Pythia 8 for EIC

RBRC Workshop: Small-x Physics in the EIC Era

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December 16th, 2021

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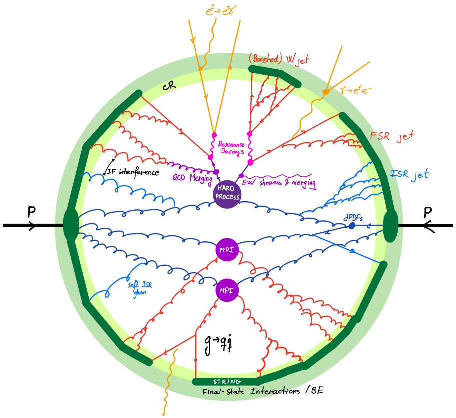
ACADEMY OF FINLAND

Outline

1. Introduction to PYTHIA 8
2. Deep inelastic scattering (DIS)
3. Photoproduction (PhP)
4. Diffractive dijets in PhP
5. Intermediate Q^2 region
6. Summary & Outlook

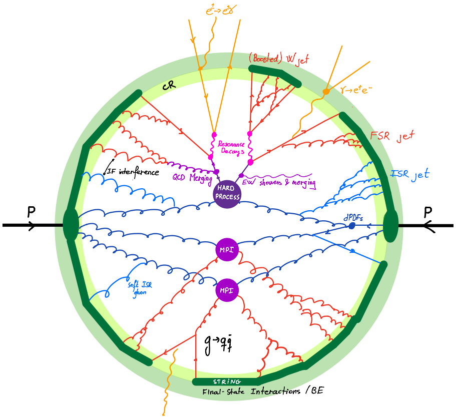


[figure by P. Skands]

Pythia event generator

(subset of) Physics covered in 8.3

- Different beam combinations:
  ee, $\gamma\gamma$, ep, γp, pp, pA, AA, DM
- Hard scattering: native LO, NLO+PS with aMC@NLO and Powheg-Box
- Parton showers: Default, Dire, Vincia
- Multiparton interactions (MPIs): Interleaved with shower evolution
- Soft physics: Diffraction, Elastic, Hadronic (re-)scattering
- Hadronization: String fragmentation, Color reconnection, Ropes & shoving



[figure by P. Skands]

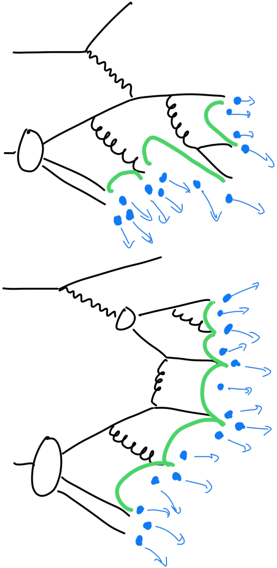
Lepton-proton collisions classified in terms photon virtuality Q^2

Deep inelastic scattering (DIS)

- High virtuality, $Q^2 > $ a few GeV^2
- Lepton scatters off from a parton by exchanging a highly virtual photon

Photoproduction

- Low virtuality, $Q^2 \lesssim 1\ \mathrm{GeV}^2$
  $\Rightarrow$ Direct and resolved contributions
- Factorize γ flux, evolve γp system
- Hard scale provided by the hadronic observable
- Also soft QCD processes, diffraction



Event generation in DIS with Pythia 8

Hard scattering

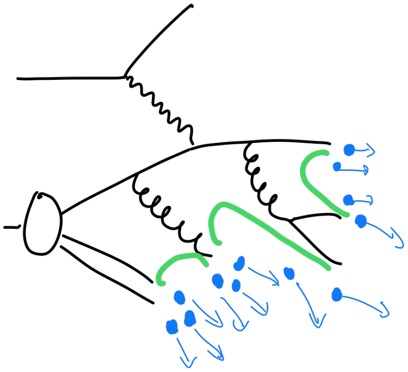
- Convolution between PDFs and matrix element (ME) for partonic scattering

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`

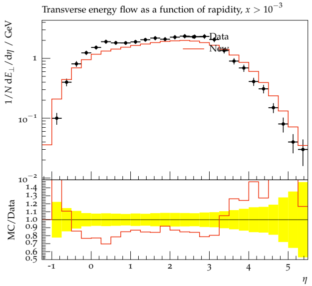
[B. Cabouat and T. Sjöstrand, EPJC 78 (2018 no.3, 226)]

