Low-x and forward physics

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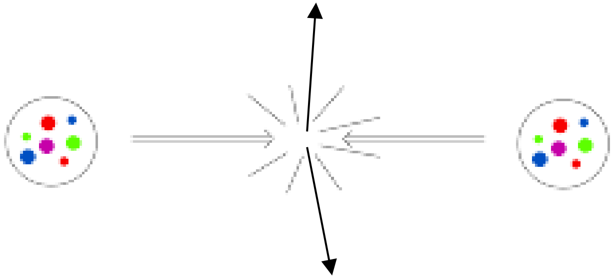
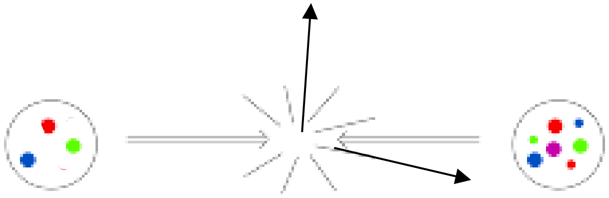
Di-hadron/-jet production kinematics

$$x_p = \frac{k_1\, e^{y_1} + k_2\, e^{y_2}}{\sqrt{s}} \qquad x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}}$$



central rapidities probe moderate x

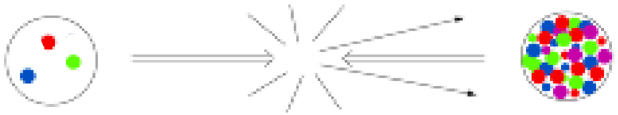
$$x_p \sim x_A \sim \frac{k}{\sqrt{S}}$$



central-forward

$$x_p \sim \frac{k}{\sqrt{S}}\, e^{y_1} \qquad x_A \sim \frac{k}{\sqrt{S}}$$

x_p increases x_A ~ unchanged



forward-forward correlations probe small x_A

x_p ~ unchanged x_A decreases

$$x_p \sim \frac{k}{\sqrt{S}}\, e^{y_1} \qquad x_A \sim \frac{k}{\sqrt{S}}\, e^{-y_2}$$

forward region ⟶ projectile parton with large LC momentum passes through soft gluon field of target, eikonal trajectory

d.o.f.: Wilson lines, $U(\vec{x}) = P\,\exp\left(-ig\int dx^-\,A^{+a}(x^-,\vec{x})\,t^a_{\mathcal{R}}\right)$

resum multiple scattering

cov. gauge field of target

structure of target encoded in Wilson line correlators (CGC):

$$S(\vec{x},\vec{y}) = \frac{1}{N_c}\left\langle \mathrm{tr}\, U(\vec{x})\, U^\dagger(\vec{y})\right\rangle \qquad \text{dipole}$$

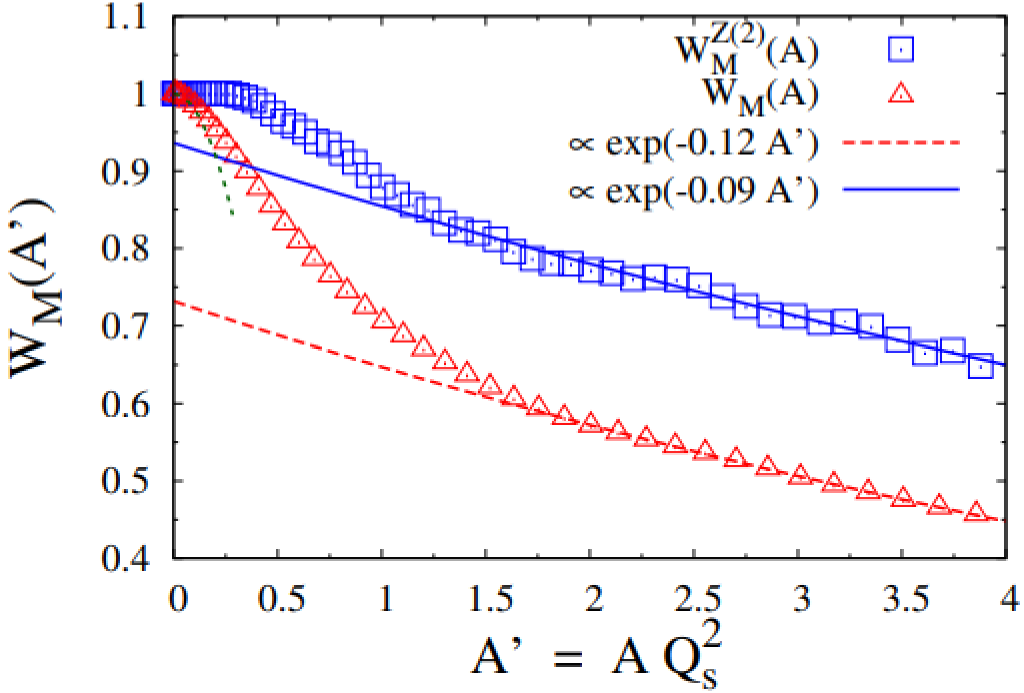
$$Q(\vec{x},\vec{y},\vec{u},\vec{w}) = \frac{1}{N_c}\langle \mathrm{tr}\; V_x V_y^\dagger V_u V_w^\dagger\rangle \qquad \text{quadrupole etc.}$$

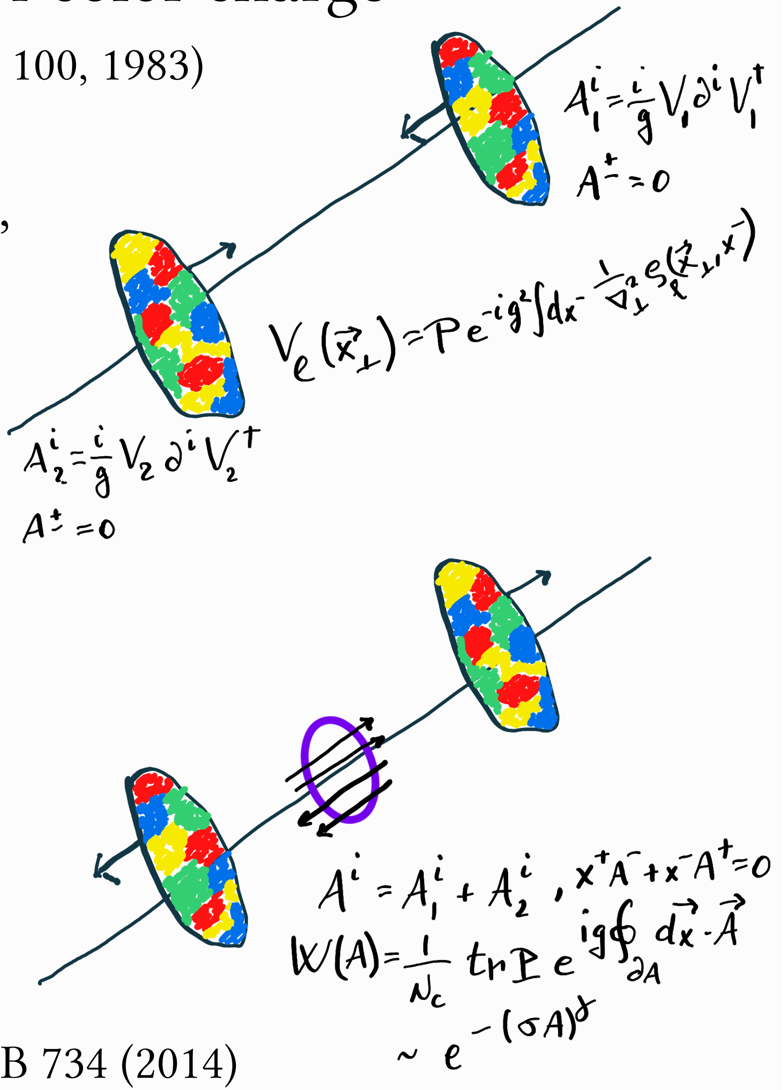
same d.o.f. / correlators that appear in DIS !

