Saturation: Recent Developments, New Ideas and Measurements

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BROOKHAVEN NATIONAL LABORATORY

Synergies of pp and pA Collisions with an Electron-Ion Collider
RIKEN BNL Research Center Workshop
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Saturation: Recent Developments,
New Ideas and Measurements
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RIKEN BNL Research Center

- Small x evolution and hadron production at NLO
- Spin at small x
- TMD physics
- Small-x physics in e+p and e+A DIS
- Particle production in pA
- Correlations

27 Presentations in 3 days

I. Balitsky ....*Higher-twist corrections to gluon TMD factorization*
G. Beuf ....*Full NLO corrections for DIS structure functions in the dipole factorization formalism*
S. Caron-Huot ....*Linear and nonlinear small-x evolution in perturbation theory*
S. Caron-Huot ....*Nuclear Theory/RIKEN Seminar: Analyticity in Spin and Causality in Conformal Theories*
G. Chirilli..................*Rapidity factorization of high-energy scattering processes at NLO*
A. Dumitru...............*Fluctuations of the gluon distribution at small-x: correlation of multiplicity and transverse momentum fluctuations*
K. Dusling ....*Collectivity from the initial state: four-particle correlations in proton-nucleus collisions*
K. Fukushima ....*Particle production in CGC*
E. Iancu ....*Particle production in proton-nucleus collisions beyond leading order*
J. Jia ....*Flow in small systems*
D. Kharzeev.............*Deep inelastic scattering as a probe of entanglement*
Y. Kovchegov...........*Small-x asymptotics of the quark helicity distribution*
A. Kovner.................*Exploring correlations in the CGC wave function: odd azimuthal anisotropy*
M. Lublinsky ....*From light-cone wave function to NLO JIMWLK*
D. Neill ....*Finding small-x like evolution in QCD final state dynamics: the problem of non-global logarithms*
P. Newman...............*Low-x physics and saturation studies for the Large Hadron Electron Collider*
A. Ogawa..................*Polarized p+A physics at forward rapidity at STAR*
R. Paatelainen ....*Toward higher-order accuracy in LCPT*
T. Peitzmann............*Opportunities for forward photon measurements in ALICE at the LHC*
A. Rezaeian...............*Elliptic flow from color-dipole orientation in pp and pA collisions*
C. Royon...................*Forward jets at HERA and Mueller-Navelet and jet gap jet events at Tevatron and LHC*
B. Schenke................*Subnucleonic fluctuations, diffraction, and small-x evolution*
S. Schlichting............*Event-by-event pre-equilibrium dynamics — from gluon saturation toward the onset of hydrodynamics*
M. Sievert.................*Quark helicity evolution at small-x*
A. Stasto....................*Low-x physics and prompt neutrino production*
D. Tapia-Takaki........*Studying gluon saturation and nuclear effects using forward heavy-ion probes and UPCs at LHC*
R. Venugopalan ....*Ridge-like correlations in small systems: status and problems*

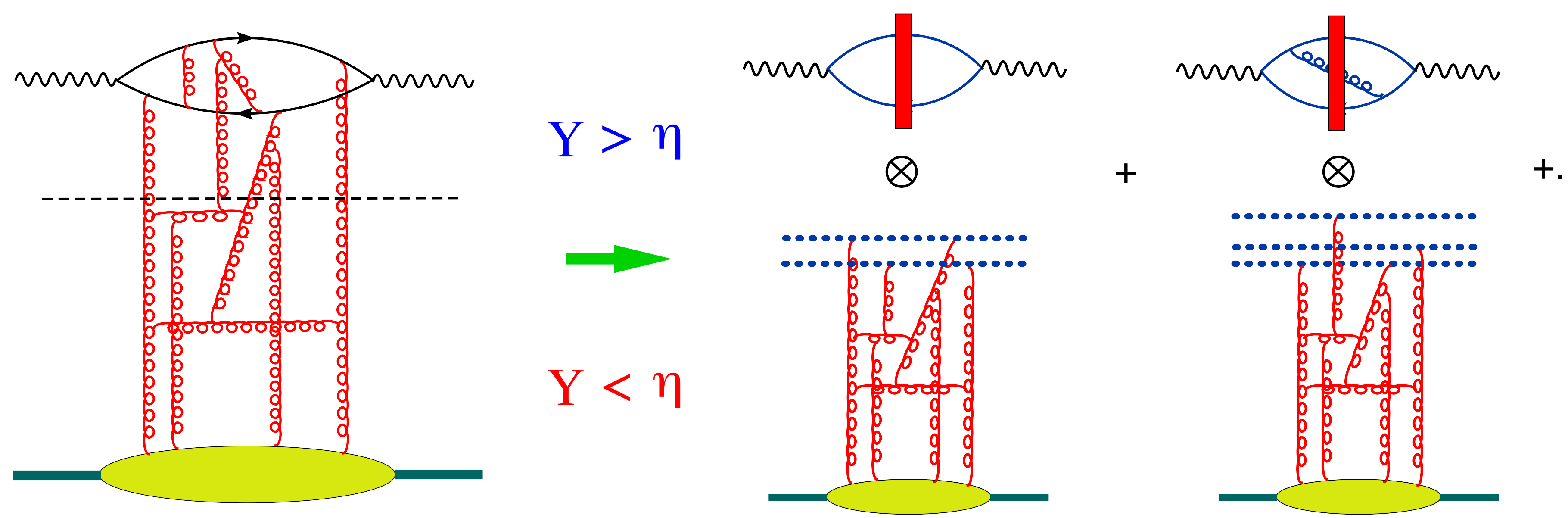
Giovanni Antonio Chirilli

Rapidity factorization of high-energy scattering processes at NLO

Rapidity factorization approach

Fast fields are quantum fields

Slow fields are classical fields



I. Balitsky, G.A. Chirilli

$$T\{\hat{j}_\mu(x)\hat{j}_\nu(y)\} = \int d^2z_1 d^2z_2\; I^{\rm LO}_{\mu\nu}(z_1,z_2,x,y)\mathrm{tr}[\{\hat{U}^\eta_{z_1}\hat{U}^{\dagger\eta}_{z_2}\}]^{\rm conf}$$

$$+\int d^2z_1 d^2z_2 d^2z_3\; I^{\rm NLO}_{\mu\nu}(z_1,z_2,z_3,x,y)[\frac{1}{N_c}\mathrm{tr}\{\hat{U}^\eta_{z_1}\hat{U}^{\dagger\eta}_{z_3}\}\mathrm{tr}\{\hat{U}^\eta_{z_3}\hat{U}^{\dagger\eta}_{z_2}\} - \mathrm{tr}\{\hat{U}^\eta_{z_1}\hat{U}^{\dagger\eta}_{z_2}\}]$$

Impact factor

Wilson lines

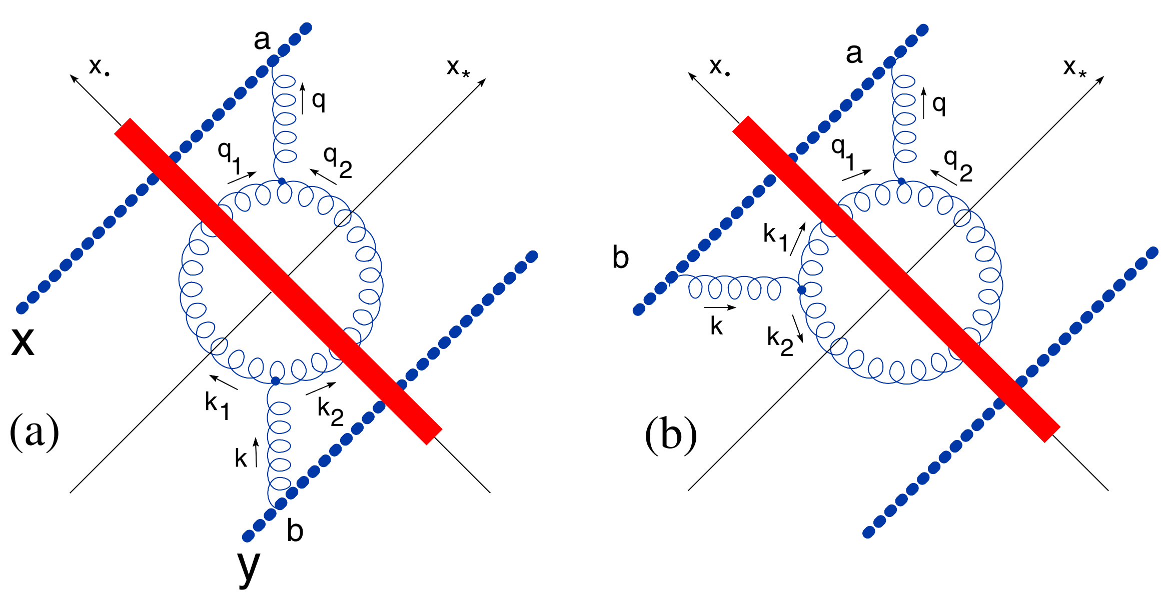
Giovanni Antonio Chirilli

Rapidity factorization of high-energy scattering processes at NLO

NLO evolution of conformal dipoles in QCD

$$
\begin{aligned}
2a\frac{d}{da}[\mathrm{tr}\{\hat U_{z_1}U^\dagger_{z_2}\}]^{\rm conf} =\ & \frac{\alpha_s}{2\pi^2}\int d^2z_3\ \Big([\mathrm{tr}\{\hat U_{z_1}\hat U^\dagger_{z_3}\}\mathrm{tr}\{\hat U_{z_3}\hat U^\dagger_{z_2}\} - N_c\mathrm{tr}\{\hat U_{z_1}\hat U^\dagger_{z_2}\}]^{\rm conf}\\
& \times\frac{z_{12}^2}{z_{13}^2z_{23}^2}\Big[1+\frac{\alpha_sN_c}{4\pi}\Big(b\ln z_{12}^2\mu^2 + b\frac{z_{13}^2-z_{23}^2}{z_{13}^2z_{23}^2}\ln\frac{z_{13}^2}{z_{23}^2}+\frac{67}{9}-\frac{\pi^2}{3}\Big)\Big]\\
& + \frac{\alpha_s}{4\pi^2}\int\frac{d^2z_4}{z_{34}^4}\Big\{\Big[-2+\frac{z_{14}^2z_{23}^2+z_{24}^2z_{13}^2-4z_{12}^2z_{34}^2}{2(z_{14}^2z_{23}^2-z_{24}^2z_{13}^2)}\ln\frac{z_{14}^2z_{23}^2}{z_{24}^2z_{13}^2}\Big]\\
& \times[\mathrm{tr}\{\hat U_{z_1}\hat U^\dagger_{z_3}\}\mathrm{tr}\{\hat U_{z_3}\hat U^\dagger_{z_4}\}\{\hat U_{z_4}\hat U^\dagger_{z_2}\} - \mathrm{tr}\{\hat U_{z_1}\hat U^\dagger_{z_3}\hat U_{z_4}\hat U^\dagger_{z_2}\hat U_{z_3}\hat U^\dagger_{z_4}\} - (z_4\to z_3)]\\
& + \frac{z_{12}^2z_{34}^2}{z_{13}^2z_{24}^2}\Big[2\ln\frac{z_{12}^2z_{34}^2}{z_{14}^2z_{23}^2}+\Big(1+\frac{z_{12}^2z_{34}^2}{z_{13}^2z_{24}^2-z_{14}^2z_{23}^2}\Big)\ln\frac{z_{13}^2z_{24}^2}{z_{14}^2z_{23}^2}\Big]\\
& \times[\mathrm{tr}\{\hat U_{z_1}\hat U^\dagger_{z_3}\}\mathrm{tr}\{\hat U_{z_3}\hat U^\dagger_{z_4}\}\mathrm{tr}\{\hat U_{z_4}\hat U^\dagger_{z_2}\} - \mathrm{tr}\{\hat U_{z_1}\hat U^\dagger_{z_4}\hat U_{z_3}\hat U^\dagger_{z_2}\hat U_{z_4}\hat U^\dagger_{z_3}\} - (z_4\to z_3)]\Big\}
\end{aligned}
$$

I. Balitsky, G.A. Chirilli



This result was obtained in rapidity factorization approach

What about other operators?

Michael Lublinsky

From light-cone wave function to NLO JIMWLK

Presented new results on calculation of H at NLO order

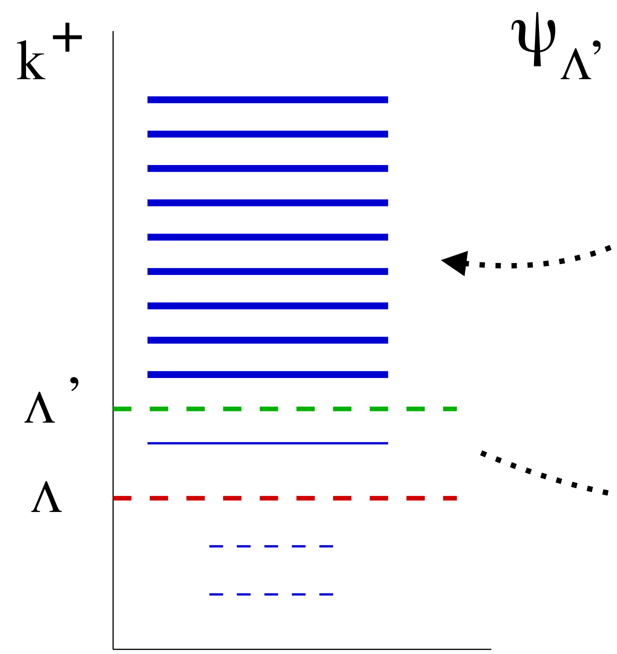
The result can be used for any operator

$$\partial_Y \left[S^{ab}(x)\right] = -H^{\text{NLO JIMWLK}} \left[S^{ab}(x)\right]$$

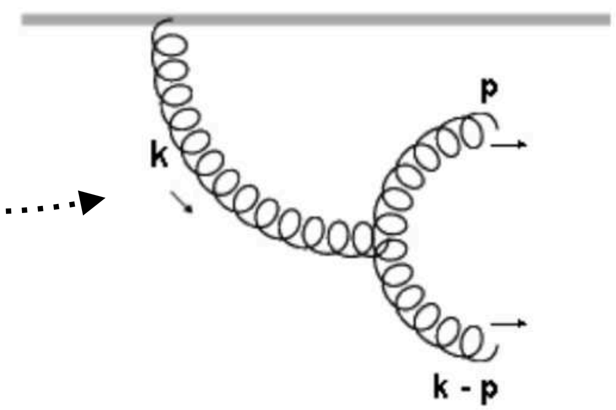
$$\partial_Y \left[S^{ab}(x) S^{cd}(y)\right] = -H^{\text{NLO JIMWLK}} \left[S^{ab}(x) S^{cd}(y)\right]$$

$$\partial_Y \left[S^{ab}(x) S^{cd}(y) S^{ef}(z)\right] = -H^{\text{NLO JIMWLK}} \left[S^{ab}(x) S^{cd}(y) S^{ef}(z)\right]$$

The form of the operator was first obtained by comparison with other results



Shock-wave



A. Kovner, M. Lublinsky, Y. Mulian

Consider gluon emission at NLO

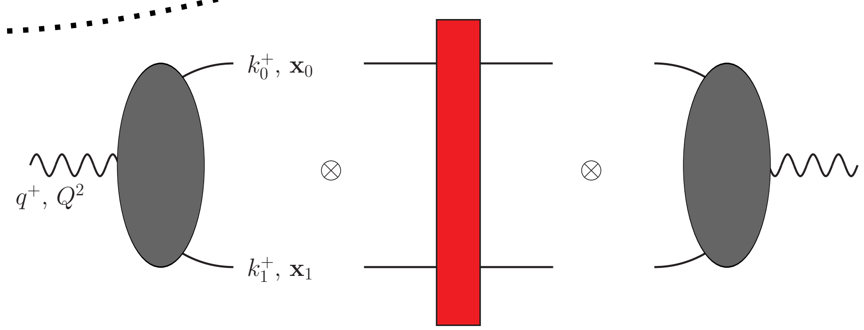
$$|\Psi_{NLO}\rangle = \mathcal{N}\,|0\rangle + \sum_i |i\rangle \Bigg[-\frac{\langle i|\,H_{int}\,|0\rangle}{E_i} + \frac{\langle i|\,H_{int}\,|j\rangle\,\langle j|\,H_{int}\,|0\rangle}{E_i\,E_j} + \\ + \frac{\langle i|\,H_{int}\,|0\rangle\,\langle j|\,H_{int}\,|0\rangle^2\,(2\,E_j - E_i)}{2\,E_i^2\,E_j^2} - \frac{\langle i|\,H_{int}\,|j\rangle\,\langle j|\,H_{int}\,|k\rangle\,\langle k|\,H_{int}\,|0\rangle}{E_i\,E_j\,E_k} \Bigg]$$

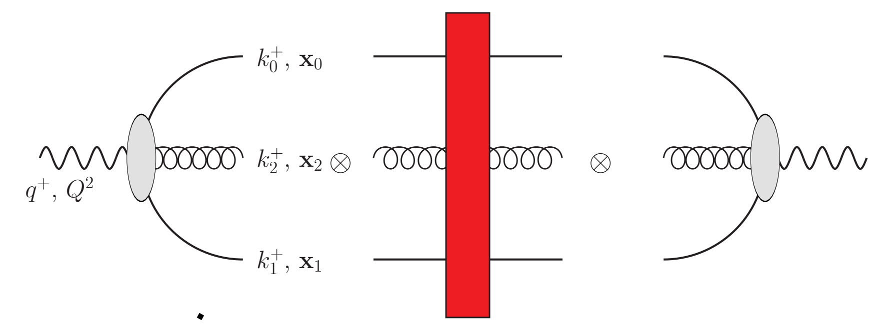
Guillaume Beuf
Full NLO corrections for DIS structure functions in the dipole factorization formalism

Now the evolution at NLO is known. What about observables?

$$
\begin{aligned}
\sigma_\lambda^\gamma &= 2N_c \widetilde{\sum_{q_0\bar{q}_1 \text{ F. states}}} \frac{2\pi\delta(k_0^+ + k_1^+ - q^+)}{2q^+} \left|\widetilde{\psi}_{\gamma_\lambda \to q_0\bar{q}_1}\right|^2 \mathrm{Re}\left[1 - \mathcal{S}_{01}\right] \\
&+ 2N_c C_F \widetilde{\sum_{q_0\bar{q}_1 g_2 \text{ F. states}}} \frac{2\pi\delta(k_0^+ + k_1^+ + k_2^+ - q^+)}{2q^+} \\
&\times \left|\widetilde{\psi}_{\gamma_\lambda \to q_0\bar{q}_1 g_2}\right|^2 \mathrm{Re}\left[1 - \mathcal{S}_{012}^{(3)}\right] + \cdots
\end{aligned}
$$

Calculated LF wave function





Demanding calculation with cumbersome expressions

Showed cancellation of UV divergencies

Typical diagram

Explicit dependence on the cut-off parameter

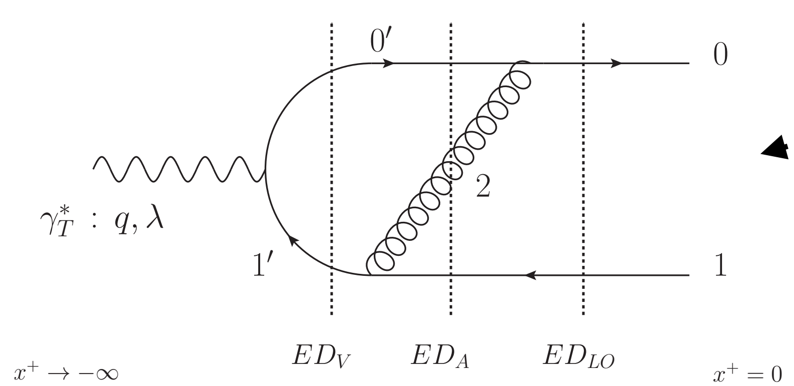
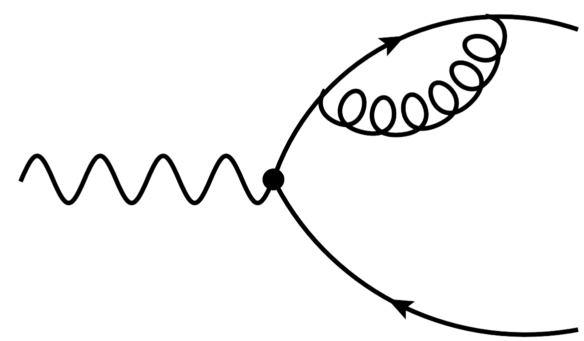


Diagram 1

Risto Paatelainen
Towards higher-order accuracy in LCPT

LCPT calculations in CGC slowly approaching the NLO level. Perturbative computation of wave functions is quite tedious (hard to automatize)

Introduce a new helicity formulation for LCPT. Perturbative (NLO) computation of wave functions is easy and can be fully automatized



One should take care of UV divergencies. Applied new Four Dimensional Helicity (FDH) scheme (T. Lappi & R. Paatelainen)

$$\psi^{\gamma_{\mathrm{T}}^{*}\to q\bar{q}}_{(\text{full})}\bigg|_{\mathrm{FDH}} = \psi^{\gamma_{\mathrm{T}}^{*}\to q\bar{q}}_{\mathrm{LO}}(\mathbf{p},z)\left(\frac{g_{\mathrm{R}}^{2}C_{\mathrm{F}}}{8\pi^{2}}\right)\left\{\left[\frac{3}{2}+\log\left(\frac{\alpha}{z}\right)+\log\left(\frac{\alpha}{1-z}\right)\right]C_{\text{full}} + \frac{1}{2}\log^{2}\left(\frac{z}{1-z}\right)-\frac{\pi^{2}}{3}+\frac{5}{2}-\log(z(1-z))\right\}+\left(\frac{g_{\mathrm{R}}^{2}C_{\mathrm{F}}}{8\pi^{2}}\right)\times\Pi+\mathcal{O}(\varepsilon)$$

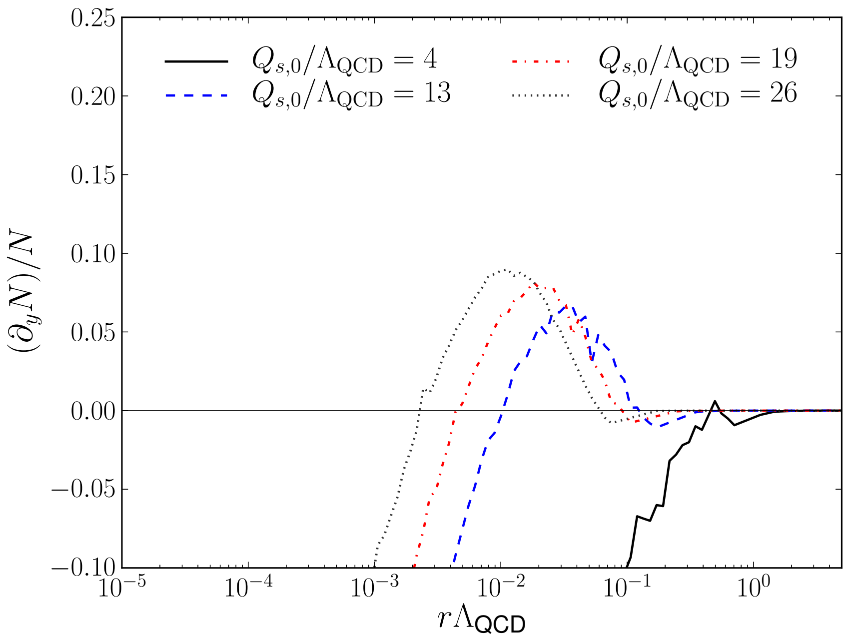
Results from two different schemes

$$\psi^{\gamma_{\mathrm{T}}^{*}\to q\bar{q}}_{(\text{full})}\bigg|_{\mathrm{CDR}} = \psi^{\gamma_{\mathrm{T}}^{*}\to q\bar{q}}_{\mathrm{LO}}(\mathbf{p},z)\left(\frac{g_{\mathrm{R}}^{2}C_{\mathrm{F}}}{8\pi^{2}}\right)\left\{\left[\frac{3}{2}+\log\left(\frac{\alpha}{z}\right)+\log\left(\frac{\alpha}{1-z}\right)\right]C_{\text{full}} + \frac{1}{2}\log^{2}\left(\frac{z}{1-z}\right)-\frac{\pi^{2}}{3}+\frac{5}{2}+\frac{1}{2}\right\}+\mathcal{O}(\varepsilon)$$

