Hard and soft photoproduction with Pythia 8

Pythia Down Under 2019

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Outline

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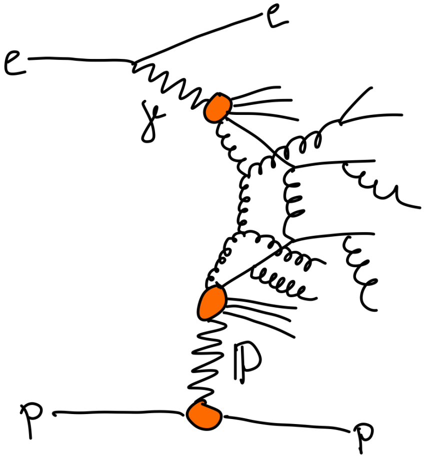
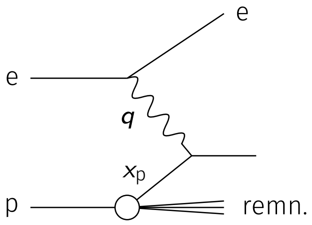
1. Photoproduction framework
   with Torbjörn
2. Hard diffraction in photoproduction
   with Christine and Torbjörn
3. Ultra-peripheral collisions at the LHC
4. Soft QCD in photoproduction
   with Christine and Torbjörn
5. Summary & Outlook



Event classification in ep

Virtuality of photon related to scattering angle of the lepton

$$Q^2_\gamma \approx 2E^2_l(1-x)(1-\cos\theta)$$



Deep inelastic scattering (DIS)

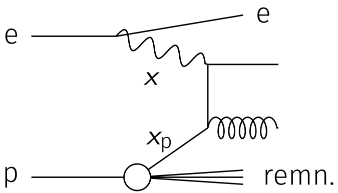
- High virtuality, $Q^2_\gamma >$ a few GeV^2
- Hard scattering between the lepton and a parton

Photoproduction

- Low virtuality, $Q^2_\gamma \lesssim 1$ GeV^2
- Factorize γ flux, evolve γp system

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

- Hard scattering between the photon and a parton
- Also soft QCD processes



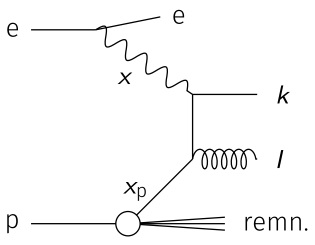
Hard processes in photoproduction

Direct processes

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

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

- Generate FSR and ISR for proton side

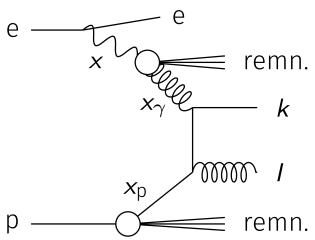


Resolved processes

- Convolute also with photon PDFs

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

- Sample x and Q^2, setup γp sub-system with $W_{\gamma\mathrm{p}}$
- Evolve γp 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

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

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

- 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

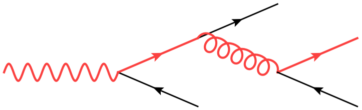
- Add a term corresponding to $\gamma \to q\bar{q}$ to (conditional) ISR probability

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

- 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



MPIs with resolved photons

MPI probability from regularized $d\sigma$

$$\frac{d\sigma^{2\to2}}{dp_T^2} \propto \frac{\alpha_s(p_T^2)}{p_T^4} \to \frac{\alpha_s(p_{T0}^2 + p_T^2)}{(p_{T0}^2 + p_T^2)^2}$$

- Monash tune (for pp):

