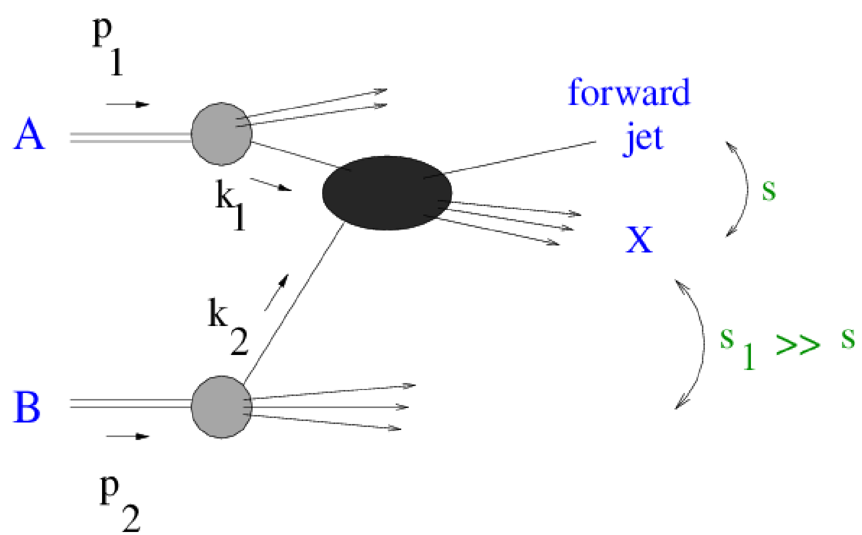
Forward jet production at the Large Hadron Collider

Krzysztof Kutak (DESY)

Based on: JHEP09(2009)121, M. Deak, H. Jung, F. Hautmann, K. Kutak

MOTIVATIONS

High pt production at the LHC



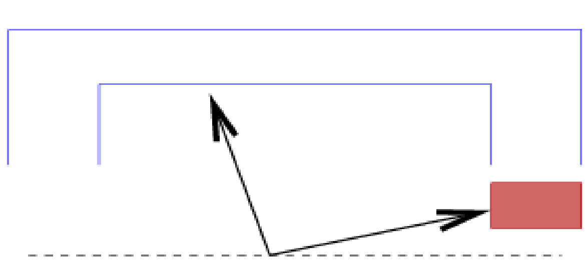
- Phase space opening for large energies
- Unique coverage of large rapidities

Physcis of hard processes with multiple hard scales

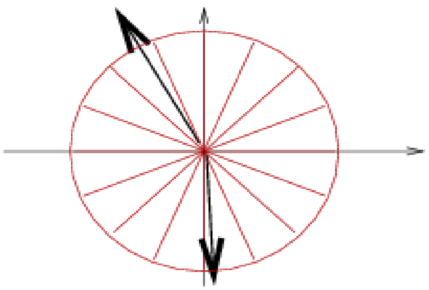
And highly sensitive to parton dynamics at $x \longrightarrow 0$ and $x \longrightarrow 1$

MEASUREMENT POSSIBILITY

- Polar angles small but far enough from beam axis
  - Measure azimuthal plane correlations



central + forward detectors



azimuthal plane

CMS Coll, CERN-LHCC-2006-001; CMS PAS FWD-08-001 (2008);

CMS Coll., TOTEM Coll, CERN-LHCC-2066-039/G -124 (2006)

CMS Coll, CERN-LHCC-2006-001; CMS PAS FWD-08-001 (2008);

M. Grothe, arXiv:0901.0998; D. d'Enterria, arXiv:0806.0883;

X. Aslanoglou et al., CERN-CMS-NOTE-2008-022 (2008)

H. Jung et al., HERA-LHC Proc. arXiv:0903.3861;

INTRODUCTION

HIGH ENERGY FACTORIZATION - RELEVANT PARAMETERS

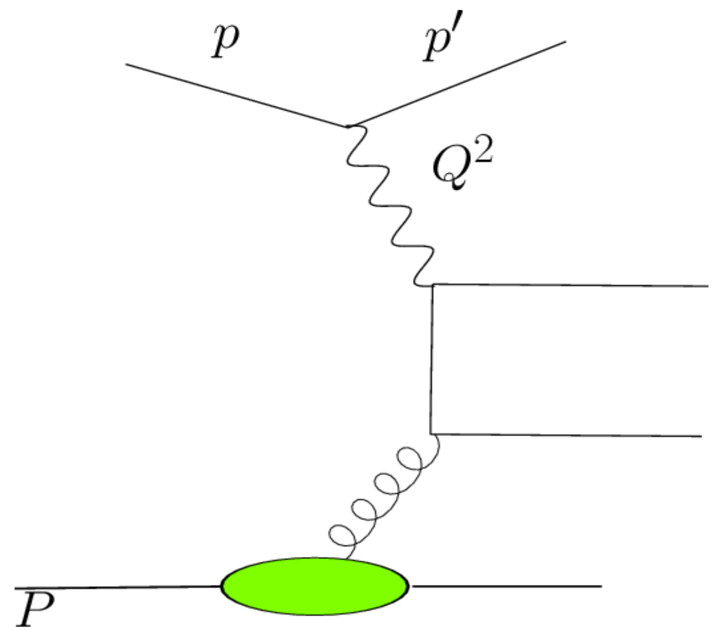
$$q^2 = (p-p')^2 = -Q^2$$

$$x = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{W^2 + Q^2 - m_P^2}{s - m_P^2}$$

$$W^2 = (q+P)^2$$

$$s = (p+P)^2$$



- DIS $\longrightarrow m_P$ smaller then other scales
- collinear factorization $\longrightarrow$ Q^2 is the largest scale(DGLAP)
- high energy factorization $\longrightarrow s$ is the largest scale(BFKL, CCFM, BK)

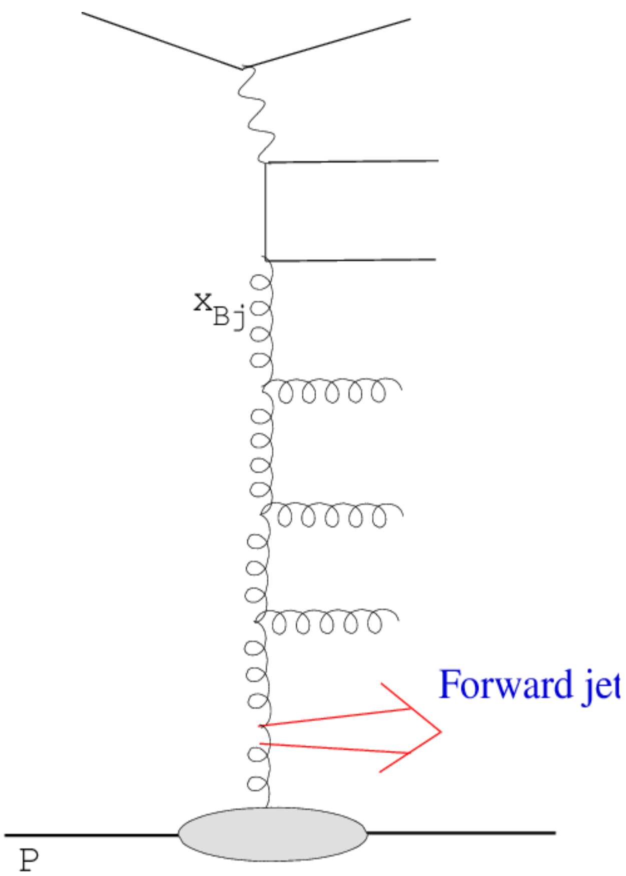
Found large terms which need to be summ $\sum_n \sum_m \alpha_s^m ln^n(s/\mu)$

Lipatov ,Fadin, Kuraev "77
Ciafaloni '89, Catani, Fiorani, Marchesini, 89
Balitsky '96, Kovchegov, 98

Cross section ~ $F_2(x,Q^2) \equiv$ matrix element $\otimes$ parton density

HIGH ENERGY FACTORISATION
- CHOICE OF OBSERVABLE

Example from jets in DIS



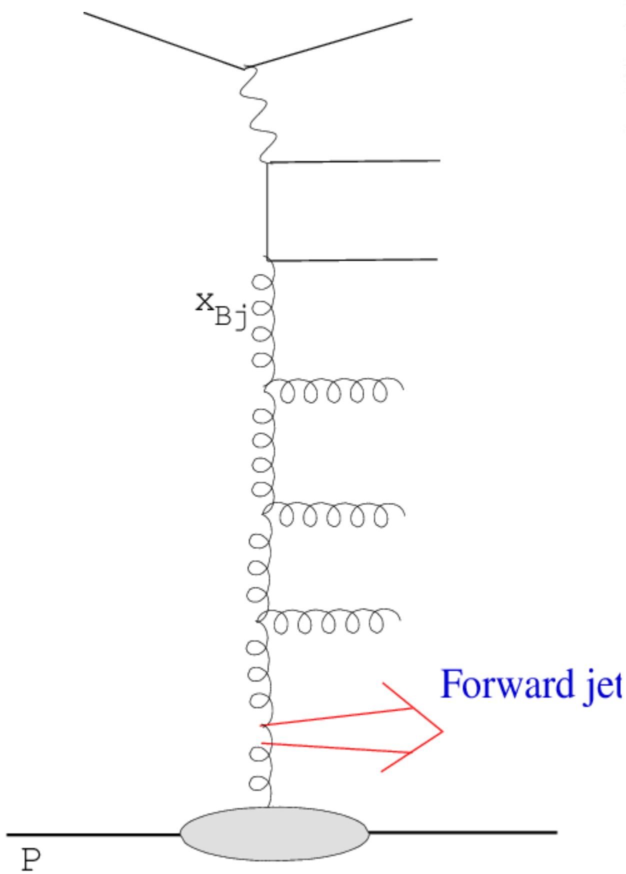
- BFKL,CCFM evolutions in energy
  - DGLAP evolution in hard scale

