TMDs: Mechanism/universality with ep and pp collisions

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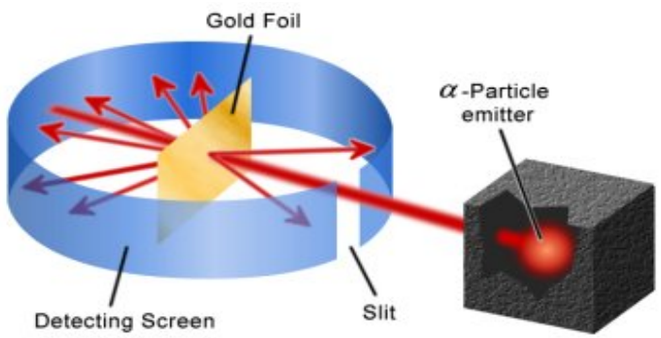
QCD Frontier 2013
Thomas Jefferson National Accelerator Facility
Newport News, VA, October 21–22, 2013

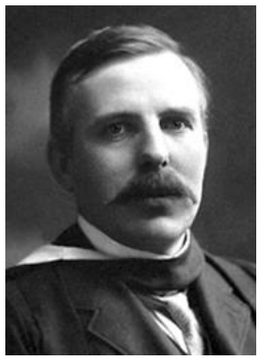
Outline

- Introduction
- Connection between SIDIS and pp data
- A new proposal for global fitting
- Summary

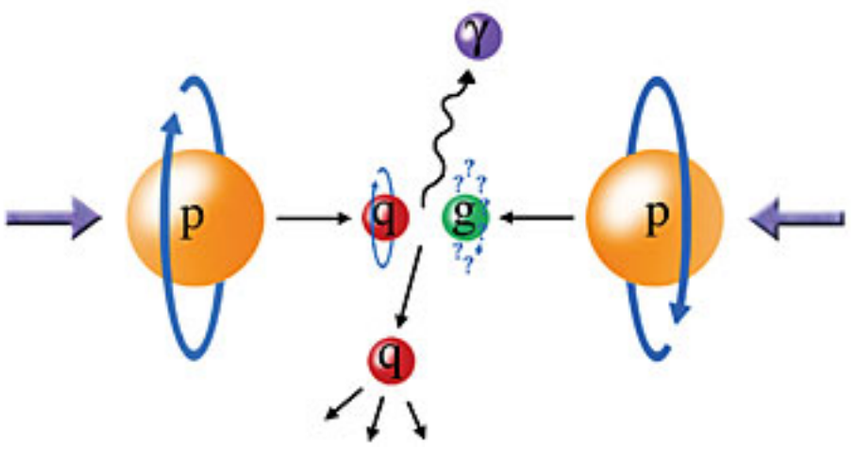
High energy scattering: a way to study structure of matter

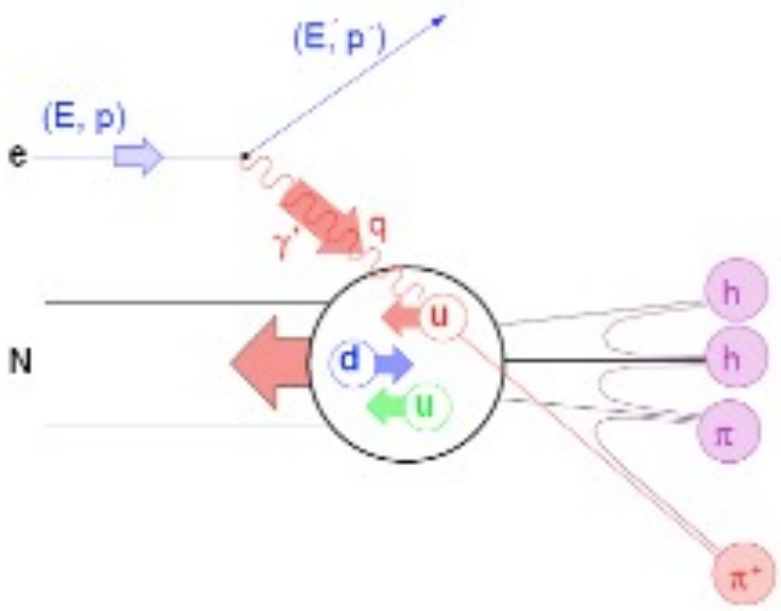
- Originated from Rutherford's experiment (1911)
  - Atomic structure: atomic nucleus (proton and neutron - nucleon)





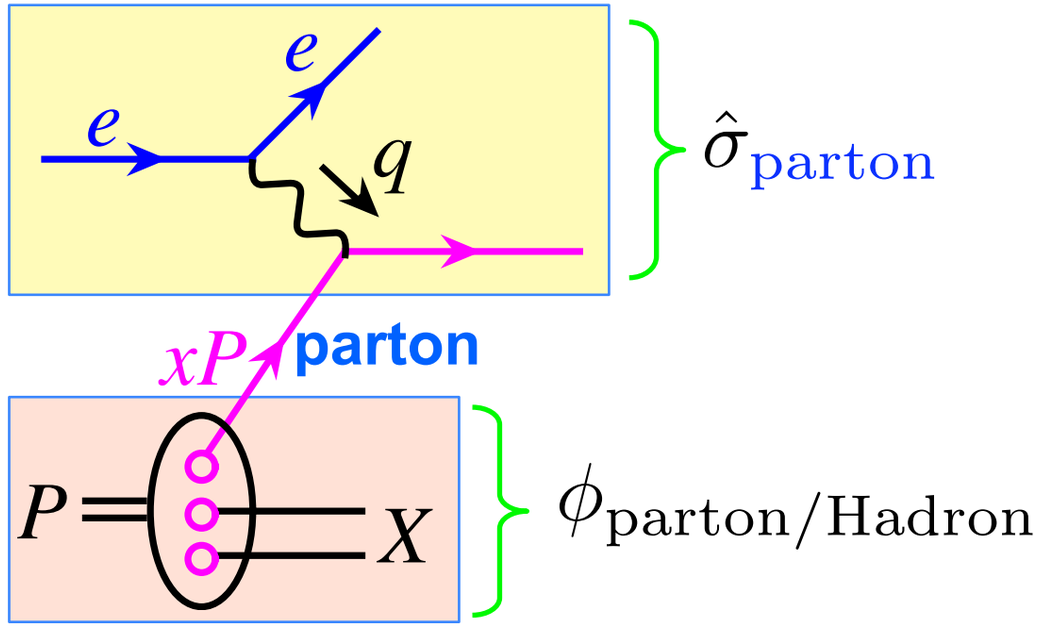
- To extract information on nucleon structure, we send a probe and measure the outcome of the collisions
  - Deep Inelastic Scattering (DIS)
  - Proton-proton collisions





Paradigm of perturbative QCD

- The common wisdom: in order to trace back what's inside hadron from the outcome of the collisions, we rely on QCD factorization



Parton Distribution Functions (PDFs): probability density for finding a parton in a hadron with longitudinal momentum fraction *x*

$$\sigma_{\rm Hadron}(Q) = \phi_{\rm parton/Hadron}(\Lambda_{QCD}) \otimes \hat{\sigma}_{\rm parton}(Q)$$

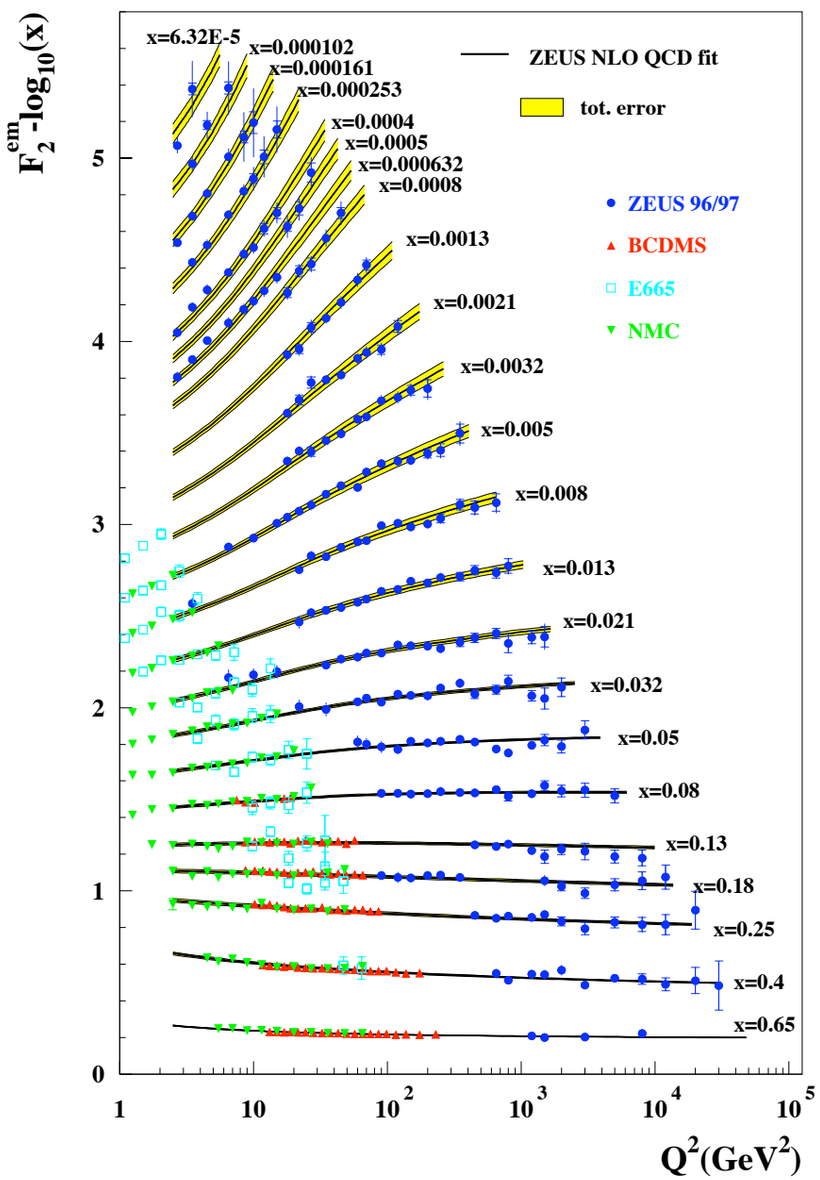
Universal (measured) **calculable**

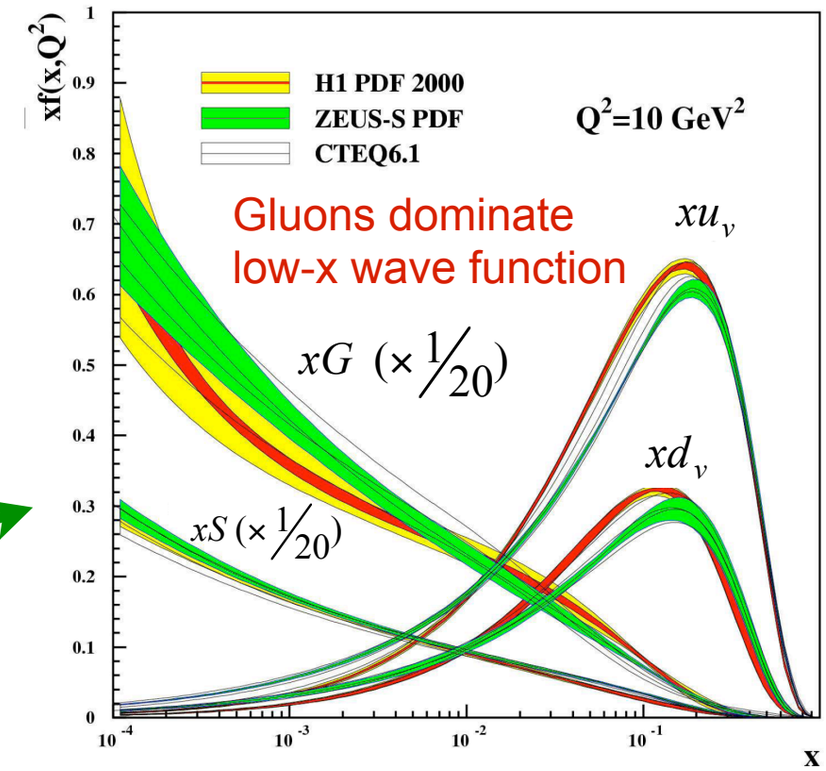
- Two important foundations
  - PDFs are universal (process-independent)
  - Partonic cross section is perturbatively calculable

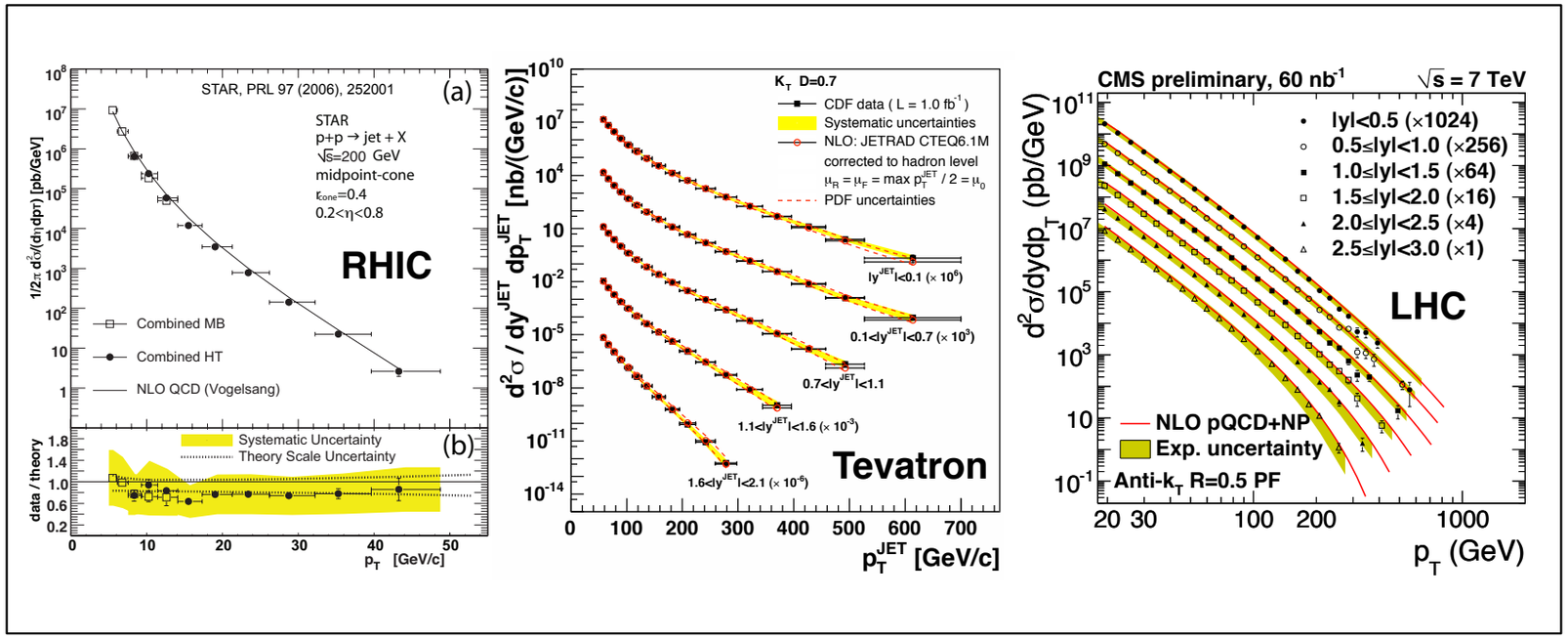
Success of QCD factorization

- Universality of PDFs: map out from one process (say DIS), used in other process (jet cross section)

