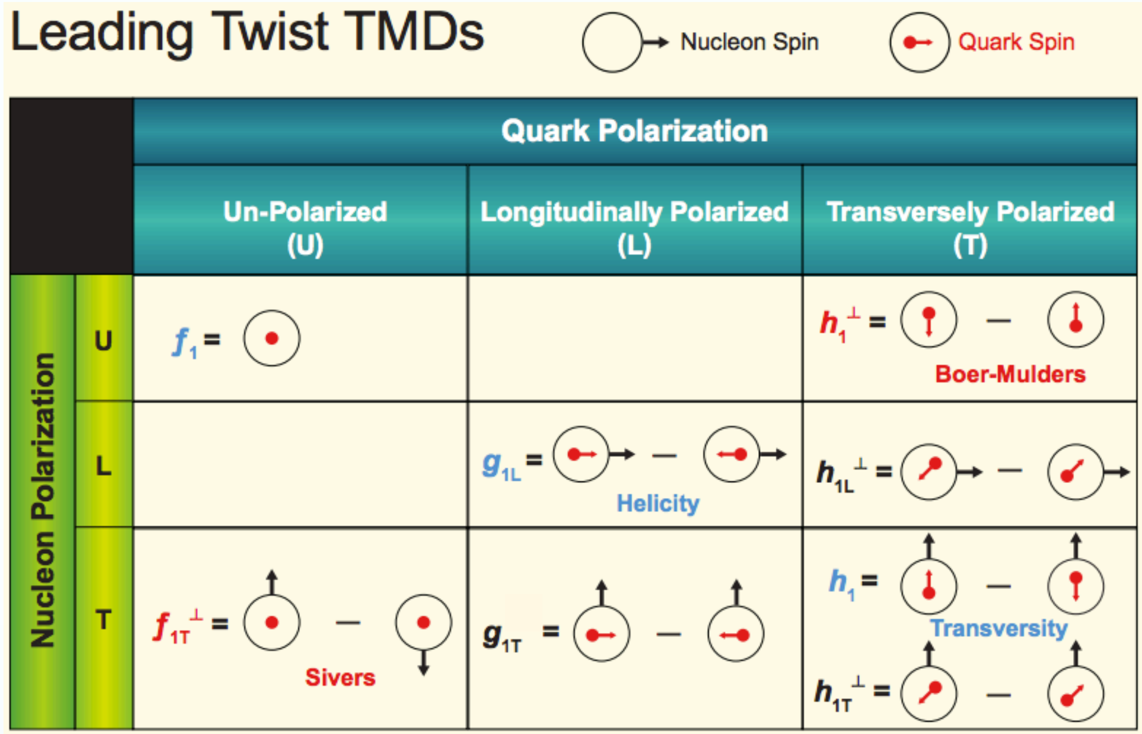
# Phenomenological extractions of TMDs: progress and new opportunities

Zhongbo Kang
UCLA

EIC User Group Meeting 2017
Trieste, Italy
July 18–22, 2017

# TMDs: rich quantum correlations

TMD PDFs

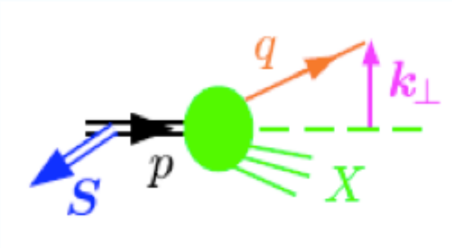



TMD FFs

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

# Besides unpolarized TMDs: Sivers and Collins

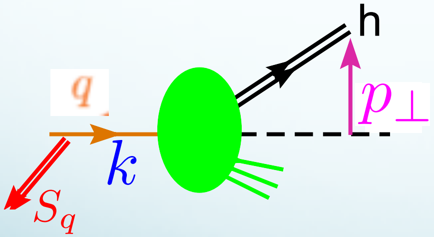
- Sivers function: non-universal




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

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

- Collins function: universal

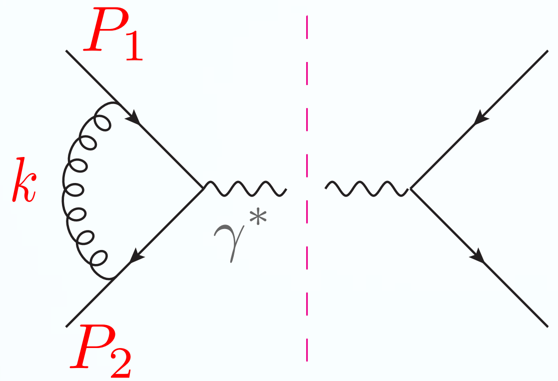



$$D_{h/q}(z, p_\perp) = D_1^q(z, p_\perp^2) + \frac{1}{z M_h} H_1^{\perp q}(z, p_\perp^2) \vec{S}_q \cdot \left(\hat{k} \times p_\perp\right)$$

