REVIEW OF TMD MEASUREMENTs

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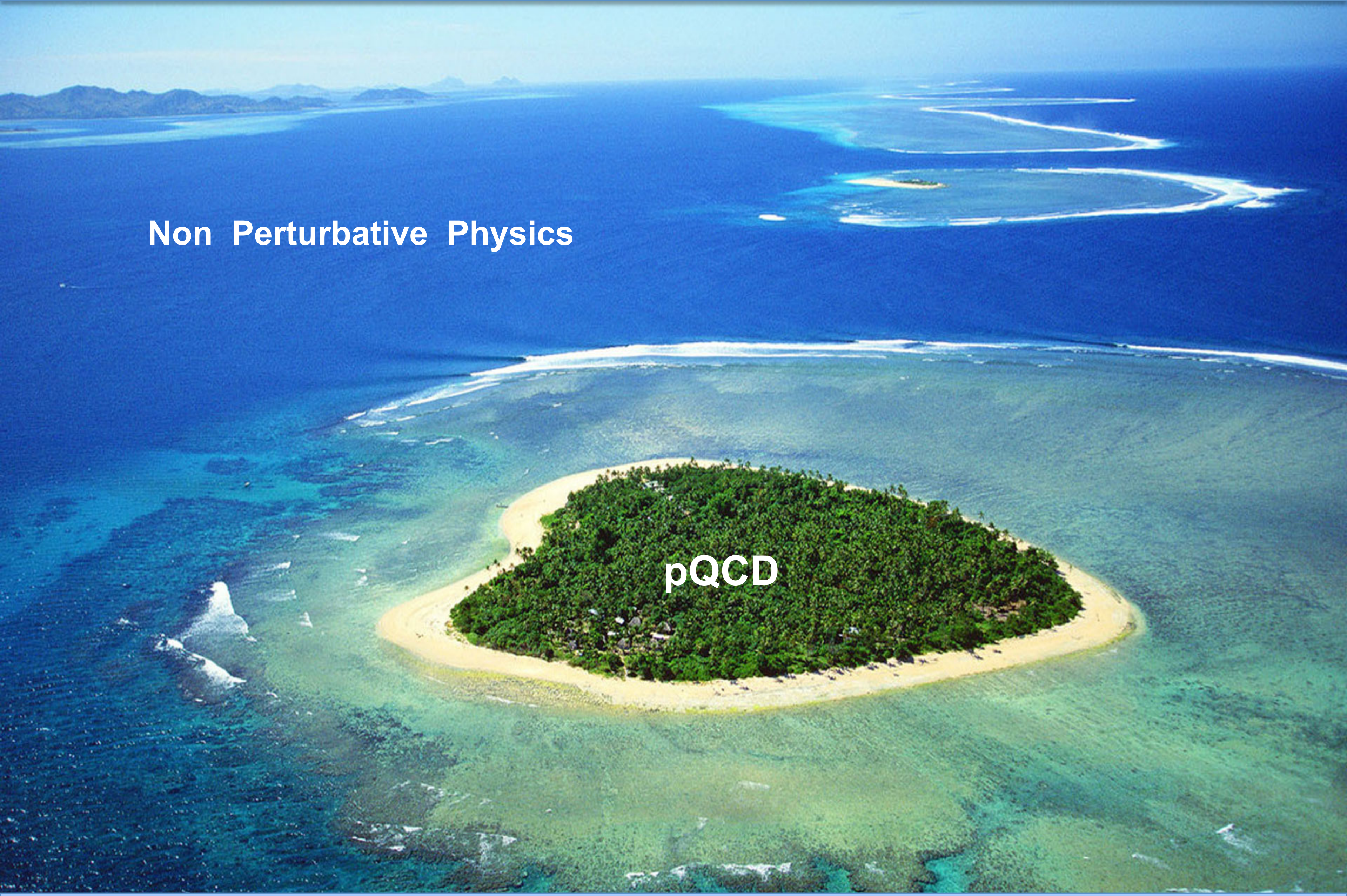
MENU2016
July 30, 2016 Kyoto University

The QCD View



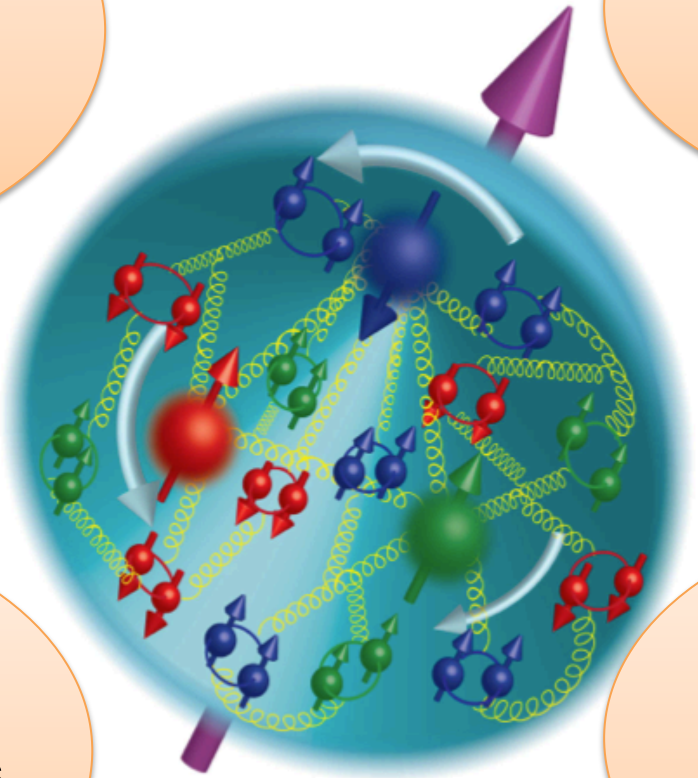
Non Perturbative Physics

pQCD

The Strong-Force Confined-Universe

Dynamic Spin
- Parton polarization
- Orbital motion
- Form Factors
- Magnetic Moment

Parton Correlations
- dPDFs
- Short range
- MPI



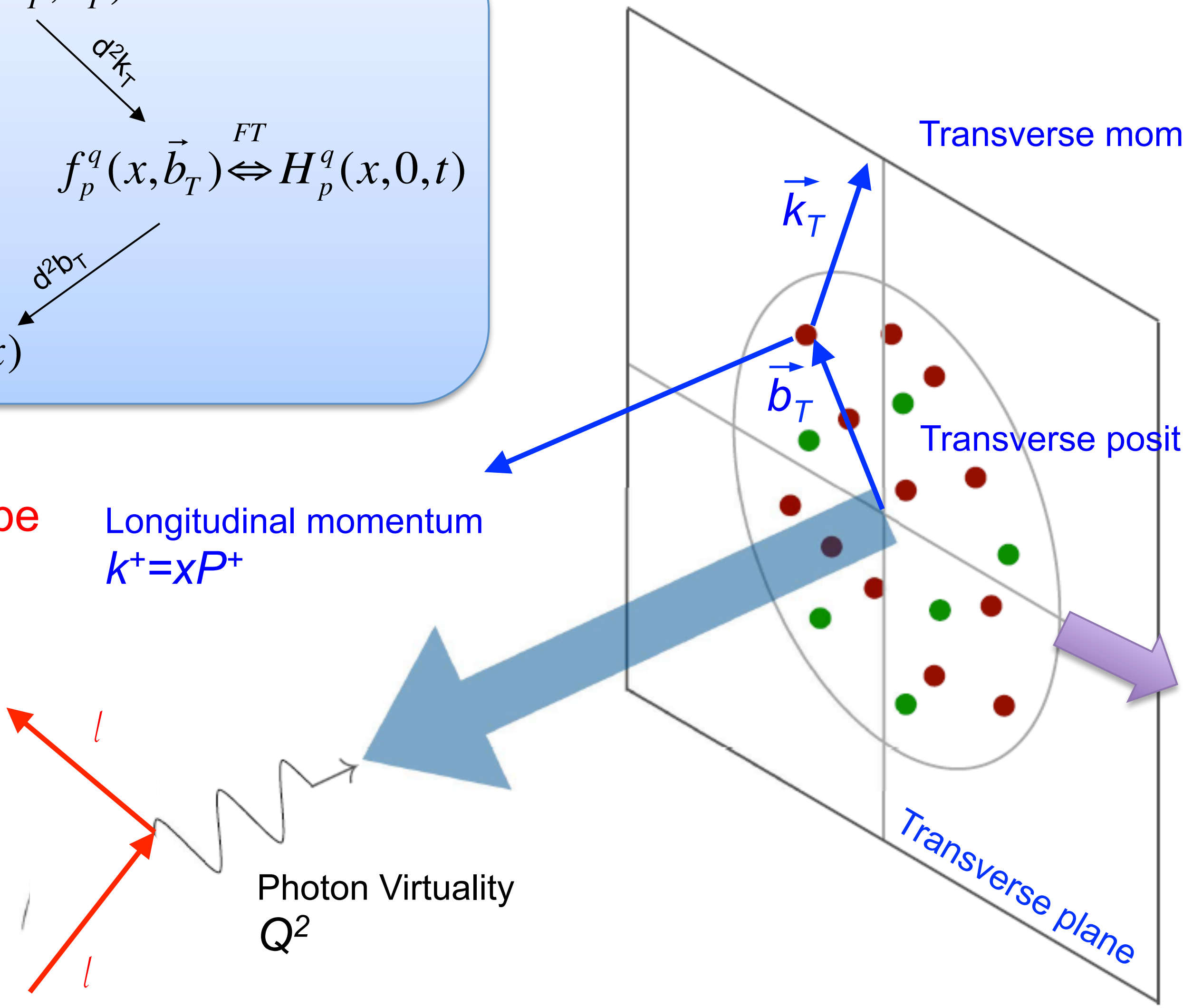
Hadronization
- Spin-orbit effects
- Parton energy loss
- Jet quenching

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

The 3D Nucleon Structure

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

Confinement Scale



Transverse momentum

$\vec{k}_T$

$\vec{b}_T$

Transverse position

High Energy Probe
Hard Scale

Longitudinal momentum
$k^+=xP^+$

Spin

l

l'

Photon Virtuality
Q^2

Transverse plane

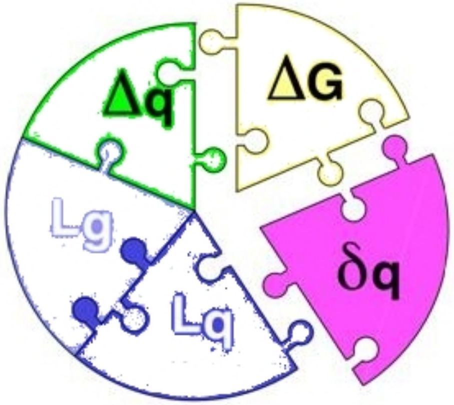
The Spin Degree of Freedom

In our exploration of the QCD micro-world

Fundamental: do not neglect spin !!

Two questions in Hadronic Physics
await explanation since too long

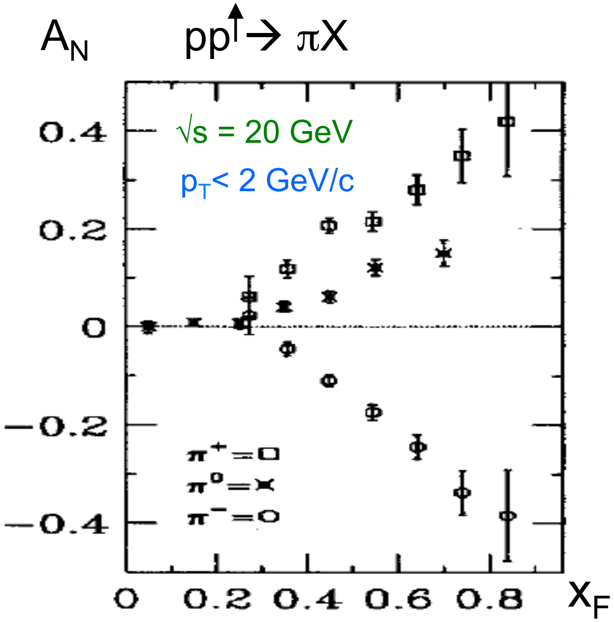
Proton Spin Budget



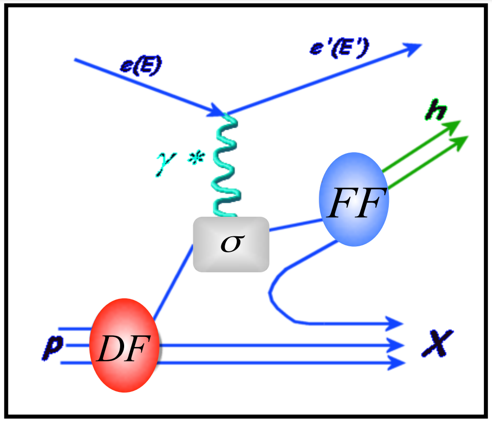
$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$

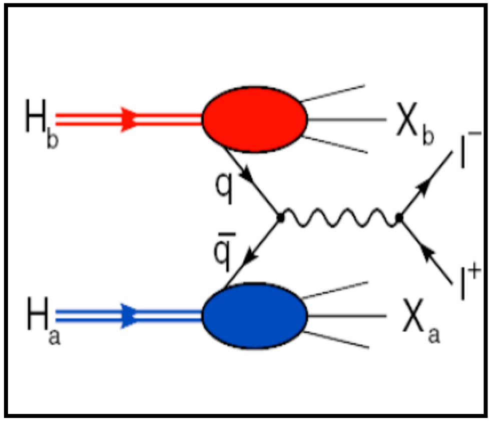
?

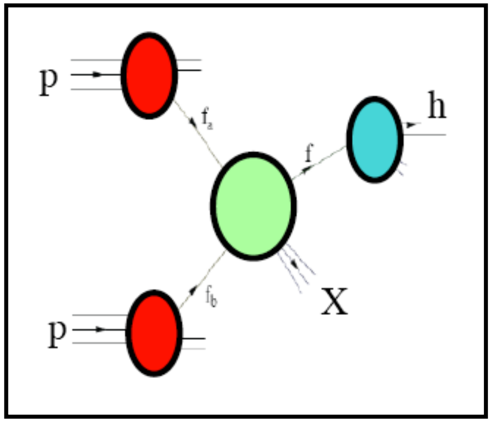
Single Spin Asymmetries



Physics reactions







SIDIS: rich phenomenology, the most explored so far

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

hermes

COMPASS

Jefferson Lab

e$^+$e$^-$ colliders: powerful fragmentation laboratories

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

BELLE

BESIII

DY: challenging for experiments (only unpolarized so far)

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

CERN

Fermilab

BROOKHAVEN NATIONAL LABORATORY

Hadron reactions: challenging for theory (ISI + FSI)

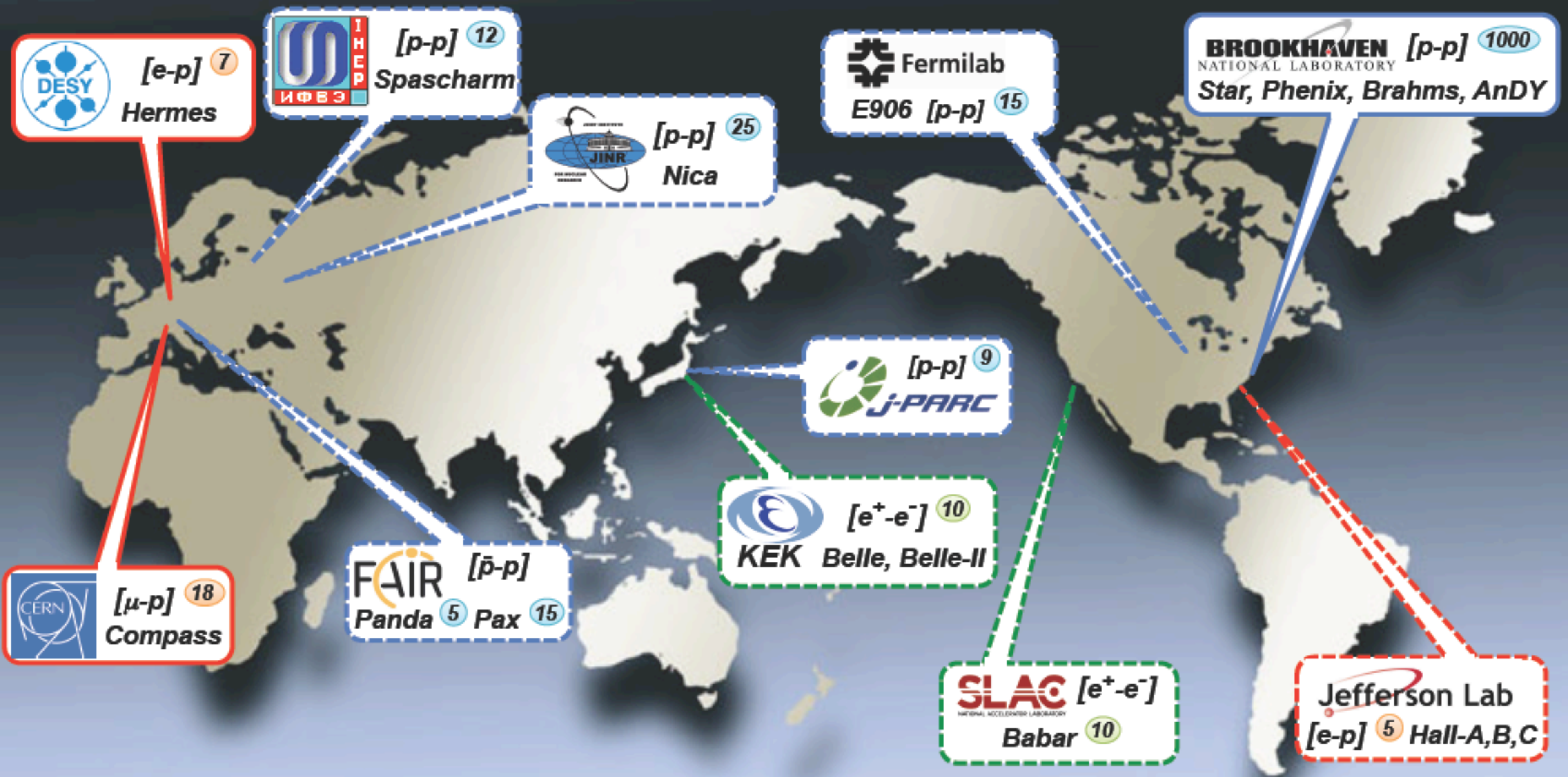
pp $$\sigma^{pp\to hX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to qq} \otimes FF$$

J-PARC

FAIR

NICA

A World-wide Challenge



Babar (e+e-): < 2007

BELLE (e+e-): < 2010

BELLEII (e+e-): 2017++

SeaQuest (pp): 2012 - 2016

RHIC (pp): 2011, 2017++

COMPASS (πp): 2016 – 2017

JPARC(pp): 2018++

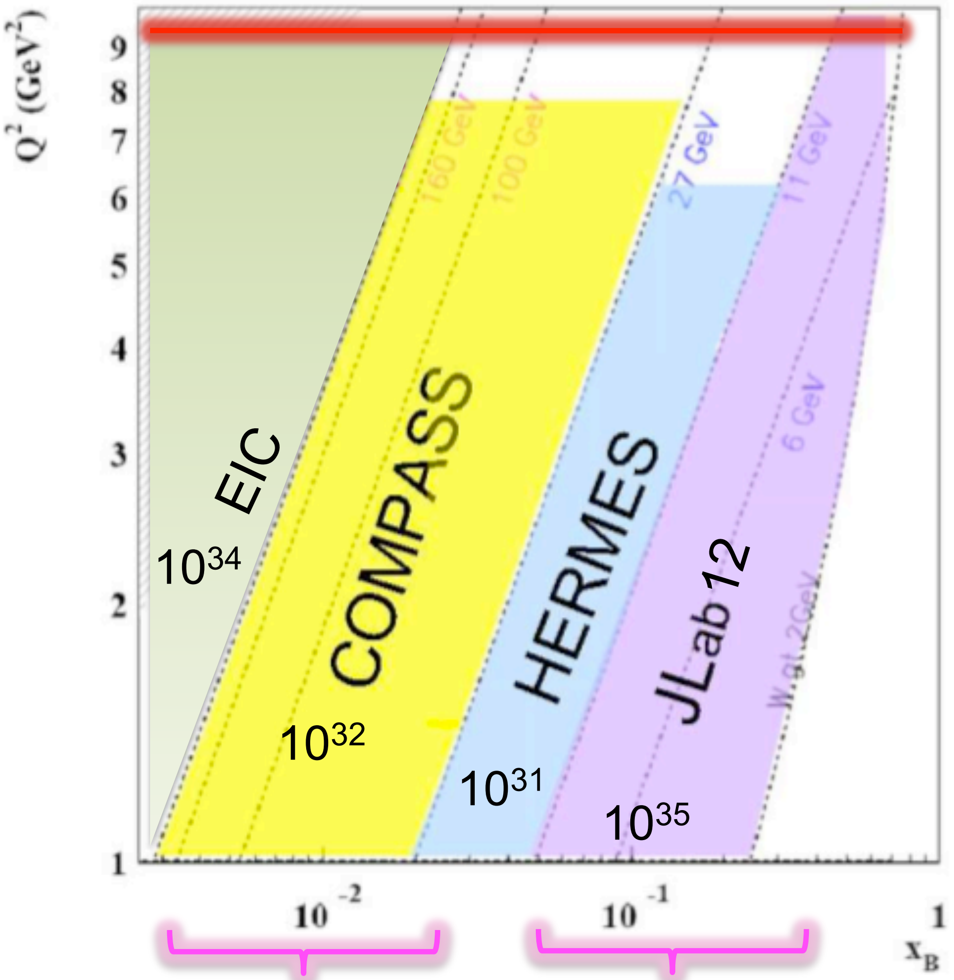
FAIR ($\bar{p}$p): 2018++

NICA (pp): 2018++

AFTER (pp): 2020++

The SIDIS Landscape

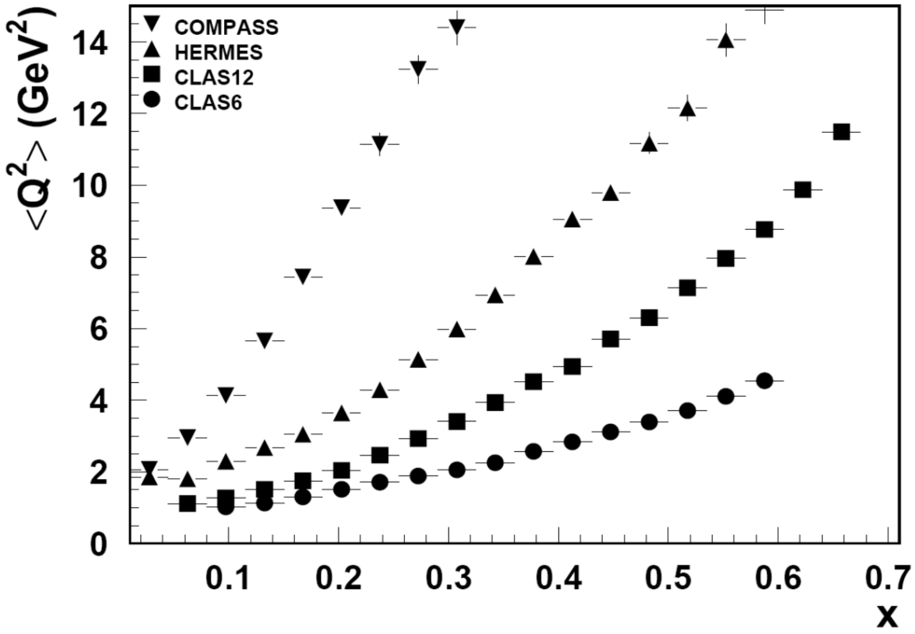
Limit defined by luminosity



Sea

Valence

Different Q^2 for same x range



HERMES: < 2007

COMPASS: < 2017 (2021++)

