Photoproduction of dijets with Pythia 8

Initial Stages 2017

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Motivation & Outline

Motivation

- $\gamma\gamma$ interactions in future e^+e^- colliders
- Photoproduction in e+p/A colliders
- Ultra-peripheral collisions (UPCs) at the LHC

⇒ Aim: Robust simulations of photoproduction in different collision systems with Pythia 8

Outline

1. Event generation in Pythia 8
2. Photon-hadron collisions
3. Photo-production in ep collisions at HERA
4. Photo-nuclear dijets in UPCs at the LHC
5. Summary & Outlook

Pythia 8

- A general-purpose Monte-Carlo event generator
- Main focus has been in pp (LHC), now several extensions
- Current public version 8.226, 8.228 to be released soon

Team:

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- Christian Bierlich — Lund University
- Nishita Desai — CNRS-Universite de Montpellier
- Nadine Fischer — Monash University
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- Philip Ilten — Massachusetts Institute of Technology
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- Christine O. Rasmussen — Lund University
- Peter Skands — Monash University

Event generation in Pythia 8

1. Hard process
   - Sample the (LO) hard process according to

$$d\sigma^X = \sum_{i,j} f_i(x_1, Q^2) \otimes f_j(x_2, Q^2) \otimes d\hat{\sigma}^{i+j\to X}$$

   - where PDFs from global DGLAP analysis
2. Partonic evolution
   - Final state radiation (FSR)
     - Splitting probabilities from DGLAP

$$d\mathcal{P}_{a\to b} = \frac{dQ^2}{Q^2}\frac{\alpha_s}{2\pi}P_{a\to bc}(z)\,dz$$

   - Initial state radiation (ISR)
     - Backwards evolution, conditional probability

$$d\mathcal{P}_{a\leftarrow b} = \frac{df_b}{f_b} = \frac{dQ^2}{Q^2}\frac{\alpha_s}{2\pi}\frac{x'f_a(x', Q^2)}{xf_b(x, Q^2)}P_{a\to bc}(z)\,dz \quad (x' = x/z)$$

Event generation in Pythia 8

- Multiple partonic interactions (MPIs) and soft processes
  - Screening parameter p_{T0} regulates $p_{\mathrm{T}} \to 0$ divergence

$$\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_{\mathrm{T}}} = \frac{1}{\sigma_{\mathrm{nd}}}\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}} \propto \frac{\alpha_{\mathrm{s}}(p_{\mathrm{T}}^2)}{p_{\mathrm{T}}^4} \to \frac{\alpha_{\mathrm{s}}(p_{\mathrm{T0}}^2 + p_{\mathrm{T}}^2)}{(p_{\mathrm{T0}}^2 + p_{\mathrm{T}}^2)^2}$$

  - Parameter energy-dependent: $p_{\mathrm{T0}}(\sqrt{s}) = p_{\mathrm{T0}}^{\mathrm{ref}}(\sqrt{s}/7\,\mathrm{TeV})^{\alpha}$
  - Tuned to data (Monash: $p_{\mathrm{T0}}^{\mathrm{ref}} = 2.28$ GeV/c, $\alpha = 0.215$)
- Common evolution scale (p_{T}) for FSR, ISR and MPIs

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_{\mathrm{T}}} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_{\mathrm{T}}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_{\mathrm{T}}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_{\mathrm{T}}}\right) \times \exp\left[-\int_{p_{\mathrm{T}}}^{p_{\mathrm{T}}^{\mathrm{max}}} \mathrm{d}p'_{\mathrm{T}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_{\mathrm{T}}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_{\mathrm{T}}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_{\mathrm{T}}}\right)\right]$$

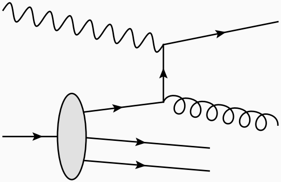
  where exp[. . .] is a Sudakov factor

3. Hadronization see C. Bierlich's talk

Photon-hadron collisions

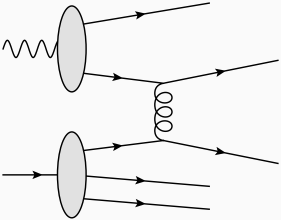
Direct processes

- Unresolved photons initiators of the process
- No MPIs
- FSR and ISR for hadron



