Recent PYTHIA 8 developments: Hard diffraction, Colour reconnection and $\gamma\gamma$ collisions

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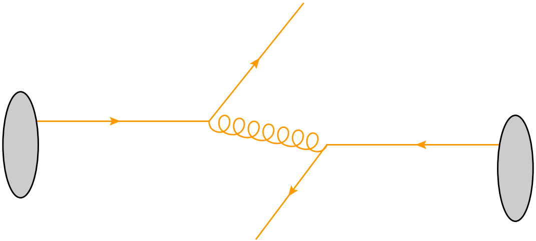
Outline

1. Introduction
   - Monte-Carlo event generation
   - PYTHIA 8 basics
2. Hard diffraction (by Christine O. Rasmussen and Torbjörn Sjöstrand)
   - PYTHIA 8 implementation
   - Dynamical rapidity gap survival
3. Colour reconnection (by Jesper Roy Christiansen, Peter Skands and T.S.)
   - The new model
   - Baryon-to-meson ratios
   - Multiplicity dependence
4. Photon-photon collisions (by I.H. and T.S.)
   - Photon PDFs
   - Parton shower
   - Beam remnants
5. Summary & outlook

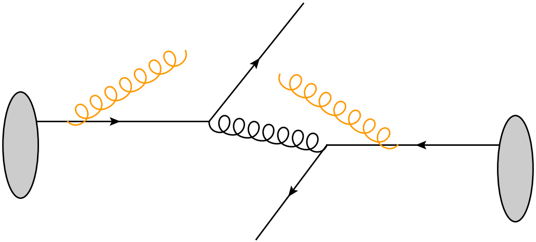
Monte-Carlo event generation



Goal: Describe all stages of an event

- Hard Process

Monte-Carlo event generation



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- Hard Process
- Initial state radiation (ISR)

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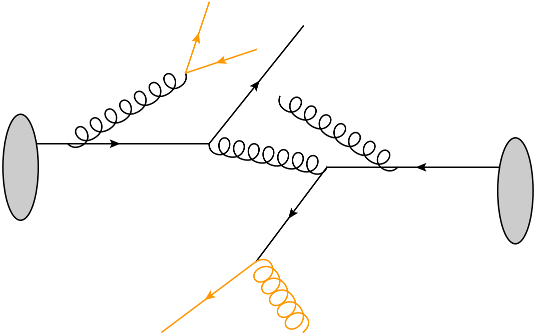

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- Initial state radiation (ISR)
- Final state radiation (FSR)

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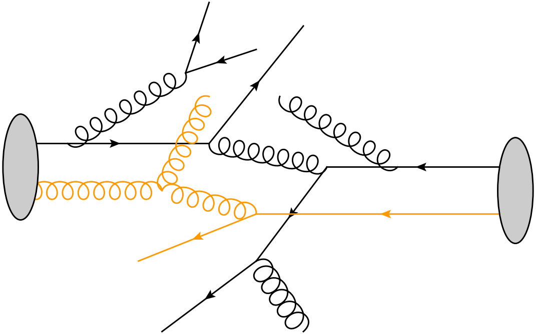

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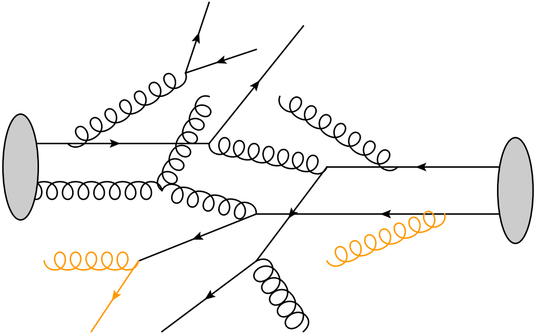

