# The TMD Experimental Program

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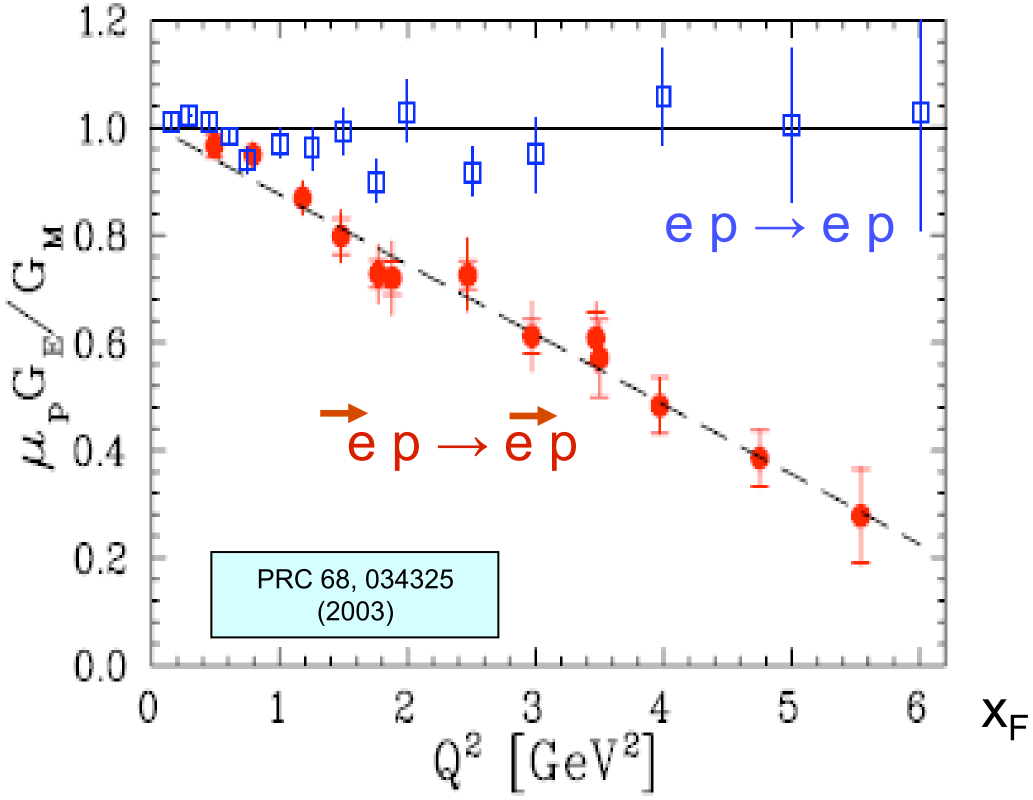
**ELBA XII Workshop**
June 26, 2012  Marciana Marina

# The Spin Degree of Freedom

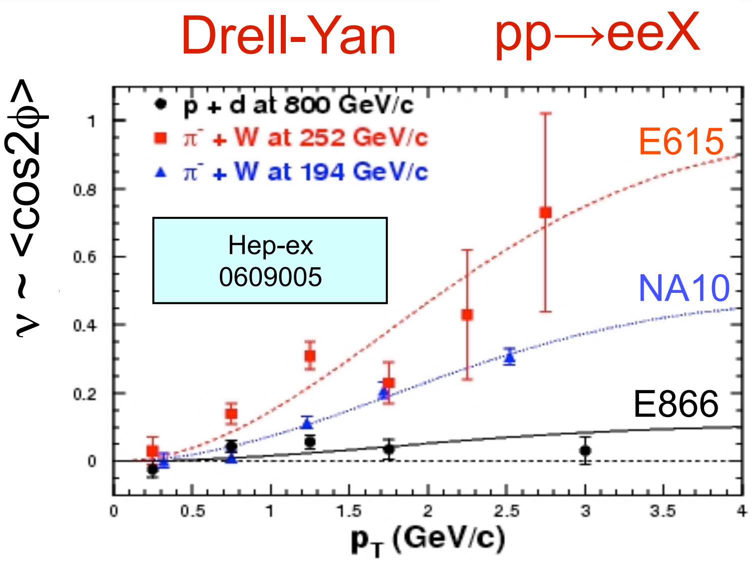
Spin degrees of freedom can explain otherwise surprising phenomena and bring new insights into nuclear matter structure

Fundamental: do not neglect it !!

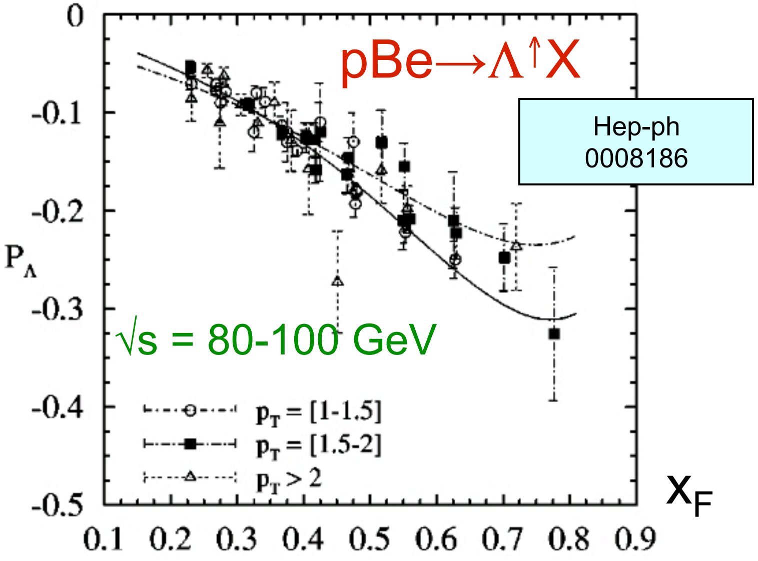


PRC 68, 034325 (2003)

# The Spin Surprising Phenomenology



Hep-ex 0609005



Hep-ph 0008186

# The Spin Structure of the Nucleon

Describe the complex nucleon structure in terms of partonic degrees of freedom of QCD

Important testing ground for QCD

*Latest news from Deep Inelastic Scattering (DIS)*

*Phys Lett B647 (2007) 8-17*

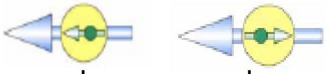
*Phys. Rev. D 75 (2007) 012007*

$\Delta\Sigma = 0.33 \pm 0.03$

*$\Delta G$ small at $0.02<x<0.3$*

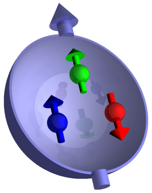
*From DIS and pp scattering*

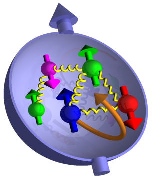
*e-print 0804.0422*



Proton's spin

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





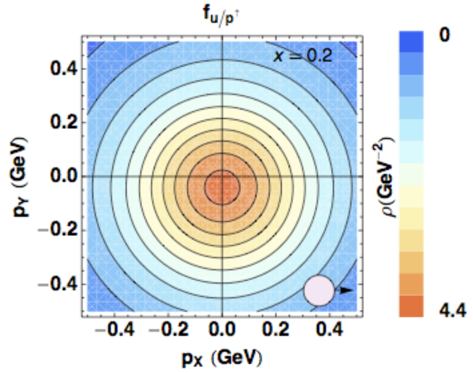
Understanding of the orbital motion of quarks is crucial!

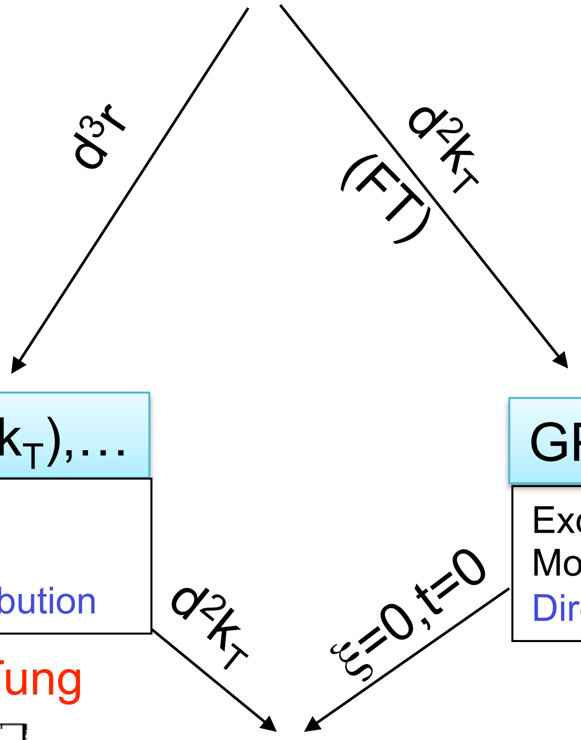
# The real experience: 3D !

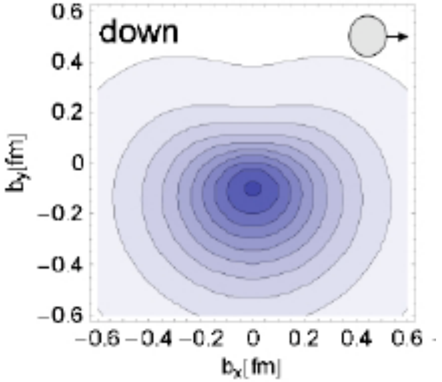
# Quantum Phase-space Distributions of Quarks

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

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







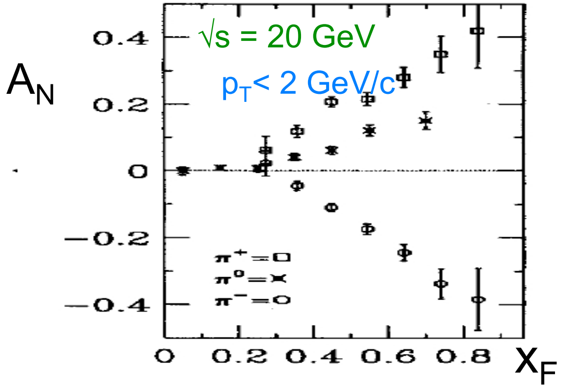
TMD PDFs: $f_p^u(x,k_T)$,…

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

May explain SSA & Lam-Tung



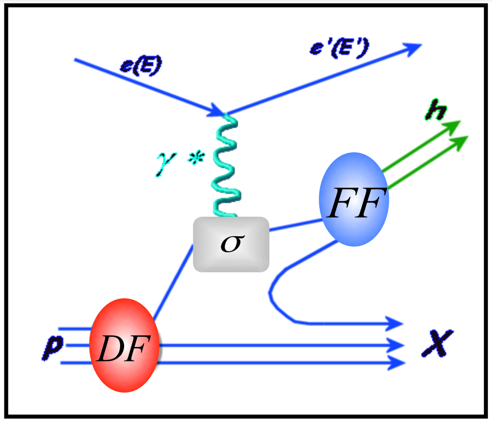
PDFs $f_p^u(x)$,…

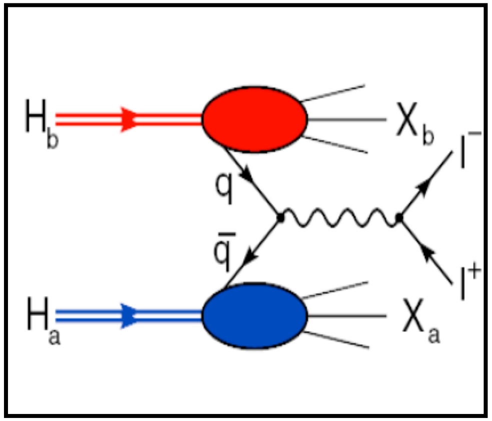
May solve
proton spin puzzle

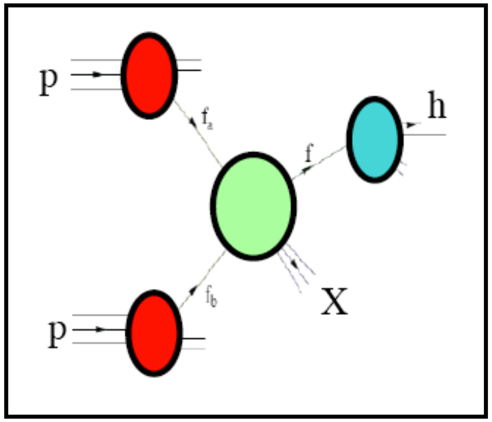
$$J_q = \frac{1}{2}\Delta\Sigma + L_q = \lim_{t\to 0}\int_{-1}^{1} dx\; x\,\left[H(x,\xi,t)+E(x,\xi,t)\right]$$

# TMD STUDIES AT PRESENT FACILITIES

# Physics reactions







SIDIS: rich phenomenology, the most explored so far

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

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

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

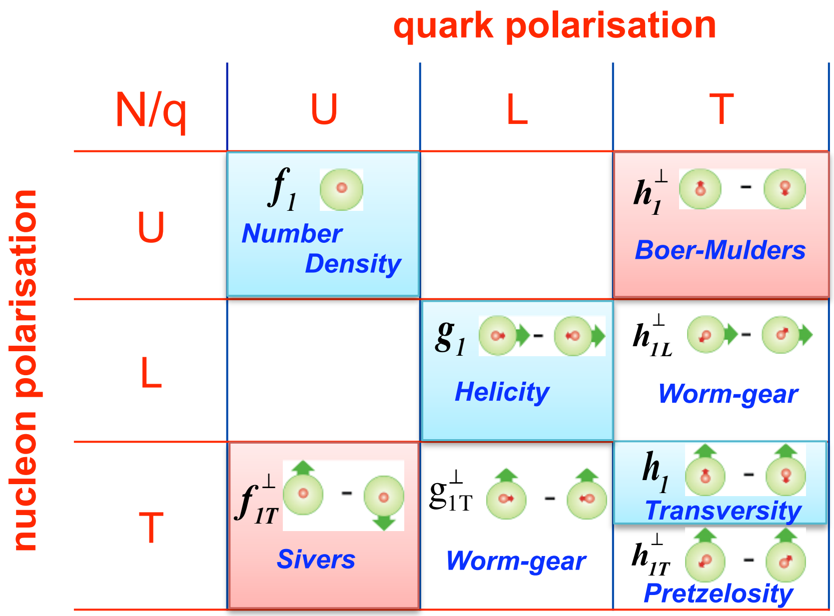
DY: challenging for experiments (only unpolarized so far)

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

Hadron reactions: challenging for theory (ISI + FSI)

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

# Leading Twist TMDs



quark polarisation

nucleon polarisation

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

**Off-diagonal elements:**

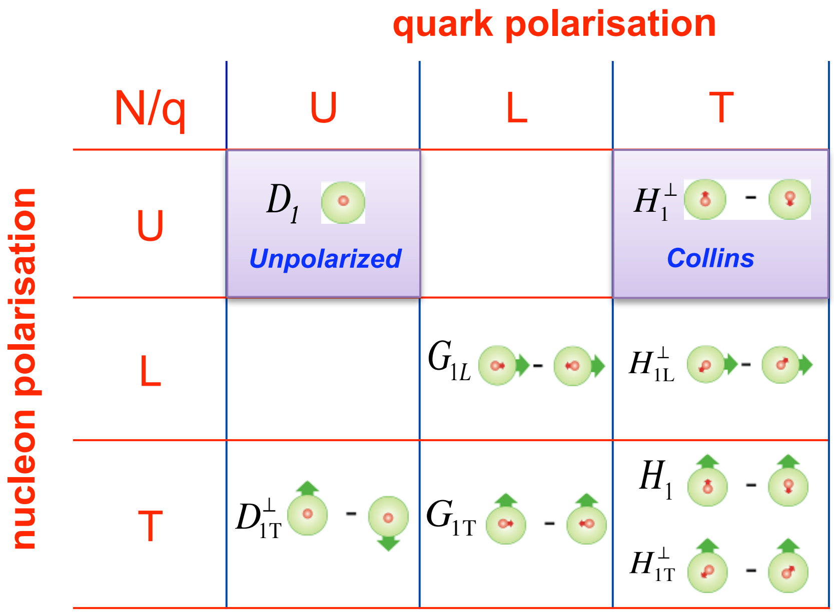
Interference between wave functions with different angular momenta: contains information about parton orbital angular motion and spin-orbit effects

Testing QCD at the amplitude level

**T-odd elements:**

→ sign change between DY and SIDIS
- universality of TMDs

**Strict prediction from TMDs + QCD !**



quark polarisation

nucleon polarisation

| N/q | U | L | T |
|---|---|---|---|
| U | $D_1$<br>Unpolarized | | $H_1^\perp$<br>Collins |
| L | | $G_{1L}$ | $H_{1L}^\perp$ |
| T | $D_{1T}^\perp$ | $G_{1T}$ | $H_1$<br>$H_{1T}^\perp$ |

# The SIDIS Case

**quark polarisation**

**nucleon polarisation**

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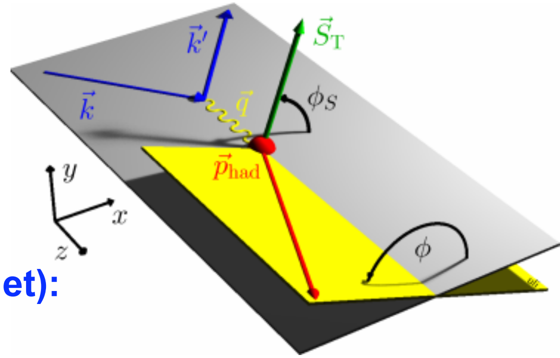


**SIDIS cross section (transversely polarized target):**

$$Q^2 \equiv -q^2$$

Negative squared 4–momentum transfer

$$\nu \equiv \frac{P\cdot q}{M} \overset{\text{lab}}{=} E - E'$$

Energy of the virtual photon

$$x = \frac{Q^2}{2\,P\cdot q} = \frac{Q^2}{2\,M\nu}$$

Bjorken scaling variable

$$z = \frac{P\cdot p}{P\cdot q} \overset{\text{lab}}{=} \frac{E_h}{\nu}$$

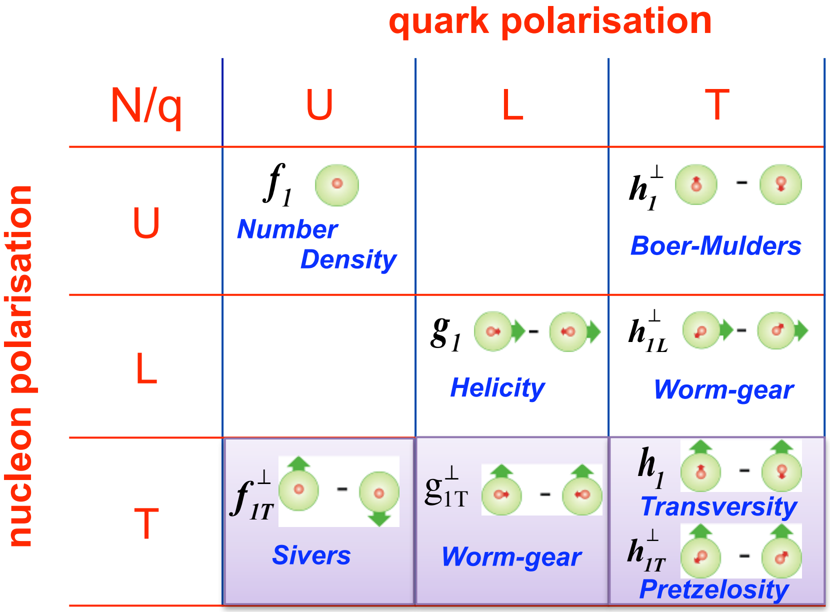
Fractional energy of the observed final state hadron

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

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

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

# The SIDIS Case



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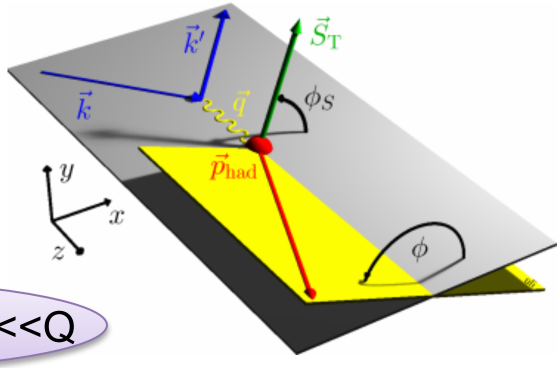
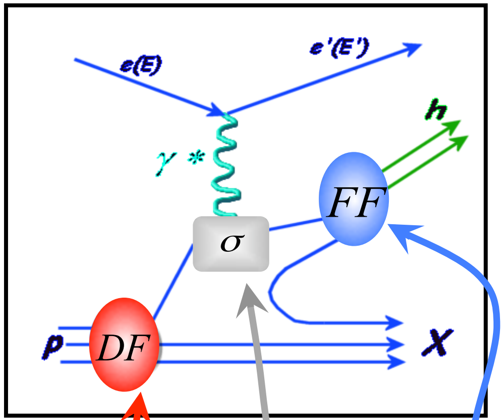
**SIDIS cross section (transversely pol. target):**



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



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

$h_1 \otimes H_1^\perp$

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

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

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

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

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

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

# First Evidences

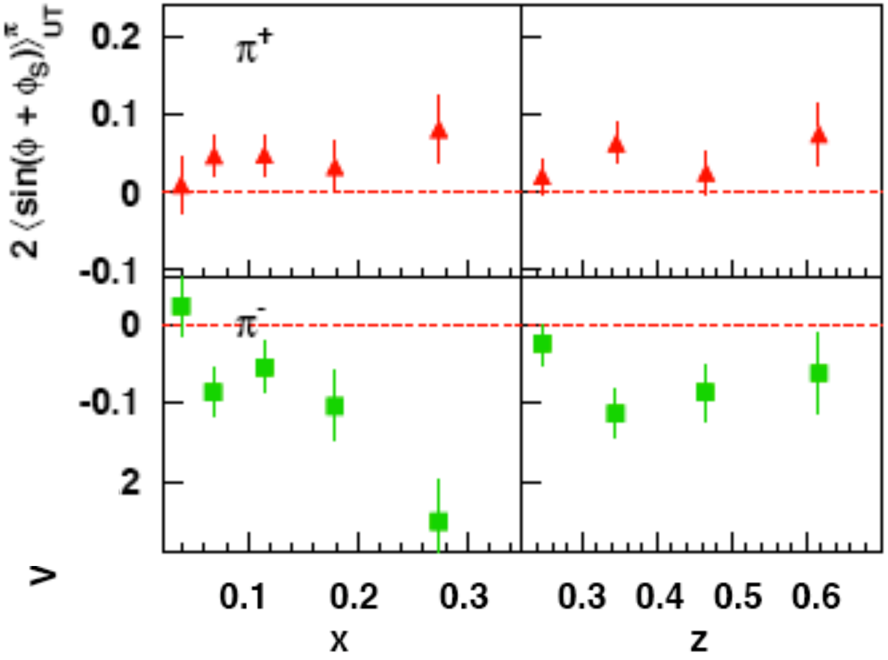
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^{\perp}$$

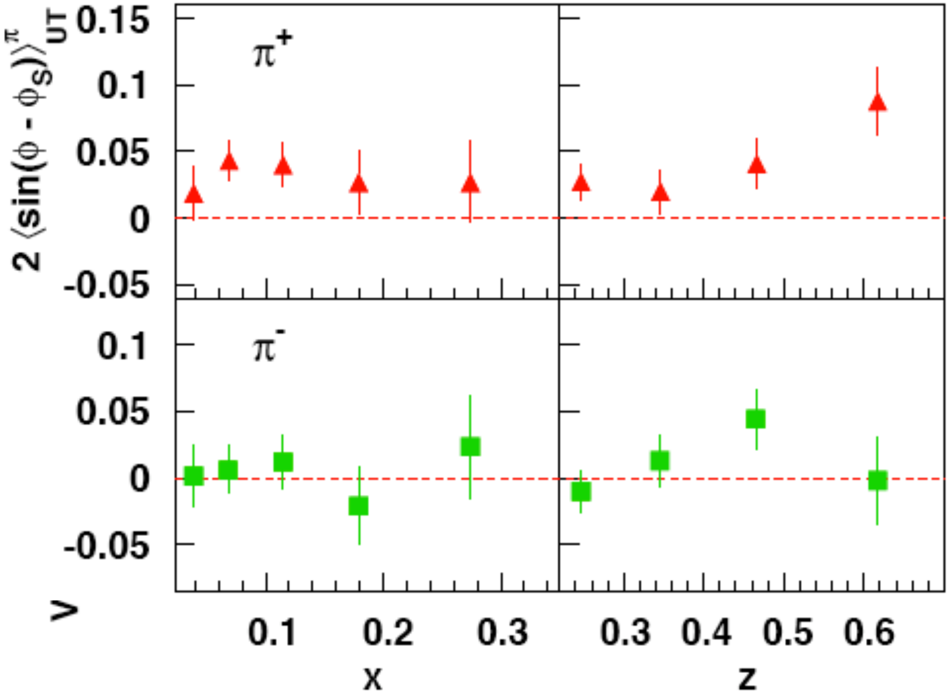
SIDIS:
ep → e'hX

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

2005: First evidence from HERMES measuring SIDIS on proton

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

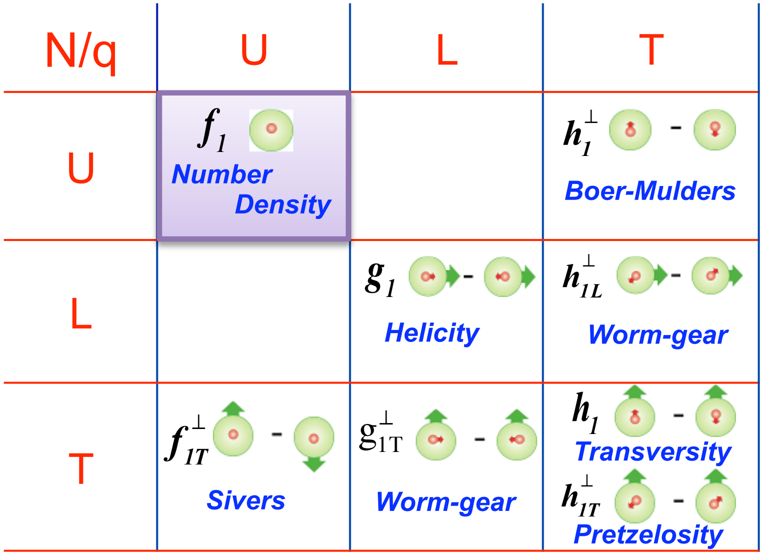




Non-zero transversity !!
Non-zero Collins function !!

Non-zero Sivers function !!

# NUMBER DENSITY



nucleon polarisation

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| T | $f_{1T}^\perp$ - *Sivers* | $g_{1T}^\perp$ - *Worm-gear* | $h_1$ - *Transversity*<br>$h_{1T}^\perp$ - *Pretzelosity* |

## (THE BASELINE)

# The hadron multiplicities

$f_1 \cdot D_1$

LO interpretation:

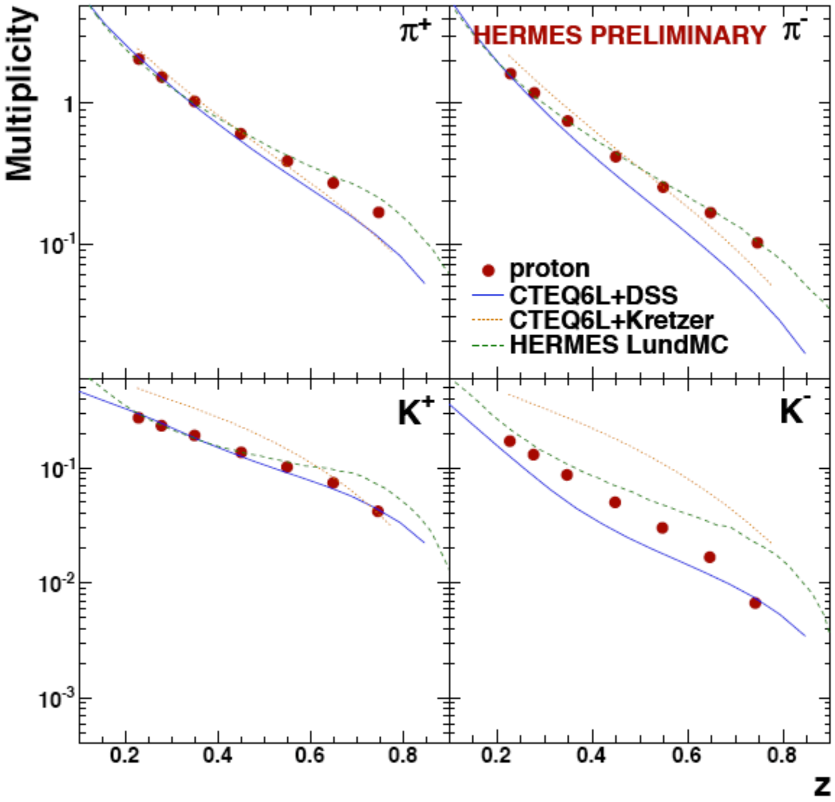
$$M_N^h = \frac{1}{N_N^{DIS}(Q^2)}\frac{dN_N^h(z,Q^2)}{dz} = \frac{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2)}$$

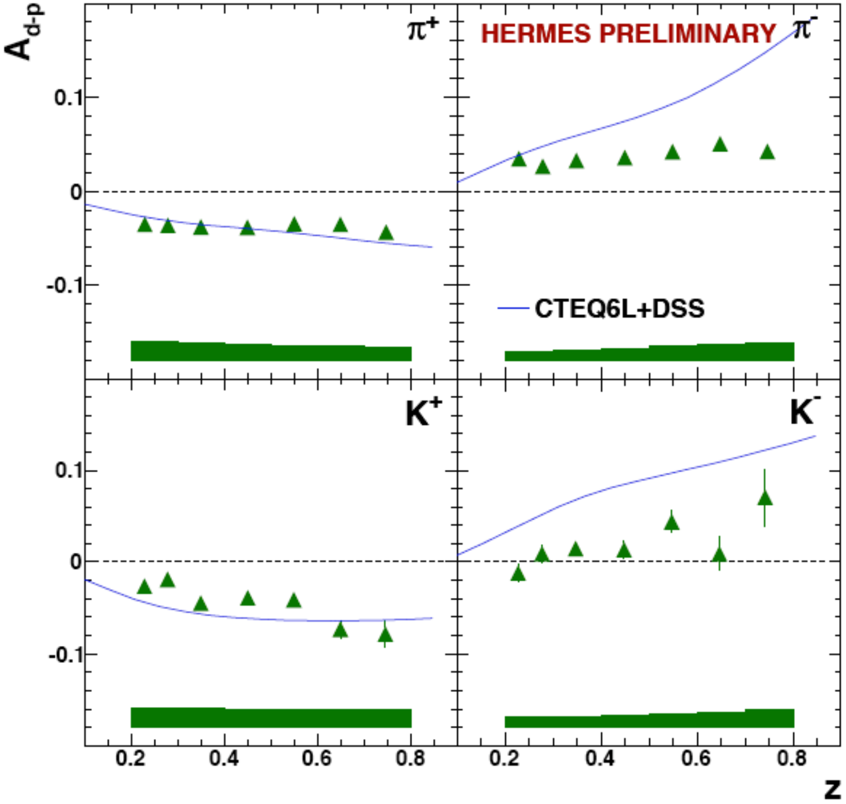
SIDIS data constrain fragmentation at low c.m. energy and bring enhanced flavor sensitivity

