NCN

Broadening and saturation effects in dijet azimuthal correlations in p-p and p-Pb collisions at E= 5.02 TeV

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Based on
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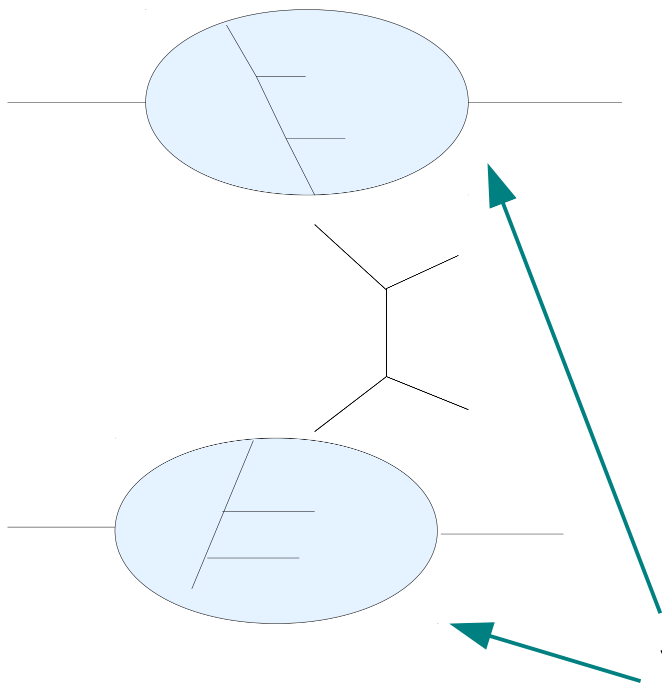
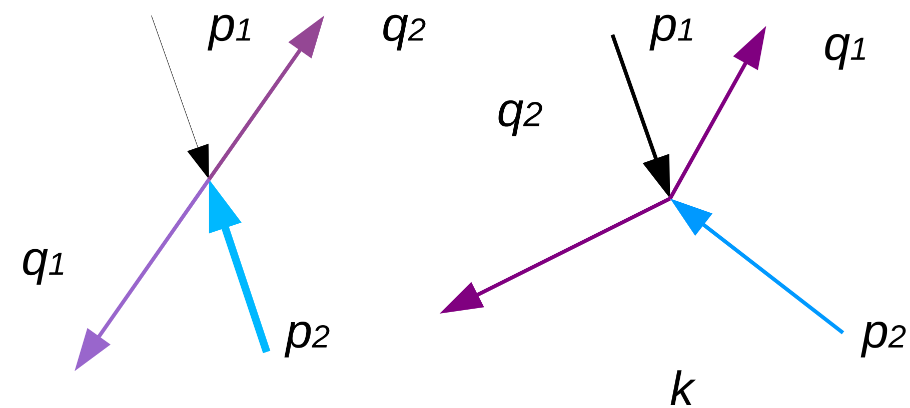
A. van Hameren, P. Kotko, K. Kutak, S. Sapeta

QCD at high energies – high energy factorization



Strongly decreasing
Longitudinal momentum
fractions of off-shell partons



$p_1+p_2=q_1+q_2$

$p_1+p_2=q_1+q_2+k$

$$\frac{d\sigma}{dPS} \propto \mathcal{F}_{a^*}(x_1, k_{\perp\,1}) \otimes \hat{\sigma}_{ab\to cd}(x_1, x_2) \otimes \mathcal{F}_{b^*}(x_2, k_{\perp\,2})$$

Ciafaloni, Catani, Hautman '93
Collins, Ellis '93

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

ITMD: generalization of HEF for forward processes

van Hameren, Kotko, Kutak, Sapeta, Petreska '15

- *accounts for saturation*
- *accounts correctly for gauge structure of the theory*
- *is consistent with Color Glass Condensate in appropriate limit*

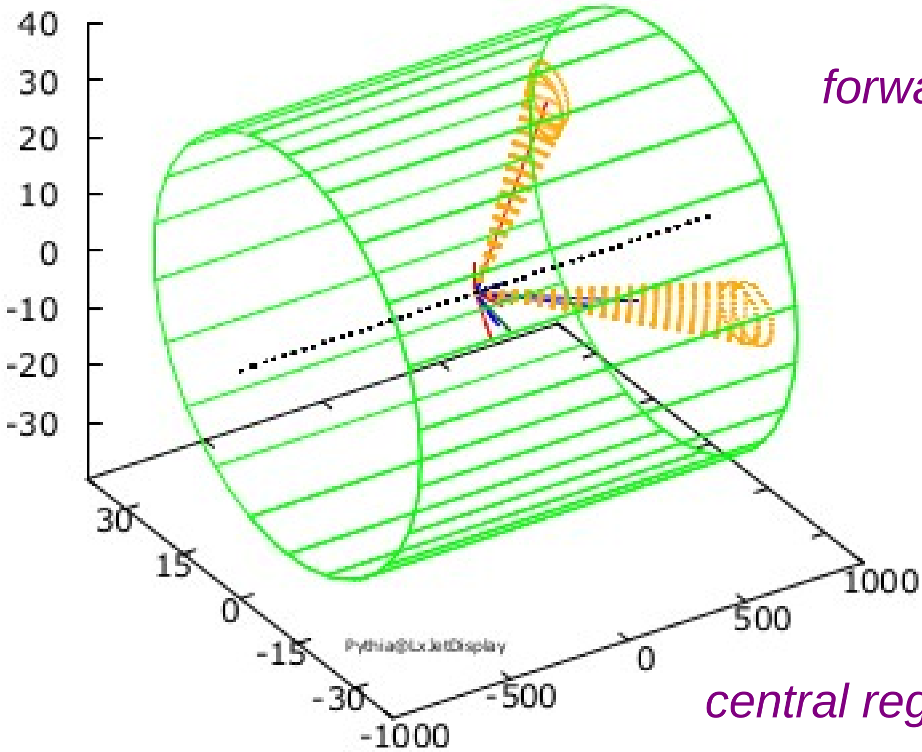
ITMD = Improved Transversal Momentum Dependent (applied already to dijets (van Hameren, Kotko, Kutak, Sapeta, Petreska'16), particle production (Albacete, Giacalone, Marquet, Matas '18) , UPC processes (Kotko, Sapeta, Staśto, Strikman '17)

