FORWARD JET PRODUCTION WITHIN SMALL-X ITMD FACTORIZATION

PIOTR KOTKO

AGH University, KRAKOW

BASED ON WORK IN COLLABORATION WITH:
T. ALTINOLUK, R. BOUSSARIE, E. BLANCO, M. BURY,
A. VAN HAMEREN, K. KUTAK, C. MARQUET, E. PETRESKA,
B. S. SAPETA, A. STASTO, M. STRIKMAN

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PLAN

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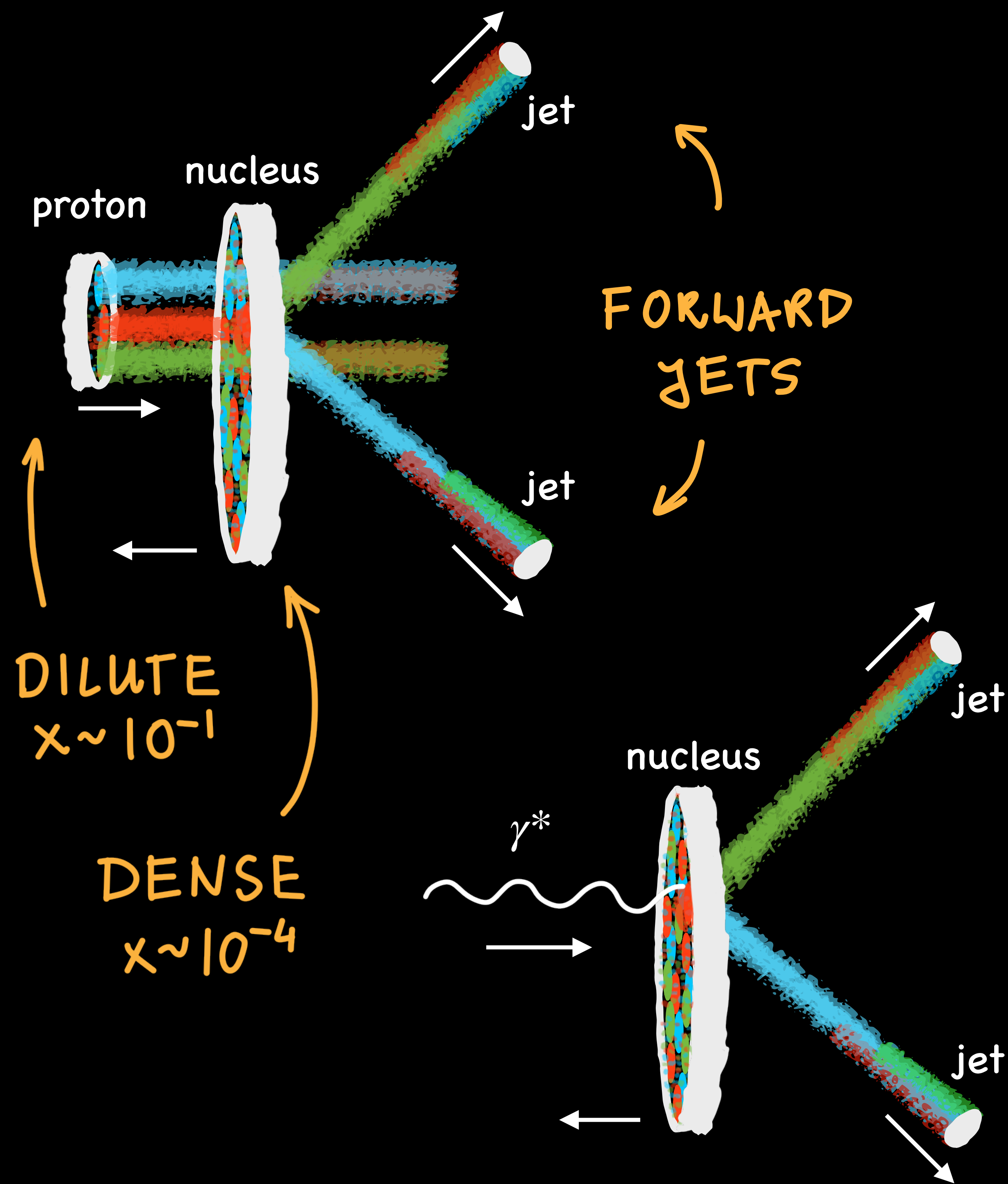
MOTIVATION



Study of high energy limit of QCD:

- **saturation of gluon density**

  Nonlinear evolution of TMD PDFs.

  Interplay of saturation and Sudakov resummation.

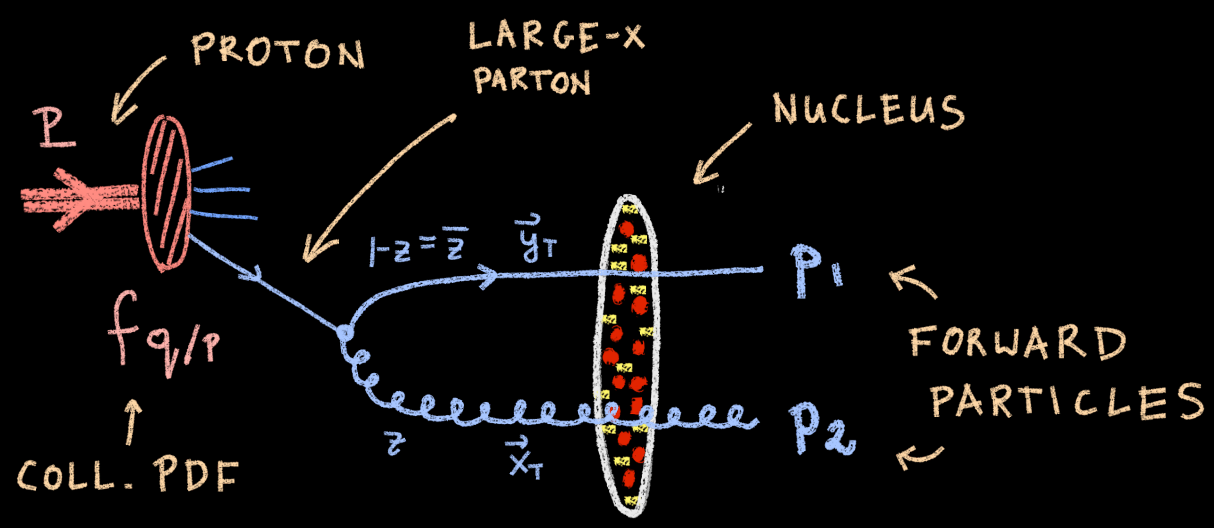
  Nonuniversality of TMD gluon PDFs.

- **k_T-factorization**

  TMD factorization beyond leading power.

INTRODUCTION

pA (dilute-dense) collisions within CGC



$$\frac{d\sigma_{qA\to 2j}}{d^3p_1 d^3p_2} \sim \int \frac{d^2x}{(2\pi)^2}\frac{d^2x'}{(2\pi)^2}\frac{d^2y}{(2\pi)^2}\frac{d^2y'}{(2\pi)^2}\, e^{-i\vec{p}_{T1}\cdot(\vec{x}_T-\vec{x}'_T)}e^{-i\vec{p}_{T2}\cdot(\vec{y}_T-\vec{y}'_T)}$$

$$\times \psi_z^*\left(\vec{x}'_T-\vec{y}'_T\right)\psi_z\left(\vec{x}_T-\vec{y}_T\right)$$ ← QUARK WAVE FUNCTION

$$\times\Big\{ S_x^{(6)}\left(\vec{y}_T,\vec{x}_T,\vec{y}'_T,\vec{x}'_T\right) - S_x^{(4)}\left(\vec{y}_T,\vec{x}_T,\bar{z}\vec{y}'_T+z\vec{x}'_T\right)$$
$$-S_x^{(4)}\left(\bar{z}\vec{y}_T+z\vec{x}_T,\vec{y}'_T,\vec{x}'_T\right) - S_x^{(2)}\left(\bar{z}\vec{y}_T+z\vec{x}_T,\bar{z}\vec{y}'_T+z\vec{x}'_T\right)\Big\}$$

CORRELATORS OF WILSON LINES

$$S_x^{(2)}\left(\vec{y}_T,\vec{x}_T\right) = \frac{1}{N_c}\left\langle \mathrm{Tr}\, U(\vec{y}_T)U^\dagger(\vec{x}_T)\right\rangle_x$$

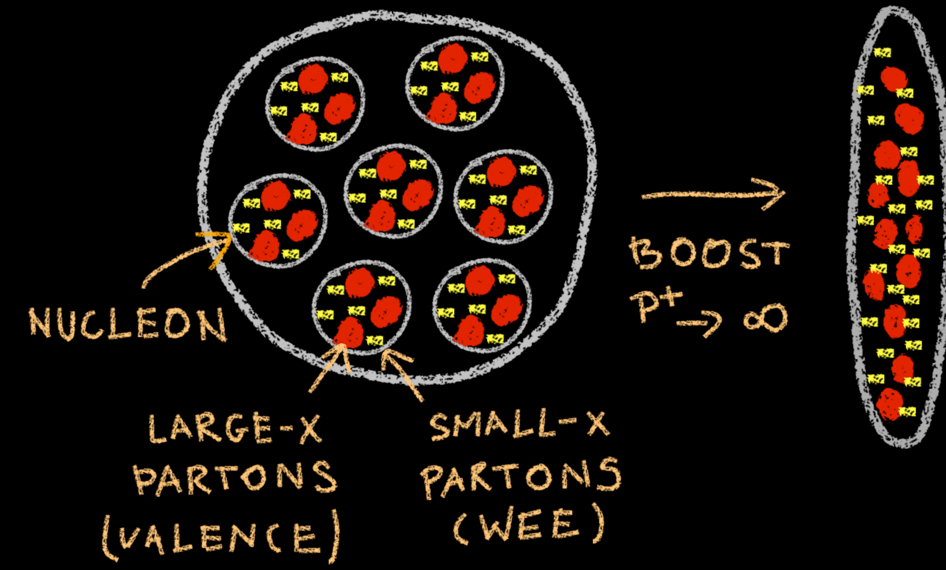
$$S_x^{(4)}\left(\vec{z}_T,\vec{y}_T,\vec{x}_T\right) = \frac{1}{2C_FN_c}\left\langle \mathrm{Tr}\left[U(\vec{z}_T)U^\dagger(\vec{y}_T)\right]\mathrm{Tr}\left[U(\vec{y}_T)U^\dagger(\vec{x}_T)\right]\right\rangle_x - S_x^{(2)}\left(\vec{z}_T,\vec{x}_T\right)$$

etc...

