Forward energy and jet flows in high energy factorisation

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Contents

- Short introduction and motivation
- High energy factorisation framework
- High energy factorisation vs. multi parton interactions (MPI)
- Energy and jet flows
- Summary and conclusions

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

Forward jets - relevant kinematics

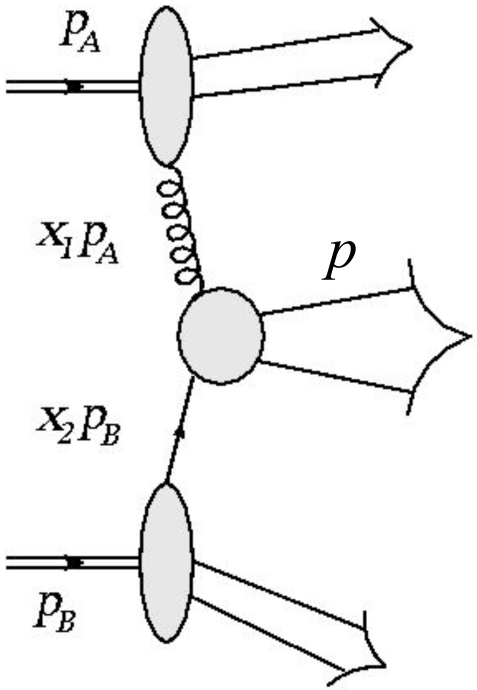
- Equation for the rapidity of the hard subprocess final state

$$p = (p_0, p_3, p_2, p_1)$$

$$p_A = \left(\frac{\sqrt{s}}{2}, \frac{\sqrt{s}}{2}, 0, 0\right)$$

$$p_B = \left(-\frac{\sqrt{s}}{2}, \frac{\sqrt{s}}{2}, 0, 0\right)$$

$$y = \frac{1}{2}\ln\frac{p_0 + p_3}{p_0 - p_3} = \frac{1}{2}\ln\frac{x_1}{x_2}$$



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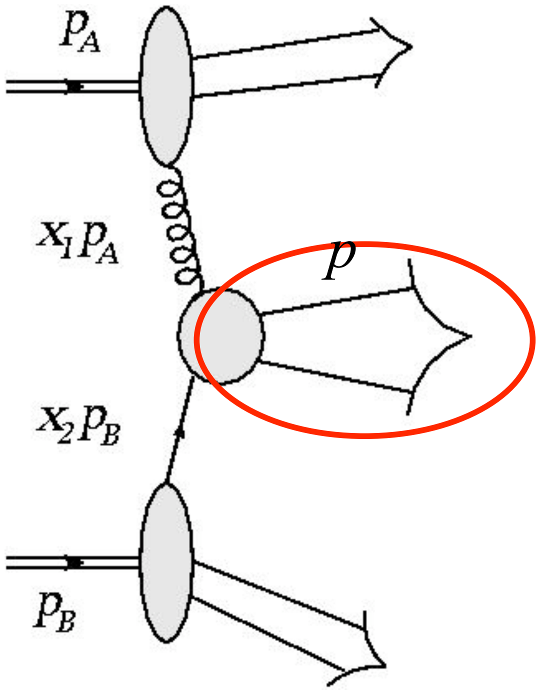
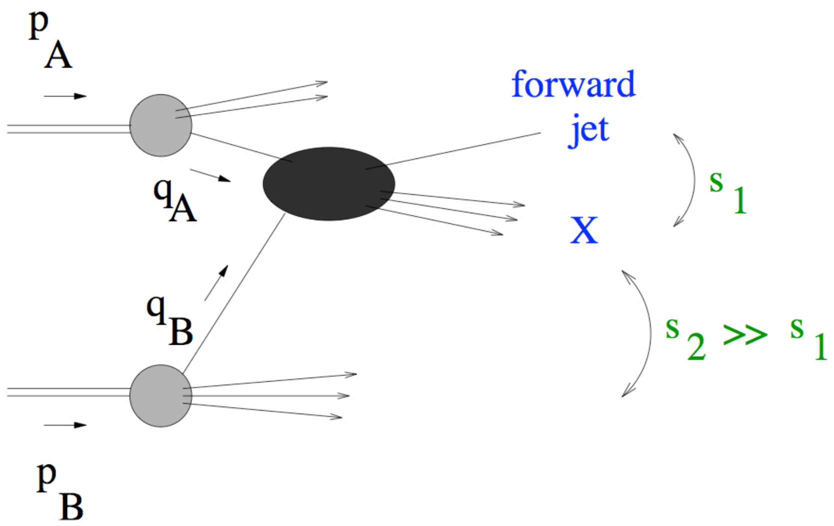


