Photon-photon and photon-hadron processes in PYTHIA 8

Photon 2017

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Motivation & Outline

Motivation

- $\gamma\gamma$ interactions in future e^+e^-colliders
- Photoproduction in e+p/A colliders
- Ultra-peripheral heavy-ion collisions

$\Rightarrow$ Aim: Robust simulations of photoproduction in different collision systems with Pythia 8

Outline

1. Event generation in Pythia 8
2. Photon-photon collisions
3. Photon-photon interactions in e^+e^- collisions
4. Photoproduction in ep collisions
5. Summary & Outlook

Event generation in PYTHIA 8

Pythia 8

- A general-purpose Monte-Carlo event generator
  $\Rightarrow$ Full event simulation
- Main focus has been in pp collisions (LHC)
- Native LO hard processes + parton showers (LL)

Team:

- Torbjörn Sjöstrand — Lund University
- Nishita Desai — CNRS-Universite de Montpellier
- Nadine Fischer — Monash University
- Ilkka Helenius — Tübingen University
- Philip Ilten — Massachusetts Institute of Technology
- Leif Lönnblad — Lund University
- Stephen Mrenna — Fermi National Accelerator Laboratory
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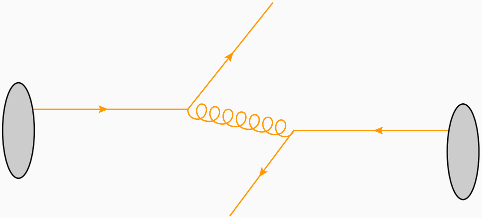
- Christine O. Rasmussen — Lund University
- Peter Skands — Monash University

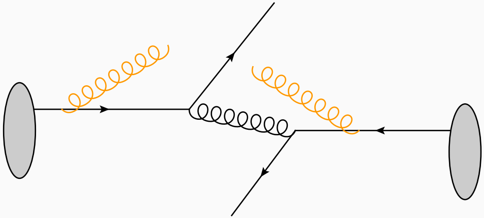


Hard process

- Sample hard process according to

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

- PDFs describe the partonic content of hadrons
  - Obtained from global DGLAP analysis

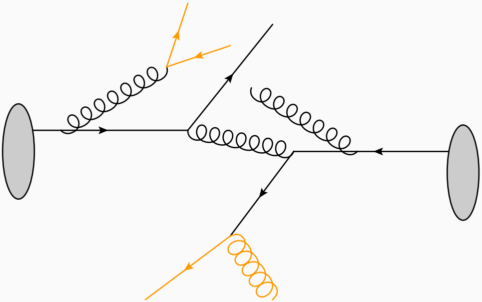


Initial state radiation (ISR)

- Trace back initiator splittings before the hard process
- Splitting probability from DGLAP (Conditional probability)

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

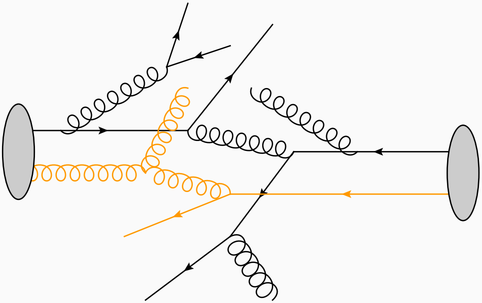
Event generation in PYTHIA 8



Final state radiation (FSR)

- Find splittings of outgoing partons
  - Includes also splittings of partons generated by ISR
- Splitting probability from DGLAP

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

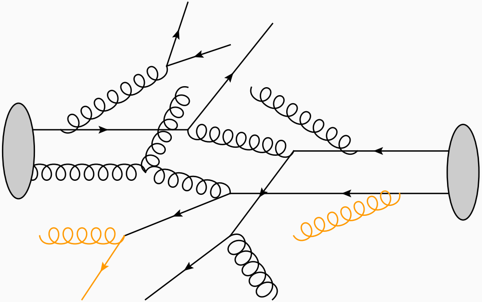


Multiparton interactions (MPI)

