Transverse Spin Physics:Theory

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Why Spin?

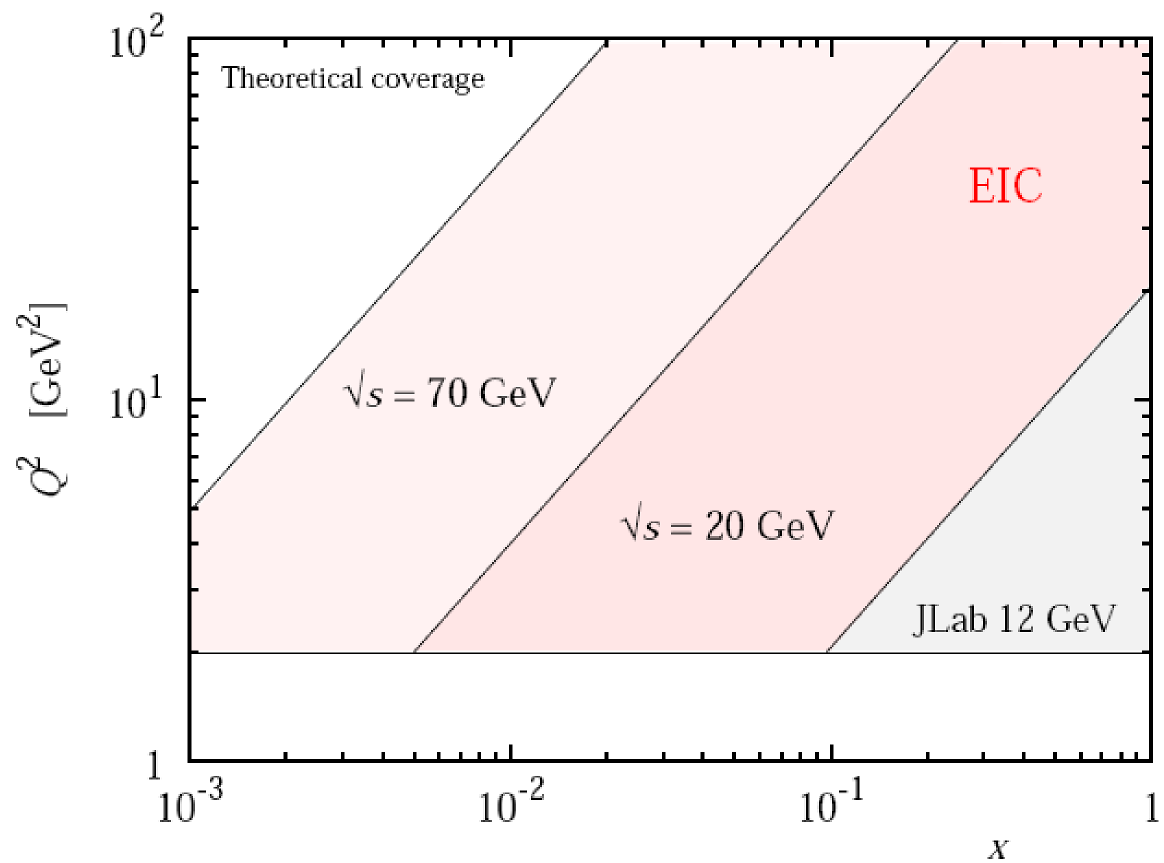
Xiangdong Ji at DIS08

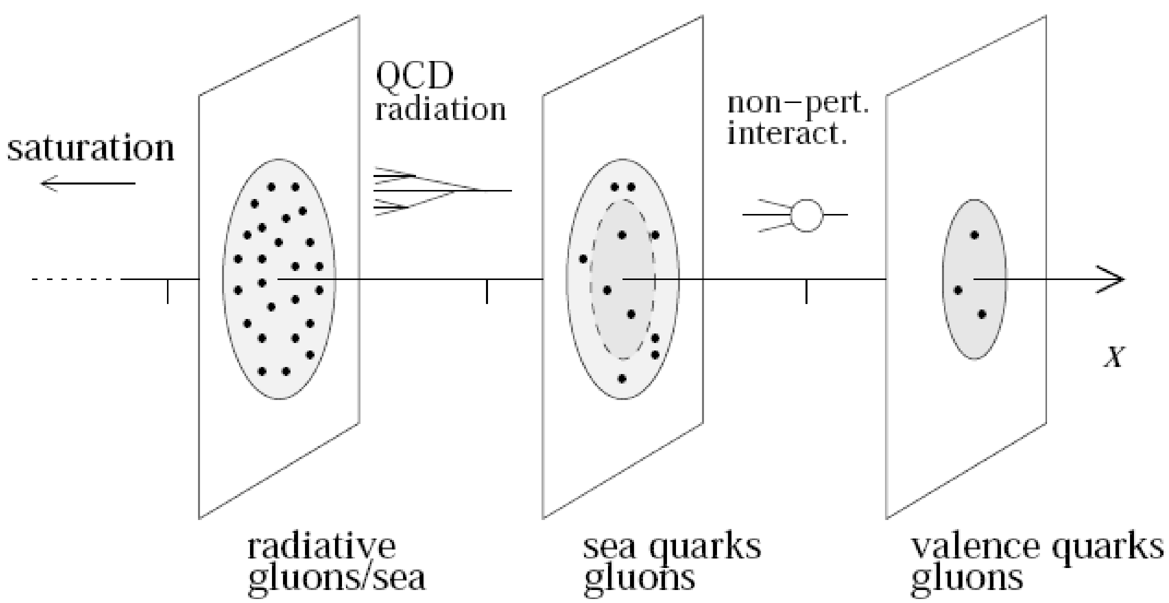
Spin is a fundamental quantum degree of freedom

Spin plays a critical role in determining the basic structure of fundamental interactions

Test of a theory is not complete without a full test of spin-dependent decays and scattering

Spin provides a unique opportunity to probe the inner structure of a composite system (such as the proton)





Nucleon is a many body dynamical system of quarks and gluons

Changing x we probe different aspects of nucleon wave function

How **partons move** and how they are distributed in **space** is one of the directions of development of nuclear physics

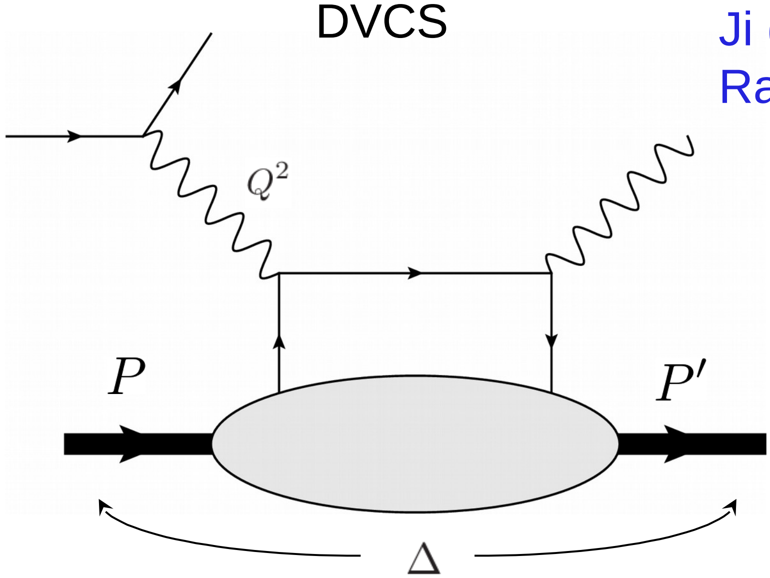
Technically such information is encoded into Generalised Parton Distributions and Transverse Momentum Dependent distributions

These distributions are also referred to as **3D (three-dimensional) distributions**

GPDs

DVCS

Ji (1997)
Radyushkin (1997)



Q^2 ensures hard scale, pointlike interaction

$\Delta = P' - P$ momentum transfer can be varied independently

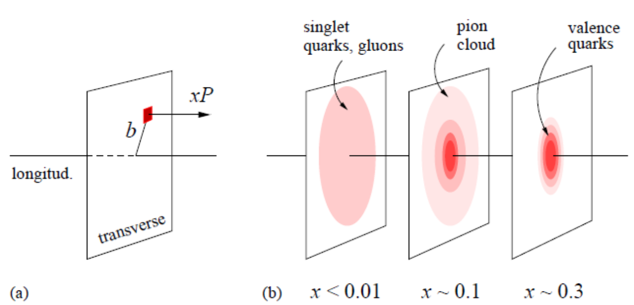
Connection to 3D structure

Burkardt (2000)
Burkardt (2003)

$$\rho(x, \vec{r}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-i\vec{\Delta}_\perp \cdot \vec{r}_\perp} H_q(x, \xi = 0, t = -\vec{\Delta}_\perp^2)$$

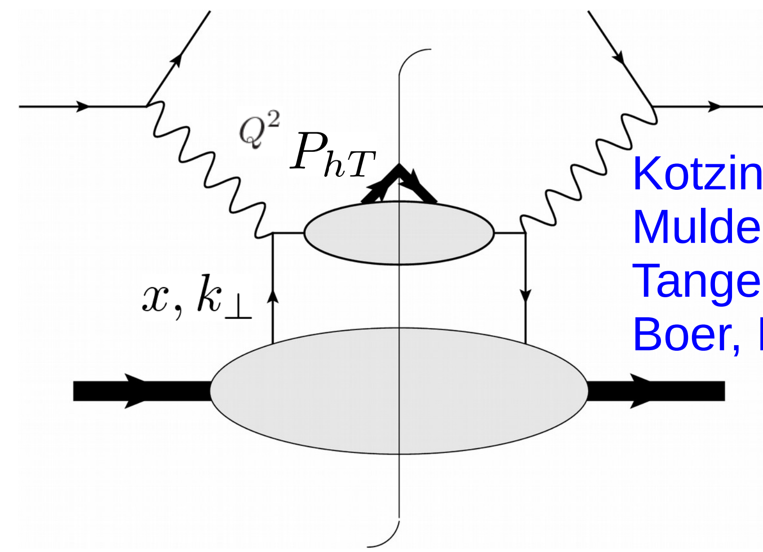
Drell-Yan frame $\Delta^+ = 0$

Weiss (2009)



