Probing gluon number density with electron-dijet correlations at EIC

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EIC PL

NCN

HORIZON 2020

The results are based on

Eur.Phys.J.C 81 (2021) 8, 741

A. van Hameren, P. Kotko, K. Kutak, S. Sapeta, E. Żarow

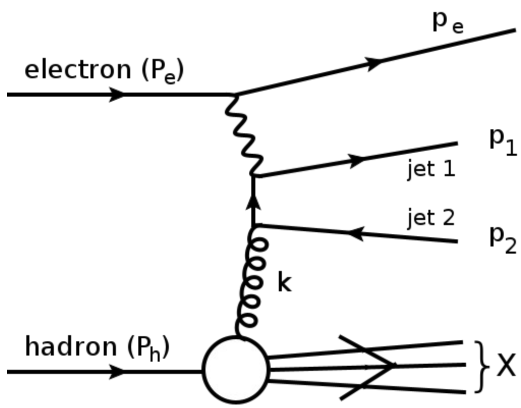
Eur.Phys.J.C 83 (2023) 10, 947

A. van Hameren, H. Kakkad. P. Kotko, K. Kutak, S. Sapeta

2502.15465

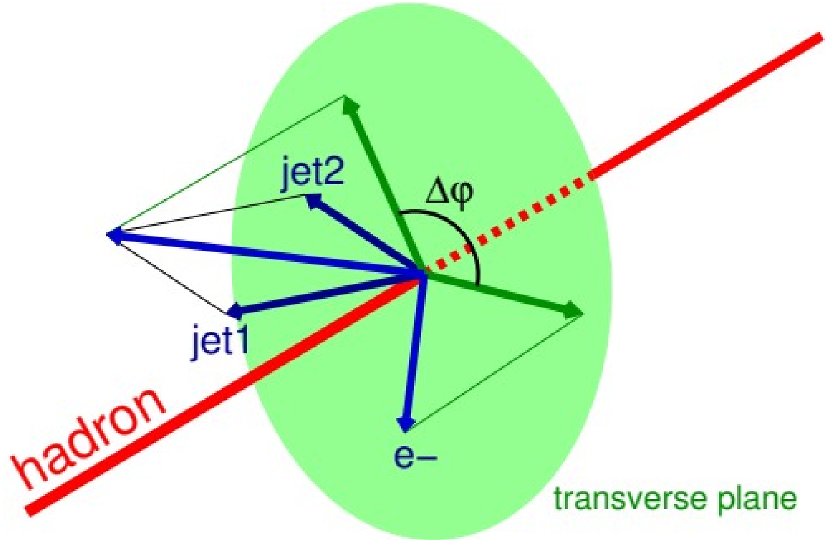
K. Kutak, W. Li, A. Stasto. R. Straka

The di-jet in DIS



$$k^\mu = xP_h^\mu + k_T^\mu$$

This process allows
to probe the Weizsacker-Williams TMD



Dijet/dihadron at EIC

Back-to-back regime using MV model + Sudakov
L. Zheng, E.C. Aschenauer, J.H. Lee, B-W. Xiao, 2014

Full CGC calculations (no Sudakov)
A. Dumitru, V. Skokov, 2018

H. Mantysaari, N. Mueller, F. Salazar, B. Schenke, 2019
F. Salazar, B. Schenke, 2020

R. Boussarie, H. Mäntysaari, F. Salazar, B. Schenke
JHEP 09 (2021) 178

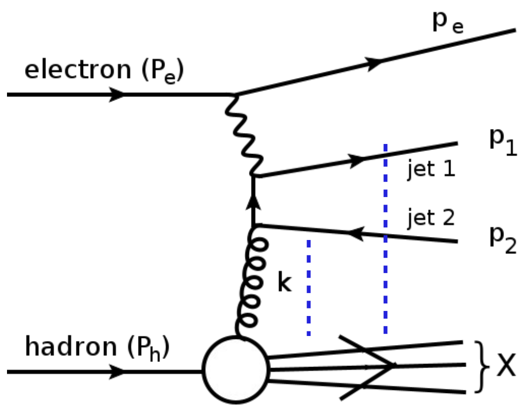
Marquet, Taels, Altinoluk, JHEP 06 (2021) 085

P. Caucal, F. Salazar, B. Schenke, T. Stebel, R. Venugopalan ‘23

P Caucal, F. Salazar, B Schenke, T. Stebel, R. Venugopalan ‘23 PRL

V. Cheung. Z. Kang, F. Salazar. R. Vogt 2409.04080,…..

The di-jet in DIS and ITMD



$$k^\mu = xP_h^\mu + k_T^\mu$$

The same gauge link structure and as in TMD 's
F. Dominguez, B. Xiao, F. Yuan
Phys.Rev.Lett. 106 (2011) 022301

F. Dominguez, C. Marquet, B. Xiao, F. Yuan
Phys.Rev. D83 (2011) 105005

ITMD = small x Improved Transverse Momentum Dependent factorization

- counts for saturation
- correct gauge structure i.e. uses gauge links to define TMD's
- takes into account kinematical effects – the whole phase space is available at LO
- is implemented in MC event generator KaTie by van Hameren , LxJet by Kotko
- valid in region $p_T > Q_s$, k_T can by any. p_T is hard final state momentum, k_T is inbalance

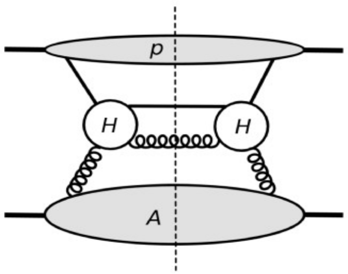
P. Kotko K. Kutak , C. Marquet , E. Petreska , S. Sapeta, A. van Hameren,
JHEP 1509 (2015) 106
A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska
JHEP 12 (2016) 034

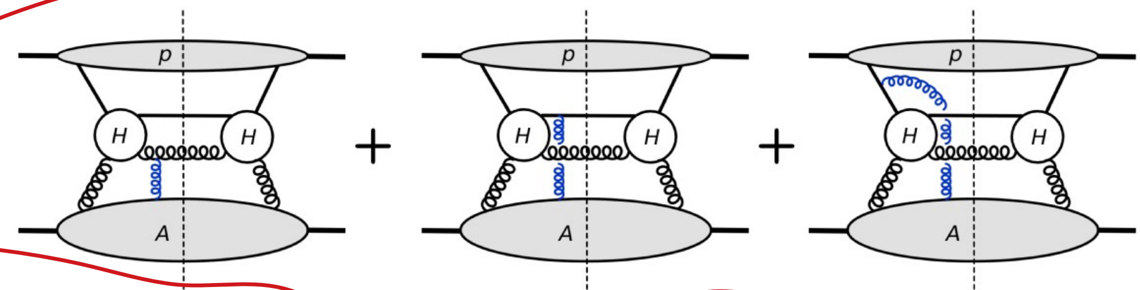
Derivation within CGC
T. Altinoluk, R. Boussarie, P. Kotko JHEP 1905 (2019) 156
T. Altinoluk, R. Boussarie, JHEP10(2019)208

Role of transverse gauge links
Boussarie, Mehtar- Tani Phys. Rev. D 103, 094012 (2021)

