Theory of transverse/forward spin physics at RHIC

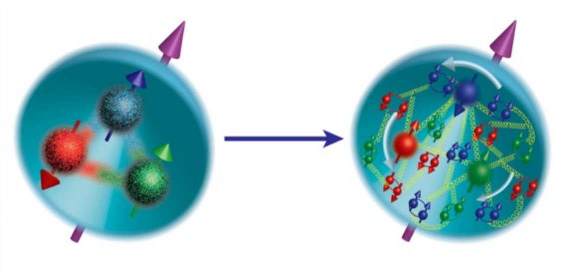
Zhongbo Kang
UCLA & CFNS

@ZhongboK

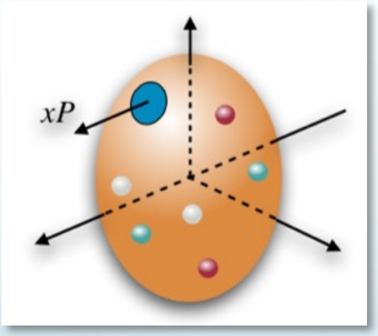
RHIC Science Programs Informative Toward EIC in the Coming Years
May 24–26, 2021

Transverse spin: a tool for imaging a proton

- Imagine of the proton

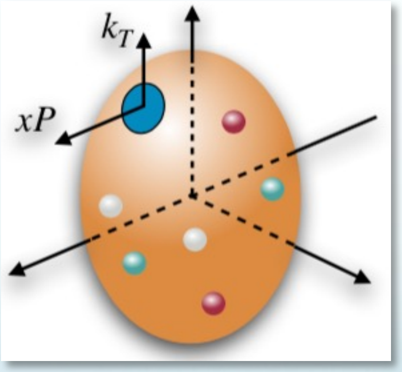


- Nucleon 1D and 3D imaging



$f(x)$

Collinear PDFs: Longitudinal motion

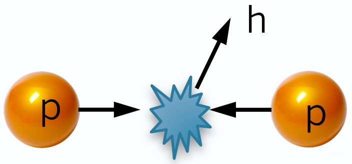


$f(x, k_T)$

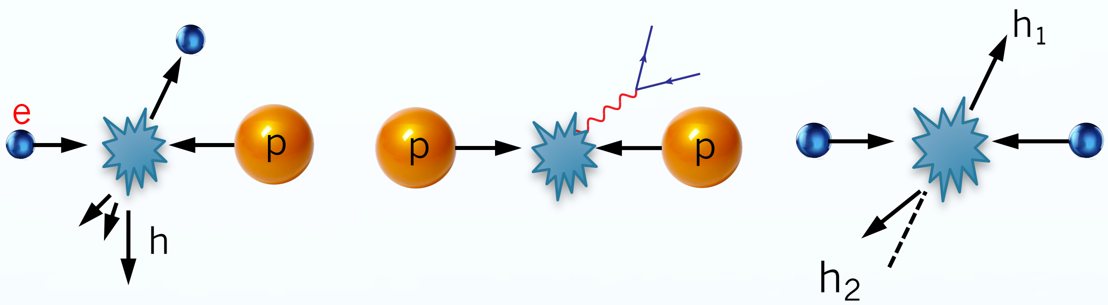
TMDs: Longitudinal + transverse motion

Hadron measurements: PDFs and TMDs

- QCD factorization frameworks
  - PDFs: RHIC process with single hard scale, e.g. $p+p \to h(p_T)+X$



  - TMDs: processes with two scales, e.g. SIDIS, Drell-Yan/W/Z, and dihadron in e+e-



- However, they are closely related to each other
  - In parton model, related via naïve equation of motion

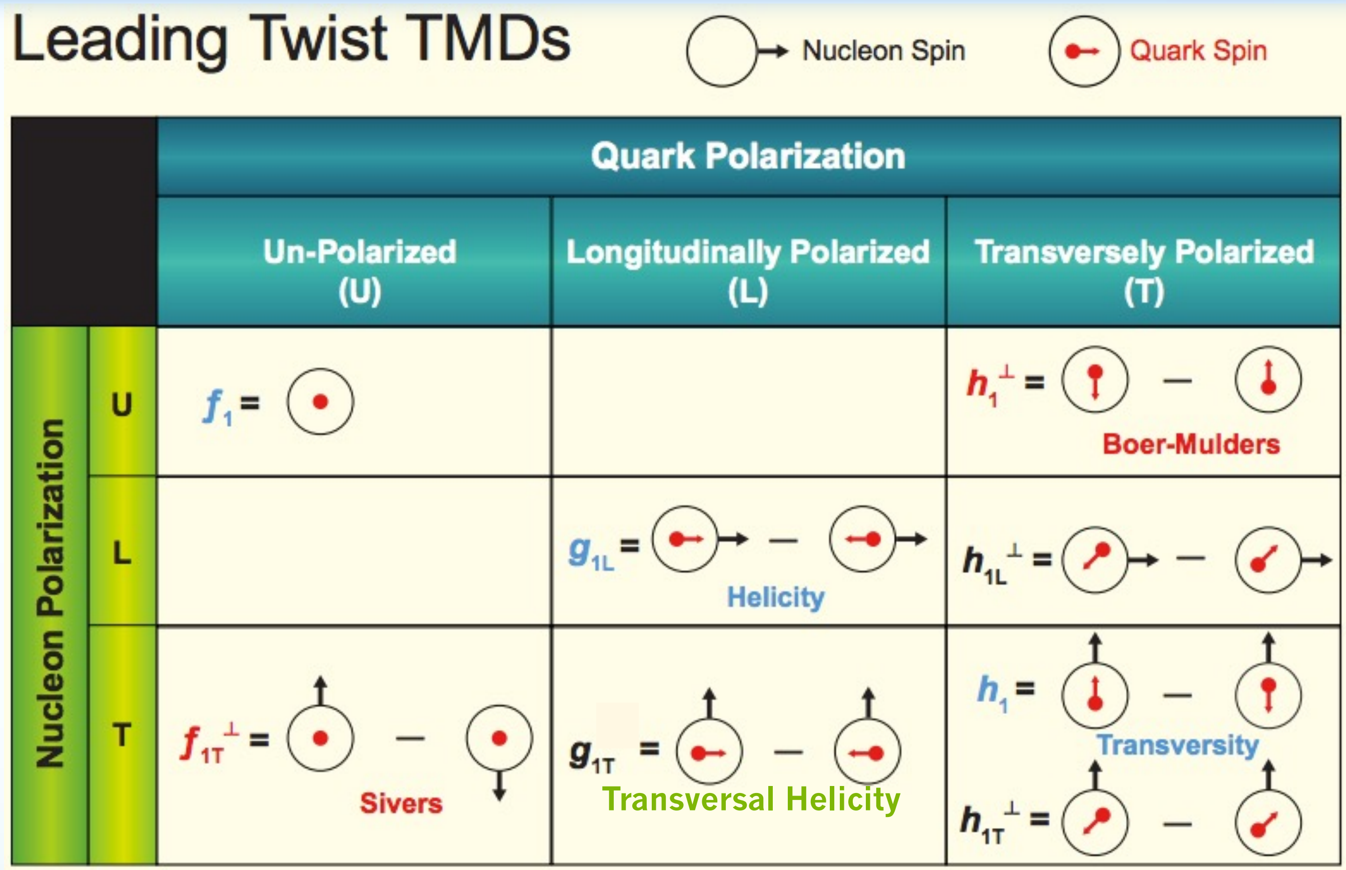
$$f(x) = \int d^2k_T\, f(x,k_T)$$

  - In pQCD, they are related via operator product expansion

$$f(x,k_T) \xrightarrow{k_T \gg \Lambda_{\rm QCD}} C(x,k_T)\otimes f(x)$$

Applying to all relevant TMDs and corresponding collinear functions

TMD parton distribution

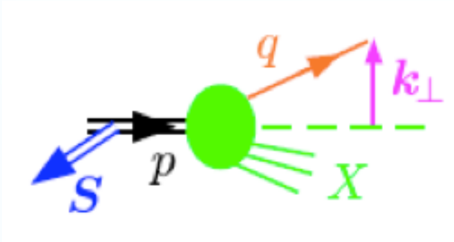


TMD fragmentation function

	Quark Polarization U	L	T
Pion	D_1		$H_1^\perp$ **Collins**

Examples: parton model

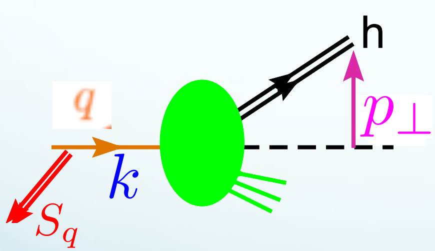
- Sivers function and Qiu-Sterman function (collinear twist-3)



$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) \equiv f_{q/h}(x,k_\perp) - \frac{1}{M} f_{1T}^{\perp q}(x,k_\perp)\,\vec{S}\cdot(\hat{p}\times\mathbf{k}_\perp)$$

$$\pi F_{FT}(x,x) = \int d^2\vec{k}_T\,\frac{k_T^2}{2M^2} f_{1T}^\perp(x,k_T^2) \equiv f_{1T}^{\perp(1)}(x)$$

- Collins function and collinear twist-3 fragmentation function

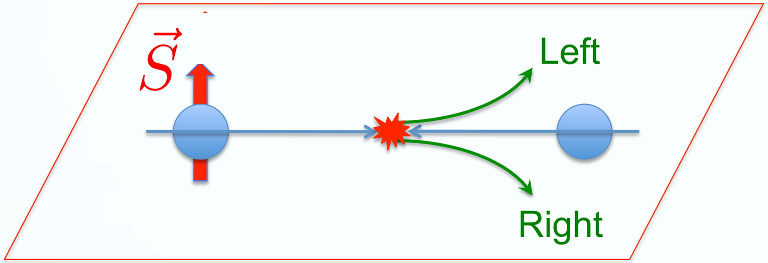


$$D_{h/q}(z,p_\perp) = D_1^q(z,p_\perp^2) + \frac{1}{zM_h} H_1^{\perp q}(z,p_\perp^2)\vec{S}_q\cdot\left(\hat{k}\times p_\perp\right)$$

$$H_1^{\perp(1)}(z) \equiv z^2\int d^2\vec{p}_\perp\,\frac{p_\perp^2}{2M_h^2} H_1^\perp(z,z^2p_\perp^2)$$

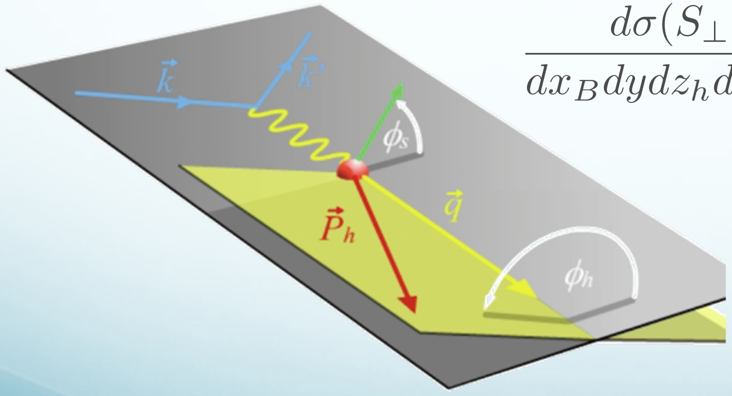
Early naïve test

- Extracting Qiu-Sterman function from $p+p \to h(p_T)+X$
  - Assuming A_N is fully generated from Qiu-Sterman mechanism



$$A_N \equiv \frac{L-R}{L+R} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- Extracting Sivers function from SIDIS process