TMDs

SIDIS



Kotzinian (1995), Mulders, Tangerman (1995), Boer, Mulders (1998)

Q^2 ensures hard scale, pointlike interaction

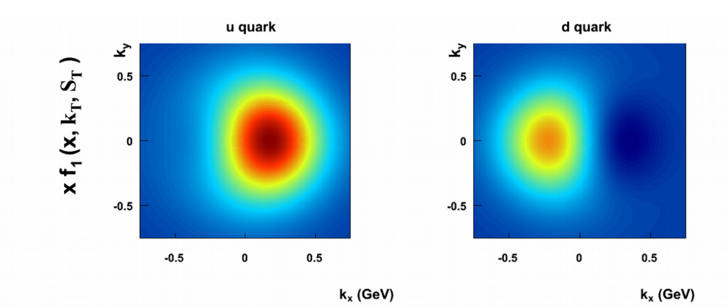
P_{hT} final hadron transverse momentum can be varied independently

Connection to 3D structure

Ji, Ma, Yuan (2004)
Collins (2011)

$$\tilde{f}(x, \vec{b}) = \int d^2k_\perp e^{-i\vec{b}\cdot\vec{k}_\perp} f(x, \vec{k}_\perp)$$

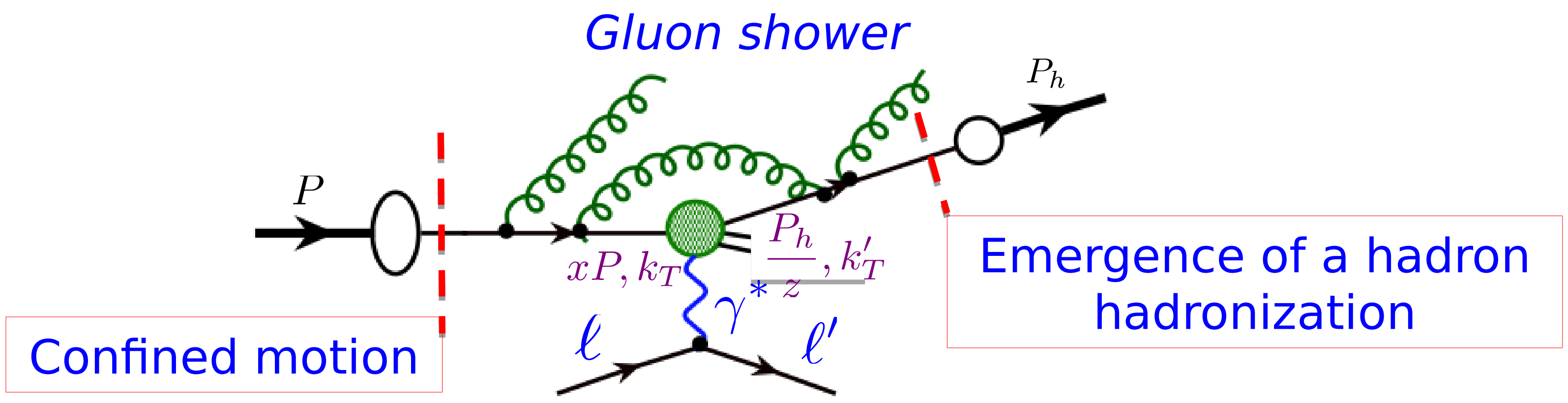
$\vec{b}$ is the transverse separation of parton fields in configuration space



AP (2012)

Why QCD evolution is interesting?

Study of evolution gives us insight on different aspects and origin of confined motion of partons, gluon radiation, parton fragmentation



Evolution allows to connect measurements at very different scales.

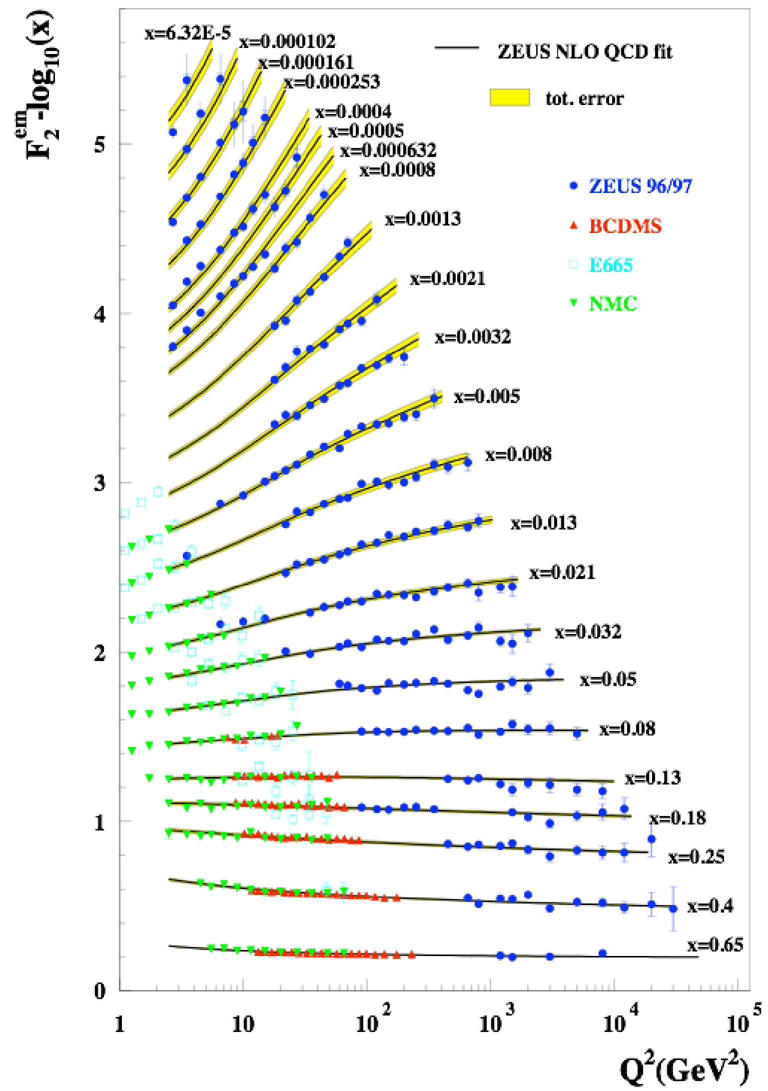
TMD evolution has also a universal non-perturbative part. The result of evolution cannot be uniquely predicted using evolution equations untill the non-perturbative part is reliably extracted from the data.

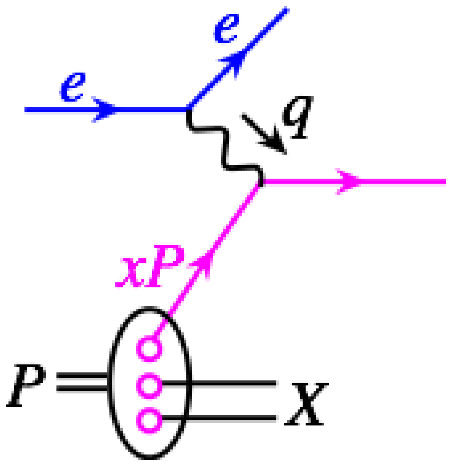
What do we mean by QCD evolution?

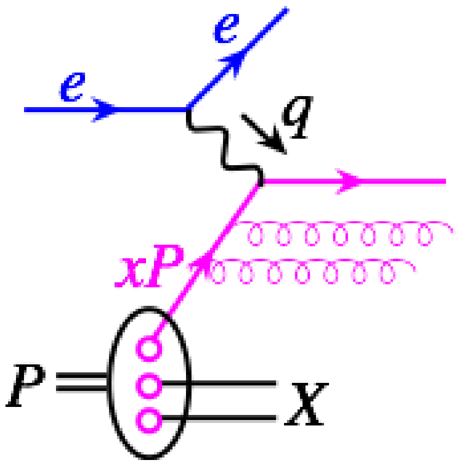
Very well known example: DGLAP evolution of collinear parton distributions

Take into account perturbative corrections

Single logarithms are resummed order by order in perturbative calculations







$$\left(\alpha_s \ln \frac{Q^2}{\mu^2}\right)^n$$

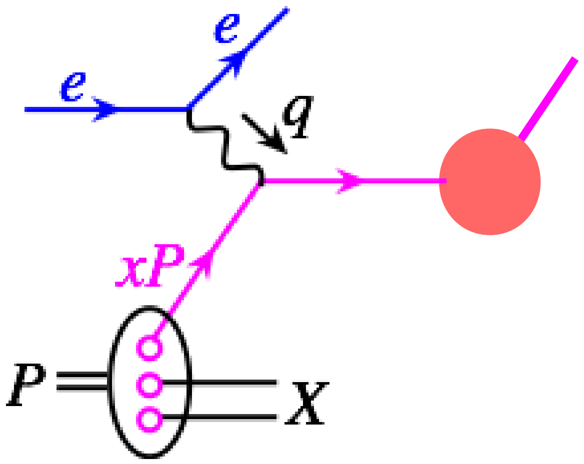
What do we mean by QCD evolution?