Resolved processes

- Photons fluctuate to hadronic state (VMD)
- Partonic content from PDFs
- Full parton-level evolution (ISR, FSR, MPI)



Photoproduction $\Rightarrow Q^2 \lesssim 1.0\ \text{GeV}^2$ (unlike in DIS)

Resolved photons

- PDFs for resolved photons from global DGLAP analysis
- Data from $\gamma^*\gamma$ events in e^+e^- (LEP)

DGLAP equations 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)
- Solution has two components:

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

  Non-perturbative input for hadron-like part fixed by data

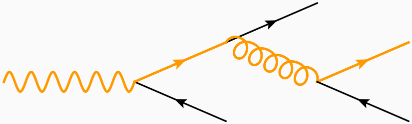
$$f_i^{\gamma,\mathrm{had}}(x, Q_0^2) = N_i x^{a_i}(1-x)^{b_i}$$

ISR with photon beams

- ISR probability based on DGLAP equations
- Add a term corresponding to $\gamma \to q\bar{q}$ splitting

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

- Corresponds to finding the beam photon during evolution
  - No further ISR
  - No MPIs below the scale
  - No need for beam remnants



Photon flux from leptons

- Flux of photons from leptons using equivalent photon approximation (EPA)

$$f_\gamma^{\mathrm{e}}(x, Q^2_{\mathrm{max}}) = \frac{\alpha_{\mathrm{em}}}{2\pi} \int_{Q^2_{\mathrm{min}}(x)}^{Q^2_{\mathrm{max}}} \frac{\mathrm{d}Q^2_\gamma}{Q^2_\gamma} \frac{(1+(1-x)^2)}{x}$$

  where x is the energy fraction of the photon wrt. lepton

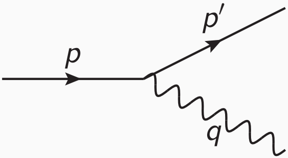
- Virtuality of the photon

$$Q^2_\gamma = -q^2 = -(p-p')^2$$

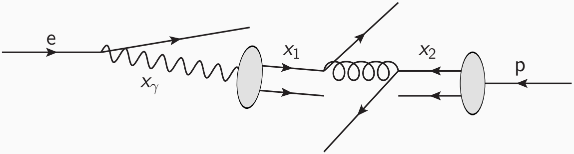
  is related to lepton scattering angle θ as

$$Q^2_\gamma \approx 2\,E_l^2(1-x)(1-\cos\theta)$$

  and $Q^2_{\mathrm{min}}(x) \approx m_l^2 x^2/(1-x)$



Resolved processes

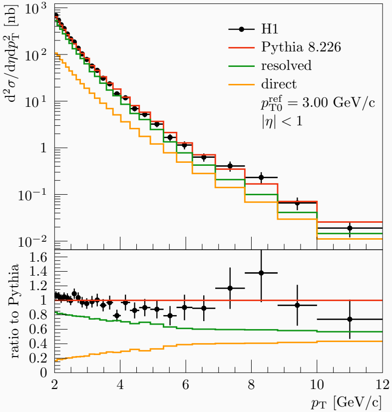


- PDFs required for hard-process sampling
  $\Rightarrow$ Define parton-inside-photon-inside-lepton PDFs

$$xf_i^l(x,Q^2) = \int_x^1 \frac{\mathrm{d}x_\gamma}{x_\gamma} x_\gamma f_l^\gamma(x_\gamma, Q^2_{\mathrm{max}}) \; \frac{x}{x_\gamma} f_\gamma^i(x/x_\gamma, Q^2)$$

- Sample x_γ and Q^2_γ for each accepted event
- Set up γp sub-collision according to sampled γ kinematics
- Perform parton-level evolution for the sub-system

Charged particle p_T spectra in ep collisions at HERA



[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
- Data best described with $p_{T0}^{ref} = 3.00$ GeV/c

$\Rightarrow$ Lower MPI probability than in pp ($p_{T0}^{ref} = 2.28$ GeV/c)

