Lepton-jet in DIS and Dijet in pp

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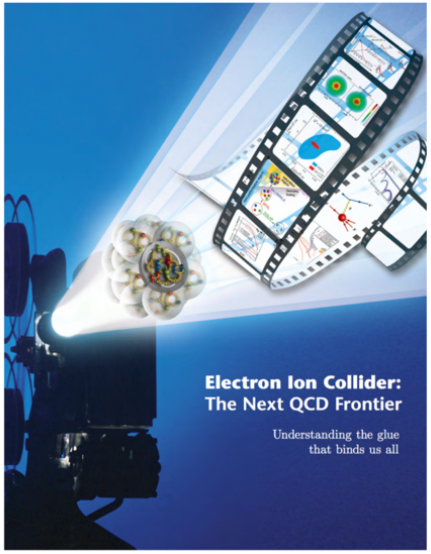
Reference: Liu, Ringer, Vogelsang, Yuan, arXiv: 1812.08077, 2007.12866, 2008.03666

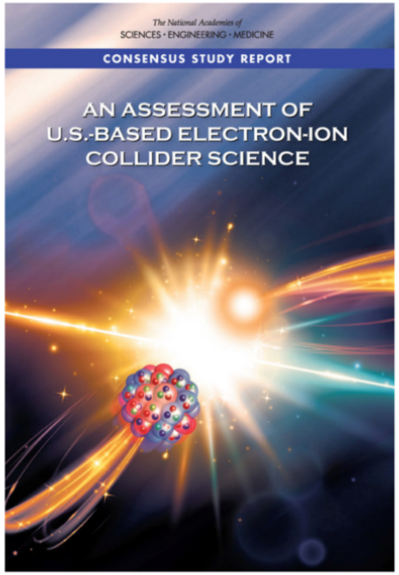
Next Big Thing in Town: Electron-Ion Collider

White paper

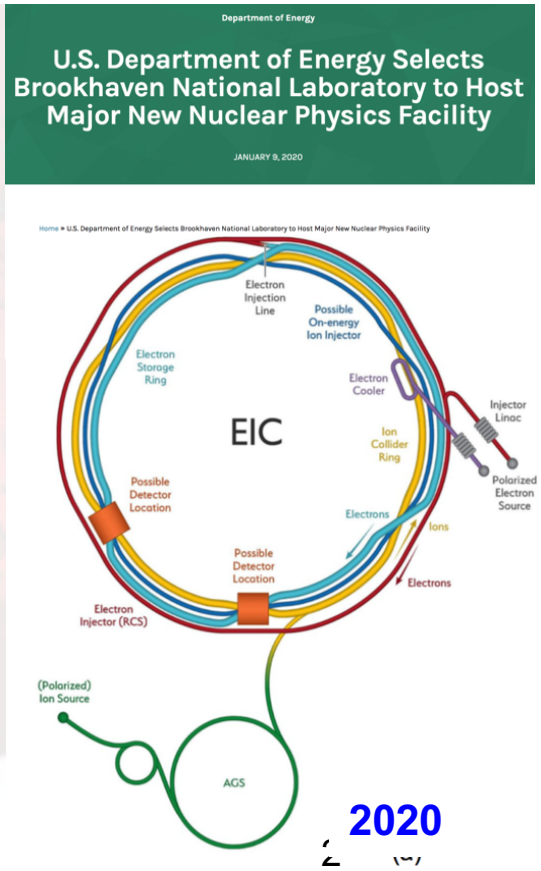


2015

National Academies evaluation



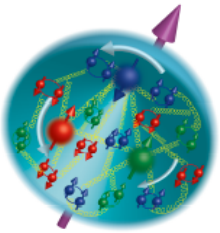
2018



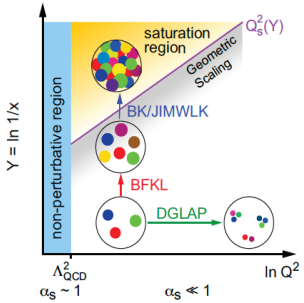
2020

Big questions

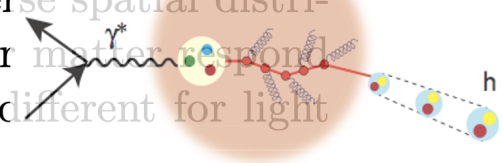
- **How are the sea quarks and gluons, and their spins, distributed and momentum inside the nucleon?** How are these quark and gluon dis correlated with overall nucleon properties, such as spin direction? What is the orbital motion of sea quarks and gluons in building the nucleon spin?



- **Where does the saturation of gluon densities set in?** Is there a sim that separates this region from that of more dilute quark-gluon matter do the distributions of quarks and gluons change as one crosses the bou this saturation produce matter of universal properties in the nucleon a viewed at nearly the speed of light?



- **How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?** How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

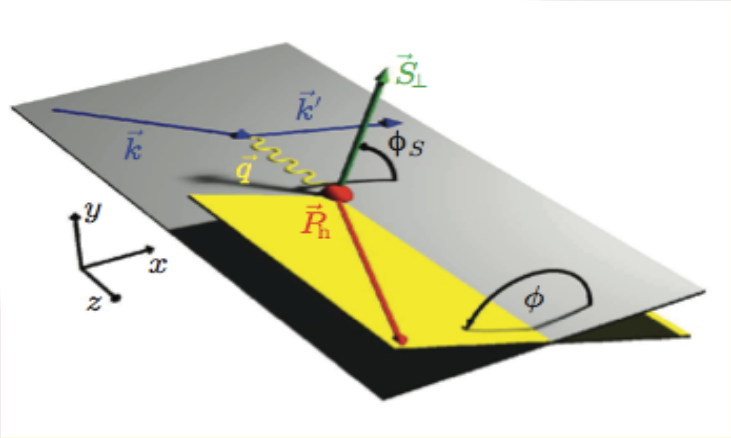


Jet @EIC has been very active in recent years

- Contribute to all three physics topics
- Nucleon/nucleus tomography studies at EIC
- Leading jet/hadron, dijet/dihadron, …

