Photon-induced processes in Pythia 8

ATLAS Workshop for photon-induced processes

Ilkka Helenius

November 3rd, 2022

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

ACADEMY OF FINLAND
CoE in Quark Matter

Outline

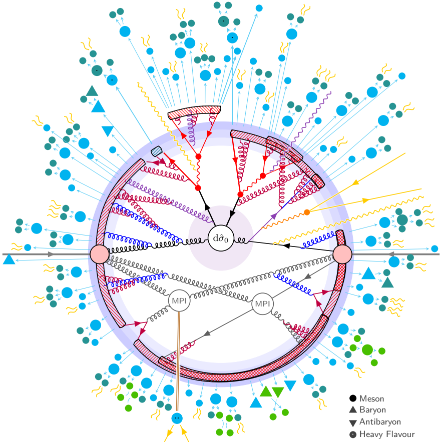
Pythia 8: A general purpose Monte-Carlo event generator

- A new manual for 8.3 release

  arXiv:2203.11601 [hep-ph]

Outline

1. Photoproduction
2. Photon-induced processes in p+p
3. Ultraperipheral heavy-ion collisions
4. Diffractive photoproduction
5. Summary & Outlook



[figure by P. Skands]

Photoproduction

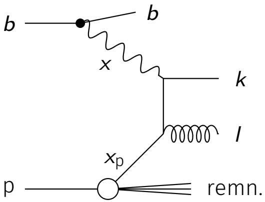
Events in e+p classified in terms of photon virtuality Q^2

- Large Q^2: Deep inelastic scattering
- Small Q^2: Photoproduction ⇒ Factorize photon flux

Direct processes

- Convolute photon flux f_γ with proton PDFs f_i^{p} and $\mathrm{d}\hat{\sigma}$

$$\mathrm{d}\sigma^{b\mathrm{p}\rightarrow kl+X} = f_\gamma^{b}(x) \otimes f_i^{\mathrm{p}}(x_{\mathrm{p}}, \mu^2) \otimes \mathrm{d}\hat{\sigma}^{\gamma i\rightarrow kl}$$

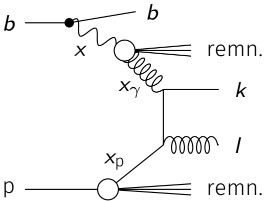


Resolved processes

- Can fluctuate into a hadronic state: photon PDFs

$$\mathrm{d}\sigma^{b\mathrm{p}\rightarrow kl+X} = f_\gamma^{b}(x) \otimes f_j^{\gamma}(x_\gamma, \mu^2) \otimes f_i^{\mathrm{p}}(x_{\mathrm{p}}, \mu^2) \otimes \mathrm{d}\sigma^{ij\rightarrow kl}$$

- Evolve γp as any hadronic collision (including MPIs)



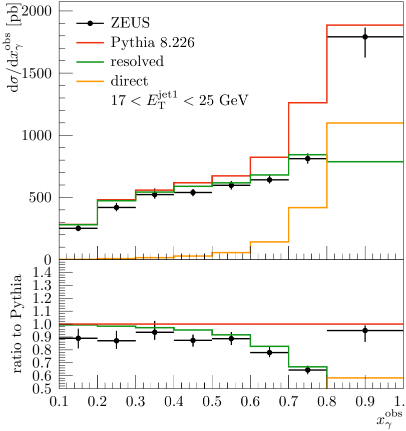
Comparison to HERA dijet photoproduction data

ZEUS dijet measurement

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

Two contributions

- Momentum fraction of partons in photon
$$x_\gamma^\mathrm{obs} = \frac{E_\mathrm{T}^\mathrm{jet1} e^{\eta^\mathrm{jet1}} + E_\mathrm{T}^\mathrm{jet2} e^{\eta^\mathrm{jet2}}}{2yE_\mathrm{e}} \approx x_\gamma$$
- Sensitivity to process type
- At high-x_γ^obs direct processes dominate



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

Comparison to HERA dijet photoproduction data

ZEUS dijet measurement

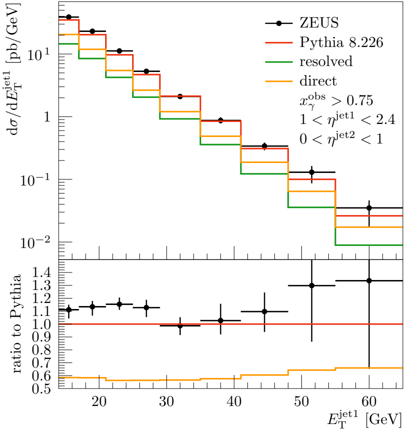
- $Q^2 < 1.0 \text{ GeV}^2$
- $134 < W_{\gamma p} < 277 \text{ GeV}$
- $E_T^{\text{jet1}} > 14 \text{ GeV}, E_T^{\text{jet2}} > 11 \text{ GeV}$
- $-1 < \eta^{\text{jet1,2}} < 2.4$