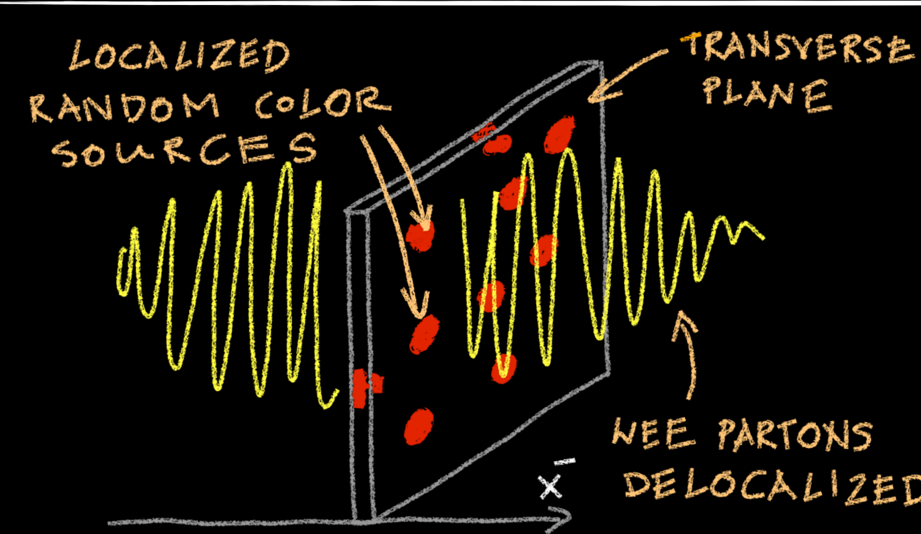
$$U(\vec{x}_T) = \mathscr{P}\exp\left\{ ig\int_{-\infty}^{+\infty} dx^+\, A_a^-\left(x^+,\vec{x}_T\right)t^a\right\}$$

[C. Marquet, 2007]

COLOR FIELD OF THE NUCLEUS



[L. McLerran, R. Venugopalan, 1993]



Large-x partons — the color source for wee partons:

$$(D_\mu F^{\mu\nu})_a(x^-,\vec{x}_T) = \delta^{\nu+}\rho_a(\vec{x}_T)\delta(x^-)$$

RANDOM DISTRIBUTION OF COLOR SOURCES

AVERAGE OVER COLOR SOURCES

GAUSSIAN FUNCTIONAL

B-JIMWLK EVOLUTION IN X → $\mathscr{W}_x[\rho]$

[Balitsky-Jalilian-Marian-Iancu-McLerran -Weigert-Leonidov-Kovner, 1996-2002]

INTRODUCTION

Summary of CGC jet/hadron production results

only full CGC calculations included

Single inclusive hadron production in pA (NLO)

[G.A. Chirilli, B.-W. Xiao, F. Yuan, 2012]
[A. Stasto, B.-W. Xiao, D. Zaslavsky, 2014]
[T. Altinoluk, N. Armesto, G. Beuf, A. Kovner, M. Lublinsky, 2015]
[E. Iancu, A.H. Mueller, D.N. Triantafyllopoulos, 2016]
[B. Ducloe, T. Lappi, Y. Zhu, 2017] PHENO

Dijet+photon production in γ^*A (NLO)

[K. Roy, R. Venugopalan, 2018, 2019]

Dijet production in diffractive γ^*A (NLO)

[R. Boussarie, A. Grabovsky, L. Szymanowski, S. Wallon, 2019] PHENO

Dijet/di-hadron production in γ^*A

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

Dijet/di-hadron production in pA

[C. Marquet, 2007] [H. Fujii, F. Gelis, R. Venugopalan, 2005]
[E. Iancu, J. Leidet, 2013] [H. Fujii, C. Marquet, K. Watanabe, 2020] PHENO

Heavy quark pair production in pA

[C. Marquet, C. Roiesnel, P. Taels, 2018]

Trijet production in γ^*A

[A. Ayala, M. Hentchinski, J. Jalilian-Marian, M.E. Tejeda-Yeomans, 2016]
[T. Altinoluk, R. Boussarie, C. Marquet, P. Taels, 2020]

Dijet+photon production in pA

[T. Altinoluk, R. Boussarie, C. Marquet, P. Taels, 2019]
[T. Altinoluk, N. Armesto, A. Kovner, M. Lublinsky, E. Petreska, 2018]

Trijet production in pA

[E. Iancu, Y. Mulian, 2018]

INTRODUCTION

Limiting cases of CGC in dilute-dense collisions

CGC

dilute-dense

three scales:

$Q_s \gg \Lambda_{\rm QCD}$ — saturation scale

k_T — jet transverse momentum imbalance

P_T — jet average transverse momentum

$P_T \gg k_T \sim Q_s$

TMD

GENERALIZED FACTORIZATION

leading twist

[F. Dominguez, C. Marquet, B. Xiao, F. Yuan, 2011]
[C. Marquet, E. Petreska, C. Roiesnel, 2016]
[C. Marquet, C. Roiesnel, P. Taels, 2018]
[T. Altinoluk, R. Boussarie, C. Marquet, P. Taels, 2019]
[T. Altinoluk, R. Boussarie, C. Marquet, P. Taels, 2020]

$P_T \sim k_T \gg Q_s$

$P_T \gg Q_s$

ITMD

"IMPROVED" TMD factorization

all kinematic twists

[PK, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren, 2015]
[A. van Hameren, PK, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, 2016]
[T. Altinoluk, R. Boussarie, PK, 2019]

DILUTE

k_T-FACTORIZATION

BFKL dynamics

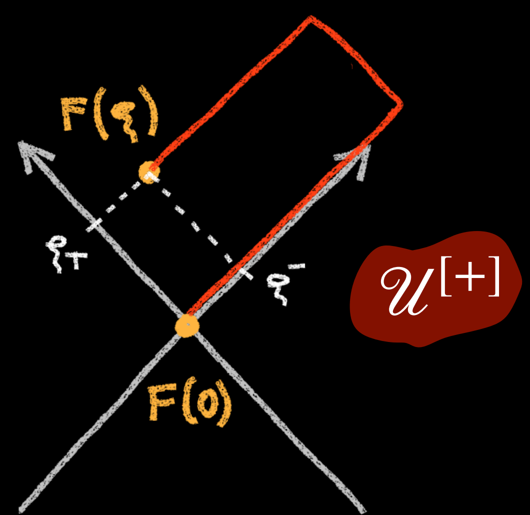
[S. Catani, M. Ciafaloni, F. Hautmann, 1991]
[M. Deak, F. Hautmann, H. Jung, K. Kutak, 2009]
[E. Iancu, J. Leidet, 2013]

Generic operator definition (unpolarized)

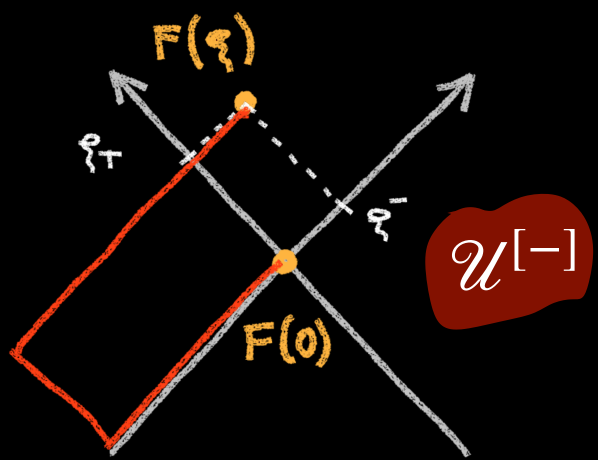
$$\mathscr{F}_g(x, k_T) = 2\int \frac{d\xi^+ d^2\xi_T}{(2\pi)^3 P^-} e^{ixP^-\xi^+ - i\vec{k}_T\cdot\vec{\xi}_T} \langle P|\,\mathrm{Tr}\left[\hat{F}^{i-}\left(\xi^+, \vec{\xi}_T, \xi^- = 0\right)\mathscr{U}_{C_1}\hat{F}^{i-}(0)\,\mathscr{U}_{C_2}\right]|P\rangle$$

GLUON FIELD $\hat{F} = F_a t^a$

WILSON LINES IN FUNDAMENTAL REPRESENTATION



FUTURE-POINTING



PAST-POINTING

Gauge links $\mathscr{U}_{C_1}, \mathscr{U}_{C_2}$ depend on the color structure of the hard process. They are build from two basic Wilson lines:

[C. Bomhof, P. Mulders, F. Pijlman, 2004]

$$\mathscr{U}^{[\pm]} = [0, (\pm\infty, \vec{0}_T, 0)] \times [(\pm\infty, \vec{0}_T, 0), (\pm\infty, \vec{\xi}_T, 0)] \times [(\pm\infty, \vec{\xi}_T, 0), (\xi^+, \vec{\xi}_T, 0)]$$

$$[x, y] = \mathscr{P}\exp\left\{ig\int_{\overline{xy}} dz_\mu A^\mu_a(z) t^a\right\}$$

STRAIGHT LINE SEGMENT

Light-cone basis:

$$v^\pm = v^\mu n^\pm_\mu, \quad n^\pm = (1,0,0,\mp 1)$$

$$v^\mu = \frac{1}{2}v^+ n^- + \frac{1}{2}v^- n^+ + v^\mu_T$$

INTRODUCTION

TMD gluon distributions: proliferation

All possible operators

$$\mathcal{F}_{qg}^{(1)} \sim \langle P|\,\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[+]}\right]|P\rangle$$

$$\mathcal{F}_{qg}^{(2)} \sim \langle P|\,\frac{\mathrm{Tr}\,\mathcal{U}^{[\Box]}}{N_c}\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[+]}\right]|P\rangle$$

$$\mathcal{F}_{qg}^{(3)} \sim \langle P|\,\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[\Box]}\mathcal{U}^{[+]}\right]|P\rangle$$

$$\mathcal{F}_{gg}^{(1)} \sim \langle P|\,\frac{\mathrm{Tr}\,\mathcal{U}^{[\Box]\dagger}}{N_c}\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[+]}\right]|P\rangle$$

$$\mathcal{F}_{gg}^{(2)} \sim \langle P|\,\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[\Box]\dagger}\right]\mathrm{Tr}\left[\hat{F}^{i-}(0)\,\mathcal{U}^{[\Box]}\right]|P\rangle$$

$$\mathcal{F}_{gg}^{(3)} \sim \langle P|\,\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[+]}\right]|P\rangle$$

$$\mathcal{F}_{gg}^{(4)} \sim \langle P|\,\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[-]}\right]|P\rangle$$

$$\mathcal{F}_{gg}^{(5)} \sim \langle P|\,\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[\Box]\dagger}\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[\Box]}\mathcal{U}^{[+]}\right]|P\rangle$$

$$\mathcal{F}_{gg}^{(6)} \sim \langle P|\,\frac{\mathrm{Tr}\,\mathcal{U}^{[\Box]}}{N_c}\frac{\mathrm{Tr}\,\mathcal{U}^{[\Box]\dagger}}{N_c}\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[+]}\right]|P\rangle$$

