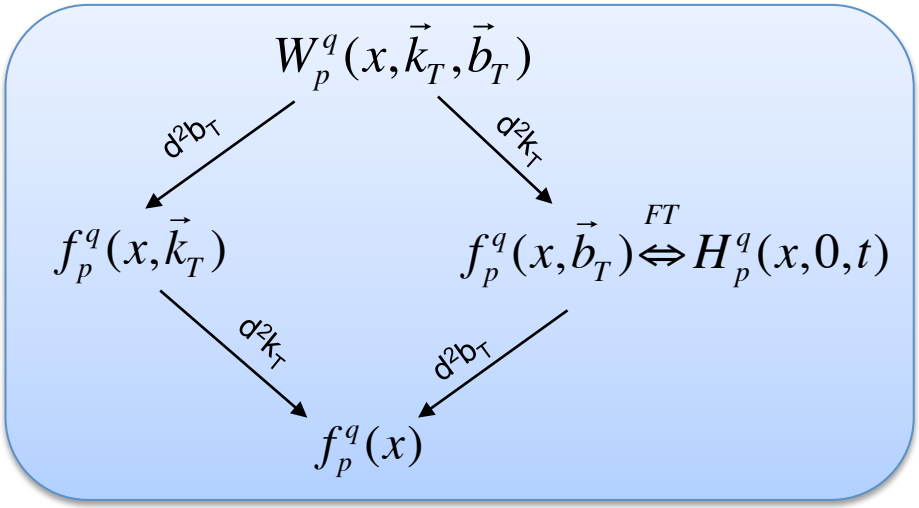
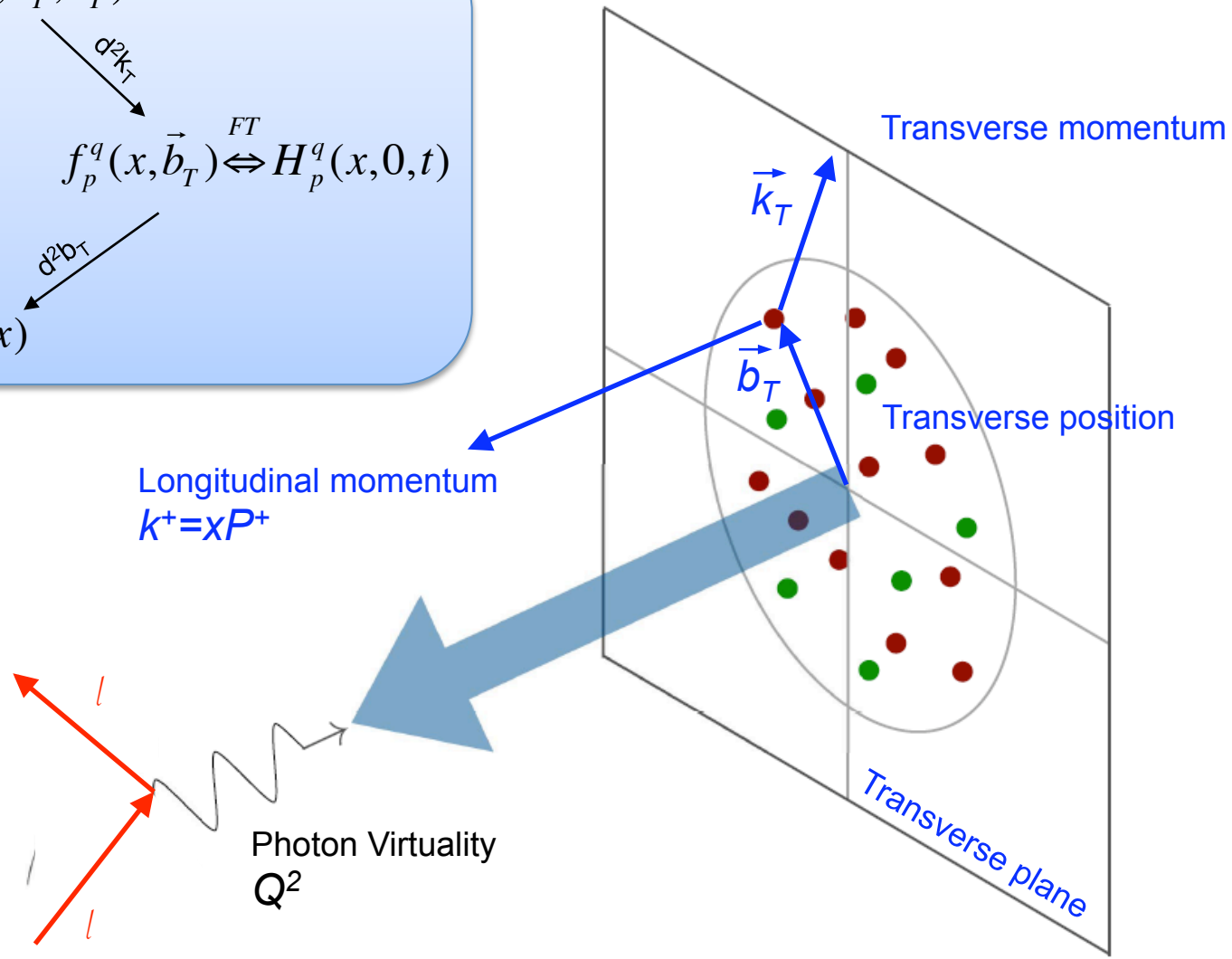
# ROLE OF KAON PRODUCTION AT JLAB12

Contalbrigo Marco
INFN Ferrara

**PSHP 2013**
13th November 2013, LNF

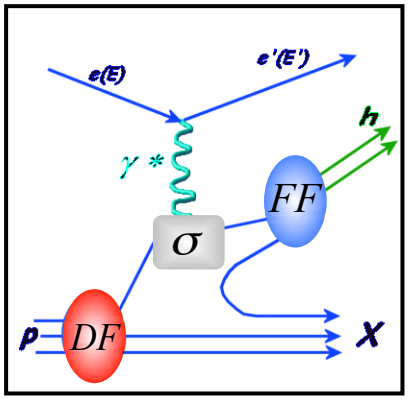
# The 3D Nucleon Structure



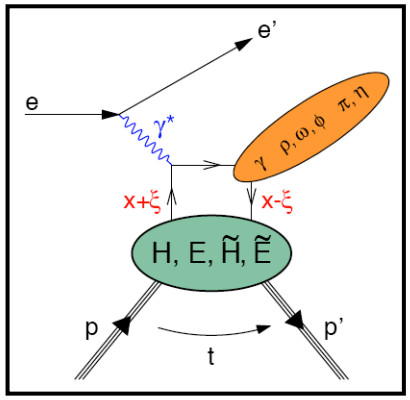
# Quantum Phase-space Distribution of Quarks

$W_p^q(x,\vec{k}_T,\vec{b}_T)$ "Mother" Wigner distributions




$d^2b_T$

$d^2k_T$ (FT)




**TMDs:** $f_p^q(x,\vec{k}_T)$

Semi-inclusive measurements
3D momentum distribution

**GPDs:** $H_p^q(x,\xi,t)$

Exclusive Measurements
1+2D spatial distribution

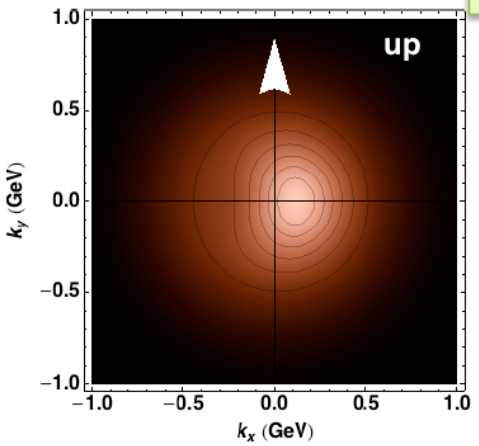
$d^2k_T$

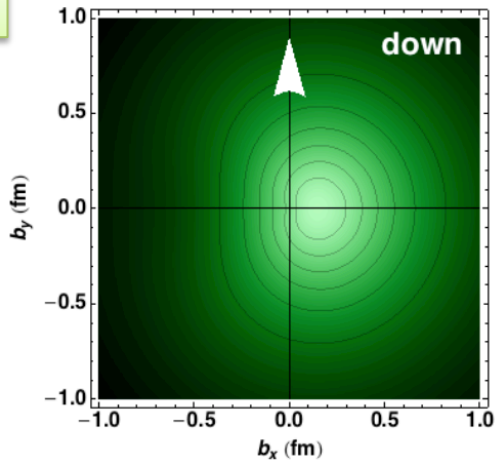
$\xi=0,t=0$

PDFs $f_p^q(x)$

# Quantum Phase-space Distribution of Quarks

$W_p^q(x,\vec{k}_T,\vec{b}_T)$ "Mother" Wigner distributions

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Semi-inclusive measurements
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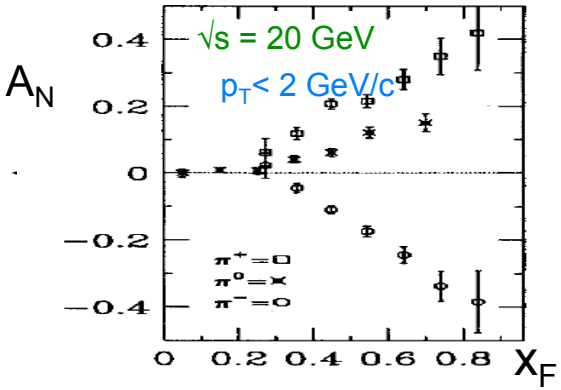
Exclusive Measurements
1+2D spatial distribution

$d^2k_T$

$\xi=0,t=0$

**PDFs** $f_p^q(x)$

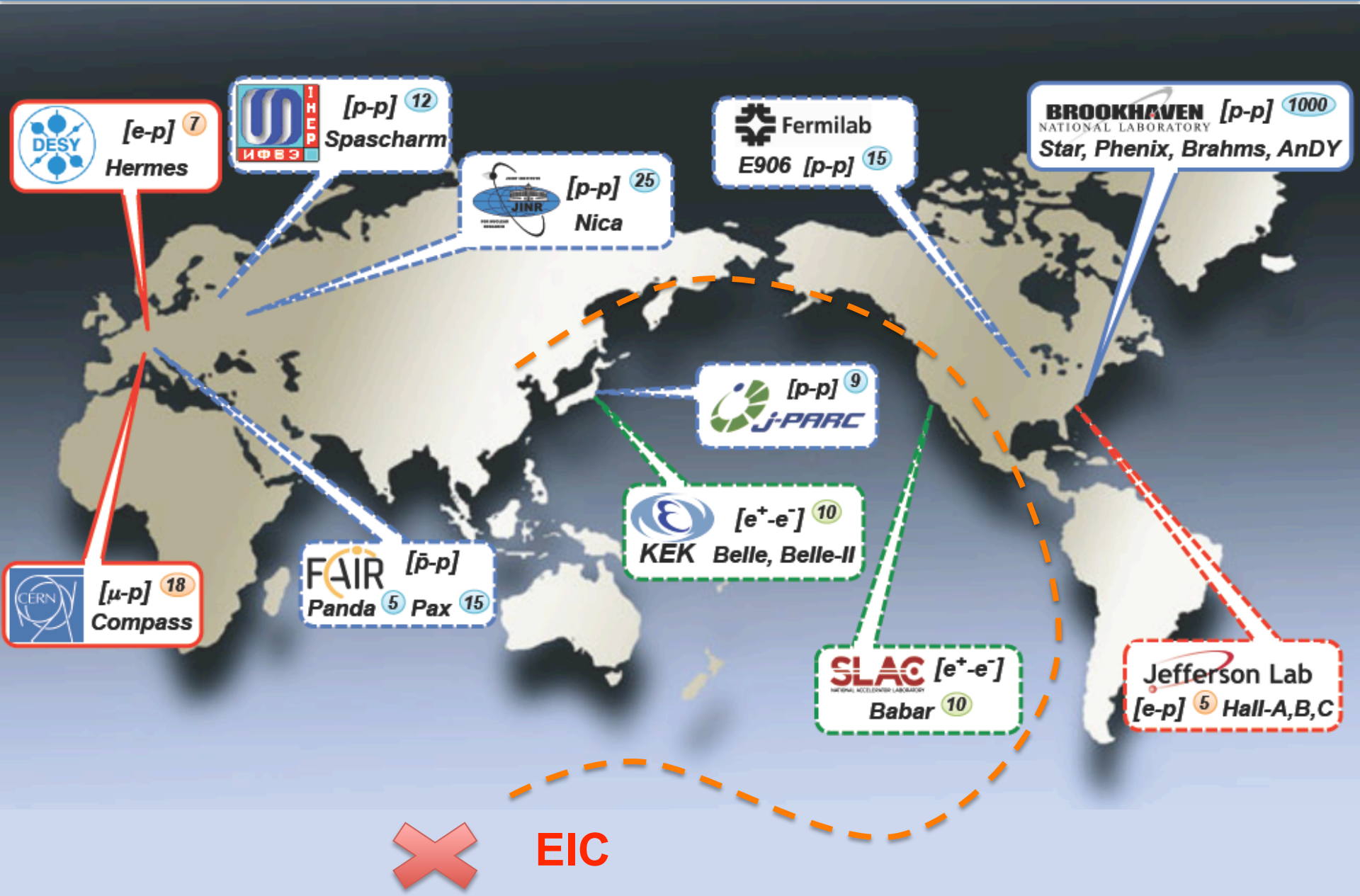
May explain SSA & Lam-Tung




May solve
proton spin puzzle

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

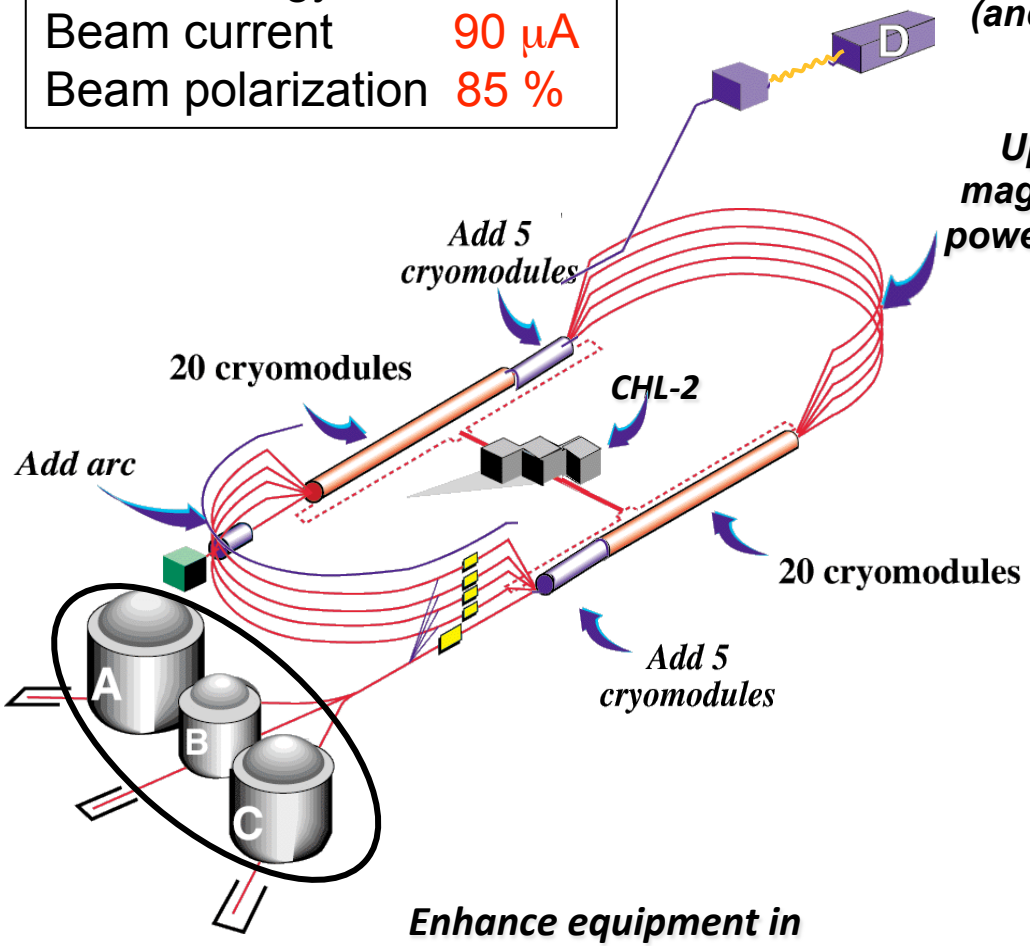
# A World-wide Challenge



# The JLAB12 Facility

# CEBAF Upgrade at Jefferson Lab

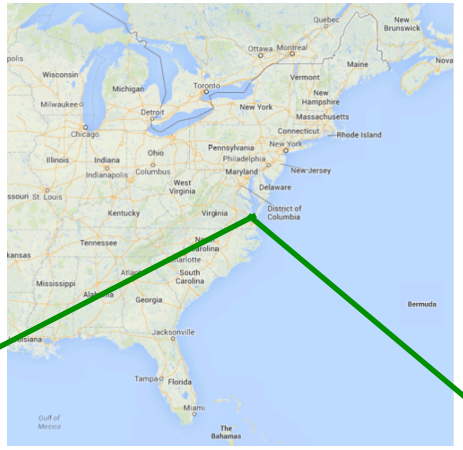
| | |
|---|---|
| Beam Energy | 12 GeV |
| Beam current | 90 μA |
| Beam polarization | 85 % |




***add Hall D (and beam line)***

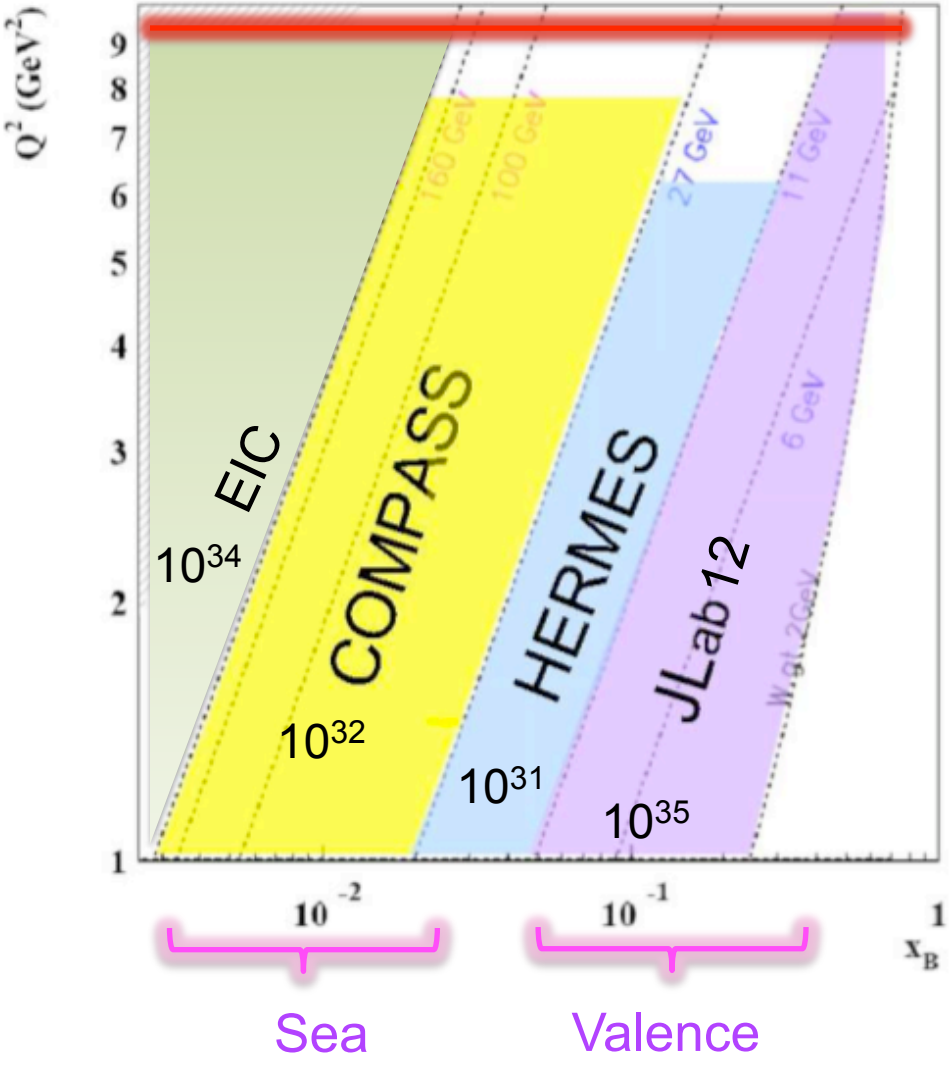
***Upgrade magnets and power supplies***

***Enhance equipment in existing halls***



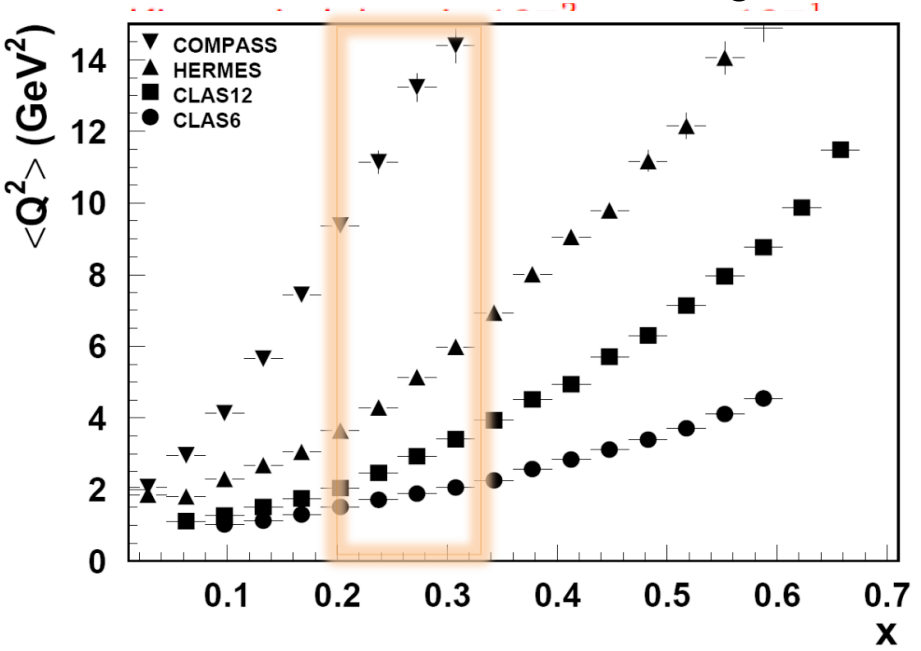
# The SIDIS Landscape

Limit defined by luminosity




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

Different $Q^2$ for same x range

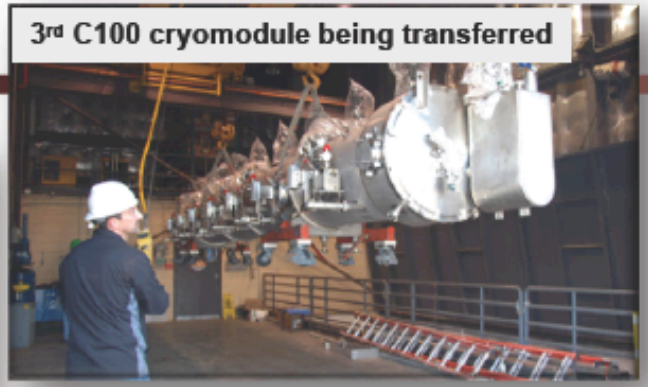



Complementary experiments

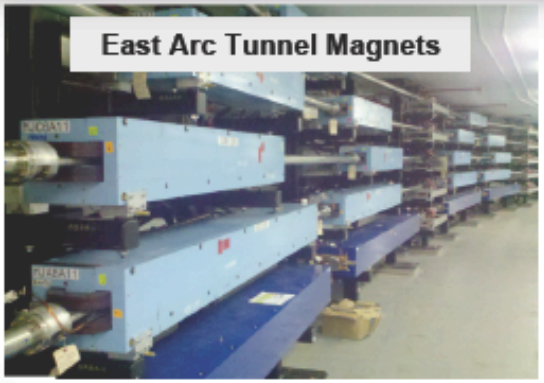
# 12 GeV Project Status

Hall D Interior

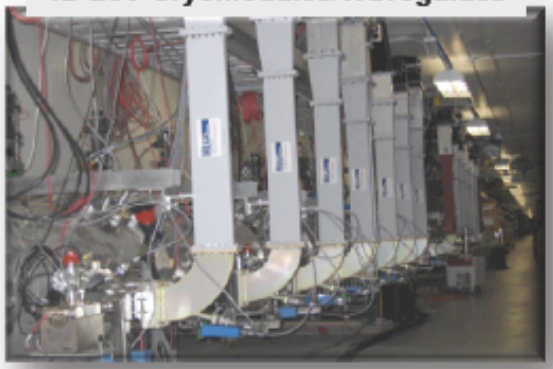

3rd C100 cryomodule being transferred




East Arc Tunnel Magnets



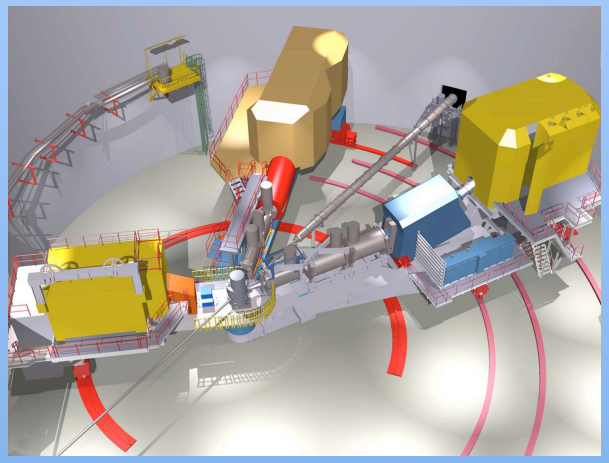
12 GeV Cryomodules/Waveguides



- Project 75% Complete, 88% Obligated
  - Civil (92%) ; Accelerator (88%) ; Physics Equip (~60%)
- We expect to be running beam to Hall A in February 2014 and Hall D later in the year
- Large user involvement in 12-GeV detector construction
- 7+ years approved, Halls have prepared initial schedule

