Transversity with di-hadron and single-hadron SIDIS in SoLID

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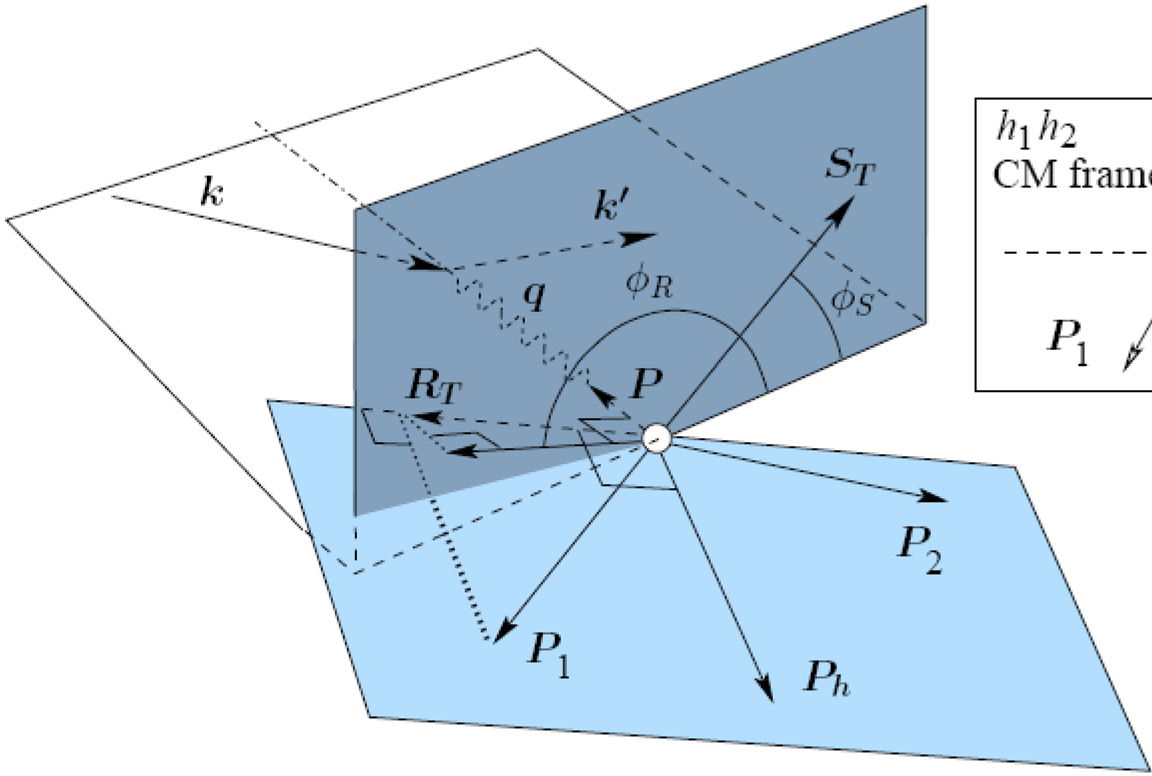
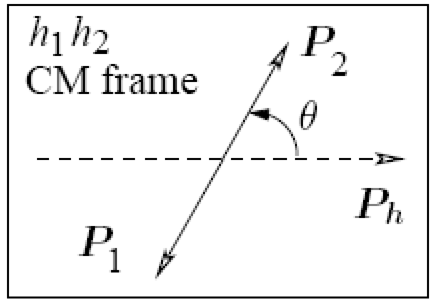
Leading Twist TMDs

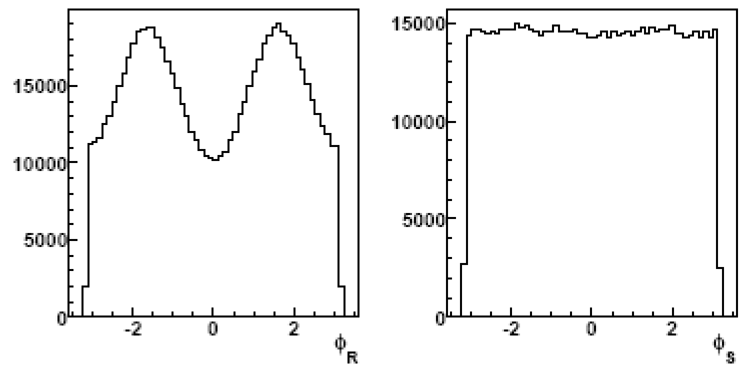
→ Nucleon Spin
→ Quark Spin

		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
Nucleon Polarization	U	$f_1 =$		$h_1^{\perp} =$ − Boer-Mulder
	L		$g_1 =$ − Helicity	$h_{1L}^{\perp} =$ −
	T	$f_{1T}^{\perp} =$ − Sivers	$g_{1T}^{\perp} =$ −	$h_{1T} =$ − Transversity $h_{1T}^{\perp} =$ − Pretzelosity

n(e, e′π⁺π⁻)X Kinematics Variables







$P_h = (P_1 + P_2)$

$R = (P_1 - P_2) / 2$

$$\phi_R \equiv \frac{(q\times k)\cdot R_T}{|(q\times k)\cdot R_T|} \arccos \frac{(q\times k)\cdot(q\times R_T)}{|q\times k||q\times R_T|}$$

$$\phi_S \equiv \frac{(q\times k)\cdot S_T}{|(q\times k)\cdot S_T|} \arccos \frac{(q\times k)\cdot(q\times S_T)}{|q\times k||q\times S_T|}$$

$Q^2 = 4\ E\ E`\ \sin^2(\theta/2)$

$x = Q^2 / (2\ P \cdot q)$

$y = (P \cdot q) / (P \cdot k)$

$z\_\pi^+\pi^- = (P \cdot P_h) / (P \cdot q)$

$M\_\pi^+\pi^- = (P_1 + P_2)^2$

Di-hadron Cross Section in DIS

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_R\,dM_h^2\,d\cos\theta} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_R\,F_{UU}^{\cos\phi_R} \\
&\quad + \varepsilon\cos(2\phi_R)\,F_{UU}^{\cos 2\phi_R} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_R\,F_{LU}^{\sin\phi_R} \\
&\quad + S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_R\,F_{UL}^{\sin\phi_R} + \varepsilon\sin(2\phi_R)\,F_{UL}^{\sin 2\phi_R}\right] \\
&\quad + S_L\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_R\,F_{LL}^{\cos\phi_R}\right] \\
&\quad + |\boldsymbol{S}_T|\Bigg[\sin(\phi_R-\phi_S)\left(F_{UT,T}^{\sin(\phi_R-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_R-\phi_S)}\right) \\
&\qquad + \varepsilon\,\sin(\phi_R+\phi_S)\,F_{UT}^{\sin(\phi_R+\phi_S)} + \varepsilon\,\sin(3\phi_R-\phi_S)\,F_{UT}^{\sin(3\phi_R-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_R-\phi_S)\,F_{UT}^{\sin(2\phi_R-\phi_S)}\Bigg] \\
&\quad + |\boldsymbol{S}_T|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_R-\phi_S)\,F_{LT}^{\cos(\phi_R-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_R-\phi_S)\,F_{LT}^{\cos(2\phi_R-\phi_S)}\Bigg]\Bigg\},
\end{aligned}
$$

How does SSA relate to transversity?

$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}(x,y,z,M_h,Q) = \frac{1}{|\boldsymbol{S}_T|}\frac{\frac{8}{\pi}\int d\phi_R\, d\cos\theta\, \sin(\phi_R+\phi_S)\,(d\sigma^{\uparrow}-d\sigma^{\downarrow})}{\int d\phi_R\, d\cos\theta\,(d\sigma^{\uparrow}+d\sigma^{\downarrow})}$$

$$= \frac{\frac{4}{\pi}\,\varepsilon\int d\cos\theta\, F_{UT}^{\sin(\phi_R+\phi_S)}}{\int d\cos\theta\,(F_{UU,T}+\varepsilon\, F_{UU,L})} \quad .$$

Where $F_{UU,T} = x\, f_1(x)\, D_1\big(z,\cos\theta, M_h\big) \quad ,$

$$F_{UU}^{\cos\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\,\frac{1}{z}\, f_1(x)\,\widetilde{D}^{\sphericalangle}\big(z,\cos\theta,M_h\big) \quad ,$$

$$F_{UT}^{\sin(\phi_R+\phi_S)} = x\frac{|\boldsymbol{R}|\sin\theta}{M_h}\, h_1(x)\, H_1^{\sphericalangle}\big(z,\cos\theta,M_h^2\big) \quad ,$$

$$|\boldsymbol{R}| = \frac{1}{2}\sqrt{M_h^2 - 2(M_1^2+M_2^2) + (M_1^2-M_2^2)^2}$$

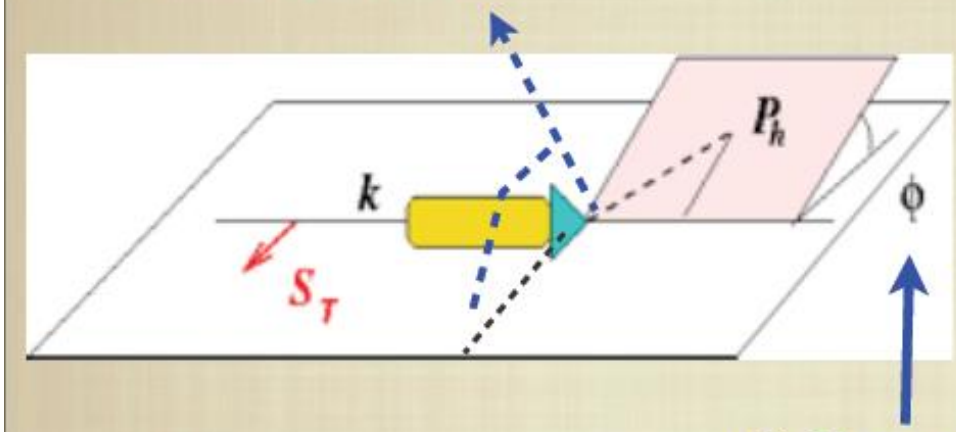
This is what we proposed to measure ...

dihadron fragmentation function (DiFF). Fitting from $e^+ e^-$ annihilation data of Belle

Why Di-hadron SIDIS?

