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High Energy Factorization
selected phenomenology results

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Based on results recently obtained in collaboration with:

M. Bury, P. Kotko, C. Marquet, E. Petreska, S. Sapeta, T.Salwa, M. Serino, A. van Hameren

High Energy Factorization

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \sum_{c,d} \int \frac{d^2k_{1t}}{\pi}\frac{d^2k_{2t}}{\pi}\frac{1}{16\pi^2(x_1x_2S)^2}\overline{|\mathcal{M}_{g^*g^*\to cd}|}^2 \delta^2(k_{1t}+k_{2t}-p_{1t}-p_{2t})\ \mathcal{F}_A(x_1,k_{1t}^2)\,\mathcal{F}_B(x_2,k_{2t}^2)\,\frac{1}{1+\delta_{cd}}$$

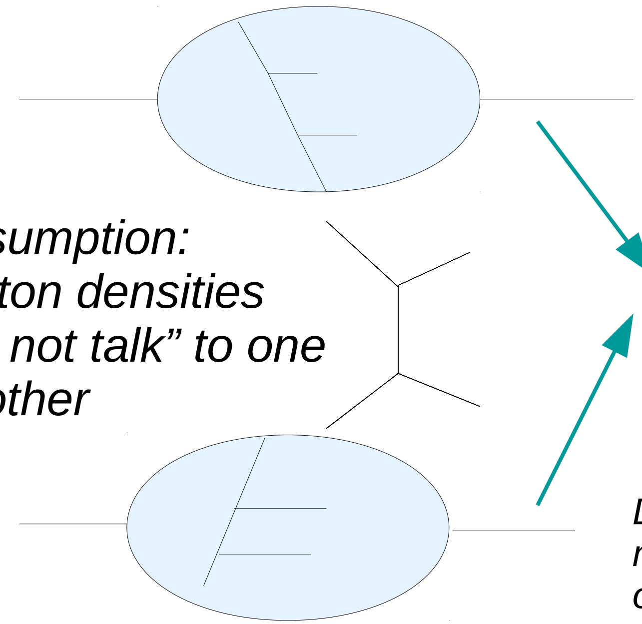
Originally written for total cross section

Gluons dominate in the t channel
Obtained for heavy quarks in final state.

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

$$\bar{x}_1 = \frac{k_1^2 + \mathbf{k}^2}{S x_1} \qquad \bar{x}_2 = \frac{k_2^2 + \mathbf{k}^2}{S x_2}$$

Assumption: parton densities "do not talk" to one another



Decreasing longitudianl momentum fractions of off-shell partons

Decreasing longitudianl momentum fractions of off-shell partons

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

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

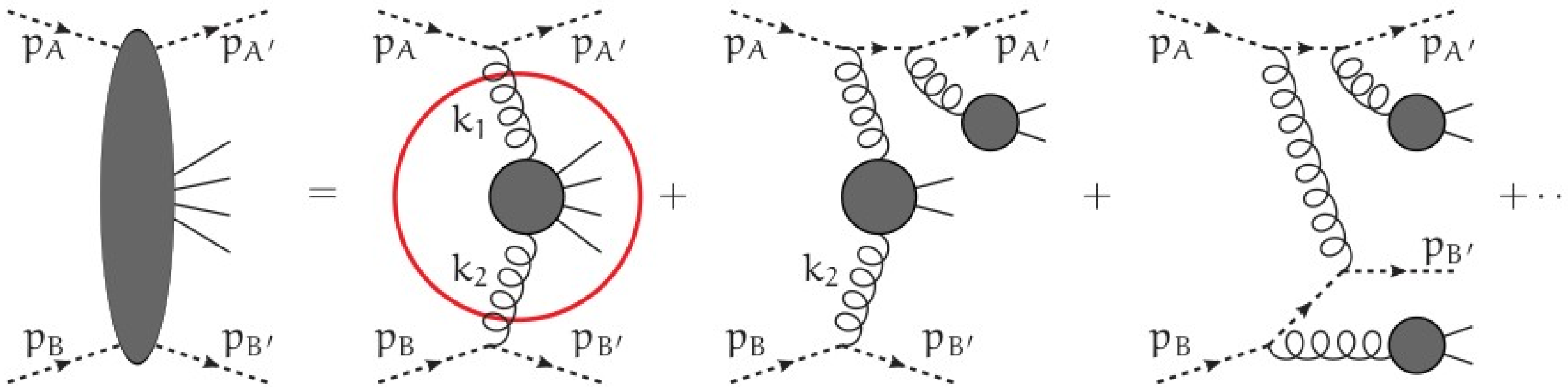
Does not take into account MPI as formulated in DGLAP i.e. emissions from independent chains

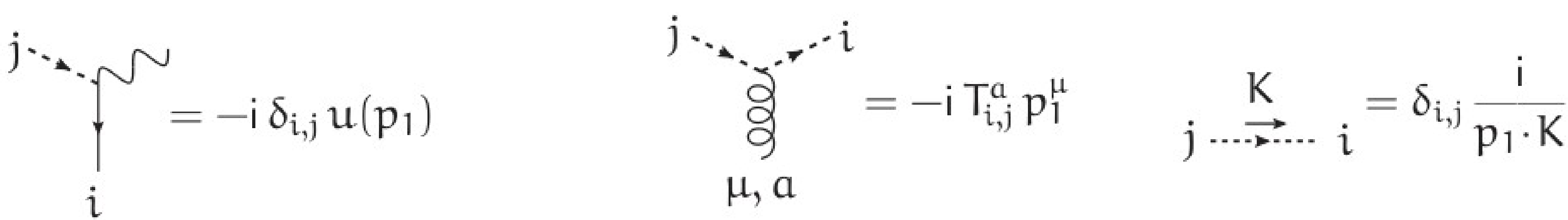
Helicity method based method for any process
KK, Kotko, van Hameren '13

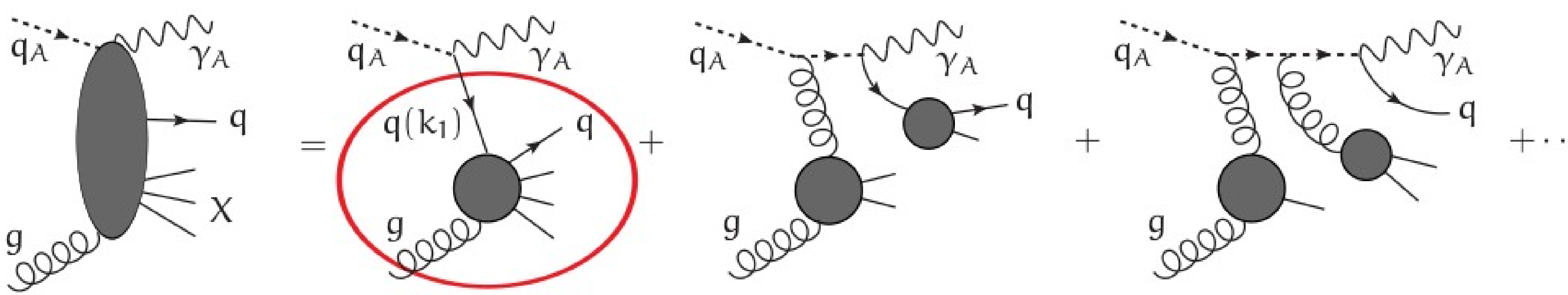
Off-shell matrix elements

One consider embeding off-shell amplitude in onshell and introduces eikonal lines

Kotko, KK, van Hameren 2013,
KK, Salwa, van Hameren 2013

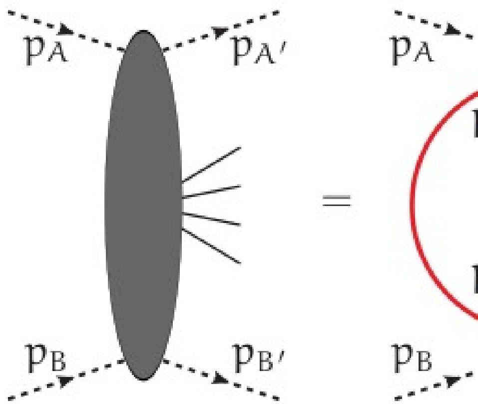


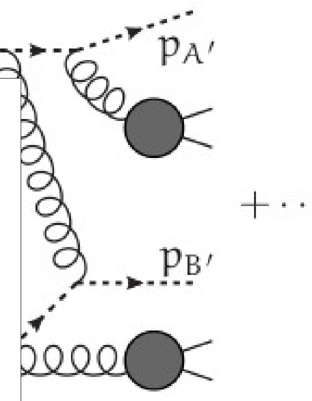




Off-shell matrix elements

Kotko, KK, van Hameren 2013,
KK, Salwa, van Hameren 2013

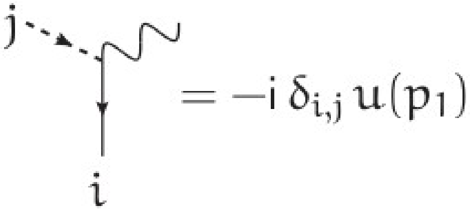


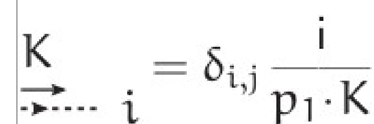


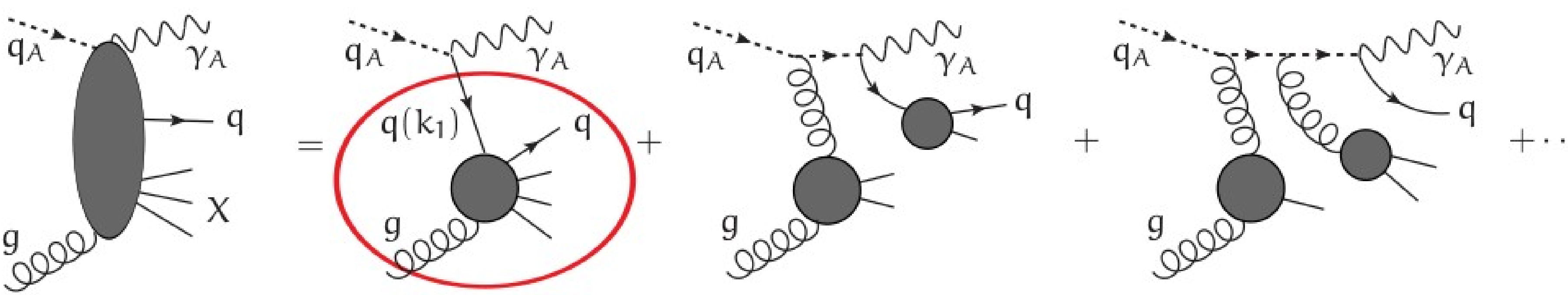
Agrees with:

Effective action based approach
Lipatov 95, Lipatov, Vyazovsky 2000

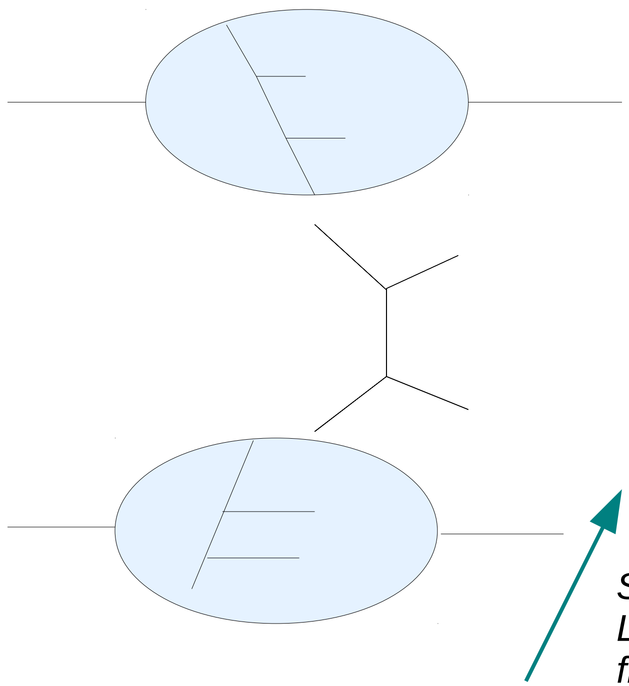
Gauge link based derivation
Kotko'14



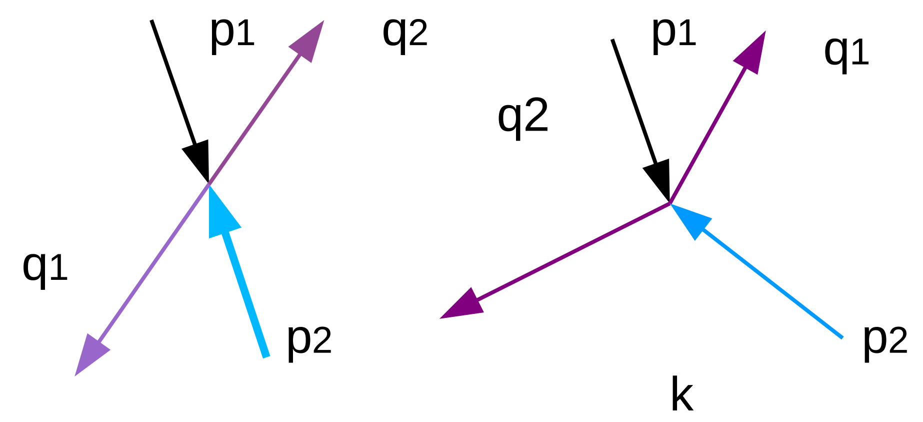




Hybrid high energy factorization



Strongly decreasing
Longitudinal momentum
fractions of off-shell partons



$p_1+p_2=q_1+q_2$

$p_1+p_2=q_1+q_2+k$

ME + parton densities in kt factorization

Theory
Gribov, Levin, Ryskin '81
Ciafaloni, Catani, Hautman '93
Collins, Ellis '93

Phenomenology
Baranov, Hautmann, Jung, Maciuła,
Marquet, Motyka, KK, Kotko, Lipatov,
van Hameren, Saleev, Szczurek,
Zotov,...