Dijet photoproduction in ep collisions at HERA

ZEUS dijet measurement

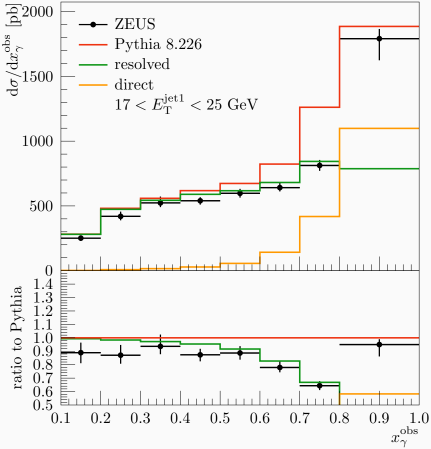
- $Q^2_\gamma < 1.0\ \text{GeV}^2$
- $134 < W_{\gamma\text{p}} < 277$ GeV
- $E_\text{T}^\text{jet1} > 14$ GeV, $E_\text{T}^\text{jet2} > 11$ GeV
- $-1 < \eta^\text{jet1,2} < 2.4$

Different contributions

- Define

$$x_\gamma^\text{obs} = \frac{E_\text{T}^\text{jet1} e^{\eta^\text{jet1}} + E_\text{T}^\text{jet2} e^{\eta^\text{jet2}}}{2yE_\text{e}}$$

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

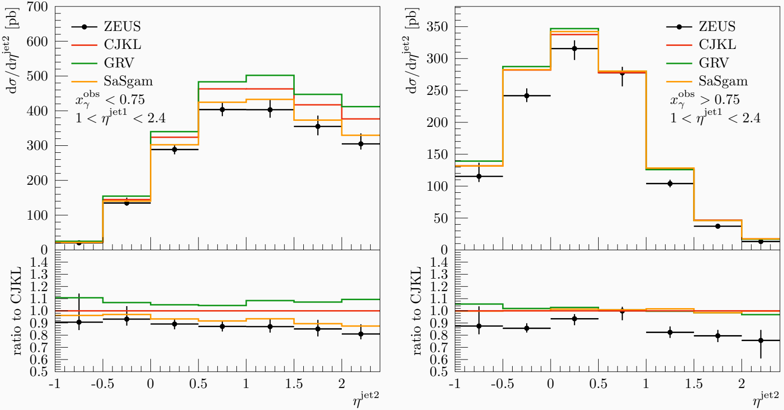


[Eur.Phys.J. C23 (2002) 615-631]

- At high-x_γ^obs direct processes dominate

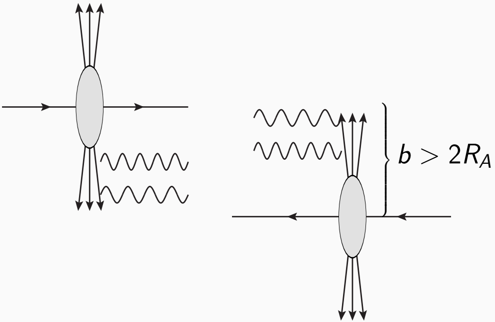
Dijet in ep collisions at HERA

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 $x_\gamma^{obs} < 0.75$ (default in Pythia 8 is CJKL)

Ultra-peripheral heavy-ion collisions



- Large impact parameter $b \Rightarrow$ No strong interaction
- EM-field of nuclei described with quasi-real photons (EPA)
  - Photon-photon (dileptons, light-by-light)
    $\Rightarrow$ Useful to calibrate the photon flux
  - Photon-nucleus (dijets, incl. hadrons, heavy flavours, ...)
    $\Rightarrow$ Can be used to probe nuclear PDFs

Photon flux from nuclei

Photon flux in impact-parameter b space

- Obtained by a Fourier transformation of the time-dependent EM-field
$$f_\gamma^A(x,b) = \frac{\alpha_{\mathrm{EM}} Z^2}{\pi^2}\left[\frac{xm}{\hbar c} K_1\left(\frac{xbm}{\hbar c}\right)\right]^2,$$
where Z is nuclear charge and K_1 modified Bessel function