Formula for TMD gluons and gauge links

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





Valid for large transversal momentum
and was obtained in a specific gauge

From *S. Sapeta*

similar diagrams with 2,3,….gluon exchanges.
All this need to be resummed

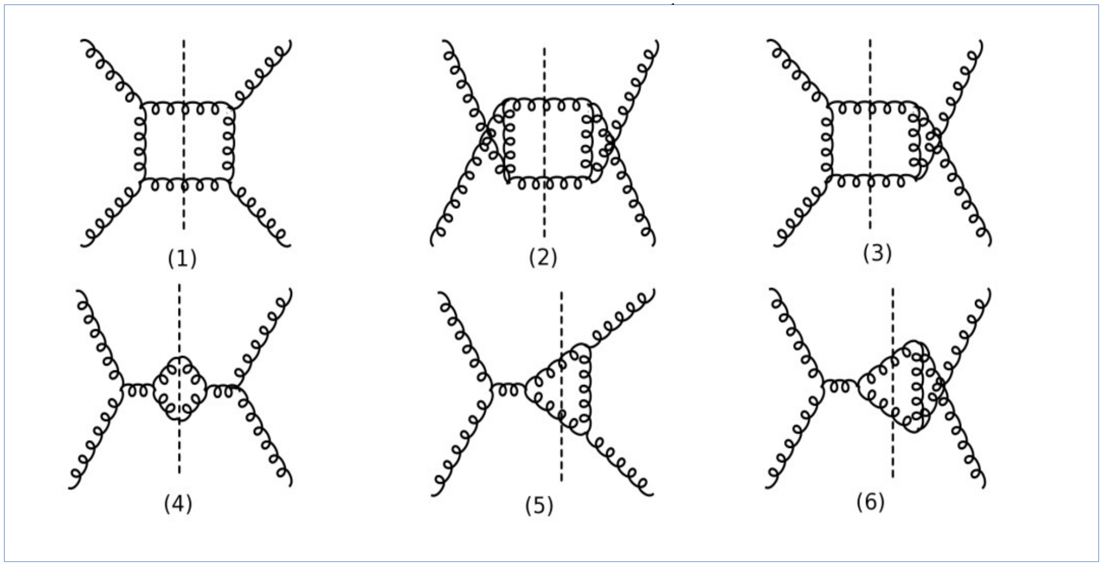
C.J. Bomhof, P.J. Mulders, F. Pijlman
Eur.Phys.J. C47 (2006) 147-162

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

Hard part defines the path of the gauge link

$$\mathcal{U}^{[C]}(\eta;\xi) = \mathcal{P}\exp\left[-ig\int_C \mathrm{d}z\cdot A(z)\right]$$

ITMD - hard factors



from

F. Dominguez, C. Marquet, Bo-Wen Xiao, F. Yuan
Phys.Rev. D83 (2011) 105005

The same gauge link and as in TMD 's

Fabio Dominguez, Bo-Wen Xiao, Feng Yuan
Phys.Rev.Lett. 106 (2011) 022301

F. Dominguez, C. Marquet, Bo-Wen Xiao, F. Yuan
Phys.Rev. D83 (2011) 105005

gauge invariant amplitudes with k_t and TMD*s*

example for g* g → g g

$$\frac{d\sigma^{pA\to ggX}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\; x_1 f_{g/p}(x_1,\mu^2)\sum_{i=1}^{6}\mathcal{F}_{gg}^{(i)} H_{gg\to gg}^{(i)}$$

Set of basic TMD's for 2, 3 and 4 jets (unpolarized)

Bury, Kotko, Kutak '18

$$\mathcal{F}_{qg}^{(1)}(x,k_T) = \text{F.T.} \left\langle \text{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$$

$$\mathcal{F}_{qg}^{(2)}(x,k_T) = \text{F.T.} \left\langle \frac{\text{Tr}\left[\mathcal{U}^{[\Box]}\right]}{N_c}\text{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$$

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$$\mathcal{F}_{gg}^{(2)}(x,k_T) = \text{F.T.}\,\frac{1}{N_c} \left\langle \text{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[\Box]\dagger}\right]\text{Tr}\left[\hat{F}^{i+}(0)\,\mathcal{U}^{[\Box]}\right]\right\rangle$$

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$$\mathcal{F}_{gg}^{(4)}(x,k_T) = \text{F.T.} \left\langle \text{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[-]}\right]\right\rangle$$

$$\mathcal{F}_{gg}^{(5)}(x,k_T) = \text{F.T.} \left\langle \text{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[\Box]\dagger}\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[\Box]}\mathcal{U}^{[+]}\right]\right\rangle$$

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Set of basic TMD's for 2, 3 and 4 jets

Bury, Kotko, Kutak '18

$$\mathcal{F}_{qg}^{(1)}(x,k_T)=\text{F.T.}\left\langle \text{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$$

dipole gluon

$$\mathcal{F}_{qg}^{(2)}(x,k_T)=\text{F.T.}\left\langle \frac{\text{Tr}\left[\mathcal{U}^{[\square]}\right]}{N_c}\text{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$$

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WW gluon

same direction pointing Wilson lines

$$\mathcal{F}_{gg}^{(4)}(x,k_T)=\text{F.T.}\left\langle \text{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[-]}\right]\right\rangle$$

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$$\mathcal{F}_{gg}^{(6)}(x,k_T)=\text{F.T.}\left\langle \frac{\text{Tr}\left[\mathcal{U}^{[\square]}\right]}{N_c}\frac{\text{Tr}\left[\mathcal{U}^{[\square]\dagger}\right]}{N_c}\text{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$$

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Set of basic TMD’s for 2, 3 and 4 jets

$$\mathcal{F}_{qg}^{(1)}(x,k_T) = \text{F.T.}\left\langle \text{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$$

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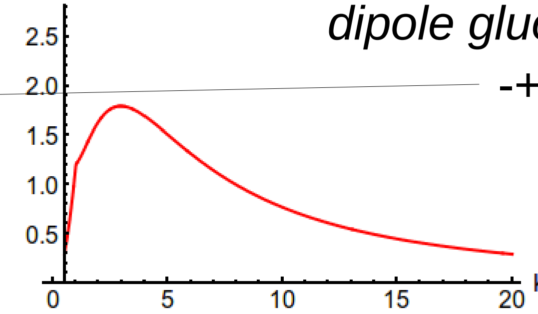
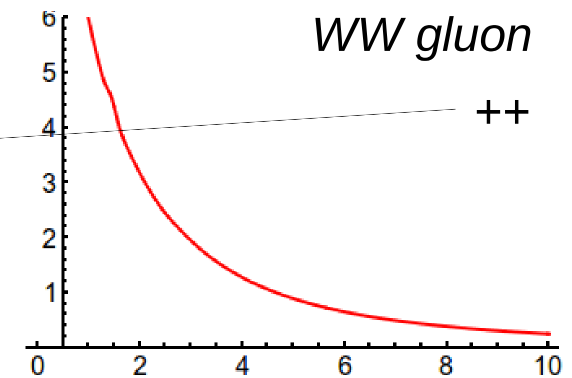
dipole gluon

-+



WW gluon

++



Set of basic TMD's for 2, 3 and 4 jets

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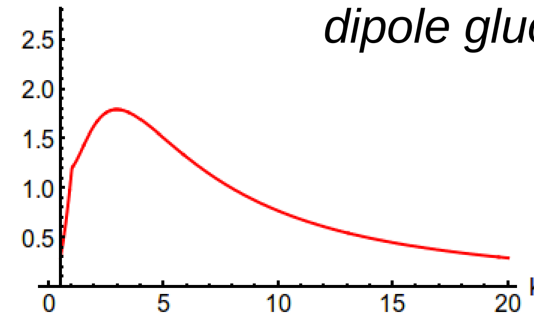
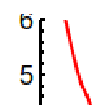
dipole gluon



WW gluon



	DIS and DY	SIDIS	hadron in pA	photon-jet in pA	Dijet in DIS	Dijet in pA
$G^{(1)}$ (WW)	$\times$	$\times$	$\times$	$\times$	$\surd$	$\surd$
$G^{(2)}$ (dipole)	$\surd$	$\surd$	$\surd$	$\surd$	$\times$	$\surd$

$$\mathcal{F}_{gg}^{(6)}(x,k_T) = \text{F.T.}\left\langle \frac{\text{Tr}\left[\mathcal{U}^{[\Box]}\right]}{N_c}\frac{\text{Tr}\left[\mathcal{U}^{[\Box]\dagger}\right]}{N_c}\text{Tr}\left[\hat F^{i+}(\xi)\,\mathcal{U}^{[+]\dagger}\hat F^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$$

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F. Dominguez, C. Marquet, B. Xiao, F. Yuan
Phys.Rev. D83 (2011) 105005

