Spin physics of Sivers, Collins, pA, and jets

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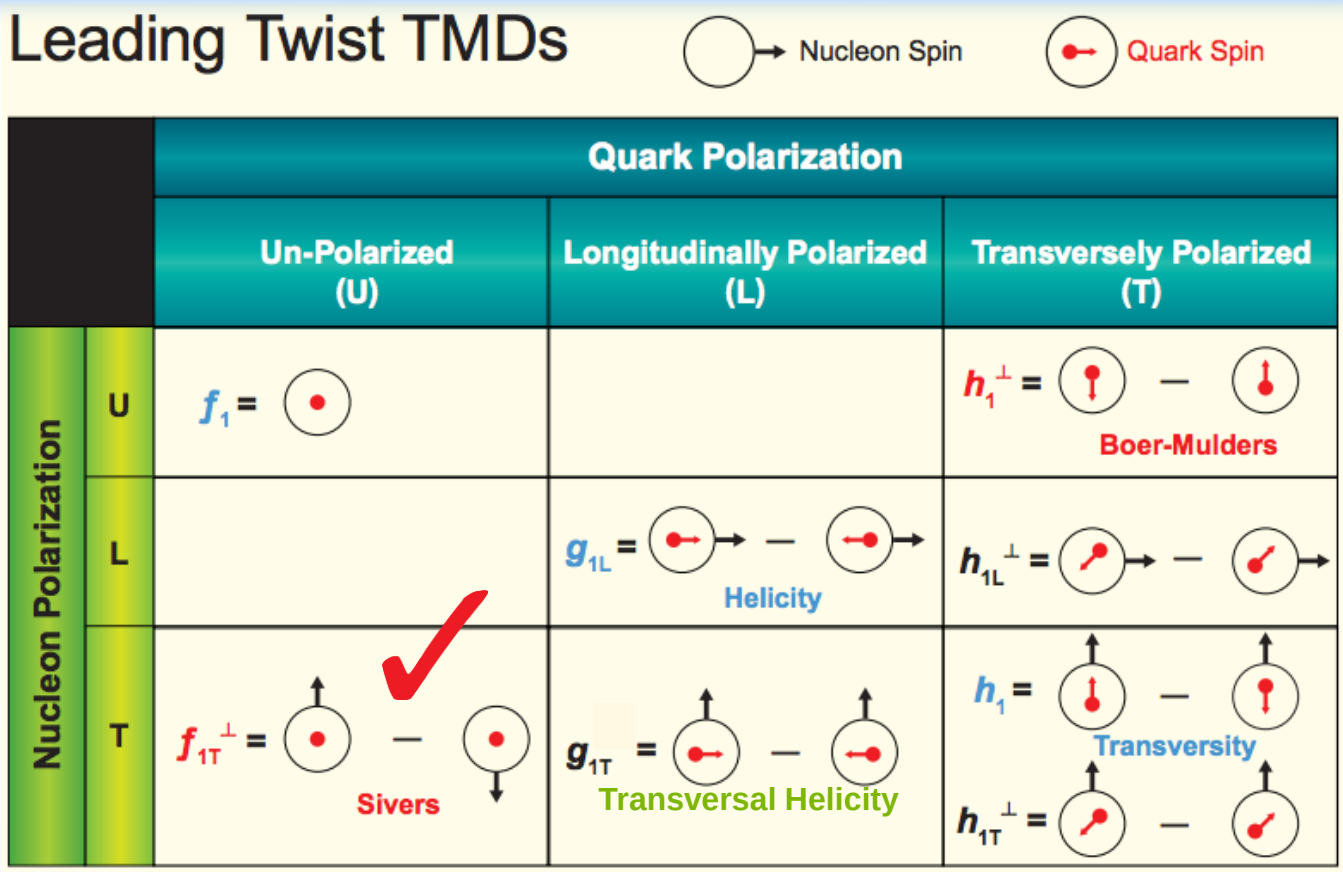
Outline

- TMDs
  - Sivers function is NOT universal: sign change from SIDIS to DY
  - Collins function is universal: same in SIDIS, e+e-, and pp
- A_N in pA
- Jet radius resummation for jet production and A_{LL}
- Summary

TMDs: rich quantum correlations

TMD parton distribution

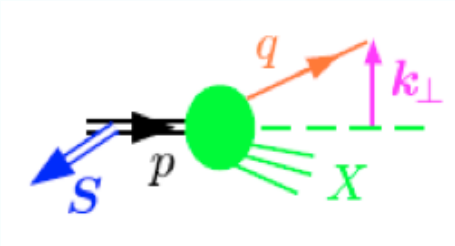


TMD fragmentation function

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

Sivers vs Collins: non-universal vs universal

- Sivers function: unpolarized quark distribution inside a transversely polarized proton

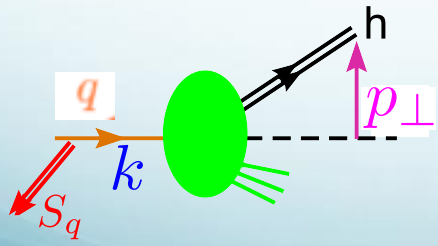


$$f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) \equiv f_{q/h}(x, k_\perp) - \frac{1}{M} f_{1T}^{\perp q}(x, k_\perp)\, \vec{S} \cdot (\hat{p} \times \mathbf{k}_\perp)$$

Spin-independent Spin-dependent

$$f_{1T}^{\perp \mathrm{DIS}}(x, k_\perp) = -f_{1T}^{\perp \mathrm{DY}}(x, k_\perp)$$

- Collins function: unpolarized hadron from a transversely polarized quark



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

$$H_1^{\perp \mathrm{SIDIS}}(z, p_\perp^2) = H_1^{\perp e^+e^-}(z, p_\perp^2) = H_1^{\perp \mathrm{pp}}(z, p_\perp^2)$$

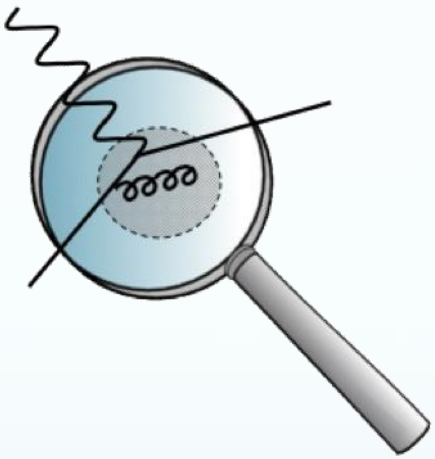
TMD evolves

- Just like collinear PDFs, TMDs also depend on the scale of the probe = evolution

Collinear PDFs

$$F(x, Q)$$

- ✓ DGLAP evolution
- ✓ Resum $\left[\alpha_s \ln(Q^2/\mu^2)\right]^n$
- ✓ Kernel: purely perturbative



TMDs

$$F(x, k_\perp; Q)$$

- ✓ Collins-Soper/rapidity evolution equation
- ✓ Resum $\left[\alpha_s \ln^2(Q^2/k_\perp^2)\right]^n$
- ✓ Kernel: can be non-perturbative when $k_\perp \sim \Lambda_{\rm QCD}$

$$F(x, Q_i)$$
$$\downarrow$$
$$R^{\rm coll}(x, Q_i, Q_f)$$
$$\downarrow$$
$$F(x, Q_f)$$

$$F(x, k_\perp, Q_i)$$
$$\downarrow$$
$$R^{\rm TMD}(x, k_\perp, Q_i, Q_f)$$
$$\downarrow$$
$$F(x, k_\perp, Q_f)$$

