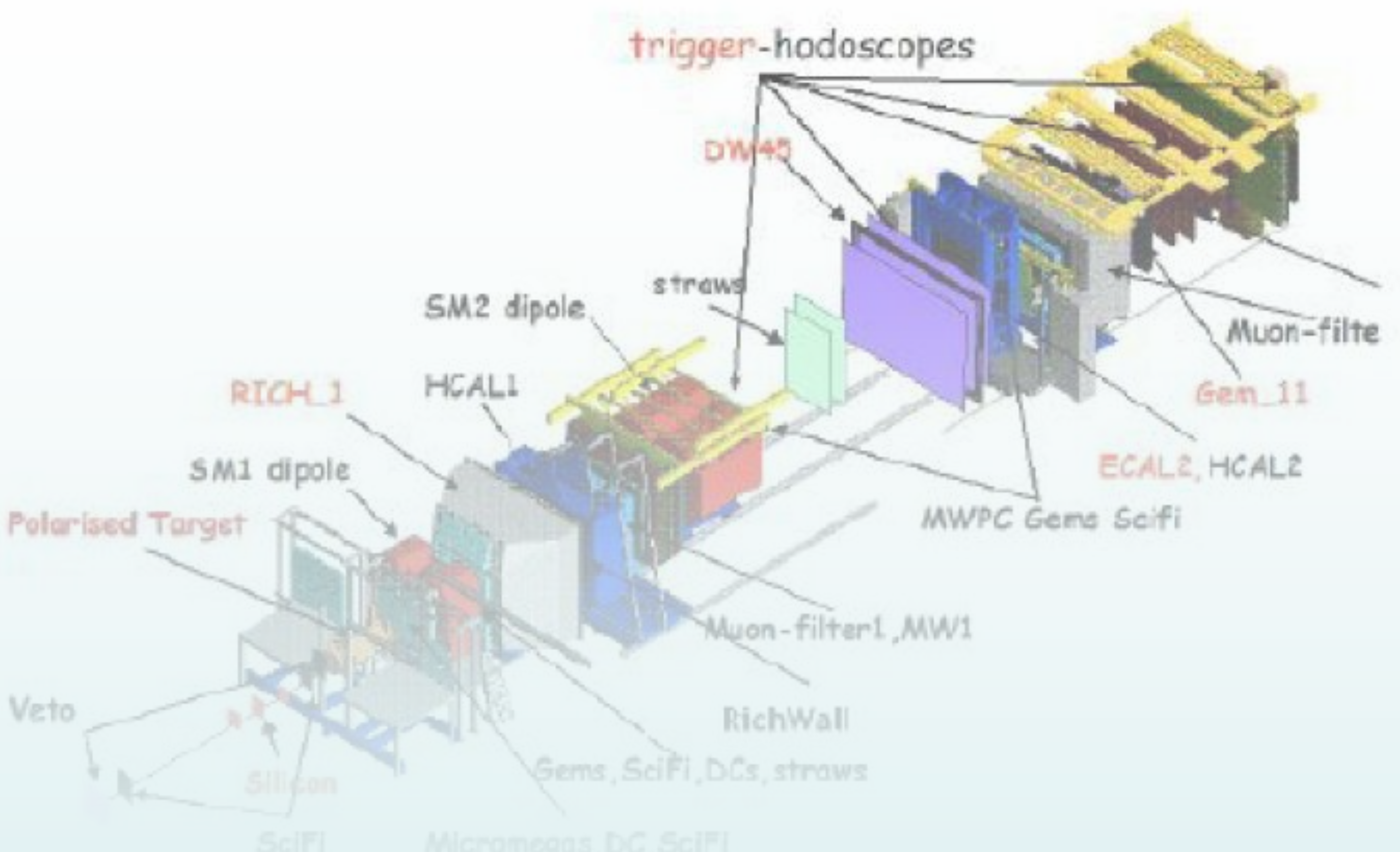
Polarized Drell-Yan + X



COMPASS Workshop: Beyond 2020

Content

- TMDs, What will we know in 2020?

  Sivers

  Transversity

  Boer Mulders

- TMD opportunities with hadron beams beyond 2020

  DY on deuterium targets: Sivers flavor separation at high Q2

  DY on hydrogen targets: pion and kaon Boer Mulders

  Drell Yan extraction of proton transversity

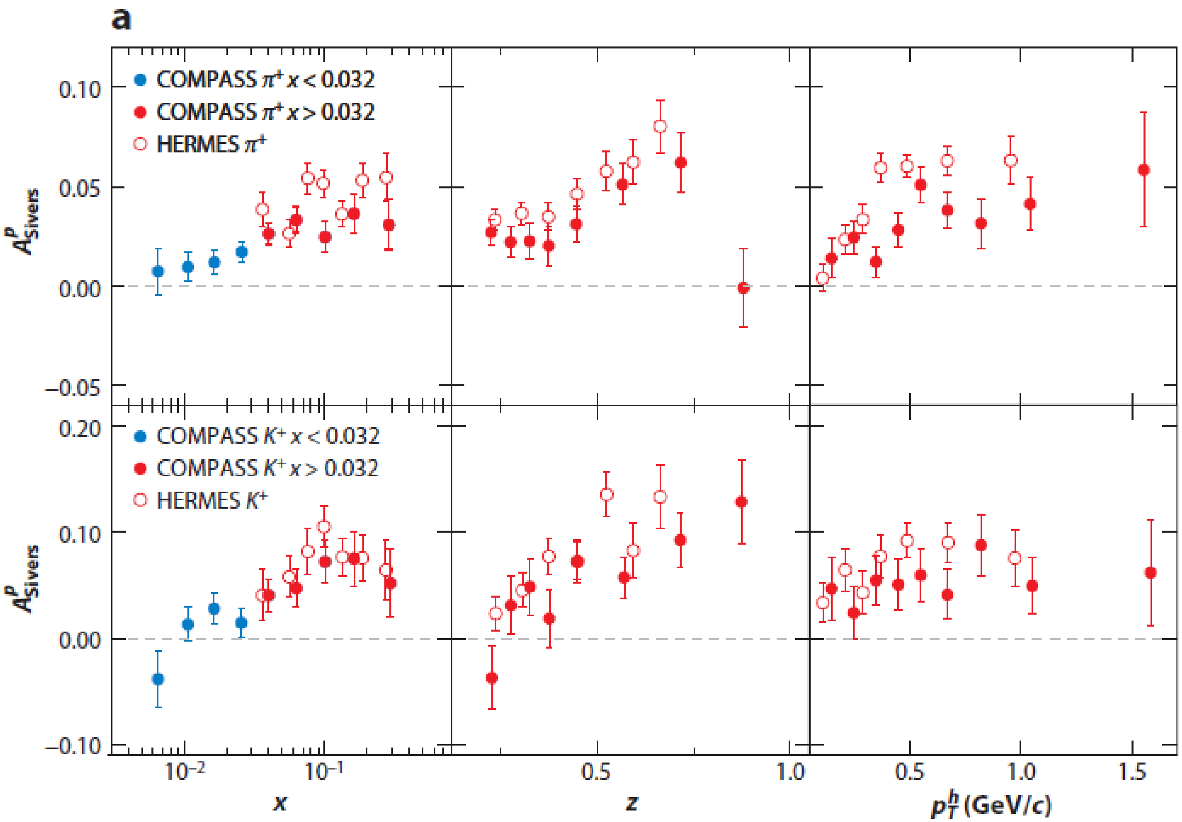
  to be studied:

  Gluon Sivers in associate J/Psi + gamma hadro-production

  Hadron A_N, jet A_N, A_T in Lambda Production, Collins in Jets

- Exclusive Drell-Yan

Sivers – SIDIS Results



Sivers Asymmetries from HERMES & COMPASS also J-Lab 6 GeV

Differences for pions may result from evolution.

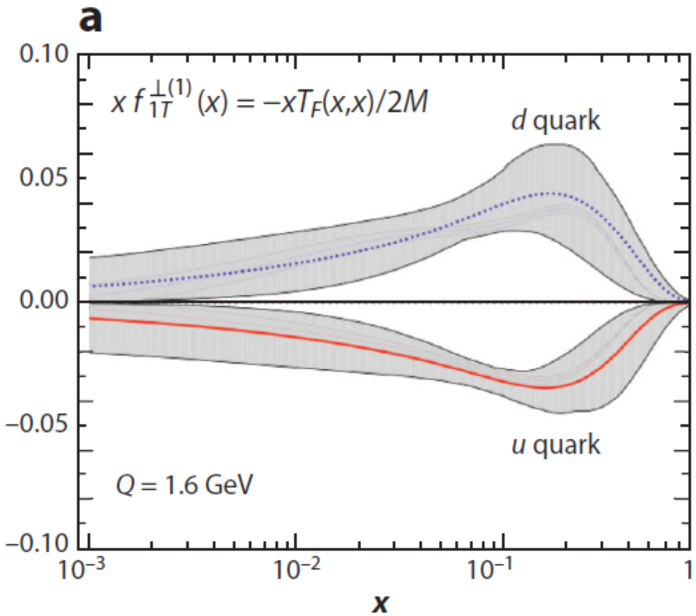
➔ need data at higher Q^2
first step, DY in COMPASS
then EIC

Sivers – Global Analysis of HERMES & COMPASS Data

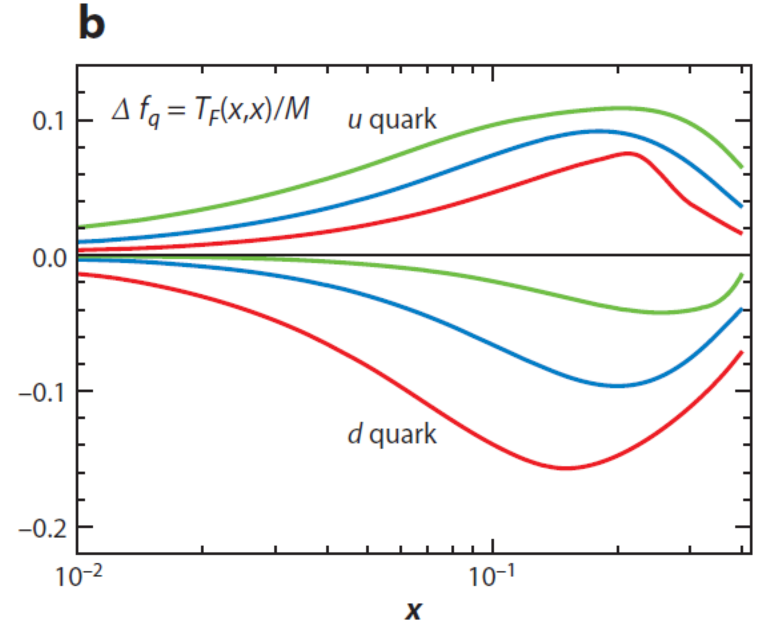
Anselmino M, et al. arXiv:1107.4446 [hep-ph] (2011)

Sun P, Yuan F. *Phys. Rev. D* 88:114012 (2013)

Leading order analysis



Full QCD analysis including TMD evolution

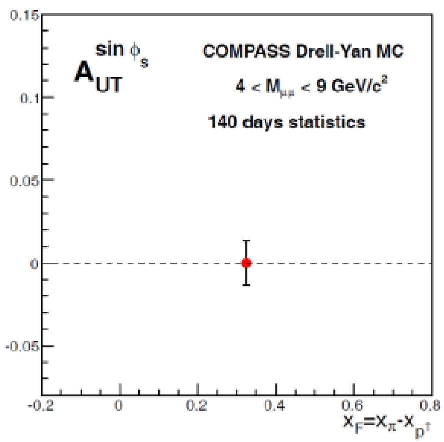


Significant errors, no data for x>0.35 ➔ J-Lab 12 GeV

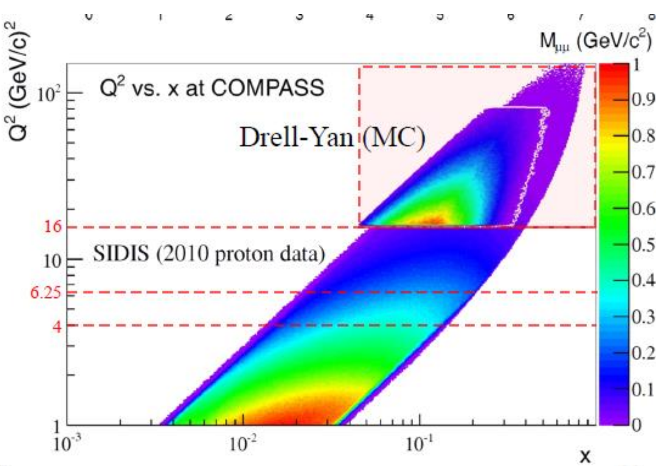
Sign Change ➔ COMPASS Drell-Yan (NSAC Milestone …)