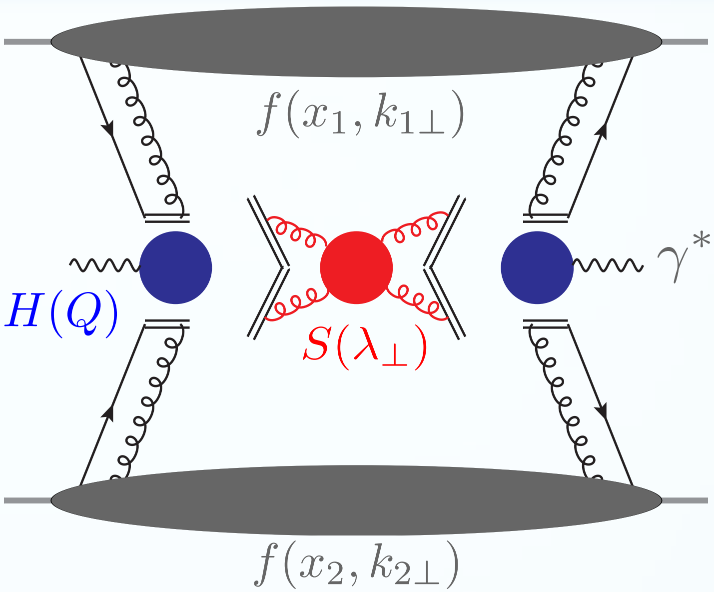
$$H_1^{\perp \mathrm{SIDIS}}(z, p_\perp^2) = H_1^{\perp e^+ e^-}(z, p_\perp^2) = H_1^{\perp \mathrm{pp}}(z, p_\perp^2)$$

# TMD factorization in a nut-shell

- Drell-Yan: $p + p \to [\gamma^* \to \ell^+\ell^-] + X$




Factorization of regions:
(1) $k // P_1$, (2) $k // P_2$, (3) k soft, (4) k hard




- Factorized form and mimic "parton model"

$$\frac{d\sigma}{dQ^2 dy d^2 q_\perp} \propto \int d^2k_{1\perp}\, d^2k_{2\perp}\, d^2\lambda_\perp H(Q) f(x_1, k_{1\perp}) f(x_2, k_{2\perp}) S(\lambda_\perp) \delta^2(k_{1\perp} + k_{2\perp} + \lambda_\perp - q_\perp)$$

$$= \int \frac{d^2b}{(2\pi)^2} e^{iq_\perp \cdot b} H(Q) f(x_1, b) f(x_2, b) S(b)$$

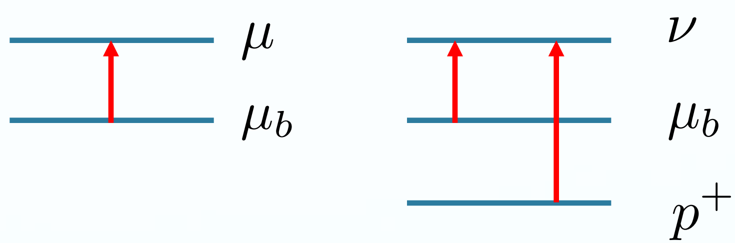
$$F(x, b) = f(x, b)\sqrt{S(b)}$$

$$= \int \frac{d^2b}{(2\pi)^2} e^{iq_\perp \cdot b} H(Q) F(x_1, b) F(x_2, b)$$

mimic "parton model"

