Pythia 8: DIS and photoproduction

MC4EIC

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November 18th, 2022

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

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CoE in Quark Matter

Outline

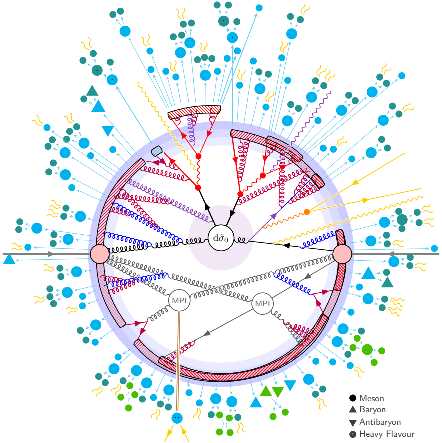
Pythia 8: A general purpose Monte-Carlo event generator

- A new manual for 8.3 release

  SciPost Phys. Codebases 8-r8.3 (2022); arXiv:2203.11601 [hep-ph]

Outline

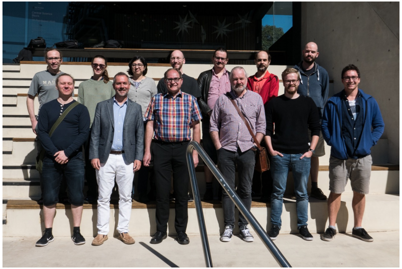
1. Deep inelastics scattering
2. Photoprodcution at HERA
3. Ultraperipheral collisions LHC
4. Photoproduction of diffractive dijets
5. Summary & Outlook



[figure by P. Skands]

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)
- 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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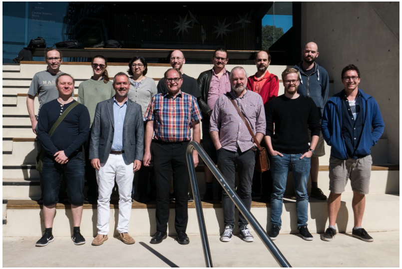


[Pythia meeting in Monash 2019]

- Spokesperson
- Codemaster
- Webmaster

`https://pythia.org`

`authors@pythia.org`

Electron-proton collisions

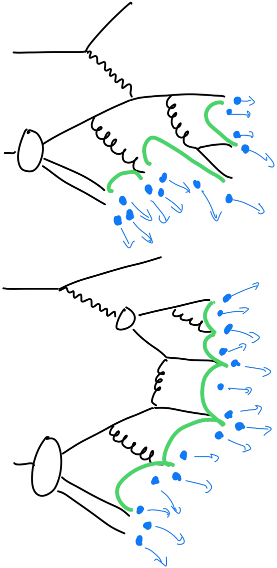
Classified in terms photon virtuality Q^2

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, $Q^2 \rightarrow 0$ GeV^2
  $\Rightarrow$ Direct and resolved contributions
- Factorize γ flux, evolve γp system
- Hard scale provided by the final state
- Also soft QCD processes, diffraction



Event generation in DIS with PYTHIA 8

Hard scattering

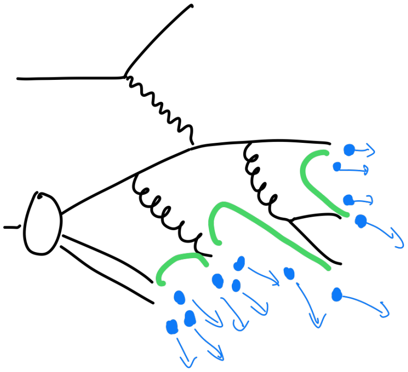
- Convolution between PDFs and matrix element (ME) for partonic scattering

