On high energy QCD factorization: theoretical basics and phenomenological applications

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Fundamental .be Interactions

High energy scattering as a probe of new physics

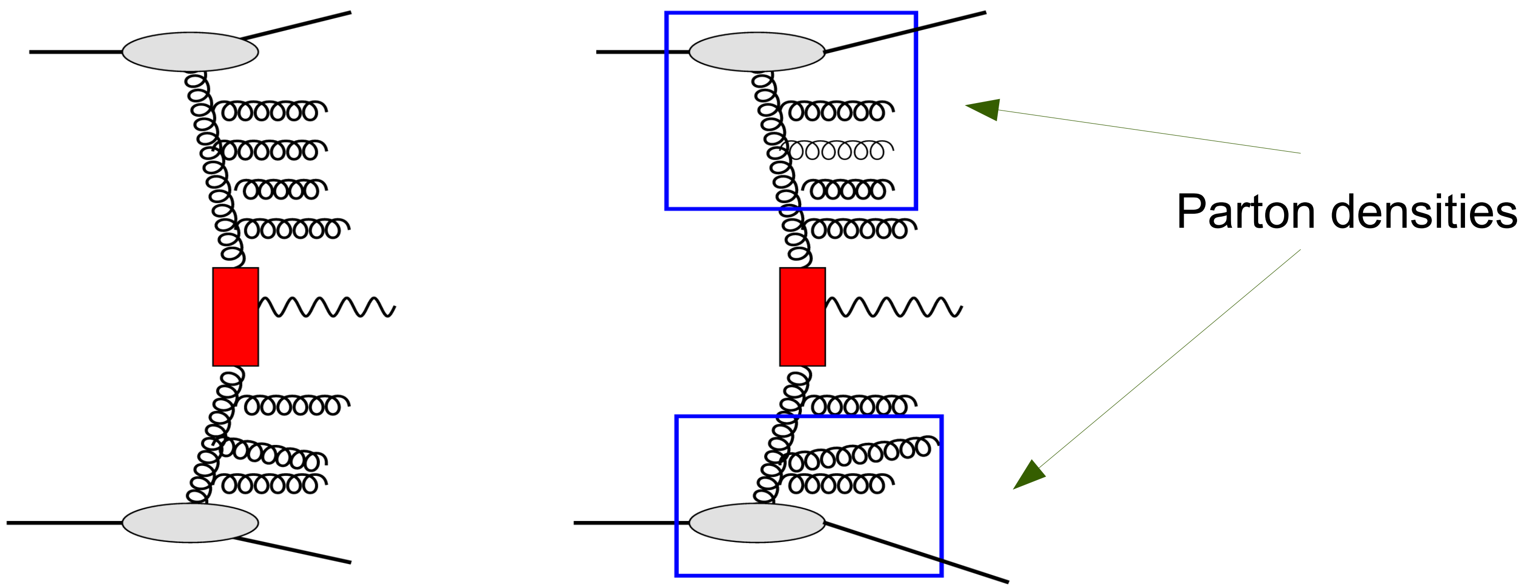
- New dynamical effects in SM
  Color Glass Condensate, Quark Gluon Plasma, saturation,..

- 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)

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

High energy factorization

Ciafaloni, Catani, Hautman '94

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
- implementation in Monte Carlo

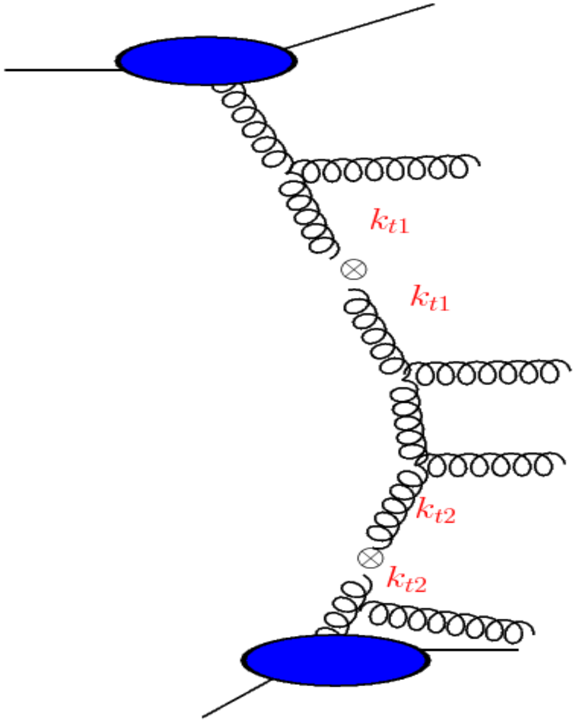
$$L = -\frac{1}{4} F^a_{\mu\nu} F^{a,\mu\nu} +$$ source terms

