Overview of TMDs at Small-x: as can be measured at EIC

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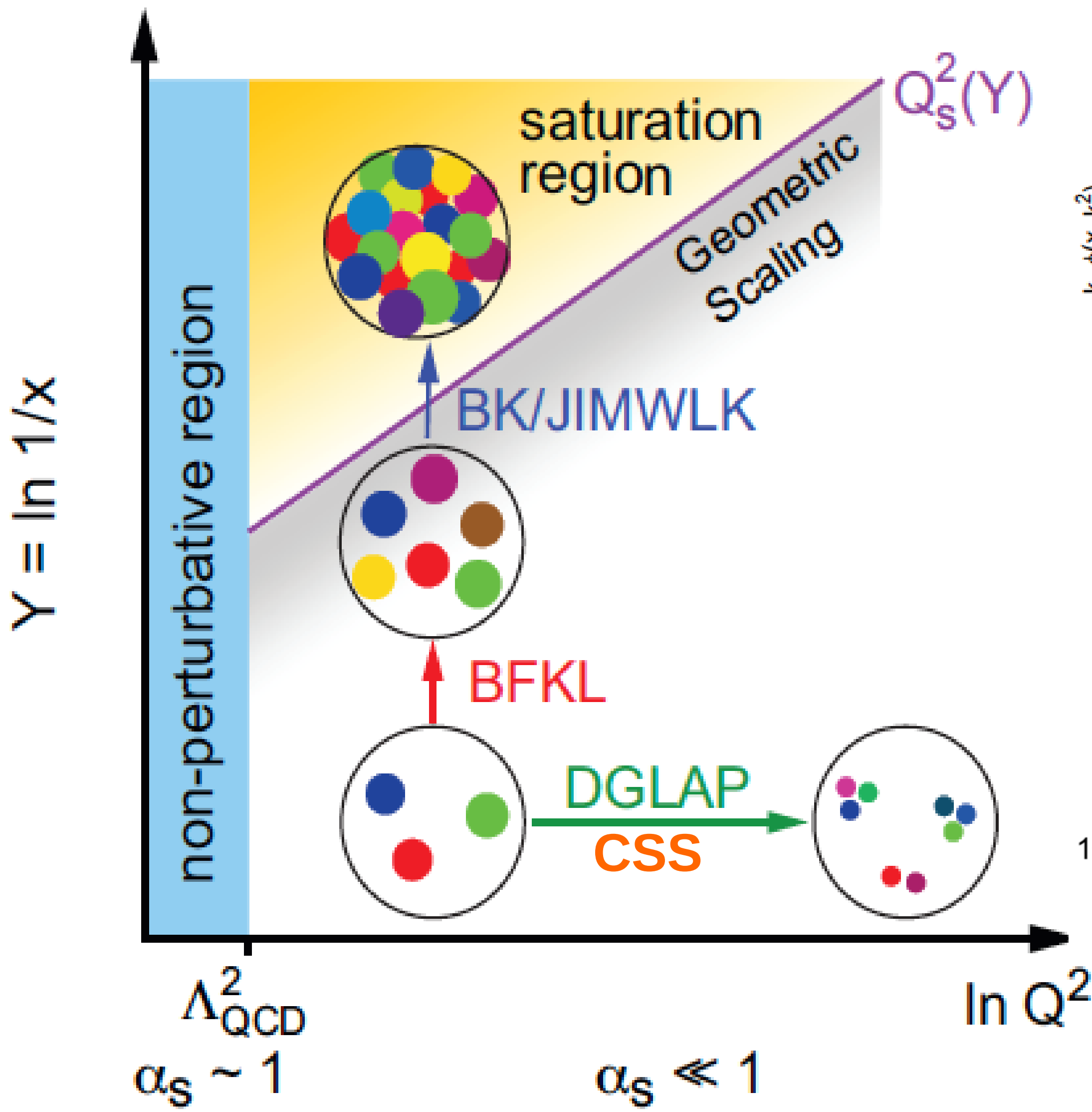
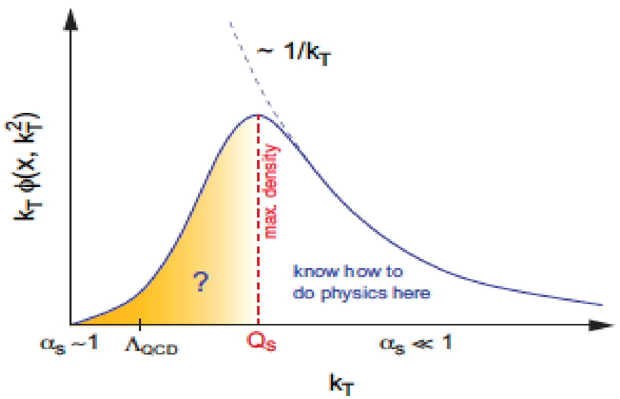
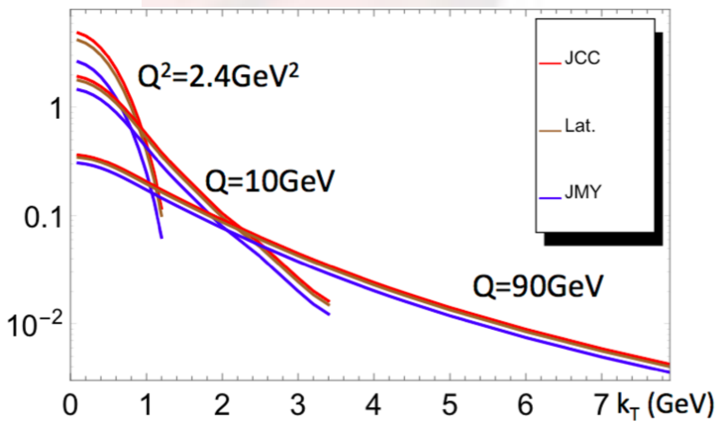
Transverse momentum distributions: A unified picture







Prokudin-Sun-Yuan, 2015
Xiao-Yuan-Zhou, 2017

Comments

- We don't lose the sensitivity to the saturation physics even with Large Q
- We gain the direct probe for the transverse momentum dependence of partons
- Beyond the leading order?
- Additional dynamics involved
  - Soft gluon resummation

(from my 2009 talk)

Among recent developments

- Spin-dependent TMD gluon at small-x
  - Related to the spin-dependent odderon, Boer-Echevarria-Mulders-Zhou, PRL 2016
  - Gluon/quark helicity distributions, Kovchegov-Pitonyak-Sievert, 2016, 2017, 2018
- Subleading power corrections in the TMD gluon/quark distributions
  - Balitsky-Tarasov, 2017, 2018
- Sudakov resummation for small-x TMDs
  - Mueller-Xiao-Yuan, PRL110, 082301 (2013); Xiao-Yuan-Zhou, NPB921, 104 (2017); Zhou 2018
  - Balitsky-Tarasov, JHEP1510,017 (2015)

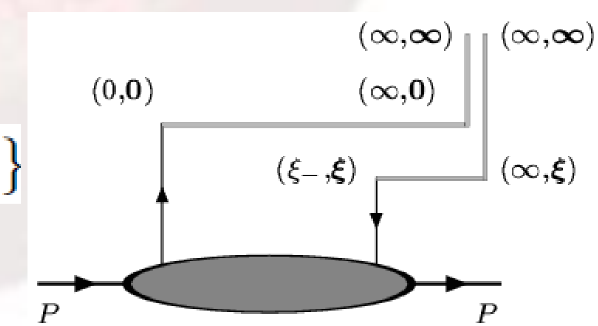
TMDs: Conventional gluon distribution

- Collins-Soper, 1981

$$xG^{(1)}(x,k_\perp) = \int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \times \langle P|F^{+i}(\xi^-,\xi_\perp)\mathcal{L}_\xi^\dagger \mathcal{L}_0 F^{+i}(0)|P\rangle$$

  - Gauge link in the adjoint representation

$$\mathcal{L}_\xi = \mathcal{P}\exp\{-ig\int_{\xi^-}^{\infty} d\zeta^- A^+(\zeta,\xi_\perp)\}$$
$$\mathcal{P}\exp\{-ig\int_{\xi_\perp}^{\infty} d\zeta_\perp\cdot A_\perp(\zeta^-=\infty,\zeta_\perp)\}$$



Physical interpretation

- Choosing light-cone gauge, with certain boundary condition (either one, but not the principal value) $A_\perp(\zeta^- = \infty) = 0$
- Gauge link contributions can be dropped
- Number density interpretation, and can be calculated from the wave functions of nucleus
  - McLerran-Venugopalan
  - Kovchegov-Mueller