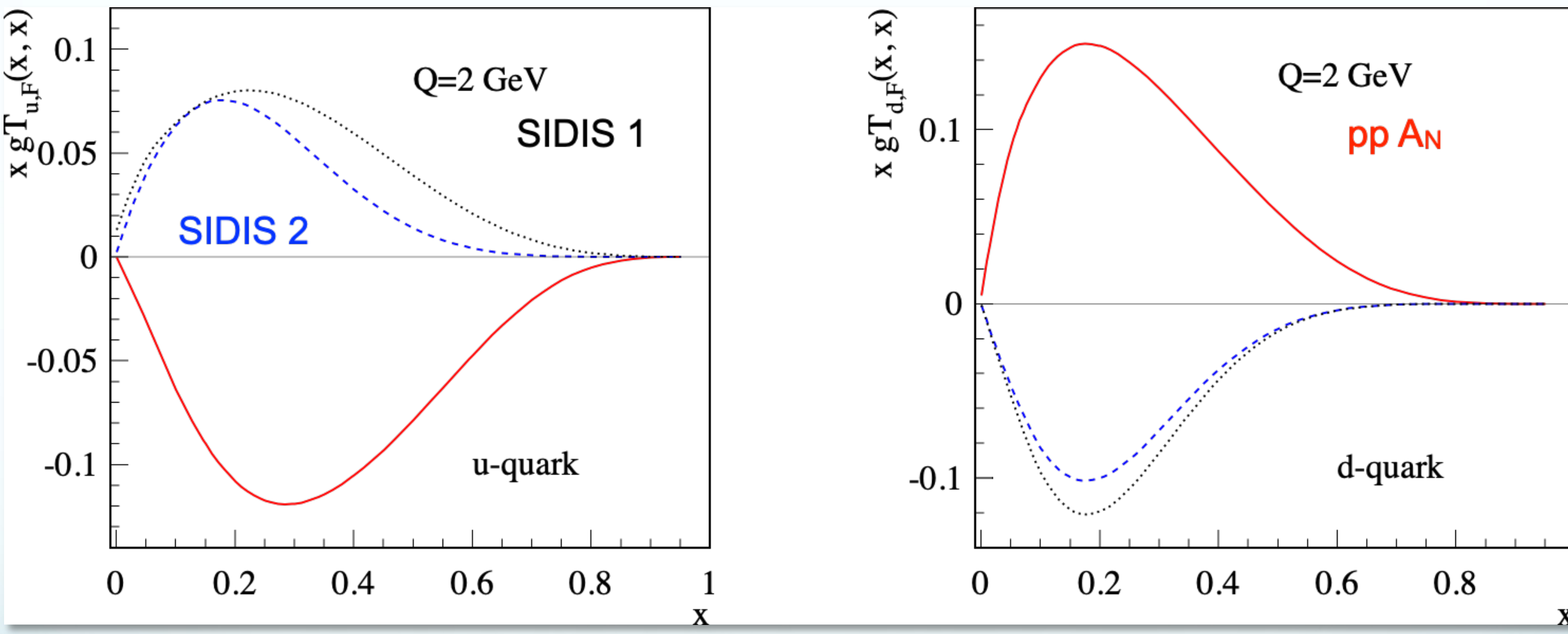


$$\frac{d\sigma(S_\perp)}{dx_B dy dz_h d^2P_{h\perp}} = \sigma_0(x_B, y, Q^2)\left[F_{UU} + \sin(\phi_h - \phi_s)\, F_{UT}^{\sin(\phi_h-\phi_s)} + \ldots\right]$$

Sign mismatch

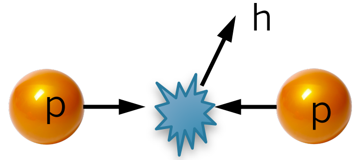
- Seems not being consistent with parton model relation

Kang, Qiu, Vogelsang, Yuan, 2010



Towards solving sign mismatch puzzle

- People quickly realized that twist-3 fragmentation functions also contribute to pp A_N (besides Qiu-Sterman contribution)
  - Early results by Kang, Yuan, Zhou, Koike, Metz, Pitonyak, Gamberg, Prokudin, ...
  - One always wonders if it is possible to perform a global analysis to include SIDS, Drell-Yan, e+e-, and pp A_N data
  - It took several years to get it done due to the hard work of our collaborators

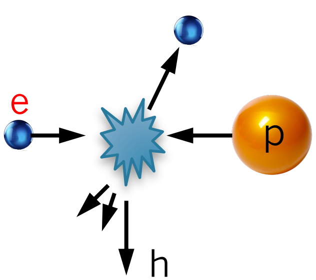


$f_{1T}^{\perp(1)}(x)$

$h_1(x) \otimes H_1^{\perp(1)}(z)$

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato arXiv: 2002.08384, PRD

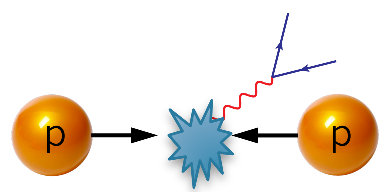
SIDIS Sivers, Collins



$f_{1T}^{\perp}(x, k_T)$

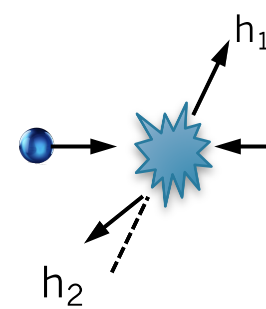
$h_1(x, k_T) \otimes H_1^{\perp}(z, p_T)$