JLab6 < 2012

JLab12: 2017++

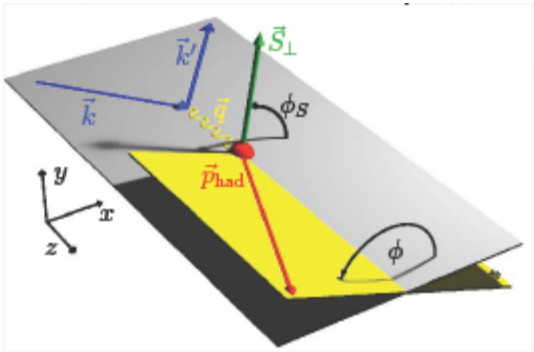
EIC: 2025++ R. Yoshida talk

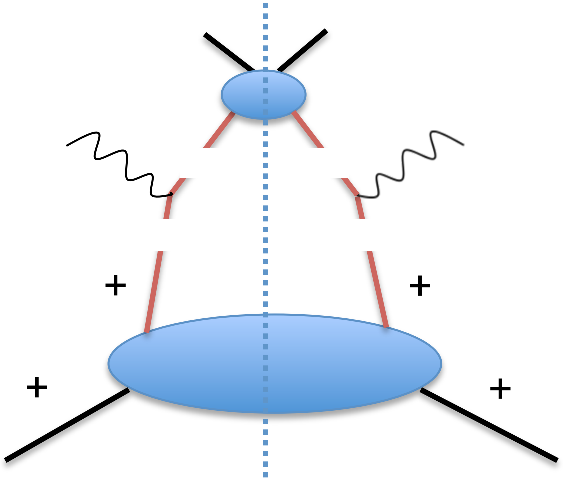
SIDIS Cross-Section & TMDs

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

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

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





Quark fragmentation

TMD Factorization holds for p_T<<Q

Quark parton distribution

Wide kinematic coverage is needed to resolve the convolution

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

Quark Correlators

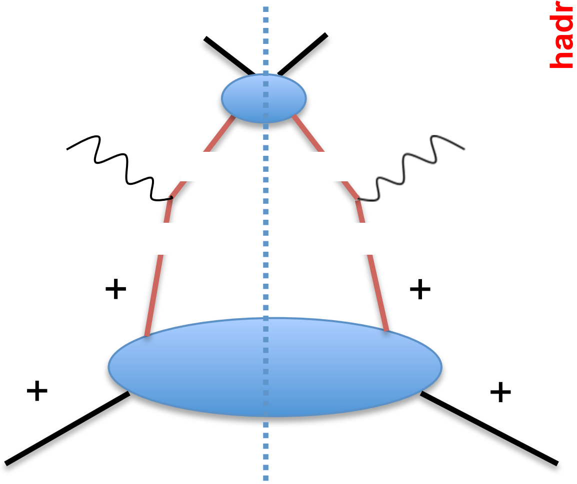
From optical theorem:
related to the imaginary part of the forward scattering

quark polarisation

hadron polarisation

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

TMD Factorization
holds for p_T<<Q



Quark fragmentation

Hard scattering

Quark-quark correlator

$$\Phi_{ij}(P,S;p) = \frac{1}{(2\pi)^4}\int d^4x\; e^{i\,p\cdot x}\langle P,S|\overline{\psi}_j(0)\mathcal{L}(0,x;\text{path})\psi_i(x)|P,S\rangle$$

Projection into
8 Lorentz structures

$$\Phi^{[\Gamma]}(x,\boldsymbol{p}_T) = \frac{1}{2}\int dp^-\; Tr(\Phi\,\Gamma)\Big|_{p^+=xP^+,\ \boldsymbol{p}_T}$$

quark polarisation

nucleon polarisation

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

First evidences

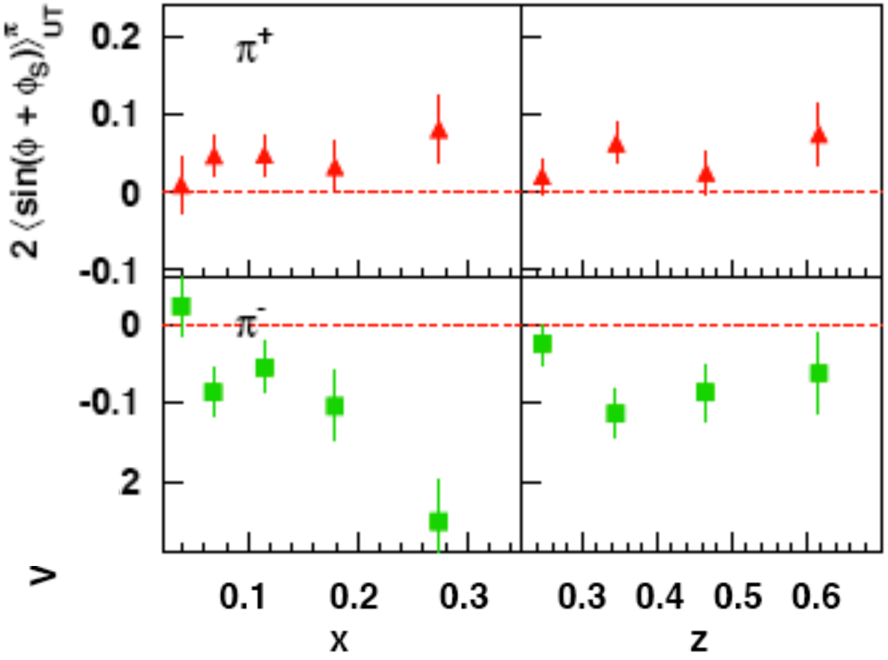
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^{\perp}$$

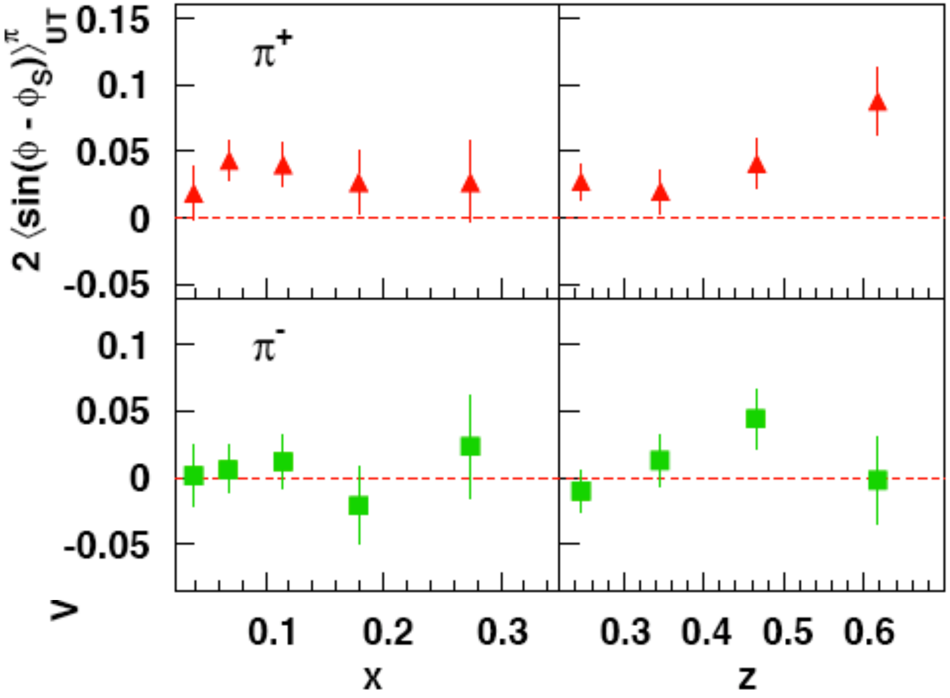
SIDIS:
ep → e'hX

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

2005: First evidence from HERMES measuring SIDIS on proton

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



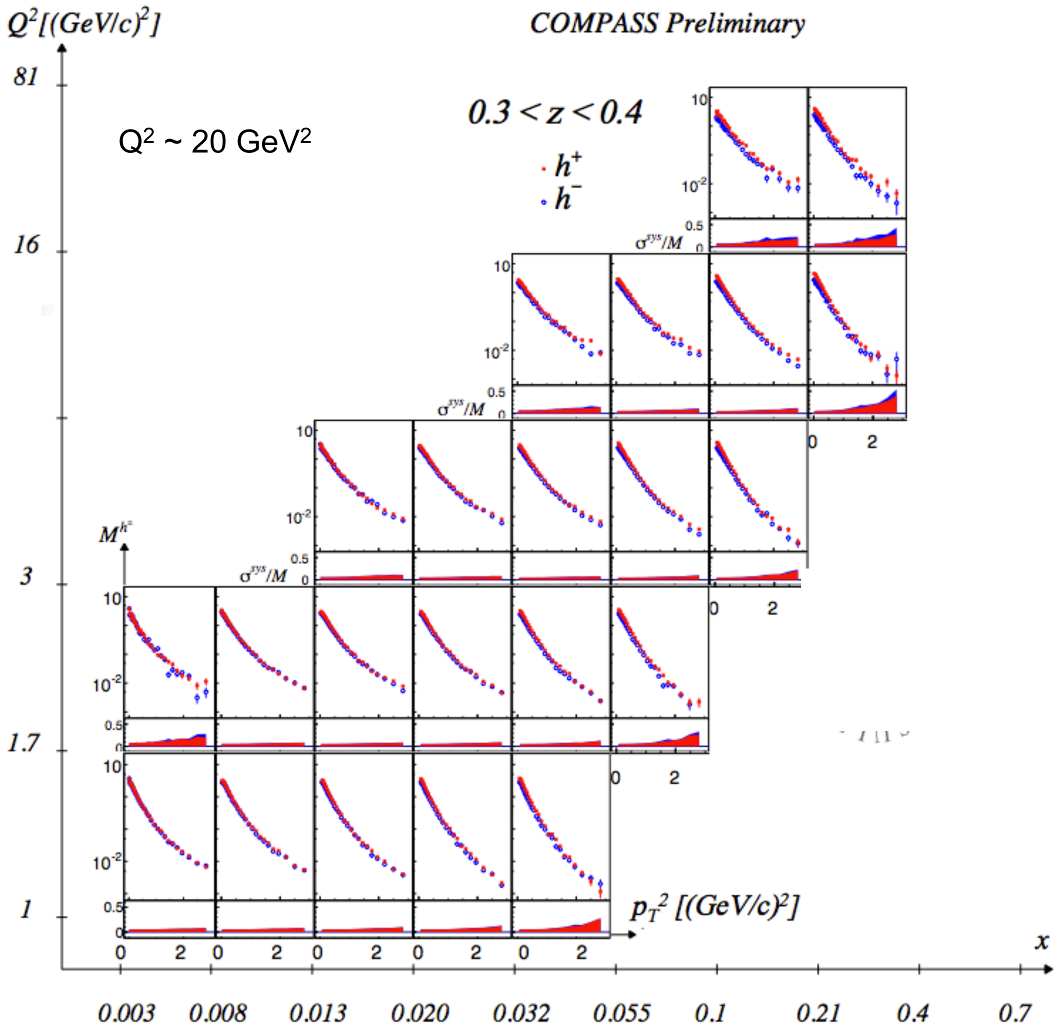


Non-zero transversity !!
Non-zero Collins function !!

Non-zero Sivers function !!

The Multi-D Approach

Umpolarized Multiplicities



Disentangle all the kinematic dependences

Asymmetries so far used to suppress systematics effects

$$A_{LL} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$A_{LL} = \frac{1}{fP_T P_B} \frac{N^+ - N^-}{N^+ + N^-}$$

They suppress also physics (i.e. evolution)

MultiD extraction of asymmertries requires multiD knowledge of nuclear effects from real fixed targets (^{6}LiD, NH_3, ^{3}He).

Outlook: work directly with cross-section differences or move to a collider (EIC)

Parton Number Density

Transverse Momentum Dependent Distr.

quark polarisation

nucleon polarisation

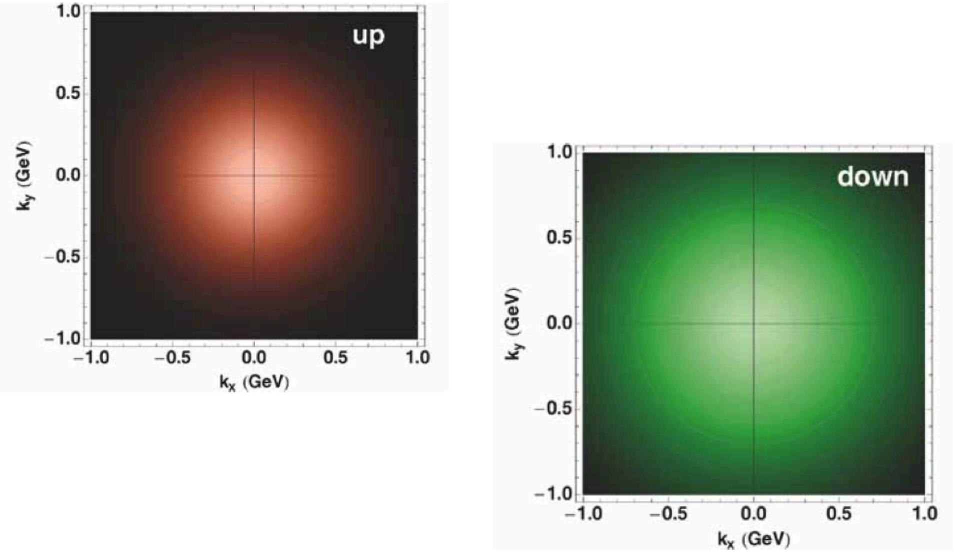
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h, h_{1T}^\perp$

$\otimes$

quark polarisation

hadron polarisation

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



Related to:

✓ Low-pT regime:
precise xsec measurements

✓ Parton correlations:
short range, MPI

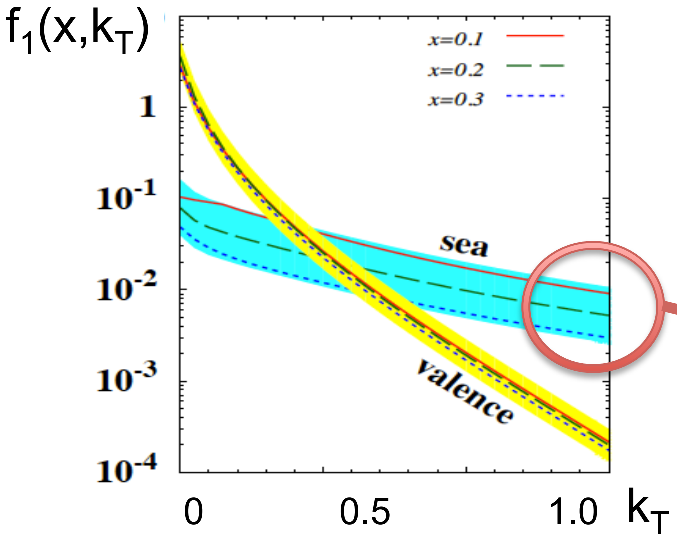
✓ Low-x physics:
color glass condensate

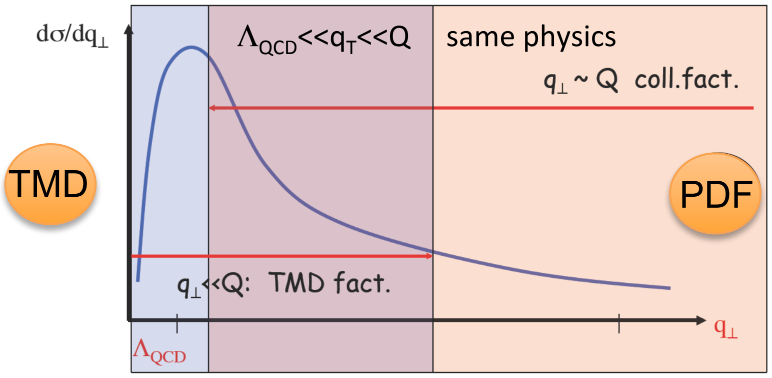
✓ Hadronization:
parton dynamic in medium

Unpolarized TMDs

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

P. Schweitzer++ [arXiv:1210.1267]

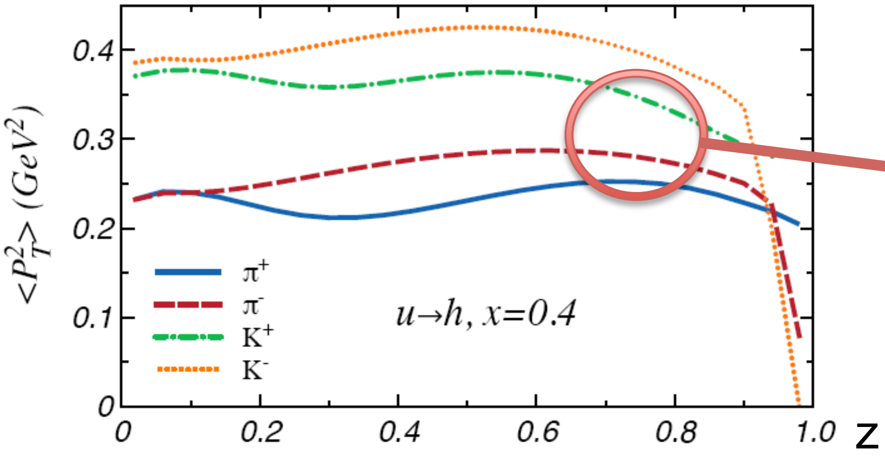




Large tiles extending up to the inverse of the gauge field fluctuation scale ρ<<M

May short range parton correlations 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

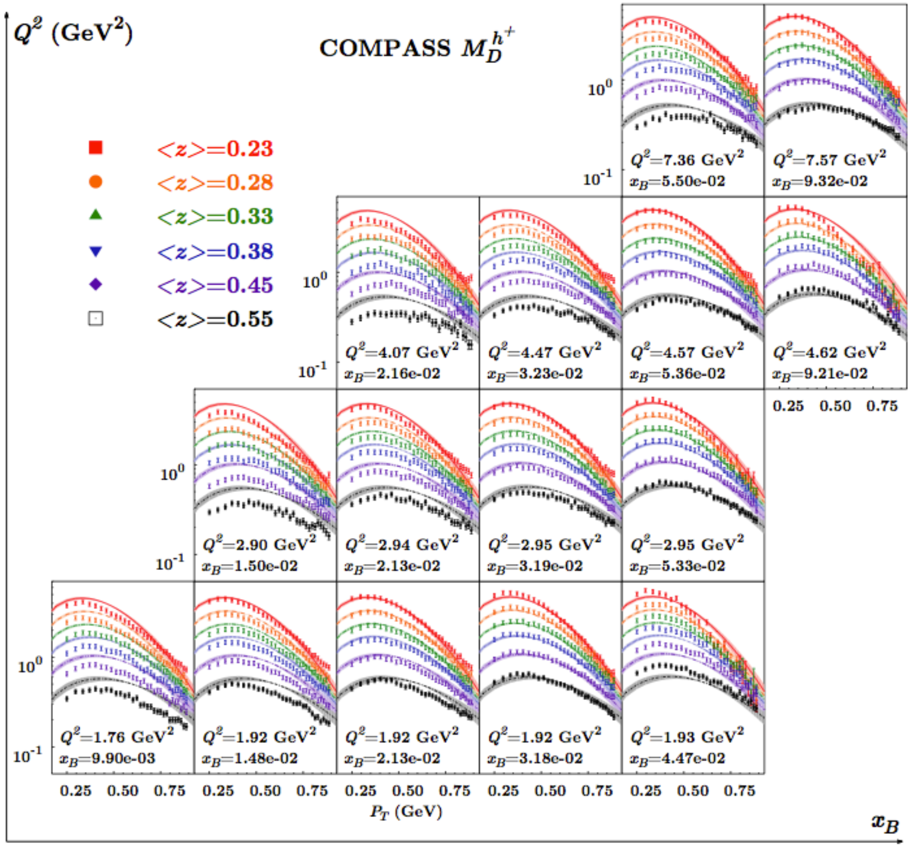
$$\sigma_{UU} \propto f_1\,(k_T\ldots) \otimes D_1\,(p_T\ldots)$$

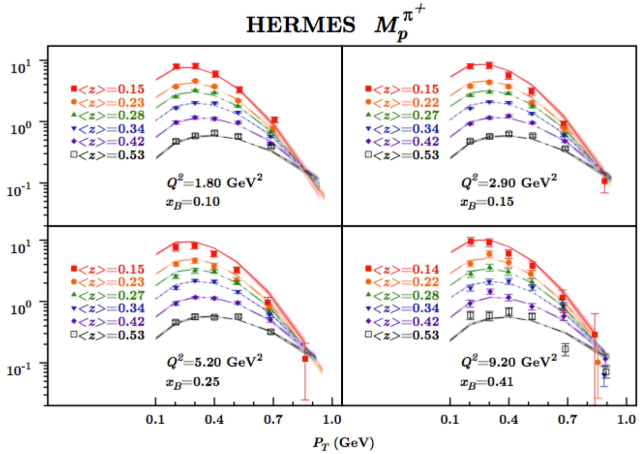
Disentanglement of z and $P_{h\perp}$: access to the transverse intrinsic quark k_T and fragmentation $p_{T,}$

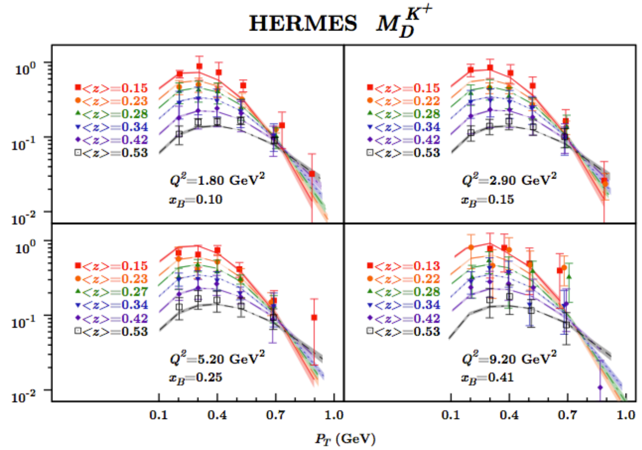
i.e. from gaussian anstaz:

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

M. Anselmino++ [arXiv:1312.6261]

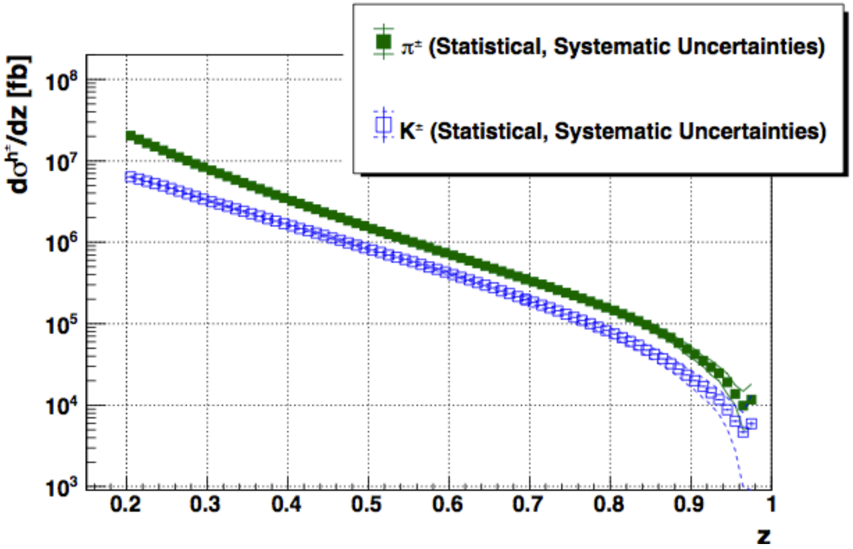




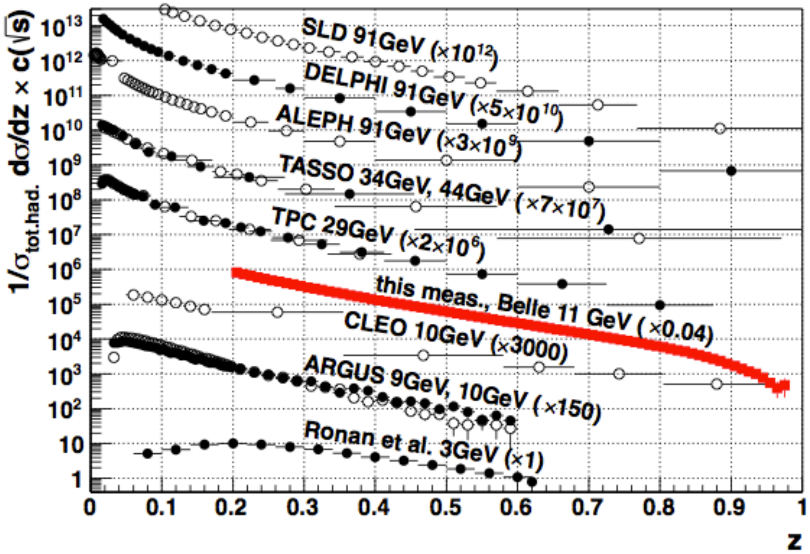


Fragmentation Functions @ B-factories

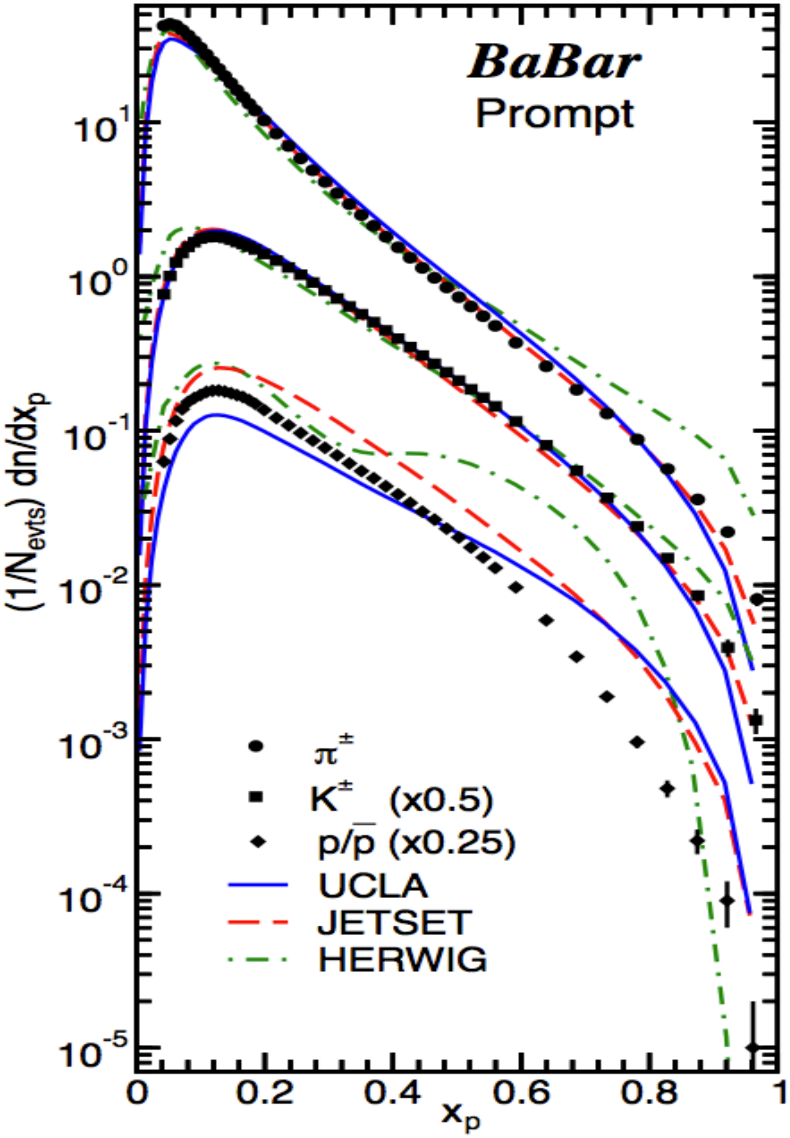
Belle [arXiv 1301.6183]



World Data (Sel.) for $e^+e^- \to \pi^\pm+X$ Production

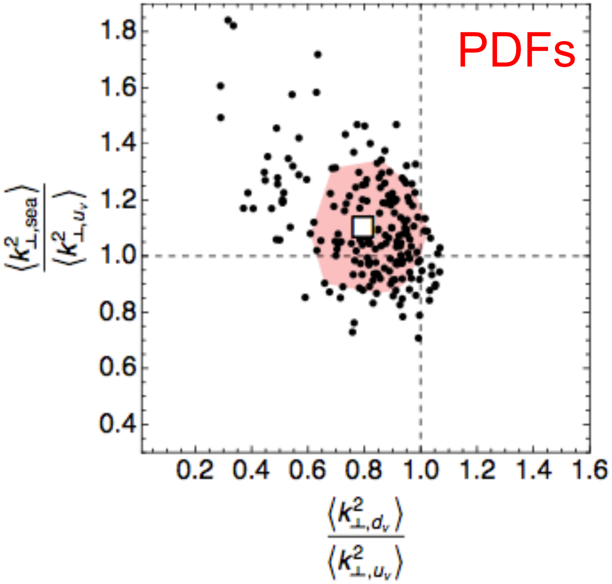


Babar [arXiv 1306.2895]



TMD Evolution

M. Anselmino++ [arXiv:1312.6261]



TMD Q^2 evolution ≠ DGLAP

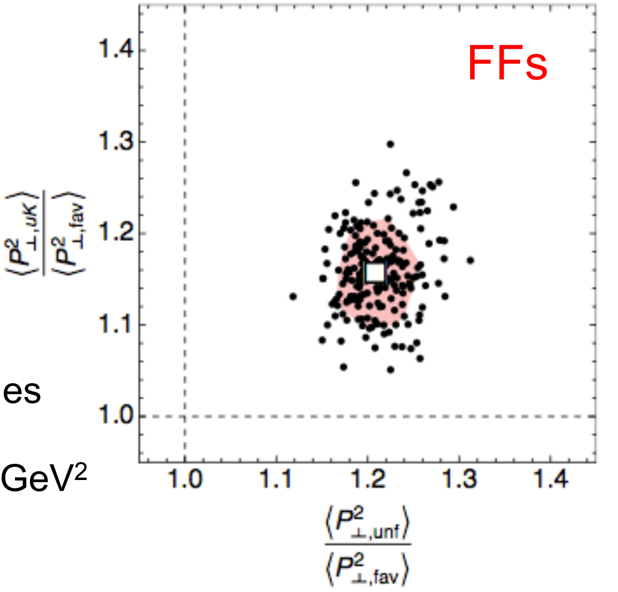
Fixed target SIDIS

Q^2 ~ few GeV^2

B-factories

Q^2 ~ 100 GeV^2

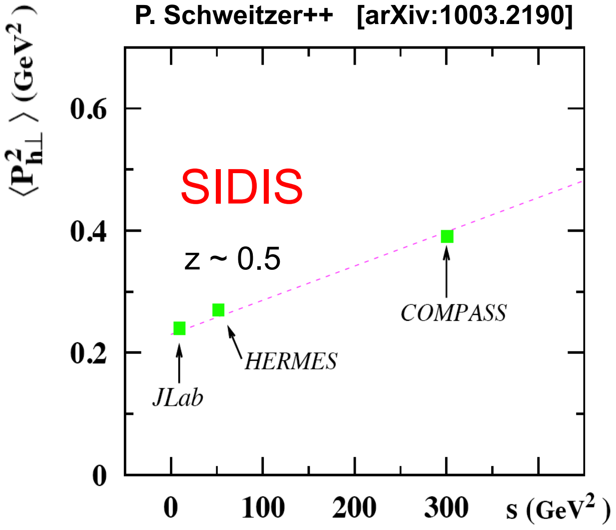
A. Signori++ [arXiv:1309.3507]



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

B-factory analyses of the p_T dependence in fragmentation are crucial for further progresses

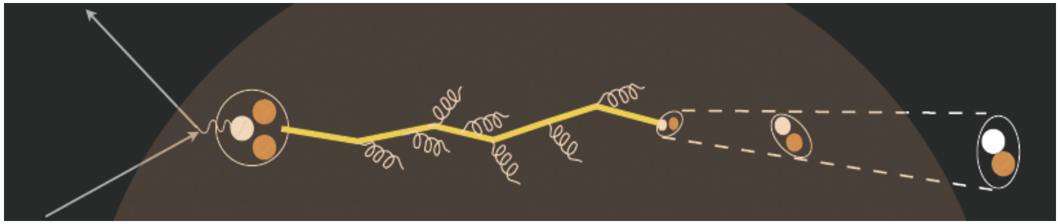
P. Schweitzer++ [arXiv:1003.2190]



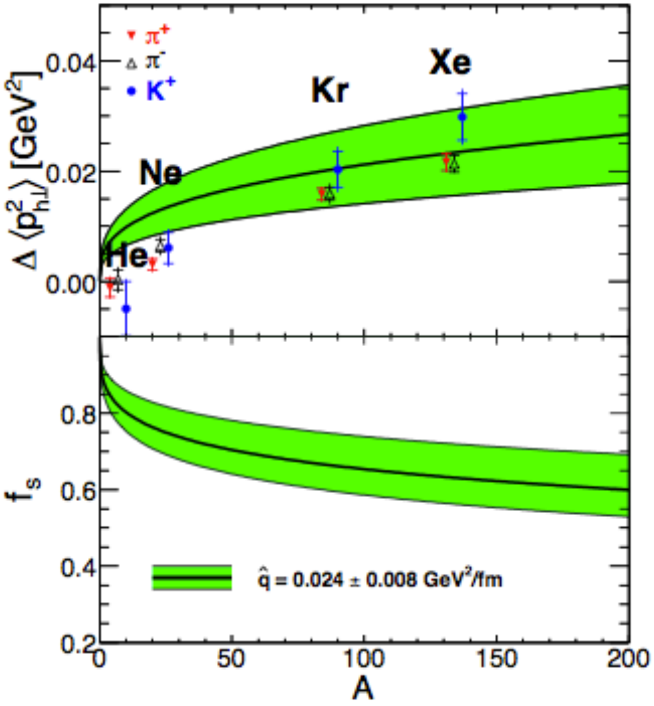
Medium modification

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

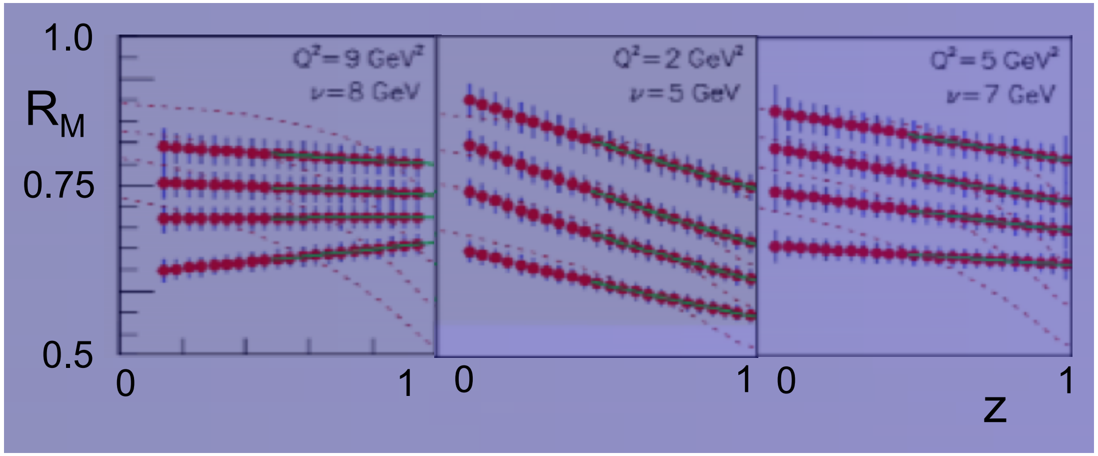


HERMES [arXiv: 0906.2478]



N-B Chang ++ [arXiv:1402.3042]

E12-06-117 Hall-B



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

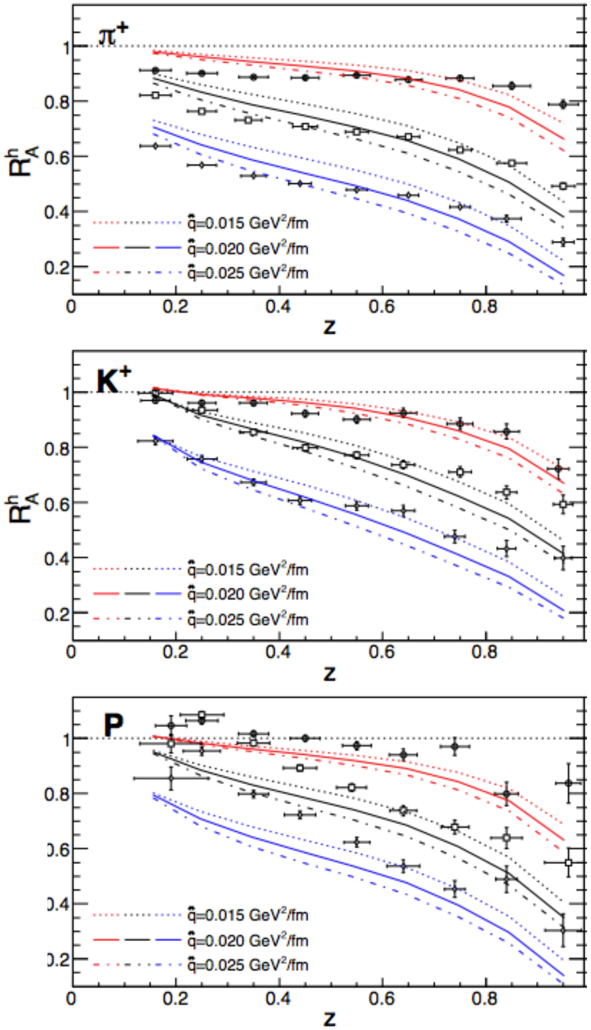
$$\frac{\langle\cos\phi\rangle^{eA}_{UU}}{\langle\cos\phi\rangle^{eN}_{UU}} \approx \frac{\langle\sin\phi\rangle^{eA}_{LU}}{\langle\sin\phi\rangle^{eN}_{LU}} \approx \frac{\alpha}{\alpha+\Delta_{2F}} = f_s$$

Medium modification

DIS

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

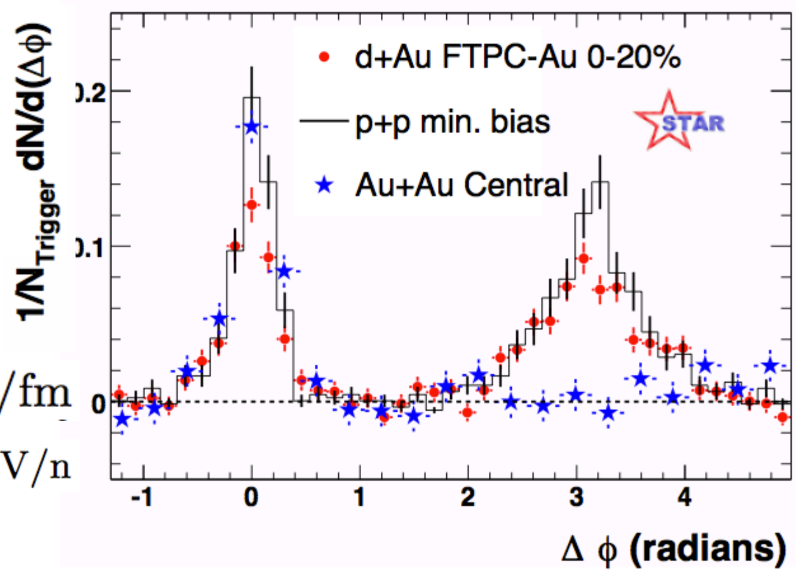
N-B Chang ++ [arXiv:1401.5109]



RHIC

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

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

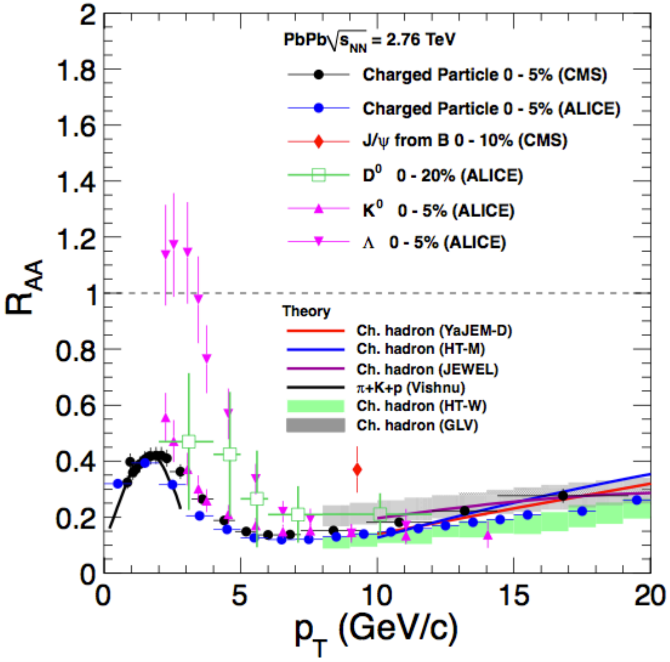


JET Coll. [arXiv:1312.5003]

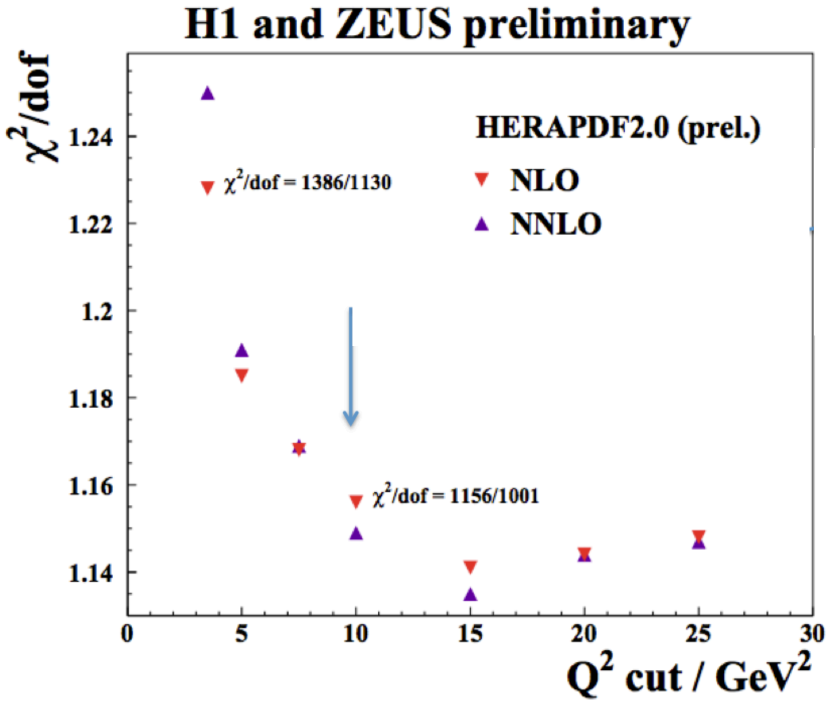
LHC

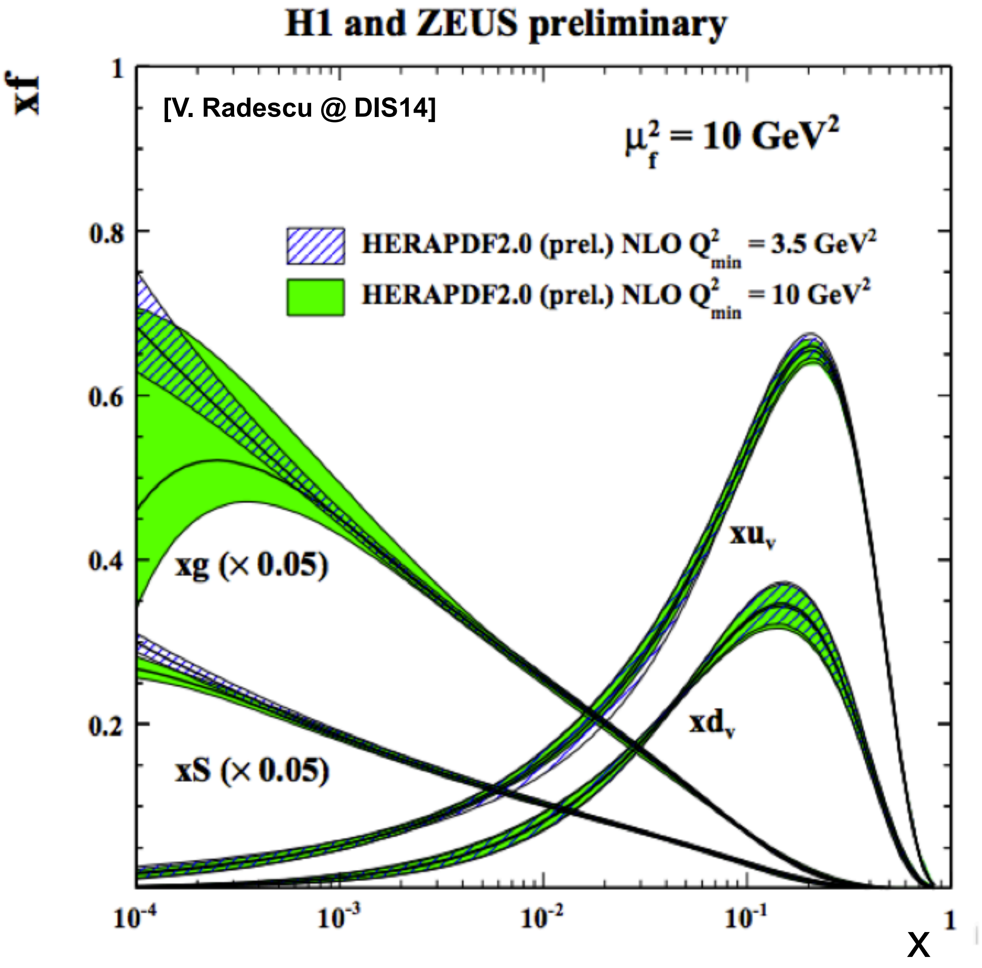
$\hat{q} \approx 1.9 \pm 0.7\ \mathrm{GeV}^2/\mathrm{fm}$

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



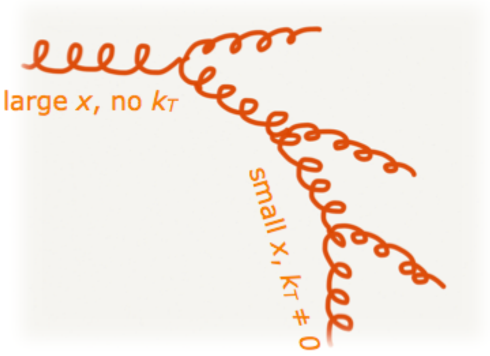
Low-x Physics

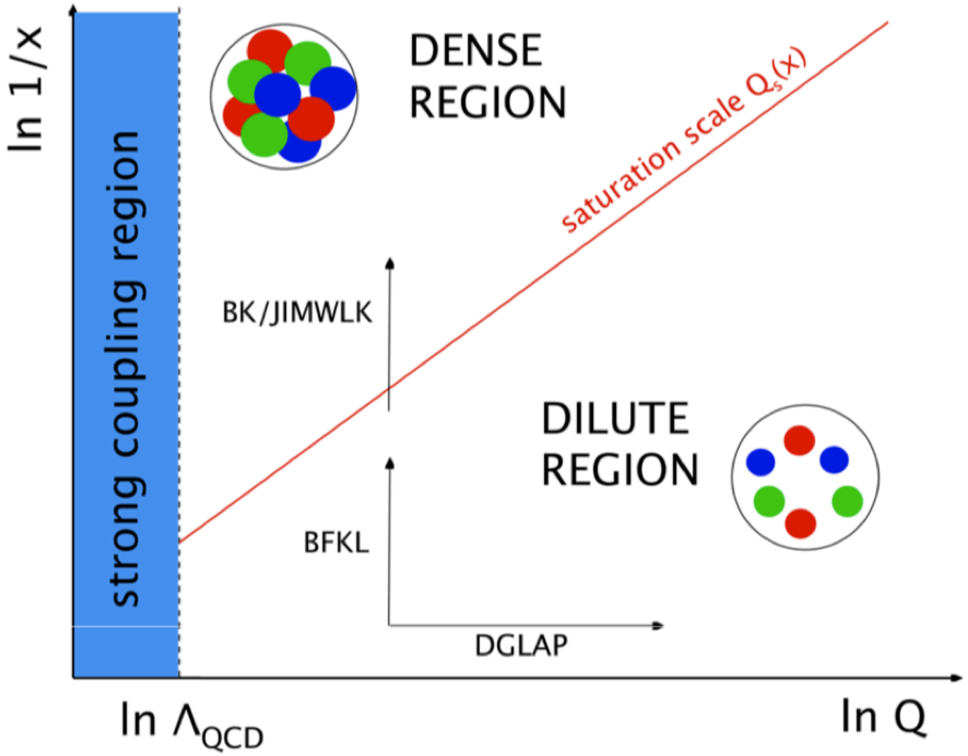




Interplay of the data cut at low Q^2 and impact on gluon at low x

QCD Phase Diagram





x low, Q^2 not too high:

- **partonic k_T** may become important!
  - are (perturbative) parton showers enough to describe this?
  - or does one need something more? k_T-dependent parton densities?

