Jet production in ultra-peripheral collisions with PYTHIA 8

COST WORKSHOP ON COLLECTIVITY IN HEAVY-ION COLLISIONS

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In collaboration with
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Outline

Motivation

- Ultra-peripheral collisions (UPCs) allows to study γp and γA, complementary to pp and pA (collectivity?)
- Provide a Monte-carlo event generator for UPCs validated against HERA data
- Model the factorization-breaking effects for diffractive dijets in photoproduction [I.H. and C.O.R., arXiv:1901.05261 [hep-ph]]

Outline

1. Event generation in Pythia 8
2. Photoproduction and ultra-peripheral collisions
3. Dynamical rapidity gap survival model for hard diffraction
4. Summary & Outlook

- A general-purpose Monte-Carlo event generator
- Use theory where available (perturbative QCD), add phenomenological models where not

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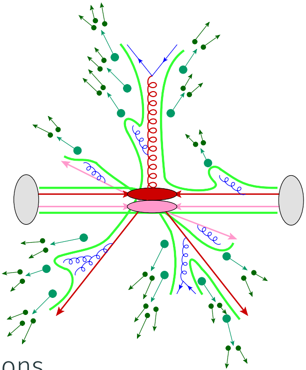
- Stefan Prestel — Lund University
- Christine O. Rasmussen — Lund University
- Peter Skands — Monash University

Event generation in PYTHIA 8

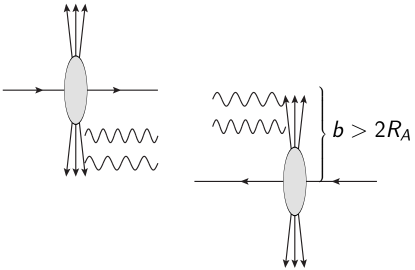
1. Hard scattering
   - Convolution of partonic cross sections and PDFs
2. Parton showers
   - Generate Initial and Final State Radiation (ISR & FSR) using DGLAP evolution
3. Multiparton interactions (MPIs)
   - Use regularized QCD $2 \to 2$ cross sections



[Figure: S. Prestel]

4. Beam remnants
   - Minimal number of partons to conserve colour and flavour
5. Hadronization
   - Using Lund string model with color reconnection
   - Decays into stable hadrons

Ultra-peripheral heavy-ion collisions



Photon flux from equivalent photon approximation

- Described with a flux of quasi-real (low-Q^2) photons

  $\Rightarrow$ Corresponds to photoproduction in ep collisions
- Flux in impact-parameter space from $b_{\text{min}}(\approx R_A + R_B)$

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

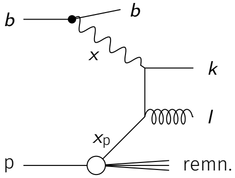
Z is nuclear charge, $\xi = b_{\text{min}} x m$, m (per-nucleon) mass

Event generation in photoproduction

Direct processes

- Cross section from convolution

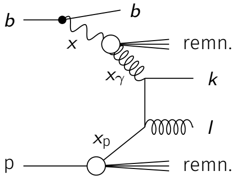
$$\mathrm{d}\sigma^{b\mathrm{p}\to kl+X} = f_{\gamma}^{b}(x) \otimes f_{i}^{\mathrm{p}}(x_{\mathrm{p}}, \mu^2) \otimes \mathrm{d}\sigma^{\gamma i\to kl}$$



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 photon kinematics and setup γp sub-system with $W_{\gamma\mathrm{p}}$
- Evolve the sub-system as any hadronic collision (incl. MPIs)

Dijet photoproduction in ep collisions at HERA

ZEUS dijet measurement

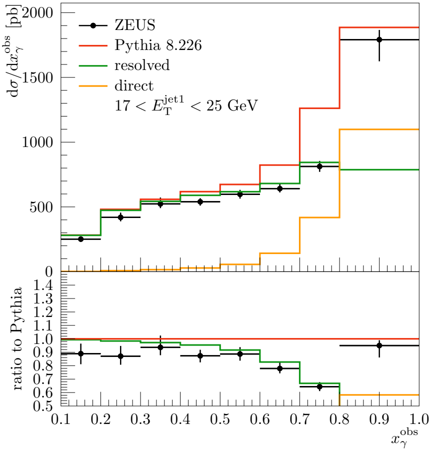
- $Q^2_\gamma < 1.0$ GeV^2
- $134 < W_{\gamma p} < 277$ GeV
- $E_T^{jet1} > 14$ GeV,
  $E_T^{jet2} > 11$ GeV
- $-1 < \eta^{jet1,2} < 2.4$

