Key observables for TMD extraction from the experimental point of view

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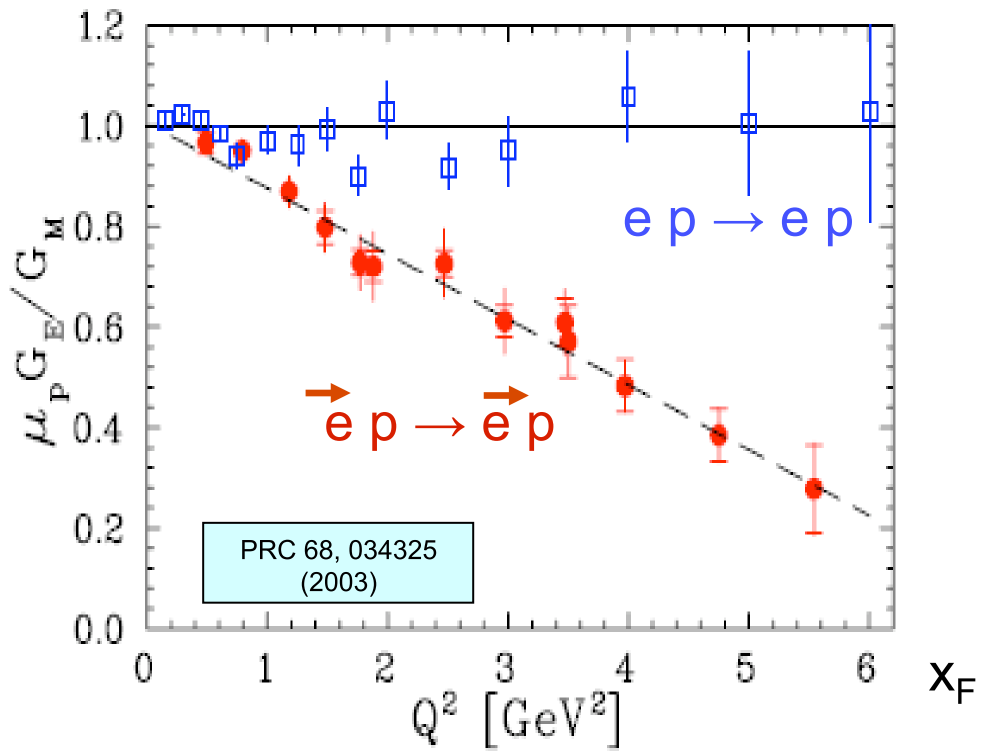
INFN Ferrara

Structure of Nucleons and Nuclei
June 10, 2013 Como

The Spin Degree of Freedom

Spin degrees of freedom can explain otherwise surprising phenomena and bring new insights into nuclear matter structure

Fundamental: do not neglect it !!



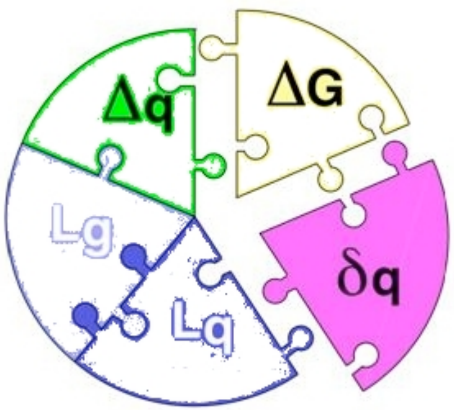
The Spin Degree of Freedom

In our exploration of the QCD micro-world

Fundamental: do not neglect spin !!

Two questions in Hadronic Physics
await explanation since too long

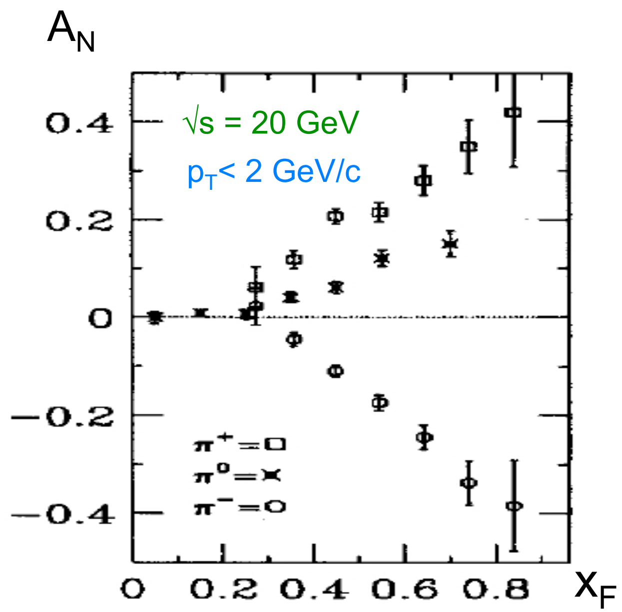
Proton Spin Budget



$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$

?

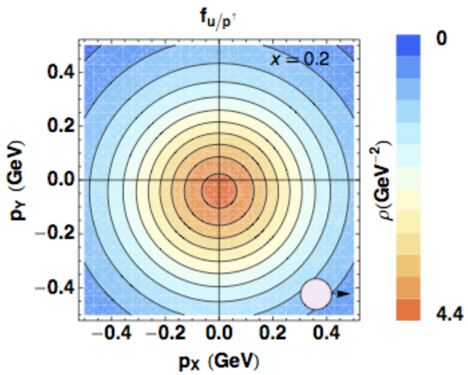
Single Spin Asymmetries



Quantum phase-space distributions of quarks

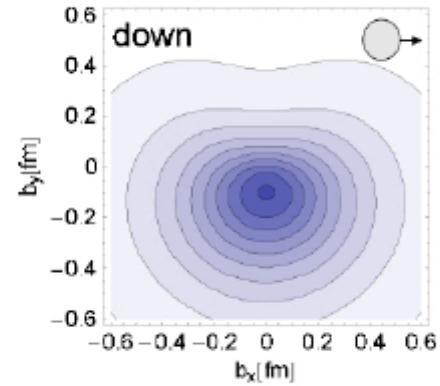
$W_p^q(x,k_T,r)$ "Mother" Wigner distributions

Probability to find a quark q in a nucleon P with a certain polarization in a position r & momentum k



d^3r

d^2k_T (FT)



TMD PDFs: $f_p^u(x,k_T)$,…

Semi-inclusive measurements
Momentum transfer to quark
Direct info about momentum distribution

GPDs: $H_p^u(x,\xi,t)$, …

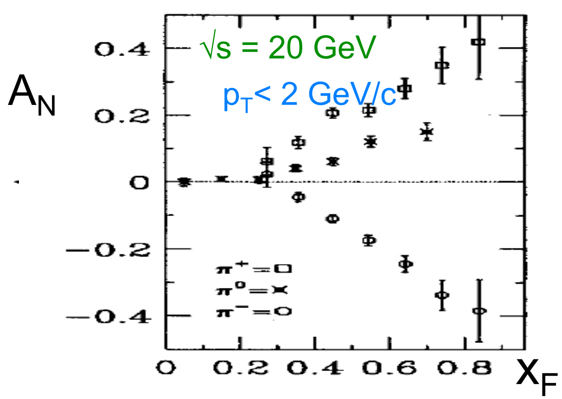
Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

d^2k_T

$\xi=0,t=0$

PDFs $f_p^u(x)$,…

May explain SSA & Lam-Tung



Mueller talk

May solve
proton spin puzzle

$$J_q = \frac{1}{2}\Delta\Sigma + L_q = \lim_{t\to 0}\int_{-1}^{1} dx\ x\ \left[H(x,!,t)+E(x,!,t)\right]$$

Leading Twist TMDs

quark polarisation (columns) / **nucleon polarisation** (rows)

N/q	U	L	T
U	f_1 *Number Density*		$h_1^{\perp}$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^{\perp}$ *Worm-gear*
T	$f_{1T}^{\perp}$ *Sivers*	$g_{1T}^{\perp}$ *Worm-gear*	h_1 *Transversity* $h_{1T}^{\perp}$ *Pretzelosity*

Number density and helicity:

Focusing here in transverse momentum dependence

Transversity:

Survives transverse momentum integration (missing leading-twist collinear piece)

Differs from helicity due to relativistic effects and no mix with gluons in the spin-1/2 nucleon

quark polarisation (columns) / **nucleon polarisation** (rows)

N/q	U	L	T
U	D_1 *Unpolarized*		$H_1^{\perp}$ *Collins*
L		G_{1L}	$H_{1L}^{\perp}$
T	$D_{1T}^{!}$	G_{1T}	H_1 $H_{1T}^{\perp}$

Off-diagonal elements:

Interference between wave functions with different angular momenta: contains information about parton orbital angular motion and spin-orbit effects

Testing QCD at the amplitude level

T-odd elements:

→ sign change between DY and SIDIS

- universality of TMDs

Strict prediction from TMDs + QCD !

First evidences

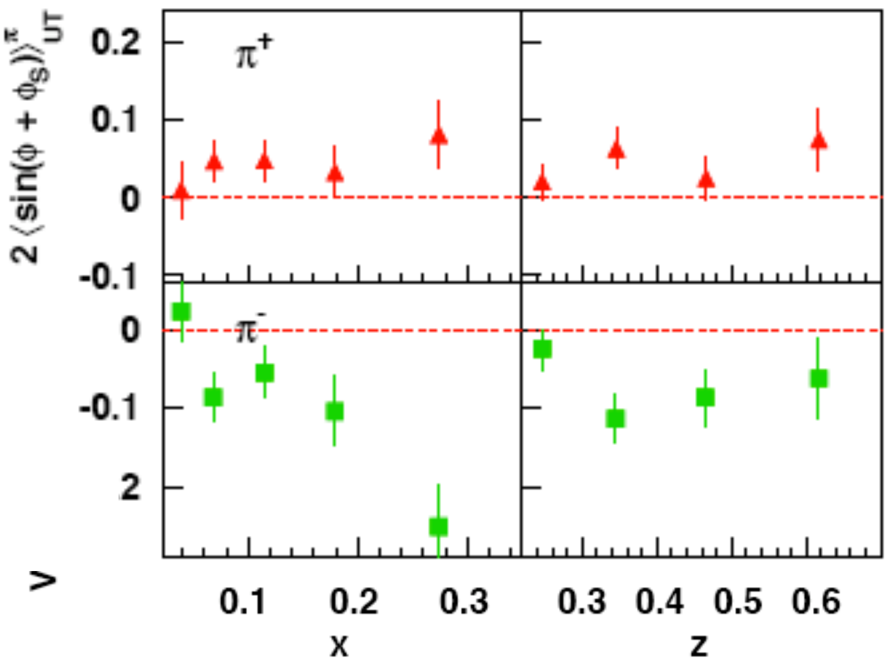
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^{\perp}$$

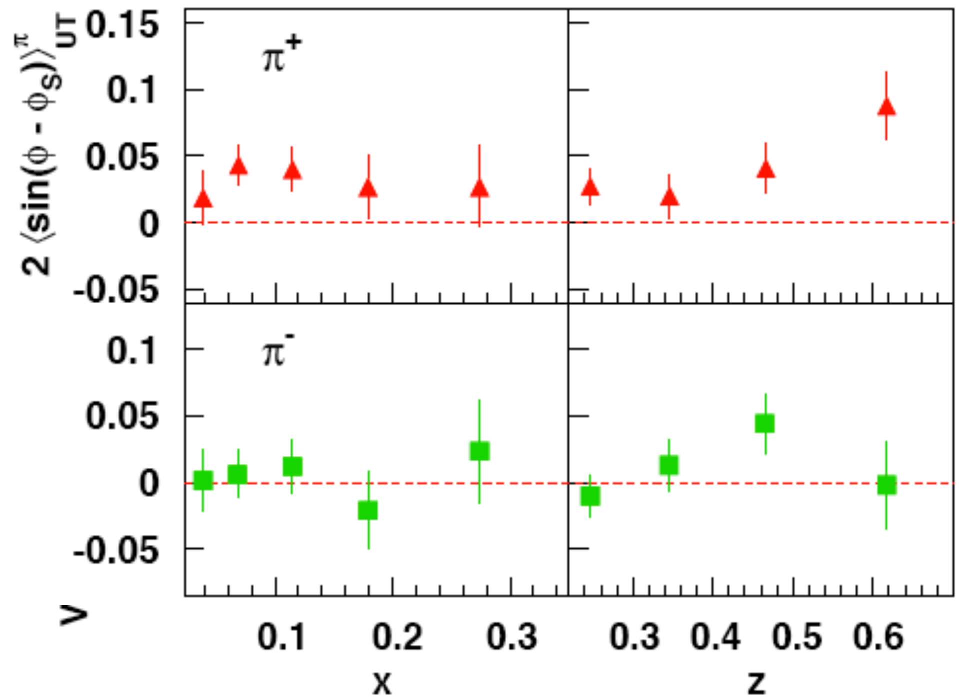
SIDIS:
ep → e'hX

$$\sigma_{UT}^{\sin(\phi-\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$$

2005: First evidence from HERMES measuring SIDIS on proton

A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002

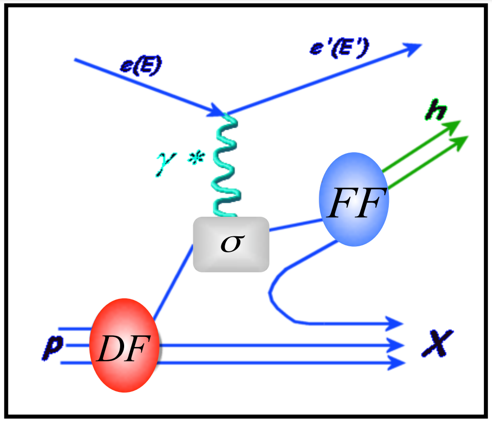




Non-zero transversity !!
Non-zero Collins function !!

Non-zero Sivers function !!

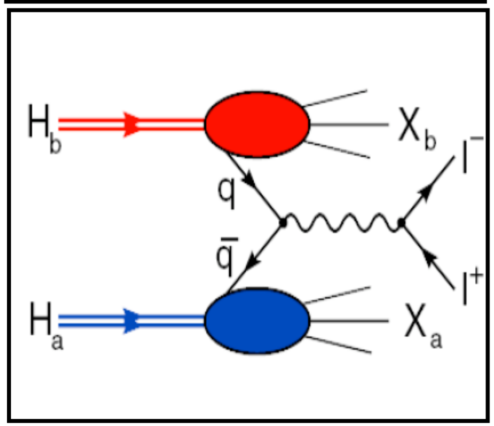
Physics reactions



SIDIS: rich phenomenology, the most explored so far

SIDIS $$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

hermes
COMPASS
Jefferson Lab



e^+e^-: B-factories as powerful fragmentation laboratories

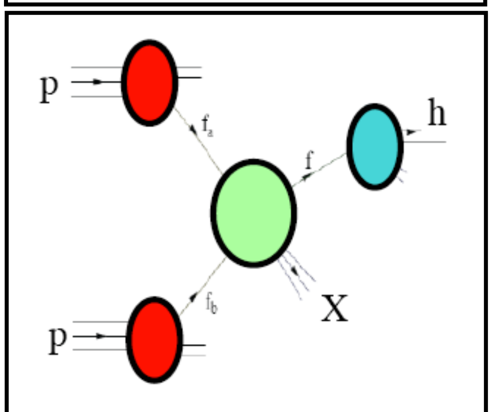
e^+e^- $$\sigma^{ee\to hhX} = \sum_q \sigma^{qq\to ee} \otimes FF \otimes FF$$

BELLE

DY: challenging for experiments (only unpolarized so far)

DY $$\sigma^{pp\to eeX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to ee}$$

CERN
Fermilab
JINR



Hadron reactions: challenging for theory (ISI + FSI)

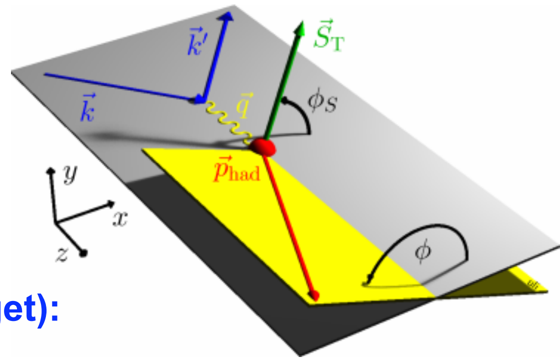
pp $$\sigma^{pp\to hX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to qq} \otimes FF$$

BROOKHAVEN
NATIONAL LABORATORY

The SIDIS case

quark polarisation / nucleon polarisation

N/q	U	L	T
U	f_1 *Number Density*		$h_1^{\perp}$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^{\perp}$ *Worm-gear*
T	$f_{1T}^{\perp}$ *Sivers*	$g_{1T}^{\perp}$ *Worm-gear*	h_1 *Transversity* $h_{1T}^{\perp}$ *Pretzelosity*



SIDIS cross section (transversely polarized target):

$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S d\phi\,dP_{h\perp}^2} \overset{Leading}{\underset{Twist}{\propto}} S_T\left\{\sin(\phi-\phi_S)F_{UT,T}^{\sin(\phi-\phi_S)}\right\}$$

$$+S_T\left\{\varepsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)}+\varepsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\right\}$$

$$+S_T\lambda_e\left\{\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right\}+\ldots$$

The SIDIS case

quark polarisation (columns) / **nucleon polarisation** (rows)

N/q	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^\perp$ *Worm-gear*
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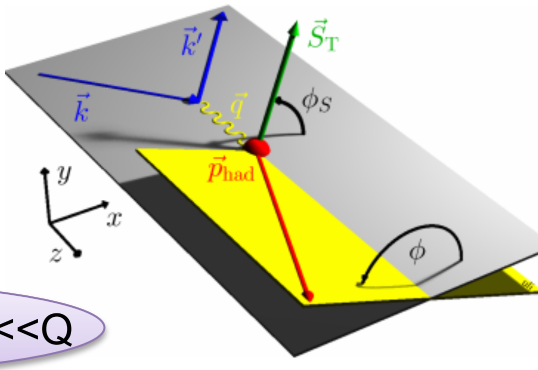
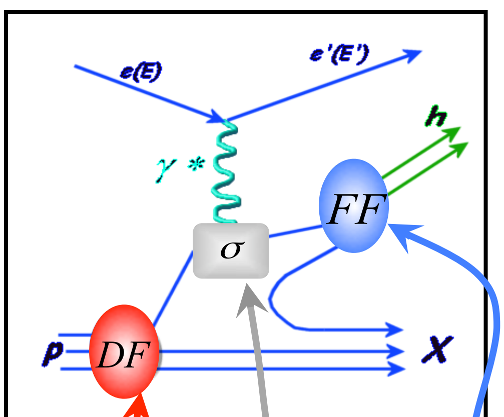


SIDIS cross section (transversely pol. target):

TMD factorization for P_T<<Q

$$f \otimes D = \int_q e_q^2 d^2 p_T d^2 k_T \ldots w(k_T, p_T) f^q(x, k_T^2) D^q(z, p_T^2)$$

Involved phenomenology due to the convolution over transverse momentum



$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

$$\frac{d^6\sigma}{dx\, dy\, dz\, d\phi_S d\phi\, dP_{h\perp}^2} \underset{Twist}{\overset{Leading}{\propto}} S_T \left\{ \sin(\phi - \phi_S) F_{UT,T}^{\sin(\phi-\phi_S)} \right\}$$

$$+ S_T \left\{ \varepsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi-\phi_S)} \right\}$$

$$+ S_T \lambda_e \left\{ \sqrt{1-\varepsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi-\phi_S)} \right\} + \ldots$$

$h_1 \otimes H_1^\perp$

$f_{1T}^\perp \otimes D_1$

$h_{1T}^\perp \otimes H_1^\perp$

$g_{1T}^\perp \otimes D_1$

Parton Number Density

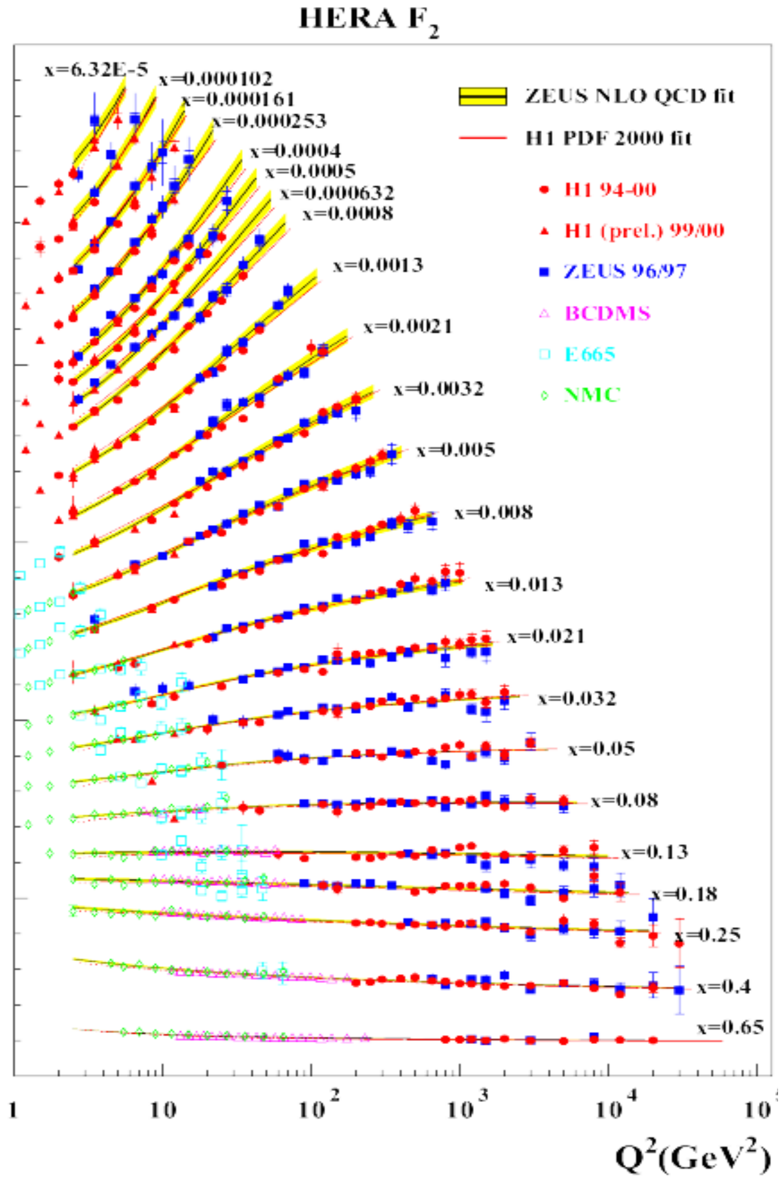
Number Density

nucleon polarisation

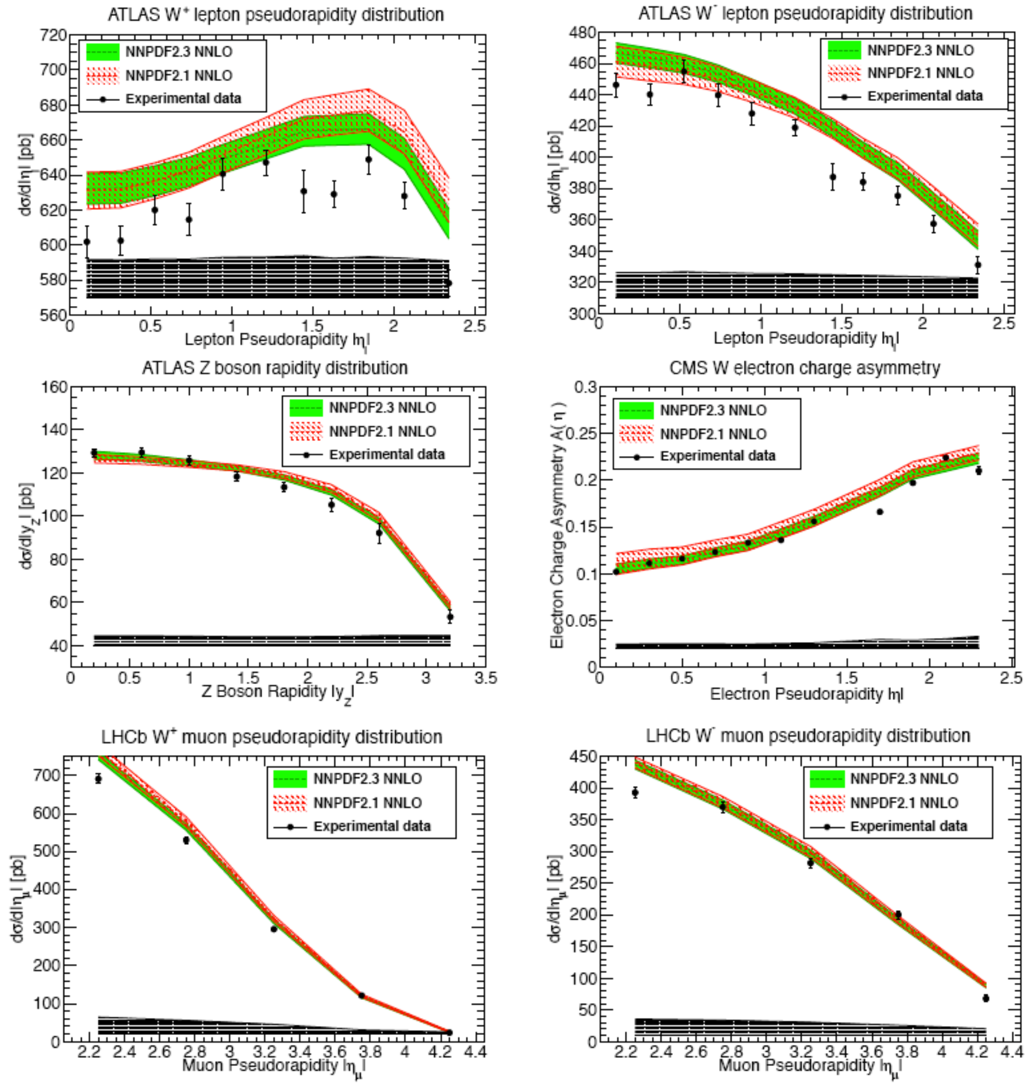
N/q	U	L	T
U	f_1 - Number Density		$h_1^\perp$ - Boer-Mulders
L		g_1 - Helicity	$h_{1L}^\perp$ - Worm-gear
T	$f_{1T}^\perp$ - Sivers	$g_{1T}^\perp$ - Worm-gear	h_1 - Transversity $h_{1T}^\perp$ - Pretzelosity

(The Baseline)