DIS



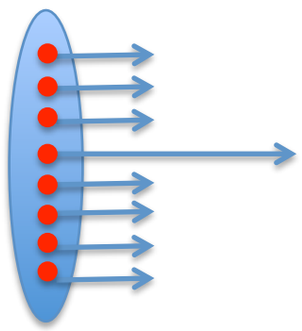




p+p→jet+X

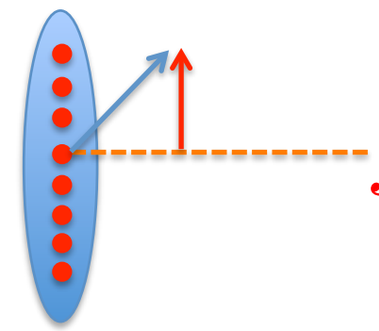
Collinear PDFs: one dimensional picture

- Collinear PDFs describes how partons are moving longitudinally inside the proton



$f(x)$

$p = x\,P$



$f(x, k_\perp)$

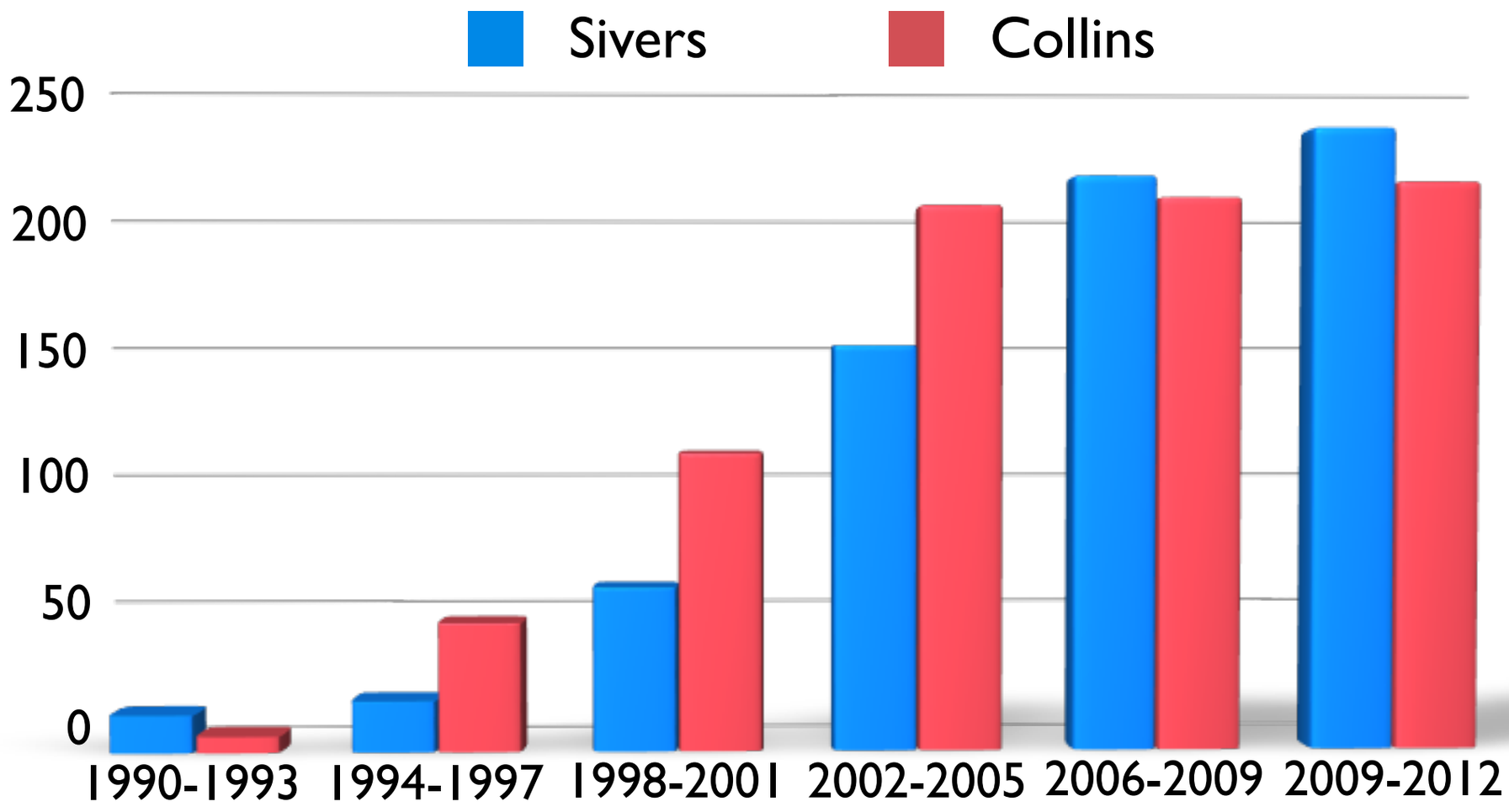
$p = x\,P + k_\perp$

- What about partons' transverse motion?
  - To map out transverse motion, the recent experimental trick: study transversely polarized particle scattering, as transverse polarization vector can correlate with parton's transverse momentum

Transverse spin phenomena

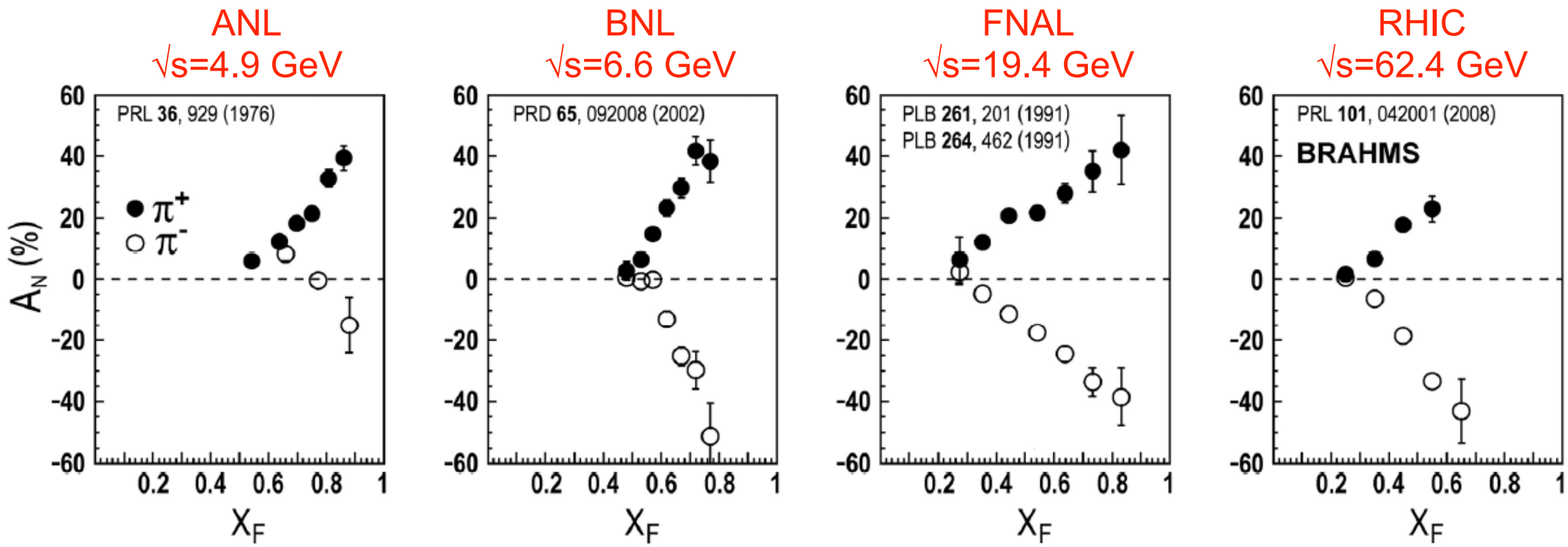
Transverse spin physics: birth and growth

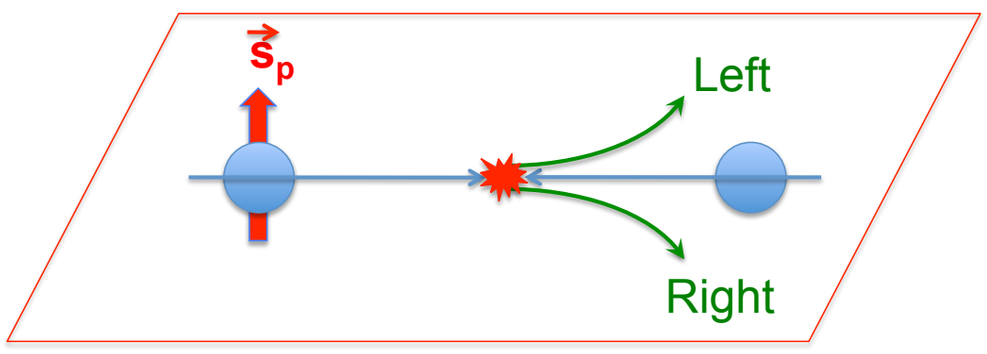
- Remarkable development of this field
  - From the sidelines in strong interaction physics
  - To center stage in our efforts to figure out QCD
- Numerous exciting new developments over past ~ 5 years
  - Differential citation grows exponentially as a function of time

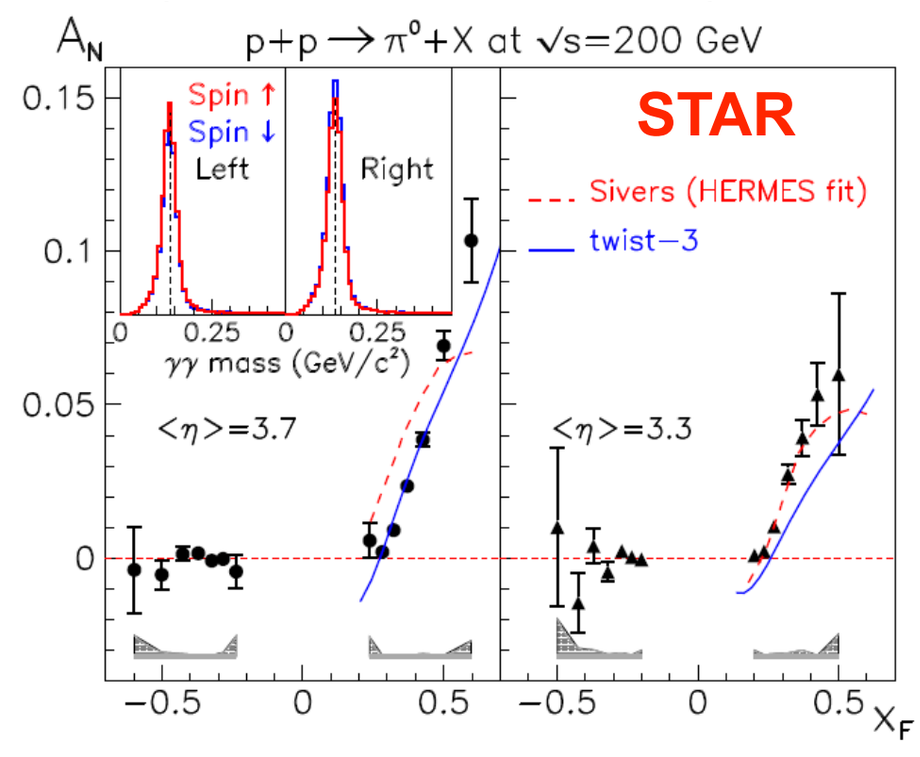


Single transverse-spin asymmetry (SSA)

- Consider a transversely polarized proton scatter with an unpolarized proton





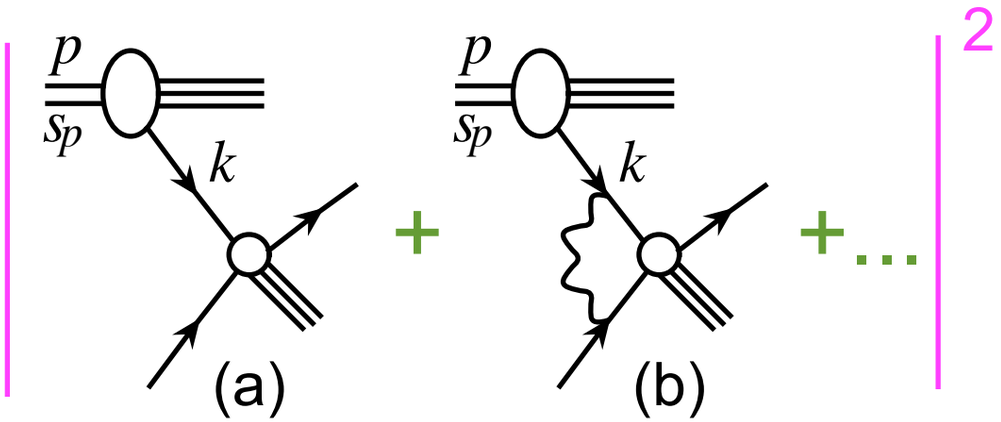


$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s}) - \sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s}) + \sigma(\ell,-\vec{s})}$$

