

Real and virtual photon production in POWHEG

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Why Monte Carlo?

- ▶ Quantum mechanics are statistical in nature → measure ensembles
- ▶ Monte Carlo methods are close to how things work in “real life”

Monte Carlo Integrators :

- ▶ Simple to implement
- ▶ Handles high-dimensional integrals, even with difficult domains
- ▶ Parallilzable with trivial error estimation

General-purpose event generators (MadGraph, Pythia, Herwig, Sherpa, Whizard, ...) :

- ▶ Simulate particle collisions
- ▶ Include physics models, parton showers (PS), hadronization
- ▶ Background estimation, detector simulation, etc.

Monte Carlo Markov Chains :

- ▶ Lattice QCD
- ▶ Fit functions in large parameter space
- ▶ Metropolis algorithm in top 10 most important algorithms of the 20th century (along Quicksort, FFT, ...)

Event generation

Instead of integrating, we can also use Monte Carlo to generate events according to a given distribution.

- ▶ Collect a set of phase-space points corresponding to events
- ▶ Events need to be assigned weights according to the distribution
- ▶ Small **weighted events** are wasteful for further processing

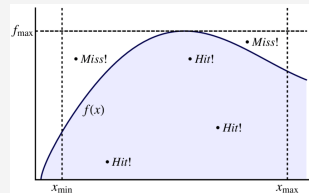
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“**hit-or-miss**” **method**, keep only events proportional to probability/weight:

- ▶ Store the maximum of the distribution $f_{\max}$ during integration for total cross section/normalization $\langle f \rangle$
- ▶ Pick phase-space points randomly and accept them with probability $f(x)/f_{\max}$
- ▶ Each accepted event gets a weight $\langle f \rangle \Rightarrow$ generates **unweighted events**
- ▶ Information about the distribution is in the number of events instead of the weight

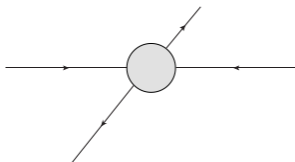


Generating full events

$$d\sigma = \sum_{a,b} \int_0^1 dx_a dx_b$$

$$\underbrace{d\hat{\sigma}_{cX}(x_a P_A, x_b P_B, \mu_F)}_{\text{partonic cross section}}$$

1. **Hard process generation:** Pick a phase space following hit-or-miss method

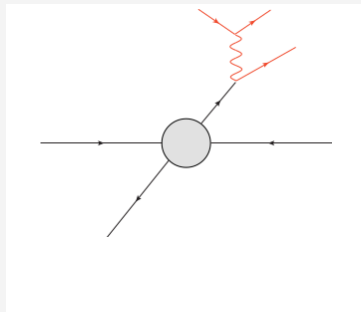


Generating full events

$$d\sigma = \sum_{a,b,c} \int_0^1 dx_a dx_b dz$$

$$\underbrace{d\hat{\sigma}_{cX}(x_a P_A, x_b P_B, \frac{P_\gamma}{z}, \mu_F)}_{\text{partonic cross section}} \underbrace{D_{Y/c}(z, \mu_F)}_{\text{fragmentation}}$$

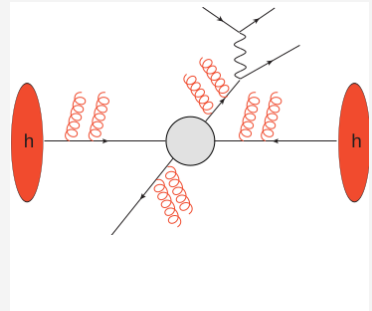
1. **Hard process generation:** Pick a phase space following hit-or-miss method
2. **Heavy resonance decay:** Heavy resonances with narrow widths are decayed before the parton shower



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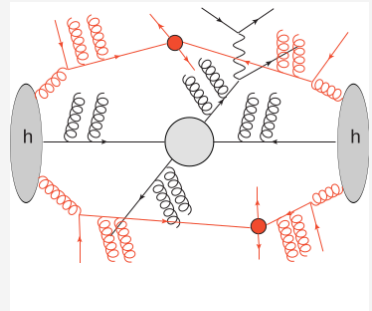
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3. **PDF and parton shower:** Any charged (QCD/QED) initial or final parton/particle can radiate



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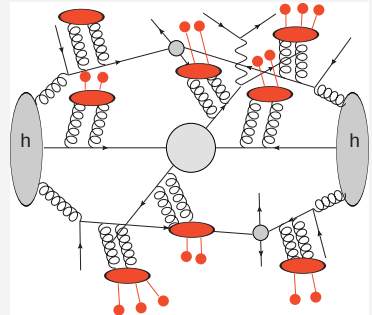
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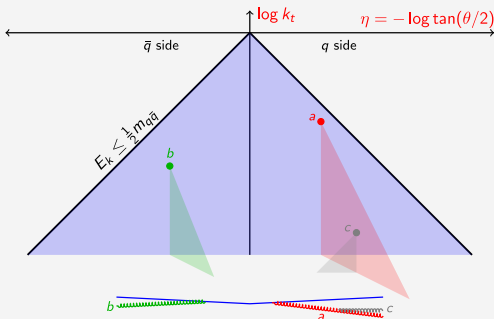
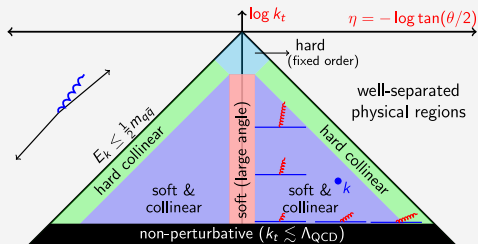
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- 5. Hadronization and hadron decays:** In the cluster model, clusters are formed and hadrons are produced. Unstable hadrons are subsequently decayed.



Parton shower

soft ($k_T \rightarrow 0$) and collinear ($\theta \rightarrow 0$ or π) approximation of the DGLAP splitting probability²

$$d\mathcal{P}_{a \rightarrow bc} = \frac{\alpha_s(k_T)}{2\pi} \frac{dQ^2}{Q^2} P_{a \rightarrow bc}(z) dz \quad (1)$$



²Soyez, G. Parton Showers and Resummations (PSR), 6-8 June 2023. 2023.