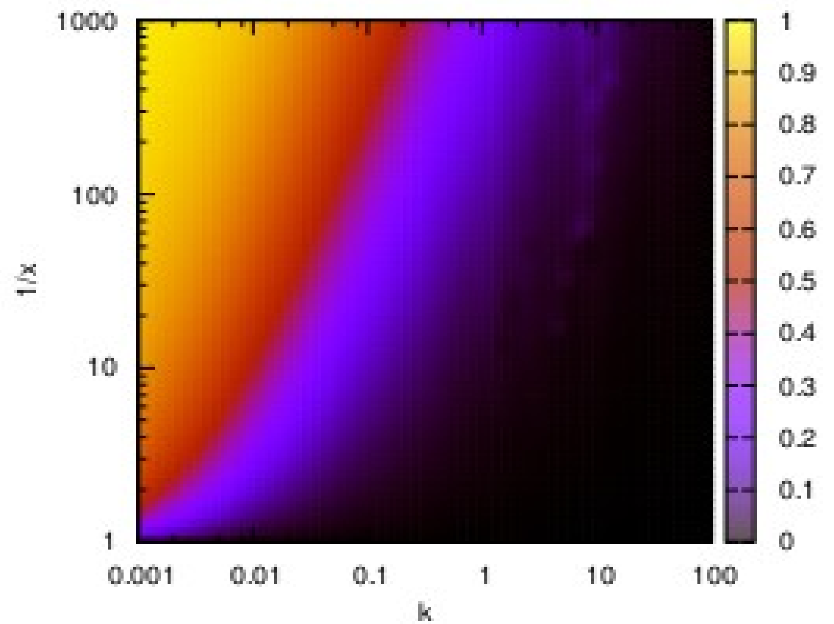
Gluons at high energies

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

L.V. Gribov, E.M. Levin, M.G. Ryskin
Phys.Rept. 100 (1983) 1-150

Larry D. McLerran, Raju Venugopalan
Phys.Rev. D49 (1994) 3352-3355

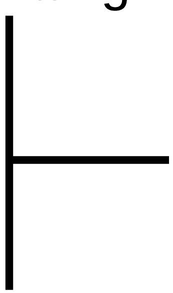
Phenomenological model:
Golec-Biernat, Wusthoff '99



On microscopic level it means that
gluon apart splitting recombine

splitting

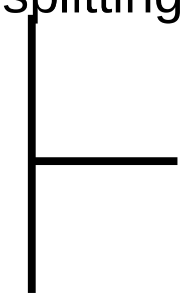
Linear evolution
Equation
BFKL



Nonlinear evolution equations
BK, JIMWLK
Balitcky-Kovchegov,

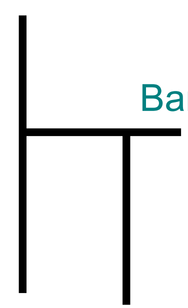
Jailian-Marian,Iancu
McLerran,Weigert,Leonidov,Kovner

splitting



-

recombination



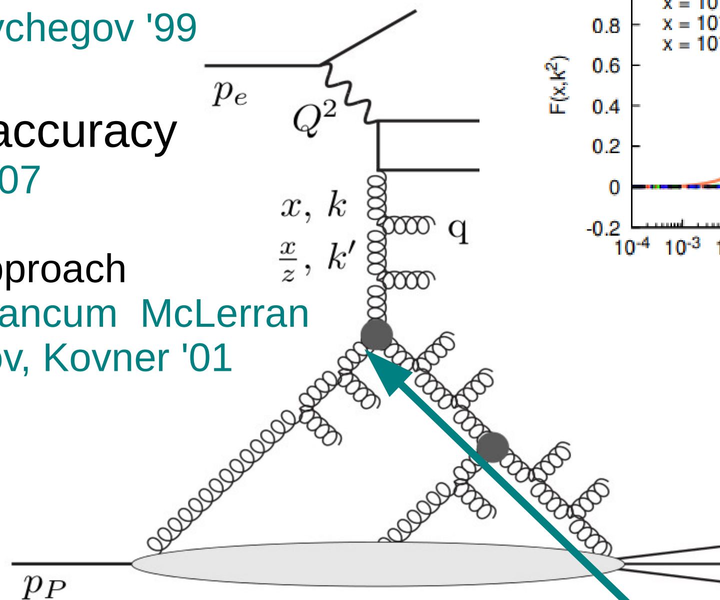
Bartels, Wusthoff'93

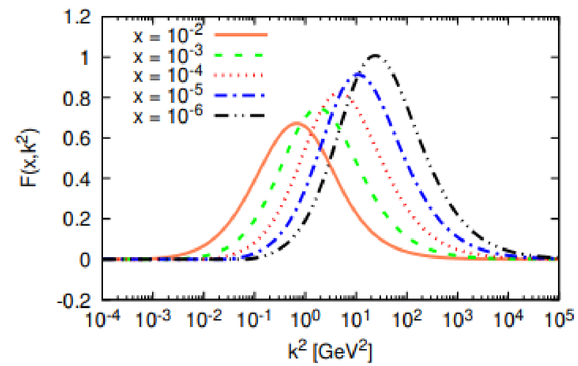
The saturation problem: supressing gluons at small kt

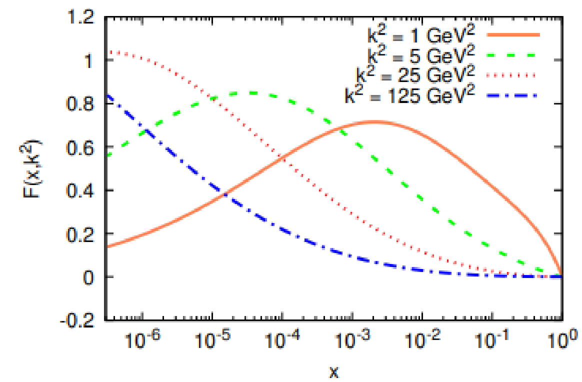
Originally formulated in coordinate space
Balitsky '96, Kovchegov '99

Now at NLO accuracy
Balitsky, Chirilli '07

More general approach
Jalian-MarianI, Iancum McLerran Weigert Leonidov, Kovner '01