Proton-deuteron asymmetry:

$$A_{d-p}^h \equiv \frac{M_d^h - M_p^h}{M_d^h + M_p^h}$$

Reflects different flavor content
Correlated systematics cancels

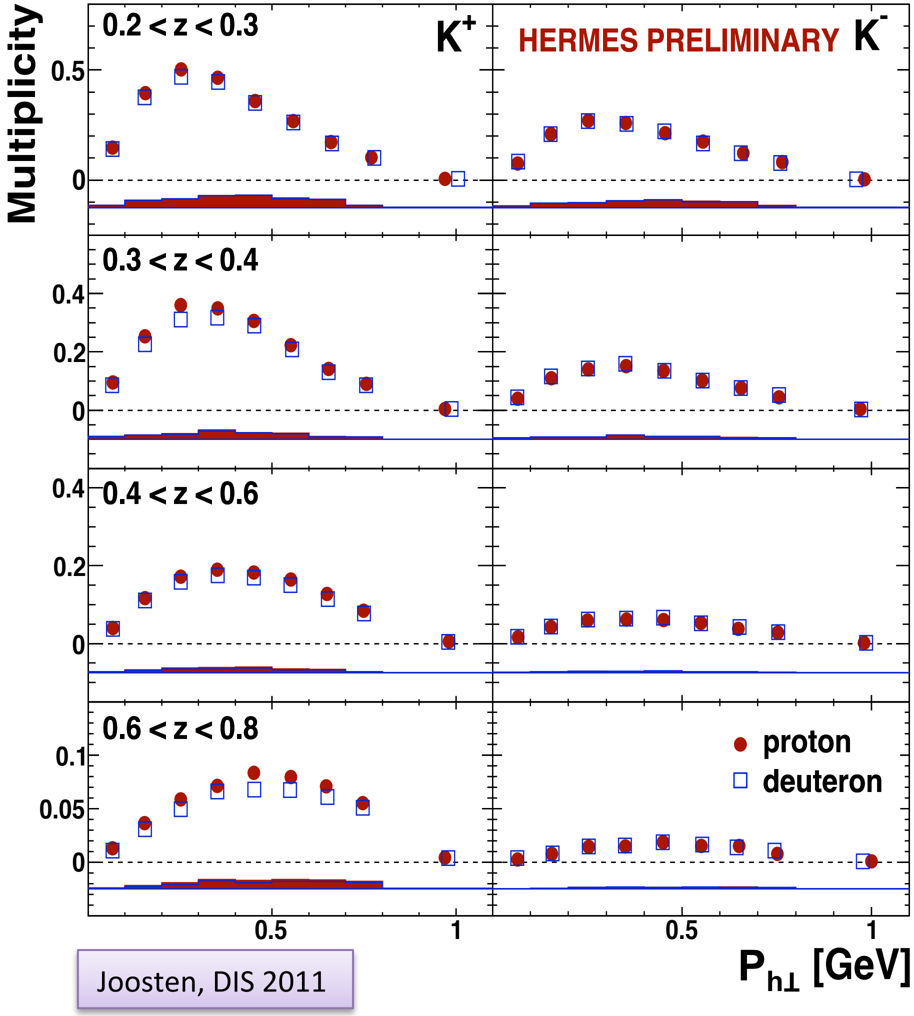




# The $P_{h\perp}$-unintegrated multiplicities $f_1 \otimes D_1$

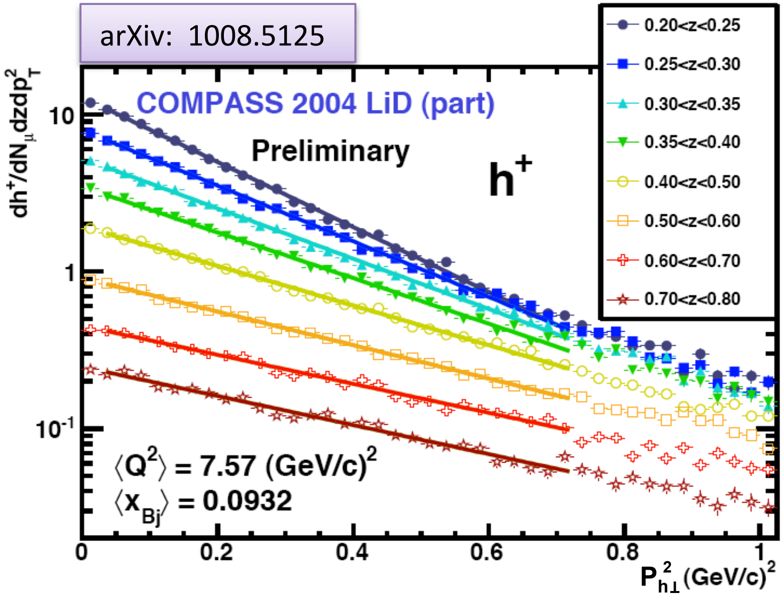
Disentanglement of z and $P_{h\perp}$: access to the transverse intrinsic quark $k_T$ and fragmentation $p_{T,}$

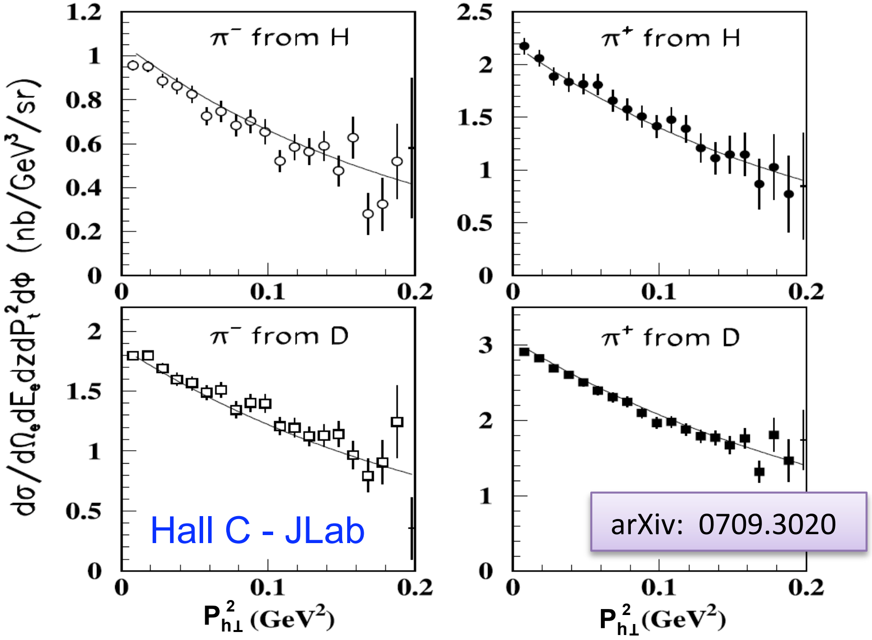
i.e. from gaussian anstaz $\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$



Joosten, DIS 2011

arXiv: 1008.5125



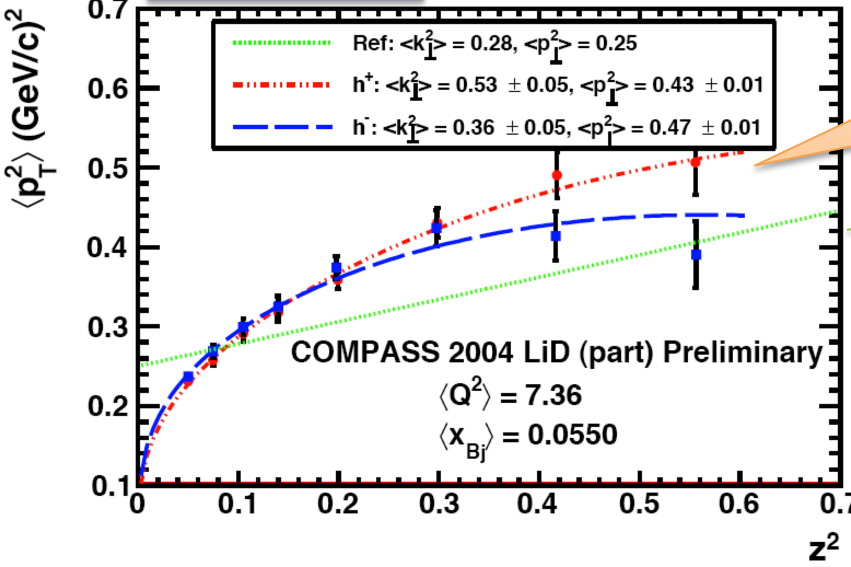


arXiv: 0709.3020

# The evolution

$f_1 \otimes D_1$

arXiv: 1008.5125

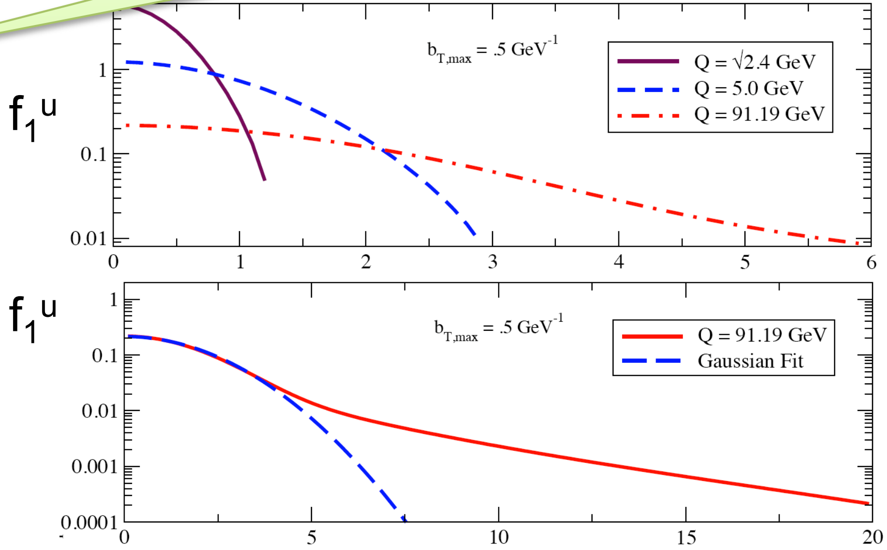


Is $p_T$ independent of z ?

$$\left\langle P_{h\perp}^2\right\rangle = z^2\left\langle k_T^2\right\rangle + z^\alpha(1-z)^\beta\left\langle p_T^2\right\rangle$$

Gaussian ansatz

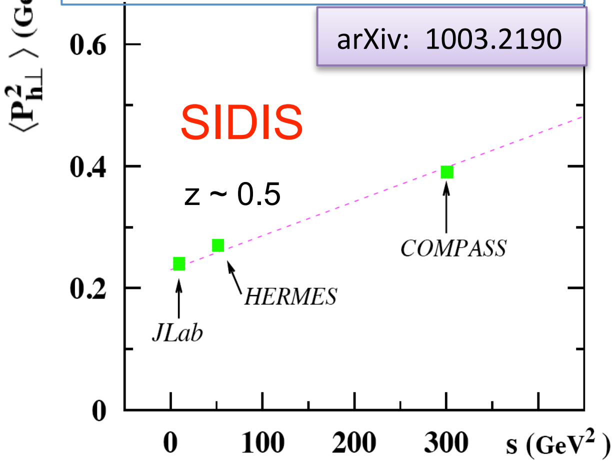
$$\left\langle P_{h\perp}^2\right\rangle = z^2\left\langle k_T^2\right\rangle + \left\langle p_T^2\right\rangle$$

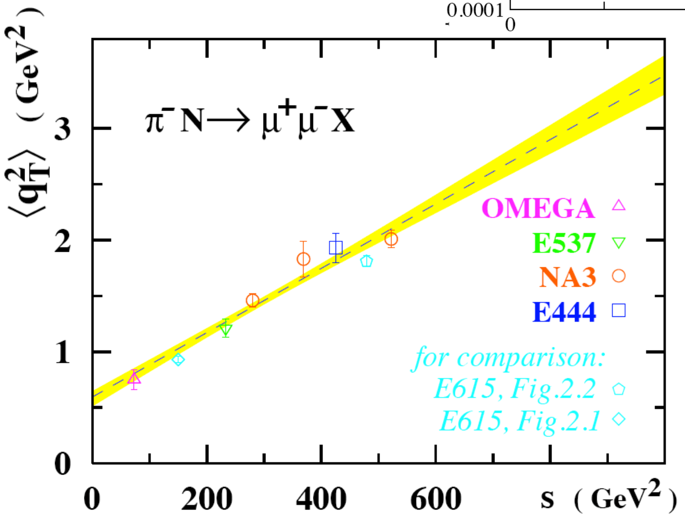


arXiv: 1101.5057

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

arXiv: 1003.2190





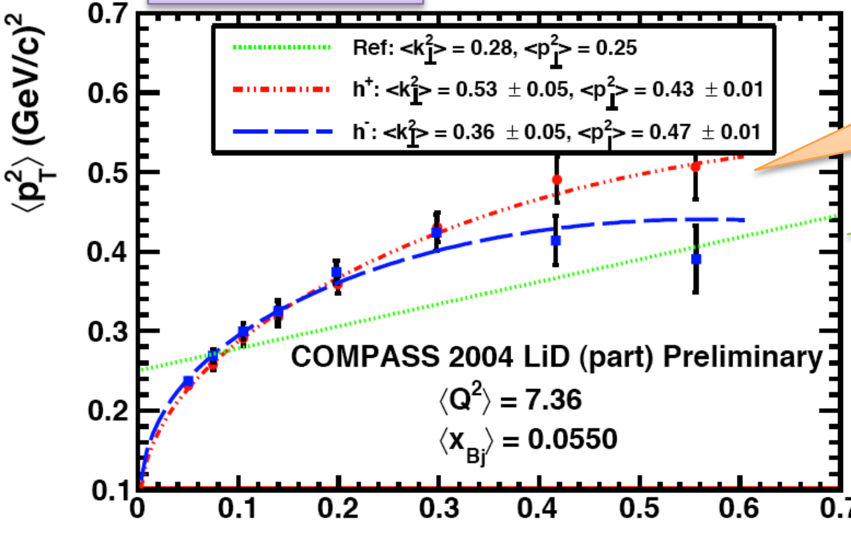
**Indirect indication of a $k_T$ and $p_T$ broadening with c.m. energy:**

**TMD $Q^2$ evolution**

# The evolution

$f_1 \otimes D_1$

arXiv: 1008.5125



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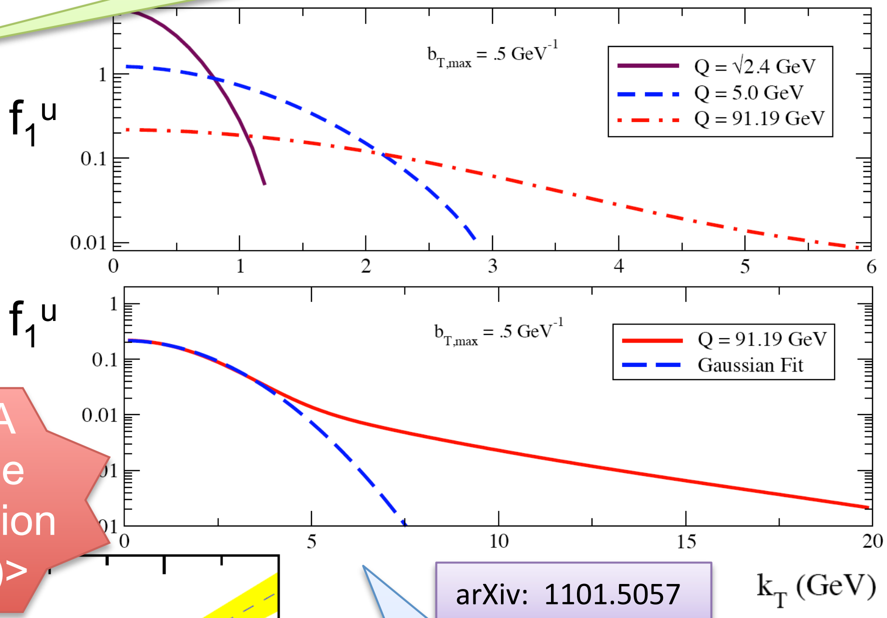
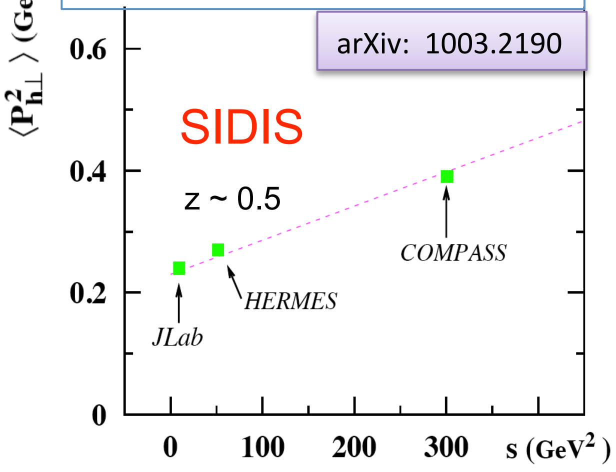


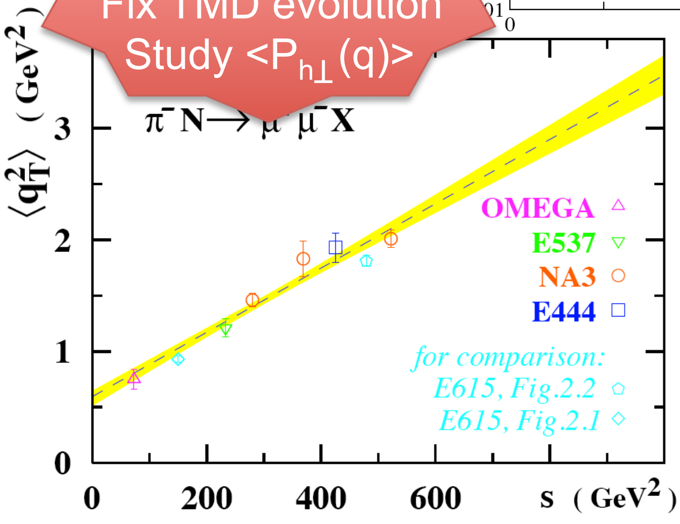
arXiv: 1101.5057

Precise DATA
Wide Q² range
Fix TMD evolution
Study $\langle P_{h\perp}(q)\rangle$

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

arXiv: 1003.2190

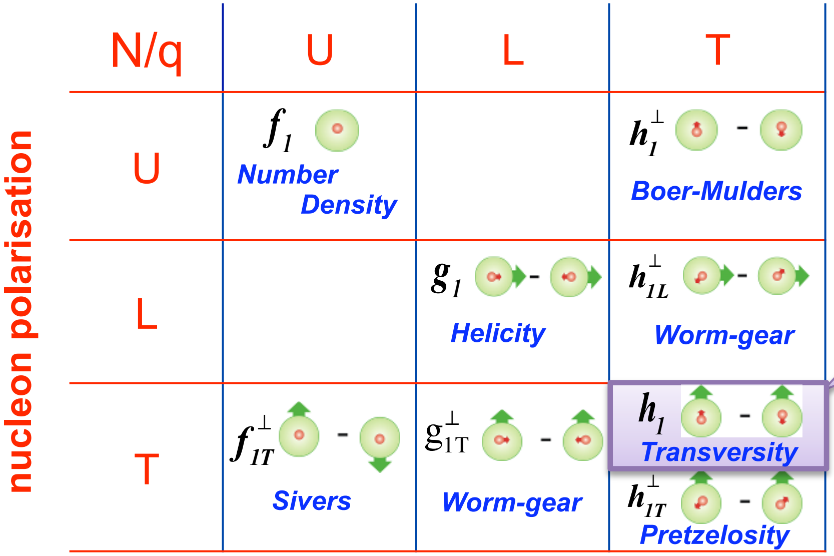




**Indirect indication of a $k_T$ and $p_T$ broadening with c.m. energy:**

**TMD Q² evolution**

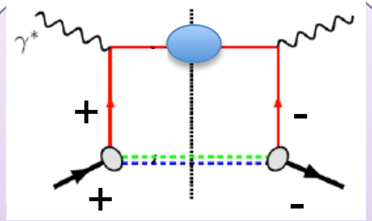
# TRANSVERSITY



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**<br>$h_{1T}^\perp$ **Pretzelosity** |

Chirally-odd



First evidence: 2005

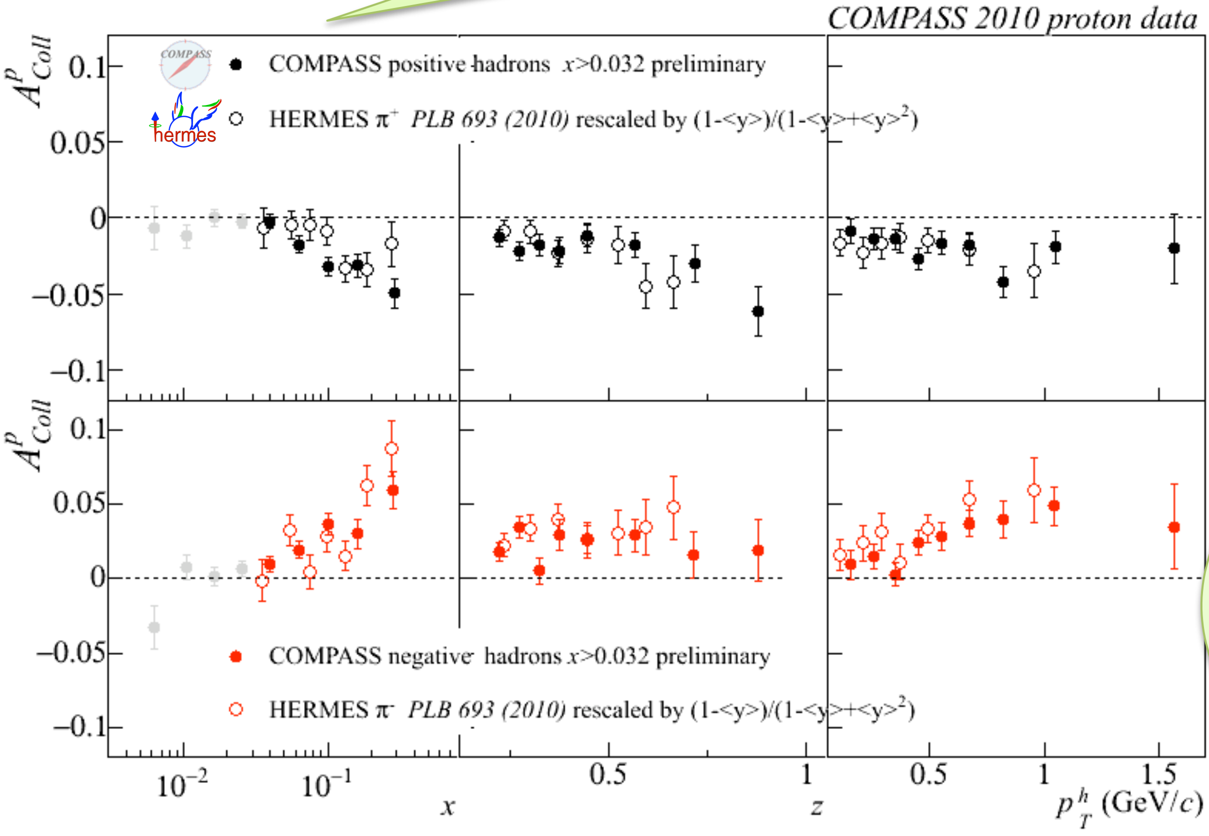
# (THE COLLINEAR MISSING PIECE)

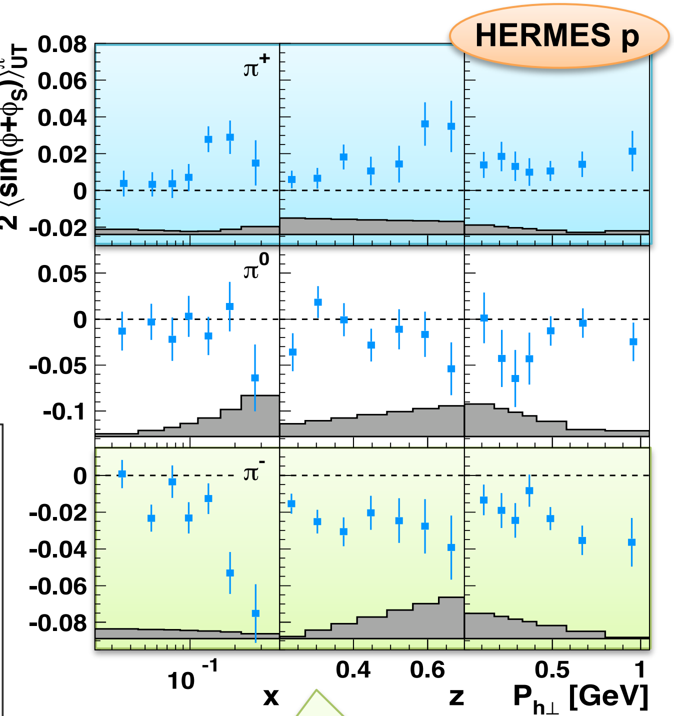
# The Collins SIDIS amplitude

$h_1 \otimes H_1^{\perp}$

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

Consistent non-zero signals for charged pions





Scattering mostly off u quark thanks to greater number density and electric charge

Opposite sign for pions reveals Collins features

# Collins frag. @ B-factories

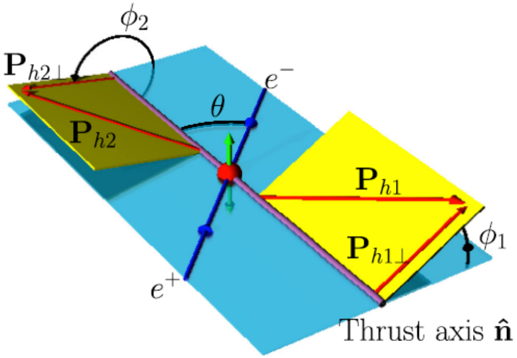
$H_1^{\perp} \otimes H_1^{\perp}$

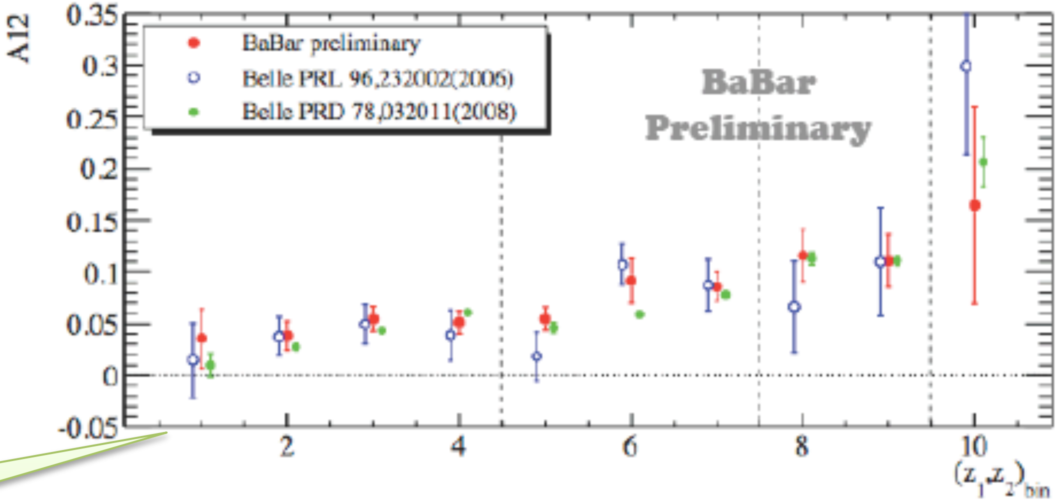
$$\frac{d\sigma(ee \to hhX)}{d\Omega dz_1 dz_2 d\phi_1 d\phi_2} \propto (1+\cos^2\theta) D_1^{(0)} D_1^{(0)} + \mu \sin^2\theta \cos(\phi_1+\phi_2) H_1^{\perp,(1)} H_1^{\perp,(1)}$$

BaBar preliminary: $\mathcal{L} \approx 45$ fb$^{-1}$

Belle Off-peak: $\mathcal{L} \approx 29$ fb$^{-1}$

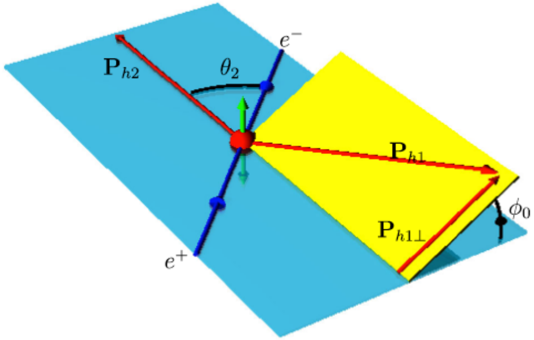
Belle full statistics (supersede previous results) $\mathcal{L} \approx 547$ fb$^{-1}$

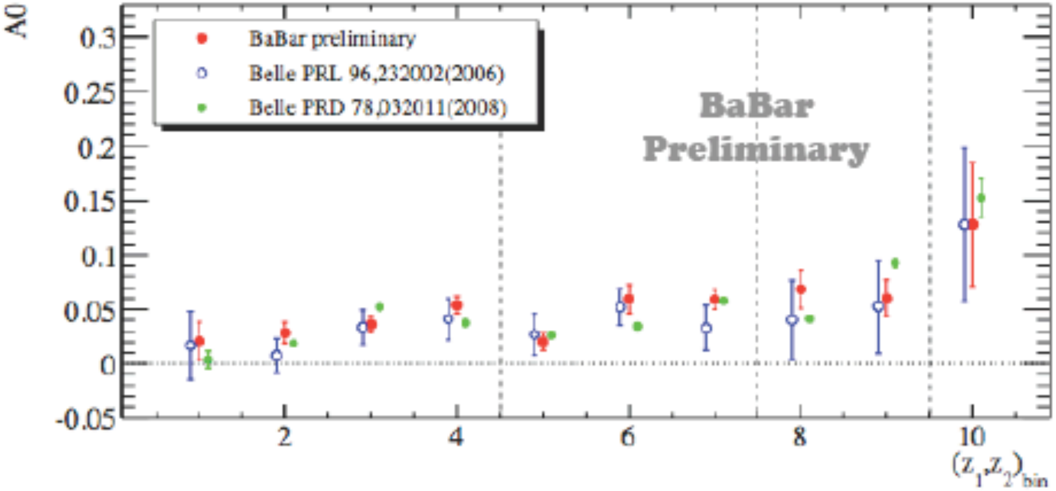




Different from zero signal!