The Collins mechanism

*J. Collins, NP **B396** (93)*



Collins angle

$$\mathbf{k} \times \mathbf{P}_h \cdot \mathbf{S}_T \propto \cos\left(\frac{\pi}{2} - \phi\right) = \sin\phi$$

transverse motion of hadron

=

spin analyzer of fragmenting quark

single-spin asymmetry → **convolution**

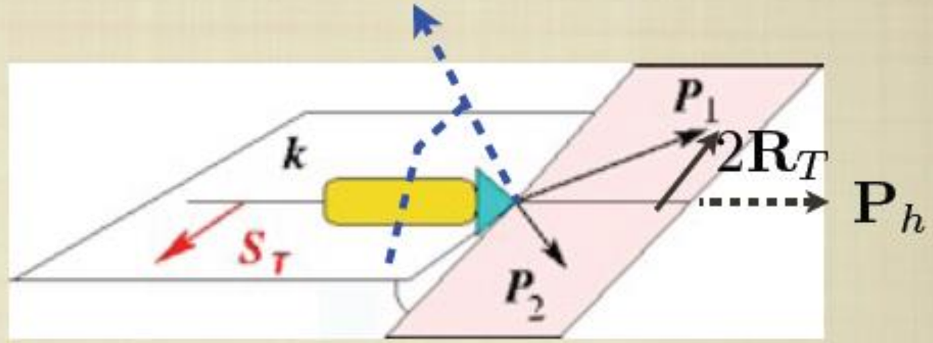
$$A_{UT}^{\sin(\phi)} \propto \left[h_1^q \otimes H_1^{\perp\, q\to h}\right]$$

Depends on x and k_T

TMD factorization

The IFF mechanism

*Collins, Heppelman, Ladinsky, NP **B420** (94)*



$$\begin{aligned}\mathbf{P}_h \times \mathbf{R}_T \cdot \mathbf{S}'_T &\propto \cos(\phi_{S'_T} - (\phi_{R_T} + \pi/2)) \\ &= \cos(\pi - \phi_S - (\phi_{R_T} + \pi/2)) \\ &= \sin(\phi_{R_T} + \phi_S)\end{aligned}$$

azimuthal orientation of hadron pair

=

spin analyzer of fragmenting quark

single-spin asymmetry → **product**

$$A_{UT}^{\sin(\phi_R+\phi_S)} \propto h_1^q(x)\, H_1^{\sphericalangle\, q\to h_1 h_2}$$

Depends only on x

collinear factorization

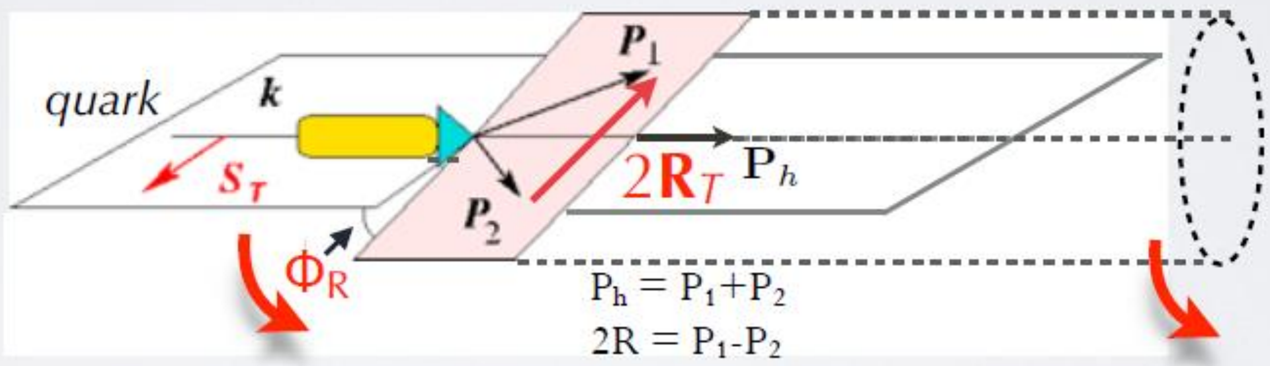
Di-hadron production

Collins, Heppelman, Ladinsky,
N.P. **B420** (94)

$R_T \ll Q$ $H_1^{\sphericalangle}$

↕

M_h
invariant mass



correlation S_T and R_T → **azimuthal asymmetry**

Di-hadron production

framework
collinear
factorization

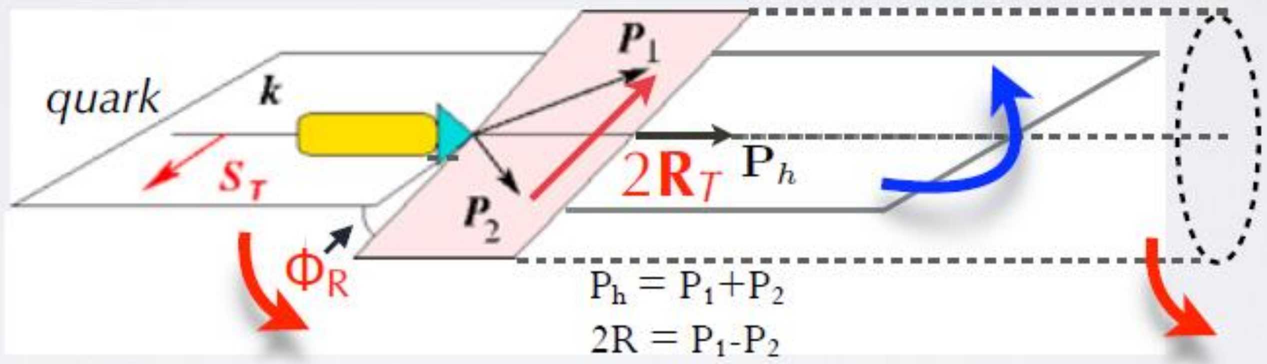
Collins, Heppelman, Ladinsky,
N.P. ***B420*** *(94)*

$R_T \ll Q$ $H_1^{\sphericalangle}$

$\updownarrow$

M_h

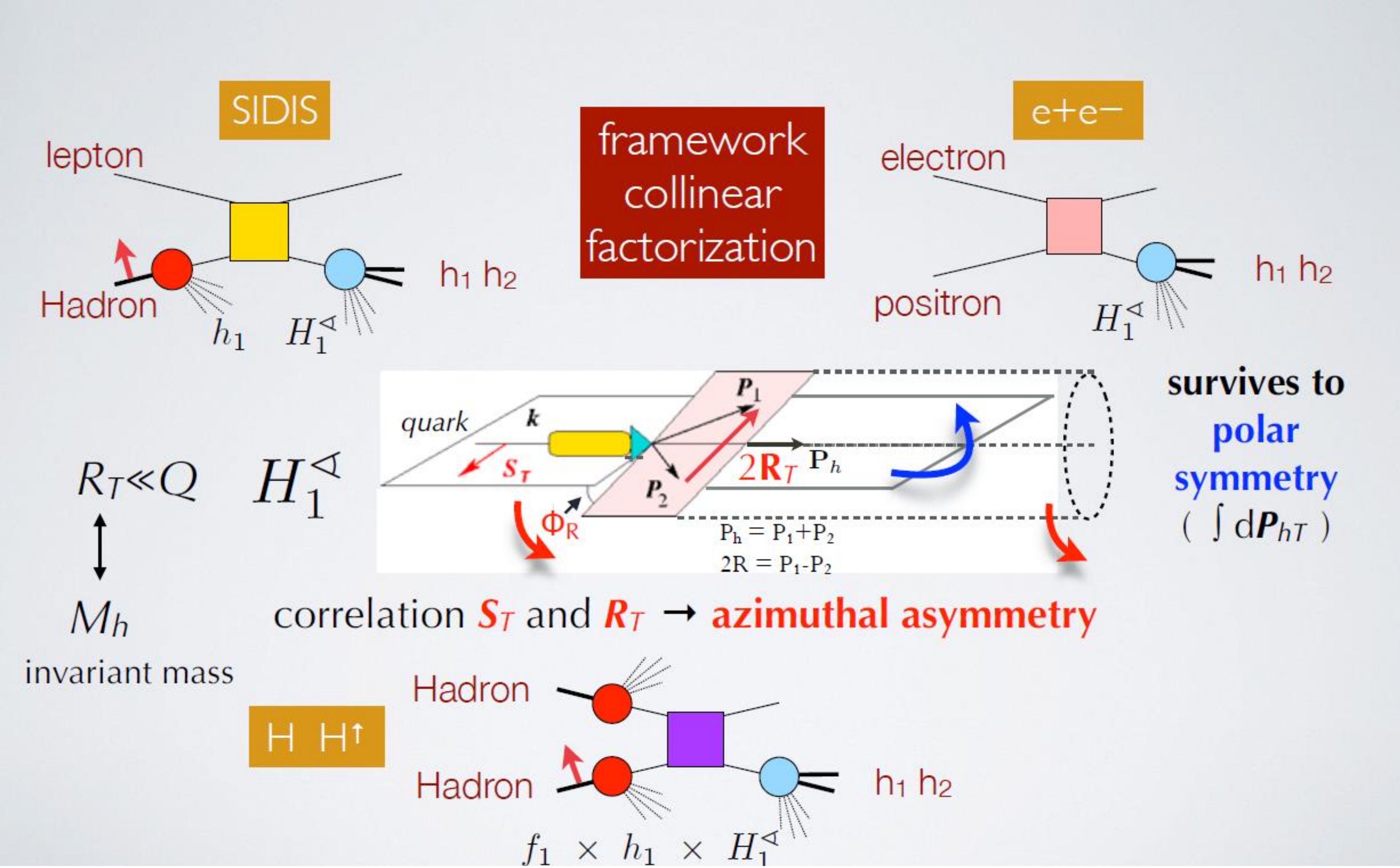
invariant mass



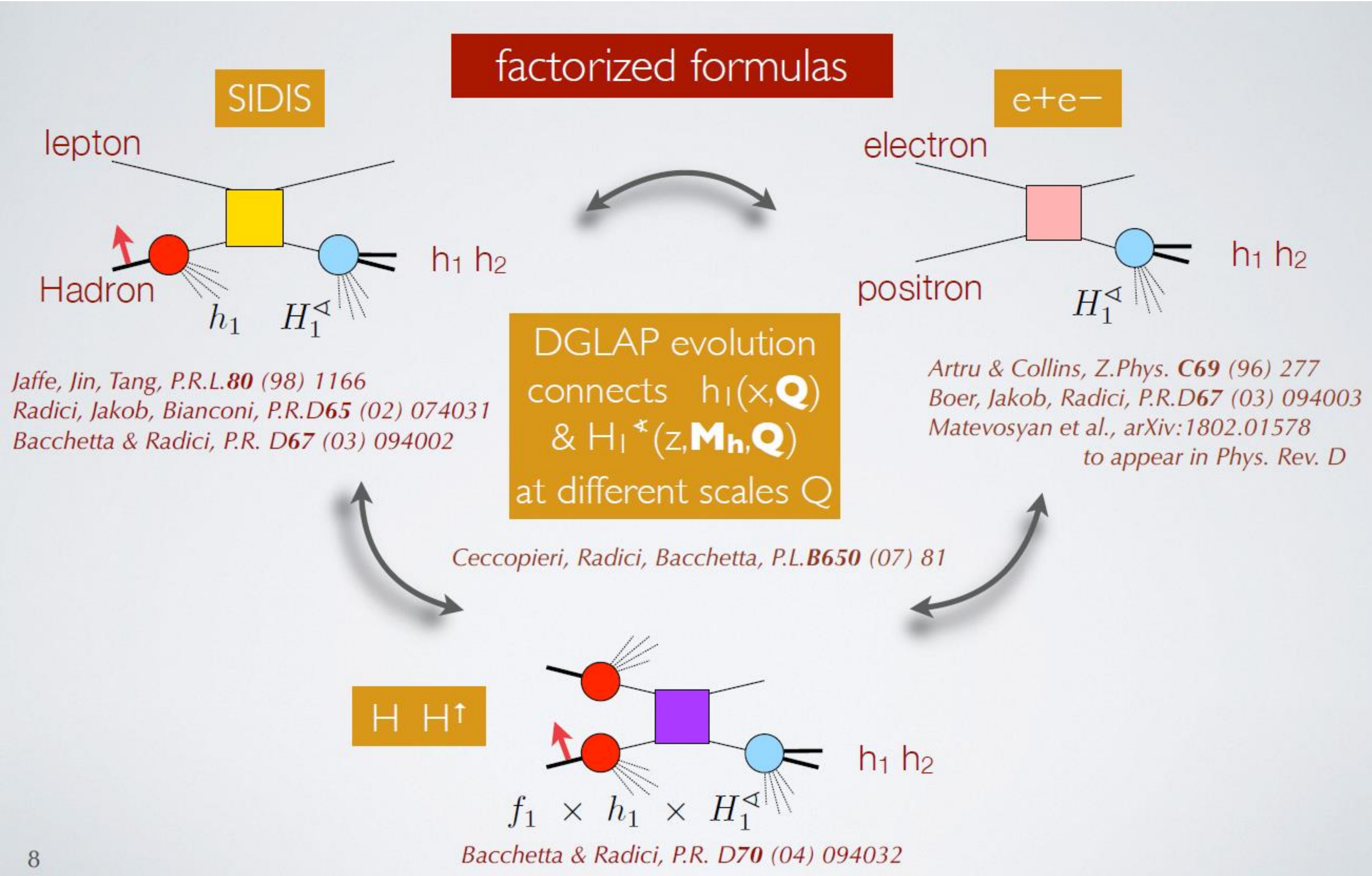
survives to
polar
symmetry
($\int d\boldsymbol{P}_{hT}$)

