Photon-photon interactions with PYTHIA 8: Current status and future plans

FCC-ee Mini-Workshop: "Physics Behind Precision"

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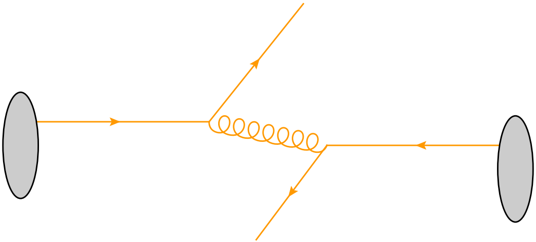
Outline

1. Introduction
   - Event generation in PYTHIA 8
2. Photon-photon interactions
   - PDFs for photons
   - Initial state radiation with photon beams
   - Beam remnant handling
   - Results
3. Future plans
   - Photon flux from electron beams
4. Summary

Event generation in Pythia 8



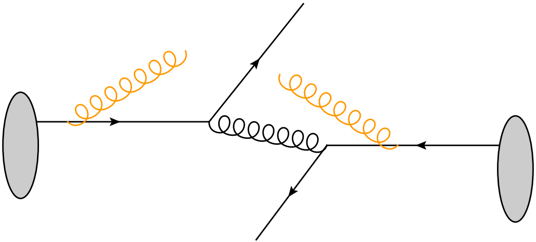
Hard process

- Collinear factorization

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

- Scale evolution for PDFs given by DGLAP equation

Event generation in PYTHIA 8

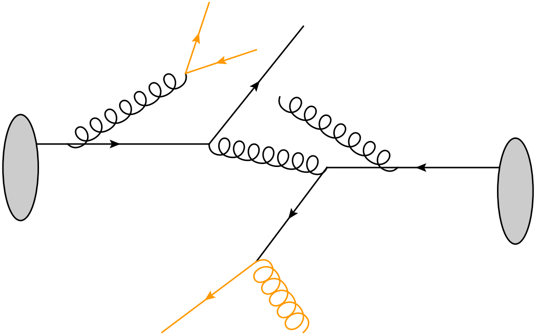


Initial state radiation (ISR)

- Backwards evolution, trace back splittings before the hard process
- Splitting probability from DGLAP (Conditional probability)

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

Event generation in PYTHIA 8

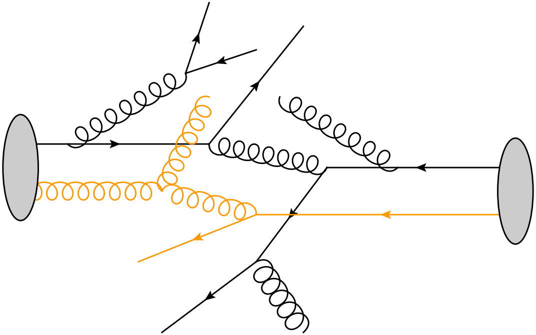


Final state radiation (FSR)

- Forward evolution, find splittings after the hard process
- Splitting probability from DGLAP

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

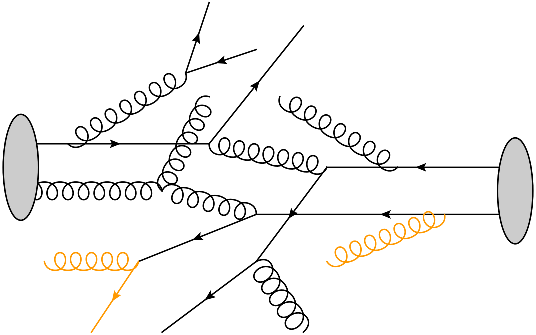
Event generation in PYTHIA 8



Multiparton interactions (MPI)

- Number of MPIs regulated by screening parameter p_{T0} (~ 2 GeV/c)
- Interleaved generation with ISR and FSR using p_T as a common evolution scale equipped with Sudakov factors

