Diffraction in photoproduction with Pythia 8

6th Workshop on QCD and Diffraction

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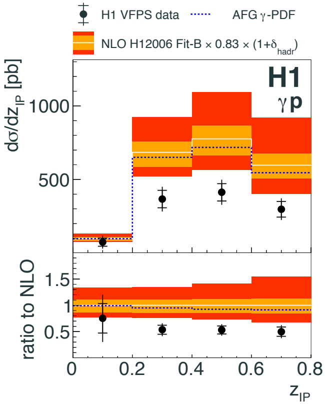
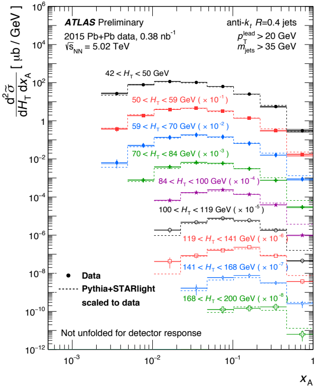
Motivation

[H1: JHEP 1505 (2015) 056]



[ATLAS-CONF-2017-011]



- Evidence for factorization breaking for diffractive dijet photoproduction at HERA
- Photoproduction can be studied in ultra-peripheral collisions (UPCs) at the LHC (with protons and nuclei)

Outline

Pythia implementation

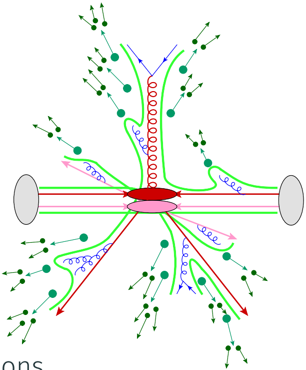
- Simulate hard diffraction in γp by combining
  1. Recently introduced photoproduction framework [I.H. and T.S.]
  2. Hard diffraction model for pp collisions [C.O.R. and T.S.]
- With an appropriate photon flux the framework can be applied to ep and also ultra-peripheral pp and pPb collisions

Outline

1. Photoproduction in Pythia 8
2. Hard diffraction in ep
3. Predictions for UPCs at the LHC
4. Soft diffraction with photons
5. Summary

Event generation in PYTHIA 8

1. Hard scattering
   - Convolution of LO partonic cross sections and PDFs
2. Parton showers
   - Generate Initial and Final State Radiation (ISR & FSR) using DGLAP evolution
3. Multiparton interactions (MPIs)
   - Use regularized QCD $2 \to 2$ cross sections



[Figure: S. Prestel]

4. Beam remnants
   - Minimal number of partons to conserve colour and flavour
5. Hadronization
   - Using Lund string model with color reconnection
   - Decays into stable hadrons

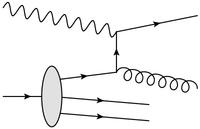
Photoproduction in Pythia 8

Photoproduction

Photoproduction: Small photon virtuality $Q^2 \lesssim 1\ \text{GeV}^2$ (cf. DIS)

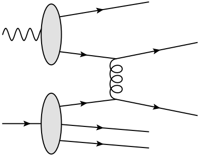
- Factorize the photon flux $f_\gamma(x)$ from the hard scattering, hard scale provided by the hard process
- Sample photon kinematics (x, Q^2) and set up γp sub-collision with $W_{\gamma\text{p}}$

Direct processes



- Photon initiator of the hard process
- No MPIs but FSR and ISR for hadron

Resolved processes

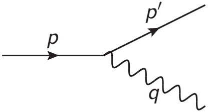


- Photon fluctuates into a hadronic state
- Partonic structure described with PDFs
- FSR and ISR for both sides and MPIs
- Also soft QCD processes possible

Photon fluxes from equivalent photon approximation (EPA)

Flux depends on the beam particle

- Photon flux from leptons, $Q^2 = -q^2$, integrated over allowed virtualities (Weizsäcker-Williams)



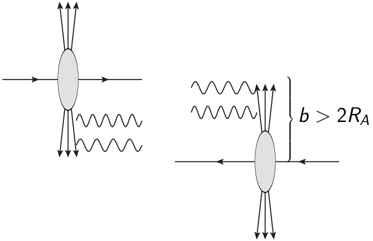
$$f_\gamma^l(x) = \frac{\alpha_{\rm em}}{2\pi}\frac{(1+(1-x)^2)}{x}\log\left[\frac{Q^2_{\rm max}}{Q^2_{\rm min}(x)}\right]$$