Sivers – Projected Results COMPASS Drell-Yan and JLab 12 GeV (eg. Hall A), as of Spin 2014

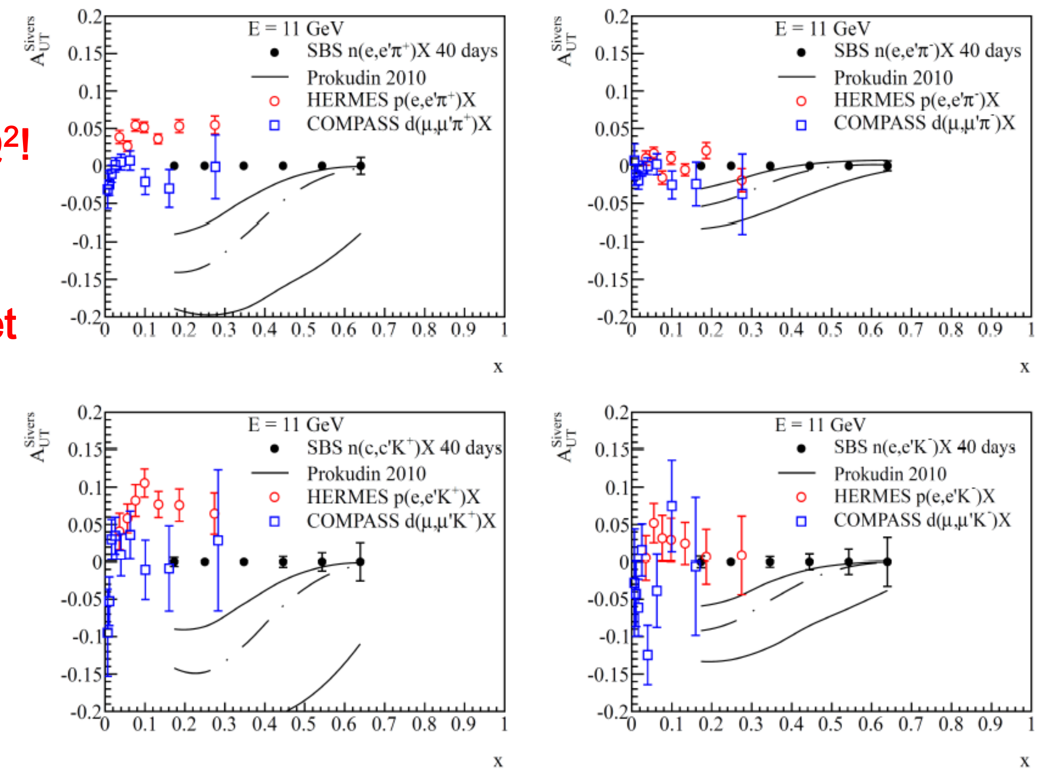
COMPASS Drell-Yan 2015+2018
B. Parsamyan



- o will observe sign!
- o somewhat higher Q^2!
- o Also expect results from FNAL P-1079 with polarized target ➔ test sea!



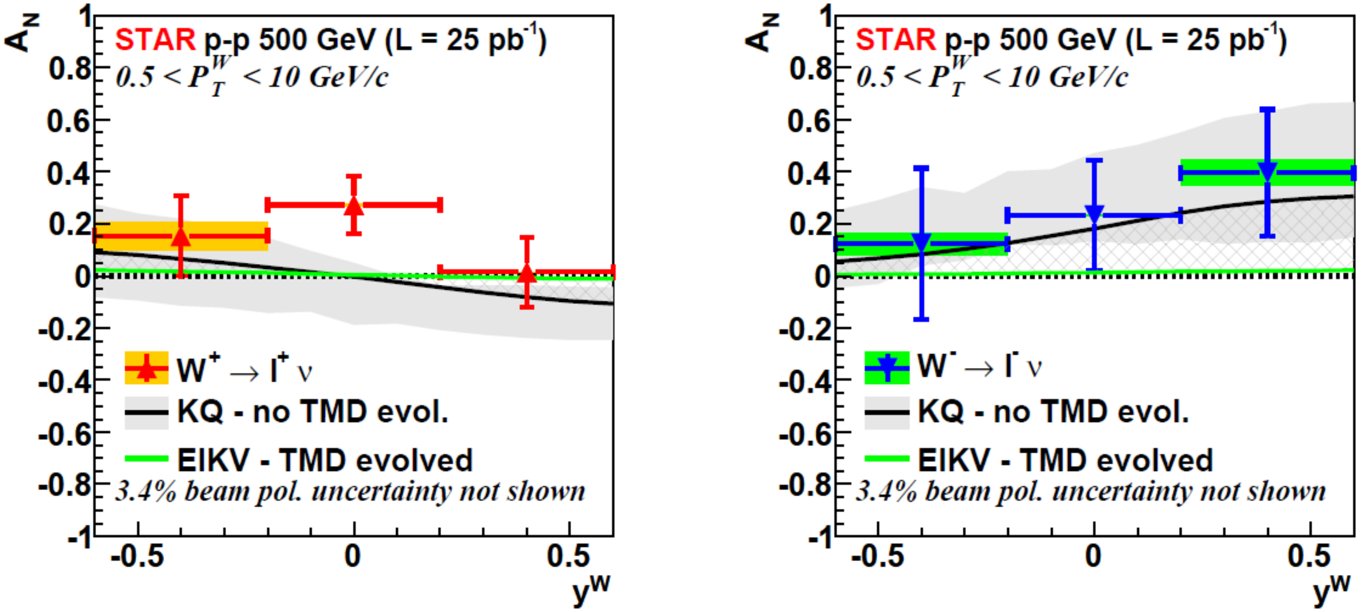
Hall A: Super Big Bite E12-09-018
K. Allada



Also: CLAS12 – Hall B, SHMS – Hall C
SOLID – Hall A
➔ precision ! and x < 0.7 but low Q^2

Sivers – A_N for W-Bosons in STAR

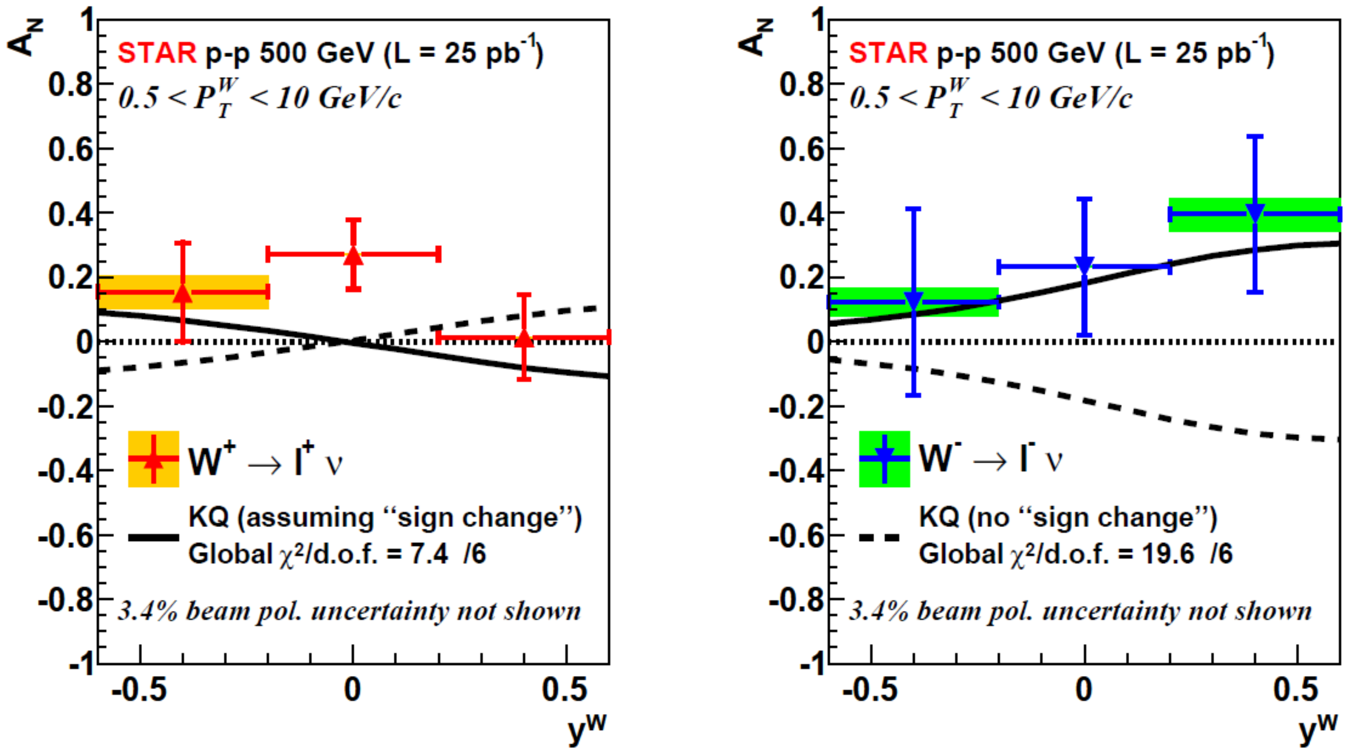
L. Adamczyk, et al. (STAR) arXiv:1511.06003, accepted to PRL, March 3rd



Comparison to two different evolution scenarios: strong TMD evolution results in A_N~0

Sivers – A_N for W-Bosons in STAR

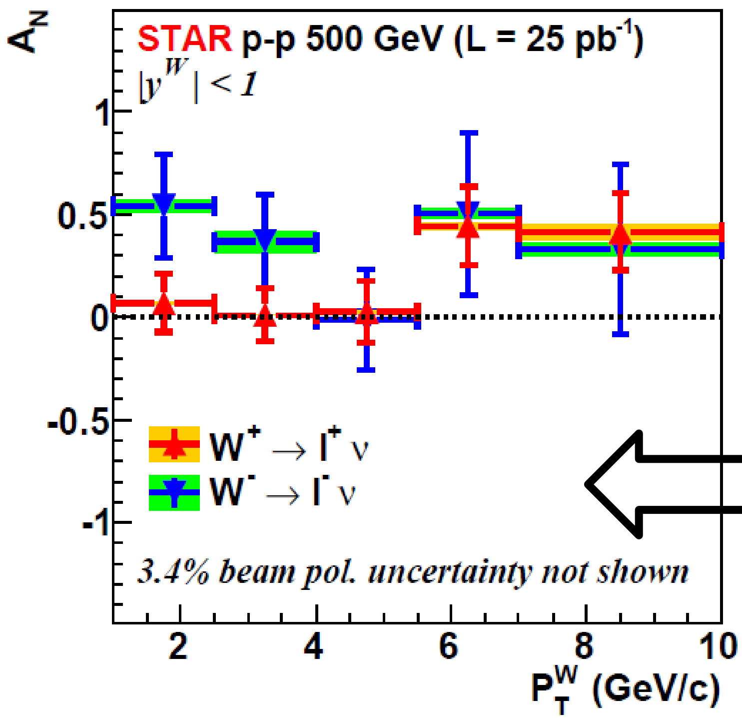
L. Adamczyk, et al. (STAR) arXiv:1511.06003, accepted to PRL, March 3rd



Assuming no evolution + sign change gives better chi2 !

