SPIN PHYSICS AND THE
3D NUCLEON STRUCTURE

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Int. School of Nuclear Physics – 37th Course
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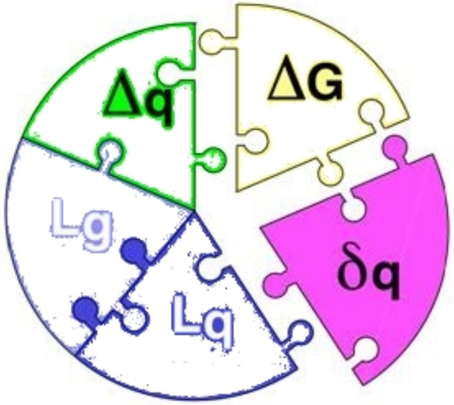
The Spin Degree of Freedom

In our exploration of the QCD micro-world

Fundamental: do not neglect spin !!

Two questions in Hadronic Physics
await explanation since too long

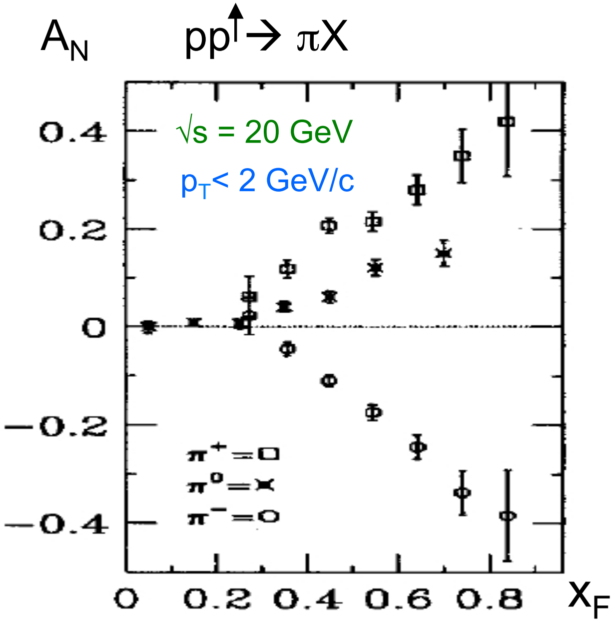
Proton Spin Budget



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

?

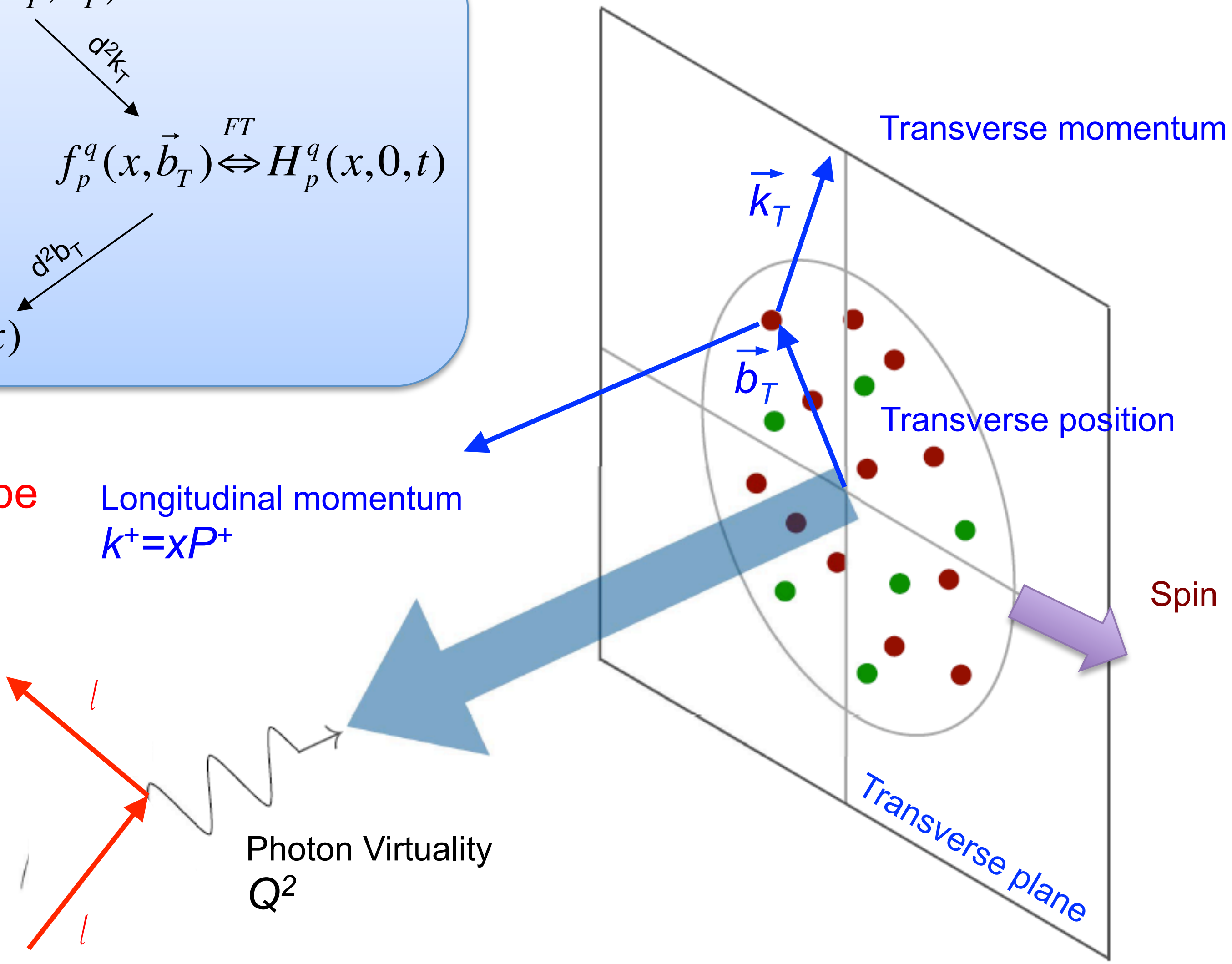
Single Spin Asymmetries



The 3D Nucleon Structure

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

Confinement Scale

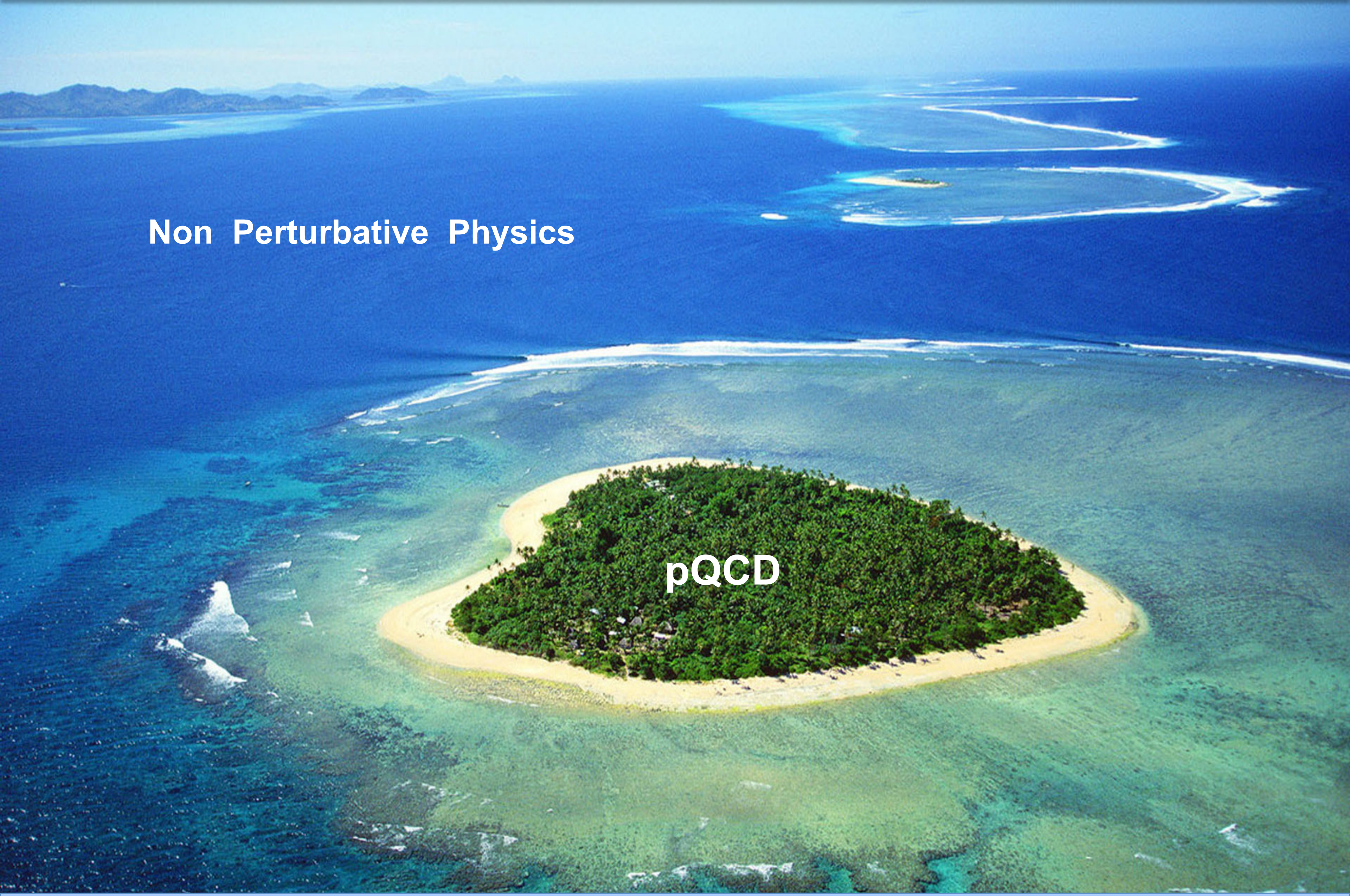


High Energy Probe
Hard Scale

Longitudinal momentum
$k^+=xP^+$

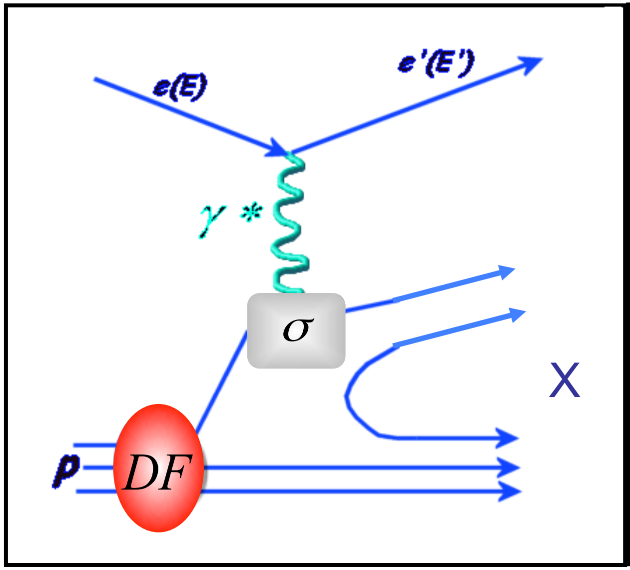
Photon Virtuality
Q^2

The QCD View



Moving Out of Collinearity

Inclusive



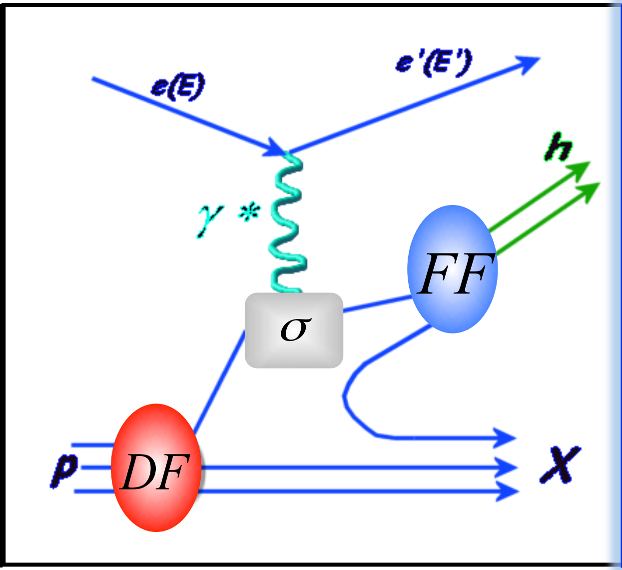
SFs (x,Q^2)

Structure functions
(unpolarized, helicity)

Sum over quark charges

$$d^2\sigma \propto F_2\left(=\sum_q e_q^2 q(x)\right)$$

Semi-inclusive



PDFs (x,z,Q^2)

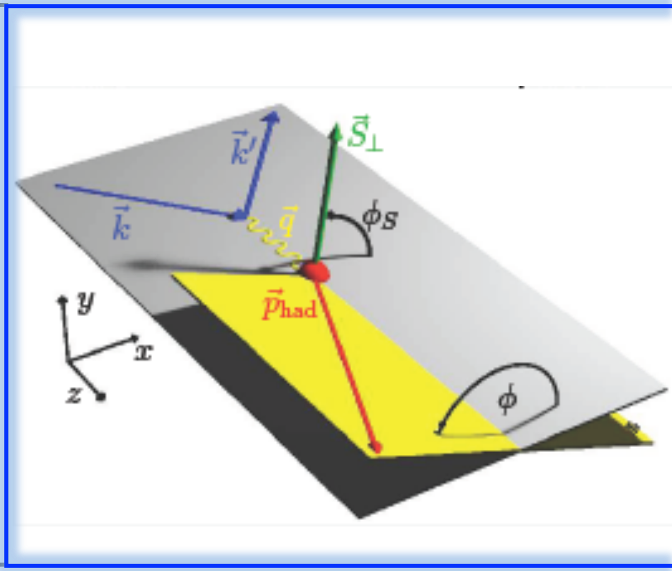
Parton distributions

$$D_u^{\pi+}(z) > D_u^{\pi-}(z)$$

Flavor sensitivity

$$d^3\sigma^h \propto \sum_q e_q^2 q(x) D_q^h(z)$$

Semi-inclusive



TMDs $(x,z,P_{h\perp},Q^2)$

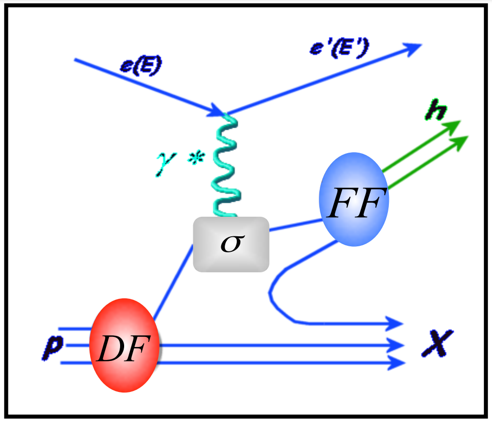
Transverse momentum
dependent parton distri.

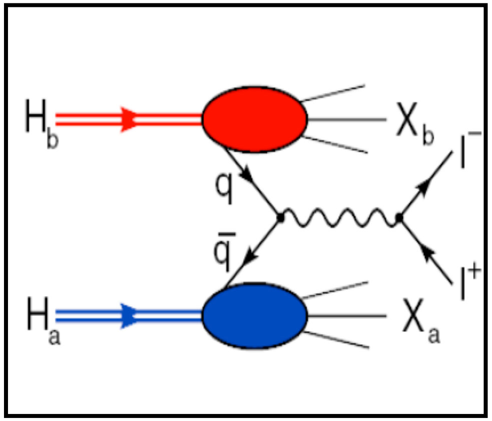
Spin-Orbit effects

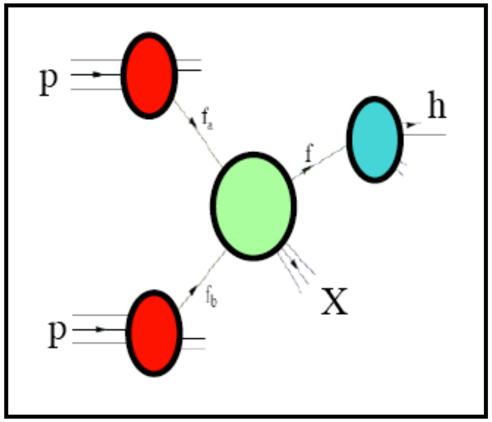
$$d^6\sigma^h \propto \sum_q e_q^2 q(x,k_T)\otimes D_q^h(z,p_T)$$

Rich and Involved phenomenology !!

