Experimental Overview

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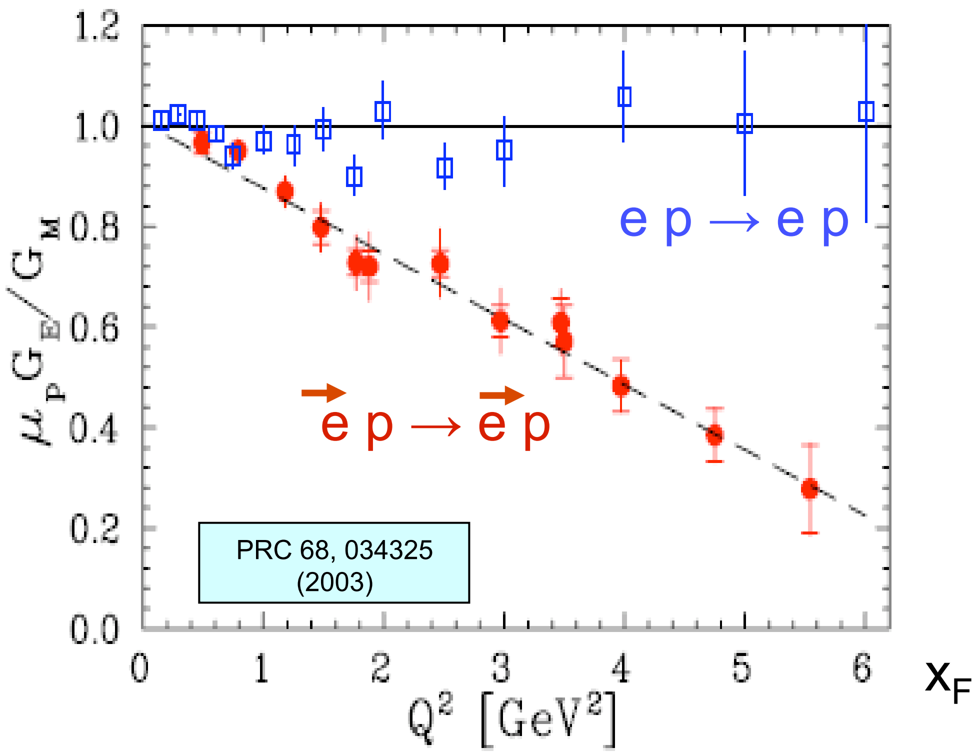
INFN Ferrara

QCD-N'12
October 22, 2012 Bilbao

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

Fundamental: do not neglect it !!



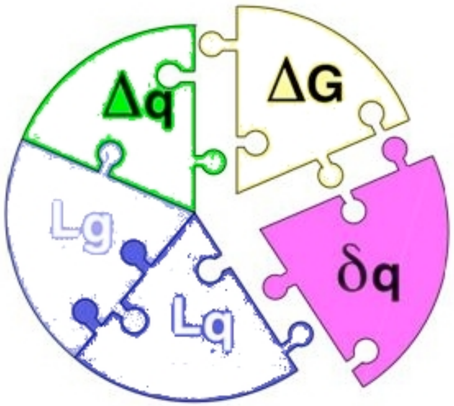
The Spin Degree of Freedom

In our exploration of the QCD micro-world

Fundamental: do not neglect spin !!

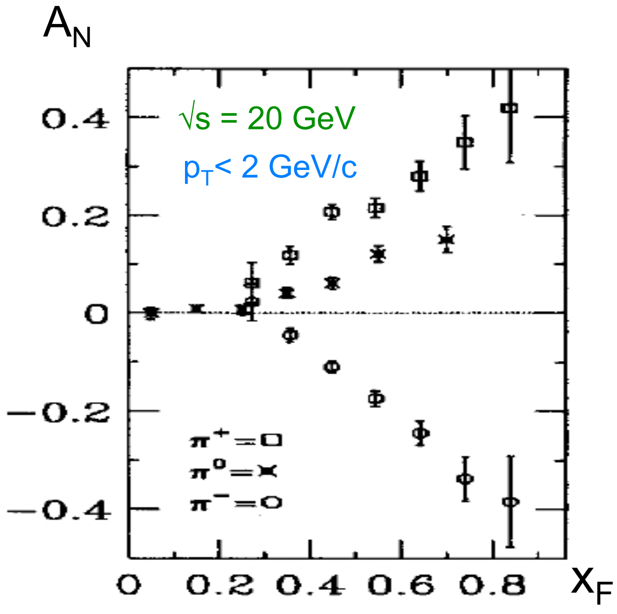
Two questions in Hadronic Physics
await explanation since too long

Proton Spin Budget



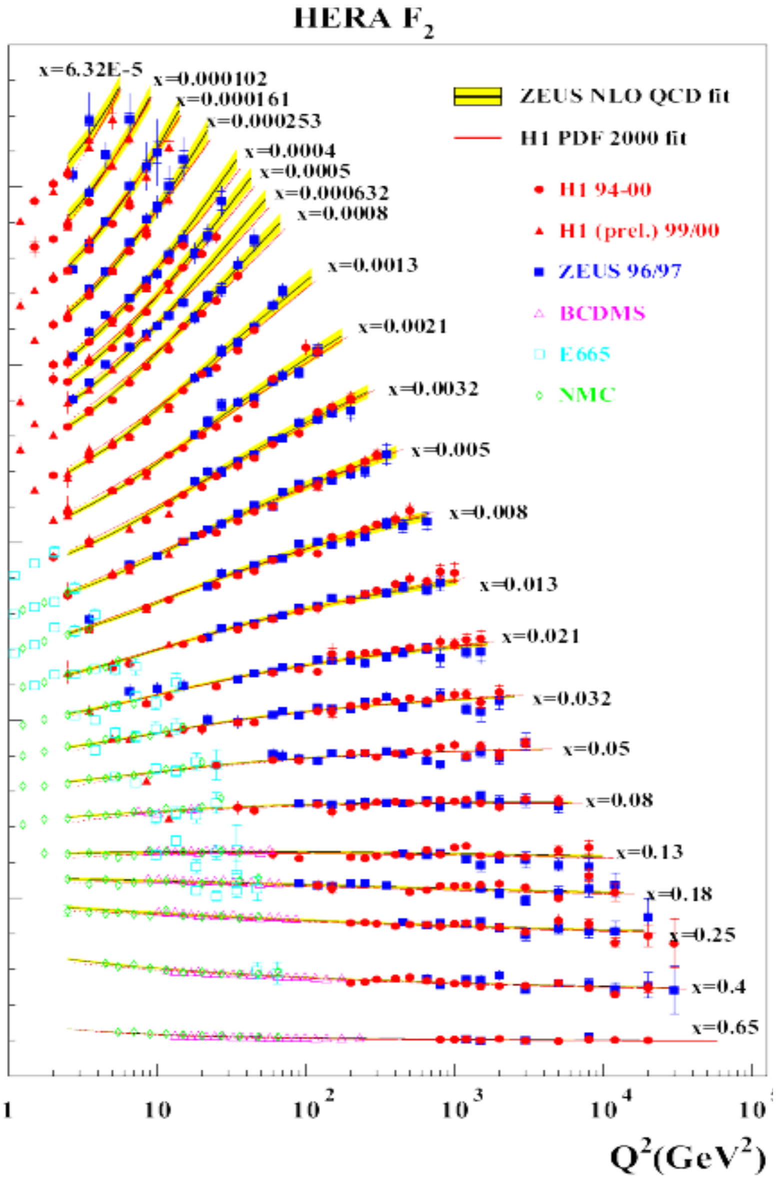
$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$

Single Spin Asymmetries

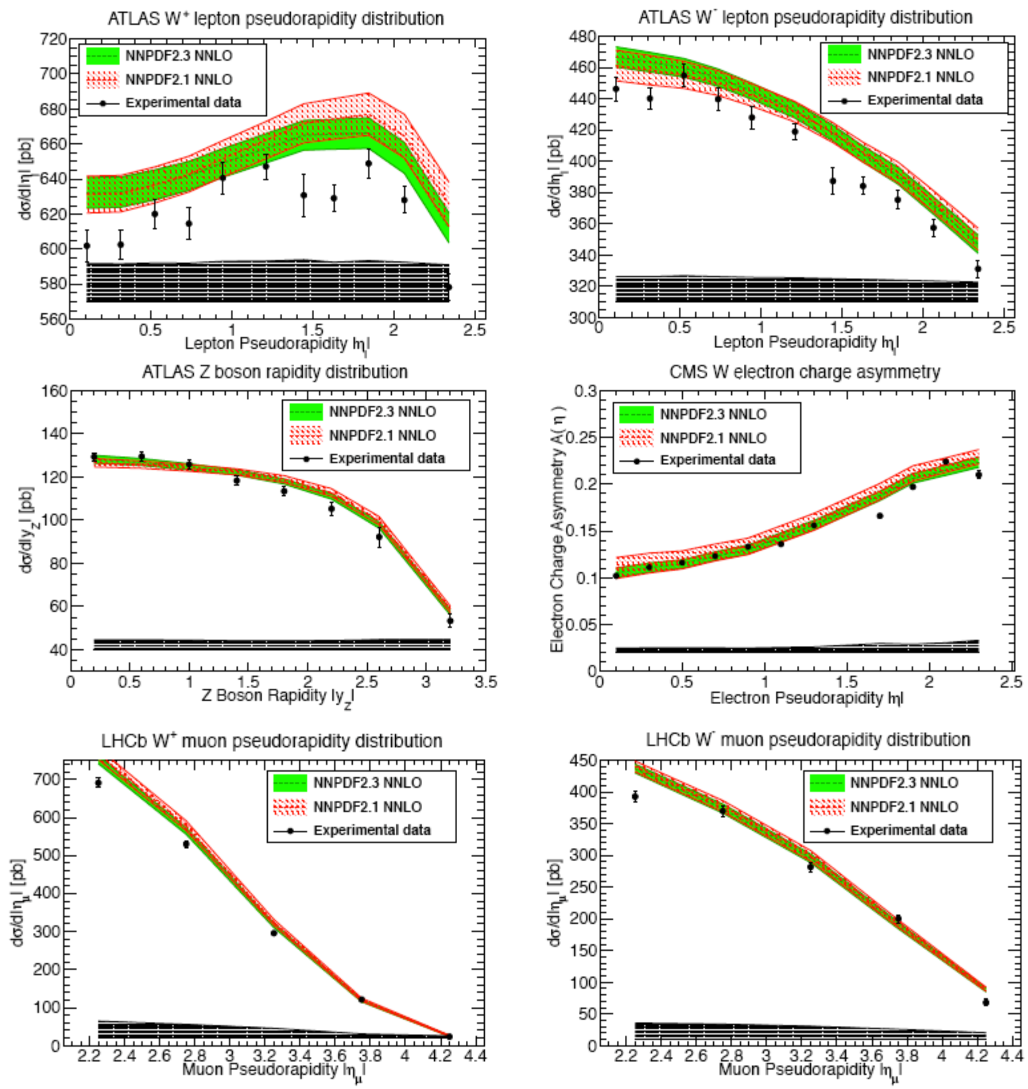


Parton Number Density

Parton Number Density

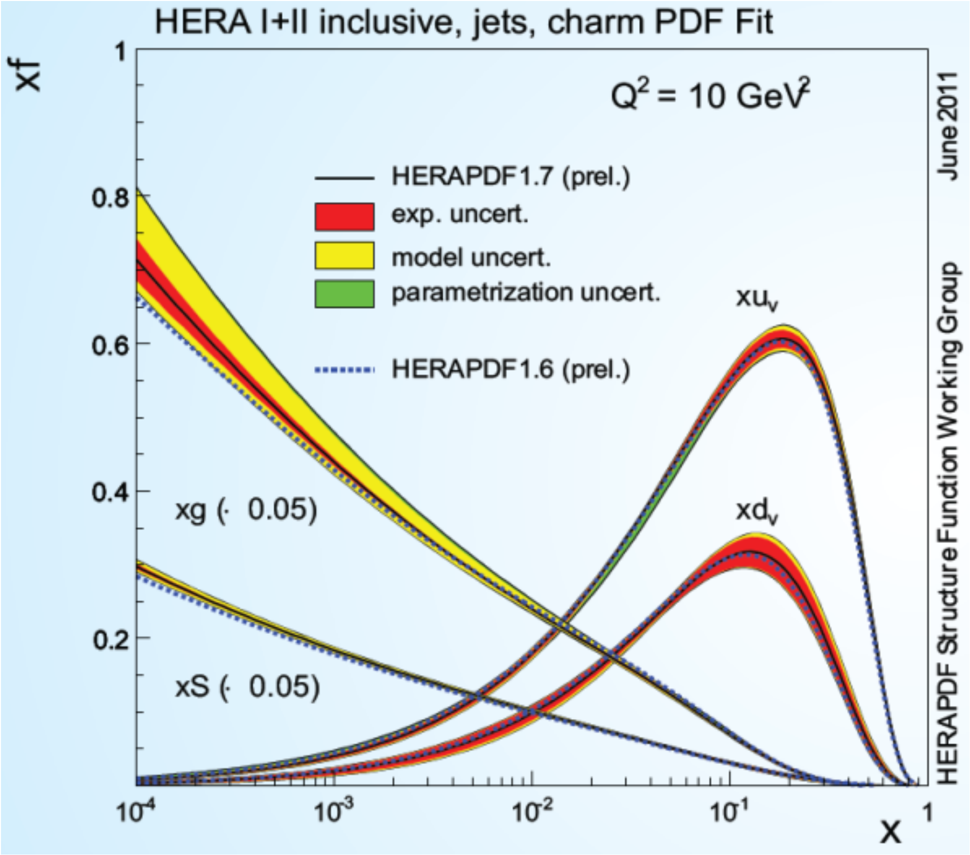


LHC gauge boson production

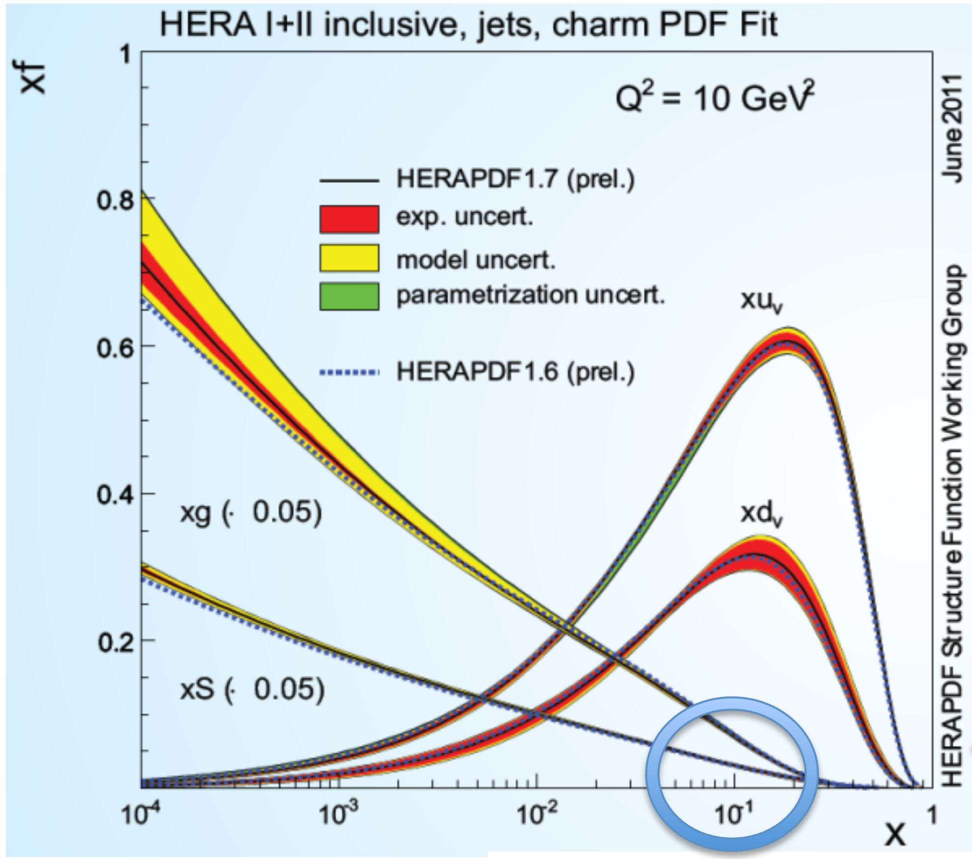


NNPDF: arXiv:1207.1303

Parton Number Density

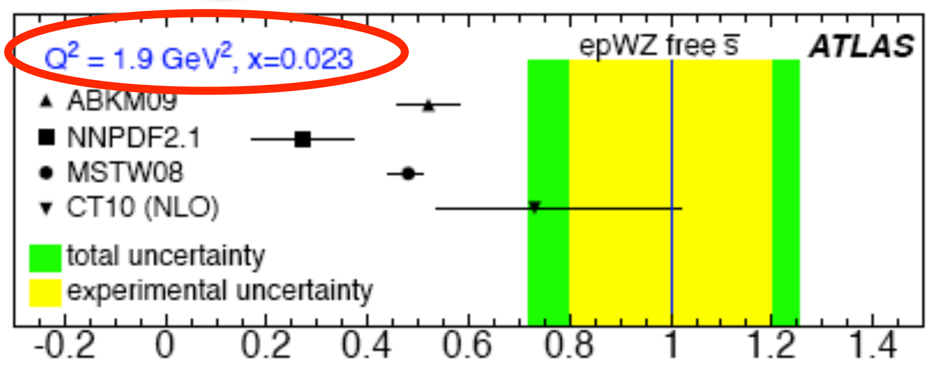


Parton Number Density



ATLAS: arXiv:1206.4051

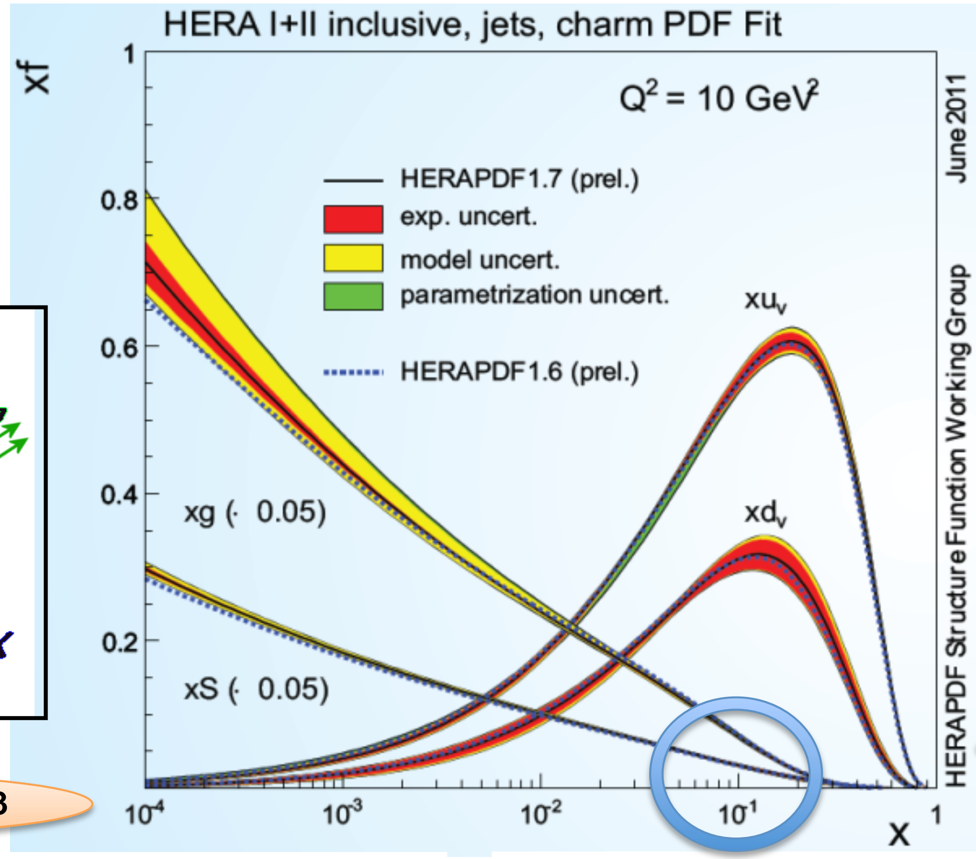
$$r_s = 0.5(s + \bar{s})/\bar{d}$$

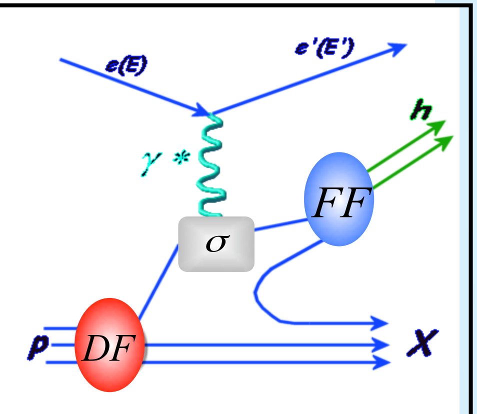


x

r_s

Parton Number Density

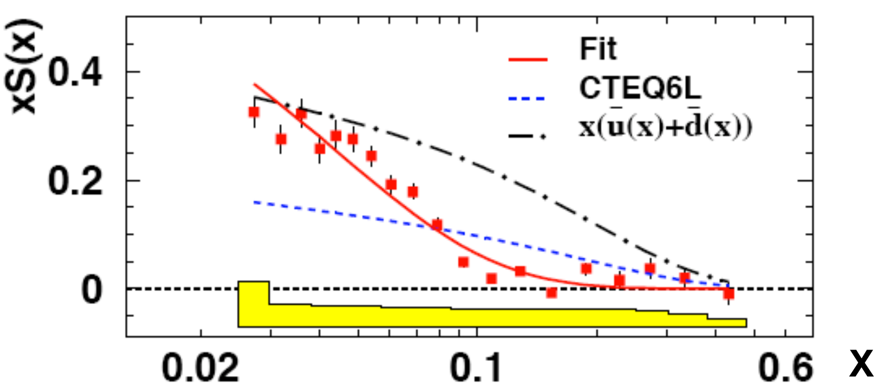


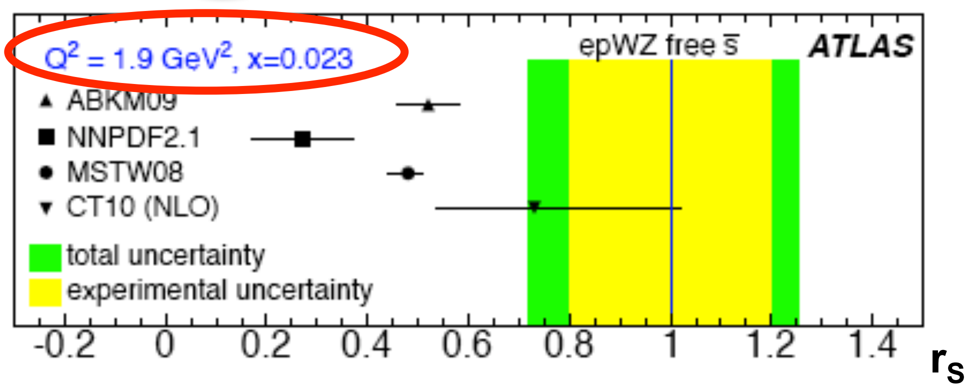


HERMES: arXiv:0803.2993

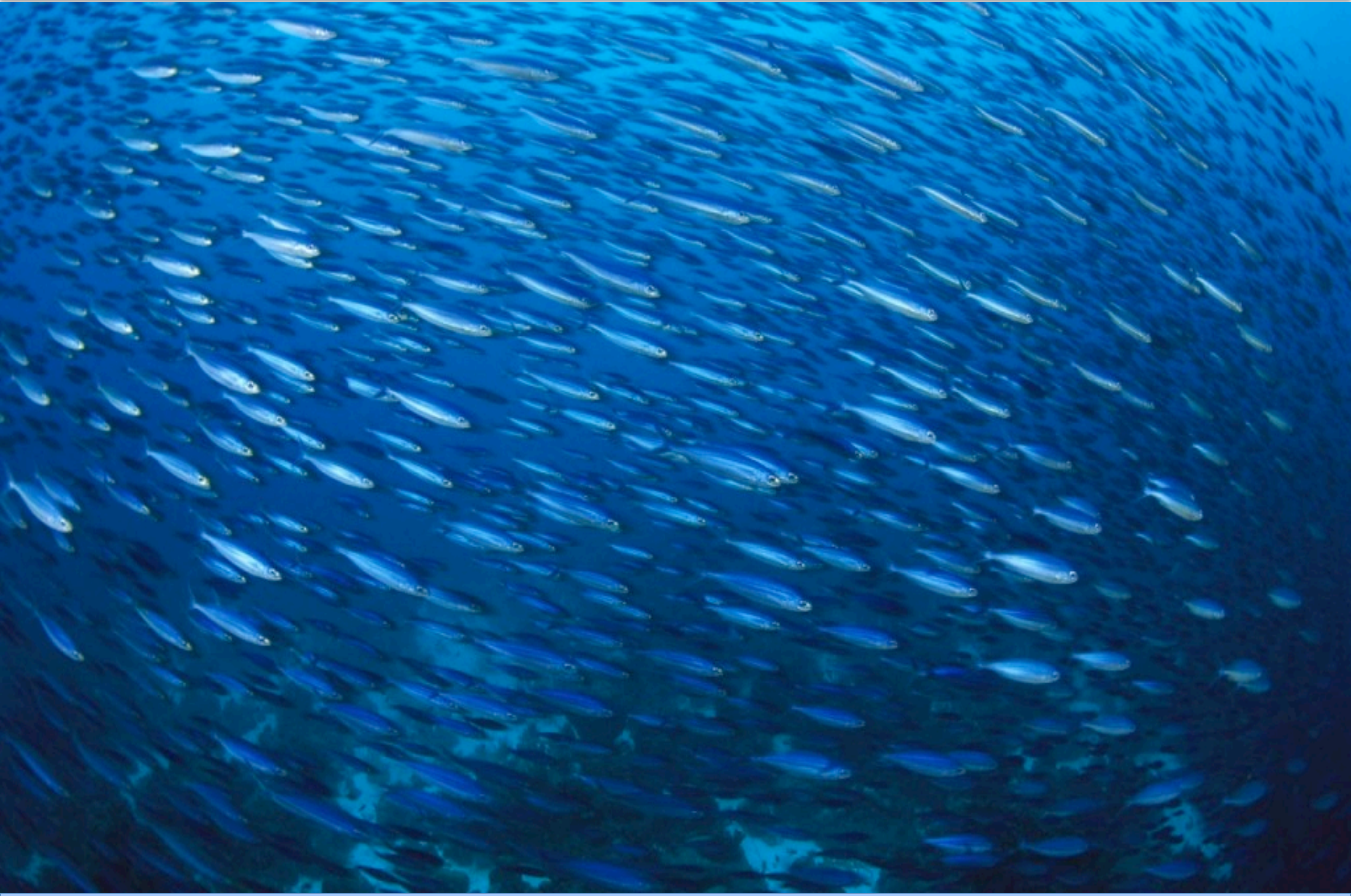
ATLAS: arXiv:1206.4051

$r_s = 0.5(s+\bar{s})/\bar{d}$

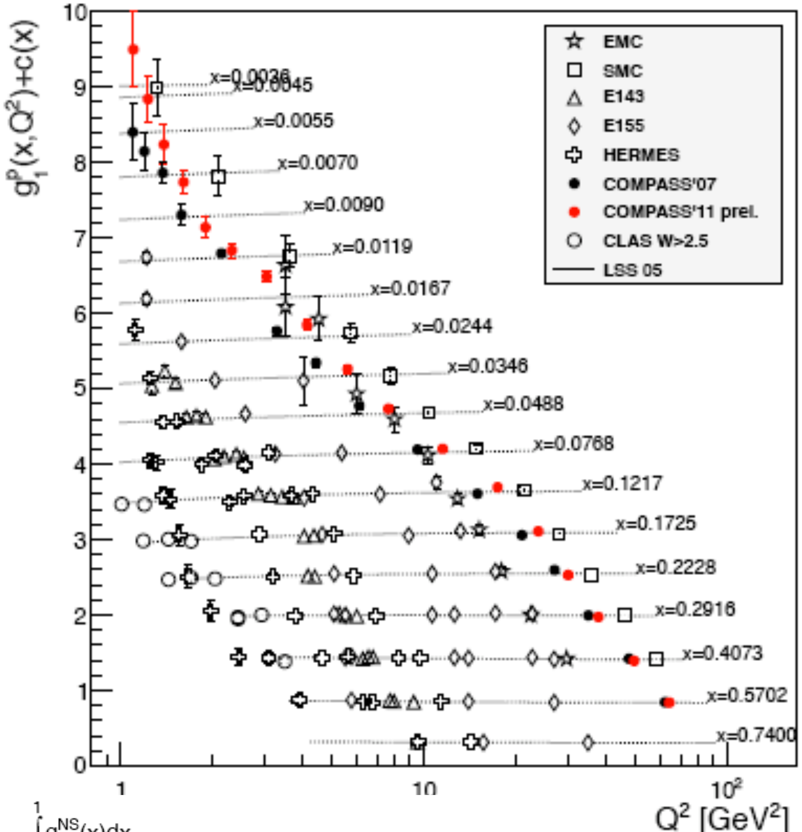




Parton Polarization

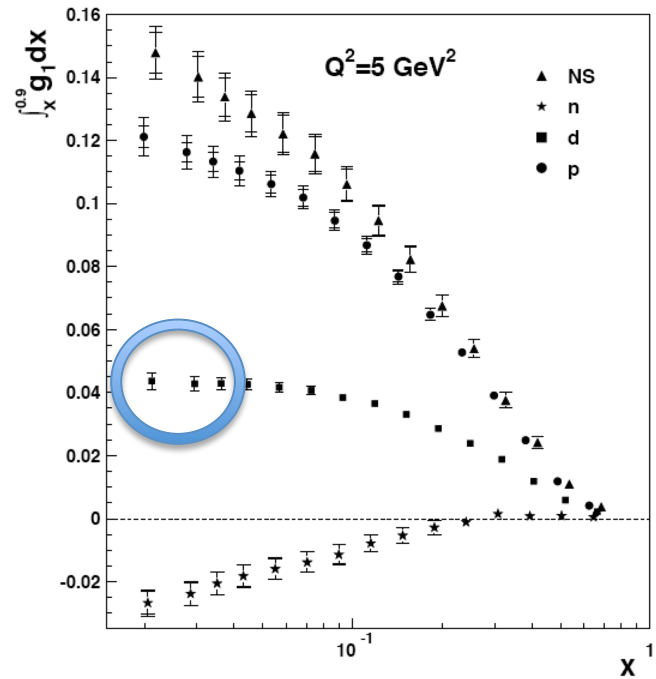


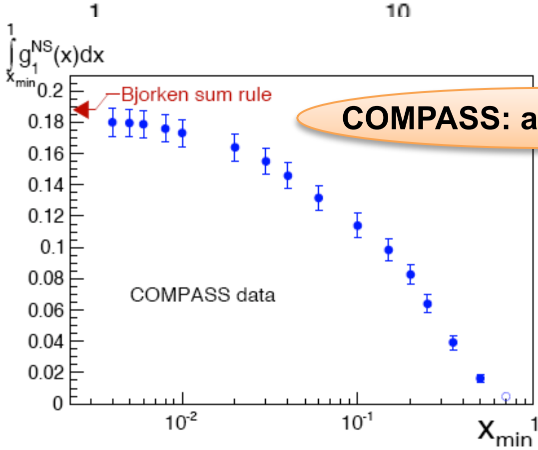
Parton Helicity from Inclusive DIS



$$\Gamma_1^d(Q_0^2) = \left(1-\frac{3}{2}\omega_D\right)\frac{1}{36}\left[a_8\Delta C_{NS}^{\overline{MS}} + 4a_0\Delta C_S^{\overline{MS}}\right]$$

$$a_0 \overset{\overline{MS}}{=} \Delta\Sigma \qquad \Delta s+\Delta\bar{s} = \frac{1}{3}(a_0-a_8)$$