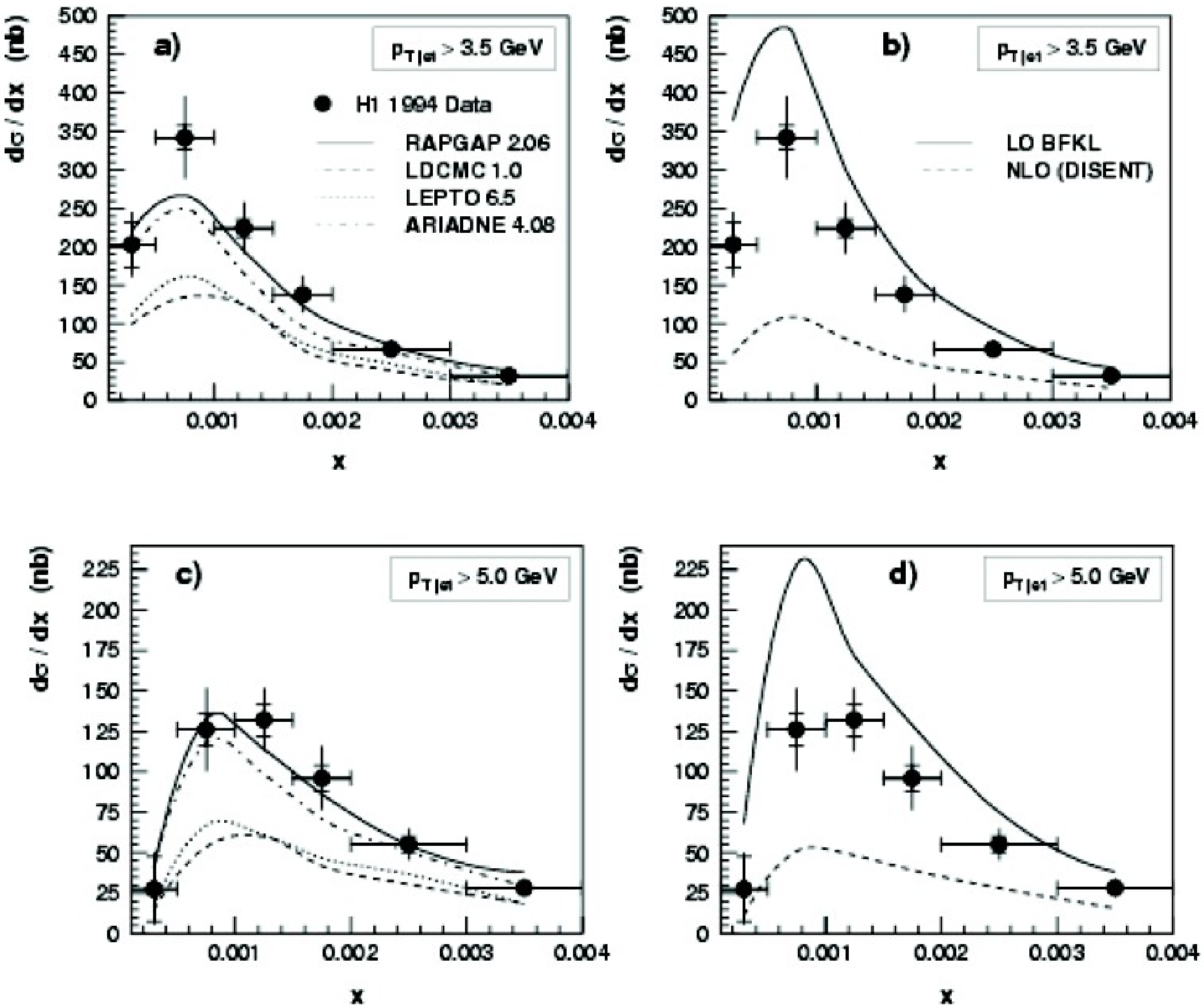
To see signature for high energy process forward jet is the perfect observable

Selection cuts: $Q^2 \sim pt^2$

In such configuration DGLAP is suppressed

HIGH ENERGY FACTORISATION
- HINT FROM DATA?





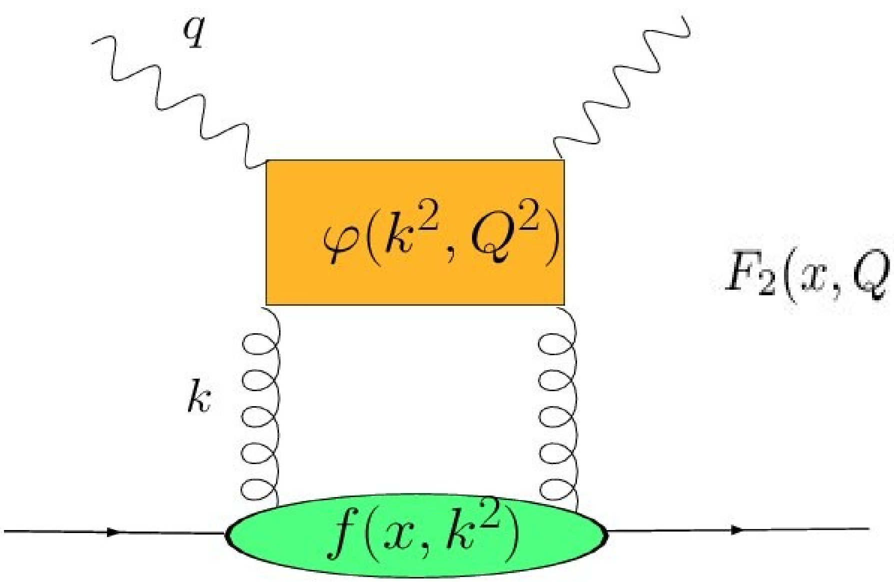
BFKL closer to data. NLO DGLAP too small

HIGH ENERGY AT FIXED TRANSVERSE MOMENTUM - MOTIVATION

- At high energies gluon dominance in the t channel
- Dominant contribution from transversal degrees of freedom
- Multiple gluon exchanges are correction of higher orders

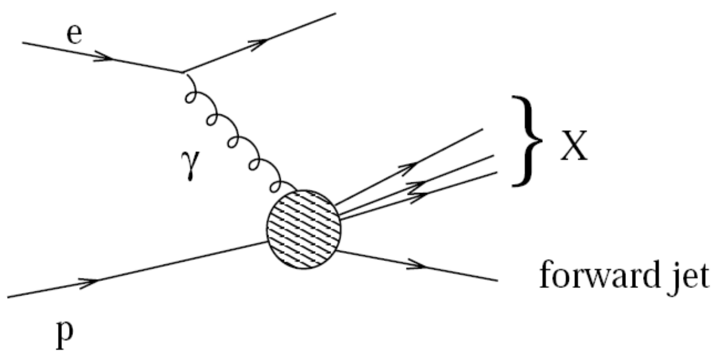
◇ Example F_2 structure function, $f(x, \mathbf{k}^2)$ gluon density
$\phi(Q^2, \mathbf{k}^2)$ hard matrix element integrated over final states

Catani et al., 1991; Ciafaloni, 1998



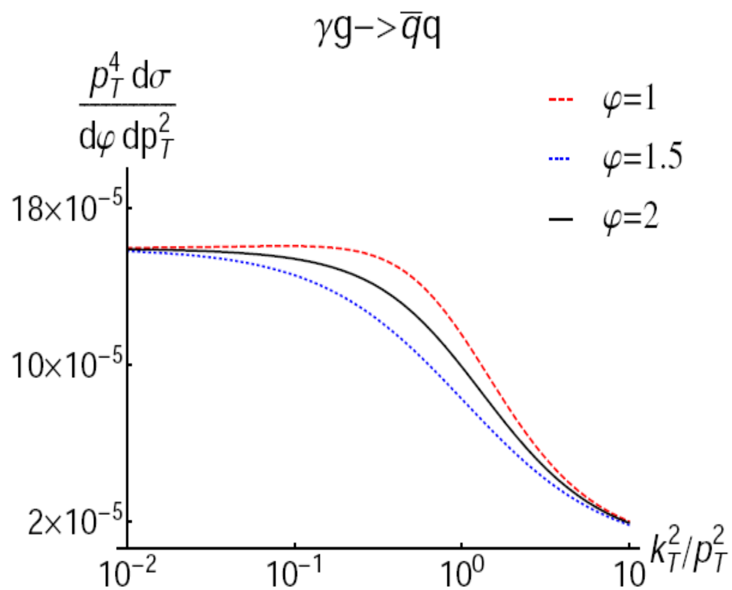
$$F_2(x, Q^2) = \frac{Q^2}{4\pi^2}\alpha_s \sum_q e_q^2 \int \frac{d\mathbf{k^2}}{\mathbf{k}^2}\phi(Q^2, \mathbf{k}^2) f(x, \mathbf{k}^2)$$