Edmond Iancu

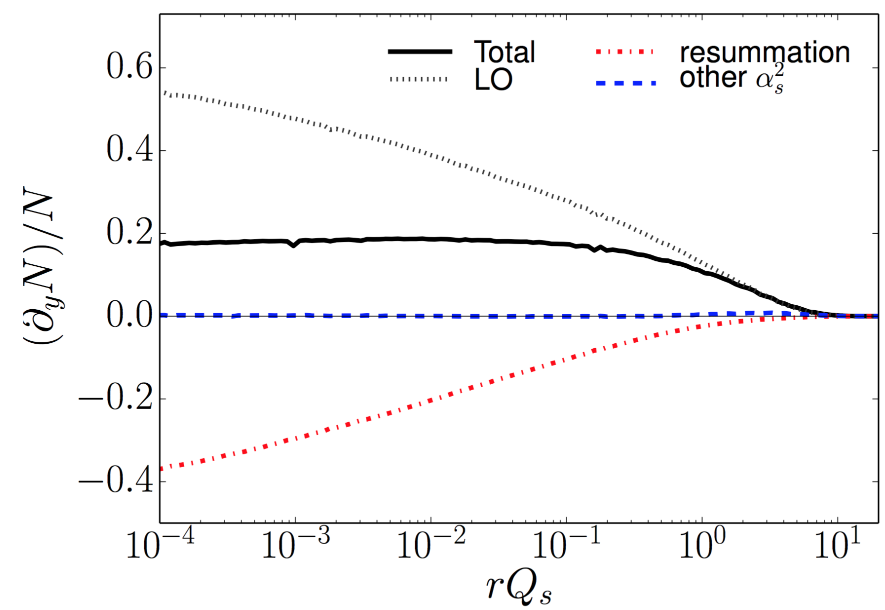
Particle production in pA collisions beyond leading order

"Negative growth" of the dipole scattering amplitude



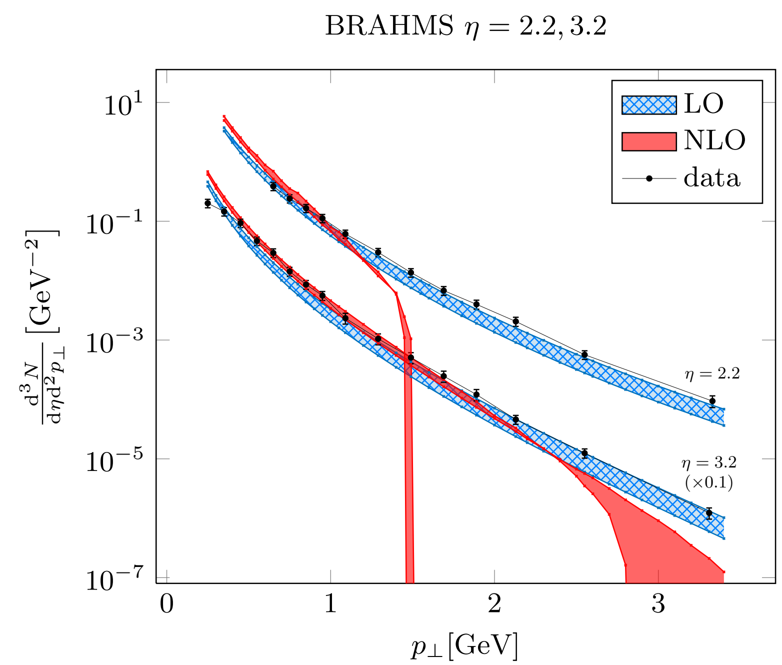
Lappi, Mäntysaari, arXiv:1502.02400

Collinear improvement of NLO BK



Lappi, Mäntysaari, arXiv:1601.06598

Negative at large p_T



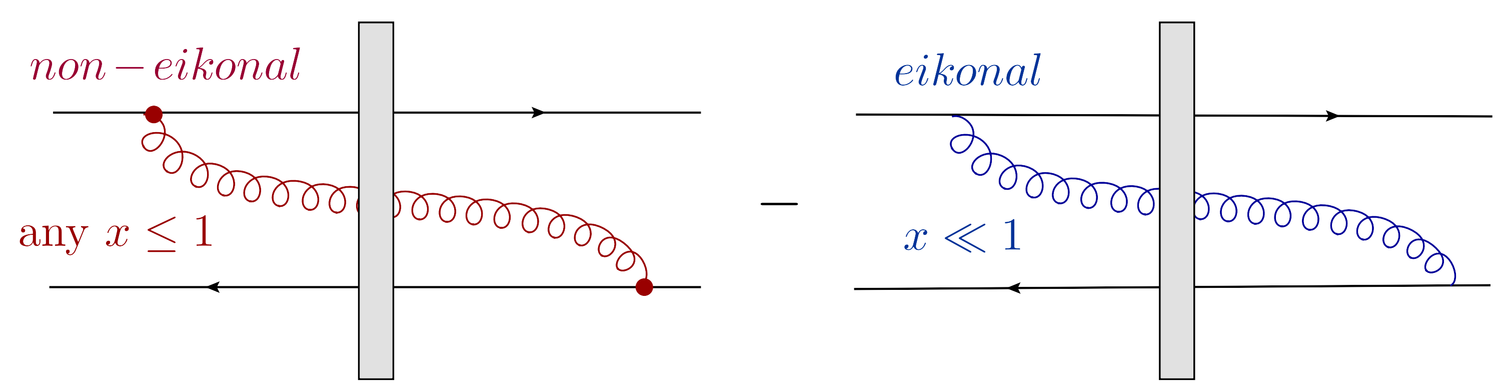
Stasto, Xiao, and Zaslavsky, arXiv:1307.4057

Rapidity subtraction in NLO impact factor

Kang, Vitev, and Xing, arXiv:1403.5221

Altinoluk, Armesto, Beuf, Kovner, and Lublinsky, arXiv:1411.2869

Ducloué, Lappi, and Zhu, arXiv:1604.00225

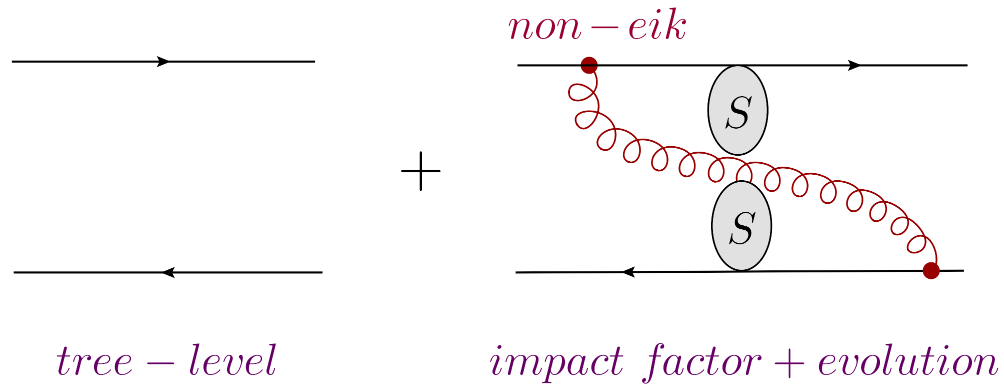


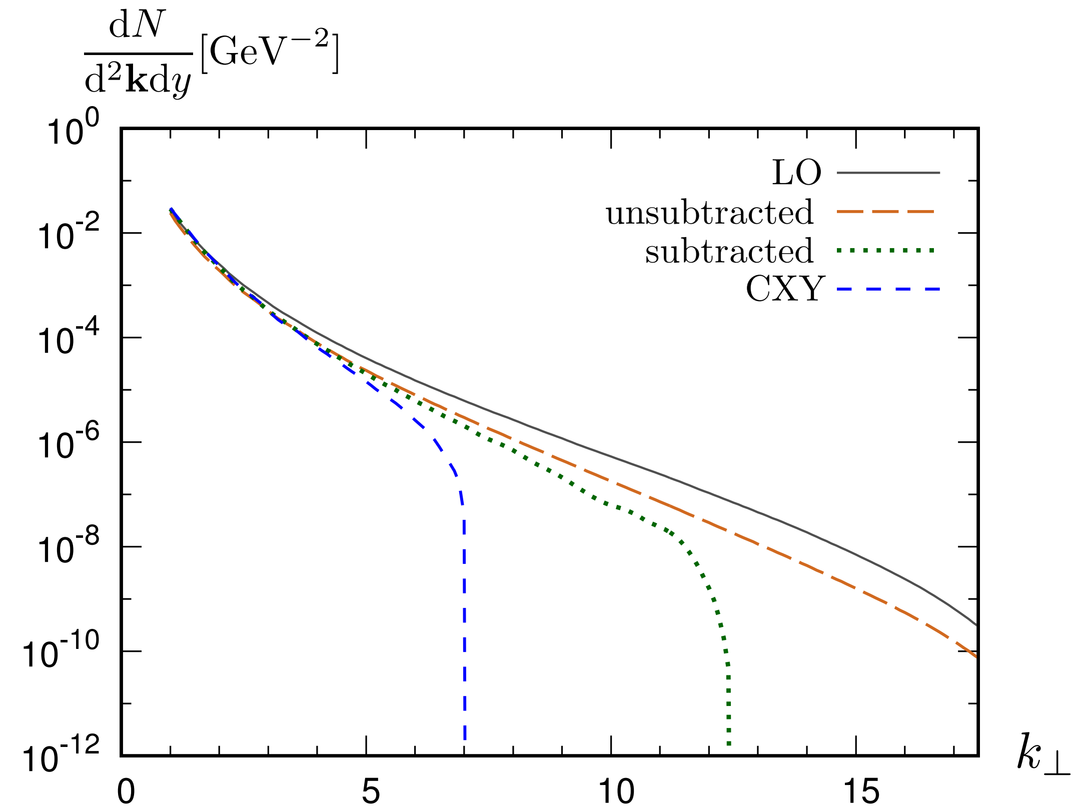
A reorganization of the perturbative expansion which avoids the rapidity subtraction *(E.I., A. Mueller and D. Triantafyllopoulos, 2016)*

Rapidity subtraction in k_T factorization (G. A. Chirilli, B.-W. Xiao, F. Yuan)

Edmond Iancu
Particle production in pA collisions beyond leading order

The strict separation between a ‘LO result’ and ‘NLO corrections’ involves a high degree of fine tuning, leading to instabilities in the presence of seemingly innocuous additional approximations

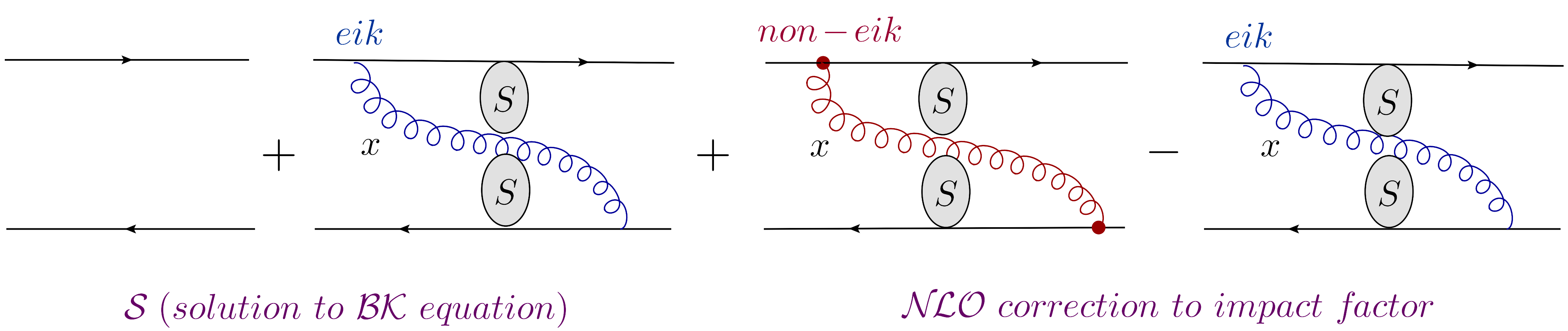




$$\frac{\mathrm{d}N}{\mathrm{d}\eta\mathrm{d}^2\boldsymbol{k}} = \mathcal{S}_0(\boldsymbol{k}) + \bar{\alpha}_s \int_{X_g}^{1} \frac{\mathrm{d}x}{x}\, \mathcal{K}(\boldsymbol{k};x)\, \mathcal{S}\big(\boldsymbol{k}, X(x)\big)$$

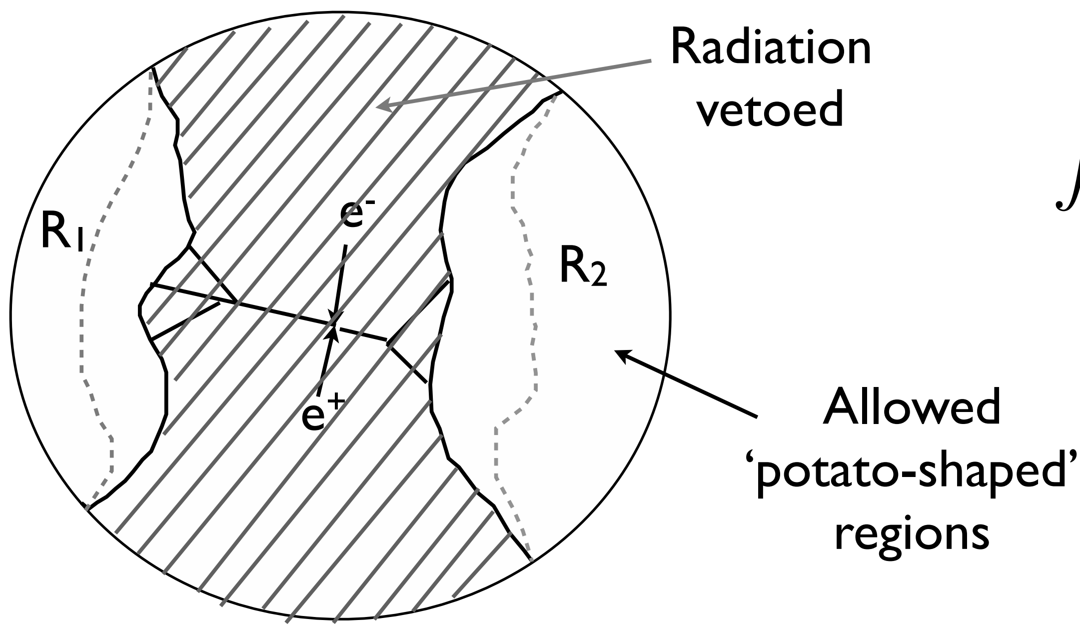
Sensible physical results: positive cross-section, but smaller than at LO

Compute emission with exact kinematics



$$\frac{\mathrm{d}N}{\mathrm{d}\eta\mathrm{d}^2\boldsymbol{k}} = \mathcal{S}(\boldsymbol{k}, X_g) + \bar{\alpha}_s \int_{X_g}^{1} \frac{\mathrm{d}x}{x}\, \big[\mathcal{K}(x) - \mathcal{K}(0)\big]\, \mathcal{S}\big(\boldsymbol{k}, X(x)\big)$$

Simon Caron-Huot
Linear and non-linear small-x evolution in pQCD



Look at this diagram in terms of energy and angular distribution

$$\int d\mathrm{Lips}(p_0)|M_3|^2 \to |M_2|^2 \overbrace{\int_{E_0}^{Q} \frac{dp_0}{p_0}}^{\sim \log(Q/E_{\mathrm{cut}})} \int \frac{d\Omega}{4\pi} \frac{\alpha_{12}}{\alpha_{10}\alpha_{02}}$$

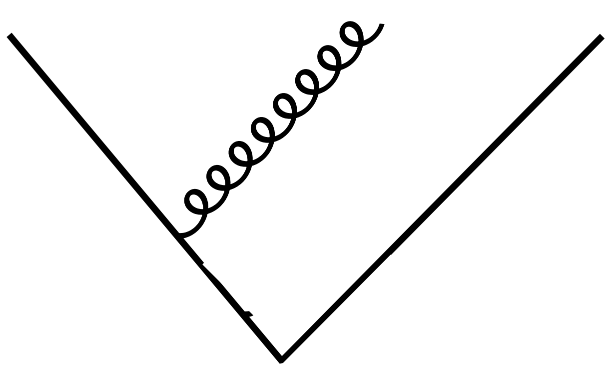
Non-global logarithm

Exploits equivalence with the physics of soft wide-angle radiation, so-called non-global logarithms

$$E\frac{d}{dE}U_{12} = \frac{\lambda}{8\pi^2}\int \frac{d^2\Omega_0}{4\pi}\frac{\alpha_{12}}{\alpha_{10}\alpha_{02}}\left(U_{10}U_{02} - U_{12}\right)$$

duality

$$\frac{d}{d\eta}U_{12} = \frac{\lambda}{8\pi^2}\int \frac{d^2 z_0}{\pi}\frac{z_{12}^2}{z_{10}z_{02}}\left(U_{10}U_{02} - U_{12}\right)$$

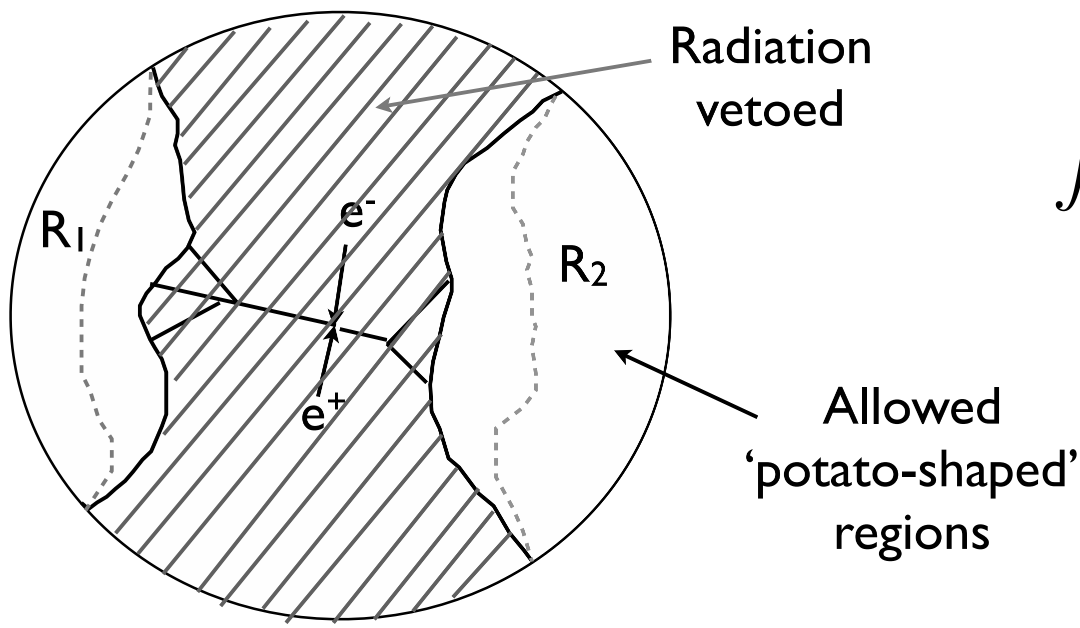


Presented result on two- and three-loop evolution for non-global logarithms

For two loops coincide with the result obtained in rapidity factorization and LCPT approaches

Simon Caron-Huot

Linear and non-linear small-x evolution in pQCD



$$\int d\mathrm{Lips}(p_0)|M_3|^2 \to |M_2|^2 \underbrace{\int_{E_0}^{Q} \frac{dp_0}{p_0}}_{\sim \log(Q/E_{\mathrm{cut}})} \int \frac{d\Omega}{4\pi} \frac{\alpha_{12}}{\alpha_{10}\alpha_{02}}$$

Non-global logarithm

Exploits equivalence with the physics of soft wide-angle radiation, so-called non-global logarithms

Used duality to construct NLO evolution and NNLO evolution kernel in N = 4 SYM.

$$\begin{aligned} K^{(2)} = & \int_{i,j,k}\int \frac{d^2\Omega_0}{4\pi}\frac{d^2\Omega_{0'}}{4\pi} K^{(2)\ell}_{ijk;00'} i f^{abc}\left(L^a_{i;0}L^b_{j;0'}R^c_k - R^a_{i;0}R^b_{j;0'}L^c_k\right) \\ & + \int_{i,j}\int \frac{d^2\Omega_0}{4\pi}\frac{d^2\Omega_{0'}}{4\pi} K^{(2)N=4,\ell}_{ij;00'}\left(f^{abc}f^{a'b'c'}U^{bb'}_0 U^{cc'}_{0'} - \frac{C_A}{2}(U^{aa'}_0 + U^{aa'}_{0'})\right)(L^a_i R^{a'}_j + R^{a'}_i L^a_j) \\ & + \int_{i,j}\int \frac{d^2\Omega_0}{4\pi}\frac{\alpha_{ij}}{\alpha_{0i}\alpha_{0j}}\gamma^{(2)}_K \left(R^a_{i;0}L^a_j + L^a_{i;0}R^a_j\right) + K^{(2)N\neq 4}. \end{aligned} \quad (3.32)$$

known

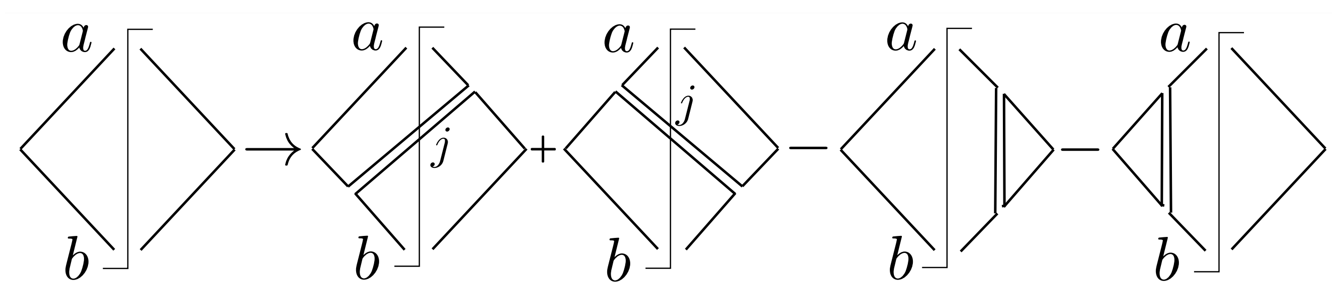
[SCH '15]

$$L^a_{i;0} \equiv (L^{a'}_i U^{a'a}_0 - R^a_i)$$

Duff Neil

Finding small-x physics in small-x jets

Non-global logarithms (log. of infra-red energy scale) vs. soft jet factorization theorems



Evolution of color dipoles

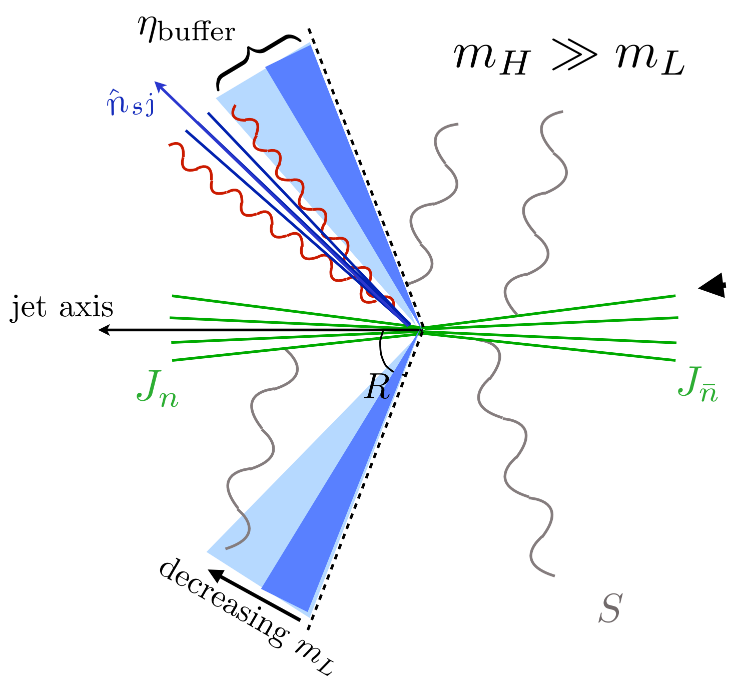
almost BK equation

$$\partial_L g_{ab} = \int_J \frac{d\Omega_j}{4\pi} W_{ab}(j)\Big(U_{abj}(L) g_{aj} g_{jb} - g_{ab}\Big)$$

$$W_{ab}(j) = \frac{a \cdot b}{a \cdot j\, j \cdot b}\,,\; j = (1, \hat{n}_j)$$

$$U_{abj}(L) = \exp\left(L \int_{S^2/J} \frac{d\Omega_q}{4\pi} W_{aj}(q) + W_{jb}(q) - W_{ab}(q)\right)$$