Digression: central region of colliding “sheets of color charge”

(sort of like setup of Gribov, Levin, Ryskin, Phys. Rept. 100, 1983)

Non-trivial spatial Wilson loop,
not the picture of “probe travels through target field”





$A_1^i = \frac{i}{g} V_1 \partial^i V_1^\dagger$

$A^\pm = 0$

$V_\ell(\vec{x}_\perp) = P e^{-ig^2 \int dx^- \frac{1}{\nabla_\perp^2} \rho_\ell(\vec{x}_\perp, x^-)}$

$A_2^i = \frac{i}{g} V_2 \partial^i V_2^\dagger$

$A^\pm = 0$

$A^i = A_1^i + A_2^i\ ,\ x^+ A^- + x^- A^+ = 0$

$W(A) = \frac{1}{N_c} \mathrm{tr}\, \mathbb{P}\, e^{ig \oint_{\partial A} d\vec{x} \cdot \vec{A}}$

$\sim e^{-(\sigma A)^\gamma}$

w/ Y. Nara & E. Petreska: PRD88 (2013); w/ T. Lappi & Y. Nara: PLB 734 (2014)

Evolution with x (or rapidity Y=log x_0/x) :

dipole (in large-Nc approx.): LL Balitsky-Kovchegov equation

$$\partial_Y S(\vec{x},\vec{y}) = \frac{\alpha_s N_c}{2\pi^2} \int d^2 z \, \frac{(\vec{x}-\vec{y})^2}{(\vec{x}-\vec{z})^2\,(\vec{z}-\vec{y})^2} \left[S(\vec{x},\vec{z})\, S(\vec{z},\vec{y}) - S(\vec{x},\vec{y})\right]$$

⟶ saturation scale Qs(x,A) where 1-S(r~2/Qs) = O(1)
⟶ anomalous dimension γ(r Qs)
⟶ note: evolution equation requires initial condition...

higher correlators: Balitsky hierarchy or JIMWLK

$$\langle \cdots \rangle = \int \mathcal{D}A^+ \, W_Y[A^+] \cdots$$

$$\partial_Y W_Y = -H_{\rm JIMWLK} \, W_Y$$

From here: rcBK, resum. of transverse logs, NLO

Single-inclusive X-section in the forward region of pA: "hybrid formalism"

LO: $$\frac{dN}{dy\, d^2p_T} = \frac{1}{(2\pi)^2} \sum_i \int f_i(x, Q^2) \otimes N_i(x, q_T) \otimes D_{i\to h}(Q^2, z)$$

A.D., Hayashigaki, Jalilian-Marian, NPA (2006)

dipole scattering amplitude

pT is acquired exclusively from scattering off the target shock wave

NLO: q ⟶ q+g (not coll. splitting), correction grows with pT

Altinoluk & Kovner, PRD83 (2011), Altinoluk et al, PRD91 (2015)
Chirilli, Xiao, Yuan, PRL 108 (2012), PRD86 (2012)
Stasto & Zaslavsky, PRL112 (2014), IJMPA31 (2016)
Iancu, Mueller, Triantafyllopoulos, JHEP12 (2016)
incl. jet in pA: L. Wang et al, PRD107 (2023); Liu, Xie, Kang, JHEP07 (2022)

Problem: obvious…

Resolution:

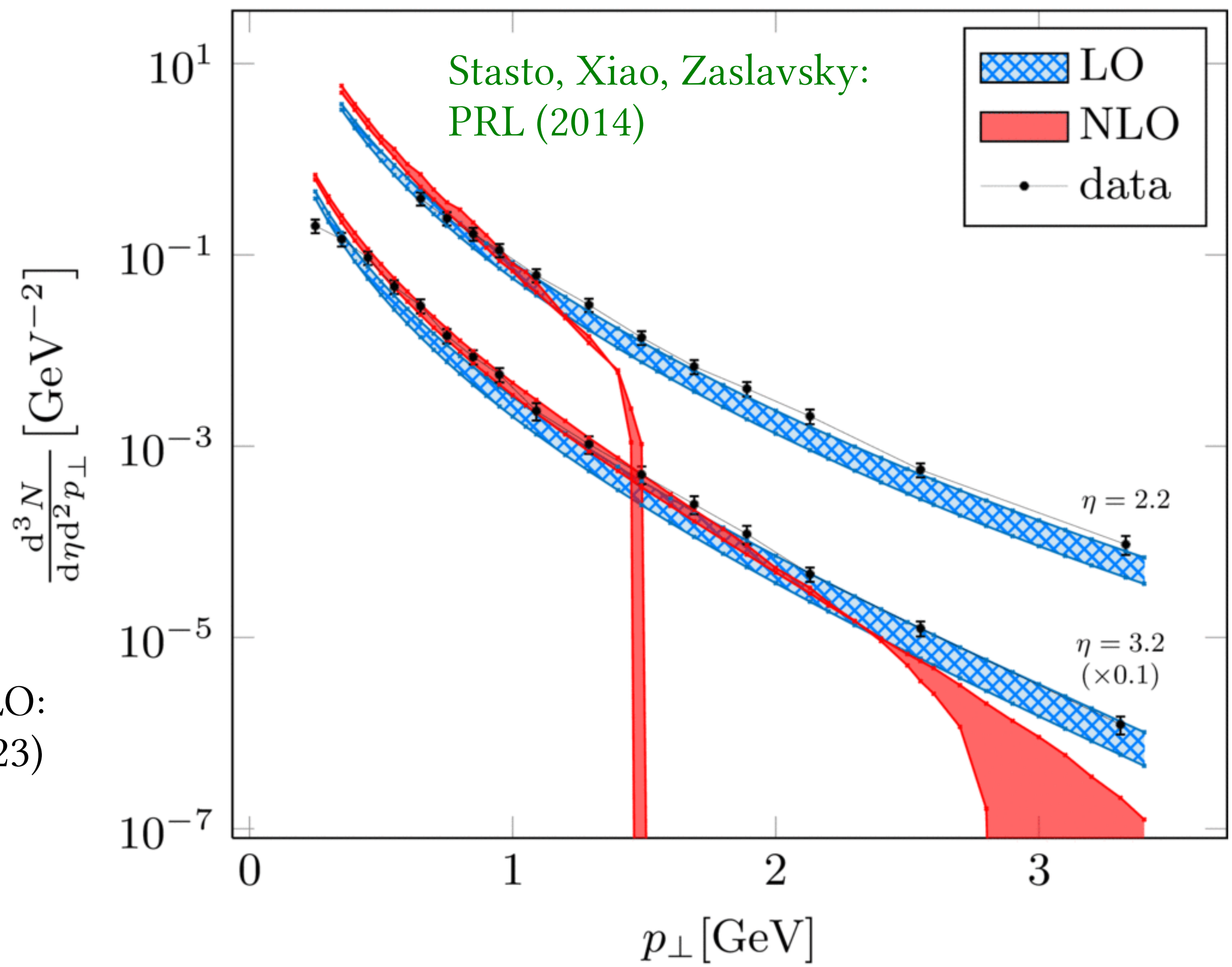
- corrected kinematics
- careful choice of rapidity cutoff
- Ioffe time cutoff
- threshold resummation

Lessons learned will benefit DIS,
working with same d.o.f.

single-inclusive production in DIS @NLO:
Bergabo & Jalilian-Marian, JHEP01 (2023)

γ-jet correlations: I. Kolbé et al,
JHEP01 (2021)

BRAHMS $\eta = 2.2, 3.2$



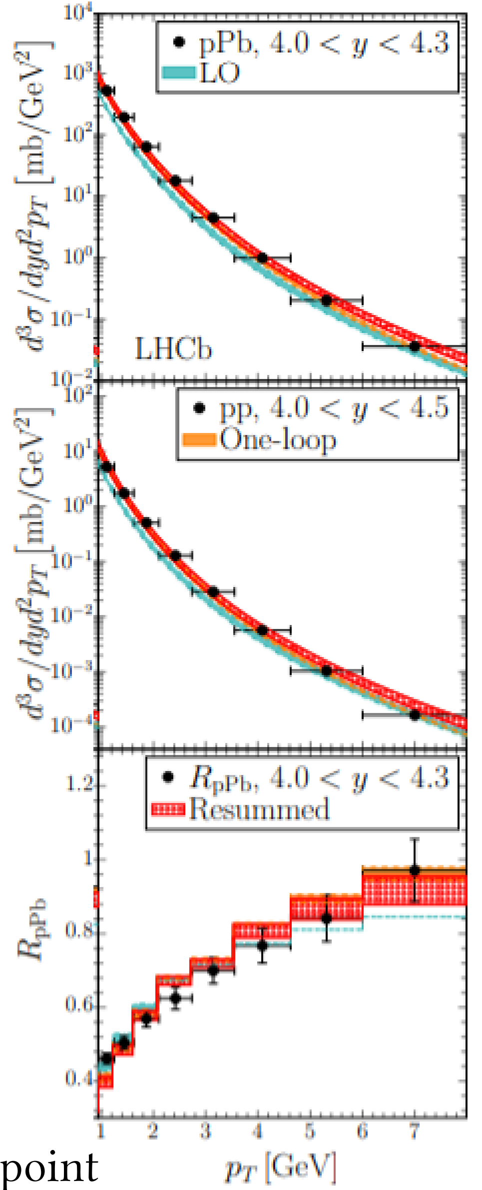
non-linear NLL QCD evolution,
charged particle production at NLO,
threshold resummation,
compared to LHCb data

figure from Shi, Wang, Wei, Xiao: arXiv:2112.06975

incorporates the growth of the scale of non-linearities (saturation momentum and of anomalous dimension)