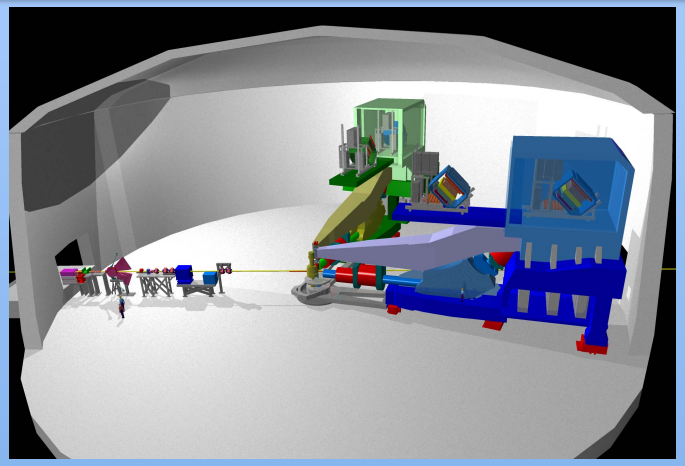
# JLab12 Experimental Halls

## Hall-C



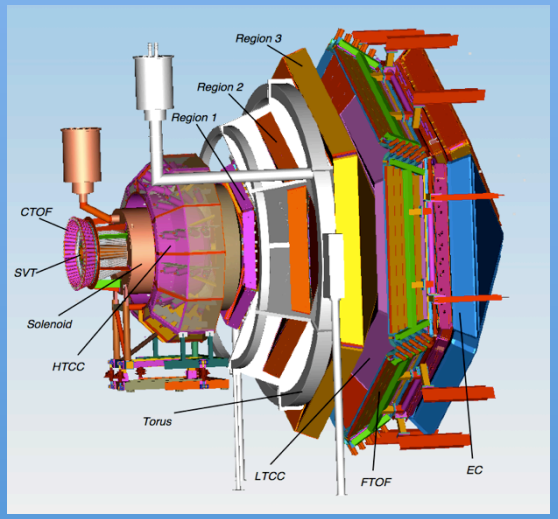
Super High Momentum Spectrometer (SHMS)
unpolarized SIDIS, hadron ID

## Hall-A



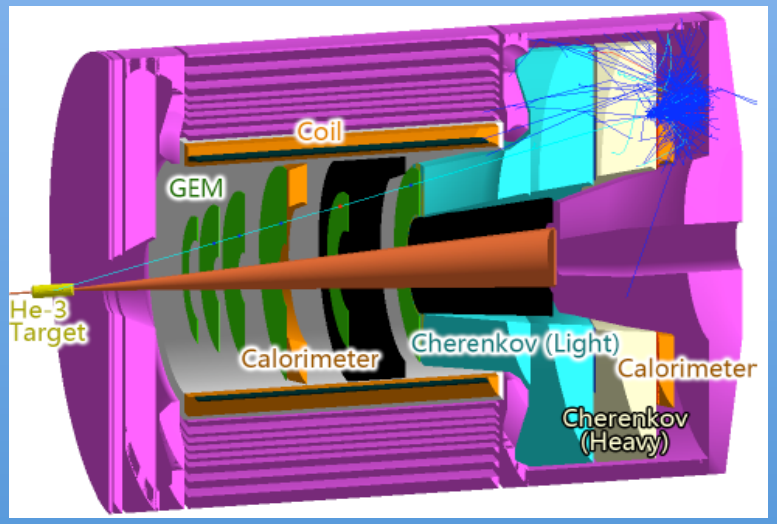
Spectrometer Pair, polarized $^3$He target
up to to $10^{38}$ cm$^{-2}$ s$^{-1}$ hadron ID

## 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

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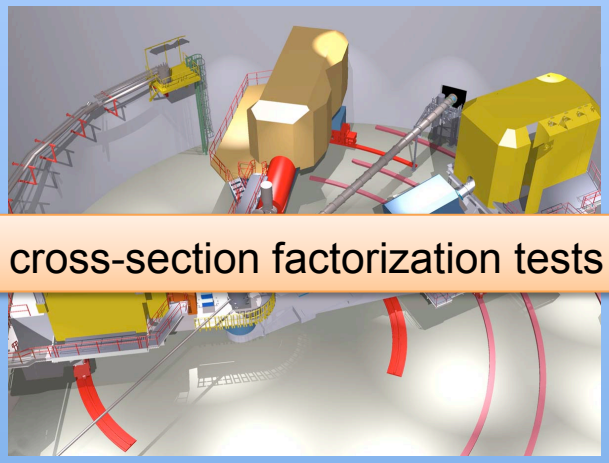

SIDIS cross-section factorization tests

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

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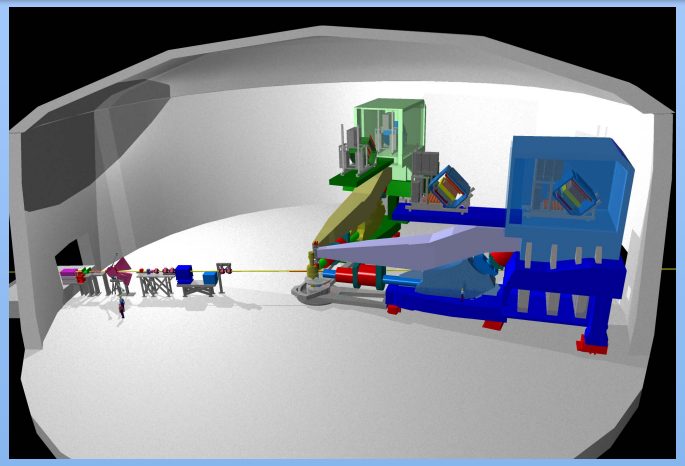

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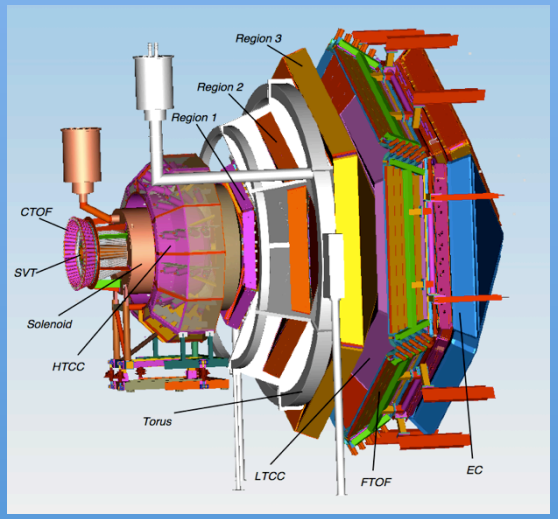


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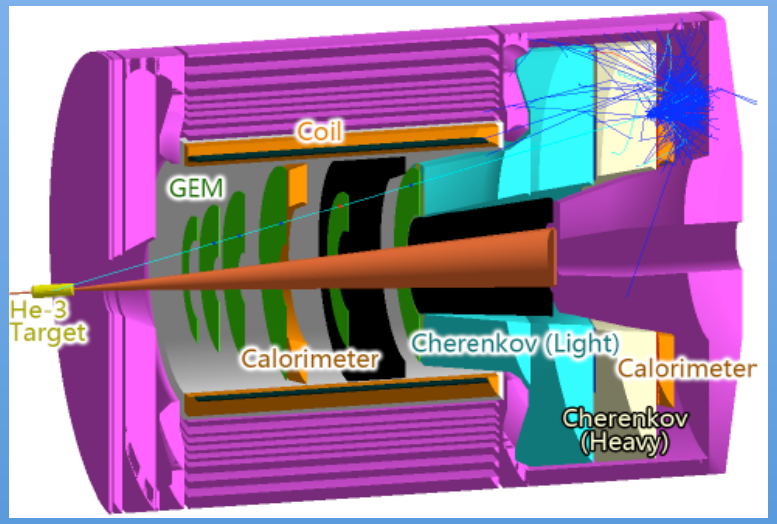


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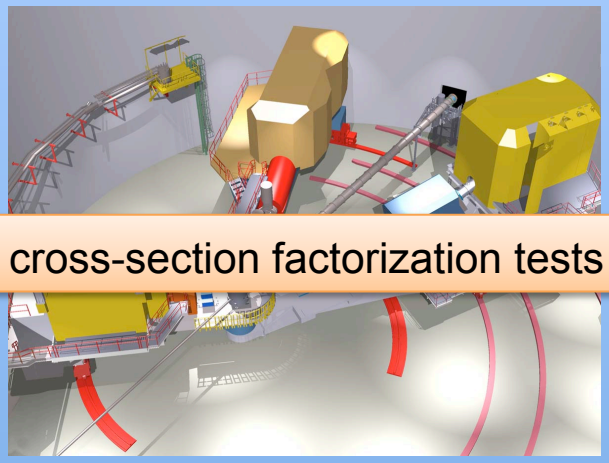

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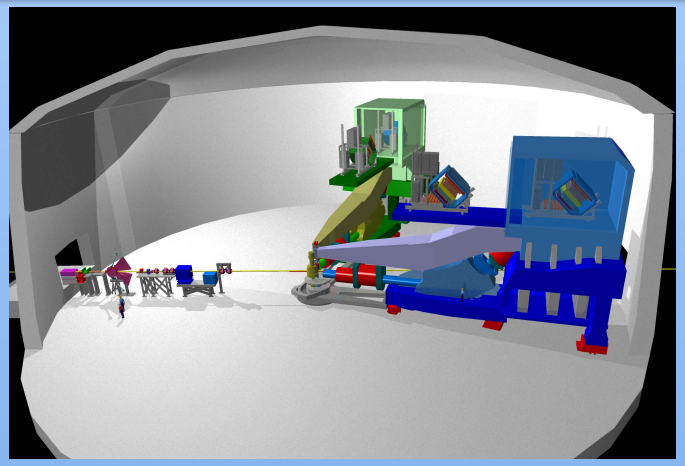

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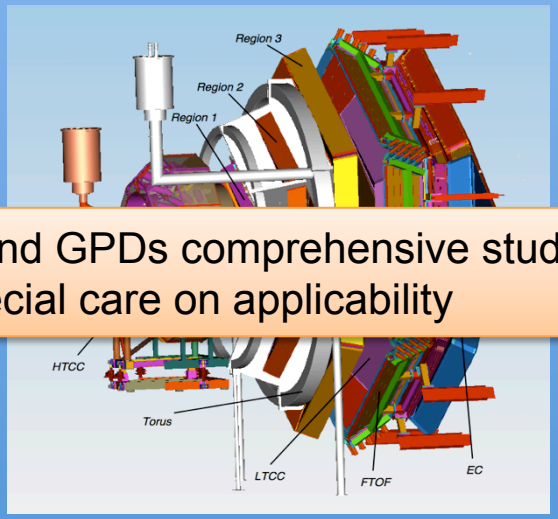


TMDs and GPDs comprehensive study,
with special care on applicability

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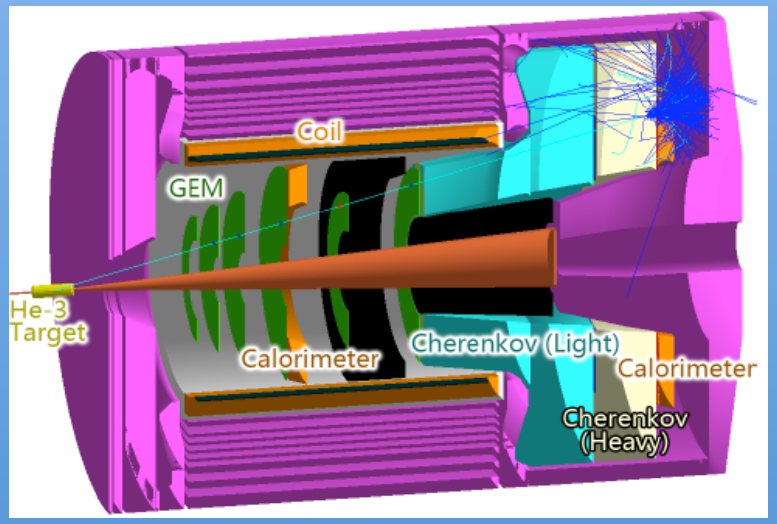


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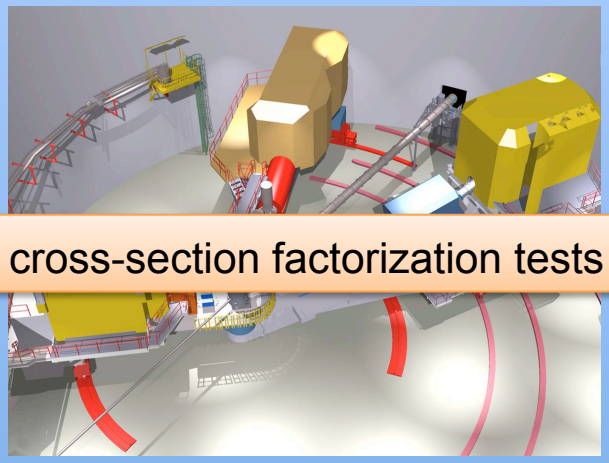

SIDIS cross-section factorization tests

Super High Momentum Spectrometer (SHMS)
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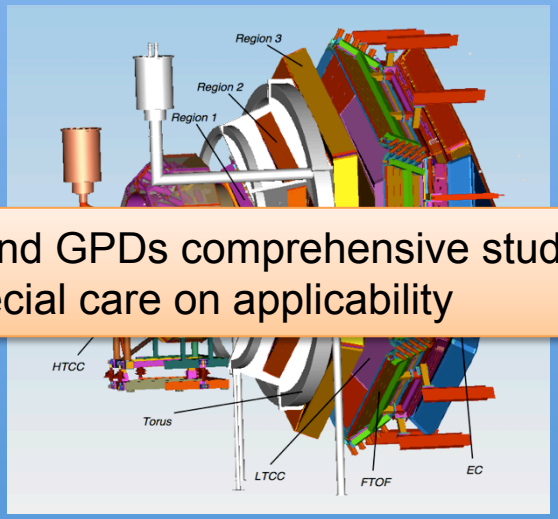
## Hall-A

Luminosity frontier
World leading $^3$He target

Spectrometer Pair, polarized $^3$He target
up to to $10^{38}$ cm$^{-2}$ s$^{-1}$ hadron ID

## Hall-B

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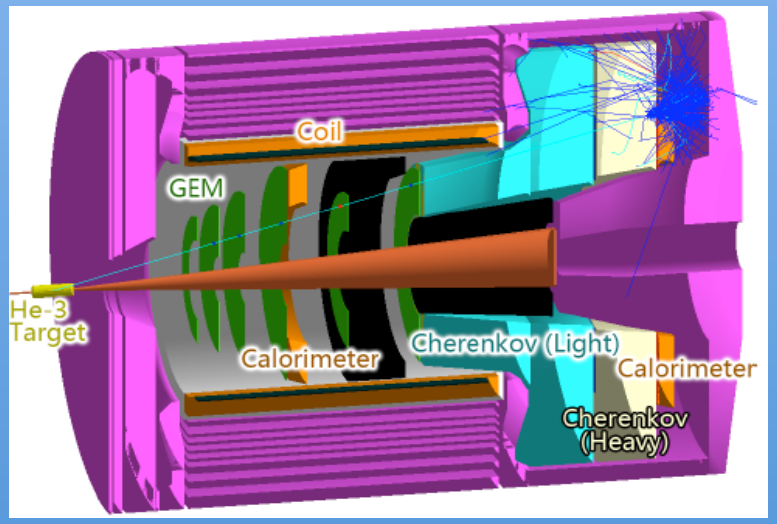


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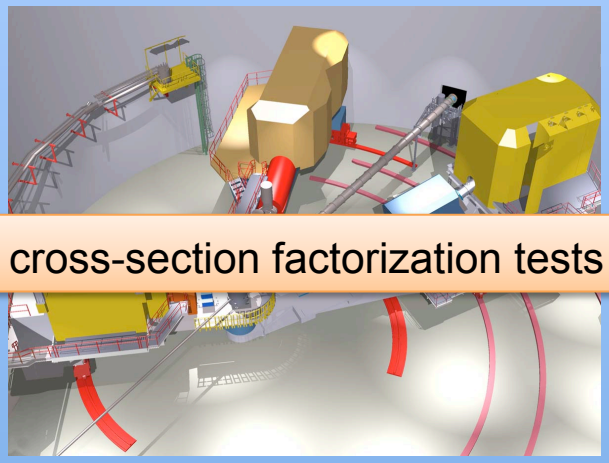

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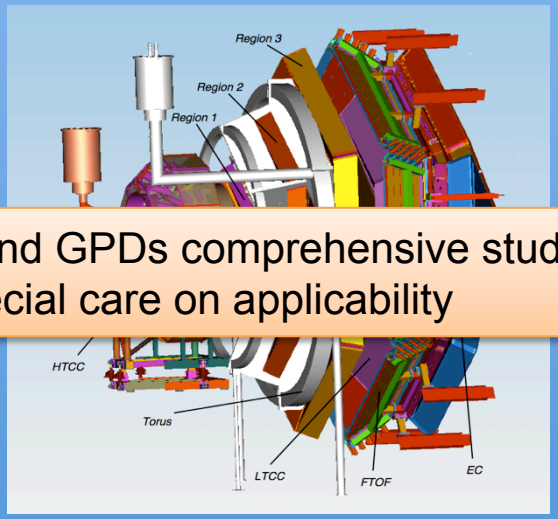


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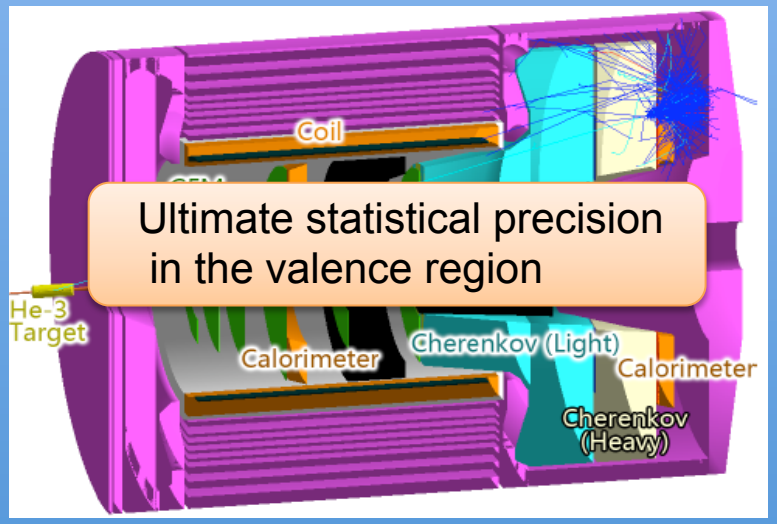


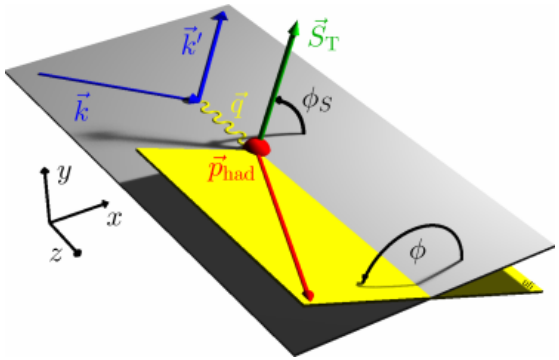

Ultimate statistical precision
in the valence region

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

# SIDIS: Transverse Momentum Dependence

# The SIDIS case

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



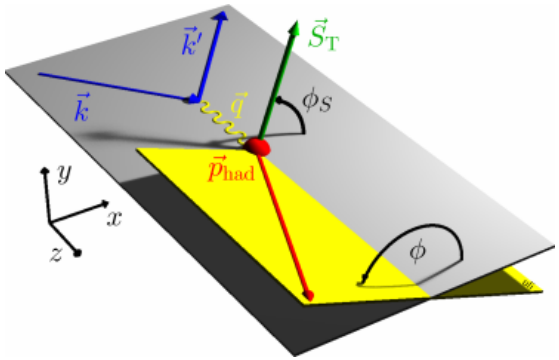

$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S d\phi\,dP_{h\perp}^2} \underset{Twist}{\overset{Leading}{\propto}} S_T\left\{\sin(\phi-\phi_S)F_{UT,T}^{\sin(\phi-\phi_S)}\right\}$$

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

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

# The SIDIS case

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




$h_1 \otimes H_1^\perp$

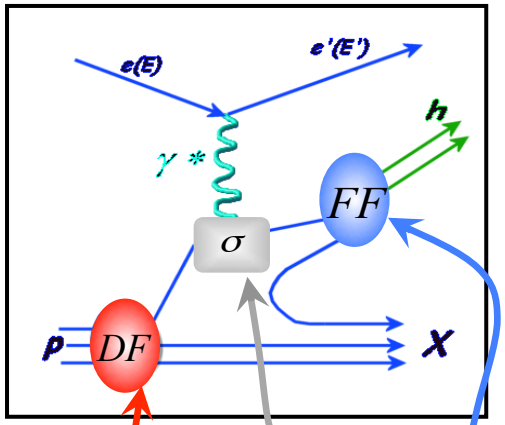
$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S d\phi\,dP_{h\perp}^2} \underset{Twist}{\overset{Leading}{\propto}} S_T\left\{\sin(\phi-\phi_S)F_{UT,T}^{\sin(\phi-\phi_S)}\right\}$$