SSA vanishes at leading twist in collinear factorization

- At leading twist formalism: partons are collinear

Kane, Pumplin, Repko, 1978

$\sigma(s_T) \sim$ 

➡ $\Delta\sigma(s_T) \sim \mathrm{Re}[(a)]\cdot\mathrm{Im}[(b)]$

  - generate phase from loop diagrams, proportional to α_s
  - helicity is conserved for massless partons, helicity-flip is proportional to current quark mass m_q

Therefore we have

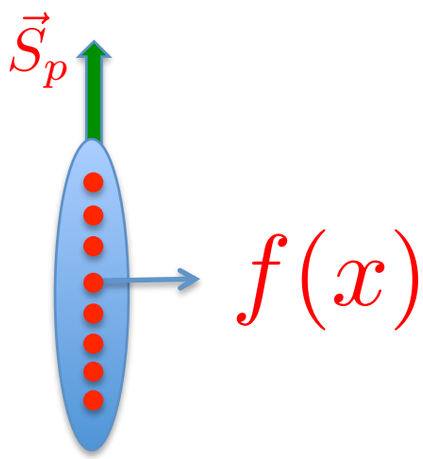
$$A_N \sim \alpha_s \frac{m_q}{P_T} \to 0$$

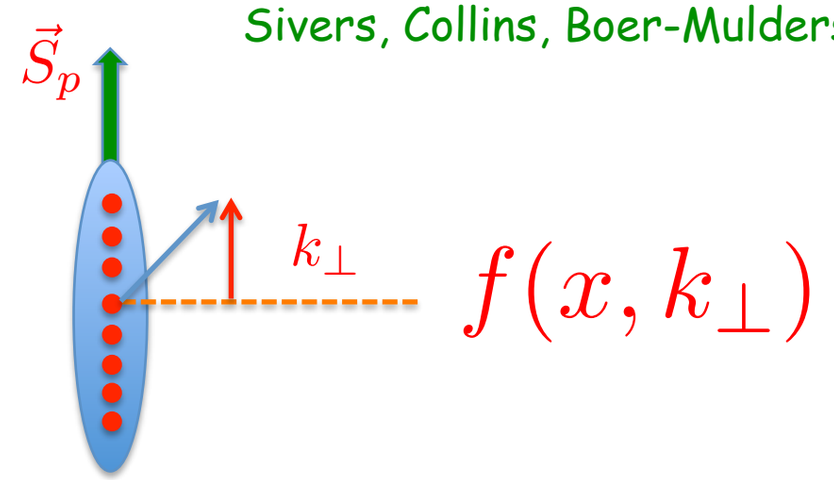
- $A_N \neq 0$: result of parton's transverse motion or correlations!

Transverse momentum dependent distributions (TMDs)

- Generalize the collinear PDFs to TMDs - TMD approach

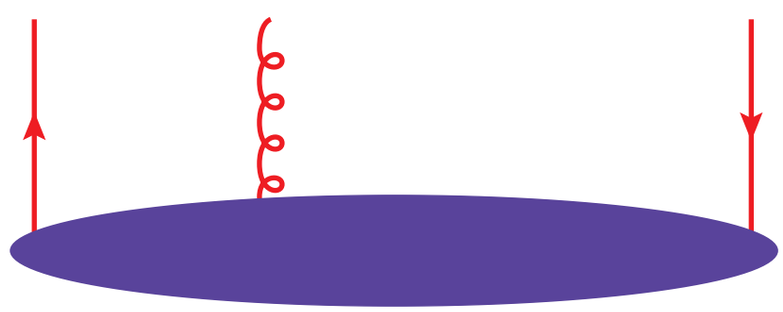
Sivers, Collins, Boer-Mulders, Ji-Ma-Yuan, ...





- Taylor expansion: $f(x, k_T) = f(x) + k_T * f'(x) + \ldots$, where $f'(x)=df(x, k_T)/dk_T$ at $k_T=0$. Net transverse motion $\langle k_T \rangle$ is contained in multi-parton correlation function - collinear twist-3 approach

Efremov-Teryaev, Qiu-Sterman, Koike, Kang, Yuan,...



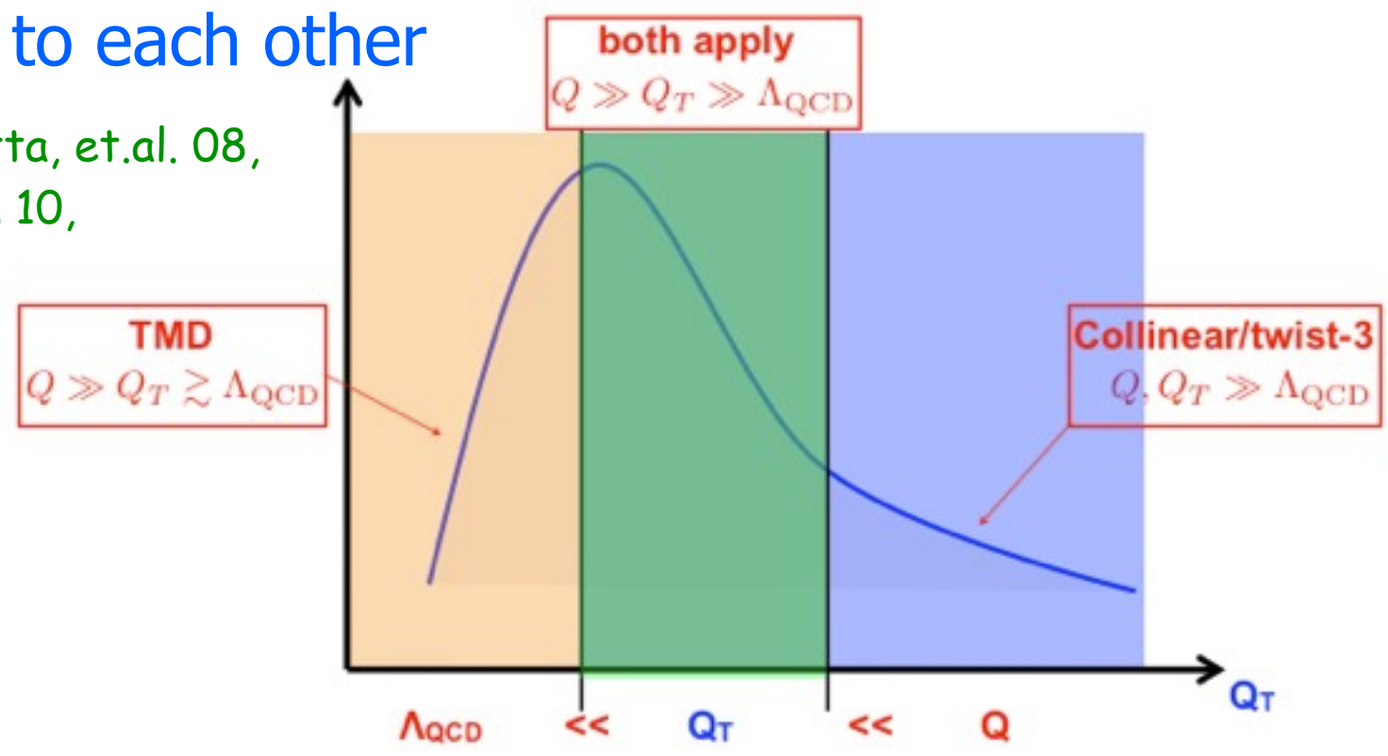
- A seemly simple extension, very interesting and non-trivial consequences: much richer QCD dynamics and hadron structure

QCD factorization theorems

- TMD factorization: $\Lambda^2_{\rm QCD} < P^2_{h\perp} \ll Q^2$ Collins-Soper, Ji-Ma-Yuan, …
  - Semi-Inclusive deep inelastic scattering (SIDIS): hadron at low pt
  - Drell-Yan production in pp collision: dilepton at low pt
  - e+e-→h1+h2+X: back-to-back dihadron production
- Collinear factorization: $\Lambda^2_{\rm QCD} \ll P^2_{h\perp}, Q^2$ Qiu-Sterman, Efremov-Teryaev, Koike, Kang, Yuan,…
  - All of above when $P_{h\perp} \sim Q$
  - Single inclusive hadron (jet, photon) production at high pt in pp collisions

    $p + p \to h(P_{h\perp}) + X$
- They are closely related to each other

  Ji-Qiu-Vogelsang-Yuan 06, Bacchetta, et.al. 08,
  Boer-Kang-Vogelsang-Yuan 10,



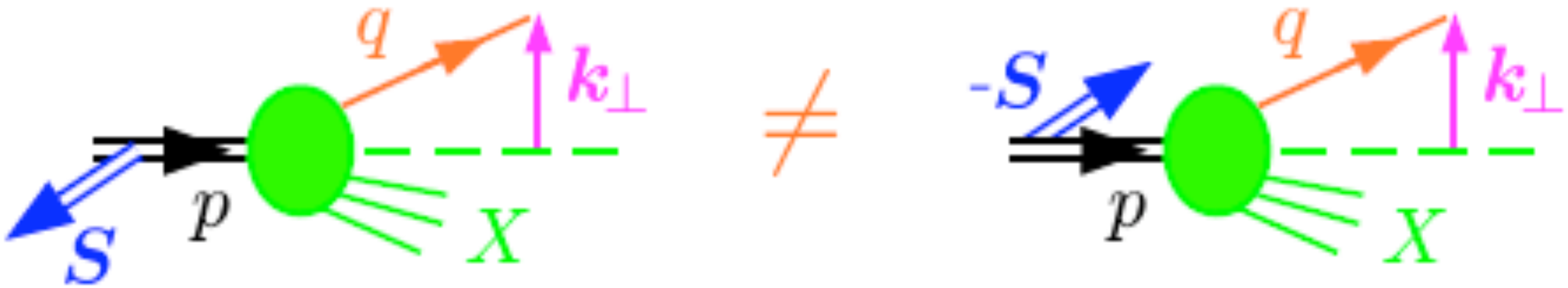
Transverse momentum dependent distribution (TMD)

- Sivers function: an asymmetric parton distribution in a polarized hadron (kt correlated with the spin of the hadron)

Spin-dependent

$$f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) \equiv f_{q/h}(x, k_\perp) + \frac{1}{2}\Delta^N f_{q/h^\uparrow}(x, k_\perp)\, \vec{S} \cdot \hat{p} \times \hat{\mathbf{k}}_\perp$$

Spin-independent



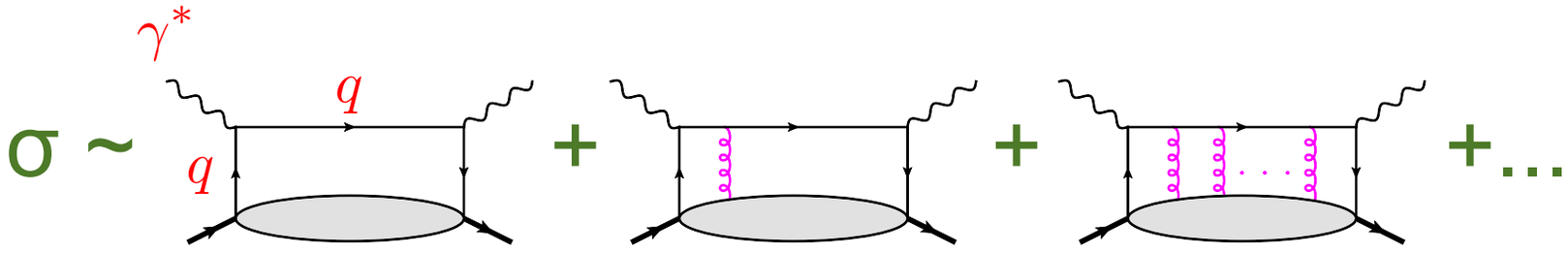
- Naive time-reversal-odd: recall momentum $\vec{p}$ and spin $\vec{S}$ change sign under time-reversal
- Such kind of correlation is forbidden in time-reversal-invariant theory (QCD), unless there is a phase. Where does the phase come from?

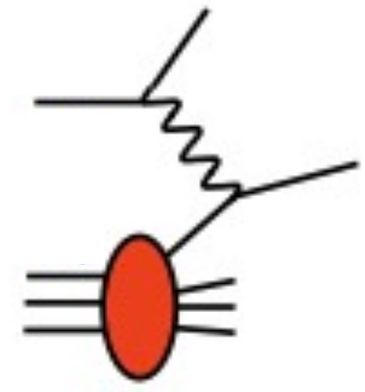
The history of Sivers function

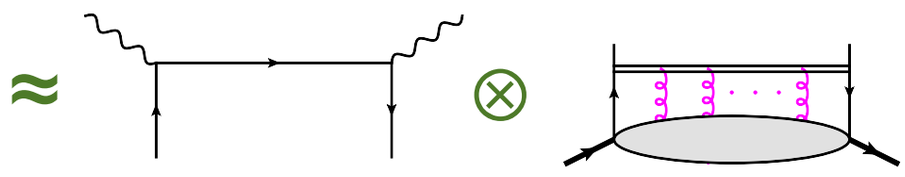
- 1990: Sivers function
  - introduce kt dependence of PDFs, generate the SSA through a correlation between the hadron spin and the parton kt
- 1993: Collins
  - show Sivers function vanishes due to time-reversal invariance
- 2002: Brodsky, Hwang, Schmidt
  - explicit model calculation show the existence of the Sivers function
  - the existence of Sivers function relies on the initial- and final-state interactions between the active parton and the remnant of the polarized hadron
- 2002: Ji, Yuan, Belitsky
  - the initial- and final-state interaction presented by Brodsky, et.al. is equivalent to the color gauge links in the definition of the TMD distribution functions
  - since the details of the initial- and final-state interaction depend on the specific scattering process, the gauge link thus the Sivers function could be process-dependent

Sivers function are process-dependent

- Existence of the Sivers function relies on the interaction between the active parton and the remnant of the hadron (process-dependent)
  - SIDIS: final-state interaction



