# Photoproduction of diffractive dijets in PYTHIA 8

DIS 2021

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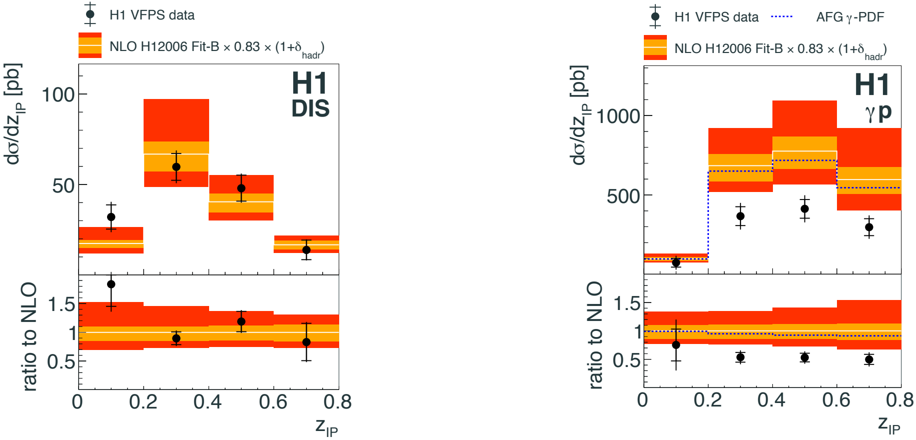
# Motivation: Diffractive dijets at HERA

[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

# Outline

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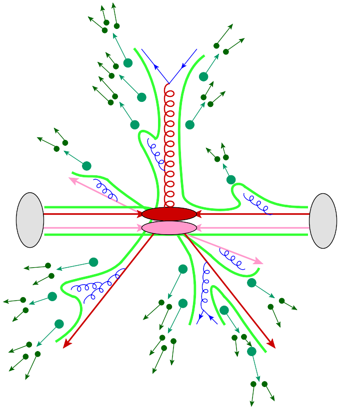
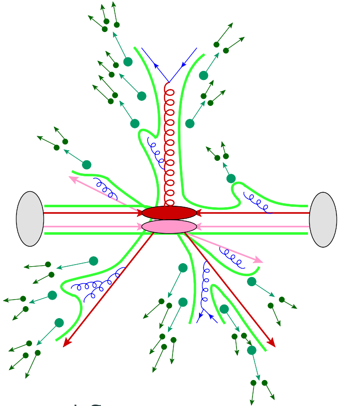
1. Event generation in PYTHIA 8
2. Photoproduction, direct and resolved processes
3. Dynamical rapidity gap survival model for hard diffraction
4. Comparison to HERA data
5. Predictions for EIC and UPCs at the LHC
6. Summary & Outlook



[Figure: S. Prestel]

# PYTHIA 8: A general-purpose Monte Carlo event generator

1. Hard scattering
   - Convolution of LO partonic cross sections and PDFs
2. Parton showers
   - Generate Initial and Final State Radiation (ISR & FSR)
3. Multiparton interactions (MPIs)
   - Use regularized QCD $2 \rightarrow 2$ cross sections
4. Beam remnants
   - Minimal number of partons to conserve colour and flavour
5. Hadronization
   - Lund string model with color reconnection



[Figure: S. Prestel]

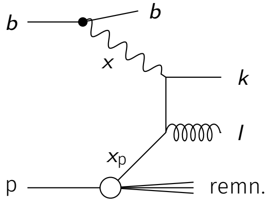
# Event generation in photoproduction

## Direct processes

- Photon initiator of the hard process (DIS-like)
- Convolute photon flux $f_\gamma$ with proton PDFs $f_i^{\mathrm{p}}$ 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

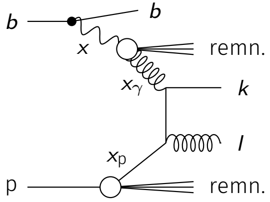



## Resolved processes

- 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 $\gamma$p sub-system with $W_{\gamma\mathrm{p}}$
- Evolve $\gamma$p as any hadronic collision (including MPIs)