- $Q_s^2 \sim A^{1/3}$ (McLerran & Venugopalan)
- $Q_s^2 \sim 1/x^\lambda$ (Mueller, Balitsky, Kovchegov)
- $\gamma(k_T, A)$ (Mueller, Triantafyllopoulos)

$$R_{pA} = \frac{1}{A}\,\frac{d\sigma^{pA\to h^\pm+X}/d^2p_T dy}{d\sigma^{pp\to h^\pm+X}/d^2p_T dy}$$



$$\leftarrow \left(\frac{k_T^2}{Q_{s,p}^2}\right)^{1-\gamma_A(k_T)} N_{\rm coll}^{\gamma_A(k_T)-1}$$

at small-x fixed point

Kharzeev, Levin, McLerran,
PLB 561 (2003)

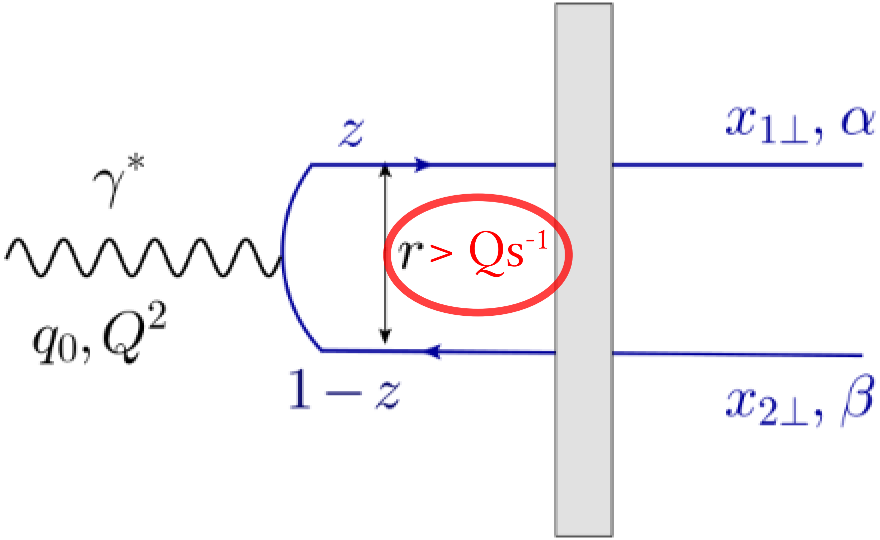
Small-x DIS at NLO:

- Boussarie, Grabovsky, Ivanov, Szymanowski, Wallon, PRL119 (2017); exclusive light VM
- Roy & Venugopalan, PRD101 (2020); incl. γ+dijet
- Caucal, Salazar, Venugopalan, JHEP11 (2021); incl. dijet
  Caucal, Salazar, Schenke, Venugopalan, JHEP11 (2022); back-2-back dijets
- Taels, Altinoluk, Beuf, Marquet, JHEP10 (2022); dijet photoproduction
- Bergabo & Jalilian-Marian, 2207.03606, 2301.03117; dihadrons
- Iancu & Mulian, 2211.04837; real corrections to dihadron
- Iancu, Mueller, Triantafyllopoulos, Wei, PRL128 (2022), JHEP10 (2022); diffr. 2+1 jets (hard q, qbar; semi-hard gluon ~ Qs)
- Fucilla, Grabovsky, Li, Szymanowski, Wallon, 2211.05774; diffractive dihadrons
- Mäntysaari & Penttala, PLB823 (2021), JHEP08 (2022);Exclusive heavy VM production
- Mäntysaari & Penttala, 2211.03504; NLO structure fcts w/ heavy quarks
- Beuf, Lappi, Paatelainen, PRD104 (2021), PRL129 (2022), PRD106 (2022); NLO dipole factorization w/ massive quarks

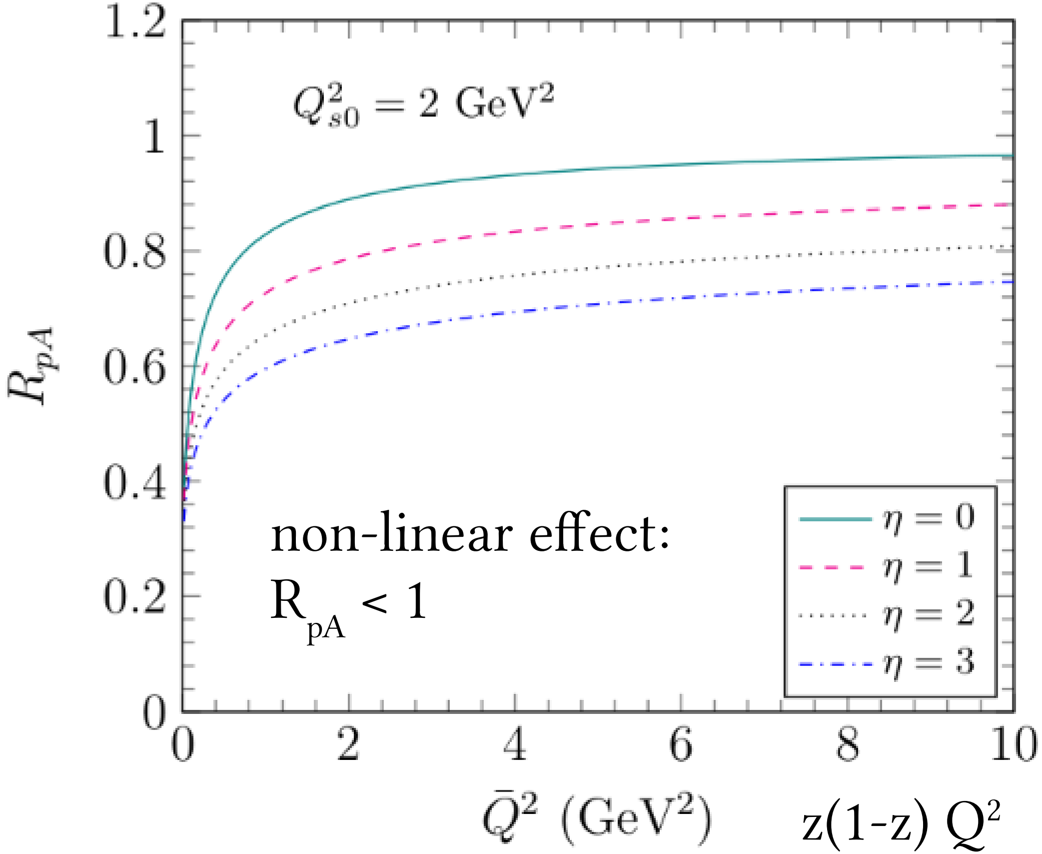
SIDIS (jets) at very forward rapidities & saturation