$f_{1T}^\perp \otimes D_1$ $\qquad$ $h_{1T}^\perp \otimes H_1^\perp$

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

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

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



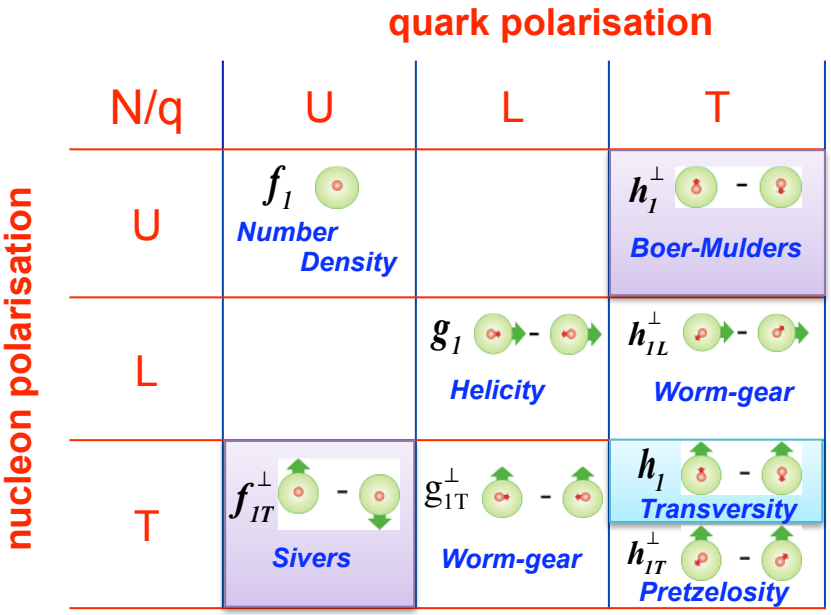

$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

TMD factorization for $P_T$<<Q

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

Involved phenomenology due to the convolution over transverse momentum

# Leading Twist TMDs




**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

# Leading Twist TMDs

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 |

$$D^{\perp,unf} \sim \frac{1}{2} D^{\perp,fav}$$

$$H^{\perp,unf} \sim -H^{\perp,fav}$$

$$fav: \quad u \to \pi^+$$

$$unf: \quad u \to \pi^-$$

Garzia, Giordano talks

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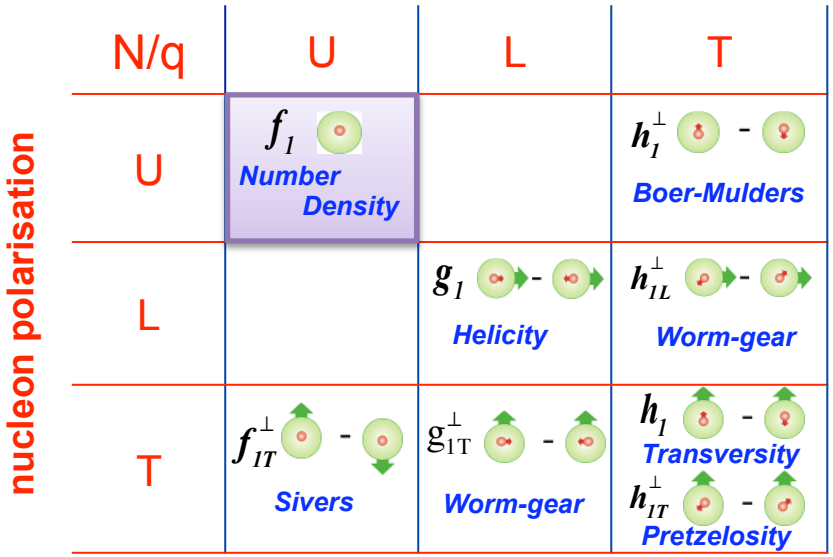
Testing QCD at the amplitude level

quark polarisation

nucleon polarisation

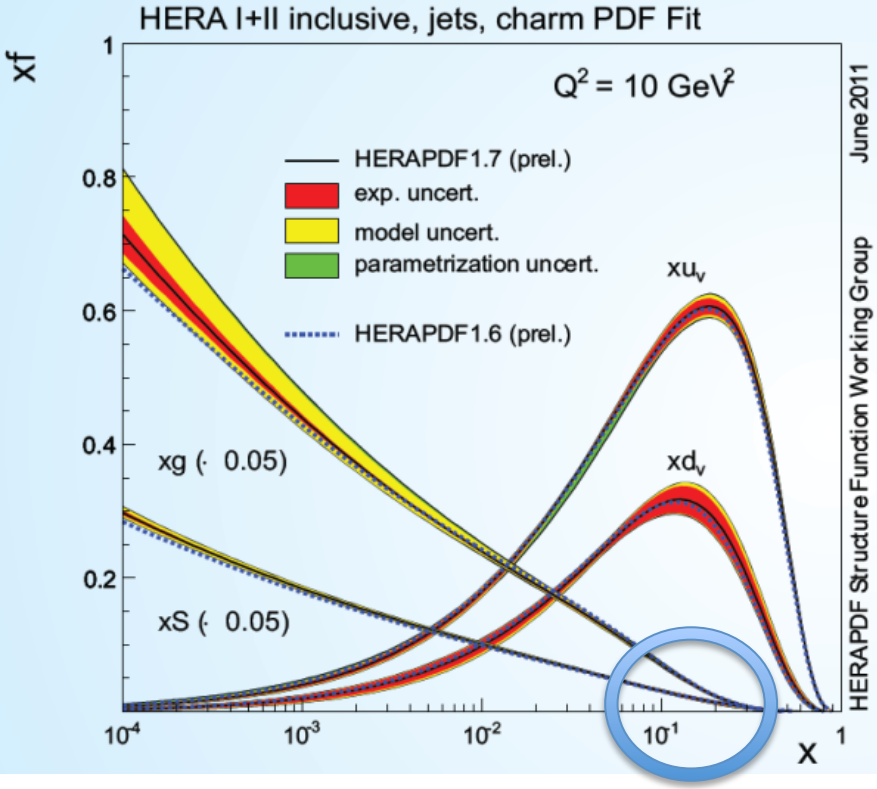
| N/q | U | L | T |
|---|---|---|---|
| U | $D_1$ Unpolarized | | $H_1^\perp$ Collins |
| L | | $G_{1L}$ | $H_{1L}^\perp$ |
| T | $D_{1T}^\perp$ | $G_{1T}$ | $H_1$; $H_{1T}^\perp$ |

# Number Density




# (The Baseline)

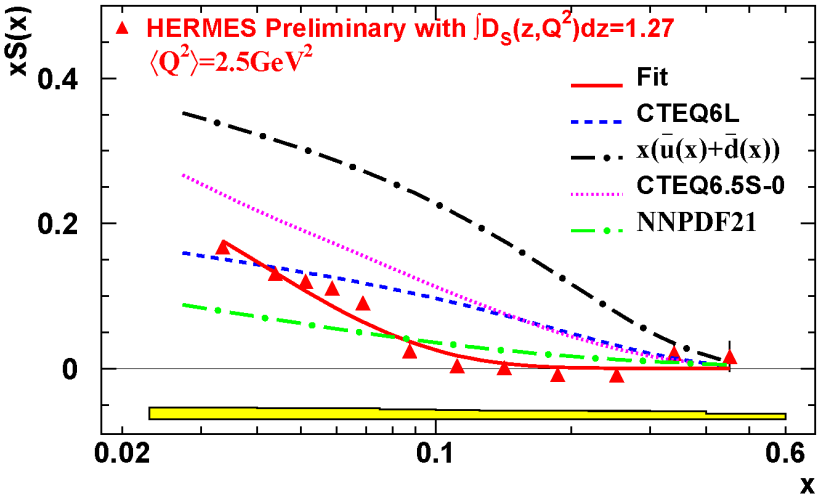
# Parton Number Density



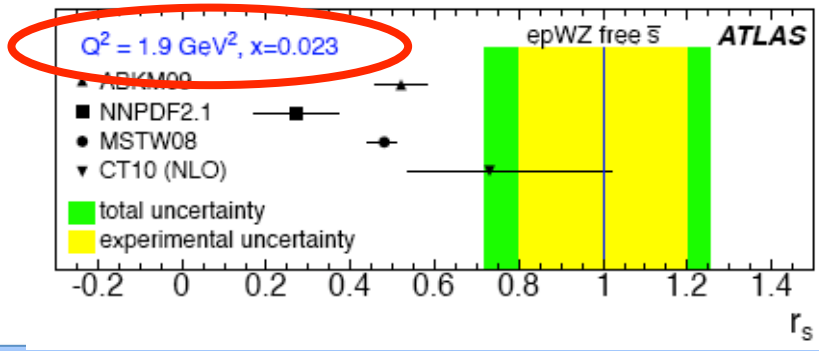

**SIDIS extraction:**

$$\int_{0.2}^{0.85} M^{K^+ + K^-}(x,z)dz = \frac{Q(x)\int D_Q^K(z)dz + S(x)\int D_S^K(z)dz}{5Q(x)+2S(x)}$$

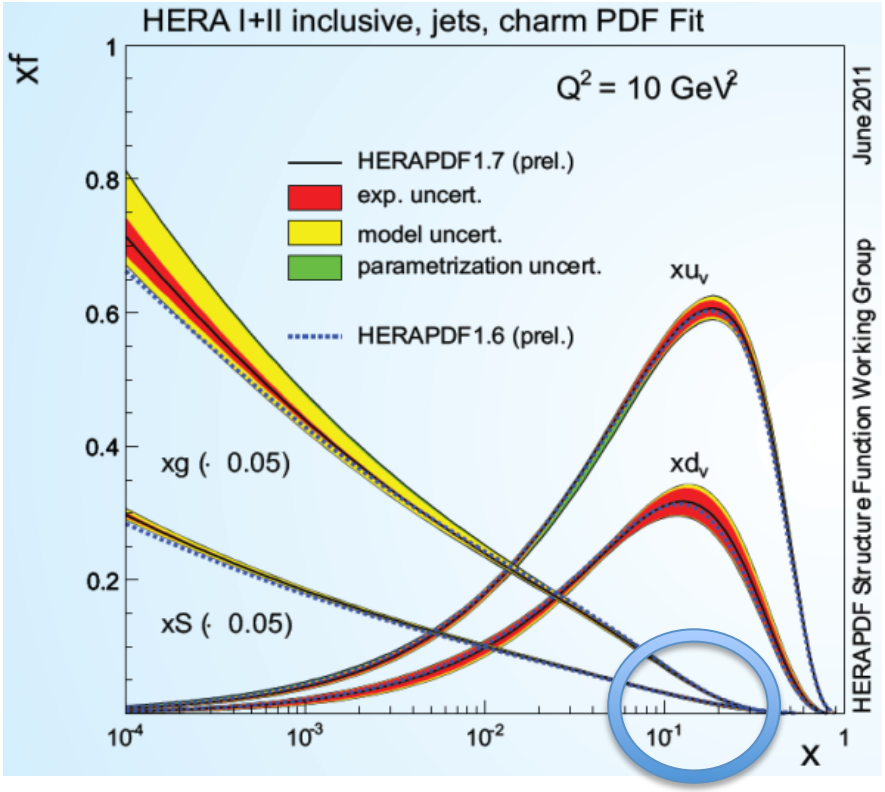
**[Jackson, DIS 2013]**

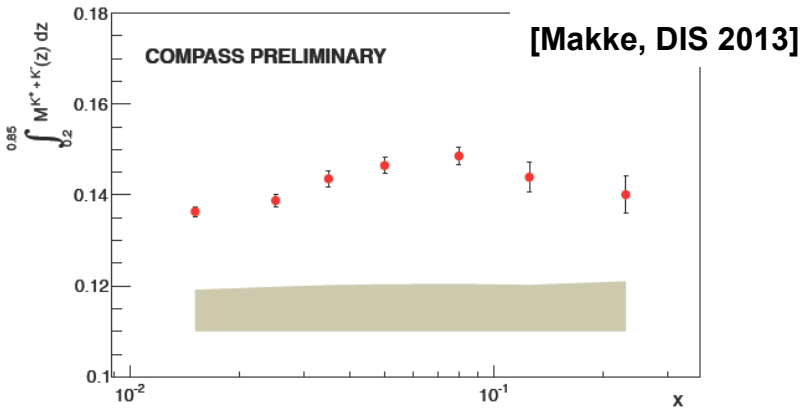



**ATLAS: arXiv:1206.4051** $r_s = 0.5(s+\bar{s})/\bar{d}$



# Parton Number Density



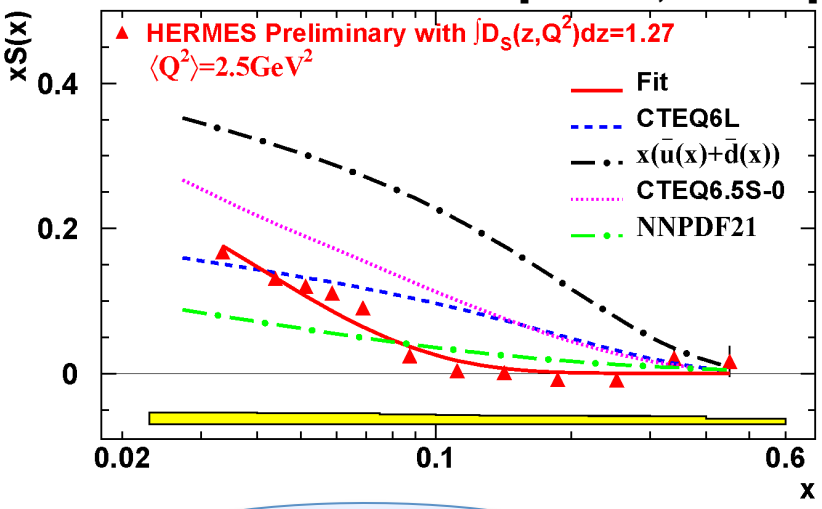




[Makke, DIS 2013]

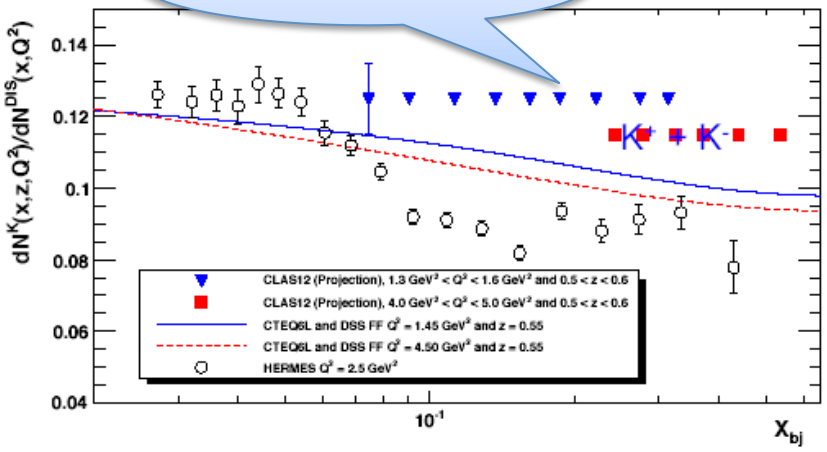
**SIDIS extraction:**

$$\int_{0.2}^{0.85} M^{K^+ + K^-}(x,z)dz = \frac{Q(x)\int D_Q^K(z)dz + S(x)\int D_S^K(z)dz}{5Q(x)+2S(x)}$$

[Jackson, DIS 2013]




E12-07-104 Hall-B



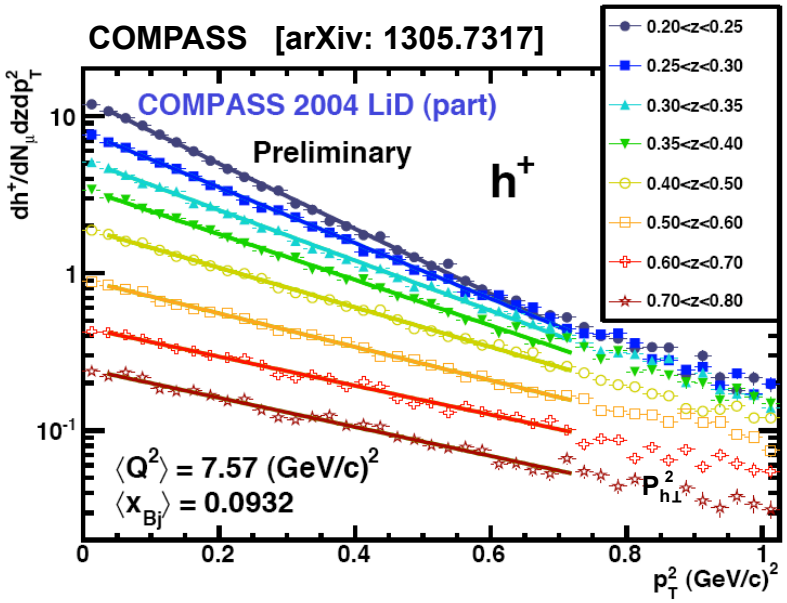
# The $P_{h\perp}$-unintegrated multiplicities $f_1 \otimes D_1$

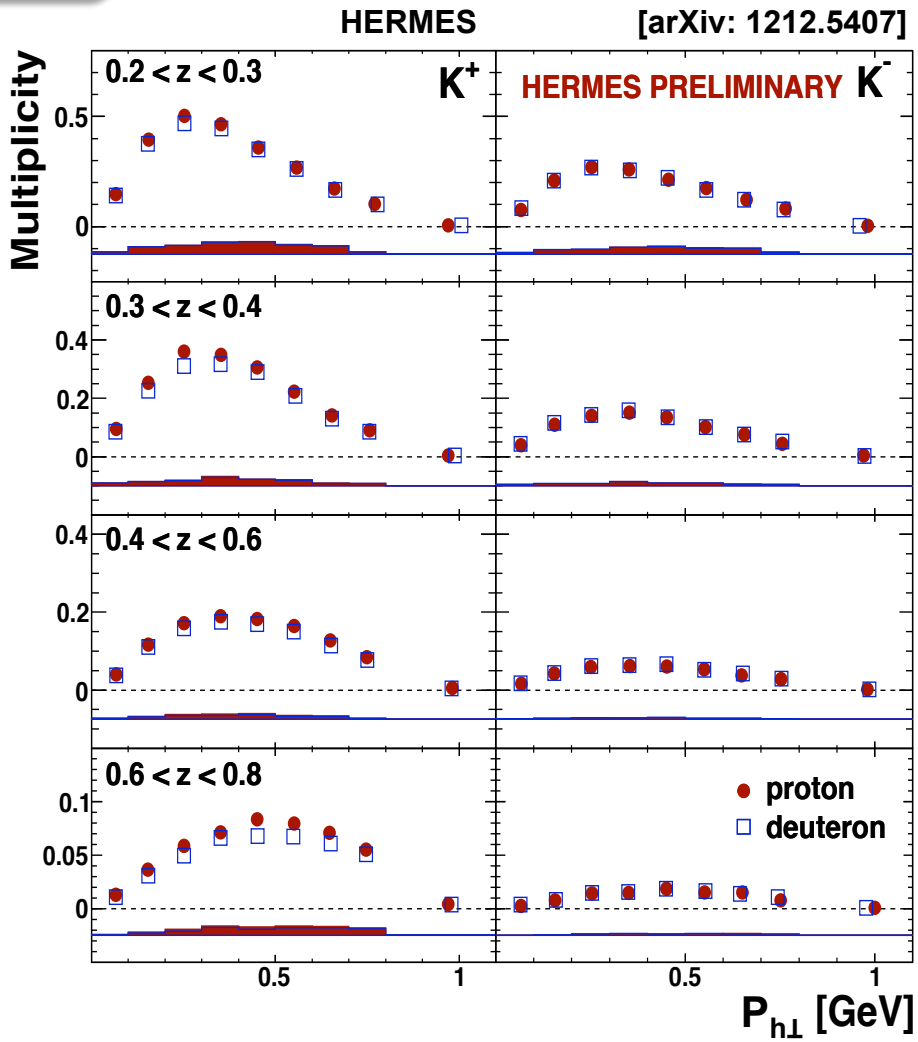
$$M_N^h(z) = \frac{1}{N_N^{DIS}(Q^2)} \frac{dN_N^h(z,Q^2)}{dz} = \frac{\sum_q e_q^2 \int dx\ f_{1q}(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 \int dx\ f_{1q}(x,Q^2)}$$

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

i.e. from gaussian anstaz:

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



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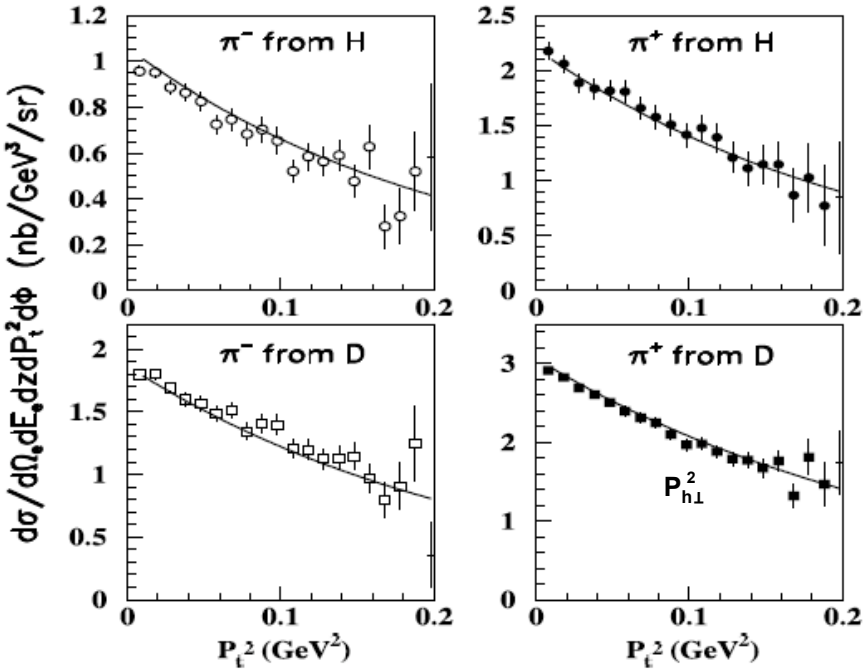
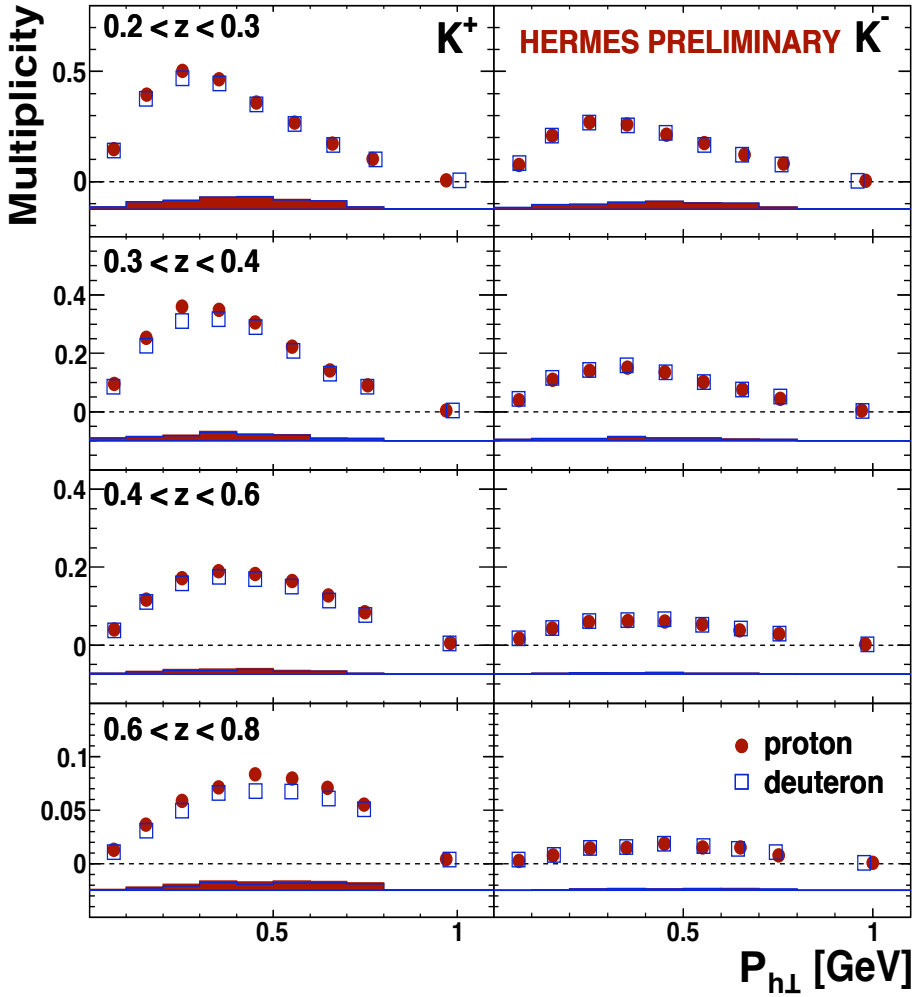
Hall-C [arXiv: 0709.3020]



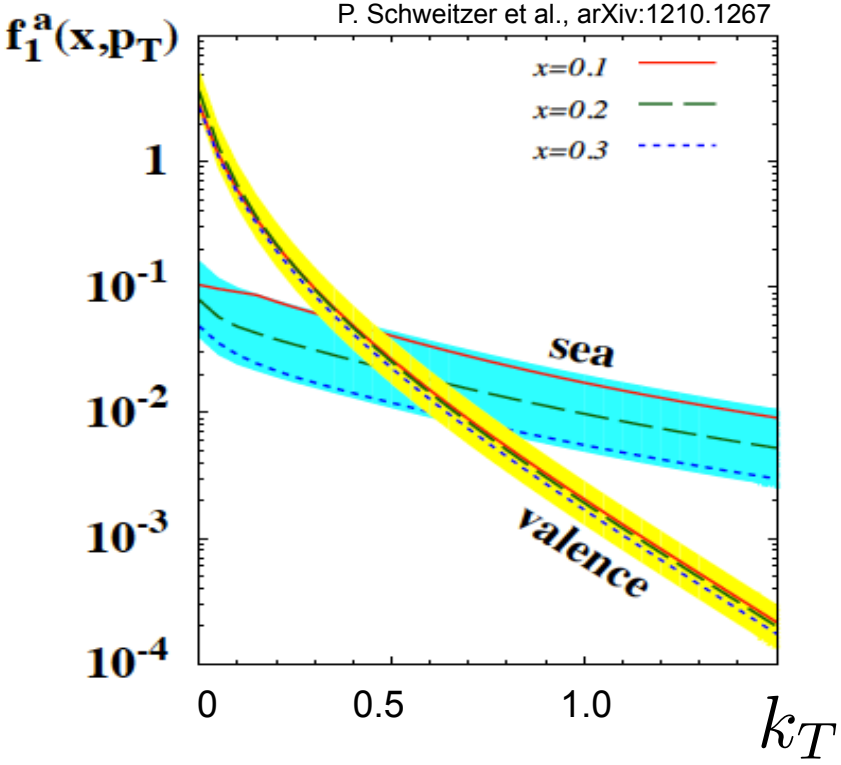

HERMES [arXiv: 1212.5407]