BFKL must be the correct theory of low-x QCD

It naturally incorporates k_T-unintegrated PDFs

Mechelen at DIS2014: no clear evidence of BFKL in experimental data

Gluon TMDs

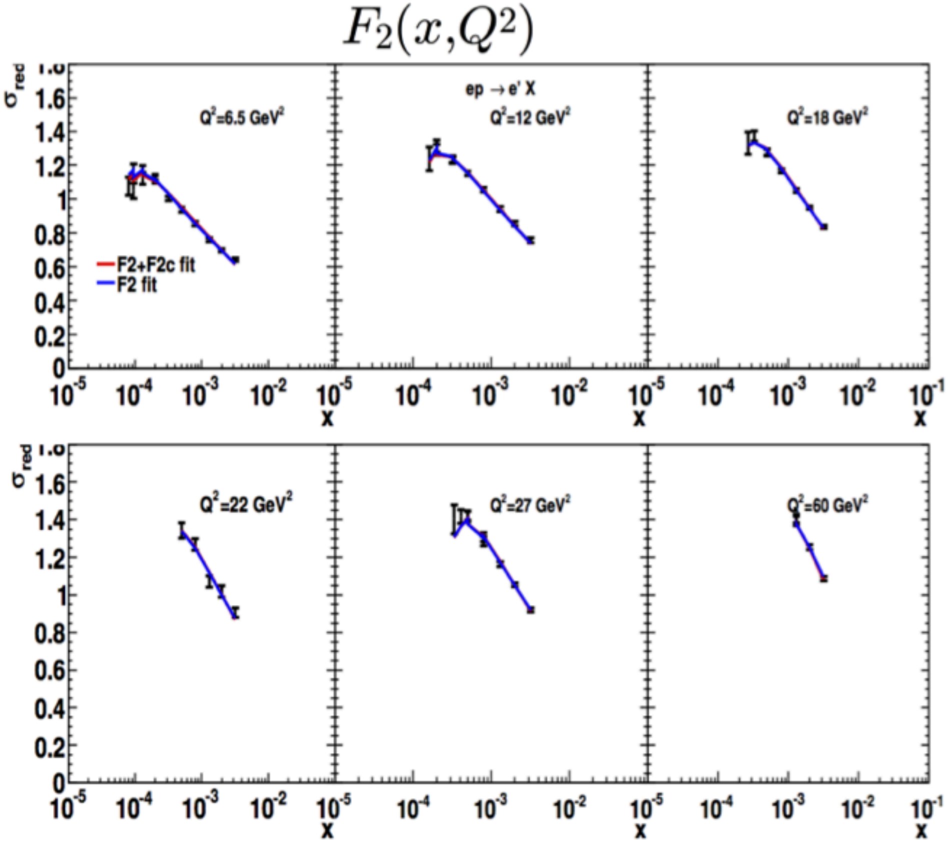
Starting distribution for gluons at q_0

$$xA_0(x,k_\perp) \quad = \quad Nx^{-B}\cdot(1-x)^C\left(1-Dx+E\sqrt{x}\right)\exp[-k_t^2/\sigma^2]$$

$$\sigma^2 = q_0^2/2$$

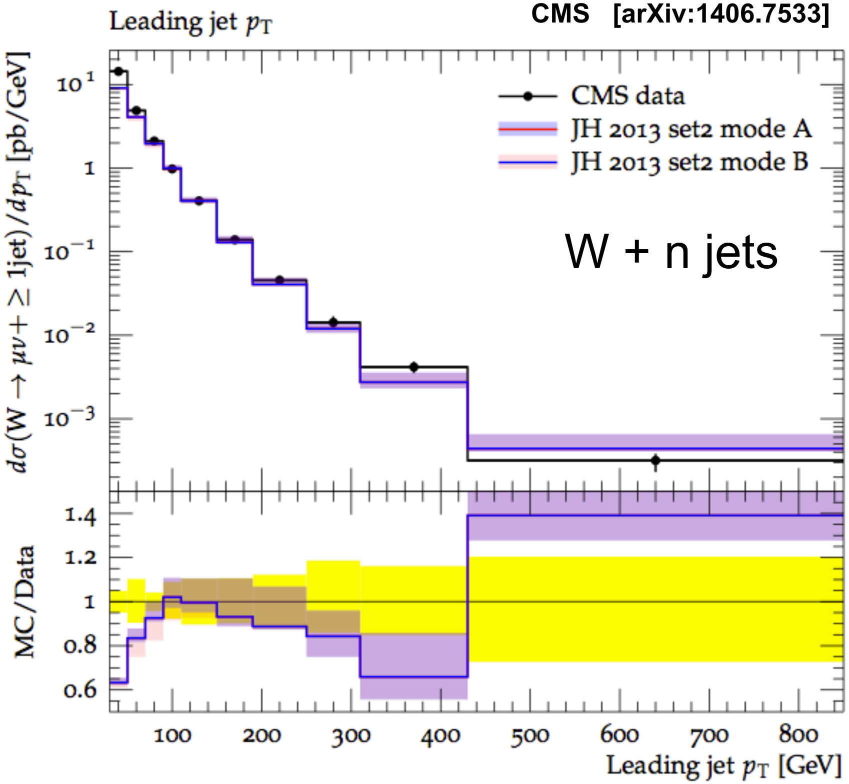
CCFM (BFKL like) evolution + Herafitter package

$F_2(x,Q^2)$



S. Dooling ++ [arXiv 1406.2994]

CMS [arXiv:1406.7533]



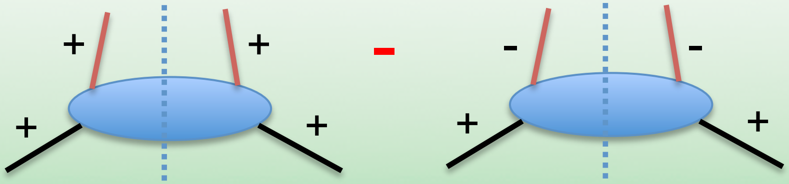
W + n jets

Parton Polarization

Helicity

$$F_{LL} \propto g_1 \otimes D_1$$

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



quark polarisation

nucleon polarisation

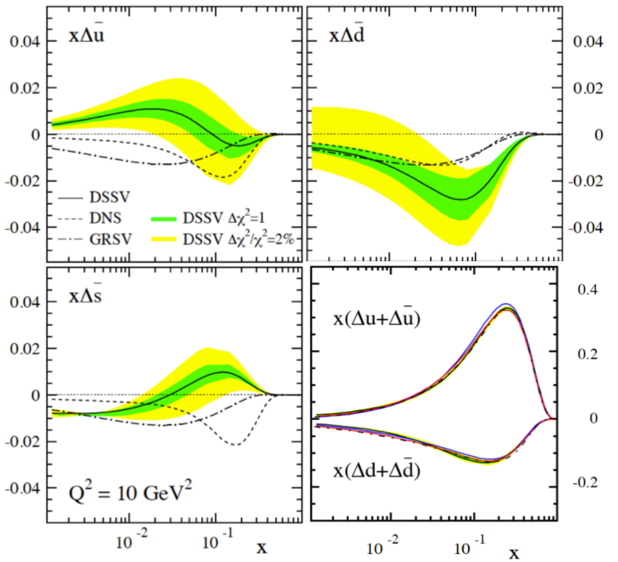
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1, h_{1T}^\perp$

quark polarisation

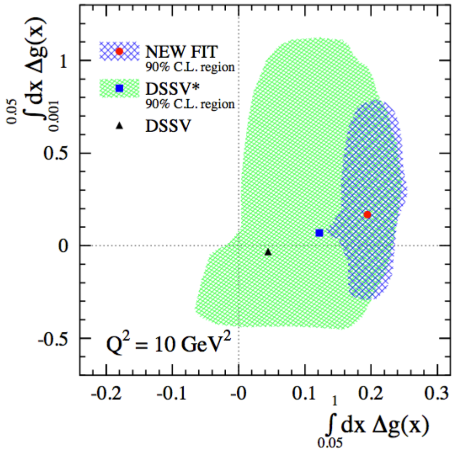
hadron polarisation

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

D. De Florian++ [arXiv:1112.0904]



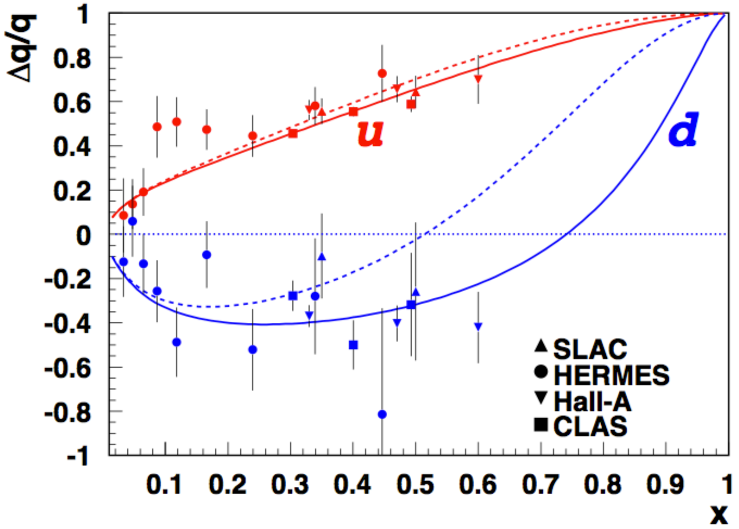
D. De Florian++ [arXiv:1404.4293]



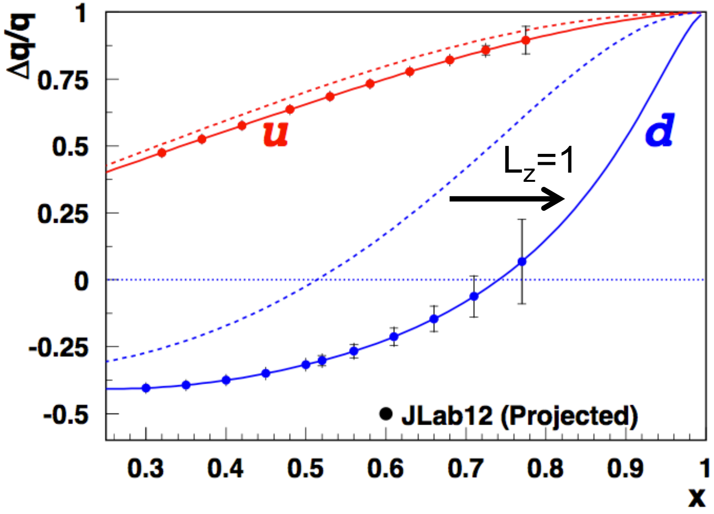
Helicity @ JLab12

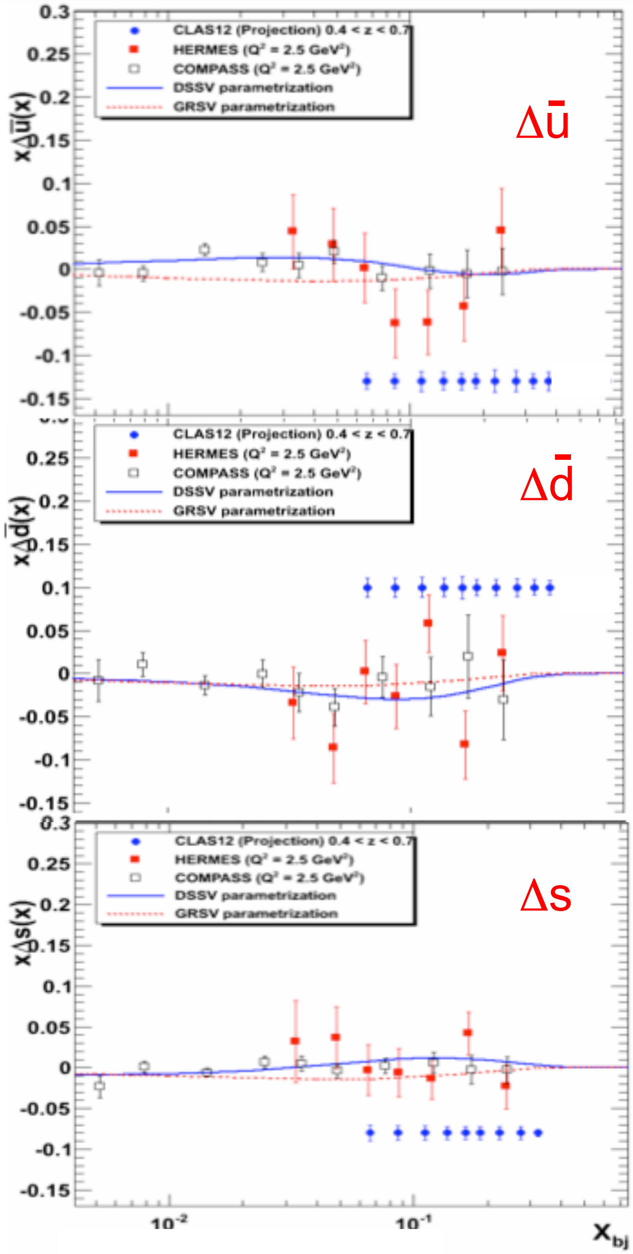
$$F_{LL} \propto g_1 \otimes D_1$$

p-d E12-09-007 Hall-B
^{3}He E12-11-007 Hall-A
E12-07-107 Hall-B



H. Avakian ++ [arXiv: 0705.1553]



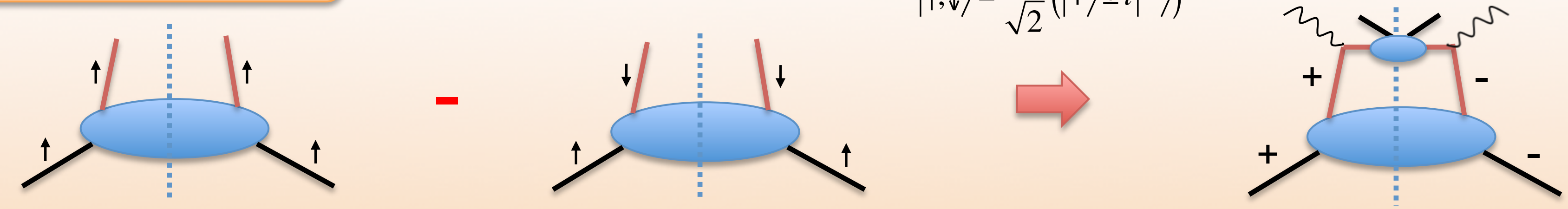


Transversity

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

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

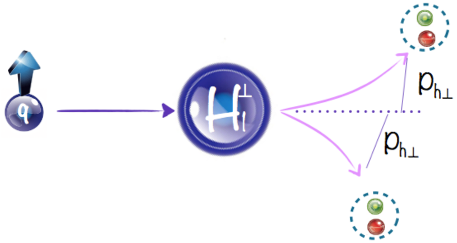
  it requires a chirally-odd fragmentation

hadron polarisation

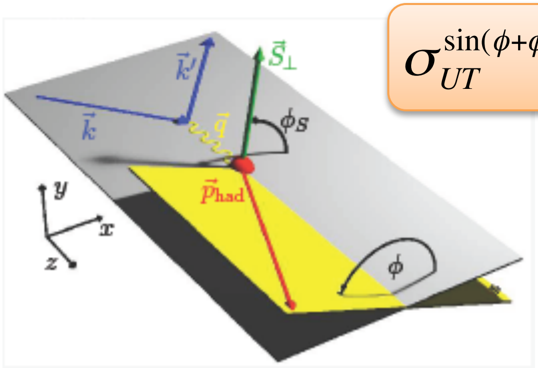
quark polarisation

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

Collins function:
a spin-p_T correlator in fragmentation

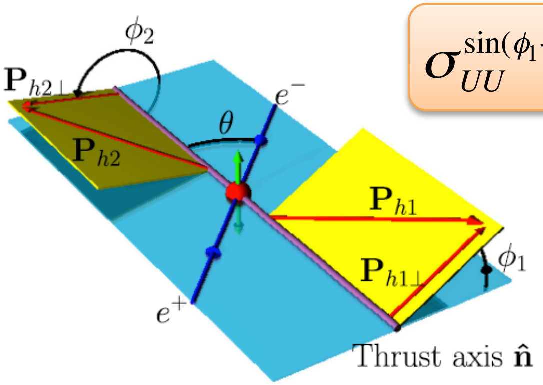


Transversity & Collins Evidences



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

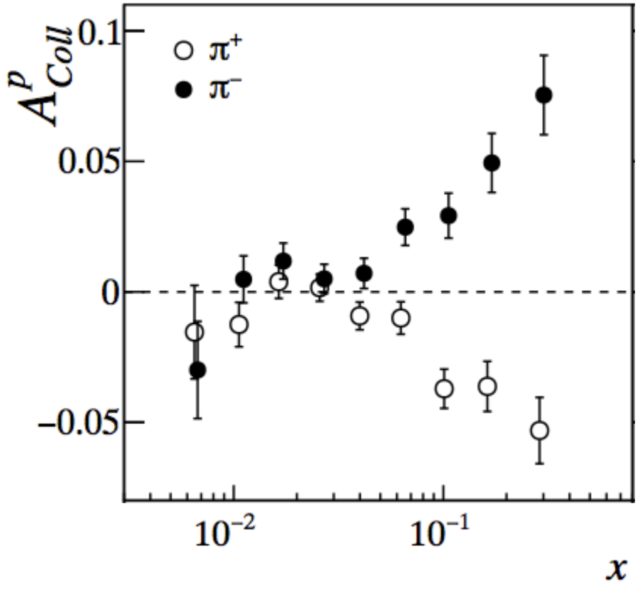
Q^2 ~ 5-7 GeV^2



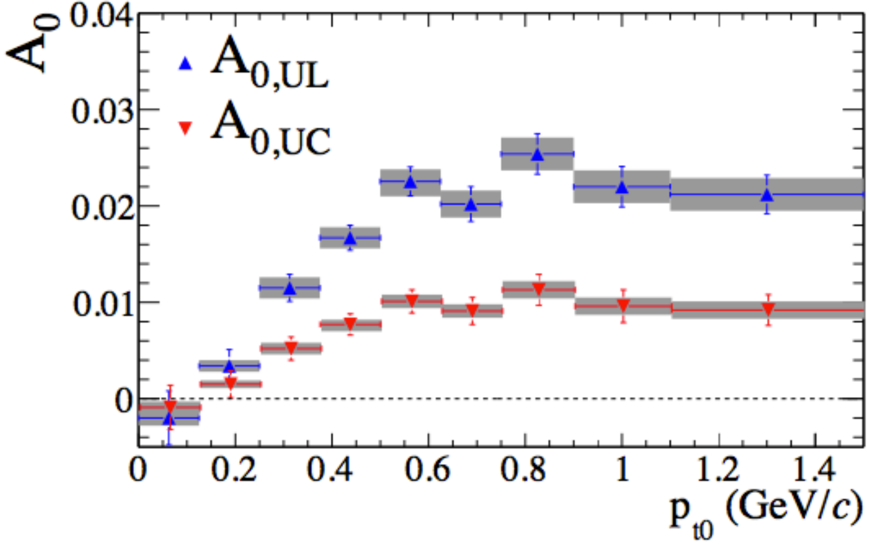
$$\sigma_{UU}^{\sin(\phi_1+\phi_2)} \propto H_1^\perp \otimes H_1^\perp$$

Q^2 ~ 110 GeV^2

HERMES	**[arXiv 0408013]**
HERMES	**[arXiv 0906.3918]**
COMPASS	**[arXiv 1005.5609]**
COMPASS	**[arXiv 1408.4405]**



Belle	**[talk at DIS2014]**
BESIII	**[arXiv 1507.06824]**
Babar	**[arXiv 1309.5278]**