Iancu, Mueller, Triantafyllopoulos, Wei, JHEP07 (2021)

$$Q^2 \gg Q_s^2, \quad z(1-z)Q^2 < Q_s^2$$



* large-z jet / hadron probes
non-linear regime at high Q^2

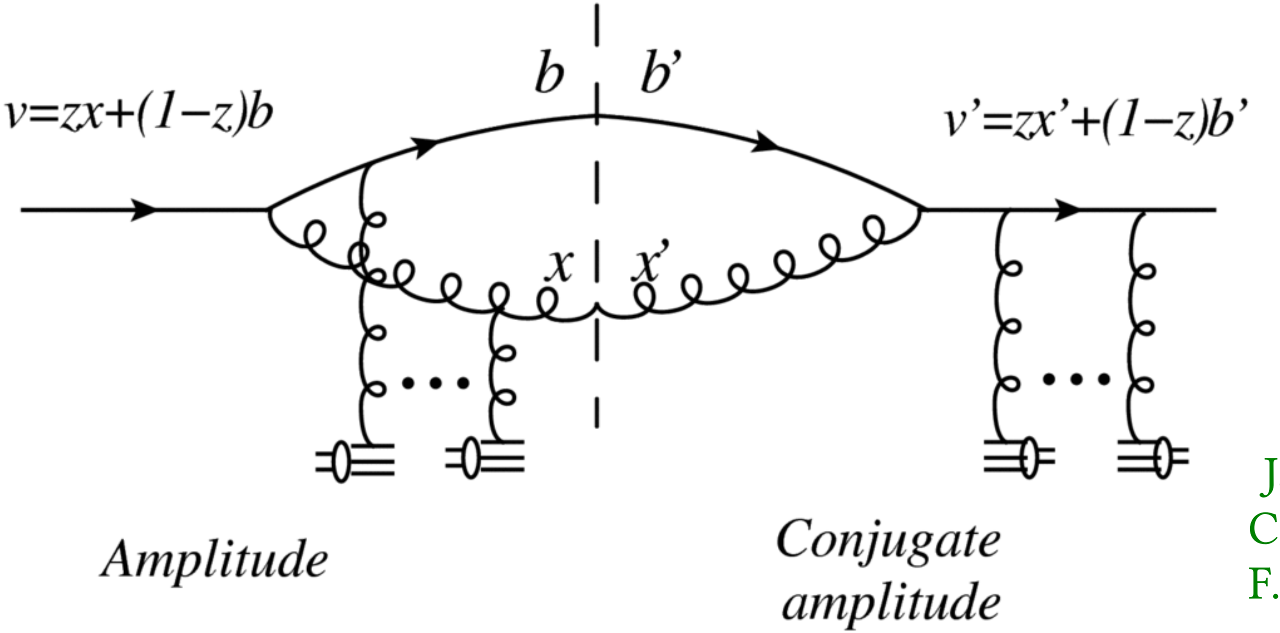


non-linear effect:
$R_{pA} < 1$

Di- hadron/jet angular correlations in pA

involves new objects (higher n-point functions) such as quadrupole:

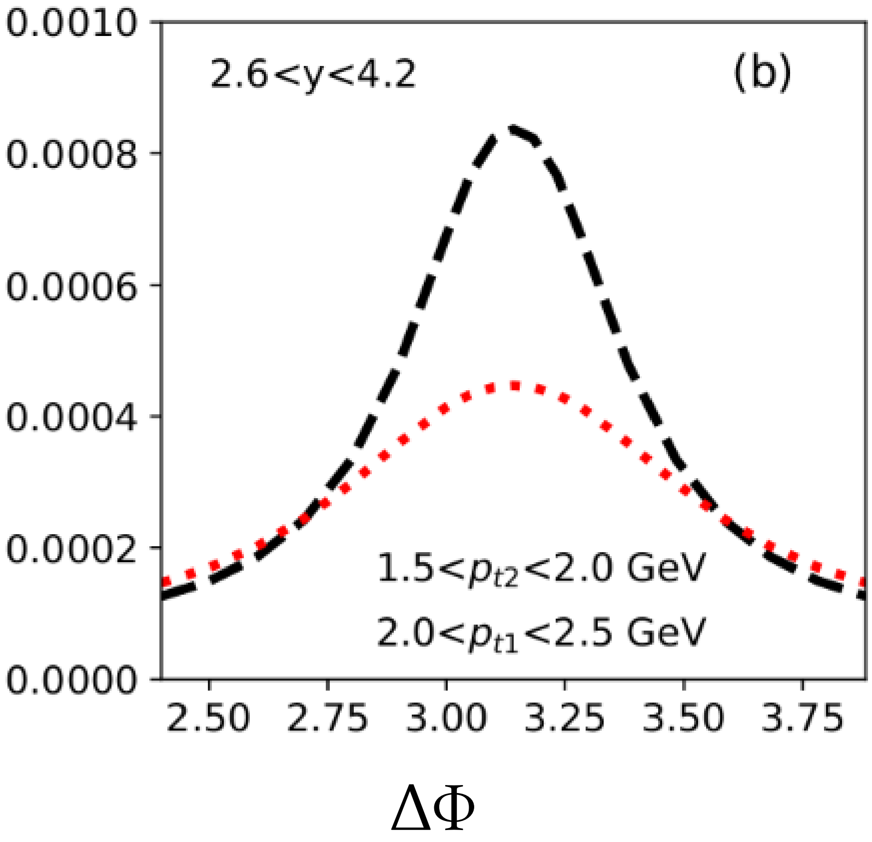
$$Q \equiv \frac{1}{N_c}\langle \mathrm{tr}\ V_x V_y^\dagger V_u V_w^\dagger \rangle$$ etc.

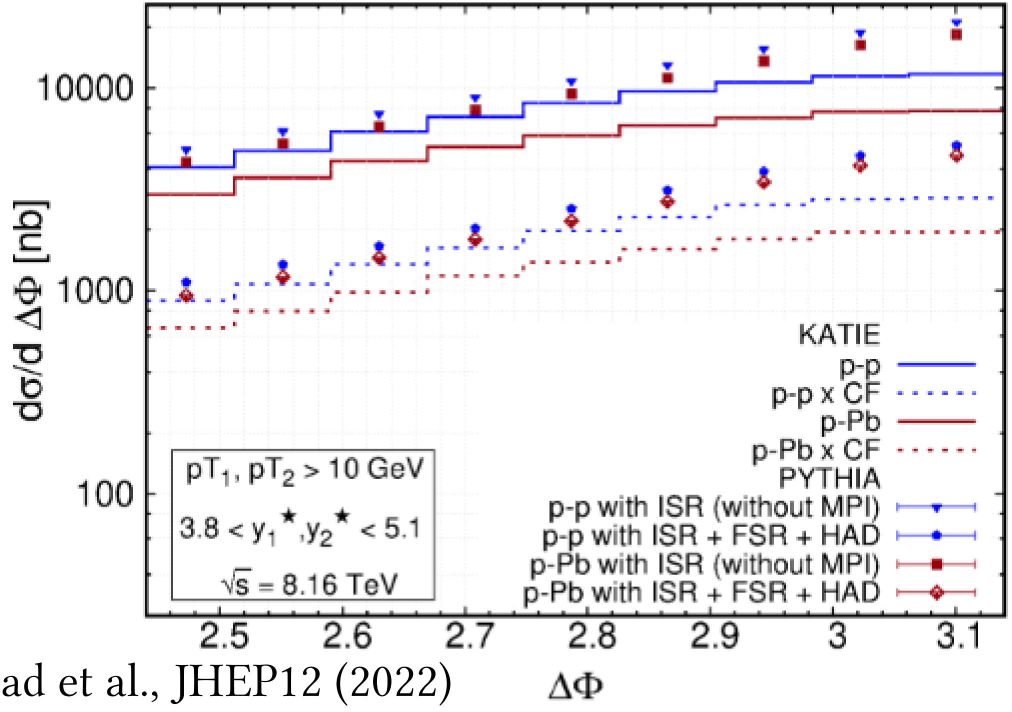


Jalilian-Marian & Kovchegov: PRD (2004)
C. Marquet: NPA (2007)
F. Dominguez et al.: PRD (2011)

