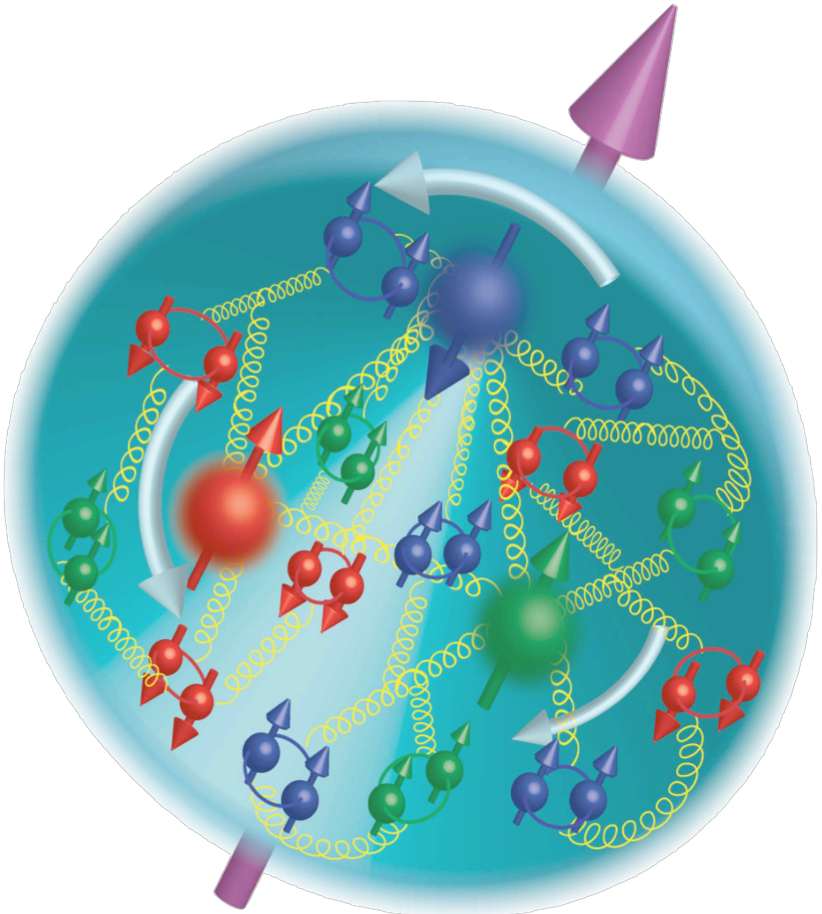
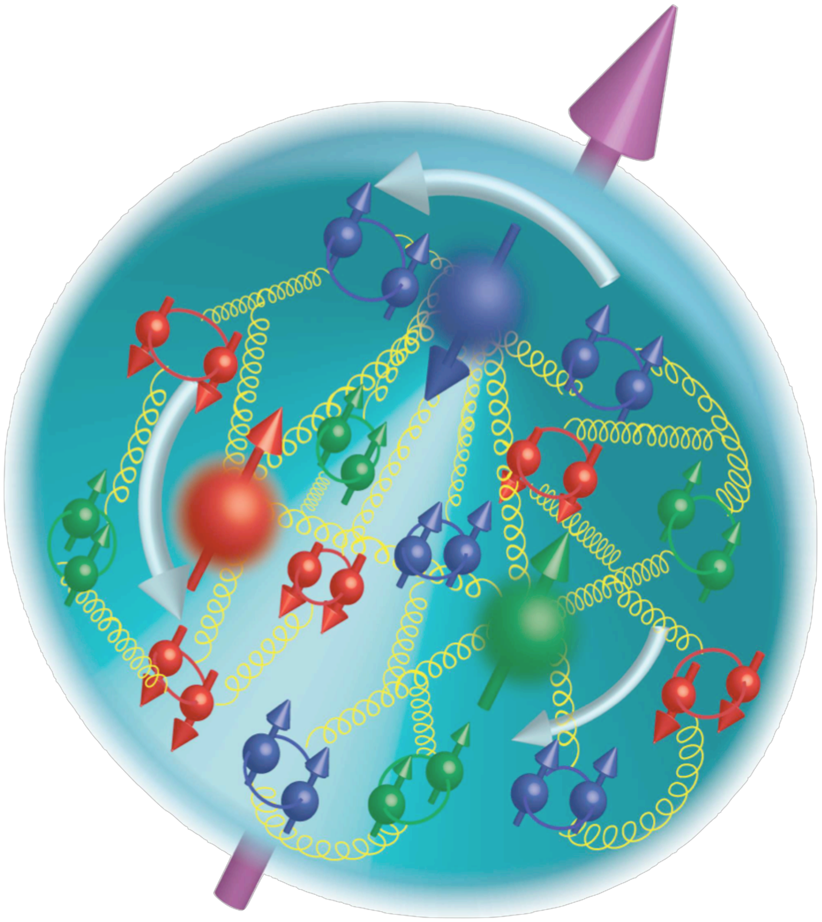


THE ORIGIN OF SPIN ASYMMETRIES

Alexei Prokudin



The origin of single transverse-spin asymmetries in high-energy collisions

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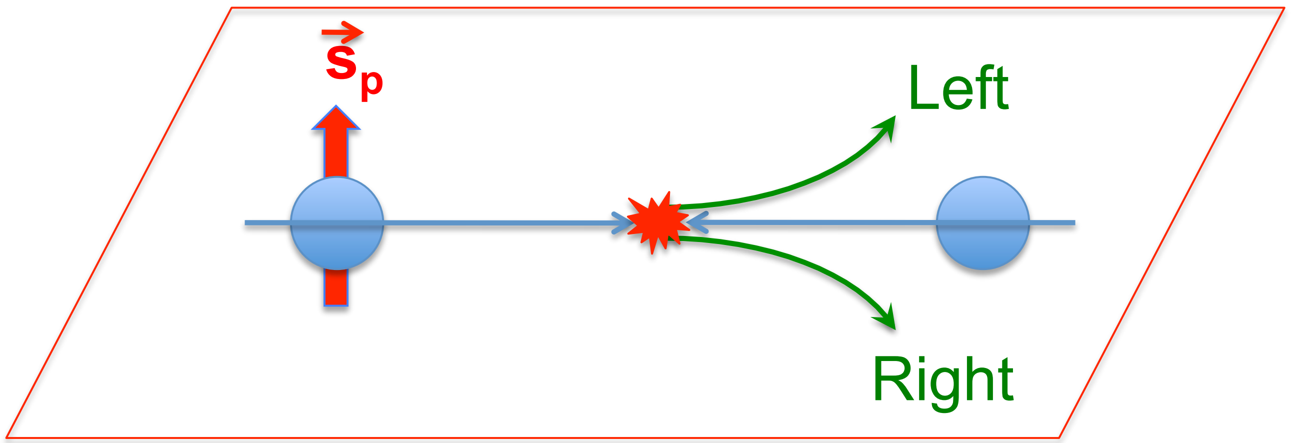
Jefferson Lab Angular Momentum (JAM) Collaboration

SINGLE SPIN ASYMMETRIES

Consider polarized hadron - hadron collisions



Count pions going to the right or to the left with respect to the spin direction

$$A_N \equiv \frac{\sigma(\vec{s}_P) - \sigma(-\vec{s}_P)}{\sigma(\vec{s}_P) + \sigma(-\vec{s}_P)}$$

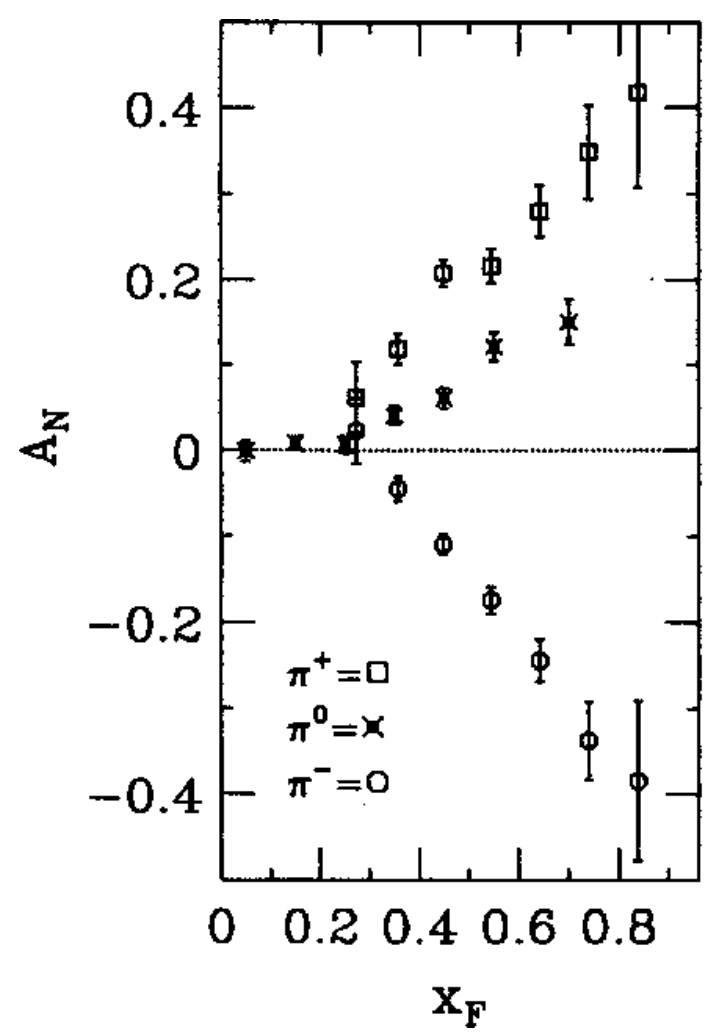
CHALLENGE OF QCD: UNDERSTANDING SPIN ASYMMETRIES