- Focus on lepton-jet correlation to probe TMD, and comparison to dijet correlation in pp collisions

TMD at EIC: Semi-inclusive DIS



quark distribution

$\otimes$

fragmentation

- Novel Single Spin Asymmetries

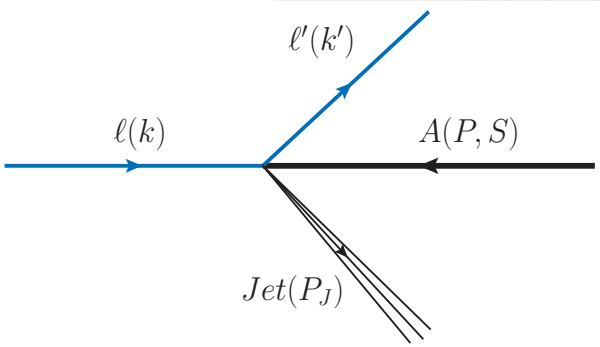
Collins: $$A_{UT}^{\sin(\phi+\phi_S)} \propto S_\perp \frac{\sum_{q,\bar{q}} e_q^2 \delta q(x)\, H_1^\perp(z)}{\sum_{q,\bar{q}} e_q^2 q(x)\, D_1(z)}$$

$$z \overset{lab}{=} \frac{E_h}{\nu}$$

Sivers: $$A_{UT}^{\sin(\phi-\phi_S)} \propto S_\perp \frac{\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp,q}(x) \cdot D_1(z)}{\sum_{q,\bar{q}} e_q^2 q(x)\, D_1(z)}$$

U: unpolarized beam
T: transversely polarized target

TMD: lepton-jet correlation



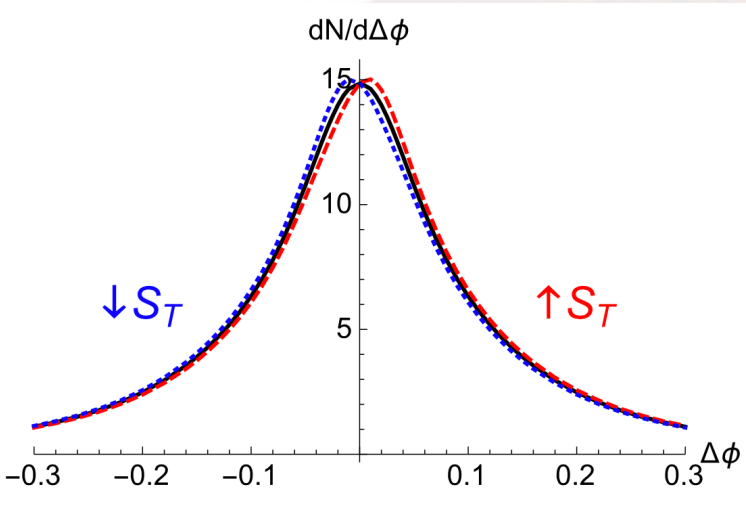
Quark distribution$\otimes$soft factor

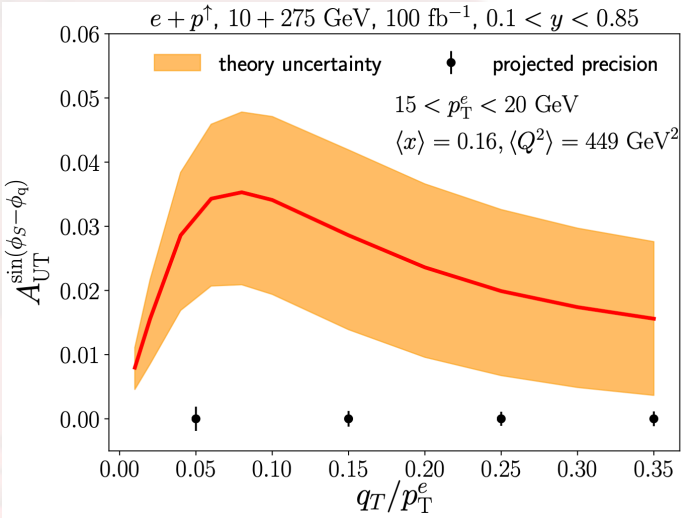
$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2k_{\ell\perp} d^2q_\perp} = \sigma_0 \int d^2k_\perp d^2\lambda_\perp x f_q(x, k_\perp, \zeta_c, \mu_F) \times H_{\rm TMD}(Q, \mu_F) S_J(\lambda_\perp, \mu_F)\, \delta^{(2)}(q_\perp - k_\perp - \lambda_\perp)\ .$$

(Lab frame)
Total transverse momentum of the lepton+jet probes the TMD quark distribution

See also, Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi, 1807.07573, 1904.04259