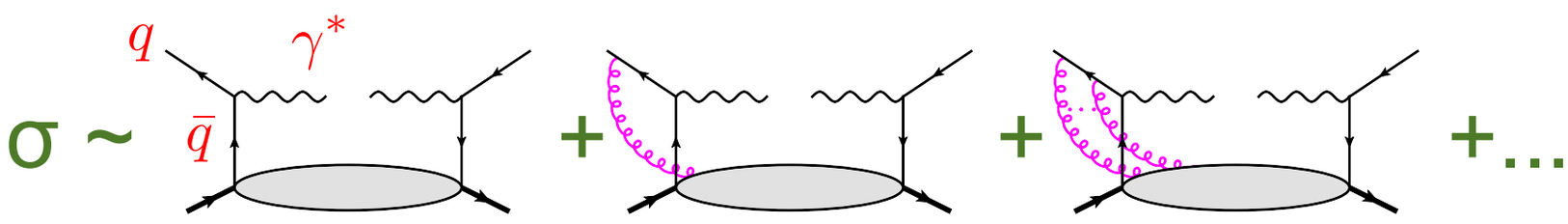


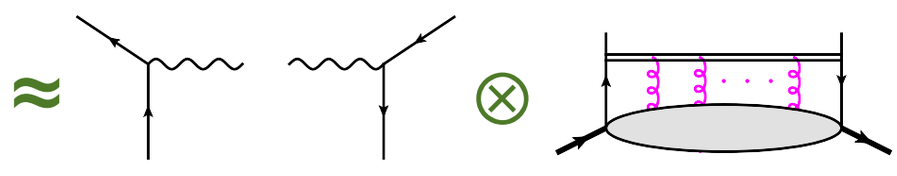


PDFs with SIDIS gauge link

$$\mathcal{P}\, e^{ig\int_y^{\infty} d\lambda\cdot A(\lambda)}$$

  - Drell-Yan: initial-state interaction





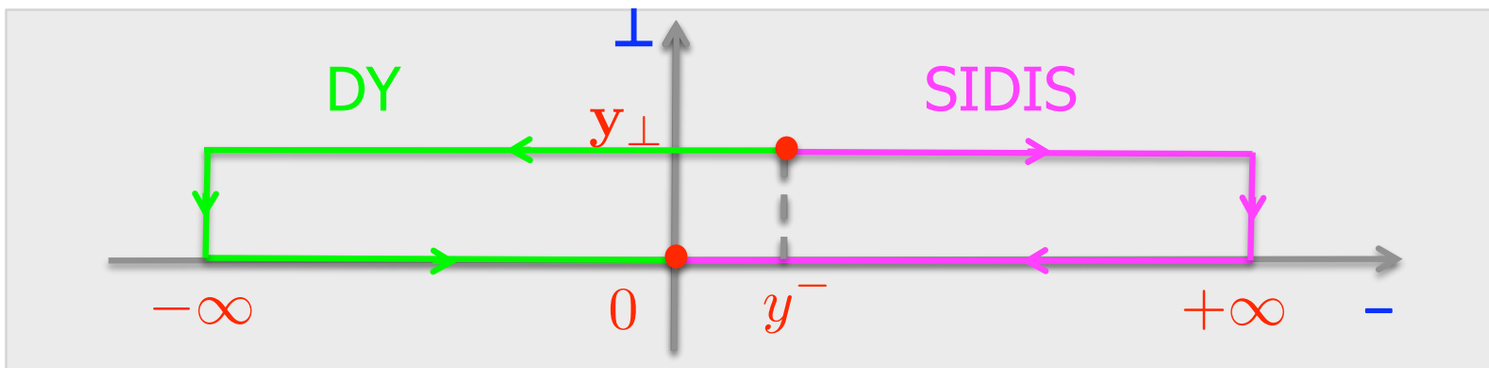
PDFs with DY gauge link

$$\mathcal{P}\, e^{ig\int_y^{-\infty} d\lambda\cdot A(\lambda)}$$

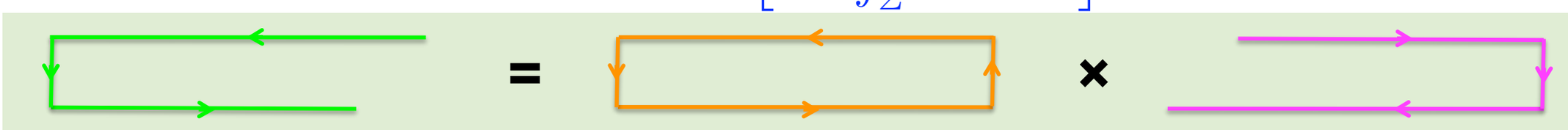
Time-reversal modified universality of the Sivers function

- Different gauge link for gauge-invariant TMD distribution in SIDIS and DY

$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int \frac{dy^- d^2y_\perp}{(2\pi)^3} e^{ixp^+y^- - i\,\mathbf{k}_\perp\cdot\mathbf{y}_\perp} \langle p,\vec{S}|\overline{\psi}(0^-,\mathbf{0}_\perp)\,\boxed{\text{Gauge link}}\,\frac{\gamma^+}{2}\psi(y^-,\mathbf{y}_\perp)|p,\vec{S}\rangle$$



Wilson Loop ~ $\exp\left[-ig\int_\Sigma d\sigma^{\mu\nu}F_{\mu\nu}\right]$ Area is NOT zero



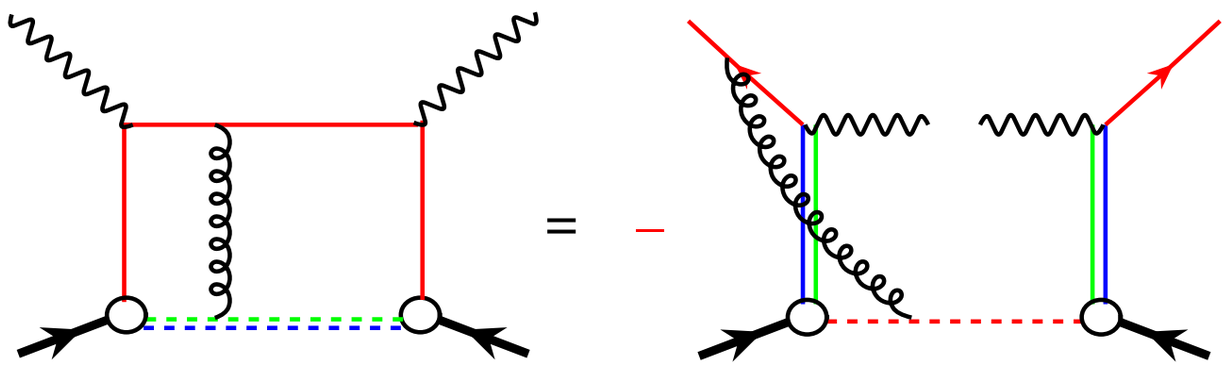
- Parity and time-reversal invariance:

$$\Delta^N f^{\rm SIDIS}_{q/h^\uparrow}(x,k_\perp) = -\Delta^N f^{\rm DY}_{q/h^\uparrow}(x,k_\perp)$$

Most critical test for TMD approach to SSA

Recap: breakdown of universality

- Sivers function is NOT universal (different from collinear PDFs), it is process-dependent
- It relies on the interactions between the active parton and the hadron remnant, it is the difference in these interactions that determine how they are related to each other in different process
  - Final-state interaction in DIS and initial-state interaction in DY leads to the "sign change" between the Sivers functions in these two different processes

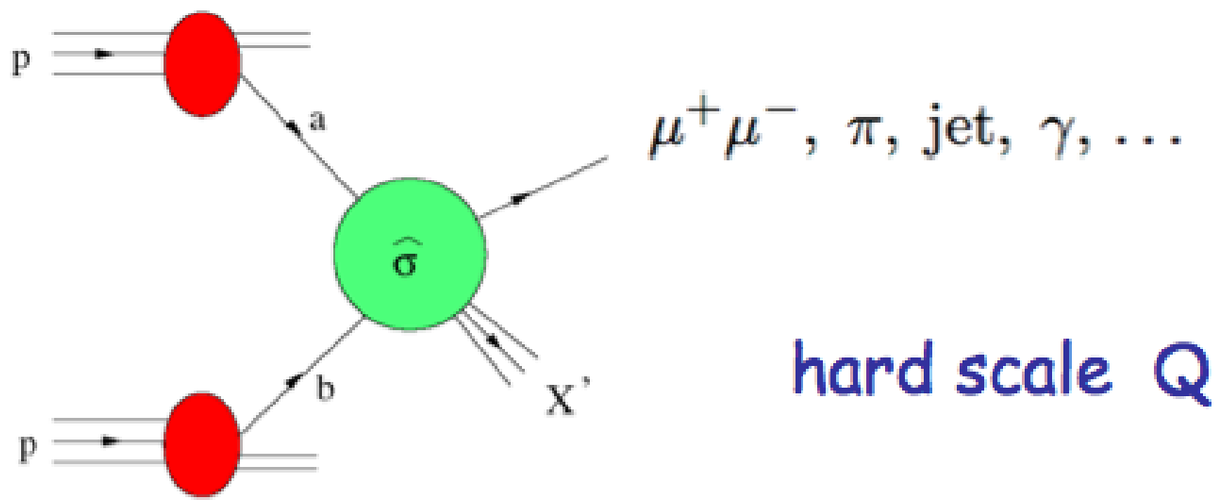


SIDIS = − DY

$$\Delta^N f^{\rm SIDIS}_{q/h^\uparrow}(x,k_\perp) = -\Delta^N f^{\rm DY}_{q/h^\uparrow}(x,k_\perp)$$

What happens to more complicated processes?

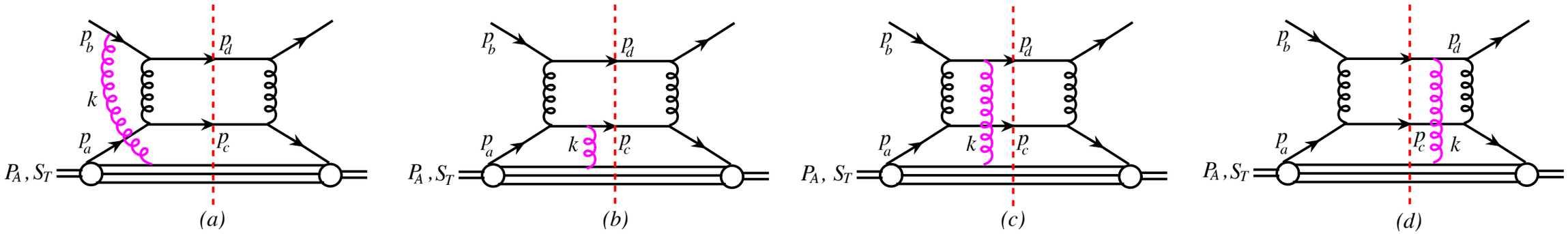
- Single inclusive particle production: p+p→h+X



Relate Sivers function in SIDIS to that in p+p collisions

Gamberg-Kang, 2011

- For inclusive hadron production: take qq′→qq′ as an example



  - Both initial-state interaction and final-state interaction contribute
  - Needs to calculate them carefully and consistently

$$f_{1T}^{\perp a, qq' \to qq'} = \frac{C_I + C_{F_c}}{C_u} f_{1T}^{\perp a, \mathrm{SIDIS}} = -\frac{3}{N_c^2 - 1} f_{1T}^{\perp a, \mathrm{SIDIS}}$$

$$C_I = -\frac{1}{2N_c^2}, \qquad C_{F_c} = -\frac{1}{4N_c^2}, \qquad C_u = \frac{N_c^2 - 1}{4N_c^2}.$$

  - Many other partonic channels: qg→qg, q$\bar{q}$→gg, ...

- A consistent factorization formalism which takes into account both initial-state and final-state interactions are called collinear twist-3 approach

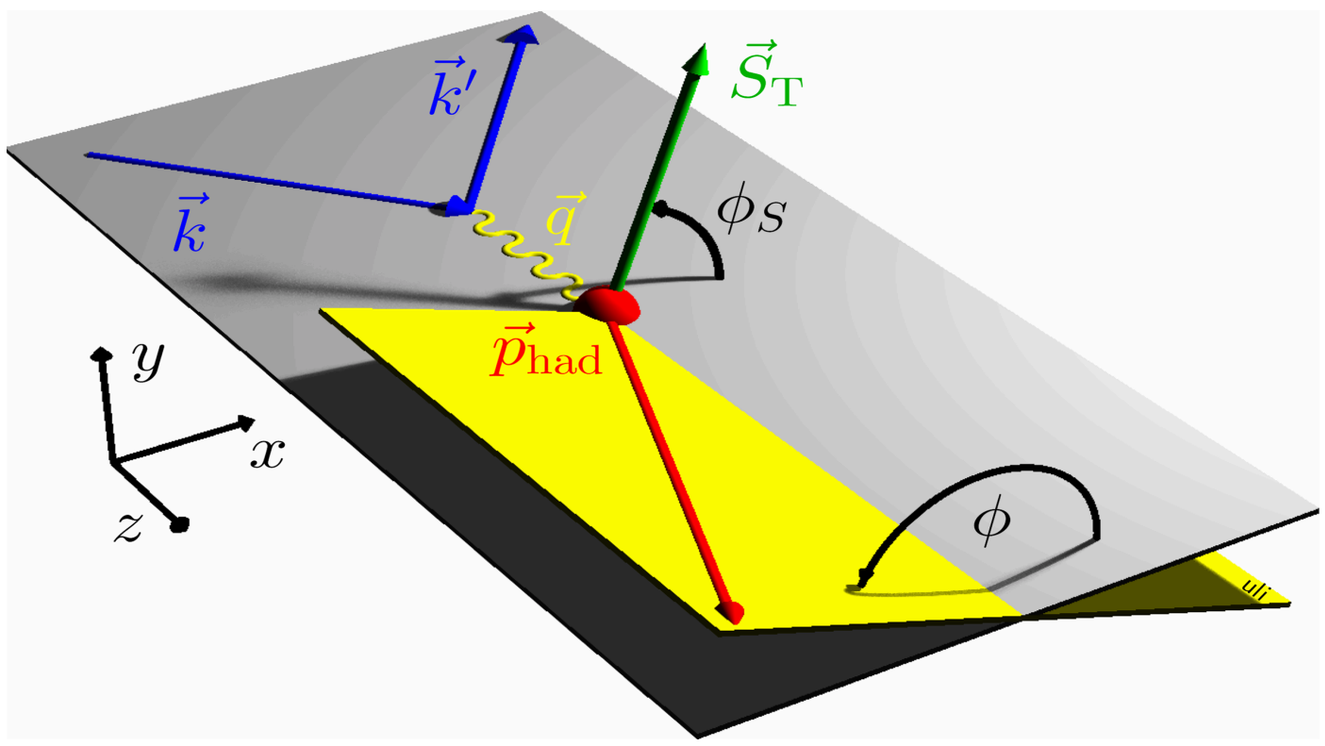
Qiu-Sterman 91, 98

Testing non-universality of Sivers effect

- Let us now confront our theory with the experiments
- First from SIDIS single spin asymmetry (Siveres effect)