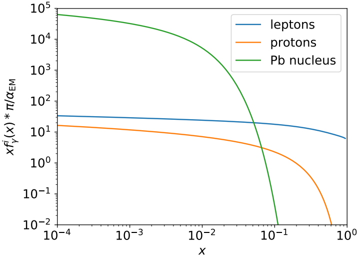
- Photon flux from protons (Drees-Zeppenfeld), take into account form factor $F_E(Q^2)$ of a proton:

$$f_\gamma^{\rm p}(x) = \frac{\alpha_{\rm em}}{2\pi}\frac{(1+(1-x)^2)}{x}\left[\log(A) - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3}\right]$$

where $A = 1 + Q_0^2/Q^2_{\rm min}$ and $Q_0^2 = 0.71\ {\rm GeV}^2$

Photon fluxes from equivalent photon approximation (EPA)





- Photon flux from heavy ions in impact-parameter space b
  ⇒ Reject events where colliding nuclei overlap

$$f_\gamma^A(x) = \frac{2\alpha_{EM} Z^2}{x\pi}\left[\xi K_1(\xi) K_0(\xi) - \frac{\xi^2}{2}\left(K_1^2(\xi) - K_0^2(\xi)\right)\right]$$

  where Z is nuclear charge, $\xi = b_{\min} x m/\hbar c$, m (per-nucleon) mass and K_i modified Bessel functions and $b_{\min} \approx R_A + R_B$
- Photon flux amplified by Z^2 but flux softer

MPIs in PYTHIA 8

- Probability for MPIs from $2 \to 2$ QCD cross sections

$$\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_{\mathrm{T}}^2} = \frac{1}{\sigma_{\mathrm{nd}}(\sqrt{s})} \frac{\mathrm{d}\sigma^{2\to 2}}{\mathrm{d}p_{\mathrm{T}}^2},$$

  where $\sigma_{\mathrm{nd}}(\sqrt{s})$ is the non-diffractive cross section
- Partonic cross section diverges at $p_{\mathrm{T}} \to 0$

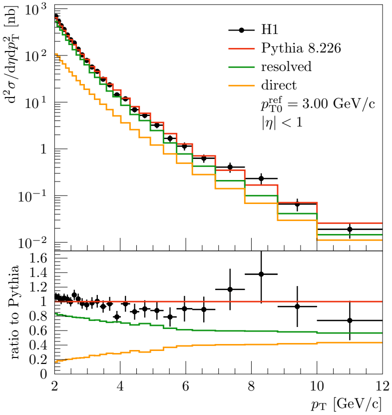
  $\Rightarrow$ Regulate the divergence with a screening parameter p_{T0}

$$\frac{\mathrm{d}\sigma^{2\to 2}}{\mathrm{d}p_{\mathrm{T}}^2} \propto \frac{\alpha_{\mathrm{s}}(p_{\mathrm{T}}^2)}{p_{\mathrm{T}}^4} \to \frac{\alpha_{\mathrm{s}}(p_{\mathrm{T0}}^2 + p_{\mathrm{T}}^2)}{(p_{\mathrm{T0}}^2 + p_{\mathrm{T}}^2)^2}$$

- Average number of interactions: $\langle n \rangle = \sigma_{\mathrm{int}}(p_{\mathrm{T0}})/\sigma_{\mathrm{nd}}$
- Parameter energy-dependent: $p_{\mathrm{T0}}(\sqrt{s}) = p_{\mathrm{T0}}^{\mathrm{ref}}(\sqrt{s}/\sqrt{s_{\mathrm{ref}}})^{\alpha}$

  (Monash tune: $p_{\mathrm{T0}}^{\mathrm{ref}} = 2.28$ GeV/c, $\alpha = 0.215$, $\sqrt{s_{\mathrm{ref}}} = 7\,\mathrm{TeV}$)
- Generated simultaneously with the parton shower

[H1: Eur.Phys.J. C10 (1999) 363-372]