TMD evolution in b-space

$$F(x, k_\perp; Q)$$

- We have a TMD above measured at a scale Q. So far the evolution is written down in the Fourier transformed space (convolution → product)

$$F(x, b; Q) = \int d^2 k_\perp e^{-ik_\perp \cdot b} F(x, k_\perp; Q)$$

- In the small b region (1/b >> Λ_{QCD}), one can then compute the evolution to this TMD, which goes like

$$F(x, b; Q_f) = F(x, b; Q_i) \exp\left\{ -\int_{Q_i}^{Q_f} \frac{d\mu}{\mu} \left(A \ln \frac{Q_f^2}{\mu^2} + B \right) \right\} \left(\frac{Q_f^2}{Q_i^2} \right)^{-\int_{c/b}^{Q_i} \frac{d\mu}{\mu} A}$$

$$A = \sum_{n=1} A^{(n)} \left(\frac{\alpha_s}{\pi} \right)^n, \qquad B = \sum_{n=1} B^{(n)} \left(\frac{\alpha_s}{\pi} \right)^n$$

calculable for small b with pQCD

Collins-Sopoer-Sterman papers
Kang, Xiao, Yuan, PRL 11, Echevarria, Idilbi, **Kang**, Vitev, 14, **Kang**, Prokudin, Sun, Yuan, 15, 16,
Aybat, Rogers, Collins, Qiu, 12,
Aybat, Prokudin, Rogers, 12, Sun, Yuan, 13, Echevarria, Idilbi, Schafer, Scimemi, 13, …

TMD evolution contains non-perturbative component

- Fourier transform back to the momentum space, one needs the whole b region (large b): need some non-perturbative extrapolation
  - Many different methods/proposals to model this non-perturbative part

$$F(x,k_\perp;Q) = \frac{1}{(2\pi)^2}\int d^2b e^{ik_\perp\cdot b}F(x,b;Q) = \frac{1}{2\pi}\int_0^\infty db\, b J_0(k_\perp b)F(x,b;Q)$$

- Eventually evolved TMDs in b-space

$$F(x,b;Q) \approx C\otimes F(x,c/b^*) \times \exp\left\{-\int_{c/b^*}^{Q}\frac{d\mu}{\mu}\left(A\ln\frac{Q^2}{\mu^2}+B\right)\right\} \times \exp\left(-S_{\text{non-pert}}(b,Q)\right)$$

longitudinal/collinear part

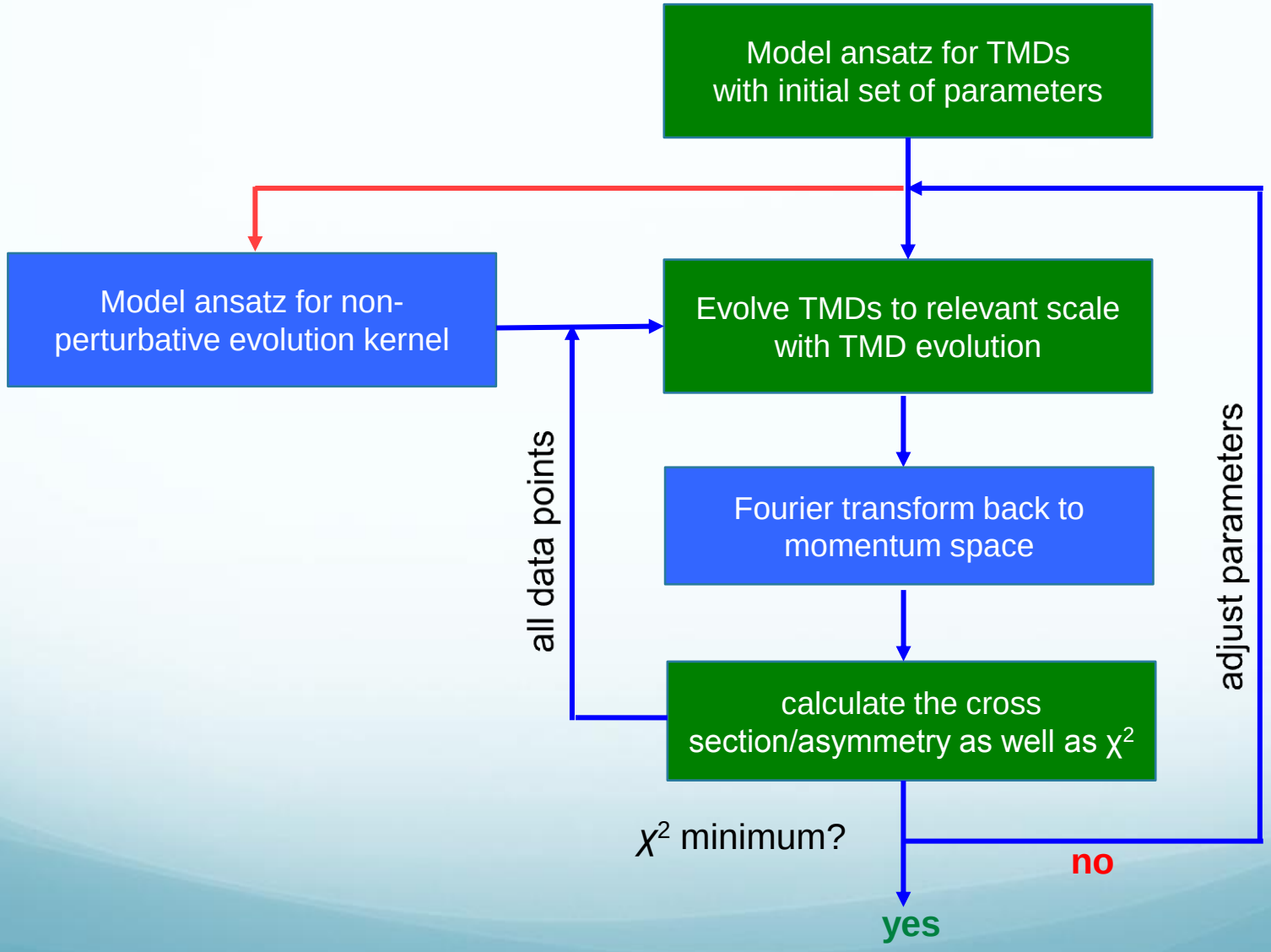
transverse part

- ✓ Non-perturbative: fitted from data
- ✓ The key ingredient – ln(Q) piece is spin-independent

Since the polarized scattering data is still limited kinematics, we can use unpolarized data to constrain/extract the key ingredient for the non-perturbative part

TMD global analysis

- Outline of a TMD global analysis: numerically more heavy



Very active field

- Available fits for unpolarized TMDs

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	NLL	✘	✘	✔	✔	98
Pavia 2013 (+Amsterdam,Bilbao) arXiv:1309.3507	No evo	✔	✘	✘	✘	1538
Torino 2014 (+JLab) arXiv:1312.6261	No evo	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NNLL	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	NLL	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
Pavia 2016	NLL	✔	✔	✔	✔	8156

