Photon-photon interactions in e^+e^- collisions with PYTHIA 8

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Motivation & Outline

Motivation

- Next large collider will (likely) be an e^+e^- collider
- Electrons emit photons which can interact
  $\Rightarrow$ Photon-photon collisions

Aim: A robust implementation of photon-photon interactions into PYTHIA 8

Outline

1. Introduction
2. $\gamma\gamma$ collisions
3. $\gamma\gamma$ in e^+e^- collisions
4. Results for e^+e^-
5. Summary & Outlook

Introduction

Event generation in PYTHIA 8

1. Hard process
   - Sample the process according to

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

2. Partonic evolution
   - Final state radiation (FSR)
     - Splitting probabilities from DGLAP

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

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

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

Event generation in PYTHIA 8

- Multiple partonic interactions (MPI)
  - Probability for a partonic interaction

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

  - Screening parameter $p_{\mathrm{T}0}$ regulates $p_\mathrm{T} \to 0$ divergence
- Common evolution scale (p_T)

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

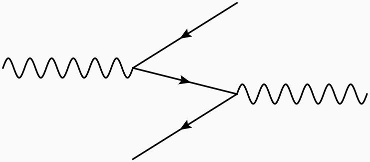
3. Hadronization
   - Colour reconnection
   - Lund string model
   - Decays to stable particles

Photon-photon collisions

Photon-photon collisions

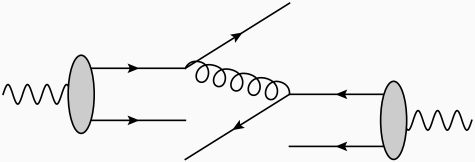
Direct processes

- 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

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

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

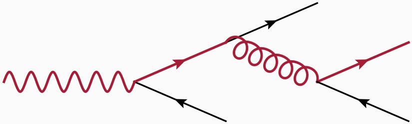
$$f_i^{\gamma,\mathrm{had}}(x,Q_0^2) = N_i x^{a_i}(1-x)^{b_i}$$

ISR with photon beams

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

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

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



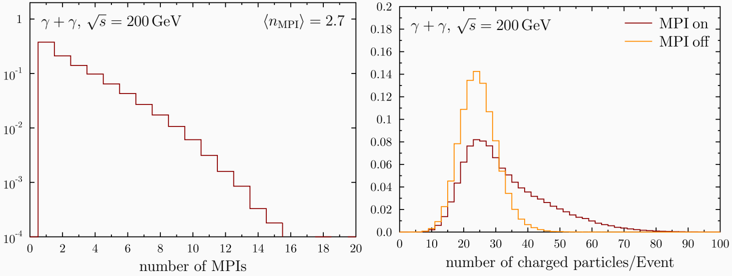
MPIs with photon beams

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

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

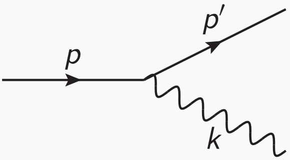
[Schuler, Sjöstrand, Z. Phys. C73 (1997)]

- 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



Photon-photon in e^+e^- collisions

- Flux of photons from leptons using equivalent photon approximation (EPA)
$$f_\gamma^e(x, Q^2_{\text{max}}) = \frac{\alpha_{\text{em}}}{2\pi} \int_{Q^2_{\text{min}}(x)}^{Q^2_{\text{max}}} \frac{dQ^2}{Q^2} \frac{(1 + (1-x)^2)}{x}$$
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 $Q^2_{\text{min}}(x) \approx m_l^2 x^2/(1-x)$

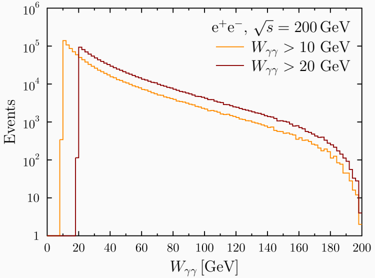


Soft processes

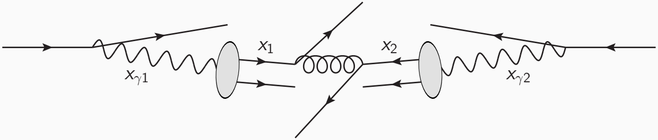
- Soft processes generated with MPI machinery