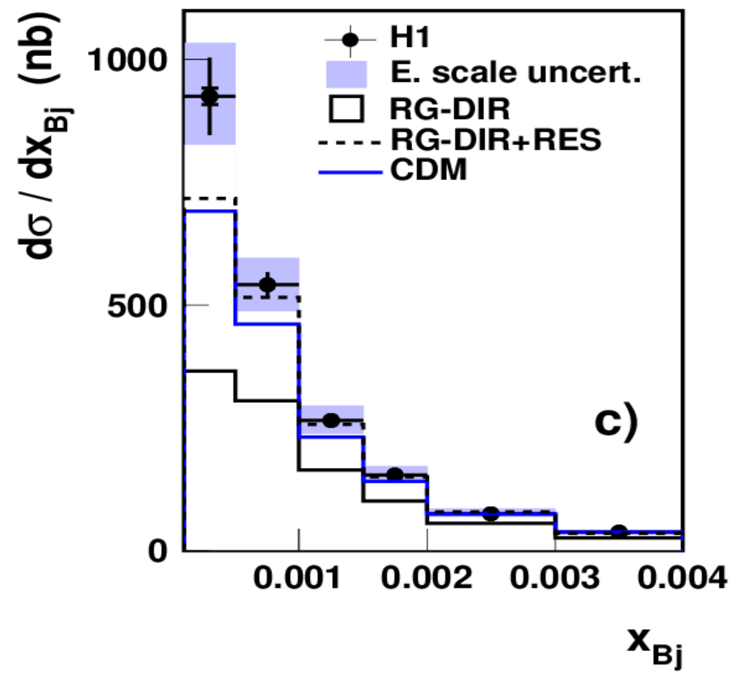
HIGH ENERGY AT FIXED TRANSVERSE MOMENTUM – FORWARD JETS AT HERA



Consistent resumation both logs of rapidity and logs of hard scale

$$\frac{d\sigma}{dx} = \int \frac{d\widehat{\sigma}}{dx} \otimes \phi_{g^*/B}$$





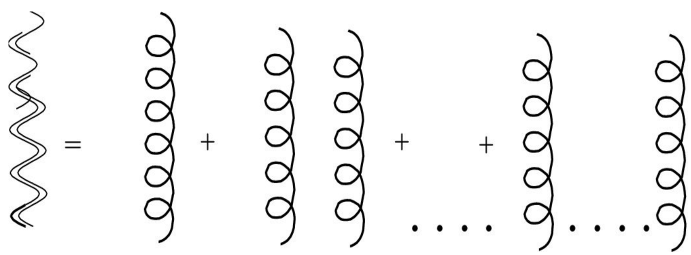
From A. Knutsson

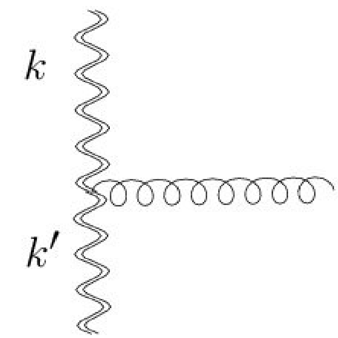
However still not satisfactory description with present understanding of physics. Still something is to be understood...

HIGH ENERGY AT FIXED TRANSVERSE MOMENTUM - FEATURES

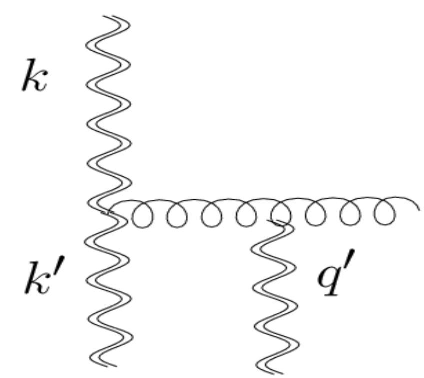
Basic evolution equations at LO like BFKL, CCFM, BK include higher orders from point of view of DGLAP because of no ordering in hard scale

$$K_{BFKL} \approx \int_{k_0^2}^{\mathbf{k^2}} \sum_{n=0}^{\infty} \left(\frac{\mathbf{k}'^2}{\mathbf{k}^2} \right)^{n-1}$$

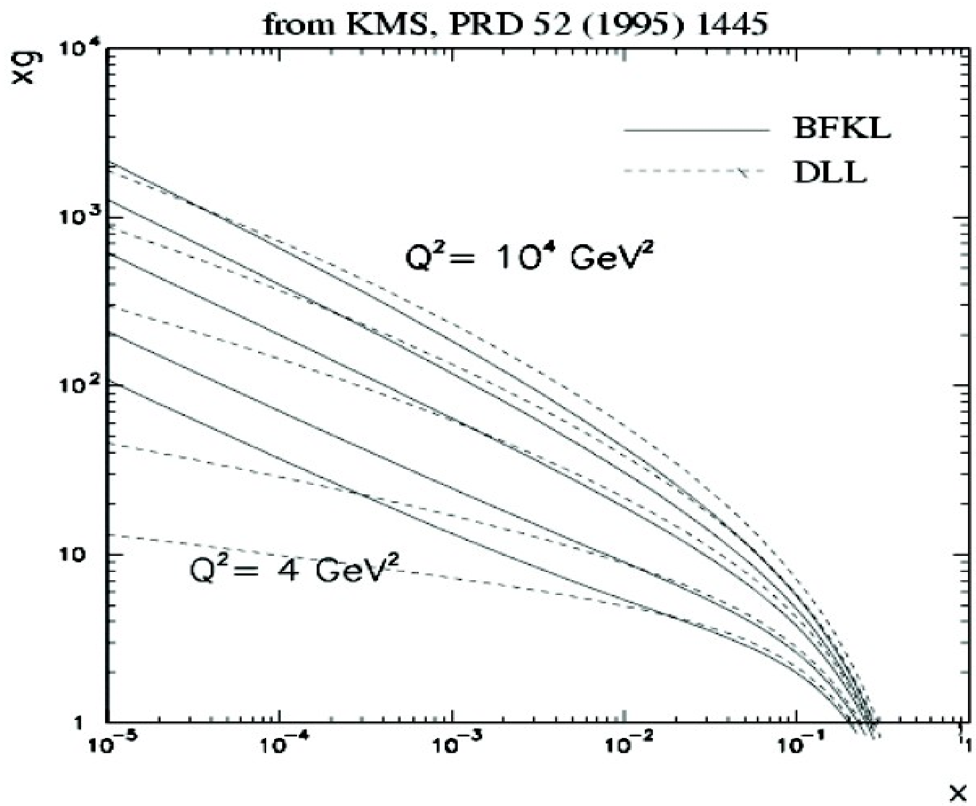


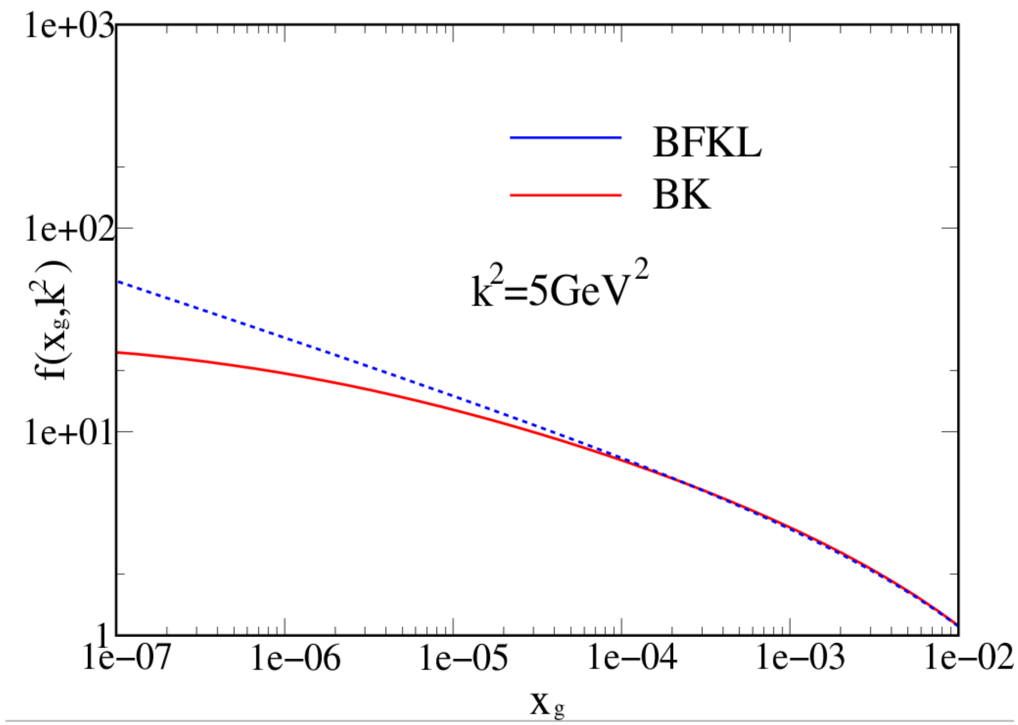


Allows for consistent formulation of problem of dense partonic system (BK).
Needed for unitarisation of cross sectionat high energies



