# ep in Pythia 8

## POETIC-8 Satellite Workshop on Monte Carlo Event Generators

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# Outline

A (biased) overview on recent PYTHIA 8 developments regarding to ep collisions

## Outline

1. DIS in PYTHIA
2. Photoproduction in PYTHIA
3. Hard diffractive photoproduction
4. Summary & Outlook

# Pythia 8

- A general-purpose Monte-Carlo event generator
- Current version 8.230, next week 8.235
- Main focus has been in pp, now extensions to ee, ep, pA, AA

Team:


- Torbjörn Sjöstrand — Lund University
- Christian Bierlich — Lund University
- Nishita Desai — CNRS-Universite de Montpellier
- Nadine Fischer — Monash University
- Ilkka Helenius — Tübingen University
- Philip Ilten — University of Birmingham
- Leif Lönnblad — Lund University
- Stephen Mrenna — Fermi National Accelerator Laboratory
- Stefan Prestel — Fermi National Accelerator Laboratory
- Christine O. Rasmussen — Lund University
- Peter Skands — Monash University

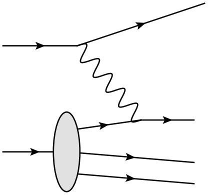
# Event classes in ep

Virtuality of photon related to scattering angle of the lepton

$$Q^2 \approx 2E_l^2(1-x)(1-\cos\theta)$$

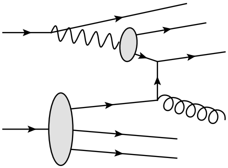
## Deep inelastic scattering (DIS)

- High virtuality, $Q^2 >$ a few GeV$^2$
- Hard process + Parton showers



## Photoproduction (PhP)

- Low virtuality, $Q^2 \lesssim 1$ GeV$^2$
- Intermediate photon may fluctuate into hadronic state $\Rightarrow$ Resolved $\gamma$
- Factorize $\gamma$ flux, set up $\gamma$p collision
- Also multiparton interactions (MPIs) possible



# DIS in PYTHIA

# DIS in PYTHIA

## Hard processes

- Neutral current, $\gamma^*/Z$ exchange, also separate contributions
- Charged current, $W^\pm$ exchange

## Parton shower

- New dipole-shower option `SpaceShower:dipoleRecoil`

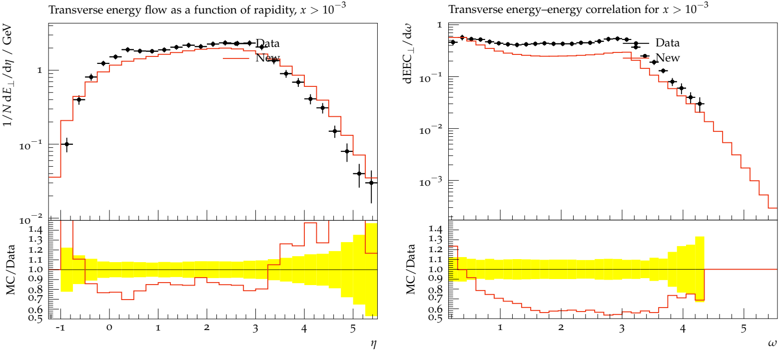
  B. Cabouat and T. Sjöstrand [arXiv:1710.00391 [hep-ph]]
- Alternative to the default global recoil approach, keeps the scattered lepton momentum intact $\Rightarrow$ suitable for DIS
- Also linking with DIRE shower is a valid option for DIS

  S. Höche and S. Prestel [Eur.Phys.J. C75 (2015) 461]

# Comparison to DIS data from HERA

B. Cabouat and T. Sjöstrand [arXiv:1710.00391 [hep-ph]]

Data from H1, [Z. Phys. C63, 377-389 (1994)]

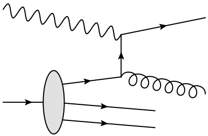



- Reasonable agreement for single-particle properties
- Below data for energy-energy correlations
- Results based on existing default tune with global recoil

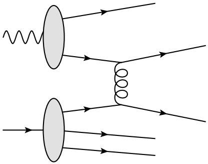
# Photoproduction

# Photoproduction in ep

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



- Resolved processes
  - Photon fluctuates into a hadronic state (VMD and anomalous)
  - Partonic structure described with PDFs
  - FSR and ISR for both sides, also MPIs