Parton Number Density

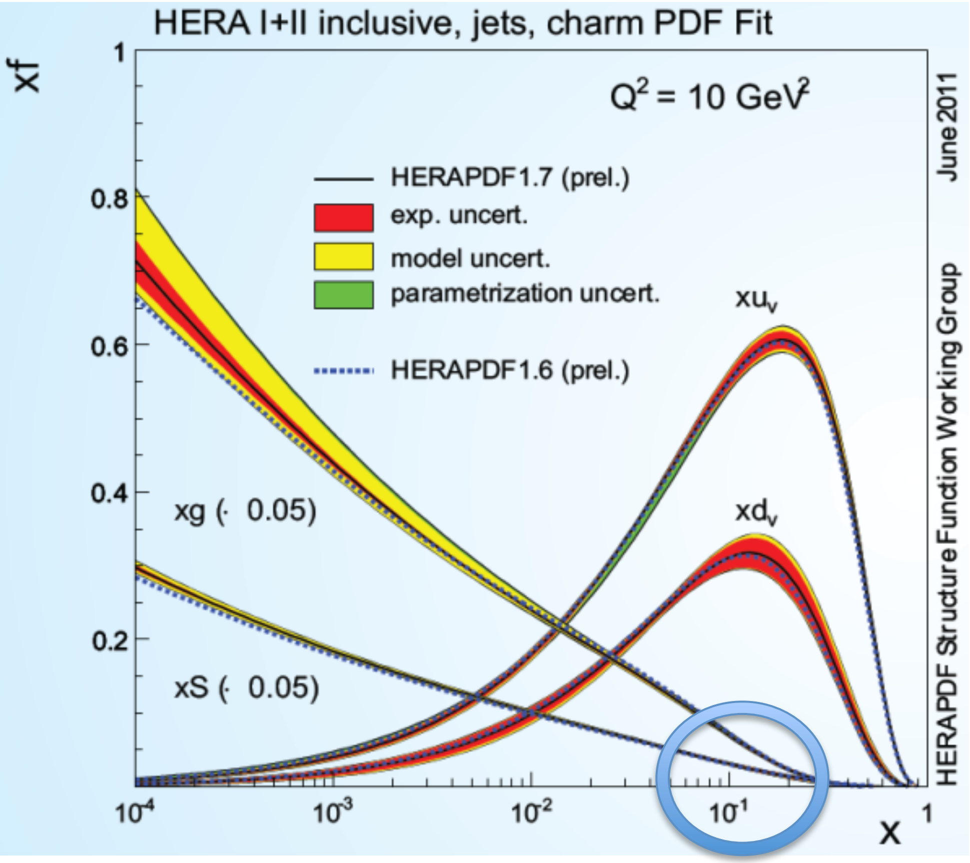


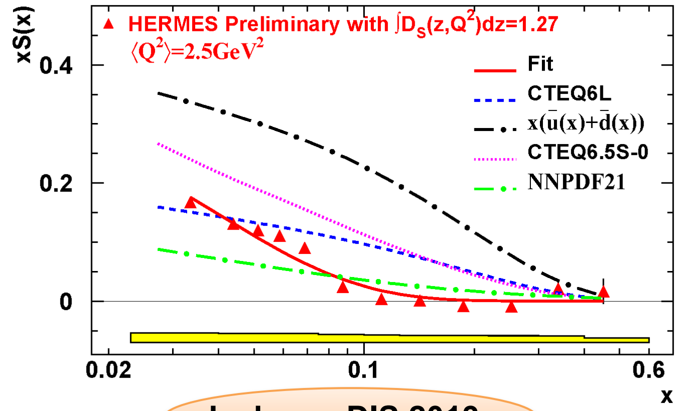
LHC gauge boson production



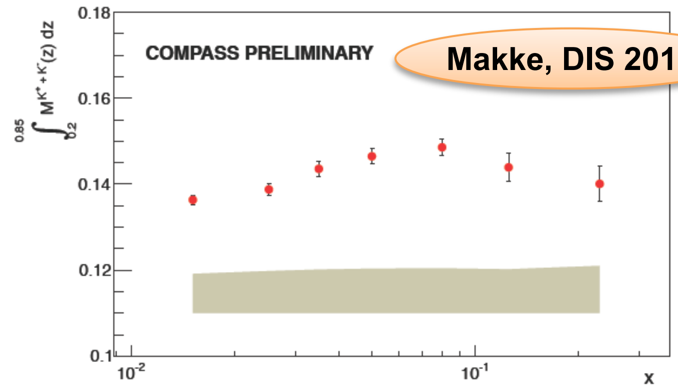
NNPDF: arXiv:1207.1303

Parton Number Density

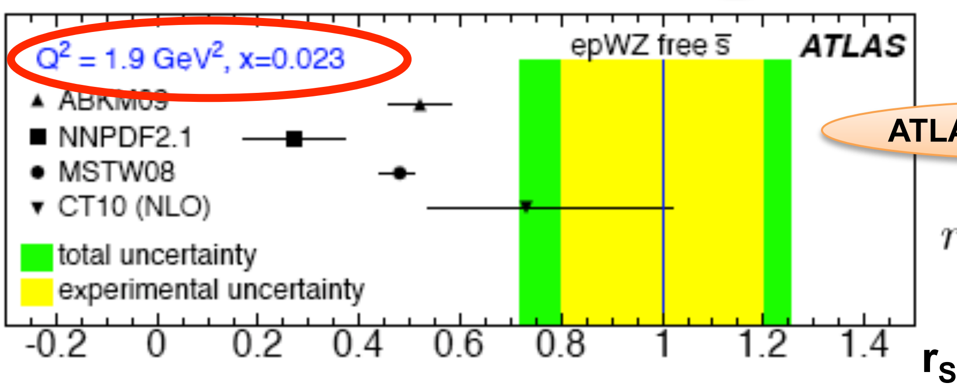




Jackson, DIS 2013

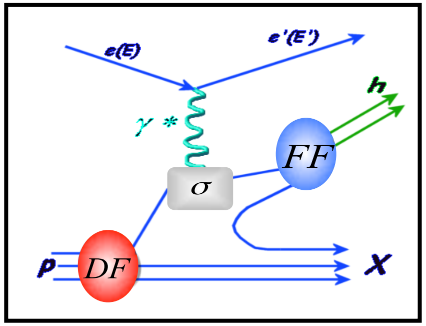


Makke, DIS 2013

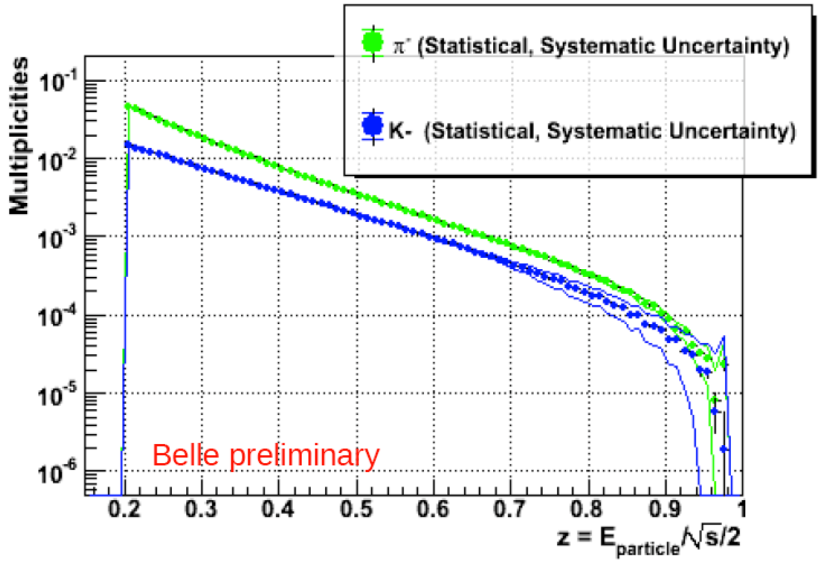


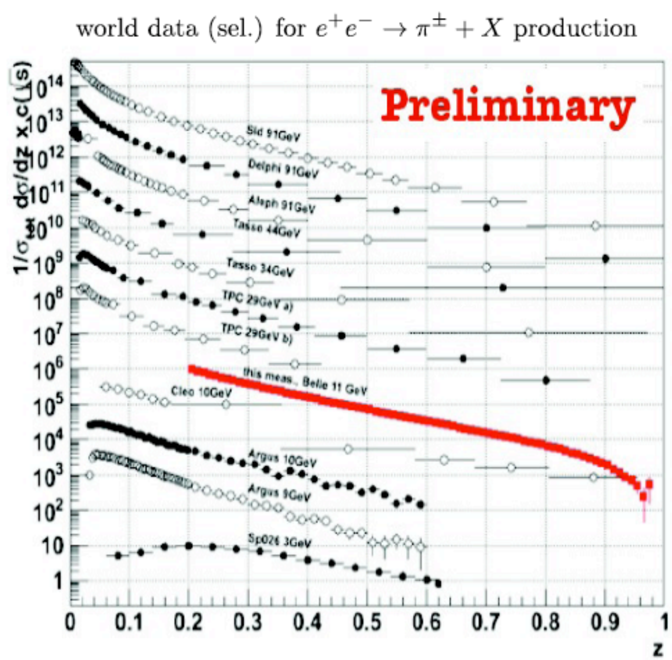
ATLAS: arXiv:1206.4051

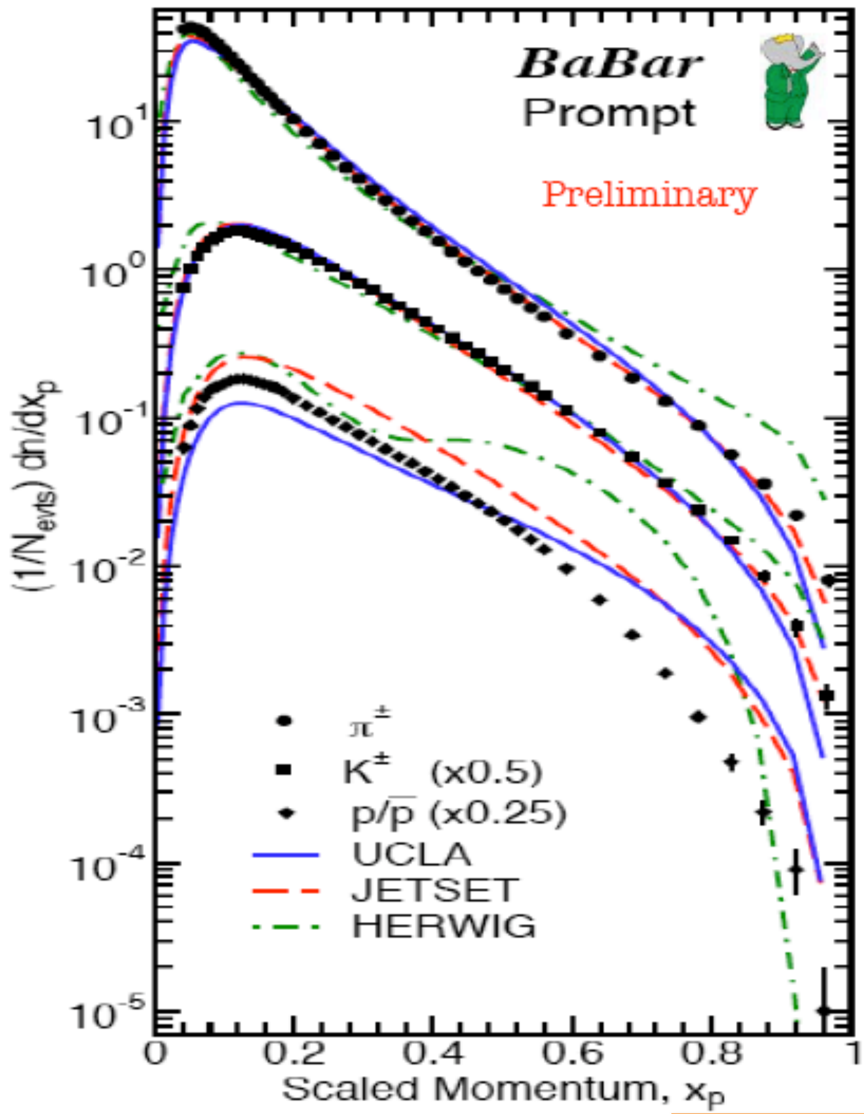
$$r_s = 0.5(s+\bar{s})/\bar{d}$$



Fragmentation Functions @ B-factories





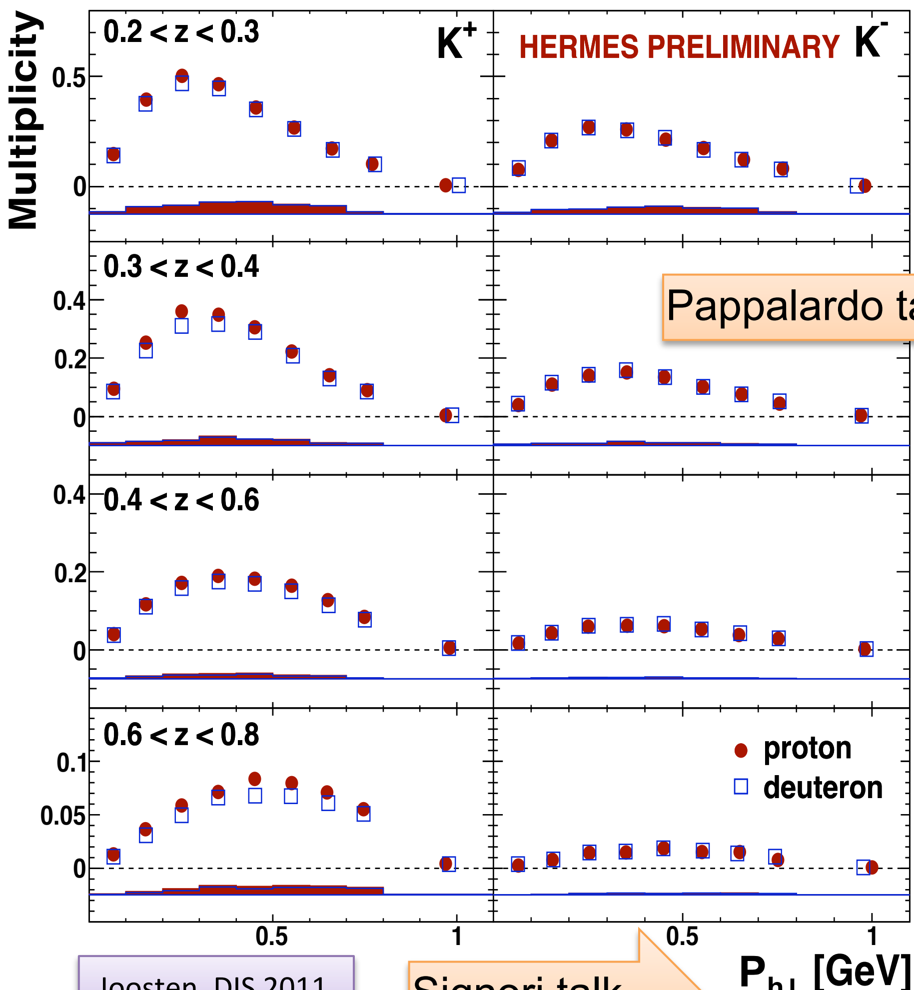


Vossen talk

The $P_{h\perp}$-unintegrated multiplicities $f_1 \otimes D_1$

Disentanglement of z and $P_{h\perp}$: access to the transverse intrinsic quark k_T and fragmentation p_T,

i.e. from gaussian anstaz $\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$

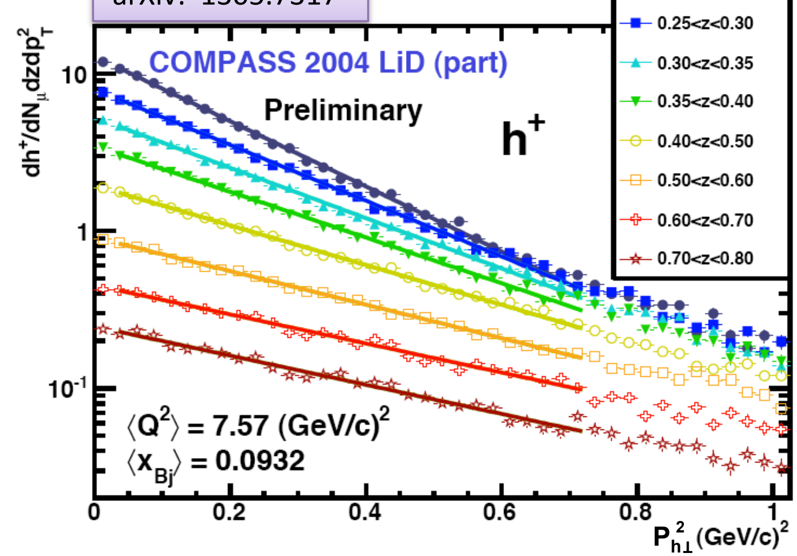


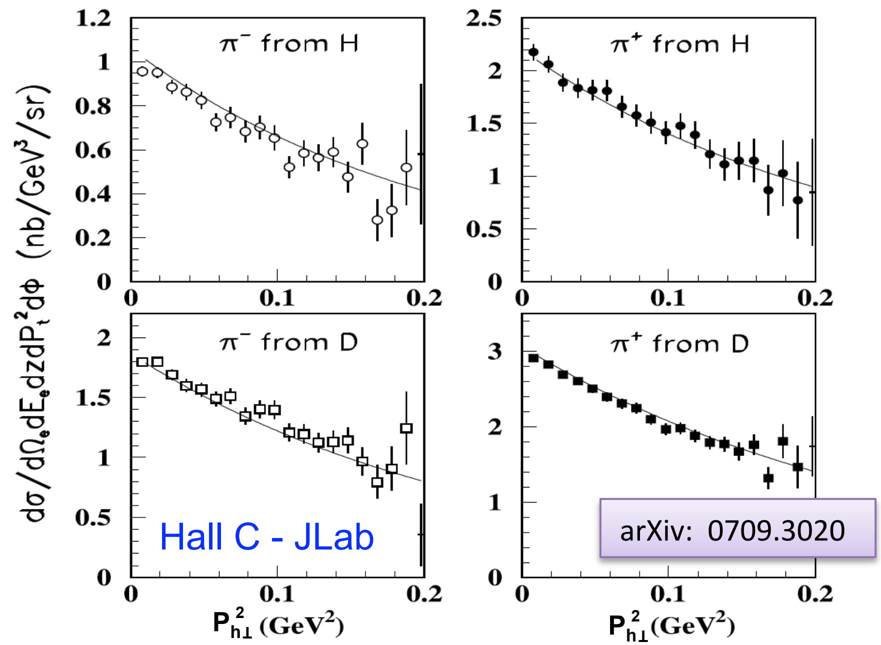
Joosten, DIS 2011

Pappalardo talk

Signori talk

arXiv: 1305.7317





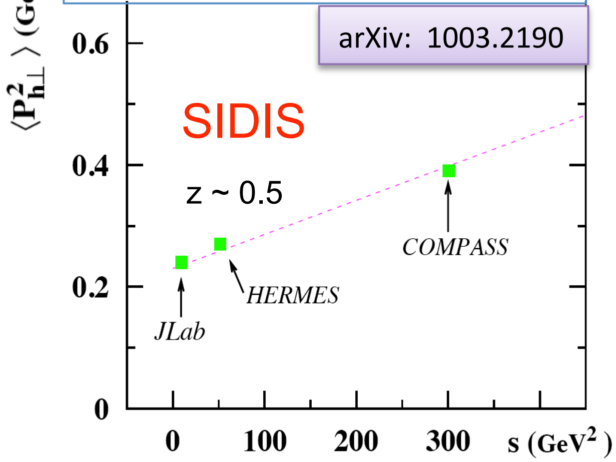
arXiv: 0709.3020

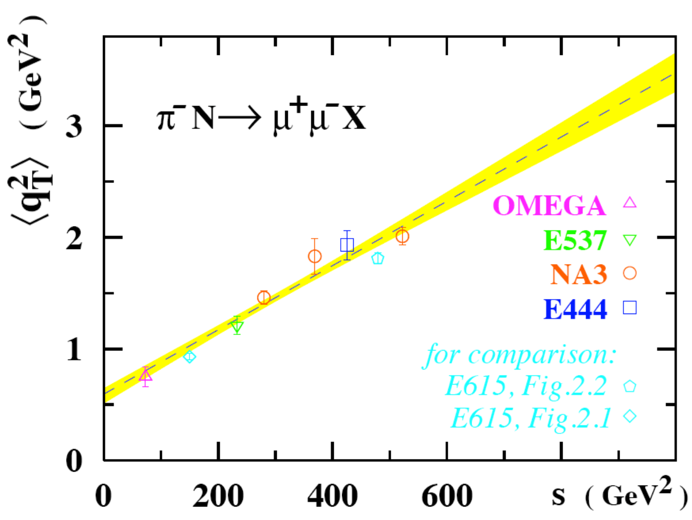
TMD Evolution

$f_1 \otimes D_1$

$$\frac{d\sigma_{UU}(P_{h\perp})}{dz\, dP^2_{h\perp}} = \frac{d\sigma_{UU}(0)}{dz\, dP^2_{h\perp}}\, e^{-P^2_{h\perp}/\overline{P^2_{h\perp}}}$$

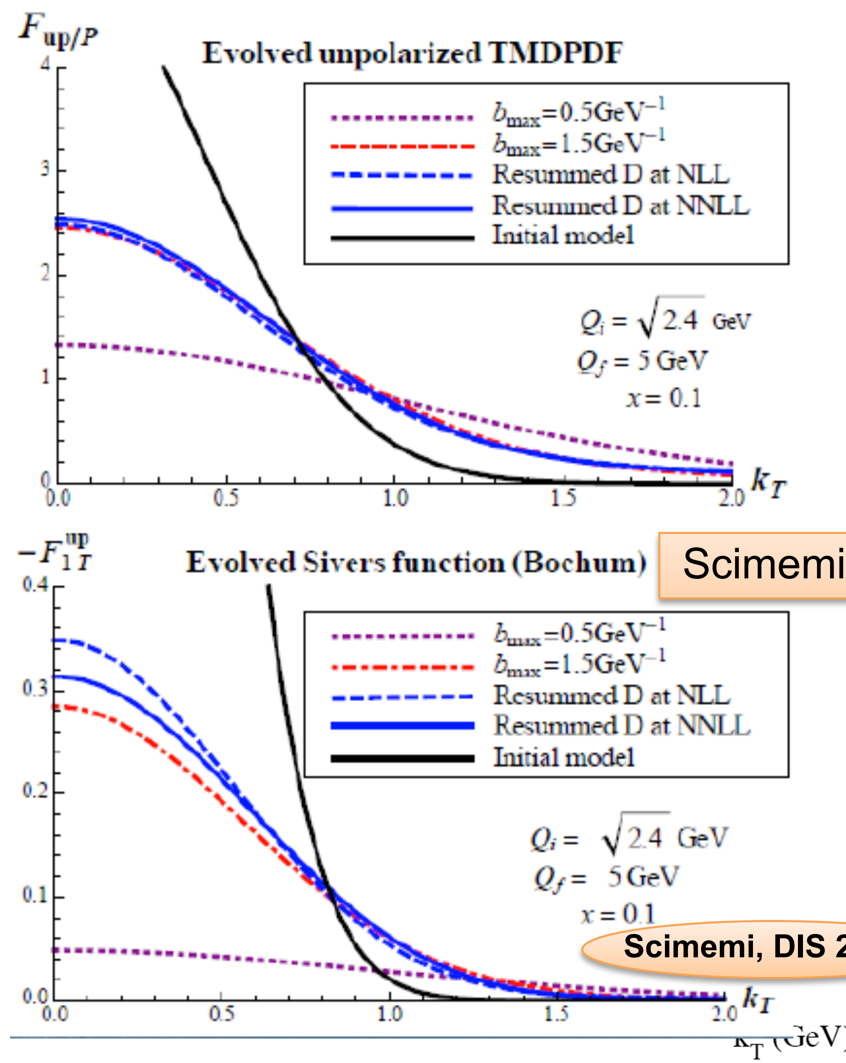
arXiv: 1003.2190





Indication of a k_T and p_T broadening with c.m. energy:

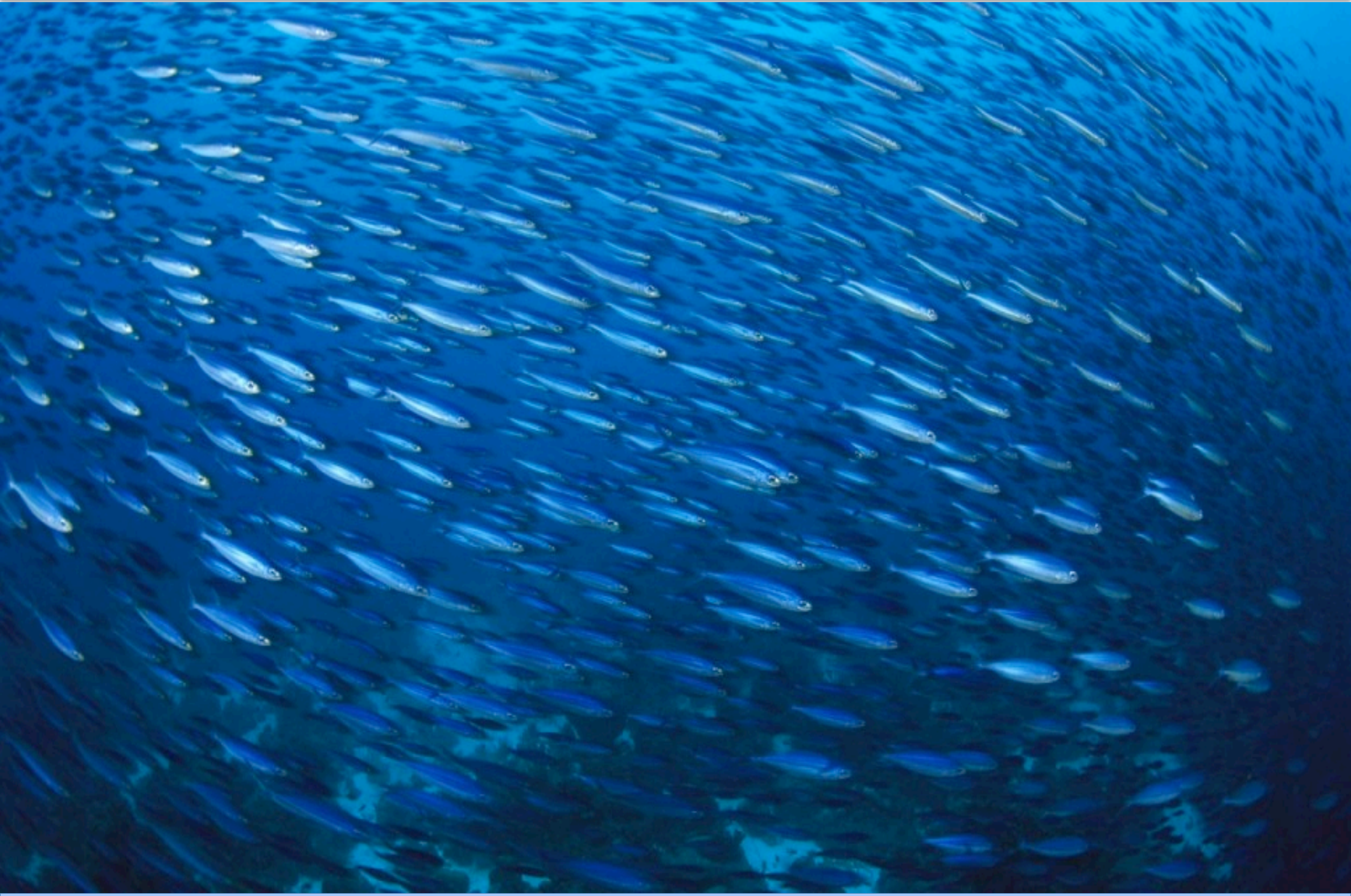
TMD Q^2 evolution



Scimemi talk

Scimemi, DIS 2013

Parton Polarization



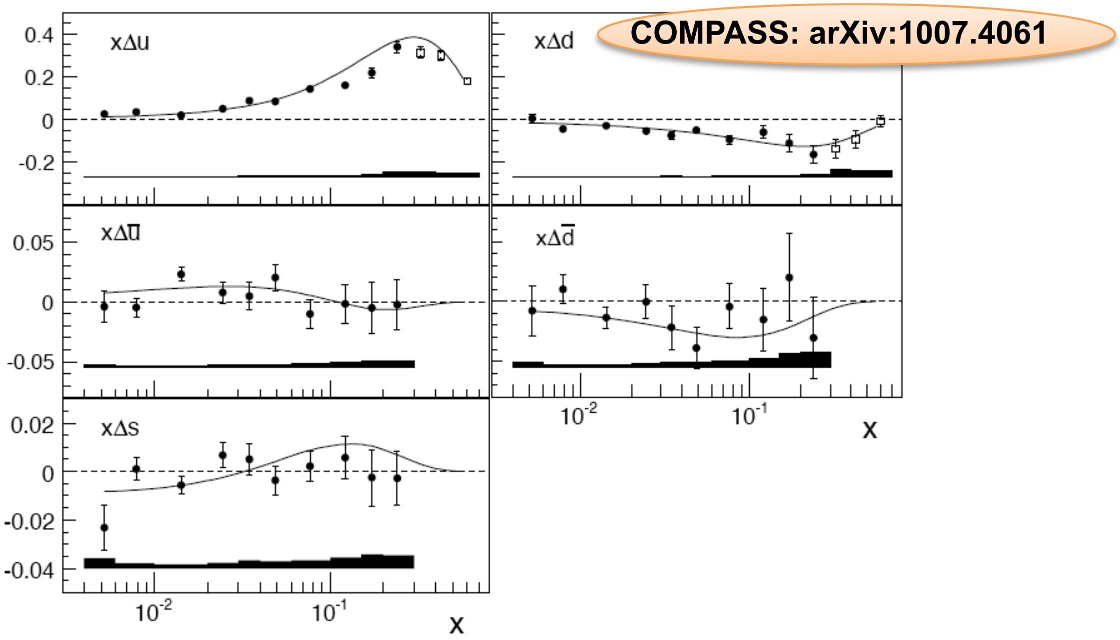
Helicity

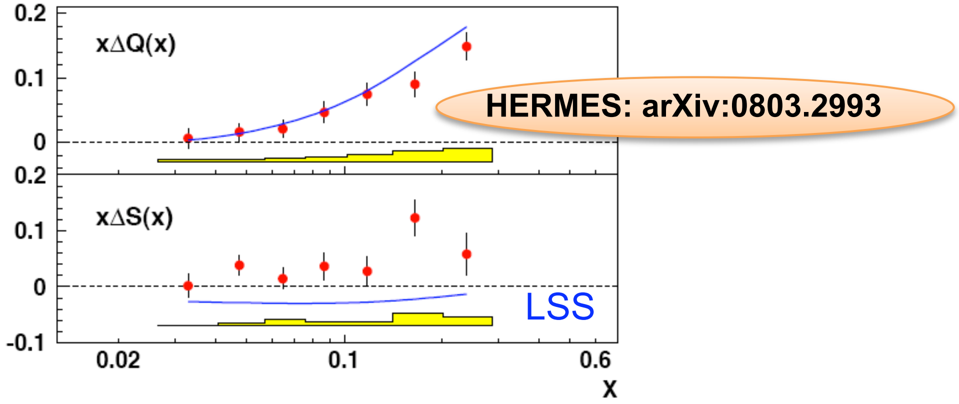
nucleon polarisation

N/q	U	L	T
U	f_1 Number Density		$h_1^{\perp}$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^{\perp}$ Worm-gear
T	$f_{1T}^{\perp}$ Sivers	$g_{1T}^{\perp}$ Worm-gear	h_1 Transversity $h_{1T}^{\perp}$ Pretzelosity

(The First Puzzle)

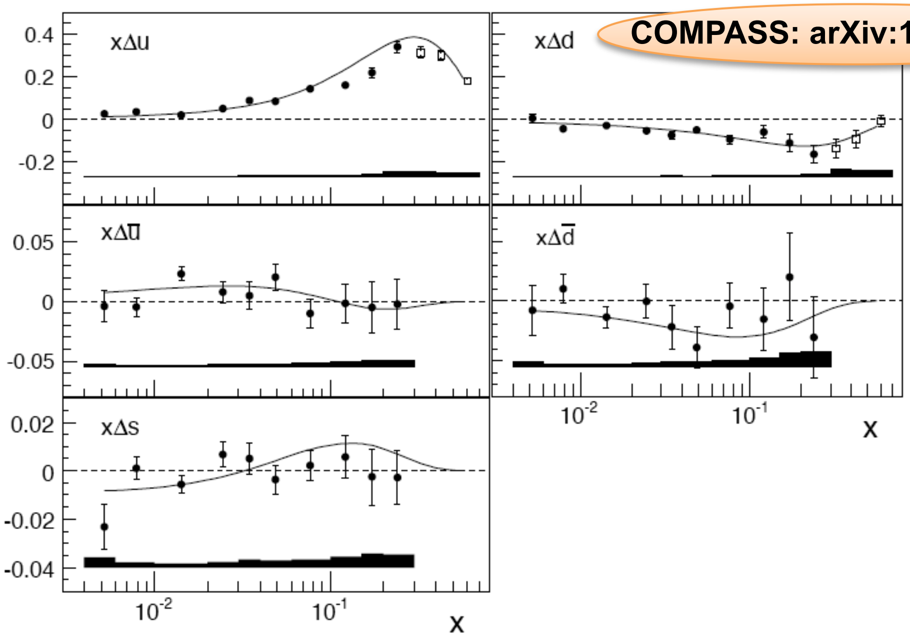
Parton Helicity from SIDIS



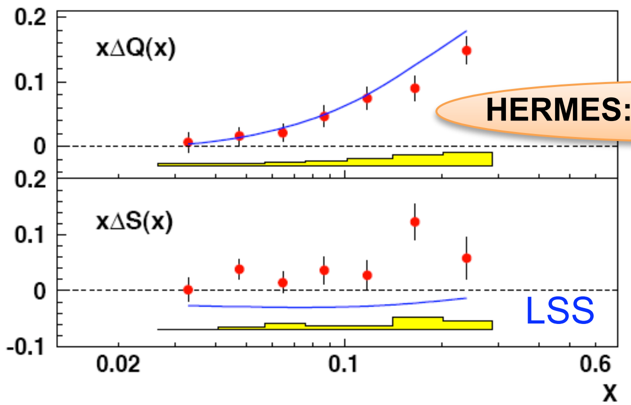


Parton Helicity from SIDIS

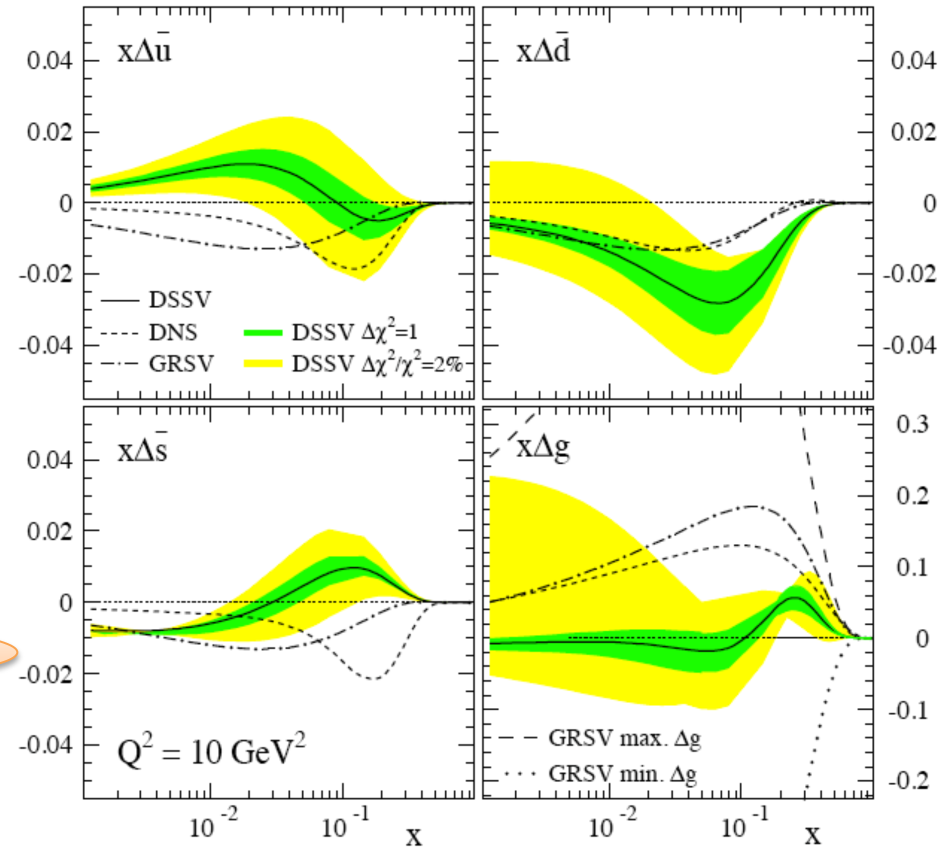
COMPASS: arXiv:1007.4061



HERMES: arXiv:0803.2993



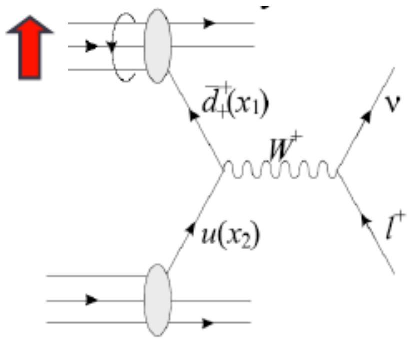
DSSV: arXiv:0804.0422



NNPDF: arXiv:1206.0201

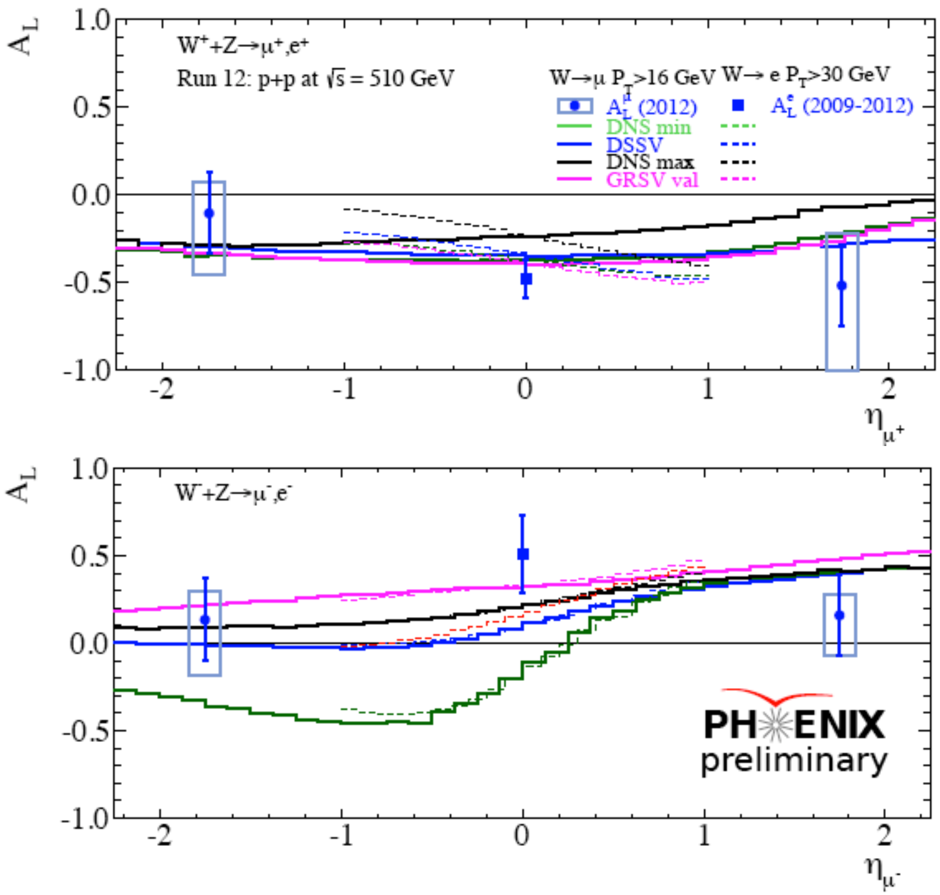
	NNPDFpol1.0	DSSV08 [5]	BB10 [2]	LSS10 [4]	AAC08 [3]
$\Delta\Sigma(Q^2)$	0.31 ± 0.10	0.25 ± 0.02	0.19 ± 0.08	0.21 ± 0.03	0.24 ± 0.07
$\Delta g(Q^2)$	-0.2 ± 1.4	-0.10 ± 0.16	0.46 ± 0.43	0.32 ± 0.19	0.63 ± 0.81