Two contributions

- Momentum fraction of partons in photon

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

- Sensitivity to process type
- At high-x_γ^{obs} direct processes dominate



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

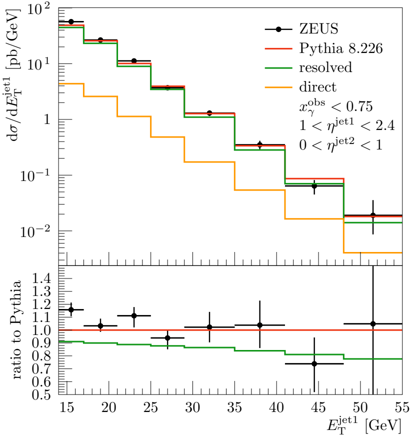
Comparison to HERA dijet photoproduction data

ZEUS dijet measurement

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

Two contributions

- Momentum fraction of partons in photon
$$x_\gamma^{\mathrm{obs}} = \frac{E_{\mathrm{T}}^{\mathrm{jet1}} e^{\eta^{\mathrm{jet1}}} + E_{\mathrm{T}}^{\mathrm{jet2}} e^{\eta^{\mathrm{jet2}}}}{2 y E_{\mathrm{e}}} \approx x_\gamma$$
- Sensitivity to process type
- At high-x_γ^{obs} direct processes dominate



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

Comparison to recent ZEUS data for charged hadrons

[ZEUS: 2106.12377 [hep-ex]]

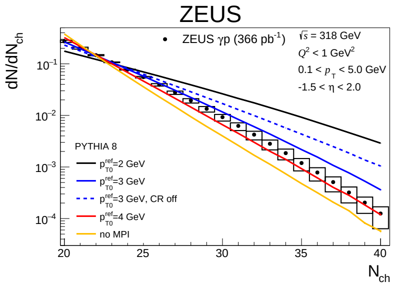
Multiplicity distributions

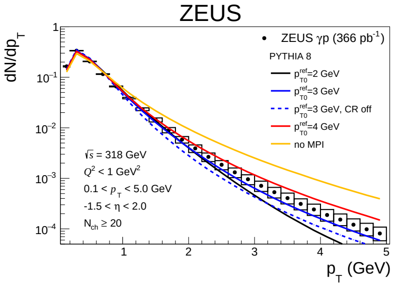
- Multiplicity distributions sensitive to MPIs with resolved photons
- ZEUS data support for MPIs but with slightly larger $p_{\mathrm{T0}}^{\mathrm{ref}}$ than in pp $\Rightarrow$ less MPIs

p_{T} spectra for $N_{\mathrm{ch}} > 20$

- Similar agreement as above
- Useful constraints for MPIs in γp system
- Goog agreement also in $c_1\{2\}$

[Rivet Analysis in preparation]





Equivalent photon approximation

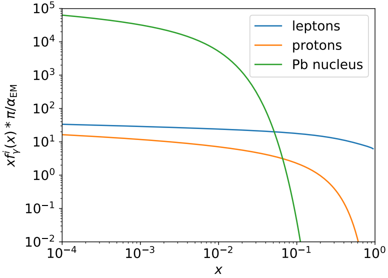
Implemented photon fluxes

- In case of a point-like lepton we have

$$f_{\gamma}^{l}(x,Q^2) = \frac{\alpha_{\mathrm{em}}}{2\pi}\frac{(1+(1-x)^2)}{x}\frac{1}{Q^2}$$

- For protons need to account the form factor

$$f_{\gamma}^{p}(x,Q^2) = \frac{\alpha_{\mathrm{em}}}{2\pi}\frac{(1+(1-x)^2)}{x}\frac{1}{Q^2}\frac{1}{(1+Q^2/Q_0^2)^4}$$



where $Q_0^2 = 0.71$ GeV^2 (Drees-Zeppenfeld) $\Rightarrow$ Large Q^2 heavily suppressed

- With heavy nuclei use b-integrated point-like-charge flux

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

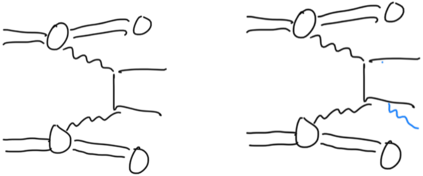
where $\xi = b_{\mathrm{min}}\,x\,m$ where b_{min} reject nuclear overlap, $Q^2 \ll 1$ GeV^2

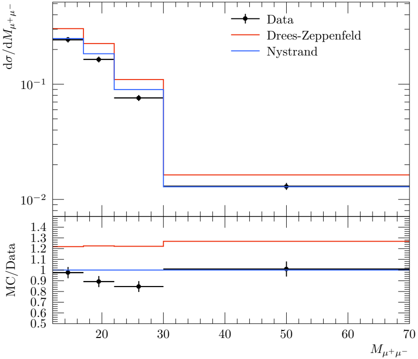
$\Rightarrow$ Can apply photoproduction framework with all these beams!