HIGH ENERGY LIMIT OF QCD

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

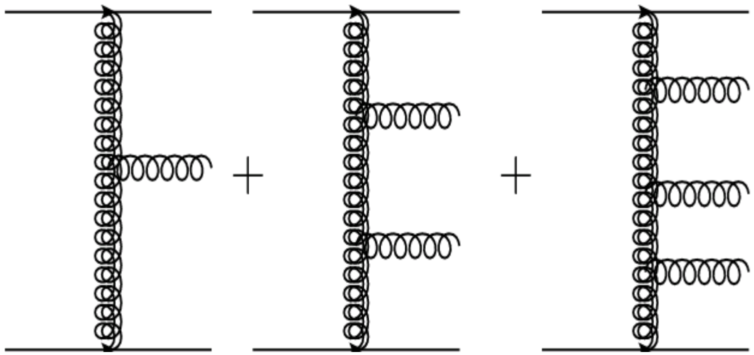
Ciafaloni, Catani, Hautman '90

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 -

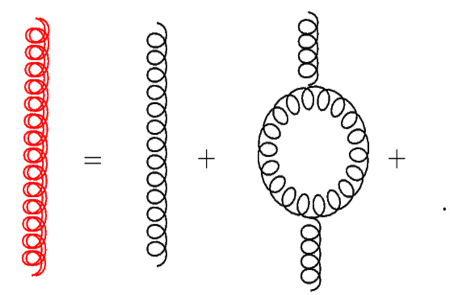
Balitsky Lipatov, Fadin, Kuraev '77

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



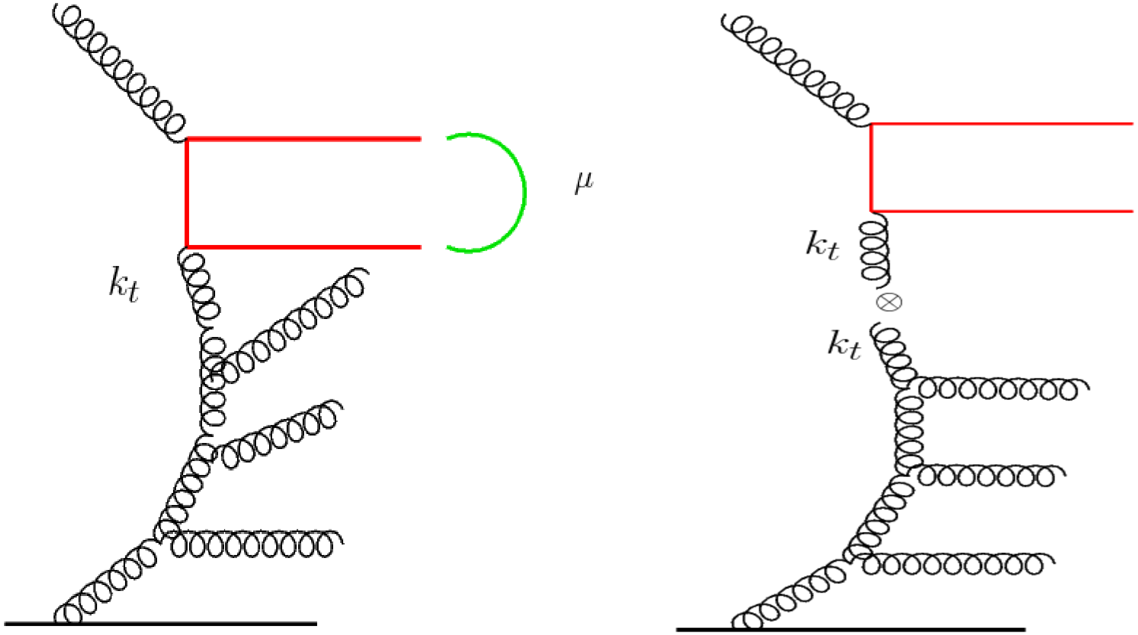
Valid for not too small x-10^{-4}

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

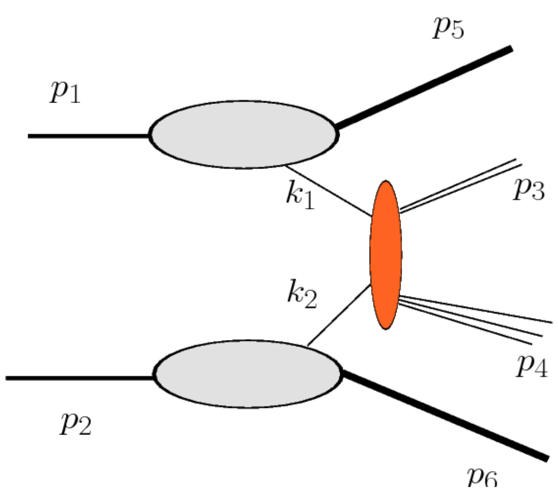


Implemented by H. Jung in Monte Carlo CASCADE

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