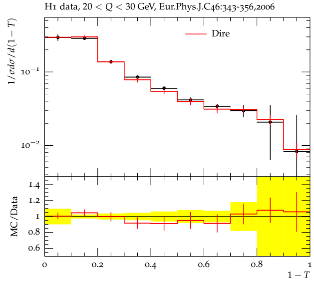
- No PS recoil for the scattered lepton
- Reasonable description of single-particle properties, such as transverse energy flow
- Results based on tune with the default global-recoil shower

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





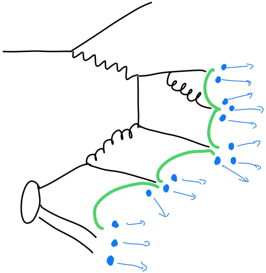
Event generation in photoproduction

Direct processes

- Photon initiator of the hard process (DIS-like)
- Convolute photon flux f_γ with proton PDFs f_i^{p} and $\mathrm{d}\hat{\sigma}$

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

- Generate FSR and ISR for proton side

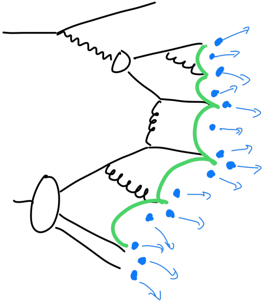


Resolved processes

- Convolute also with photon PDFs

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

- Sample x and Q^2, setup $\gamma\mathrm{p}$ sub-system with $W_{\gamma\mathrm{p}}$
- Evolve $\gamma\mathrm{p}$ as any hadronic collision (including MPIs)



Comparison to HERA photoproduction data

ZEUS dijet measurement

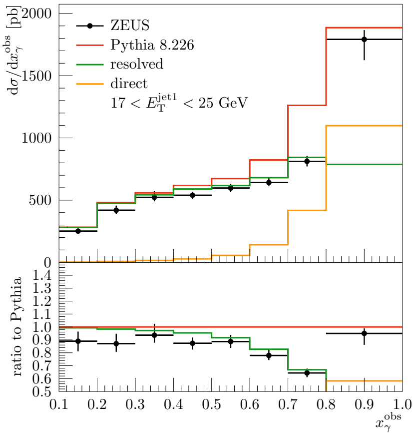
- $Q^2 < 1.0\ \text{GeV}^2$
- $134 < W_{\gamma p} < 277\ \text{GeV}$
- $E_T^{\text{jet1}} > 14\ \text{GeV},\ E_T^{\text{jet2}} > 11\ \text{GeV}$
- $-1 < \eta^{\text{jet1,2}} < 2.4$

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]

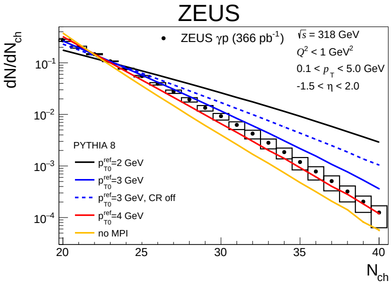
Comparison to recent ZEUS data for charged hadrons [ZEUS: 2106.12377 [hep-ex]]

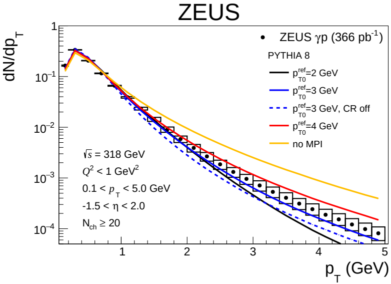
Multiplicity distributions

- Multiplicity distributions sensitive to MPIs with resolved photons
- ZEUS data support for MPIs but with slightly larger p_{T0}^{ref} than in pp $\Rightarrow$ less MPIs (Good description also for γp multiplicities in UPCs at LHC, see backup)

p_T spectra for $N_{ch} > 20$

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





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

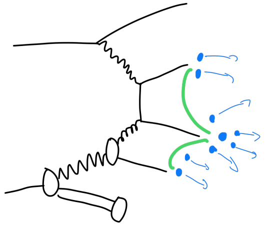
- Direct: Pomeron flux and diffractive PDFs (dPDFs)

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

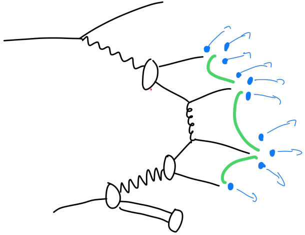
- Resolved: photon PDFs

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

Direct:



Resolved:



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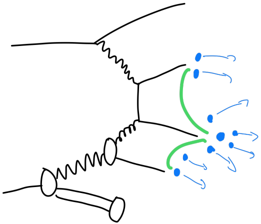
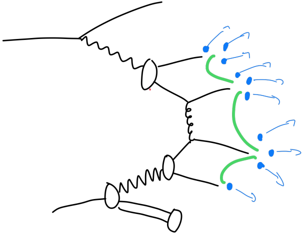
Dynamical rapidity gap survival model