HEF = High Energy Factorization Catani, Ciafaloni Hautman '93

See also talk by: Piotr Kotko

Poster by: Andreas van Hameren

Dilute-dense: forward-forward



forward region

central region

The collisions we consider:

e.g minimal p_T 20 GeV

both jets are forward → $y > 2.7$

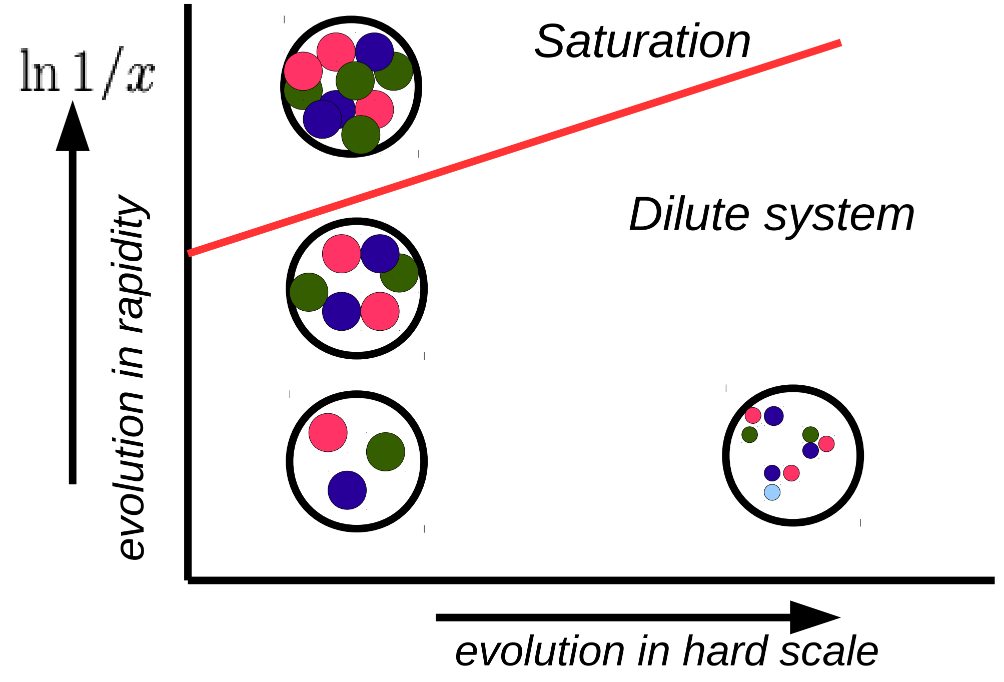
From: Piotr Kotko
LxJet

There is certain class of processes where one can assume that partons in one of hadrons are just collinear with hadron and in other are not

Saturation

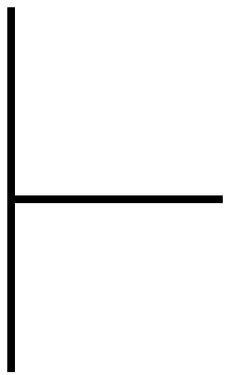
Saturation – state where number of gluons stops growing due to high occupation number. Way to fulfill unitarity requirements in high energy limit of QCD.

Gribov, Levin, Ryskin '81



On microscopic level it means that
gluon apart splitting recombine

splitting

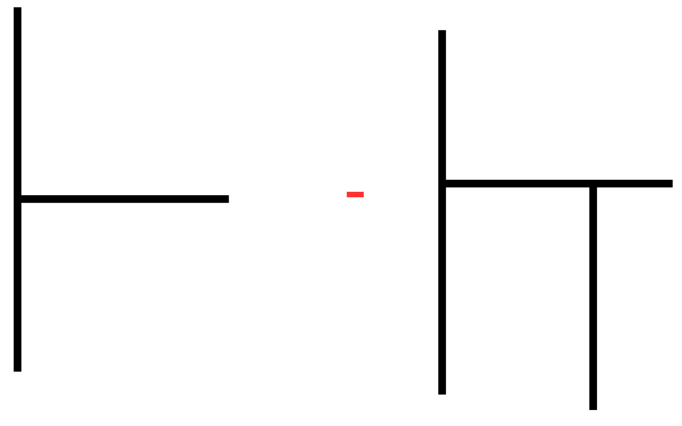


Linear evolution
Equation
BFKL

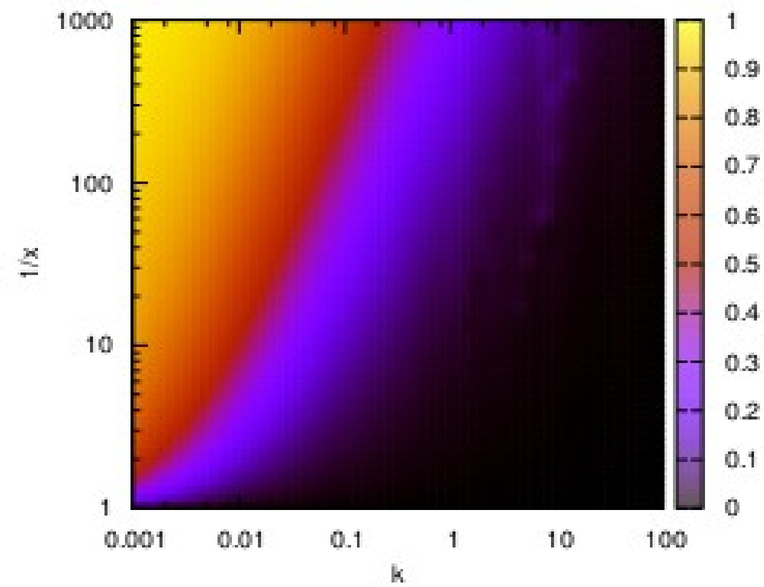
Nonlinear evolution
equations

splitting

recombination



Saturation



Saturation – state where number of gluons stops growing due to high occupation number. Way to fulfill unitarity requirements in high energy limit of QCD.