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

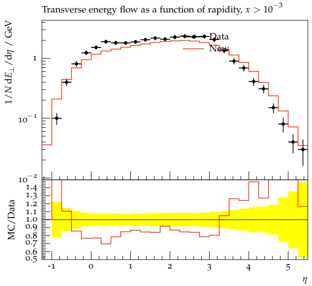


DIS with Pythia

Alternative shower model `dipoleRecoil`

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

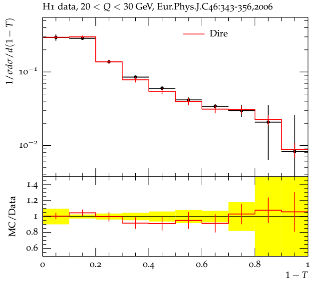
- No PS recoil for the scattered lepton
- Reasonable description of single-particle properties, such as transverse energy flow
- Results based on tune with the default global-recoil shower



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



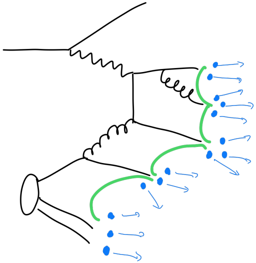
Event generation in photoproduction

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

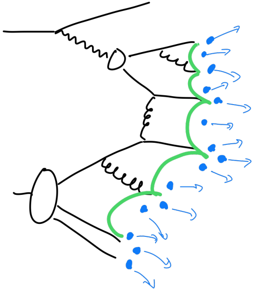


Resolved processes

- 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)



Evolution equation and PDFs for resolved photons

DGLAP equation for photons

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

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

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

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

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

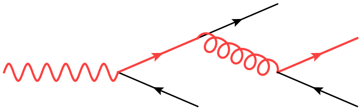
  - $f_i^{\gamma,\mathrm{pl}}$: Calculable from perturbative QCD
  - $f_i^{\gamma,\mathrm{had}}$: Requires non-perturbative input fixed in a global analysis

ISR probability based on DGLAP evolution

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

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

- Corresponds to 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



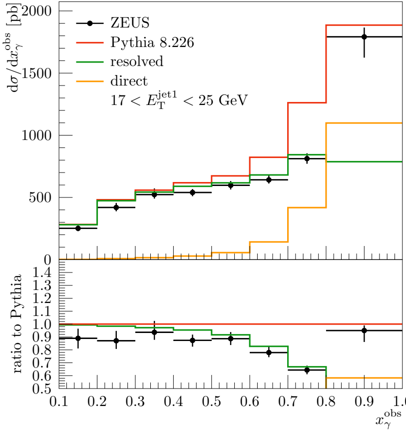
Comparison to HERA dijet photoproduction data

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]

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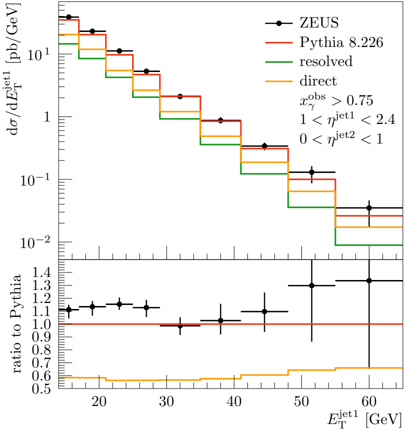

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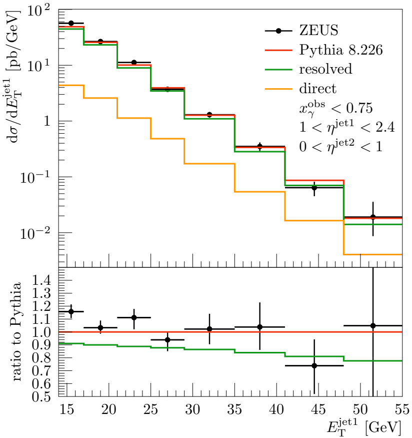


[ZEUS: Eur.Phys.J. C23 (2002) 615-631]