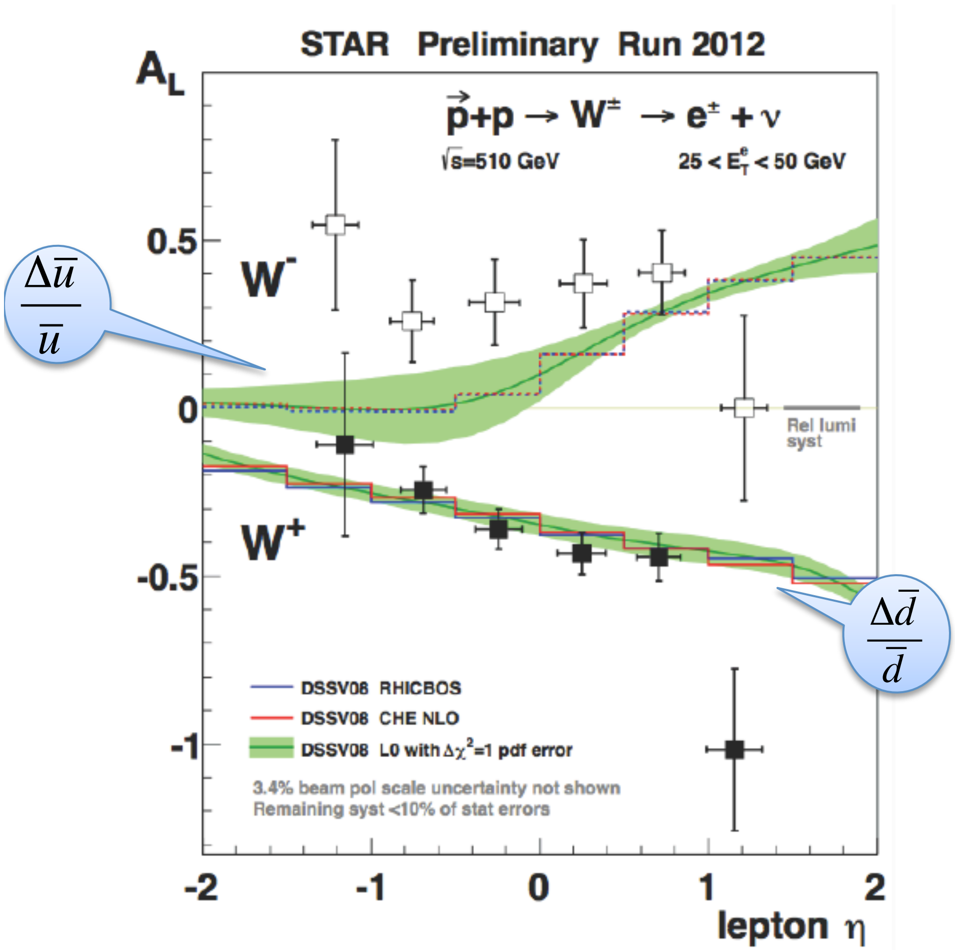
Parton Helicity from W



Charge + Rapidity

Flavor

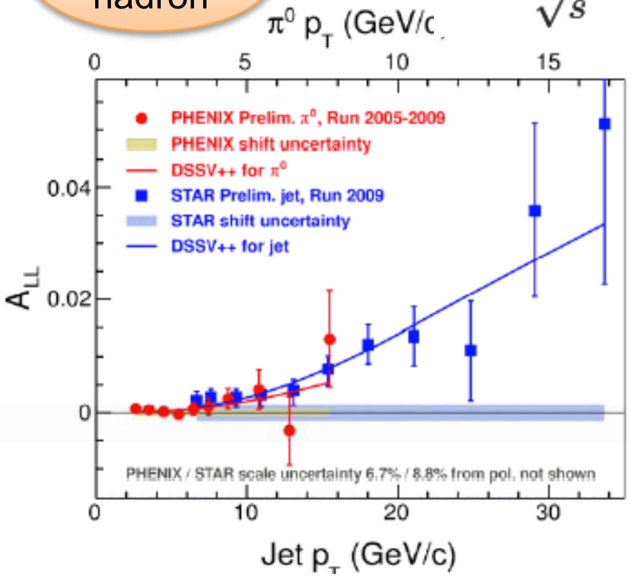




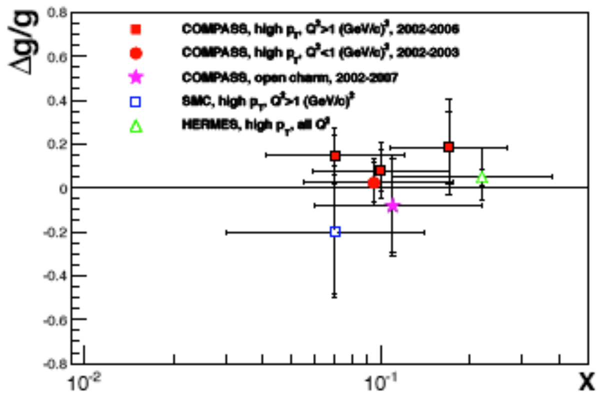
Gluon Helicity

pp inclusive hadron

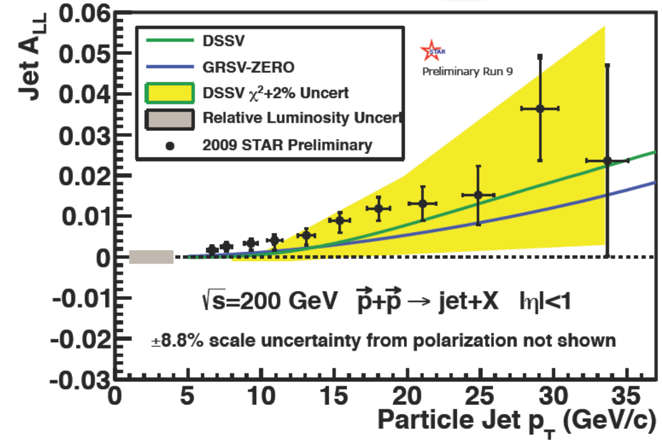
$$x \sim \frac{2p_T}{\sqrt{s}}$$



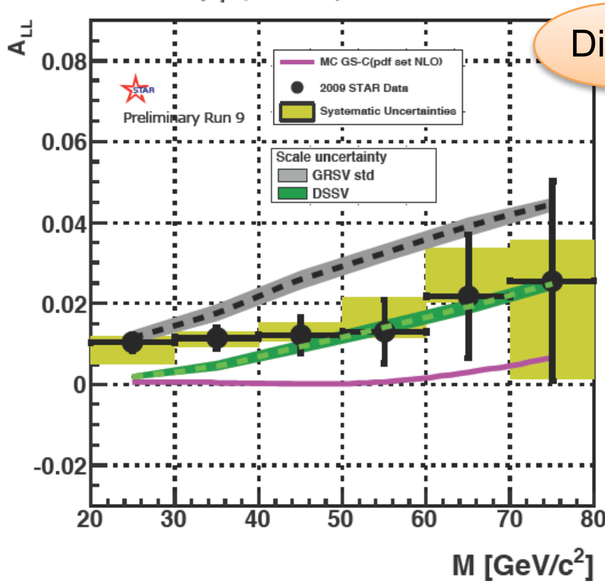
SIDIS high-p_T & open charm



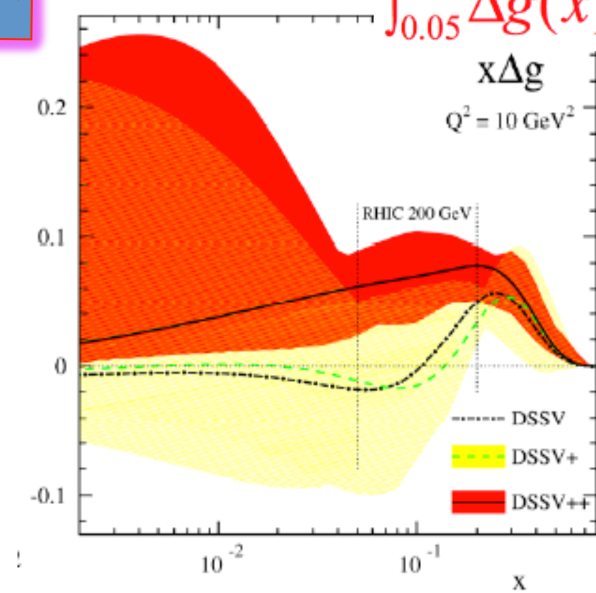
Inclusive Jet in pp



Di-Jet

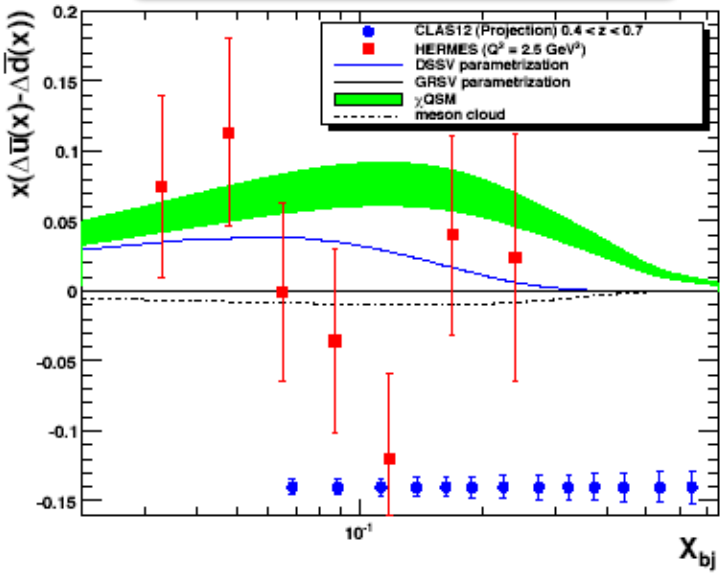


$$\int_{0.05}^{0.2} \Delta g(x)\, dx = 0.1 \pm^{0.06}_{0.07}$$

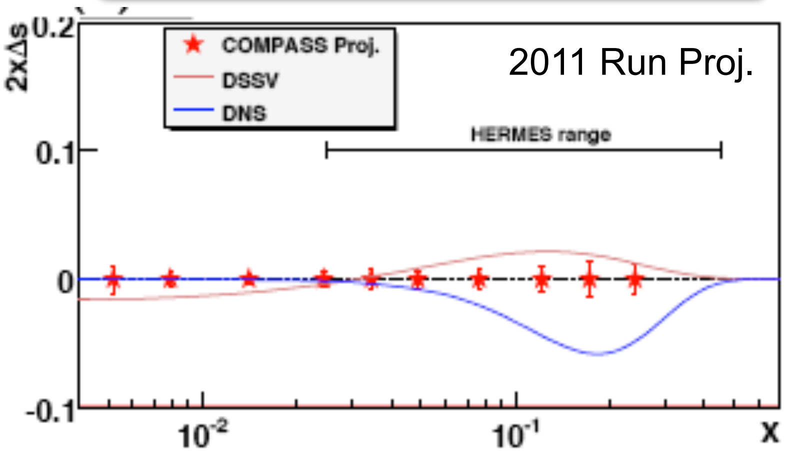


Zhang talk

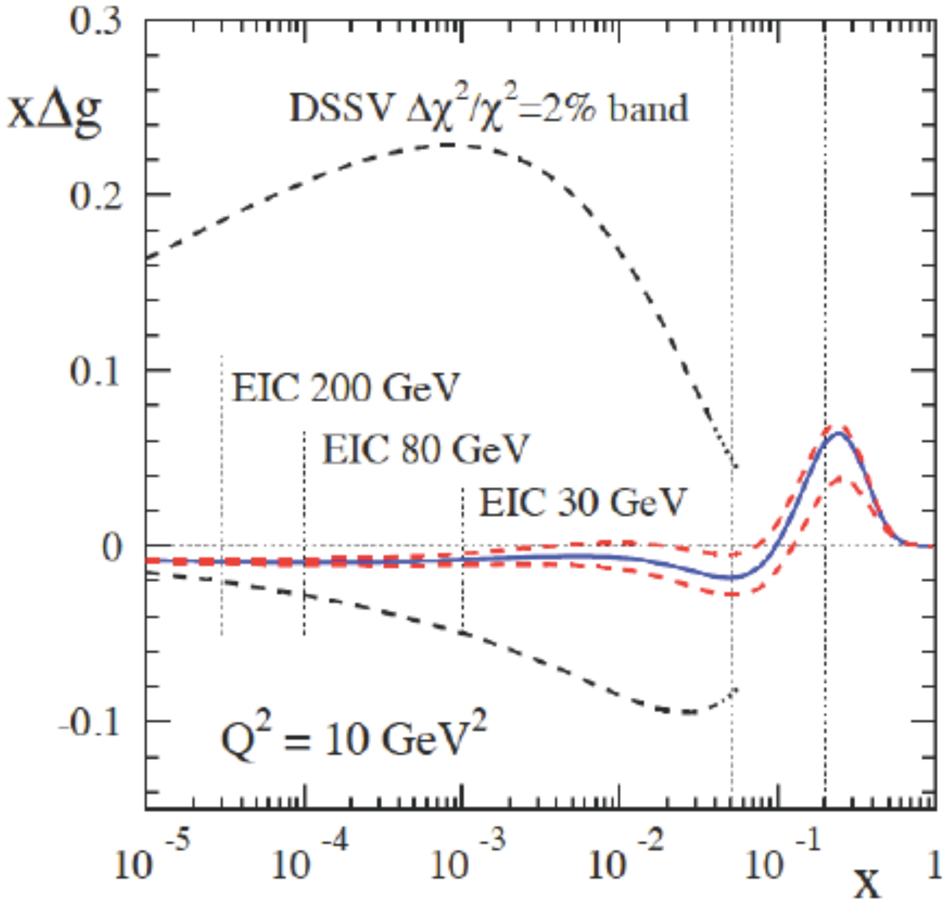
Valence Δq @ CLAS12



Middle-sea Δq @ COMPASS



Sea Δq and ΔG @ EIC

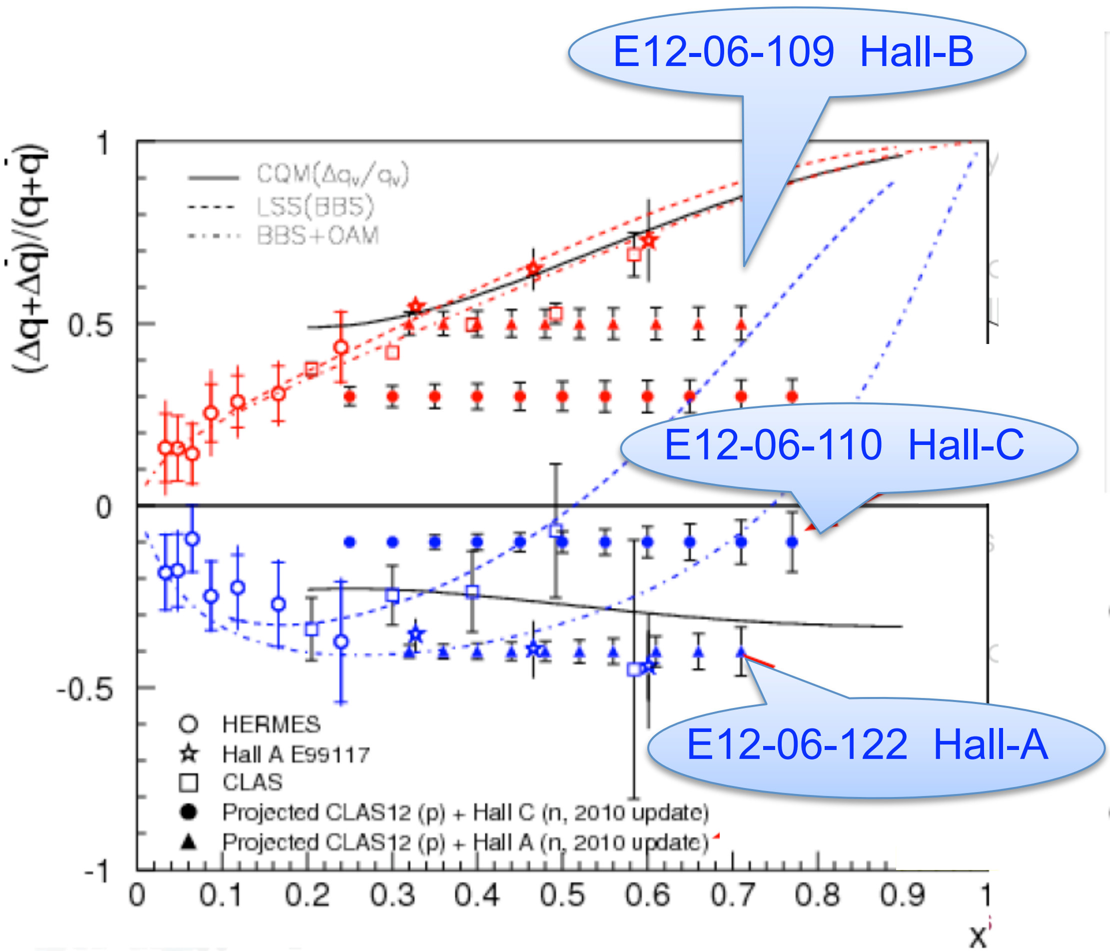


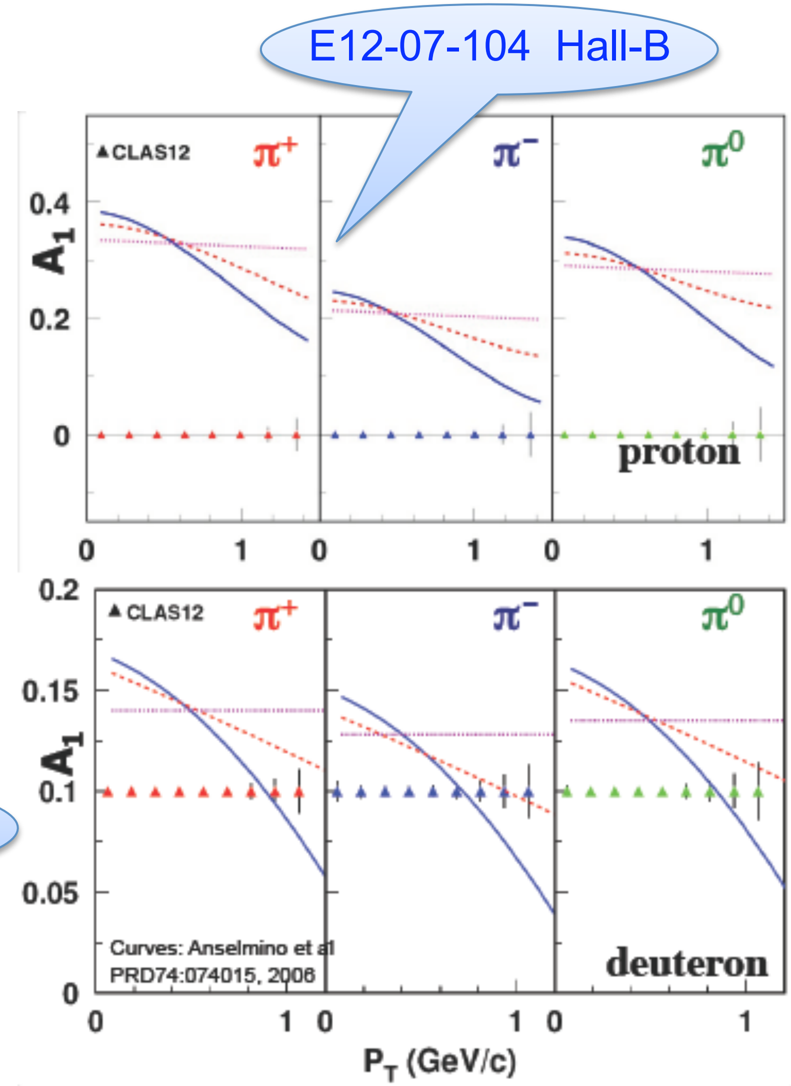
Quark Helicity

Quark helicity at high-x is sensitive to orbital angular momentum.

Cisbani talk

Transverse momentum dependence of quark helicity vs number density





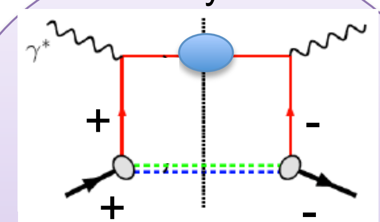
Point Transverse

Transversity

nucleon polarisation

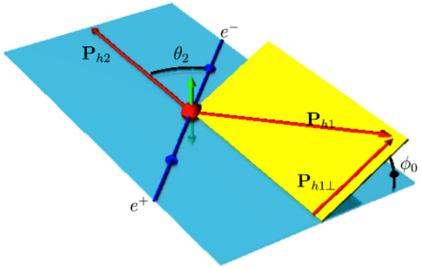
N/q	U	L	T
U	f_1 - *Number Density*		$h_1^\perp$ - *Boer-Mulders*
L		g_1 - *Helicity*	$h_{1L}^\perp$ - *Worm-gear*
T	$f_{1T}^\perp$ - *Sivers*	$g_{1T}^\perp$ - *Worm-gear*	h_1 - *Transversity* $h_{1T}^\perp$ - *Pretzelosity*

Chirally-odd

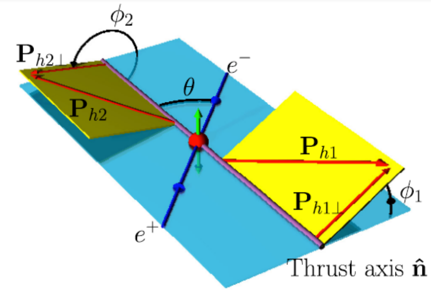


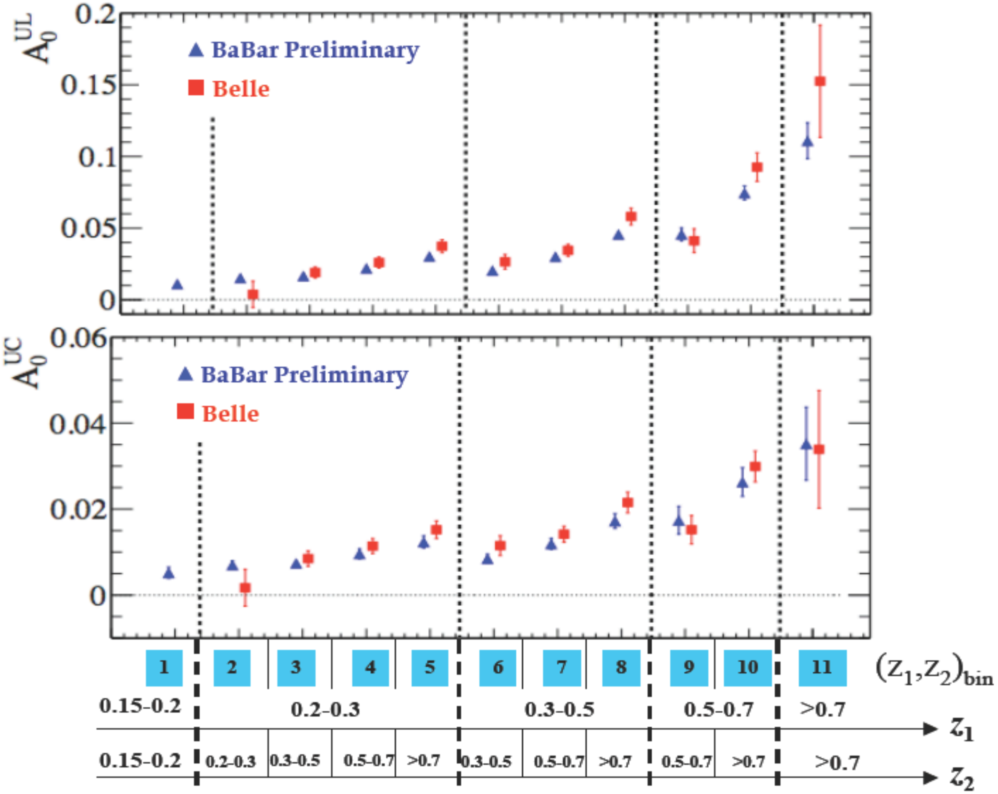
First evidence: 2005

(The Collinear Missing Piece)

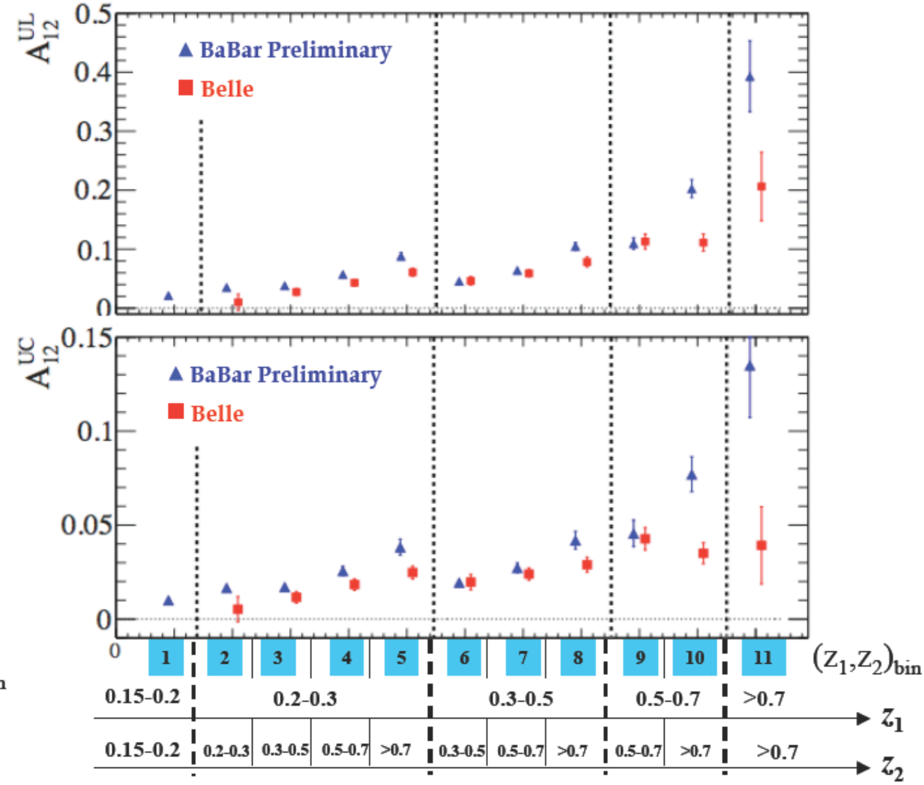


COLLINS SIGNALs





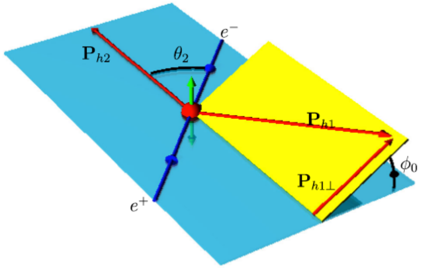
Garzia, DIS 2013



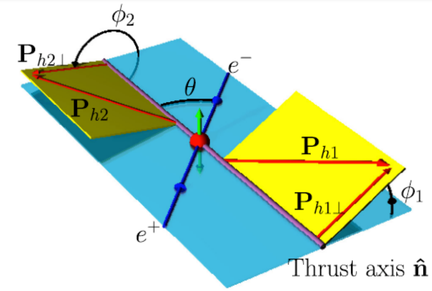
BELLE, PRD 86 (2012) 039905(E)