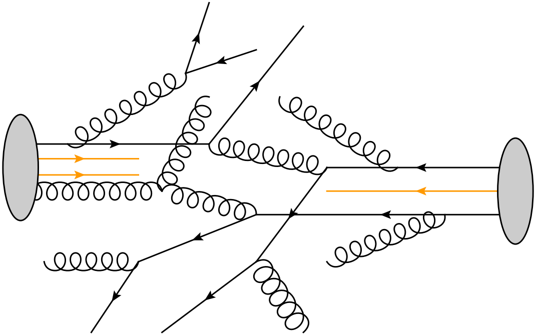
Event generation in PYTHIA 8



Multiparton interactions (MPI)

- Number of MPIs regulated by screening parameter p_{T0} $(\sim 2\ \mathrm{GeV/c})$
- Interleaved generation with ISR and FSR using p_T as a common evolution scale equipped with Sudakov factors
  $\Rightarrow$ Further emissions from partons generated by MPIs

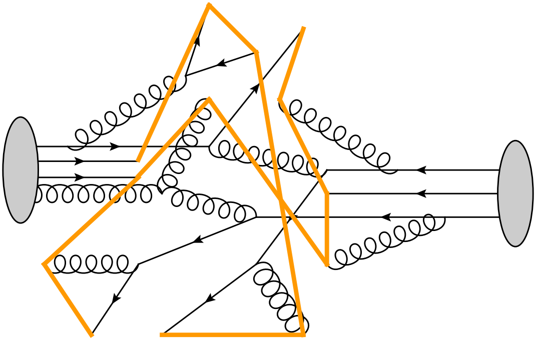
Event generation in PYTHIA 8



Beam Remnants

- Add required number of partons to conserve flavour and colour
- Add primordial k_T for the partons
- Fix the momentum of remnant partons to obtain total momentum conservation

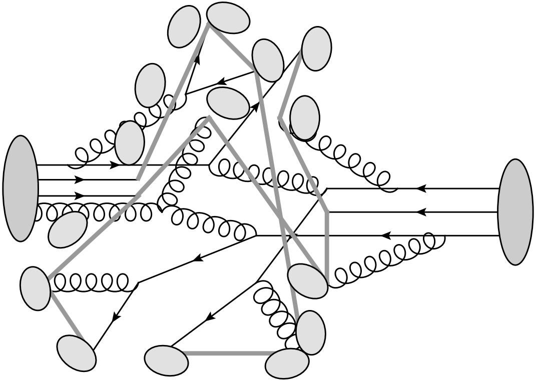
Event generation in Pythia 8



Hadronization with Lund string model

- Connect partons with colour strings
- Allow colour strings to be reconnected (Colour reconnection)

Event generation in PYTHIA 8



Hadronization with Lund string model

- Connect partons with colour strings
- Allow colour strings to be reconnected (Colour reconnection)
- Let the strings decay and form hadrons
- Decays to stable hadrons

Photon-photon collisions

Motivation

- Give access to many interesting processes and test QCD factorization
- Background for future $\mathrm{e}^+\mathrm{e}^-$ colliders, higher rate with higher luminosity
- Aim for a new robust model exploiting PYTHIA 8 developments

Current status (PYTHIA 8.215)

- Can generate hard processes in resolved $\gamma\gamma$ interaction with real photons
- Can generate ISR and FSR with photon beams
- Beam remnants with primordial k_T can be added
- Events can be hadronized

Resolved photons

- Partonic structure of resolved photons described with PDFs
- PDFs obtained via global QCD analysis

DGLAP equations for photons

- Additional term due to $\gamma \rightarrow \mathrm{q}\bar{\mathrm{q}}$ splittings

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

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

- Solution has two components:

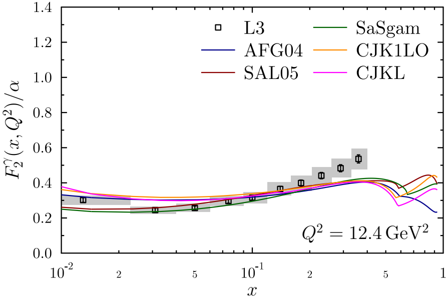
$$f_i^{\gamma}(x,Q^2) = f_i^{\gamma,\mathrm{pl}}(x,Q^2) + f_i^{\gamma,\mathrm{had}}(x,Q^2)$$