$\gamma\gamma \to \mu^+\mu^-$ in proton-proton collisions

Elastic-elastic contribution

- Photons have small k_T proportional to Q^2
- Muons almost back-to-back (Aco ≈ 0)
- Small effect from FSR





[ATLAS: PLB 777 (2018) 303-323]

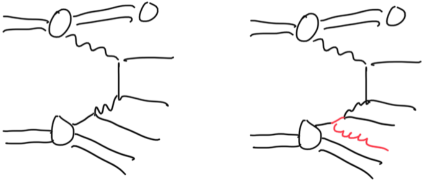
Clean process to calibrate flux

- Reasonable agreement with ATLAS data using EPA, DZ can be improved

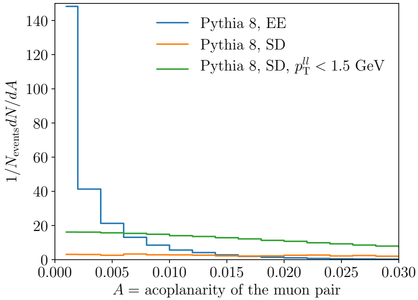
$\gamma\gamma \to \mu^+\mu^-$ in proton-proton collisions

Single-dissociative contribution

- Other γ from elastic flux, other as a part of DGLAP evolved proton PDFs
- Dissociative side will get primordial-k_T sampled from gaussian with width $\mathcal{O}$(GeV)
- Also QCD ISR generated, significant p_T



- Cuts on p_T^{ll} suppress events with ISR



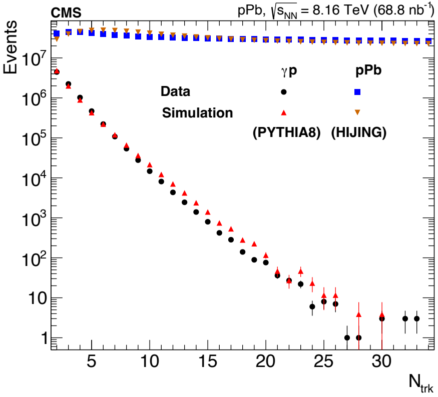
Double dissociative

- Both photons from PDFs with primordial-k_T and ISR

$\Rightarrow$ Large acoplanarity

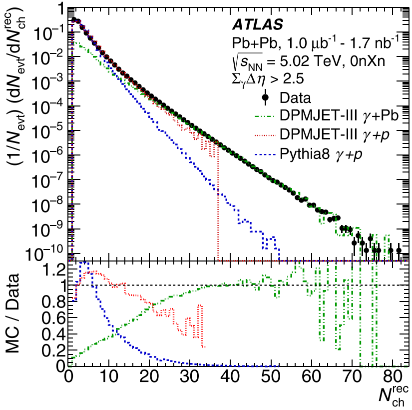
Ultra-peripheral heavy-ion collisions

(Pb $\rightarrow \gamma$)+p: [CMS: Murillo Quijada, QM2022]



- Multiplicities well reproduced with γp

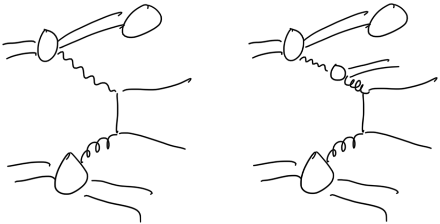
(Pb $\rightarrow \gamma$)+Pb:[ATLAS: PRC 104, 014903 (2021)]

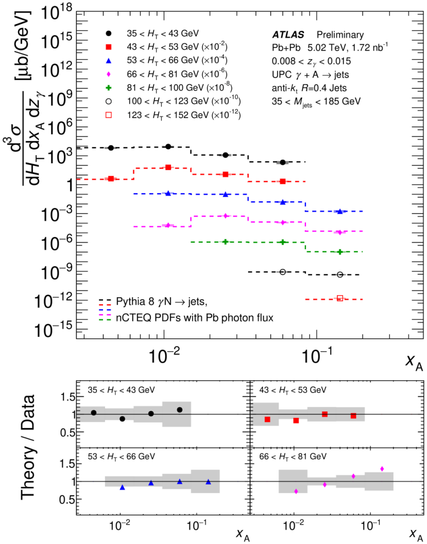


- High multiplicities missed with γp
  $\Rightarrow$ Multi-nucleon interactions

Dijets in ultra-peripheral heavy-ion collisions

- Novel constraints for nuclear PDFs, x_A to estimate probed nuclear x
- Pythia setup with nucleon target only
  $\Rightarrow$ Not a realistic background for jet reconstruction
- Good agreement out of the box when accounting both direct and resolved





[ATLAS: Gilbert DIS2022]

Hard diffraction in PYTHIA 8

Hard diffraction in photoproduction

- Process with a hard scale, desribed with a colour-neutral Pomeron (IP) exchange
- Experimentally identified from rapidity gap

