JLAB CLAS12 TMDs PROGRAM

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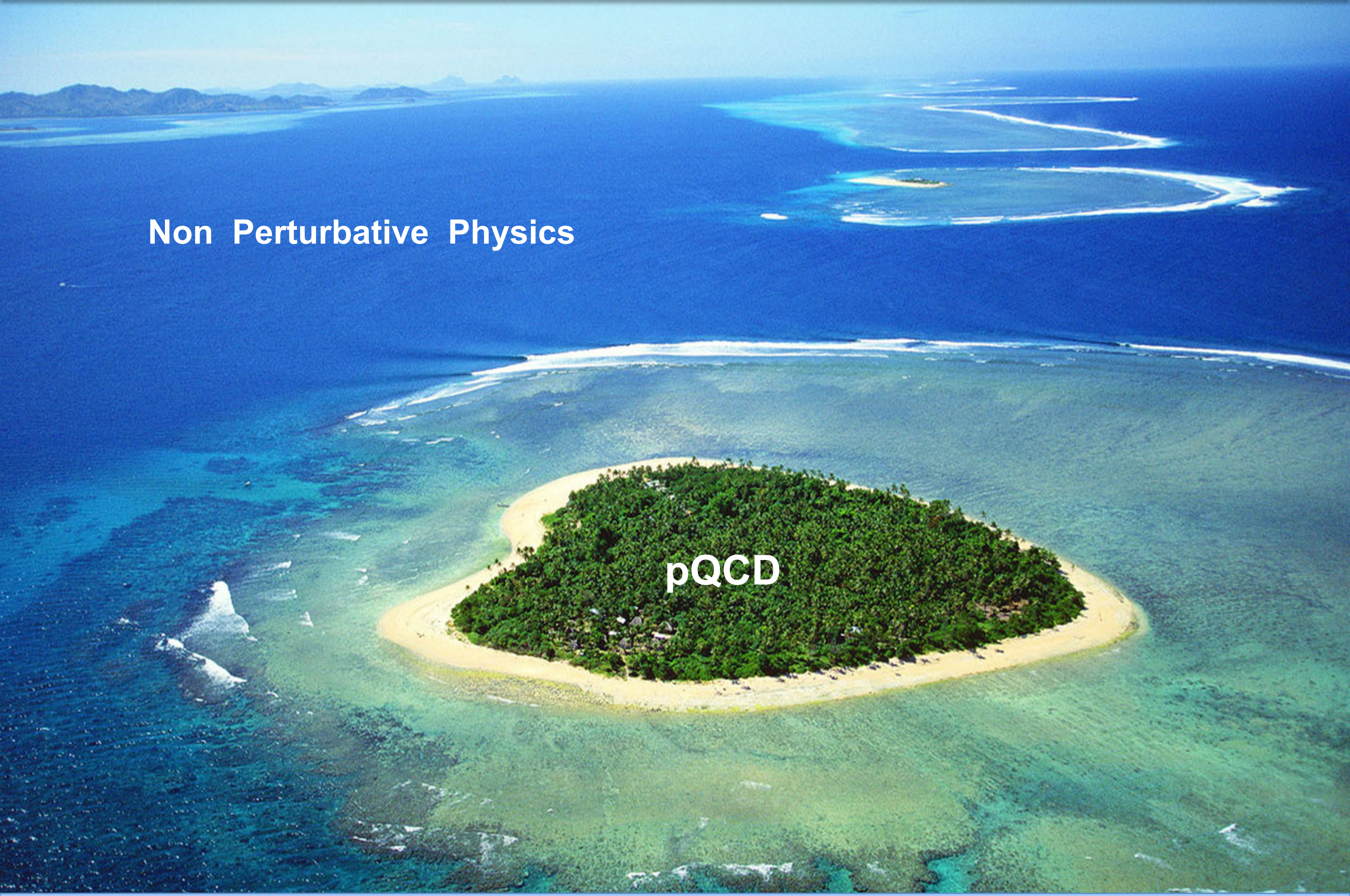
INFN Ferrara

Parton TMDs at large x – ECT*16
April 12, 2016 Trento

The QCD View



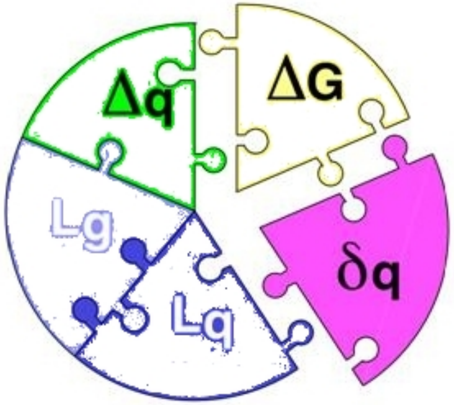
The Spin Degree of Freedom

In our exploration of the QCD micro-world

Fundamental: do not neglect spin !!

Two questions in Hadronic Physics
await explanation since too long

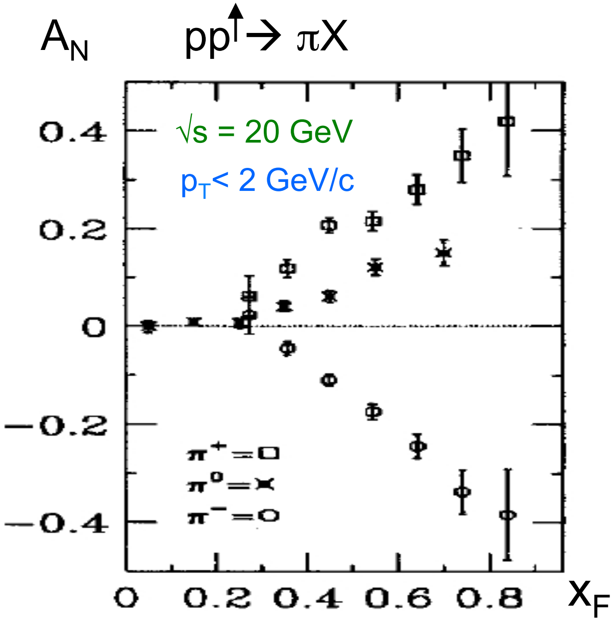
Proton Spin Budget



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

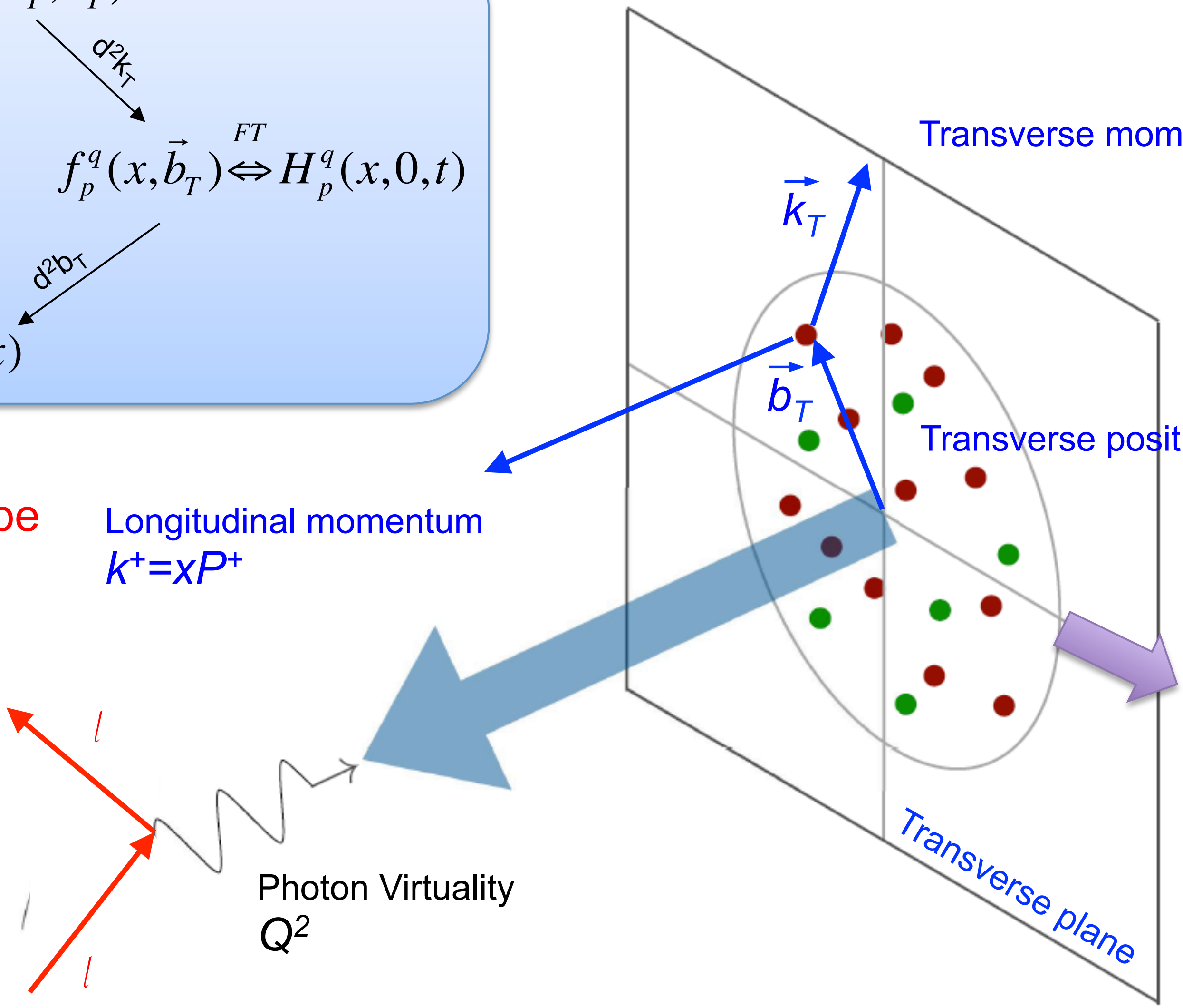
?

Single Spin Asymmetries



The 3D Nucleon Structure

$$\begin{tikzcd}
 & W_p^q(x,\vec{k}_T,\vec{b}_T) \arrow[dl, "d^2b_T"'] \arrow[dr, "d^2k_T"] & & \\
f_p^q(x,\vec{k}_T) \arrow[dr, "d^2k_T"] & & f_p^q(x,\vec{b}_T) \arrow[dl, "d^2b_T"'] \arrow[r, Leftrightarrow, "FT"] & H_p^q(x,0,t) \\
 & f_p^q(x) & &
\end{tikzcd}$$



Confinement Scale

Transverse momentum

Transverse position

High Energy Probe
Hard Scale

Longitudinal momentum
$k^+=xP^+$

Spin

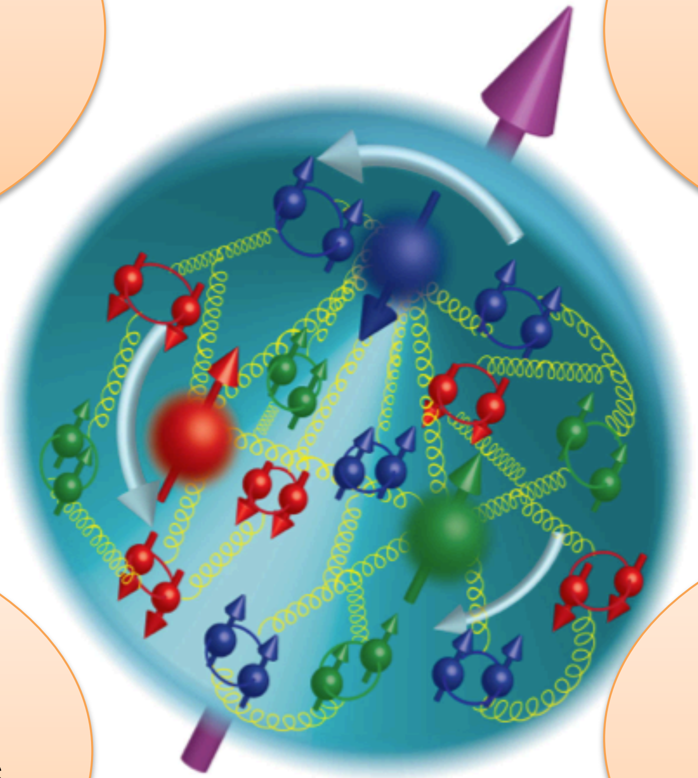
Photon Virtuality
Q^2

Transverse plane

3D Vision and Parton Dynamics

Dynamic Spin
- Parton polarization
- Orbital motion
- Form Factors
- Anomalous MM

Parton Correlations
- Short range
- MPI

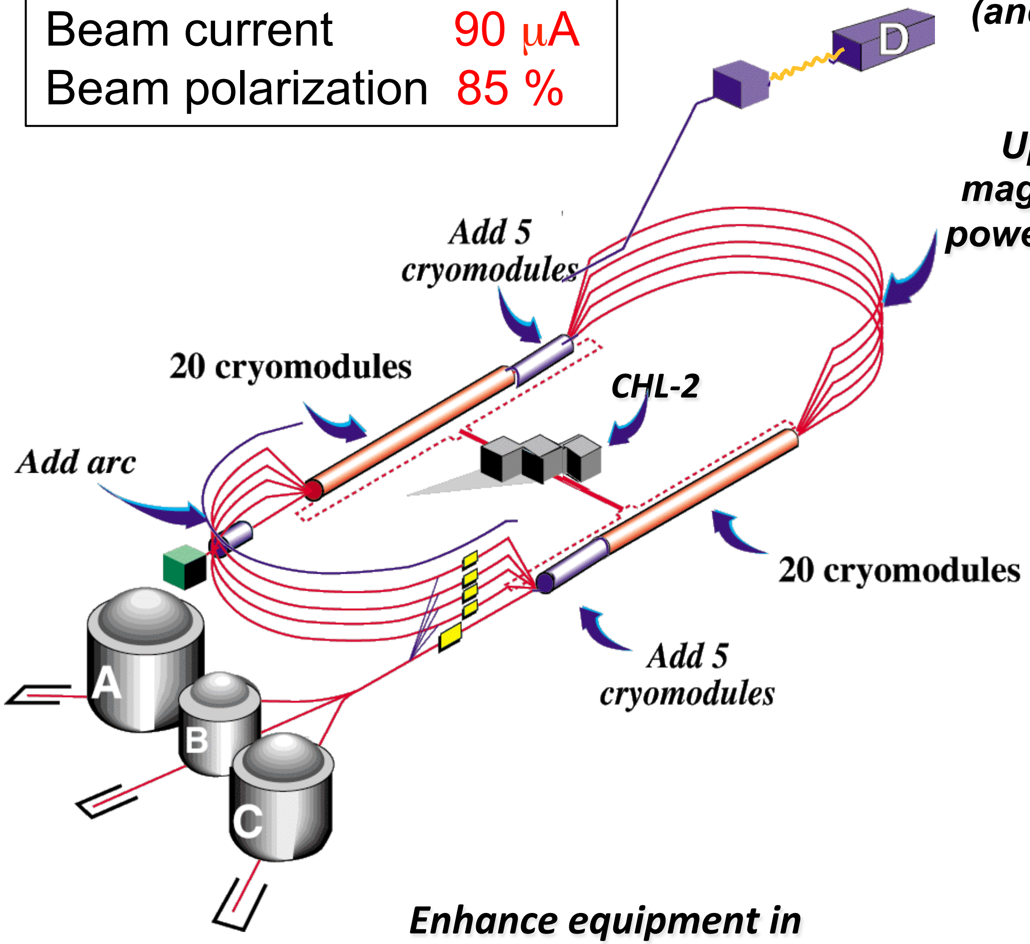


Hadronization
- Spin-orbit effects
- Parton energy loss
- Jet quenching

Color charge density
- Nucleon tomography
- Diffractive physics
- Gluon saturation

CEBAF Upgrade at Jefferson Lab

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



Enhance equipment in existing halls

CLAS12 Timeline (indicative)

2016: Installation

2017: Commissioning
Hydrogen Target

2018: Deuteron Target
(BoNuS for proton spectator tagging)

2019: Polarized NH_3, ND_3

Beam is being delivered to the Halls

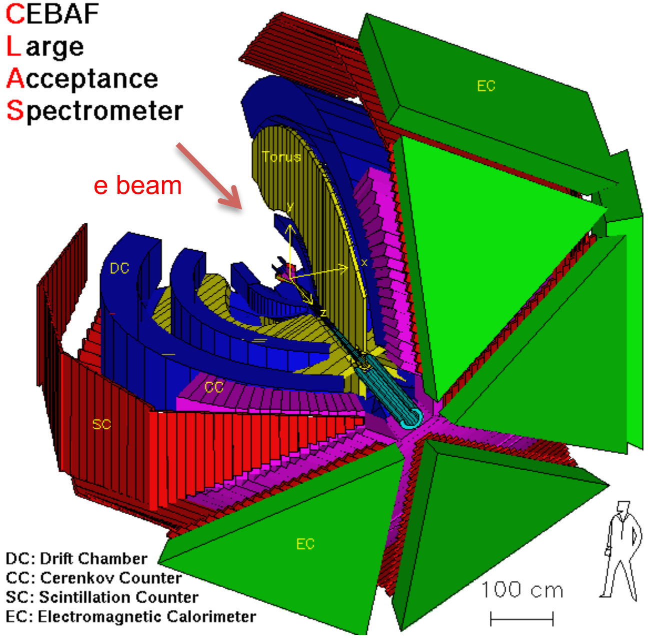
Hall-B Mission

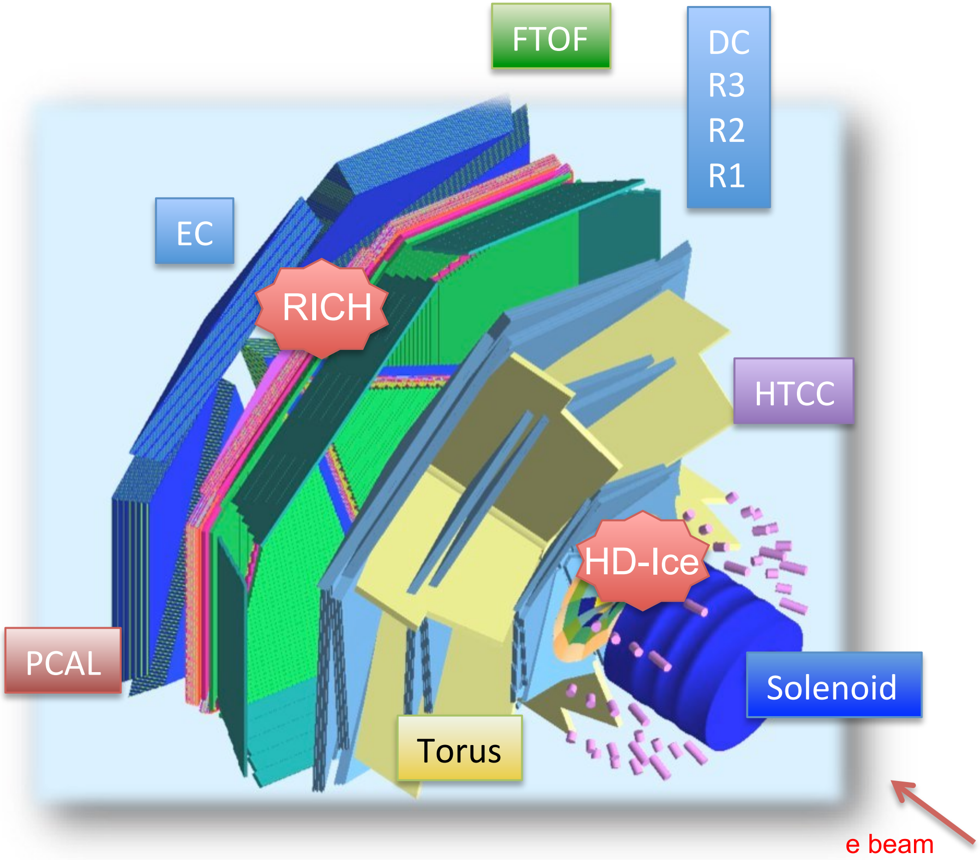
Comprehensive measurements based on : High luminosity up to 10^{35} cm^{-2} s^{-1}
Large acceptance (current & target fragmentation)
Polarized beam and targets
Multi-particle final state measurements