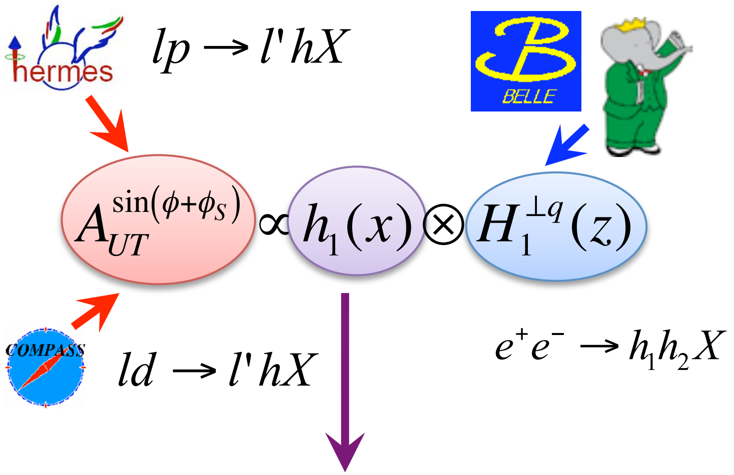
At low z little memory of the struck quark





# Transversity signals

$h_1 \otimes H_1^{\perp}$



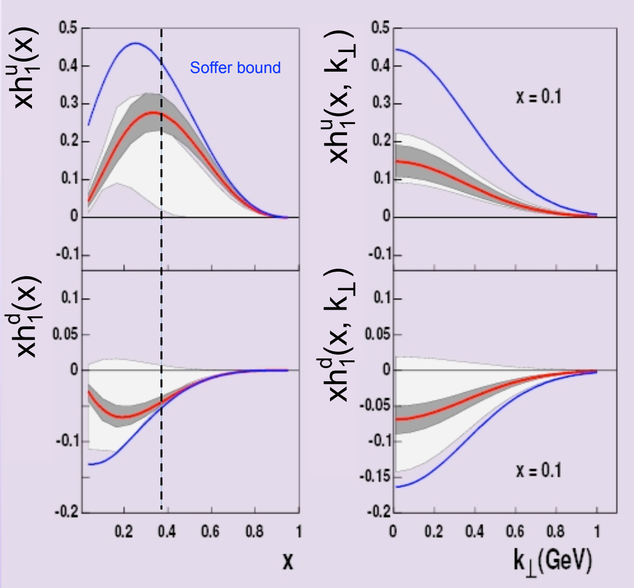
$lp \rightarrow l'hX$

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

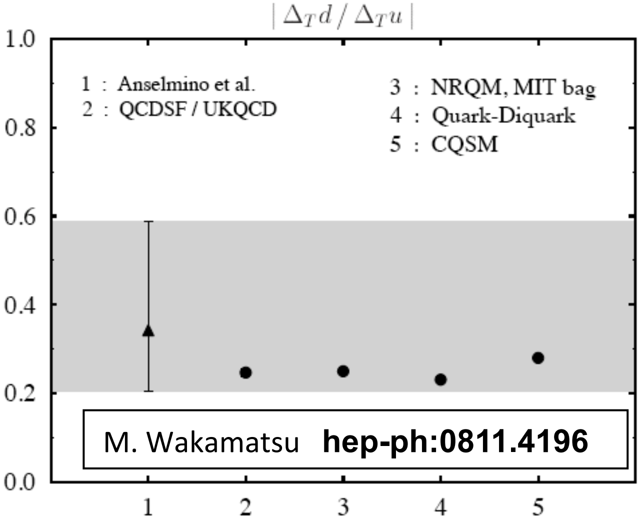
$ld \rightarrow l'hX$

$e^+e^- \rightarrow h_1h_2X$

## First extraction of Transversity!



Anselmino et al. Phys. Rev. D 75 (2007)



M. Wakamatsu **hep-ph:0811.4196**

## Tensor charge

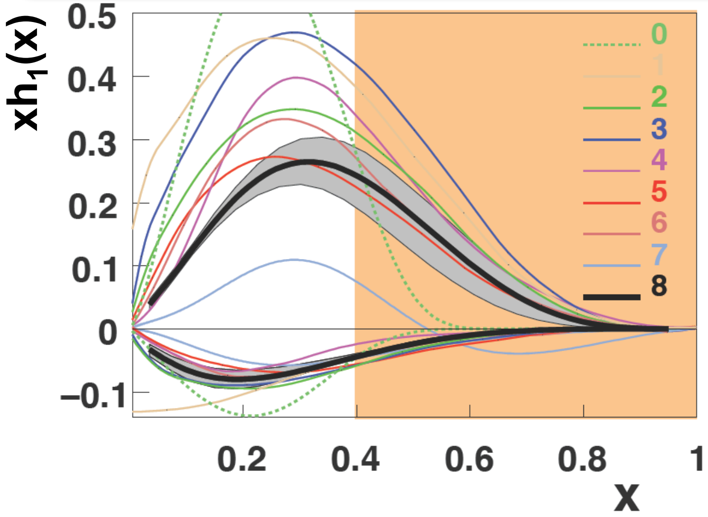
$$\int_0^1 dx\left[h_1^q(x) - \bar{h}_1^q(x)\right] = \delta q$$

$$\delta u = 0.54^{+0.09}_{-0.22}$$

$$\delta d = -0.23^{+0.09}_{-0.16}$$

M. Anselmino et al
**hep-ph:0812.4366**

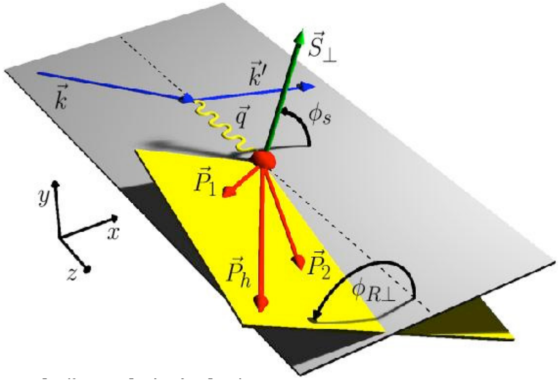
- Existing data limited to x < 0.3
- Gaussian ansatz
- Evolution from high energy colliders

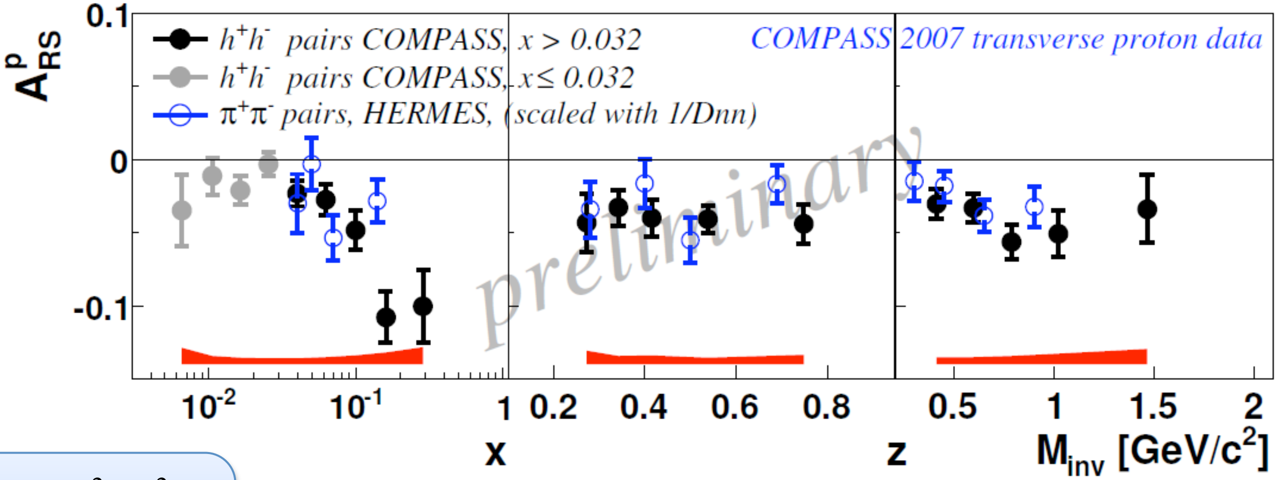


**0.** chiral color-dielectric model [Barone et al. PLB 390 (97)]
**1.** Soffer bound [Soffer et al. PRD 65 (02)]
**2.** $h_1=g_1$ [Korotkov et al. EPJC 18 (01)]
**3.** chiral quark-soliton model [Schweitzer et al., PRD 64 (01)]
**4.** chiral quark-soliton model [Wakamatsu, PLB 509 (01)]
**5.** light-cone constituent quark model [Pasquini et al., PRD 72 (05)]
**6.** quark-diquark model [Cloet, Bentz, Thomas, PLB 659 (08)]
**7.** quark-diquark model [Bacchetta, Conti, Radici, PRD 78 (08)]
**8.** parametrization [Anselmino et al., arXiv:0807.0173]

# Two hadron asymmetries

$h_1 \otimes H_1^{\triangleleft}$

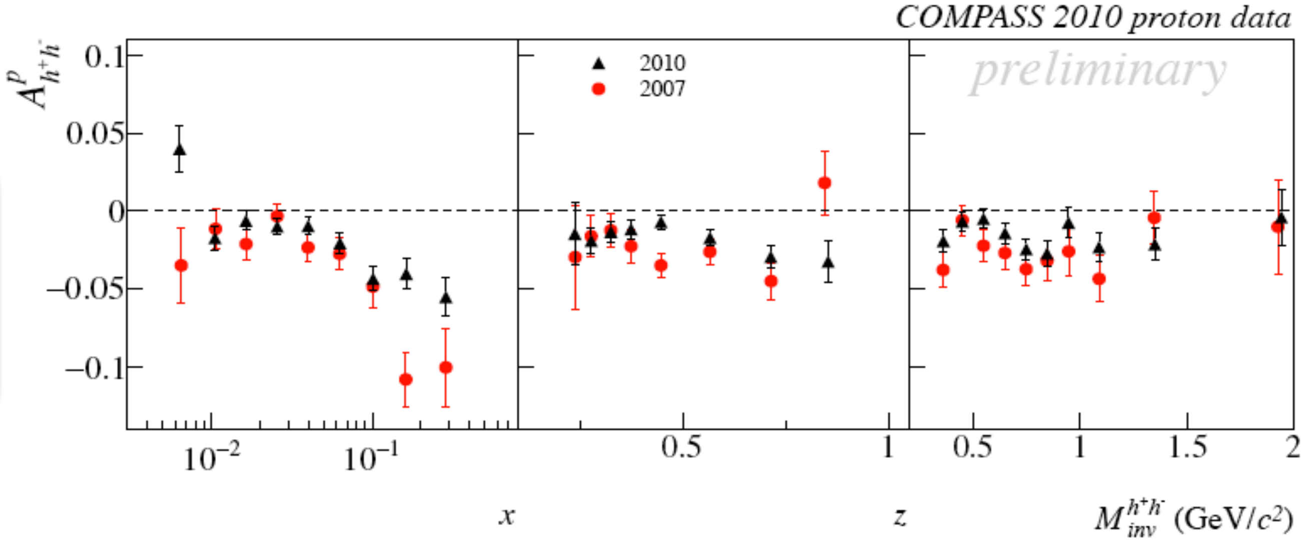




$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta} \propto \frac{\sum_q e_q^2 h_1(x,Q^2) H_1^{\triangleleft}(z,M_h^2,Q^2)}{\sum_q e_q^2 f_1(x,Q^2) D_1^{\triangleleft}(z,M_h^2,Q^2)}$$

Issue with unknown pp-terms in partial wave expansion

- Survives $P_h$ integration
- Collinear factorization (simple product)
- DGLAP volution
- Universality



# Transversity signals

$h_1 \otimes H_1^{\triangleleft}$

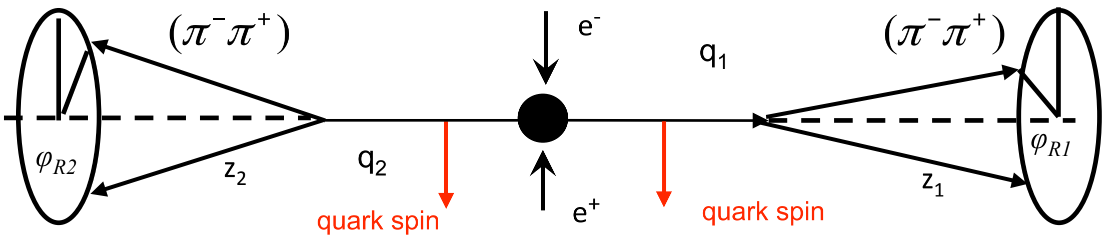
$lp \to l'\pi^+\pi^- X$

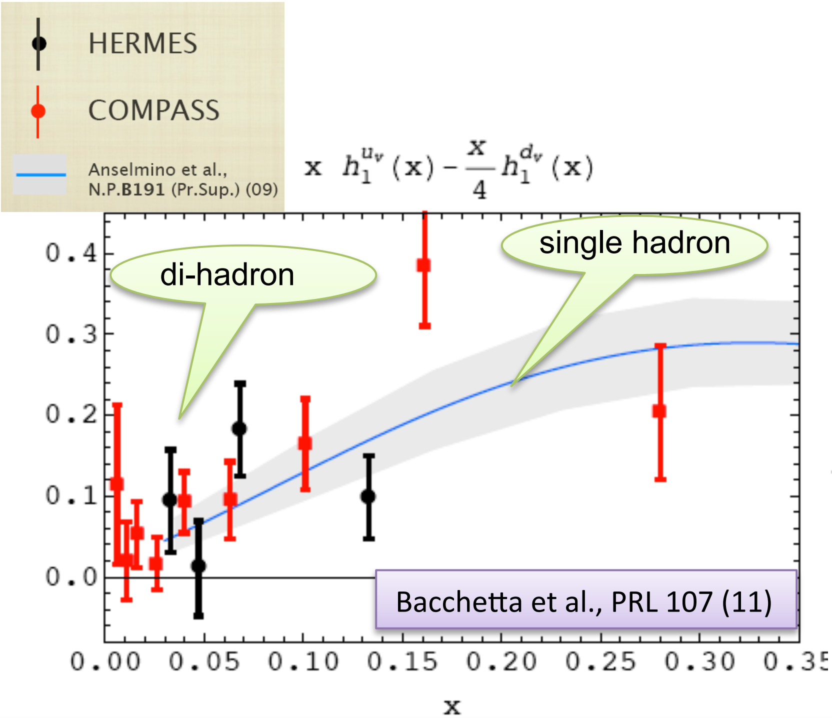
$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)} \propto \sin\vartheta\; h_1(x) \otimes H_1^{\triangleleft q}(z)$

1st collinear extraction !

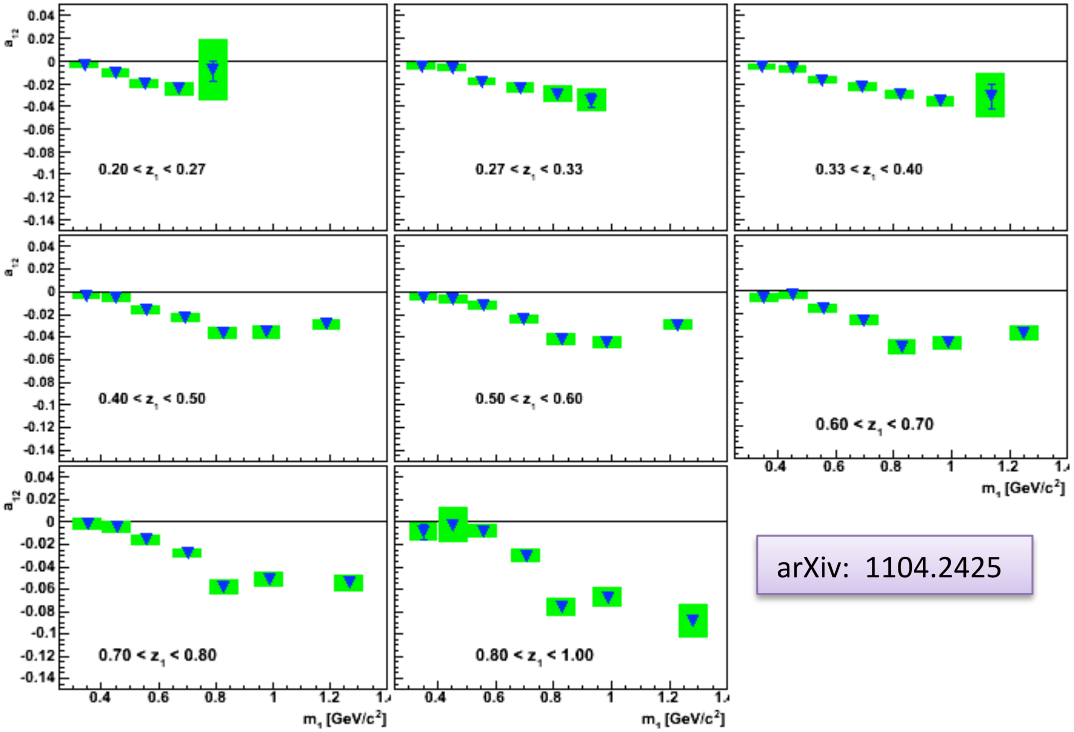
$e^+e^- \to (\pi^+\pi^-)(\pi^+\pi^-)X$

Different from zero correlations !





Bacchetta et al., PRL 107 (11)



arXiv: 1104.2425

# Transversity signals

$h_1 \otimes H_1^{\triangleleft}$

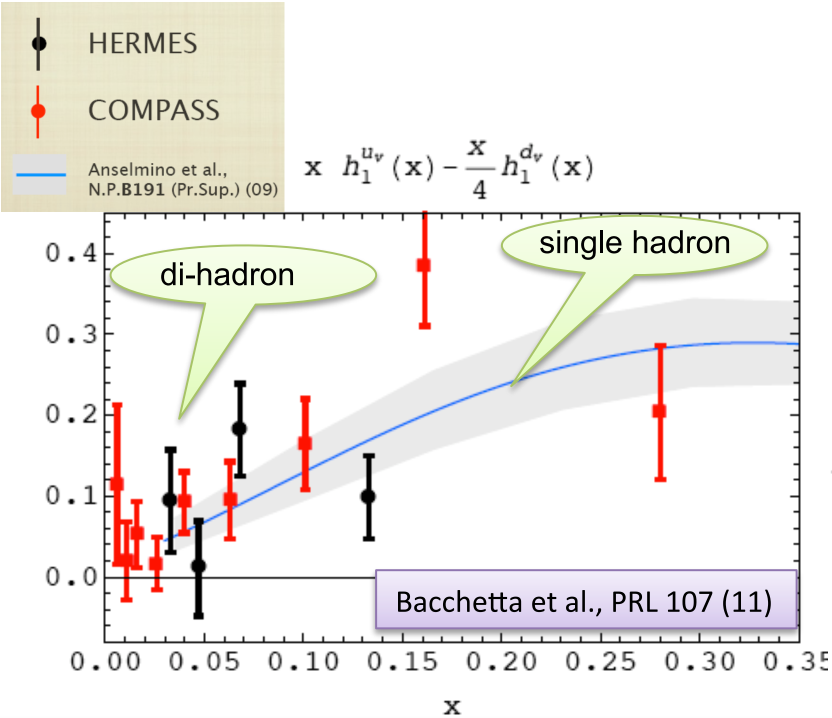
$lp \to l'\pi^+\pi^- X$

hermes COMPASS

Precise DATA
wide x range
test TMD formalism
tensor charge

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

1st collinear extraction !

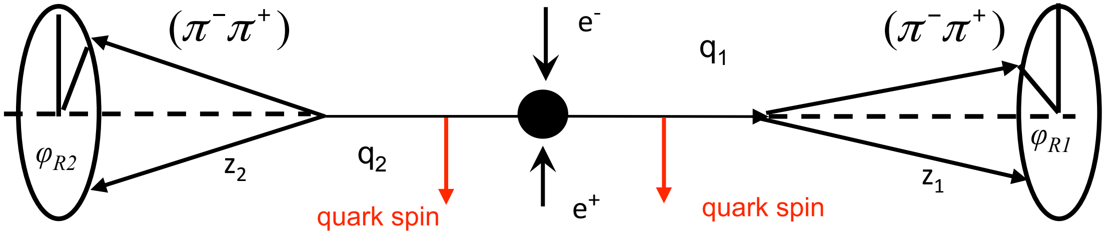


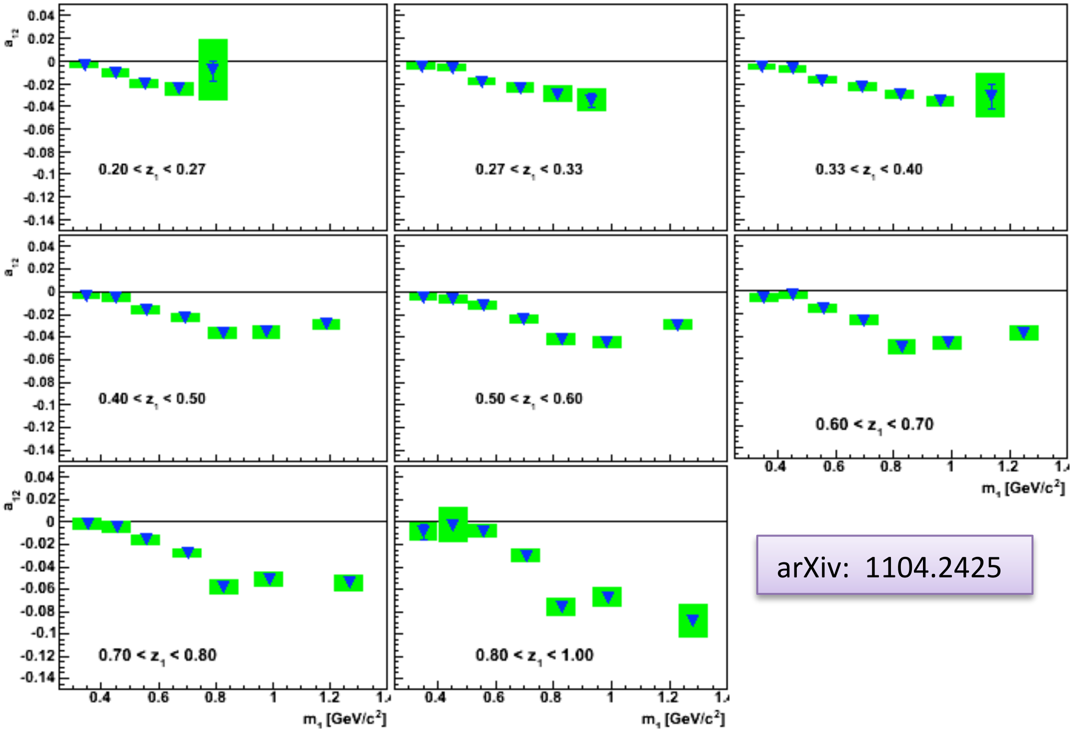
Bacchetta et al., PRL 107 (11)

BELLE

$e^+e^- \to (\pi^+\pi^-)(\pi^+\pi^-)X$

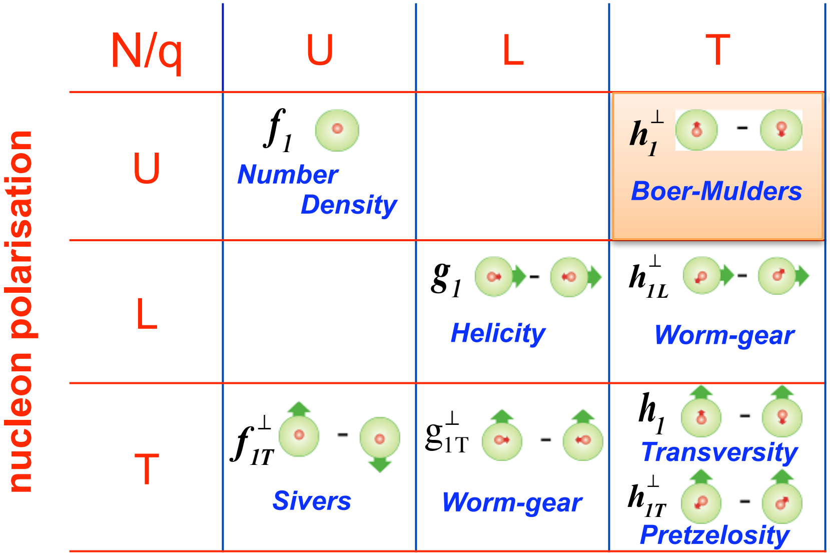
Different from zero correlations !





arXiv: 1104.2425

# CAHN & BOER-MULDERS



nucleon polarisation

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

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

## (THE NEGLECTED EFFECTS)

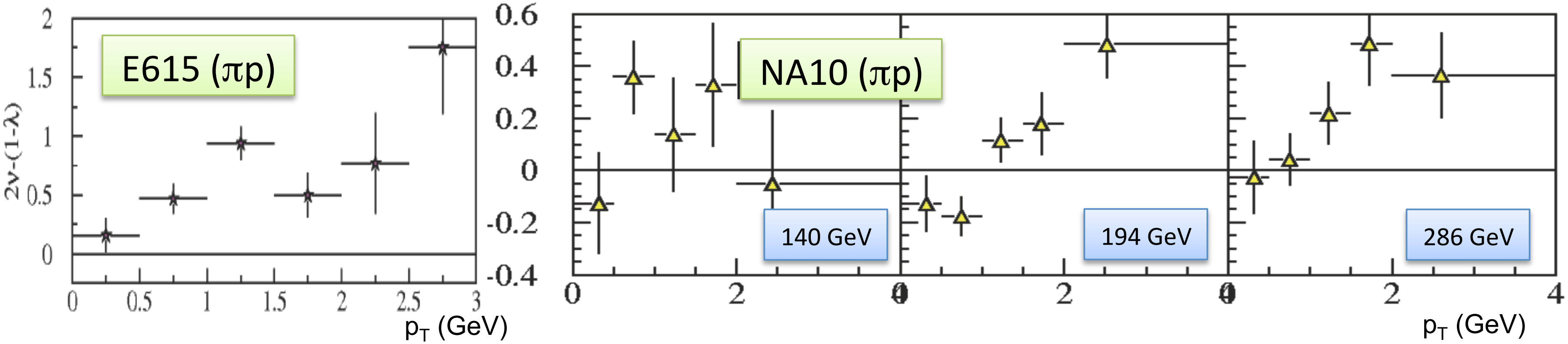
# The Lam-Tung relation

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

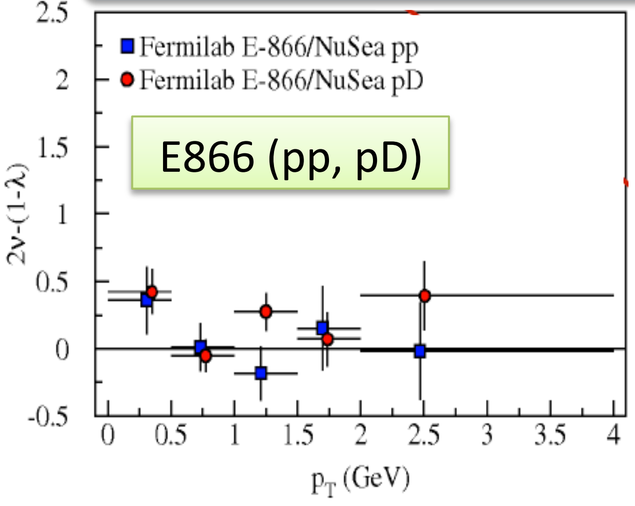
$$\frac{d\sigma^{DY}(hp \to eeX)}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

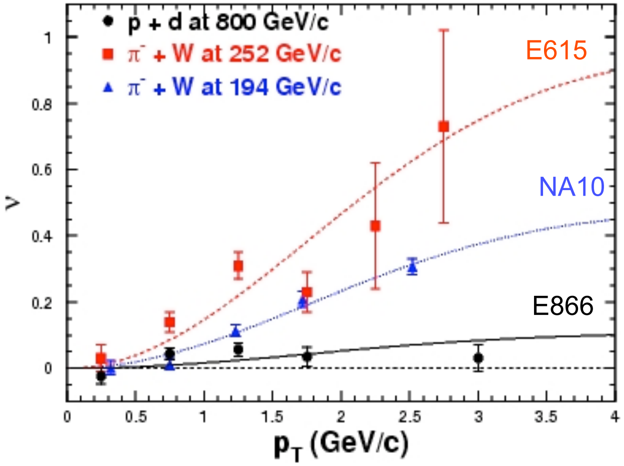
$$(1-\lambda) = 2\nu$$

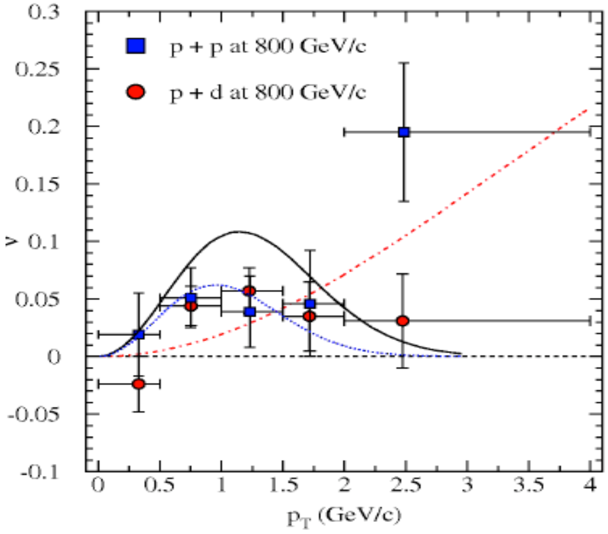
Preserved by NLO and resummation
Analogous of SIDIS Callan-Gross



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







# The azimuthal modulation

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

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

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

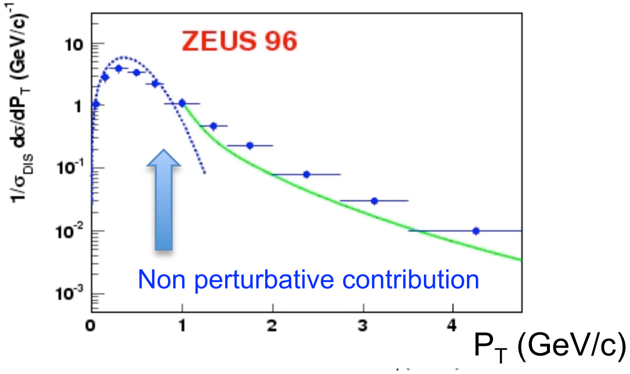
$h_1^{\perp} \otimes H_1^{\perp}$

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

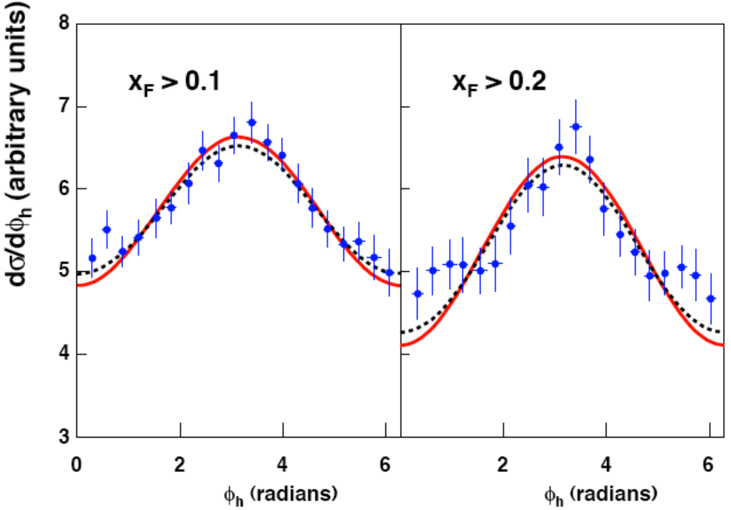
Cahn PLB 78 (1978)

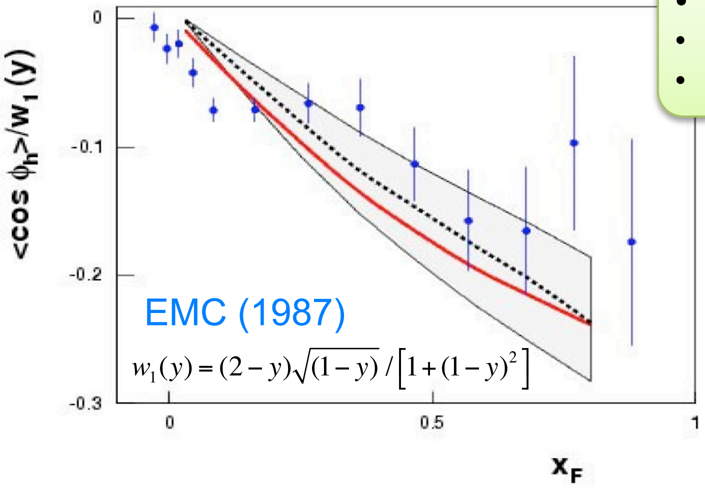
Leading-twist contribution introduced
by Boer & Mulders in 1998

Boer & Mulders PRD 57 (1998)



Till 2008: qualitative agreement with Cahn expectations





- No hadron identification
- No charge separation
- Poor statistics for cos2ϕ

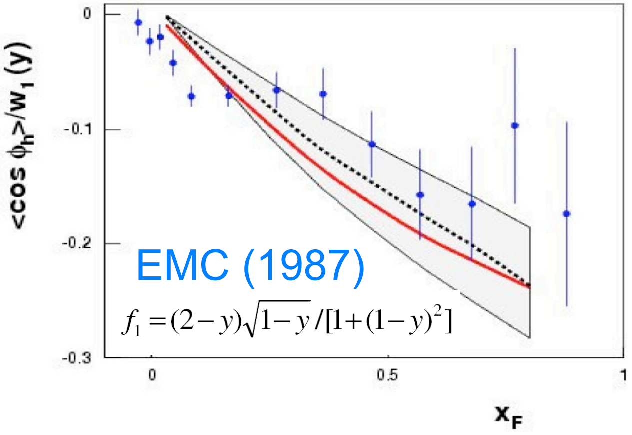
# The azimuthal modulation

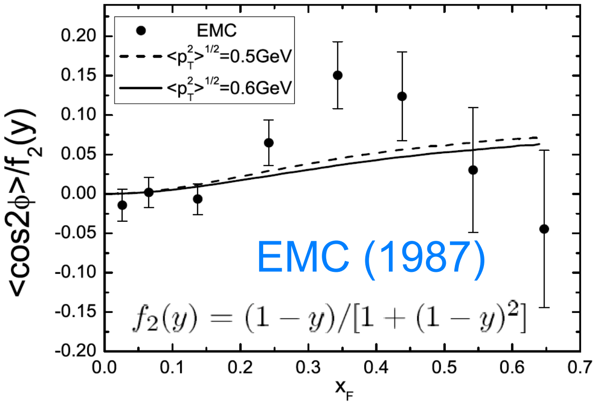
$h_1^\perp \otimes H_1^\perp$

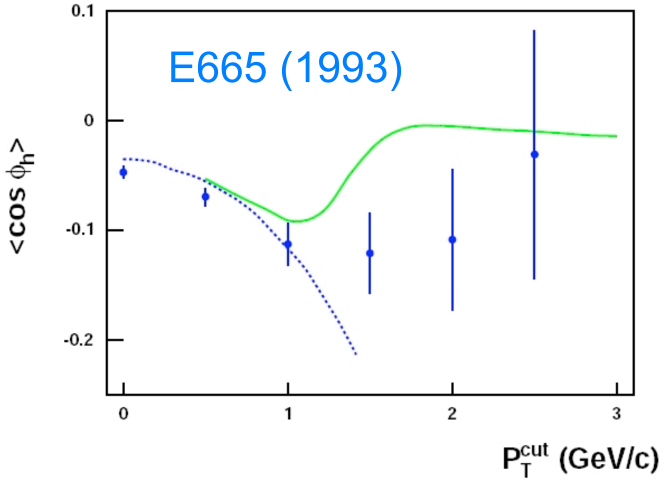
Up to 2008

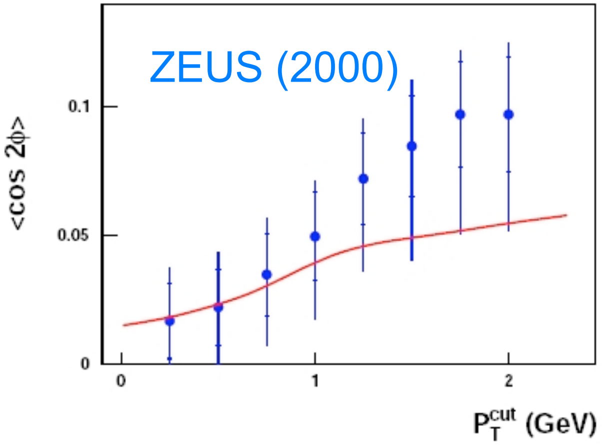
cosϕ

cos2ϕ









Qualitative agreement with expectations based on Cahn model, but investigation far to be conclusive

- No hadron identification
- No charge separation
- Poor statistics for cos2ϕ

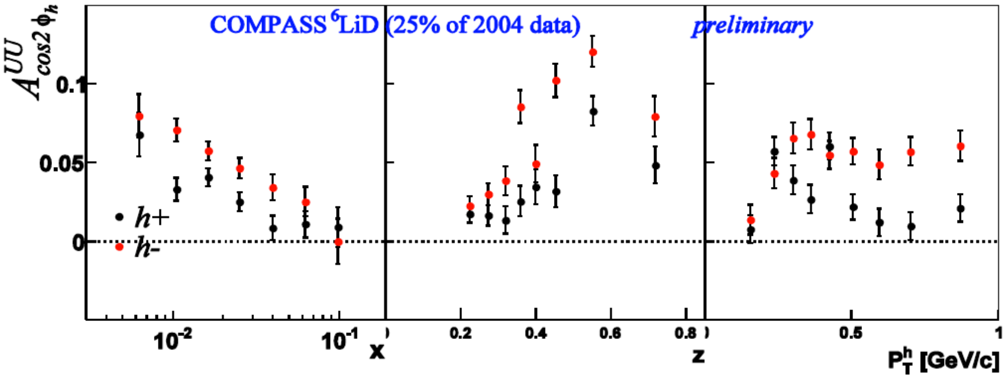
# The SIDIS cos2ϕ dependence

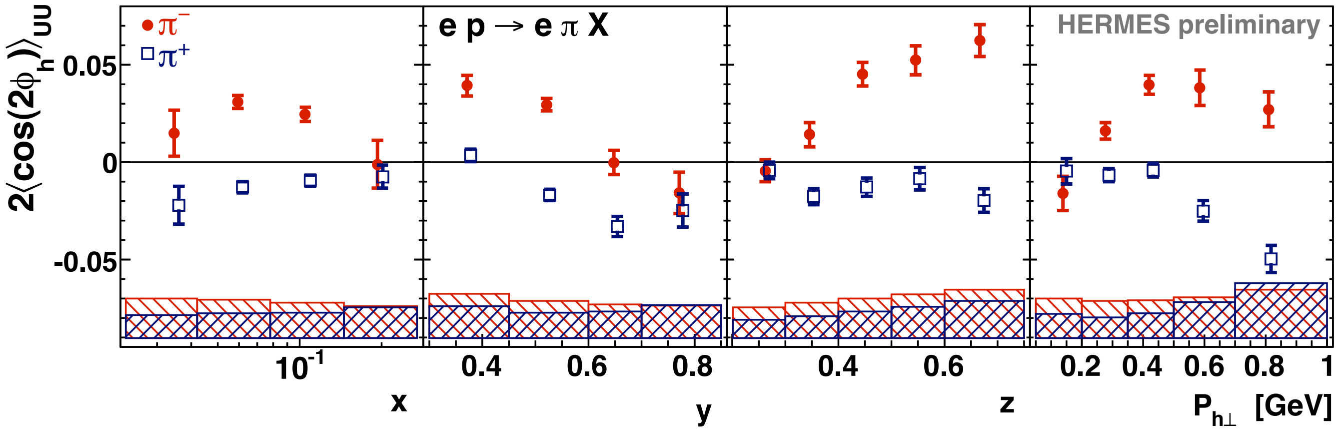
$h_1^\perp \otimes H_1^\perp$

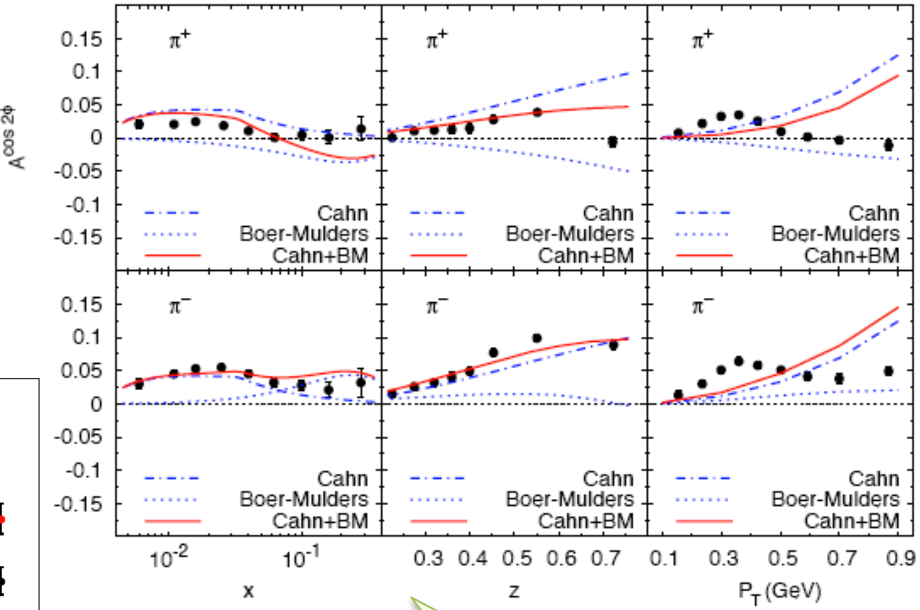
$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[ f_1 \otimes D_1 + \ldots \right] / Q^2$$

Non-zero !