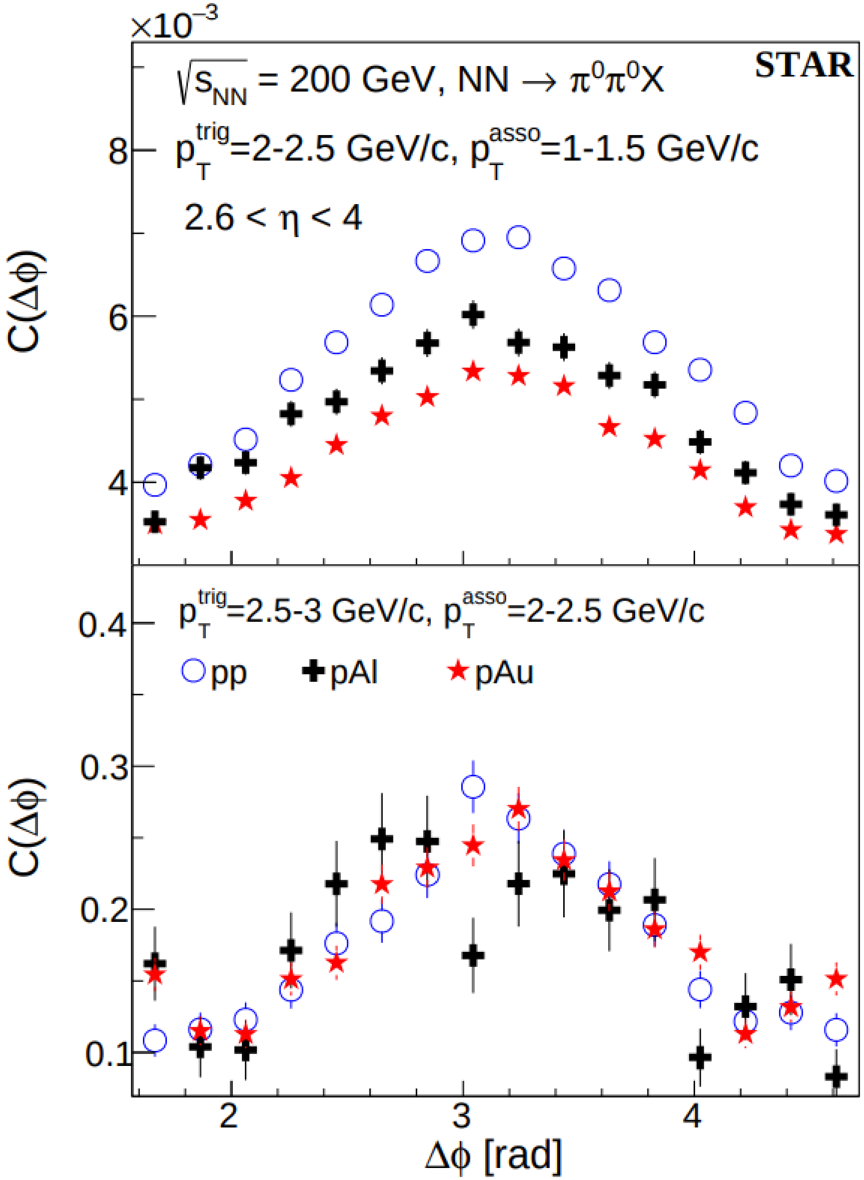
Angular decorrelation for dense target (pp vs. pA)

Albacete, Marquet: PRL 2010
Stasto, Xiao, Yuan: arXiv:1109.1817
Lappi, Mantysaari: 2012
← Albacete, Giacalone, Marquet, Matas,
PRD99 (2019)

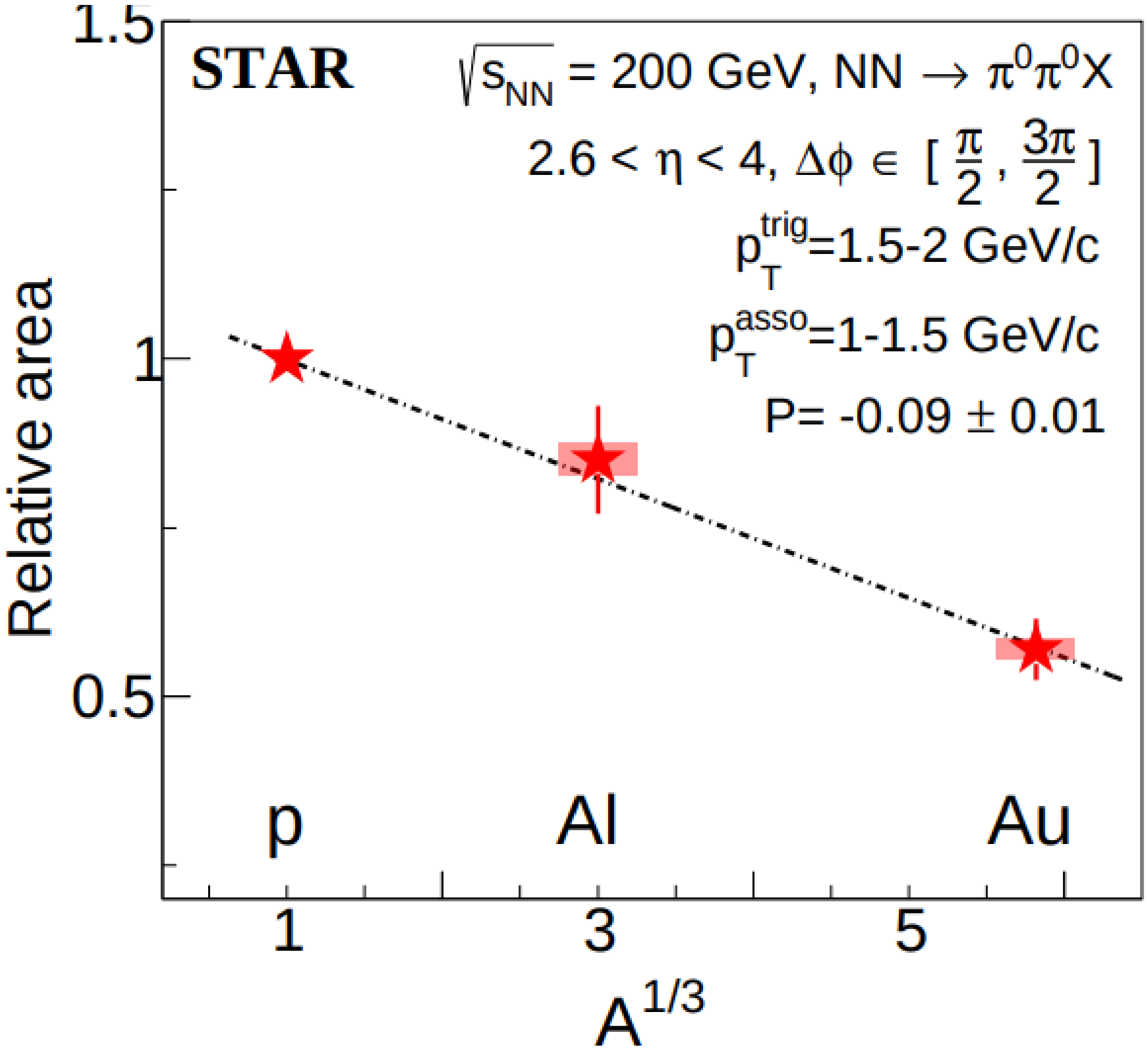




dijets @LHC →
Abdullah Al-Mashad et al., JHEP12 (2022)


×10⁻³
STAR
$\sqrt{s_{NN}}$ = 200 GeV, NN → $\pi^0\pi^0X$
p_T^{trig}=2-2.5 GeV/c, p_T^{asso}=1-1.5 GeV/c
2.6 < η < 4
8
6
4
C(Δφ)
p_T^{trig}=2.5-3 GeV/c, p_T^{asso}=2-2.5 GeV/c
○ pp
✚ pAl
★ pAu
0.4
0.3
0.2
0.1
C(Δφ)
2
3
4
Δφ [rad]

PRL 129 (2022)


STAR
$\sqrt{s_{NN}}$ = 200 GeV, NN → $\pi^0\pi^0X$
2.6 < η < 4, Δφ ∈ [$\frac{\pi}{2}$, $\frac{3\pi}{2}$]
p_T^{trig}=1.5-2 GeV/c
p_T^{asso}=1-1.5 GeV/c
P= -0.09 ± 0.01
1.5
1
0.5
Relative area
p
Al
Au
1
3
5
$A^{1/3}$

Dijet in small-x DIS: the TMD connection

$$\gamma^* + p/A \to j_{q_1} + j_{q_2} + X \ , \qquad \vec{Q}_\perp = (\vec{q}_1 - \vec{q}_2)/2 \ , \quad \vec{k}_\perp = \vec{q}_1 + \vec{q}_2$$

near back-to-back limit, high Q⊥: CGC Dipole, Quadrupole ↔ WW TMD(s)

Dominguez, Marquet, Xiao, Yuan, PRD83 (2011)
Dominguez, Qiu, Xiao, Yuan, PRD85 (2012)