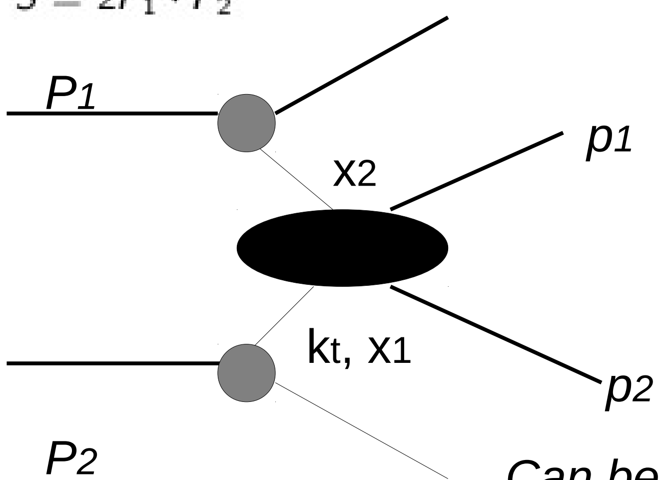
Helicity based methods for ME
Kotko, K.K, van Hameren, '12

Hybrid formula for cross section

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

Deak, Jung, KK, Hautmann '09

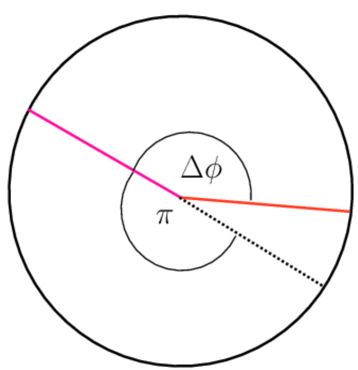
$S = 2P_1 \cdot P_2$



- logs of x
- logs of hard scale

Can be obtained from CGC after neglecting nonlinearities
In that limit gluon density is so called dipole gluon density.
Laidet, Iancu '13

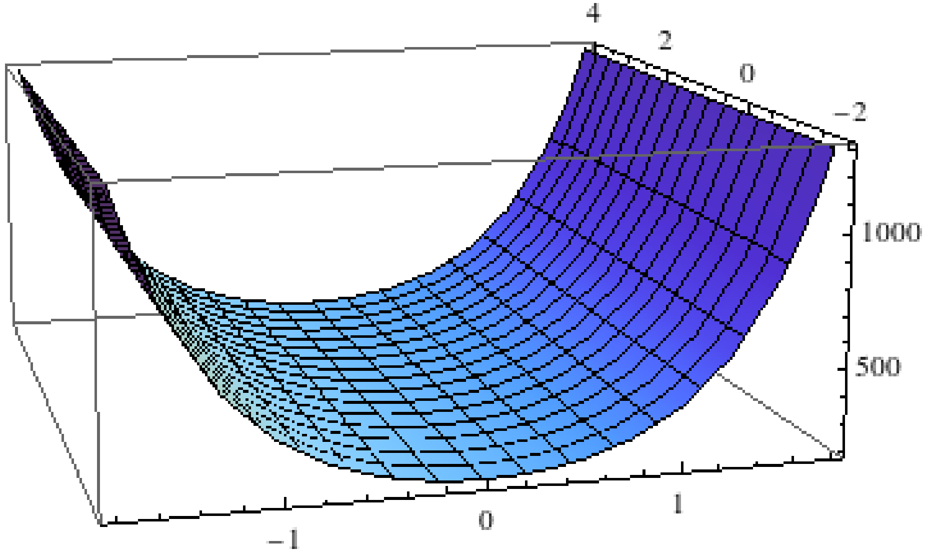
The refinement of formula above for dilute-dense: talk of Cyrille Marquet



In azimuthal plane

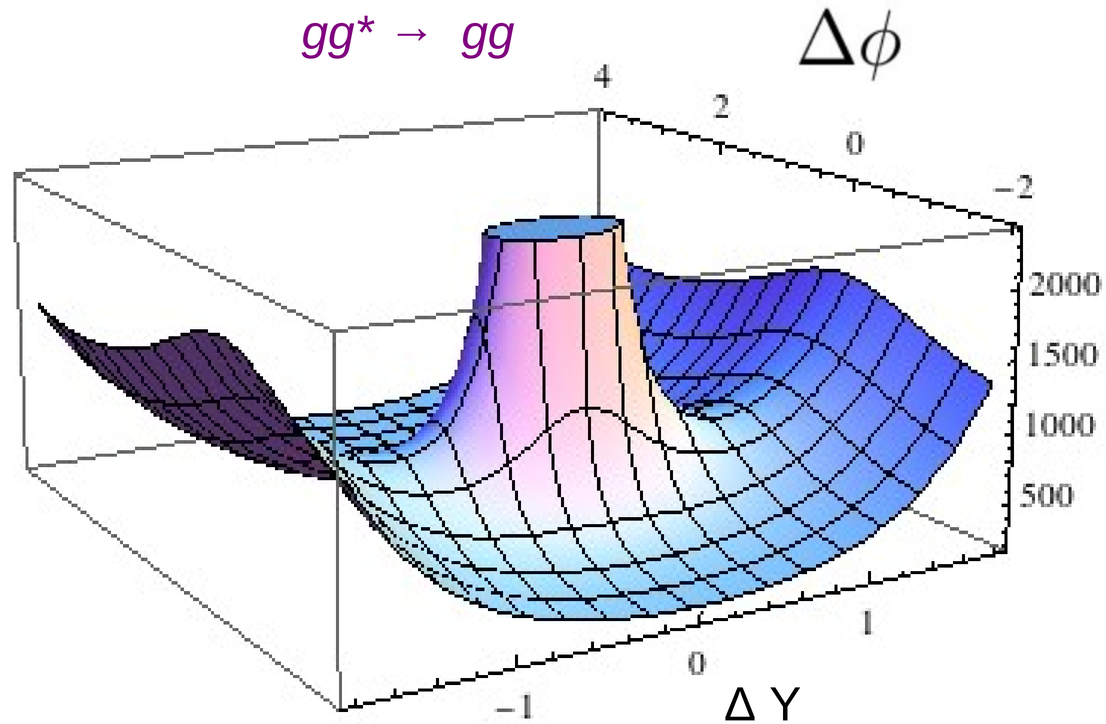
Example of matrix element for hybrid factorization

gg → gg



Two on-shell partons 2 → 2 ME

gg → gg*



One off-shell parton 2 → 2 ME

Bad approximation by collinear physics of region where angle between produced jets is small

Numerical tools for HEF

AVHLIB

http://bitbucket.org/hameren/avhlib (A. van Hameren)

·*complete Monte Carlo program for tree-level calculations*
·*any process within the Standard Model*
·*any initial-state partons on-shell or off-shell*
·*employs numerical Dyson-Schwinger recursion to calculate helicity amplitudes*
·*automatic phase space optimization*

AMP4HEF

http://bitbucket.org/hameren/amp4hef (A.van Hameren, M.Bury, K.Bilko, H.Milczarek)

·only provides tree-level matrix elements (or color-ordered helicity amplitudes)
·employs BCFW recursion to calculate color-ordered helicity amplitudes
·available processes (plus those with fewer on-shell gluons):

$$\emptyset \to g\, g + 4g \qquad \emptyset \to \bar{q}\, q + 3g \qquad \emptyset \to \bar{q}^*\, q + 3g$$

$$\emptyset \to g^*\, g + 4g \qquad \emptyset \to g^* + \bar{q}\, q + 2g \qquad \emptyset \to \bar{q}\, q^* + 3g$$

$$\emptyset \to g^*\, g^* + 4g$$

Easy to use in Fortran and C++

LxJet

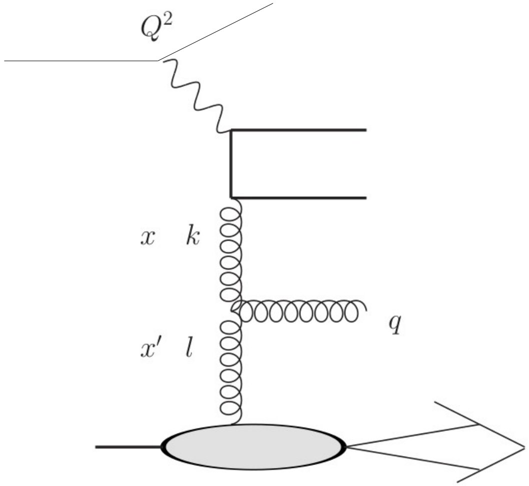
http://annapurna.ifj.edu.pl/~pkotko/LxJet.html (P. Kotko)

•*hybrid high energy factorization suitable for forward jets,*
•*implemented helicity tree-level amplitudes for all channels for dijets and three jets*
•*recursive relation for color ordered tree-level amplitudes with single off-shell leg for arbitrary number of gluons*
•*currently the native phase space generator is up to three final state partons*

Evolution

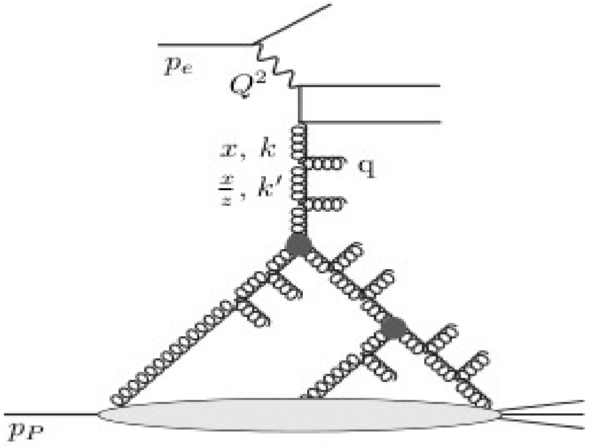
BFKL reummation of logs 1/x. Dependence on x and k_t

$$\mathcal{F} = \mathcal{F}_0 + K \otimes \mathcal{F}$$



Balitsky-Kovchegov reummation of logs 1/x + rescatterings.
Dependence on x, k_t and shape of the target

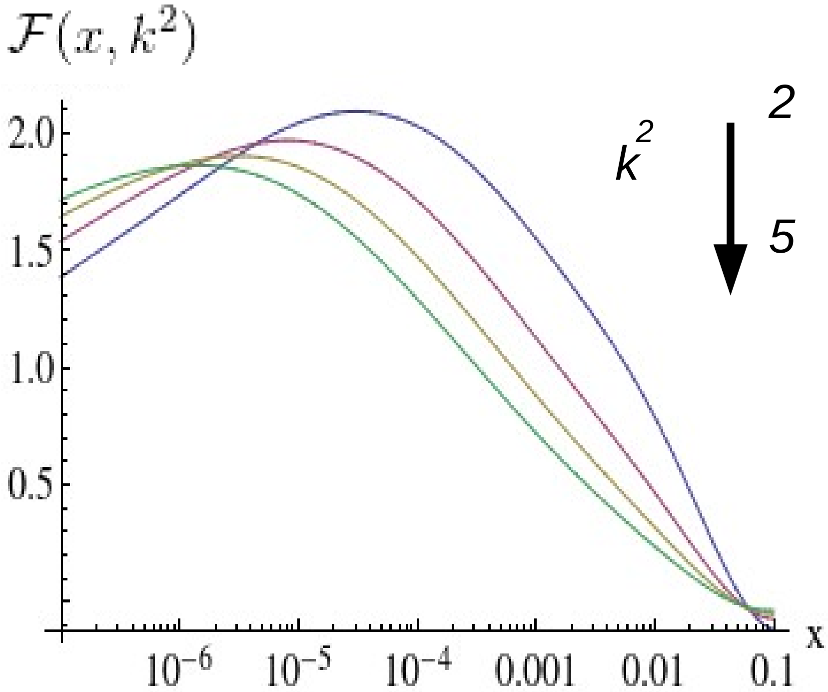
$$\mathcal{F} = \mathcal{F}_0 + K \otimes \mathcal{F} - \frac{1}{R^2} V \otimes \mathcal{F}^2$$