Issue on DATA consistency







arXiv: 0912.5194

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

# The SIDIS cos2ϕ dependence

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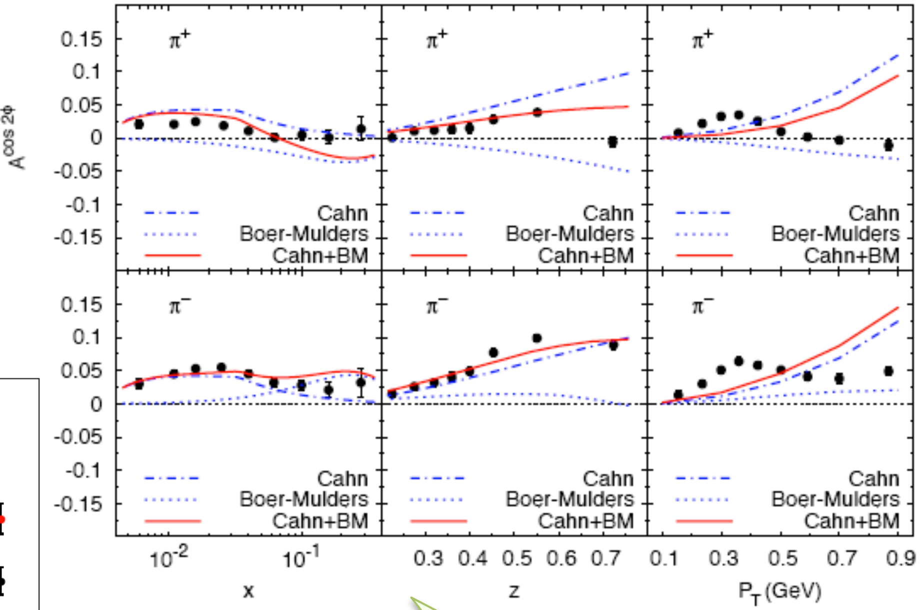
$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp} + \left[ f_1 \otimes D_1 + \ldots \right] / Q^2$$

Non-zero !

Issue on DATA consistency



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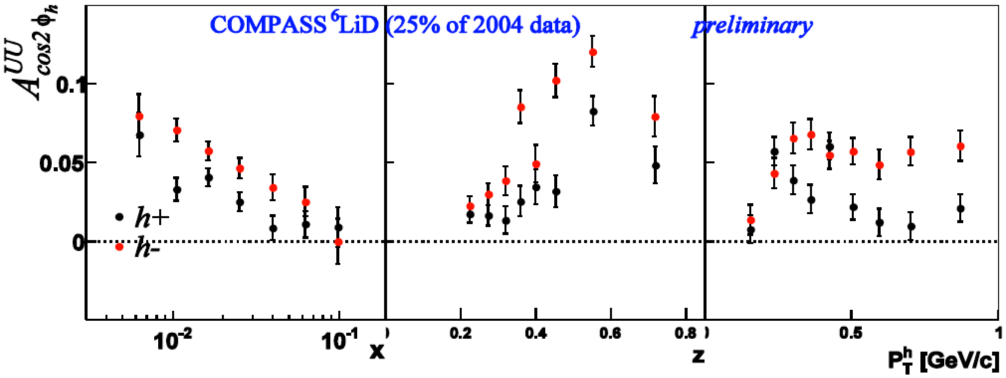
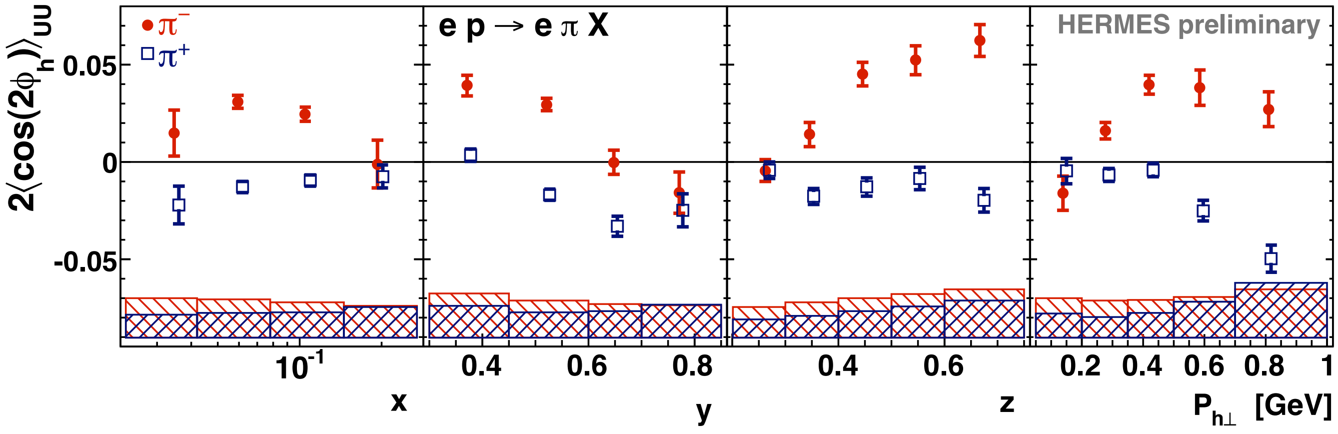
Can be explained by large uncertainty on Cahn and neglected HT effects





Precise DATA
wide kine. range
to isolate
sub-leading terms

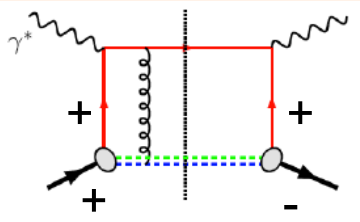
# SIVERS

nucleon polarisation

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

Naïve-T-odd

Non-trivial gauge link

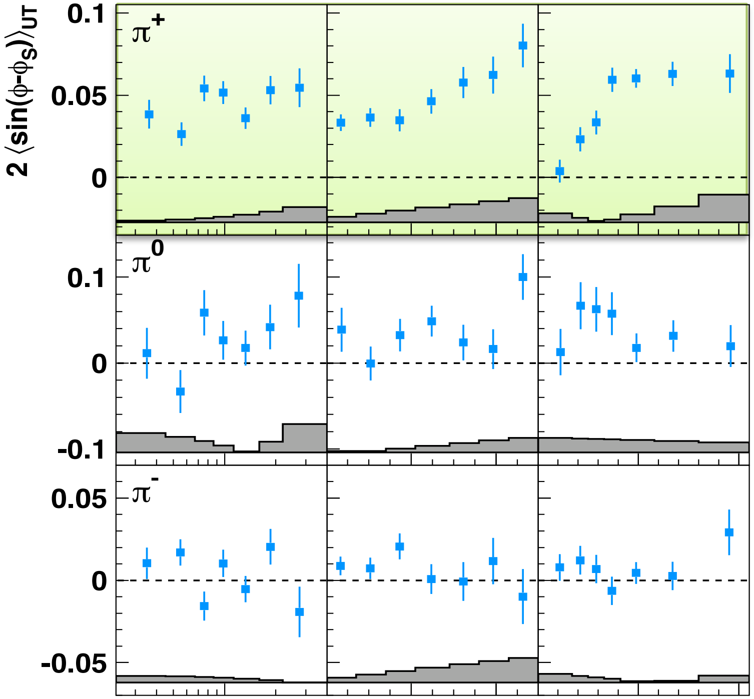


Process dependence

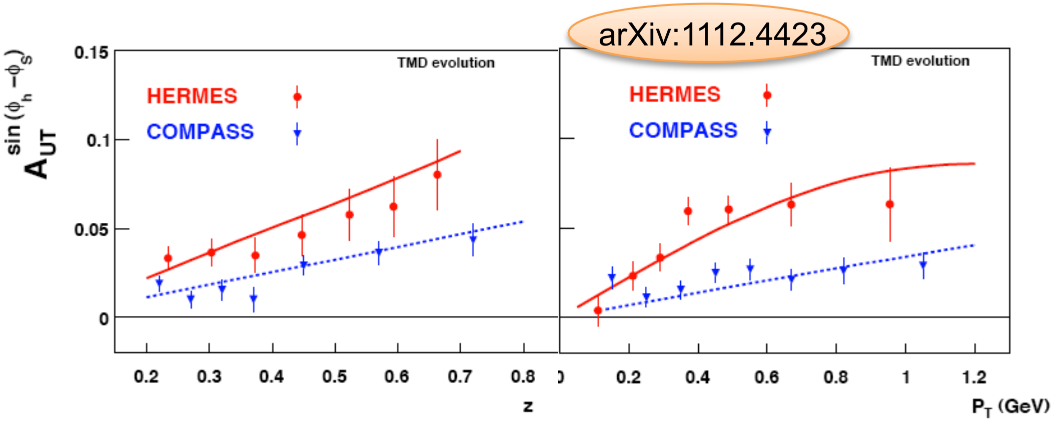
# (THE TMD CHALLENGE)

# The Sivers signals

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



arXiv:1112.4423

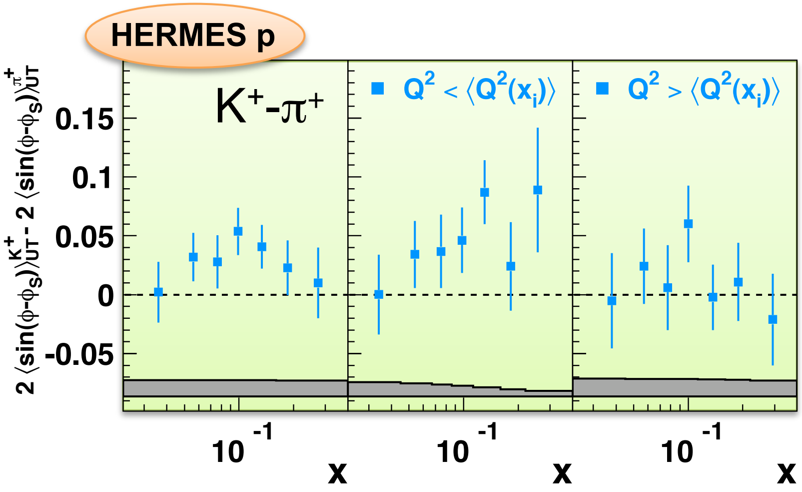


**Non zero ! for positive hadrons on proton**

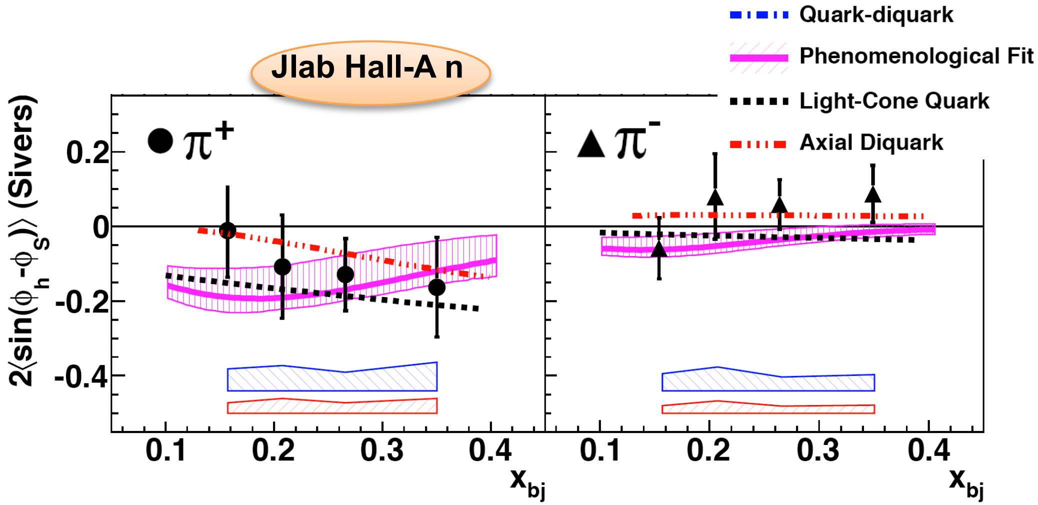
Flavor tagging: $K^+$ signals larger than $\pi^+$

No signal on deuteron target

HERMES p

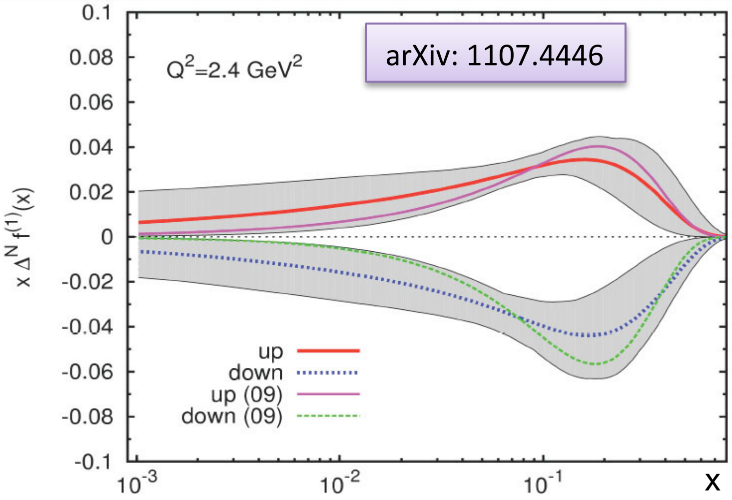


Jlab Hall-A n



# The Sivers challenges

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

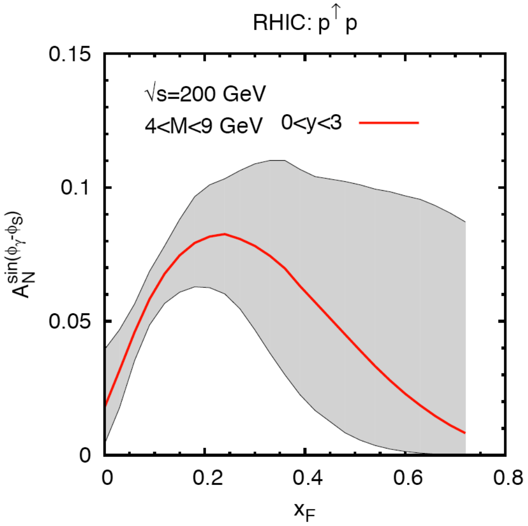


arXiv: 1107.4446

***From SIDIS to Drell-Yan:***

Sign change as a crucial test of TMDs factorization

arXiv: 0901.3078



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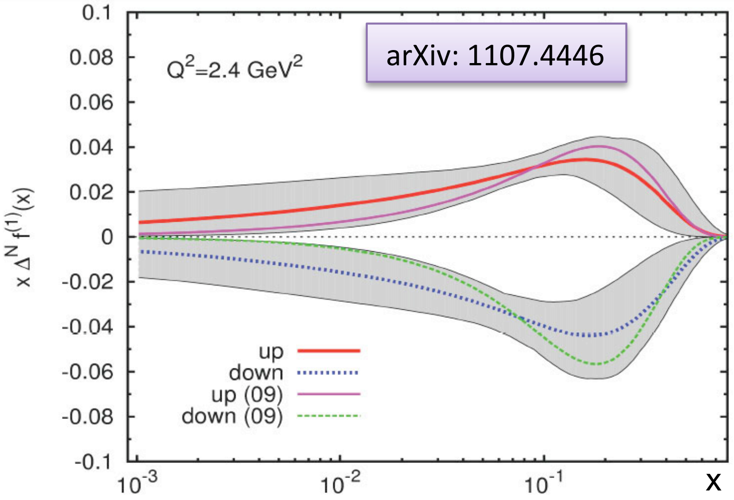
$f_{1T}^{\perp} \otimes D_1$



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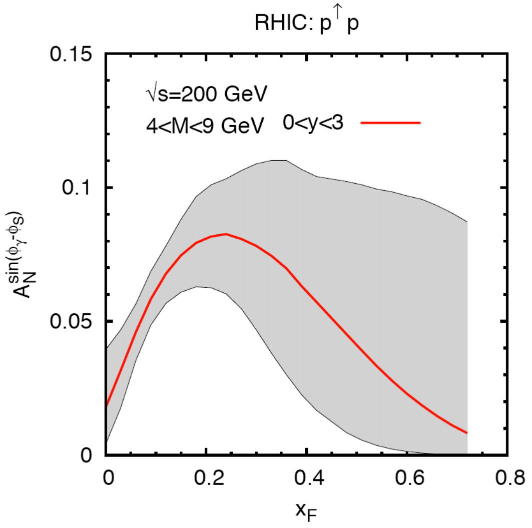
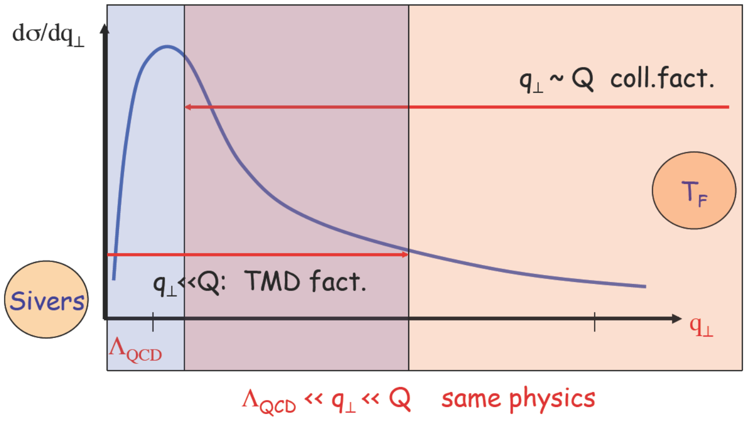


***From SIDIS to pp:*** A possible candidate to explain SSA

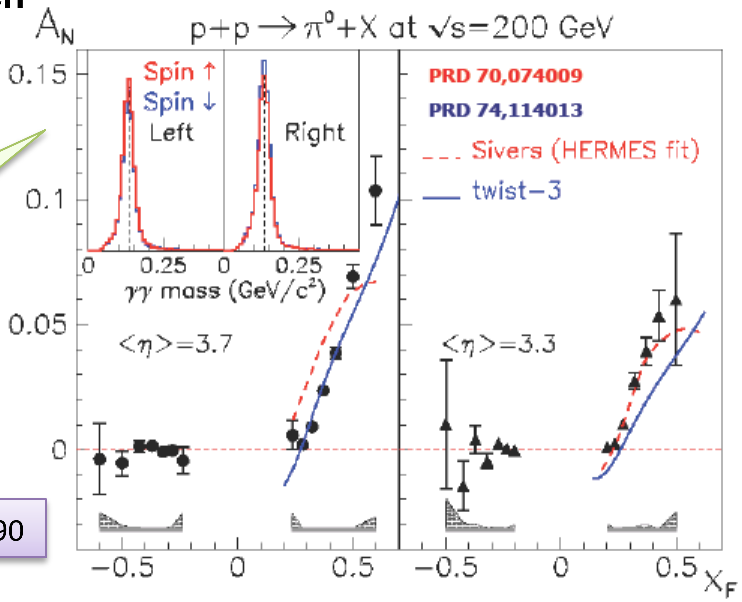
**Coverage at large $p_T$ and relation with twist-3 collinear approach**

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



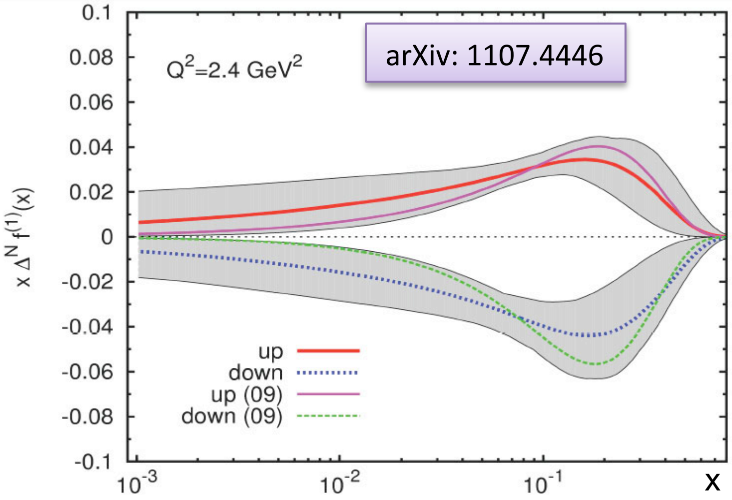
After 1st promising results a sign mismatch was found

arXiv: 0801.2990



# The Sivers challenges

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



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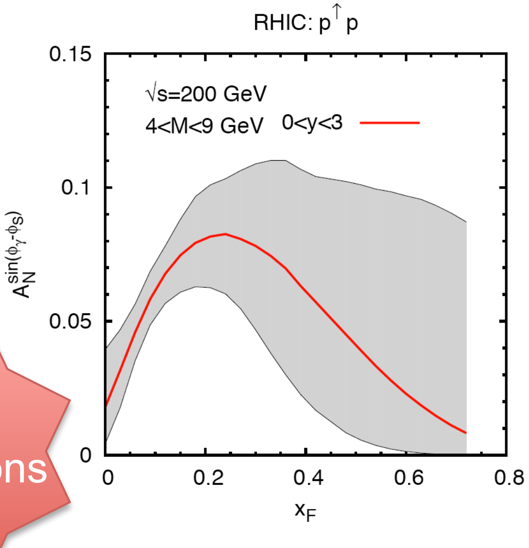

Precise DATA
wide kine. range
match other reactions
test TMD factor.

***From SIDIS to pp:*** A possible candidate to explain SSA

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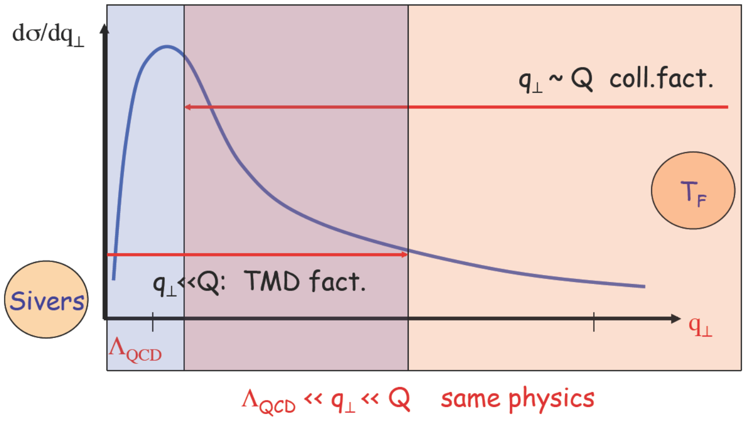
$$gT_{q,F}(x,x) = -\int d^2k_{\perp} \frac{|k_{\perp}|^2}{M} f_{1T}^{\perp q}(x,k_{\perp}^2)|_{\mathrm{SIDIS}}$$



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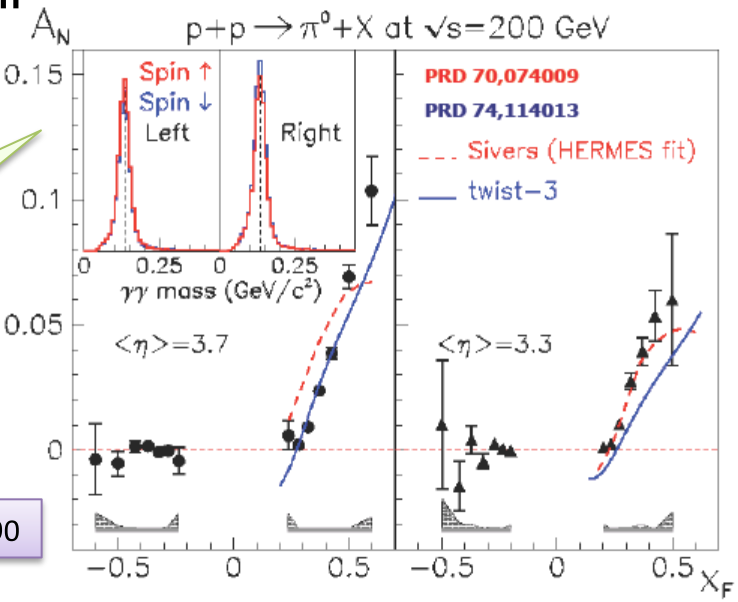


# Honour and Duty

TMDs describe a new class of phenomena providing novel insights into the rich nuclear structure

Experiments have got access to all PDFs and FFs, but in a convoluted way, first generation non-zero results provide promises but also open questions

Full coverage of valence region not achieved

Limited knowledge on $P_{h\perp}$ dependences

Flavor decomposition often missing

Evolution properties to be defined

Role of the higher twist to be quantified

Universality ⟷ Fundamental test of QCD

↔

large x coverage

wide $P_{h\perp}$ acceptance

hadron ID

large $Q^2$ coverage

multi-dimensional analysis

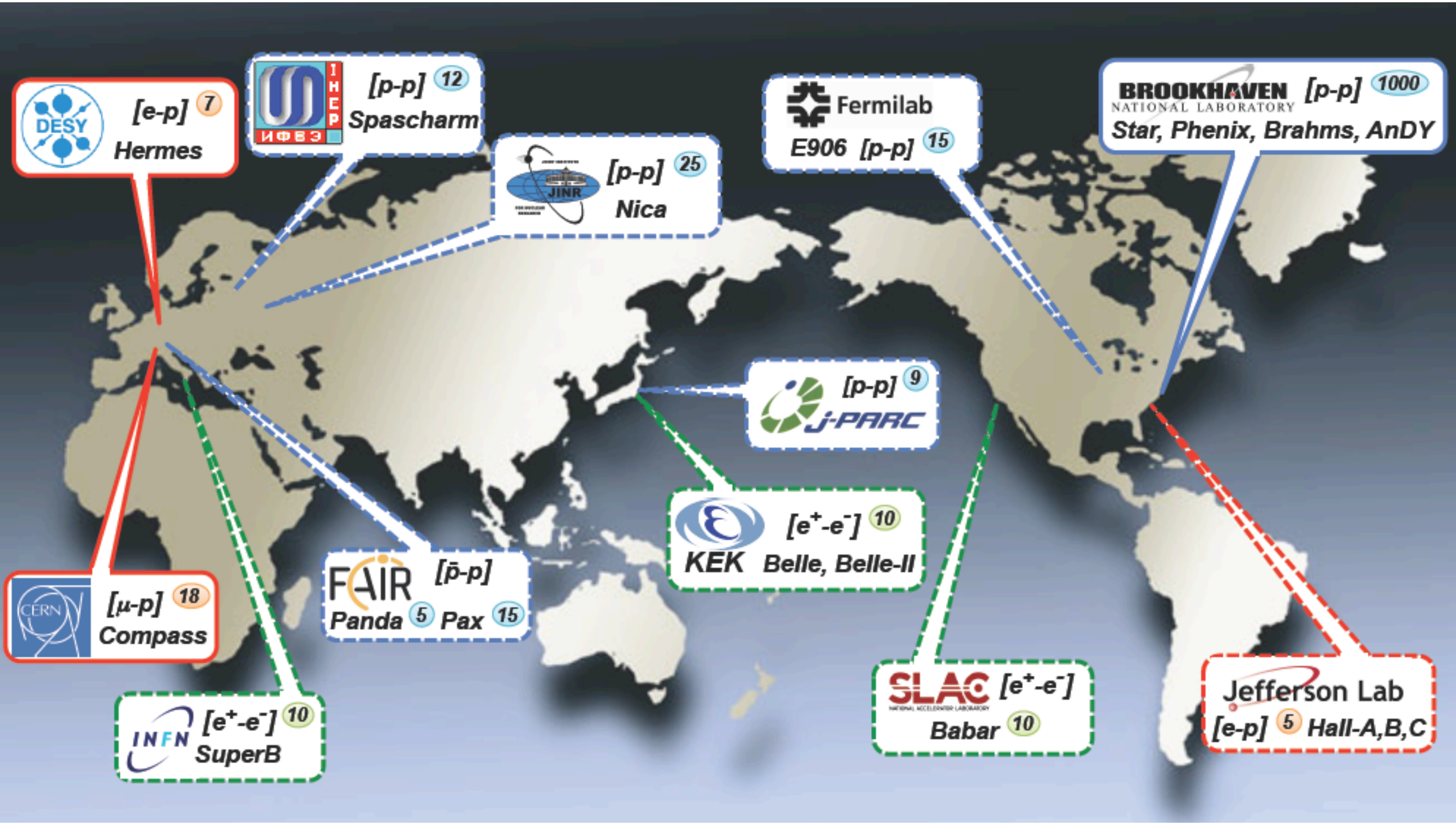
complementary channels

Still incomplete phenomenology is asking for new inputs

**Crucial: completeness**
**flavor tagging, wide acceptance and four-fold differential extraction in all variables ($x,z,Q^2,P_T$) to have all dependencies resolved**

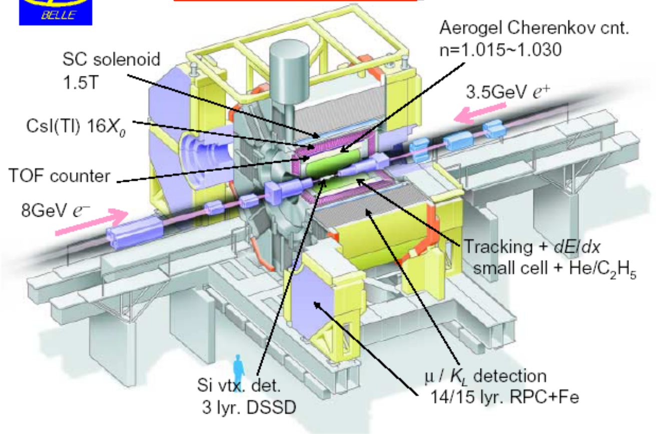
# TMD Studies at Future Facilities

# A World-wide Challenge

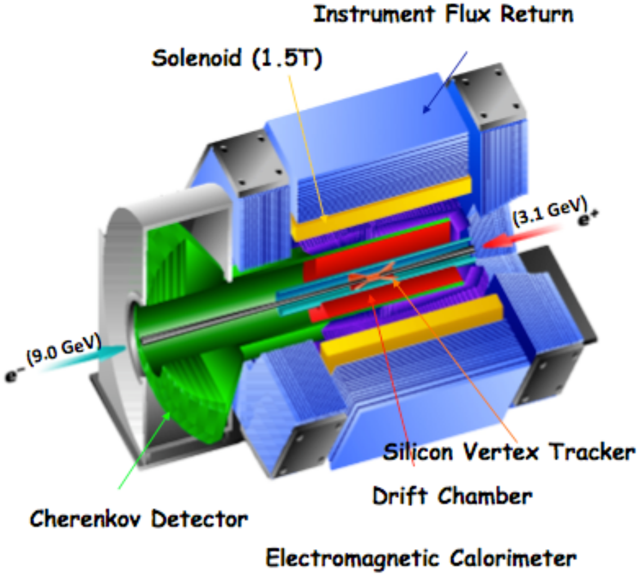


# Fragmentation @ e+e- Colliders

Belle Detector



Babar Detector



Different detector: systematic check !