Physics reactions







SIDIS: rich phenomenology, the most explored so far

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

e^+e^- colliders: powerful fragmentation laboratories

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

DY: challenging for experiments (only unpolarized so far)

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

Hadron reactions: challenging for theory (ISI + FSI)

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

DIS Cross-Section

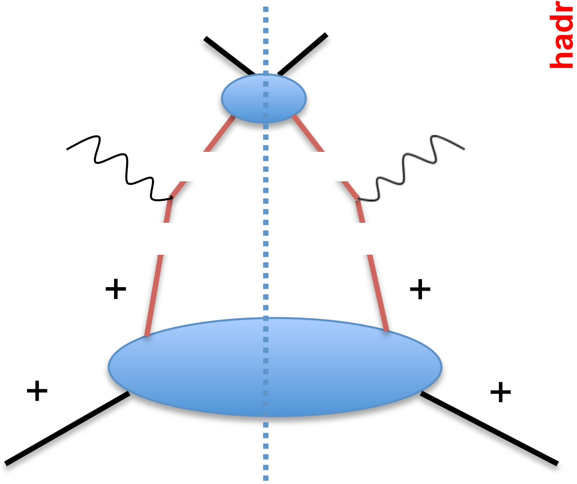
From optical theorem:
related to the imaginary part of the forward scattering

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

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

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

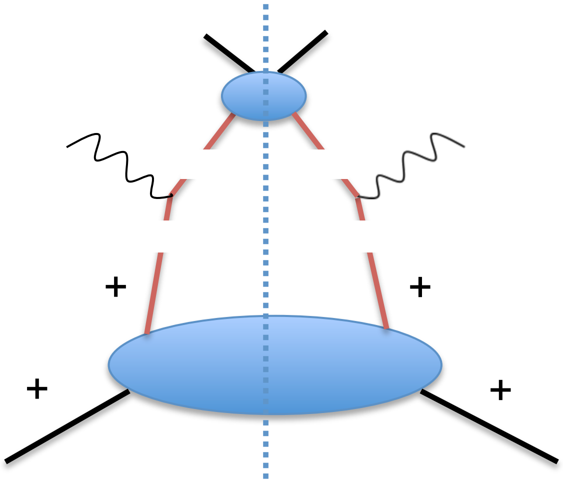
nucleon polarisation

N/q	U	L	T
U	f_1		$\boldsymbol{h}_1^{\perp}$
L		g_1	$\boldsymbol{h}_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	$h_1, h_{1T}^{\perp}$

DIS Cross-Section

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

TMD Factorization holds for p_T<<Q



Quark fragmentation

Hard scattering

Quark-quark correlator

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

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

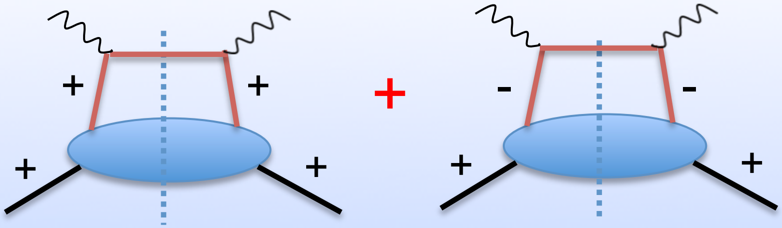
$$+ S_L\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}\right] + S_T\lambda_e\left[\sqrt{1-\varepsilon^2}\,\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right]$$

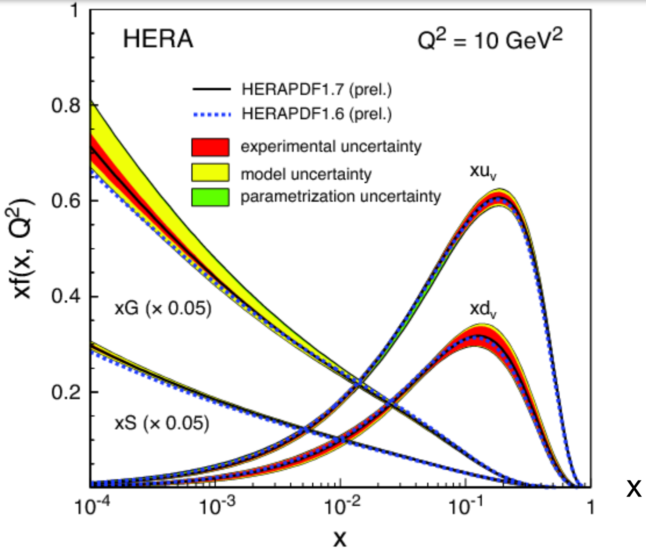
Parton Number Density

Unpolarized TMDs

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

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





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nucleon polarisation

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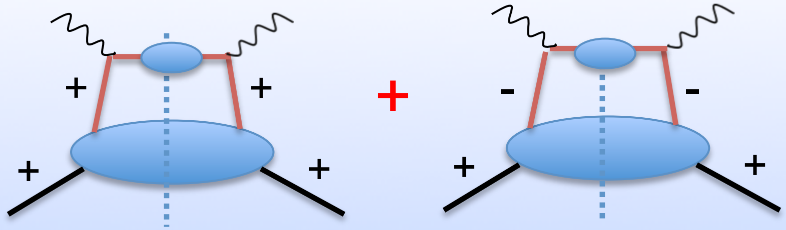

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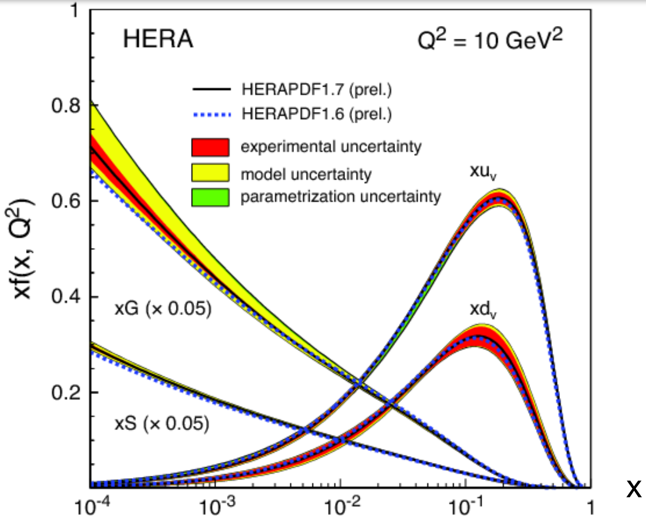
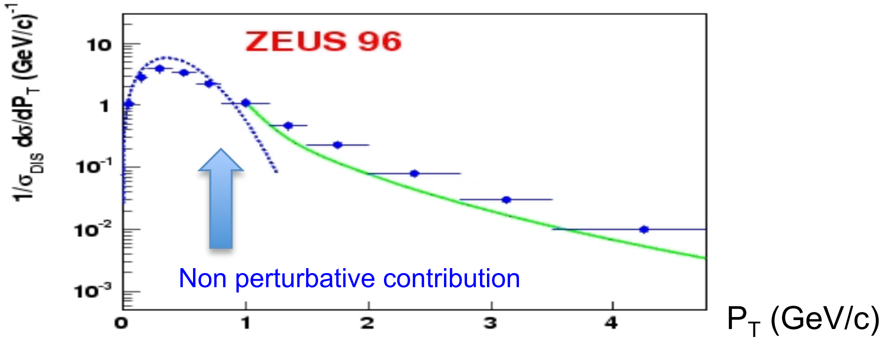
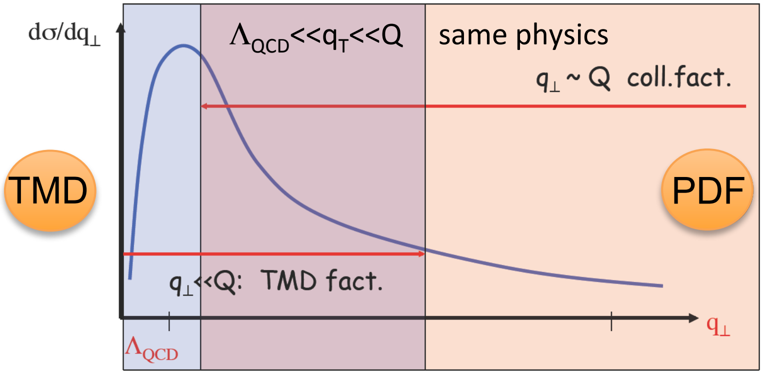
quark polarisation

hadron polarisation

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



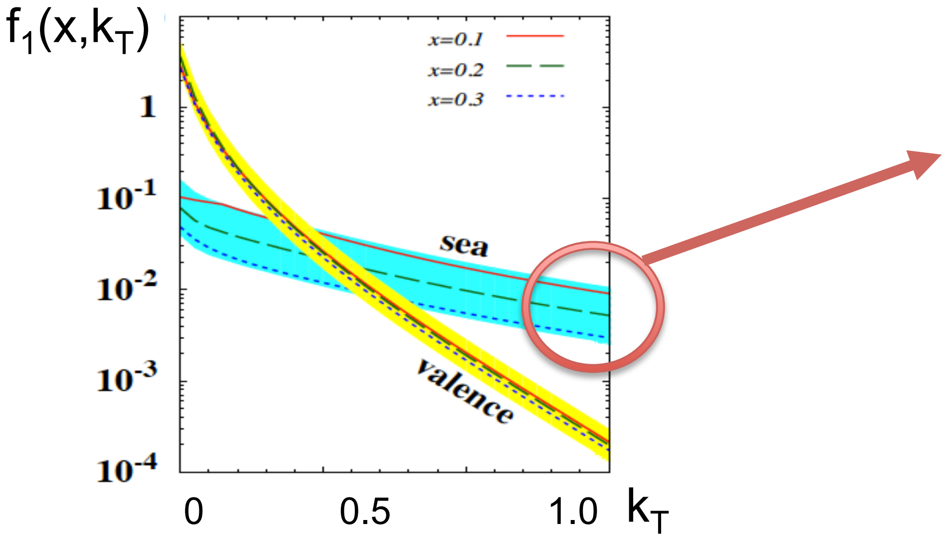




The $P_{h\perp}$-unintegrated multiplicities

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

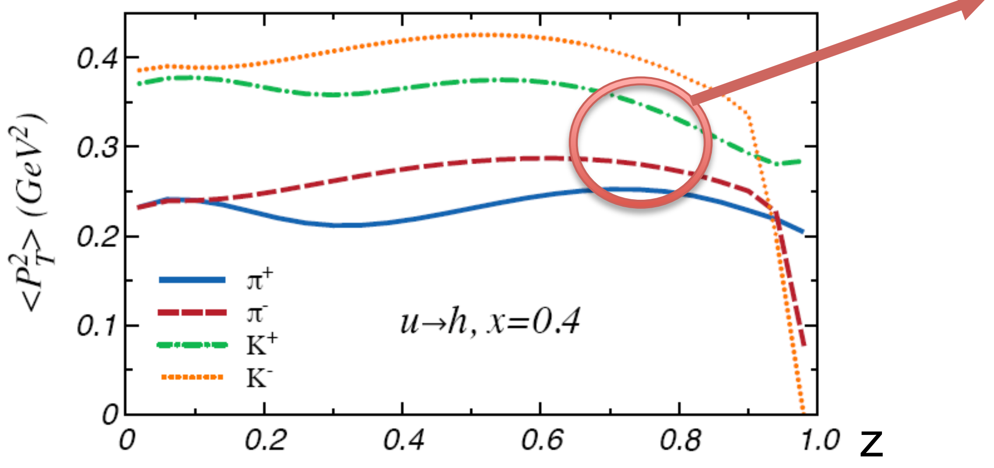
P. Schweitzer++ [arXiv:1210.1267]



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

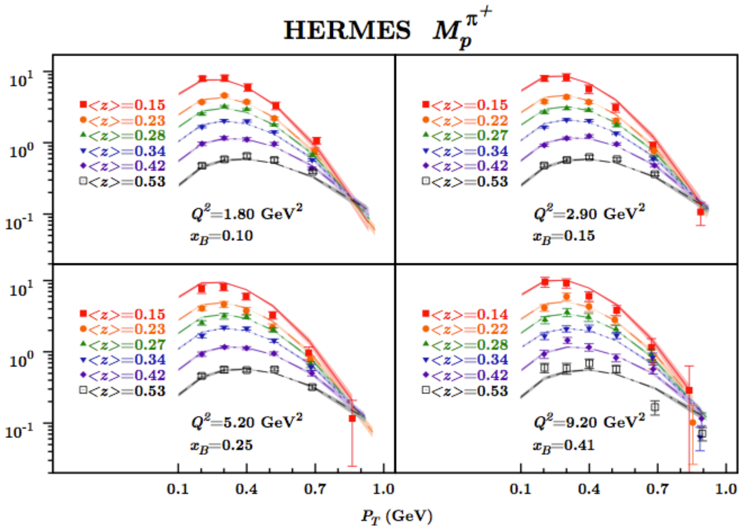
The $P_{h\perp}$-unintegrated multiplicities

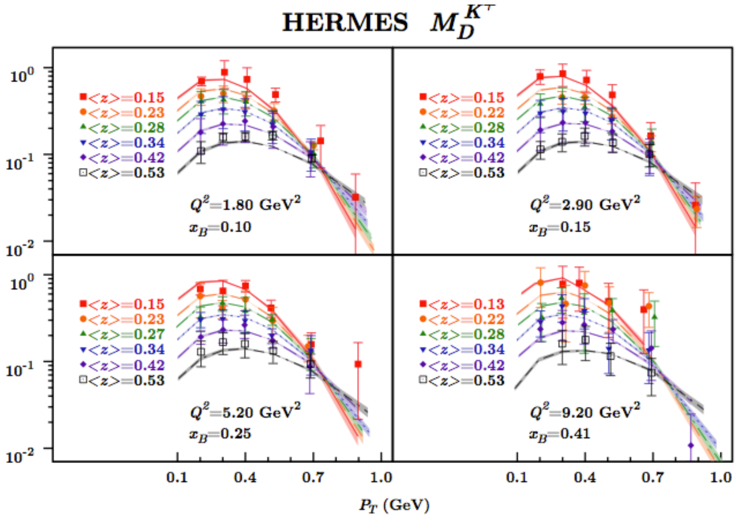
$$\sigma_{UU} \propto f_1(x,k_T) \otimes D_1(z,p_T)$$

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

i.e. from gaussian anstaz:

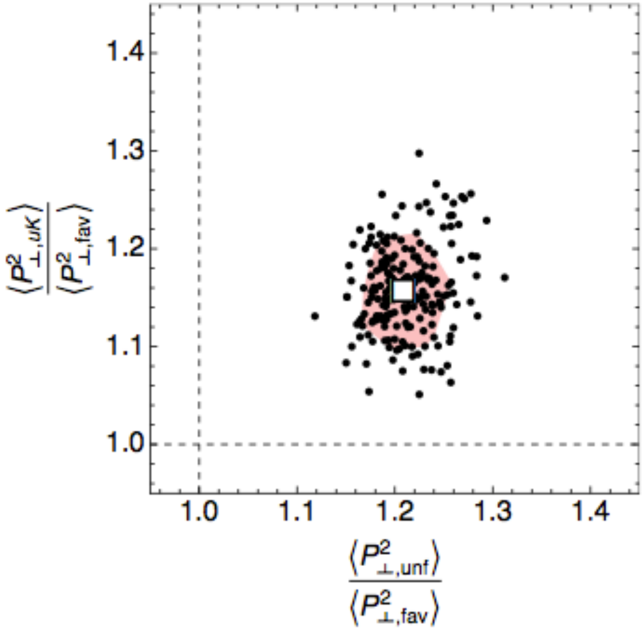
$$\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$$