6 GeV

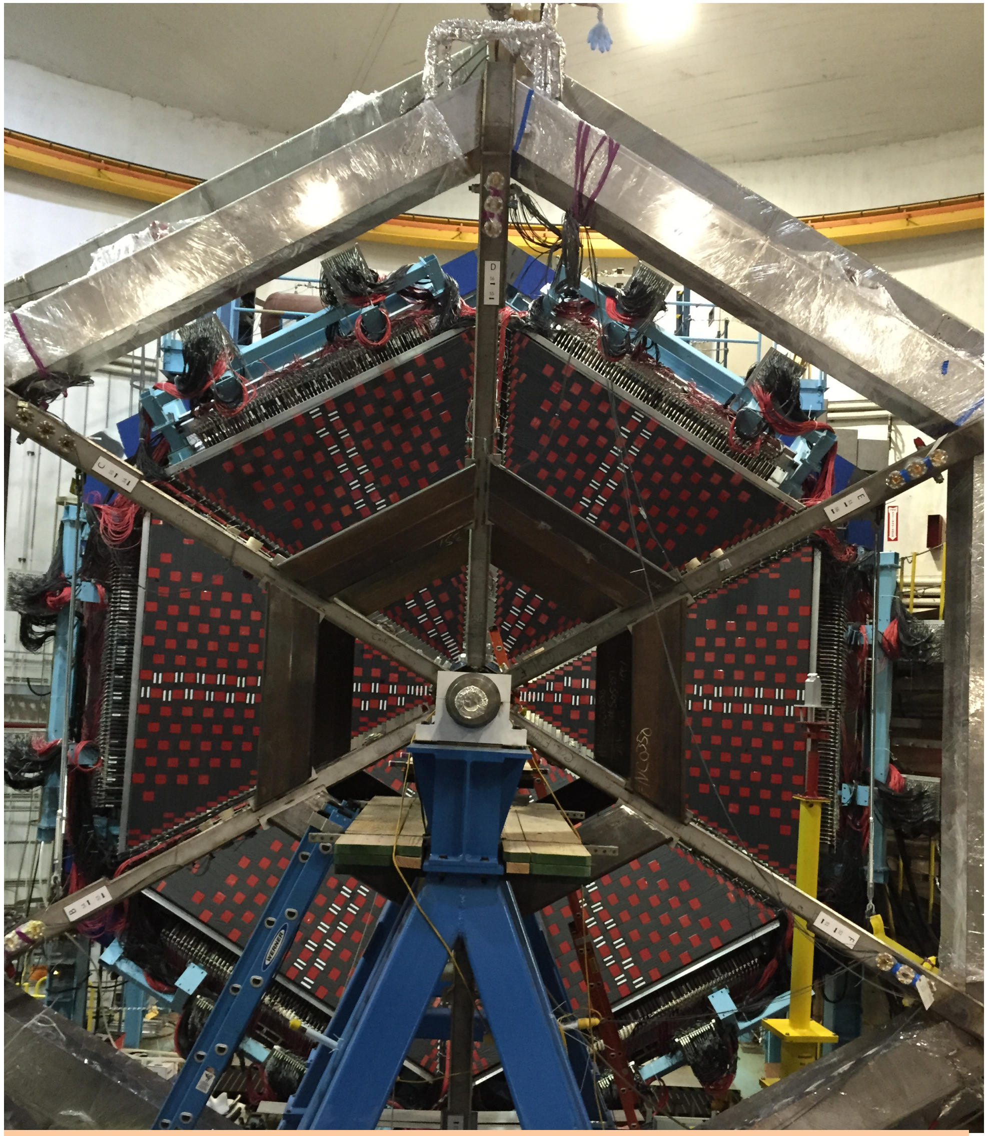
12 GeV

NIM A503, 513 (2003)

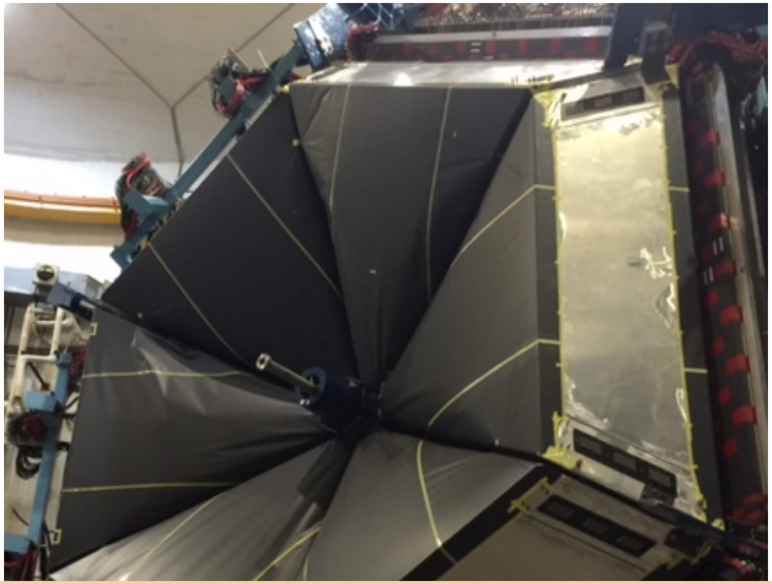




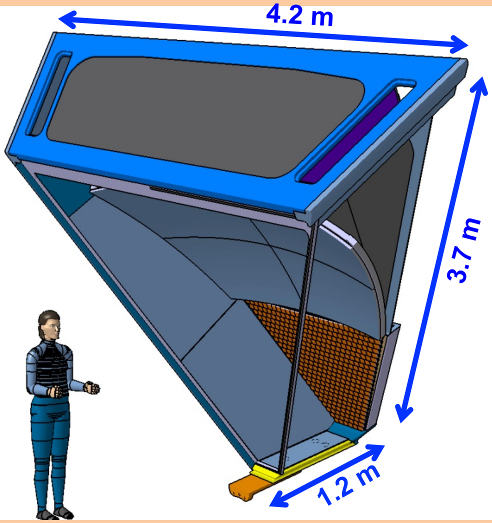
CLAS12 Forward Detector



Torus + Time-of-Flight Wall (Hadron ID)



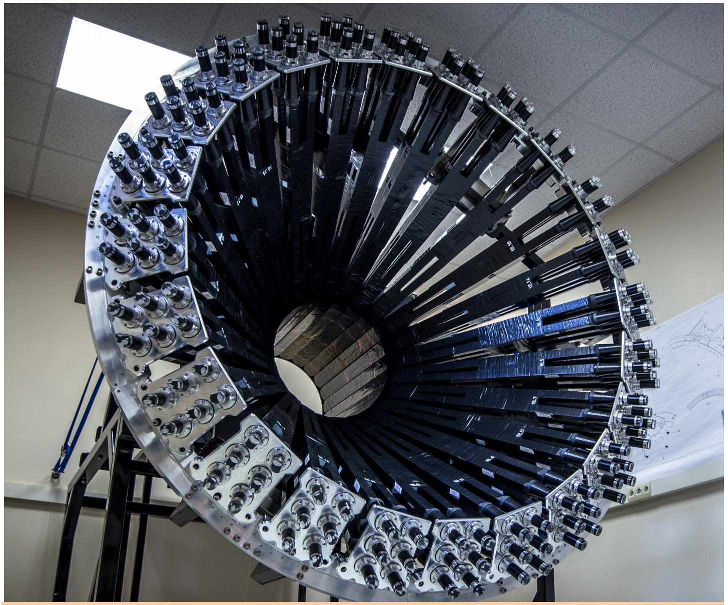
Low-Threshold Gas Cherenkov (pion ID)



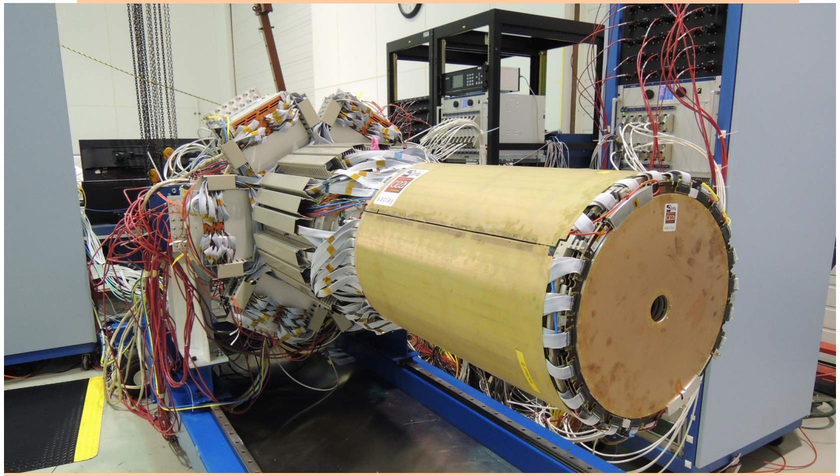
Ring-Imaging Cherenkov (Hadron ID)

CLAS12 Central Detector

High-Threshold Gas Cherenkov (elec. ID)



Central Neutron Detector

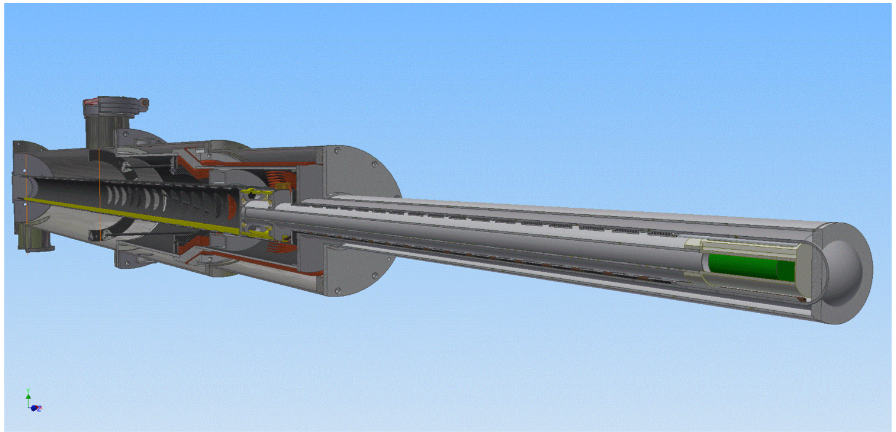


Silicon + MicroMegas Vertex Detector

Polarized Targets

Solid state targets:

NH_3	P = 0.90	f = 0.15	FOM = 0.14
ND_3	P = 0.40	f = 0.28	FOM = 0.11



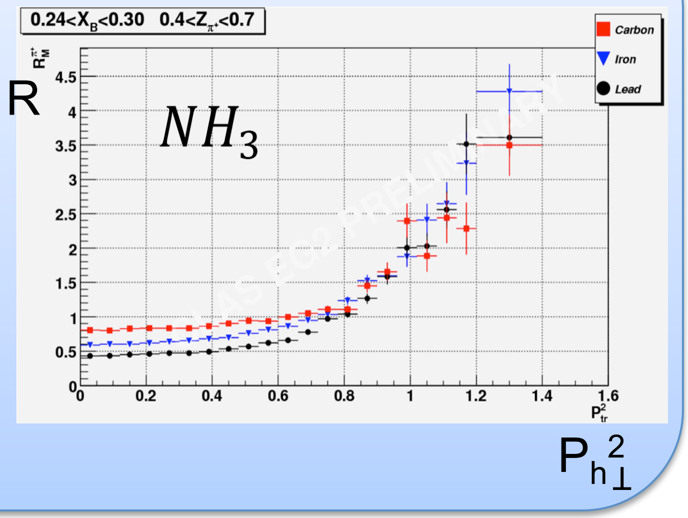
New approach HD-ice target:

HD-ice P = 0.75 f = 0.33 FOM = 0.25 *under test with charged beam*

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**



Disadvantages:

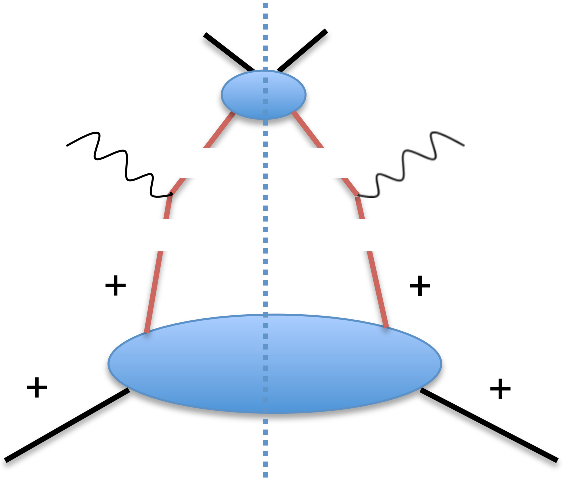
- **Very long polarizing times (months)**
- **Sensitivity to local heating by charged beams**

DIS Cross-Section

Wide kinematic coverage is needed to resolve the convolution

$$F_{UU} = f \otimes D = x \sum_q e_q^2 \int d^2 p_T d^2 k_T \;\; \delta^{(2)}(\mathbf{P}_{h\perp} - z\mathbf{k}_T - \mathbf{p}_T) \; w(\mathbf{k}_T, \mathbf{p}_T) \; f^q(x, k_T^2) \; D^q(z, p_T^2)$$

TMD Factorization holds for $p_T << Q$



Quark fragmentation

Hard scattering

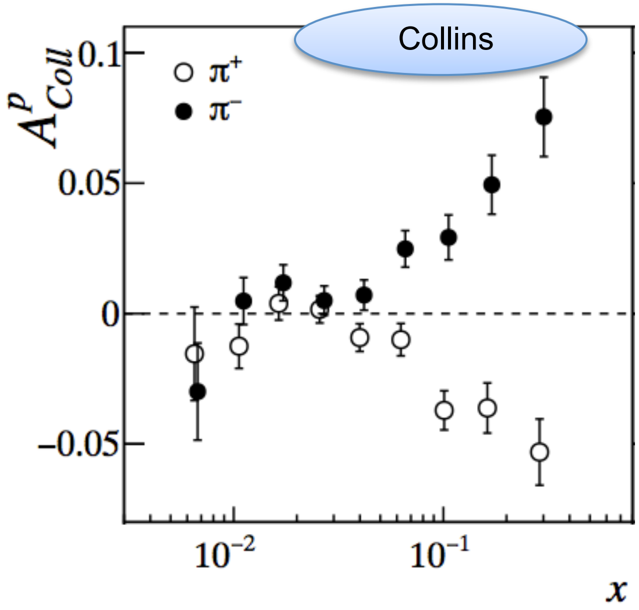
Quark-quark correlator

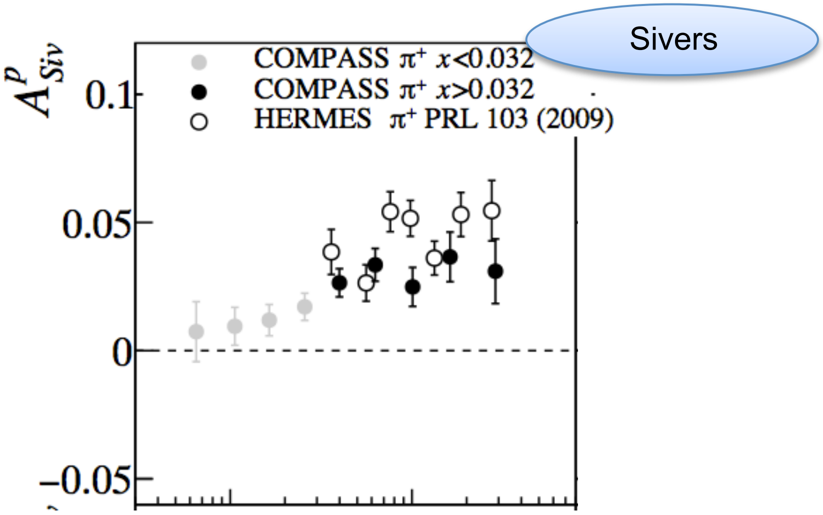
$$\frac{d^6\sigma}{dx dQ^2 dz dP_h d\phi d\phi_S} \overset{LT}{\propto} \left[F_{UU} + \varepsilon \cos(2\phi) F_{UU}^{\cos(2\phi)}\right] + S_L\left[\varepsilon \sin(2\phi) F_{UL}^{\sin(2\phi)}\right]$$