1. Generate diffractive events with dPDFs (PDF)

Direct:



Resolved:



Hard diffraction in photoproduction

- Process with a hard scale, desribed with a colour-neutral Pomeron (IP) exchange
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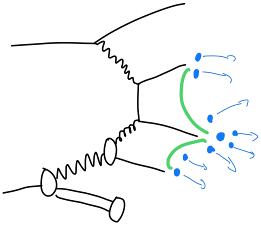
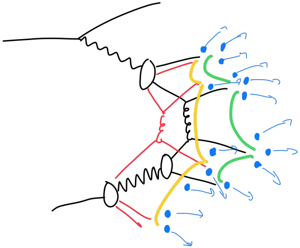
Dynamical rapidity gap survival model

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
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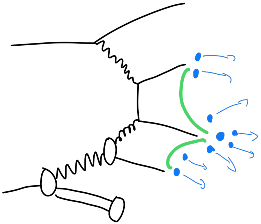
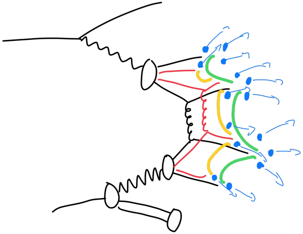
Dynamical rapidity gap survival model

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

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- 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

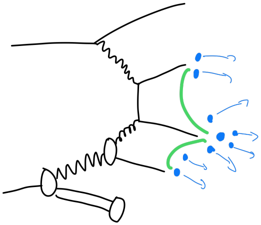
Implemented from PYTHIA 8.235 onwards

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

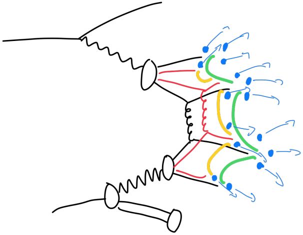
Same idea applied for pp collisions at the LHC

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

Direct:

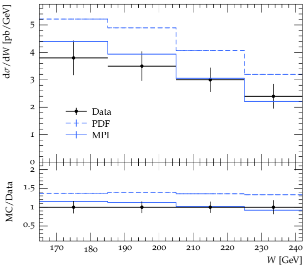


Resolved:

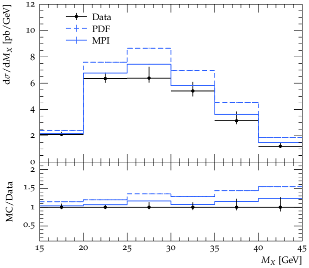


Comparisons to HERA data

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_T^{jets} and $x_{I\!P}$ $\Rightarrow$ More MPIs

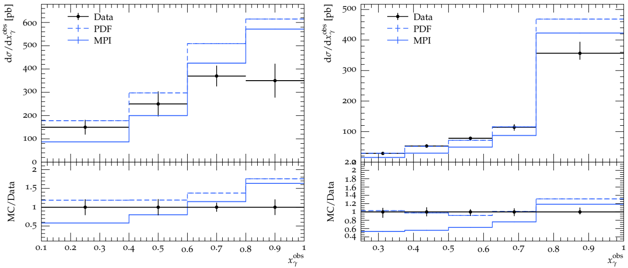
Cuts	H1	ZEUS
Q^2_{max} [GeV^2]	0.01	1.0
$E_{T,\text{min}}^{\text{jet1}}$ [GeV]	5.0	7.5
$E_{T,\text{min}}^{\text{jet2}}$ [GeV]	4.0	6.5
$x_{I\!P}^{\text{max}}$	0.03	0.025

Pythia setup

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

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

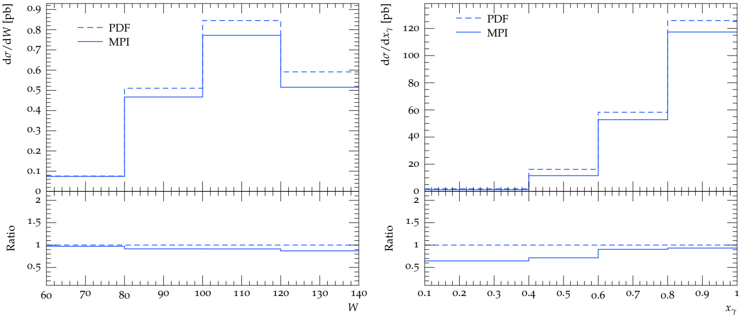
Cuts	H1	ZEUS
Q^2_{max} [GeV^2]	0.01	1.0
$E_{T,min}^{jet1}$ [GeV]	5.0	7.5
$E_{T,min}^{jet2}$ [GeV]	4.0	6.5
x_{IP}^{max}	0.03	0.025