- Several partonic interactions in one collision
- Probability for a partonic interaction from $2 \to 2$ processes

$$\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_{\mathrm{T}}} = \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}}$$

Event generation in PYTHIA 8



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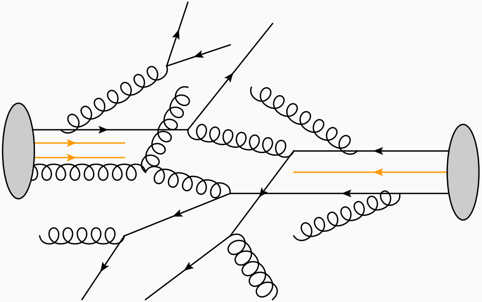
$\Rightarrow$ Further emissions from partons generated in MPIs

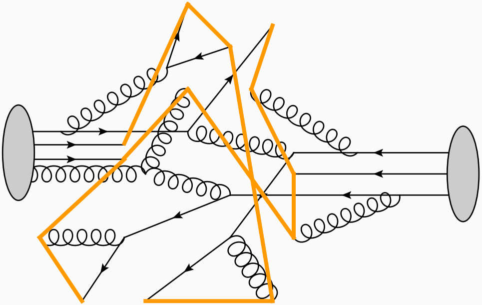
Event generation in PYTHIA 8



Beam Remnants

- Add partons to conserve flavour and colour
- Add primordial k_T for the partons
- Fix momenta of remnants to conserve total momentum

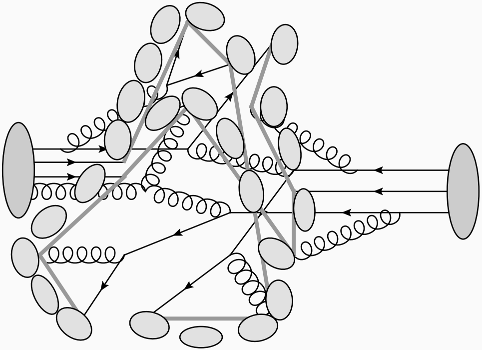
Event generation in PYTHIA 8



Hadronization with Lund string model

- Connect partons with colour strings
- Allow reconnection of colour strings

Event generation in Pythia 8



Hadronization with Lund string model

- Connect partons with colour strings
- Allow reconnection of colour strings
- Let the strings fragment to hadrons
- Decays to stable hadrons

Event generation in PYTHIA 8

MPIs and soft processes

- Cross section for $2 \to 2$ QCD processes diverge when $p_\mathrm{T} \to 0$

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

- Screening parameter p_T0 regulates $p_\mathrm{T} \to 0$ divergence
- 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, $\alpha = 0.215$)

Simultaneous partonic evolution

- Common evolution scale p_T, from $p_\mathrm{T}^\mathrm{hard}$ to $p_\mathrm{T}^\mathrm{min}$ ($\sim \Lambda_\mathrm{QCD}$)

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

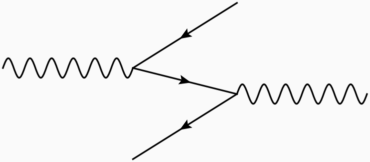
where exp[. . .] is a Sudakov factor

Photon-photon collisions

Photon-photon collisions

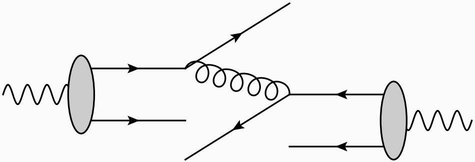
Direct processes

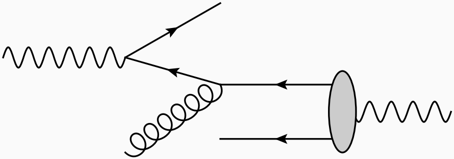
- Unresolved photons initiators of the process
- No MPIs or ISR (but FSR)



Resolved processes

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





Direct-Resolved processes

- no MPIs (but ISR for resolved side + FSR)