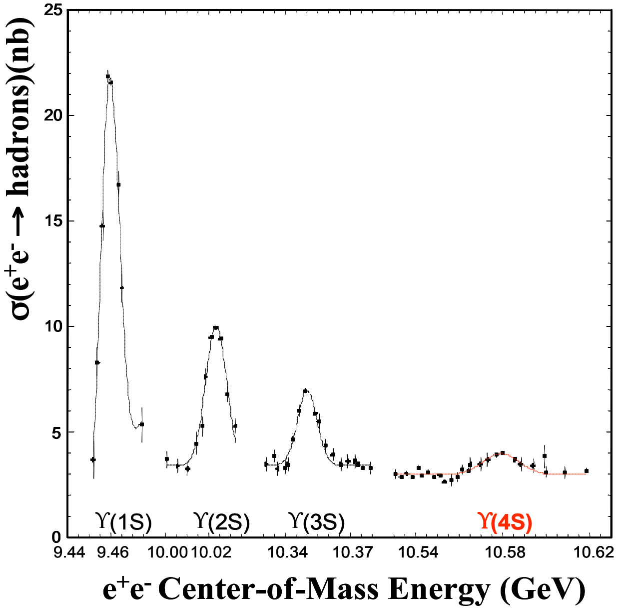
Hadrons in opposite hemispheres:

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

Dependence on transverse momentum

FFs for various hadron: 2π, kaons, (ρ, … Λ)

Scale dependence: look for different c.m. energies



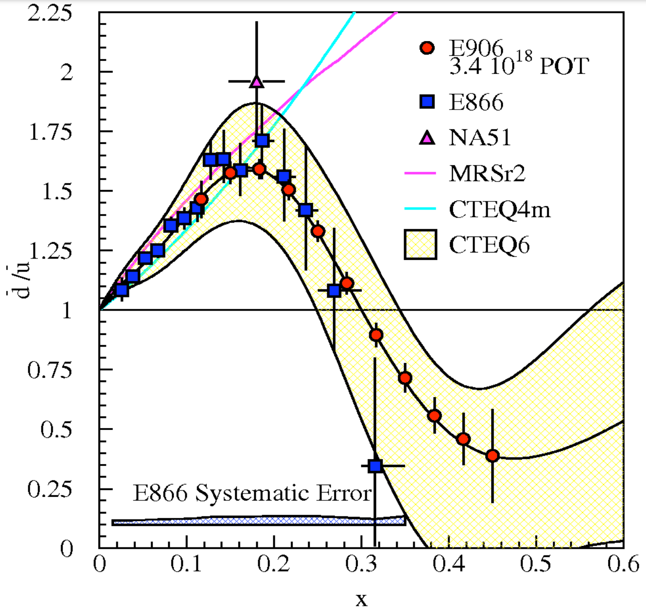
# pp, pd Drell-Yan in the States

## Unpolarized @ Fermilab to access Boer-Mulders

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

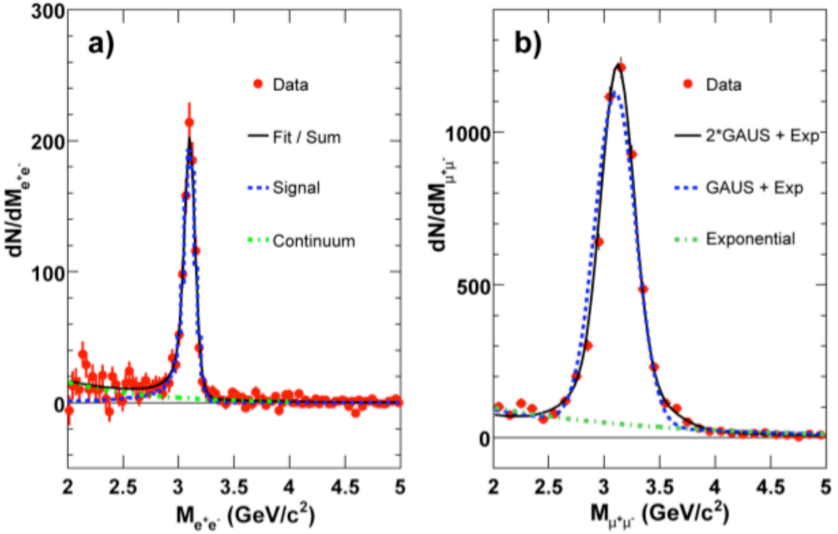
E906: test run this year

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

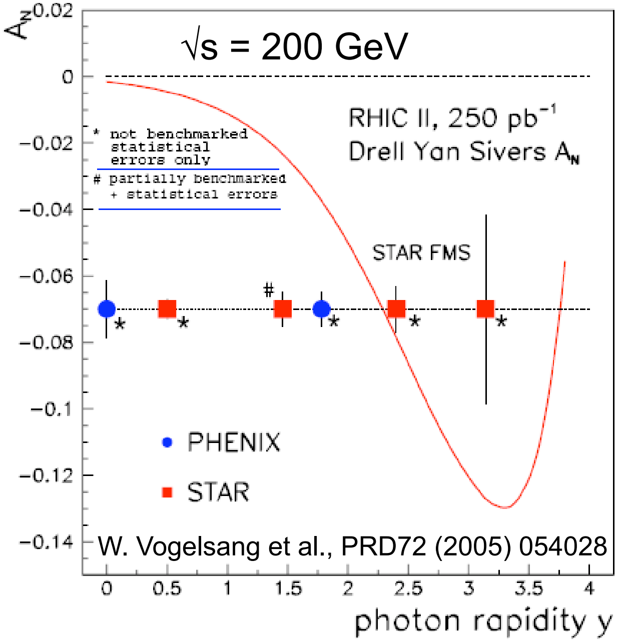


## Polarized @ Brookhaven to access Sivers

$e^+e^-$: |η|<0.35 $\mu^+\mu^-$ : 1.2<|η|<2.2

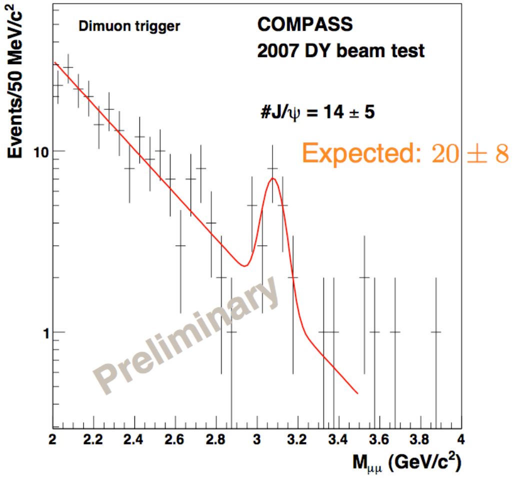


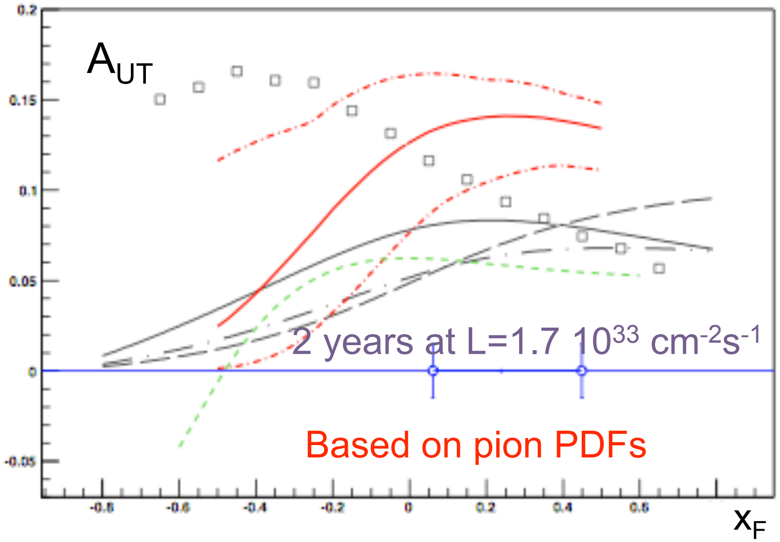
RHIC experiments: preparatory phase



# Valence antiquark Drell-Yan in Europe

## Pion beam @ CERN





- solid and dashed: Efremov et al, PLB612(2005)233;
- dot-dashed: Collins et al, PRD73(2006)014021;
- solid, dot-dashed: Anselmino et al, PRD79(2009)054010;
- boxes: Bianconi et al, PRD73(2006)114002;
- short-dashed: Bacchetta et al, PRD78(2008)074010.

## Anti-proton beam @ FAIR

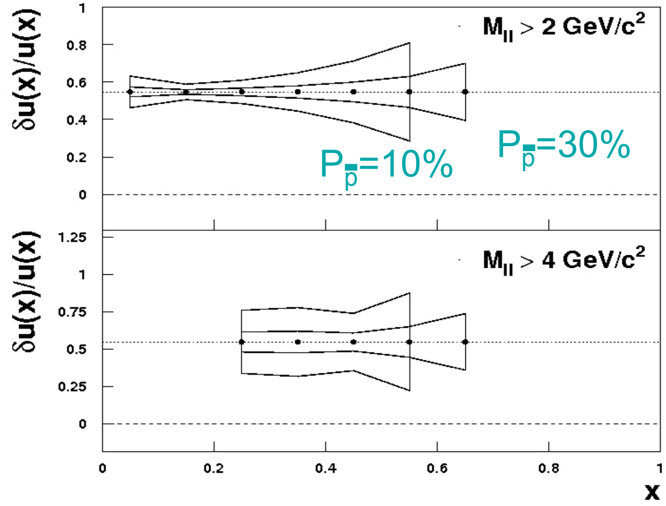
PANDA: unpolarized target (s=30 GeV²)

PAX: polarized collider (s=200 GeV²)

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

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

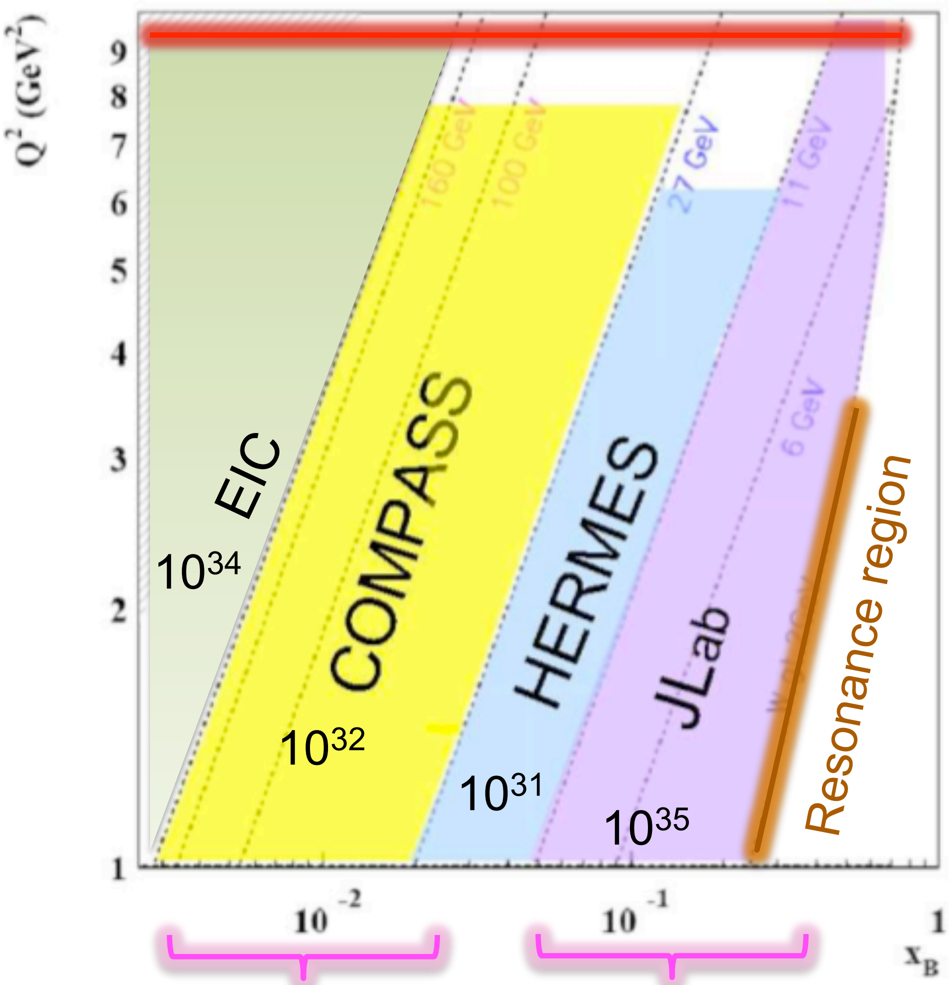
1year run: 10 % precision on the $h_{1u}(x)$ in the valence region



# THE TMDs ON THE SIDIS LANSCAPE

# The SIDIS Landscape

Limit defined by luminosity

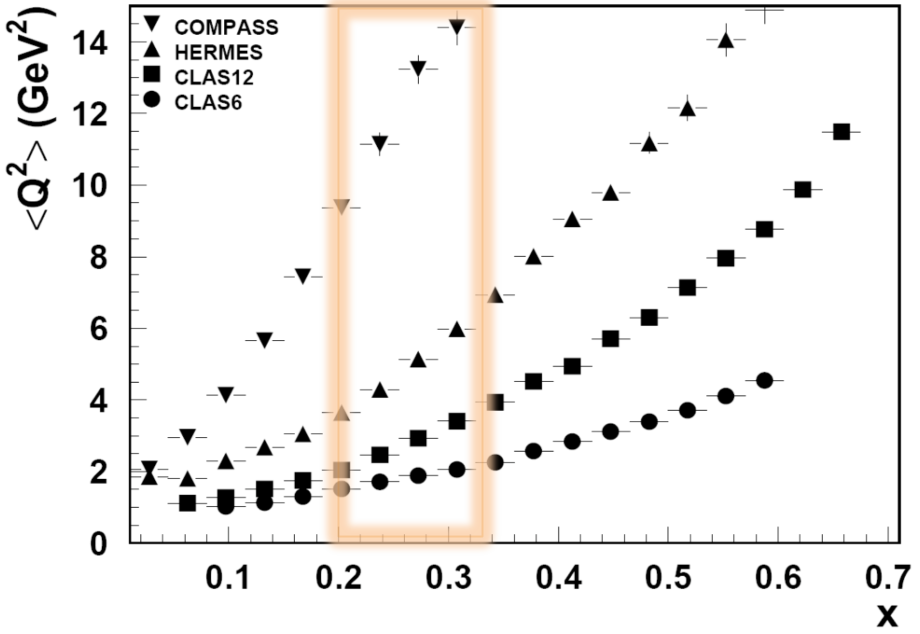


Sea

Valence

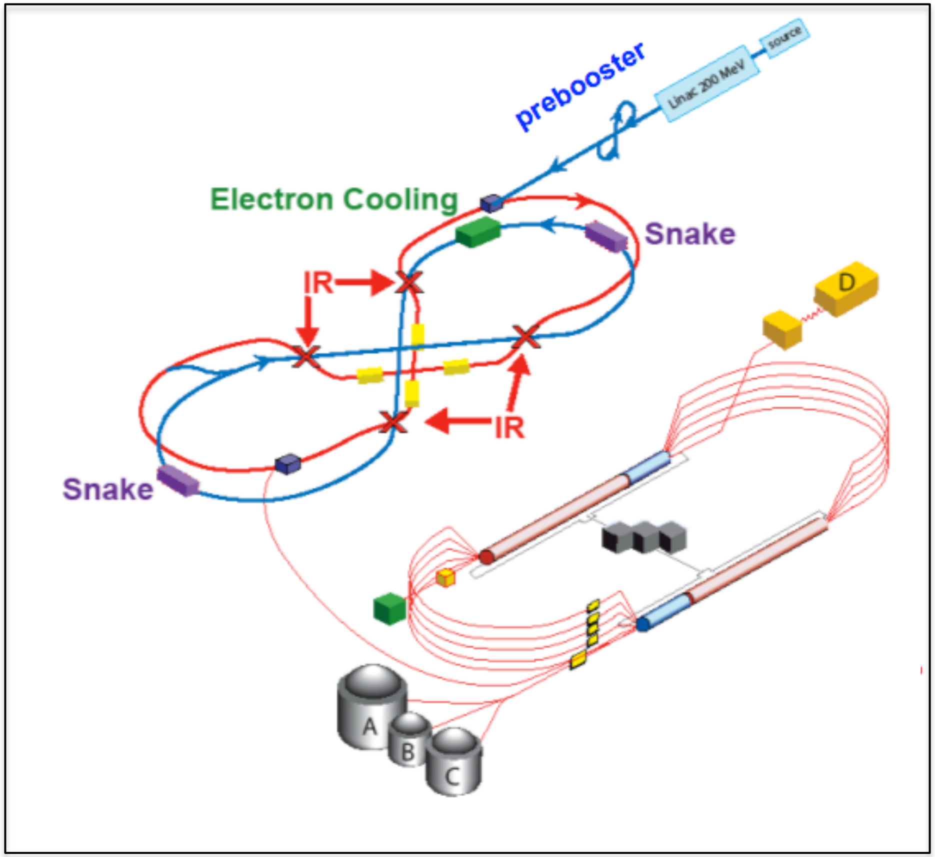
$$\frac{d\sigma(ep\rightarrow e'hX)}{dxdy\ dzdP_{h\perp}}\propto\sum_q e_q^2 C\left[q(x,k_T)D_q^h(z,p_T)\right]$$

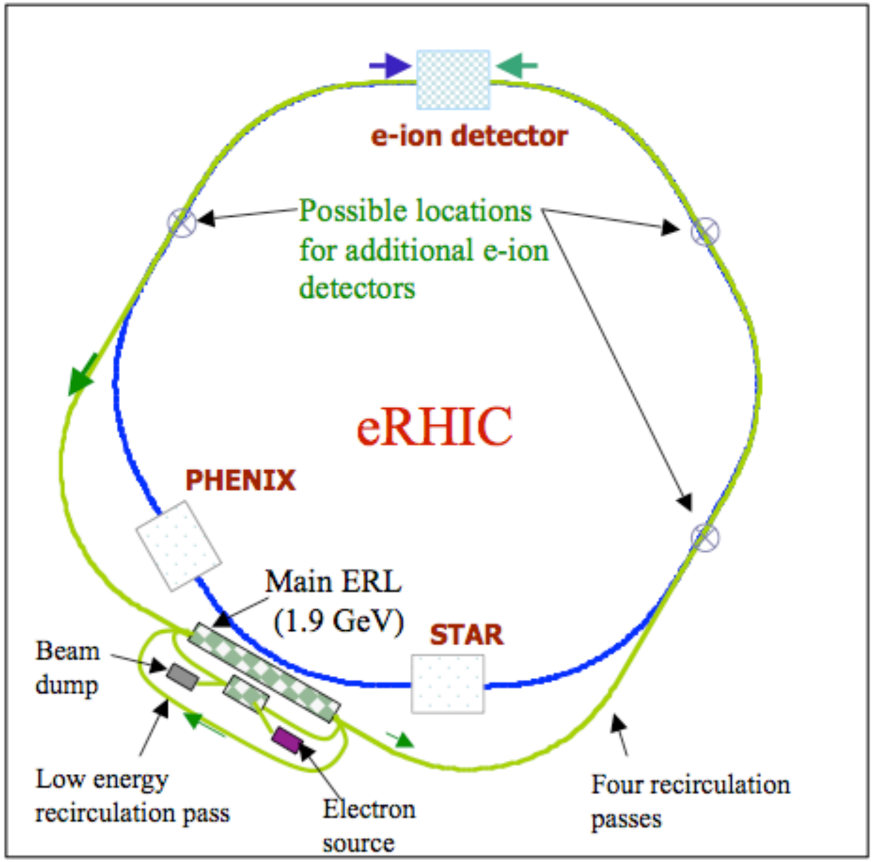
Different Q² for same x range



Complementary experiments

# Electron Ion Collider





30-225 GeV protons
3 – 9 GeV electrons
$\sqrt{s} \sim 20\text{-}90$ GeV
L~ 0.7-6 $10^{34}$ $cm^{-2}$ $s^{-1}$

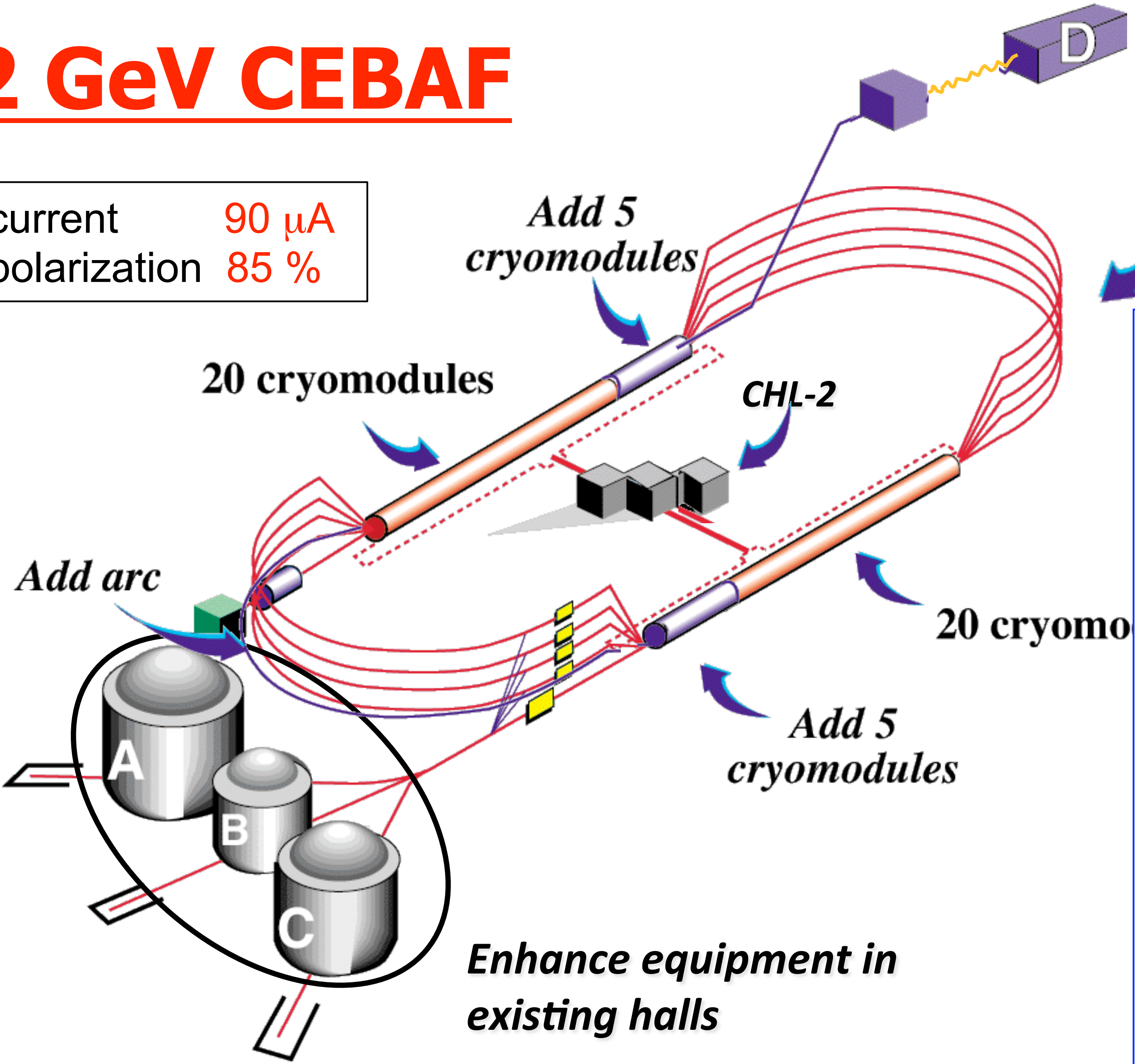
e,p polarization greater than 70 %

50-250 GeV protons
3 – 10 GeV electrons
$\sqrt{s} \sim 25\text{-}100$ GeV
L~ 0.5-3 $10^{33}$ $cm^{-2}$ $s^{-1}$

High luminosity is better than high-energy: Sudakov suppression (soft gluon radiation)

# 12 GeV CEBAF

| | |
|---|---|
| Beam current | 90 μA |
| Beam polarization | 85 % |



Enhance equipment in existing halls

***2008-2014:***
*Construction* ***(funded at 99%)***

***May 2012***

*6 GeV Accelerator Shutdown starts*

***May 2013***
*Accelerator Commissioning starts*

***October 2013***

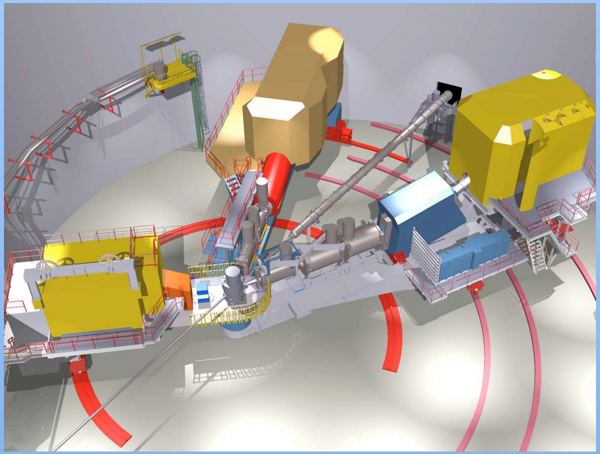
*Hall Commissioning starts*

***2013-2015***

*Pre-Ops (beam commissioning)*

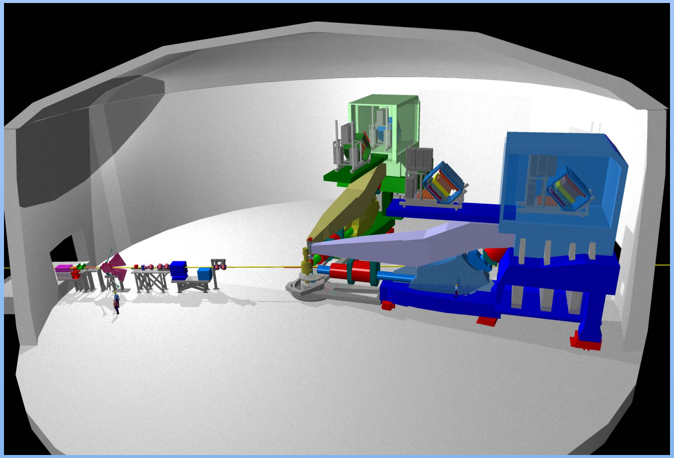
# SIDIS @ JLab12

**Hall-C**



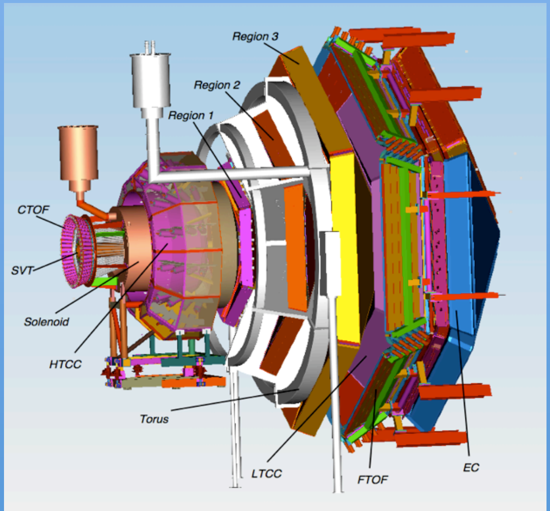
Super High Momentum Spectrometer (SHMS)
unpolarized SIDIS, hadron ID

**Hall-A**



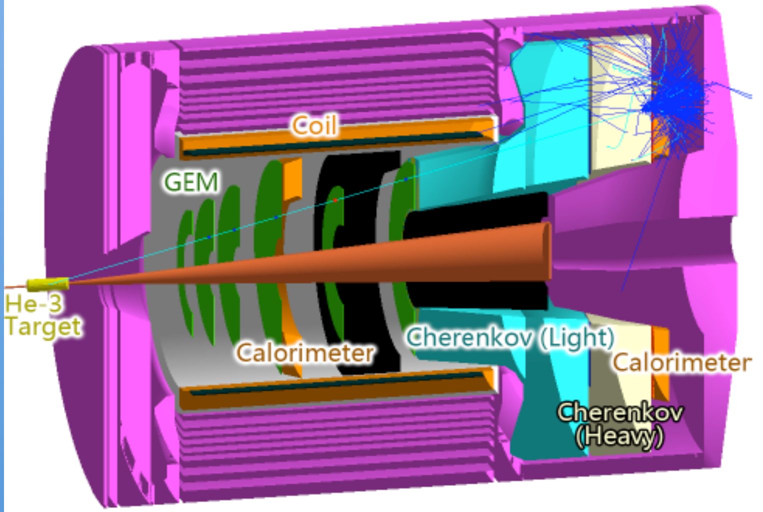
Spectrometer Pair, polarized $^{3}$He target
up to to $10^{37}$ cm$^{-2}$ s$^{-1}$ hadron ID

**Hall-B**



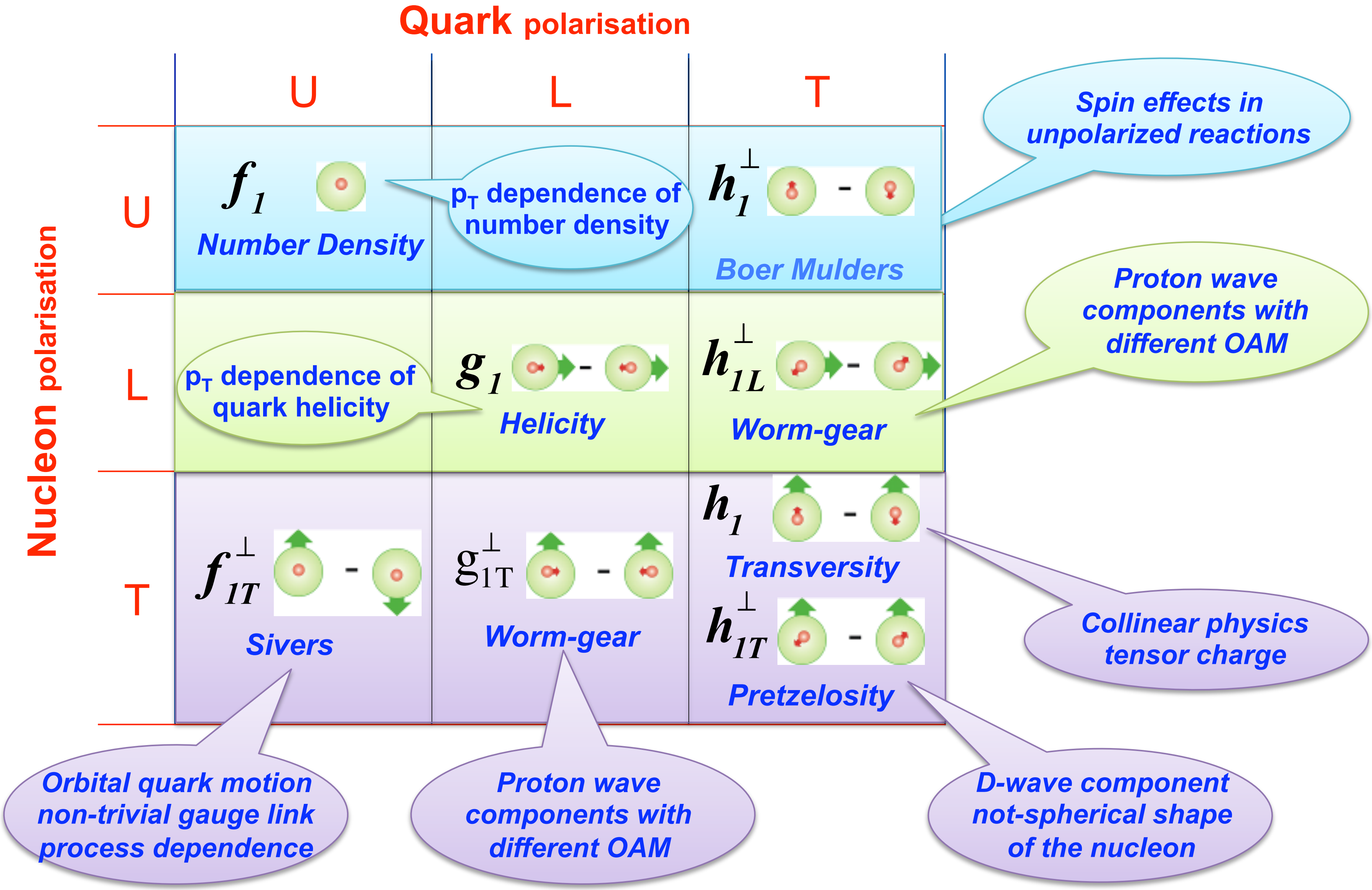
CLAS12 H,D polarized targets up to $10^{35}$ cm$^{-2}$ s$^{-1}$
complete" acceptance, hadron ID