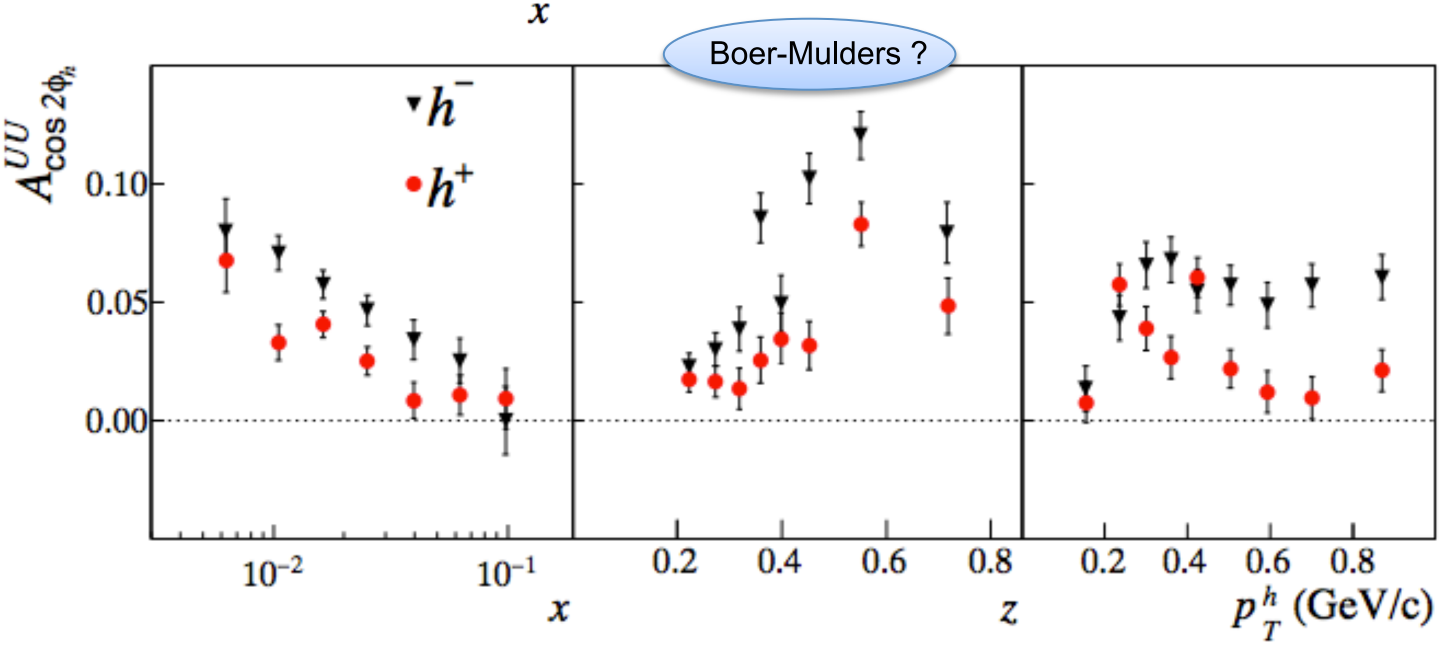
$$+ S_T\left[\sin(\phi - \phi_S) F_{UT}^{\sin(\phi-\phi_S)} + \varepsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi-\phi_S)}\right]$$

$$+ S_L \lambda_e \left[\sqrt{1-\varepsilon^2} F_{LL}\right] + S_T \lambda_e \left[\sqrt{1-\varepsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi-\phi_S)}\right] + O\left(\frac{1}{Q}\right)$$

TMD x Range

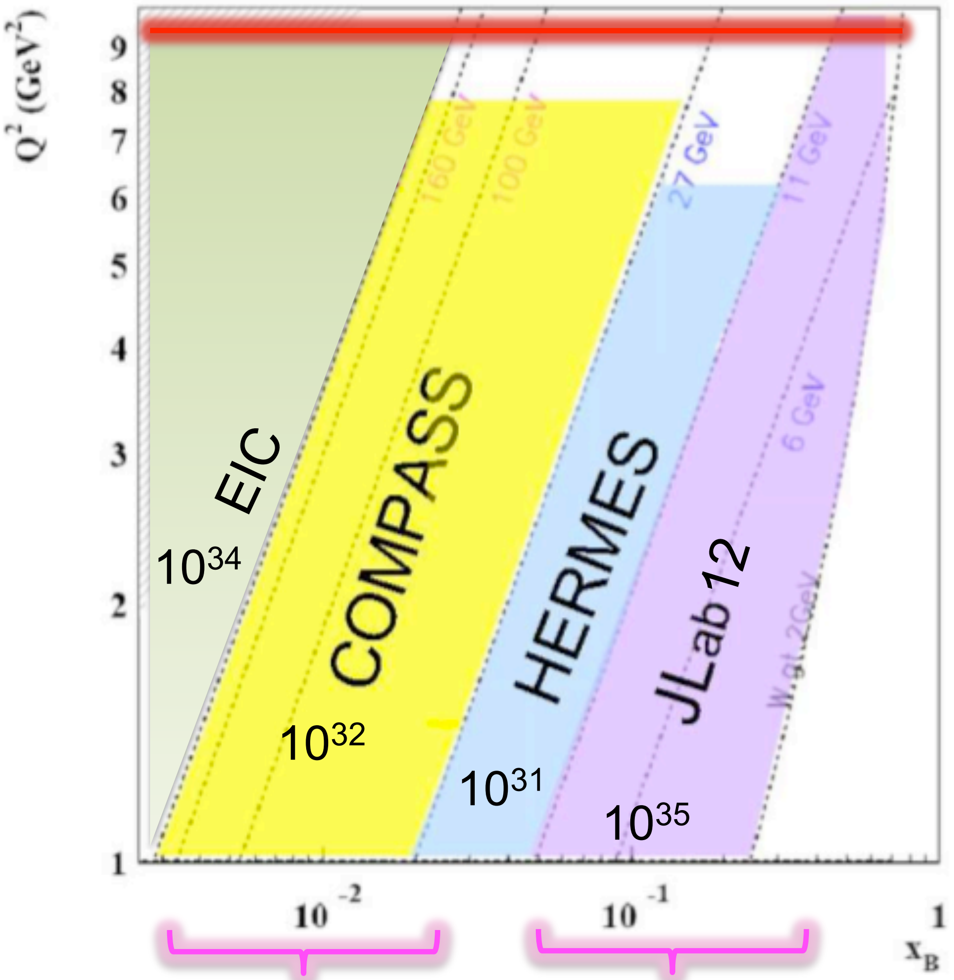

Collins


Sivers


Boer-Mulders ?

The SIDIS Landscape

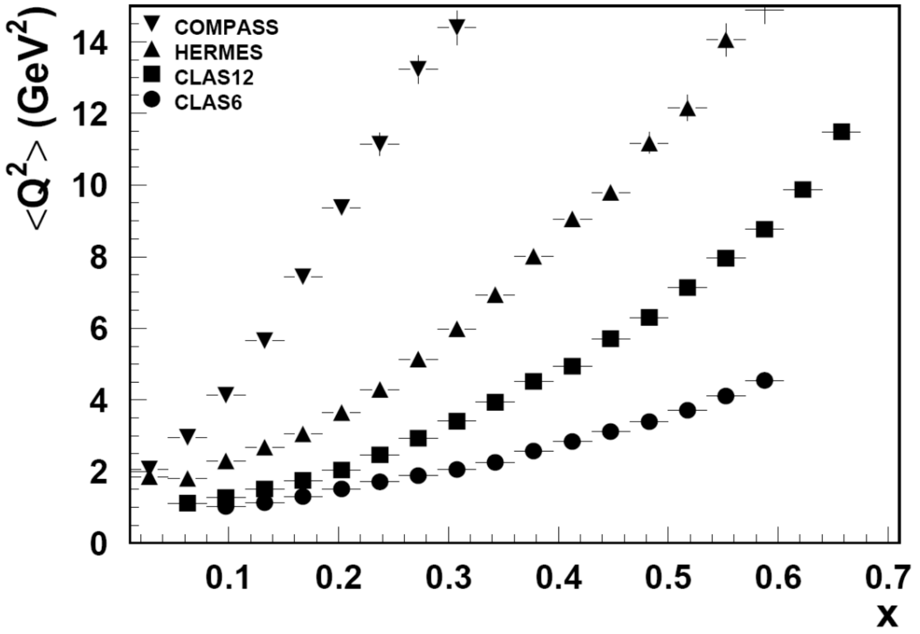
Limit defined by luminosity



Sea

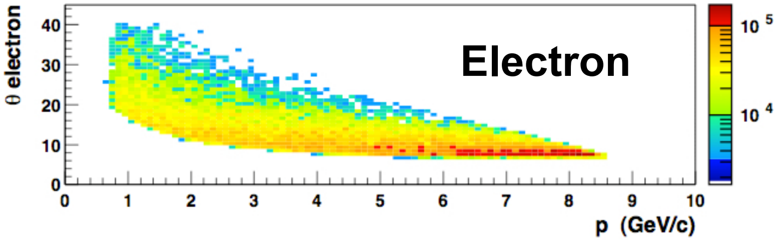
Valence

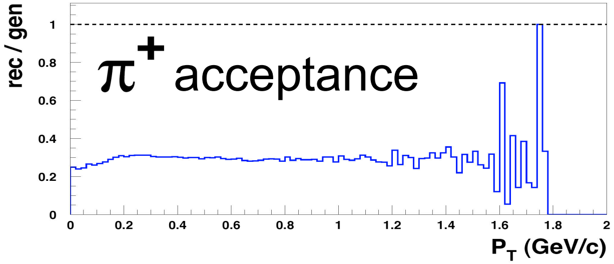
Different Q^2 for same x range



Complementary experiments

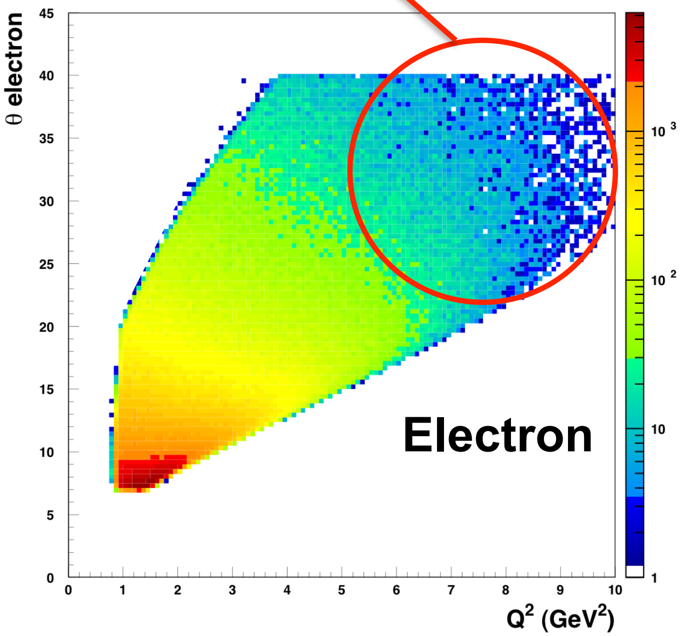
CLAS12 Kinematic Coverage

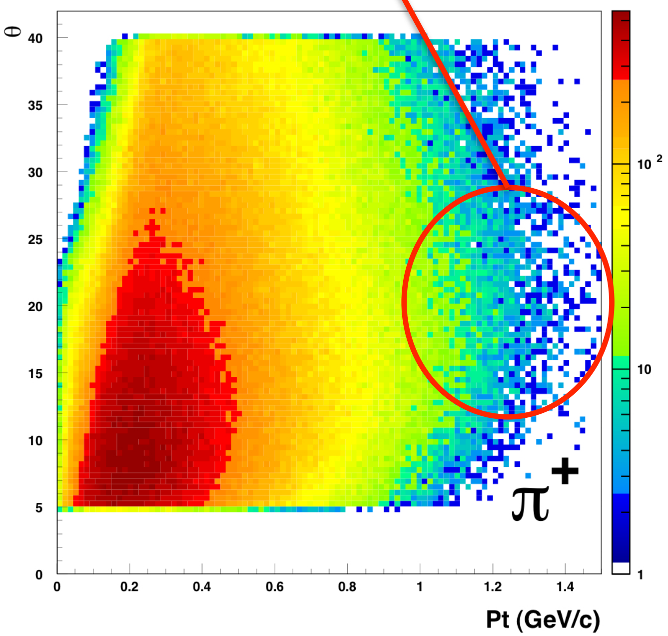




Large electron scattering angles (> 20°) mandatory to reach high Q^2 values

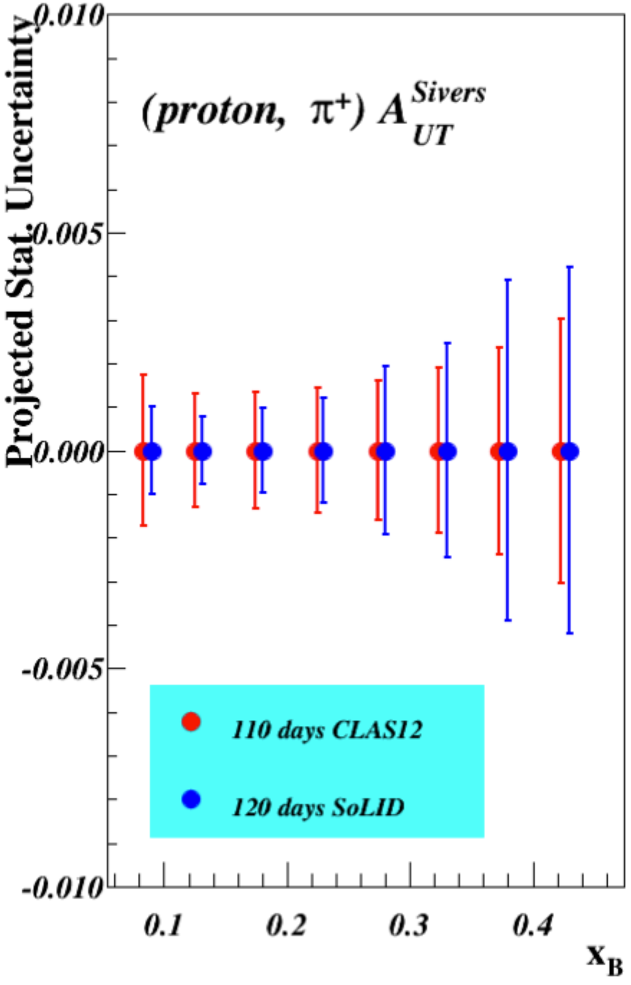
Intermediate anguar range (15-25°) mandatory to reach high P_T values

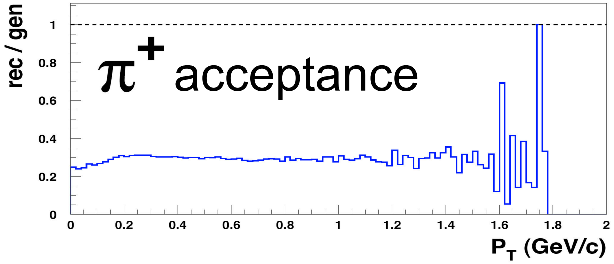




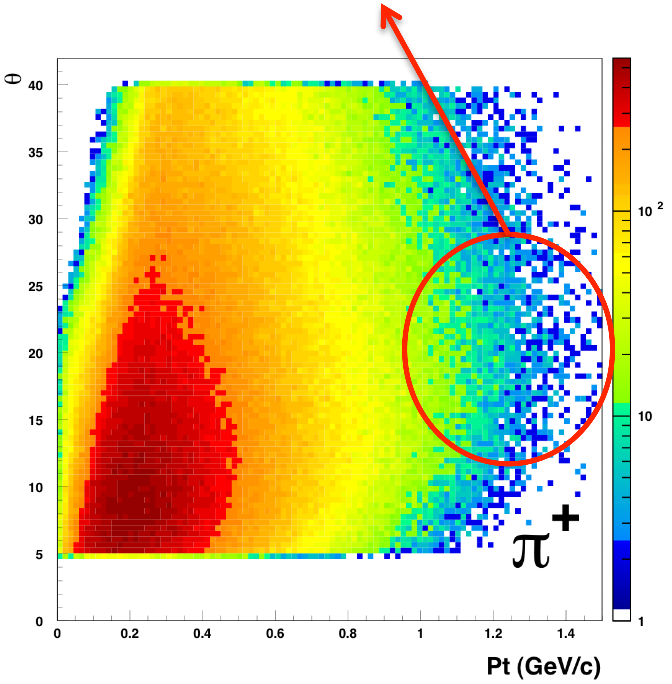
The CLAS12 forward detector is suitable for high-Q^2 and high-p_T measurements since designed to cover up to 40 degrees angles

CLAS12 Kinematic Coverage





Intermediate anguar range (15-25^o) mandatory to reach high P_T values

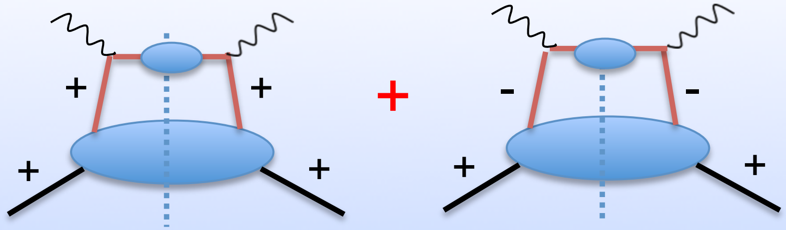


The CLAS12 forward detector is suitable for high-Q^2 and high-p_T measurements since designed to cover up to 40 degrees angles

Unpolarized TMDs

$\Phi^{[\gamma^+]}$

$$f_1(x) = q^+(x) + q^-(x)$$



quark polarisation

nucleon polarisation

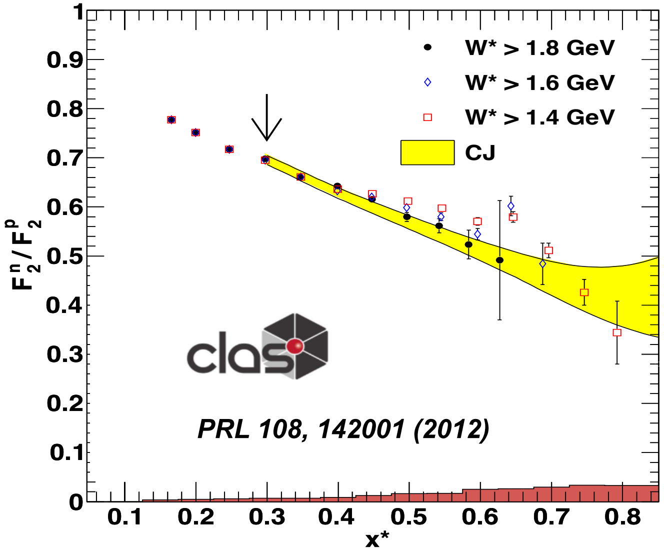
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1, h_{1T}^\perp$

quark polarisation

hadron polarisation

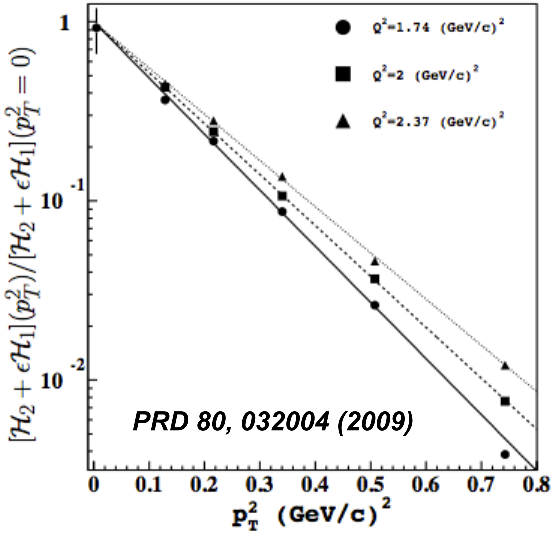
N/q	U	L	T
U	D_1		$H_1^\perp$

Scattering on deuterium with proton spectator tagging



PRL 108, 142001 (2012)