Sivers asymmetries

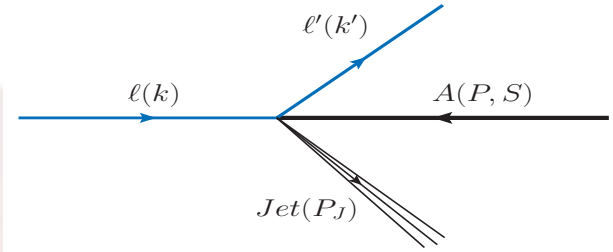


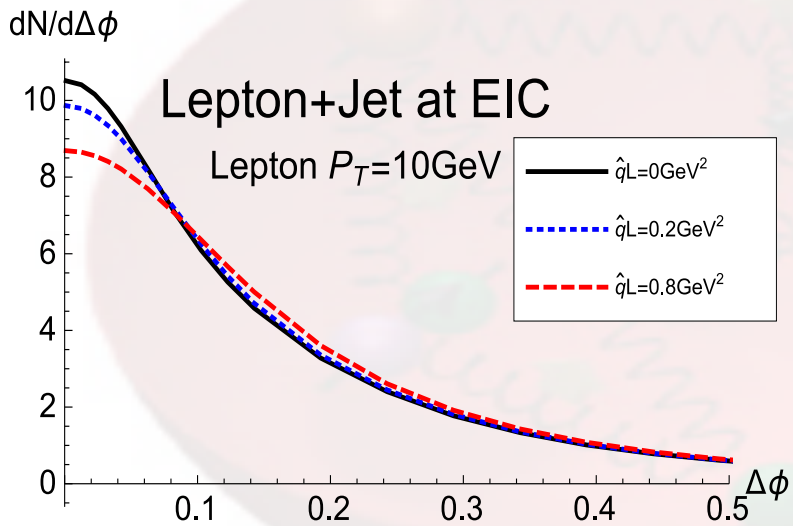


Originally proposed by Boer, Voegelsang, for pp collisions in 2003

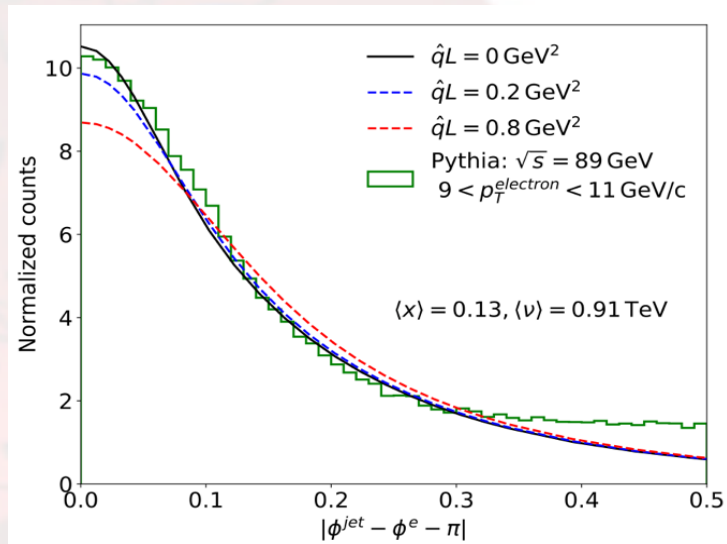
Arratia, Kang, Prokudin, Ringer, 2007.07281

eA collisions to probe the jet P_T-broadening in cold nuclei





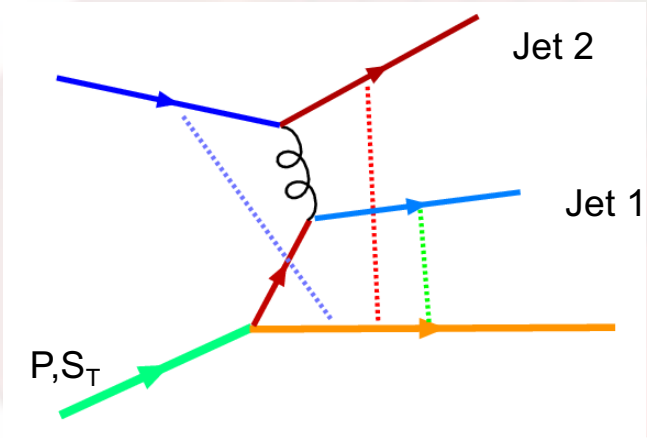
Liu-Ringer-Vogelsang-Yuan
1812.08077, 2007.12866

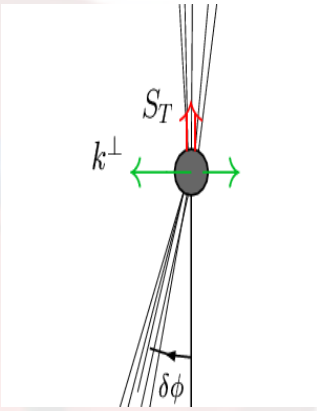


Arratia-Song-Ringer-Jacak
1912.05931

Dijet-correlation at RHIC

- Initial state and/or final state interactions



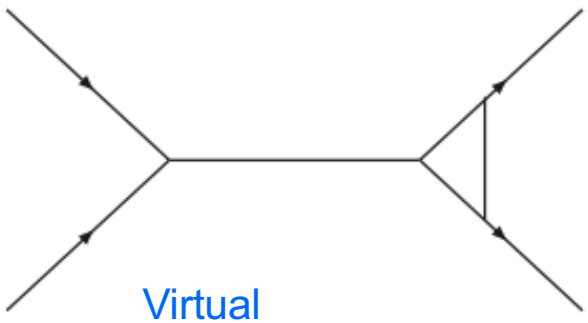


Boer-Vogelsang 03

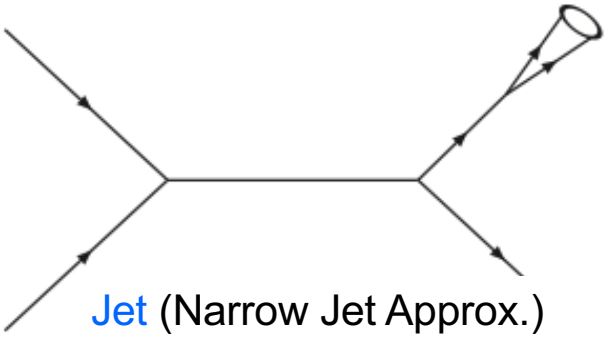
Standard (naïve) Factorization breaks!