**Hall-A**



SOLID $^{3}$He, $NH_3$ polarized targets
up to $10^{36}$ cm$^{-2}$ s$^{-1}$ large acceptance, pion ID

# Leading Twist TMDs



**Quark** polarisation

**Nucleon** polarisation

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

$p_T$ dependence of number density

*Spin effects in unpolarized reactions*

$p_T$ dependence of quark helicity

*Proton wave components with different OAM*

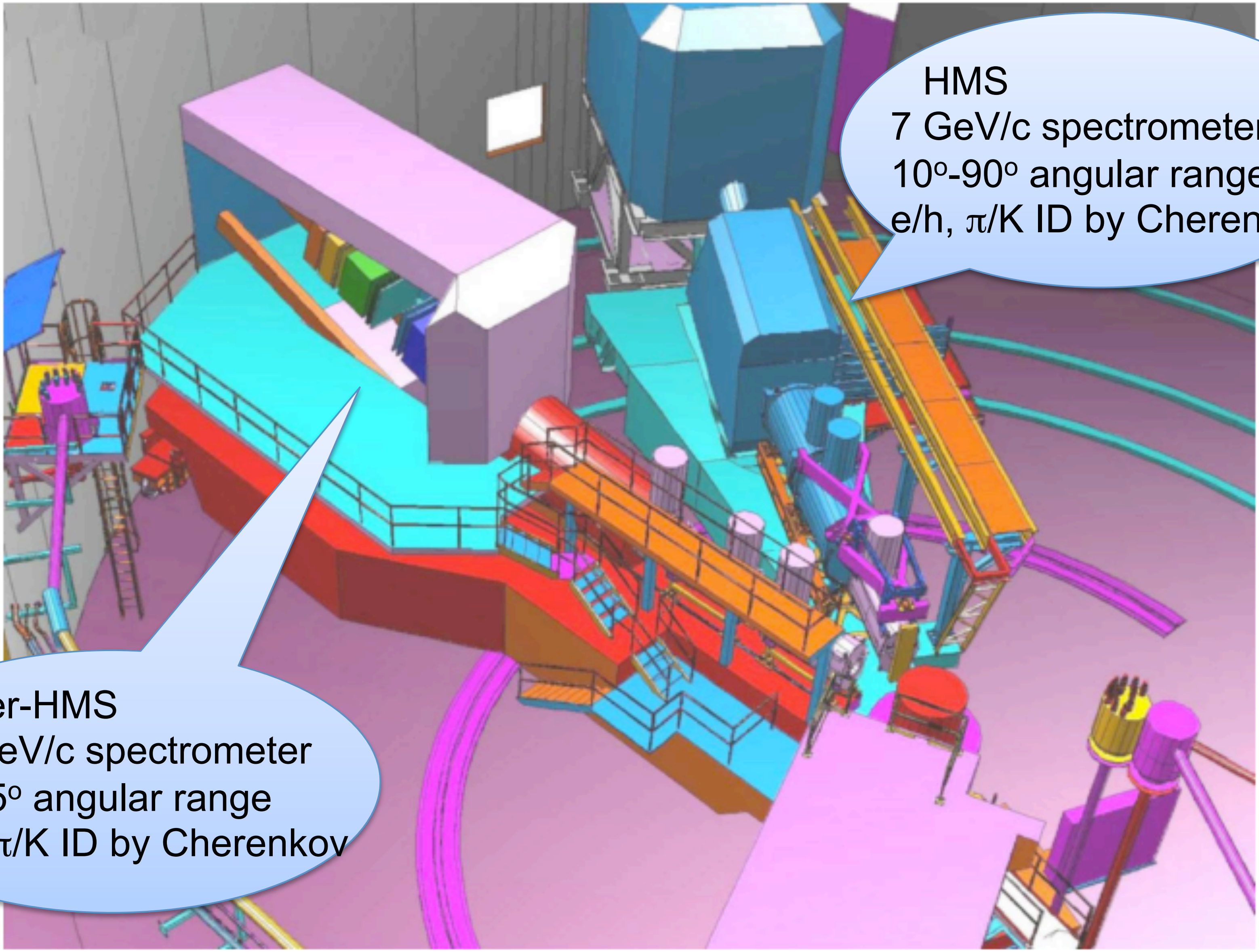
*Collinear physics tensor charge*

*Orbital quark motion non-trivial gauge link process dependence*

*Proton wave components with different OAM*

*D-wave component not-spherical shape of the nucleon*

# The Hall-C High-momentum Spectrometers



HMS
7 GeV/c spectrometer
$10^o$-$90^o$ angular range
e/h, π/K ID by Cherenkov

Super-HMS
11 GeV/c spectrometer
$5^o$-$25^o$ angular range
e/h, π/K ID by Cherenkov

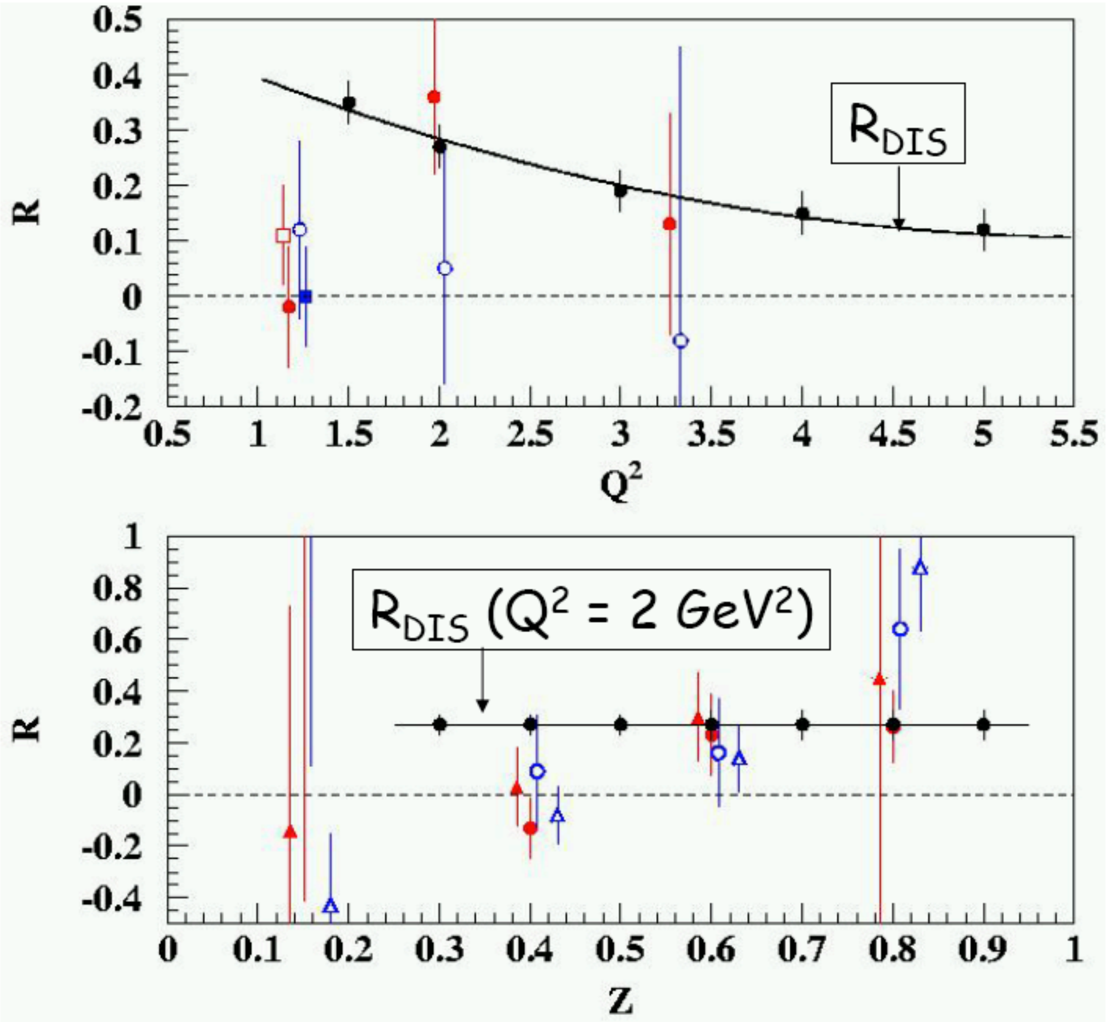
# Longitudinal Cross-section

E12-06-104

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

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

To be accounted in any TMD asymmetry interpretation



$R_{DIS}$ → 0 at $Q^2$ → ∞ due to scattering off spin-½ quarks

$R_{DIS}$ sensitive to gluon and higher-twist effects

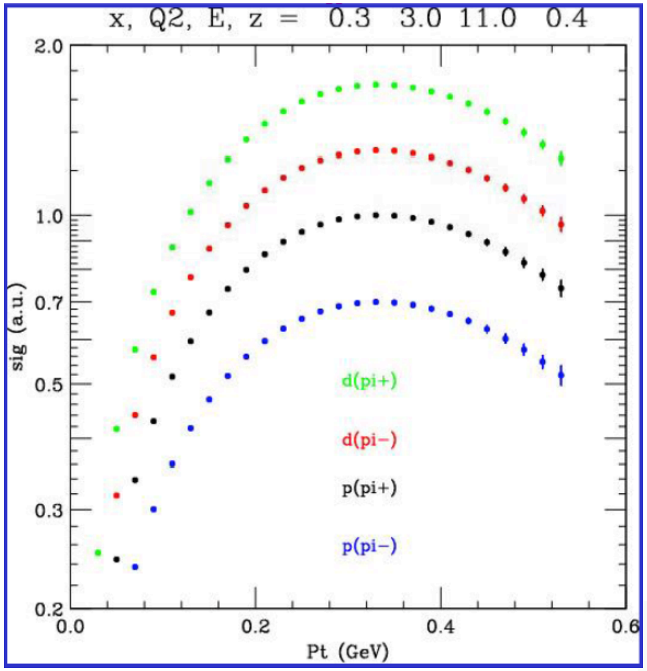
$R_{SIDIS}$(z,pT) = un-integrated $R_{DIS}$

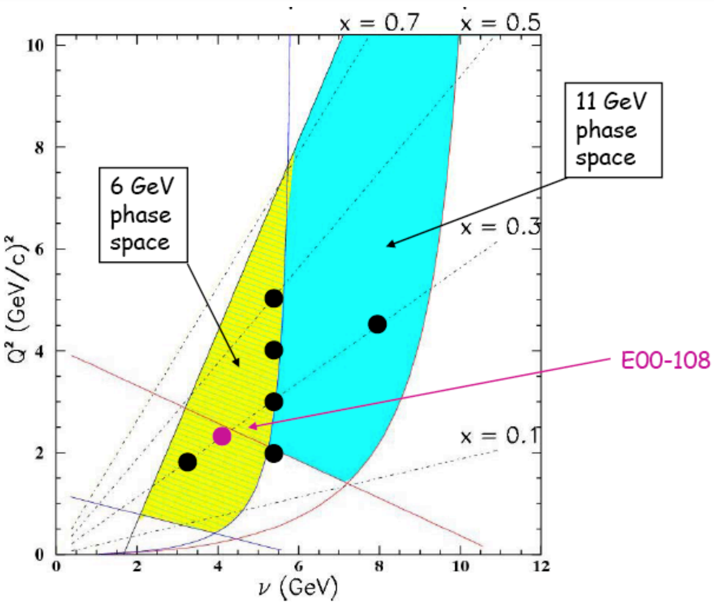
# $P_{h\perp}$ Dependence

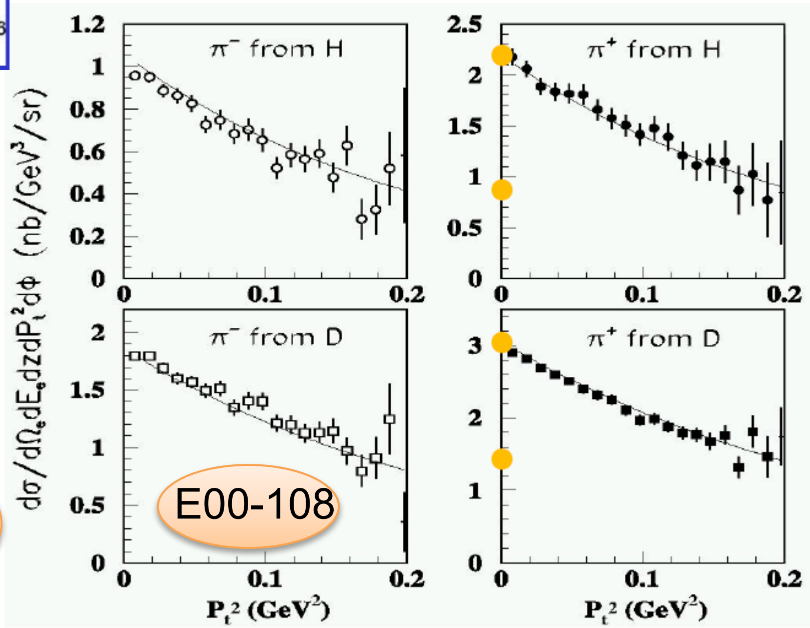
E12-09-017

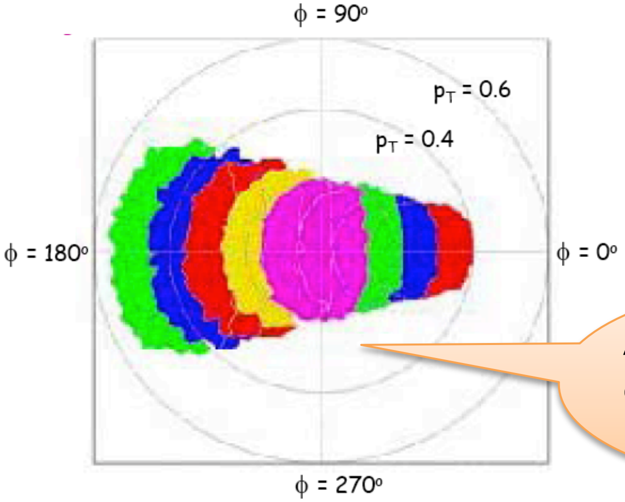
Map pf $p_T$ dependence for pion off proton and deuteron targets

$P_t = p_t + z\,k_t + O(k_t^2/Q^2)$









At $p_T$ > 0.2 GeV/c use dependencies measured in CLAS12 experiment

# The CLAS12 Spectrometer

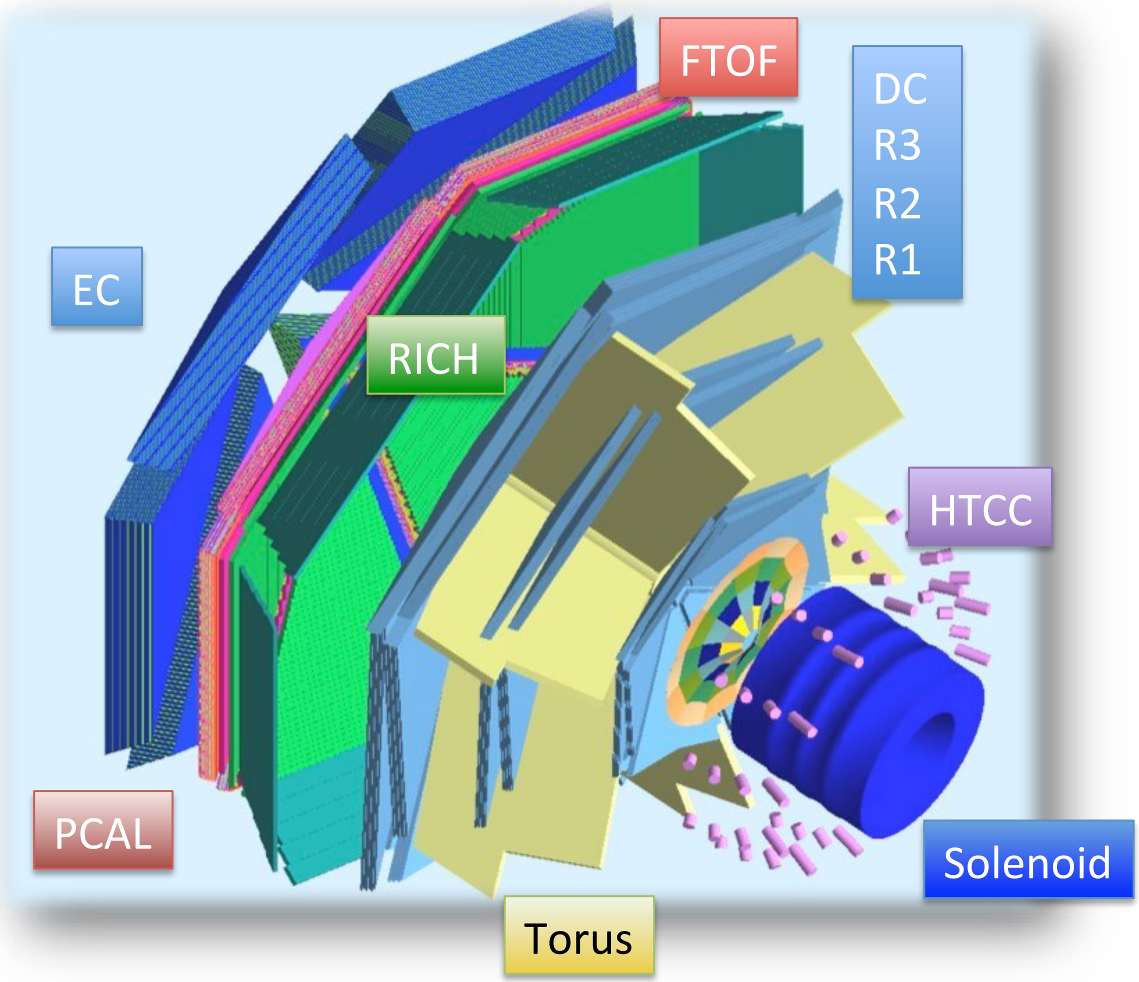
Luminosity up to $10^{35}$ cm$^{-2}$ s$^{-1}$

Highly polarized electron beam

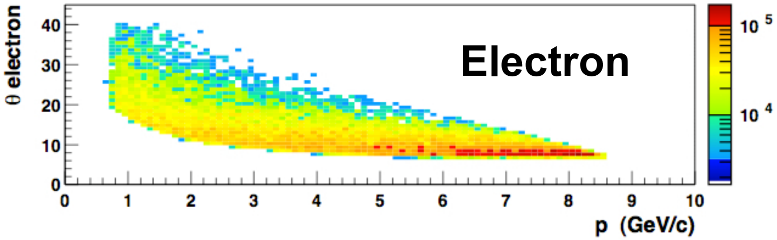
H and D polarized targets

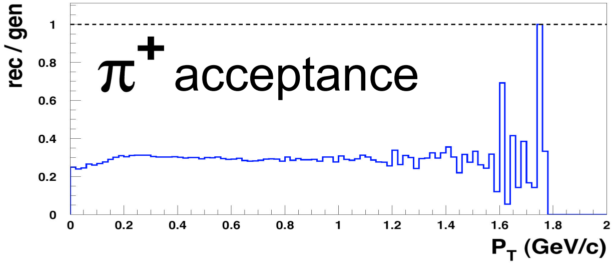
Broad kinematic range coverage (current to target fragmentation)

TOF + RICH for hadron ID



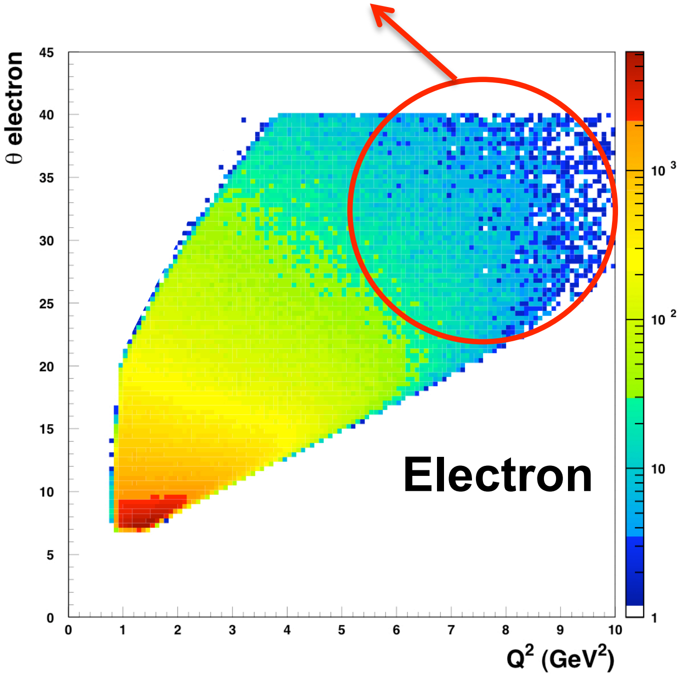
# CLAS12 Kinematic Coverage

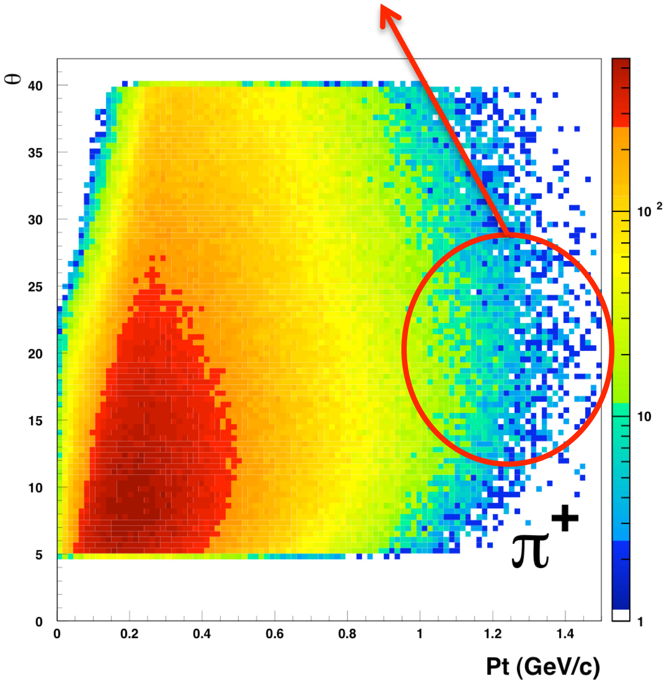




Large electron scattering angles (> 20°) mandatory to reach high $Q^2$ values

Intermediate anguar range (15-25°) mandatory to reach high $P_T$ values





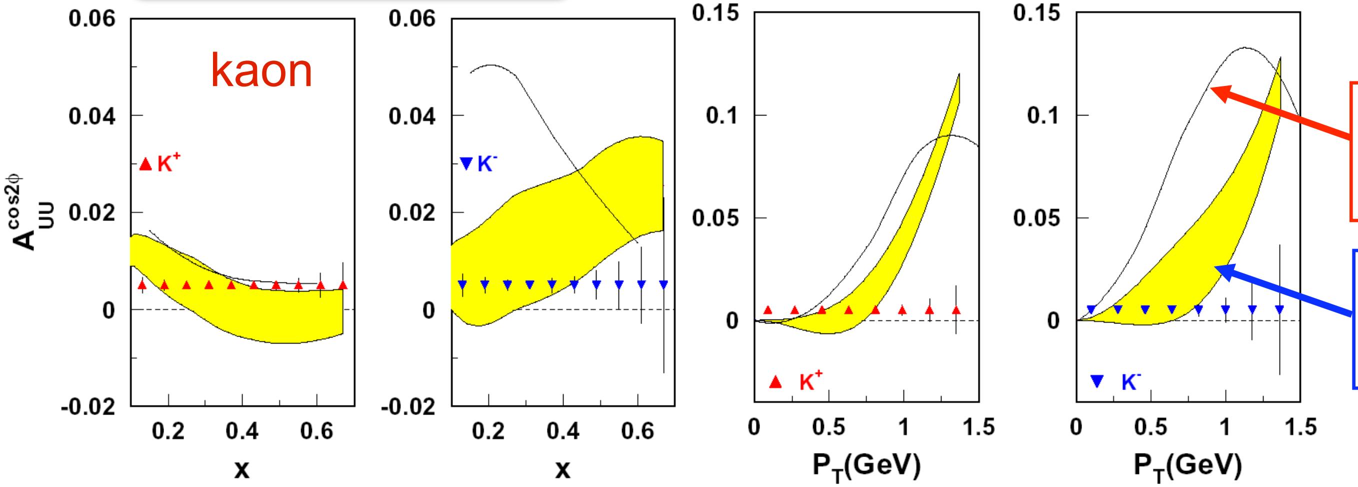
The CLAS12 forward detector is perfectly suitable for high-$Q^2$ and high-$p_T$ measurements since designed to cover up to 40 degrees angles

# Unpolarized Target @ CLAS12

$$F_{UU}^{\cos 2\phi} \propto h_1^{\perp} H_1^{\perp}$$

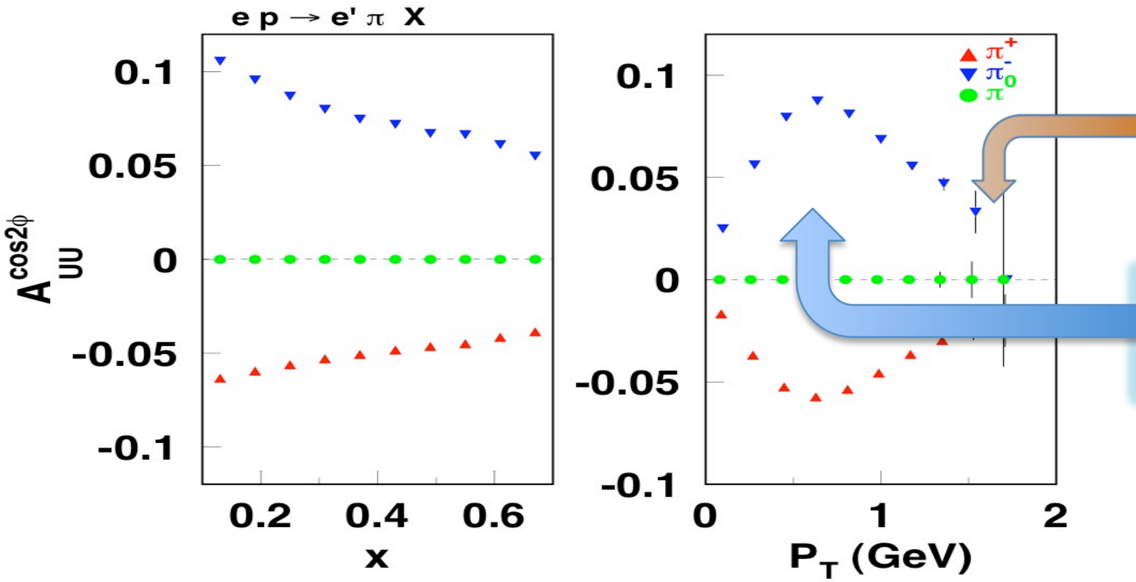
Boer-Mulders spin-orbit effect

**56 d @ $10^{35}$ $s^{-1}cm^{-2}$**
**$LH_2$ $LD_2$ targets**



**Line:** Phys Rev D78 045022
*Boer-Mulders from Sivers*
*Collins from e+e- data*

**Band:** Phys Rev D78 034035
*Boer-Mulders from DY data*
*Collins from chiral limit*



Perturbative region
Collinear factorization

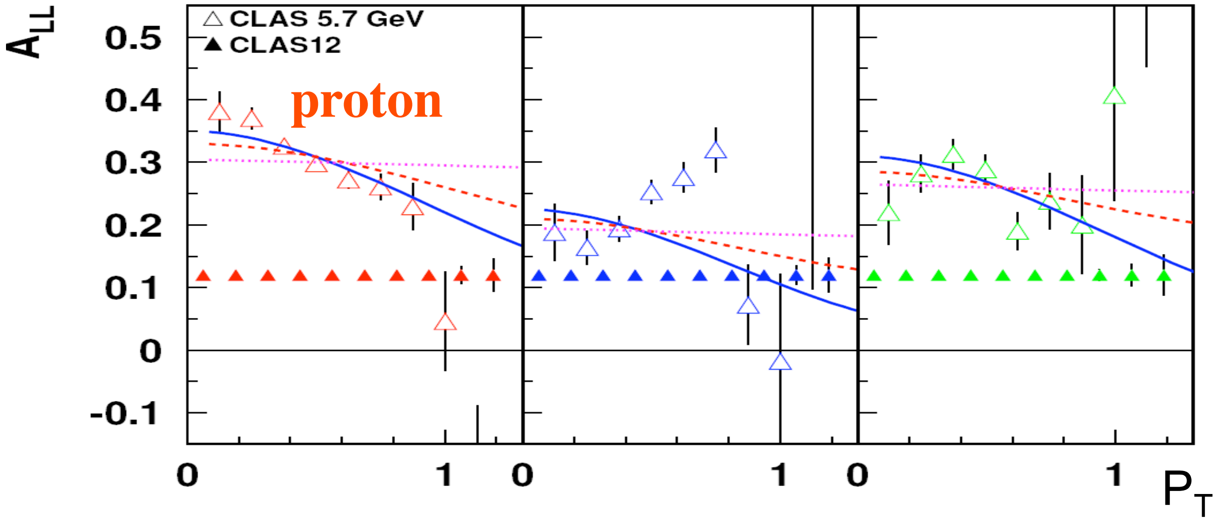
Non-perturbative
TMD factorization

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

# Polarized Beam @ CLAS12

$$F_{LL} \propto g_{1L} D_1$$

Helicity dependence of $k_T$-distribution of quarks



M.Anselmino et al hep-ph/0608048
**Phys.Rev.D74:074015,2006**

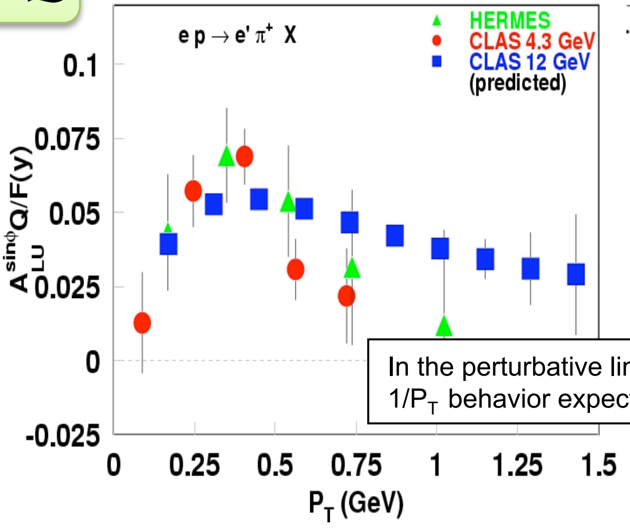
$$f_1^q(x,k_\perp) = f_1^q(x)\frac{1}{\pi\mu_0^2}exp(-\frac{k_\perp^2}{\mu_0^2})$$

$$g_1^q(x,k_\perp) = g_1^q(x)\frac{1}{\pi\mu_2^2}exp(-\frac{k_\perp^2}{\mu_2^2})$$

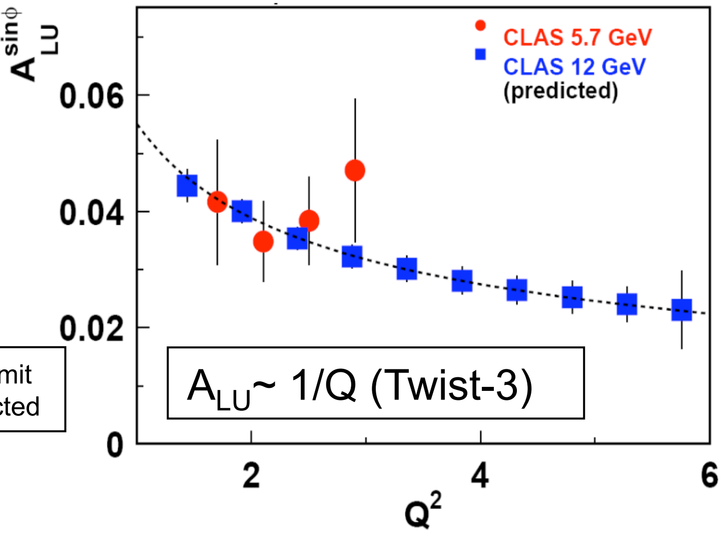
$\mu_0^2=0.25GeV^2$ $\mu_D^2=0.2GeV^2$

$$F_{LU}^{\sin\phi} \propto \left[e\ H_1^\perp + \ldots\right]/Q$$

Measurements of kinematic ($x,Q^2,z,P_T$) will probe HT distribution functions



In the perturbative limit
$1/P_T$ behavior expected



$A_{LU}$~ 1/Q (Twist-3)

