Phenomenology with unintegrated parton showers

Michal Deák

Instituto de Fisica d'Altas Energias,

Universidad Autonoma de Barcelona

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- Motivation and introduction to BFKL and CCFM equations
- Implementation in Monte Carlo generators
- Shortly on fits
- Application to the LHC physics
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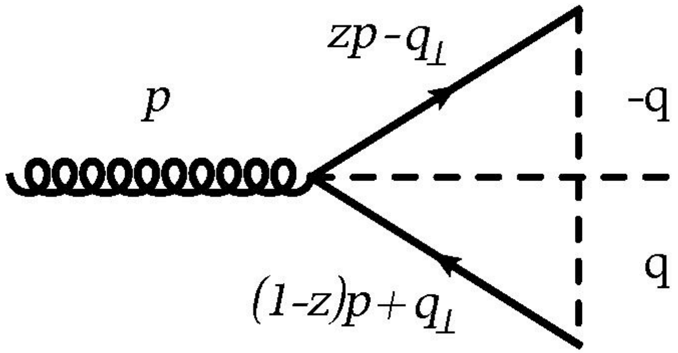
Introduction

- Transversal momentum in DGLAP based Monte Carlo generators
  - Probabilistic interpretation of the splitting function
  - Sudakov form-factor - probability of no-emission

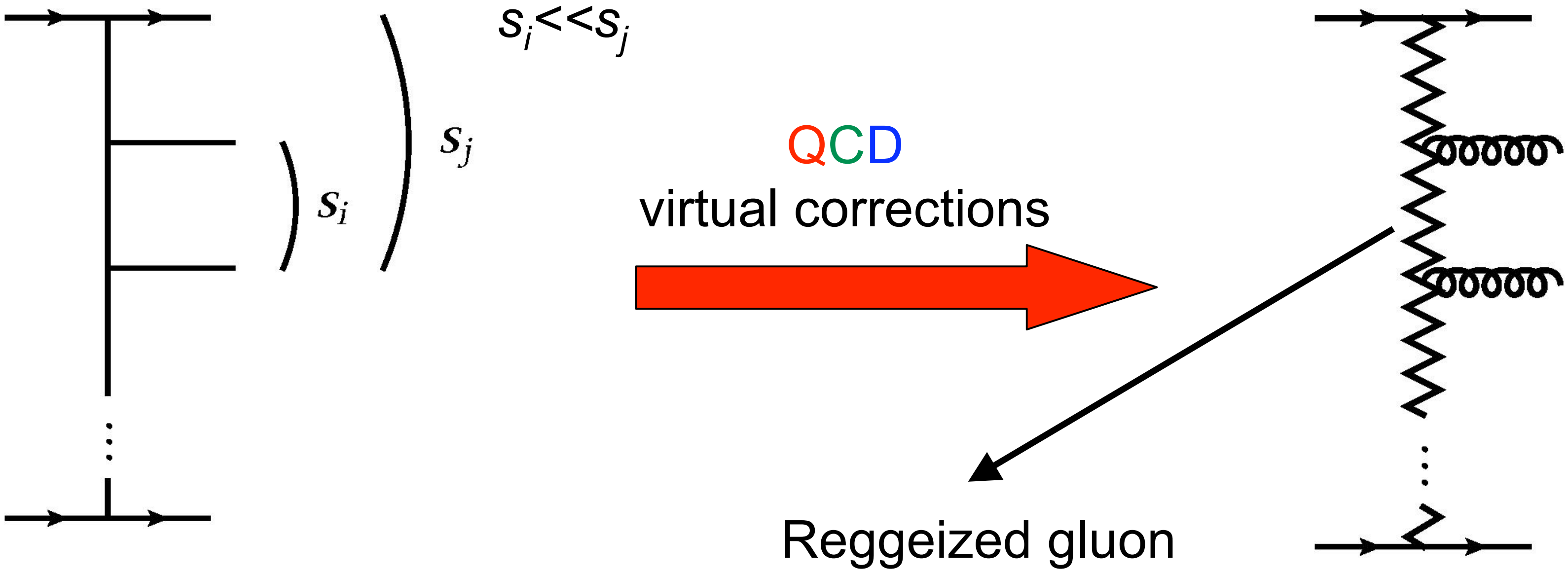


- Using relation between the scale and *z* and q_T

- Using the on-shell condition for the emitted parton and generating azimuthal angle → full information about the momentum of the emitted parton
- Additional boosts and reshufling to match the momentum
- Approach goes beyond the validity of approximation of the splitting functions