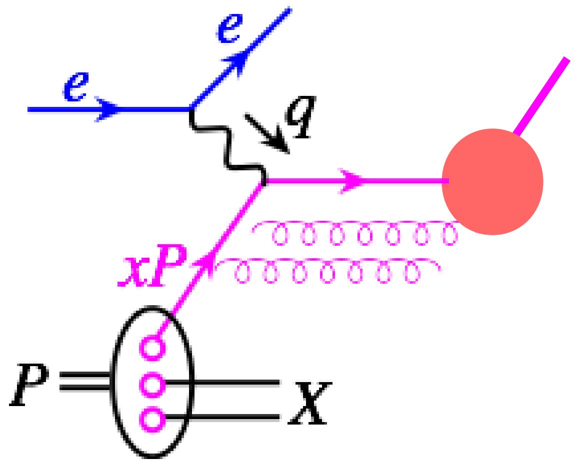
TMD factorization is applicable in case two different scales are observed in processes such as SIDIS, Drell-Yan, W/Z production in hadron-hadron collisions.
Kinematical regime: $Q_T \ll Q$

For SIDIS Q_T is transverse momentum of the photon in hadron – proton c.m. frame

Again we need to take into account perturbative corrections

Double logarithms are resummed order by order in perturbative calculations





$$\left(\alpha_s \ln^2 \frac{Q^2}{Q_T^2}\right)^n$$

Approaches to TMD evolution

Collins-Soper-Sterman (CSS) resummation framework

Collins-Soper-Sterman 1985
ResBos: C.P. Yuan, P. Nadolsky
Qiu-Zhang 1999, Vogelsang, etc...
Kang-Xiao-Yuan 2011
Sun-Yuan 2013

“New” Collins approach

Collins 2011
Aybat-Rogers 2011,
Aybat-Collins-Rogers-Qiu, 2012
Aybat-Prokudin-Rogers 2012
Anselmino-Boglione-Melis 2012
Prokudin-Bacchetta 2013
Echevarria-Idilbi-Kang-Vitev 2014
Collins-Rogers 2015
Kang-Prokudin-Sun-Yuan 2015
Collins et al 2016

Soft Collinear Effective Theory (SCET)

Echevarria-Idilbi-Schafer-Scimemi 2012
D'Alesio-Echevarria-Melis-Scimemi 2014
Echevarria-Scimemi-Vladimirov 2016

TMD evolution in a nut shell

TMD functions are measured at scale Q $\qquad f(x, k_\perp; Q)$

Evolution is performed in Fourier space

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

Standard CSS formalism, evolution starts from

$$\mu_b = c/b, \ \ c = 2e^{-\gamma_E}$$

$$\tilde{f}(x, b; Q) = \tilde{f}(x, b; \mu_b) e^{-S_{pert}(b)}$$

$$S_{pert}(b) = \int_{\mu_b}^{Q} \frac{d\mu}{\mu} \left(A \ln \frac{Q^2}{\mu^2} + B \right)$$

Perturbative Sudakov factor

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

TMD evolution in a nut shell

Calculation is perturbative, valid only in region $b \ll 1/\Lambda_{QCD}$

Fourier transform in momentum space involves non-perturbative region

$$f(x, k_\perp; Q) = \int_0^{\infty} \frac{bdb}{2\pi} J_0(k_\perp b) \tilde{f}(x, b; Q)$$

Non perturbative contribution to be fitted from experimental data.

$$\tilde{f}(x, b; Q) = \tilde{f}(x, b_*; c/b_*) e^{-S_{pert}(b_*)} e^{-S_{NP}(b)}$$

Non perturbative Sudakov factor

- The non perturbative part of evolution is the main reason of different predictions
- Very interesting object to investigate
- Universal in different processes

Collins, Rogers 2015
Prokudin, Sun, Yuan 2015
Collins et al 2016

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

8 functions in total (at leading twist)

Each represents different aspects of partonic structure

Each depends on Bjorken-x, transverse momentum, the scale

Each function is to be studied

Kotzinian (1995), Mulders, Tangerman (1995), Boer, Mulders (1998)

TMD distributions

N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

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This talk

Kotzinian (1995), Mulders, Tangerman (1995), Boer, Mulders (1998)

N \ q	U	L	T
U	D_1		$H_1^{\perp}$
L		G_{1L}	$H_{1L}^{\perp}$
T	$H_{1T}^{\perp}$	G_{1T}	H_1 $H_{1T}^{\perp}$

8 functions describing fragmentation of a quark into spin ½ hadron

Mulders, Tangerman (1995), Meissner, Metz, Pitonyak (2010)

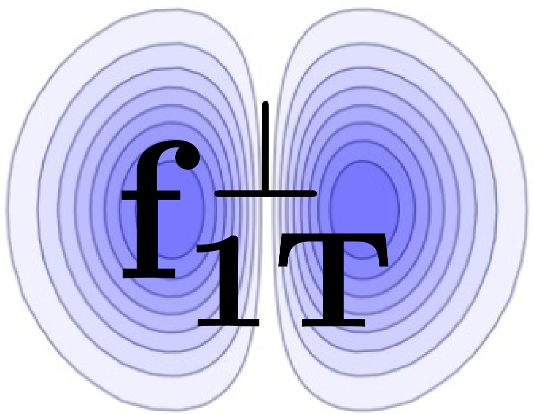
N \ q	U	L	T
U	D_1		$H_1^{\perp}$
L		G_{1L}	$H_{1L}^{\perp}$
T	$H_{1T}^{\perp}$	G_{1T}	H_1 $H_{1T}^{\perp}$

8 functions describing fragmentation of a quark into spin ½ hadron

This talk

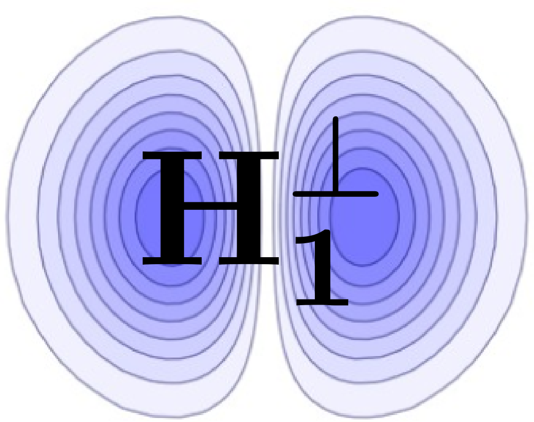
See talk of Daniel Pitonyak

Mulders, Tangerman (1995), Meissner, Metz, Pitonyak (2010)



Sivers function

Non universal

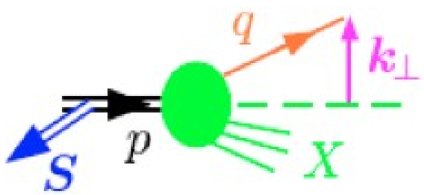


Collins function

Universal

Sivers function: unpolarized quark distribution inside a transversely polarized nucleon

Sivers 1989



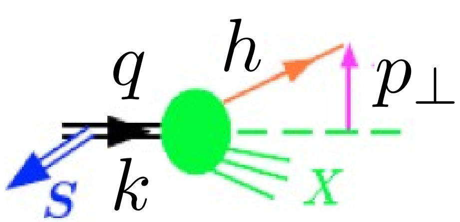
$$f_{q/h^\uparrow}(x,\vec{k}_\perp,\vec{S}) = f_{q/h}(x,k_\perp^2) - \frac{1}{M} f_{1T}^{\perp q}(x,k_\perp^2)\vec{S}\cdot(\hat{P}\times\vec{k}_\perp)$$

Spin independent

Spin dependent

Collins function: unpolarized hadron from a transversely polarized quark

Collins 1992



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

Sivers function: $f_{1T}^{\perp q}$ describes strength of correlation $\vec{S}\cdot(\hat{P}\times\vec{k}_\perp)$

Sivers 1989

Collins function: $H_1^{\perp q}$ describes strength of correlation $\vec{s}_q\cdot(\hat{k}\times\vec{p}_\perp)$

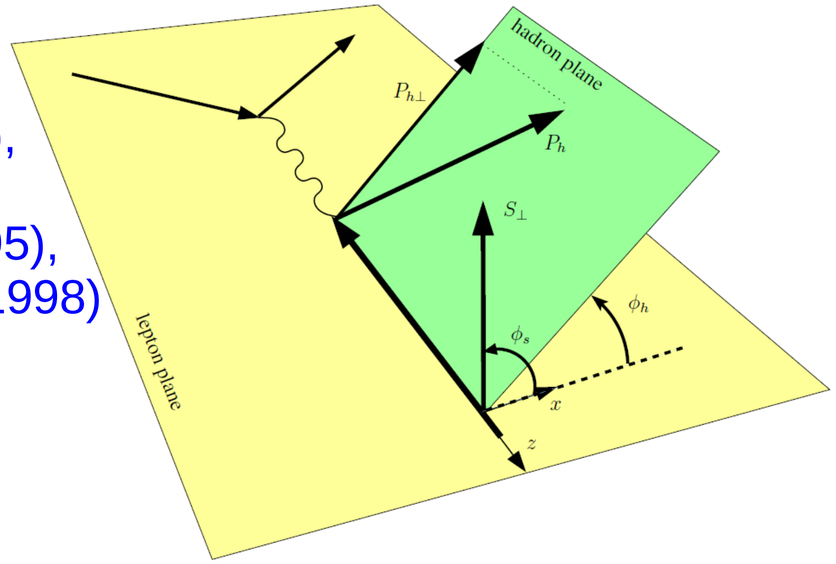
Collins 1992

Both functions extensively studied experimentally, phenomenologically, theoretically

Sivers function and Collins function can give rise to Single Spin Asymmetries in scattering processes. For instance in Semi Inclusive Deep Inelastic process

$\ell P \to \ell' \pi X$

Kotzinian (1995), Mulders, Tangerman (1995), Boer, Mulders (1998)



$$d\sigma(S) \sim \sin(\phi_h+\phi_S)h_1\otimes H_1^{\perp} + \sin(\phi_h-\phi_S)f_{1T}^{\perp}\otimes D_1 + \ldots$$