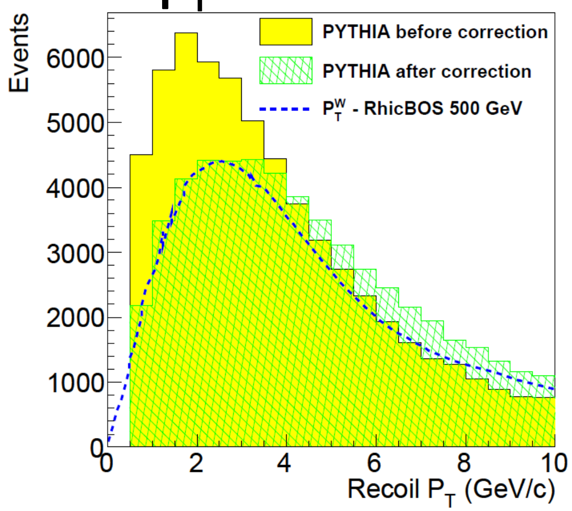
Sivers – A_N for W-Bosons in STAR

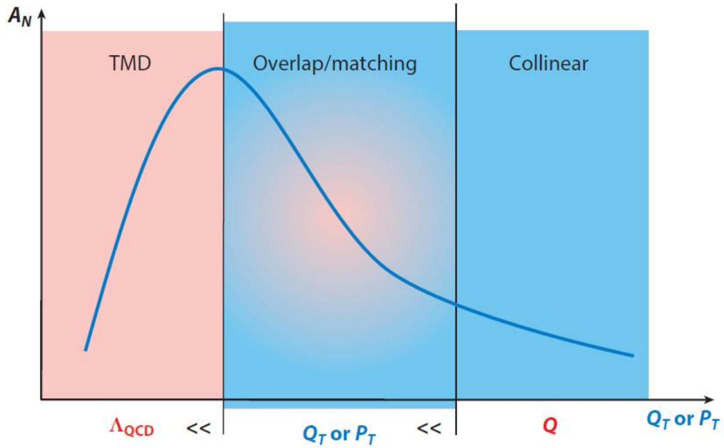
L. Adamczyk, et al. (STAR) arXiv:1511.06003, accepted to PRL, March 3rd



$p_T > \Lambda_{QCD}$

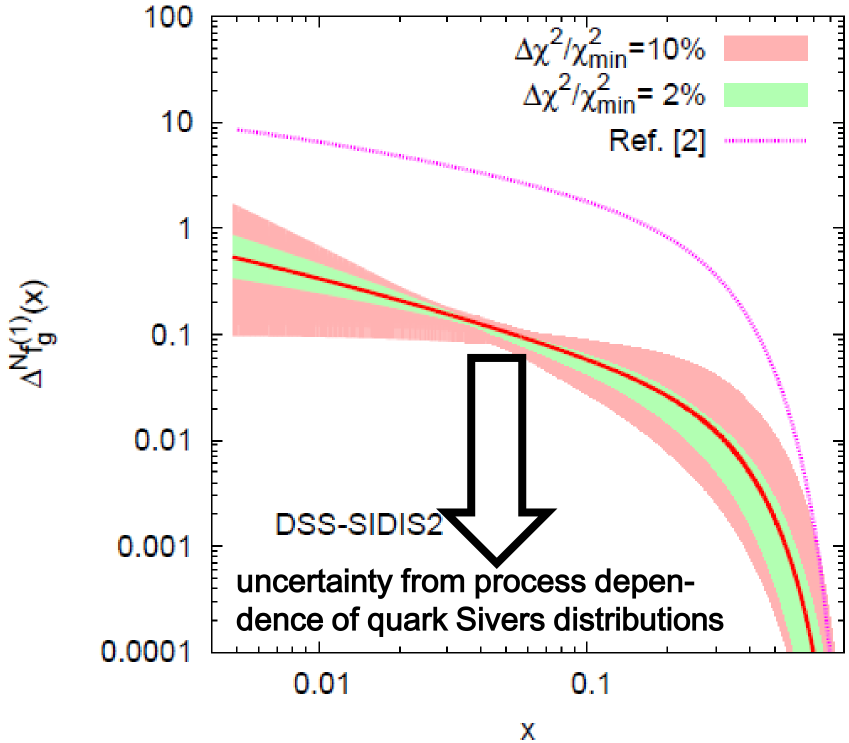
W-p_T



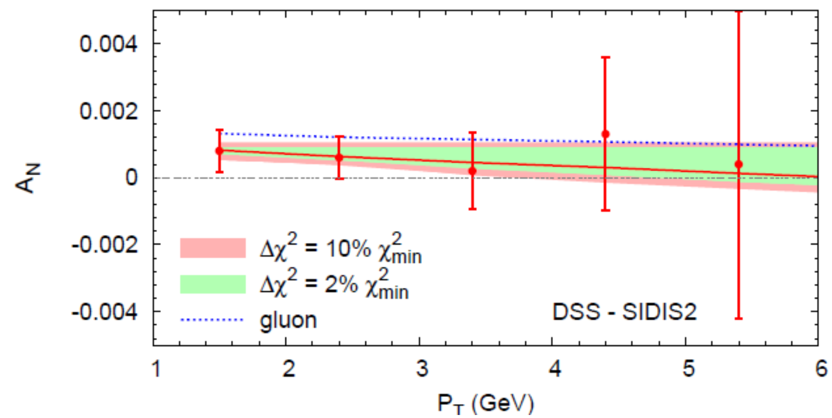


Gluon Sivers from A_N for Neutral Pions

U. D'Alesio, F. Murgia, C. Pisano
JHEP 1509(2015)119



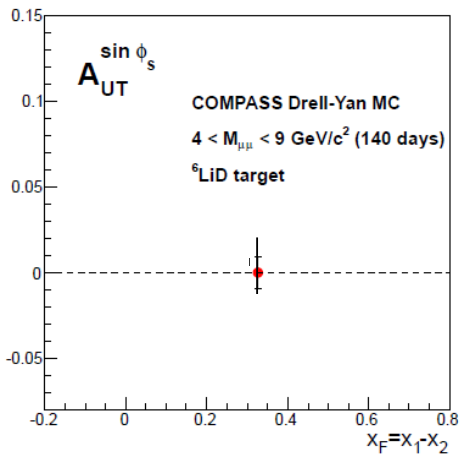
Fit to PHENIX A_N for π^0
A. Adare et al. PRD90 012006(2014)
(Thesis John Koster, UIUC)

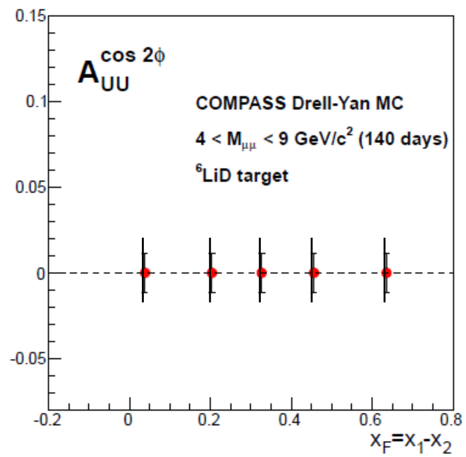


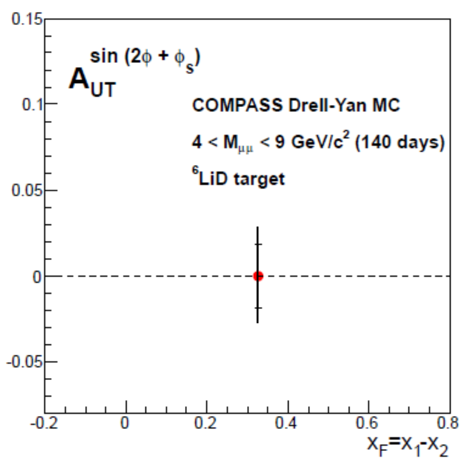
Bounds also from comparison of COMPASS Sivers results for SIDIS on proton and deuteron targets: Phys.Lett. B643 (2006)
S. Gardner and S. Brodsky

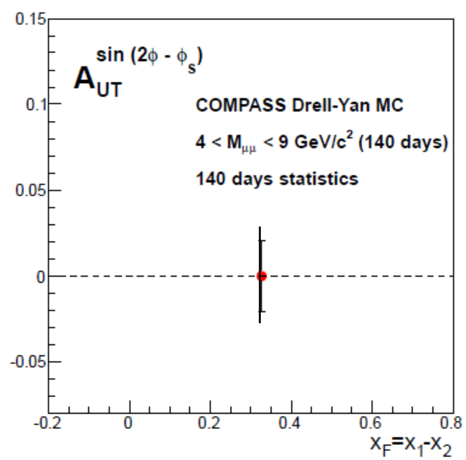
However, constraints have large uncertainties and don't extend to low x: D. Boer et al. arXiv:1504.04332v2

Future COMPASS Contributions: Flavor Separation! Measure Sivers Asymmetry at Higher Q^2 in Drell-Yan









Projections with ^{6}LiD target with P=0.5 and f=0.5.

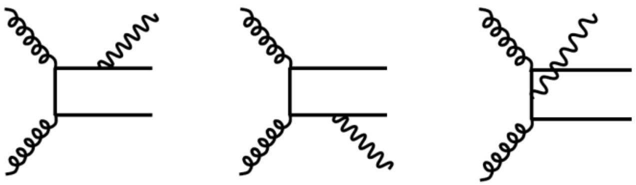
Combine with COMPASS II *NH_3* measurement to determine flavor dependent Sivers Distributions.

Additional data at higher Q^2 for testing evolution and validating experimental asymmetries as leading twist in origin.

Sivers: additional Channels for Consideration ➔ use low intensity hadron beam without absorber…

(I) Gluon Sivers: Associated J/Psi + γ has very small color octet contribution and is well suited for measuring the gluon Sivers distribution D. Boer et al. arXiv:1504.04332v2 and references therein

$$g + g \to \gamma + (c\bar{c})(^3S_1^{(1)})(\to J/\psi)$$



or, following Gardner and Brodsky - Phys.Lett. B643 (2006)

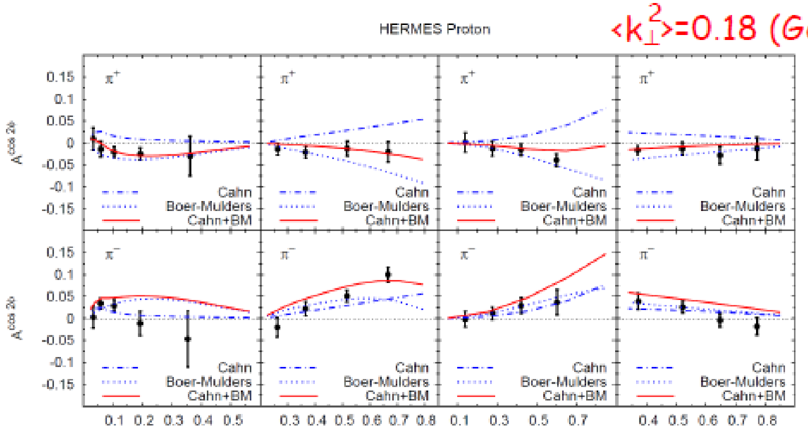
$$g + g \to s\bar{s} \to K^- K^+ + X$$

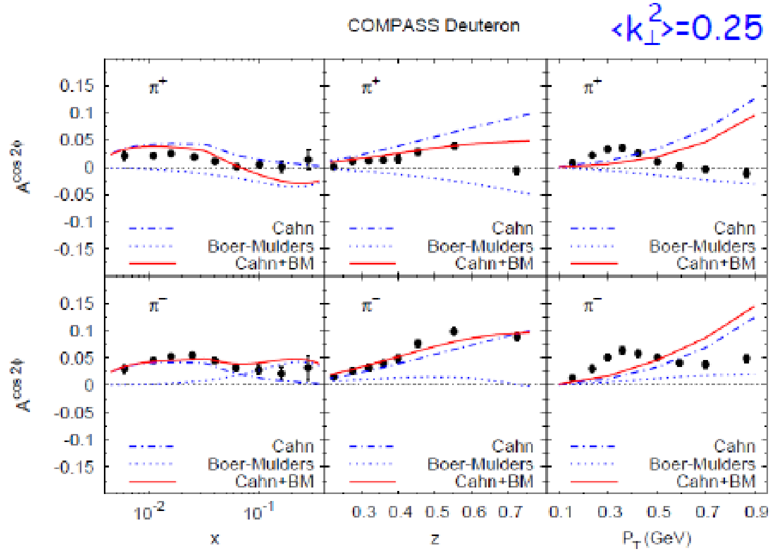
(II) Quark Sivers: measure A_N for inclusive hadrons and for jets (if possible) and analyze combined with corresponding RHIC results for information on evolution, factorization and universality.