M. Anselmino++ [arXiv:1312.6261]

A. Signori++ [arXiv:1309.3507]



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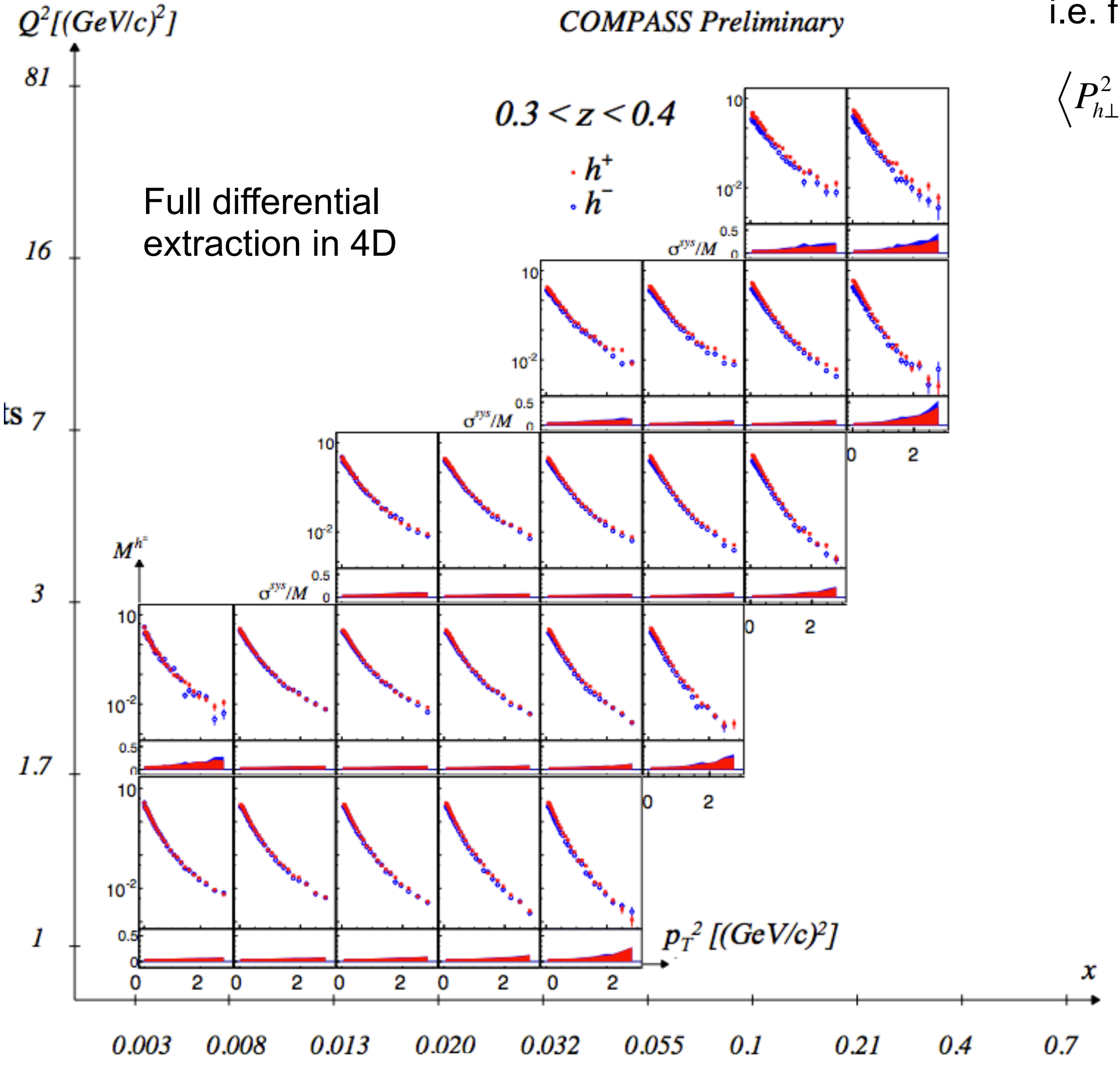
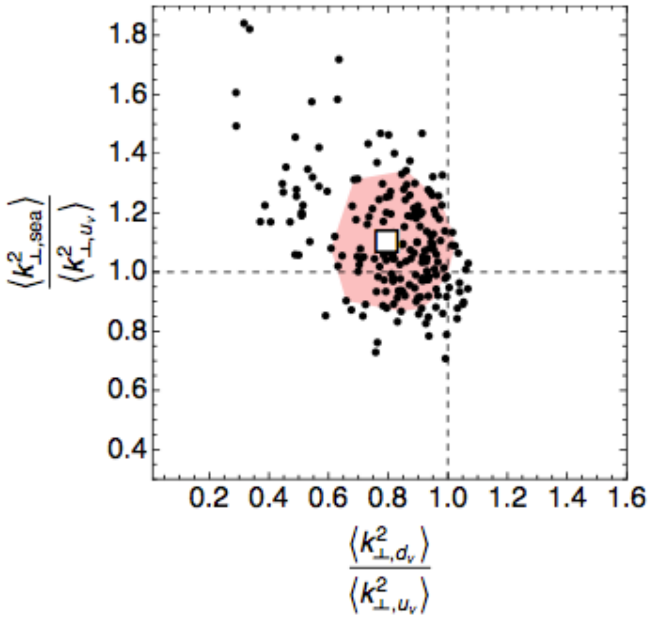


Full differential extraction in 4D

M. Anselmino++ [arXiv:1312.6261]

A. Signori++ [arXiv:1309.3507]



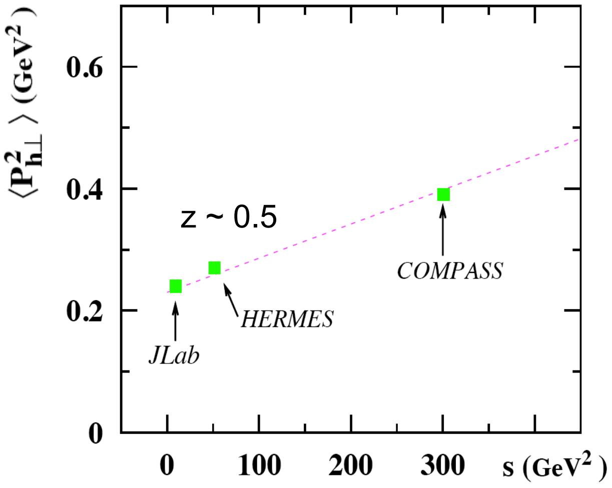
SIDIS alone does not provide clear sensitivity on k_T, p_T flavor dependence

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

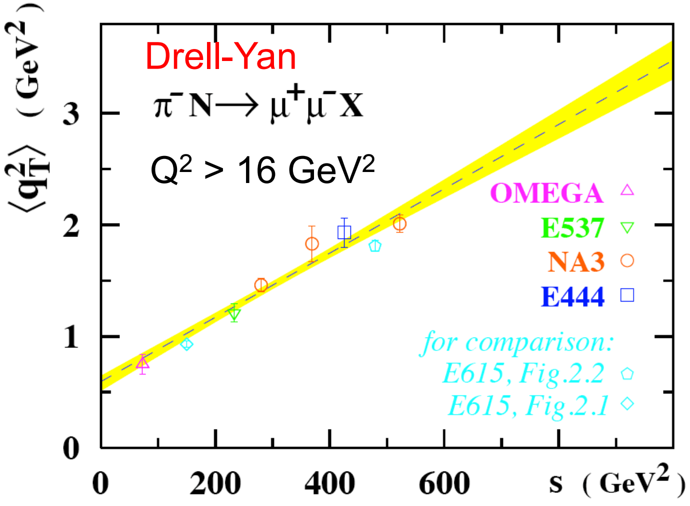
≠

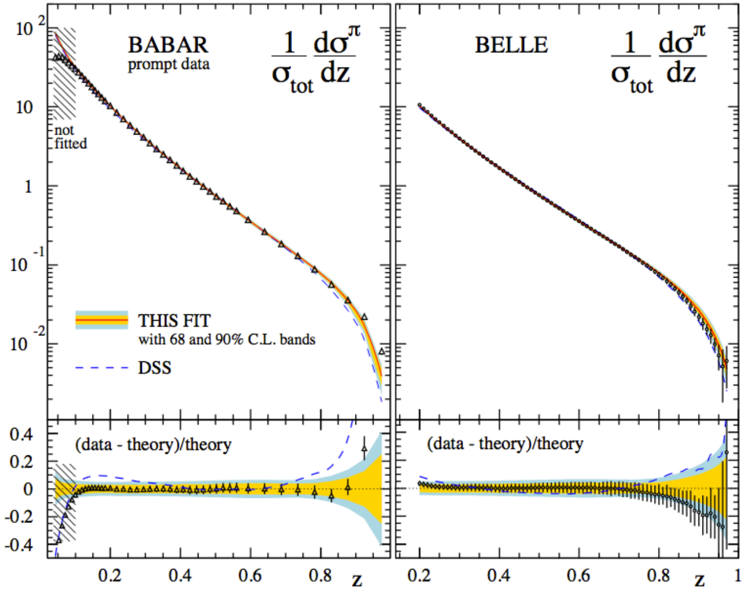
DGLAP

B-factories

Q^2 ~ 100 GeV^2

But still collinear





Medium modification

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

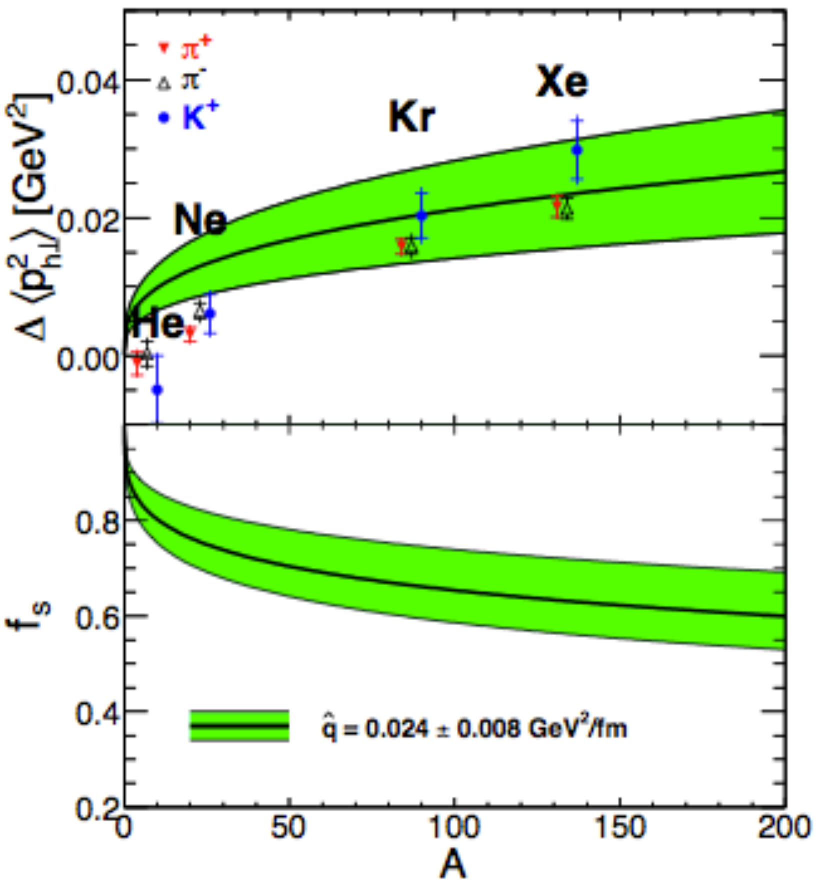
- primordial transverse momentum,
- gluon radiation of the struck quark,
- the formation and soft multiple interactions of the "pre-hadron"
- the interaction of the formed hadrons with the surrounding hadronic medium

N-B Chang ++ [arXiv:1402.3042]

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

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

HERMES **[arXiv: 0906.2478]**

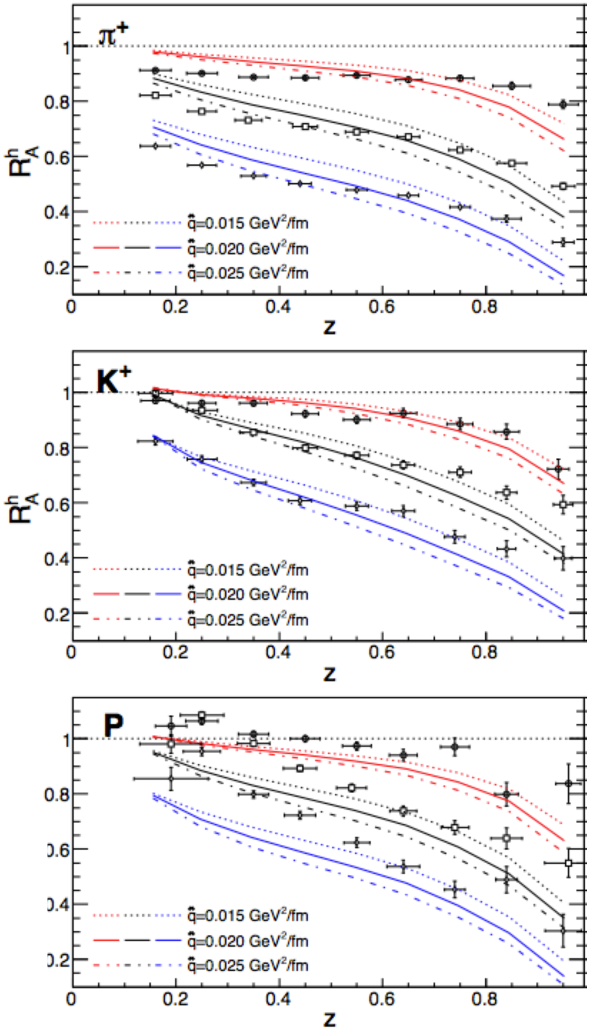


Medium modification

DIS

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

N-B Chang ++ [arXiv:1401.5109]

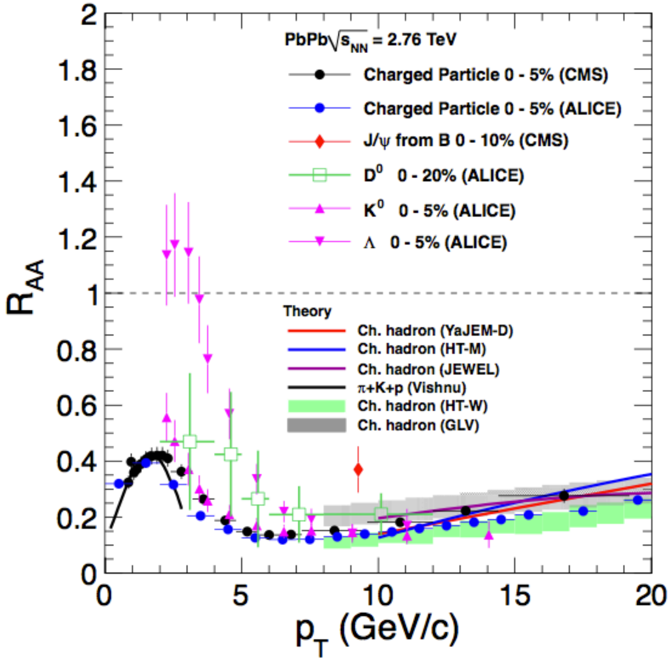


LHC

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

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

JET Coll. [arXiv:1312.5003]



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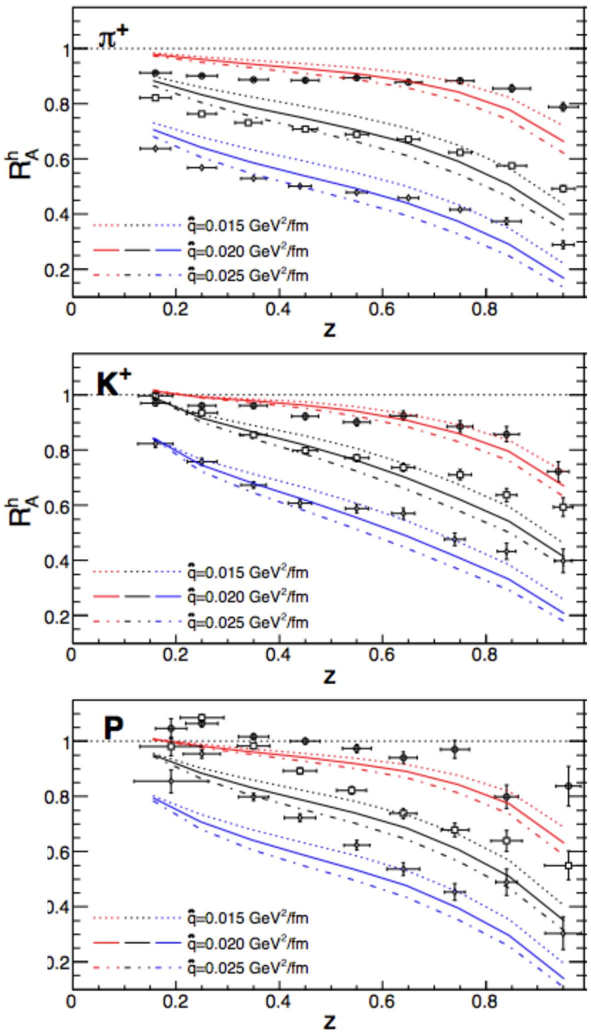