Sivers function

Large – N_c result $f_{1T}^{\perp u} = -f_{1T}^{\perp d}$ Pobylitsa 2003

➔ Confirmed by phenomenological extractions

➔ Confirmed by experimental measurements

Relation to GPDs (E) and anomalous magnetic moment Burkardt 2002

$$f_{1T}^{\perp q} \sim \kappa^q$$

➔ Predicted correct sign of Sivers asymmetry in SIDIS

➔ Shown to be model-dependent Meissner, Metz, Goeke 2007

➔ Used in phenomenological extractions Bacchetta, Radici 2011

Sivers function

Sum rule

Burkardt 2004

- Conservation of transverse momentum
- Average transverse momentum shift of a quark inside a transversely polarized nucleon

$$\langle k_T^{i,q} \rangle = \varepsilon_T^{ij} S_T^j f_{1T}^{\perp(1)q}(x)$$

$$f_{1T}^{\perp(1)q}(x) = \int d^2 k_\perp \frac{k_\perp^2}{2M^2} f_{1T}^{\perp q}(x, k_\perp^2)$$

- Sum rule

$$\sum_q \int_0^1 dx \langle k_T^{i,q} \rangle = 0 \qquad \sum_q \int_0^1 dx\, f_{1T}^{\perp(1)q}(x) = 0$$

Sivers function

Extractions

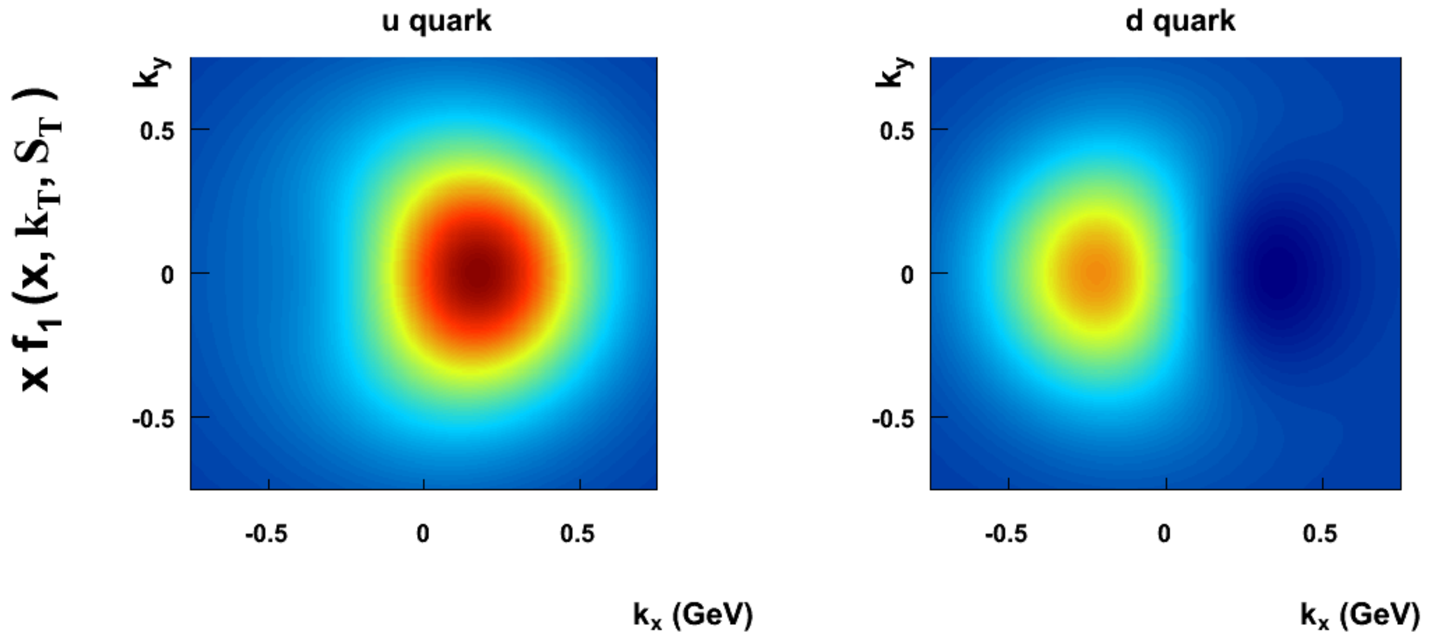
- Many extractions without taking into account TMD evolution

  Efremov et al 2005, Vogelsang, Yuan 2005, Anselmino et al 2005,
  Collins et al 2006, Anselmino et al 2009, 2011, 2016, Bacchetta Radici 2011

- Extractions with TMD evolution Echevarria et al 2014, Sun Yuan 2013

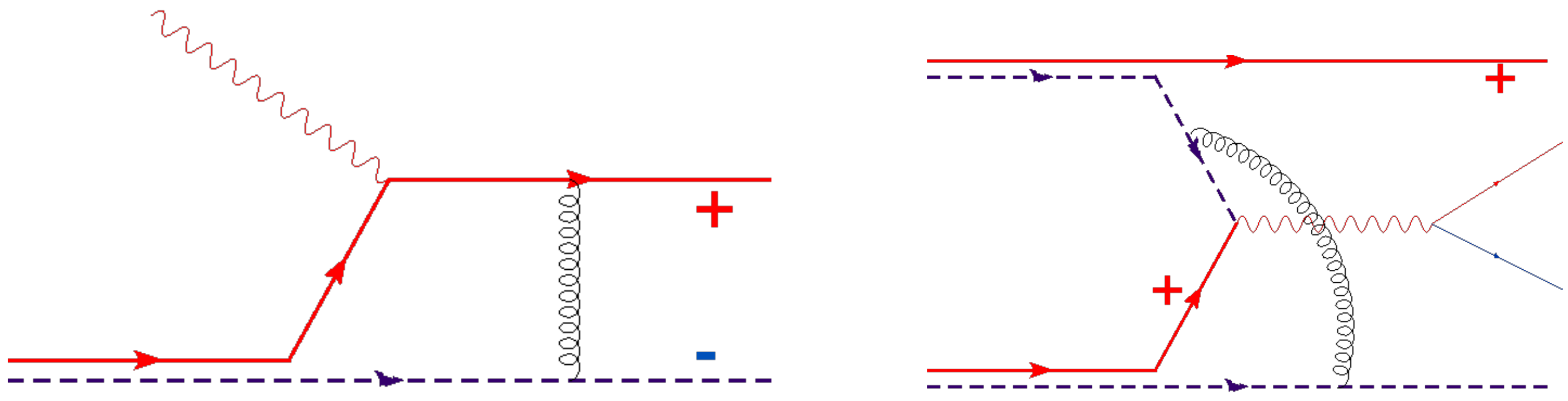
- Relation to the tomography of the nucleon

Anselmino et al 2011



- Agreement with the sum rule and large N_c prediction

Colored objects are surrounded by gluons, profound consequence of gauge invariance: Sivers function has opposite sign when gluon couple after quark scatters (SIDIS) or before quark annihilates (Drell-Yan)



$$f_{1T}^{\perp SIDIS} = - f_{1T}^{\perp DY}$$

Brodsky,Hwang,Schmidt;
Belitsky,Ji,Yuan;
Collins;
Boer,Mulders,Pijlman;
Kang, Qiu;
Kovchegov, Sievert;
etc

Crucial test of TMD factorization and collinear twist-3 factorization
Several labs worldwide aim at measurement of Sivers effect in Drell-Yan
BNL, CERN, GSI, IHEP, JINR, FERMILAB etc
Barone et al., Anselmino et al., Yuan,Vogelsang, Schlegel et al., Kang,Qiu, Metz,Zhou etc
The verification of the sign change is a DOE milestone

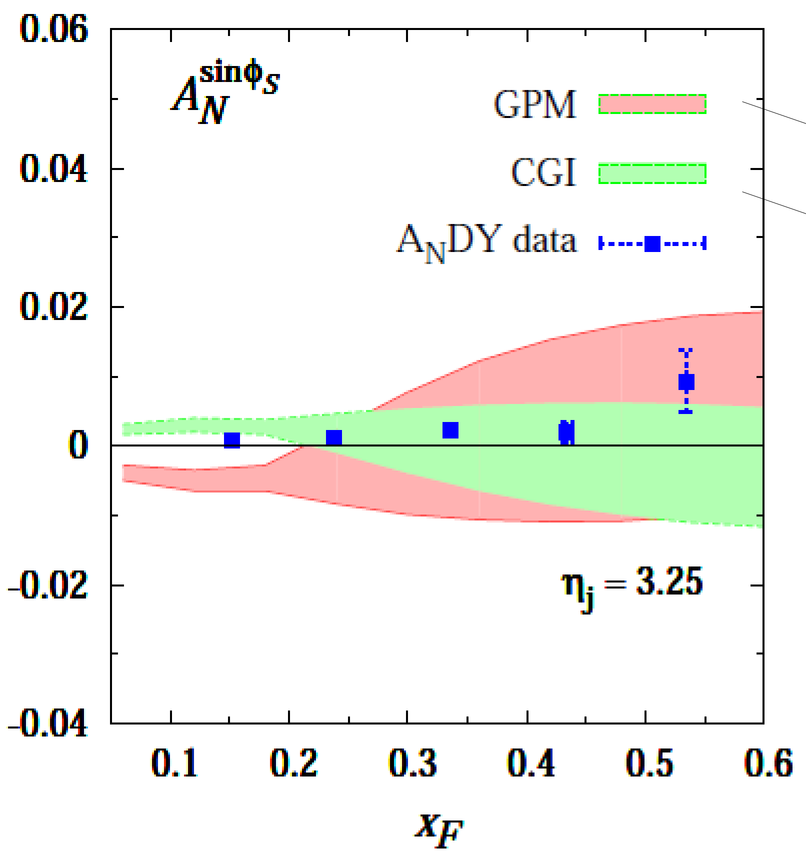
Process dependence of Sivers function

- Indication on process dependence of Sivers functions from analysis of A_N in $\ell N^{\uparrow} \to \ell X$

Metz et al 2012

- Indication on process dependence from AnDY data on A_N in $p^{\uparrow} p \to jet X$

