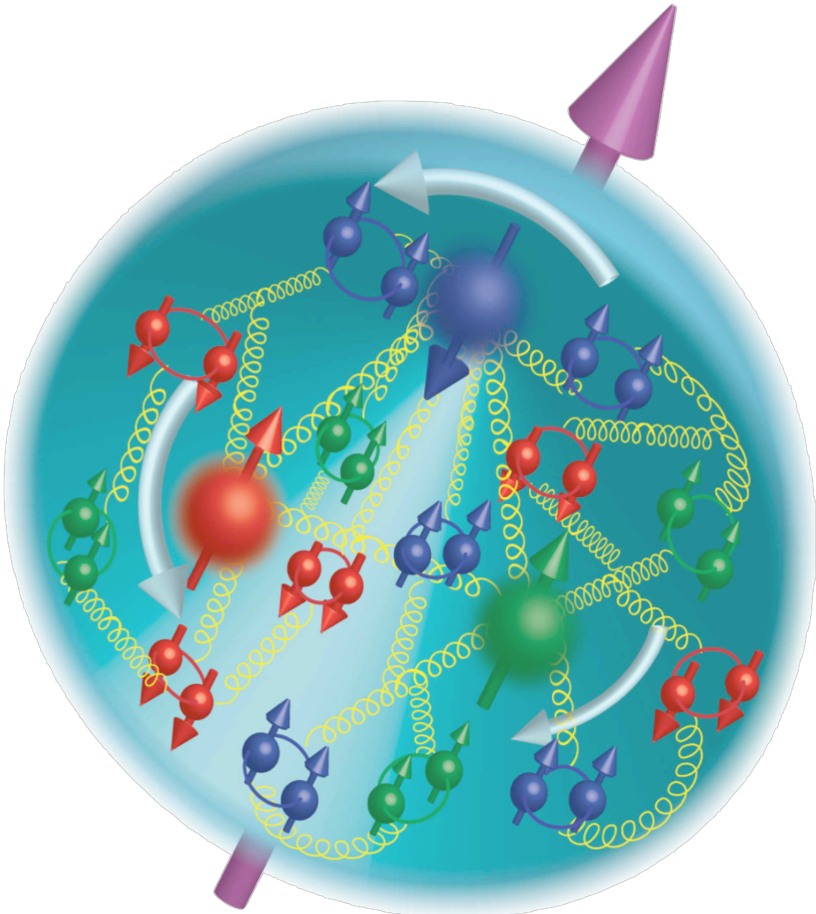
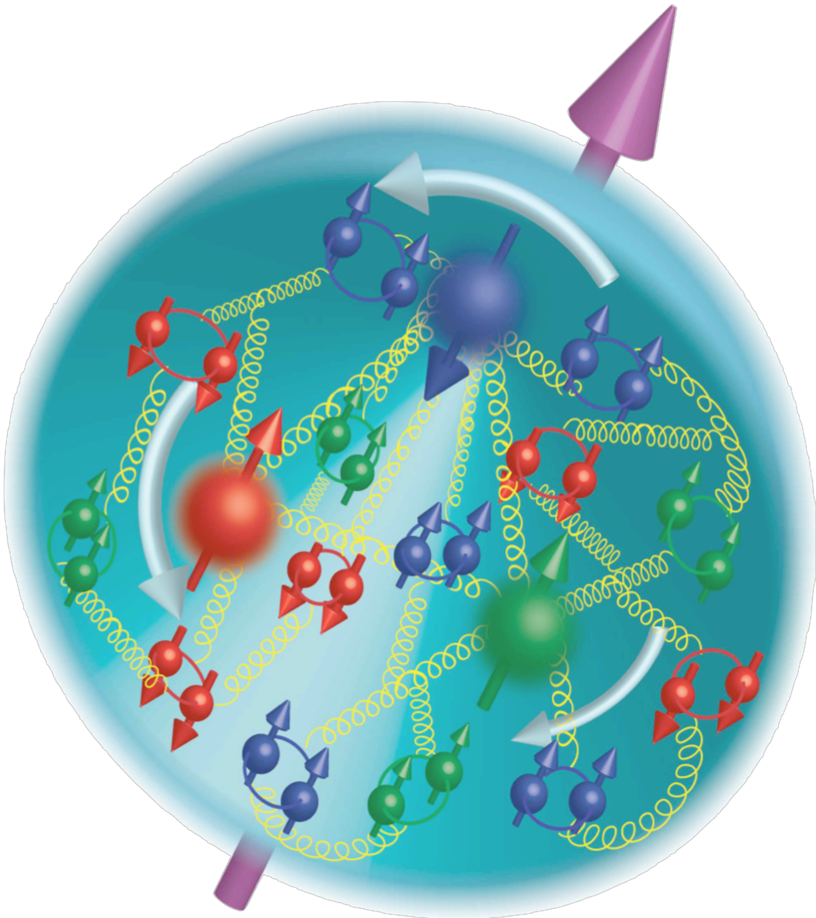


THE ORIGIN OF SPIN ASYMMETRIES

Alexei Prokudin



arXiv:2002.08384

JLAB-THY-20-3151

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

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Jefferson Lab Angular Momentum (JAM) Collaboration

“Experiments with spin have killed more theories than any other single physical parameter”