# $P_{h1}$ & Flavor Dependence

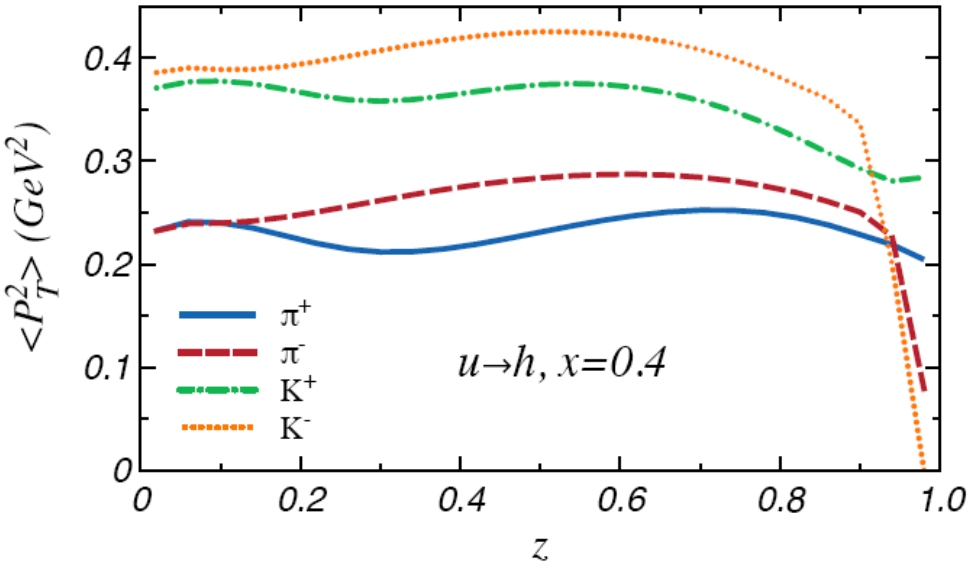
•$k_T$-distributions of TMDs depend on flavor and spin

P. Schweitzer et al., arXiv:1210.1267




Difference in hadronic transverse momentum distributions may come from fragmentation

H. Matevosyan et al., arXiv: 1111.1740

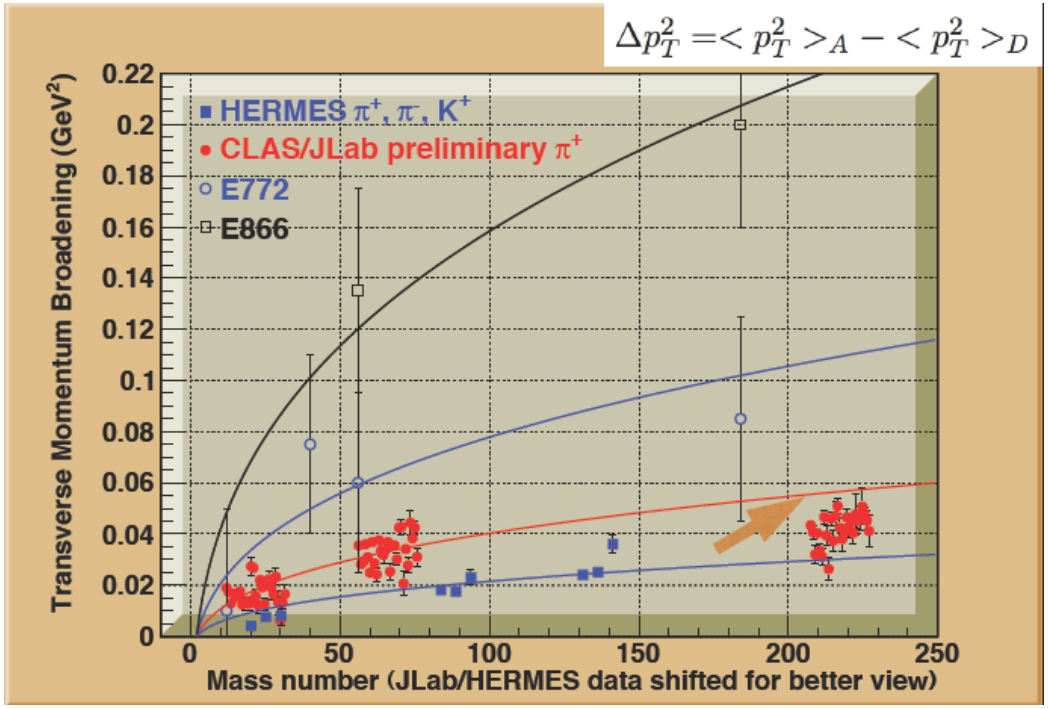


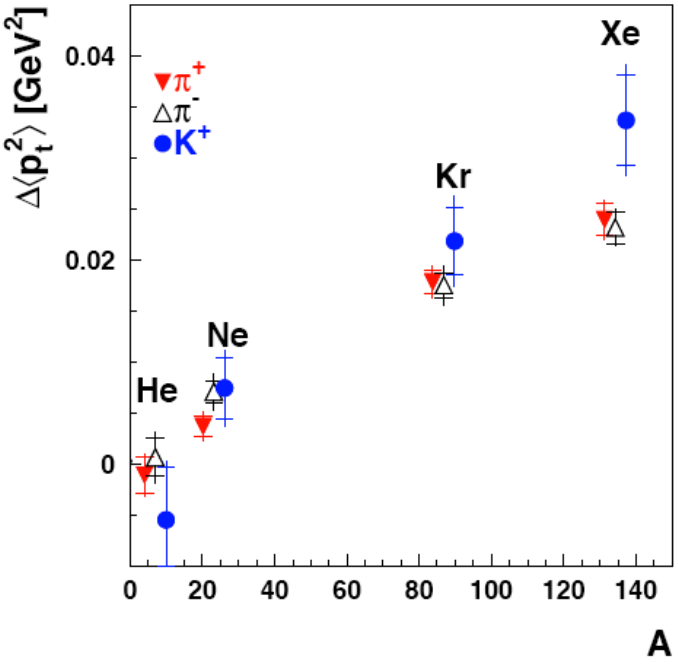

Final states with sensitivity to different parton types will be critical to separate contributions to the complex nucleon 3D structure

# Medium modification

In terms of the QCD, there are several contributions to $P_T$ distribution of hadrons produced in SIDIS:

- primordial transverse momentum,
- gluon radiation of the struck quark,
- the formation and soft multiple interactions of the "pre-hadron"
- the interaction of the formed hadrons with the surrounding hadronic medium

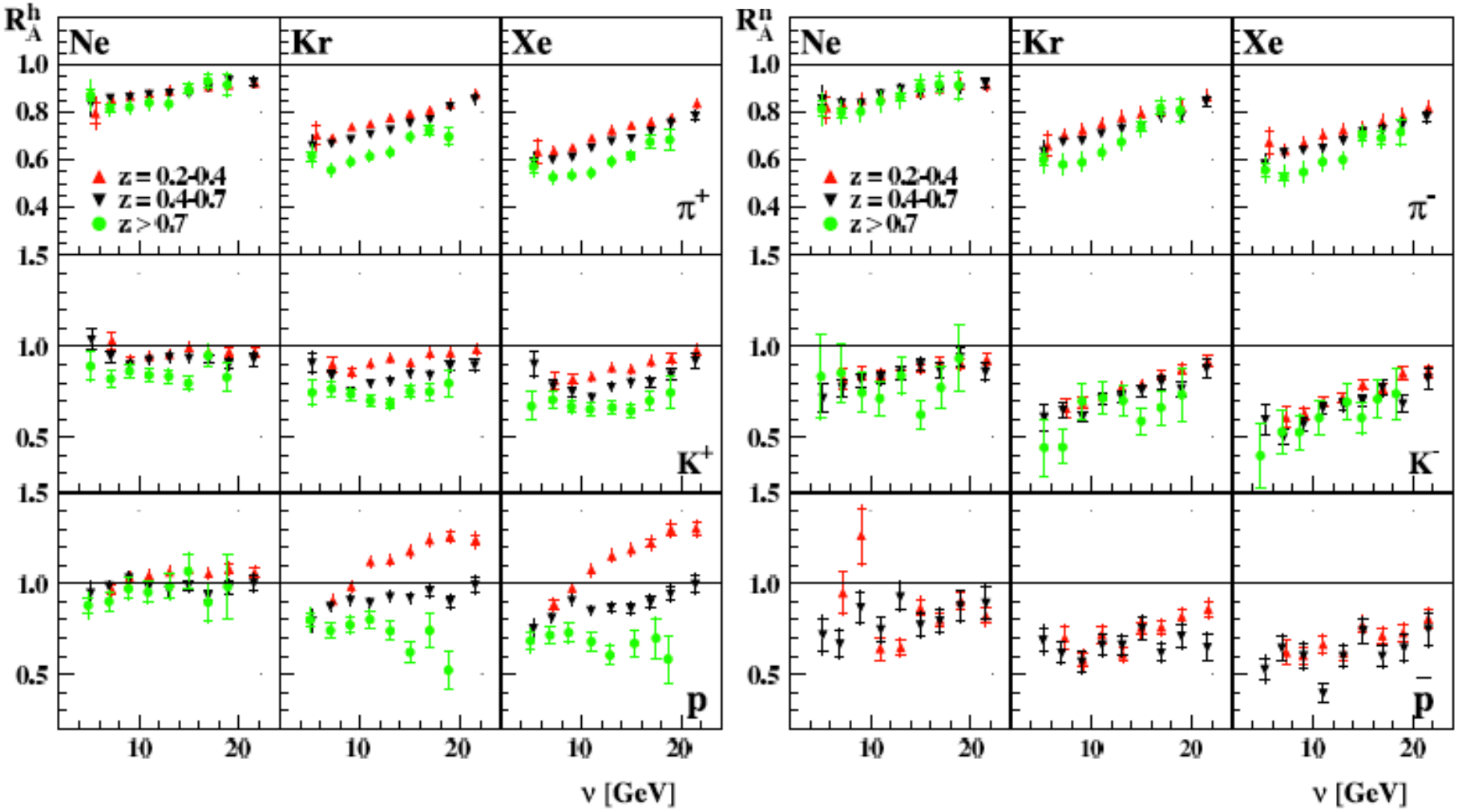


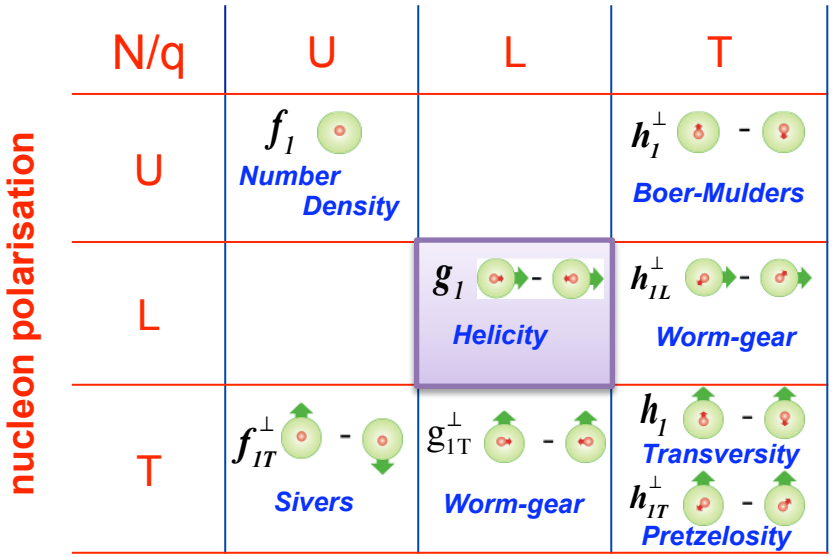
# Medium modification

$$R_M(z,\nu,Q^2,p_t^2) = \left.\frac{\frac{N_h(z,\nu,Q^2,p_t^2)}{N_{DIS}}}{\frac{N_h(z,\nu,Q^2,p_t^2)}{N_{DIS}}}\right|_A \Big/ \left.\frac{\frac{N_h(z,\nu,Q^2,p_t^2)}{N_{DIS}}}{\frac{N_h(z,\nu,Q^2,p_t^2)}{N_{DIS}}}\right|_D \propto \left.\frac{\frac{\Sigma e_f^2 q_f(x,Q^2,p_T^2) D_f^h(z,Q^2,k_T^2)}{\Sigma e_f^2 q_f(x,Q^2,p_T^2)}}{\frac{\Sigma e_f^2 q_f(x,Q^2,p_T^2) D_f^h(z,Q^2,k_T^2)}{\Sigma e_f^2 q_f(x,Q^2,p_T^2)}}\right|_A \Big/ \left.\frac{\frac{\Sigma e_f^2 q_f(x,Q^2,p_T^2) D_f^h(z,Q^2,k_T^2)}{\Sigma e_f^2 q_f(x,Q^2,p_T^2)}}{\frac{\Sigma e_f^2 q_f(x,Q^2,p_T^2) D_f^h(z,Q^2,k_T^2)}{\Sigma e_f^2 q_f(x,Q^2,p_T^2)}}\right|_D$$

Brooks talk



# Helicity

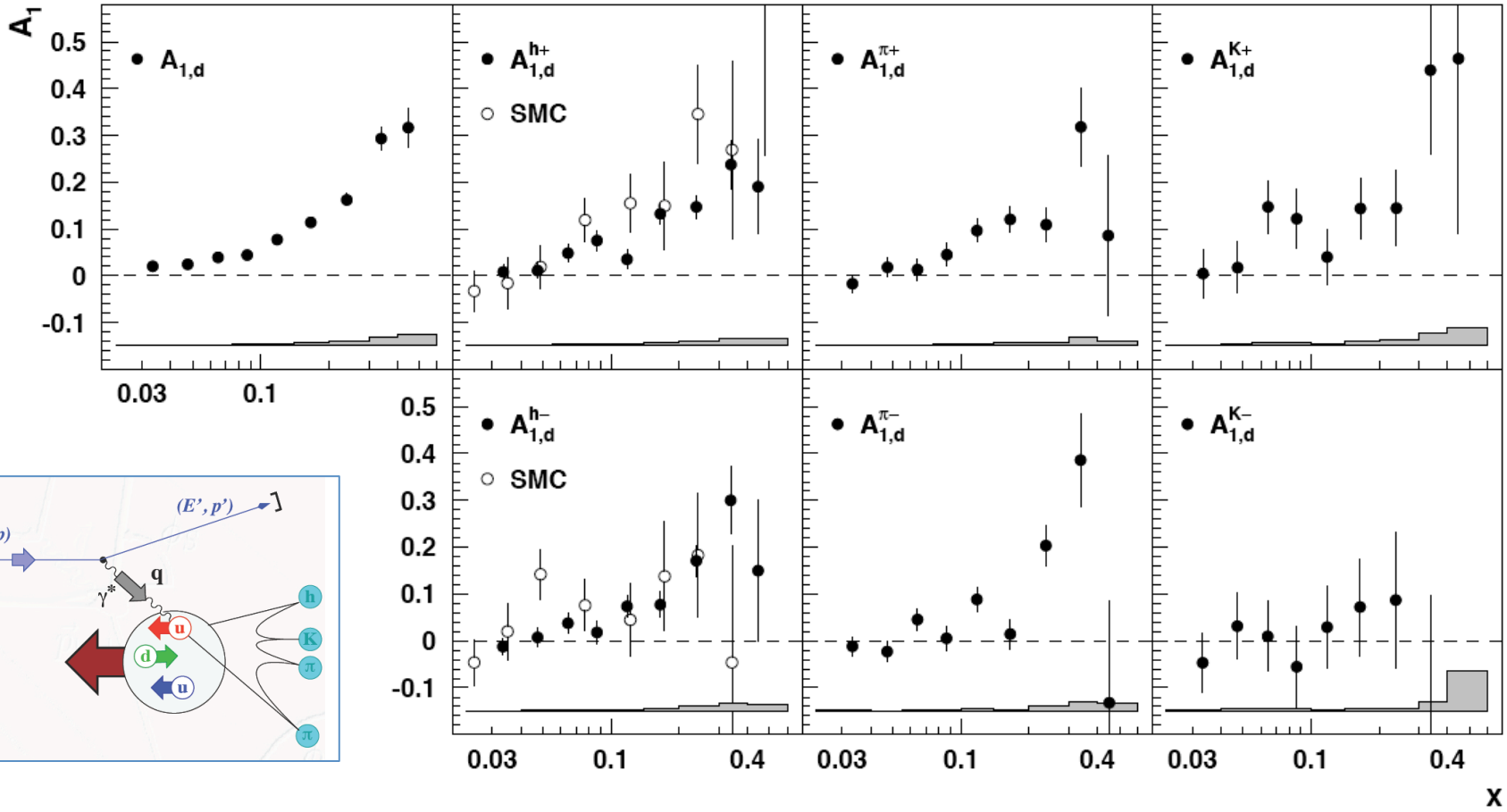


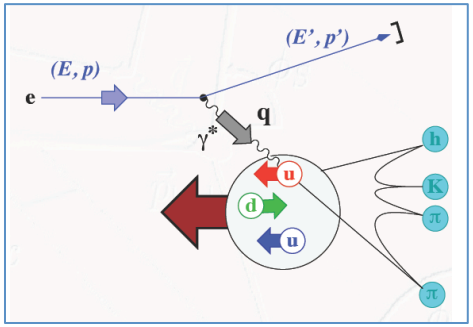

# (The First Puzzle)

# Parton Helicity from SIDIS

$g_1 \otimes D_1$

$$A_1^h(x) = \frac{\sum_q e_q^2 \Delta q(x) \int D_q^h(z)dz}{\sum_{q'} e_{q'}^2 q'(x) \int D_{q'}^h(z)dz} = \sum_q P_q^h(x) \frac{\Delta q(x)}{q(x)}$$

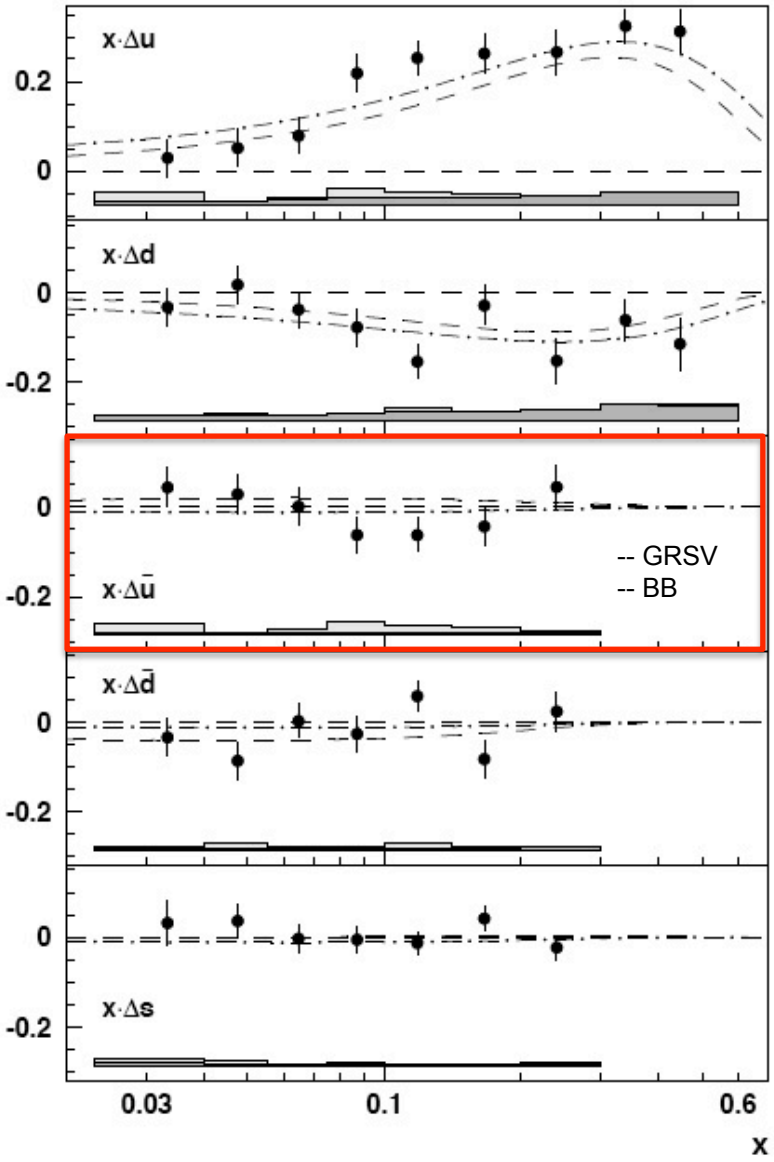


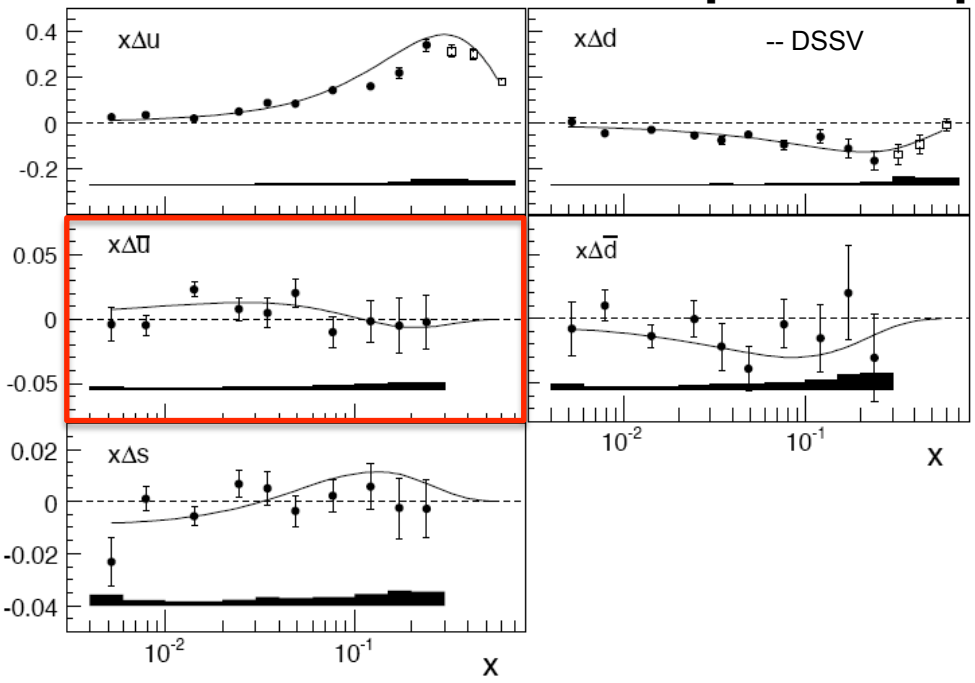
# Parton Helicity from SIDIS

$g_1 \otimes D_1$

HERMES [hep-ex/0407032]