Comparison to recent ZEUS data for charged hadrons

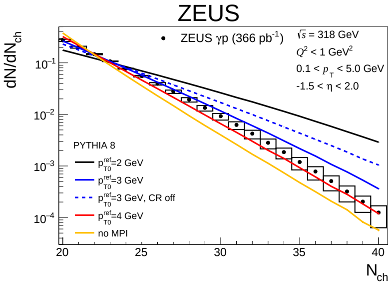
Multiplicity distributions

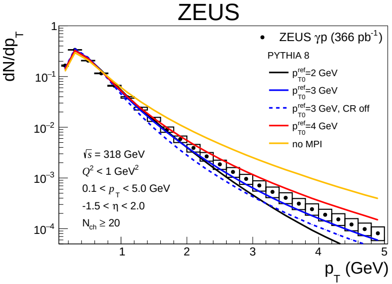
- Multiplicity distributions sensitive to MPIs with resolved photons
- ZEUS data support for MPIs but with slightly larger p_{T0}^{ref} than in pp $\Rightarrow$ less MPIs

p_T spectra for $N_{ch} > 20$

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

[Rivet Analysis in preparation]





Equivalent photon approximation

Implemented photon fluxes

- In case of a point-like lepton we have

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

- For protons need to account the form factor

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

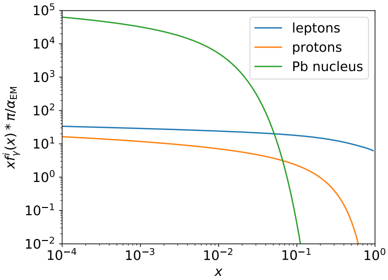
where $Q_0^2 = 0.71$ GeV^2 (Drees-Zeppenfeld) ⇒ Large Q^2 heavily suppressed

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

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

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

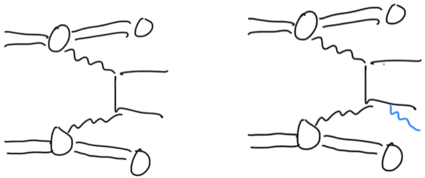
⇒ Can apply photoproduction framework with all these beams!

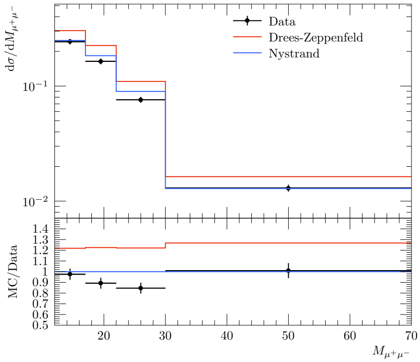


$\gamma\gamma \to \mu^+\mu^-$ in proton-proton collisions

Elastic-elastic contribution

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





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

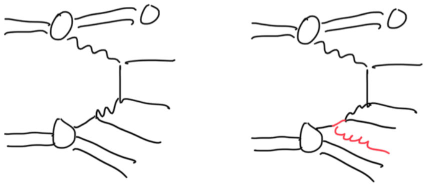
Clean process to calibrate flux

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

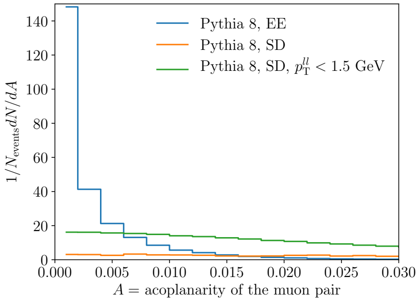
$\gamma\gamma \to \mu^+\mu^-$ in proton-proton collisions

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



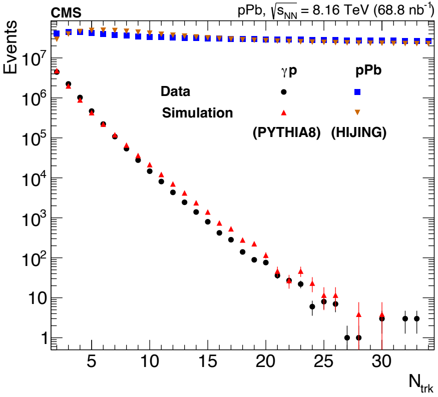
Double dissociative

- Both photons from PDFs with primordial-k_T and ISR

$\Rightarrow$ Large acoplanarity

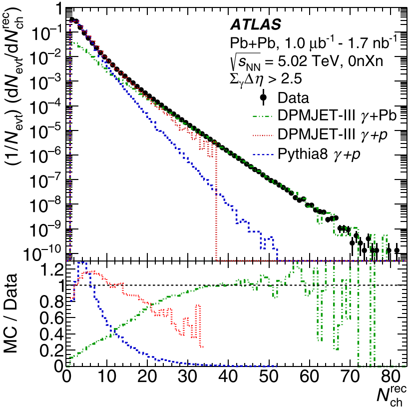
Ultra-peripheral heavy-ion collisions

$(\mathrm{Pb} \to \gamma)+p$: [CMS: Murillo Quijada, QM2022]