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

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

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

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

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

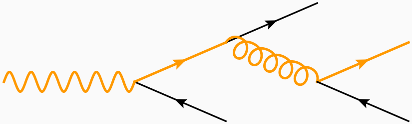
$$f_i^{\gamma,\rm had}(x,Q_0^2) = N_i x^{a_i}(1-x)^{b_i}$$

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-photon in e^+e^- collisions

Photon flux from leptons

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

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

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

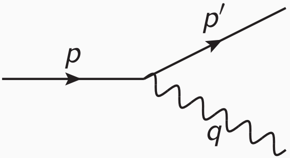
- Virtuality of the photon

$$Q^2 = -k^2 = -(p - p')^2$$

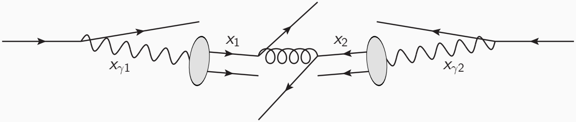
  is related to lepton scattering angle θ as

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

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



Hard processes

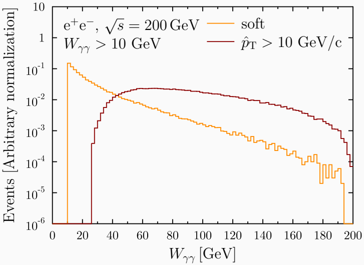


- PDFs required for hard-process sampling

  ⇒ Define parton-inside-photon-inside-lepton PDFs

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

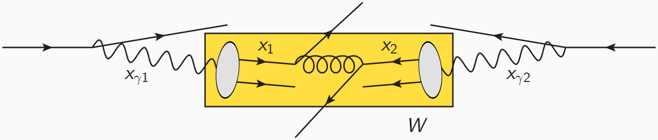
- Sample x_γ value each time PDFs are called
- Set up $\gamma\gamma$ sub-collision according to sampled x_γ
- $W_{\gamma\gamma}$ depends on phase-space cuts



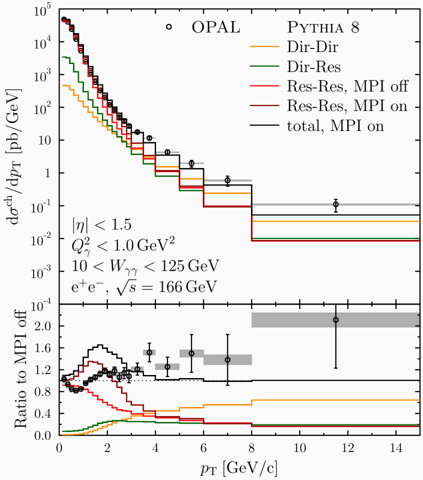
- e^+e^- collisions at $\sqrt{s} = 161$ and 172 GeV

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

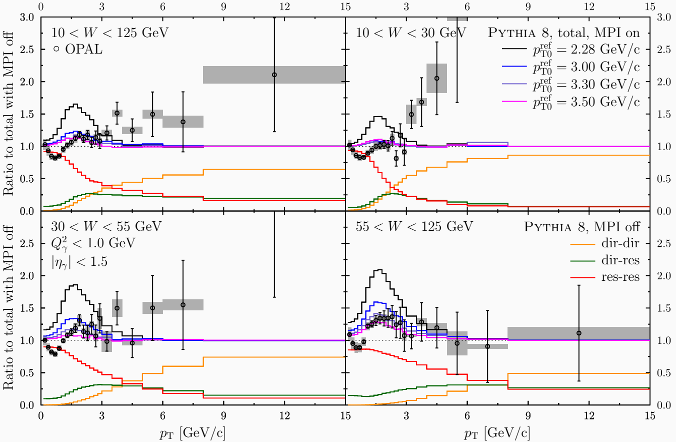
Compare with OPAL data

- 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 $p_{\mathrm{T0}}^{\mathrm{ref}}$ with data binned in W