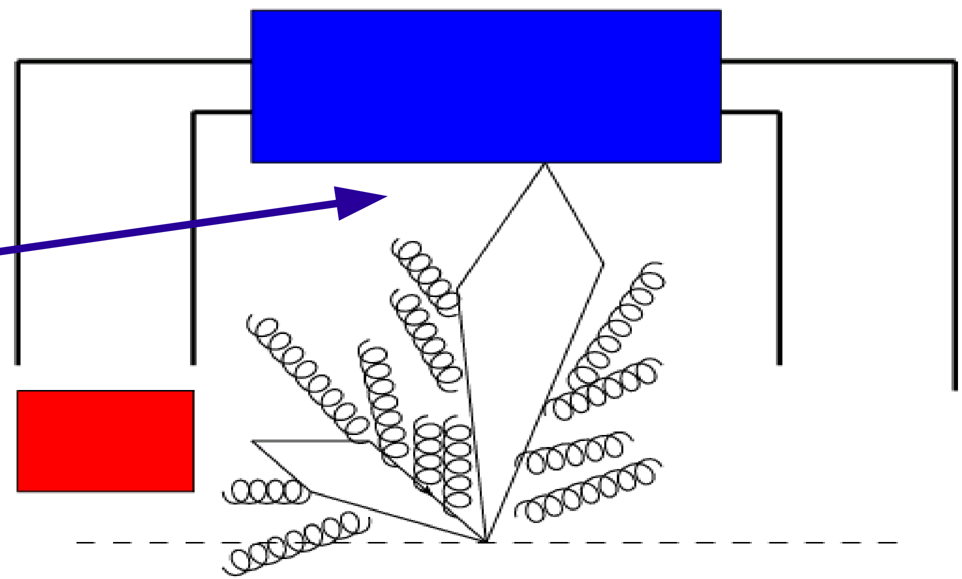
Deak, Jung, Hautmann & Kutak '09

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

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

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);

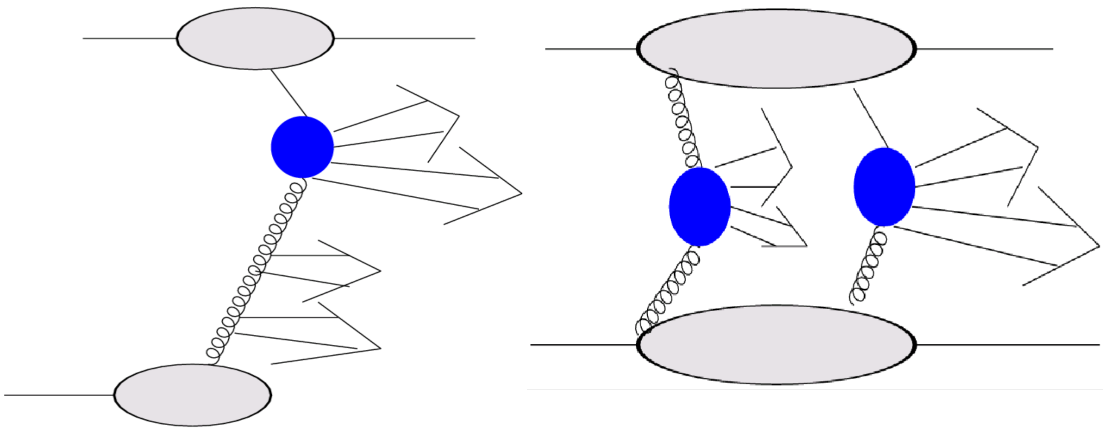
M. Grothe, arXiv:0901.0998; D. d'Enterria, arXiv:0806.0883;

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

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

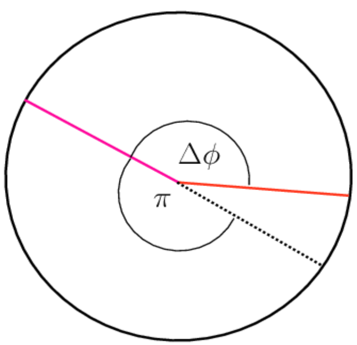
Cross section as a function of the azimuthal difference for different rapidities