# TMD evolution in b-space

- TMDs contain collinear and rapidity divergences: two evolutions




- The well-known Collins-Soper-Sterman (CSS) solution

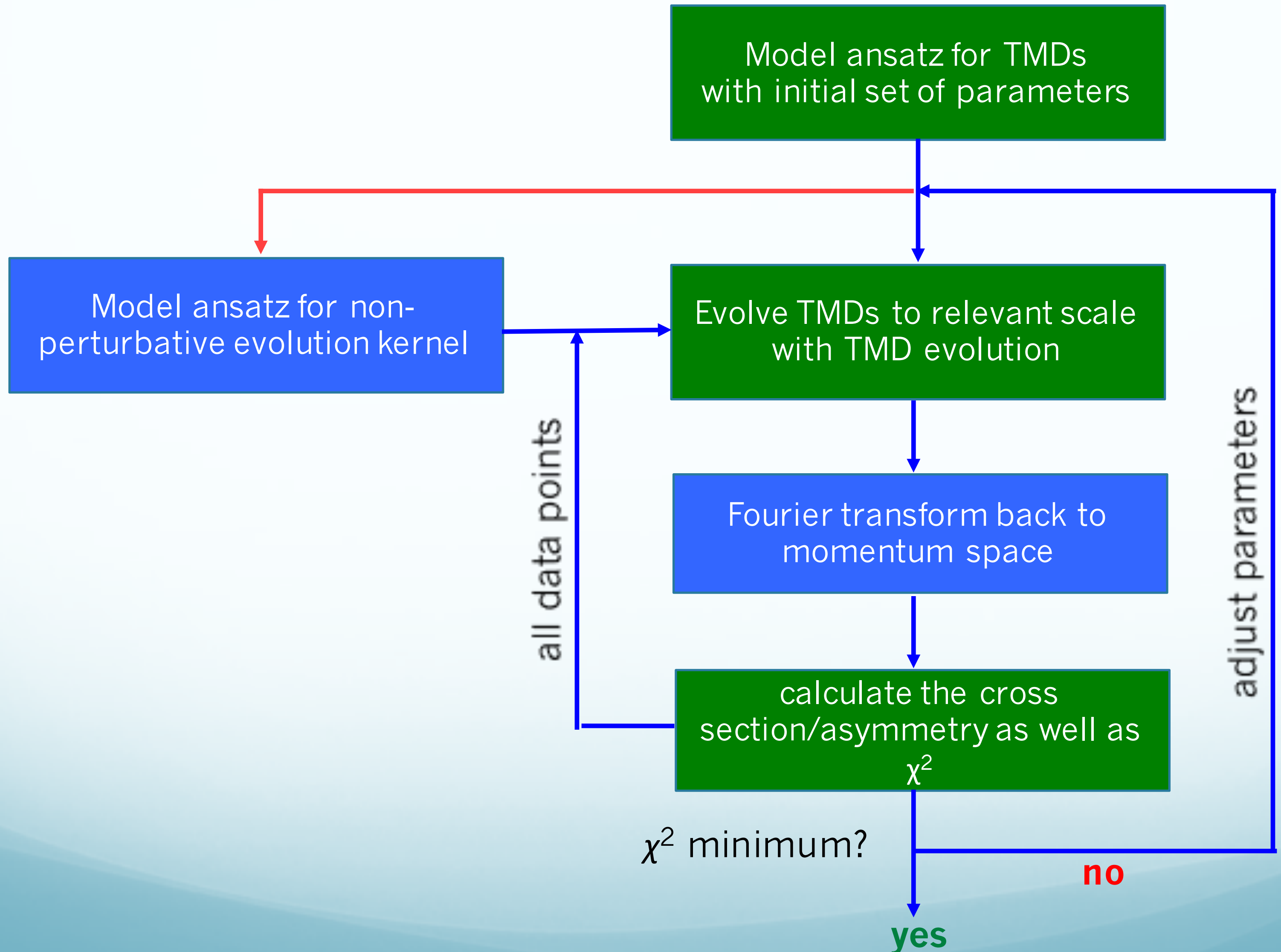
$$F(x,b;Q_f) = F(x,b;Q_i)\exp\left\{-\int_{Q_i}^{Q_f}\frac{d\mu}{\mu}\left(A\ln\frac{Q_f^2}{\mu^2}+B\right)\right\}\left(\frac{Q_f^2}{Q_i^2}\right)^{-\int_{c/b}^{Q_i}\frac{d\mu}{\mu}A}$$

- TMD evolution contains non-perturbative contributions

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

# TMD global analysis

- Outline of a TMD global analysis: numerically more heavy



# Different fits to date: unpolarized quark TMDs

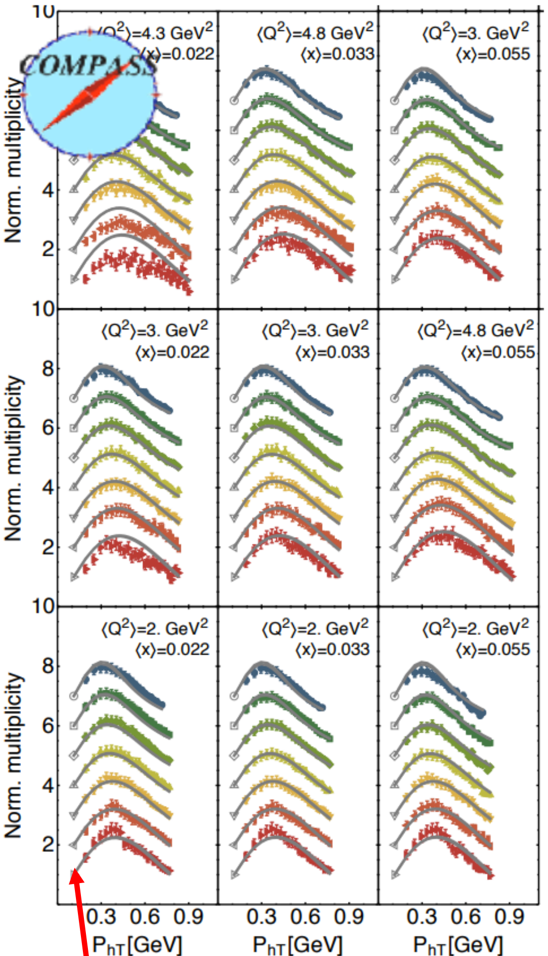
| | Framework | HERMES | COMPASS | DY | Z production | N of points |
|---|---|---|---|---|---|---|
| KN 2006 hep-ph/0506225 | NLL/NLO | ✘ | ✘ | ✔ | ✔ | 98 |
| Pavia 2013 arXiv:1309.3507 | No evo | ✔ | ✘ | ✘ | ✘ | 1538 |
| Torino 2014 arXiv:1312.6261 | No evo | ✔ (separately) | ✔ (separately) | ✘ | ✘ | 576 (H) 6284 (C) |
| DEMS 2014 arXiv:1407.3311 | NNLL/NLO | ✘ | ✘ | ✔ | ✔ | 223 |
| EIKV 2014 arXiv:1401.5078 | NLL/LO | 1 (x,Q$^2$) bin | 1 (x,Q$^2$) bin | ✔ | ✔ | 500 (?) |
| Pavia 2016 arXiv:1703.10157 | NLL/LO | ✔ | ✔ | ✔ | ✔ | 8059 |
| SV 2017 arXiv:1706.01473 | NNLL/ NNLO | ✘ | ✘ | ✔ | ✔ | 309 |