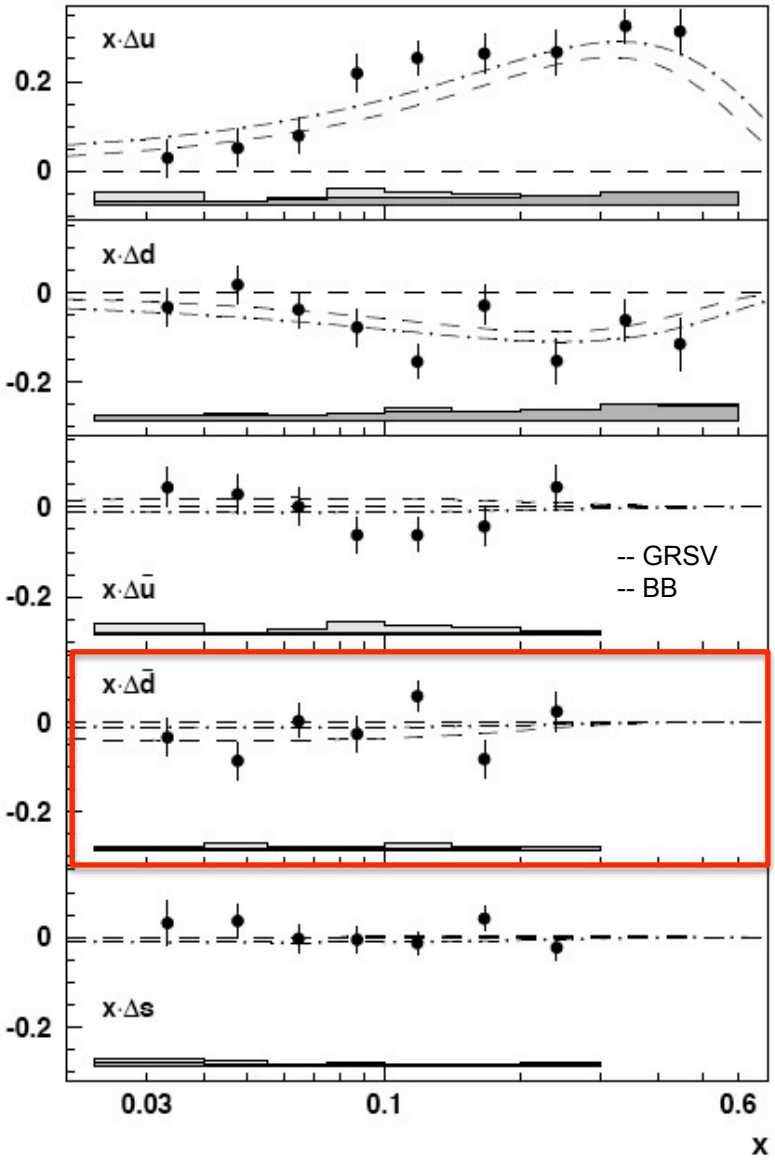

COMPASS [arXiv:1007.4061]



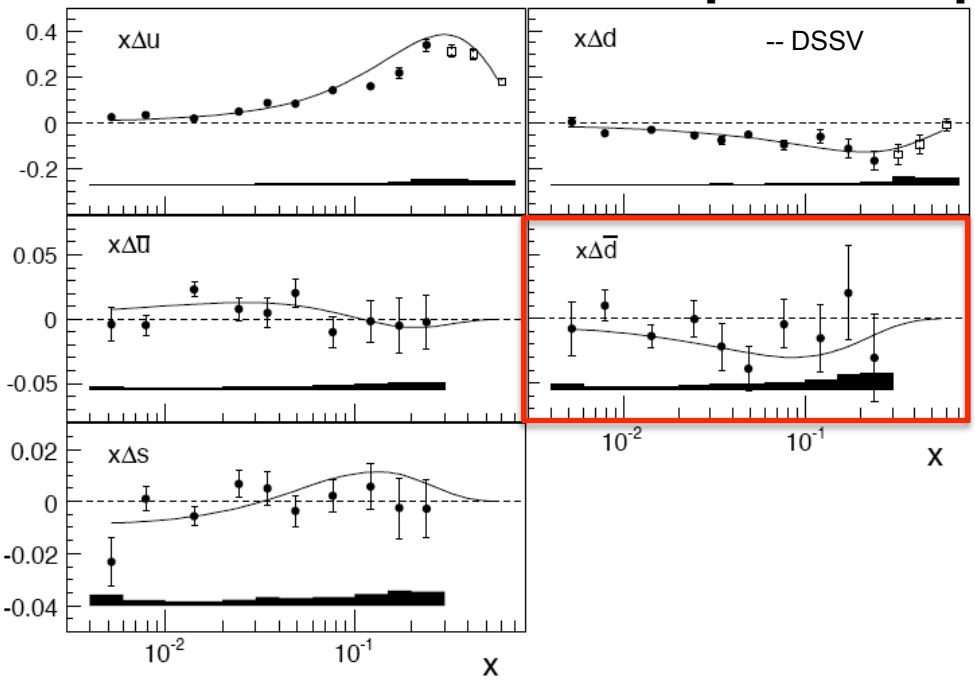
# Parton Helicity from SIDIS

$g_1 \otimes D_1$

HERMES [hep-ex/0407032]

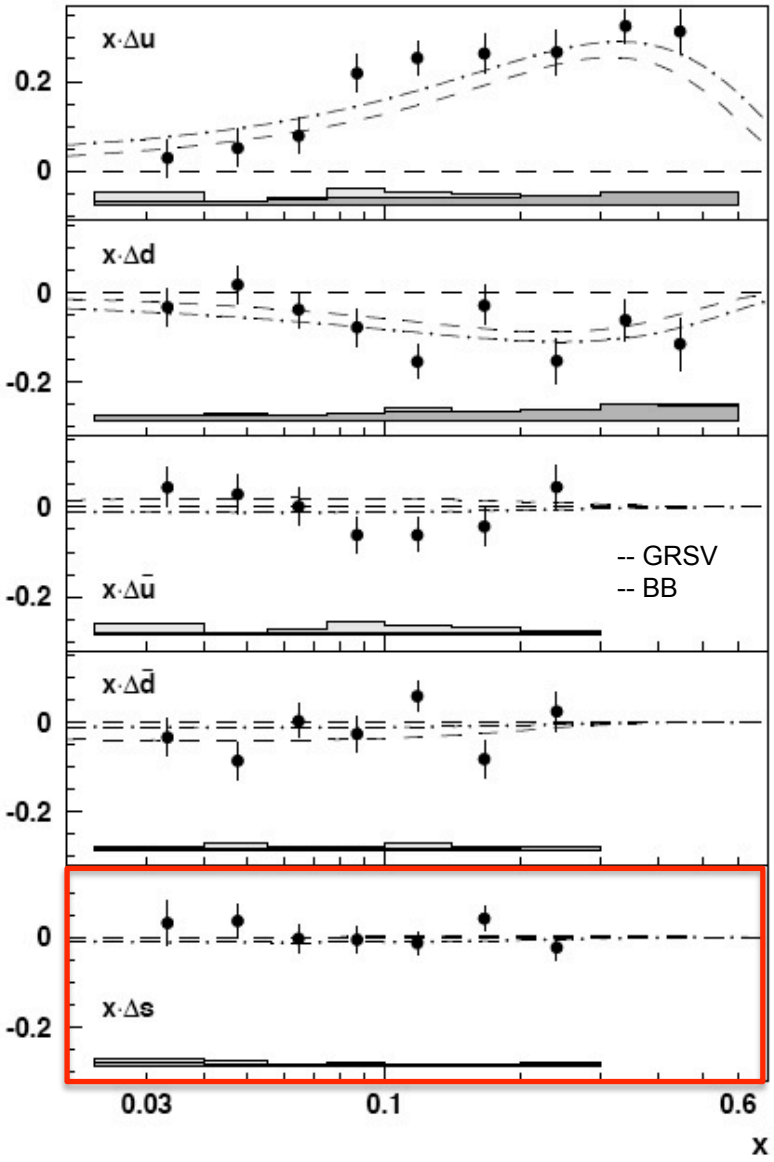



COMPASS [arXiv:1007.4061]

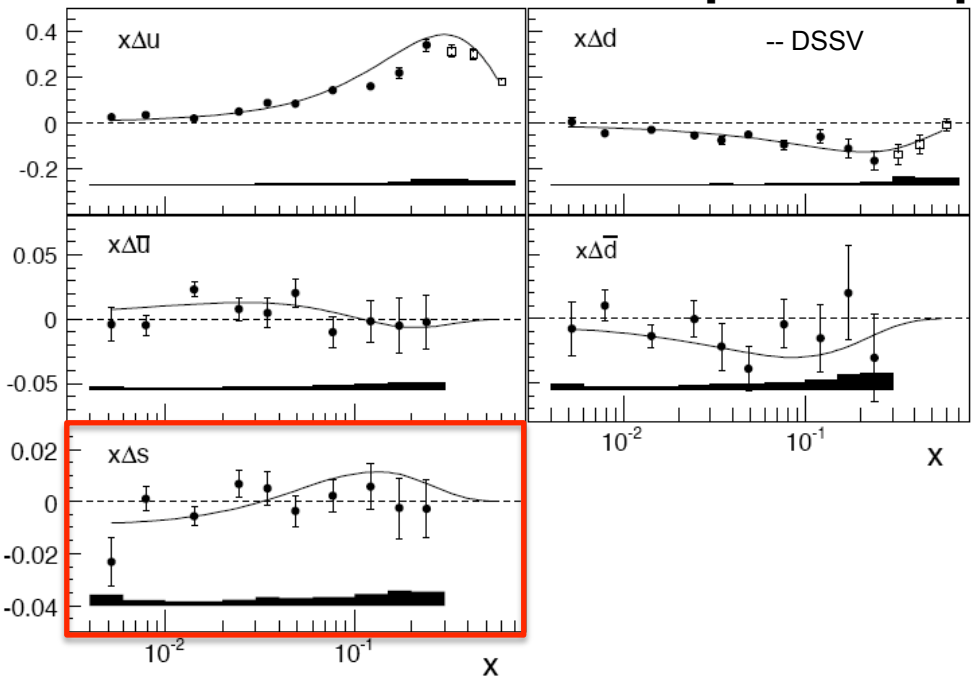


# Parton Helicity from SIDIS

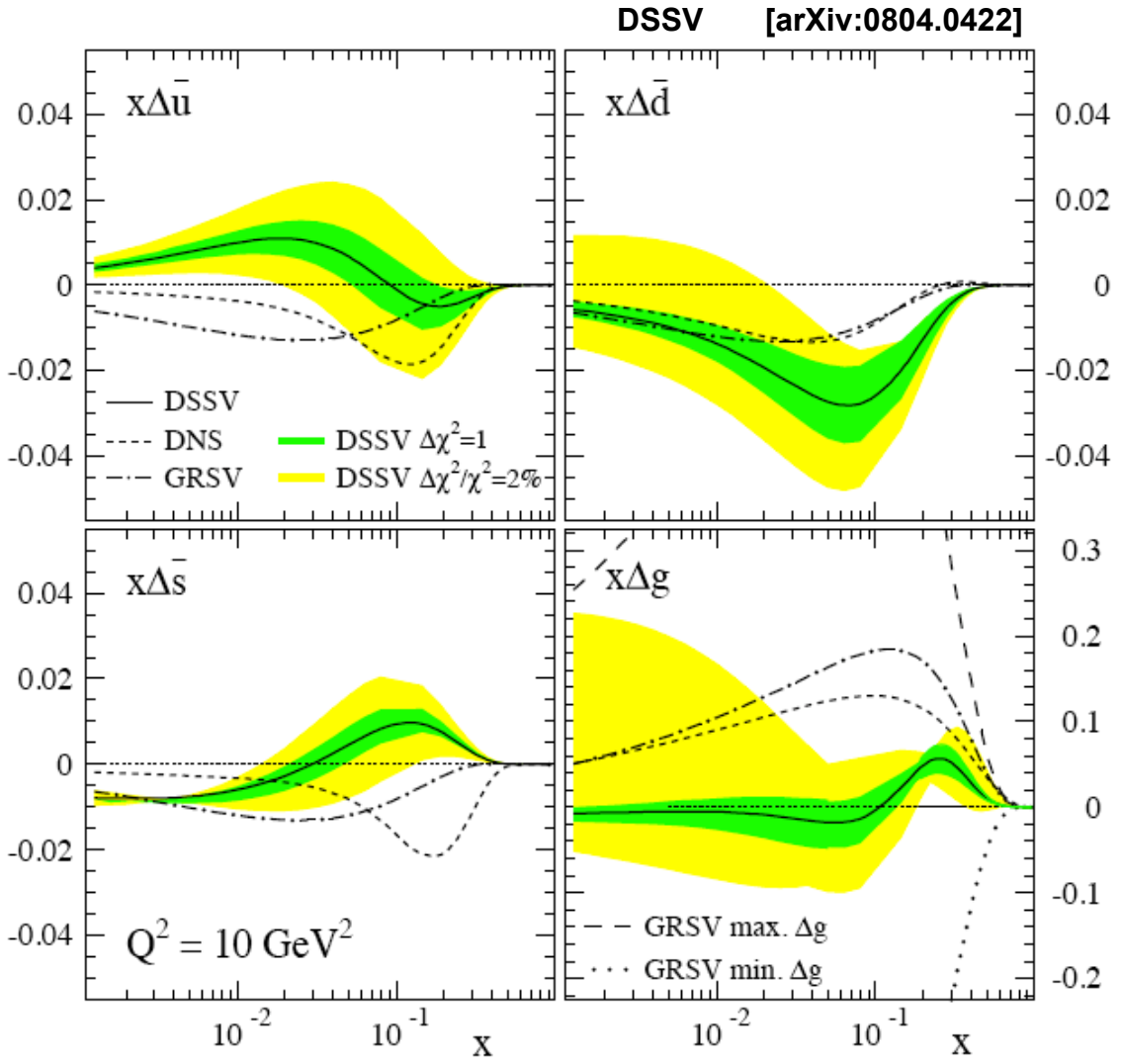
HERMES [hep-ex/0407032]




COMPASS [arXiv:1007.4061]

