Monte Carlo event generation of photon-photon collisions at colliders

PHOTON2015

Ilkka Helenius
in collaboration with Torbjörn Sjöstrand

Lund University
Department of Astronomy
and Theoretical Physics

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Outline

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2. Monte Carlo event generation
   - Parton distribution functions
   - Parton showers
3. Photon-photon collisions
   - Evolution equations for photons
   - Initial state radiation
   - Beam remnants
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Motivation

Goal

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

Why consider $\gamma + \gamma$ collisions?

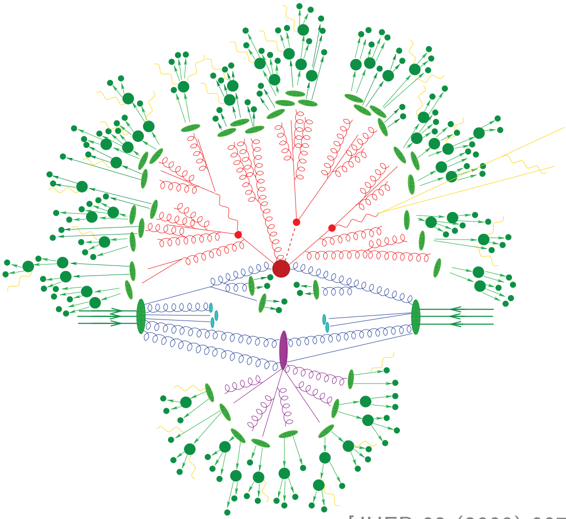
- Interesting on its own right
- Background for the future $\mathrm{e}^+ + \mathrm{e}^-$ collisions

$\gamma + \gamma$ collisions were included in PYTHIA6 event generator

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

$\Rightarrow$ New simpler and more robust implementation

- Goal: Simulate the whole event



[JHEP 02 (2009) 007]

Several components:

1. Hard process
2. Parton showers
3. Multiple interactions
4. Beam remnants
5. Hadronization
6. Decays

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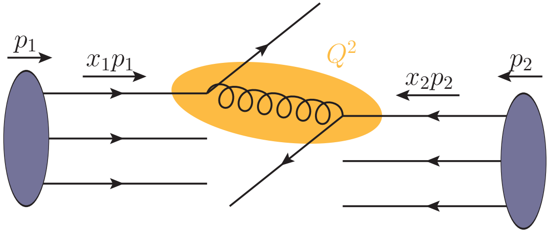
Hard process

Proton-proton collision:

- Composite beams, interactions happens between the partons



Collinear Factorization

Factorize long and short distance physics:

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

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

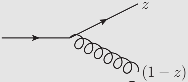
Parton distribution functions (PDFs)

DGLAP evolution

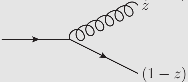
- DGLAP equations give the scale dependence of PDFs

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

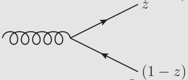
The splitting functions in leading order (LO)



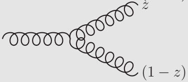
$$P_{qq}(z) = \frac{4}{3}\left[\frac{1+z^2}{(1-z)_+} + \frac{3}{2}\delta(1-z)\right]$$



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



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

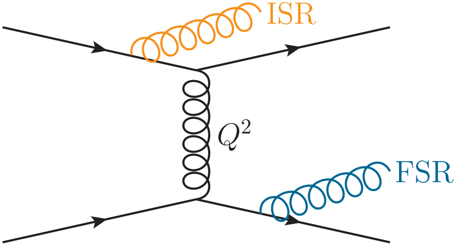


$$P_{gg}(z) = 6\left[\frac{z}{(1-z)_+} + \frac{1-z}{z} + z(1-z) + \frac{11-\frac{2}{3}n_f}{12}\delta(1-z)\right]$$

Parton showers

The partons taking part to hard process can emit additional partons

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



Also the emitted partons can radiate additional partons
$\Rightarrow$ Parton showers

Parton showers

Final state radiation

- Probability for splittings from DGLAP evolution

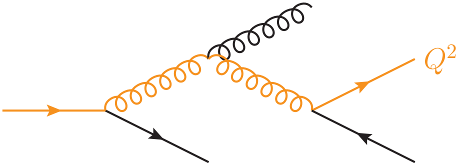
$$\mathrm{d}\mathcal{P}_{a\to bc} = \frac{\mathrm{d}Q^2}{Q^2}\frac{\alpha_s}{2\pi}P_{a\to bc}(z)\,\mathrm{d}z$$

Initial state radiation

- Splitting probability based on conditional probability

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

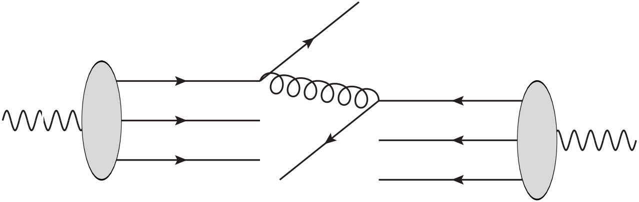
where $x' = x/z$



Showers generated by evolving down the common evolution scale $p^2_{T\mathrm{evo}}$ from $p^2_{T\mathrm{max}}$ to $p^2_{T\mathrm{min}}$

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

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
- 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

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

- 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

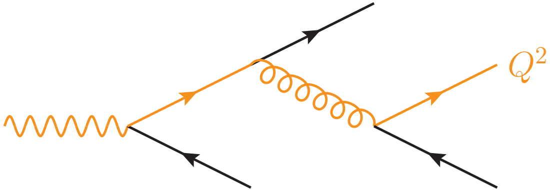
ISR with photon beams

Different DGLAP evolution

- The splitting probability for ISR is modified

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

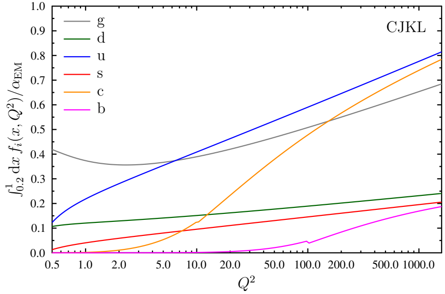
- Possibility to end up to the original photon during the evolution



