# Photon-photon collisions with PYTHIA8

## MCnet 2015

Ilkka Helenius
in collaboration with Torbjörn Sjöstrand

Lund University
Department of Astronomy
and Theoretical Physics

24.9.2015

# Outline

# Motivation

## Goal

- Simulate photon-photon collisions with PYTHIA8 Monte Carlo Event Generator

Why consider $\gamma + \gamma$ collisions?

- Interesting on its own right
- Background for the future $\mathrm{e}^{+} + \mathrm{e}^{-}$ collisions

Why not just use PYTHIA6?

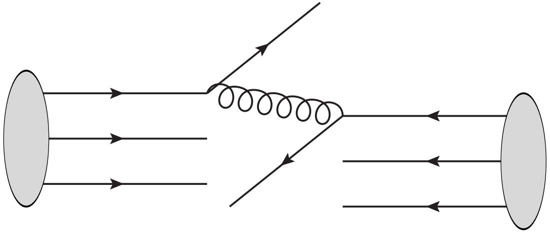
- The PYTHIA6 model got quite complicated and fragile
- New sets of photon PDFs since PYTHIA6
- Lots of developments in the event generation in PYTHIA8

$\Rightarrow$ New simpler and more robust implementation

# Hard process

Proton-proton collision:

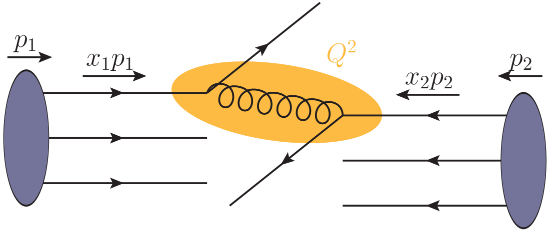
- Composite beams, interactions happens between the partons



# Hard process

Proton-proton collision:

- Composite beams, interactions happens between the partons




## Collinear Factorization

Factorize long and short distance physics:

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

- $\mathrm{d}\hat{\sigma}^{i+j\to k+l}$ from perturbative QCD
- $f_i(x, Q^2)$ non-perturbative but universal *parton distribution functions*

# Parton distribution functions (PDFs)

## 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 $P_{ij}(z)$ are splitting functions for $j \to ik$ splitting ($\mathrm{q} \to \mathrm{qg}$, $\mathrm{q} \to \mathrm{gq}$, $\mathrm{g} \to \mathrm{q\bar{q}}$ and $\mathrm{g} \to \mathrm{gg}$)

## PDFs obtained through a global analysis

1. Parametrize $f_i(x,Q^2)$ at chosen initial scale $Q_0$ ($\sim 1\,\mathrm{GeV}$)

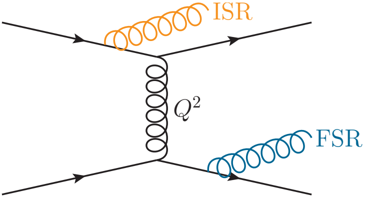
$$f_i(x,Q_0^2) = N_i x^{a_i} (1-x)^{b_i} F(x, c_i, \ldots)$$

2. Use DGLAP equations to calculate $f_i(x,Q^2)$ at $Q > Q_0$
3. Calculate cross section with the evolved PDFs
4. Fit to data to obtain the values for parameters $a_i, b_i, c_i, \ldots$

# Parton showers

The partons taking part to hard process can emit additional partons

- After the interaction:
  Final state radiation (FSR)
- Before the interaction:
  Initial state radiation (ISR)




Splitting probabilities from DGLAP evolution

- Final state radiation

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

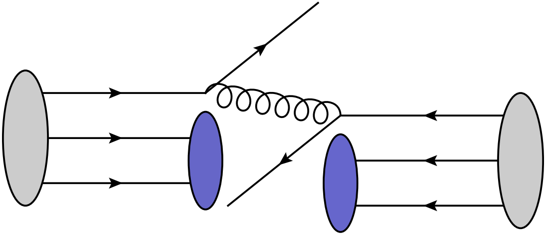
- Initial state radiation (Backwards evolution)