**2000h @ $10^{35}$ $s^{-1}cm^{-2}$**
**$NH_3$ and $ND_3$ target**
**$P_{beam}$ = 85 %**

# Transversely Polarized HD-Ice Target

**HD-Ice target vs standard nuclear targets (less luminosity for higher purity)**

**Advantages:**

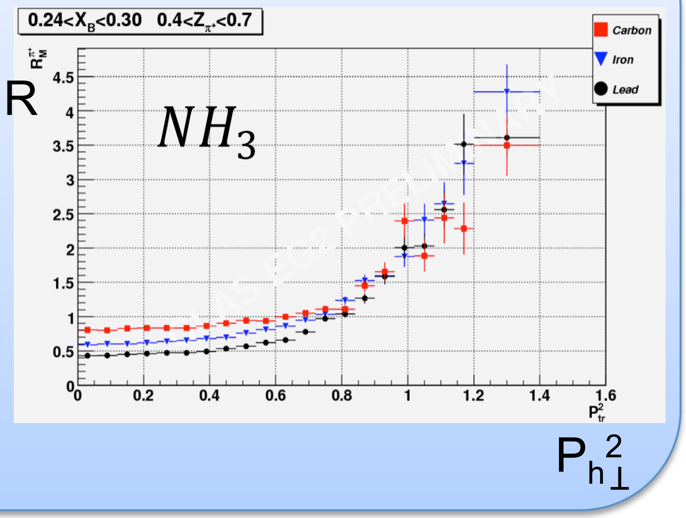
- **Minimize nuclear background**
  **smaller dilution, no attenuation at large $p_T$**
- **Weak holding field (BdL ~ 0.1 Tm)**
  **wide acceptance, negligible beam deflection**

Deuterium dilution is under control

Suitable for di-hadron and recoil proton

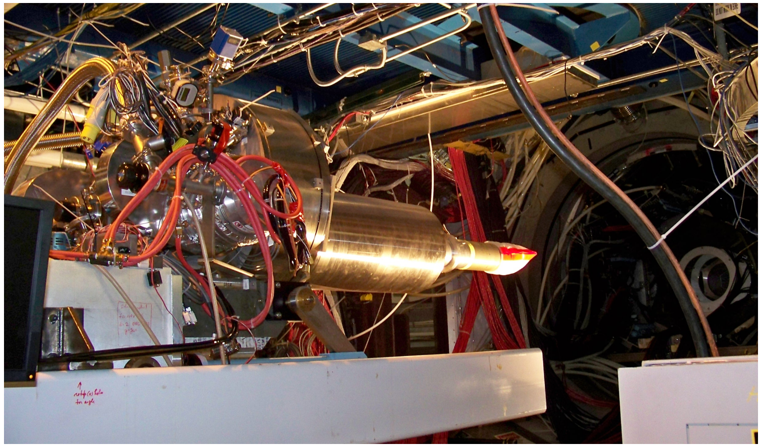
**Disadvantages:**

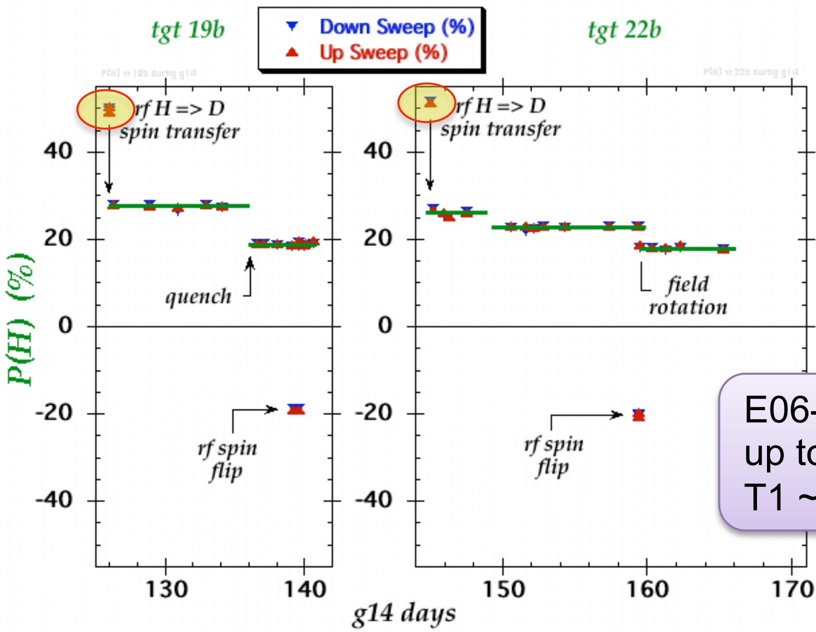
- **Very long polarizing times (months)**
- **Sensitivity to local heating by charged beams**



*HD-ice ran from Nov/11 to May/12 at Jlab*

*R&D work required to run with electron beams*





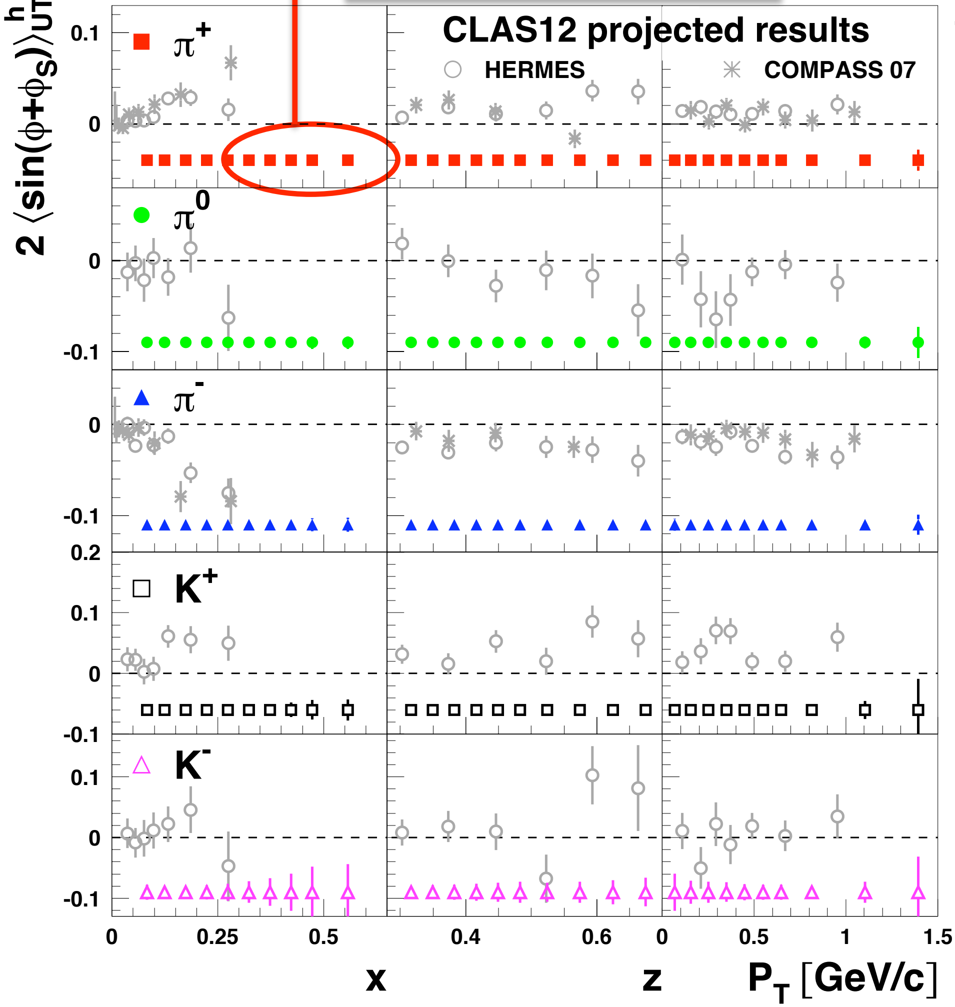
E06-101
up to $10^8$ γ/s
T1 ~ years

# CLAS12 Projections

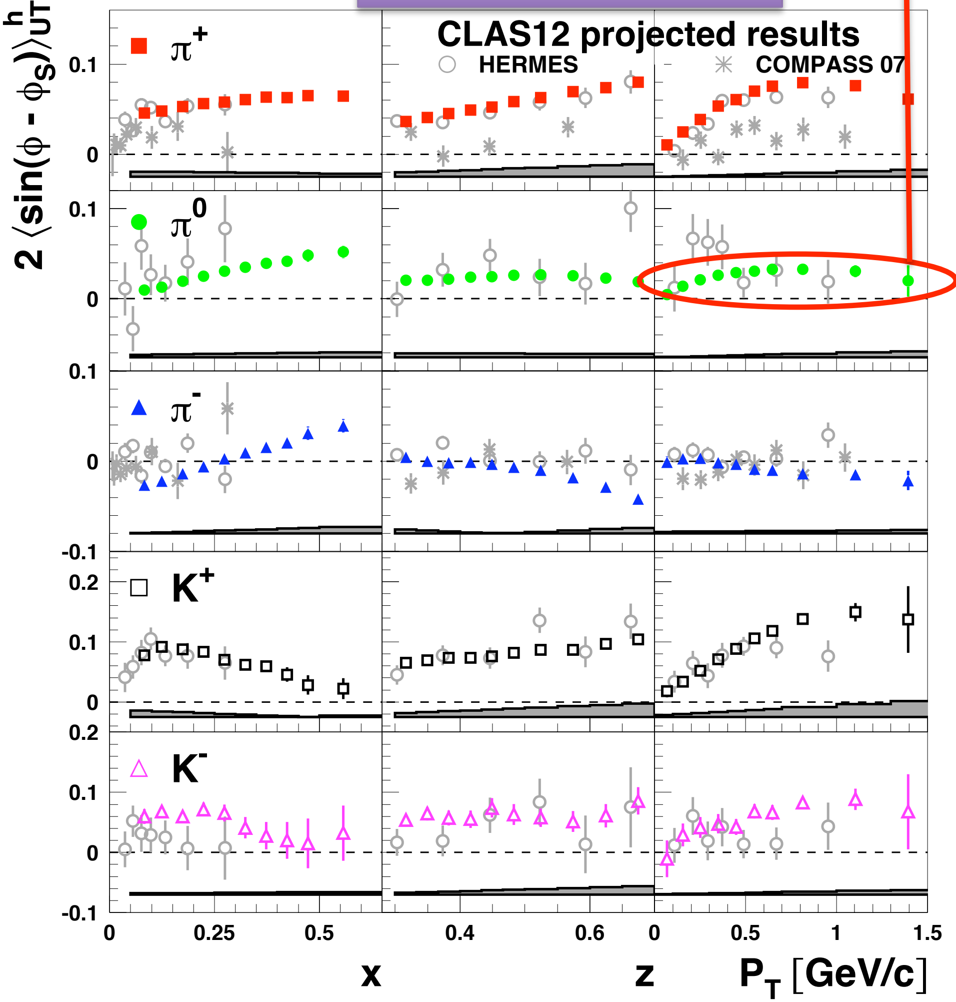
Large x important to constrain the tensor charge

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

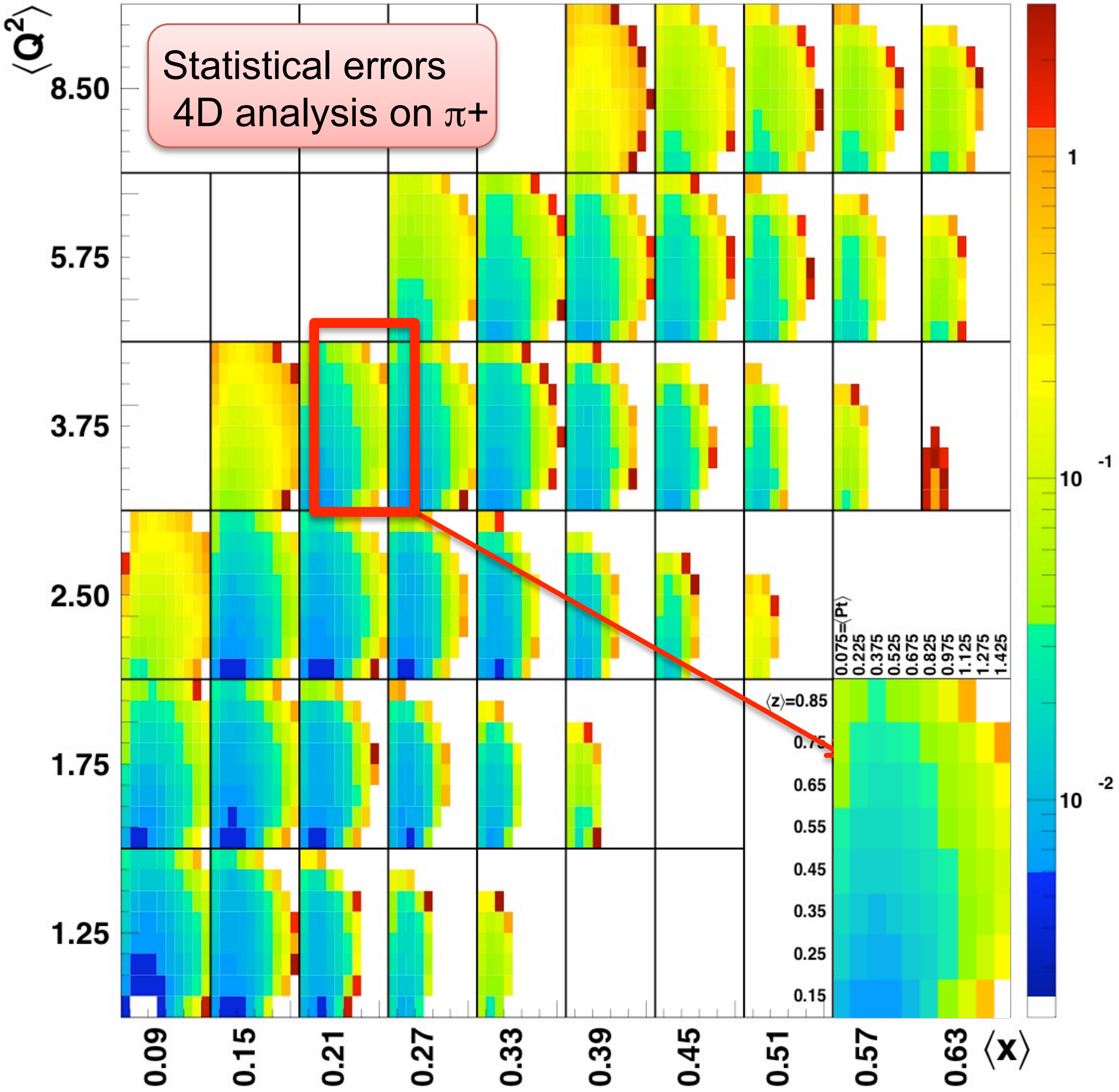
Collins asymmetry



Sivers asymmetry

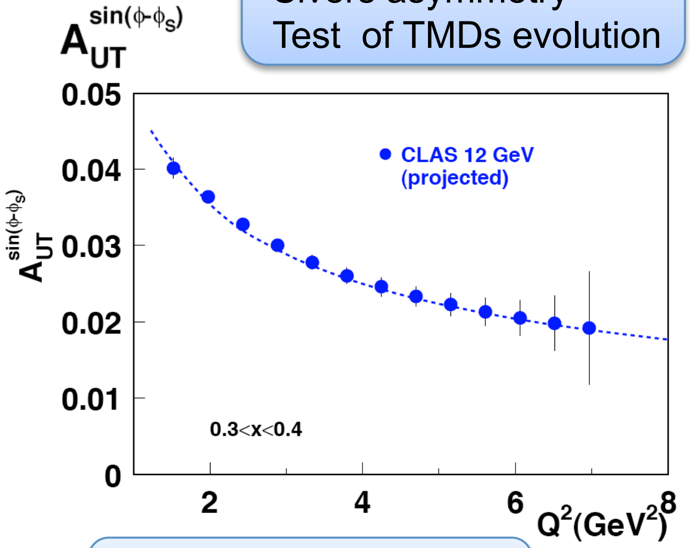


# Statistical Precision

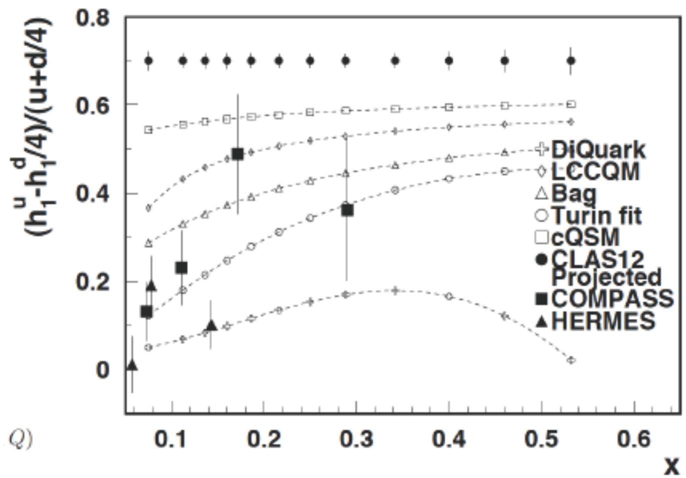


Statistical errors
4D analysis on π+

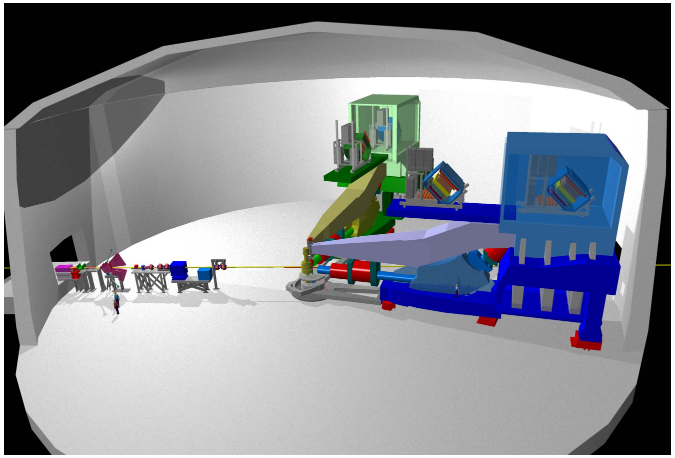
Q² dependence of
Sivers asymmetry
Test of TMDs evolution



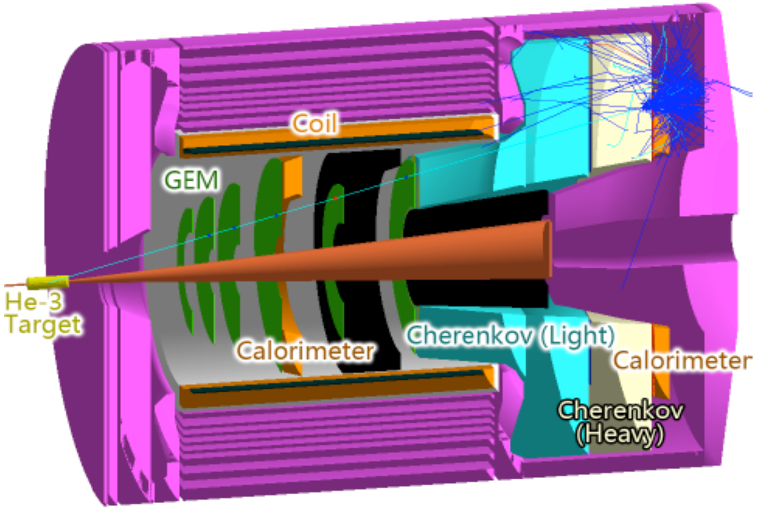
Di-hadron channel
Test of TMDs extraction



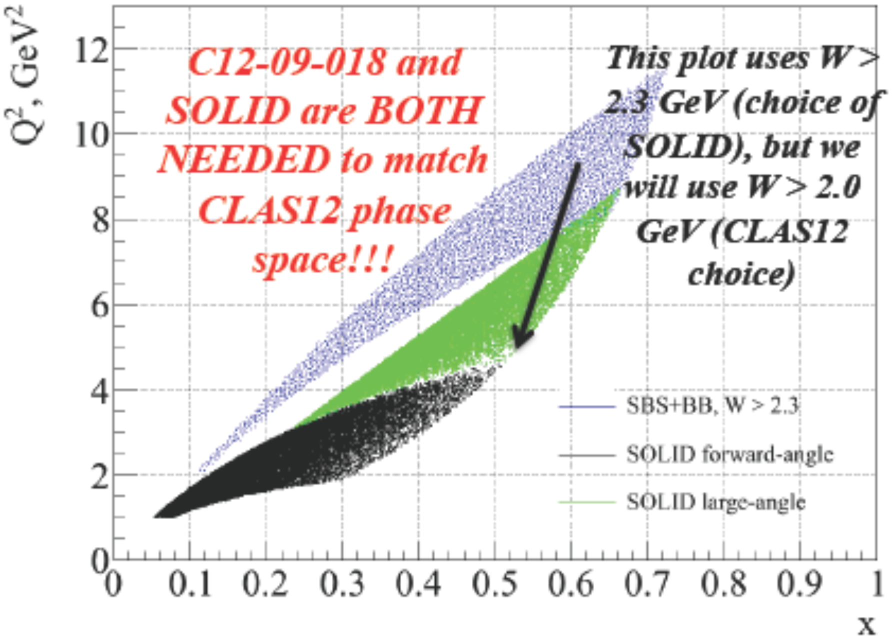
# The Hall-A High-Luminosity Spectrometers



Present: spectrometer pair

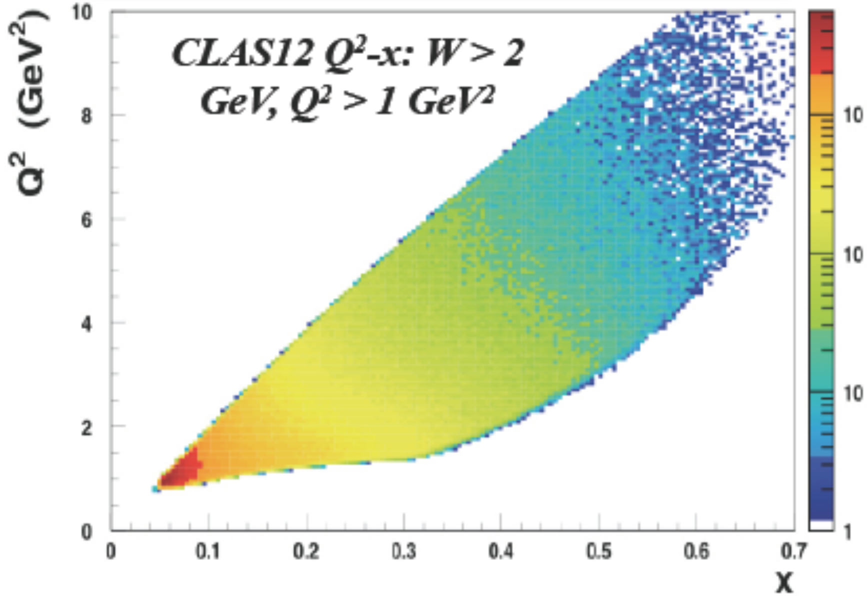


Future: large acceptance detector



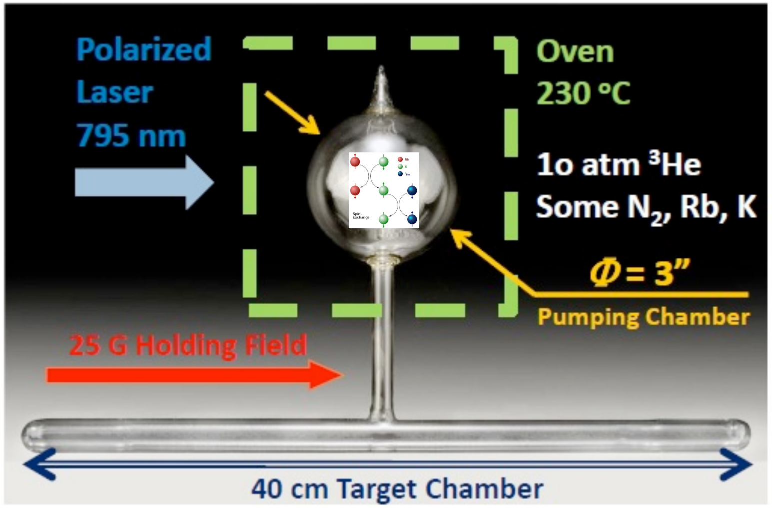
*C12-09-018 and SOLID are BOTH NEEDED to match CLAS12 phase space!!!*

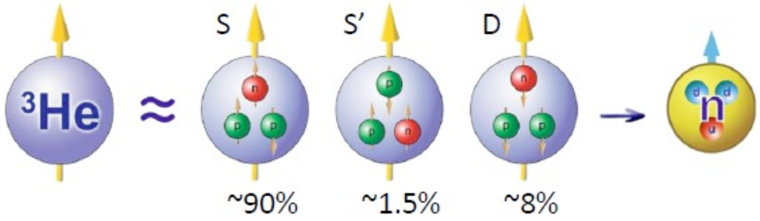
*This plot uses W > 2.3 GeV (choice of SOLID), but we will use W > 2.0 GeV (CLAS12 choice)*



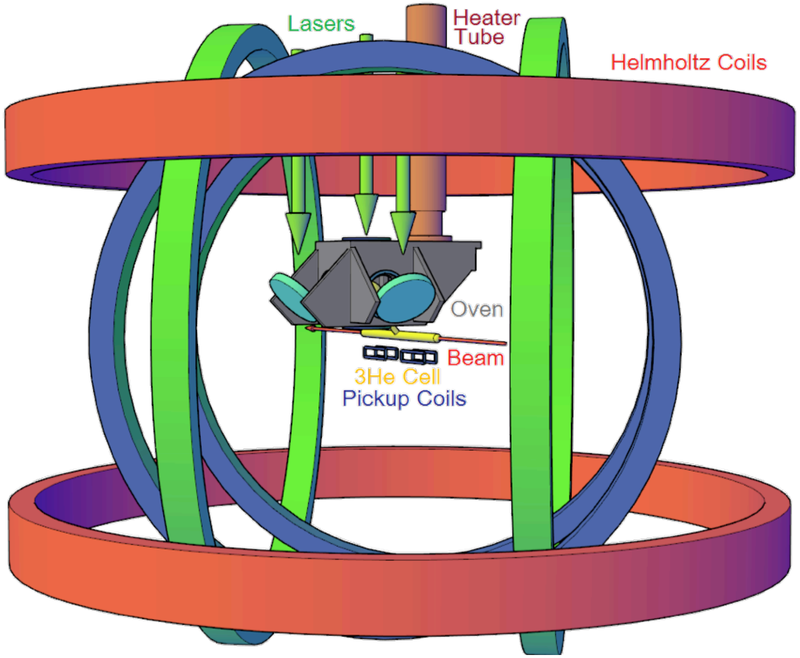
*CLAS12 $Q^2$-x: W > 2 GeV, $Q^2$ > 1 $GeV^2$*

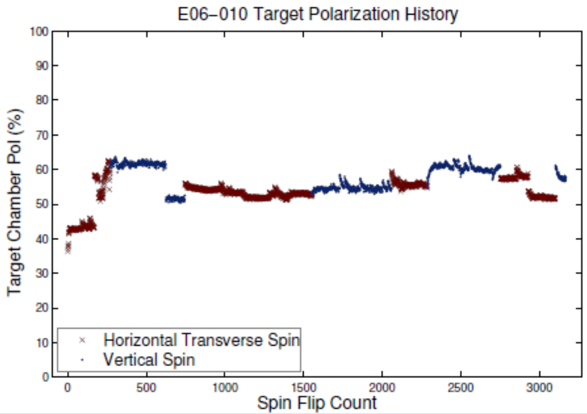
# $^3$He(n) Polarized Target





- Use 3 COMET lasers (narrow line, high power) for optical pumping of Rb vapor
- Fast spin exchange (via K) by $^3$He hyperfine interaction in oven; small part of $N_2$ to quench soft photon depolarization of Rb
- Polarized $^3$He diffuses to the target chamber
- 3D holding magnet field: spin to any direction
- 20 minutes spin flip / NMR and EPR polarimetries
- Superior performances:
  - Steady 65% polarization @ 15 uA beam (world record)

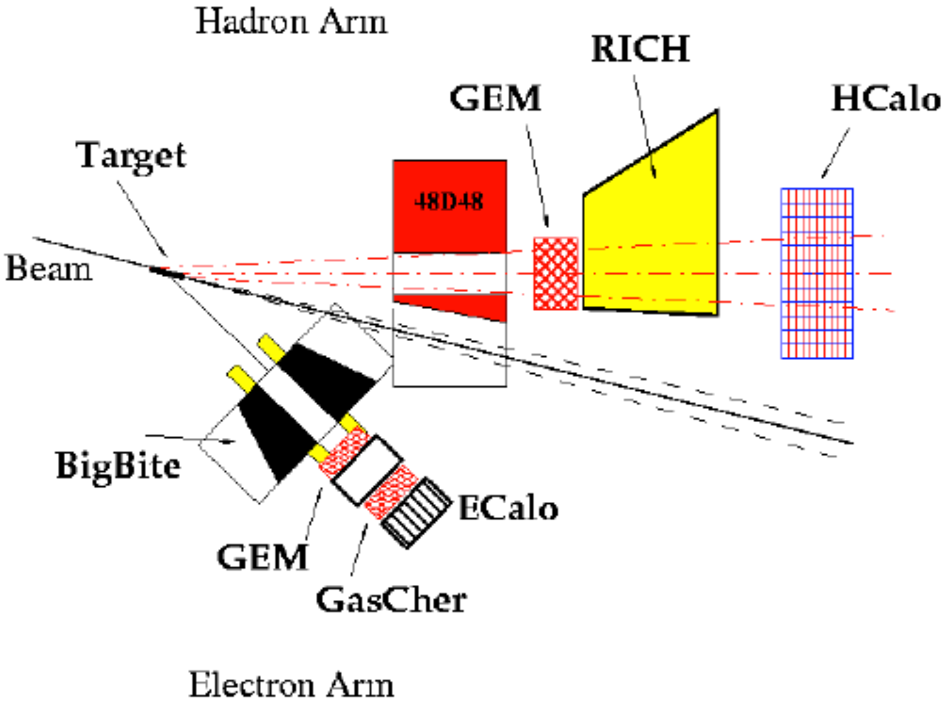




# SIDIS with Super-BigBite

SBS Tracker rate 60 kHz cm$^{-2}$

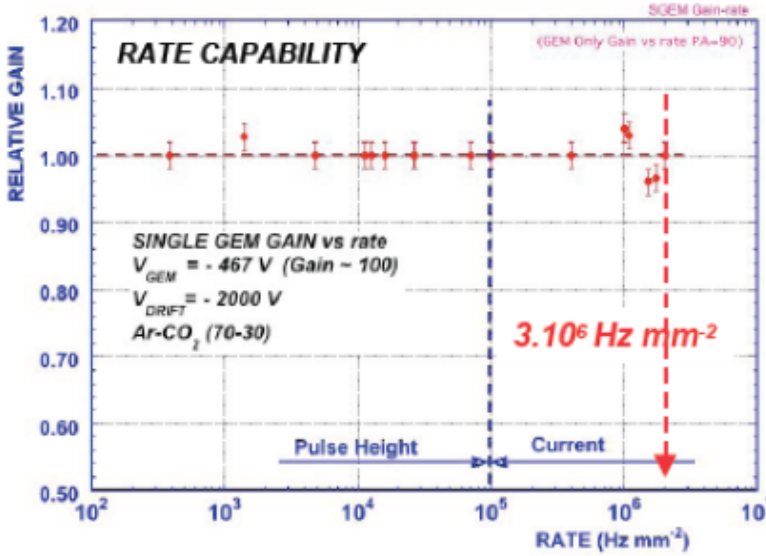
3xGEM support rate > 10 Mhz cm$^{-2}$



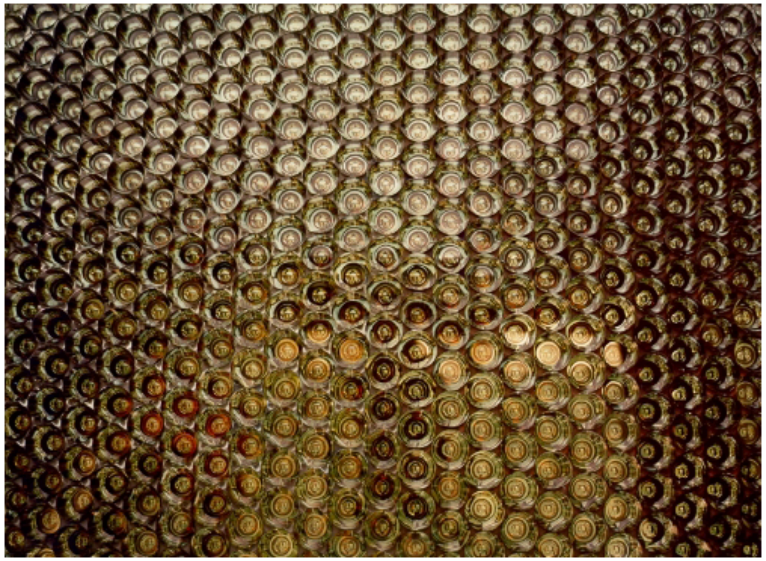
RICH PID

High segmentation of photon detector (2000 PMTs)