Factorization of the diffractive cross section

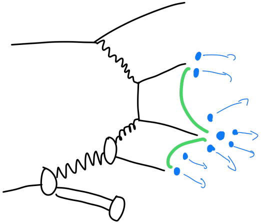
- Direct: Pomeron flux and diffractive PDFs (dPDFs)

$$\mathrm{d}\sigma^{\text{2jets}}_{\text{direct}} = f_{\gamma}^{b}(x) \otimes \mathrm{d}\sigma^{\gamma j \rightarrow \text{2jets}} \otimes f_{j}^{\mathrm{IP}}(z_{\mathrm{IP}}, \mu^2) \otimes f_{\mathrm{IP}}^{\mathrm{p}}(x_{\mathrm{IP}}, t)$$

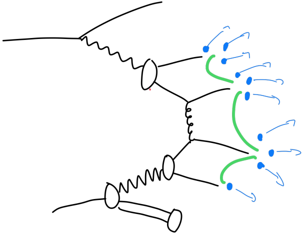
- Resolved: photon PDFs

$$\mathrm{d}\sigma^{\text{2jets}}_{\text{resolved}} = f_{\gamma}^{b}(x) \otimes f_{i}^{\gamma}(x_{\gamma}, \mu^2) \otimes \mathrm{d}\sigma^{ij \rightarrow \text{2jets}} \otimes f_{j}^{\mathrm{IP}}(z_{\mathrm{IP}}, \mu^2) \otimes f_{\mathrm{IP}}^{\mathrm{p}}(x_{\mathrm{IP}}, t)$$

Direct:



Resolved:



Hard diffraction in PYTHIA 8

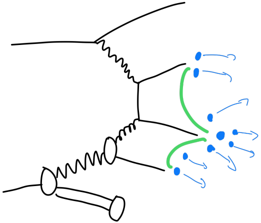
Hard diffraction in photoproduction

- Process with a hard scale, desribed with a colour-neutral Pomeron (IP) exchange
- Experimentally identified from rapidity gap

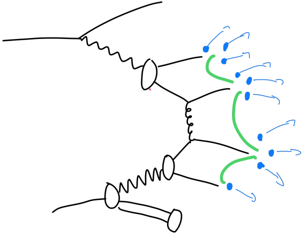
Dynamical rapidity gap survival model

1. Generate diffractive events with dPDFs (PDF)

Direct:



Resolved:



Hard diffraction in Pythia 8

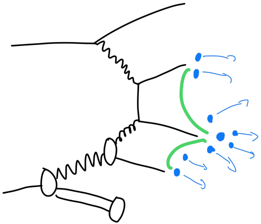
Hard diffraction in photoproduction

- Process with a hard scale, desribed with a colour-neutral Pomeron (IP) exchange
- Experimentally identified from rapidity gap

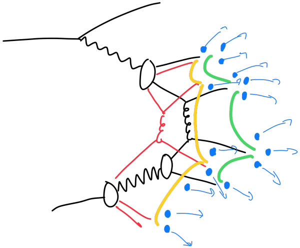
Dynamical rapidity gap survival model

1. Generate diffractive events with dPDFs (PDF)
2. Reject events where MPIs in γp system (MPI)

Direct:



Resolved:



Hard diffraction in Pythia 8

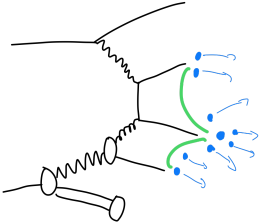
Hard diffraction in photoproduction

- Process with a hard scale, desribed with a colour-neutral Pomeron (IP) exchange
- Experimentally identified from rapidity gap

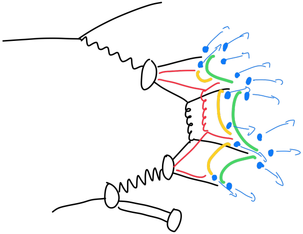
Dynamical rapidity gap survival model

1. Generate diffractive events with dPDFs (PDF)
2. Reject events where MPIs in γp system (MPI)
3. Evolve γIP system, allow MPIs

Direct:



Resolved:



Hard diffraction in PYTHIA 8

Hard diffraction in photoproduction

- Process with a hard scale, desribed with a colour-neutral Pomeron (IP) exchange
- Experimentally identified from rapidity gap

Dynamical rapidity gap survival model

1. Generate diffractive events with dPDFs (PDF)
2. Reject events where MPIs in γp system (MPI)
3. Evolve γIP system, allow MPIs

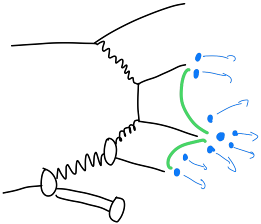
Implemented from PYTHIA 8.235 onwards

[I.H. and C.O. Rasmussen, EPJC 79 (2019) no.5, 413]

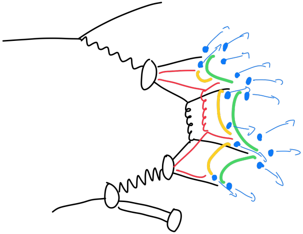
Same idea applied for pp collisions at the LHC

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

Direct:

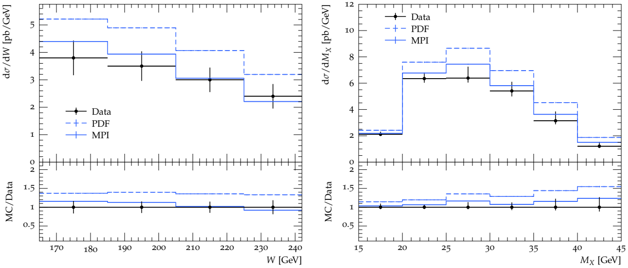


Resolved:



Comparisons to HERA data

H1: [EPJC 51 (2007) 549] ZEUS: [EPJC 55 (2008) 177]



- PDF selection overshoots the data by 20–50 %
- Impact of the MPI rejection increases with W
- Stronger suppression in H1 analysis due to looser cuts on $E_{\mathrm{T}}^{\mathrm{jets}}$ and $x_{I\!P}$ $\Rightarrow$ More MPIs

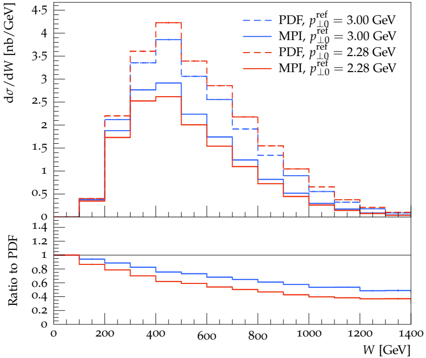
Cuts	H1	ZEUS
Q^2_{max} [GeV^2]	0.01	1.0
$E_{\mathrm{T,min}}^{\mathrm{jet1}}$ [GeV]	5.0	7.5
$E_{\mathrm{T,min}}^{\mathrm{jet2}}$ [GeV]	4.0	6.5
$x_{I\!P}^{\mathrm{max}}$	0.03	0.025

PYTHIA setup

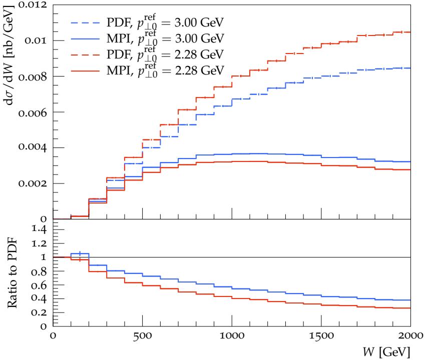
- dPDFs from H1 fit B LO
- γPDFs from CJKL
- $p_{\mathrm{T0}}^{\mathrm{ref}} = 3.00$ GeV/c (Tuned to inclusive charged particle data from γp at HERA)

Predictions for diffractive dijets in UPC

pPb $\sqrt{s} = 5.0$ TeV



pp $\sqrt{s} = 13$ TeV



- Extended *W* range wrt. HERA, especially in pp (harder flux)
- Stronger suppression from MPIs than at HERA

$\Rightarrow$ Ideal process to study factorization-breaking effects in hard diffraction

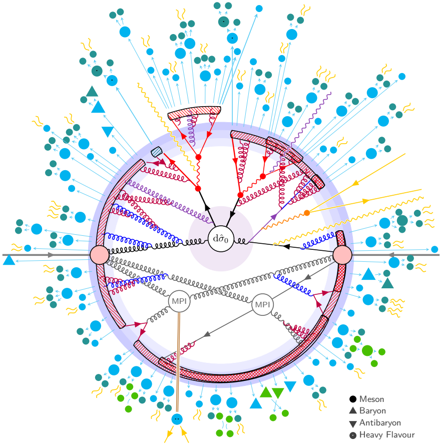
Summary & Outlook

Photon-induced processes in Pythia 8.3

- Photoproduction framework tested against HERA data
- Can be applied to purely hadronic collisions with appropriate fluxes
  - Fluxes in place for leptons, protons and heavy nuclei
  - Possibility to feed in externally provided flux

Outlook

- Subsequent resolved-photon nucleon interactions for γ+A (Angantyr model)

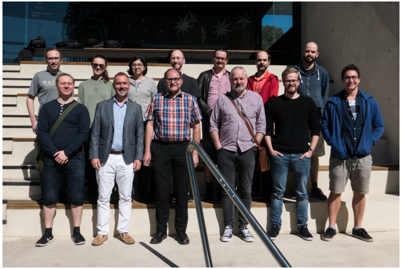


[figure by P. Skands]

Backup slides

PYTHIA Collaboration

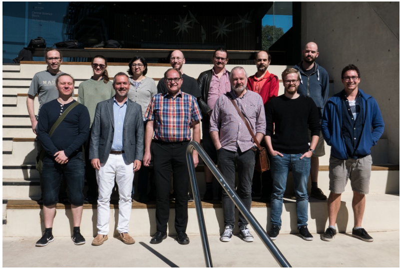
Christian Bierlich	(Lund University)
Nishita Desai	(TIFR, Mumbai)
Leif Gellersen	(Lund University)
Ilkka Helenius	(University of Jyväskylä)
Philip Ilten	(University of Cincinnati)
Leif Lönnblad	(Lund University)
Stephen Mrenna	(Fermilab)
Stefan Prestel	(Lund University)
Christian Preuss	(ETH Zurich)
Torbjörn Sjöstrand	(Lund University)
Peter Skands	(Monash University)
Marius Utheim	(University of Jyväskylä)
Rob Verheyen	(University College London)