<https://indico.cern.ch/event/1202436/contributions/5288130/attachments/2660262/4608836/lund.pdf>.

Parton shower

Sudakov Form Factor and Leading Logarithms

Emission probability:

$$\begin{aligned}\mathcal{P}_{\text{no}}(0 \leq t < T) &= \lim_{n \rightarrow \infty} \prod_{i=0}^{n-1} \mathcal{P}_{\text{no}}(T_i \leq t < T_{i+1}) \\ &= \lim_{n \rightarrow \infty} \prod_{i=0}^{n-1} (1 - P_{\text{em}}(T_i \leq t < T_{i+1})) \\ &= \exp \left(- \lim_{n \rightarrow \infty} \sum_{i=0}^{n-1} \mathcal{P}_{\text{em}}(T_i \leq t < T_{i+1}) \right) \\ &= \exp \left(- \int_0^T \frac{\mathcal{P}_{\text{em}}(t)}{dt} dt \right)\end{aligned}$$

$$\mathcal{P}_{\text{first}}(T) = 1 - \mathcal{P}_{\text{no}}(T) \implies d\mathcal{P}_{\text{first}}(T) = d\mathcal{P}_{\text{em}}(T) \exp \left(- \int_0^T \frac{\mathcal{P}_{\text{em}}(t)}{dt} dt \right)$$

In momentum space there is no time $t \implies$ use $t \sim 1/Q$ (Heisenberg)

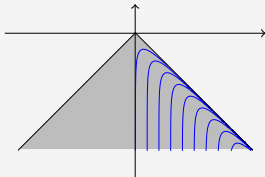
Parton shower

Angular vs k_T ordered shower

Angular ordered parton shower

$$Q^2 = E_a^2 \theta_{a \rightarrow bc}^2 \quad (2)$$

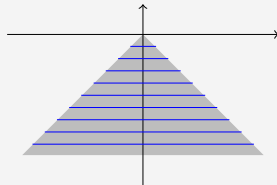
- ▶ Successive emission has a smaller angle compared to the previous one
- ▶ Small dead zone at $\ln p_T^2/\tilde{s}$
- ▶ Correct color factors for observables insensitive to azimuthal correlations



Transverse-momentum-ordered parton shower

$$Q^2 = k_T^2 \quad (3)$$

- ▶ Ordered by their transverse momentum k_T relative to their parent parton
- ▶ Resums large logarithms of the form $\alpha_s^n \ln^{2n}(M^2/k_T^2)$, with M the hard scale
- ▶ Color factors in improved leading-color approximation



Matrix Elements vs Parton Showers

Matrix Elements:

- + Fixed order $\Rightarrow$ good for hard jets
- + contains all α_s terms up to a given order
- + good in high p_T^2
- expensive to compute $\Rightarrow$ only few emissions

Parton Showers:

- + Always finite
- + Contains higher order logarithms
 - Only valid in soft/collinear regions
- + Any number of emission

$\Rightarrow$ Combine the two to get the best of both worlds via NLO Matching or Multi-jet Merging

- ▶ Hard emissions by fixed order predictions
- ▶ Further emissions probabilities from PS

NLO Matching

Madgraph5 - MC@NLO

NLO observable

$$\begin{aligned} \langle \mathcal{O} \rangle &= \int d\phi_n (B_n + V_n) \mathcal{O}_n(\phi_n) \sim \text{hard final state} + \text{virtual radiation (loop)} \\ &+ \int d\phi_{n+1} B_{n+1} \mathcal{O}_{n+1}(\phi_{n+1}) \sim \text{real radiation} \end{aligned}$$

NLO Matching

Madgraph5 - MC@NLO

Handle divergences between B_{n+1} and V_n with universal FKS subtraction terms:

$$\begin{aligned} \langle \mathcal{O} \rangle = & \int d\phi_n (B_n + V_n + B_n \otimes I_1) \mathcal{O}_n(\phi_n) \sim \text{hard final state} + \text{virtual radiation (loop)} + \int \text{counter terms} \\ & + \int d\phi_{n+1} (B_{n+1} \mathcal{O}_{n+1}(\phi_{n+1}) - B_n \otimes D_1 \mathcal{O}_n(\phi_{n+1})) \sim \text{real radiation} - \text{counter terms} \end{aligned}$$

Attaching a emission to the LO by the PS overlaps with Real correction:

$$PS_n \sim \text{diagram 1} + \text{diagram 2}$$

NLO Matching

Madgraph5 - MC@NLO

Avoid double counting between NLO and PS³:

$$\begin{aligned}
 \langle \mathcal{O} \rangle = & \int d\phi_n (B_n + V_n + B_n \otimes I_1) PS_n(\mathcal{O}_n, \phi_n) \sim \text{hard final state} + \text{virtual radiation (loop)} + \int \text{counter terms} \\
 & + \int d\phi_{n+1} (B_{n+1} - B_n \bar{P}_{n+1}) PS_{n+1}(\mathcal{O}_{n+1}, \phi_{n+1}) \sim \text{real radiation} - \text{counter terms} \\
 & + \int d\phi_{n+1} (B_n \bar{P}_{n+1} - B_n \otimes D_1) PS_n(\mathcal{O}_n, \phi_{n+1}) \sim \text{counter terms} - \text{counter terms}
 \end{aligned}$$

with PS :

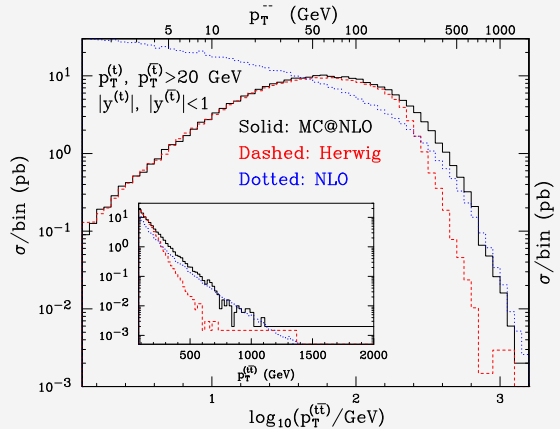
$$\begin{aligned}
 PS_n & \sim \text{hard final state} + \text{virtual radiation (loop)} + \dots \\
 PS_{n+1} & \sim \text{real radiation} + \dots
 \end{aligned}$$

³Campbell, J. <https://indico.fnal.gov/event/9650/attachments/74470/89343/MCGenerators.pdf>,
 Gellersen, L. CTEQ Summer School 2022. 2022. <https://indico.cern.ch/event/1131319/contributions/4895915/attachments/2477520/4252738/gellersenPSMM.pdf>.