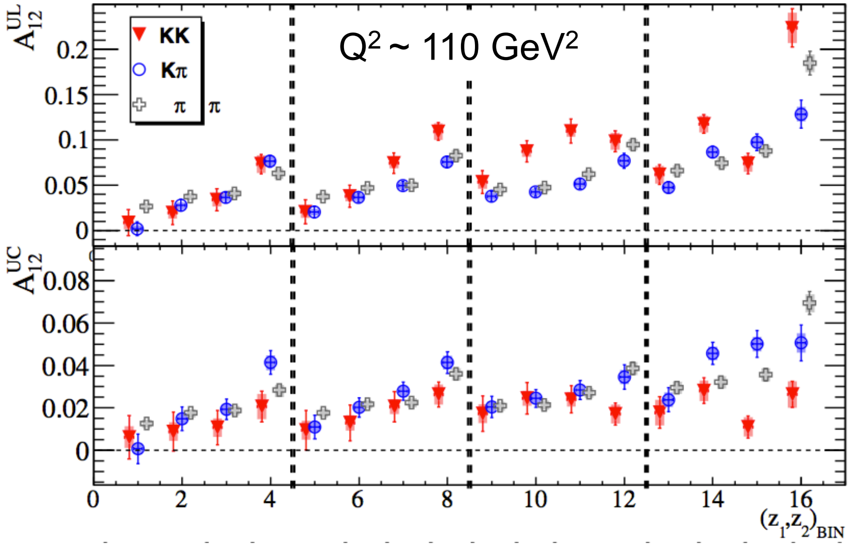
Fragmentation Functions @ B-factories

Crucial to seek un-integrated FFs at e^+e^- machines for

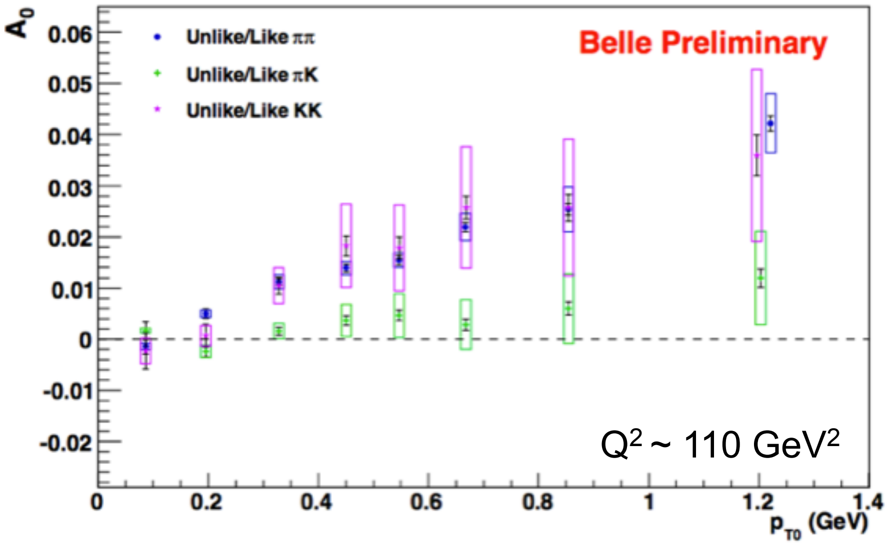
- evolution
- flavor separation

The Collins fragmentation analysis provides a benchmark

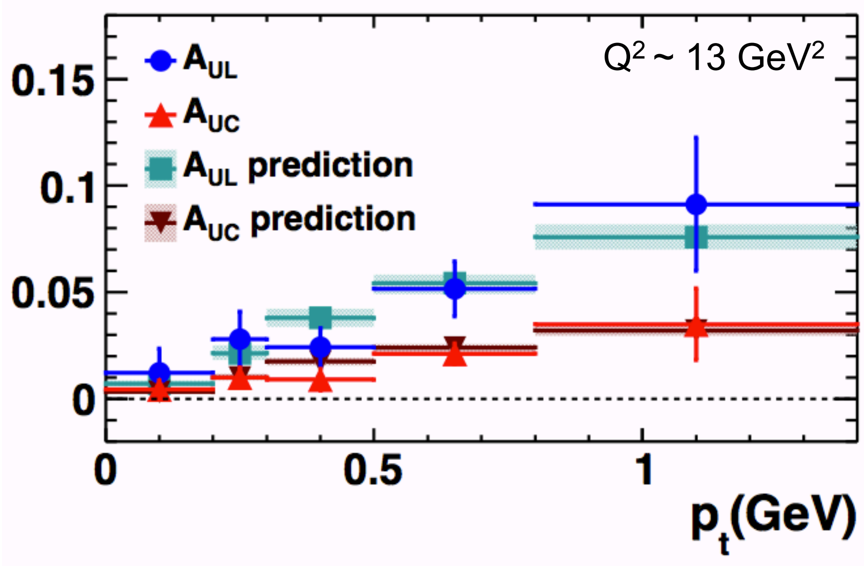
Babar [arXiv 1506.05864]



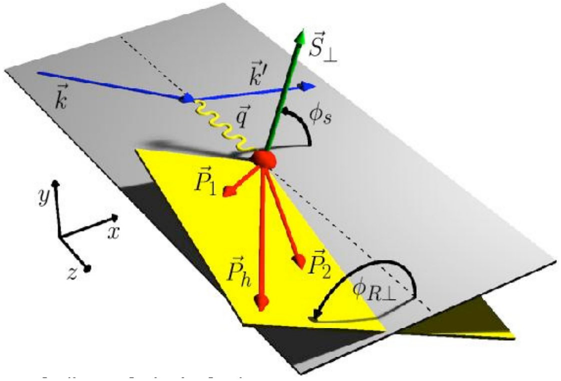
F. Giordano [talk at DIS2014]

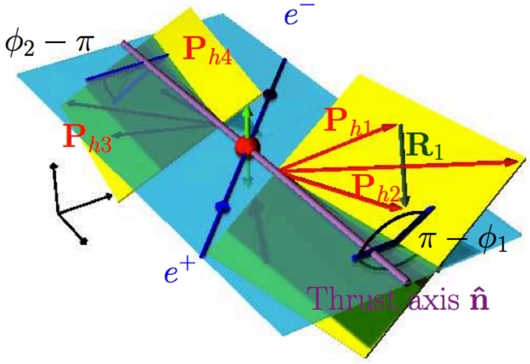


BESIII [arXiv 1507.06824]



Di-Hadron Channel



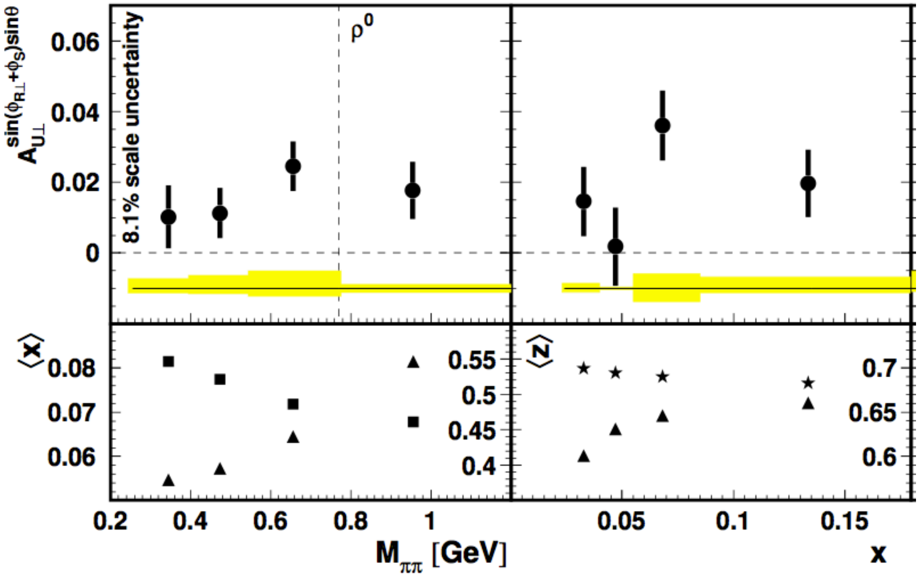


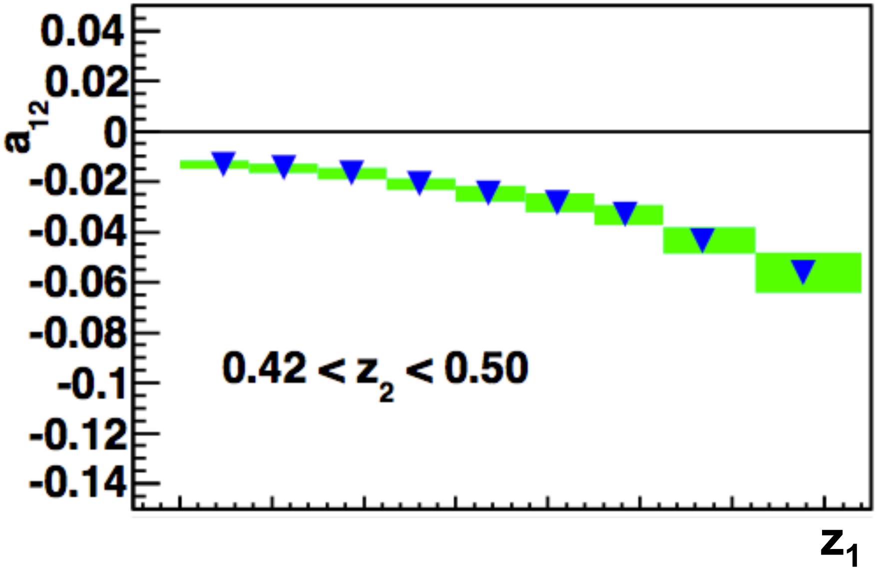
HERMES [arXiv 0803.2367]

COMPASS [arXiv 1212.6150]

COMPASS [arXiv 1401.7873]

Belle [arXiv 1104.2425]



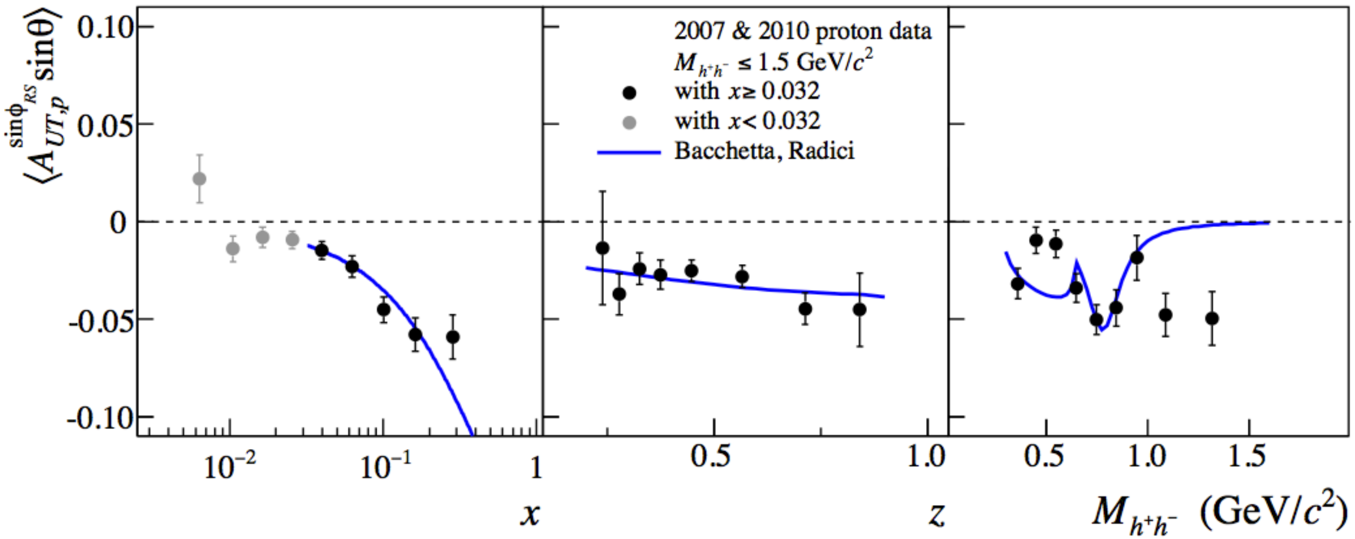


Di-Hadron Channel

$$ep^{\uparrow} \rightarrow (\pi^{+}\pi^{-})X$$

M. Radici++ [arXiv 1503.03495]

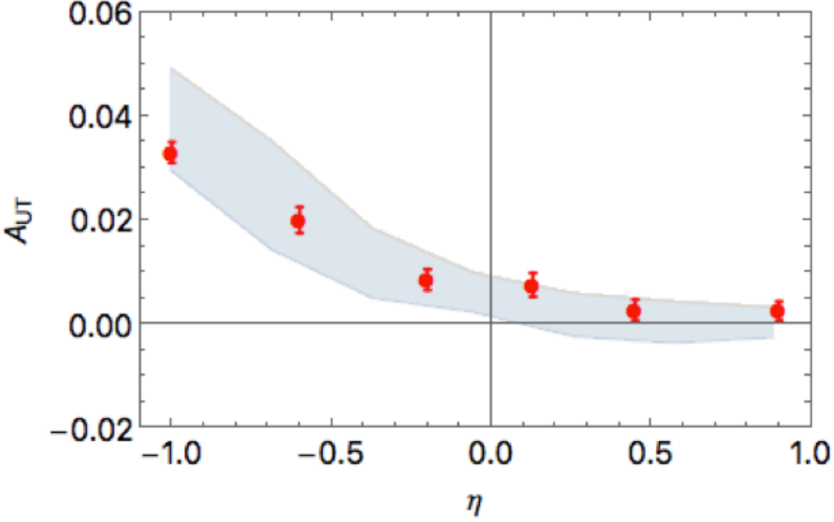
COMPASS [arXiv 1401.7873]

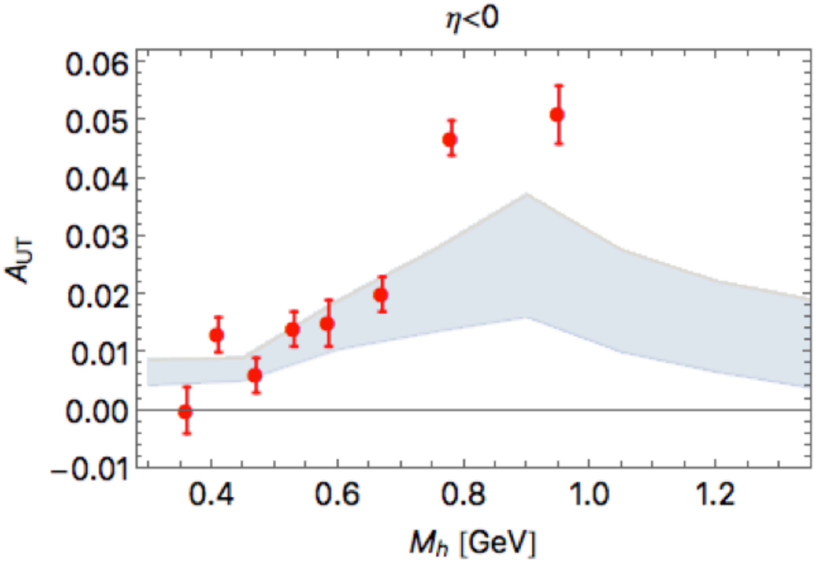


$$pp^{\uparrow} \rightarrow (\pi^{+}\pi^{-})X$$

STAR [arXiv 1504.00415]

M. Radici and S. Pisano [arXiv 1511.03220]





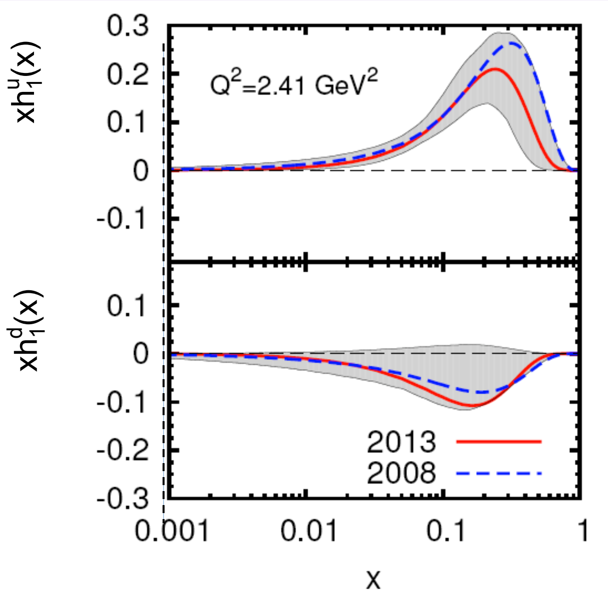
Transversity Signals

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

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

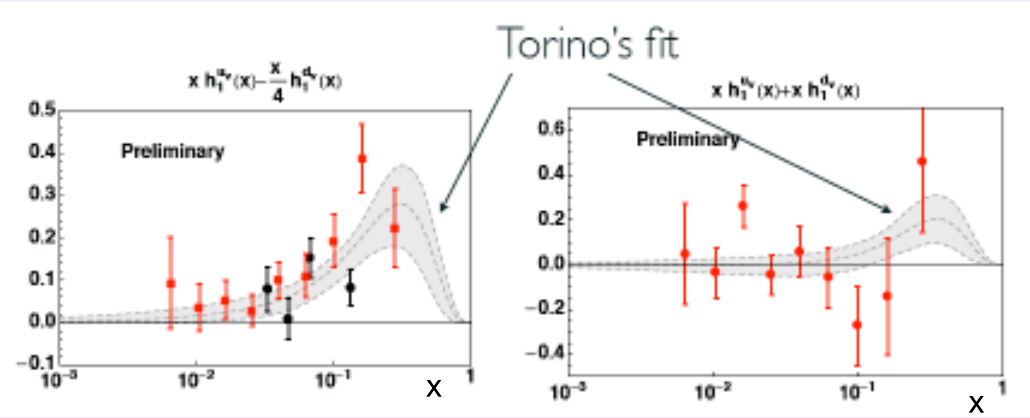
Cross-check of the TMD formalism
Evolution from colliders to
fixed-target experiments

1st extraction of Transversity!



M. Anselmino++ [arXiv:1303.3822]

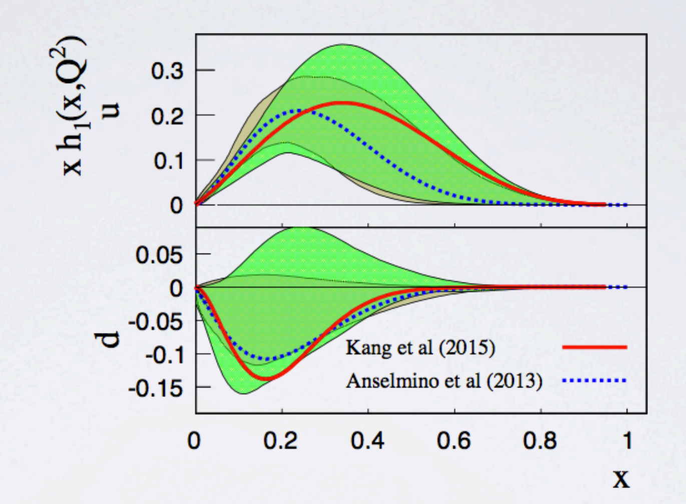
Collinear extraction !



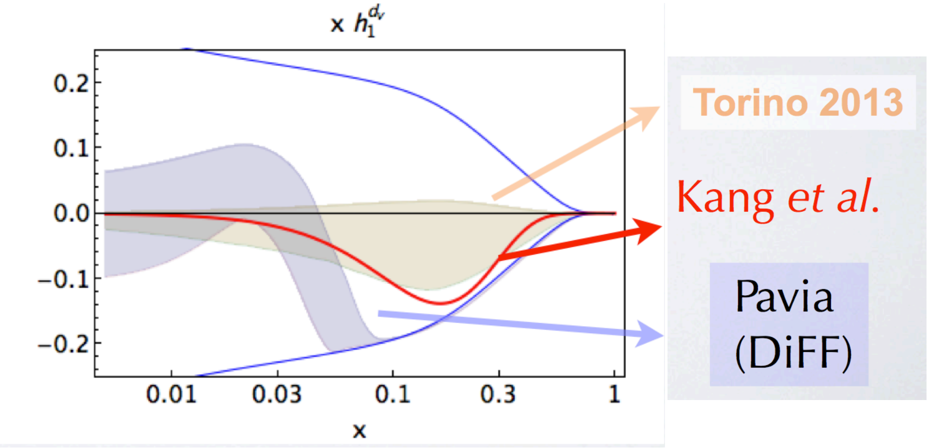
A. Bacchetta++ [arXiv:1206.1836]

Transversity & Tensor Charge

Distributions:



x



How well is Soffer bound know at large x ?