correlation $\boldsymbol{S}_T$ and $\boldsymbol{R}_T$ → **azimuthal asymmetry**

Di-hadron production

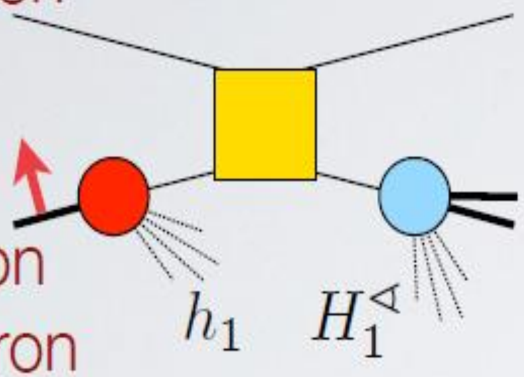


Extract h1 from Di-hadron Data



Exp. Data for Di-hadron Production

SIDIS ℓ $H^\uparrow \to \ell'$ $(h_1\, h_2)$ X



hermes

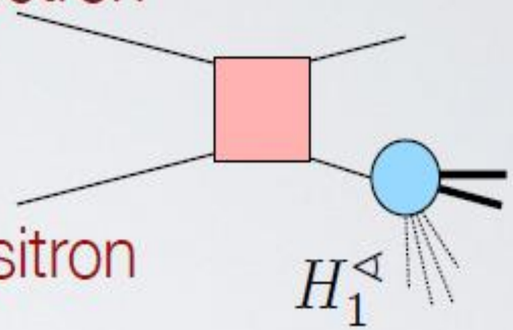
COMPASS

*Airapetian et al., JHEP **0806** (08) 017*

*Adolph et al., P.L. **B713** (12)*

*Braun et al., E.P.J. Web Conf. **85** (15) 02018*

e+e− → $(h_1\, h_2)$ X



BELLE

*Vossen et al., P.R.L. **107** (11) 072004*

D_1 ~~*Seidl et al., P.R. **D96** (17) 032005*~~

STAR

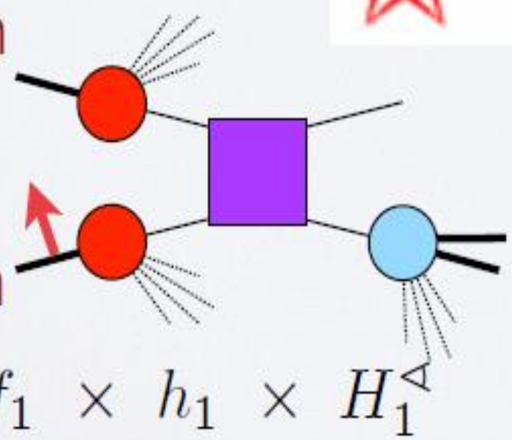
run 2006 (s=200)

*Adamczyk et al. (STAR), P.R.L. **115** (2015) 242501*

~~run 2011 (s=500)~~

~~*Adamczyk et al. (STAR), P.L. **B780** (18) 332*~~

H $H^\uparrow \to (h_1\, h_2)$ X

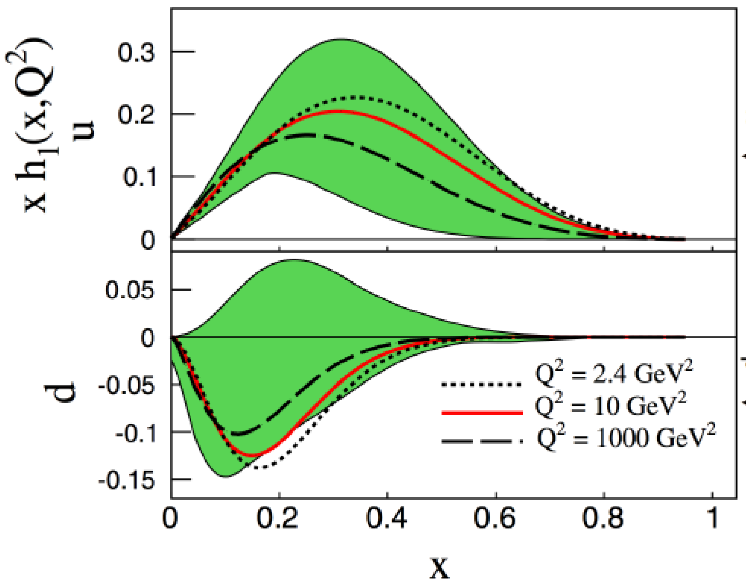


$A_{UT}\,(\eta, M_h, P_T)$

7

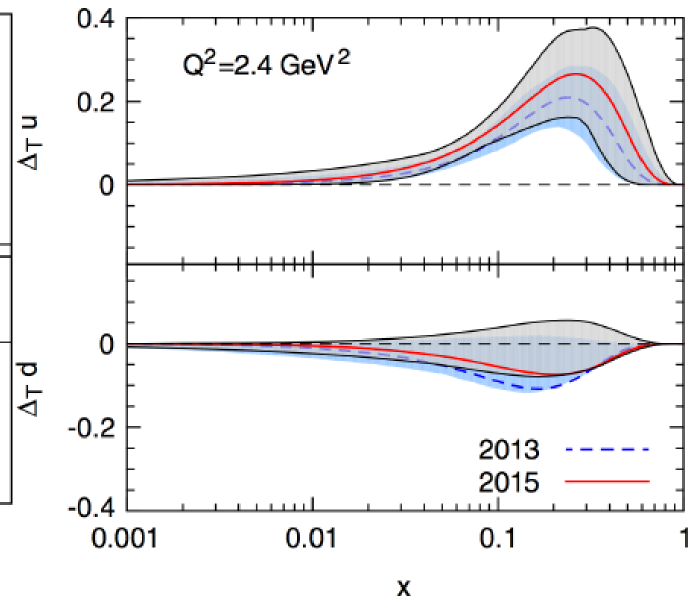
Latest Transversity Result

Single-hadron SIDIS



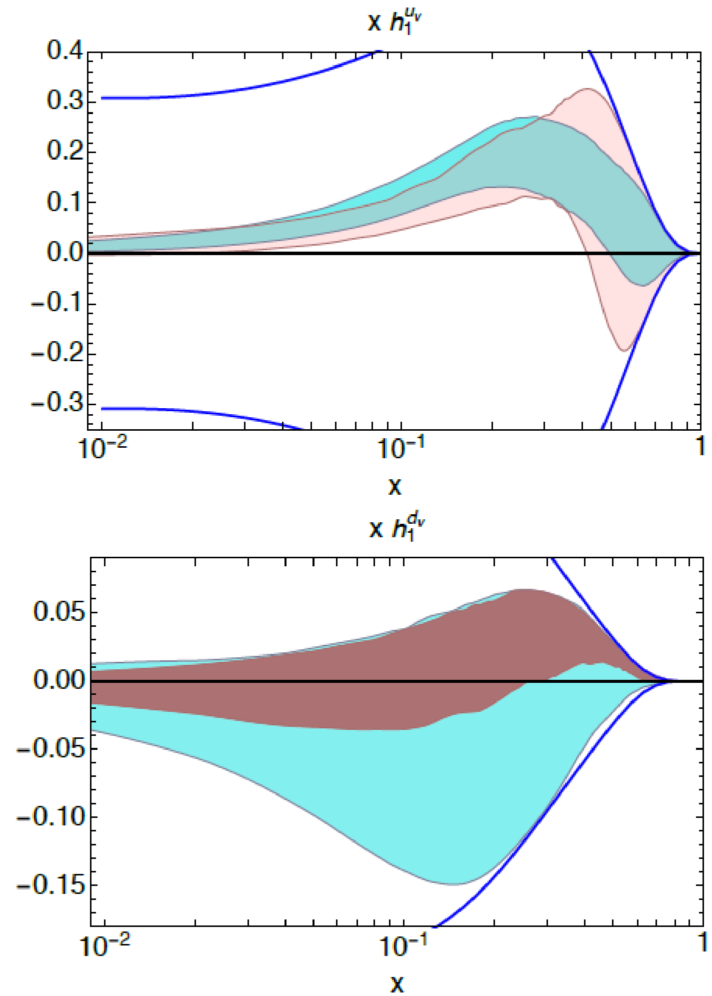
Z. Kang et al,
PRD.93.014009 (2016)

Single-hadron SIDIS



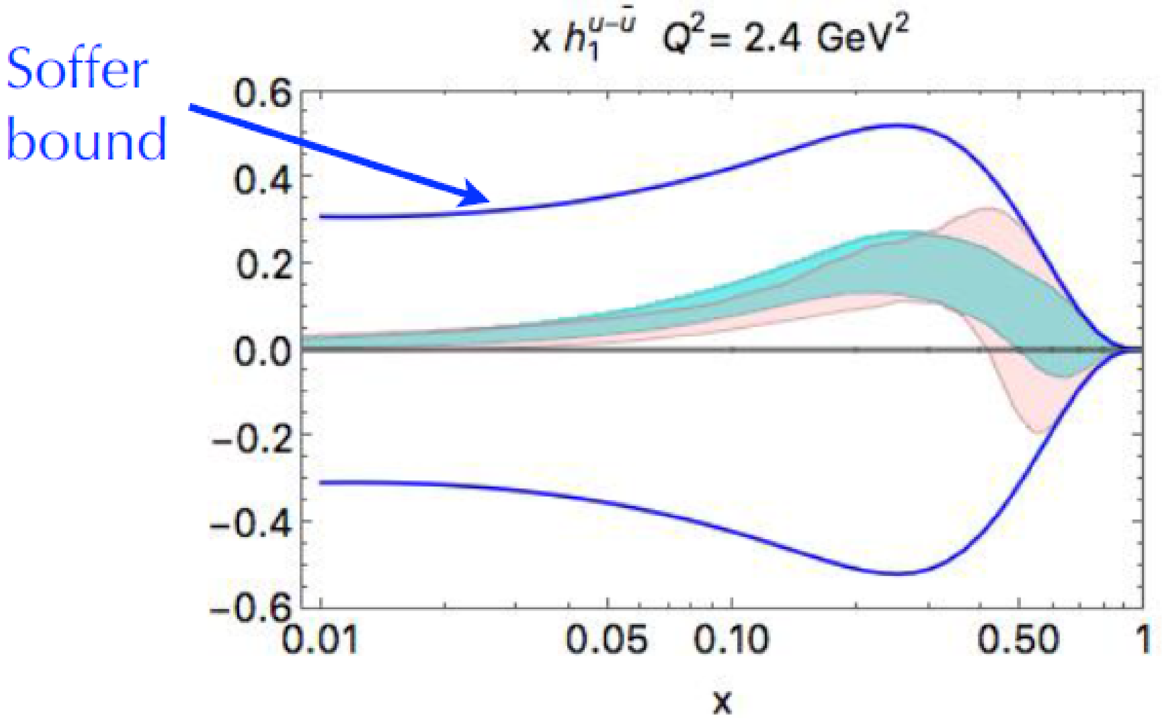
M. Anselmino et al,
PRD.92.114023 (2015)

Di-hadron SIDIS



M. Radici and A. Bacchetta,
PRL.120.192001 (2018)

Latest Result of h_1^u



Radici & Bacchetta, P.R.L. ***120*** *(18) 192001*

global fit

up

higher precision

old fit (only SIDIS data)