# Comparion to HERA photoproduction data

## ZEUS dijet measurement

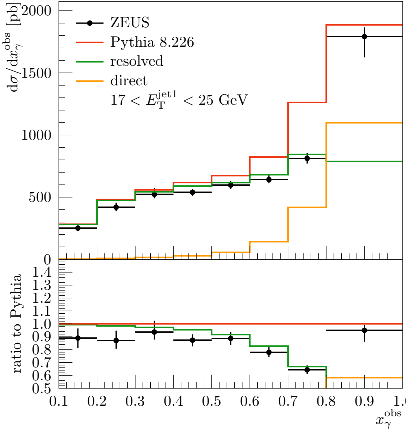
- $Q^2 < 1.0\ \mathrm{GeV}^2$
- $134 < W_{\gamma p} < 277\ \mathrm{GeV}$
- $E_T^{\mathrm{jet1}} > 14\ \mathrm{GeV},\ E_T^{\mathrm{jet2}} > 11\ \mathrm{GeV}$
- $-1 < \eta^{\mathrm{jet1,2}} < 2.4$

## Two contributions

- Momentum fraction of partons in photon

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

- Sensitivity to process type
- At high-$x_\gamma^{\mathrm{obs}}$ direct processes dominate




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

# 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

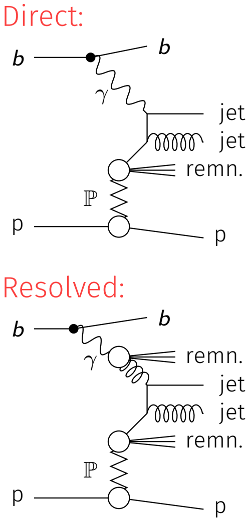
## Factorization of the diffractive cross section

- Direct: Pomeron flux and diffractive PDFs

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

- Resolved: photon PDFs

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



## Hard diffraction in photoproduction

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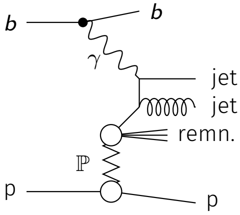
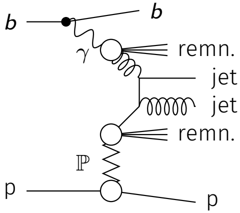
## Dynamical rapidity gap survival model

1. Generate diffractive events with dPDFs (PDF)

Direct:




Resolved:



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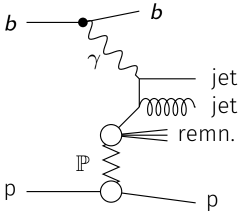
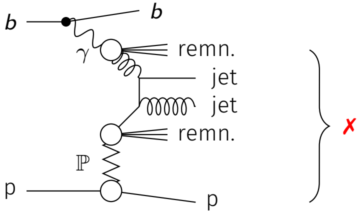
1. Generate diffractive events with dPDFs (PDF)
2. Reject events where MPIs in $\gamma$p system (MPI)

Direct:




Resolved:



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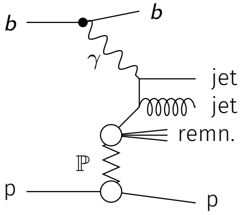
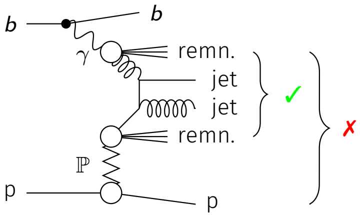
3. Evolve $\gamma$IP system, allow MPIs

Direct:




Resolved:



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1. Generate diffractive events with dPDFs (PDF)
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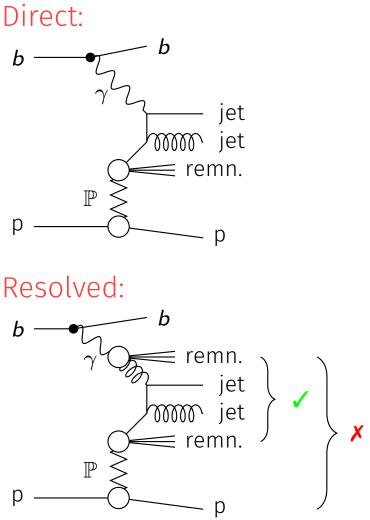
Implemented from PYTHIA 8.235 onwards

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

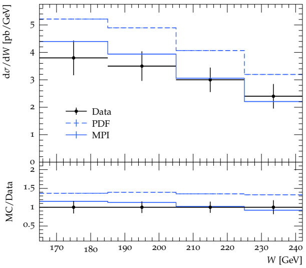
Same idea applied for pp collisions at the LHC

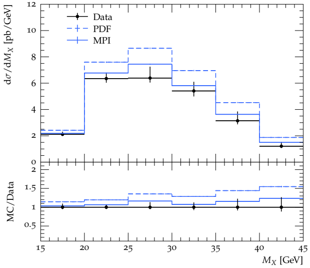
[C.O. Rasmussen and T. Sjöstrand, JHEP 1602 (2016) 142]



# 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 $E_T^{\text{jets}}$ and $x_{\mathbb{P}}$ $\Rightarrow$ More MPIs

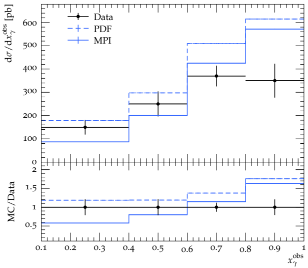
| Cuts | H1 | ZEUS |
|---|---|---|
| $Q^2_{\text{max}}$ [GeV$^2$] | 0.01 | 1.0 |
| $E_{T,\text{min}}^{\text{jet1}}$ [GeV] | 5.0 | 7.5 |
| $E_{T,\text{min}}^{\text{jet2}}$ [GeV] | 4.0 | 6.5 |
| $x_{\mathbb{P}}^{\text{max}}$ | 0.03 | 0.025 |

## Pythia setup

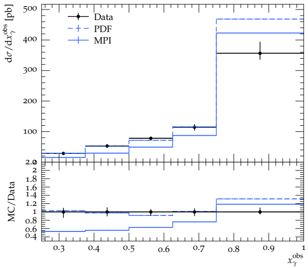
- dPDFs from H1 fit B LO
- $\gamma$PDFs from CJKL
- $p_{T0}^{\text{ref}} = 3.00$ GeV/$c$ (Tuned to inclusive charged particle data from $\gamma$p at HERA)

# Comparisons to HERA data

H1: [EPJC 51 (2007) 549]




ZEUS: [EPJC 55 (2008) 177]




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

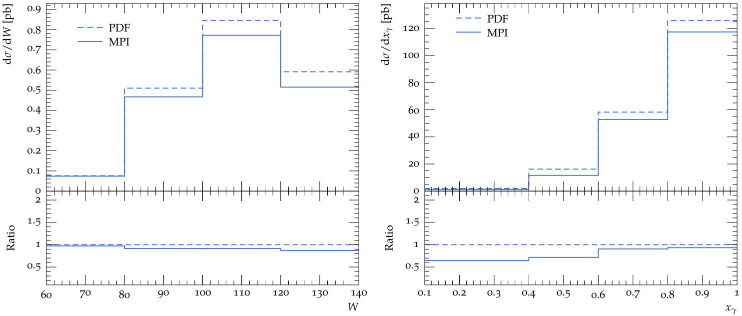
| Cuts | H1 | ZEUS |
|---|---|---|
| $Q^2_{max}$ [GeV$^2$] | 0.01 | 1.0 |
| $E_{T,min}^{jet1}$ [GeV] | 5.0 | 7.5 |
| $E_{T,min}^{jet2}$ [GeV] | 4.0 | 6.5 |
| $x_{IP}^{max}$ | 0.03 | 0.025 |

| $\chi^2$ 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 $x_\gamma$ where cross section small