COMPASS: arXiv:1001.4654

a_0 (3 GeV^2)= 0.35 ± 0.03 ± 0.05

ΔS= -0.08 ± 0.03

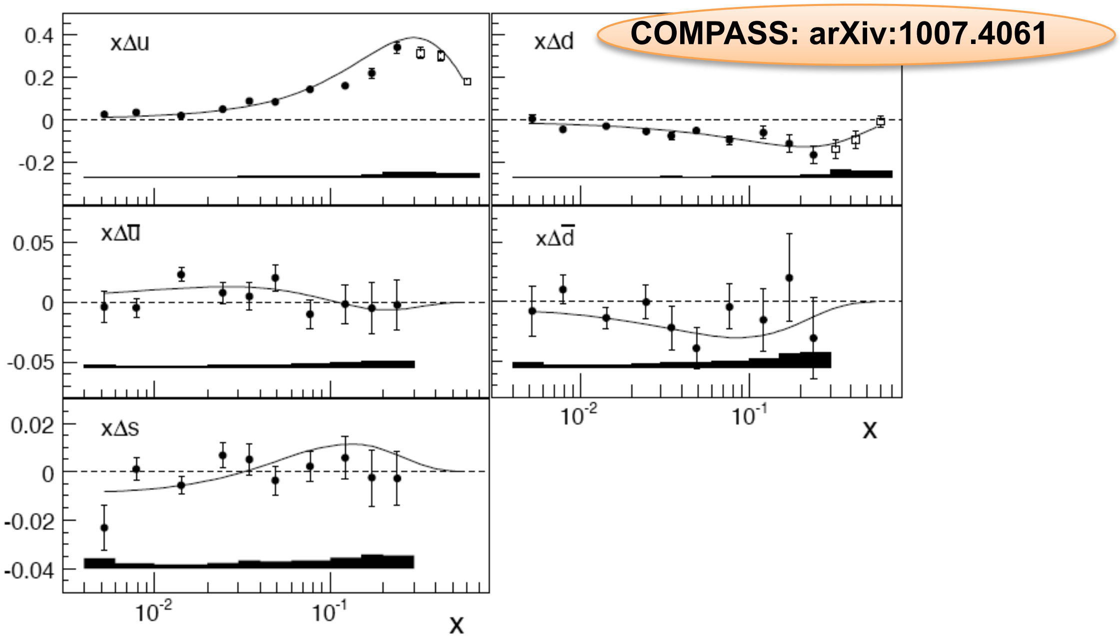
COMPASS: arXiv:0609038

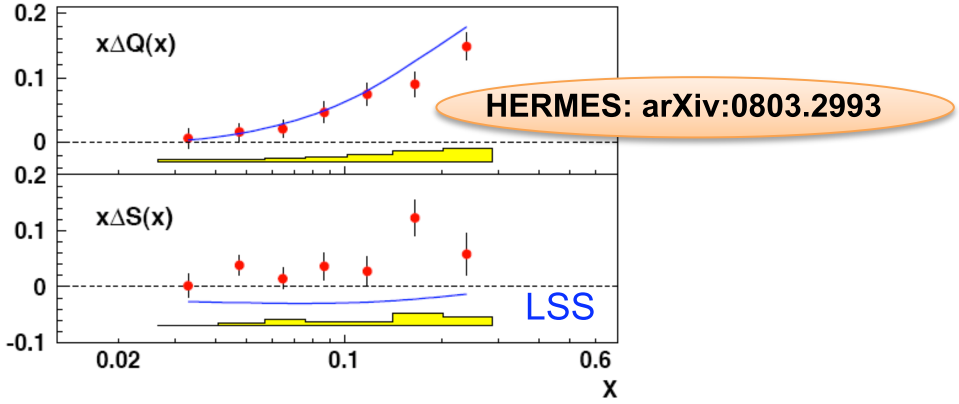
a_0 (5 GeV^2)= 0.33 ± 0.03 ± 0.03

ΔS= -0.09 ± 0.02

HERMES: arXiv:0609039

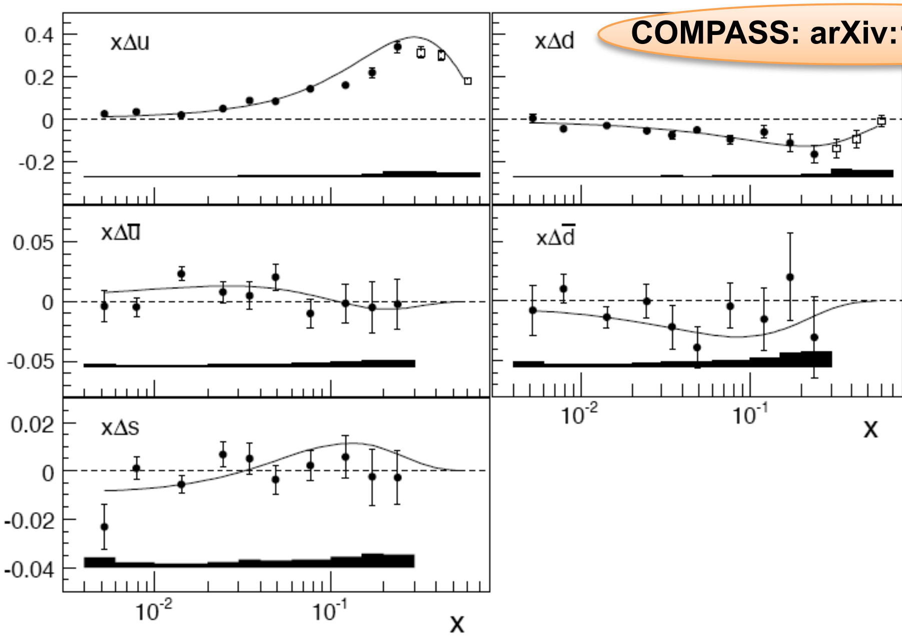
Parton Helicity from SIDIS



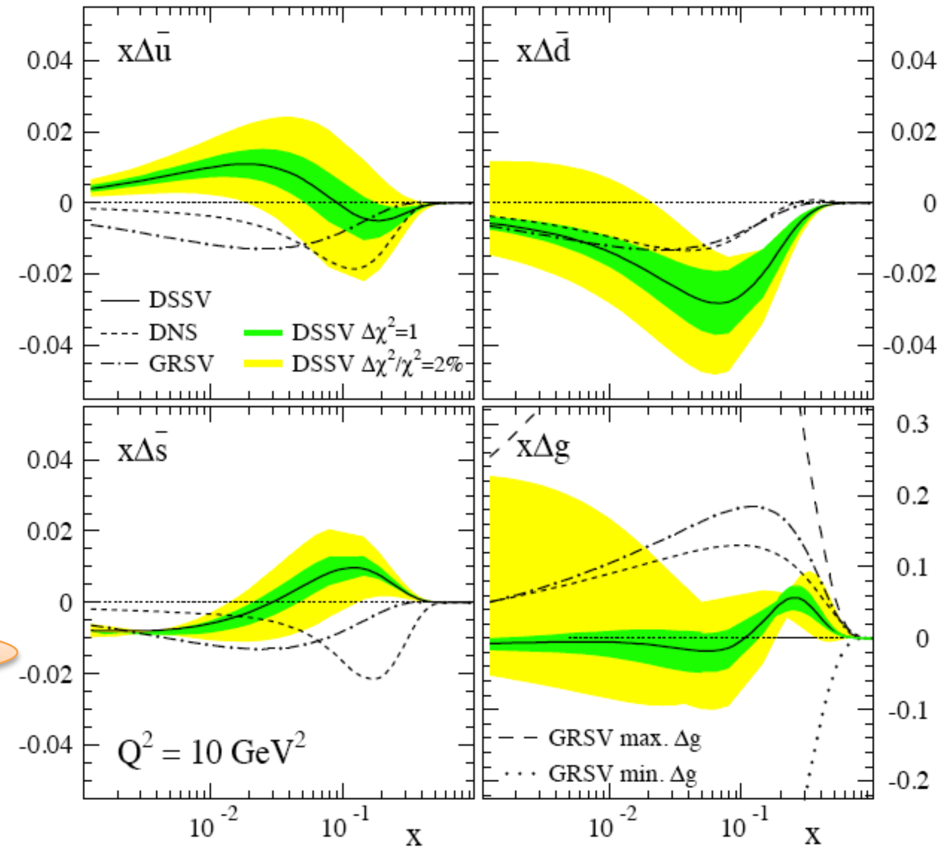


Parton Helicity from SIDIS

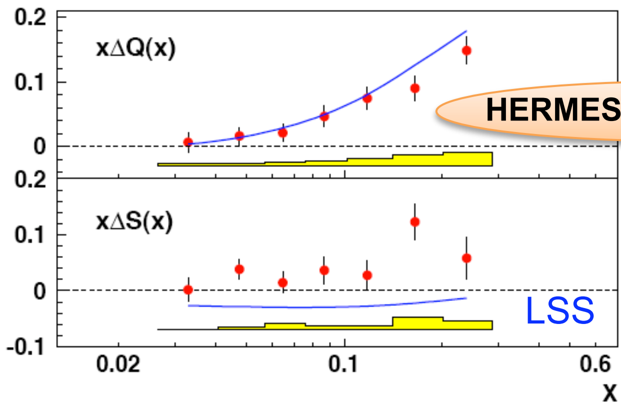
COMPASS: arXiv:1007.4061



DSSV: arXiv:0804.0422



HERMES: arXiv:0803.2993



NNPDF: arXiv:1206.0201

	NNPDFpol1.0	DSSV08 [5]	BB10 [2]	LSS10 [4]	AAC08 [3]
$\Delta\Sigma(Q^2)$	0.31 ± 0.10	0.25 ± 0.02	0.19 ± 0.08	0.21 ± 0.03	0.24 ± 0.07
$\Delta g(Q^2)$	-0.2 ± 1.4	-0.10 ± 0.16	0.46 ± 0.43	0.32 ± 0.19	0.63 ± 0.81

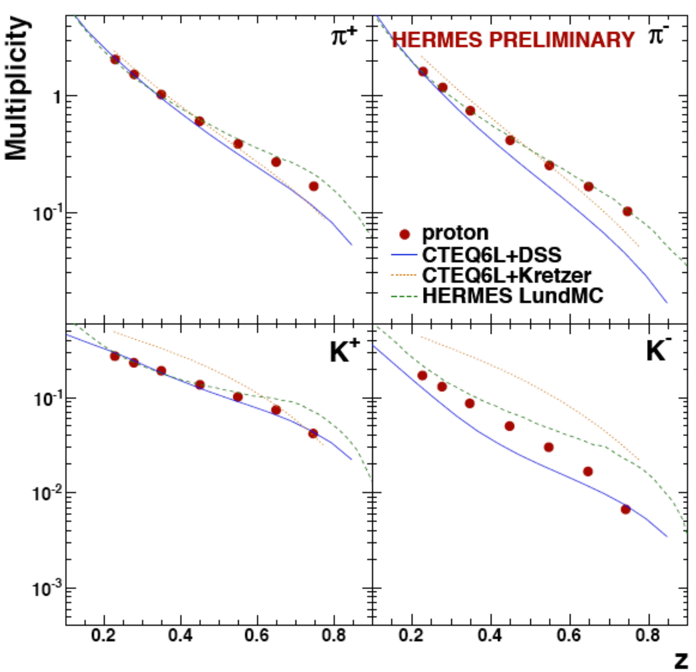
Parton Fragmentation from SIDIS

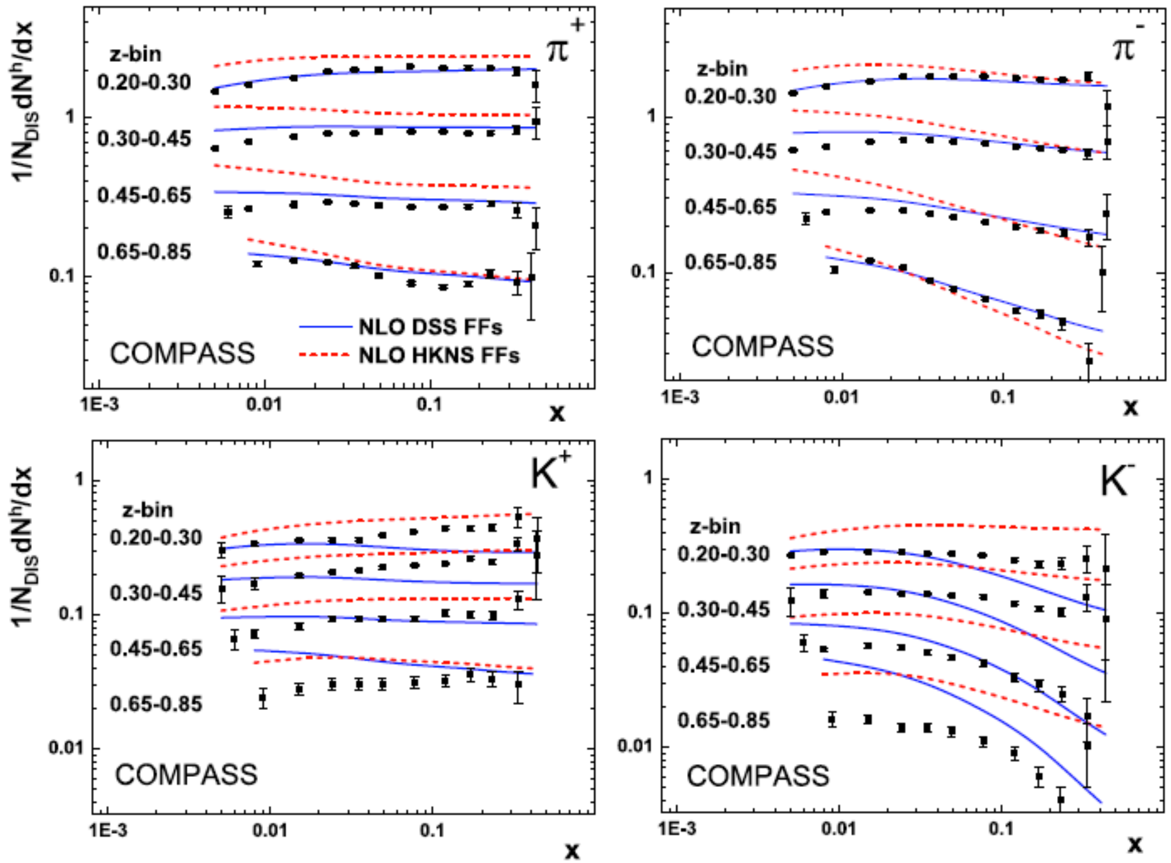
LO interpretation:

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

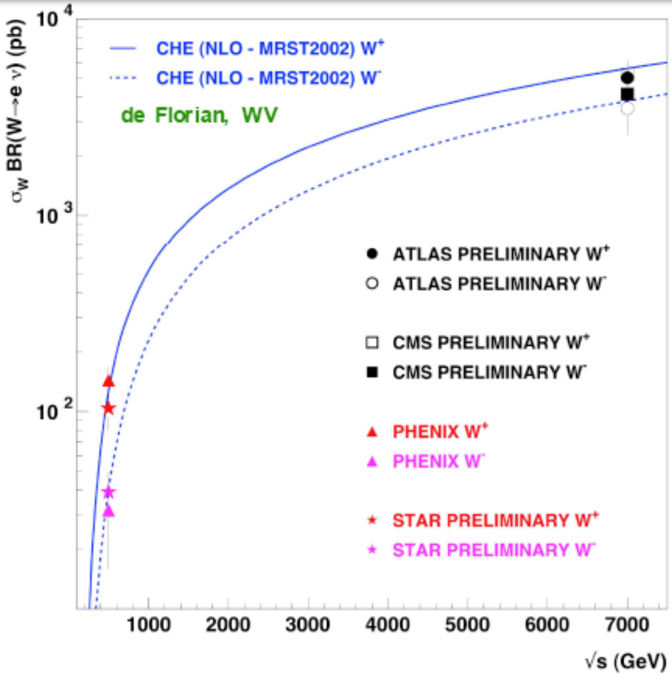
SIDIS data constrain fragmentation at low c.m. energy and bring enhanced flavor sensitivity

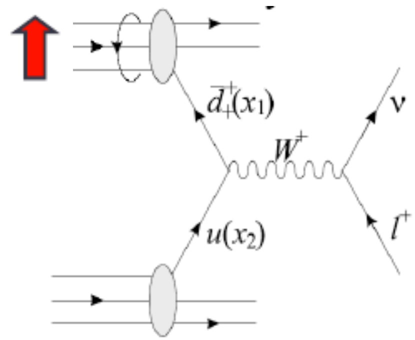
A lot of data but only preliminary results