Experiment proved this prediction wrong

QCD had a very simple prediction

$$\cancel{A_N \propto \alpha_s \frac{m_q}{P_T}} \to 0$$

Kane, Pumplin, Repko (1978)



$$A_N \simeq 40\%$$

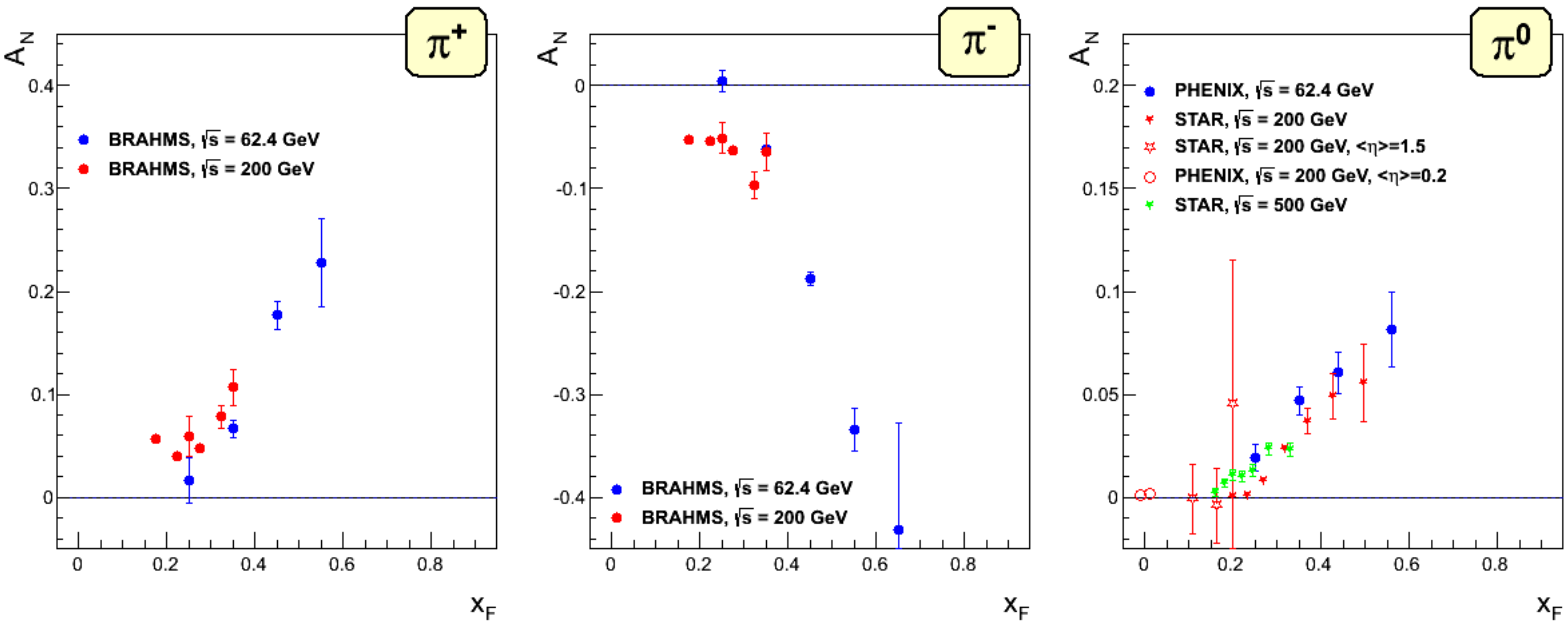
Fermilab experiment E704 (1991)

$$\sqrt{s} \simeq 19\ (\mathrm{GeV})$$

CHALLENGE OF QCD: UNDERSTANDING SPIN ASYMMETRIES

Asymmetry survives with growing collision energy

RHIC: STAR, BRAHMS, PHENIX



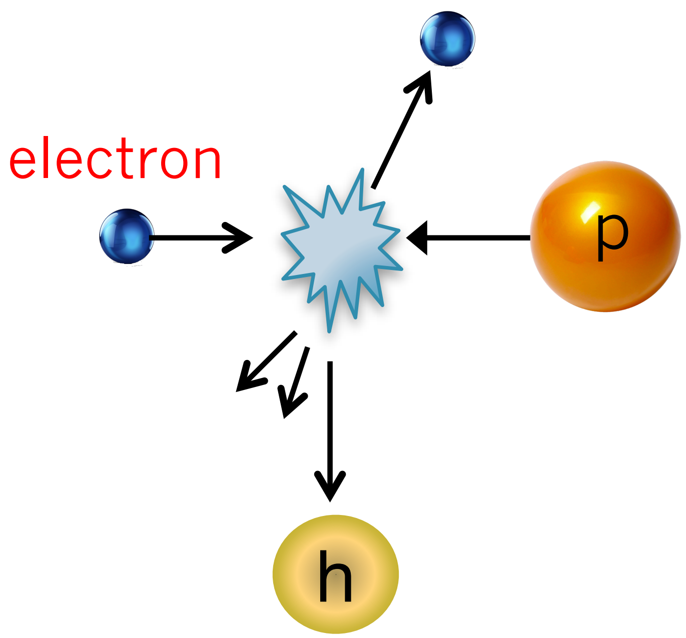
"The RHIC SPIN Program: Achievements and Future Opportunities", Aschenauer et al (15)

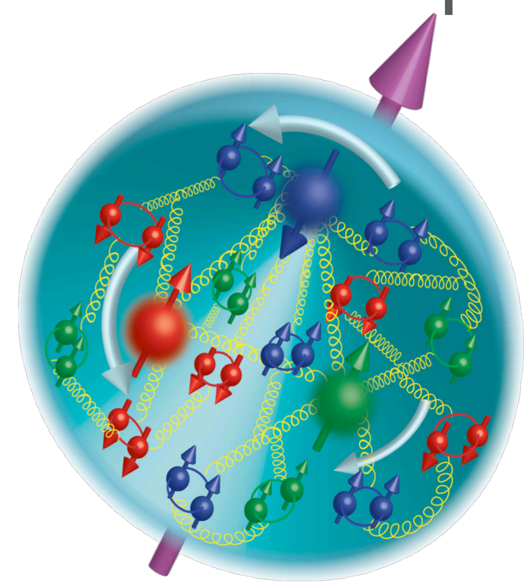
FAILURE OF QCD?


QCD
BETTER
UNDERSTANDING OF QCD!

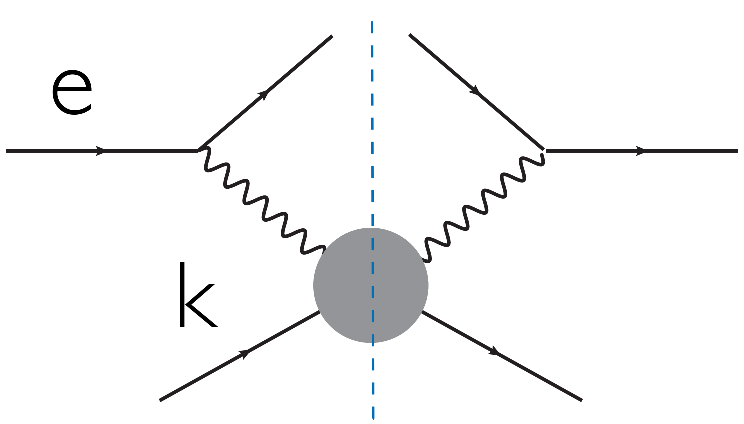
QCD FACTORIZATION IS THE KEY!

We need a probe to “see” quarks and gluons

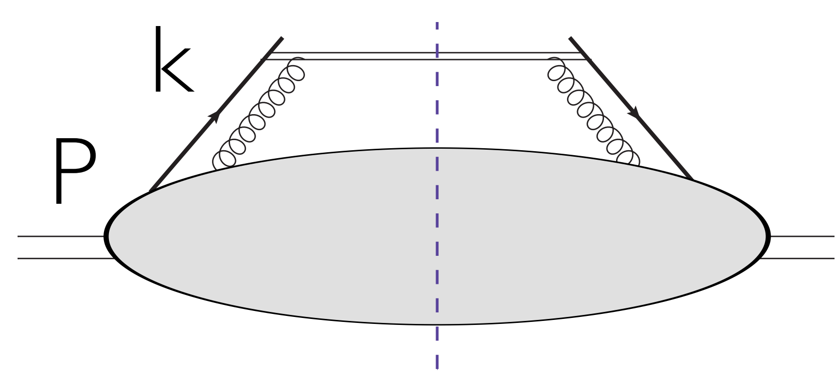




$\sigma \approx$



$\otimes$



$+\mathcal{O}\left(\frac{M^2}{Q^2}\right)$

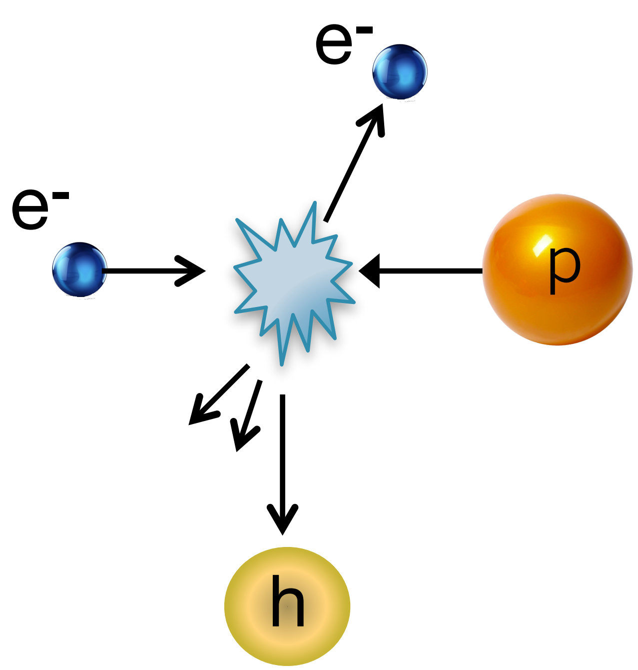
Factorization Probe Structure Power corrections

TRANSVERSE MOMENTUM DEPENDENT FACTORIZATION

The confined motion (k_T dependence) is encoded in TMDs

Semi-Inclusive DIS

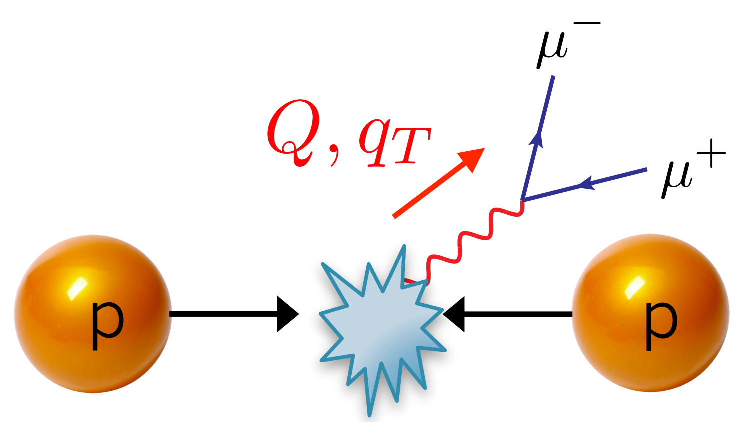
$$\sigma \sim f_{q/P}(x, k_T) D_{h/q}(x, k_T)$$



