# On high energy QCD factorization: theoretical basics and phenomenological applications

Krzysztof Kutak

Universiteit Antwerpen

# High energy scattering as a probe of new physics

- New dynamical effects in SM
  Color Glass Condensate, Quark Gluon Plasma,
  saturation,..

- Production of new particles not included in SM
  gravitons, SUSY, LED,...

To separate a "new physics signal" from the old background one needs to understand the behavior of QCD cross section at high energies (constraints, uncertainties of pdf sets, NLO calculations)

# Quantum Chromodynamics

QCD ingridients:

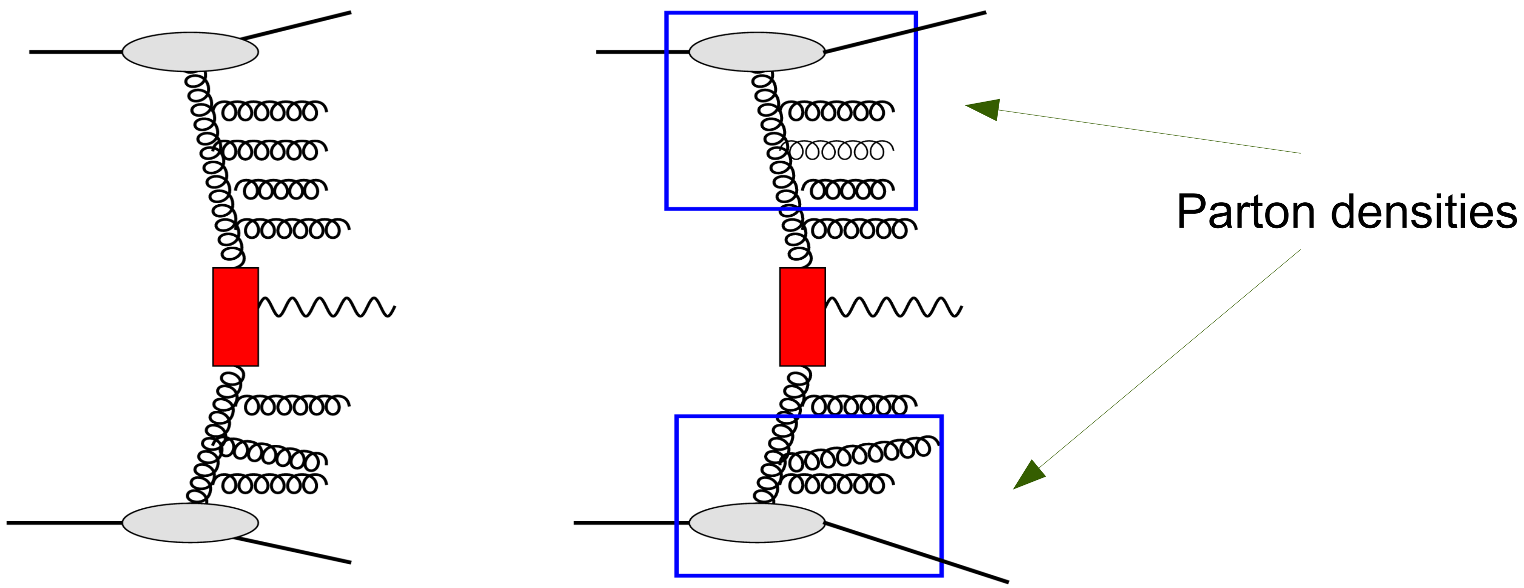
- Quarks and anti-quarks (spin 1/2)
  - 3 colors
  - 6 flavors

- Gluons
  - 8 colors pairwise combinations of quark colors

$$L = -\frac{1}{4} F^a_{\mu\nu} F^{a,\mu\nu} + \sum_{\text{flavors}} \bar{q}^k (i\gamma_\mu D^\mu + m_q)^{kl} q^l$$

# pQCD calculations

- Asymptotic freedom of QCD allows for perturbative calculations
  - Matrix element + factorization theorems
    - Factorization theorems allow for decomposition of process under some ordering condition into long and short  distant parts (ep, pp, pA)

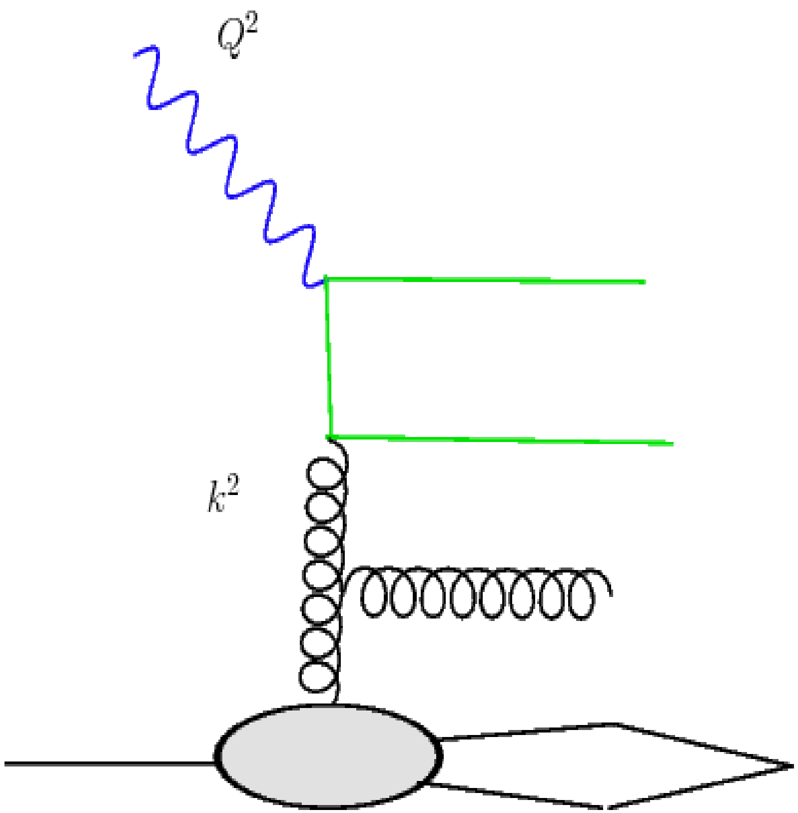



Matrix element  convoluted with resumed  contributions of higher orders - Collinear Factorization , High Energy Factorization

Observable ~  parton density $\otimes$ ME $\otimes$ parton density

# Collinear factorisation and DGLAP

Dokshitzer, Gribov, Lipatov, Altarelli, Parisi




Assumption: Q>>k

- Good description of inclusive processes($F_2$)