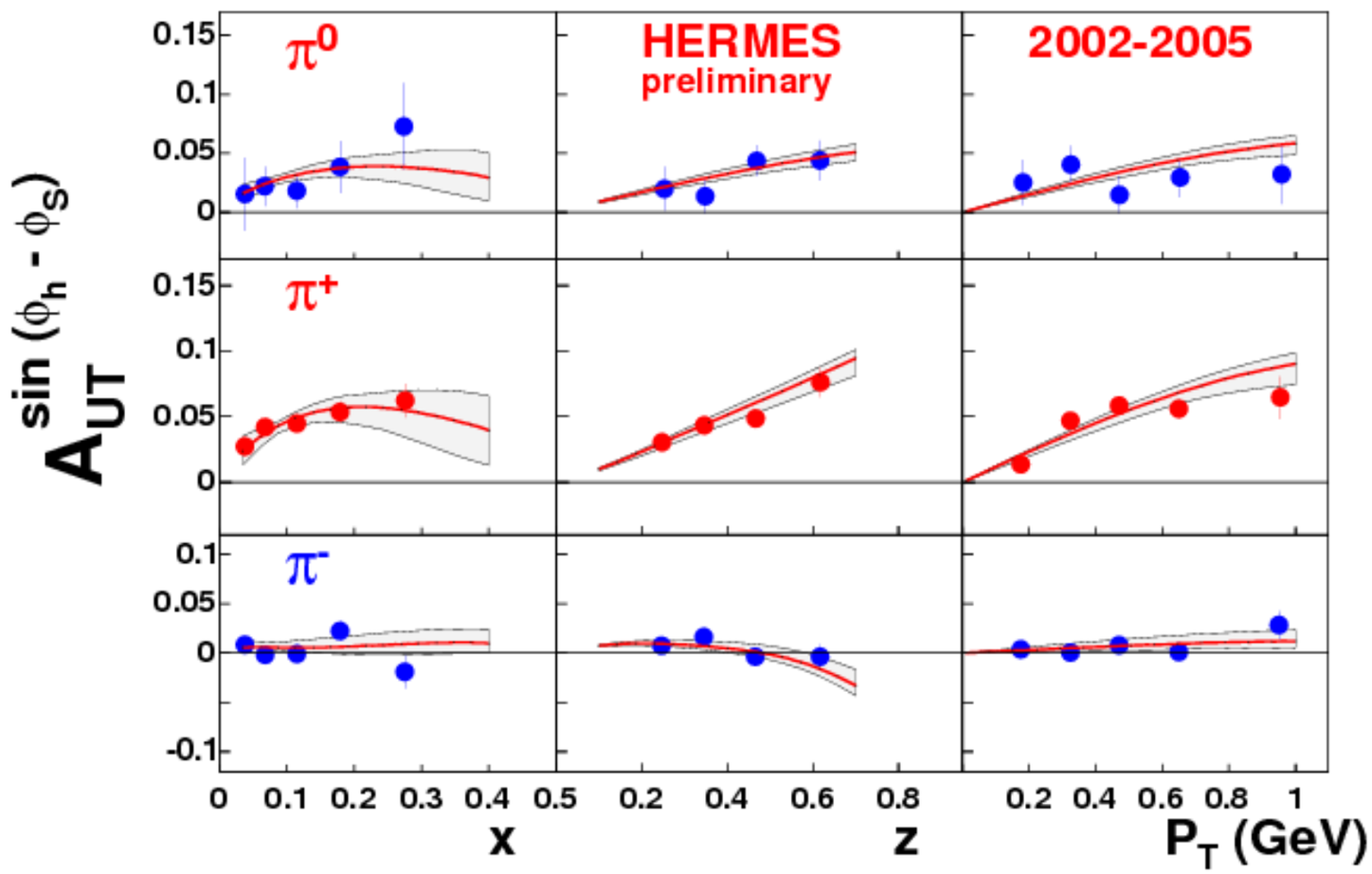
$$\ell + p^{\uparrow} \to \ell' + \pi(p_T) + X$$

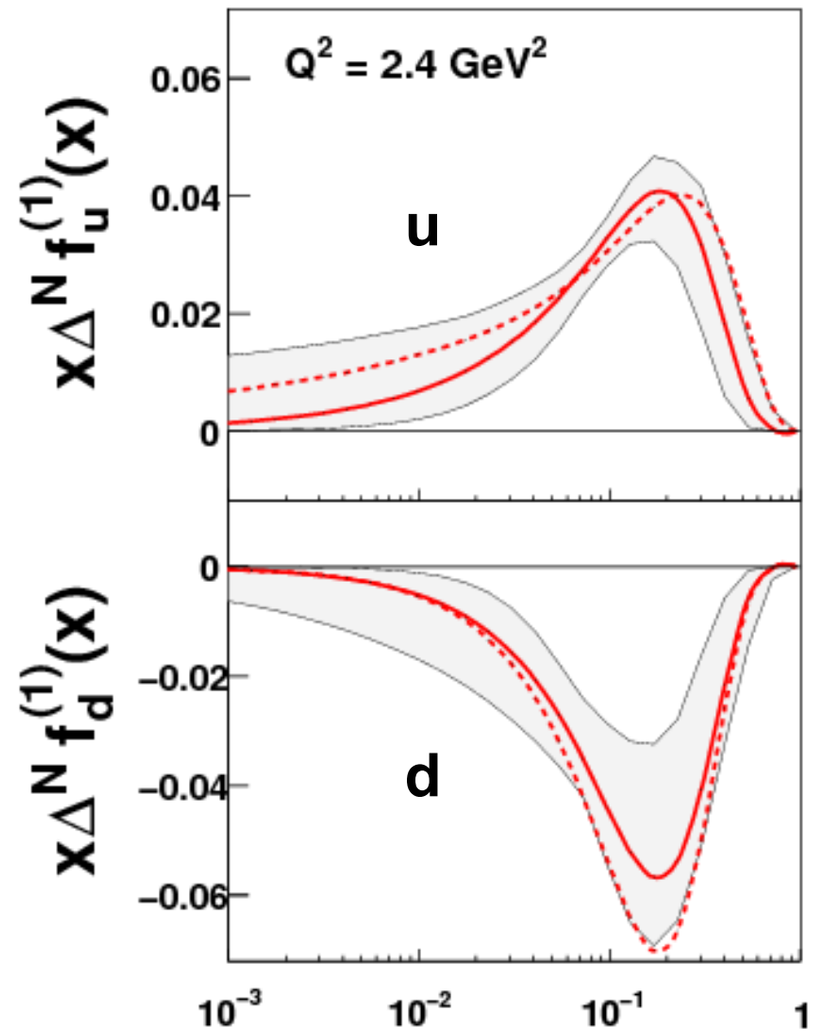
$$\Delta\sigma \propto A_{UT}^{\text{Collins}} \sin(\phi + \phi_S) + A_{UT}^{\text{Sivers}} \sin(\phi - \phi_S)$$



Sivers function from SIDIS $\ell + p^{\uparrow} \to \ell' + \pi(p_T) + X : \quad p_T \ll Q$

- Extract Sivers function from SIDIS (HERMES&COMPASS)





Anselmino, et.al., 2009

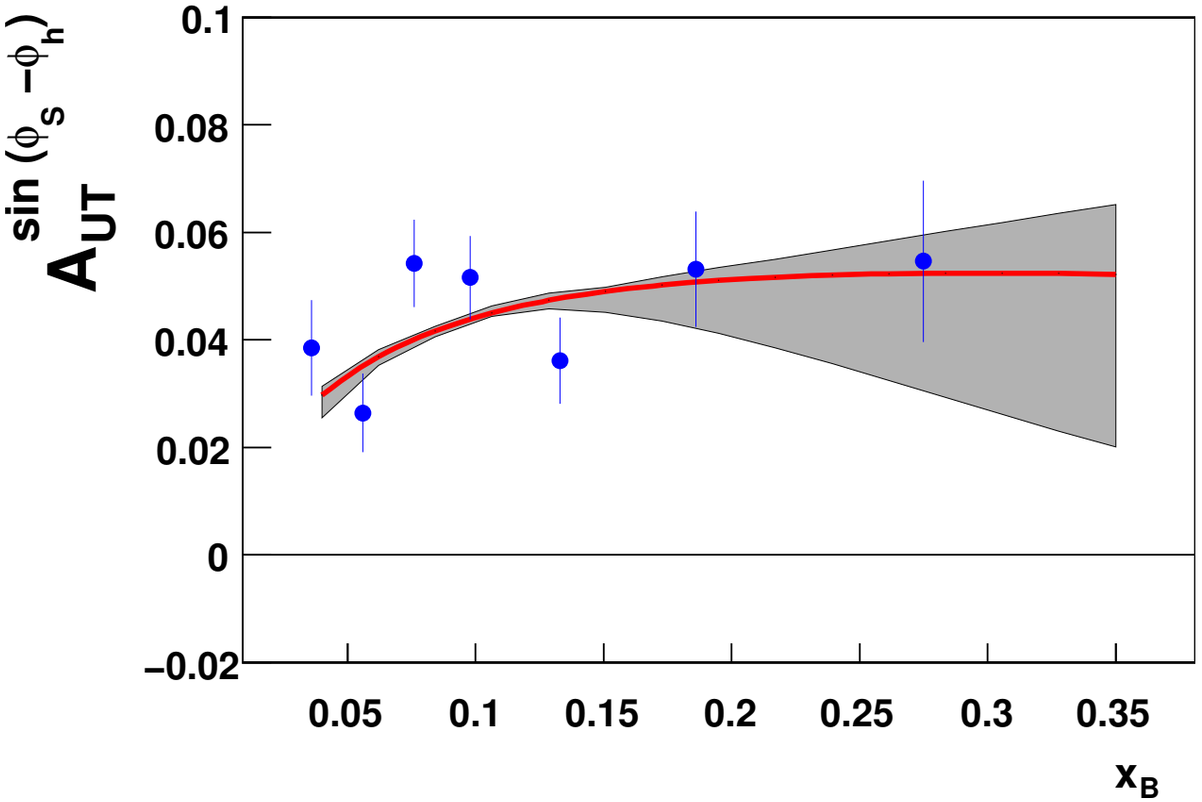
Slightly different extraction

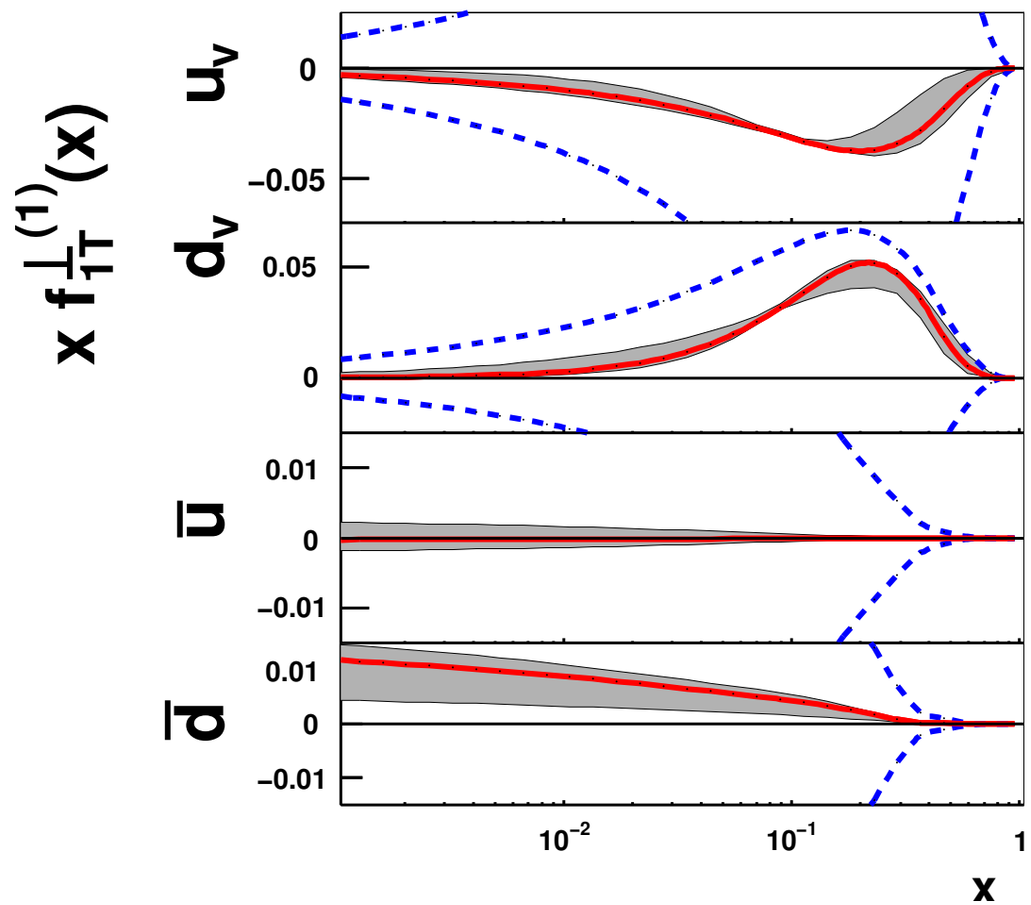
- More freedom on the large-x region

Gamberg-Kang-Prokudin, PRL, 1302.3218

$$f_{1T}^{\perp q}(x,k_\perp^2) \propto x^\alpha (1-x)^\beta h(k_\perp) f_{q/A}(x,k_\perp^2),$$