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- Radiation from MPIs

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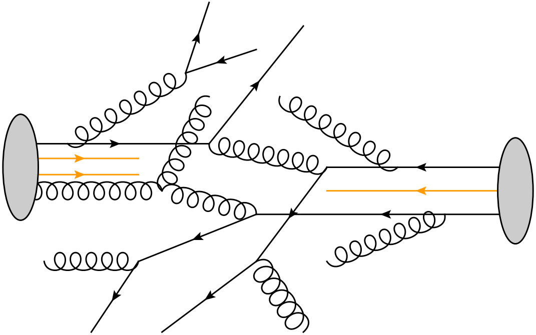

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- Hard Process
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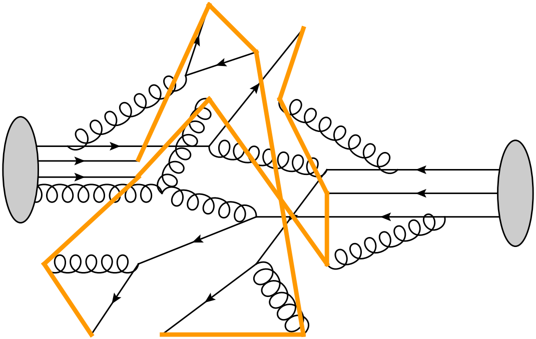
- Radiation from MPIs
- Beam remnants

Monte-Carlo event generation



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- Hadronization

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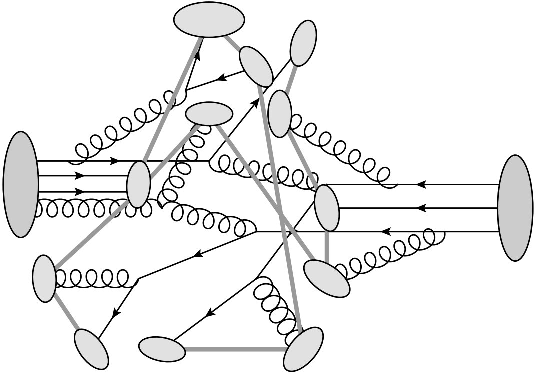

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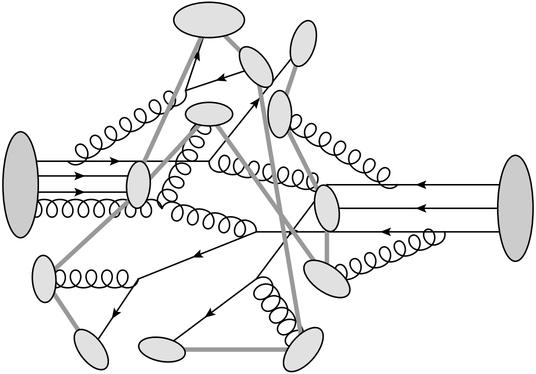

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- Hard Process
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- Multiparton interactions (MPI)
- Radiation from MPIs
- Beam remnants
- Hadronization
- Decays to stable hadrons

Pythia 8 basics

Interleaved evolution

- Evolve down using a common p_T-scale

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_T} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_T} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_T} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_T}\right)$$
$$\times \exp\left[-\int_{p_T}^{p_T^{\max}} \mathrm{d}p'_T \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_T} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_T} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_T}\right)\right]$$

- Sample a p_T value for all possibilities
- Pick the one with highest p_T and continue the evolution from there
- Number of MPIs regulated with screening parameter p_{T0} $(\sim 2\,\mathrm{GeV})$

Lund string model for hadronization

- Connect partons with colour strings
- Colour connections can be shuffled (Colour reconnection)
- Strings decay and form hadrons