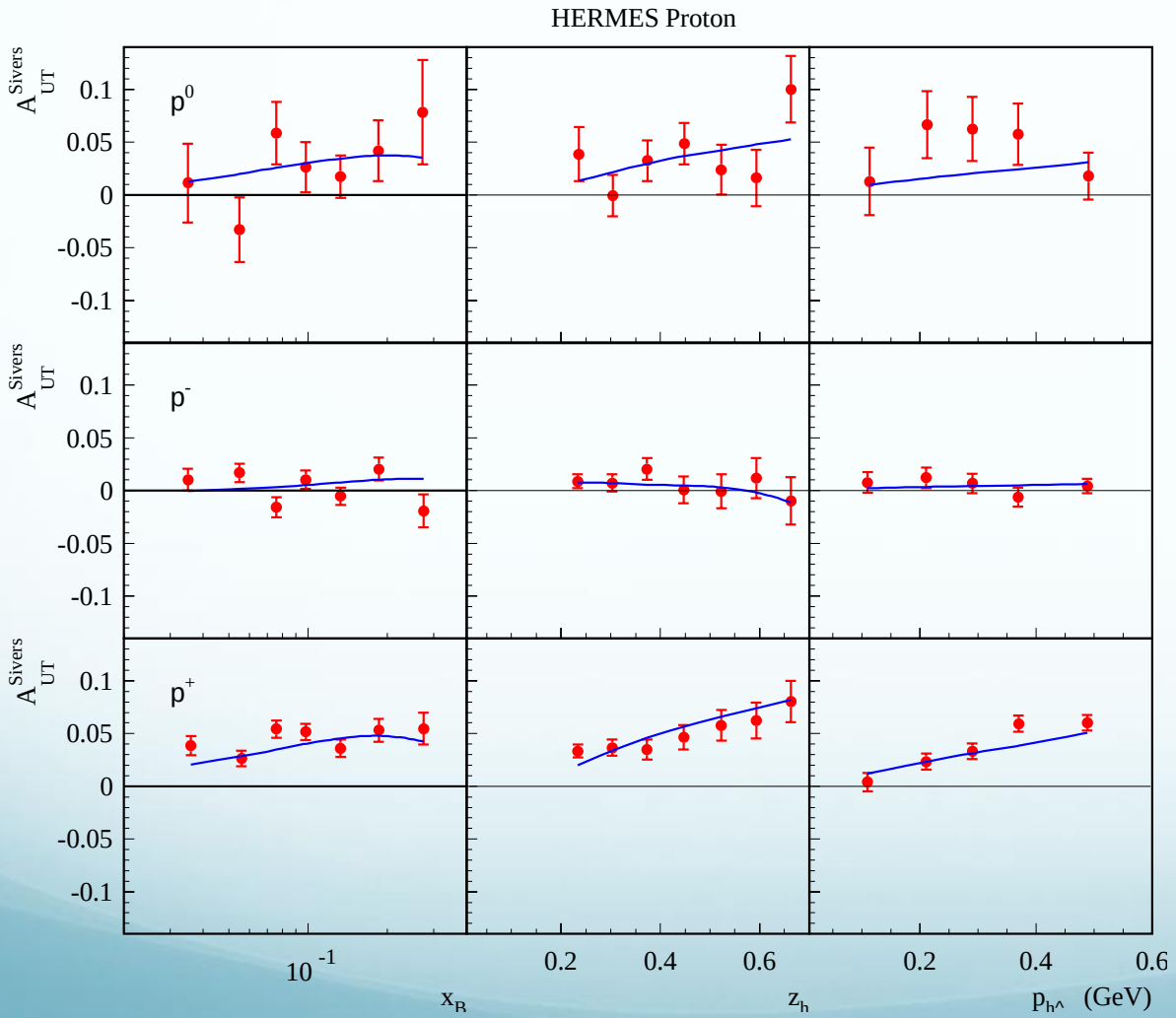
- Similar for polarized TMDs

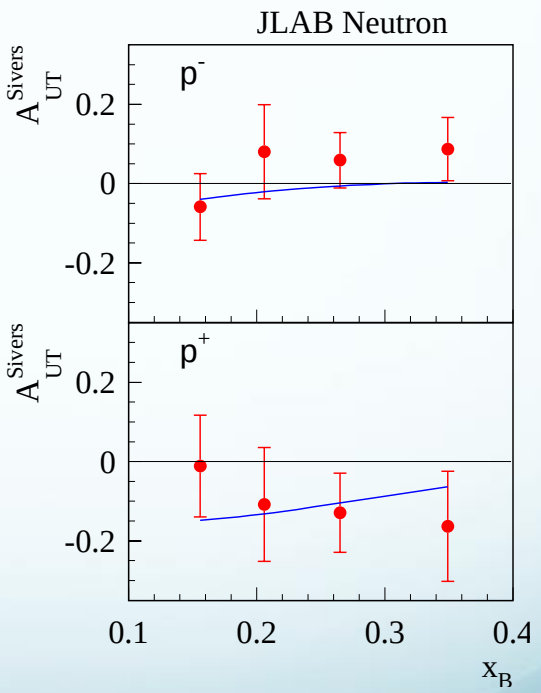
Bacchetta, QCD Evolution 2016

Example: Sivers function

- Example of the fit: JLab, HERMES, COMPASS

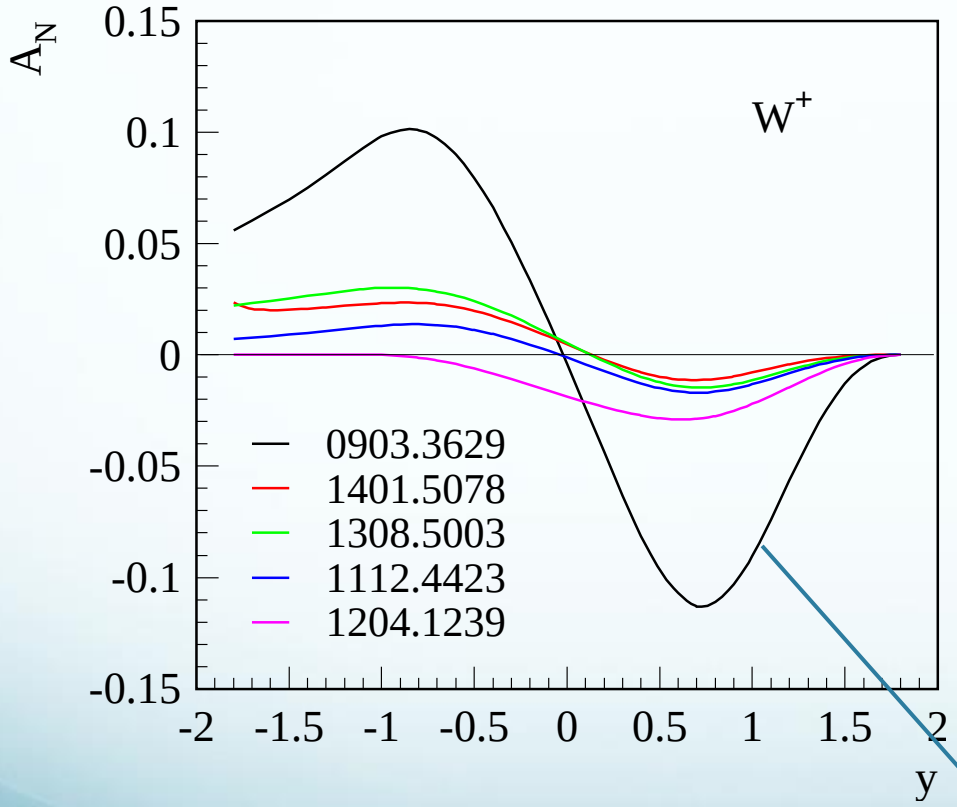
Echevarria, Idilbi, Kang, Vitev, 14



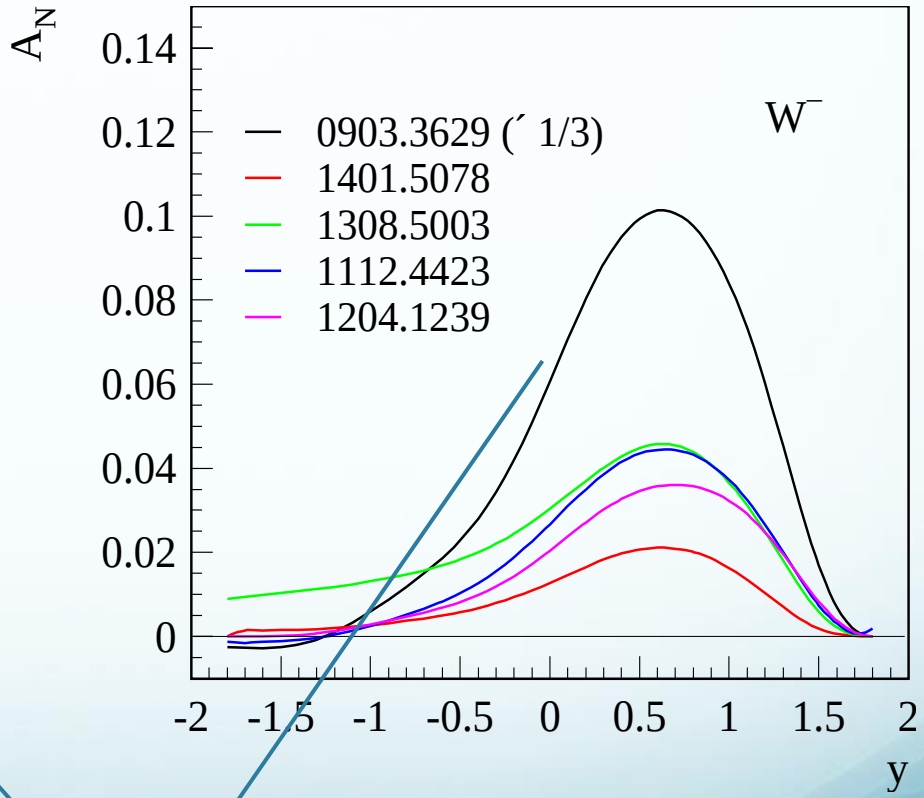


Uncertainty in the evolution formalism

- Even the evolution formalism itself has large room to improve – non-perturbative Sudakov needs further improvement