DY Sivers



$f_{1T}^{\perp}(x, k_T)$

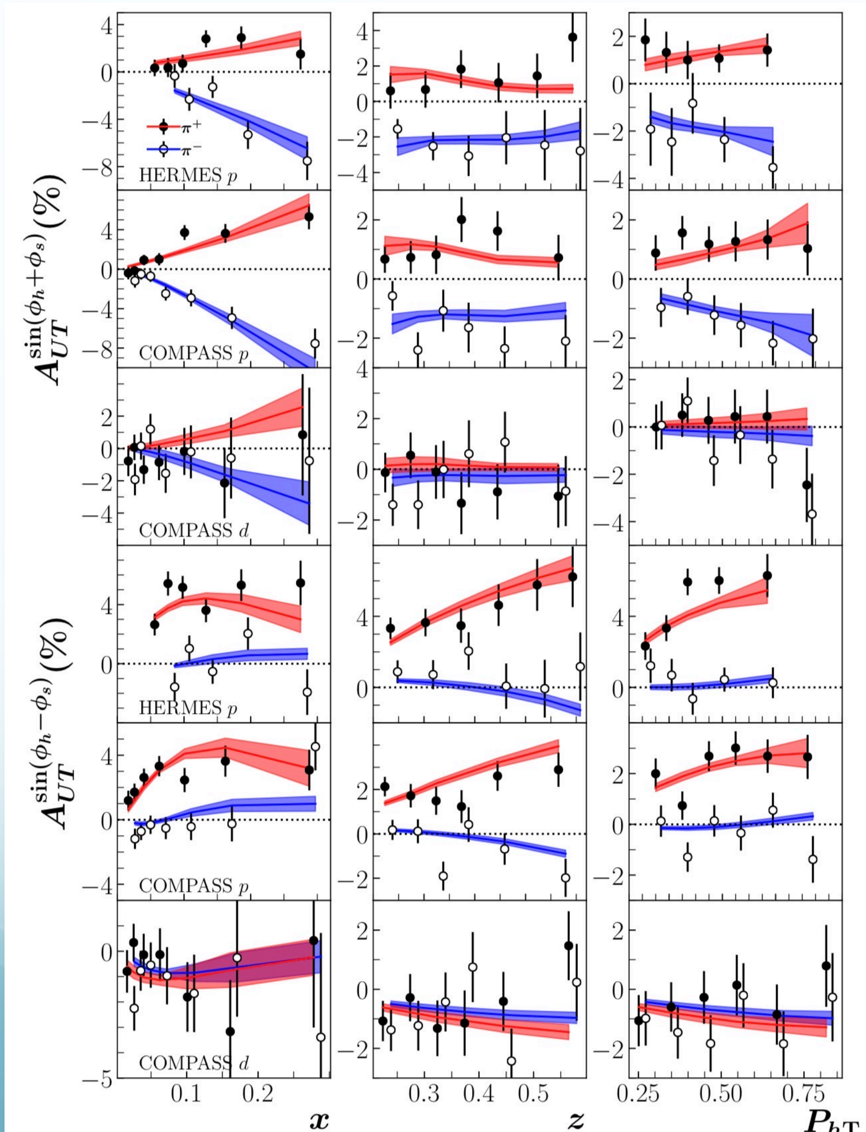
e+e- Collins

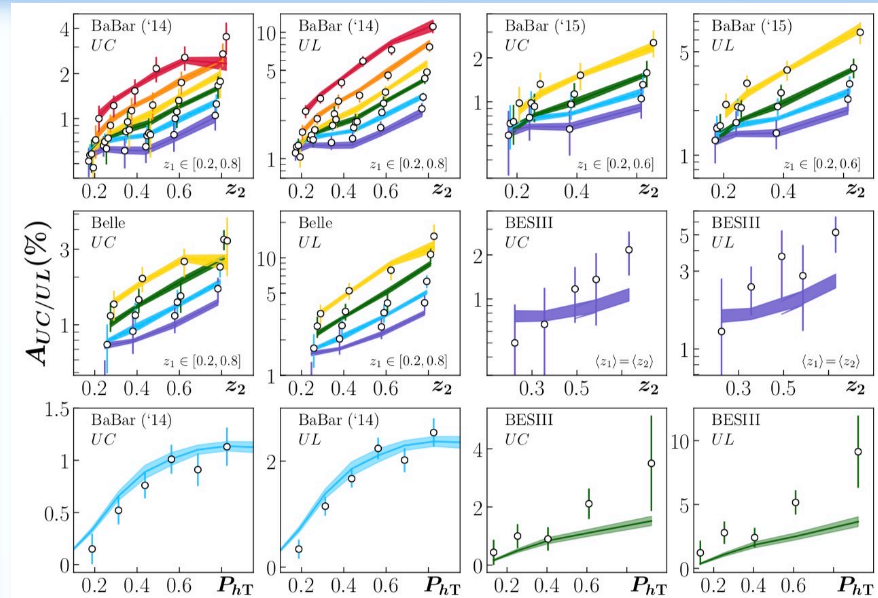


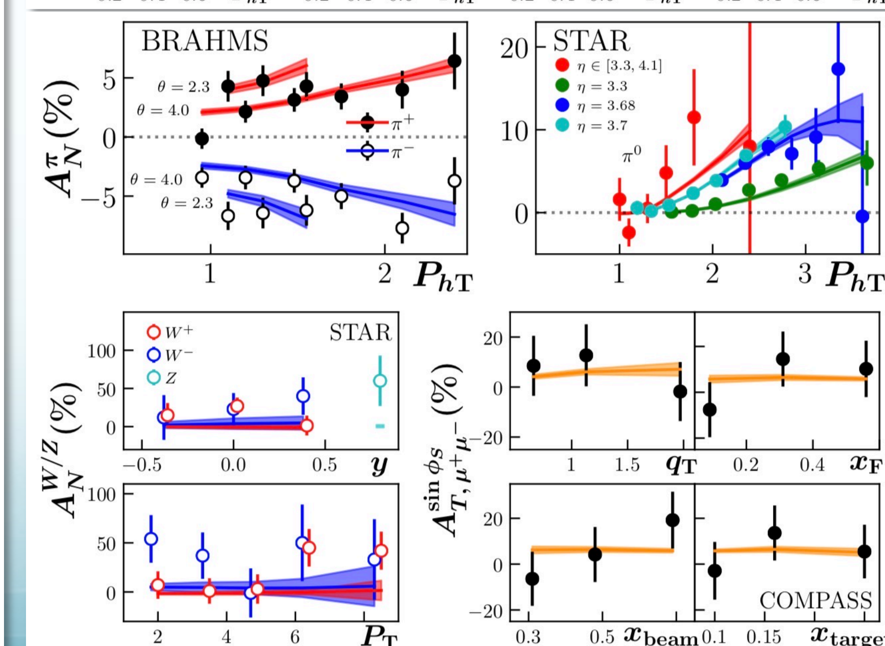
$H_1^{\perp}(z, p_T)$

Global fit

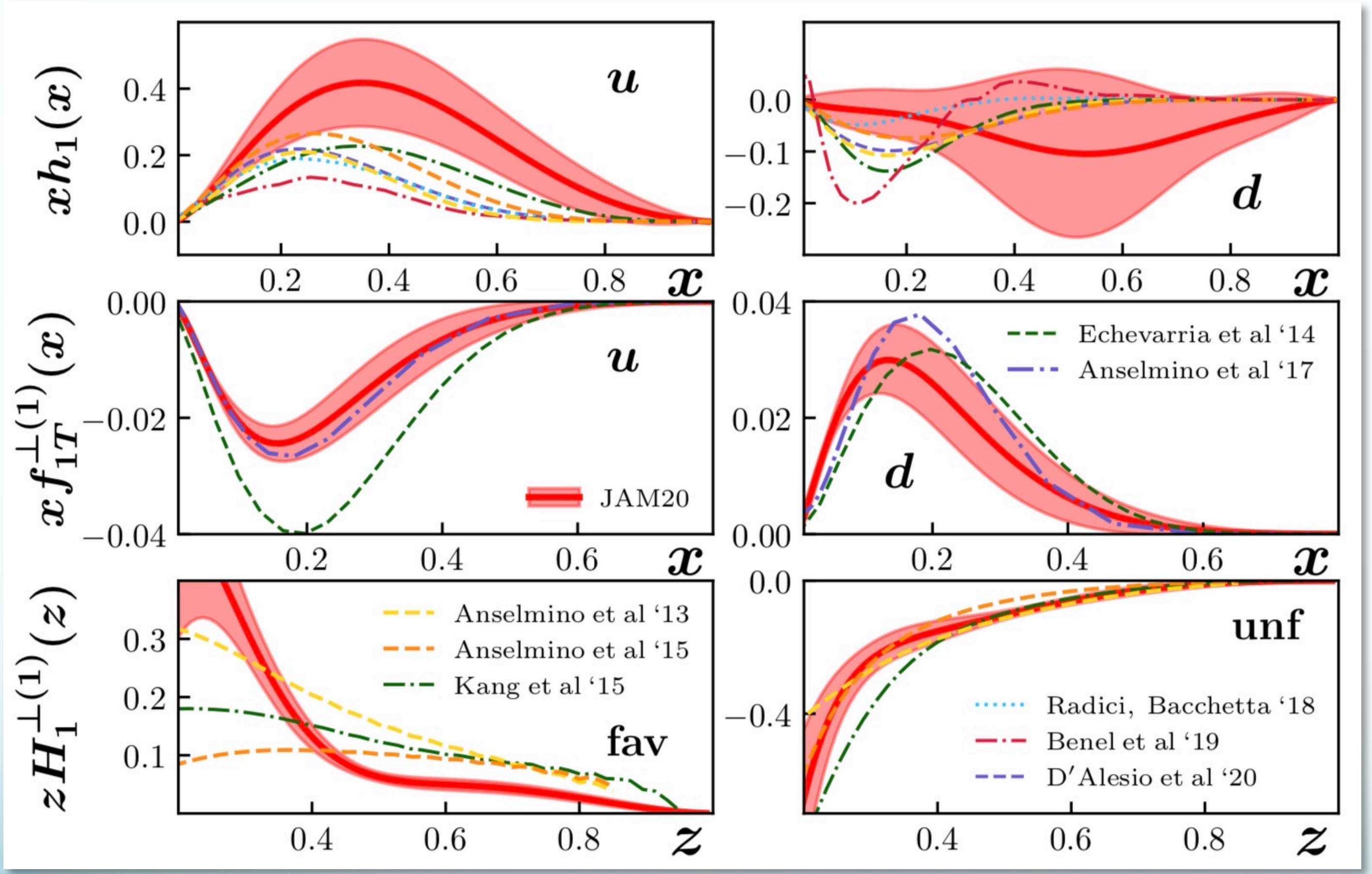
$$\chi^2/N_{\text{pts.}} = 520/517 = 1.01$$







Extracted functions



transversity

Qiu-Sterman function [Sivers first moment]

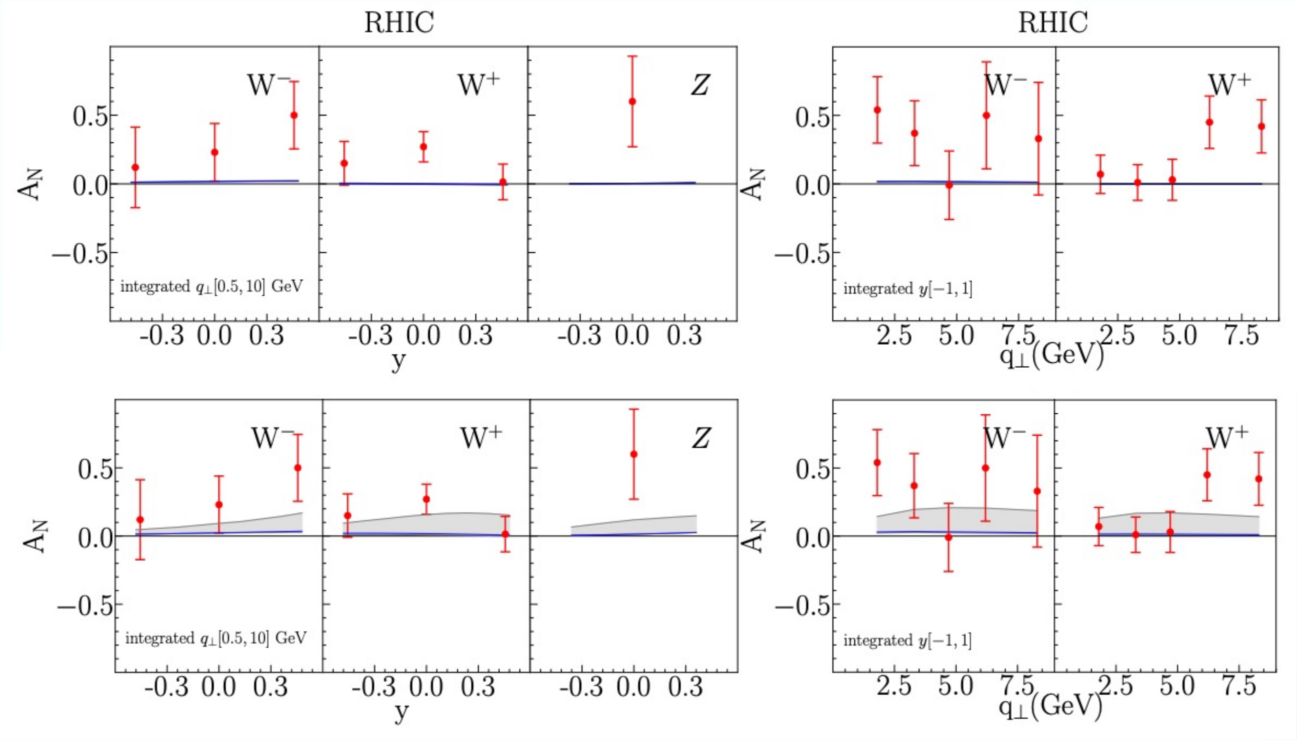
Twist-3 FFs [Collins first moment]

Remaining issue: TMD evolution or sea contribution?

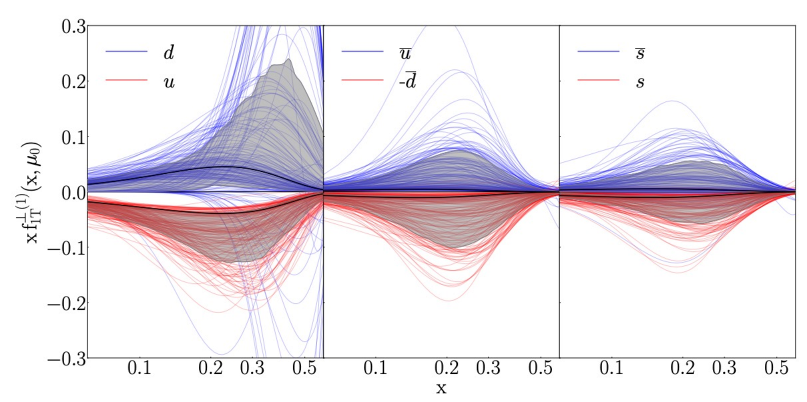
- Our recent fit shows some difficulties in describing STAR A_N for W/Z boson