NLO Matching

Madgraph5 - MC@NLO

- ▶ Smooth transition between lower and high scales
- ▶ Needs shower implementation with correct counterterms
- ▶ Regulates low p_T region
- ▶ Can lead to many events with negative weights



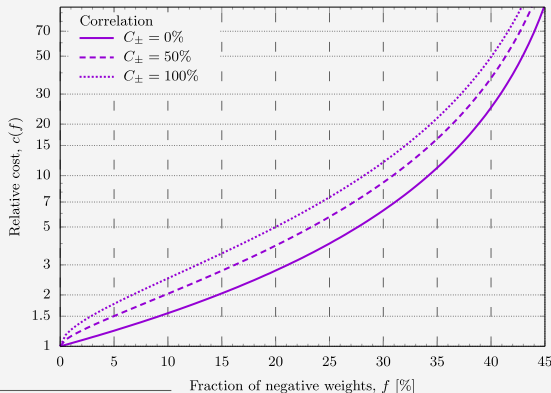
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⁴Nason, P. & Webber, B. *Ann. Rev. Nucl. Part. Sci.* **62**, 187–213. arXiv: 1202.1251 [hep-ph] (2012).

NLO Matching

Negative weighted events

- ▶ Large negative fractions (f) of negative weighted events reduce statistical power⁵
- ▶ Efficiency $\epsilon(f) = 1 - 2f$
- ▶ Relative cost $c(f) = \frac{1 + C_{\pm} \sqrt{1 - \epsilon(f)^2}}{\epsilon(f)^2}$



⁵Frederix, R. et al. *JHEP* **07**, 238. [arXiv: 2002.12716 \[hep-ph\]](https://arxiv.org/abs/2002.12716) (2020).

NLO Matching

POsitive Weight Hardest Emission Generator (POWHEG)

- ▶ POWHEG attaches first emission to n -particle state with a modified Sudakov factor such that NLO accuracy is preserved.

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

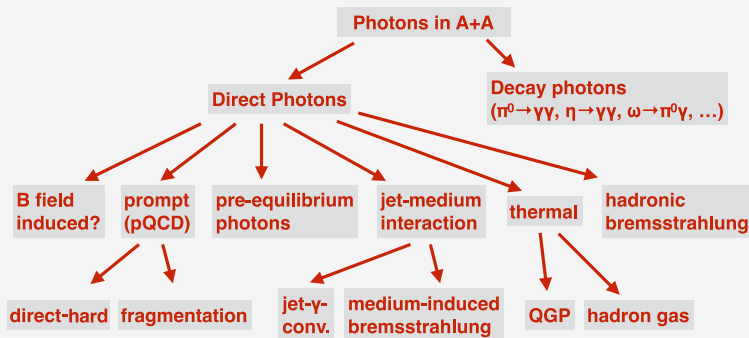
- ▶ Sudakov Δ_R is no emission probability. This can be seen from singular behavior as $R \rightarrow \infty$ thus the no emission probability goes to 0.
- ▶ solve for p_T with random $r \in (0, 1)$, where U is the upper bound of the Sudakov factor $f \sim \frac{R}{B}$ similar to splitting of $P_{a \rightarrow bc}$.

$$\log \Delta^U(p_T) = \log(r)$$

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

Photons

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

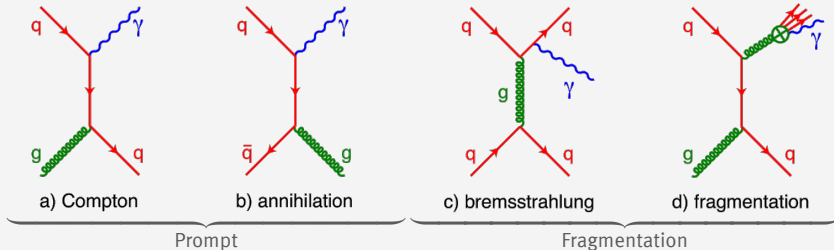


Direct-hard: directly produced in the hard collisions, computed in perturbative non-thermal QCD.

Thermal: are expected to be produced in quark gluon plasma

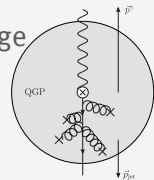
$$dN_{\gamma}^{\text{thermal}} = dN_{\gamma}^{\text{direct}} - dN_{\gamma}^{\text{prompt}}$$

Prompt photons



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

- 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} .)
- Fragmentation contributions can be reduced by isolation cones



Photon Fragmentation

- ▶ Similar photon splitting kernels to Altarelli-Parisi with $C_F \rightarrow Q_i^2$ and $C_A \rightarrow 0$

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

- ▶ Evolution equations for the photon fragmentation functions

$$\frac{dD_{\gamma/q}(\mu_F^2)}{d \ln \mu_F^2} = \frac{\alpha}{2\pi} P_{\gamma q} \otimes D_{\gamma/\gamma}(\mu_F^2) + \frac{\alpha_s(\mu_F^2)}{2\pi} \times [P_{qq} \otimes D_{\gamma/q}(\mu_F^2) + P_{gq} \otimes D_{\gamma/g}(\mu_F^2)]$$

$$\frac{dD_{\gamma/g}(\mu_F^2)}{d \ln \mu_F^2} = \frac{\alpha}{2\pi} P_{\gamma g} \otimes D_{\gamma/\gamma}(\mu_F^2) + \frac{\alpha_s(\mu_F^2)}{2\pi} \times [P_{qg} \otimes D_{\gamma/q}(\mu_F^2) + P_{gg} \otimes D_{\gamma/g}(\mu_F^2)]$$