H1 measurement

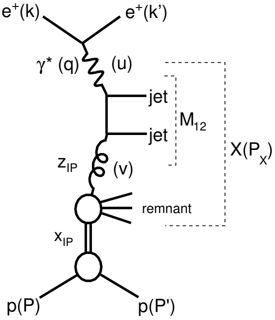
- $E_\mathrm{p} = 820$ GeV, $E_\mathrm{e} = 27.5$ GeV
- $< W_{\gamma\mathrm{p}} > \approx 200$ GeV
- $Q^2_\mathrm{max} = 0.01$ GeV^2

Comparison to Pythia 8

- Resolved contribution dominates
- Good agreement with the data using $p_{\mathrm{T0}}^{\mathrm{ref}} = 3.00$ GeV/c
  - $p_{\mathrm{T0}}^{\mathrm{ref}}$ controls $\mathcal{P}_{\mathrm{MPI}}$ $\Rightarrow \langle n_{\gamma\mathrm{p}} \rangle < \langle n_{\mathrm{pp}} \rangle$
- No constraints on $W_{\gamma\mathrm{p}}$ dependence (same as pp)

Hard diffraction in in ep

Hard diffraction in ep



[Figure: H1: JHEP 1505 (2015) 056]

Diffractive dijets

- Photon interacts with Pomeron from proton producing jets
- Can be DIS or photoproduction
- Signature: scattered proton or a rapidity gap between proton and Pomeron remnant

Factorized cross section for diffractive dijets

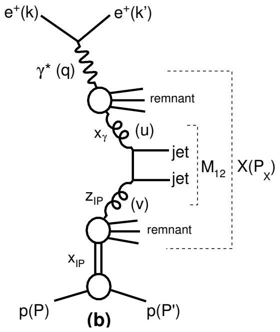
- Direct: $d\sigma^{2\text{jets}} = f^{e}_{\gamma}(x) \otimes d\sigma^{\gamma j \to 2\text{jets}} \otimes f^{\mathbb{P}}_{j}(z_{\mathbb{P}}, \mu^2) \otimes f^{p}_{\mathbb{P}}(x_{\mathbb{P}}, t)$
- Resolved: $d\sigma^{2\text{jets}} = f^{e}_{\gamma}(x) \otimes f^{\gamma}_{i}(x_{\gamma}, \mu^2) \otimes d\sigma^{ij \to 2\text{jets}} \otimes f^{\mathbb{P}}_{j}(z_{\mathbb{P}}, \mu^2) \otimes f^{p}_{\mathbb{P}}(x_{\mathbb{P}}, t)$

  where $f^{p}_{\mathbb{P}}$ is Pomeron flux and $f^{\mathbb{P}}_{j}$ diffractive PDF (dPDF) and f^{γ}_{i} photon PDF (γPDF)

Hard diffraction in Pythia 8

Dynamical rapidity gap survival

- Originally introduced for pp [C.O.R. and T.S.: JHEP 1602 (2016) 142]



[Figure: H1: JHEP 1505 (2015) 056]

ep implementation [I.H., C.O.R., T.S.]

- Select diffractive events based on dPDFs (γ or proton)
  (PDF selection)
- Check whether MPIs between (resolved) photon and proton
- Reject events where MPIs shroud the diffractive signature
  (MPI selection)

Comparisons to HERA data

Event selection

H1: [JHEP 1505 (2015) 056]

- $Q^2 < 2$ GeV^2, $0.2 < y < 0.7$
- $0.01 < x_{\mathbb{P}} < 0.024$, $z_{\mathbb{P}} < 0.8$
- $E_T^{\text{jet1}} > 5.5$, $E_T^{\text{jet2}} > 4.0$ GeV
- $-1.0 < \eta^{\text{jet1,2}} < 2.5$

ZEUS: [E.P.J. C55, 177–191(2008)]

- $Q^2 < 1$ GeV^2, $0.2 < y < 0.85$
- $x_{\mathbb{P}} < 0.025$
- $E_T^{\text{jet1}} > 7.5$, $E_T^{\text{jet2}} > 6.5$ GeV
- $-1.5 < \eta^{\text{jet1,2}} < 1.5$

Event-level variables

- $x_\gamma^{\text{obs}} = \frac{\sum_{\text{jet}}(E^{\text{jet}} - p_z^{\text{jet}})}{\sum_{i\in X}(E^i - p_z^i)}$
- $z_{\mathbb{P}}^{\text{obs}} = \frac{\sum_{\text{jet}}(E^{\text{jet}} + p_z^{\text{jet}})}{\sum_{i\in X}(E^i + p_z^i)}$