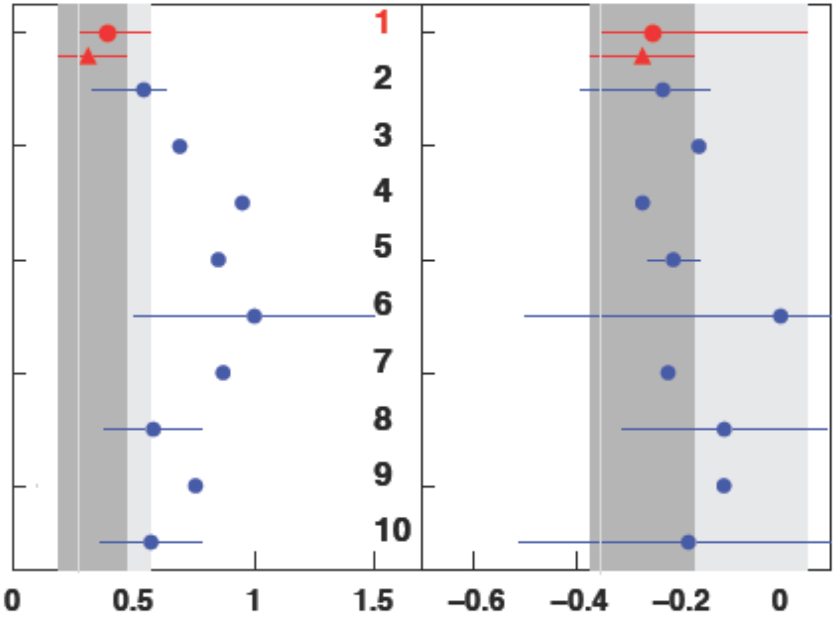
Charges:

$$\delta q \equiv \int_0^1 dx\,[\Delta_T q(x) - \Delta_T \bar{q}(x)]$$

Anselmino++ **[arXiv 1303.3822]**

● $\delta u = 0.39^{+0.18}_{-0.12}$ ● $\delta d = -0.25^{+0.30}_{-0.10}$

▲ $\delta u = 0.31^{+0.16}_{-0.12}$ ▲ $\delta d = -0.27^{+0.10}_{-0.10}$



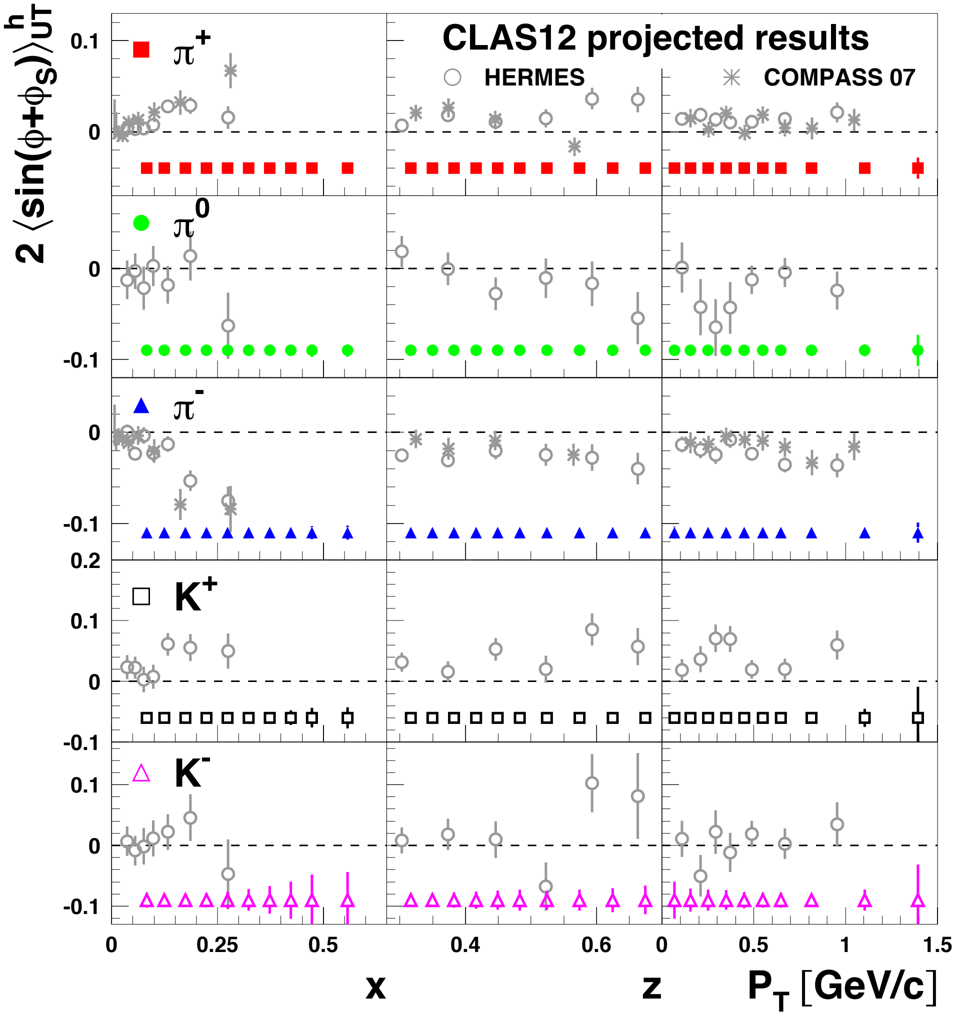
Δu = 0.787 **Δd = -0.319**

Transversity @ JLab12

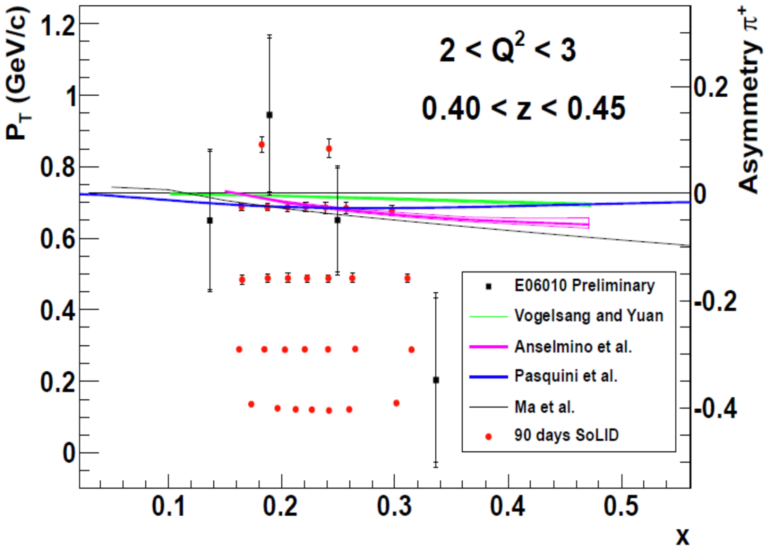
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^{\perp}$$

E12-09-018 Hall-A
E12-11-108 Hall-A
C12-11-111 Hall-B

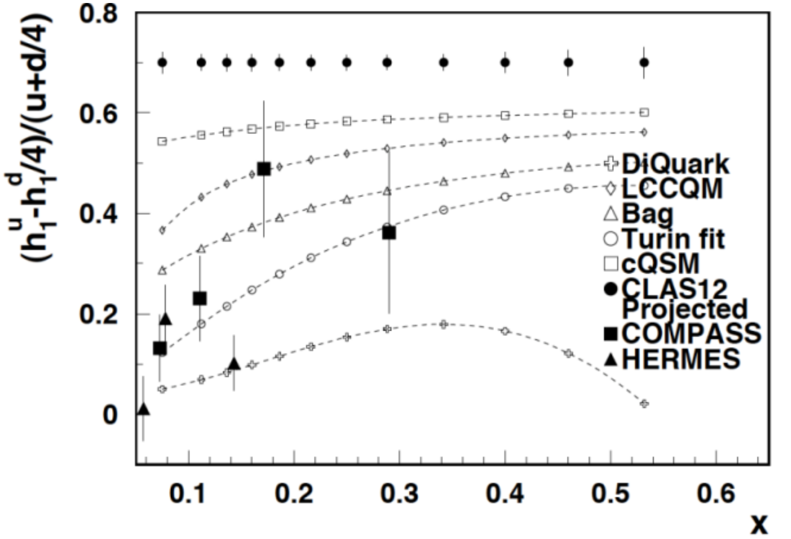
Single hadron channel:



Neutron (^{3}He) : E12-10-006 Hall-A



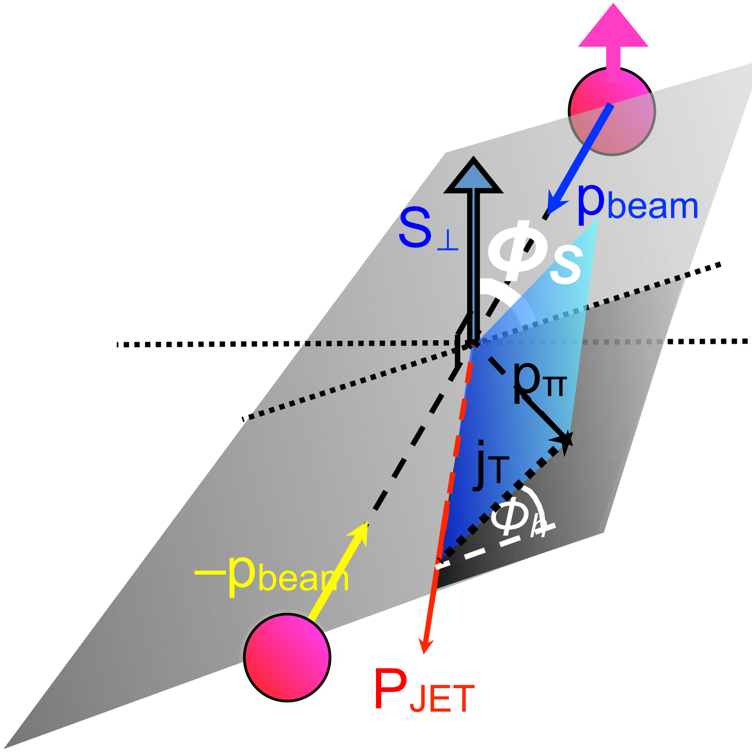
Di-hadron channel: E12-12-109 Hall-B

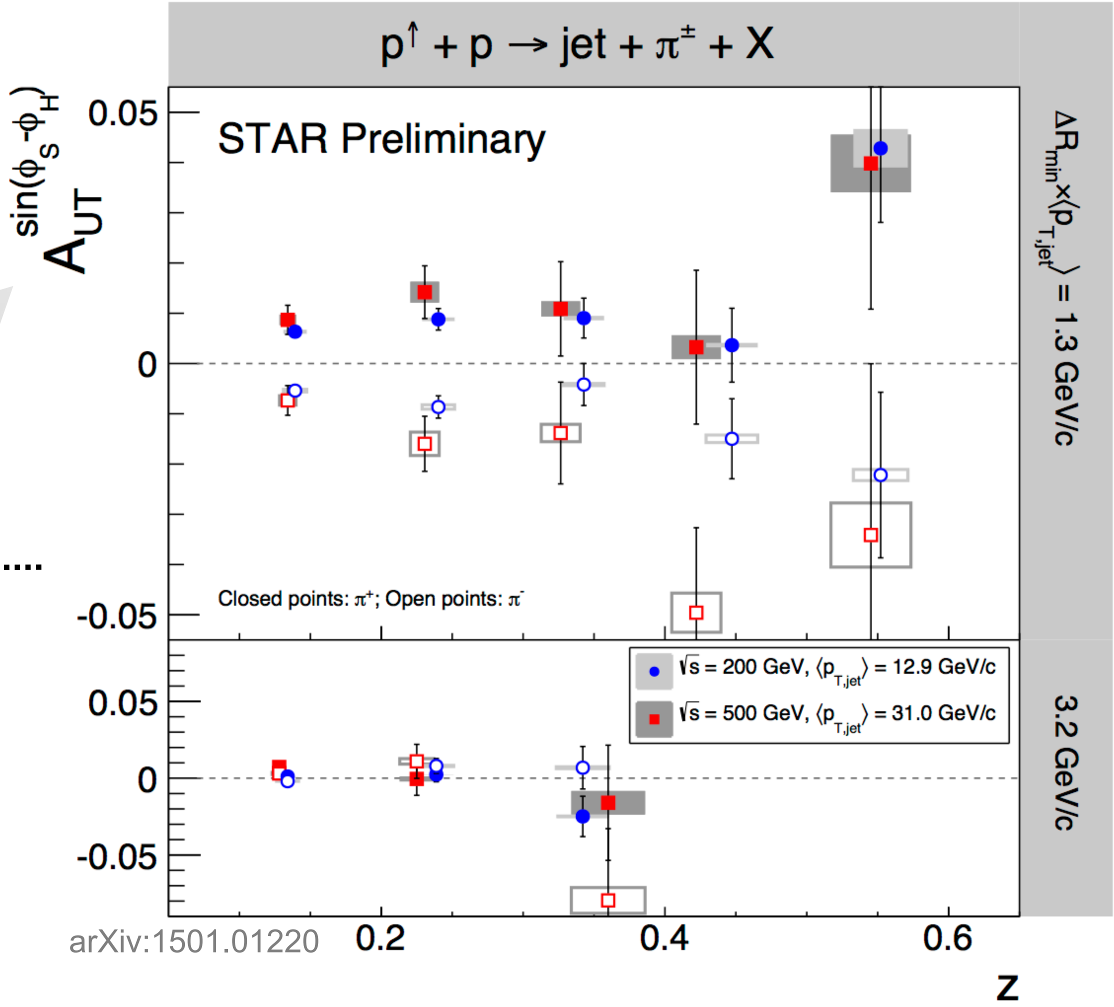


Transversity @ JLab12

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

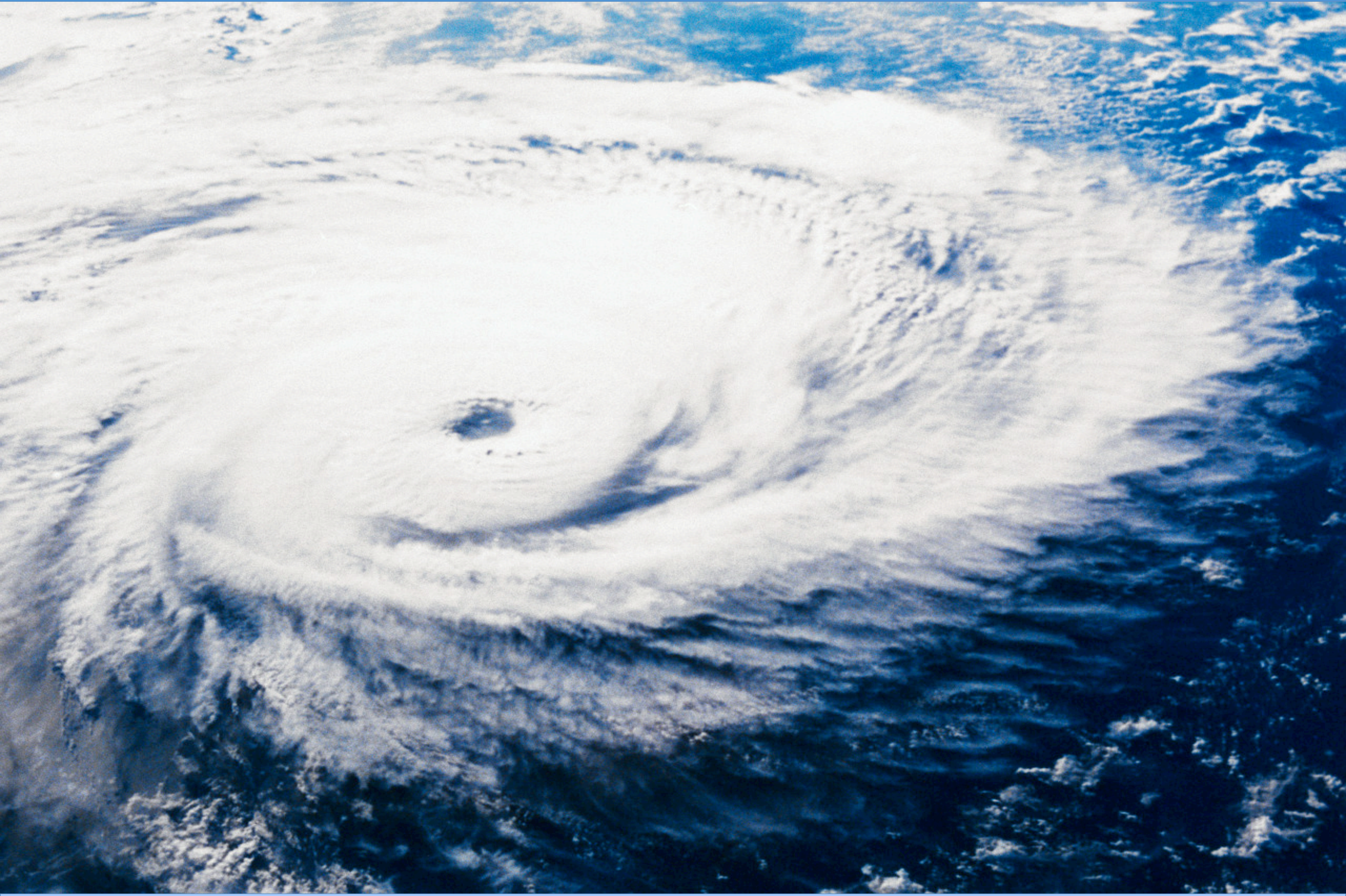
Hadron in jet channel:





arXiv:1501.01220

Spin-Orbit Effects



Transverse Momentum Dependent Distr.

quark polarisation

nucleon polarisation

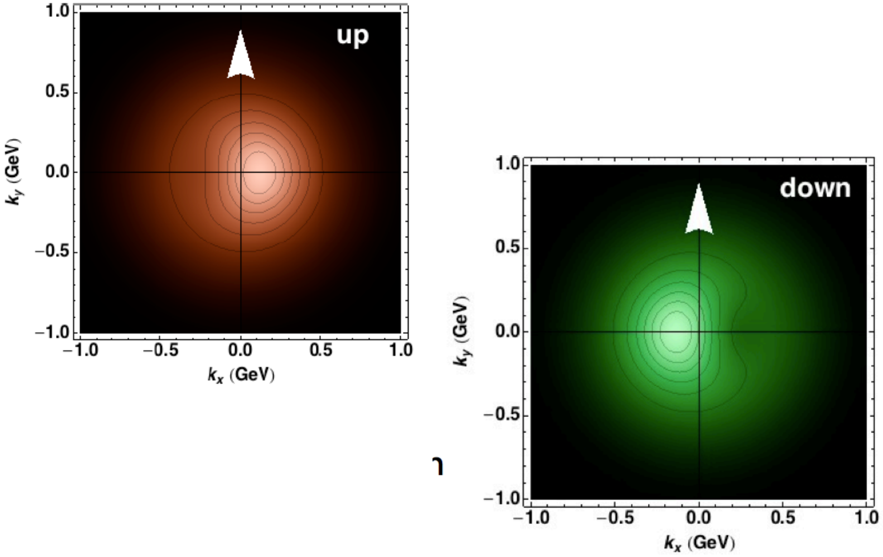
N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	$h, h_{1T}^{\perp}$

$\otimes$

quark polarisation

hadron polarisation

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



Off-diagonal elements:

Interference between wave functions with different angular momenta: testing QCD at the amplitude level

T-odd elements:

→ Sign change between DY and SIDIS
Generalized universality of TMDs

Related to:

- ✓ Parton Spin-Orbit effects: may explain pp SSA & DY Lam-Tung
- ✓ Parton Orbital motion

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$\otimes$

quark polarisation

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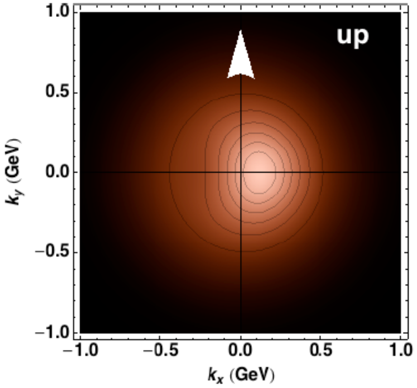

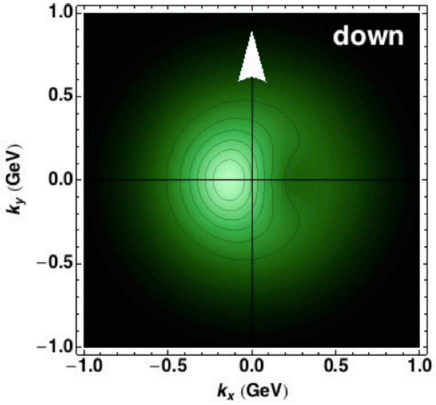

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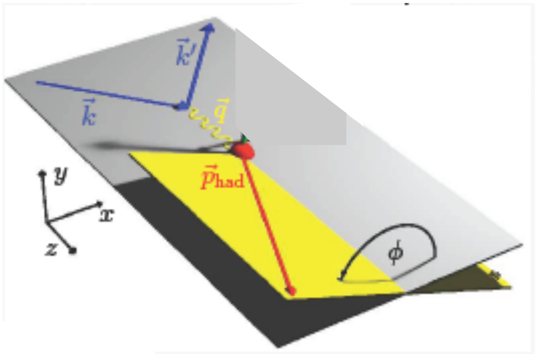
Boer-Mulders Signals



SIDIS:
ep → e'hX

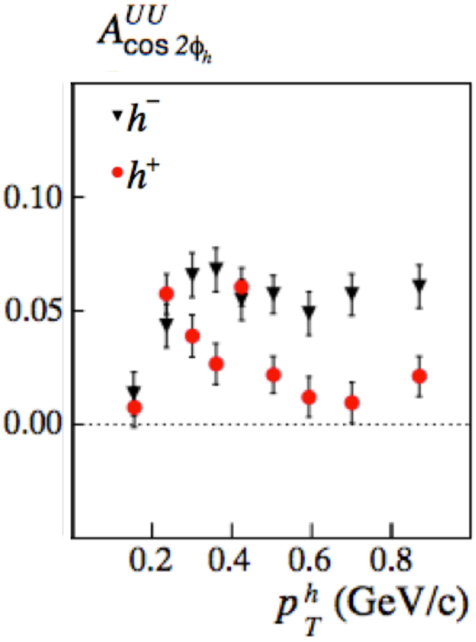
$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp}$$

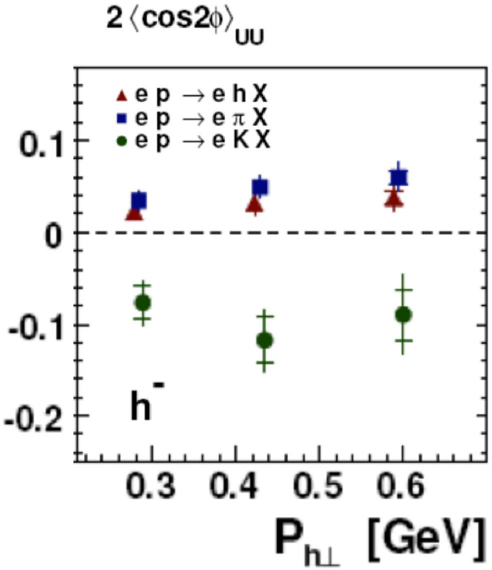
Drell-Yan:
π,pp → e+e-X

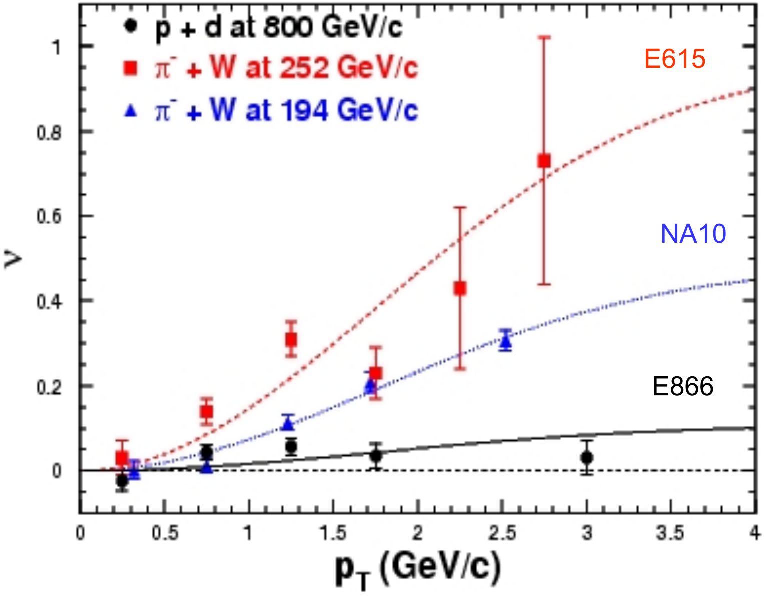
$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes h_1^{\perp}$$

Unpol. SIDIS

May explain the Lam-Tung relation violation in Drell-Yan







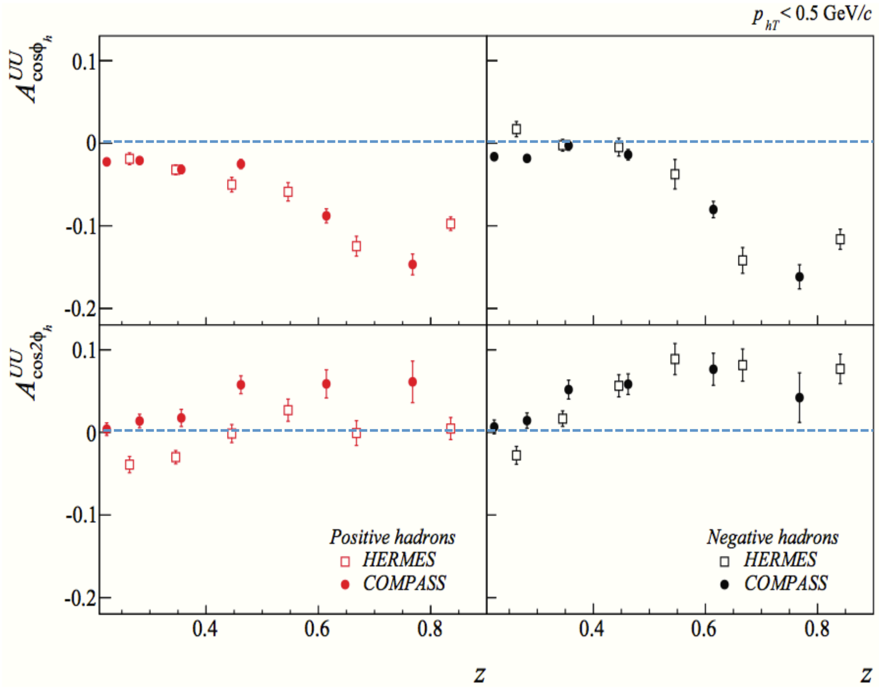
COMPASS [arXiv:1401.6284]