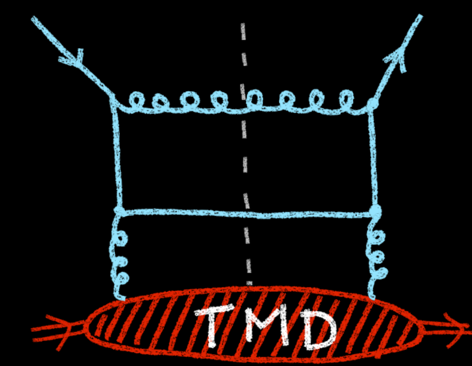
$$\mathcal{F}_{gg}^{(7)} \sim \langle P|\,\frac{\mathrm{Tr}\,\mathcal{U}^{[\Box]}}{N_c}\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[\Box]\dagger}\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[+]}\right]|P\rangle$$

WILSON LOOP → $\mathcal{U}^{[\Box]} = \mathcal{U}^{[+]}\mathcal{U}^{[-]\dagger}$

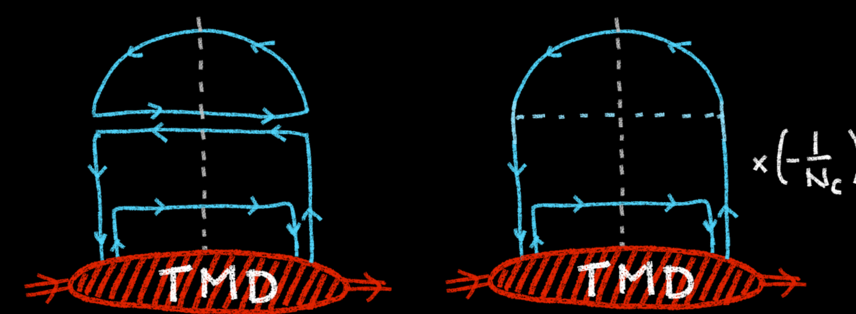
[M. Bury, PK , K. Kutak, 2018]

Example

What is the TMD gluon distribution for the following process:



Two independent color flows:



$$\rightsquigarrow \frac{N_c}{2C_F}\mathcal{F}_{qg}^{(2)} - \frac{1}{2N_cC_F}\mathcal{F}_{qg}^{(1)}$$

Gluon TMD for any multiparticle process is given by a linear combination of these "basis" TMDs.

Small-x limit of TMD gluon distributions

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

LIMIT

$x \to 0.$

Dependence on x is only via the small-x evolution equations:

- BFKL (Balitsky-Fadin-Kuraev-Lipatov).
- BK (Balitsky-Kovchegov) and modifications
- JIMWLK (Balitsky-Jalilian-Marian-Iancu-McLerran-Weigert-Leonidov-Kovner)

Correspondence to CGC

Example:

DIPOLE GLUON DISTRIBUTION

$$\mathcal{F}^{(1)}_{qg} \sim \int \frac{d^2x_T d^2y_T}{(2\pi)^4} k_T^2 e^{-i\vec{k}_T\cdot(\vec{x}_T - \vec{y}_T)} \langle \mathrm{Tr}\left[U(\vec{x}_T)U^\dagger(\vec{y}_T)\right]\rangle_x$$

WILSON LINES

$$U(\vec{x}_T) = \mathcal{P} \exp\left\{ ig \int_{-\infty}^{+\infty} dx^+ \, A_a^-\left(x^+, \vec{x}_T\right) t^a \right\}$$

AVERAGE OVER CGC COLOR SOURCES

$$\langle \ldots \rangle_x \to \frac{\langle \Omega | \ldots | \Omega \rangle}{\langle \Omega | \Omega \rangle}$$

Intensively studied:

[D. Kharzeev, Y. Kovchegov, K. Tuchin, 2003]
[B. Xiao, F. Yuan, 2010]
[F. Dominguez, C. Marquet, B. Xiao, F. Yuan, 2011]
[A. Metz, J. Zhou, 2011]
[E. Akcakaya, A. Schafer, J. Zhou, 2012]
[C. Marquet, E. Petreska, C. Roiesnel, 2016]
[I. Balitsky, A. Tarasov, 2015, 2016]
[D. Boer, P. Mulders, J. Zhou, Y. Zhou, 2017]
[C. Marquet, C. Roiesnel, P. Taels, 2018]
[Y. Kovchegov, D. Pitonyak, M. Sievert, 2017,2018]
[T. Altinoluk, R. Boussarie, 2019]
[R. Boussarie, Y. Mehtar-Tani, 2020]

FRAMEWORK

Small-x Improved TMD Factorization (ITMD)

Factorization formula for forward dijets in p-p and p-A collisions

[PK, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren, 2015]

$$\frac{d\sigma_{pA\to 2j+X}}{dy_1 dy_2 d^2p_{T1} d^2p_{T2}} \sim \sum_{a,c,d} f_{a/p}(x_1,\mu) \sum_{i=1,2} K^{(i)}_{ag\to cd}(k_T)\, \Phi^{(i)}_{ag\to cd}(x_2,k_T)$$

RAPIDITY — TRANSVERSE MOMENTA — COLLINEAR PROTON PDF — GAUGE INVARIANT OFF-SHELL HARD FACTORS — TMD GLUON DISTRIBUTIONS AT SMALL-X

$x_2 \ll x_1$ $\quad |\vec{p}_{T1}+\vec{p}_{T2}| = k_T$

TWO PER CHANNEL ($g^*q\to gq$, $g^*g\to gg$, $g^*g\to q\bar{q}$)

ITMD factorization formula has been proven from the Color Glass Condensate (CGC) theory.

⇒ RESUMMATION OF KINEMATIC TWISTS AND NEGLECTING GENUINE TWISTS.

[T. Altinoluk, R. Boussarie, PK, 2019]

$$\Lambda_{QCD} \ll Q_s \ll P_T$$

SATURATION SCALE

Obtaining small-x TMD gluon distributions

Using CGC theory one can derive a relation between the small-x TMDs using:

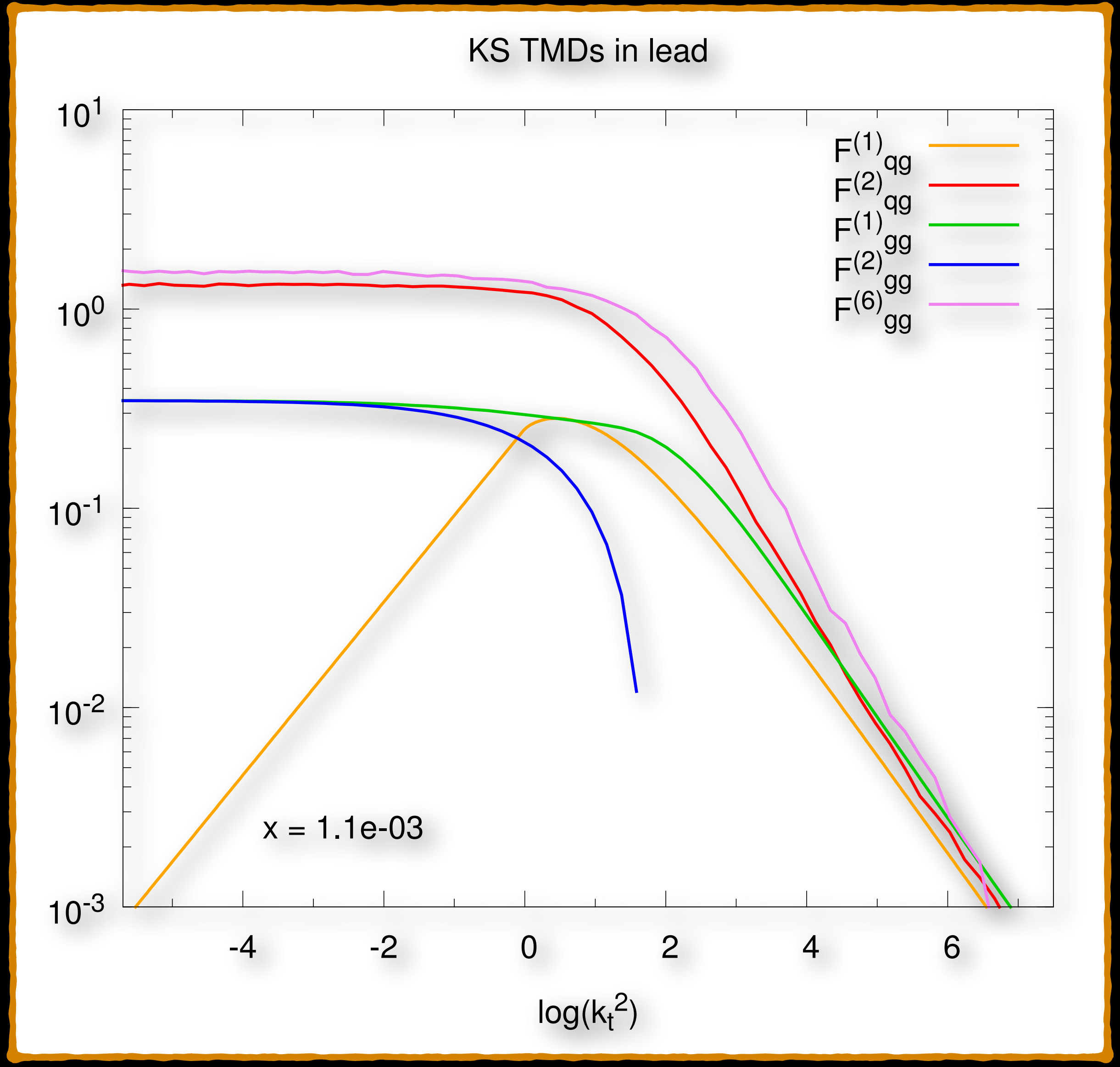
(i) large N_c limit

(ii) mean field (Gaussian) approximation.