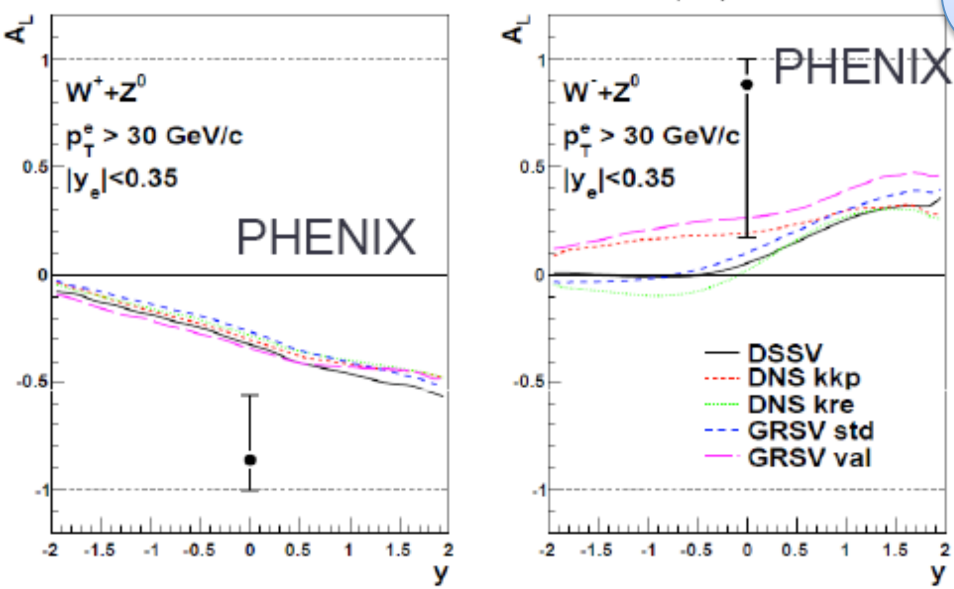
Parton Helicity from W

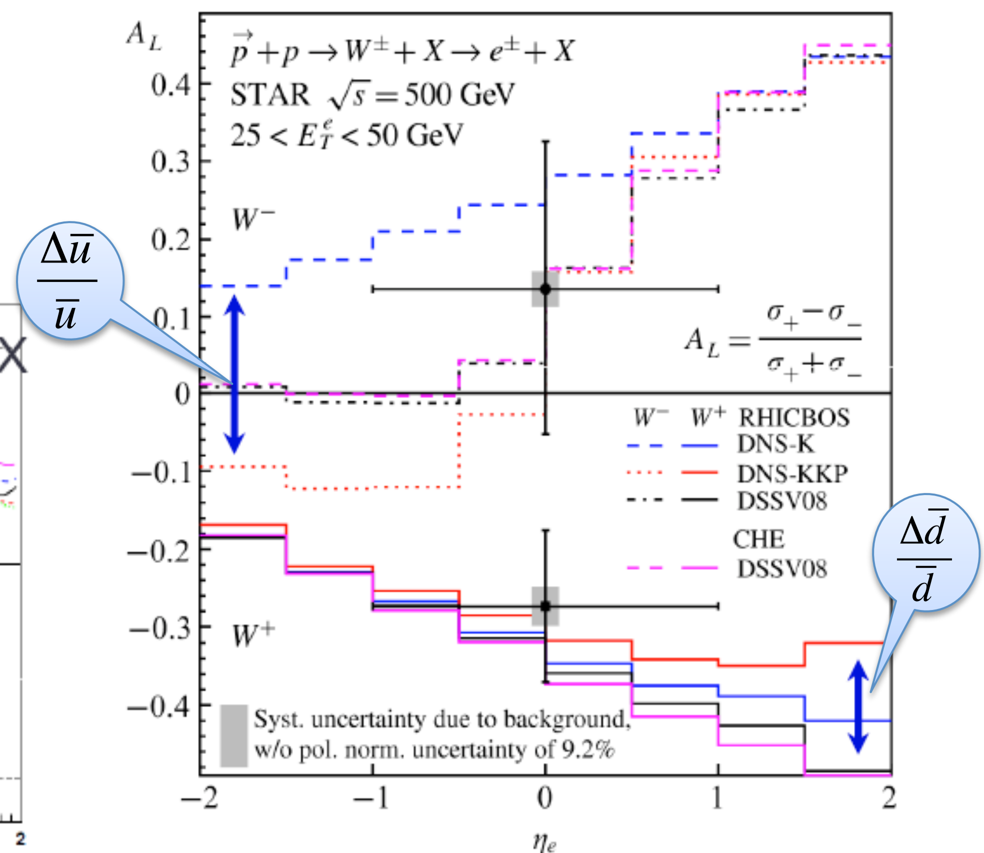




Charge + Rapidity

Flavor



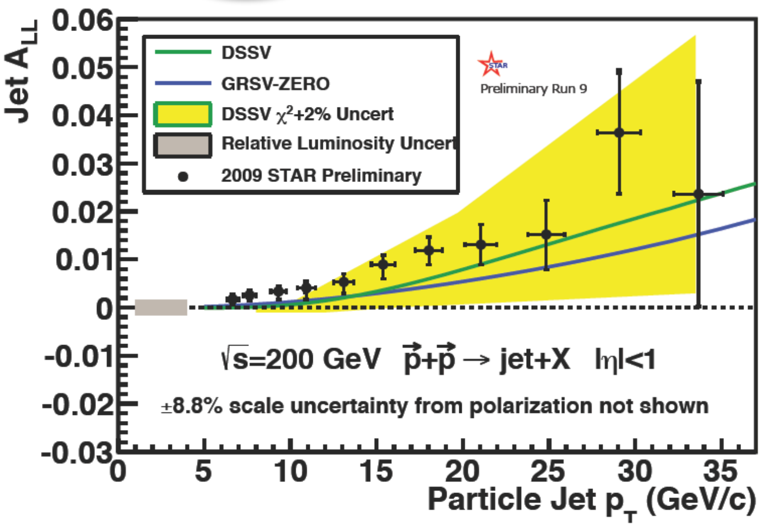


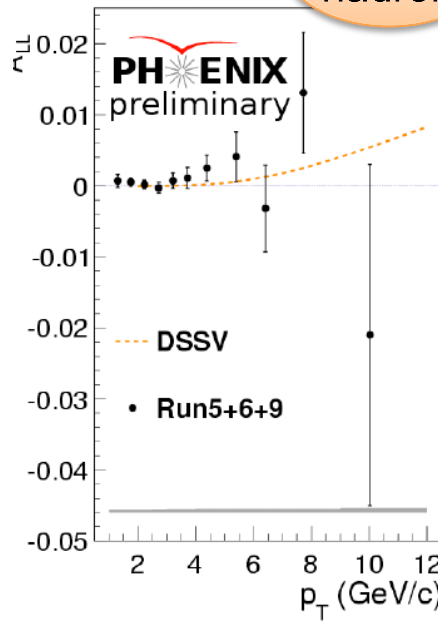
Gluon Helicity

Inclusive Jet

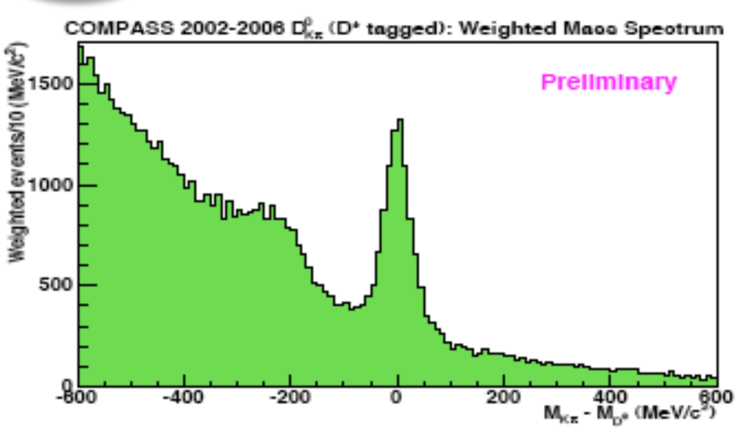
$$x \sim \frac{2p_T}{\sqrt{s}}$$

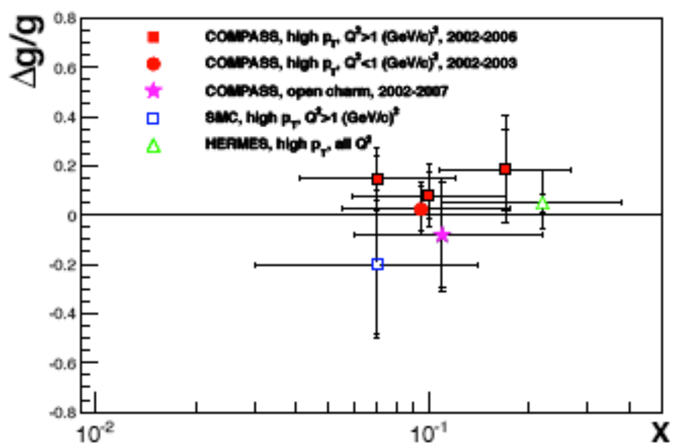
Inclusive hadron





Heavy Flavor

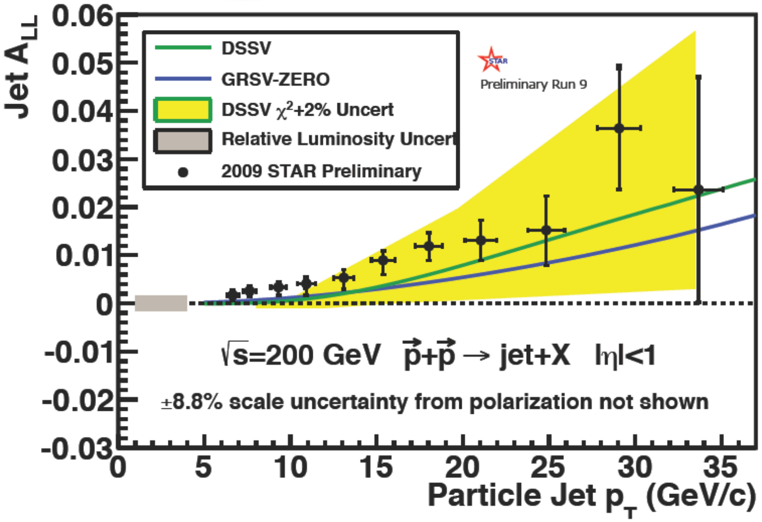




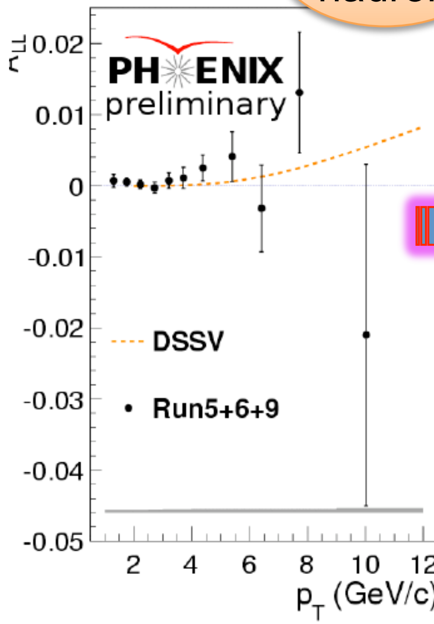
Gluon Helicity

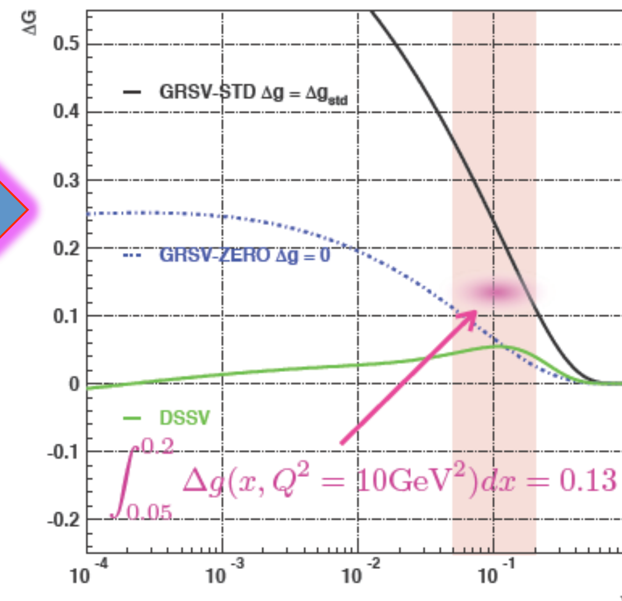
Inclusive Jet

$x \sim \frac{2p_T}{\sqrt{s}}$

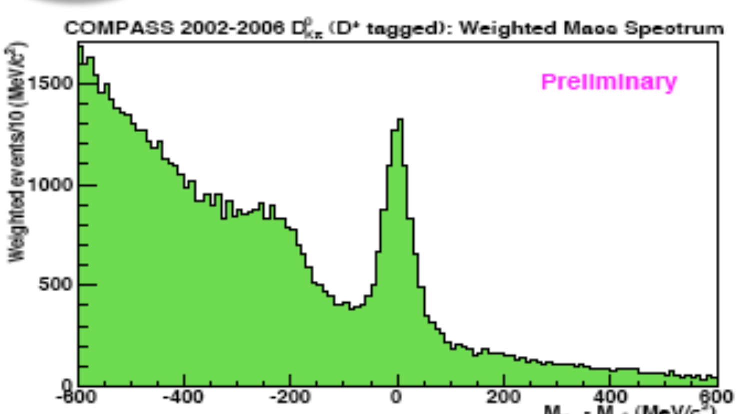


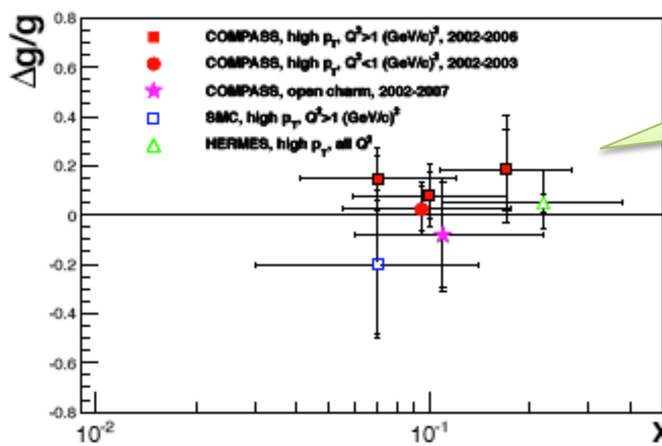
Inclusive hadron





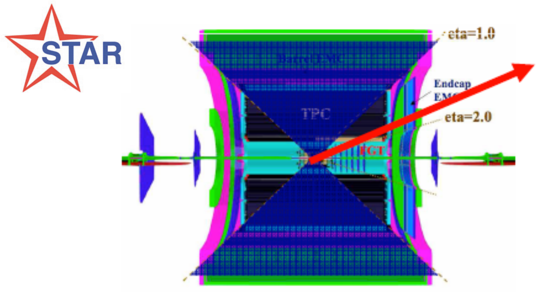
Heavy Flavor

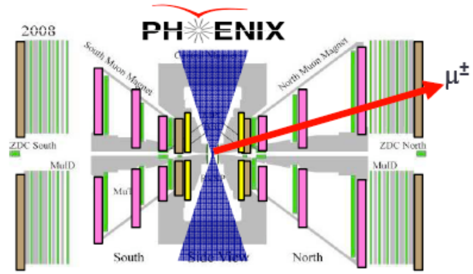


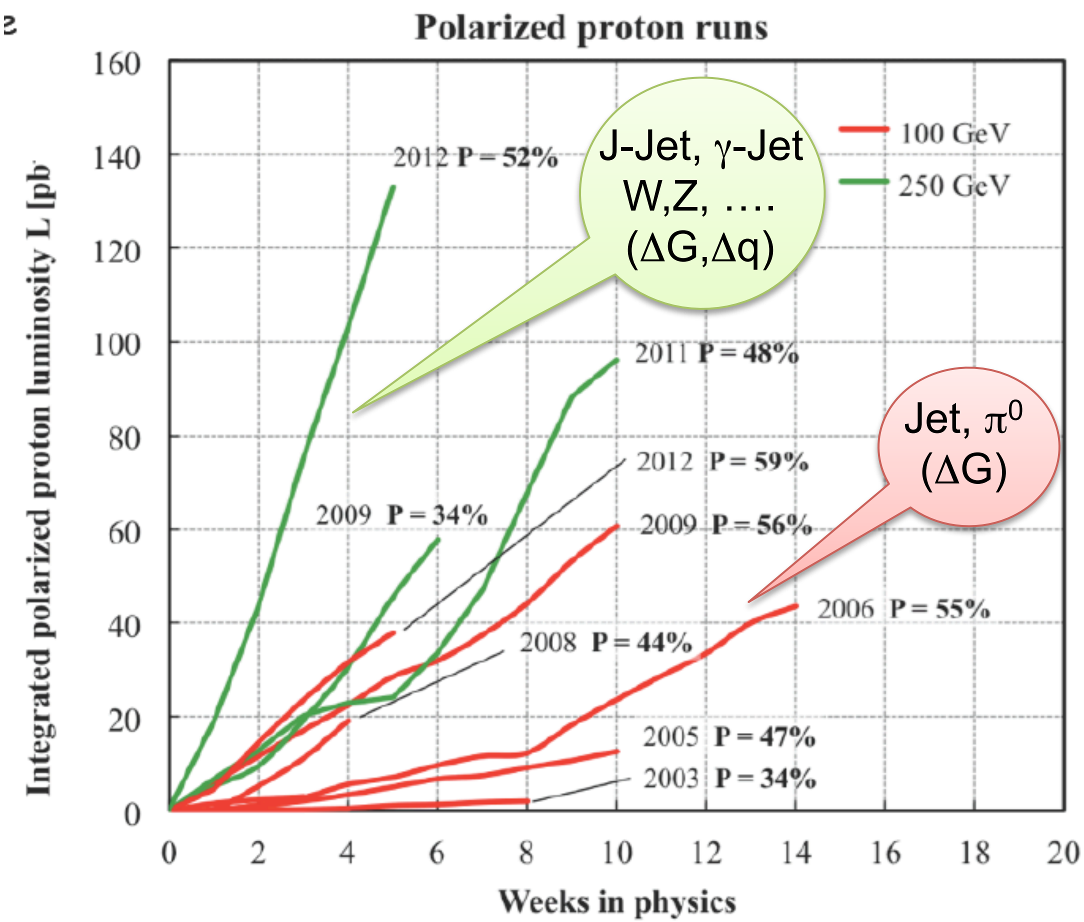


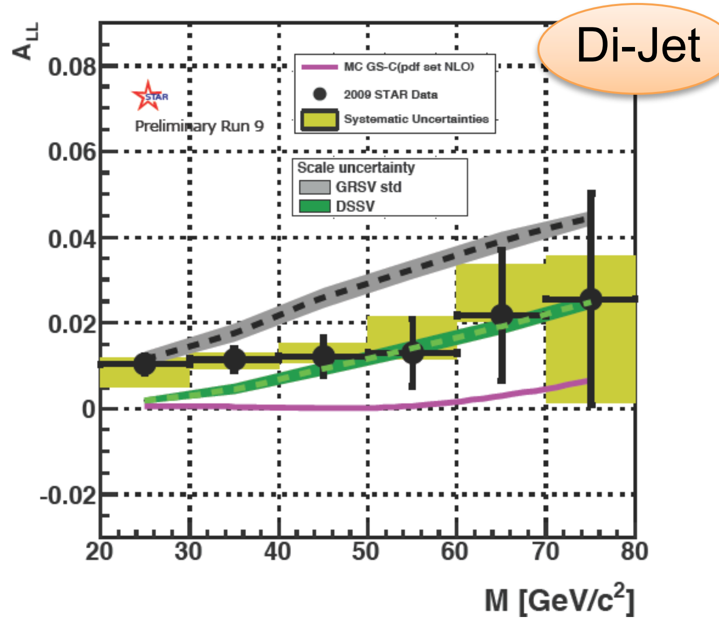
Strong constrain at intermediate x

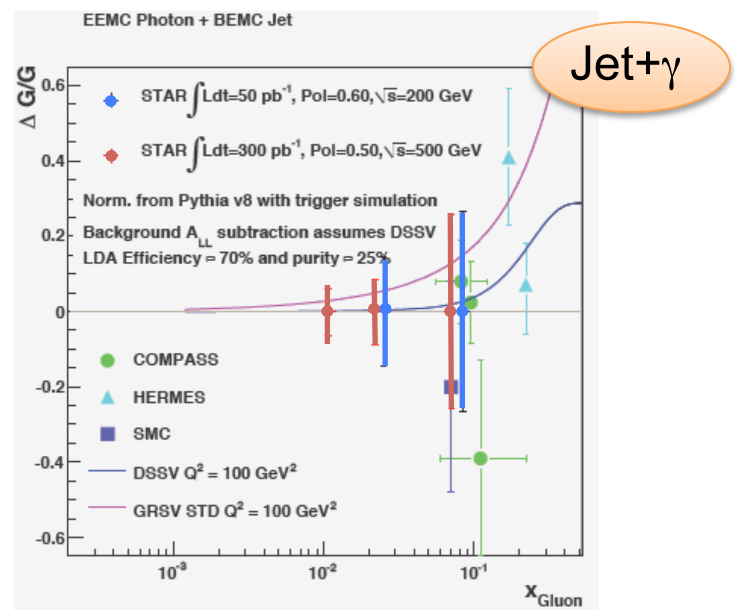
Landscape @ RHIC





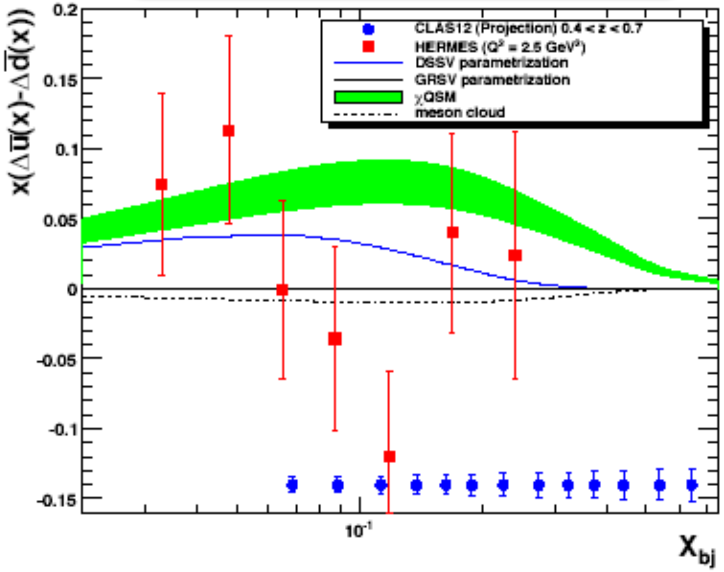




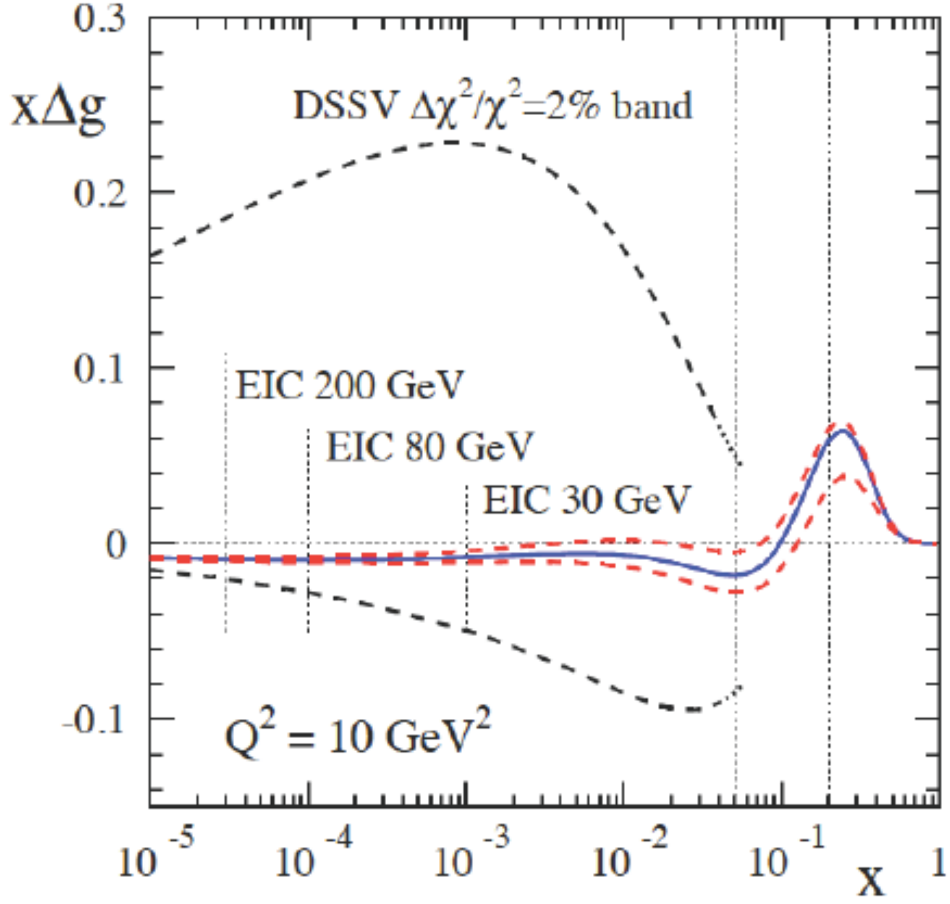


Parton Helicity

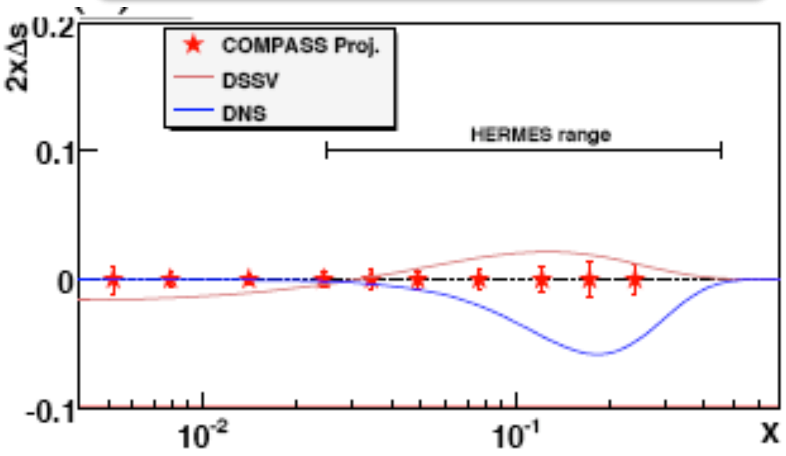
Valence Δq @ CLAS12



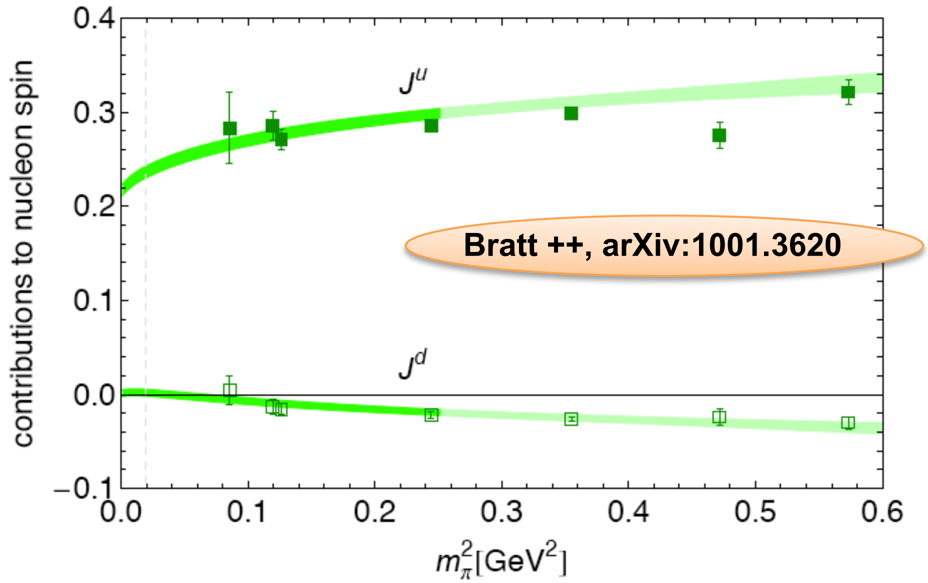
Sea Δq and ΔG @ EIC

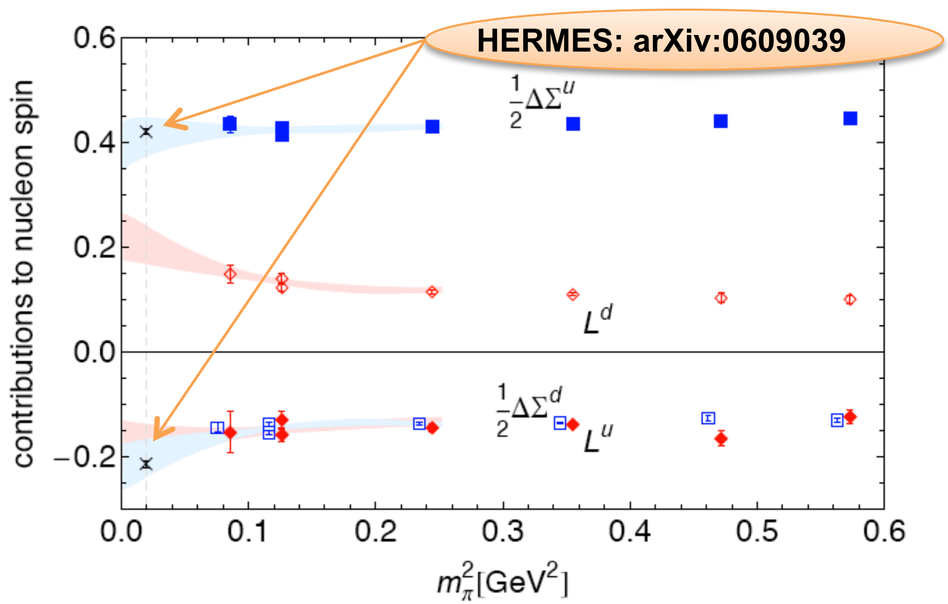


Middle-sea Δq @ COMPASS

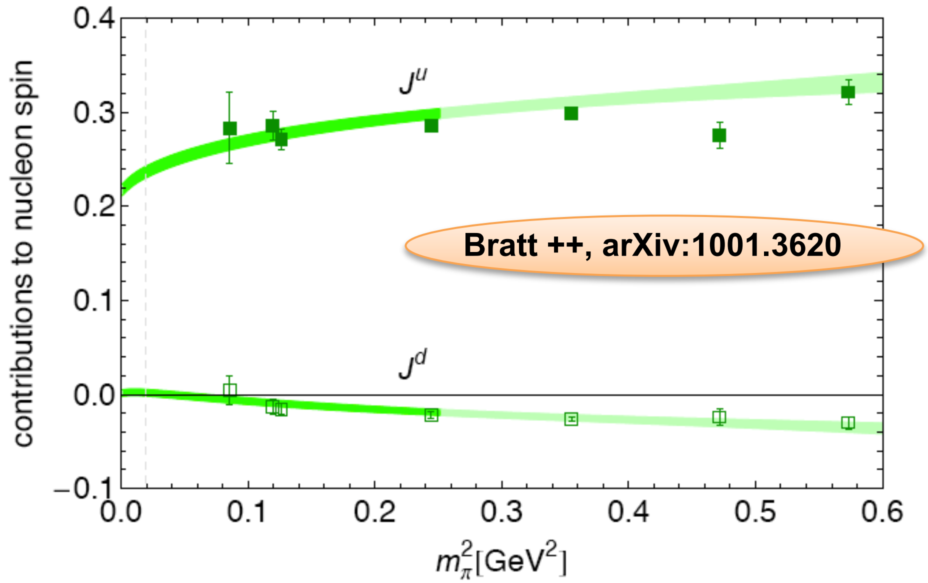


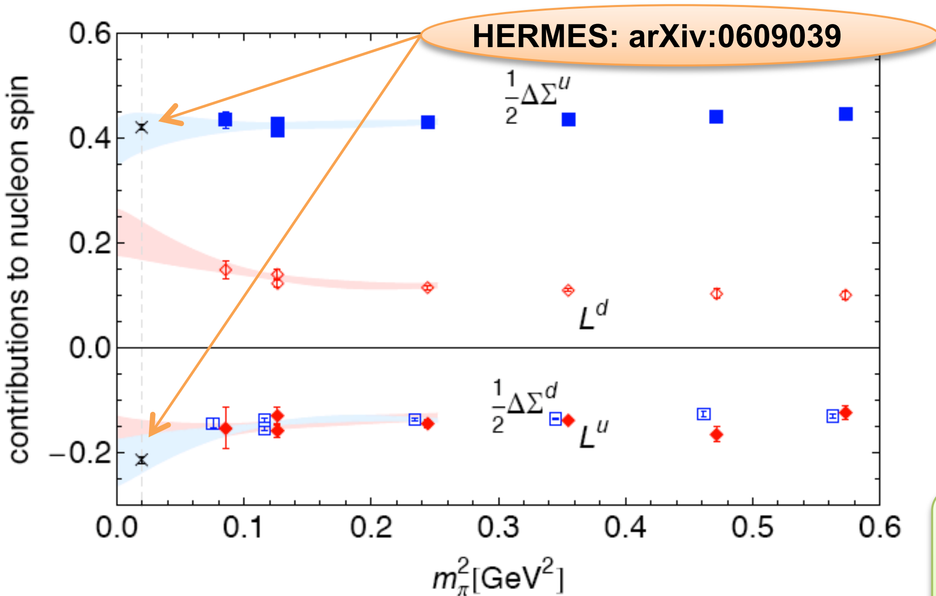
From Lattice



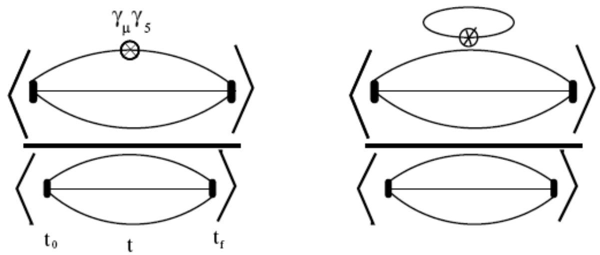


From Lattice





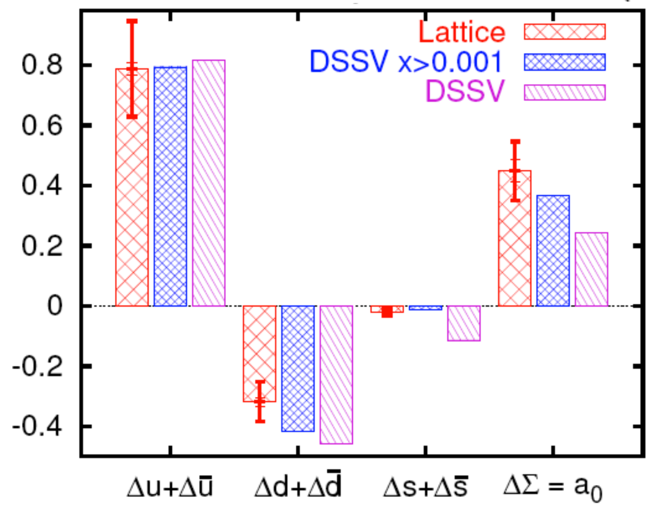
With disconnected diagrams



Bali ++,: arXiv:1112.3354

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.45(4)(9)$$

$$\Delta s = -0.020(10)(4)$$



Liu ++, arXiv:1203.6388

L_q mainly from sea and up to 50 % of the proton spin

The Spin Structure of the Nucleon

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

Important testing ground for QCD

Latest news from Deep Inelastic Scattering (DIS)

Phys Lett B647 (2007) 8-17

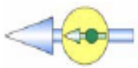
Phys. Rev. D 75 (2007) 012007

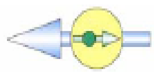
$\Delta\Sigma = 0.33 \pm 0.03$

$\Delta G \sim 0.1$ for $0.05 < x < 0.2$

From pp scattering and DIS

e-print 0804.0422

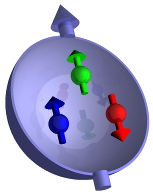


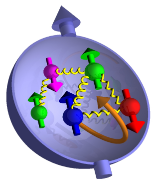


Proton's spin

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

J_q J_g

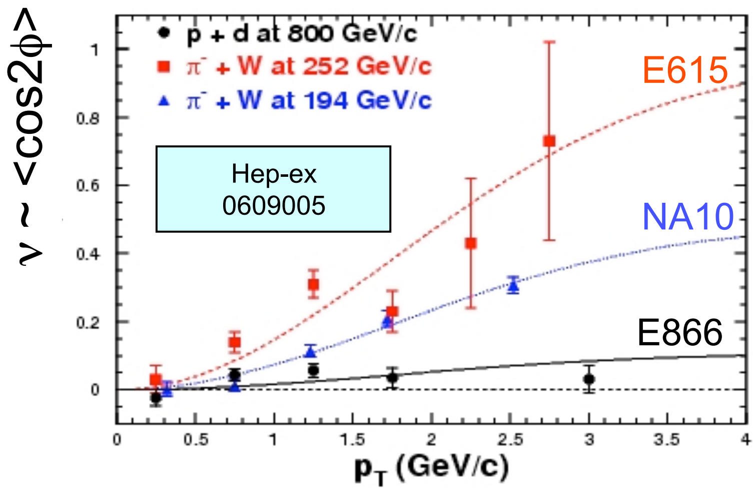


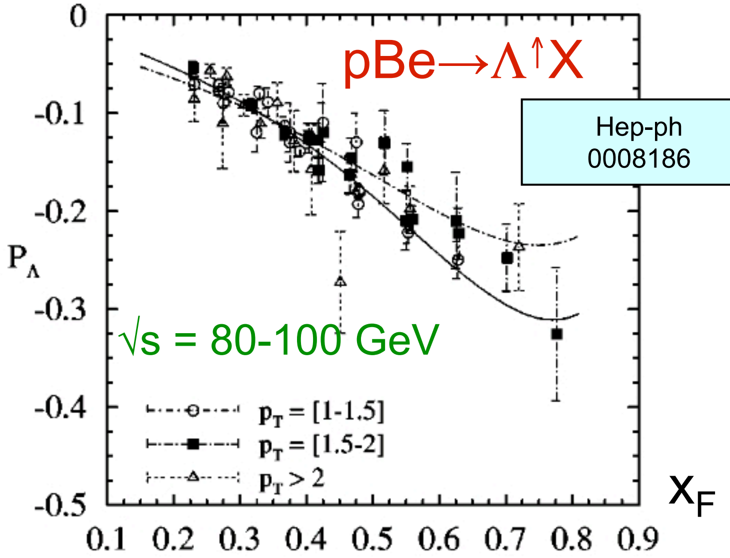


Understanding of the orbital motion of quarks is crucial!

The Spin Surprising Phenomenology

Drell-Yan $pp \to eeX$



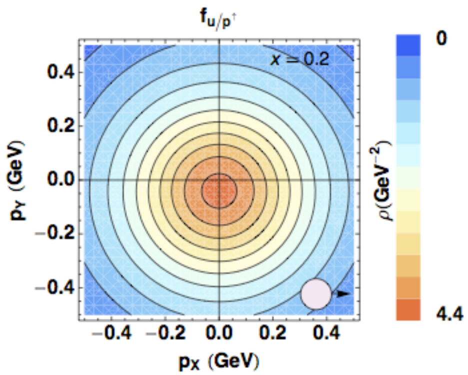


The Real Experience: 3D !

Quantum phase-space distributions of quarks

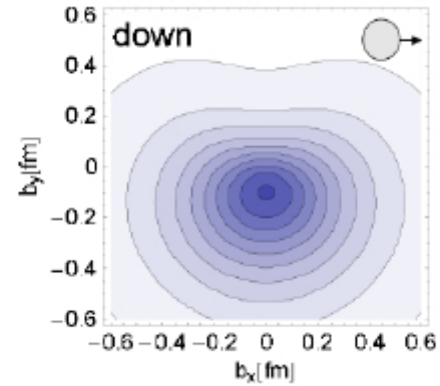
$W_p^q(x,k_T,r)$ "Mother" Wigner distributions

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



d^3r

d^2k_T (FT)



TMD PDFs: $f_p^u(x,k_T)$,…

Semi-inclusive measurements
Momentum transfer to quark
Direct info about momentum distribution

GPDs: $H_p^u(x,\xi,t)$, …

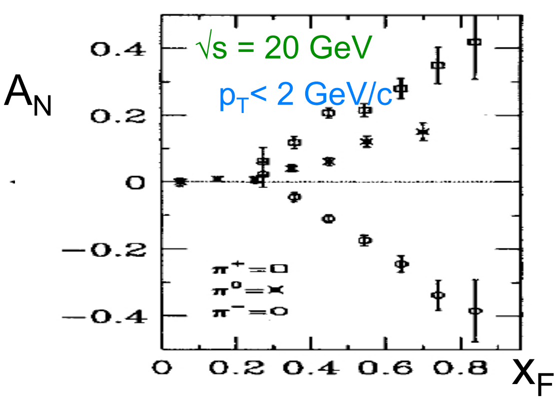
Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

d^2k_T

$\xi=0,t=0$

PDFs $f_p^u(x)$,…

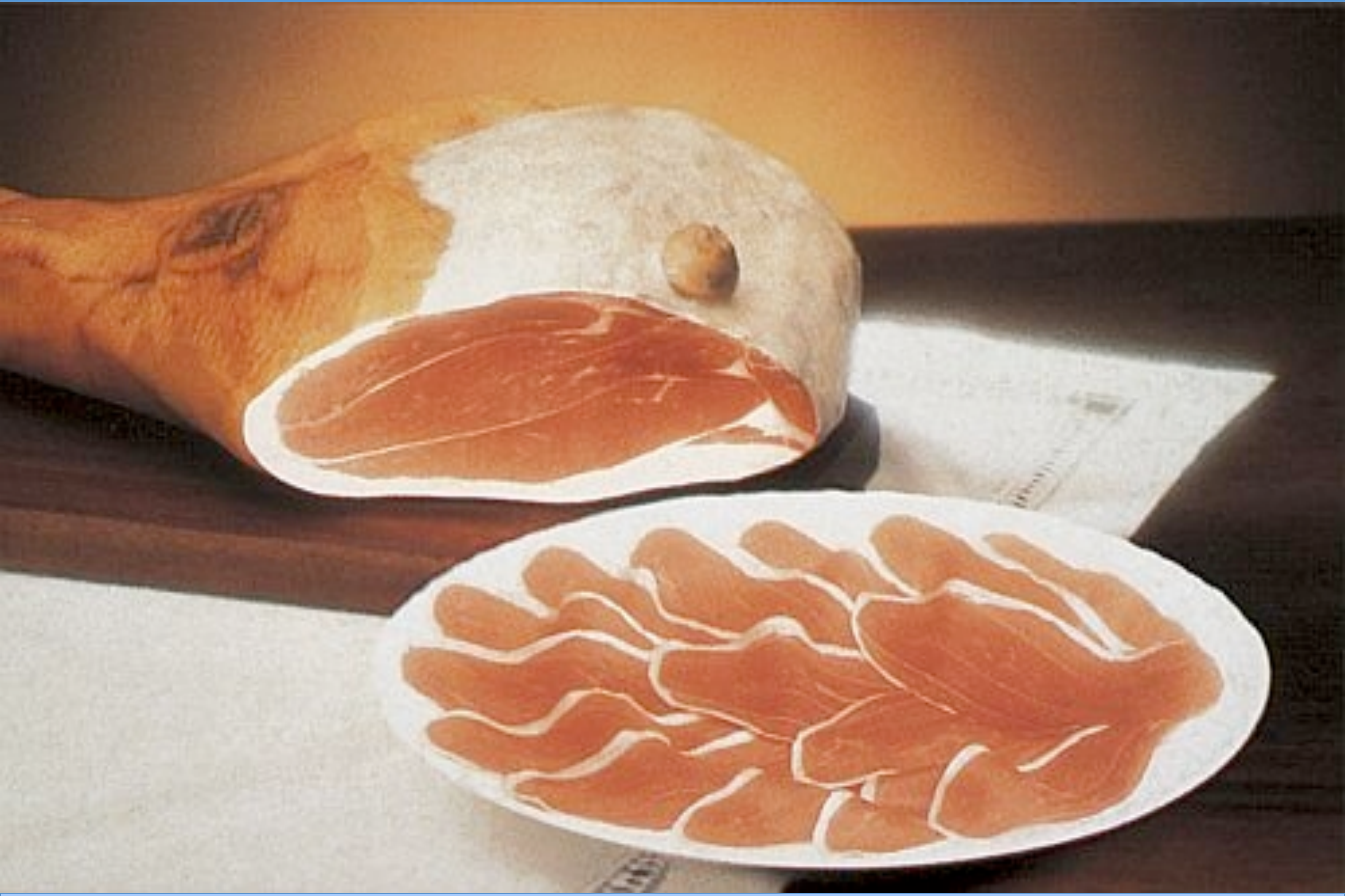
May explain SSA & Lam-Tung



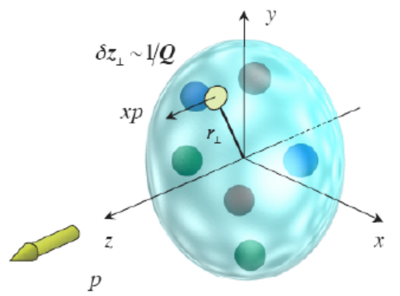
May solve
proton spin puzzle

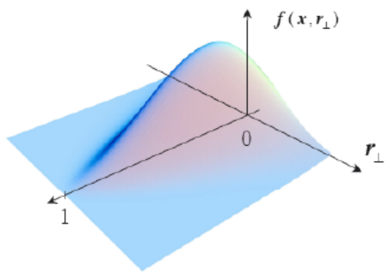
$$J_q = \frac{1}{2}\Delta\Sigma + L_q = \lim_{t\to 0}\int_{-1}^{1} dx\ x\ \left[H(x,\xi,t)+E(x,\xi,t)\right]$$

Tomography



Generalized parton distributions



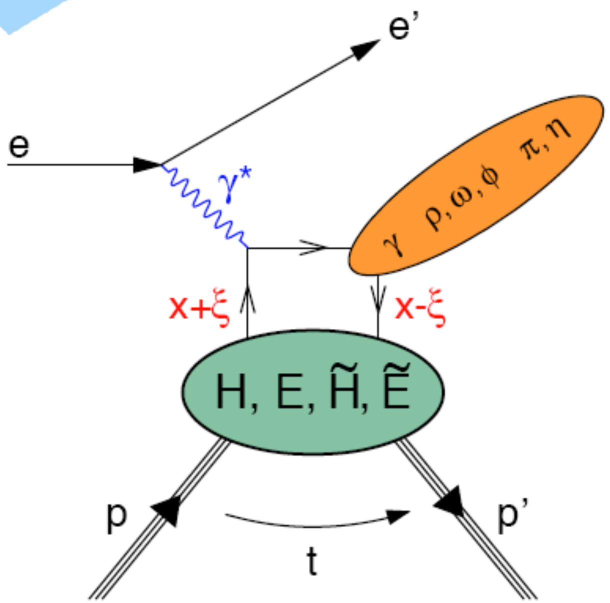


Encompass parton distributions and form factors

longitudinal momentum and transverse spatial position correlated information

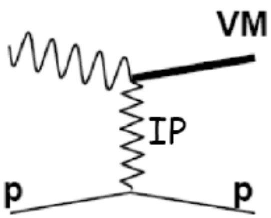
Access OAM $L_q = J_q - \frac{1}{2}\Delta\Sigma$ via Ji sum rule

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



- Sensitivity of different final states to different GPDs
- 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
- DVCS (γ) → $H, E, \tilde{H}, \tilde{E}$
- Vector mesons (ρ, ω, ϕ) → H, E
- Pseudoscalar mesons (π, η) → $\tilde{H}, \tilde{E}$