HERMES [arXiv:1204.4161]

Azimuthal Modulations of F_{UU}

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

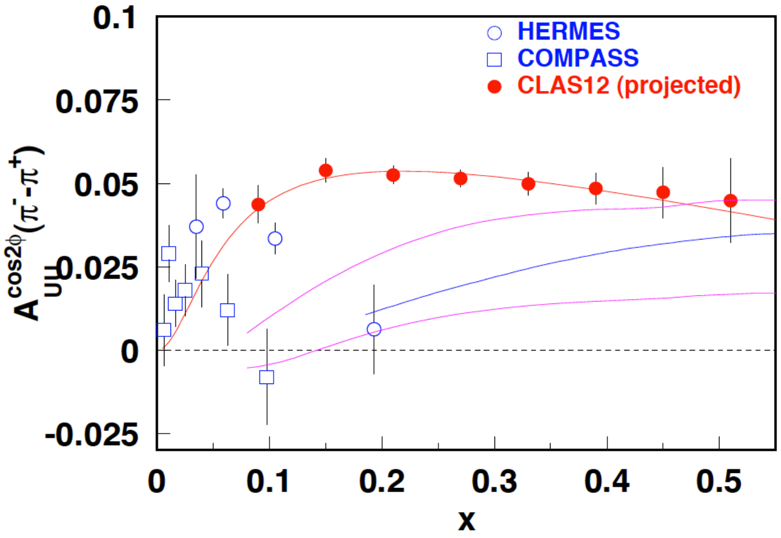
Intrinsic k_T Cahn kinematical effect



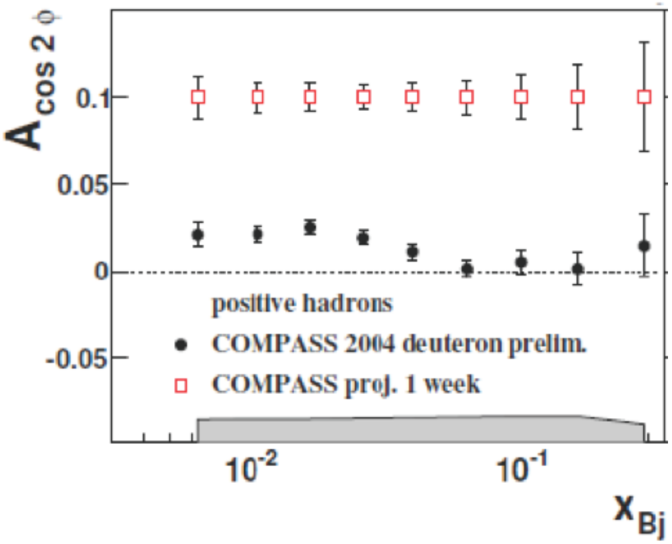
$$F_{UU}^{\cos2\phi} \propto h_1^{\perp} H_1^{\perp} + [f_1 D_1 + \ldots]/Q^2$$

Boer-Mulders spin-orbit effect

JLab12:



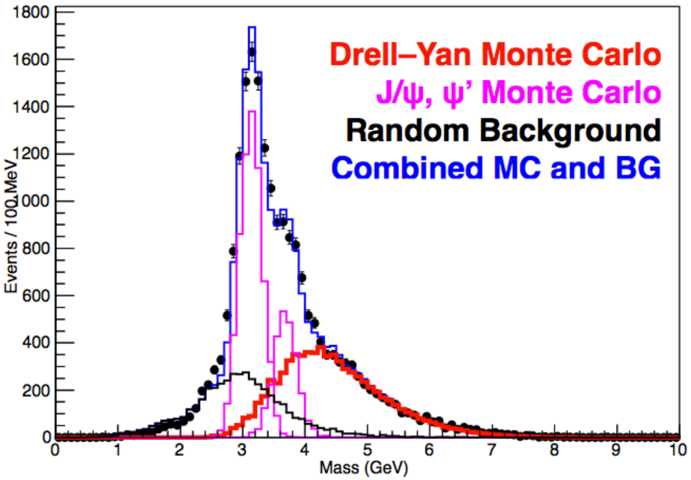
COMPASS-II:

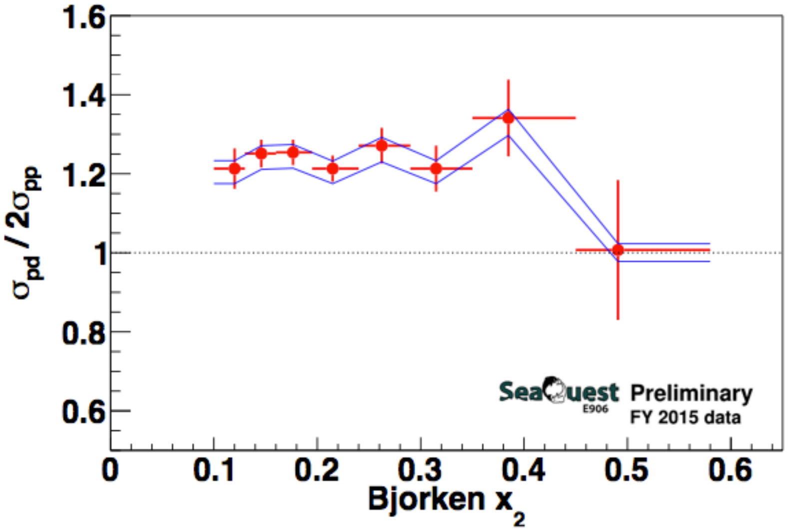


Drell-Yan Ongoing Studies

σ_{pp}, σ_{pd} at

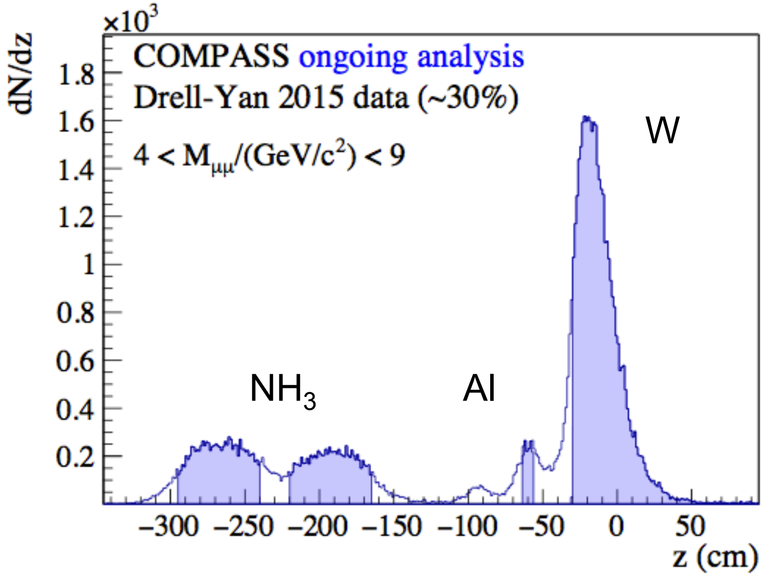
SeaQuest



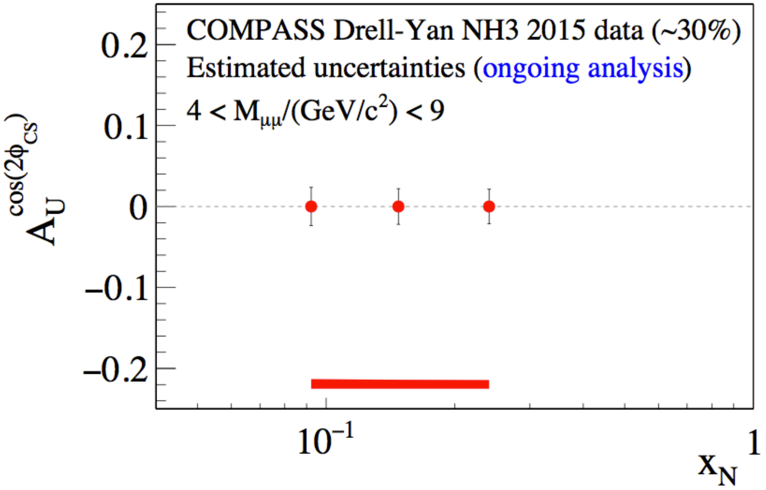


$\sigma_{\pi p}$ at

COMPASS



$A_{UU}^{\cos(2\phi)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$ (Boer-Mulders)



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$\otimes$

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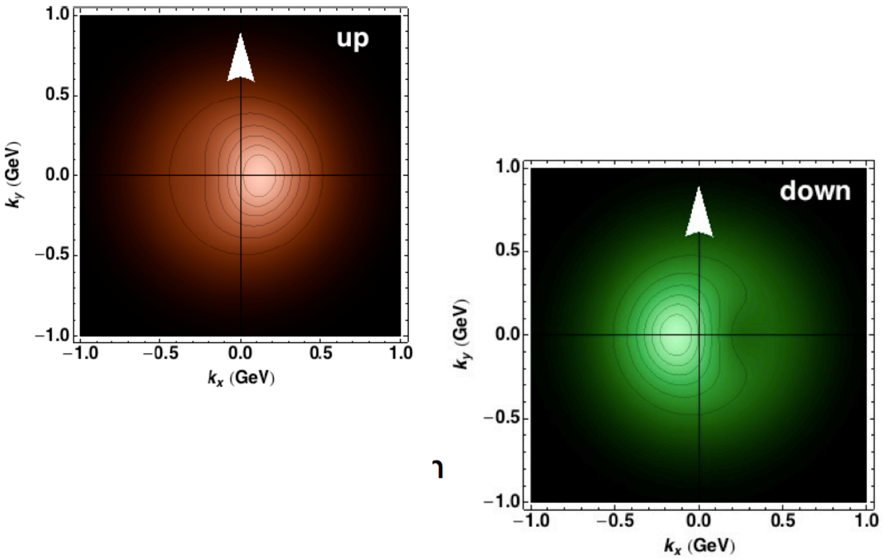

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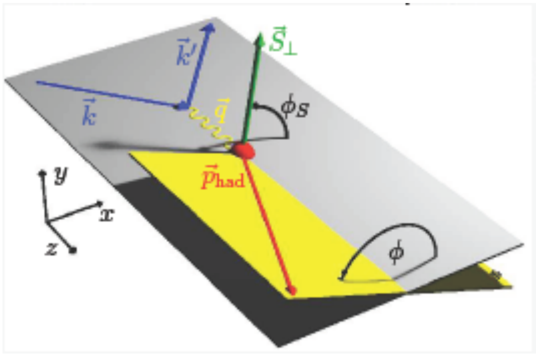
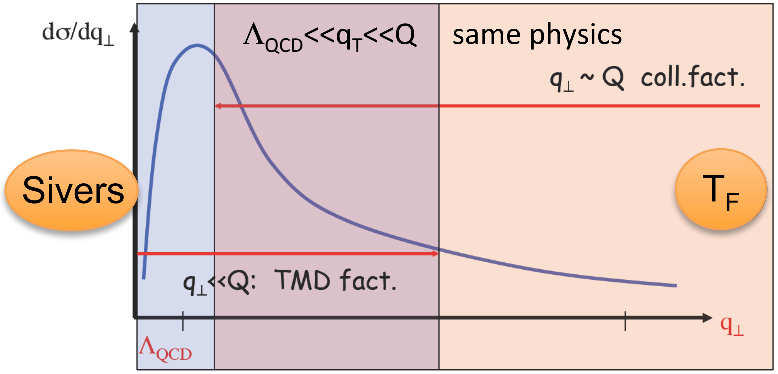
Sivers Signals

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



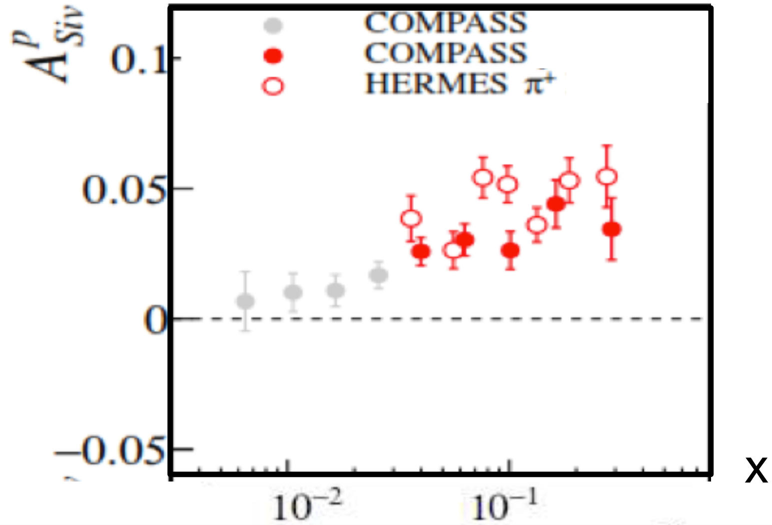


$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

Sivers from polarized SIDIS ⟷ **May generate the misterious hadronic SSA**

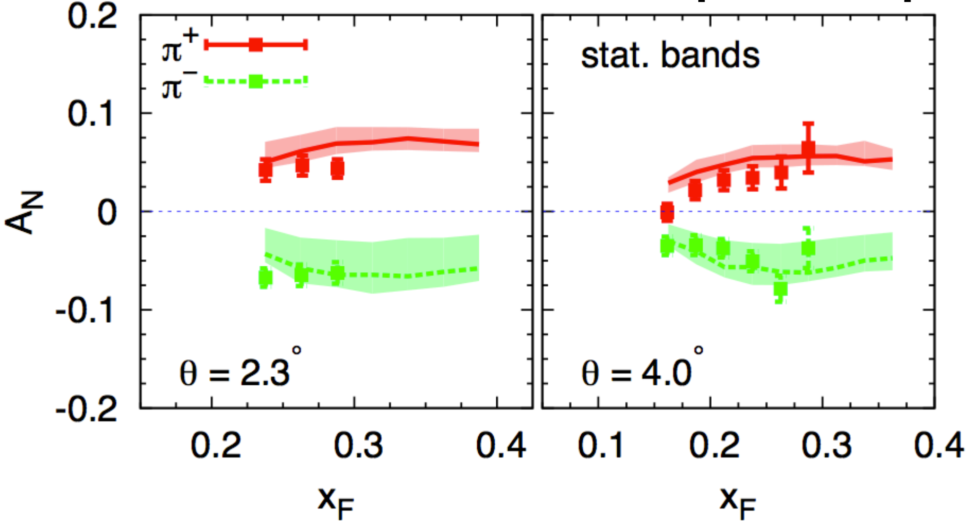
HERMES **[arXiv:0906.3918]**

COMPASS **[arXiv:1205.5122]**



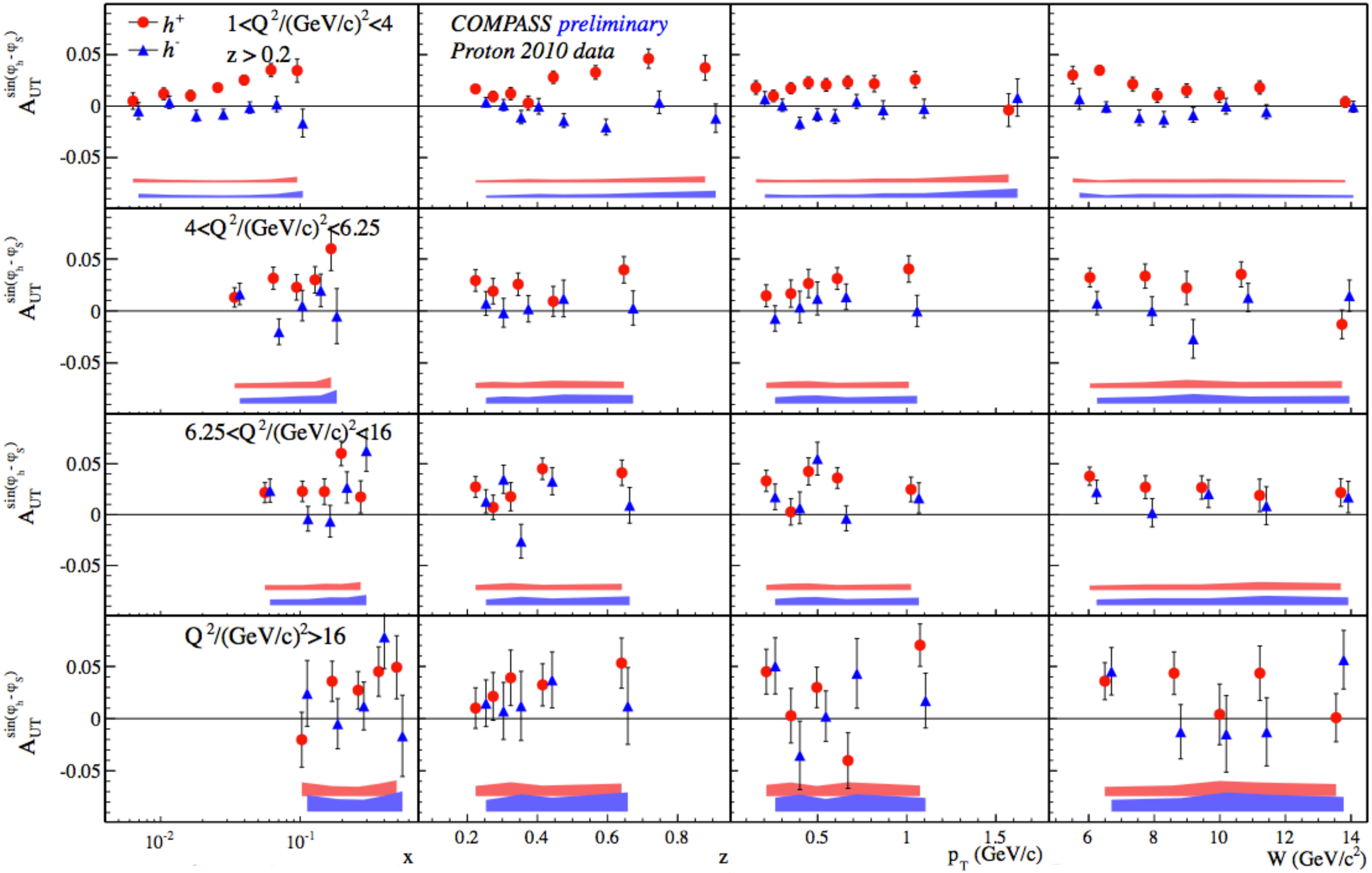
$p^\uparrow p \to \pi X$

M. Anselmino et al. [arXiv 1304.7691]



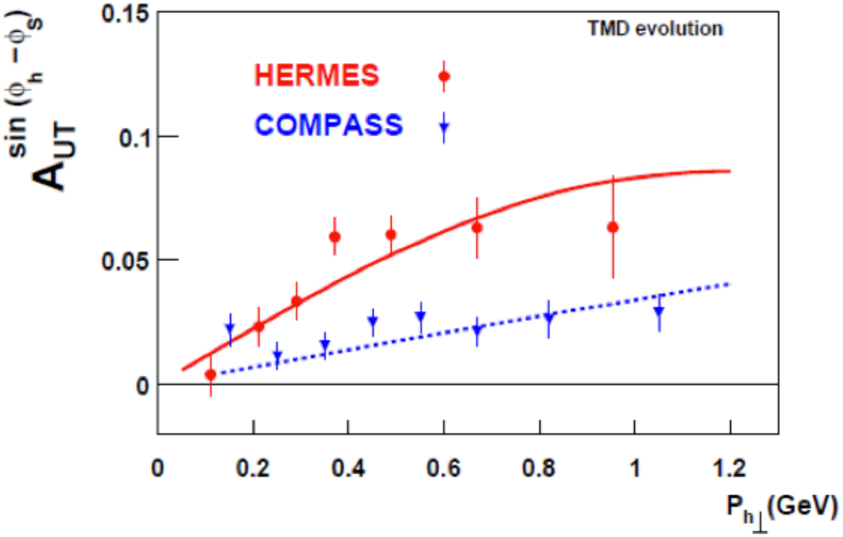
Sivers Signals

Toward multiD analyses



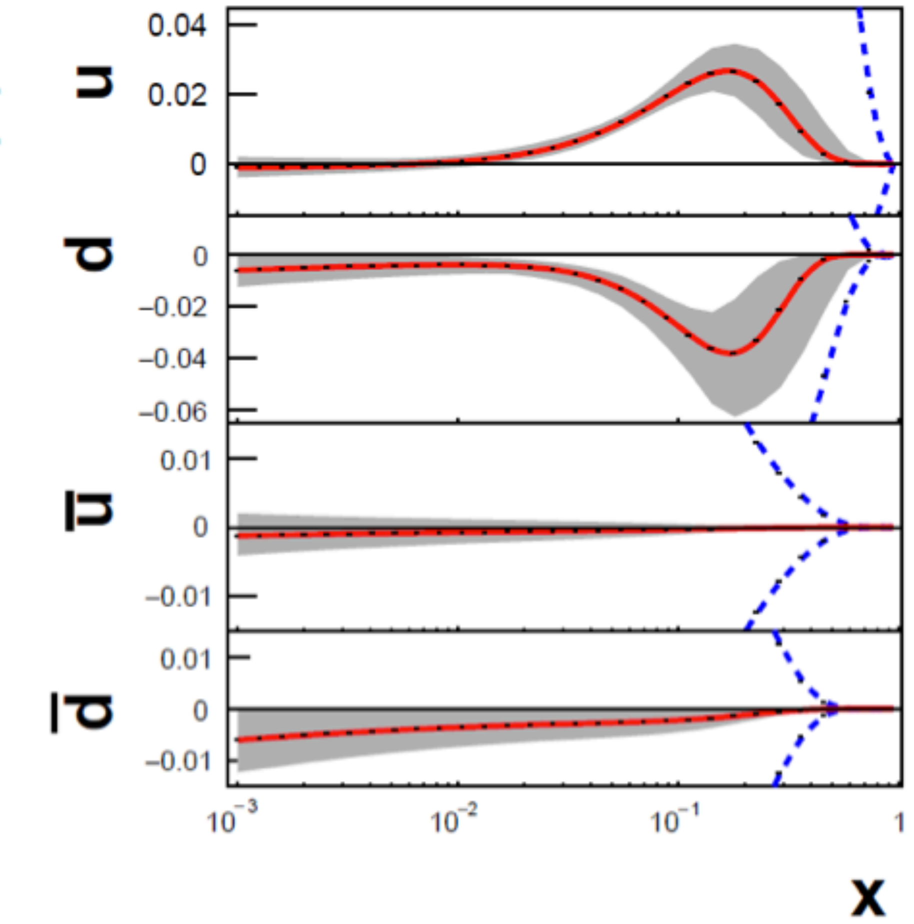
The Sivers Function

Evolution may play a role

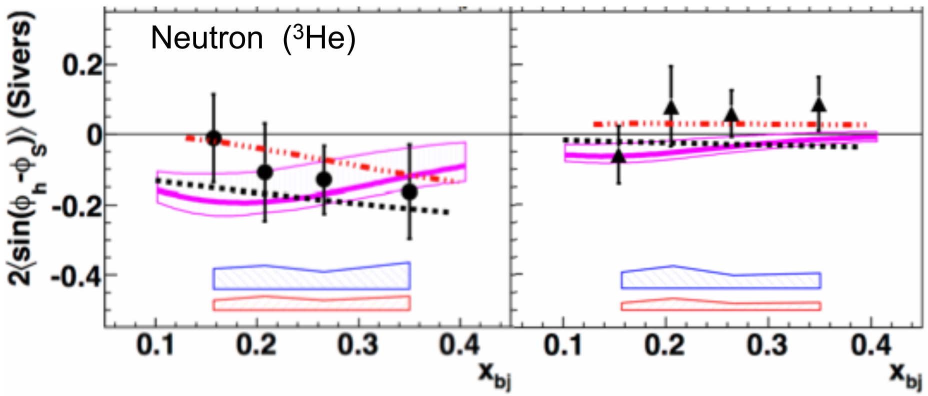


Role of the sea ?