Becchetta-Bomhof-Mulders-Pijlman, 04-06
Collins-Qiu 08; Vogelsang-Yuan 08
Rogers-Mulders 10

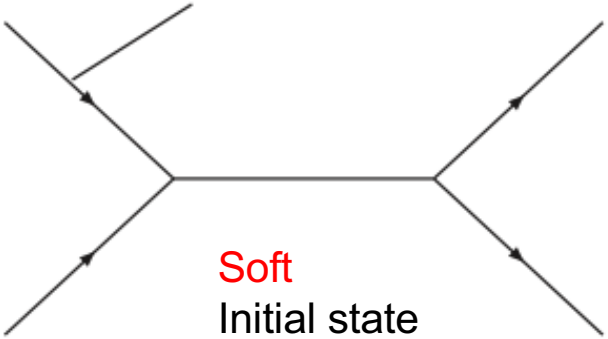
Unpolarized case: Soft and collinear gluon



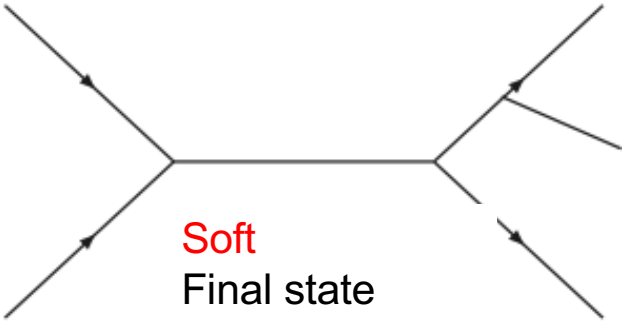
Virtual
Ellis-Sexton 86



Jet (Narrow Jet Approx.)
Jager-Stratmann-Vogelsang 2004



Soft
Initial state



Soft
Final state
(out of jet cone)

TMD factorization at one-loop order

- Divergences cancelled out between virtual, jet, sot contributions (dimension regulation applied)
- Final results :double logs, single logs, ..

$$W^{(1)}(b_\perp)|_{logs.} = \frac{\alpha_s}{2\pi}\left\{ h^{(0)}_{q_iq_j\to q_iq_j}\left[-\ln\left(\frac{\mu^2 b_\perp^2}{b_0^2}\right)\left(\mathcal{P}_{qq}(\xi)\delta(1-\xi') + \mathcal{P}_{qq}(\xi')\delta(1-\xi)\right) - \delta(1-\xi) \right.\right.$$
$$\left. \times\delta(1-\xi')\left(C_F \ln^2\left(\frac{Q^2 b_\perp^2}{b_0^2}\right) + \ln\left(\frac{Q^2 b_\perp^2}{b_0^2}\right)\left(-3C_F + C_F \ln\frac{1}{R_1^2} + C_F \ln\frac{1}{R_2^2}\right)\right)\right]$$
$$\left. -\delta(1-\xi)\delta(1-\xi')\ln\left(\frac{Q^2 b_\perp^2}{b_0^2}\right)\Gamma^{(qq')}_{sn}\right\}, \qquad (71)$$

Quark channel: $q_iq_j \to q_iq_j$ TMD quark distributions $\otimes$ Soft factor

Sun, C.-P. Yuan, F. Yuan, 1506.06170

Next-to-leading Logs (NLL)

- Jet size-dependence (Banfi-Dasgupta 2004)
- Matrix form (Kidonakis-Sterman 1997)

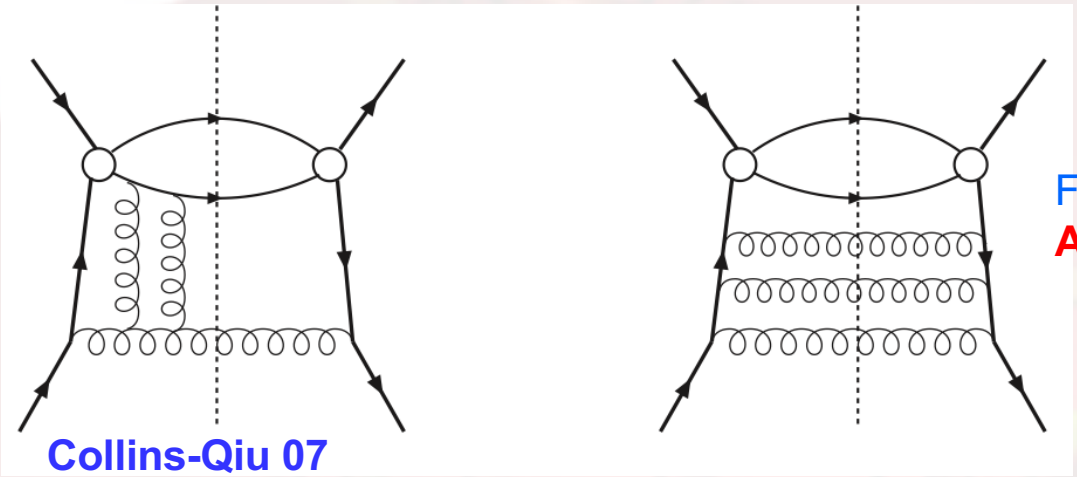
$$x_1 f_a(x_1, \mu = b_0/b_\perp) x_2 f_b(x_2, \mu = b_0/b_\perp) e^{-S_{\rm Sud}(Q^2, b_\perp)}$$
$$\mathrm{Tr}\left[\mathbf{H}_{ab\to cd}\exp[-\int_{b_0/b_\perp}^{Q}\frac{d\mu}{\mu}\gamma^{s\dagger}]\mathbf{S}_{ab\to cd}\exp[-\int_{b_0/b_\perp}^{Q}\frac{d\mu}{\mu}\gamma^{s}]\right]$$