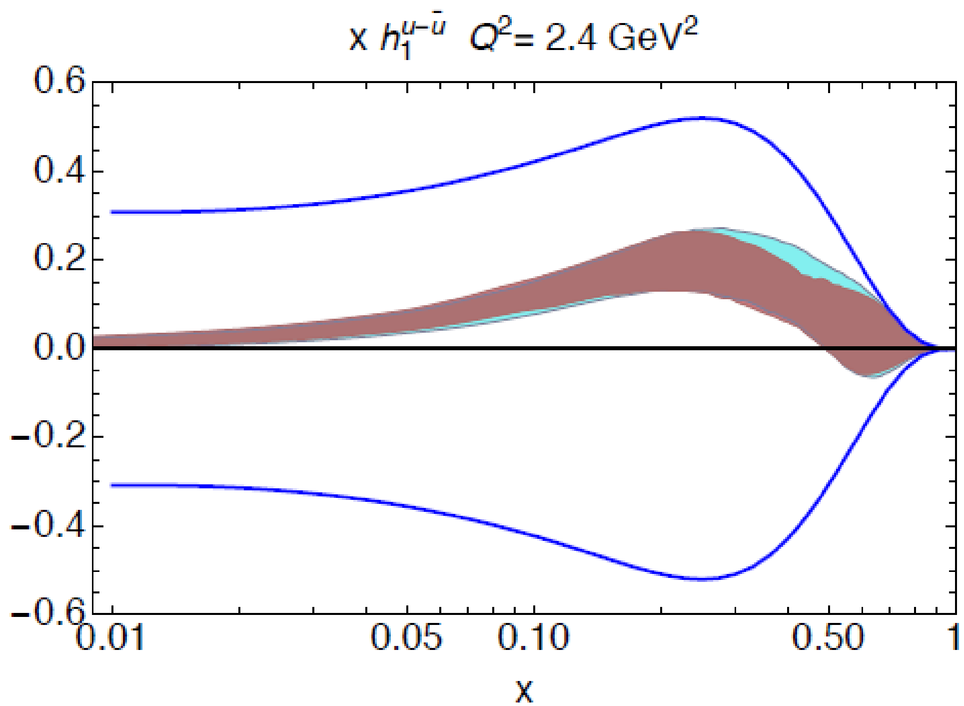
Radici et al., JHEP ***1505*** *(15) 123*

up

insensitive to uncertainty on gluon D_1

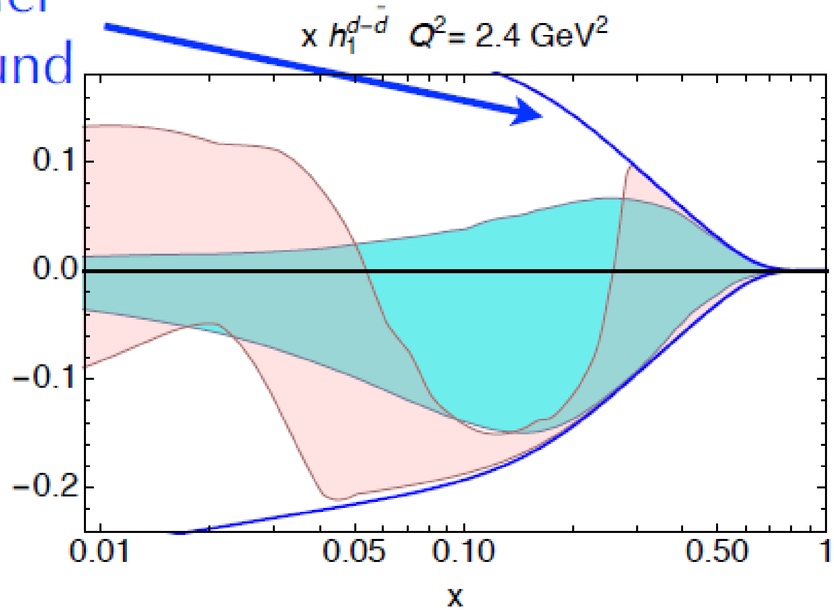
$D_1^g(Q_0) = 0$

$$D_1^g(Q_0) = \begin{cases} 0 \\ D_1^u/4 \\ D_1^u \end{cases}$$



Latest Result of h_1^d

Soffer bound



Radici & Bacchetta, P.R.L. ***120*** *(18) 192001*

global fit

old fit

Radici et al., JHEP ***1505*** *(15) 123*

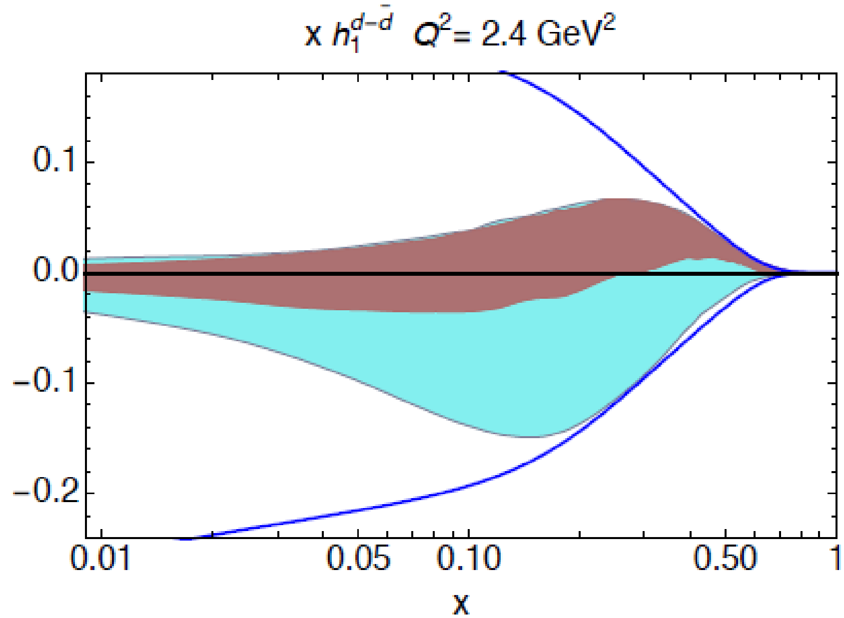
down

down

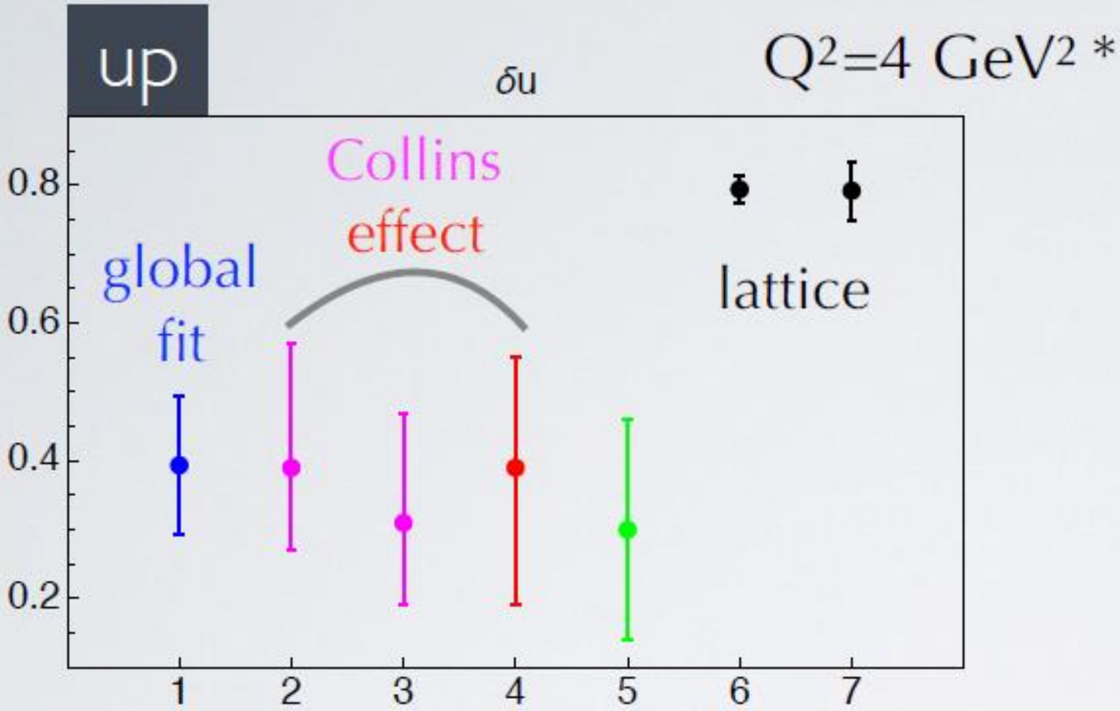
sensitive to uncertainty on gluon D_1

$$D_1^g(Q_0) = 0$$

$$D_1^g(Q_0) = \begin{cases} 0 \\ D_1^u/4 \\ D_1^u \end{cases}$$

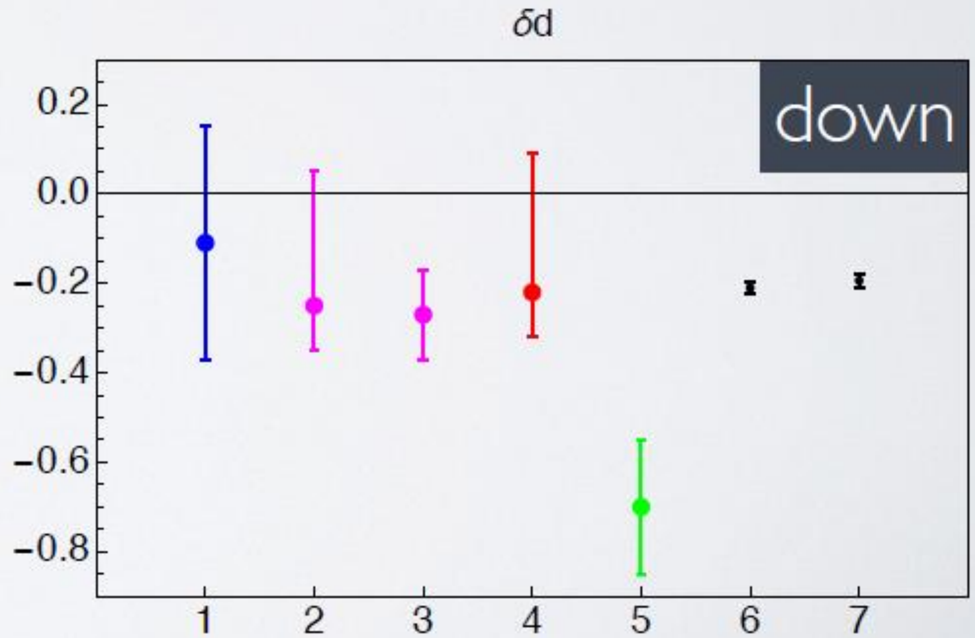


Tensor Charge: $\delta q(Q^2) = \int dx\, h_1^{q-\bar{q}}(x,Q^2)$



incompatibility for up

compatible for down
but with large errors
(except JAM)