- If $x_1 \sim 10^{-5}$ and $x_2 \sim 0.1$ then $y \sim 4.5$ -- very forward!

Simple kinematics + dynamics



- 2 distinct scales s_1 and s_2
- In the cross section of this process will appear logarithms of the form

$$\ln\left(\frac{s_2}{s_1}\right) \sim \ln\left(\frac{x_2}{x_1}\right) \overset{x_2 \sim 1}{\sim} \ln\left(\frac{1}{x_1}\right)$$

- Can be resummed by the BFKL equation
  - Works in inclusive case
- Exclusive states possible with **CCFM** equation implemented in Monte Carlo **CASCADE**
- Parton showers based on the **CCFM** equation

Cross section

- The dominant processes for forward jet production

$$qg^* \to qg$$
$$gg^* \to gg$$
$$gg^* \to q\bar{q}$$

- One parton off-shell carrying a small x
- Goal is to calculate the cross section

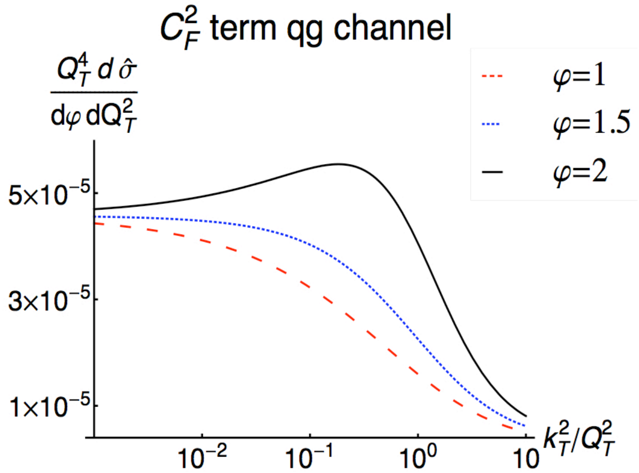
$$\frac{d\sigma}{dQ_t^2 d\varphi} = \sum_a \int \phi_{a/A} \otimes \frac{d\hat{\sigma}}{dQ_t^2 d\varphi} \otimes \phi_{g^*/B}$$

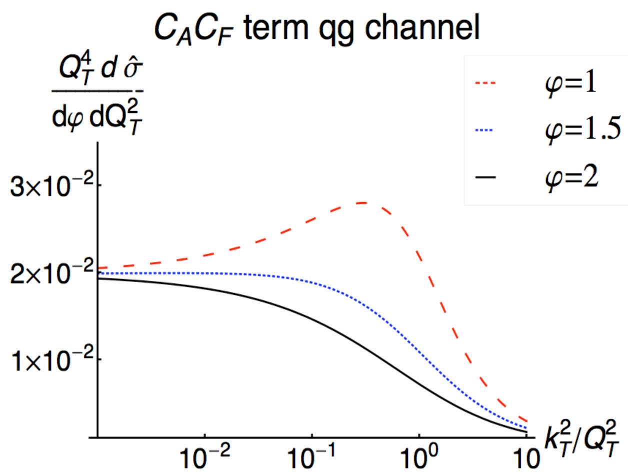
M. D., F. Hautmann, H. Jung, K. Kutak, JHEP **09**, 121 (2009). 0908.0538

- Off-shell matrix element convoluted with unintegrated parton density functions (uPDFs)
- In **CASCADE** done by generating emissions in a parton shower

Matrix element study

- Some properties of the off-shell matrix elements of the relevant processes studied - decomposed into non-abelian and abelian part





$$qg^* \longrightarrow qg$$
$$gg^* \longrightarrow gg$$
$$gg^* \longrightarrow q\bar{q}$$