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

$\Rightarrow$ Showers generated by evolving down a common evolution scale

# Beam Remnants

After parton shower beam remnants need to be constructed



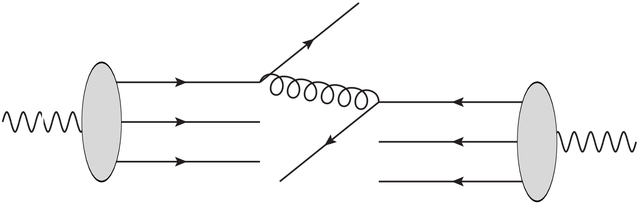
## Add partons to final state

- Decide whether the parton from the beam is a valence parton
- Add required number of partons so that flavour is preserved
- Construct the kinematics so that total momenta is conserved
  - Choose $x$'s according to PDFs and rescale

- After all partons are created the event can be hadronized

# Photon-photon collisions

- High-energy photons can fluctuate into a hadronic state with equal quantum numbers
- The hard interaction happens between the partons



⇒ To simulate these collisions PDFs for photons are required

- Can be obtained from global DGLAP analysis

# PDFs for photon

## DGLAP equations for photons

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

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

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

- Solution has two components:

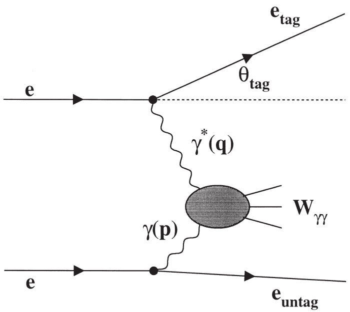
$$f_i^{\gamma}(x,Q^2) = f_i^{\gamma,\mathrm{pl}}(x,Q^2) + f_i^{\gamma,\mathrm{had}}(x,Q^2)$$

- Point-like part, calculated from pQCD
- Hadron-like part need non-perturbative input which is fixed by data

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

# Data for photon PDFs

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




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

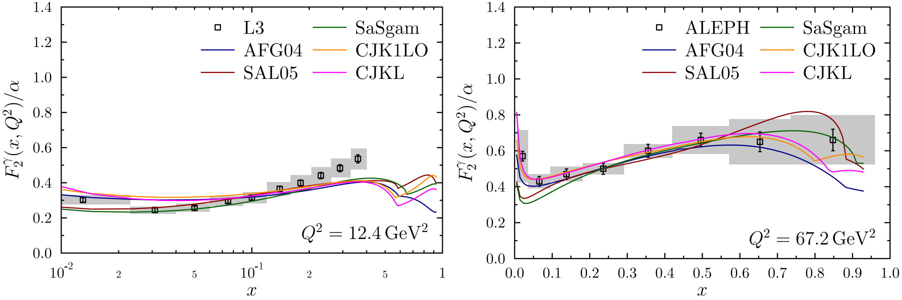
**"Photon DIS"**

- Other electron emits a virtual photon $(\gamma^*)$
  - $\Rightarrow$ 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

# Photon PDF fits

- 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)]
  - Provides a parametrization for the PDFs
  - Provides point-like and hadron-like parts separately

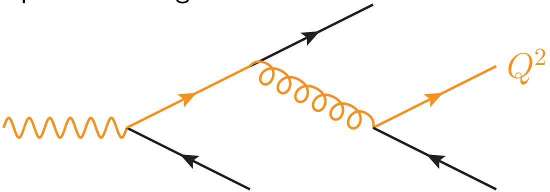
# ISR with photon beams

## Different DGLAP evolution

- The splitting probability for ISR is modified

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

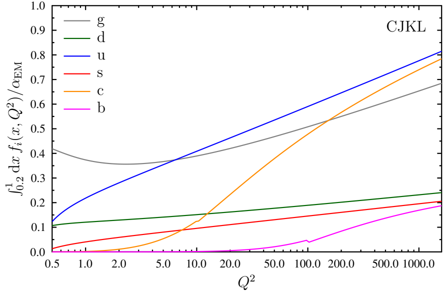
- New term in ISR algorithm corresponding the probability to find the original beam photon during evolution