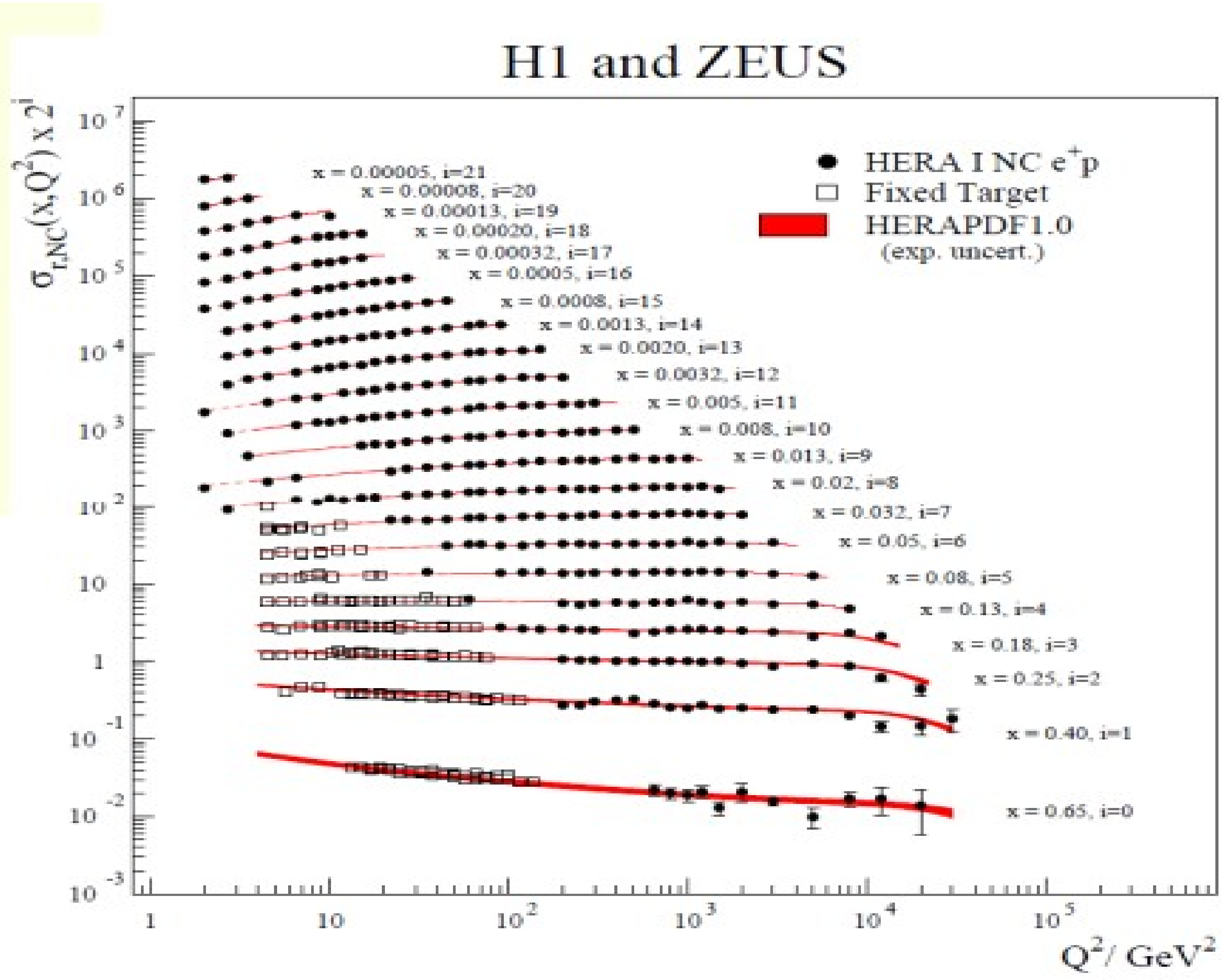
  Vermasseren, Vogt, Moch '04

- Kernels known up to NNLO

- Implemented in many Monte Carlo generators: PYTHIA,RapGap, HERWIG, MadEvent

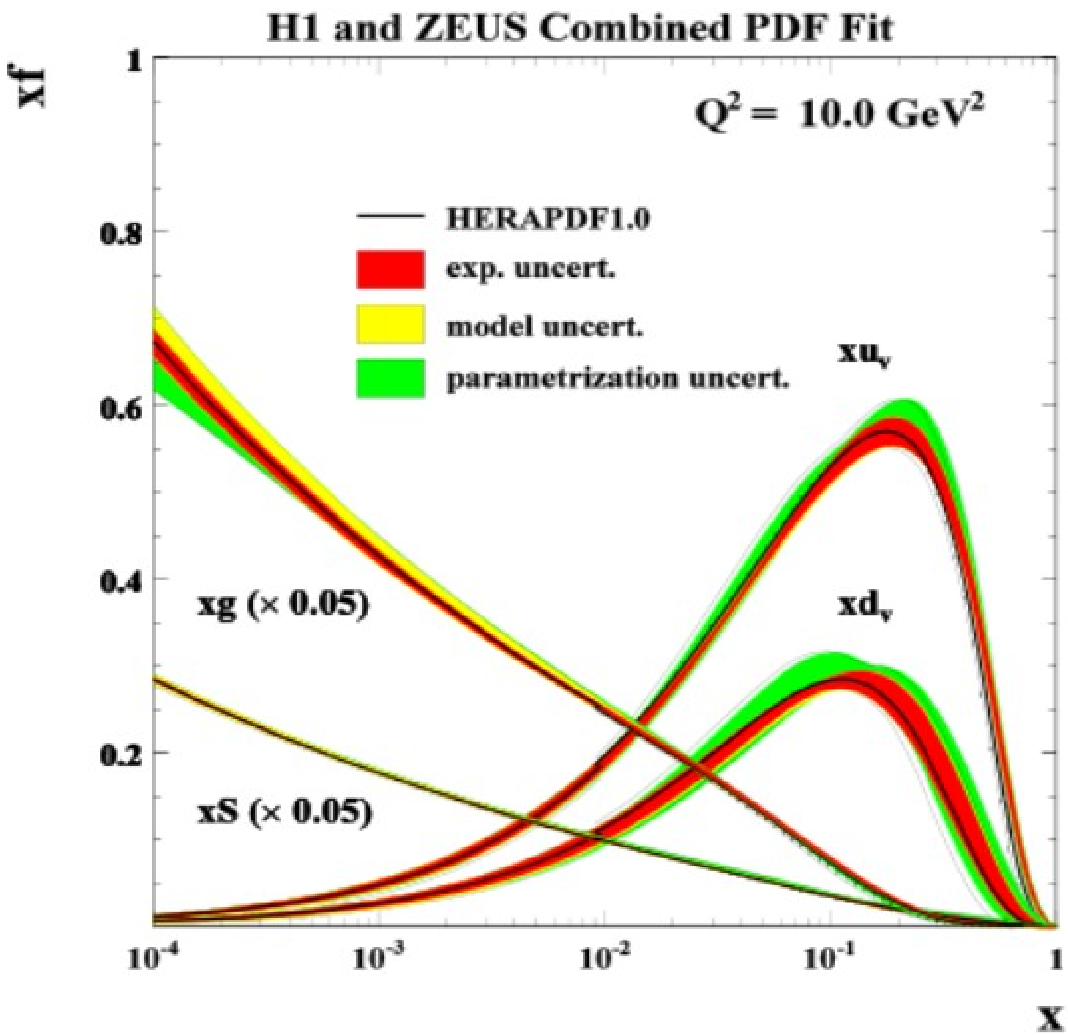
$$Q\frac{d}{dQ}D_q(x_B,Q^2) = K_{\mathrm{DGLAP}}D_q(x_B,Q^2)$$

# DGLAP and inclusive data




Good fit but strongly depends on the form of assumed input

# DGLAP- parton densities




arxiv:0911.0884

Strong power like growth of gluon density may lead to violation of unitarity bound

$$\sigma_{tot} \overset{E\to\infty}{\leq} \ln^2 E$$

Inconsistencies with applications to dense systems since for this one needs direct access to gluonic degrees of freedom.