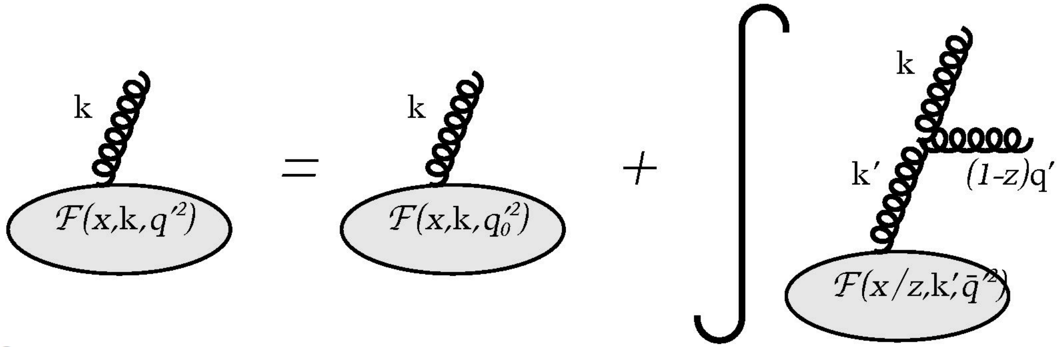
Q_T=transversal energy in terms of final state pt's

- Dependence on transvrsal momentum of the off-shell gluon
- Dynamical cut-off at $k_T \sim Q_T$ set by coherence effects
  - Non-negligible contribution from finite tail
- DGLAP based parton showers do not allow for such a hard emissions in the chain

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

CCFM equation

- The CCFM equation
  - Includes BFKL kernel
  - 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)

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

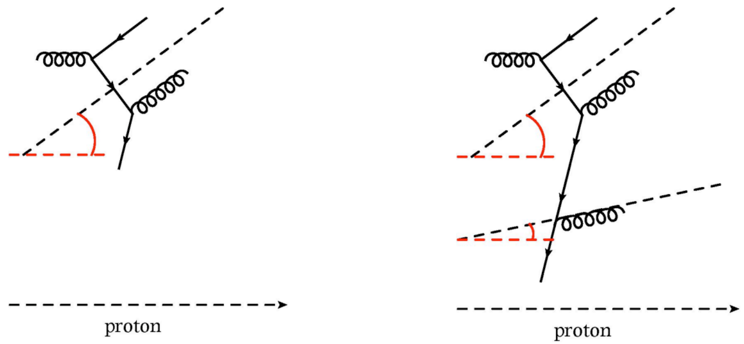
Details of the convolution

- The initial state off-shell gluon directly from the CCFM-parton shower-evolved uPDF

$$qg^* \longrightarrow qg$$
$$gg^* \longrightarrow gg$$
$$gg^* \longrightarrow q\bar{q}$$

- On-shell parton obtained from CCFM evolved uPDF
  – Transversal momentum neglected in the matrix element of the hard subprocess, but included in the kinematics of the final state
  – $k_\perp$ integrated up to the hard scale given by the angle

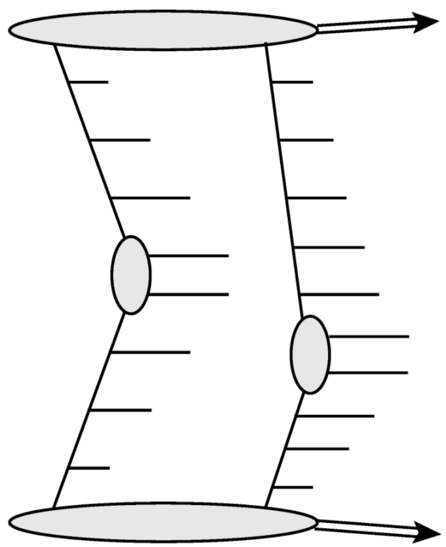
- Quarks evolved by one-loop CCFM: only valence component included



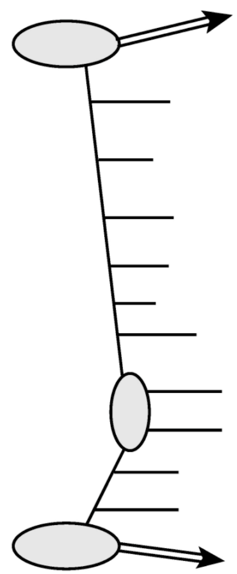
High energy factorisation and MPI

- 1. MPI effectively generate certain amount of pt-non-ordering of showered partons
- 2. MPI increase the jet multiplicity of the parton showers
- 3. MPI increase the number of hard jets in the process
- pt-unordered parton showers (1.) increase jet Multiplicity (2.) and number of hard jets (3.)