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

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



Hard processes



- Sample process above certain p_T

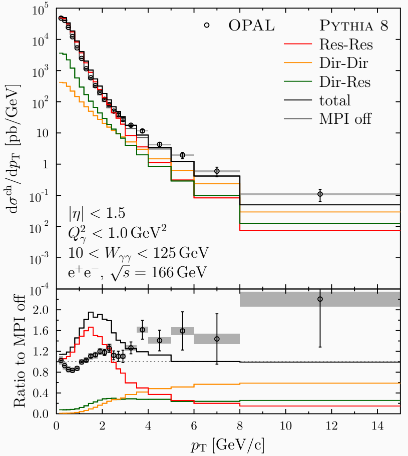
  $\Rightarrow$ Define parton-inside-photon-inside-lepton PDFs

$$
\begin{aligned}
xf_i^l(x, Q^2) &= \int_x^1 \frac{\mathrm{d}x_\gamma}{x_\gamma}\, x_\gamma f_l^\gamma(x_\gamma, Q^2_{\mathrm{max}})\, \frac{x}{x_\gamma} f_\gamma^i(x/x_\gamma, Q^2) \\
&= \frac{\alpha_{\mathrm{em}}}{2\pi} \int_x^1 \frac{\mathrm{d}x_\gamma}{x_\gamma} \log\left(\frac{Q^2_{\mathrm{max}}}{Q^2_{\mathrm{min}}(x_\gamma)}\right) (1 + (1 - x_\gamma)^2)\, \frac{x}{x_\gamma} f_\gamma^i(x/x_\gamma, Q^2)
\end{aligned}
$$

- Sample x_γ value each time PDFs are called
- $\gamma\gamma$ sub-collision is set up according to sampled x_γ

Results

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

Summary

Summary & Outlook

Currently included (Pythia 8.219)

- Hard processes with parton showers for resolved $\gamma\gamma$
- Resolved $\gamma\gamma$ interactions within e^+e^-

Next release

- MPIs and soft processes for resolved $\gamma\gamma$ also within e^+e^-
- Direct processes with scattered leptons
- Direct-Resolved processes (?)

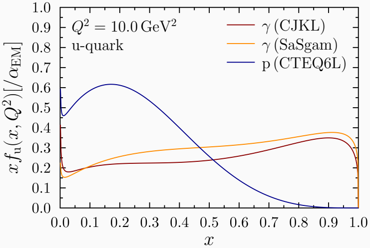
$\Rightarrow$ Full simulations of $\gamma\gamma$ events with (quasi-)real photons

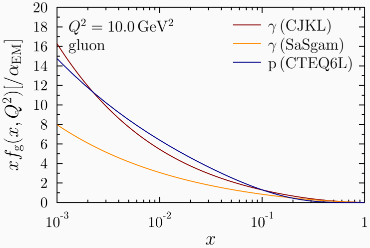
Future

- Further study of MPIs in $\gamma\gamma$
- Implement $\gamma\gamma$ in pp
- Include photons with high virtuality