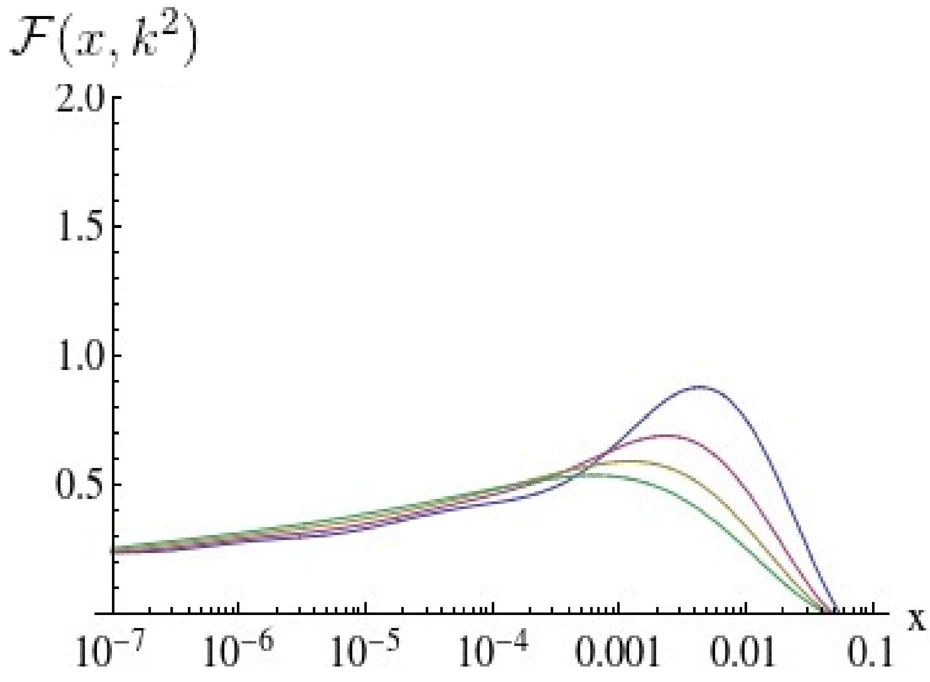


BK formulated for large nucleus
often used as a model for proton

Numerical solutions and phenomenological applications:
Lublinsky, Levin, Maor;
Golec-Biernat, Motyka, Stasto;
KK, Kwiecinski;
Marquet, Soyez'
Albacete, Armesto, Milhano, Salgado,…..

Glue in p vs. glue in Pb



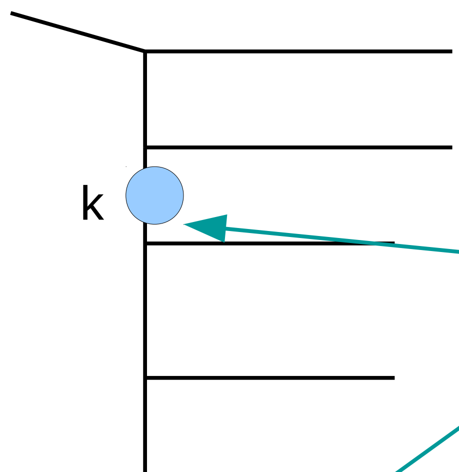


Maximum → emergence of saturation scale

Introducing hard scale dependence

The relevance in low x physics
at linear level rcognized by:
Catani, Ciafaloni, Fiorani,Marchesini;
Kimber,Martin,Ryskin;
Collins, Jung

μ and k



μ hard scale

Survival probability of the gap without emissions

Survival probability of the gap without emissions

Kimber, Martin, Ryskin procedure '01:

$$T_s(\mu^2,k^2)=\exp\left(-\int_{k^2}^{\mu^2}\frac{dk'^2}{k'^2}\frac{\alpha_s(k'^2)}{2\pi}\sum_{a'}\int_0^{1-\Delta}dz'P_{a'a}(z')\right)$$

$$\Delta = \frac{\mu}{\mu+k}$$

$$\mathcal{F}(x,k^2,\mu^2)\sim\partial_{\lambda^2}(T(\lambda^2,\mu^2)xg(x,\lambda^2))|_{\lambda^2=k^2}$$

KK procedure '14 :

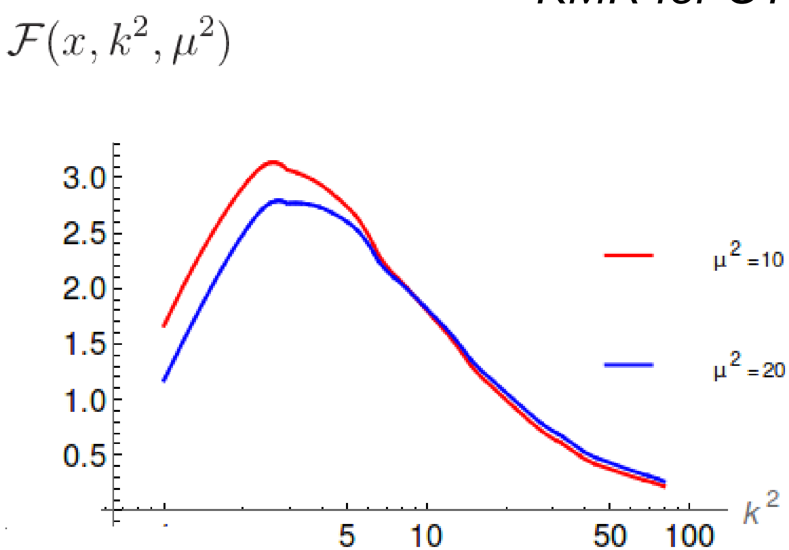
Motivated by paper by Mueller, Yuan, Xiao '13

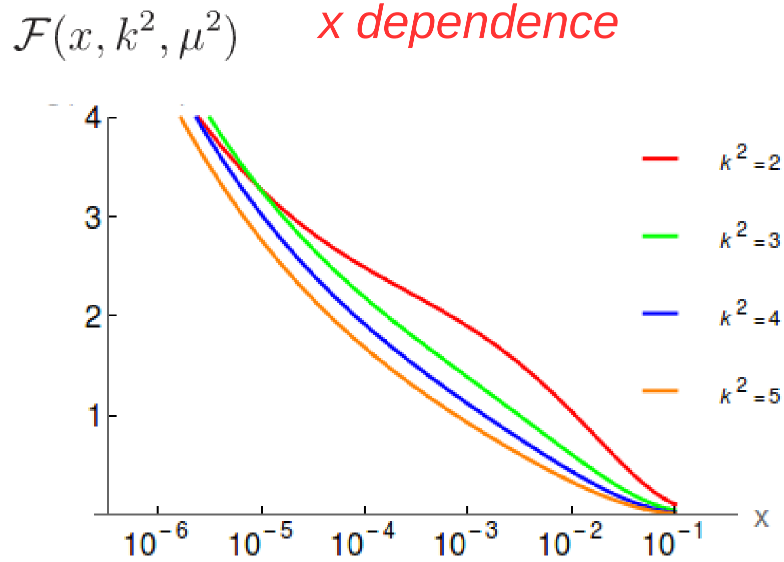
$$\mathcal{F}(x,k^2,\mu^2):=\theta(\mu^2-k^2)T_s(\mu^2,k^2)\frac{xg(x,\mu^2)}{xg_{hs}(x,\mu^2)}\mathcal{F}(x,k^2)+\theta(k^2-\mu^2)\mathcal{F}(x,k^2)$$