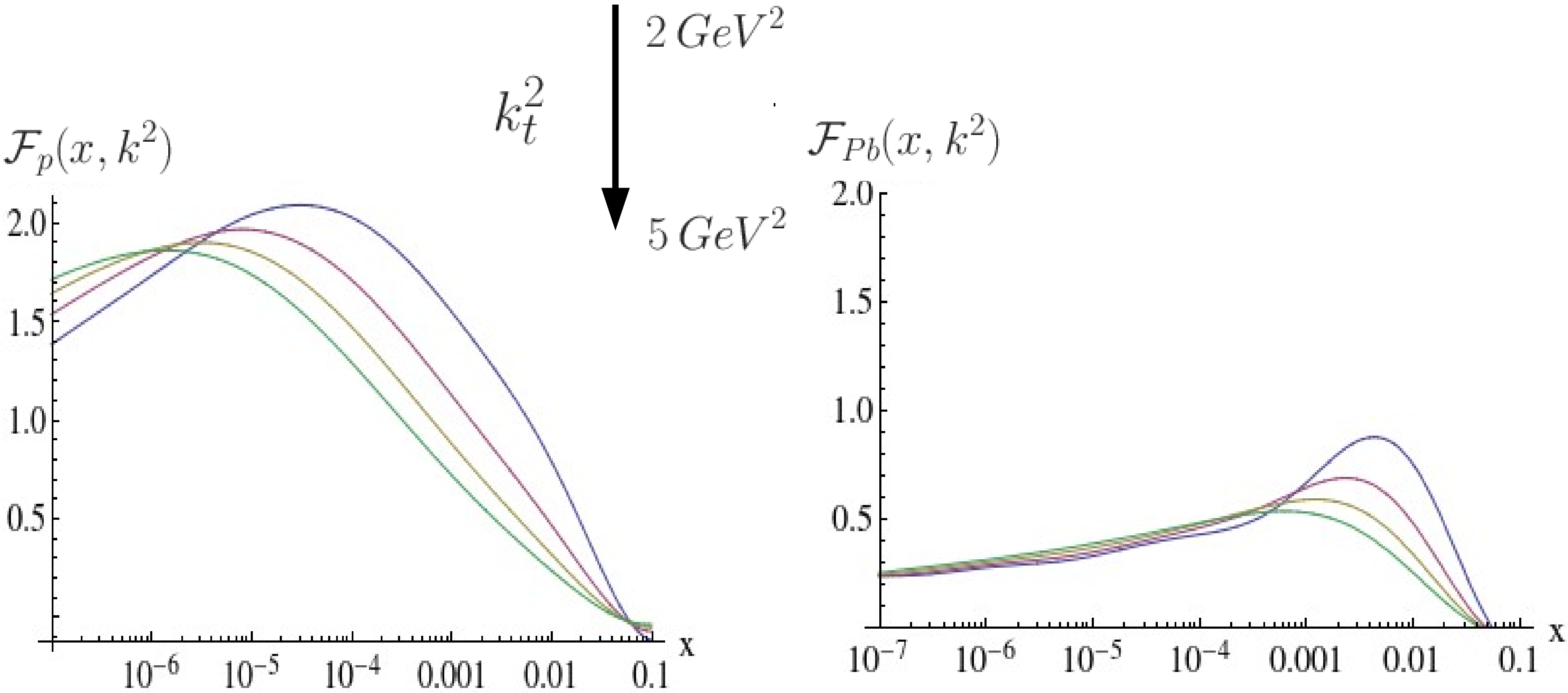
Solution of Balitsky Kovchegov equation

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

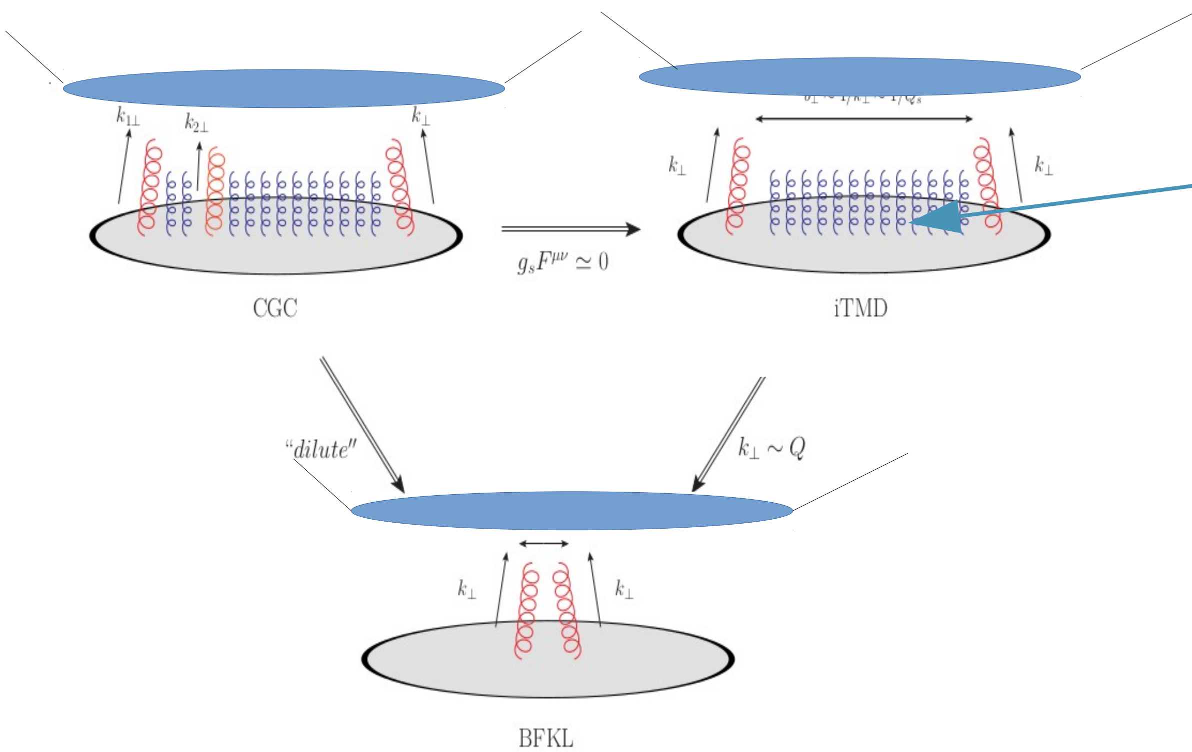
Glue from BK in p vs. glue in Pb – dipole gluon



Maximum signalize emergence of saturation scale

ITMD from Color Glass Condensate

T. Altinoluk, R. Boussarie, P. Kotko JHEP 1905 (2019) 156
T. Altinoluk, R. Boussarie, JHEP10(2019)208

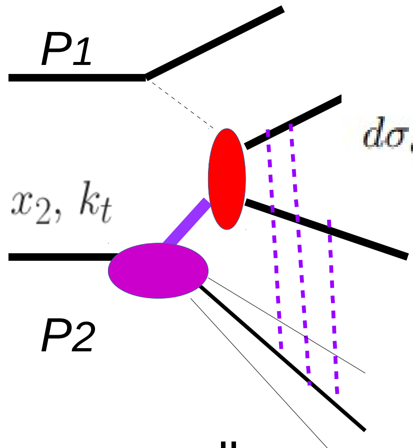


Multiple soft emissions

from R. Boussarie
Initial Stages 2019

Wandzura-Wilczek approximmation ITMD neglects higher genuine twist contributions i.e. hard gluon exchanges between the target and the amplitude, while it resums all kinematic twist

ITMD with Sudakov for dijets in DIS



P. Kotko, KK. S. Sapeta, A. van Hameren, E. Zarow, EPJC

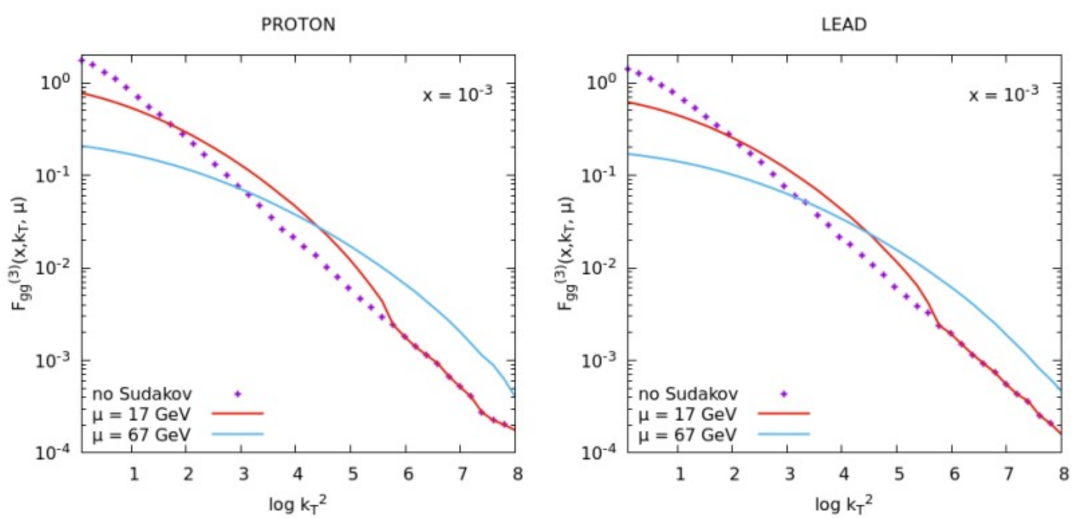
$$d\sigma_{eh\to e'+2j+X} = \int \frac{dx}{x}\frac{d^2k_T}{\pi}\, \mathcal{F}^{(3)}_{gg}(x, k_T, \mu)\, \frac{1}{4xP_e\cdot P_h}\, d\Phi(P_e, k; p_e, p_1, p_2)\, |\overline{M}_{eg^*\to e'+2j}|$$

This process allows
to probe the Weizsacker-Williams TMD

$$S^{g\to q\bar{q}}_{\mathrm{Sud}}(\mu, b_T) = \frac{\alpha_s N_c}{4\pi} \ln^2 \frac{\mu^2 b_T^2}{4e^{-2\gamma_E}}$$

A. Mueller, B-W. Xiao, F. Yuan, 2013

The Weizsacker-Williams TMD with Sudakov resummation
to account for soft emissions