Taken from Bacchetta, Wednesday

- ✓ It is easier to fit either SIDIS or DY, but quite difficult to fit both
- ✓ Pavia group tried very hard, to fit both SIDIS and DY

# New fit: Pavia group

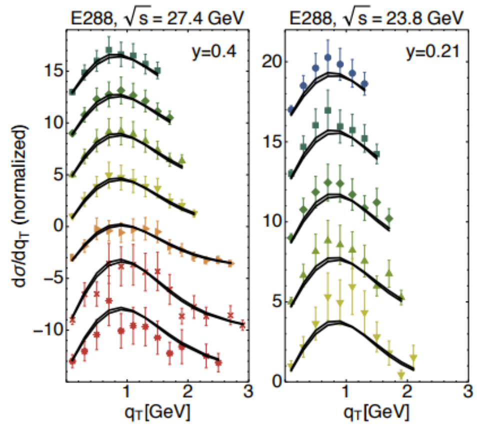
## SIDIS




First points are not fitted, but used as normalization to avoid problems related to data normalization

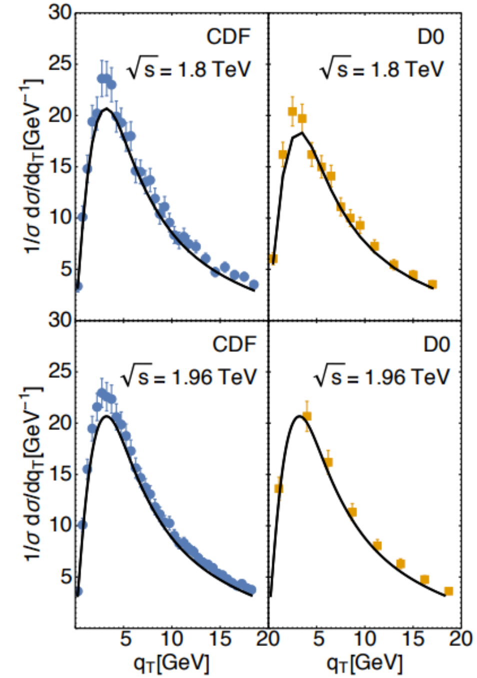
## Drell-Yan

Fermilab




Taken from Bacchetta, Wednesday

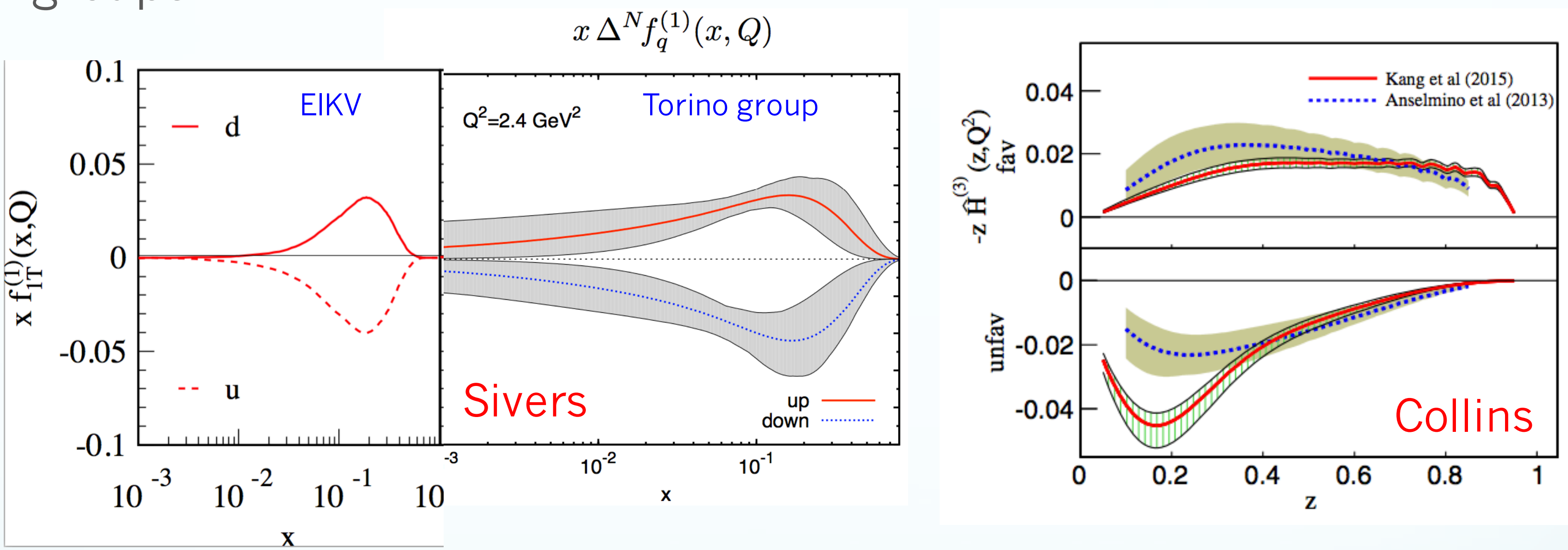