Different contributions

- Define

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

  to discriminate direct and resolved processes
  (=x_γ in γ at LO parton level)



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

- At high-x_γ^{obs} direct processes dominate

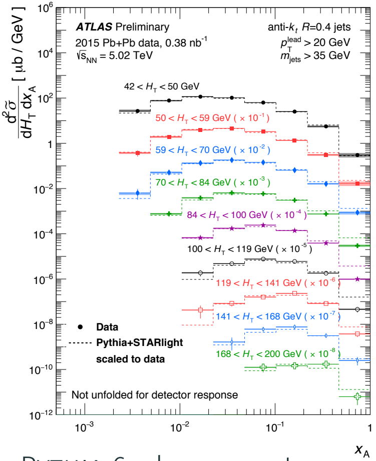
Dijets in ultra-peripheral collisions by ATLAS [ATLAS-CONF-2017-011]

Event selection

- anti-k_T with $R = 0.4$
- $p_T^{\text{lead}} > 20$ GeV, $p_T^{\text{jets}} > 15$ GeV, $|\eta^{\text{jets}}| < 4.4$

Event-level variables:

- $m_{\text{jets}} = \sqrt{(\Sigma_i E_i)^2 - |\Sigma_i \vec{p}_i|^2}$
- $y_{\text{jets}} = \frac{1}{2} \log\left(\frac{\Sigma_i E_i + \Sigma_i p_{zi}}{\Sigma_i E_i - \Sigma_i p_{zi}}\right)$
- $H_T = \Sigma_i p_{Ti}$
- $x_A = \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}}$



- Preliminary data compared to PYTHIA 6 where events reweighted with photon flux from STARLIGHT
- In PYTHIA 8 photon flux can be set by the user

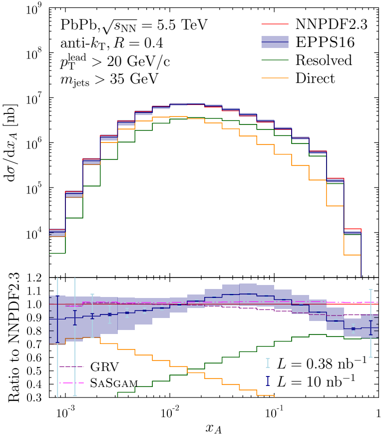
Dijets in ultra-peripheral collisions with PYTHIA 8

Dominant contributions

- Large x_A: resolved
- Small x_A: direct
- Weak dependence on γPDF

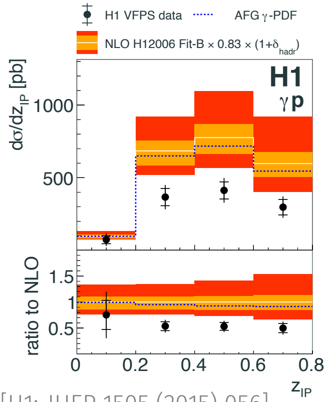
Sensitivity to nPDFs

- Data not public, estimate the statistical uncertainty at different luminosities
- Potential to constrain nPDFs down to $x \sim 10^{-3}$
- With lower p_T^{jets} can extend the low-x reach further



[I.H., arXiv:1811.10931 [hep-ph]]
[see also Guzey, Klasen, arXiv:1902.05126 [hep-ph]]

Factorization breaking in hard diffraction

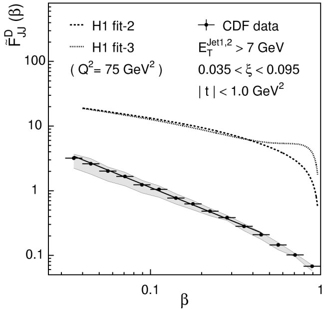


[H1: JHEP 1505 (2015) 056]

- Factorization breaking observed at Tevatron
- Similar results from pp collisions at the LHC

- Factorization-based calculation overshoot the data in photoproduction regime by a factor of two
- But good agreement in DIS