Sun, C.-P. Yuan, F. Yuan, PRL 2014

$$S_{\rm Sud}(Q^2, b_\perp) = \int_{b_0^2/b_\perp^2}^{Q^2}\frac{d\mu^2}{\mu^2}\left[\ln\left(\frac{Q^2}{\mu^2}\right)A + B + D_1 \ln\frac{Q^2}{P_T^2 R_1^2} + D_2 \ln\frac{Q^2}{P_T^2 R_2^2}\right]$$

D: color-factor for the jet
R: jet size

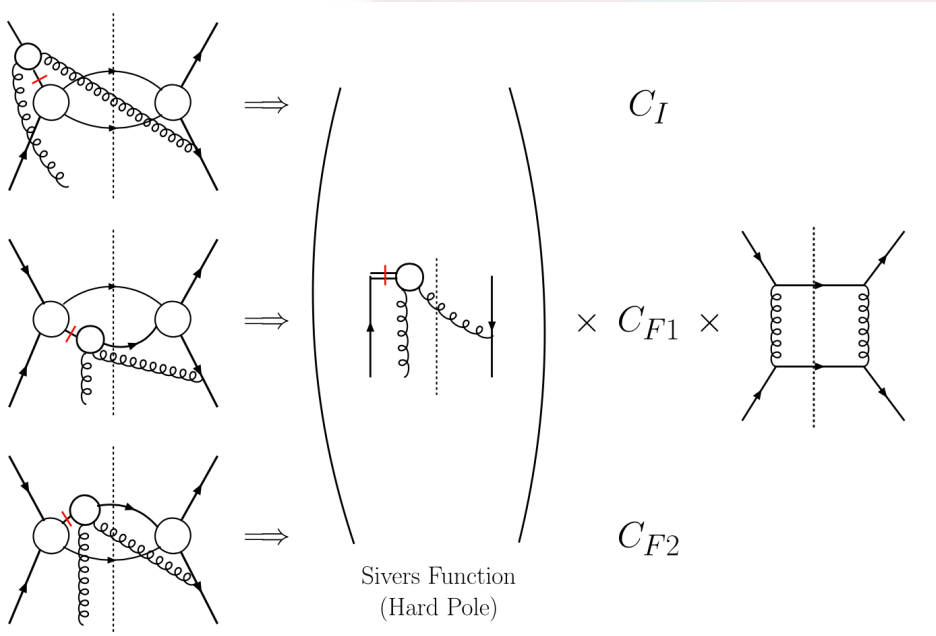
Factorization breaking effects



Factorizable, $A^{(1)}$

- In collinear calculations, it appears at α_s^3 corrections, will affect $A^{(3)}$ coefficient

Polarized case: collinear gluon radiation



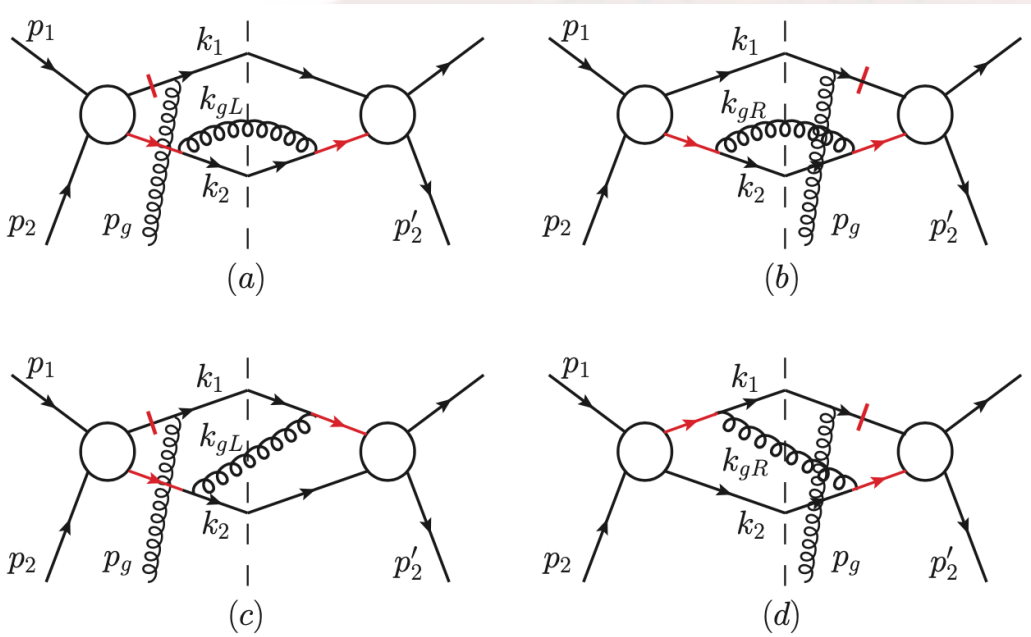
C_I,C_{F1},C_{F2}:
Leading order initial/final state interaction contributions

Gluon radiation parallel to the incoming hadrons can be factorized into relevant TMDs

Qiu, Vogelsang, Yuan, 0706.1196
Based on twist-3 formalism

See also, Kang, Lee, Shao, Terry, 2008.05470

We also need to study soft gluons



Much more complicated:
Apply the leading power analysis and Eikonal approximation

