Saturation, coherence and exclusive final states

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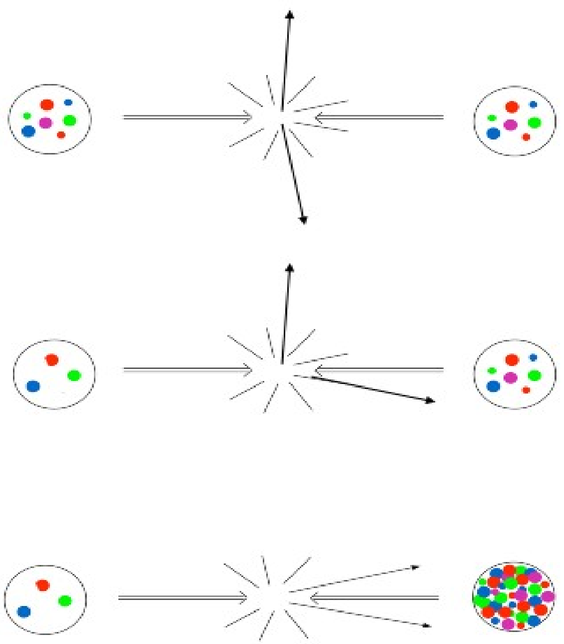
Supported by grant: LIDER/02/35/L-2/10/NCBiR/2011

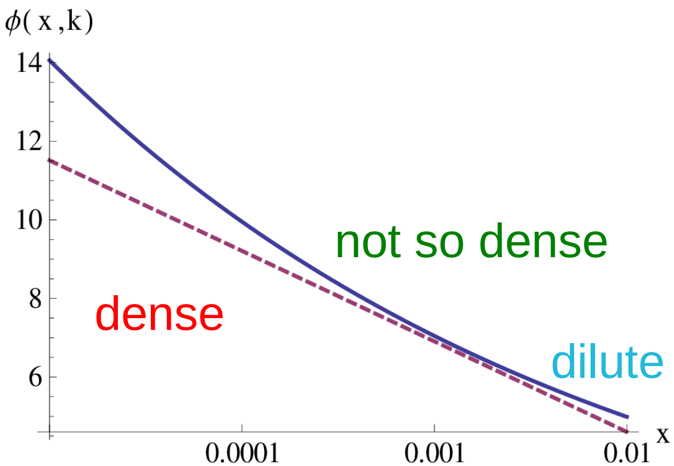
LHC as a scaner of gluon



central-central i.e.
not so dense-not so dense

forward-central i.e.
dilute – not so dense

forward-forward i.e.
dilute -dense



QCD at high energies – high energy factorization

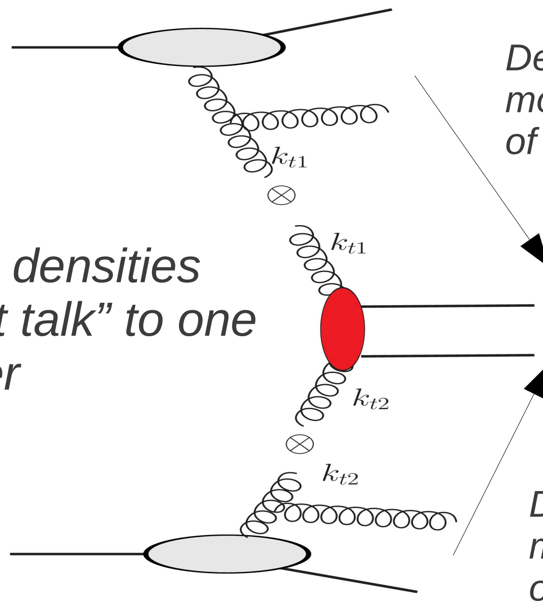
$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \sum_{a,b,c,d} \int \frac{d^2k_{1t}}{\pi}\frac{d^2k_{2t}}{\pi}\frac{1}{16\pi^2(x_1x_2S)^2}\overline{|\mathcal{M}_{ab\to cd}|}^2\delta^2(\vec{k}_{1t}+\vec{k}_{2t}-\vec{p}_{1t}-\vec{p}_{2t})$$
$$\times\, \mathcal{F}_{a/A}(x_1,k_{1t}^2,\mu^2)\,\mathcal{F}_{b/B}(x_2,k_{2t}^2,\mu^2)\,\frac{1}{1+\delta_{cd}}$$

$$k_1^\mu = x_1 P_1^\mu + \bar{x}_1 P_2^\mu + k_{1t}^\mu \qquad k_2^\mu = x_2 P_2^\mu + \bar{x}_2 P_1^\mu + k_{2t}^\mu$$

$$\bar{x}_1 = \frac{k_1^2+\mathbf{k}^2}{Sx_1} \qquad \bar{x}_2 = \frac{k_2^2+\mathbf{k}^2}{Sx_2}$$

Parton densities "do not talk" to one another

$$|\mathcal{M}_{ab\to cd}|^2 = \frac{2x_1 k_1^{\mu_1}k_1^{\nu_1}}{k_1^2}\frac{2x_2 k_2^{\mu_2}k_2^{\nu_2}}{k_2^2}\mathcal{M}_{ab\to cd\,\mu_1\nu_1}\mathcal{M}^*_{ab\to cd\,\mu_2\nu_2}$$



Decreasing longitudianl momentum fractions of off-shell partons

Decreasing longitudianl momentum fractions of off-shell partons

Gribov, Levin, Ryskin '81
Ciafaloni, Catani, Hautman '93

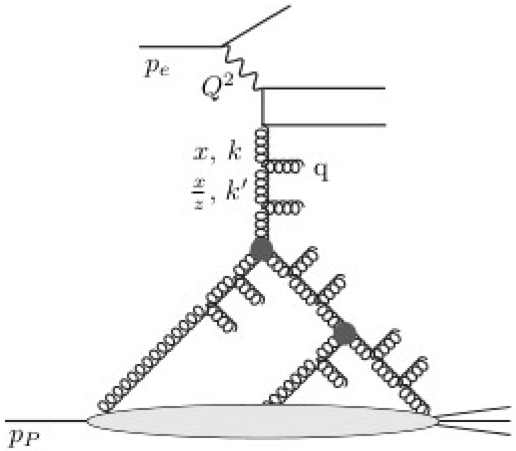
Originally derived for quarks in final state. Lipatov provided general framework.