- **Natural to compare MPI with pt-unordered parton Showers**
  - Different mechanisms



multiple pt-ordered chains



one pt-unordered chain

Phenomenological results

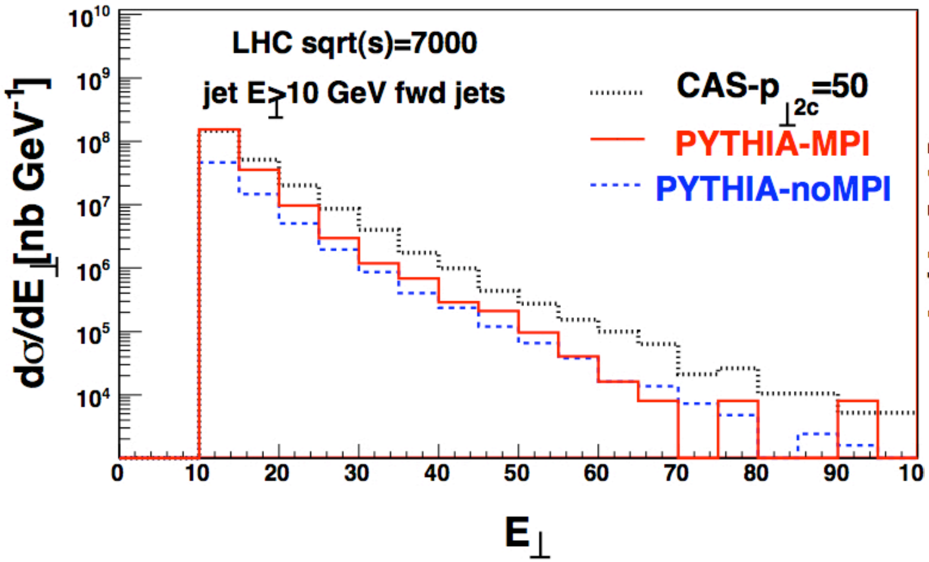
Parameters and settings

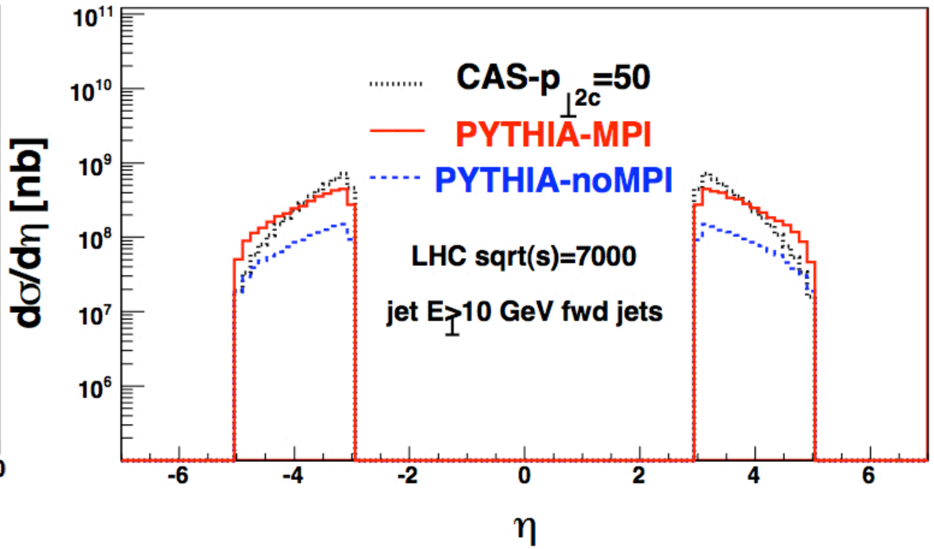
- Hard matrix elements included in Cascade MC generator:
  - gluon uPDFs fitted from HERA data
  - quark CTEQ6.0 PDF evolved by CCFM
- Pythia settings: - CTEQ 5L PDFs
  - q^2 ordering for initial state parton shower, with and without MPI
- Jets on parton level; jet algorithm - kt-clus