Photon-nucleus interactions

- Integrate over $b > 2R_A$ to reject hadronic interactions
$$f_\gamma^A(x) = \frac{2\alpha_{\mathrm{EM}} Z^2}{\pi}\left[\xi\, K_1(\xi) K_0(\xi) - \frac{\xi^2}{2}\left(K_1^2(\xi) - K_0^2(\xi)\right)\right],$$
where $\xi = 2R_A xm/\hbar c$
- Primitive approach, does not account for the tails of the nuclear density

PYTHIA 8.228

- No internal implementation of the photon flux from nuclei
- However, possibility to feed in external photon flux
- Implementation of nuclear PDFs, default EPS09LO

  ⇒ Can study UPC sensitivity to nuclear PDFs at the LHC

Photo-nuclear dijet production

- ATLAS analysis [ATLAS-CONF-2017-011]

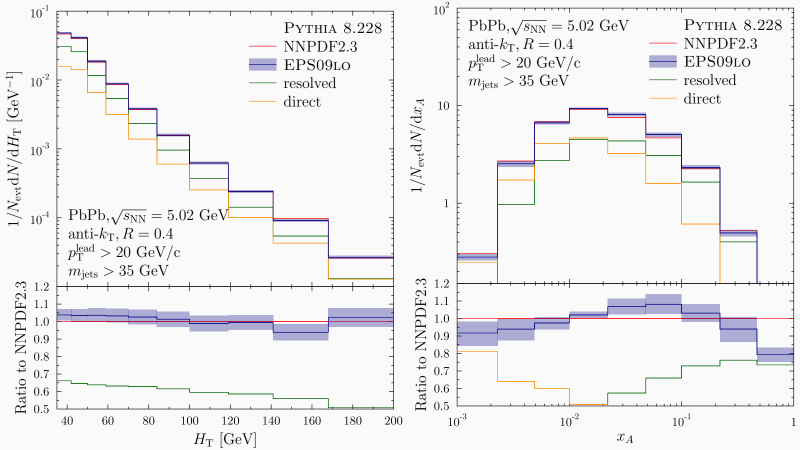
  anti-k_T, $R = 0.4$, $p_\mathrm{T}^\mathrm{lead} > 20$ GeV, $p_\mathrm{T}^\mathrm{jets} > 15$ GeV, $|\eta| < 4.4$
- Event-level variables:

$$m_\mathrm{jets} = \sqrt{(\Sigma_i E_i)^2 - \left|\Sigma_i \vec{p}_i\right|^2}, \qquad H_\mathrm{T} = \Sigma_i p_{\mathrm{T}i}$$

$$y_\mathrm{jets} = \frac{1}{2}\log\left(\frac{\Sigma_i E_i + \Sigma_i p_{zi}}{\Sigma_i E_i - \Sigma_i p_{zi}}\right) \qquad x_A = \frac{m_\mathrm{jets}}{\sqrt{s}} \mathrm{e}^{-y_\mathrm{jets}}$$

Results for UPC dijets

Differential photo-nuclear dijet distributions (Preliminary)



- The expected nPDF features visible in x_A
- Small-x gluon uncertainties underestimated in EPS09

Summary & Outlook

Present: Pythia 8.226

- Full simulations of $\gamma\gamma$ and γ-hadron collisions
- Automatic mixing of direct and resolved contributions
- Implementation of photon flux from leptons (EPA)

$\Rightarrow$ Ready for FCC-ee studies

$\Rightarrow$ Can simulate photoproduction in ep collisions

Soon: Pythia 8.228

- Nuclear PDFs for hard processes to study γA
- Possibility to feed in external photon flux (e.g. from nuclei)

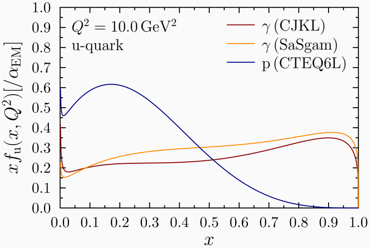
$\Rightarrow$ Allow simulations photo-nuclear interactions in UPCs and to study sensitivity to nuclear PDFs (e.g. dijets)