In the twist-3 formalism, keep the momentum flow from the quark-gluon quark correlation in the polarized nucleon

Liu, Ringer, Vogelsang, Yuan, 2008.03666

Leading contributions: same structure as the unpolarized case

$$\mathcal{H}^{\beta}_{\text{twist-3}}\Big|_{p_1^\mu p_1^\nu} = \frac{\alpha_s}{2\pi^2}\frac{q_\perp^\beta}{(q_\perp^2)^2} 2\ln\frac{Q^2}{q_\perp^2},$$

Initial state radiation

$$\mathcal{H}^{\beta}_{\text{twist-3}}\Big|_{k_1^\mu k_1^\nu} = \frac{\alpha_s}{2\pi^2}\frac{q_\perp^\beta}{(q_\perp^2)^2}\left[\ln\frac{Q^2}{q_\perp^2} + \ln\frac{1}{R_1^2} + \ln\frac{\hat{u}}{\hat{t}}\right]$$

final state radiation

$$\mathcal{H}^{\beta}_{\text{twist-3}}\Big|_{k_2^\mu k_2^\nu} = \frac{\alpha_s}{2\pi^2}\frac{q_\perp^\beta}{(q_\perp^2)^2}\left[\ln\frac{Q^2}{q_\perp^2} + \ln\frac{1}{R_2^2} + \ln\frac{\hat{t}}{\hat{u}}\right]$$

final state radiation

$$\mathcal{H}^{\beta}_{\text{twist-3}}\Big|_{k_1^\mu p_1^\nu, p_1^\mu k_1^\nu} = \frac{\alpha_s}{2\pi^2}\frac{q_\perp^\beta}{(q_\perp^2)^2}\left[2\ln\frac{Q^2}{q_\perp^2} + 2\ln\frac{\hat{u}}{\hat{t}}\right],$$

Interference between initial/final

$$\mathcal{H}^{\beta}_{\text{twist-3}}\Big|_{k_2^\mu p_1^\nu, p_1^\mu k_2^\nu} = \frac{\alpha_s}{2\pi^2}\frac{q_\perp^\beta}{(q_\perp^2)^2}\left[2\ln\frac{Q^2}{q_\perp^2} + 2\ln\frac{\hat{t}}{\hat{u}}\right],$$

Interference between initial/final

$$\mathcal{H}^{\beta}_{\text{twist-3}}\Big|_{k_1^\mu k_2^\nu, k_2^\mu k_1^\nu} = \frac{\alpha_s}{2\pi^2}\frac{q_\perp^\beta}{(q_\perp^2)^2}\left[2\ln\frac{Q^2}{q_\perp^2} - 2\ln\frac{\hat{s}^2}{\hat{t}\hat{u}}\right].$$

Interference between final

Adding the color factors

- qq'→qq' channel

$$= H^{\text{Sivers}}_{qq'\to qq'} \frac{ib_\perp^\beta}{2} \frac{\alpha_s}{2\pi} x_1 x_2 \Bigg\{ -\ln \frac{\mu^2 b_\perp^2}{b_0^2} \Big[f_q(x_1,\mu) \mathcal{P}^T_{q'g\to q'g} \otimes T_{Fq'}(x_2,x_2,\mu)$$

TMD Sivers

$$+ T_{Fq'}(x_2,x_2,\mu) \mathcal{P}_{a'\to q} \otimes f_{a'}(x_1,\mu) \Big]$$

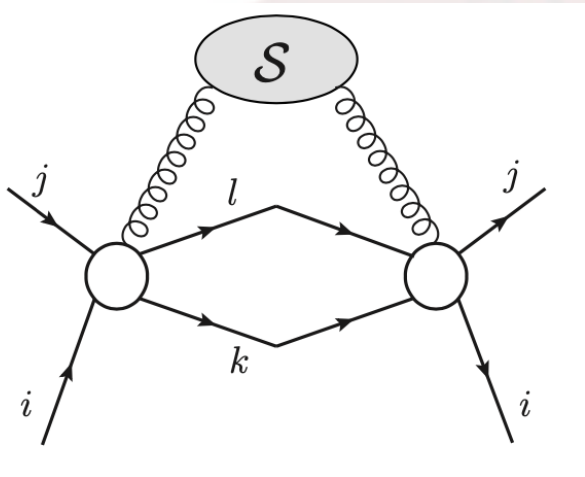
TMD unpolarized quark

$$+ f_q(x_1,\mu) T_{Fq'}(x_2,x_2,\mu) C_F \left[\ln^2\left(\frac{Q^2 b_\perp^2}{b_0^2}\right) - \left(\frac{3}{2} - \ln\frac{1}{R_1^2} - \ln\frac{1}{R_2^2}\right) \ln\frac{Q^2 b_\perp^2}{b_0^2} \right] \Bigg\}$$