Resummation of Sudakov effects



One can introduce cut-off, “thrust” (effectively cut-off in energy)

Evolution through study of jet substructure

$$U_{abj} \to 1.$$

At large values of non-global logarithm L it is possible to simplify it to the BFKL equation

$$\partial_L g_{ab} = \int_{S^2} \frac{d\Omega_j}{4\pi} \frac{a \cdot b}{a \cdot j\, j \cdot b}\Big(g_{aj} g_{jb} - g_{ab}\Big)$$

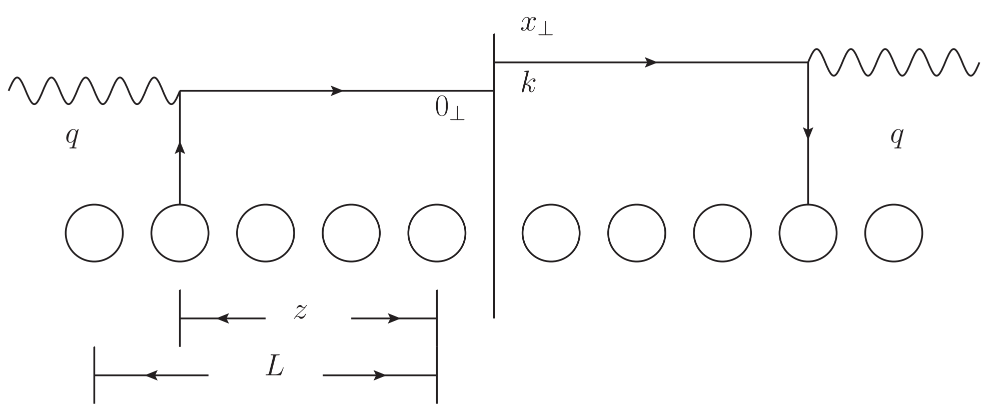
duality

$$\leftrightarrow$$

$$\partial_Y S_{\vec{a}\vec{b}} = \frac{\alpha_s C_A}{\pi} \int_{\mathbb{R}^2} \frac{d\Omega_j}{2\pi} \frac{x^2_{\vec{a}\vec{b}}}{x^2_{\vec{a}\vec{j}} x^2_{\vec{j}\vec{b}}}\Big(S_{\vec{a}\vec{j}} S_{\vec{j}\vec{b}} - S_{\vec{a}\vec{b}}\Big)$$

Al Mueller
Medium induced transverse momentum broadening in hard processes

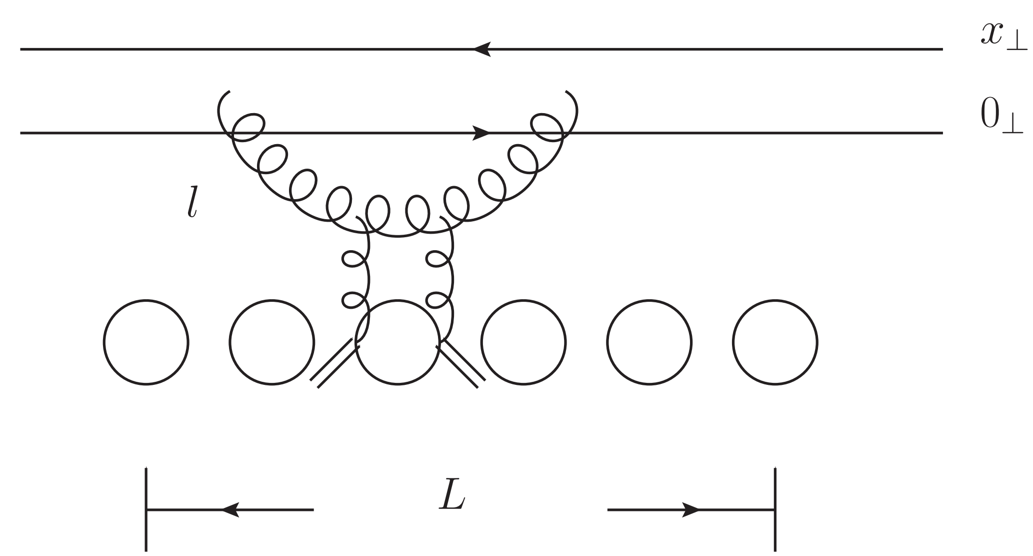
Transverse momentum broadening of partons in hard processes in the presence of medium.



$$\frac{dN}{d^2b\,d^2k_\perp} = \int \frac{d^2x_\perp}{(2\pi)^2} e^{-ik_\perp\cdot x_\perp} \rho x q_N\left(x, \frac{1}{x_\perp^2 + 1/Q^2}\right) \times \int_0^L dz e^{-\mathcal{E}},$$

$$\mathcal{E}_{\rm Sud} = 2\frac{\alpha_s C_F}{2\pi}\int_{q_+/[Q^2x_\perp^2]}^{q_+}\frac{dl_+}{l_+}\int_{1/x_\perp^2}^{\frac{l_+}{q_+}Q^2}\frac{dl_\perp^2}{l_\perp^2} = \frac{\alpha_s C_F}{2\pi}\ln^2(Q^2x_\perp^2).$$

Factorize the vacuum radiation contribution and medium related P_T broadening effects into the Sudakov factor and medium dependent distributions, respectively.



Medium induced radiation

A.H. Mueller, Bin Wu, Bo-Wen Xiao and Feng Yuan, Phys.Rev. D95 (2017), 034007

Matthew D. Sievert

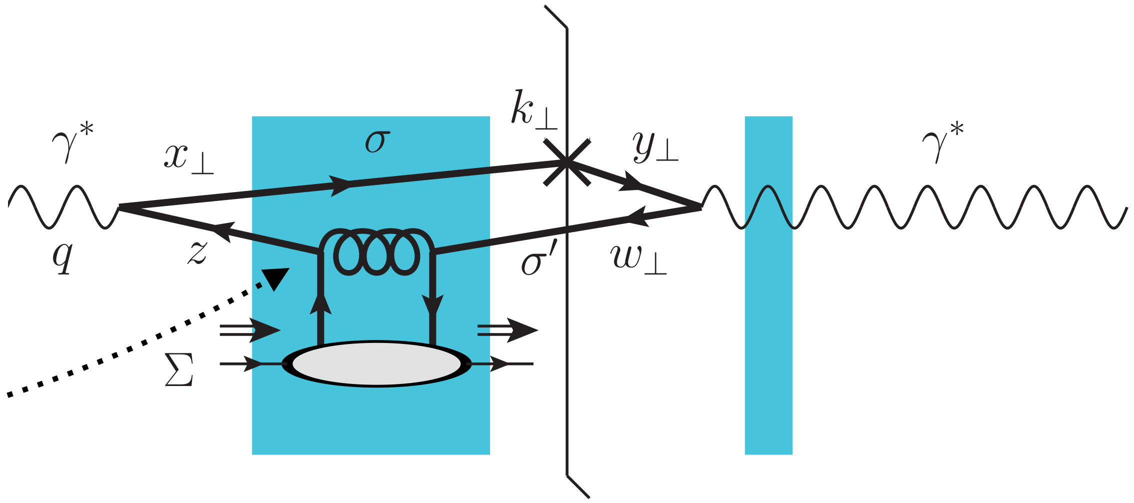
Quark helicity evolution at small x

E. Aschenaur et al, arXiv:1509.06489

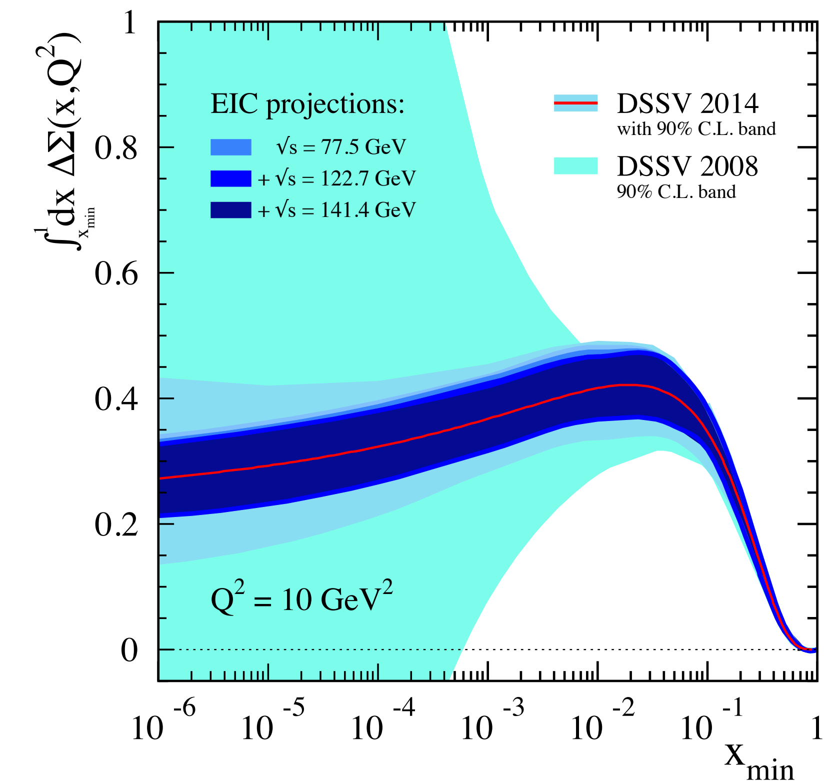
Understanding the proton spin at small x

Small-x helicity evolution (quark helicity TMD & PDF, g_1 structure function)

Numerical and analytic solution at large N_c



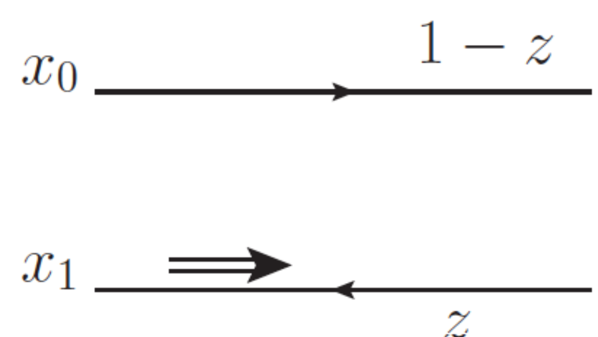
Polarized interaction



$$g_1^S(x,Q^2) = \frac{N_c\, N_f}{2\,\pi^2 \alpha_{EM}} \int\limits_{z_i}^{1} \frac{dz}{z^2(1-z)} \int dx_{01}^2 \left[\frac{1}{2} \sum_{\lambda\sigma\sigma'} |\psi^T_{\lambda\sigma\sigma'}|^2_{(x_{01}^2,z)} + \sum_{\sigma\sigma'} |\psi^L_{\sigma\sigma'}|^2_{(x_{01}^2,z)} \right] G(x_{01}^2, z)$$

$$\Delta q^S(x,Q^2) = \frac{N_c\, N_f}{2\pi^3} \int\limits_{z_i}^{1} \frac{dz}{z} \int\limits_{\frac{1}{zs}}^{\frac{1}{zQ^2}} \frac{dx_{01}^2}{x_{01}^2}\, G(x_{01}^2, z)$$

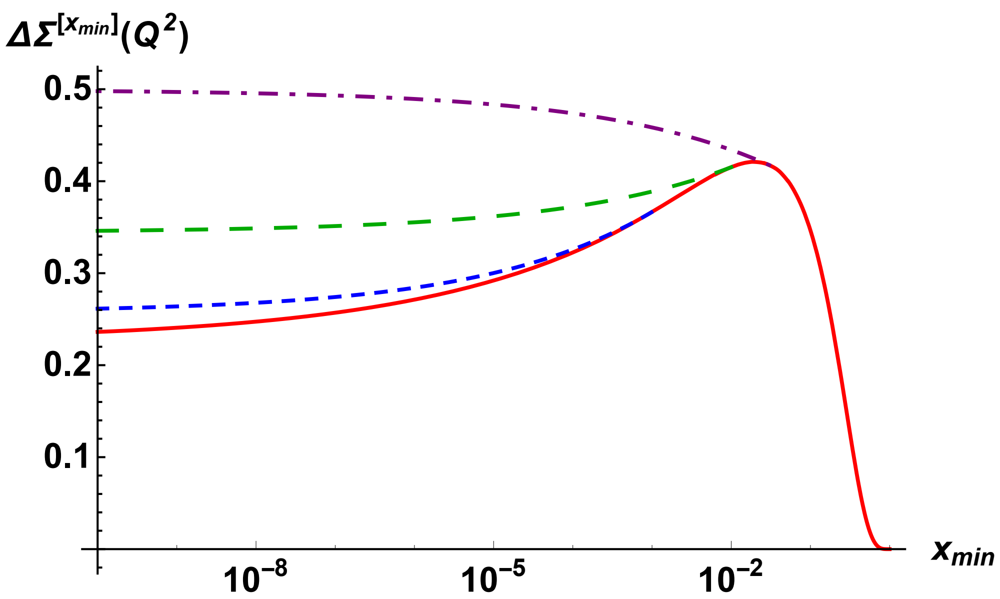
Depend on polarized dipole amplitude



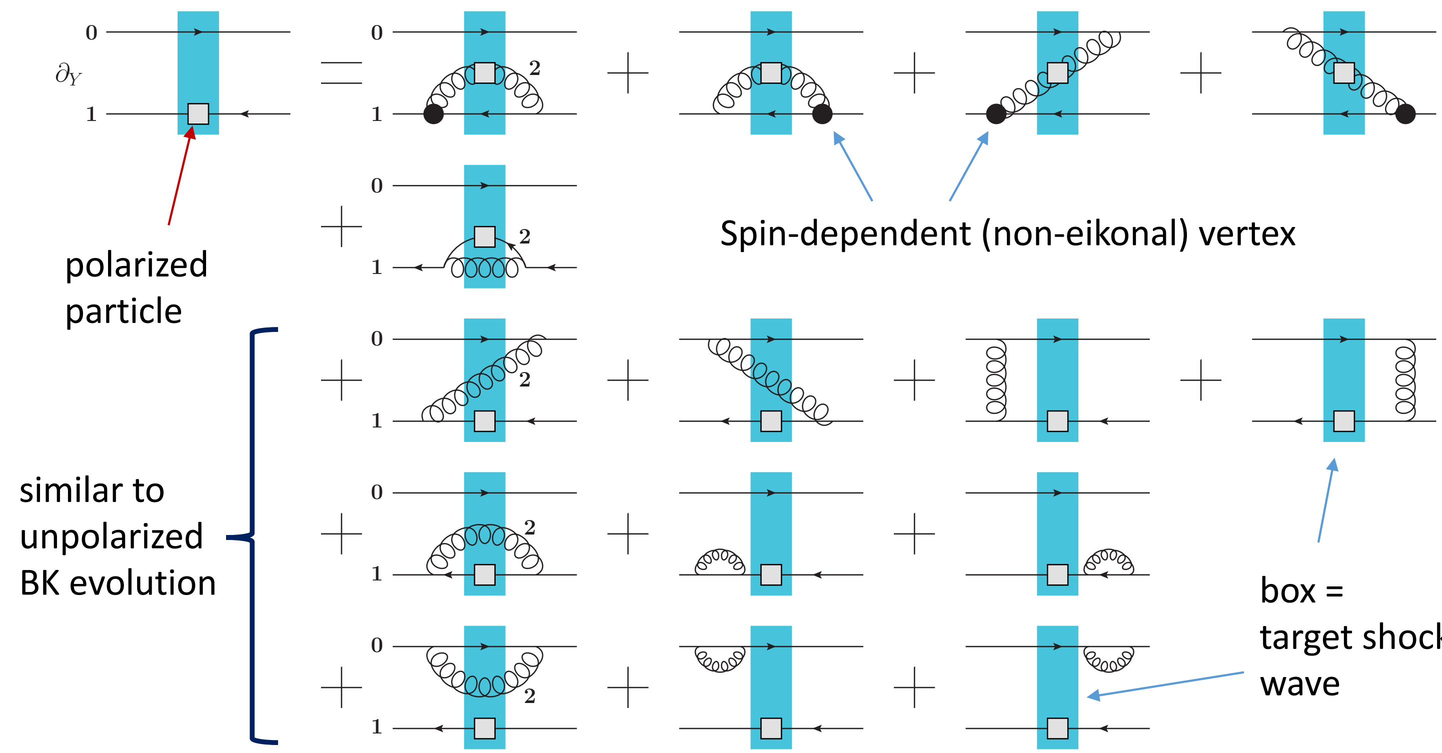
Yuri Kovchegov

Small x asymptotics of the quark helicity distribution

Found evolution equation for polarized dipole



One can construct an evolution equation for the polarized dipole:



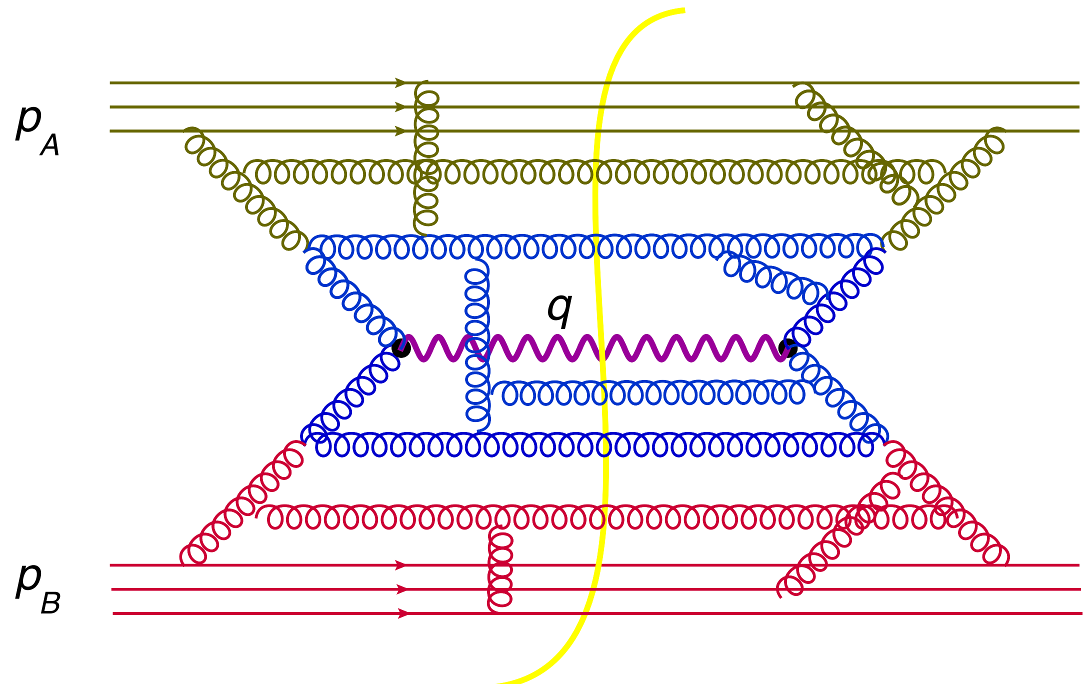
$$G_{10}(z) = G_{10}^{(0)}(z) + \frac{\alpha_s N_c}{2\pi} \int\limits_{z_i}^{z} \frac{dz'}{z'} \int\limits_{\rho'^2}^{x_{10}^2} \frac{dx_{21}^2}{x_{21}^2} \left[2\,\Gamma_{02,\,21}(z')\,S_{21}(z') + 2\,G_{21}(z')\,S_{02}(z') + G_{12}(z')\,S_{02}(z') - \Gamma_{01,\,21}(z') \right]$$

$$g_1^S(x, Q^2) \sim \Delta q^S(x, Q^2) \sim g_{1L}^S(x, k_T^2) \sim \left(\frac{1}{x}\right)^{\alpha_h} \approx \left(\frac{1}{x}\right)^{2.31\,\sqrt{\frac{\alpha_s N_c}{2\pi}}}$$

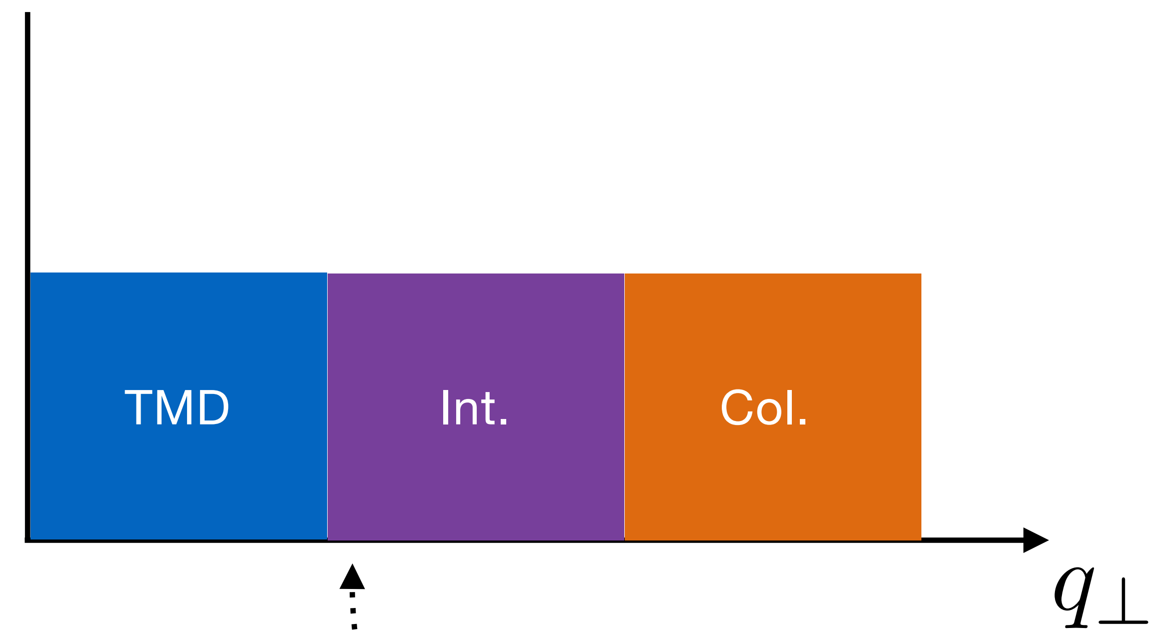
Analytic result: $\alpha_h = \frac{4}{\sqrt{3}} \sqrt{\frac{\alpha_s N_c}{2\pi}} \approx 2.3094 \sqrt{\frac{\alpha_s N_c}{2\pi}}$

Ian Balitsky

Higher-twist corrections to gluon TMD factorization



Particle production in pp at small transverse momentum



What is going on here (corrections to the TMD factorization)

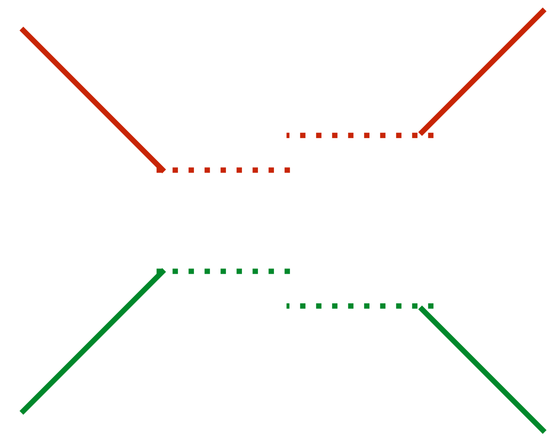
$$\frac{d\sigma}{d\eta d^2 q_\perp} = \sum_f \int d^2 b_\perp e^{i(q,b)_\perp} \mathcal{D}_{f/A}(x_A, b_\perp, \eta) \mathcal{D}_{f/B}(x_B, b_\perp, \eta) \sigma(f f \to H)$$

What is a form of the corrections to this result (Y-term)?