- Forward jets rapidity: $-3 < \eta < -5$
- Central jets rapidity: $-2 < \eta < 2$
- $E_\perp > 10$ GeV

Pt and rapidity spectra of forward jets

Forward jet
-3 < η < -5



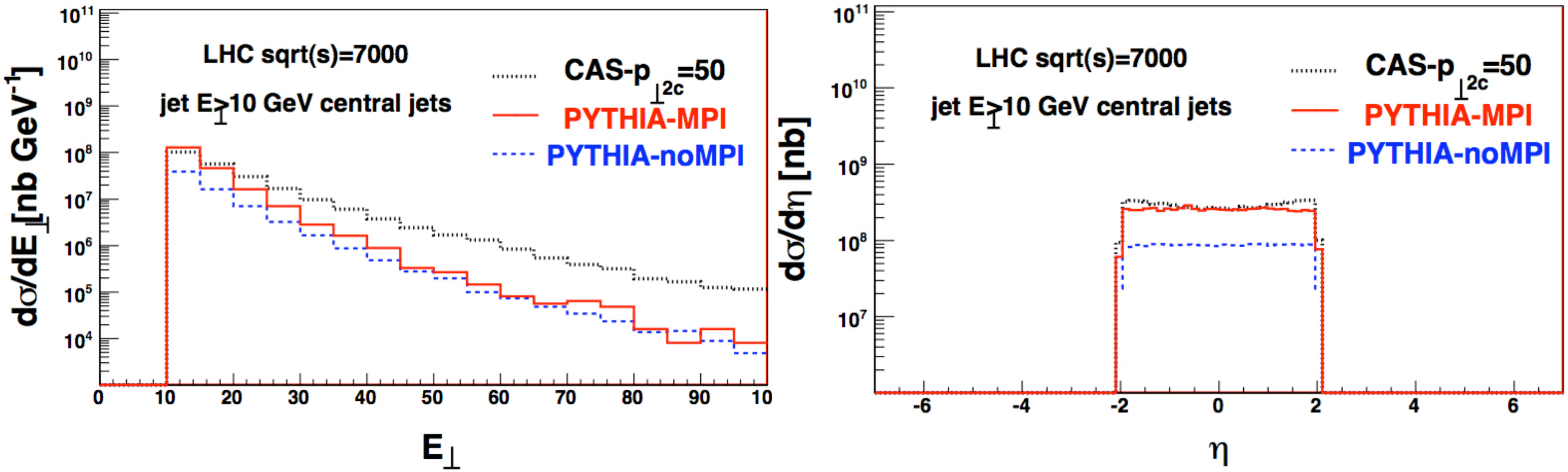


- Different slopes of cross sections
- k_T of incoming gluon allows for harder spectrum - CCFM parton showers not ordered in k_T
- MPI only shift the jet rapidity cross section by a factor