HIGH ENERGY AT FIXED TRANSVERSE MOMENTUM - FEATURES





- BFKL, CCFM, grows like power of energy. Faster than DGLAP
  - Recombination of gluons slows down the growth to logarithmic

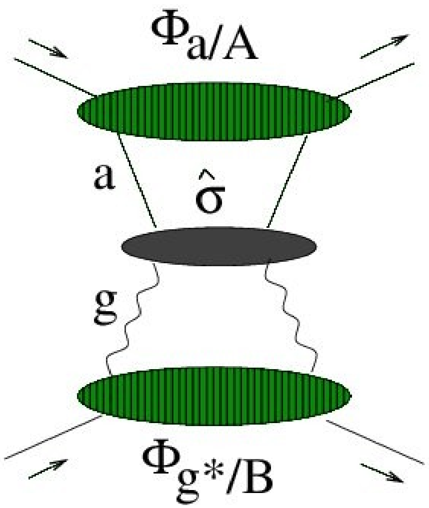
FORWARD JETS AT LHC

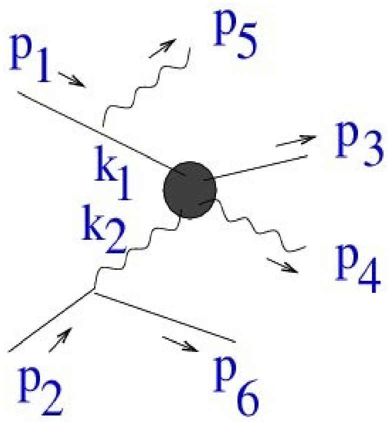
HIGH ENERGY AT FIXED TRANSVERSE MOMENTUM – FORWARD JETS AT LHC

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

Consistent resumation both logs of rapidity and logs of hard scale

Deak, Jung, Hautmann & K JHEP(2009) 121





◇ ϕ_a near-collinear, large-x; ϕ_{g^*} $k_\perp$-dependent, small-x

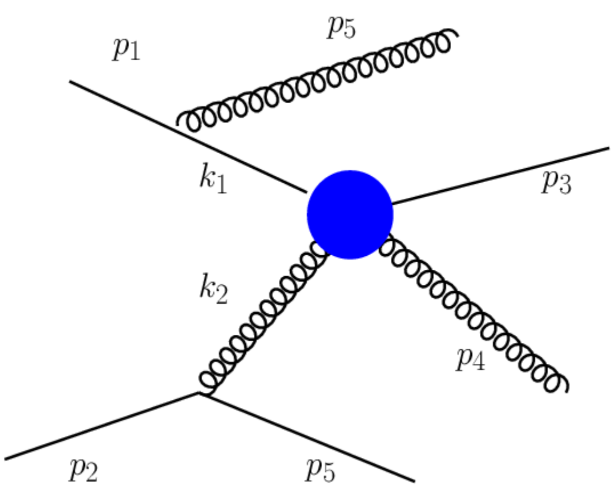
◇ $\widehat{\sigma}$ off-shell continuation of hard-scattering matrix elements

HARD SCATTERING CROSS SECTIONS qg qg

- Matrix elements for fully exclusive events with forward jets
- Both quark and gluon channels found to be important for realistic phenomenology

$$\mathcal{M}_{qg\to qg} = g^4 \left(\frac{k_1\, k_2}{k_1\, p_2} \right)^2 \left[\frac{(N_c^2-1)}{(4N_c^2)} \frac{(k_1\, p_2)^2 + (p_2\, p_3)^2}{(k_1\, p_4)\,(p_3\, p_4)} + \frac{C_1 C_A}{(2C_F)} \frac{(k_1\, p_2)^2 + (p_2\, p_3)^2}{(k_1\, p_4)\,(p_3\, p_4)} \times \right.$$

$$\left. \left(\frac{(p_3\, p_4)\,(k_1\, p_2)}{(k_1\, p_3)\,(p_2\, p_4)} + \frac{(k_1\, p_4)\,(p_2\, p_3)}{(k_1\, p_3)\,(p_2\, p_4)} - 1 \right) \right]$$



$k_2 \to 0$

$$\mathcal{M}_{qg\to qg} = g^4 (s^2 + u^2) \left[\frac{1}{t^2} - \frac{4}{9su} \right]$$

- in collinear limit reduce to standard matrix elements.
  - gauge invariant with respect to incoming gluon

HARD SCATTERING CROSS SECTIONS gg   gg

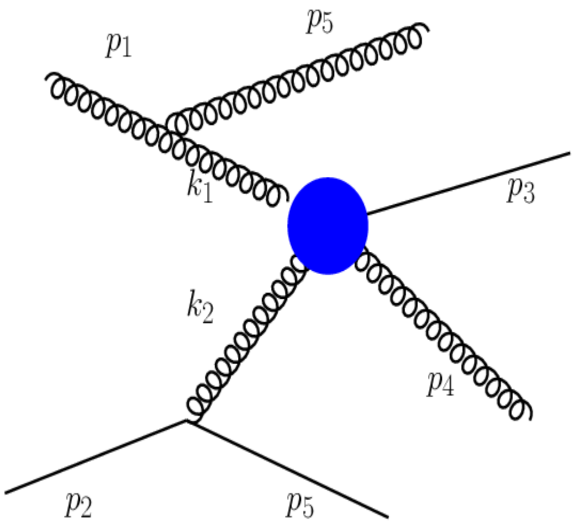
- Matrix elements for fully exclusive events with forward jets
- Both quark and gluon channels found to be important for realistic phenomenology

$$\mathcal{M}_{gg\to gg} = \frac{g^4 N_c^2}{(N_c^2-1)} \left(\frac{k_1\, k_2}{k_1\, p_2}\right)^2 \frac{(p_3\, p_4)(k_1\, p_2)+(k_1\, p_4)(p_2\, p_3)+(p_2\, p_4)(k_1\, p_3)}{(p_2\, p_4)(k_1\, p_4)(p_3\, p_4)(k_1\, p_2)(p_2\, p_3)(k_1\, p_3)} \times$$

$$\left[(p_2\, p_4)^4+(k_1\, p_2)^4+(p_2\, p_3)^4\right]$$

$$k_2 \to 0$$

$$\mathcal{M}_{gg\to gg} = \frac{g^4 N_c^2}{(N_c^2-1)} \frac{(s^4+t^4+u^4)(s^2+t^2+u^2)}{s^2 t^2 u^2}$$



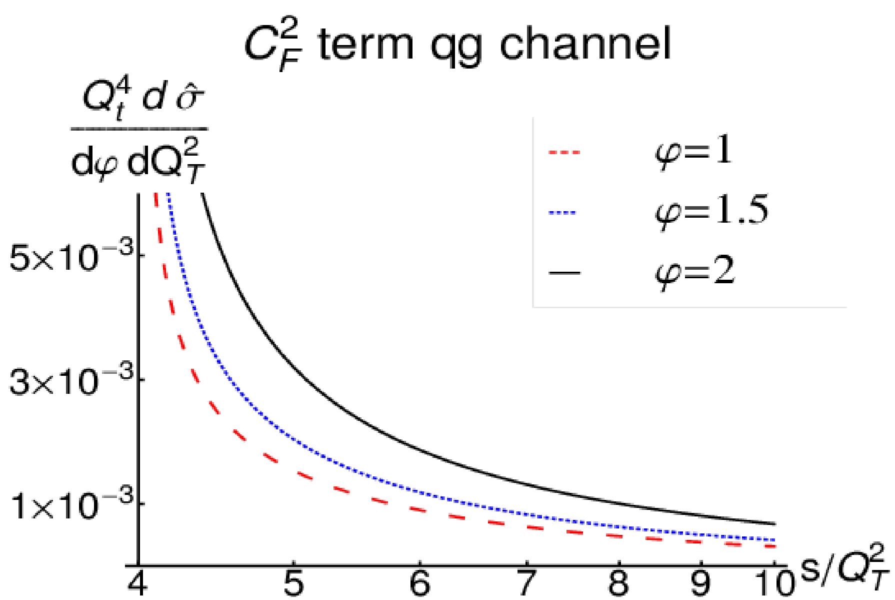
- in collinear limit reduce to standard matrix elements.
  - gauge invariant with respect to incoming gluon