[Pythia meeting in Monash 2019]

Pythia Collaboration

Christian Bierlich	(Lund University)
Nishita Desai	(TIFR, Mumbai)
Leif Gellersen	(Lund University)
Ilkka Helenius	(University of Jyväskylä)
Philip Ilten	(University of Cincinnati)
Leif Lönnblad	(Lund University)
Stephen Mrenna	(Fermilab)
Stefan Prestel	(Lund University)
Christian Preuss	(ETH Zurich)
Torbjörn Sjöstrand	(Lund University)
Peter Skands	(Monash University)
Marius Utheim	(University of Jyväskylä)
Rob Verheyen	(University College London)



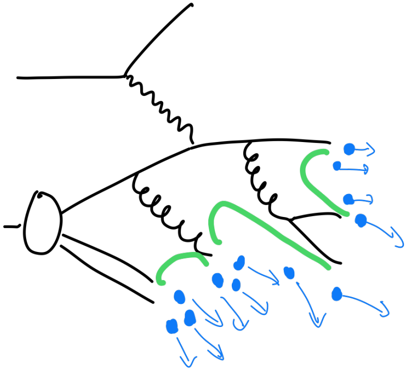
[Pythia meeting in Monash 2019]

- Spokesperson
- Codemaster
- Webmaster

`https://pythia.org`

`authors@pythia.org`

Event generation in DIS with PYTHIA 8



Hard scattering

- Convolution between PDFs and matrix element (ME) for partonic scattering

Parton shower

- Final state radiation (FSR)
- Initial state radiation (ISR) for hadron
- QED emissions from leptons (omitted)

Hadronization

- String hadronization with colour reconnections
- Decays to stable hadrons

DIS with Pythia

Alternative shower model `dipoleRecoil`

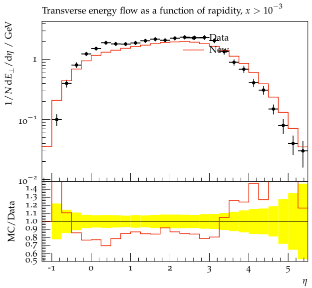
[B. Cabouat and T. Sjöstrand, EPJC 78 (2018 no.3, 226)]

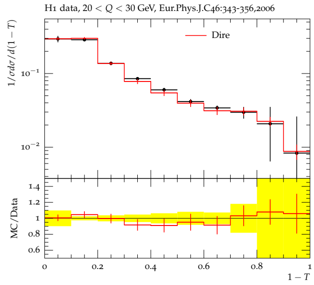
- No PS recoil for the scattered lepton
- Reasonable description of single-particle properties, such as transverse energy flow
- Results based on tune with the default global-recoil shower

Completely new shower DIRE

[S. Höche, S. Prestel, EPJC 75 (2015) no.9, 461]

- Correct soft-gluon interference at lowest order
- Inclusive NLO corrections to collinear splittings
- Good agreement with HERA data e.g. for thurst T





Evolution equation and PDFs for resolved photons

DGLAP equation for photons

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

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

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

- Resulting PDFs has point-like (or anomalous) and hadron-like components

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

  - $f_i^{\gamma,\mathrm{pl}}$: Calculable from perturbative QCD
  - $f_i^{\gamma,\mathrm{had}}$: Requires non-perturbative input fixed in a global analysis

Evolution equation and ISR for resolved photons

ISR probability based on DGLAP evolution

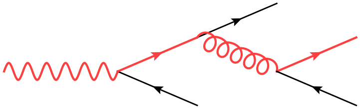
- Add a term corresponding to $\gamma \rightarrow \mathrm{q}\overline{\mathrm{q}}$ to (conditional) ISR probability

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

- Corresponds to ending up to the beam photon during evolution

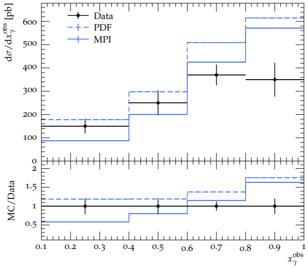
$\Rightarrow$ Parton originated from the point-like part of the PDFs

  - No further ISR or MPIs below the scale of the splitting
  - No need for beam remnants

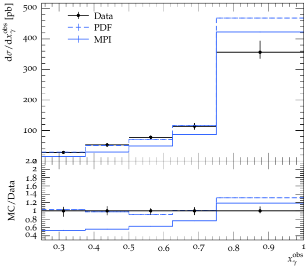


Comparisons to HERA data

H1: [EPJC 51 (2007) 549]



ZEUS: [EPJC 55 (2008) 177]