Hard diffraction

Christine O. Rasmussen

Hard diffraction in PYTHIA 8

Hard diffraction = Diffractive events with a hard process

Selection of diffractive events using PDFs

- Generate hard process as usual, get parton flavour i, x and Q^2
- Split normal hadronic PDFs into non-diffractive and diffractive parts

$$f_i(x, Q^2) = f_i^{\mathrm{ND}}(x, Q^2) + f_i^{\mathrm{D}}(x, Q^2)$$

- The diffractive PDF are factorized as

$$f_i^{\mathrm{D}}(x, Q^2) = \int_x^1 \frac{\mathrm{d}x_{\mathbb{P}}}{x_{\mathbb{P}}} \int_{t_{\min}}^{t_{\max}} \mathrm{d}t \, f_{\mathbb{P}/p}(x_{\mathbb{P}}, t) \, f_{i/\mathbb{P}}(x/x_{\mathbb{P}}, Q^2)$$

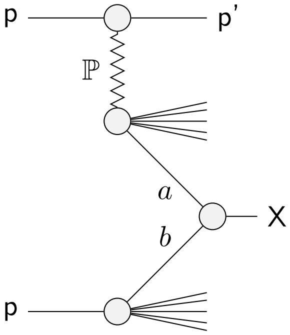
- Use PDFs to determine whether hard process of diffractive origin
- The probabilities for either sides to be diffractive are

$$\mathcal{P}_{\mathrm{B}} = f_i^{\mathrm{D}}(x_a, Q^2)/f_i(x_a, Q^2)$$
$$\mathcal{P}_{\mathrm{A}} = f_i^{\mathrm{D}}(x_b, Q^2)/f_i(x_b, Q^2)$$

Dynamical rapidity gap survival

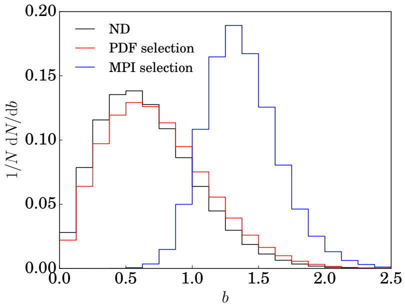
Generate parton shower and MPIs to see whether the rapidity gap survives

Single diffractive event



- MPIs generated for proton-proton and pomeron-proton system
- If rapidity gap survives event considered as diffractive

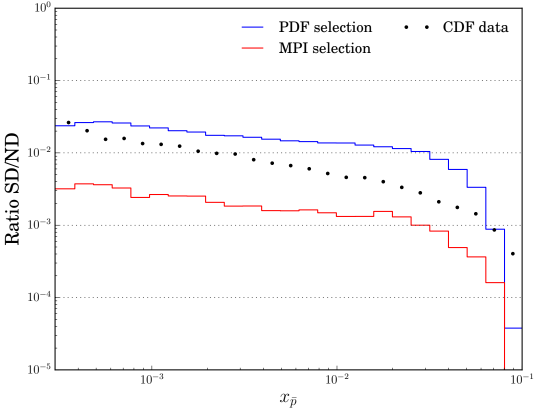
Impact parameter distributions



- PDF selection similar as ND
- After MPIs the events with larger b (lower multiplicity) survives

Preliminary results

Comparison with CDF data for $\mathrm{p}+\bar{\mathrm{p}}$ [Phys.Rev.D86 (2012) 032009]



- Too much suppression due to MPIs
- Suppression constant in $x_{\bar{p}}$
- Better description with reduced number of MPIs (larger p_{T0})
- Uncertainties in PDFs not yet considered

Colour reconnection

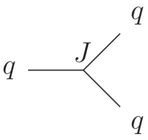
Jesper Roy Christiansen

The new colour reconnection (CR) model

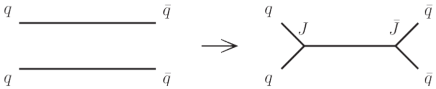
The new CR model reshuffles the colours just prior to hadronization based on three main principles:

- Use the SU(3) colour rules to determine if two strings are colour compatible
- Use a simplistic space-time picture to tell if the two strings coexist
- Minimize λ string-length measure to find which colour configurations are preferred