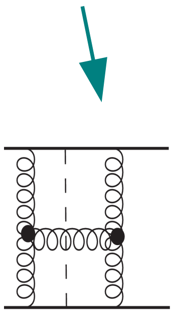
Recently new approach consistent with Lipatov's action allowed for formulation and numerical calculation of any tree level amplitude with off-shell gluons in initial state
Van Hameren, Kotko, KK '12

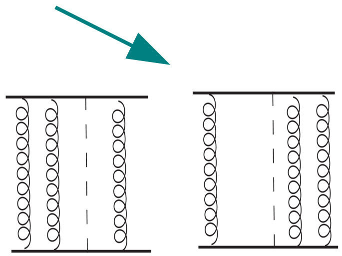
Generalized to p-A
Dominguez, Huan, Marquet,Xiao '10

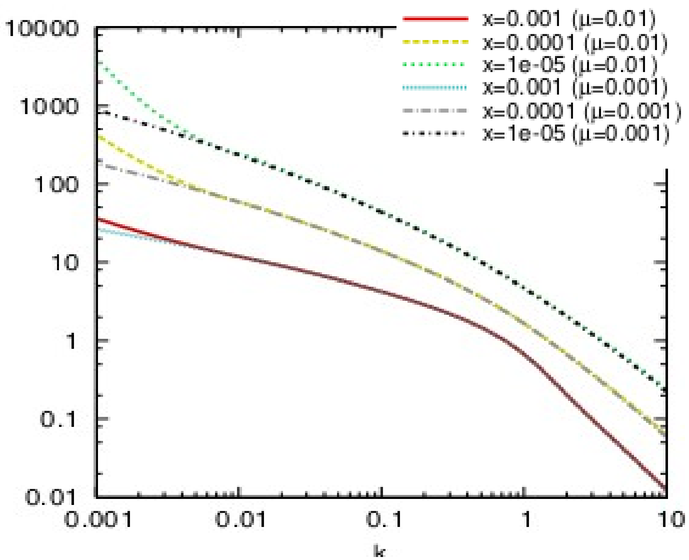
The BFKL an BK evolutions - solutions

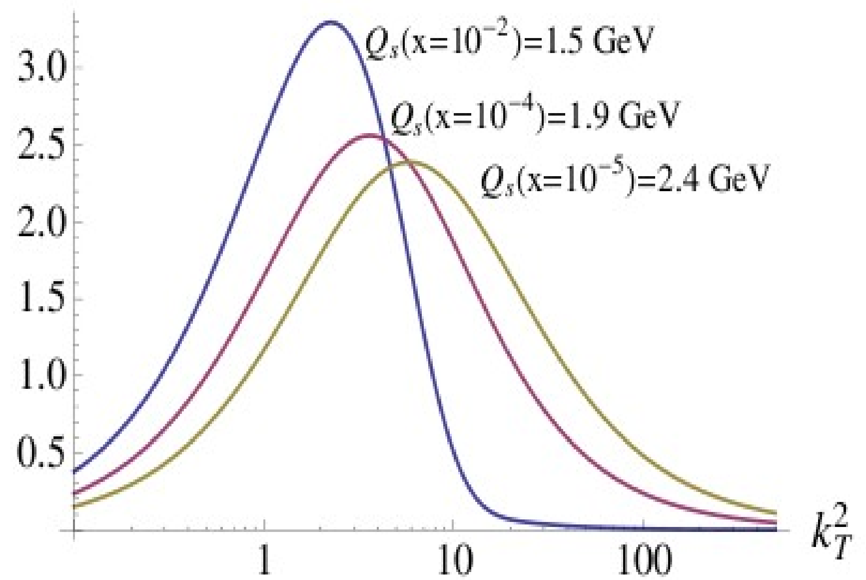
$$\mathcal{F}(x,k^2) = \mathcal{F}_0(x,k^2) + \overline{\alpha}_s \int_{x/x_0}^{1} \frac{dz}{z} \int_0^\infty \frac{dl^2}{l^2} \left[\frac{l^2\mathcal{F}(x/z,l^2) - k^2\mathcal{F}(x/z,k^2)}{|k^2-l^2|} + \frac{k^2\mathcal{F}(x/z,k^2)}{\sqrt{(4l^4+k^4)}} \right]$$