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

with $p_{T0}^{ref} = 2.28$ GeV, $\alpha = 0.215$, $\sqrt{s_{ref}} = 7.0$ TeV

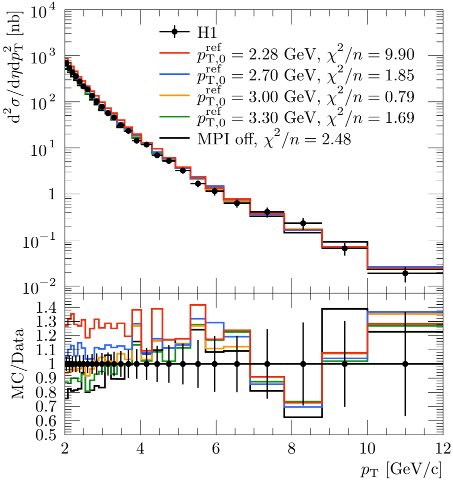
- Retune for γp (and $\gamma\gamma$) $\quad (p_{T0} \sim 1/d)$

Inclusive charged-particle production by H1

- $< W_{\gamma p} > \approx 200$ GeV, $Q_\gamma^2 < 0.01$ GeV^2
- Same $W_{\gamma p}$-depedence as in pp, vary p_{T0}^{ref}
- Best agreement with $p_{T0}^{ref} = 3.00$ GeV

$\Rightarrow$ Less MPIs than with protons

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



Comparion to HERA photoproduction data (main69.cc)

ZEUS dijet measurement

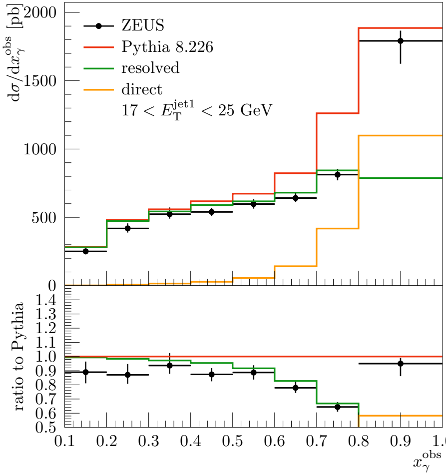
- $Q^2_\gamma < 1.0$ GeV^2
- $134 < W_{\gamma p} < 277$ GeV
- $E_T^{\text{jet1}} > 14$ GeV, $E_T^{\text{jet2}} > 11$ GeV
- $-1 < \eta^{\text{jet1,2}} < 2.4$

Two contributions

- Momentum fraction of partons in photon

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

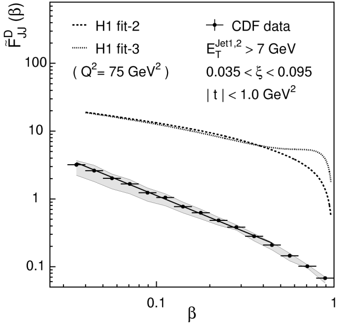
- Sensitivity to process type
- At high-x_γ^{obs} direct processes dominate



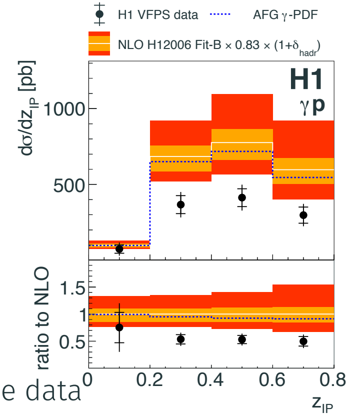
[ZEUS: Eur.Phys.J. C23 (2002) 615-631]

Hard diffraction: dijets

pp: [CDF: PRL 84 (2000) 5043-5048]



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



- Factorization-based calculations overshoot the data
  - By a factor of two in photoproduction
  - By order-of-magnitude in pp

Hard diffraction in PYTHIA 8 (main68.cc)

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

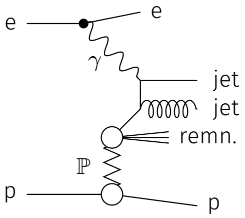
- Direct: Pomeron flux and diffractive PDFs

$$d\sigma^{\text{2jets}}_{\text{direct}} = f^{e}_{\gamma}(x) \otimes d\sigma^{\gamma j \to \text{2jets}} \otimes f^{\mathbb{P}}_{j}(z_{\mathbb{P}}, Q^2) \otimes f^{p}_{\mathbb{P}}(x_{\mathbb{P}}, t)$$