Gribov, Levin, Ryskin '81

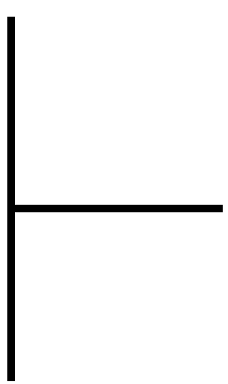
Phenomenological status:
book "QCD at high energy" Kovchegov Levin '12

See poster by: M. Hentschinski

On microscopic level it means that gluon apart splitting recombine

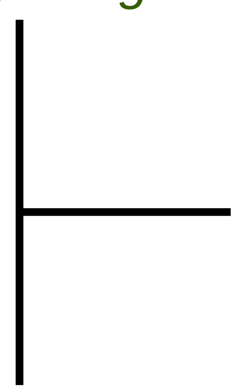
splitting

Linear evolution equation
BFKL



Nonlinear evolution equations

splitting



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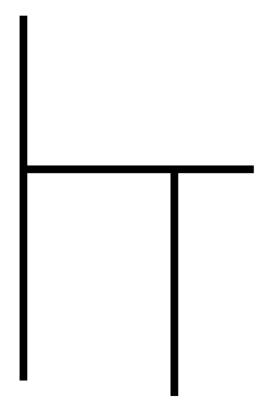
recombination