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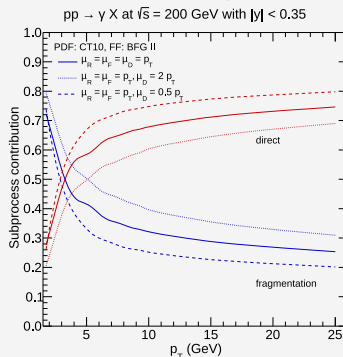
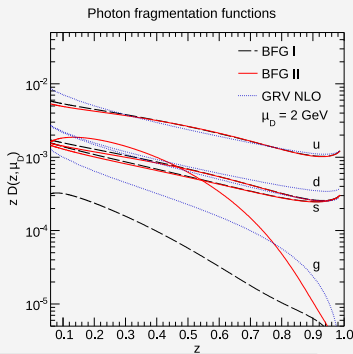
- ▶ Using $D_{\gamma/\gamma}(z, \mu_F) = \delta(1 - z)$ at EM-LO thus $\mu_F^2 \frac{d}{d\mu_F^2} D_{\gamma/c}(z, \mu_F) = \frac{\alpha}{2\pi} P_{\gamma c}(z)$ gives:

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

Photon Fragmentation

Measured:

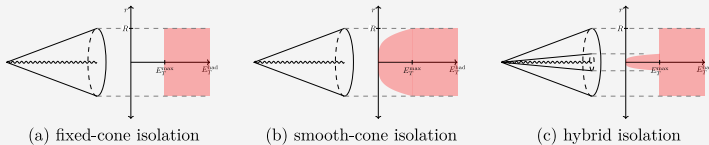
- ▶ Prompt photons in e^+e^- collisions (limited data)
- ▶ Prompt photons in hadronic collisions⁶
- ▶ In vector meson production, assuming dominating hadronic fluctuations of the photon at low scales (VMD)⁷: $D_{\gamma,i}^{\text{had}}(z, \mu_s) = \sum_{V=\rho,\omega,\phi} \frac{4\pi\alpha}{f_V^2} D_{V/i}(z, \mu_s)$



⁶Adare, A. et al. *Phys. Rev. C* **87**, 054907. arXiv: 1208.1234 [nucl-ex] (2013).

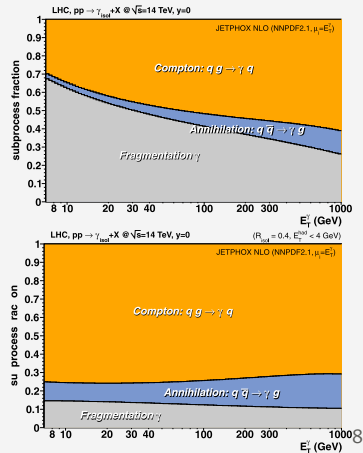
⁷Klasen, M. & König, F. *Eur. Phys. J. C* **74**, 3009. arXiv: 1403.2290 [hep-ph] (2014).

Photon isolation



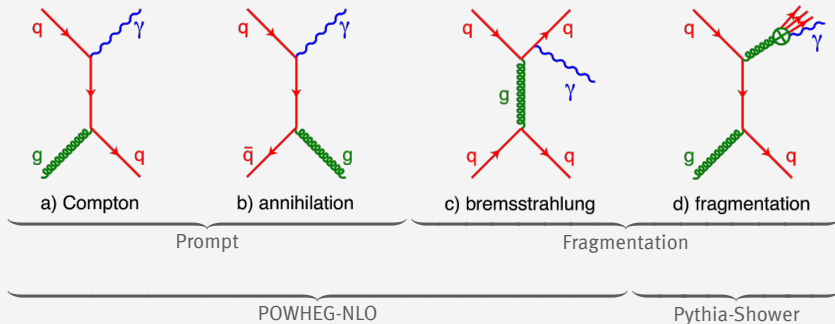
Simple boost invariant definition of a fixed-cone (a):

- ▶ 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



⁸d'Enterria, D. & Rojo, J. *Nucl. Phys. B* **860**, 311–338. arXiv: 1202.1762 [hep-ph] (2012).

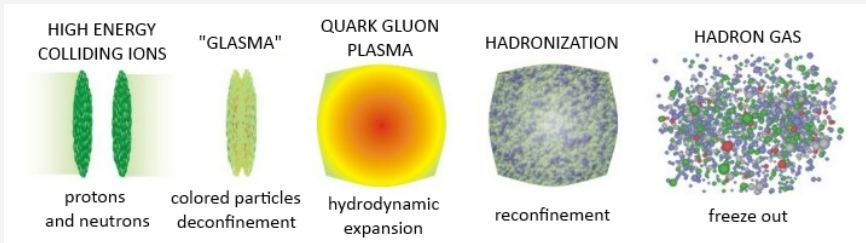
POsitive Weight Hardest Emission Generator (POWHEG)



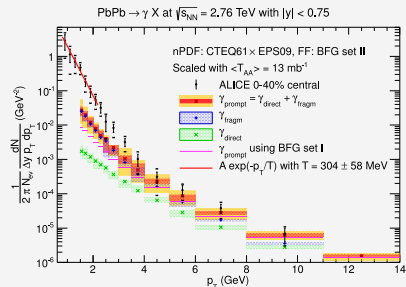
- Separation between NLO and fragmentation contribution is non-trivial in NLO+PS
- In order to regulate the divergences we must include pure QCD di-/trijet production at LO