RHIC

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

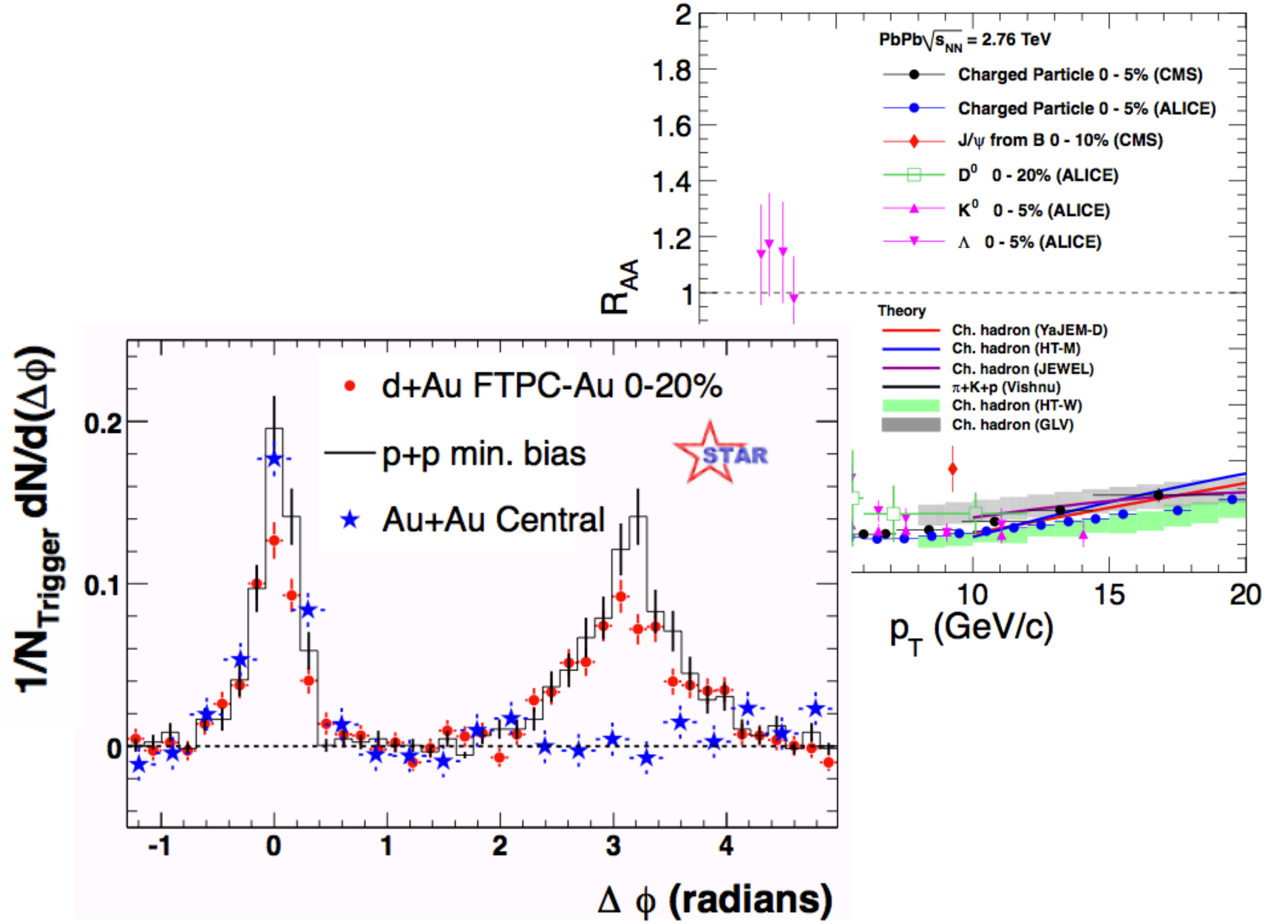
Au+Au $\sqrt{s} = 200\ \mathrm{GeV/n}$

LHC

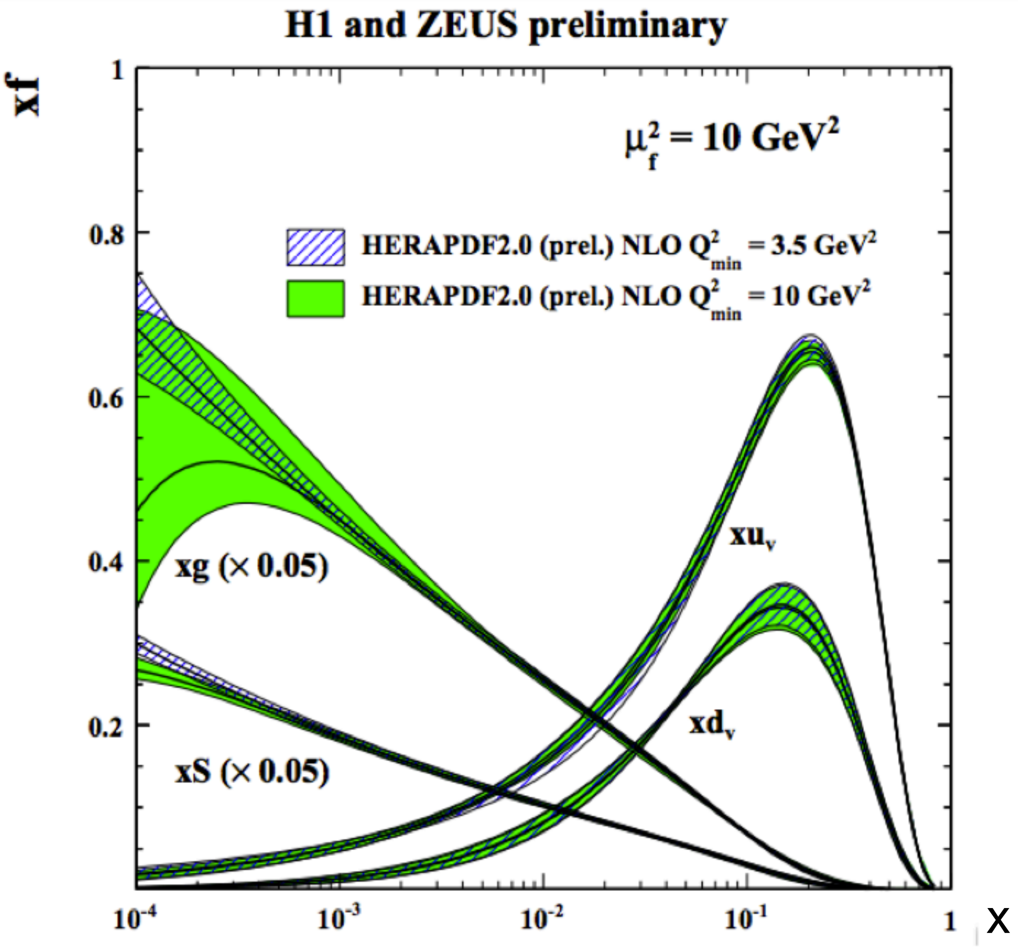
$$\hat{q} \approx 1.9 \pm 0.7\ \mathrm{GeV}^2/\mathrm{fm}$$

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

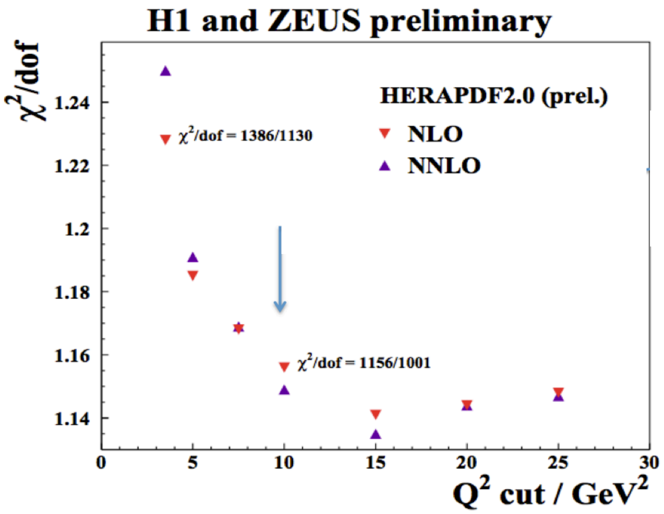
JET Coll. [arXiv:1312.5003]

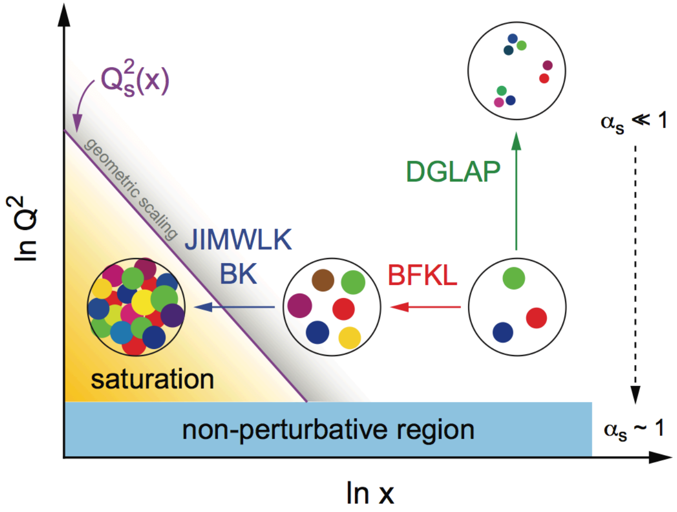


Low-x Physics



[V. Radescu @ DIS14]





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

F. Hautmann and H. Jung [arXiv 1312.7875]

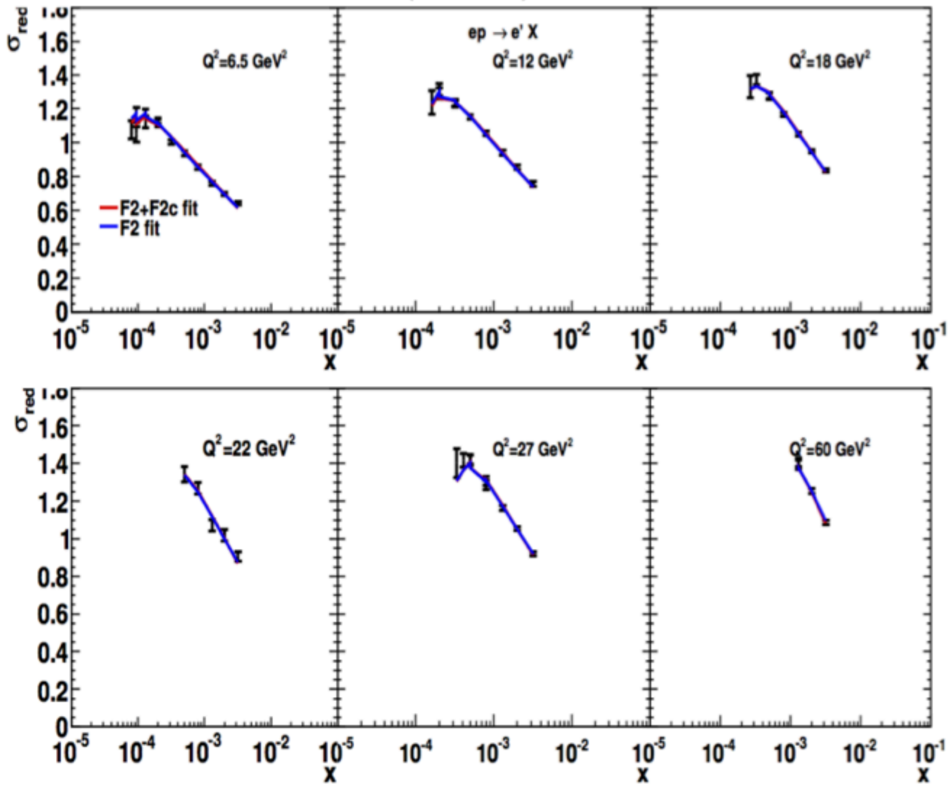
Starting distribution for gluons at q_0

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

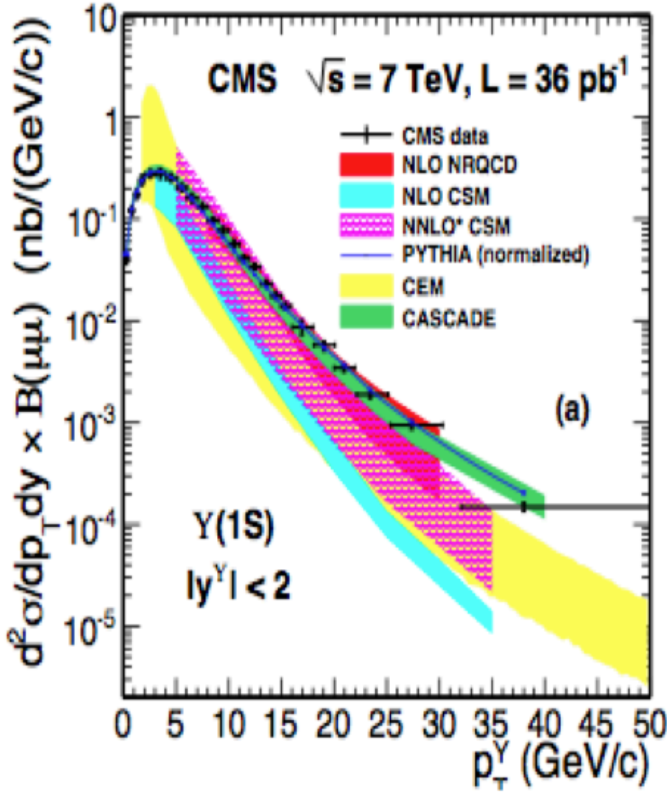
$\sigma^2 = q_0^2/2$

CCFM (BFKL like) evolution + Herafitter package

$F_2(x,Q^2)$



$g^* g^* \to \Upsilon g$ CMS [arXiv:1303.5900]

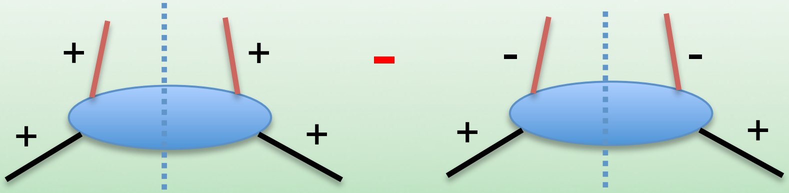


Parton Polarization

Helicity

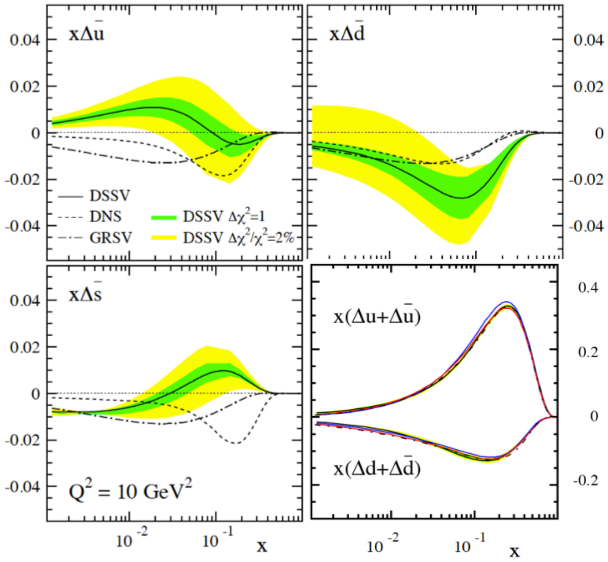
$\Phi^{[\gamma^+\gamma^5]}$

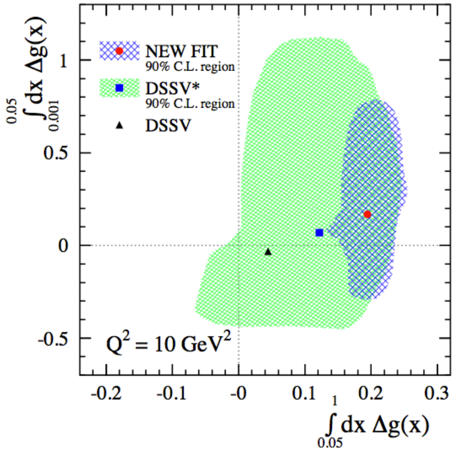
$$f_1(x) = q^+(x) - q^-(x)$$



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

D. De Florian++ [arXiv:1112.0904]





quark polarisation

nucleon polarisation

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quark polarisation

hadron polarisation

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

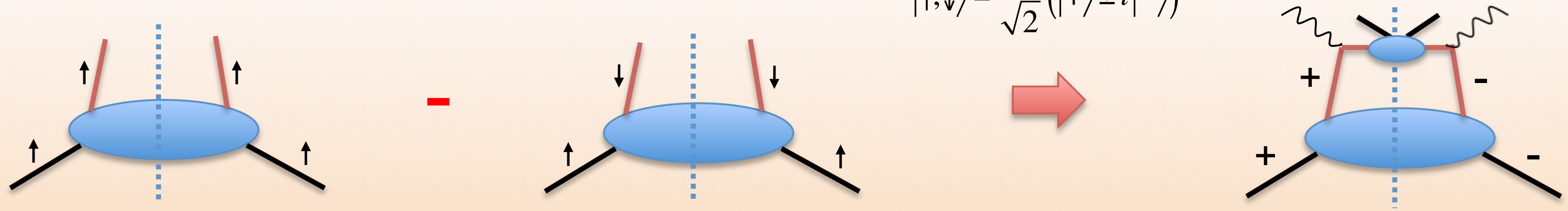
Transversity

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

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

Chirally-odd

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



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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