All TMDs needed for dijet production can be calculated from the dipole gluon distribution $\mathcal{F}_{qg}^{(1)}$.

We used $\mathcal{F}_{qg}^{(1)}$ obeying the BK equation (with subleading corrections based on the Kwiecinski-Martin-Stasto equation) and fitted to HERA data.

[K. Kutak, J. Kwieciński, 2003]
[K. Kutak, S. Sapeta, 2012]



[A. Van Hameren, PK, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, 2016]

It is possible to relax the assumptions (i) and (ii) using the JIMWLK equation.

Prove of concept:

[C. Marquet, E. Petreska, C. Roiesnel, 2016]

PHENOMENOLOGY

ITMD vs ATLAS data

Measurement of dijet azimuthal correlations in p+p and p+Pb. [ATLAS, Phys. Rev. C100 (2019)]

$\sqrt{S} = 5.02\,\text{TeV}$ rapidity: $2.7 < y_1, y_2 < 4.5$

$$C_{12} = \frac{1}{N_1} \frac{dN_{12}}{d\Delta\phi}$$

NUMBER OF DIJETS

AZIMUTHAL ANGLE BETWEEN JETS

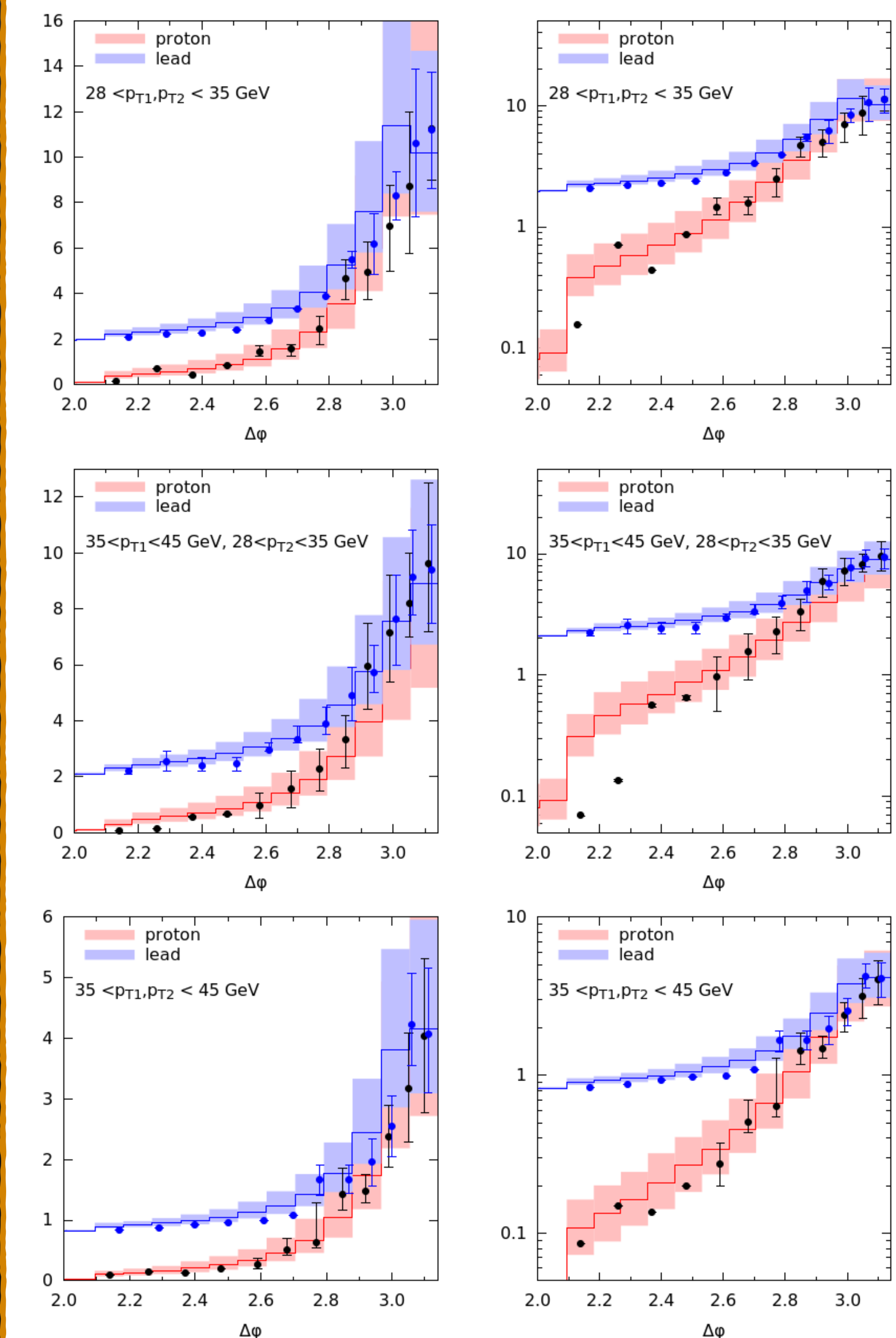
NUMBER OF LEADING JETS

We study an interplay of saturation and Sudakov resummation vs the **shape** of C_{12}.

Good description of the broadening effects

Similar study for RHIC in the back-to-back limit:

[A. Stasto, S-Y. Wei, B-W. Xiao, F. Yuan, 2018]



A. Van Hameren, P. Kotko, K. Kutak, S. Sapeta, Phys. Lett. B795 (2019) 511

ITMD for jets in DIS

ITMD factorization formula for DIS is almost the same as the k_T-factorization formula in inclusive DIS, but probes different TMD gluon distribution

[PK, K. Kutak, S. Sapeta, A. Stasto, M. Strikman, 2017]

$$d\sigma_{\gamma^* A\to 2j+X} \sim \int \frac{dx}{x} \int d^2k_T \, \mathcal{F}_{gg}^{(3)}(x,k_T,\mu) \, d\sigma_{\gamma^* g^* \to j_1 j_2}(x,k_T,\mu)$$

WEIZSÄCKER-WILLIAMS TMD GLUON DISTRIBUTION

OFF-SHELL PHOTON-GLUON FUSION

Weizsacker-Williams TMD gluon distribution is the **true gluon number distribution.**

It is not probed in inclusive processes nor in jet production in pA (at large N_c).

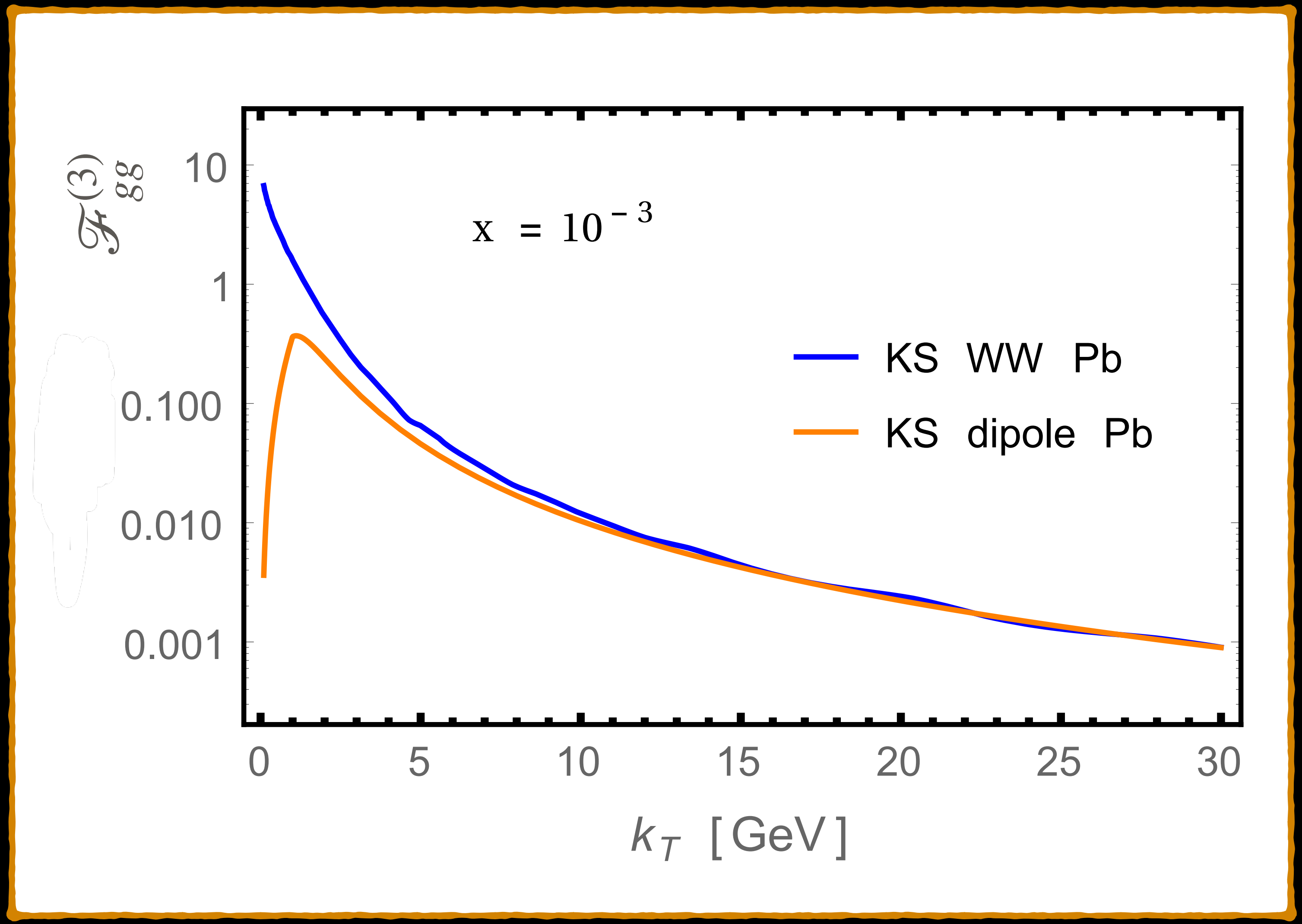
Multi jet/hadron production at EIC will be a unique probe.

