



Spin Structure of the Nucleon

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Plan

- Introduction
- Tools: DIS, SIDIS, pp & Experiments
- Helicities
- Transverse structure & transverse momentum
- What's next?
 - Examples from on COMPASS-II: GPD, DY

Static Quark model

$$|p \uparrow\rangle = \frac{1}{\sqrt{18}} \left\{ 2|u \uparrow u \uparrow d \downarrow\rangle - |u \uparrow u \downarrow d \uparrow\rangle - |u \downarrow u \uparrow d \uparrow\rangle + (u \leftrightarrow d) \right\}$$

$$\Delta u = \langle p \uparrow | N_{u \uparrow} - N_{u \downarrow} | p \uparrow \rangle = \frac{3}{18} (10 - 2) = \frac{4}{3}$$

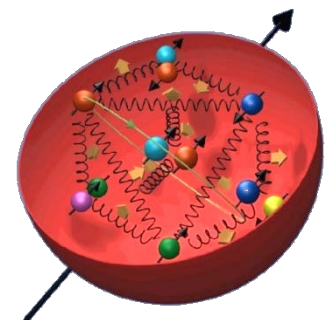
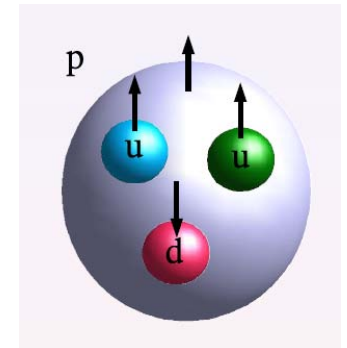
$$\Delta d = \langle p \uparrow | N_{d \uparrow} - N_{d \downarrow} | p \uparrow \rangle = \frac{3}{18} (2 - 4) = -\frac{1}{3}$$

$$\Delta \Sigma = \Delta u + \Delta d = 1$$

SQM: up and down quarks carry the nucleon spin!

EMC: Quarks spins contribute little (1987/88)

$$\Delta \Sigma = 0.12$$



Parton Distribution Functions

Three twist-2 PDFs

$q(x)$
 $f_1^q(x)$

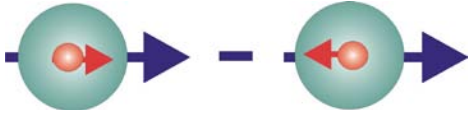


unpolarised PDF

quark with momentum xP in a nucleon

well known – unpolarized DIS

$\Delta q(x)$
 $g_1^q(x)$

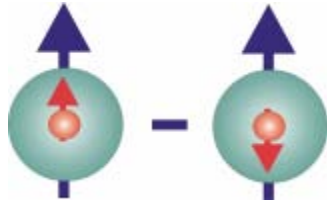


helicity PDF

quark with spin parallel to the nucleon spin in a longitudinally polarised nucleon

known – polarized DIS

$\Delta_T q(x)$
 $h_1^q(x)$



transversity PDF

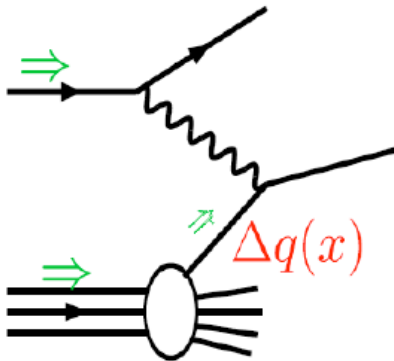
quark with spin parallel to the nucleon spin in a transversely polarised nucleon

chiral odd, poorly known

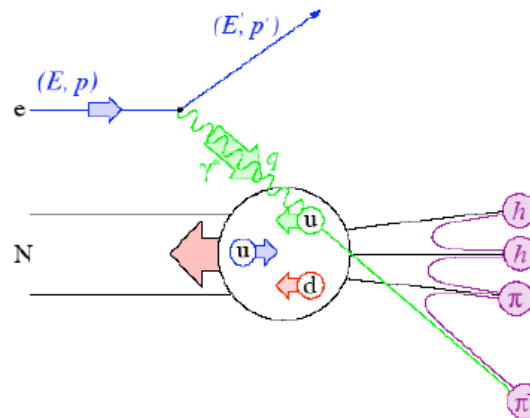
Tools to study the spin structure

Factorization of hard interaction and fragmentation
(additional input from e^+e^-)