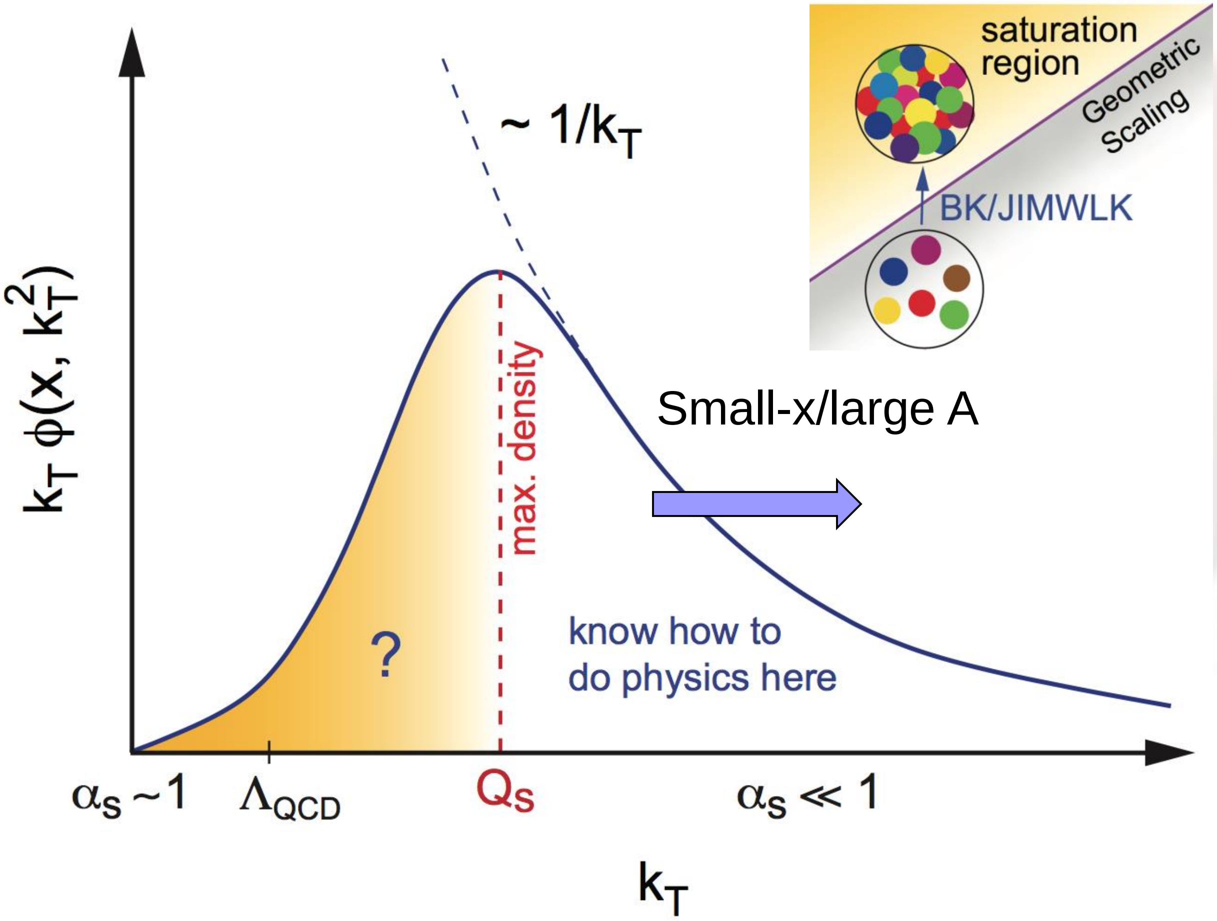
Classic YM theory

- McLerran-Venugopalan

$$xG^{(1)}(x,k_\perp) = \frac{S_\perp}{\pi^2\alpha_s}\frac{N_c^2-1}{N_c}\int\frac{d^2r_\perp}{(2\pi)^2}\frac{e^{-ik_\perp\cdot r_\perp}}{r_\perp^2}\left(1-e^{-\frac{r_\perp^2 Q_s^2}{4}}\right)$$

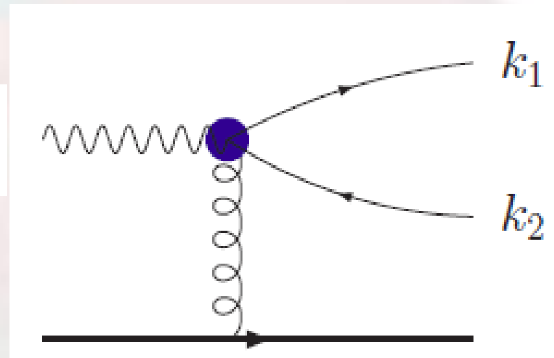
  - See also, Kovchegov-Mueller
  - We can reproduce this gluon distribution using the TMD definition with gauge link contribution, following BJY 02, BHPS 02
  - WW gluon distribution is the conventional one

Saturation at small-x/large A



DIS dijet probes **WW** gluons

$$\gamma_T^* A \to q(k_1) + \bar{q}(k_2) + X$$



- Hard interaction includes the gluon attachments to both quark and antiquark
- The q_t dependence is the gluon distribution w/o gauge link contribution at this order

Dominguez-Marquet-Xiao-Yuan 2011

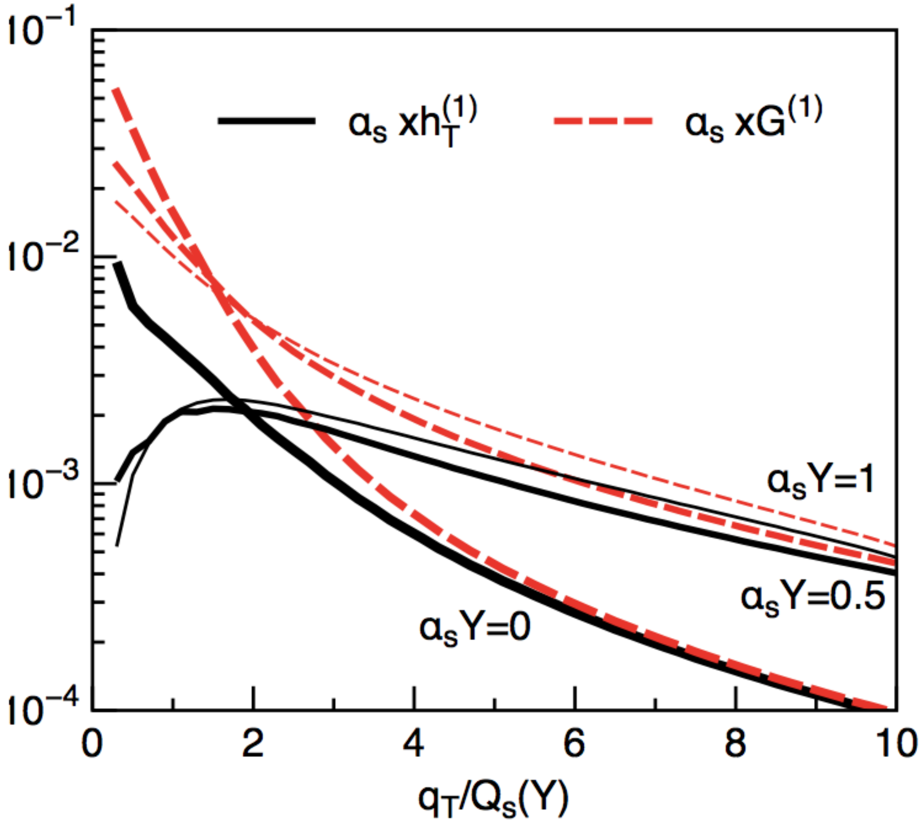
Golden channel for an EIC

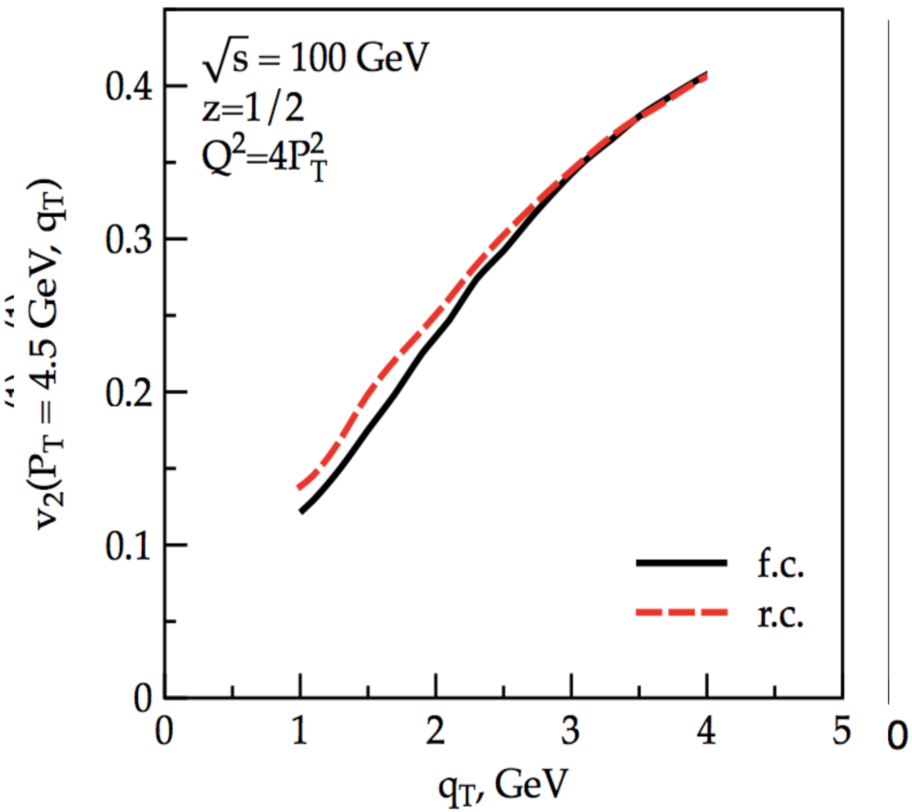
- Directly probe the Weizsacker-Williams gluon distribution in nucleus
  - Non-Abelian manifest
- Factorization is very clear

- Various channels within DIS processes
  - Heavy flavor
  - Real/virtual photon

Linearly polarized gluon TMD at small-x

Metz-Zhou 2011; Dumitru-Lappi-Skokov 2015





Dumitru-Lappi-Skokov 2015

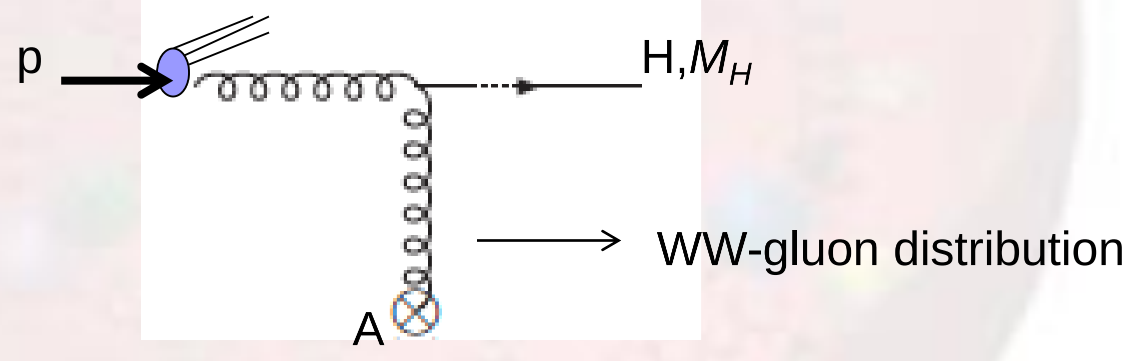
QCD evolution at high energy

- BFKL/BK-JIMWLK (small-x)
- Sudakov (TMD)