# MPI and parton shower generation in PYTHIA 8

## Common evolution scale ($p_{\mathrm{T}}$) for FSR, ISR and MPIs

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_{\mathrm{T}}} = \left( \frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_{\mathrm{T}}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_{\mathrm{T}}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_{\mathrm{T}}} \right) \times \exp\left[ -\int_{p_{\mathrm{T}}}^{p_{\mathrm{T}}^{\mathrm{max}}} \mathrm{d}p'_{\mathrm{T}} \left( \frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_{\mathrm{T}}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_{\mathrm{T}}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_{\mathrm{T}}} \right) \right]$$

where exp[. . .] is a Sudakov factor

## Simultaneous partonic evolution

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

- Probability for MPIs from $2 \to 2$ QCD processes
- Partonic cross section diverges at $p_{\mathrm{T}} \to 0$

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

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

- pp: Power-law in $\sqrt{s}$

  $p_{\mathrm{T0}}(\sqrt{s}) = p_{\mathrm{T0}}^{\mathrm{ref}}(\sqrt{s}/7\ \mathrm{TeV})^{\alpha}$

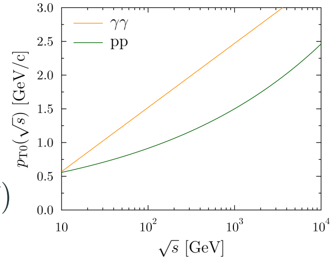
  $p_{\mathrm{T0}}^{\mathrm{ref}} = 2.28$ GeV/c, $\alpha = 0.215$

  (Monash tune)
- $\gamma\gamma$: Logarithmic in $\sqrt{s}$

  $p_{\mathrm{T0}}(\sqrt{s}) = p_{\mathrm{T0}}^{\mathrm{ref}} + \alpha \log\left(\sqrt{s}/100\ \mathrm{GeV}\right)$

  $p_{\mathrm{T0}}^{\mathrm{ref}} = 1.52$ GeV/c, $\alpha = 0.413$

  (I.H., T. Sjöstrand, *in prep.*)
- Parametrization for $\gamma$p?



# Parton showers in photoproduction

## DGLAP equations for photons

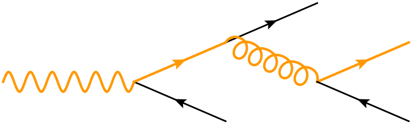
- Additional term due to $\gamma \rightarrow q\bar{q}$ splittings

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

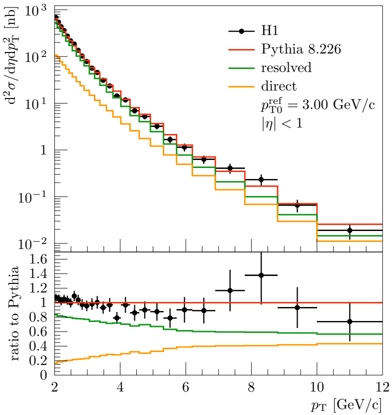
## Add corresponding term to ISR probability

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

- Corresponds to finding the beam photon during evolution
  - No further ISR
  - No further MPIs
  - No need for beam remnants



# Charged particle $p_T$ spectra in ep collisions at HERA




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

## H1 measurement

- $E_p = 820$ GeV, $E_e = 27.5$ GeV
- $< W_{\gamma p} > \approx 200$ GeV
- $Q^2_\gamma < 0.01$ GeV$^2$

## Comparison to Pythia 8

- Resolved contribution dominates
- Good agreement with the data using $p_{T0}^{ref} = 3.00$ GeV/c

$\Rightarrow$ MPI probability between pp and $\gamma\gamma$

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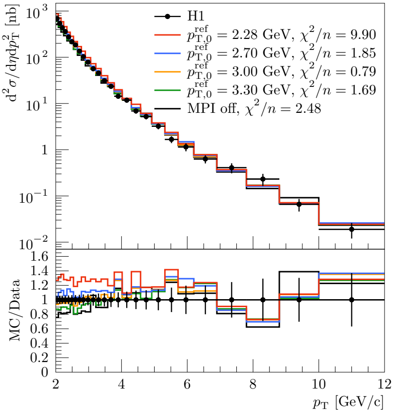


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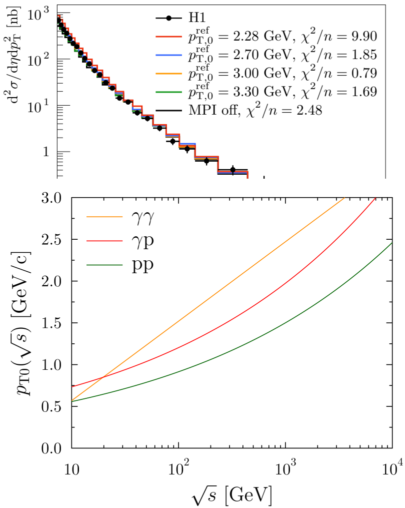