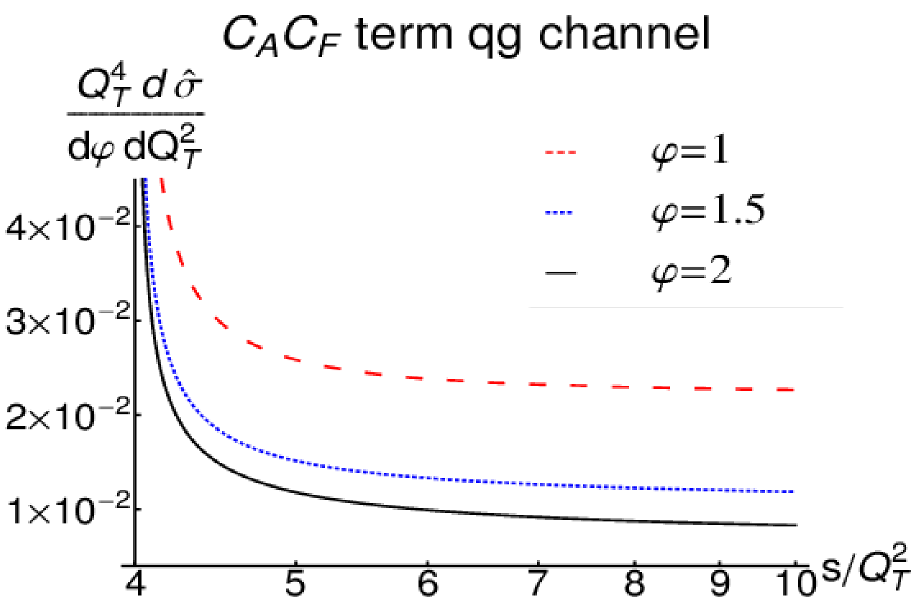
ENERGY DEPENDENCE qg CHANNEL

$Q_T =$ final-state transverse energy (in terms of two leading jets p_t's)

$$s = (k_1 + k_2)^2$$

$$\cos\varphi = Q_T \cdot k_T / |Q_T||k_T|$$





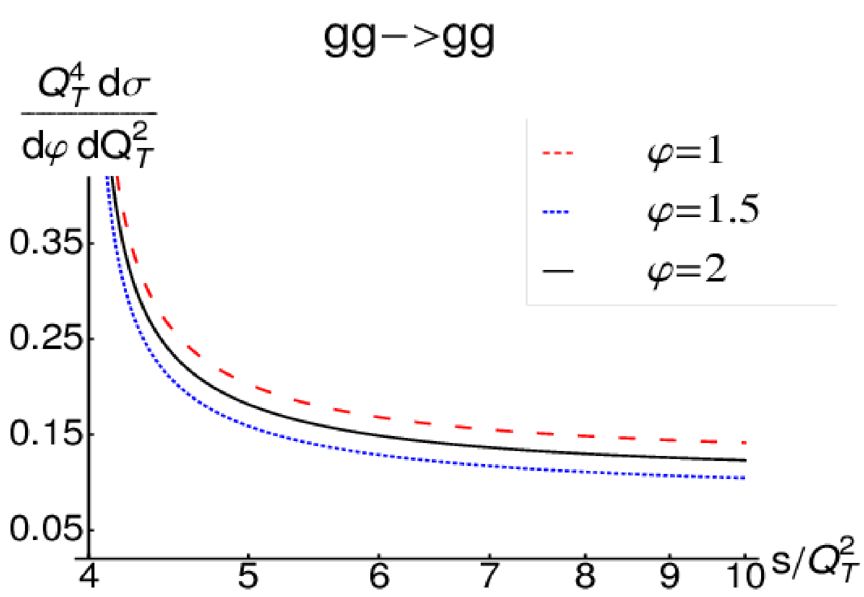
Nonabelian contribution constant at high energy and dominates

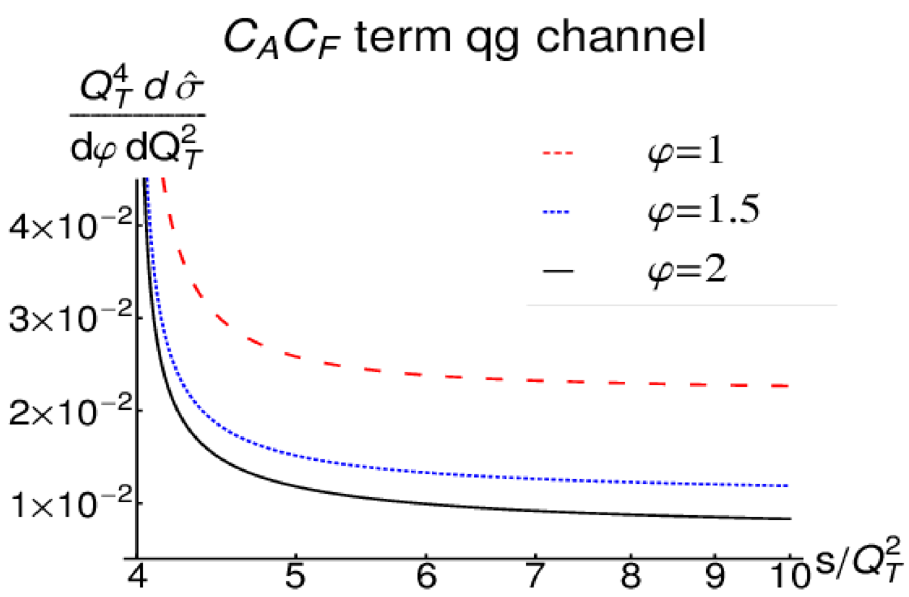
ENERGY DEPENDENCE gg CHANNEL vs. qg CHANNEL

Q_T = final-state transverse energy (in terms of two leading jets p_t's)

$$s = (k_1 + k_2)^2$$

$$\cos\varphi = Q_T \cdot k_T / |Q_T||k_T|$$



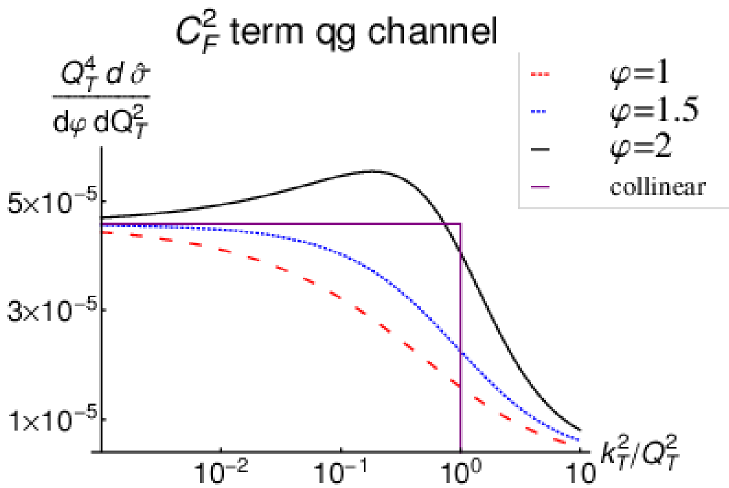


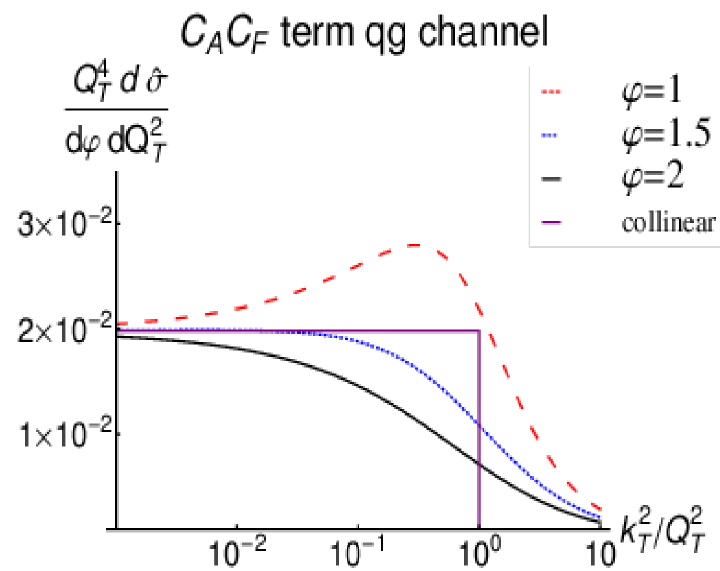
Gluon contribution dominates on matrix element level