- Multiplicities well reproduced with γp

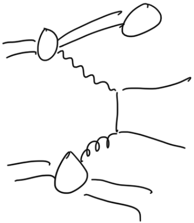
$(\mathrm{Pb} \to \gamma)+\mathrm{Pb}$: [ATLAS: PRC 104, 014903 (2021)]

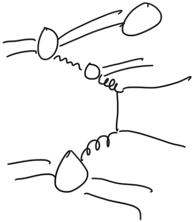


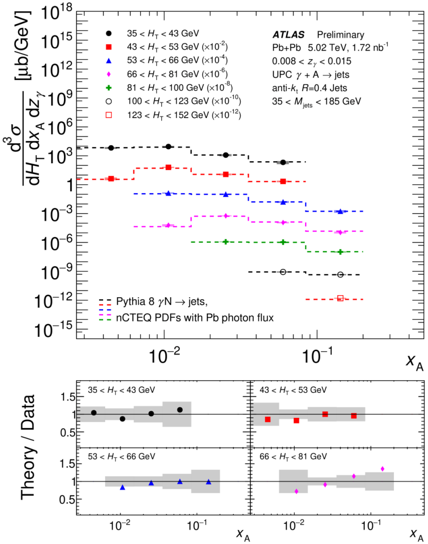
- High multiplicities missed with γp
  $\Rightarrow$ Multi-nucleon interactions

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



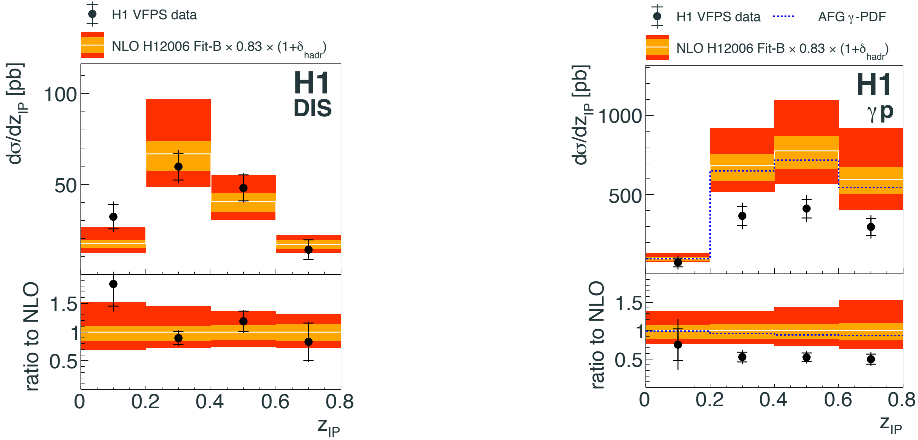




[ATLAS: Gilbert DIS2022]

Diffractive dijets at HERA

[H1: JHEP 1505 (2015) 056]



- H1 data and factorization-based NLO calculation in DIS (high Q^2) in agreement
- NLO calculation overshoot the data in photoproduction (low Q^2)

$\Rightarrow$ Factorization broken in hard diffraction at low Q^2 similarly as in pp

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

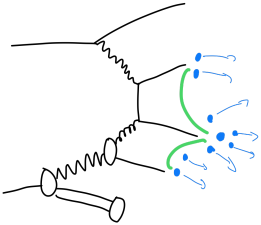
- Direct: Pomeron flux and diffractive PDFs (dPDFs)

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

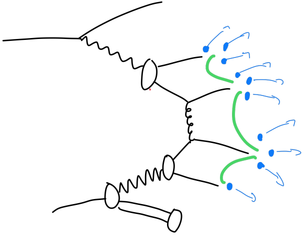
- Resolved: photon PDFs

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

Direct:



Resolved:



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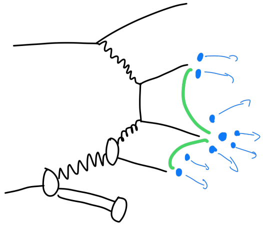
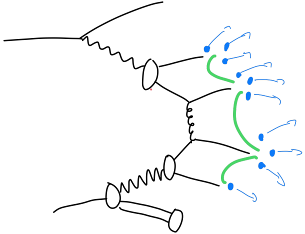
Dynamical rapidity gap survival model

1. Generate diffractive events with dPDFs (PDF)

Direct:



Resolved:



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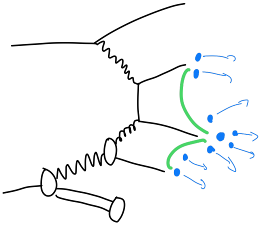
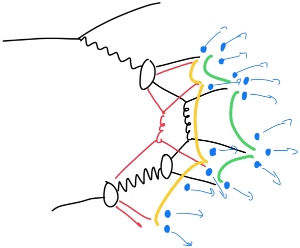
Dynamical rapidity gap survival model

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

Direct:



Resolved:



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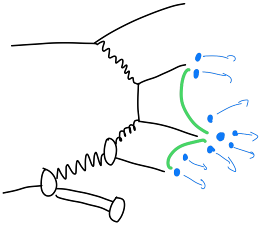
Dynamical rapidity gap survival model

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

Direct:



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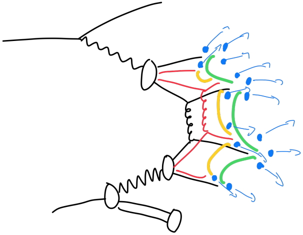

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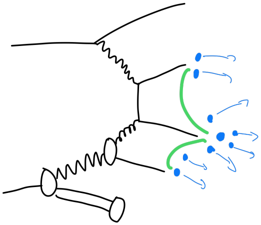
Implemented from PYTHIA 8.235 onwards

[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:



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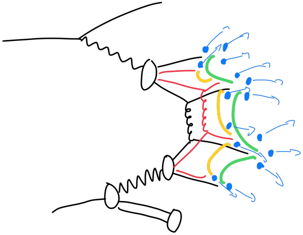
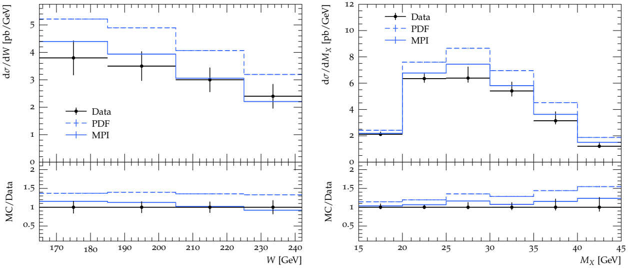


Comparisons to HERA data

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 $x_{\mathbb{P}} \Rightarrow$ More MPIs

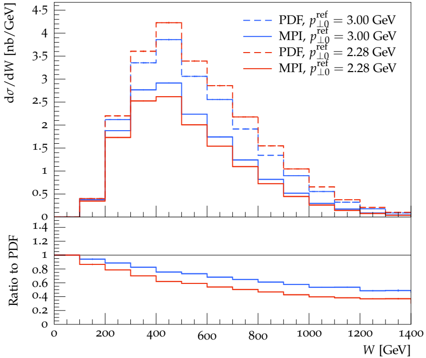
Cuts	H1	ZEUS
Q^2_{max} [GeV^2]	0.01	1.0
$E^{\text{jet1}}_{\text{T,min}}$ [GeV]	5.0	7.5
$E^{\text{jet2}}_{\text{T,min}}$ [GeV]	4.0	6.5
$x^{\text{max}}_{\mathbb{P}}$	0.03	0.025