Extending the study to the transverse momentum

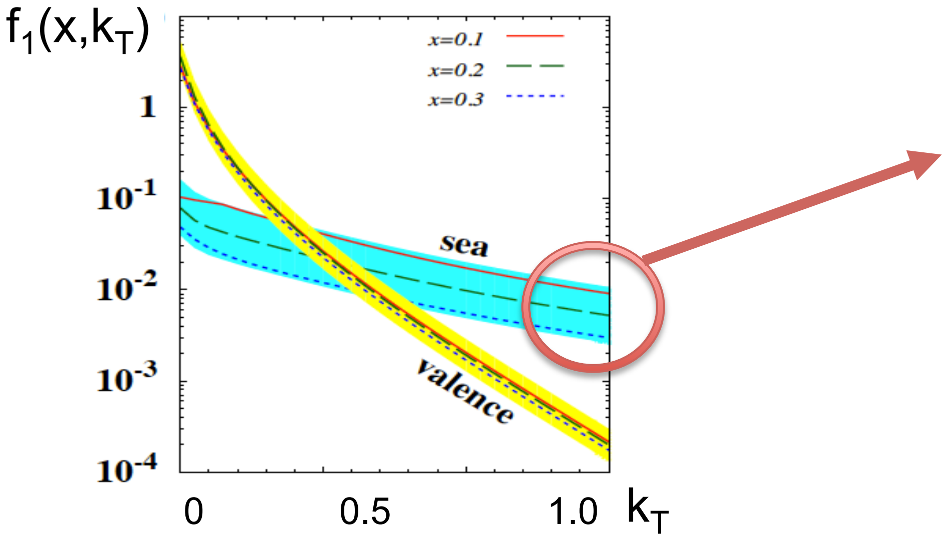


PRD 80, 032004 (2009)

The $P_{h\perp}$-unintegrated multiplicities

$$\sigma_{UU} \propto f_1\,(k_T\ldots)\otimes D_1\,(p_T\ldots)$$

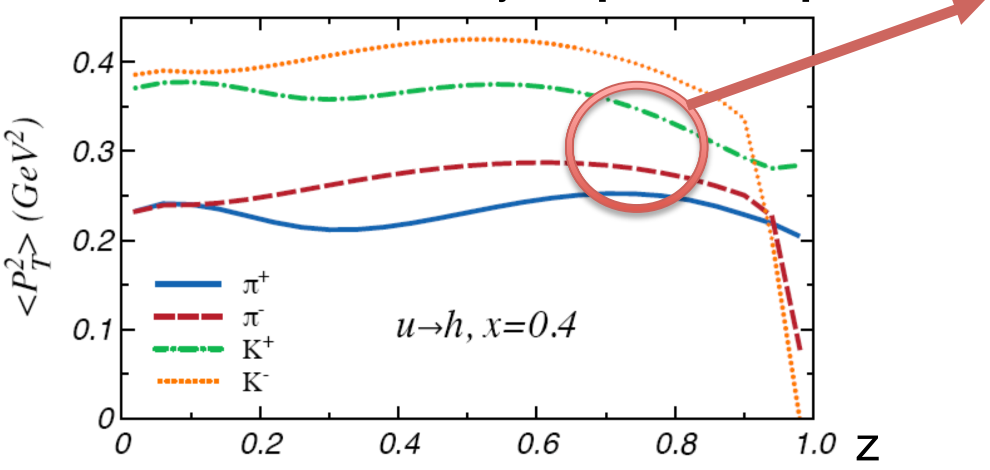
P. Schweitzer++ [arXiv:1210.1267]



Large tiles extending up to the inverse of the gauge field fluctuation scale ρ<<M

Short range parton correlations may manifest also in pp MPI

Matevosyan++ [arXiv:1111.1740]



Reflect different fragmentation

May be enhanced in medium.

Parton propagation in cold matter as complementary study to QGP

The $P_{h\perp}$-unintegrated multiplicities

$$\sigma_{UU} \propto f_1\,(k_T\ldots)\otimes D_1\,(p_T\ldots)$$

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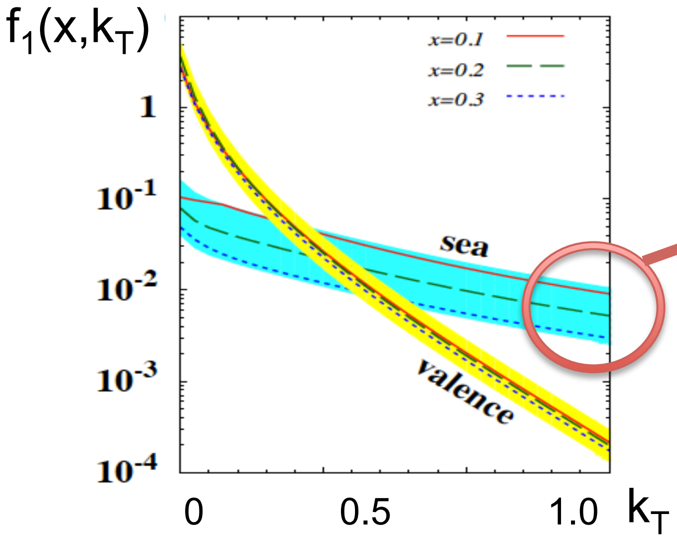
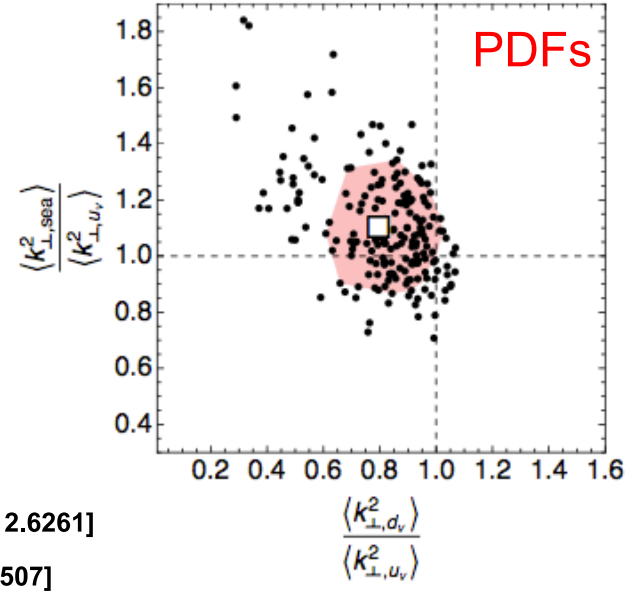
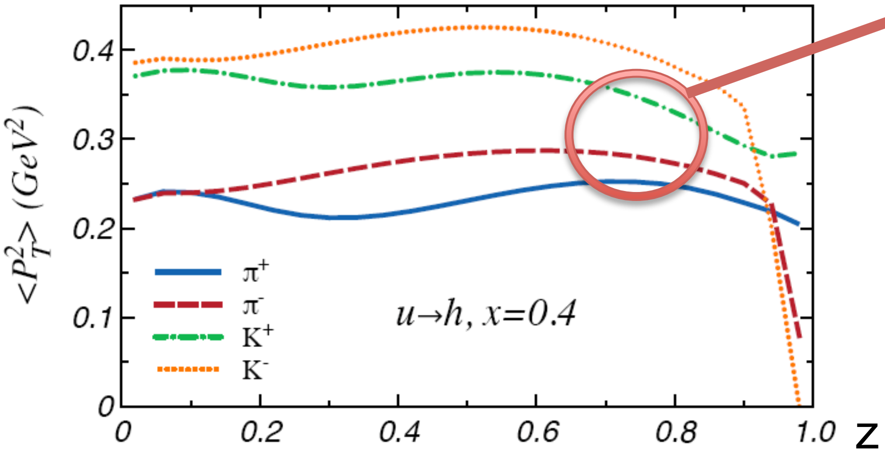


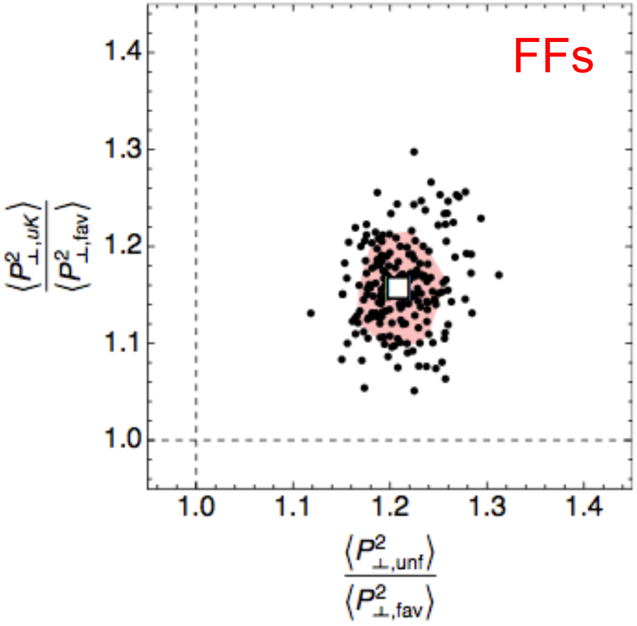


M. Anselmino++ [arXiv:1312.6261]

A. Signori++ [arXiv:1309.3507]

Matevosyan++ [arXiv:1111.1740]



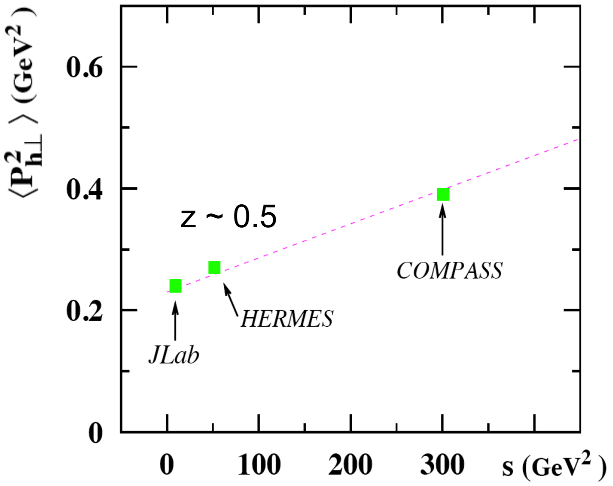


TMD Evolution

TMD evolution:

k_T and p_T broadening with c.m. energy

P. Schweitzer++ [arXiv:1003.2190]



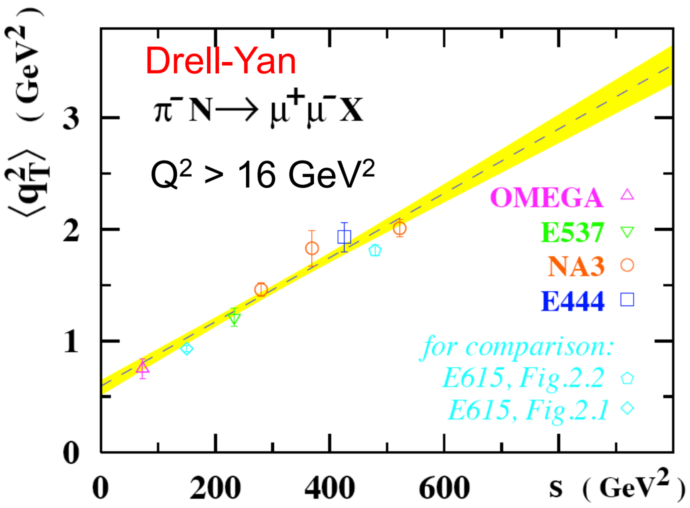
Fixed target SIDIS

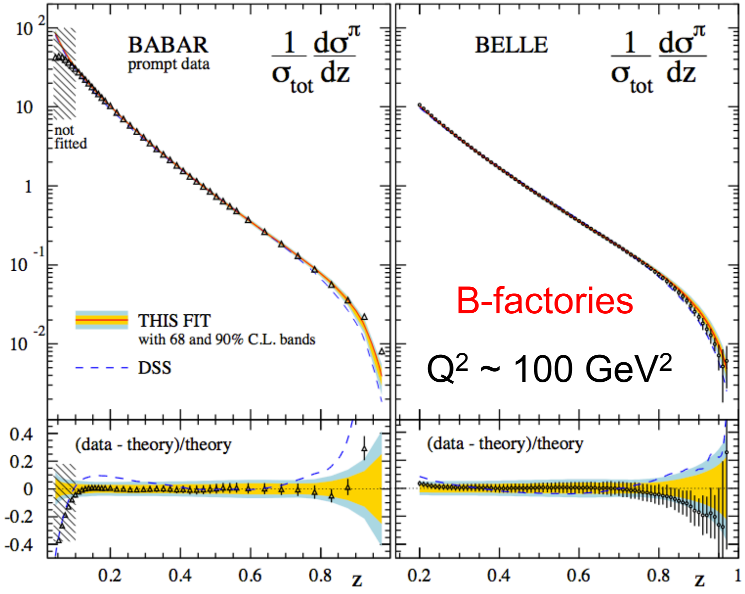
Q^2 ~ few GeV^2

TMD Q^2 evolution

≠

DGLAP

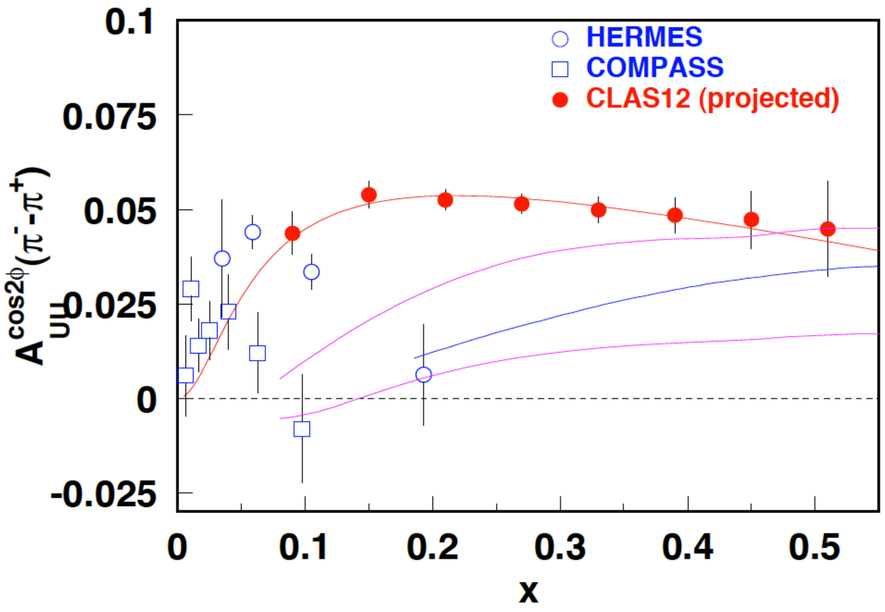




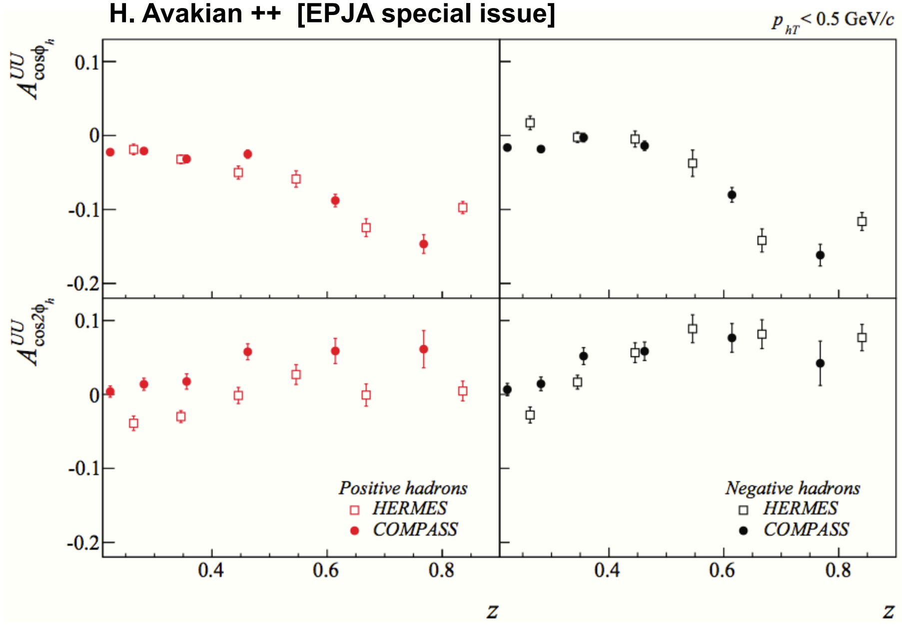
Azimuthal Modulations @ CLAS

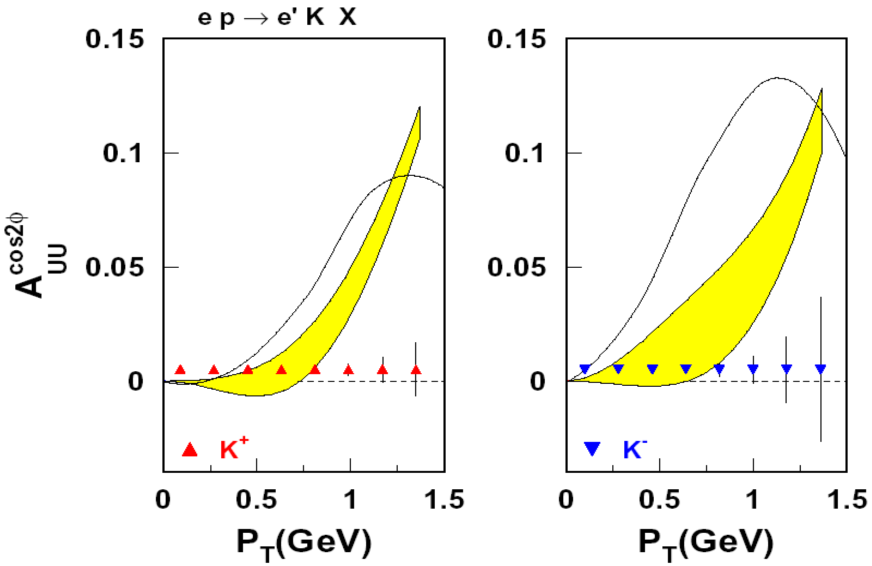
Boer-Mulders spin-orbit effect

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



H. Avakian ++ [EPJA special issue]





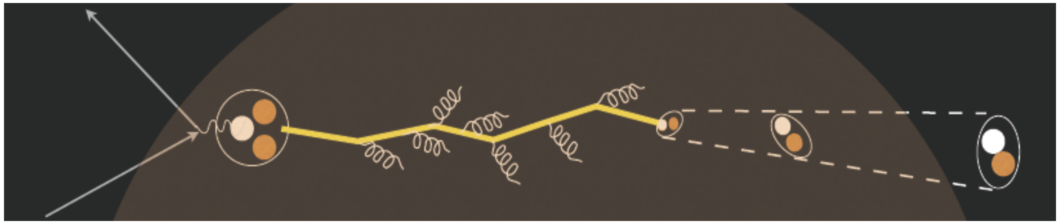
Kaon identification possible with the RICH detector