BFKL

- High energy factorisation
  - Multi-regge kinematics

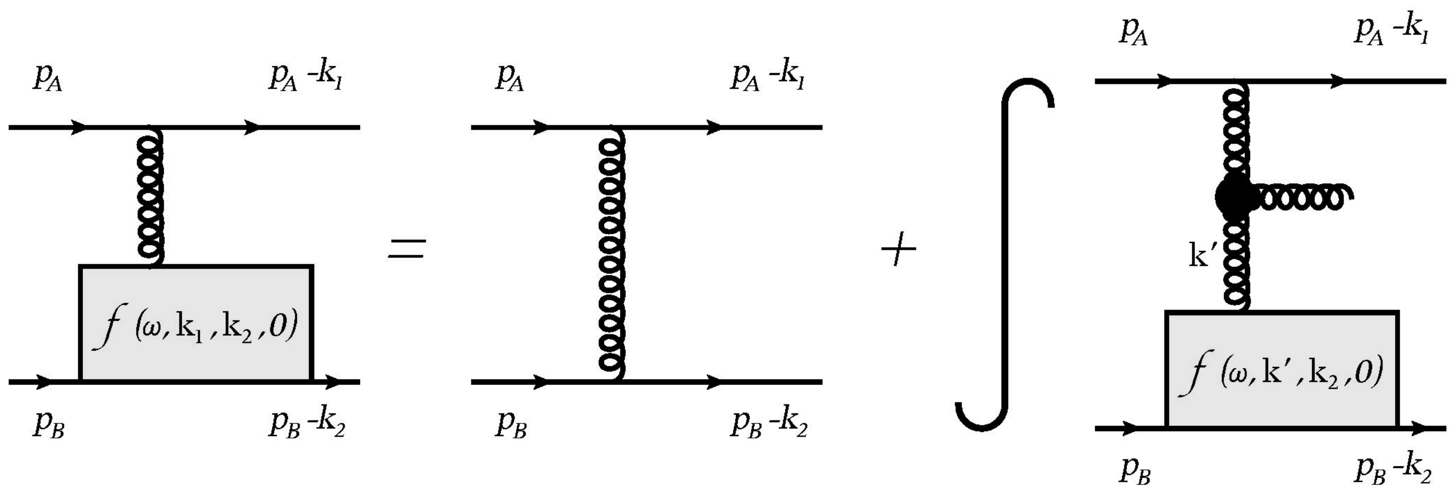


$$-i\frac{g^{\mu\nu}}{k^2}e^{\frac{N_C\alpha_S}{4\pi^2}\ln(\mathbf{k}^2/s)\Delta y}$$

BFKL

- BFKL equation (for 0 momentum exchange) for gluon Green function

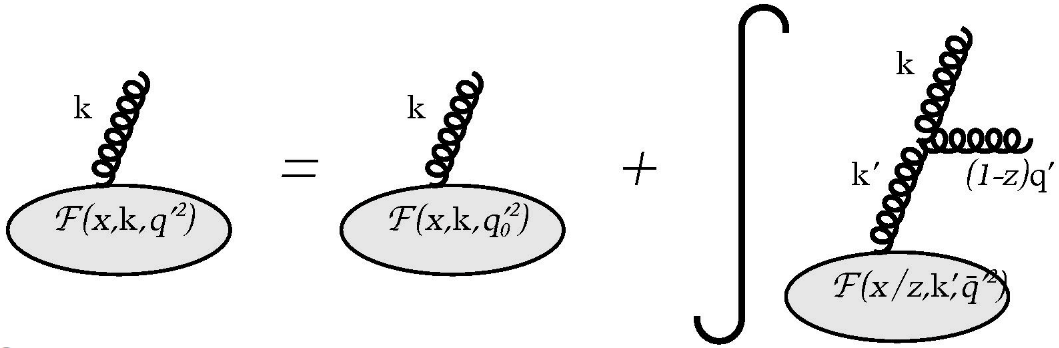
$$(\omega - 2\epsilon_R(-\mathbf{k}_1^2))f(\omega,\mathbf{k}_1,\mathbf{k}_2,\mathbf{0}) = \delta^2(\mathbf{k}_1-\mathbf{k}_2) + \frac{N_C\alpha_S}{\pi^2}\int d^2\mathbf{k}'\frac{f(\omega,\mathbf{k}',\mathbf{k}_2,\mathbf{0})}{(\mathbf{k}'-\mathbf{k}_1)^2}$$