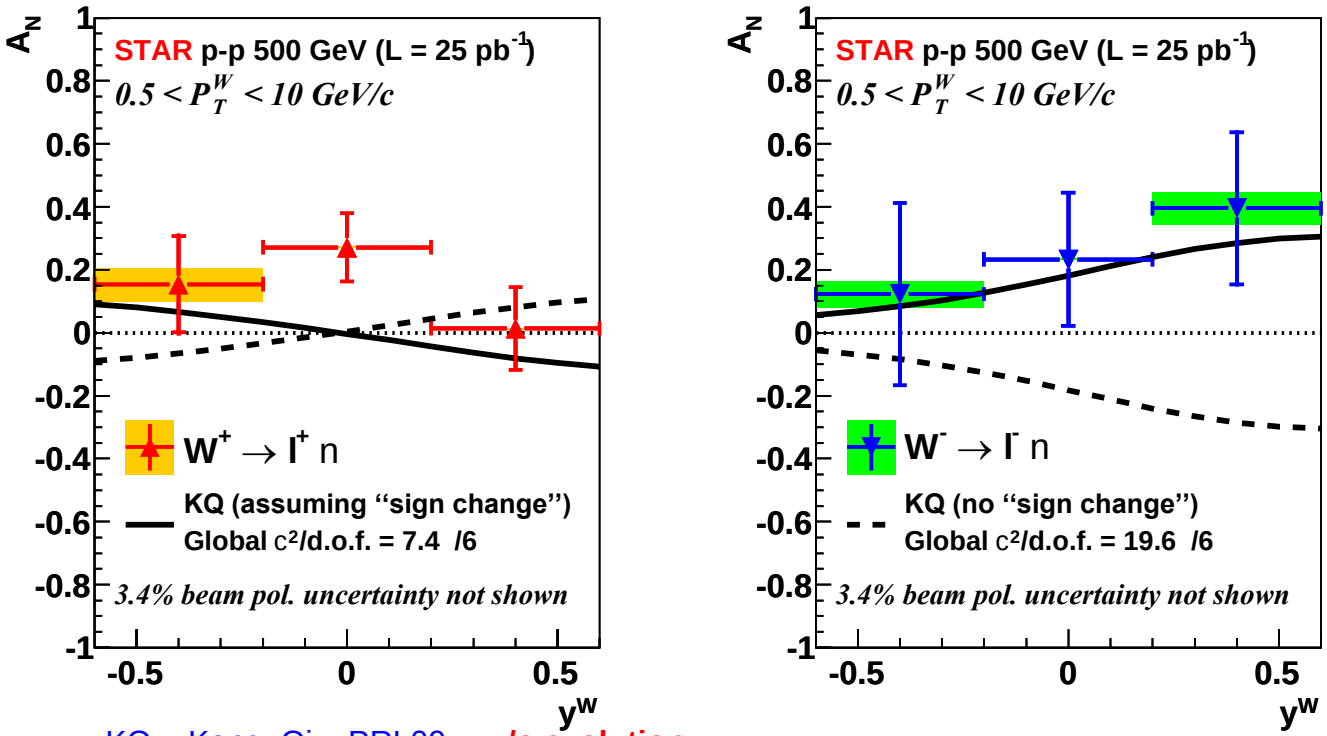
Kang, 2015



w/o TMD evolution

Experimental evidence of sign change

- STAR measurements: the data favors sign change
- Both theory and experiment has large uncertainty: hope to be improved in the near future (2017 run)

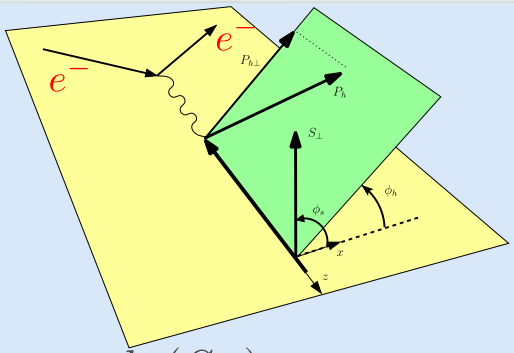


KQ = Kang, Qiu, PRL09 – **w/o evolution**

STAR, PRL 16, arXiv:1511.06003

Collins asymmetry from SIDIS and e+e-

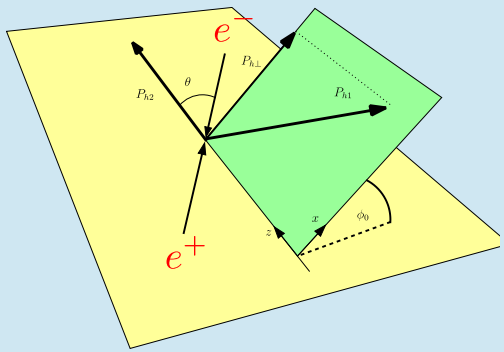
- SIDIS and e+e-: combined global analysis



$$F_{UT}^{\sin(\phi_h+\phi_s)} \sim h_1(x_B, k_\perp) H_1^\perp(z_h, p_\perp)$$

transversity Collins function

$$\frac{d\sigma(S_\perp)}{dx_B dy dz_h d^2 P_{h\perp}} = \sigma_0(x_B, y, Q^2) \left[F_{UU} + \sin(\phi_h + \phi_s) \frac{2(1-y)}{1+(1-y)^2} F_{UT}^{\sin(\phi_h+\phi_s)} + \ldots \right]$$



$$Z_{\text{collins}}^{h_1 h_2} \sim H_1^\perp(z_1, p_{1\perp}) H_1^\perp(z_2, p_{2\perp})$$

Collins function

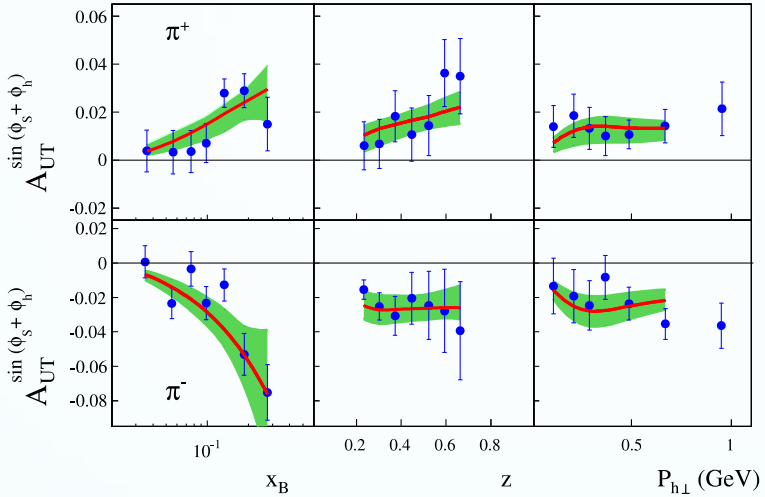
$$\frac{d\sigma^{e^+e^- \to h_1 h_2 + X}}{dz_{h1} dz_{h2} d^2 P_{h\perp} d\cos\theta} = \frac{N_c \pi \alpha_{\text{em}}^2}{2Q^2} \left[\left(1 + \cos^2\theta\right) Z_{uu}^{h_1 h_2} + \sin^2\theta \cos(2\phi_0) Z_{\text{collins}}^{h_1 h_2} \right]$$