Pt and rapidity spectra of central jets

Central jet

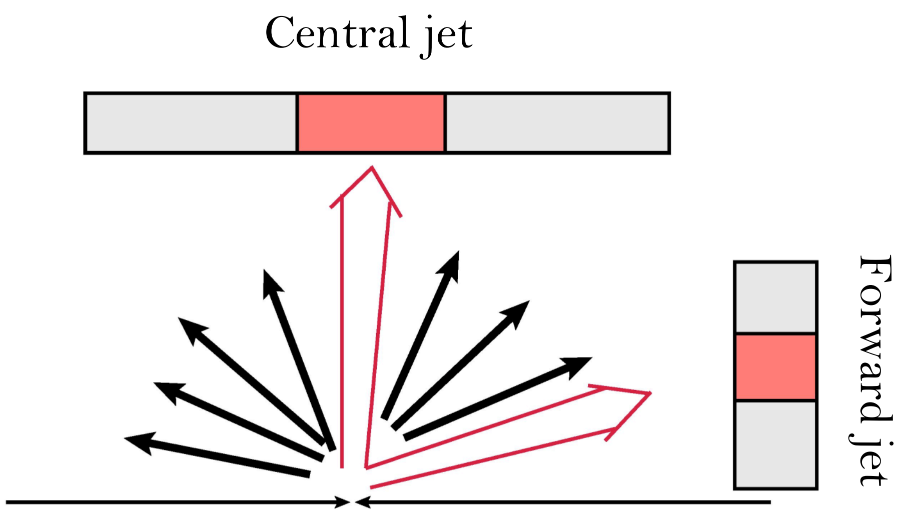
$-2 < \eta < 2$



- 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

Phenomenological results

- Select:
  - a central jet $-2 < \eta < -1$
  - and a forward jet $4 < \eta < 5$
- Looking at:
  - particle flow and minijets **away from jets**
  - particle flow and minijets **between the jets**