$\Rightarrow$ Available energy and kinematical cuts typically applied for diffraction push the kinematics to region where no room for MPIs

# Diffractive dijets in UPCs

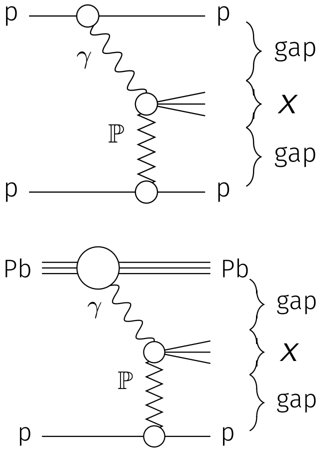
- Apply the dynamical rapidity gap survival model to UPCs in pp and pPb
- In pPb the photon flux from Pb dominates ($\propto Z^2$), p neglected

Kinematics similar to HERA

- $E_{\mathrm{T}}^{\mathrm{jet1(2)}} > 8(6)$ GeV, $|\eta^{\mathrm{jet1,2}}| < 4.4$
- $M_{\mathrm{jets}} > 14$ GeV, $x_{\mathrm{IP}} < 0.025$

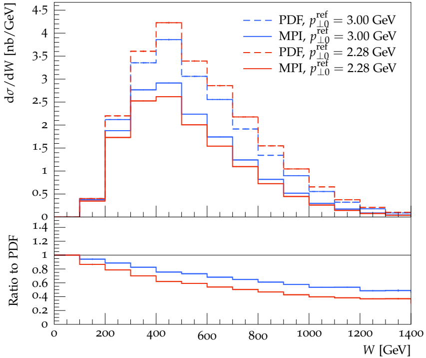
PYTHIA setup

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

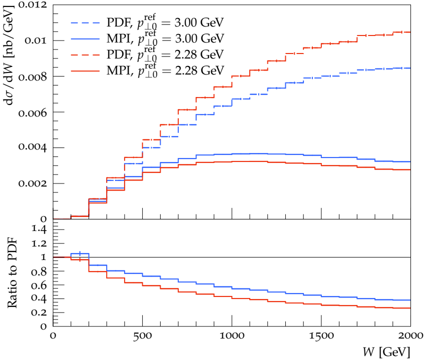


# Predictions for diffractive dijets in UPC

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

# Summary & Conclusions

## Photoproduction in Pythia 8

- Full simulations of direct and resolved contributions
- Good description of different HERA data
- Can be applied also to ultra-peripheral collisions

## Diffractive dijets in photoproduction

- Implemented dynamical rapidity gap survival model for $\gamma$p (and $\gamma\gamma$), originally introduced for pp

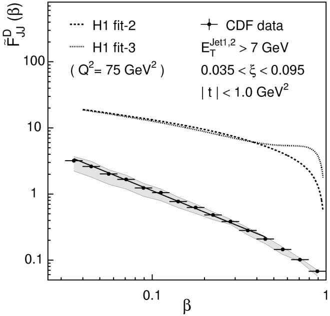
$\Rightarrow$ Uniform framework to describe the observed factorization breaking for hard diffraction in pp and ep relying only on MPI description in Pythia

- Support from HERA data
- Only mild effects expected at EIC energies
- Pronounced suppression predicted in UPCs at the LHC

# Backup slides

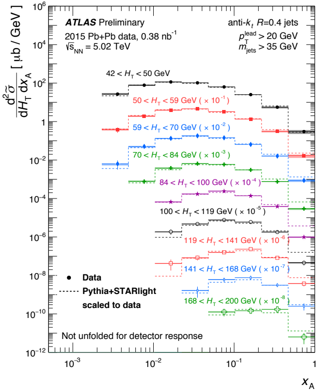
# Motivation: Diffractive dijets in hadronic collisions