Mueller-Xiao-Yuan 2013
Balistky-Tarasov 2014
Xiao-Yuan-Zhou 2016

Sudakov resummation at small-x

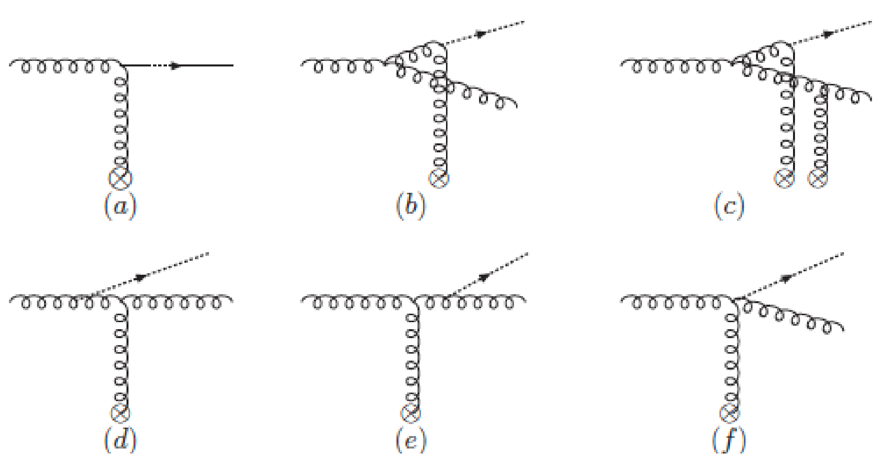
- Take massive scalar particle production *p+A->H+X* as an example to demonstrate the double logarithms, and resummation

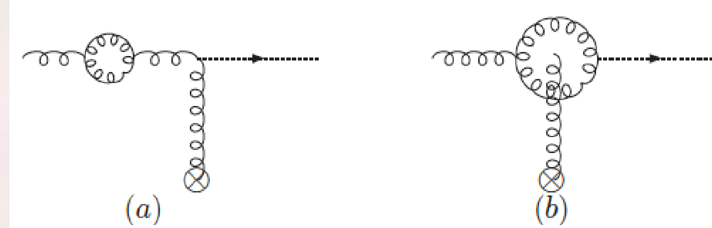


$$\frac{d\sigma^{(\mathrm{LO})}}{dyd^2k_\perp} = \sigma_0 \int \frac{d^2x_\perp d^2x'_\perp}{(2\pi)^2} e^{ik_\perp \cdot r_\perp} x_0 g_p(x_0) S^{(WW)}(x_\perp, x'_\perp)$$

$$S_Y^{WW}(x_\perp, y_\perp) = -\left\langle \mathrm{Tr}\left[\partial_\perp^\beta U(x_\perp) U^\dagger(y_\perp) \partial_\perp^\beta U(y_\perp) U^\dagger(x_\perp)\right]\right\rangle_Y$$

Explicit one-loop calculations





$$x_0 g_p(x_0) \int \frac{d\xi}{\xi} \mathbf{K}_{DMMX} \otimes S^{WW}(x_\perp, y_\perp) + \left(-\frac{1}{\epsilon}\right) S^{WW}(x_\perp, y_\perp) \mathcal{P}_{g/g} \otimes x_0 g(x_0) ,$$

- Collinear divergence → DGLAP evolution
- Small-x divergence → BK-type evolution

Dominguiz-Mueller-Munier-Xiao, 2011

Soft vs Collinear gluons

- Radiated gluon momentum

$$k_g = \alpha_g p_1 + \beta_g p_2 + k_{g\perp} \ ,$$

- Soft gluon, $\alpha \sim \beta << 1$
- Collinear gluon, $\alpha \sim 1$, $\beta << 1$
- Small-x collinear gluon, $1-\beta << 1$, $\alpha \rightarrow 0$
  - Rapidity divergence

Final result

- Double logs at one-loop order

$$\frac{d\sigma^{(\mathrm{LO+NLO})}}{dyd^2k_\perp}|_{k_\perp\ll Q} = \sigma_0 \int \frac{d^2x_\perp d^2x'_\perp}{(2\pi)^2} e^{ik_\perp\cdot r_\perp} S^{WW}_{Y=\ln 1/x_a}(x_\perp, x'_\perp) x g_p(x, \mu^2 = \frac{c_0^2}{r_\perp^2}) \left\{1 + \frac{\alpha_s}{\pi} C_A \left[\beta_0 \ln\frac{Q^2 r_\perp^2}{c_0^2} - \frac{1}{2}\left(\ln\frac{Q^2 r_\perp^2}{c_0^2}\right)^2 + \frac{\pi^2}{2}\right]\right\},$$

- Include both BFKL (BK) and Sudakov

$$\frac{d\sigma^{(\mathrm{resum})}}{dyd^2k_\perp}|_{k_\perp\ll Q} = \sigma_0 \int \frac{d^2x_\perp d^2x'_\perp}{(2\pi)^2} e^{ik_\perp\cdot r_\perp} e^{-S_{sud}(Q^2, r_\perp^2)} S^{WW}_{Y=\ln 1/x_a}(x_\perp, x'_\perp) \times x g_p(x, \mu^2 = c_0^2/r_\perp^2)\left[1 + \frac{\alpha_s}{\pi}\frac{\pi^2}{2} N_c\right],$$

Mueller-Xiao-Yuan 2012

Sudakov leading double logs+small-x logs in hard processes

- Each incoming parton contributes to a half of the associated color factor in Sudakov
  - Initial gluon radiation, aka, TMDs

$$\frac{d\sigma}{dy_1 dy_2 dP_\perp^2 d^2k_\perp} \propto H(P_\perp^2) \int d^2x_\perp d^2y_\perp e^{ik_\perp\cdot(x_\perp - y_\perp)} \widetilde{W}_{x_A}(x_\perp, y_\perp)$$

Sudakov

$$\Rightarrow H(P_\perp^2) \int d^2x_\perp d^2y_\perp e^{ik_\perp\cdot R_\perp} e^{-S_{sud}(P_\perp, R_\perp)} \widetilde{W}_{x_A}(x_\perp, y_\perp)$$

Mueller-Xiao-Yuan 2013

TMD at small-x: Sudakov and BFKL (BK)

- Start with the factorized TMDs, with full operator definitions
- Calculate the high order corrections in dipole formalism
  - With proper subtraction
- Solve the TMD evolution with BK-evolved dipole (quadrupole) amplitude

Subtracted TMD at small-x

$$f_g^{(sub.)}(x, r_\perp, \mu_F, \zeta_c) = f_g^{unsub.}(x, r_\perp)\sqrt{\frac{S^{\bar{n},v}(r_\perp)}{S^{n,\bar{n}}(r_\perp)S^{n,v}(r_\perp)}}$$

WW-gluon
Dipole gluon

Subtract the endpoint
Singularity (Collins 2011)

$$\zeta_c^2 = x^2(2v\cdot P)^2/v^2$$

- TMD evolution follows Collins 2011
  - with resummation, doesn't depend on scheme
  - Beta_0 term missing though
- Small-x evolution follows the relevant BK-evolution, respectively
  - Dipole: BK
  - WW: DMMX

Final results

$$xG^{(1)}(x, k_\perp, \zeta_c = \mu_F = Q)$$

→ Hard scale entering TMD Factorization, e.g., Higgs

$$-\frac{2}{\alpha_S}\int \frac{d^2x_\perp d^2y_\perp}{(2\pi)^4} e^{ik_\perp\cdot r_\perp}\mathcal{H}^{WW}(\alpha_s(Q))e^{-S_{sud}(Q^2,r_\perp^2)}$$
$$\times \mathcal{F}^{WW}_{Y=\ln 1/x}(x_\perp, y_\perp) \ ,$$