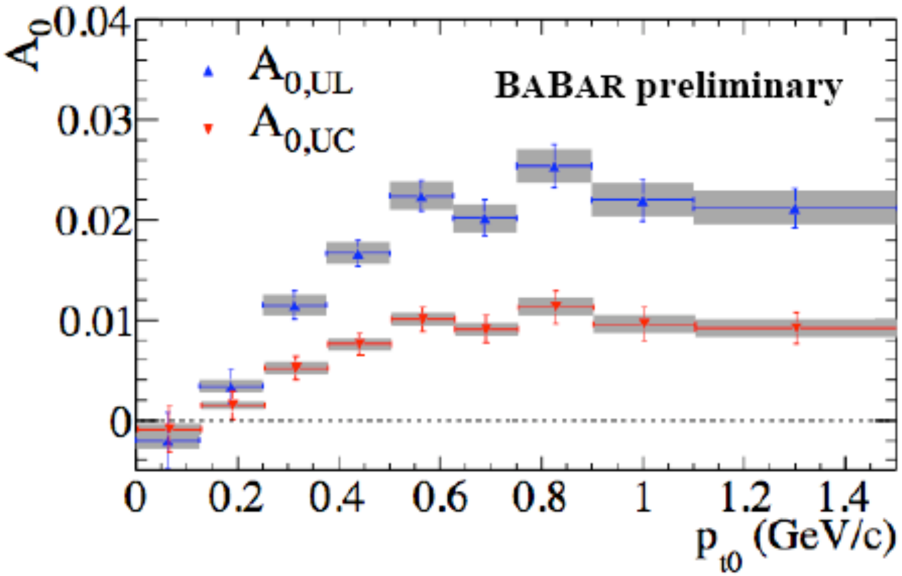
Fragmentation @ e+e- Colliders

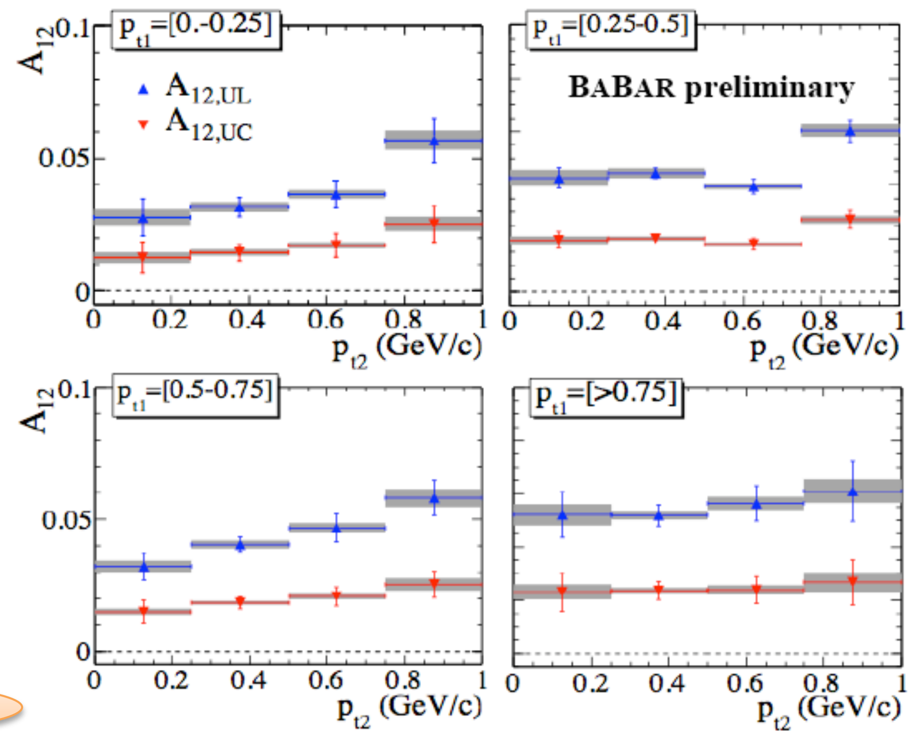
$H_1^\perp \otimes H_1^\perp$



COLLINS SIGNALs







Garzia, DIS 2013

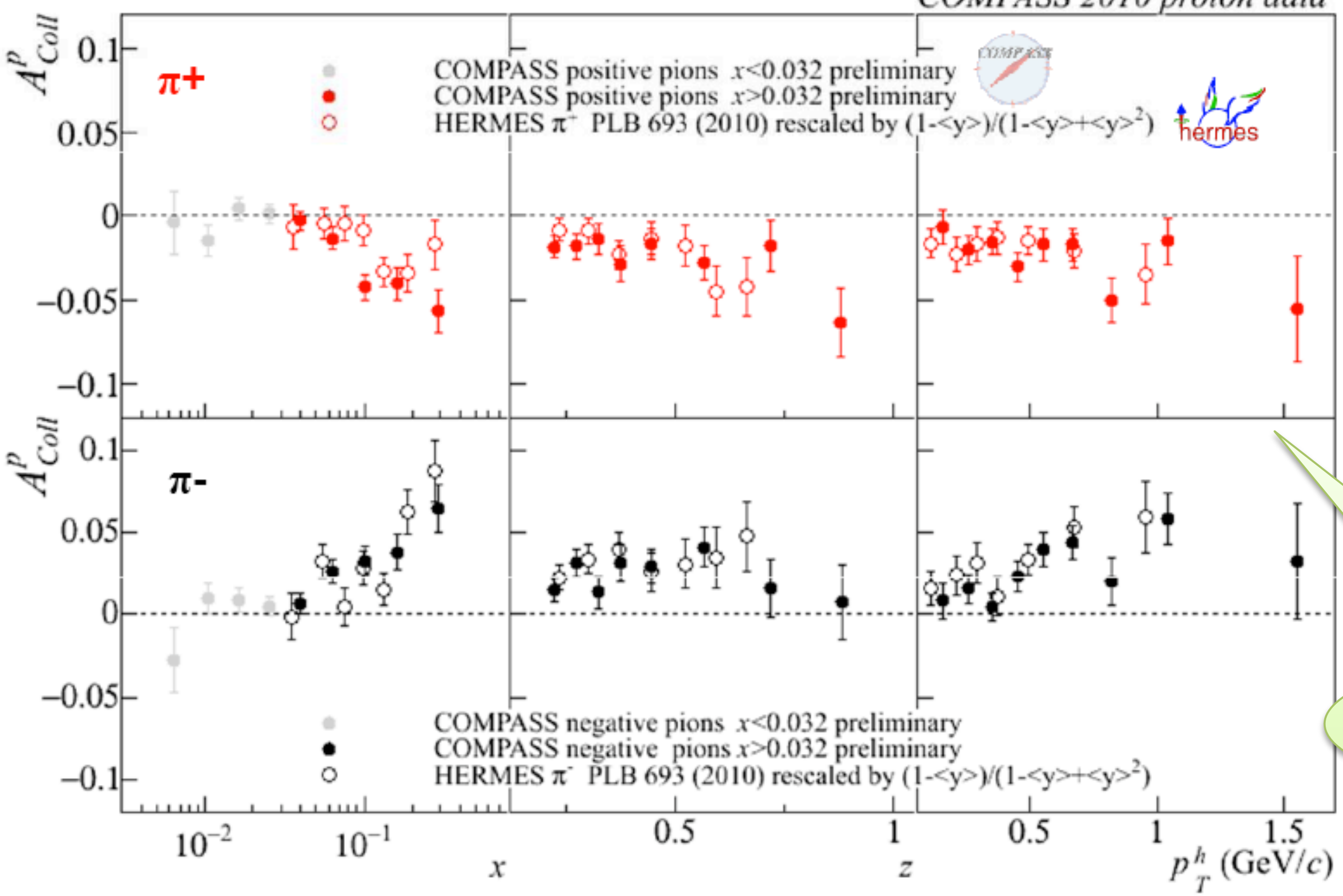
$h_1 \otimes H_1^{\perp}$

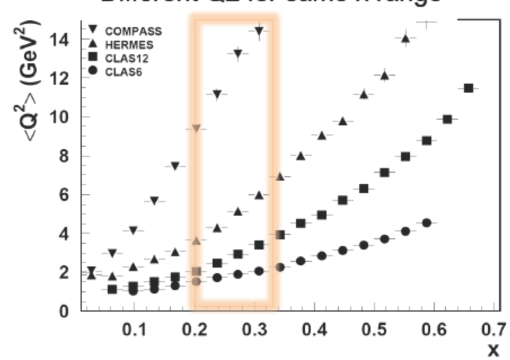
CLEAR NON ZERO SIGNALS !

$$A_{UT}^{\sin(\phi+\phi_S)} \propto \frac{\sum_q e_q^2 h_1^q(x,p_T^2) \otimes_\omega H_1^{q,\perp}(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,k_T^2)}$$

Consistent results at different Q^2
→ No higher twits
→ No strong evolution

COMPASS 2010 proton data





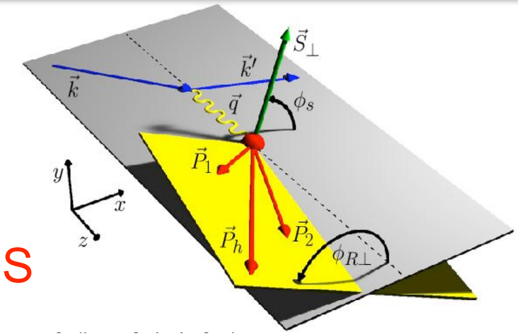
Bressan talk

Opposite sign for pions reveals Collins features

Two hadron asymmetries

$h_1 \otimes H_1^{\triangleleft}$

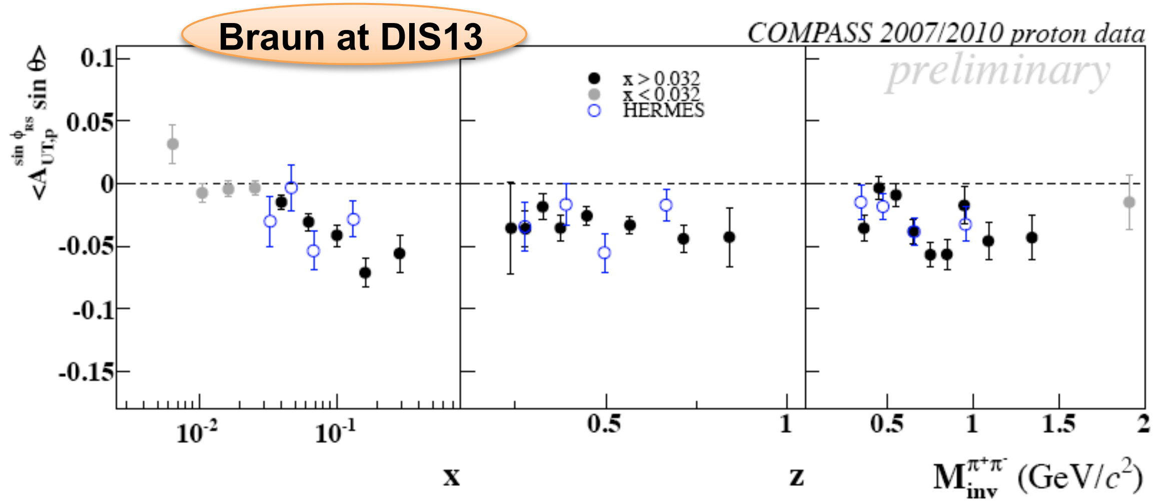
SIDIS



COMPASS, arXiv: 1202.6150

HERMES, arXiv: 0803.2367

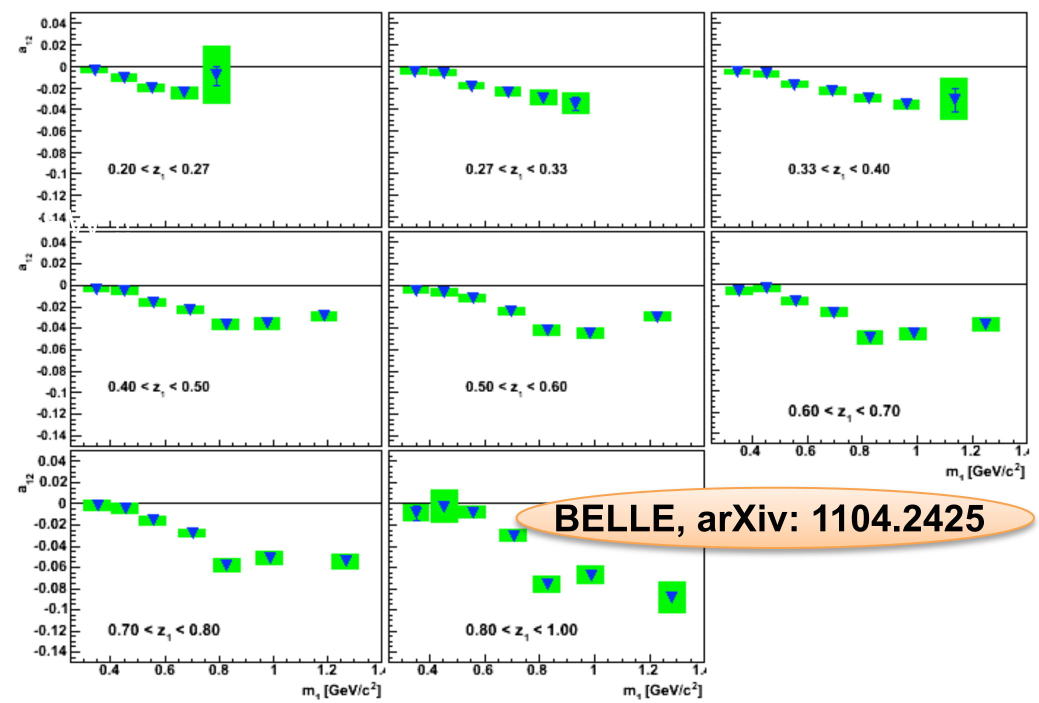
Braun at DIS13



$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta} \propto \frac{\sum_q e_q^2 h_1(x,Q^2) H_1^{\triangleleft}(z,M_h^2,Q^2)}{\sum_q e_q^2 f_1(x,Q^2) D_1^{\triangleleft}(z,M_h^2,Q^2)}$$

- Survives P_h integration
- Collinear factorization (simple product)
- DGLAP volution
- Universality
- Issue: unknown pp-terms in PW expansion

Belle



BELLE, arXiv: 1104.2425

Transversity Signals

$lp \to l' hX$

$e^+e^- \to h_1 h_2 X$

$$A_{UT}^{\sin(\phi+\phi_S)} \propto h_1(x) \otimes H_1^{\perp q}(z)$$

$ld \to l' hX$

$lp \to l' \pi^+ \pi^- X$

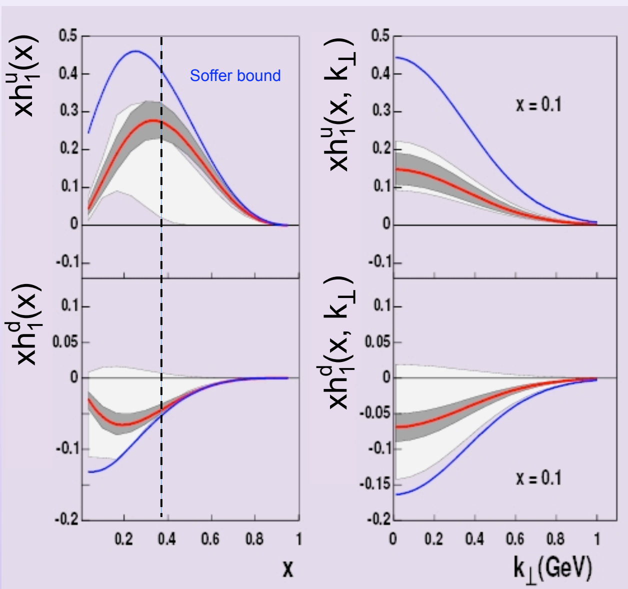
$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)} \propto \sin\vartheta\, h_1(x) \otimes H_1^{\sphericalangle q}(z)$$

Existing data limited to x < 0.3

FF evol.. from high energy colliders

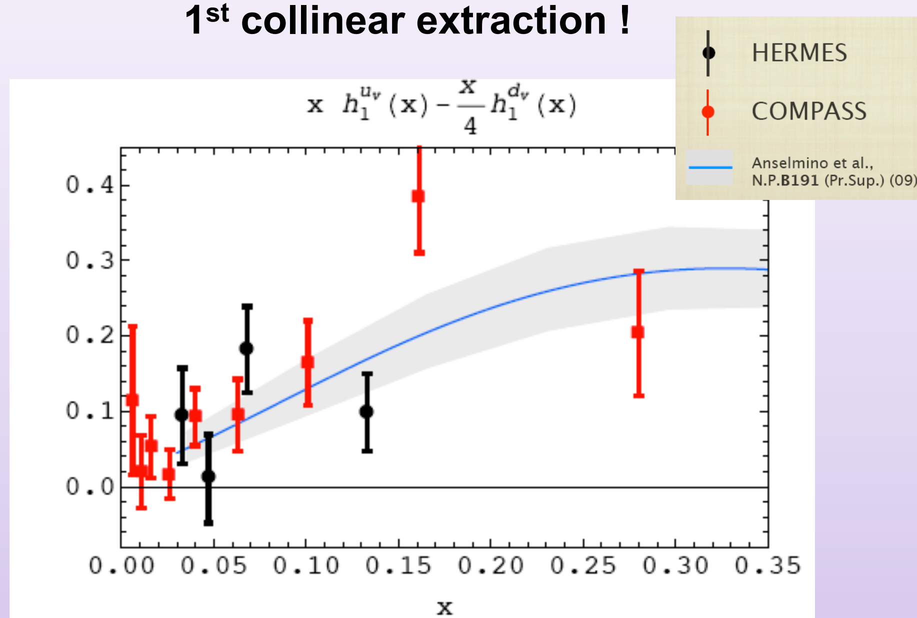
Braun talk

1st extraction of Transversity!



Anselmino ++ arXiv: 0701006

1st collinear extraction !



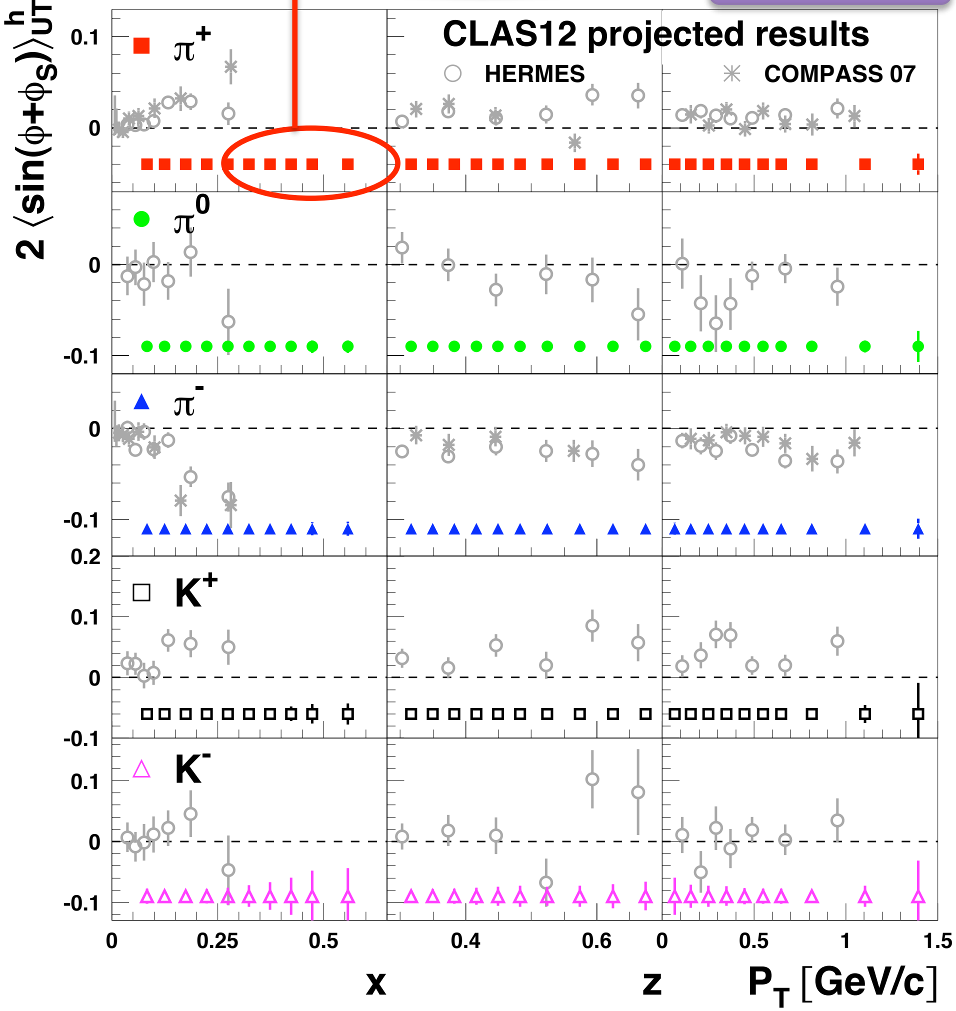
Bacchetta ++ arXiv: 1104.3855

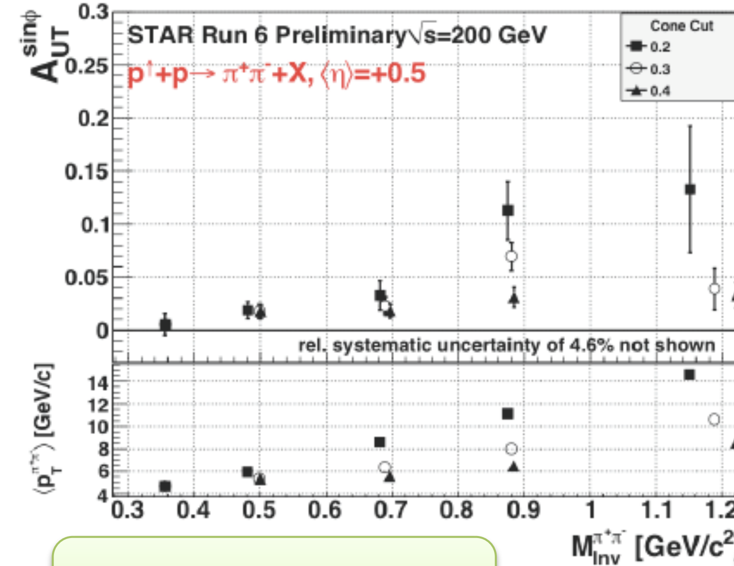
Transversity @ JLab12 2014+

Large x important to constrain the tensor charge

C12-11-111 Hall-B

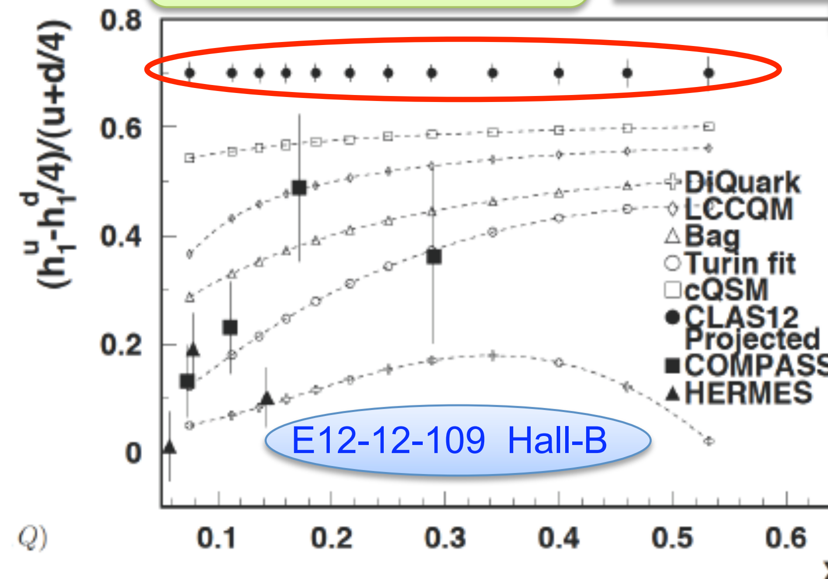
Proton





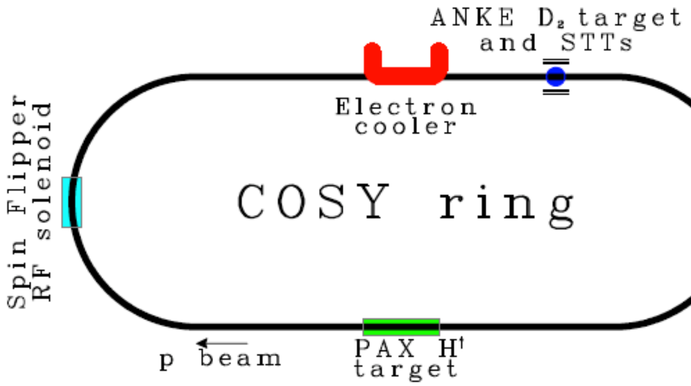
Di-hadron channel for h_1
Test of TMDs extraction

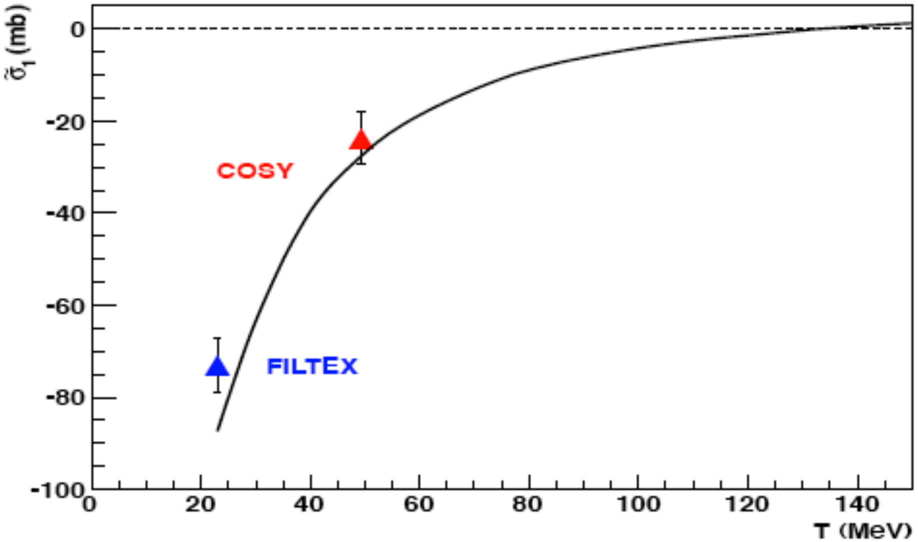
Pereira talk



Polarized Drell-Yan 2018+

Spin-filtering with protons:





Anti-proton beam @ FAIR

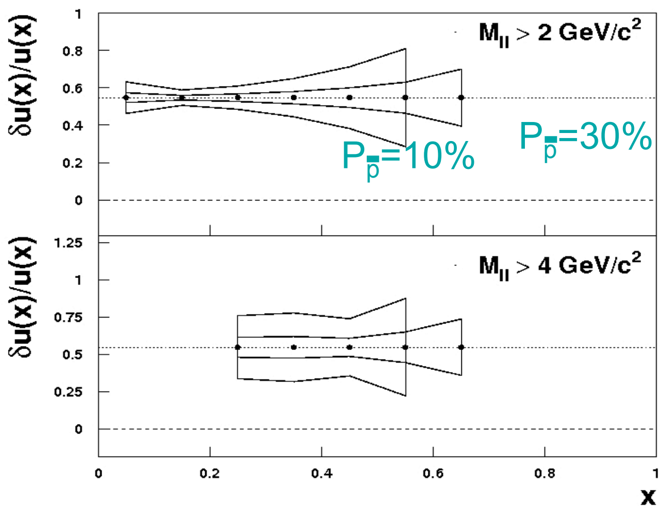
PANDA: unpolarized target (s=30 GeV^2)

PAX: polarized collider (s=200 GeV^2)

$$A_{TT} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} \approx \hat{a}_{TT} \frac{h_{1u}(x_1)\ h_{1u}(x_2)}{u(x_1)\ u(x_2)}$$

- u-dominance
- $|h_{1u}|>|h_{1d}|$

1year run: 10 % precision on the $h_{1u}(x)$ in the valence region



Angular-Momentum Effects

Pretzelosity

nucleon polarisation

N/q	U	L	T
U	f_1 Number Density		$h_1^\perp$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^\perp$ Worm-gear
T	$f_{1T}^\perp$ Sivers	$g_{1T}^\perp$ Worm-gear	h_1 Transversity $h_{1T}^\perp$ Pretzelosity

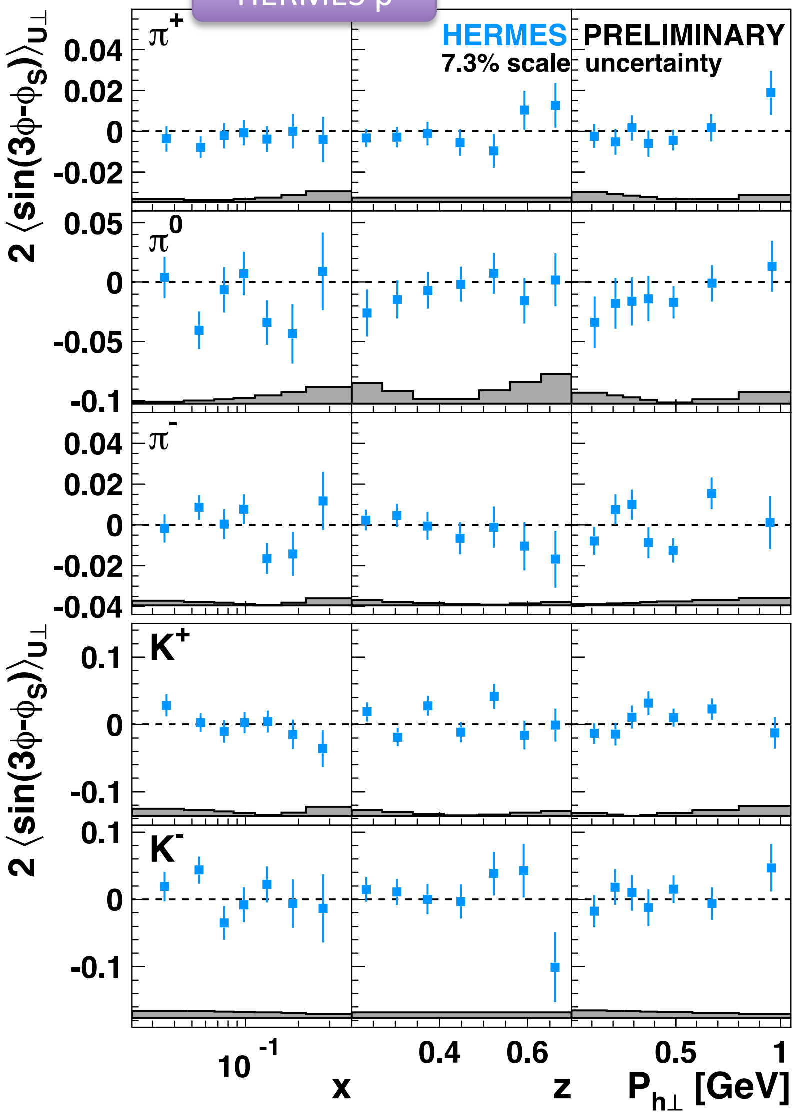
Sensitive to the D-wave component and the non spherical shape of the nucleon

(The D-Wave)

The Pretzelosity

$h_{1T}^{\perp} \otimes H_1^{\perp}$

HERMES p



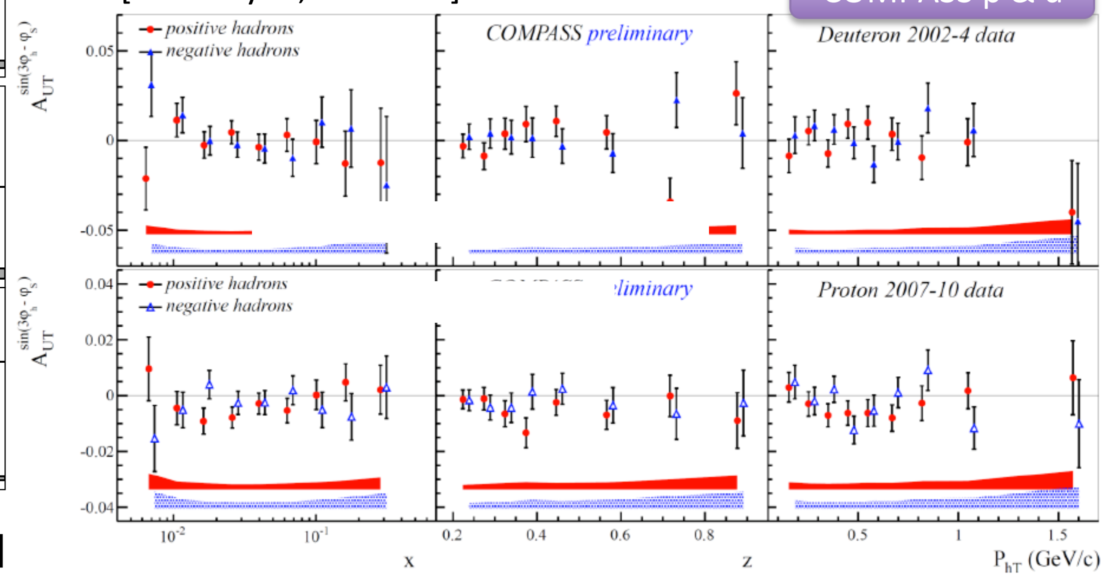
$$h_{1T}^{\perp(1)q}(x) = g_1^q(x) - h_1^q(x)$$ no-gluon models

$$\left|h_{1T}^{\perp(1)q}(x)\right| + \left|h_1^q(x)\right| \le f_1^q(x)$$ positivity bound

Asymmetry suppressed vs Collins by a factor $\sim \left|P_{h\perp}^2\right|$

[Parsamyan, DIS 2013]

