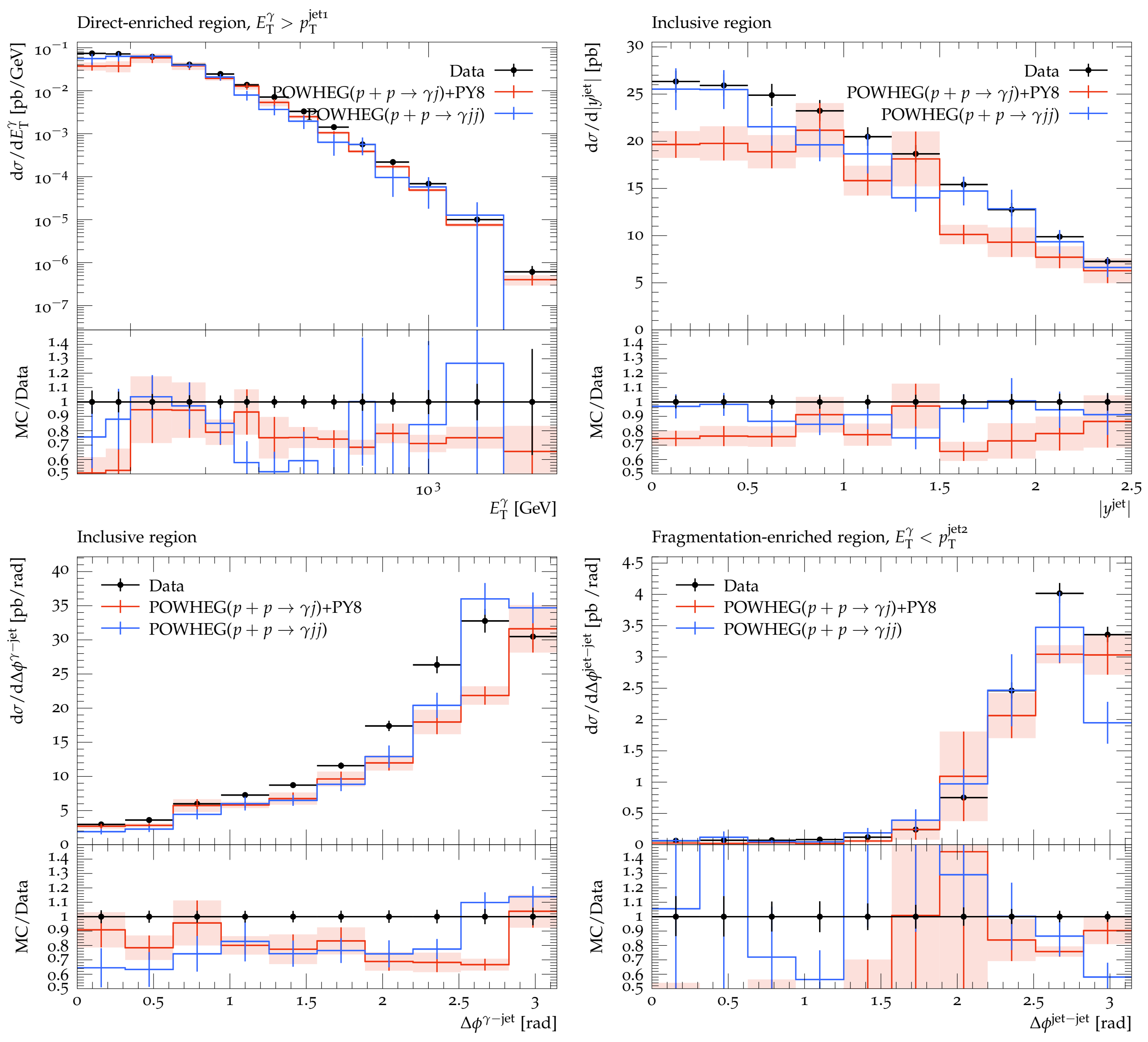


(a) fixed-cone isolation (b) smooth-cone isolation (c) hybrid isolation

We stick to the simple boost invariant definition of a fixed-cone (a), where the cone radius around the photon is defined as $R^{\mathrm{iso}} = \sqrt{\Delta\phi^2 + \Delta n^2}$. The activity in the cone is measured by the transverse momenta p_T of the particles. The photon is isolated if the sum of the transverse momenta does not exceed a threshold $E_T^{\mathrm{max}} = p_T^{\mathrm{iso}} \geq \sum_{i=1}^{\Delta R_i < R_{\mathrm{max}}} p_T^i$.