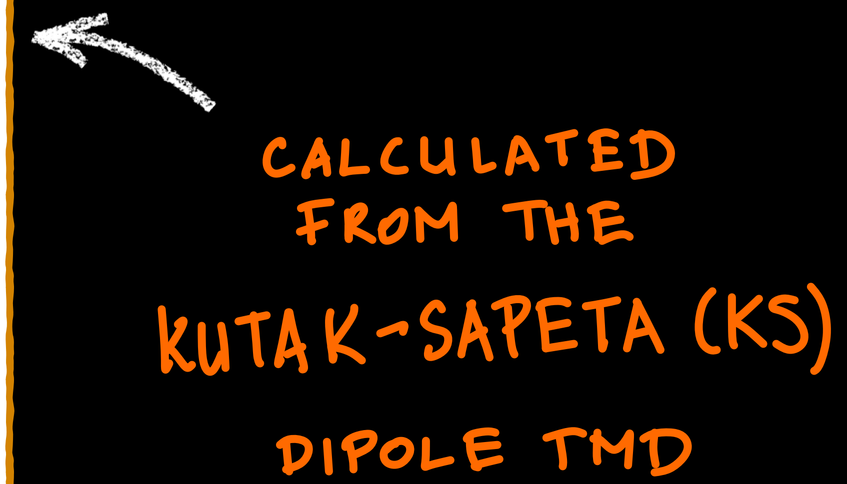
Also studied in the back-to-back regime

[L. Zheng, E.C. Aschenauer, J.H. Lee, B-W. Xiao, 2014]
[L. Zheng, E.C. Aschenauer, J.H. Lee, B-W. Xiao, Z-B. Yin, 2018]

PHENOMENOLOGY Weizsacker-Williams TMD gluon distribution

Using the same approximations as for other gluon TMDs we can calculate the Weizsacker-Williams TMD from the dipole distribution.



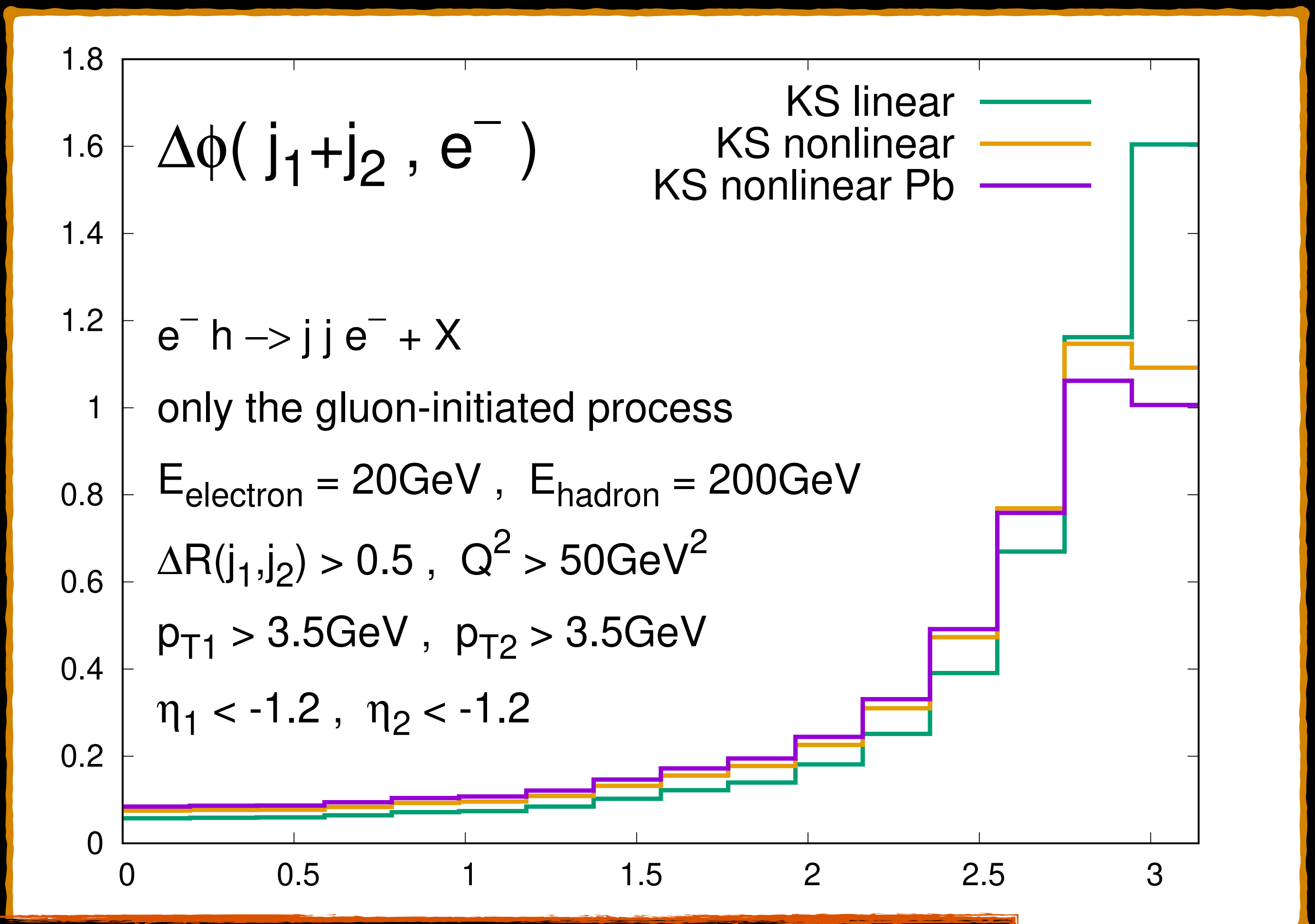


- Very different behavior at small k_T
- Convergence at large k_T

[PK, K. Kutak, S. Sapeta, A. Stasto, M. Strikman, 2017]

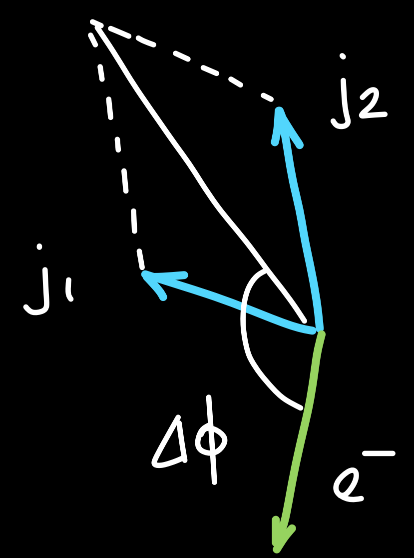
PHENOMENOLOGY DIS pilot studies

ITMD for dijets in γA collisions has been so far studied in ultraperipheral heavy ion collisions at LHC for dijet azimuthal imbalance. [PK, K. Kutak, S. Sapeta, A. Stasto, M. Strikman, 2017]



A. van Hameren, EIC yellow report seminar

At EIC one can study also angle between final states and the final state lepton.



Detailed study in progress

ITMD* for three and more jets in pA collisions

If we ignore linearly polarized gluon contribution for multi-jet processes, the ITMD framework (called ITMD*) can be formulated (and automatized).

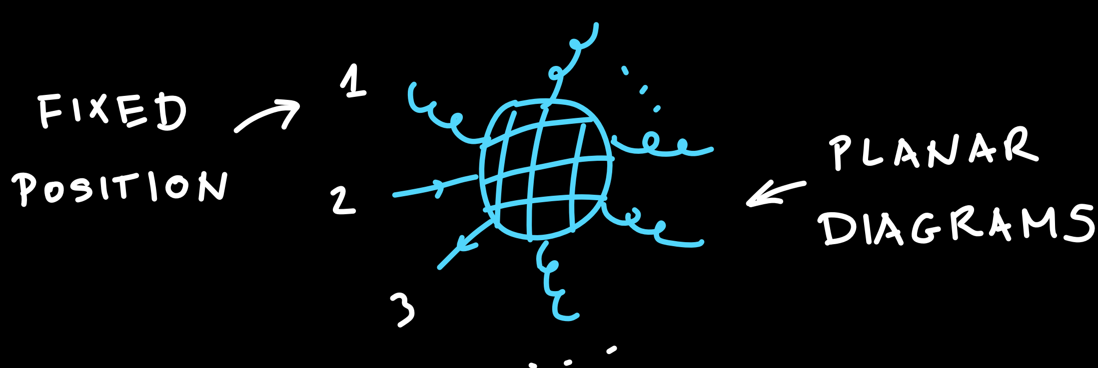
[M. Bury, PK , K. Kutak, 2018]

[M. Bury, A. van Hameren, PK, K. Kutak, 2020]

$$\frac{d\sigma_{pA\to 3j+X}}{dP\,.\,S} \sim \int \frac{dx_1 dx_2}{x_1 x_2} \int d^2k_T \sum_{partons} f_{a/p}(x_1,\mu)\; \vec{\mathscr{A}}^\dagger\; \mathbf{\Phi}(x_2,k_T,\mu)\; \vec{\mathscr{A}}$$