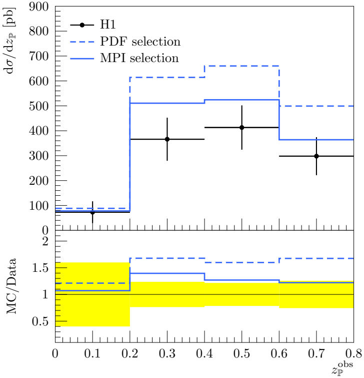
  where X is the diffractive (γ-$\mathbb{P}$) system

Default Pythia setup

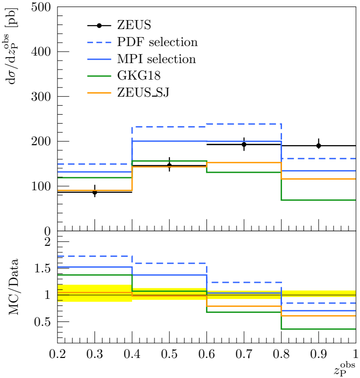
- dPDFs from H1 fit B LO
- γPDFs from CJKL
- $p_{\text{T0}}^{\text{ref}} = 3.00$ GeV$/c$

z_{IP}^{obs} distributions

H1: [JHEP 1505 (2015) 056]



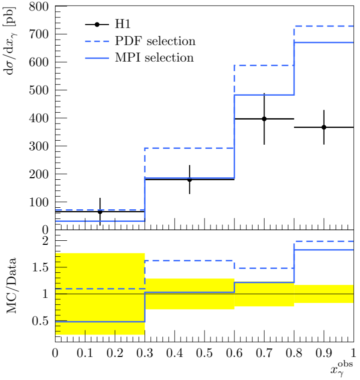
ZEUS: [E.P.J. C55, 177–191(2008)]



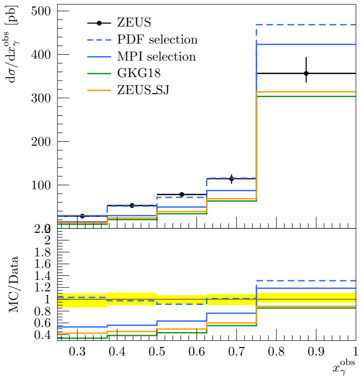
- Pure factorization-based result overshoot both data
- Better (not perfect) agreement with MPI rejection
- Sensitive to the dPDFs

x_γ^{obs} distributions

H1: [JHEP 1505 (2015) 056]



ZEUS: [E.P.J. C55, 177–191(2008)]

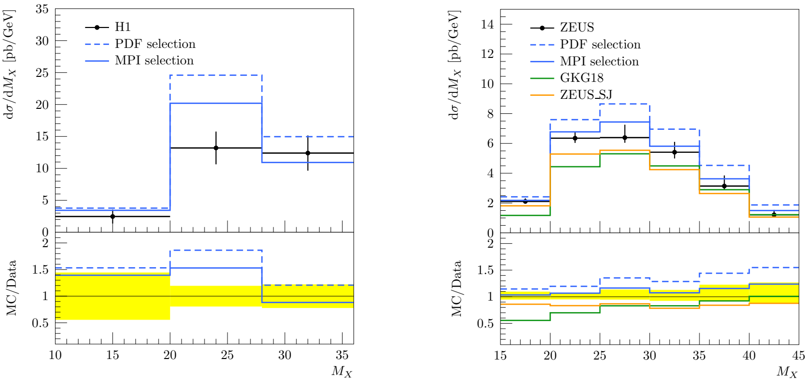


- Suppression from MPIs stronger towards smaller x_γ^{obs} since direct processes dominate at large x_γ^{obs}
- Reasonable agreement with H1 but not very good with ZEUS
- Observable sensitive to jet selection parameters

Invariant mass distributions

H1: [JHEP 1505 (2015) 056]

ZEUS: [E.P.J. C55, 177–191(2008)]



- MPI suppression stronger at high M_X
- Very good description of the data with the H1 fit B dPDFs
- Data favours calculations with MPI selection

Predictions for UPCs at the LHC

Predictions for UPCs at the LHC

Theoretical setup

- pp and pPb collisions, flux from Pb dominates the latter
- Jet selection with anti-k_T algorithm with $R = 1.0$