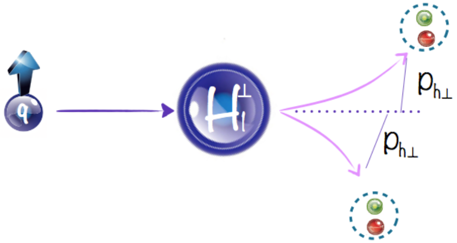
    it requires a chirally-odd fragmentation

hadron polarisation

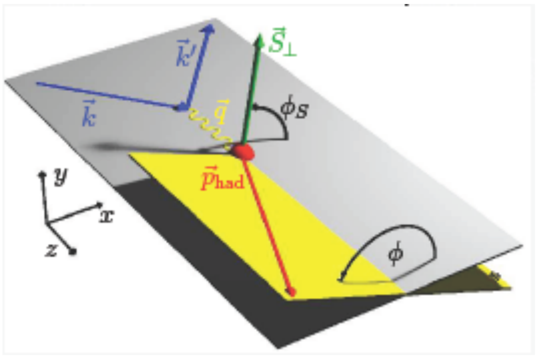
quark polarisation

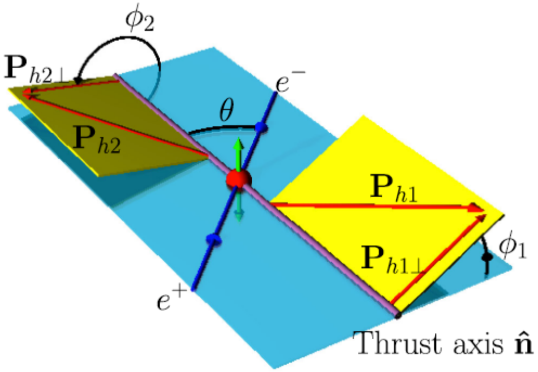
N/q	U	L	T
U	D_1		$H_1^\perp$

Collins function:
a spin-p_T correlator in fragmentation

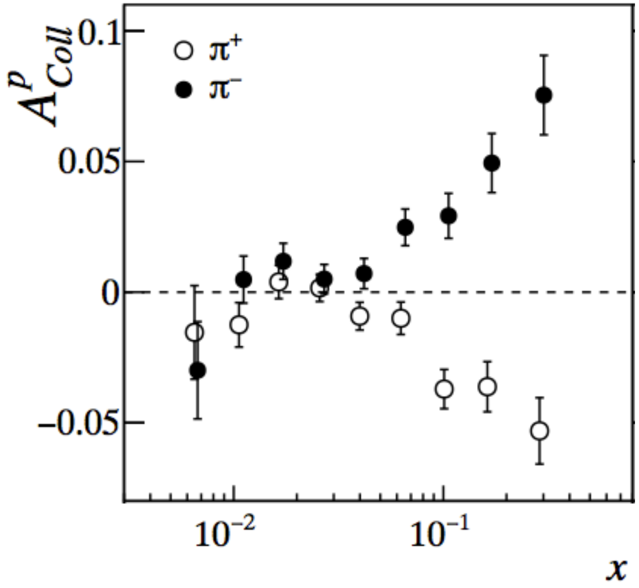


Transversity & Collins Evidences

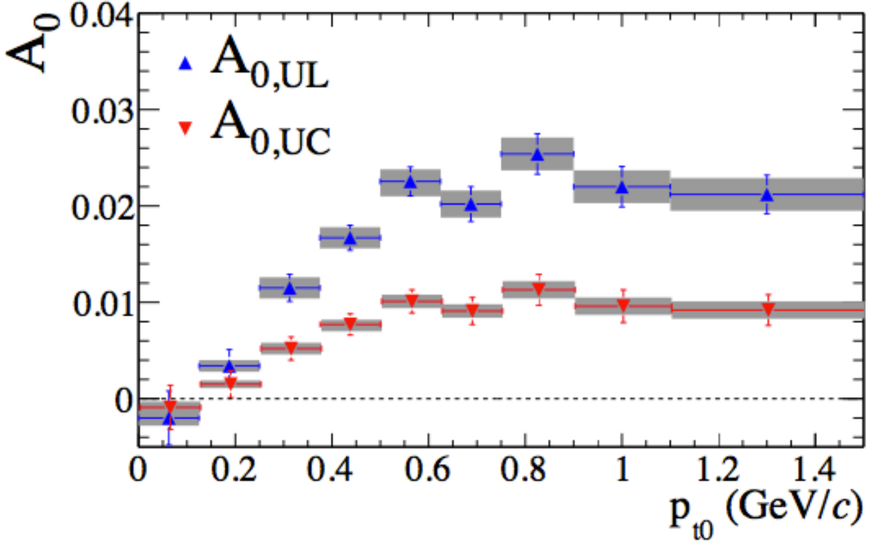




HERMES	**[arXiv 0408013]**
HERMES	**[arXiv 0906.3918]**
COMPASS	**[arXiv 1005.5609]**
COMPASS	**[arXiv 1408.4405]**

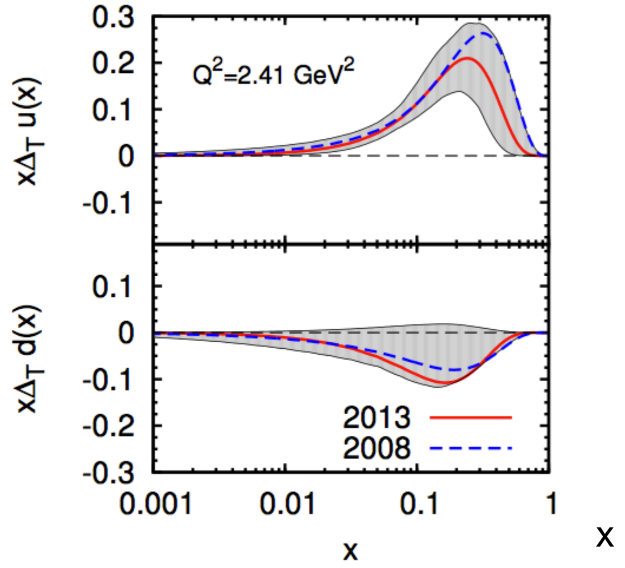


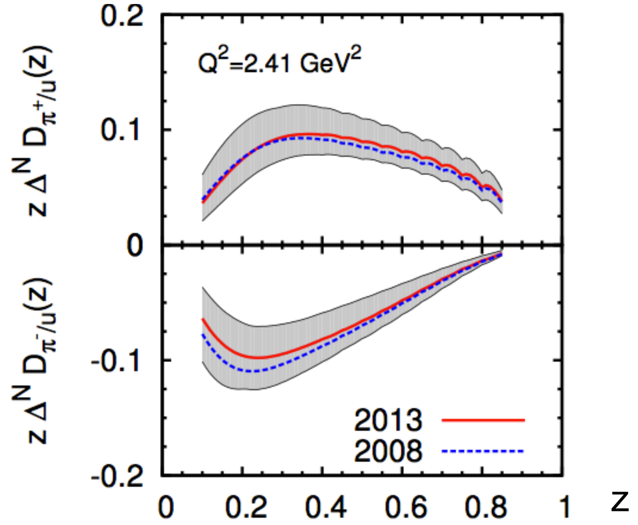
Belle	**[talk at DIS2014]**
BESIII	**[arXiv 1507.06824]**
Babar	**[arXiv 1309.5278]**



Transversity & Tensor Charge

Distributions:



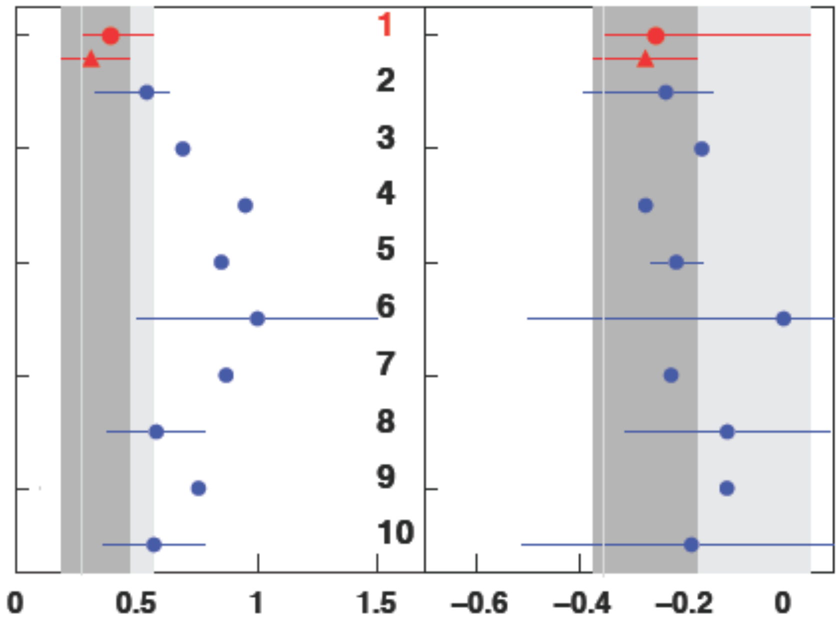


Charges:

Anselmino++ **[arXiv 1303.3822]**

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

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

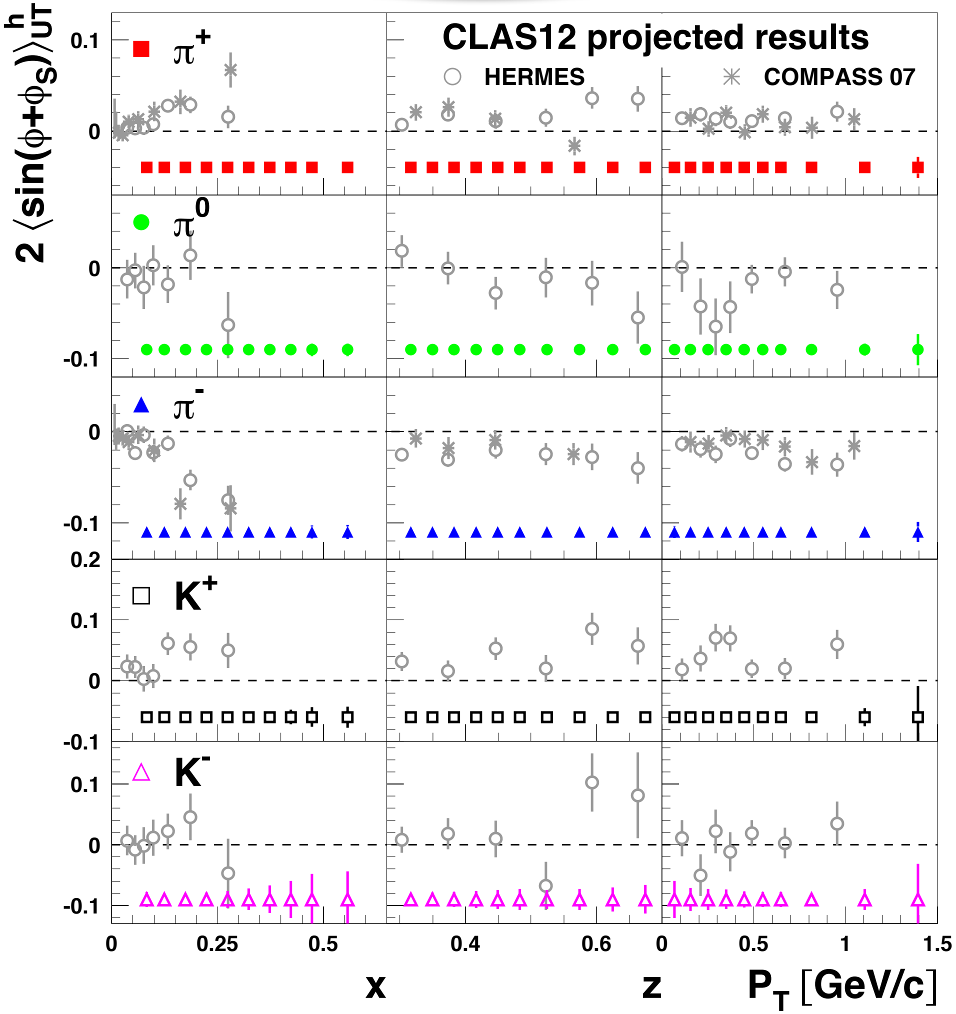


Δu = 0.787 **Δd = -0.319**

Transversity @ JLab12 2016+

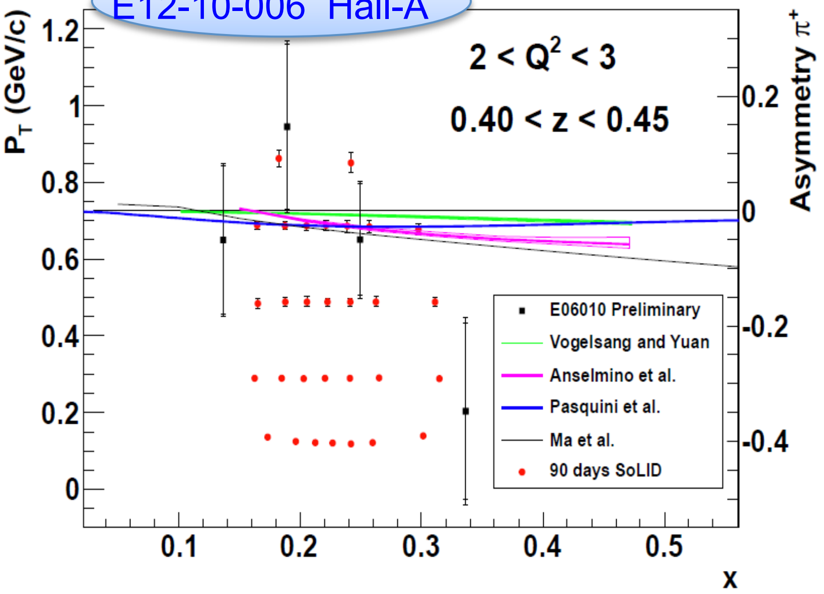
H target

C12-11-111 Hall-B

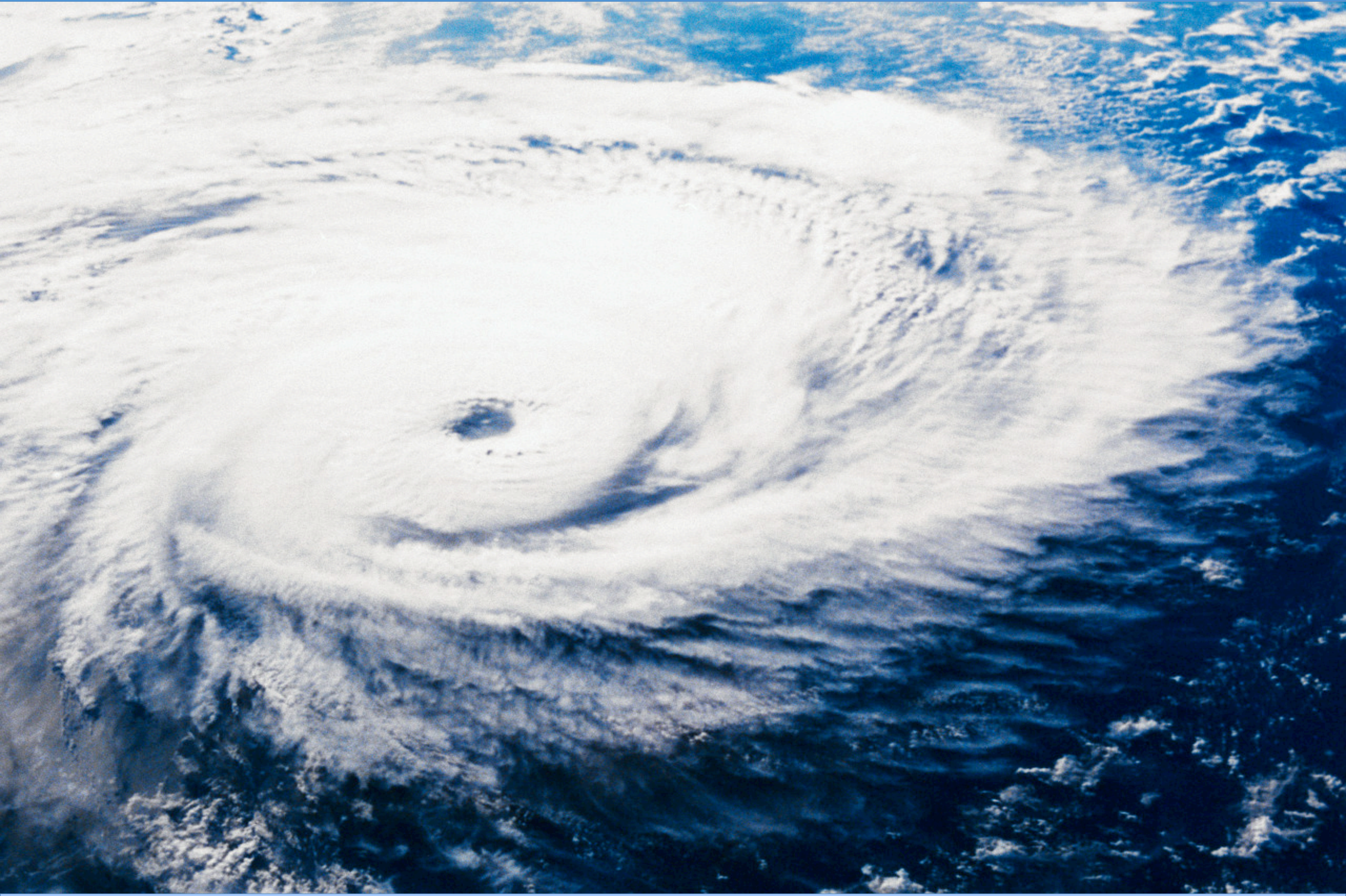


^{3}He target

E12-10-006 Hall-A

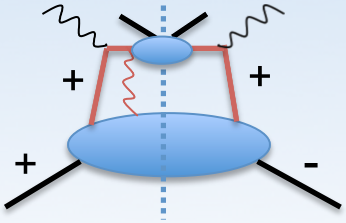


Spin-Orbit Effects



The Sivers Function

T-odd



$\Delta L_z = 1$:

quark polarisation

nucleon polarisation

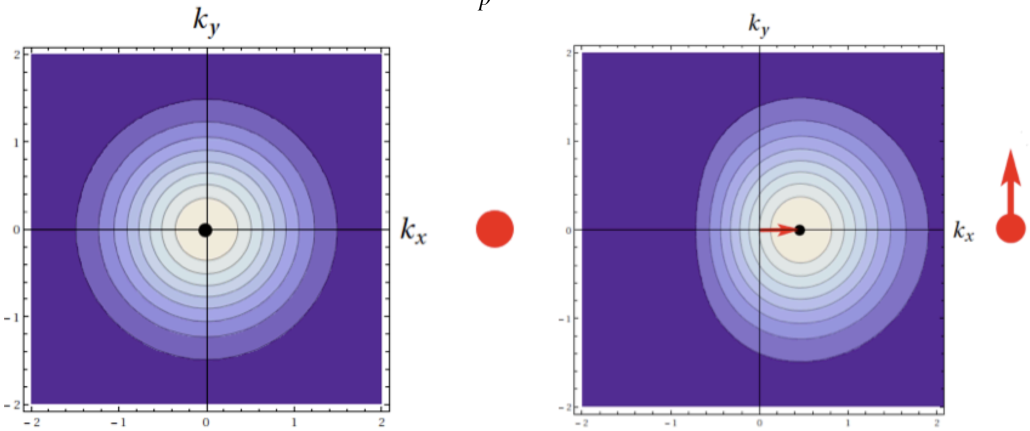
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1, h_{1T}^\perp$

quark polarisation

hadron polarisation

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

$$f^{S_T}(x,k_\perp) = f(x,k_\perp) - \frac{k_\perp}{M_p}\, f_{1T}^\perp(x,k_\perp)\; S_T\cdot(\hat{p}\times\hat{k}_\perp)$$