Corrections are suppressed as $\dfrac{q_\perp^2}{Q^2}$

Ian Balitsky

Higher-twist corrections to gluon TMD factorization

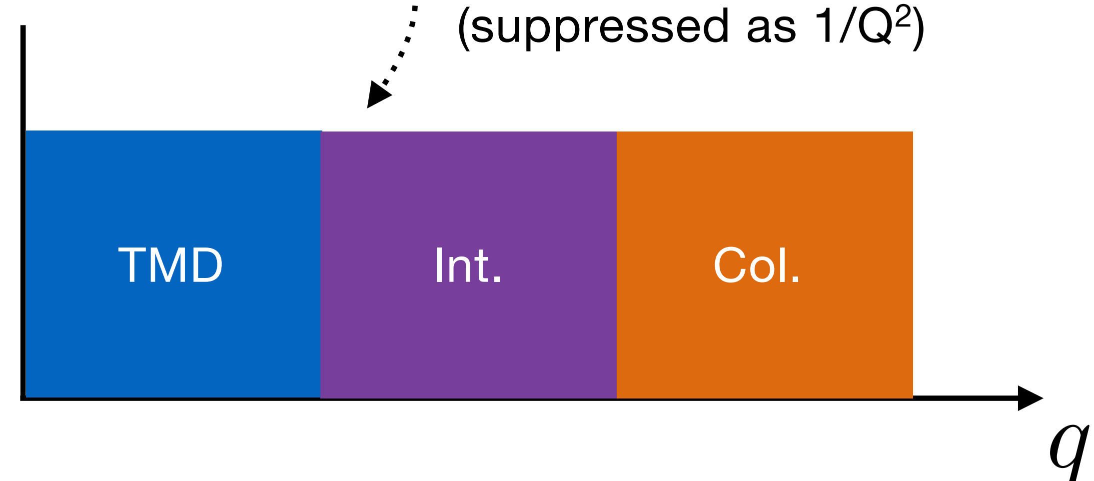


Product of two distribution functions

Leading order result

$$
\begin{aligned}
W(p_A,p_B,q) \;=\;& \frac{64/s^2}{N_c^2-1}\int d^2x_\perp\, \frac{2}{s}\int dx_\bullet dx_*\ \cos\left(\alpha_q x_\bullet + \beta_q x_* - (q,x)_\perp\right)\\
&\times \Big\{ \langle p_A|\hat U^{mi}_*(x_\bullet,x_\perp)\hat U^{mj}_*(0)|p_A\rangle \langle p_B|\hat V^n_{\bullet i}(x_*,x_\perp)\hat V^n_{\bullet j}(0)|p_B\rangle\\
&- \frac{4N_c^2}{N_c^2-4}\,\frac{\Delta^{ij,kl}}{Q^2}\,\frac{2}{s}\int_{-\infty}^{x_\bullet} dx'_\bullet\ d^{abc}\langle p_A|\hat U^a_{*i}(x_\bullet,x_\perp)\hat U^b_{*j}(x'_\bullet,x_\perp)\hat U^c_{*r}(0)|p_A\rangle\\
&\qquad \times \frac{2}{s}\int_{-\infty}^{x_*} dx'_*\ d^{mpq}\langle p_B|\hat V^m_{\bullet k}(x_*,x_\perp)\hat V^p_{\bullet l}(x'_*,x_\perp)\hat V^{qr}_\bullet(0)|p_B\rangle \Big\}
\end{aligned}
$$

Subleading term (suppressed as $1/Q^2$)



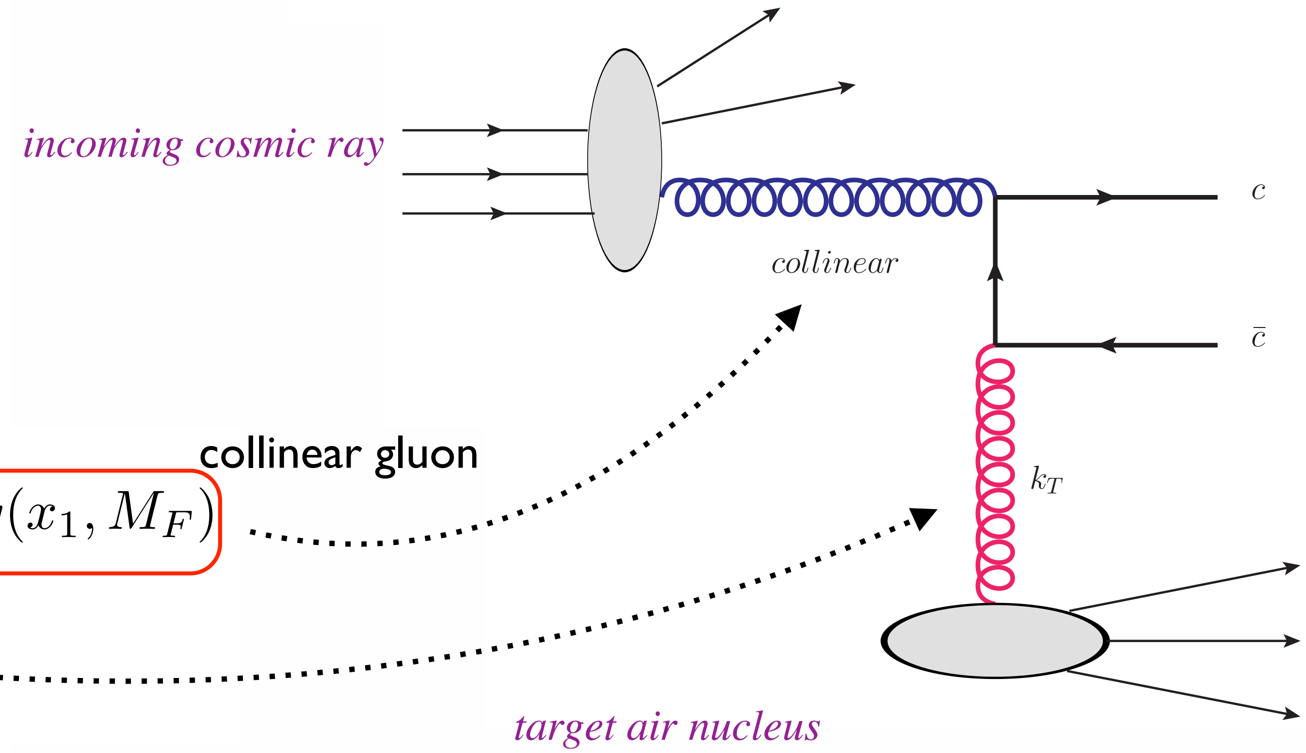
Ian Balitsky, A.T., arXiv:1706.01415

Anna Staśto

Low x physics and prompt neutrino production

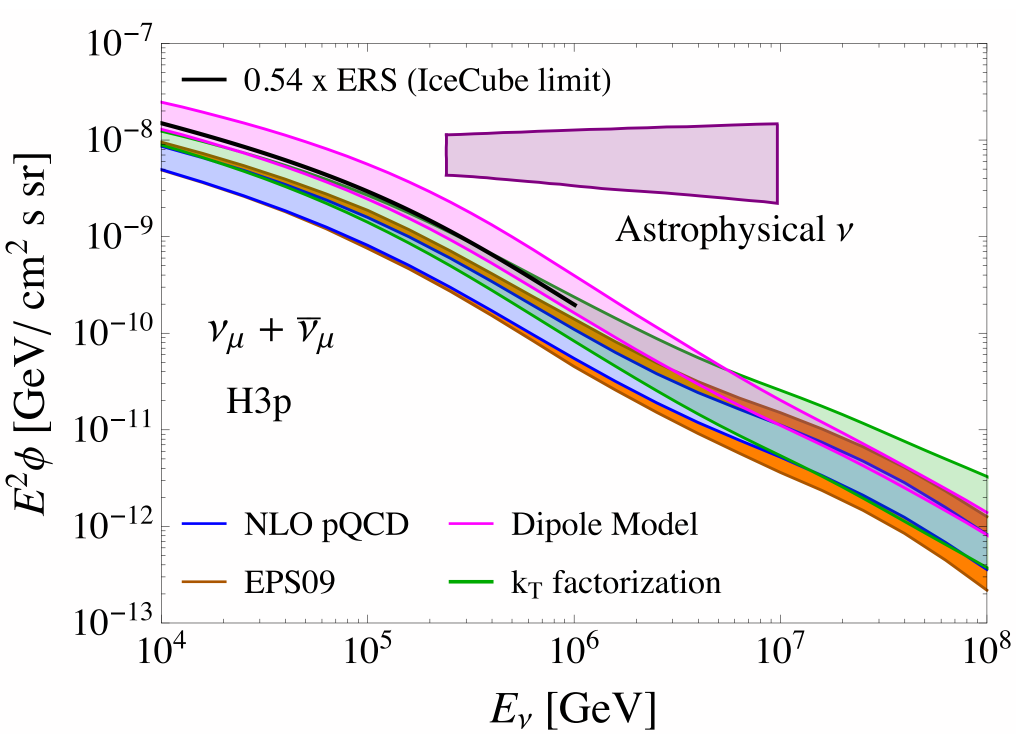
Prompt neutrinos - decay of charmed or bottom mesons

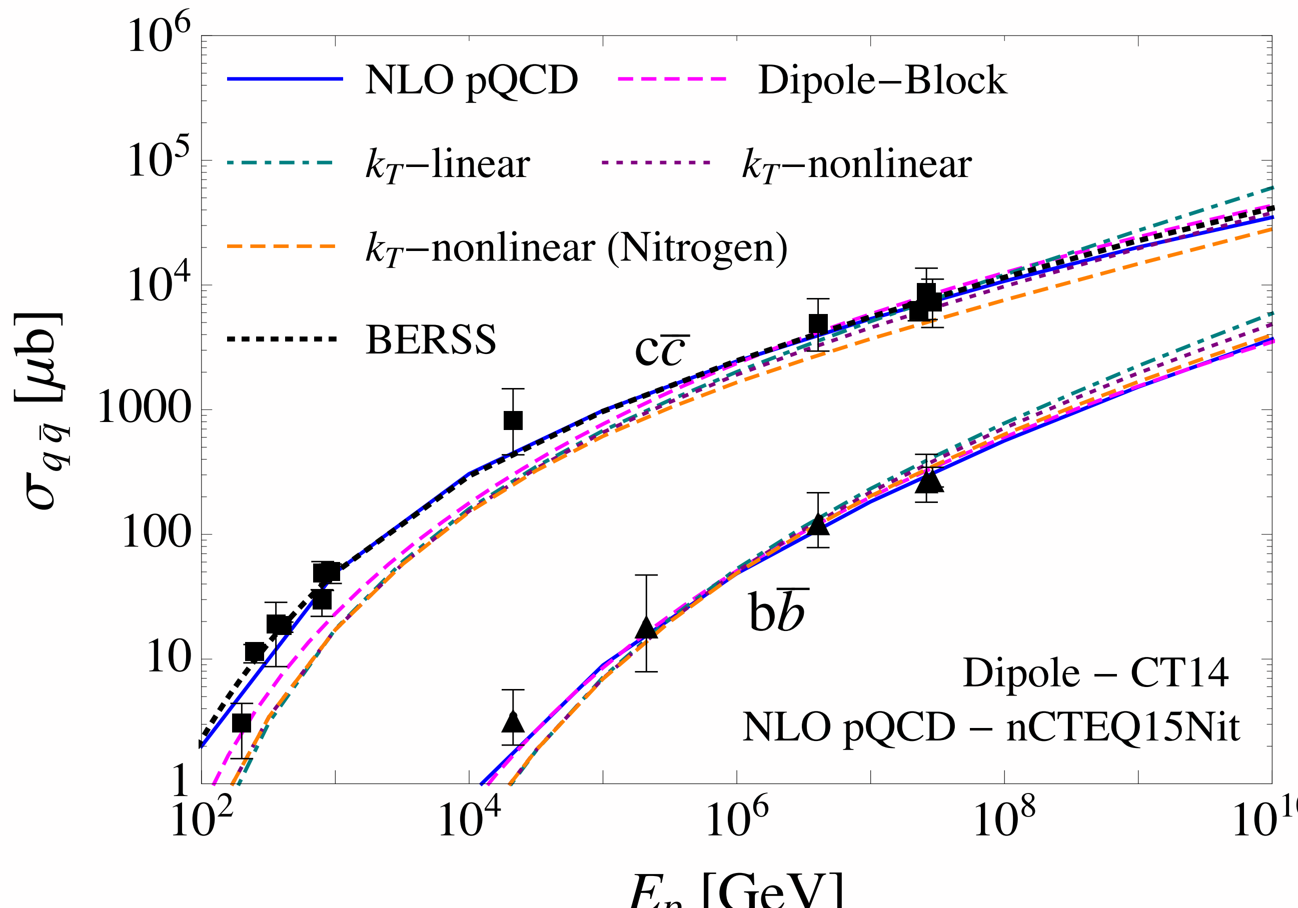
Hybrid k_T factorization calculation



$$\sigma(pp \to q\bar{q}X) = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\, dz\, dx_F\, \delta(zx_1 - x_F)\boxed{x_1 g(x_1, M_F)}$$
$$\times \int \frac{dk_T^2}{k_T^2}\hat{\sigma}^{\rm off}(z,\hat{s},k_T)\boxed{f(x_2,k_T^2)}$$

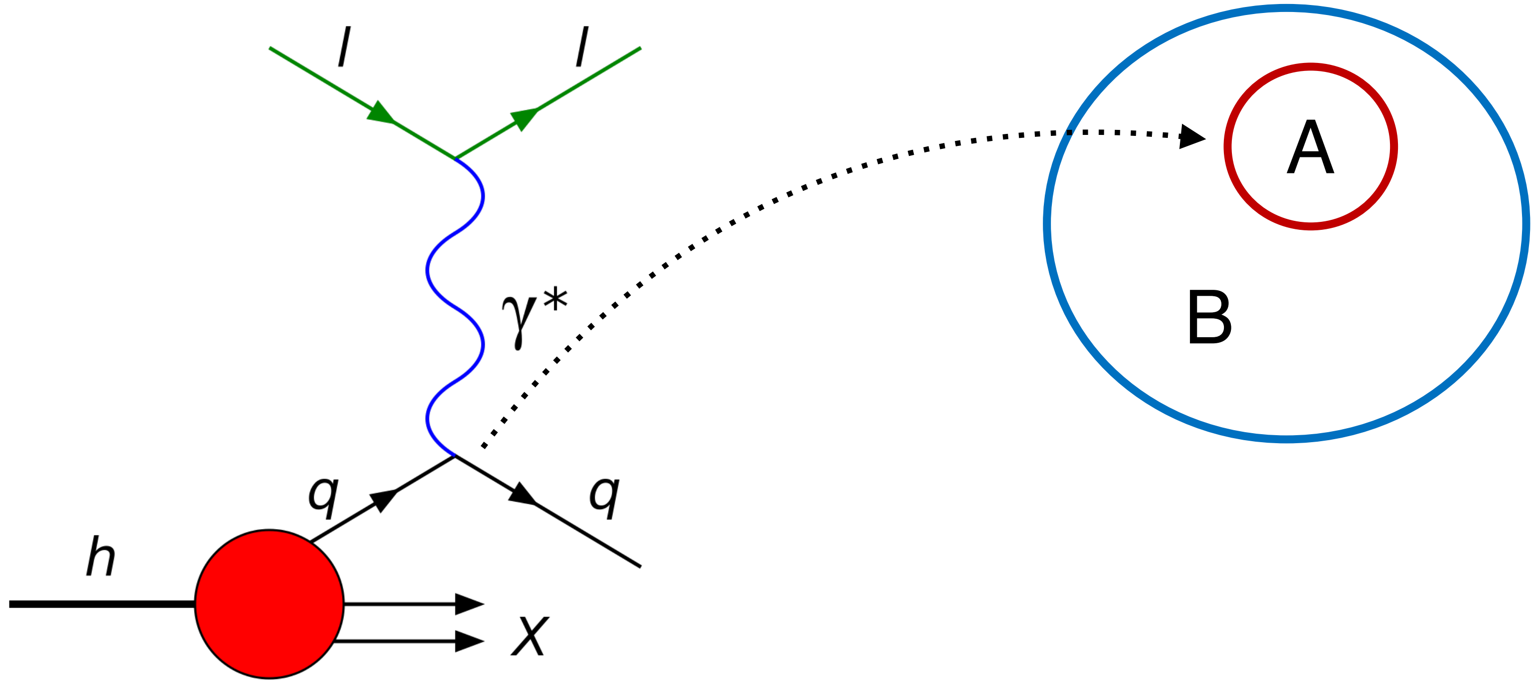
Unintegrated gluon density obtained from the resummed small x evolution equation with non-linear term





Dmitri Kharzeev

Deep Inelastic Scattering as a probe of entanglement



DIS probes only a part of the proton's wave function (region A)

We sum over all hadronic final states; in quantum mechanics, this corresponds to accessing the density matrix of a mixed state

$$\rho_A = \sum_n \alpha_n^2 |\Psi_n^A\rangle\langle\Psi_n^A|$$

probability of a state with n partons (multiplicity)

$$\alpha_n^2 = p_n$$

The entanglement entropy

$$S = -\sum_n p_n \ln p_n$$

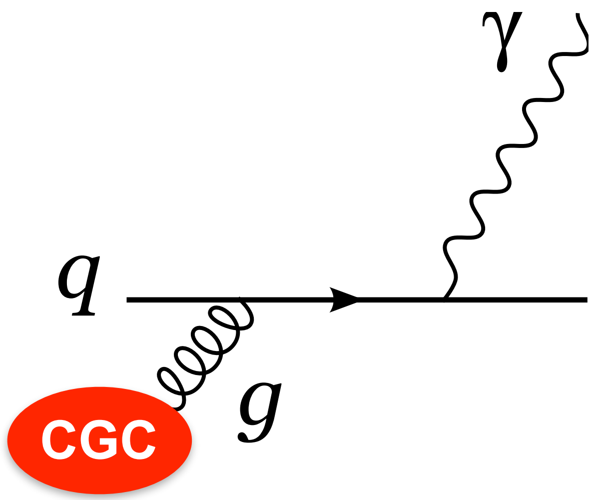
Relation between the entanglement entropy and parton distribution (1D-model)

$$S = \ln[xG(x)]$$

At small-x the entanglement entropy is maximal and the proton is a maximally entangled state

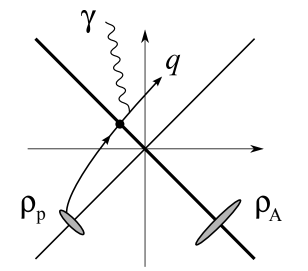
Can extract entanglement entropy from measurements of multiplicity

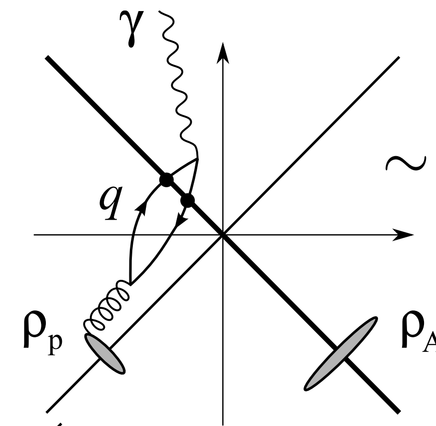
Compton Scattering



Photons in pA at high energies (LO)

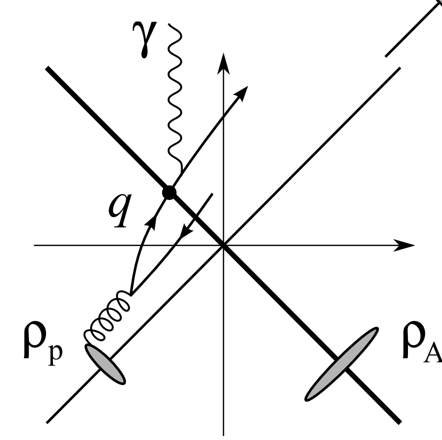
Gelis-Mehtar-Tani (2006)





Annihilation

$$\sim\ \alpha_e \langle (g\rho_p)^2 \rangle \langle U U^\dagger U U^\dagger \rangle$$

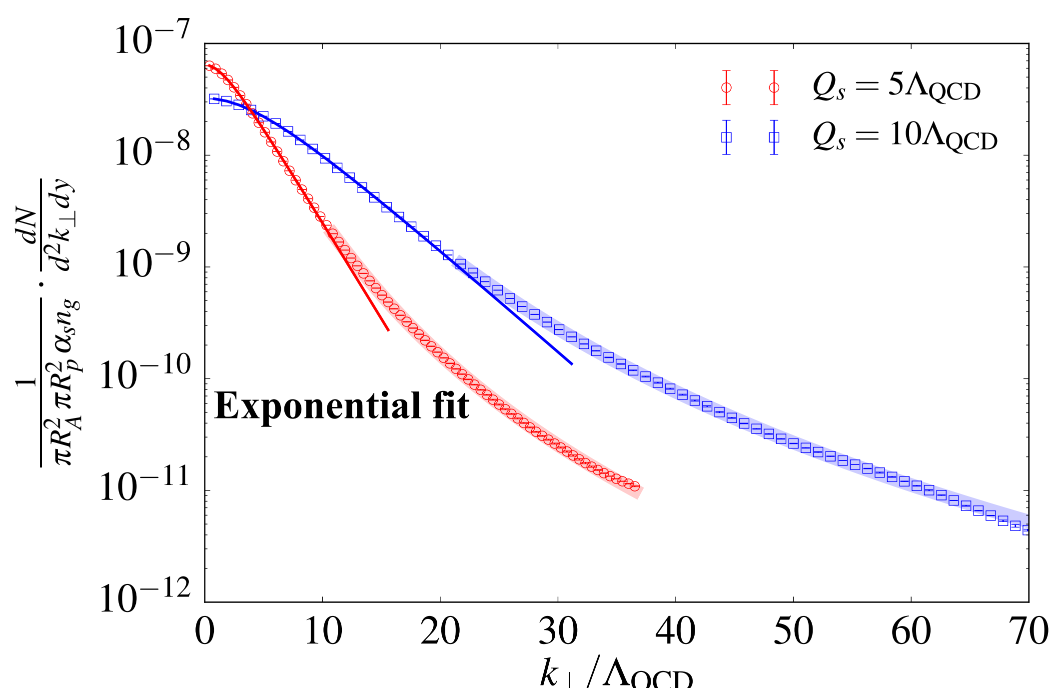


Bremsstrahlung

$$\sim\ \alpha_e \delta n_q \langle U U^\dagger \rangle \quad \text{(evolution)}$$

$$\sim\ \alpha_e \langle (g\rho_p)^2 \rangle \langle U U^\dagger U U^\dagger \rangle$$

Benic-Fukushima (2016)



Annihilation

Bremsstrahlung Diagram

Benic-Fukushima-Garcia-Montero-Venugopalan (2016)

$$\mathcal{M}^\mu(\boldsymbol{p},\boldsymbol{q},\boldsymbol{k}_\gamma) = -q_f e g^2 \int_{\boldsymbol{k}_\perp,\boldsymbol{k}_{1\perp}} \int_{\boldsymbol{x}_\perp \boldsymbol{y}_\perp} \frac{\rho_p^a(\boldsymbol{k}_{1\perp})}{\boldsymbol{k}_{1\perp}^2}\, e^{i\boldsymbol{k}_\perp\cdot\boldsymbol{x}_\perp + i(\boldsymbol{P}_\perp - \boldsymbol{k}_\perp - \boldsymbol{k}_{1\perp})\cdot\boldsymbol{y}_\perp}$$
$$\times\, \bar{u}(\boldsymbol{q})\{T_g^\mu(\boldsymbol{k}_{1\perp})U(\boldsymbol{x}_\perp)^{ba}t^b + T_{q\bar q}^\mu(\boldsymbol{k}_\perp,\boldsymbol{k}_{1\perp})\tilde U(\boldsymbol{x}_\perp)t^a\tilde U^\dagger(\boldsymbol{y}_\perp)\}v(\boldsymbol{p})$$

Structure is simple but the full expression is…

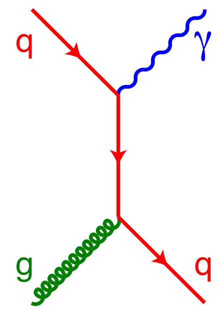
Necessary conditions for correctness

- ✔ Gauge invariance (Coulomb/Light-cone)
- ✔ Ward identity: $k_{\gamma\mu}\mathcal{M}^\mu(\boldsymbol{p},\boldsymbol{q},\boldsymbol{k}_\gamma) = 0$ satisfied separately for T_g and T_{qq}
- ✔ Leading-twist (perturbative)
- ✔ Soft-photon limit (Low-Burnett-Kroll theorem)