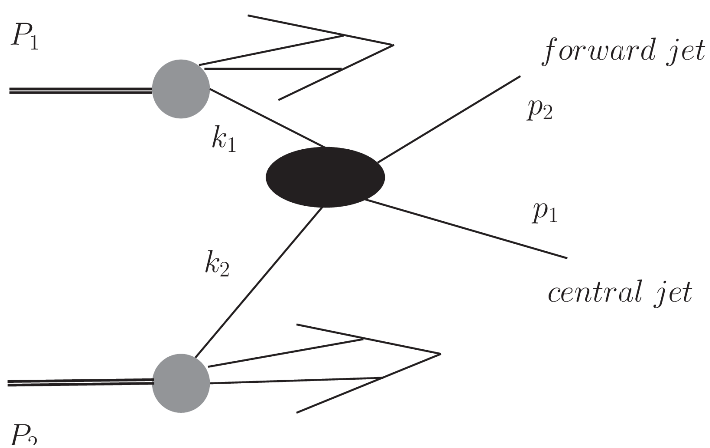
$$\mathcal{F}(x,k^2) = \mathcal{F}_0(x,k^2) + \overline{\alpha}_s \int_{x/x_0}^{1} \frac{dz}{z} \int_0^\infty \frac{dl^2}{l^2} \left[\frac{l^2\mathcal{F}(x/z,l^2) - k^2\mathcal{F}(x/z,k^2)}{|k^2-l^2|} + \frac{k^2\mathcal{F}(x/z,k^2)}{\sqrt{(4l^4+k^4)}} \right]$$
$$-\frac{2\alpha_s^2\pi}{N_c R^2} \int_{x/x_0}^{1} \frac{dz}{z} \left\{ \left[\int_{k^2}^\infty \frac{dl^2}{l^2} \mathcal{F}(x/z,l^2) \right]^2 + \mathcal{F}(x/z,k^2) \int_{k^2}^\infty \frac{dl^2}{l^2} \ln\left(\frac{l^2}{k^2}\right) \mathcal{F}(x/z,l^2) \right\}$$

High energy prescription and forward-central di-jets

Deak, Jung, Hautmann Kutak
JHEP 0909:121,2009

$$\frac{d\sigma}{dy_1 dy_2 dp_{1t} dp_{2t} d\phi} = \sum_{a,c,d} \frac{p_{t1} p_{t2}}{8\pi^2 (x_1 x_2 S)^2} \overline{|\mathcal{M}_{ag\to cd}|}^2 x_1 f_{a/A}(x_1,\mu^2)\, \phi_{g/B}(x_2, k_t^2, \mu^2) \frac{1}{1+\delta_{cd}}$$

$$S = 2P_1 \cdot P_2$$



- Resummation of logs of x and logs of hard scale
- Knowing well parton densities at largr x one can get information about low x physics
- Framework goes recently under name … framework"

$$x_1 = \frac{1}{\sqrt{S}}\left(p_{t1} e^{y_1} + p_{t2} e^{y_2}\right) \xrightarrow{y_1 \sim 0,\, y_2 \gg 0} \sim 1$$

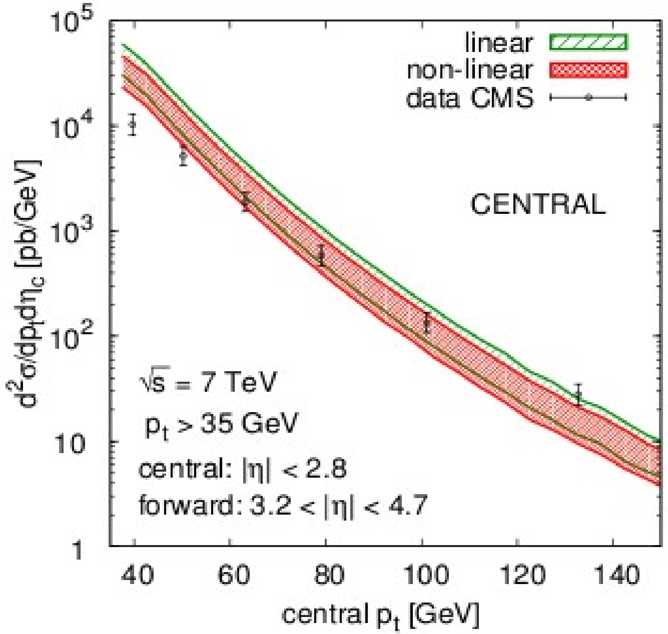
$$x_2 = \frac{1}{\sqrt{S}}\left(p_{t1} e^{-y_1} + p_{t2} e^{-y_2}\right) \qquad \ll 1$$