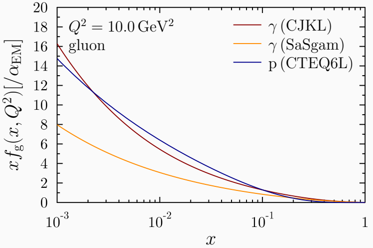
Future

- A detailed implementation of the photon flux from hadrons

Backup slides

Photon PDFs





- More large-x quarks due to $\gamma \to q\bar{q}$ splittings
- CJKL and SaSgam analysis agree for quarks

- Similar behaviour as with protons
- CJKL ~ 2 more gluons than SaSgam

- CJKL includes also data from LEP-II and is used for Pythia 8

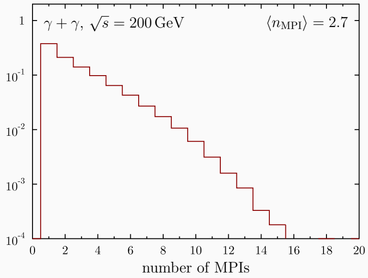
MPIs with photon beams

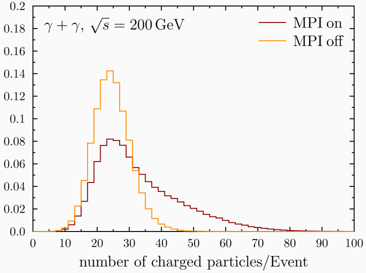
- Parametrization for $\sigma_{\mathrm{tot}}(s)$

$$\sigma_{\mathrm{tot}}^{\gamma\gamma}(s) \approx 211\, s^{0.0808} + 215\, s^{-0.4525} \quad [\mathrm{nb}]$$

[Schuler, Sjöstrand, Z. Phys. C73 (1997)]

- We use $\sigma_{\mathrm{nd}}^{\gamma\gamma}(s) \sim 0.7\, \sigma_{\mathrm{tot}}^{\gamma\gamma}(s)$ (based on PYTHIA 6)
- Otherwise use the same parameters as for protons



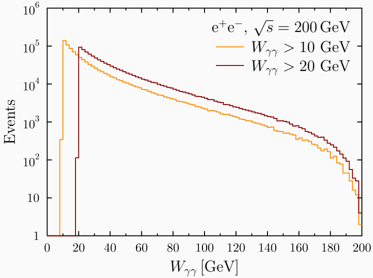


Soft processes

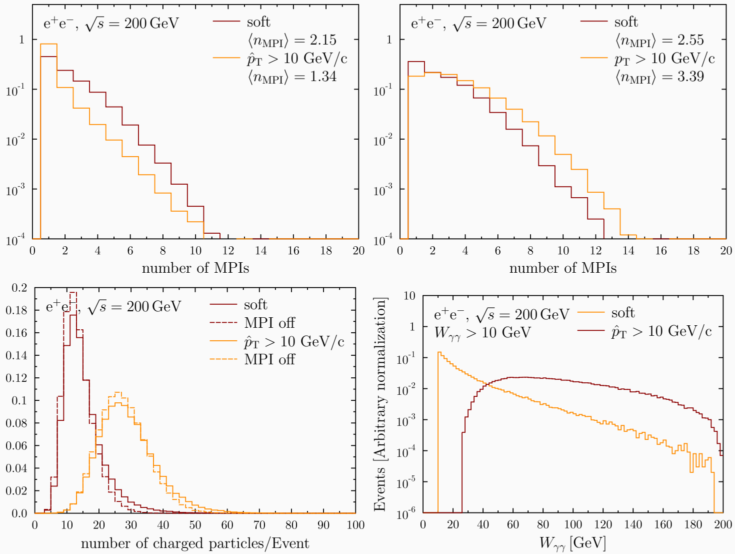
- Soft processes generated with MPI machinery

$$\sigma_{\text{nd}} = \left(\frac{\alpha_{\text{em}}}{2\pi}\right)^2 \int_{x_1^{\text{min}}}^{1} \mathrm{d}x_1 \int_{x_2^{\text{min}}}^{1} \mathrm{d}x_2 \frac{1+(1-x_1)^2}{x_1} \frac{1+(1-x_2)^2}{x_2}$$
$$\log\left(\frac{Q^2_{\text{max}}}{Q^2_{\text{min}}(x_1)}\right) \log\left(\frac{Q^2_{\text{max}}}{Q^2_{\text{min}}(x_2)}\right) \sigma^{\gamma\gamma}_{\text{nd}}(W^2_{\gamma\gamma})$$