Needs careful study: kinematics, rates, experimental feasibility!

Boer-Mulders Distributions from SIDIS and DY

V. Barone, S. Melis and A. Prokudin Phys. Rev. D81, 114026 (2010)





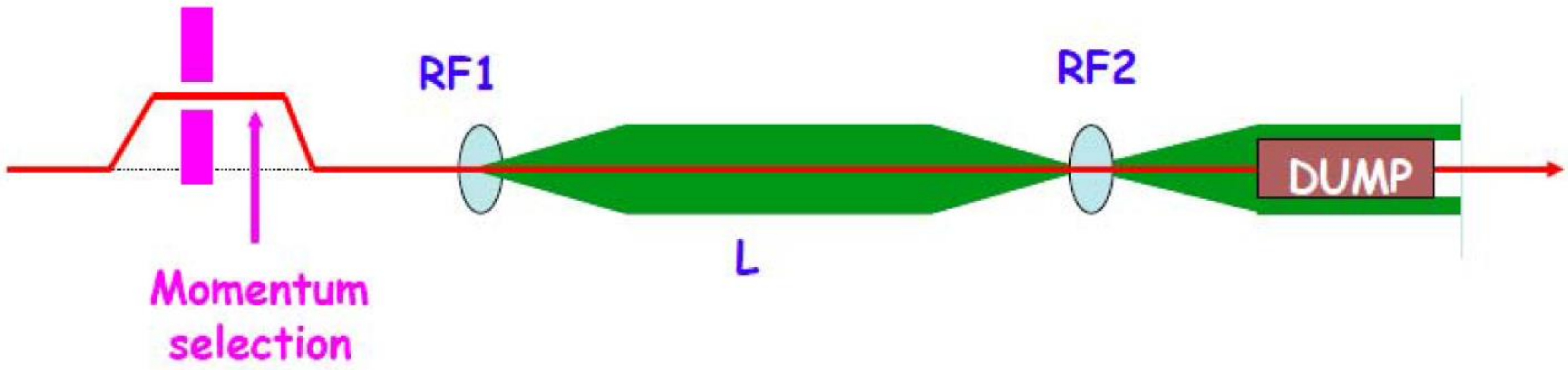
- ✔ Same sign of Cahn contribution for positive and negative pion
- ✔ BM contribution opposite in sign for positive and negative pions

$$\langle \cos 2\phi \rangle \propto h_1^\perp H_1^\perp + \text{Cahn}$$

$$\langle \cos \phi \rangle \propto -h_1^\perp H_1^\perp - \text{Cahn}$$

Fit to pp DY would determine BM for sea quarks if other contributions to ν are understood

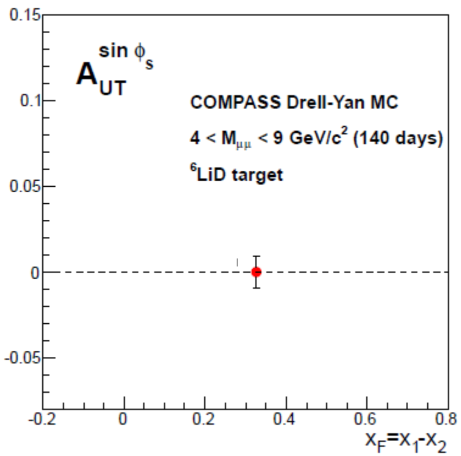
Possibility of RF Separated Pion, Kaon and Anti-Proton Beams?

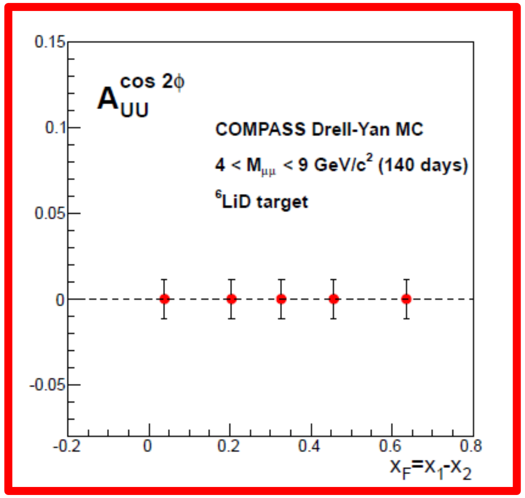


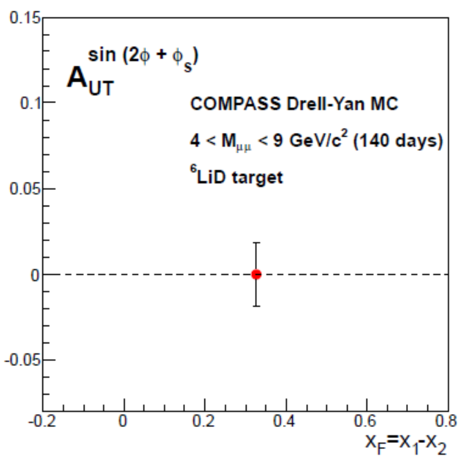
Particle type	From CKM beam	Antiproton beam
Beam momentum (GeV/c)	60	100
Momentum spread (%)	± 1	± 2
Angular emittance H,V (mrad)	± 3.5, ± 2.5	± 3.5, ± 2.5
Solid angle (μsterad)	10-12π	10-12π
% wanted particles lost on dump	37	20

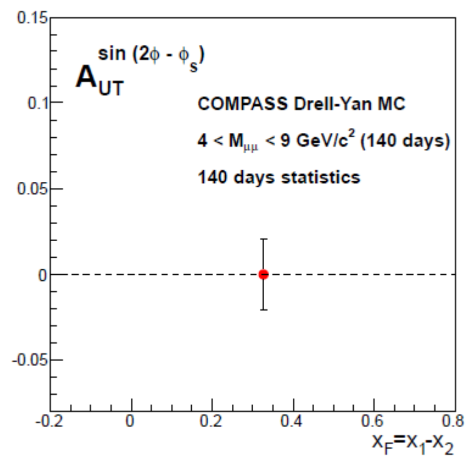
Kaon and Anti-Protons Flux possibly reaching 10^7p./s

Future COMPASS Contributions: Pion and Kaon Boer-Mulders Functions Using a Hydrogen Target









beam BMF

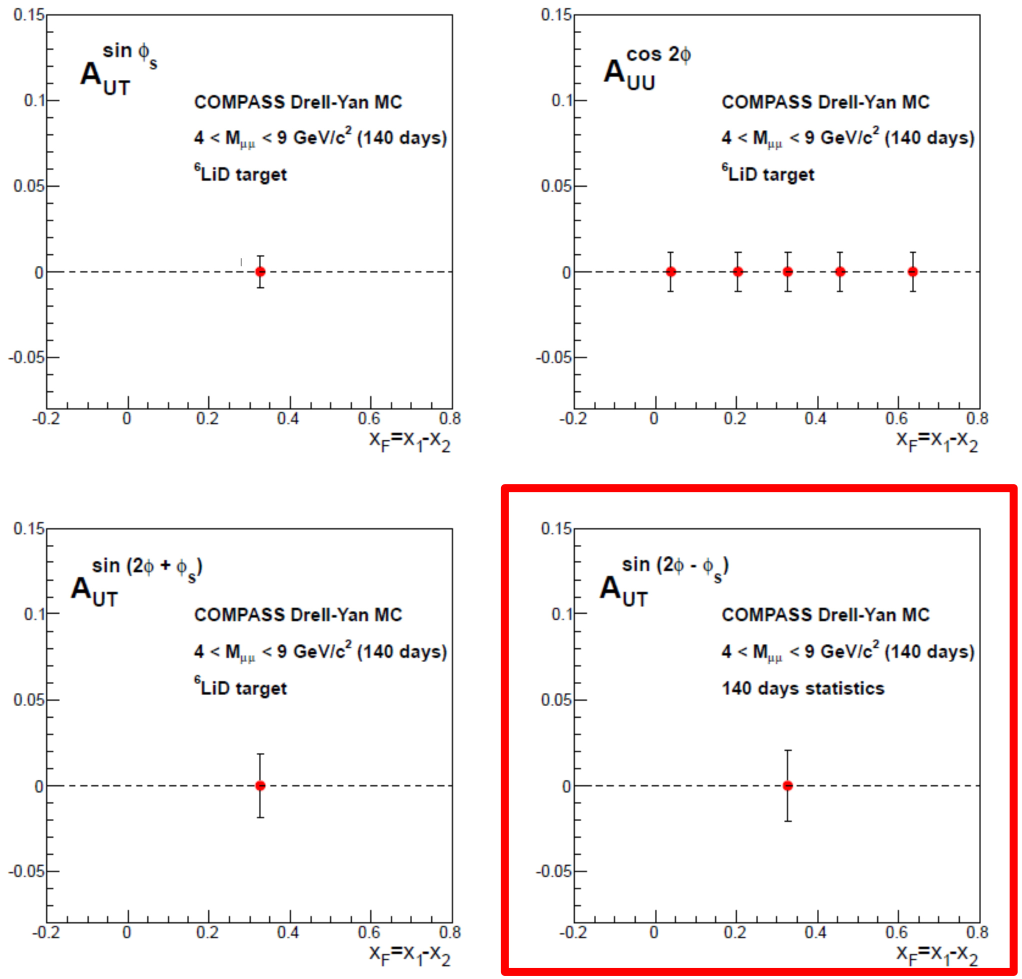
$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

target BMF

with p-BMF from SIDIS solve for pion and kaon beam BMF. Use anti—protons and CPT to get p-BMF and compare!

Combination of unpolarized pion- and kaon-PDF and pion- and Kaon-BMF will provide greatly increased knowledge of meson structure! Eg. first comparison of Meson and Baryon BMF and first comparison of BMF for different mass mesons.

Future COMPASS Contributions: Using Pion BMF Measure Quark Transversity



beam BMF

$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$$

target BMF

with pion-BMF from DY on proton target:

extract quark transversity using NH_3 and ^{6}LiD runs

Provides important cross check for Collins based extraction of quark transversity (magnitude of flavor contributions).

How to Extract Transversity Distributions and Determine the Tensor Charge ?