Pythia setup

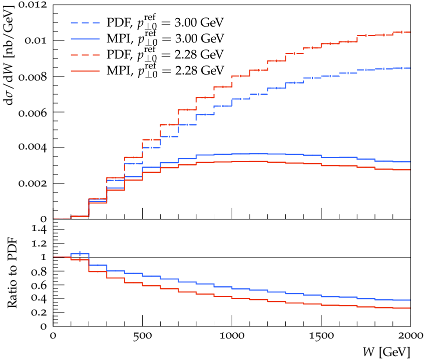
- dPDFs from H1 fit B LO
- γPDFs from CJKL
- $p_{\text{T0}}^{\text{ref}} = 3.00$ GeV/c (Tuned to inclusive charged particle data from γp at HERA)

Predictions for diffractive dijets in UPC

pPb $\sqrt{s} = 5.0$ TeV



pp $\sqrt{s} = 13$ TeV

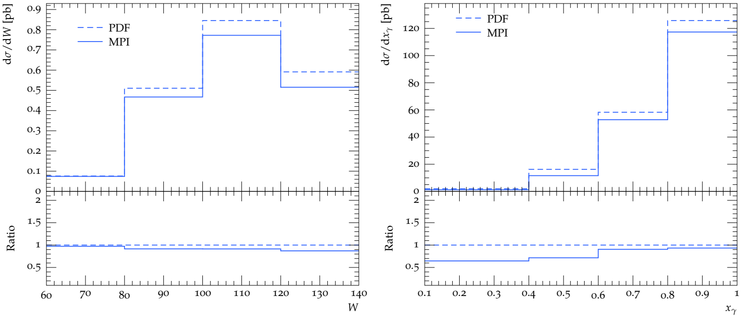


- Extended W range wrt. HERA, especially in pp (harder flux)
- Stronger suppression from MPIs than at HERA

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

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 ($E_T^{\text{jet1}} > 5.0$ GeV, $E_T^{\text{jet2}} > 4.0$ GeV)

Summary & Outlook

PYTHIA 8.3

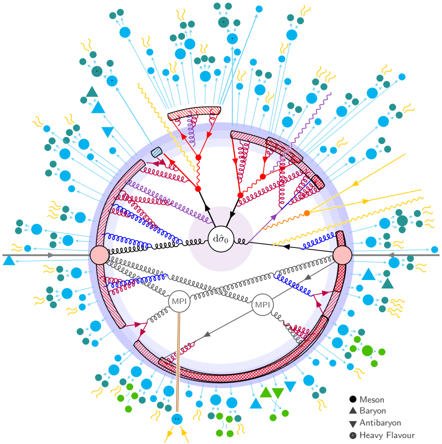
- DIS with two parton showers
- Framework for photoproduction

⇒ Can be applied also to ultra-peripheral collisions

  - Photon fluxes in place for protons and heavy nuclei

Future

- Subsequent resolved-photon nucleon interactions for γ+A (Angantyr model)
- Consider intermediate Q^2 region

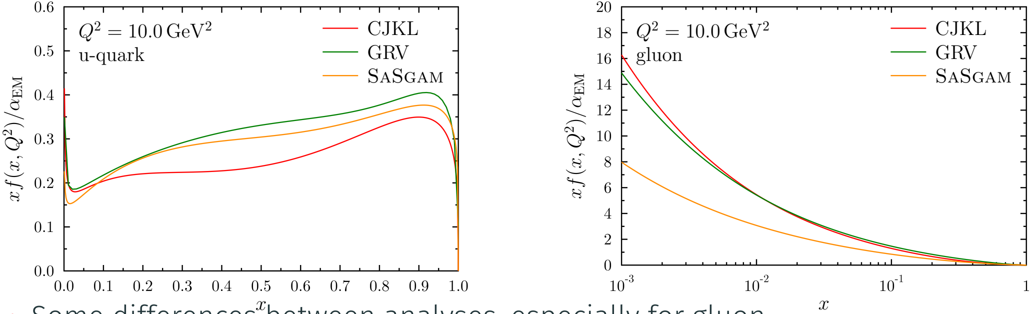


[figure by P. Skands]