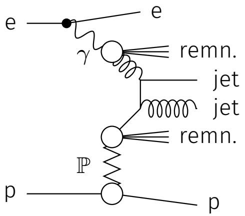
- Resolved: photon PDFs

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

Direct:



Resolved:



Hard diffraction in PYTHIA 8 (`main68.cc`)

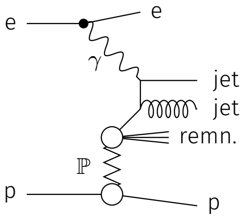
Hard diffraction in photoproduction

- Process with a hard scale, desribed with a colour-neutral Pomeron ($\mathbb{P}$) exchange
- Experimentally identified from rapidity gap

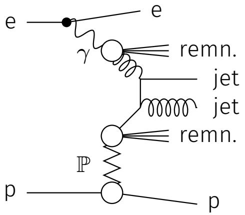
Dynamical rapidity gap survival model

1. Generate diffractive events with dPDFs (PDF)

Direct:



Resolved:



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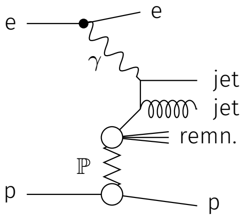
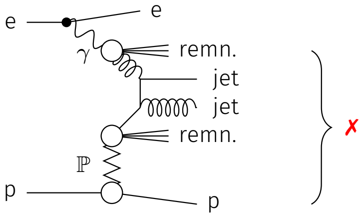
Dynamical rapidity gap survival model

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

Direct:



Resolved:



Hard diffraction in Pythia 8 `(main68.cc)`

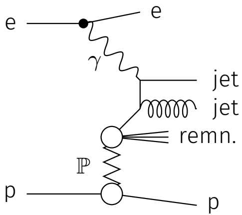
Hard diffraction in photoproduction

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

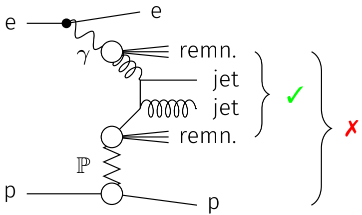
Dynamical rapidity gap survival model

1. Generate diffractive events with dPDFs (PDF)
2. Reject events where MPIs in γp system (MPI)
3. Evolve $\gamma\mathbb{IP}$ system, allow MPIs for this system

Direct:



Resolved:



Hard diffraction in PYTHIA 8 (main68.cc)

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Dynamical rapidity gap survival model

1. Generate diffractive events with dPDFs (PDF)
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3. Evolve γIP system, allow MPIs for this system

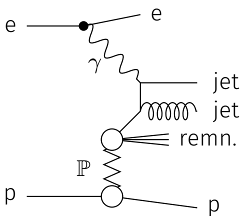
Implemented from PYTHIA 8.235 onwards

[I.H. and C.O. Rasmussen, arXiv:1901.05261 [hep-ph]]

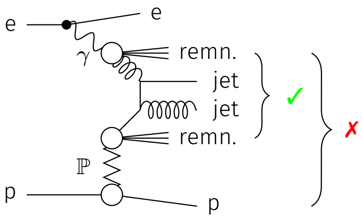
Model originally introduced for pp collisions

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

Direct:

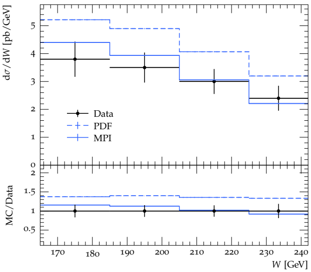


Resolved:

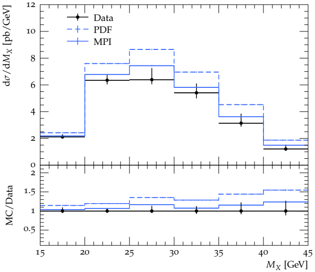


Comparisons to HERA data

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_{IP} $\Rightarrow$More MPIs