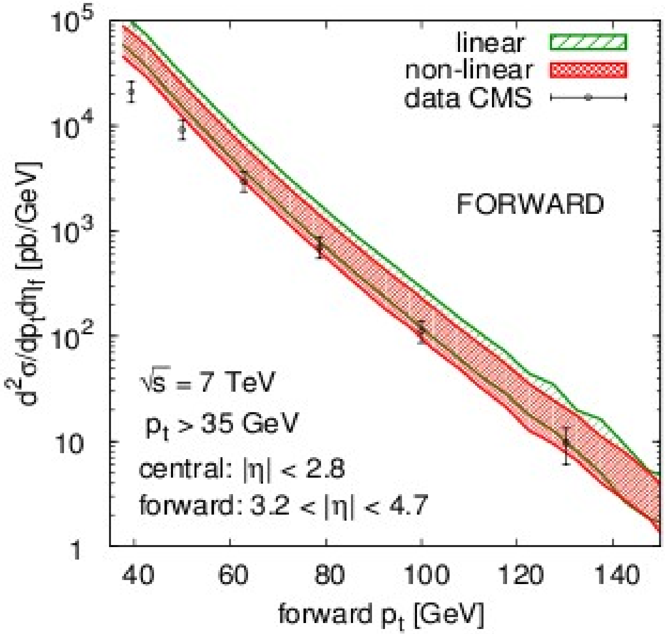
$$k_1^\mu = x_1 P_1^\mu$$

$$k_2^\mu = x_2 P_2^\mu + k_t^\mu$$

Pt spectra

S.Sapeta. KK ,12

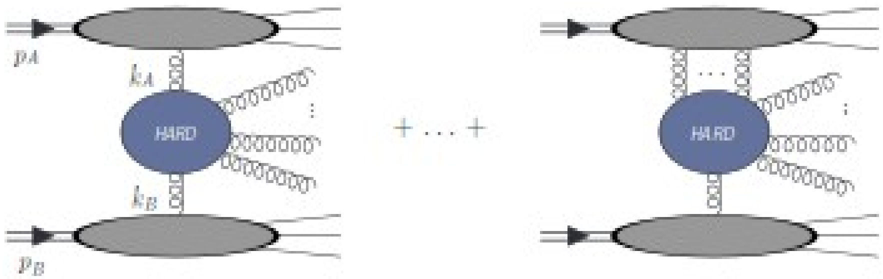




Corrections of higher orders
Included. Kin. Constr DGLAP spf

HEF applied to three jets

Van Hameren, Kotko, KK ,13



$$k_A^\mu = x_A p_A^\mu + k_{T\,A}^\mu, \quad k_B^\mu = x_B p_B^\mu + k_{T\,B}^\mu \sim x_B p_B, \quad x_A \ll x_B$$

p-p and p-Pb collisions

CM energy $5\,\mathrm{TeV}$ and $7\,\mathrm{TeV}$

$p_{T\,1} > p_{T\,2} > p_{T\,3} > p_{T\,\mathrm{cut}}$

anti-k_T clustering with $R = 0.5$

collinear PDF $\Rightarrow$ CTEQ10 NLO set, scale choice $\mu = a\,(E_1 + E_2 + E_3)$, where the variation of a gives the (large) theoretical uncertainty

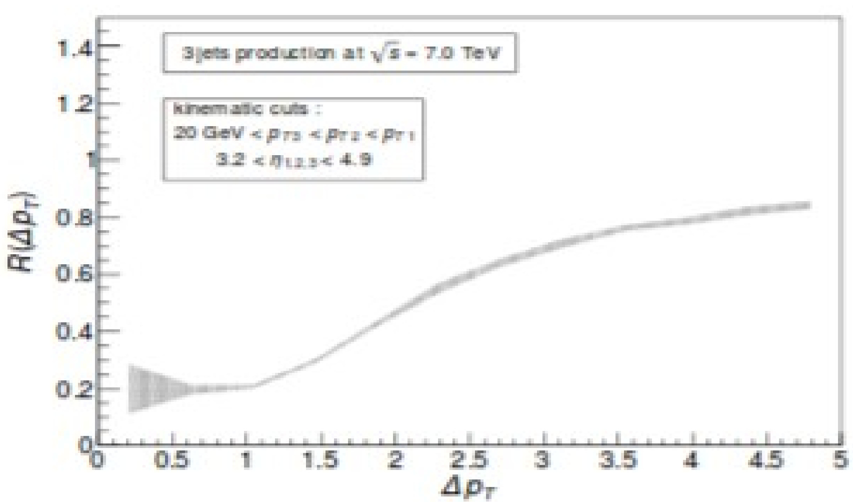
calculations are made and cross-checked using `LxJet` and `OSCARS`

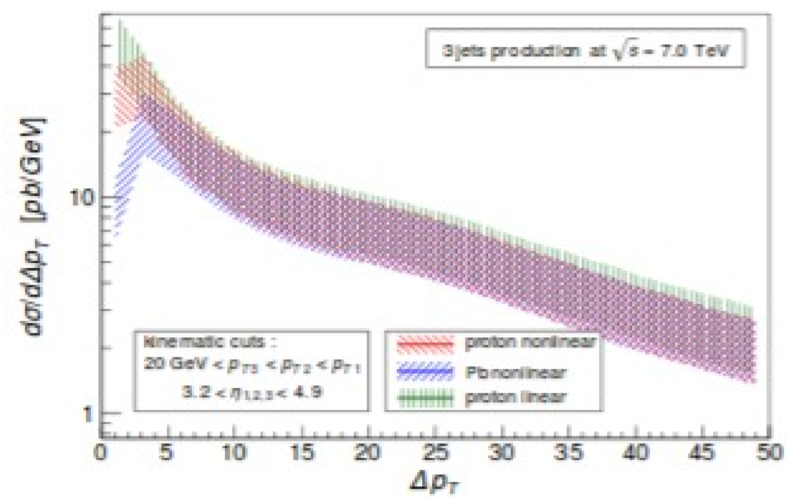
all the jets are in the forward region $3.2 < \eta_{1,2,3} < 4.9$

$p_{T\,\mathrm{cut}} = 20\,\mathrm{GeV}$

Implemented in MC codes: C++ code `LxJet` (dijets, trijets), `fortran` code of A. van Hameren (any process) – OSCARS (Off-shell Currents And Related Stuff))