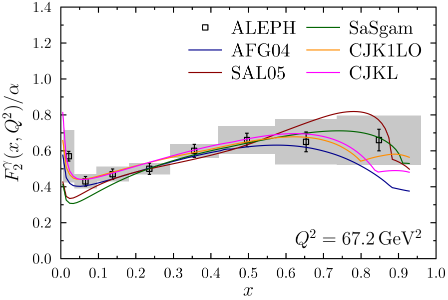
  Hadron-like part need non-perturbative input which is fixed by data

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

Photon PDFs

- Several groups have performed photon PDF analyses





- Reasonable agreement between the data and the fits
- Currenty we are using PDFs from CJKL analysis [PRD 68 014010 (2003)]
  - Leading order analysis, consistent with LO MC
  - Provides a parametrization for the PDFs
  - Provides point-like and hadron-like parts separately

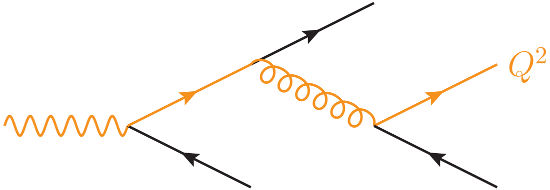
ISR with photon beams

Different DGLAP evolution

- Need to add a term corresponding to $\gamma \to \mathrm{q\bar{q}}$ splitting

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

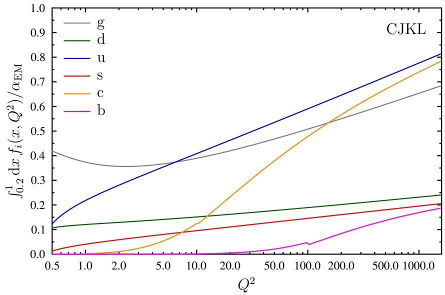
- Possibility to end up to the original photon during the evolution
  $\Rightarrow$ No further emissions
  $\Rightarrow$ No need for beam remnants



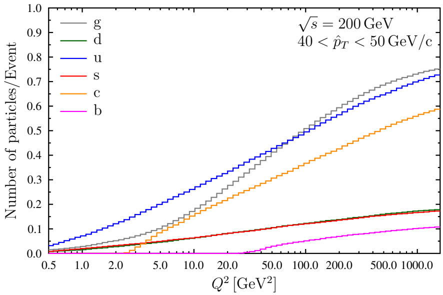
ISR vs PDFs

Backwards evolution should give same number of partons as PDF evolution

- The PDFs integrated over relevant region of x



- Number of particles produced below Q^2 from ISR algorithm



- Qualitatively similar behaviour but also some differences due to different inputs
- CJKL analysis uses ACOT(χ) scheme to deal with heavy quark masses
  $\Rightarrow$ Some differences in scale evolution

Beam remnants

Valence content of resolved photon

- Two "valence" quarks ($q\bar{q}$ pair), flavors can fluctuate
- Decompose PDFs to valence and sea parts

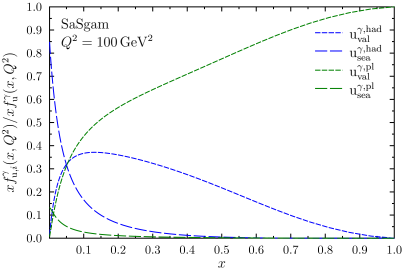
$$f_i^\gamma(x,Q^2) = f_{i,\mathrm{val}}^\gamma(x,Q^2) + f_{i,\mathrm{sea}}^\gamma(x,Q^2)$$

- Decide whether the parton from beam is a valence quark
  - If yes: Other valence quark is the corresponding (anti)quark
  - If not: Sample valence flavour using PDFs

A problem:

- Decomposition not provided
- CJKL: Valence content for hadron-like part

$$f_{i,\mathrm{val}}^\gamma = f_{i,\mathrm{val}}^{\gamma,\mathrm{had}} + f_i^{\gamma,\mathrm{pl}}$$