Bartels, Kutak '07

# High energy factorization

High energy factorization basic facts:

- gluon dominates (quark contributions neglected at LO)
- taking into account kinematics of the collision precisely enough at LO (takes into account some parts of NLO and NNLO of DGLAP)
- sums up large logarithms of energy
- allows for formation of dense system which then saturates

Ciafaloni, Catani, Hautman '94

- implementation in Monte Carlo

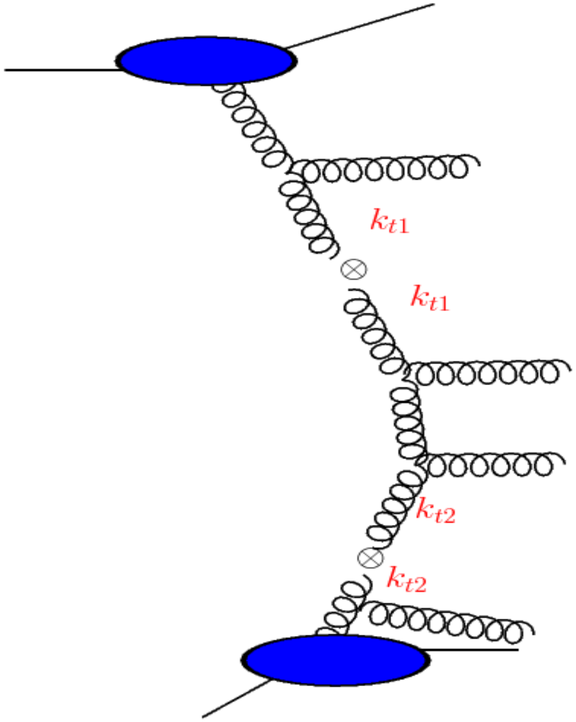
$$L = -\frac{1}{4}F^a_{\mu\nu}F^{a,\mu\nu} + \text{ source terms}$$

# HIGH ENERGY LIMIT OF QCD

$$\sigma = \int dx_1 dx_2 d^2 k_{1T} d^2 k_{2T} f(x_1, k_{1T}) \hat{\sigma} f(x_2, k_{2T})$$

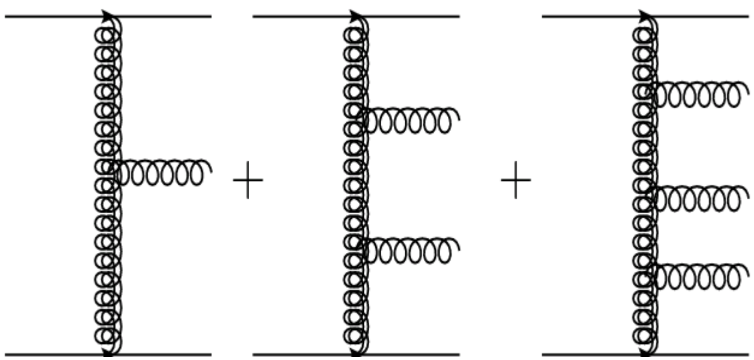
Ciafaloni, Catani, Hautman '90

Implemented in Monte Carlo generator CASCADE
(H. Jung )




- Parton density depends on kt
  - Off shell initial state partons off shellness ~-kt $^2$
    - In collinear limit reduces to collinear factorizati

# High energy limit of QCD basic equation: BFKL



$$+ \ldots = \Sigma_n^{\infty} \ln^n s/s_0$$

$$\partial_Y f(Y,k^2) = K_{BFKL} \otimes f(Y,k^2)$$

f(x,k )  - sum up diagrams -

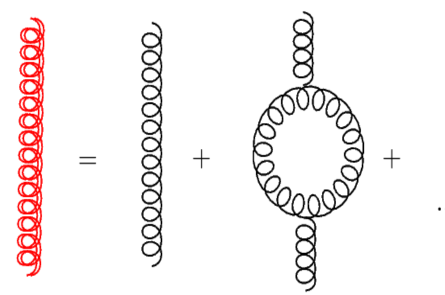
Balitsky Lipatov, Fadin, Kuraev '77

s-square of total energy

Y~ln1/x ~total energy

- Known also for SM YM
- Studied also in context of AdS/CFT
- Known up to NLO
- No hard scale: “evolution without observer”
- No useful Monte Carlo implementation

Reggeized gluon



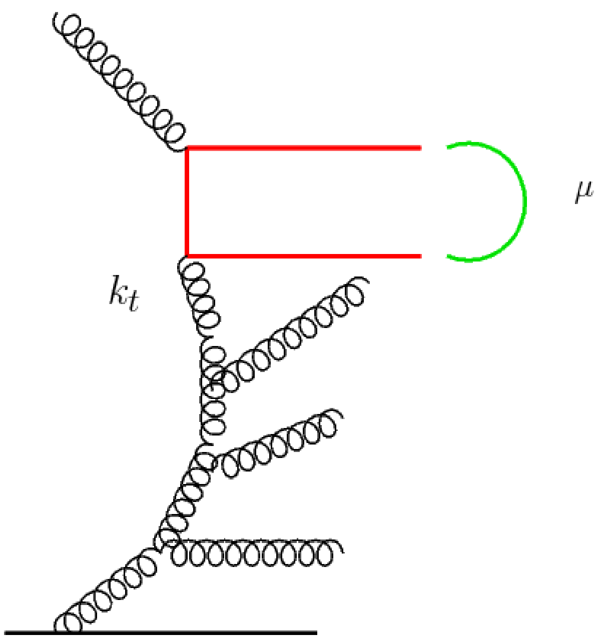

Valid for not too small x-10$^{-4}$

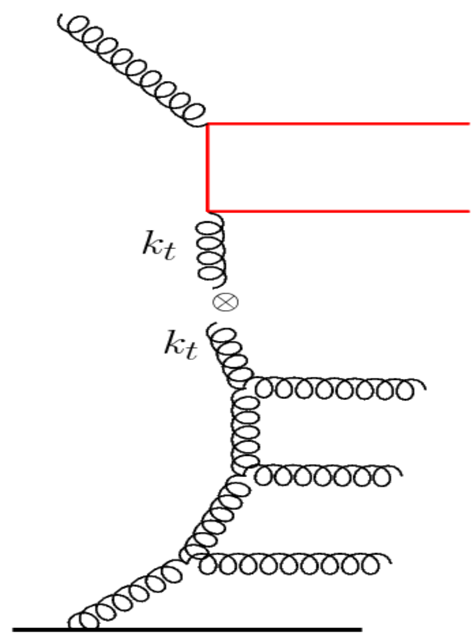
# CCFM evolution equation - evolution with observer