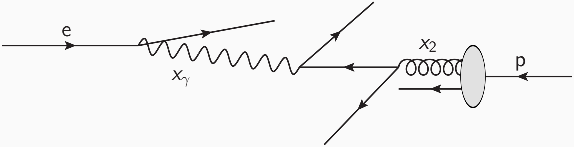
- Good agreement with the data using $p_{\mathrm{T0}}^{\mathrm{ref}} = 3.3$ GeV/c
- More hadrons from MPIs with higher W

Photoproduction in ep collisions

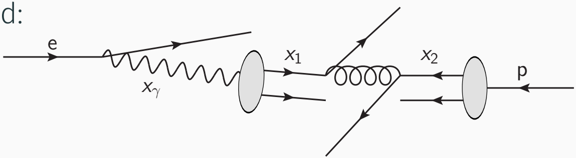
- Working e^+e^- framework with resolved photons easy to extend to ep collisions
- Photoproduction = small Q^2 (unlike in DIS)

Two components

- Direct:

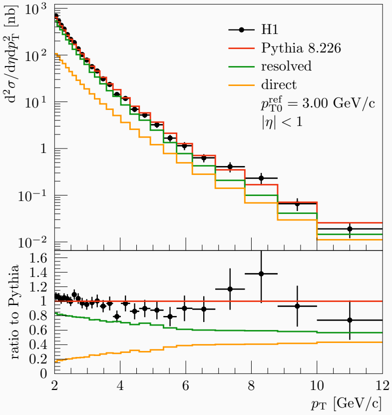


- Resolved:



Now W invariant mass of γp 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

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 ($\gamma\gamma$))

ZEUS dijet measurement

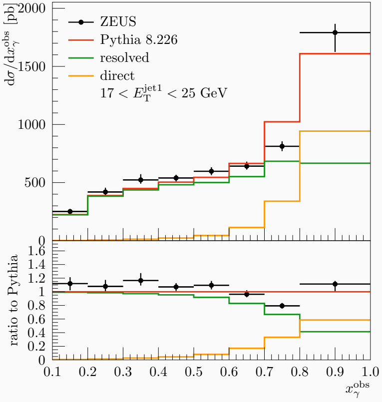
- $Q^2_\gamma < 1.0$ GeV^2
- $134 < W_{\gamma p} < 277$ GeV
- $E_T^{\text{jet1}} > 14$ GeV, $E_T^{\text{jet2}} > 11$ GeV
- $-1 < \eta^{\text{jet1,2}} < 2.4$

Different contributions

- Define

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

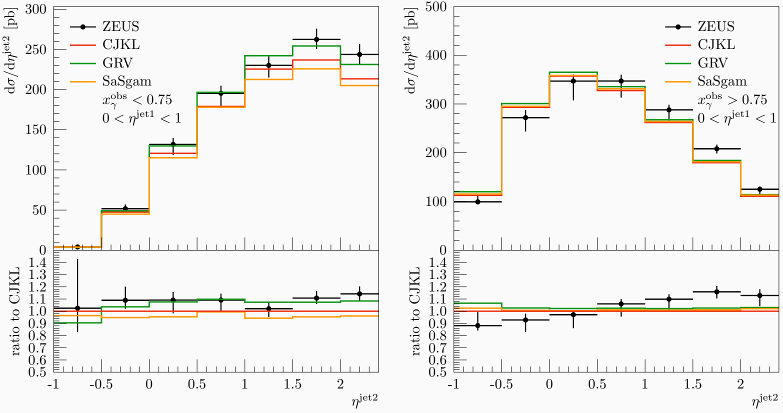
  to discriminate direct and resolved processes (=x_γ at LO parton level)
- At high-x_γ^{obs} direct processes dominate