The saturation problem: supressing gluons below Q_s

Originally formulated in coordinate space
Balitsky '96, Kovchegov '99

Fit AAMQS '10

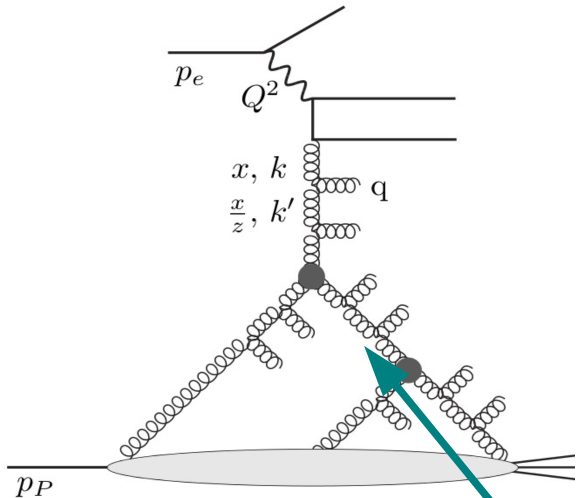
NLO accuracy
Balitsky, Chirilli '07

and solved
Lappi, Mantysaari '15

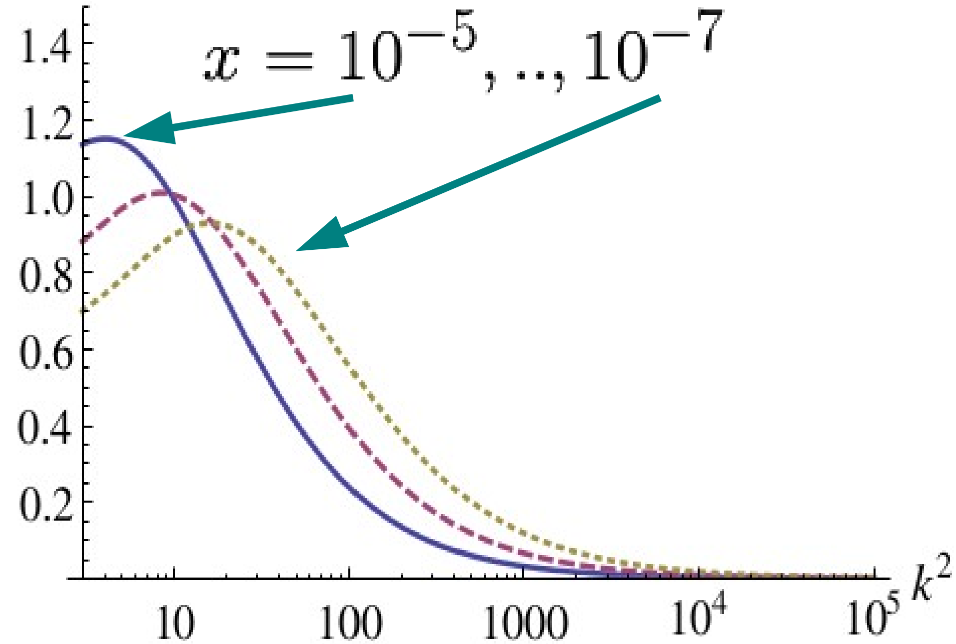
Kinematic corrections
Iancu at el

Solved b dependent
Stasto, Golec-Biernat '02

with kinematic corrections and b
Cepila, Contrares, Matas '18



Bartels, Wusthoff '95



solution of Balitsky-Kovchegov for gluon density

The BK equation for dipole gluon density

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

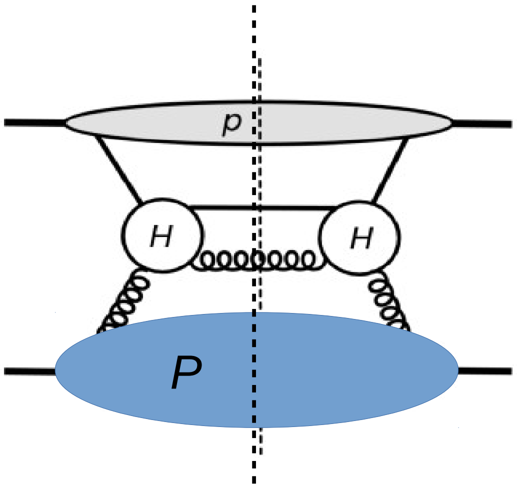
hadron's radius

Kwiecinski, Kutak '02
Nikolaev, Schafer '06

Fit to F_2 data
KK. Sapeta '12

Definition of TMD

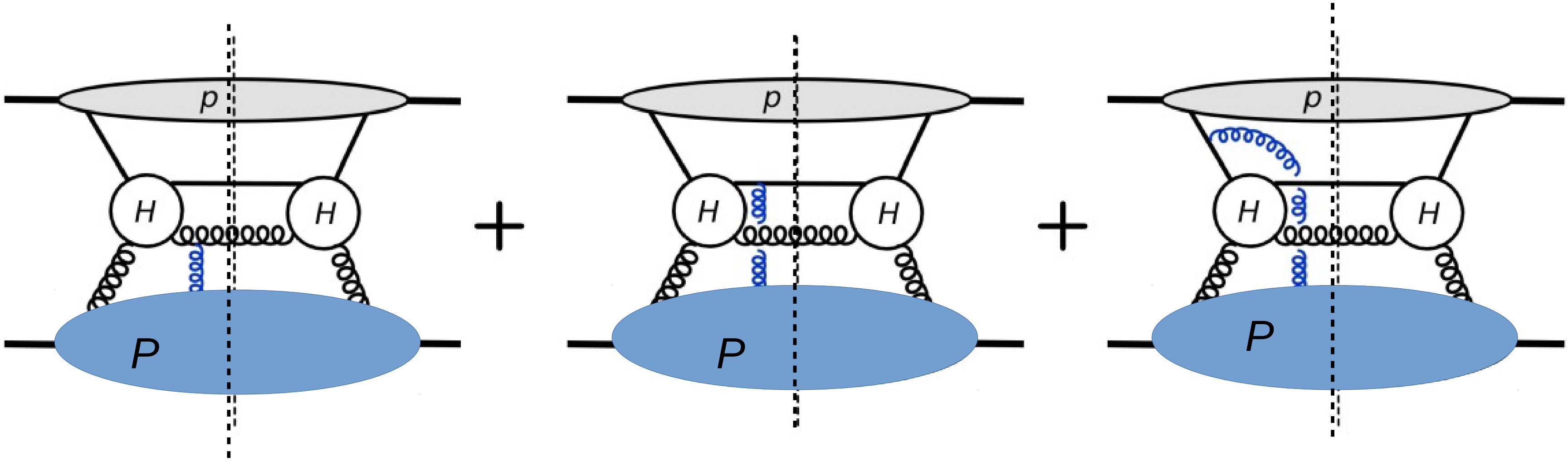
The used factorization formula for HEF is strictly valid for large transversal momentum and was obtained in a specific gauge. Ultimately we want to go beyond this



Naive definition

$$\mathcal{F}\left(x,k_T\right) = 2\int \frac{d\xi^- d^2\xi_T}{\left(2\pi\right)^3 P^+}\, e^{ixP^+\xi^- - i\vec{k}_T\cdot\vec{\xi}_T}\ \langle P|\,\mathrm{Tr}\left\{\hat{F}^{i+}\left(0\right)\hat{F}^{i+}\left(\xi^+=0,\xi^-,\vec{\xi}_T\right)\right\}|P\rangle$$

Definition of TMD – gauge links



+ similar diagrams with 2,3,….gluon exchanges.

Bomhof, Mulders, Pijlman '06

All this need to be resummed

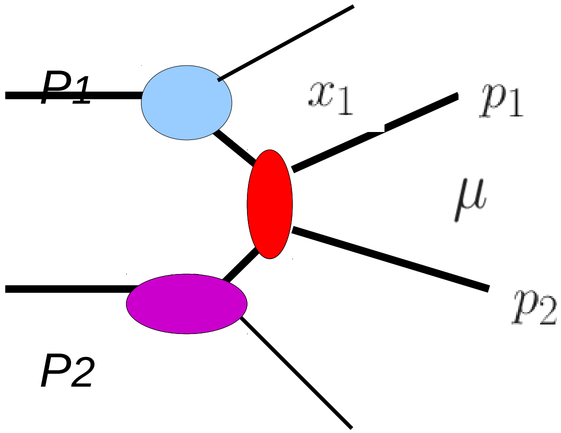
This is achieved via gauge link which renders the gluon density gauge invariant

$$\mathcal{F}\left(x,k_T\right)=2\int\frac{d\xi^- d^2\xi_T}{(2\pi)^3\,P^+}\,e^{ixP^+\xi^- - i\vec{k}_T\cdot\vec{\xi}_T}\,\langle P|\,\mathrm{Tr}\left\{\hat{F}^{i+}\left(0\right)\mathcal{U}_{C_1}\hat{F}^{i+}\left(\xi\right)\mathcal{U}_{C_2}\right\}|P\rangle$$

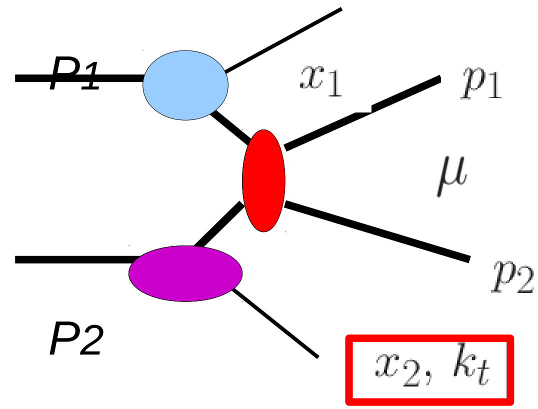
Hard part defines the path of the gauge link

ITMD for dijets

$$\frac{d\sigma_{\rm SPS}^{P_1P_2\to {\rm dijets}+X}}{dy_1dy_2dp_{1t}dp_{2t}d\Delta\phi} = \frac{p_{1t}p_{2t}}{8\pi^2(x_1x_2s)^2}\sum_{a,c,d} x_1 f_{a/P_1}(x_1,\mu^2)\,|\overline{\mathcal{M}_{ag^*\to cd}}|^2 \quad \mathcal{F}_{g/P_2}(x_2,k_t^2)\frac{1}{1+\delta_{cd}}$$



can be be used for estimates of saturation effects



Generalization but no possibility to calculate decorelations since no kt in ME
Dominguez, Marquet, Xiao, Yuan '11

We found a method to include kt in ME and express the factorization formula in terms of gauge invariant sub amplitudes → more direct relation to two fundamental gluon densities: dipole gluon density and Weizacker-Williams gluon density
Conjecture Kotko, K.K, Marquet, Petreska, Sapeta, van Hameren '15
Proof Altinoluk, Bousarie, Kotko '19 see also Altinoluk, Bousarie '19

gauge invariant amplitudes and TMDs

$$\frac{d\sigma^{pA\to {\rm dijets}+X}}{d^2P_td^2k_tdy_1dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\sum_{a,c,d} x_1 f_{a/p}(x_1,\mu^2)\sum_{i=1}^{2} K_{ag^*\to cd}^{(i)}\Phi_{ag\to cd}^{(i)}\ \frac{1}{1+\delta_{cd}}$$

ITMD formula

Here presented just for gluons

$$d\sigma \sim \vec{\mathcal{A}}^\dagger \, \mathbf{\Phi}_{gg\to gg} \, \vec{\mathcal{A}}$$

$$\mathbf{\Phi}_{gg\to gg} = \begin{pmatrix} \Phi_1 & \Phi_2 \\ \Phi_2 & \Phi_1 \end{pmatrix}$$