RBRC Transversity Workshop 2000 →
Measure CFF and IFF asymmetries in Belle !
Measure IFF in p-p

SIDIS

~ $\delta q(x)$ x $CFF(z)$
~ $\delta q(x)$ x $IFF(z)$

e^+e^-

~ $CFF(z_1)$ x $CFF(z_2)$
~ $IFF(z_1)$ x $IFF(z_2)$

pp → jets

~ $G(x_1) x \delta q(x_2)$ x $CFF(z)$

pp → $h^+ + h^- + X$

~ $G(x_1) x \delta q(x_2)$ x $IFF(z)$

πp → $l^+ + l^-$ +X Drell-Yan

~ $h_1^{\perp}(x_1)$ x $\delta q(x_2)$

Transversity, δq(x)
Tensor Charge

Theory

Lattice QCD: Tensor Charge = $\Sigma_{q=u,d}\int_0^1 \delta q(x)dx$

Transversity & Tensor Charge Extracted With TMD Evolution and Recent Data Sets

Z.-B. Kang., A. Prokudin, P. Sun, F. Yuan - Phys.Rev. D93 (2016) 1, 014009

Experiment	hadron	Target	dependence	# ndata	χ^2	$\chi^2/ndata$
COMPASS [97]	π^+	LiD	x	9	11.16	1.24
COMPASS [97]	π^-	LiD	x	9	9.08	1.01
COMPASS [97]	π^+	LiD	z	8	3.26	0.41
COMPASS [97]	π^-	LiD	z	8	7.29	0.91
COMPASS [97]	π^+	LiD	$P_{h\perp}$	6	4.19	0.70
COMPASS [97]	π^-	LiD	$P_{h\perp}$	6	4.50	0.75
COMPASS [96]	π^+	NH_3	x	9	21.46	2.38
COMPASS [96]	π^-	NH_3	x	9	6.23	0.69
COMPASS [96]	π^+	NH_3	z	8	7.80	0.98
COMPASS [96]	π^-	NH_3	z	8	10.29	1.29
COMPASS [96]	π^+	NH_3	$P_{h\perp}$	6	3.82	0.64
COMPASS [96]	π^-	NH_3	$P_{h\perp}$	6	3.85	0.64
HERMES [95]	π^+	H	x	7	5.37	0.77
HERMES [95]	π^-	H	x	7	12.61	1.80
HERMES [95]	π^+	H	z	7	3.04	0.43
HERMES [95]	π^-	H	z	7	3.23	0.46
HERMES [95]	π^+	H	$P_{h\perp}$	6	1.60	0.27
HERMES [95]	π^-	H	$P_{h\perp}$	6	4.82	0.80
JLAB [9]	π^+	^{3}He	x	4	3.90	0.98
JLAB [9]	π^-	^{3}He	x	4	3.11	0.78
				140	130.65	0.93

Experiment	Observable	dependence	# ndata	χ^2	$\chi^2/ndata$
BELLE [12]	A_0^{UL}	z	16	13.02	0.81
BELLE [12]	A_0^{UC}	z	16	11.54	0.72
$BABAR$[98]	A_0^{UL}	z	36	34.61	0.96
$BABAR$[98]	A_0^{UC}	z	36	15.17	0.42
$BABAR$[98]	A_0^{UL}	$P_{h\perp}$	9	9.09	1.01
$BABAR$[98]	A_0^{UC}	$P_{h\perp}$	9	4.33	0.48
			122	87.76	0.72

Data sets from SIDIS (HERMES, JLab, COMPASS) and e^+e^- (Belle, BaBar)

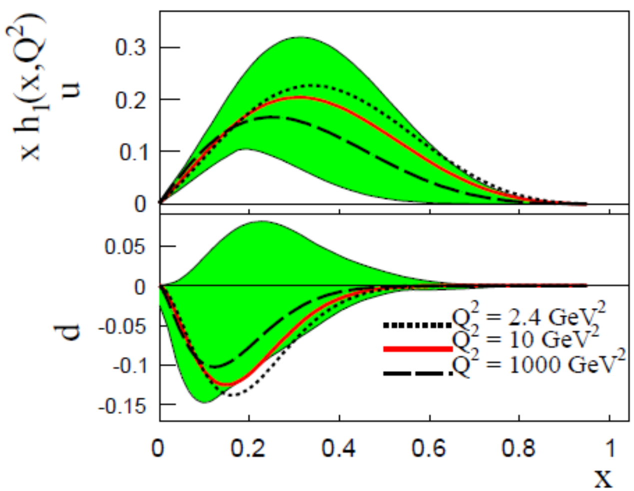
Fit describes data sets well!

Transversity and the Tensor Charge Extracted Using TMD Evolution and Recent Data Sets

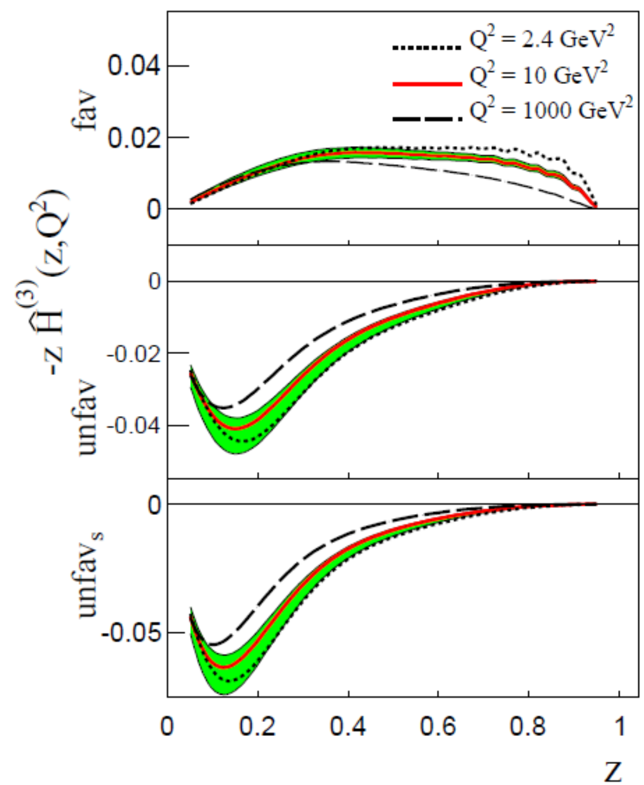
Z.-B. Kang., A. Prokudin, P. Sun, F. Yuan - Phys.Rev. D93 (2016) 1, 014009

Results given at
Q^2=2.4, 10 and 1000 GeV^2

up and down
transversity distributions



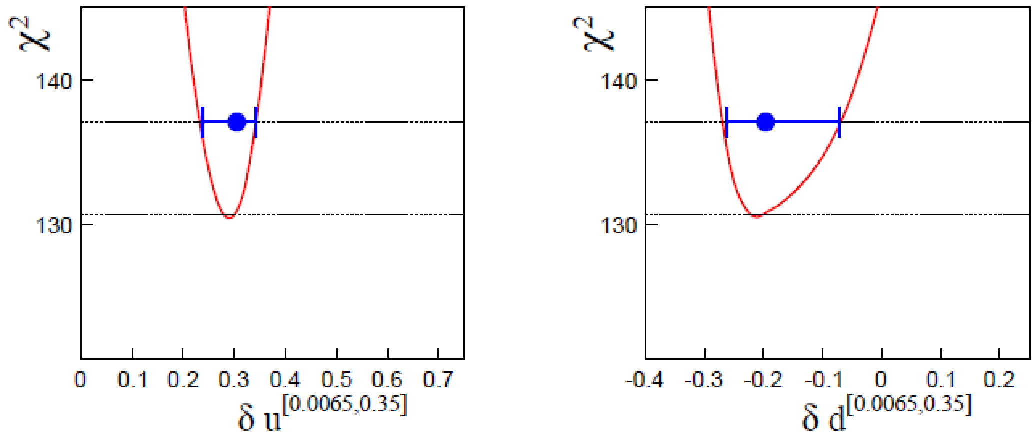
Favored and unfavored
Collins FF



Transversity and the Tensor Charge Extracted Using TMD Evolution and Recent Data Sets

Z.-B. Kang., A. Prokudin, P. Sun, F. Yuan - Phys.Rev. D93 (2016) 1, 014009

up and down contributions to tensor charge



Integrals in data region

$$\delta u^{[0.0065,0.35]} = +0.30^{+0.04}_{-0.07}$$

$$\delta d^{[0.0065,0.35]} = -0.20^{+0.12}_{-0.07}$$

Integrals in [0,1]

$$\delta u^{[0,1]} = +0.39^{+0.07}_{-0.11}$$

$$\delta d^{[0,1]} = -0.22^{+0.14}_{-0.08}$$

Limitations of the Collins Based Tensor Charge Extraction ➔ Reduce Ability for L-QCD Test

(1) no data at $x > 0.35$ ➔ extrapolation uncertainty (➔JLab 12 GeV !)

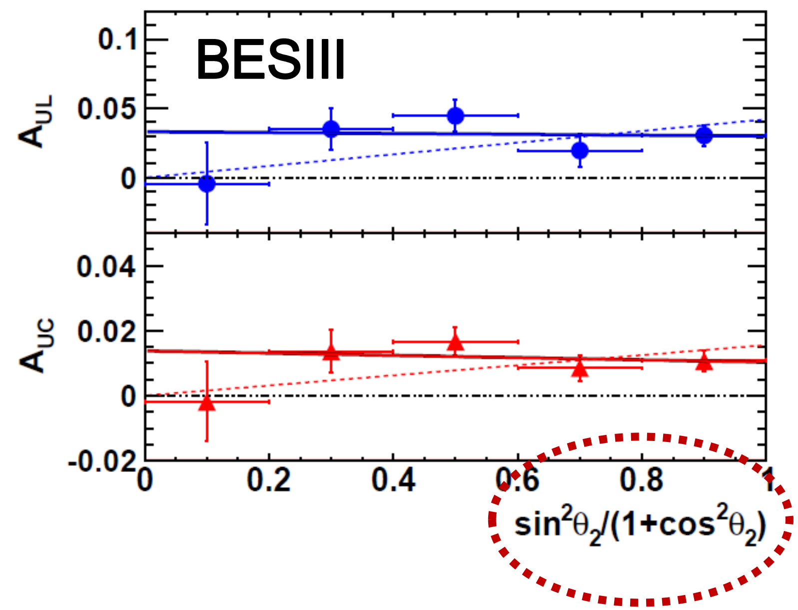
(2) model dependence in k_T dependence of quark distributions and FFs (➔ weighting !?, Jlab 12 GeV, Belle II)

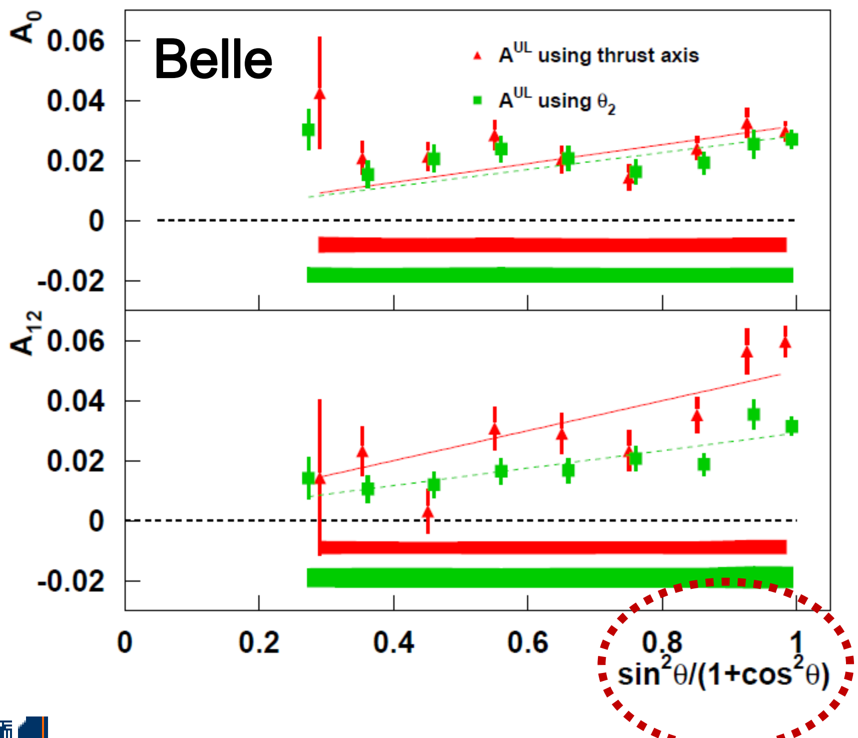
(3) all SIDIS data at low Q^2 : are we really measuring spin effects at leading twist? Is the Collins mechanism in jets in e+e- the same as in low Q^2-SIDIS without observable jets? (➔ Collins in jets in pp and in ep at EIC)

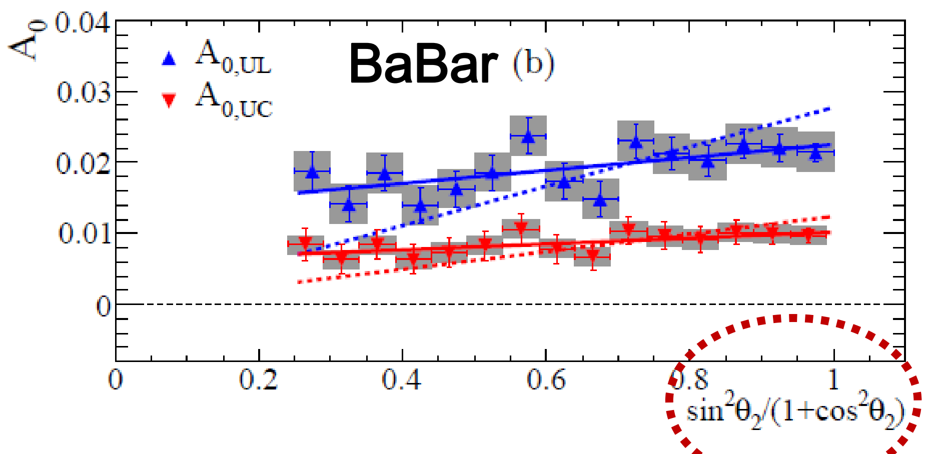
(4) ratio method in e^+e^- for Collins asymmetry assumes that only Collins mechanism is flavor dependent! (➔ no Collins fix, ➔ IFF!)