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

Dijet in ep collisions at HERA

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

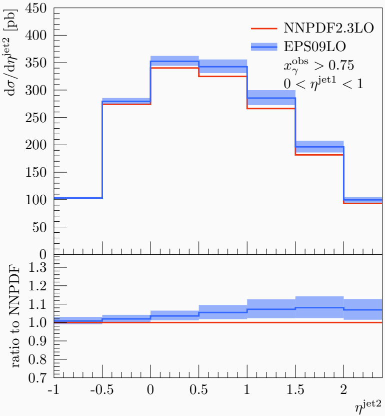


- Good agreement with data ($p_{\rm T0}^{\rm ref}$ fixed to H1 data with CJKL)
- Some sensitivity to photon PDFs with $x_\gamma^{\rm obs} < 0.75$ (CJKL default in Pythia 8)

Photoproduction and nuclear PDFs

Test sensitivity to nPDFs

- HERA kinematics but Pb instead of p
- Use $x_\gamma^{\mathrm{obs}} > 0.75$ to reduce photon PDF uncertainties
- Nuclear PDFs used only for hard process (not in parton showers or MPIs)



Ongoing work

- Nuclear PDFs into Pythia 8
- Photon flux from protons and ions
- A more involved model for nuclei

Summary

Summary & Outlook

Current status (Pythia 8.226)

- Full simulations of $\gamma\gamma$ collisions with (quasi-)real photons (Parton showers, MPIs, soft and hard QCD processes)
- Automatic mixing of direct and resolved contributions
- Implementation of photon flux from leptons (EPA)
  - $\Rightarrow$ Ready for FCC-ee studies
  - $\Rightarrow$ Can also simulate photoproduction in ep

Conclusions

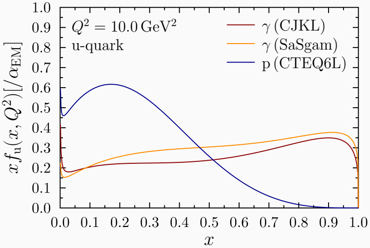
- Good agreement with data from LEP and HERA
- Data favors less MPIs with photons than with protons

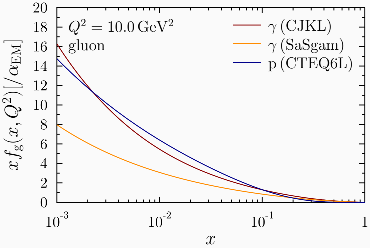
Future (not that far)

- Nuclear PDFs to study γA
- Photon flux from protons and nuclei

Backup slides

Photon PDFs





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

- Similar behaviour as with protons
- CJKL $\sim$ 2 more gluons than SaSgam

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

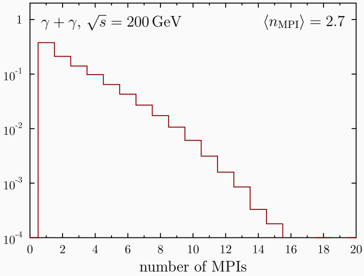
MPIs with photon beams

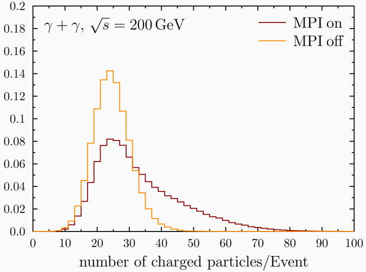
- Parametrization for $\sigma_{\text{tot}}(s)$