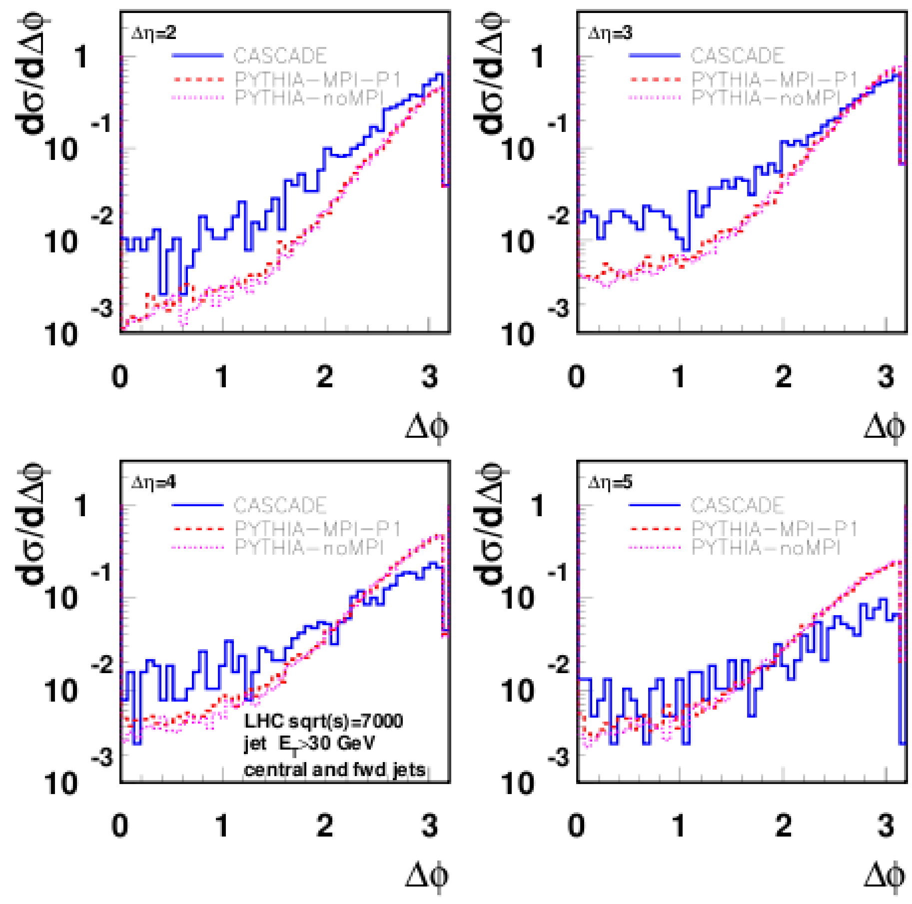
Deak,Jung,Hautmann, Kutak '10



Single chain

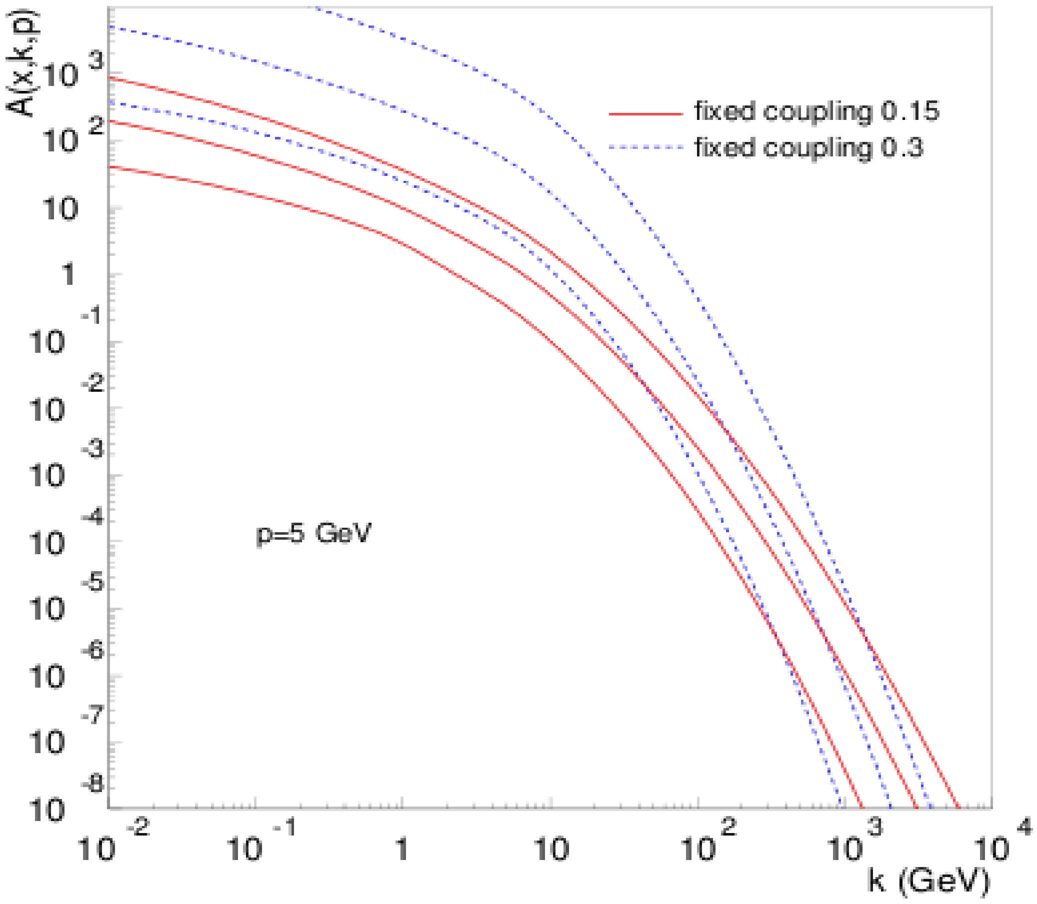
Multiple interactions





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

Towards dense partonic system and saturation



From Avsar, Stasto '10

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