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⇒ MPI probability between pp and $\gamma\gamma$

# Dijet photoproduction in ep collisions at HERA

## ZEUS dijet measurement

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

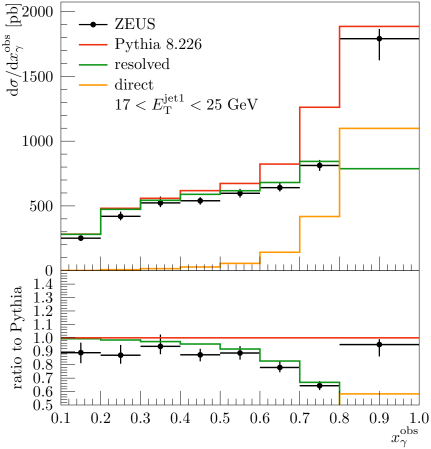
## Different contributions

- Define

$$x_\gamma^{\text{obs}} = \frac{E_T^{\text{jet1}} e^{\eta^{\text{jet1}}} + E_T^{\text{jet2}} e^{\eta^{\text{jet2}}}}{2yE_e}$$

  to discriminate direct and resolved processes (=$x$ in $\gamma$ at LO parton level)

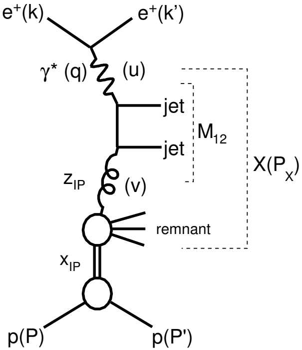
- At high-$x_\gamma^{\text{obs}}$ direct processes dominate




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

# Hard diffractive photoproduction

# Hard diffraction in ep




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

## Diffractive dijets

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

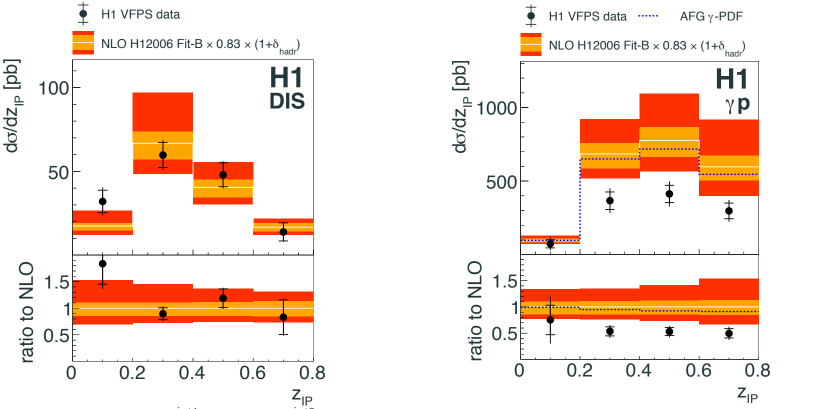
## Factorized cross section in hard diffraction

- DIS: $\mathrm{d}\sigma^{\text{2jets}} = f_i^{\mathrm{IP}}(z_{\mathrm{IP}}, \mu^2) \otimes f_{\mathrm{IP}}^{\mathrm{p}}(x_{\mathrm{IP}}, t) \otimes \mathrm{d}\sigma^{ie\to\text{2jets}}$
- PhP: $\mathrm{d}\sigma^{\text{2jets}} = f_\gamma^{\mathrm{e}}(x_\gamma) \otimes f_i^{\mathrm{IP}}(z_{\mathrm{IP}}, \mu^2) \otimes f_{\mathrm{IP}}^{\mathrm{p}}(x_{\mathrm{IP}}, t) \otimes \mathrm{d}\sigma^{i\gamma\to\text{2jets}}$

where $f_{\mathrm{IP}}^{\mathrm{p}}$ is Pomeron flux and $f_i^{\mathrm{IP}}$ diffractive PDF (dPDF)

# Breaking of factorization

Diffractive dijet cross section in DIS and photoproduction




$$z_{\mathbb{P}}^{\text{obs}} = \frac{E_T^{\text{jet1}} e^{\eta^{\text{jet1}}} + E_T^{\text{jet2}} e^{\eta^{\text{jet2}}}}{2 x_{\mathbb{P}} E_p}$$