1- global fit *Radici & Bacchetta, P.R.L. 120 (18) 192001*

2,3- Torino *Anselmino et al., P.R. D87 (13) 094019* * $Q^2=1$

4- TMD fit *Kang et al., P.R. D93 (16) 014009* * $Q^2=10$

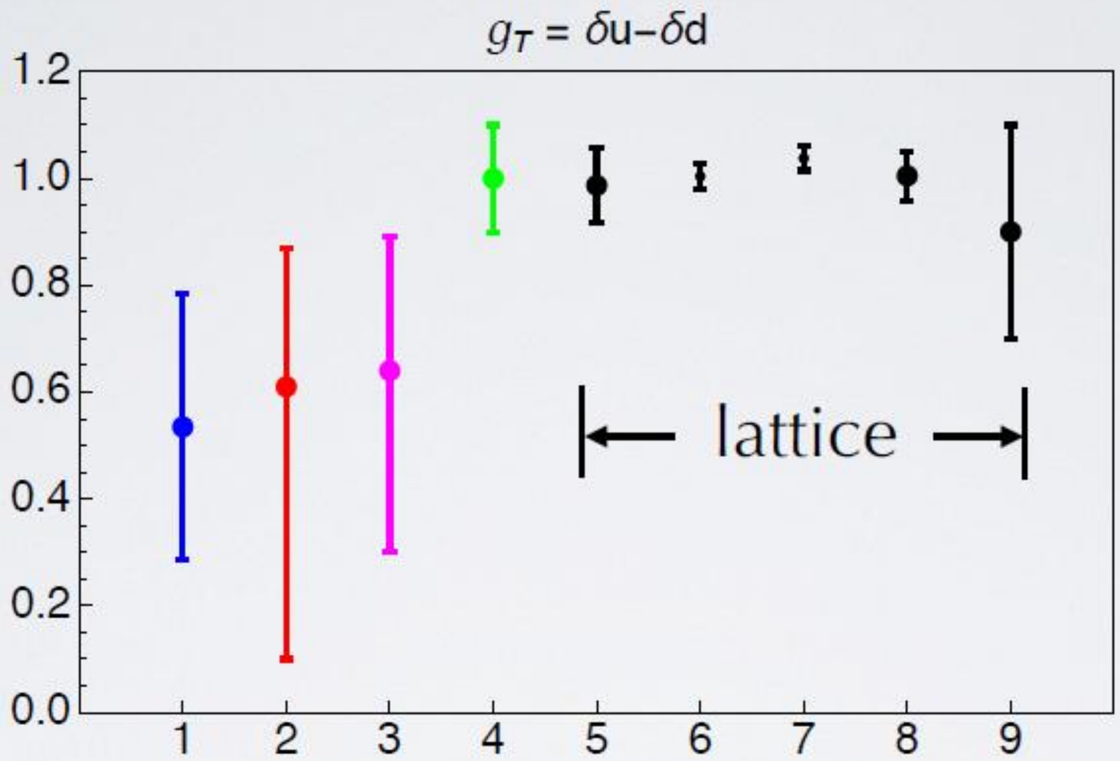
5- JAM fit *Lin et al., P.R.L.120 (18) 152502* {Collins effect + lattice $g_T=\delta u-\delta d$ * $Q_0^2=2$

6- ETMC17 *Alexandrou et al., P.R. D95 (17) 114514; E P.R. D96 (17) 099906*

7- PNDME16 *Bhattacharya et al., P.R. D94 (16) 054508*

Isovector Tensor Charge: $g_T = \delta u - \delta d$

Q^2=4 GeV^2 *



incompatibility (except JAM)

Radici & Bacchetta, P.R.L. 120 (18) 192001 — 1) global fit '17

Kang et al., P.R. D93 (16) 014009 — 2) "TMD fit" * Q^2=10

Anselmino et al., P.R. D87 (13) 094019 — 3) Torino fit * Q^2=1

Lin et al., P.R.L. 120 (18) 152502 — 4) JAM fit '17 * Q_0^2=2

5) PNDME '16 — *Bhattacharya et al., P.R. D94 (16) 054508*

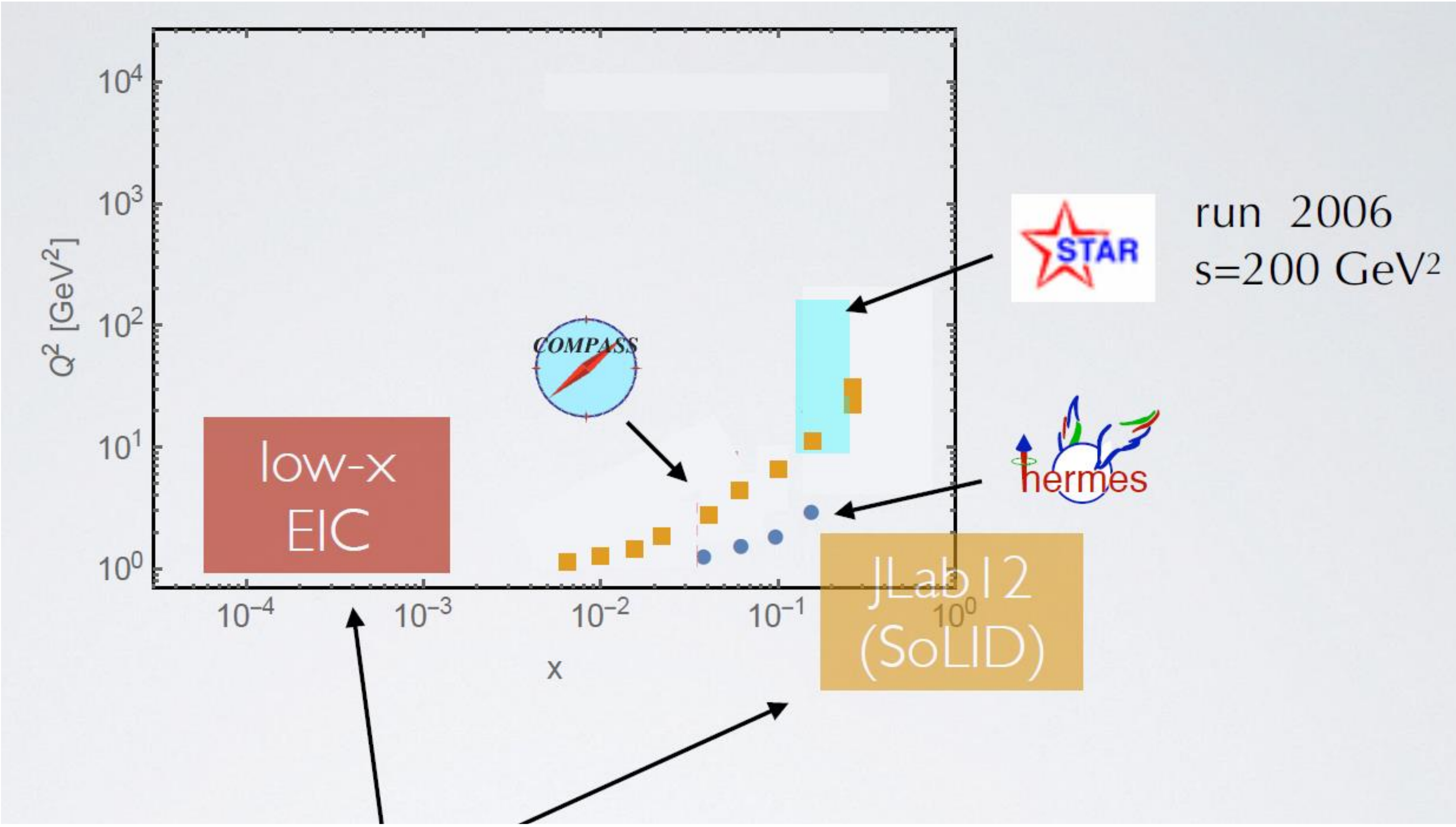
6) ETMC '17 — *Alexandrou et al., P.R. D95 (17) 114514; E P.R. D96 (17) 099906*

7) LHPC '12 — *Green et al., P.R. D86 (12)*

8) RQCD '14 — *Bali et al., P.R. D91 (15)*

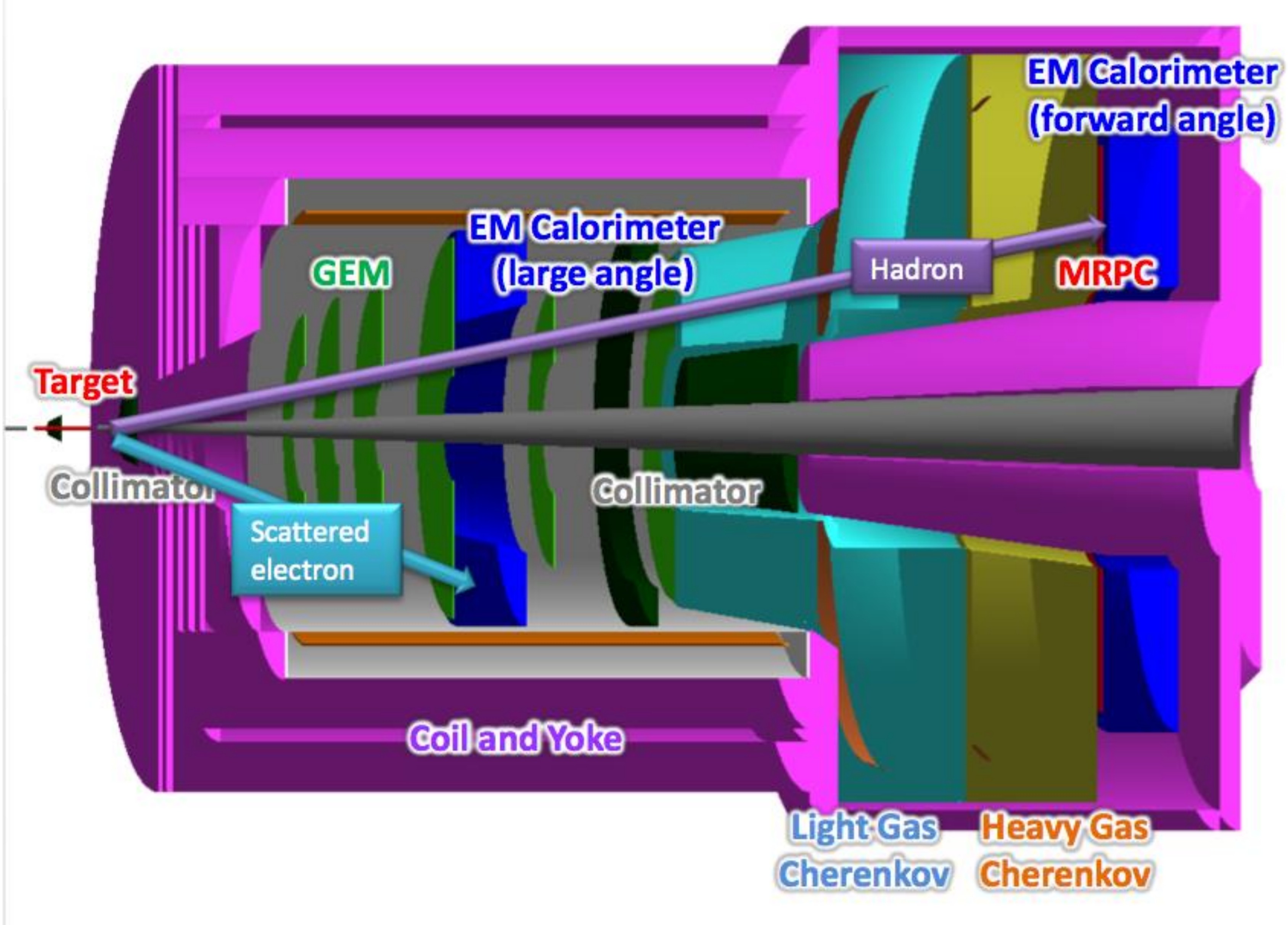
9) RBC-UKQCD — *Aoki et al., P.R. D82 (10)*

More Constraints on Exptrapolation



Need more data ……

SoLID, in SIDIS Configuration



Electron will be detected by either FAEC (8^o-15^o) or LAEC(16^o-24^o)
Hadrons will be detected by FAEC
Trigger: electron + 1 hadron coincident
Energy threshold: FAEC = 0.8 GeV, LAEC = 3.0 GeV
15 μA beam current, 11 and 8.8 GeV beam, Luminosity = 10^{36} (n)/cm^2/s