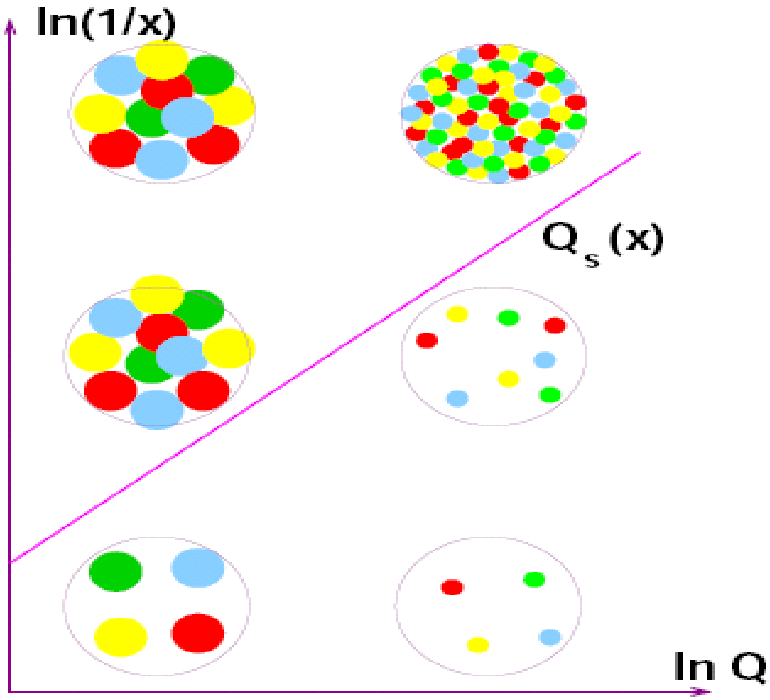
BFKL and CCFM are linear
and predict strong growth of number of
gluons. The growth has to be stopped.

High energy factorization and saturation

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

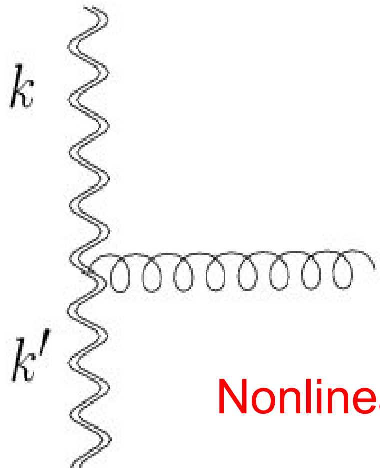
Cross sections change their behaviour from power like to logarithmic like.