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

Quark Gluon Plasma

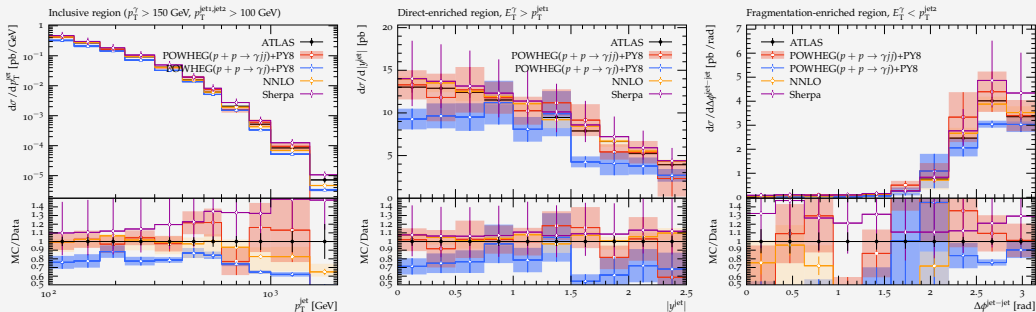


- ▶ Thermal photons are produced by the constituents of the plasma (quarks and gluons)
- ▶ Medium decreases jet-momentum $\rightarrow$ jet quenching
- ▶ Suppressed back-to-back correlation
- ▶ Photon probes the gluon density and QGP properties
- ▶ Good agreement in higher p_T perturbative region



Preliminary: Photon and jets observables

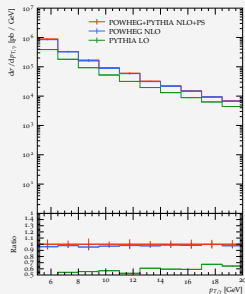
- Isolated-photon plus two-jet production in pp collisions at $\sqrt{s} = 13$ TeV and POWHEG $(pp \rightarrow \gamma j) + \text{Pythia8}$ and POWHEG $(pp \rightarrow \gamma jj) + \text{Pythia8}$ predictions ($\Delta R = 0.4$ and $E_{T,\text{cut}}^{\text{iso}} \equiv 0.0042 \cdot E_T^\gamma + 4.8 \text{ GeV}$)⁹.



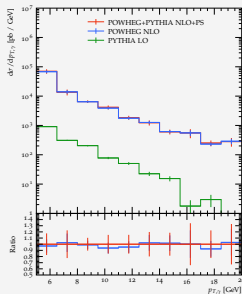
⁹Aad, G. et al. JHEP **03**, 179. arXiv: 1912.09866 [hep-ex] (2020), Badger, S. et al. arXiv: 2304.06682 [hep-ph] (Apr. 2023).

Preliminary: FoCal studies

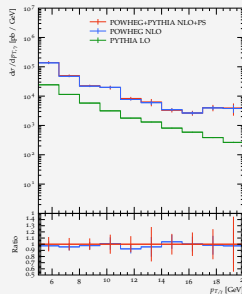
Predictions for isolated prompt photons in the FOCAL experiment at $\sqrt{s} = 14\text{TeV}$ are shown. The cuts applied on the photon are $3.4 < \eta^\gamma < 5.8$ with a fixed isolation cone of $R_{\text{iso}} = 0.4$ and $E_T^{\text{iso}} = 5\text{GeV}$.



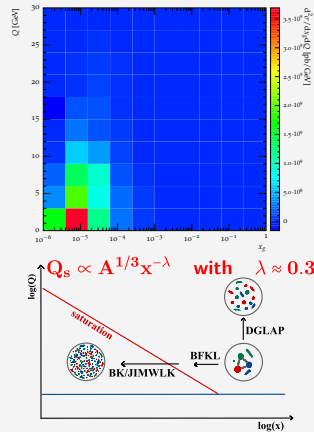
(a) $qq \rightarrow \gamma + (X)$



(b) $gg \rightarrow \gamma + (X)$

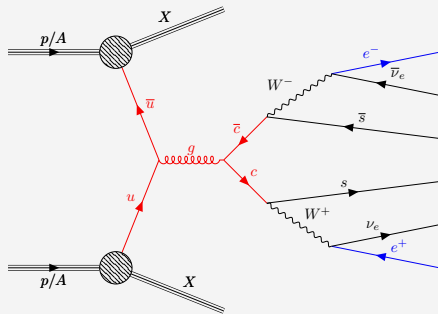
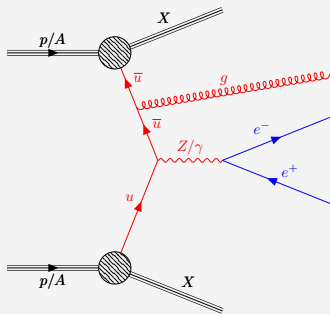


(c) $qq \rightarrow \gamma + (X)$



Virtual photons

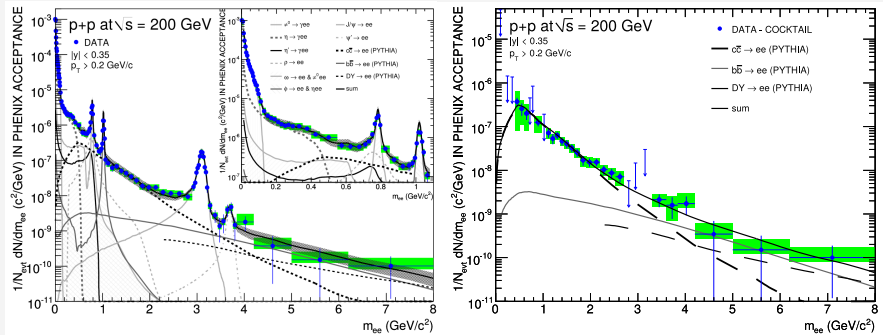
- ▶ Exactly same feynman diagrams as real photons but the photon is off-shell and branches into a **lepton pair (ee)**
- ▶ Kroll-Wada theorem relates low invariant mass dileptons to on-shell photons¹⁰
- ▶ Huge background from light flavour decays in low invariant electron pair mass region
- ▶ Huge background from heavy flavour decays in the intermediate mass region



¹⁰Kroll, N. M. & Wada, W. *Phys. Rev.* **98**, 1355–1359. <https://link.aps.org/doi/10.1103/PhysRev.98.1355> (5 June 1955).