Collins asymmetry: global analysis

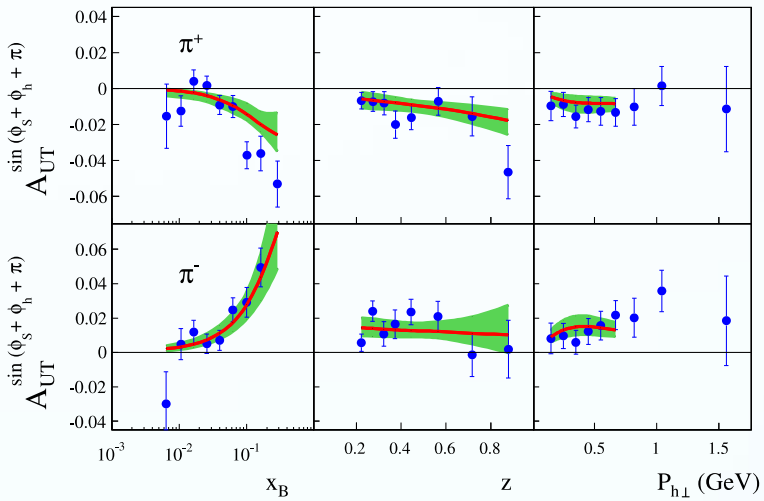
- Fitting of SIDIS data

Kang, Prokudin, Sun, Yuan, PRD 15 & 16

HERMES

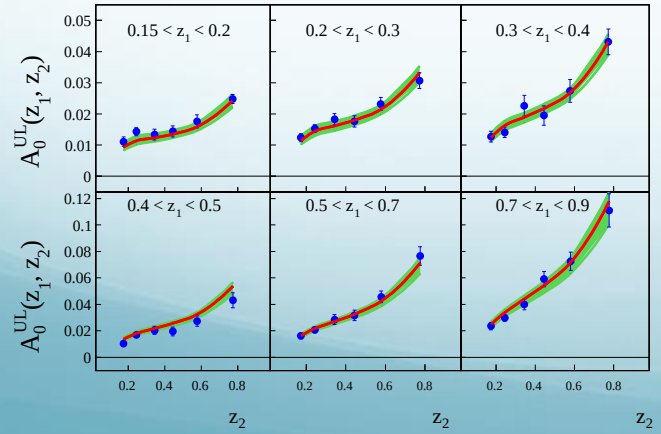


COMPASS

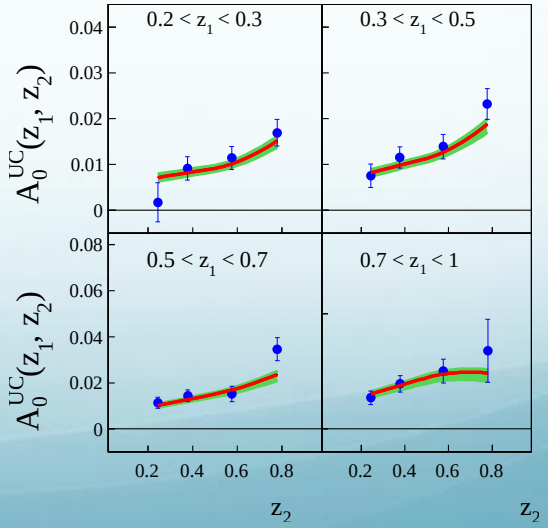


- Fitting of e+e- data

BaBar

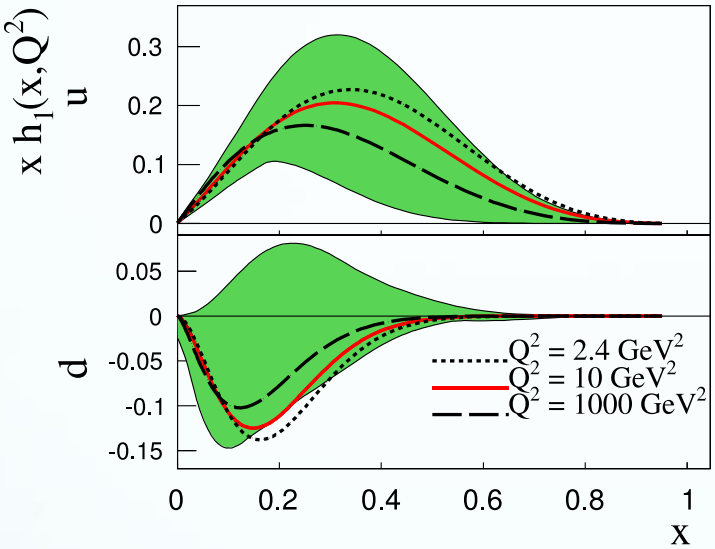


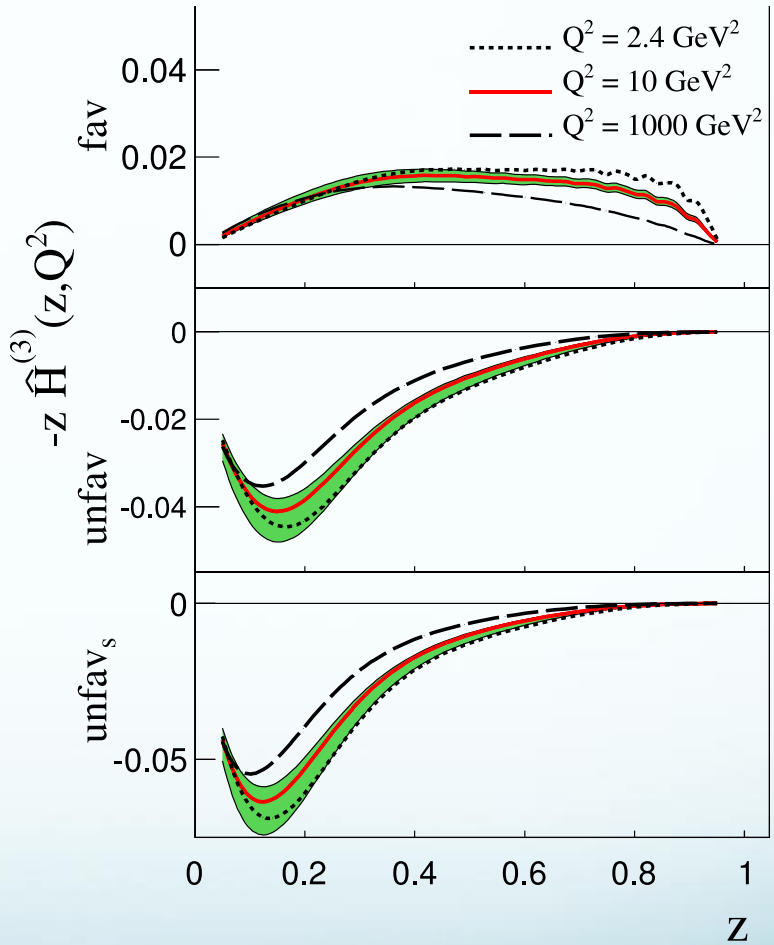
Belle



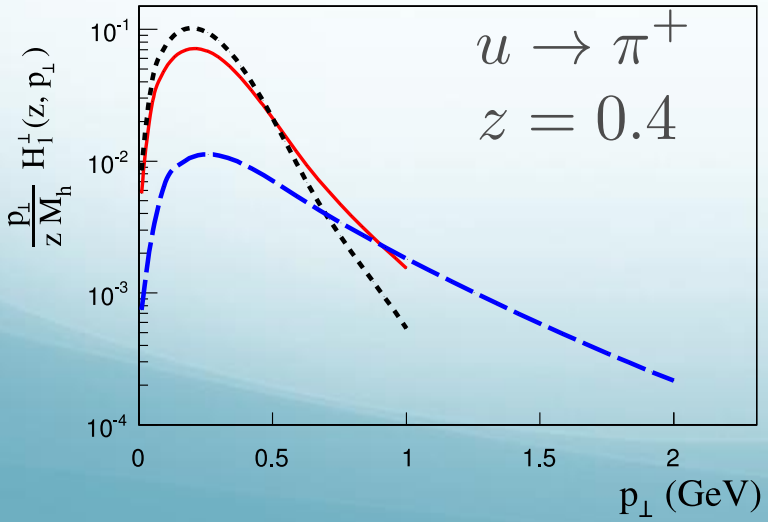
Fitted TMDs

- Fitted quark transversity and Collins function: x (z) -dependence





- Collins function: pt-dependence



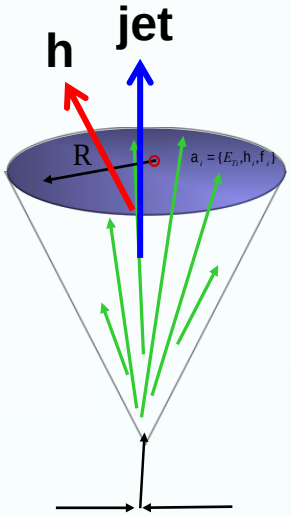
$\text{fav}: \quad u \to \pi^+$

$\text{unfav}: \quad d \to \pi^+$

$\text{unfav}_s: \quad s \to \pi$

Collins asymmetry in p+p

- Collins asymmetry can also be studied through the azimuthal distribution of hadrons inside a jet in p+p collisions