V. S. Fadin, E. A. Kuraev, and L. N. Lipatov, Phys. Lett. B60, 50 (1975);
E. A. Kuraev, L. N. Lipatov, and V. S. Fadin, Sov. Phys. JETP 44, 443 (1976);
E. A. Kuraev, L. N. Lipatov, and V. S. Fadin, Sov. Phys. JETP 45, 199 (1977);
I. I. Balitsky and L. N. Lipatov, Sov. J. Nucl. Phys. 28, 822 (1978)

CCFM

- The CCFM equation
  - Accounts for low x physics
  - Coherence effects
  - Angular ordering
- The equation



$$\mathcal{F}(x,\mathbf{k},\mathbf{q}'^2) = \mathcal{F}(x,\mathbf{k},\mathbf{q}_0'^{\,2}) + \int_{\mathbf{q}_0'^{\,2}}^{\mathbf{q}'^2} \frac{d^2\bar{\mathbf{q}}'}{\bar{\mathbf{q}}'^2} \frac{N_C \alpha_S}{\pi}$$

$$\int_x^{1-\frac{Q_0}{|\mathbf{q}'|}} \frac{dz}{z} \mathcal{F}(x/z,\mathbf{k}',\bar{\mathbf{q}}'^2) \left(\frac{\Delta_{NS}(\mathbf{k}'^2,(z\bar{\mathbf{q}}')^2)}{z} + \frac{1}{1-z} \right) \Delta_S(\mathbf{q}'^2_0,(z\bar{\mathbf{q}}')^2)$$

M. Ciafaloni, Nucl. Phys. B296, 49 (1988);
S. Catani, F. Fiorani, and G. Marchesini, Phys. Lett. B234, 339 (1990);
S. Catani, F. Fiorani, and G. Marchesini, Nucl. Phys. B336, 18 (1990);
G. Marchesini, Nucl. Phys. B445, 49 (1995)

Monte Carlo implementation

- Monte Carlo means random numbers
- Probabilistic interpretation of the kernel of the CCFM equation

$$\mathcal{F}(x,\mathbf{k},\mathbf{q}'^2) = \mathcal{F}(x,\mathbf{k},\mathbf{q}_0'^2) + \int_{\mathbf{q}_0'^2}^{\mathbf{q}'^2} \frac{d^2\bar{\mathbf{q}}'}{\bar{\mathbf{q}}'^2}\frac{N_C\alpha_S}{\pi}$$

$$\int_x^{1-\frac{Q_0}{|\mathbf{q}'|}} \frac{dz}{z}\mathcal{F}(x/z,\mathbf{k}',\bar{\mathbf{q}}'^2)\left(\frac{\Delta_{NS}(\mathbf{k}'^2,(z\bar{\mathbf{q}}')^2)}{z}+\frac{1}{1-z}\right)\Delta_S(\mathbf{q}'^2_0,(z\bar{\mathbf{q}}')^2)$$