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

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

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



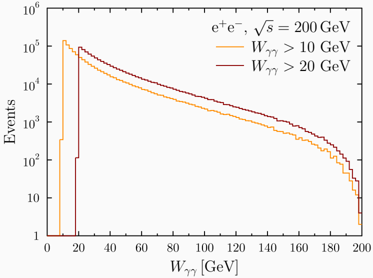


Soft processes

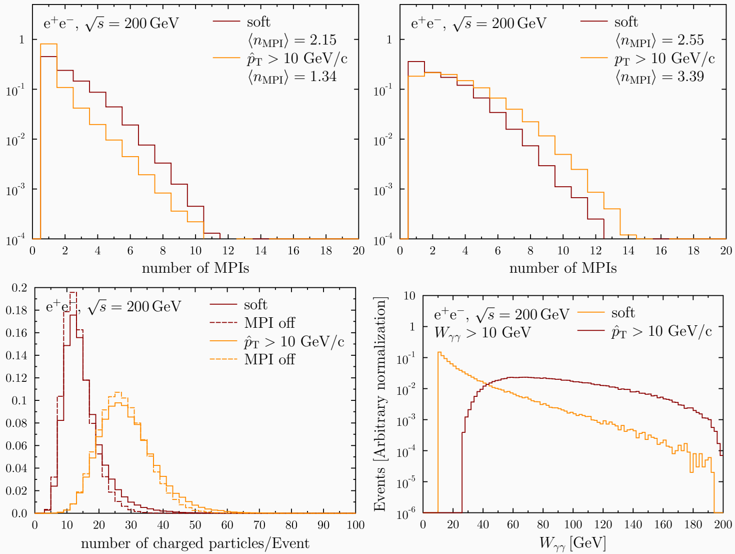
- Soft processes generated with MPI machinery

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

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



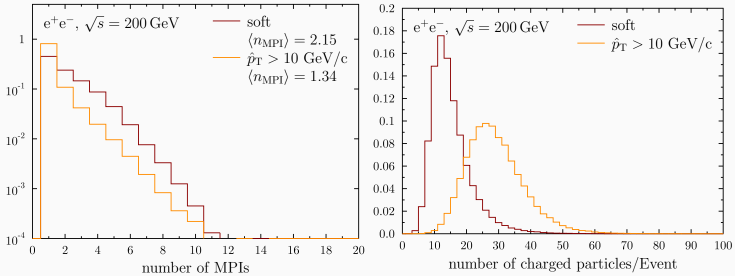
MPIs in e^+e^-



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

MPIs in e^+e^-

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



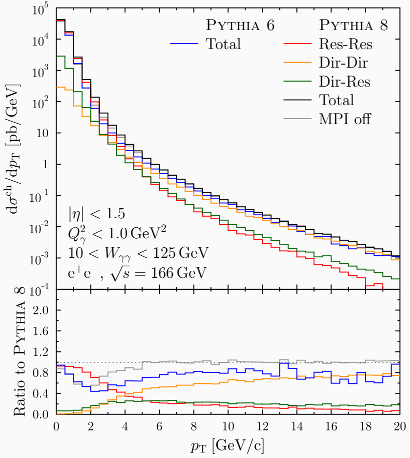
- Hard processes generate less MPIs than soft ones
  - $\gamma \to q\bar{q}$ splittings in ISR eliminate further MPIs

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

- Still more charged particles for hard processes

Charged particle p_T spectra

Combination of direct and resolved processes

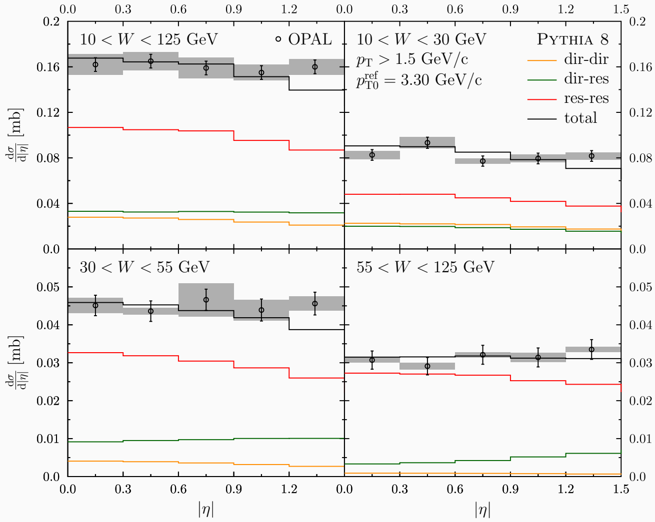


- Resolved processes dominate at low p_T
- Direct processes take over above $p_T \sim 5$ GeV/c

Comparison with Pythia 6:

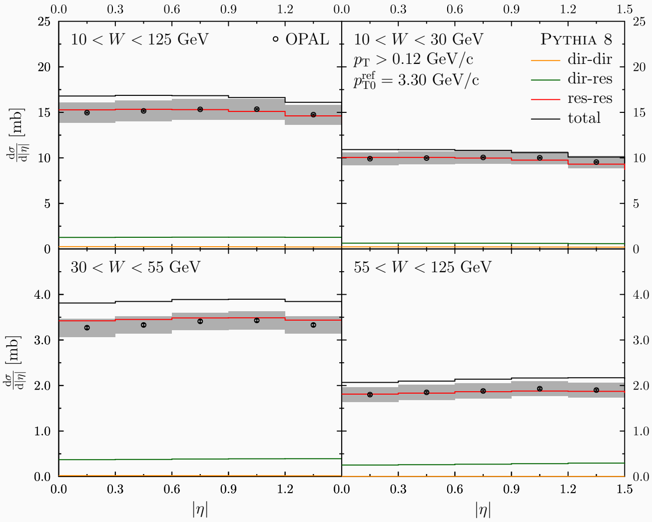
- Difference at $p_T \sim 2$ GeV/c due to MPIs
- high-p_T difference mainly from PDF sets

Pseudorapidity dependence



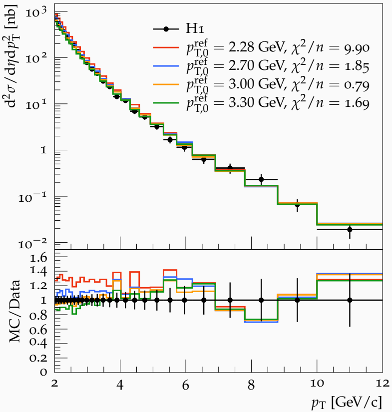
- Also η dependence looks good

Pseudorapidity dependence



- PYTHIA 8 result slightly above the data with $p_T > 0.12$ GeV/c

Charged particle p_T spectra in ep collisions at HERA



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

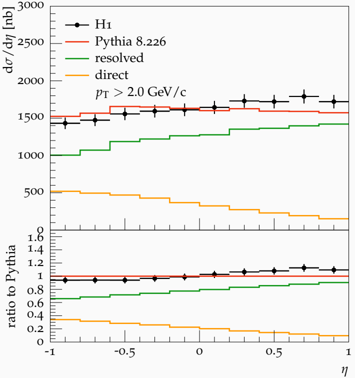
H1 measurement

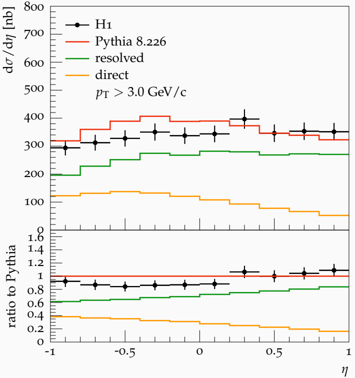
- $E_p = 820$ GeV, $E_e = 27.5$ GeV
- $< W_{\gamma p} > \approx 200$ GeV

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 ($\gamma\gamma$))

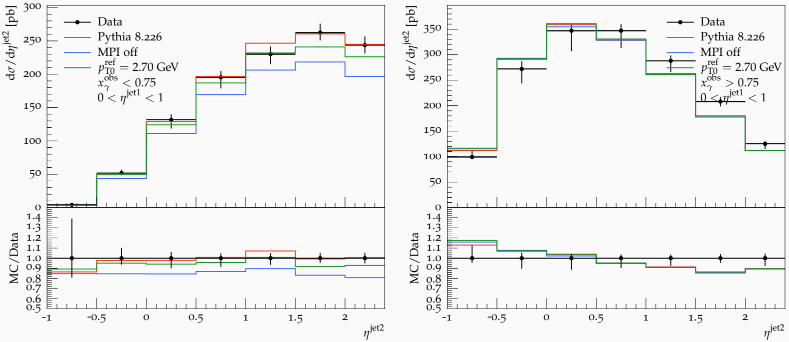
Charged particle η dependence in ep collisions at HERA





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

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



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