Gamberg, Kang, AP 2013
D'Alesio et al 2013



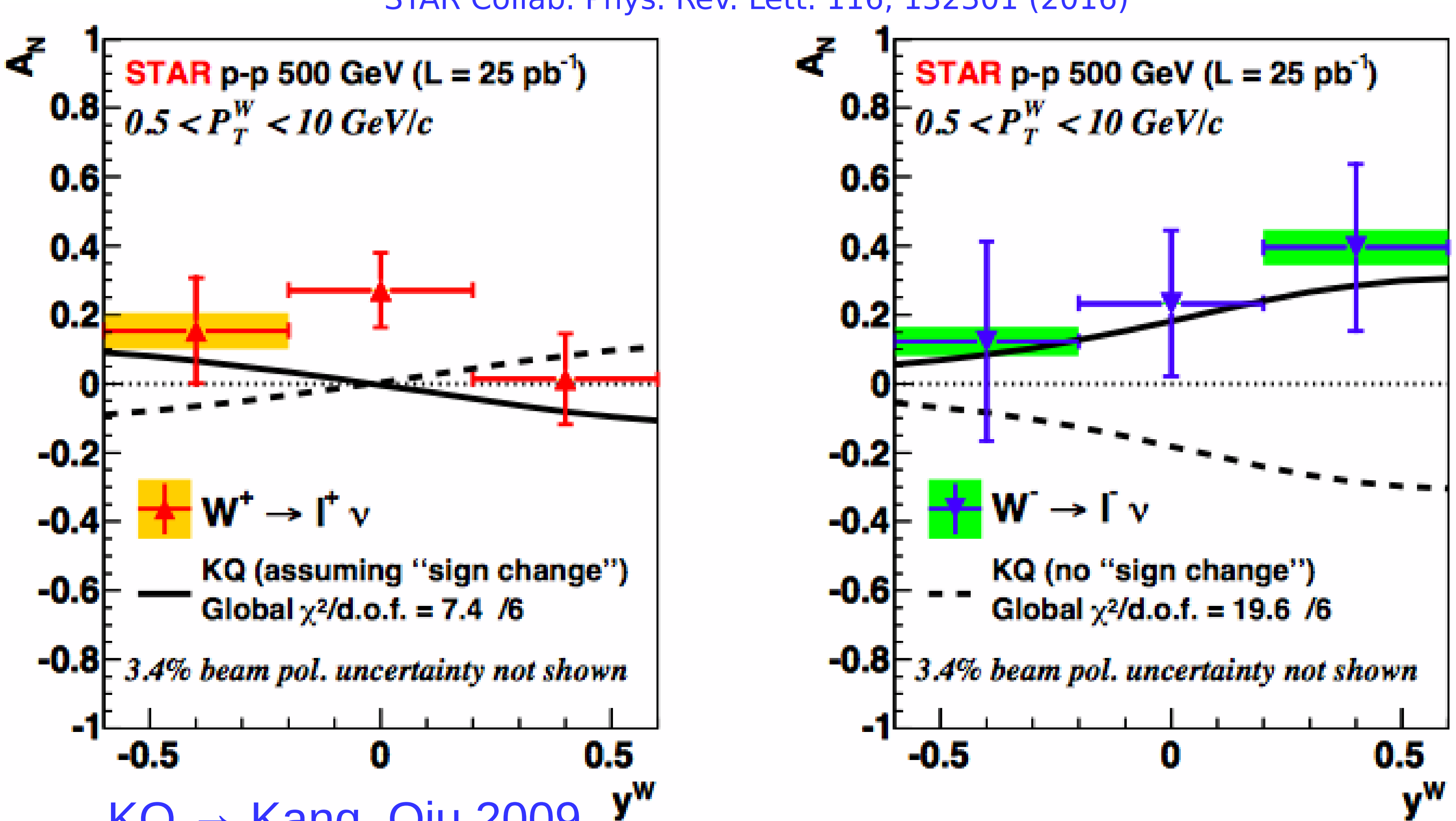
No sign change
Sign change

Process dependence of Sivers function

STAR 2015

- First experimental hint on the sign change: A_N in W and Z production

STAR Collab. Phys. Rev. Lett. 116, 132301 (2016)



KQ → Kanq, Qiu 2009

$$p^\uparrow p \rightarrow W^\pm X$$
$$p^\uparrow p \rightarrow Z^0 X$$

- Sign change $\chi^2/d.o.f \sim 1.2$
- No sign change $\chi^2/d.o.f \sim 3.2$

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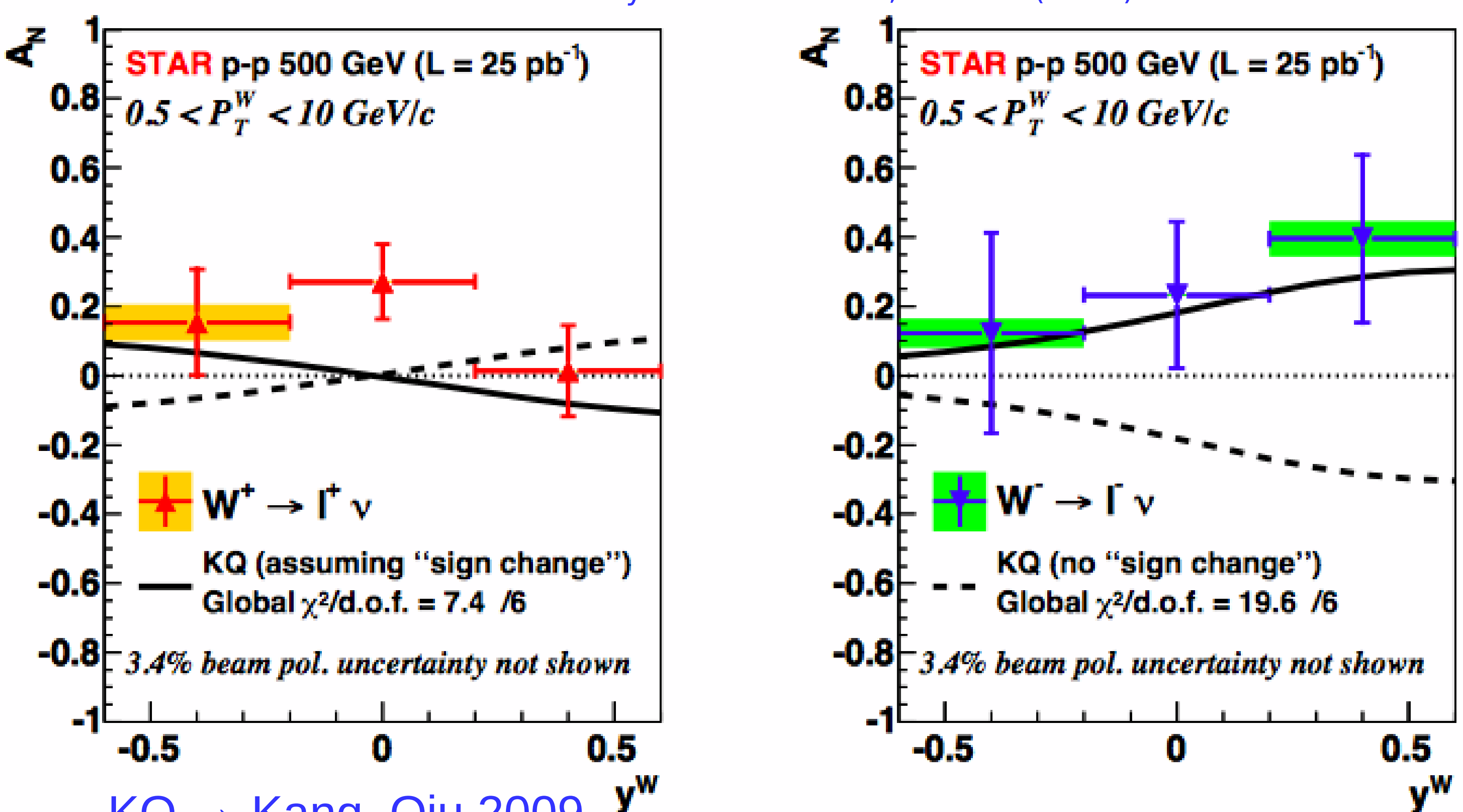

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- Large uncertainties of predictions
- No antiquark Sivers functions