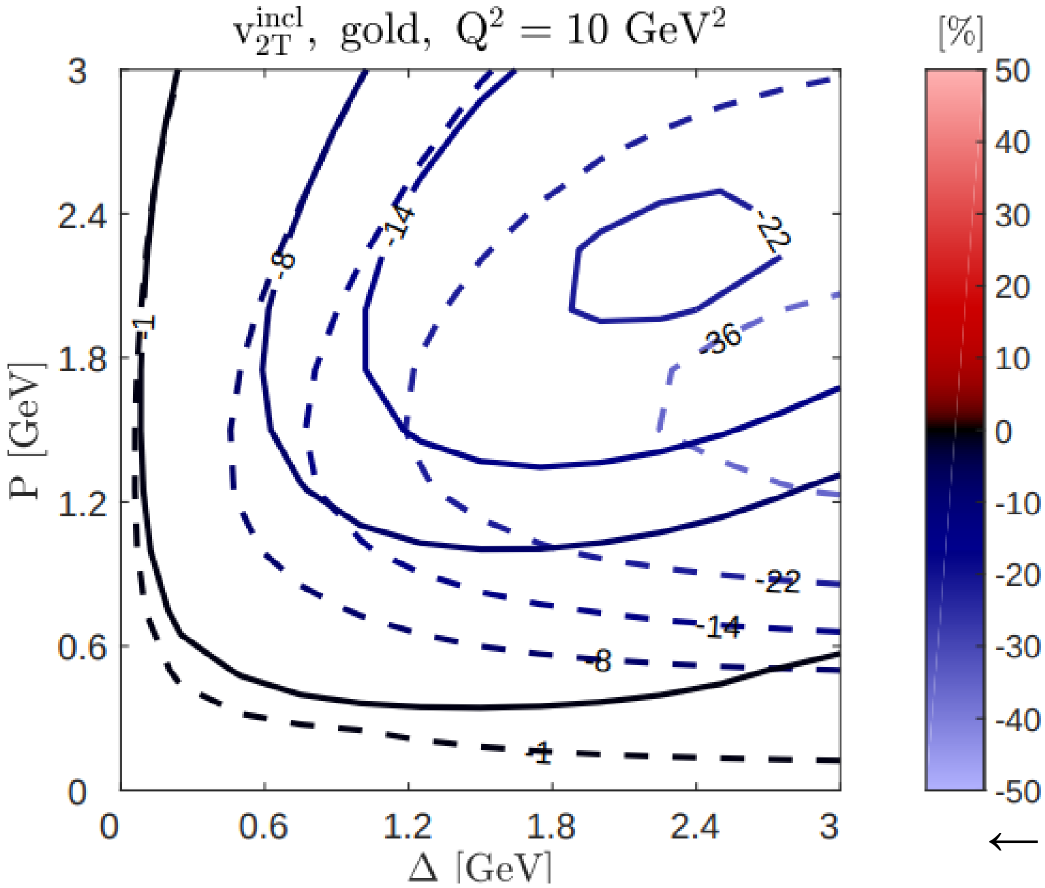
$$d\sigma_{\rm CGC} = \underbrace{d\sigma_{\rm TMD} + \overbrace{\mathcal{O}\left(\frac{k_\perp}{Q_\perp}\right)}^{\text{kinematic}}}_{d\sigma_{\rm ITMD}} + \overbrace{\mathcal{O}\left(\frac{Q_s}{Q_\perp}\right)}^{\text{genuine}} ,$$

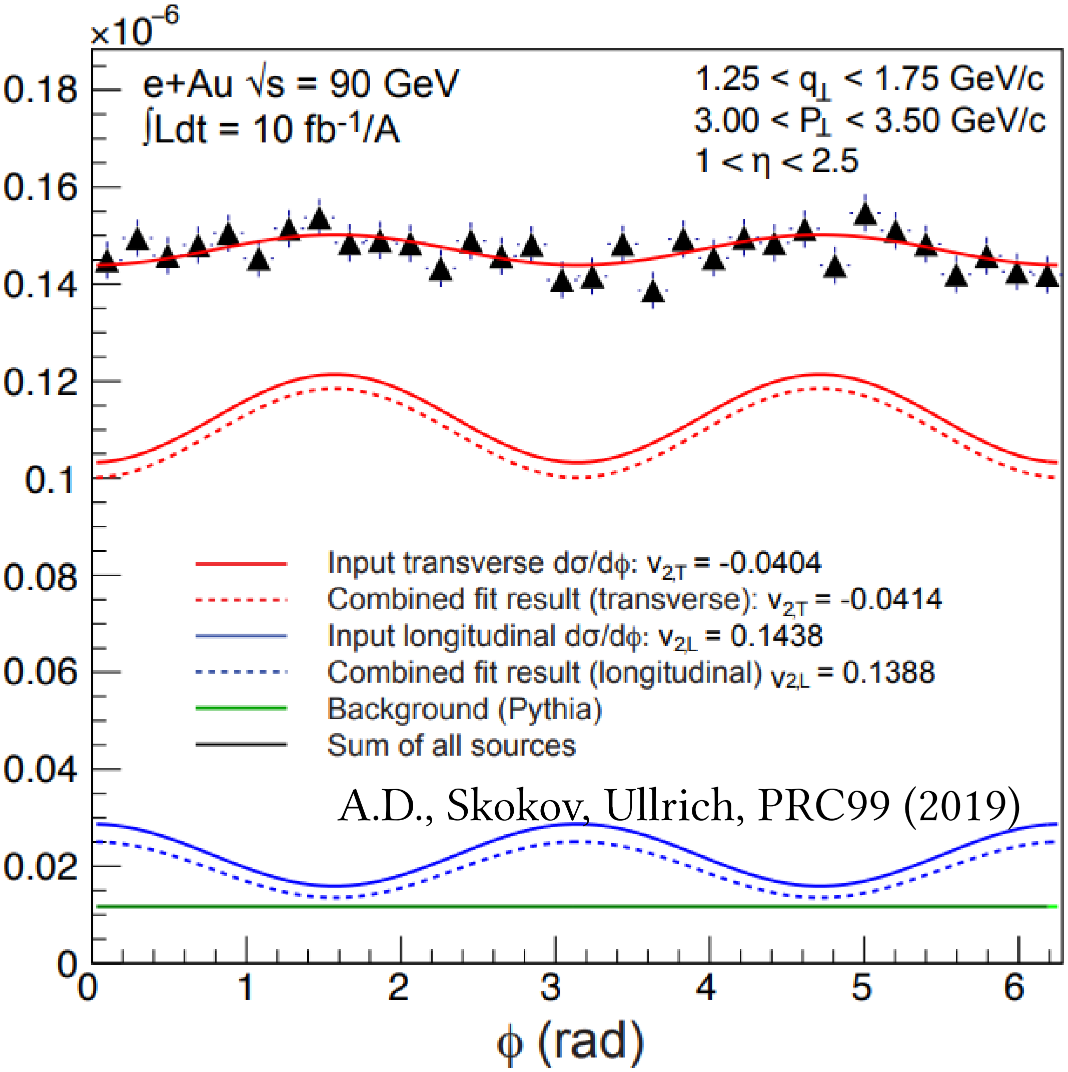
Boussarie et al, JHEP05 (2019),
JHEP10 (2019), JHEP09 (2021)
$Q\overline{Q}$ in DIS, pA: Altinoluk, Marquet, Taels,
JHEP06 (2021)

CGC ⟶ WW TMD(s) $xG(x,k_\perp^2)$, $xh(x,k_\perp^2)$ at small x:

Metz & Zhou, PRD84 (2011); MV model
A.D., Lappi, Skokov, PRL115 (2015); JIMWLK // A.D. & Skokov, PRD94 (2016), pwr correction
Marquet, Petreska, Roiesnel, JHEP10 (2016); JIMWLK // Albacete et al (2019), *op. cit.*; rcBK

~ cos(2Φ) azimuthal dependence
due to lin. polarized gluons
$[\ \Phi = \angle(\vec{Q}_\perp, \vec{k}_\perp)\ ]$