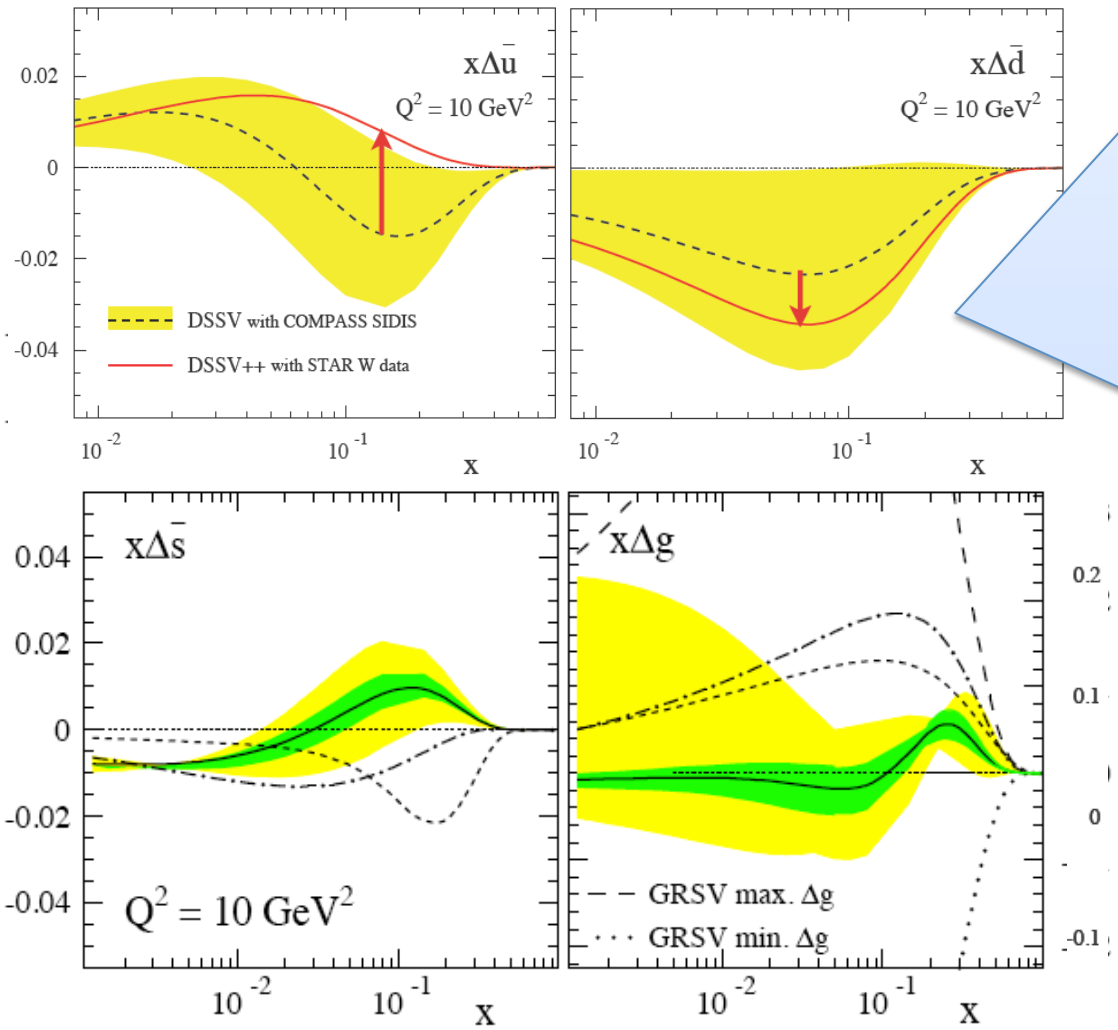


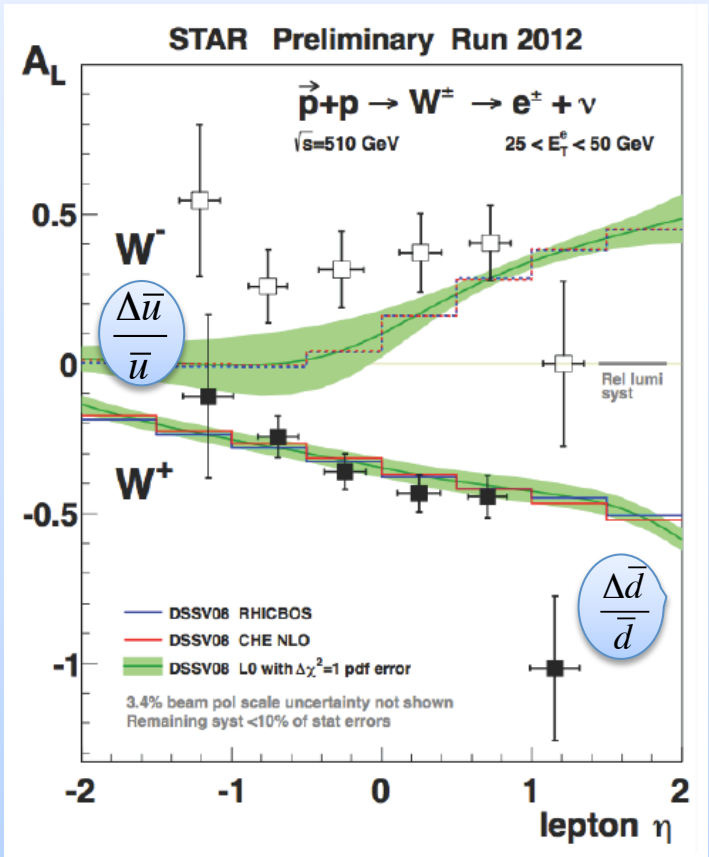
# Sea Parton Helicity from RHIC



# Sea Parton Helicity from RHIC

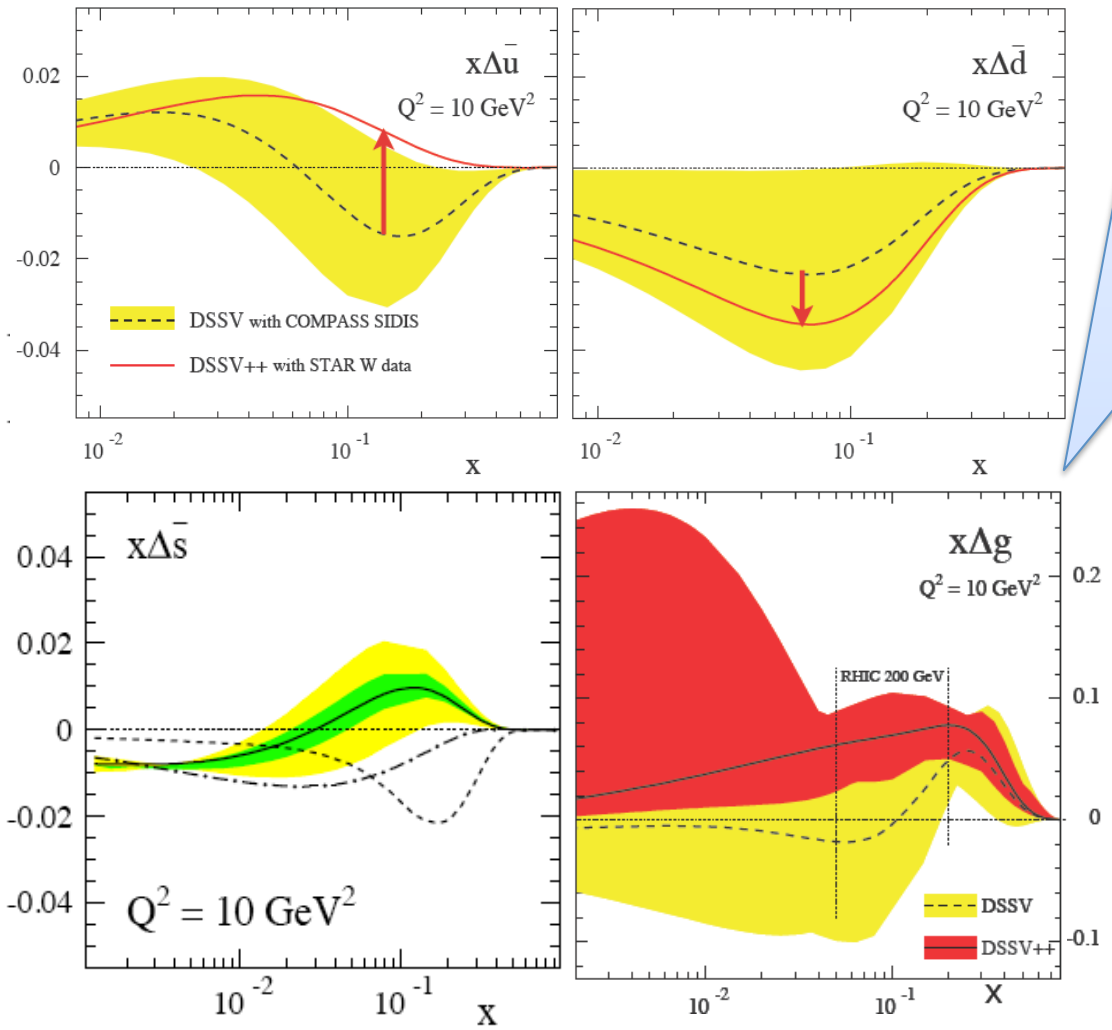
**DSSV++ [arXiv:1304.0079]**

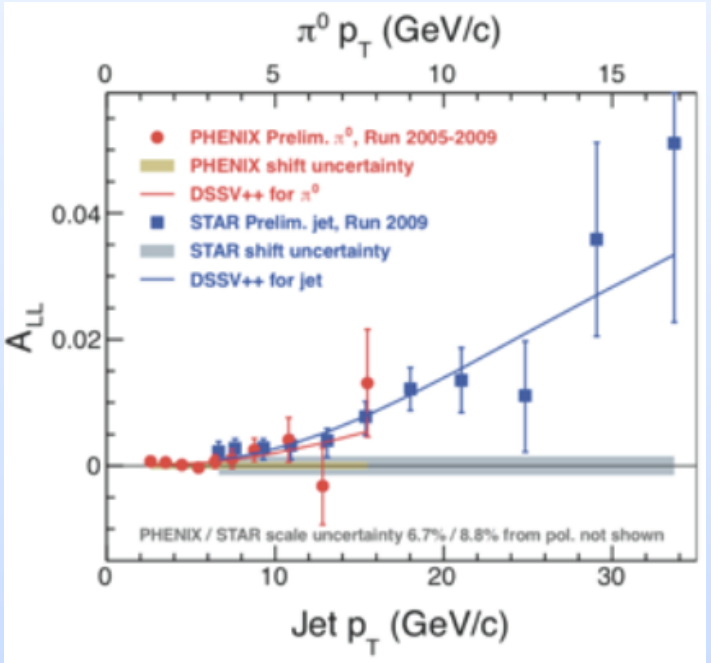


# Gluon Parton Helicity from RHIC

**DSSV++ [arXiv:1304.0079]**

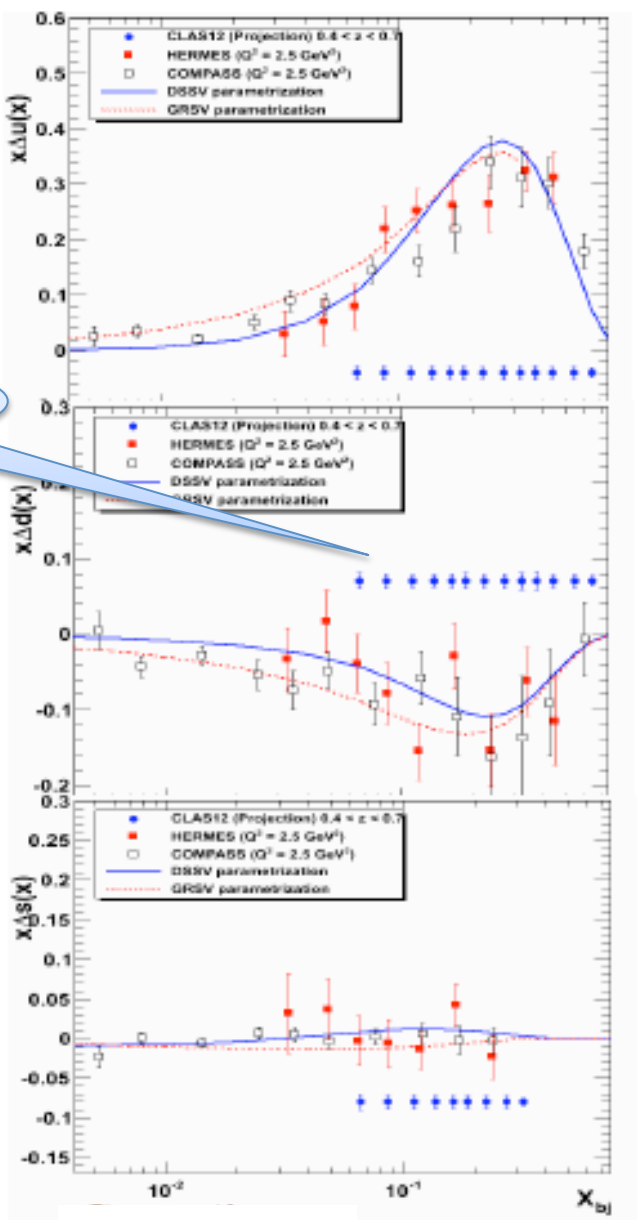


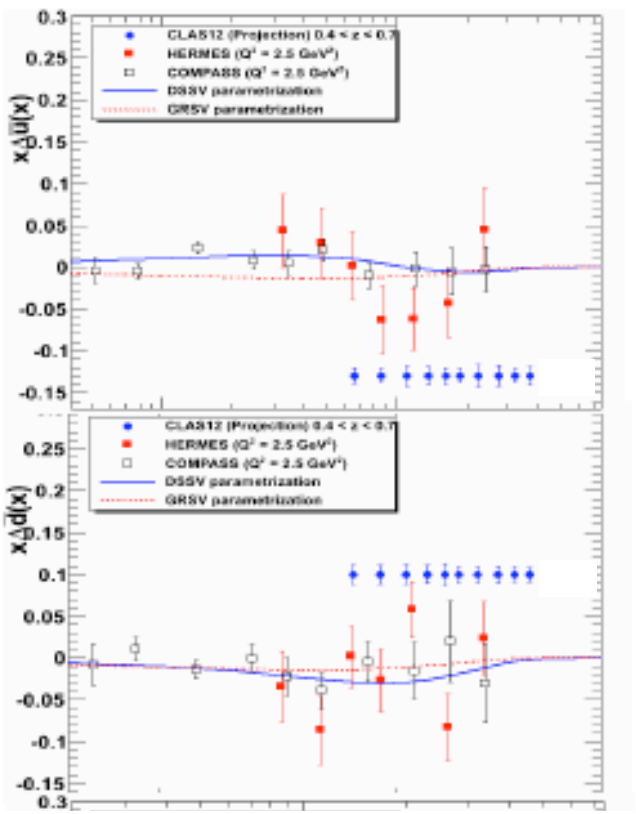



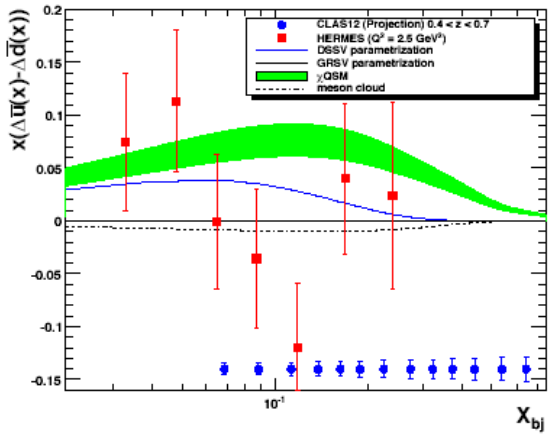

$$\int_{0.05}^{0.2} dx\, \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2) = 0.1^{+0.06}_{-0.07}$$

# Quark Helicity at High-x

E12-07-104 Hall-B



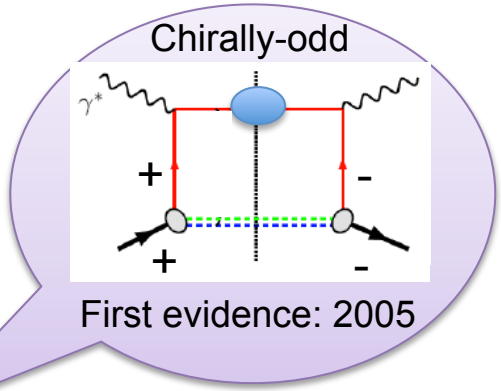



# TRANSVERSITY

nucleon polarisation

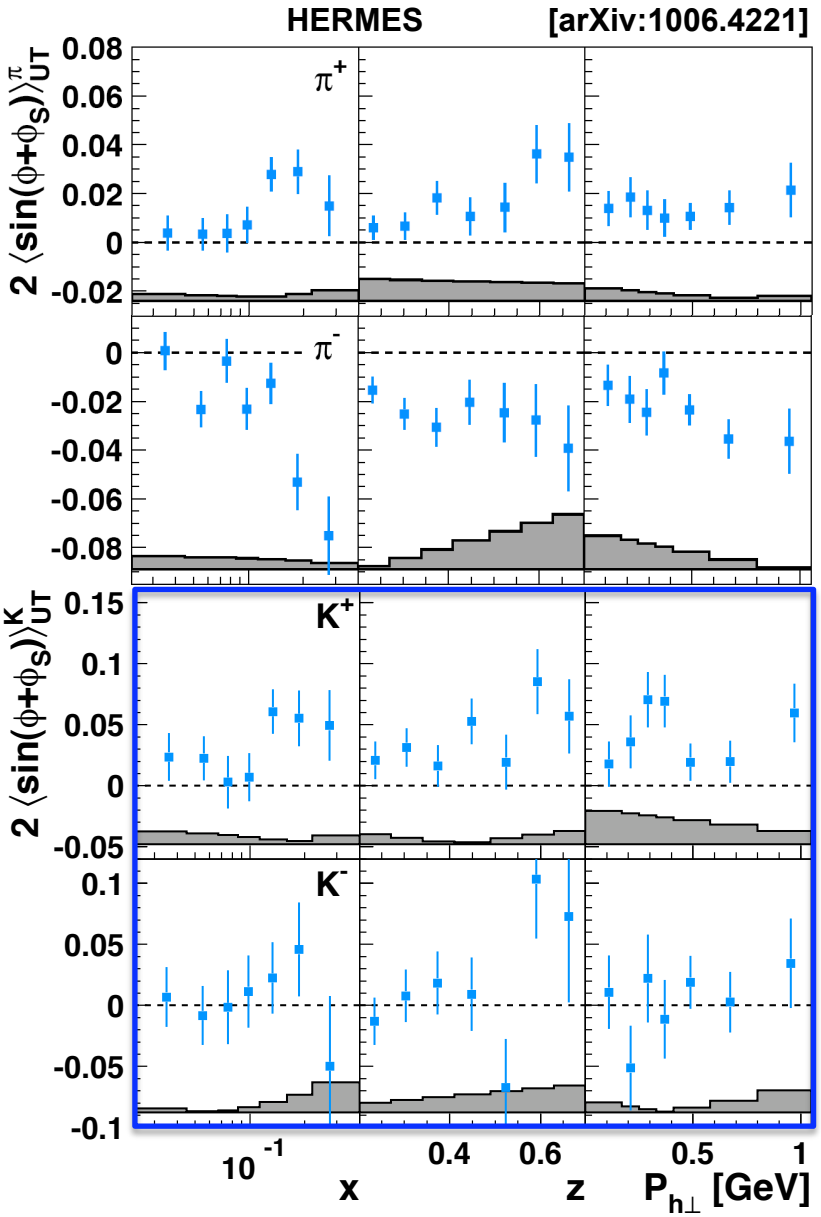
| N/q | U | L | T |
|---|---|---|---|
| U | $f_1$ *Number Density* | | $h_1^\perp$ *Boer-Mulders* |
| L | | $g_1$ *Helicity* | $h_{1L}^\perp$ *Worm-gear* |
| T | $f_{1T}^\perp$ *Sivers* | $g_{1T}^\perp$ *Worm-gear* | $h_1$ *Transversity*<br>$h_{1T}^\perp$ *Pretzelosity* |




# (THE COLLINEAR MISSING PIECE)

# The Collins Amplitude

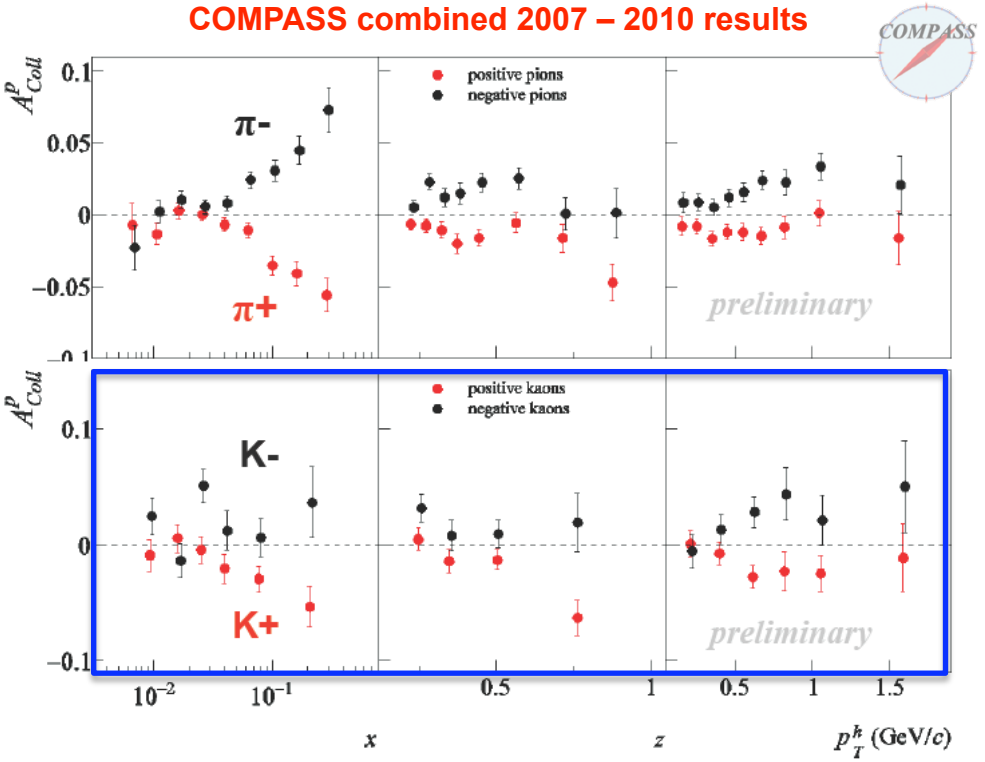
$h_1 \otimes H_1^\perp$




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

[Martin at DIS13]

COMPASS combined 2007 – 2010 results



# Transversity Signals

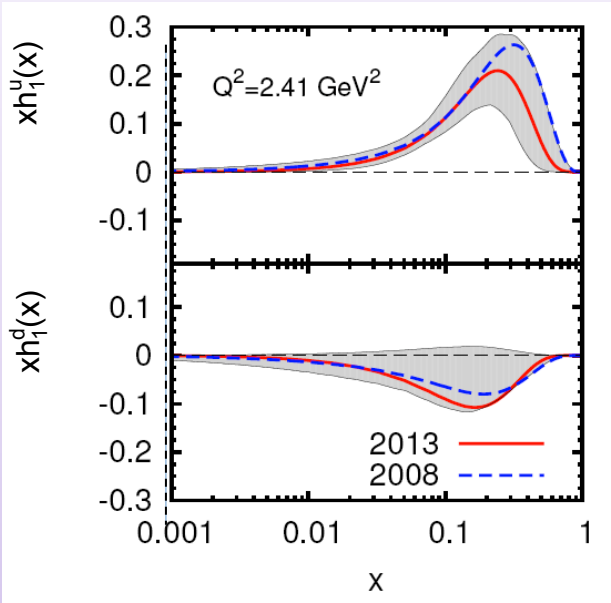
$$A_{UT}^{\sin(\phi+\phi_S)} \propto h_1(x) \otimes H_1^{\perp q}(z)$$

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

Existing data limited to x < 0.3

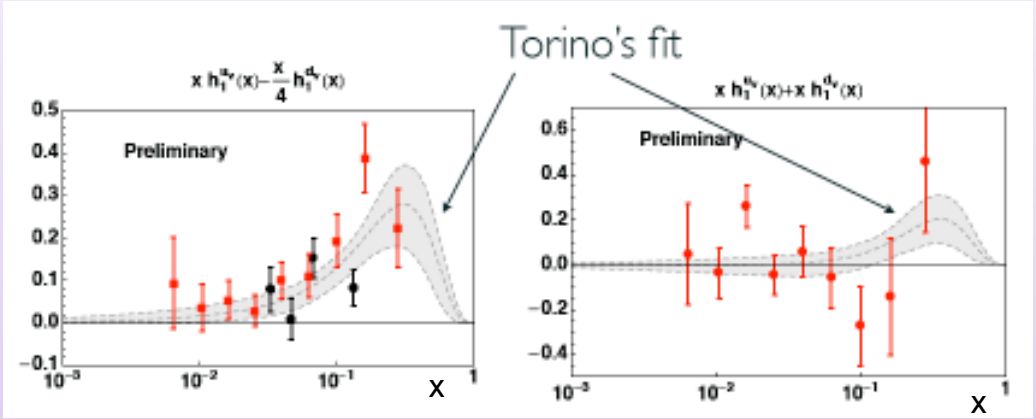
FF evol.. from high energy colliders

**1st extraction of Transversity!**




**Anselmino++** **[arXiv:1303.3822]**

**Collinear extraction !**



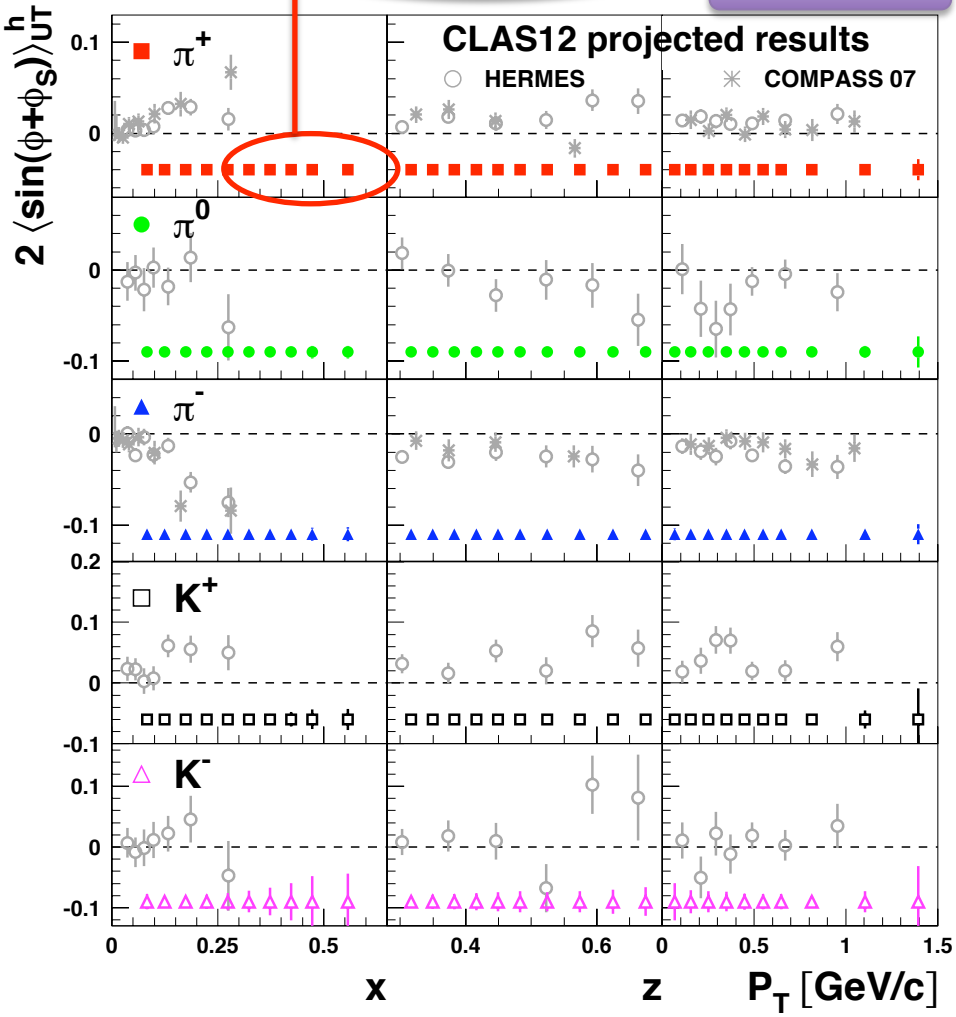

**Bacchetta++** **[arXiv:1212.3568]**

# Transversity @ JLab12

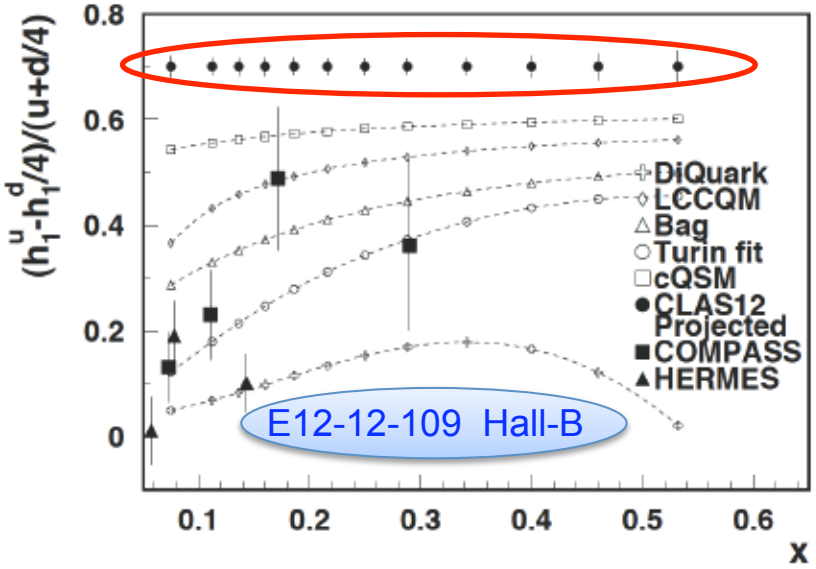
Large x important to constrain the tensor charge

C12-11-111 Hall-B

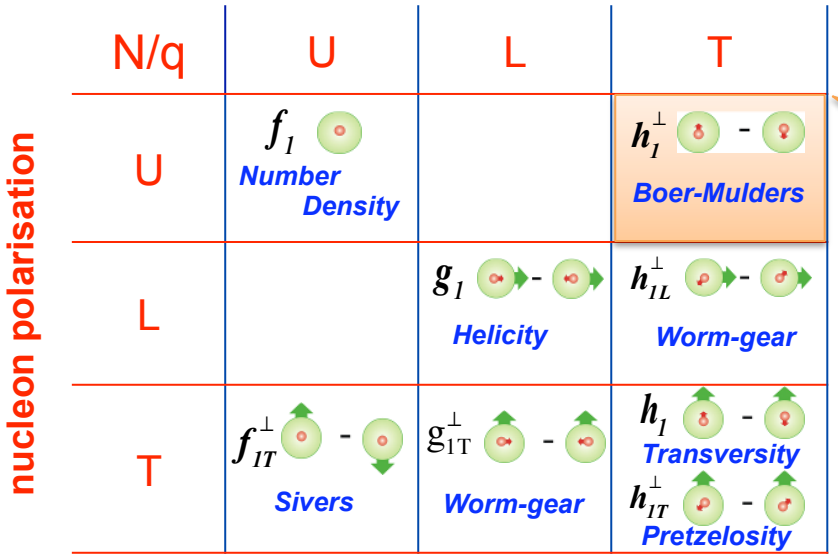
Proton




Di-hadron channel for $h_1$
Test of TMDs extraction



# Cahn & Boer-Mulders




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

# (The Neglected Effects)

# The Azimuthal Modulation

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

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

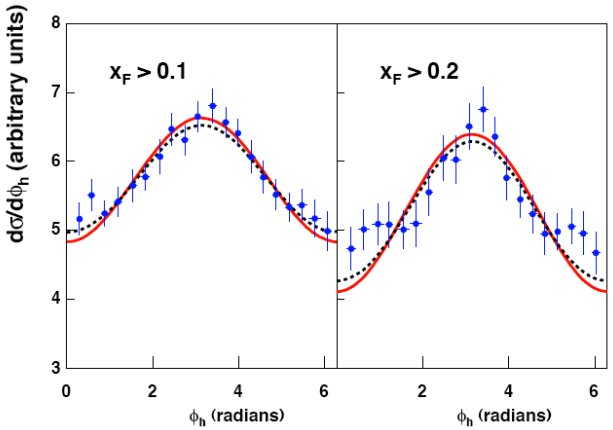
Cahn PLB 78 (1978)

Boer & Mulders PRD 57 (1998)

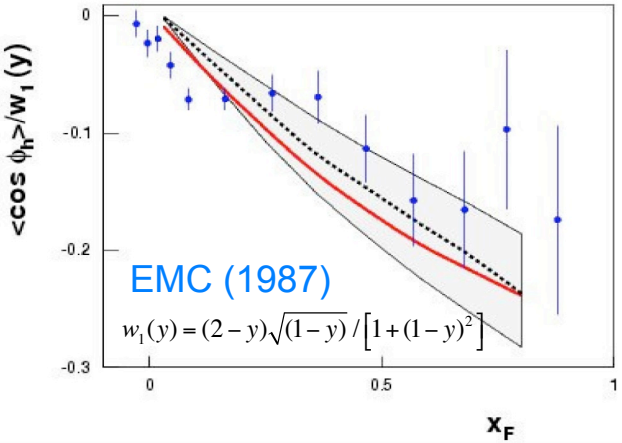
Kinematical effect predicted since 1978 by Cahn due to non-zero intrinsic $k_T$

Leading-twist contribution introduced by Boer & Mulders in 1998

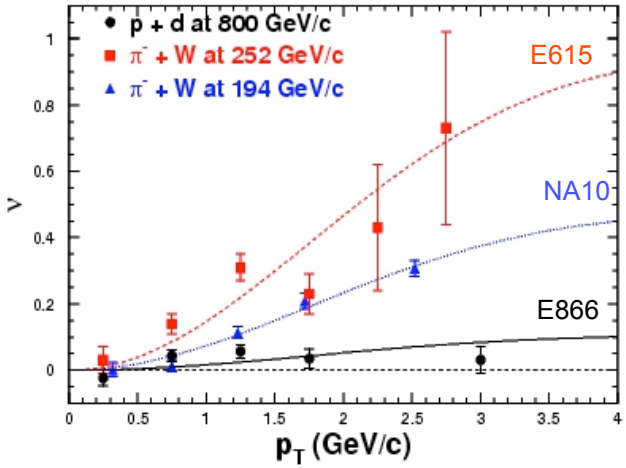
SIDIS: qualitative agreement with Cahn expectations till 2008




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

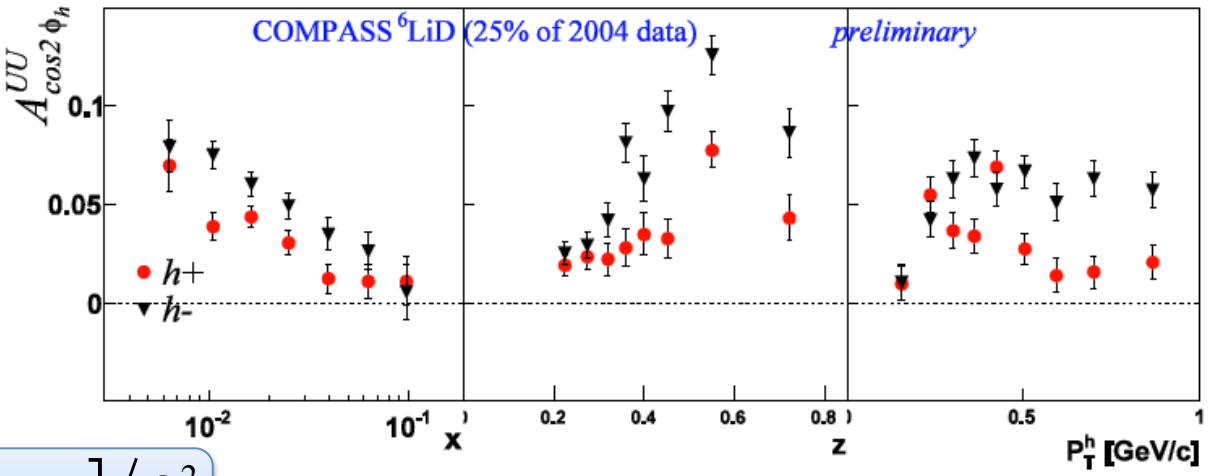



DY: violation of Lam-Tung relation



# Unpolarized Cross-section

cos2ϕ non-zero !