E. Boglione [talk at QCD-N16]



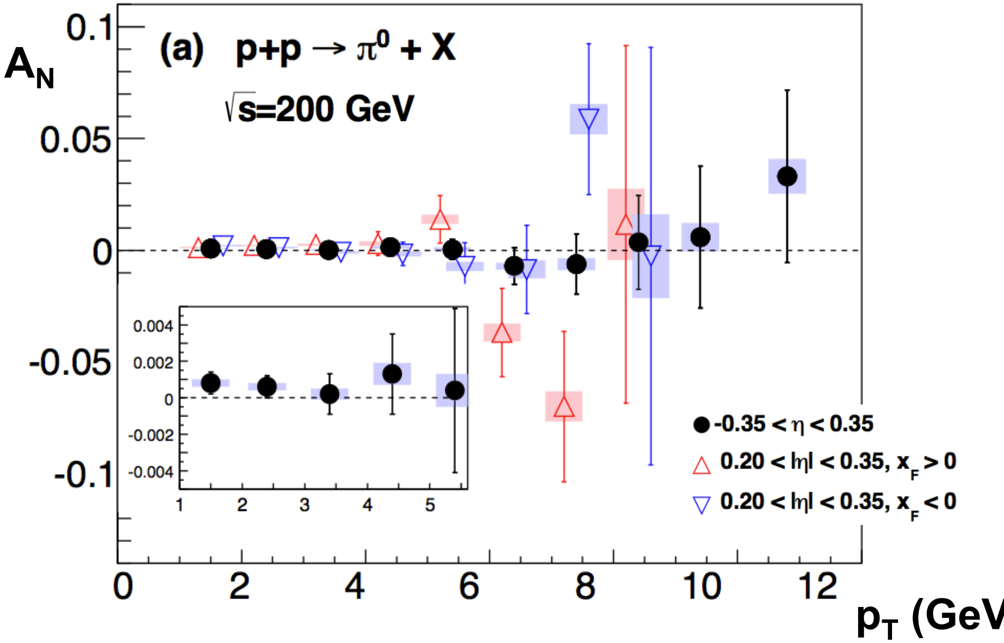
Flavor decomposition

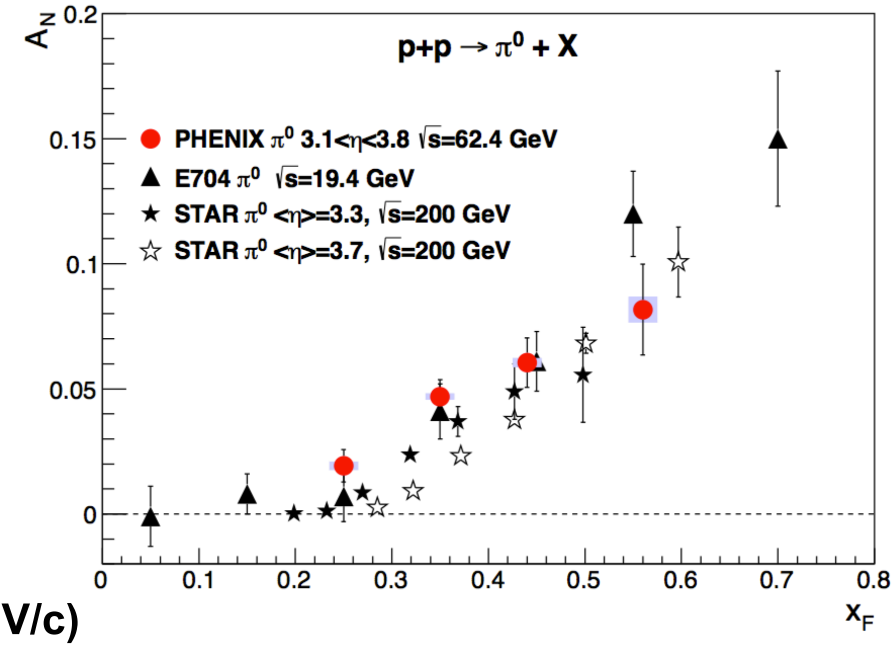


X. Qian *et al.*, PRL 107, 072003 (2011).

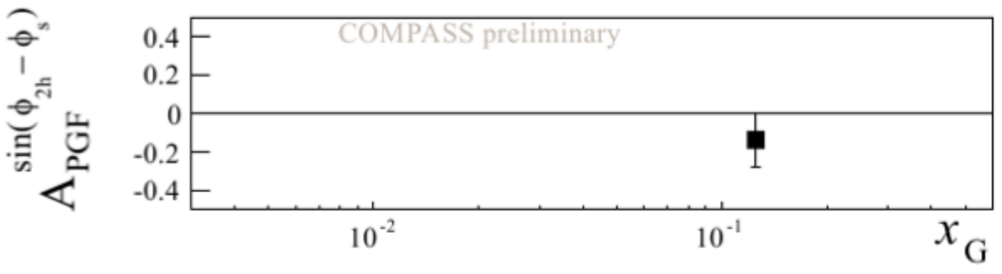
Sivers in the Sea ?

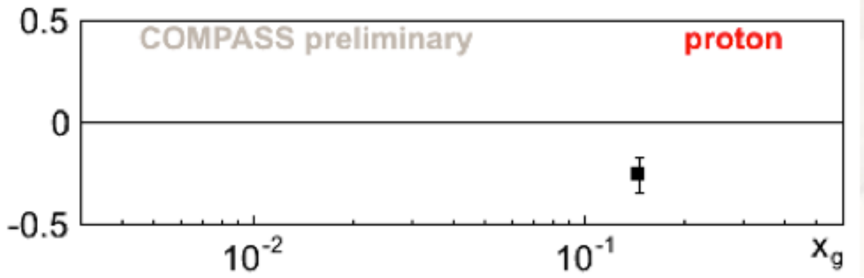
A_N @ RICH: mid rapidity (gluon+sea) and Forward (valence) rapidity PHENIX [arXiv: 1312.1995]





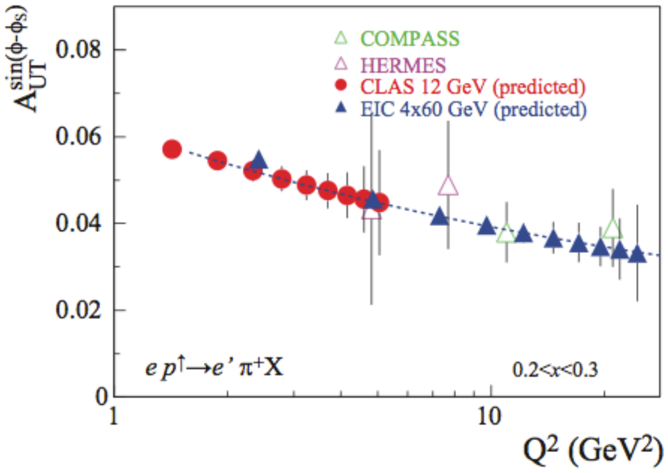
PGF @ COMPASS: gluon Sivers from deuterium and proton targets



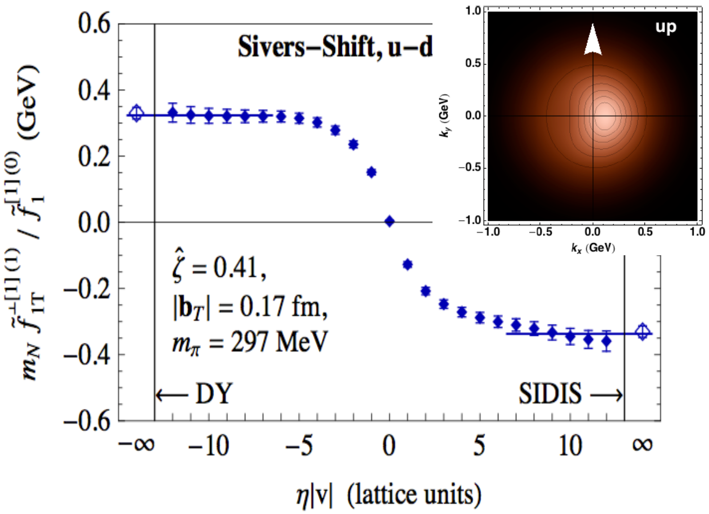


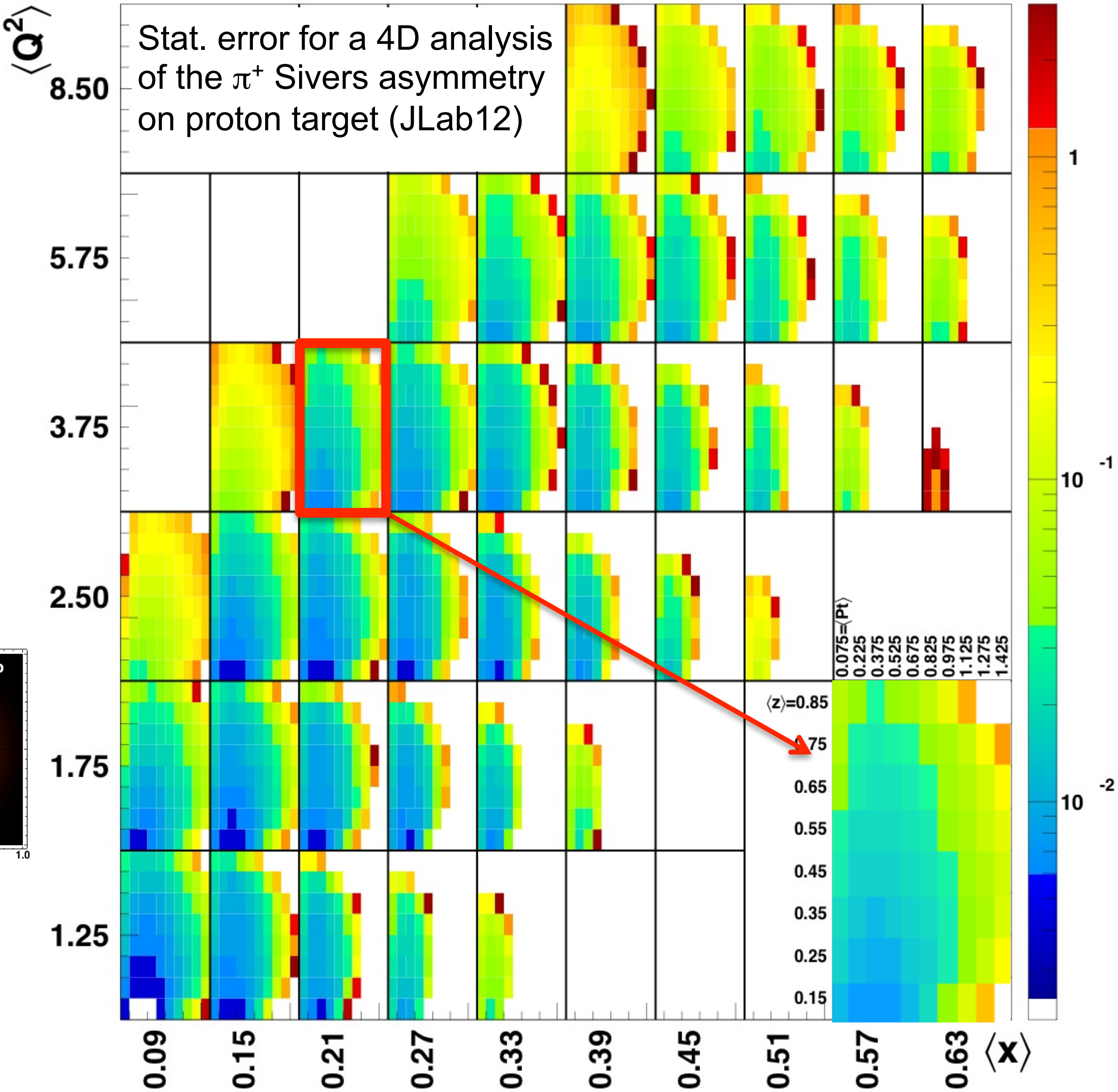
Sivers Mapping

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



Lattice $\langle k_\perp \rangle$

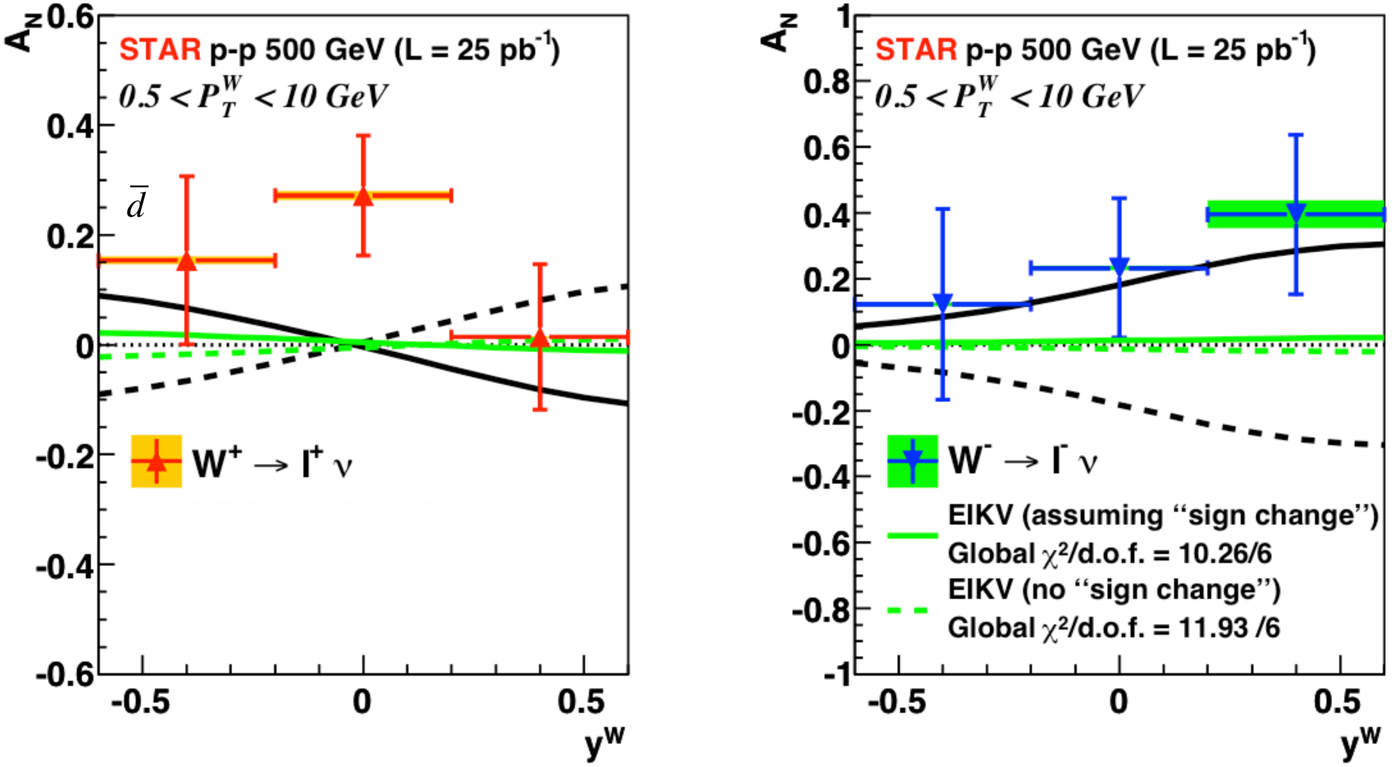




Stat. error for a 4D analysis of the π^+ Sivers asymmetry on proton target (JLab12)

Sivers Sign Change

Weak boson production p p → WX @ STAR



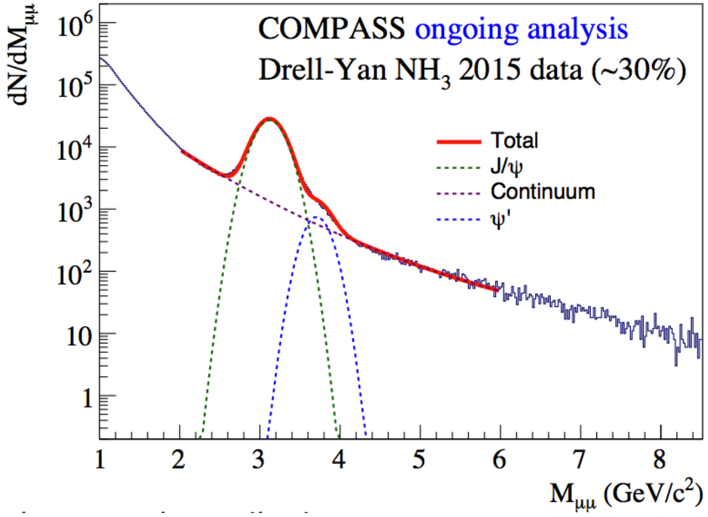
STAR [arXiv: 1511.06003]

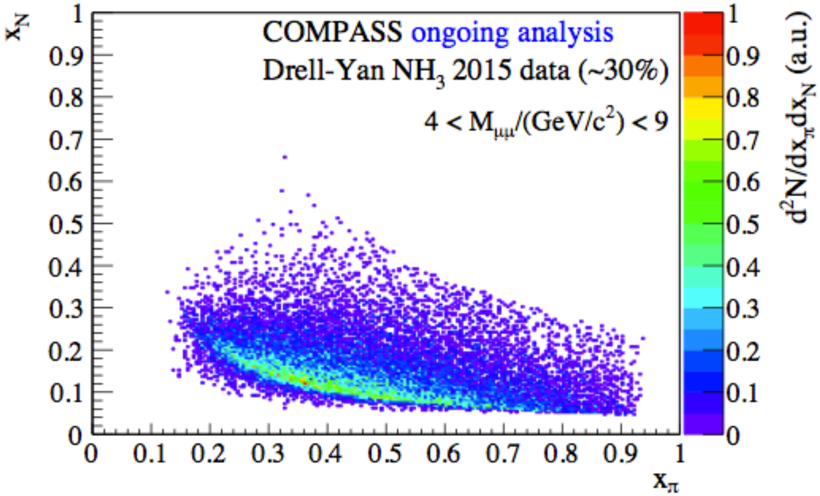
Solid line: assumption of sign change for Sivers
Dashed line: assumption of no sign change for Sivers
KQ prediction (unevolved)
EIKV prediction (largest predicted evolution effect)

Kang and Qiu, [PRL 103 (2009) 172001]
Echevarria++, [PRD 89 (2014) 074013]

Sivers Sign Change

Drell-Yan reaction pp → eeX at COMPASS





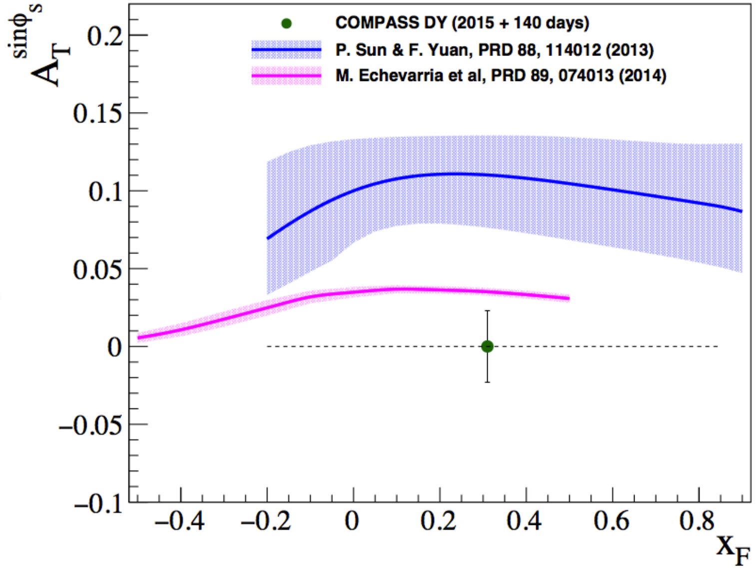
Pion beam on NH$_3$ target

$A_{UU}^{\cos(2\phi)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$ Boer-Mulders

$A_{UT}^{\sin(\phi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$ Sivers

$A_{UT}^{\sin(2\phi-\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$ transversity

$A_{UT}^{\sin(2\phi+\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$ pretzelosity



Conclusions

The last decade provided many evidences that correlation of partonic transverse degrees of freedom in the nucleon do exist and manifest in hadronic interactions

Next step: Moving from phenomenology to rigorous treatment (predictive power)

New data coming from SIDIS, DY, e+e- and pp reactions should allow to:

- Constrain models in the valence region
- Test factorization, universality and evolution
- 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

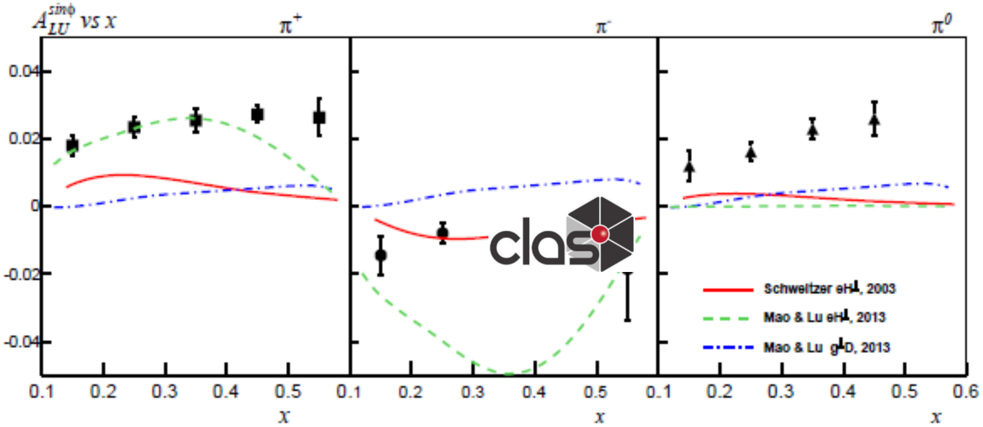
A comprehensive study provides access to the peculiar dynamics of the QCD confined world

Higher-twists

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"



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

E12-06-112 Hall-B