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 ($E_e = 18$ GeV, $E_p = 275$ 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 ($E_T^{jet1} > 5.0$ GeV, $E_T^{jet2} > 4.0$ 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

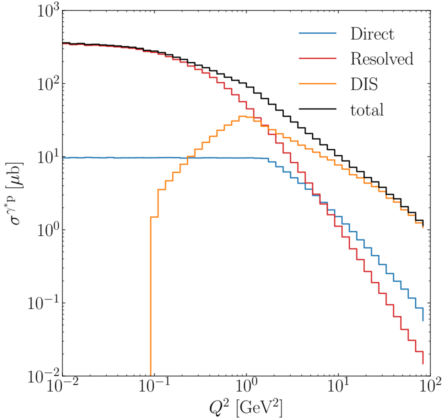
$$\sigma_{\mathrm{tot}}^{\gamma^* \mathrm{p}} = \tilde{\sigma}_{\mathrm{DIS}}^{\gamma^* \mathrm{p}} \exp\left[-\frac{\tilde{\sigma}_{\mathrm{Dir}}^{\gamma^* \mathrm{p}}}{\tilde{\sigma}_{\mathrm{DIS}}^{\gamma^* \mathrm{p}}}\right] + \tilde{\sigma}_{\mathrm{Dir}}^{\gamma^* \mathrm{p}} + \tilde{\sigma}_{\mathrm{Res}}^{\gamma^*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

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

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

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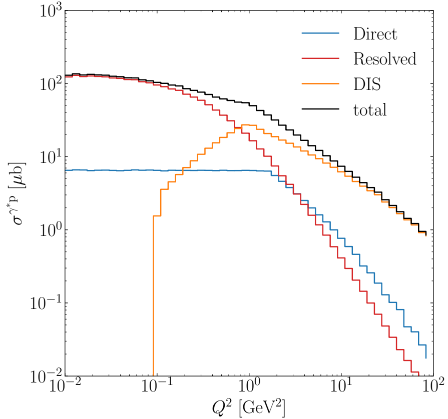
- $\tilde{\sigma}_{\mathrm{Res}}^{\gamma^* \mathrm{p}} = \sigma_{\mathrm{Res}}^{\gamma^* \mathrm{p}} \left[\frac{m_\rho^2}{m_\rho^2+Q^2}\right]^2 \left[\frac{W^2}{W^2+Q^2}\right]^n$
- $\tilde{\sigma}_{\mathrm{Dir}}^{\gamma^* \mathrm{p}} = \sigma_{\mathrm{Dir}}^{\gamma^* \mathrm{p}}(\hat{p}_{\mathrm{T,min}}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

$p_{\mathrm{T,min}} = 1.3$ 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?

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

where

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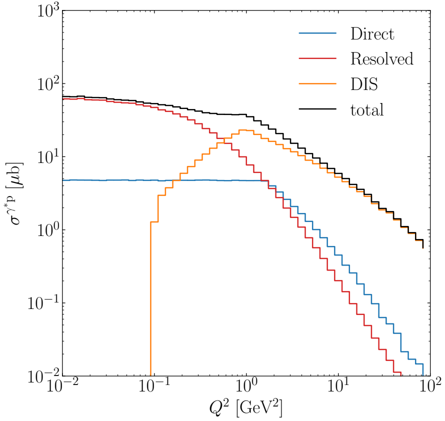
- $\tilde{\sigma}_{\mathrm{Dir}}^{\gamma^* \mathrm{p}} = \sigma_{\mathrm{Dir}}^{\gamma^* \mathrm{p}}(\hat{p}_{\mathrm{T,min}} = max(Q, p_{\mathrm{T,min}}))$

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

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



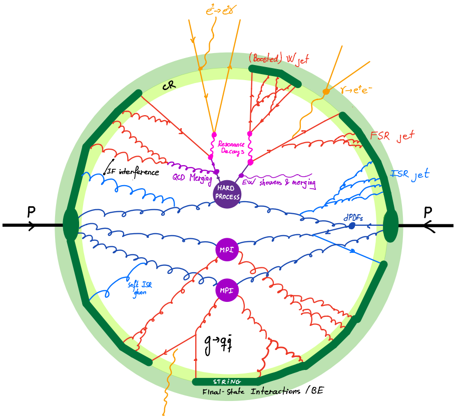
Intermediate: $0.2 \lesssim Q^2 \lesssim 2.0$ GeV^2

Pythia 8.3 capabilities in ep

- DIS (high Q^2) events with `dipoleRecoil` option and DIRE
- Photoproduction ($Q^2 = 0$) including direct and resolved contributions
    - Also hard diffraction with dynamical rapidity gap survival

Outlook

- New data from HERA and UPCs at the LHC provide further constraints
- For a complete setup need also the region between DIS and PhP!