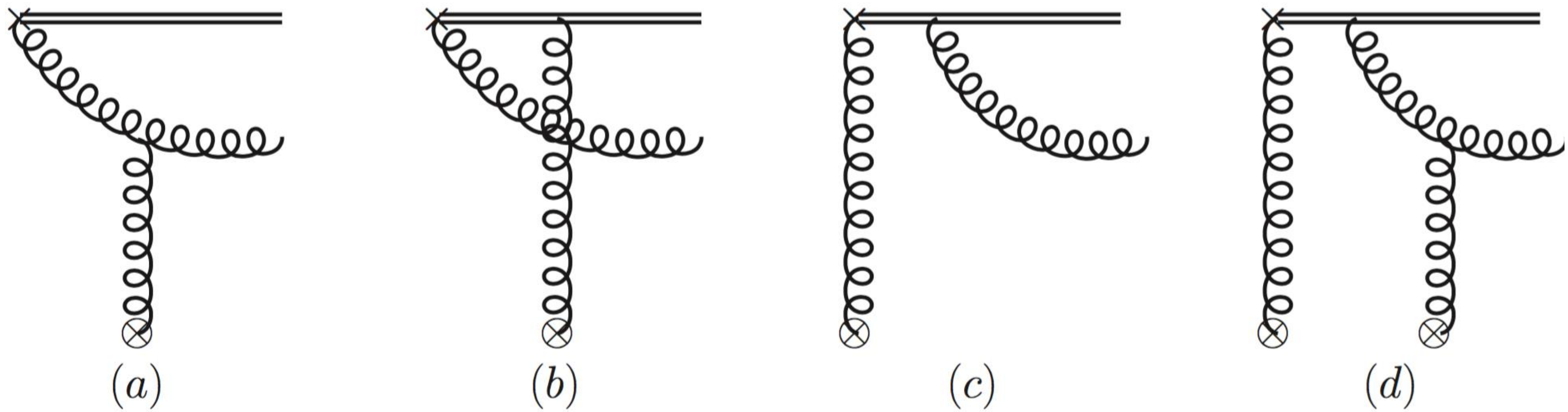
Small-x evolution

Pert. corrections

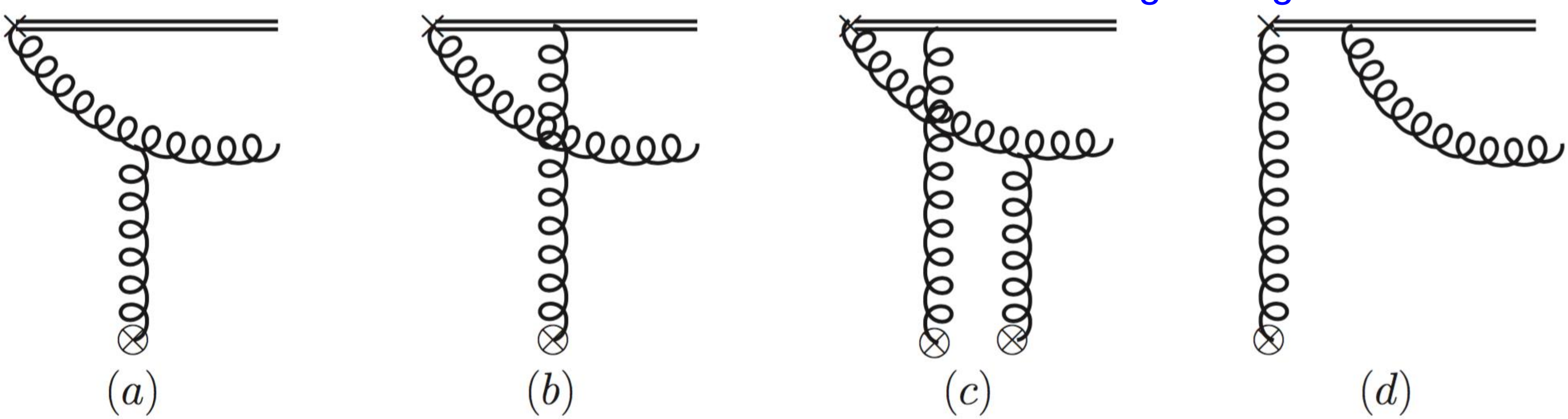
Sudakov resum.

One-loop examples

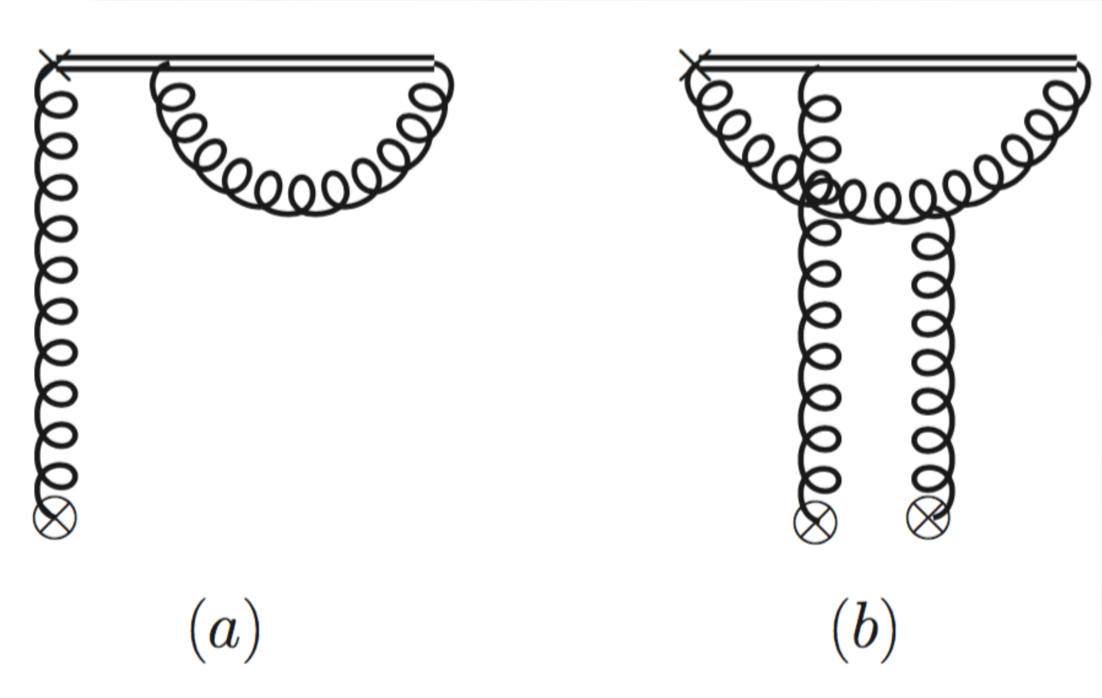
Gauge link goes to $-\infty$



Gauge link goes to $+\infty$



Virtual is the same



One-loop result

- WW-gluon (universal)

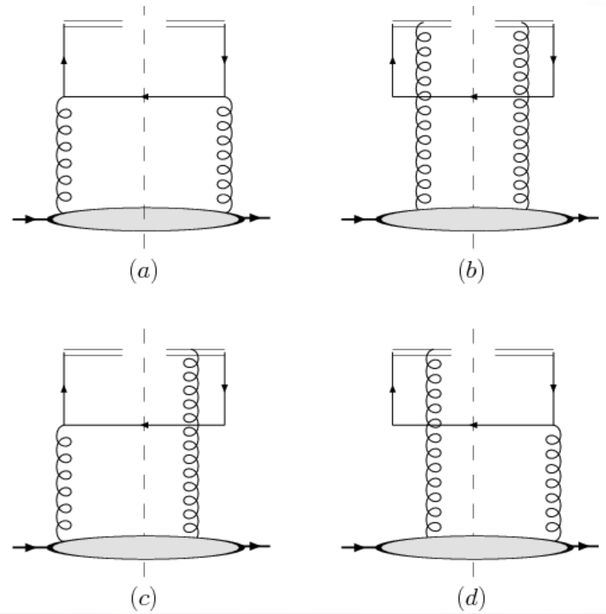
$$xG^{(WW)}_{(-\infty)}(x,r_\perp)|^{(1)} =$$

Sudakov double logs

$$\frac{\alpha_s}{2\pi}C_A\left\{\left(\frac{-2}{\alpha_s}\right)\mathcal{F}^{(WW)}(r_\perp)\left[\frac{1}{2}\left(\ln\frac{\zeta_c^2}{\mu^2}\right)^2-\frac{1}{2}\left(\ln\frac{\zeta_c^2 r_\perp^2}{c_0^2}\right)^2\right]\right.$$
$$\left.+\ln\left(\frac{1}{x}\right)\left(\frac{-2}{\alpha_s}\right)\int \mathbf{K}_{\rm DMMX}\otimes\mathcal{F}^{(WW)}(x_g,r_\perp)\right\}\ ,$$

Small-x logs (BK-type of evolution)

TMD quark at small-x



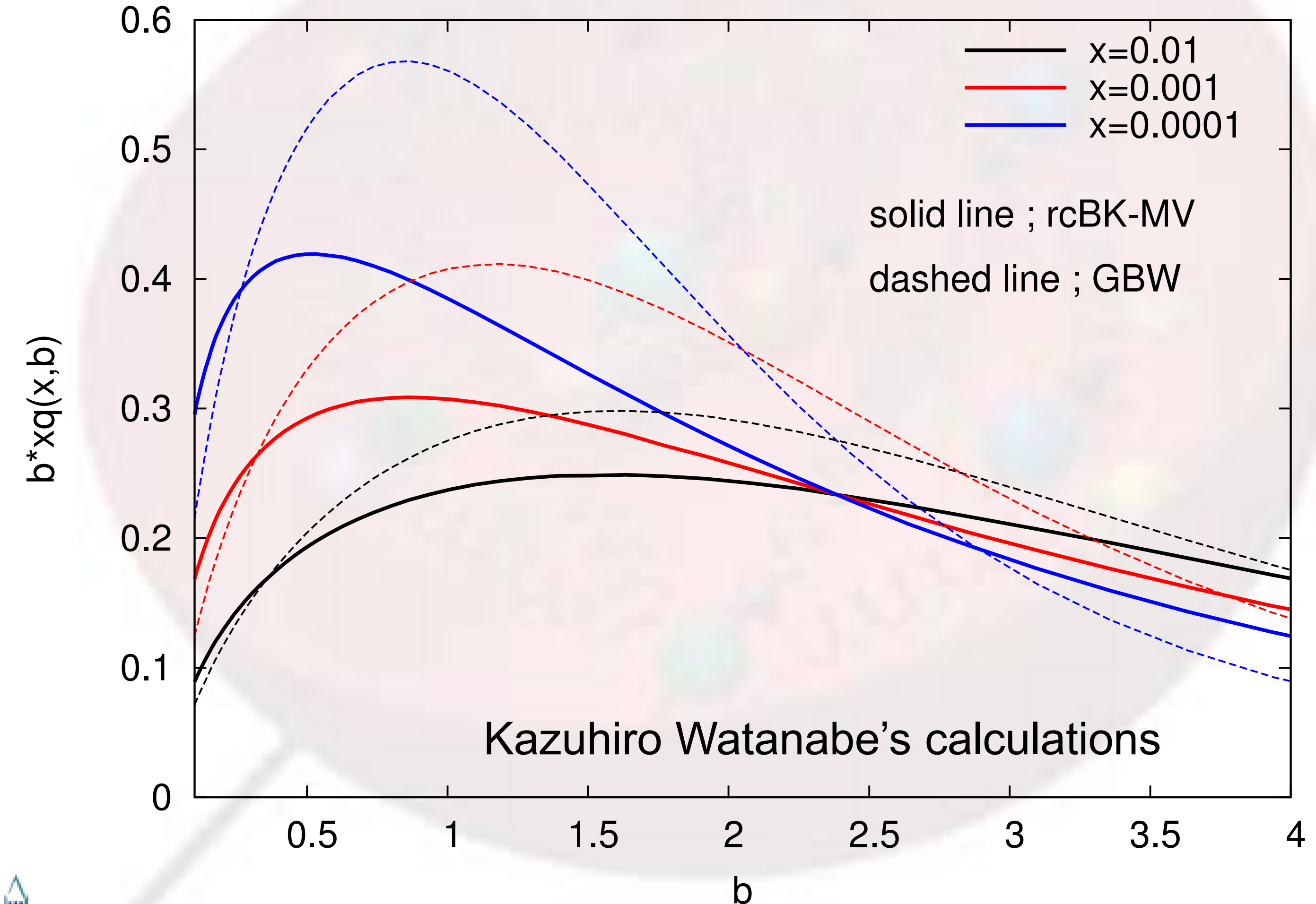
McLerran-Venugopalan 98

$$q(x,k_\perp) = \frac{N_c}{8\pi^4}\int\frac{dx'}{x'^2}\int d^2b d^2q_\perp F(q_\perp,x')A(q_\perp,k_\perp)$$