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

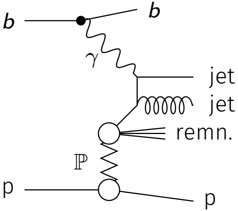


Hard diffraction in photoproduction

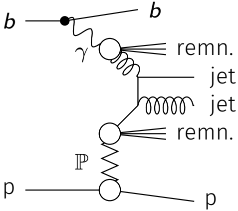
Starting point: Assume factorization of the cross section

- Direct: $\mathrm{d}\sigma^{\text{2jets}} = f_{\gamma}^{b}(x) \otimes \mathrm{d}\sigma^{\gamma j \to \text{2jets}} \otimes f_{j}^{\mathbb{P}}(z_{\mathbb{P}}, \mu^2) \otimes f_{\mathbb{P}}^{\mathrm{p}}(x_{\mathbb{P}}, t)$
- Resolved: $\mathrm{d}\sigma^{\text{2jets}} = f_{\gamma}^{b}(x) \otimes f_{i}^{\gamma}(x_{\gamma}, \mu^2) \otimes \mathrm{d}\sigma^{ij \to \text{2jets}} \otimes f_{j}^{\mathbb{P}}(z_{\mathbb{P}}, \mu^2) \otimes f_{\mathbb{P}}^{\mathrm{p}}(x_{\mathbb{P}}, t)$

Direct:



Resolved:



Dynamical rapidity gap survival for resolved events

1. Generate diffractive events with dPDFs (PDF selection)

Hard diffraction in photoproduction

Starting point: Assume factorization of the cross section

- Direct: $\mathrm{d}\sigma^{\text{2jets}} = f_\gamma^b(x) \otimes \mathrm{d}\sigma^{\gamma j\rightarrow\text{2jets}} \otimes f_j^{\mathbb{P}}(z_{\mathbb{P}},\mu^2) \otimes f_{\mathbb{P}}^{\mathrm{p}}(x_{\mathbb{P}},t)$
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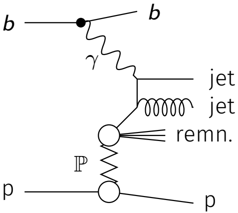
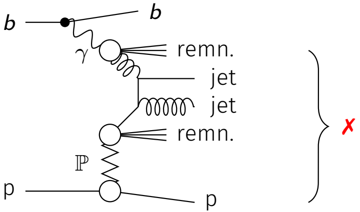
Direct:



Resolved:



Dynamical rapidity gap survival for resolved events

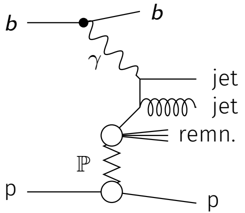
1. Generate diffractive events with dPDFs (PDF selection)
2. Reject events where MPIs in γp system (MPI selection)

Hard diffraction in photoproduction

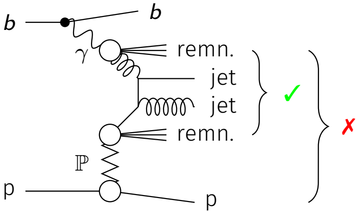
Starting point: Assume factorization of the cross section

- Direct: $\mathrm{d}\sigma^{\text{2jets}} = f_\gamma^b(x) \otimes \mathrm{d}\sigma^{\gamma j \to \text{2jets}} \otimes f_j^{\mathbb{P}}(z_{\mathbb{P}}, \mu^2) \otimes f_{\mathbb{P}}^{\mathrm{p}}(x_{\mathbb{P}}, t)$
- Resolved: $\mathrm{d}\sigma^{\text{2jets}} = f_\gamma^b(x) \otimes f_i^\gamma(x_\gamma, \mu^2) \otimes \mathrm{d}\sigma^{ij \to \text{2jets}} \otimes f_j^{\mathbb{P}}(z_{\mathbb{P}}, \mu^2) \otimes f_{\mathbb{P}}^{\mathrm{p}}(x_{\mathbb{P}}, t)$

Direct:



Resolved:



Dynamical rapidity gap survival for resolved events

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

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

Comparisons to HERA data

H1 2007: [EPJC 51 (2007) 549]

- $Q^2 < 0.01\ \mathrm{GeV}^2$
- $x_{I\!P} < 0.03$
- $E_T^{\mathrm{jet1}} > 5.0,\ E_T^{\mathrm{jet2}} > 4.0\ \mathrm{GeV}$
- $-1.0 < \eta^{\mathrm{jet1,2}} < 2.0$