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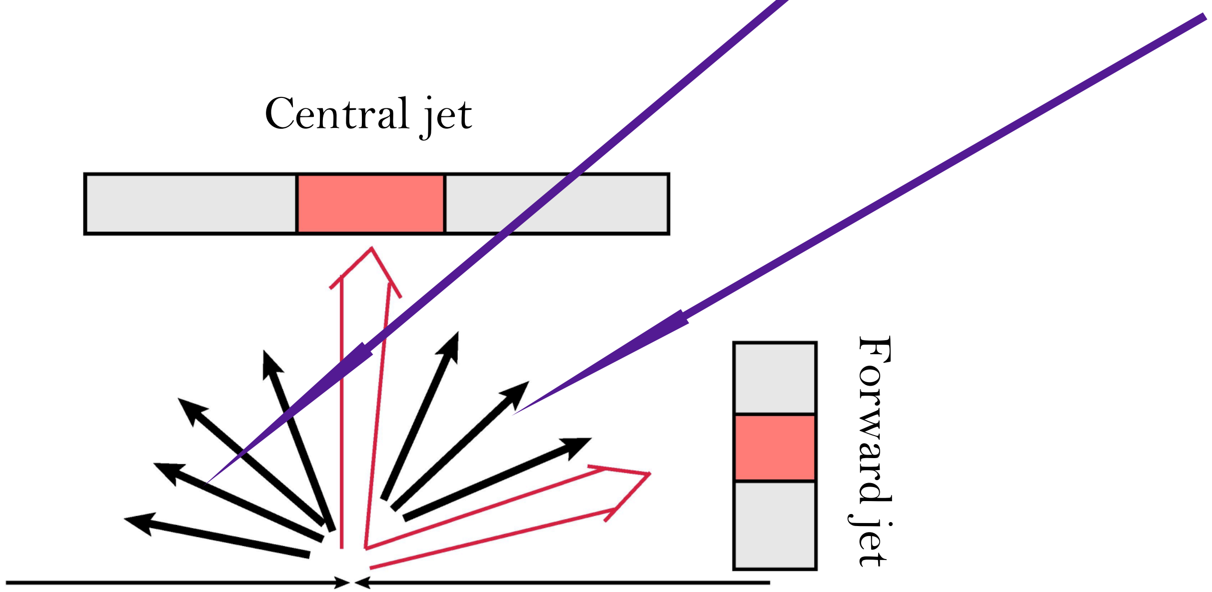
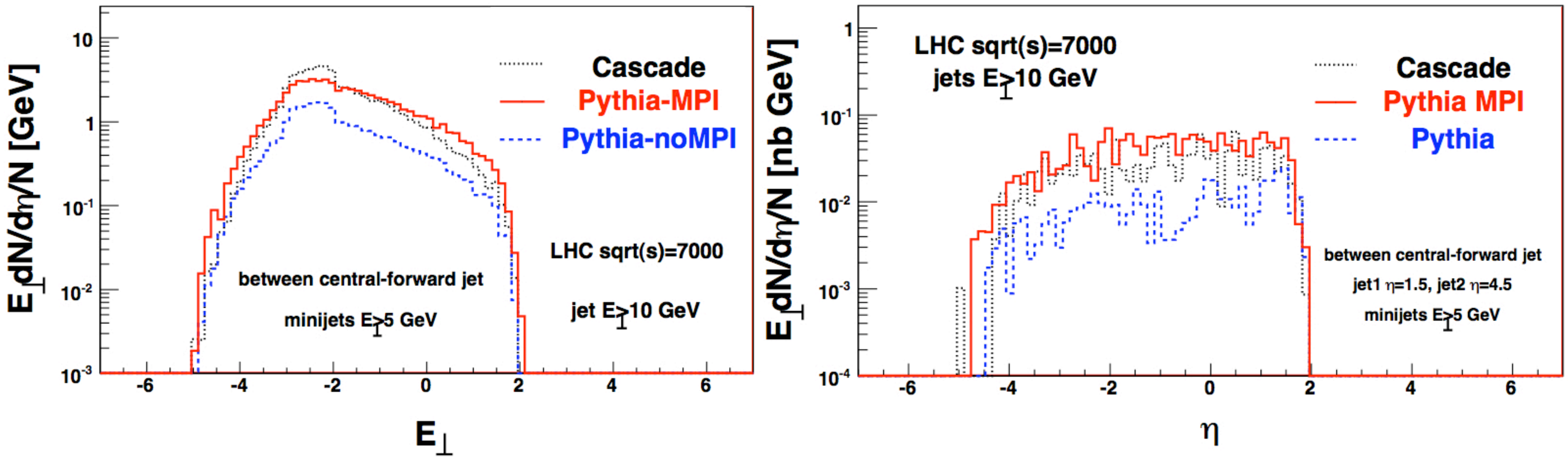
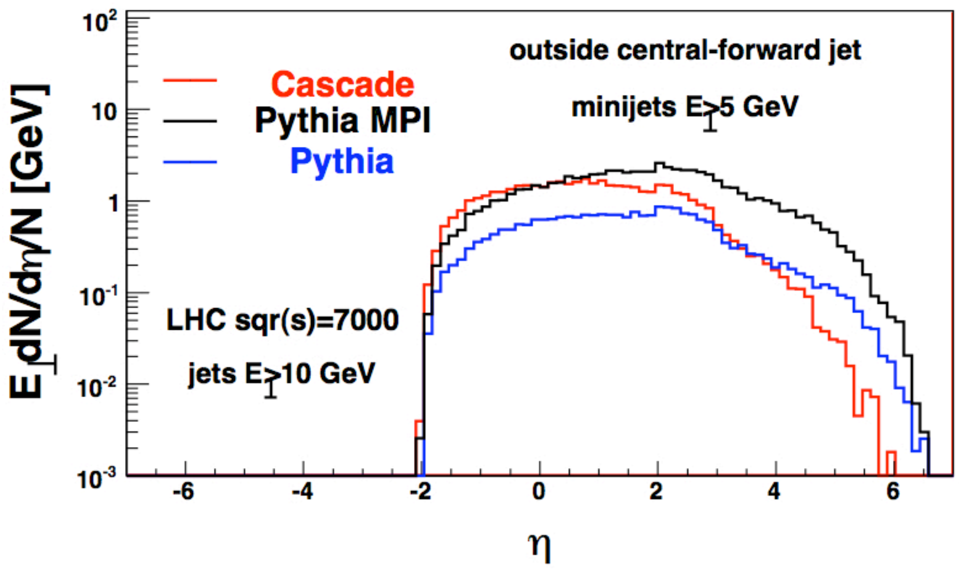