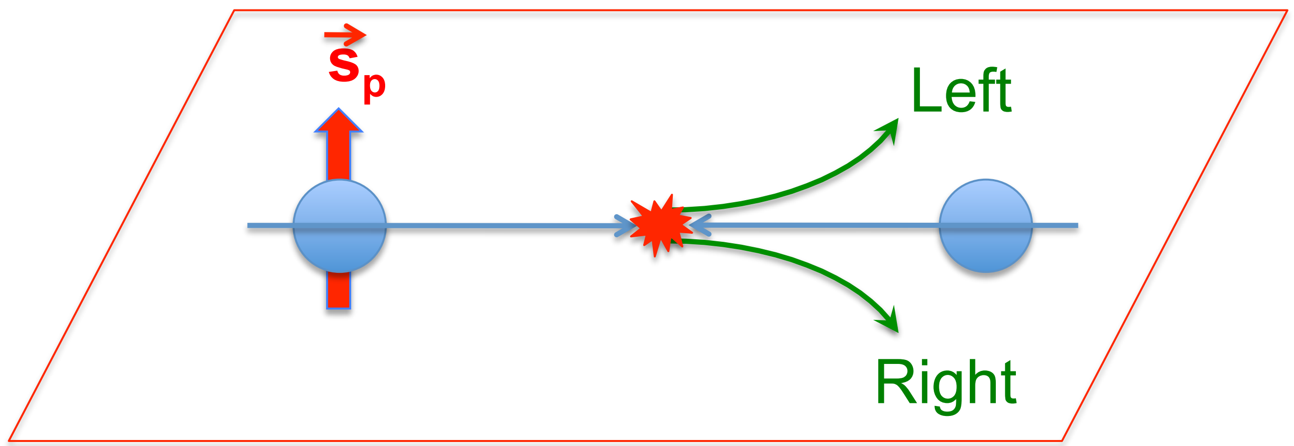
Elliot Leader, Spin in Particle Physics, Cambridge U. Press (2001)

“Polarisation data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self- protection”

J. D. Bjorken, Proc. Adv. Research Workshop on QCD Hadronic Processes, St. Croix, Virgin Islands (1987).

SINGLE SPIN ASYMMETRIES

Consider polarized hadron - hadron collisions



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

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

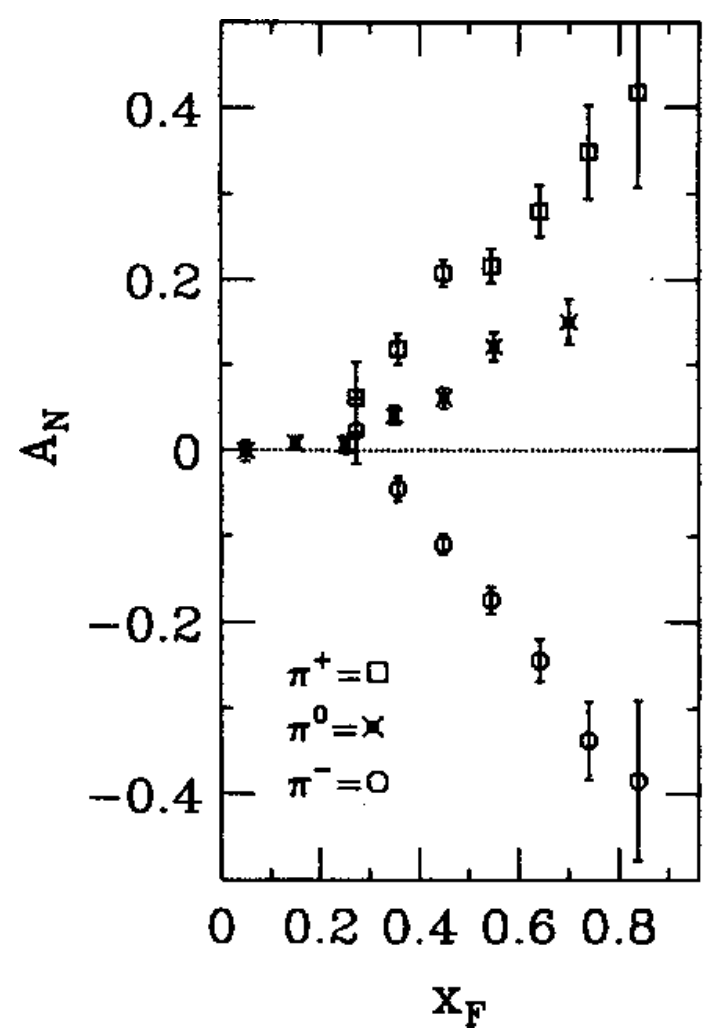
CHALLENGE OF QCD: UNDERSTANDING SPIN ASYMMETRIES

QCD had a very simple prediction

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

Kane, Pumplin, Repko (1978)

Experiment proved this prediction wrong



$$A_N \simeq 40\%$$

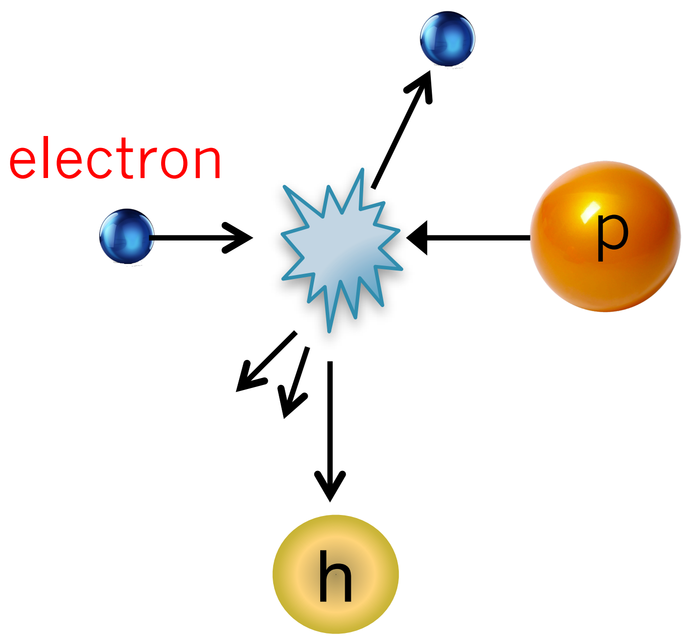
Fermilab experiment E704 (1991)

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

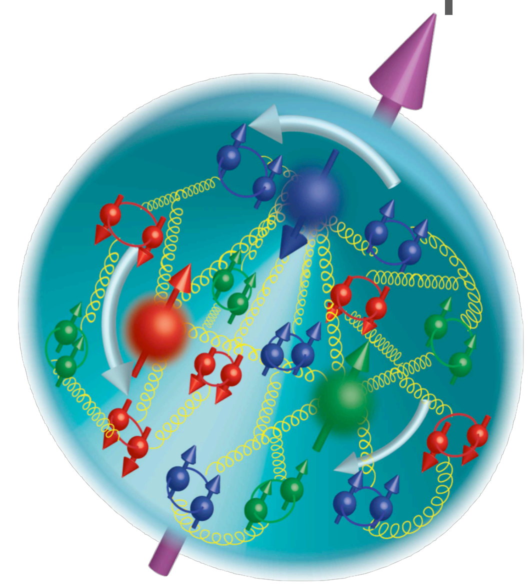
FAILURE OF QCD?