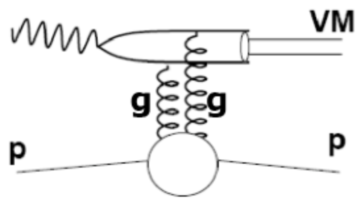
VM production



Soft

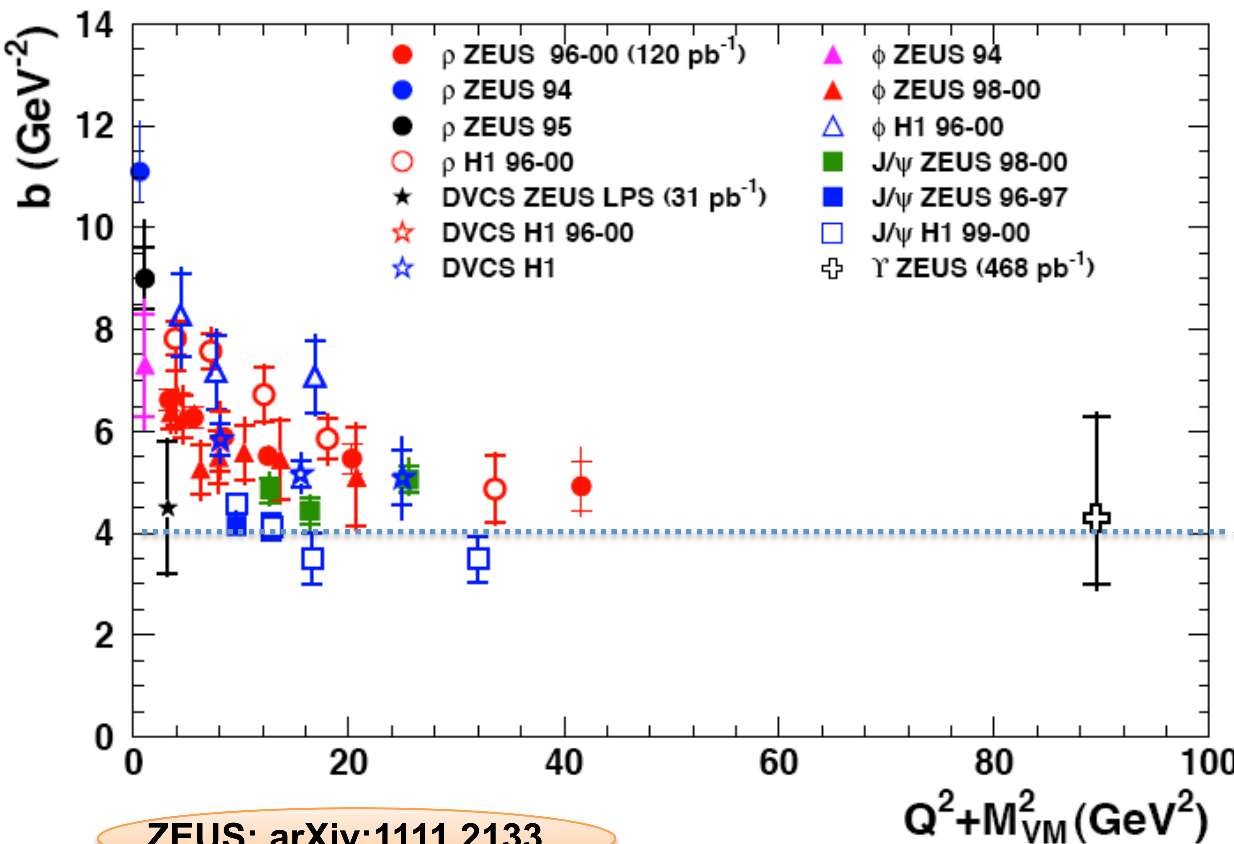
$$\sigma(W) \propto W^{\delta}$$

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$



Hard

informations on the transverse position of partons is incorporated in the t dependence of GPDs



ZEUS: arXiv:1111.2133

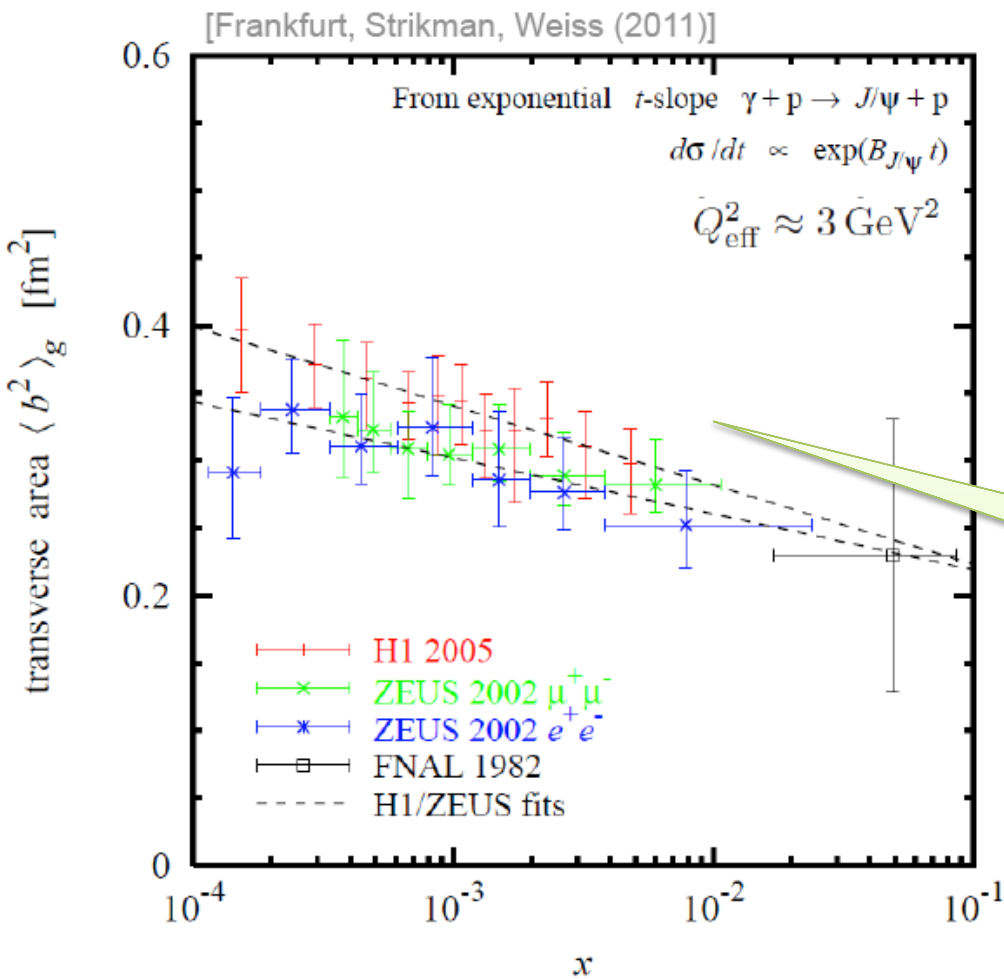
$$\sigma \sim e^{-b|t|}$$

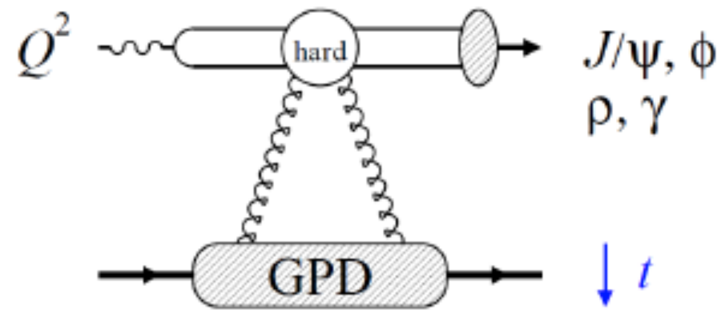
Universality of b slope

Point like configuration

Asymptotic behaviour reflecting target radius

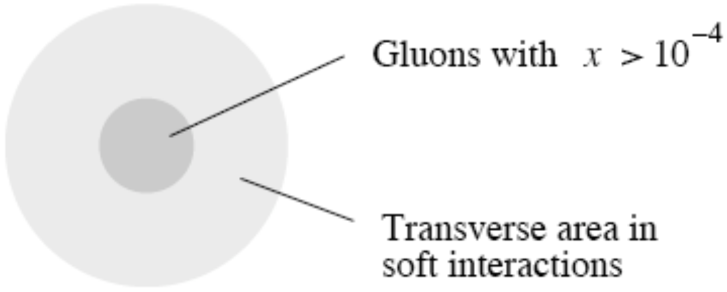
Gluon Imaging





From t slope
→ average impact parameter

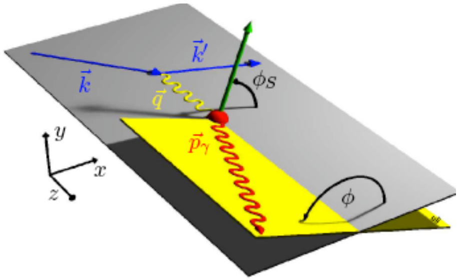
~0.6 of the transverse
e.m. radius squared

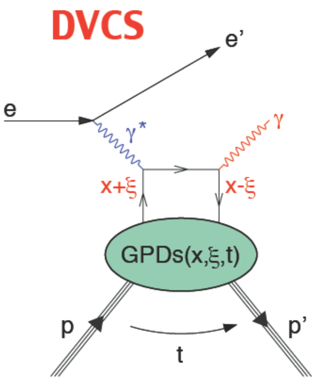


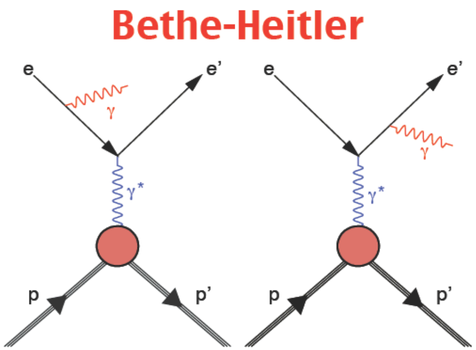
DVCS Interference

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

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







DVCS Interference

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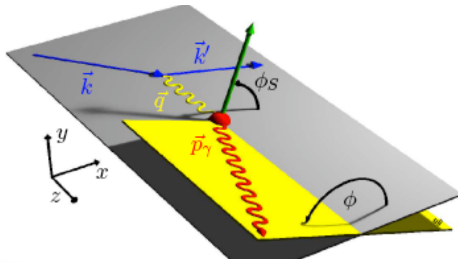
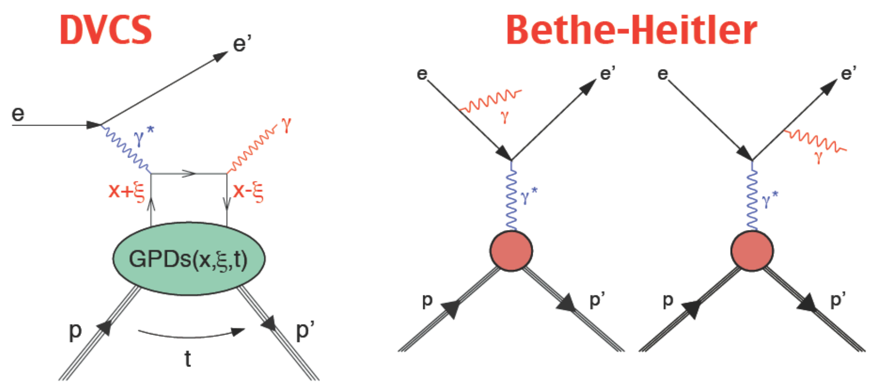
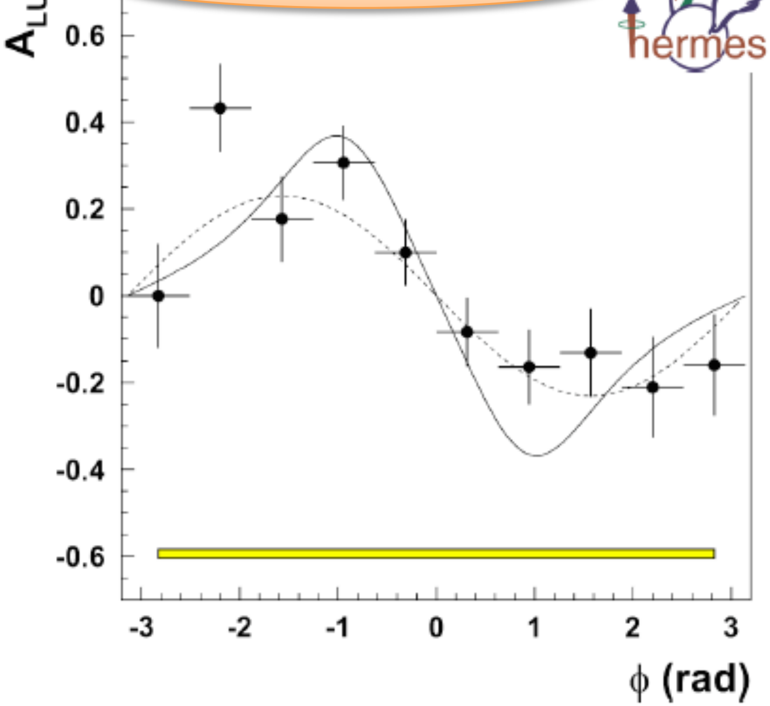


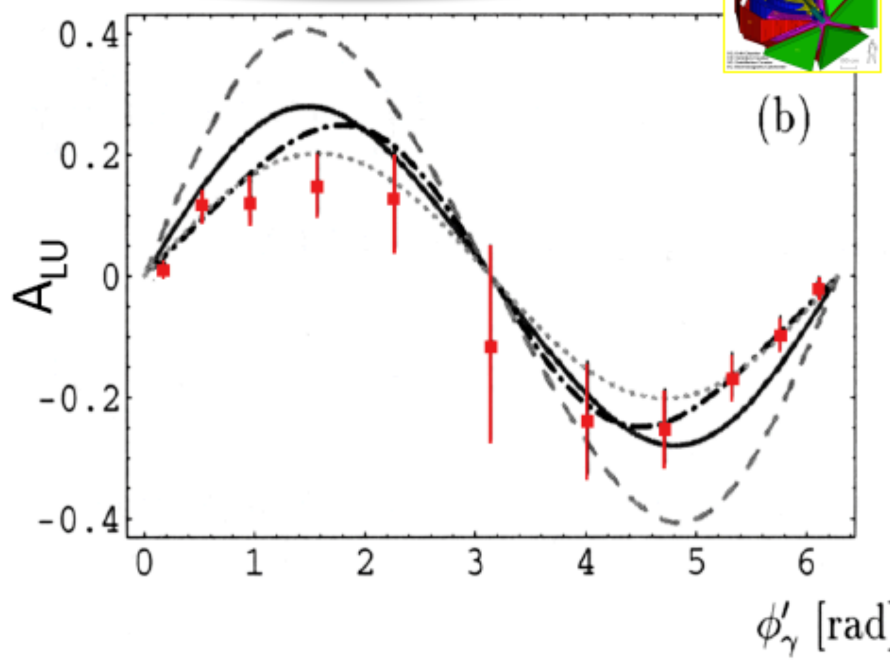


FIRST SIGNALS

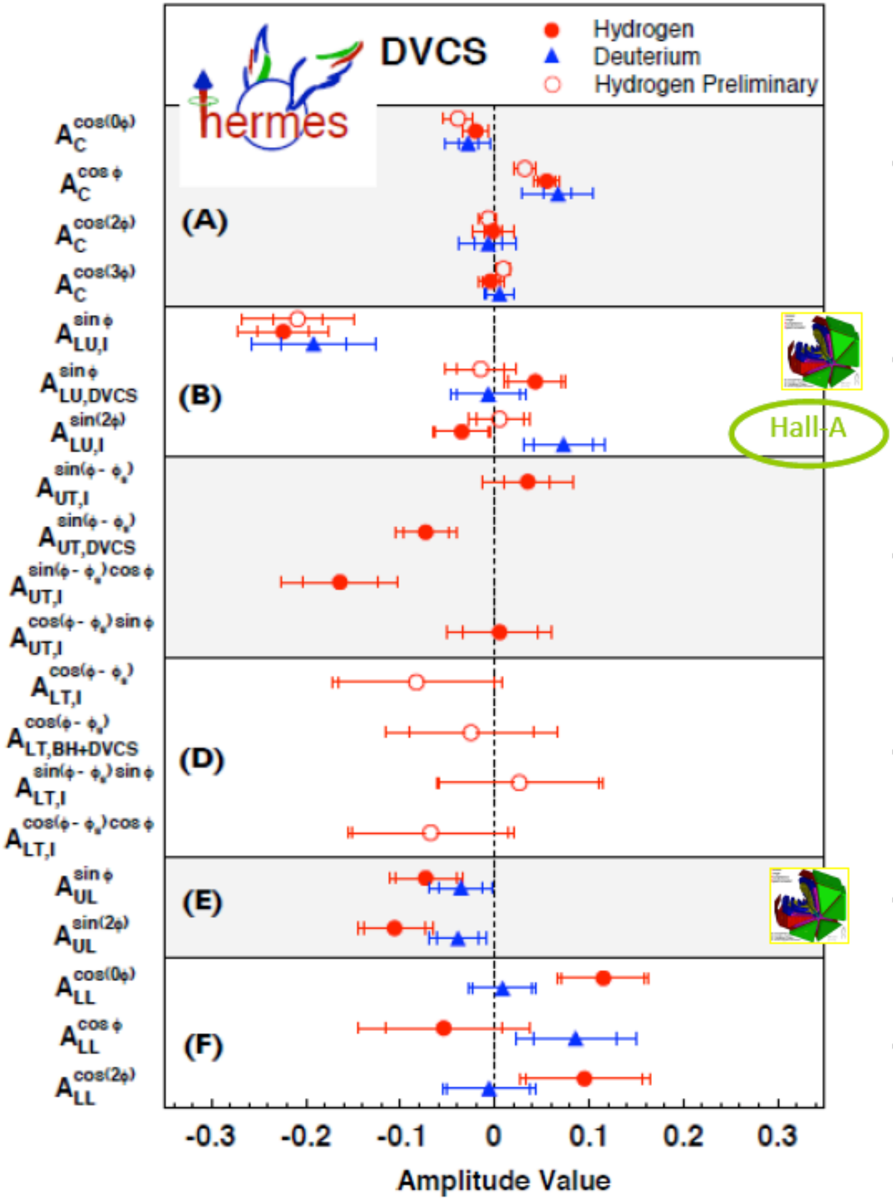
HERMES: arXiv:0106068



CLAS: arXiv:0107043



DVCS Repository



→charge asymmetry

Re (H)

→beam-spin asymmetry

Im (H)

→ transverse target spin asymmetry

Im (H-E)

→ transverse-target double-spin

Re (H-E)

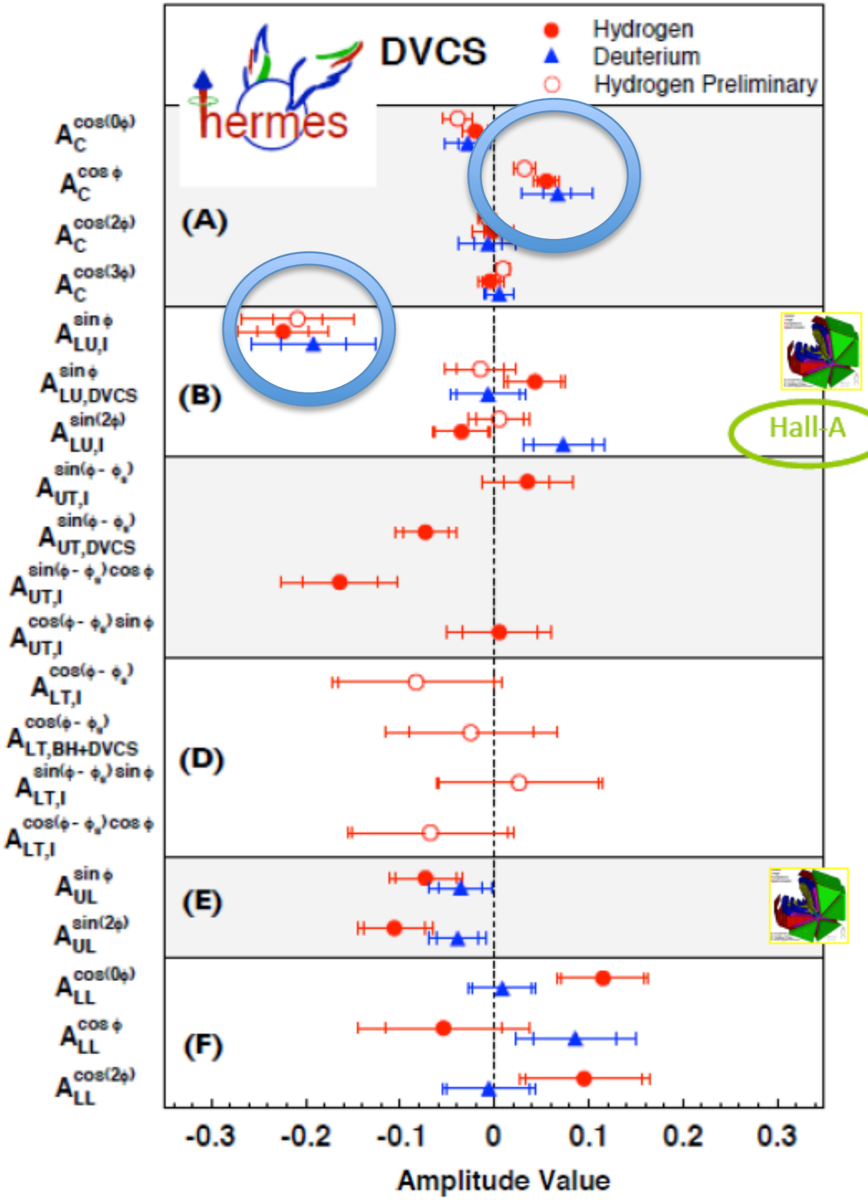
→ longitudinal target spin asymm.

Im $(\tilde{H})$

→ longitudinal-target double-spin

Re $(\tilde{H})$

DVCS Repository



→charge asymmetry

Re (H)

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→ transverse target spin asymmetry

Im (H-E)

→ transverse-target double-spin

Re (H-E)

→ longitudinal target spin asymm.

Im $(\widetilde{H})$

→ longitudinal-target double-spin

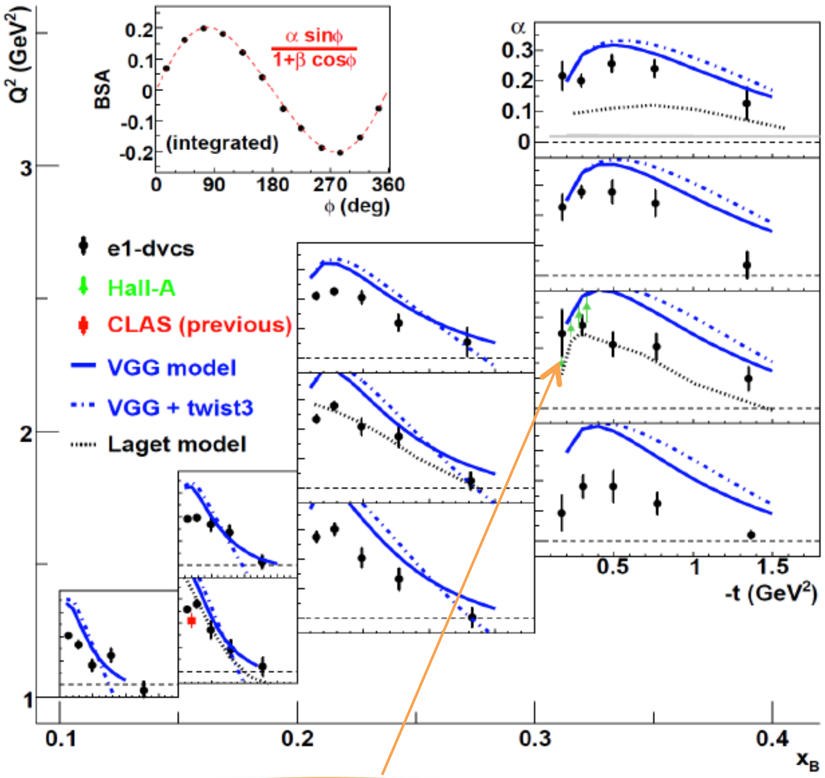
Re $(\widetilde{H})$

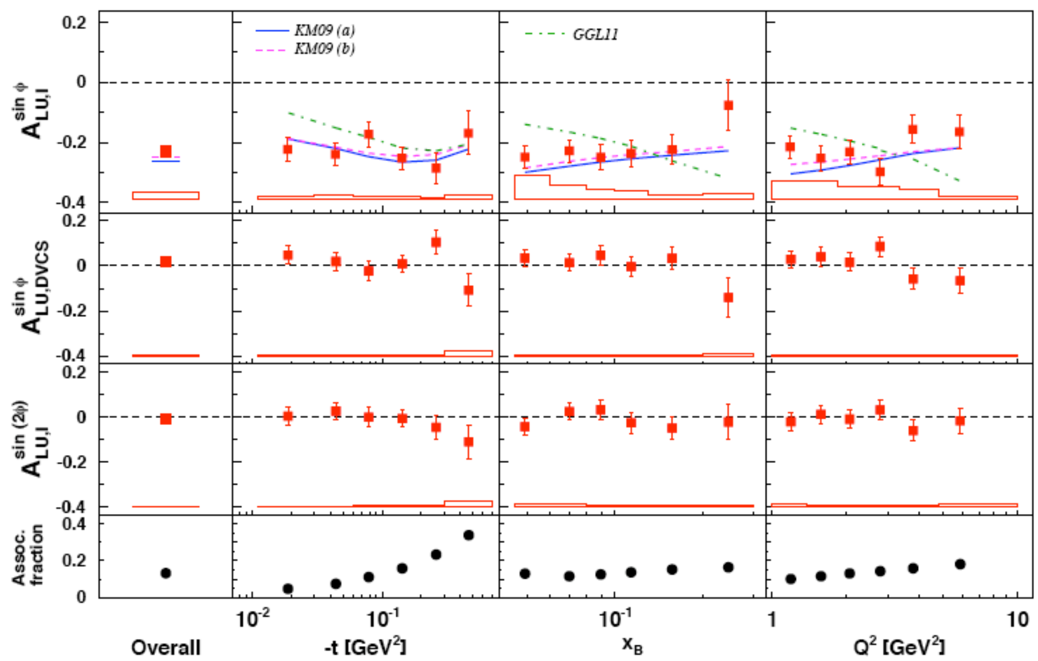
DVCS Beam-Spin Asymmetry

$$\mathcal{A}_{LU}(\phi): \quad d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi) \propto \mathrm{Im}[F_1\mathcal{H}]\cdot\sin\phi$$

CLAS: arXiv:0711.4805

HERMES: arXiv:1203.6287





Hall-A: nucl-ex/0607029

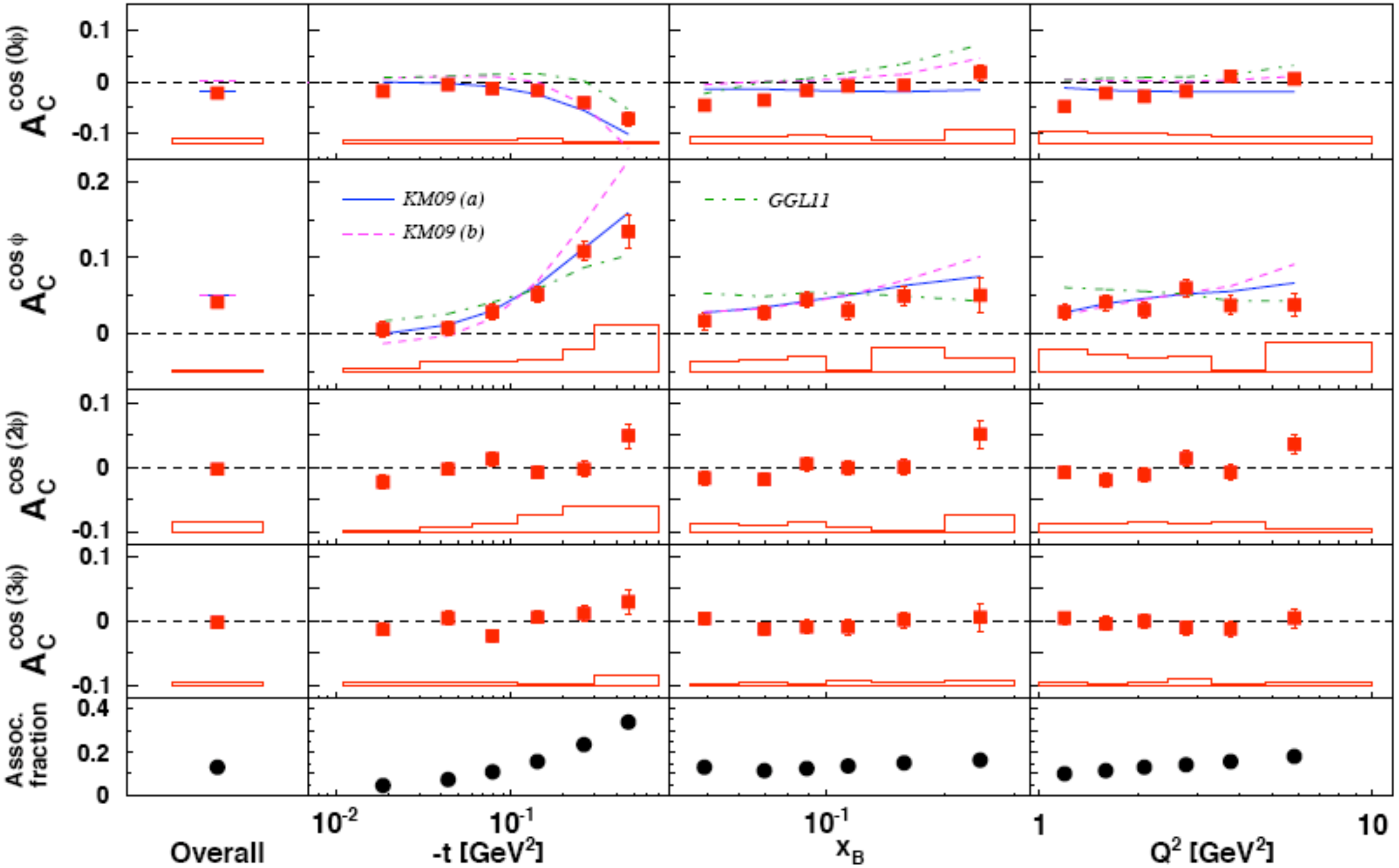
$$\sigma_{LU}(\phi; P_l, e_l) = \sigma_{UU}(\phi)\cdot\{1 + P_l A_{LU}^{DVCS}(\phi) + e_l P_l A_{LU}^{\mathcal{I}}(\phi) + e_l A_C(\phi)\}$$

DVCS Beam-Charge Asymmetry

$\mathcal{R}e(\mathcal{F}_1\mathcal{H})$

$$A_C(\phi): \quad d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \propto \mathrm{Re}[F_1\mathcal{H}]\cdot\cos\phi$$

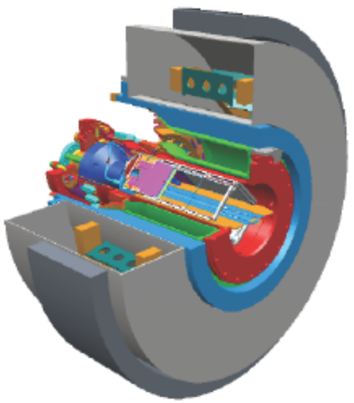
HERMES: arXiv:1203.6287

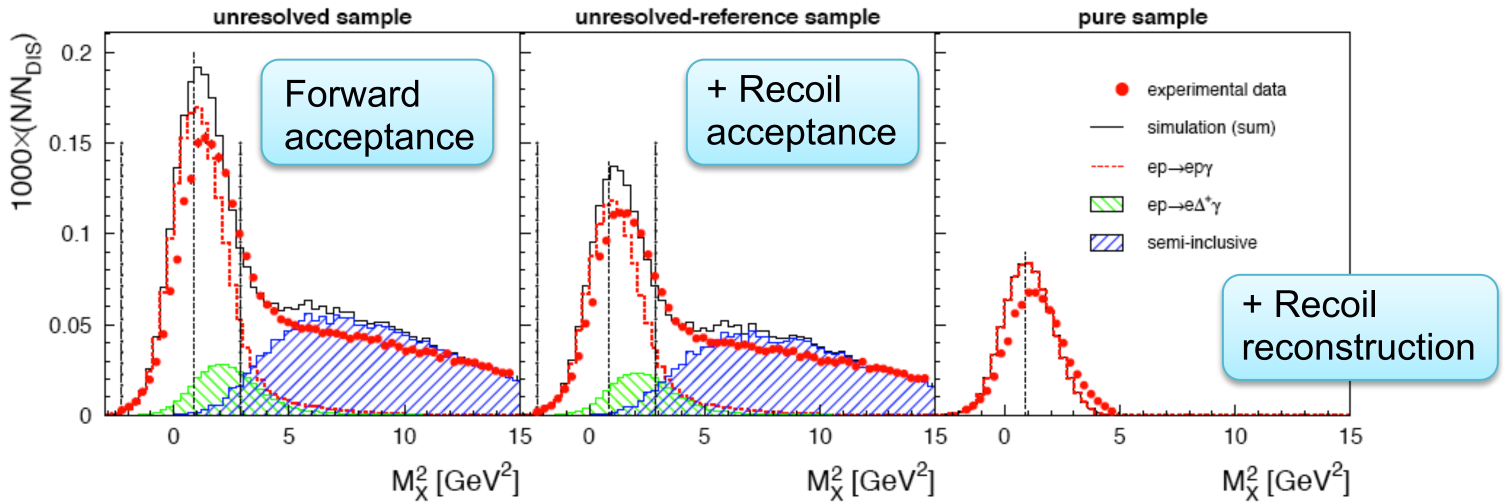


$$A_C^{\cos 0\phi} \propto -\frac{t}{Q} A_C^{\cos\phi}$$

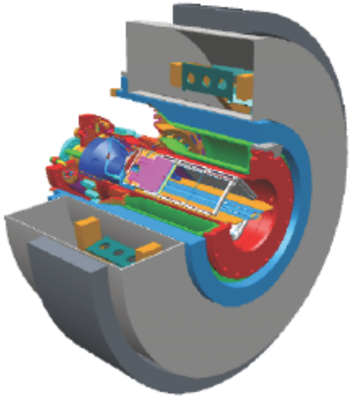
$$A_C^{\cos\phi} \propto F_1 \mathrm{Re}\mathcal{H}$$