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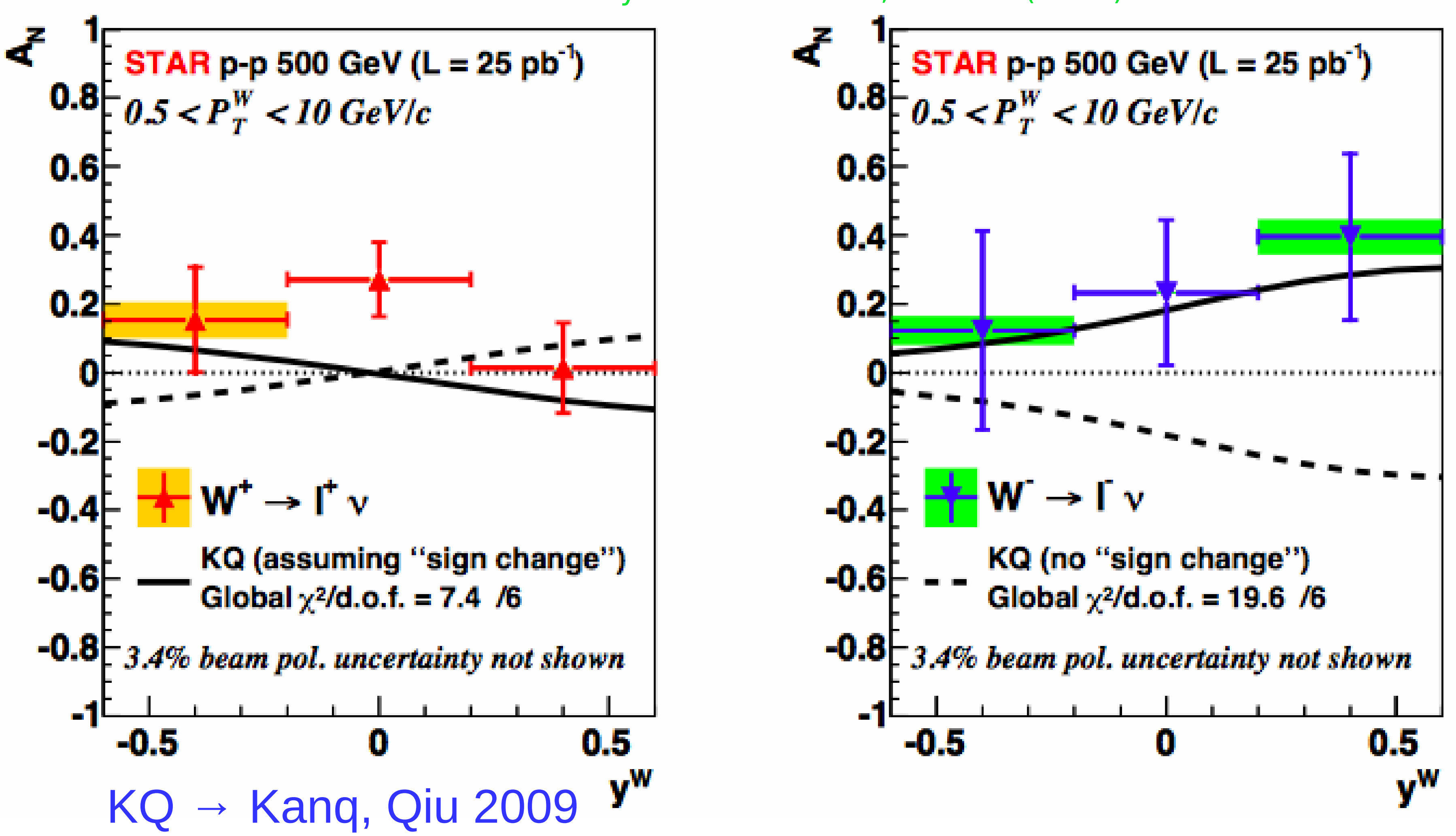

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Anselmino et al 2016 in preparation

Process dependence of Sivers function

Anselmino et al 2016 in preparation

STAR 2015

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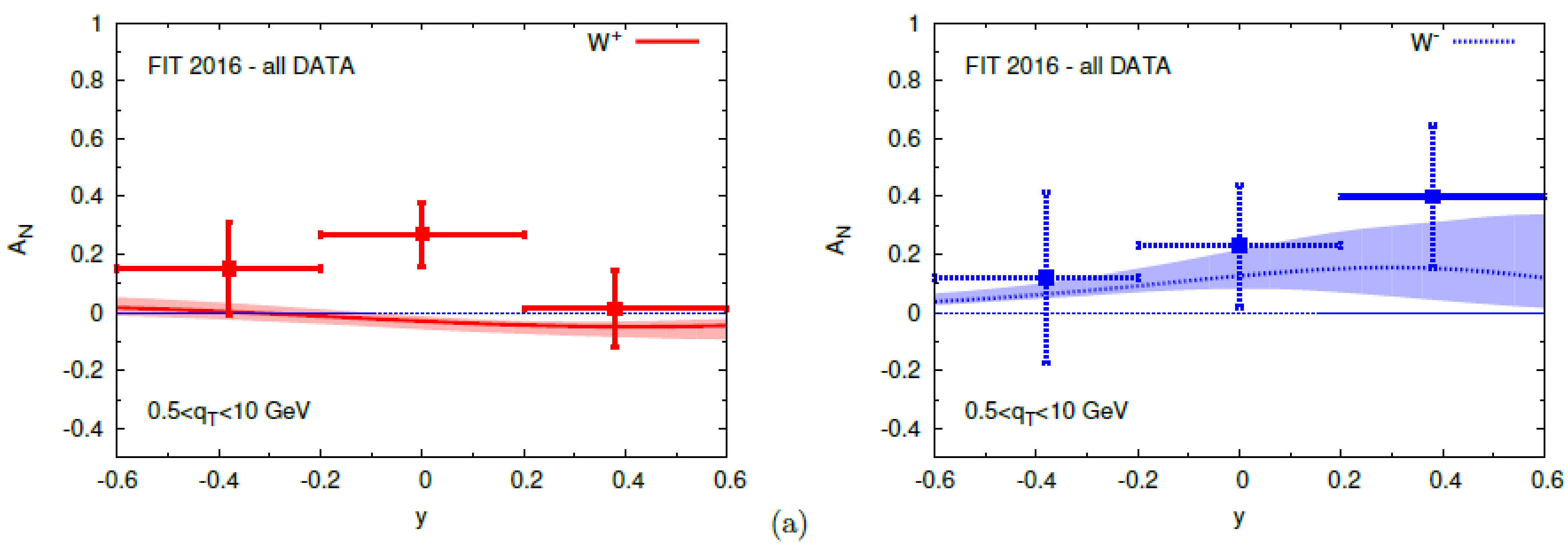
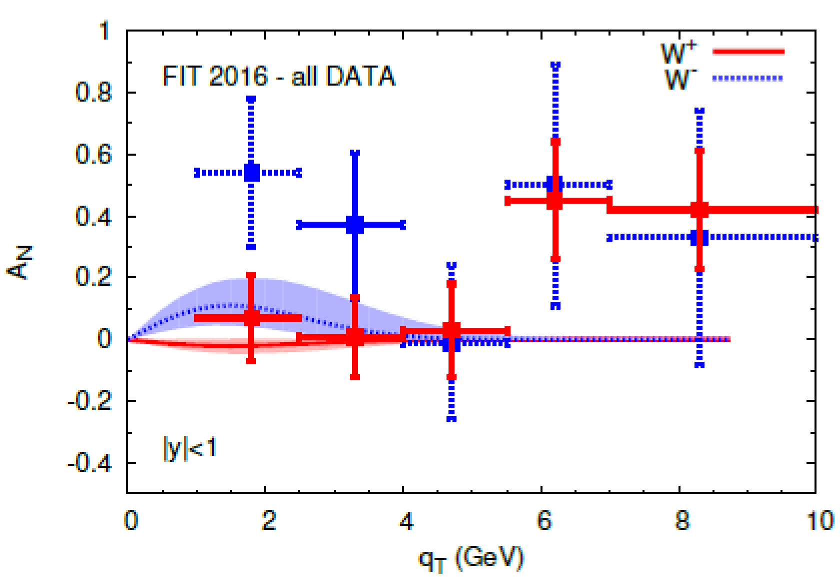


(a)

$$p^{\uparrow}p \to W^{\pm}X$$



- Results with sign change
- No TMD evolution
- Antiquark Sivers functions included

Process dependence of Sivers function

Anselmino et al 2016 in preparation

STAR 2015

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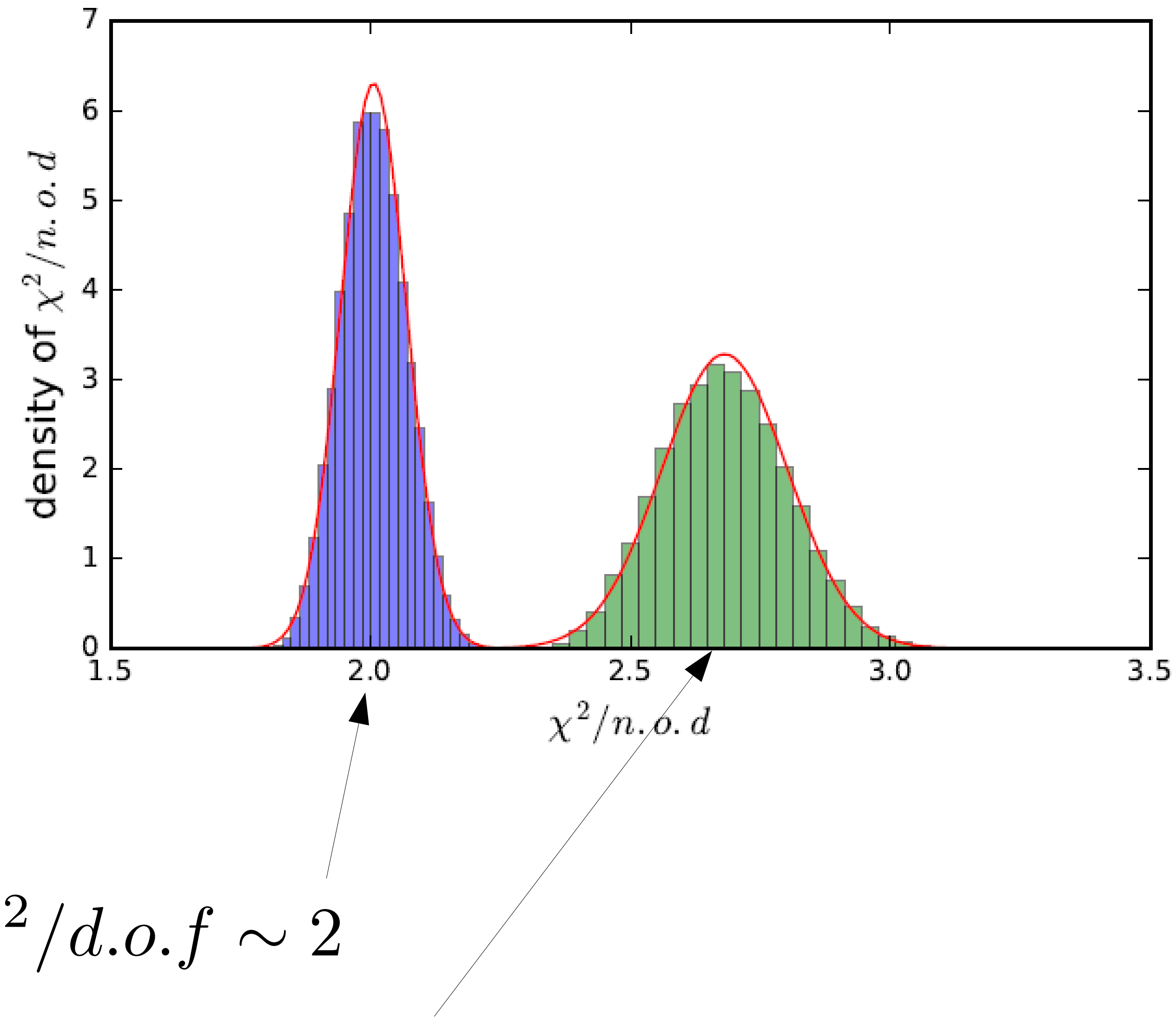