- Can be calculated from the dipole amplitude, and can be applied to DIS and Drell-Yan processes
  - Universality

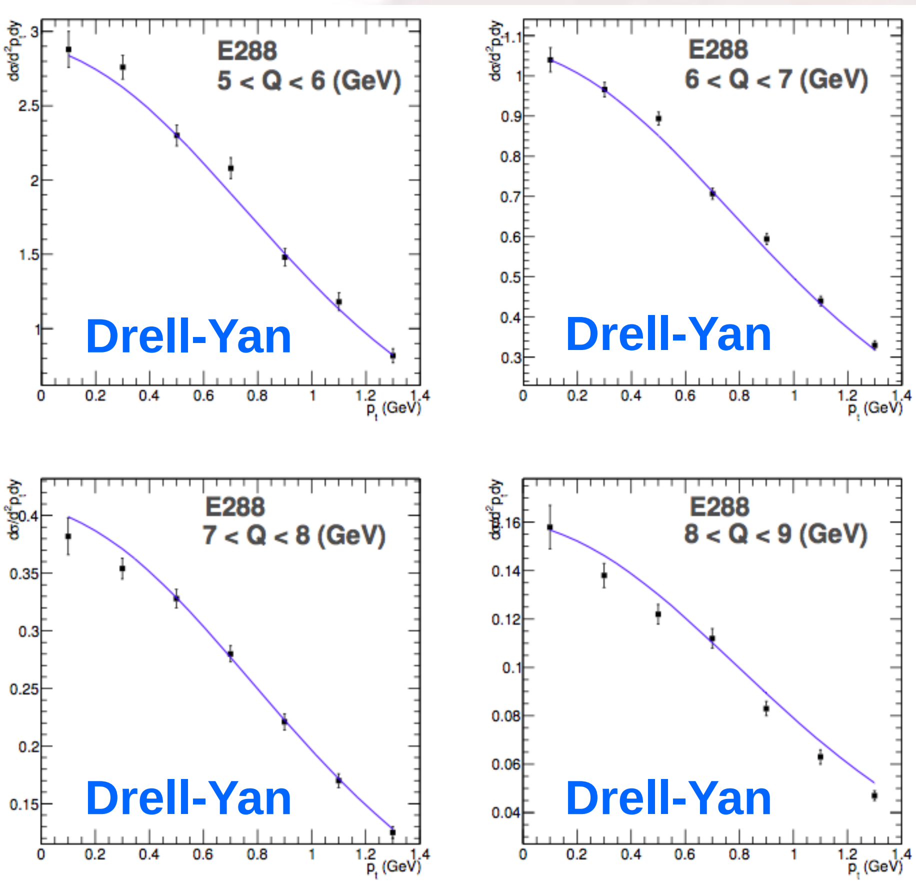
Marquet-Xiao-Yuan 2009

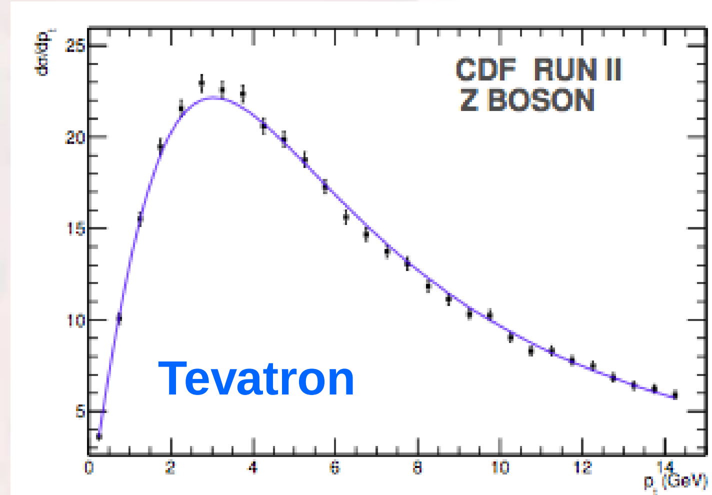
TMD quark at small-x

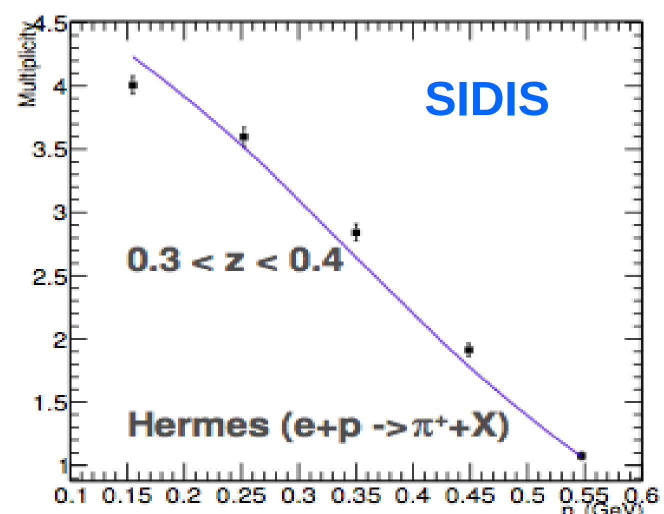


What we know the TMD quarks (not small-x)