A_0 Collins Asymmetries Show Incorrect θ_2-Dependence: Physics or Systematic Effect?

$$R_0^U / R_0^L = 1 + \cos(2\phi_0) \frac{\sin^2\theta}{1 + cos^2\theta} \times \left\{ \frac{f \left(H_1^{\perp,fav} \overline{H}_1^{\perp,fav} + H_1^{\perp,dis} \overline{H}_1^{\perp,dis} \right)}{\left(D_1^{fav} \overline{D}_1^{fav} + D_1^{dis} \overline{D}_1^{dis} \right)} \right.$$

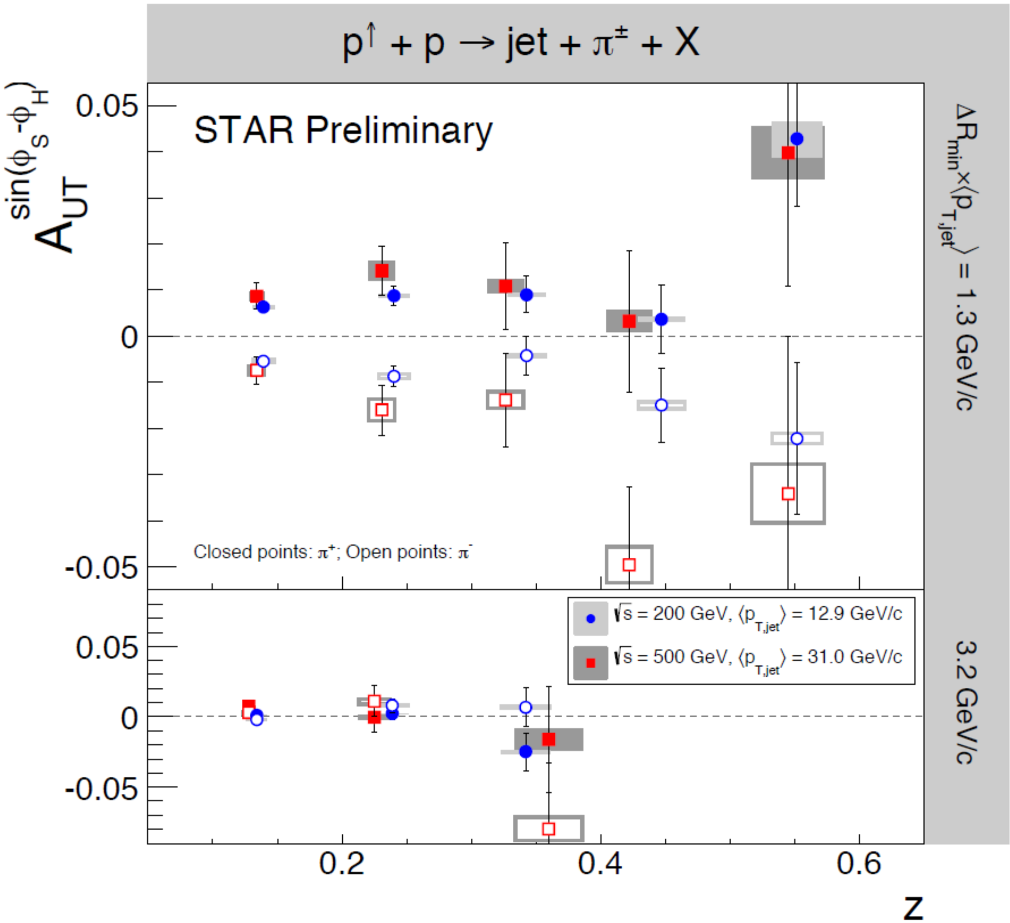






Alternatives: Collins in Jets in hadron-p↑ at RHIC and COMPASS or e-p ↑ at EIC

Taken from: RHIC Cold QCD Plan, Aidala, Aschenauer, et al.



First measurement of Collins asymmetries for $\pi^{+,-}$ in jets!

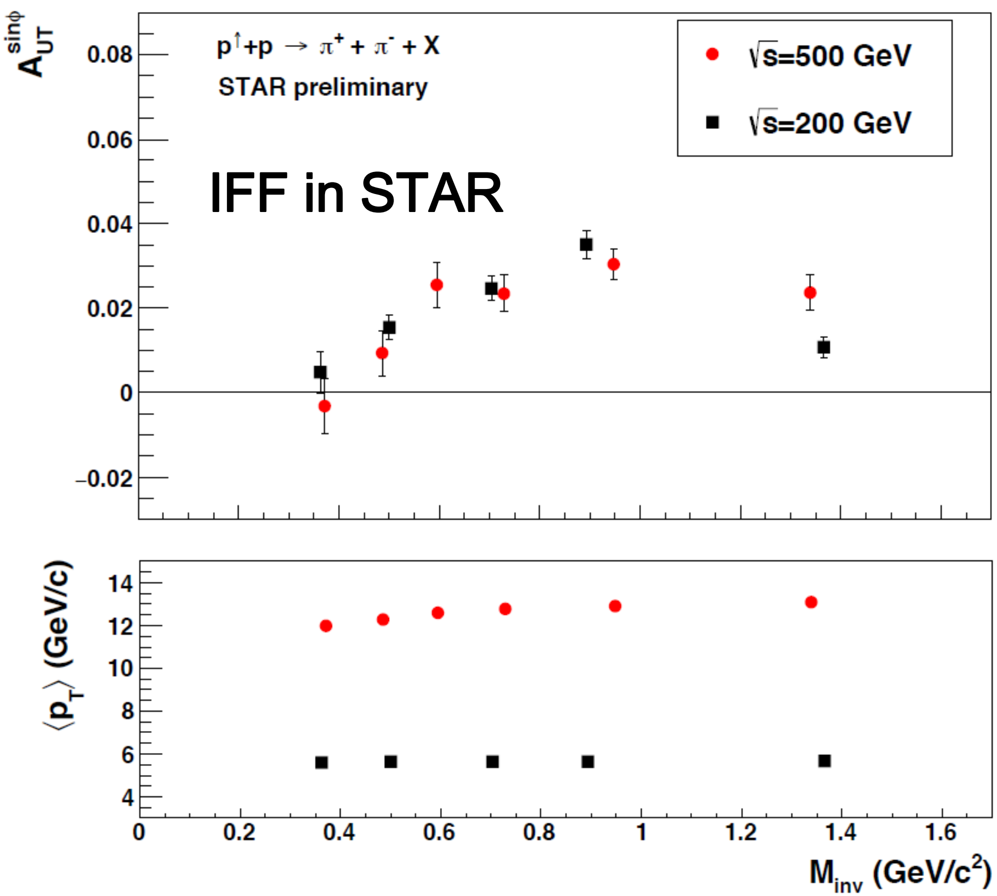
and first measurement of Collins asymmetries involving transversity distributions at high scales!

Comparison of e+e- & SIDIS extraction of transversity with e+e- & p-p extraction will provide information on process dependence.

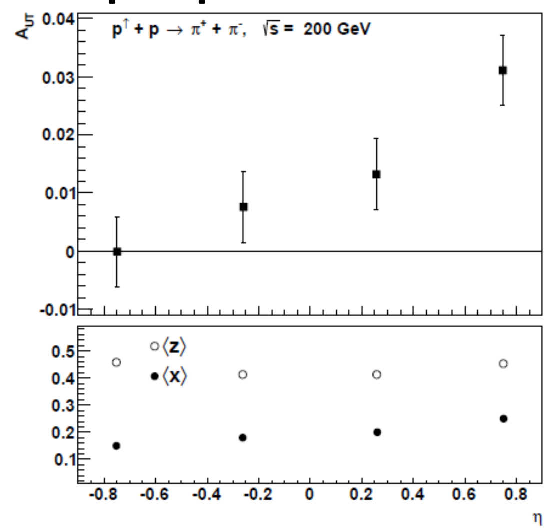
Collins-in-jet-channel will be also available at EIC.

Should check if this could be done with low intensity hadron beams in COMPASS tests factorization, universality and evolution.

Alternatives: di-Hadron IFF Asymmetries in hadron-p↑ M. Ablikim et al. Phys.Rev.Lett. 115(2015)242501



η-dependence

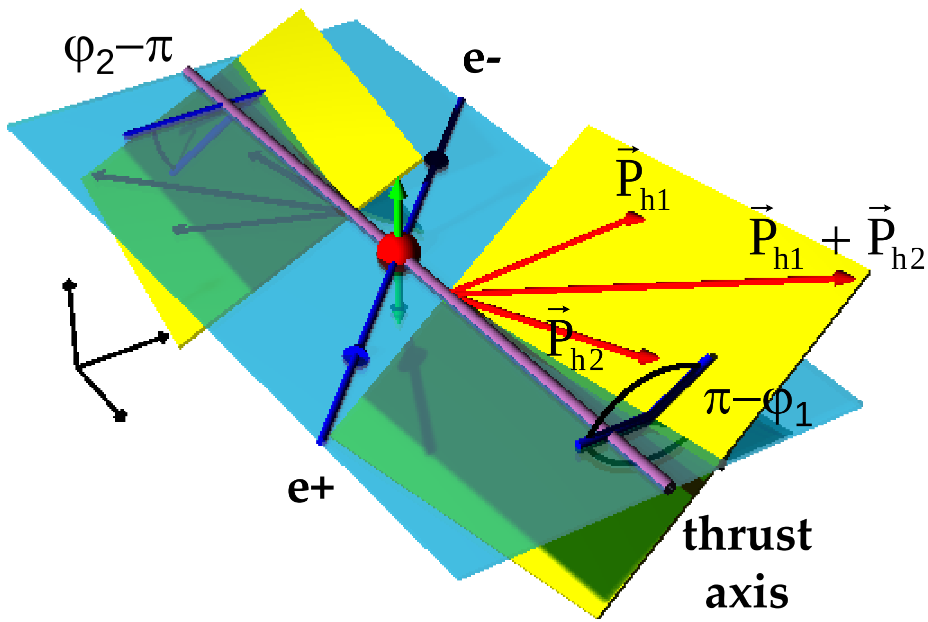


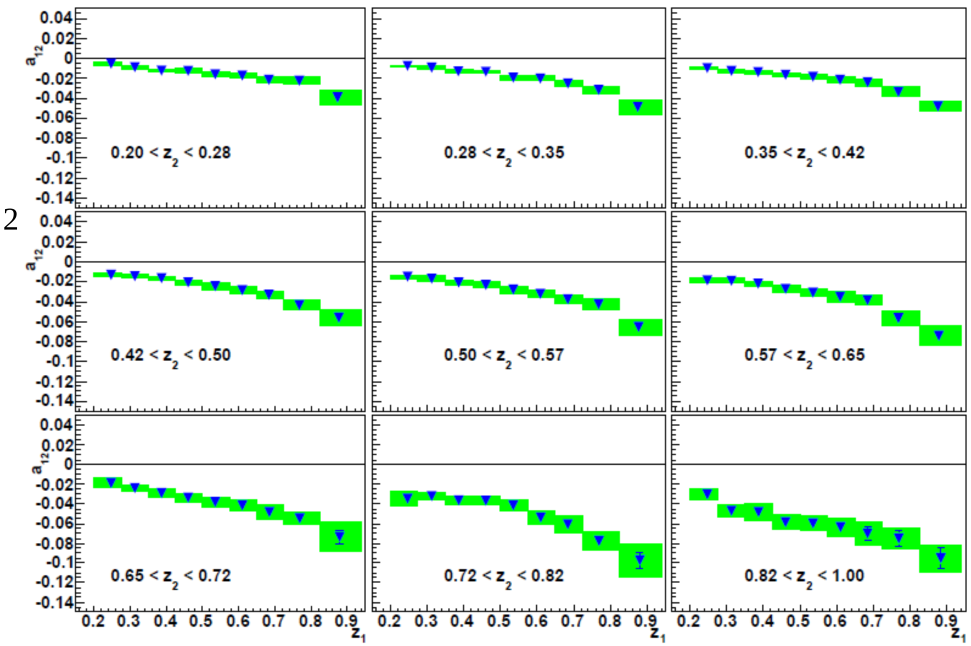
No TMD Factorization & process dependence well understood!