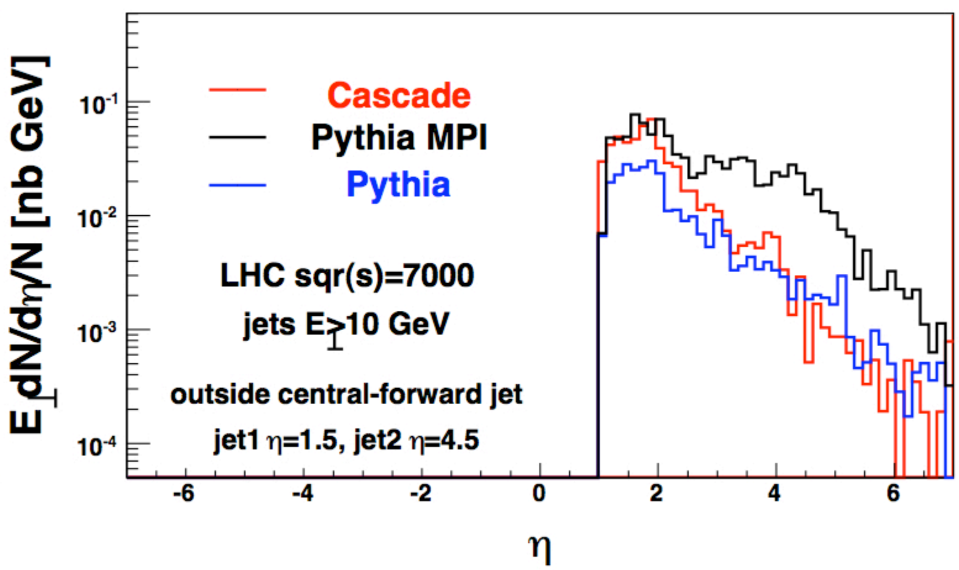
Minijet and particle energy flow between central and forward jet



- Both MPI and high energy factorisation produce more jets with higher transversal energy

Minijet and particle energy flow away from central and forward jet





- Both MPI and high energy factorisation produce more jets with higher transversal energy

Forward jets - Summary

- Calculations of gauge invariant matrix elements of relevant processes in Monte Carlo implementation suitable form
- Convolution with the uPDFs in Monte Carlo generator **`CASCADE`**
- Study of jet transversal energy and rapidity cross sections of forward jets and a central jet
- Comparison with **`PYTHIA`** Monte Carlo generator with multi-parton interactions (MPI)
- Difference between the high energy factorisation enhanced jet activity and MPI jet activity

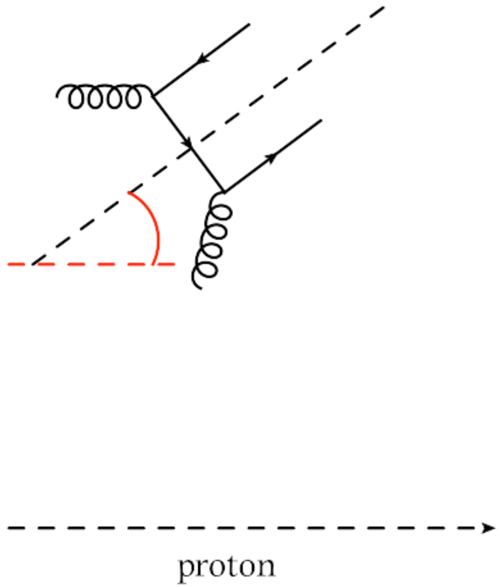
Conclusions

- LHC opens phase space for large center of mass energies and for presence of multiscales
- This brings perturbative corrections which are summed up by high energy factorisation
- An approach which allows for studies of forward jets at the LHC
- Proposal of observables which allow for discrimination between different approaches

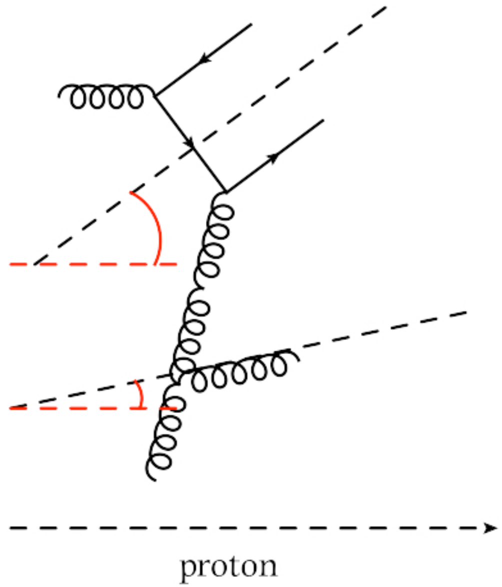
CASCADE

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

1.



2.



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- Angular ordering for small angles

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