Backup slides

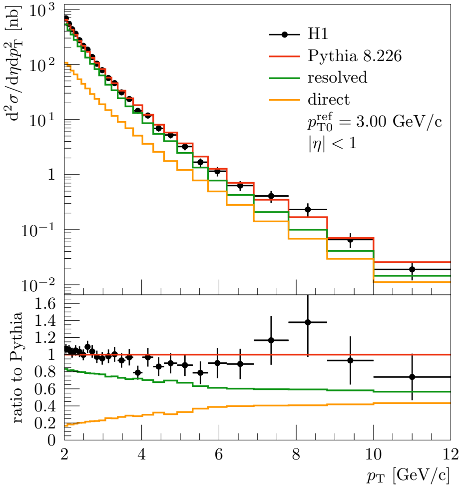
PDFs for resolved photons

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

Charged particle p_T spectra in ep collisions at HERA



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

H1 measurement

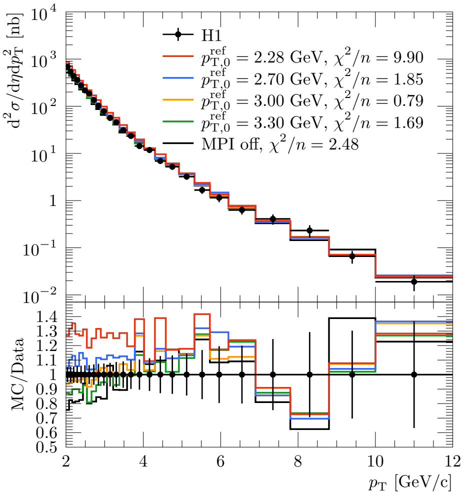
- $E_p = 820$ GeV, $E_e = 27.5$ GeV
- $< W_{\gamma p} > \approx 200$ GeV
- $Q^2_\gamma < 0.01$ GeV^2

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 $\gamma\gamma$

Charged particle p_T spectra in ep collisions at HERA



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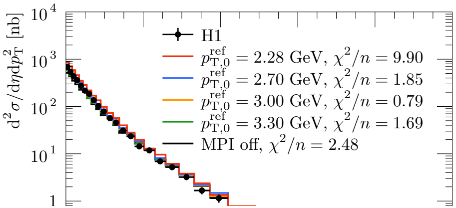
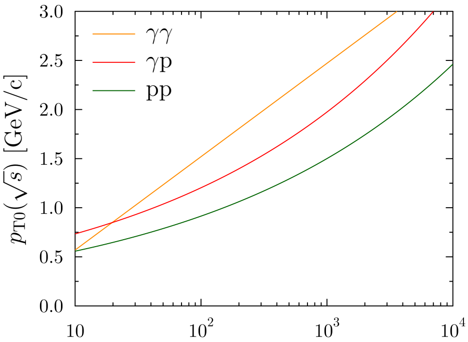




H1 measurement

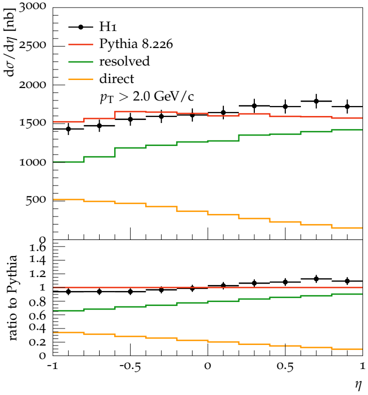
- $E_p = 820$ GeV, $E_e = 27.5$ GeV
- $< W_{\gamma p} > \approx 200$ GeV
- $Q^2_\gamma < 0.01$ GeV^2