Should check if this is possible with low intensity hadron beams on polarized targets in COMPASS. Evolution, statistical precision (?)!

IFF measurement at BELLE

A. Vossen et al., Phys. Rev. Lett. 107(2011)
formerly Freiburg/COMPASS





$$e^+e^- \to (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}\, X$$

$$A \propto H_1^{\sphericalangle}(z_1, m_1) H_1^{\sphericalangle}(z_2, m_2) \cos(\phi_1 + \phi_2)$$

Artru and Collins, *Z. Phys. C69, 277 (1996)*

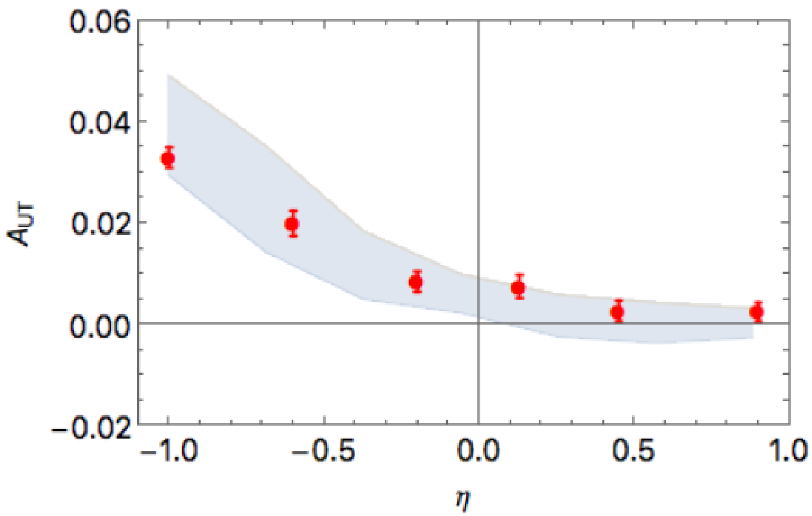
Boer, Jakob, and Radici, PRD67, 094003 (2003)

No double ratios needed to cancel radiative and acceptance effects!

Transversity Extraction from IFF

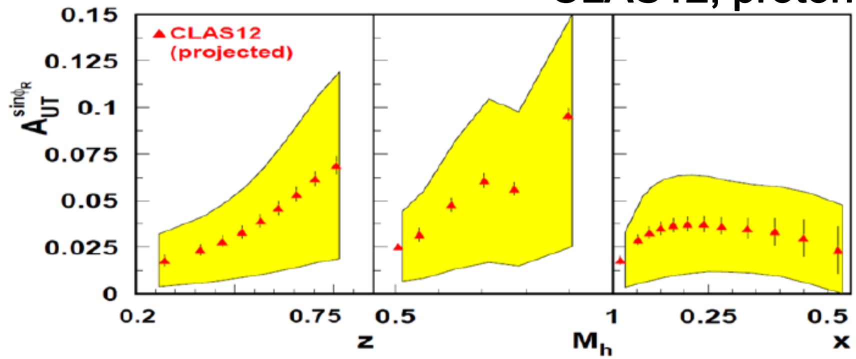
Recent Review S. Pisano, M. Radici arXiv:1511.03220

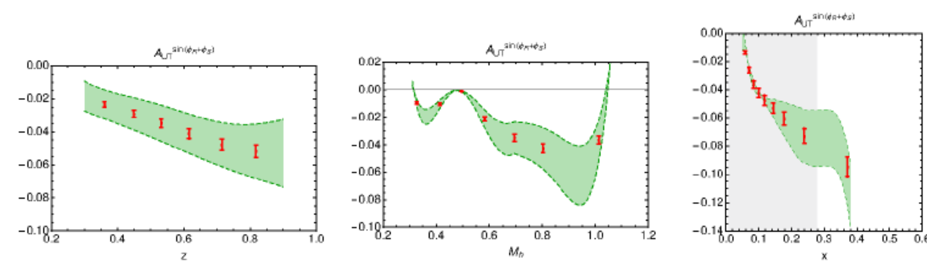
Comparison of prediction based on fit to SIDIS and e+e- IFF data & STAR IFF asymmetry data in p-p



Comparison of projections for CLAS12 and SOLID. Experimental errors vs uncertainties from fit to SIDIS and e+e- IFF data

CLAS12, proton





SOLID, He-3

Precise IFF data from COMPASS and RHIC will have very large impact on uncertainties for transversity extracted from IFF.

Precise comparison to Collins extractions measures breaking of Universality for Collins function in hadron collisions.

Transversity: Suggestions for Channels with Hadron Beams at COMPASS to be Studied

$$hp^{\downarrow} \longrightarrow l + \bar{l} + X \qquad \text{(Drell - Yan based on beam BMF)}$$

$$hp^{\downarrow} \longrightarrow jet(pion) + X \quad \text{(Collins in Jets)}$$

$$hp^{\uparrow} \longrightarrow \Lambda^{\uparrow} + X \qquad \text{(Lambda FF needs to be measured e + e-)}$$

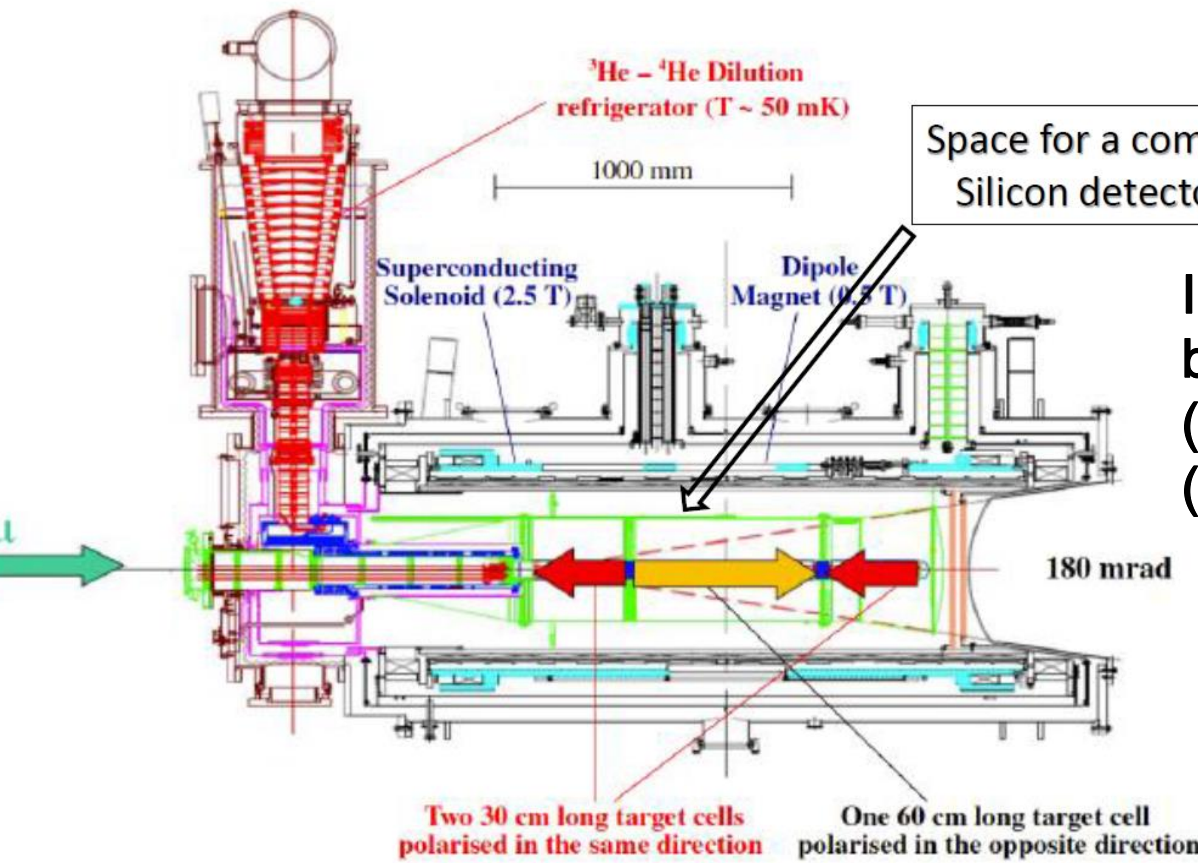
$$hp^{\uparrow} \longrightarrow \pi^{-} + \pi^{+} + X \qquad \text{(IFF available from Belle)}$$

Avoiding many of the problems in the current Collins based extraction!

Measurements of quark transversity as input to Tensor Charge

	1991	2002-2008	2009-2018	2018-2024
p+p	**E704, 1991** **Large forward SSA**	**STAR, PHENIX, BRAHMS** **Inclusive A_N**	**RHIC** **Collins in jets, IFF**	**COMPASS** **hadron beam**
SIDIS		HERMES COMPASS Collins , (IFF)	COMPASS proton-target, IFF JLab ^{3}He	JLab 12 GeV Collins, IFF
$e^{+}+e^{-}$		BELLE Collins FF	BELLE, Babar, BESII Collins, IFF, p_T dependence	BELLE II p_T dependence Lambda

Consider Possible Addition of a Si-Recoil Detector to the Polarized Target



Initial ideas and first work by Dubna (I. Savin), Munich (J. Friedrich) and at CERN (F. Gautheron and A. Magnon)

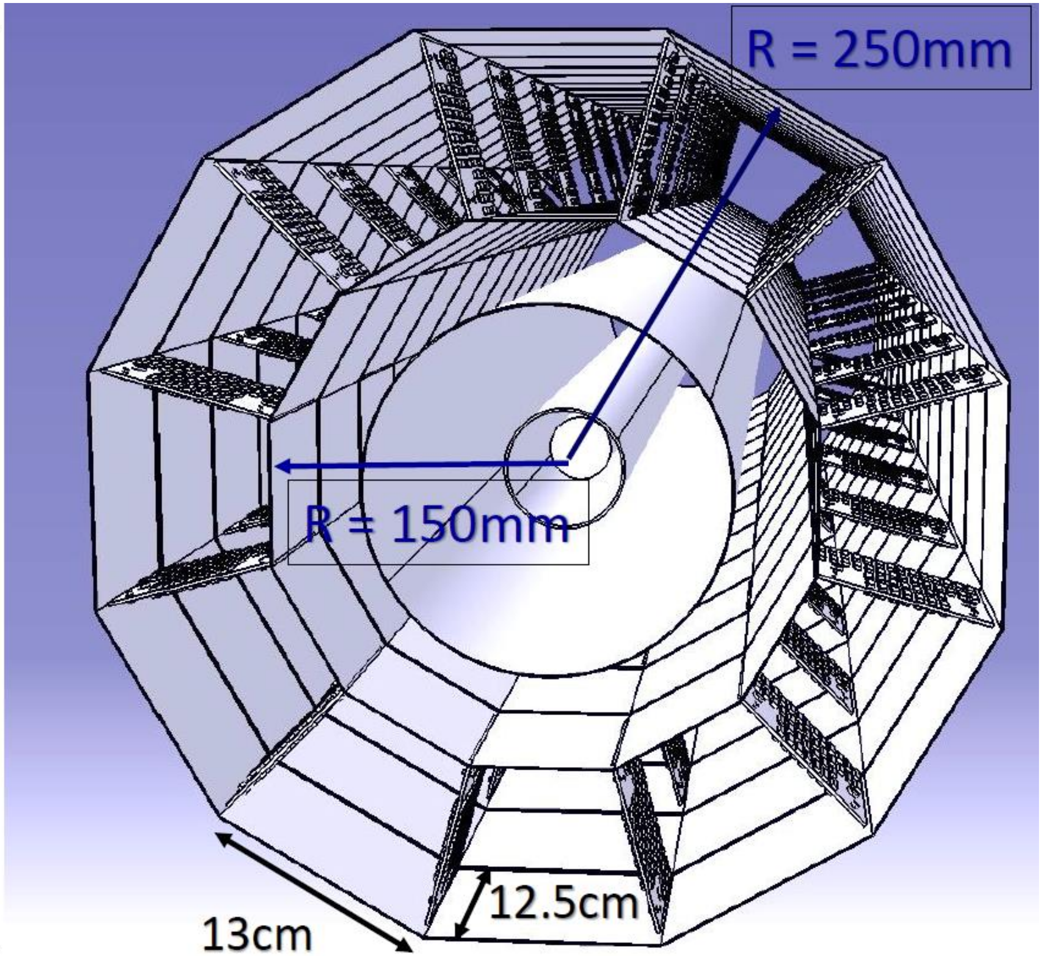
Slide: A. Magnon and F. Gautheron

Consider Possible Addition of a Si-Recoil Detector to the Polarized Target

A preliminary sketch of the 2-layers Si station to be inserted in the vacuum space of the COMPASS PT.