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




- A significant suppression of diffractive dijets observed in $p+\overline{p}$
- Similar results also at the LHC

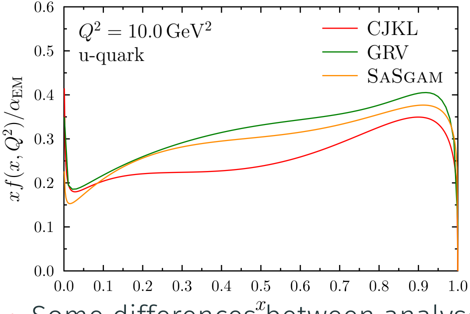
- Dijets in ultra-peripheral collisions at the LHC

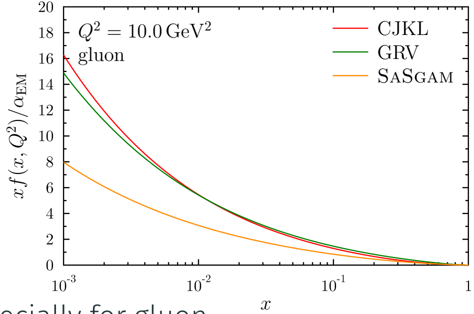



[ATLAS-CONF-2017-011]

# PDFs for resolved photons

Comparison of different photon PDF analysis



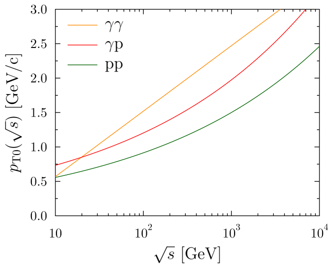




- Some differences between analyses, especially for gluon
  $\Rightarrow$ Theoretical uncertainty for resolved processes
- CJKL used as a default in PYTHIA 8, others via LHAPDF5 but only for hard-process generation

# MPIs with resolved photons

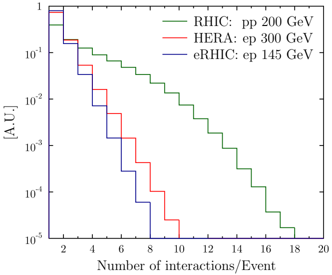
## Parametrization for $\gamma$p

- $p_{T0}$ 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

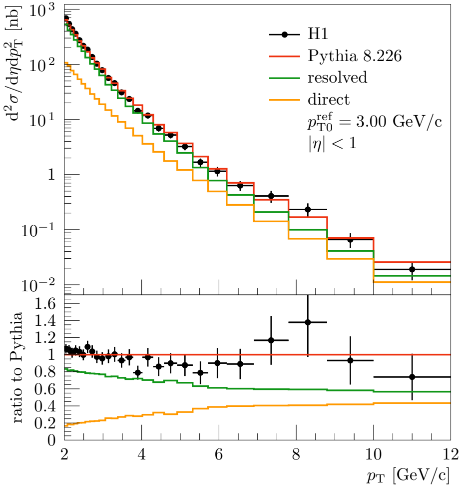



## Number of MPIs in different colliders

- 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
- $Q_\gamma^2 < 0.01$ GeV$^2$

## Comparison to PYTHIA 8

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

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

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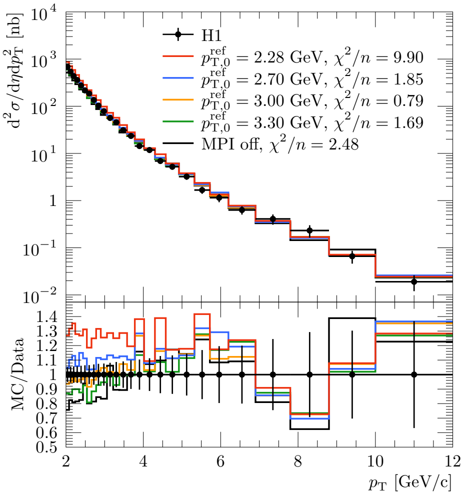