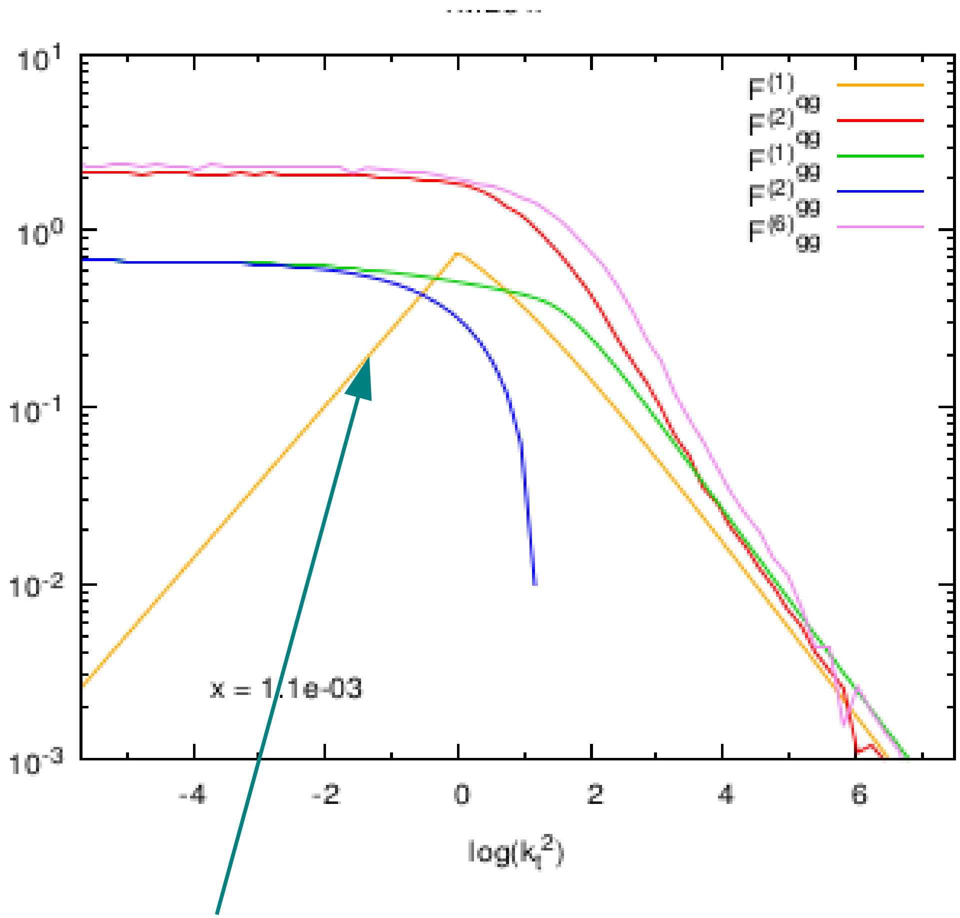
$$\Phi_1 = \frac{1}{2N_c^2}\left(N_c^2\mathcal{F}_{\rm gg}^{(1)} - 2\mathcal{F}_{\rm gg}^{(3)} + \mathcal{F}_{\rm gg}^{(4)} + \mathcal{F}_{\rm gg}^{(5)} + N_c^2\mathcal{F}_{\rm gg}^{(6)}\right)$$

$$\Phi_2 = \frac{1}{N_c^2}\left(N_c^2\mathcal{F}_{\rm gg}^{(2)} - 2\mathcal{F}_{\rm gg}^{(3)} + \mathcal{F}_{\rm gg}^{(4)} + \mathcal{F}_{\rm gg}^{(5)} + N_c^2\mathcal{F}_{\rm gg}^{(6)}\right)$$

Was extended to 3 and 4 jet final states *KK, Bury, Kotko' 18*

Plots of ITMD gluons

Kotko, K.K, Marquet, Petreska, Sapeta, van Hameren '16



Similar structure obtained from solutions of JIMWLK

Marquet, Petreska, Roiesnel '16

Standard HEF gluon density

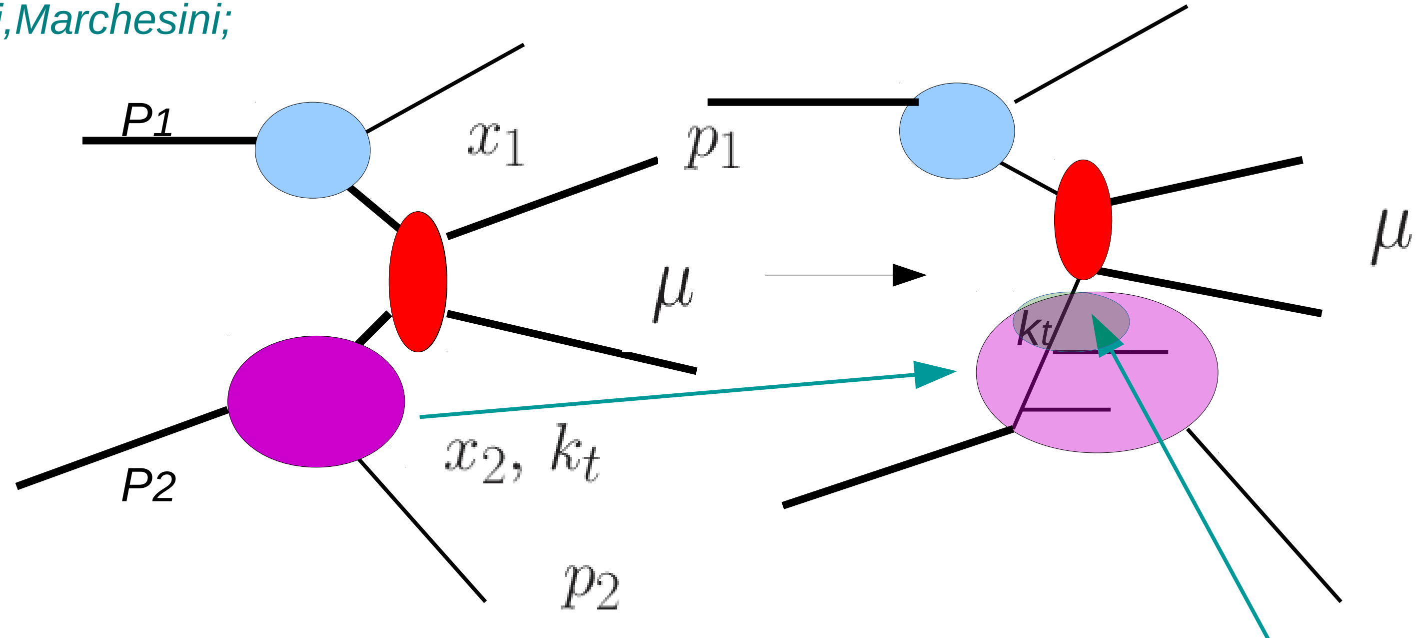
The other densities are flat at low kt → less saturation