- Stronger suppression at low-x_γ^{obs} (more MPIs)
- ZEUS cuts select events at high-x_γ^{obs} region
- Some theoretical uncertainty from γPDFs, dPDFs and scale variation

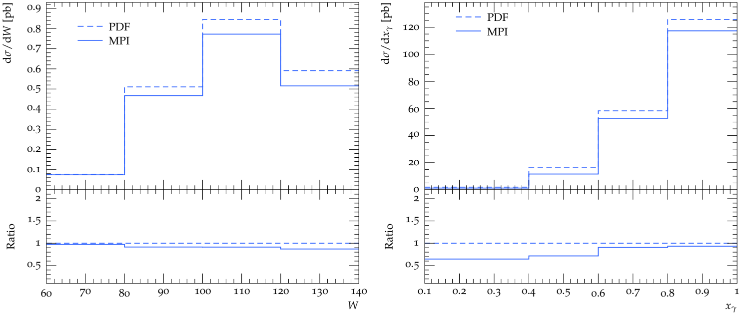
Cuts	H1	ZEUS
Q^2_{max} [GeV^2]	0.01	1.0
$E_{T,min}^{jet1}$ [GeV]	5.0	7.5
$E_{T,min}^{jet2}$ [GeV]	4.0	6.5
x_{IP}^{max}	0.03	0.025

χ^2 analysis	PDF	MPI
H1	5.2	1.4
ZEUS	9.6	5.1
H1 & ZEUS	7.6	3.4

(with all data points)

Predictions for EIC

Repeat the H1 analysis at EIC kinematics ($E_\mathrm{e} = 18$ GeV, $E_\mathrm{p} = 275$ GeV)



- Only up to $\sim 10\%$ effects in the considered W range
- Noticeable suppression only at low x_γ where cross section small

$\Rightarrow$ Available energy and kinematical cuts for diffraction push the kinematics to region where only little room for MPIs ($E_\mathrm{T}^\mathrm{jet1} > 5.0$ GeV, $E_\mathrm{T}^\mathrm{jet2} > 4.0$ GeV)

Intermediate Q^2 region

Solid theory for $Q^2 = 0$ and at high Q^2

$\Rightarrow$ What happens in between?

Pythia 6 (inspired) model ($\neq$ Pythia 8)

- Select suitable scales and suppress contributions by hand

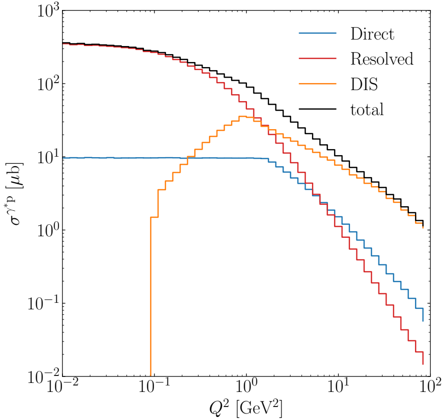
$$\sigma_{\text{tot}}^{\gamma^* \text{p}} = \tilde{\sigma}_{\text{DIS}}^{\gamma^* \text{p}} \exp\left[-\frac{\tilde{\sigma}_{\text{Dir}}^{\gamma^* \text{p}}}{\tilde{\sigma}_{\text{DIS}}^{\gamma^* \text{p}}}\right] + \tilde{\sigma}_{\text{Dir}}^{\gamma^* \text{p}} + \tilde{\sigma}_{\text{Res}}^{\gamma^* \text{p}}$$

where

- $\tilde{\sigma}_{\text{DIS}}^{\gamma^* \text{p}} = \left[\frac{Q^2}{Q^2+m_\rho^2}\right]^2 \sigma_{\text{DIS}}^{\gamma^* \text{p}}$
- $\tilde{\sigma}_{\text{Res}}^{\gamma^* \text{p}} = \sigma_{\text{Res}}^{\gamma^* \text{p}} \left[\frac{m_\rho^2}{m_\rho^2+Q^2}\right]^2 \left[\frac{W^2}{W^2+Q^2}\right]^n$
- $\tilde{\sigma}_{\text{Dir}}^{\gamma^* \text{p}} = \sigma_{\text{Dir}}^{\gamma^* \text{p}}(\hat{p}_{\text{T,min}} = max(Q, p_{\text{T,min}}))$

$p_{\text{T,min}} = 1.3$ GeV, $n = 3$, $m_\rho = 0.7755$ GeV

$\sqrt{s} = 318$ GeV, $W_{\text{min}} = 100$ GeV:



Intermediate: $0.5 \lesssim Q^2 \lesssim 5.0$ GeV^2

Intermediate Q^2 region

Solid theory for $Q^2 = 0$ and at high Q^2

$\Rightarrow$ What happens in between?