- Linear equation based on strong ordering in angle
- Interpolates between DGLAP and BFKL
- Gluon density is build by constructive interference of gluons
- Sumes up also logs of hard scale

$$\mathcal{A}(x, k_t^2, \mu) = K_{CCFM} \otimes \mathcal{A}(x, k_t^2, \mu)$$

Catani, Fiorani, Marchesini '90



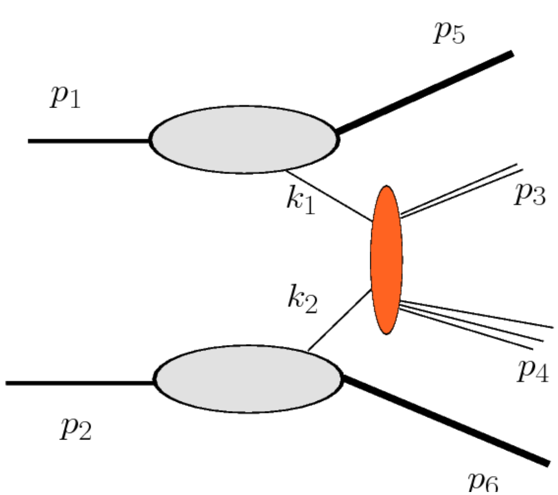




Implemented by H. Jung in Monte Carlo CASCADE

# High energy factorization and forward jets

$$\frac{d\sigma}{d^2p_{t1}d^2p_{t2}dy_1dy_2} = \sum_a \int d^2k_t \phi_{a/A}(x_1,\mu) \otimes |M|^2 \otimes \phi_{g^*/B}(x_2,k_t^2,\mu)$$

Consistent resumation both logs of rapidity and logs of hard scale




*Deak, Jung, Hautmann & Kutak '09*

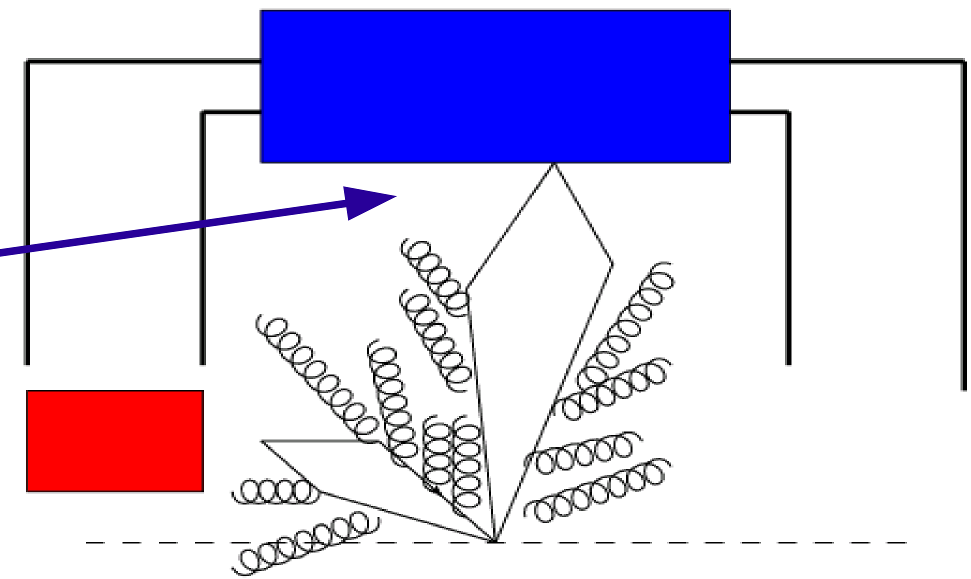
Knowing well parton densities at largr x one can get information about low x physics

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

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

# Measurement

- Polar angles small but far enough from beam axis
    - Measure: spectra of jets, angular correlations



central detector

Antwerp experimental group involved

forward detector

(CASTOR, HF)


*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);*

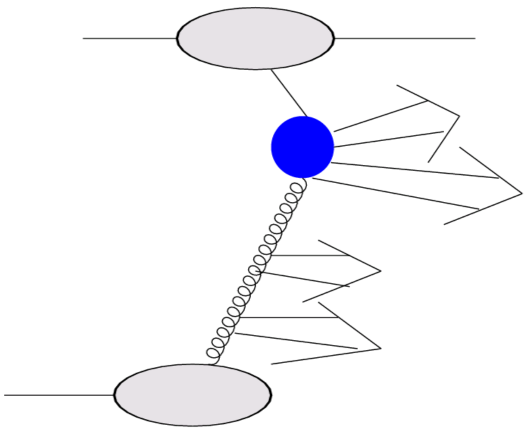
*M. Grothe, arXiv:0901.0998; D. d'Enterria, arXiv:0806.0883;*

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

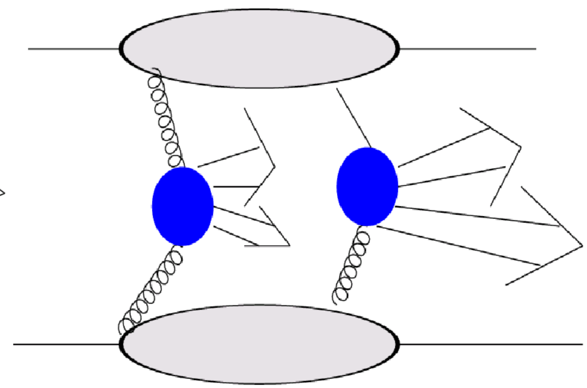
*H. Jung et al., HERA-LHC Proc. arXiv:0903.3861;*