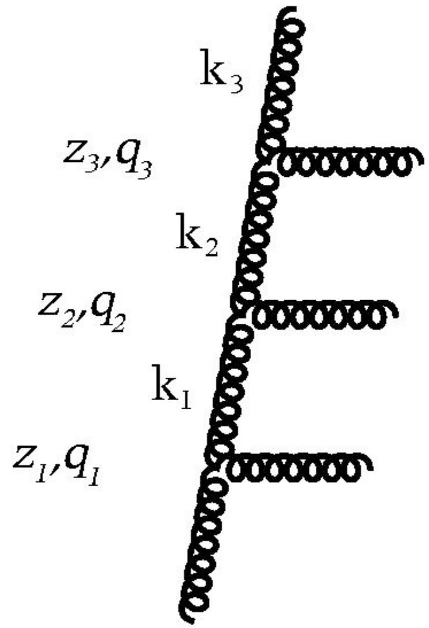
Gluon splitting function -
gives the probability of a gluon emission in a small scale interval

Sudakov form factor -
gives the probability of gluon not being emitted

Monte Carlo implementation

- Generate splitting after splitting according to the probability distributions obtained from the kernel of the equation (BFKL or CCFM)
  - first find the new value of the scale using Sudakov form factor satisfying the ordering
  - then find the values of z and k_T
- starting from some uPDF - forward evolution (implemented in Smallx)
- Inefficient

- Backward evolution more efficient

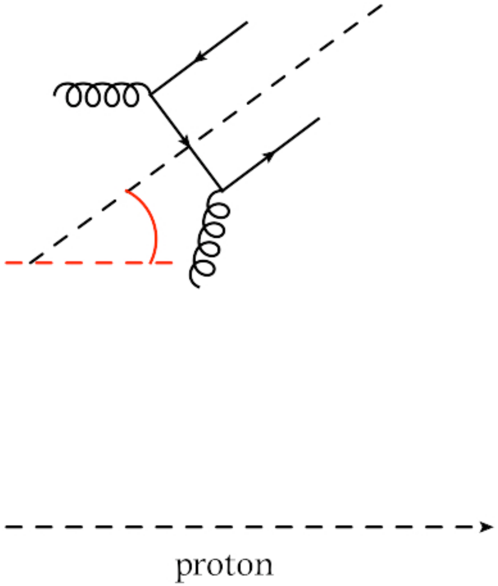


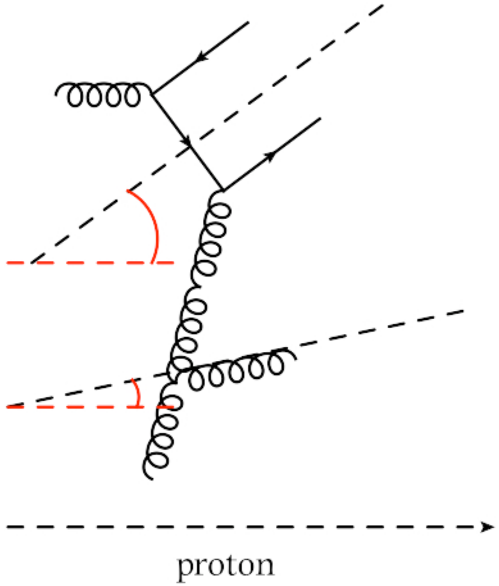
CASCADE

- Monte Carlo generator **CASCADE** (H. Jung, Comput. Phys. Commun. 143, 100 (2002). hep-ph/0109102) - implementation of the CCFM equation
  - Backward evolution algorithm for initial state parton showers for
    - Exact kinematics in each step of the parton shower
    - No difference between parton shower evolved uPDF and CCFM evolved uPDF
    - Gluon chains
    - Valence quarks/Non-singlet uPDFs from one-loop CCFM equation
  - Final state parton showers by Pythia algorithm
  - Hadronisation of partons by the Lund String Model
  - Gluon uPDFs obtained from fits to HERA data

CASCADE

- The largest angle = the angle of the hard subprocess final state system

1. 

2. 