Thomas Peitzmann

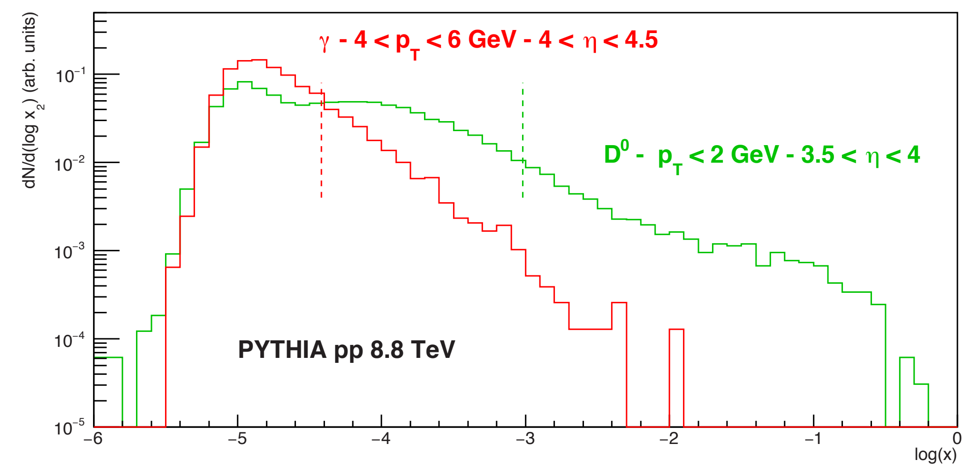
Opportunities for Forward Photon Measurements in ALICE at the LHC

Cleaner observables (EM probes):



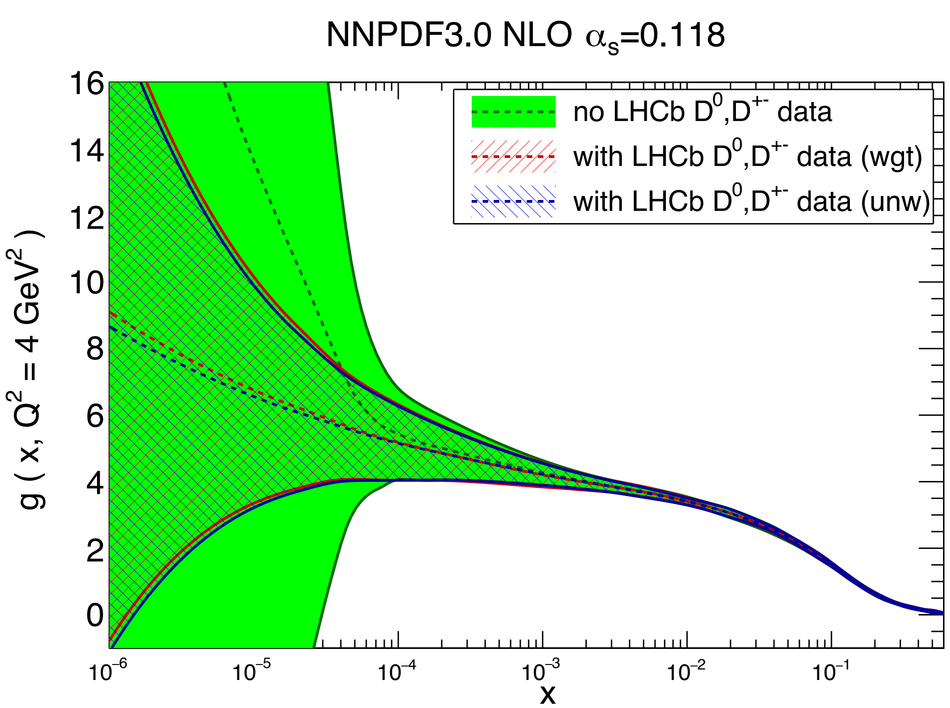
- no final state interaction
- well-understood production process
- well-defined kinematics

real photons: sensitivity to gluons at LO, clear kinematic relation



large cross section at small x

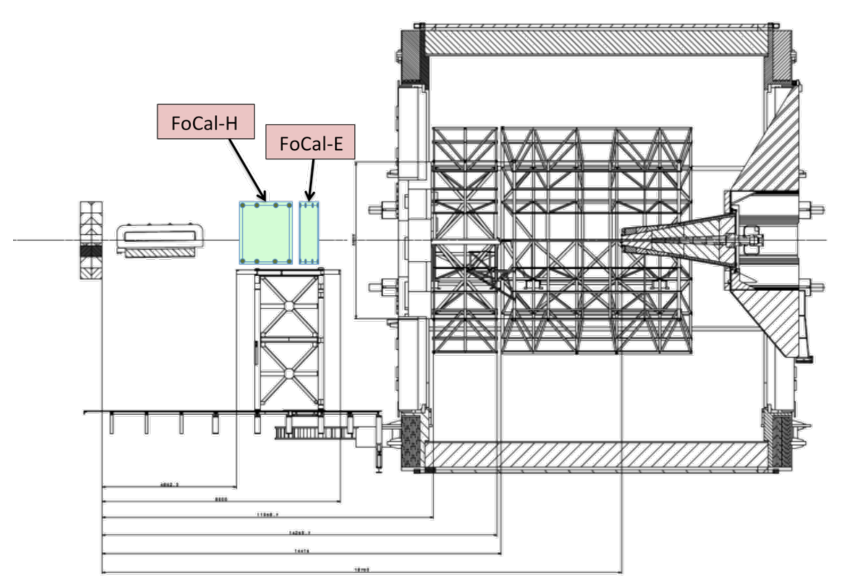
- interpretation of hadronic observables remains inconclusive
  - final state modifications in p–A collisions?
  - production process not fully understood for many hadrons
  - kinematic relation to Bjorken-x uncertain (e.g. fragmentation)
- best alternative candidate: open charm
  - direct sensitivity to gluons
  - final state interactions?



Usage of forward D measurements by LHCb can constrain gluon distribution

ALICE

FoCal in ALICE



electromagnetic calorimeter for γ and π^0 measurement

preferred scenario:
- at z ≈ 7m (outside magnet)
  3.3 < η < 5.3
  (space to add hadr. calorimeter)

under internal discussion
possible installation in LS3

Adrian Dumitru

Fluctuations of the gluon distribution at small-x: correlation of multiplicity and transverse momentum fluctuations

High-energy observable:

$$\langle O[A^+] \rangle = \frac{1}{Z} \int \mathcal{D}A^+ \, W[A^+] \, O[A^+]$$

$$W[A^+] \quad = \quad e^{-S[A^+]}$$

MV model (no quantum corrections):

$$S[\rho] = \int \mathrm{d}x^- \mathrm{d}^2 x_\perp \frac{\mathrm{tr}\, \rho(x^-, x_\perp)\, \rho(x^-, x_\perp)}{2\mu^2(x^-)}$$

Quantum corrections modify the weight:

$$S_G[\rho] = \int \mathrm{d}^2 x_\perp \mathrm{d}^2 y_\perp \, \frac{\mathrm{tr}\, \rho(x_\perp)\, \rho(y_\perp)}{\mu^2(x_\perp - y_\perp)}$$

E. Iancu, K. Itakura and L. McLerran

Proposed new calculation scheme for the functional integral through effective action

$$e^{-V_{\rm eff}[X(q)]} = \int \mathcal{D}A^+(q) \, W[A^+(q)] \, \delta(X(q) - O[A^+(q)])$$

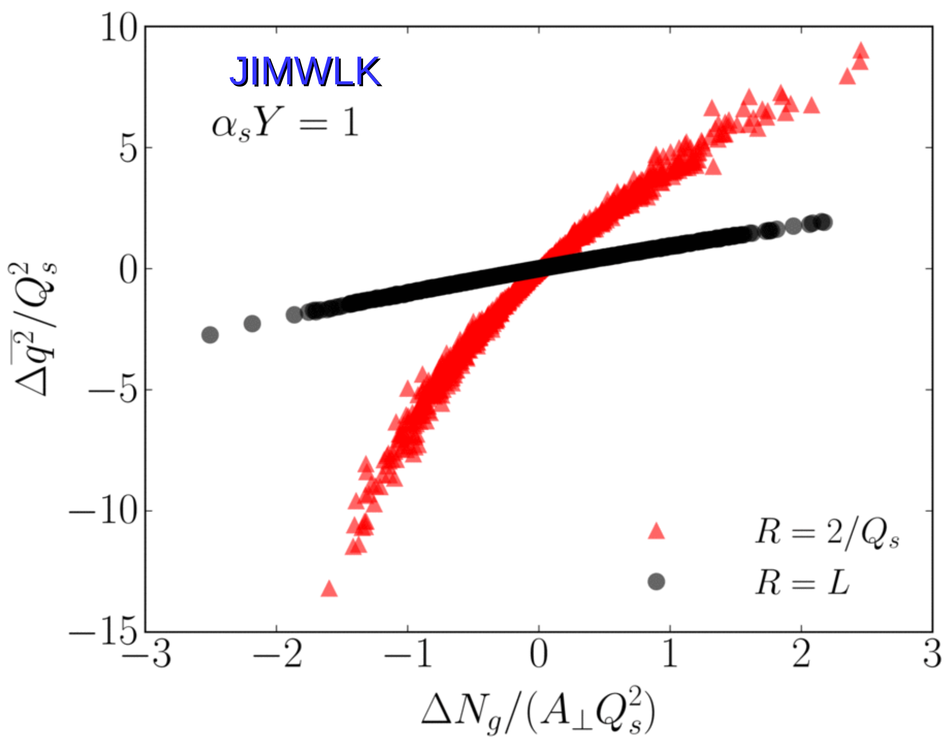
$$\frac{\delta V_{\rm eff}[X(k)]}{\delta X(q)} = 0 \to X_s(q) \equiv \langle X(q) \rangle$$

Adrian Dumitru, Vladimir Skokov

Adrian Dumitru

Fluctuations of the gluon distribution at small-x: correlation of multiplicity and transverse momentum fluctuations

$$\frac{\delta V_{\rm eff}[X(k)]}{\delta X(q)} = 0 \rightarrow X_s(q) \equiv \langle X(q)\rangle$$



Consider fluctuations around this result

One can understand how this fluctuations affect observables (multiplicity etc.)

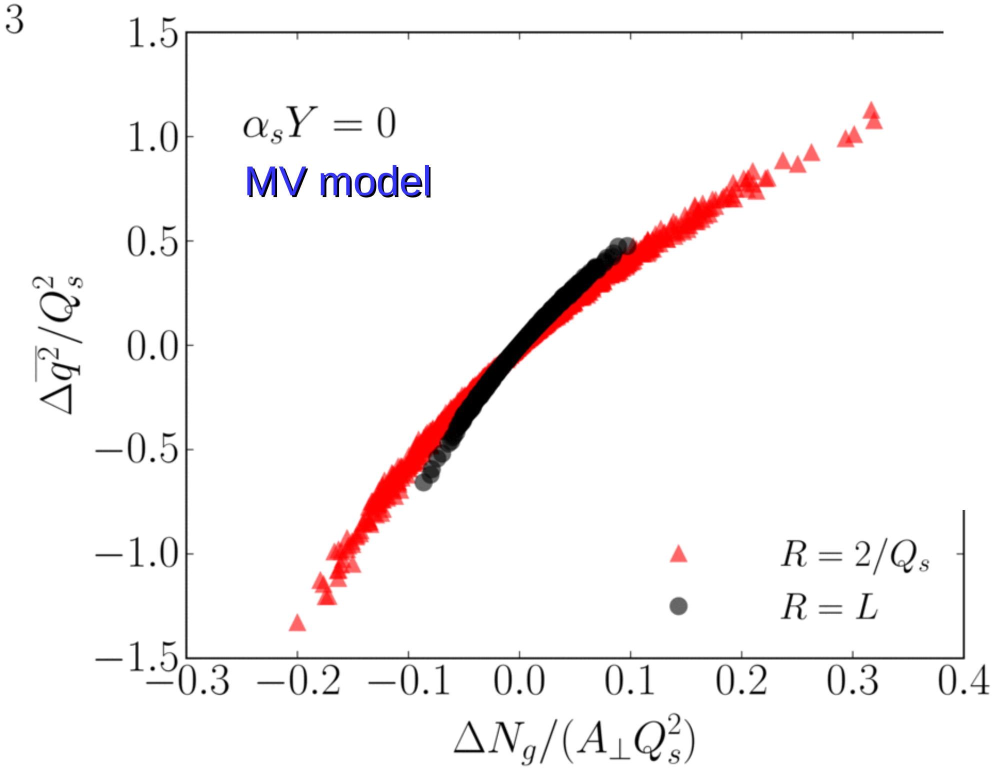
$$\Delta\overline{q^2}[\eta(q)] = \frac{\Delta N_g[\eta(q)]}{\int \frac{d^2q}{(2\pi)^2} X_s(q)\eta(q)}$$

$$\Delta N_g \simeq N_c A_\perp \, \Delta\overline{q^2}$$

for small amplitude fluctuations

ΔN_g increases with $\Delta\overline{q^2}$

Evolution modifies spectrum of fluctuations

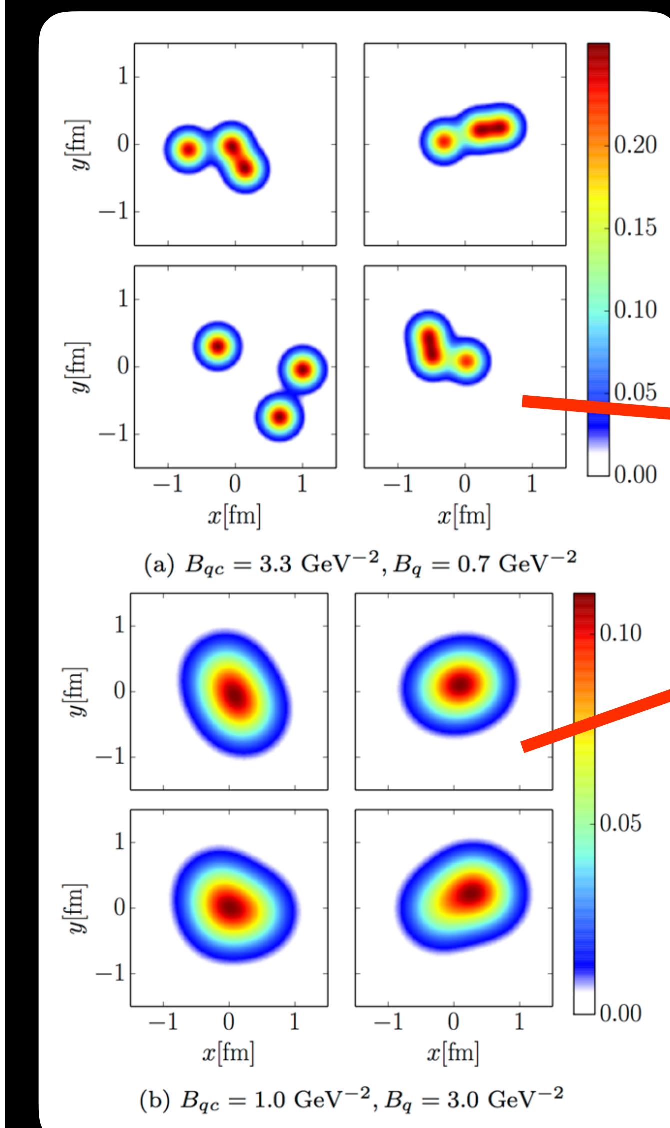


Björn Schenke
Subnucleonic fluctuations, diffraction, and small-x fluctuations

$$\frac{d\sigma^{\gamma^* p \to V p}}{dt} = \frac{1}{16\pi} \left| \langle \mathcal{A}^{\gamma^* p \to V p}(x, Q^2, \Delta) \rangle \right|^2$$

Shape fluctuations of the proton's gluon distribution are needed to describe incoherent diffractive vector meson data from HERA

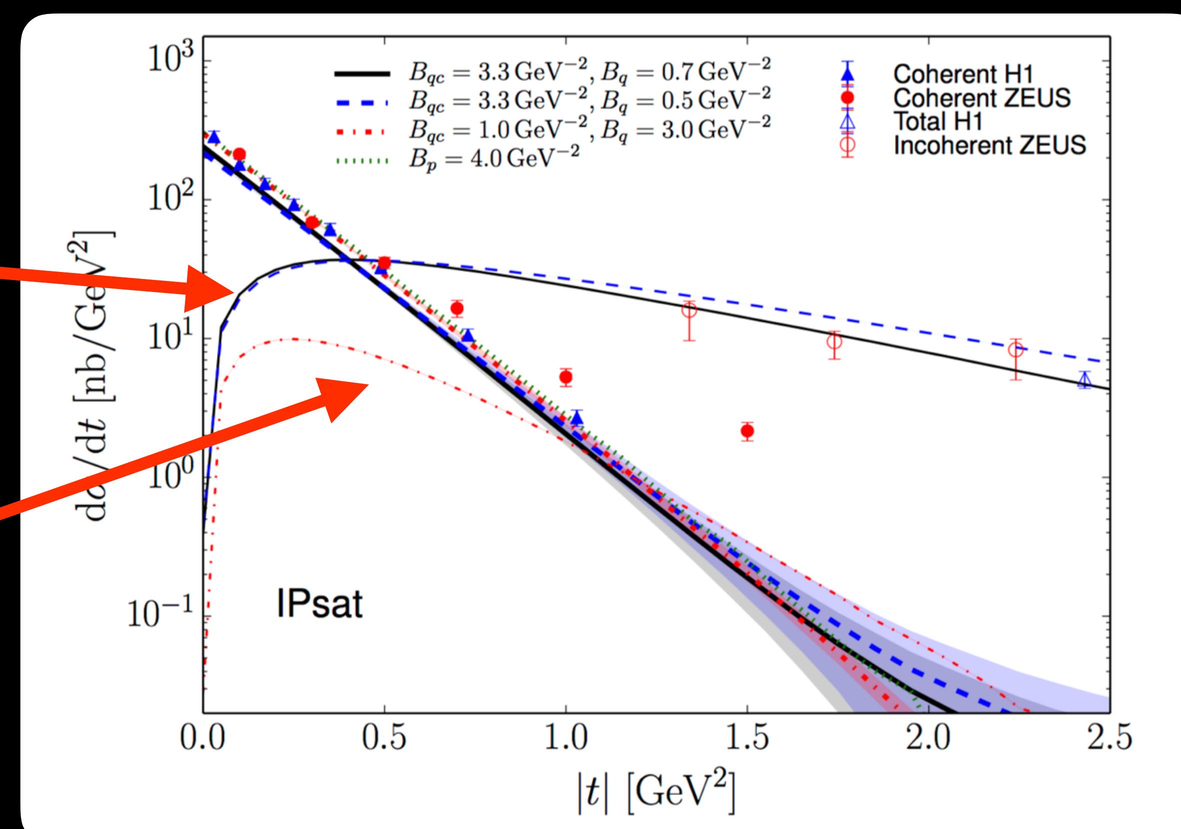
Assume 3 valence quark-like hot spots



(a) $B_{qc} = 3.3\ \mathrm{GeV}^{-2}, B_q = 0.7\ \mathrm{GeV}^{-2}$

(b) $B_{qc} = 1.0\ \mathrm{GeV}^{-2}, B_q = 3.0\ \mathrm{GeV}^{-2}$

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301
Phys.Rev. D94 (2016) 034042



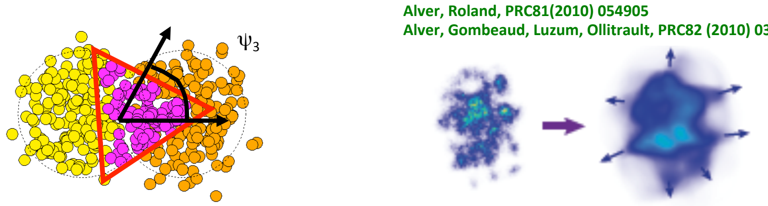
H1 collaboration, Eur. Phys. J. C46 (2006) 585,
Phys. Lett. B568 (2003) 205
ZEUS collaboration, Eur. Phys. J. C24 (2002) 345
Eur. Phys. J. C26 (2003) 389

Raju Venugopalan

Probing extreme QCD through ridge-like correlations in small systems: status and problems

The ridge in A+A collisions

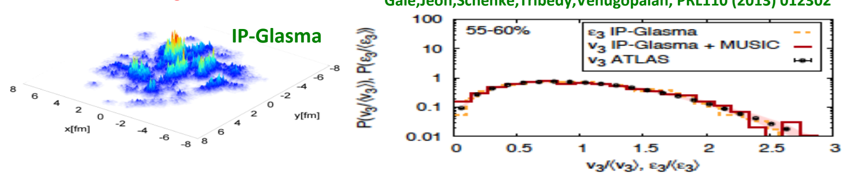
Alver, Roland, PRC81(2010) 054905
Alver, Gombeaud, Luzum, Ollitrault, PRC82 (2010) 03491



Structure of ridge-correlations can be understood as hydrodynamic flow driven by event-by-event fluctuations in nucleon positions

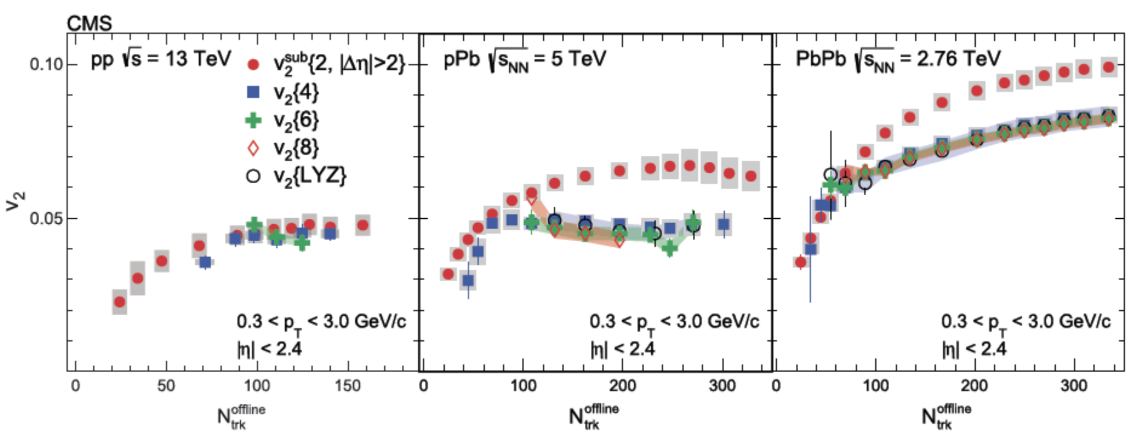
$$\frac{1}{N_{\rm trig}N_{\rm assoc.}}\frac{d^2N}{d\Delta\Phi} = 1 + V_1\,Cos(\Delta\Phi) + V_2\,Cos(2\Delta\Phi) + \cdots$$

Gale,Jeon,Schenke,Tribedy,Venugopalan, PRL110 (2013) 012302

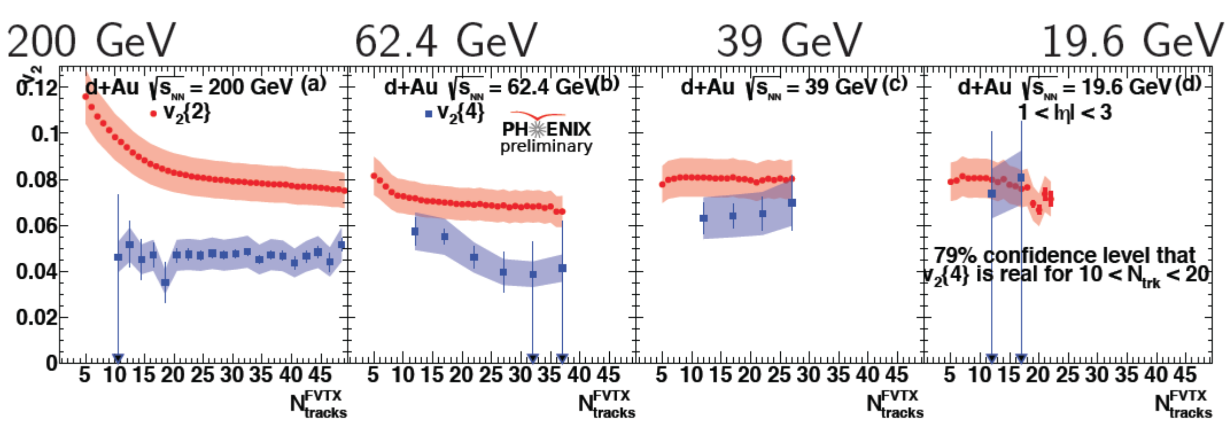


Some evidence of sensitivity of data to sub-nucleon scale fluctuations

Collectivity across system size

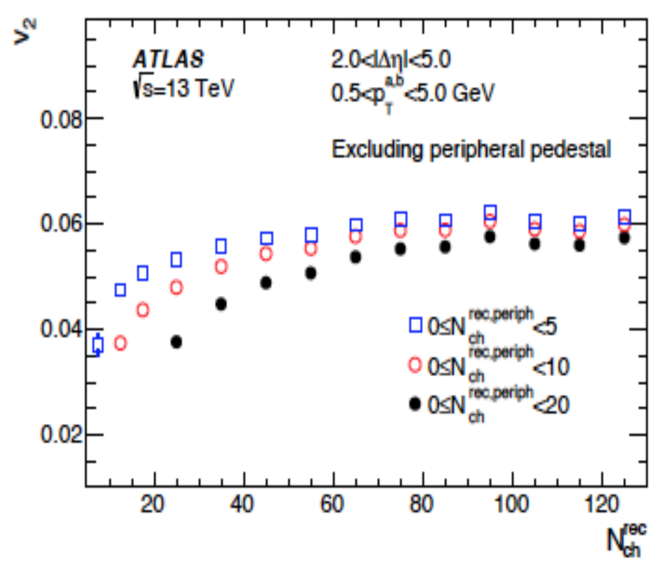


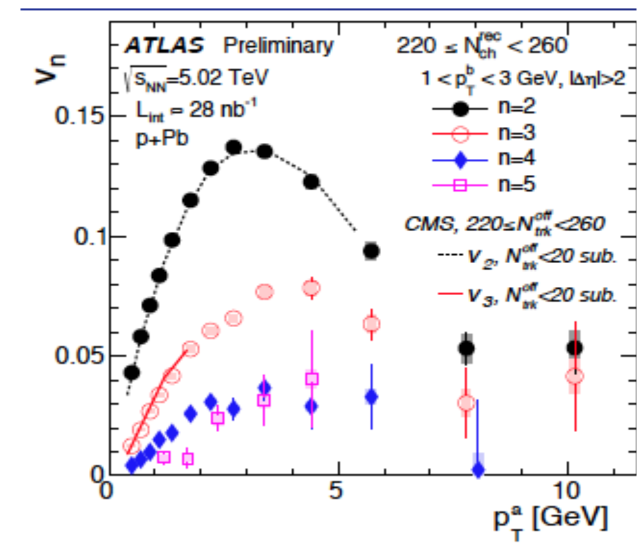
Collectivity across wide energy scales



Strong final state interactions? Hydrodynamics fits to the data, but correlations are observed up to high transverse momenta and small multiplicity.