ZEUS 2008: [EPJC 55 (2008) 177]

- $Q^2 < 1\ \mathrm{GeV}^2,\ 0.2 < y < 0.85$
- $x_{I\!P} < 0.025$
- $E_T^{\mathrm{jet1}} > 7.5,\ E_T^{\mathrm{jet2}} > 6.5\ \mathrm{GeV}$
- $-1.5 < \eta^{\mathrm{jet1,2}} < 1.5$

Observables

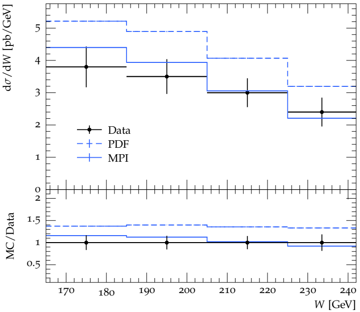
- $W_{\gamma p}$ (H1)
- M_X (ZEUS)
- $z_{I\!P}^{\mathrm{obs}} = \frac{\sum_{\mathrm{jet}}(E^{\mathrm{jet}}+p_z^{\mathrm{jet}})}{\sum_{i\in X}(E^i+p_z^i)}$
- $x_\gamma^{\mathrm{obs}} = \frac{\sum_{\mathrm{jet}}(E^{\mathrm{jet}}-p_z^{\mathrm{jet}})}{\sum_{i\in X}(E^i-p_z^i)}$

Default Pythia setup

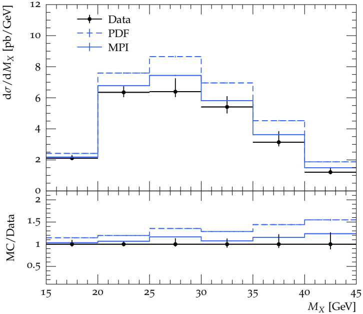
- dPDFs from H1 fit B LO
- γPDFs from CJKL
- $p_{\mathrm{T0}}^{\mathrm{ref}} = 3.00\ \mathrm{GeV}/c$
  (Tuned to HERA γp data)

Invariant mass distributions

H1 2007:



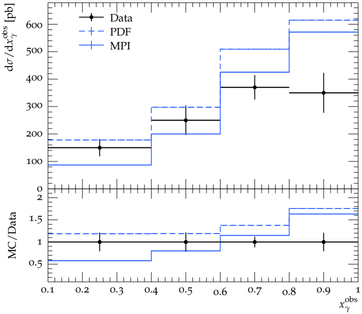
ZEUS 2008:



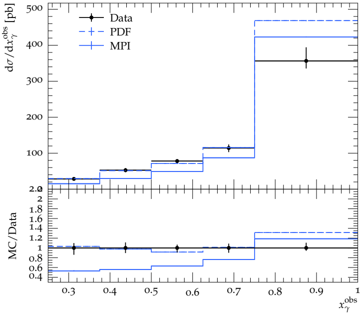
- PDF selection overshoots the data by 20–50 %
- Impact of the MPI rejection increases with W and M_X
- Stronger suppression in H1 analysis due to looser cuts on E_T^{jets} and $x_{\mathbb{P}}$

x_γ^{obs} distributions

H1 2007:



ZEUS 2008:

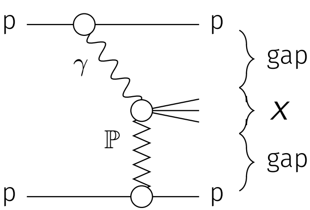


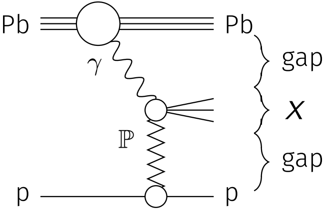
- Stronger suppression at low-x_γ^{obs} as more room for MPIs
- ZEUS cuts force the cross section to high-x_γ^{obs} region

χ^2/n_{df}	H1 2007	ZEUS 2008	H1 & ZEUS
PDF selection	5.20	9.64	7.63
MPI selection	1.42	5.10	3.44

Hard diffraction in UPCs

- Apply the dynamical rapidity gap survival model to UPCs in pp and pPb (currently not applicable to γPb)
- In pPb the photon flux from Pb dominates (p neglected)