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

$$\frac{d\sigma}{dy d^2 p_{\perp}^{\text{jet}} dz d^2 j_T} = F_{UU} + \sin(\phi_S - \phi_H) F_{UT}^{\sin(\phi_S - \phi_H)}$$

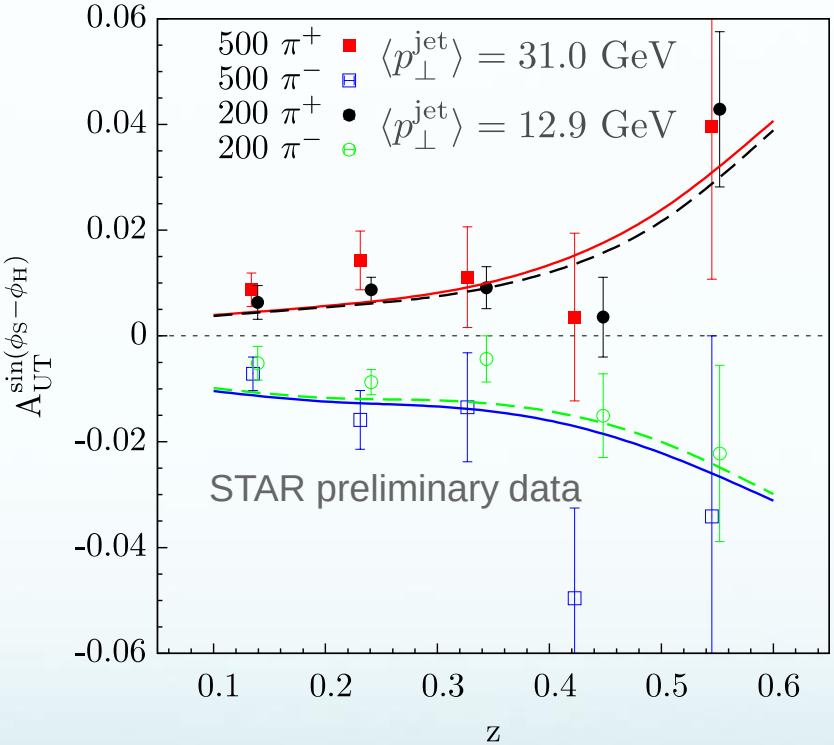
$$F_{UT}^{\sin(\phi_S-\phi_H)} \propto h_1^a(x_1) \otimes f_{b/B}(x_2) \otimes \frac{j_T}{zM_h} H_1^{\perp c}(z, j_T^2) \otimes H_{ab\to c}^{\text{Collins}}(\hat{s}, \hat{t}, \hat{u})$$

j_T : hadron transverse momentum with respect to the jet direction

- Such an asymmetry has been measured by STAR at RHIC
  - Could be used to test the universality of the Collins functions

Hadron azimuthal distribution in a jet

- Indicate the universality of the Collins function in pp collisions
- w/o TMD evolution

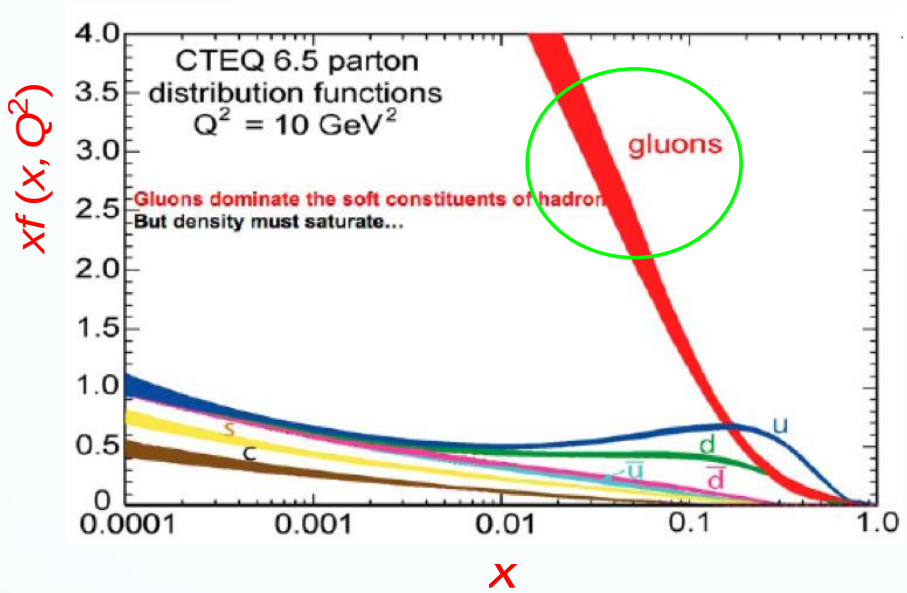


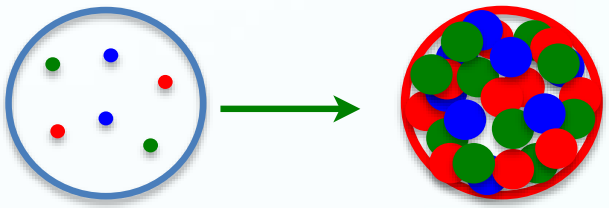
Kang, Prokudin, Ringer, Sun, Yuan, 16, in preparation

Collins function from a Gaussian fit: Anselmino, et.al., arXiv: 1510.05389

Single spin asymmetry in p+A collisions

- Parton density increases dramatically in forward pA collisions





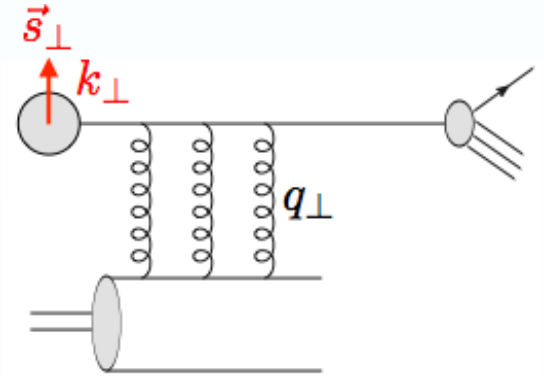
- If one shoots a transversely polarized proton to such a dense system (heavy nucleus in high energy), what happens?
  - Saturation scale Q_s = typical k_T for partons in the dense system

Kang, Yuan, 2011

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{p_T \ll Q_s} \approx \frac{Q_{sp}^2}{Q_{sA}^2} \qquad \left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{p_T \gg Q_s} = 1$$

Reasoning behind

- kt-odd TMDs pick up the slope of unintegrated gluon distribution from the nucleus, which is controlled by saturation scale