Pythia 6 (inspired) model ($\neq$ Pythia 8)

- Select suitable scales and suppress contributions by hand

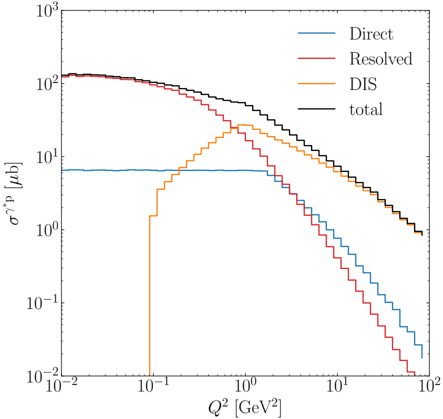
$$\sigma_{\mathrm{tot}}^{\gamma^* \mathrm{p}} = \tilde{\sigma}_{\mathrm{DIS}}^{\gamma^* \mathrm{p}} \exp\left[-\frac{\tilde{\sigma}_{\mathrm{Dir}}^{\gamma^* \mathrm{p}}}{\tilde{\sigma}_{\mathrm{DIS}}^{\gamma^* \mathrm{p}}}\right] + \tilde{\sigma}_{\mathrm{Dir}}^{\gamma^* \mathrm{p}} + \tilde{\sigma}_{\mathrm{Res}}^{\gamma^* \mathrm{p}}$$

where

- $\tilde{\sigma}_{\mathrm{DIS}}^{\gamma^* \mathrm{p}} = \left[\frac{Q^2}{Q^2+m_\rho^2}\right]^2 \sigma_{\mathrm{DIS}}^{\gamma^* \mathrm{p}}$
- $\tilde{\sigma}_{\mathrm{Res}}^{\gamma^* \mathrm{p}} = \sigma_{\mathrm{Res}}^{\gamma^* \mathrm{p}} \left[\frac{m_\rho^2}{m_\rho^2+Q^2}\right]^2 \left[\frac{W^2}{W^2+Q^2}\right]^n$
- $\tilde{\sigma}_{\mathrm{Dir}}^{\gamma^* \mathrm{p}} = \sigma_{\mathrm{Dir}}^{\gamma^* \mathrm{p}}(\hat{p}_{\mathrm{T,min}} = max(Q, p_{\mathrm{T,min}}))$

$p_{\mathrm{T,min}} = 1.3$ GeV, $n = 3$, $m_\rho = 0.7755$ GeV

$\sqrt{s} = 140$ GeV, $W_{\mathrm{min}} = 10$ GeV:



Intermediate: $0.3 \lesssim Q^2 \lesssim 3.0$ GeV^2

Intermediate Q^2 region

Solid theory for $Q^2 = 0$ and at high Q^2

$\Rightarrow$ What happens in between?

Pythia 6 (inspired) model ($\neq$ Pythia 8)

- Select suitable scales and suppress contributions by hand

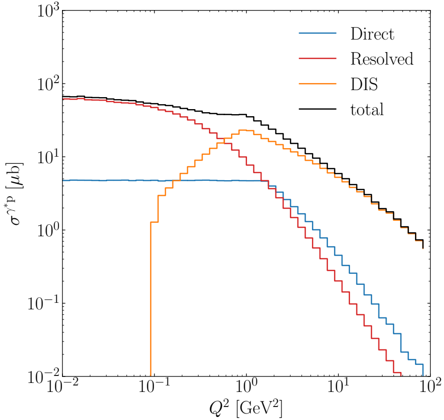
$$\sigma^{\gamma^* \mathrm{p}}_{\mathrm{tot}} = \tilde{\sigma}^{\gamma^* \mathrm{p}}_{\mathrm{DIS}} \exp\left[-\frac{\tilde{\sigma}^{\gamma^* \mathrm{p}}_{\mathrm{Dir}}}{\tilde{\sigma}^{\gamma^* \mathrm{p}}_{\mathrm{DIS}}}\right] + \tilde{\sigma}^{\gamma^* \mathrm{p}}_{\mathrm{Dir}} + \tilde{\sigma}^{\gamma^* \mathrm{p}}_{\mathrm{Res}}$$

where

- $\tilde{\sigma}^{\gamma^* \mathrm{p}}_{\mathrm{DIS}} = \left[\frac{Q^2}{Q^2 + m_\rho^2}\right]^2 \sigma^{\gamma^* \mathrm{p}}_{\mathrm{DIS}}$
- $\tilde{\sigma}^{\gamma^* \mathrm{p}}_{\mathrm{Res}} = \sigma^{\gamma^* \mathrm{p}}_{\mathrm{Res}} \left[\frac{m_\rho^2}{m_\rho^2 + Q^2}\right]^2 \left[\frac{W^2}{W^2 + Q^2}\right]^n$
- $\tilde{\sigma}^{\gamma^* \mathrm{p}}_{\mathrm{Dir}} = \sigma^{\gamma^* \mathrm{p}}_{\mathrm{Dir}}(\hat{p}_{\mathrm{T,min}} = max(Q, p_{\mathrm{T,min}}))$

$p_{\mathrm{T,min}} = 1.3$ GeV, $n = 3$, $m_\rho = 0.7755$ GeV

$\sqrt{s} = 85$ GeV, $W_{\mathrm{min}} = 10$ GeV:



Intermediate: $0.2 \lesssim Q^2 \lesssim 2.0$ GeV^2