Introducing hard scale dependence

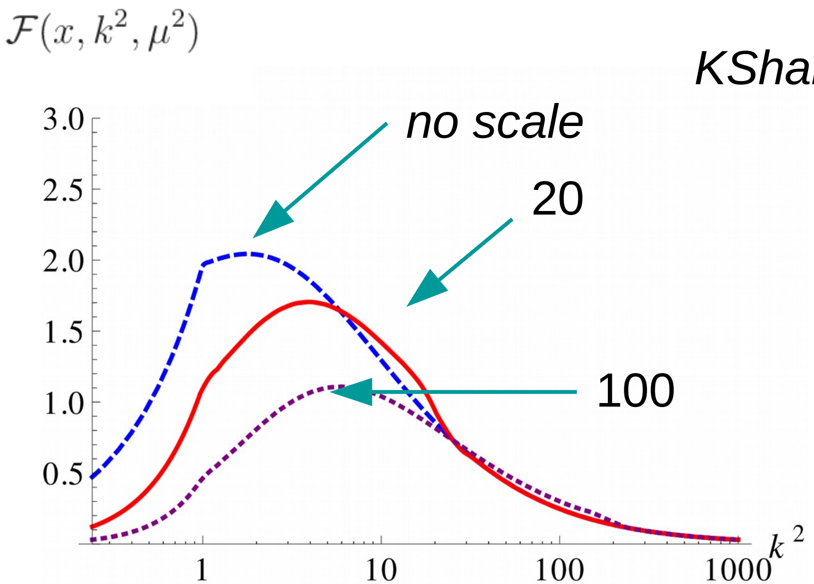
KMR for CTEQ 10 NLO

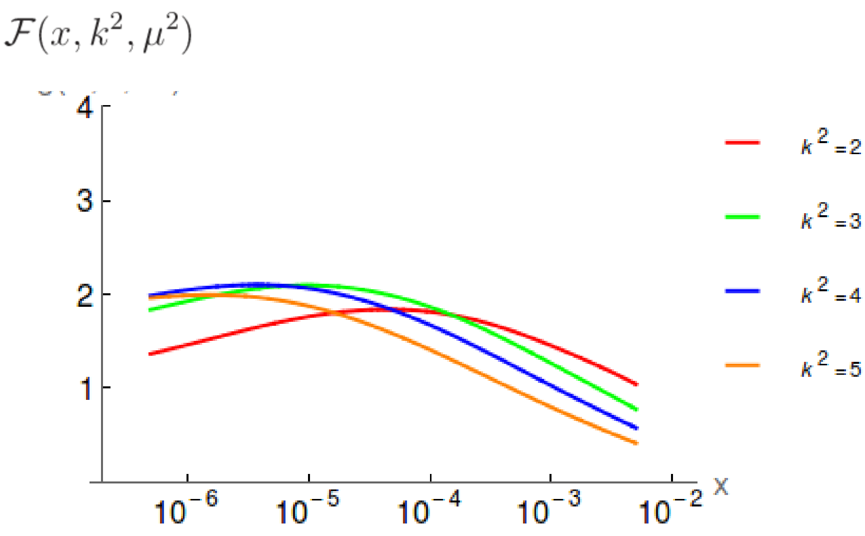
Fundamental difference.
x dependence



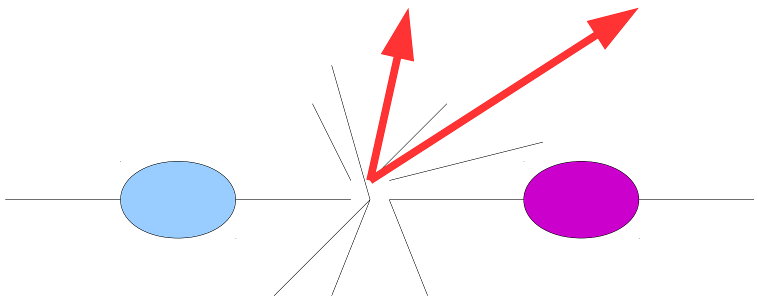


KShardscale



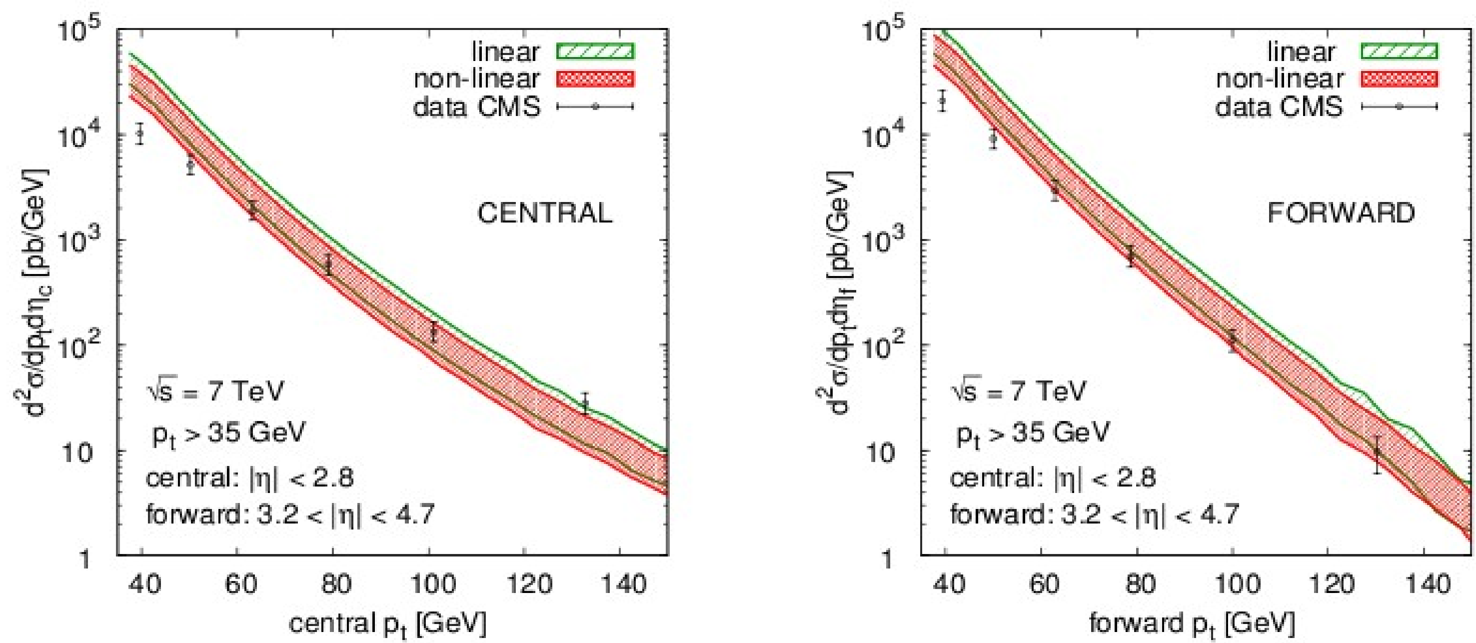


Central-forward di-jets



Di-jets p_t spectra

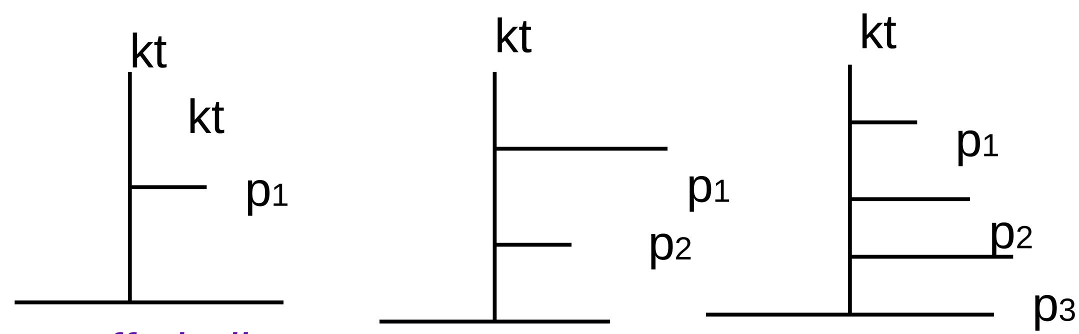
S.Sapeta. KK ,12



Reasonable agreement.

No usage of traditional parton shower

Gluon emissions are unordered in pt and udd up to $k_t = |p_1+p_2+.....p_n|$

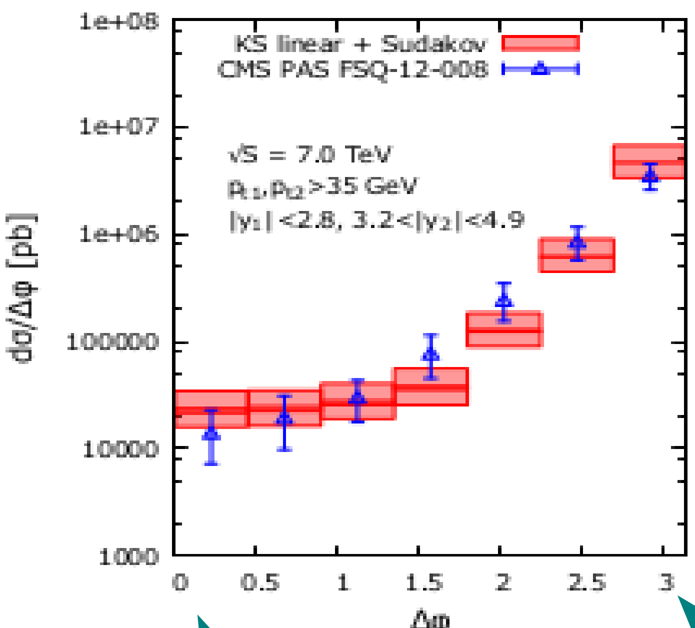


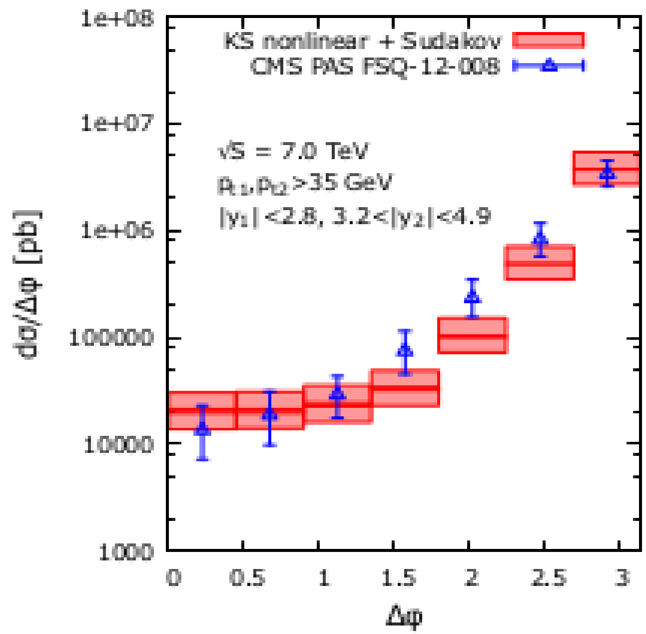
During evolution time incoming gluon becomes off-shell

Crucial effect of higher order corrections

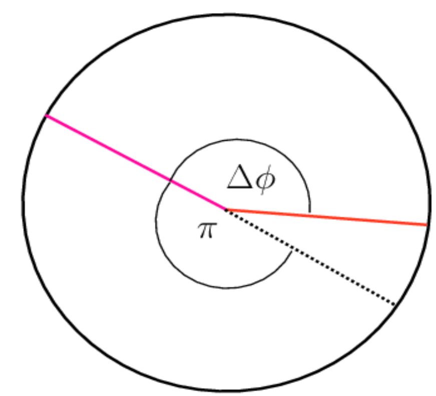
Decorelations inclusive scenario forward-central

van Hameren,, Kotko, K.K, Sapeta '14

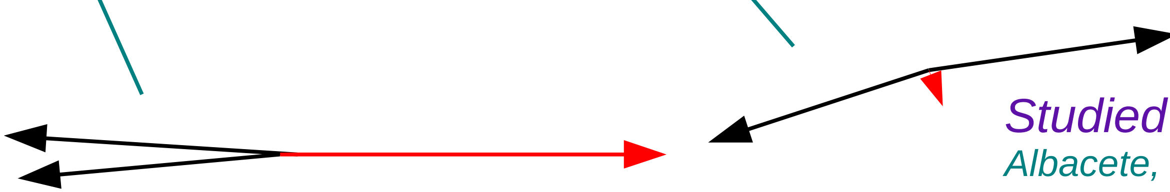




pt1,pt2 >35, leading jets
|y1|<2.8, 3.2<|y2|<4.7
No further requirement on jets



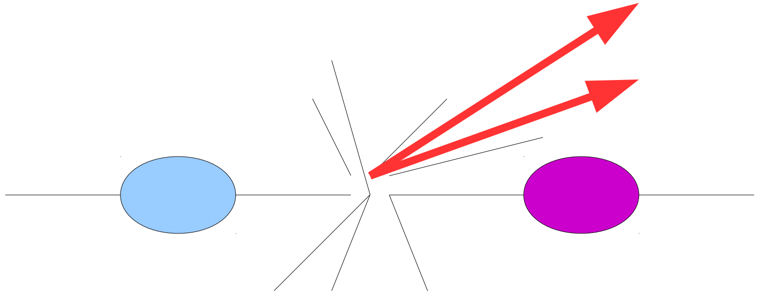
Sudakov effects by reweighing implemented in LxJet Monte Carlo
P. Kotko