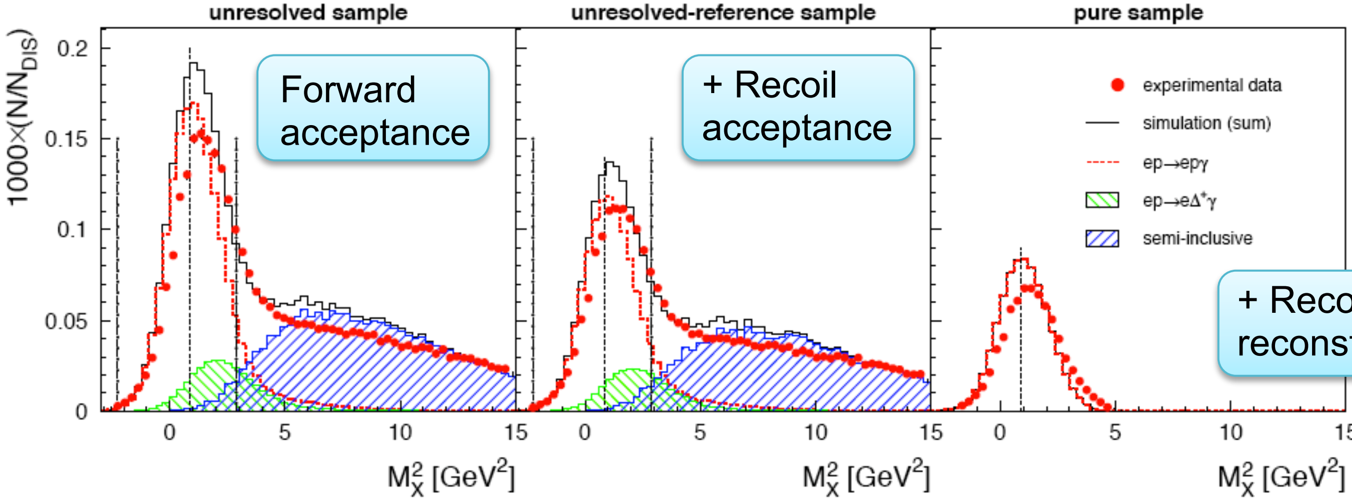
The Pure DVCS Sample

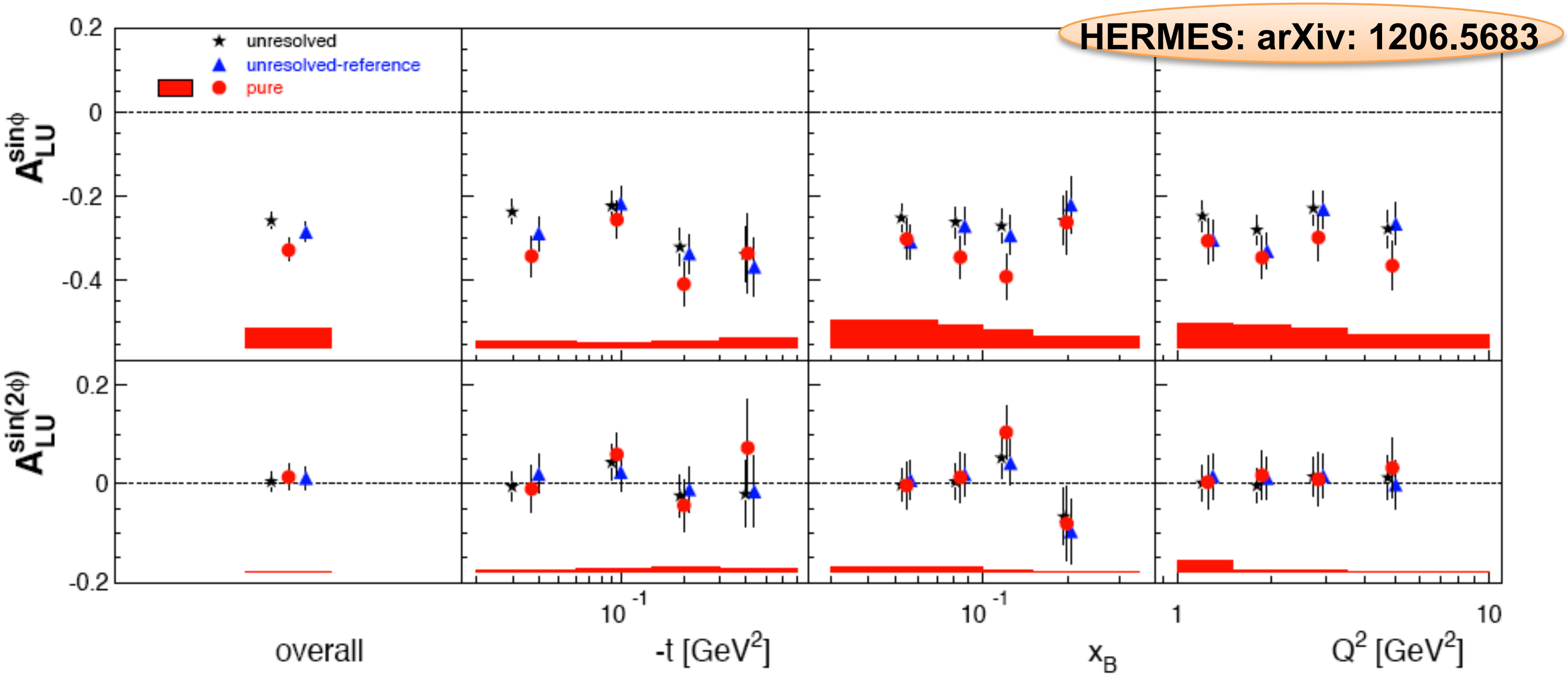




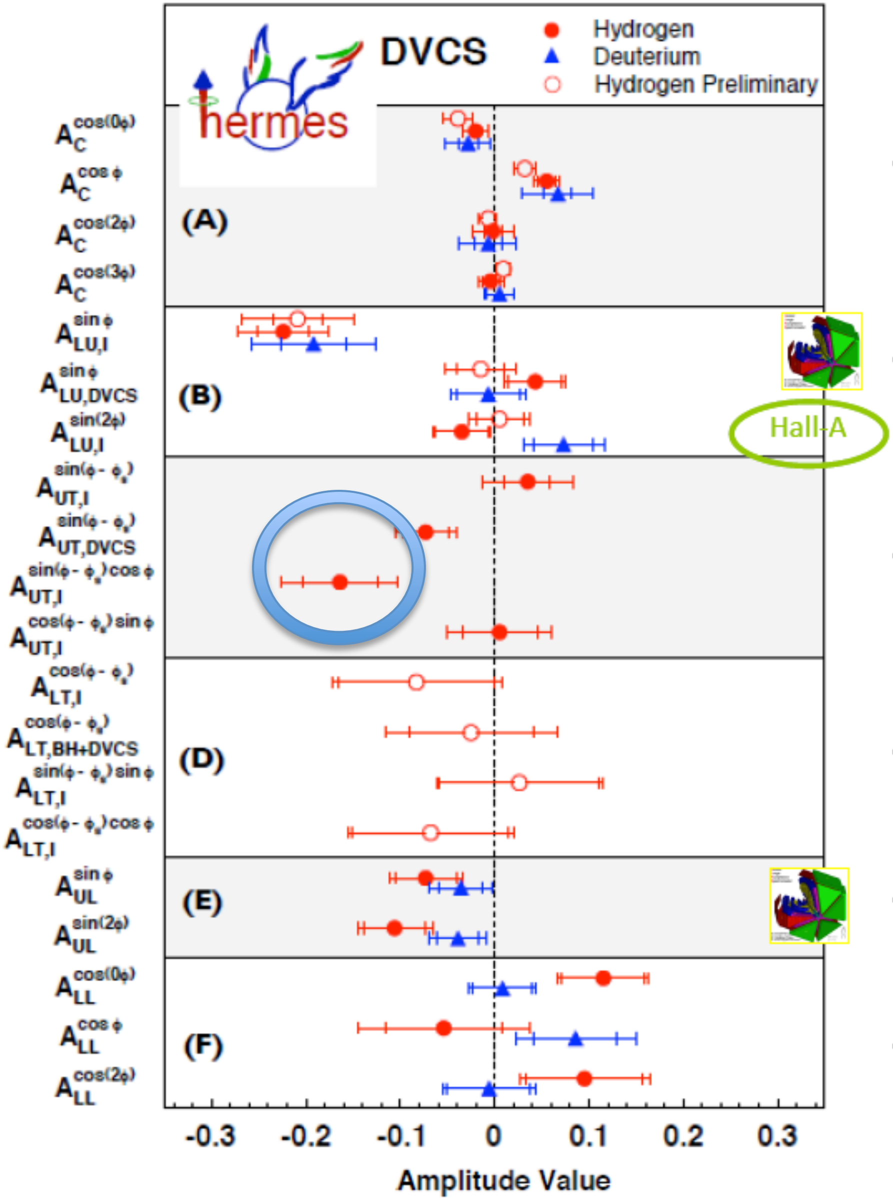
The Pure DVCS Sample







DVCS Repository



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

→charge asymmetry

Re (H)

→beam-spin asymmetry

Im (H)

→ transverse target spin asymmetry

Im (H-E)

→ transverse-target double-spin

Re (H-E)

→ longitudinal target spin asymm.

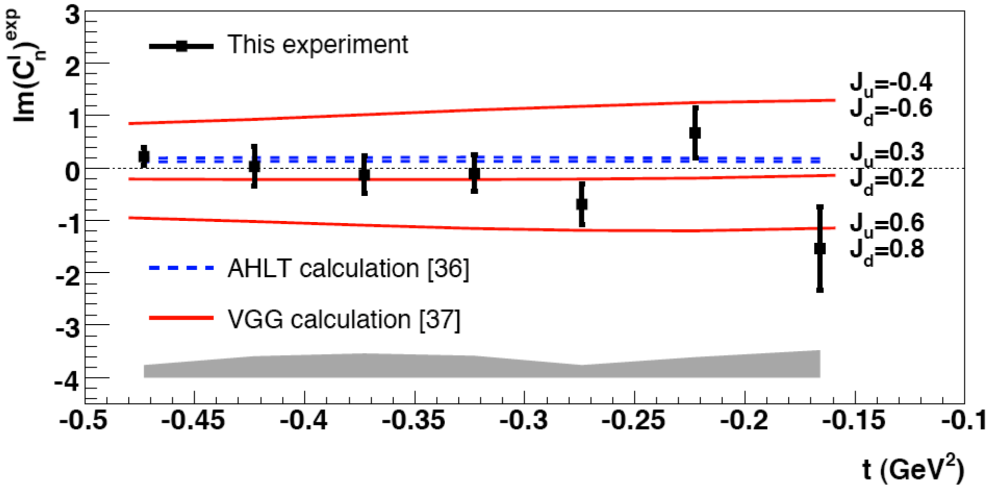
Im ($\tilde{H}$)

→ longitudinal-target double-spin

Re ($\tilde{H}$)

DVCS & OAM

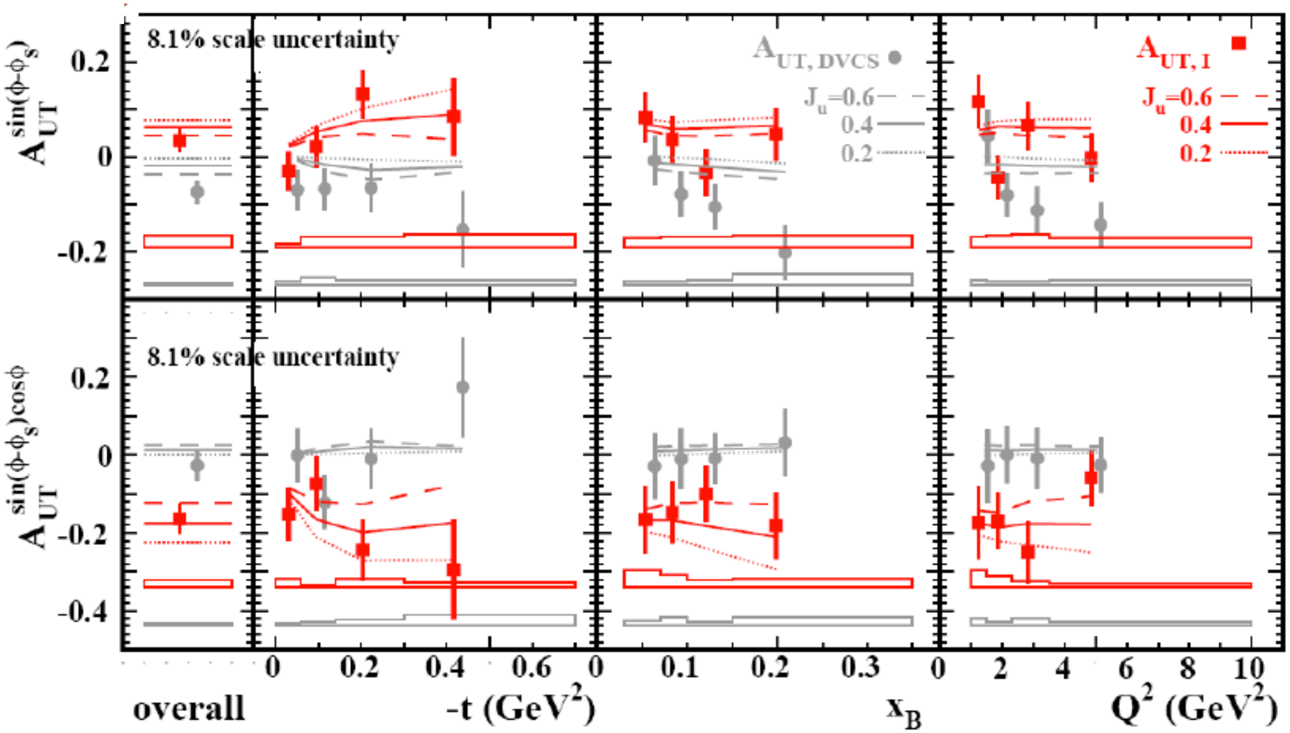
$Im(\mathcal{F}_2\mathcal{E})$



nDVCS: beam spin cross-section difference

Hall-A: arXiv: 0709.0450

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



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

HERMES: arXiv: 0802.2499

pDVCS: transverse target spin asymmetry

DVCS @ COMPASS 2014+

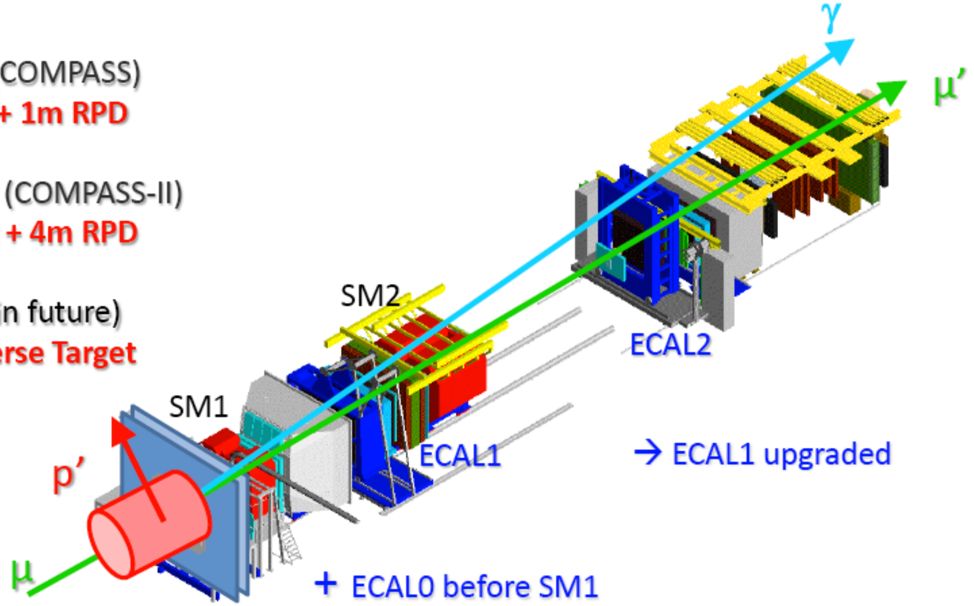
$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto \boxed{c_0^{Int} + c_1^{Int}\cos\phi} \quad \text{and} \quad c_{0,1}^{Int} \sim \mathcal{R}e(F_1\mathcal{H})$$

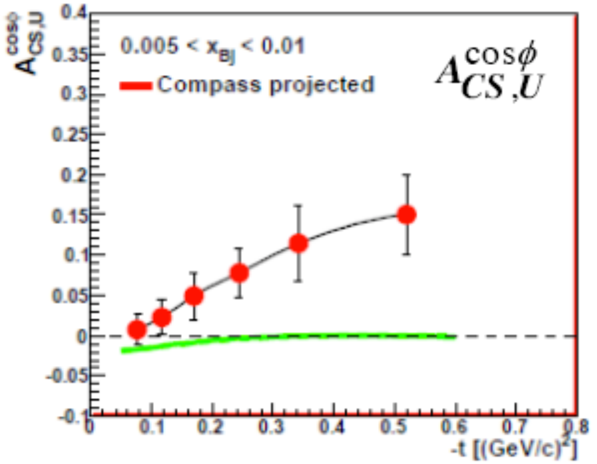
$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto \boxed{d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int}\sin\phi} \quad \text{and} \quad s_1^{Int} \sim \mathcal{I}m(F_1\mathcal{H})$$

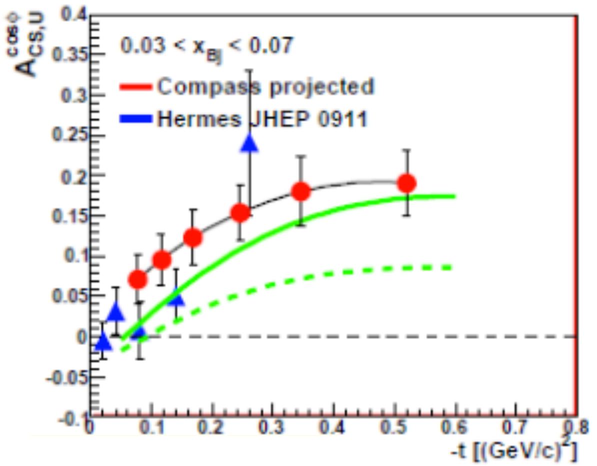
Tests in 2008-09 (COMPASS)
40cm LH2 target + 1m RPD

Phase 1: 2012-16 (COMPASS-II)
2.5 m LH2 target + 4m RPD

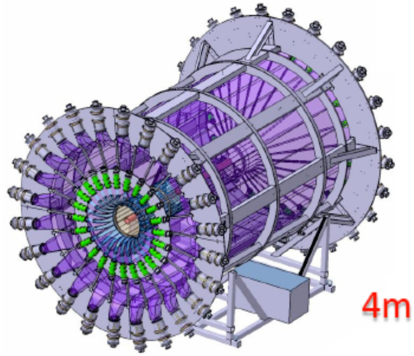
Phase 2: > 2016 (in future)
Polarised Transverse Target integrating RPD







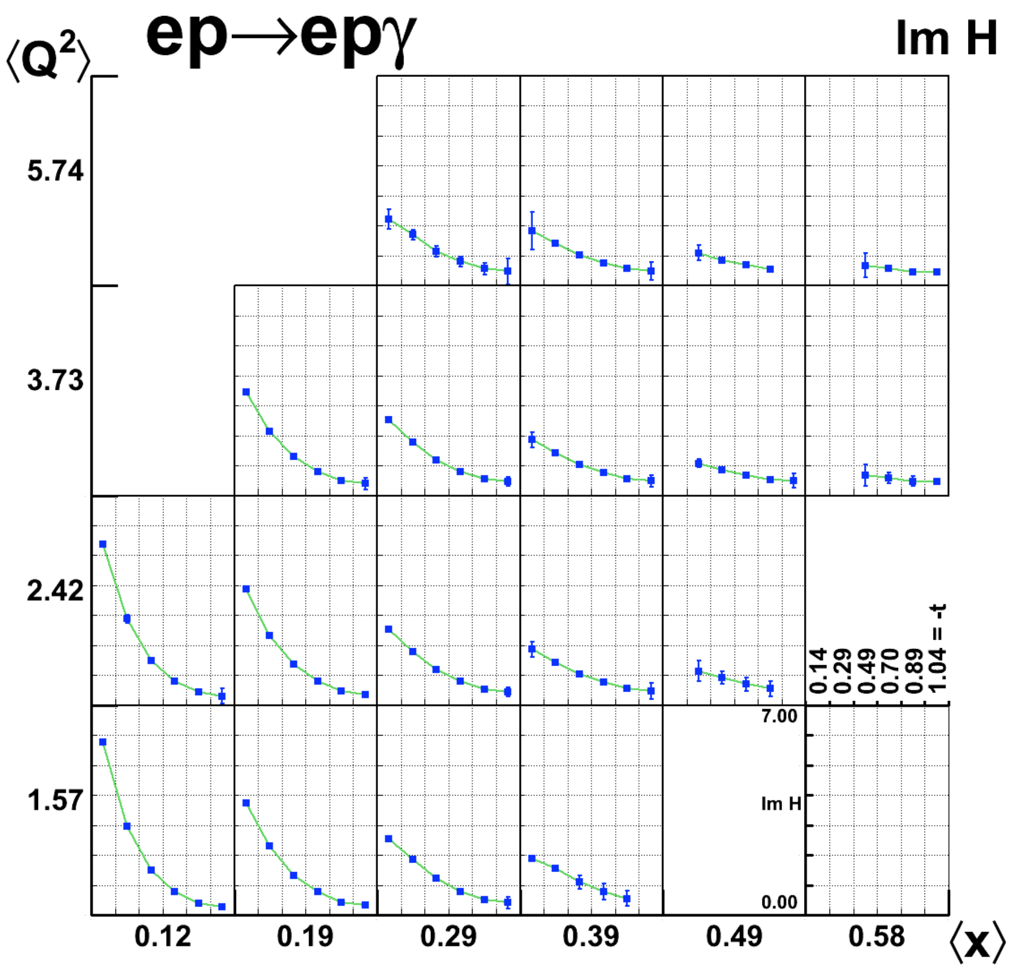
Prototype of the 2.5m long LH2 target

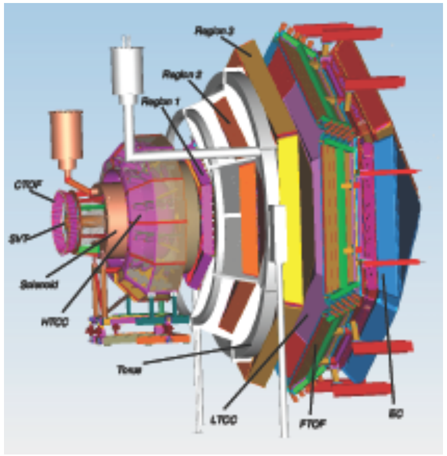


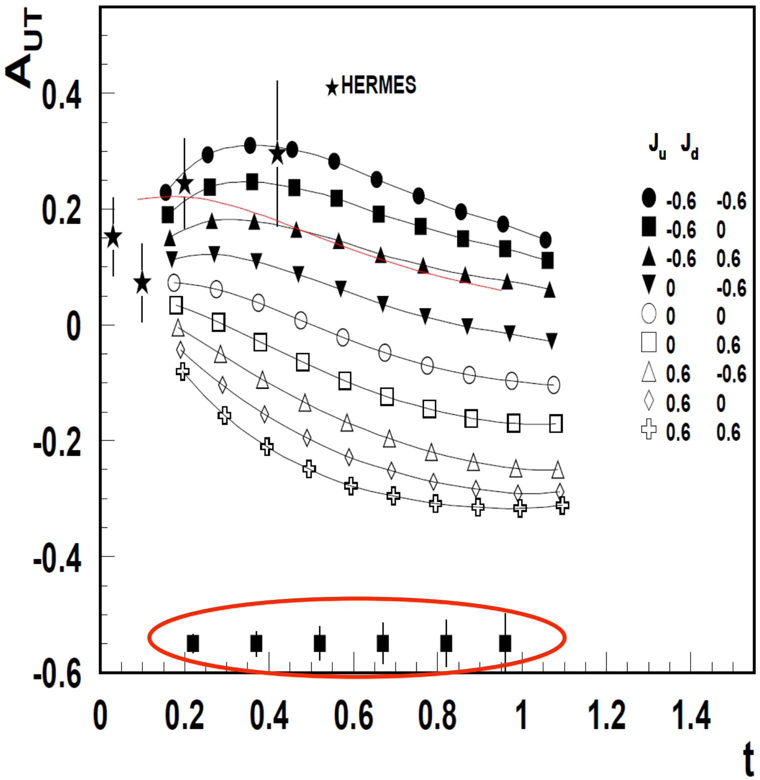
4m long ToF barrel

DVCS @ CLAS12 2015+

Broad program with polarized beam +
long. & transversely polarized target
@ L ~ 10^{35} cm^{-2} s^{-1}



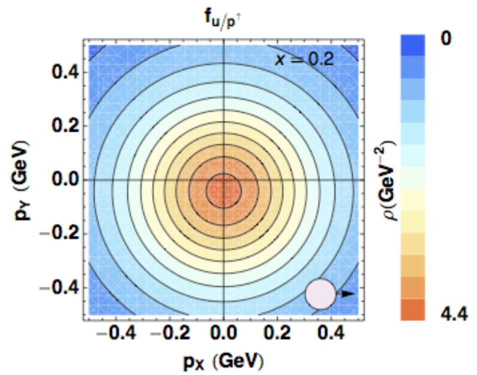




Quantum phase-space distributions of quarks

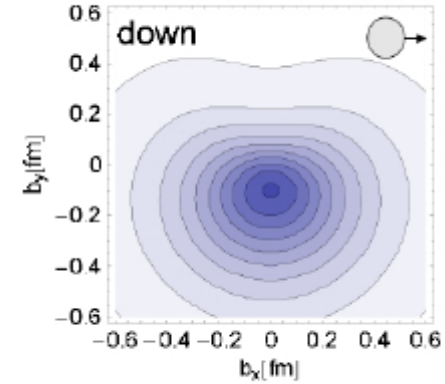
$W_p^q(x,k_T,r)$ "Mother" Wigner distributions

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



d^3r

d^2k_T (FT)



TMD PDFs: $f_p^u(x,k_T)$,…

Semi-inclusive measurements
Momentum transfer to quark
Direct info about momentum distribution

GPDs: $H_p^u(x,\xi,t)$, …

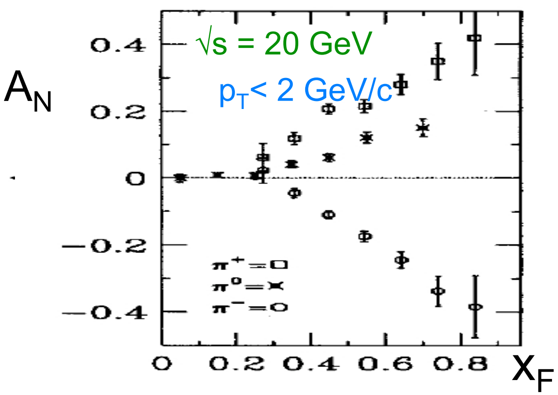
Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

d^2k_T

$\xi=0, t=0$

PDFs $f_p^u(x)$,…

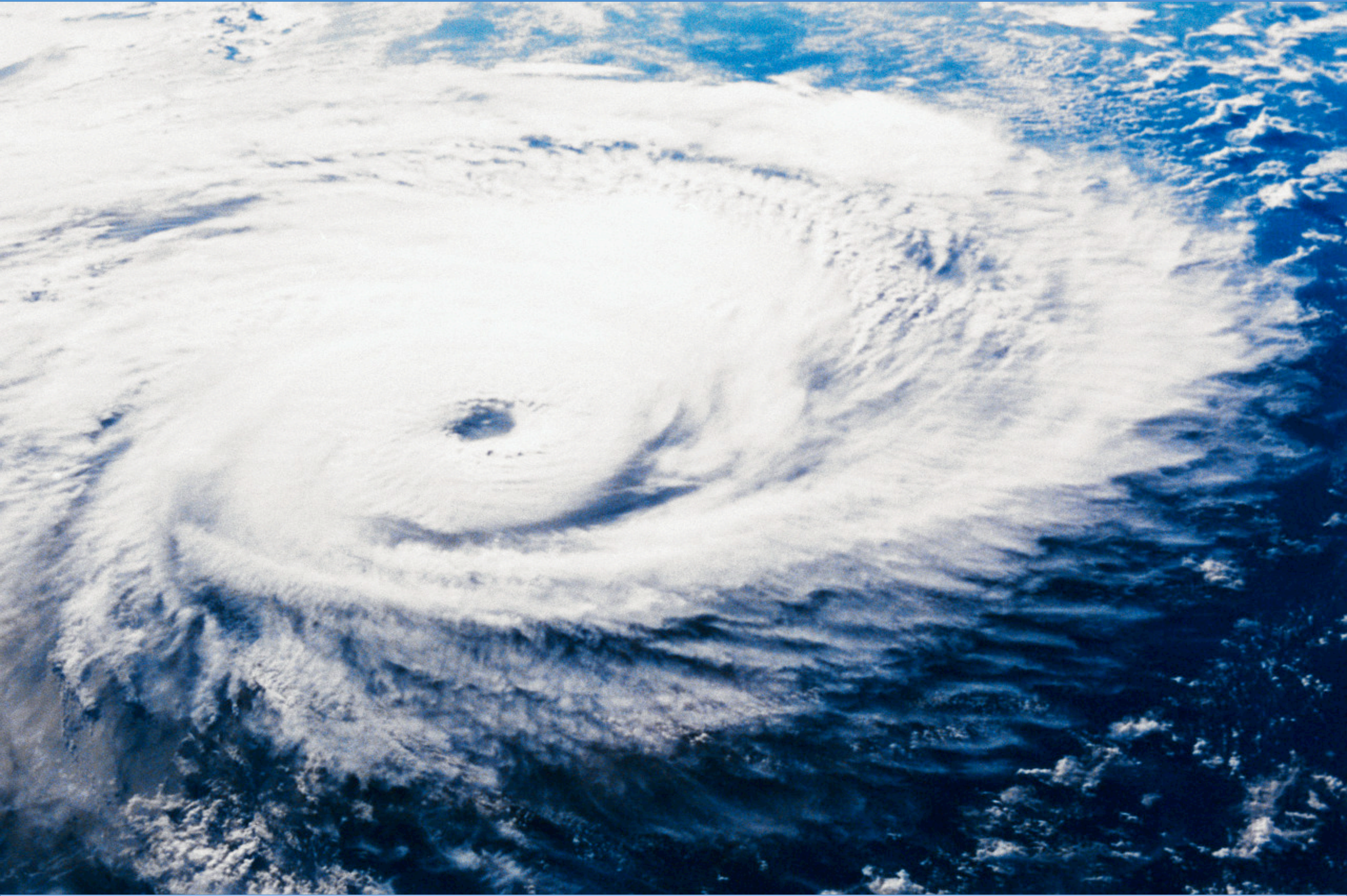
May explain SSA & Lam-Tung



May solve
proton spin puzzle

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

Spin-Orbit Effects



Leading Twist TMDs

quark polarisation

nucleon polarisation

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

Number density and helicity:

Focusing here in transverse momentum dependence

Transversity:

Survives transverse momentum integration (missing leading-twist collinear piece)

Differs from helicity due to relativistic effects and no mix with gluons in the spin-1/2 nucleon

Off-diagonal elements:

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

Testing QCD at the amplitude level

T-odd elements:

➔ sign change between DY and SIDIS

- universality of TMDs

Strict prediction from TMDs + QCD !

quark polarisation

nucleon polarisation

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

First evidences

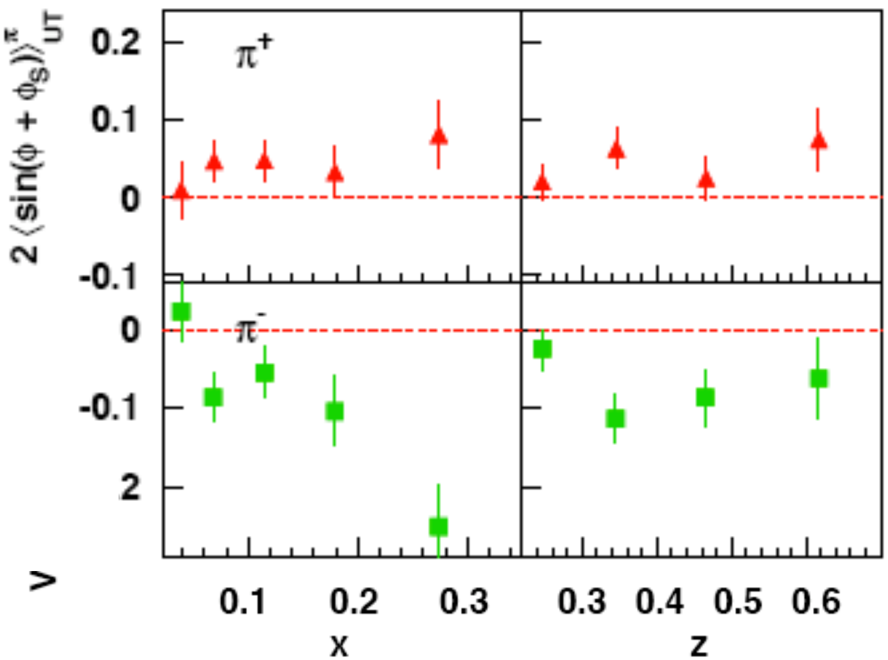
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^{\perp}$$

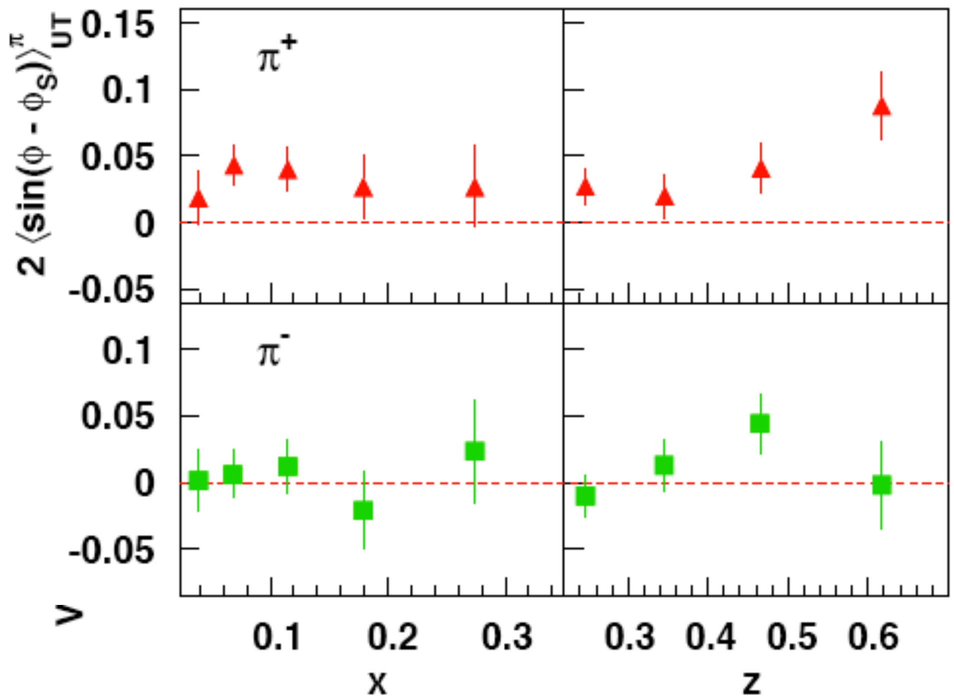
SIDIS:
ep → e'hX

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

2005: First evidence from HERMES measuring SIDIS on proton

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

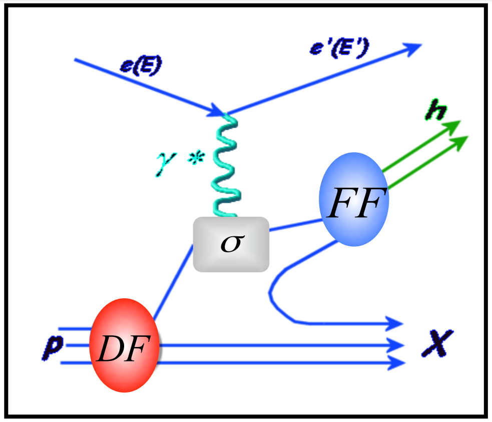




Non-zero transversity !!
Non-zero Collins function !!