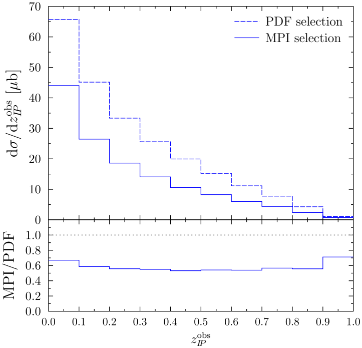
$$E_T^{\text{jet1}} > 8 \text{ GeV} \qquad -4.4 < \eta^{\text{jet1,2}} < 4.4$$
$$E_T^{\text{jet2}} > 6 \text{ GeV} \qquad M_{\text{jets}} > 14 \text{ GeV}$$

- Currently no cut on $x_{I\!P}$ as in HERA comparisons
- No need for Q^2 cut since always low in UPCs where photoproduction framework applicable

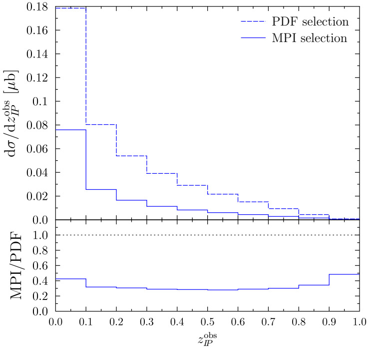
  Results still preliminary

z_{IP}^{obs} distributions

pPb @ $\sqrt{s_{NN}} = 5.0$ TeV:



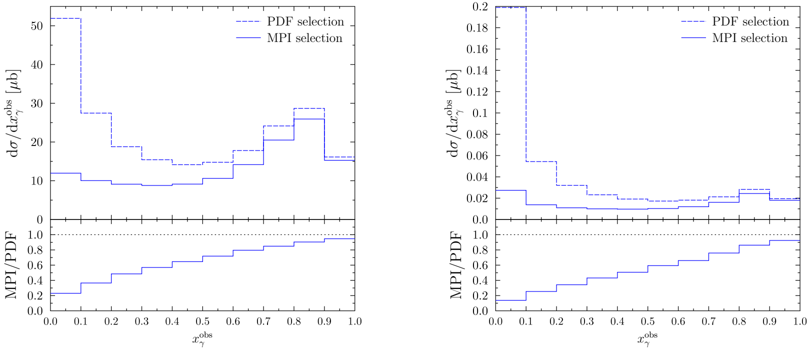
pp @ $\sqrt{s_{NN}} = 5.0$ TeV:



- Rejecting events with MPIs for γp system supresses cross section by 40 % (60 %) in pPb (pp)
- Supression stronger in pp since the harder flux leads to larger $W_{\gamma p}$ where more room for MPIs

x_γ^{obs} distributions

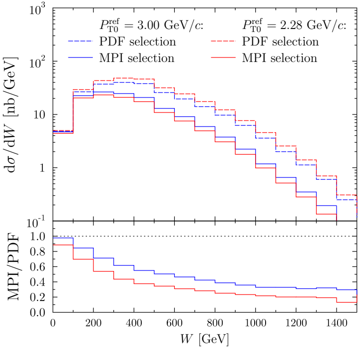
pPb @ $\sqrt{s_{\text{NN}}} = 5.0$ TeV: pp @ $\sqrt{s_{\text{NN}}} = 5.0$ TeV:



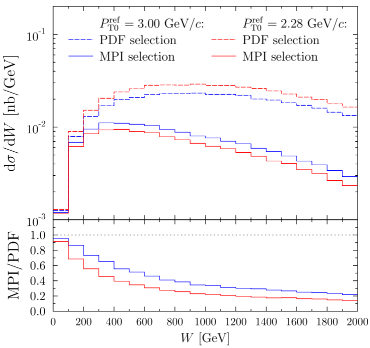
- Pure factorization-based result generates a large number of events at small-x_γ^{obs} due to small-x gluons in γPDFs
- These are effectively cut out with MPI selection

Invariant mass of γp system

pPb @ $\sqrt{s_{NN}} = 5.0$ TeV:



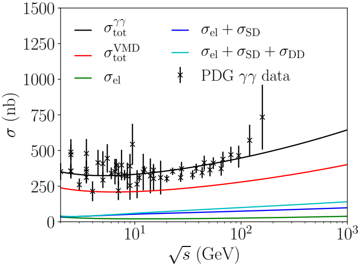
pp @ $\sqrt{s_{NN}} = 5.0$ TeV:

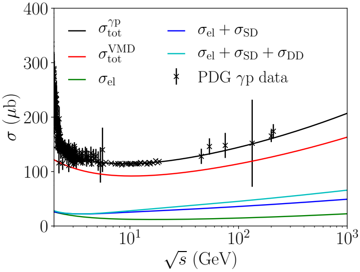


- Average number of MPIs grow towards higher $W_{\gamma p}$
  $\Rightarrow$ Stronger suppression with MPI selection at high $W_{\gamma p}$
- $p_{T0}(W)$ in γp unconstrained beyond HERA kinematics
  $\Rightarrow$ Lower p_{T0}^{ref} leads to further MPI suppression (higher $\mathcal{P}_{MPI}$)

Soft diffraction with photons

- New: Photoproduction framework extented to elastic and soft diffractive processes using SaSDL model [I.H., C.O.R., T.S.]





- Will be implemented also within ep, e^+e^- and UPCs for the next release

Summary

Hard diffraction in ep

- Hard diffraction with dynamical rapidity gap survival for photoproduction implemented into Pythia (8.235)
  - No additional parameters required
- Reasonable description of HERA data with MPI selection
- Several theoretical uncertainties (dPDFs, γPDFs, p_{T0} value)
  Could be reduced by taking ratio to DIS (as in H1 analysis)

Hard diffraction in UPCs

- Larger effect from MPI rejection due to higher $W_{\gamma p}$
- Can study hard diffraction also with nuclear target in PbPb
  - Expect stronger MPI suppression due to several NN interactions
  - Pythia simulations will require to combine photoproduction with the recent Pythia heavy-ion model Angantyr

[C. Bierlich, G. Gustafson, L. Lönnblad and H. Shah: JHEP 1810 (2018) 134]

Backup slides

MPI and parton shower generation

Common evolution scale (p_T) for FSR, ISR and MPIs

- Probability for something to happen at given p_T

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_T} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_T} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_T} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_T} \right)$$
$$\times \exp\left[- \int_{p_T}^{p_T^{\max}} \mathrm{d}p'_T \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_T} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_T} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_T} \right) \right]$$

where $\exp[\ldots]$ is a Sudakov factor
(probability that nothing else has happened before p_T)

Simultaneous partonic evolution

1. Start the evolution from a scale related to the hard process
2. Sample p_T values for each $\mathcal{P}_i$, pick one with highest p_T
3. Continue from the sampled p_T until reach $p_{T\min} \sim \Lambda_{\mathrm{QCD}}$

Partonic evolution for resolved photons

DGLAP equations for photons

- Additional term due to $\gamma \to q\bar{q}$ splittings

$$\frac{\partial f_i^{\gamma}(x, Q^2)}{\partial \log(Q^2)} = \frac{\alpha_{\mathrm{em}}}{2\pi} e_i^2 P_{i\gamma}(x) + \frac{\alpha_s(Q^2)}{2\pi} \sum_j \int_x^1 \frac{dz}{z} P_{ij}(z) f_j(x/z, Q^2)$$

  where $P_{i\gamma}(x) = 3(x^2 + (1-x)^2)$ for quarks, 0 for gluons (LO)

- Solution has two components:

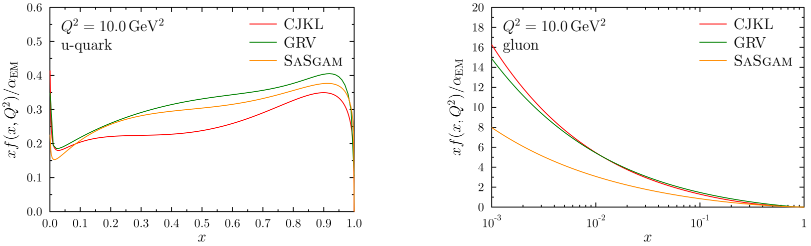
$$f_i^{\gamma}(x, Q^2) = f_i^{\gamma,\mathrm{pl}}(x, Q^2) + f_i^{\gamma,\mathrm{had}}(x, Q^2)$$