# Cross section as a function of the azimuthal difference for different rapidities

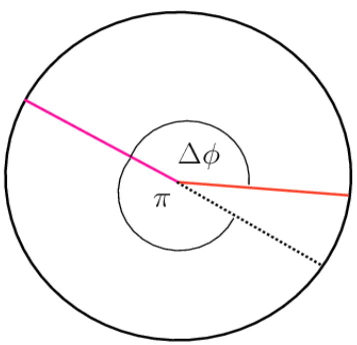
Deak,Jung,Hautmann, Kutak

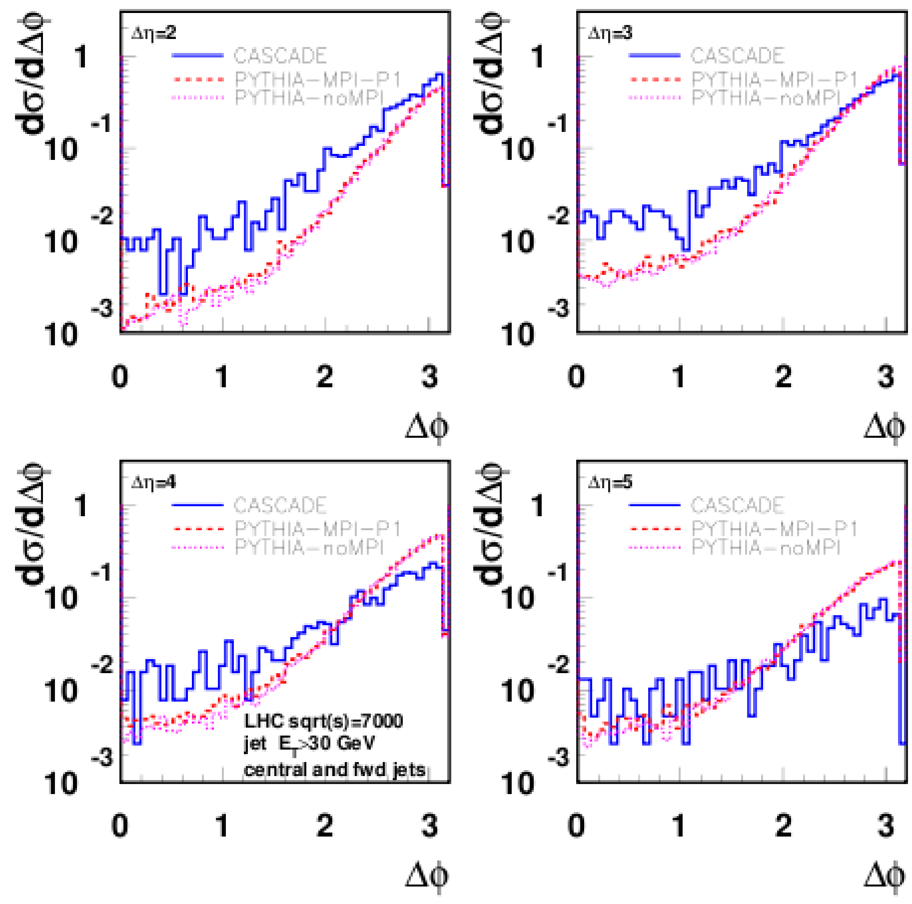


Single chain



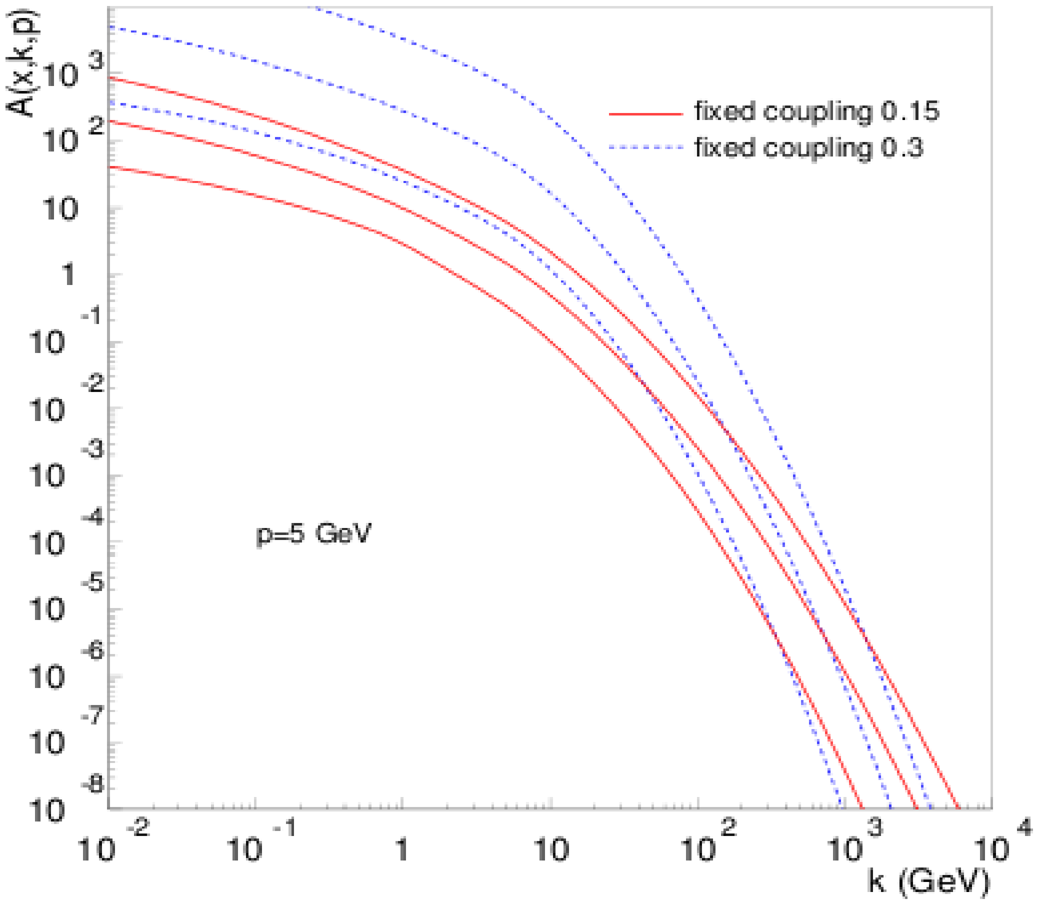
Multiple interactions




- Observable which measures jet activity in the parton shower
  - Noticeable differences between different approaches

# Towards dense partonic system and saturation




From Avsar, Stasto '10

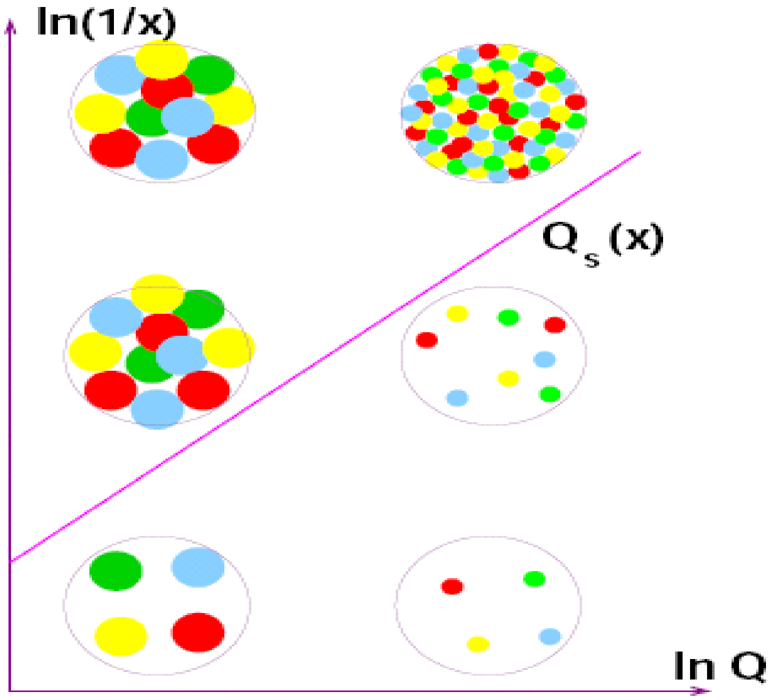
$$\sigma_{\rm tot} \stackrel{E\to\infty}{\leq} \ln^2 E$$

BFKL and CCFM are linear
and predict strong growth of number of
gluons. The growth has to be stopped.