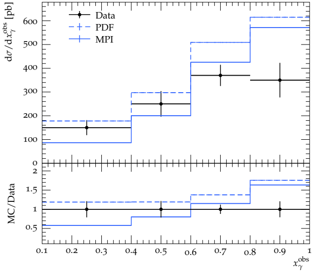
Cuts	H1	ZEUS
Q^2_{max} [GeV^2]	0.01	1.0
$E^{jet1}_{T,min}$ [GeV]	5.0	7.5
$E^{jet2}_{T,min}$ [GeV]	4.0	6.5
x^{min}_{IP}	0.03	0.025

Pythia setup

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

Comparisons to HERA data

H1: [EPJC 51 (2007) 549]



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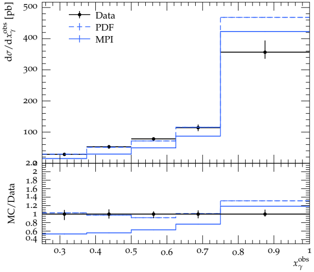


- Stronger suppression at low-x_γ^{obs} (more MPIs)
- ZEUS cuts select events at high-x_γ^{obs} region
- Some theoretical uncertainty from γPDFs, dPDFs and scale variation

Cuts	H1	ZEUS
Q^2_{max} [GeV^2]	0.01	1.0
$E^{jet1}_{T,min}$ [GeV]	5.0	7.5
$E^{jet2}_{T,min}$ [GeV]	4.0	6.5
x^{min}_{IP}	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 observables)

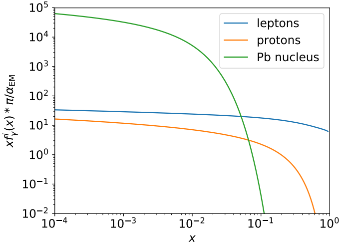
Photon flux from protons

- Take the proton form factor into account

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

where $A = 1 + Q_0^2/Q_{\mathrm{min}}^2$ and $Q_0^2 = 0.71\ \mathrm{GeV}^2$

- The form factor suppress contribution from high-Q^2 $\Rightarrow$ photoproduction regime

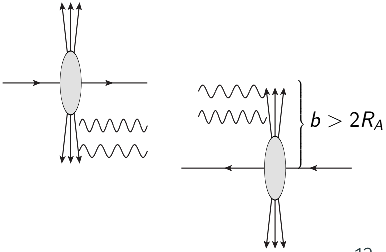


UPCs with heavy ions

- Define photon flux in impact-parameter space to reject events where colliding nuclei overlap

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

where Z charge, $\xi = b_{\mathrm{min}}xm$



Diffractive dijets in UPCs

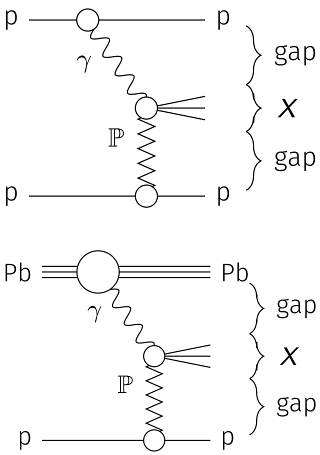
- Apply the dynamical rapidity gap survival model to UPCs in pp and pPb
- In pPb the photon flux from Pb dominates ($\propto Z^2$), p neglected

Kinematics similar to HERA

- $E_T^{\text{jet1(2)}} > 8(6)$ GeV, $|\eta^{\text{jet1,2}}| < 4.4$
- $M_{\text{jets}} > 14$ GeV, $x_{\mathbb{P}} < 0.025$

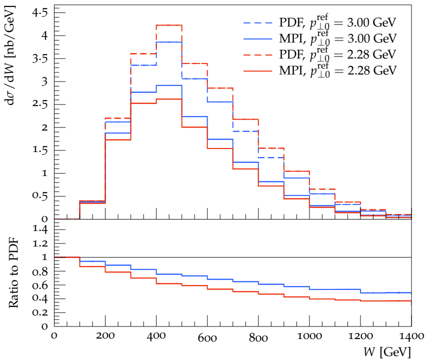
PYTHIA setup

- Same PDFs as for HERA
- Vary MPI parameter:
  $p_{T0}^{\text{ref}} = 3.00$ GeV (HERA γp)
  $p_{T0}^{\text{ref}} = 2.28$ GeV (LHC pp)