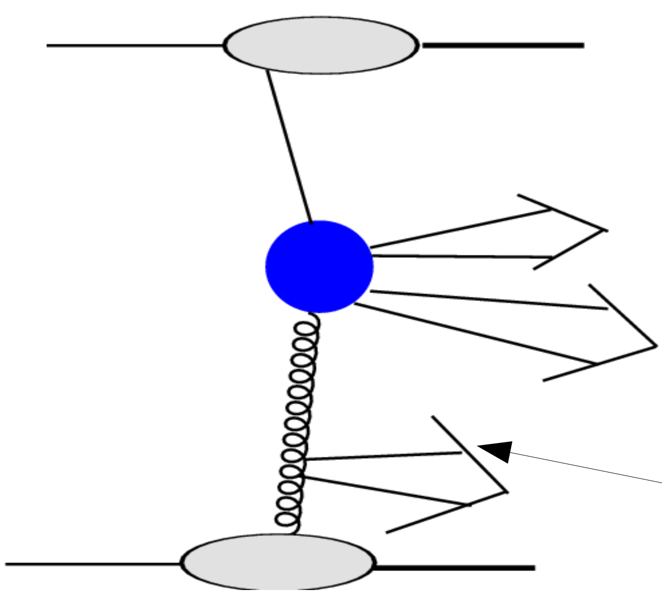
BEHAVIOR AT LARGE kt qg CHANNEL

k_T = transversal momentum of incoming gluon = transverse momentum carried away by extra jets

$k_T/Q_T \to 0$ leading order process







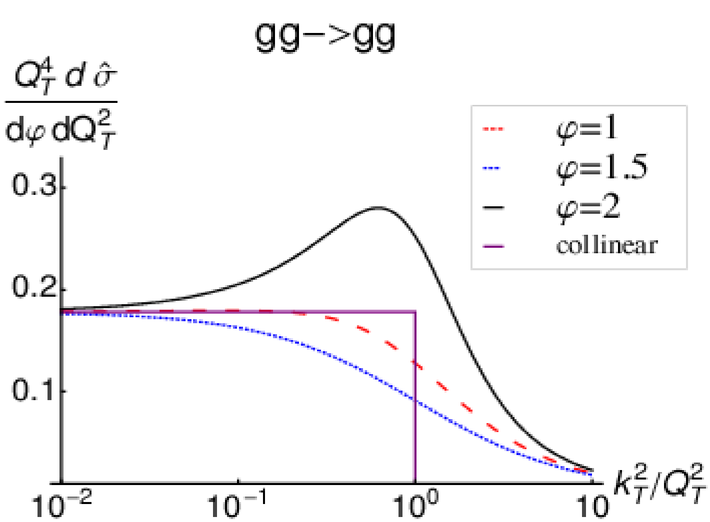
- dynamical cut-off at $k_T \sim Q_T$ set by coherence effects
  - ▷ non-negligible terms from finite k_T tail

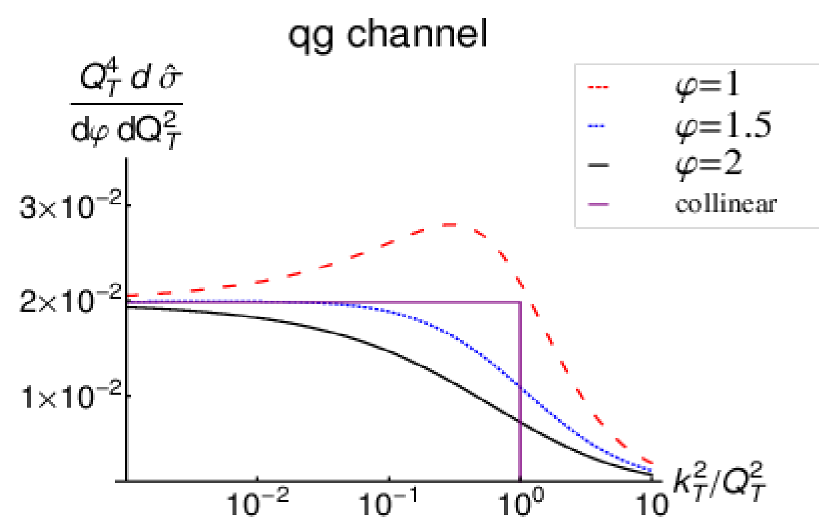
Such hard emission is not possible at LO DGAP parton shower. High energy approach allows for it

BEHAVIOR AT LARGE kt gg vs. qg

k_T = transversal momentum of incoming gluon = transverse momentum carried away by extra jets

$k_T/Q_T \to 0$ leading order process



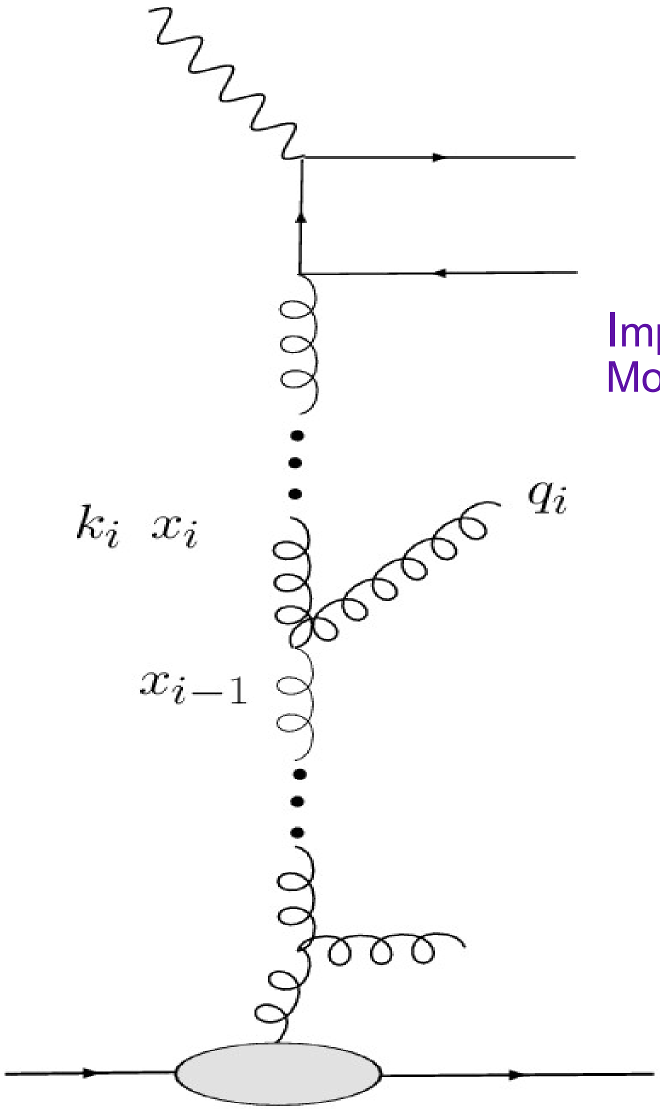


[Deák, Hautmann, Jung, & K JHEP09(2009)121]

- gluon dominates on matrix element level

PARTON DENSITY FROMM CCFM

Equation based on strong ordering in angle and coherence effects at high energies. Interpolates between DGLAP and BFKL .



Implemented in CASCADE Monte Carlo (H. Jung)

$$p = \frac{q}{1-z} \qquad z = \frac{x_i}{x_{i-1}} \qquad \overline{p} = \frac{\overline{q}}{1-z}$$

$$\xi = \frac{z_i p_i^2}{x_i^2 E}$$

Sudakov form factor. No branching.

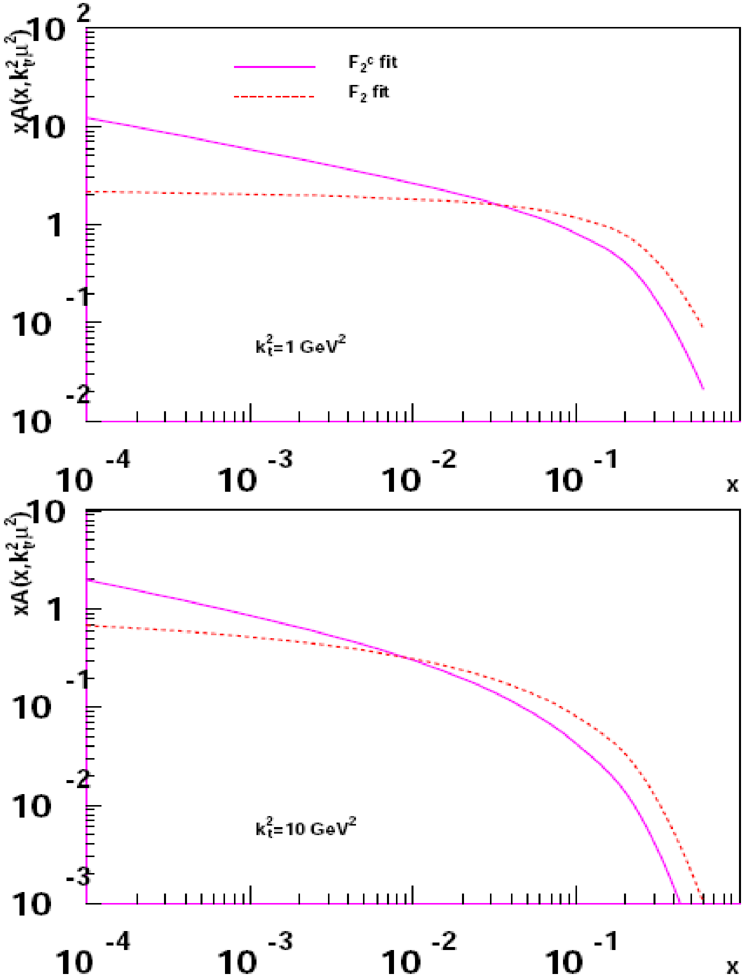
$$\mathcal{A}(x,k,\overline{p}) = \overline{\alpha}_s \int_x^1 dz \int \frac{d^2p}{\pi p^2} \theta(\overline{p} - zp) \Delta_s(\overline{p}, zp)$$