Backup slides

Photon PDFs

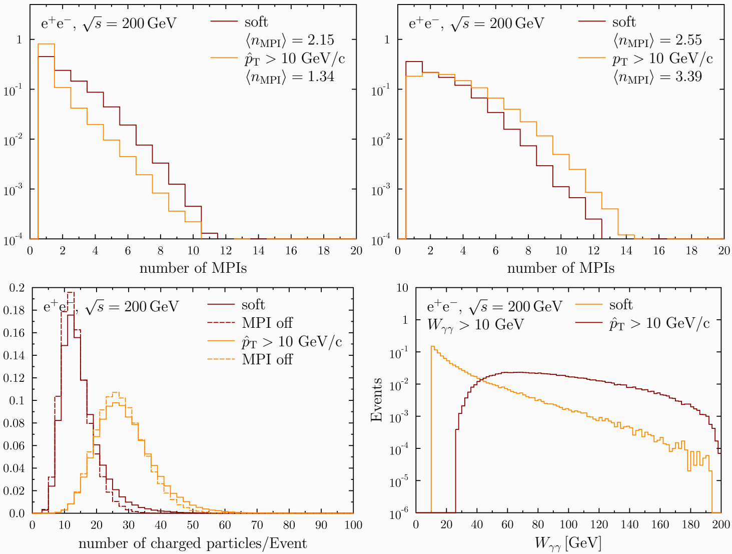




- More large-x quarks due to $\gamma \to \mathrm{q\overline{q}}$ splittings
- CJKL and SaSgam analysis agree for quarks
- Similar behaviour as with protons
- CJKL $\sim$ 2 more gluons than SaSgam

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

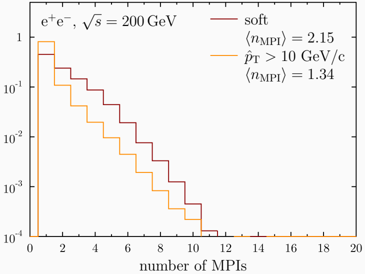
MPIs in e^+e^-

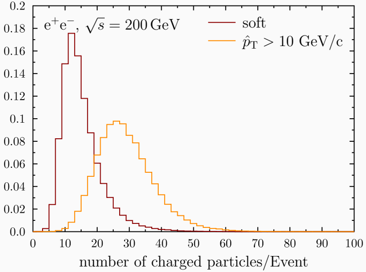


e+e−, √s = 200 GeV
soft
⟨n_MPI⟩ = 2.15
p̂_T > 10 GeV/c
⟨n_MPI⟩ = 1.34
number of MPIs
e+e−, √s = 200 GeV
soft
⟨n_MPI⟩ = 2.55
p_T > 10 GeV/c
⟨n_MPI⟩ = 3.39
number of MPIs
e+e−, √s = 200 GeV
soft
MPI off
p̂_T > 10 GeV/c
MPI off
number of charged particles/Event
e+e−, √s = 200 GeV
W_γγ > 10 GeV
soft
p̂_T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

MPIs in e^+e^-

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





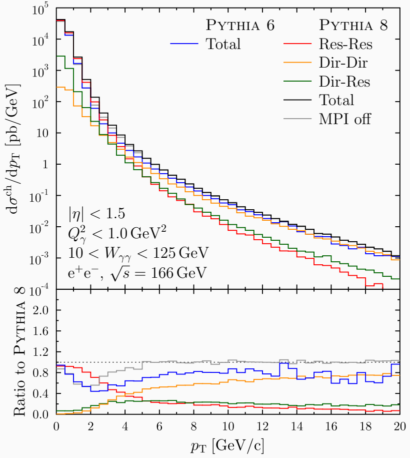
- Hard processes generate less MPIs as soft ones
  - $\gamma \to q\bar{q}$ splittings in ISR eliminate further MPIs

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

- Still more charged particles for hard processes

Charged particle p_T spectra

Combination of direct and resolved processes



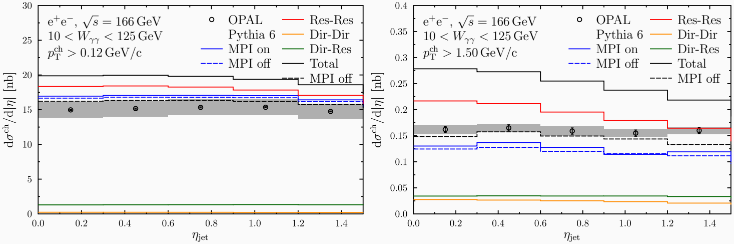
- Resolved processes dominate at low p_T
- Direct processes take over above $p_\mathrm{T} \sim 5$ GeV/c

Comparison with Pythia 6:

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

Charged particle cross section in η

Compare with OPAL data [Eur. Phys. J. C6 (1999) 253-264]



- Cross section flat in η up to $\eta = 1.5$
- Contribution mainly from resolved processes
- Good agreement when no MPIs included
- Very small effect from MPIs in PYTHIA 6