Meng, Olness, Soper (1992)
Ji, Ma, Yuan (2005)
Idilbi, Ji, Ma, Yuan (2004)
Collins (2011)

Drell-Yan

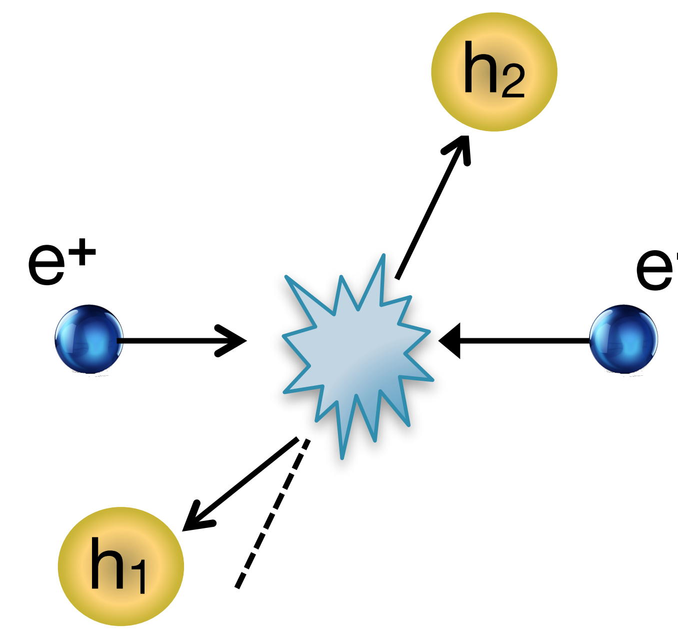
$$\sigma \sim f_{q/P}(x, k_T) f_{q/P}(x, k_T)$$



Collins, Soper, Sterman (1985)
Ji, Ma, Yuan (2004)
Collins (2011)

Dihadron in e+e-

$$\sigma \sim D_{h_1/q}(x, k_T) D_{h_2/q}(x, k_T)$$

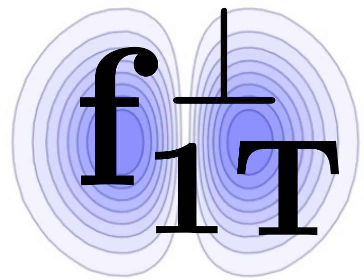


Collins, Soper (1983)
Collins (2011)

Small scale → $q_T \ll Q$ ← Large scale

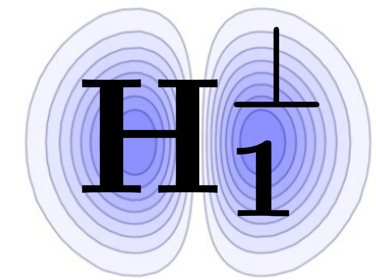
SIVERS AND COLLINS EFFECTS

Sivers function $\mathbf{f_{1T}^{\perp}}$



Sivers 1989

Collins function $\mathbf{H_1^{\perp}}$



Collins 1992

- Describes unpolarized quarks inside of transversely polarized nucleon
- Describes fragmentation of transversely polarized quark into an unpolarized nucleon
- Generates asymmetries in SIDIS and DY

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

- Generates asymmetries in SIDIS and e^+e^-

Kotzinian (1995)
Mulders, Tangerman (1995)
Boer, Jakob, Mulders (1997)

- Changes sign in DY w.r.t. SIDIS

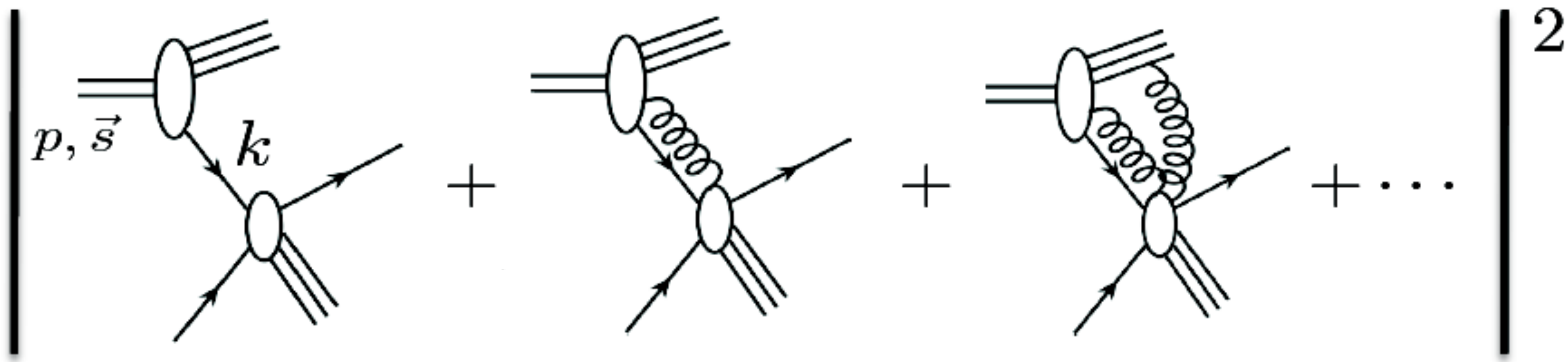
Brodsky, Hwang, Schmidt (2002)
Collins (2002)

- Universal in SIDIS, e^+e^-, and PP

Metz, Collins (2004)
Yuan (2008)

TWIST-3 FACTORIZATION

$\sigma(Q, \vec{s}) \propto$



Qiu, Sterman (1991)

Large scale → $q_T \simeq Q$ ← Large scale

Multi-parton correlations (twist-3 functions) contribute to the cross section and are dominant for asymmetries in PP scattering

TMD AND COLLINEAR FACTORIZATIONS ARE RELATED

TMDs and collinear PDFs and FFs are related via Operator Product Expansion in CSS formalism

Collins, Soper, Sterman (1985)

TMD and collinear twist-3 (CT3) formalisms are “unified” in intermediate region of q_T

Ji, Qiu, Vogelsang, Yuan (2006)

TMD and twist-3 (CT3) functions are related by integral relations

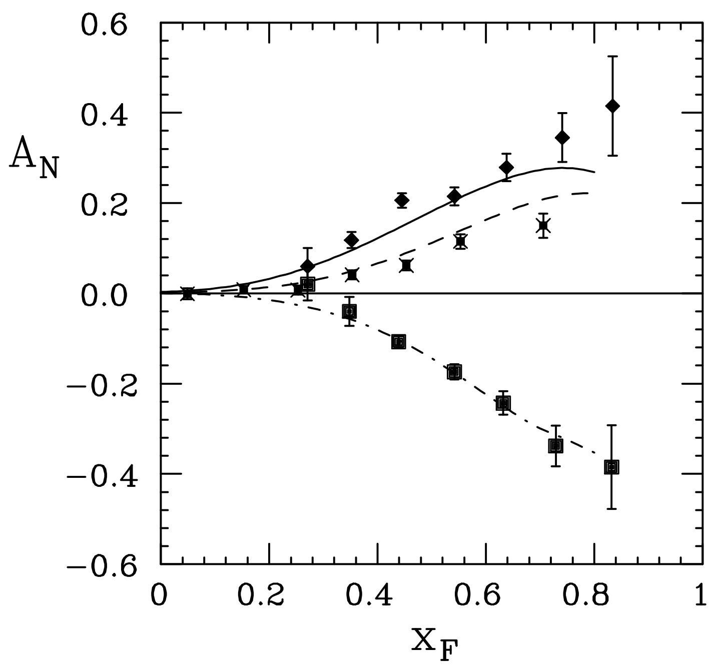
Boer, Mulders, Pijlman (2003)

$$\pi F_{FT}(x,x) = f_{1T}^{\perp(1)}(x)$$

Qiu-Sterman matrix element *The first k_T moment of Sivers function*

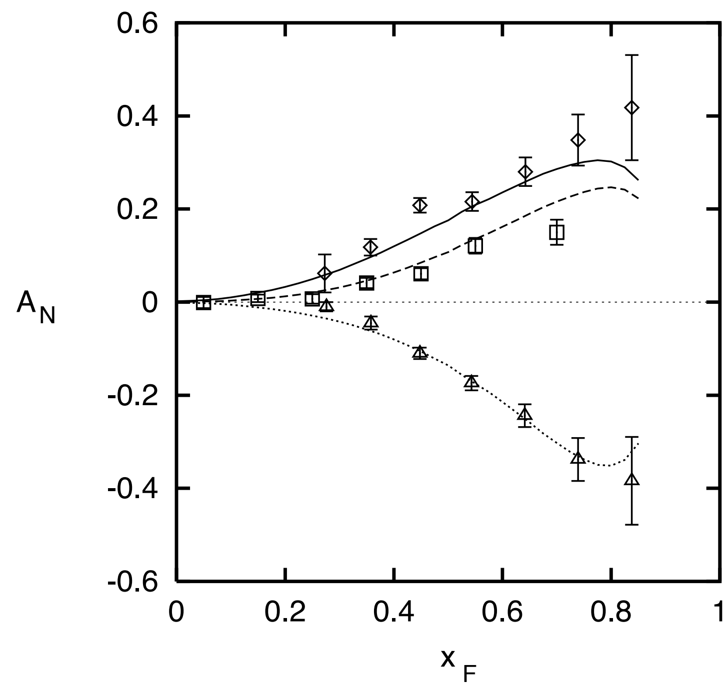
TOWARDS THE SOLUTION OF 40 YEAR OLD PUZZLE

Anselmino, Murgia (1998)



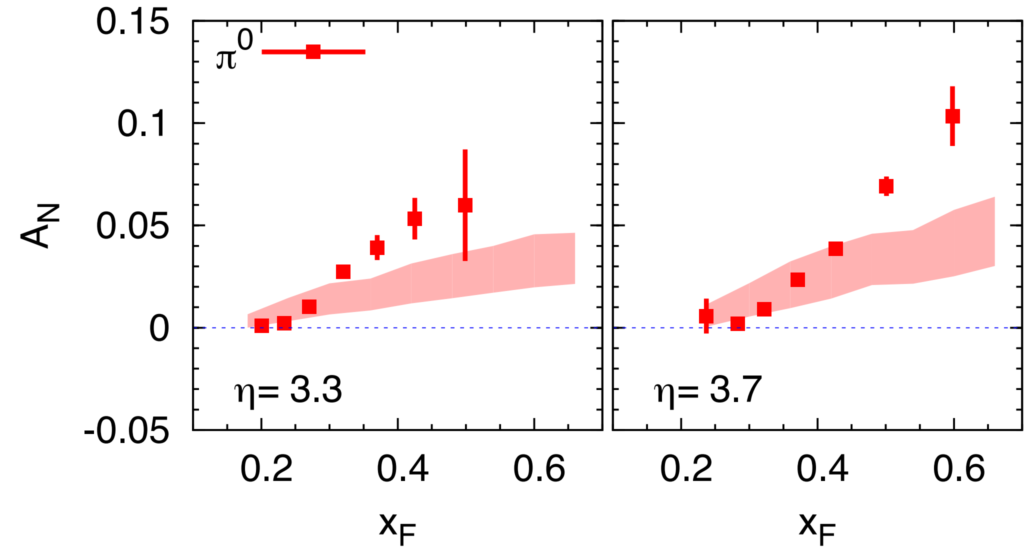
Sivers effect TMD fit

Anselmino, Boglione, Murgia (1999)