Observable suggested to study BFKL effects
Sabio-Vera, Schwensen '06

Studied also context of RHIC
Albacete, Marquet '10

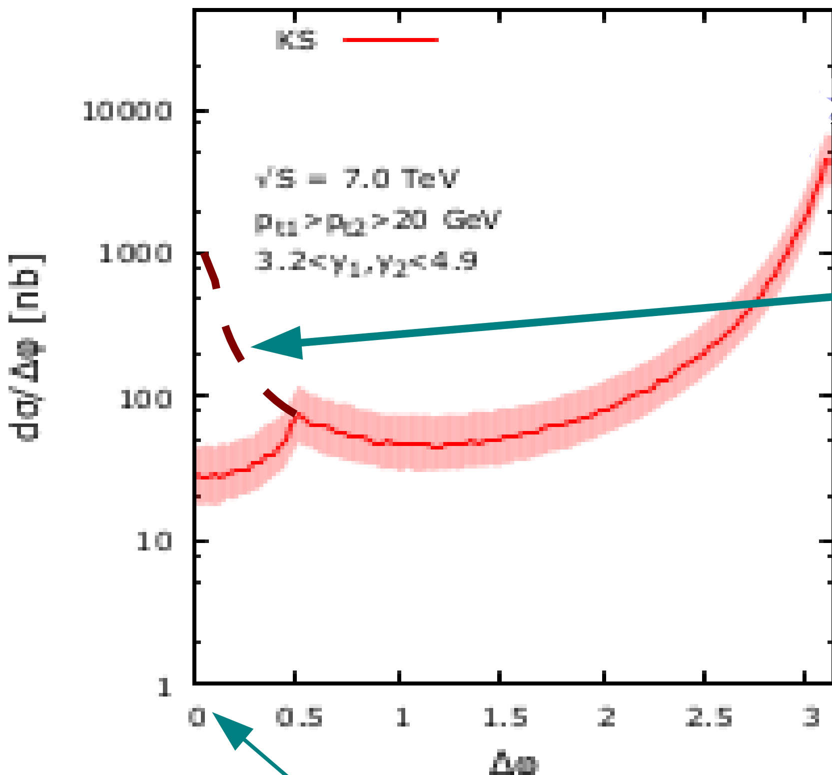
Forward-forward di-jets

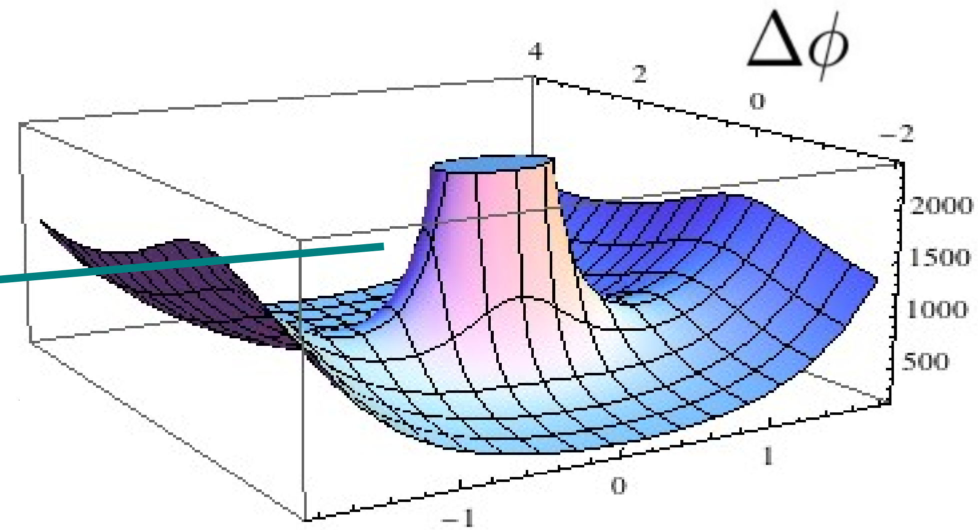


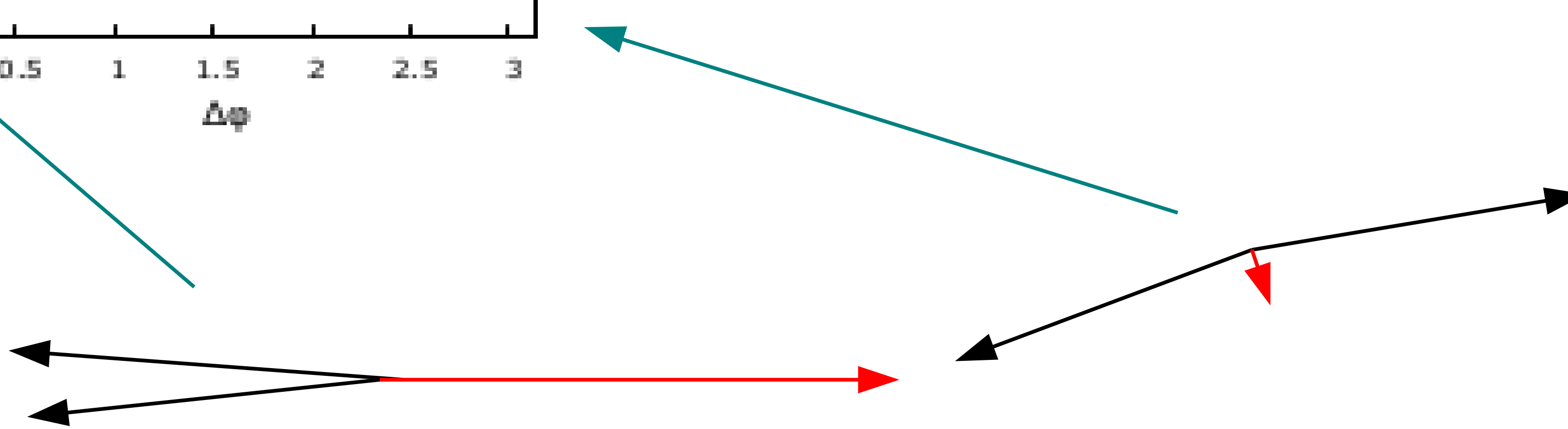
Results for decorelations p+p

Divergence regularized by jet algorithm

A. van Hameren, Kotko,KK,Marquet, Sapeta '14



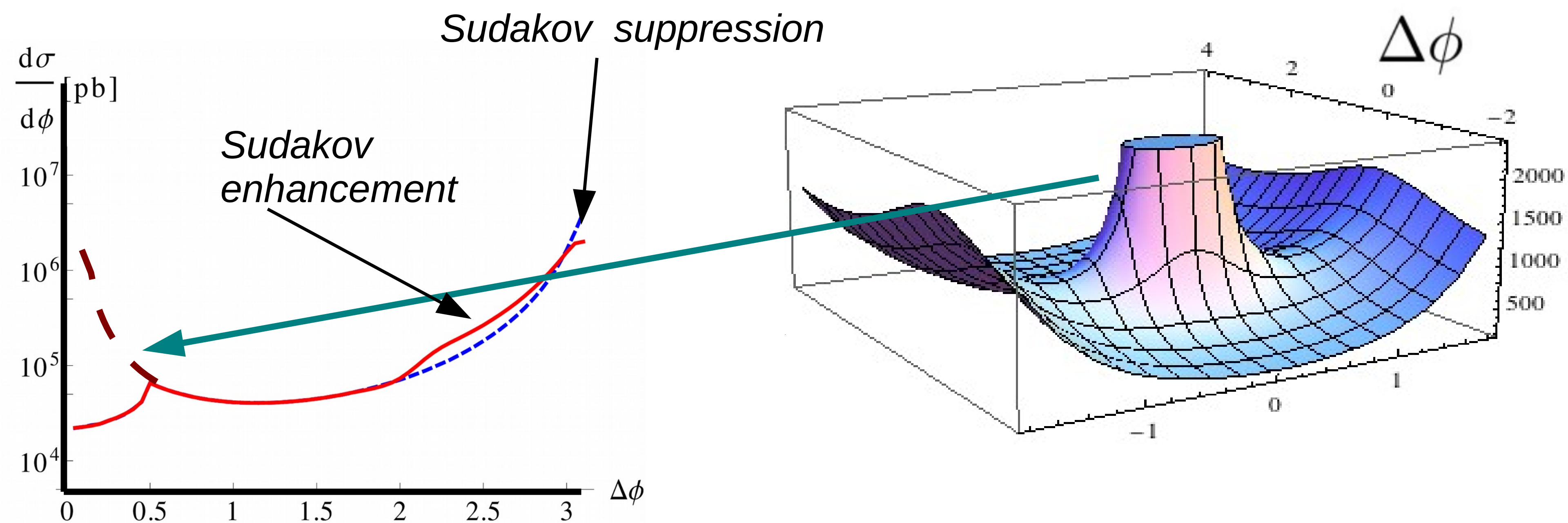


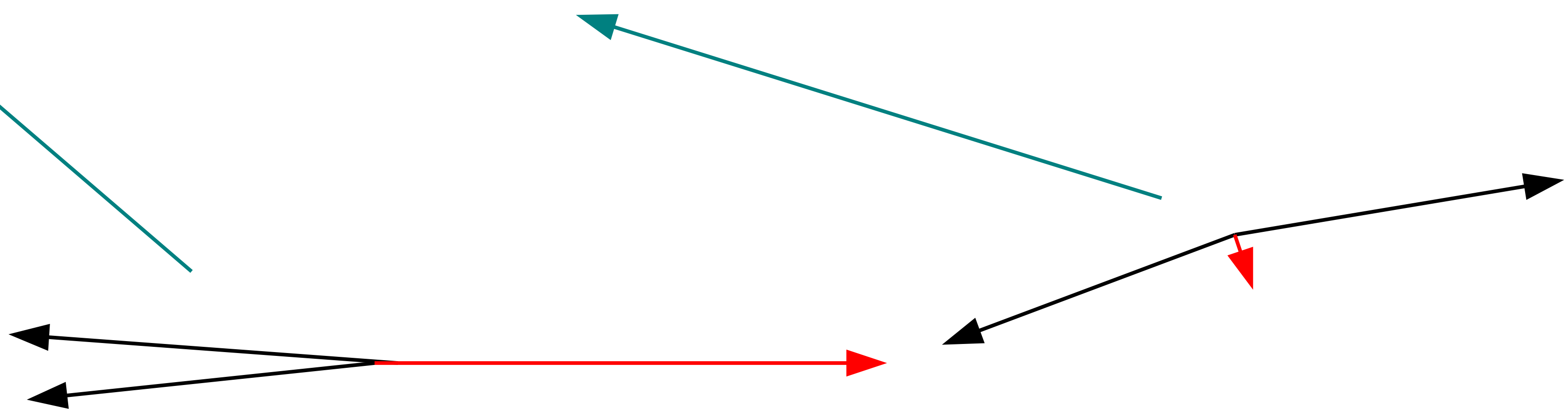


Results for decorelations p+p

Divergence regularized
by jet algorithm

KK '14

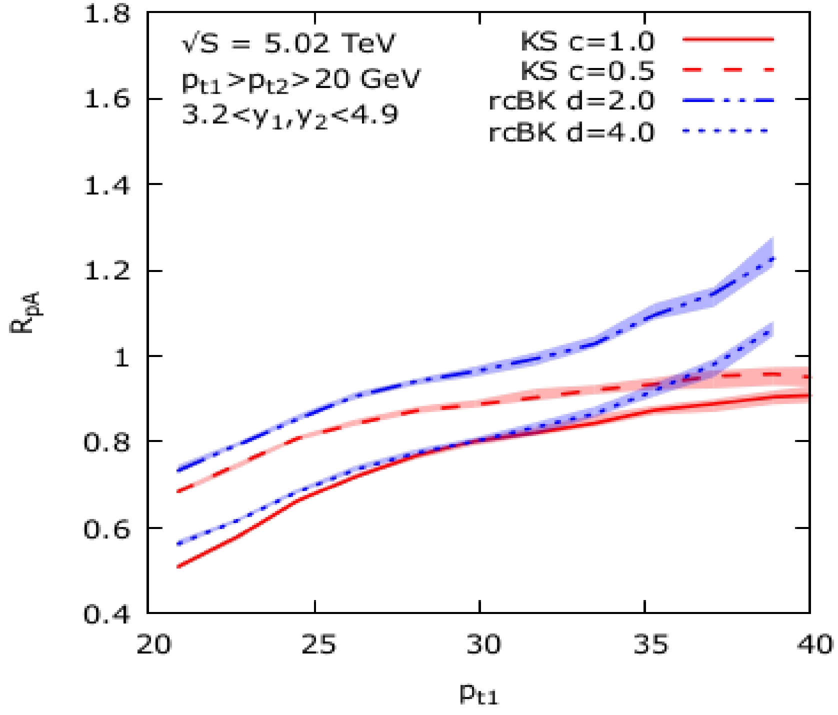


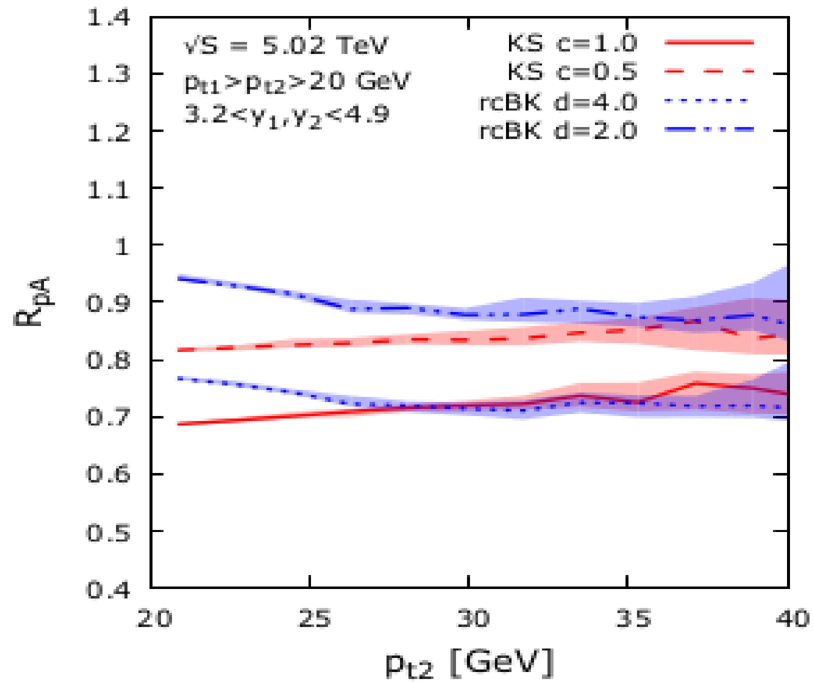


Forward-forward dijets

R_{pA} = p+Pb / p+p

A. van Hameren, Kotko,KK,Marquet, Sapeta '14

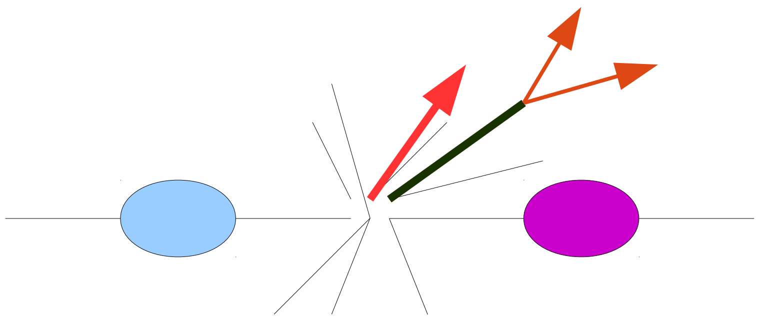




rcBK: above unity at large pt
KS: reaches unity at large pt

Studies of sub-leading jet gives more pronounced signal of nonlinear effects.