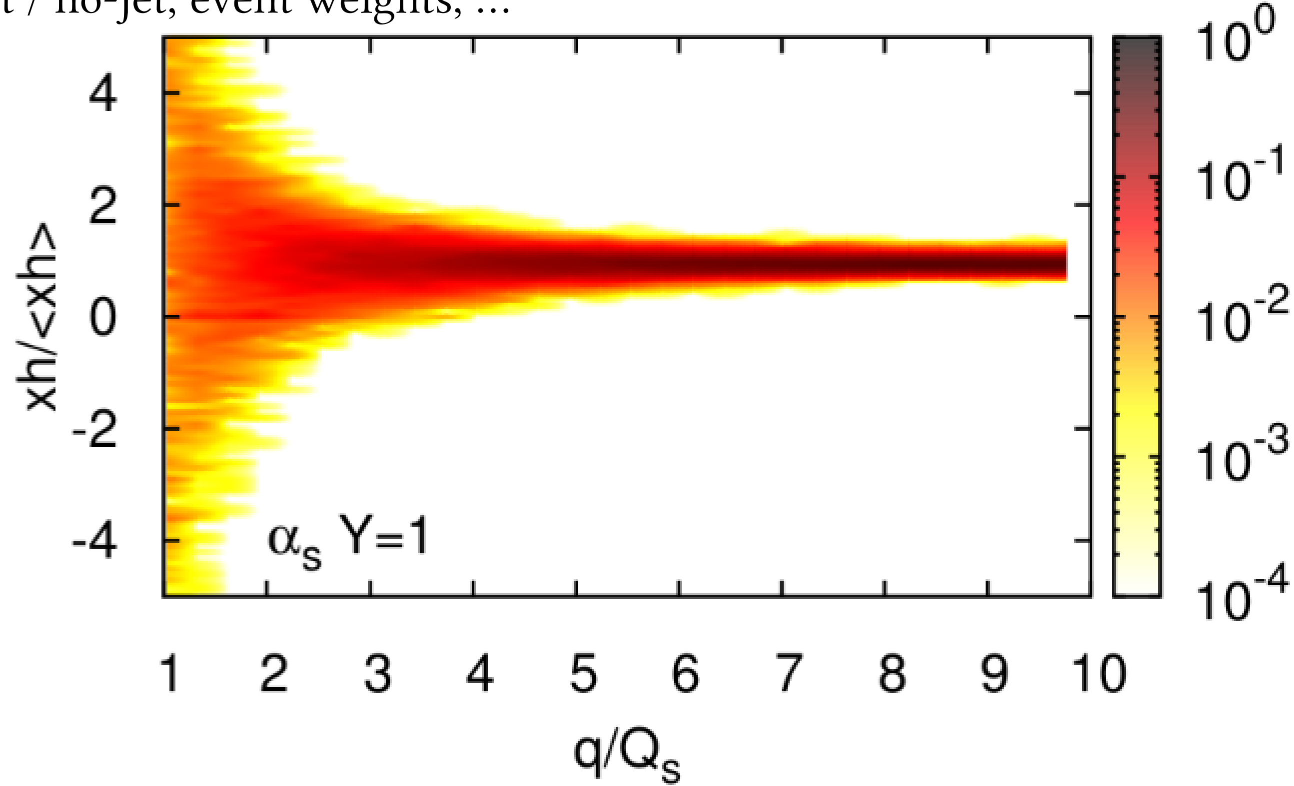
A.D., Skokov, Ullrich, PRC99 (2019)

← Mantysaari, Mueller, Salazar, Schenke, PRL124 (2020)

Reweighting techniques ?

$$\langle O \rangle = \int DA^+ \, W_Y[A^+] \, O[A^+] \;\rightarrow\; \langle O \rangle_w = \int DA^+ \, W_Y[A^+] \, w[A^+] \, O[A^+]$$

experimentally: high mult., high E_T, jet / no-jet, event weights, ...

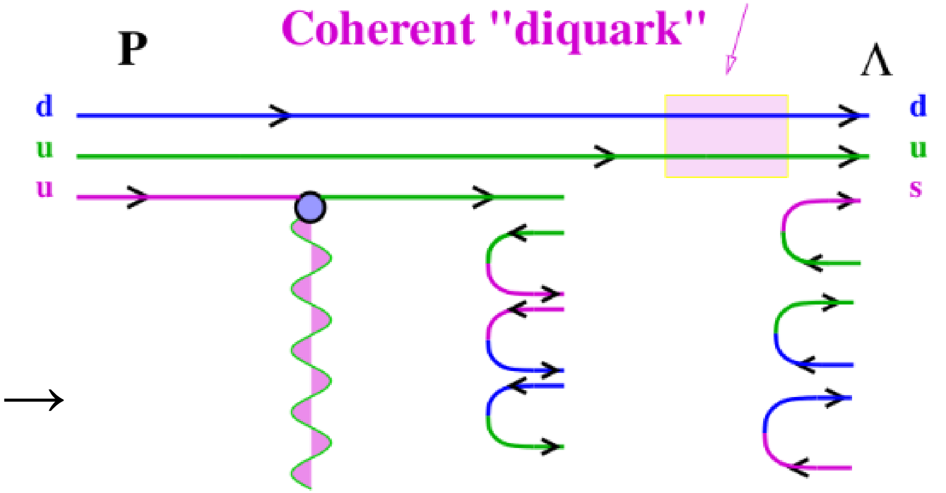


Example: functional distribution of lin. pol. WW xh(x,k) in LL JIMWLK ensemble (V. Skokov, 2017)

Proton fragmentation in pp / pA & DIS (high mult.) ? :

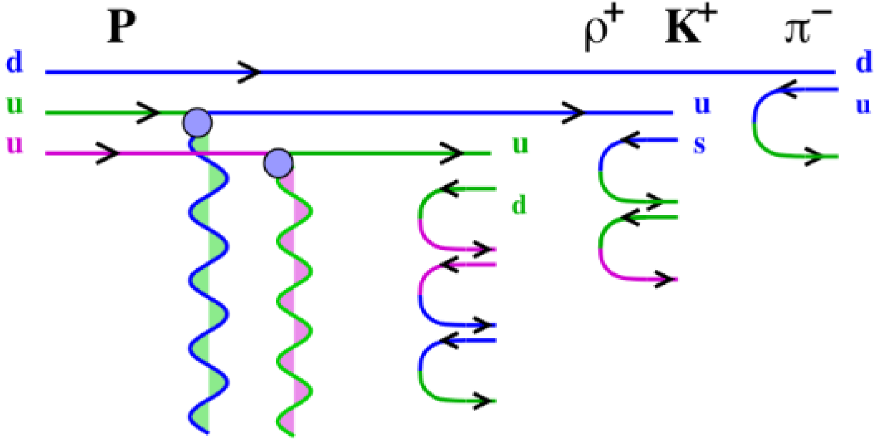
(Yu. Dokshitzer, hep-ph/0106348, 0306287
M. Strikman et al, 1996 – today)

typical inelastic p+p produces leading baryon ⟶
(leading particle effect)

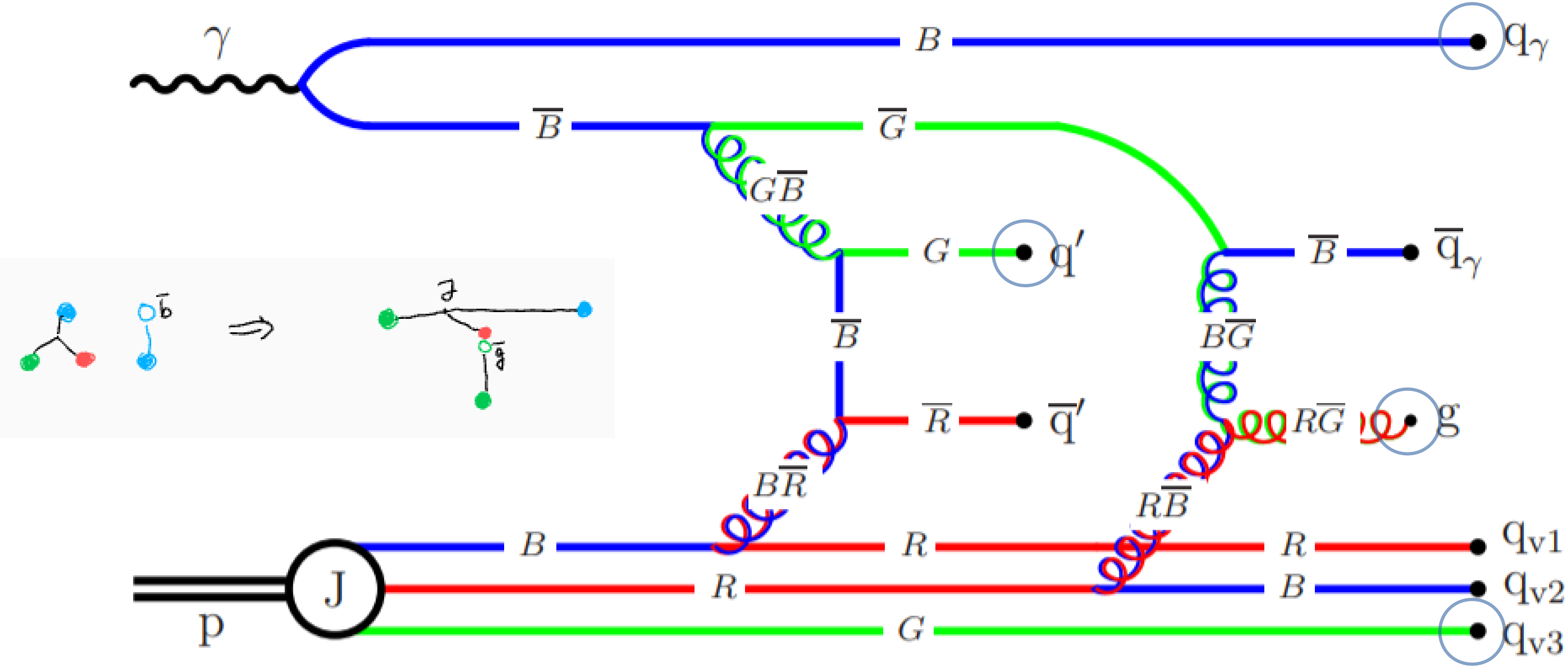


If the proton passes through a **strong** field it should "decay" into a beam of leading mesons ⟶

This is not "stopping": $t \longrightarrow -p_T^2$ at high E,
light-cone momentum is conserved !