- Colour epsilon tensor corresponds to a junction structure

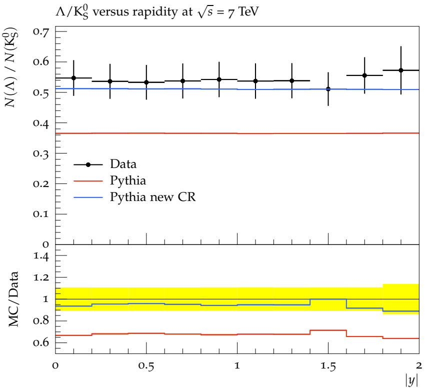
$q^i q^j q^k \epsilon^{ijk} \longrightarrow$ 

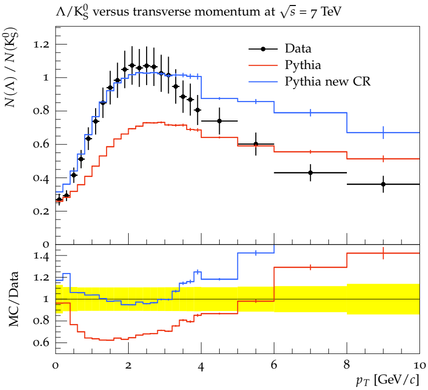
- New type of reconnection



Tests - Λ/K_s

Comparison to CMS data at $\sqrt{s} = 7.0\,\mathrm{TeV}$ [JHEP 05 (2011) 064]



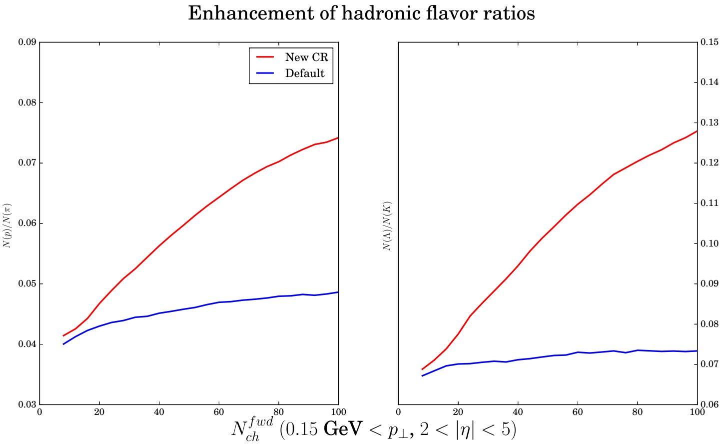


- Model parameters tuned to overall yield
- (No rate change in e^+e^-)

- Λ/K_S is better described by the new model
- Still some discrepancy at $p_T > 5\,\mathrm{GeV/c}$

Multiplicity dependent particle ratios

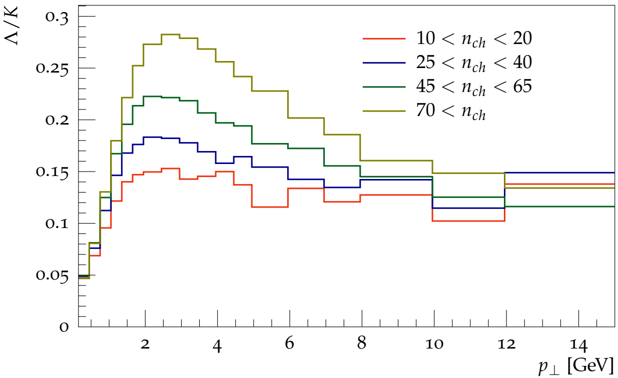
p/π and Λ/K ratios at $|\eta| < 1$ and $\sqrt{s} = 7\,\mathrm{TeV}$



- Higher multiplicity $\rightarrow$ more CR $\rightarrow$ more baryon enhancement
- Great observables to test baryon/strangeness enhancement for new models