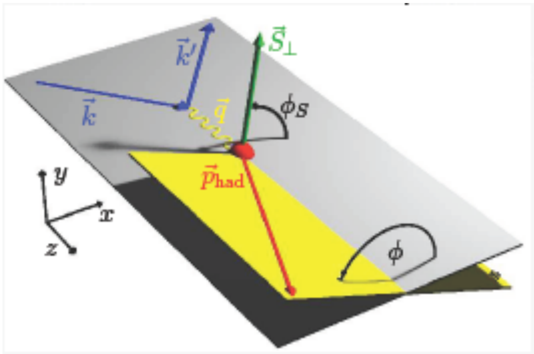
Sivers:

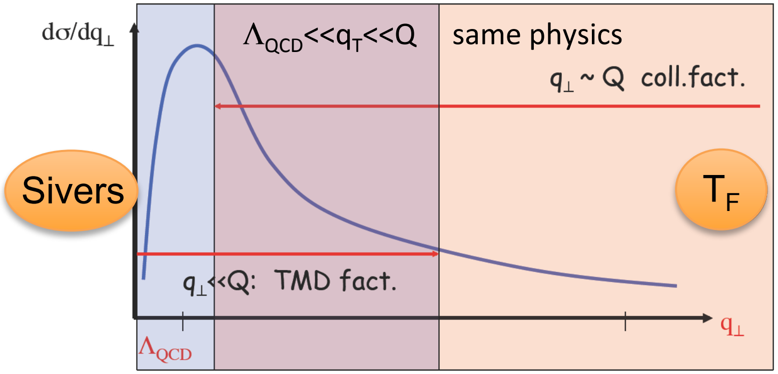
- Correlation of quark k_T with nucleon spin
- Does not survive k_T integration
- Exists as T-odd due to FSI (specific gauge-link)

  FSI break T-reversal symmetry
- Should change sign between SIDIS and DY
- Related to orbital motion

  interference between proton wave-function with $\Delta L_z = 1$

Sivers Signals



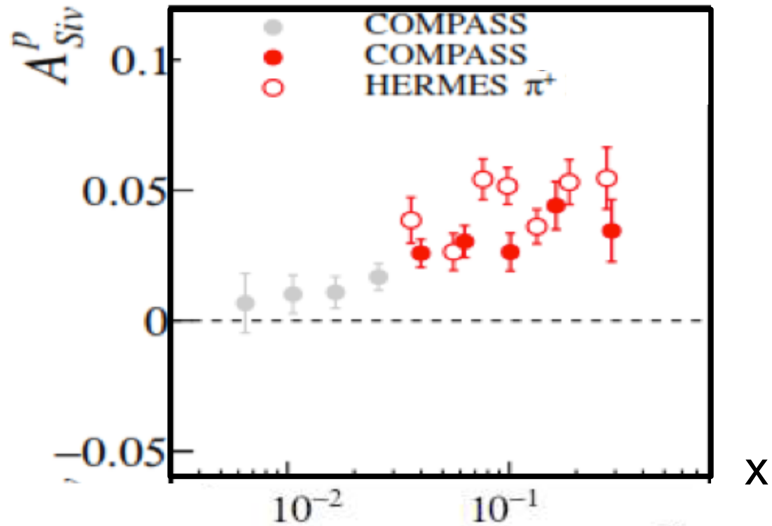


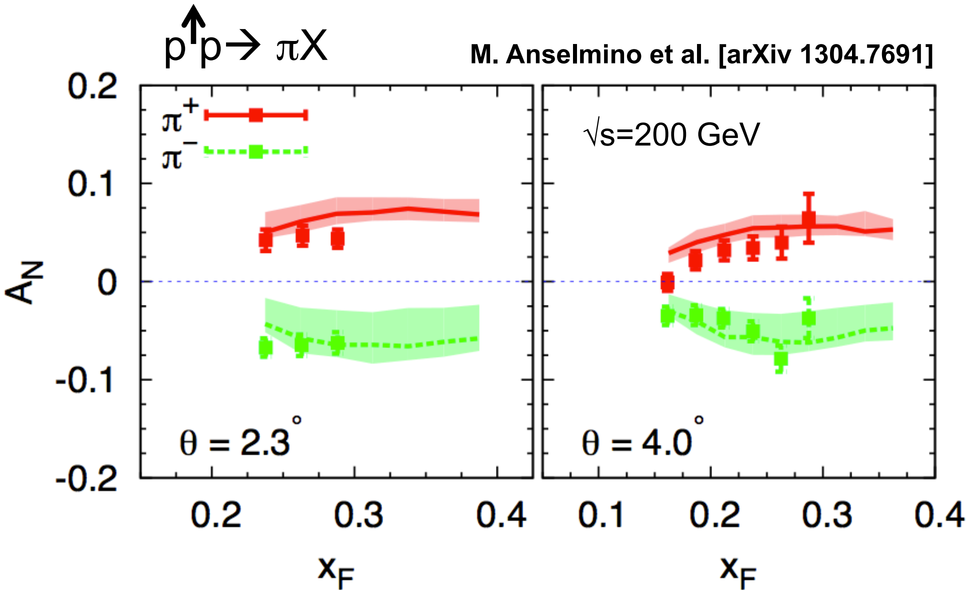
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

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

HERMES **[arXiv:0906.3918]**

COMPASS **[arXiv:1205.5122]**

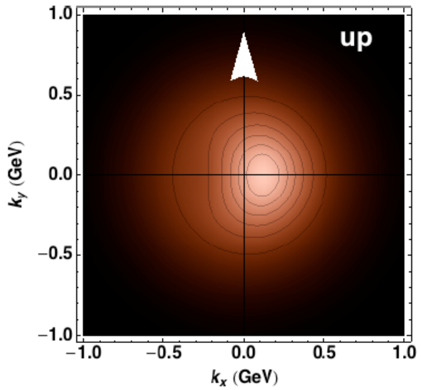


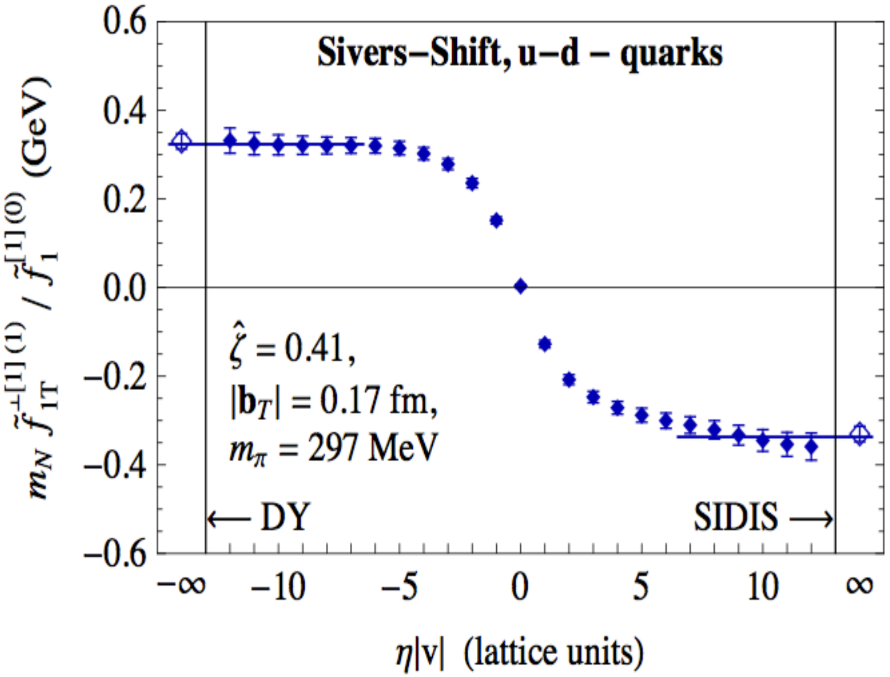


M. Anselmino et al. [arXiv 1304.7691]

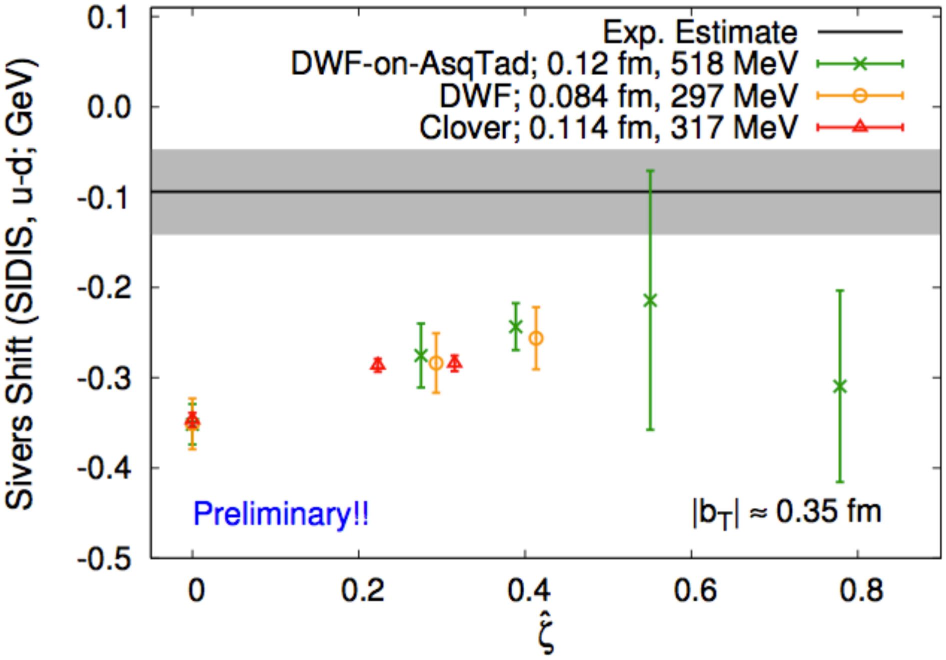
Sivers on Lattice

$$m_h \frac{\tilde{f}_{1T}^{\perp[1](1)}(0,\ldots)}{\tilde{f}_1^{[1](0)}(0,\ldots)} = \frac{\int dx \int d^2k_T\, k_y \Phi^{[\gamma^+]}(x,k_T,S_T=(1,0))}{\int dx \int d^2k_T\, \Phi^{[\gamma^+]}(x,k_T,S_T=(1,0))}$$

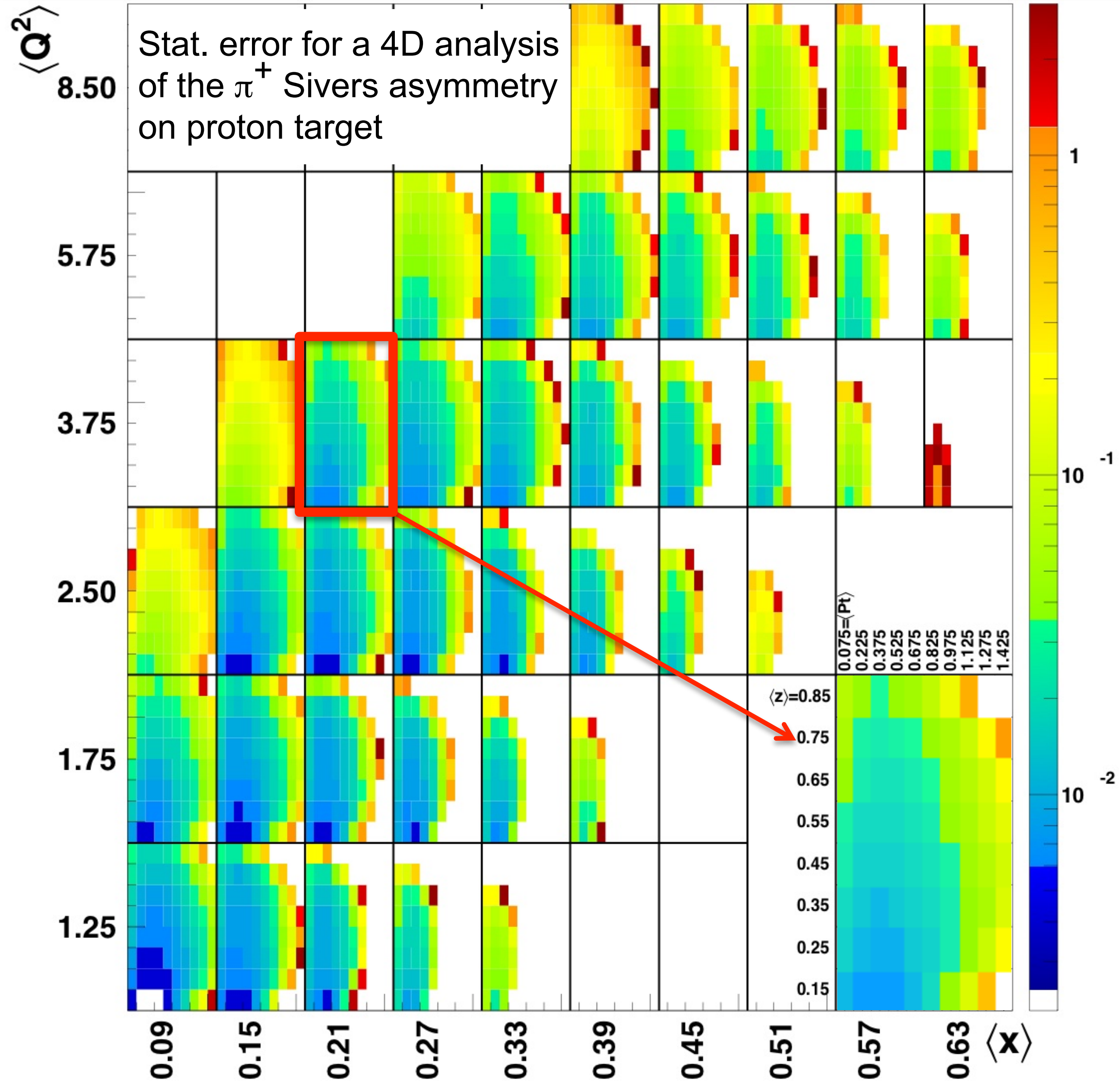




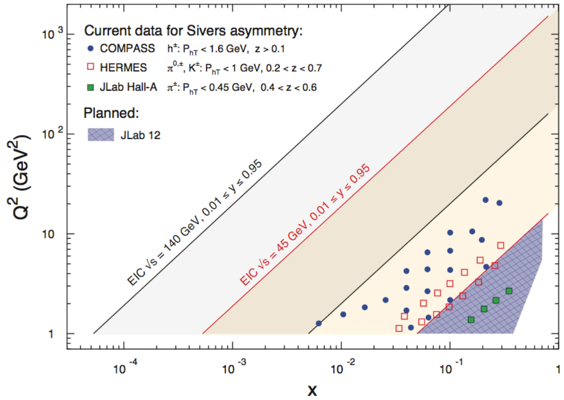
M. Engelhardt++ [arXiv:1506.07826]