We do not take into account
linearly polarised gluons

Monte Carlo tools for k_T dependent initial states

KaTie (A. van Hameren) Comput.Phys.Commun. 224 (2018) 371-380

- Monte Carlo program for tree-level calculations e-p, p-p, p-A, A-A
- any process within the Standard Model (High Energy Factorization)
- initial-state partons on-shell or off-shell dependent on factorization framework
- employs numerical Dyson-Schwinger recursion to calculate helicity amplitudes
- automatic phase space optimization
- It can be used together with CASCADE to account for initial and final state state showers for example using PB TMD

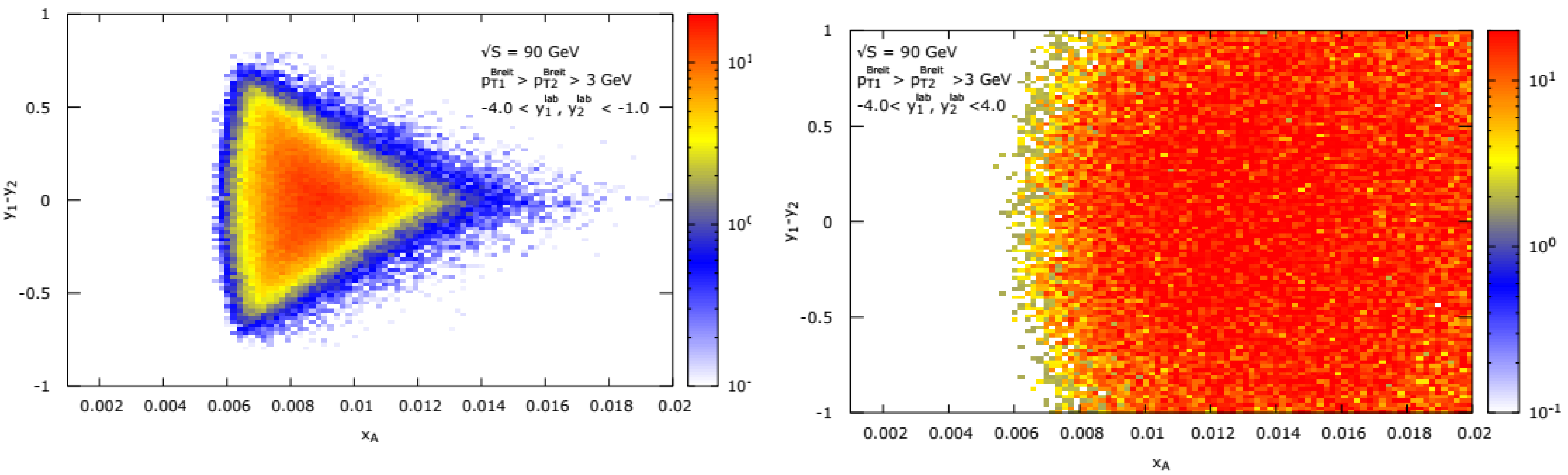
Ongoing work on developments at NLO accuracy

Low x region

P. Kotko, KK. S. Sapeta, A. van Hameren, E. Zarow, '20 EPJC

For clarity:

$k = P\,x_A + k_T \quad x_{Bj} = Q^2/(P.q)$



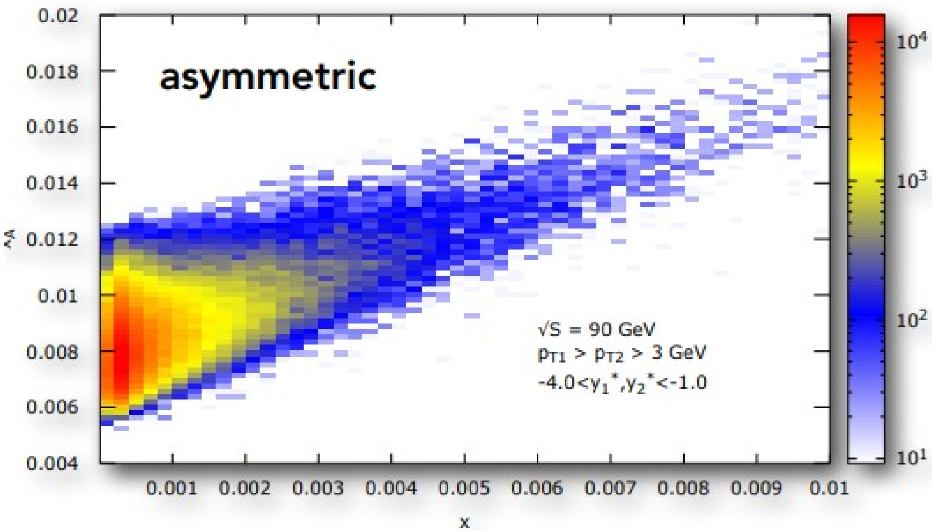
The asymmetric rapidity cuts guarantee good focusing of the cross section around smaller values of x required by the formalism.

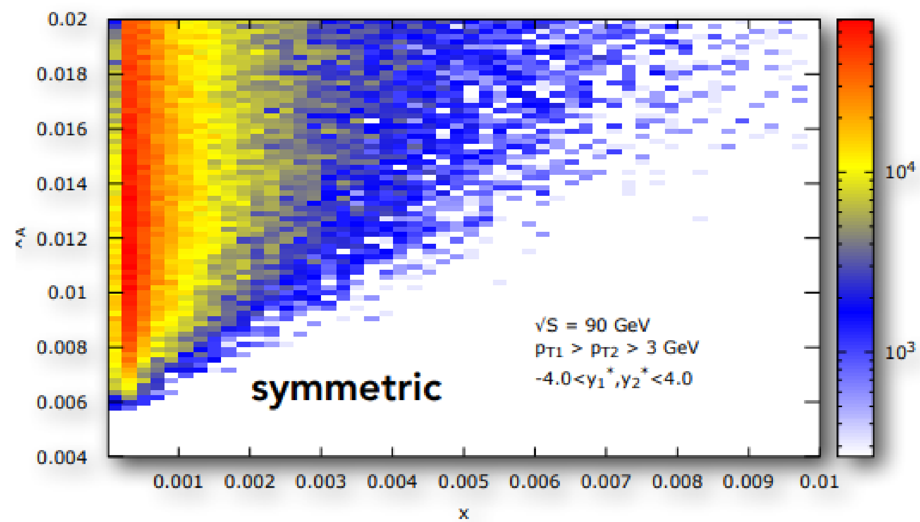
x_{Bj} vs. x_A

P. Kotko, KK. S. Sapeta, A. van Hameren, E. Zarow, ‘20 EPJC

For clarity:

$k = P\,x_A + k_T \quad x_{Bj} = Q^2/(P.q)$



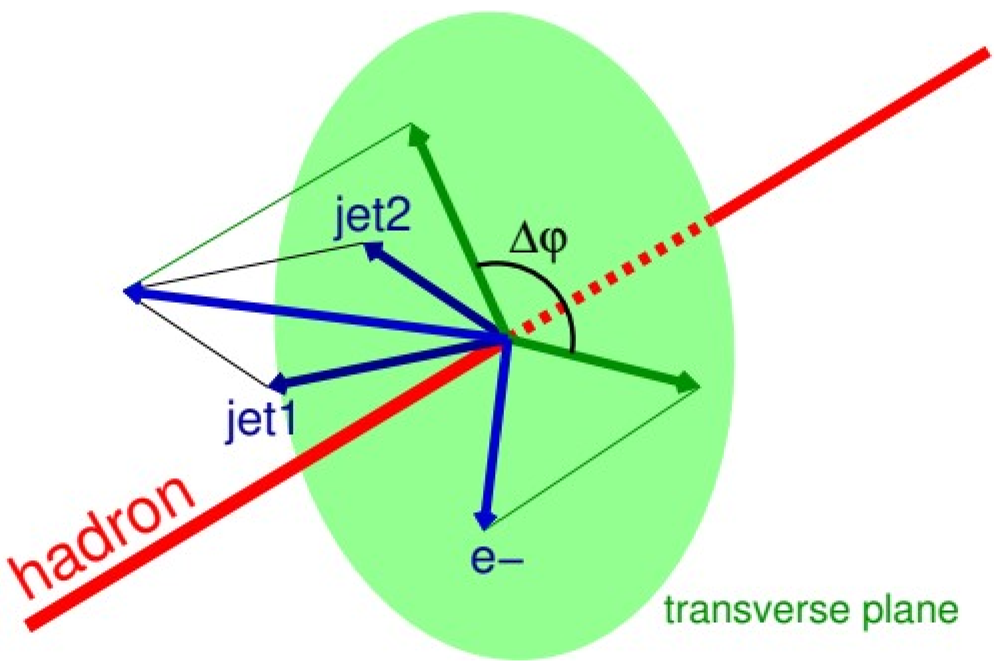


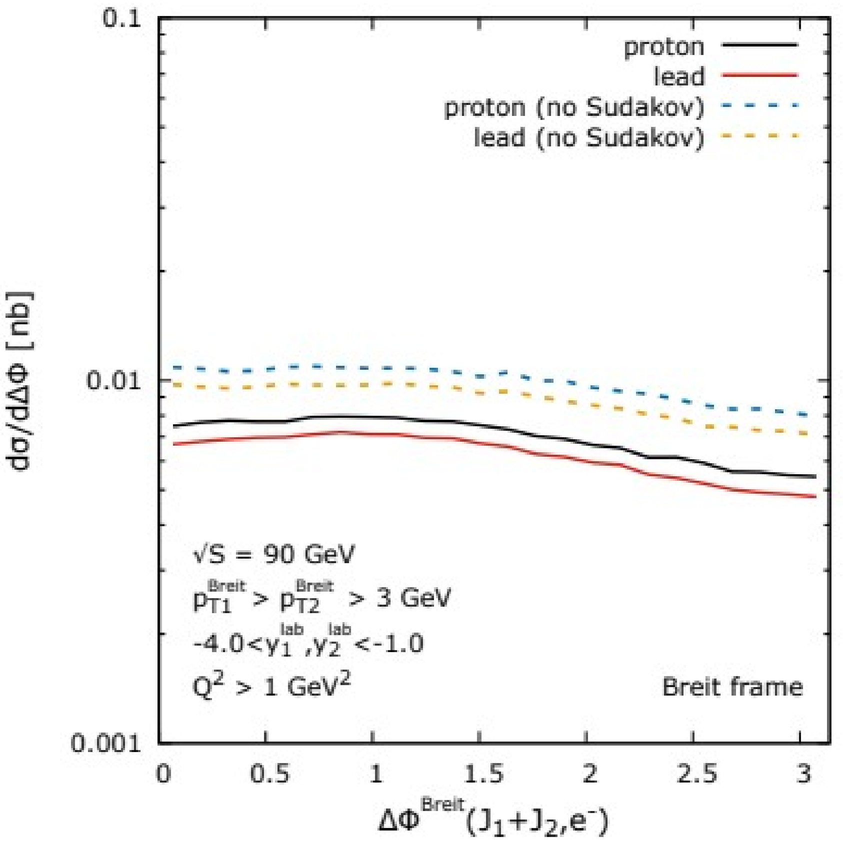
For asymmetric window $x_{Bj} \sim 10^{-4}$, $x_A \sim 5\ 10^{-3}$

From P. Kotko DIS 2021

Azimuthal correlations EIC kinematics

angle between di-jet and electron

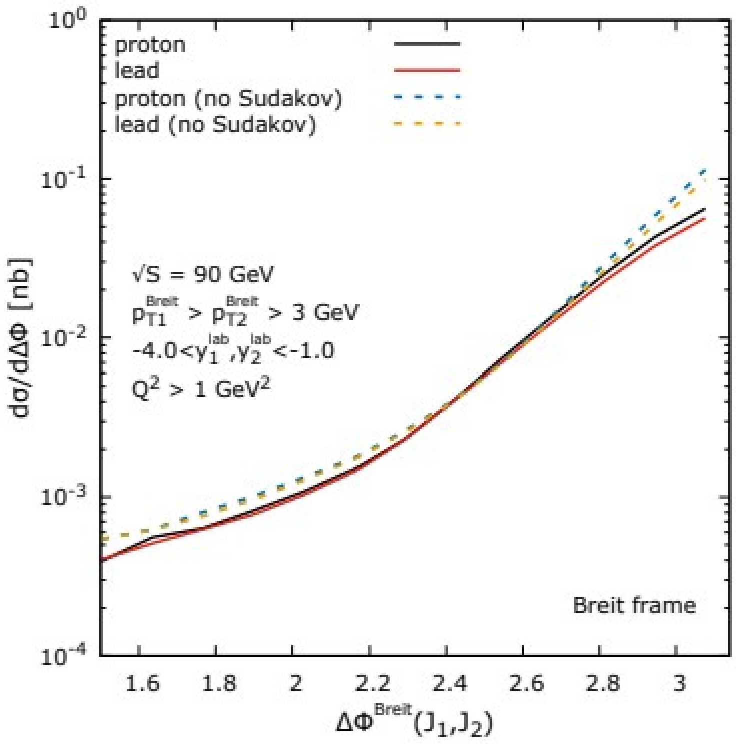




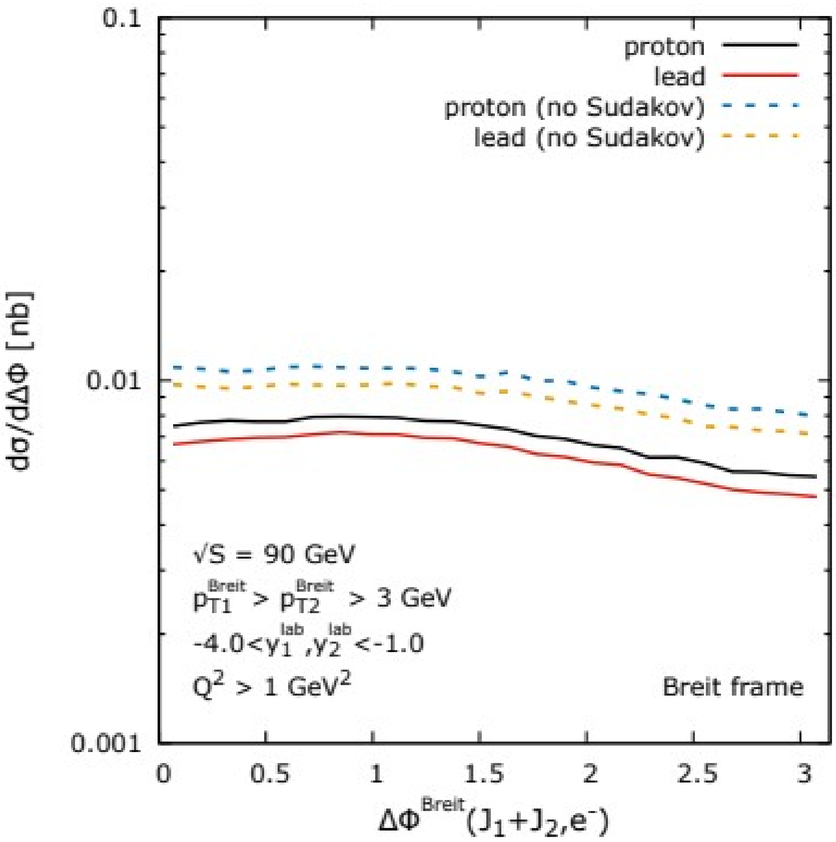
Large Sudakov effects.