Gribov, Levin, Ryskin '83

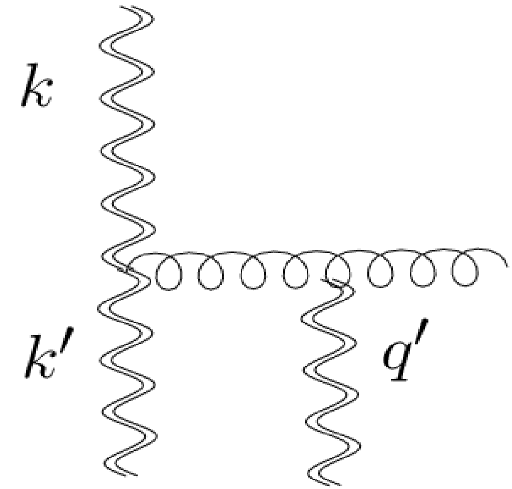


On microscopic level it means that gluon apart from

splitting



recombination

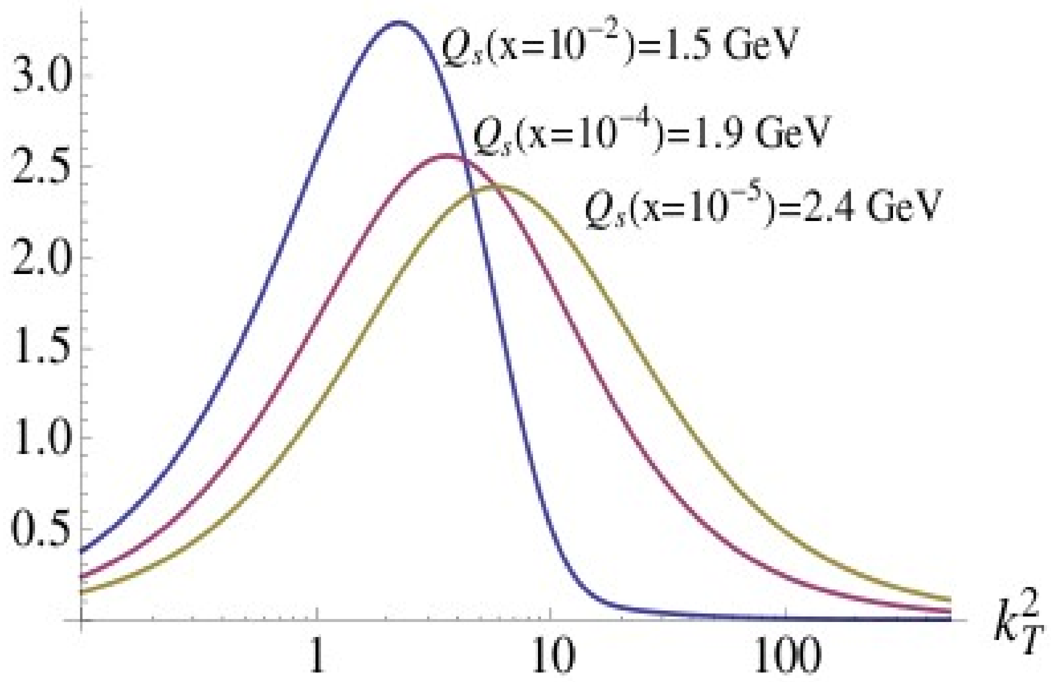


Nonlinear evolution equation BK

Balitsky, Kovchegov

PROPERTIES OF GLUON DENSITY

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



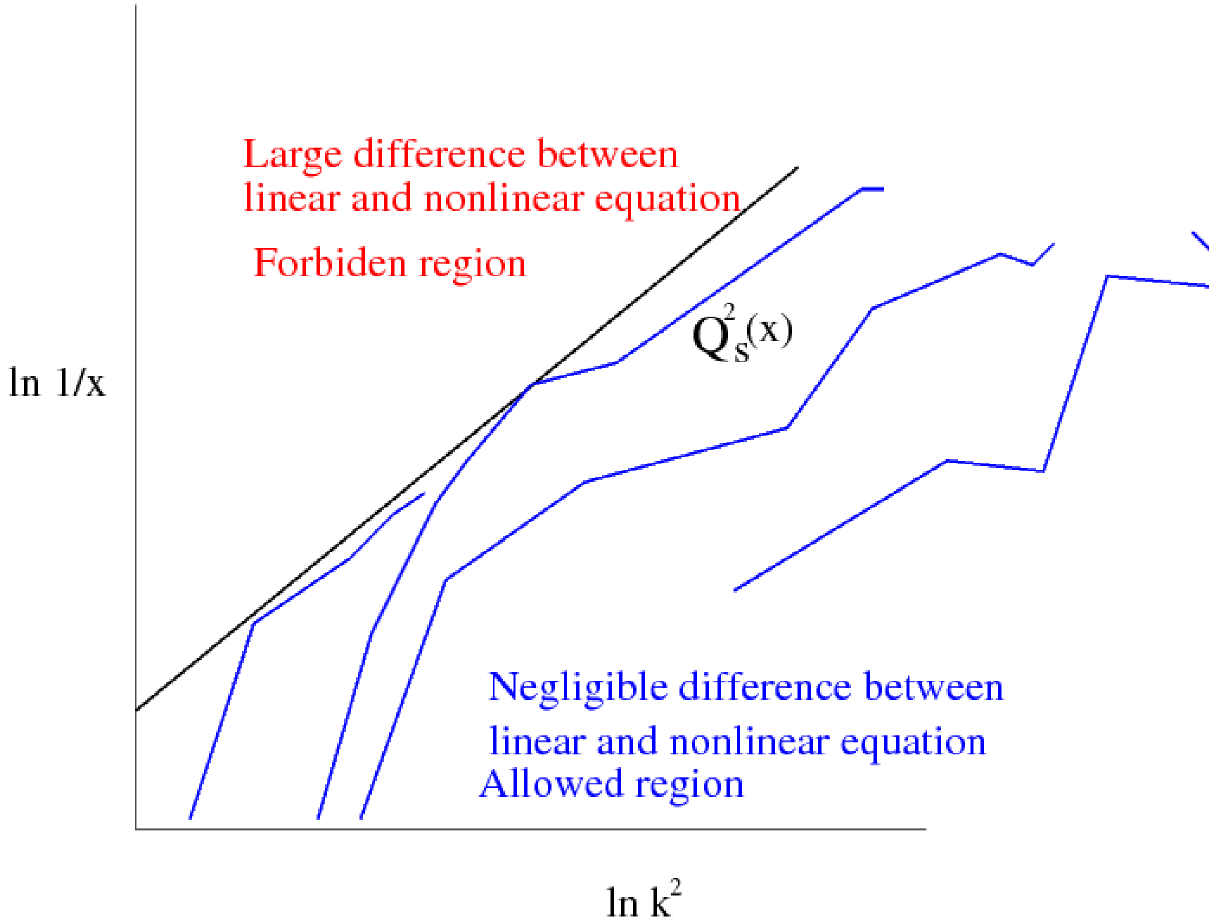
Solution of BK equation

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