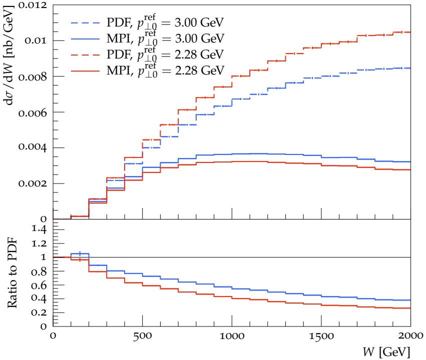


Predictions for diffractive dijets in UPC

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

Soft photoproduction (main04.cc with main04_photons.cmnd)

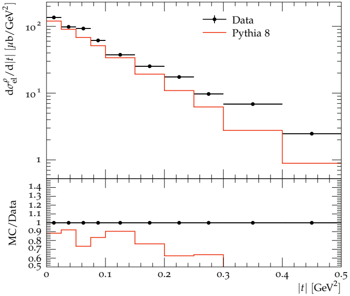
Soft QCD process implemented for photoproduction

- Based on Schuler and Sjöstrand model in PYTHIA 6
- Vector meson dominance (VMD) with ρ, ω, ϕ and J/Ψ mesons for
  - Soft diffraction (high- and low-mass)
  - Elastic scattering
- Non-diffractive from MPI machinery
- Total Cross section parametrized as

$$\sigma_{\text{tot}}^{AB}(s) = X^{AB}\, s^{\epsilon} + Y^{AB}\, s^{-\eta}$$

where $\epsilon = 0.0808$ and $\eta = 0.4525$ are universal, X^{AB} and Y^{AB} process-dependent

Elastic ρ production at $\langle W_{\gamma p}\rangle = 70$ GeV



[Data from ZEUS: Z.Phys. C69 (1995) 39-54]

Exclusive J/Ψ photoproduction [ZEUS: Z.Phys. C75 (1997) 215–228]

Produced via elastic scattering

- Parametrized with

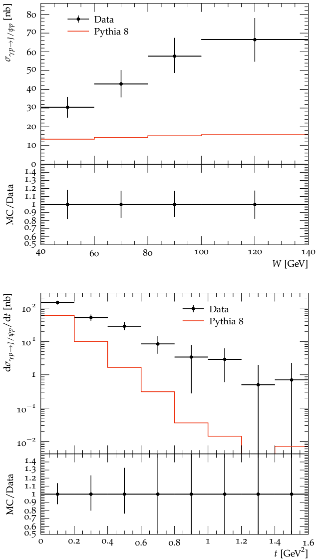
$$\frac{d\sigma_{el}}{dt} = (1+\rho^2)\frac{\sigma_{tot}^2(s)}{16\pi}\exp(B_{el}(s)t)$$

where $B_{el}(s) = 2b_A + 2b_B + 4s^{\epsilon} - 4.2$

- $b_{A,B}$ process-dependent

Comparison to HERA data

- Energy (W) dependence too flat
- Too steep $|t|$-depedence (also for ϕ)
- New parametrizations for σ_{tot} and σ_{el} based on HERA data?
- Can be measured in UPCs at the LHC



Summary & Conclusions

Current status of photoproduction

- Include both hard and soft processes
- Internal setup for ep (and ee), can be applied to UPCs with appropriate flux

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Pythia::setPhotonFluxPtr(PDF*, PDF*)
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- Now also hard diffraction with dynamical rapidity gap survival