BETTER UNDERSTANDING OF QCD!

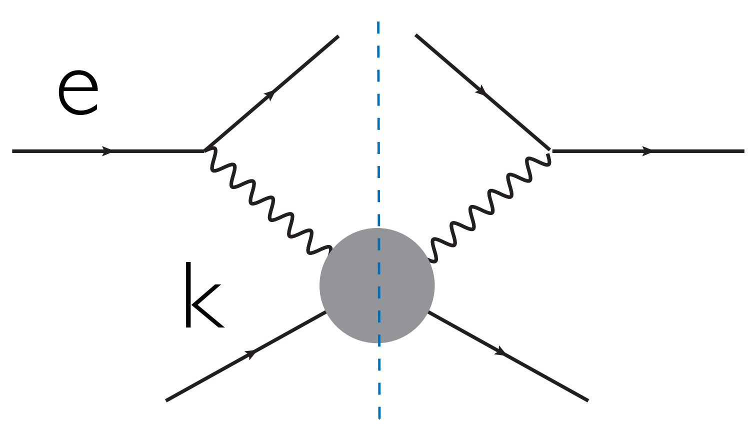
QCD FACTORIZATION IS THE KEY!



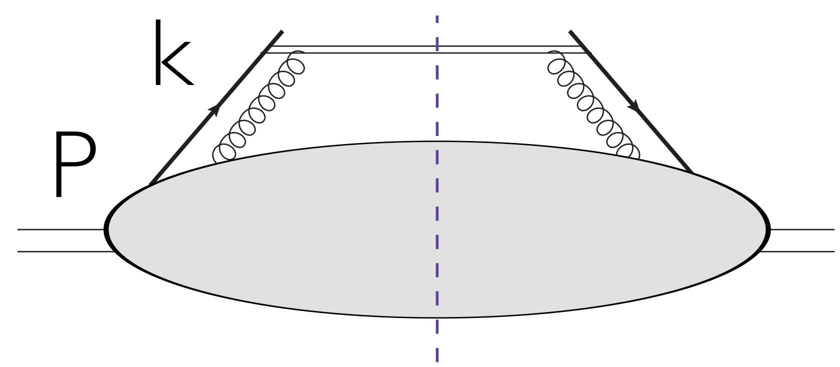
We need a probe to “see” quarks and gluons



$$\sigma \approx$$



$$\otimes$$



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

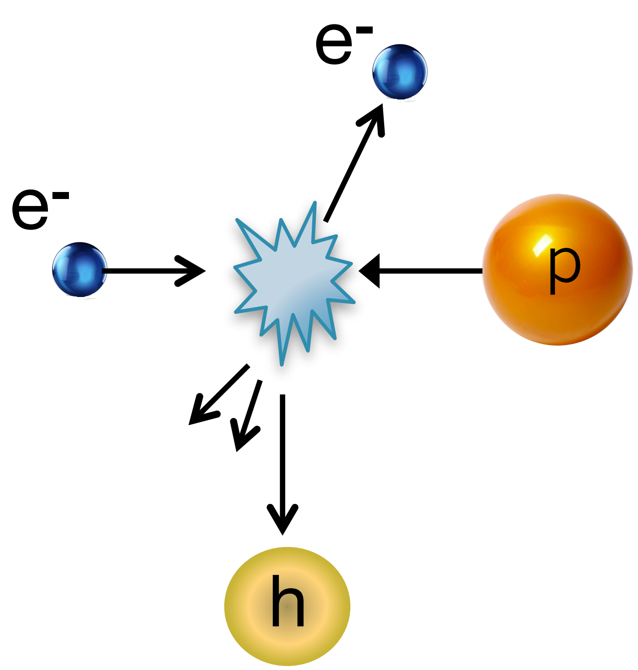
Factorization Probe Structure Power corrections

TRANSVERSE MOMENTUM DEPENDENT FACTORIZATION

The confined motion (k_T dependence) is encoded in TMDs

Semi-Inclusive DIS

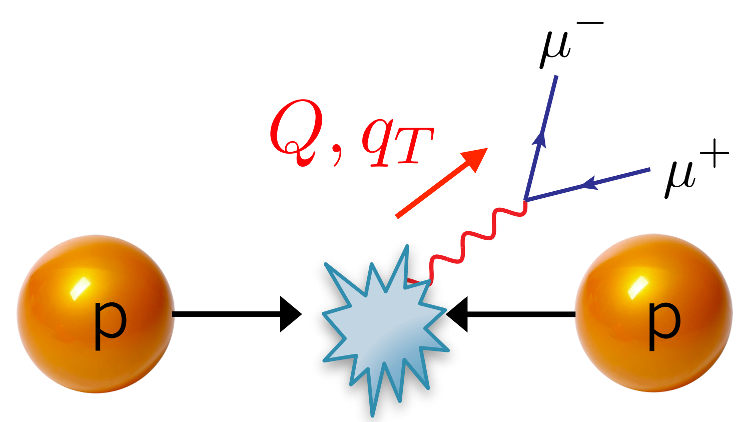
$$\sigma \sim f_{q/P}(x, k_T) D_{h/q}(x, k_T)$$