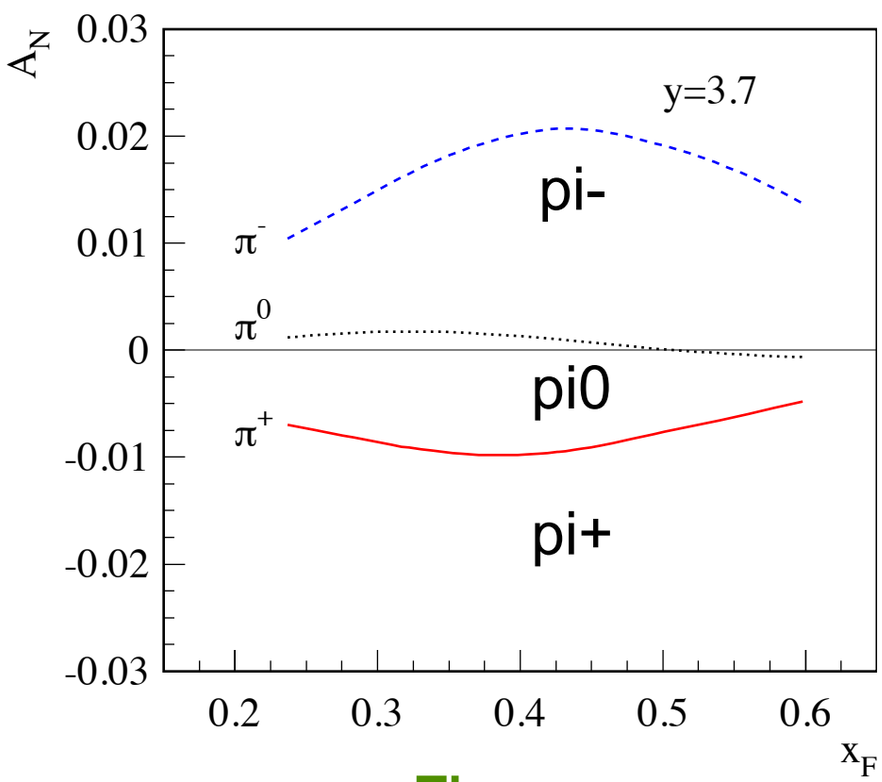
β_u and $\beta_{\rm d}$ are independent



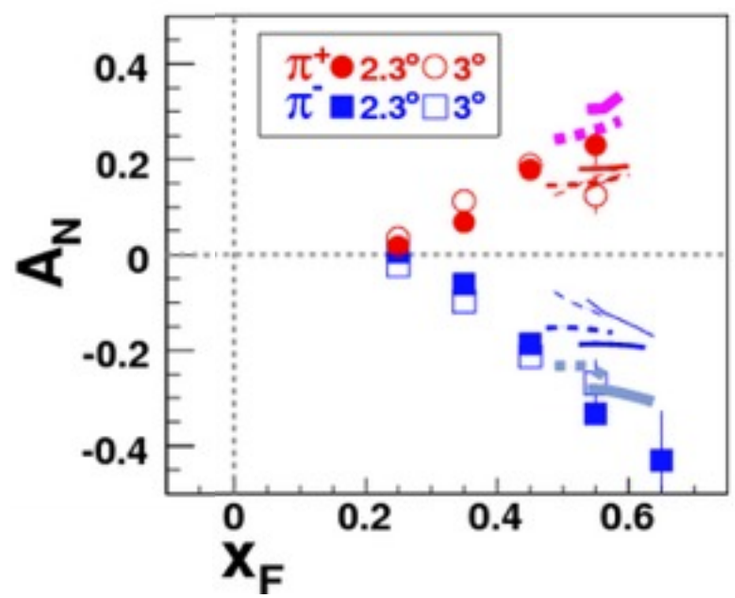


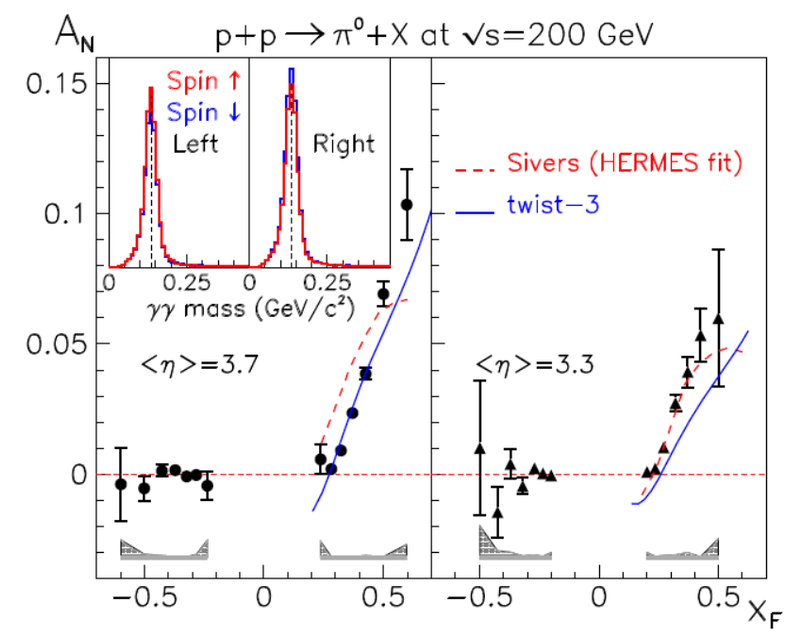
Predict the single spin asymmetry in p+p collisions

- Use the Sivers function from SIDIS, combining with the calculated relation (from complicated initial-state and final-state interactions), one can calculate the single spin asymmetry in p+p collisions
  - If this is the only contribution to the spin asymmetry



Theory





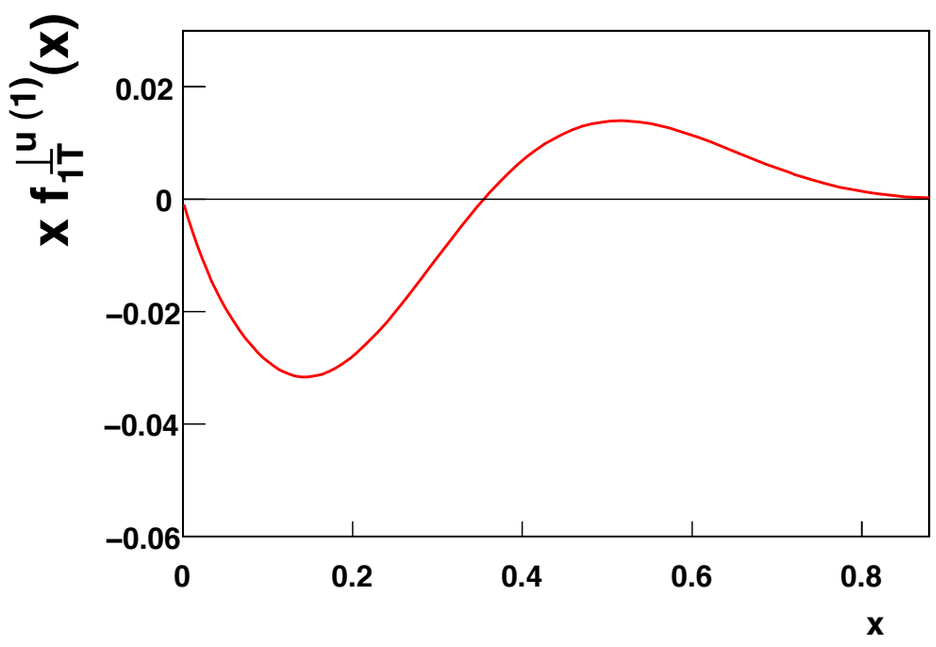
Experiment

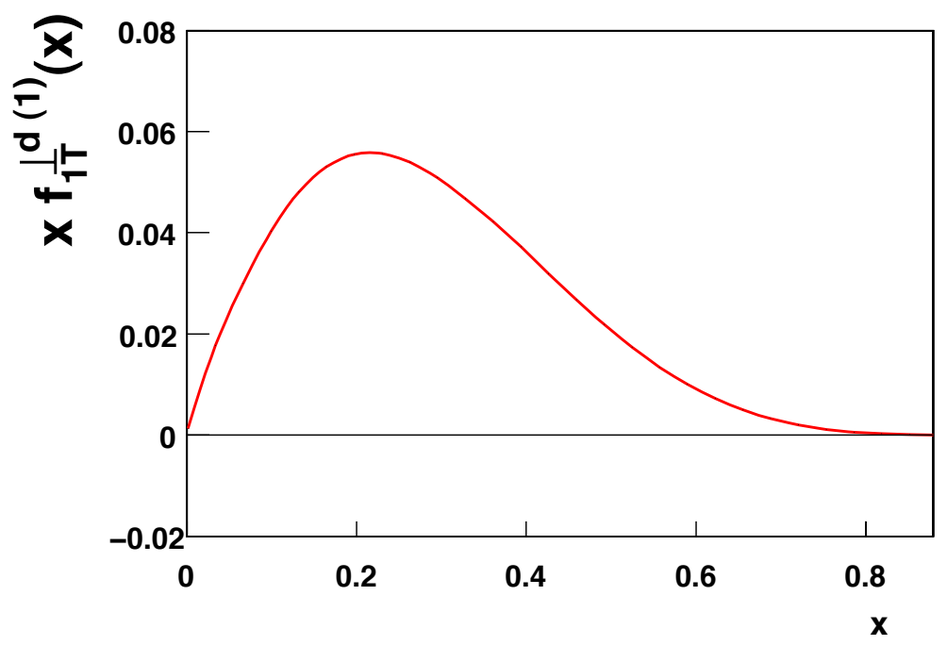
Kang-Qiu-Vogelsang-Yuan, 2011

Sign mismatch?

More flexible functional form for Sivers function

- Since Sivers type contributions were expected to be the main source for the single spin asymmetry for hadron production in pp collisions for a long time in the past, let us try to work on our formalism
  - Use a more flexible functional form for Sivers function: they don't have probability interpretation, thus need not to be positive definite
  - Maybe a node in x is just what we need: SIDIS and pp covers slightly different x region