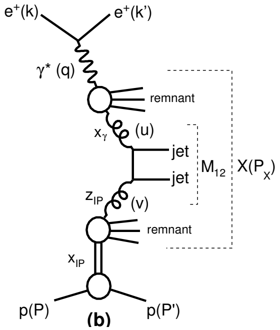
[H1: JHEP 1505 (2015) 056]

- Good agreement with data and NLO pQCD in DIS
- NLO overshoots the data by factor of 2 in photoproduction

## Dynamical rapidity gap survival

- Originally introduced for pp

  C. O. Rasmussen and T. Sjöstrand [JHEP 1602 (2016) 142]




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

## ep implementation

I.H., C. O. Rasmussen and T. Sjöstrand

- Select diffractive events based on dPDFs ($\gamma$ or proton)
- Check whether MPIs between (resolved) photon and proton
- Reject events where MPIs shroud the diffractive signature

# Comparison to ZEUS measurement (preliminary)

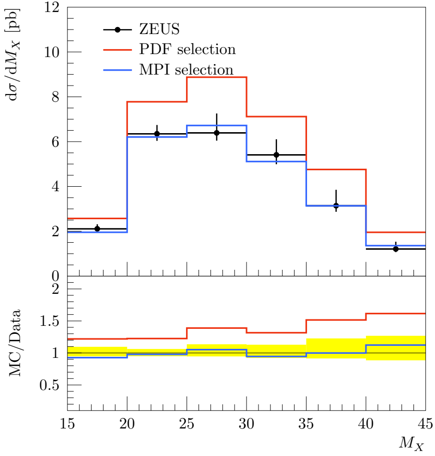
## ZEUS diffractive dijets

- $Q^2_\gamma < 1.0$ GeV$^2$
- $0.2 < y < 0.85$
- $E_T^{\text{jet1}} > 7.5$ GeV, $E_T^{\text{jet2}} > 6.5$ GeV
- $-1.5 < \eta^{\text{jet1,2}} < 1.5$

## Pythia setup

- Pomeron flux: H1 Fit B
- Diffractive PDF: H1 Fit B LO
- PDF selection overshoots the data by $\sim 40\%$
- Good agreement with MPI selection

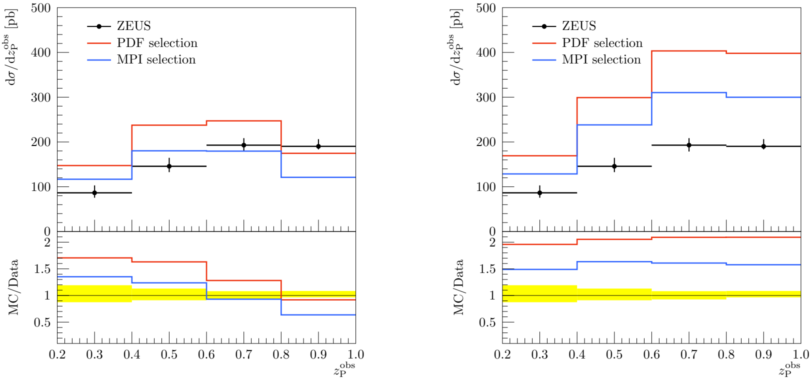
Mass of the hadronic system




[ZEUS: Eur.Phys.J. C55, 177–191 (2008)]

# Comparison to ZEUS measurement

Diffractive PDF: H1 Fit B LO | Diffractive PDF: H1 Fit A NLO




[ZEUS: Eur.Phys.J. C55, 177–191 (2008)]

- Some distributions not that well described
- Results very sensitive to Pomeron PDFs (and flux)

  ⇒ Promising results but large uncertainties from dPDFs

# Summary & Outlook

## Current ep capabilities of Pythia 8.230

- DIS with new `SpaceShower:dipoleRecoil` shower
- Photoproduction including
  - Automatic mixing of direct and resolved processes
  - Full parton-level evolution including MPIs for resolved $\gamma$p
  - Possible to use photon flux from nuclei

## Next release (8.235, next week)

- Soft diffraction for $\gamma\gamma$ and $\gamma$p
- Hard diffractive photoproduction in ep based on
  - Diffractive PDFs
  - Dynamical rapidity gap survival based on MPIs

# Summary & Outlook

## Future work

- Soft diffraction in ep
- Hard diffraction in DIS
- Smooth merging of photoprodcution and DIS
- Combine photoproduction framework with Angantyr heavy-ion model [C. Bierlich]
  - MC for $eA$ collisions
  - Capability to simulate $\gamma A$ interactions in ultra-peripheral heavy ion collisions with a proper nuclear target

For MCEG development RIVET analyses for HERA data would be very welcome