Dielectron studies

Hadronic cocktail description in PHENIX¹¹



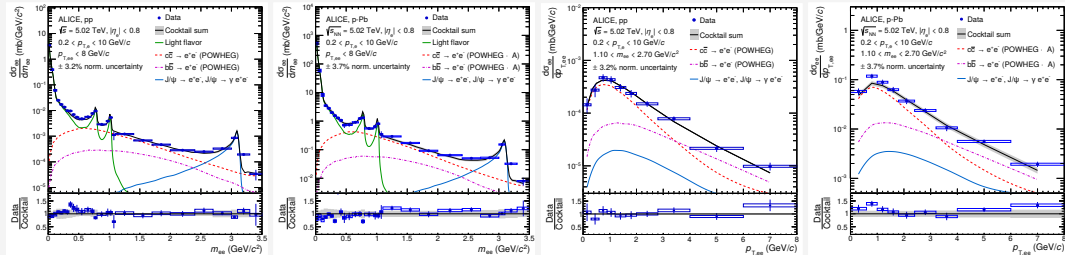
Dilepton as a clock in nuclear collisions:

- ▶ Pre-equilibrium effects around $m_{ee} \gtrsim 2 \text{ GeV}$
- ▶ 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 $m_{ee} \lesssim 1 \text{ GeV}$

¹¹Adare, A. et al. *Phys. Rev. Lett.* **104**, 132301. arXiv: 0804.4168 [nucl-ex] (2010).

Dielectron studies

ALICE analysis¹² uses template PYTHIA/POWHEG cc/bb distributions for the cocktail.



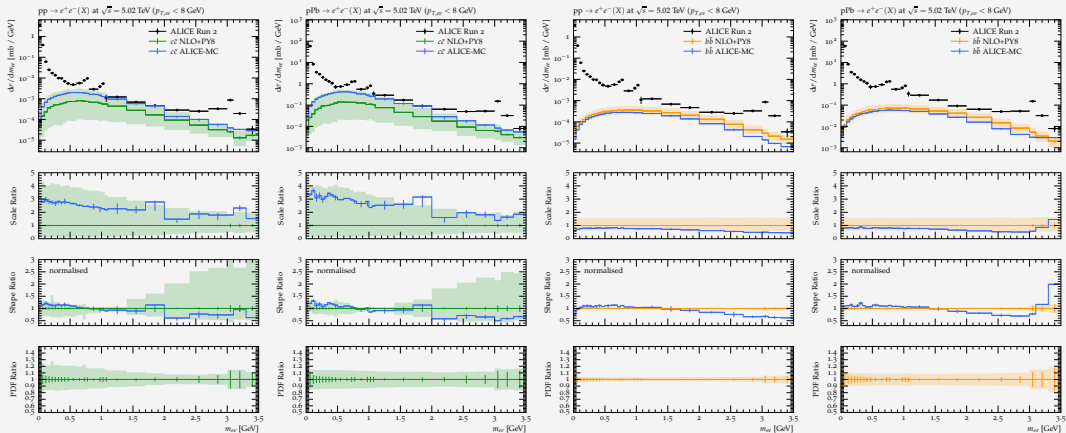
But:

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

¹²Acharya, S. et al. *Phys. Rev. C* **102**, 055204. arXiv: 2005.11995 [nucl-ex] (2020).

Dielectron studies

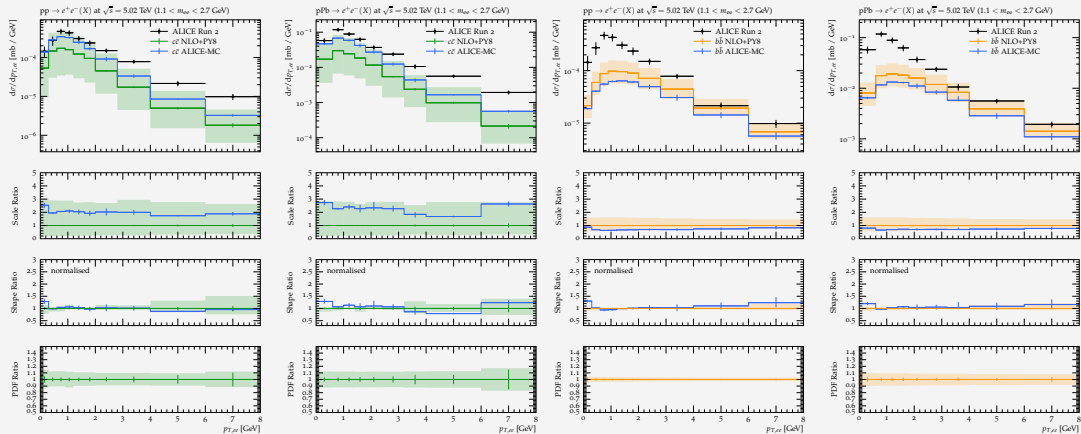
Full PDF and scale uncertainty of open heavy quark production via POWHEG¹³.



¹³Andronic, A. et al. [arXiv: 2401.12875 \[hep-ph\]](https://arxiv.org/abs/2401.12875) (Jan. 2024).