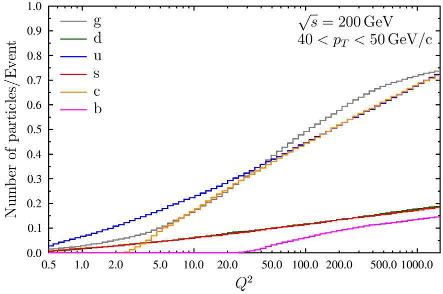
- The FSR is not modified

ISR comparison

- The PDFs integrated over relevant region of x



- Number of particles 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(χ) scheme to deal with heavy quarks
  $\Rightarrow$ Some differences in scale evolution

ACOT(χ) scheme for heavy quarks

DIS kinematics

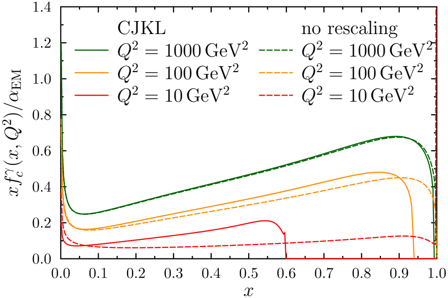
- Limit for heavy quark production

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

- 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

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

Beam remnants

Proton

- Three valence quarks
- Use PDFs to determine whether interacting quark is sea or valence
- Construct the beam remnants conserving momenta, color and valence content

Photon

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

Summary & Outlook

Summary

- Implement photon-photon collisions into PYTHIA8 event generator
- Current state
  - Included PDFs for photons to generate the hard process
  - Modified beam remnant handling without ISR
  - Modified the ISR algorithm to include the $\gamma \to q\bar{q}$ splittings

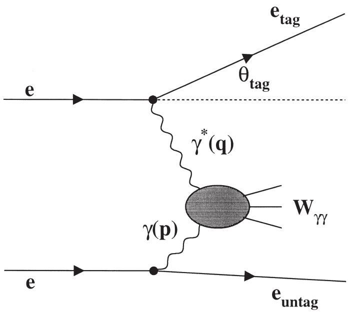
Outlook

- Modify the beam remnant handling with ISR
- Include possibility for multiple partonic interactions (MPI)
- Consider also virtual photons

Backup

Data for photon PDFs

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



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

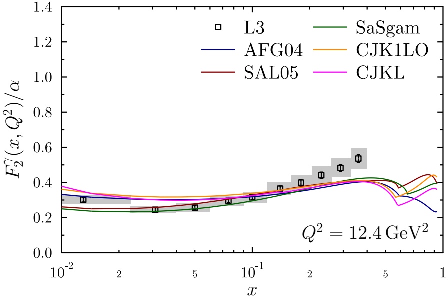
"Photon DIS"

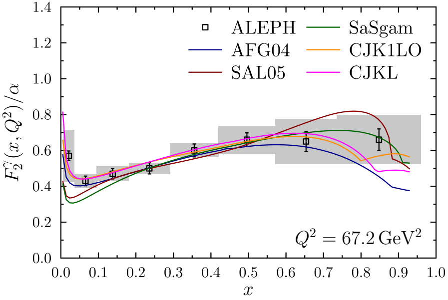
- Other electron emits a virtual photon (γ^{*})
  - $\Rightarrow$ This electron is measured
- Other electron is not detected as the scattering angle is small
  - $\Rightarrow$ Photon from this electron has small virtuality
- Also $W_{\gamma\gamma}$ need to be measured to construct kinematics

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

Photon PDF fits

- Several groups have performed photon PDF analyses





- Reasonable agreement between the data and the fits
- Some differences between different analyses
- Currently we are using CJKL analysis
  - Leading order analysis suitable for MC generators
  - Includes also LEP-II data
  - Provides the point-like and hadron-like components separately

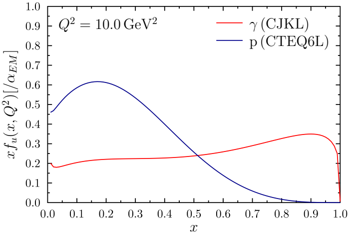
Comparison to p+p collisions

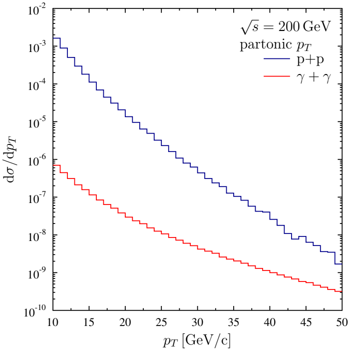
Comparison to proton PDFs

- Photon DGLAP evolution
$$\frac{\partial f_i(Q^2)}{\partial \log(Q^2)} = \frac{\alpha_{\mathrm{EM}}}{2\pi} k_i + \frac{\alpha_s(Q^2)}{2\pi} P_{ij} \otimes f_j(Q^2)$$
has the $\gamma \to q\bar{q}$ splitting
- Partons take larger fraction of momenta

Hard process

- Cross section lower due to small coupling constant ($\alpha_{\mathrm{EM}}^2 \sim 10^{-4}$)
- The slope of the cross section less steep
$\Rightarrow$ More high-p_T partons





ISR with photon beams

- The x-distribution for the specific kinematics