Collins effect TMD fit

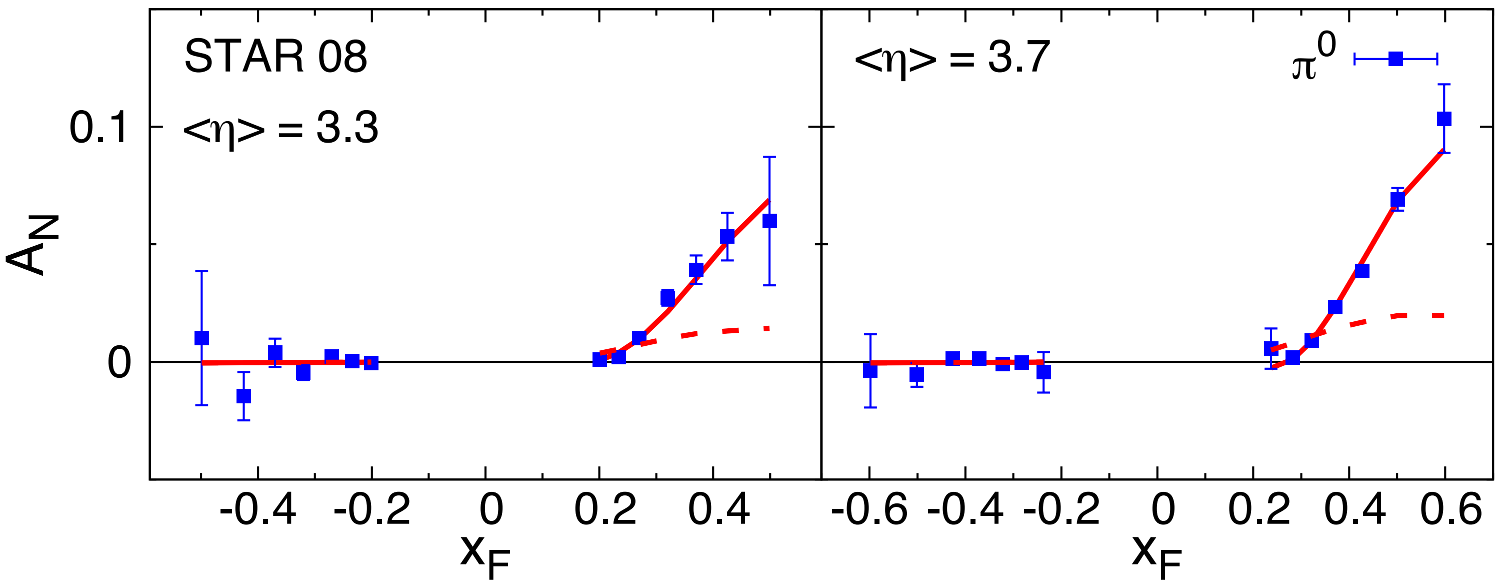
Anselmino, Boglione, D'Alesio, Leader, Melis, Murgia, Prokudin (2013)



TMD Collins effect only from SIDIS

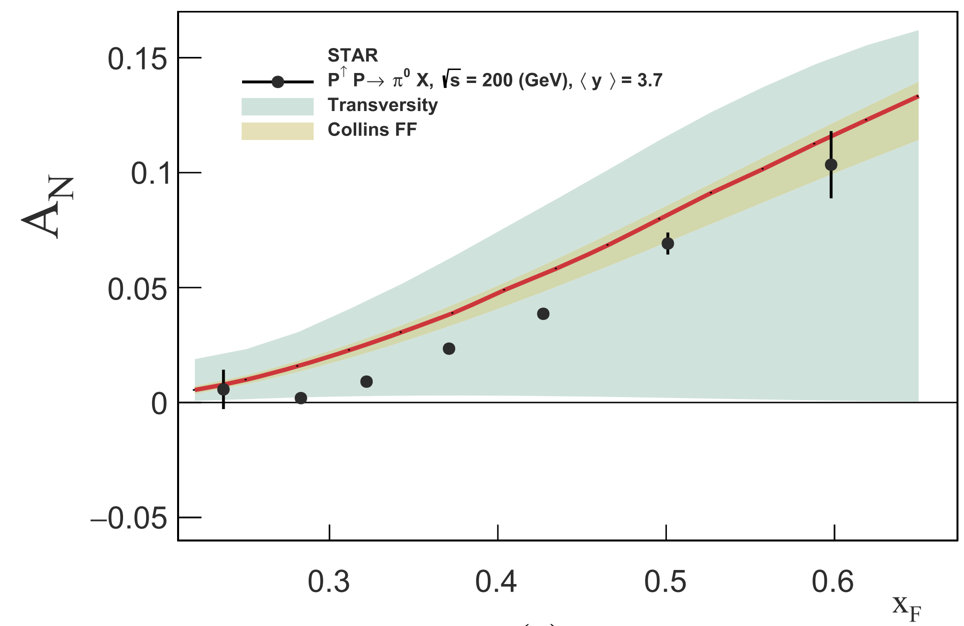
TOWARDS THE SOLUTION OF 40 YEAR OLD PUZZLE

Kanazawa, Koike, Metz, Pitonyak PRD 89 (2014)



Explanation using fit of twist-3 fragmentation functions

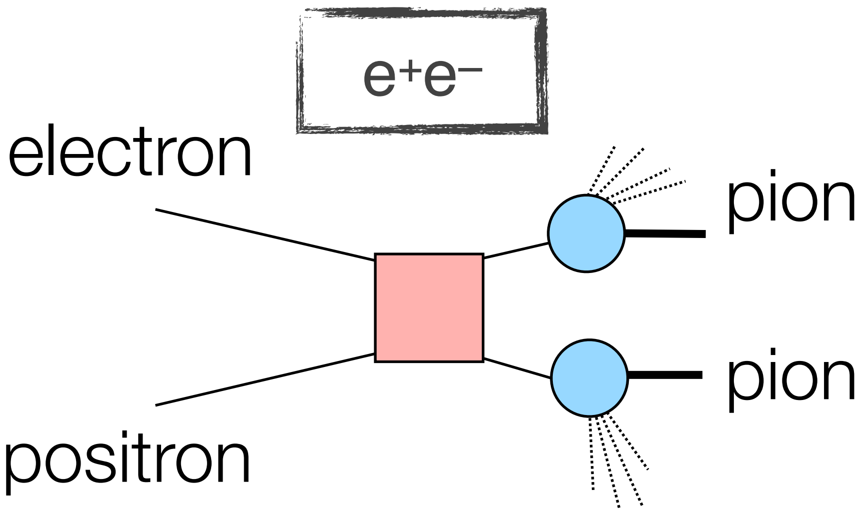
Gamberg, Kang, Pitonyak, Prokudin PLB 770 (2017)



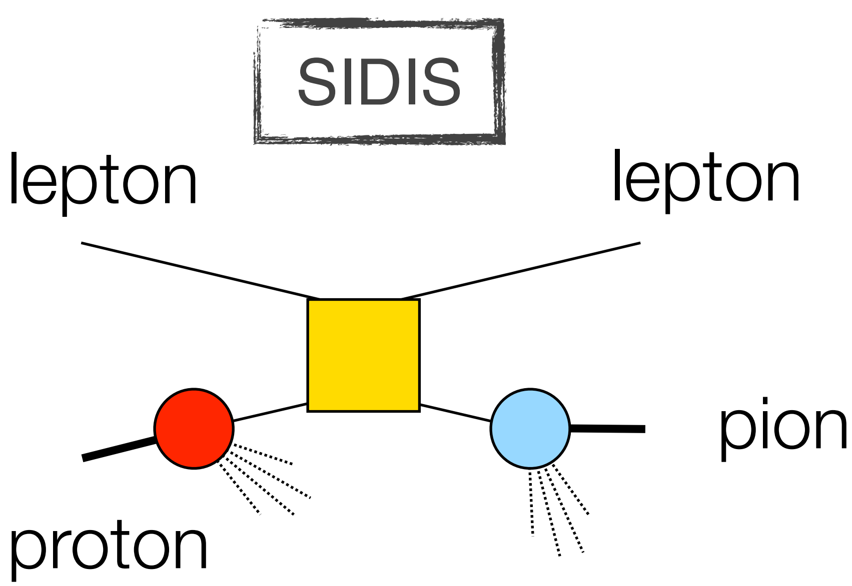
Prediction of A_N at STAR using only SIDIS and e^+e^- data information only