[1] http://annapurna.ifj.edu.pl/~pkotko/LxJet.html

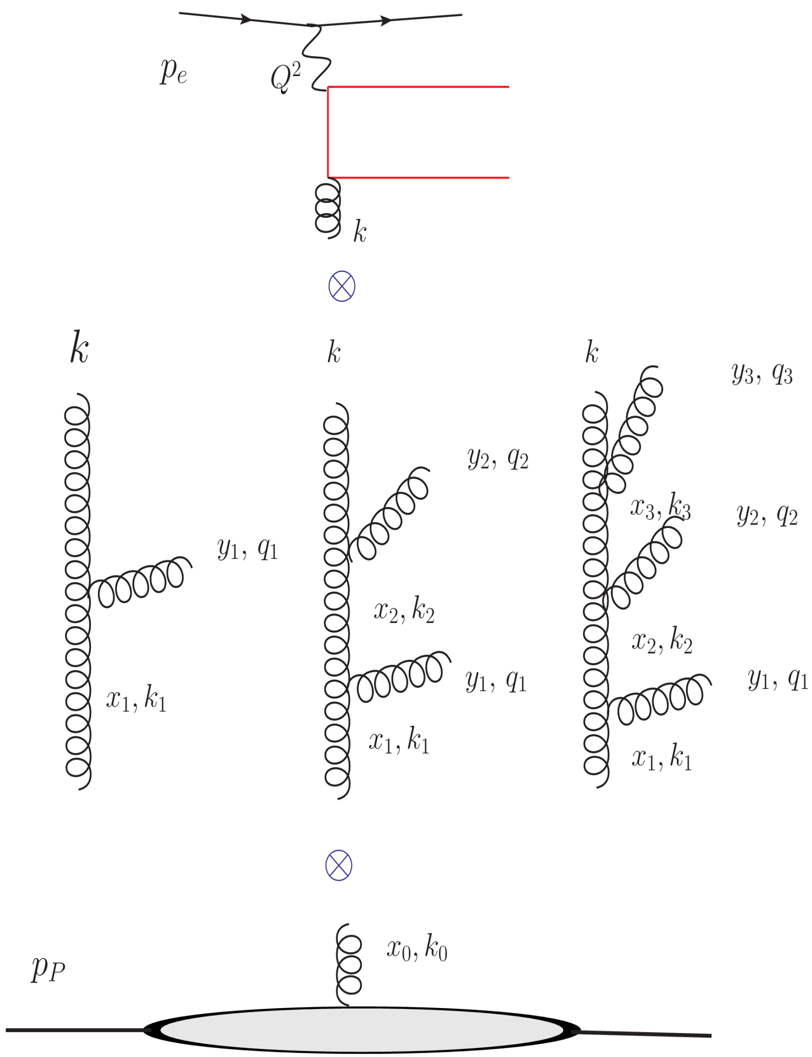




CCFM evolution equation - evolution with observer

Catani,Ciafaloni,Fiorani Marchesin '88

Recent review: *Avsar, Iancu '09*



In $x \to 1$ *region where emitted gluons are soft the dominant contribution to the amplitude comes from the angular ordered region.*

$$\bar{\xi} > \xi_i > \xi_{i-1} > \ldots > \xi_1 > \xi_0$$

The same structure for $x \to 0$ *although the softest emitted gluons are harder than internal.*

$$q_i = \alpha_i\, p_P + \beta_i\, p_e + q_{t\,i} \qquad s = (p_P + p_e)^2$$

$$\eta_i = \frac{1}{2}\ln(\xi_i) \equiv \frac{1}{2}\ln\left(\frac{\beta_i}{\alpha_i}\right) = \ln\left(\frac{|\mathbf{q}_i|}{\sqrt{s}\,\alpha_i}\right) \qquad \tan\frac{\theta_i}{2} = \frac{|\mathbf{q}_i|}{\sqrt{s}\,\alpha_i}$$

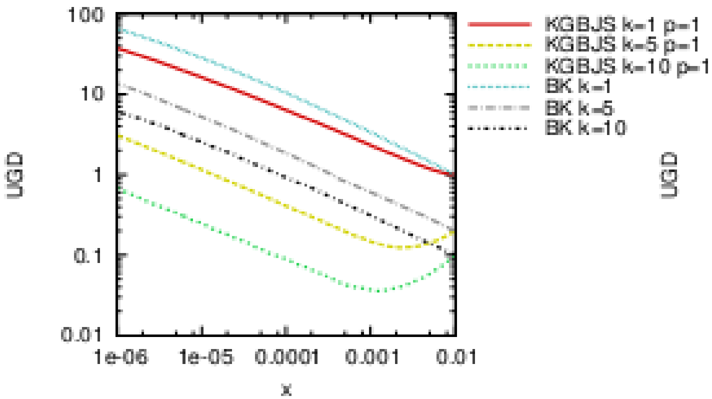
$$\bar{\xi} = p^2/(x^2 s)$$

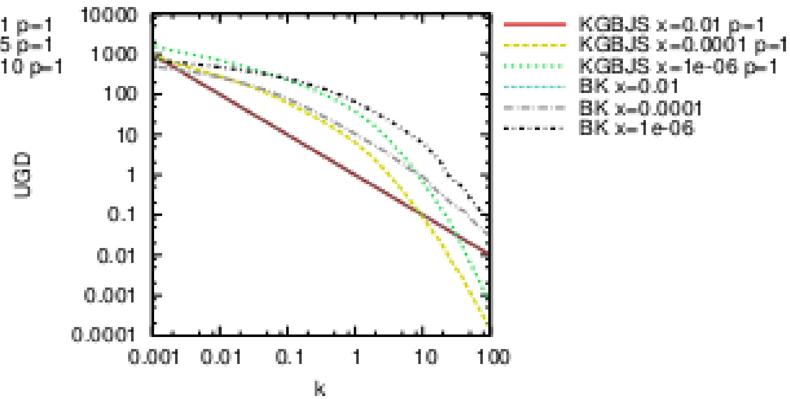
$$z_i = x_i/x_{i-1}$$

$$dP_i^\theta = \frac{\alpha_S}{2\pi}dz_i\frac{d^2q_i}{q_i^2}P_{gg}(z_i)\theta(q_i - z_{i-1}q_{i-1})(1-z_i)$$

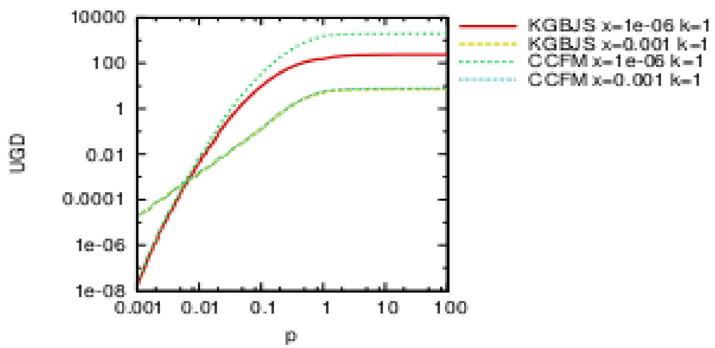
Implemented in CASCADE Monte Carlo Jung ***02***