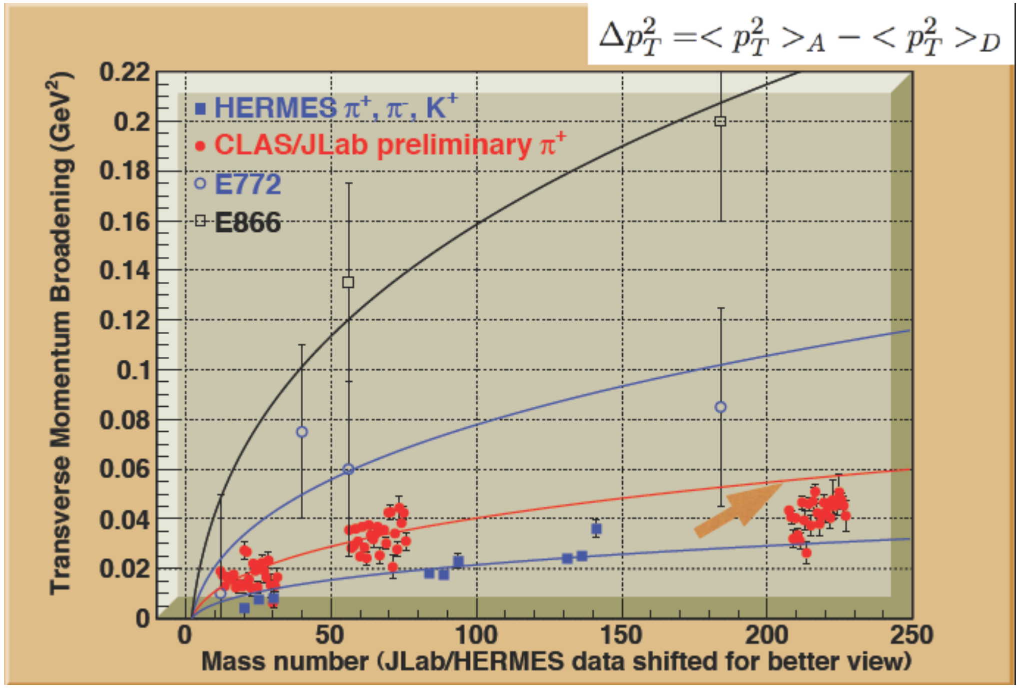
Medium modification

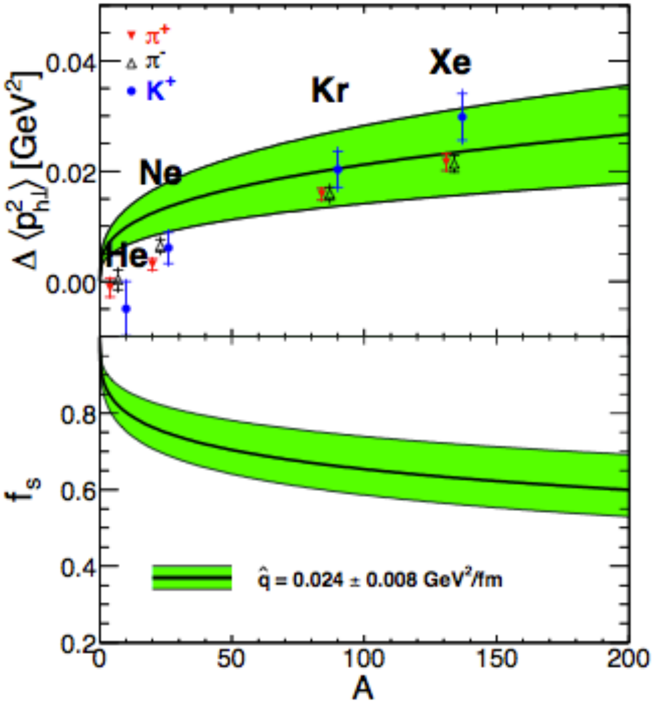
In terms of the QCD, there are several contributions to P_T distribution of hadrons produced in SIDIS:

- 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

HERMES [arXiv: 0906.2478]







N-B Chang ++ [arXiv:1402.3042]

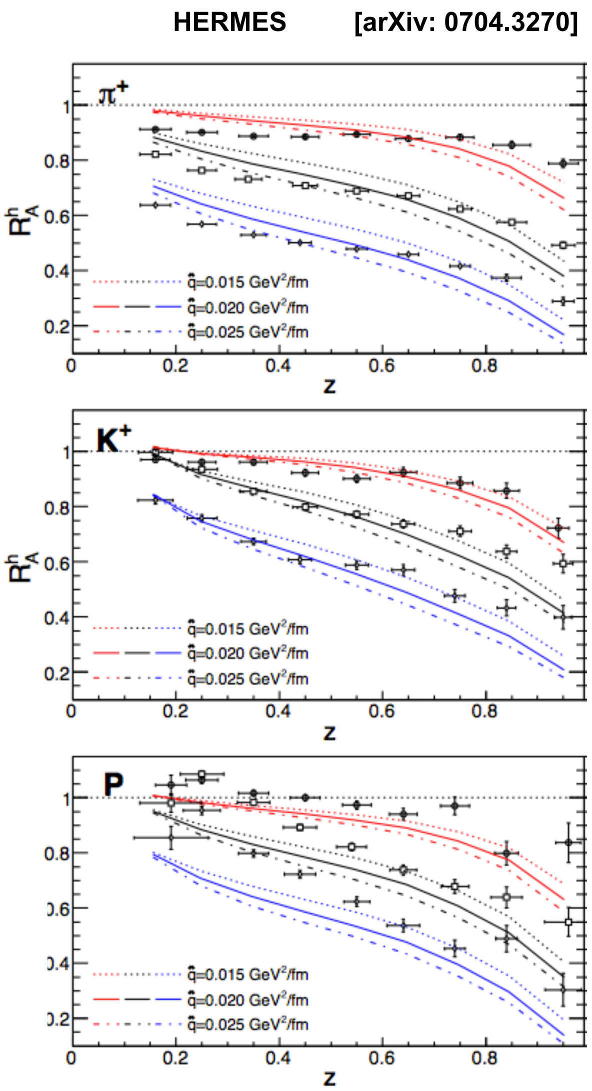
$$\Delta_{2F} = 3\sqrt{2}\hat{q}_0 r_0 A^{1/3}/4$$

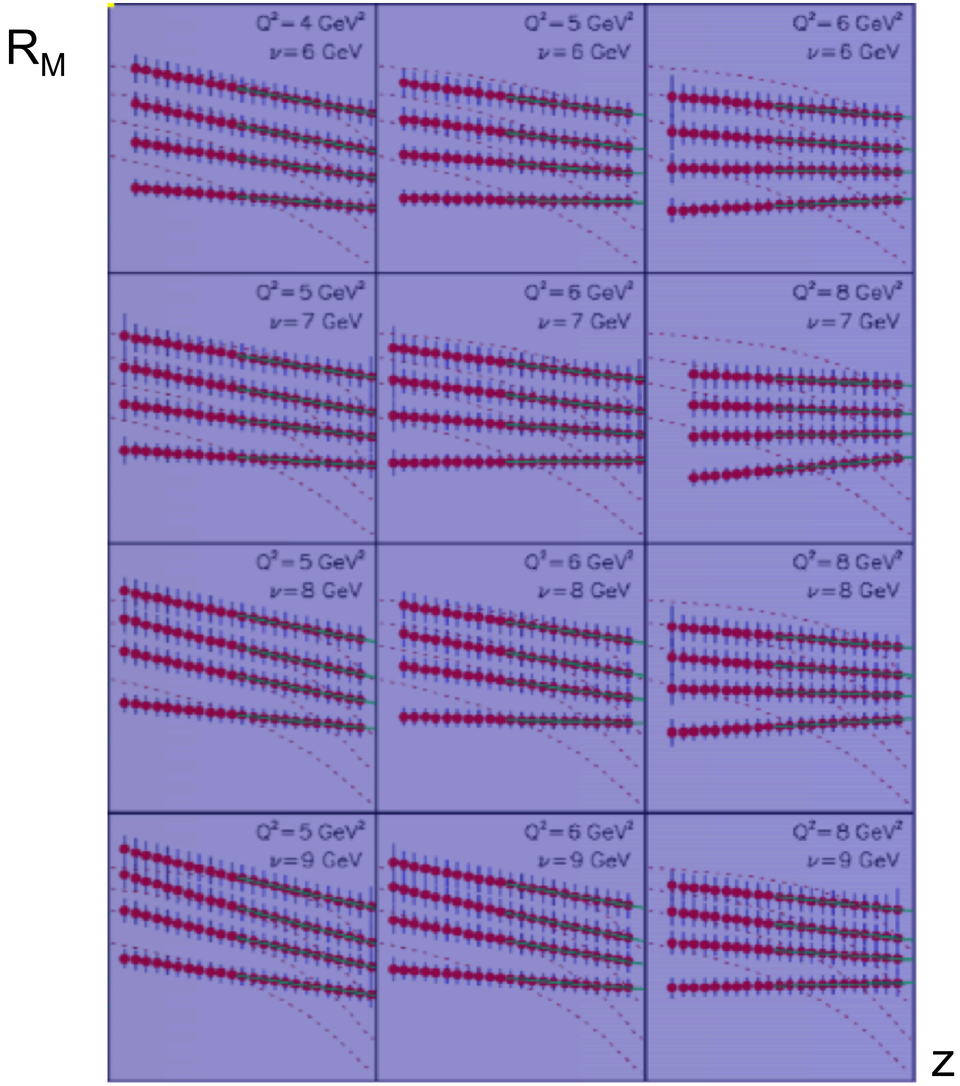
$$\frac{\langle \cos\phi \rangle^{eA}_{UU}}{\langle \cos\phi \rangle^{eN}_{UU}} \approx \frac{\langle \sin\phi \rangle^{eA}_{LU}}{\langle \sin\phi \rangle^{eN}_{LU}} \approx \frac{\alpha}{\alpha + \Delta_{2F}} = f_s$$

Medium modification

HERMES

CLAS12



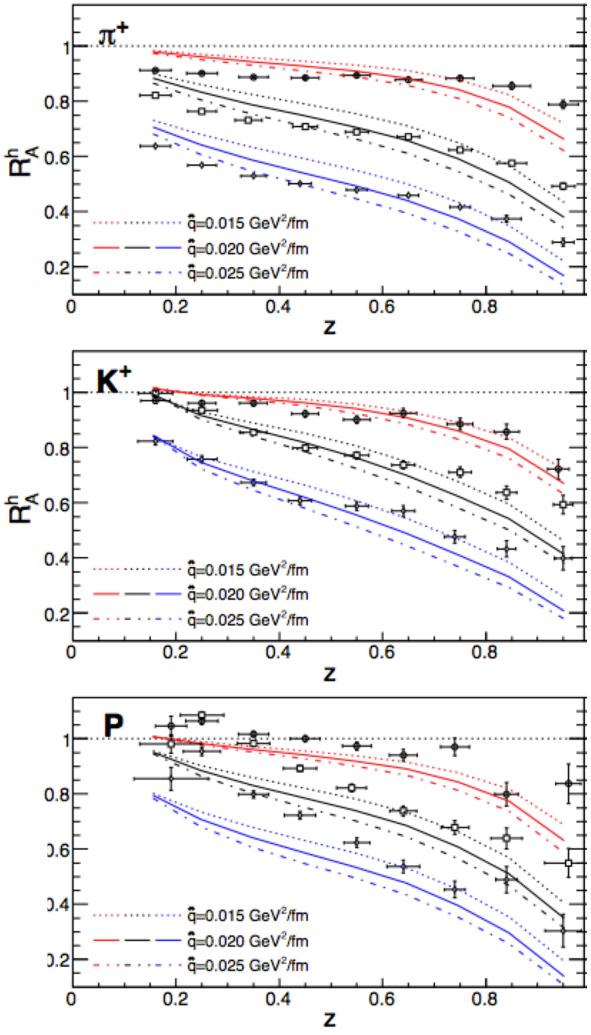


Medium modification

DIS

$$\hat{q}_0 \approx 0.020 \pm 0.005\ \mathrm{GeV}^2/\mathrm{fm}$$

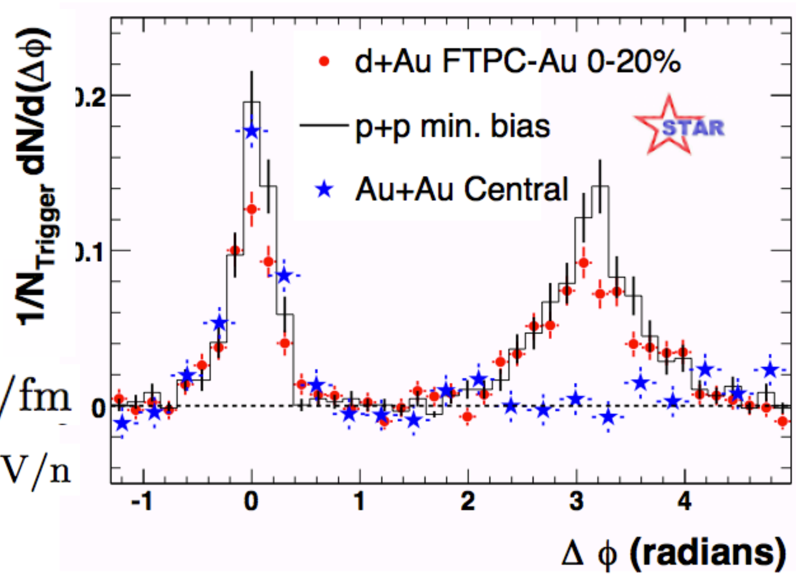
N-B Chang ++ [arXiv:1401.5109]



RHIC

$$\hat{q} \approx 1.2 \pm 0.3\ \mathrm{GeV}^2/\mathrm{fm}$$

Au+Au $\sqrt{s} = 200\ \mathrm{GeV/n}$

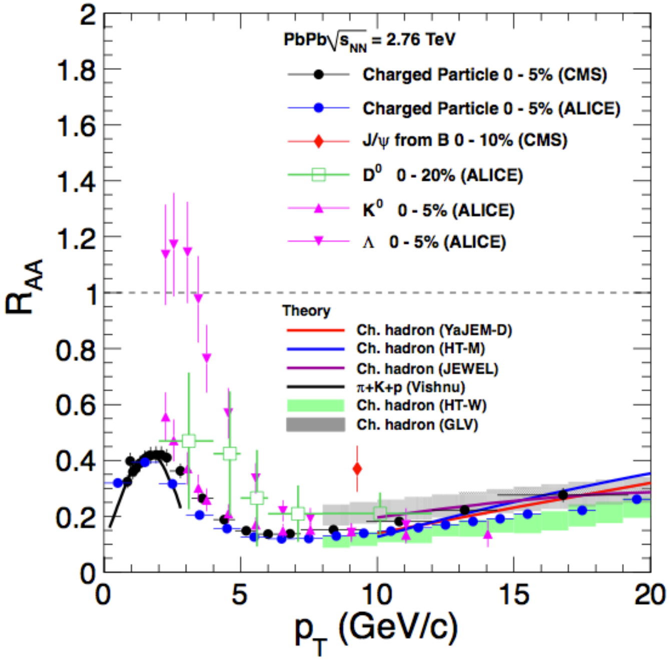


JET Coll. [arXiv:1312.5003]