w/o weight

w/ weight ~13



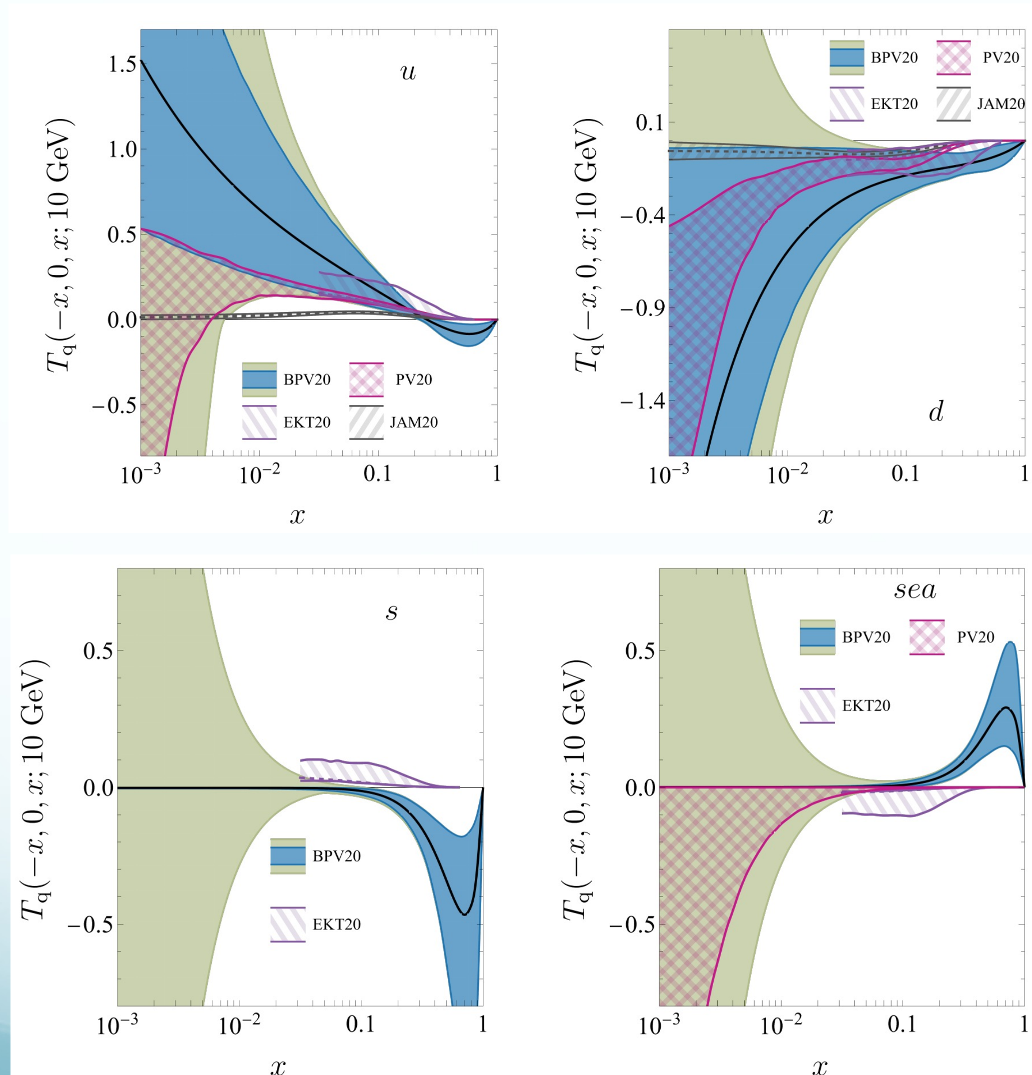
Extracted Sivers functions



Echevarria, Kang, Terry
2009.10710, JHEP

Another global fit

- Large sea quark Sivers functions can seemly resolve the issue



Similar u/d Sivers

Large sea Sivers at large x

Bury, Prokudin, Vladimirov
2103.03270, JHEP

Keep in mind

- There are two contributions for single spin asymmetry of W/Z

$$
\begin{aligned}
\frac{d\sigma^W}{dy d^2\vec{q}_T} =& \sigma_0^W \Big\{ F_{UU} + S_{AL}F_{LU} + S_{BL}F_{UL} + S_{AL}S_{BL}F_{LL} \\
&+ |\vec{S}_{AT}| \left[\sin(\phi_V - \phi_{S_A}) F_{TU}^{\sin(\phi_V - \phi_{S_A})} + \cos(\phi_V - \phi_{S_A}) F_{TU}^{\cos(\phi_V - \phi_{S_A})} \right] \\
&+ |\vec{S}_{BT}| \left[\sin(\phi_V - \phi_{S_B}) F_{UT}^{\sin(\phi_V - \phi_{S_B})} + \cos(\phi_V - \phi_{S_B}) F_{UT}^{(\cos\phi_V - \phi_{S_B})} \right] \\
&+ |\vec{S}_{AT}| S_{BL} \left[\sin(\phi_V - \phi_{S_A}) F_{TL}^{\sin(\phi_V - \phi_{S_A})} + \cos(\phi_V - \phi_{S_A}) F_{TL}^{\cos(\phi_V - \phi_{S_A})} \right] \\
&+ S_{AL} |\vec{S}_{BT}| \left[\sin(\phi_V - \phi_{S_B}) F_{LT}^{\sin(\phi_V - \phi_{S_B})} + \cos(\phi_V - \phi_{S_B}) F_{LT}^{\cos(\phi_V - \phi_{S_B})} \right] \\
&+ |\vec{S}_{AT}| |\vec{S}_{BT}| \Big[\cos(2\phi_V - \phi_{S_A} - \phi_{S_B}) F_{TT}^{\cos(2\phi_V - \phi_{S_A} - \phi_{S_B})} + \cos(\phi_{S_A} - \phi_{S_B}) F_{TT}^1 \\
&\qquad + \sin(2\phi_V - \phi_{S_A} - \phi_{S_B}) F_{TT}^{\sin(2\phi_V - \phi_{S_A} - \phi_{S_B})} + \sin(\phi_{S_A} - \phi_{S_B}) F_{TT}^2 \Big] \Big\}.
\end{aligned}
$$

$$
\begin{aligned}
F_{TU}^{\sin(\phi_V - \phi_{S_A})} =& \mathcal{C}^W \left[(v_q^2 + a_q^2) \frac{\hat{q}_T \cdot \vec{k}_{aT}}{M_A} f_{1T}^\perp \bar{f}_1 \right], \\
F_{TU}^{\cos(\phi_V - \phi_{S_A})} =& -\mathcal{C}^W \left[2 v_q a_q \frac{\hat{q}_T \cdot \vec{k}_{aT}}{M_A} g_{1T} \bar{f}_1 \right],
\end{aligned}
$$

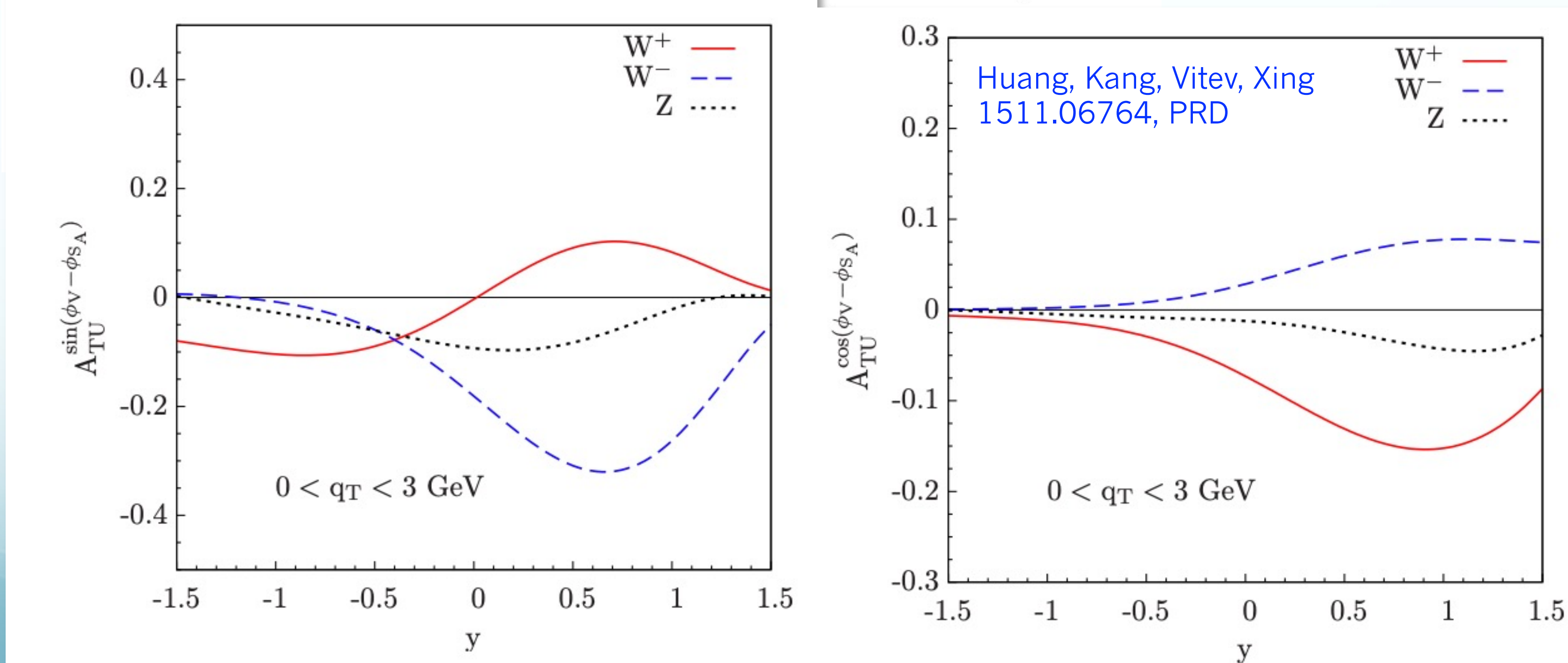
  - Yellow term: Sivers function $f_{1T}^{\perp}$
  - Green term: transversal helicity function g_{1T}
  - Better to separate them via azimuthal angular dependence

Be careful in measuring A_N of W/Z

- There are two contributions for single spin asymmetry of W/Z

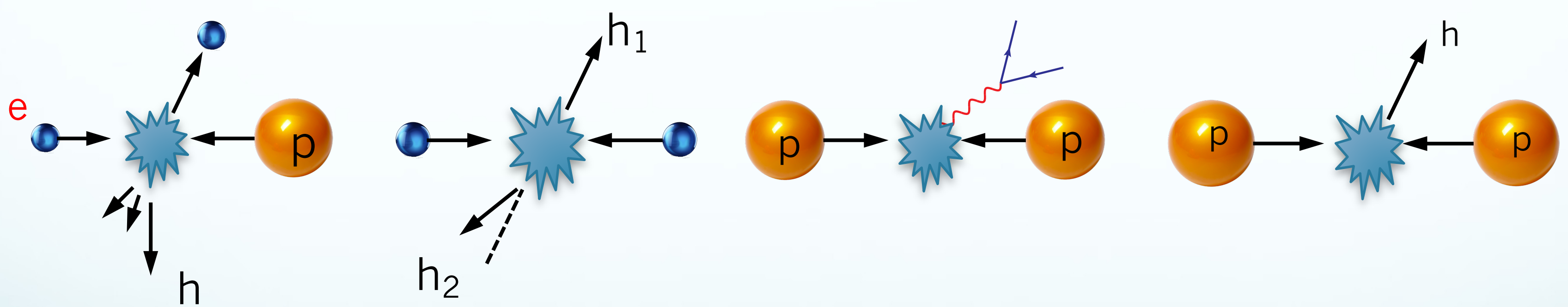
$$\frac{d\sigma^W}{dy d^2\vec{q}_T} = \sigma_0^W \Big\{ F_{UU} + S_{AL}F_{LU} + S_{BL}F_{UL} + S_{AL}S_{BL}F_{LL}$$
$$+ |\vec{S}_{AT}| \left[\sin(\phi_V - \phi_{S_A}) F_{TU}^{\sin(\phi_V - \phi_{S_A})} + \cos(\phi_V - \phi_{S_A}) F_{TU}^{\cos(\phi_V - \phi_{S_A})}\right]$$
$$+ |\vec{S}_{BT}| \left[\sin(\phi_V - \phi_{S_B}) F_{UT}^{\sin(\phi_V - \phi_{S_B})} + \cos(\phi_V - \phi_{S_B}) F_{UT}^{(\cos\phi_V - \phi_{S_B})}\right]$$
$$+ |\vec{S}_{AT}| S_{BL} \left[\sin(\phi_V - \phi_{S_A}) F_{TL}^{\sin(\phi_V - \phi_{S_A})} + \cos(\phi_V - \phi_{S_A}) F_{TL}^{\cos(\phi_V - \phi_{S_A})}\right]$$
$$+ S_{AL} |\vec{S}_{BT}| \left[\sin(\phi_V - \phi_{S_B}) F_{LT}^{\sin(\phi_V - \phi_{S_B})} + \cos(\phi_V - \phi_{S_B}) F_{LT}^{\cos(\phi_V - \phi_{S_B})}\right]$$

$$F_{TU}^{\sin(\phi_V - \phi_{S_A})} = \mathcal{C}^W \left[(v_q^2 + a_q^2) \frac{\hat{q}_T \cdot \vec{k}_{aT}}{M_A} f_{1T}^{\perp} \bar{f}_1\right],$$
$$F_{TU}^{\cos(\phi_V - \phi_{S_A})} = -\mathcal{C}^W \left[2 v_q a_q \frac{\hat{q}_T \cdot \vec{k}_{aT}}{M_A} g_{1T} \bar{f}_1\right],$$