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

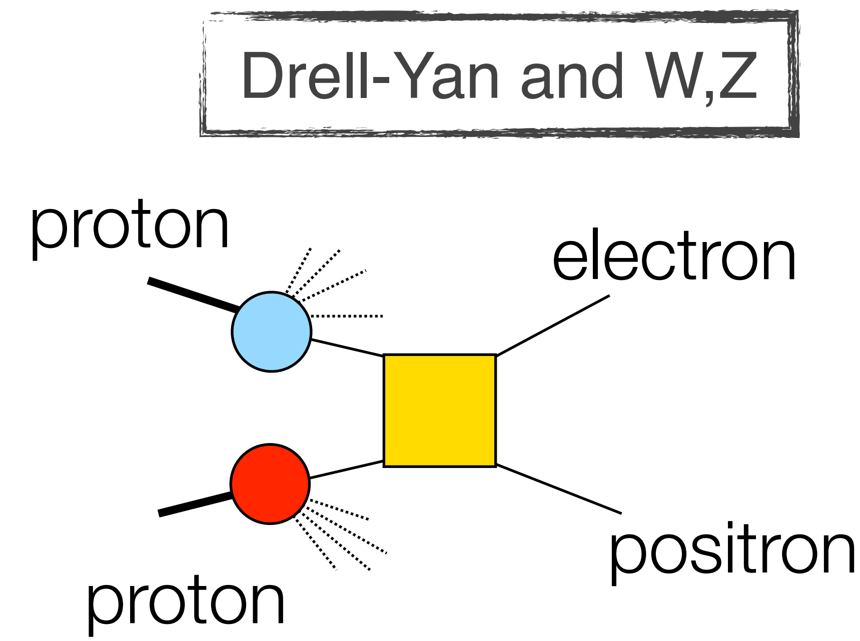


Collins asymmetries
BELLE, BaBar, BESIII data

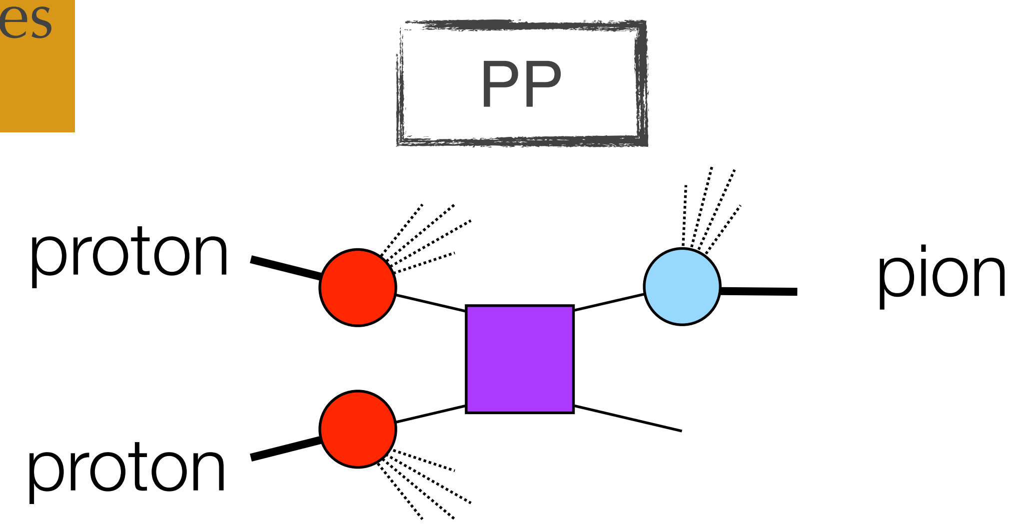


Sivers, Collins asymmetries
COMPASS, HERMES, JLab data

To demonstrate the common origin of SSAs in various processes, we will combine all available data and extract a universal set of non perturbative functions that describes all of them



Sivers asymmetries
COMPASS, STAR data



A_N asymmetry
STAR, PHENIX, BRAHMS data

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

The relevant set of collinear functions to extract

$h_1(x)$ transversity

$F_{FT}(x,x)$ Qiu-Sterman function

$H_1^{\perp(1)}(z)$ the first moment of Collins FF

$\tilde{H}(z)$ fragmentation twist-3 function

Flexible parametrization

$$F^q(x) = \frac{N_q\, x^{a_q}(1-x)^{b_q}\,(1+\gamma_q\, x^{\alpha_q}(1-x)^{\beta_q})}{\mathrm{B}[a_q+2, b_q+1] + \gamma_q \mathrm{B}[a_q+\alpha_q+2, b_q+\beta_q+1]}$$

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

$\tilde{H}(z)$ fragmentation twist-3 function

Plays role in A_N in PP, generates asymmetry in SIDIS

$$A_{UT}^{sin\phi_S}(x,z) \sim h_1(x)\tilde{H}(z)$$

This function is totally unconstrained in the current fit as data from COMPASS and HERMES are unavailable at the moment

We set it to zero in our analysis making it consistent with small asymmetry observed by COMPASS and HERMES

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

The relevant set of TMD functions to extract

$$\mathcal{G}_f(k_T^2) = \frac{1}{\pi \langle k_T^2 \rangle_f} e^{-\frac{k_T^2}{\langle k_T^2 \rangle_f}}$$

$$h_1(x, k_T) = h_1(x)\mathcal{G}_h(k_T^2)$$

transversity

$$f_{1T}^{\perp}(x, k_T) = \frac{2M^2}{\langle k_T^2 \rangle_{f_{1T}^{\perp}}} \pi F_{FT}(x, x) \mathcal{G}_{f_{1T}^{\perp}}(k_T^2)$$

Sivers function

$$H_1^{\perp}(z, zp_T) = \frac{2z^2 M^2}{\langle p_T^2 \rangle_{H_1^{\perp}}} H_1^{\perp(1)}(z) \mathcal{G}_{H_1^{\perp}}(z^2 p_T^2)$$

Collins function

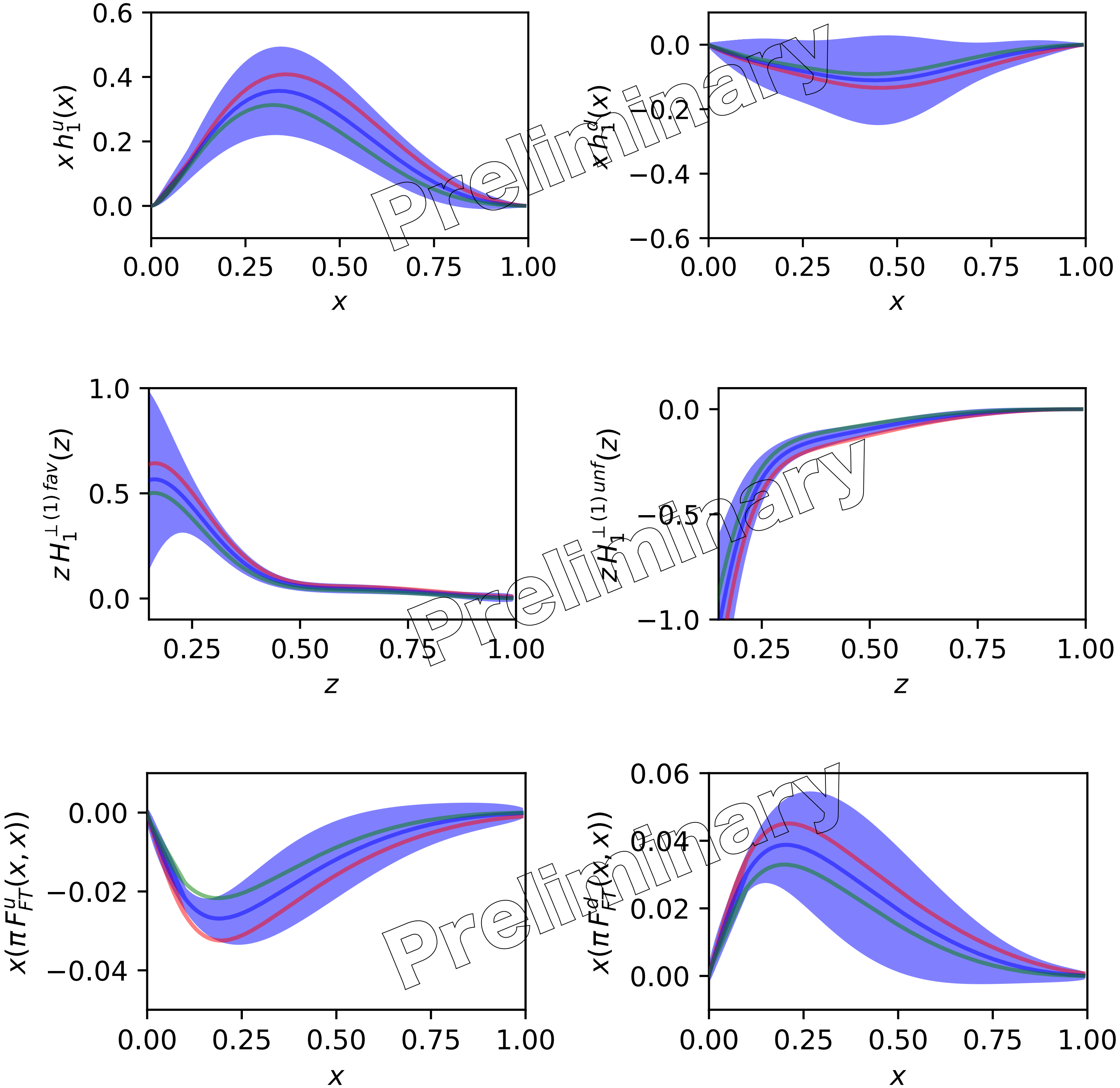
UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

Observable	**Reactions**	**NP Function(s)**
$A_{\mathrm{SIDIS}}^{\mathrm{Siv}}$	$e + (p,d)^{\uparrow} \to (\pi^+, \pi^-) + X$	$f_{1T}^{\perp}$
$A_{\mathrm{SIDIS}}^{\mathrm{Col}}$	$e + (p,d)^{\uparrow} \to (\pi^+, \pi^-, \pi^0) + X$	$h_1, H_1^{\perp}$
$A_{\mathrm{SIA}}^{\mathrm{Col}}$	$e^+ + e^- \to \pi^+\pi^-(UC, UL) + X$	$H_1^{\perp}$
$A_{\mathrm{DY}}^{\mathrm{Siv}}$	$\pi^- + p^{\uparrow} \to \mu^+\mu^- + X$	$f_{1T}^{\perp}$
$A_{\mathrm{DY}}^{\mathrm{Siv}}$	$p^{\uparrow} + p \to (W^+, W^-, Z) + X$	$f_{1T}^{\perp}$
A_N	$p^{\uparrow} + p \to (\pi^+, \pi^-, \pi^0) + X$	$h_1, F_{FT}(= \frac{1}{\pi} f_{1T}^{\perp(1)}), H_1^{\perp(1)}, \tilde{H}$

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)