Azimuthal correlations EIC kinematics

angle between dijets

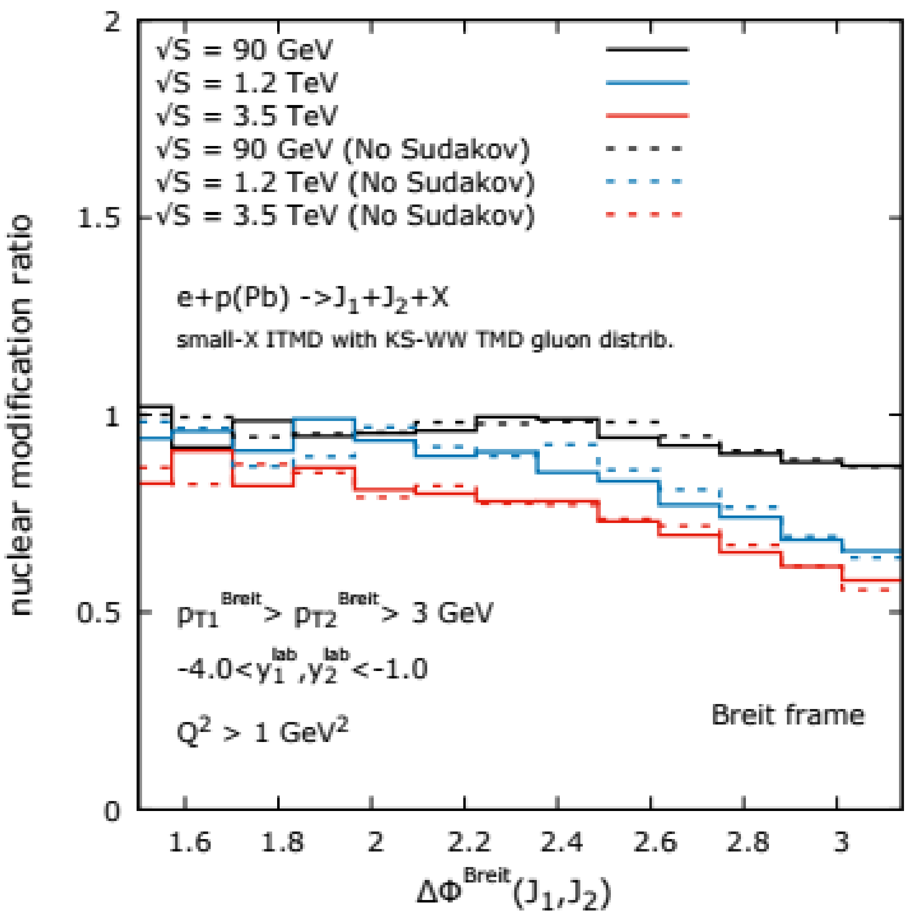


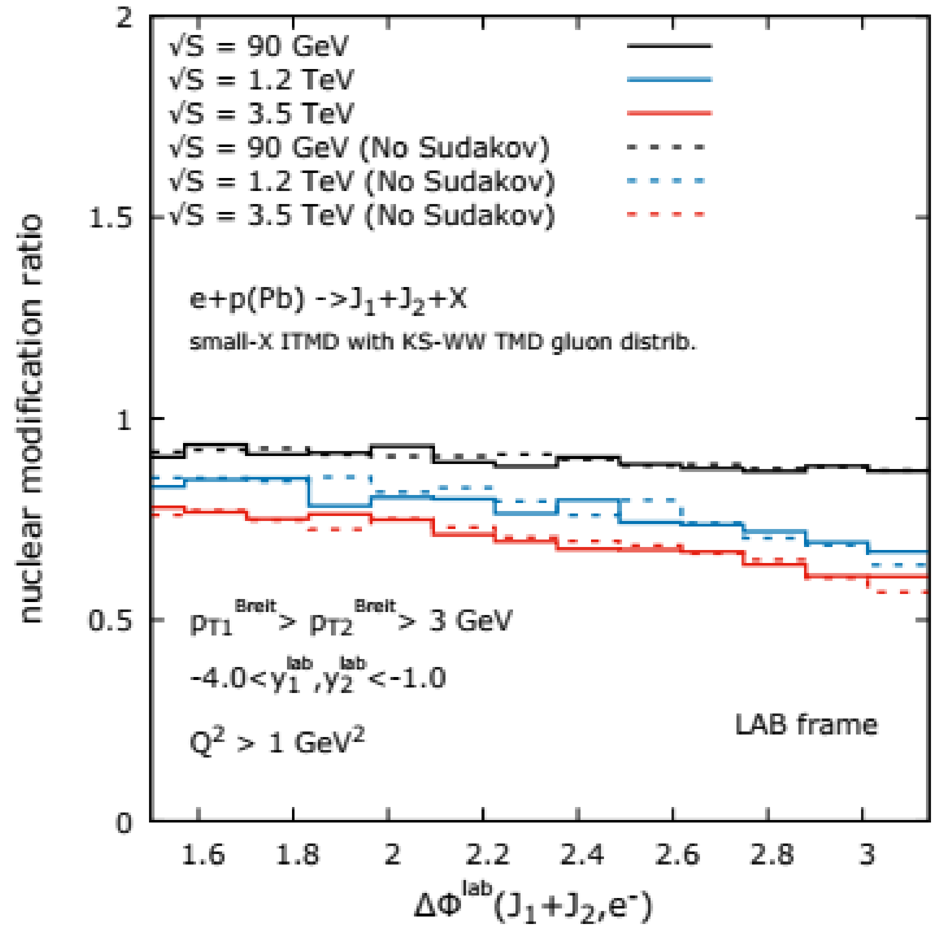
angle between di-jet and electron



Large Sudakov effects.

Energy dependence of nuclear modification factor





Evidently the larger energy the more visible saturation effects are.
Sudakov effects in RpA cancel to large extent.

F_2 structure function – kt factorization

$$F_2(x,Q^2) = S(Q^2,k^2,\beta)\otimes \mathcal{F}(x/z,k^2)\Theta\left(1-\frac{x}{z}\right)$$

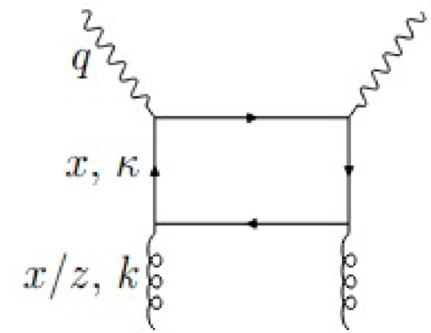
derived in the linear regime
Catani, Ciafaloni,Hautman '90

longitudinal momentum fraction of the photon carried by the quark

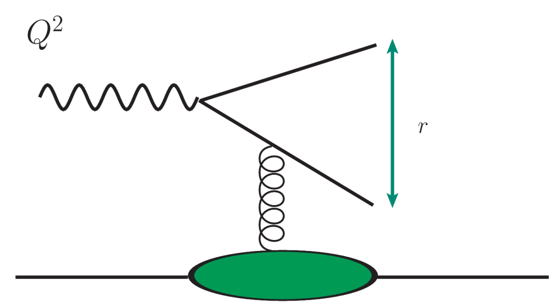
$$z = \left[1+\frac{\kappa'^2+m_q^2}{\beta(1-\beta)Q^2}+\frac{k^2}{Q^2}\right]^{-1}$$

shifted quark momentum

In the kt factorization



In the dipole formalism



$$F_2(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{em}}\int_0^1 dz\int d^2r(|\psi_L(z,r)|^2+|\psi_T(z,r)|^2)\sigma(x,r)$$