  - Point-like part from perturbative QCD
  - Non-perturbative input required for the hadron-like part

$$f_i^{\gamma,\mathrm{had}}(x, Q_0^2) = N_i x^{a_i} (1-x)^{b_i}$$

PDFs for resolved photons

Comparison of different photon PDF analysis



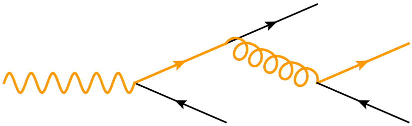
- Some differences between analyses, especially for gluon
  $\Rightarrow$ Theoretical uncertainty for resolved processes
- CJKL used as a default in Pythia 8, others via LHAPDF5 but only for hard-process generation

ISR with resolved photons

- ISR probability based on DGLAP equations
- Add a term corresponding to $\gamma \to q\bar{q}$ splitting

$$\mathrm{d}\mathcal{P}_{a \leftarrow b} = \frac{\mathrm{d}Q^2}{Q^2} \frac{\alpha_\mathrm{s}}{2\pi} \frac{x' f_a^\gamma(x', Q^2)}{x f_b^\gamma(x, Q^2)} P_{a \to bc}(z)\,\mathrm{d}z + \frac{\mathrm{d}Q^2}{Q^2} \frac{\alpha_\mathrm{em}}{2\pi} \frac{e_b^2\, P_{\gamma \to bc}(x)}{f_b^\gamma(x, Q^2)}$$

- Corresponds to finding the original photon during evolution
  $\Rightarrow$ Parton originated from the point-like part of the PDF
  - No further ISR
  - No MPIs below the scale
  - No need for beam remnants



MPIs with resolved photons

MPI probability depends on p_{T0}

- Current parametrization

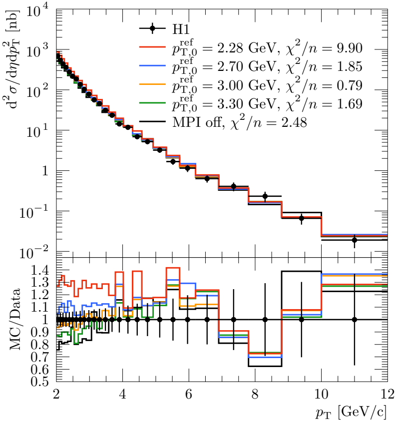
  $$p_{\mathrm{T0}}(\sqrt{s}) = p_{\mathrm{T0}}^{\mathrm{ref}}(\sqrt{s}/\sqrt{s_{\mathrm{ref}}})^{\alpha}$$

  tuned to pp data
- New parametrization for γp
  - Data sensitive to MPIs
  - Wide range in $W_{\gamma \mathrm{p}}$

Inclusive charged-particle production by H1

- $E_{\mathrm{p}} = 820$ GeV, $E_{\mathrm{e}} = 27.5$ GeV
- $< W_{\gamma \mathrm{p}} > \ \approx 200$ GeV
- Assume same α as in pp, vary $p_{\mathrm{T0}}^{\mathrm{ref}}$

[H1: Eur.Phys.J. C10 (1999) 363-372]



- Sensitive to MPIs $p_{\mathrm{T}} < 4$ GeV
- Optimal with $p_{\mathrm{T0}}^{\mathrm{ref}} = 3.00$ GeV

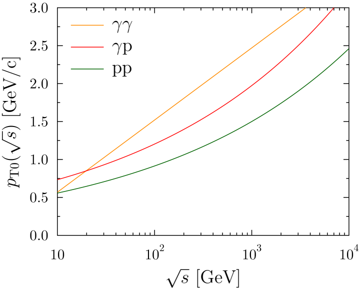
MPIs with resolved photons

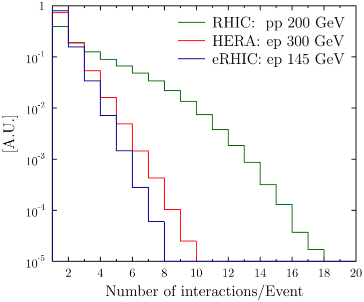
Parametrization for γp

- p_{T0} values between $\gamma\gamma$ (using LEP data) and pp
- Relevant energies:
  - HERA: $W_{\gamma p} \approx 200$ GeV
  - eRHIC: $W_{\gamma p} \approx 100$ GeV

Number of MPIs in different colliders

- Non-diffractive events with resolved photons
- Less MPIs in ep than pp
  - Larger p_{T0}
  - Point-like PDF in PS