# High energy factorization and saturation

Saturation – state where number of gluons stops growing due to high ocupation number

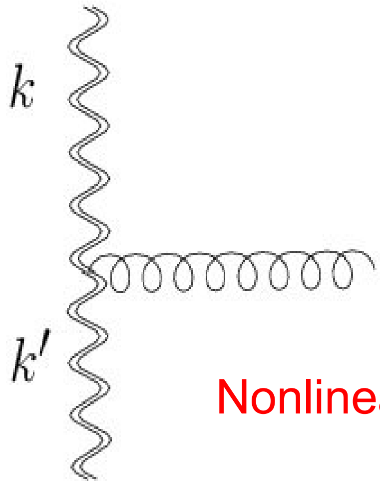
Cross sections change their behaviour from power like to logarithmic like.



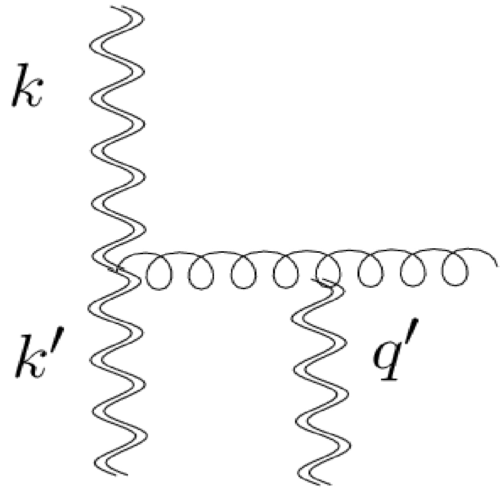

Gribov, Levin, Ryskin '83

On microscopic level it means that gluon apart from

splitting




recombination

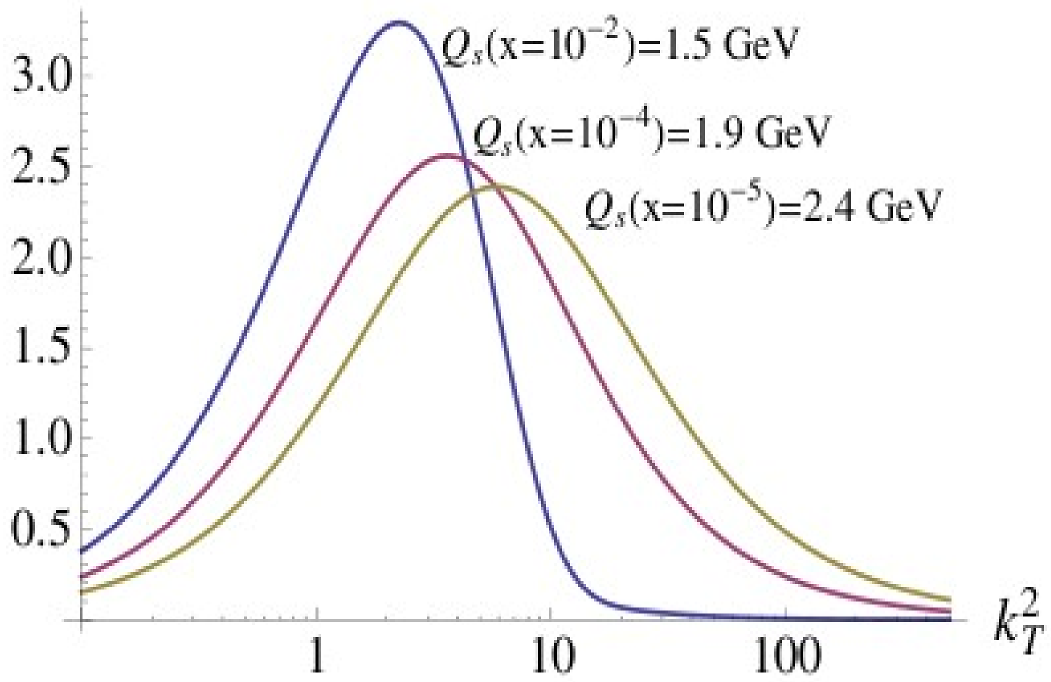



Nonlinear evolution equation BK

Balitsky, Kovchegov

# PROPERTIES OF GLUON DENSITY

Saturation allows to define well mean number of gluons and mean momentum