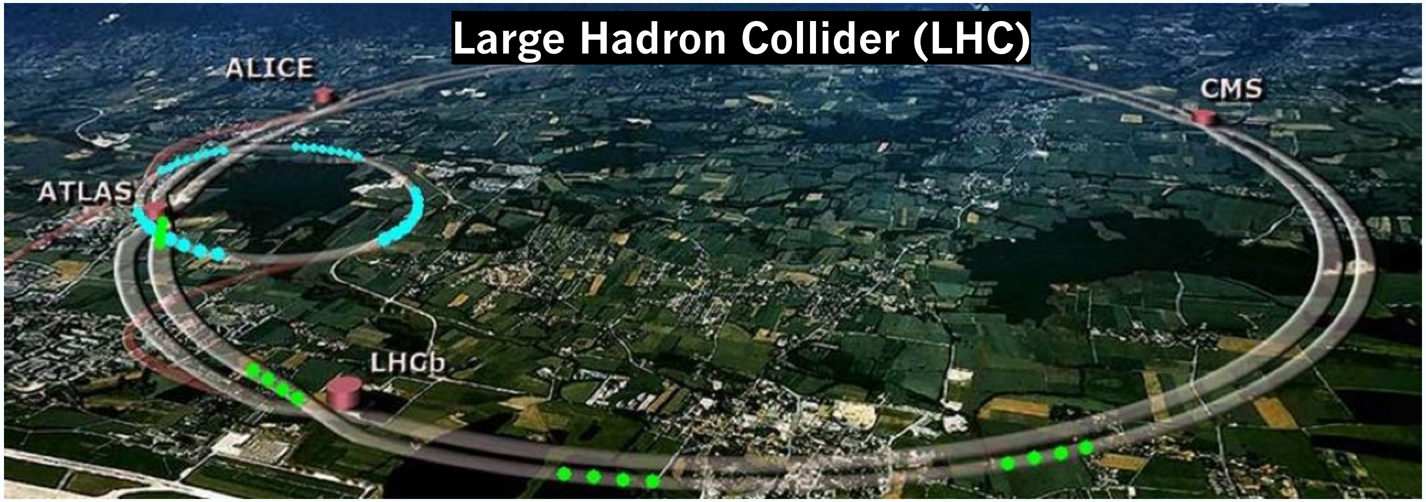


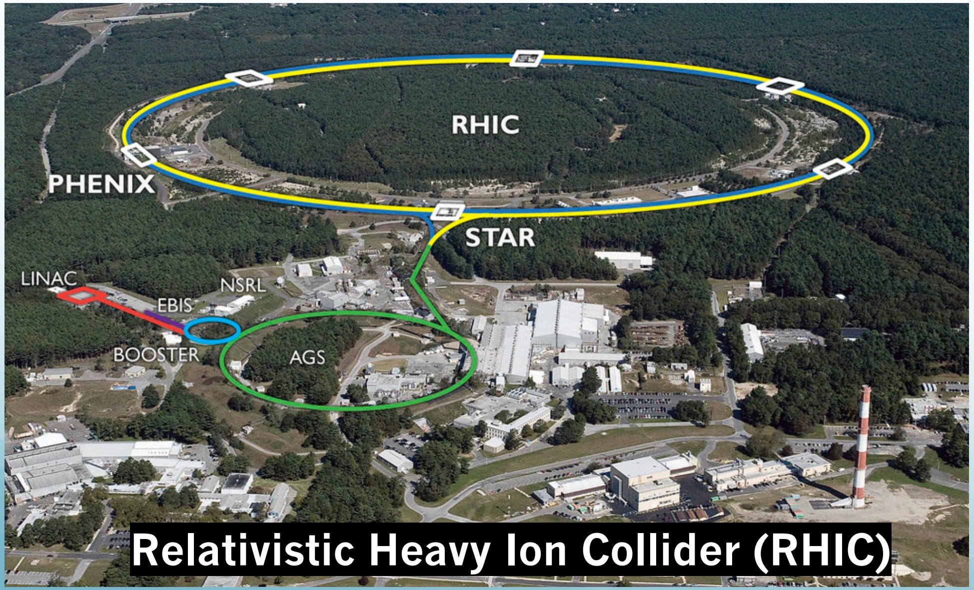
Moving forward

- The current spin measurements
  - SIDIS, DY/W/Z, e+e-: always involve two TMDs
  - hadron in pp: involve several contributions (incoming proton + final hadron)
- Next step:
  - Separately study TMDPDF and TMDFF via different processes
  - One TMD at a time if possible

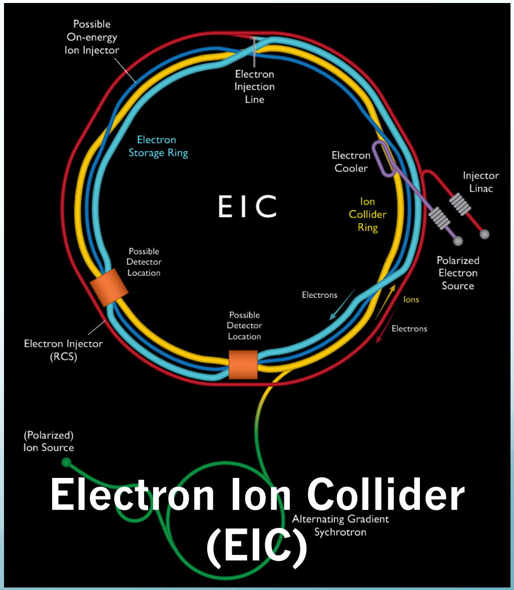


Using jets for TMDs: LHC→RHIC→EIC



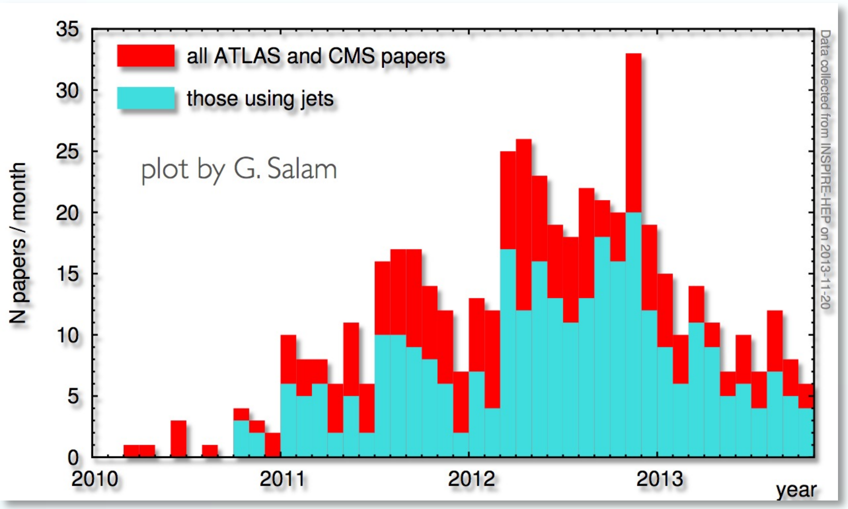


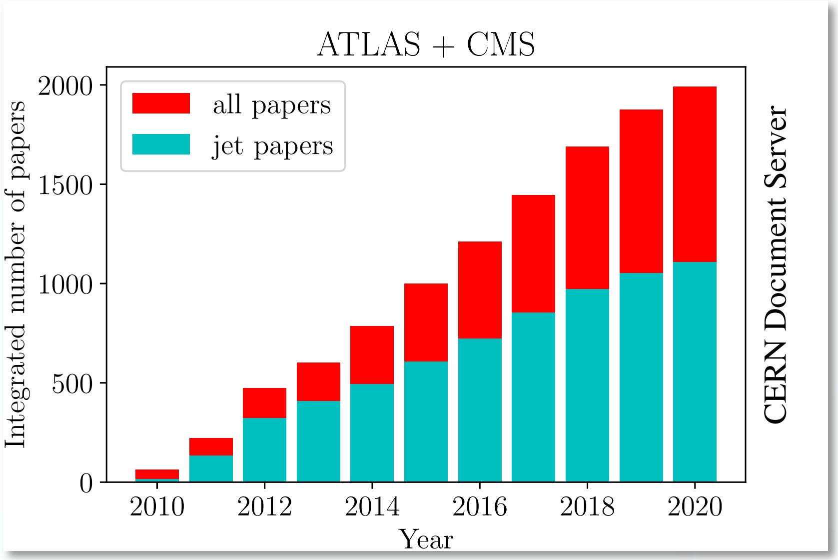
~ 2030



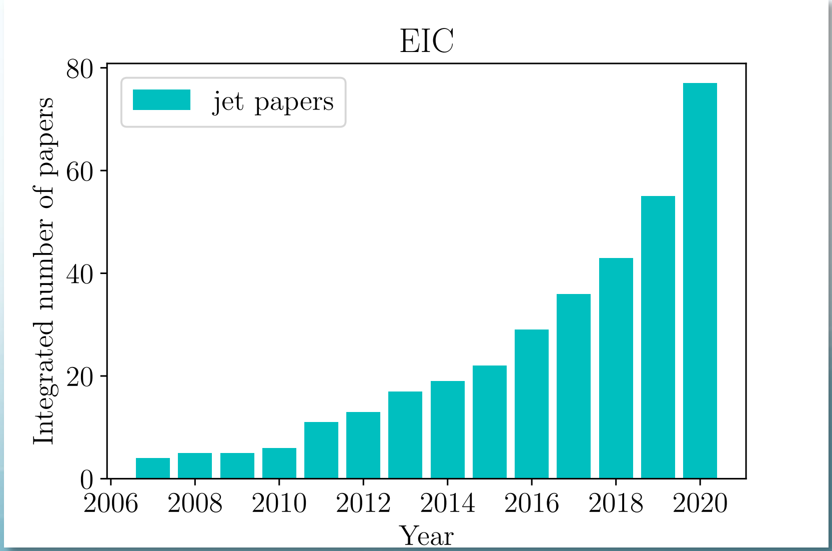
Renaissance of jet physics

- They are most common at the LHC
  - At the LHC, 60% of ATLAS & CMS papers use jets in their analysis!



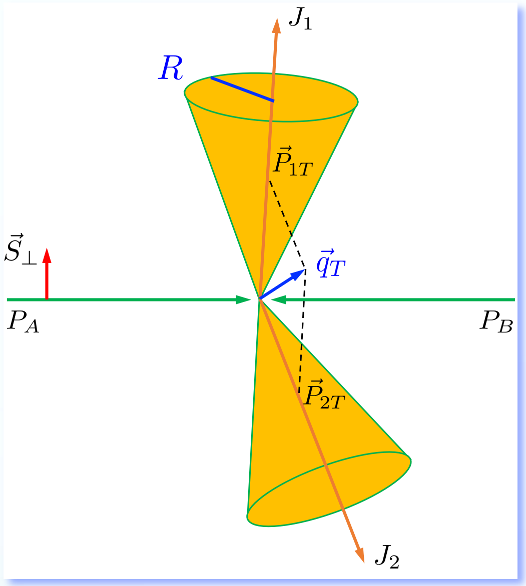


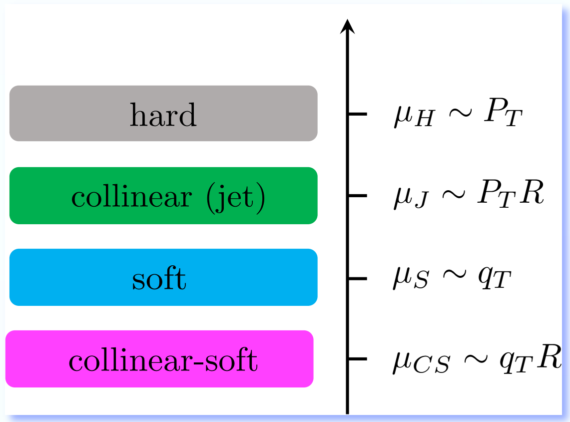
- Active study at the EIC
  - EIC jet papers grow exponentially



TMDPDF: jet production

- To be more sensitive to the *small* parton transverse motion
  - One could further measure a small transverse momentum in the experiment, such as momentum imbalance (q_T) in a dijet or photon+jet production





- Construction of the theory formalism is nontrivial
  - Multiple scales in the problem
  - We would rely on effective field theory

Kang, Lee, Shao, Terry, 20
Buffing, **Kang**, Lee, Liu, 18

$$\sigma(s_\perp) - \sigma(-s_\perp) \propto \boxed{f_{1T}^{\perp a}(x_a, k_{aT})} \otimes f_b(x_b, k_{bT})$$
$$\otimes \mathrm{Tr}[S_{ab}(q_T) H_{ab\to cd}(P_T)] \otimes S_c^{\mathrm{cs}}(q_T R) S_d^{\mathrm{cs}}(q_T R) J_c(P_T R) J_d(P_T R)$$

TMD factorization

- It is known that TMD factorization is broken, so what's your rational here?
  - For unpolarized cross section
    - TMD factorization is broken by so-called Glauber gluons. Within SCET, people has derived factorization formalism by not including Glauber mode in the first place
    - Within this framework, we can easily derive the contribution of soft-gluon radiation, as encoded in various soft functions