$\Rightarrow$ Can describe observed factorization-breaking effects in ep and pp

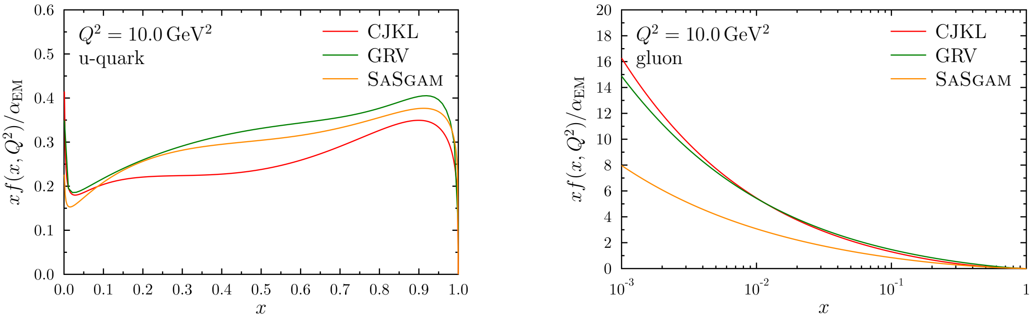
Future directions

- Improved description for soft processes
- Combine with ANGANTYR for *eA* and UPCs in *AA*
- Smooth merging with DIS (currently handled separately)

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

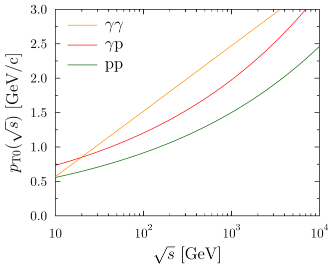
MPIs with resolved photons

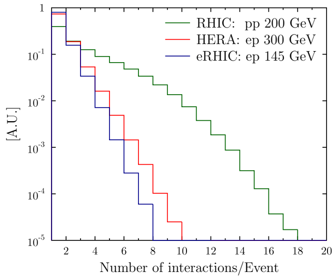
Parametrization for γp

- 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

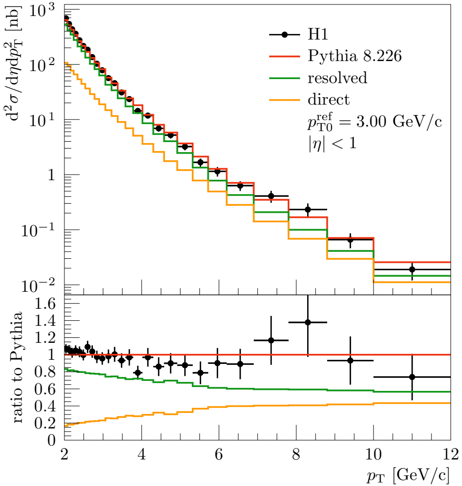
Number of MPIs in different colliders

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





Charged particle p_T spectra in ep collisions at HERA



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

H1 measurement

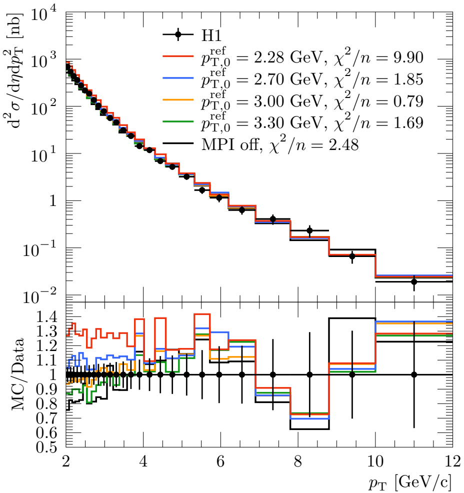
- $E_p = 820$ GeV, $E_e = 27.5$ GeV
- $< W_{\gamma p} > \approx 200$ GeV
- $Q^2_\gamma < 0.01$ GeV^2

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



[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
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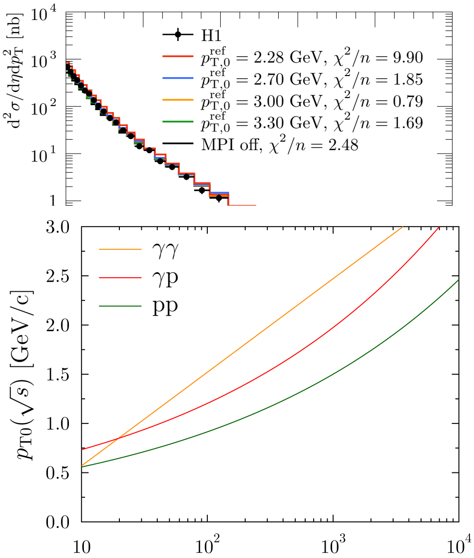