VECTOR OF COLOR ORDERED OFF-SHELL AMPLITUDES

MATRIX OF TMD GLUON DISTRIBUTIONS

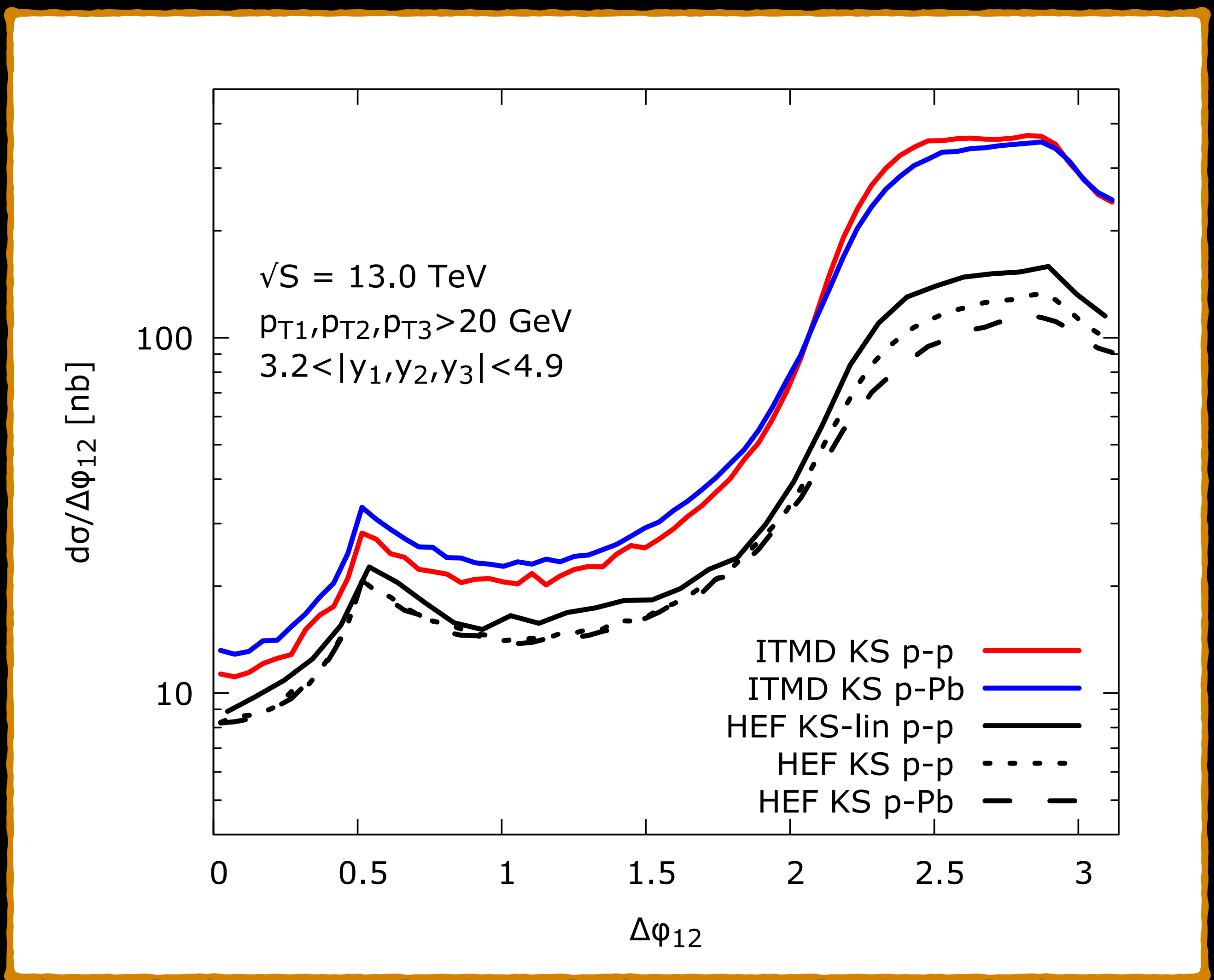


CHANNEL	DIM
$g^*q \to qgg$	6×6
$g^*q \to q\bar{q}q$	6×6
$g^*q \to qgg$	6×6
$g^*q \to qq\bar{q}$	4×4

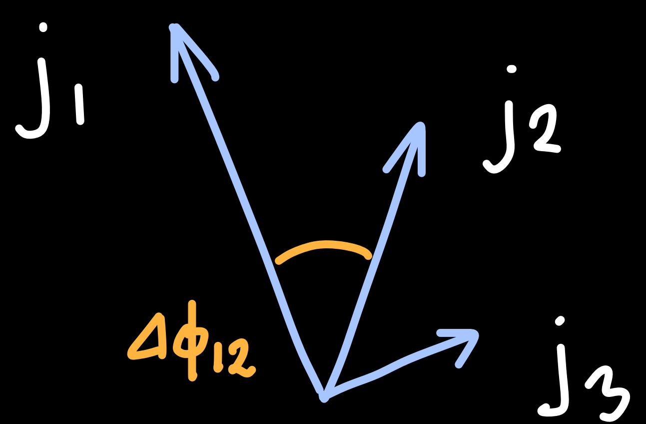
PHENOMENOLOGY

Three forward jets at LHC within ITMD*

Using the large N_c limit to the TMD matrix, and in the mean field approximation, the same TMD operators contribute as for dijets.



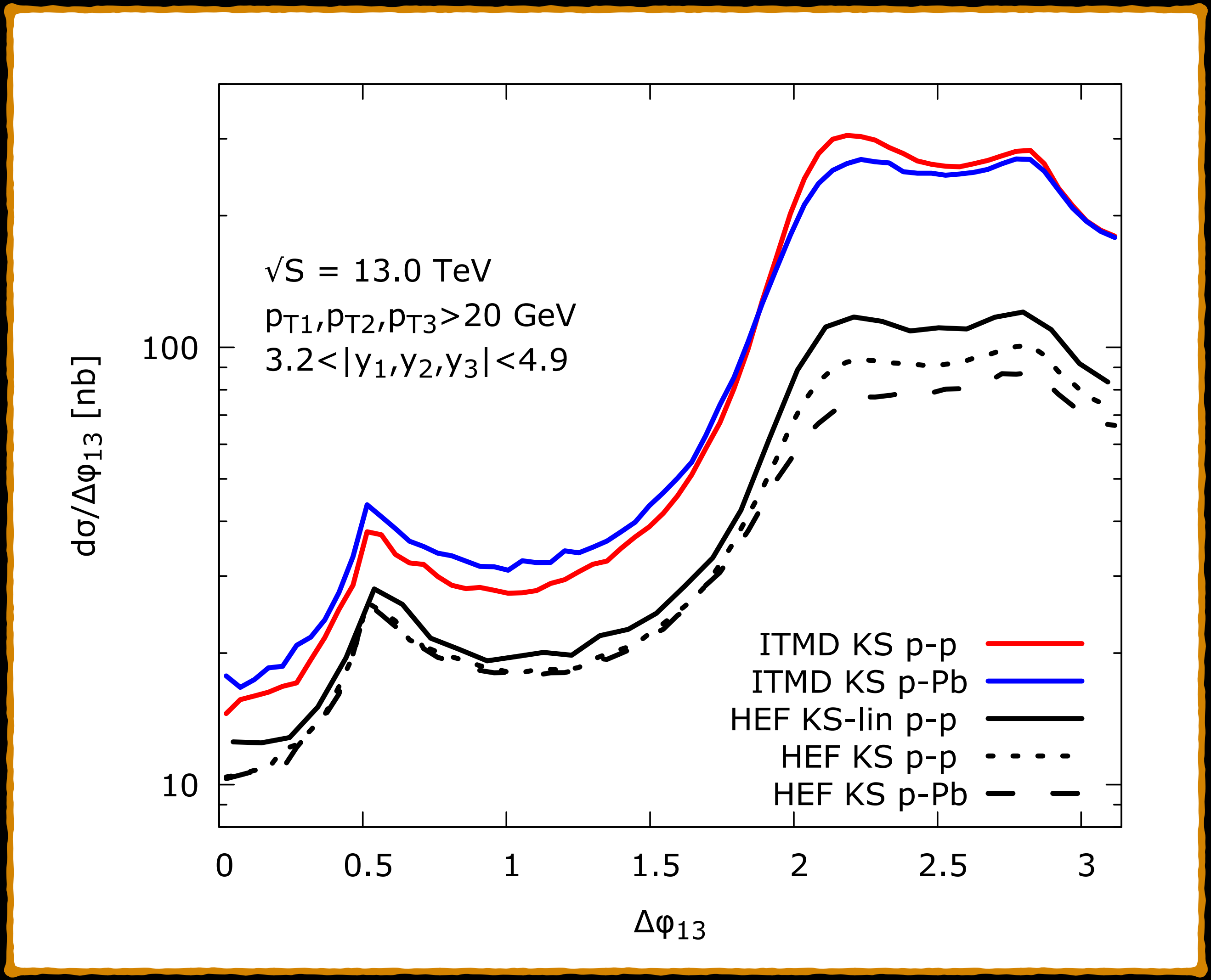
Azimuthal angle between the leading jets



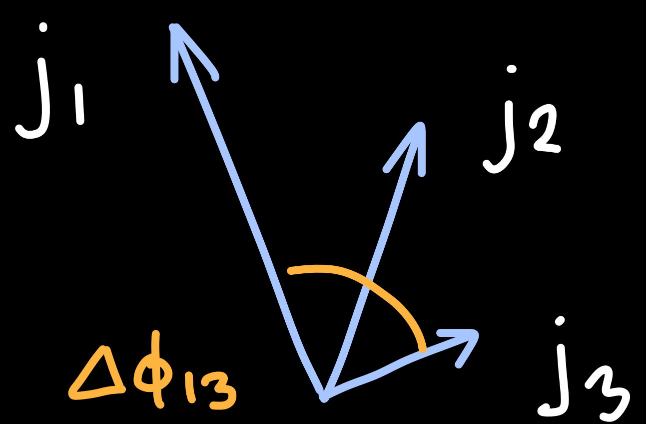
[M. Bury, A. van Hameren, PK, K. Kutak, 2020]

PHENOMENOLOGY Three forward jets at LHC within ITMD*

Using the large N_c limit to the TMD matrix, and in the mean field approximation, the same TMD operators contribute as for dijets.



Azimuthal angle between the leading and the soft jet



[M. Bury, A. van Hameren, PK, K. Kutak, 2020]