Kang, Lee, Shao, Terry, 20
Buffing, **Kang**, Lee, Liu, 18

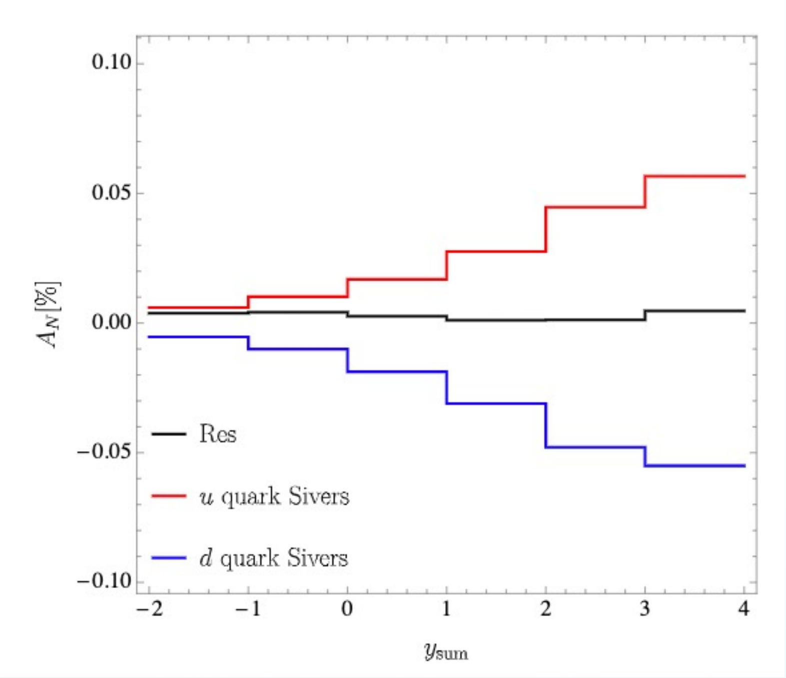
$$\sigma(s_\perp)+\sigma(-s_\perp)\propto f_a(x_a,k_{aT})\otimes f_b(x_b,k_{bT}) \otimes \mathrm{Tr}[\boldsymbol{S}_{ab}(q_T)\boldsymbol{H}_{ab\to cd}(P_T)]\otimes S_c^{\mathrm{cs}}(q_TR)S_d^{\mathrm{cs}}(q_TR)J_c(P_TR)J_d(P_TR)$$

  - For polarized cross section
    - A generalized TMD formalism has existed in the literature by Bacchetta, Boer, Mulders, Qiu, Vogelsang, Yuan, etc during 2006 or so, which is crucial for process-dependence of the TMDPDF, e.g. Sivers function. However, they did not address the contribution of soft-gluon radiation, which is crucial for TMD evolution
    - We assume soft function is the same as those in the unpolarized case, a rather nature assumption. Implement such soft functions into the above generalized TMD formalism would become the most natural formalism for us to check factorization breaking

$$\sigma(s_\perp)-\sigma(-s_\perp)\propto f_{1T}^{\perp a}(x_a,k_{aT})\otimes f_b(x_b,k_{bT}) \otimes \mathrm{Tr}[\boldsymbol{S}_{ab}(q_T)\boldsymbol{H}_{ab\to cd}(P_T)]\otimes S_c^{\mathrm{cs}}(q_TR)S_d^{\mathrm{cs}}(q_TR)J_c(P_TR)J_d(P_TR)$$

A challenging measurement

- The asymmetry is small, due to the cancelation between u and d Sivers function



Need flavor separation, how?

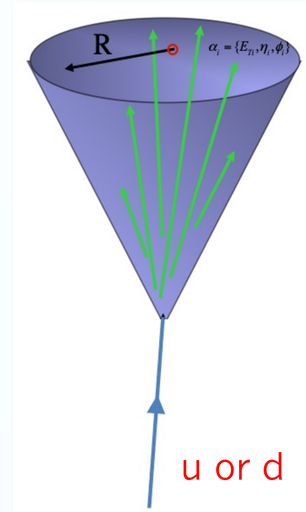
- Brainstorm

u $+\frac{2}{3}e$

d $-\frac{1}{3}e$

jet charge

Kang, Liu, Mantry, Shao, 20



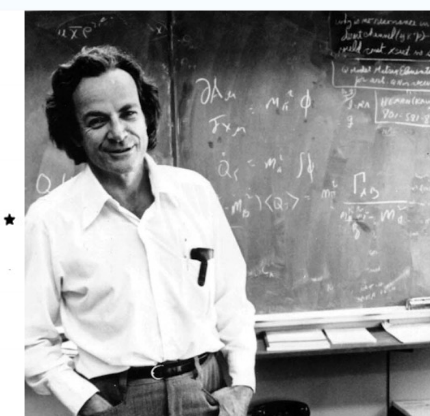
counting particle charges reconstructs initiating quark charge

Nuclear Physics B136 (1978) 1–76

A PARAMETRIZATION OF THE PROPERTIES OF QUARK JETS *

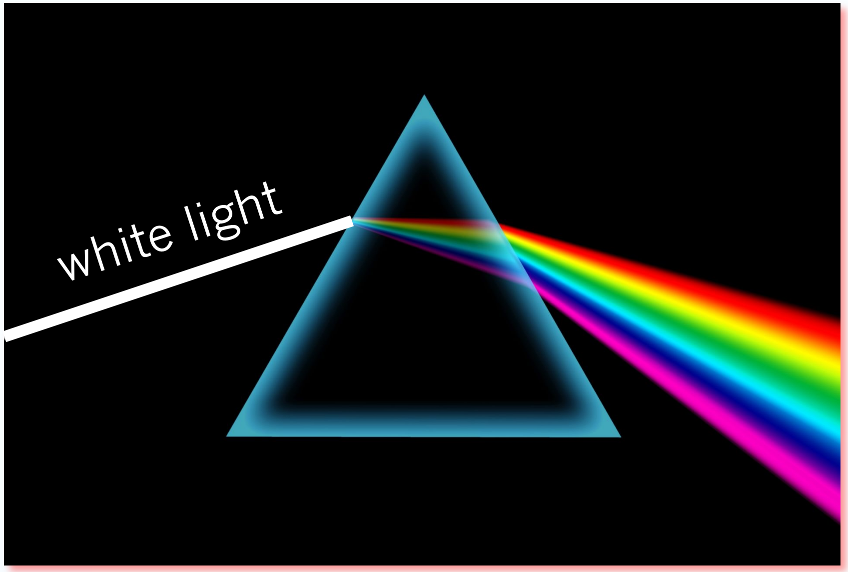
R.D. FIELD and R.P. FEYNMAN
California Institute of Technology, Pasadena, California 91125, USA

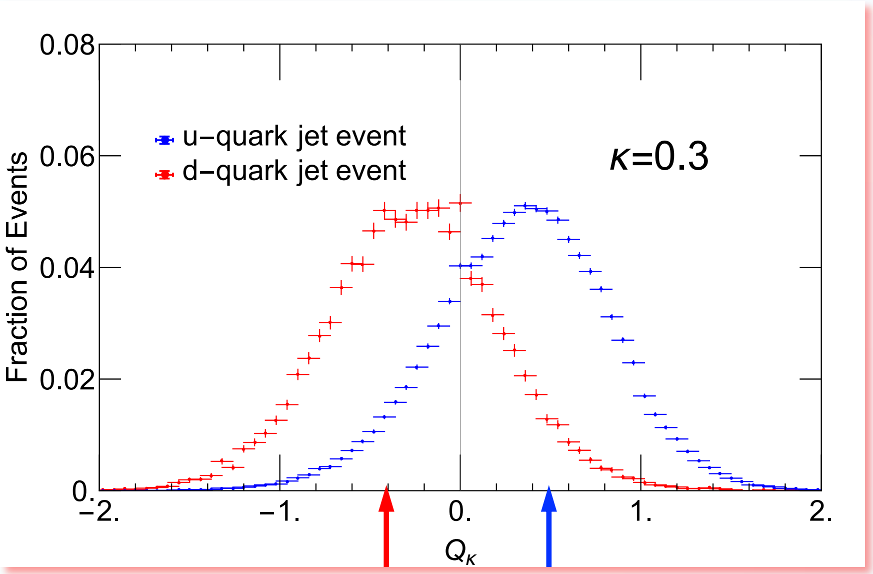
Received 11 October 1977



Jet charge: a flavor prism

- Recall: light prism (University Physics)





- Jet charge definition
  - A weighted sum of charges for hadrons inside the jet

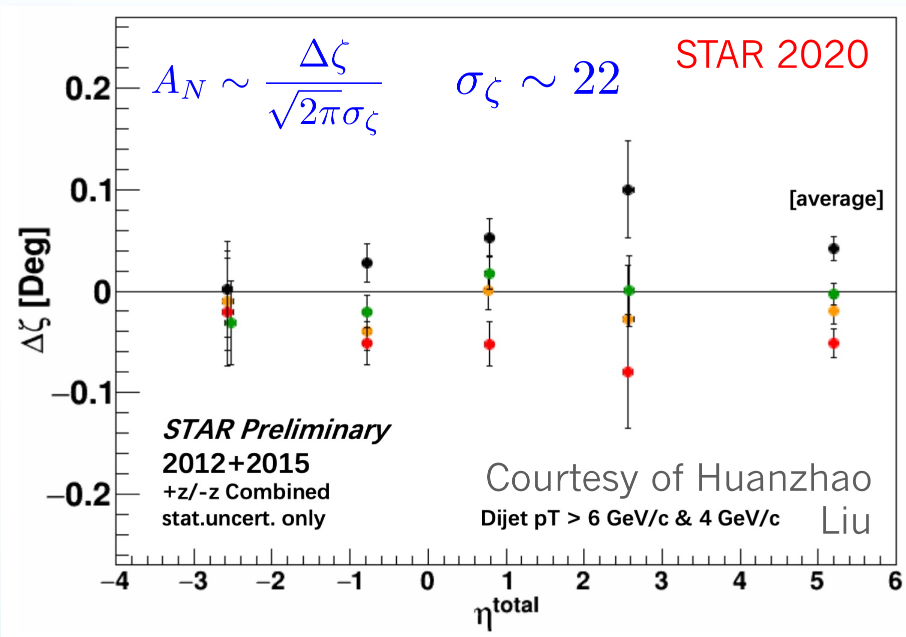
$$Q_\kappa \equiv \sum_{h \in \text{jet}} z_h^\kappa Q_h$$

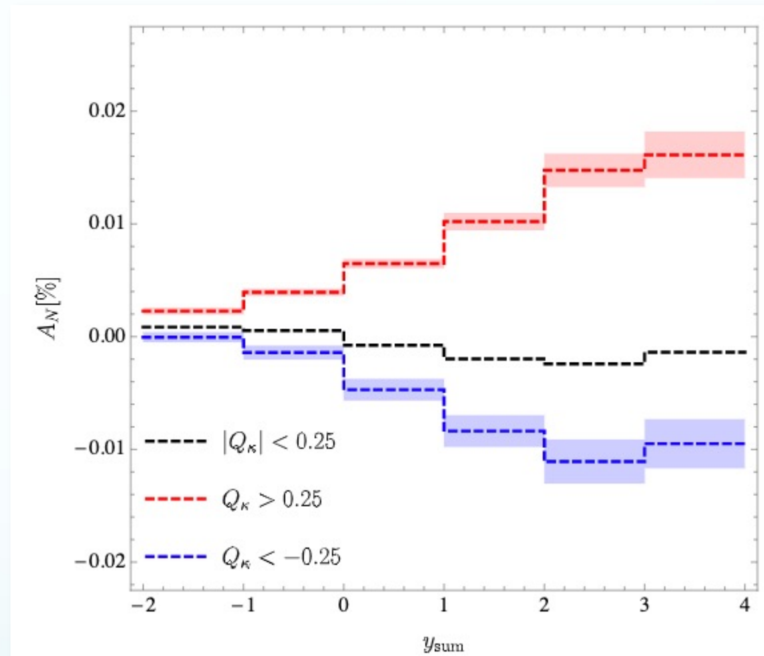
Charge of the hadron

$$z_h = \frac{p_{hT}}{p_{JT}} \qquad \kappa = 0.3, 0.4, \cdots, 1.0$$

Spin asymmetry sorted by jet charge

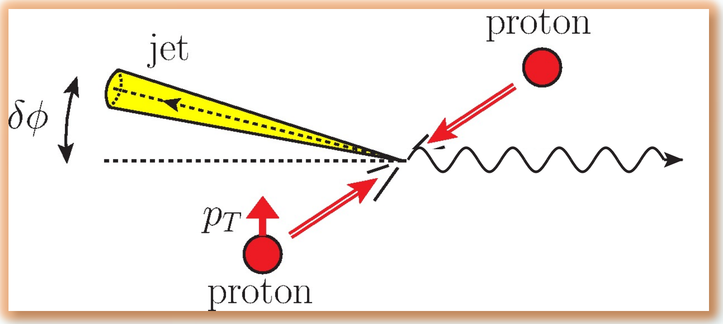
- Certainly possible, due to RHIC experimentalists' hard work