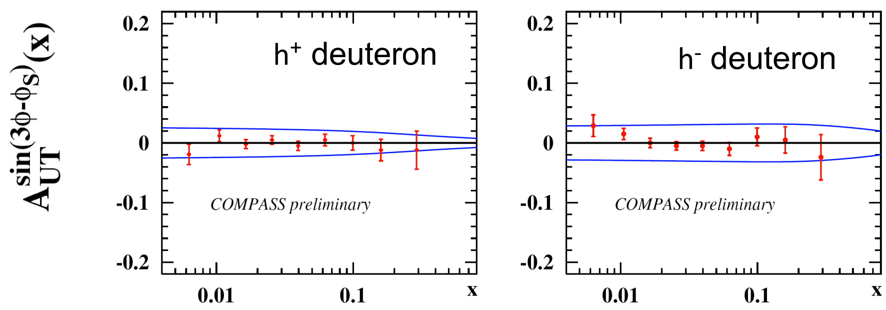
COMPASS p & d



The Pretzelosity

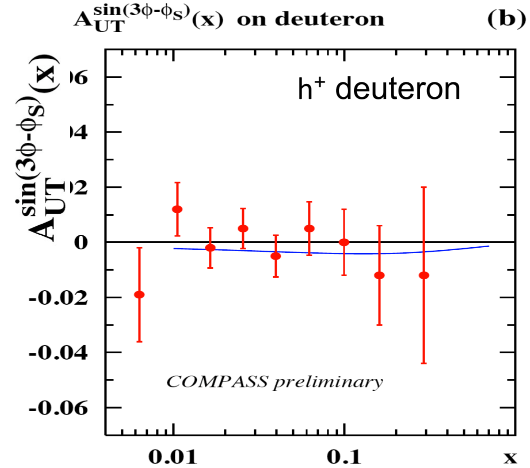
$h_{1T}^{\perp} \otimes H_1^{\perp}$

Statistical power of existing data is not enough to observe significant signals



Positivity bound

Avakian, PRD78



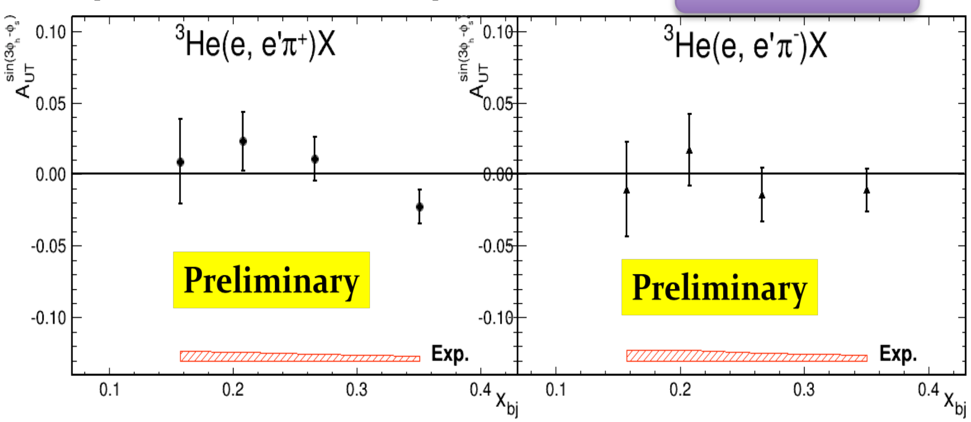
Covariant model

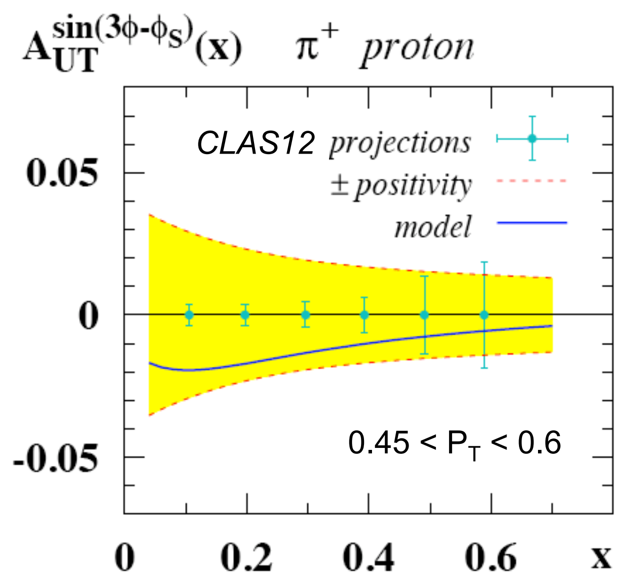
arXiv: 0812.3246

Parsamyan talk

[Chen, QCD Evol. 2013]

Hall-A ^3He





Worm Gear

nucleon polarisation

N/q	U	L	T
U	f_1 Number Density		$h_1^{\perp}$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^{\perp}$ Worm-gear
T	$f_{1T}^{\perp}$ Sivers	$g_{1T}^{\perp}$ Worm-gear	h_1 Transversity $h_{1T}^{\perp}$ Pretzelosity

Proton wave-components with different OAM

The only T-even and chirally-even off-diagonal TMD

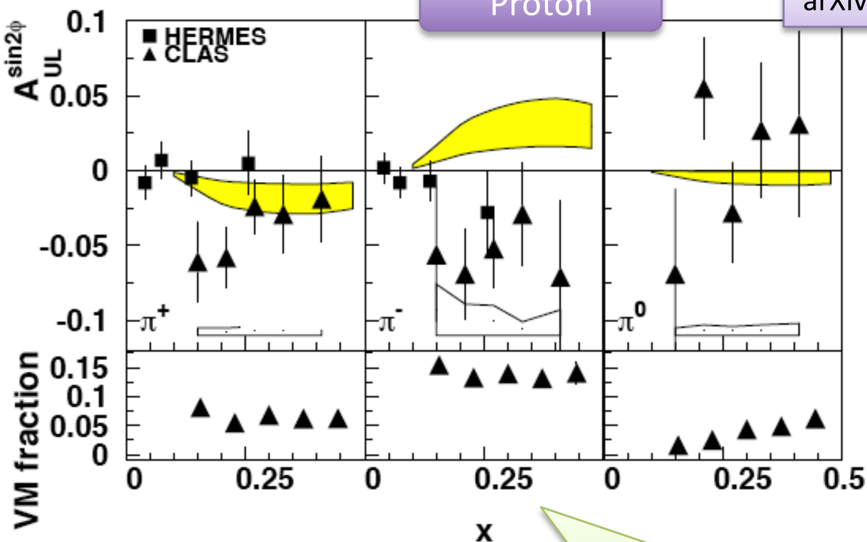
(The Standard OAM Effect)

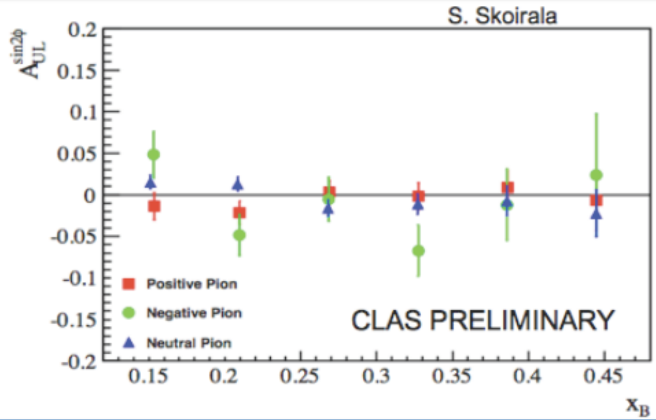
The $A_{UL}^{\sin 2\phi}$ Asymmetry

$h_{1L}^{\perp} \otimes H_1^{\perp}$

Proton

arXiv: 1003.4549





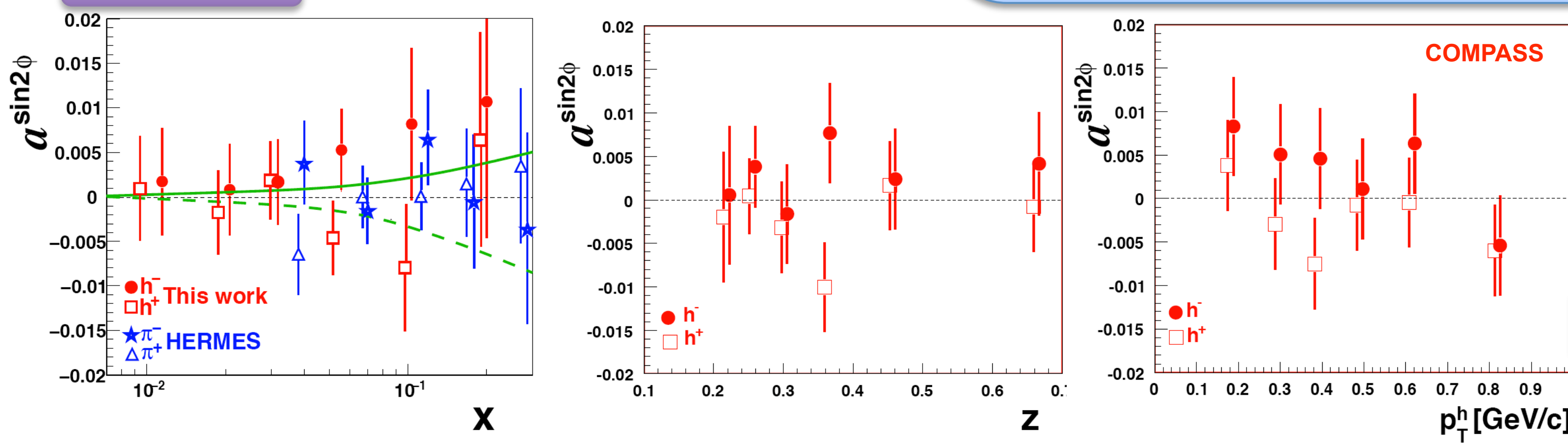
Unexpected pattern needs more statistics to be verified

Statistics not enough to investigate relations supported by many theoretical models:

$$g_{1T}^{q} = -h_{1L}^{\perp q}$$ (model-dependent relation)

$$h_{1L}^{q(1)}(x) \overset{WW}{\approx} -x^2 \int_x^1 \frac{dy}{y} h_1^q(y)$$ (Wandura-Wilczek type approximation)

Deuteron

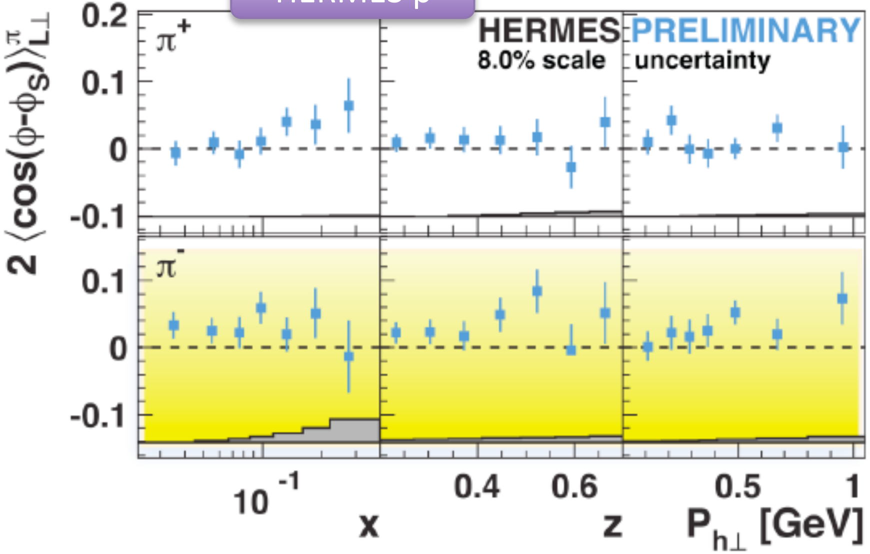


arXiv: 1007.1562

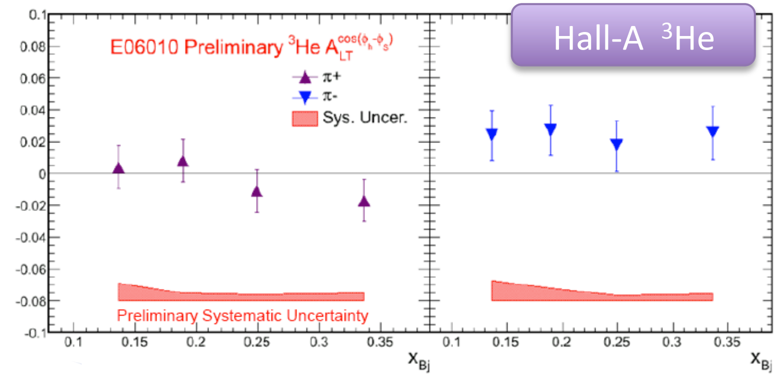
The $A_{LT}^{\cos(\phi-\phi_S)}$ Asymmetry

$g_{1T}^{\perp} \otimes D_1$

HERMES p



Hall-A ^{3}He



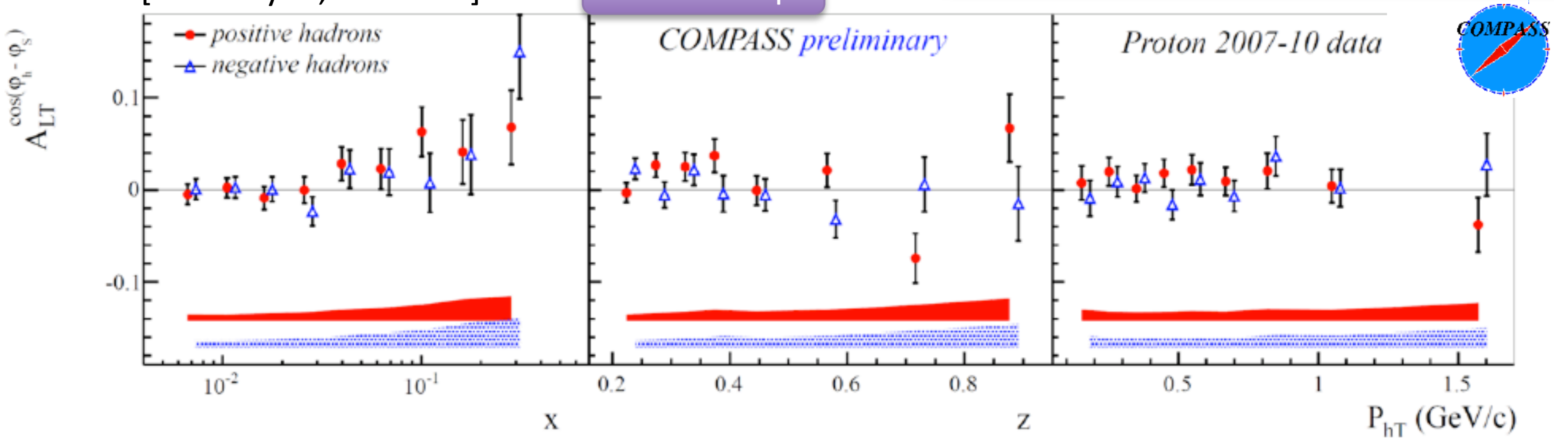
First evidences found by the experiments
Statistics not enough to investigate relations supported by many theoretical models:

$$g_{1T}^{q} = -h_{1L}^{\perp q}$$ (model-dependent relation)

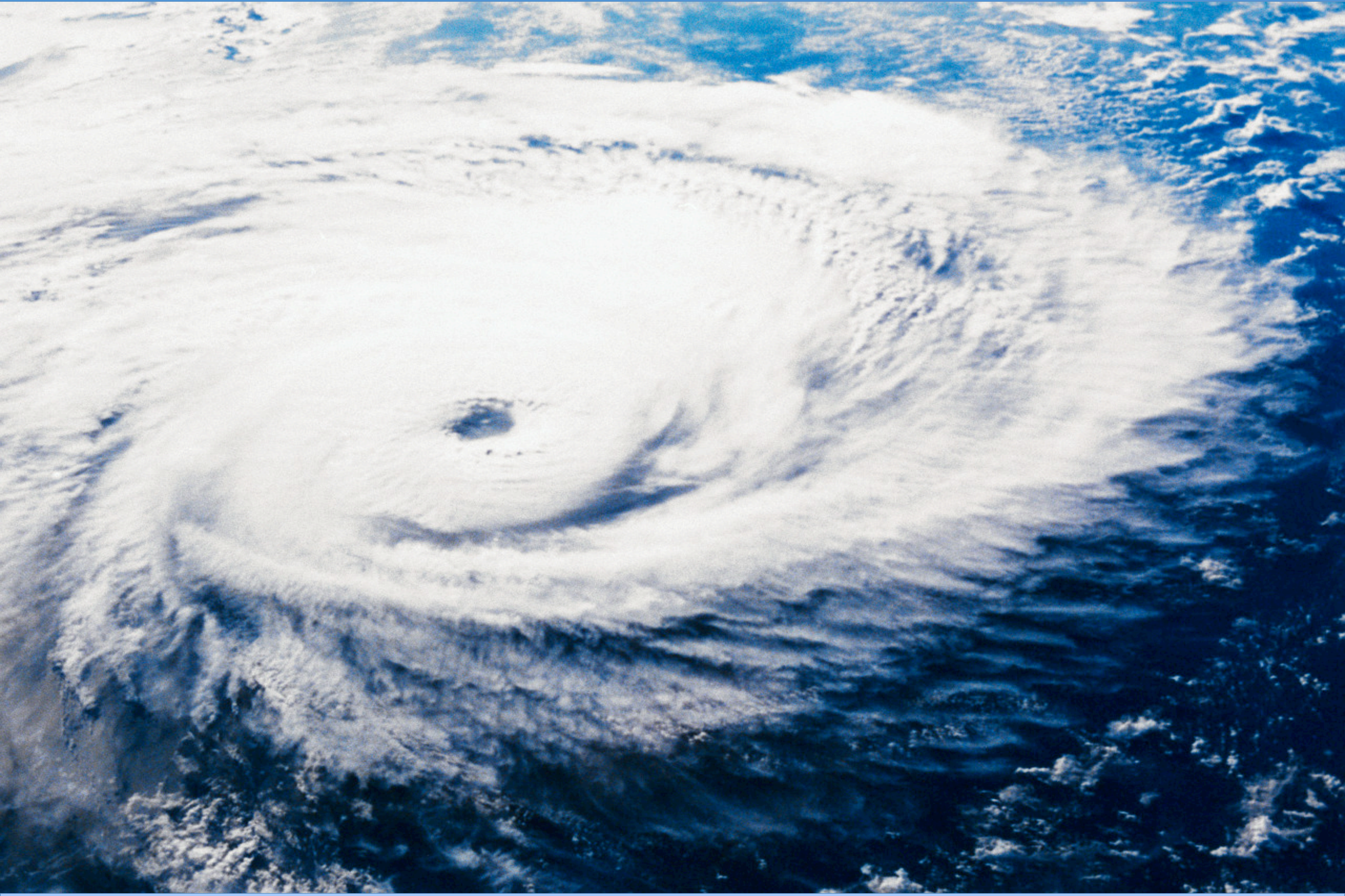
$$g_{1T}^{q(1)}(x) \overset{WW-type}{\approx} x \int_x^1 \frac{dy}{y} g_1^q(y)$$ (Wandura-Wilczek type approximation)

[Parsamyan, DIS 2013]

COMPASS p



Spin-Orbit Effects

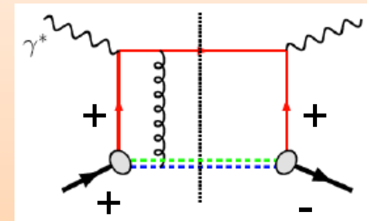


Sivers

nucleon polarisation

N/q	U	L	T
U	f_1 Number Density		$h_1^\perp$ Boer-Mulders
L		g_1 Helic	Worm-gear
T	$f_{1T}^\perp$ Sivers	$g_{1T}^\perp$ Worm-gear	h_1 Transversity $h_{1T}^\perp$ Pretzelosity

Naïve-T-odd
Non-trivial gauge link



Process dependence

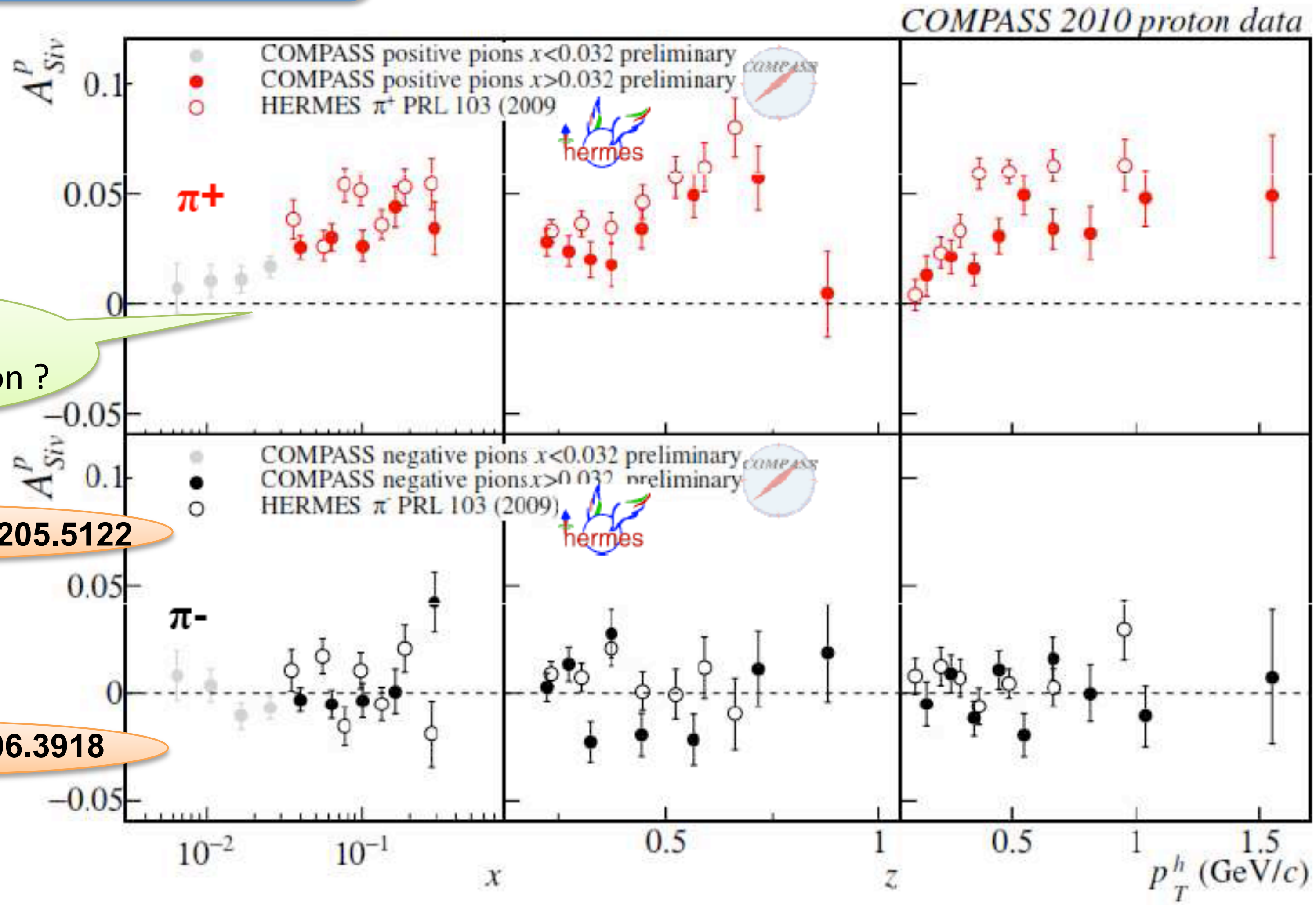
(The TMD Challenge)

The Sivers signals

$f_{1T}^{\perp} \otimes D_1$

$$A_{UT}^{\sin(\phi-\phi_S)} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,p_T^2) \otimes_\omega D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,k_T^2)}$$

CLEAR NON ZERO SIGNALS !



Systematic shift:
Sivers Q^2 evolution ?

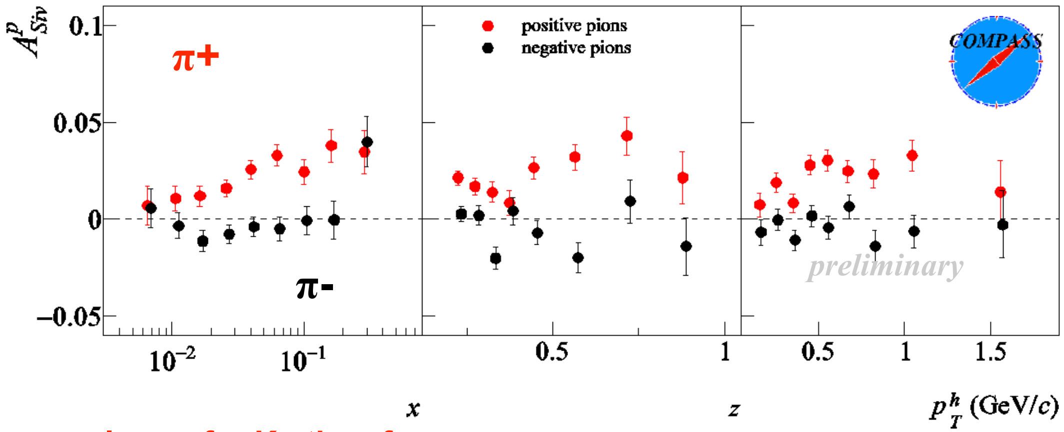
COMPASS, arXiv: 1205.5122

HERMES, arXiv: 0906.3918

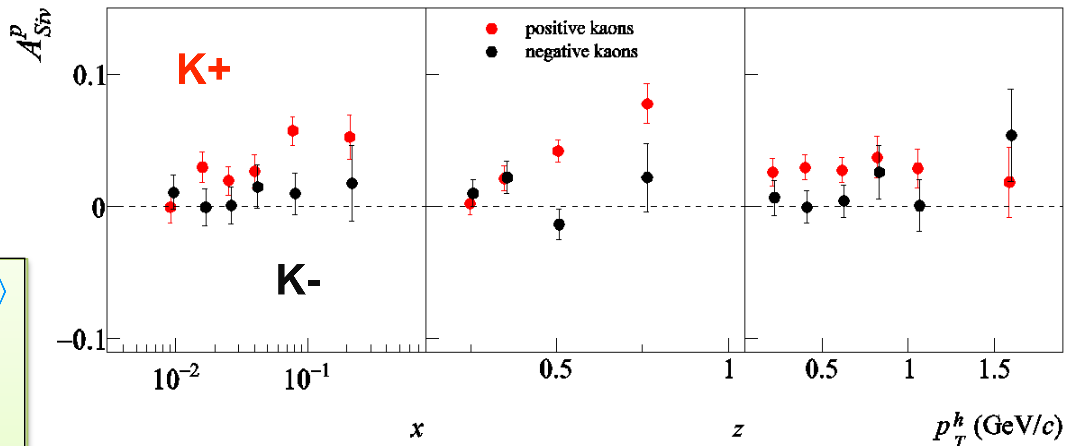
The Kaon Sivers signals

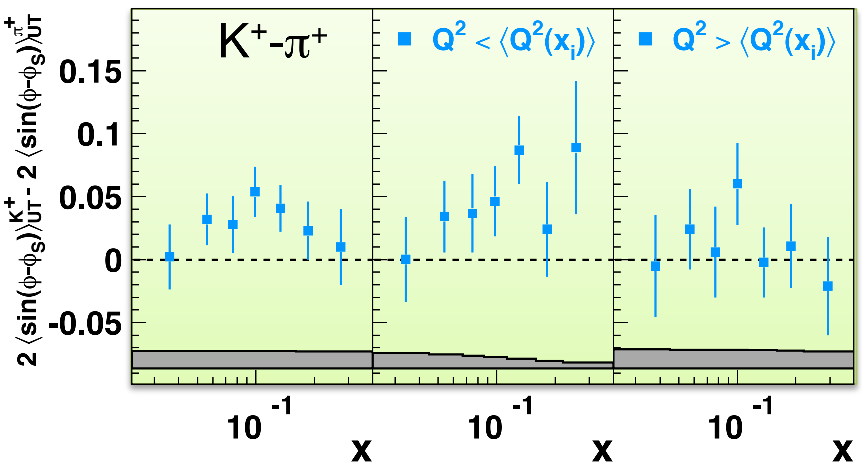
$f_{1T}^{\perp} \otimes D_1$

combined 2007 – 2010 results



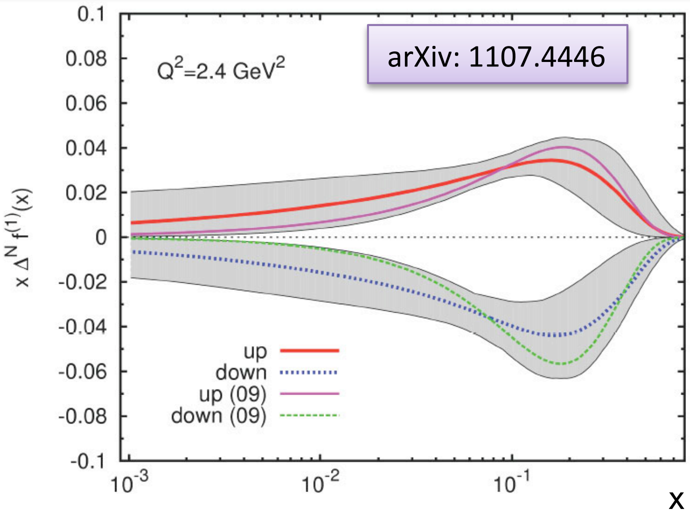
larger for K+ than for π+





The Sivers challenges - I

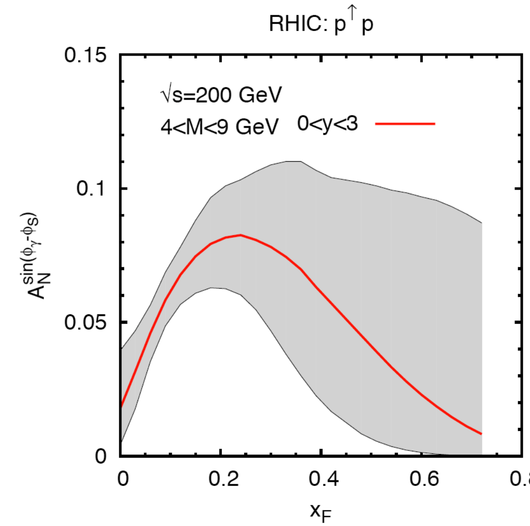
$f_{1T}^{\perp} \otimes D_1$



From SIDIS to Drell-Yan:

Sign change as a crucial test of TMDs factorization

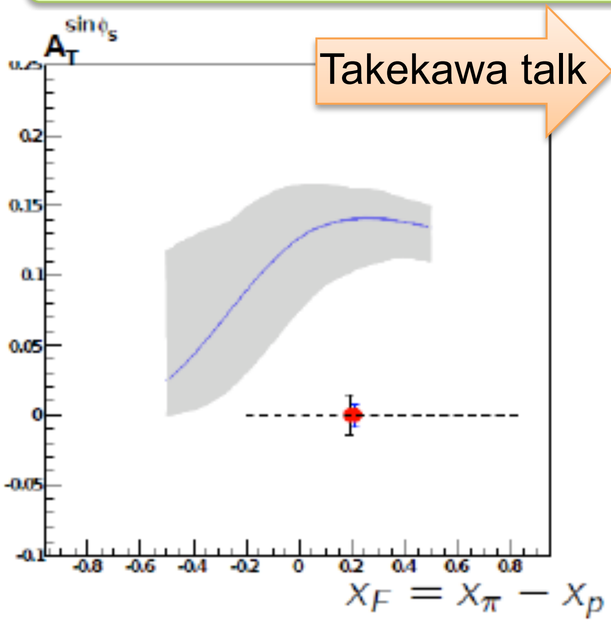
arXiv: 0901.3078

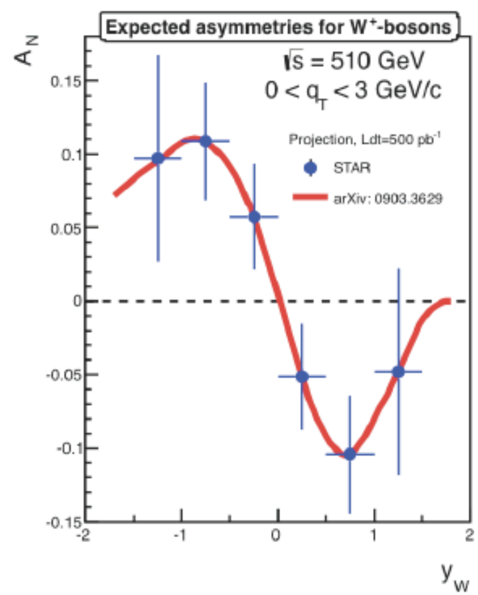


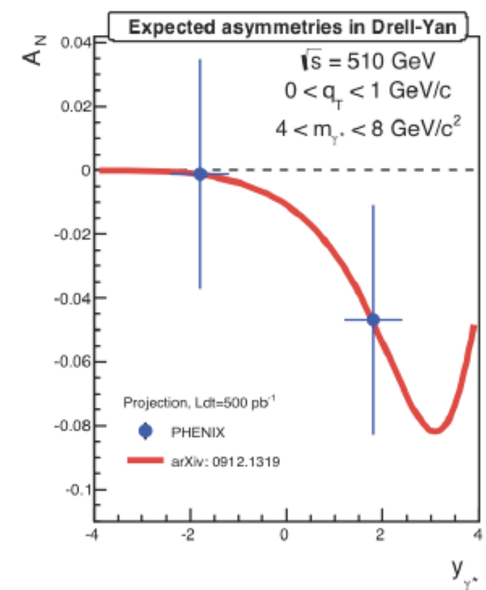
$\pi H^{\uparrow}$ @ CERN

$p^{\uparrow}p$ @ Brookhaven

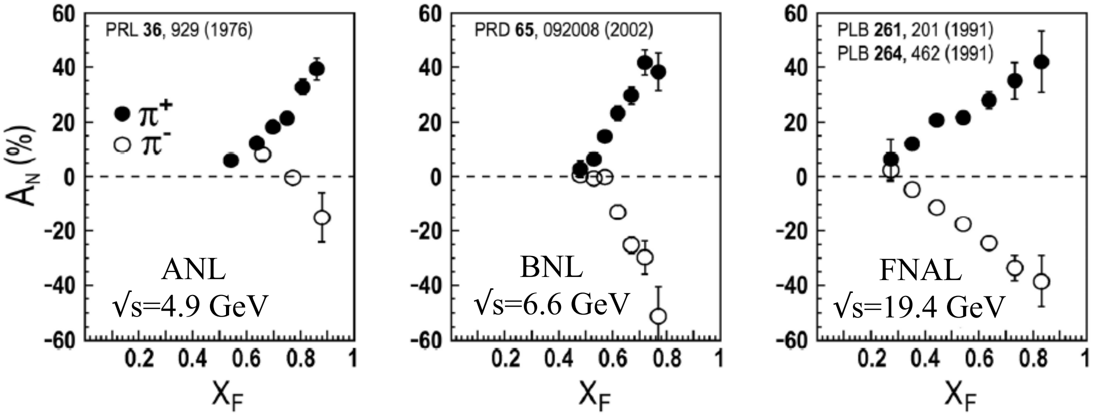
Takekawa talk

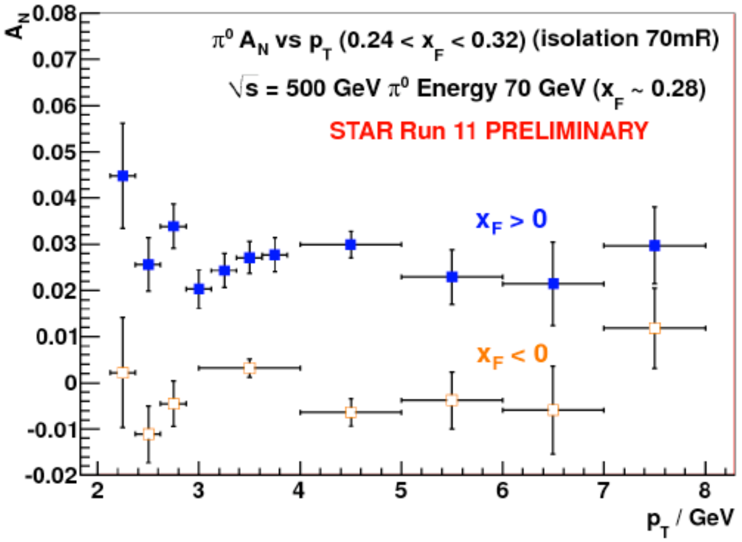






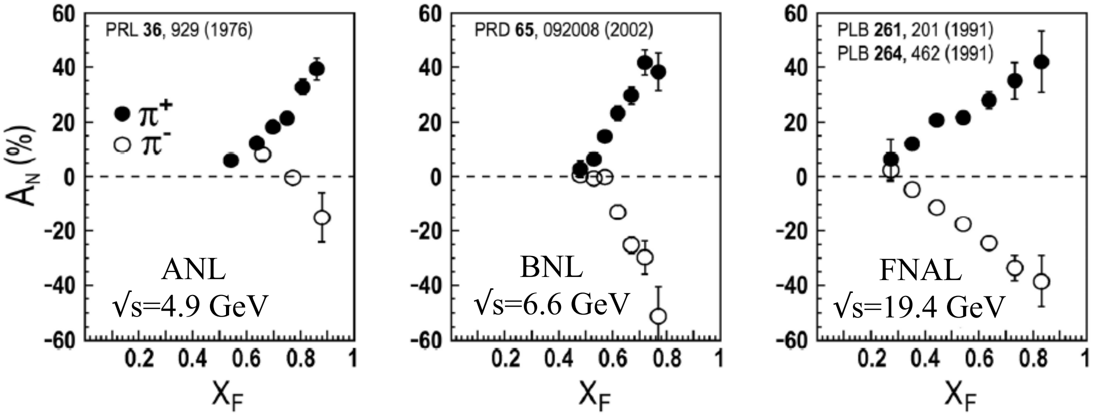
The Sivers challenges - II

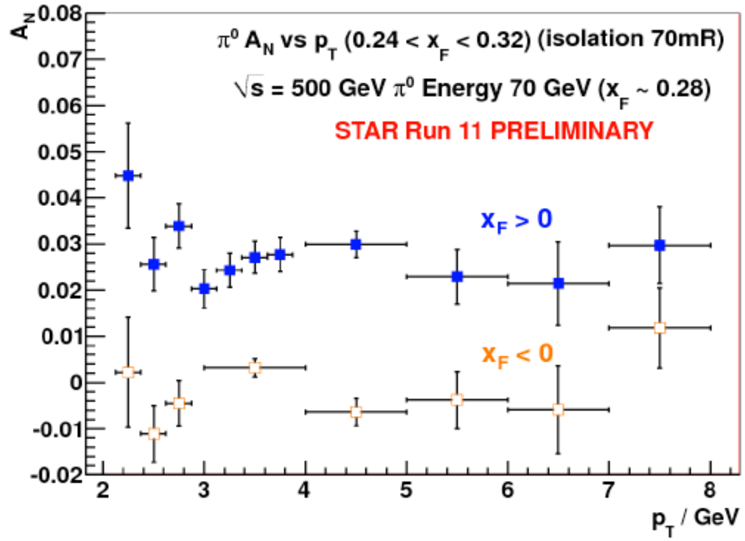




The Sivers challenges - II

$f_{1T}^{\perp} \otimes D_1$

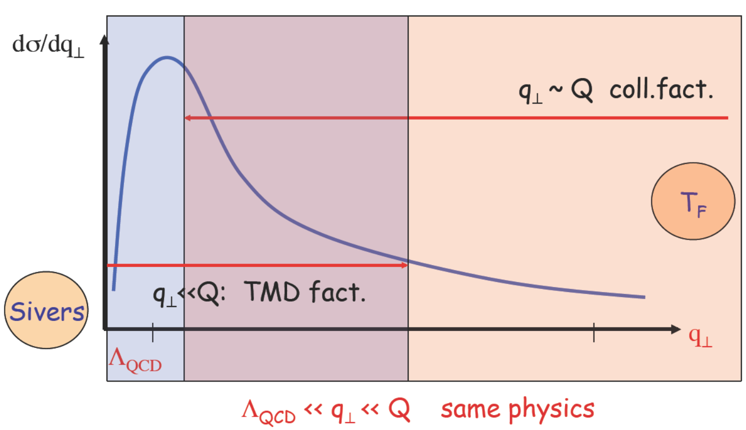




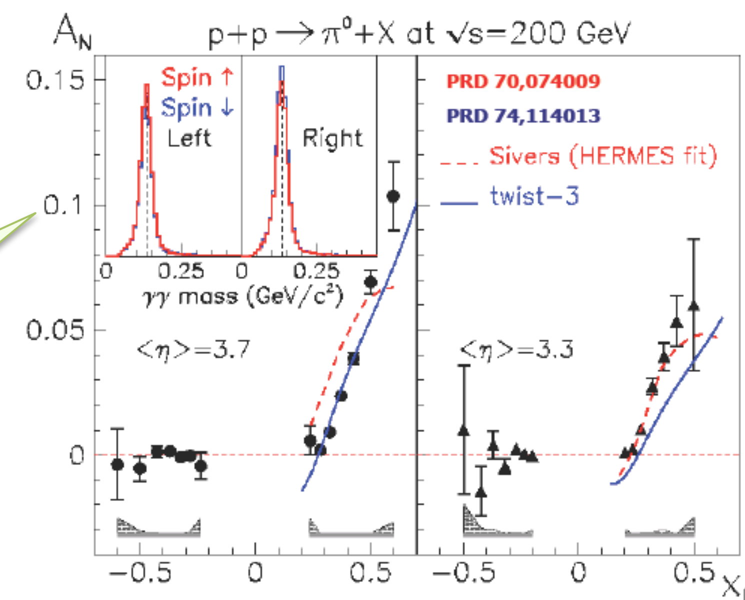
From SIDIS to pp: A possible candidate to explain SSA

Coverage at large p_T and relation with twist-3 collinear approach

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$



After 1st promising results a sign mismatch was found

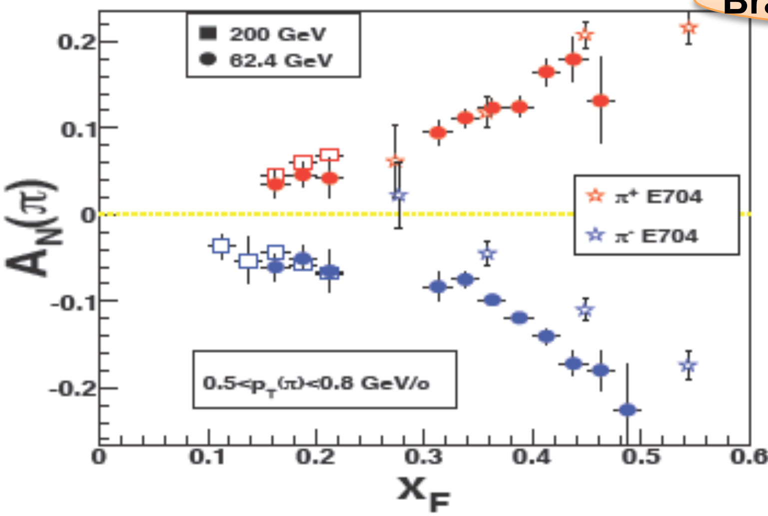


arXiv: 0801.2990

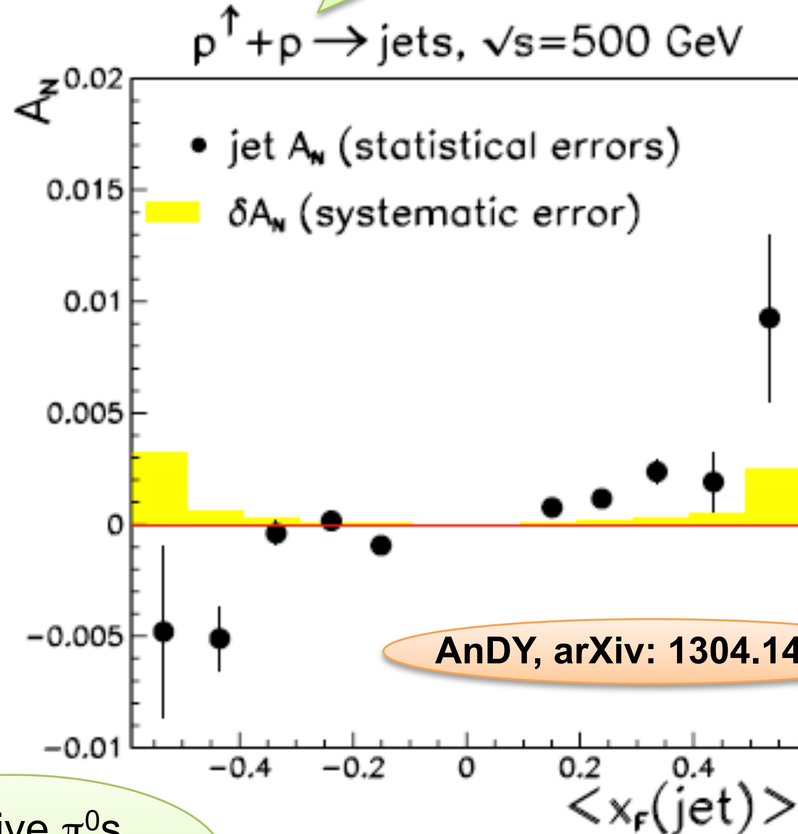
The Sivers challenges - II

$f_{1T}^{\perp} \otimes D_1$

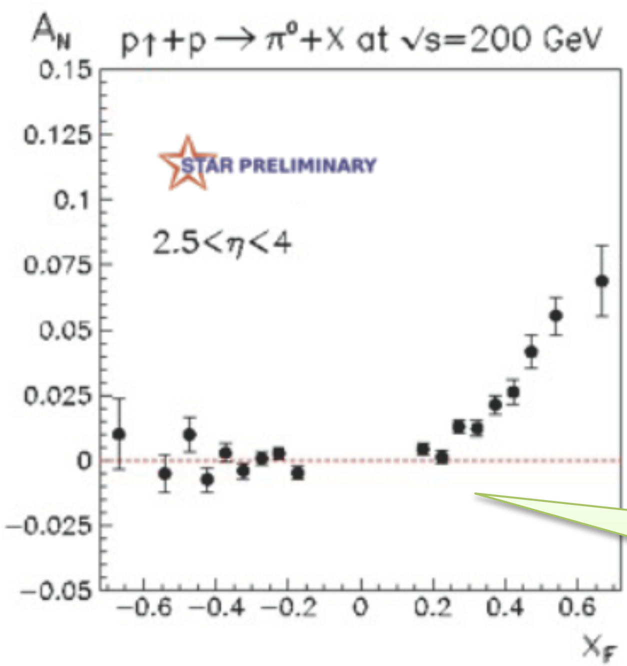
Brahms, PRL 101 (2008) 042001



Inclusive Jets,
No FF involved



AnDY, arXiv: 1304.1454

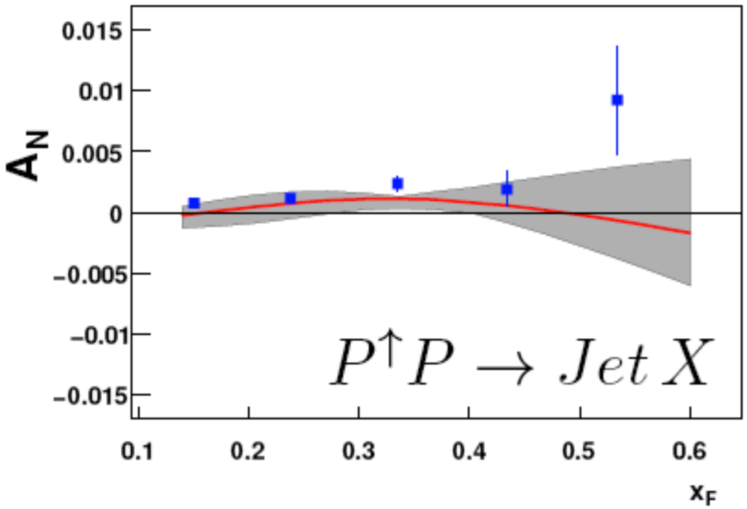


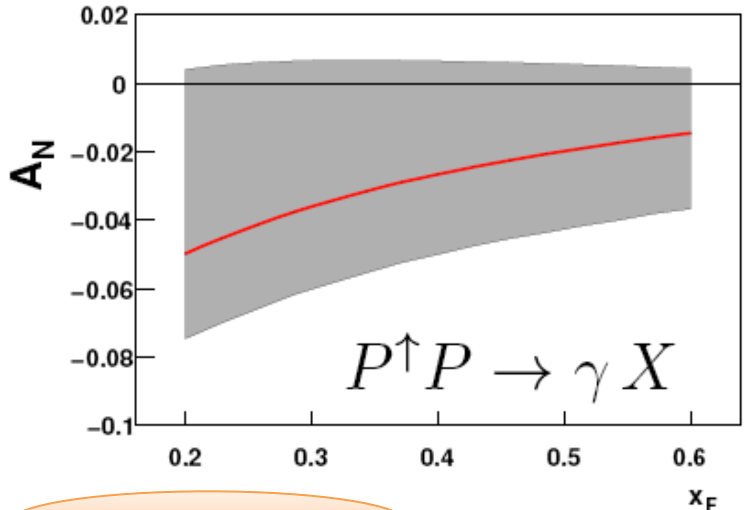
Inclusive π^0s,
Collins FF cancels ?

The Sivers challenges - II

$f_{1T}^{\perp} \otimes D_1$

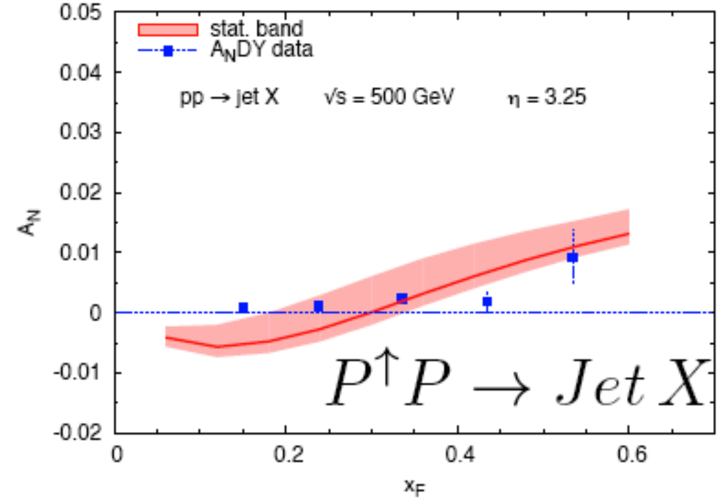
w/ color factors



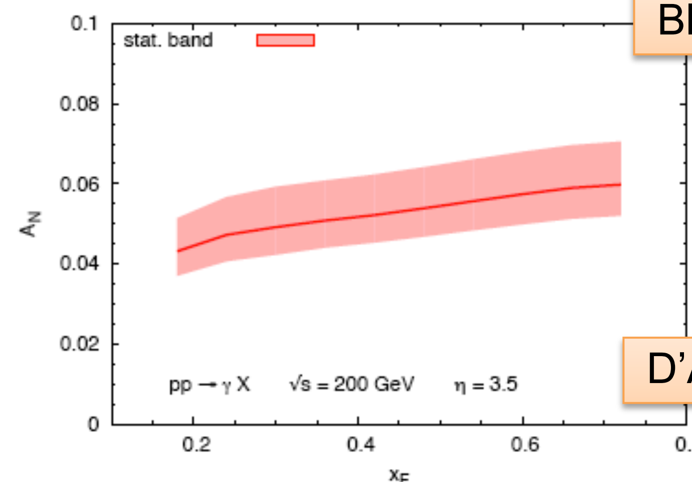


arXiv: 1302.3218

w/o color factors



Bland talk

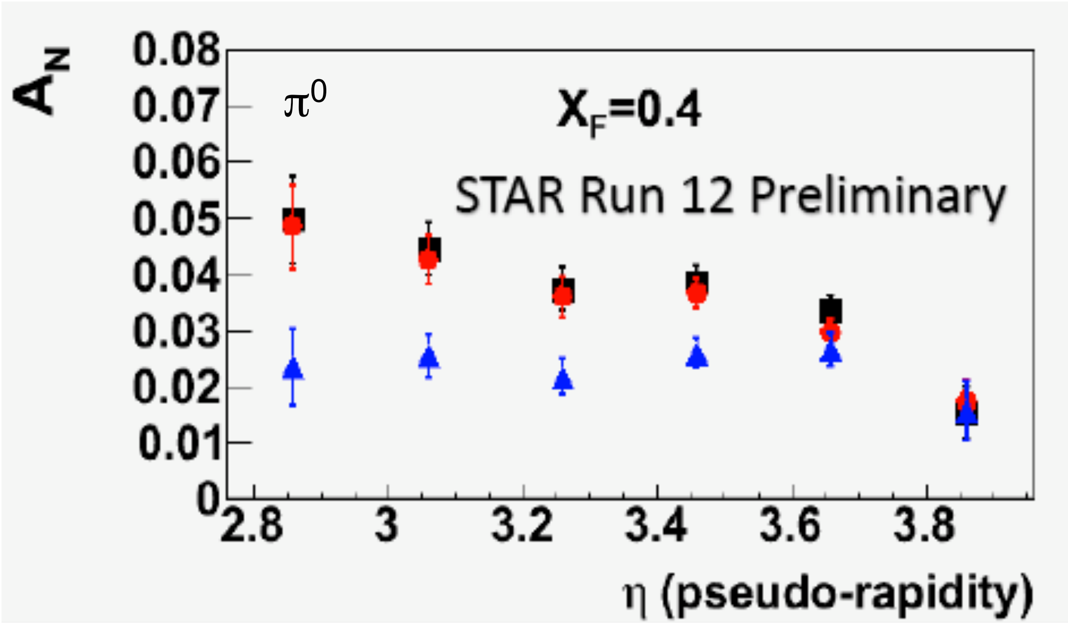


D'Alesio talk

arXiv: 1304.7691

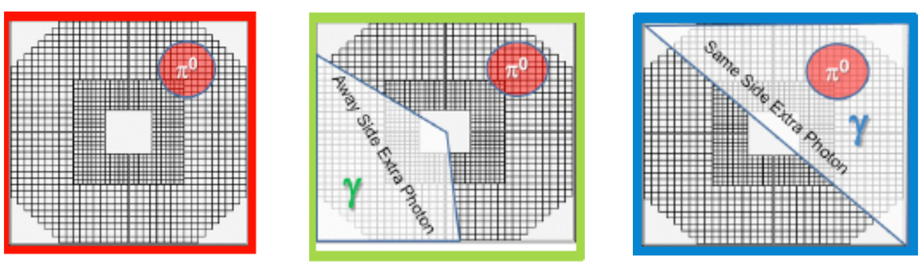
The Sivers challenges - II

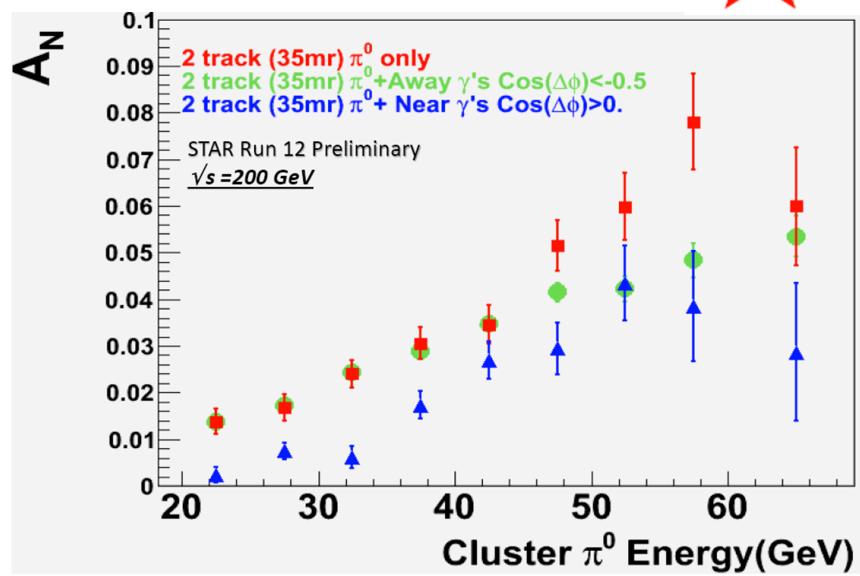
$f_{1T}^{\perp} \otimes D_1$



Heppelmann, DIS 2013

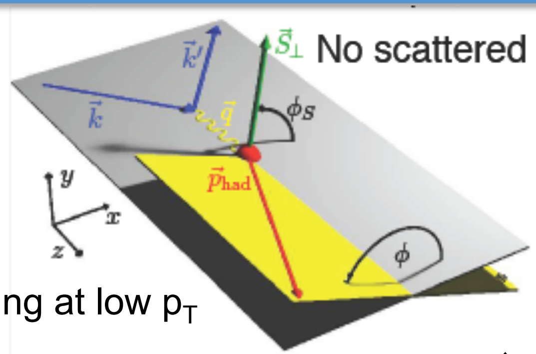
Asymmetry depends on isolation criteria (jet-like fragmentation)





Inclusive hadron SSA in SIDIS

$f_{1T}^{\perp} \otimes D_1$



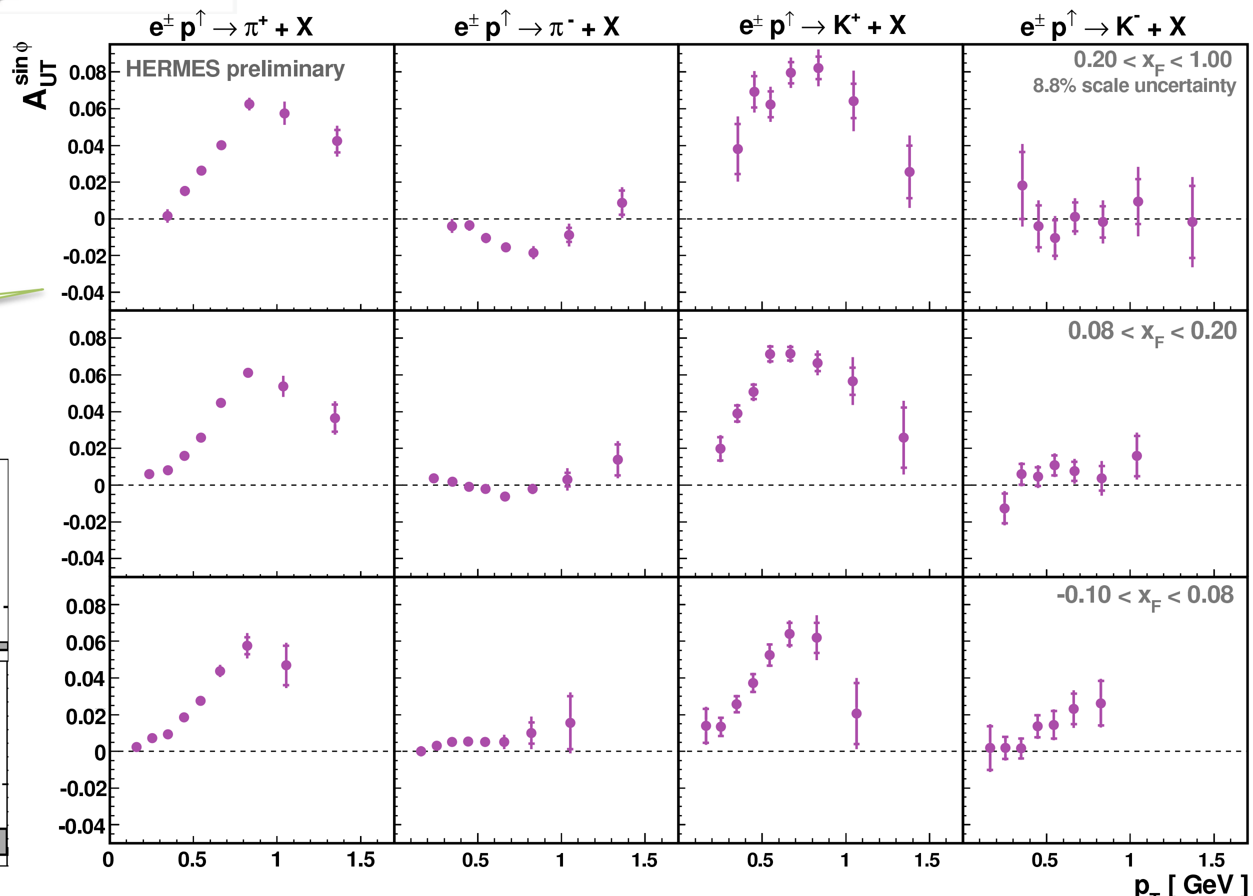
No scattered beam detected → **p_T, x_F** with respect to **e beam** (not q-vector)

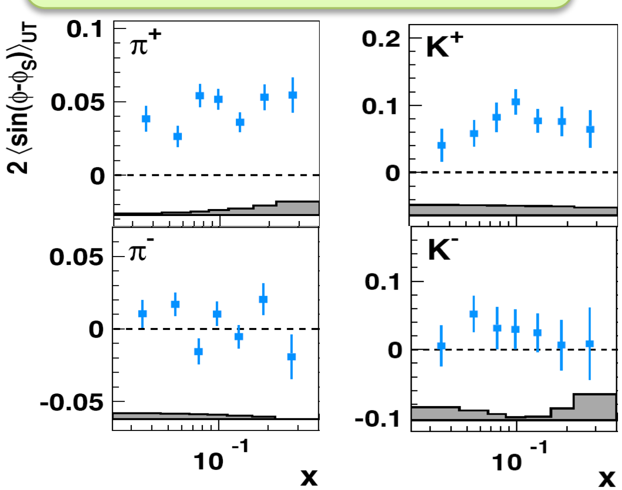
Sivers modulation $\sin(\phi-\phi_S)$ can survives as $\sin(\phi)$

$$A(x_F, p_T, \phi) = \frac{\sigma_{UT}(x_F, p_T, \phi)}{\sigma_{UU}(x_F, p_T)} = A_{UT}^{\sin\phi}(x_F, p_T)\sin\phi$$

- A_{UT} is vanishing at low p_T
- Q^2 increases with p_T approaching DIS regime
- Study transition from perturbative to non-perturbative regime

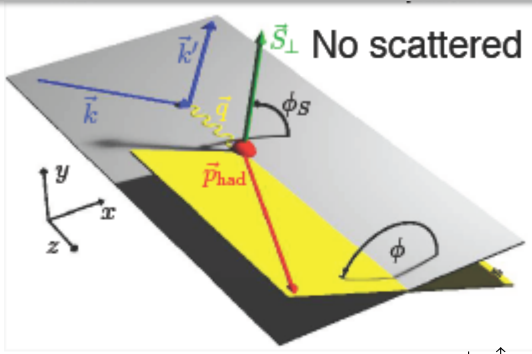
Non-zero signals for positive hadrons resembling Sivers