## Z production




- Is this really an experimental issue, or theoretical issue (e.g., power corrections at low Q)?
- It would be great that COMPASS releases the updated data

# Sivers and Collins extraction: Status

- Within the region constrained by the experimental data, the spin-dependent TMDs seem to be rather consistent among different groups

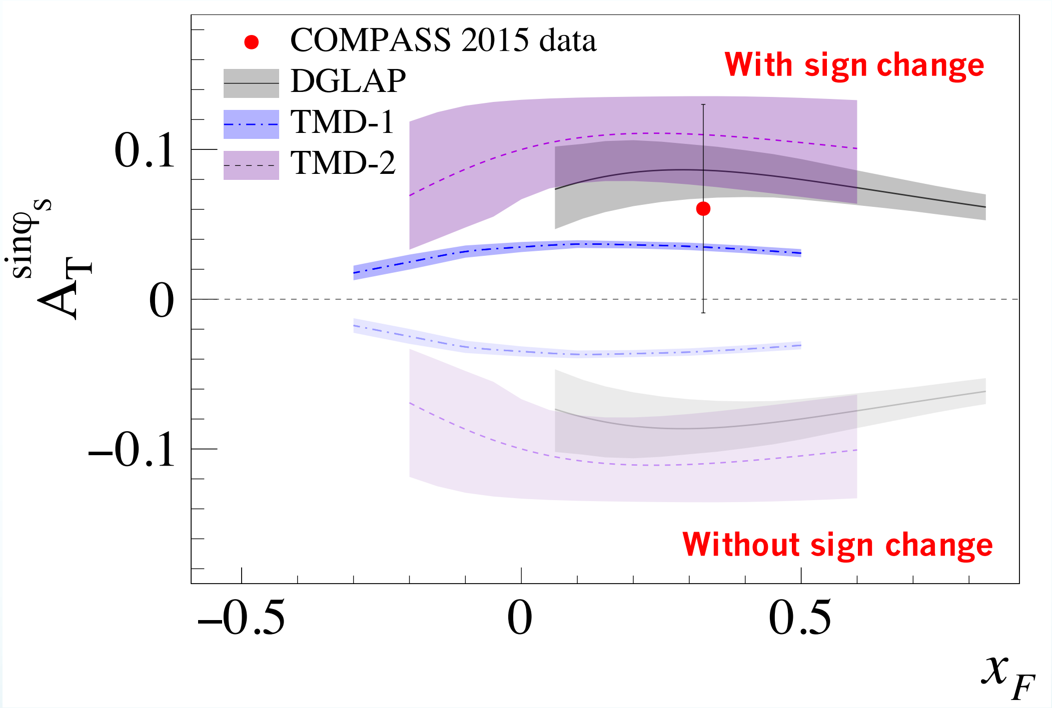



- TMD evolution cancels between the ratios?? Need more data on the absolute cross section
- However, the extrapolations can be very different