Three forward jets at LHC within ITMD*

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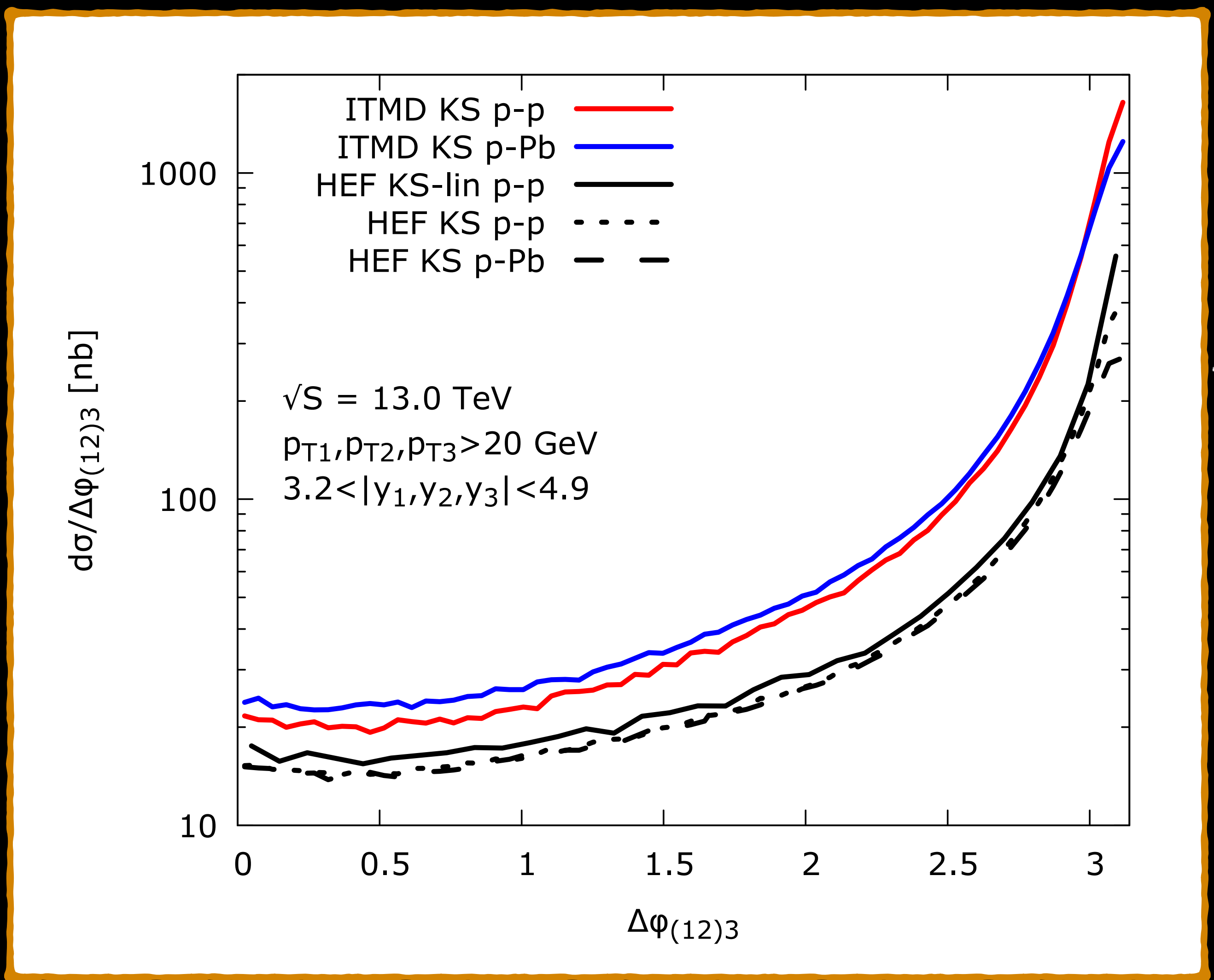
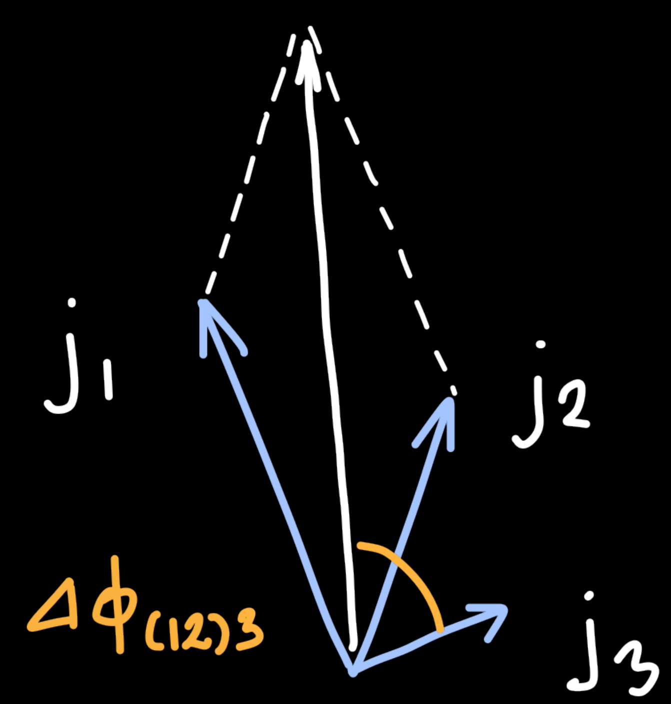


[M. Bury, A. van Hameren, PK, K. Kutak, 2020]

Azimuthal angle between the plane spanned by the leading jets and the soft jet



PHENOMENOLOGY KaTie Monte Carlo

KaTie https://bitbucket.org/hameren/katie

- parton level event generator, like ALPGEN, HELAC, MADGRAPH, etc.
- arbitrary processes within the standard model (including effective Higgs-gluon coupling) with several final-state particles.
- 0, 1, or 2 off-shell intial states.
- produces (partially un)weighted event files, for example in the LHEF format.
- requires LHAPDF. TMD PDFs can be provided as files containing rectangular grids, or with TMDlib.
- a calculation is steered by a single input file.
- employs an optimization stage in which the pre-samplers for all channels are optimized.
- during the generation stage several event files can be created in parallel.
- event files can be processed further by parton-shower program like CASCADE.
- (evaluation of) matrix elements now separately available, including C++ interface.

A. van Hameren, EIC yellow report seminar

7

SUMMARY

PARTICLE PRODUCTION in dilute-dense collisions

CGC

- cross section structure:
  - projectile wave function
  - color averages of straight infinite Wilson lines
- all kinematic twists
- multiple interactions (genuine twist)
- hard to compute and automatize
- domain: jets of any hardness

ITMD

- cross section structure:
  - off-shell gauge invariant amplitudes
  - many TMD gluon distributions
- all kinematic twists
- no genuine twists
- has been automatized and implemented into MC codes
- domain: quite hard jets, but not neglecting saturation scale

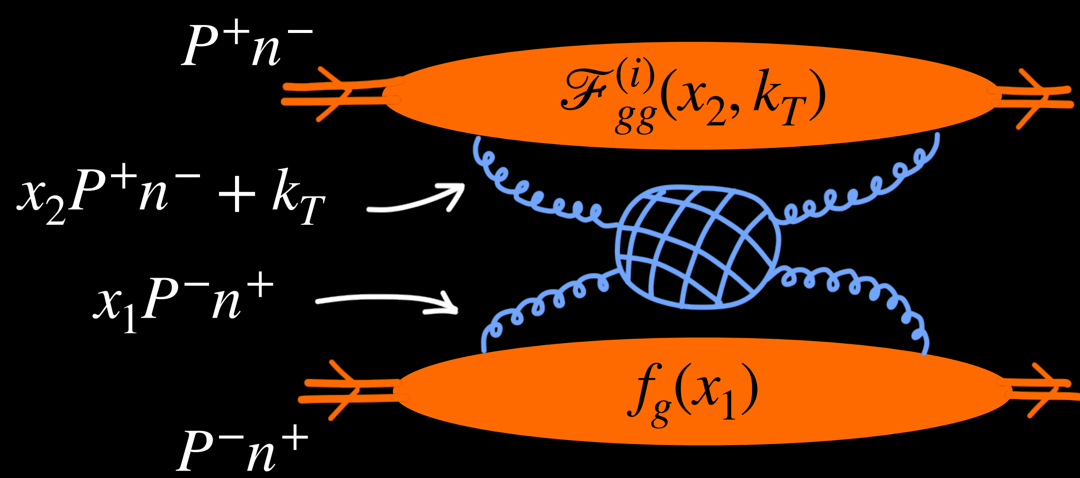
FUTURE PLANS

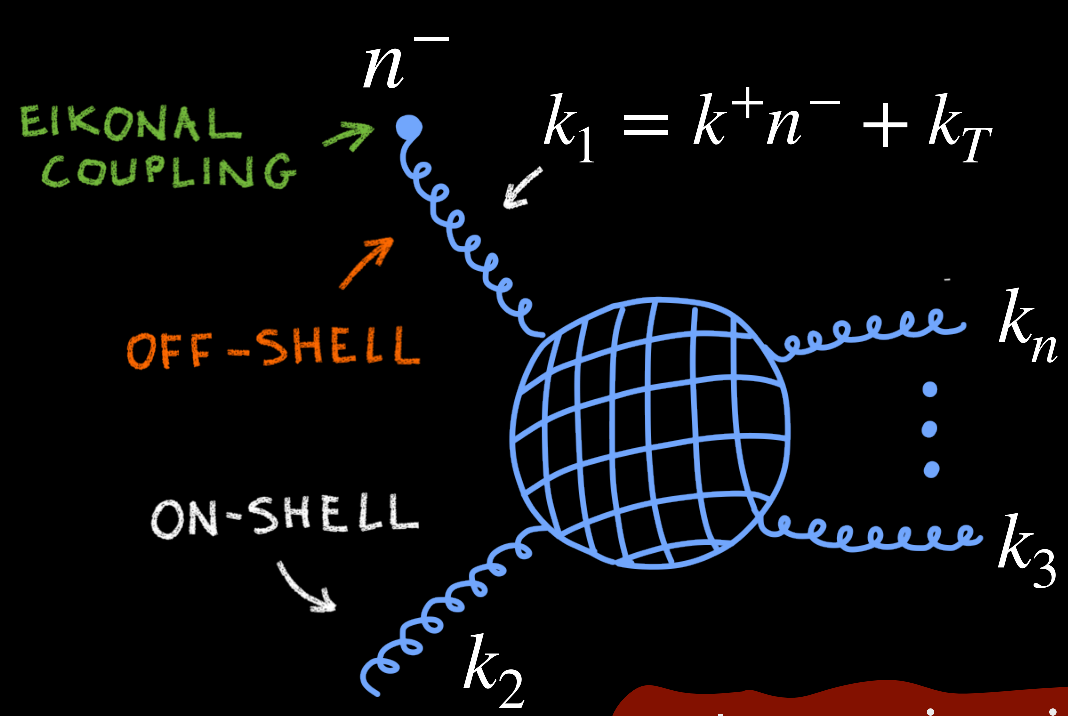
- Data-driven small-x TMD gluon distributions from JIMWLK equation (collaboration with lattice QCD experts K. Cichy and P. Korcyl)
- Improvement of the Sudakov resummation (basing on calculations by A. Mueller, B. Xiao, F. Yuan)
- Inclusion of linearly polarized gluons in higher multiplicity jet calculations (extending ITMD* to full ITMD)
- Automated NLO calculations for off-shell gauge invariant amplitudes (result for any number of gluons with same helicity at NLO is ready)