Sun-Issacson-Yuan-Yuan, 2014

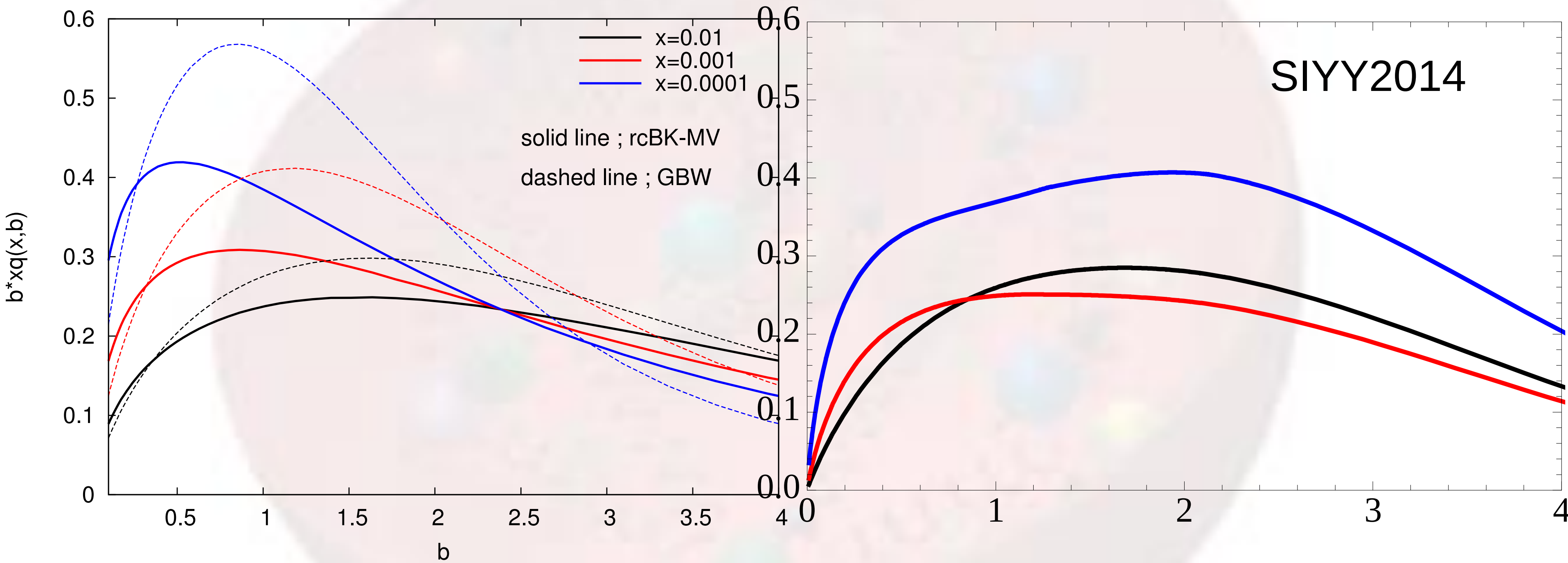






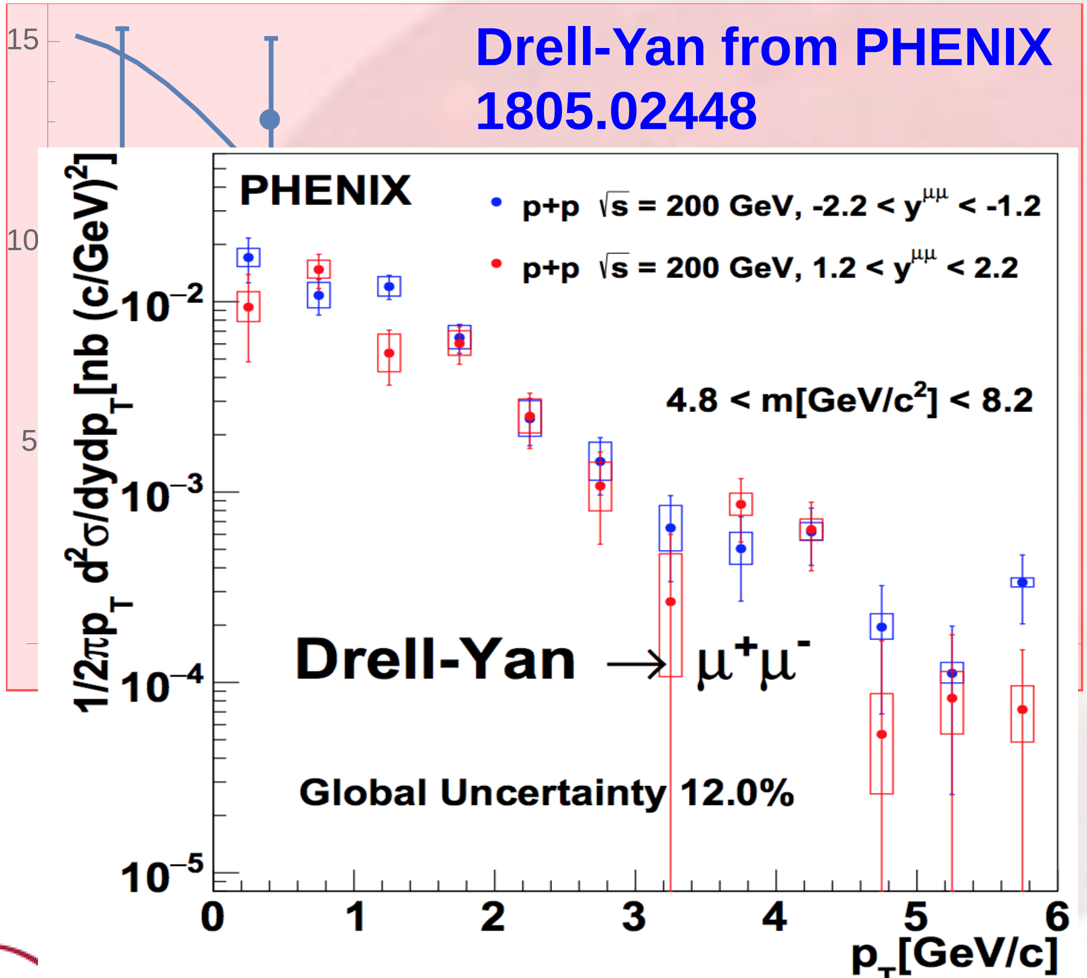
See also, BLNY 2002

TMD quark at small-x: CGC vs Collinear



- Realistic comparison will shed light on the TMD quarks at small-x (work in progress)

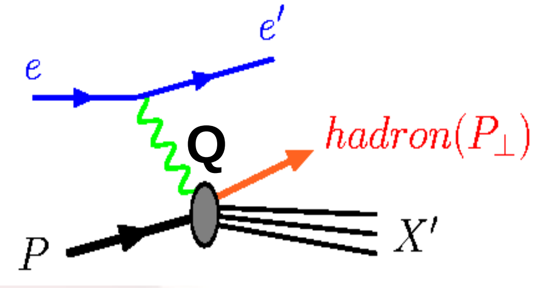
We need more data at small-x



LHCb, pp and pA:
Drell-Yan and Upsilon

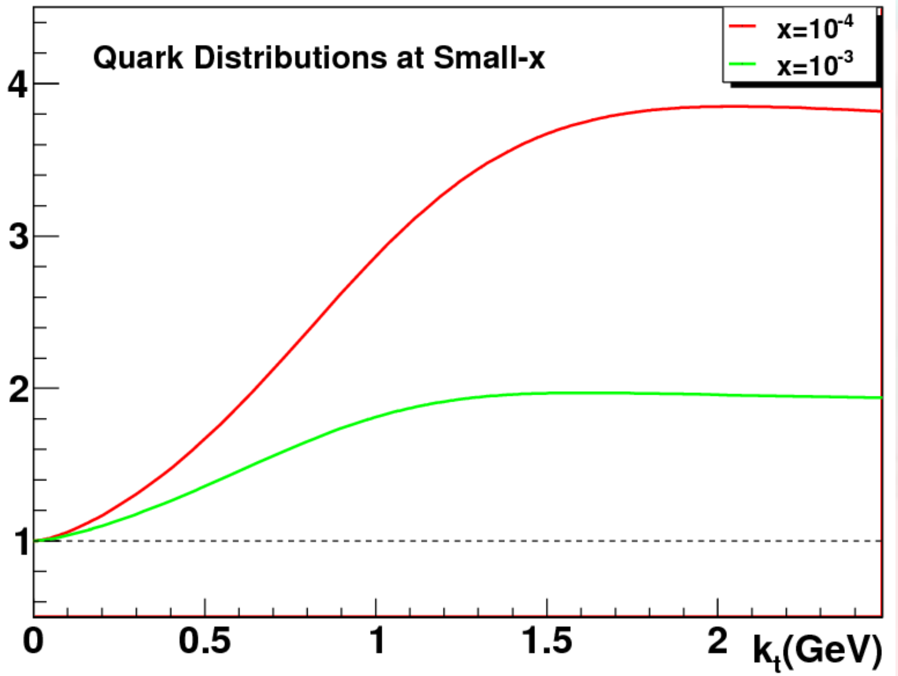
EIC:
SIDIS and di-hadron

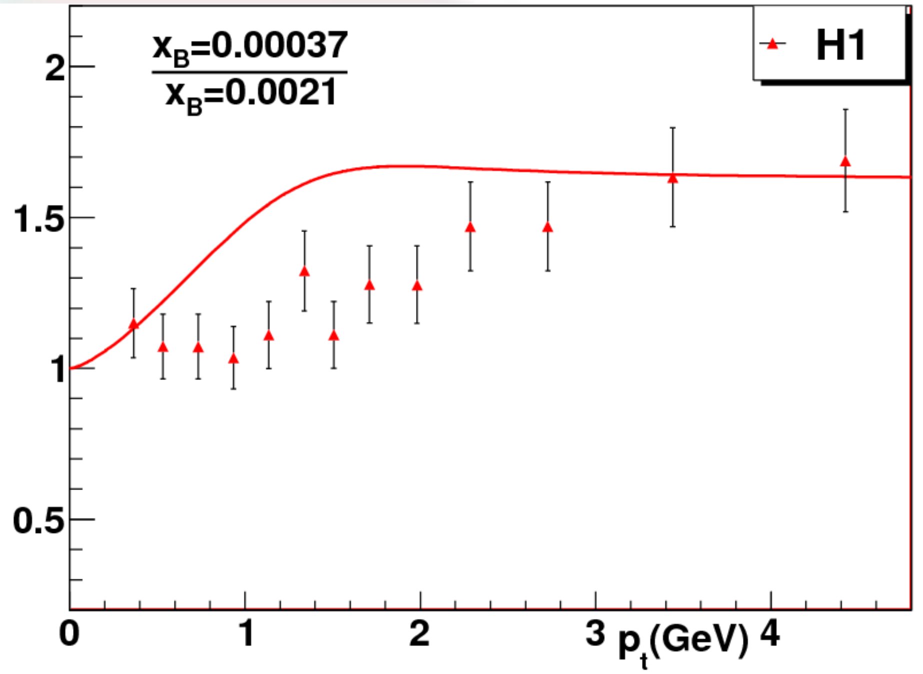
SIDIS at small-x



- What are the relevant scales
  - Q, virtuality of the photon
  - Pt, transverse momentum of hadron
  - Qs, saturation scale
- We are interested in the region of Q>>Qs, Pt
  - TMD factorization makes sense

Implication from HERA



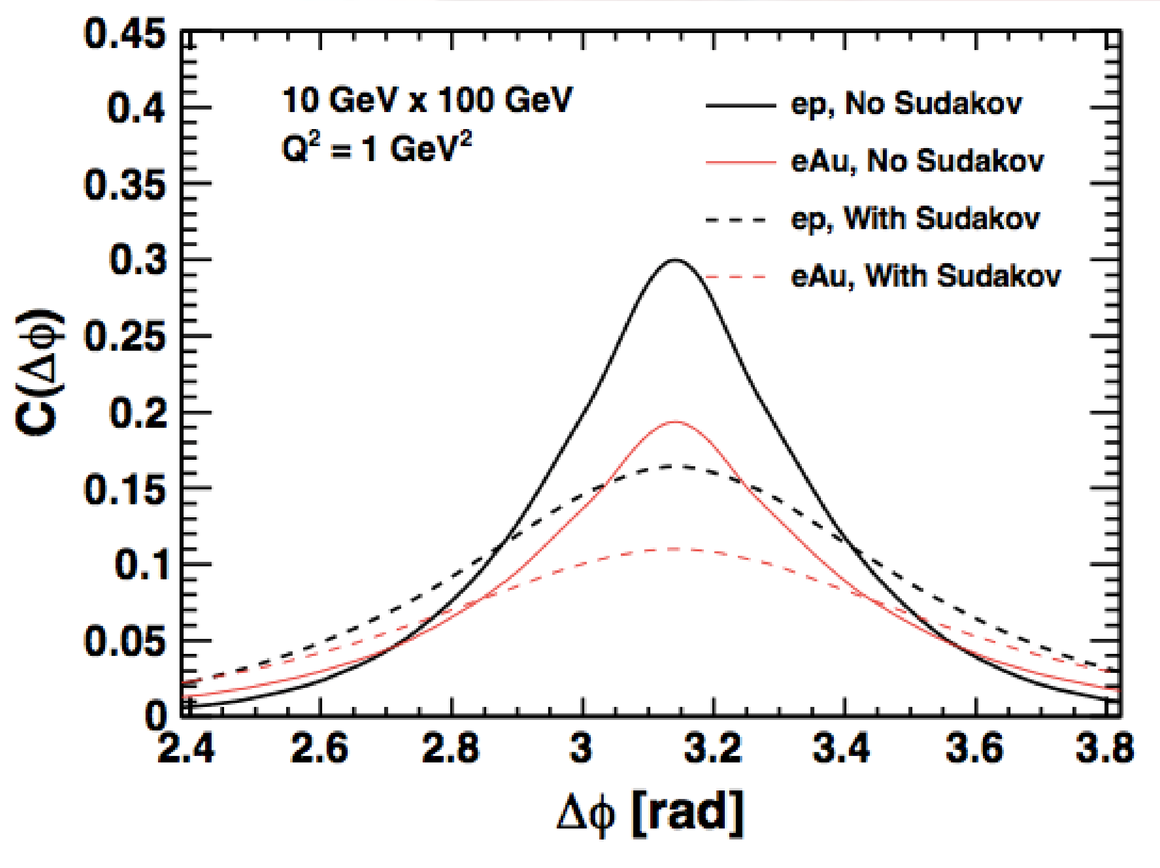


Ratio relative to that at 10^{-2}

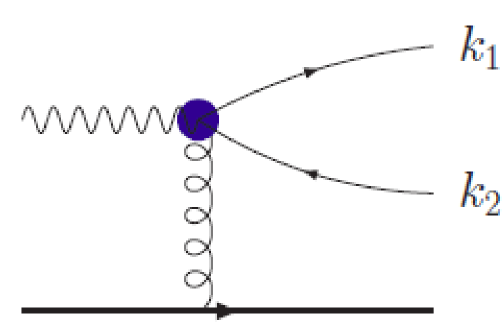
What EIC can offer

- Precise, detailed, mapping of quark distribution at small-x
  - TMD fragmentation functions will be well understood too
- Electron-nucleus (*eA*) collisions provide information on the nuclear modification of quark distribution at small-x
  - BK evolution shall become more evident