Not negligible differences at large kt → differences at small angles

Other relevant effects – Sudakov form factor in ISR

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

Survival probability of the gap without emissions



If hard scale is larger than kt the phase space opens for hard scale reusmmation

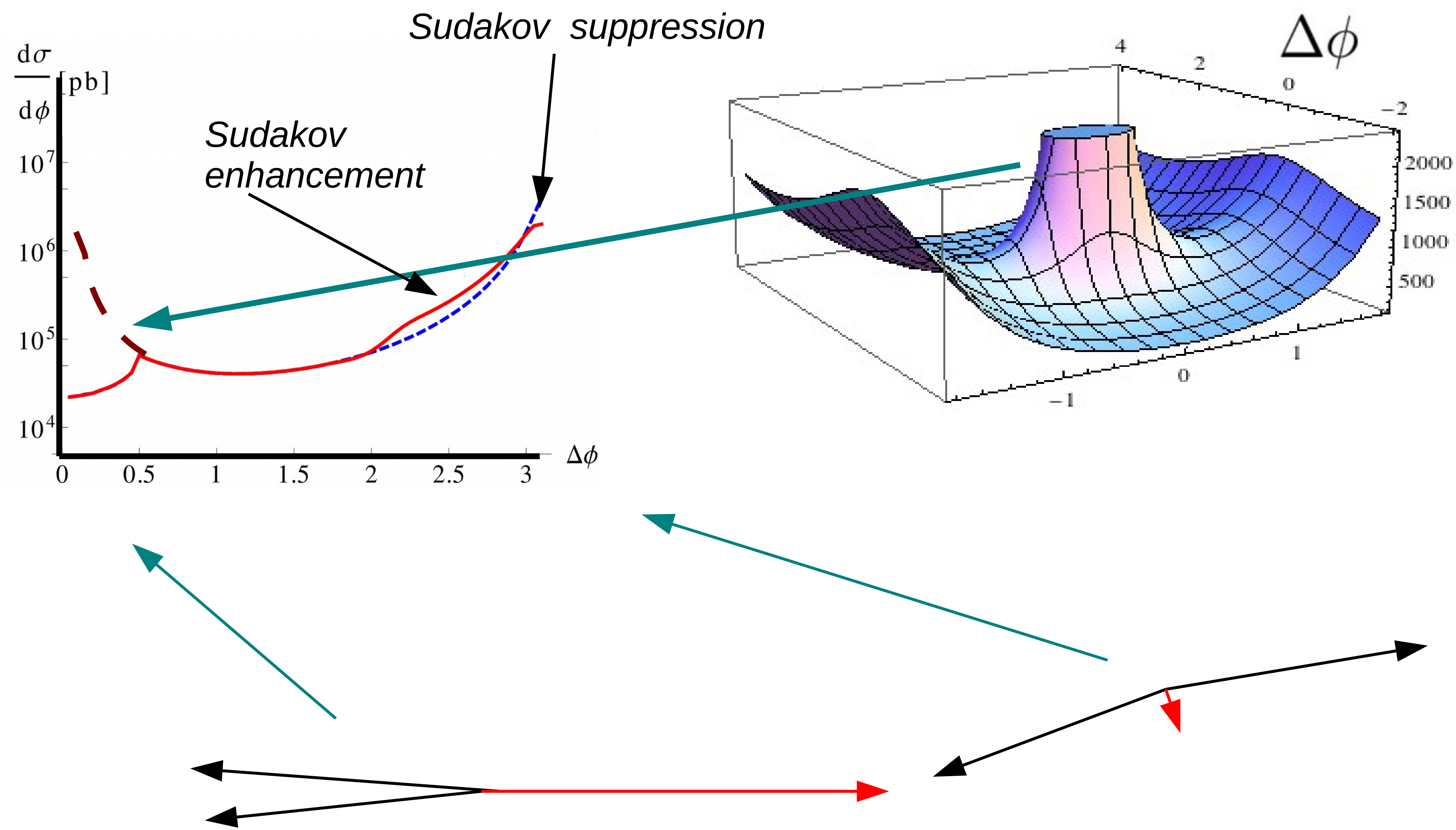
Survival probability of the gap without emissions

Mueller, Xiao, Yuan '12
Mueller, Xiao, Yan '13
Van Hameren, Kotko, Kutak, Sapeta '14
Xiao, Yuan, Zhou '17
Zhou' 16
Kutak '14

Other relevant effects – Sudakov form factor in ISR

Divergence regularized by jet algorithm

K.K '14



ITMD with Monte Carlo tools

KaTie (A. van Hameren)

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

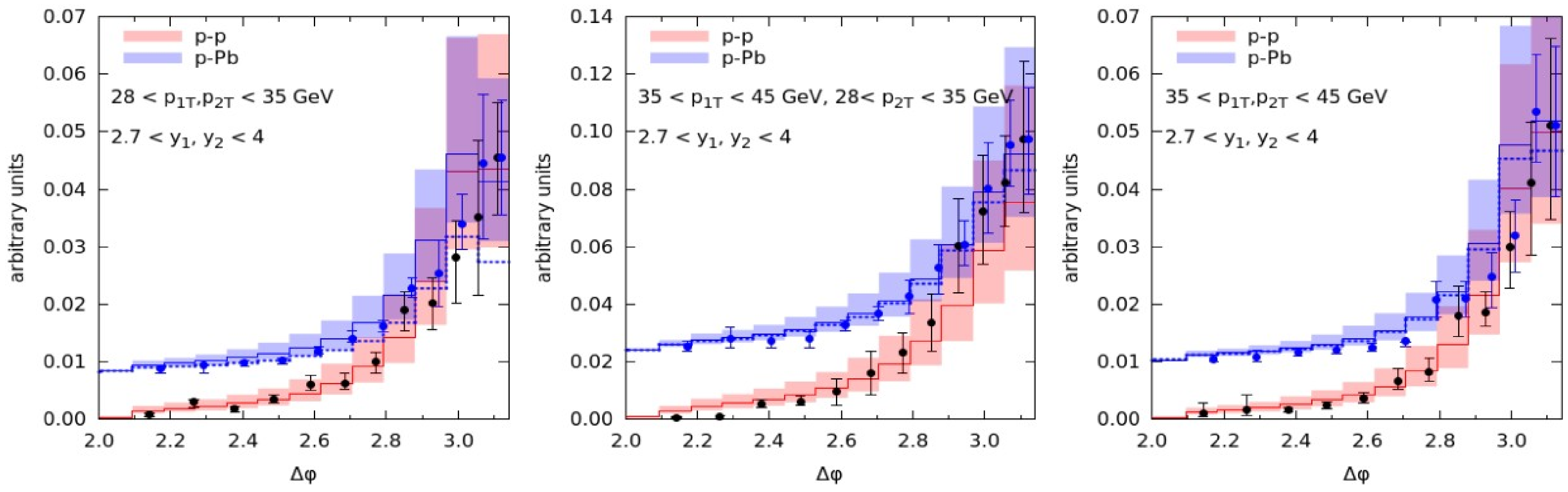
LxJet (P. Kotko)