BACKUP

FRAMEWORK Off-shell hard factors

Partonic amplitudes at high energy

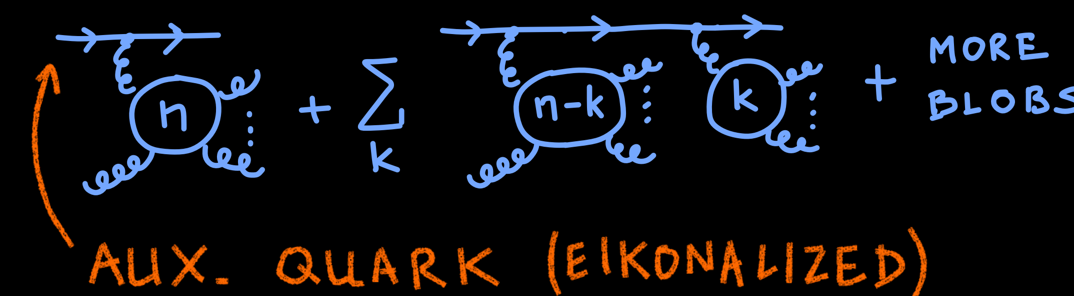




not gauge invariant

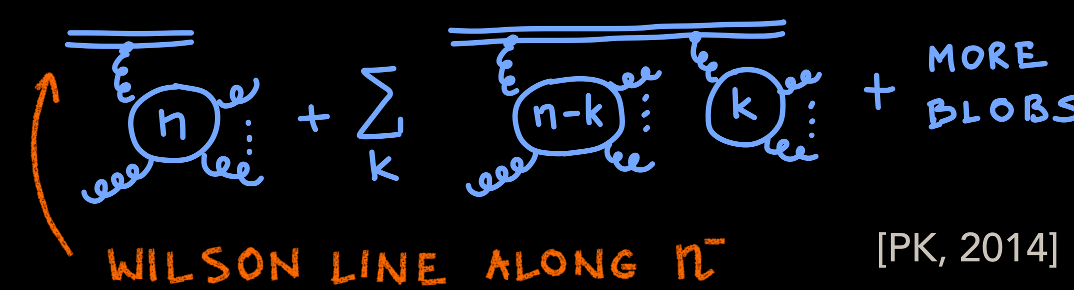
Tree-level (automatic) techniques

- "embedding"



[A. van Hameren, PK, K. Kutak, 2013]

- ME of straight infinite Wilson line



[PK, 2014]

- Berends-Giele + gauge inv. restoration

[A. Van Hameren, PK, K. Kutak, 2012]

- Off-shell BCFW

[A. Van Hameren, 2014]
[A. Van Hameren, M. Serino, 2014]

Consistent with the Lipatov's high energy effective action. [L. Lipatov, 1995]

FRAMEWORK Off-shell hard factors

Off-shell MHV tree amplitudes

$$\mathcal{M}\left(1^*, 2^-, 3^+, \ldots, n^+\right) \sim g^{n-2} \frac{\langle 1^* 2\rangle^4}{\langle 1^* 2\rangle \langle 23\rangle \langle 34\rangle \ldots \langle n 1^*\rangle}$$

SPINOR PRODUCTS

$\langle ij\rangle = \langle k_i - | k_j + \rangle$

$| k_j \pm \rangle = \frac{1}{2}(1 \pm \gamma_5) u(k_j)$

FOR OFF-SHELL LEG:

$$\langle 1^* j\rangle = \langle k^+ n^- - | k_j + \rangle$$

gauge invariance is essential

[A. Van Hameren, PK, K. Kutak, 2012]
[A. Van Hameren, 2014]

Beyond tree level

There exist low multiplicity analytic results within the Lipatov's effective action approach.

[M. Nefedov, V. Saleev, 2017]
[M. Nefedov, 2019]

On going project towards automated one-loop corrections in "embedding" approach.

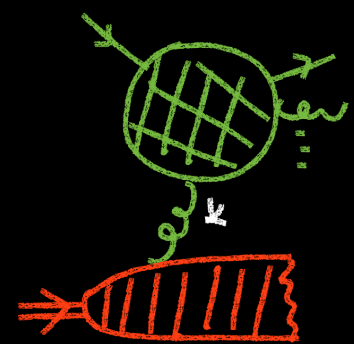
[A. Van Hameren, 2017]
[E. Blanco, A. Van Hameren, PK, K. Kutak, in preparation...]

Proof of the ITMD formula

[T. Altinoluk, R. Boussarie, PK, 2019]

TERMINOLOGY

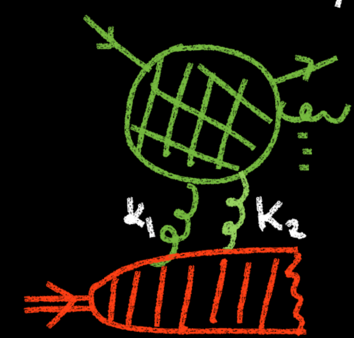
ONE-BODY



$\mathcal{O}_1 \sim \langle P | F_a^{-i}(x) | X \rangle$

$\mathcal{H}_1(k_T) \otimes \tilde{\mathcal{O}}_1(k_T)$

TWO-BODY, etc.



$\mathcal{O}_2 \sim \langle P | F_a^{-i}(x) F_b^{-j}(y) | X \rangle$

$\mathcal{H}_2(k_{T1}, k_{T2}) \otimes \tilde{\mathcal{O}}_2(k_{T1}, k_{T2})$

LEADING TWIST

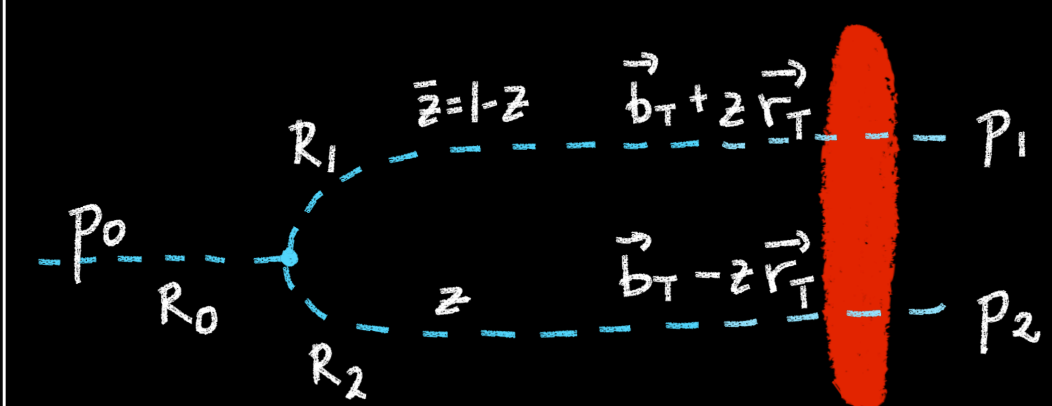
$$\mathcal{A}_{LT} = \mathcal{H}_1(0) \otimes \tilde{\mathcal{O}}_1(k_T)$$

NEXT-TO LEADING TWIST

$$\mathcal{A}_{NLT} = \vec{k}_T \cdot (\vec{\partial}_T \mathcal{H}_1)(0) \otimes \tilde{\mathcal{O}}_1(k_T)$$ KINEMATIC TWIST

$$+ \mathcal{H}_2(0,0) \otimes \tilde{\mathcal{O}}_2(k_{T1}, k_{T2})$$ GENUINE TWIST

GENERIC 1→2 CGC AMPLITUDE



$$\vec{k}_T = \vec{p}_{T1} + \vec{p}_{T2}$$

$$\vec{P}_T = \bar{z}\vec{p}_{T1} - z\vec{p}_{T2}$$

R_i - COLOR REPRESENTATION

$$\mathcal{A} = \delta(p_1^+ + p_2^+ - p_0^+) \int d^2b_T d^2r_T \, e^{-i(\vec{P}_T \cdot \vec{r}_T + \vec{k}_T \cdot \vec{b}_T)}$$

$$\times \frac{r_T^\mu}{r_T^2} \Big\{ U^{R_1}(\vec{b} + \bar{z}\vec{r}) T^{R_0} U^{R_2}(\vec{b} - z\vec{r})$$

$$- U^{R_1}(\vec{b}) T^{R_0} U^{R_2}(\vec{b}) \Big\} \Gamma_\mu$$

WILSON LINE IN REPR. R_i

COLOR GENERATORS

DIRAC STRUCTURE

Proof of the ITMD formula

[T. Altinoluk, R. Boussarie, PK, 2019]

STEP #1 TAYLOR EXPANSION IN $\vec{r}_T$

$$\mathscr{A}^{(n)} = \delta(p_1^+ + p_2^+ - p_0^+) \int d^2b_T d^2r_T\, e^{-i(\vec{P}_T\cdot\vec{r}_T + \vec{k}_T\cdot\vec{b}_T)} \frac{r_T^\mu \Gamma_\mu}{r_T^2}$$
$$\frac{1}{n!} r_T^{\alpha_1}\ldots r_T^{\alpha_n} \sum_{i=0}^{n} \binom{n}{i} \bar{z}^i (-z)^{n-i} \left(\partial_{\alpha_1}\ldots\partial_{\alpha_i} U^{R_1}(\vec{b})\right) T^{R_0} \left(\partial_{\alpha_{i+1}}\ldots\partial_{\alpha_n} U^{R_2}(\vec{b})\right)$$

STEP #2 ISOLATION OF 1-BODY CONTRIBUTIONS

$$\mathscr{A}^{(n)}_{1-\text{body}} = \delta(p_1^+ + p_2^+ - p_0^+) \int d^2b_T d^2r_T\, e^{-i(\vec{P}_T\cdot\vec{r}_T + \vec{k}_T\cdot\vec{b}_T)} \frac{r_T^\mu \Gamma_\mu}{r_T^2}$$
$$\vec{r}_T^{\,\alpha} \sum_{j=0}^{n} \frac{(i\vec{k}_T\cdot\vec{r}_T)^j}{(j+1)!} \left\{ \partial_\alpha U^{R_1}(\vec{b}) T^{R_0} U^{R_2}(\vec{b}) \bar{z}^{(j+1)} + U^{R_1}(\vec{b}) T^{R_0} \partial_\alpha U^{R_2}(\vec{b}) (-z)^{(j+1)} \right\}$$

STEP #3 RESUMMATION & INTEGRATION

$$\mathscr{A}_{1-\text{body}} = \delta(p_1^+ + p_2^+ - p_0^+) \int d^2b_T\, e^{-i\vec{k}_T\cdot\vec{b}_T} \frac{\Gamma_i}{k_T^2} (k_T^i \delta^{jl} + k_T^j \delta^{il} - k_T^l \delta^{ij})$$
$$\left\{ \left(\frac{P_T^l}{P_T^2} + \frac{p_{2T}^l}{p_{2T}^2} \right) \partial_j U^{R_1}(\vec{b}) T^{R_0} U^{R_2}(\vec{b}) + \left(\frac{P_T^l}{P_T^2} - \frac{p_{1T}^l}{p_{1T}^2} \right) U^{R_1}(\vec{b}) T^{R_0} \partial_j U^{R_2}(\vec{b}) \right\}$$

STEP #4 SQUARE THE AMPLITUDE
COLOR ALGEBRA
$\Rightarrow$ ITMD