...

$$\frac{|\mathbf{q}_i|}{1 - z_i} > \frac{z_{i-1}|\mathbf{q}_{i-1}|}{1 - z_{i-1}}$$

Fitting uPDFs F_2

$$xA_0(x, k_T, \bar{q}_0) = N \cdot x^{-B} \cdot (1-x)^C \cdot (1-Dx) \cdot \exp\left(-\frac{(k_T-\mu)^2}{2\sigma^2}\right)$$

Used in the CASCADE MC generator:
Evolve PDF according to the CCFM equation.

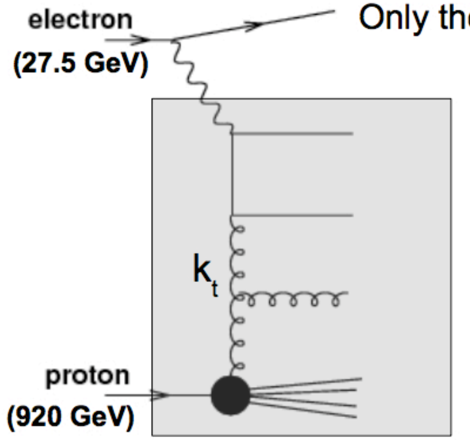
•First goal determine the x-dependence.

•Use the proton structure function (sigma reduced for positrons).
Latest combined measurement from H1 and ZEUS. (JHEP 1001:109 (2010))

Should be fairly insensitive to the kt-dependent part of the gluon. Inclusive measurement with minimum restrictions on the hadronic final state.