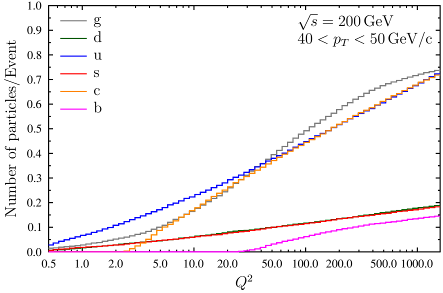

- Needs to be taken account in the beam remnant handling

# ISR comparison

- The PDFs integrated over relevant region of $x$




- Number of partons produced below $Q^2$ from ISR algorithm




Backwards evolution should produce the same results as the PDF evolution

- Heavy quarks disappears at the mass thresholds
- CJKL analysis uses ACOT($\chi$) scheme to deal with heavy quarks
  $\Rightarrow$ Some differences in scale evolution

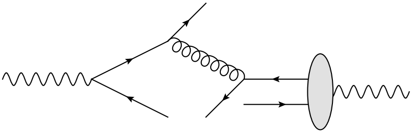
# Beam remnants

## Photon remnants

- Two "valence" quarks, flavors can fluctuate
  - Valence quarks from hadron-like PDF component
  - Quarks from $\gamma \rightarrow \mathrm{q}\bar{\mathrm{q}}$ splittings
- Use the information in the PDFs to determine whether the parton from beam was a valence quark
  - Yes: Beam remnant is the corresponding (anti-)quark
  - No: Sample the valence content according to PDFs
- If ISR ends up to the original photon no need for remnants

## Three possibilities

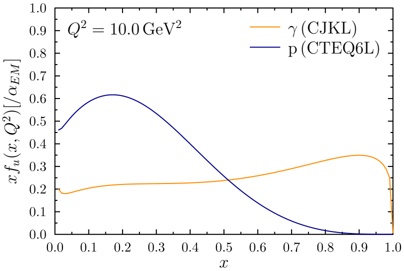
- Remnants from both beams
- Remnants from one beam
- No remnats

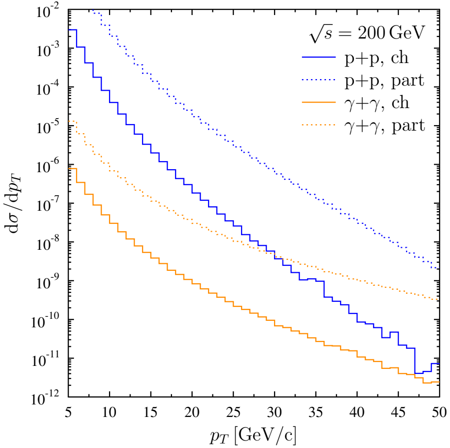


# Charged particle $p_T$ spectrum

## Comparison to p+p

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




- Generated with ISR+FSR
- No MPI considered yet

# Summary & Outlook

## Summary

- Implement photon-photon collisions into PYTHIA8 event generator
- Current status
  - Included PDFs for photons to generate the hard process
  - Modified the ISR algorithm to include the $\gamma \rightarrow \mathrm{q\bar{q}}$ splittings
  - Modified beam remnant handling with and without ISR
- Developments will be included to public PYTHIA8 version soon

## Outlook

- Consider also virtual photons and photon emission from electron beam
- Include possibility for MPI

# Backup

# ACOT($\chi$) scheme for heavy quarks

## DIS kinematics

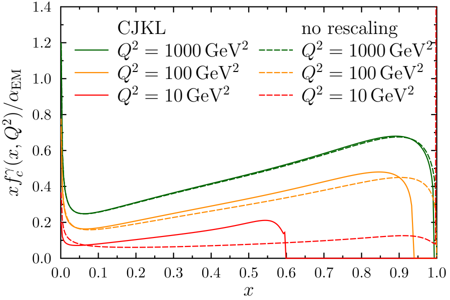
- Limit for heavy quark production

$$W^2 = Q^2(x^{-1} - 1) > (2m_H)^2$$

- In ACOT($\chi$) 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

$$x \to x/(1 + 4m_H^2/Q^2)$$

# ISR with photon beams

- The $x$-distribution for the specific kinematics