CR and Flow-like effects

Particle ratios with different multiplicities



- Flow-like effects observed in pp is potentially connected with CR
- Repeat typical HI observable: Λ/K as function of $p_{\perp}$ separated into different multiplicity intervals (or centrality)
- Qualitative similar effect seen in the model as in HI collisions

Photon-photon collisions

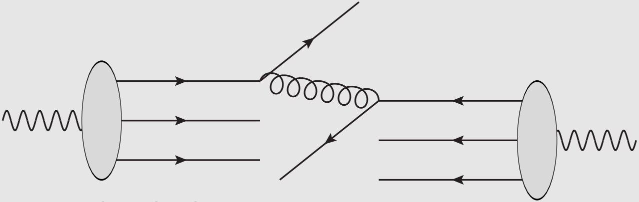
Photon-photon collisions

Motivation

- Interesting on its own right
- Background for future e^+e^- colliders
- Aim for a new robust model exploiting PYTHIA 8 developments

Framework

- High-energy photons can fluctuate into a hadronic state
- The hard interaction occurs between the partons



- Can be generated with photon PDFs

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

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

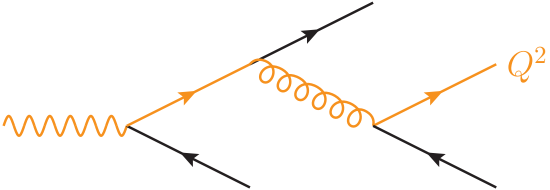
ISR with photon beams

Splitting probability for backwards evolution from DGLAP

- New term corresponding to $\gamma \rightarrow \mathrm{q\bar{q}}$ splitting

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

- Probability to find the original beam photon during backwards evolution



- No need to construct the beam remnants

Beam remnants

Photon remnants

- Two "valence" quarks, flavors can fluctuate
- Decompose the PDFs to valence and sea parts

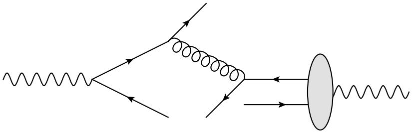
$$f_i^{\gamma}(x, Q^2) = f_{i,\mathrm{val}}^{\gamma}(x, Q^2) + f_{i,\mathrm{sea}}^{\gamma}(x, Q^2)$$

- Decide whether parton is valence quark and construct remnants
- Need to have room for massive partons: $W_{\mathrm{rem}} > W_1 + W_2$
  Definitive limit when two valence quarks interact without k_T:

$$\sqrt{s(1 - x_1)(1 - x_2)} > m_{\mathrm{val},1} + m_{\mathrm{val},2}$$

- Reject hard processes and splittings that violate this condition

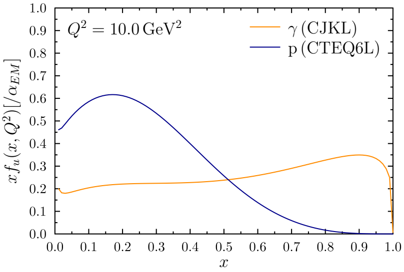
- Remnants for both beams
- Remnants for one beam
- No remnats

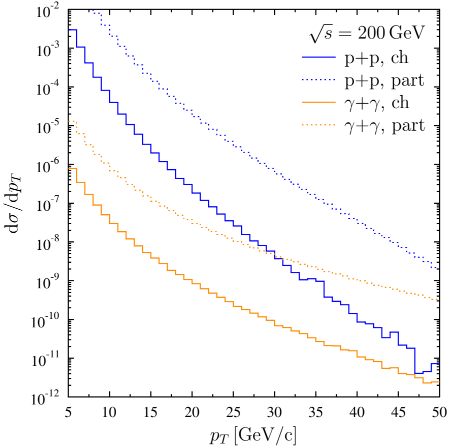


Charged particle p_T spectrum

Comparison to p+p

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





- Generated with ISR+FSR
- No MPI considered yet

Summary & Outlook

New model for hard diffraction available

- Dynamical rapidity gap survival
- Some disagreement with the CDF data
- Potentially improved with new Pomeron flux