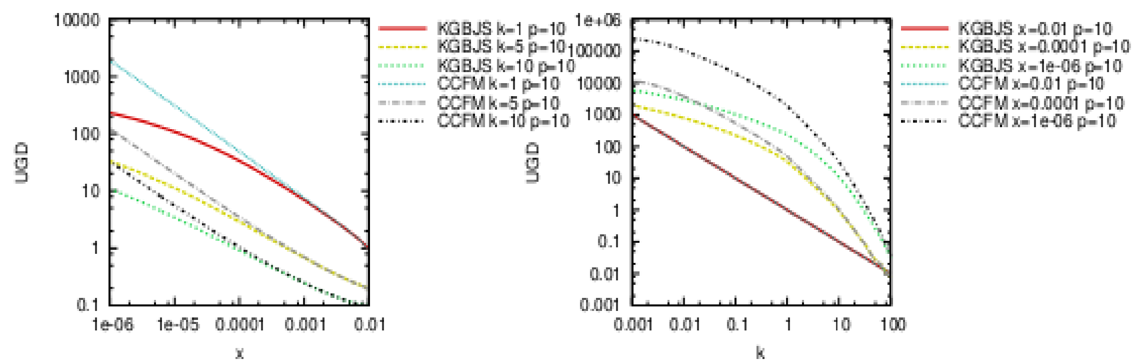
The KGBJS equation – nonlinear ext. of CCFM





Toton, KK '13





$$
\begin{aligned}
\phi(x,k) &= \tilde{\phi}_0(x,k) \\
&+ \bar{\alpha}_s \int_{x/x_0}^{1} \frac{\mathrm{d}z}{z} \int \frac{\mathrm{d}^2\mathbf{q}}{\pi q^2} \theta(q^2-\mu^2)\Delta_R(z,k,\mu) \\
&\left(\phi(\frac{x}{z},k'^2) - \frac{q^2}{\pi R^2}\delta(q^2-k^2)\phi^2(\frac{x}{z},q^2)\right)
\end{aligned}
$$

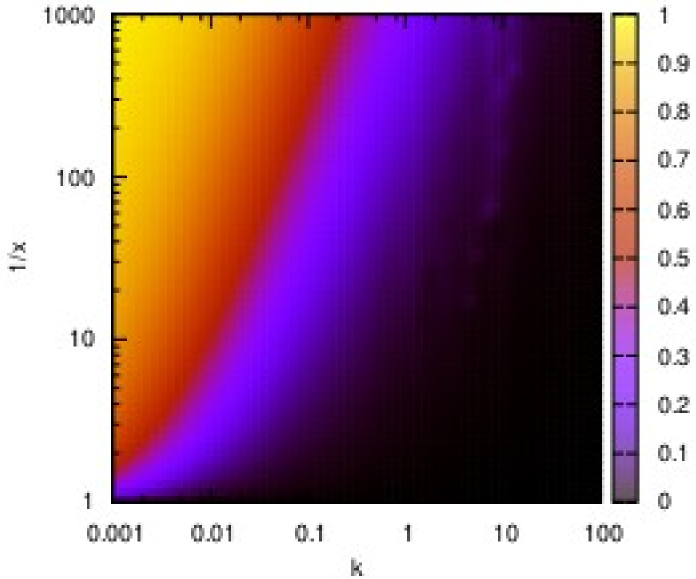
$$
\begin{aligned}
\mathcal{E}(x,k^2,p) &= \mathcal{E}_0(x,k^2,p) \\
&+ \bar{\alpha}_s \int_{x/x_0}^{1} \frac{\mathrm{d}z}{z} \int \frac{\mathrm{d}^2\bar{\mathbf{q}}}{\pi \bar{q}^2} \theta(p - z\bar{q})\Delta_{ns}(z,k,\bar{q}) \\
&\left(\mathcal{E}\left(\frac{x}{z},k'^2,\bar{q}\right) - \frac{\bar{q}^2}{\pi R^2}\delta(\bar{q}^2-k^2)\,\mathcal{E}^2(\frac{x}{z},\bar{q}^2,\bar{q})\right)
\end{aligned}
$$

$$
\Delta_R(z,k,\mu) = \exp\left(-\bar{\alpha}_s \log\frac{1}{z}\log\frac{k^2}{\mu^2}\right)
$$

$$
\Delta_{ns} = \exp\left(-\bar{\alpha}_s \ln\frac{1}{z}\ln\frac{k^2}{zq^2}\right) \quad \text{for} \quad k^2 > zq^2
$$