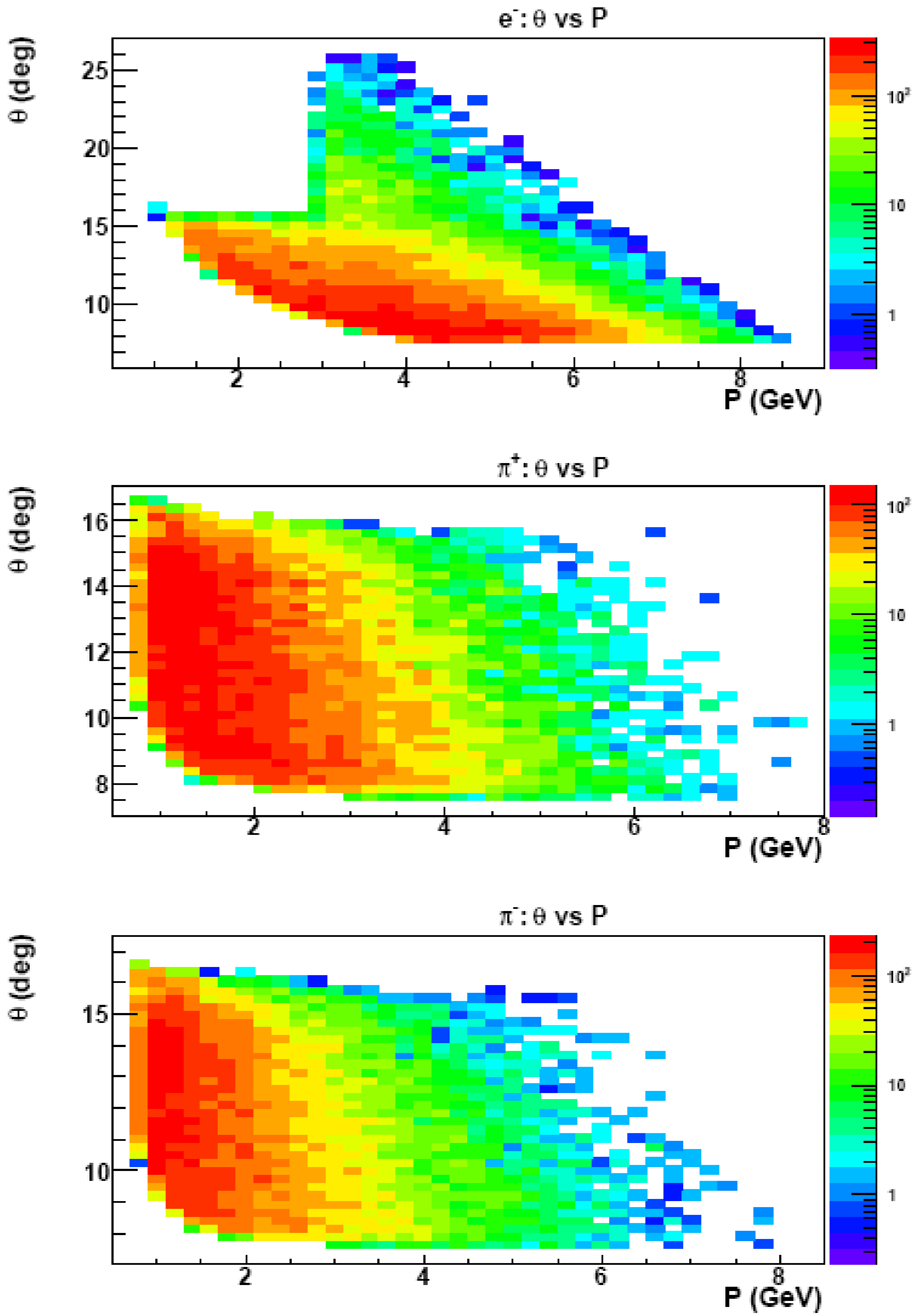
Experiment Strategy

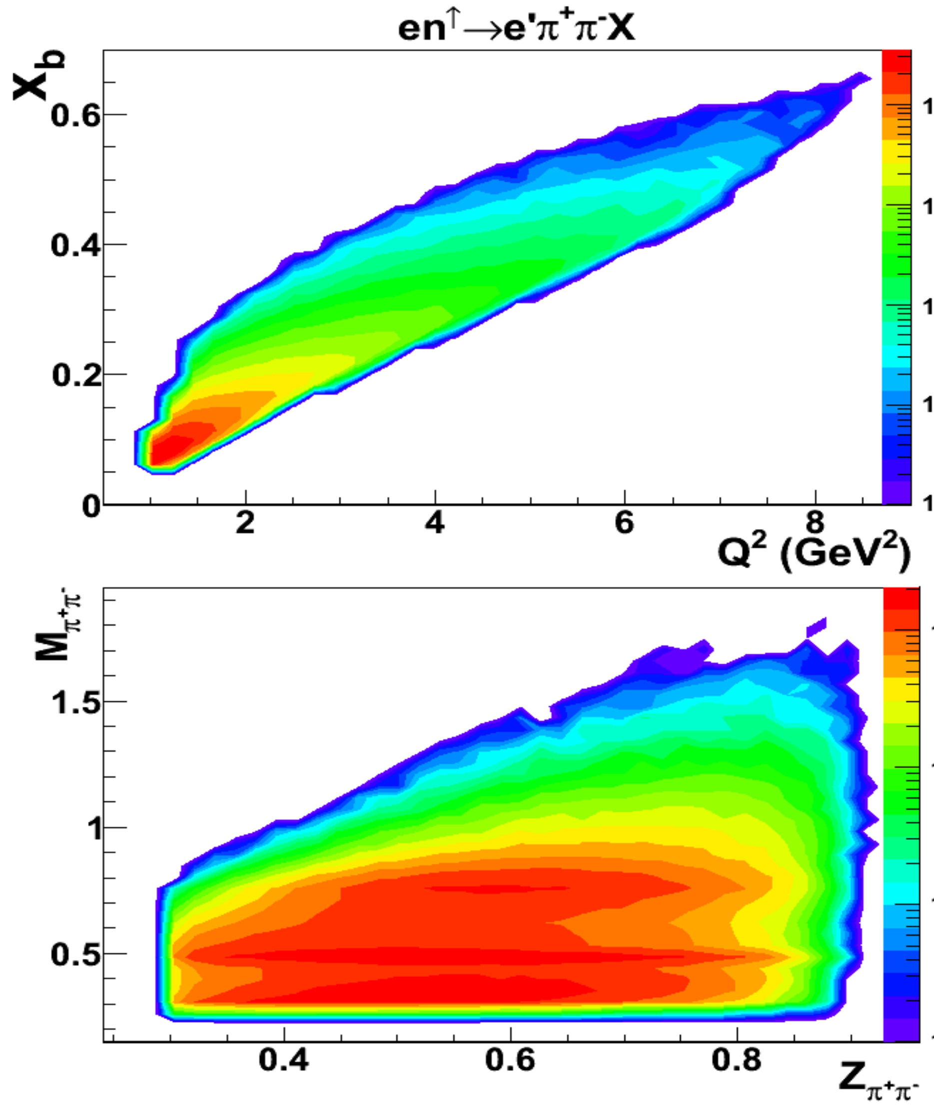
- 11 and 8.8 GeV electron beam, transversely polarized ^3He target
- Measure the single target spin asymmetries (SSA) of dihadron production, $^3He^{\uparrow}(e\ , e'\pi^+\pi^-)X$, in deep inelastic scattering (DIS) region
- Map the SSA data in a 4-D space of x, Q^2, $z\_\pi^+\pi^-$ and $M\_\pi^+\pi^-$

Goal

- Extract neutron SSA, need to correct the contribution from proton
- Combine with world data of dihadron fragmentation functions (DiFF) to extract transversity, h_1.
- Combine with transversity from transverse proton target experiment (SoLID E12-11-108 or CLAS E12-12-009) to do flavor separation
- Extract tensor charge