Specialized Monte Carlo for di-jets and tri-jets for ITMD and HEF processes

Signature of saturation in forward-forward dijets

ATLAS 1901.10440

van Hameren, Kotko, Kutak, Sapeta '19

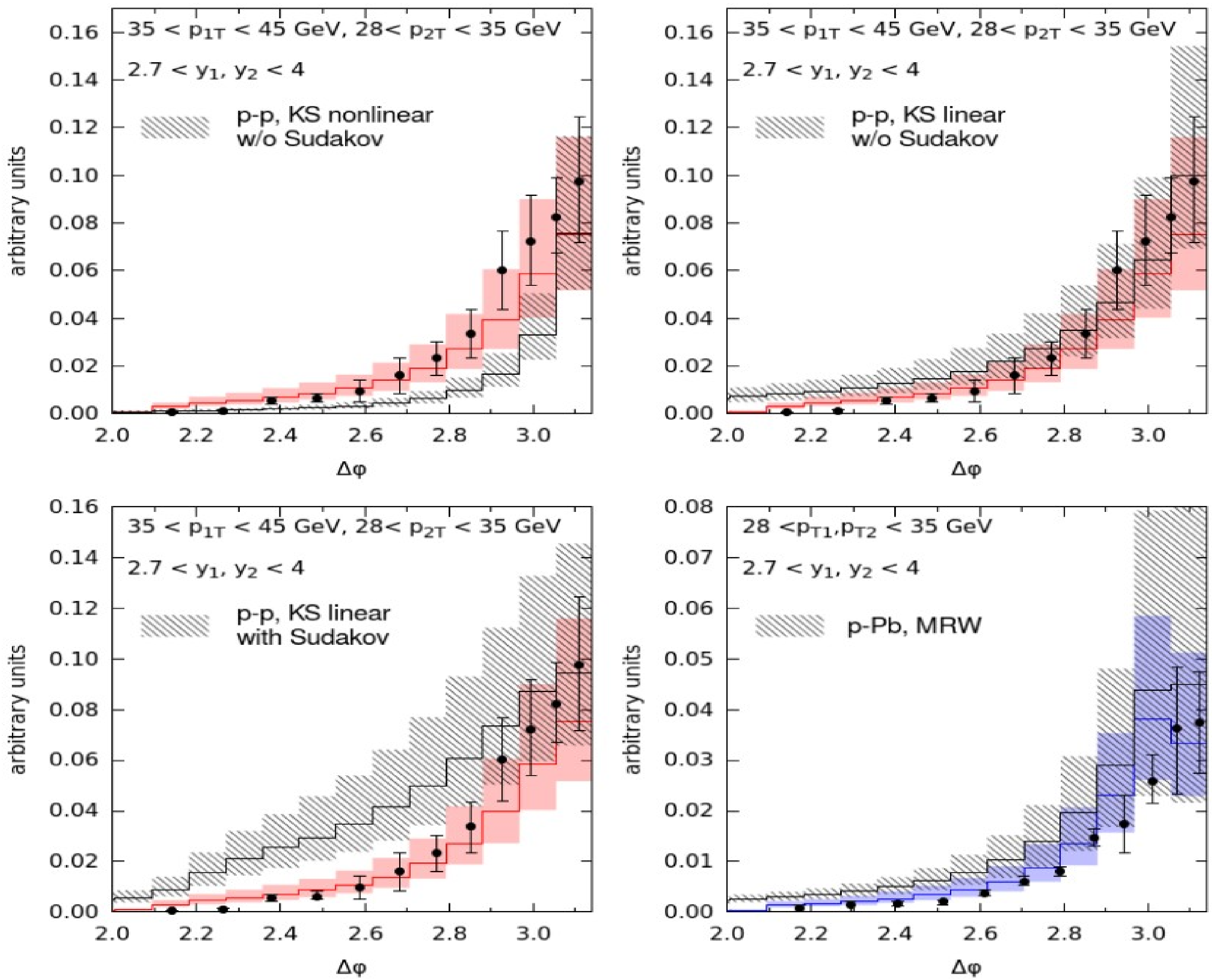


Data: number of dijets normalized to number of single inclusive jets. We can not calculate that. We can compare shapes.

Procedure: fit normalization to p-p data. Use that both for p-p and p-Pb. Shift p-Pb data