- x_i^{min} from lower cut for invariant mass ($W^2_{\gamma\gamma} \approx x_1 x_2 s$)
- Sub-collisions biased towards low $W_{\gamma\gamma}$

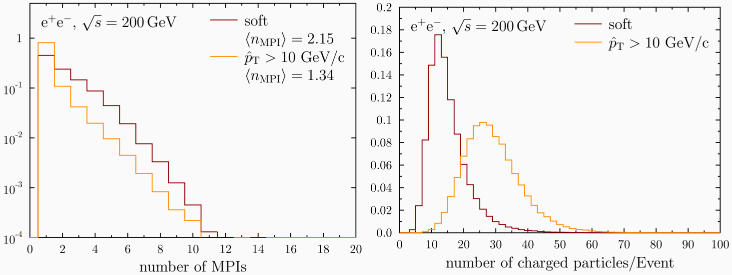


MPIs in e^+e^-


e+e−, √s = 200 GeV
soft
⟨n_MPI⟩ = 2.15
p̂_T > 10 GeV/c
⟨n_MPI⟩ = 1.34
number of MPIs
e+e−, √s = 200 GeV
soft
⟨n_MPI⟩ = 2.55
p_T > 10 GeV/c
⟨n_MPI⟩ = 3.39
number of MPIs
e+e−, √s = 200 GeV
soft
MPI off
p̂_T > 10 GeV/c
MPI off
number of charged particles/Event
e+e−, √s = 200 GeV
W_γγ > 10 GeV
soft
p̂_T > 10 GeV/c
Events [Arbitrary normalization]
W_γγ [GeV]

MPIs in e^+e^-

- The evolution of $\gamma\gamma$ system is done as before



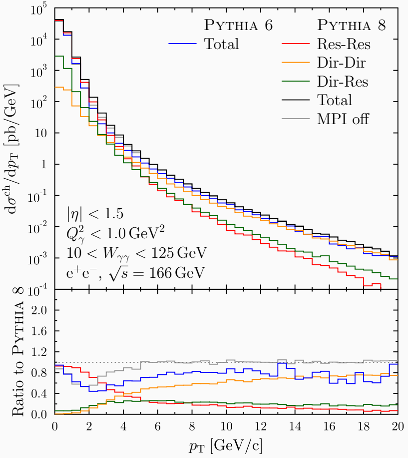
- Hard processes generate less MPIs than soft ones
  - $\gamma \to q\bar{q}$ splittings in ISR eliminate further MPIs

$$\mathrm{d}\mathcal{P}_{\text{ISR}} \propto \frac{\mathrm{d}p_{\text{T}}^2}{p_{\text{T}}^2} \quad \mathrm{d}\mathcal{P}_{\text{MPI}} \propto \frac{\mathrm{d}p_{\text{T}}^2}{p_{\text{T}}^4}$$

- Still more charged particles for hard processes

Charged particle p_T spectra

Combination of direct and resolved processes



- Resolved processes dominate at low p_T
- Direct processes take over above $p_T \sim 5$ GeV/c

Comparison with Pythia 6:

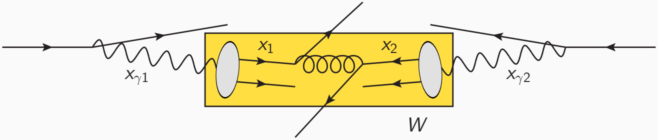
- Difference at $p_T \sim 2$ GeV/c due to MPIs
- high-p_T difference mainly from PDF sets