Z + jet

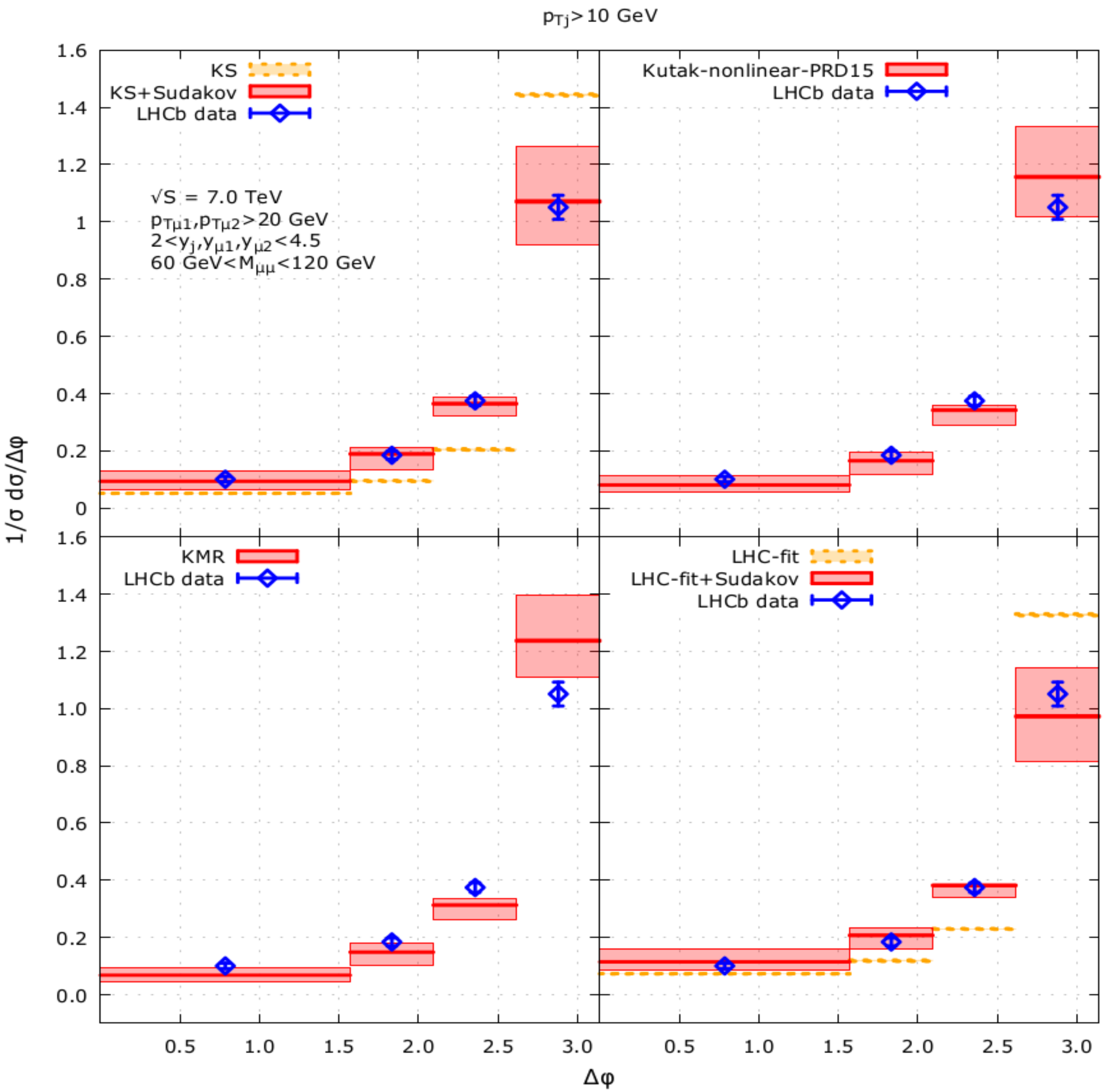


Decorelations in Z0 + jet

Kotko, KK van Hameren '15

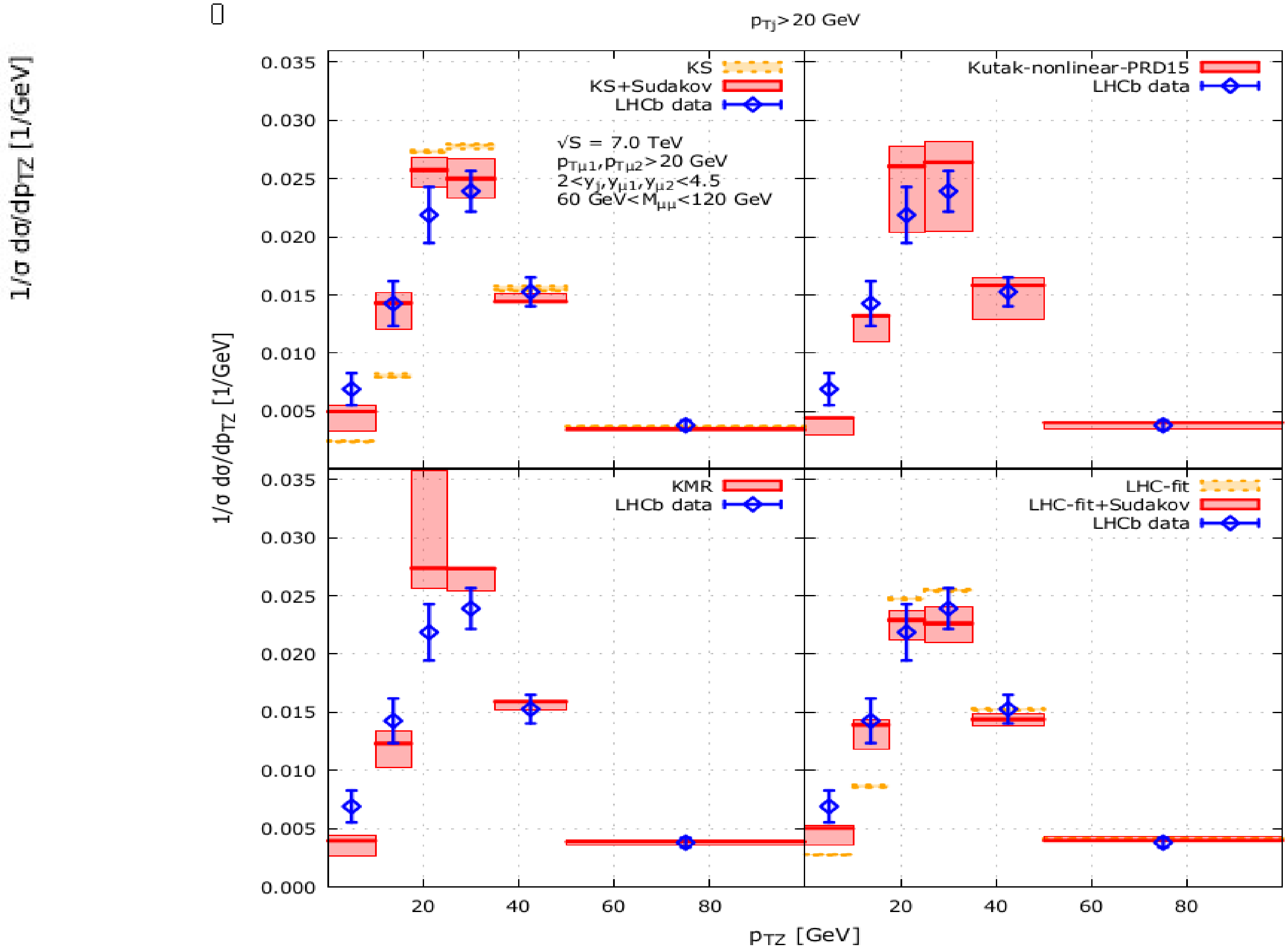
$g^*q \to q\mu^+\mu^-,\ g^*\bar{q} \to \bar{q}\mu^+\mu^-$

1/σ dσ/Δφ



Z0 pt spectrum

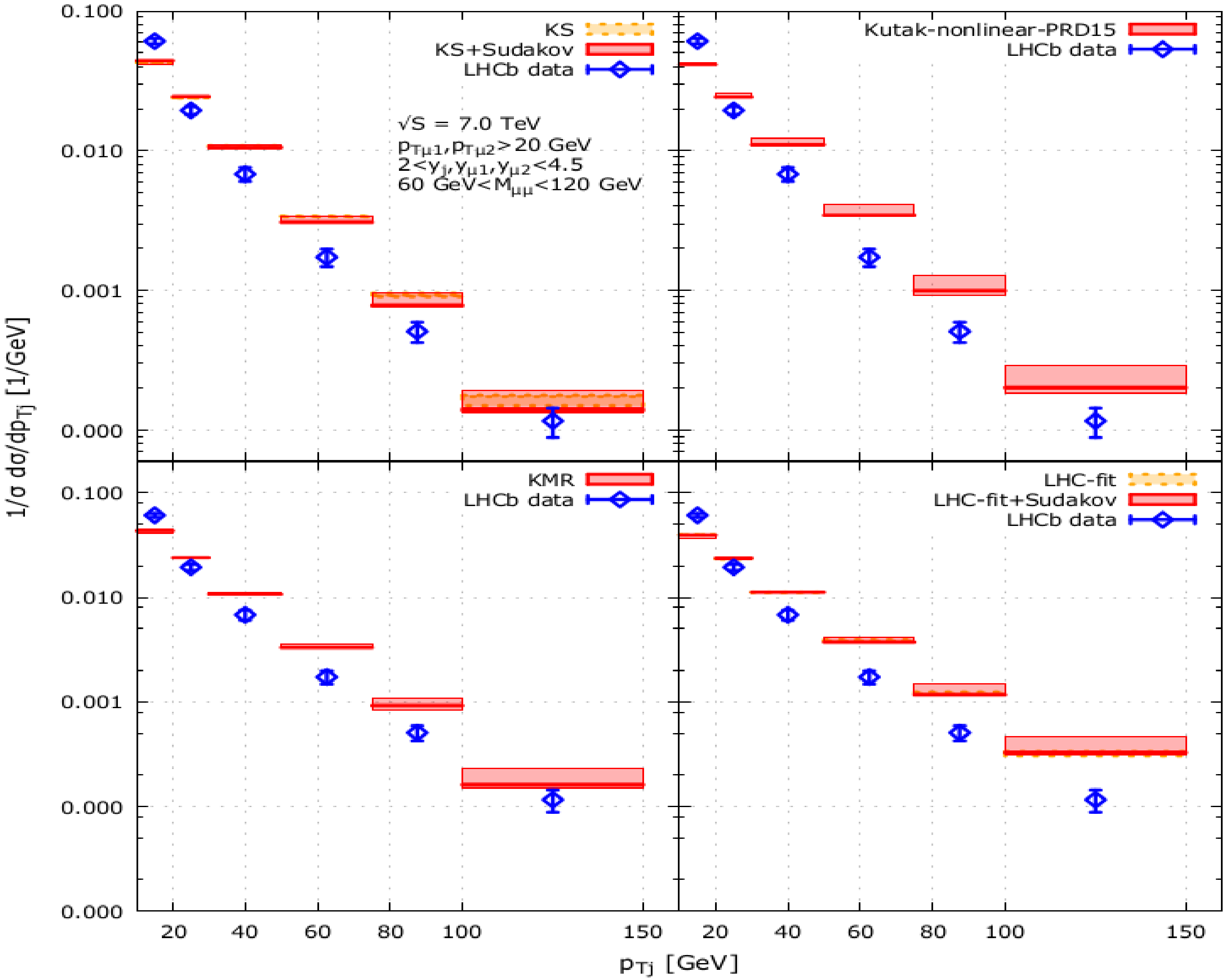
$g^*q \to q\mu^+\mu^-,\ g^*\bar{q} \to \bar{q}\mu^+\mu^-$



Colorless final state.
No color rescatterings.
Description OK

Message: calculation with hard scale dependent gluon closer to data

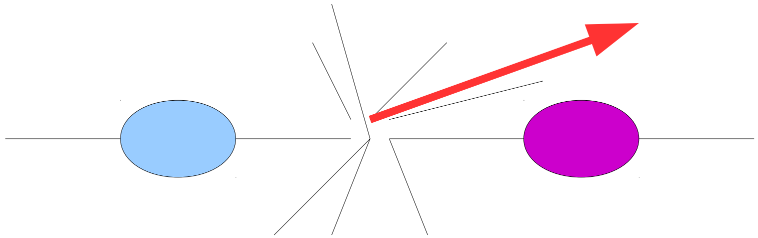
Jet pt spectrum



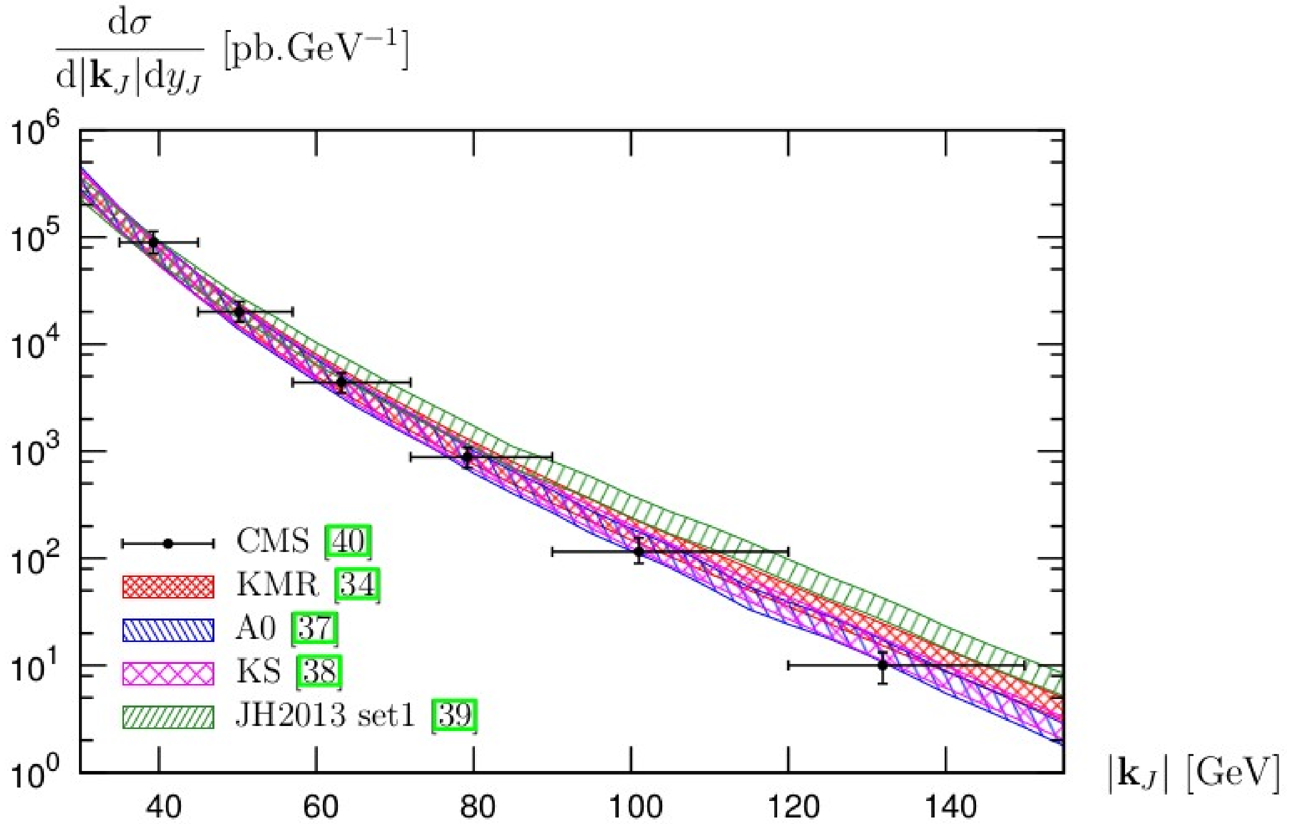
Good tendency but probably effects of final state interactions not taken into account.