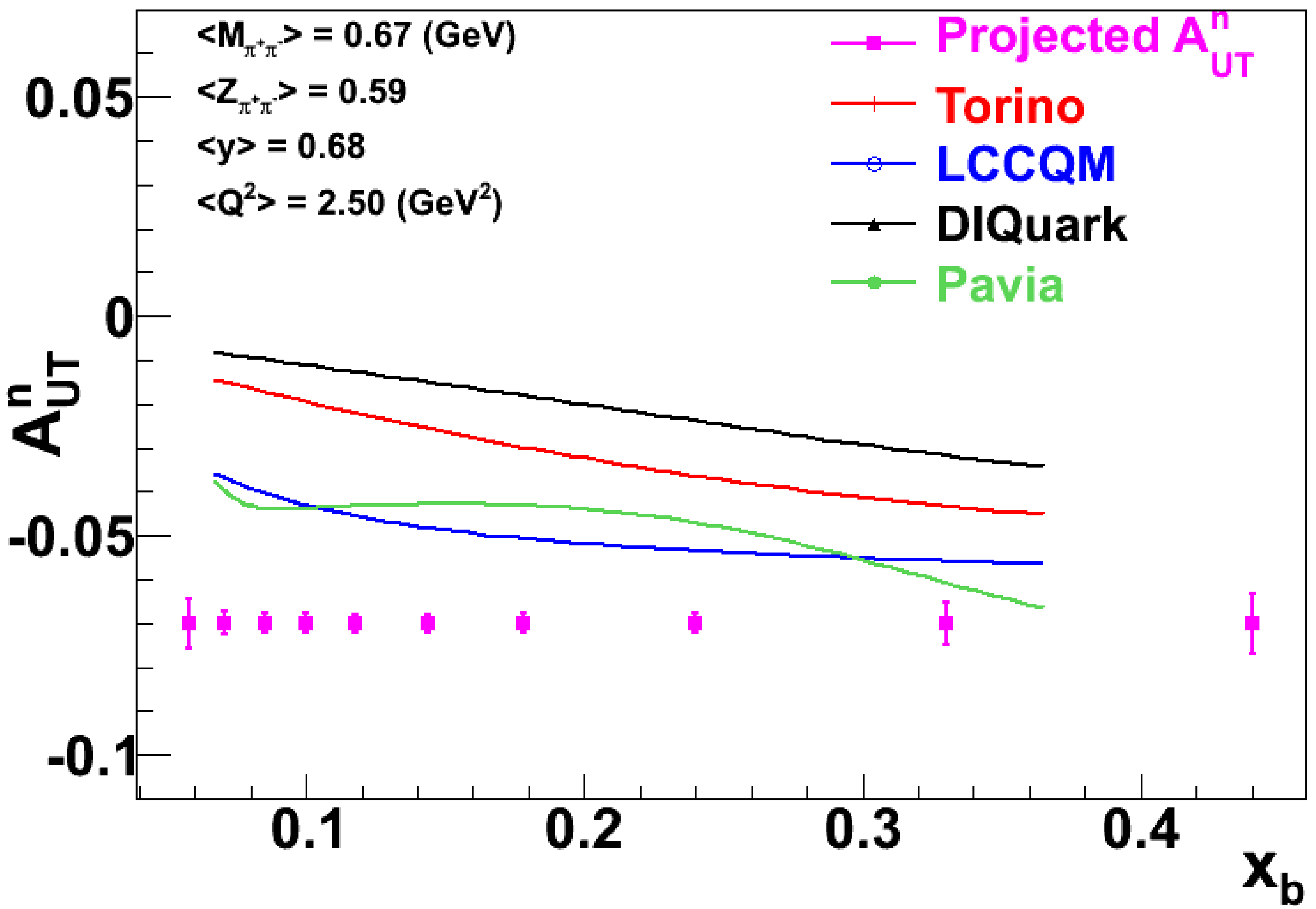
Kinematic coverages





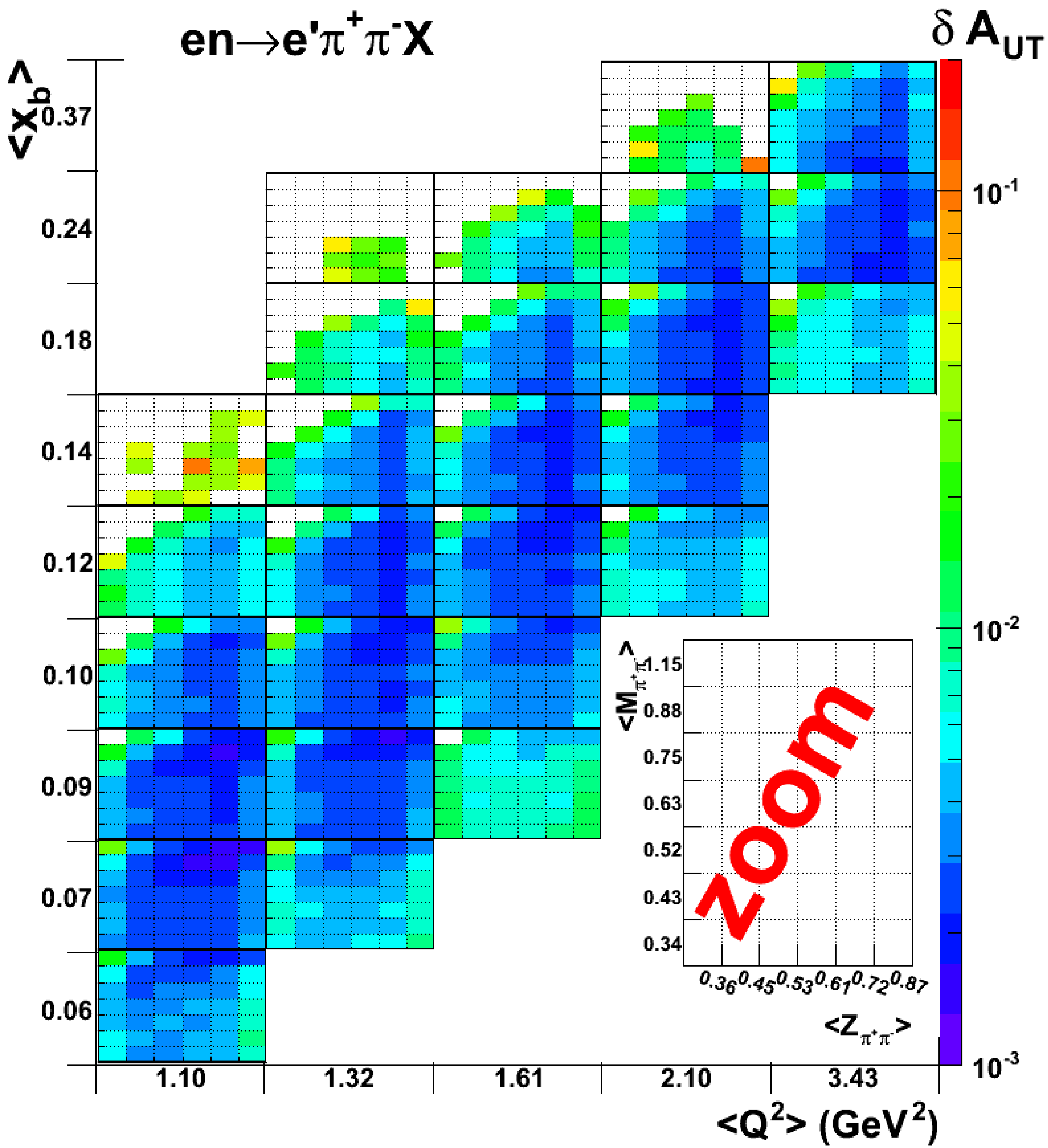
Q^2 >1.0 GeV^2
x > 0.05
W_$\pi^+\pi^-$ > 2.3 GeV
z_$\pi^+\pi^-$ > 0.3
M_$\pi^+\pi^-$ > 1.414 GeV/c

Projection



Projected statistics error for one ($M_{\pi\pi}$,$z_{\pi\pi}$) bin, integrated over all y and Q^2 of 48 days of 11 GeV data of this experiment.

Projected statistics errors



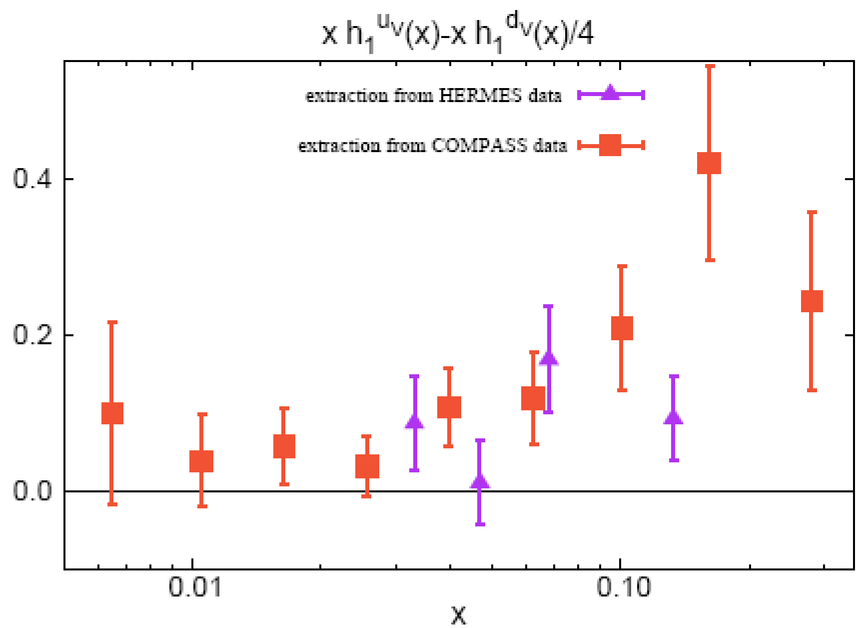
- 48 days of 11 GeV data
- Polarized ^{3}He target, (~60% polarization)
- Lumi=10^{36} (n)/s/cm^2
- Wide x_b and Q^2 coverages
- Bin central values labeled on axises
- Z scale (color) represent stat. error
- Measure transversity via $\pi^+\pi^-$dihadron channel
- Combine with proton data can do flavor separation

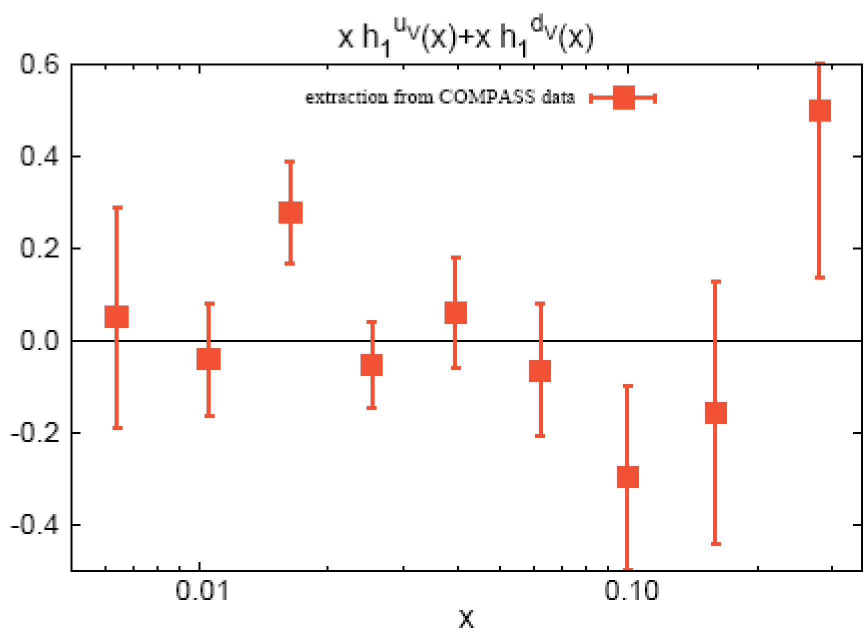
Flavor Separation

$$A_{UT,n}^{\sin(\phi_R+\phi_S)\sin\theta}(x,y,z,M_{\pi\pi},Q)$$
$$= -\frac{B(y)}{A(y)}\frac{|\boldsymbol{R}|}{M_{\pi\pi}}\frac{H_{1,sp}^{\sphericalangle,u}(z,M_{\pi\pi})\left[4\,h_1^{d-\bar{d}}(x) - h_1^{u-\bar{u}}(x)\right]}{D_1^u(z,M_{\pi\pi})\left[f_1^{u+\bar{u}}(x) + 4\,f_1^{d+\bar{d}}(x)\right] + D_1^s(z,M_{\pi\pi})\,f_1^{s+\bar{s}}(x)},$$

$$A_{UT,p}^{\sin(\phi_R+\phi_S)\sin\theta}(x,y,z,M_{\pi\pi},Q)$$
$$= -\frac{B(y)}{A(y)}\frac{|\boldsymbol{R}|}{M_{\pi\pi}}\frac{H_{1,sp}^{\sphericalangle,u}(z,M_{\pi\pi})\left[4h_1^{u-\bar{u}}(x) - h_1^{d-\bar{d}}(x)\right]}{D_1^u(z,M_{\pi\pi})\left[4f_1^{u+\bar{u}}(x) + f_1^{d+\bar{d}}(x)\right] + D_1^s(z,M_{\pi\pi})\,f_1^{s+\bar{s}}(x)},$$