Similarly: Gluon TMDs



Di-hadron azimuthal Correlations at the Electron-ion Collider



Zheng, Aschenauer,Lee,Xiao, Phys.Rev. D89 (2014) 074037

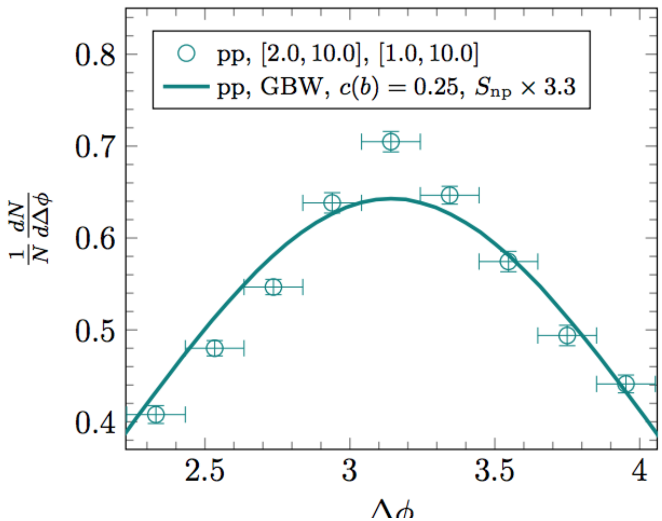
Short summary

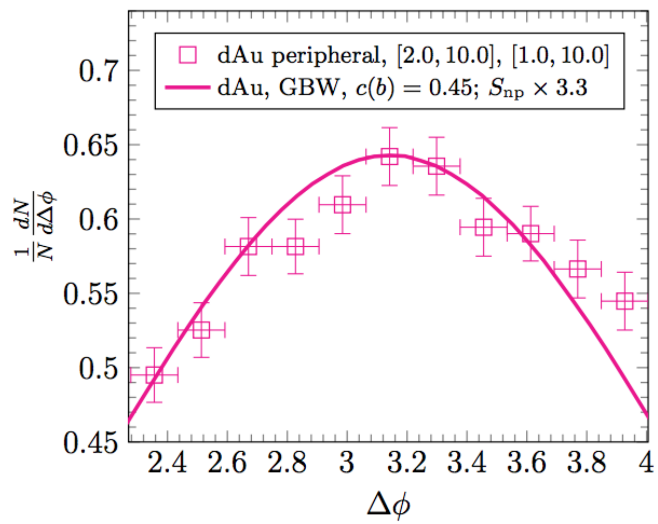
- Theory developments since the last INT program provide solid ground to study TMDs at small-x
- Looking forward to new data from RHIC/LHC, and of course, EIC

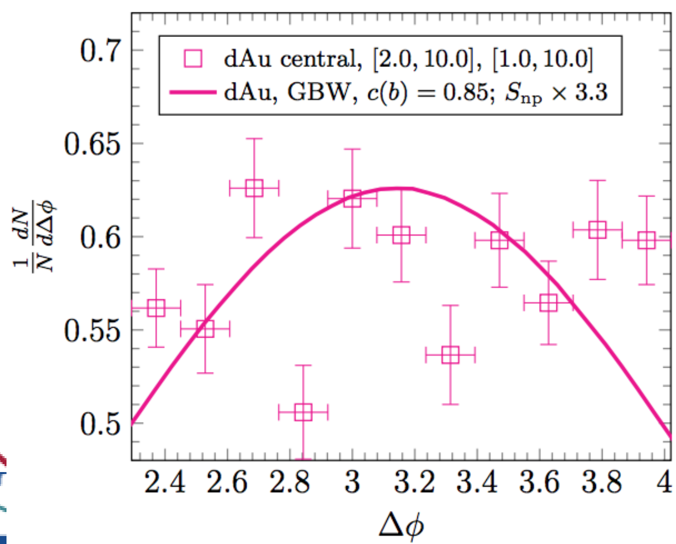
Strategy forward

- Establish the case for the TMDs at small-x
  - Common language between hadron physics and small-x physics communities
- Extend to the GPDs/DVCS at small-x
  - Tons of data when EIC is on-line!!
- Extend to Wigner distributions at small-x
  - Nucleon/nucleus tomography, finally!

Including Sudakov effects: Compare to RHIC Data







Saturation and Sudakov resummation in a single formula to describe both pp and dAu,

Stasto-Wei-Xiao-Yuan, 1805.0571

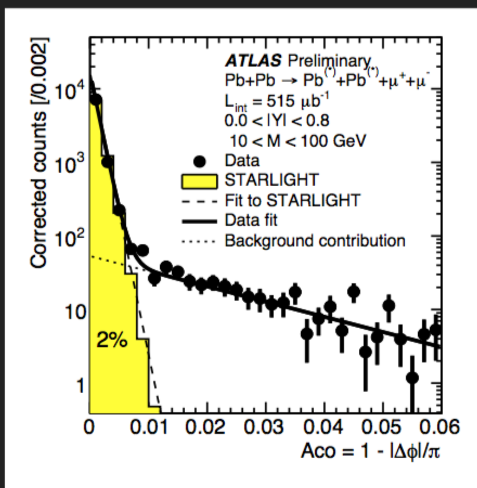
More exclusive processes?

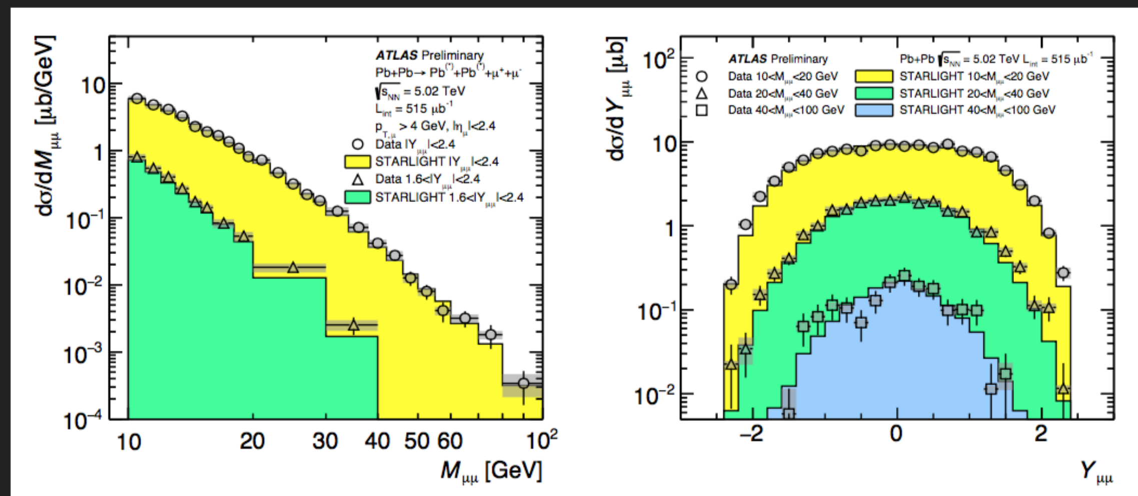
UPC MEASUREMENTS

EXCLUSIVE DIMUON PRODUCTION

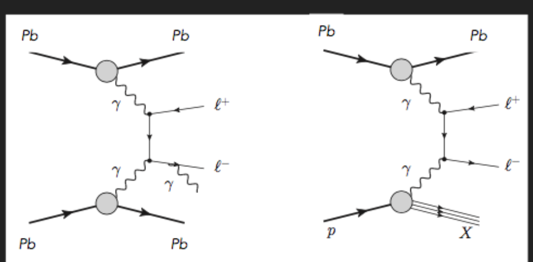
Steinberg @QM18

ATLAS-CONF-2016-025





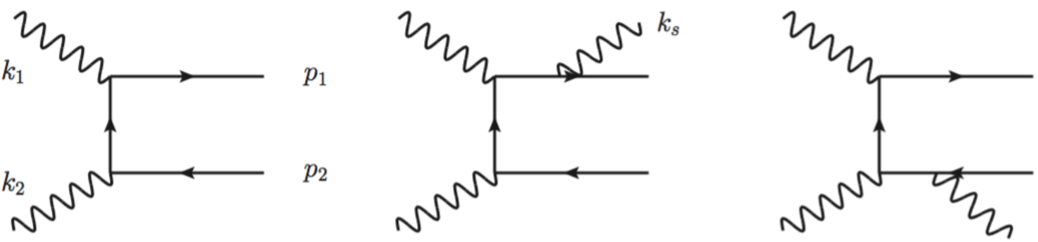
NLO QED dissociation



Exclusive dimuon event distributions corrected for trigger, reco & vertex efficiency, systematics cover whether long Aco tails are all signal or all background

STARLIGHT 1.1 provides good description of fully-corrected dimuon distributions, with hint of small excess at high $Y_{\mu\mu}$ (but NB missing physics: e.g. higher-order QED)