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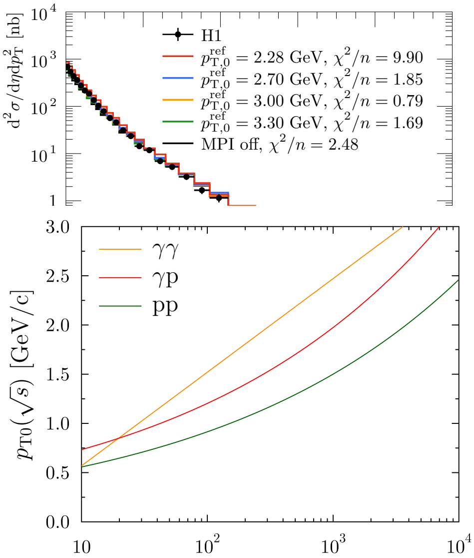


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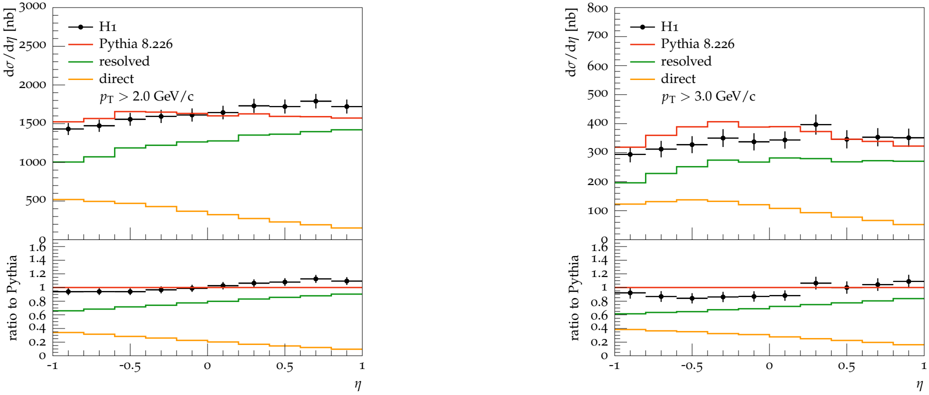
# Charged-particle $\eta$ dependence



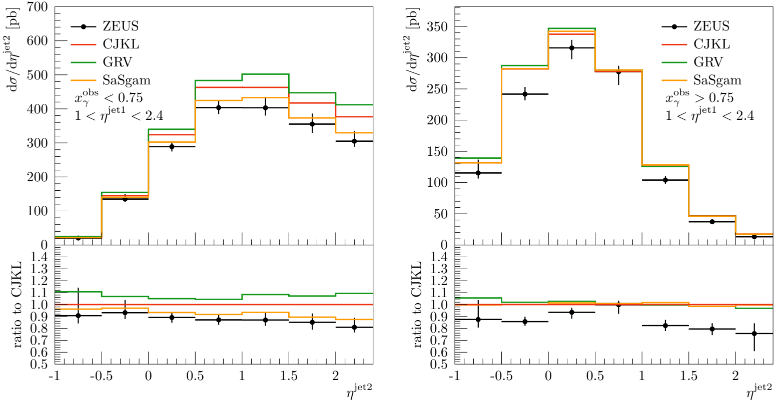

[H1: Eur.Phys.J. C10 (1999) 363-372]

- Good agreement also for charged-particle $\eta$ 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 %
- $\sim$ 10 % uncertainty from photon PDFs for $x_\gamma^{obs} < 0.75$