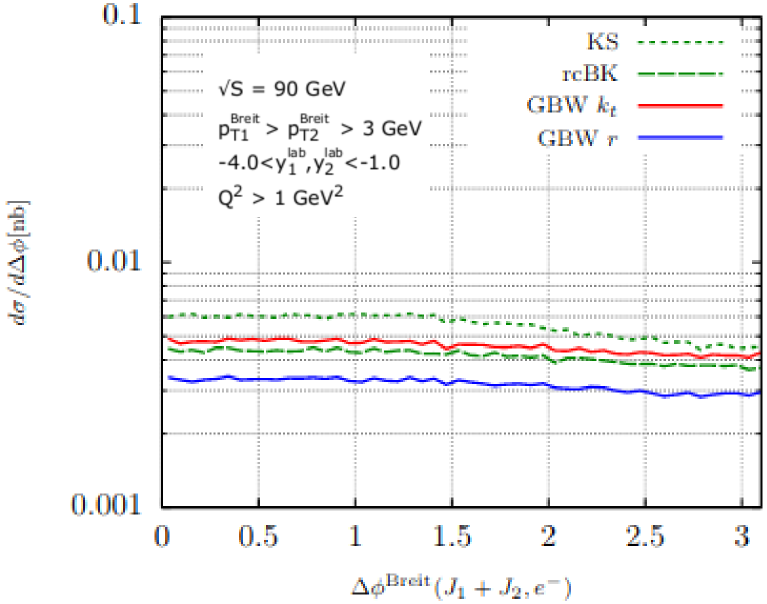
Already known
at NLO accuracy
Beuf

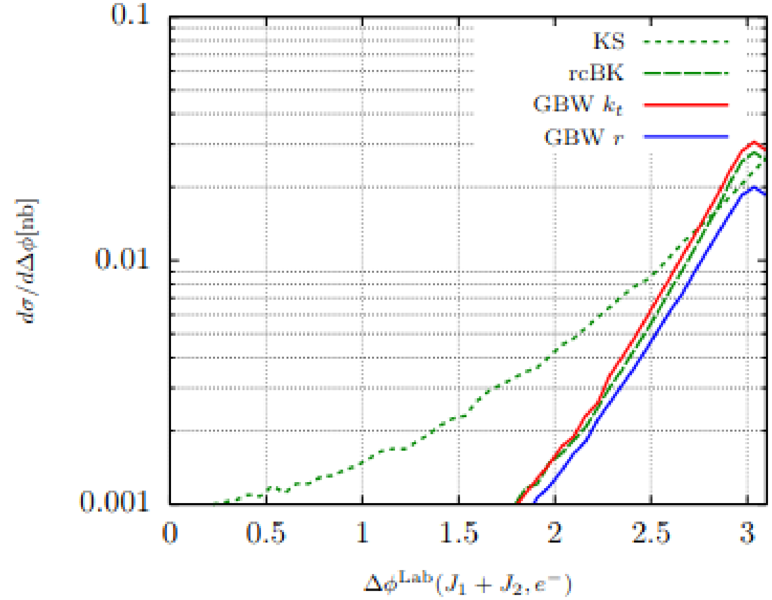
wave function

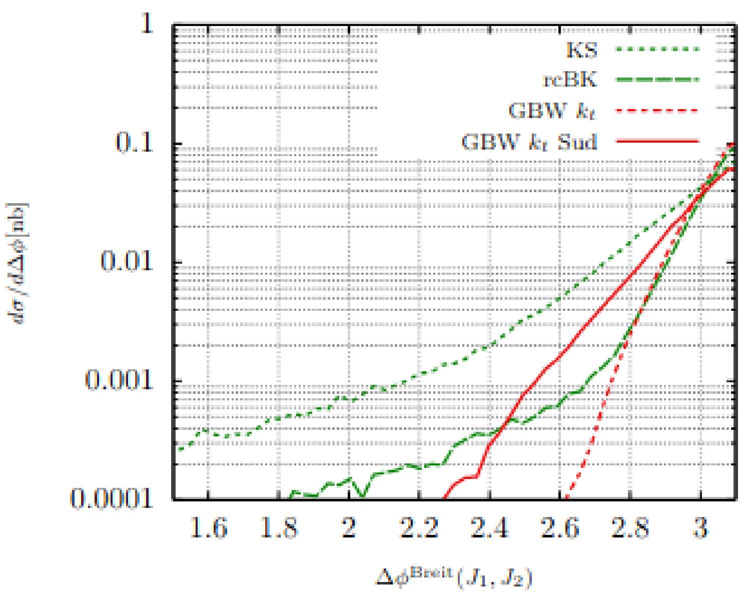
dipole cross section

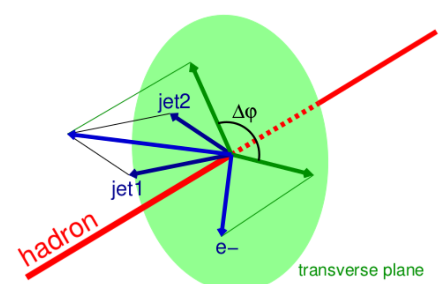
Dijets in DIS – detailed kinematics vs approximate kinematics

Goda, Kutak, Sapeta '23



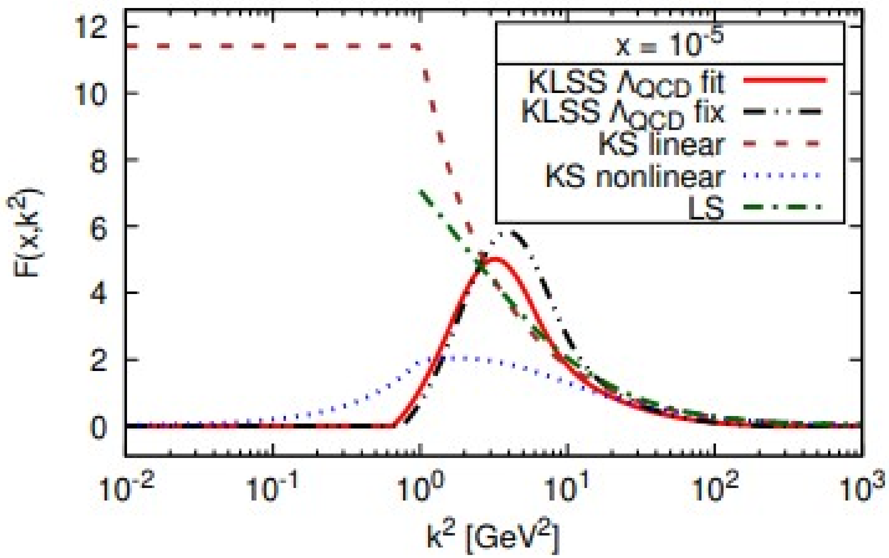


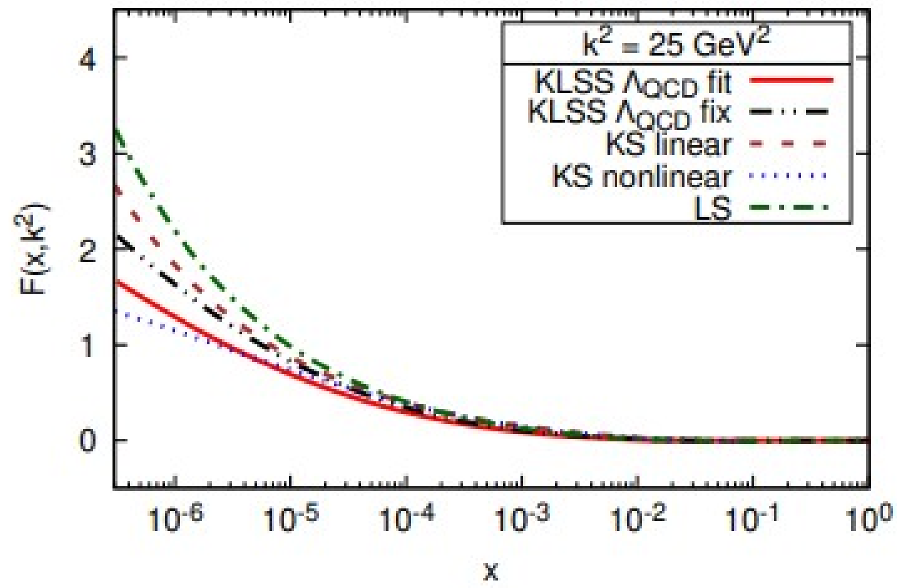




-	σ_0 [mb]	x_0 (10^{-4})	λ	χ^2/dof
r-GBW	1.907e+01	2.582e+00	3.219e-01	4.438e+00
r-GBW-massive	2.384e+01	1.117e+00	3.082e-01	5.274e+00
k_t-GBW	3.344e+01	1.333e+00	3.258e-01	4.396e+00
rc-k_t-GBW	1.520e+01	2.648e+00	3.211e-01	2.447e+00

New solution and fit of BK in the momentum space





Main feature features:

- Integration over k_t to get F_2 extends below k_t =1 GeV
- the kernel accounts for anticollinear configuration in the DGLAP