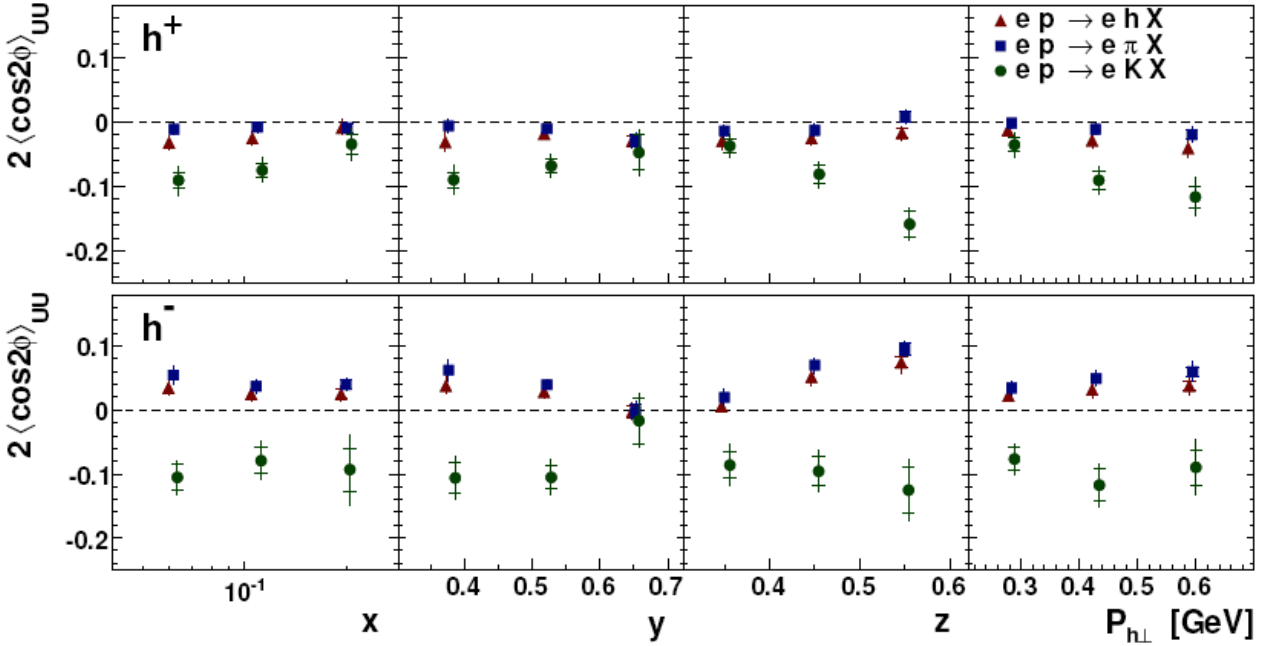



$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp} + \left[ f_1 \otimes D_1 + \ldots \right] / Q^2$$

Striking difference among hadron types

Inconsistency among experiments for $h^+$ ?

HERMES [arXiv:1204.4161]



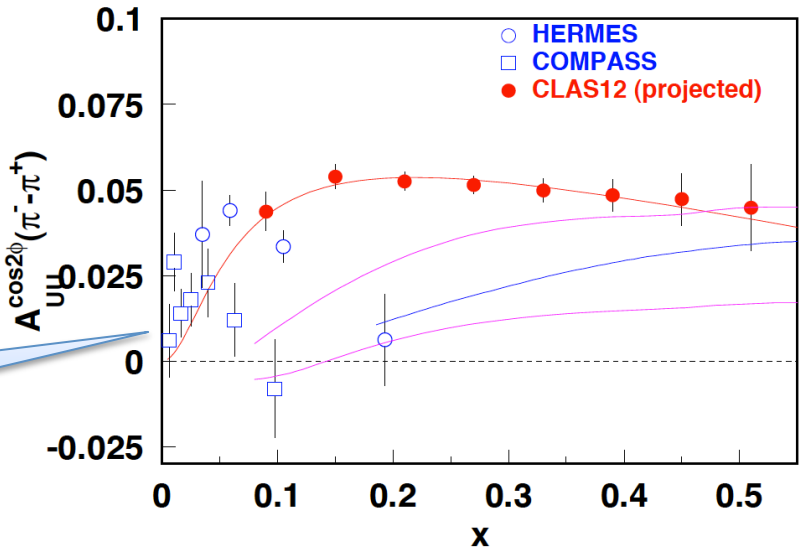
# The SIDIS cos2ϕ $p_T$ dependence

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

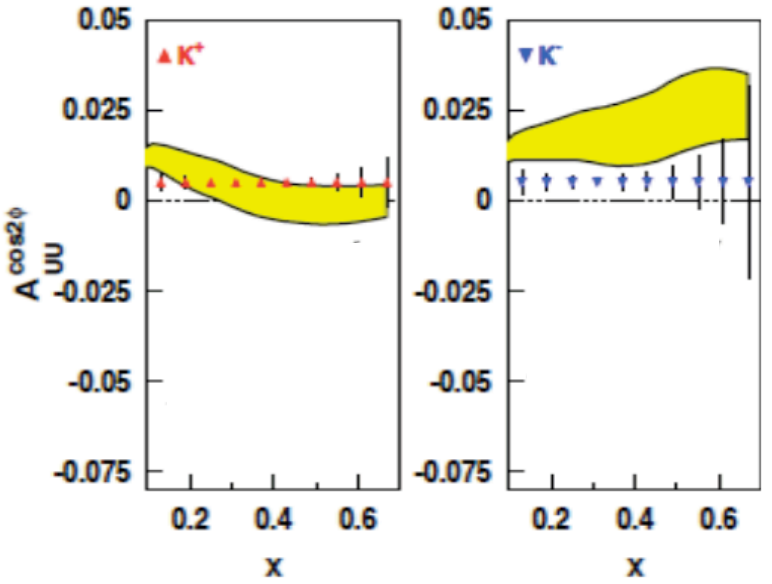
Boer-Mulders spin-orbit effect

$$F_{UU}^{\cos 2\phi} \propto h_1^{\perp} H_1^{\perp} + [f_1 D_1 + \ldots] / Q^2$$

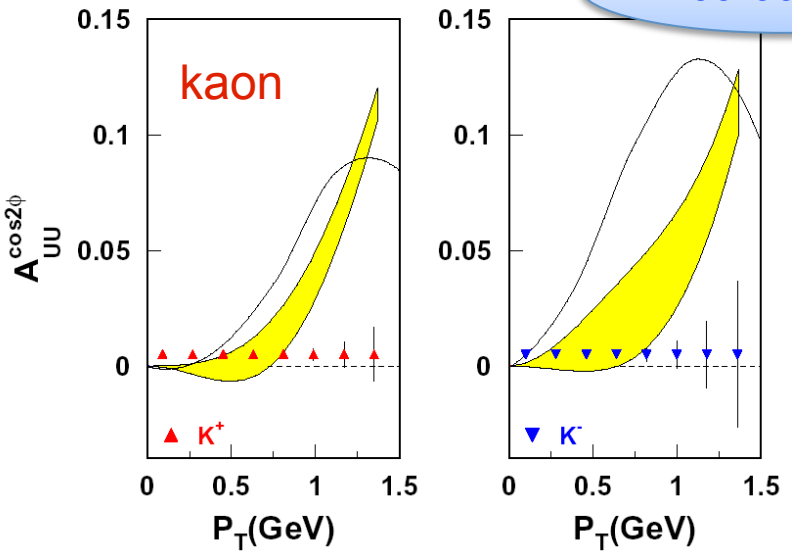
E12-06-112 Hall-B



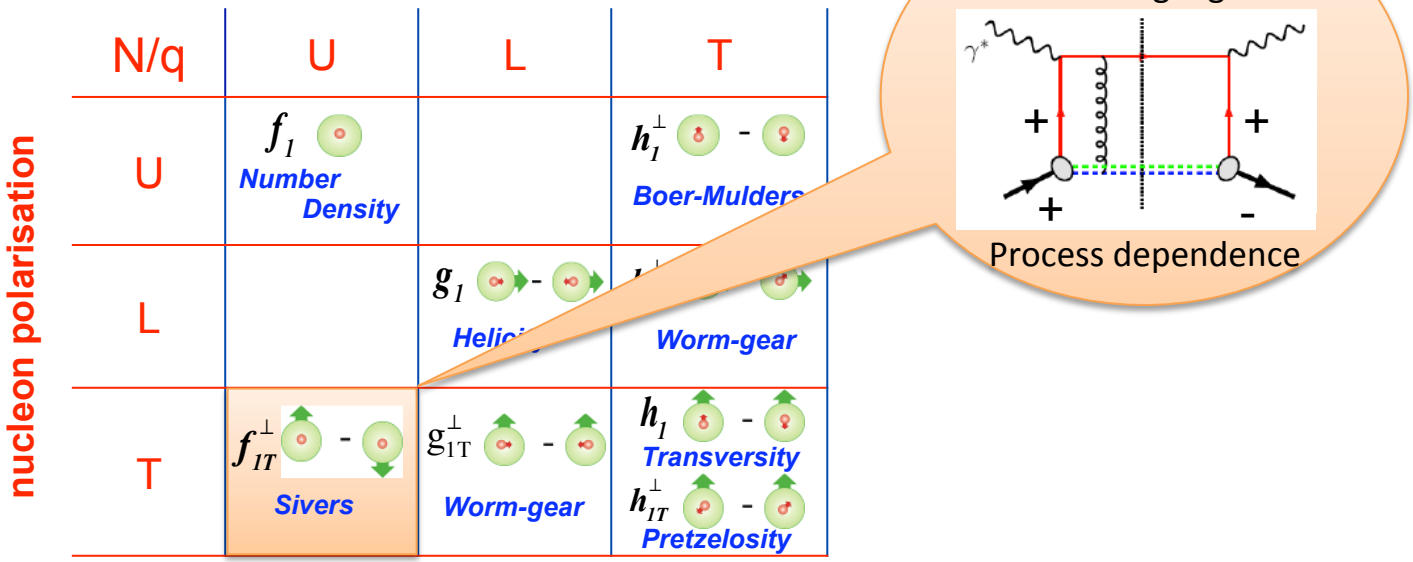

ep → e' KX




E12-09-008 Hall-B



# SIVERS




# (THE TMD CHALLENGE)

# The Sivers Signals

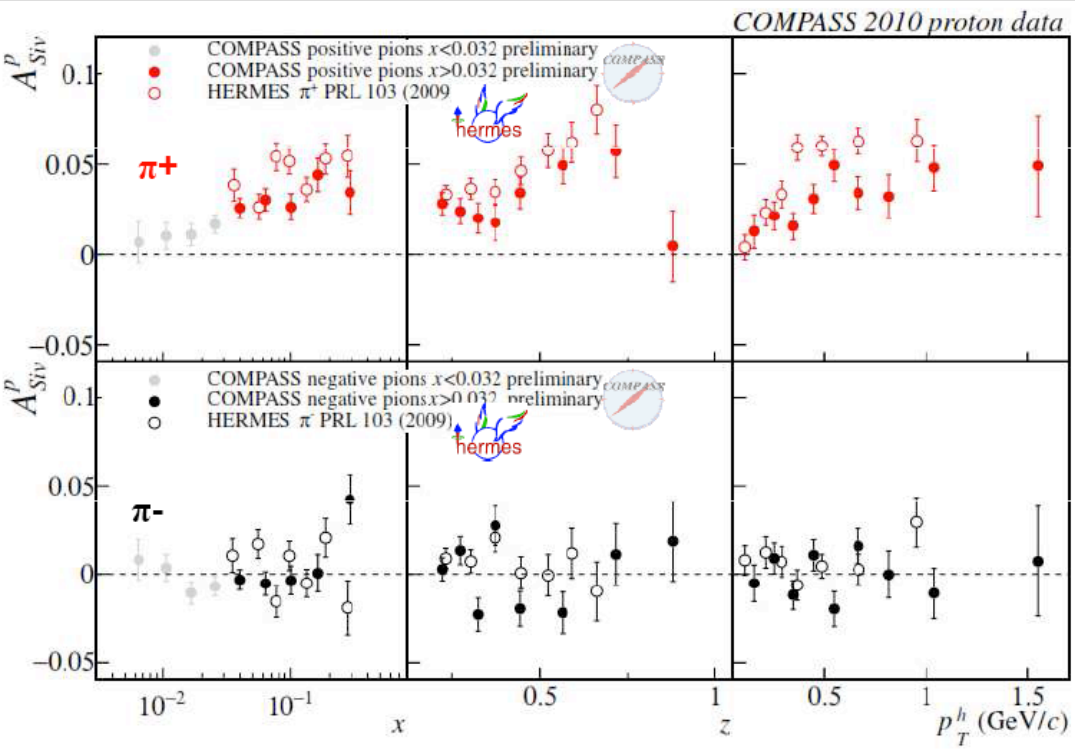


$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto f_1^{\perp} \otimes D_1$$

**Clear not-zero signals**

**COMPASS [arXiv: 1205.5122]**

**HERMES [arXiv: 0906.3918]**



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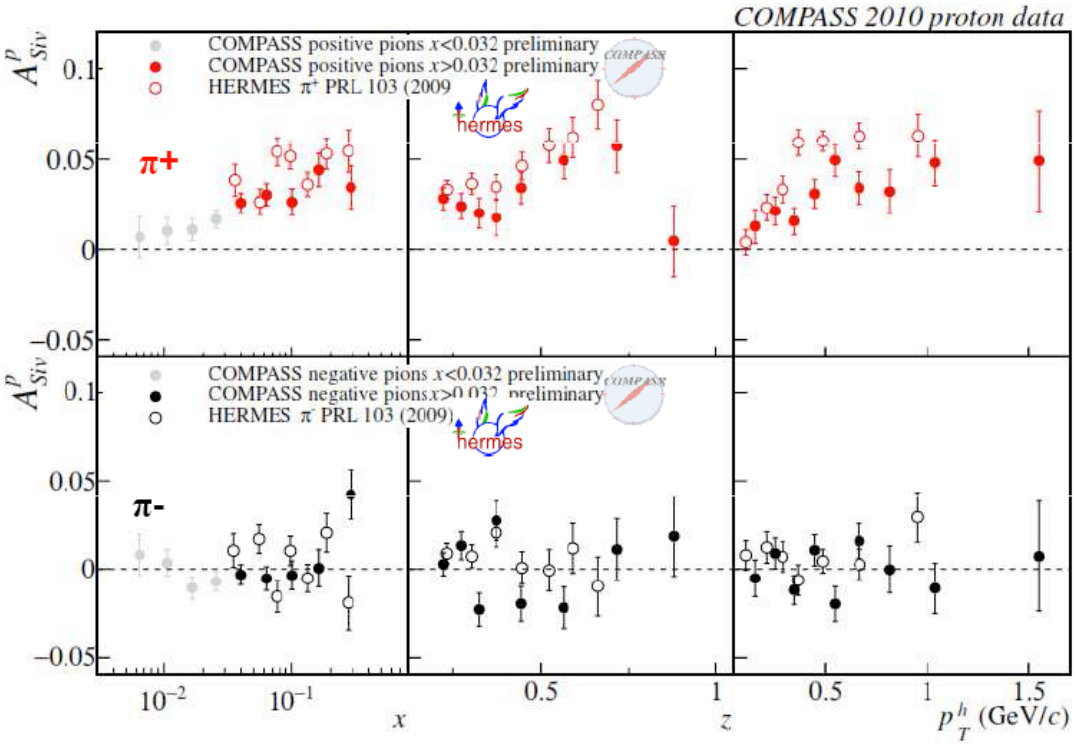
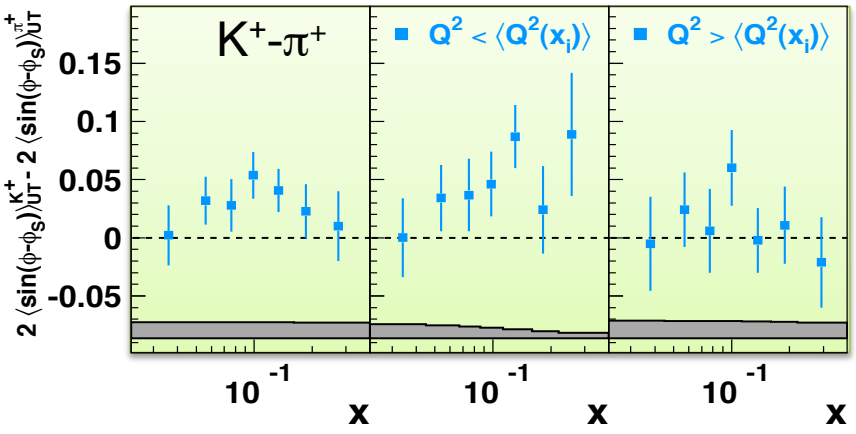
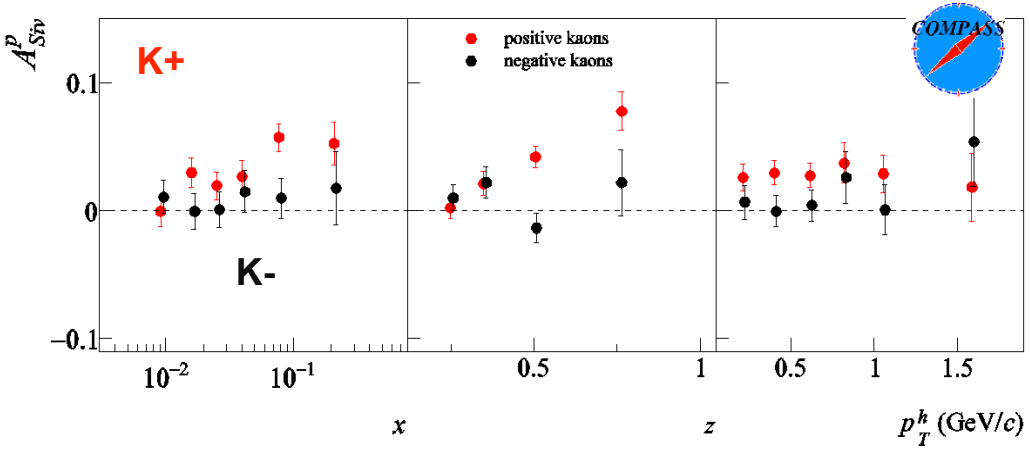



**combined 2007 – 2010 results**

**K⁺ amplitudes larger than π⁺:**

**HERMES** **[arXiv:0906.3918]**

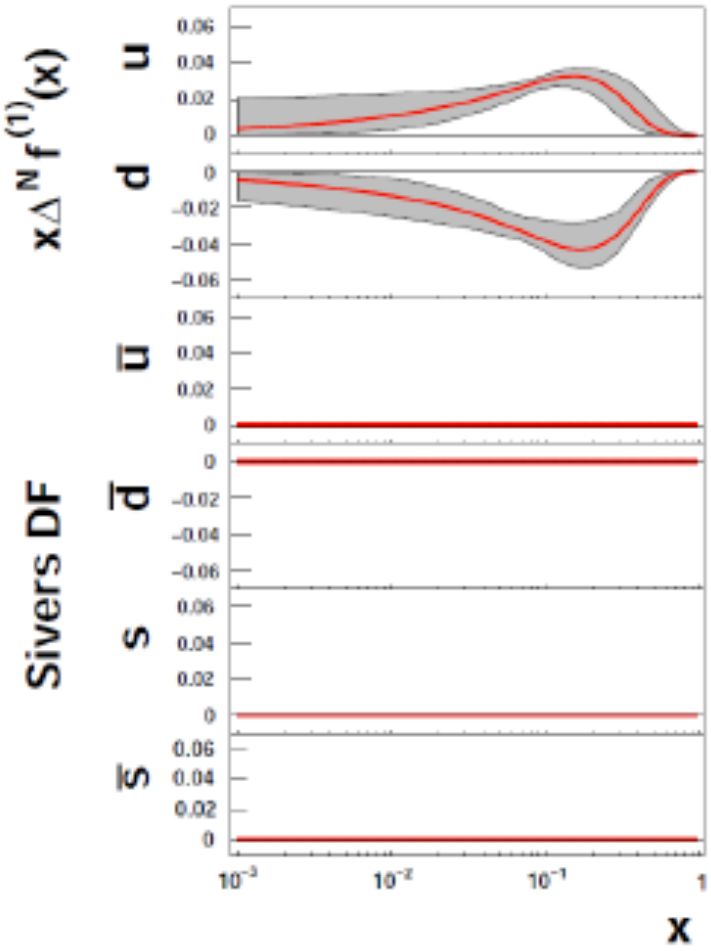


# The Sivers Distributions

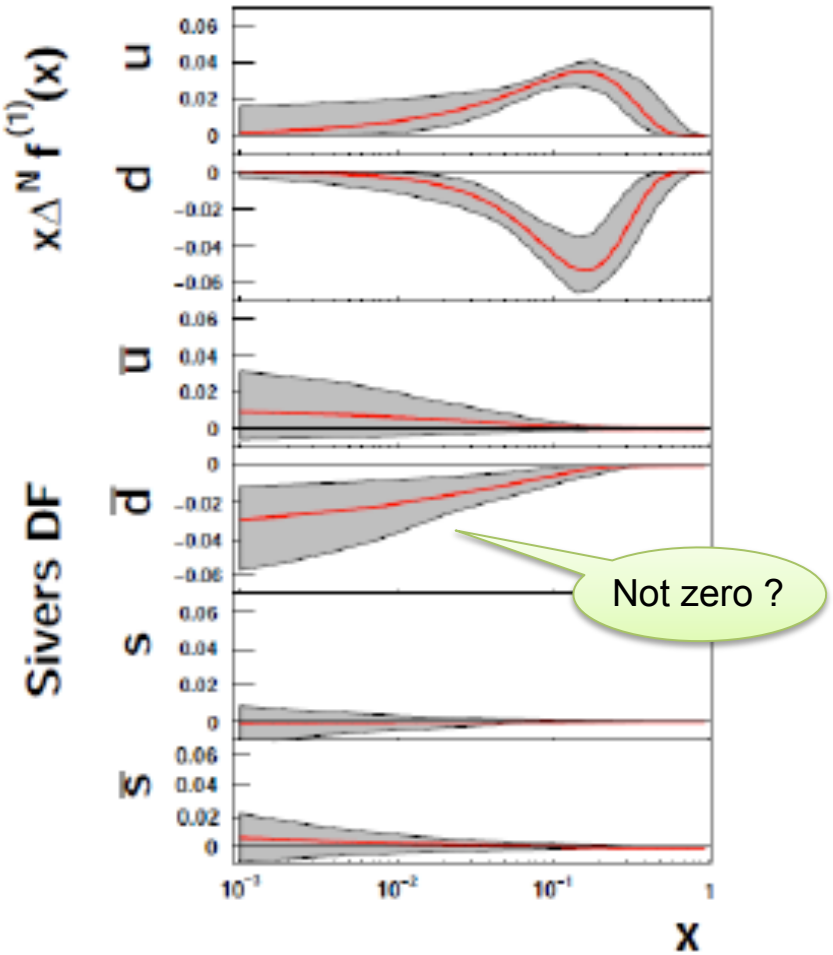
$f_{1T}^{\perp} \otimes D_1$

**Without sea:**




**With sea:**

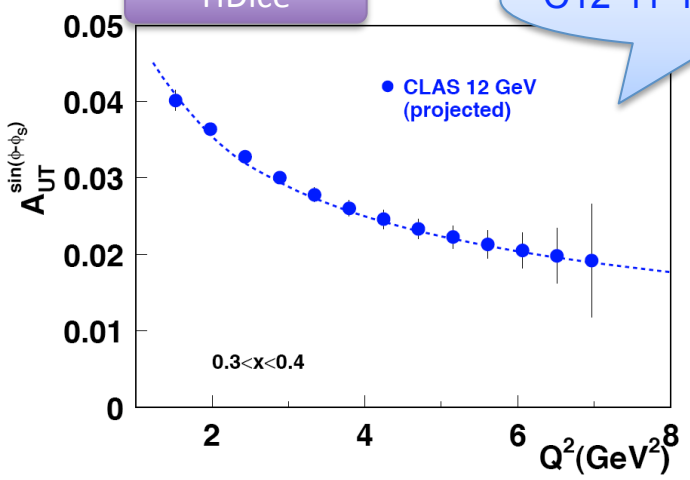
[arXiv:1012.3565]