Photoproduction of charged hadrons in LEP

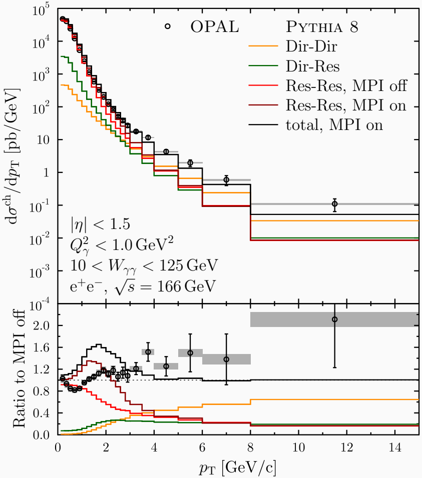
- e^+e^- collisions at $\sqrt{s} = 161$ and 172 GeV

OPAL measurment

- "Anti-tagged events" = Scattered leptons not seen
  $\Rightarrow$ Quasi-real photons ($Q^2 < 1$ GeV^2)
- Sum of ECAL and HCAL less than 45 GeV to remove $e^+e^- \to q\bar{q}$ background
- Cuts in W (= invariant mass of hadronic final state)



Charged particle p_T spectra



[Eur. Phys. J. C6 (1999) 253-264]

Combination of Direct and Resolved processes

- Resolved processes dominate at low p_T
- Direct processes take over above $p_T \sim 5$ GeV/c

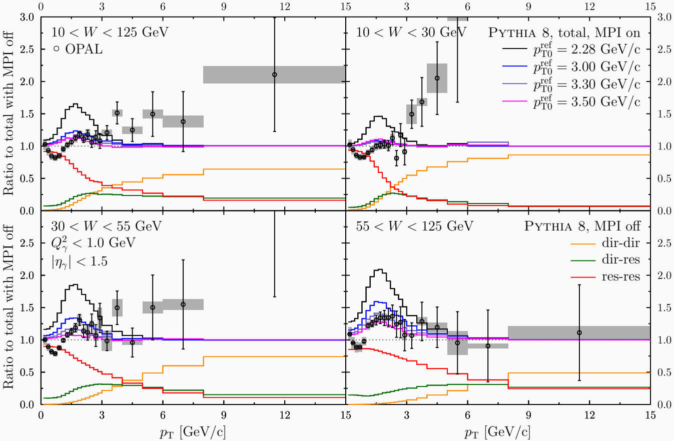
Compare with OPAL data

- Agreement without MPIs
- "Out of the box" MPIs generates too much hadrons at $p_T \sim 2$ GeV/c

$\Rightarrow$ Value of p_{T0}^{ref} in $\gamma\gamma$?