Photon and jets observables

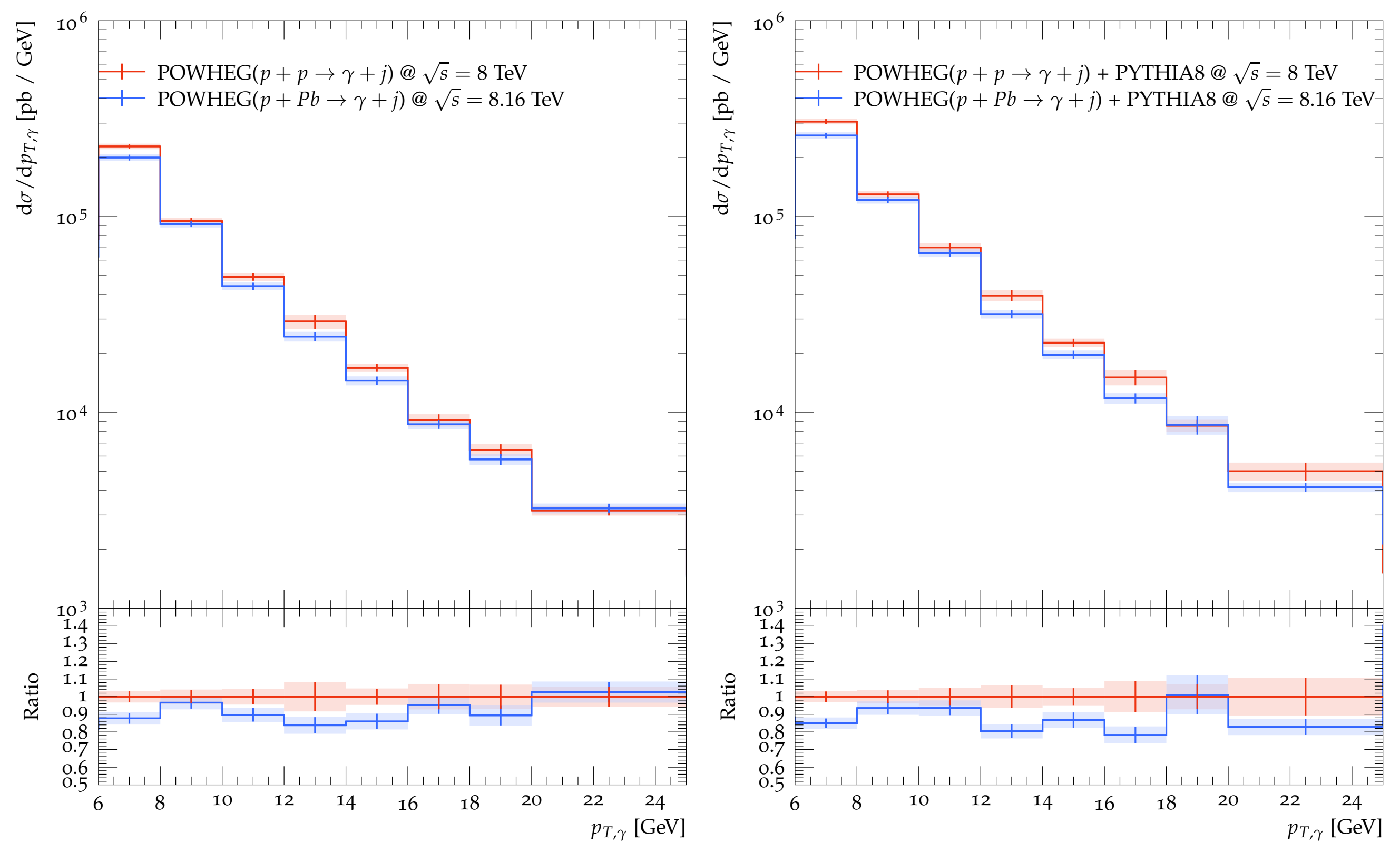
The following figures show some observables in a measurement of isolated-photon plus two-jet production in pp collisions at $\sqrt{s} = 13$ TeV [6] and POWHEG ($pp \rightarrow \gamma j$) + Pythia and POWHEG ($pp \rightarrow \gamma jj$) predictions. The red shaded band is the MSHT20nlo_as118 PDF uncertainty while the vertical bars are numerical uncertainties.



The process with an additional jet achieves certain characteristics of the distributions better than the process with a parton shower.