Kinematics similar to HERA

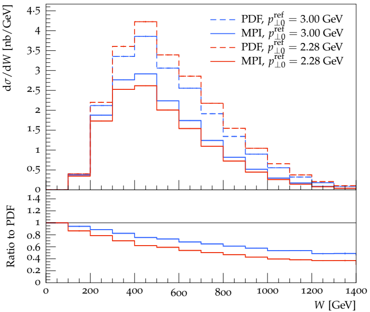
- $E_{\mathrm{T}}^{\mathrm{jet1(2)}} > 8(6)$ GeV
- $M_{\mathrm{jets}} > 14$ GeV
- $x_{\mathbb{P}} < 0.025$

Pythia setup

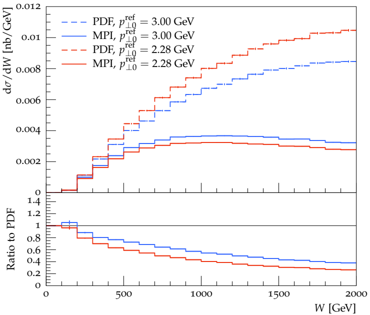
- Same PDFs as for HERA
- Vary MPI parameter:
  $p_{\mathrm{T0}}^{\mathrm{ref}} = 3.0$ GeV (HERA γp)
  $p_{\mathrm{T0}}^{\mathrm{ref}} = 2.28$ GeV (LHC pp)

Invariant mass distributions

pPb $\sqrt{s} = 5.0$ TeV



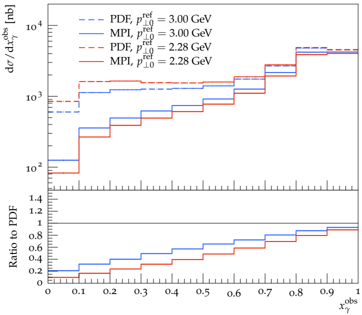
pp $\sqrt{s} = 13$ TeV



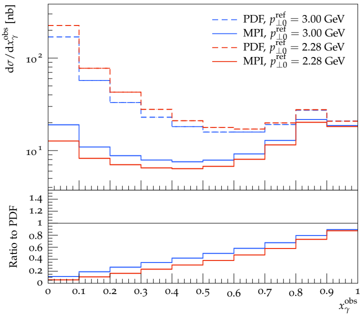
- Extended W range wrt. HERA, especially in pp (harder flux)
- Stronger suppression from MPIs than at HERA
- Two-fold effect from lower $p_{\mathrm{T}0}^{\mathrm{ref}}$, increases cross section for PDF selection but MPI selection rejects more events

x_γ^{obs} distributions

pPb $\sqrt{s} = 5.0$ TeV



pp $\sqrt{s} = 13$ TeV



- Enhanced MPI-suppression towards at small-x_γ^{obs} since more momentum left for MPIs
- The gap-survival effects more pronounced in UPCs at the LHC compared to HERA $\Rightarrow$ Ideal place to constrain models

Summary & Outlook

Photoproduction in Pythia 8

- Good description of the HERA data
- Can be applied also to ultra-peripheral collisions with appropriate photon flux
- Potential to constrain nPDFs with photo-nuclear dijets

Diffractive dijets in photoproduction

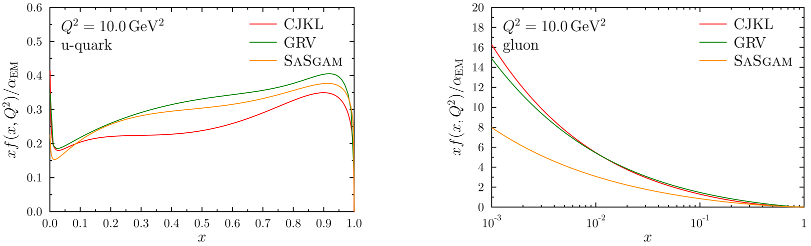
- Implementation of dynamical rapidity gap survival model for γp (and $\gamma\gamma$), originally introduced for pp

  ⇒ Uniform framework to describe the observed factorization breaking for hard diffraction in pp and ep
- Applicable also for UPCs (currently with proton target)