New colour reconnection model

- Includes also junction structures
- Better description of the baryon-to-meson ratios
- Multiplicity dependence similar as obtained from flow in heavy-ions

Photon-photon collisions

- Can now produce fully hadronized events with hard processes
- Model the photon emissions from electrons and consider virtuality
- Include soft interactions and MPIs

Backup

Soft diffraction

- Diffractive and elastic events calculated with Pomeron-based parametrization of Schuler–Sjöstrand

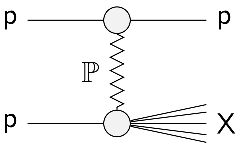


Figure: SD

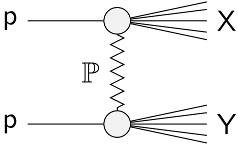


Figure: DD

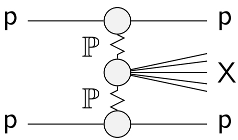


Figure: CD

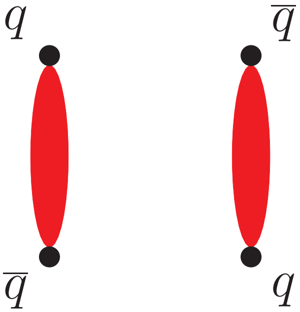
- Non-diffractive (ND) cross section from

$$\sigma_{\mathrm{ND}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}} - \sum_{\mathrm{X=S,C,D}} \sigma_{\mathrm{XD}},$$

where σ_{tot} calculated using Donnachie-Landshoff parametrisation

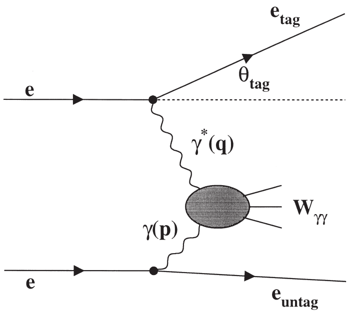
Multiple strings

- What happens for multiple strings?
  - QCD quadropole? We have no idea how to hadronize this
  - Instead use several dipoles!
  - Multiple possible pairings ⇒ Colour reconnection!



Data for photon PDFs

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



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

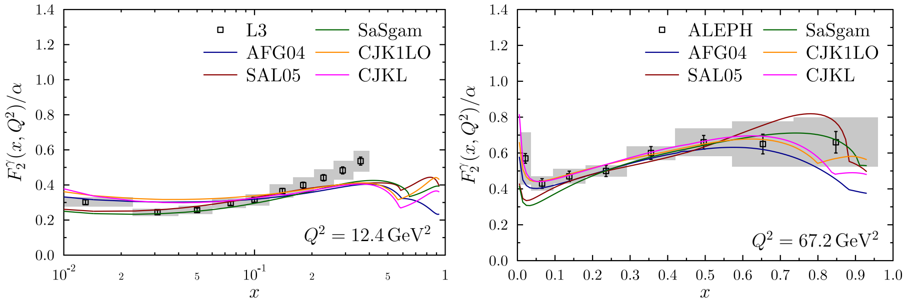
"Photon DIS"

- 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
- 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

ACOT(χ) scheme for heavy quarks

DIS kinematics

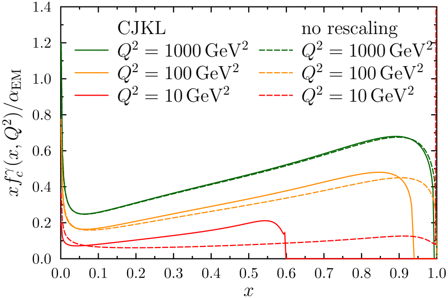
- Limit for heavy quark production

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

- In ACOT(χ) scheme this is taken into account by rescaling

$$x \rightarrow \chi = x(1 + 4m_H^2/Q^2)$$

- 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

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