Message: possibly larger rescatterings as compared to color neutral Z0 therefore data is not described

Single inclusive forward jet



Single inclusive p_t jet spectra



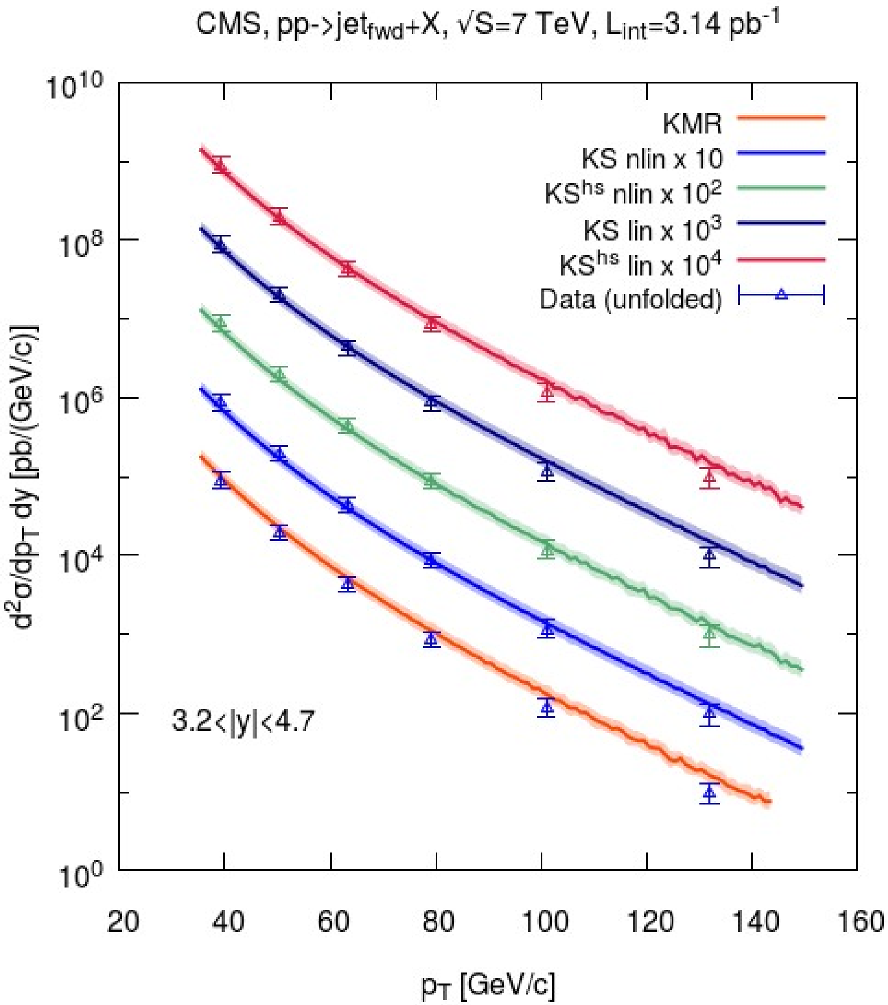
Decloue, Szymanowski, Wallon '15

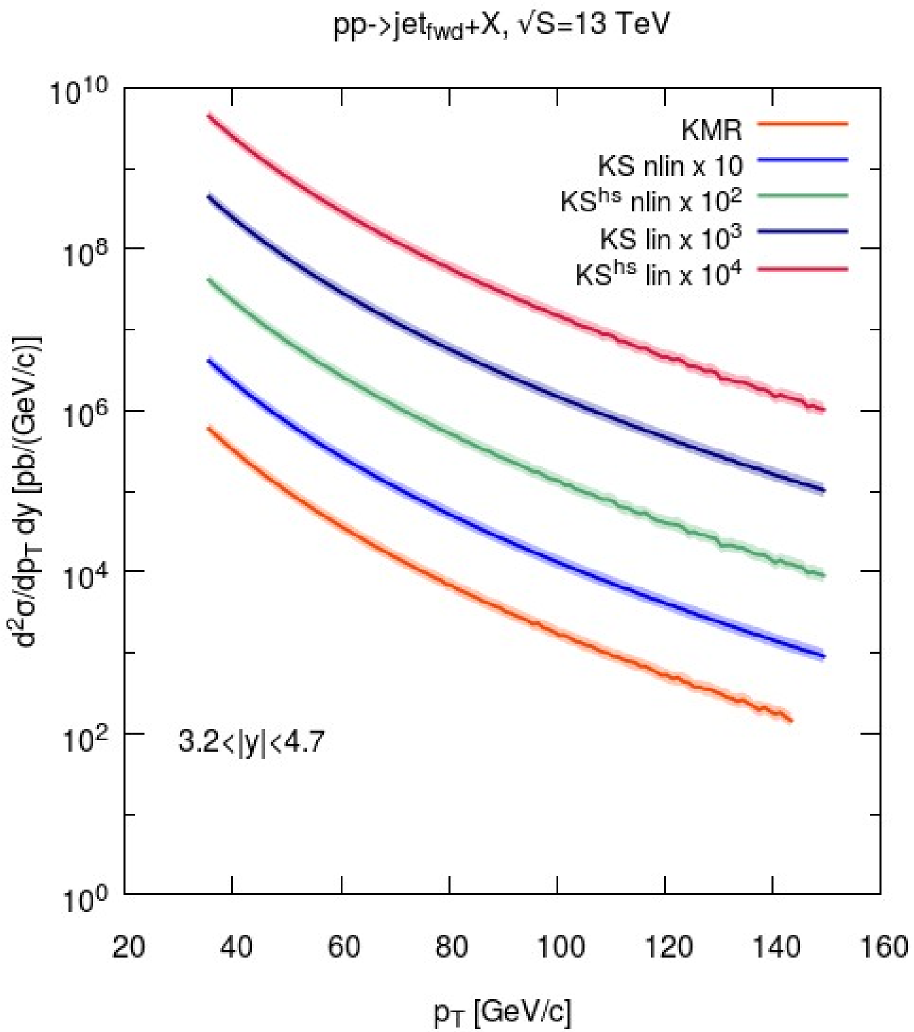
$$\frac{d\sigma}{dy_1 dp_{1t}} = \frac{1}{2}\frac{\pi\, p_{1,t}}{(x_1 x_2 S)^2}\sum_{a,b,c}\overline{|\mathcal{M}_{ab\to c}|}^2 x_1 f_{a/A}(x_1,\mu^2)\,\mathcal{F}_{b/B}(x_2,p_{1t}^2,\mu^2)$$