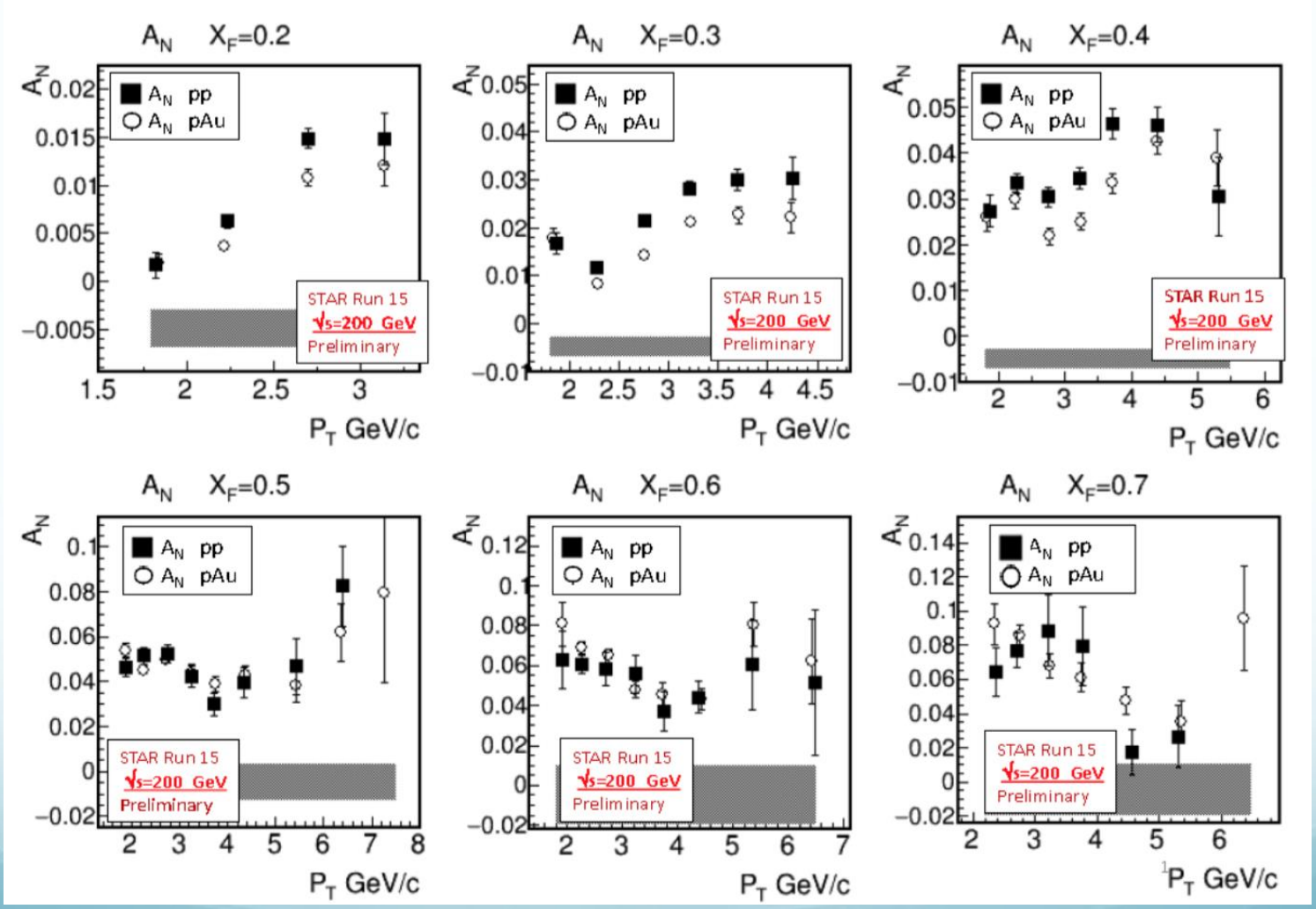
$$p_\perp = z\,(k_\perp + q_\perp)$$

$$\frac{d\sigma}{dy d^2 p_\perp} = \frac{K}{(2\pi)^2} \int d^2 b \int_{x_F}^{1} \frac{dz}{z^2} \int d^2 k_\perp x \epsilon^{\alpha\beta} s_\perp^\alpha k_\perp^\beta f_{1T}^{\perp,q}(x, k_\perp^2) F(x_A, q_\perp = p_\perp/z - k_\perp) D_{h/q}(z)$$

- Similar to the final-state Collins function

Recent STAR measurements

- No apparent suppression from pp to pA



What could be the reasons?

- Two possibilities
  - The mechanisms (e.g. Sivers/Collins) to generate the SSAs could be completely wrong, maybe other mechanism such as diffractions Aschenauer, 2016
  - We are not yet at the saturation region

- We will need more data to pin down the mechanisms, right now let us not give up our current understanding/pQCD formalism yet
  - If we are not in the saturation region, then to describe the single hadron SSAs, we use the collinear twist-3 formalism
  - The only change from pp to pA will be simply the proton PDFs to nuclear PDFs

$$A_N = \frac{\sigma_{UT}^{\text{Sivers}} + \sigma_{UT}^{\text{Collins}}}{\sigma_{UU}}$$

$$f_{b/B}(x') \to f_{b/B}(x')|_{\text{nucleus}}$$

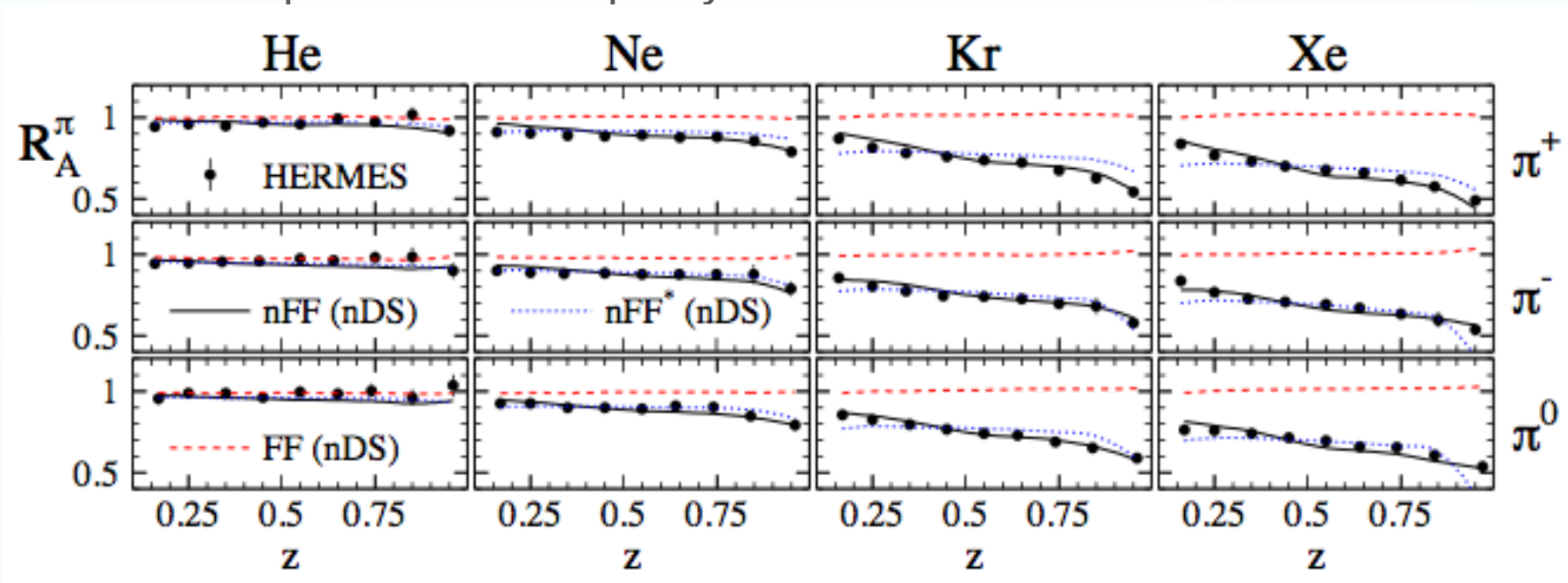
$$\sigma_{UT}^{\text{Sivers}} = T_{a,F}(x,x) \otimes f_{b/B}(x') \otimes H_{ab\to c}^{\text{Siv}} \otimes D_c^h(z)$$

$$\sigma_{UT}^{\text{Collins}} = f_{a/A}(x) \otimes f_{b/B}(x') \otimes H_{ab\to c}^{\text{Col}} \otimes D_c^{(3)}(z)$$

$$\sigma_{UU} = f_{a/A}(x,x) \otimes f_{b/B}(x') \otimes H_{ab\to c} \otimes D_c^h(z)$$