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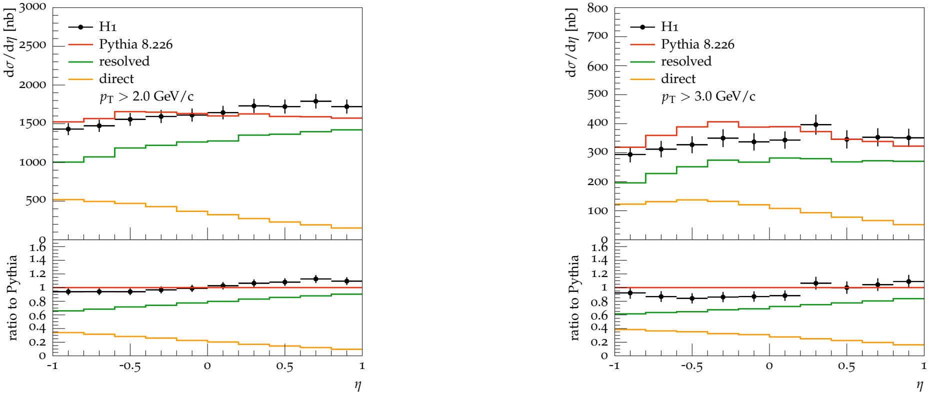
Charged-particle η dependence

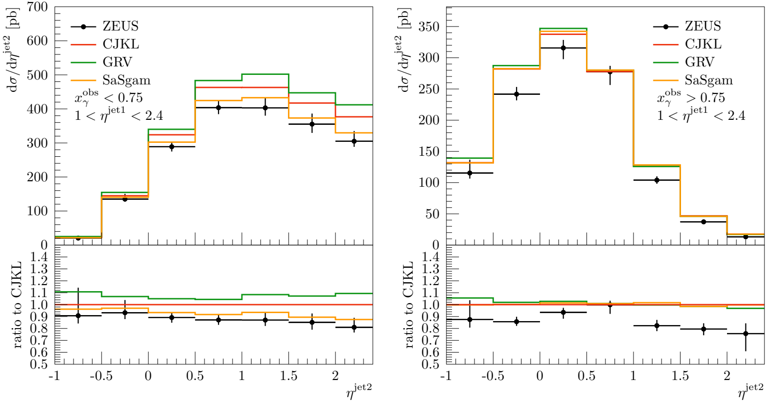


[H1: Eur.Phys.J. C10 (1999) 363-372]

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

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 $x_\gamma^{obs} < 0.75$

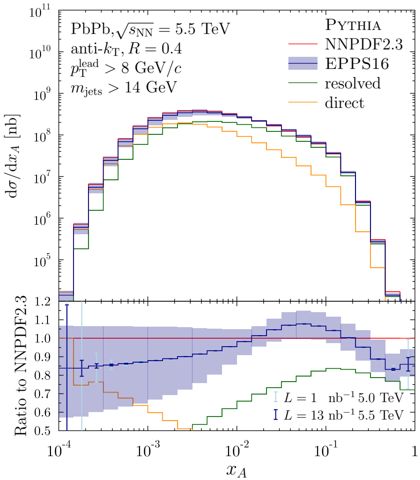
Predictions for dijets in UPCs

Event selection similar to HERA

- anti-k_T with $R = 0.4$
- $p_T^{\text{lead}} > 8$ GeV, $p_T^{\text{jets}} > 6$ GeV
- $|\eta^{\text{jets}}| < 4.4$, $m_{\text{jets}} > 14$ GeV
- Event-level variables:
  - $H_T = \Sigma_i p_{Ti}$, $x_A = \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}}$