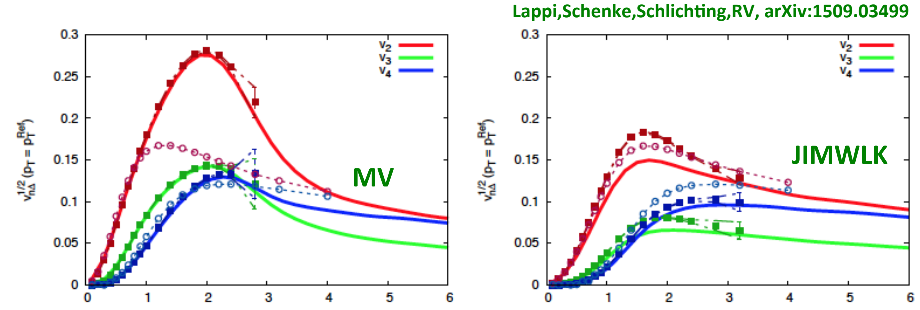
Issues with the hydrodynamic paradigm: III





Tracing azimuthal initial state correlations

Lappi, arXiv:1501.05505
Lappi,Schenke,Schlichting,RV, arXiv:1509.03499



What about 4-particle correlations?

$$\frac{d^mN}{\prod_{i=1}^m d^2\mathbf{p}_{i\perp}} = \frac{1}{(4\pi^3 B)^m}\prod_{i=1}^m \int d^2\mathbf{b}_i \int d^2\mathbf{r}_i\; e^{-b_i^2/E}\; e^{-r_i^2/4B} e^{i\mathbf{p}_{i\perp}\cdot\mathbf{r}_i}\left\langle \prod_{j=1}^m D(\mathbf{b}_j + \frac{\mathbf{r}_j}{2}, \mathbf{b}_j - \frac{\mathbf{r}_j}{2})\right\rangle$$

$$\kappa_n\{m\} = \int d^2\mathbf{p}_{1\perp}...d^2\mathbf{p}_{m\perp}\frac{d^mN}{\prod\limits_{k=1}^m d^2\mathbf{p}_{k\perp}}\prod_{j=1}^{m/2}\prod_{l=\frac{m}{2}+1}^{m} e^{ni(\phi_j^p-\phi_l^p)}$$

$$c_n\{4\} = \frac{\kappa_n\{4\}}{\kappa_0\{4\}} - 2\left(\frac{\kappa_n\{2\}}{\kappa_0\{2\}}\right)^2$$

First initial state results on $c_n\{4\}$, SC{m,n}
Kevin Dusling's talk at 10:30 am Friday

Dusling,Mace,RV, in preparation

Kevin Dusling

Collectivity from the initial state: Four-particle correlations in proton-nucleus collisions

Collectivity from four-particle initial state correlations has remained elusive…

Compute $v_2\{m\}$ systematically for the first time in an initial state framework

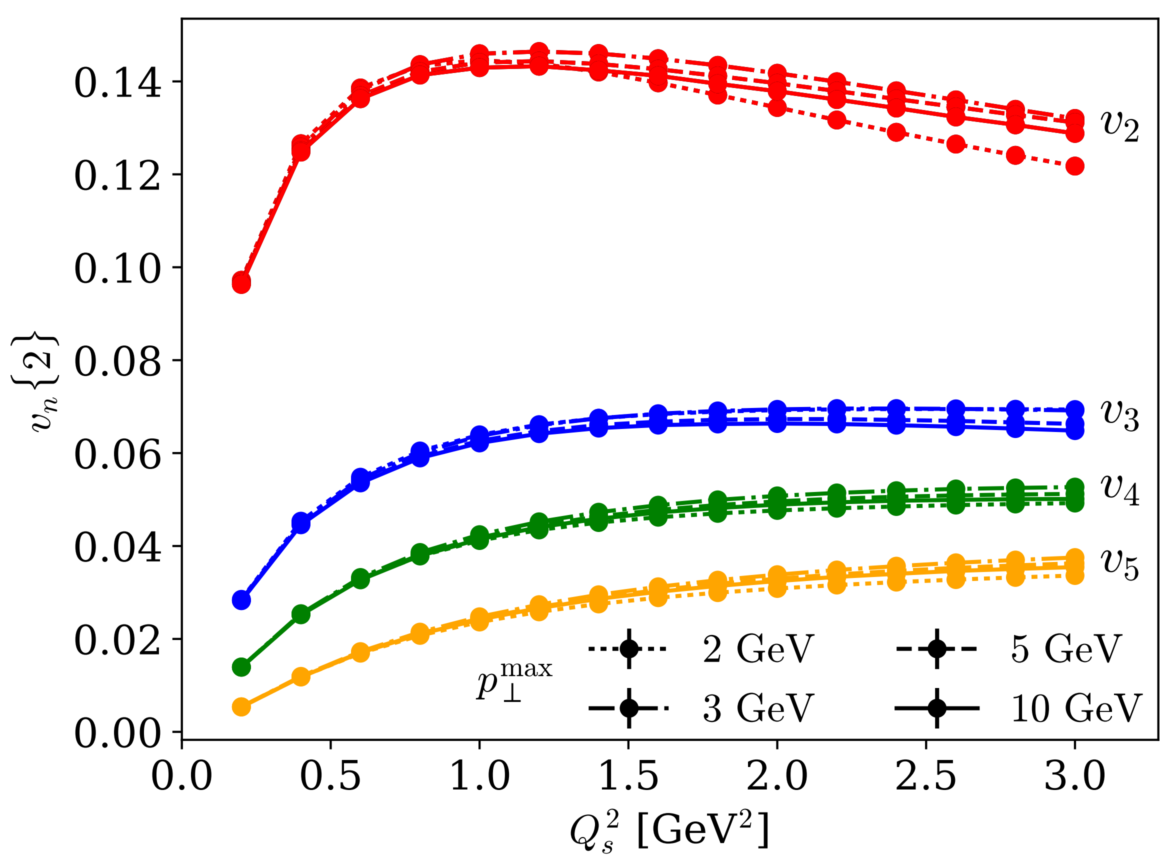
First computation of the average of the product of four light-like “dipole” Wilson-line correlators

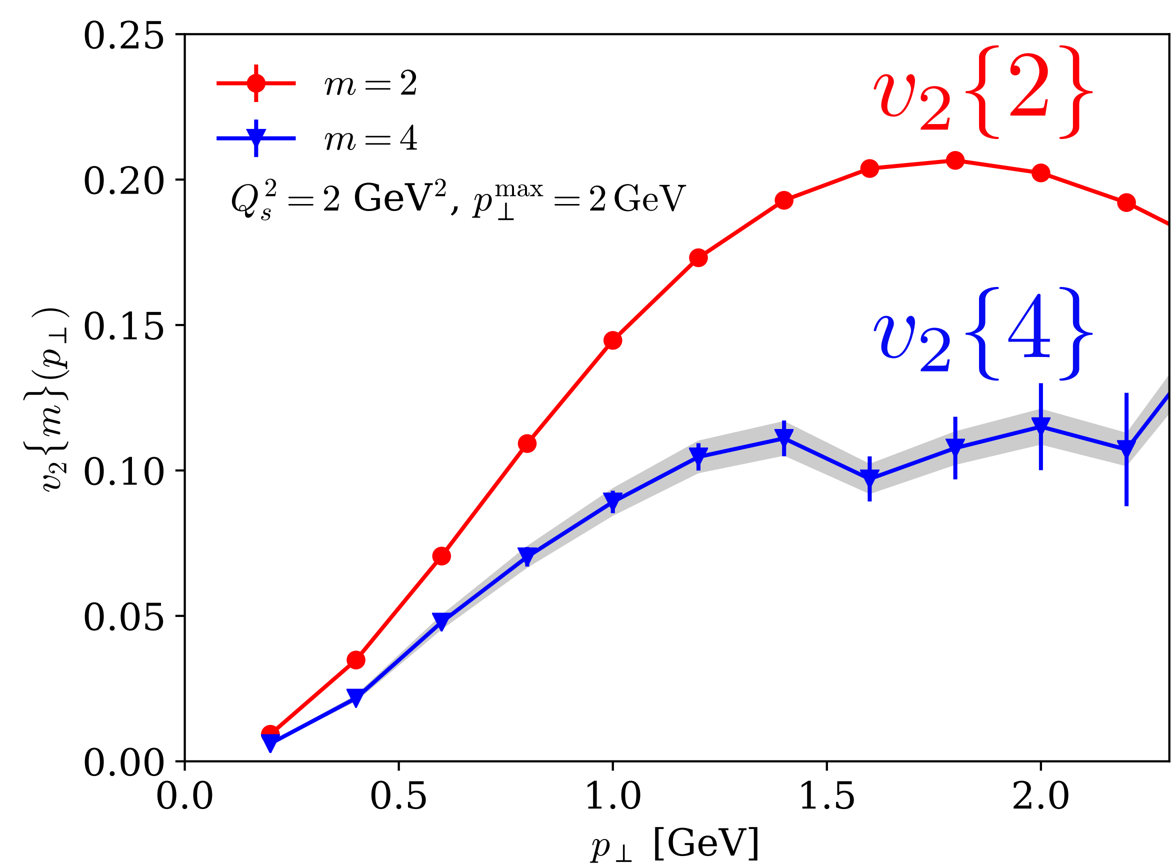
$$W_q(\mathbf{b_i}, \mathbf{k_{i\perp}}) = \frac{1}{\pi^2} e^{-|\mathbf{b_i}|^2/B} e^{-|\mathbf{k_i}|^2 B}$$

Quark distribution

$$\frac{d^m N}{d^2\mathbf{p_{i\perp}} \cdots d^2\mathbf{p_{m\perp}}} = \prod_{i=1}^{m} \int d^2\mathbf{b_i} \int \frac{d^2\mathbf{k_i}}{(2\pi)^2} W_q(\mathbf{b_i}, \mathbf{k_{i\perp}})$$

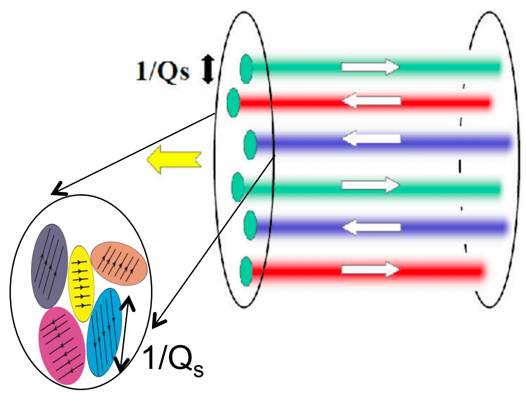
$$\cdot \int d^2\mathbf{r_i} e^{i(\mathbf{p_{i\perp}} - \mathbf{k_{i\perp}})\cdot \mathbf{r_i}} \left\langle \prod_{j=1}^{m} D\left(\mathbf{b_j} + \frac{\mathbf{r_j}}{2}, \mathbf{b_j} - \frac{\mathbf{r_j}}{2}\right) \right\rangle .$$

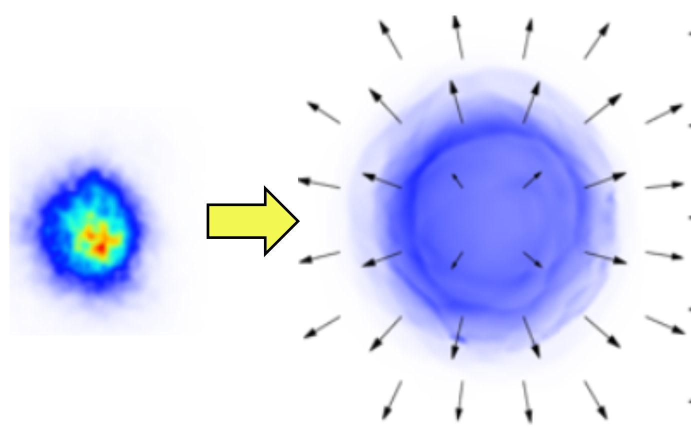




Kevin Dusling, Mark Mace and Raju Venugopalan ArXiv:1705.00745

Jiangyong Jia
"Long-range collectivity" in small systems





Summary of collectivity in small system

- Collectivity associated with ridge must involve many particles in multiple η ranges → access via subevent cumulant methods

Challenge for both initial & final state scenarios?

- LHC v_2 associated with ridge does not turn off at low N_{ch}.
- RHIC $v_2\{4\}$ increases and approach $v_2\{2\}$ at lower $\sqrt{s}$

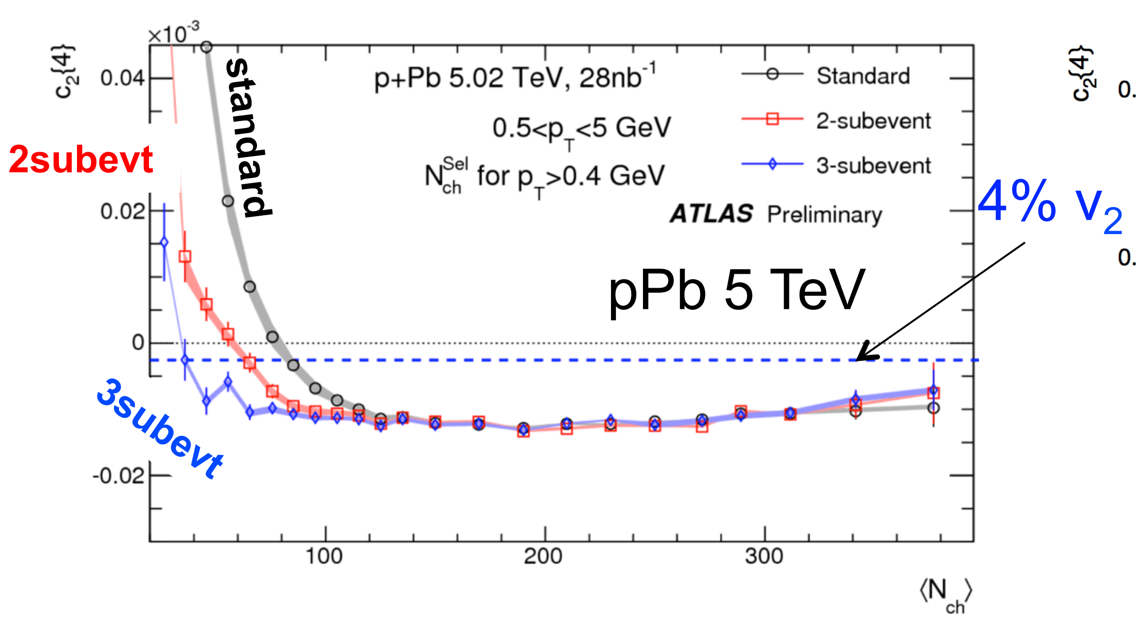
Challenge (or not) for initial state only scenarios?

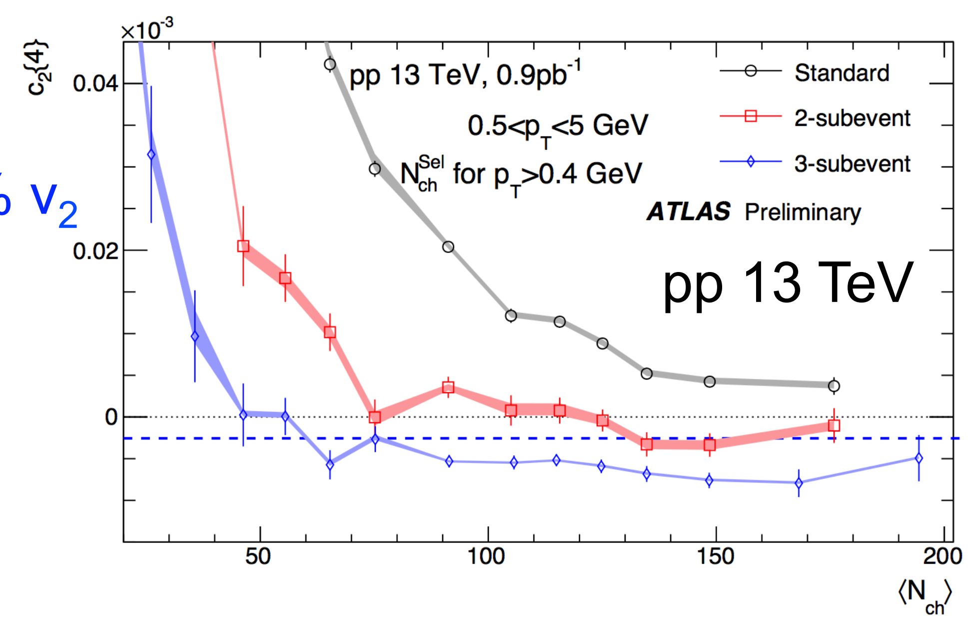
- LHC $v_2^{pp} < v_2^{pPb}$ in all N_{ch} and all $\sqrt{s}$.
- LHC $c_2\{4\}$ <0 down to very low N_{ch} and more negative at higher p_T.
- RHIC geometry scan suggest ordering of v_n follows that of ε_n.
- LHC 5% v_2 at p_T~10 GeV.
- LHC symmetric cumulants SC(2,3), SC(2,4) similar to PbPb

Coexistence of initial state & final state scenarios?

Key issue: How to constrain timescales for onset of collectivity?

Long-range collectivity via subevent cumulants





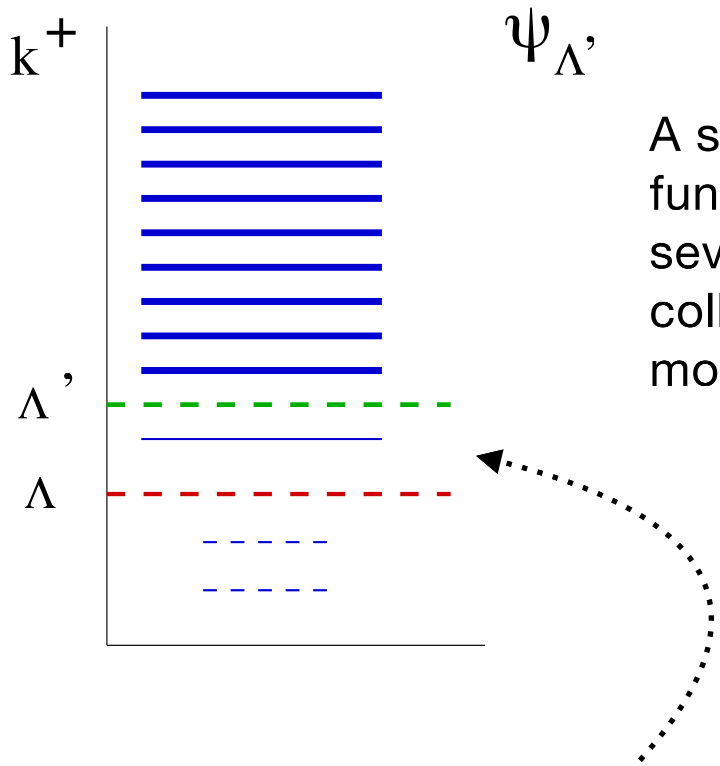
arXiv:1701.03830

pPb: methods consistent for N_{ch}>100, but split below that

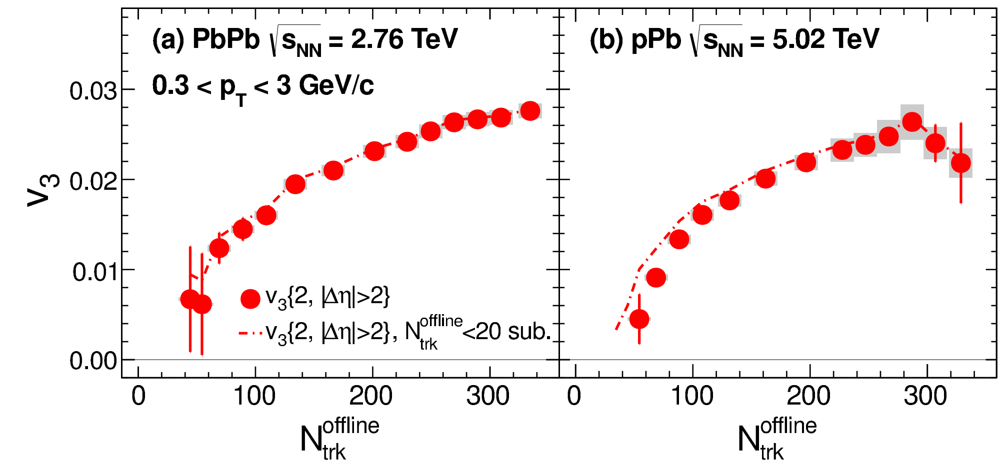
Alex Kovner
Exploring correlations in the CGC wave function

Study correlated structure of the initial wave function

Better approximation to the CGC state?