We know already the ratio not change much

- For example: SIDIS multiplicity distribution

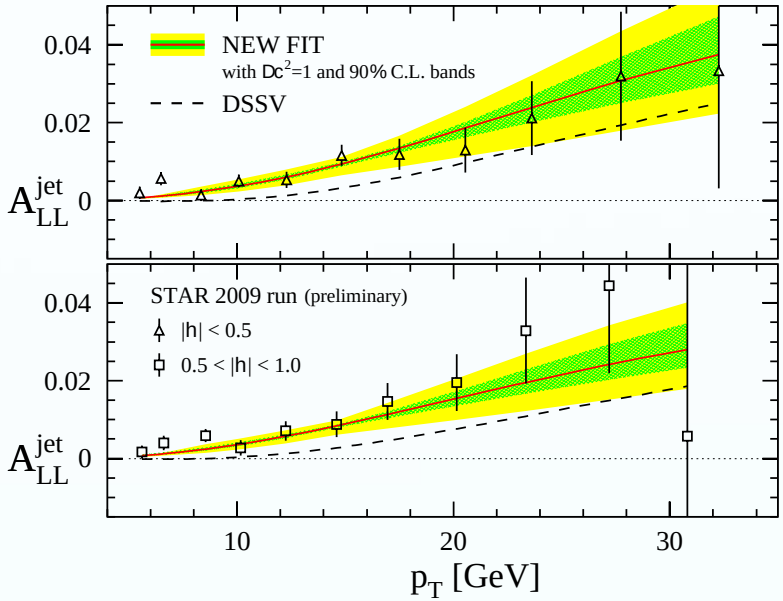


$$R_A^H(\nu, Q^2, z, p_T^2) = \frac{\left(\frac{N^H(\nu,Q^2,z,p_T^2)}{N^e(\nu,Q^2)}\right)_A}{\left(\frac{N^H(\nu,Q^2,z,p_T^2)}{N^e(\nu,Q^2)}\right)_d}$$

- The change from nuclear PDFs is very small

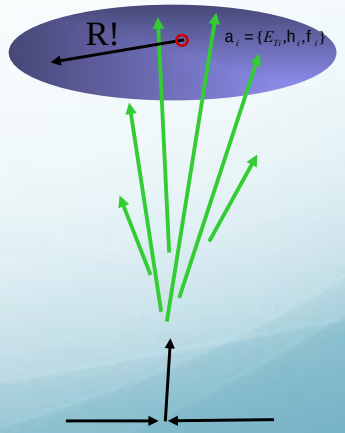
Jet A_{LL} is important in constraining $\Delta g(x)$

- Jet A_{LL} is important



- Jet is defined through a jet radius R
  - When R is small, it leads to large logarithms of

$$[\alpha_s \ln(R)]^n \quad \text{or} \quad [\alpha_s \ln^2(R)]^n$$



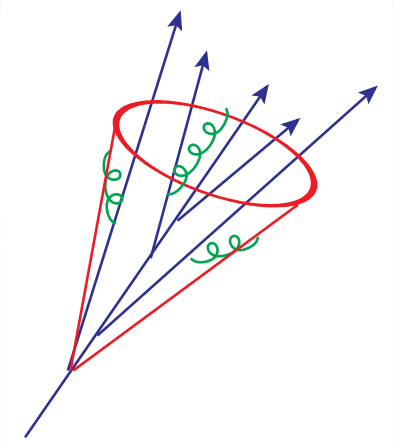
New development

- Semi-inclusive jet function $J_c(z, \omega_J, \mu)$

$$z = \frac{\omega_J}{\omega}$$

$$\omega_J = \text{jet energy}$$

$$\omega = \text{parton energy initializing the jet}$$



- Purely perturbative calculable, follows DGLAP evolution equation

$$\mu \frac{d}{d\mu} J_i(z, \omega_J, \mu) = \frac{\alpha_s(\mu)}{\pi} \sum_j \int_z^1 \frac{dz'}{z'} P_{ji}\left(\frac{z}{z'}, \mu\right) J_j(z', \omega_J, \mu)$$

more details, see, Ringer's talk at QCD evolution 2016

- Natural scale for jet function: pT*R
  - Evolve from this scale to the hard interaction scale pT, one resums the log(R)

Kang, Ringer, Vitev, 2016, to appear

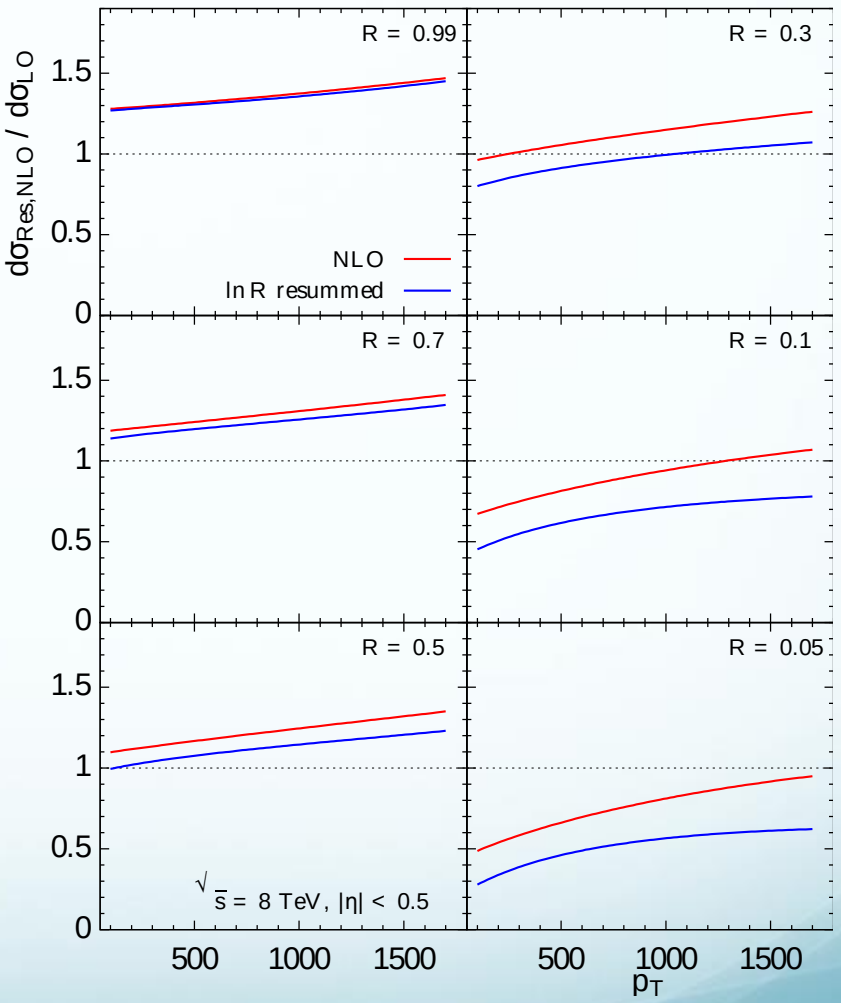
Nice properties using jet function

- The short-distance hard functions are the same for single hadron/jet production

$$\frac{d\sigma^h}{dy dp_T} \sim \sum_{c=q,g} \int \frac{dz_c}{z_c} H_{ab\to c}(\hat{p},\mu)\, D_c^h(z_c,\mu),$$

$$\frac{d\sigma^{\rm jet}}{dy dp_T} \sim \sum_{c=q,g} \int \frac{dz_c}{z_c} H_{ab\to c}(\hat{p},\mu)\, J_c(z_c,\omega_J,\mu),$$

- Effect for jet production in unpolarized pp
- Stay tuned for polarized pp and A_{LL} effect



Summary

- Study on TMDs are extremely active in the past few years, lots of progress have been made
- A_N for hadron seems still puzzling, not give up pQCD framework yet
- New development on jet radius resummation might affect our analysis of Δg

Thank you!