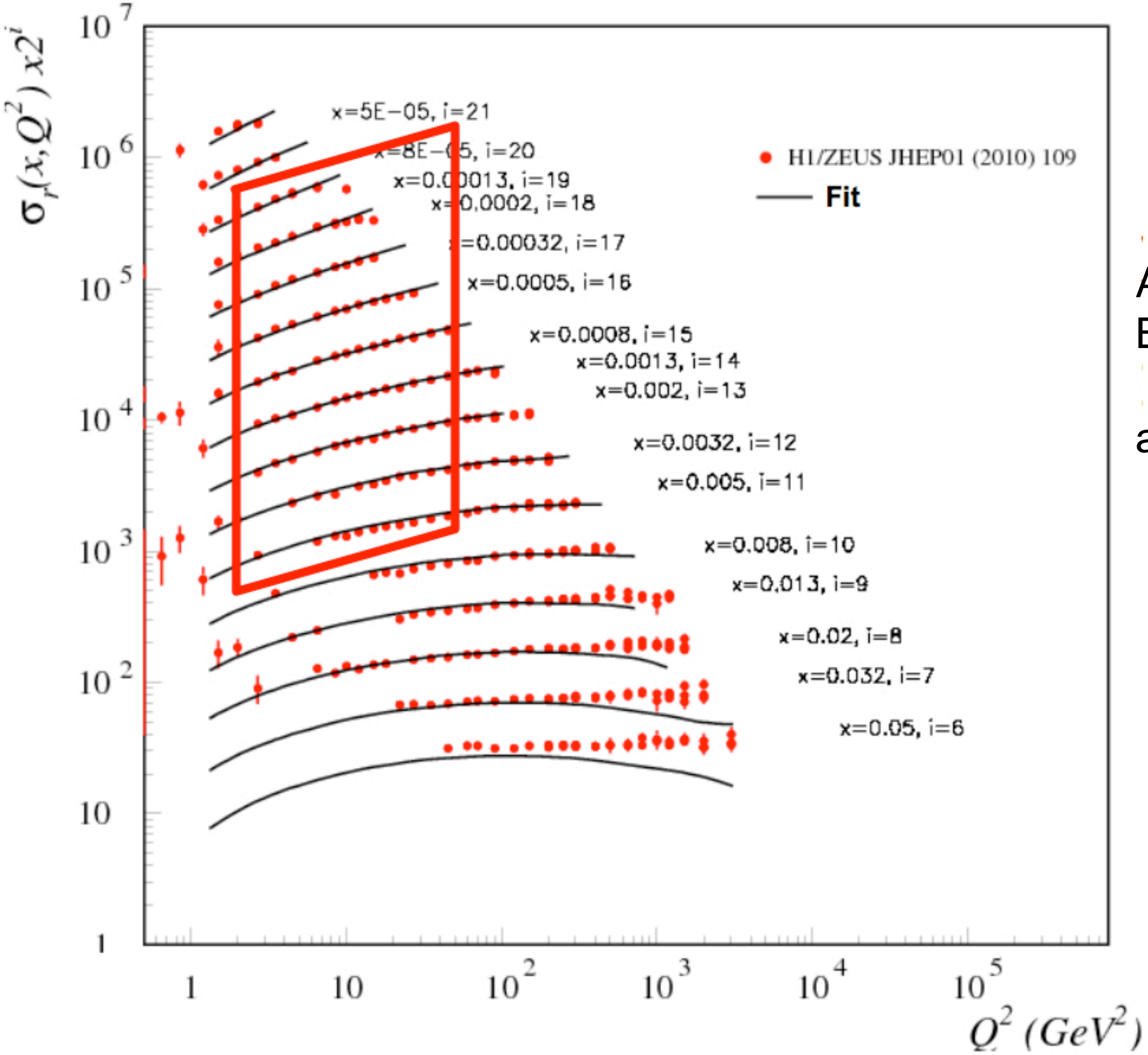
Fitting program
Profit

Only the electron detected



"Dont care" about the rest

Fitting uPDFs F_2



$\chi^2/nd=2.2$

A. Bacchetta, H. Jung,
B. A. Knutsson, K. Kutak,
and F. von Samson-Himmelstjerna,
arxiv: 1001.4675

- possibility to use more exclusive observables more sensitive on k_T

Predictions for LHC physics

Forward jets - motivation

- Probes small-x parton densities

- Important signal for BFKL dynamics

(Kepka et al., Phys. Lett. B655, 236 (2007). hep-ph/0609299, Eur. Phys. J. C55, 259 (2008). hep-ph/0612261)

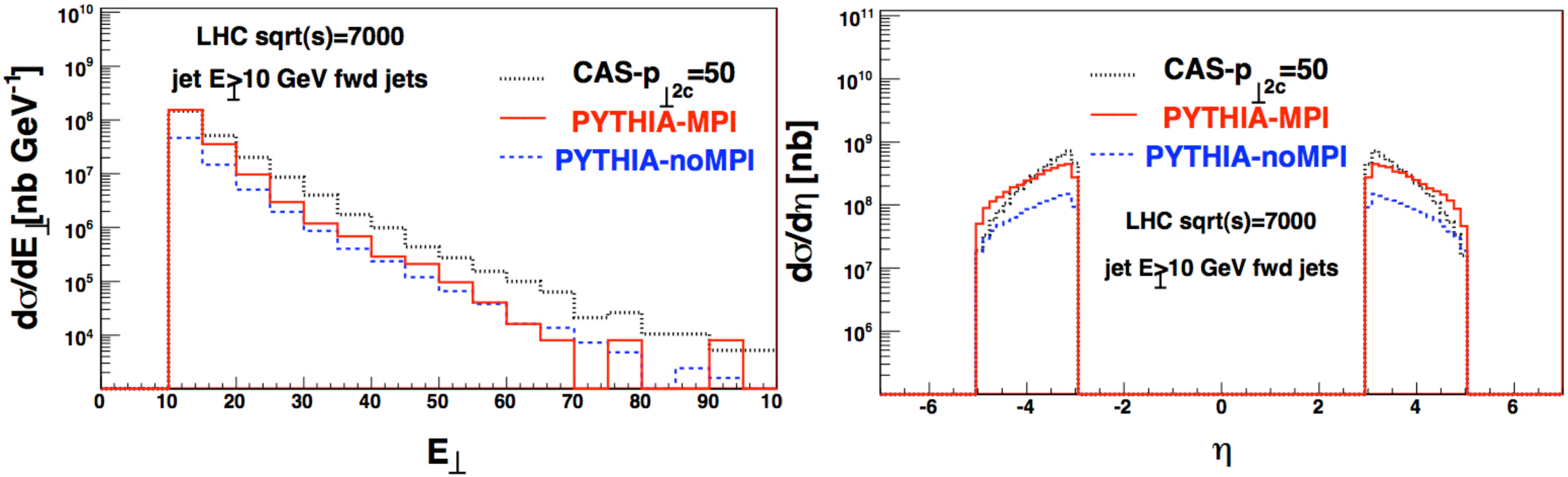
- Extensive coverage of large rapidity regions at the LHC experiments ($3<|\eta|<5$ and $-5.2>\eta>-6.6$)
  - Possibility to study two jet correlations