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

Drell-Yan

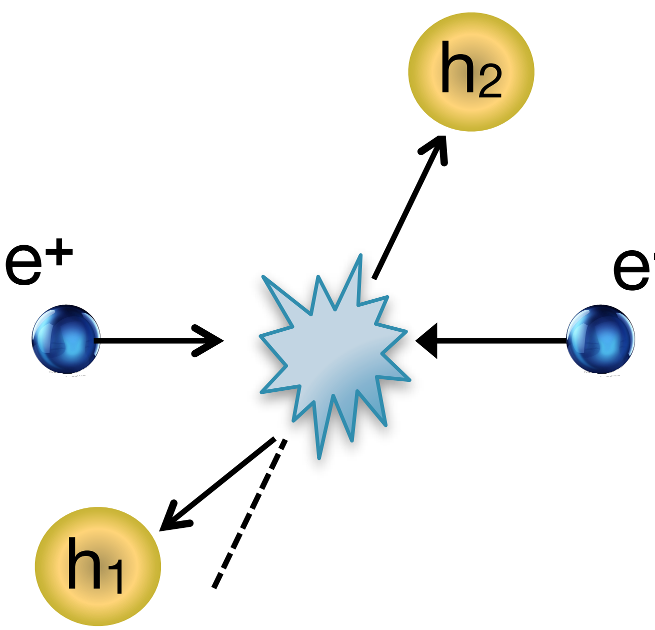
$$\sigma \sim f_{q/P}(x, k_T) f_{q/P}(x, k_T)$$



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

Dihadron in e^+e^-

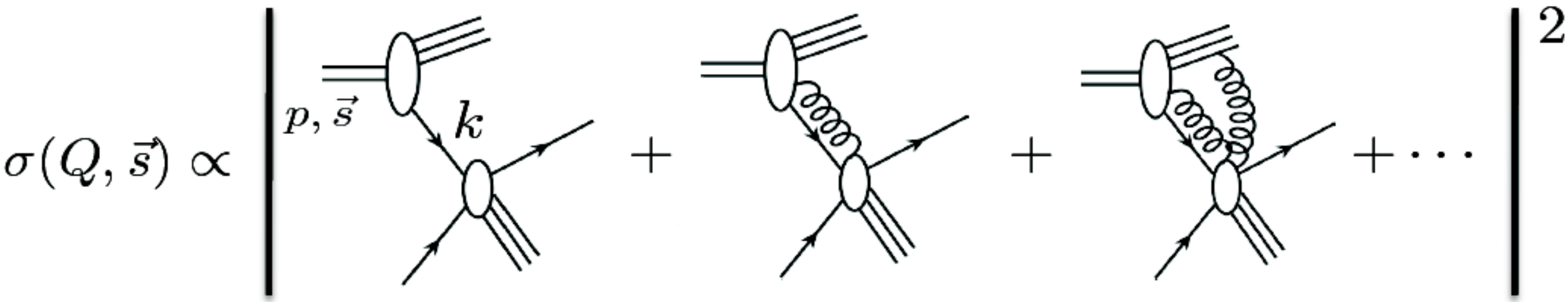
$$\sigma \sim D_{h_1/q}(x, k_T) D_{h_2/q}(x, k_T)$$



Collins, Soper (1983)
Collins (2011)

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

TWIST-3 FACTORIZATION



Qiu, Sterman (1991)

Large scale $\rightarrow$ $q_T \simeq Q$ $\leftarrow$ 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)

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

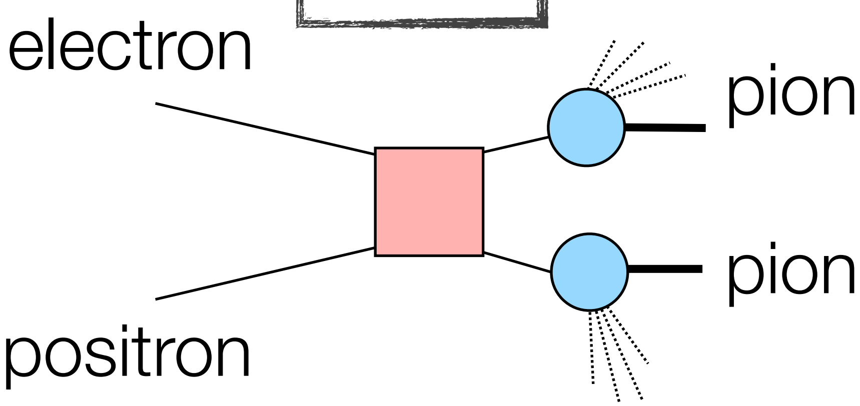
Qiu-Sterman matrix element

The first k_T moment of Sivers function

UNIVERSAL GLOBAL FIT 2020

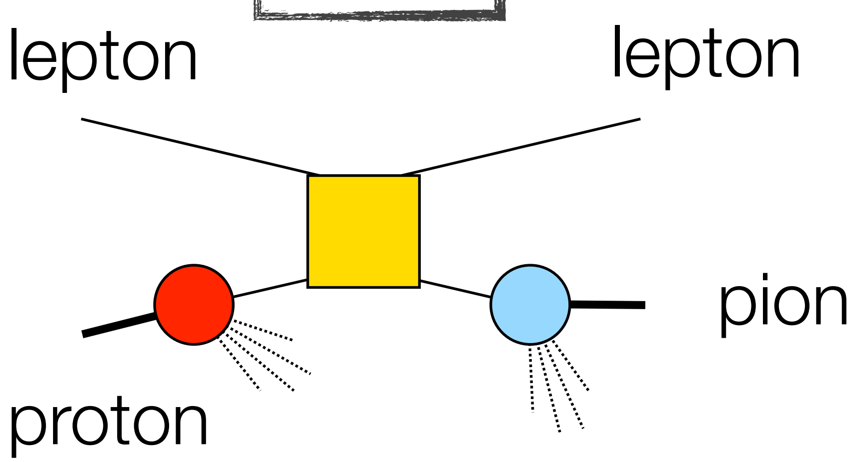
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