Inclusive hadron SSA in SIDIS

$f_{1T}^{\perp} \otimes D_1$



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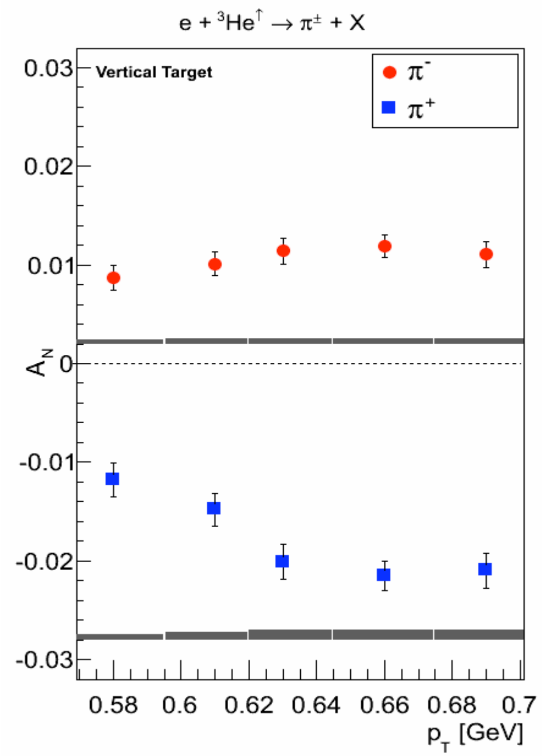
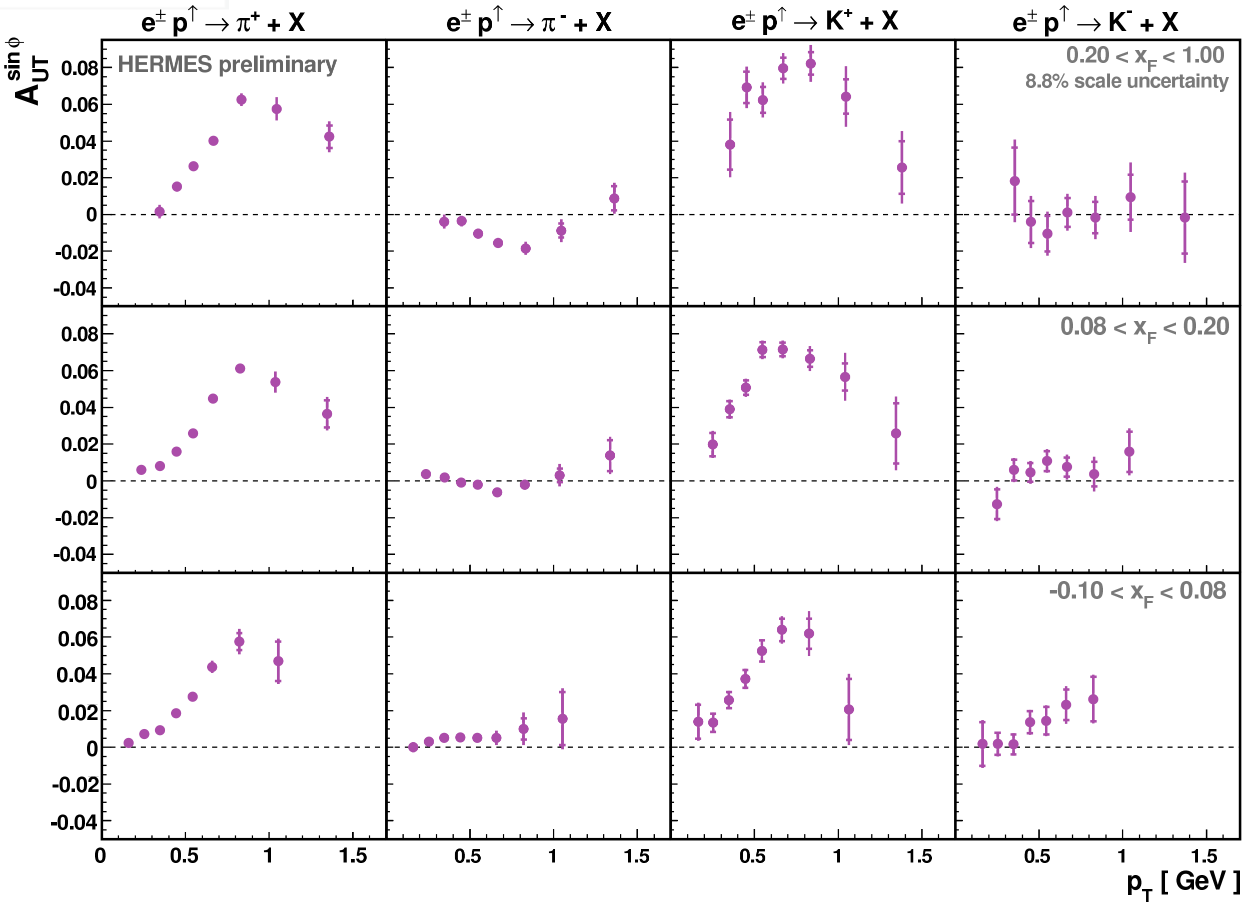
Chen, QCD Evolution 13

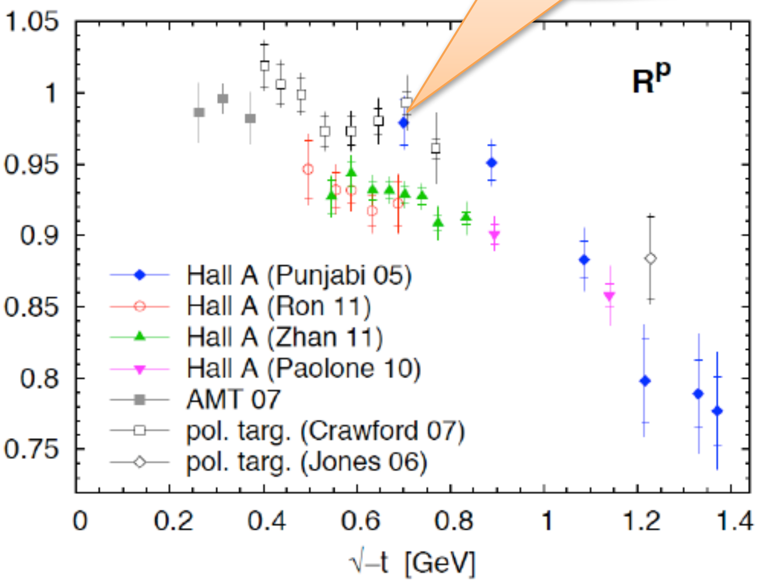


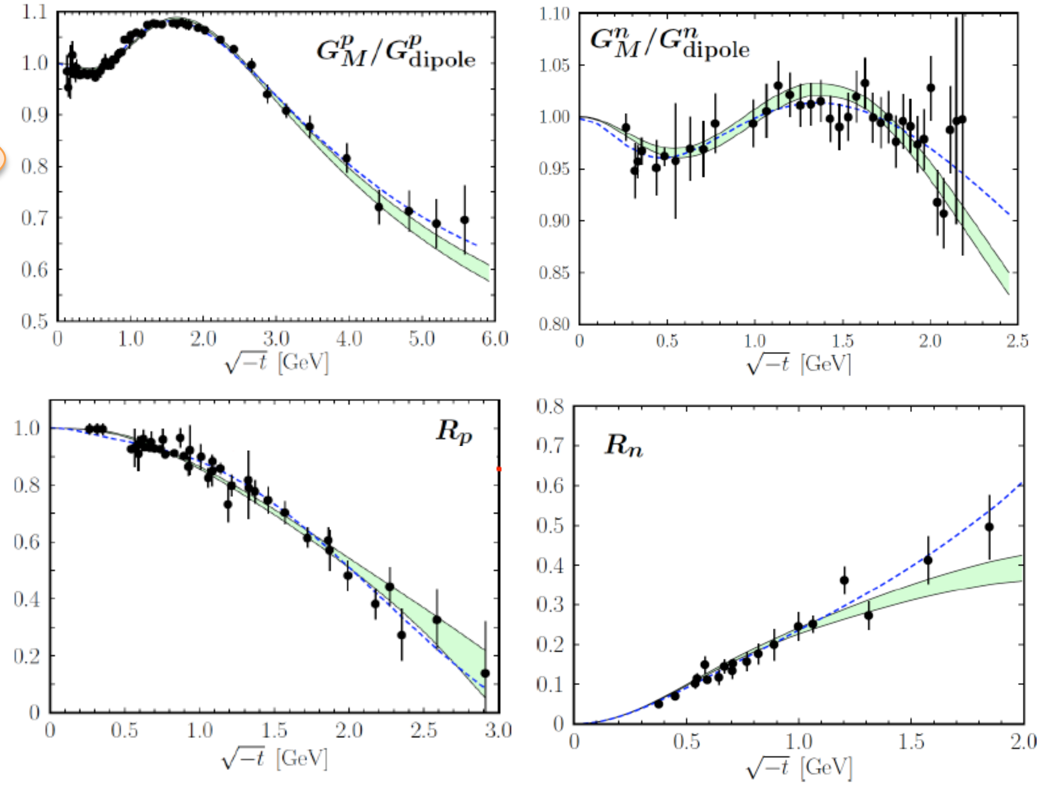


OAM Glimpses

$$R^p = G_E^p / (G_M^p / \mu_p)$$

Inconsistency in DATA ?





- obtain at μ = 2 GeV

$$J_v^u = 0.230^{+0.009}_{-0.024} \qquad J_v^d = -0.004^{+0.010}_{-0.016}$$

Diehl et al. arXiv: 1302.4604

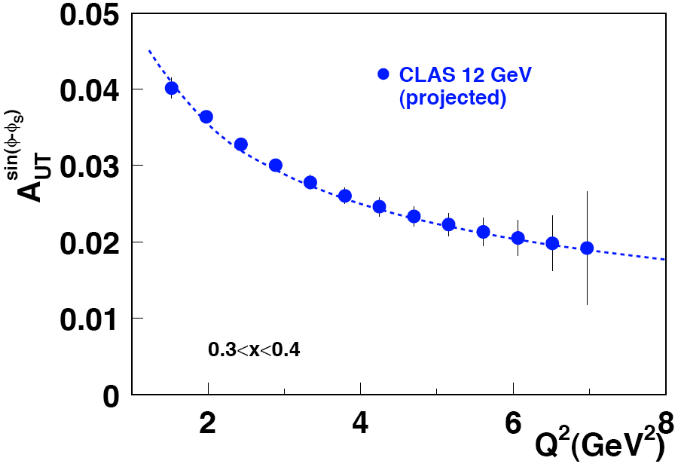
- within errors consistent with determination from Sivers distrib. and model for chromodynamic lensing:

$$J_v^u = 0.214^{+0.009}_{-0.013} \qquad J_v^d = -0.029^{+0.021}_{-0.008}$$

Bacchetta talk

Bacchetta et al. arXiv: 1107.5755

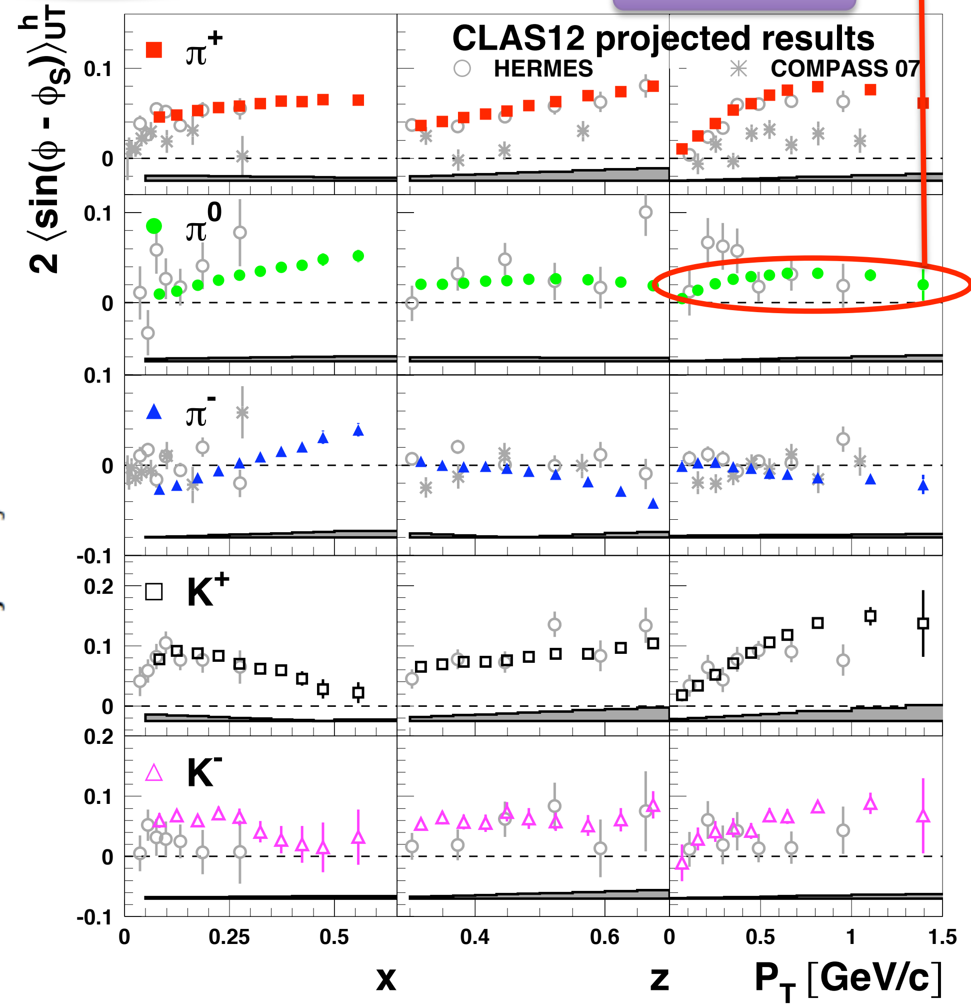
Sivers @ JLab12 2014+



High resolution and broad range in p_T to test perturb. non-perturb. transient and for Bessel function analysis

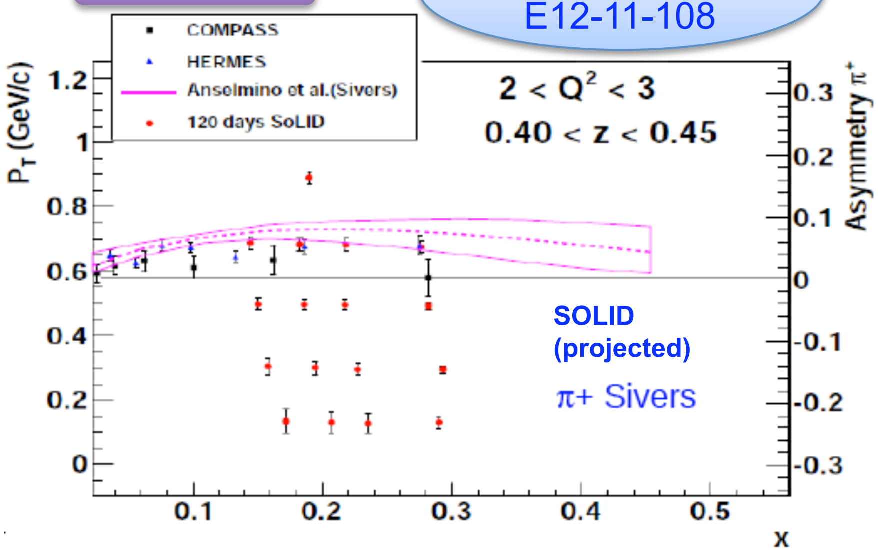
C12-11-111 Hall-B

Proton



Proton & ^{3}He

E12-10-006 Hall-A
E12-11-108



Cahn & Boer-Mulders

nucleon polarisation

N/q	U	L	T
U	f_1 Number Density		$h_1^{\perp}$ - Boer-Mulders
L		g_1 - Helicity	$h_{1L}^{\perp}$ - Worm-gear
T	$f_{1T}^{\perp}$ - Sivers	$g_{1T}^{\perp}$ - Worm-gear	h_1 - Transversity $h_{1T}^{\perp}$ - Pretzelosity

Naïve-T-odd
Chirally-odd
Spin effect in unpolarized reactions

(The Neglected Effects)

The azimuthal modulation

$h_1^\perp \otimes H_1^\perp$

$$\frac{d^5\sigma^{ep\to e'hX}}{dx\,dy\,dz\,d\phi\,dP_{h\perp}^2} \propto \{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi)F_{UU}^{\cos(\phi)} + \varepsilon\,\mathrm{s}\cos(2\phi)F_{UU}^{\cos(2\phi)}\}$$

$\left(f_1 \otimes D_1\right)/Q$

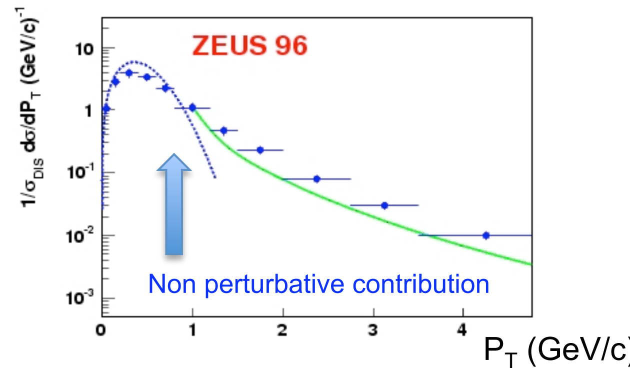
$h_1^\perp \otimes H_1^\perp$

Kinematical effect redicted since 1978
by Cahn due to non-zero intrinsic k_T

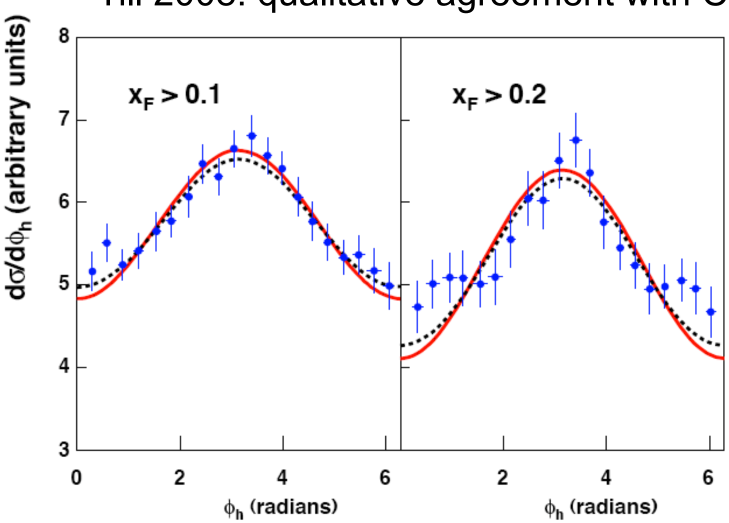
Cahn PLB 78 (1978)

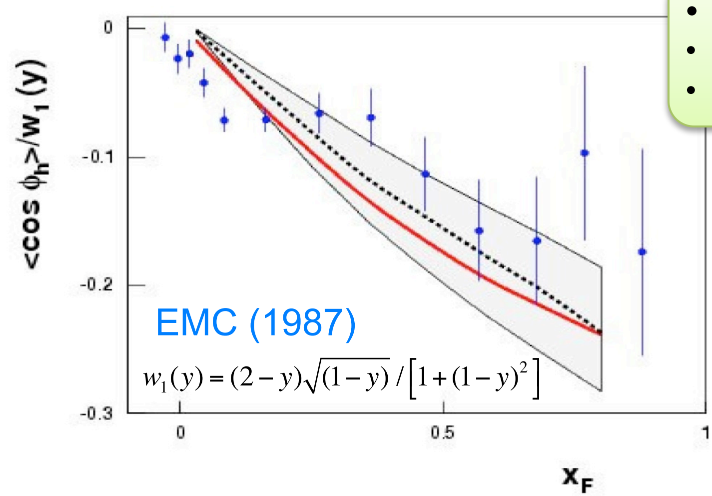
Leading-twist contribution introduced
by Boer & Mulders in 1998

Boer & Mulders PRD 57 (1998)



Till 2008: qualitative agreement with Cahn expectations





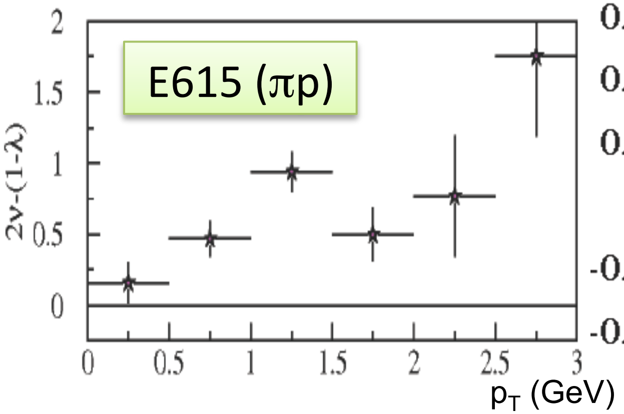
- No hadron identification
- No charge separation
- Poor statistics for $\cos 2\phi$

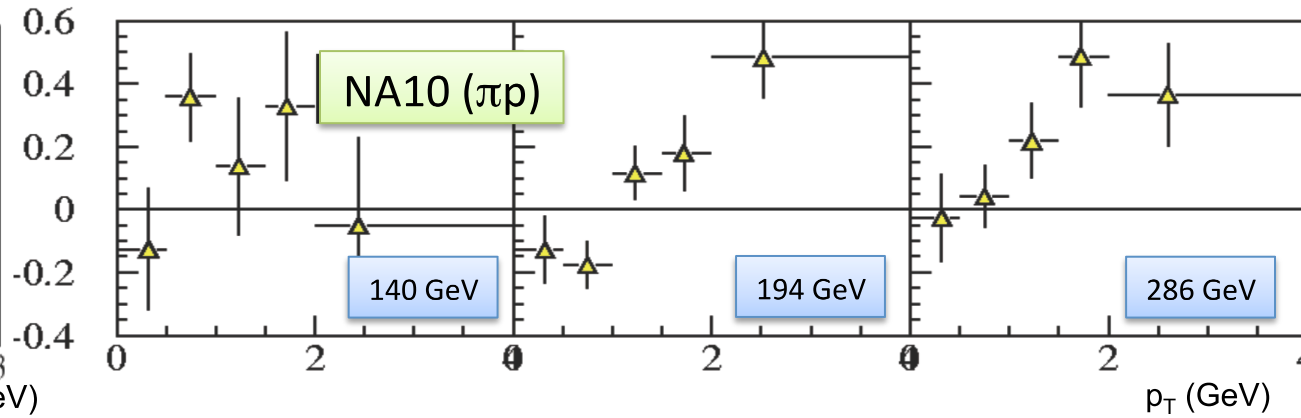
$$\frac{d\sigma^{hp \to eeX}}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

$h_1^{\perp} \otimes h_1^{\perp}$

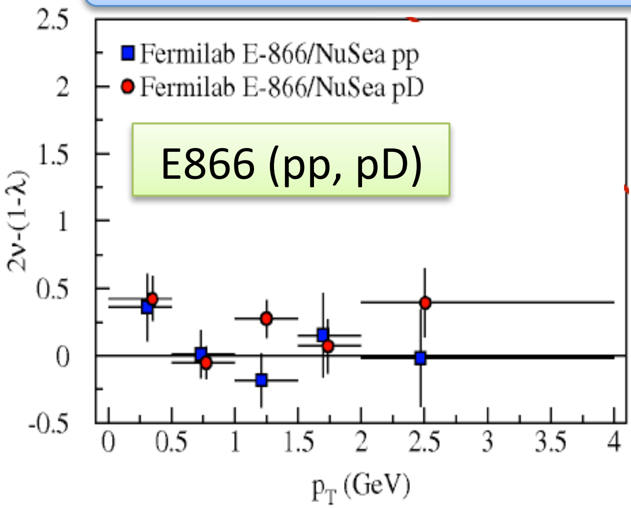
$$(1 - \lambda) = 2\nu$$

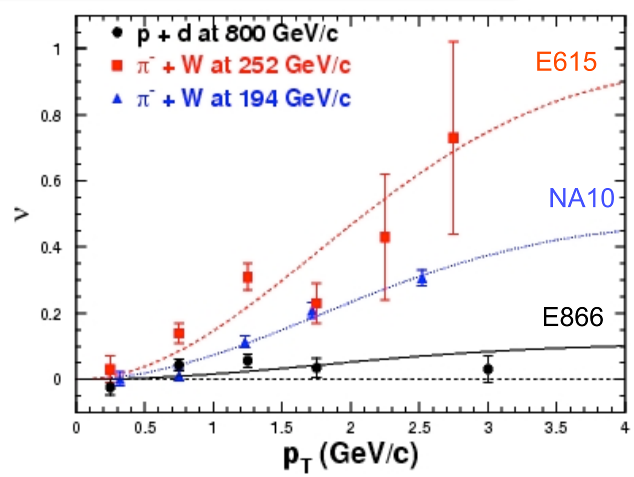
Preserved by NLO and resummation
Analogous of SIDIS Callan-Gross

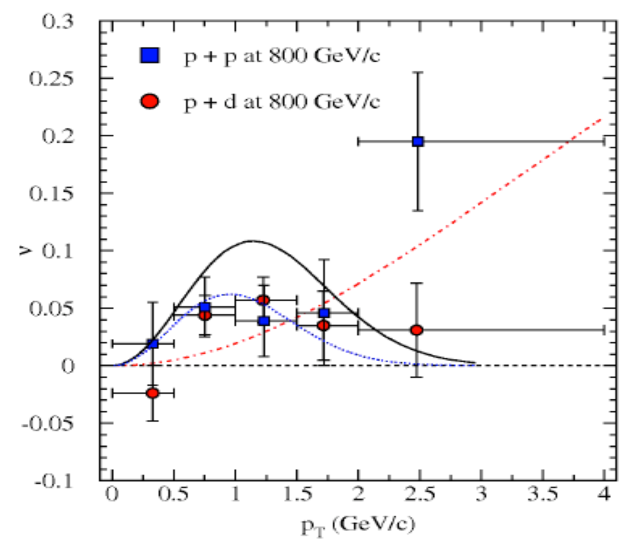




Boer-Mulders offers a possible explanation $\nu \approx h_{1q}^{\perp} \times h_{1\bar{q}}^{\perp}$







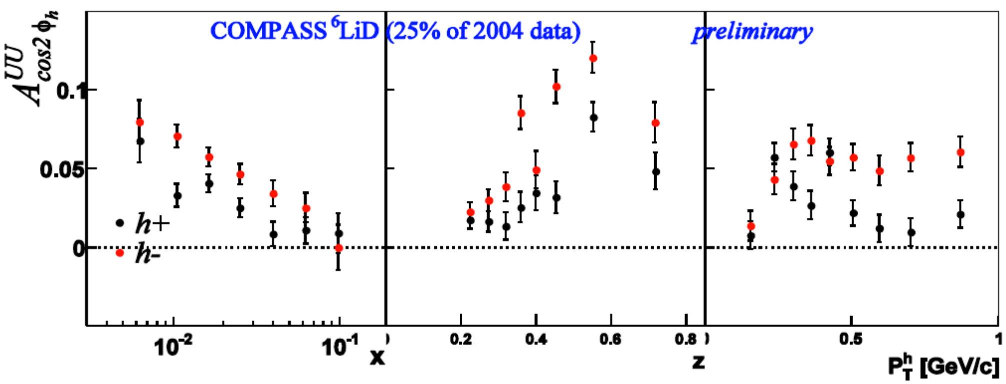
The SIDIS cos2ϕ dependence

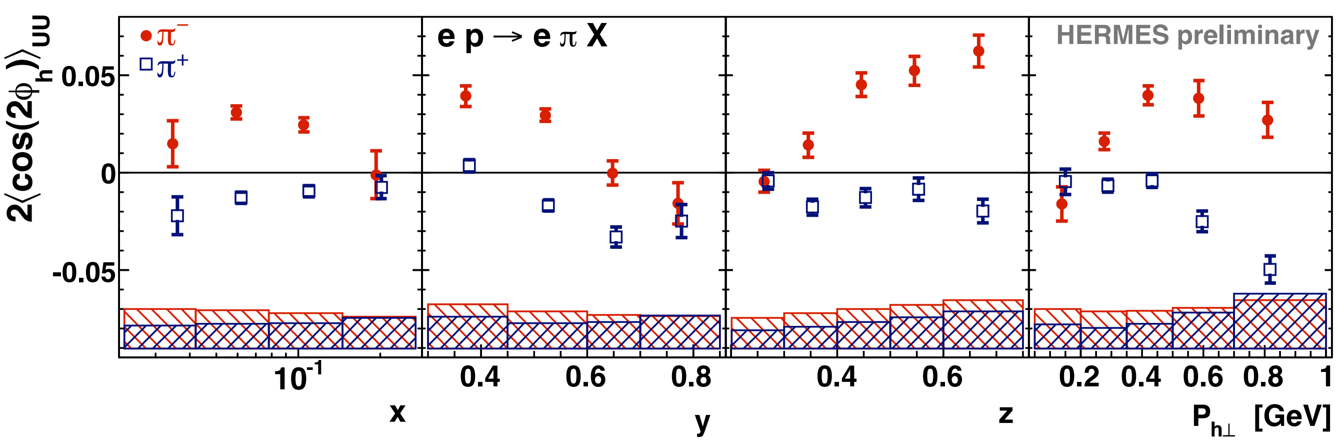
$h_1^{\perp} \otimes H_1^{\perp}$

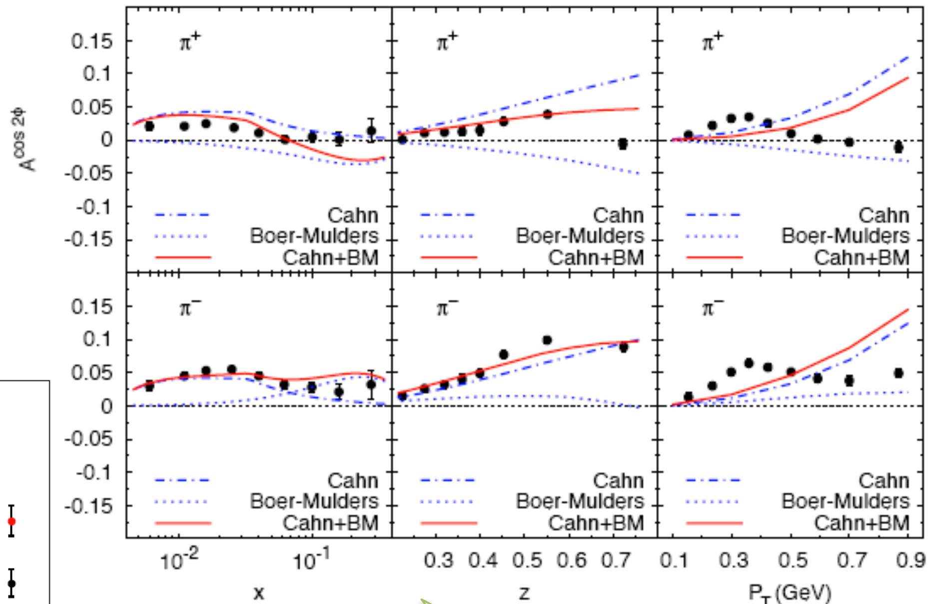
$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp} + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$

Non-zero !