Results from PYTHIA 8

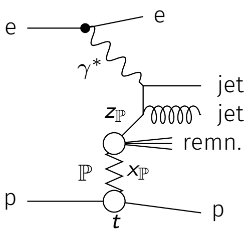
- Resolved dominant at high-x_A, direct at low-x_A
- Sensitive to nuclear PDFs
- Statistical uncertainty estimated at different luminosities



[I.H., arXiv:1811.10931]

[also Guzey, Klasen, arXiv:1902.05126]

Hard diffraction in DIS



Diffractive dijets

- Virtual photon interacts with Pomeron from proton producing jets
- Signature: scattered proton or a rapidity gap between proton and Pomeron remnant

Factorized cross section for diffractive dijets

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

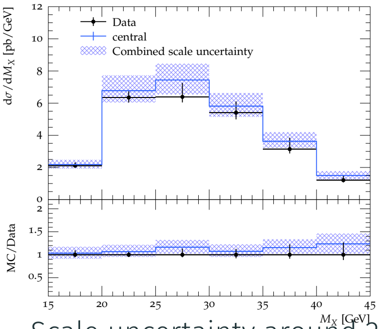
  where f_{IP}^{p} is Pomeron flux and f_i^{IP} diffractive PDF (dPDF)
- Factorization verifed by H1 and ZEUS at HERA

Theoretical uncertainties

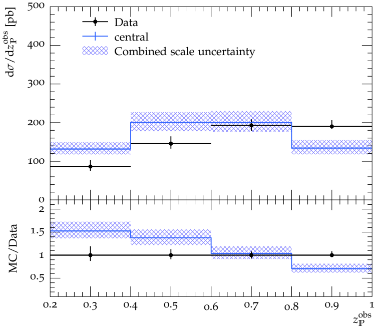
Largest uncertainties arise from

- LO ME (vary factorization and renormalization scales)
- diffractive PDFs (H1fitB, ZEUS-SJ and GKG18A)

ZEUS 2008:



ZEUS 2008:



- Scale uncertainty around 20 %

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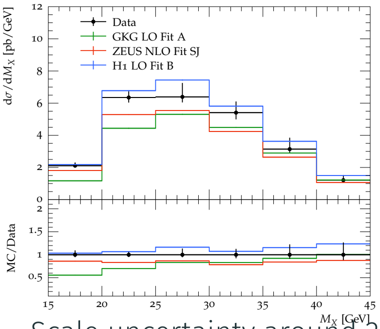

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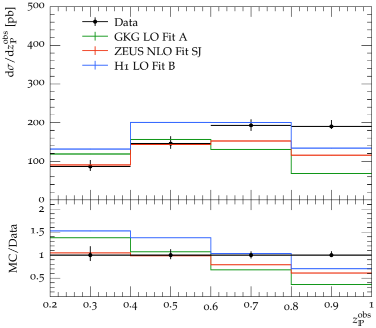
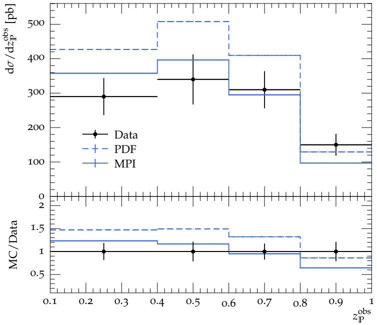


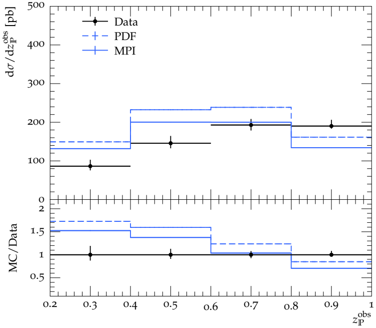
- Scale uncertainty around 20 %
- Better agreement for the shape of $z_{\mathrm{IP}}^{\mathrm{obs}}$ with ZEUS-SJ

z_{IP}^{obs} distributions

H1 2007:



ZEUS 2008:



- MPI suppression not dependent on z_{IP}^{obs}
- Better agreement with H1 data after MPI rejection
- Shape a bit off in both cases, observable sensitive to
  - dPDFs, Jet reconstruction