# Sivers @ JLab12

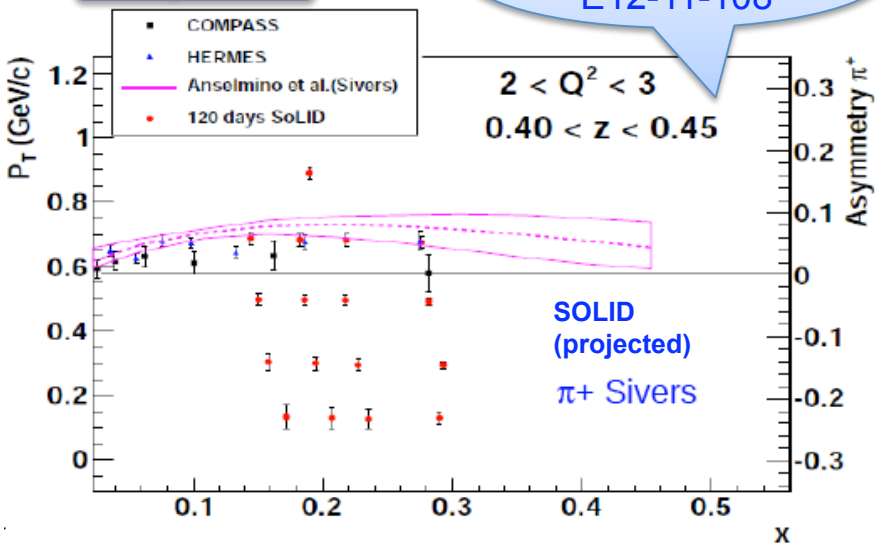
HDice

C12-11-111 Hall-B

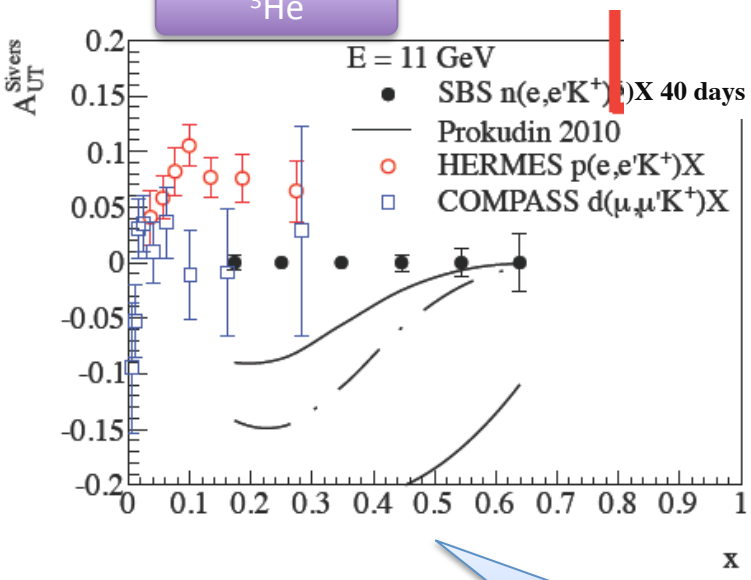



$NH_3$ & $^3$He

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

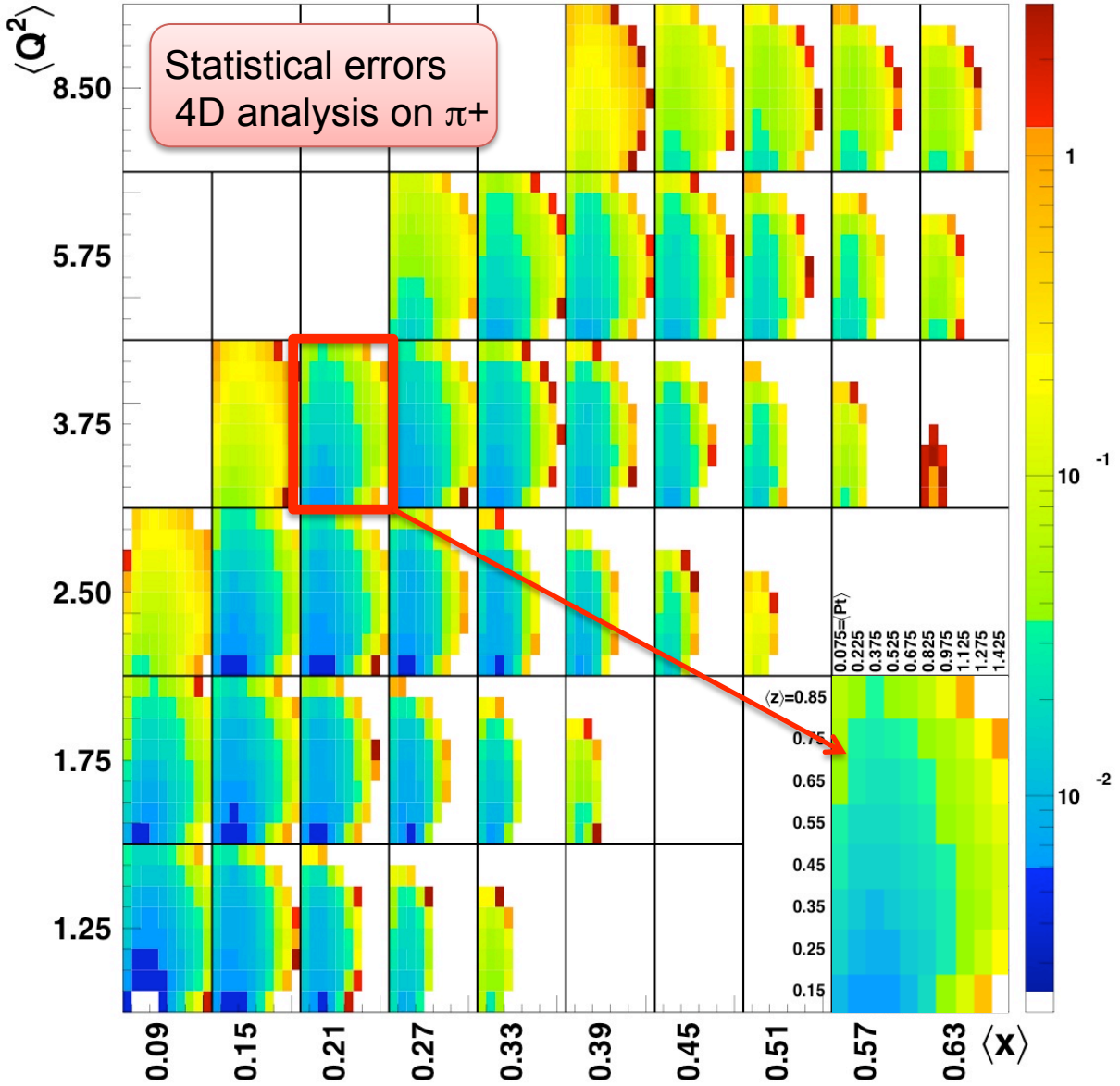



$^3$He



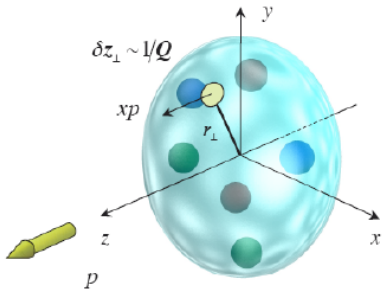

E12-11-007 Hall-A

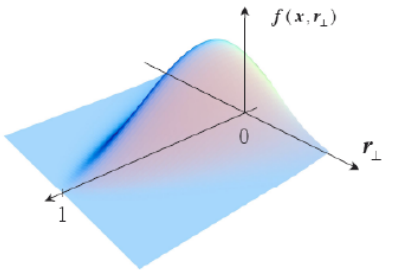
# Multi-D Analysis

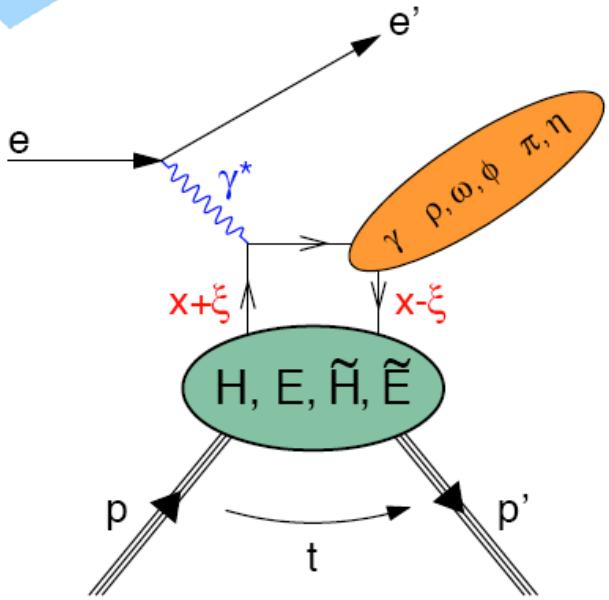


# Hard Exclusive: Transverse Position Dependence

# Generalized parton distributions




Encompass parton distributions and form factors

Longitudinal momentum and transverse spatial position correlated information

Access OAM $L_q = J_q - \frac{1}{2}\Delta\Sigma$ via Ji sum rule

$$J_q = \lim_{t\to 0} \int_{-1}^{1} dx\, x\left[H_q(x,\xi,t) + E_q(x,\xi,t)\right]$$

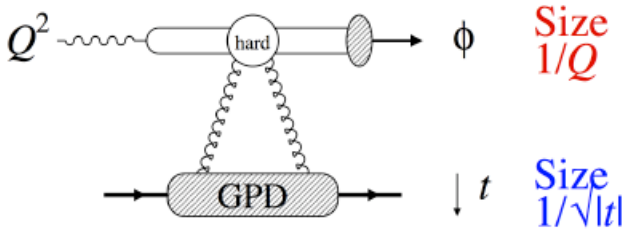
quark polarisation

| nucleon polarisation | N/q | U | L | T |
|---|---|---|---|---|
| | U | $H$ | | $\mathcal{E}_T$ |
| | L | | $\tilde{H}$ | |
| | T | $E$ | | $H_T, \tilde{H}_T$ |

The process of meson production

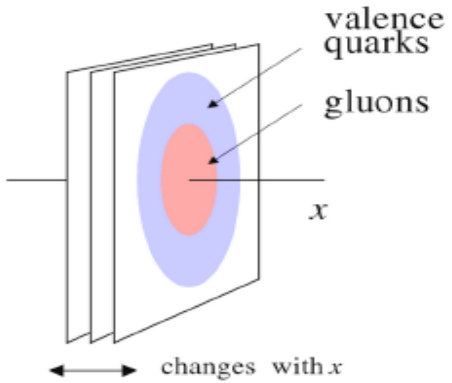
- $\phi$ production (gluon&strange sea)
- $\rho$, $\omega$ production (gluon&sea&valence quarks)

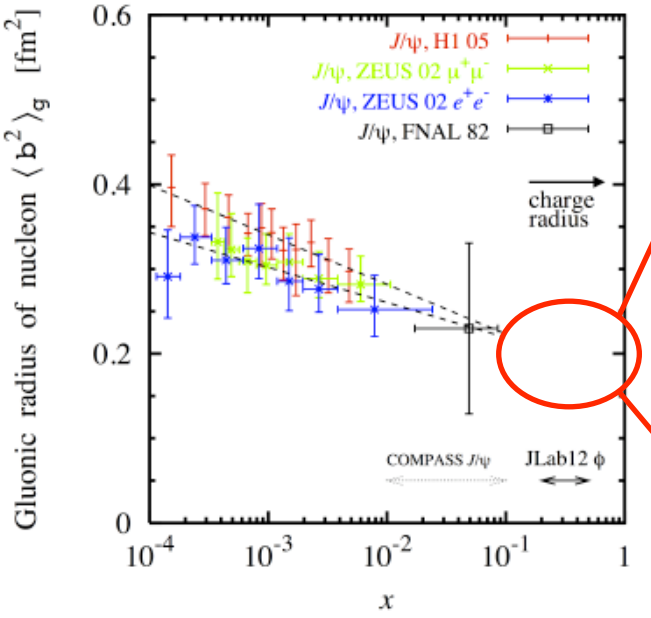
# Exclusive ϕ and the Gluonic Radius

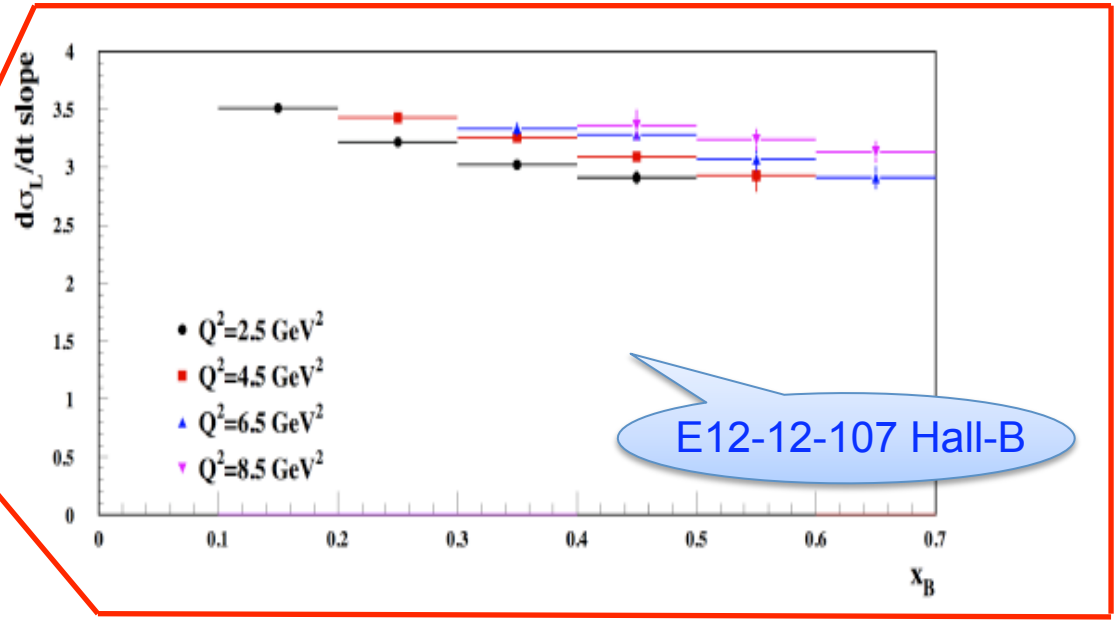



Dominance of small-size configurations at $Q^2 \sim$ few GeV$^2$

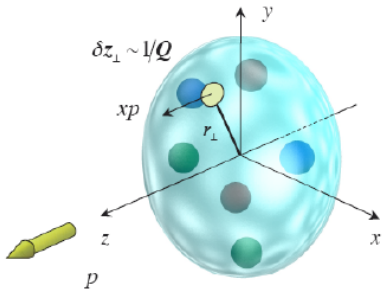
From t slope of $d\sigma/dt\ (ep \rightarrow ep\phi)$
→ average impact parameter

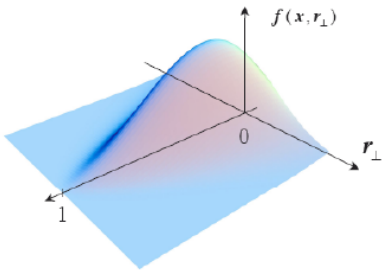


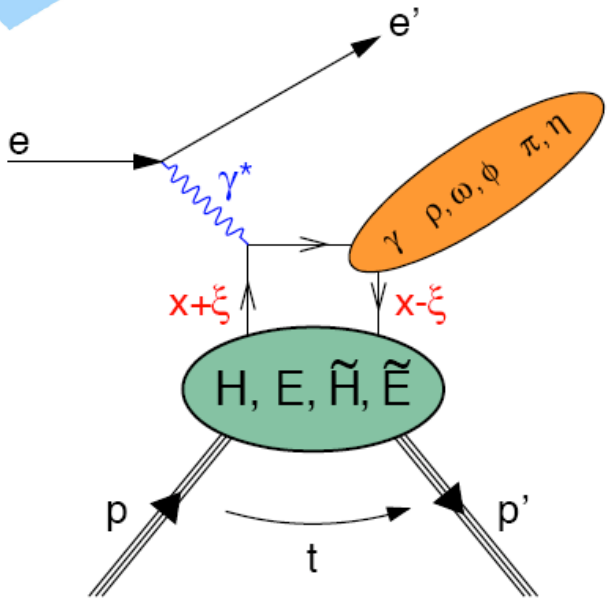



# Generalized parton distributions

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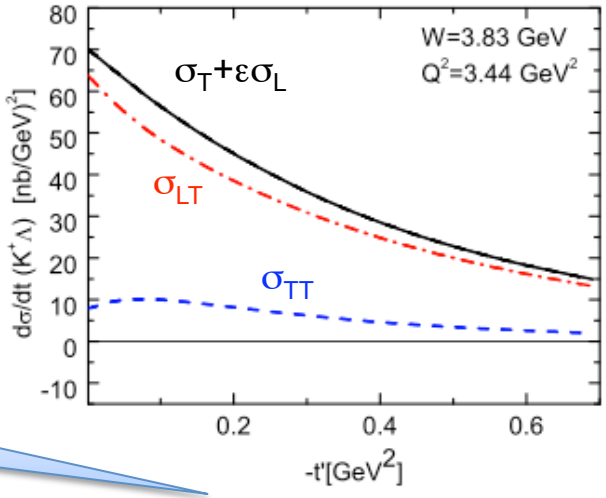
|---|---|---|---|
| U | $H$ | | $\mathcal{E}_T$ |
| L | | $\tilde{H}$ | |
| T | $E$ | | $H_T, \tilde{H}_T$ |

Factorization only for **longitudinally polarized γ*** $\sigma_T$ suppressed by $1/Q^2 \rightarrow$ at large $Q^2$, $\sigma_L$ dominates

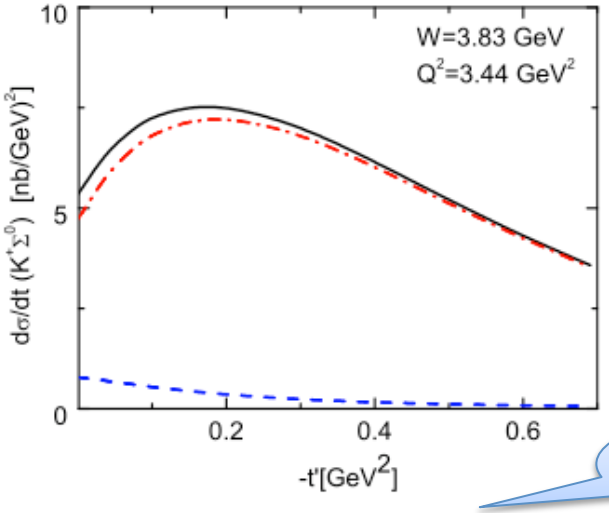
# Exclusive Kaons

At JLab12 dominant contribution from transverse photon:
possible access to the chiral-odd GPDs (and spatial distribution of transversely polarized quarks)

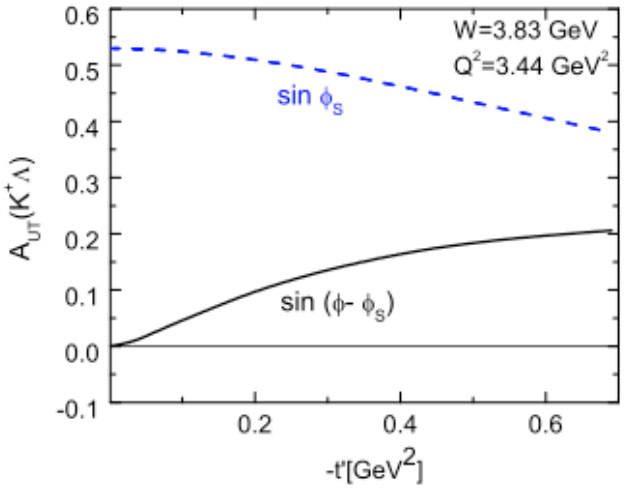
$\gamma p \to K^+\Lambda$



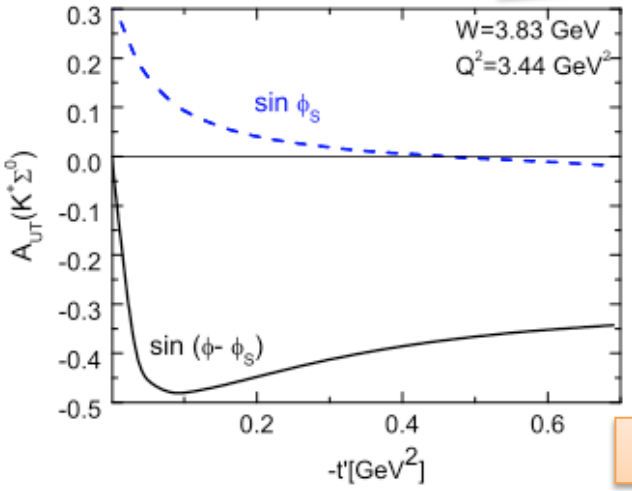

$\gamma p \to K^+\Sigma^0$




$H_T$ effects



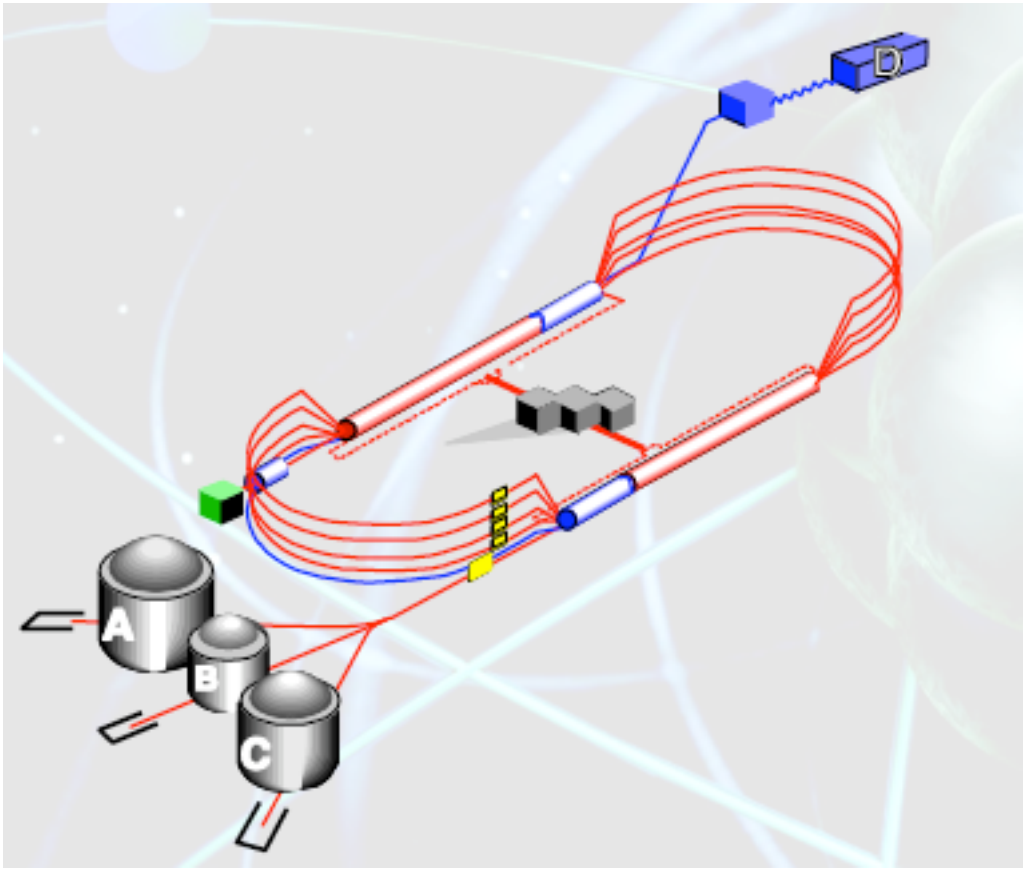

$E_T$ effects




Goloskokov talk

# The JLab12 Charge

**Start of Accelerator commissioning expected in November and running beam to Hall-A in February 2014**




**Complete mapping (3D) of the nucleon in the valence region**
**High potential of the complementary programs of 3 experimental halls**