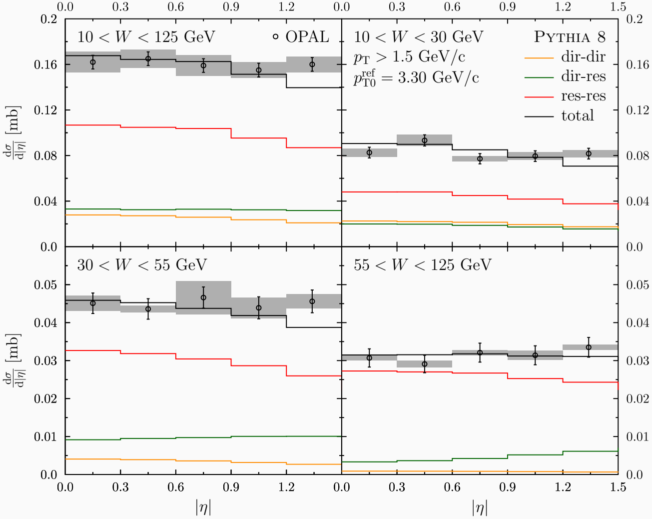
Invariant mass dependence

- Constrain p_{T0}^{ref} with data binned in W



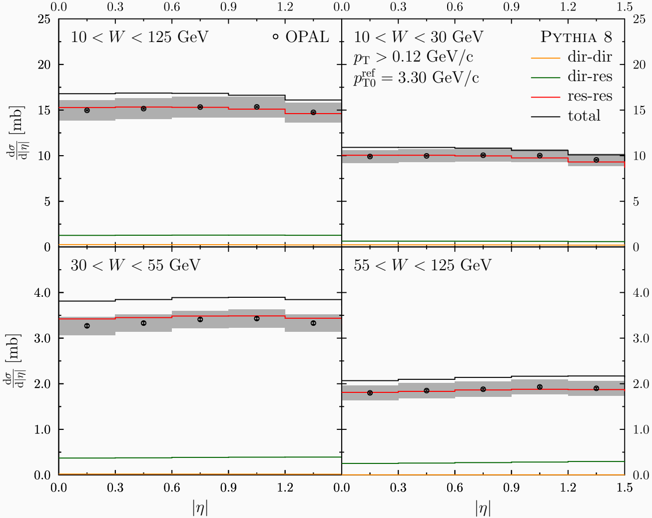
- Good agreement with the data using $p_{T0}^{ref} = 3.3$ GeV/c
- More hadrons from MPIs with higher W

Pseudorapidity dependence



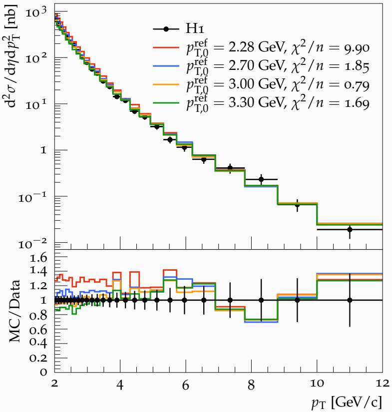
- Also η dependence looks good

Pseudorapidity dependence



- PYTHIA 8 result slightly above the data with $p_{\mathrm{T}} > 0.12$ GeV/c

Charged particle p_T spectra in ep collisions at HERA



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

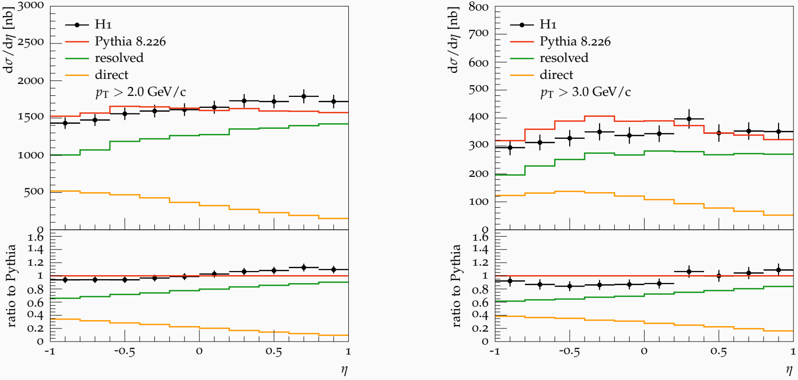
H1 measurement

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

Comparison to Pythia 8

- Resolved contribution dominates
- Data best described with $p_{T0}^{ref} = 3.00$ GeV/c (Between 2.28 Gev/c (pp) and 3.30 Gev/c ($\gamma\gamma$))

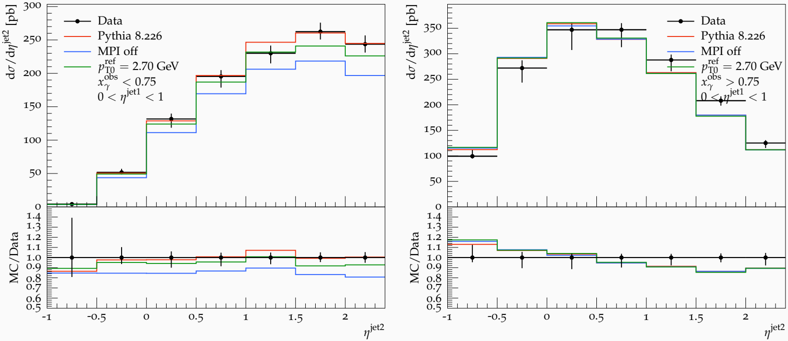
Charged particle η dependence in ep collisions at HERA



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

Dijet in ep collisions at HERA

Pseudorapidity dependence of dijets [Eur.Phys.J. C23 (2002) 615-631]



- Good agreement with the data
- Some sensitivity to MPIs with $x_\gamma^{obs} < 0.75$