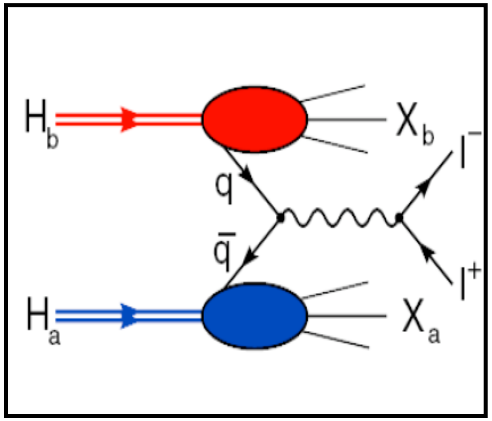
Non-zero Sivers function !!

Physics reactions



SIDIS: rich phenomenology, the most explored so far

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

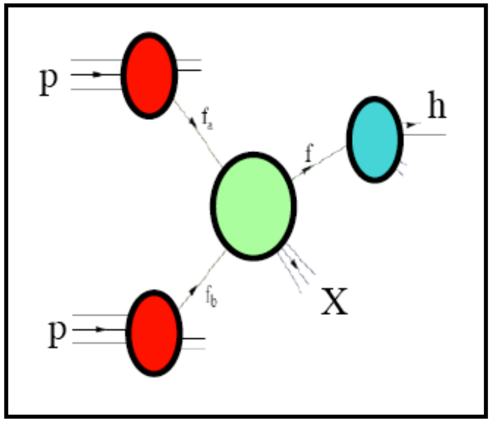


e⁺e⁻: B-factories as powerful fragmentation laboratories

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

DY: challenging for experiments (only unpolarized so far)

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



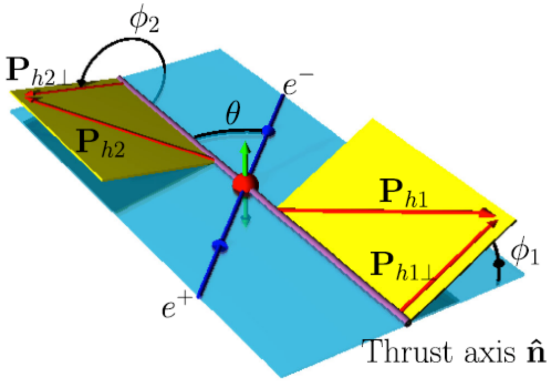
Hadron reactions: challenging for theory (ISI + FSI)

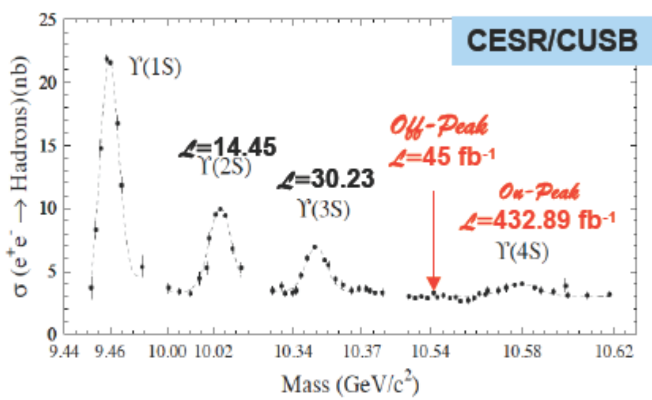
pp $\sigma^{pp\to hX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to qq} \otimes FF$

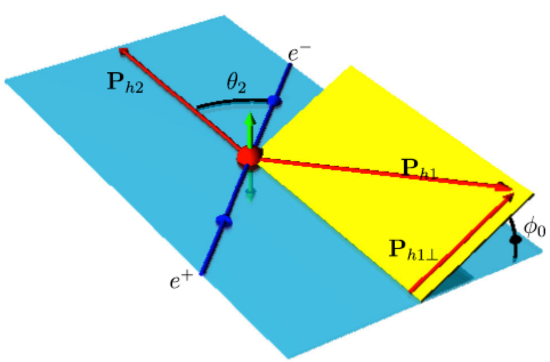
Fragmentation @ e+e- Colliders

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

COLLINS SIGNALs



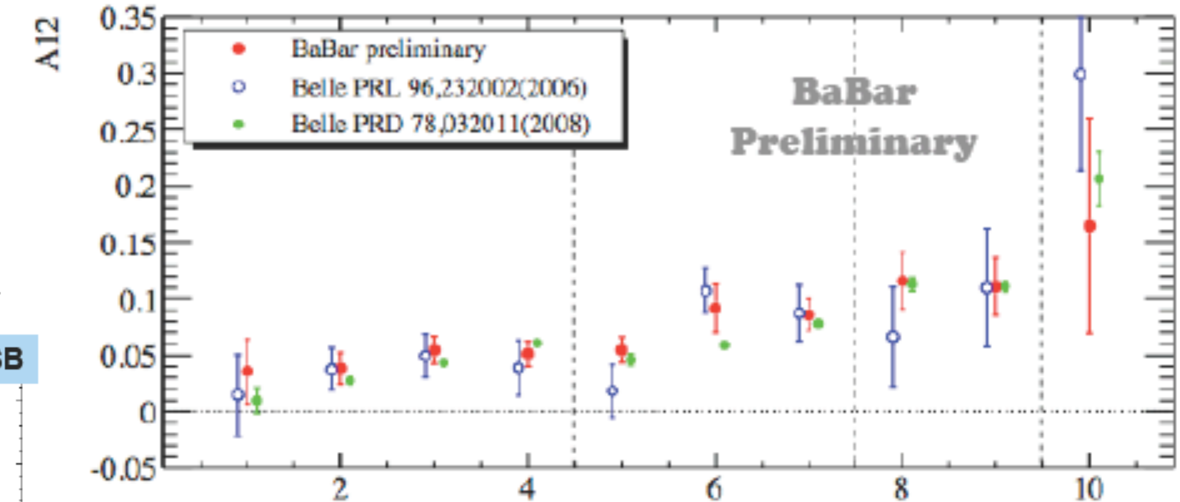




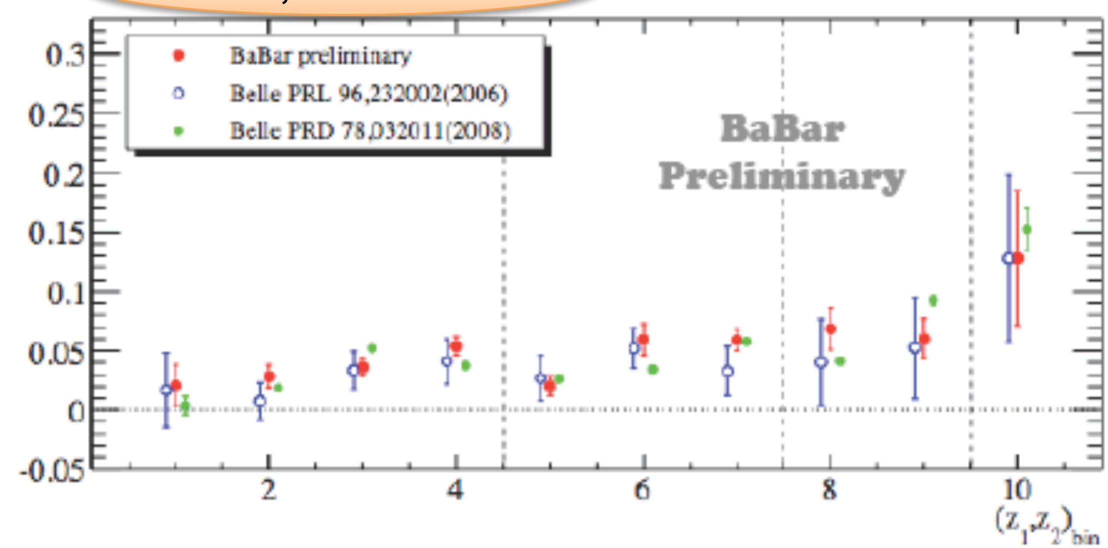
BaBar preliminary: $\mathcal{L}$≈45 fb^{-1}

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

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



Garzia ++, arXiv: 1201.4678

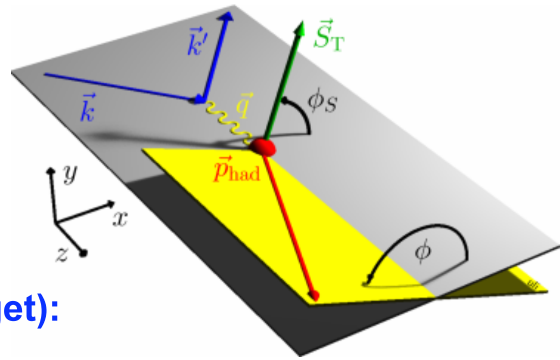


The SIDIS case

quark polarisation (columns) / **nucleon polarisation** (rows)

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

SIDIS cross section (transversely polarized target):



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

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

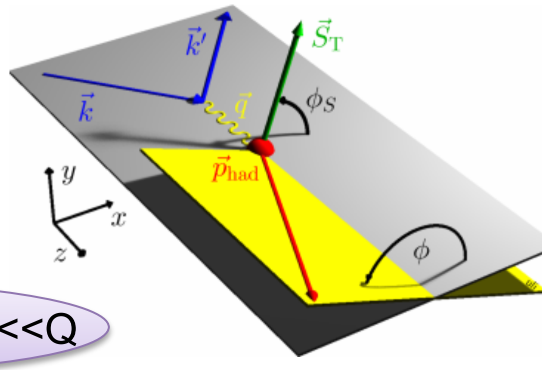
$$+S_T\lambda_e\left\{\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right\}+\ldots$$

The SIDIS case

quark polarisation / **nucleon polarisation**

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

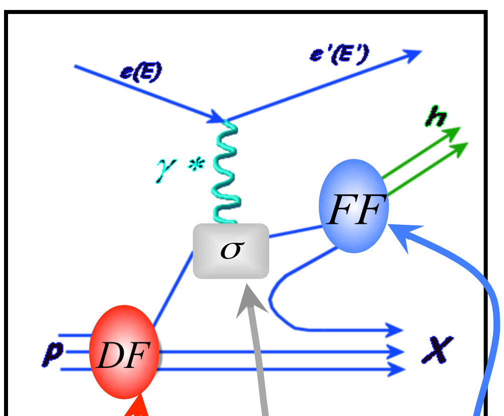
SIDIS cross section (transversely pol. target):



TMD factorization for $P_T \ll Q$

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

Involved phenomenology due to the convolution over transverse momentum



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

$h_1 \otimes H_1^\perp$

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

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

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

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

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

Number Density

nucleon polarisation

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

(The Baseline)

The azimuthal modulation

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

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

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

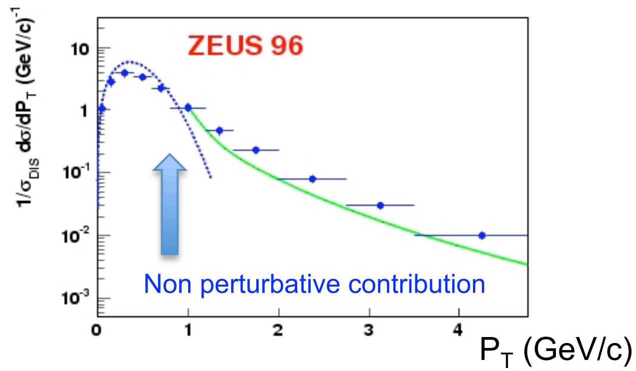
$h_1^{\perp} \otimes H_1^{\perp}$

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

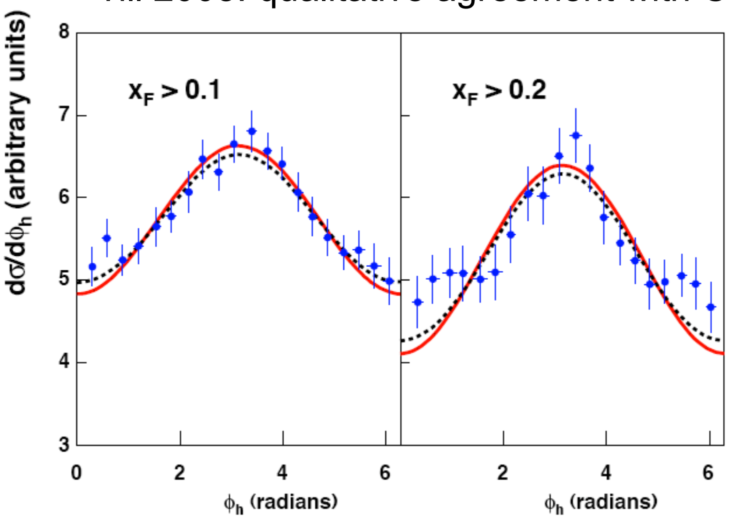
Cahn PLB 78 (1978)

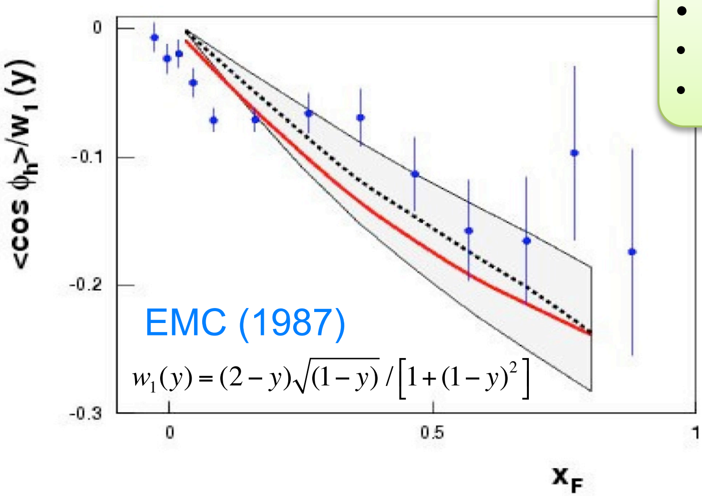
Leading-twist contribution introduced by Boer & Mulders in 1998

Boer & Mulders PRD 57 (1998)



Till 2008: qualitative agreement with Cahn expectations





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

The Lam-Tung relation

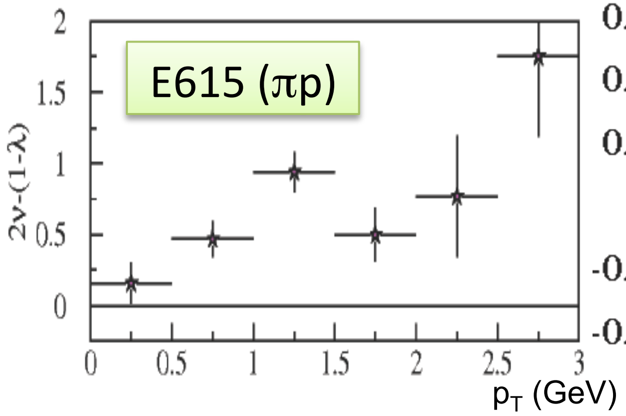
$h_1^\perp \otimes h_1^\perp$

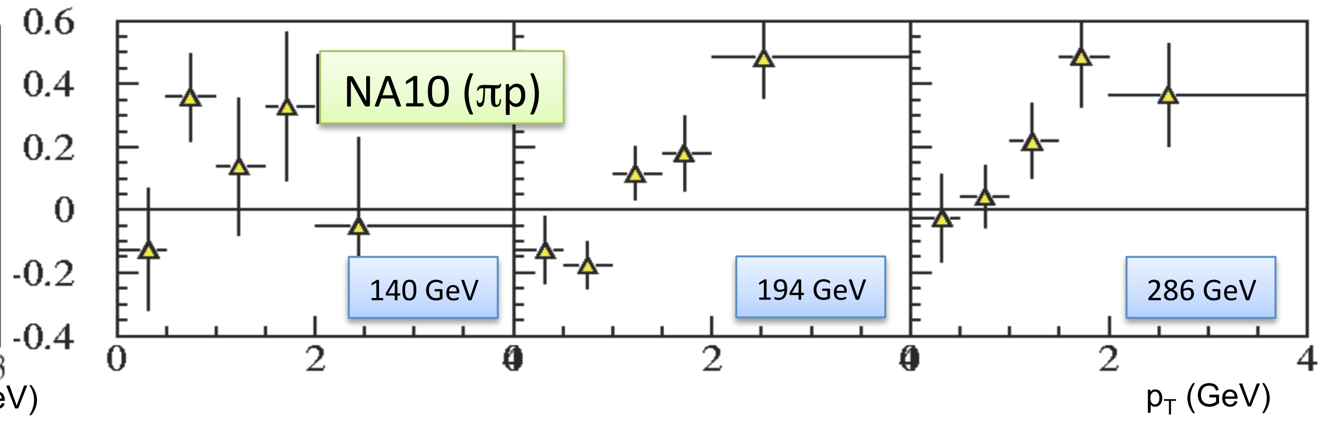
$$\frac{d\sigma^{hp\to eeX}}{d\Omega} \propto 1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi$$

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

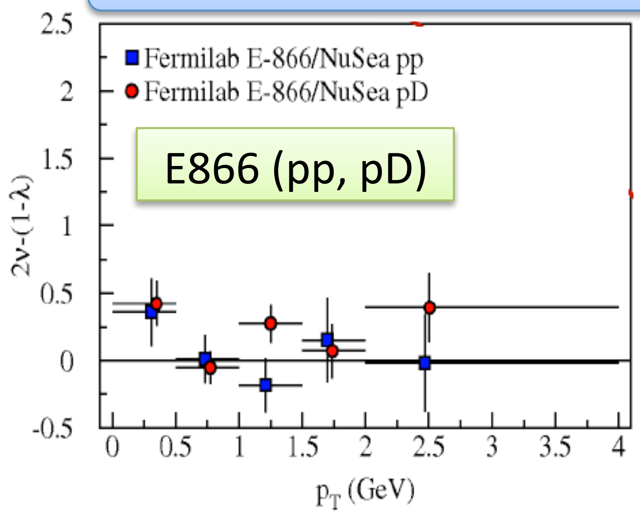
$$(1-\lambda)=2\nu$$

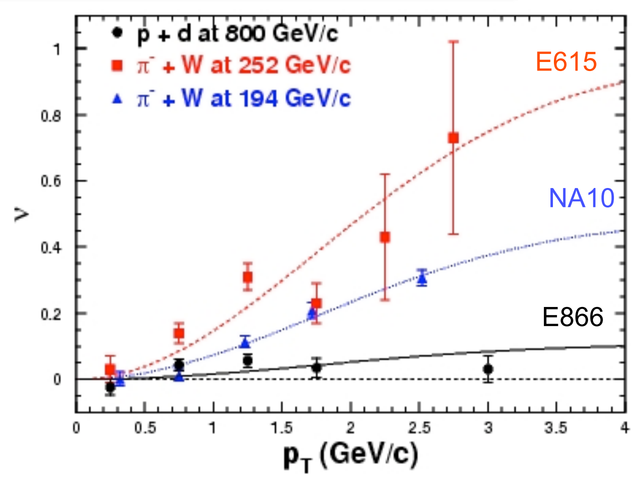
Preserved by NLO and resummation
Analogous of SIDIS Callan-Gross

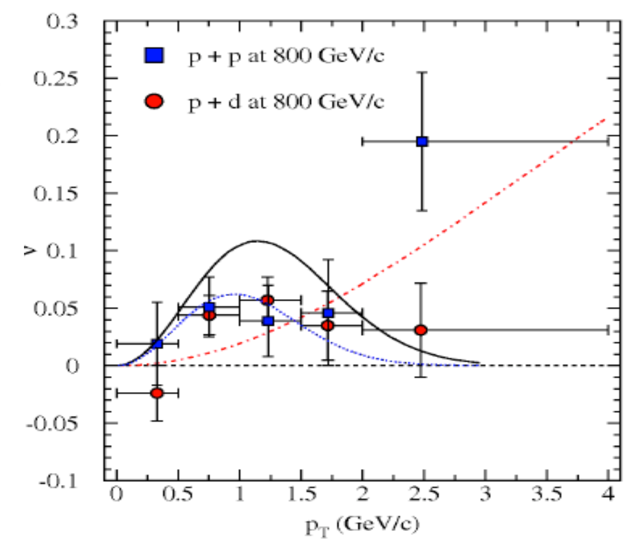




Boer-Mulders offers a possible explanation $\nu \approx h_{1q}^\perp \times h_{1\bar{q}}^\perp$

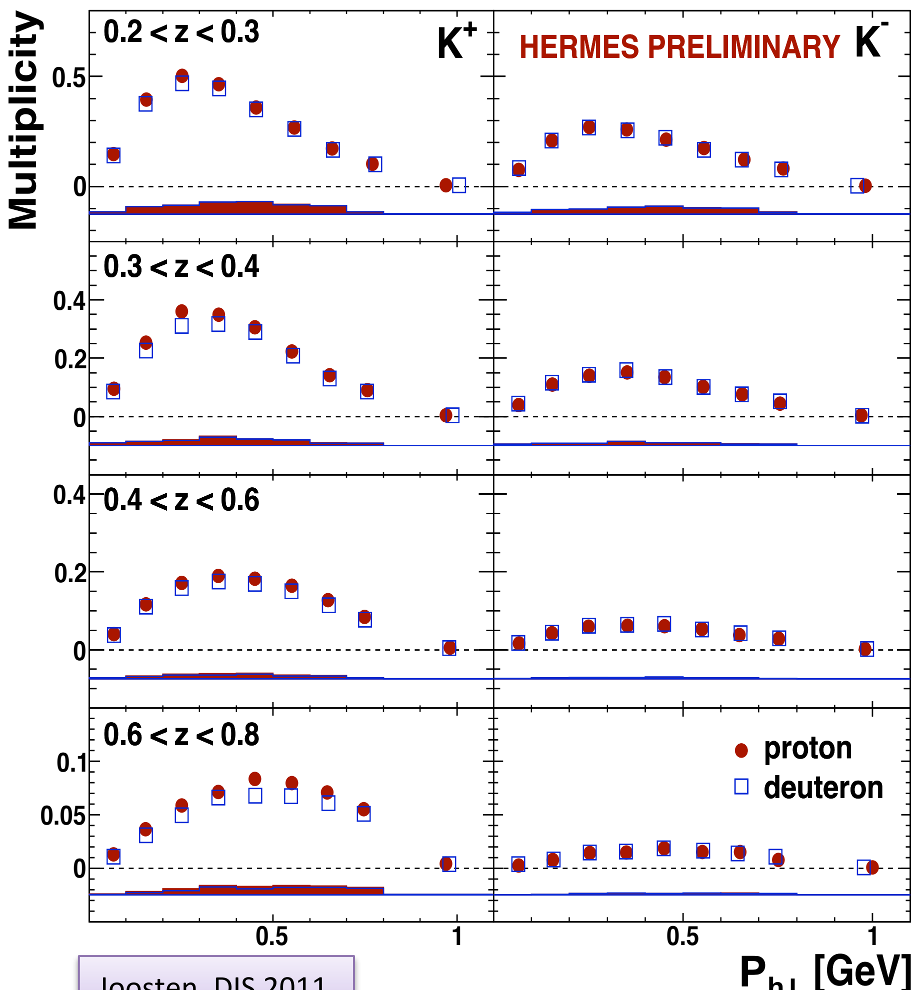






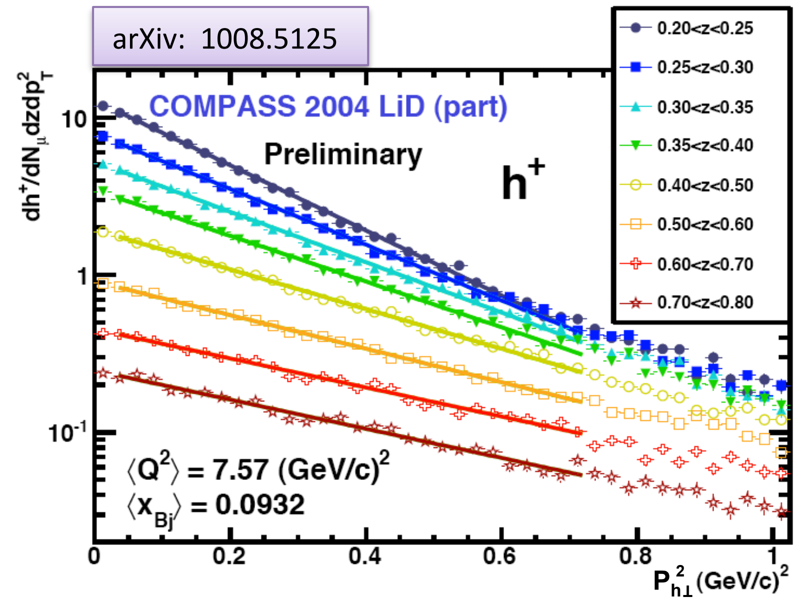
Disentanglement of z and $P_{h\perp}$: access to the transverse intrinsic quark k_T and fragmentation p_T,

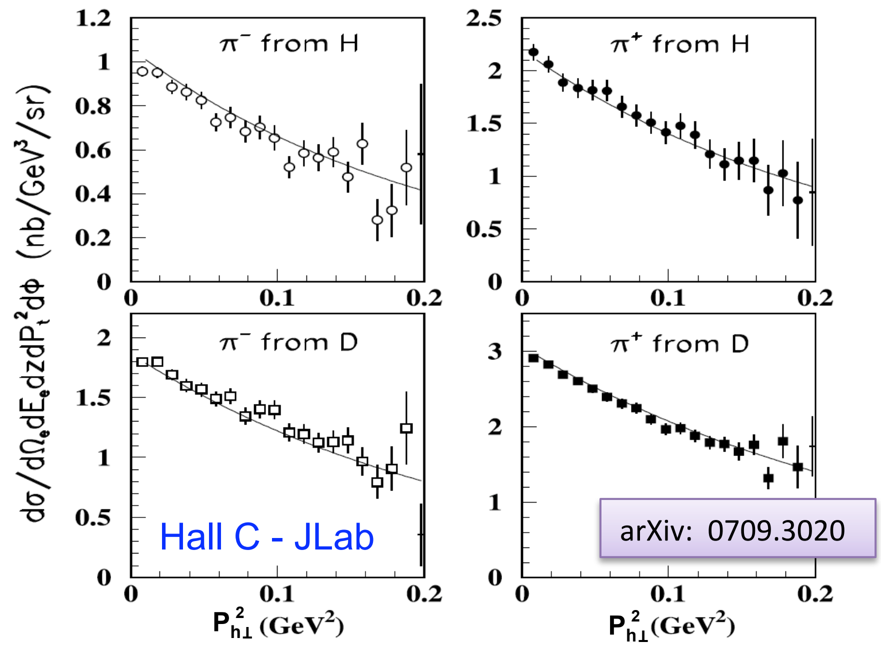
i.e. from gaussian anstaz $\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$



Joosten, DIS 2011

arXiv: 1008.5125





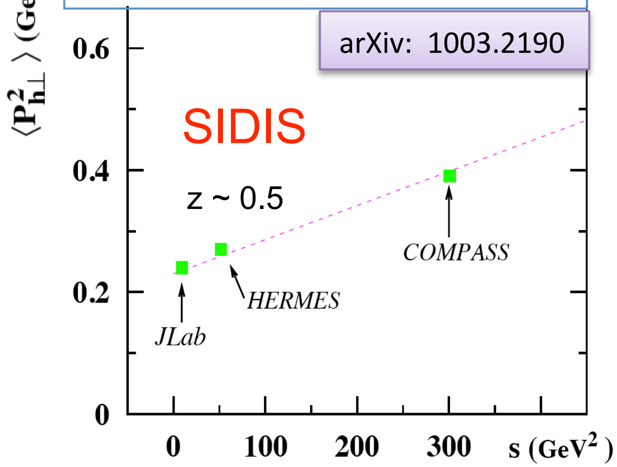
arXiv: 0709.3020

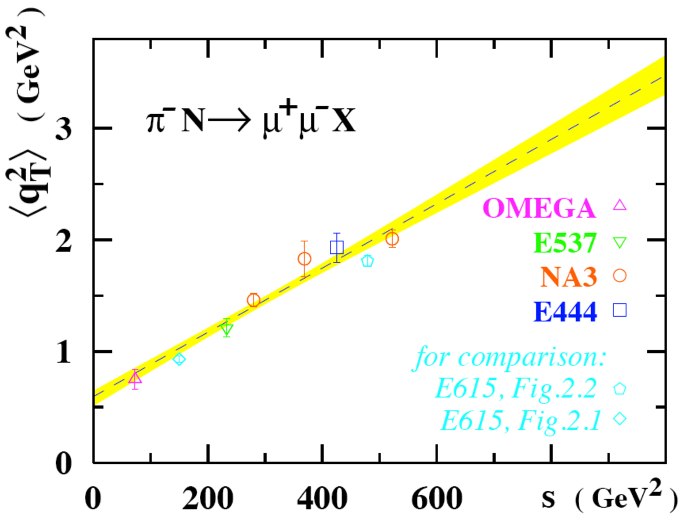
The Evolution

$f_1 \otimes D_1$

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

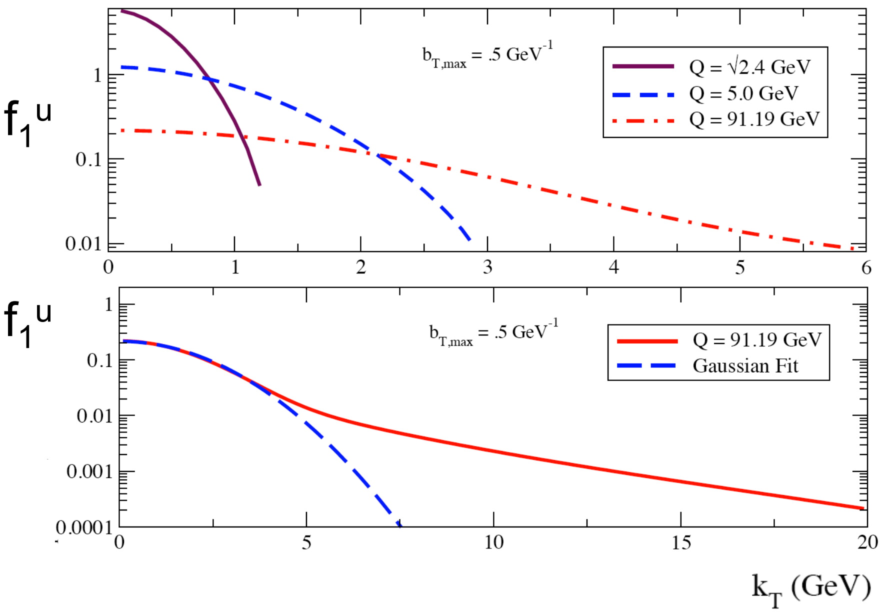
arXiv: 1003.2190





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

TMD Q^2 evolution



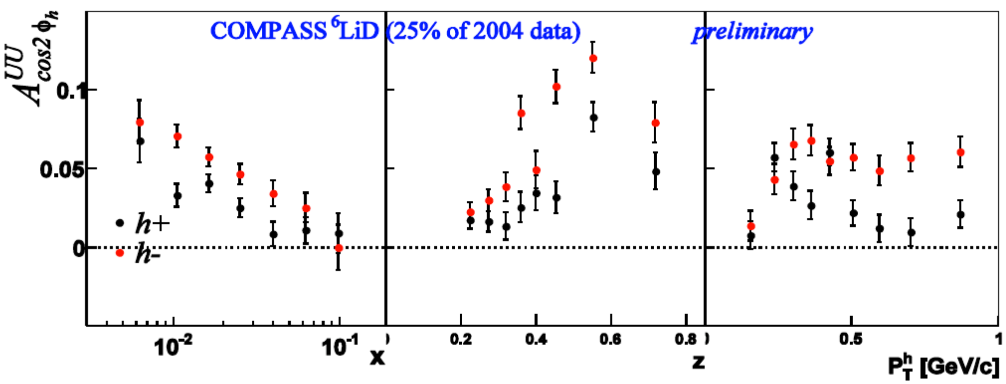
arXiv: 1101.5057

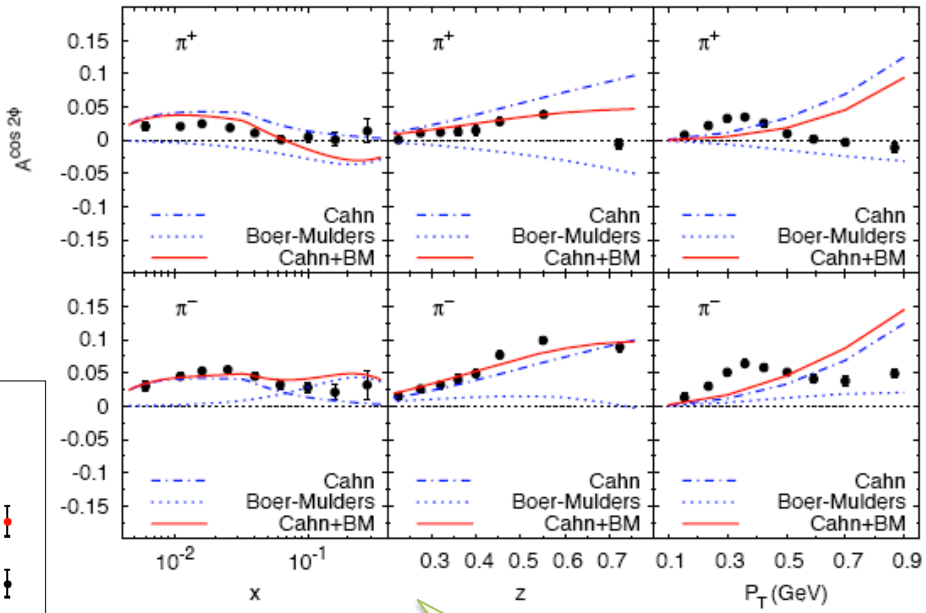
The SIDIS cos2ϕ dependence

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

Non-zero !