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

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

CCFM with saturation – first steps



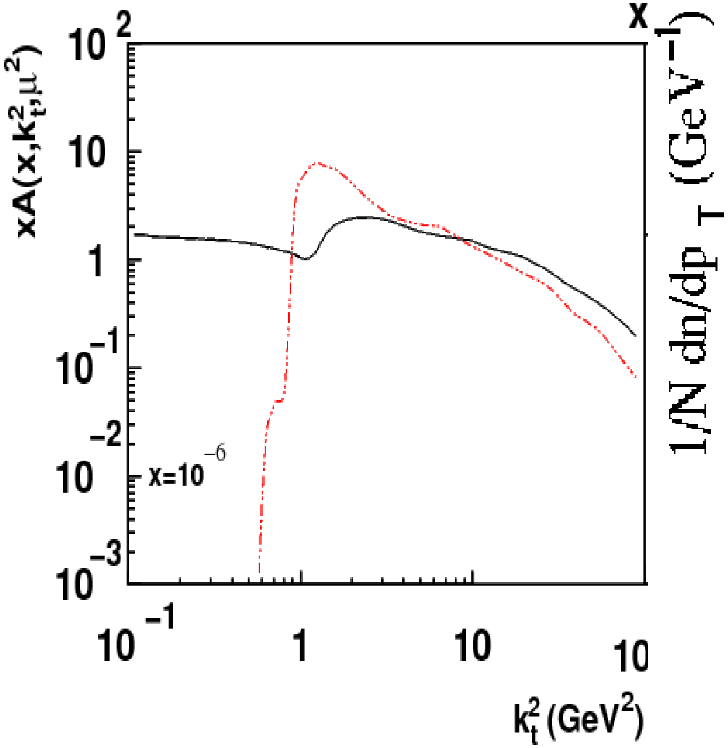
Jung, Kutak '09

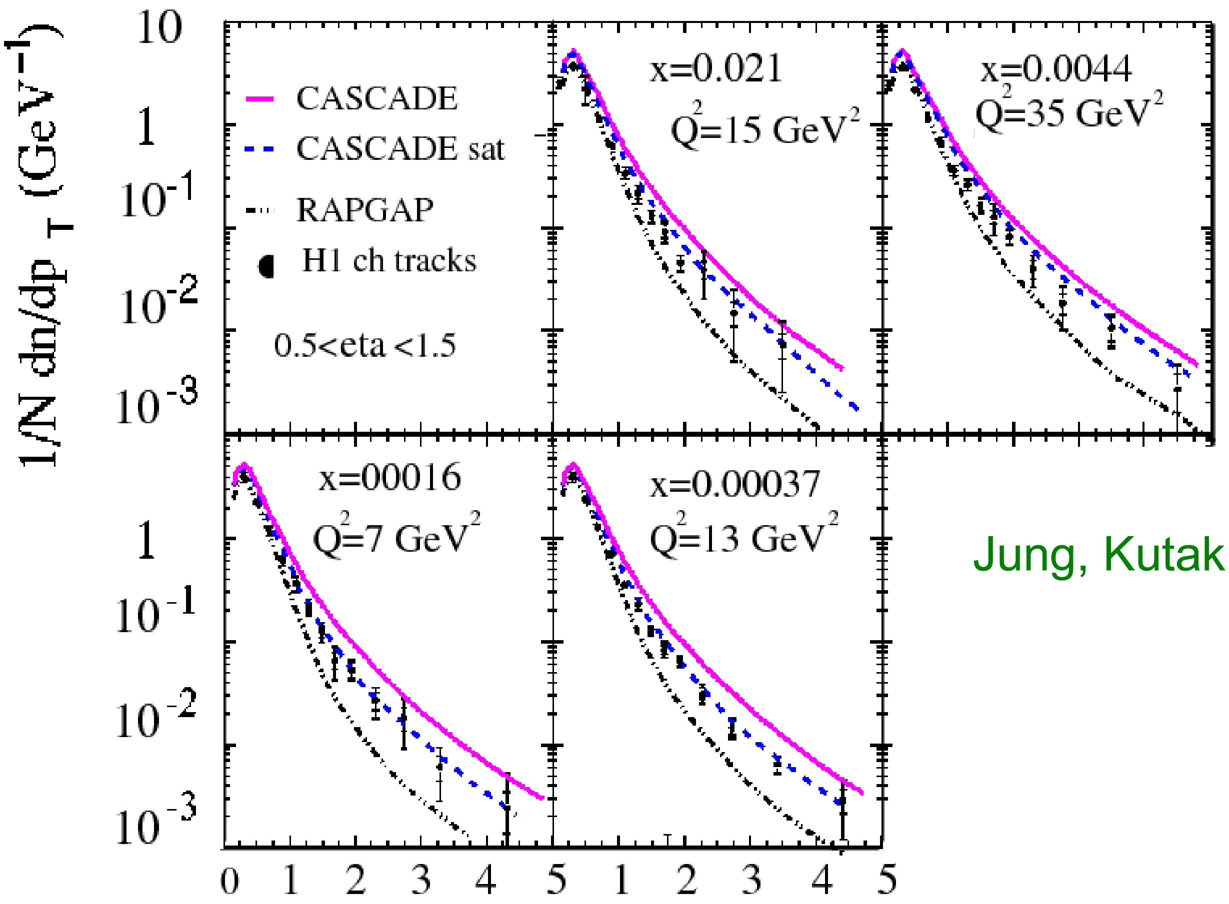
Avsar, Iancu '09

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

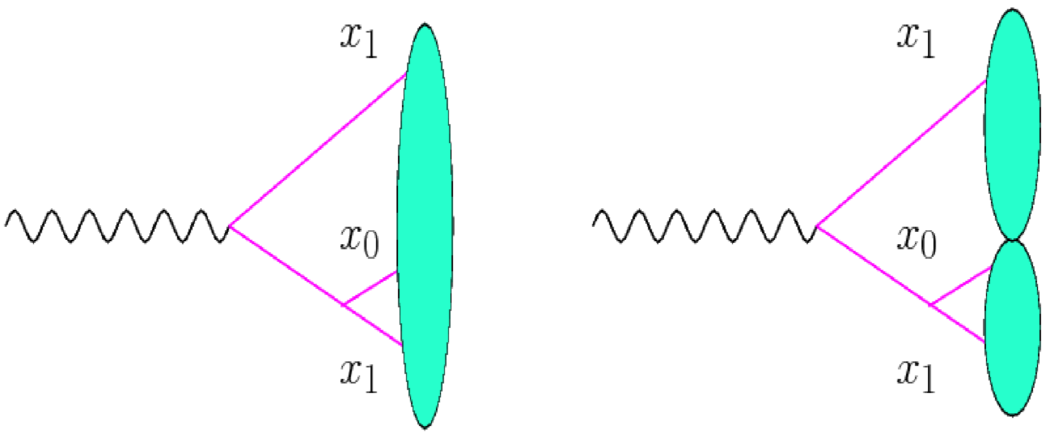
High energy factorization and Color Glass Condensate

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