A single high p_T parton in the wave function is most likely accompanied by several lower p_T partons, who collectively balance the transverse momentum

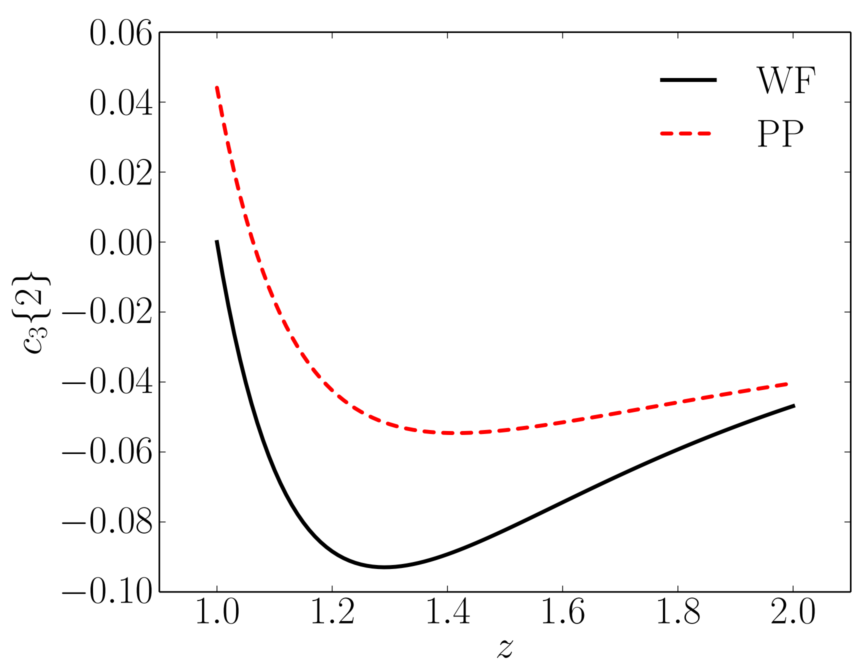


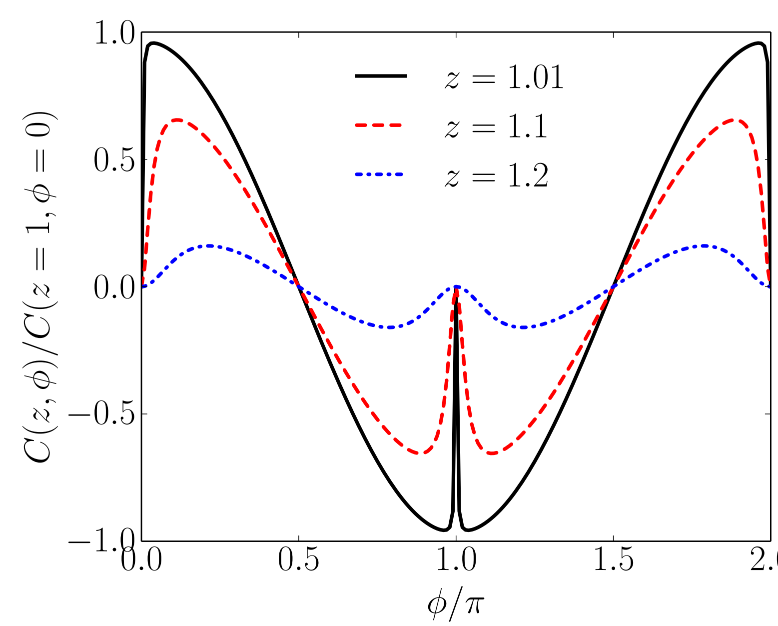
double inclusive spectrum

$$\frac{1}{2}\frac{\frac{d^6N}{d^2k\,d^2p\,d\eta_k\,d\eta_p}(k,p)-\frac{d^6N}{d^2k\,d^2p\,d\eta_k\,d\eta_p}(k,-p)}{\frac{N_c^4S_\perp^2\mu^4\lambda^4}{k^4p^4}} = \frac{\alpha_s N_c}{S_\perp p^2}C(z=p/k,\phi)$$

The reproduce v_3 one should take into account correlations of soft gluons

correlation function



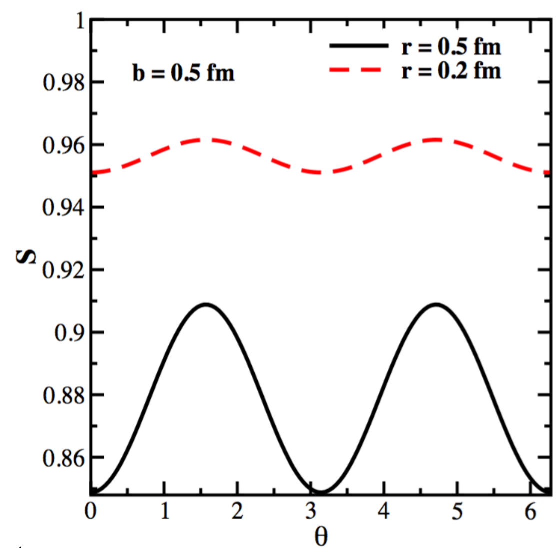


third cumulants

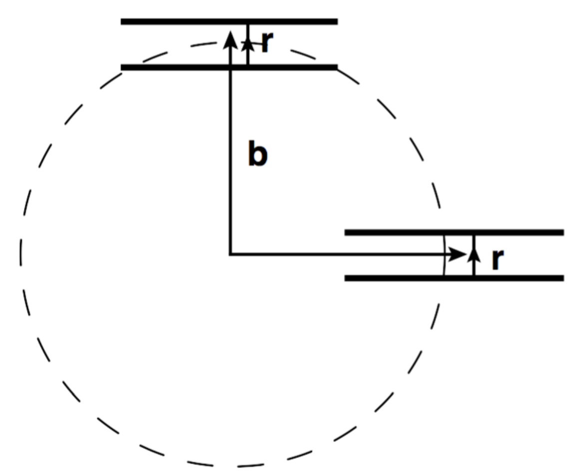
A. Kovner, M. Lublinsky and V. Skokov, arXiv:1612.07790 [hep-ph]

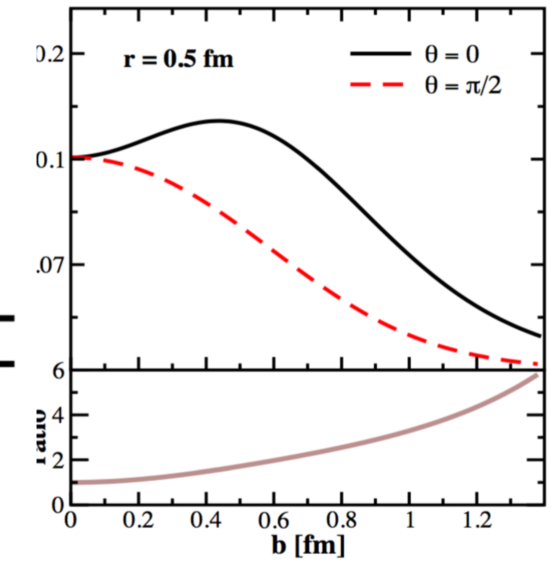
Color dipole orientation as an origin of elliptic flow

$$N_{2g}(b,r,\theta) = \mathcal{N}_0(b,r) + \mathcal{N}_\theta(b,r)\cos(2\theta) \qquad S(\boldsymbol{b},\boldsymbol{r}) = \exp\{-N_{2g}(\boldsymbol{b},\boldsymbol{r})\}$$

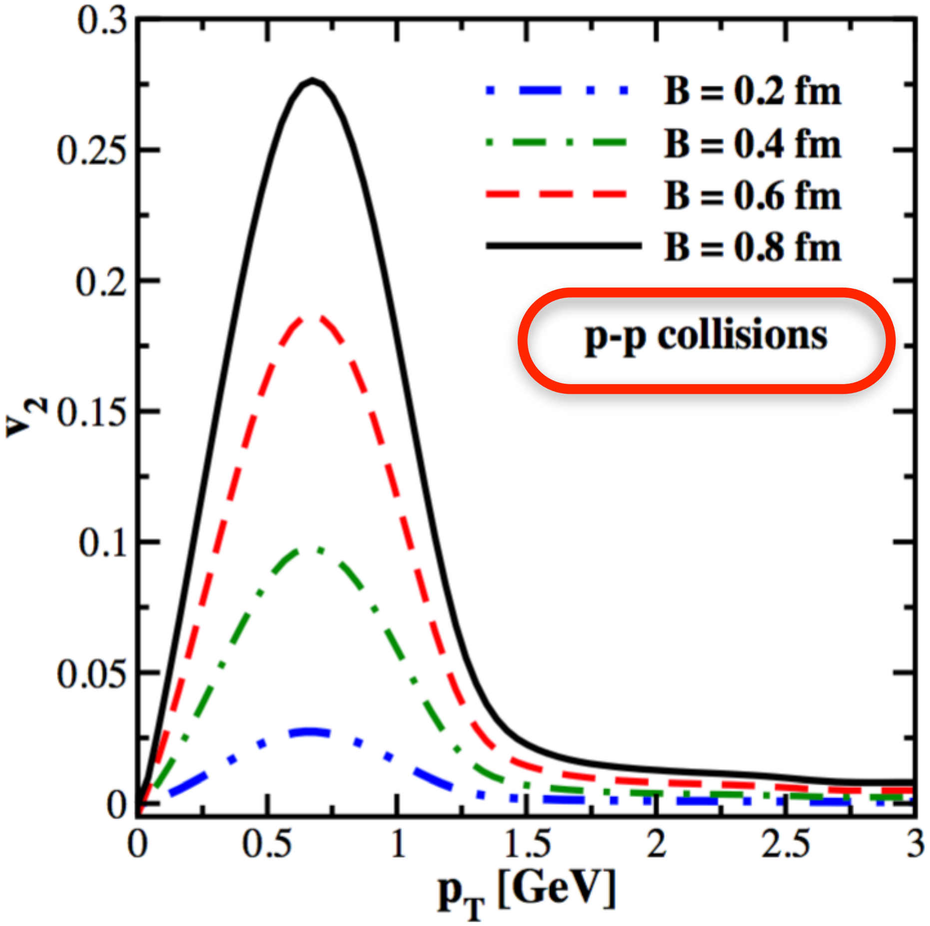


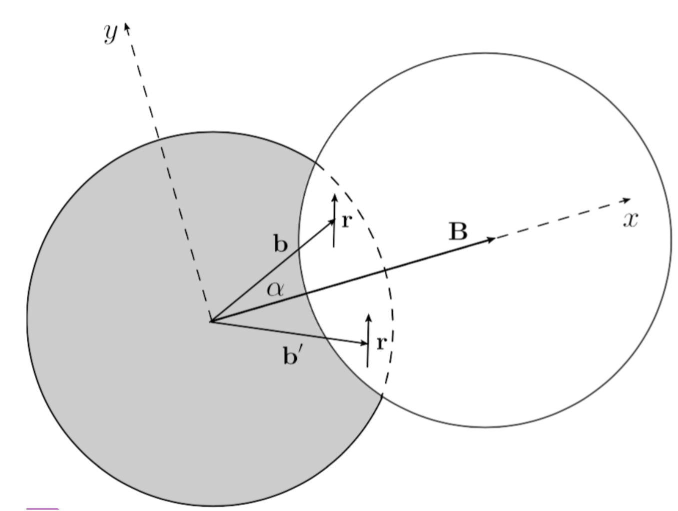
S(b||r) < S(b⊥r)





The scattering is stronger when the dipole orientation is (anti)parallel to its impact parameter ($\theta = 0$ or $\theta = \pi$) than for a dipole perpendicular on b ($\theta = \pi/2$).





✦ **The difference between 'parallel' and 'perpendicular' scattering increases with the dipole size r and also with the impact parameter b.**

$$v_2(p,b) = -\frac{\int r\mathrm{d}r\, e^{-\mathcal{N}_0(b,r)} J_2(pr) \int \mathrm{d}\theta\, e^{-\mathcal{N}_\theta(b,r)\cos(2\theta)}\cos(2\theta)}{\int r\mathrm{d}r\, e^{-\mathcal{N}_0(b,r)} J_0(pr) \int \mathrm{d}\theta\, e^{-\mathcal{N}_\theta(b,r)\cos(2\theta)}} = \frac{\int r\mathrm{d}r\, e^{-\mathcal{N}_0(b,r)} J_2(pr)\, I_1(\mathcal{N}_\theta(b,r))}{\int r\mathrm{d}r\, e^{-\mathcal{N}_0(b,r)} J_0(pr)\, I_0(\mathcal{N}_\theta(b,r))},$$

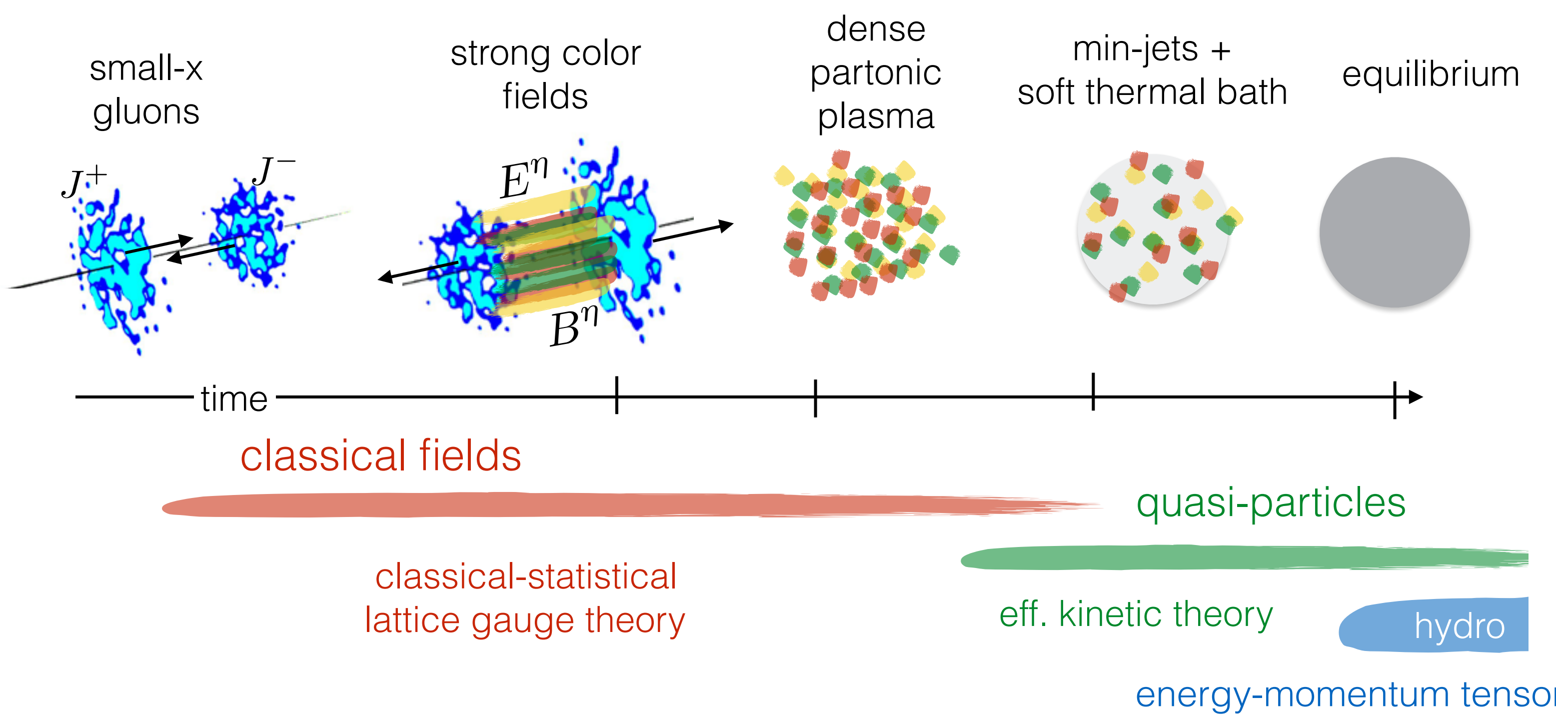
$$N(\mathbf{b}||\mathbf{r}) > \mathbf{N}(\mathbf{b}\perp\mathbf{r})$$

$$\mathcal{N}_\theta > 0 \longrightarrow v_2 > 0$$

E. Iancu and A. Rezaeian, arXiv:1702.03943

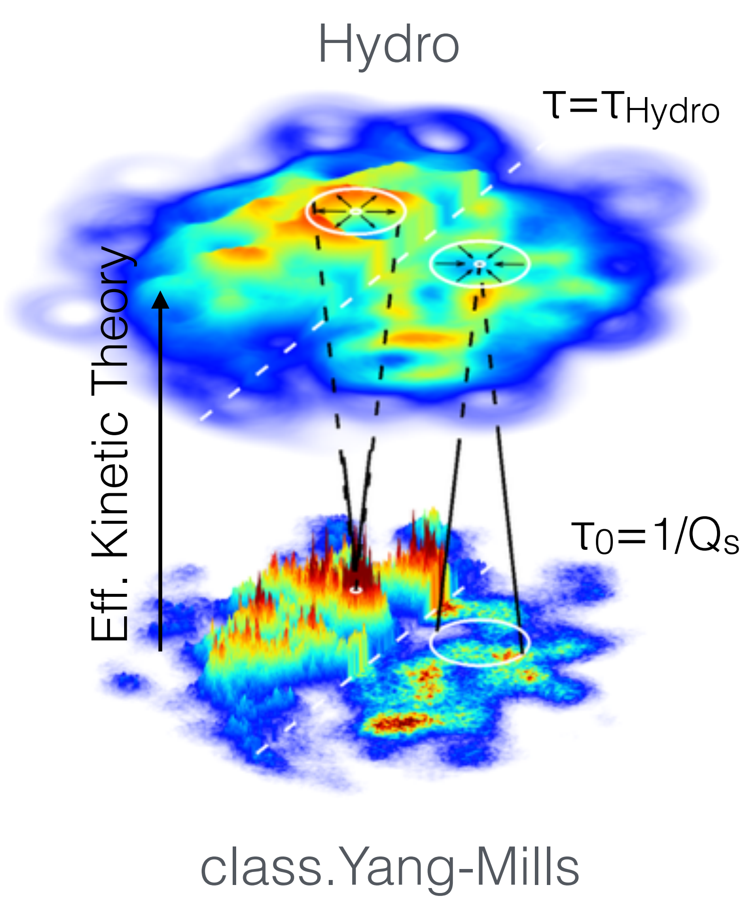
Sören Schlichting

Event-by-event pre-equilibrium dynamics — from gluon saturation towards the onset of hydrodynamics



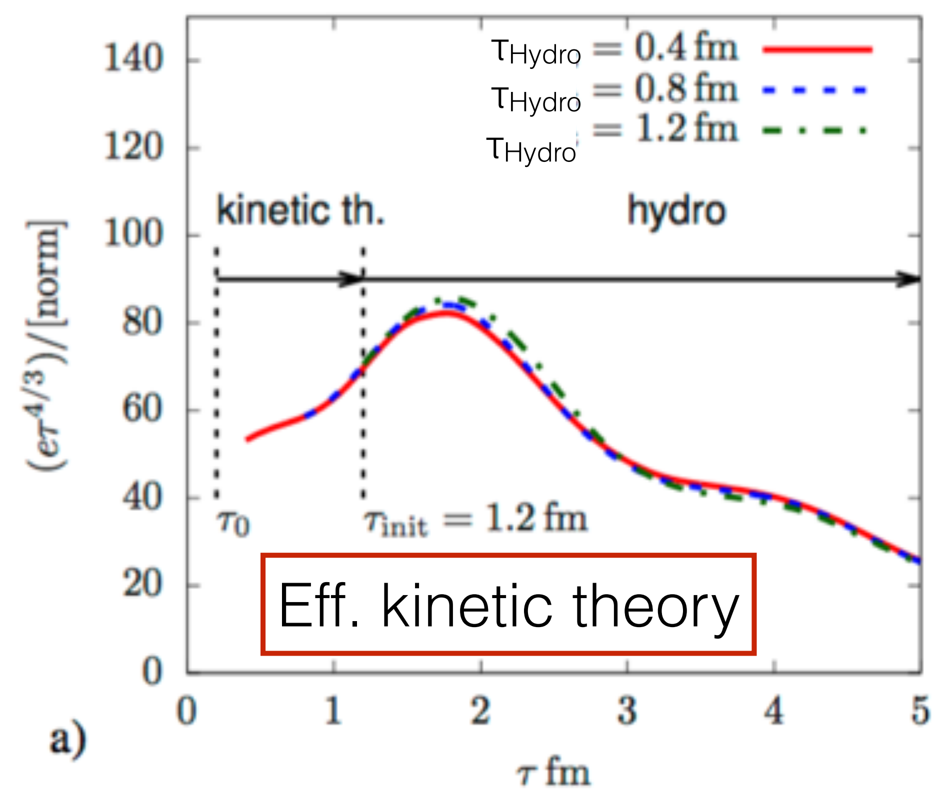
Extract energy-momentum tensor $T^{\mu\nu}(x)$ from classical statistical lattice simulation

Evolve $T^{\mu\nu}$ from initial time $\tau_0 \sim 1/Q_s$ to hydro initialization time τ_{Hydro} using eff. kinetic theory description

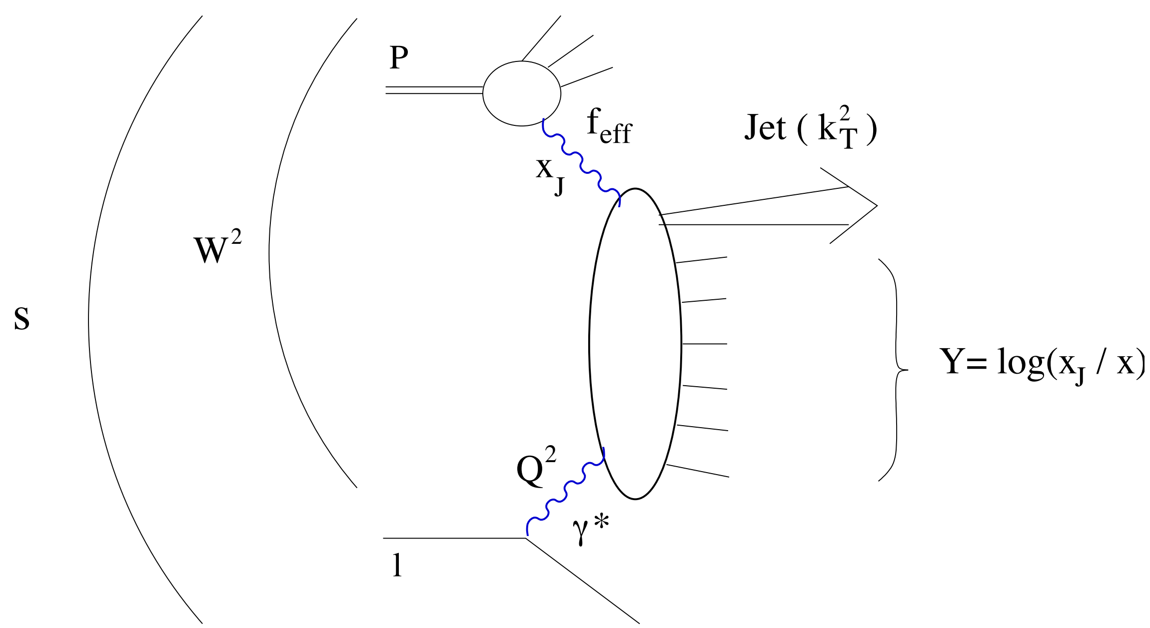


$$T^{\mu\nu}(\tau,x) = T^{\mu\nu}_{BG}\Big(Q_s(x)\tau\Big) + \int_{Disc} G^{\mu\nu}_{\alpha\beta}\Big(\tau,\tau_0,x,x_0,Q_s(x)\Big)\ \delta T^{\alpha\beta}(\tau_0,x_0)$$

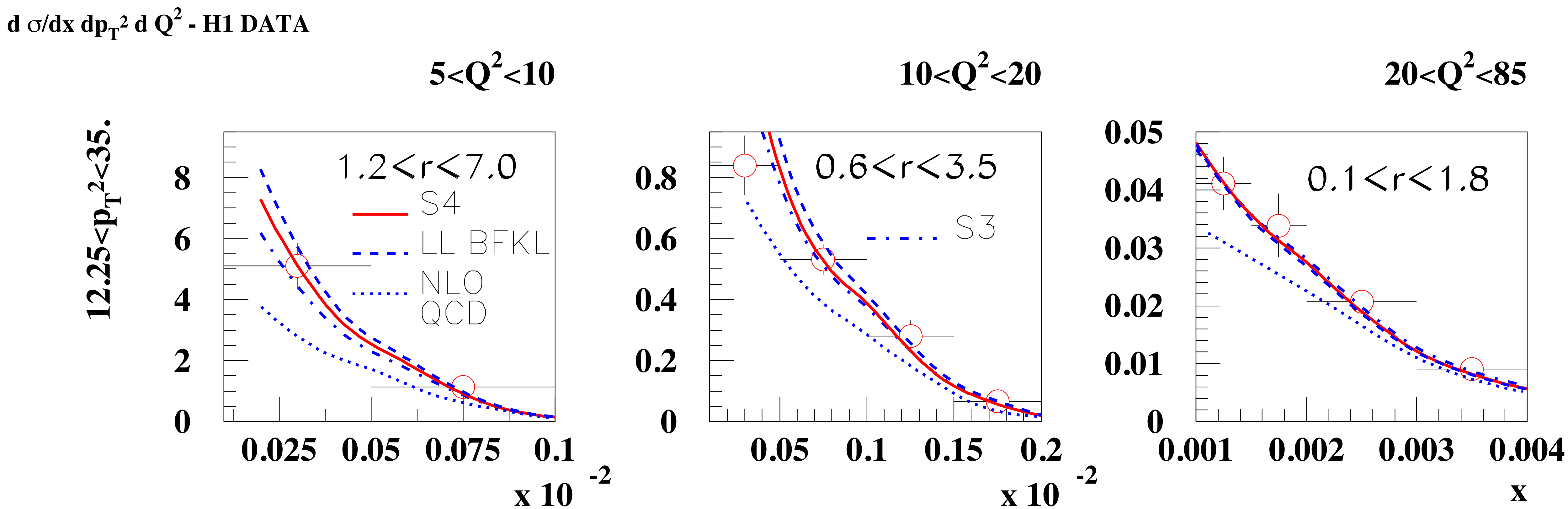
Energy density in the central region of Pb+Pb collision