# Drell-Yan process

- First experimental hint on the sign change in Drell-Yan

COMPASS, 1704.00488

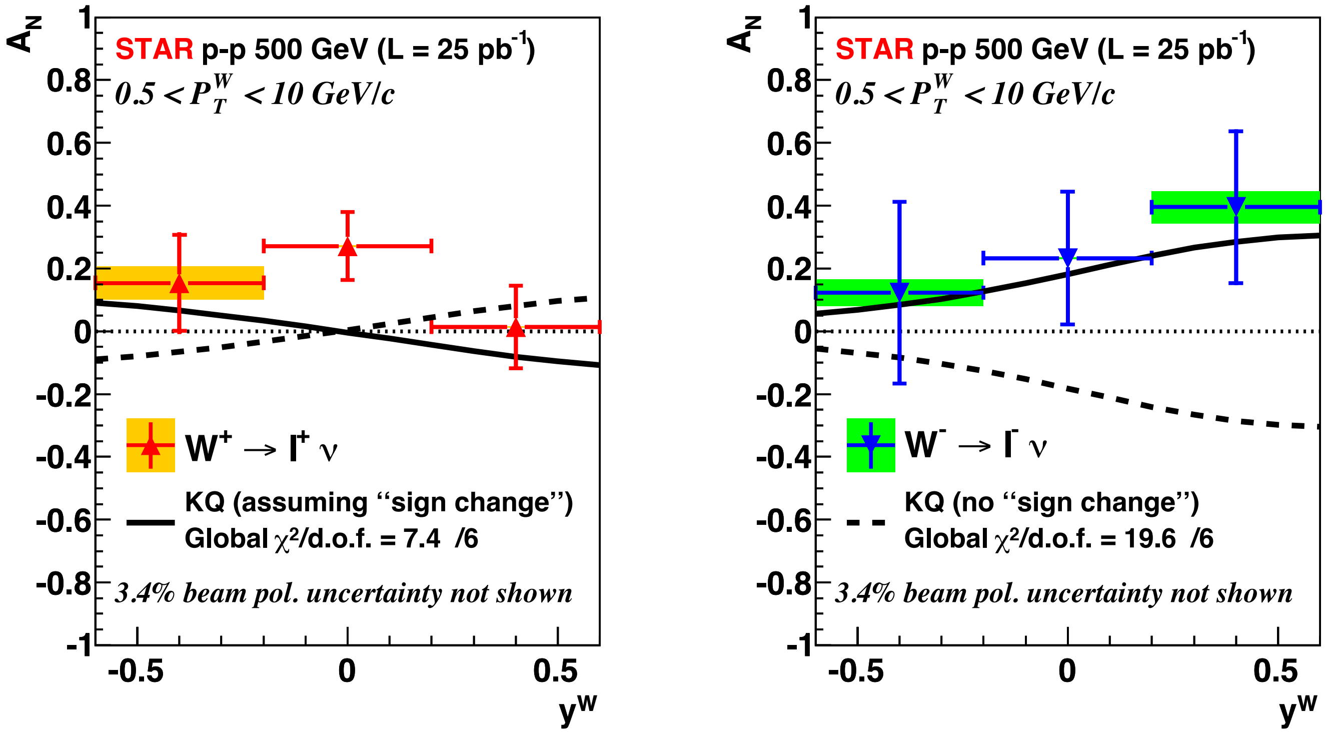



- Different TMD extrapolations: differ by a factor of several

# 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 2017 run

STAR, PRL 16, arXiv:1511.06003




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

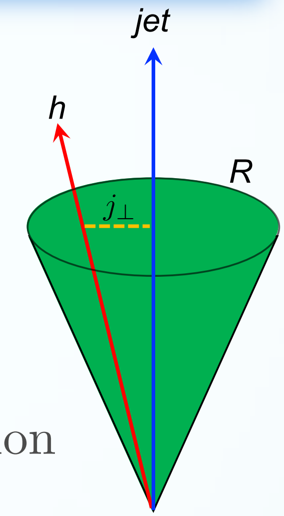
# TMD hadron distribution inside the jet

- Definition

$$F(z_h, j_\perp; p_T) = \frac{d\sigma^h}{dp_T d\eta dz_h d^2 j_\perp} \Big/ \frac{d\sigma}{dp_T d\eta}$$

$$z_h = p_T^{\rm h}/p_T^{\rm jet}$$

$j_\perp$ : hadron transverse momentum with respect to the jet direction




- Factorization formalism within SCET

Kang, Liu, Ringer, Xing, 1705.08443

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

- Re-factorization of semi-inclusive fragmenting jet function

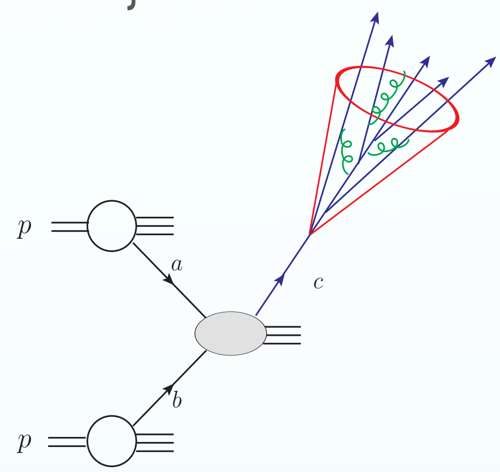
$$\mathcal{G}_c^h(z, z_h, \omega_J R, \boldsymbol{j}_\perp, \mu) = \mathcal{H}_{c\to i}(z, \omega_J R, \mu) \int d^2\boldsymbol{k}_\perp d^2\boldsymbol{\lambda}_\perp \delta^2\left(z_h \boldsymbol{\lambda}_\perp + \boldsymbol{k}_\perp - \boldsymbol{j}_\perp\right) \times D_{h/i}(z_h, \boldsymbol{k}_\perp,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