2-5% occupancy with 50 ns gate width

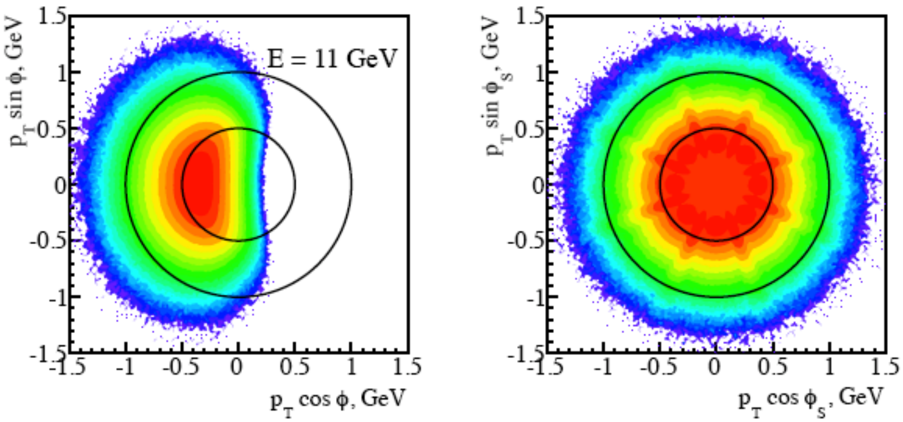


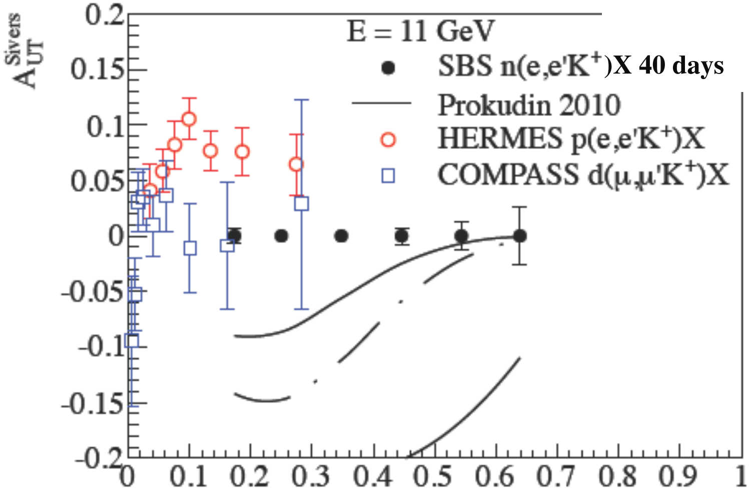
J. Benlloch et al, IEEE NS-45(1998)234



~20% of the HERMES RICH PMT array

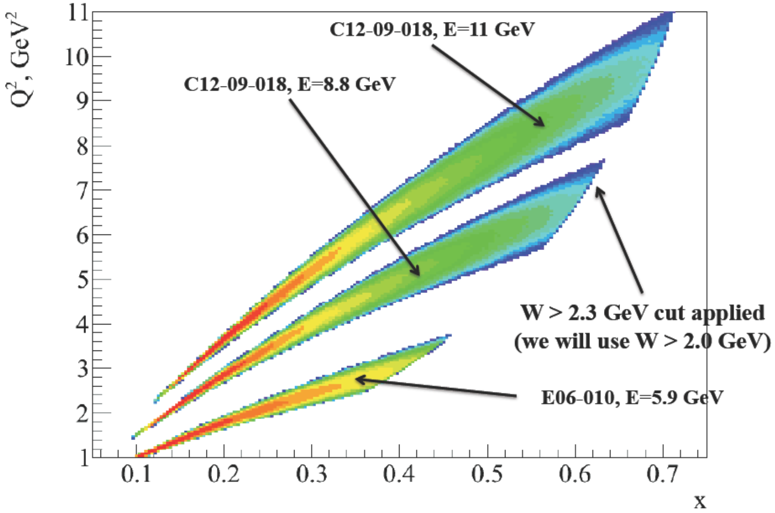
# SIDIS with Super-BigBite

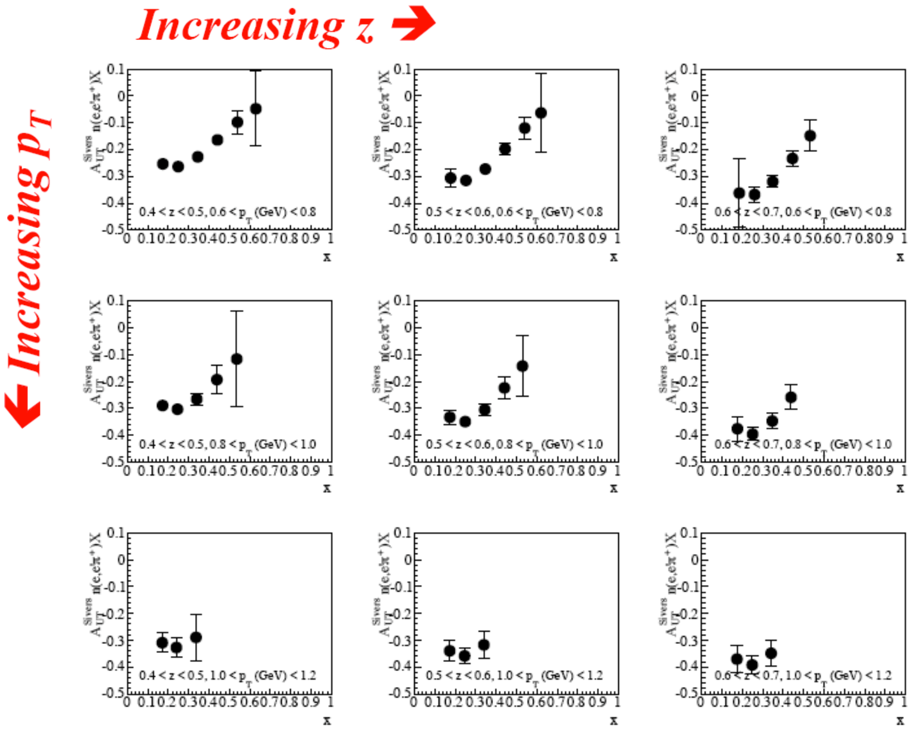




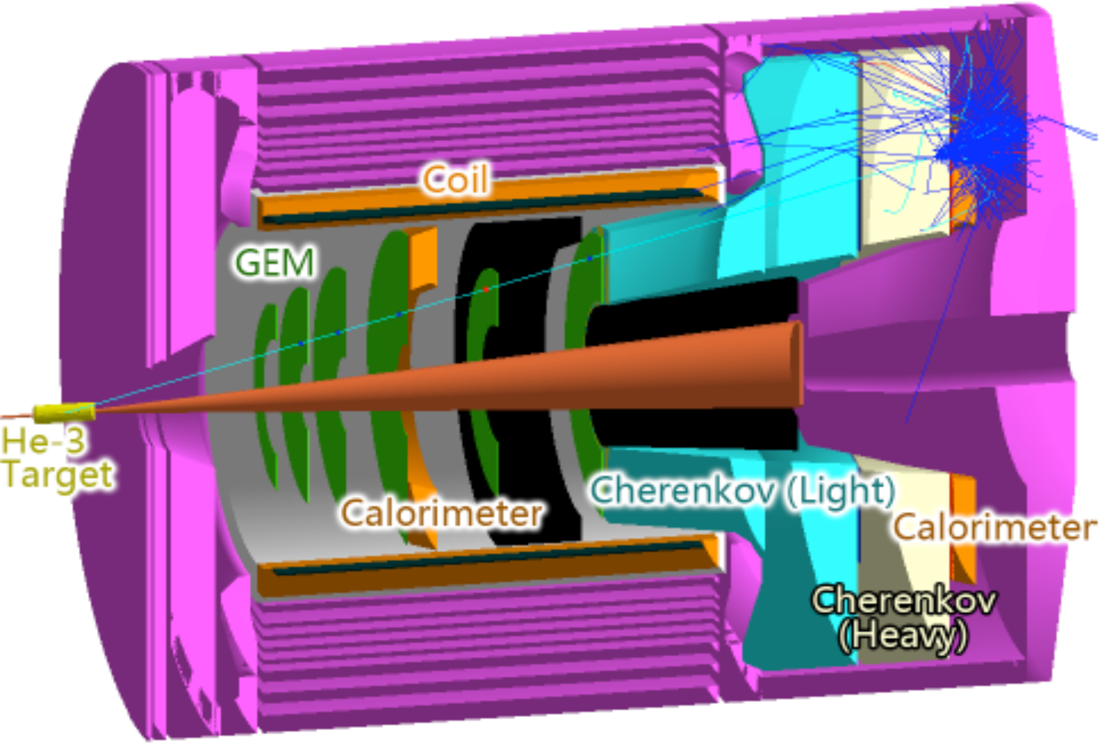
Precise 3D measurement on $^3$He with hadron ID

- ✓ neutron TMD
- ✓ flavor separation





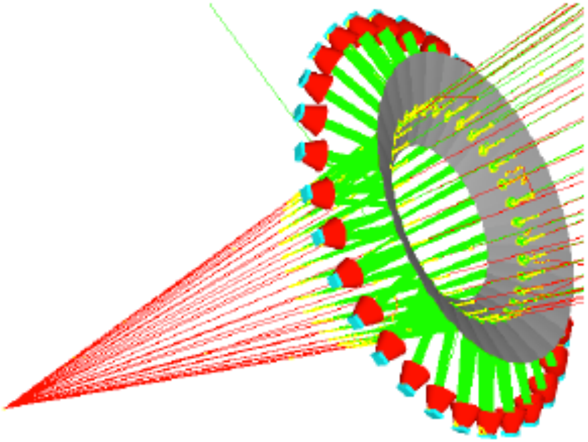
# SIDIS with SOLID



Luminosity: up to $10^{36}$ $cm^{-2}$ $s^{-1}$

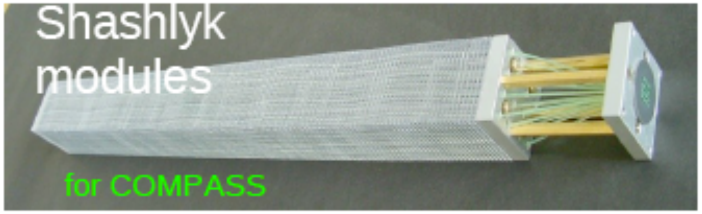
Acceptance:

| | |
|---|---|
| Electron | 8-26 degrees |
| Pion | 8-16 degrees |



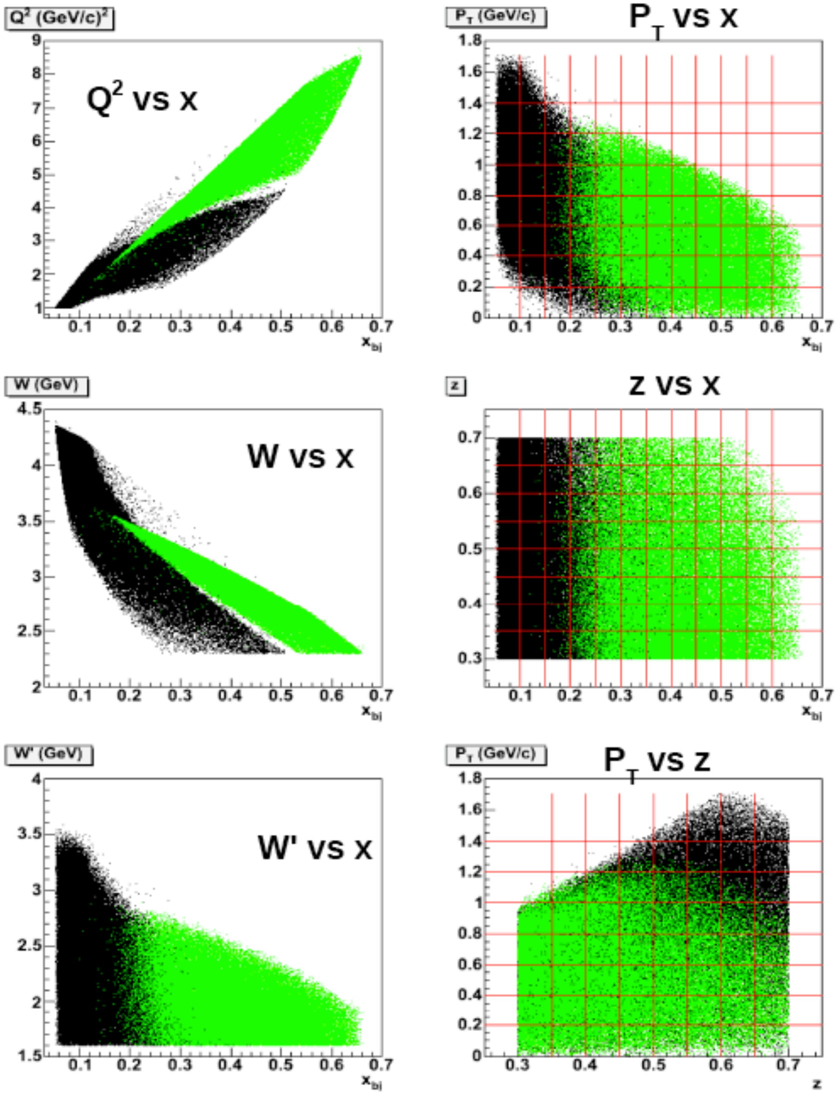
Particle ID with Cherenkov Detectors:

| | |
|---|---|
| Electrons | $CF_4$ + CSI GEMs<br>$CO_2$ + MA-PMTs |
| Pions | $C_4F_{10}$ + PMTs |



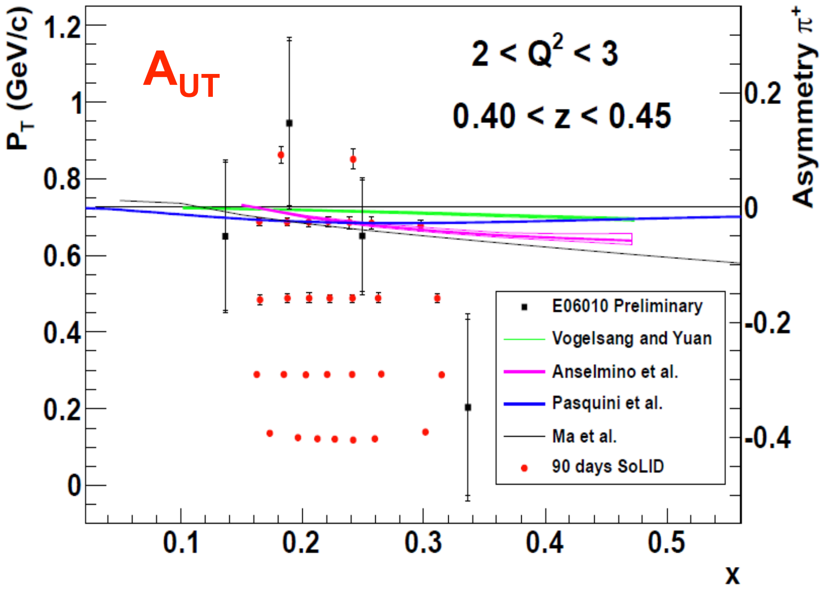
Shashlyk /SciFi calorimeter

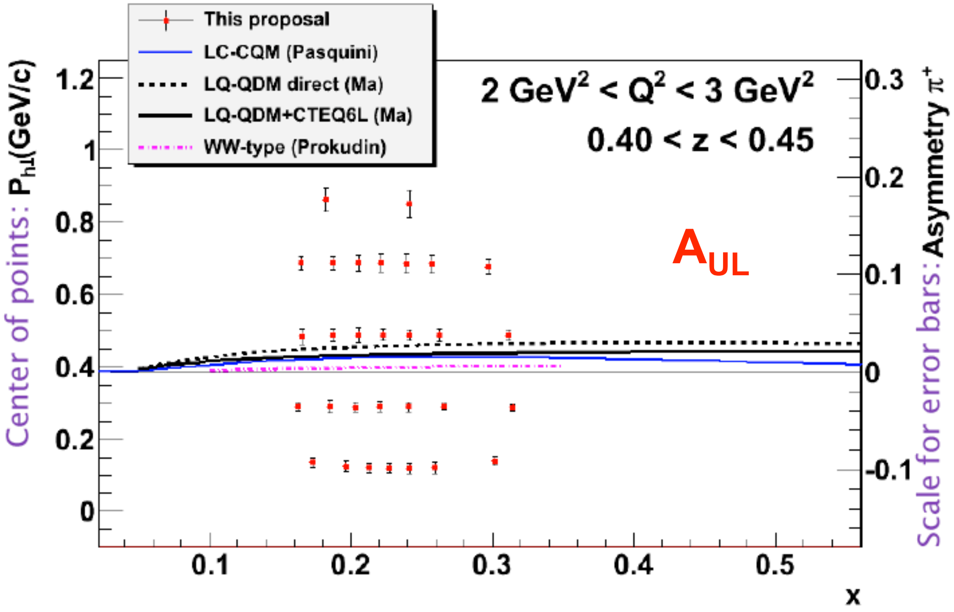
# SIDIS with SOLID



Forward detector

Large angle detector



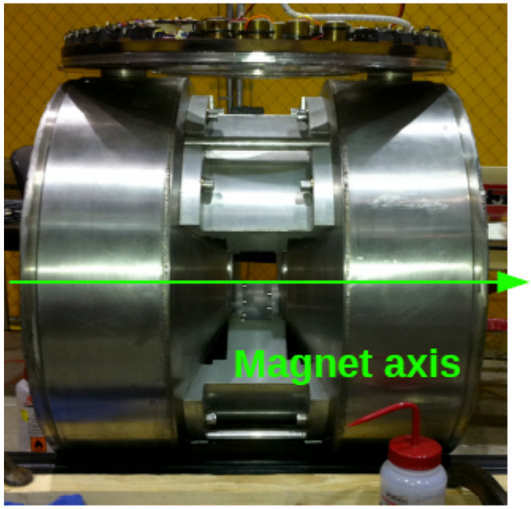


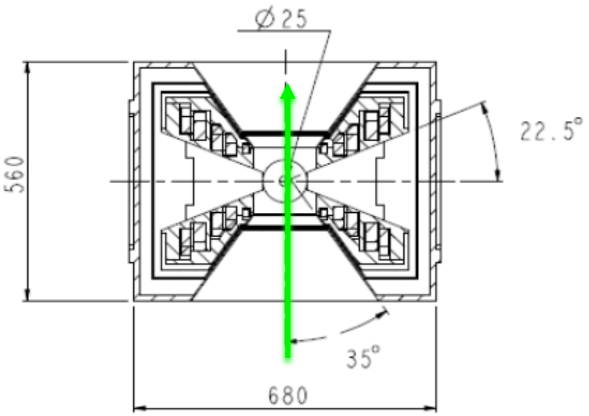
# SOLID with Proton Target

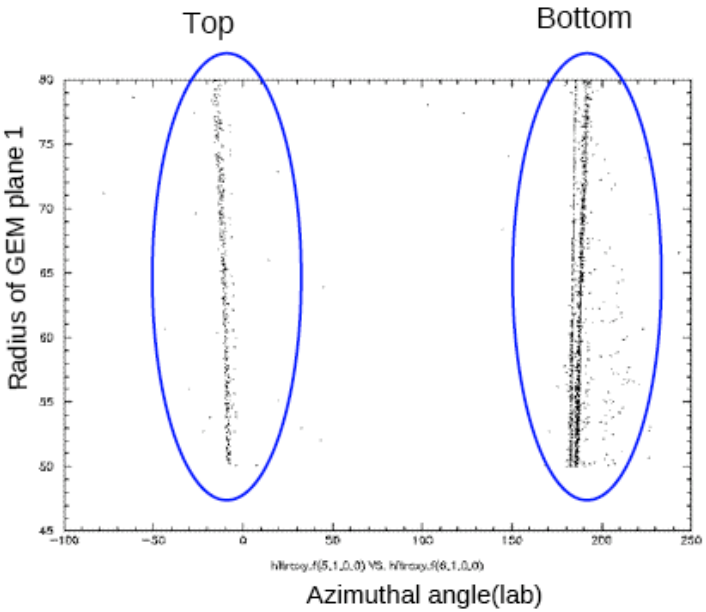
3 cm $NH_3$ polarized target

Dynamic Nuclear Polarization (DNP) by microwave

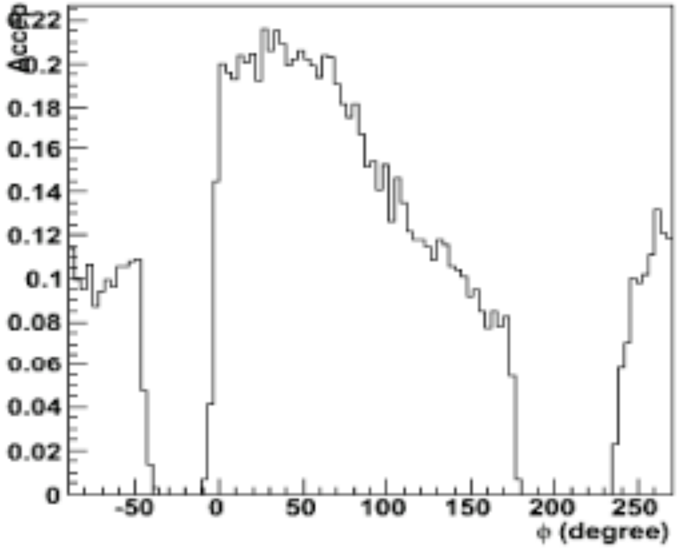
1k refrigerator







Forward Angle 82.92 msr @ 0.6-8 GeV



5T holding field:

Upgrade to enlarge opening in transverse direction ±25°

Beam chicane to compensate target deflection

Sheet of flame background:
high rates prevent measurement in localized area

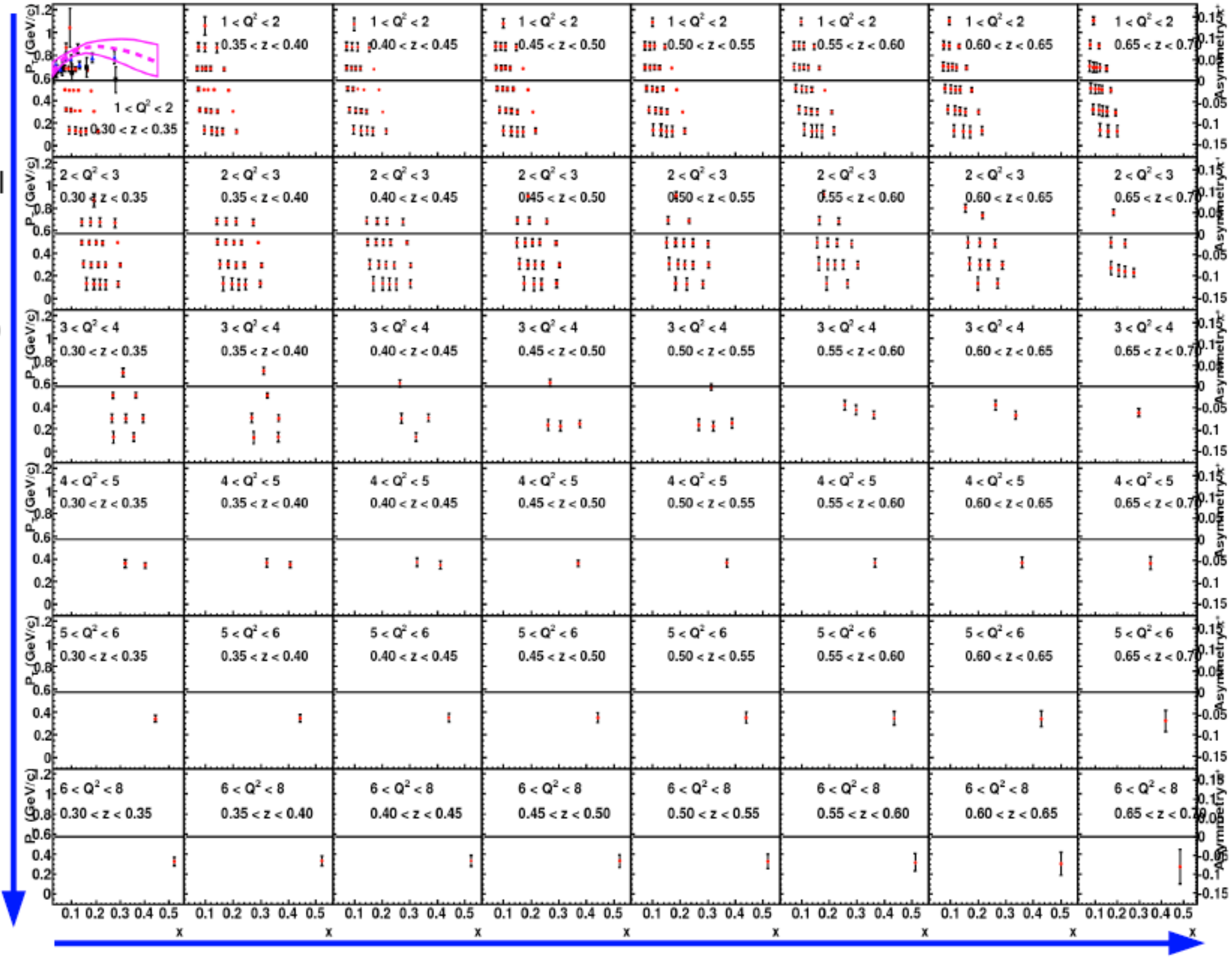
# SIDIS with SOLID

$Q^2 = 1.0$ (GeV/c)$^2$

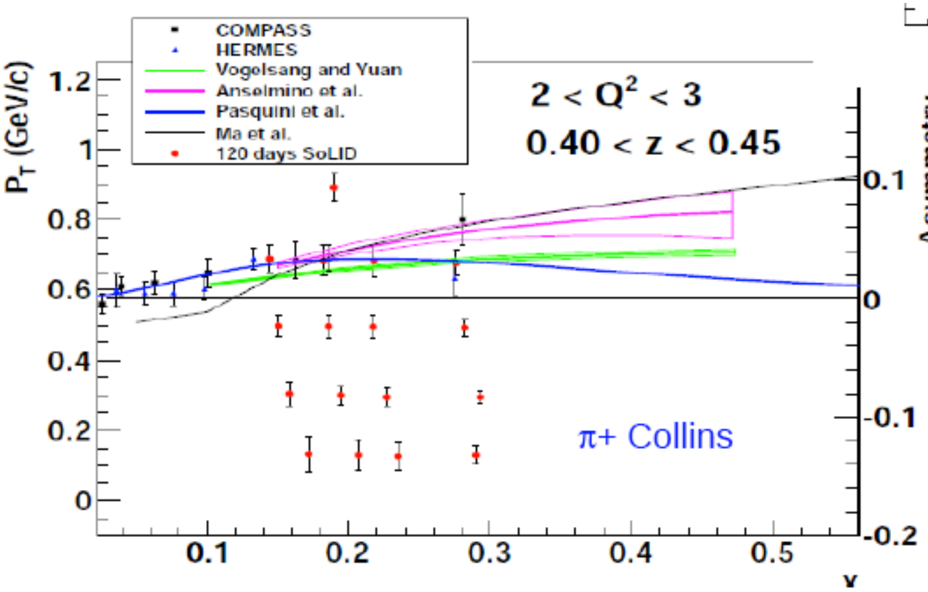
Multi-dimensional binning in $x$, $Q^2$, $p_T$, $z$

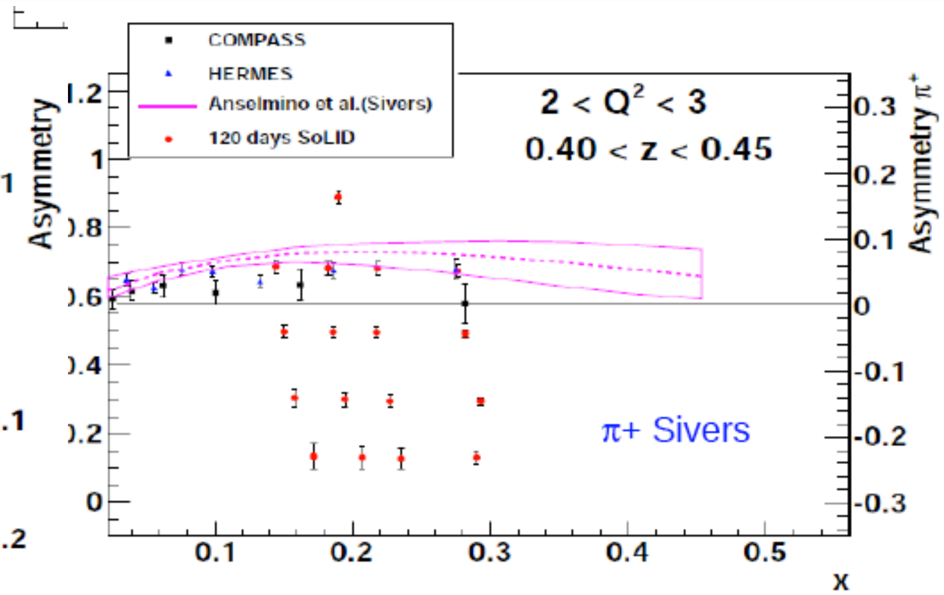
(674 bins in total)

$Q^2 = 8$ (GeV/c)$^2$

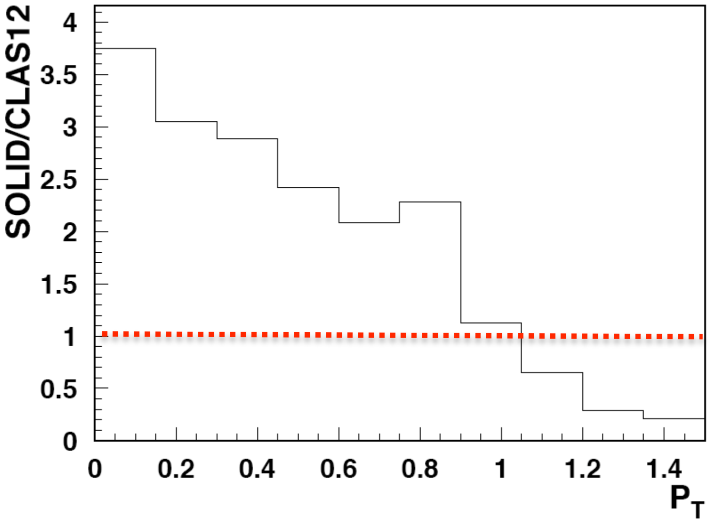


# SIDIS with SOLID

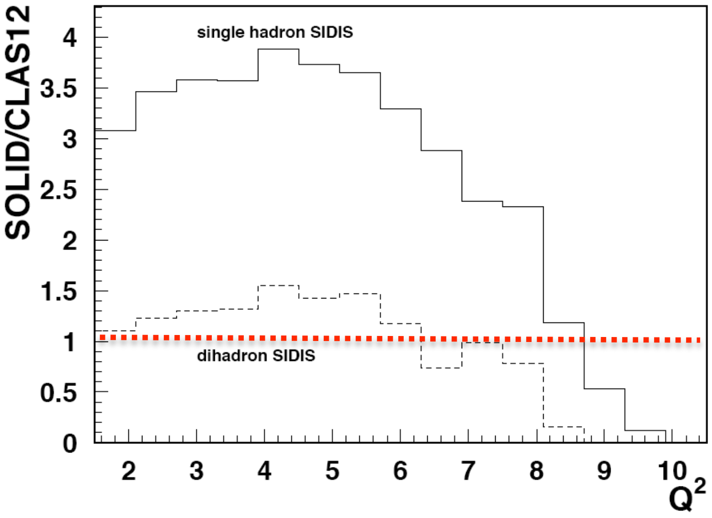




yield ratios



yield ratios



# The JLab12 Charge

**Complete 3D mapping (momentum space) of the nucleon in the valence region**
**High potentiality of the complementary programs of 3 experimantal halls**

- Access to leading-twist poorly known or unmeasured TMDs
  (3D picture in momentum space, relativistic effects, spin-orbit effects, nucleon tomography);

* UPA: ***Number density, Cahn, Boer-Mulders***

* SSA: ***Transversity, Sivers, Pretzelosity, $h_{1L}$ worm-gear function***s;

* DSA: ***Helicity, $g_{1T}$ worm-gear function***;

- Multi dimensional analysis in x, $Q^2$, z, $p_T$ thanks to large-acceptance and high-luminosity;

* ***precise mapping of the valence*** (tensor charge);

* ***disentangle parton distribution from fragmentation functions*** (x vs z);

* ***isolate sub-leading-twist effects*** from 1/Q dependence (g$_2$ as side product) ;

* ***flavor decomposition of pT dependence*** (Bessel analysis);

* ***investigate perturbative to non-perturbative QCD transient*** from $p_T$ dependence;