Note that full available space for this detector is 100mm(*) < R < 310mm

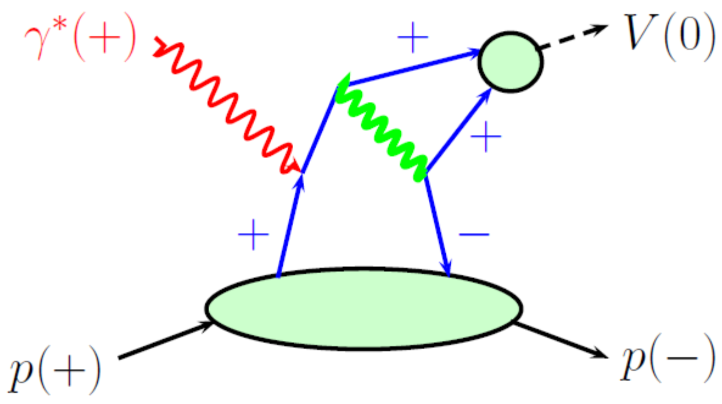
(*) Radius of present μwave cavity reduced by a factor of 2



Slide: A. Magnon and F. Gautheron

e-p: Transversity GPD H_T

S. V. Goloskokov, P. Kroll, Eur.Phys.J. C74 (2014) 2725



$\mathcal{M}_{0-,++}$ and to the subprocess $\gamma^* q \to (q\bar{q})q$

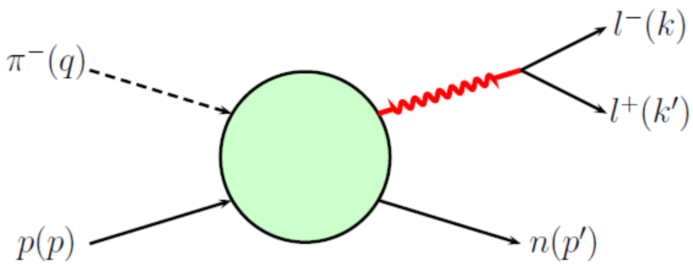
H_T can play a significant role in describing exclusive helicity flip amplitudes:

Can describe HERMES Spin Density Matrix Elements in Exclusive ρ_0 Electro-production Eur.Phys.J. C62 (2009) 659-695

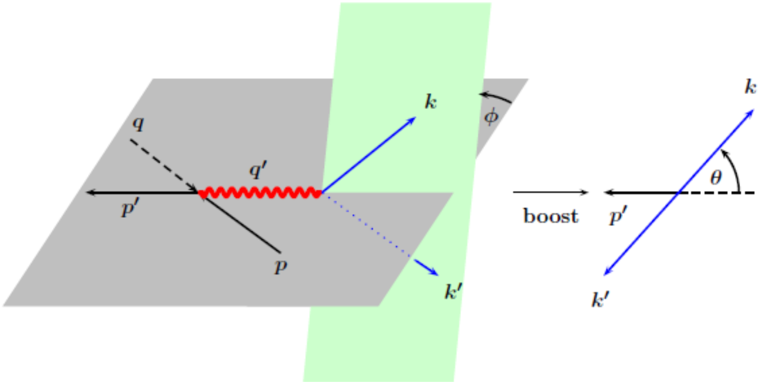
Additional theoretical work in progress (eg. A. Pivovarov and O.V. Teryaev).

DY: Transversity GPD H_T dominates transverse-σ

S. V. Goloskokov, P. Kroll, Phys.Lett. B748 (2015) 323-327



H_T can play a significant role in describing exclusive helicity flip amplitudes in exclusive DY:



$$\frac{d\sigma}{dt dQ'^2 d\cos\theta d\phi} = \frac{3}{8\pi}\left\{\sin^2\theta \frac{d\sigma_L}{dt dQ'^2} + \frac{1+\cos^2\theta}{2}\frac{d\sigma_T}{dt dQ'^2} + \frac{\sin(2\theta)\cos\phi}{\sqrt{2}}\frac{d\sigma_{LT}}{dt dQ'^2} + \sin^2\theta\cos(2\phi)\frac{d\sigma_{TT}}{dt dQ'^2}\right\}$$

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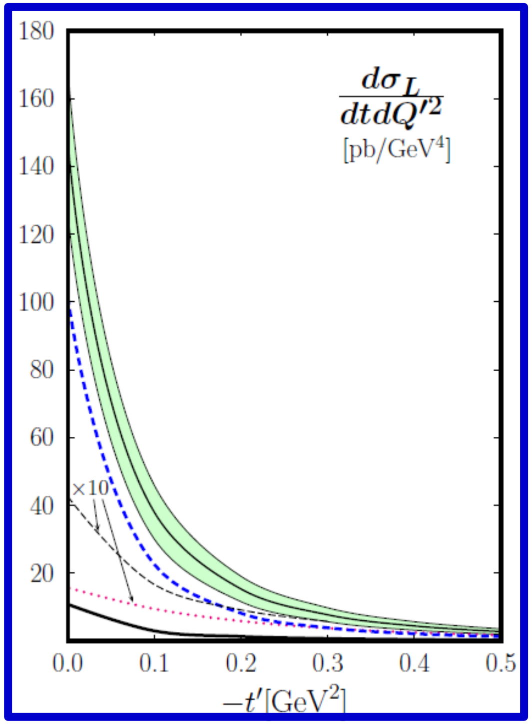

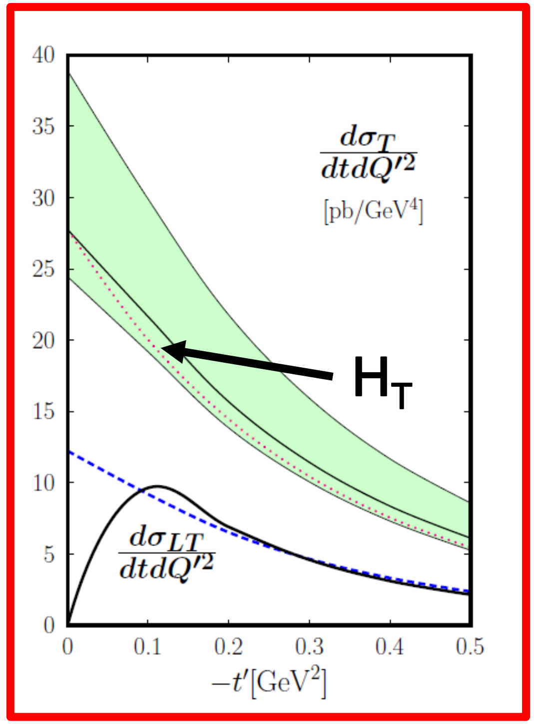

Calculations for
S=20 and 30 GeV²
COMPASS π
S= 360 GeV
➔ σ_L=30fb

p $_\pi$=60 GeV may
➔ be possible, then
➔ σ_L~15pb, σ_T~3pb

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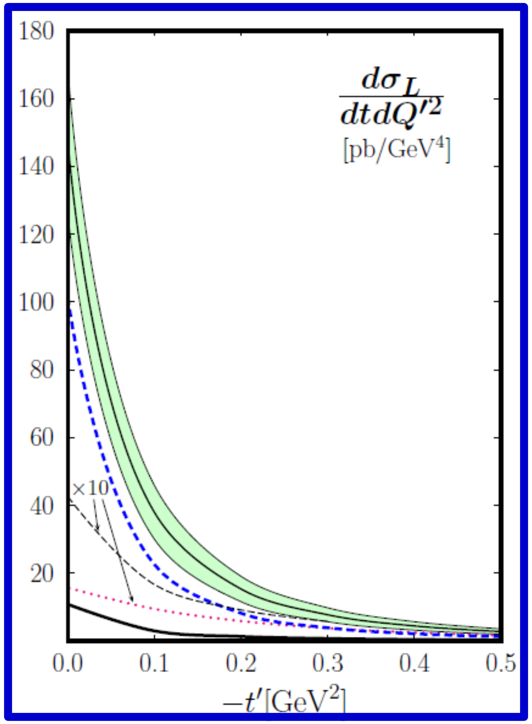

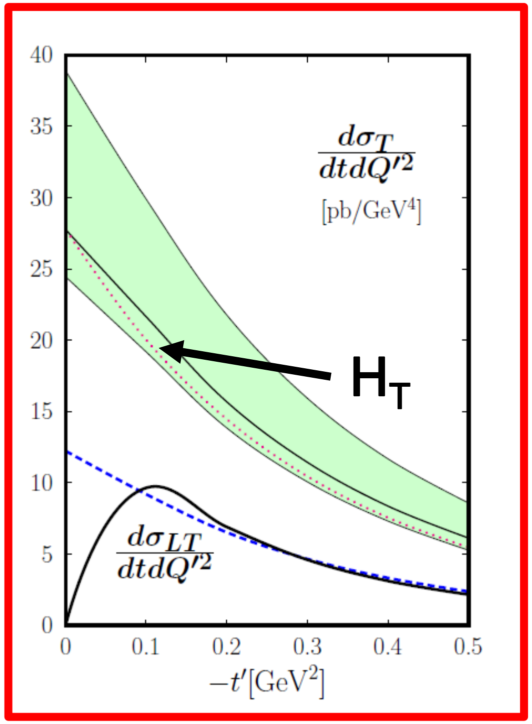

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➔ σ_L~15pb, σ_T~3pb

Can we achieve p $_\pi$= 20GeV and high M2 pion flux by lowering the SPS extraction momentum and the M2 optics?

In addition, need to measure neutron missing mass with good precision!

Summary

- Highly interesting and novel Drell-Yan Measurements appear possible:

  - flavor separation of quark Sivers distribution (^{6}LiD target, pion beam)
  - measurement of BMF for pions and kaons (dense H-target, RF separated beam)
  - measurement of p-BMF with anti-protons and CPT (dense H-target, RF sep-beam)
  - measurement independent of FF for transversity (NH_3 target)
  - DY access to transversity GPD (would need low beam momentum!!)

- Possible interesting TMD channels for low intensity hadron beam on polarized target without absorber (beam rate reduced by factor 20)

  - Gluon Sivers through associate J/Psi + γ hadro production
  - Gluon Sivers through-hadro production of K^+K^- pairs (large QCD/Jet cross section)
  - Quark Sivers through A_N for jets
  - Quark Transversity through IFF, Lambda FF and Collins in Jets

Some of the hadro-production channels are similar to RHIC.In some cases they may be well suited for high statistical precision. In addition the low Q^2 Data in TMD and co-linear channels in p-p will help to test evolution, Factorization and universality for TMDs.