M. Deak, F. Hautmann, H. Jung, K. Kutak, JHEP 09, 121 (2009). 0908.0538

Pt and rapidity spectra of forward jets

Forward jet

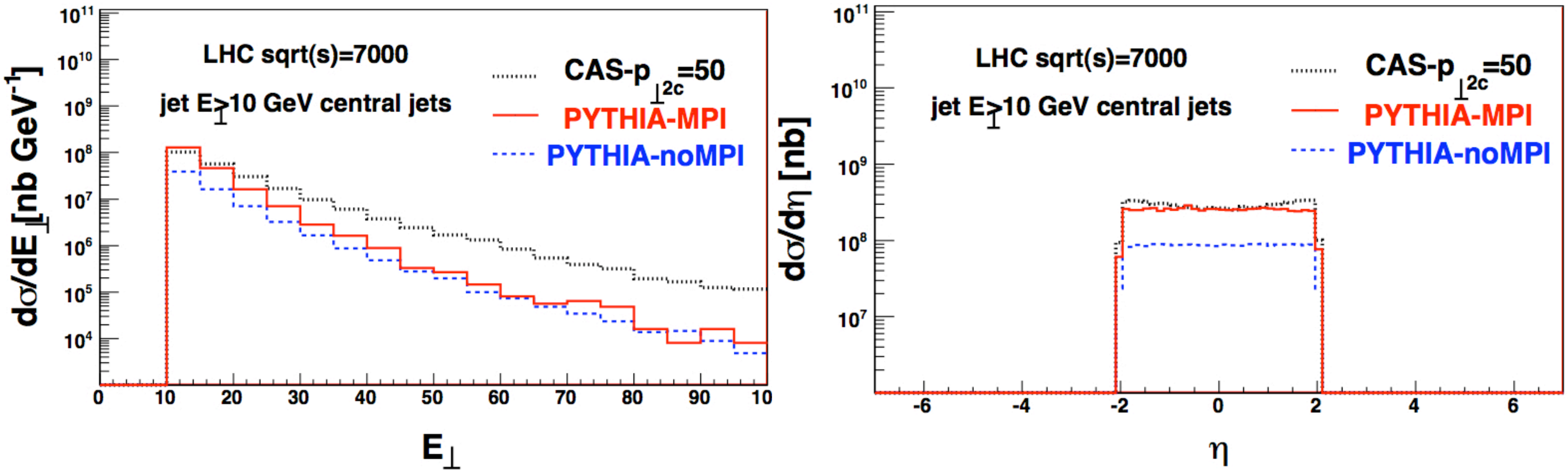
-3 < η < -5



- Different slopes of cross sections
- k_T of incoming gluon allows for harder spectrum - CCFM parton showers not ordered in k_T
- MPI only shift the jet rapidity cross section by a factor

Pt and rapidity spectra of central jets

Central jet
$-2 < \eta < 2$



Different slopes of cross sections
k_T of incoming gluon allows for harder spectrum - CCFM parton showers not ordered in k_T
MPI only shift the jet rapidity cross section by a factor
Rapidity cross sections agree for central rapidity region