Also, baryon junction models: γ-p w/ double parton interaction in Pythia :

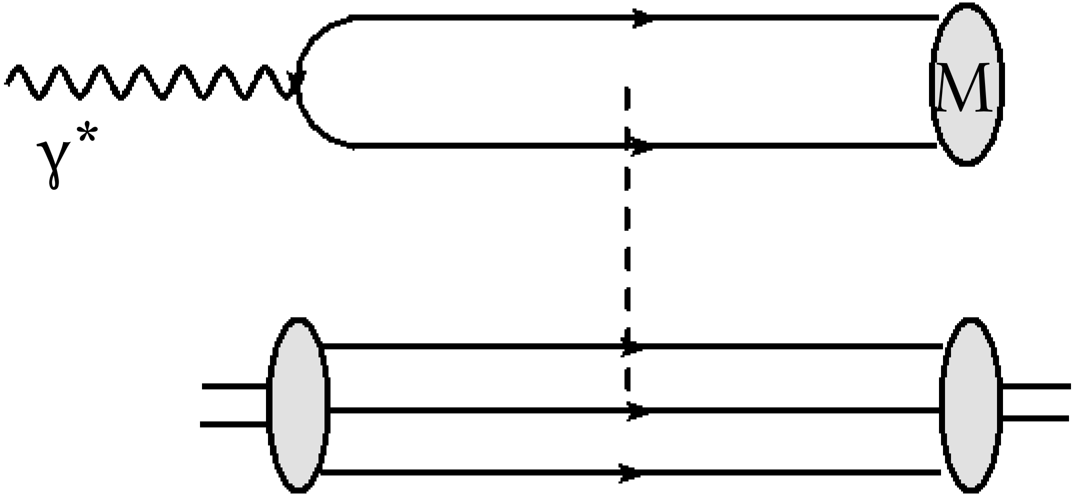


* The three circled quarks are at the endpoints of the strings that join in a junction (gluon viewed as a "kink" on the string)

(Sjöstrand & Skands, hep-ph/0402078)

Exclusive processes, diffraction, rapidity gaps:

$|\langle\mathcal{A}\rangle|^2$ vs. $\left\langle|\mathcal{A}|^2\right\rangle$



- impact parameter dependence (GPDs)
- hot spot fluctuations in the proton
- C-odd singlet exchange / Odderon
- diffr. structure functions
- rapidity gap distributions
- diffr. mass distributions
- ...

$$x = \frac{Q^2 + M^2}{W^2 + Q^2 - m_p^2}$$

$$-t_{\min} = \left[\frac{Q^2 + M^2}{W^2/m_p}\right]^2$$

Summary “low-x and forward physics” :

- forward region: kinematic asymmetry $x_P >> x_T$
- eikonal propagation through target, resummation of mult. scattering
- d.o.f. = Wilson lines, X-sec ~ Wilson line correlators, universal description of p+p, p+A, UPC, DIS
- connection to TMDs

- single & double inclusive production probes non-linear QCD evolution exciting data on angular correlations in p+A from STAR!
- much recent work to push theory to NLO accuracy

Snowmass 2021, 2022 White Papers:

M. Begel et al., 2209.14872; M. Hentschinski et al., 2203.08129

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Thank you !

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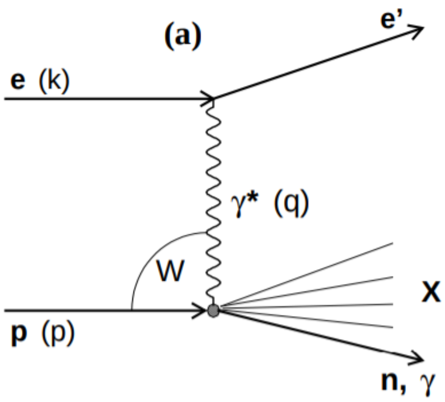
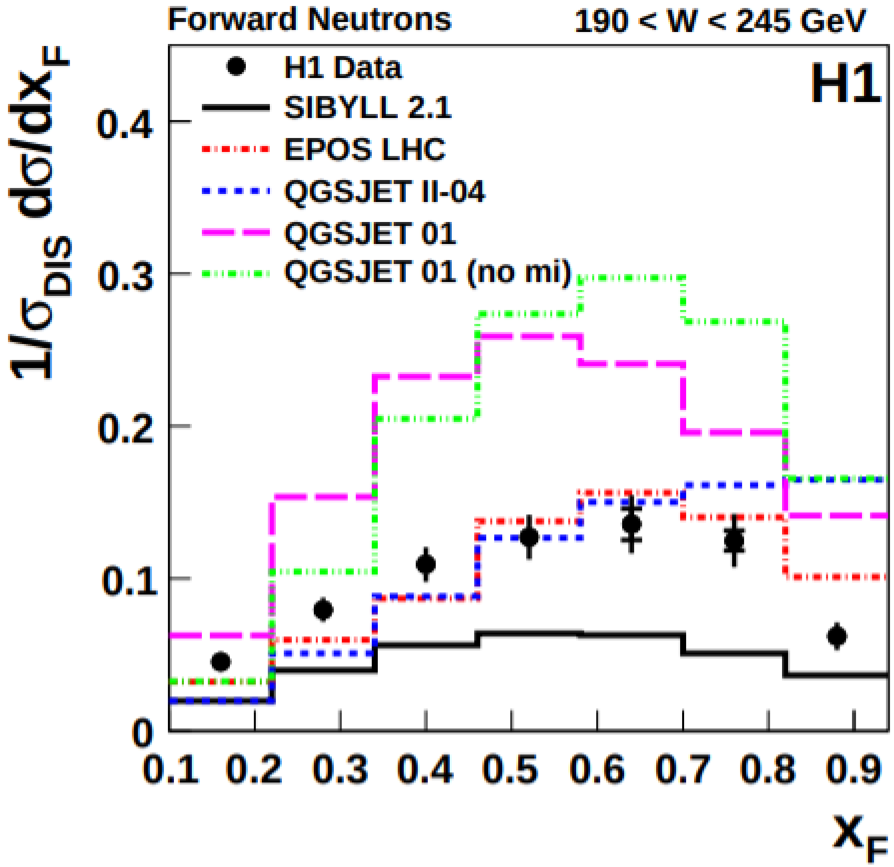
Backup

Forward neutrons in DIS (H1 collab.: 1404.0201)





<table>
<tr><th colspan="2">NC DIS Selection</th></tr>
<tr><td colspan="2">$6 < Q^2 < 100 \text{ GeV}^2$
$0.05 < y < 0.6$
$70 < W < 245$ GeV</td></tr>
<tr><th>Forward photons</th><th>Forward neutrons</th></tr>
<tr><td>$\eta > 7.9$
$0.1 < x_F < 0.7$
$0 < p_T^* < 0.4$ GeV</td><td>$\eta > 7.9$
$0.1 < x_F < 0.94$
$0 < p_T^* < 0.6$ GeV</td></tr>
<tr><th colspan="2">W ranges for cross sections $\frac{1}{\sigma_{DIS}} \frac{d\sigma}{dx_F}$</th></tr>
<tr><td colspan="2">$70 < W < 130$ GeV
$130 < W < 190$ GeV
$190 < W < 245$ GeV</td></tr>
</table>