Saturation scale in KGBJS

BK

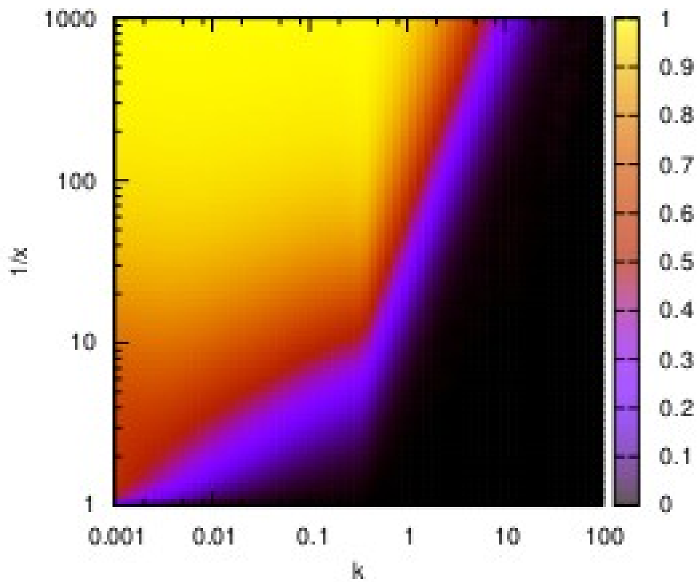


Relative differences between linear and nonlinear

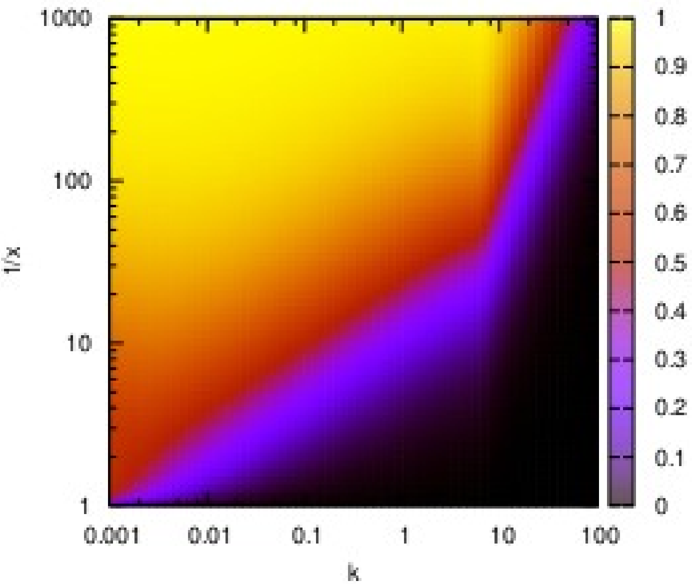
K.K, A. Stasto Eur.Phys.J.C41:343-351,2005

$$\beta(x,k,p) = \frac{|\mathcal{E}_{CCFM}(x,k,p) - \mathcal{E}_{KGBJS}(x,k,p)|}{\mathcal{E}_{CCFM}(x,k,p)}$$

KGBJS



p=1

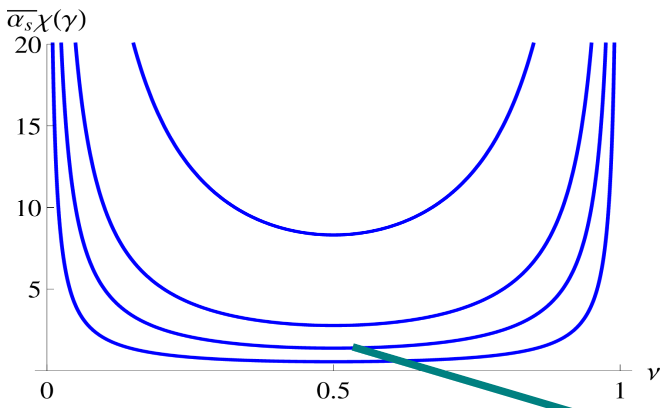


p=10

Toton, KK '13

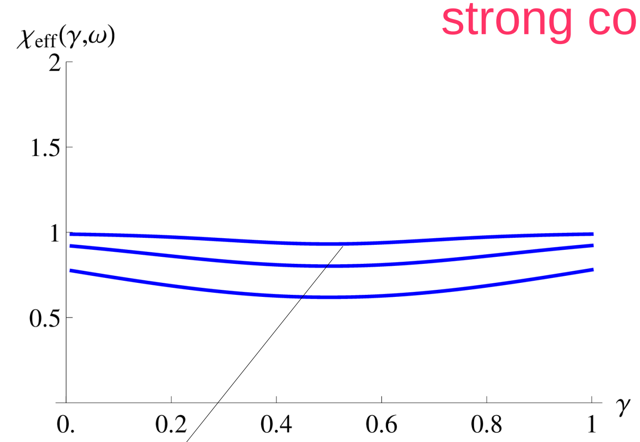
Gluon density at the large coupling values