e+e−



Collins asymmetries
BELLE, BaBar, BESIII data

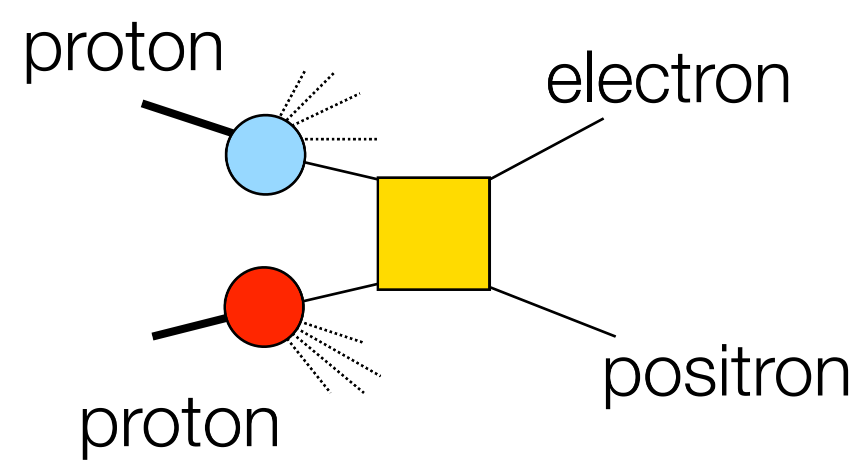
SIDIS



Sivers, Collins asymmetries
COMPASS, HERMES, JLab data

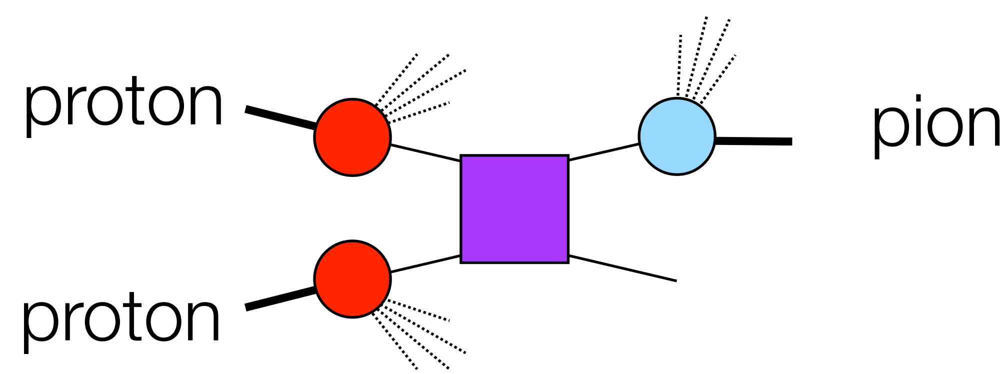
To demonstrate the common origin of SSAs in various processes, we will combine all available data and extract a universal set of non perturbative functions that describes all of them

Drell-Yan and W,Z



Sivers asymmetries
COMPASS, STAR data

PP



A_N asymmetry
STAR, PHENIX, BRAHMS data

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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

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

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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~~

Appears as noise in our fit

Flexible parametrization

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

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

Observable	Reactions	Non-Perturbative Function(s)	$\chi^2/N_{\text{pts.}}$
$A_{\text{SIDIS}}^{\text{Siv}}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^\perp(x,k_T^2)$	$150.0/126 = 1.19$
$A_{\text{SIDIS}}^{\text{Col}}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,k_T^2), H_1^\perp(z,z^2p_\perp^2)$	$111.3/126 = 0.88$
$A_{\text{SIA}}^{\text{Col}}$	$e^+ + e^- \to \pi^+\pi^-(UC,UL)+X$	$H_1^\perp(z,z^2p_\perp^2)$	$154.5/176 = 0.88$
$A_{\text{DY}}^{\text{Siv}}$	$\pi^- + p^\uparrow \to \mu^+\mu^- + X$	$f_{1T}^\perp(x,k_T^2)$	$5.96/12 = 0.50$
$A_{\text{DY}}^{\text{Siv}}$	$p^\uparrow + p \to (W^+,W^-,Z)+X$	$f_{1T}^\perp(x,k_T^2)$	$31.8/17 = 1.87$
A_N^h	$p^\uparrow + p \to (\pi^+,\pi^-,\pi^0)+X$	$h_1(x), F_{FT}(x,x) = \frac{1}{\pi} f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z)$	$66.5/60 = 1.11$

- JAM uses Bayesian inference in order to sample the posterior distribution of all parameters.
- Multistep strategy in the Monte Carlo framework is used.

Sato, Andres, Ethier, Melnitchouk (2019)

- Around 1000 MC samples are drawn from Bayesian posterior distributions and are analyzed.

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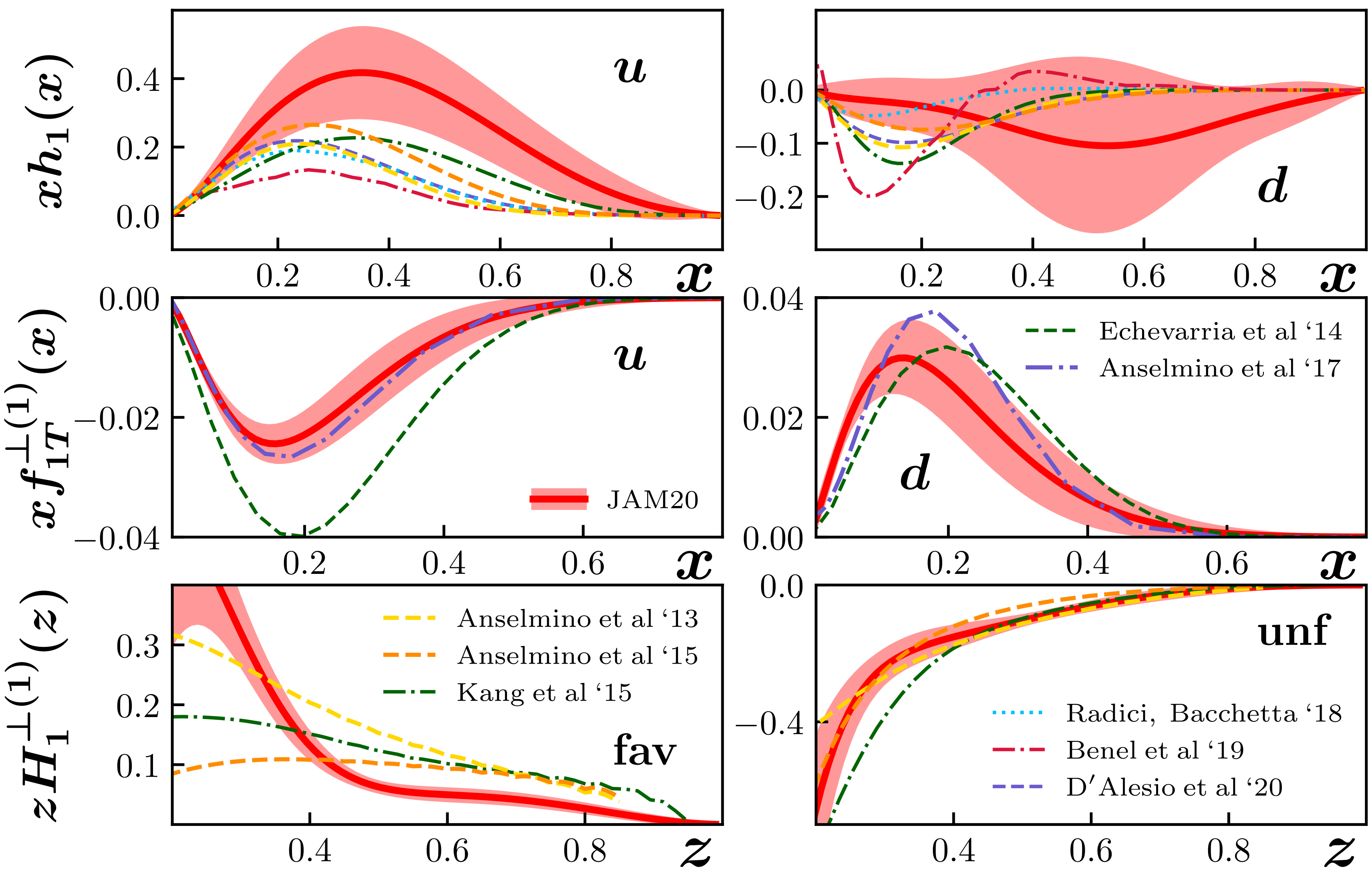
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)