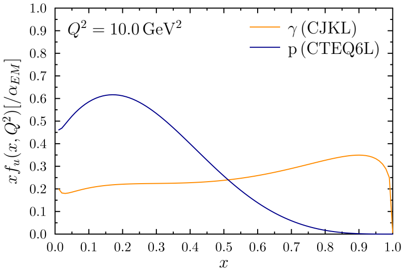
- Add minimal number of partons to conserve flavour, e.g. if
  - a valence quark from beam $\Rightarrow$ Add the other valence quark
  - a gluon from beam $\Rightarrow$ Add the valence quarks
  - a sea quark from beam $\Rightarrow$ Add the valence quarks + one companion quark

Need invariant mass for remnants

- Condition: $W_{\mathrm{rem}} > W_1 + W_2$
- Definitive limit when interaction between two valence quarks: $\sqrt{s(1-x_1)(1-x_2)} > m_1 + m_2$

$\Rightarrow$ Reject hard processes and ISR violating this condition

- Also primordial k_T increases the invariant mass



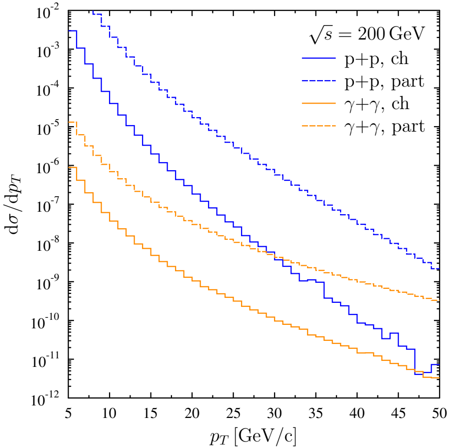
Results

Charged particle p_T spectrum

- $\gamma\gamma$ generated with
  - CJKL PDFs for photons
  - ISR and FSR
  - Beam remnants with primordial k_T
- MPIs are not included

Comparison to p+p

- Cross section smaller due to EM-coupling ($\alpha_{em}^2 \sim 10^{-4}$)
- Harder spectra due to larger number of large-x partons



- p_T spectra of the hard $2 \to 2$ scattering showed for comparison (dashed)

Future plans

Soft processes and MPI

- Include also soft QCD processes
- For MPIs need a model for total $\gamma\gamma$ cross section

Photon emissions from electrons

- Needed to get the rate of $\gamma\gamma$ interactions in $\mathrm{e^+e^-}$
- Photon flux machine dependent
  - For a circular collider (FCC-ee) bremsstrahlung dominant (EPA)

$$x f_{\gamma}^{\mathrm{e}}(x, Q^2) = \frac{\alpha_{em}}{2\pi} \log(Q^2/m_{\mathrm{e}}^2)(1 + (1-x)^2)$$

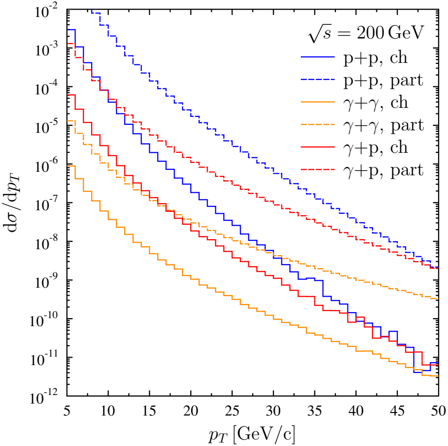
  - For linear $\mathrm{e^+e^-}$ collider with tighter bunches larger flux of photons
    $\Rightarrow$ Need more flexible form for photon flux
- Consider also photon virtuality (so far only real photons)

Bonus: γp collisions

Once $\gamma\gamma$ is set up, easy to extend to γp

- Still need to make sure that remnants can be added
- γp not yet included to public version
- Also the photon emissions from proton could be included