Z+QQbar - motivation

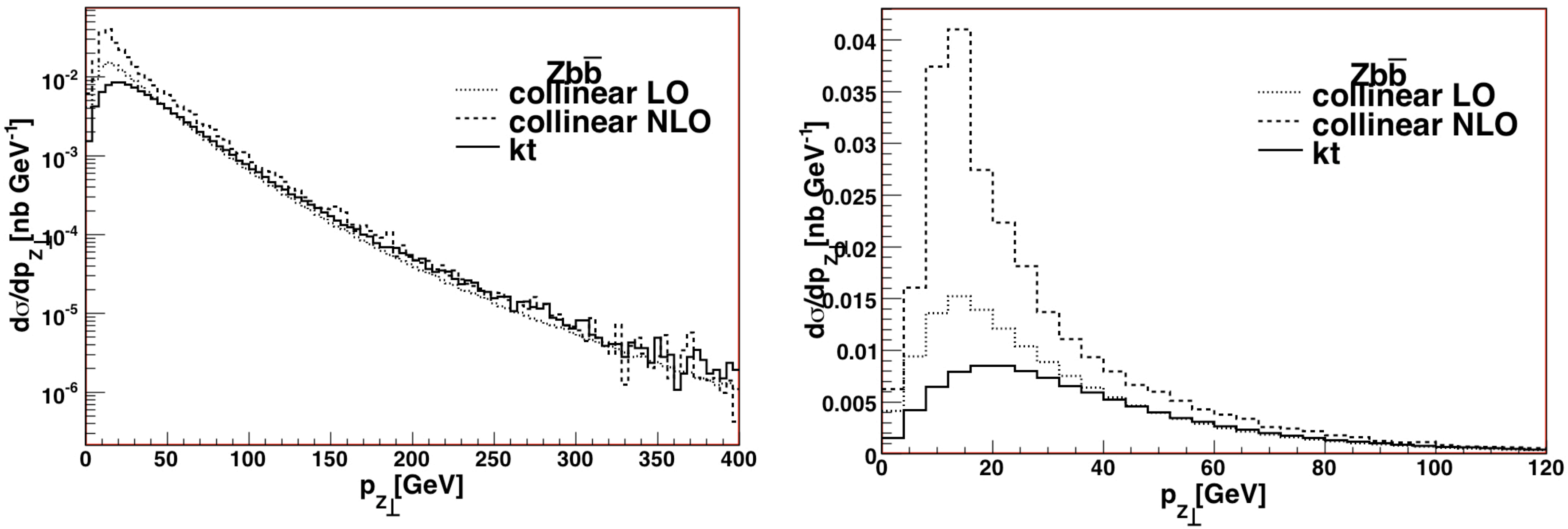
- Motivation
  - Well known properties of electroweak gauge bosons and quarks in the Standard Model - easy test of QCD
  - Background for Higgs production and beyond the Standard Model processes like SUSY particles production

- Gluon channel
  - *gg→Z+Q+Qbar* M. Deak and F. Schwennsen, JHEP 09, 035 (2008). 0805.3763
    - Fixed number of flavours scheme for heavy quarks
    - For light quarks we can rely on gluon dominance
- Formula for the cross section

$$d\sigma(pp \to q\,(W/Z)\,\bar{q}\,X) = \int \frac{d\alpha}{\alpha} \int d\vec{q}_1^{\,2} \int \frac{d\phi_1}{2\pi} \mathcal{A}(\alpha, \vec{q}_1^{\,2}, \mu^2) \times \int \frac{d\beta}{\beta} \int d\vec{q}_2^{\,2} \int \frac{d\phi_2}{2\pi} \mathcal{A}(\beta, \vec{q}_2^{\,2}, \mu^2) d\hat{\sigma}(g^* g^* \to q\,(W/Z)\,\bar{q})$$

Z+Q+Qbar - cross sections

- Results obtained from convolution with uPDFs using **CASCADE** - transversal momentum of the *Z* boson p_{ZT}



- Collinear denotes Monte Carlo generator **Mcfm** (J. Campbell, K. Ellis. http://mcfm.fnal.gov/)
- <u>Broadening</u> of the kinematic peak - <u>small-x effects</u> (S. Berge, P. M. Nadolsky, F. Olness, C. P. Yuan, Phys. Rev. D72, 033015 (2005). hep-ph/0410375)

Summary

- Unintegrated parton density functions based on solution of the CCFM equation implemented in Monte Carlo programs

- Successful fits to HERA F_2 and less inclusive data

- Applied to LHC physics