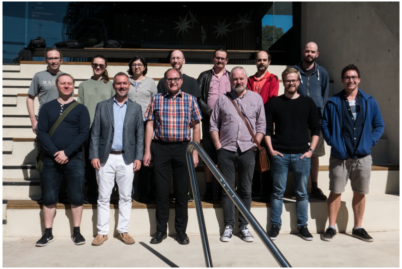


[figure by P. Skands]

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]

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- Christian Bierlich (Lund University)
- Nishita Desai (TIFR, Mumbai)
- Leif Gellersen (Lund University)
- Ilkka Helenius (University of Jyväskylä)
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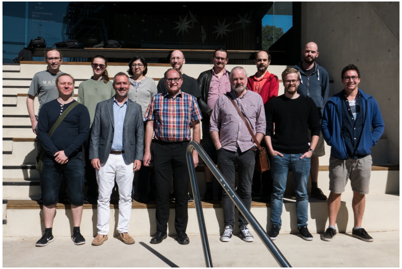


[Pythia meeting in Monash 2019]

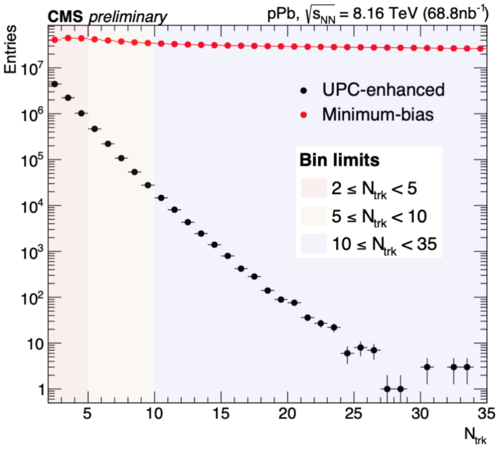
- Spokesperson
- Codemaster
- Webmaster

`https://pythia.org`

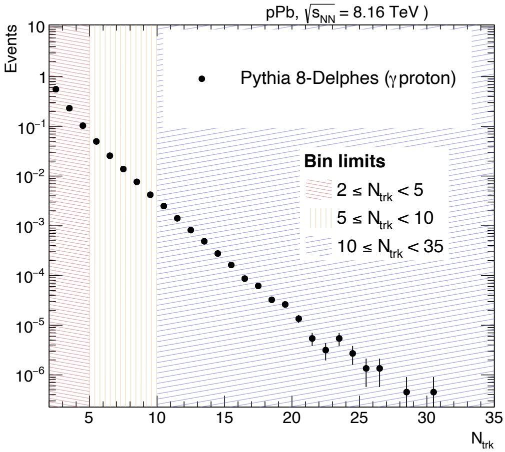
`authors@pythia.org`

CMS data for γp in UPCs at the LHC

CMS Data



Pythia8 + detector fast simulation



[J. A. Murillo Quijada, DIS2021]

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

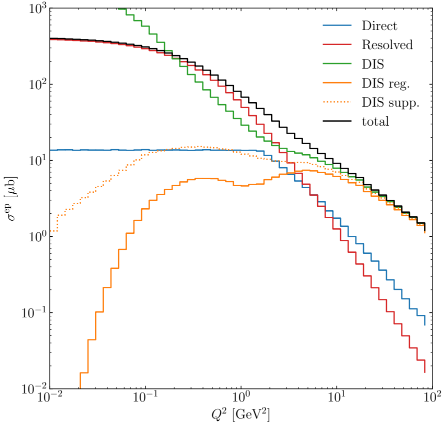
$$\sigma_{\text{tot}}^{\gamma^* \text{p}} = \tilde{\sigma}_{\text{DIS}}^{\gamma^* \text{p}} \exp\left[-\frac{\tilde{\sigma}_{\text{Dir}}^{\gamma^* \text{p}}}{\tilde{\sigma}_{\text{DIS}}^{\gamma^* \text{p}}}\right] + \tilde{\sigma}_{\text{Dir}}^{\gamma^* \text{p}} + \tilde{\sigma}_{\text{Res}}^{\gamma^*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

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:



Unmodified DIS cross section diverges at $Q^2 \to 0$ GeV^2