Backup slides

PDFs for resolved photons

Comparison of different photon PDF analysis

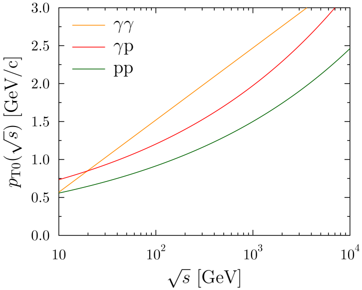


- Some differences between analyses, especially for gluon
  $\Rightarrow$ Theoretical uncertainty for resolved processes
- CJKL used as a default in Pythia 8, others via LHAPDF5 but only for hard-process generation

MPIs with resolved photons

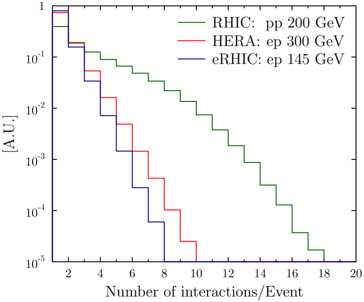
Parametrization for γp

- 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

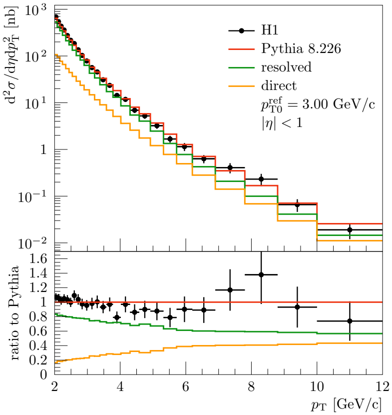


Number of MPIs in different colliders

- 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

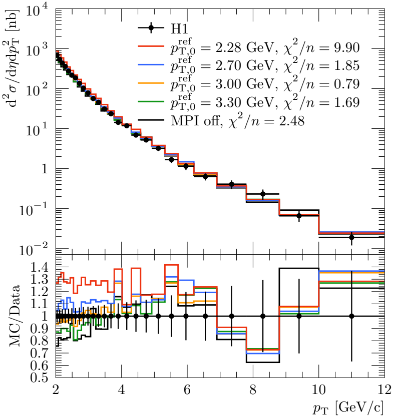
- $E_p = 820$ GeV, $E_e = 27.5$ GeV
- $< W_{\gamma p} > \approx 200$ GeV
- $Q_\gamma^2 < 0.01$ GeV^2

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 $\gamma\gamma$

Charged particle p_T spectra in ep collisions at HERA



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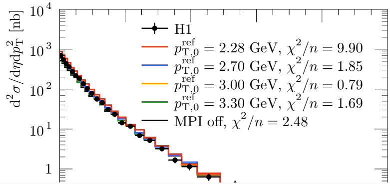

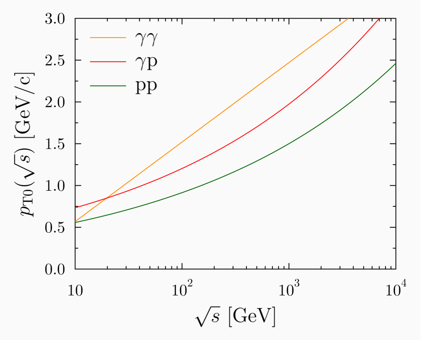

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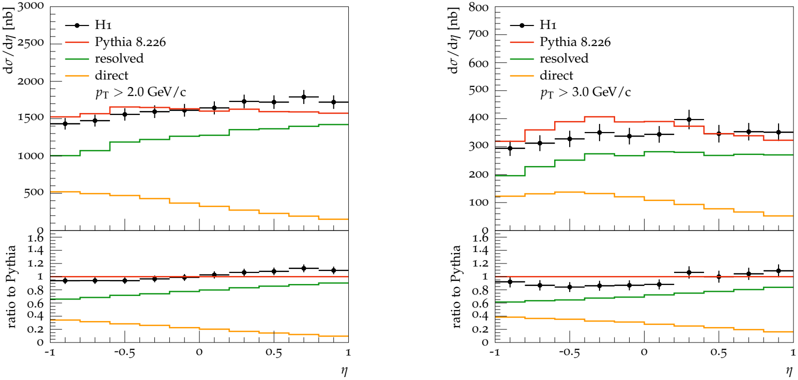
$\Rightarrow$ MPI probability between pp and $\gamma\gamma$