Transversity

$h_1(x)$

Collins FF

$H_1^{\perp(1)}(z)$

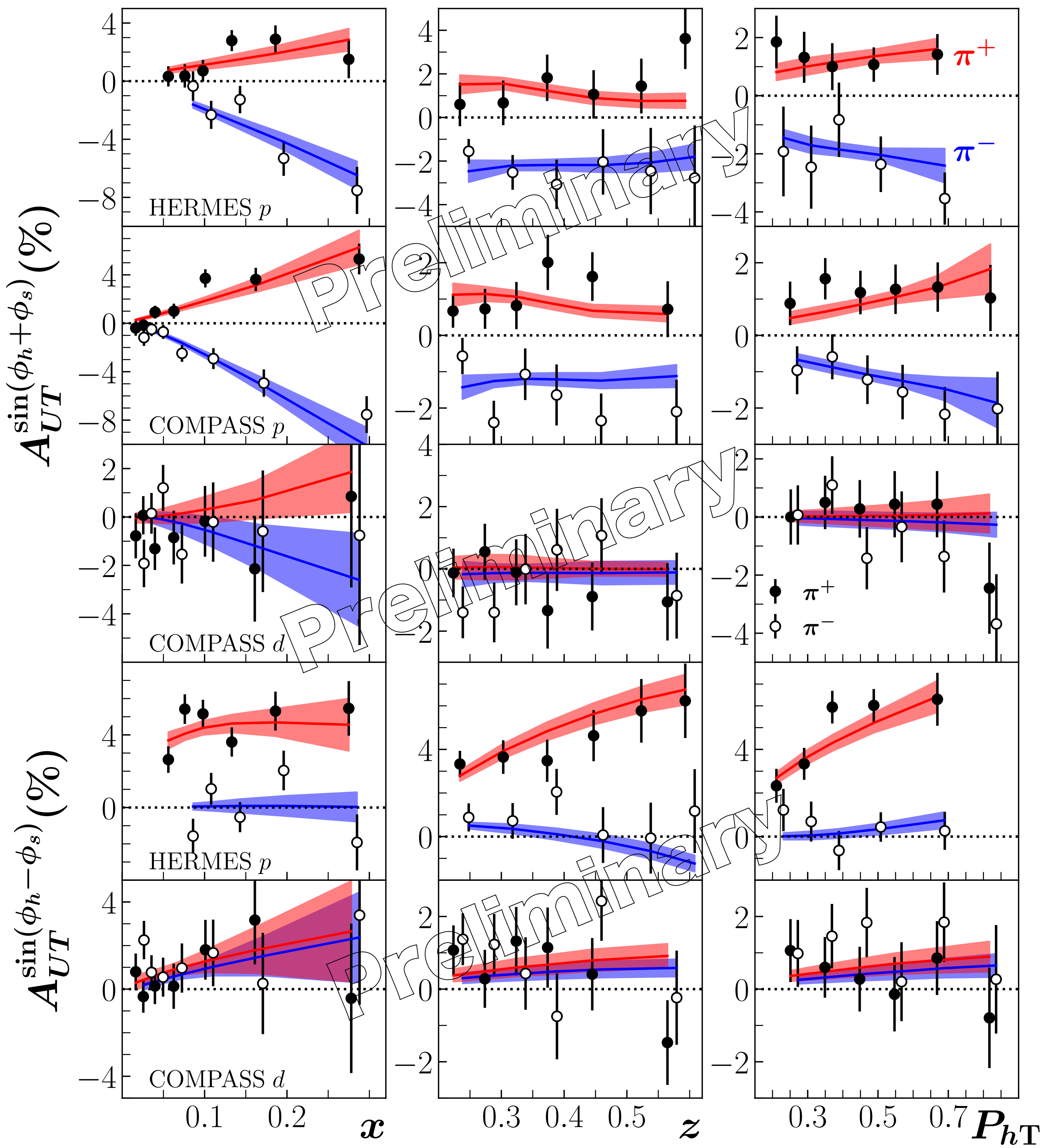
Sivers

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

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

SIDIS



Collins asymmetry

$$\frac{\chi^2}{npoints} = \frac{107.1}{126} = 0.85$$

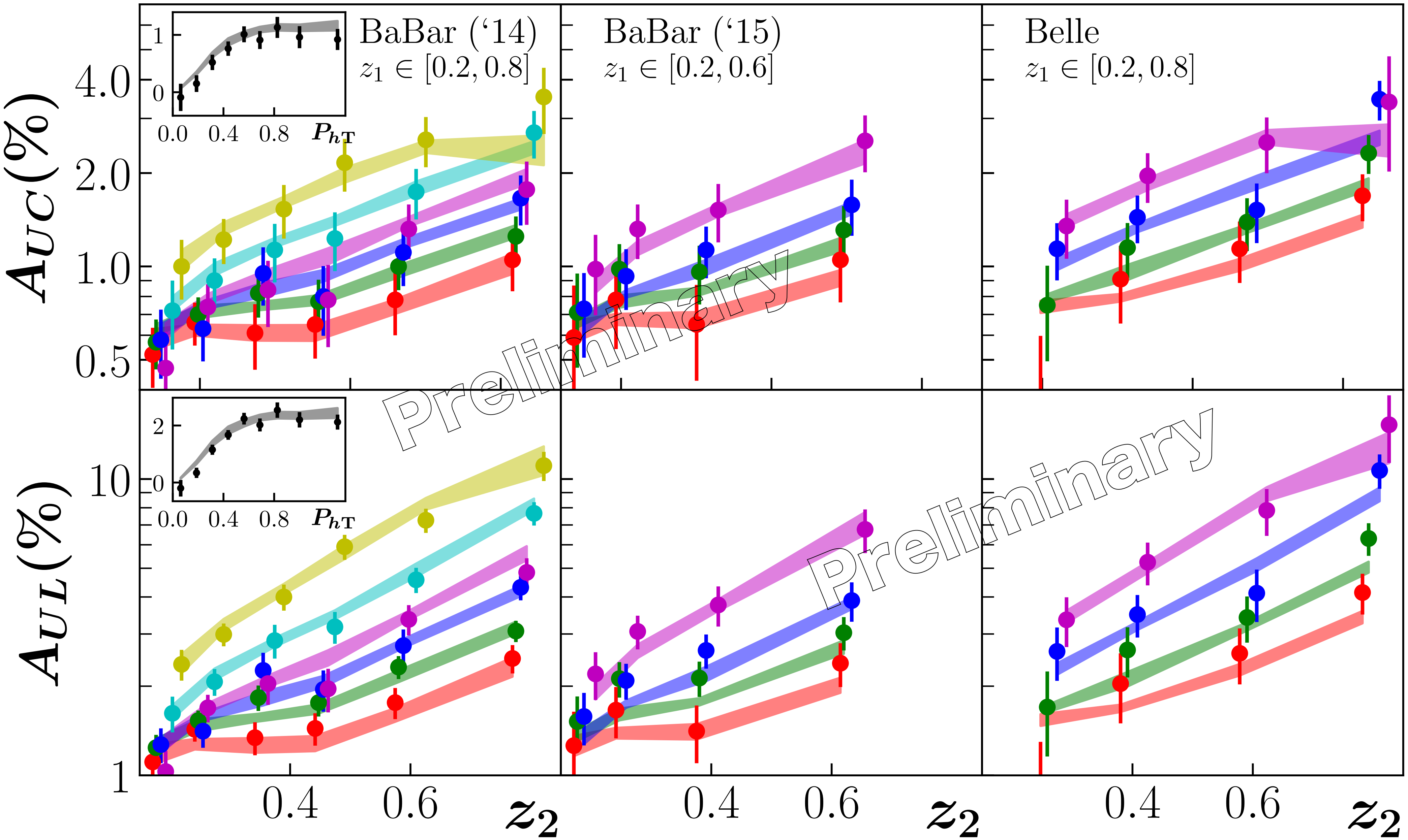
Sivers asymmetry

$$\frac{\chi^2}{npoints} = \frac{85.4}{88} = 0.97$$

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

e^+e^-

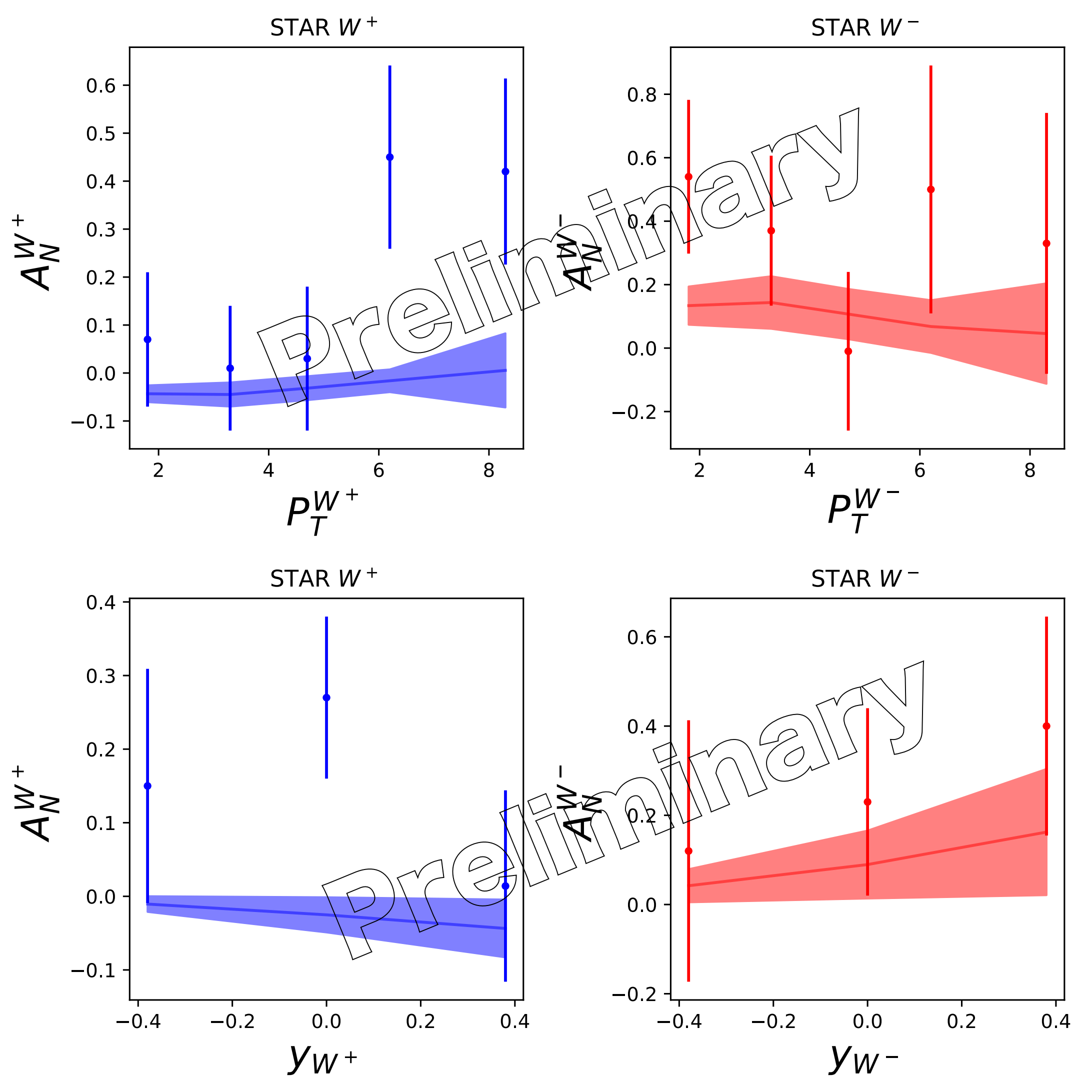