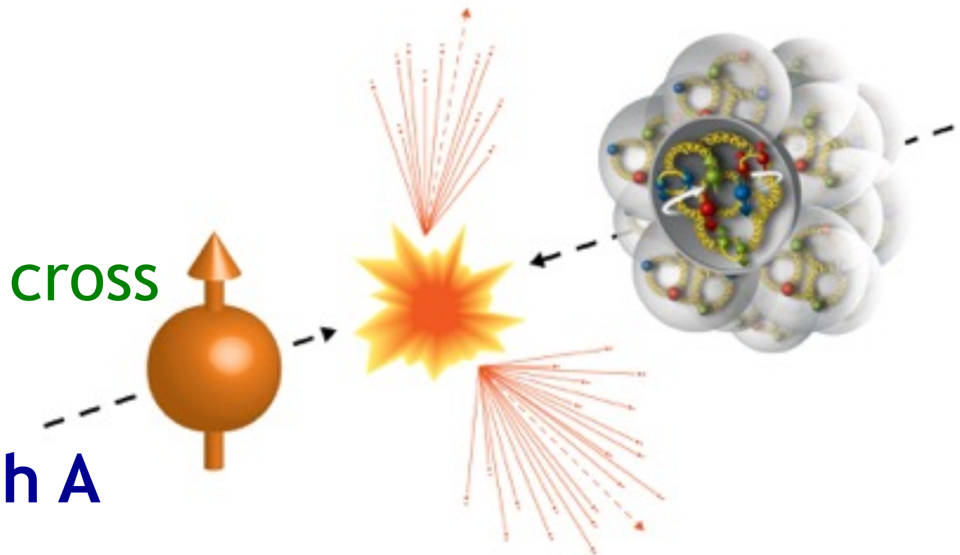
A. Kurkela, A. Mazeliauskas, J.-F. Paquet, S. Schlichting, D. Teaney (arXiv:1704.05242)



- Full implementation of BFKL NLL kernel for many jet proceeses at HERA, Tevatron and LHC
- Forward jets at HERA: DGLAP NLO fails to describe HERA data, good description of data using BFKL NLL formalism
- Mueller Navelet jets: Larger decorrelation expected for BFKL formalism, unfortunately suffers a lot of higher order corrections, NLL BFKL with saturation in progress
- Jet veto measurements in ATLAS: mainly not related to BFKL resummation effects
- Jet gap jets:
  - NLL BFKL cross section implemented in HERWIG (Kernel)
  - Fair description of D0 and CDF data
  - Full NLL calculation in progress
  - Jet gap jet events in diffraction: clean tests of BFKL, modulo the survival probability (and its depndence on kinematics)



- STAR @ RHIC can reach the saturation region at forward rapidity in p+A
- Polarized protons
- Scanning A ➔ Au, Al, …
- p_T scan and rapidity/x scan may allow to cross saturation scale Q_s^2 (x)



STAR can study evolution of $Q^2_s(x)$ with A

- First results on Transverse Single Spin Asymmetry A_N
  - Small to no suppression in p+Au
- Results coming soon for
  - Di-hadron angular correlation
  - R_{pA} for π^0 and photons

RHIC 2015

- $\vec{p} + p, L_{\text{int}} = 40 + 50\ \text{pb}^{-1}$
- $\vec{p} + Al, L_{\text{int}} = 1.0\ \text{pb}^{-1}$
- $\vec{p} + Au, L_{\text{int}} = 0.45\ \text{pb}^{-1}$

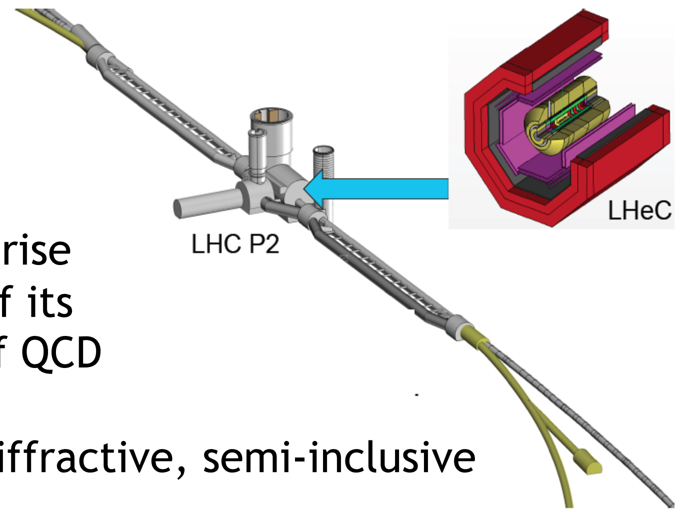
- Future forward upgrade at STAR is proposed, including saturation/pA physics at forward and mid-rapidity

STAR at RHIC offers unique opportunities to study low-x

Paul Newman

Low x physics and saturation: from HERA to future DIS and the LHeC

Summary

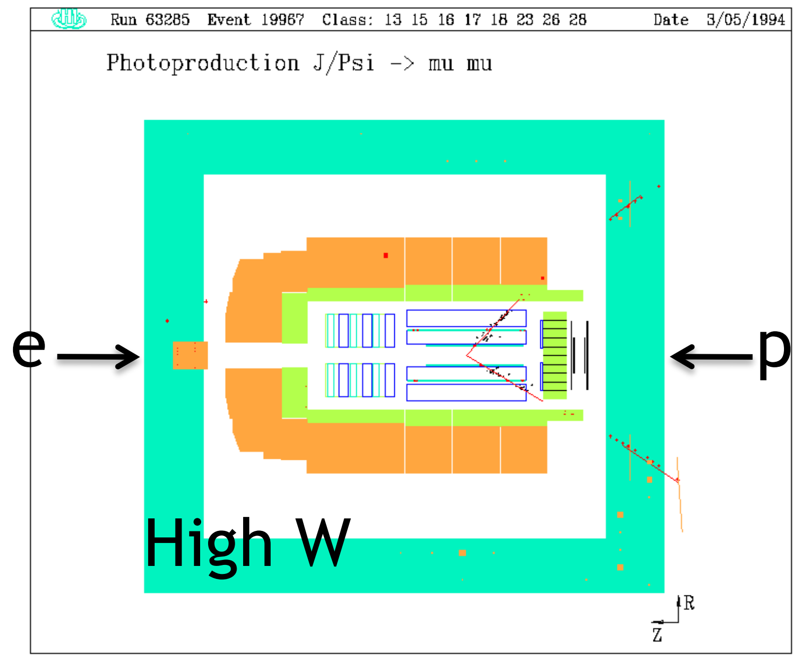


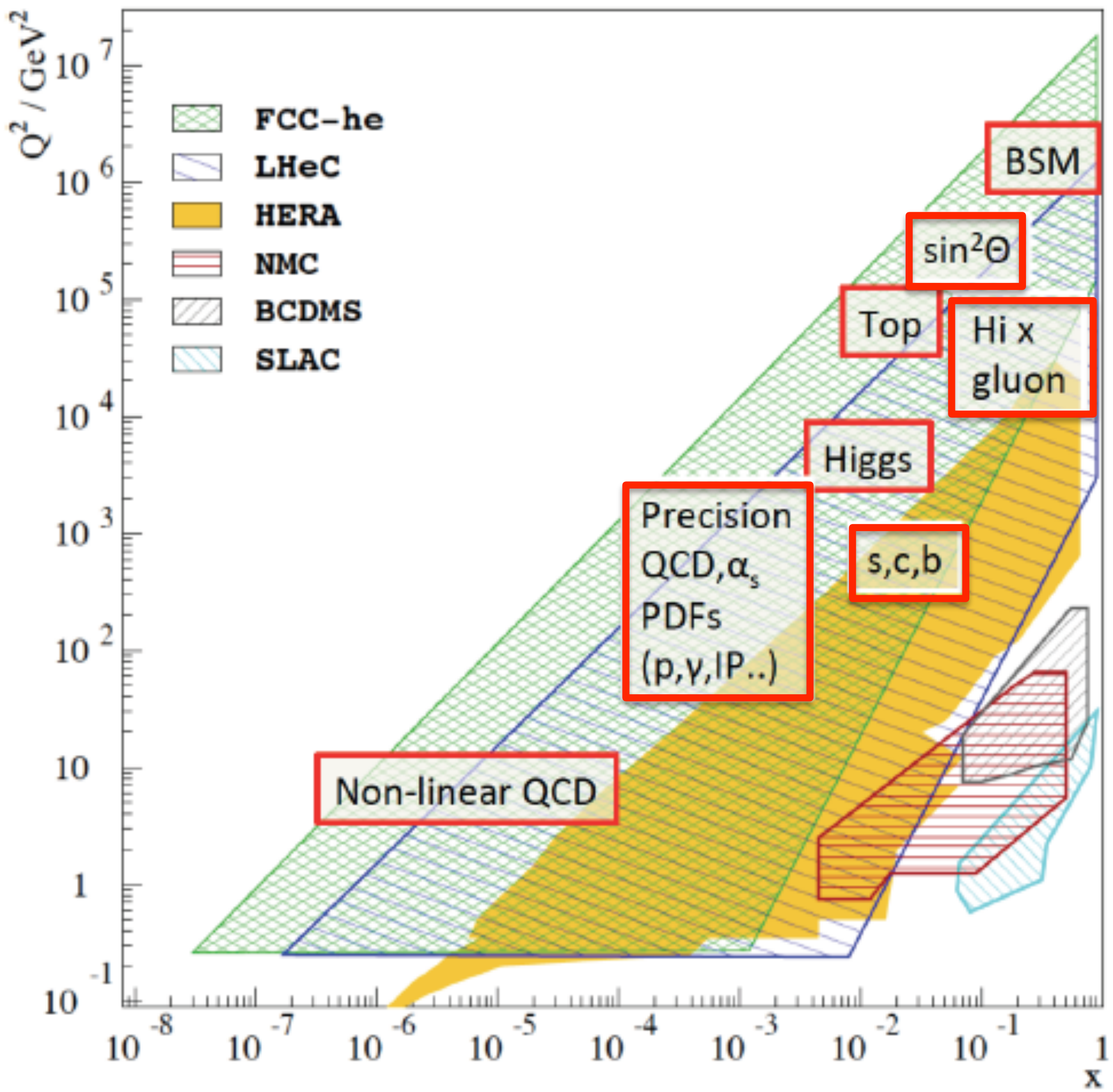
- Future DIS facilities are vital to fully establish and characterise saturation and the dynamics of its onset → the energy frontier of QCD

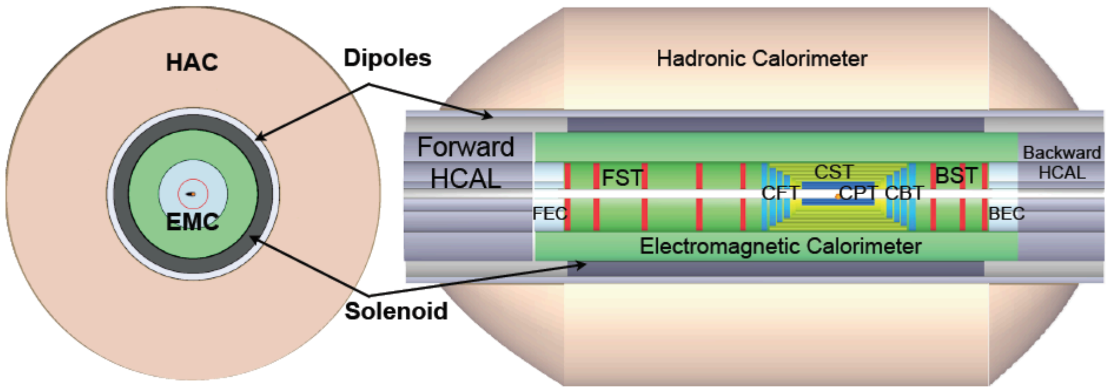
- Needs ep and eA inclusive, diffractive, semi-inclusive over a range of energies

- Complementarity beween EIC and LHeC

- LHeC working towards next CERN Council European Strategy exercise (2020) with a view to running in later stages of LHC (post-LS4, from ~2031) … lots to do!

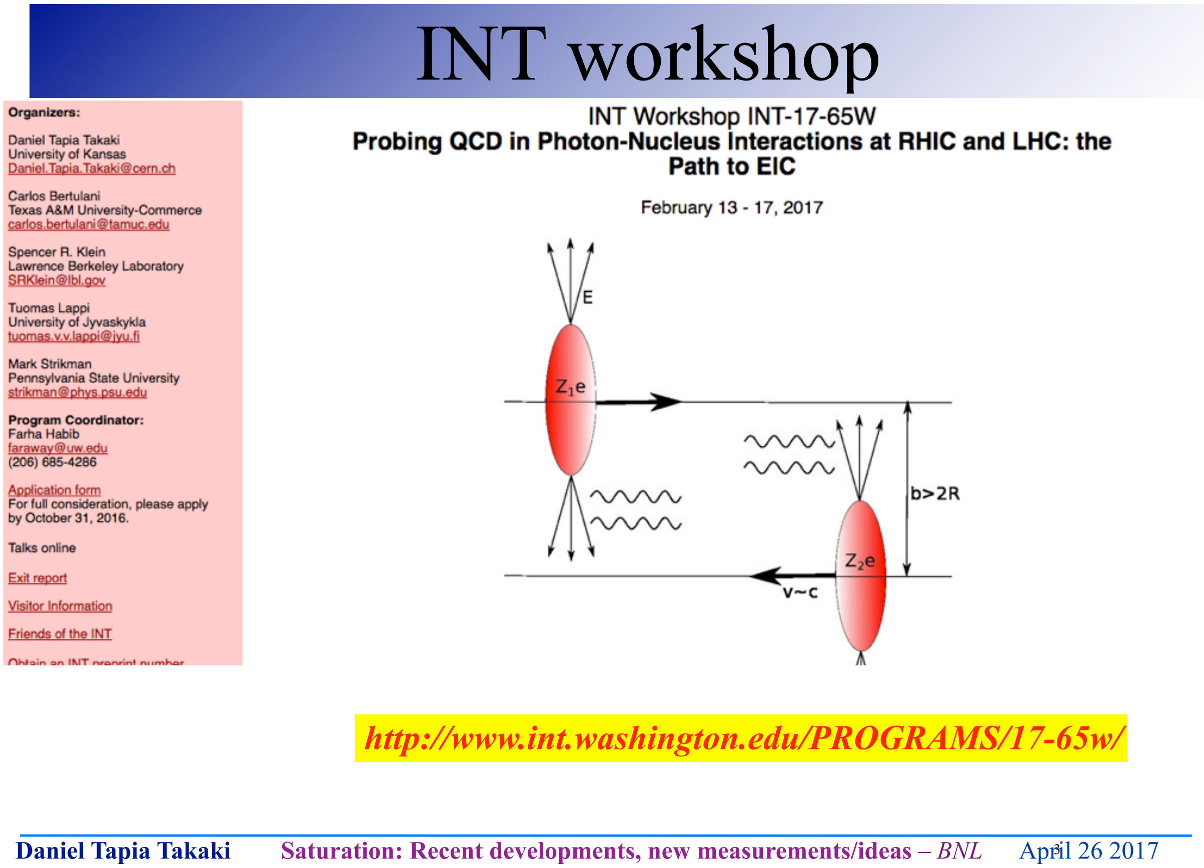


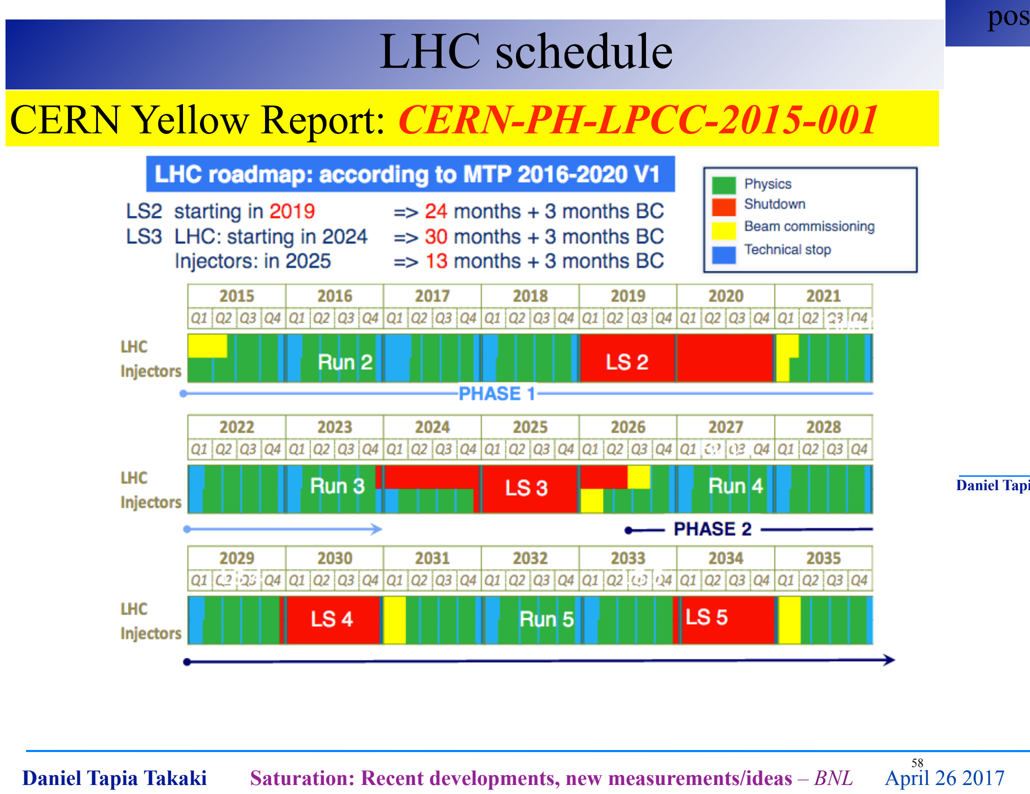


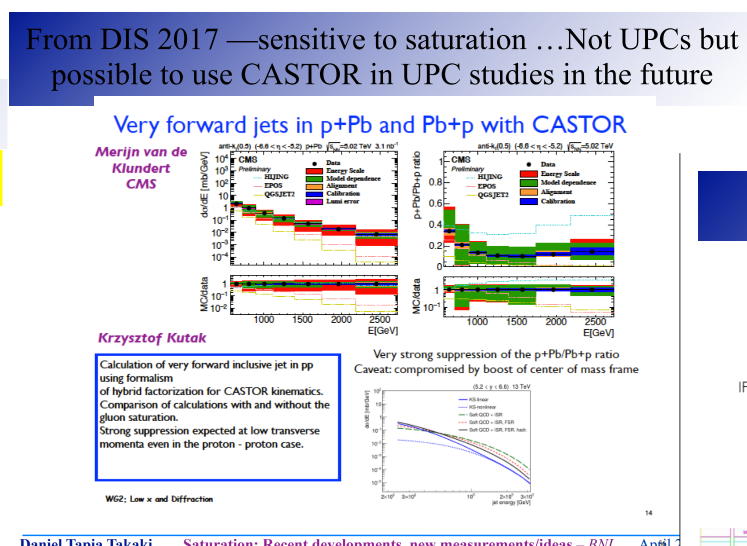


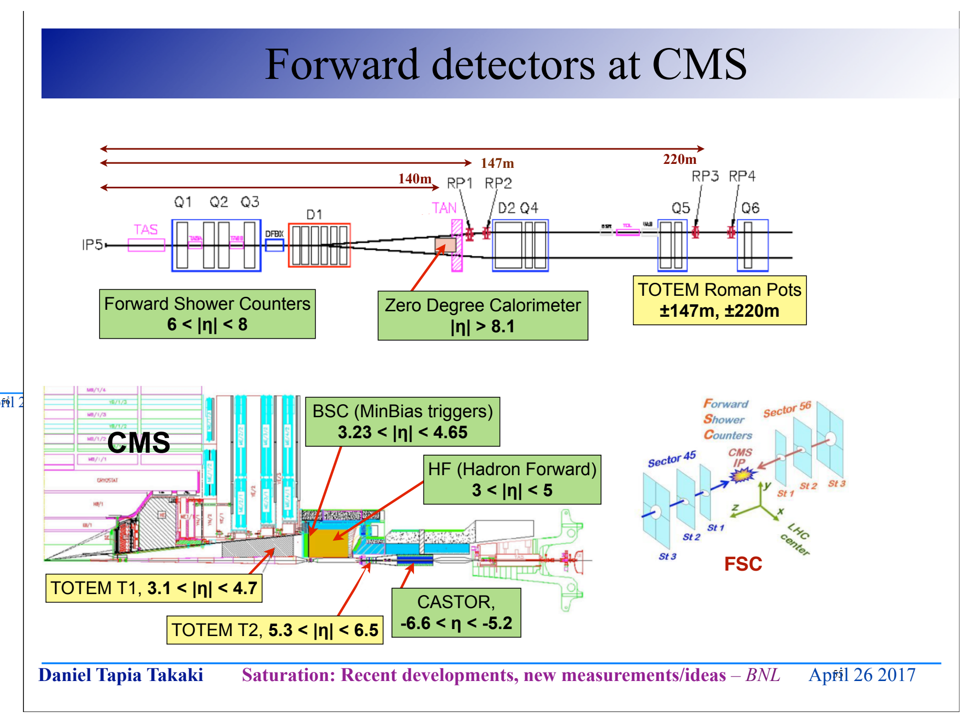
Daniel Tapia Takaki

Studying gluon saturation and nuclear gluon effects using forward heavy-ion probes and UPCs









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Saturation: Recent Developments, New Ideas and Measurements

April 26-28, 2017

Tuomas Lappi (U. Jyvaskyla)
Vladimir Skokov (RBRC)
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Proceedings of RIKEN BNL Research Center Workshop

Volume 129

RBRC
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- Small x evolution and hadron production at NLO
- Spin at small x
- TMD physics
- Small-x physics in e+p and e+A DIS
- Particle production in pA
- Correlations

27 Presentations in 3 days

I. Balitsky .... *Higher-twist corrections to gluon TMD factorization*
G. Beuf .... *Full NLO corrections for DIS structure functions in the dipole factorization formalism*
S. Caron-Huot .... *Linear and nonlinear small-x evolution in perturbation theory*
S. Caron-Huot .... *Nuclear Theory/RIKEN Seminar: Analyticity in Spin and Causality in Conformal Theories*
G. Chirilli .... *Rapidity factorization of high-energy scattering processes at NLO*
A. Dumitru .... *Fluctuations of the gluon distribution at small-x: correlation of multiplicity and transverse momentum fluctuations*
K. Dusling .... *Collectivity from the initial state: four-particle correlations in proton-nucleus collisions*
K. Fukushima .... *Particle production in CGC*
E. Iancu .... *Particle production in proton-nucleus collisions beyond leading order*
J. Jia .... *Flow in small systems*
D. Kharzeev .... *Deep inelastic scattering as a probe of entanglement*
Y. Kovchegov .... *Small-x asymptotics of the quark helicity distribution*
A. Kovner .... *Exploring correlations in the CGC wave function: odd azimuthal anisotropy*
M. Lublinsky .... *From light-cone wave function to NLO JIMWLK*
D. Neill .... *Finding small-x like evolution in QCD final state dynamics: the problem of non-global logarithms*
P. Newman .... *Low-x physics and saturation studies for the Large Hadron Electron Collider*
A. Ogawa .... *Polarized p+A physics at forward rapidity at STAR*
R. Paatelainen .... *Toward higher-order accuracy in LCPT*
T. Peitzmann .... *Opportunities for forward photon measurements in ALICE at the LHC*
A. Rezaeian .... *Elliptic flow from color-dipole orientation in pp and pA collisions*
C. Royon .... *Forward jets at HERA and Mueller-Navelet and jet gap jet events at Tevatron and LHC*
B. Schenke .... *Subnucleonic fluctuations, diffraction, and small-x evolution*
S. Schlichting .... *Event-by-event pre-equilibrium dynamics — from gluon saturation toward the onset of hydrodynamics*
M. Sievert .... *Quark helicity evolution at small-x*
A. Stasto .... *Low-x physics and prompt neutrino production*
D. Tapia-Takaki .... *Studying gluon saturation and nuclear effects using forward heavy-ion probes and UPCs at LHC*
R. Venugopalan .... *Ridge-like correlations in small systems: status and problems*