weak coupling



$$\chi(\gamma) = 2\psi(1) - \psi(1-\gamma) - \psi(\gamma)$$

strong coupling



Pochinski ,'02
Stasto '07

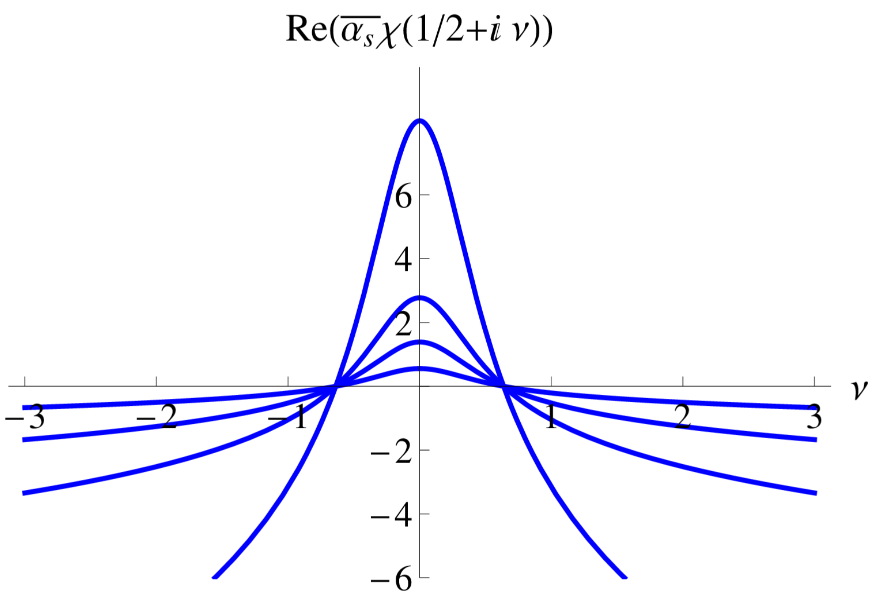
weak coupling

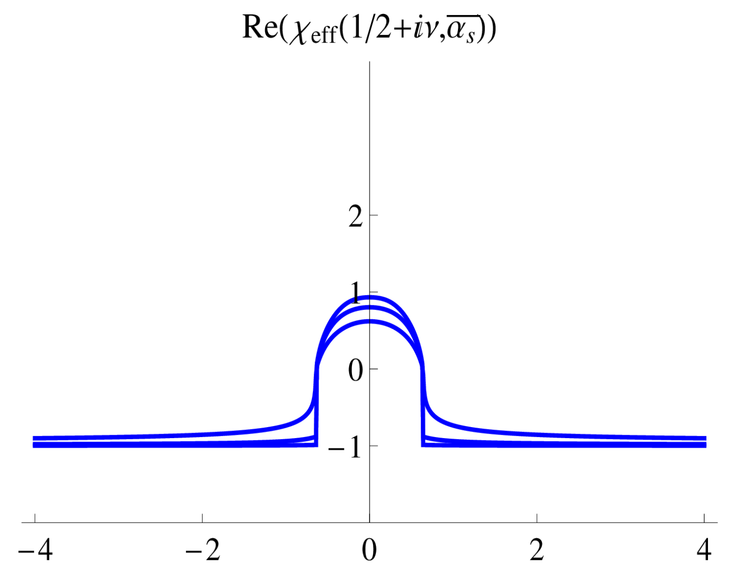
$$f(x,k^2) = \frac{1}{2\pi}\int_{-\infty}^{\infty} d\nu\,(k^2)^{1/2+i\nu}\bar{f}(x_0,1/2+i\nu)\,x^{-\bar{\alpha}_s\chi(1/2+i\nu)}$$

critical point dominates
at large coupling

strong coupling

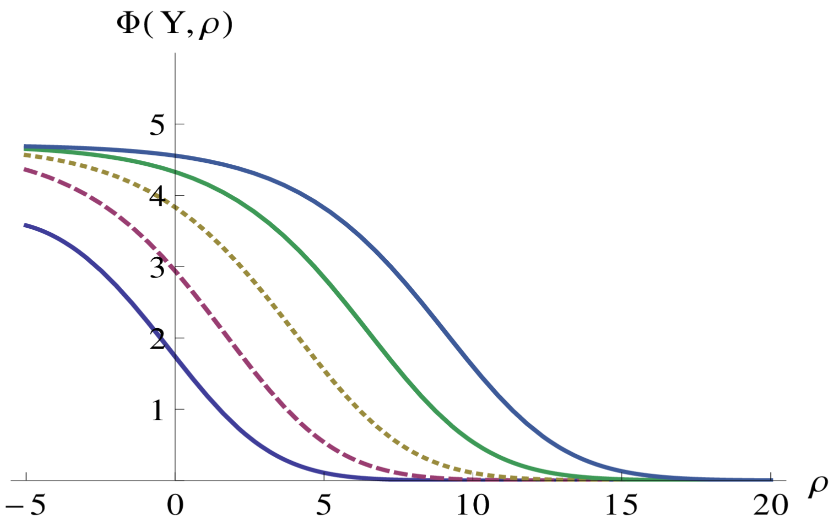
Surowka, KK '13

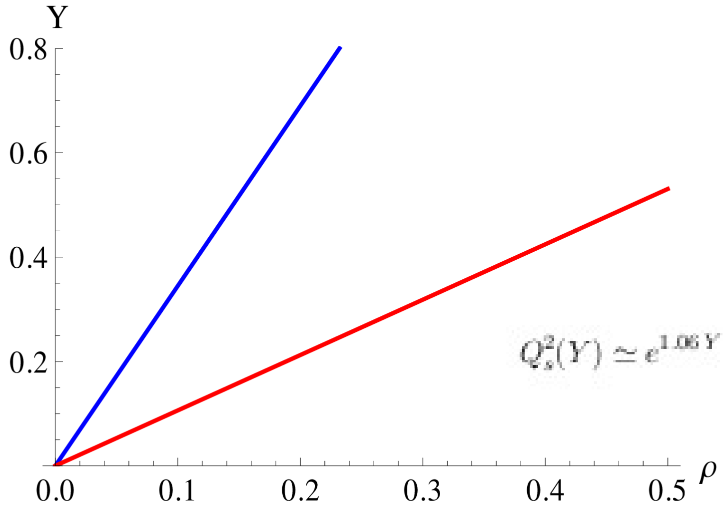




Gluon density at the large coupling values

Surowka, KK '13





Nonlinear nonlinear equation valid at strong coupling limit

$$\partial_Y \Phi(Y,\rho) = \frac{1}{2}\lambda'_{st}\partial_\rho^2\Phi(Y,\rho) + \frac{1}{2}\lambda'_{st}\partial_\rho\Phi(Y,\rho) + (\lambda_{st} + \lambda'_{st}/8)\Phi(Y,\rho) - \frac{\bar{\alpha}_s}{\pi R^2}\Phi^2(Y,\rho)$$

Conclusions and outlook

- *LHC gives oportunity to test parton densities both when the parton density is probed at low x and at low, medium and large kt at some external scale.*

- *The interplay of saturation and coherence leads to new features of saturation scale*

- *The results for jets give some theoretical hints for saturation*