Dumitru, Hayashigski, Jalilian-Marian '05

Single inclusive p_t jet spectra

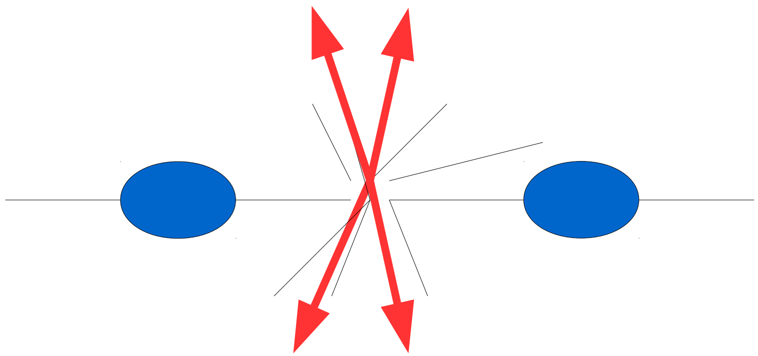
Preliminary *KK,Bury, Sapeta*





$|3.2| < y <|4.7|$

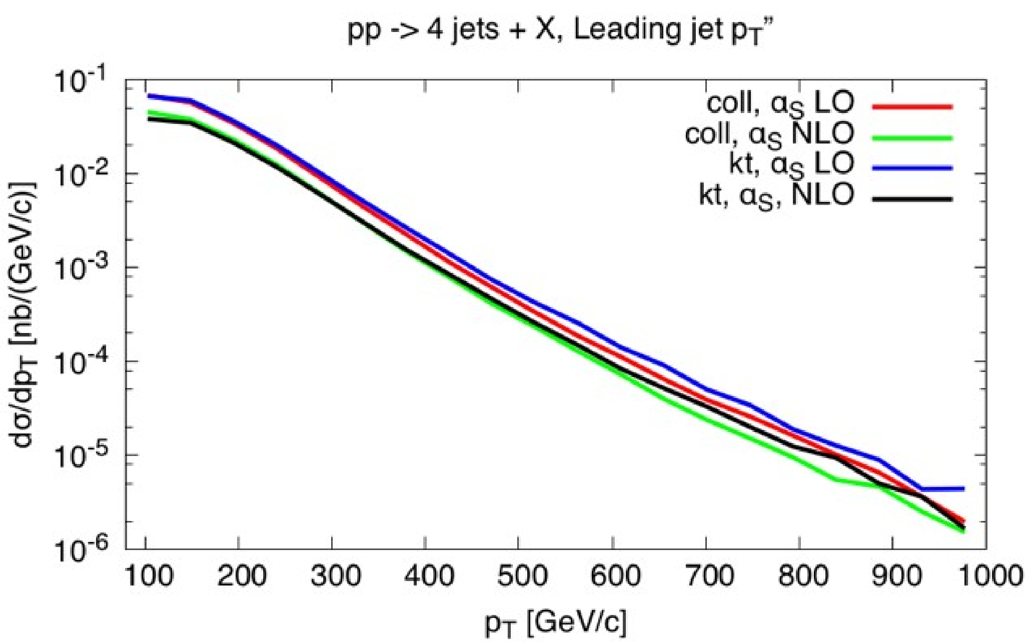
4 inclusive central jets

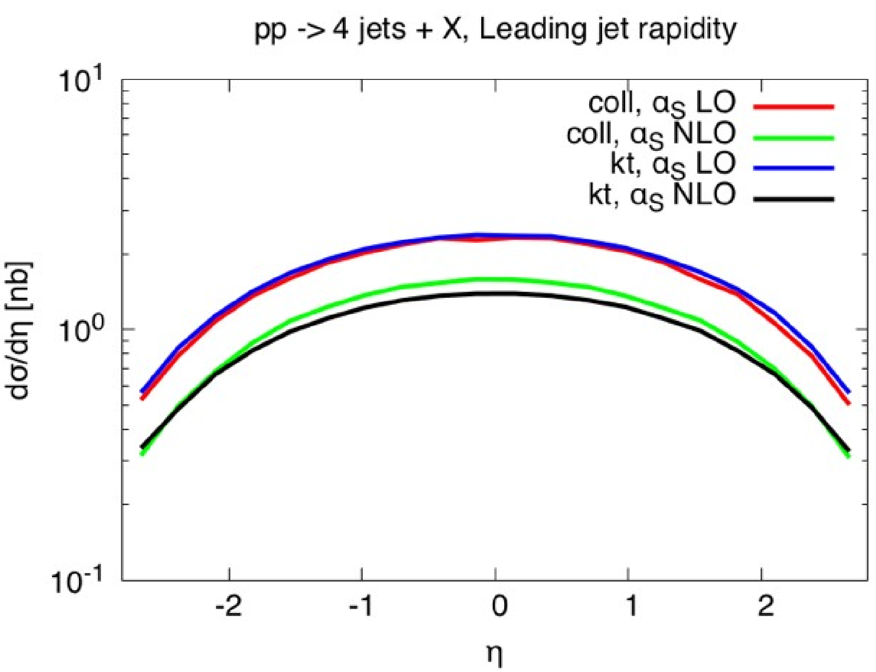


HEF and central jets

p_t spectra of leading jets

preliminary
KK, M.Serino, A. van Hameren





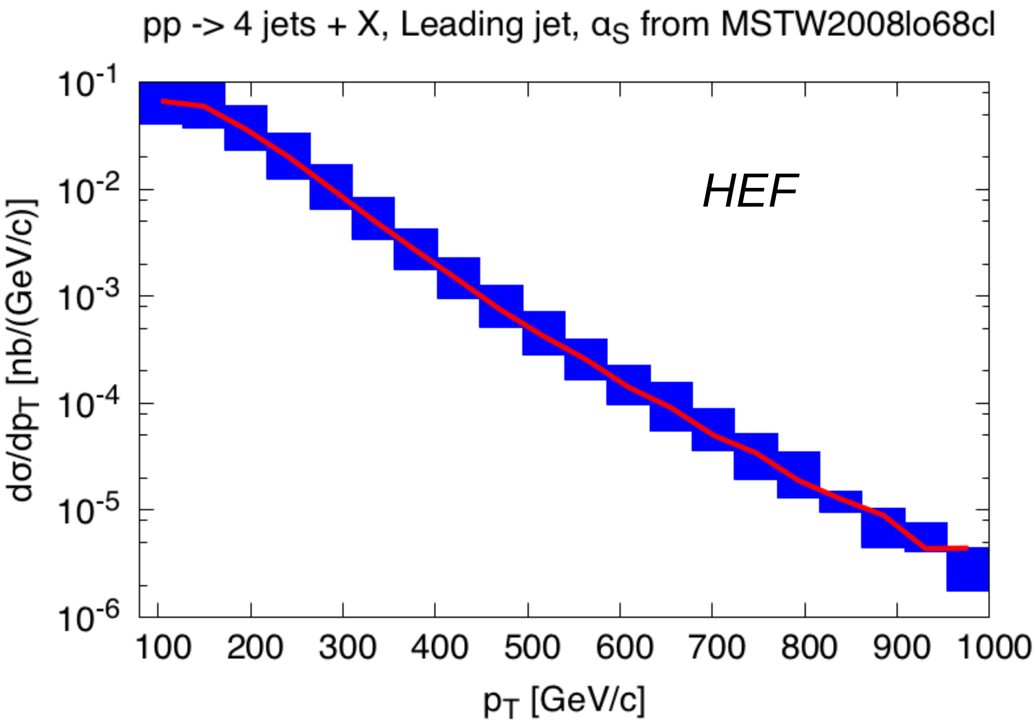
- *on both sides unintegrated pdfs.*
- *all channels take into account i.e. off-shell quarks and off-shell gluons*
- *gluon density obtained using the KMR prescription.*
- *the underlying collinear pdf is at NLO accuray*

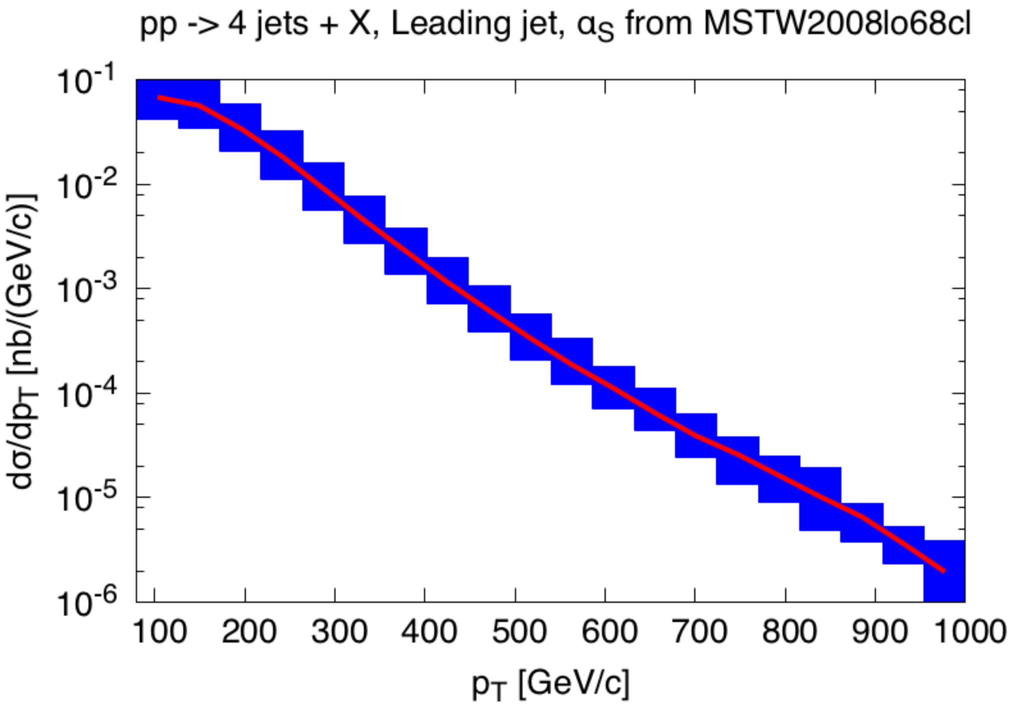
HEF and central jets

preliminary

KK, Serino, van Hameren

pt spectra of leading jets





- *on both sides unintegrated pdfs.*
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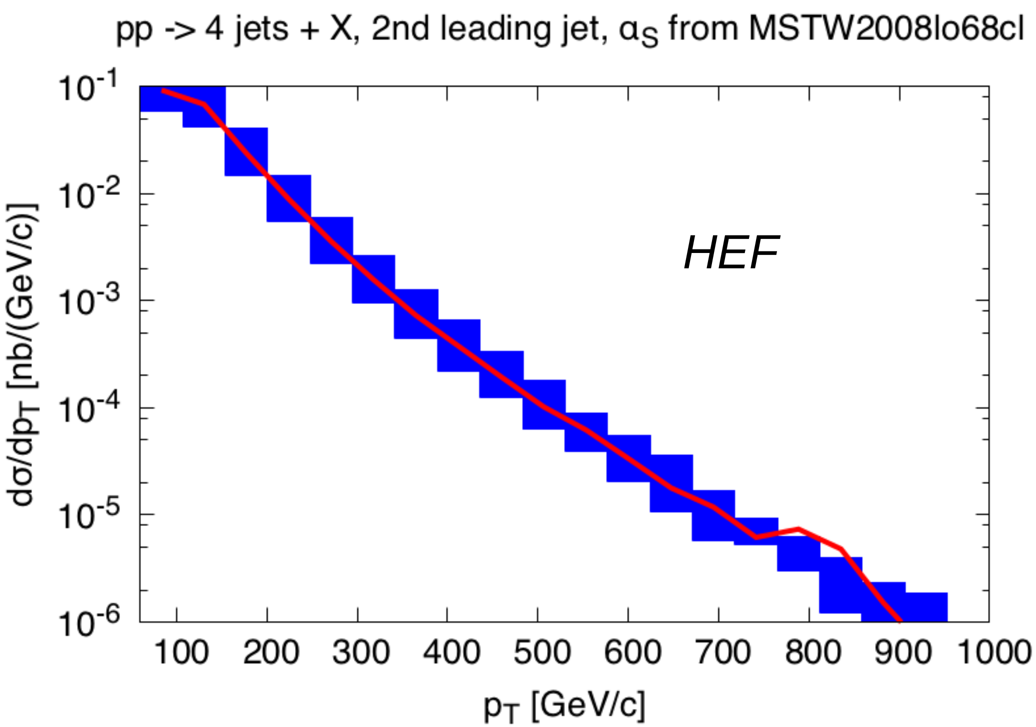
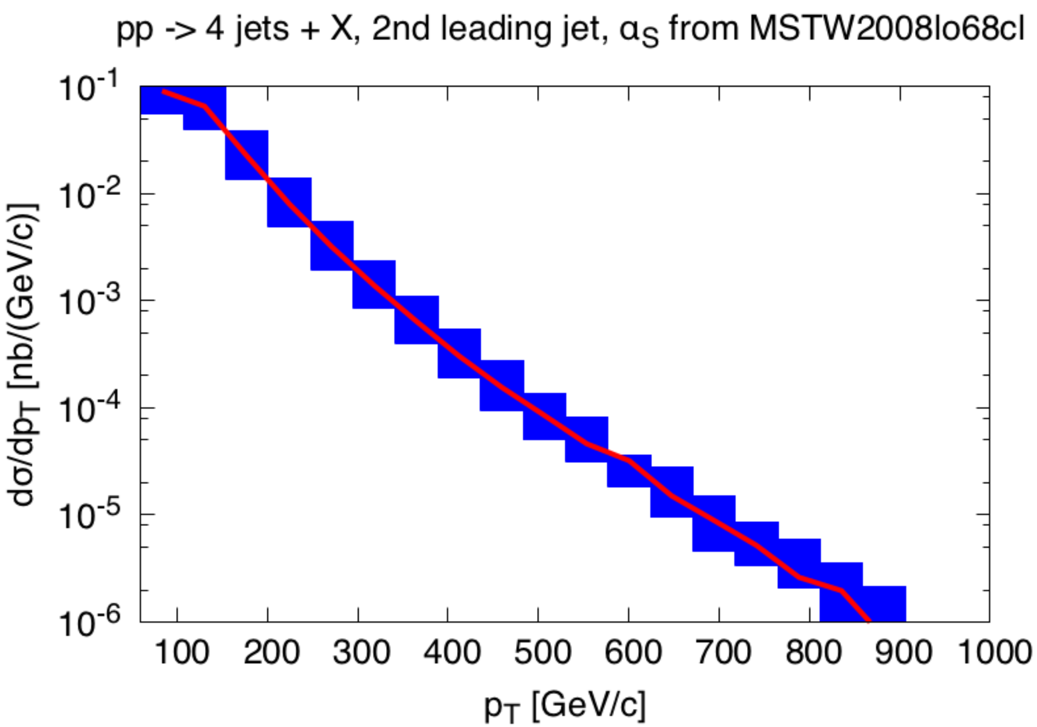
HEF and central jets

pt spectra of second jet





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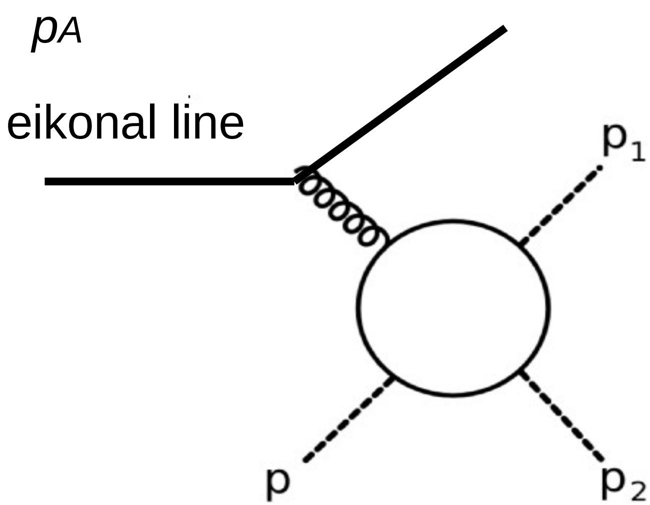
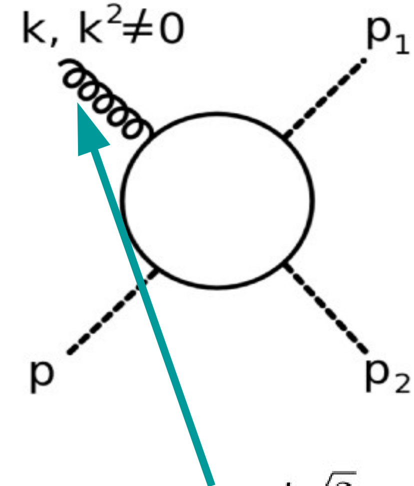
BACK UP

Example of matrix element for hybrid factorization



Decomposition
of propagator

$$g_{\mu\nu} = g_{\mu\nu\perp} + \frac{p_{A\mu}p_\nu + p_{A\nu}p_\mu}{s}$$



$$k = x_2 p_A + k_T$$

$$\epsilon^0_\mu = \frac{i\sqrt{2}\,x_2}{|k_t|} p_{A\,\mu}$$

$$x_2 = k_\mu p^\mu / p_{A\nu} p^\nu$$

Polarization sum
for onshell gluons

Polarization of off-shell gluon

$$\sum_{\lambda=\pm} \epsilon^\lambda_\mu \epsilon^{\lambda*}_\nu = g_{\mu\nu} - \frac{p_{A\mu}q_\nu + q_\mu p_{A\nu}}{q^\rho p_{A\rho}}$$

Effective action based approach
Lipatov 95, Lipatov, Vyazovsky 2000

Gauge link based derivation
Kotko'14