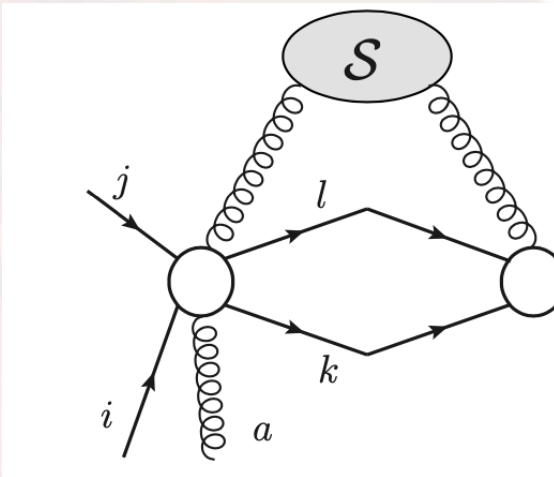
Soft factor associated with the jets

- Similar results for qg→qg and qqbar→gg channels

Factorization breaks down beyond LLA



unpolarized



polarized

The matrix form for the unpolarized case doesn't apply for the polarized case

Final results at the LLA'

$$\frac{d^4\sigma}{d\Omega d^2 q_\perp} = \sum_{abcd} \int \frac{d^2\vec{b}_\perp}{(2\pi)^2} e^{i\vec{q}_\perp\cdot\vec{b}_\perp} W^{uu}_{ab\to cd}(x_1, x_2, b_\perp) \ ,$$

$$\frac{d\Delta\sigma(S_\perp)}{d\Omega d^2\vec{q}_\perp} = \epsilon^{\alpha\beta} S^\alpha_\perp \sum_{abcd} \int \frac{d^2\vec{b}_\perp}{(2\pi)^2} e^{i\vec{q}_\perp\cdot\vec{b}_\perp} W^{T\beta}_{ab\to cd}(x_1, x_2, b_\perp)$$

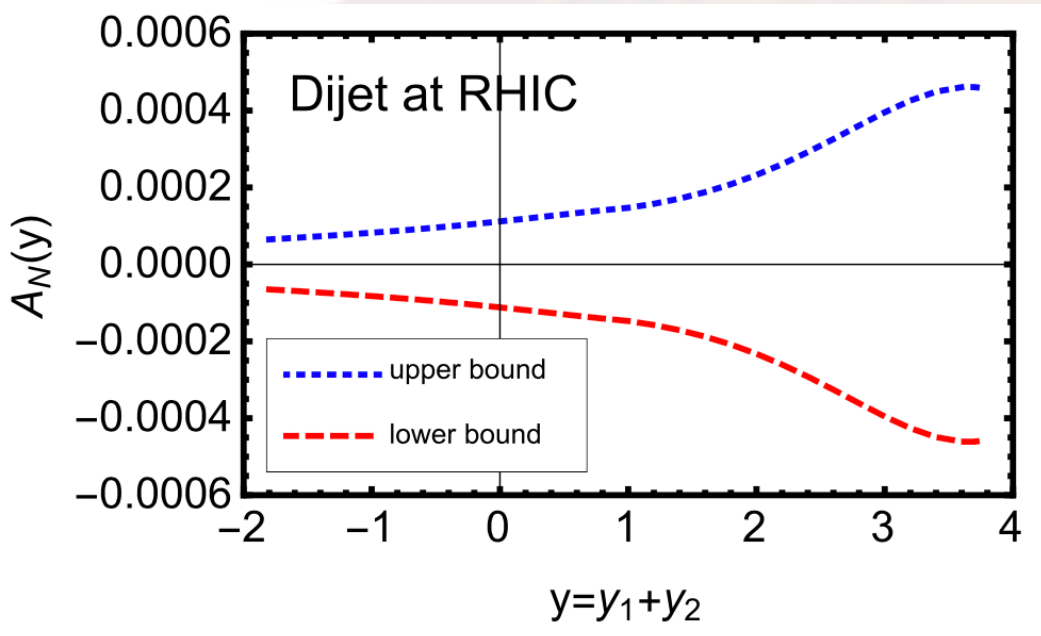
$$W^{T\beta}_{ab\to cd}\Big|_{\mathrm{LLA}'} = \frac{ib^\beta_\perp}{2} x_1 f_a(x_1,\mu_b) x_2 T_{Fb}(x_2,\mu_b) H^{\mathrm{Sivers}}_{ab\to cd}(P_T, x_1, x_2) e^{-S^T_{\mathrm{Sud}}(Q^2, b_\perp)} \ ,$$

$$W^{uu}_{ab\to cd}\Big|_{\mathrm{LLA}'} = x_1 f_a(x_1,\mu_b) x_2 f_b(x_2,\mu_b) H^{uu}_{ab\to cd}(P_T, x_1, x_2) e^{-S^T_{\mathrm{Sud}}(Q^2, b_\perp)} \ ,$$

$$S^T_{\mathrm{Sud}}(Q^2, b_\perp) = \int_{b_0^2/b_\perp^2}^{Q^2} \frac{d\mu^2}{\mu^2} \left[\ln\left(\frac{Q^2}{\mu^2}\right) A + B + D_1 \ln\frac{1}{R_1^2} + D_2 \ln\frac{1}{R_2^2} \right]$$

TMD Sivers and unpolarized parton, soft gluon associated with jets

Predictions for RHIC



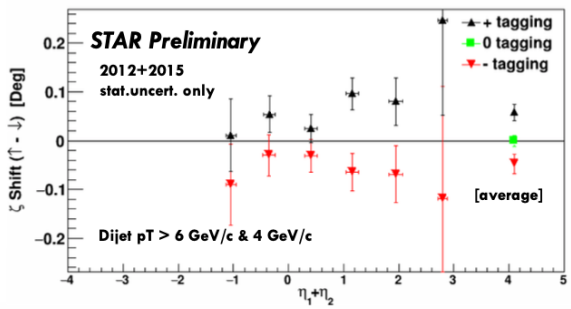
Strong cancellation between up and down quark Sivers functions. Here shows the upper and lower bounds correspond to uncertainties from SIDIS (10% of its value)

STAR 2007 data show consistent with 0, uncertainty around 10^{-2}
STAR Coll., Phys.Rev.Lett. 99 (2007) 142003