The procedure allows for visualization of broadening

Other possible scenarios



Summary

New evidence for saturation

Necessity to have both Sudakov resummation and nonlinearities

ITMD is not anymore a conjecture – proof from CGC

Set of basic TMD's – for any final state jets

KK, Bury, Kotko' 18

$$\mathcal{F}_{gg}^{(1)}(x,k_T) = 2\int \frac{d\xi^- d^2\xi_T}{(2\pi)^3 P^+} e^{ixP^+\xi^- - i\vec{k}_T\cdot\vec{\xi}_T} \left\langle \frac{\mathrm{Tr}\left[\mathcal{U}^{[\square]\dagger}\right]}{N_c} \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$$

$$\mathcal{F}_{gg}^{(2)}(x,k_T) = 2\int \frac{d\xi^- d^2\xi_T}{(2\pi)^3 P^+} e^{ixP^+\xi^- - i\vec{k}_T\cdot\vec{\xi}_T} \frac{1}{N_c}\left\langle \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[\square]\dagger}\right]\mathrm{Tr}\left[\hat{F}^{i+}(0)\,\mathcal{U}^{[\square]}\right]\right\rangle$$

$$\mathcal{F}_{gg}^{(3)}(x,k_T) = 2\int \frac{d\xi^- d^2\xi_T}{(2\pi)^3 P^+} e^{ixP^+\xi^- - i\vec{k}_T\cdot\vec{\xi}_T} \left\langle \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle ,$$

$$\mathcal{F}_{gg}^{(4)}(x,k_T) = 2\int \frac{d\xi^- d^2\xi_T}{(2\pi)^3 P^+} e^{ixP^+\xi^- - i\vec{k}_T\cdot\vec{\xi}_T} \left\langle \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[-]}\right]\right\rangle ,$$

$$\mathcal{F}_{gg}^{(5)}(x,k_T) = 2\int \frac{d\xi^- d^2\xi_T}{(2\pi)^3 P^+} e^{ixP^+\xi^- - i\vec{k}_T\cdot\vec{\xi}_T} \left\langle \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[\square]\dagger}\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[\square]}\mathcal{U}^{[+]}\right]\right\rangle ,$$

$$\mathcal{F}_{gg}^{(6)}(x,k_T) = 2\int \frac{d\xi^- d^2\xi_T}{(2\pi)^3 P^+} e^{ixP^+\xi^- - i\vec{k}_T\cdot\vec{\xi}_T} \left\langle \frac{\mathrm{Tr}\left[\mathcal{U}^{[\square]}\right]}{N_c}\frac{\mathrm{Tr}\left[\mathcal{U}^{[\square]\dagger}\right]}{N_c} \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle ,$$

$$\mathcal{F}_{gg}^{(7)}(x,k_T) = 2\int \frac{d\xi^- d^2\xi_T}{(2\pi)^3 P^+} e^{ixP^+\xi^- - i\vec{k}_T\cdot\vec{\xi}_T} \left\langle \frac{\mathrm{Tr}\left[\mathcal{U}^{[\square]}\right]}{N_c} \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[\square]\dagger}\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle .$$

ITMD for 3 jets – basic TMDS

KK, Bury, Kotko' 18

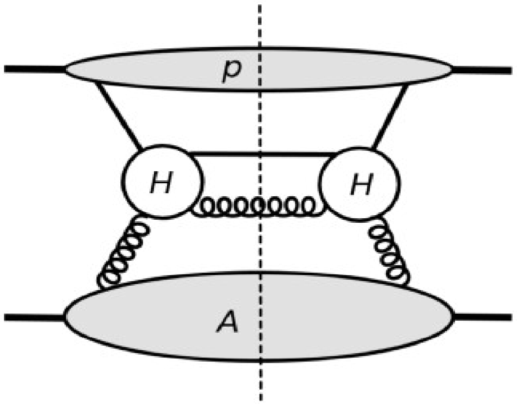
$$\mathbf{\Phi}_{gg\to ggg} = \begin{pmatrix} \Phi_1 & \Phi_2 & \Phi_2 & \Phi_3 & \Phi_3 & \Phi_4^* \\ \Phi_2 & \Phi_1 & \Phi_3 & \Phi_4^* & \Phi_2 & \Phi_3 \\ \Phi_2 & \Phi_3 & \Phi_1 & \Phi_2 & \Phi_4^* & \Phi_3 \\ \Phi_3 & \Phi_4^* & \Phi_2 & \Phi_1 & \Phi_3 & \Phi_2 \\ \Phi_3 & \Phi_2 & \Phi_4^* & \Phi_3 & \Phi_1 & \Phi_2 \\ \Phi_4^* & \Phi_3 & \Phi_3 & \Phi_2 & \Phi_2 & \Phi_1 \end{pmatrix}$$

$$\Phi_1 = \frac{1}{4N_c^2}\left((N_c^2+2)\mathcal{F}_{\rm gg}^{(1)} - 4\mathcal{F}_{\rm gg}^{(2)} - 4\mathcal{F}_{\rm gg}^{(3)} + 3N_c^2\mathcal{F}_{\rm gg}^{(6)} + 2\mathcal{F}_{\rm gg}^{(7)}\right),$$

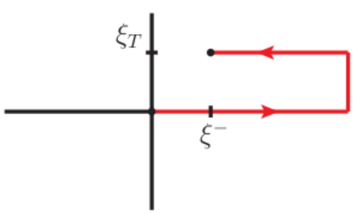
$$\Phi_2 = -\frac{1}{2N_c^2}\left(-2\mathcal{F}_{\rm gg}^{(1)} + 4\mathcal{F}_{\rm gg}^{(2)} + 2\mathcal{F}_{\rm gg}^{(3)} + \mathcal{F}_{\rm gg}^{(4)} + \mathcal{F}_{\rm gg}^{(5)} - 2N_c^2\mathcal{F}_{\rm gg}^{(6)} - 2\mathcal{F}_{\rm gg}^{(7)}\right)$$

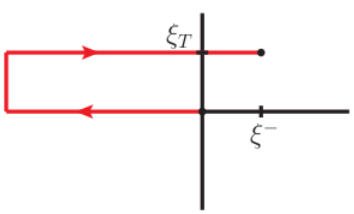
$$\vdots$$

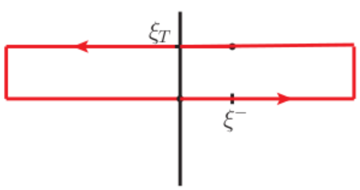
Backup - Definition of TMD



$$\mathcal{F}\left(x,k_T\right)=2\int\frac{d\xi^- d^2\xi_T}{\left(2\pi\right)^3 P^+}\,e^{ixP^+\xi^- - i\vec{k}_T\cdot\vec{\xi}_T}\,\left\langle P\right|\mathrm{Tr}\left\{\hat{F}^{i+}\left(0\right)\mathcal{U}_{C_1}\hat{F}^{i+}\left(\xi\right)\mathcal{U}_{C_2}\right\}\left|P\right\rangle$$







$\mathcal{U}^{[+]}$ $\mathcal{U}^{[-]}$ $\mathcal{U}^{[\square]}=\mathcal{U}^{[-]\dagger}\mathcal{U}^{[+]}$