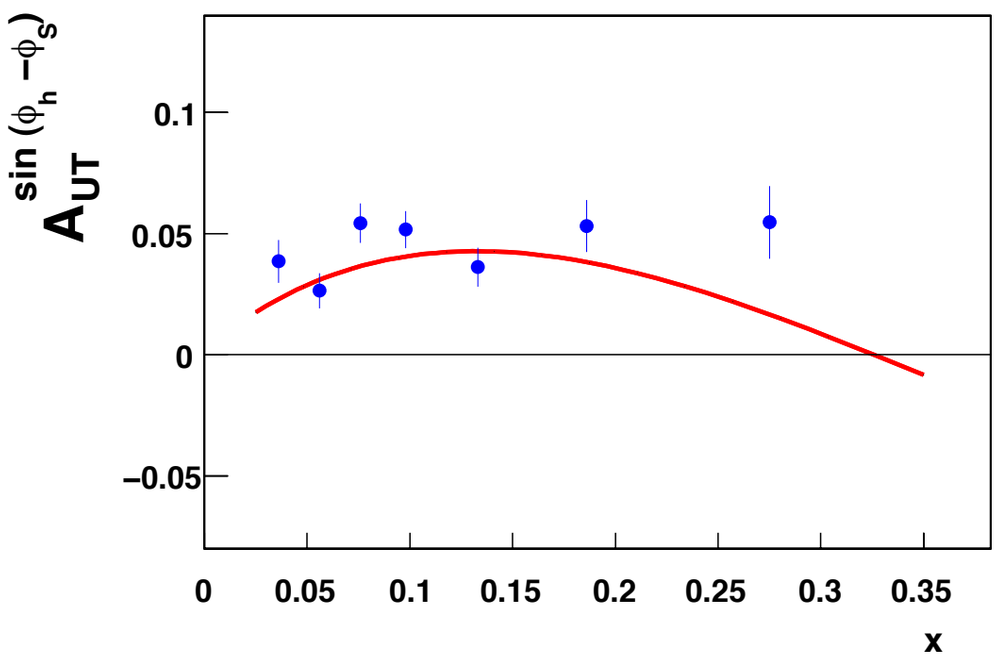


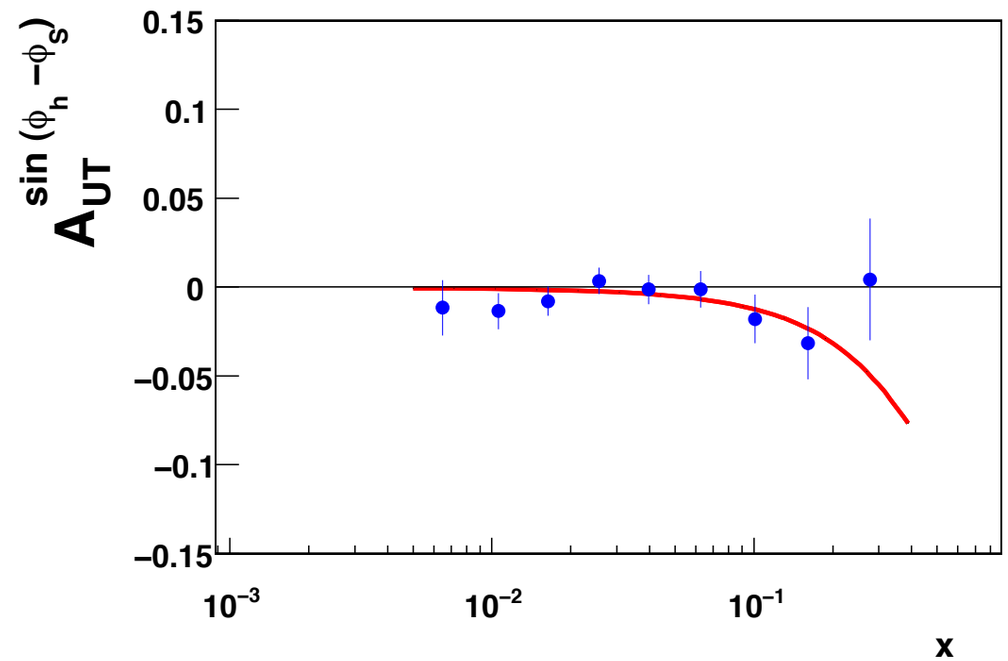
Kang-Prokudin, PRD, 2012

Works fine with SIDIS and STAR pi0 data

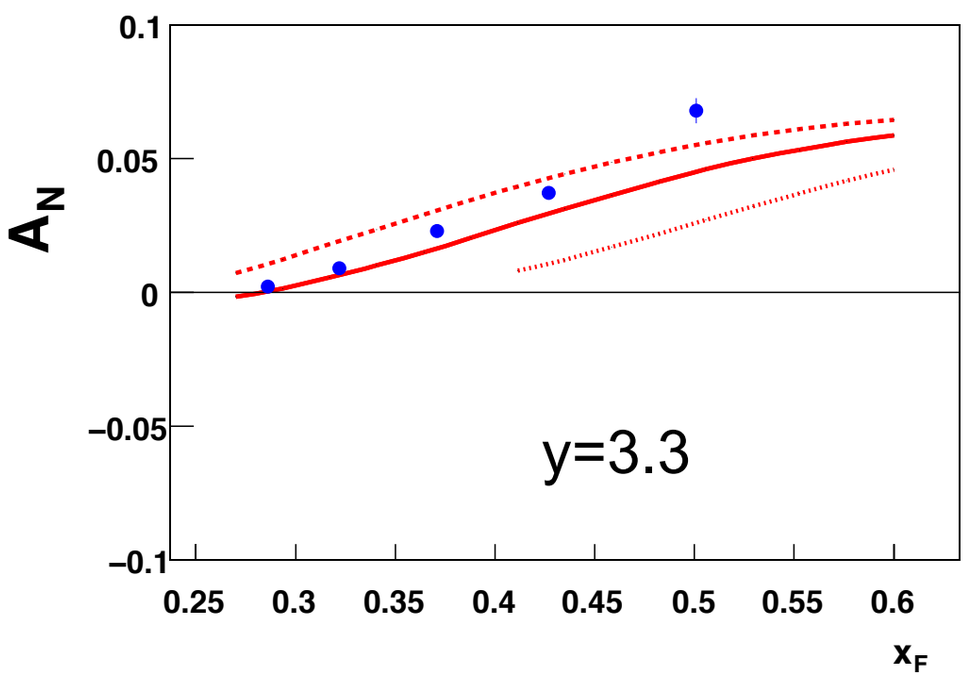
- SIDIS data comparison

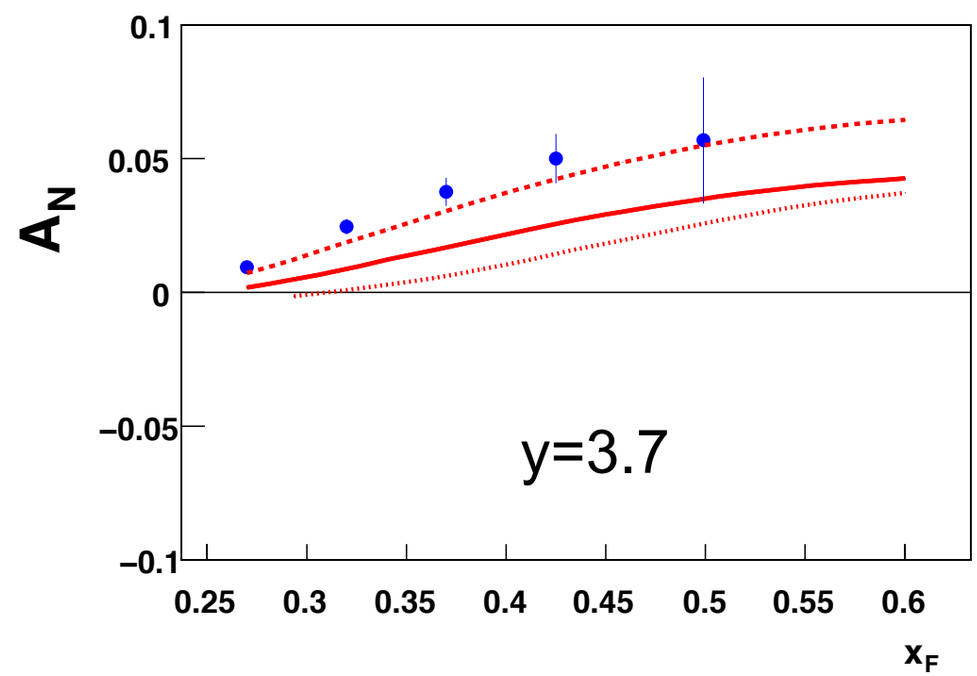
Kang-Prokudin, PRD, 2012





- STAR pi0 comparison

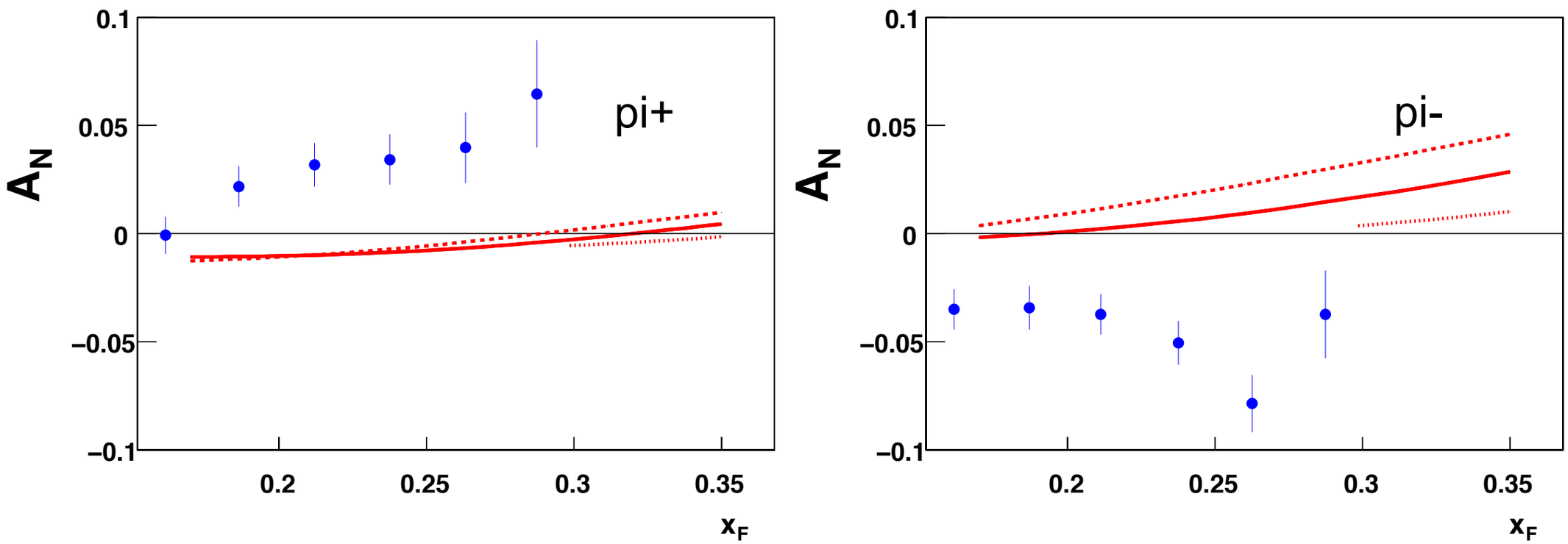




Fails for BRAHMS pi+ and pi-

- BRAHMS charged pion comparison

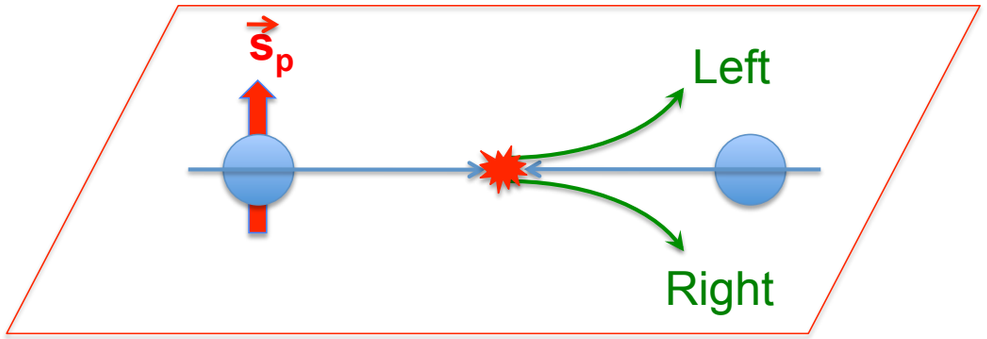
Kang-Prokudin, PRD, 2012

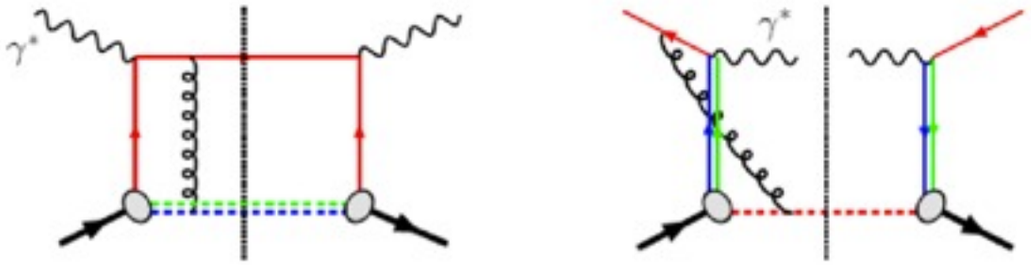


Recap: sign change and sign mismatch of Sivers effect

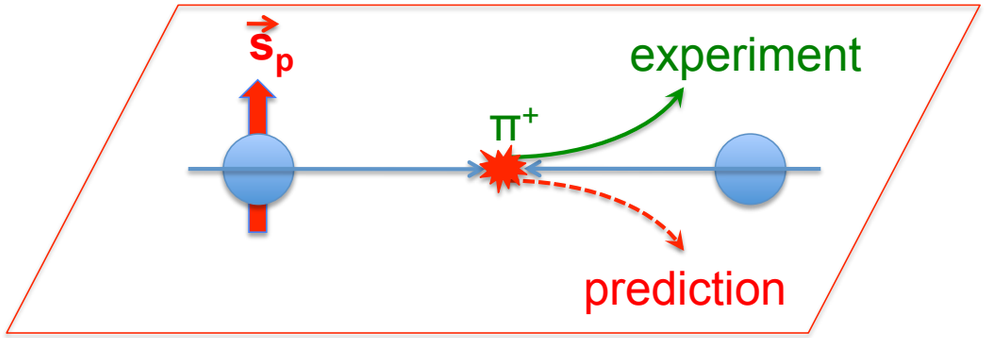
- Single transverse spin asymmetry is a left-right asymmetry
- Sivers effect has been proposed as one of the important contributions
- Sivers function depends on the interaction between the active parton and the remnant
- Final-state interaction in SIDIS and initial-state interaction in DY makes Sivers function opposite
- In pp collision, both FSI and ISI contributes. Take them consistently and use the Sivers function extracted from SIDIS to predict asymmetry in pp, one predicts the particle goes to right while experiments observes them go to left

Kang-Qiu-Vogelsang-Yuan, 2011





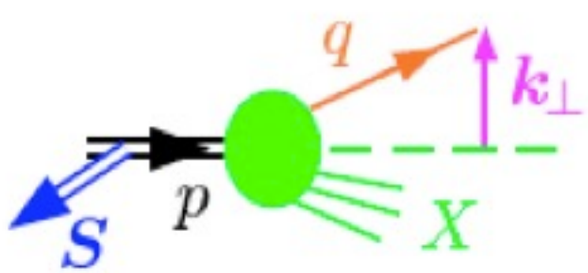
$$\Delta^N f^{\rm SIDIS}_{q/h^\uparrow}(x,k_\perp) = -\Delta^N f^{\rm DY}_{q/h^\uparrow}(x,k_\perp)$$



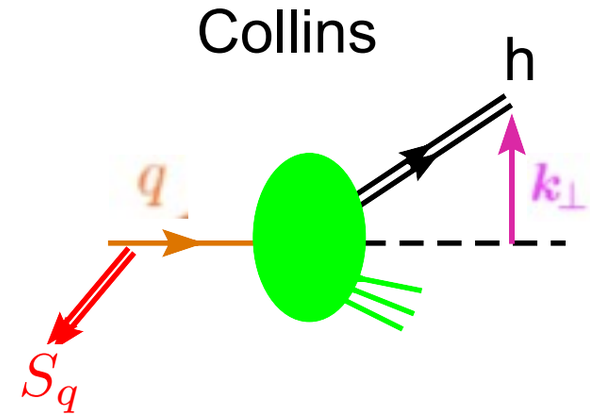
Other potential important contributions?

- Besides the usual Sivers-type contributions to the hadron spin asymmetry in pp collisions, there are also contributions from hadronization process (Collins contribution in the fragmentation function)

Sivers



Collins



Efremov-Teryaev 82, 84, Qiu-Sterman 91, 98 Kang-Yuan-Zhou 2010, Metz-Pitonyak 2012

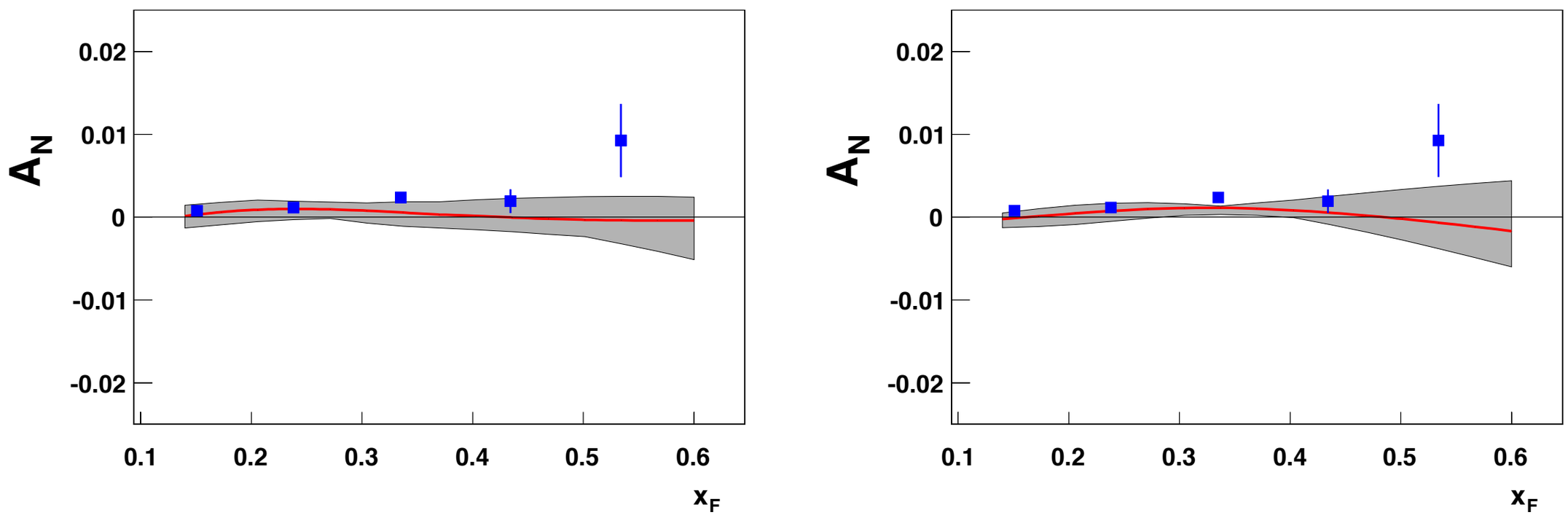
p+p→h+X

$$A_N = A_N|^{\mathrm{PDFs}} + A_N|^{\mathrm{FFs}}$$

New opportunity: jet spin asymmetry

- Now there is a new unique opportunity for studying the non-universality of the Sivers effect
  - The single transverse spin asymmetry of inclusive jet production: since there is no fragmentation function involving, there should be no Collins contribution