Transversity

$h_1(x)$

Sivers

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

Collins FF

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

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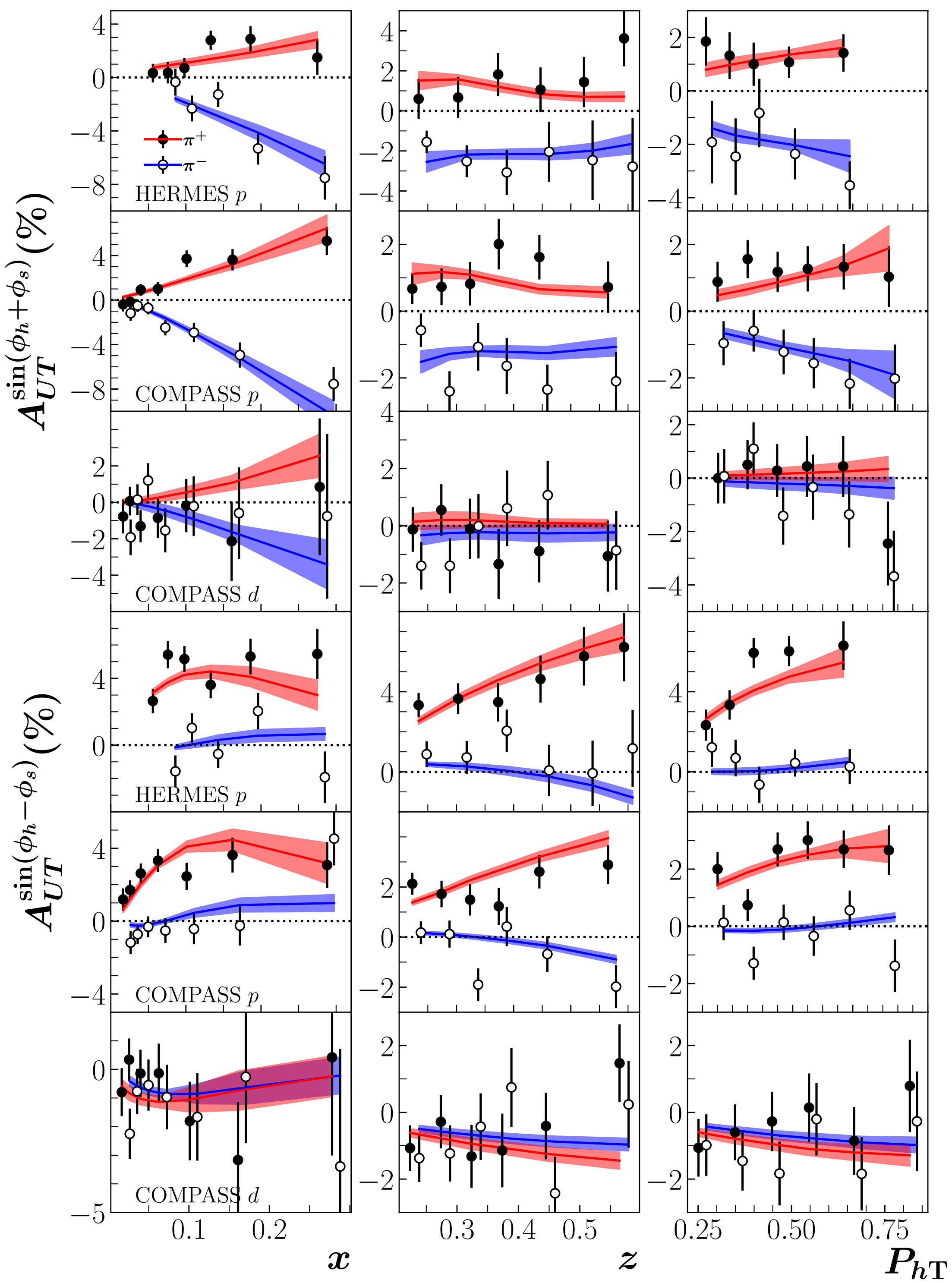
SIDIS