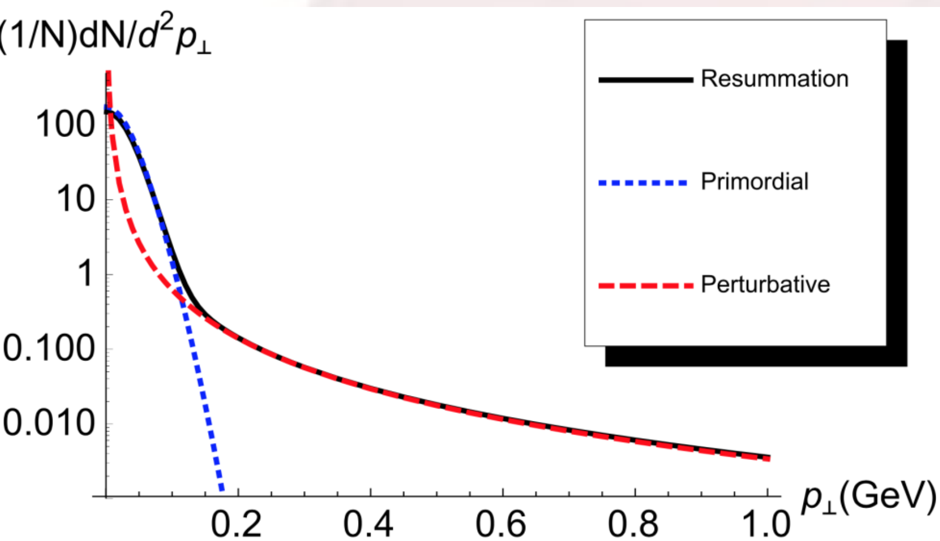
Sudakov in QED

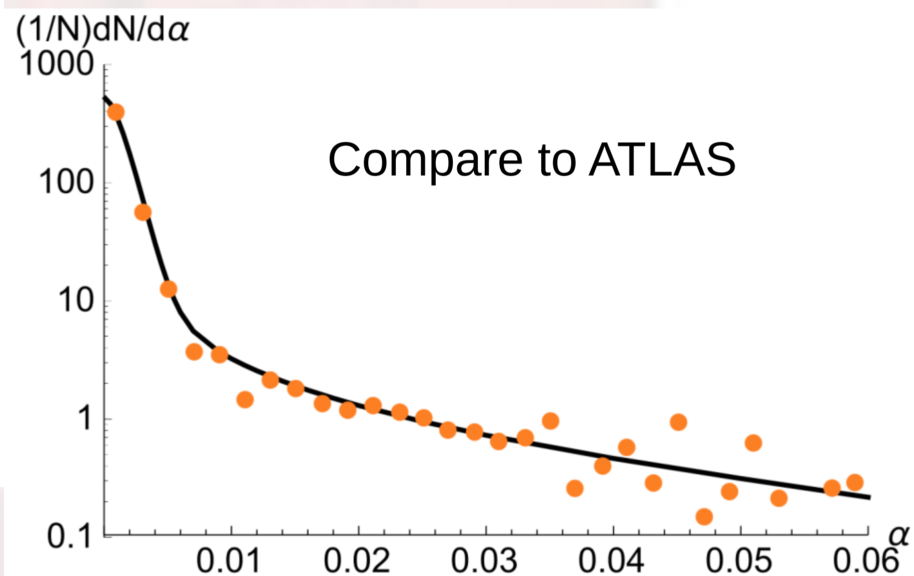


$$\frac{\alpha}{\pi^2}\frac{1}{\ell_\perp^2}\ln\frac{Q^2}{\ell_\perp^2+m_\mu^2}$$

Sudakov Factor

$$\begin{cases} -\frac{\alpha}{2\pi}\ln^2\frac{Q^2 r_\perp^2}{c_0^2} & , \quad m_\mu r_\perp < 1 \\ -\frac{\alpha}{2\pi}\ln\frac{Q^2}{m_\mu^2}\left[\ln\frac{Q^2 r_\perp^2}{c_0^2}+\ln\frac{m_\mu^2 r_\perp^2}{c_0^2}\right] & , \quad m_\mu r_\perp > 1 \end{cases}$$



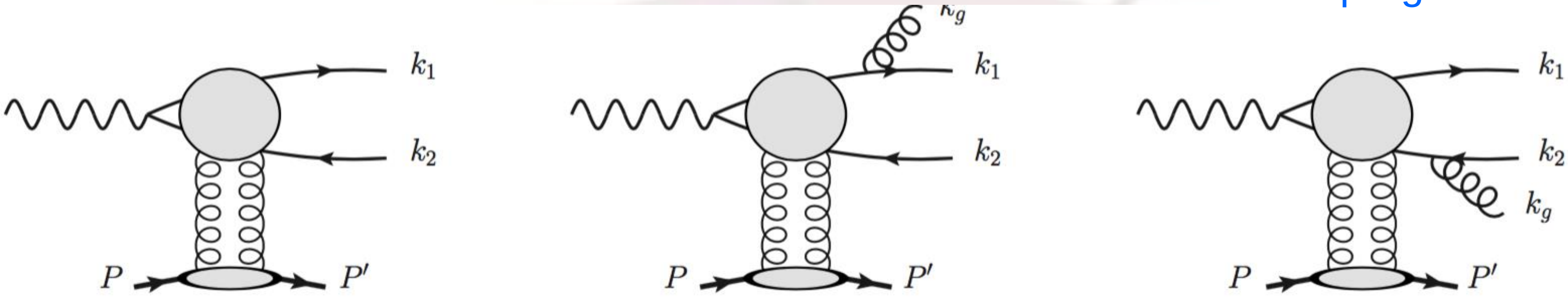


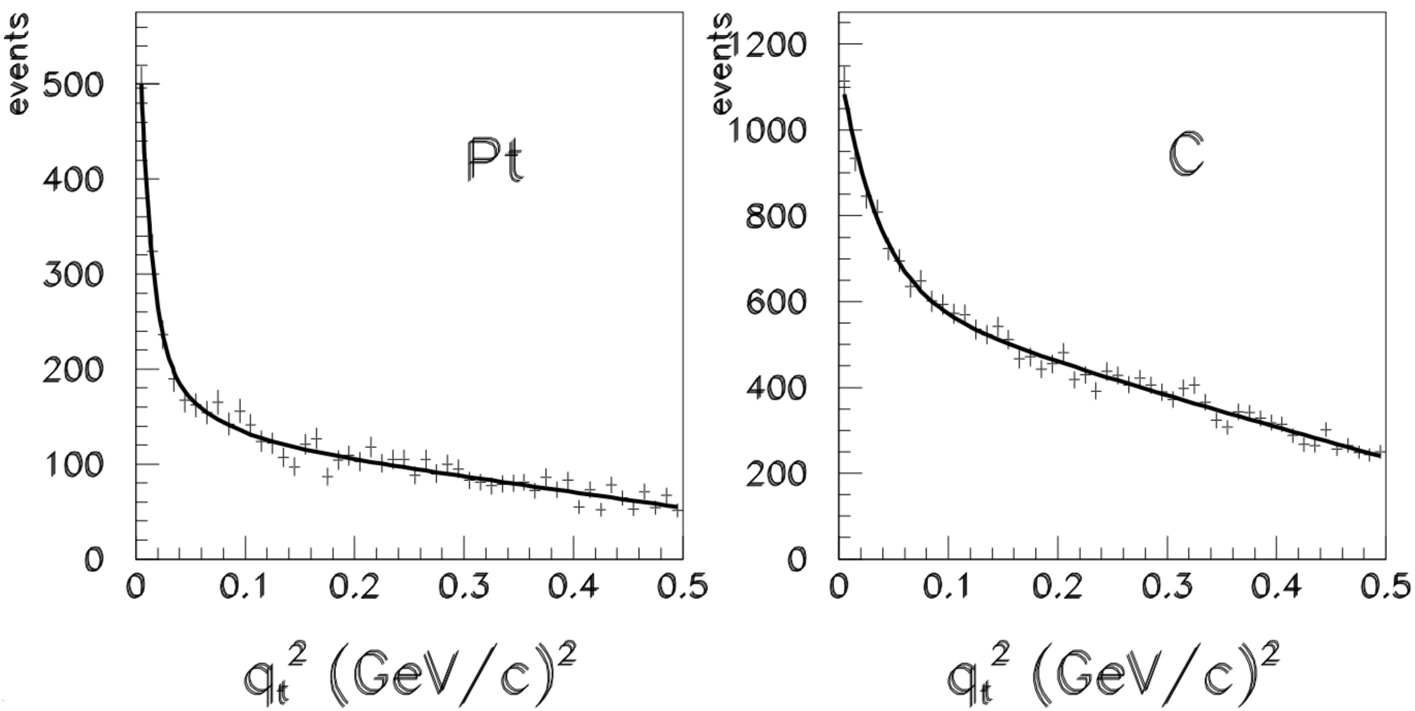
α=ΔΦ/π

Klein-Mueller-Xiao-Yuan, preliminary

Diffractive Dijet

Work in progress





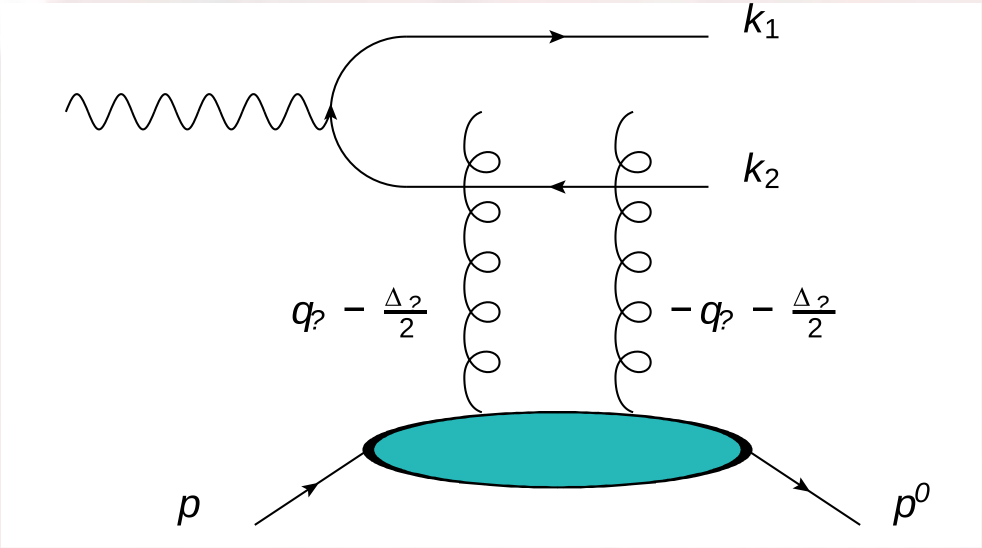
E791 coll.

Coherent scattering of pion on nuclear targets

Probing 3D Tomography of Protons at Small-x at EIC

Diffractive back-to-back dijet productions at EIC:

Hatta-Xiao-Yuan,1601.01585



- In the Breit frame, by measuring the recoil of final state proton, one can access Δ_T. By measuring jets momenta, one can approximately access q_T.
- The diffractive dijet cross section is proportional to the square of the Wigner distribution.

Back-up