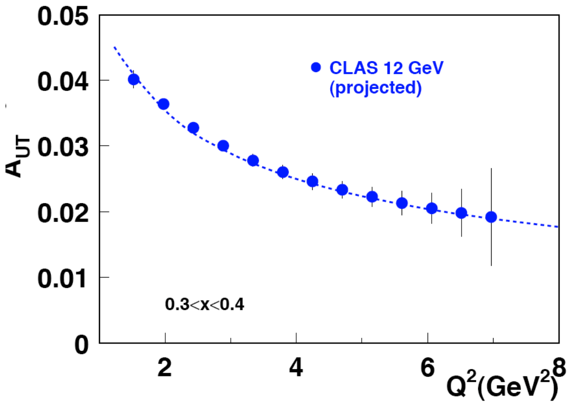


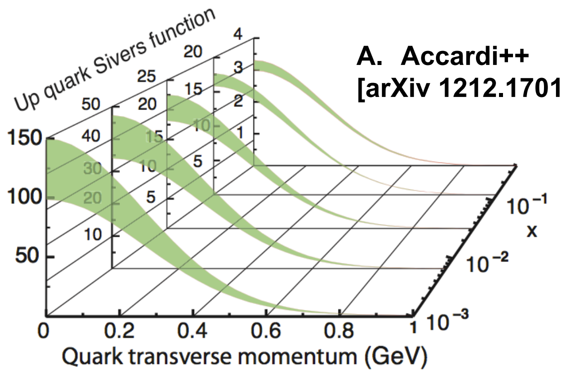
Sivers Mapping @ JLab12 + EIC



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



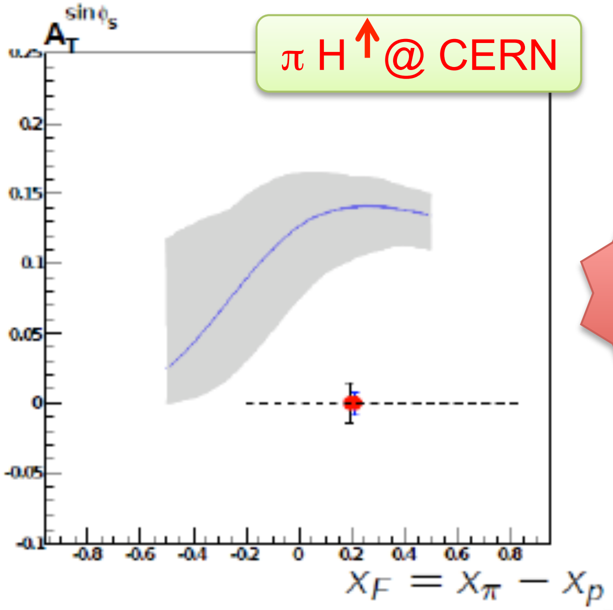




A. Accardi++
[arXiv 1212.1701]

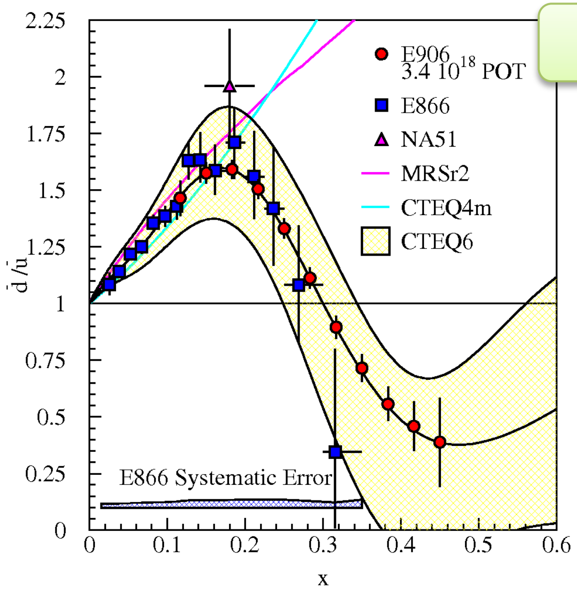
The Drell-Yan Landscape 2015+

π H↑ @ CERN

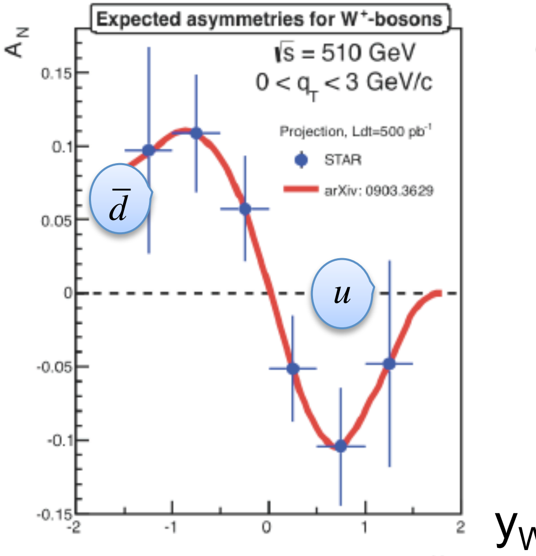


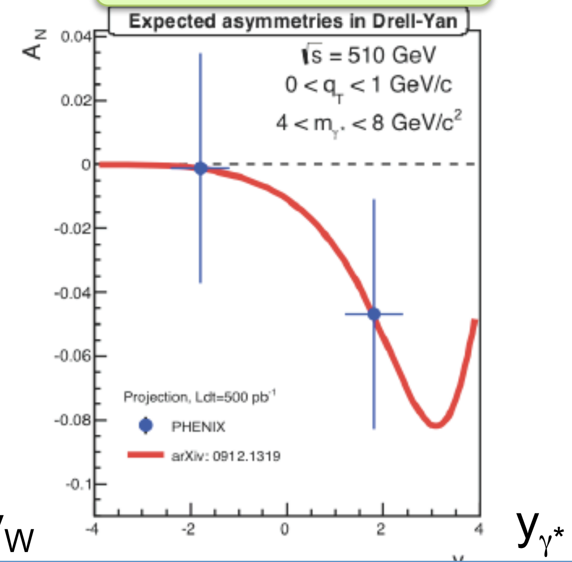
TMD SIGN CHANGE ?

pp, pd @ Fermilab

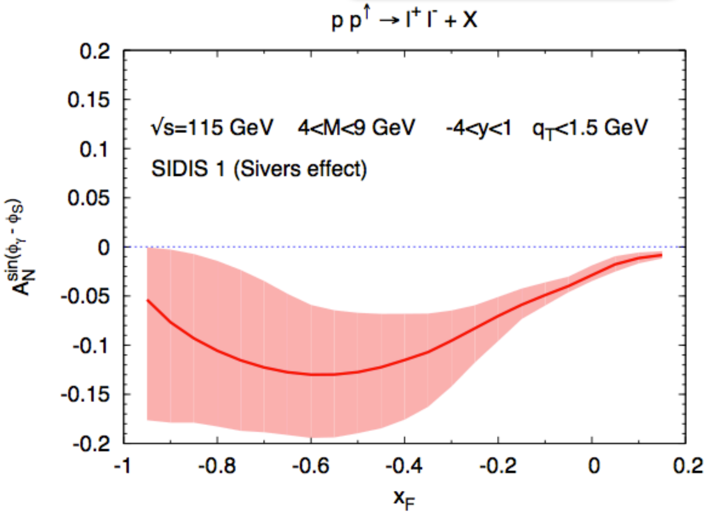


p↑p @ Brookhaven





pp↑ @ AFTER

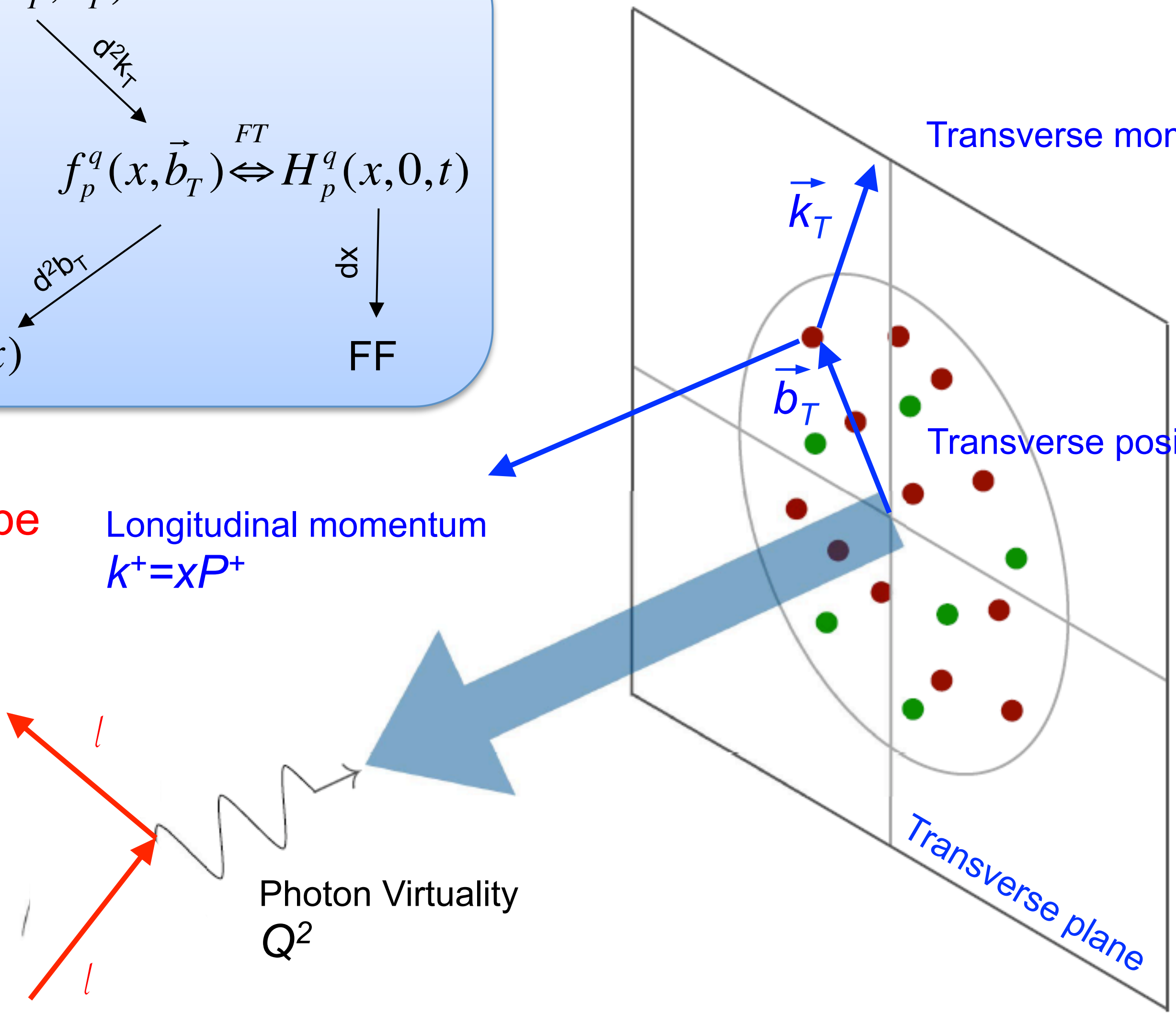


The 3D Nucleon Structure

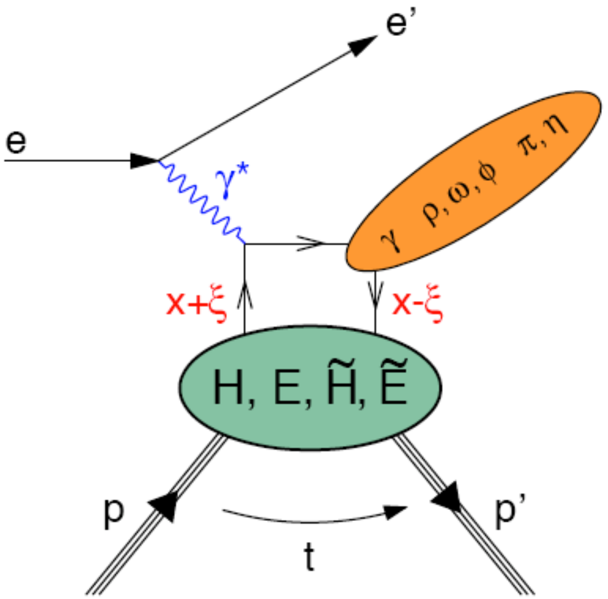
$$\begin{tikzcd}
 & W_p^q(x,\vec{k}_T,\vec{b}_T) \arrow[dl, "d^2b_T"'] \arrow[dr, "d^2k_T"] & & \\
f_p^q(x,\vec{k}_T) \arrow[dr, "d^2k_T"] & & f_p^q(x,\vec{b}_T) \arrow[r, Leftrightarrow, "FT"] \arrow[dl, "d^2b_T"'] & H_p^q(x,0,t) \arrow[d, "dx"] \\
 & f_p^q(x) & & \text{FF}
\end{tikzcd}$$

Confinement Scale

High Energy Probe
Hard Scale



Generalized parton distributions



- 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 $L_q = J_q - ½\Delta\Sigma$ 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:

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

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

Parton 3D Dynamic

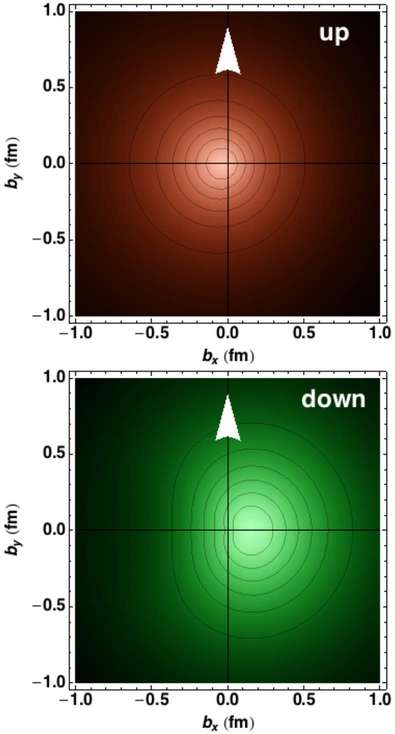
GPD E:

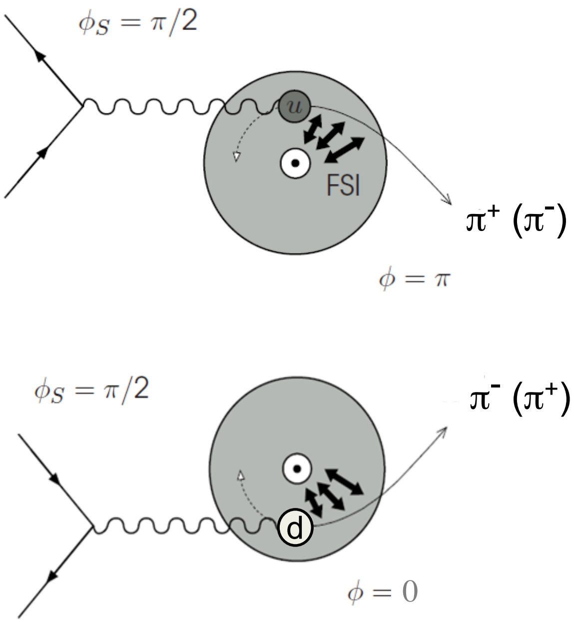
Imbalance in the probed parton spatial distribution

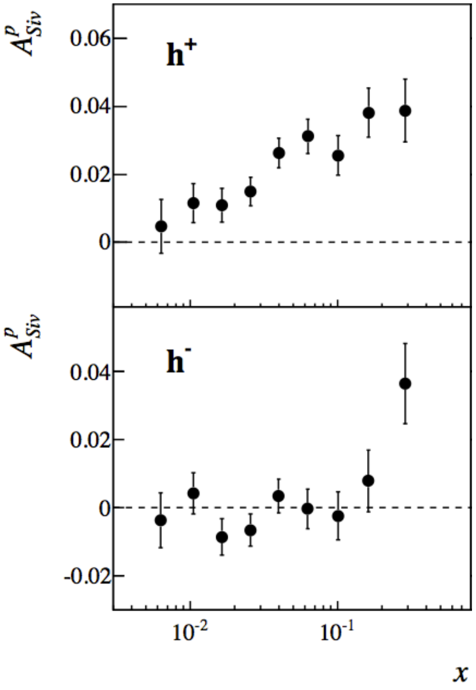
$$q_X(x,\mathbf{b}_\perp) = q(x,\mathbf{b}_\perp) - \frac{1}{2M}\frac{\partial}{\partial b_y}\mathcal{E}_q(x,\mathbf{b}_\perp)$$

Sivers TMDs:

Imbalance in the observed hadron momentum distribution







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

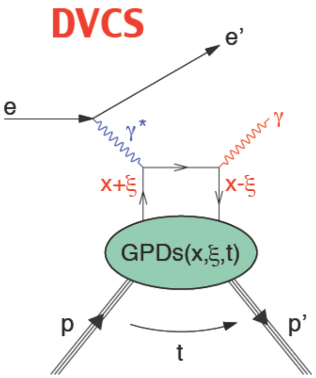
$$f_{1T}^{\perp q} \sim -\kappa^q$$

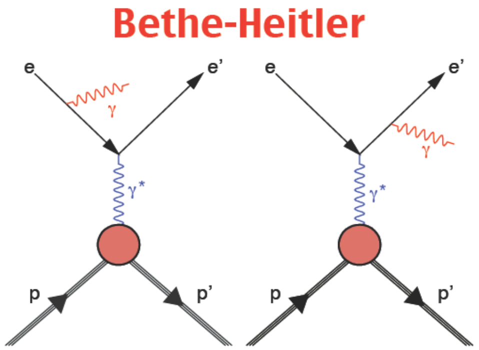
Orbital Motion

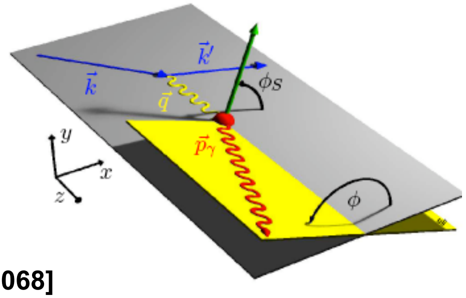
DVCS Interference

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

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

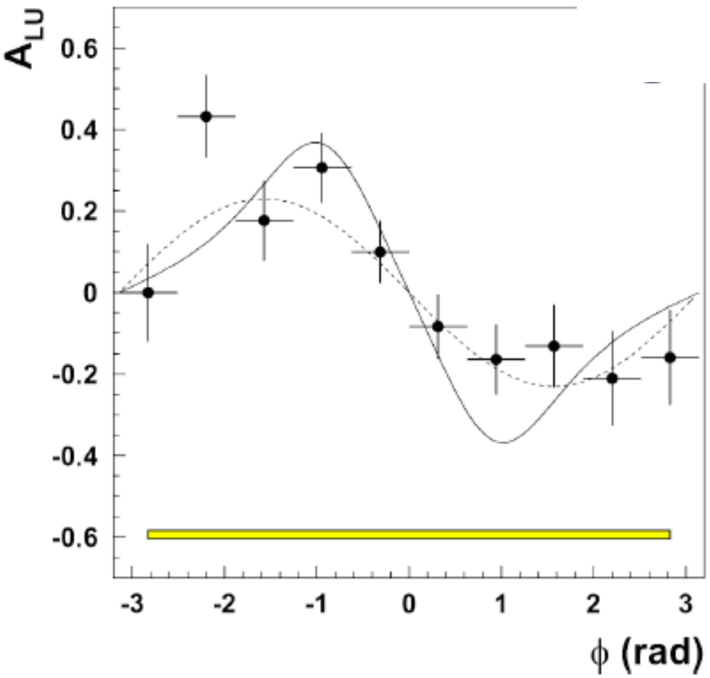

DVCS


Bethe-Heitler

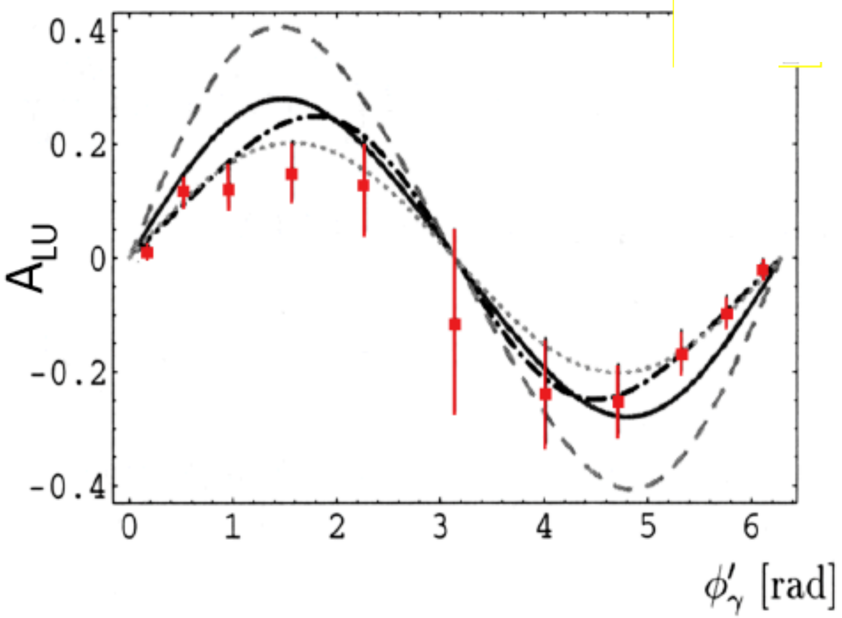


FIRST SIGNALS:

HERMES **[arXiv:0106068]**

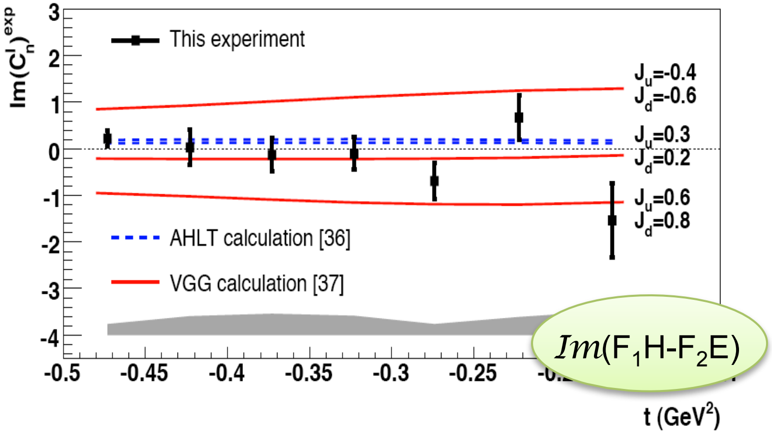


CLAS **[arXiv:0107043]**

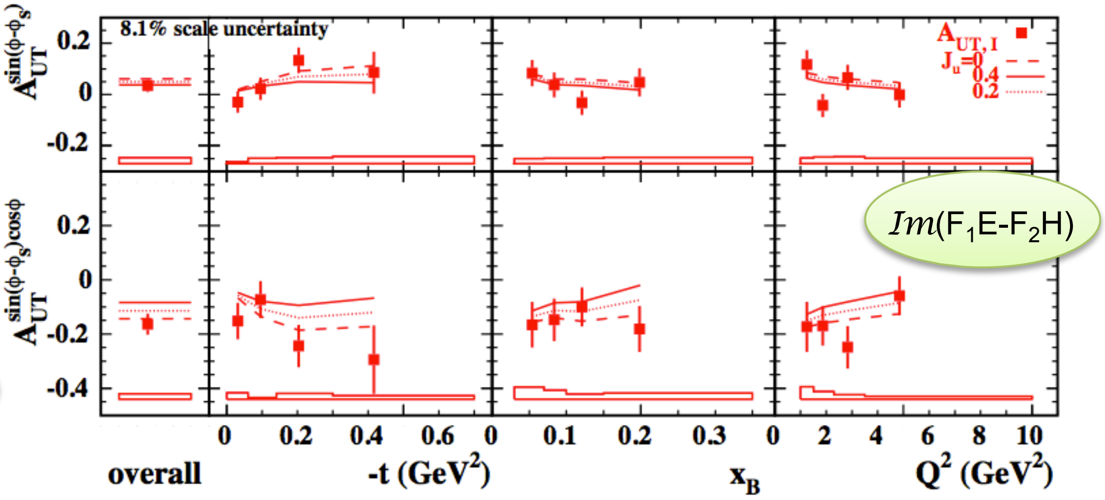


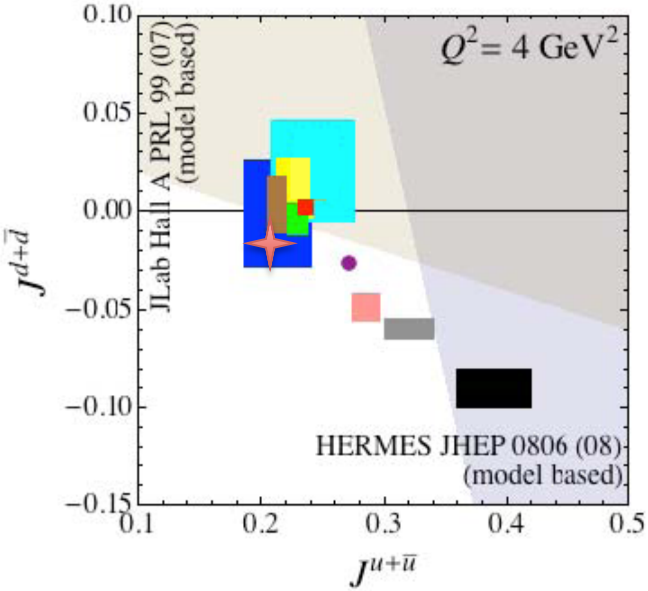
OAM Glimpse

A_{LU} on (neutron) deuteron


Jlab Hall-A [arXiv:0709.0450]

A_{UT} on proton HERMES [arXiv:0802.2499]





GPD models: J^q as free parameter in ansatz for E

- 🟦 Goloskokov & Kroll, EPJ C59 (09) 809
- 🟫 Diehl et al., EPJ C39 (05) 1
- 🟪 Guidal et al., PR D72 (05) 054013
- 🟥 Liuti et al., PRD 84 (11) 034007
- ✦ Bacchetta et al. 1107.5755

- 🟦 LHPC−1, PR D77 (08) 094502
- 🟥 LHPC−2, PR D82 (10) 094502
- 🟩 QCDSF, arXiv:0710.1534

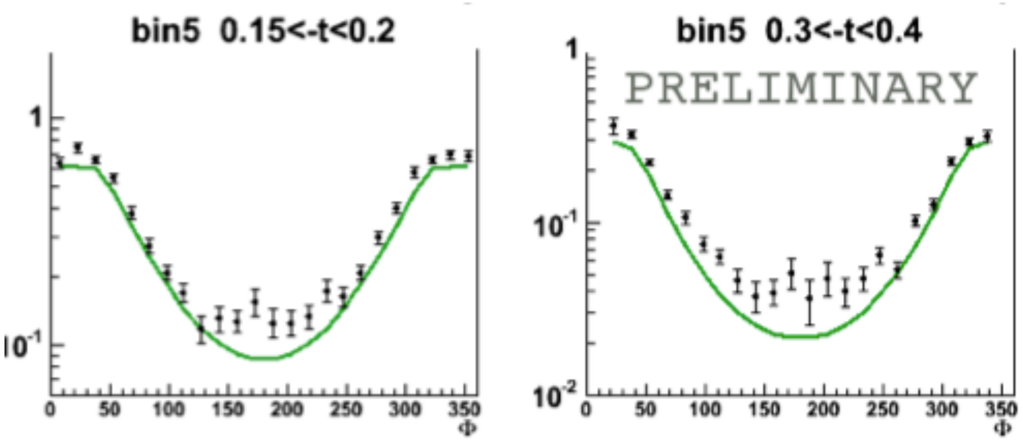
} lattice

- 🟨 Wakamatsu, EPJ A44 (10) 297
- ⬛ Thomas, PRL 101 (08) 102003
- ⬜ Thomas, INT 2012 workshop

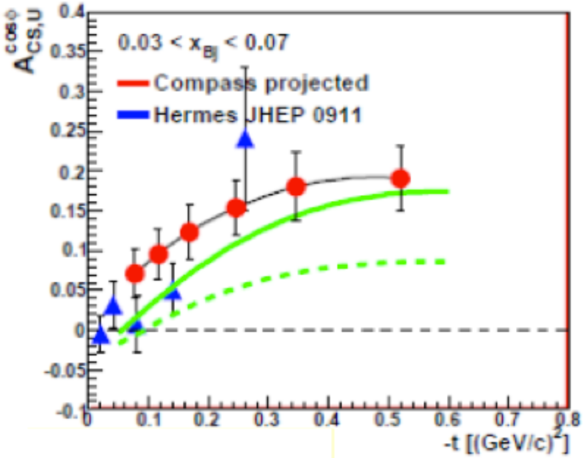
Upcoming DVCS

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

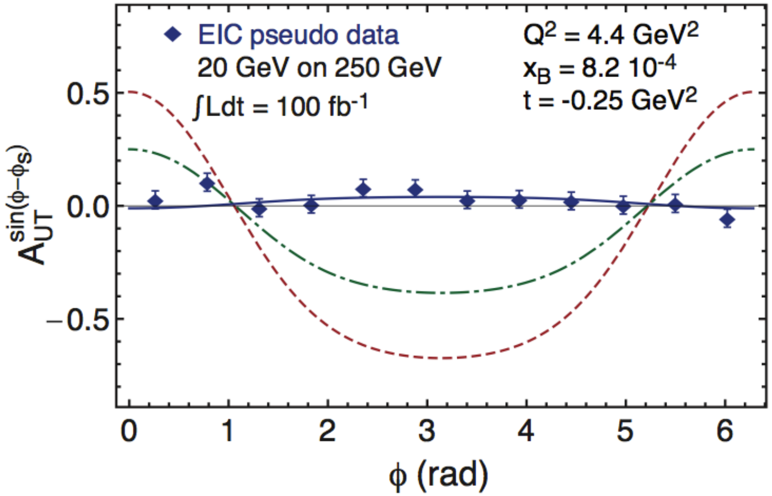
JLab6 (H):



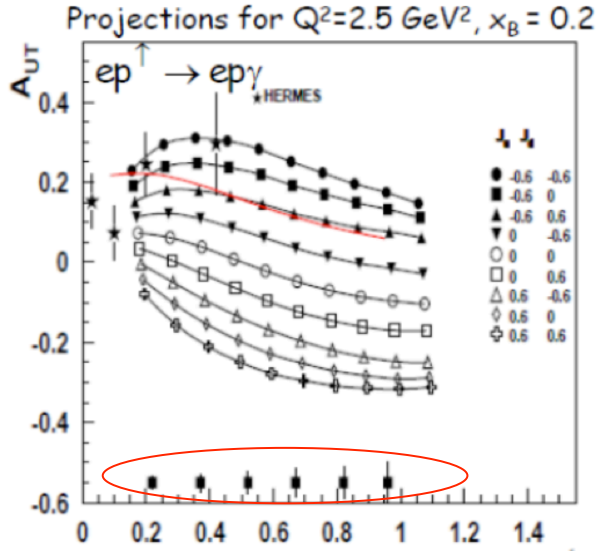
COMPASS-II (H):



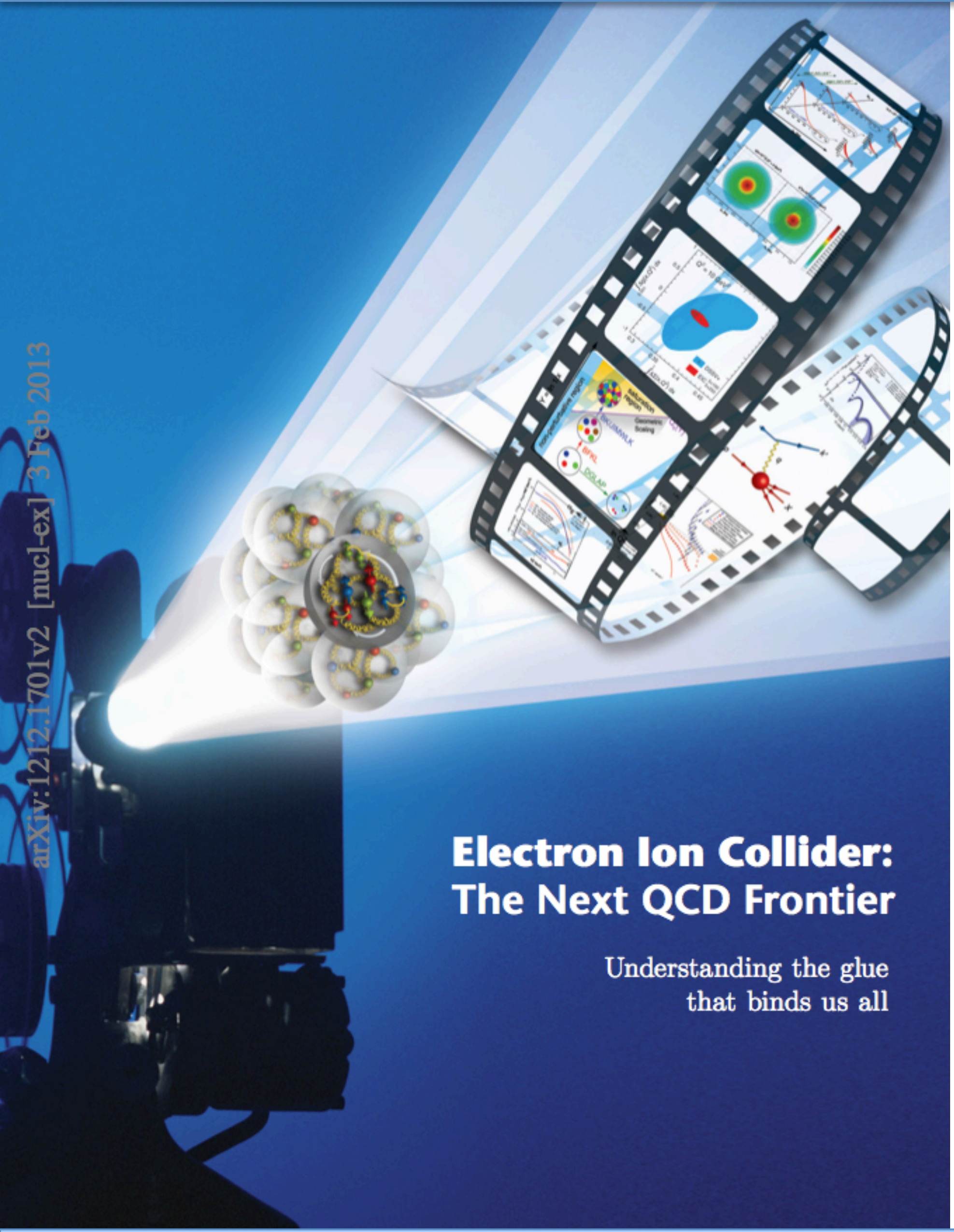
EIC: Simultaneous binning in x, Q^2 and t



JLab12 (H & E):



The Next QCD Frontier



Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

3D nucleon:
A just-started endeavor on
NPQCD dynamics with many
connections with other QCD topics

Parton correlators do exist
and probe the parton dynamics

Many new measurements
planned in the near future
in various laboratories

JLab12 will provide a
comprehensive study in the valence

EIC is a unique opportunity
for a comprehensive study
and possible breakthroughs