LHC

$$\hat{q} \approx 1.9 \pm 0.7\ \mathrm{GeV}^2/\mathrm{fm}$$

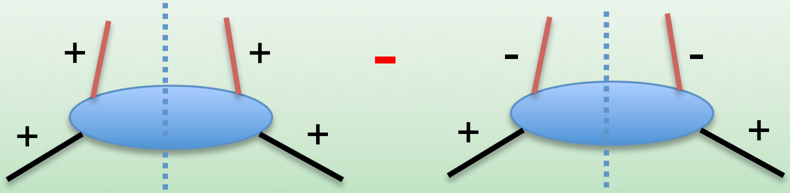
Pb+Pb $\sqrt{s} = 2.76\ \mathrm{TeV/n}$



Quark Helicity

$\Phi^{[\gamma^+\gamma^5]}$

$$g_1(x) = q^+(x) - q^-(x)$$



quark polarisation

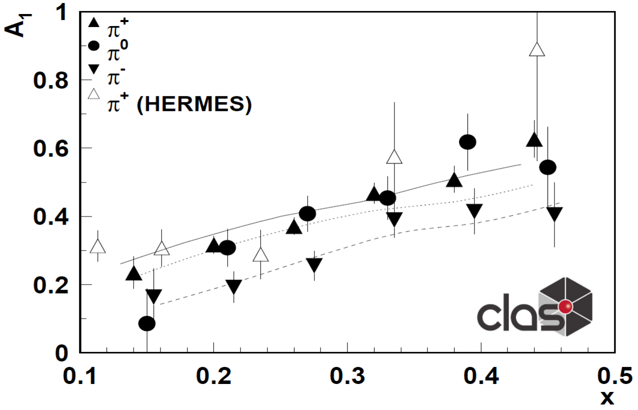
nucleon polarisation

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1, h_{1T}^\perp$

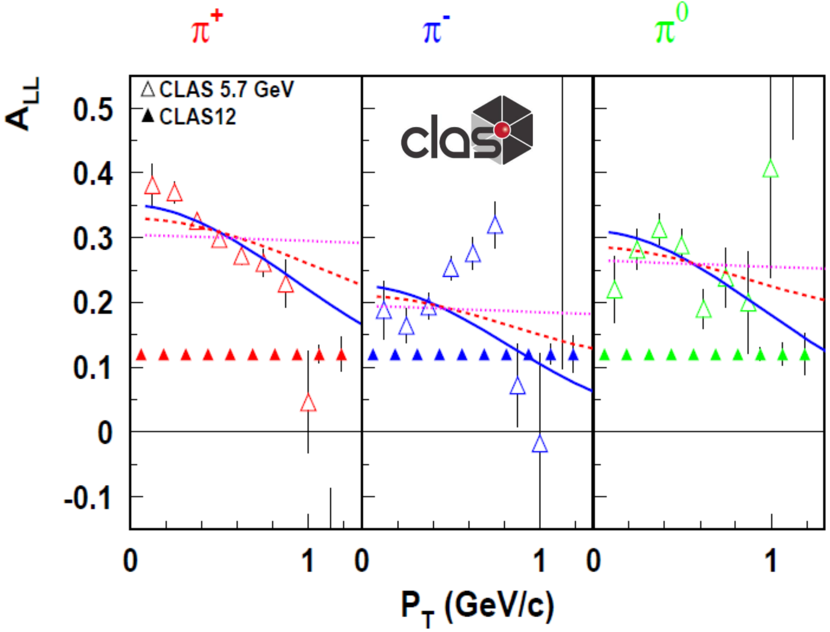
quark polarisation

hadron polarisation

N/q	U	L	T
U	D_1		$H_1^\perp$



High-statistics (x10) on 2009 data in progress



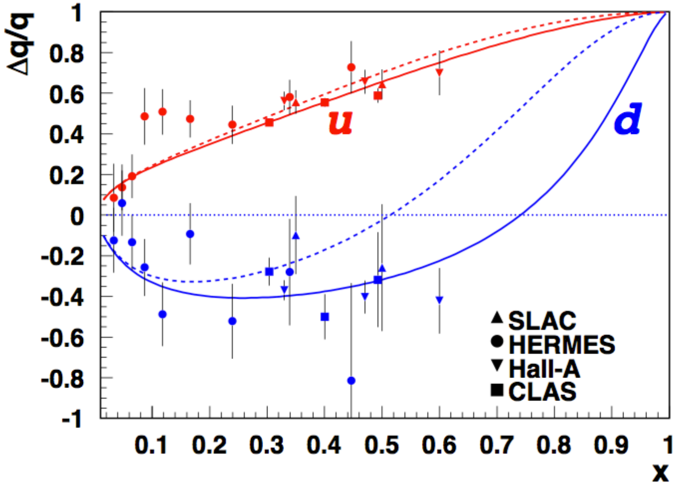
H. Avakian et al. PRL 105: 262002 (2010) [arXiv 1003.4549]

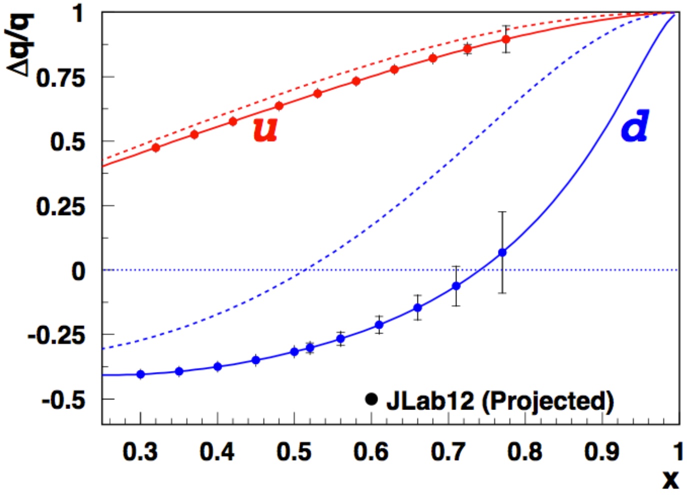
H. Avakian et al. E12-07-107 @ 12 GeV

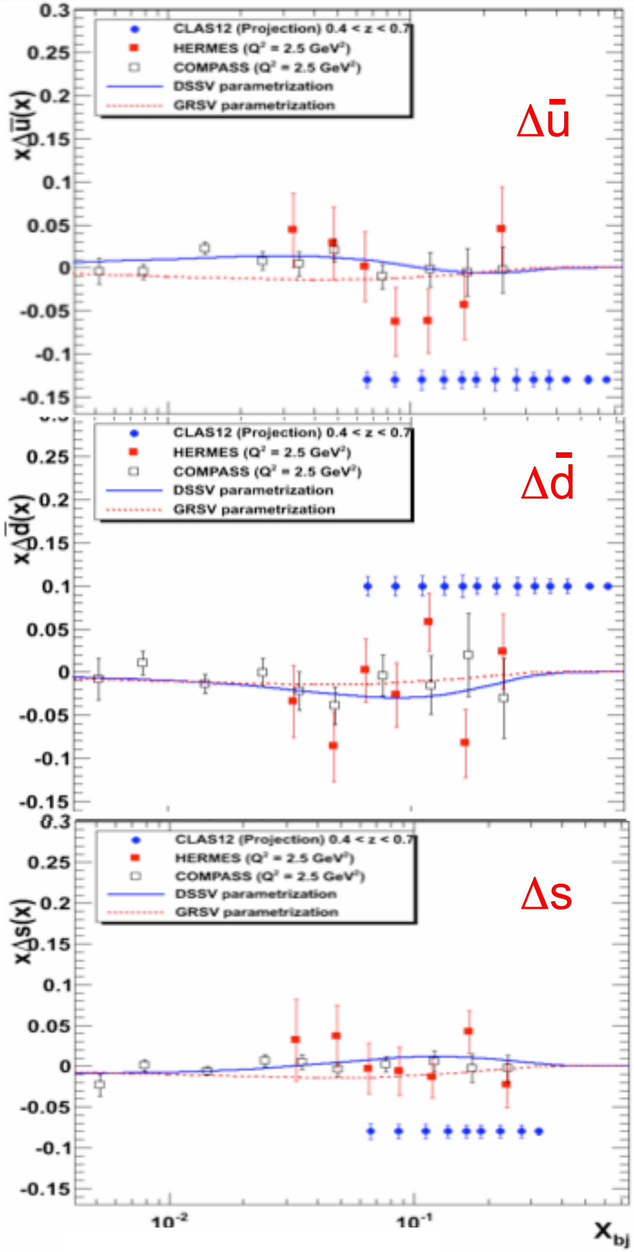
Quark Helicity

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

H. Avakian [arXiv: 0757.1553]







@CLAS12

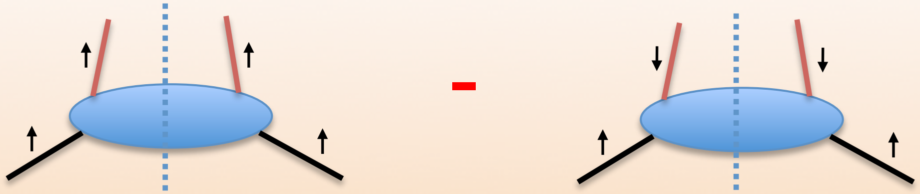
Transversity

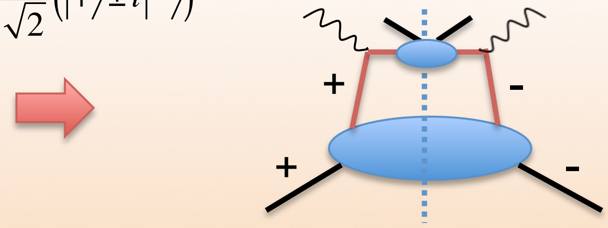
$\Phi^{[i\sigma^{i+}\gamma^5]}$

$h_1(x) = q^\uparrow(x) + q^\downarrow(x)$

Chirally-odd

$|\uparrow,\downarrow\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle \pm i|-\rangle\right)$





quark polarisation

nucleon polarisation

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1, h_{1T}^\perp$

Transversity:
different from helicity distribution as rotation and boost do not commute

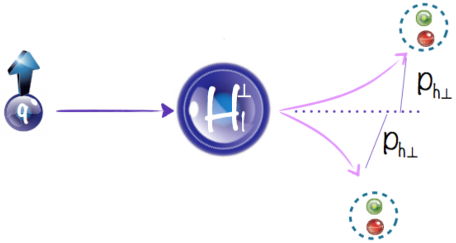
- sensitive to the relativistic effects
- related to the tensor charge
- non-singlet type evolution
- chirally-odd
  - it requires a chirally-odd fragmentation

hadron polarisation

quark polarisation

N/q	U	L	T
U	D_1		$H_1^\perp$

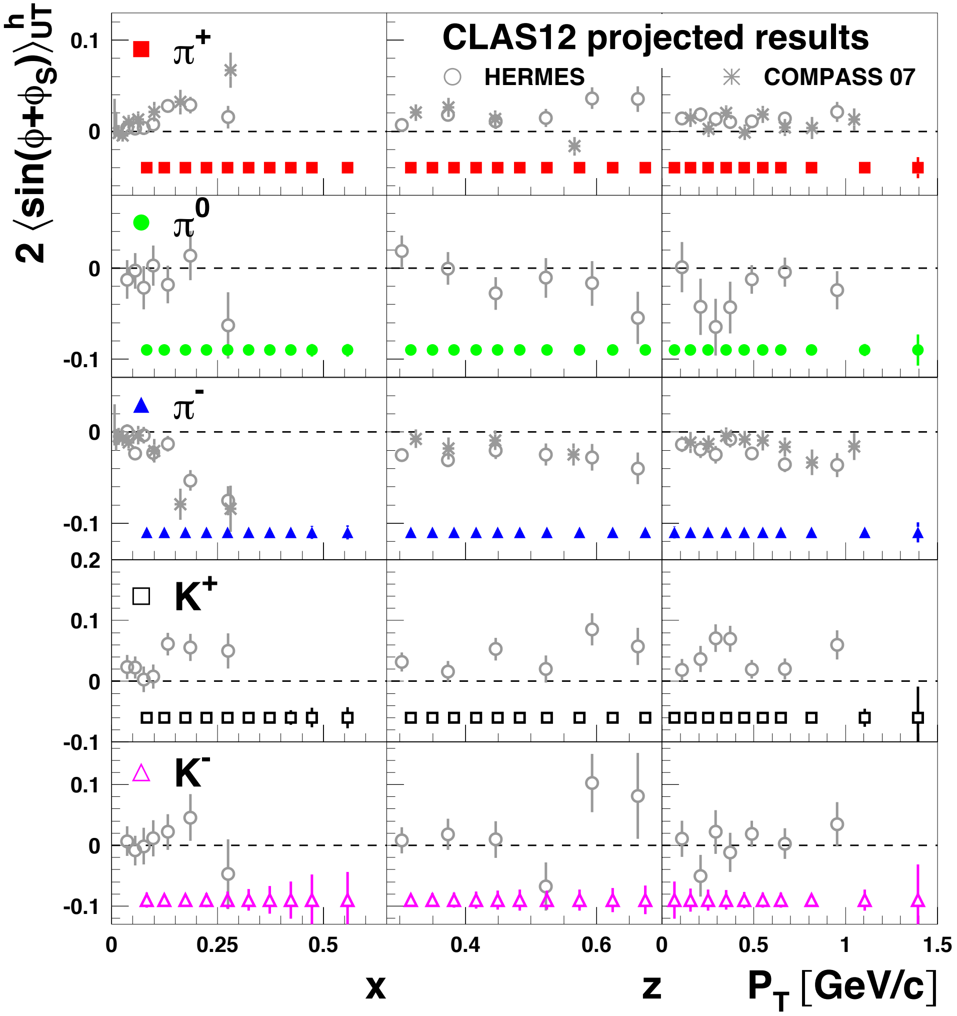
Collins function:
a spin-p_T correlator in fragmentation



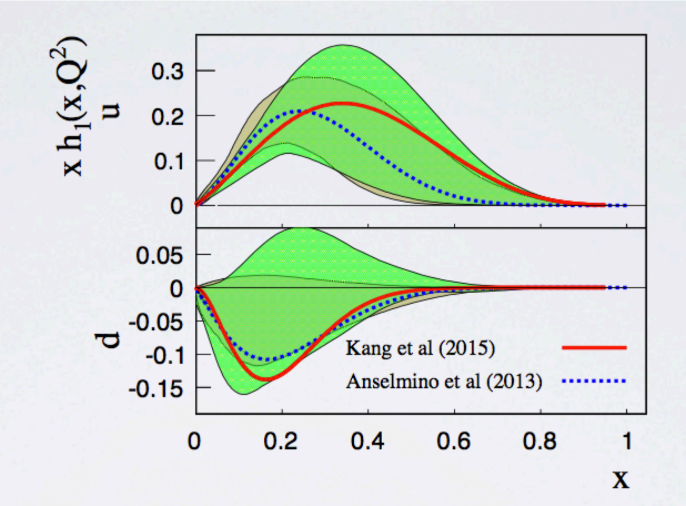
Transversity @ CLAS12

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

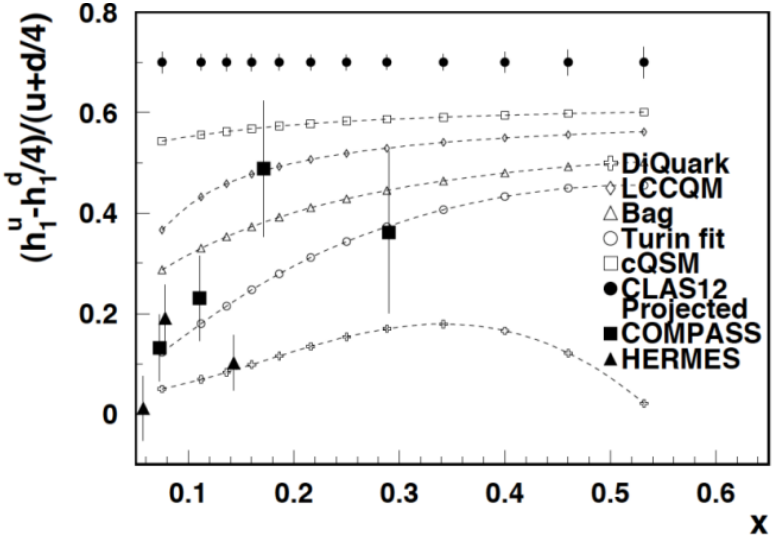
Single hadron channel: C12-11-111 Hall-B



Distributions:

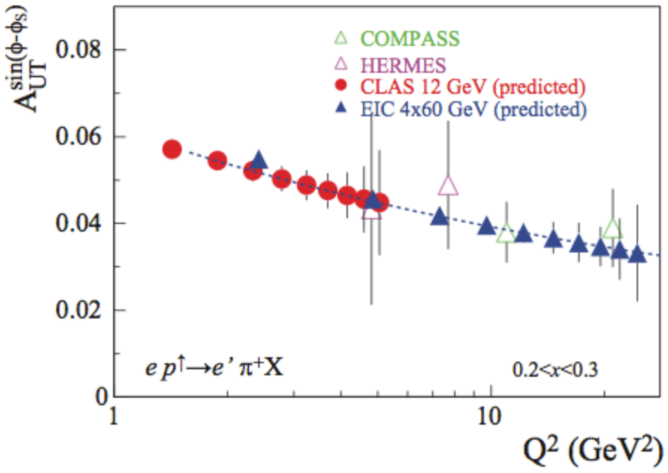


Di-hadron channel:

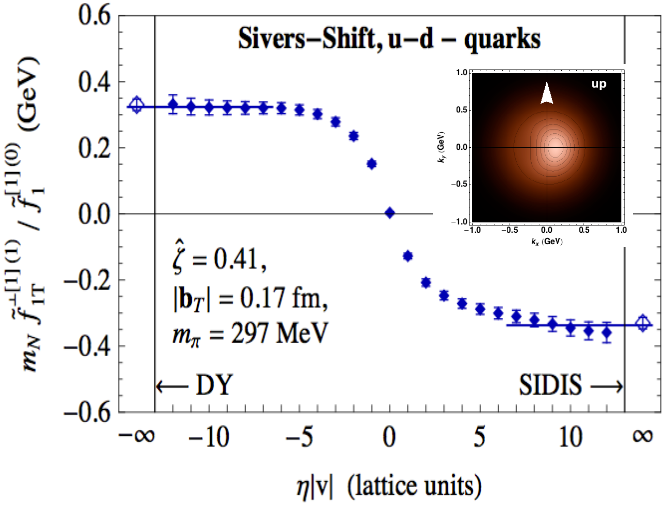


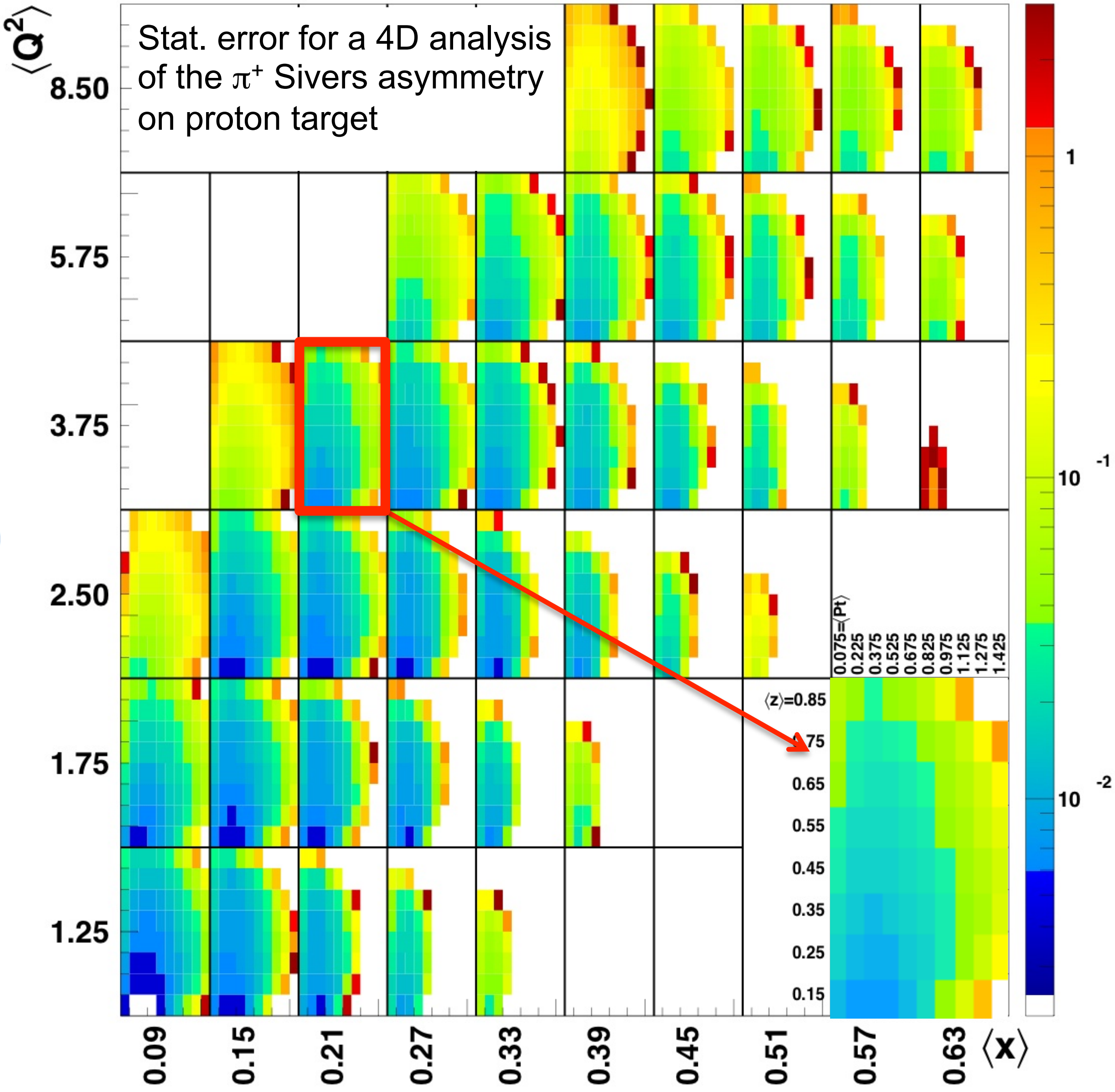
Sivers Mapping @ CLAS12

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



Lattice $\langle k_{\perp} \rangle$





Stat. error for a 4D analysis of the π^+ Sivers asymmetry on proton target

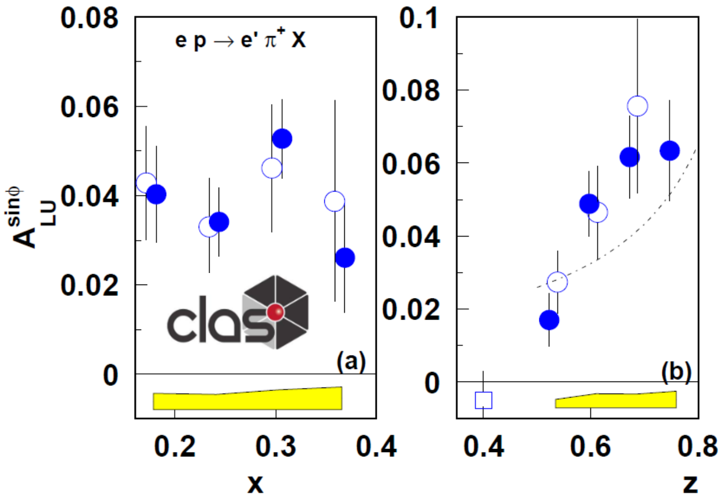
Higher-twists @ CLAS

A_{LU} is proportional to the structure function

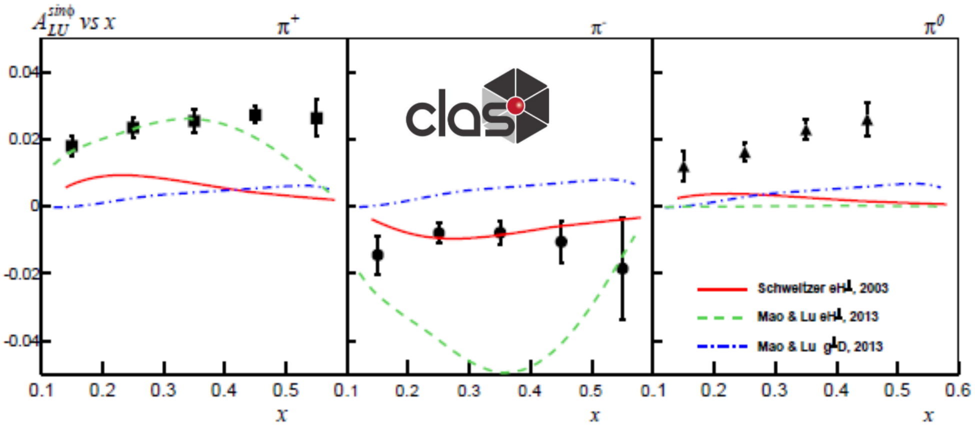
$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^\perp + \frac{M_h}{M}\,f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^\perp D_1 + \frac{M_h}{M}\,h_1^\perp\frac{\tilde{E}}{z}\right)\right]$$

e(x): twist-3 PDF sensitive to qGq correlations "transverse force"

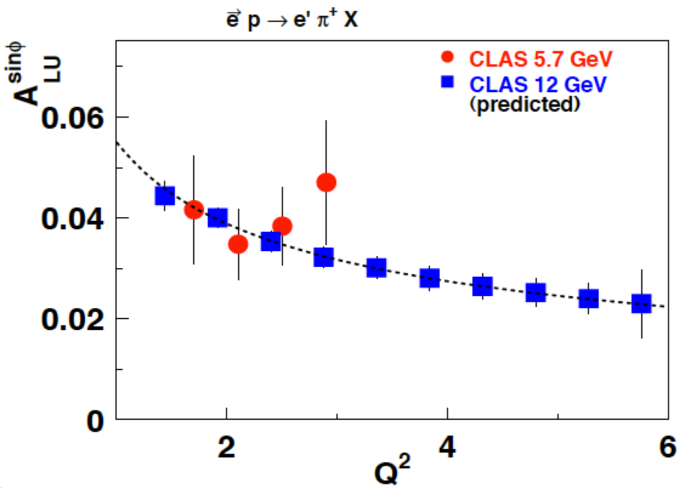
H. Avakian *et al.*, PRD69, 112004 (2004)@4.3 GeV



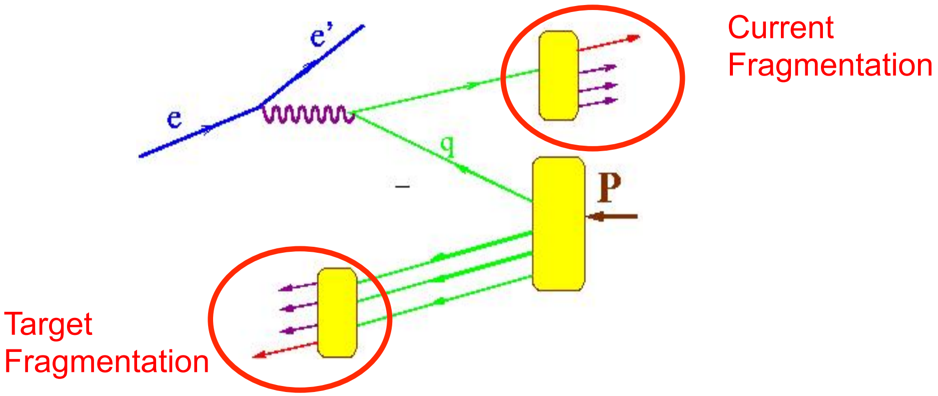
W. Gohn *et al.*, PRD89, 072011 (2014)@5.5 GeV



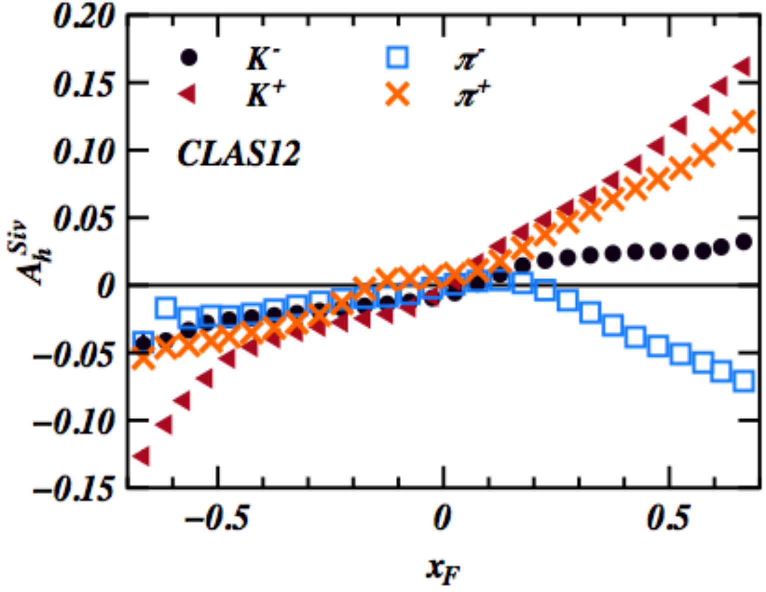
→ Entire structure function is twist-3, so in commonly used Wandzura-Wilczek approximation entire asymmetry = 0



The Target Fragmentation Region



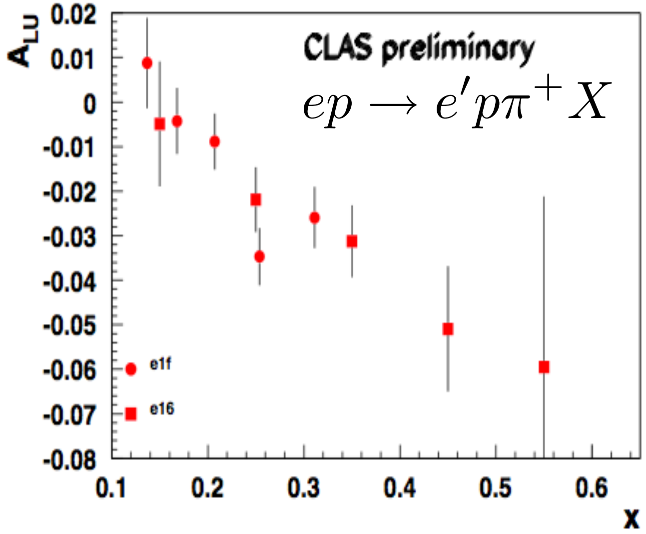
Matevosyan++ [arXiv:1502.02669]

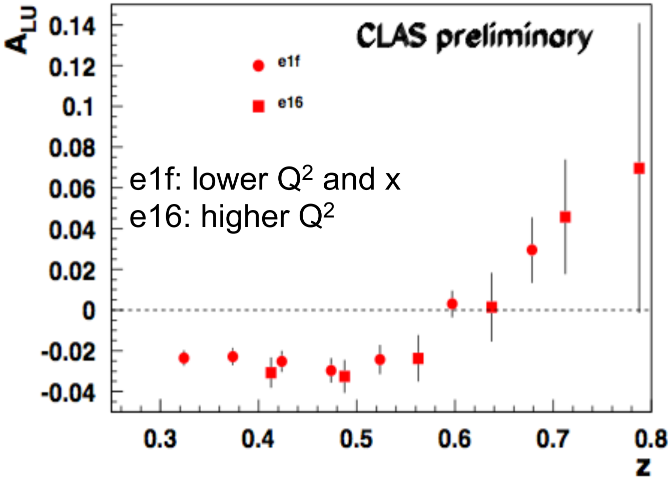


TMD kinematic dependences (Sivers), both in current and target fragmentation regions

M. Anselmino++ [arXiv:1112.2604]

$$\mathcal{F}_{LU}^{\sin(\phi_1-\phi_2)} = \frac{|\vec{P}_{1\perp}\vec{P}_{2\perp}|}{m_N m_2}\mathcal{C}[w_5 M_L^{\perp,h} D_1]$$





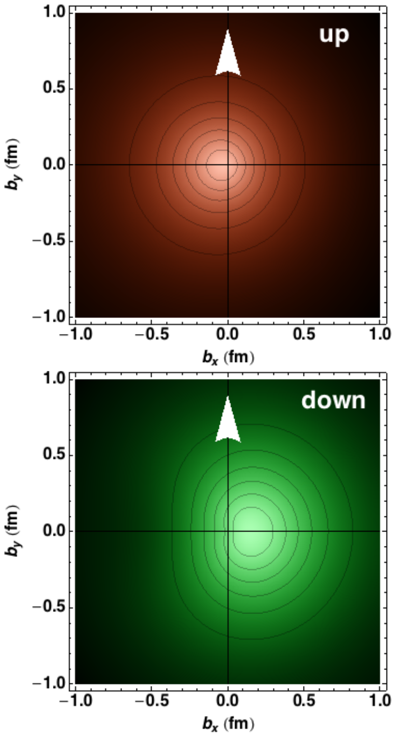
e1f: lower Q^2 and x
e16: higher Q^2

Parton 3D Dynamic

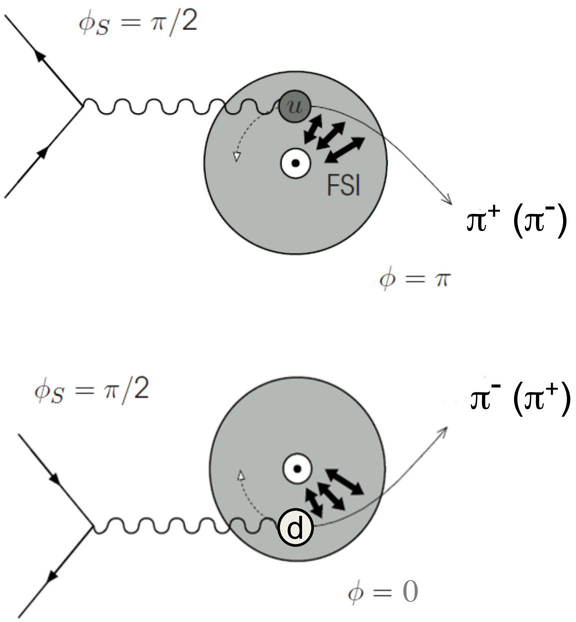
GPD E:

Imbalance in the probed parton spatial distribution

$$q_X(x,\mathbf{b}_\perp) = q(x,\mathbf{b}_\perp) - \frac{1}{2M}\frac{\partial}{\partial b_y}\mathcal{E}_q(x,\mathbf{b}_\perp)$$

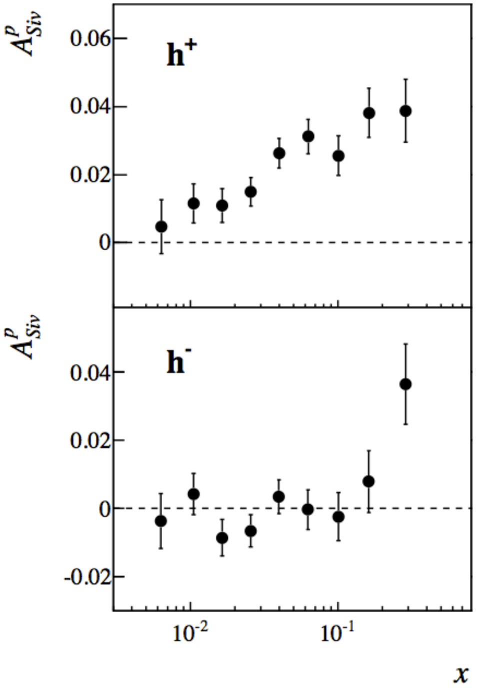


$$\int_{-1}^{1} dx \int d^2\mathbf{b}_\perp \mathcal{E}_q(x,\mathbf{b}_\perp) = F_{2,q}(0) = \kappa_q$$



Sivers TMDs:

Imbalance in the observed hadron momentum distribution

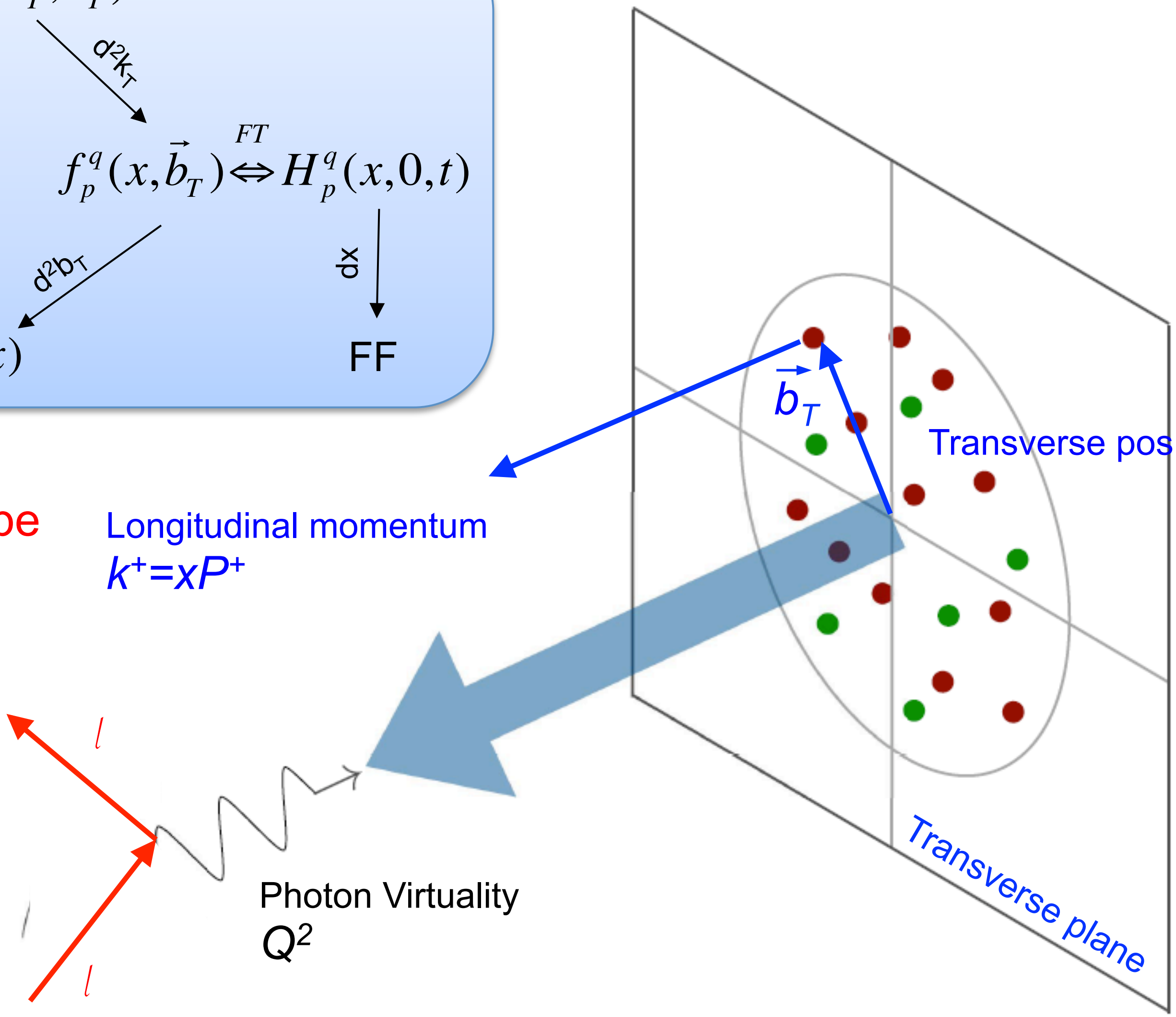


$$f_{1T}^{\perp q} \sim -\kappa^q$$

The 3D Nucleon Structure

$$\begin{tikzcd}
W_p^q(x,\vec{k}_T,\vec{b}_T) \arrow[dr, "d^2k_T"] & & \\
& f_p^q(x,\vec{b}_T) \arrow[r, Leftrightarrow, "FT"] \arrow[dl, "d^2b_T"'] & H_p^q(x,0,t) \arrow[d, "dx"] \\
f_p^q(x) & & \text{FF}
\end{tikzcd}$$