# Characteristics: hadron in the jet

- Soft radiation has to happen inside the jet
  - Only the soft radiation inside the jet can change the hadron transverse momentum with respect to the jet axis
- Restricts soft radiation to be within the jet
  - Cuts half of the rapidity divergence

$$\int_0^\infty \frac{dy}{y} \Rightarrow \int_0^{\tan^2\frac{R}{2}} \frac{dy}{y}$$

$$y \sim \frac{\ell^+}{\ell^-}$$

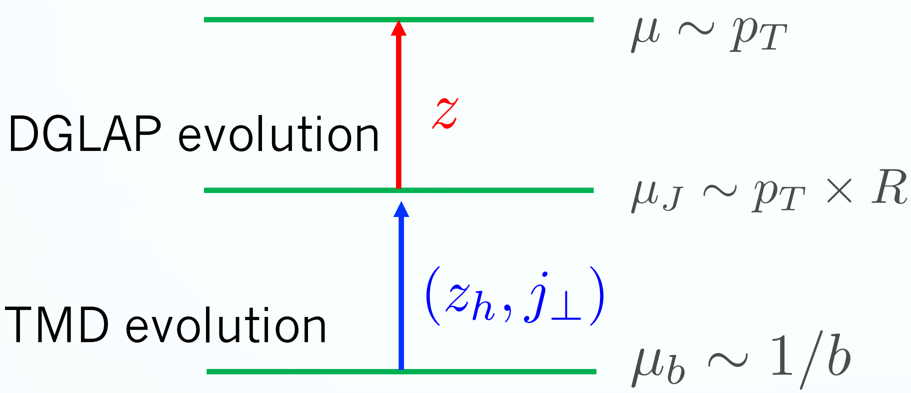



- Rapidity divergence cancel between restricted "soft factor" and TMD FFs
  - At least up to this order, the combined evolution is the same as the usual TMD evolution in SIDIS, e+e-; justify the use of same TMD evolution here

$$\sqrt{S(b)}D_c^h(z_h, b)_{\mathrm{e^+e^-}} \Rightarrow S(b, R)D_c^h(z_h, b)_{\mathrm{pp}}$$

# TMD + DGLAP evolution

- Evolution structure



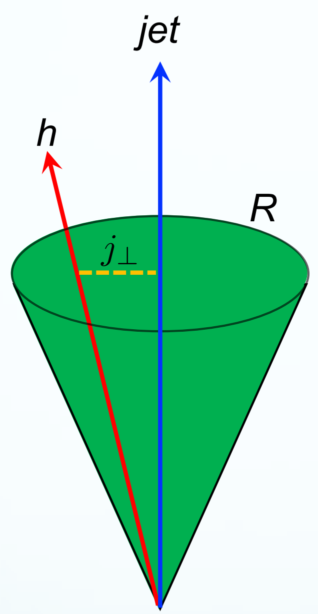

Resum ln(R)

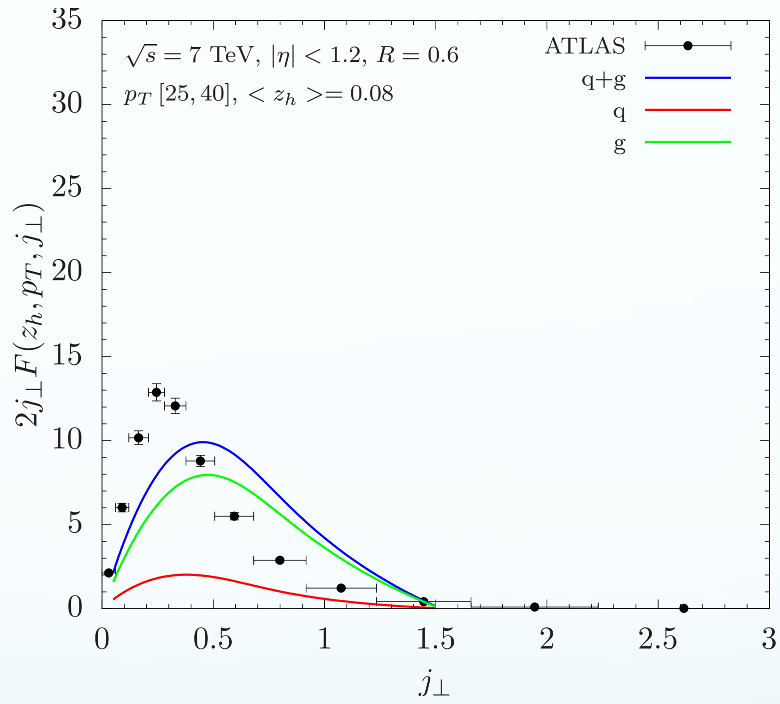
Evolve TMD FFs from $\boldsymbol{\mu}_b$ to pT*R

- TMD FFs thus are related to the usual TMD FFs in SIDIS at scale pT*R
- Thus hadron TMD distribution inside the jet could be used to test the universality of TMD FFs from SIDIS, e+e- processes

# Hadron TMD distribution inside jets

- Unpolarized p+p collisions: very sensitive to gluon TMDs



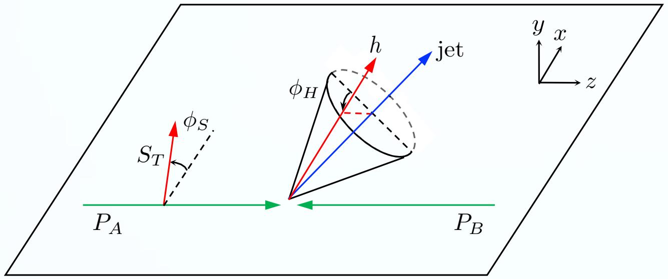




- Issue of non-global logarithms (NGLs)?