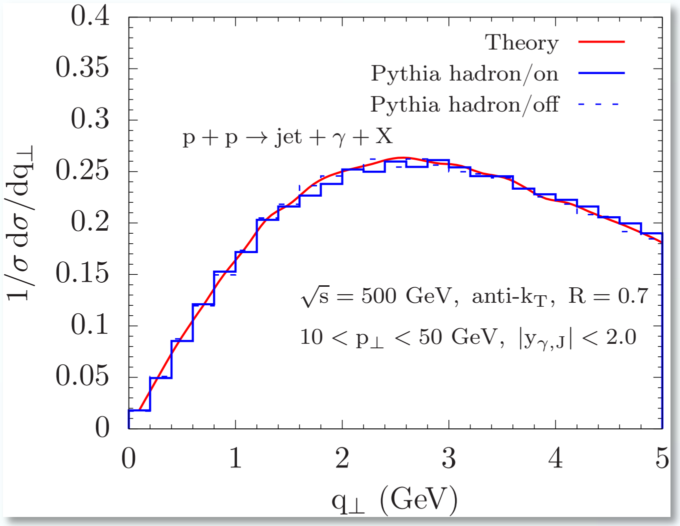




Photon+Jet

- RHIC often performs back-to-back photon+jet production



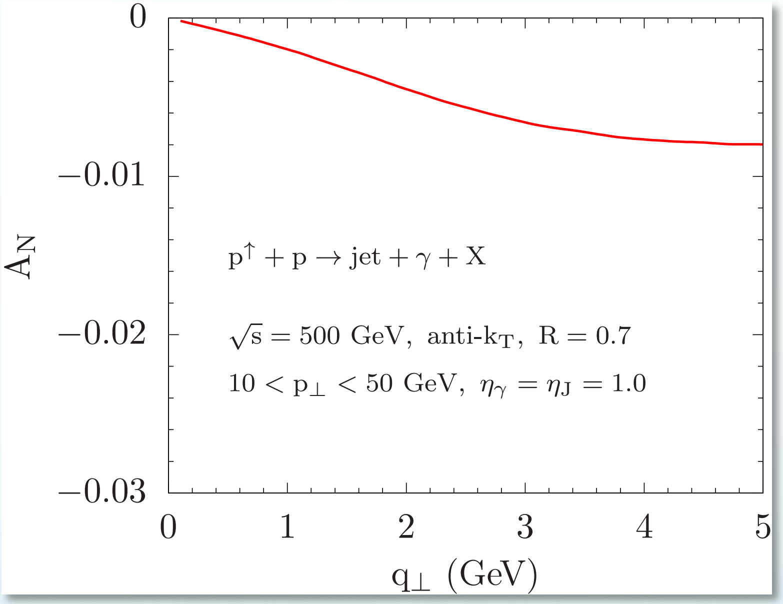


Buffing, Kang, Lee, Liu, 1812.07549

$$\frac{d\sigma}{dy_J dy_\gamma dp_\perp d^2\vec{q}_\perp} = \sum_{a,b,c} \int d\phi_J \int \prod_i^4 d^2\vec{k}_{i\perp} \delta^{(2)}(\vec{q}_\perp - \sum_i^4 \vec{k}_{i\perp})$$
$$\times f_a^{\text{unsub}}(x_a, k_{1\perp}^2) f_b^{\text{unsub}}(x_b, k_{2\perp}^2) S_{n\bar{n}n_J}^{\text{global}}(\vec{k}_{3\perp})$$
$$\times S_{n_J}^{cs}(\vec{k}_{4\perp}, R) H_{ab\to c\gamma}(p_\perp) J_c(p_\perp R)$$

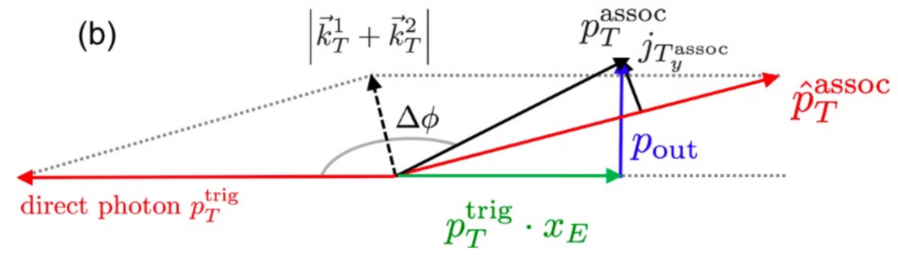
Phenomenology at RHIC

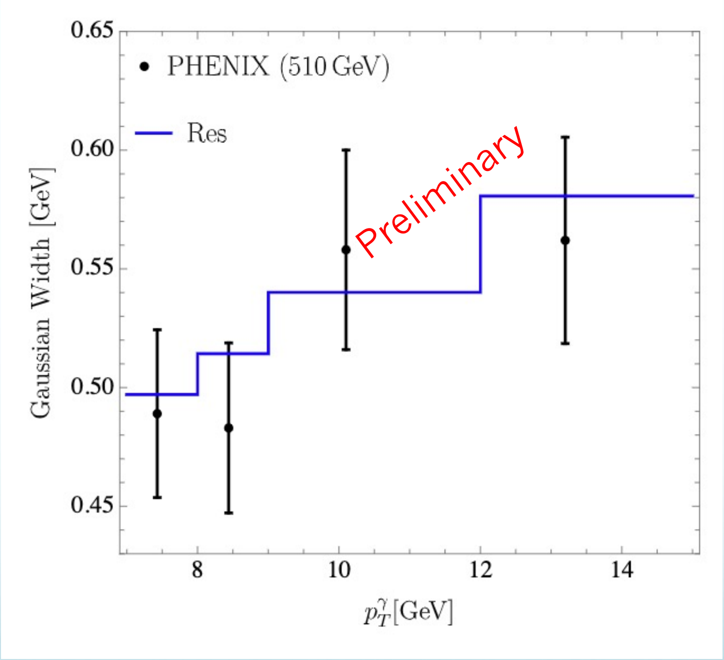
- Prediction for Sivers asymmetry is around 1% level
  - Sivers functions in SIDIS from our earlier extraction 1401.5078
  - TMD evolution has a strong effect (suppress asymmetry), but not so much for unpolarized cross section



Photon+hadron correlation

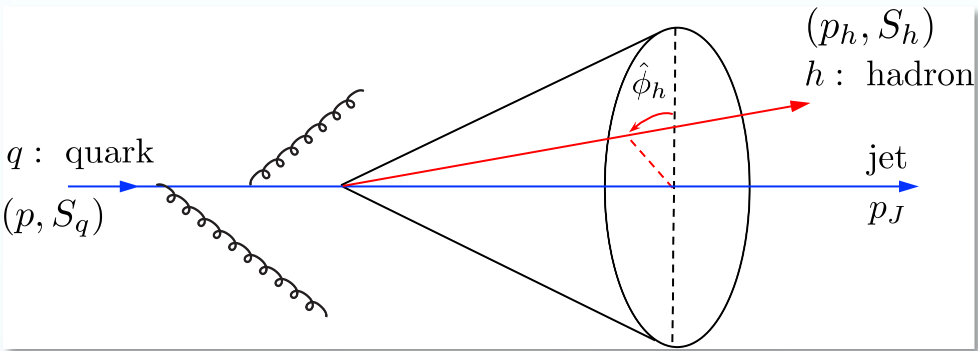
- It is possible to make comparison with PHENIX measurement now

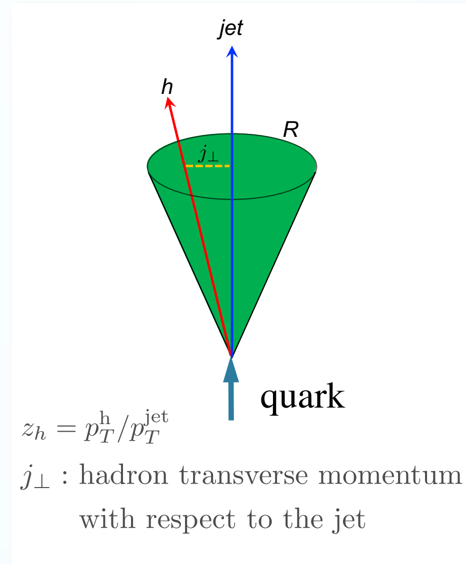




TMDFF: jet substructure of inclusive jets

- For single inclusive jet production, it involves collinear PDFs
  - Via jet substructure to probe TMD fragmentation functions
  - Apparent advantage: only one TMD FF is probed
- Jet fragmentation function



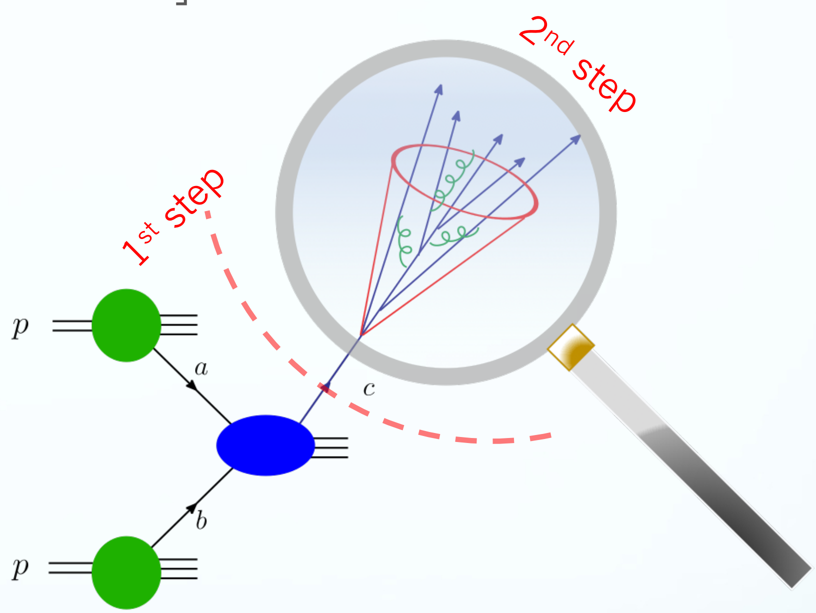


  - measures only the z_h distribution (integrated over jT), one probes collinear FFs
  - measures both zh and jT distribution (3D), one probes TMD FFs

Factorization for jet substructure

- Involving only collinear PDFs, but TMD FFs
  - 1st step: the production of the jet [collinear fact.]
  - 2nd step: jet substructure [TMD fact.]
  - Thus only involve TMD FFs
  - Different soft function

Kang, Lee, Liu, Ringer, 18, 19
Kang, Liu, Ringer, Xing, 17
Kang, Ringer, Vitev, 16