Dielectron studies

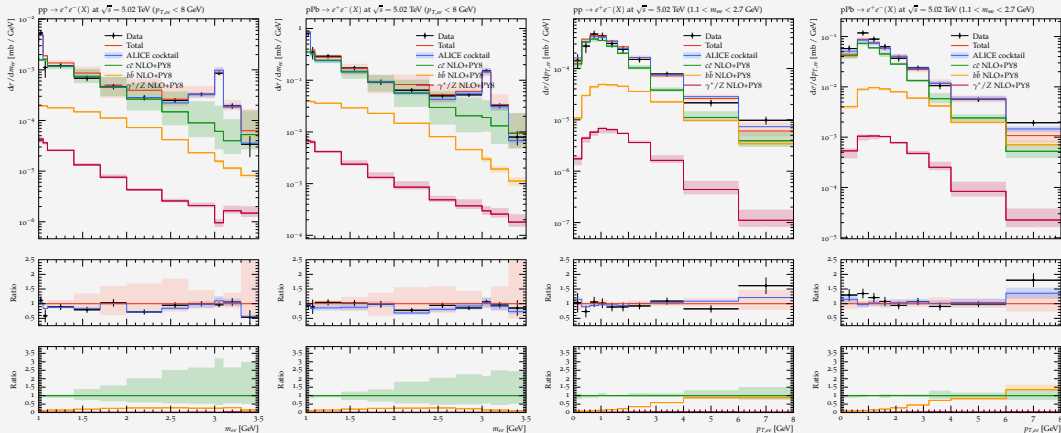
Full PDF and scale uncertainty of open heavy quark production via POWHEG¹⁴.



¹⁴Andronic, A. et al. [arXiv: 2401.12875 \[hep-ph\]](https://arxiv.org/abs/2401.12875) (Jan. 2024).

Dielectron studies

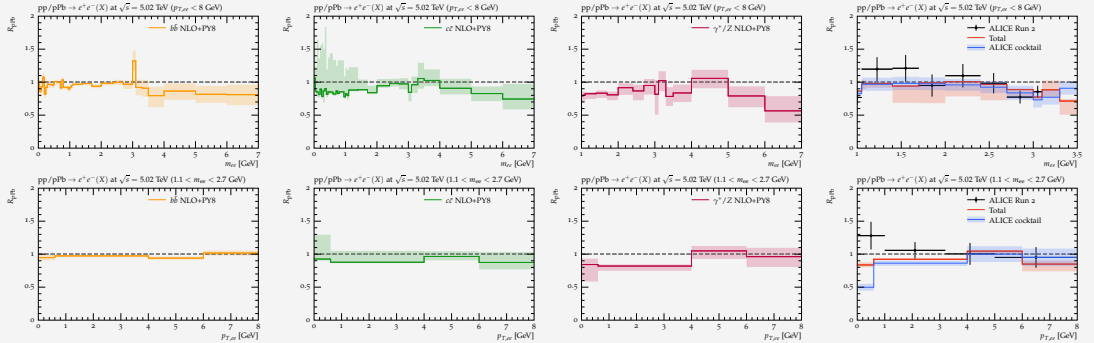
More realistic normalized uncertainties and added Drell-Yan contribution improve the fitted cocktail.



Dielectron studies

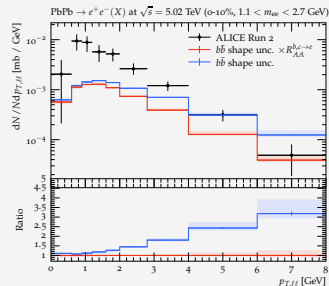
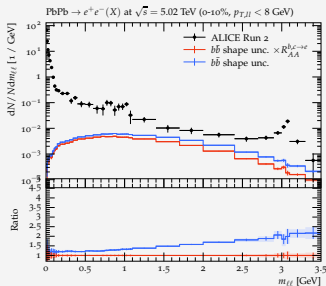
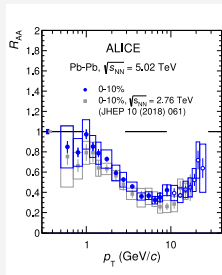
R_{pPb}

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



Dielectron studies

Open bottom production $\text{PbPb} \rightarrow b\bar{b}(X)$ with and without including a $R_{AA}^{b,c \rightarrow e}$ factor¹⁵.



¹⁵Acharya, 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).

New DIS process in POWHEG-BOX-RES

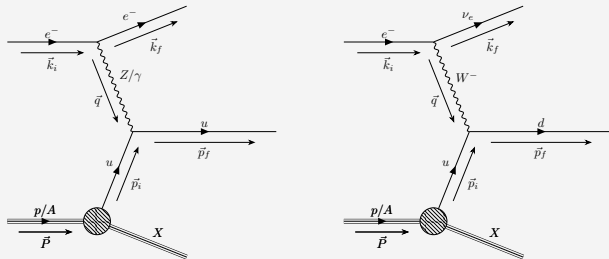
DIS differs from proton-proton in its typical variables¹⁶:

- ▶ Boson virtuality $Q^2 = -q^2 = -(k_i - k_f)^2$
- ▶ Björken- x $x_B = \frac{Q^2}{2P \cdot q}$
- ▶ Inelasticity $y_{\text{DIS}} = \frac{P \cdot q}{P \cdot k_i} = \frac{p_i \cdot q}{p_i \cdot k_i}$
- ▶ Fixed lepton beam energy

must be preserved to avoid spurious higher-order corrections in inclusive quantities.

⇒ Different phase space mapping for initial state radiation

⇒ Momentum conservation through adjusting parton momenta

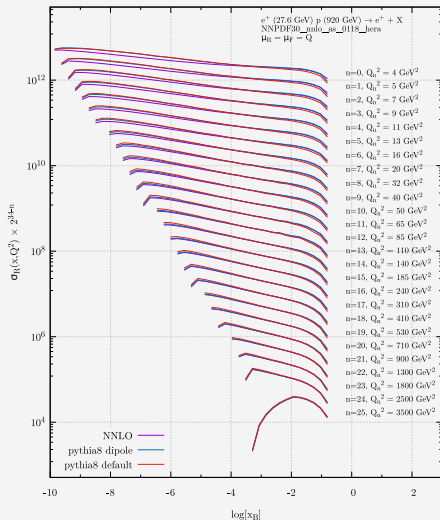


¹⁶Banfi, A. et al. [arXiv: 2309.02127 \[hep-ph\]](https://arxiv.org/abs/2309.02127) (Sept. 2023).