Charged-particle η dependence

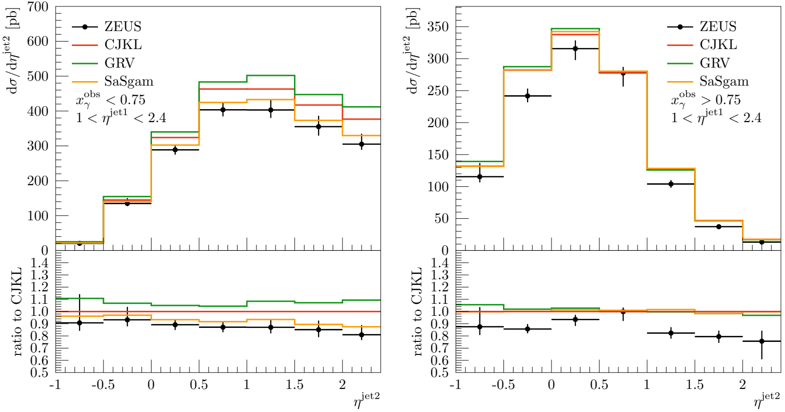


[H1: Eur.Phys.J. C10 (1999) 363-372]

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

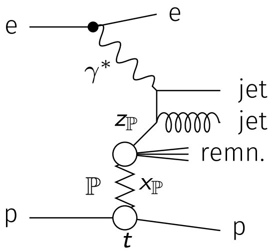
Dijet in ep collisions at HERA

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 $x_\gamma^{obs} < 0.75$

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

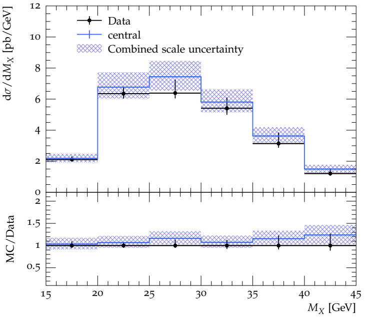
  where $f_{\mathrm{IP}}^{\mathrm{p}}$ is Pomeron flux and f_j^{IP} diffractive PDF (dPDF)
- Factorization verifed by H1 and ZEUS at HERA

Theoretical uncertainties

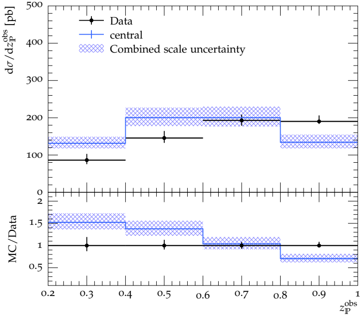
Largest uncertainties arise from

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

ZEUS 2008:



ZEUS 2008:



- Scale uncertainty around 20 %

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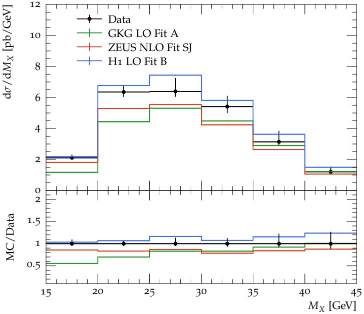
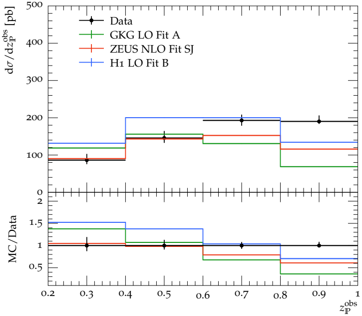
ZEUS 2008:



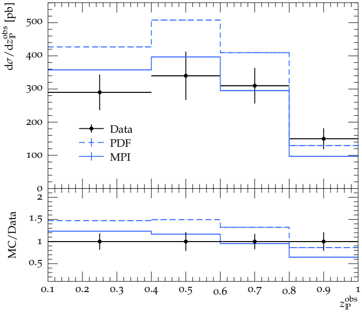
ZEUS 2008:



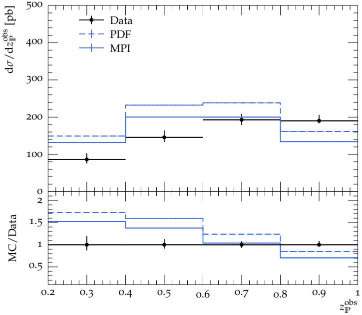
- Scale uncertainty around 20 %
- Better agreement for the shape of $z_{\mathbb{P}}^{obs}$ with ZEUS-SJ

$z_{I\!P}^{obs}$ distributions

H1 2007:



ZEUS 2008:



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