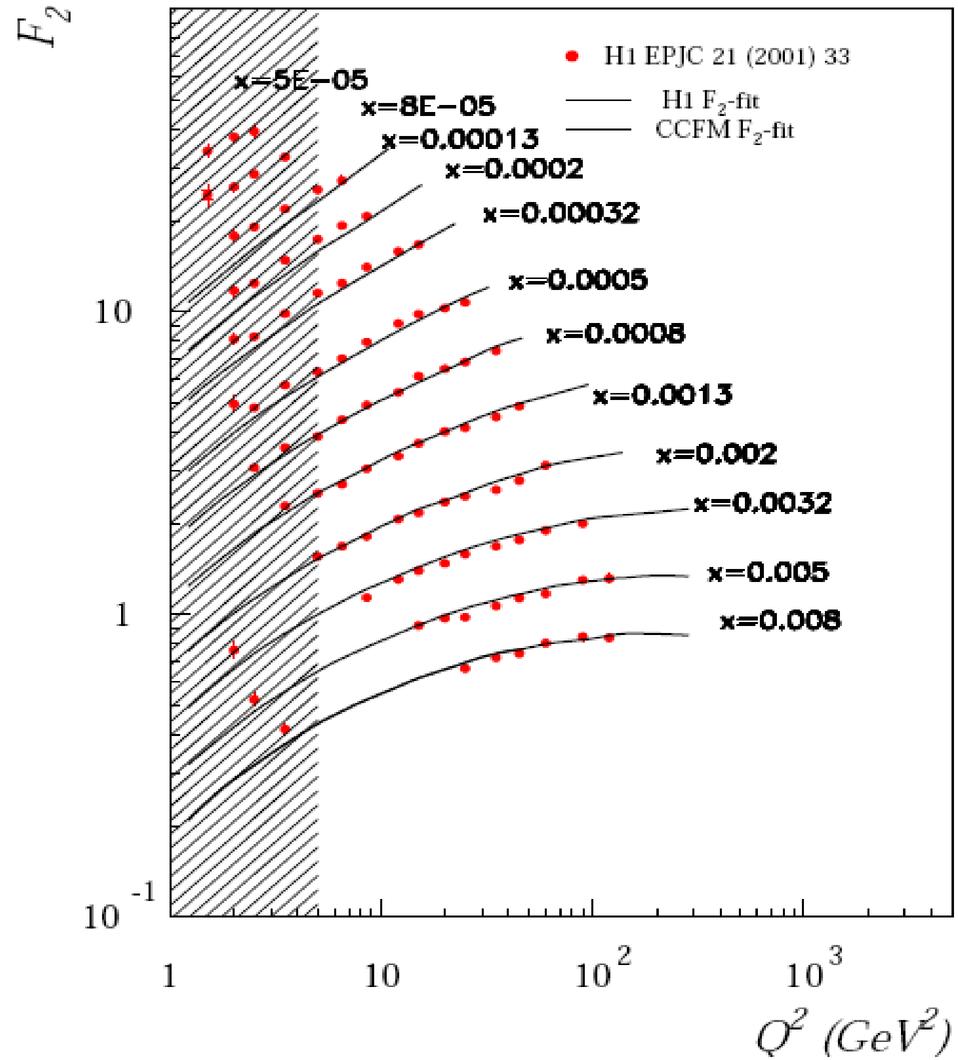
$$\times \left(\frac{\Delta_{ns}(k,z,p)}{z} + \frac{1}{1-z} \right) \mathcal{A}\left(\frac{x}{z}, |k + (1-z)p, p| \right)$$

Non-Sudakov form factor. Regularizes 1/z singularity

CCFM CONSTRAINED BY HERA DATA

from Jung et .al hep-ph/0611093v1





- Good description.
- Might be used to jet physics at higher energies

PHENOMENOLOGY

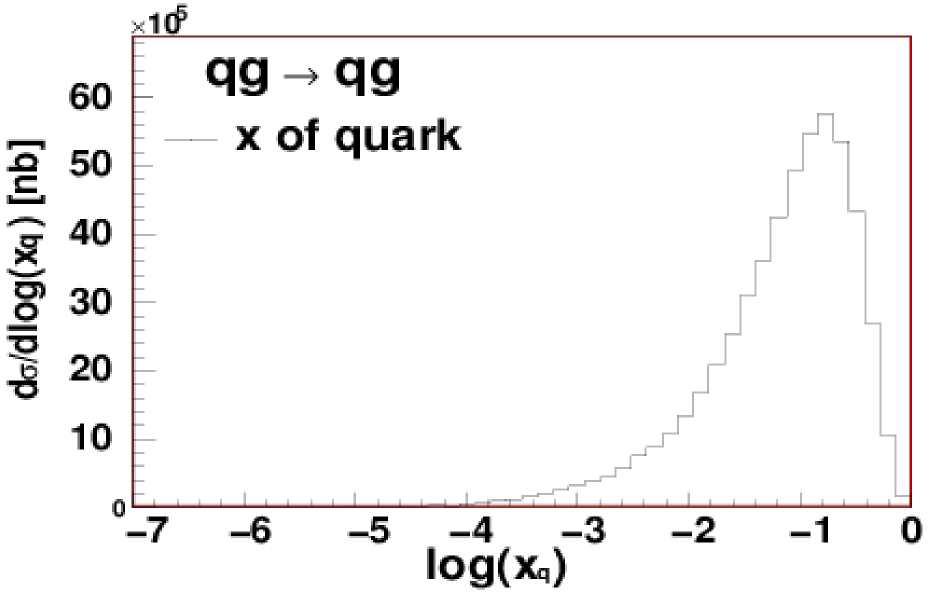
- We can calculate the convolution formula for the cross section using a Monte Carlo generator and study jet observables
- Look for small-x dynamics effects
- To prominent forward detectors at the CMS experiment
  - HF forward calorimeter $3 < y < 5$
  - CASTOR calorimeter $5.3 < y < 6$
- We can study two jet correlations - one jet in the central rapidity region- the other in the forward rapidity region

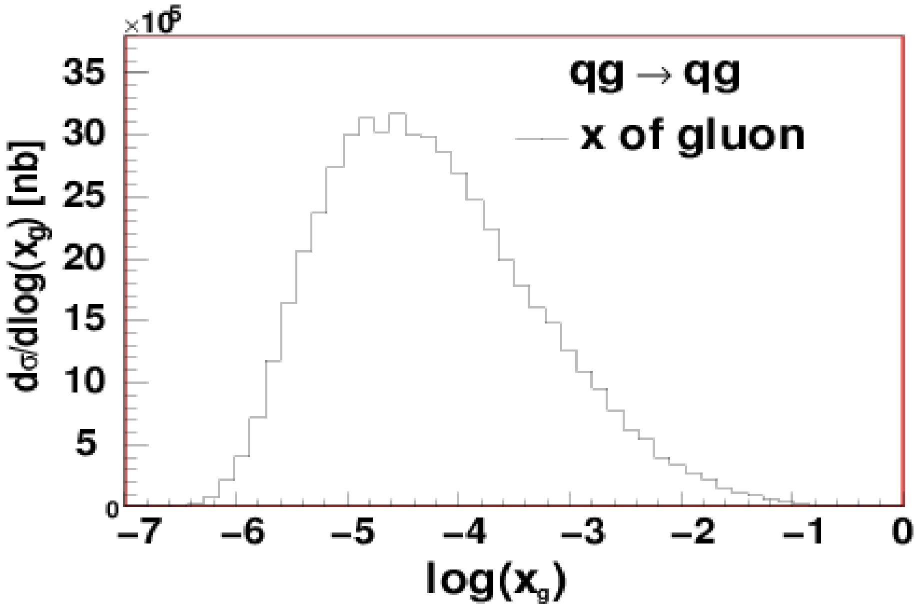
Central jet	Forward jet	
$\lvert y_j \rvert < 2$	$4. < y_j < 6.6$	$3 < y_j < 5$
$p_{jt} > 20\mathrm{GeV}$	$p_{jt} > 20\mathrm{GeV}$	