Dijet photoproduction in ep collisions at HERA

ZEUS dijet measurement

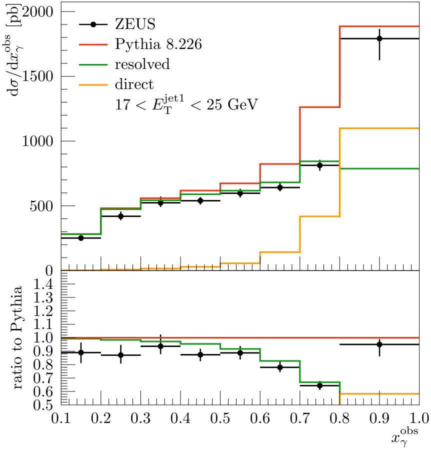
- $Q^2_\gamma < 1.0\ \text{GeV}^2$
- $134 < W_{\gamma p} < 277\ \text{GeV}$
- $E_\text{T}^\text{jet1} > 14\ \text{GeV}$,
  $E_\text{T}^\text{jet2} > 11\ \text{GeV}$
- $-1 < \eta^\text{jet1,2} < 2.4$

Different contributions

- Define

$$x_\gamma^\text{obs} = \frac{E_\text{T}^\text{jet1} e^{\eta^\text{jet1}} + E_\text{T}^\text{jet2} e^{\eta^\text{jet2}}}{2yE_\text{e}}$$

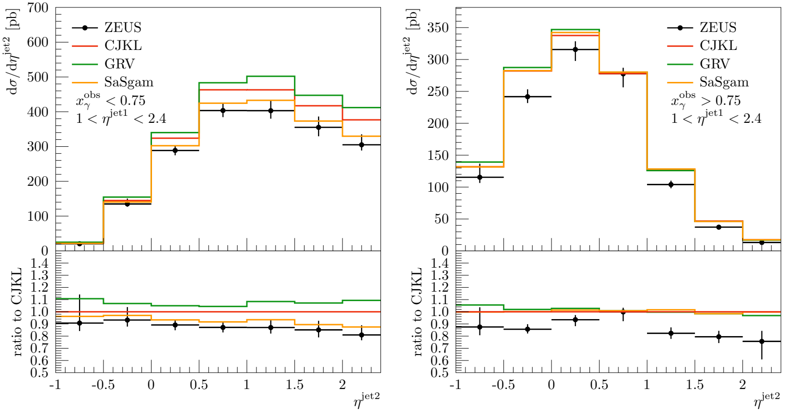
  to discriminate direct and resolved processes
- Corresponds to x of partons from γ in LO (=1 for direct)



[ZEUS: Eur.Phys.J. C23 (2002) 615-631]

Dijet in ep collisions at HERA

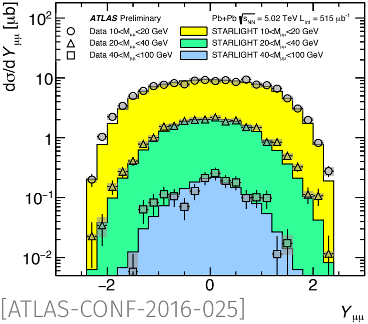
Pseudorapidity dependence of dijets [Eur.Phys.J. C23 (2002) 615-631]



- Simulations tend to overshoot the dijet data by ∼10 %
- ∼ 10 % uncertainty from photon PDFs for $x_\gamma^{obs} < 0.75$

High-mass dimuons in ultraperipheral Pb+Pb at the LHC

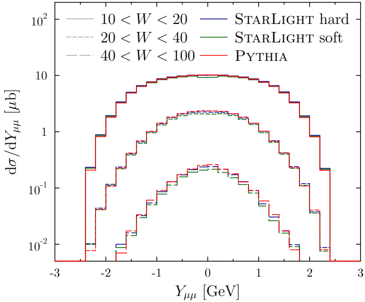
$\mathrm{Pb+Pb} \rightarrow \mu^{+} + \mu^{-} + \mathrm{Pb}^{*} + \mathrm{Pb}^{*}$



[ATLAS-CONF-2016-025]

- Data well described by STARLIGHT MC

⇒ Confirms EPA for Pb+Pb at the LHC



- PYTHIA hard-sphere flux agrees with STARLIGHT
- Small difference at high-W from nuclear density ($\sim$ high-x_{γ})