Confinement Scale



Transverse position

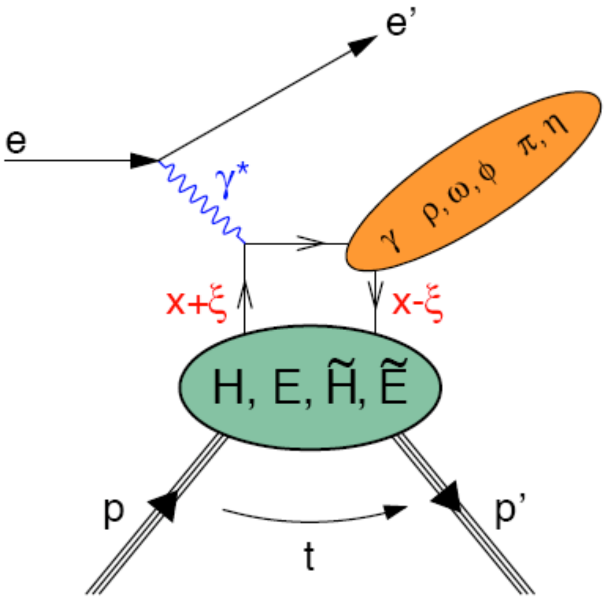
High Energy Probe
Hard Scale

Longitudinal momentum
$k^+=xP^+$

Photon Virtuality
Q^2

Generalized parton distributions

Exclusive reaction:



- For spin-1/2 target 4 chiral-even leading-twist quark GPDs: $H, E, \tilde{H}, \tilde{E}$
- $H, \tilde{H}$ conserve nucleon helicity, $E, \tilde{E}$ involve nucleon helicity flip
- Sensitivity of different final states to different GPDs
- DVCS (γ) → $H, E, \tilde{H}, \tilde{E}$
- Vector mesons (ρ, ω, ϕ) → H, E
- Pseudoscalar mesons (π, η) → $\tilde{H}, \tilde{E}$

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

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

Collinear PDFs as forward limit:

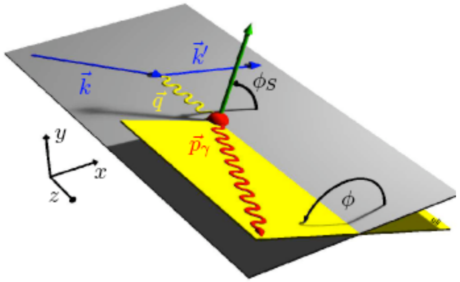
$$\int d^2 b_T H(x, b_T) = f_1(x)$$

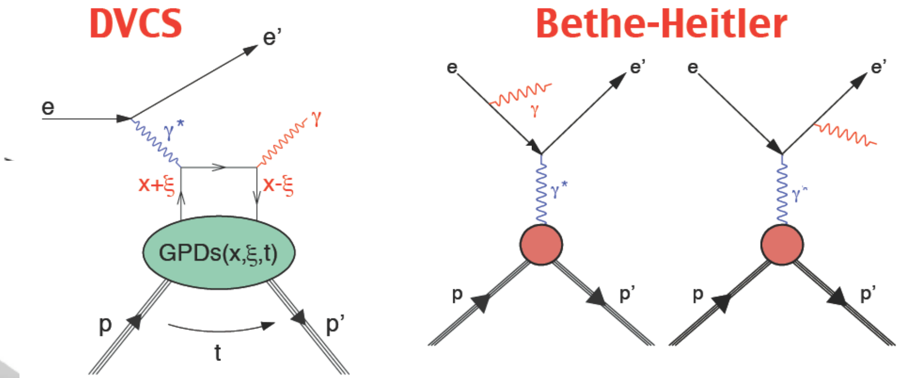
$$\int d^2 b_T \tilde{H}(x, b_T) = g_1(x)$$

DVCS Interference

Informations on the real and imaginary part of the QCD scattering amplitude

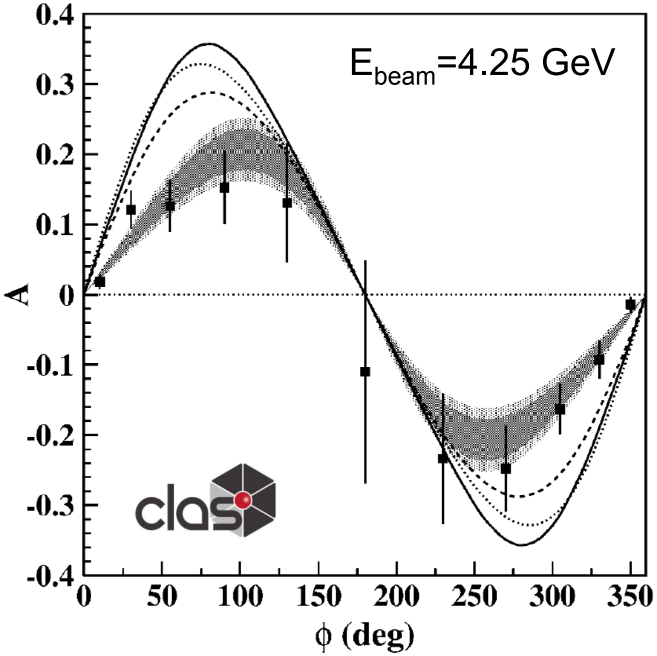
$$\frac{d^4\sigma}{dQ^2\,dx_B\,dt\,d\phi} \propto \left(|\mathcal{T}_{\mathrm{DVCS}}|^2 + |\mathcal{T}_{\mathrm{BH}}|^2 + \mathcal{I}\right)$$





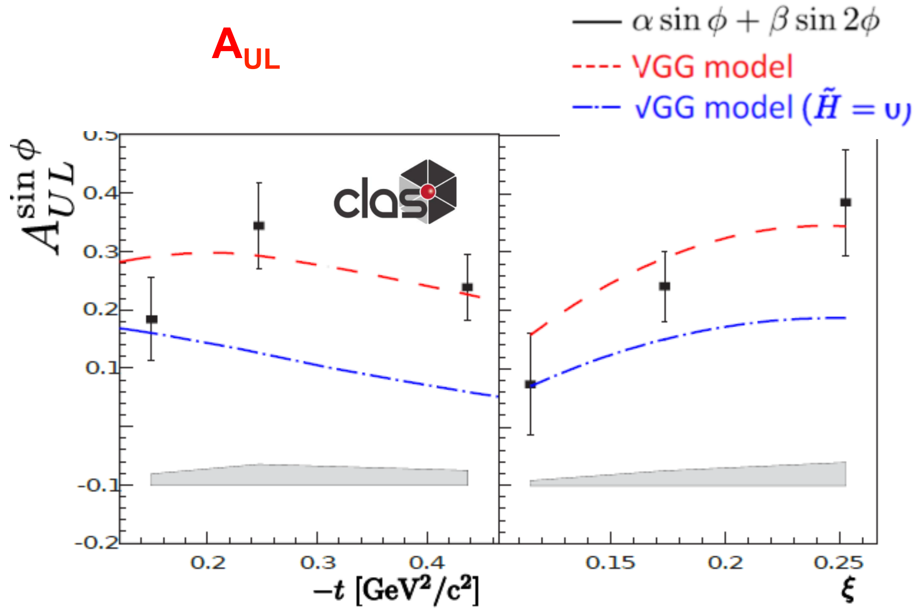
A_{LU}

S. Stepanyan et al., Phys. Rev. Lett. 87, 182002 (2001).



S. Chen et al., Phys. Rev. Lett. 97, 072002 (2006).

A_{UL}

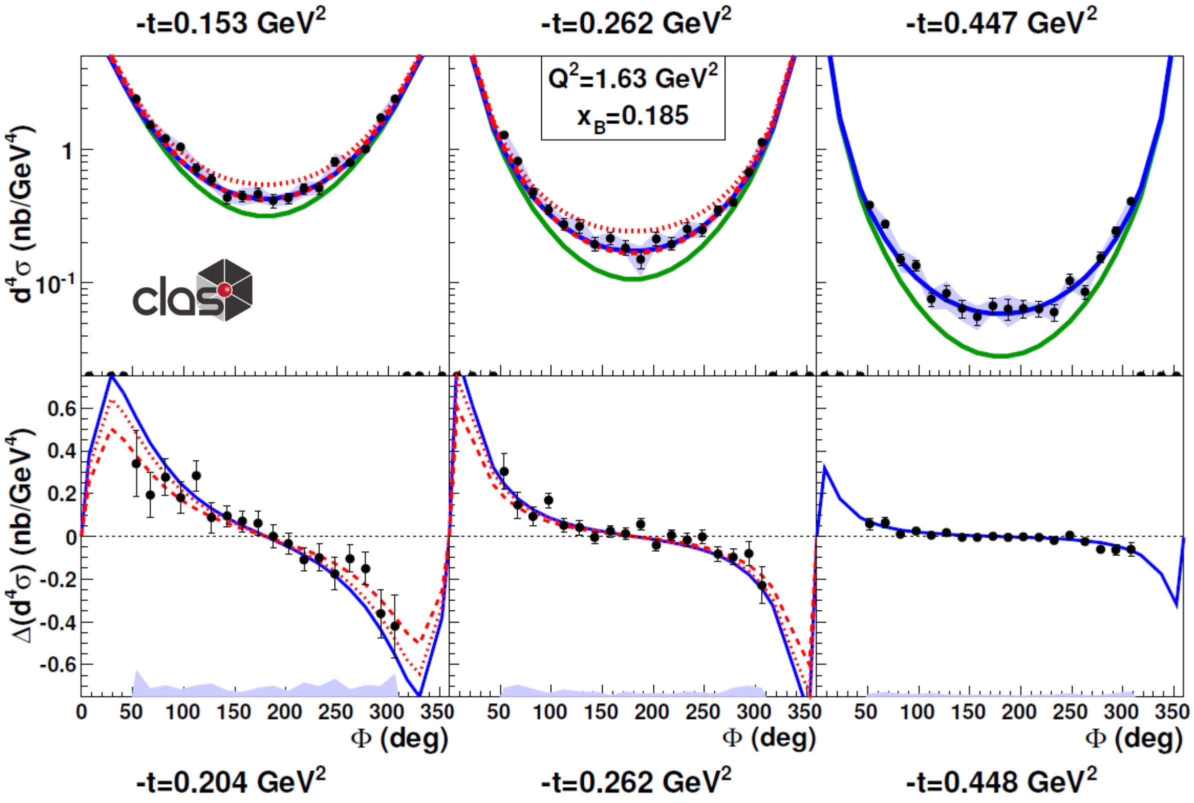


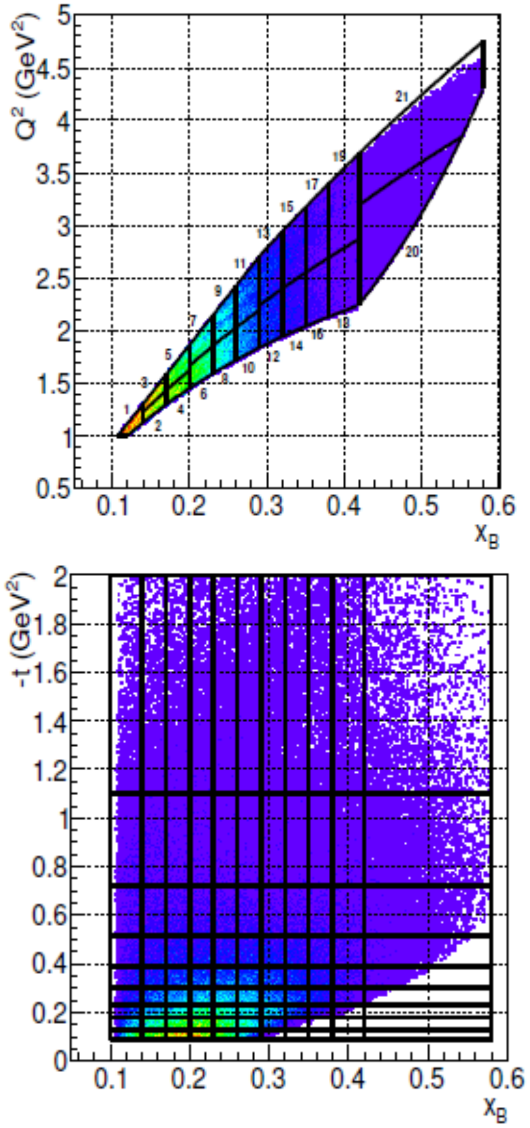
DVCS X-sec on Proton @ CLAS

DVCS xsec on LH$_2$ in a large kinematics domain (110 bins)

$$\frac{d^4\sigma^{ep\to e'p\gamma}}{dx\,dQ^2dt\,d\varphi}$$

🟩 BH only
🟦 VGG (H only)
┈ KM10 (Kumericki, Mueller)
╍ KM10a





H. S. Jo et. al. [arXiv: 1504.02009]

Quark Orbital Momentum @ CLAS12

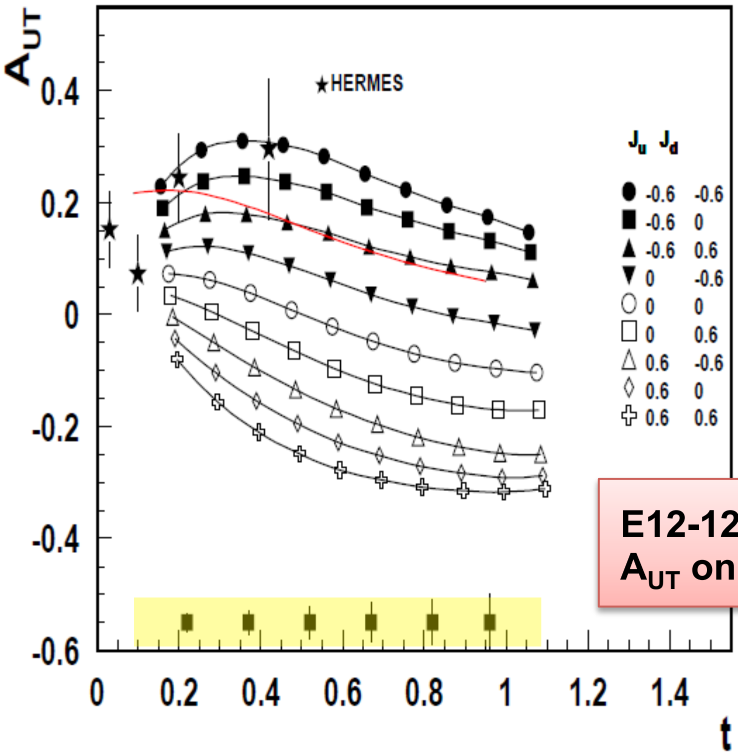
To access E_u & E_d both E_p & E_n are needed

$$J_q = \frac{1}{2}\int_{-1}^{+1} dx\, x\, [H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$

$$(H,E)_u(\xi,\xi,t) = 9/15[\,4(H,E)_p-(H,E)_n\,]$$

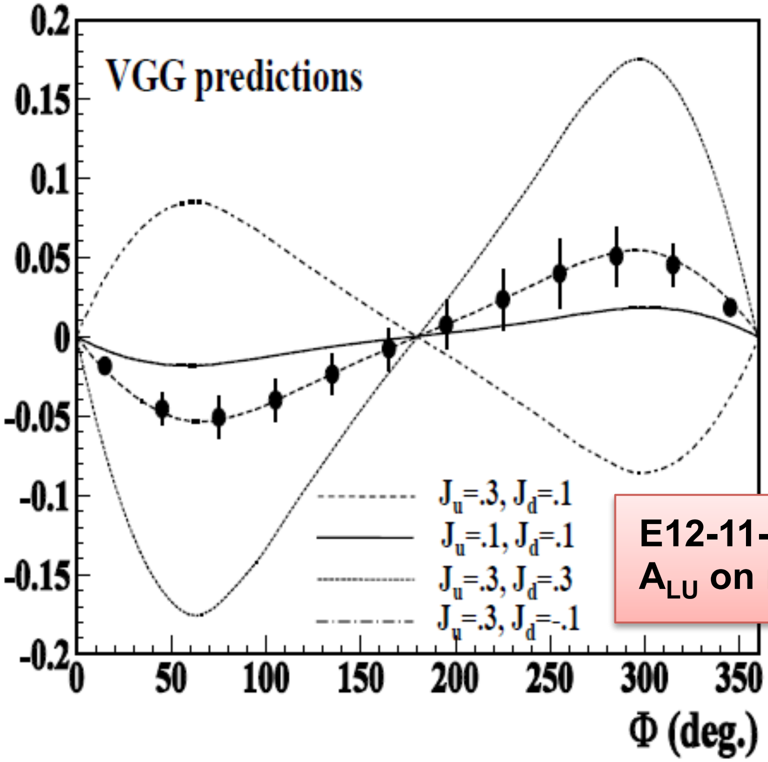
$$(H,E)_d(\xi,\xi,t) = 9/15[\,4(H,E)_n-(H,E)_p\,]$$

Proton GPD



E12-12-010
A_{UT} on proton

Neutron GPD



E12-11-003
A_{LU} on neutron

Conclusions

CLAS @ HallB: a wide-acceptance high-luminosity high-polarization experiment for a comprehensive study of the partonic transverse degree of freedoms in the nucleon

Precise mapping of TMDs (pdf & FF) and GPDs in a multi-D approach

- Constrain models in the valence region
- Test factorization
- Study higher twist effects
- Investigate non-perturbative to perturbative transition (along P_T)
- Flavor separation via proton and deuteron targets and hadron ID
- Test of Lattice QCD calculations: tensor charge
- Access to OAM