Nuclear effects

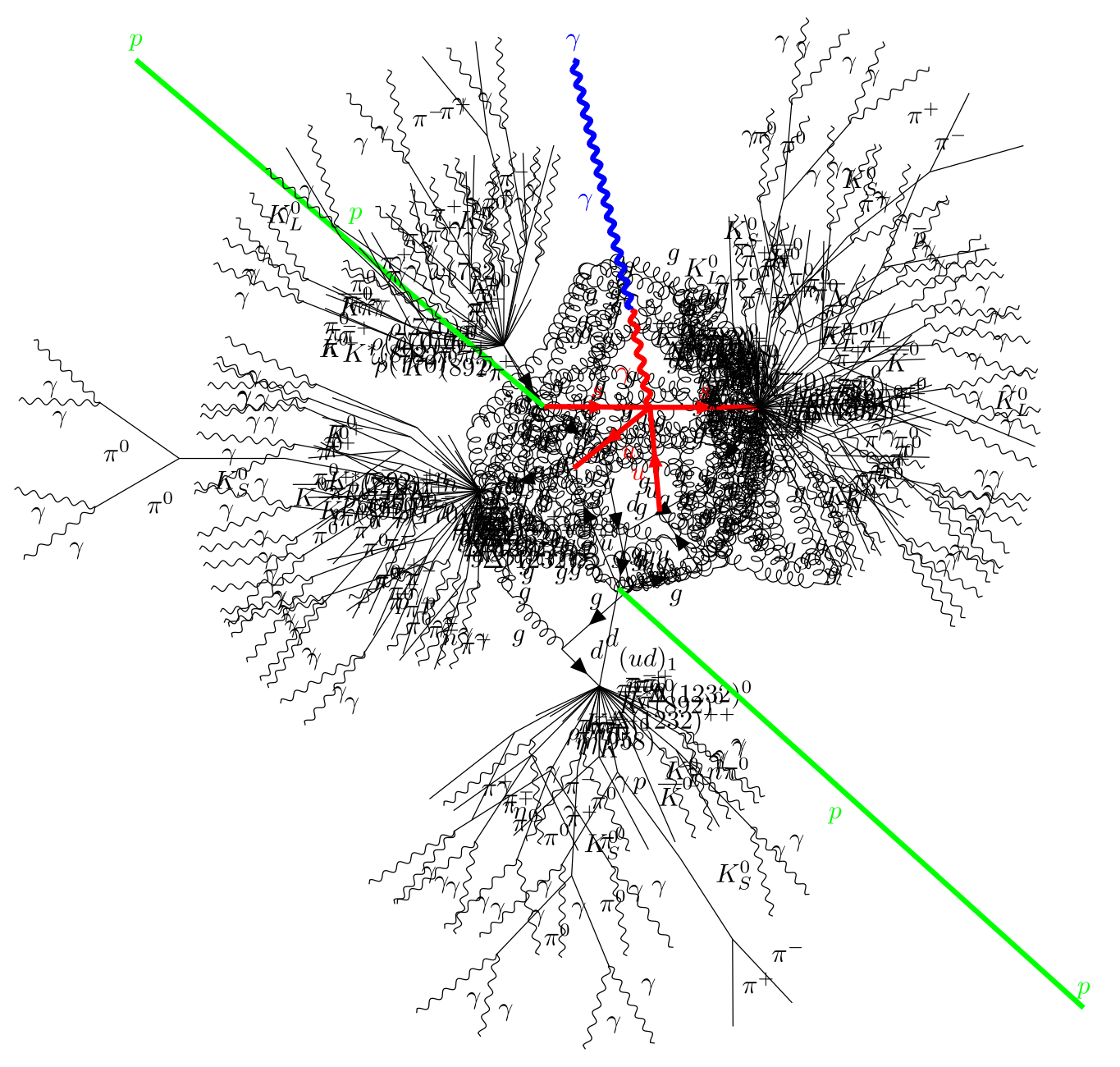
The figure below shows the p_T spectrum of the prompt produced photons in POWHEG with and without parton shower effects. R_{pA} is the ratio of the cross section for pA to the cross section for pp collisions. The pA cross section is calculated similarly to pp collisions, but replacing a proton with an A nucleus and adjusting the centre of mass energy. Here NNPDF40_nlo_as_01180 is used for proton and nNNPDF30_nlo_as_0118_A208_Z82 for lead. The photon is confined to $|y| < 0.8$ with an isolation cone of $R^{\mathrm{iso}} = 0.4$ and an isolation energy of $p_T^{\mathrm{iso}} = 2$ GeV.



The shaded bands represent the PDF uncertainties. In the pPb case we only consider the dominant nuclear PDF uncertainties. The inclusion of parton showers from Pythia increases the cross section by a factor of approximately 1.5. p_T-distributions of inclusive photons are well described > 4 GeV, but scale and nuclear PDF uncertainties are large at low p_T.

Example event

The Feynman diagram on the right shows a generated proton-proton event with parton shower effects and hadron decays. In green are the initially colliding protons. The hard process is colored in red and compressed into one vertex. The real photon is colored in blue. One observes many π^0 decays from jets into even more photons.



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