$$\frac{\chi^2}{npoints} = \frac{149.6}{176} = 0.85$$

UNIVERSAL GLOBAL FIT 2020

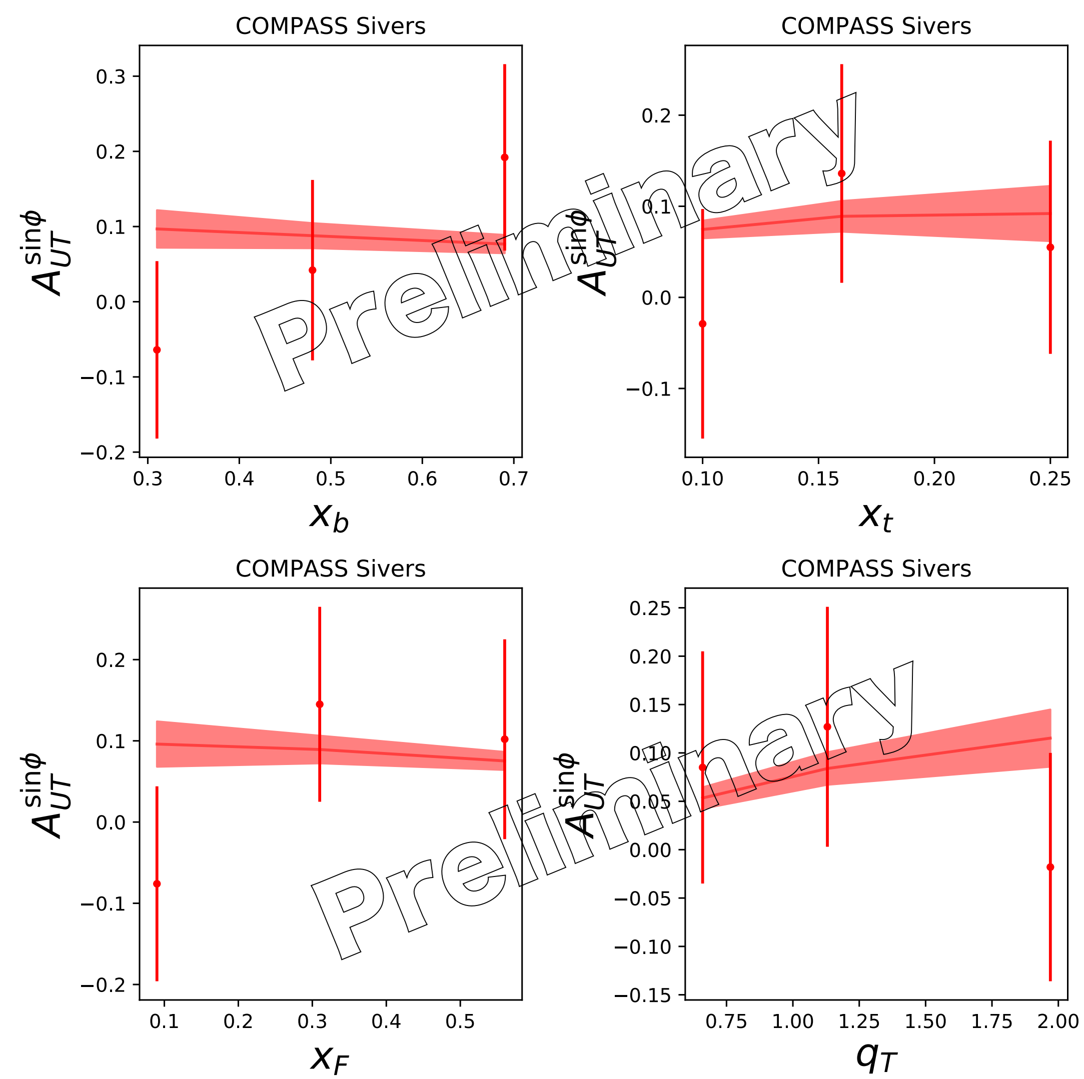
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

Drell-Yan



$$\frac{\chi^2}{npoints} = \frac{29.8}{17} = 1.75$$

STAR



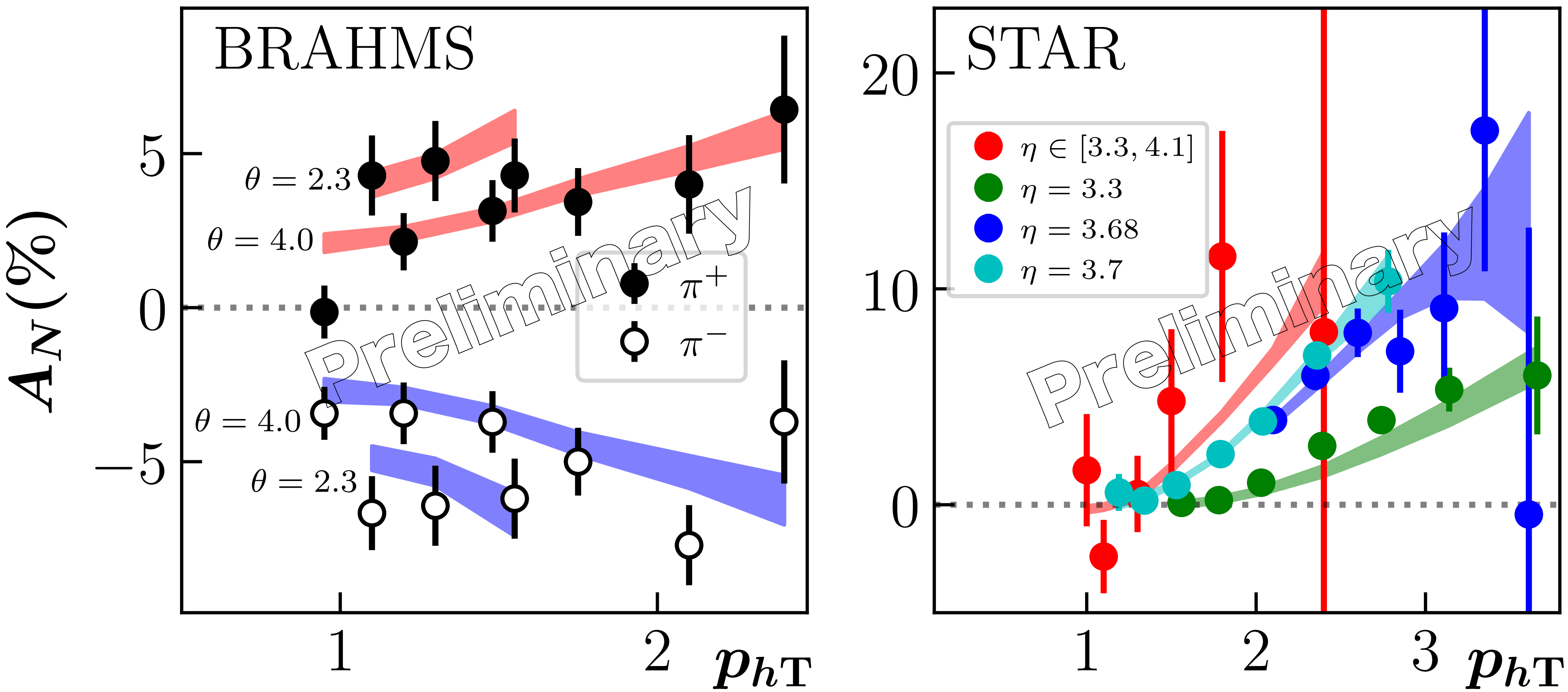
$$\frac{\chi^2}{npoints} = \frac{7.6}{12} = 0.63$$

COMPASS DY

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

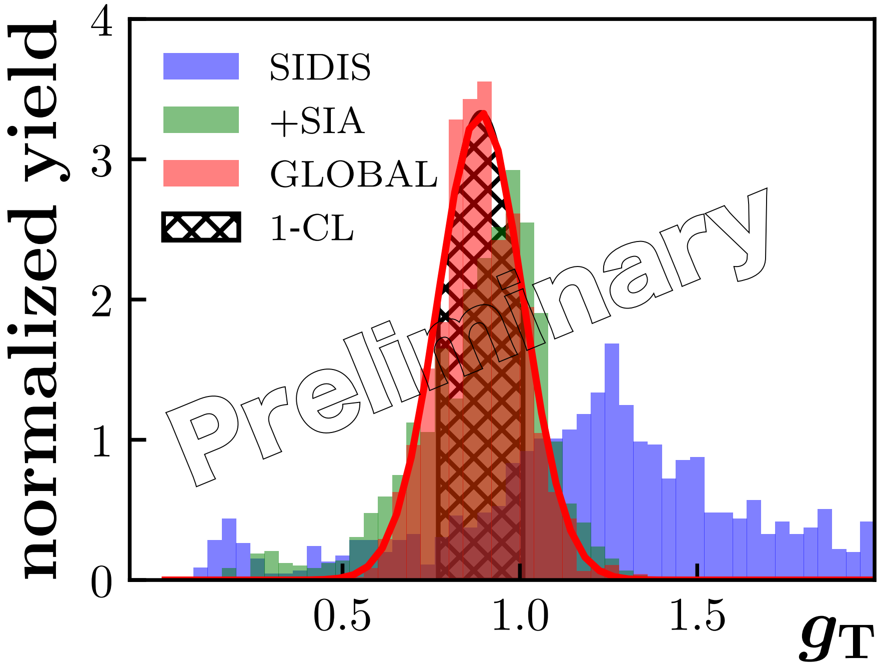
proton-proton A_N



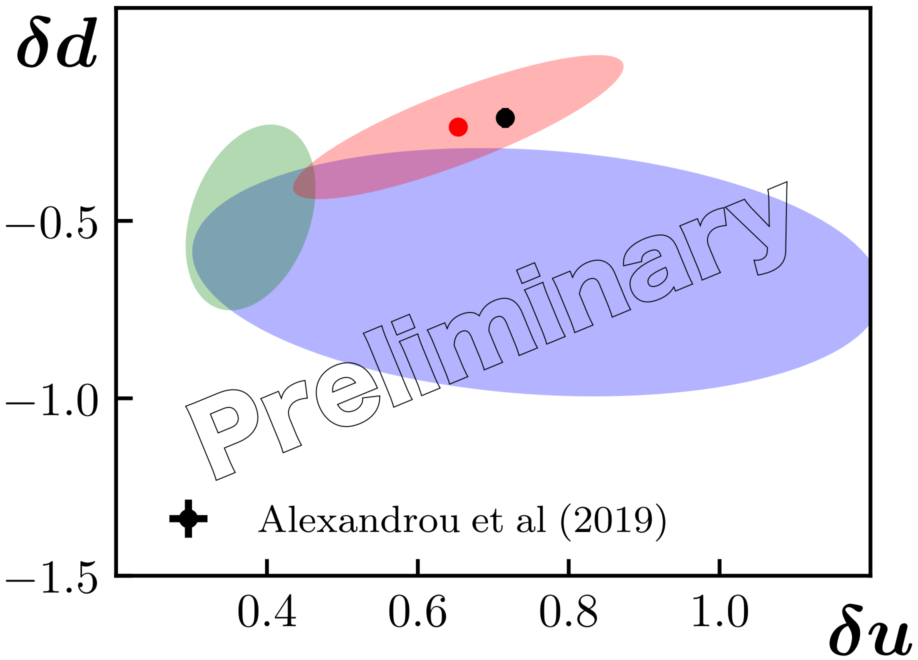
$$\frac{\chi^2}{npoints} = \frac{72.0}{60} = 1.2$$