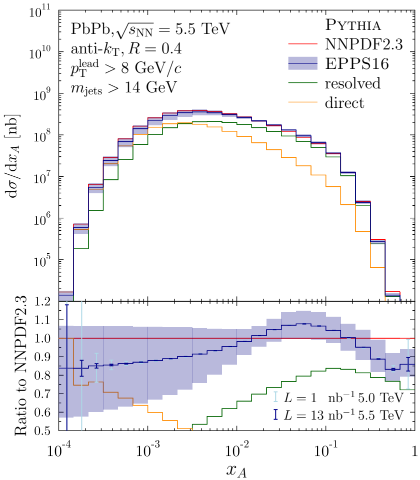
# Predictions for dijets in UPCs

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

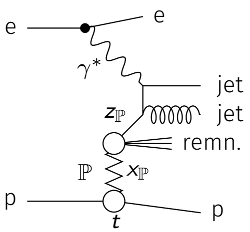
- Resolved dominant at high-$x_A$, direct at low-$x_A$
- Sensitive to nuclear PDFs
- Statistical uncertainty estimated at different luminosities




[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

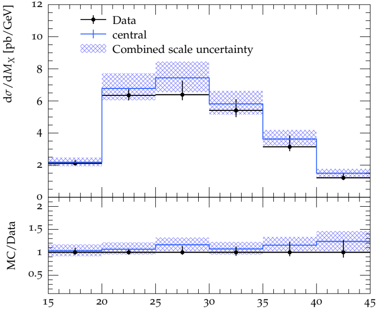
- DIS: $d\sigma^{2\text{jets}+X} = f_i^{IP}(z_{IP}, \mu^2) \otimes f_{IP}^{p}(x_{IP}, t) \otimes d\sigma^{ie\to 2\text{jets}}$
  where $f_{IP}^{p}$ is Pomeron flux and $f_j^{IP}$ diffractive PDF (dPDF)
- Factorization verifed by H1 and ZEUS at HERA

# Theoretical uncertainties

Largest uncertainties arise from

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

ZEUS 2008:

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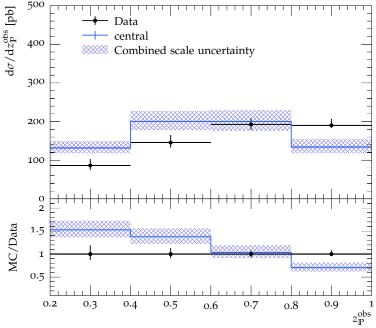


- Scale uncertainty around 20 %

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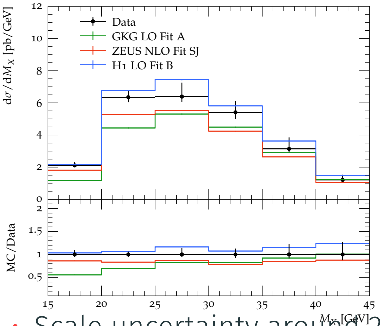
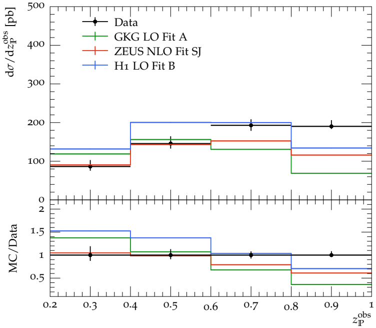
- diffractive PDFs (H1fitB, ZEUS-SJ and GKG18A)

ZEUS 2008:



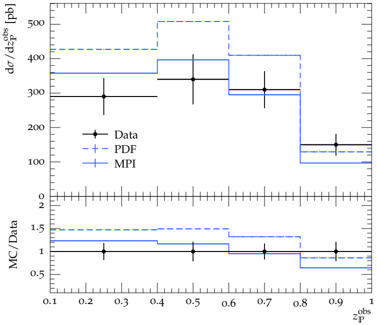

ZEUS 2008:



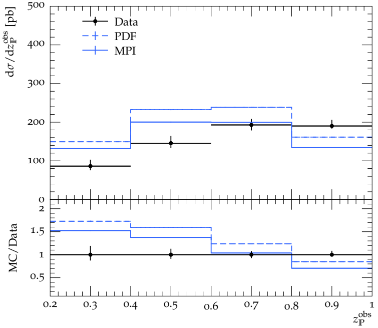

- Scale uncertainty around 20 %
- Better agreement for the shape of $z_{\mathbb{P}}^{obs}$ with ZEUS-SJ

# $z_{IP}^{obs}$ distributions

H1 2007:

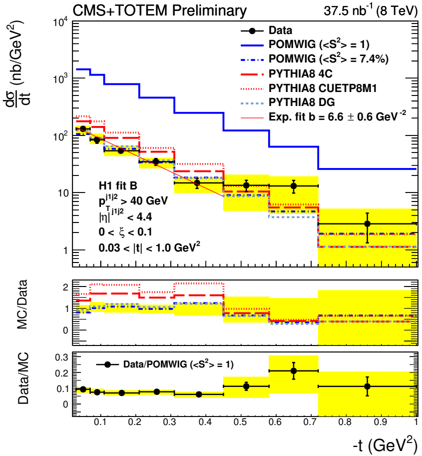


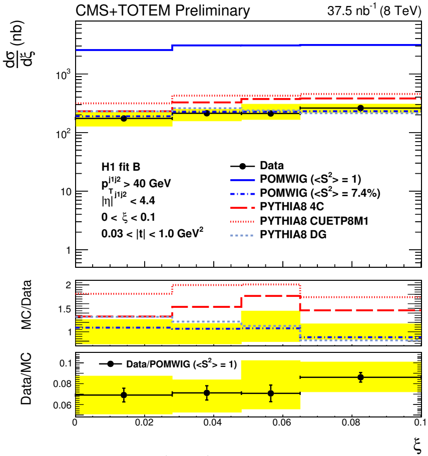

ZEUS 2008:




- 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

# Diffractive dijets in pp




- Dynamical rapidity gap survival model in PYTHIA 8 (DG) provide a good description of the measurement (Survival probability < 10%)

# Ultra-peripheral collisions (UPCs) (main70.cc)

## 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 $Q_0^2 = 0.71\ \mathrm{GeV}^2$

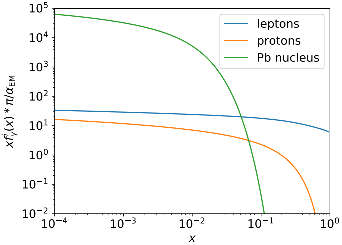
- The form factor suppress contribution from high-$Q^2$ $\Rightarrow$ photoproduction regime

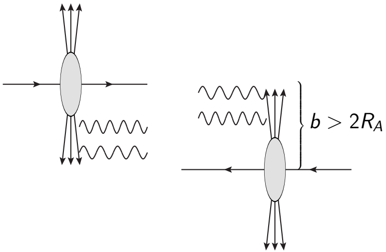
## UPCs with heavy ions

- 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, $\xi = b_{\mathrm{min}}xm$



# Soft QCD photoproduction

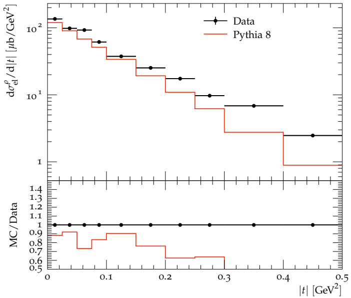
Soft QCD process implemented for photoproduction

- Based on Schuler and Sjöstrand model in PYTHIA 6
- Vector meson dominance (VMD) with $\rho$, $\omega$, $\phi$ and $J/\Psi$ mesons for
  - Soft diffraction (high- and low-mass)
  - Elastic scattering
- Non-diffractive from MPI machinery
- Total Cross section parametrized as

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

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

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




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