Issue on DATA consistency







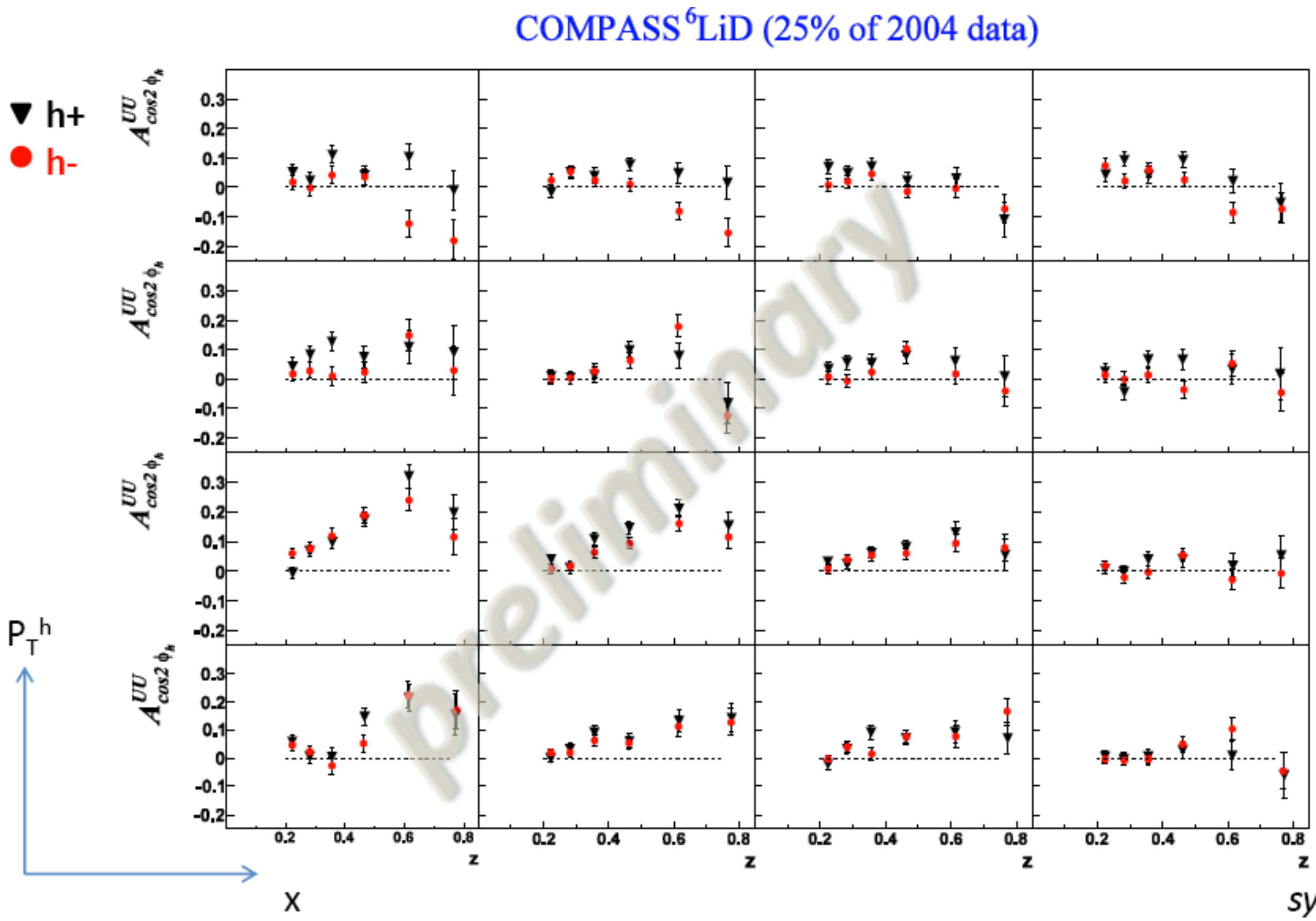
arXiv: 0912.5194

Can be explained by large uncertainty on Cahn and neglected HT effects

arXiv: 1204.4161

The SIDIS cos2ϕ dependence

$h_1^\perp \otimes H_1^\perp$



$sys \approx 2 \cdot stat$

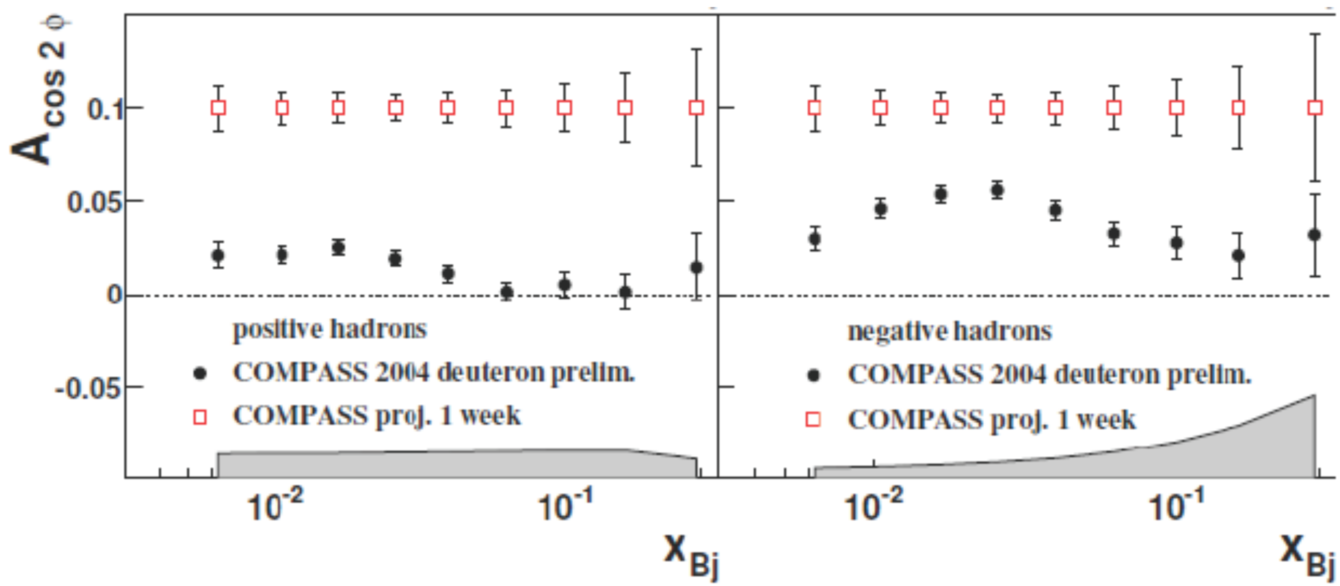
Multidimensional analysis is mandatory

Clean high statistics samples from COMPASS-II and CLAS12

The SIDIS Landscape 2014+

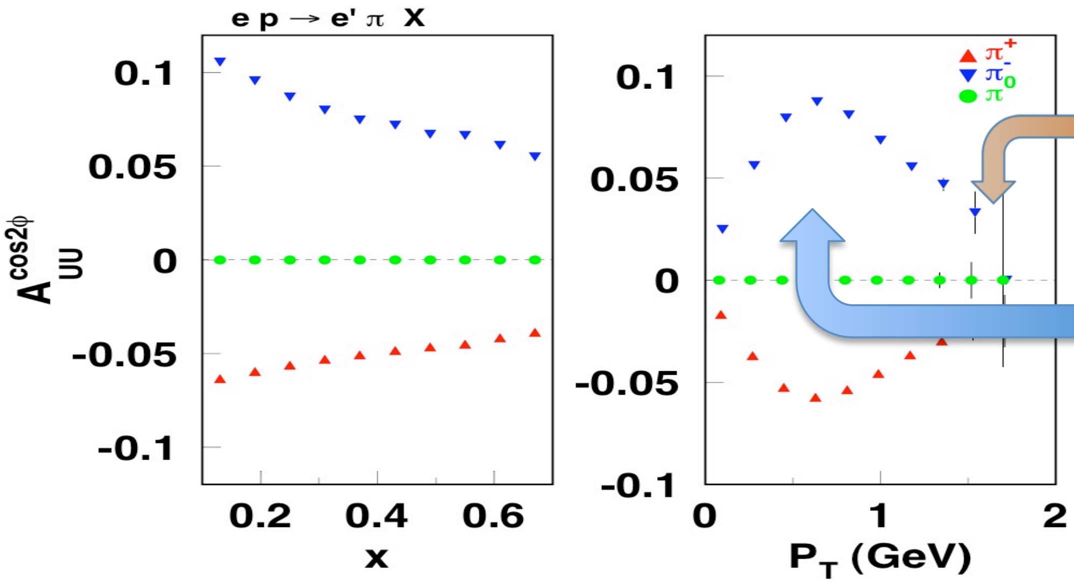
COMPASS-II:

LH_2 target
160 GeV/c muons



CLAS12:

LH2 target
12 GeV/c electrons
$L \sim 10^{35}\ cm^{-2}s^{-1}$



Perturbative region
Collinear factorization

Non-perturbative
TMD factorization

$\Lambda_{QCD} \ll P_T \ll Q$

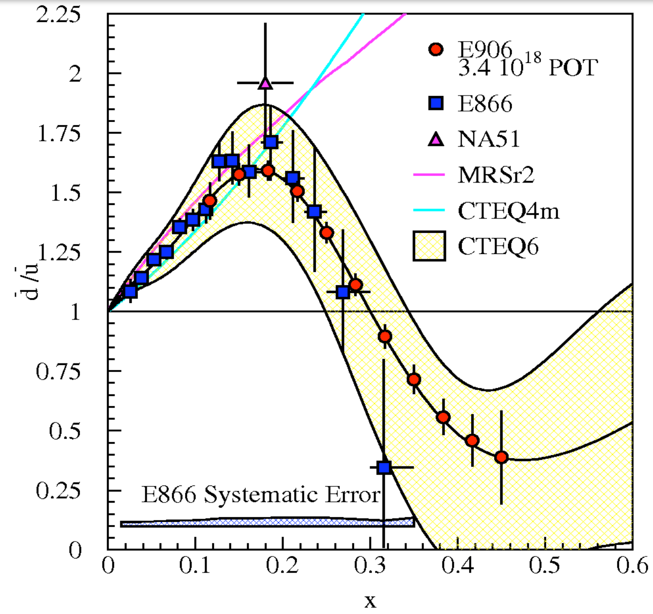
The Drell-Yan Landscape 2014+

Proton beam @ Fermilab

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

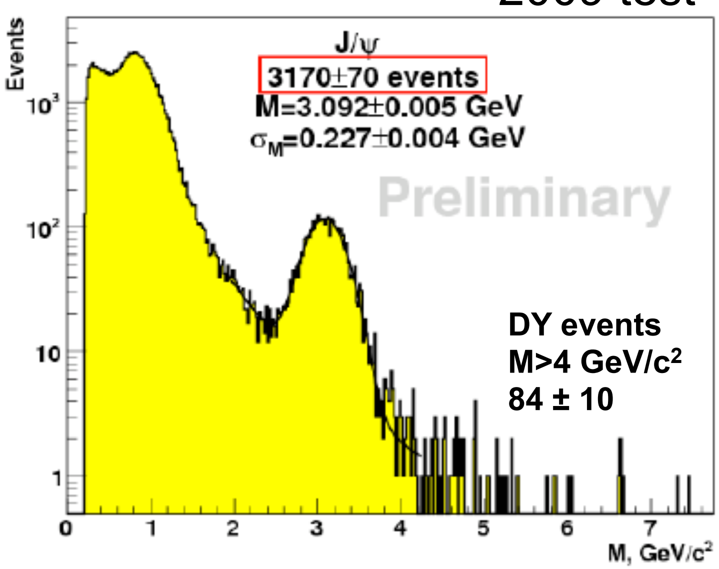
E906: test run this year

Extends E866 measurements at 120 GeV
xsec scales as 1/s
background scales as s.



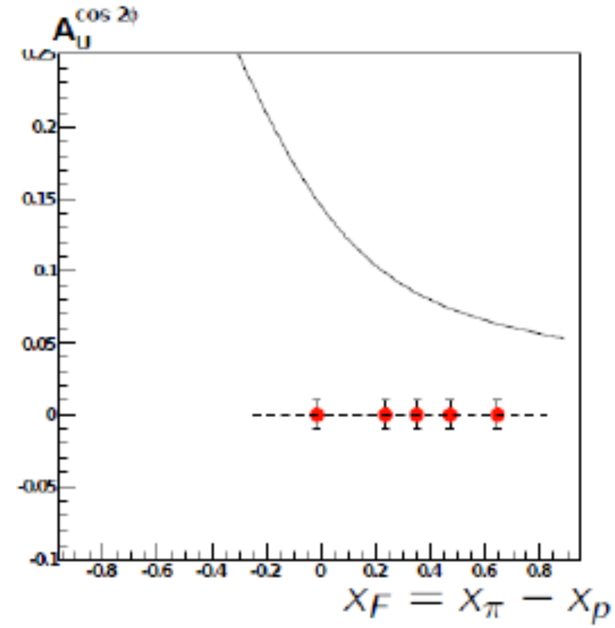
Pion beam @ CERN

2009 test



Boer-Mulders
$\otimes$
Boer-Mulders

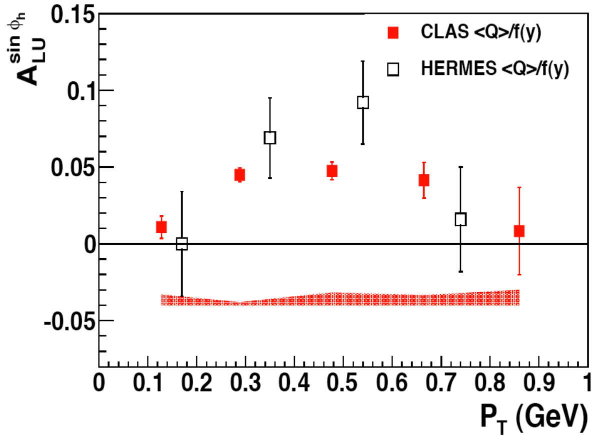
2 years
$4 < M < 9$ GeV/c^2

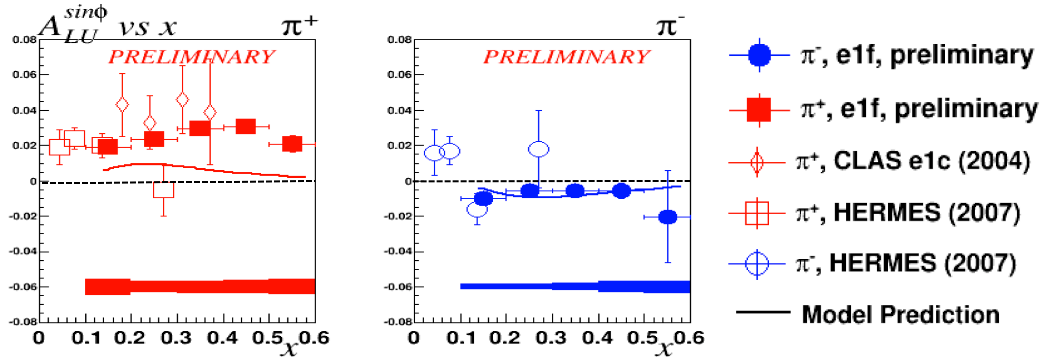


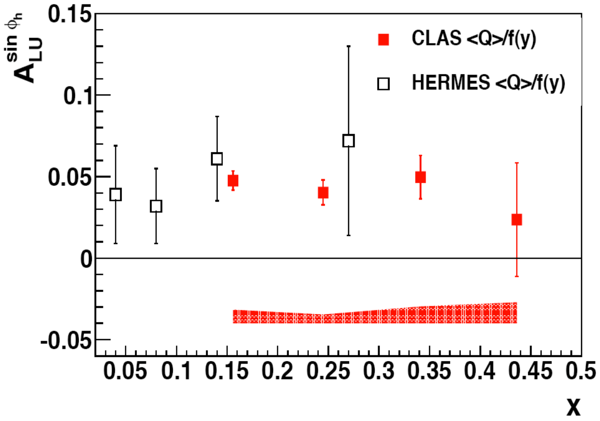
Higher Twists
(The Second Level)

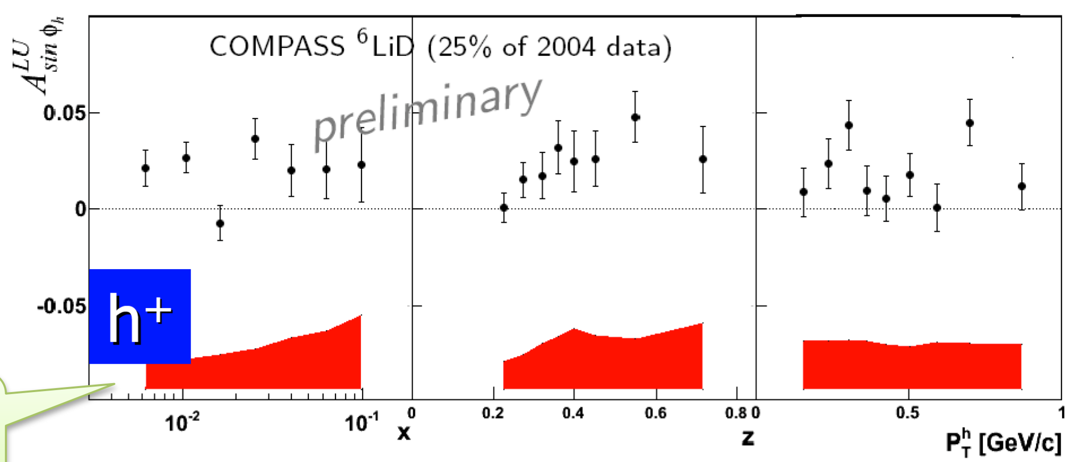
Higher-twist effects

$$\sigma_{LU}^{\sin(\phi)} \propto \left[e \otimes H_1^{\perp} + g^{\perp} \otimes D_1 + \ldots \right] / Q$$





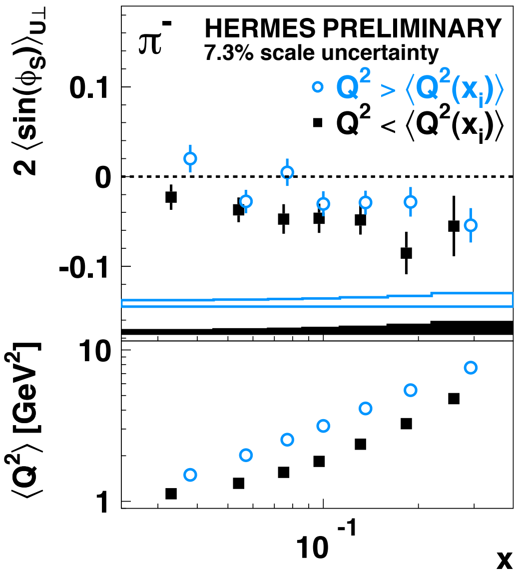


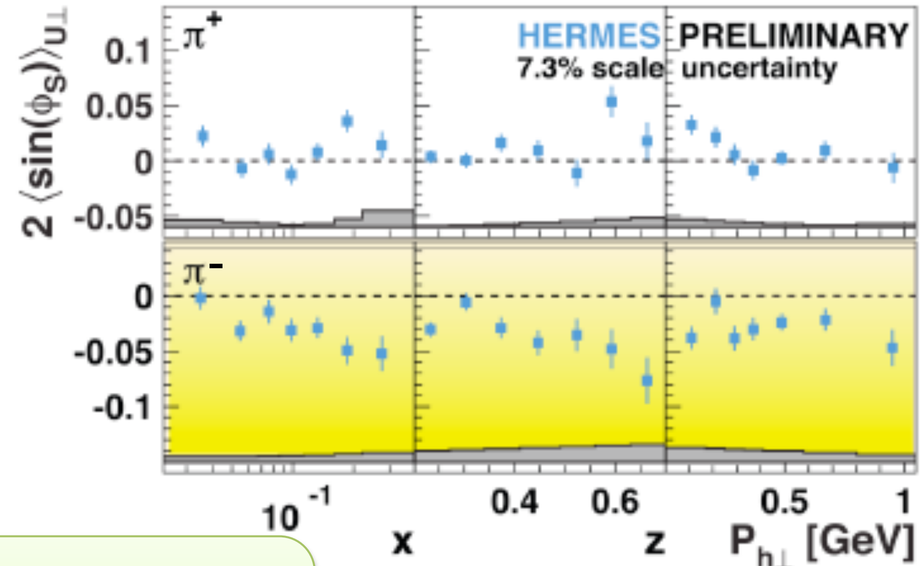


Non zero up to the COMPASS energies

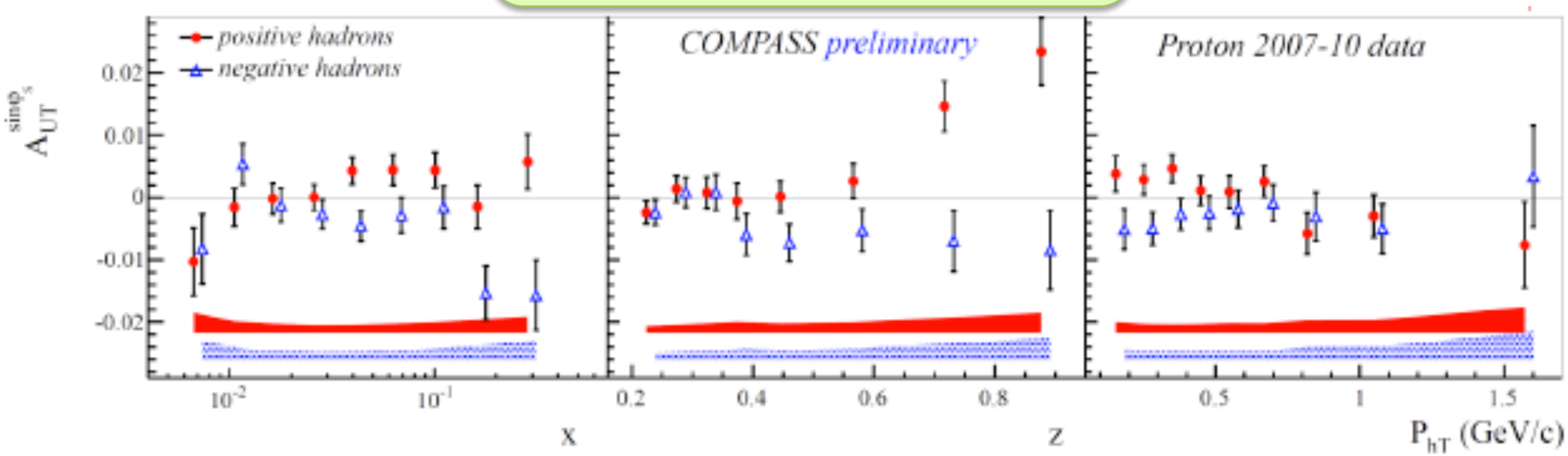
Higher-twist effects

$$\sigma_{UT}^{\sin(\phi)} \propto \left[h_1 \otimes H_1^{\perp} + f_T \otimes D_1 + \ldots \right] / Q$$





Similar pattern but different amplitude: visible effect of the different average Q^2 ?



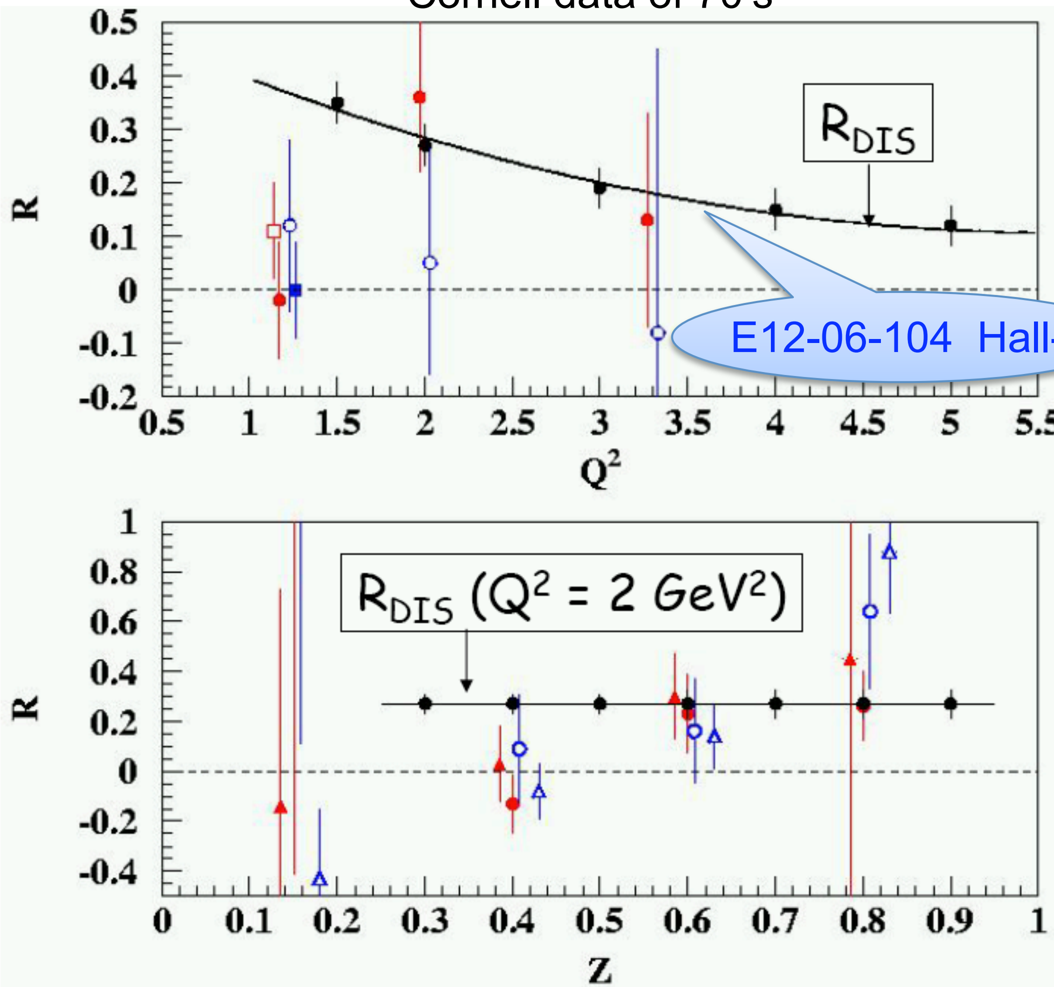
Longitudinal Cross-section @ JLab12

$$\frac{d^5\sigma^{ep\rightarrow e'hX}}{dx\,dy\,dz\,d\phi\,dP^2_{h\perp}} \propto \{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi)F_{UU}^{\cos(\phi)}+\varepsilon\,\mathrm{s}\cos(2\phi)F_{UU}^{\cos(2\phi)}\}$$

Knowledge on $R = \sigma_L/\sigma_T$ in SIDIS is non-existing!

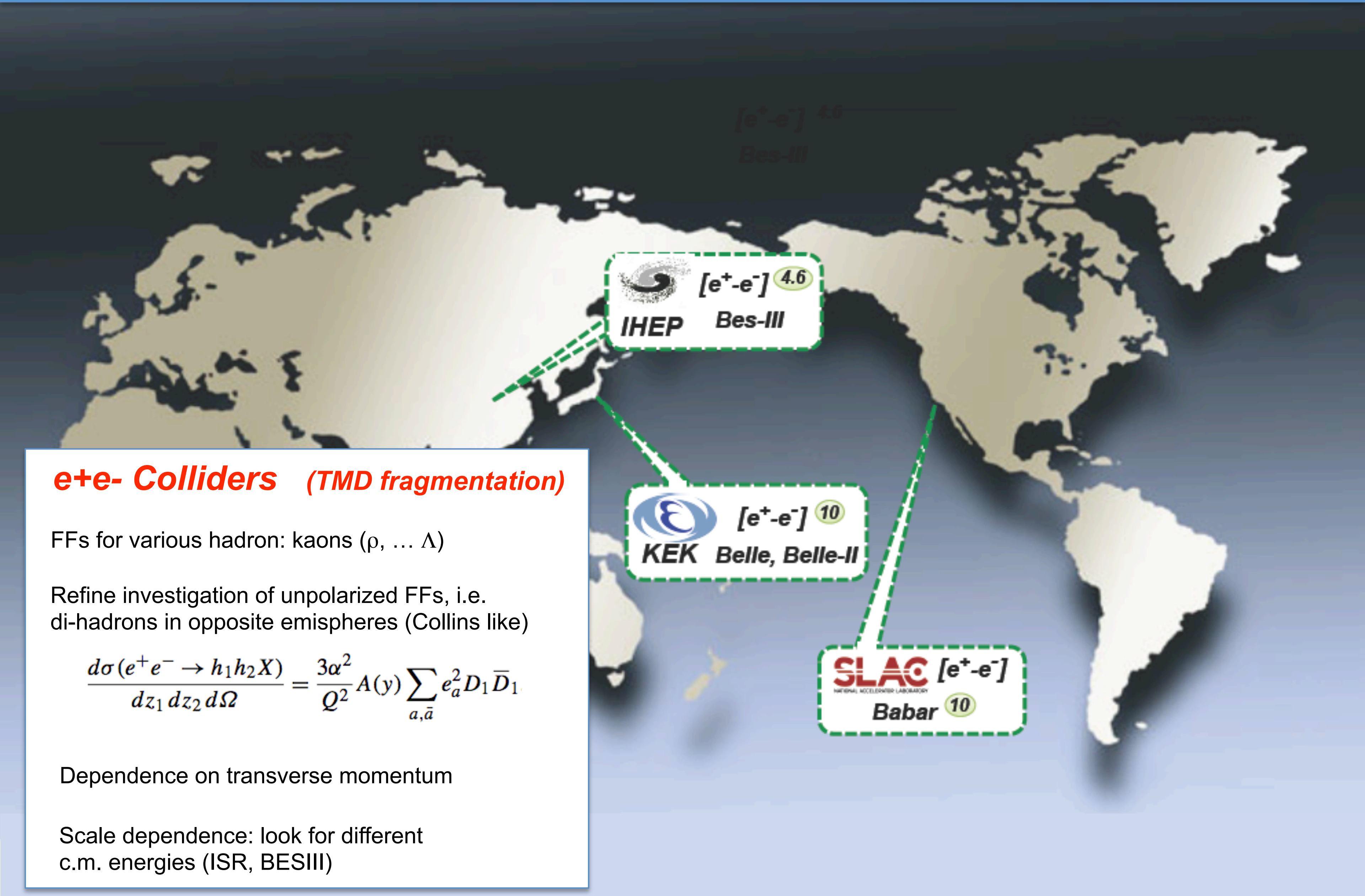
To be accounted in any TMD asymmetry interpretation

Cornell data of 70's



- $R_{DIS}\rightarrow 0$ at $Q^2\rightarrow\infty$ due to scattering off spin-½ quarks
- R_{DIS} sensitive to gluon and higher-twist effects
- $R_{SIDIS}(z,pT)$ = un-integrated R_{DIS}

Higher-twist effects



e+e- Colliders *(TMD fragmentation)*

FFs for various hadron: kaons (ρ, … Λ)

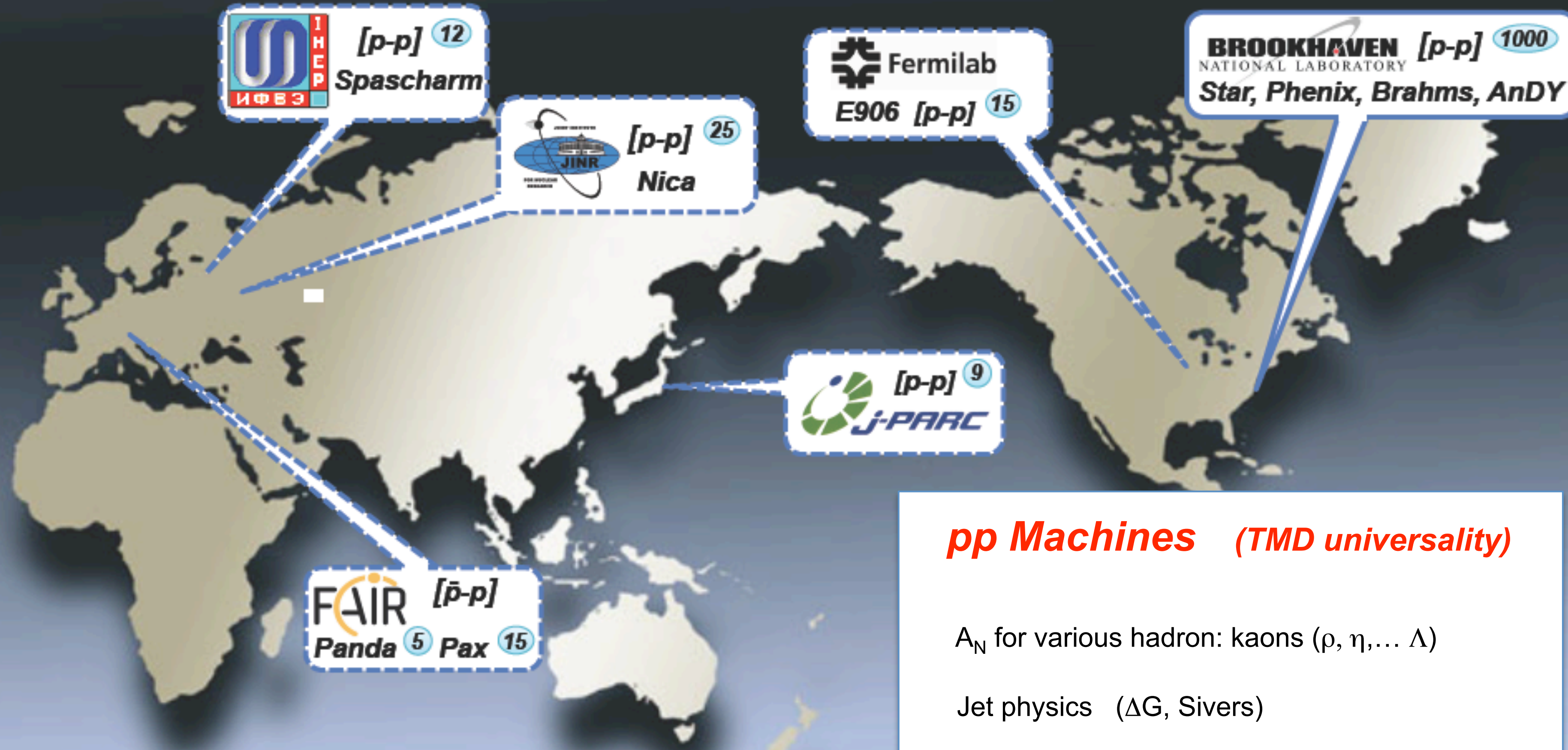
Refine investigation of unpolarized FFs, i.e.
di-hadrons in opposite emispheres (Collins like)

$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{dz_1\, dz_2\, d\Omega} = \frac{3\alpha^2}{Q^2} A(y) \sum_{a,\bar{a}} e_a^2 D_1 \bar{D}_1$$

Dependence on transverse momentum

Scale dependence: look for different
c.m. energies (ISR, BESIII)

Higher-twist effects



pp Machines ***(TMD universality)***

A_N for various hadron: kaons (ρ, η,… Λ)

Jet physics (ΔG, Sivers)

DY and gauge bosons (Δq, Sivers)

Di-hadron (Transversity)

Scale dependence

Higher-twist effects

DIS Experiments *(TMD disentanglement)*

Multidimensional analysis

Flavor separation: various hadron types and different targets

TMD formalism: di-hadron vs single-hadron h_1 extraction, inclusive SSA measurements

Scale dependence & Higher twists

A World-wide Challenge