- Sign change $\chi^2/d.o.f \sim 2$
- No sign change $\chi^2/d.o.f \sim 2.68$

Process dependence of Sivers function

Anselmino et al 2016 in preparation

STAR 2015

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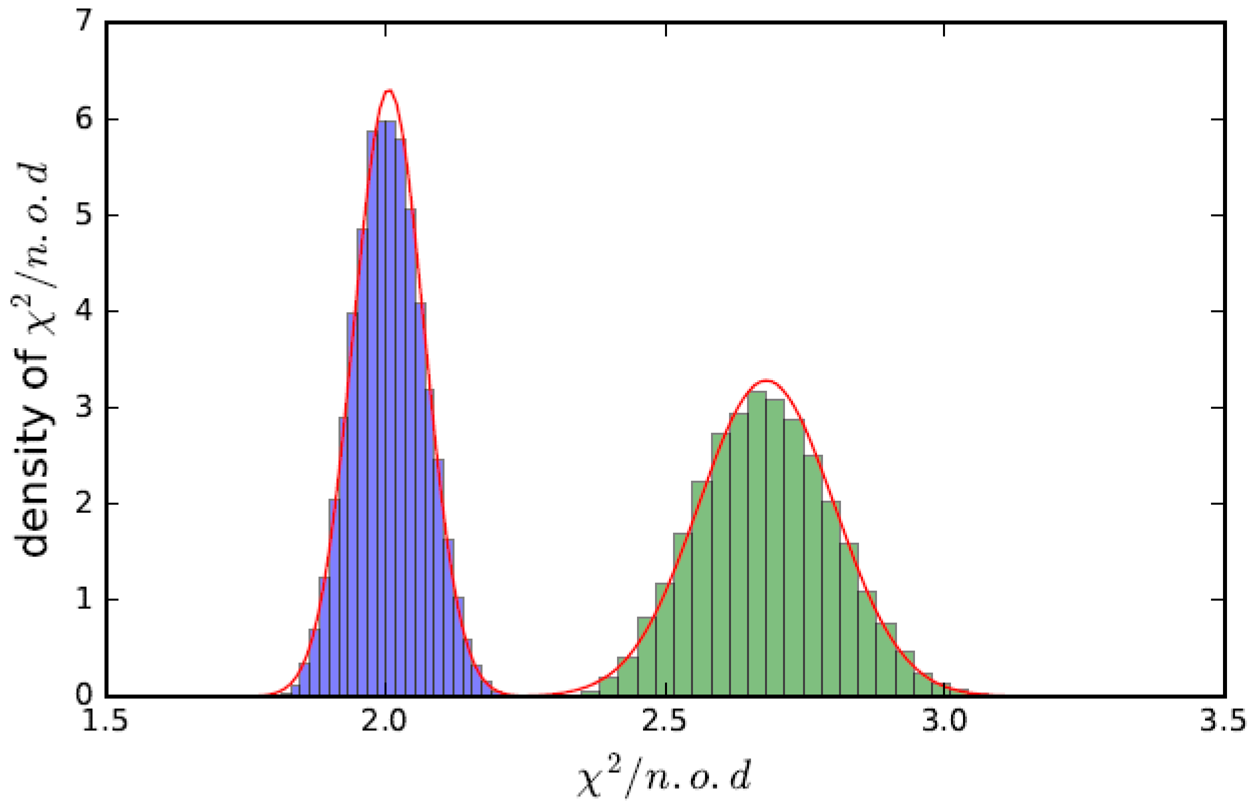


- STAR results *hint* on sign change
- Sign change $\chi^2/d.o.f \sim 2$
- More precise data is needed
- No sign change $\chi^2/d.o.f \sim 2.68$
- Drell-Yan measurements are needed

Collins function

Schafer-Teryaev sum rule

Schafer Teryaev 1999
Meissner, Metz, Pitonyak 2010

- Conservation of transverse momentum

$$\langle P_T^i(z)\rangle \sim H_1^{\perp(1)}(z) \qquad H_1^{\perp(1)}(z) = \int d^2p_\perp \frac{p_\perp^2}{2z^2M_h^2} H_1^\perp(z,p_\perp^2)$$

- Sum rule

$$\sum_h \int_0^1 dz \langle P_T^i(z)\rangle = 0$$

- If only pions are considered $H_1^{\perp fav}(z) \sim -H_1^{\perp unf}(z)$

Universality of TMD fragmentation functions

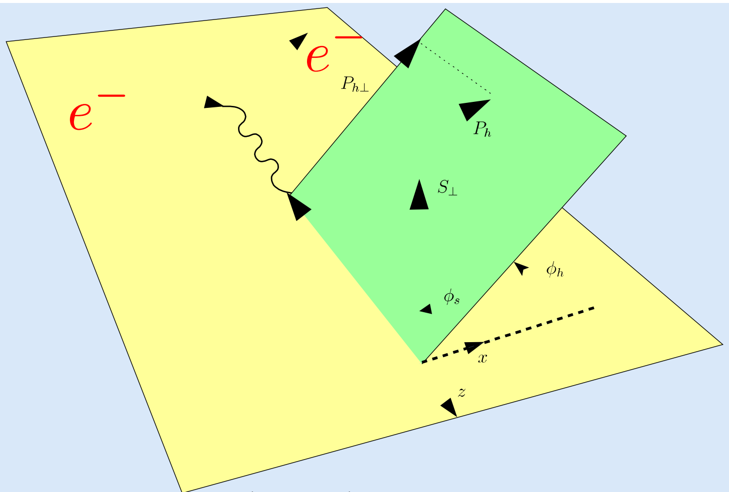
Metz 2002, Metz, Collins 2004, Yuan 2008
Gamberg, Mukherjee, Mulders 2011
Boer, Kang, Vogelsang, Yuan 2010

$$H_1^\perp(z)|_{SIDIS} = H_1^\perp(z)|_{e^+e^-} = H_1^\perp(z)|_{pp}$$

- Very non trivial results
- Agrees with phenomenology, allows global fits

Transversity and Collins FF

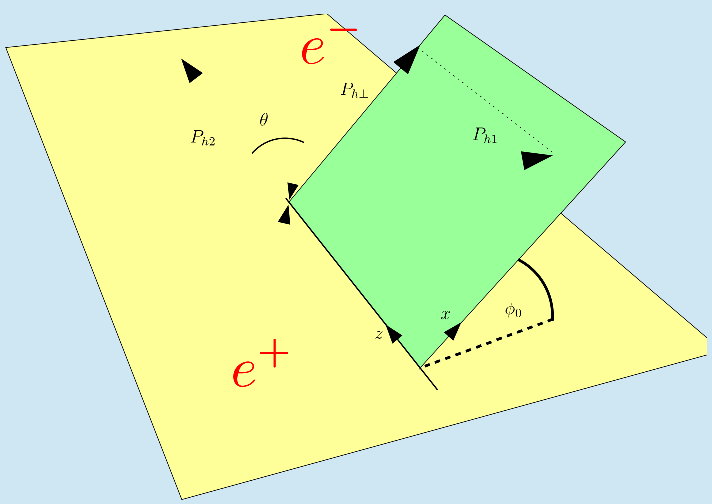
- SIDIS and e+e-: combined global analysis