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

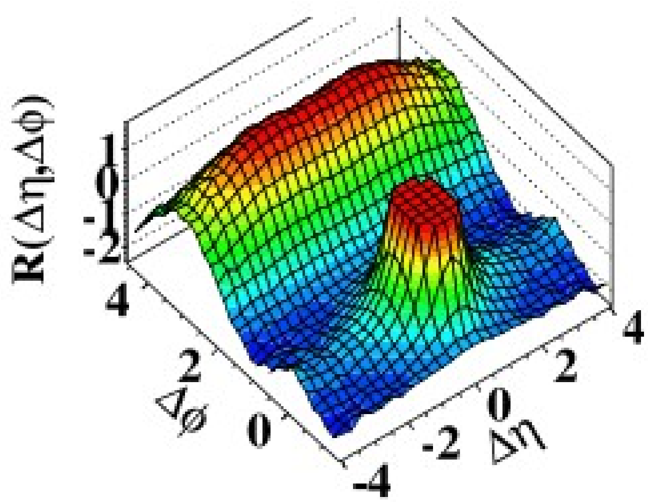
JIMWLK, Balitsky chain

Practical calculations in Color Glass Condensate

make use of expansion of correlators in terms

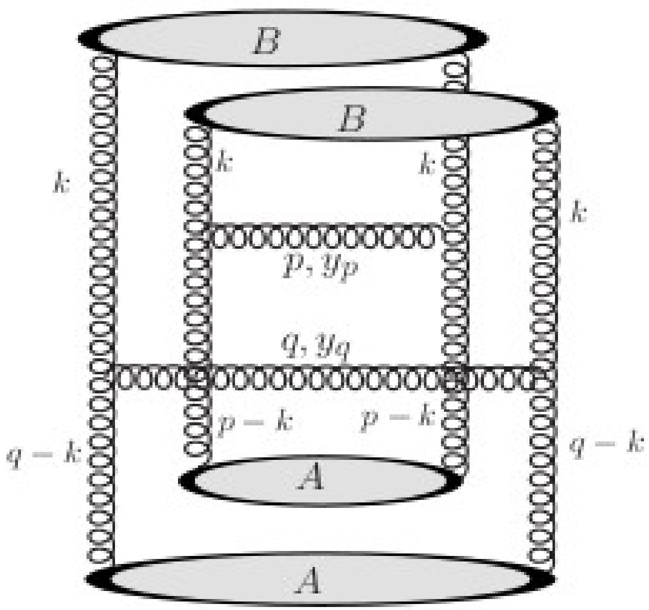
of gluon density obtained from high energy factorisation

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



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