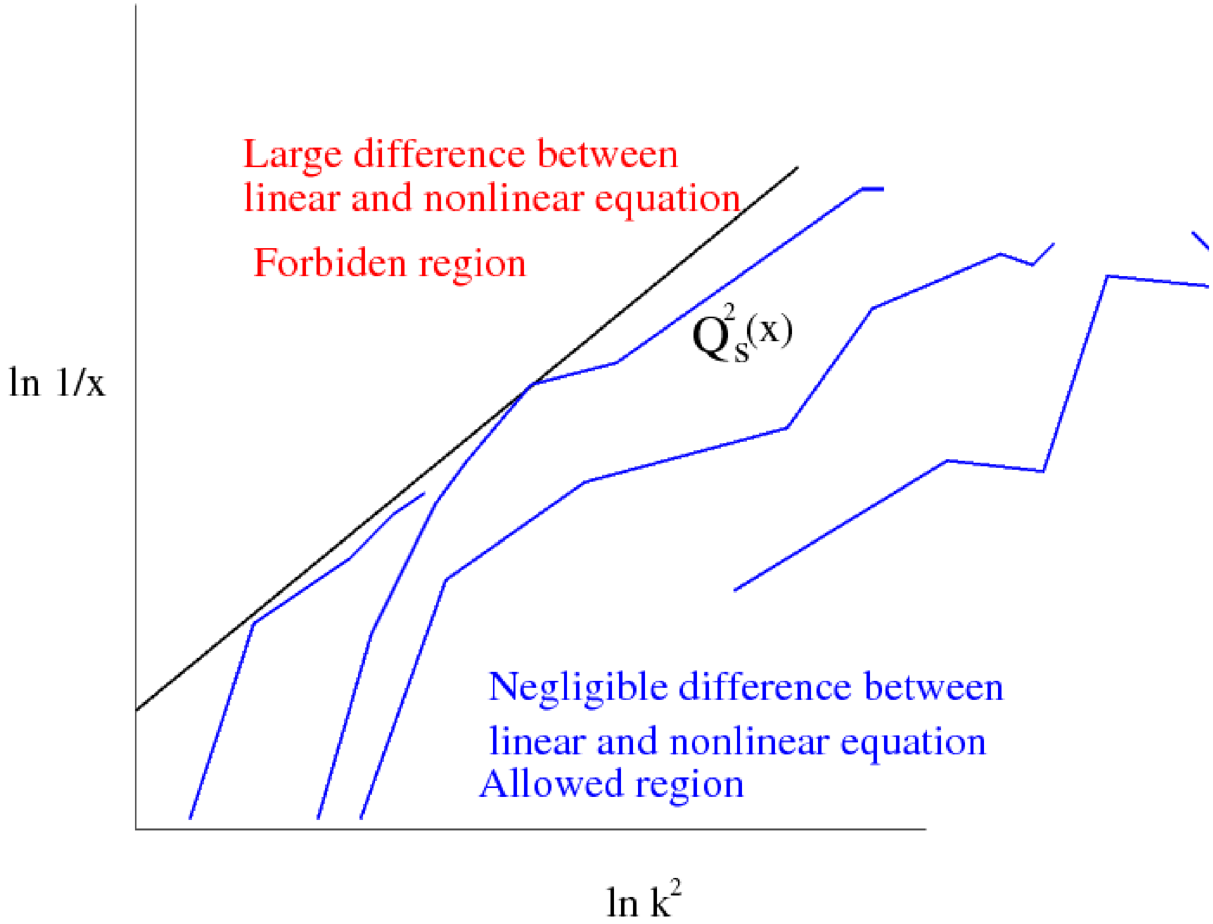

Solution of BK equation

$$\langle k_t^2 \rangle \sim Q_s^4(x)$$

$$\langle n \rangle \sim Q_s^2(x)$$

Saturation scale.
Most gluons have momentum of order of saturation scale

# CCFM with saturation – first steps



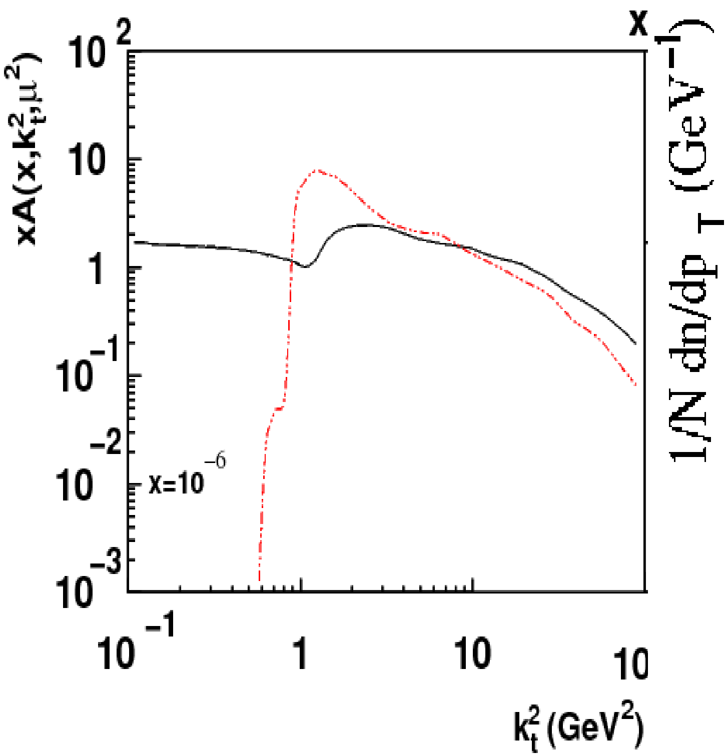

Jung, Kutak '09

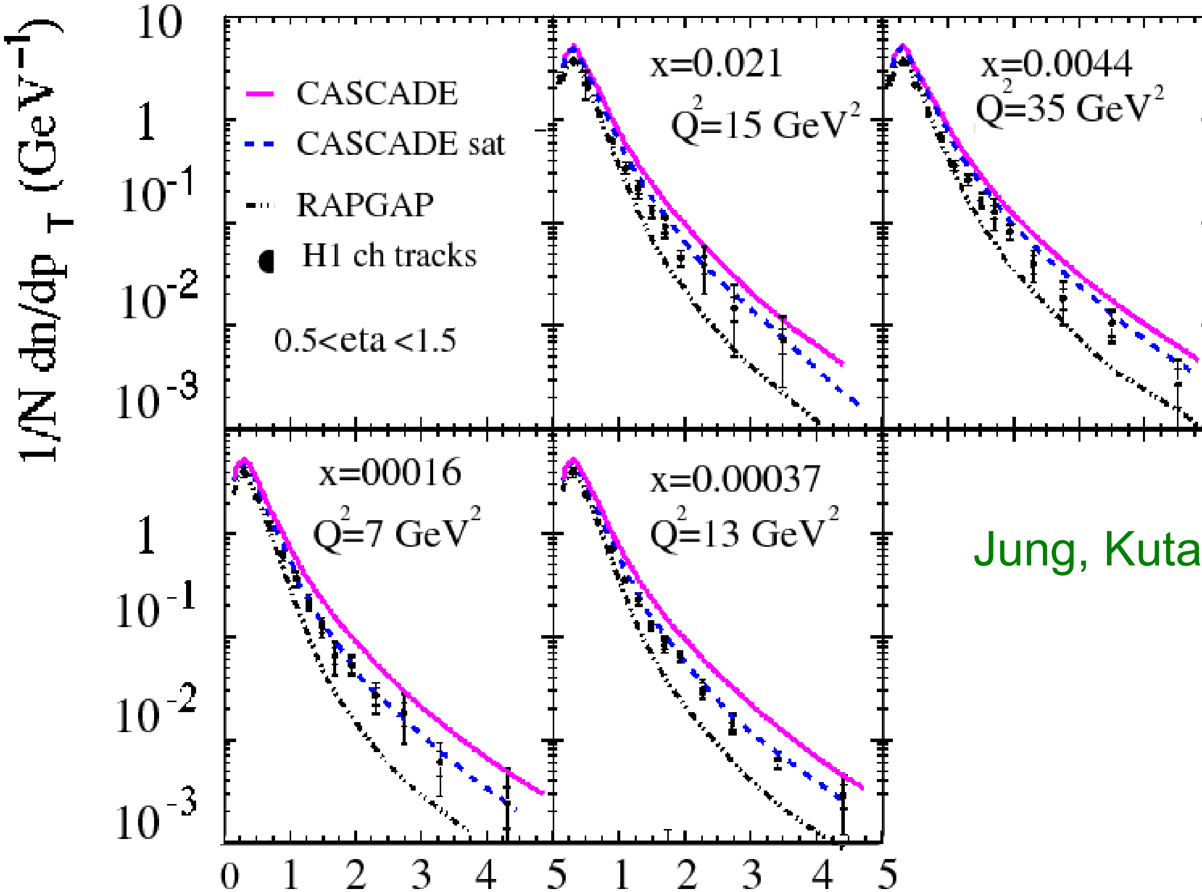
Avsar, Iancu '09

Final formulation
is still an open question

- Introduce line which will introduce effectively saturation effects in evolution.
  - Trajectories which enter the saturation region are rejected.