Dasgupta, Salam, 01, Banfi, Marchesini, Smye, 02, ...

# Collins asymmetry in p+p

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



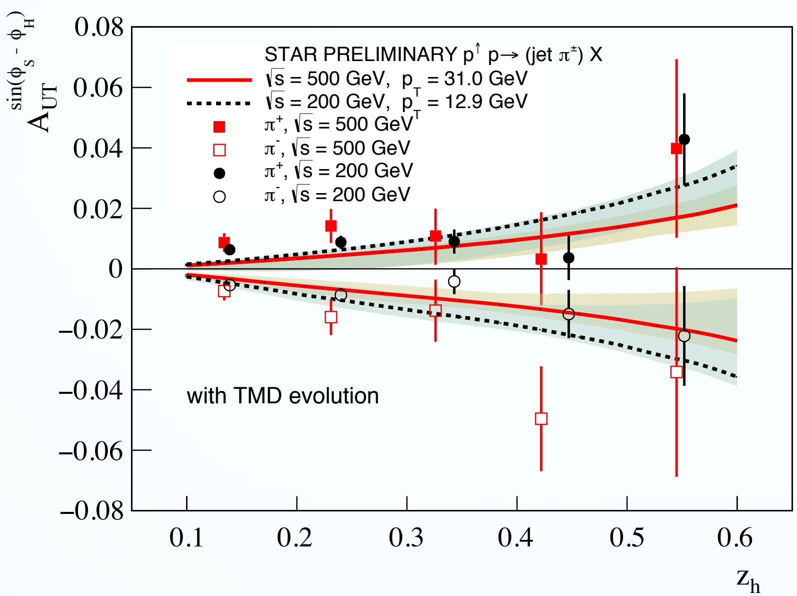

$$p^{\uparrow}\left[\vec{S}_{\perp}(\phi_S)\right] + p \to [\text{jet}\, h(\phi_H)] + X$$

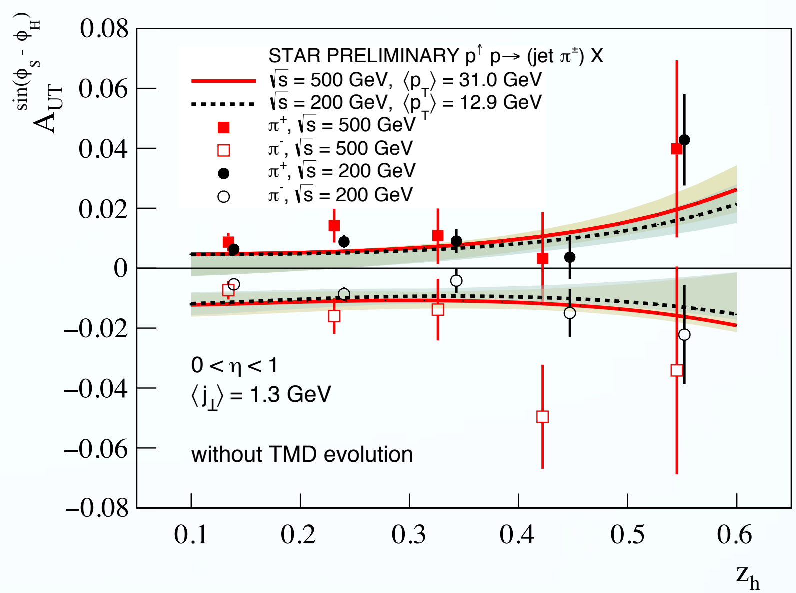
$$\frac{d\sigma}{dy d^2 p_{\perp}^{\text{jet}} dz d^2 j_T} = F_{UU} + \sin(\phi_S - \phi_H) F_{UT}^{\sin(\phi_S-\phi_H)}$$

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

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

# Calculated Collins azimuthal asymmetry




- *Universality of Collins function between e+p, e+e, and p+p*
- *Test TMD evolution*

Kang, Prokudin, Ringer, Yuan, 1707.00913

# TMD study

- Study on TMDs are extremely active in the past few years, lots of progress have been made

- With great excitement, we look forward to the future experimental results from COMPASS/RHIC, as well as Jefferson Lab, of course also LHC, most importantly, the EIC

- Better strategy for fitting, more observables/channels for TMDs

Thank you!