First test: Charged particle spectra



- $\mathrm{d}\sigma^{\gamma\gamma} < \mathrm{d}\sigma^{\gamma \mathrm{p}} < \mathrm{d}\sigma^{\mathrm{pp}}$

Summary & Outlook

Current status

- Can generate hard processes for resolved $\gamma\gamma$ interactions
- Parton showers can handle photon beams
- Beam remnants with primordial k_T can be added
- Events can be hadronized

$\Rightarrow$ Included into PYTHIA 8.215

Future plans

- Model the photon flux from electron beams
- Consider virtuality of the photons
- Add soft interactions and MPIs
- Develop further $\gamma\mathrm{p}$ and ep machinery

Backup

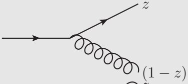
Parton distribution functions (PDFs)

- PDFs can not be calculated from first principles of QCD
- However, the Q^2 depedence is given by DGLAP evolution equations:

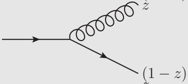
$$\frac{\partial f_i(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \sum_j \int_x^1 \frac{\mathrm{d}z}{z} P_{ij}(z)\, f_j(x/z,Q^2)$$

where j runs over the parton flavours

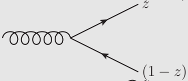
The leading order (LO) splitting functions



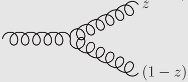
$$P_{qq}(z) = \frac{4}{3}\left[\frac{1+z^2}{(1-z)_+} + \frac{3}{2}\delta(1-z)\right]$$



$$P_{qg}(z) = \frac{4}{3}\left[\frac{1+(1-z)^2}{z}\right]$$



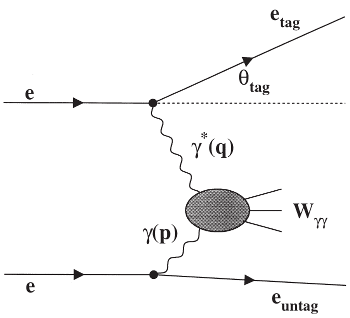
$$P_{gq}(z) = \frac{1}{2}\left[z^2 + (1-z)^2\right]$$



$$P_{gg}(z) = 6\left[\frac{z}{(1-z)_+} + \frac{1-z}{z} + z(1-z) + \frac{11-\frac{2}{3}n_f}{12}\delta(1-z)\right]$$

Data for photon PDFs

- Photon structure functions can be measured in $e^{-}+e^{+}$ collisions



[Phys.Lett.B436 (1998) 403-416]

"Photon DIS"

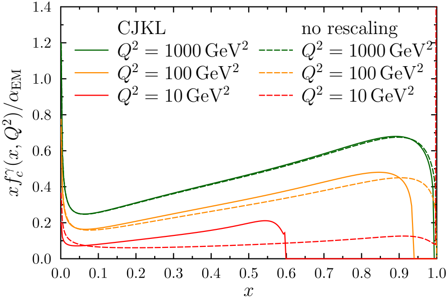
- Other electron emits a virtual photon (γ^{*})
  - $\Rightarrow$ This electron is measured
- Other electron is not detected as the scattering angle is small
  - $\Rightarrow$ Photon from this electron has small virtuality
- Also $W_{\gamma\gamma}$ need to be measured to construct kinematics

- Data available mainly from different LEP experiments ($\mathcal{O}(200)$ points)
- Precision and kinematic coverage more limited than for proton PDFs

ACOT(χ) scheme for heavy quarks

DIS kinematics

- Limit for heavy quark production
  $$W^2 = Q^2(x^{-1} - 1) > (2m_H)^2$$
- In ACOT(χ) scheme this is taken into account by rescaling
  $$x \to \chi = x(1 + 4m_H^2/Q^2)$$
- In CJKL the heavy quark PDFs are zero for $x > 1/(1 + \frac{4m_H^2}{Q^2})$



$\gamma + \gamma$ kinematics

- Heavy quark limit not related to Q^2 but $\sqrt{s}$ $\Rightarrow$ Undo rescaling
  $$x \to x/(1 + 4m_H^2/Q^2)$$