# CCFM with saturation – first steps




Jung, Kutak '09

- Gluon density suppresed at low k.
  - This affects pt distribution of charged particles

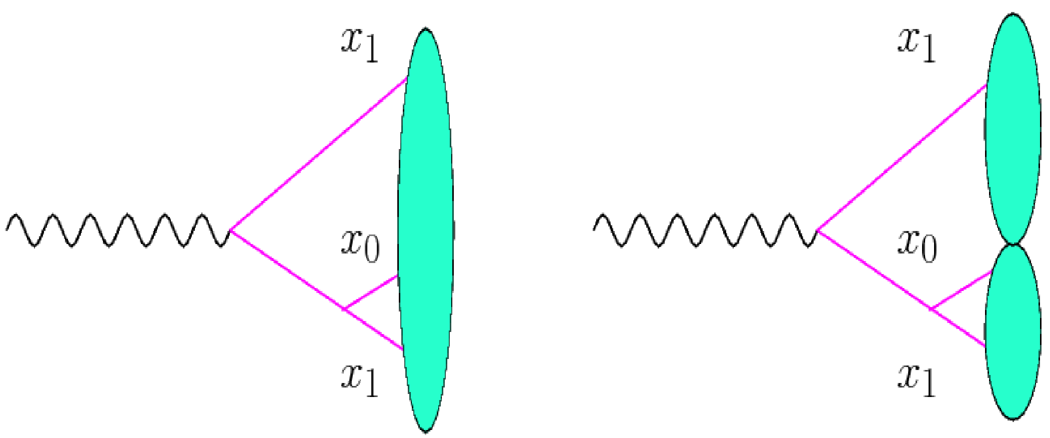
# High energy factorization and Color Glass Condensate

McLerran, Venugopalan,Iancu, Leonidov,Weigert,...

Colour: The gluons are coloured

Glass: Slow evolution of associated fields

Condensate: Vere high density of massless gluons




$$\frac{\partial}{\partial Y}\langle\mathcal{D}_{01}\rangle = \frac{g^2}{8\pi^3}\int d^2x_2\,[\langle\mathcal{D}_{02}\mathcal{D}_{21}\rangle - N_c\langle\mathcal{D}_{01}\rangle]\,K_{021}$$

$$\langle\mathcal{D}_{02}\rangle = d_{02}$$

$$\langle\mathcal{D}_{02}\mathcal{D}_{21}\rangle - \langle\mathcal{D}_{02}\rangle\langle\mathcal{D}_{21}\rangle = d_{0221}$$

+ infinite number of equations equations for corelators of higher order

JIMWLK, Balitsky chain

$$K_{021} = \frac{x_{01}^2}{x_{02}^2 x_{21}^2}$$

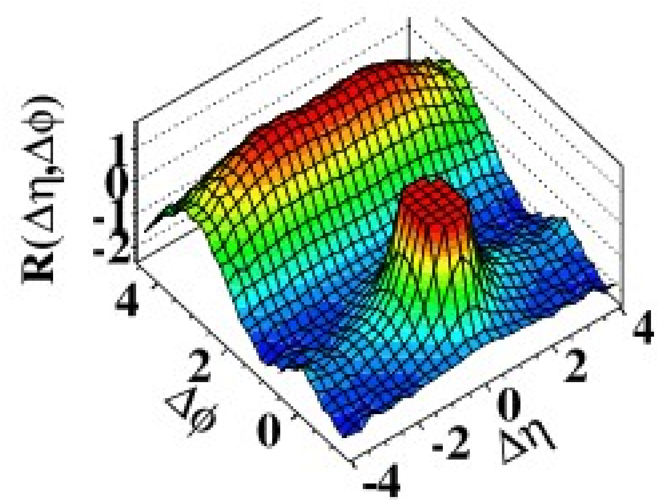
Practical calculations in Color Glass Condensate

make use of expansion of correlators in terms

of gluon density obtained from high energy factorisation

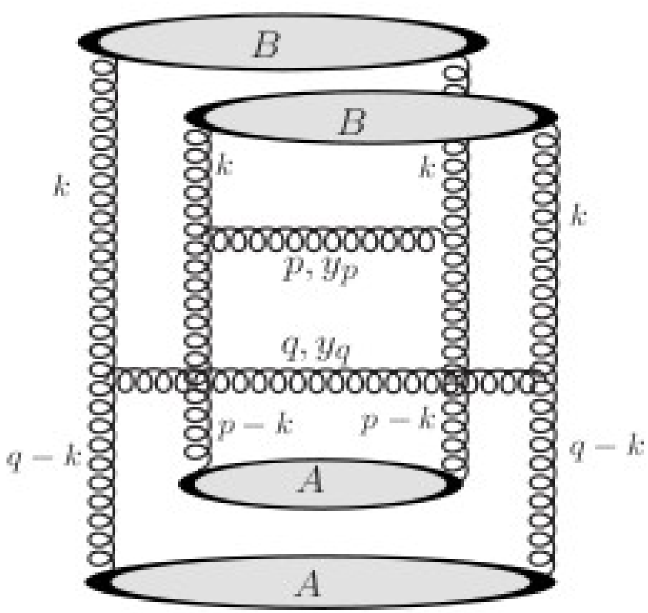
# Color Glass Condensate and high multiplicity events in pp collision at LHC

More detailed discussion during Xavier Janssen's talk




CMS '10

Ridge-like structure of correlated charged particles pairs with momenta in the range qt, pt, 1-3 GeV.
Not really expected in pp. Similar objects are showing up in AA collision due to eliptic flow- signature of collective expansion. Subleading for pp – not so dense system




Possible explanations:

- momentum conservation (P. Van Mechelen; P. Bozek '10)
  - CGC effects in pp – correlation in production on distances 1/Qs and existence of maximum of gluon density selects:

$$|\mathbf{p}_\perp - \mathbf{k}_\perp| \sim Q_s \quad |\mathbf{q}_\perp - \mathbf{k}_\perp| \sim Q_s$$

Dumitru et. al. '10

# Conclusions

- LHC opens phase space for large center-of -mass energies and for presence of multi-scales
  - Already we have exciting new results from LHC
    - Many, new challenging issues ahead