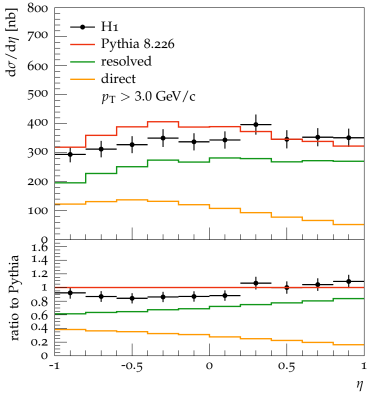
Comparison to Pythia 8

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

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

Charged-particle η dependence



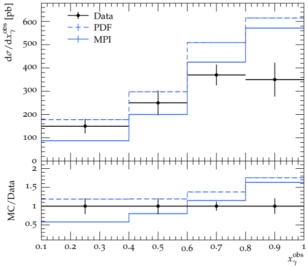


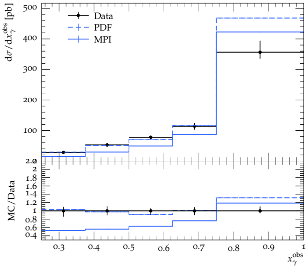
[H1: Eur.Phys.J. C10 (1999) 363-372]

- Good agreement also for charged-particle η dependence
- Resolved contribution dominates the cross section

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)

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

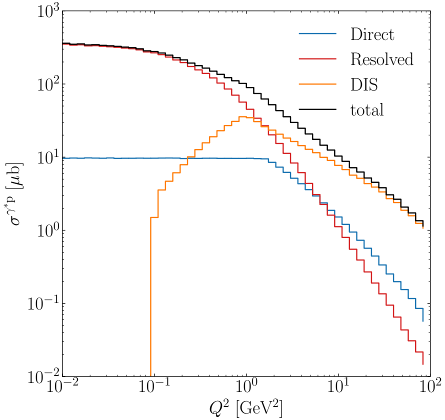
$$\sigma_{\text{tot}}^{\gamma^* \text{p}} = \tilde{\sigma}_{\text{DIS}}^{\gamma^* \text{p}} \exp\left[-\frac{\tilde{\sigma}_{\text{Dir}}^{\gamma^* \text{p}}}{\tilde{\sigma}_{\text{DIS}}^{\gamma^* \text{p}}}\right] + \tilde{\sigma}_{\text{Dir}}^{\gamma^* \text{p}} + \tilde{\sigma}_{\text{Res}}^{\gamma^*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

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

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

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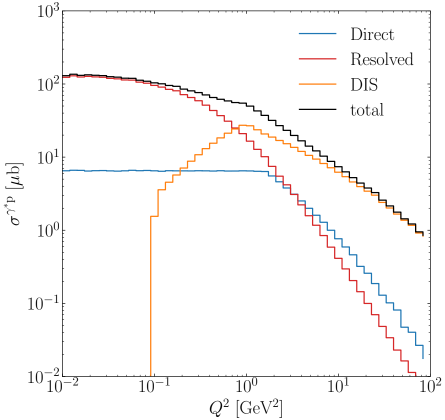
- $\tilde{\sigma}_{\text{Res}}^{\gamma^* \text{p}} = \sigma_{\text{Res}}^{\gamma^* \text{p}} \left[\frac{m_\rho^2}{m_\rho^2 + Q^2}\right]^2 \left[\frac{W^2}{W^2 + Q^2}\right]^n$
- $\tilde{\sigma}_{\text{Dir}}^{\gamma^* \text{p}} = \sigma_{\text{Dir}}^{\gamma^* \text{p}}(\hat{p}_{\text{T,min}} = max(Q,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

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

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

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

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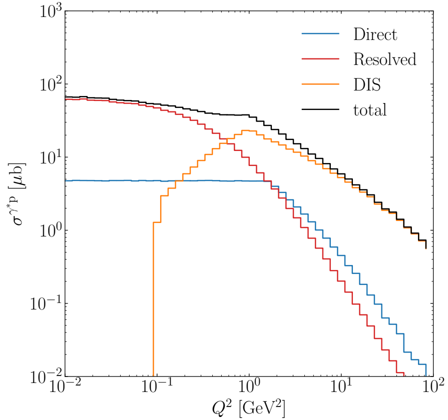
- $\tilde{\sigma}_{\text{Dir}}^{\gamma^* \text{p}} = \sigma_{\text{Dir}}^{\gamma^* \text{p}}(\hat{p}_{\text{T,min}} = max(Q, p_{\text{T,min}}))$

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

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



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