Collins asymmetry

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

Sivers asymmetry

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

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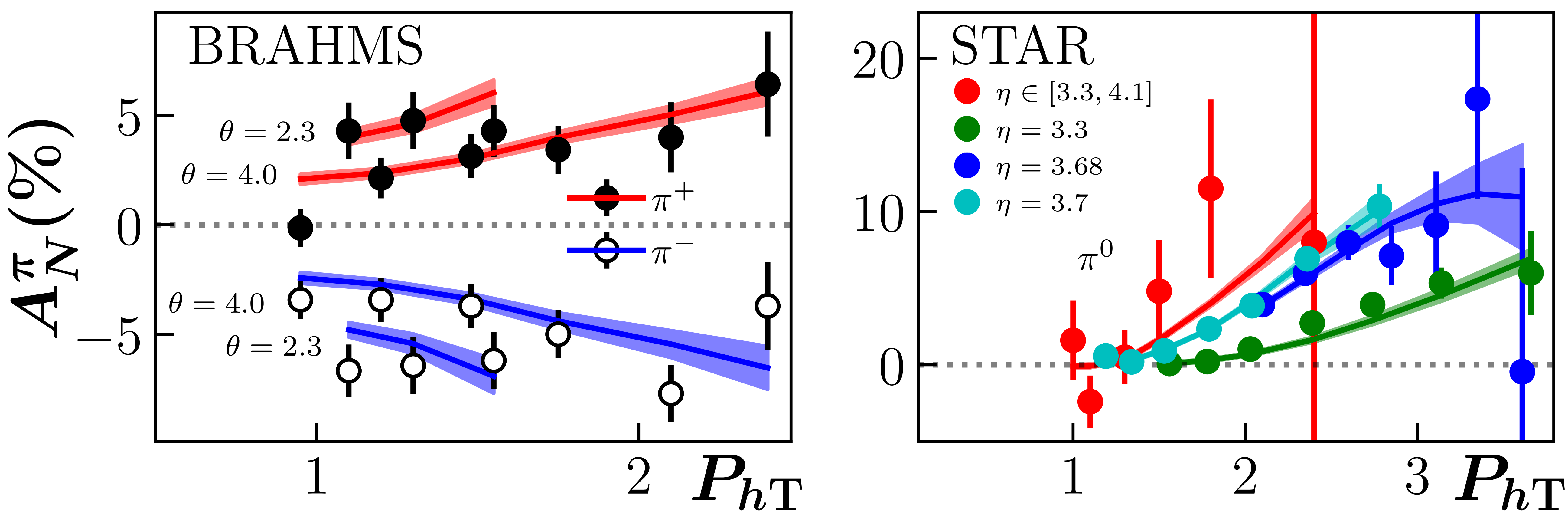
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

proton-proton A_N



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

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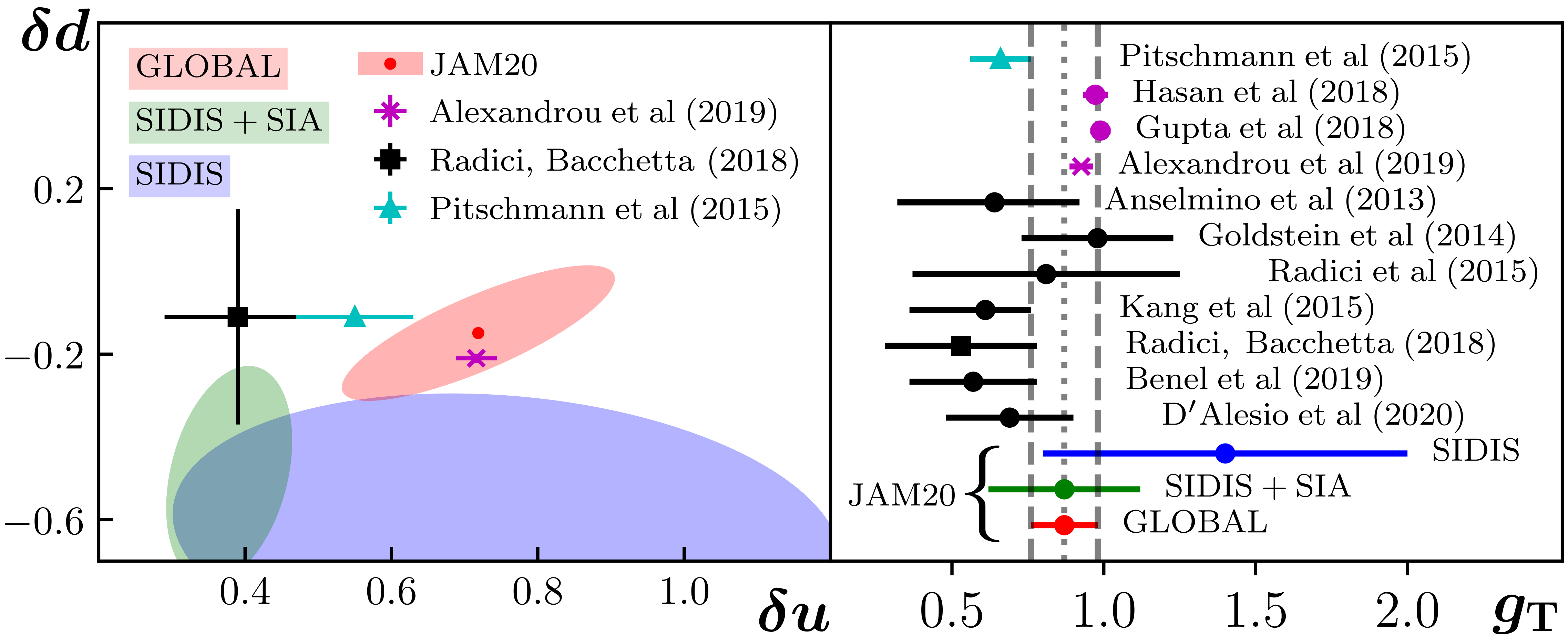
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)



- Tensor charge from up and down quarks is constrained and compatible with lattice results
- Isovector tensor charge $g_T = \delta u - \delta d$
  gT = 0.89± 0.12 compatible with lattice results