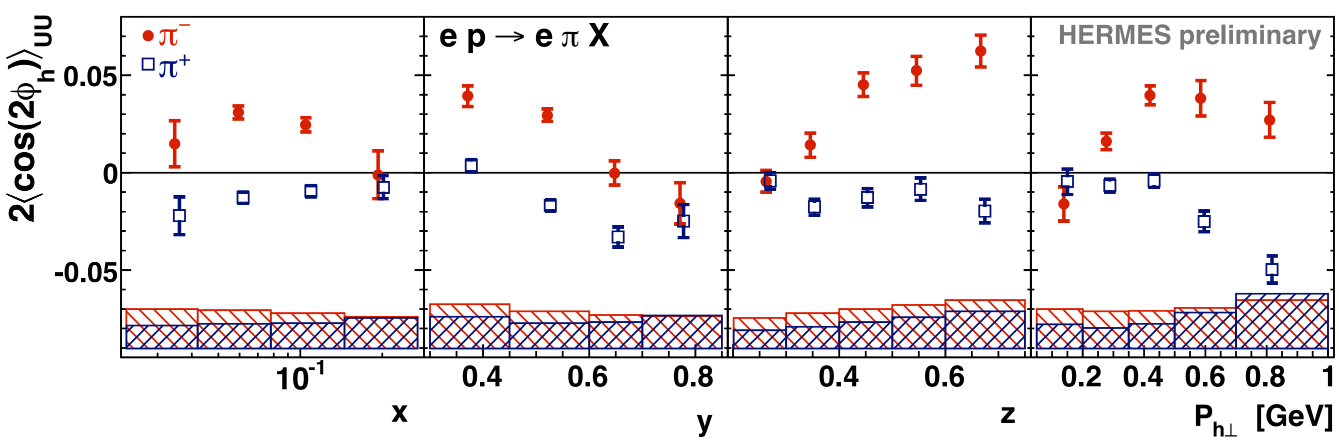
Issue on DATA consistency





arXiv: 0912.5194

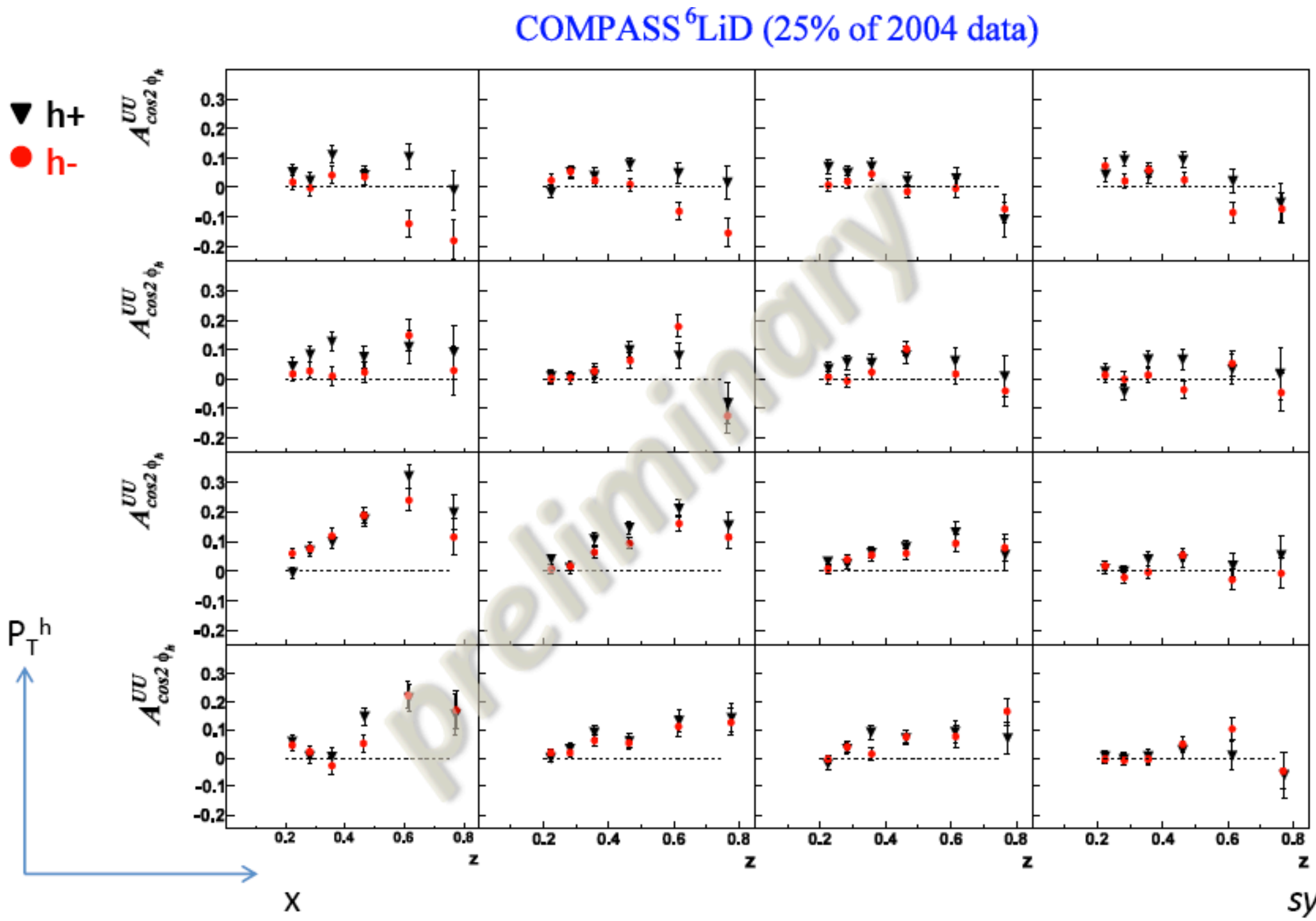
Can be explained by large uncertainty on Cahn and neglected HT effects



arXiv: 1204.4161

The SIDIS cos2ϕ dependence

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



sys ≈ 2 · stat

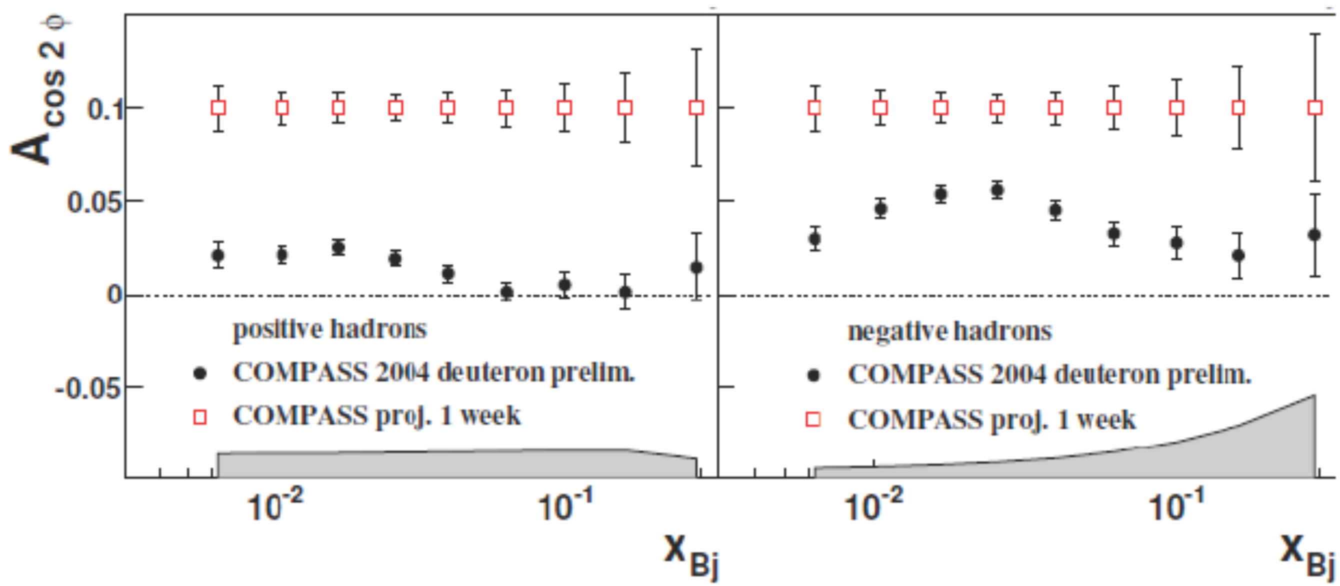
Multidimensional analysis is mandatory

Clean high statistics samples from COMPASS-II and CLAS12

The SIDIS Landscape 2014+

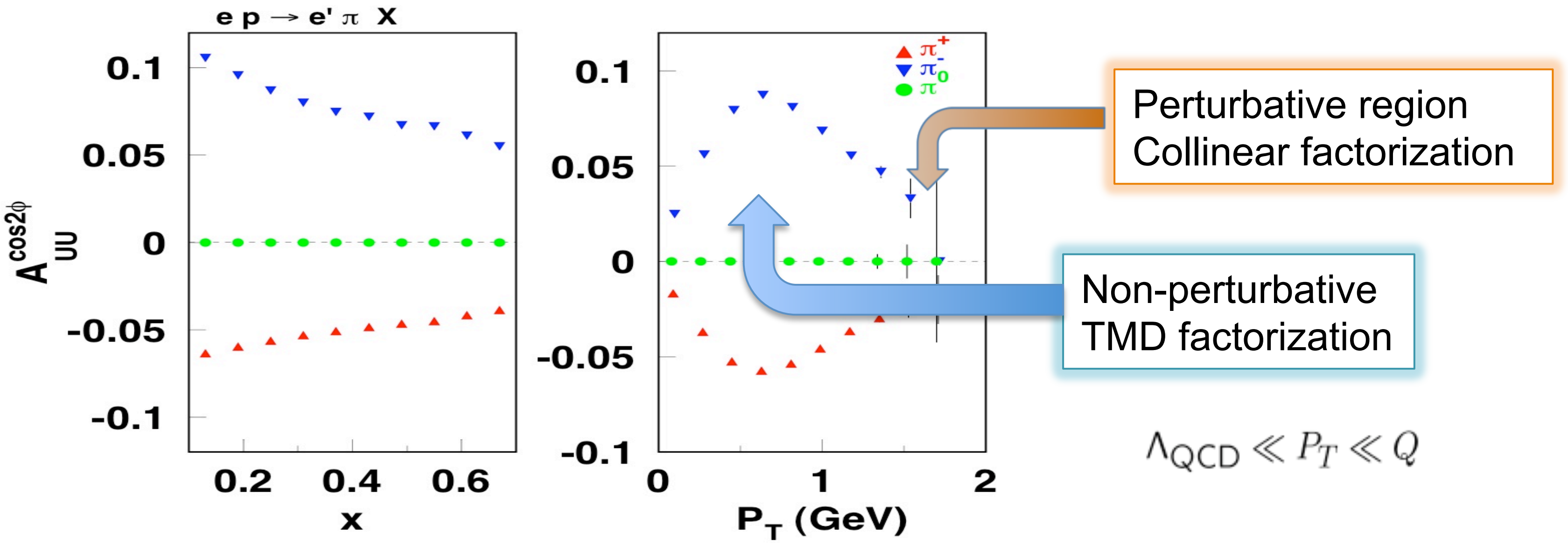
COMPASS-II:

LH_2 target
160 GeV/c muons



CLAS12:

LH2 target
12 GeV/c electrons
$L \sim 10^{35}$ $cm^{-2}s^{-1}$



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

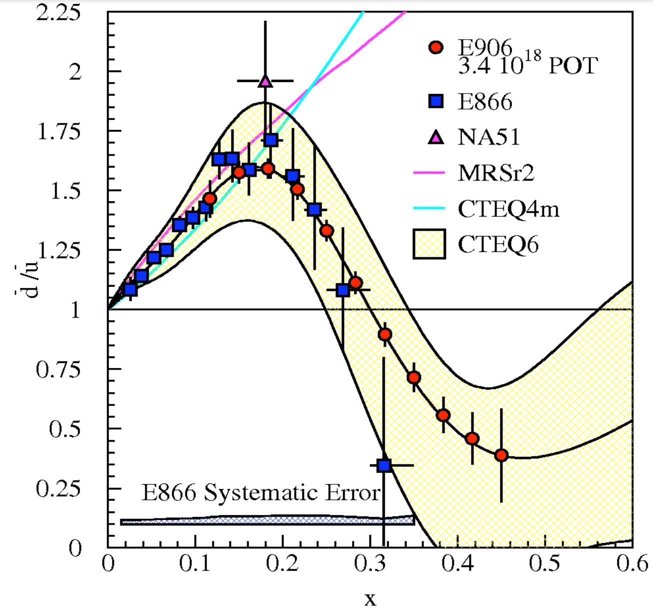
The Drell-Yan Landscape 2014+

Proton beam @ Fermilab

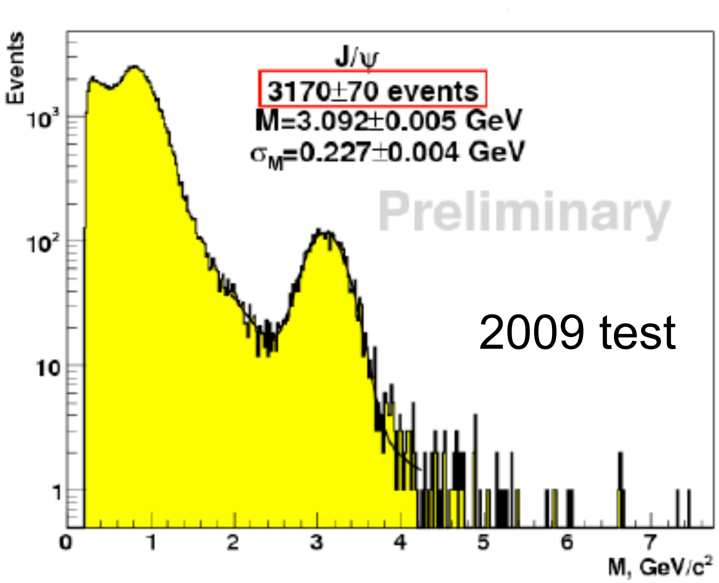
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

E906: test run this year

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



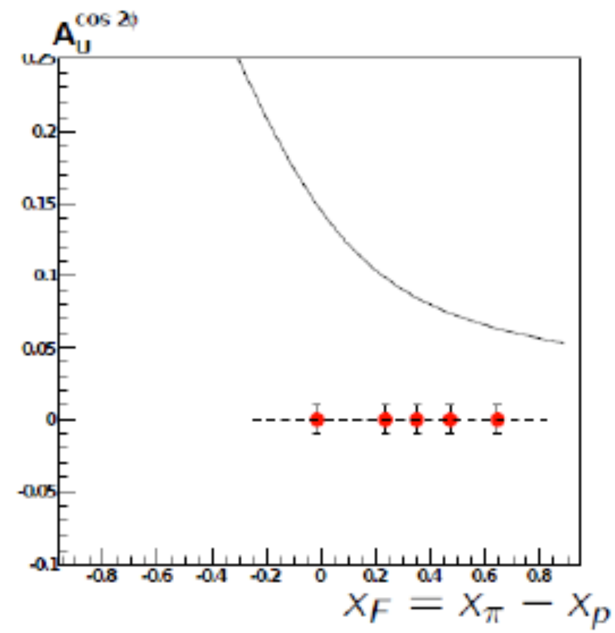
Pion beam @ CERN



2009 test

Boer-Mulders
⊗
Boer-Mulders

2 years
4 < M < 9 GeV/c^2

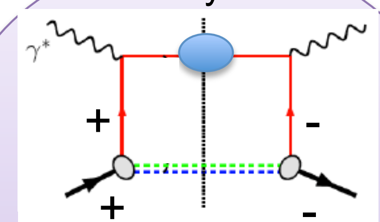


Transversity

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

nucleon polarisation

Chirally-odd



First evidence: 2005

(The Collinear Missing Piece)

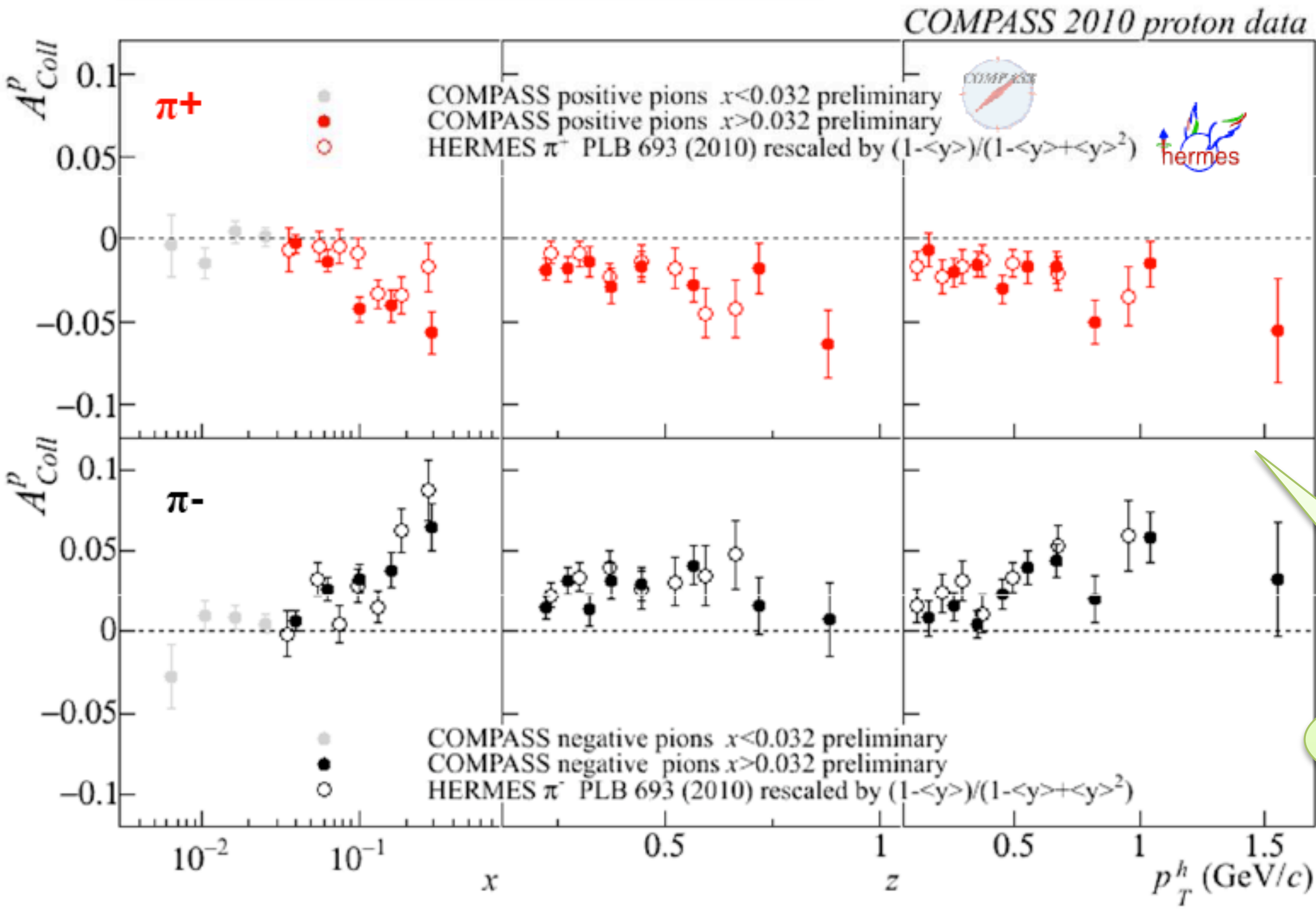
The Collins SIDIS amplitude

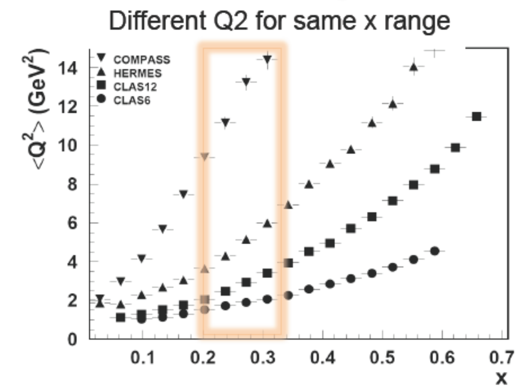
$h_1 \otimes H_1^{\perp}$

CLEAR NON ZERO SIGNALS !

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

Consistent results at different Q^2
→ No higher twits
→ No strong evolution

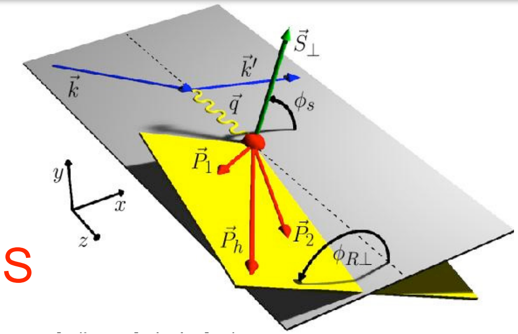




Opposite sign for pions reveals Collins features

Two hadron asymmetries

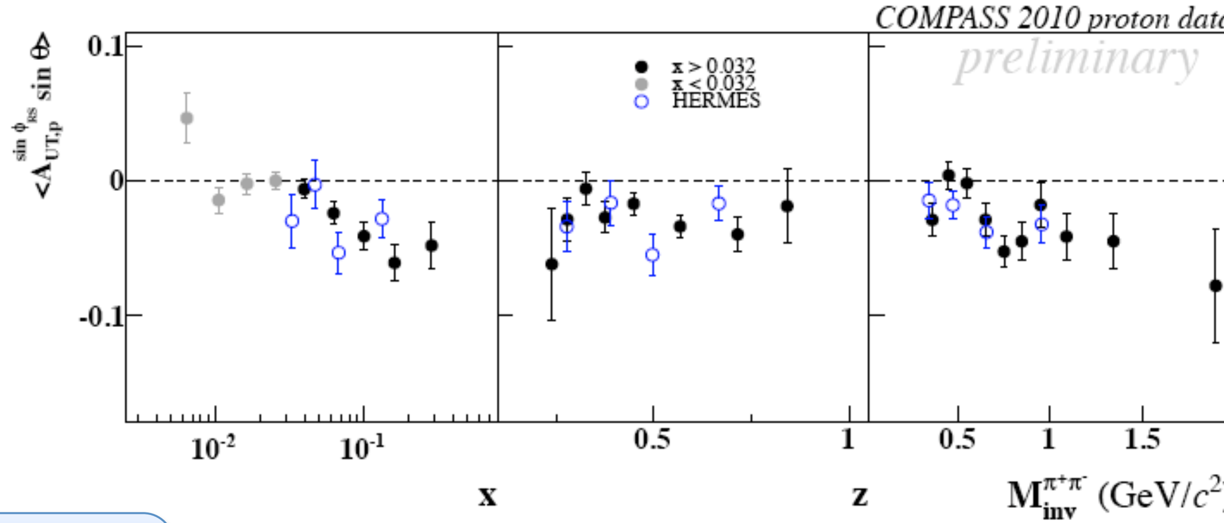
$h_1 \otimes H_1^{\sphericalangle}$



SIDIS

COMPASS, arXiv: 1202.6150

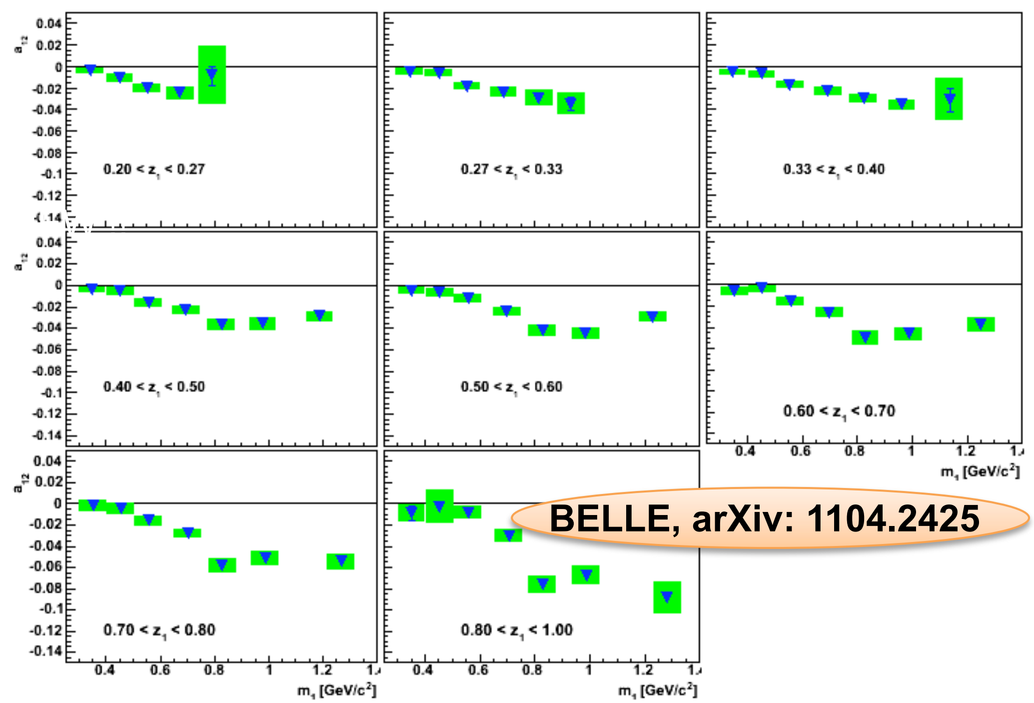
HERMES, arXiv: 0803.2367



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

- Survives P_h integration
- Collinear factorization (simple product)
- DGLAP volution
- Universality
- Issue: unknown pp-terms in PW expansion

Belle



BELLE, arXiv: 1104.2425

Transversity Signals

hermes $lp \to l' hX$

BELLE $e^+e^- \to h_1 h_2 X$

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

COMPASS $ld \to l' hX$

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

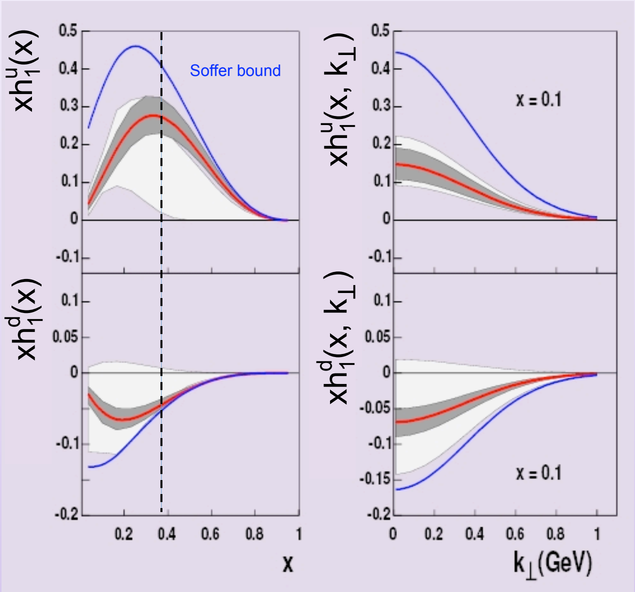
BELLE

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

Existing data limited to x < 0.3

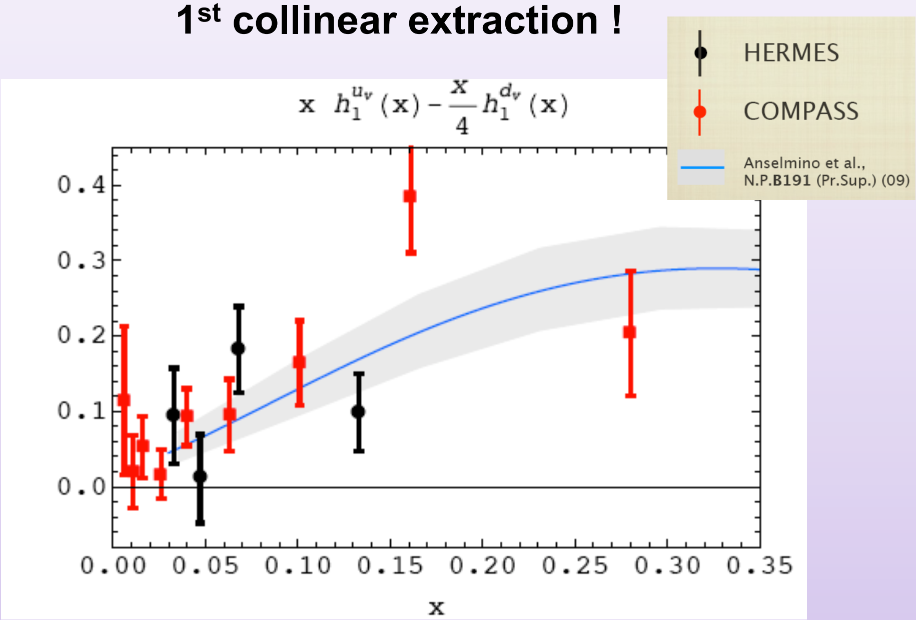
FF evol.. from high energy colliders

1st extraction of Transversity!