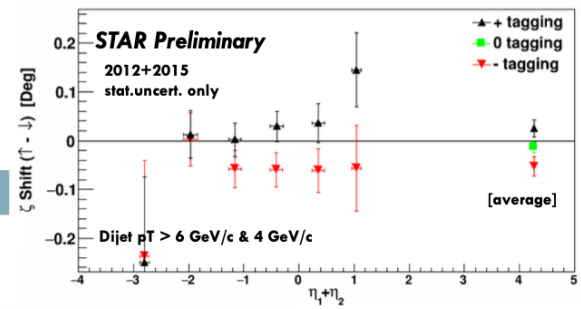
2012+2015 Data — Dijet Sivers Asymmetry

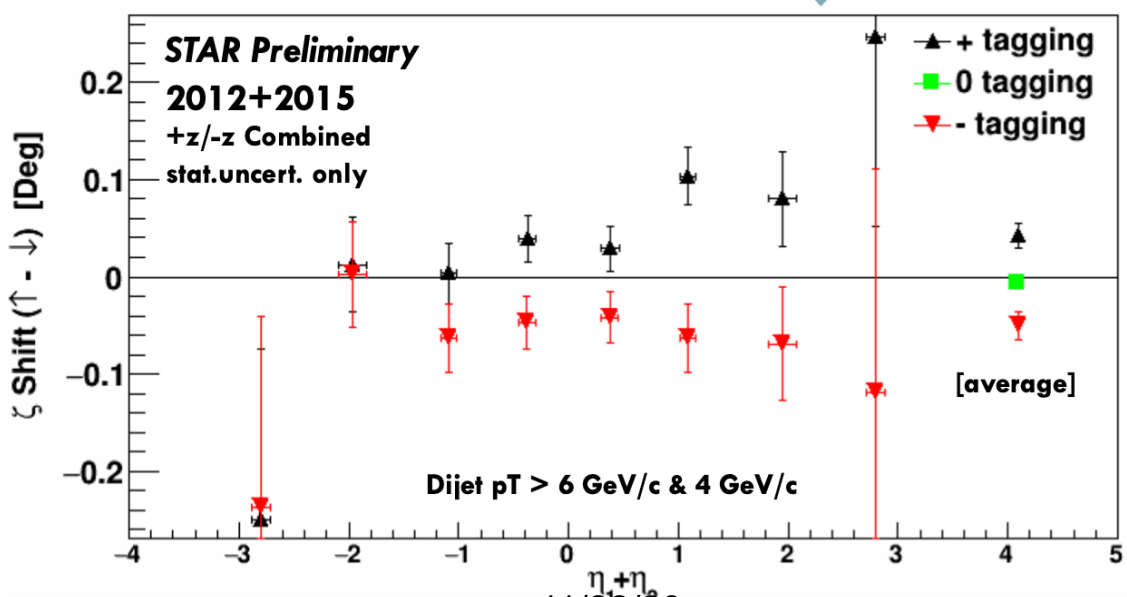
Fatemi@EINN

+z Beam



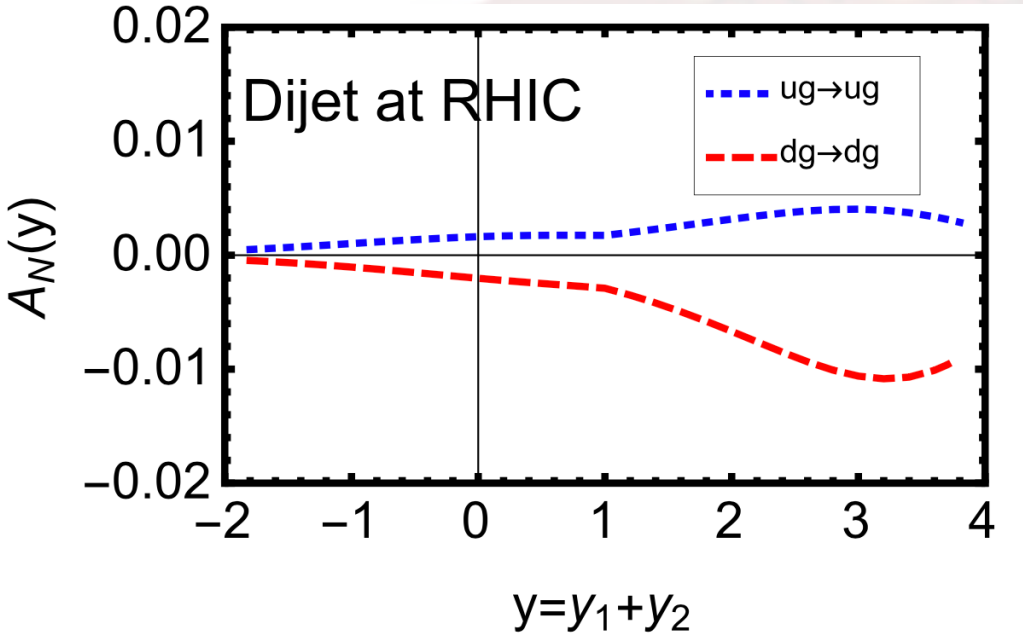
-z Beam (flipped to be along +z)





- **Nice separation between plus-tagging and minus-tagging.**
- **There appears to be an η1+ η2 dependency: an enhanced kinematical selection of qg events is expected at larger η1+ η2.**
- **zero-tagging is consistent with zero.**

If we can separate up and down…



- At the same order as recent STAR measurements
- Factorization breaking effects can be estimated
  - NLL correction as a rough estimate, ~a few percent

Summary

- Soft gluon radiation contribution at one-loop order
- Demonstrated that the SSA factorization is valid at the leading logarithmic order
- Factorization breaks down at next-to-leading logarithmic
- Need to further investigation