δu and δd Q^2=4 GeV^2

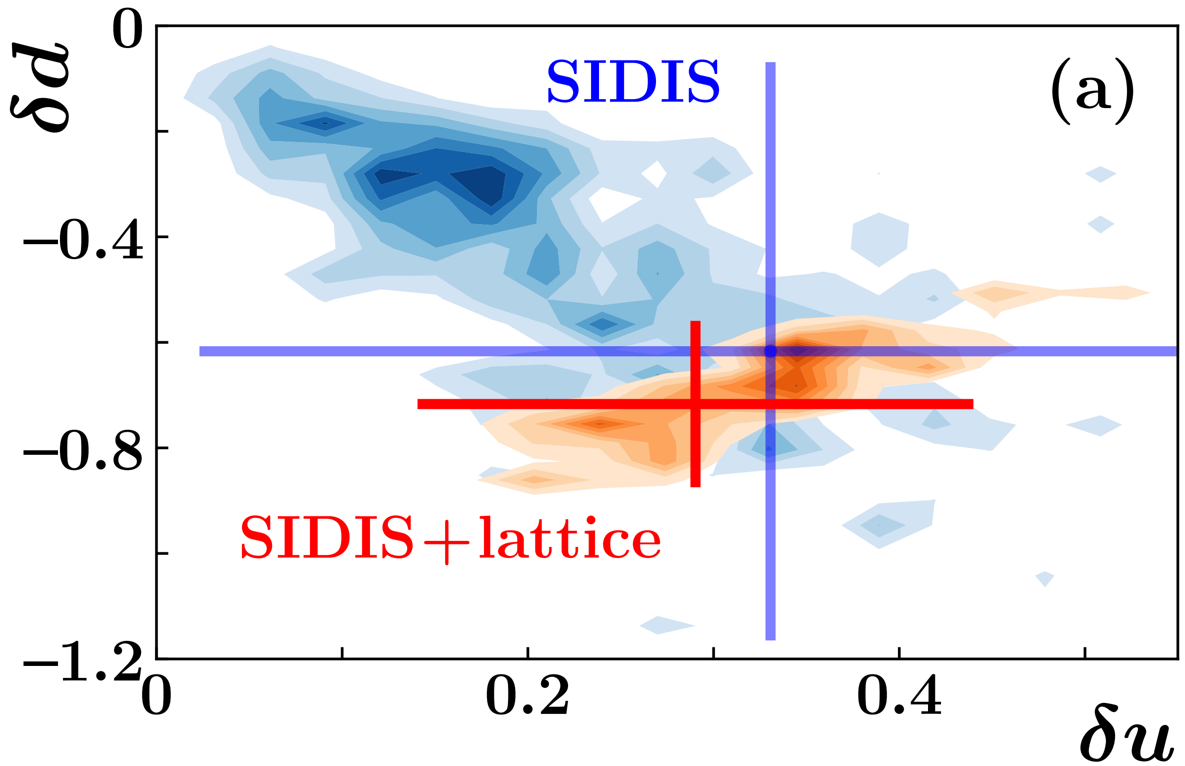
δu= 0.65 ± 0.22

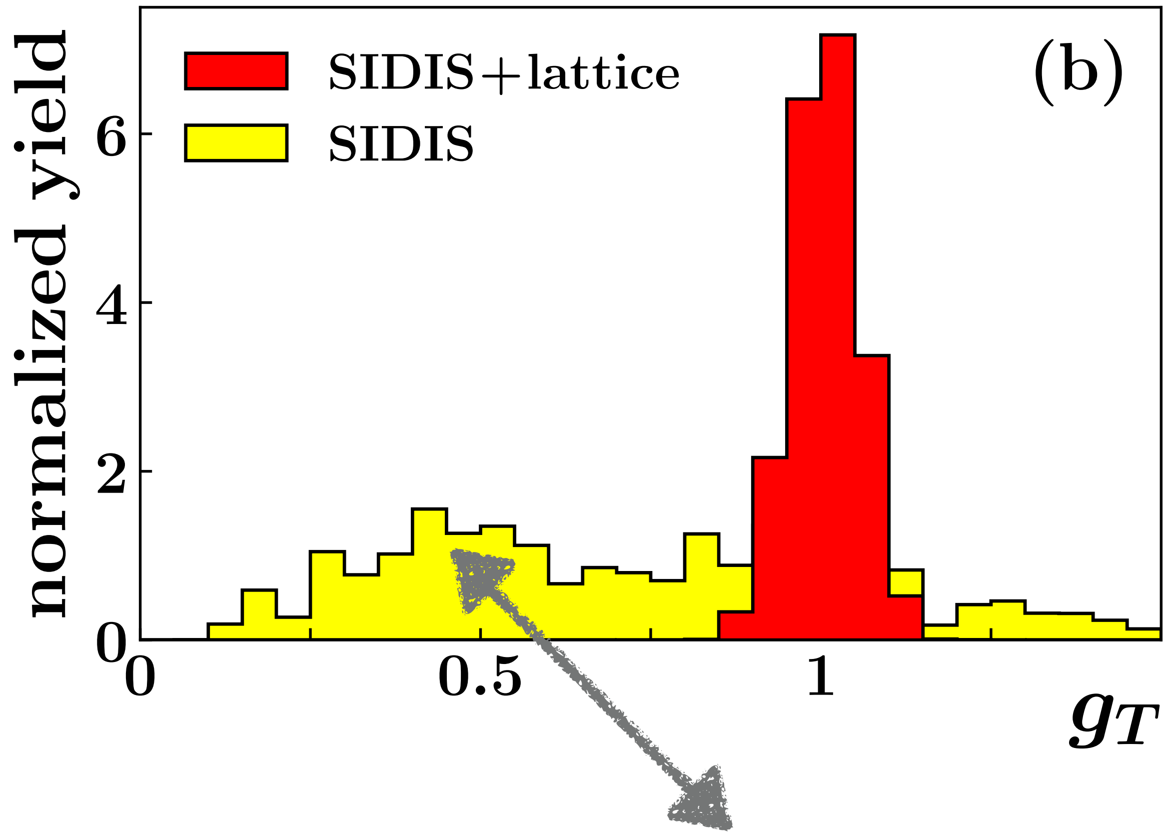
δd= -0.24 ± 0.2

TMD AND LATTICE

Lin, Melnitchouk, Prokudin, Sato, Shows PRL 2018

First JAM analysis of SIDIS data including lattice QCD constraints on g_T





Any analysis based on a single fit would have given a wrong result on g_T

Analysis of probability density distribution of results used in JAM is crucial in obtaining correct results

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