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)



- Isovector tensor charge $g_T = \delta u - \delta d$
  gT = 0.89±0.12 compatible with lattice results



- Tensor charge from up and down quarks is constrained and compatible with lattice results

δu and δd Q^2=4 GeV^2

δu= 0.65 ± 0.22

δd= -0.24 ± 0.2

THEORETICAL AND PHENOMENOLOGICAL DEVELOPMENT

- Shown for the first time that transverse spin asymmetries in a variety of processes SIDIS, Drell-Yan, e^+e^-, and proton proton scattering have the same origin
- Extracted a universal set of non perturbative functions responsible for spin asymmetries
- Shown consistency of phenomenological results with lattice QCD in extraction of isovector tensor charge and individual contributions from up and down quark

BACKUP SLIDES

TREATMENT OF EVOLUTION

TMDs are parametrized with gaussian k_T dependence (no widening with Q^2) and x-,z- dependent collinear functions evolved in Q^2

Evolution in collinear functions are done by Q^2 parametrization using Duke, Owned method Phys. Rev. D 30, 49 (1984)

$$N_0 + N_1 \log\left(\frac{\log(Q^2/\Lambda^2)}{\log(Q_0^2/\Lambda^2)}\right)$$

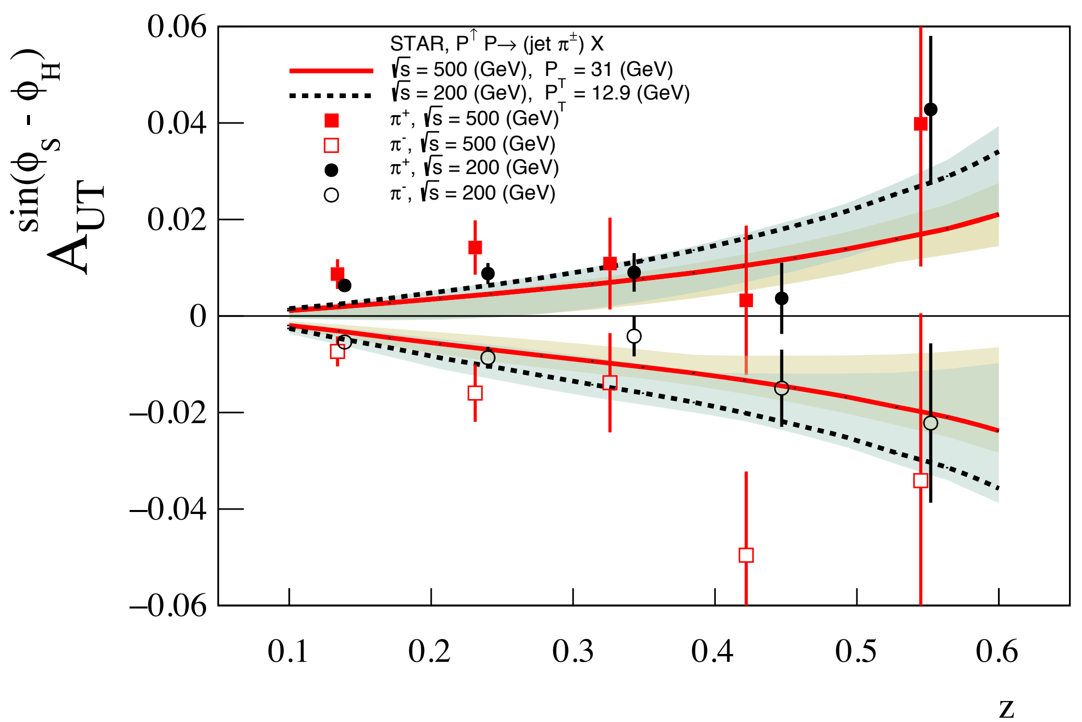
Success is achieved with Gaussian shapes for the transverse momentum dependence further implies that the effects are dominantly non-perturbative and intrinsic to the hadron wavefunctions.

TREATMENT OF EVOLUTION

Results of this approach are consistent with resummation for asymmetries

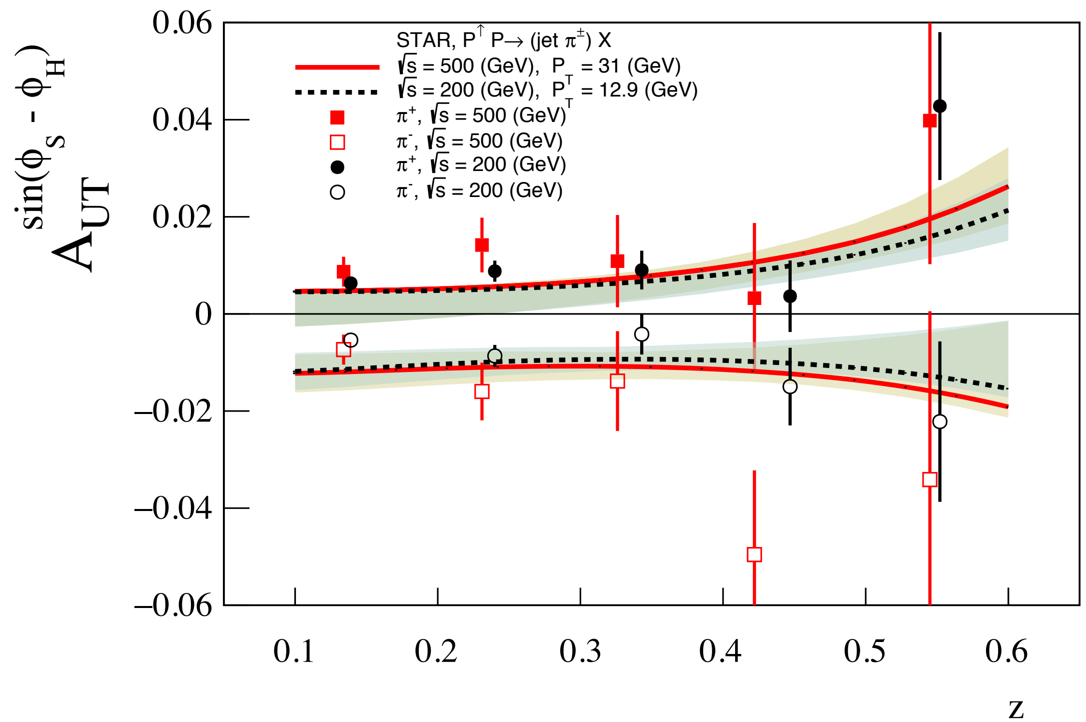
Kang, Prokudin, Ringer, Yuan (2017)

NLL TMD evolution



functions: Kang, Prokudin, Sun, Yuan (2015)

Gaussian Torino model



functions: Anselmino et al (2015)

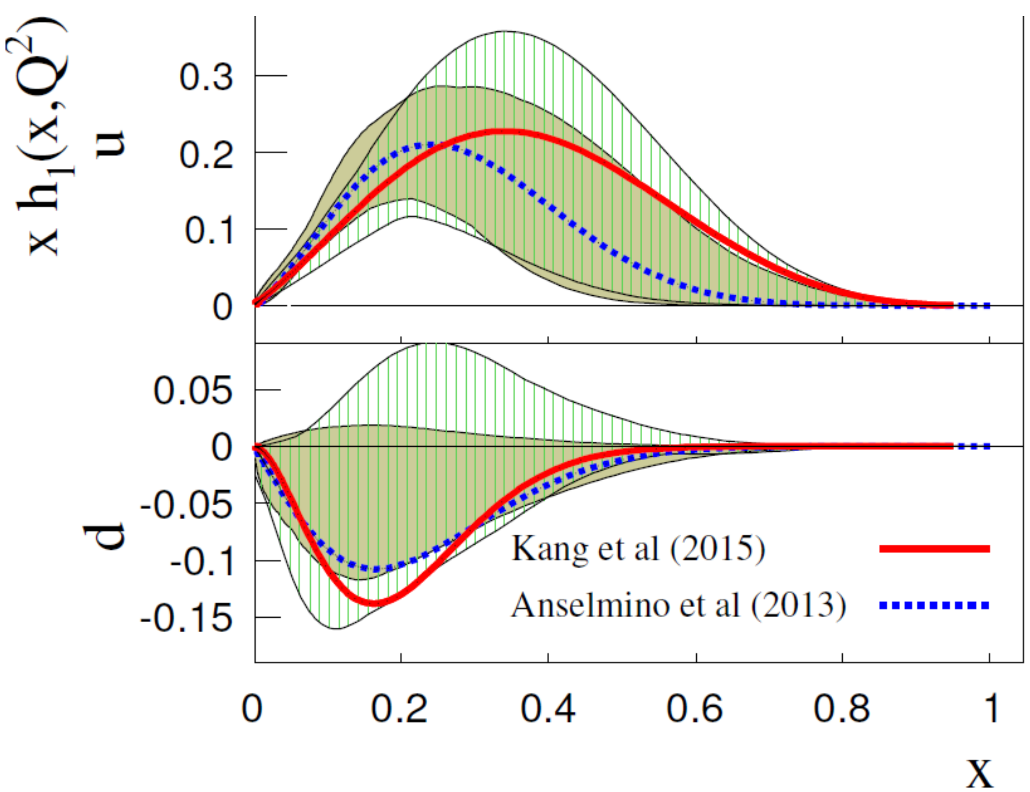
TREATMENT OF EVOLUTION

Results of this approach are consistent with resummation for asymmetries

Kang, Prokudin, Ringer, Yuan (2017)

NLL TMD evolution

Gaussian Torino model



functions: Kang, Prokudin, Sun, Yuan (2015)

functions: Anselmino et al (2013)