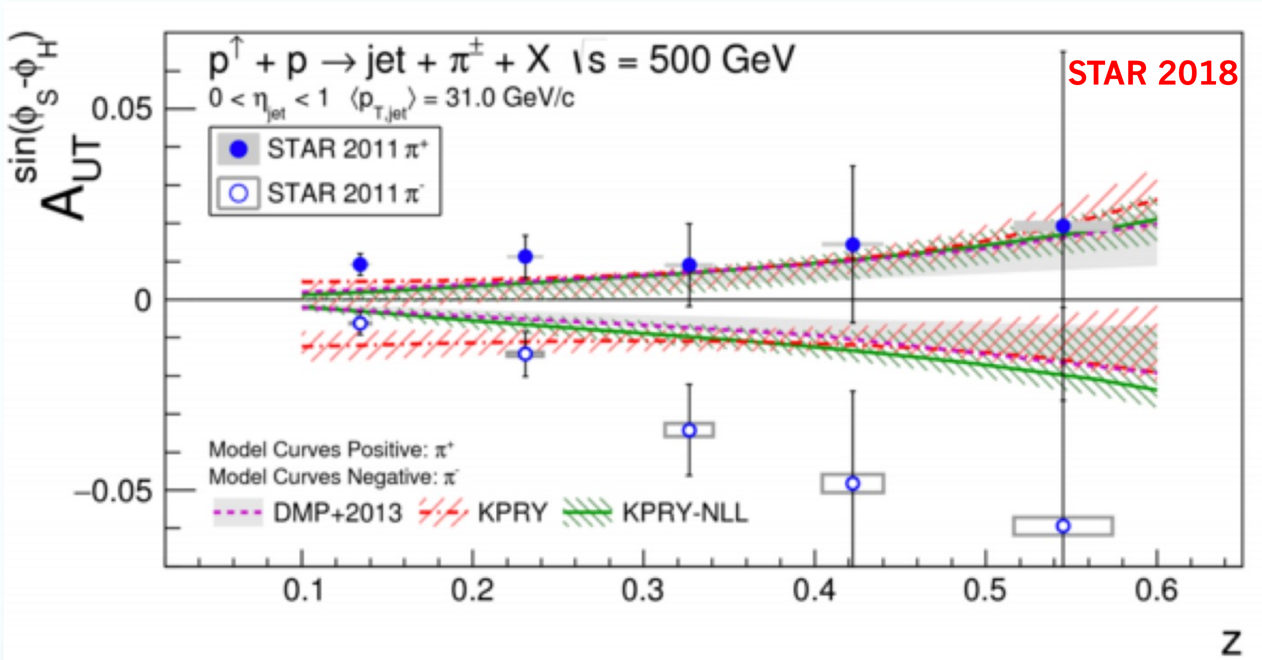


$$\frac{d\sigma}{dp_T d\eta dz_h d^2 j_\perp} \propto \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c^h(z, z_h, p_T R, j_\perp, \mu)$$

$$\mathcal{G}_c^h(z, z_h, p_T R, \boldsymbol{j}_\perp, \mu) = \mathcal{H}_{c\to i}(z, p_T R, \mu) \int d^2\boldsymbol{k}_\perp d^2\boldsymbol{\lambda}_\perp \delta^2\left(z_h \boldsymbol{\lambda}_\perp + \boldsymbol{k}_\perp - \boldsymbol{j}_\perp\right) \times D_{h/i}(z_h, \boldsymbol{k}_\perp, \mu, \nu) S_i(\boldsymbol{\lambda}_\perp, \mu, \nu R)$$

Recent application: Collins asymmetry [inclusive jet]

$$p^{\uparrow}\left[\vec{S}_{\perp}(\phi_S)\right]+p\to[\text{jet}\,h(\phi_H)]+X$$



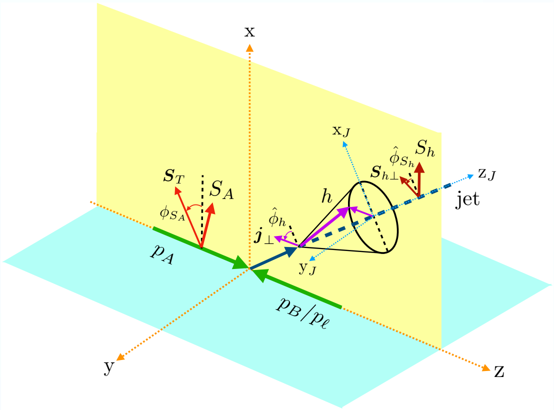
- Only sensitive to collinear transersity distribution
- Universality of Collins function between e+p, e+e, and p+p
- Test TMD evolution

Kang, Prokudin, Ringer, Yuan, 1707.00913

Inclusive jet: polarized jet fragmentation

- In the single inclusive jet production, consider all the possible polarization for both incoming proton and final-state hadron in jet
  - Due to the inclusive nature of jet production, we are sensitive to collinear unpolarized PDFs, or longitudinal/transverse polarized collinear PDFs (helicity/transversity)

Kang, Kyle, Zhao, arXiv:2005.02398



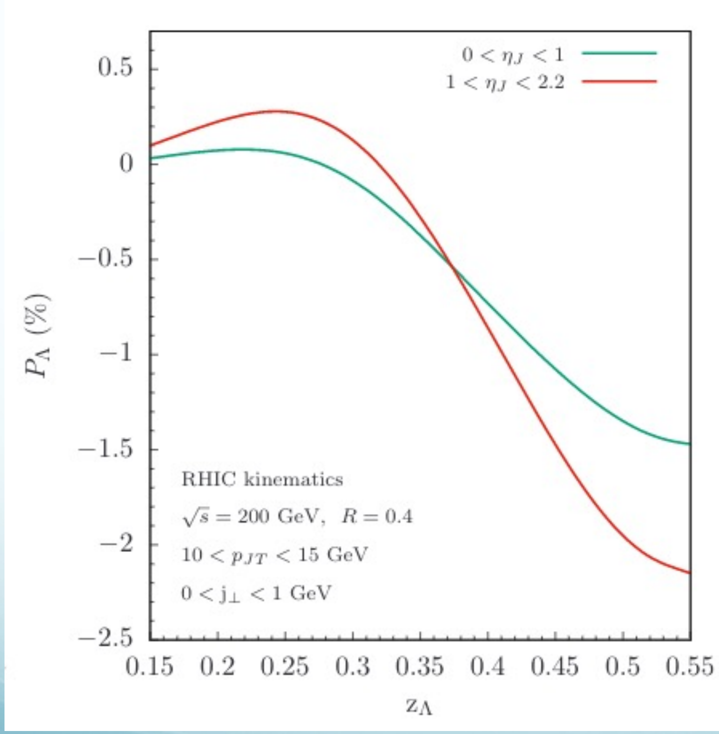
Collins effect

$$\frac{d\sigma^{p(S_A)+p/e\to(\text{jet}\,h(S_h))X}}{dp_{JT}\,d\eta_J\,dz_h\,d^2\boldsymbol{j}_\perp} = F_{UU,U} + |\boldsymbol{S}_T|\sin(\phi_{S_A}-\hat{\phi}_h)F_{TU,U}^{\sin(\phi_{S_A}-\hat{\phi}_h)} + \Lambda_h\left[\lambda F_{LU,L} + |\boldsymbol{S}_T|\cos(\phi_{S_A}-\hat{\phi}_h)F_{TU,L}^{\cos(\phi_{S_A}-\hat{\phi}_h)}\right]$$
$$+ |\boldsymbol{S}_{h\perp}|\Big\{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})F_{UU,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})} + \lambda\cos(\hat{\phi}_h-\hat{\phi}_{S_h})F_{LU,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})}$$
$$+ |\boldsymbol{S}_T|\big(\cos(\phi_{S_A}-\hat{\phi}_{S_h})F_{TU,T}^{\cos(\phi_{S_A}-\hat{\phi}_{S_h})} + \cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_{S_A})F_{TU,T}^{\cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_{S_A})}\big)\Big\}$$

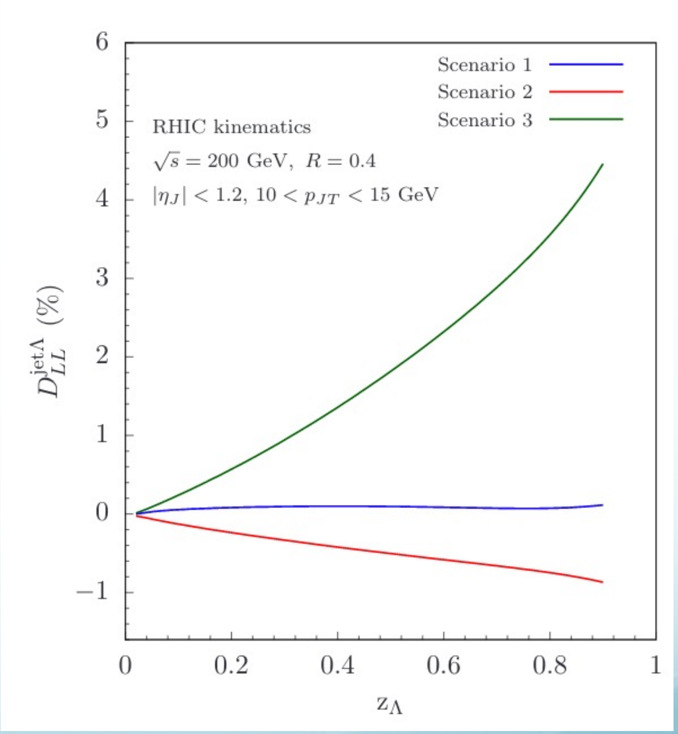
Lambda polarization

Other possible measurements

- Hadron polarization
  - Lambda transverse polarization in unpolarized pp collisions
  - Lambda transverse spin transfer in single transversely polarized pp collisions
    - Recent COMPASS measurement (2021): transversity fragmentation function
  - Longitudinal polarization is also possible



Transverse polarization in unpolarized pp



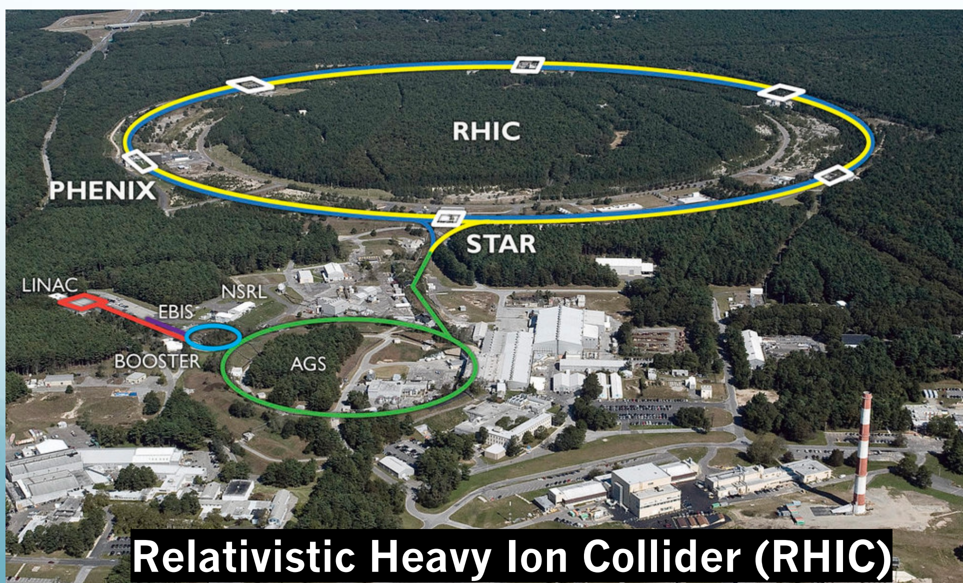
Longitudinal spin transfer

Summary

- Transverse spin has been a very useful tool for 3D imaging of the proton: we have often used hadron

- For 3D imaging, jet observables have become quite promising and provide interesting new opportunities
  - TMDPDF: dijet, photon+jet; TMDFF: jet substructure
  - jet charge, TMD factorization breaking

- It would be great to perform some of these measurements at RHIC, to inform what we would expect for EIC



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