Proton data from:
SoLID E12-11-108
CLAS12 E12-12-009



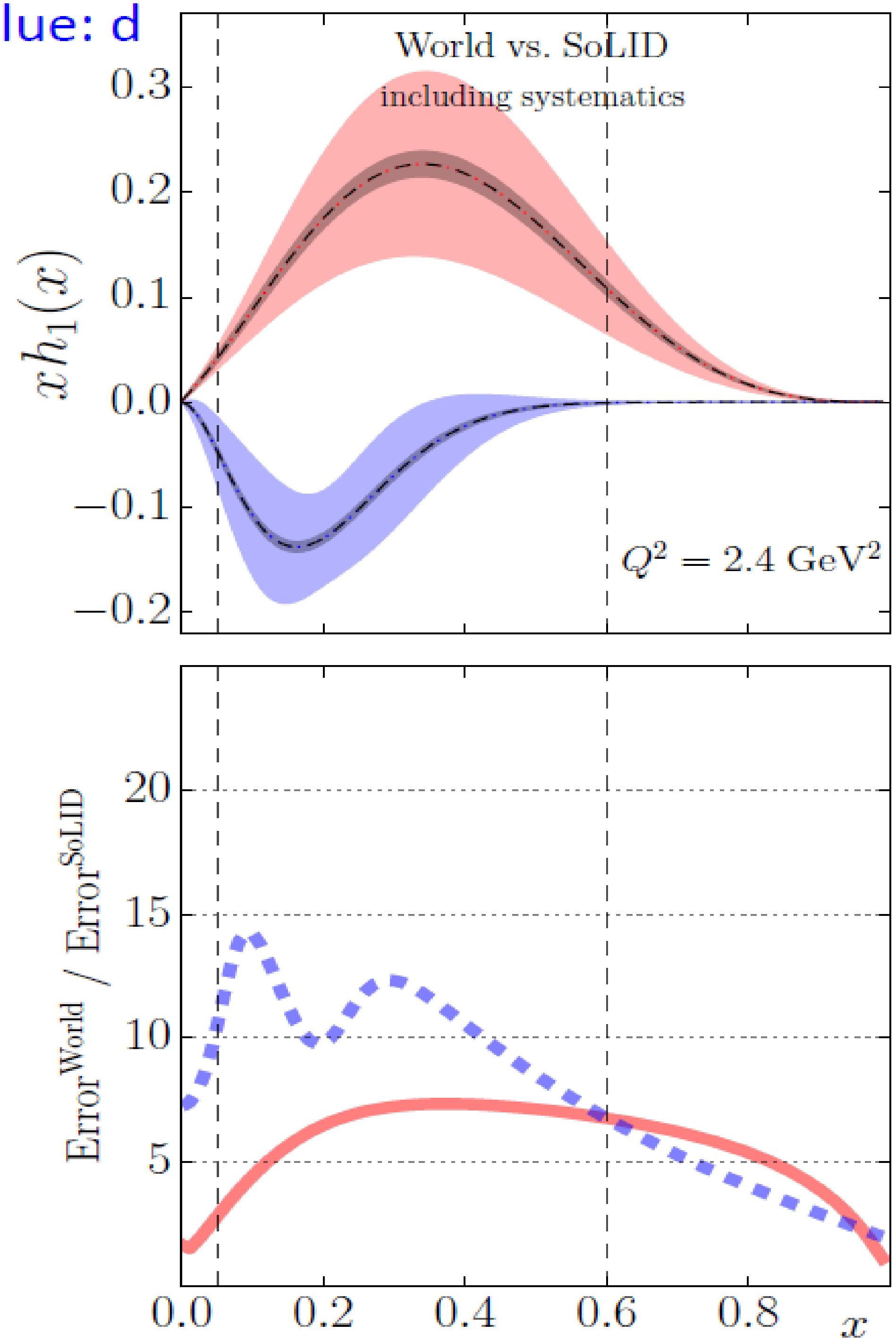


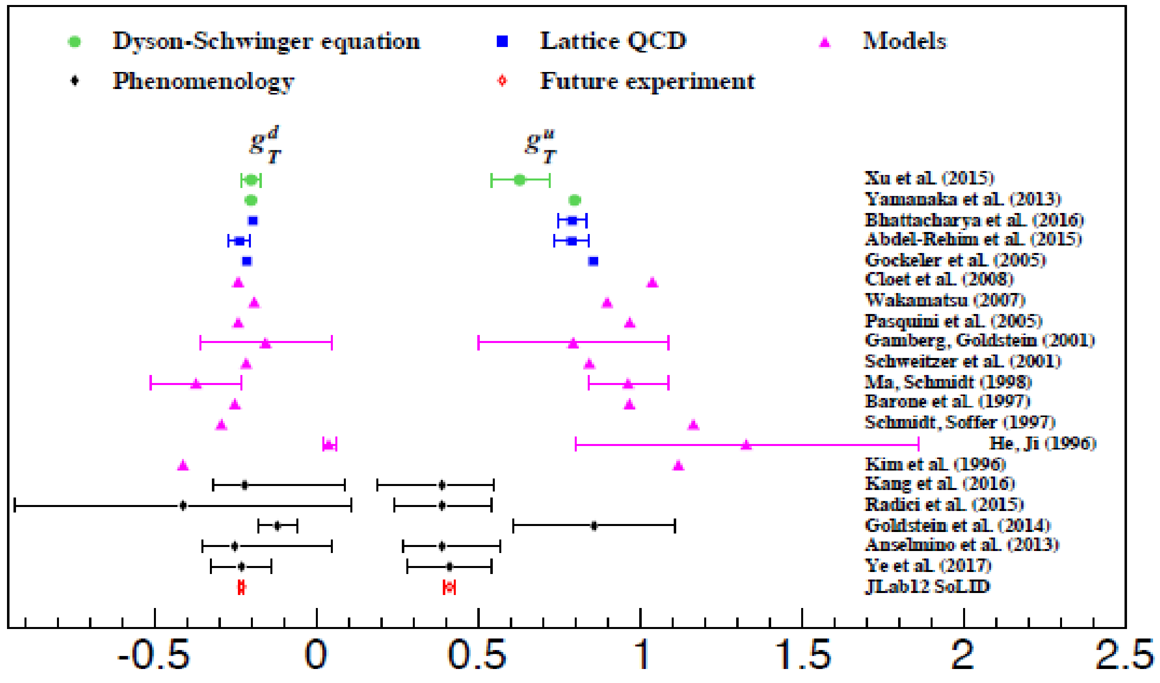
Transversity extracted via DiFF using HERMES proton data and COMPASS proton(NH_3) and deuteron (^{6}LiD) data

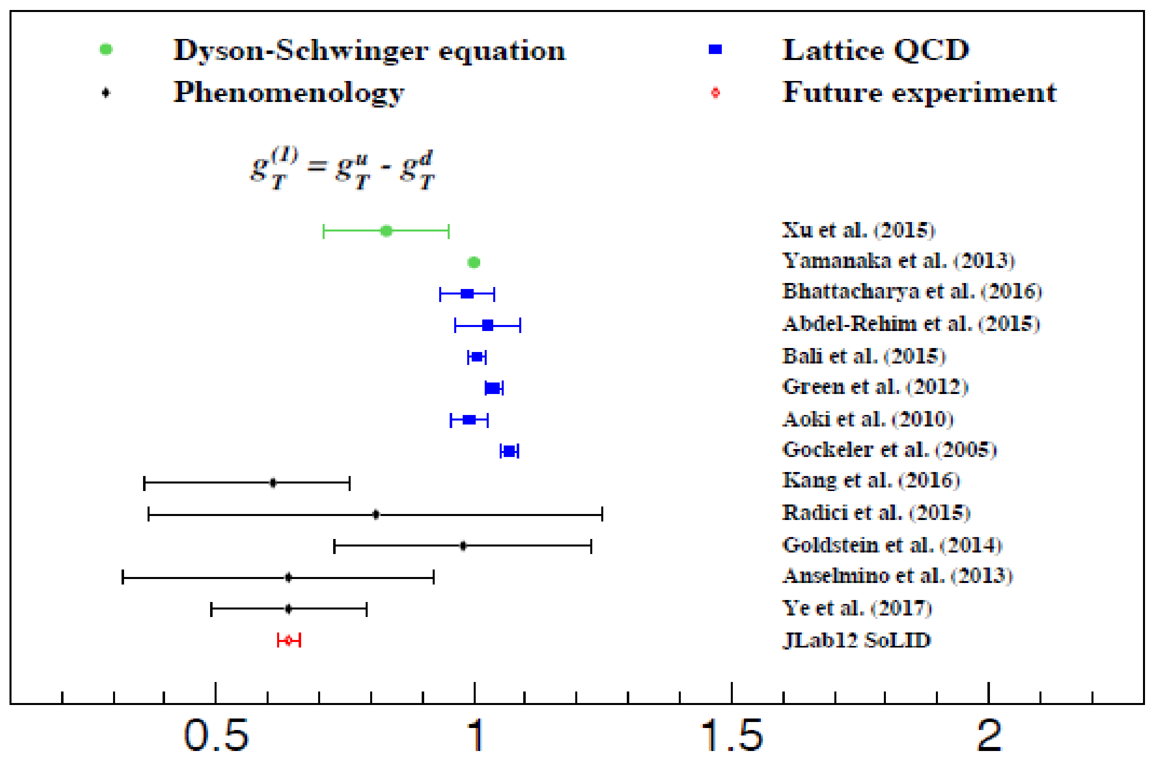
Phys.Rev.Lett. 107 (2011) 012001

Impact from SoLID, Single-hadron

Red: u
blue: d







Z. Ye et al., PLB 767, 91 (2017)

Summary

• The transversity distribution, h_1, can be extracted in both single-hadron process and di-hadron process.

• Latest transversity result extracted from COMPASS, HERMES and STAR (only 2006 data set) by M. Radici and A. Bacchetta) has been present. Inclusion of STAR p-p↑ data increases precision of up quark. Large uncertainty still exists on down quark due to unconstrained gluon unpolarized di-hadron fragmentation function.

• Tensor charge based on latest transversity has also been present and compared to lattice calculation. The result of up quark does not agree with lattice calculation, while d quark seems agree well.

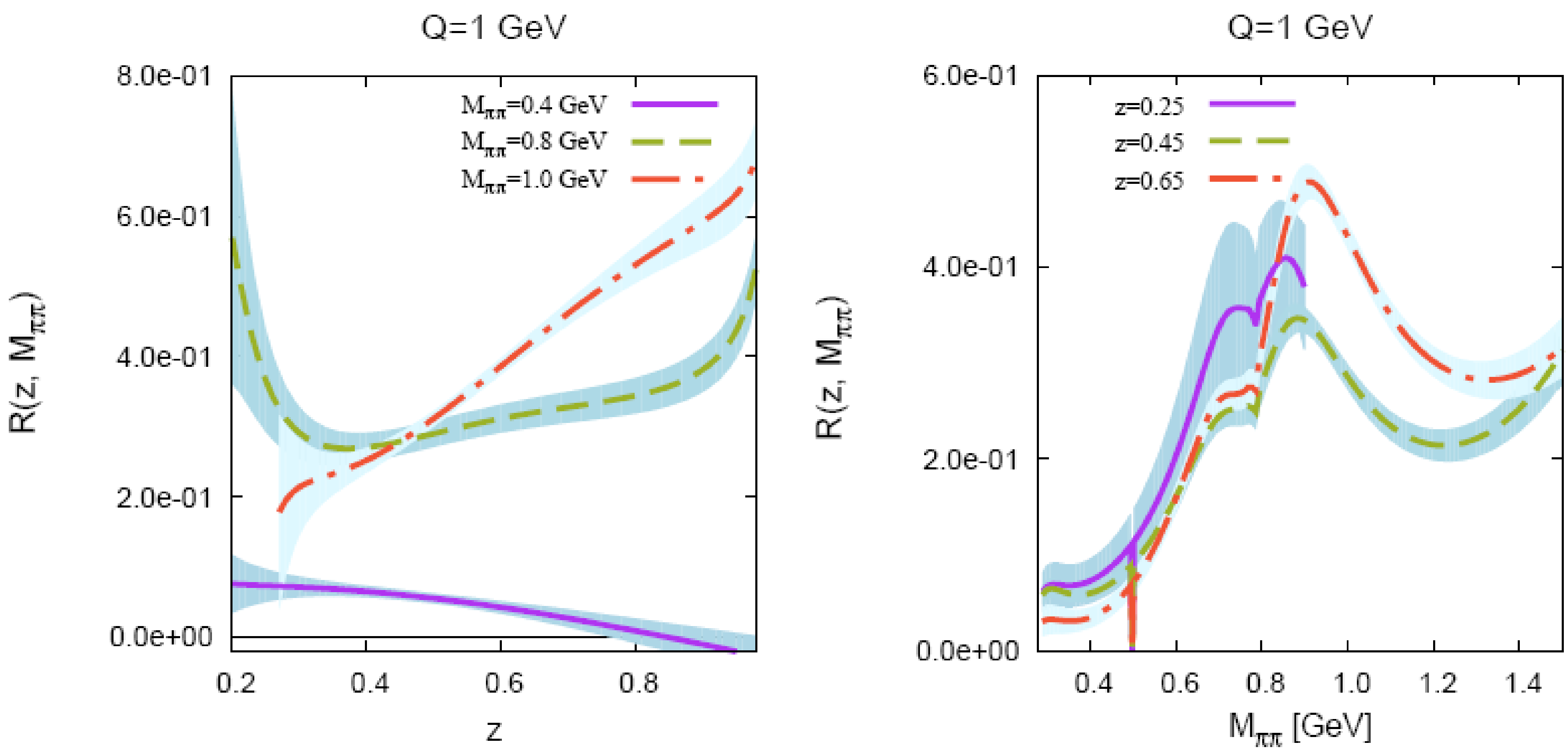
• Currently no low x or high x data available. EIC and Jlab 12 GeV programs, especially the SoLID programs will fill these gaps.

• SoLID programs will have very high impact on transversity and tensor charge. It will help a lot in decreasing the uncertainty and constraining the global fit.

Back up

Previous DiFF

Fitting from the Belle asymmetry, ***A.Vossen et al (Belle), PRL107 (11)***



$$R(z, M_{\pi\pi}) = \frac{|\boldsymbol{R}|}{M_{\pi\pi}} \frac{H_{1,sp}^{\sphericalangle u}(z, M_{\pi\pi}; Q_0^2)}{D_1^u(z, M_{\pi\pi}; Q_0^2)}$$

A.Courtoy, A.Bacchetta, M.Radici, A.Bianconi, PRD 85 (12)