Data: AnDY at BNL, arXiv:1304.1454



Gamberg-Kang-Prokudin, PRL, 1302.3218

  - Left: use the Sivers function from Anselmino et.al.
  - Right: our own extraction for Sivers function (more freedom on high-x region)

Observation from this new comparison

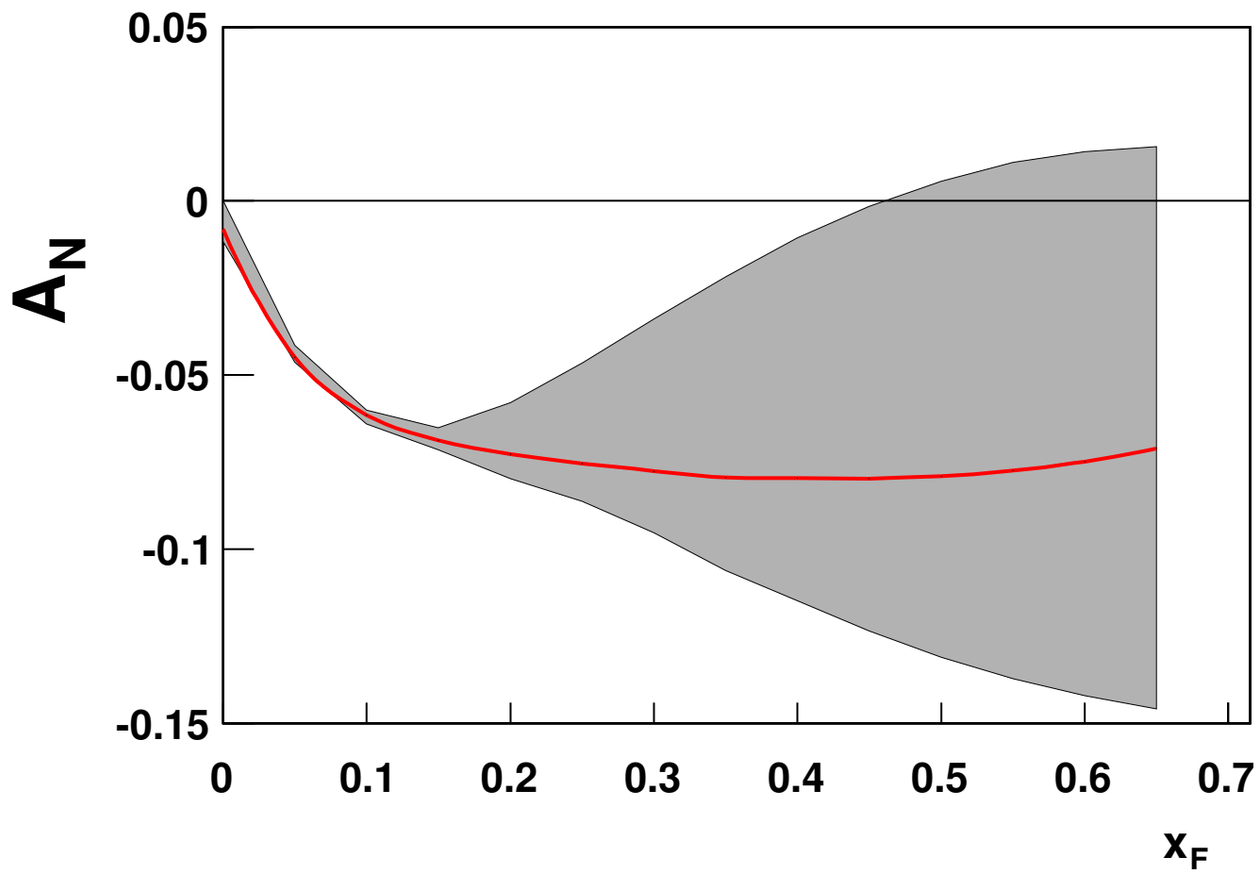
- After taking the initial-state and final-state interactions (process-dependence) of the Sivers effect carefully and consistently, the calculated jet spin asymmetry is roughly consistent with the recent AnDY experimental data
  - At least it is not in disagreement with the data (not like the hadron production case), which gives us confidence on the formalism
  - Because of the jet spin asymmetry is rather small, needs more data to claim the verification/confirm of the process dependence

- As the small-size of the jet spin asymmetry is caused by the cancelation between u and d quark Sivers functions (opposite sign), an ideal process to test the process dependence is still Drell-Yan production
  - Now with the electric charge weight, it compensates the cancelation

Prediction for Drell-Yan spin asymmetry

- At RHIC CM energy 500 GeV:

Gamberg-Kang-Prokudin, PRL, 1302.3218



The drawback of the current analysis

- Current analysis based on the operator relation between Sivers function and twist-3 Qiu-Sterman function

$$T_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

  - For SIDIS, we use TMD factorization with the Sivers function $f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$
  - For inclusive hadron in pp collisions, we use twist-3 factorization with the Qiu-Sterman function $T_{q,F}(x,x)$
  - In order to have a single parameterization to describe both processes, we use the above operator relation
  - However, the right-hand side can be really integrated out only when we assume some sort of Gaussian form for the kt-dependence for the TMDs
  - One immediate drawback is that: the energy evolution for the TMDs is difficult to be implemented

A new proposal

- Incorporate the energy evolution within the QCD resummation formalism, thus working with the collinear twist-3 correlation function directly (instead of working with the TMDs directly)
  - Take SIDIS Sivers effect as an example Kang-Xiao-Yuan, PRL, 1106.0266

$$\frac{d\sigma}{dx_B dy dz_h d^2P_{h\perp} d\phi_s} = \sigma_0 \left[F_{UU} + |s_\perp| \sin(\phi_h - \phi_s) F_{UT}^{\sin(\phi_h-\phi_s)} \right]$$

$$F_{UT}^{\sin(\phi_h-\phi_s)} = -\frac{1}{4\pi} \int_0^\infty db\, b^2 J_1(q_\perp b) W_{UT}(b, Q, x_B, z_h)$$

$$W_{UT}(b, Q, x_B, z_h) = e^{-S(b,Q)} \sum_q e_q^2 T_{q,F}(x_B, x_B, \mu = c/b) D_{h/q}(z_h, \mu = c/b)$$

  - Energy evolution for the Sivers function is included in the Sudakov factor (also need the non-perturbative part, which can be fixed through the low energy HERMES and COMPASS multiplicity data)

$$S(b, Q) = \int_{c^2/b^2}^{Q^2} \frac{d\mu^2}{\mu^2} \left[A(\alpha_s(\mu)) \ln\left(\frac{Q^2}{\mu^2}\right) + B(\alpha_s(\mu)) \right]$$

Single functional form for Qiu-Sterman function

- Now for inclusive hadron production we still use the usual collinear twist-3 formalism to describe the single spin asymmetry

$$E_h \frac{d\Delta\sigma(s_\perp)}{d^3P_h}\bigg|_{\rm Sivers} = \epsilon_{\alpha\beta} s_\perp^\alpha P_{h\perp}^\beta \frac{\alpha_s^2}{S} \sum_{a,b,c} \int \frac{dz}{z^2} D_{h/c}(z) \int \frac{dx'}{x'} f_{b/B}(x') \int \frac{dx}{x} \left[\frac{1}{z\hat{u}}\right]$$
$$\times \left[T_{a,F}(x,x) - x\frac{d}{dx}T_{a,F}(x,x)\right] H_{ab\to c}^{\rm Sivers}(\hat{s},\hat{t},\hat{u})\delta\left(\hat{s}+\hat{t}+\hat{u}\right)$$

  - Thus we have a unified formalism which can describe both SIDIS and pp data
  - At the same time, both TMD evolution and the collinear evolution are nicely incorporated in these formalisms

- For hadron case, we have also Collins effect

$$E_h \frac{d\Delta\sigma(s_\perp)}{d^3P_h}\bigg|_{\rm Collins} = \epsilon_{\alpha\beta} s_\perp^\alpha P_{h\perp}^\beta \frac{\alpha_s^2}{S} \sum_{a,b,c} \int \frac{dx}{x} h_a(x) \int \frac{dx'}{x'} f_{b/B}(x') \int \frac{dz}{z^2} \left[\hat{H}_c(z) - z\frac{d\hat{H}_c(z)}{dz}\right]$$
$$\times \left[\frac{1}{z}\frac{x-x'}{x(-\hat{u})+x'(-\hat{t})}\right] H_{ab\to c}^{\rm Collins}(\hat{s},\hat{t},\hat{u})\delta\left(\hat{s}+\hat{t}+\hat{u}\right)$$

Again for the Collins function

- For the Collins function side, we have the operator relation

$$\hat{H}_q(z) = -z^2 \int d^2k_\perp \frac{|k_\perp|^2}{M_h} H_1^{\perp q}(z, z^2 k_\perp^2)$$

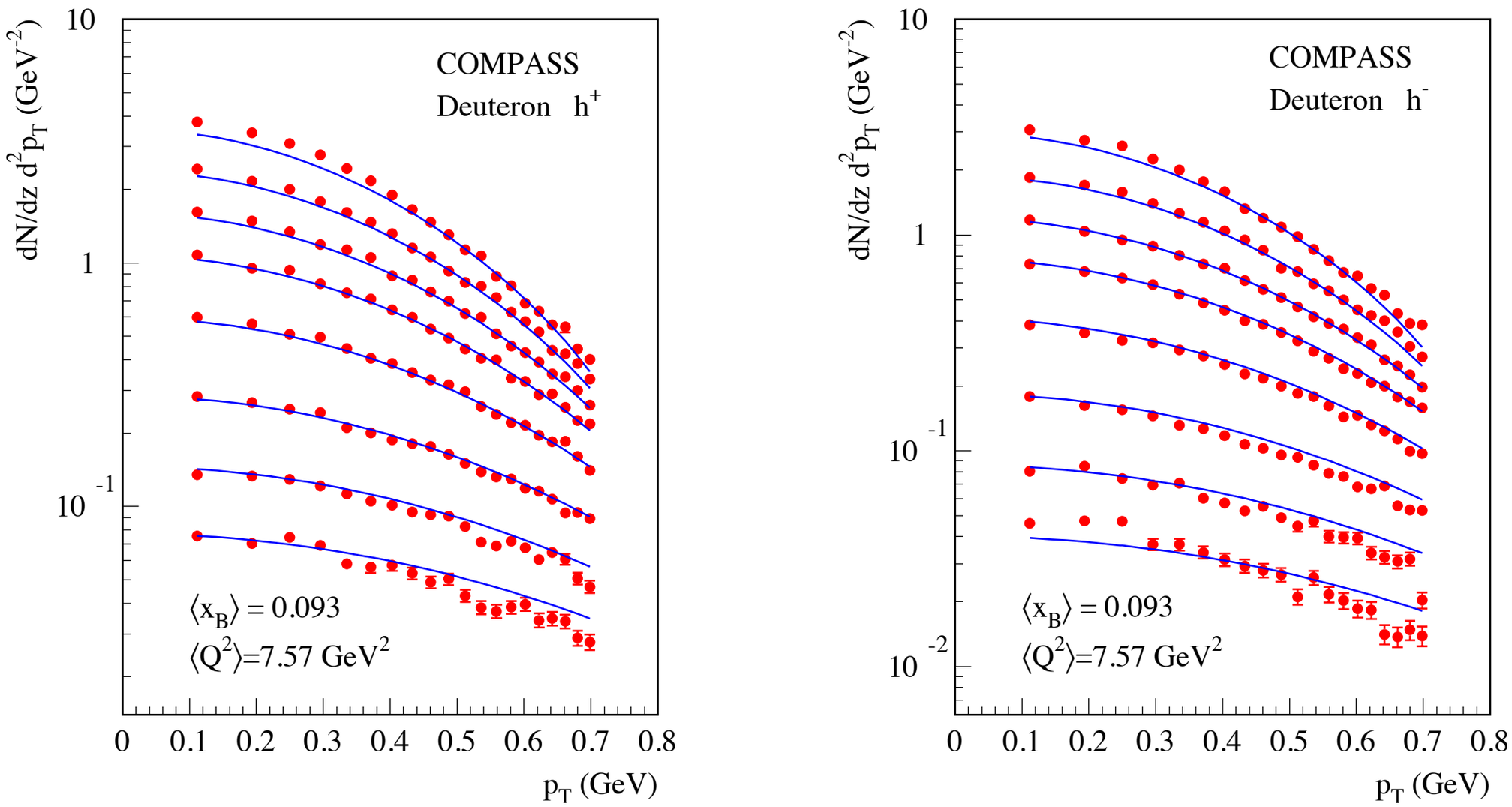
- At the same time, a similar resummation formalism which can be easily written down for the Collins asymmetry in SIDIS, and in e^+e^- processes

Gamberg-Kang-Prokudin, in preparation

  - QCD resummation formalism for SIDIS Sivers effect
  - QCD resummation formalism for SIDIS Collins effect, and for back-to-back dihadron correlation $\cos(2\phi)$ in e^+e^- collisions
  - For inclusive hadron production in pp collisions, use collinear twist-3 formalisms, we will include both Sivers and Collins type contributions
  - Perform such a true global fitting on all the experimental data will enable us learn a great deal about the underlying mechanism and test the universality of the Sivers and Collins effect

The resummation formalism could work

- Very preliminary result based on the resummation formalism (naive extrapolation from DY plus an adjustable fragmentation function parameter)



The comparison with the COMPASS data (deuteron target) The data points from top to bottom correspond to different z region: [0.2, 0.25], [0.25, 0.3], [0.3, 0.35], [0.35, 0.4], [0.4, 0.5], [0.5, 0.6], [0.6, 0.7], and [0.7, 0.8].

Summary

- The existence of Sivers function relies on the initial-state and final-state interactions
- Sivers effect is process dependent, and test this process-dependence is very important to understand the single transverse spin asymmetry and associated QCD factorization formalism
- The AnDY jet spin asymmetry gives us some confidence on the QCD formalism for the spin asymmetery
- Drell-Yan process still remains to be the most important and critical test for this process-dependence, we hope to have this measurement as soon as possible
- A new global fitting procedure is proposed, and should be used in the future analysis of all the experimental data

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Thank you