Anselmino ++ arXiv: 0701006

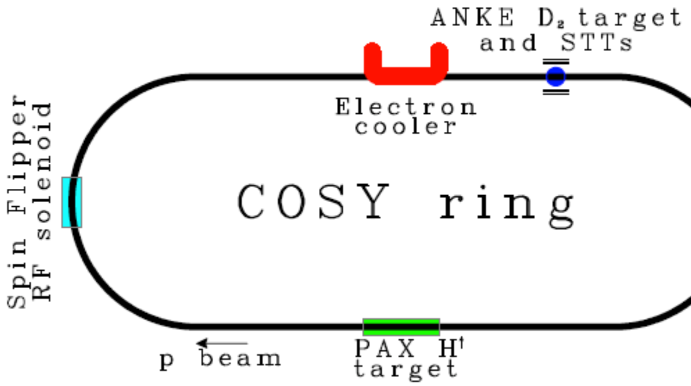
1st collinear extraction !

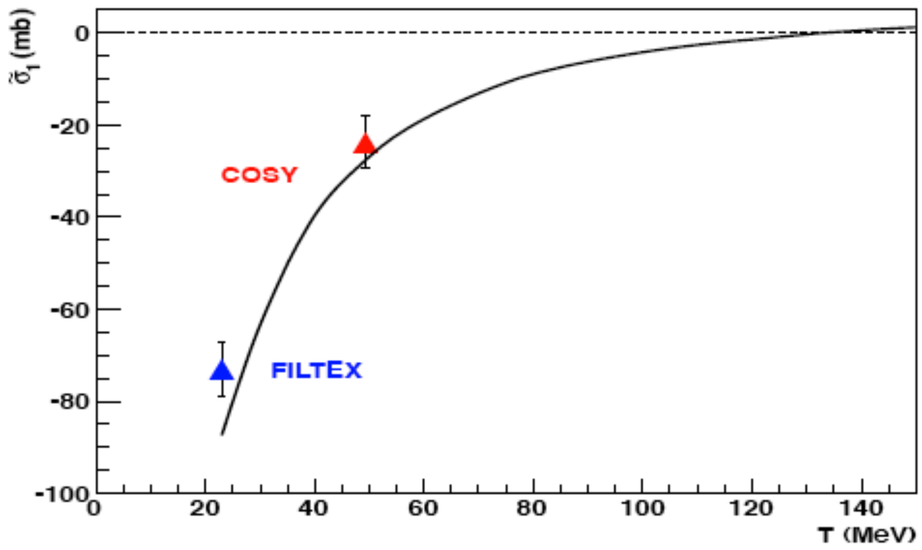


Bacchetta ++ arXiv: 1104.3855

Polarized Drell-Yan 2018+

Spin-filtering with protons:





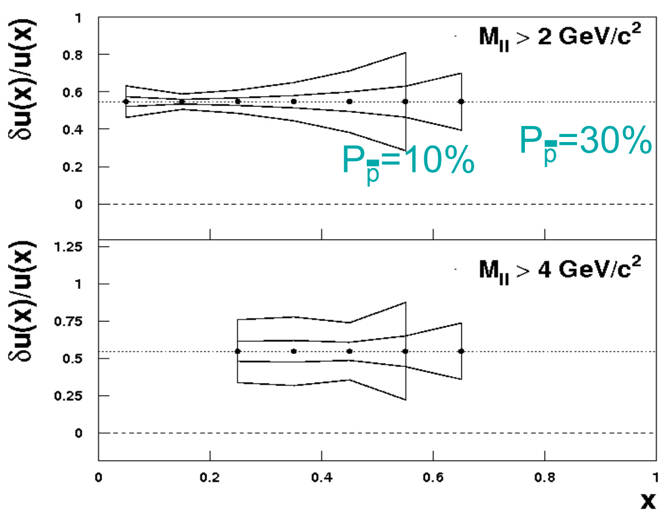
Anti-proton beam @ FAIR

PANDA: unpolarized target (s=30 GeV^2)

PAX: polarized collider (s=200 GeV^2)

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

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



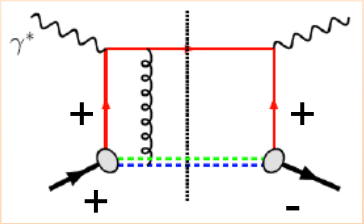
- u-dominance
- $|h_{1u}|>|h_{1d}|$

Sivers

nucleon polarisation

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

Naïve-T-odd
Non-trivial gauge link



Process dependence

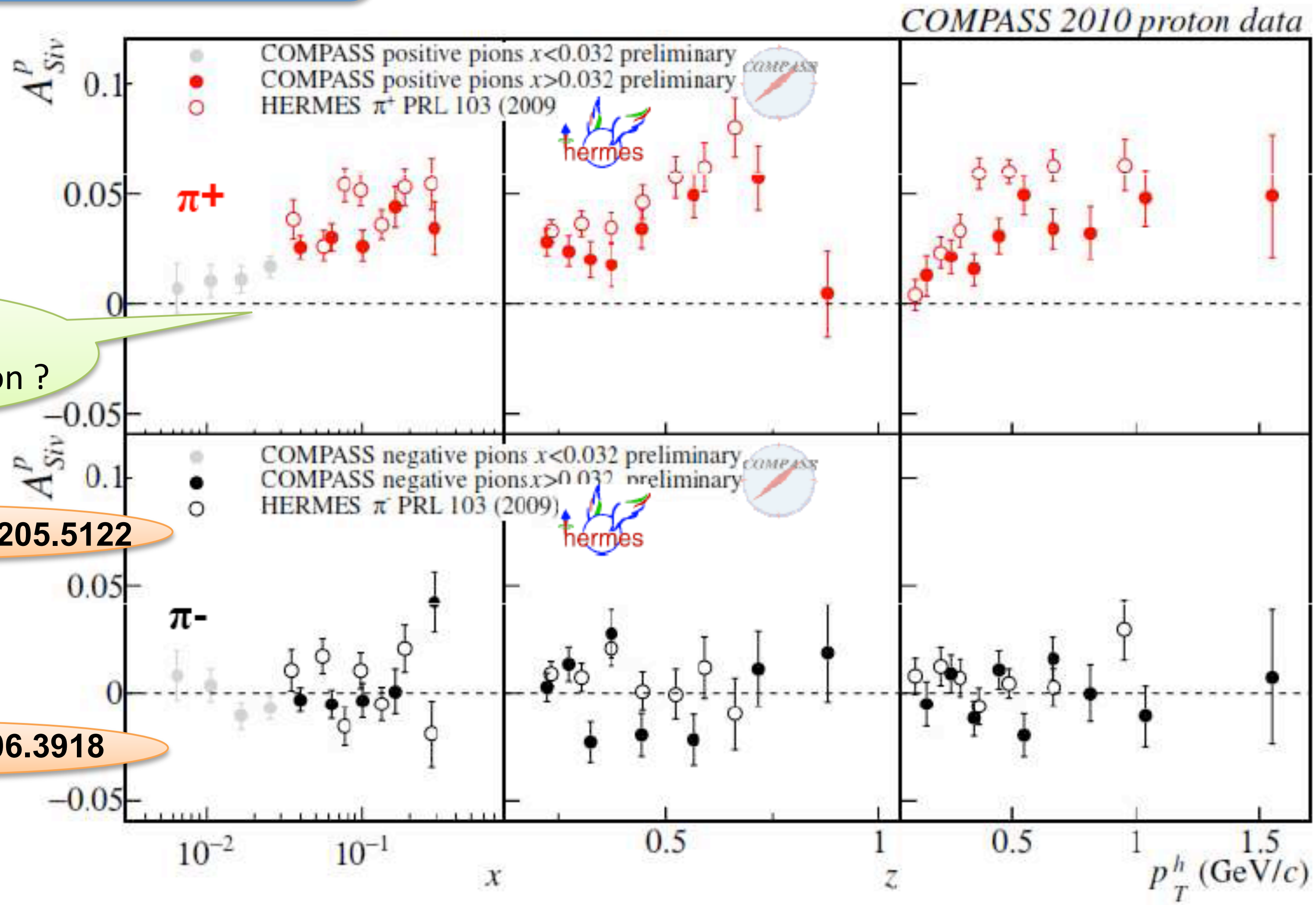
(The TMD Challenge)

The Sivers signals

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

$$A_{UT}^{\sin(\phi-\phi_S)} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,p_T^2) \otimes_\omega D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,k_T^2)}$$

CLEAR NON ZERO SIGNALS !



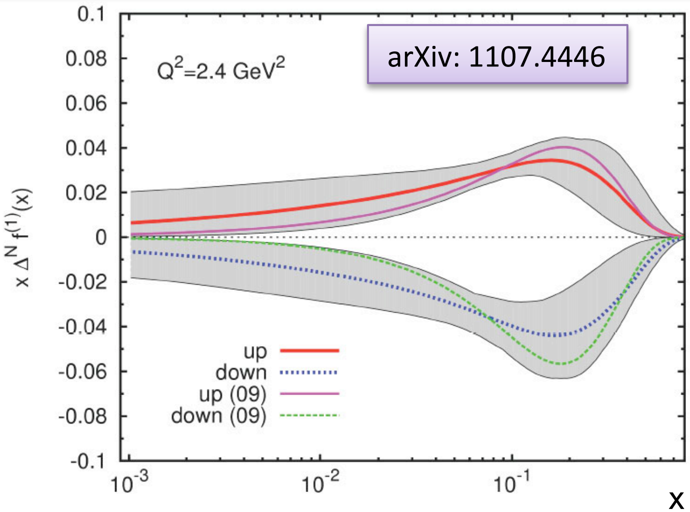
Systematic shift:
Sivers Q^2 evolution ?

COMPASS, arXiv: 1205.5122

HERMES, arXiv: 0906.3918

The Sivers challenges - I

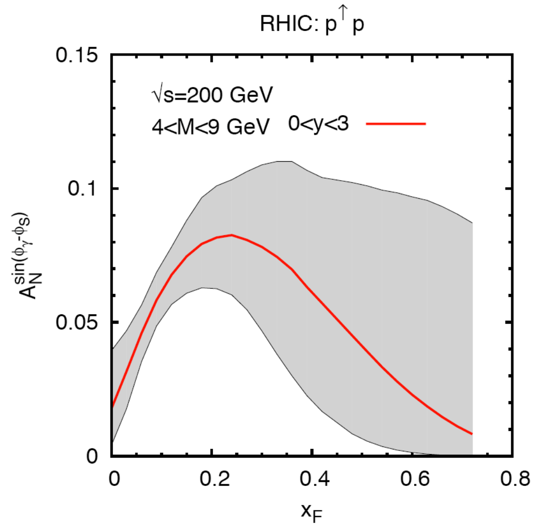
$f_{1T}^{\perp} \otimes D_1$



From SIDIS to Drell-Yan:

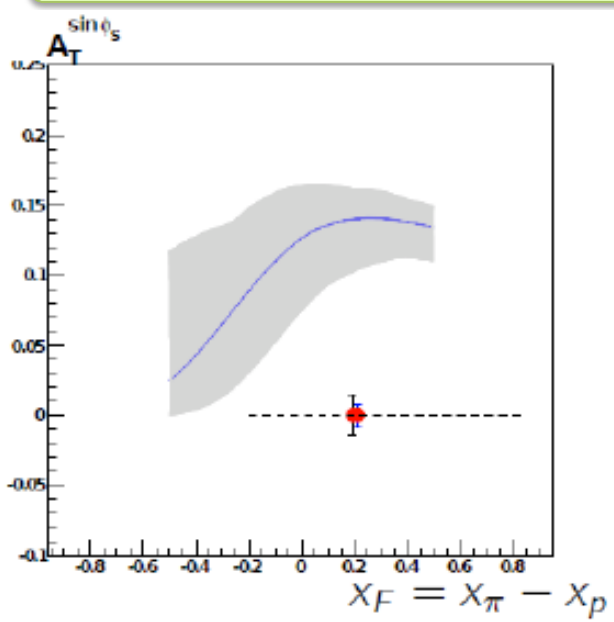
Sign change as a crucial test of TMDs factorization

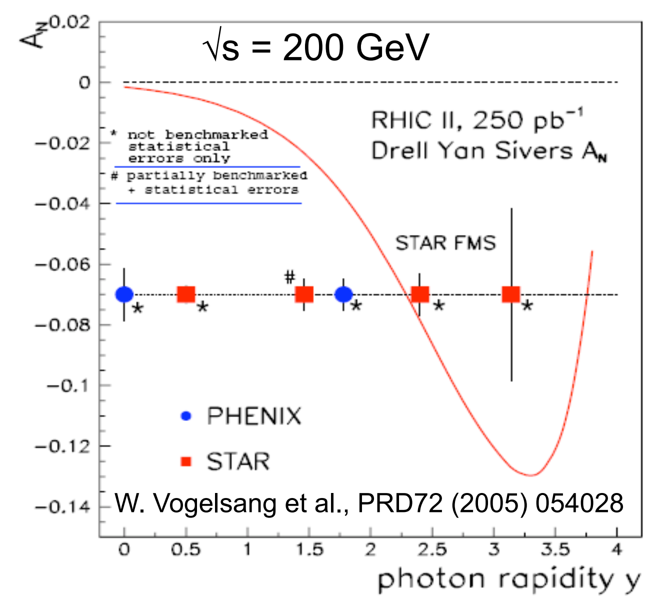
arXiv: 0901.3078



π H↑ @ CERN

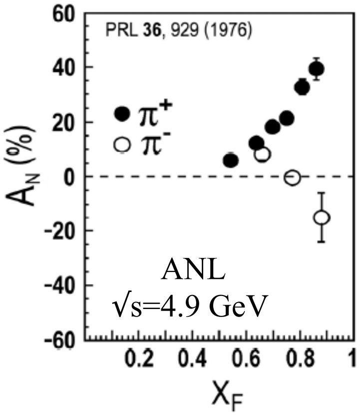
p↑p @ Brookhaven

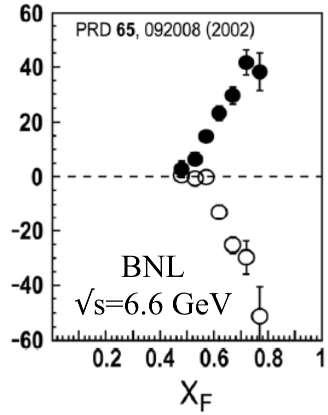


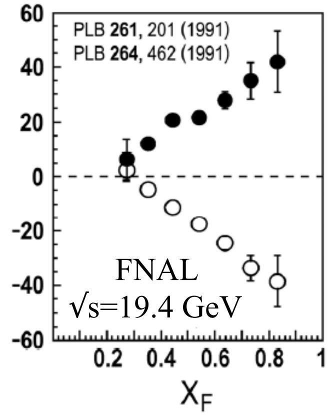


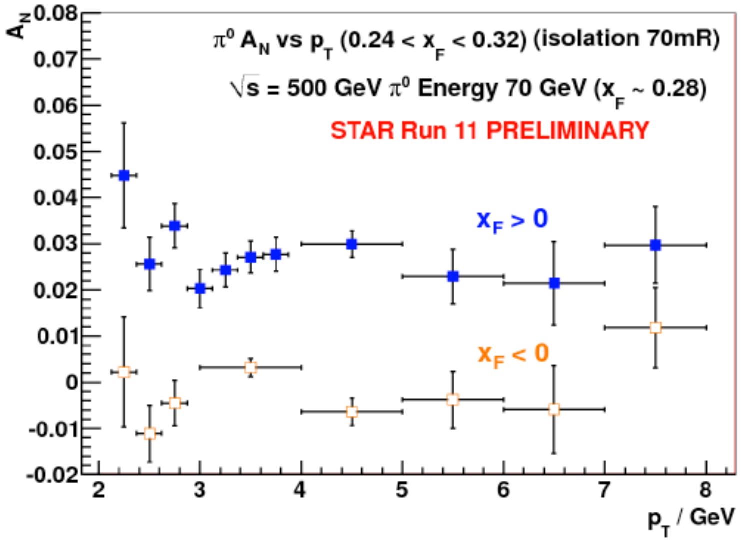
The Sivers challenges - II

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



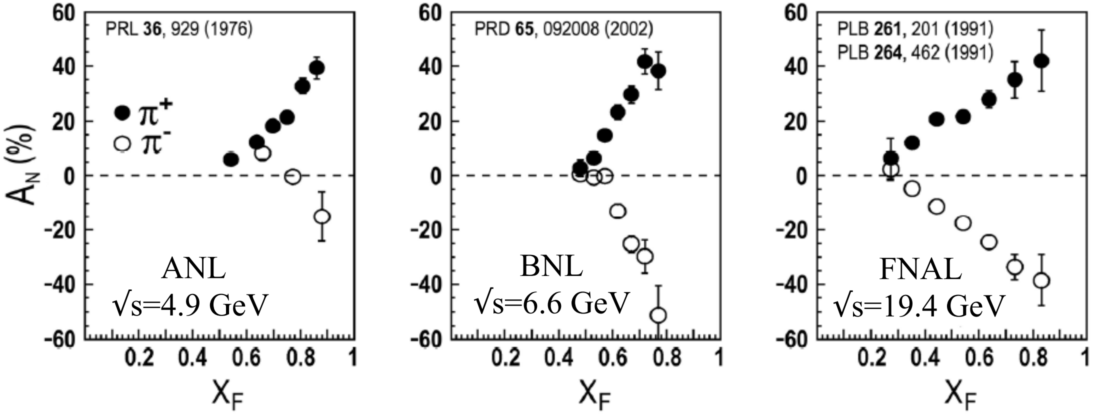


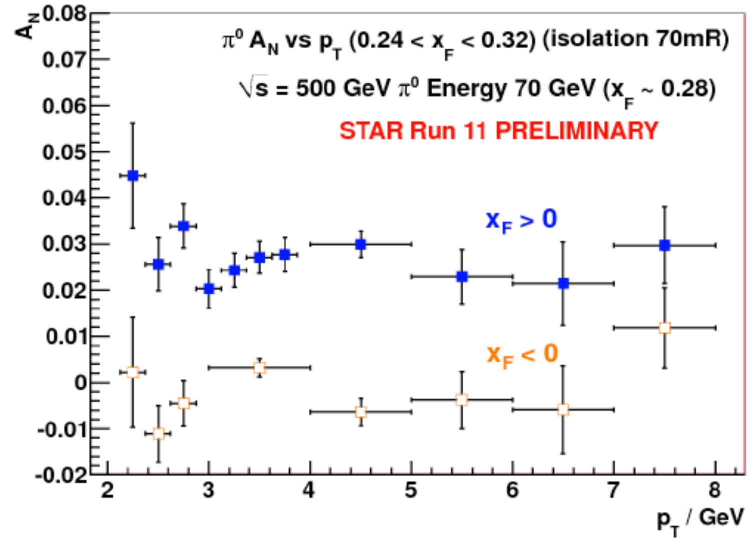




The Sivers challenges - II

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

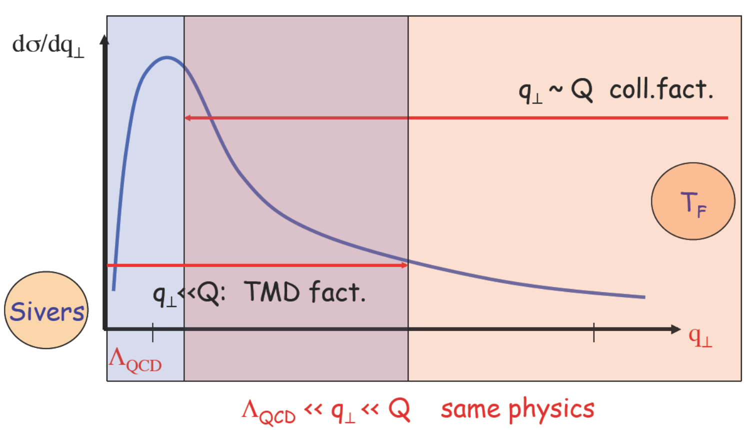




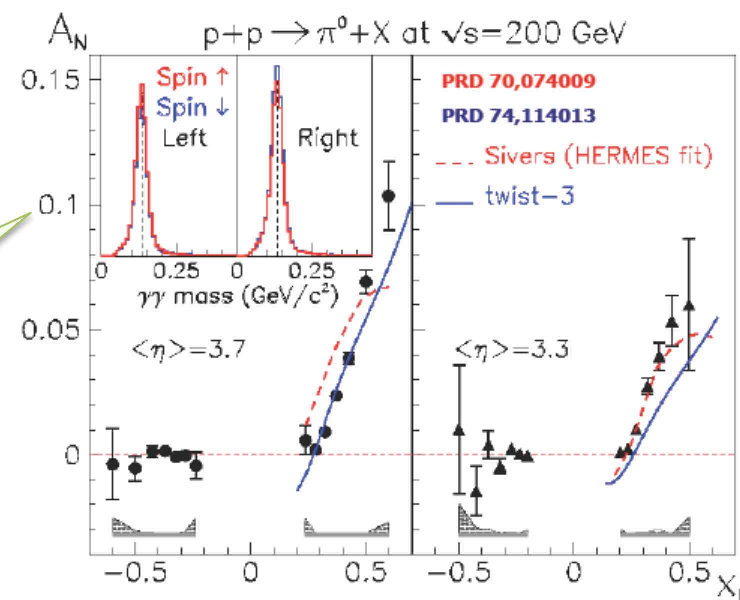
From SIDIS to pp: A possible candidate to explain SSA

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

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



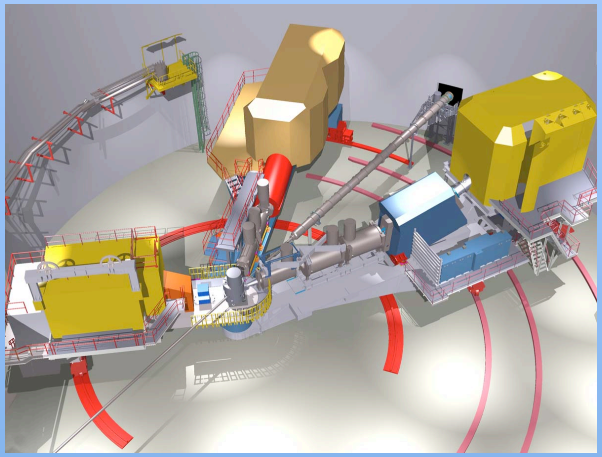
After 1st promising results a sign mismatch was found



arXiv: 0801.2990

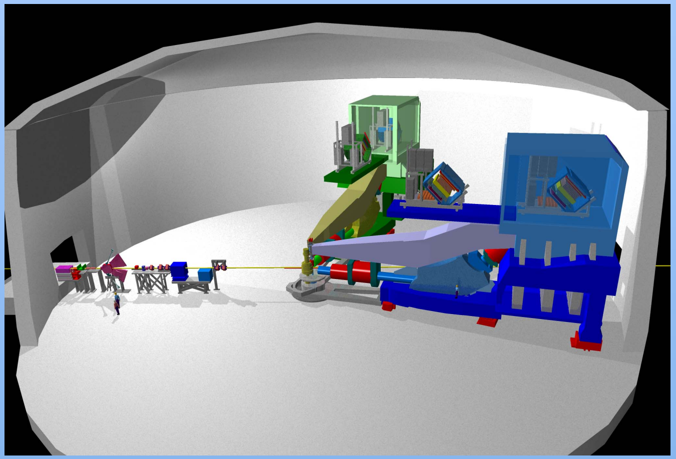
SIDIS @ JLab12 2014+

Hall-C



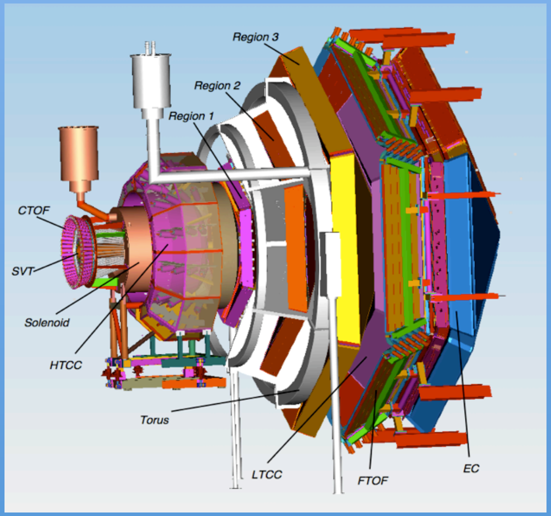
Super High Momentum Spectrometer (SHMS)
unpolarized SIDIS, hadron ID

Hall-A



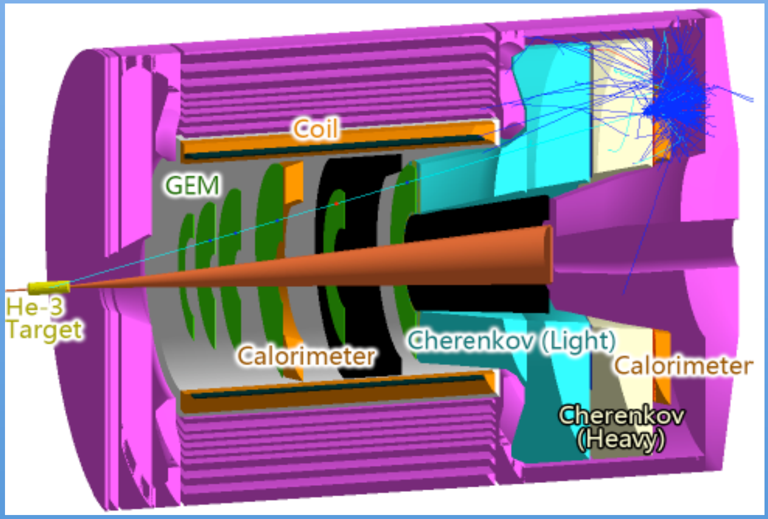
Spectrometer Pair, polarized ^{3}He target
up to to 10^{37} cm^{-2} s^{-1} hadron ID

Hall-B



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

Hall-A



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

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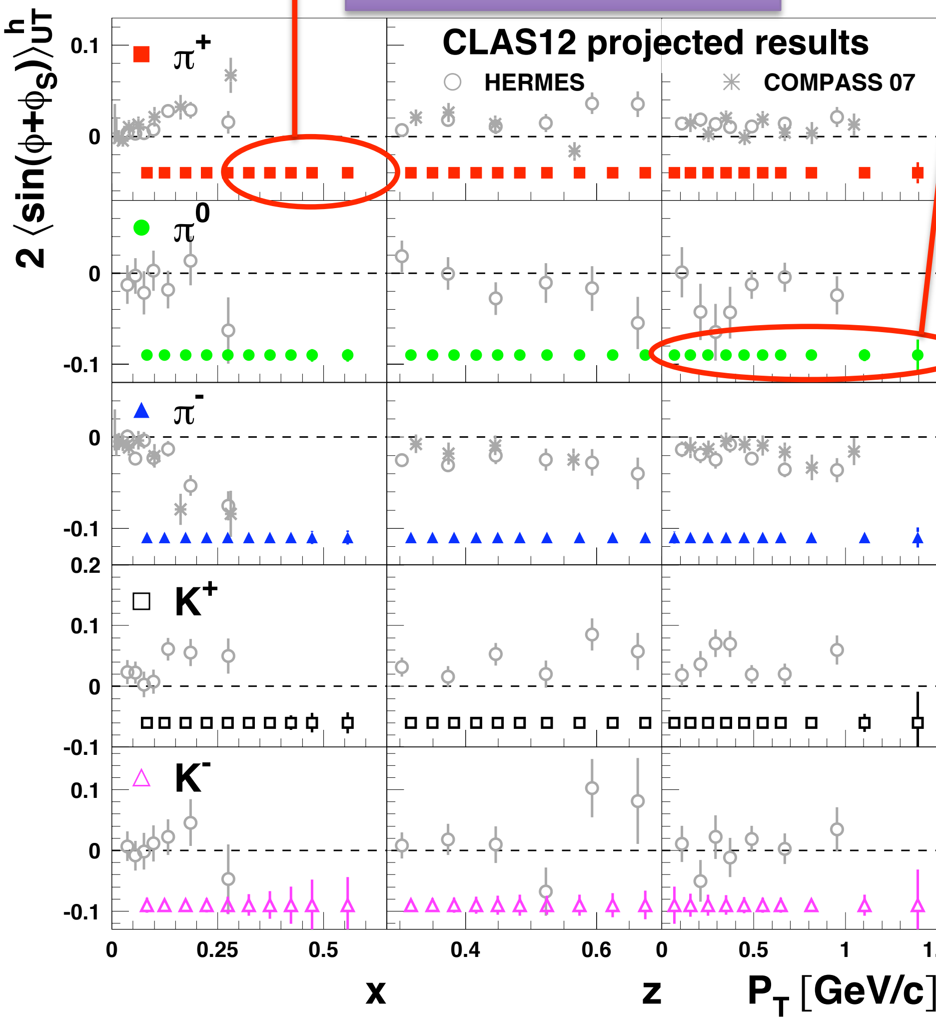
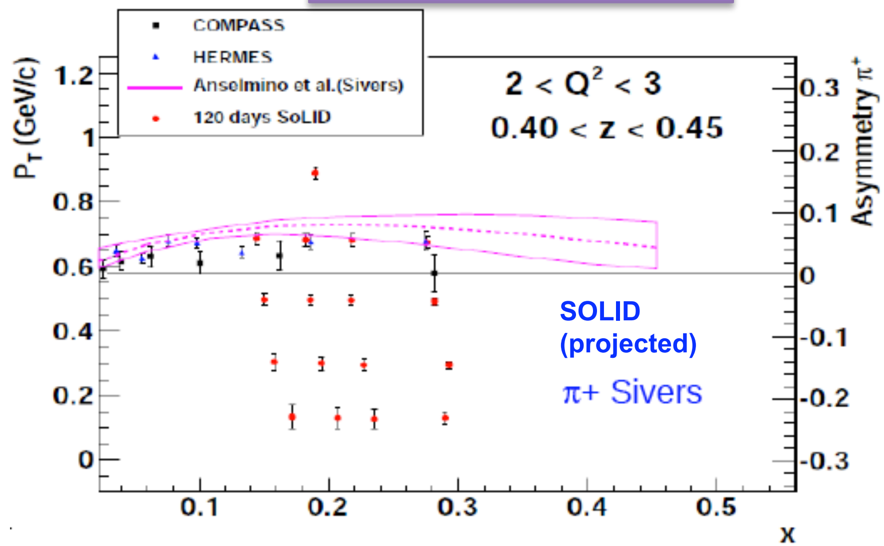
Large x important to constrain the tensor charge

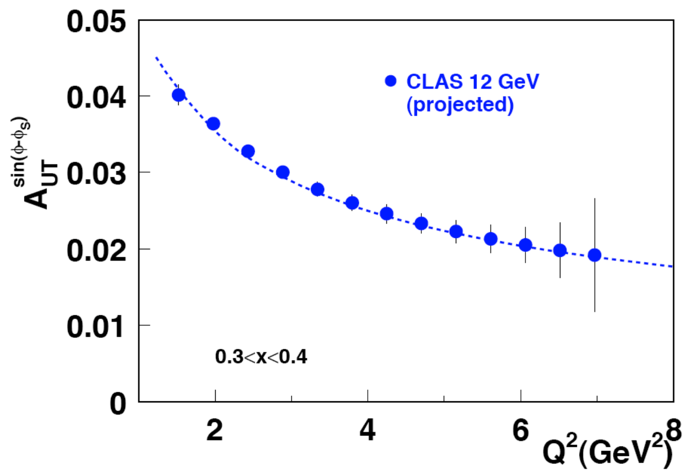
High resolution and broad range in p_T to test perturb. non-perturb. transient and for Bessel function analysis

Collins asymmetry



Sivers asymmetry





The Spin Physics Landascape