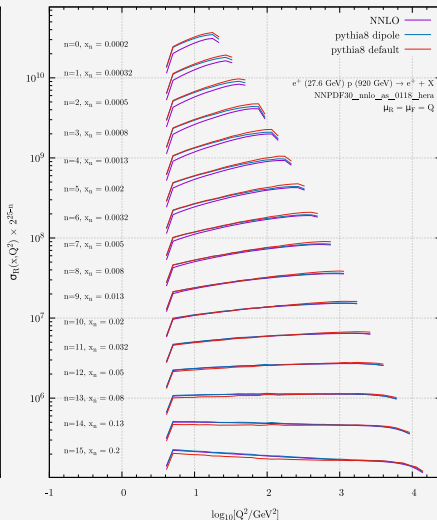
New DIS process in POWHEG-BOX-RES

$$\text{Comparison to NNLO in } \sigma_R(x, Q^2) = \frac{x_{\text{DIS}} Q^4}{2\pi\alpha^2(1+(1-y_{\text{DIS}})^2)} \frac{d^2\sigma}{dx_{\text{DIS}} dQ^2}$$

$Q^2 < 15000 \text{ GeV}^2$, with $Q_n < Q < Q_{n+1}$



$x_B < 0.32$, with $x_n < x_B < x_{n+1}$

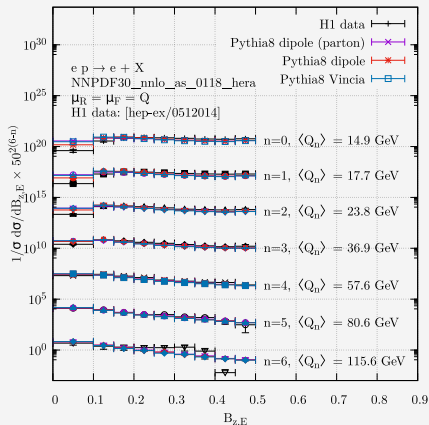
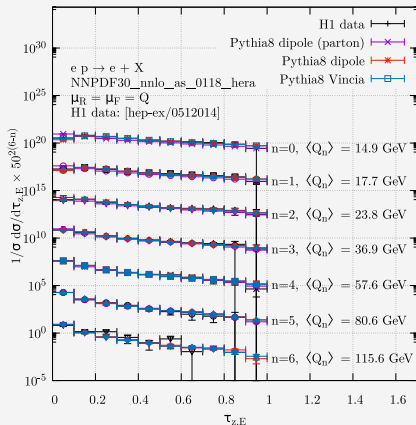


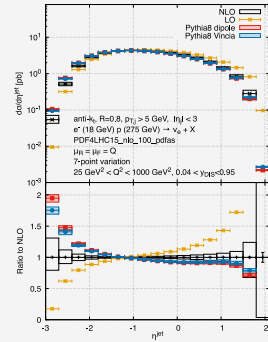
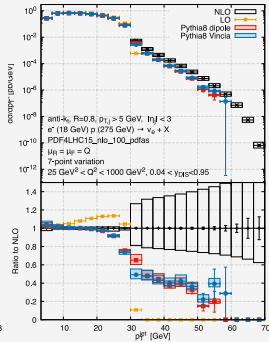
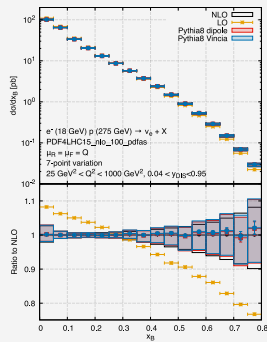
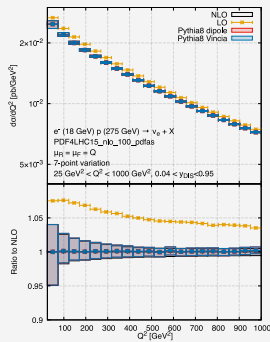
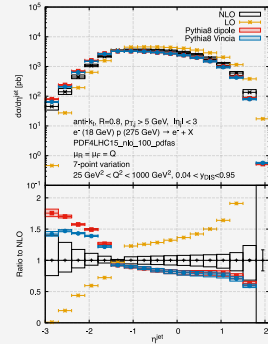
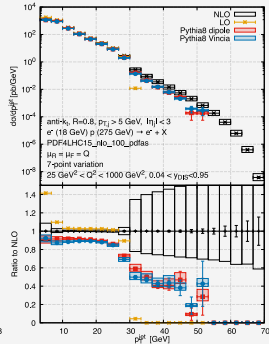
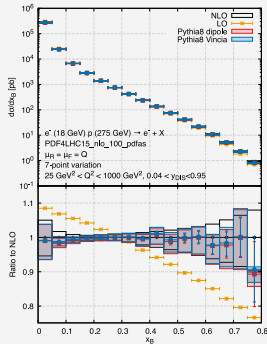
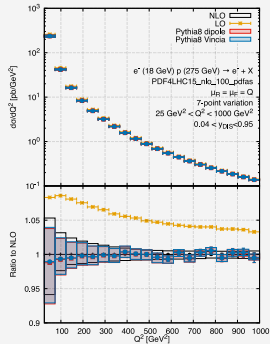
New DIS process in POWHEG-BOX-RES

Comparison against HERA

$$\tau_{z,Q} = 1 - \frac{\sum_h 2|\vec{p}_{z,h}|}{Q},$$

$$B_{z,E} = \frac{\sum_h |\vec{p}_{T,h}|}{2 \sum_h |\vec{p}_h|},$$





Summary

- ▶ Parton shower can be a substitute for fragmentation functions
- ▶ Access to nPDFs at very small x
- ▶ Despite same topologies processes involving a single photon are phenomenologically different
- ▶ Search for saturation and transition to QGP
- ▶ Ingredient for MiNLO(') photon+jets in POWHEG
- ▶ Large scale uncertainties can be reduced/shifted by normalizing to shape uncertainty
- ▶ DIS in POWHEG with dipole Pythia performs best

Thank you!