TOWARD JET OBSERVABLES

- CASCADE
  - unintegrated gluon density from CCFM (can be run in DGLAP mode too)
  - unintegrated valence quark density from integrated CTEQ 6.1, CCFM-like evolution [Deak, Hautmann, Jung, K in preparation]
  - no sea quarks → ongoing activity [Deak, Hautmann, Jung, K in preparation]
- PYTHIA
  - integrated pdfs CTEQ 5L
  - sea quarks included but small contribution
  - virtuality ordered shower used
  - run in no multiple interactions mode
- jetfinder we used → kt-clus run on hadron level after parton showering

LONGITUDINAL MOMENTA BEFORE COLLISION



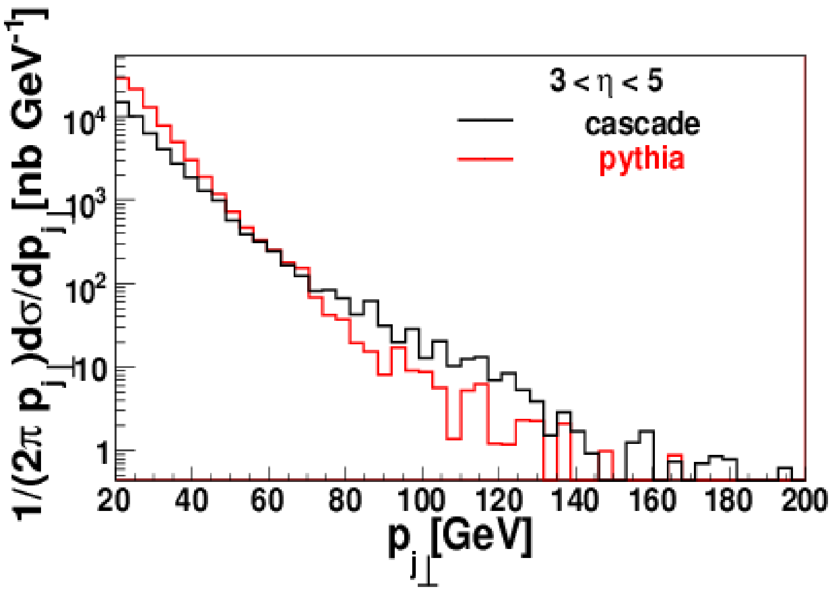


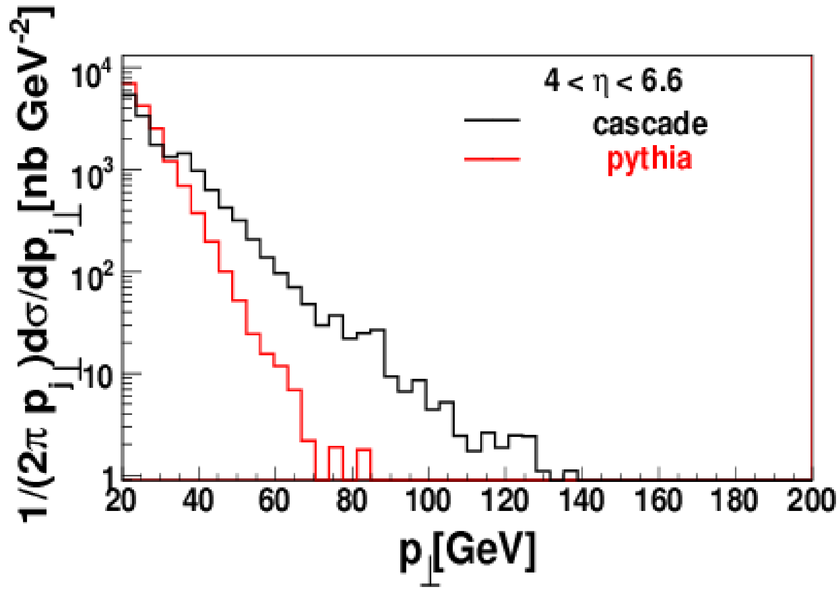
[Deák, Hautmann, Jung, & K in preparation]

- incoming gluon carrying low momentum fraction
  - incoming quark carrying large momentum fraction

pt SPECTRA OF PRODUCED JETS

Central jet	Forward jet	Central jet	Forward jet
$\vert y_j \vert < 2$	$3 < y_j < 5$	$\vert y_j \vert < 2$	$4. < y_j < 6.6$
$p_{jt} > 20\mathrm{GeV}$	$p_{jt} > 20\mathrm{GeV}$	$p_{jt} > 20\mathrm{GeV}$	$p_{jt} > 20\mathrm{GeV}$



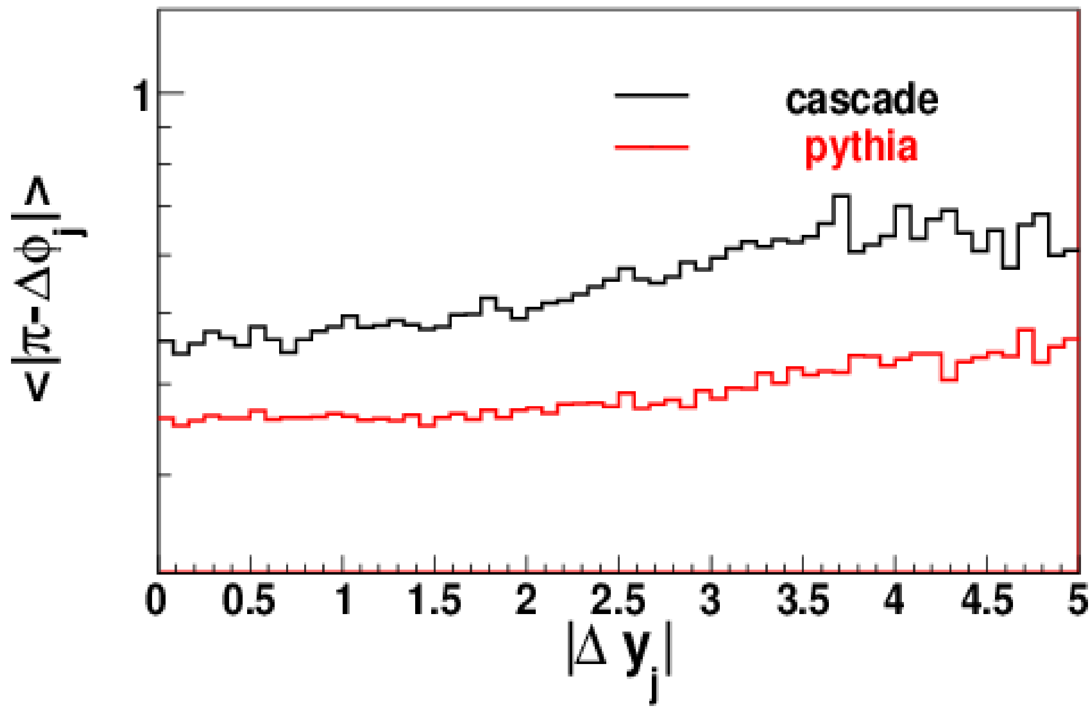


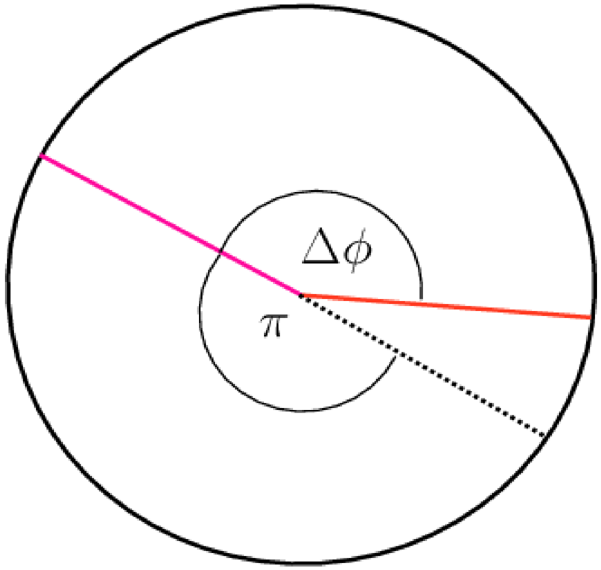
[Deák, Hautmann, Jung, & K in preparation]

- k_T of incoming gluon allows for harder spectrum
  - CASCADE uses CCFM like parton showers which are not ordered in k_T

DECORRELATIONS

Average deviation from back-to-back configuration depending on the rapidity distance





- Larger deccorelations from CASCADE
  - Consistent with more jet activity

Conclusions and outlook

- We have claculated matrix elements relevant for forward jet physics at LHC
  - One can study effects of long rapidity corelations in p p
    - Implementation into full hadron level MC generator
      - Significant effects from small x dynamics

- Jets in the central region – initiated by sea quarks
  - Jets in the central region – initiated by two offshell gluons
    - Multijet processes