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

transversity — Collins function

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



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

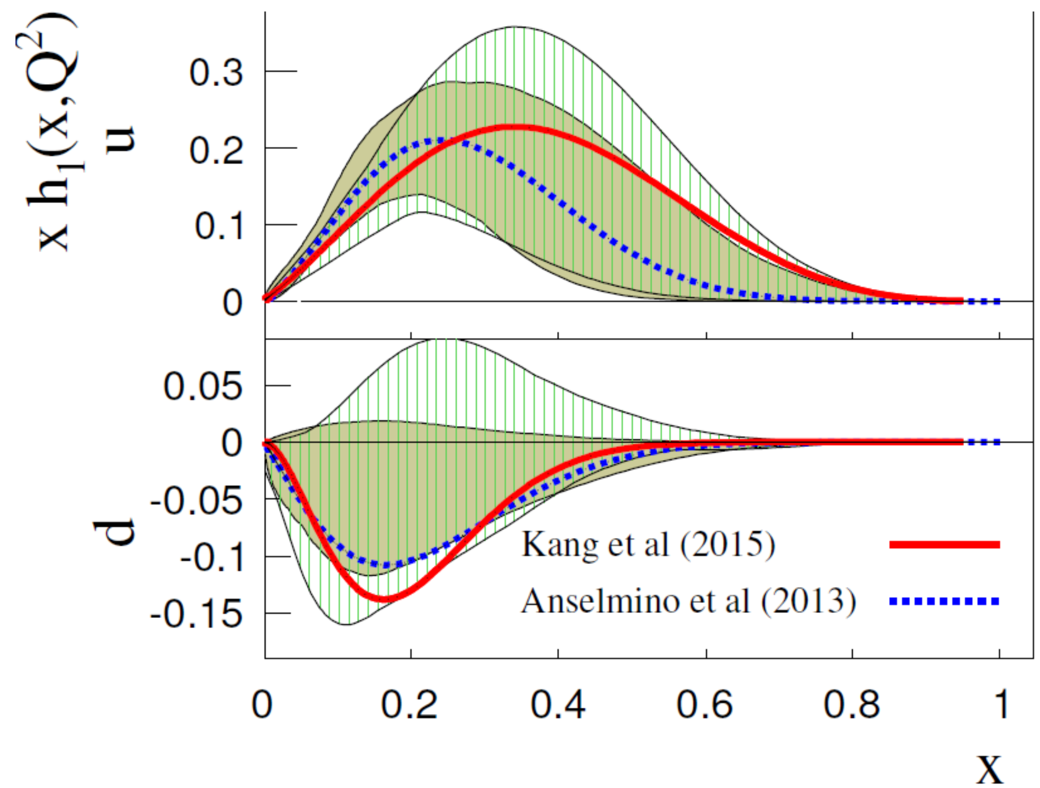
Collins function

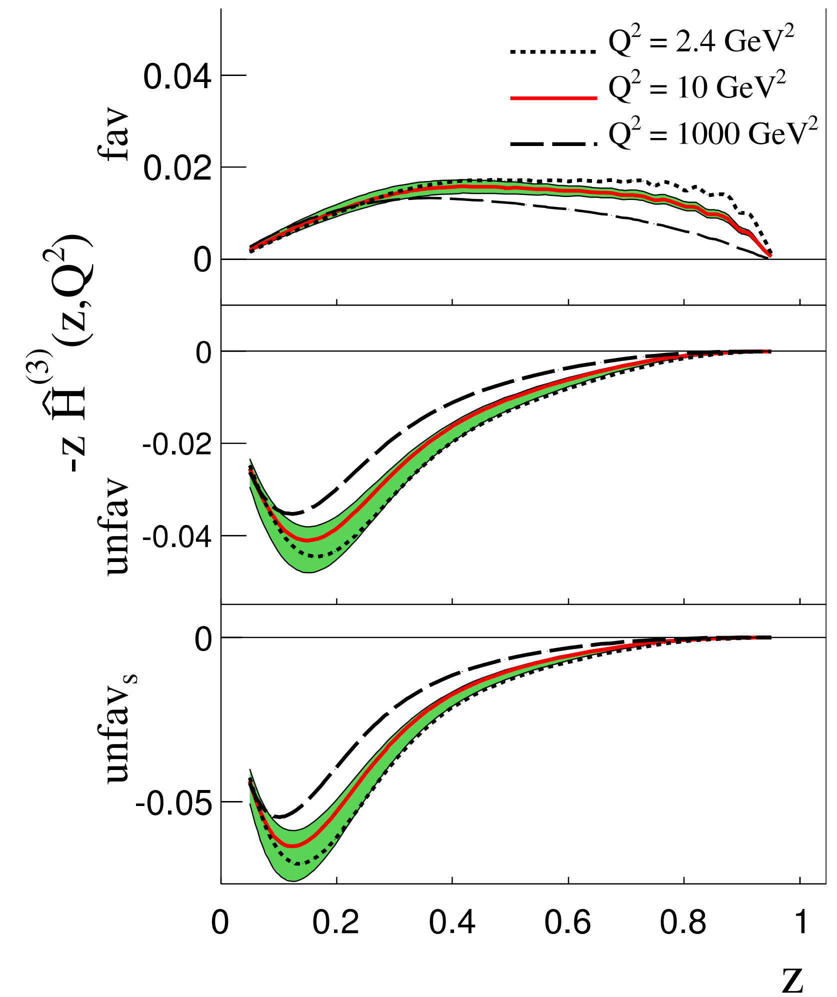
$$\frac{d\sigma^{e^+e^-\to h_1 h_2 + X}}{dz_{h1}\, dz_{h2}\, d^2P_{h\perp}\, d\cos\theta} = \frac{N_c \pi \alpha_{\rm em}^2}{2Q^2}\left[\left(1+\cos^2\theta\right) Z_{uu}^{h_1 h_2} + \sin^2\theta\cos(2\phi_0) Z_{\rm collins}^{h_1 h_2}\right]$$

Transversity and Collins FF

Kang-Prokudin-Sun-Yuan 2015
Anselmino et al 2015

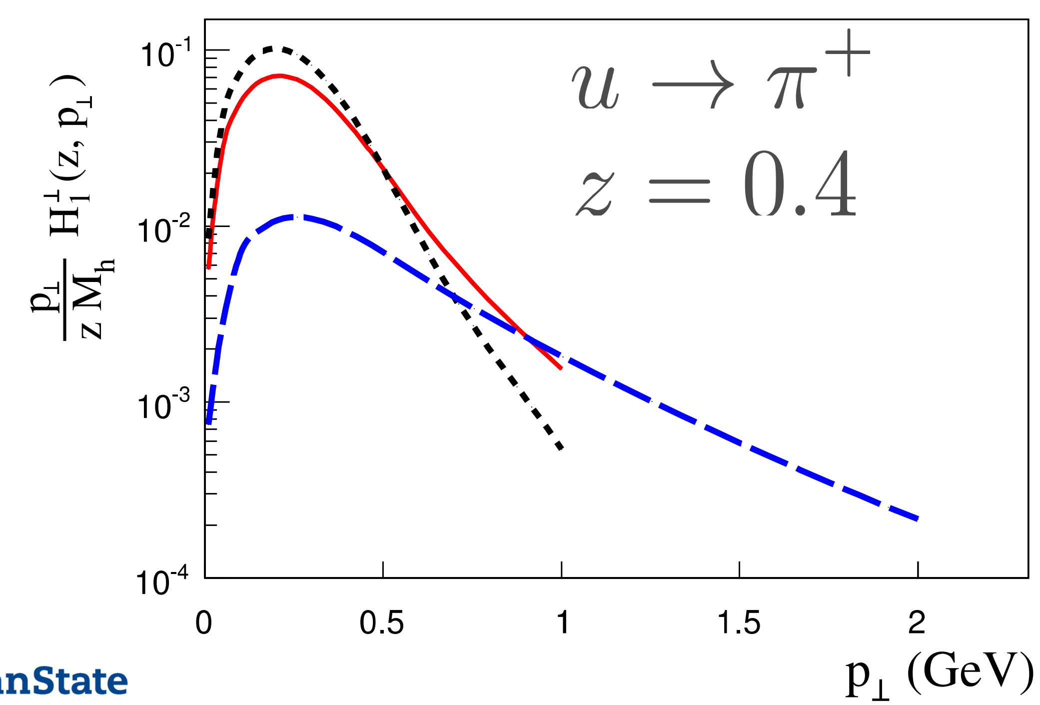
- Fitted quark transversity and Collins function: x (z) -dependence





$$\mathrm{fav}: \quad u \to \pi^+$$
$$\mathrm{unfav}: \quad d \to \pi^+$$
$$\mathrm{unfav}_s: \quad s \to \pi$$

- Collins function: pt-dependence



Compatible with LO extraction
Anselmino et al 2009, 2013, 2015

Precision matters

Precision of extraction depends on precision of calculations

Leading Log (LL):	$A^{(1)}$		
Next-to Leading Log (NLL):	$A^{(1,2)}$	$B^{(1)}$	$C^{(1)}$
Next-to-Next-to Leading Log (NNLL):	$A^{(1,2,3)}$	$B^{(1,2)}$	$C^{(1)}$

Kang, AP, Sun, Yuan 2015
Echevarria, Scimemi, Vladimirov 2016

Precision is important!

$C^{(1)}$ means that one should use NLO collinear distributions

Is the phenomenology complete at this point?

No good understanding of asymmetries is possible without unpolarized cross-section description

Presently *or soon* available fits

	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

From Alessandro Bacchetta's talk at QCD Evolution 2016

No good understanding of asymmetries is possible without unpolarized cross-section description

- Phenomenology/theory is not yet complete
- Relation to collinear treatment should be refined
- Phenomenology with transition to collinear treatment (Y term) is to be performed
- Target mass corrections are not yet included in TMD formalism
- Better understanding of factorization and process mechanisms is needed

Summary

- TMD related studies have been extremely active in the past few years, lots of progress have been made
- We look forward to the future experimental results from COMPASS, RHIC, Jefferson Lab, LHC, Fermilab, future Electron Ion Collider
- Many TMD related groups are created throughout the world:

  Italy, Netherlands, Belgium, Germany, Japan, China, Russia, and the USA

DOE funded topical collaboration dedicated to TMDs

Topical Collaboration for the Coordinated Theoretical Approach to Transverse Momentum Dependent (TMD) Hadron Structure in QCD

TMD Collaboration

The TMD Collaboration
Spokespersons: William Detmold (MIT) and Jianwei Qiu (BNL)

Co-Investigators - (in alphabetical order of institutions):
Jianwei Qiu and Raju Venugopalan (Brookhaven National Laboratory)
Thomas Mehen (Duke University)
Ted Rogers (Jefferson Laboratory and Old Dominion University)
Alexei Prokudin (Jefferson Laboratory and Penn State University at Berks)
Feng Yuan (Lawrence Berkeley National Laboratory)
Christopher Lee and Ivan Vitev (Los Alamos National Laboratory)
William Detmold, John Negele and Iain Stewart (MIT)
Matthias Burkardt and Michael Engelhardt (New Mexico State University)
Leonard Gamberg (Penn State University at Berks)
Andreas Metz (Temple University)
Sean Fleming (University of Arizona)
Keh-Fei Liu (University of Kentucky)
Xiangdong Ji (University of Maryland)
Simonetta Liuti (University of Virginia)

- 5 years of funding
- 18 institutions
- Theory, phenomenology, lattice QCD
- Several postdoc and tenure track positions to be created
- “To address the challenges of extracting novel quantitative information about the nucleon’s internal landscape”
- “To provide compelling research, training, and career opportunities for young nuclear theorists”