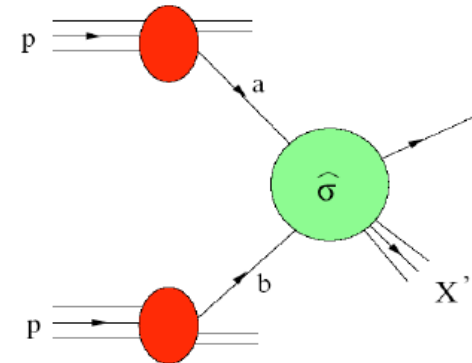
DIS



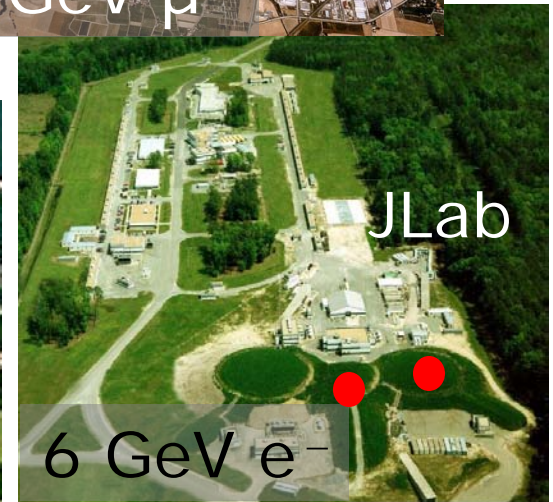
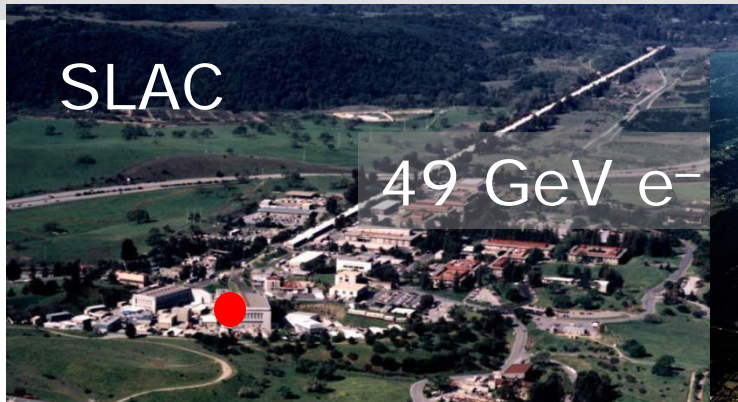
SIDIS



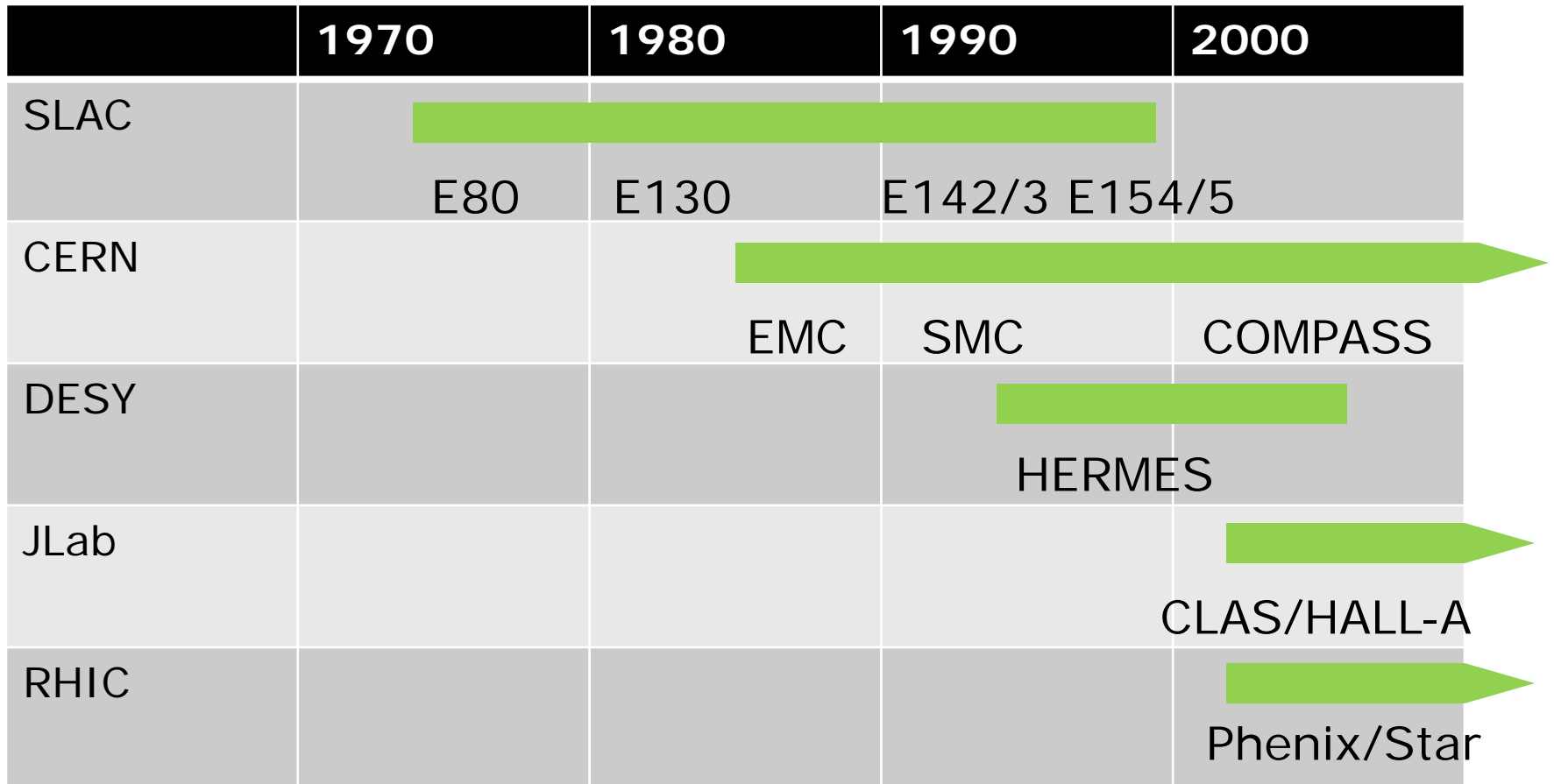
pp



Laboratories



Experiments



A worldwide effort since decades

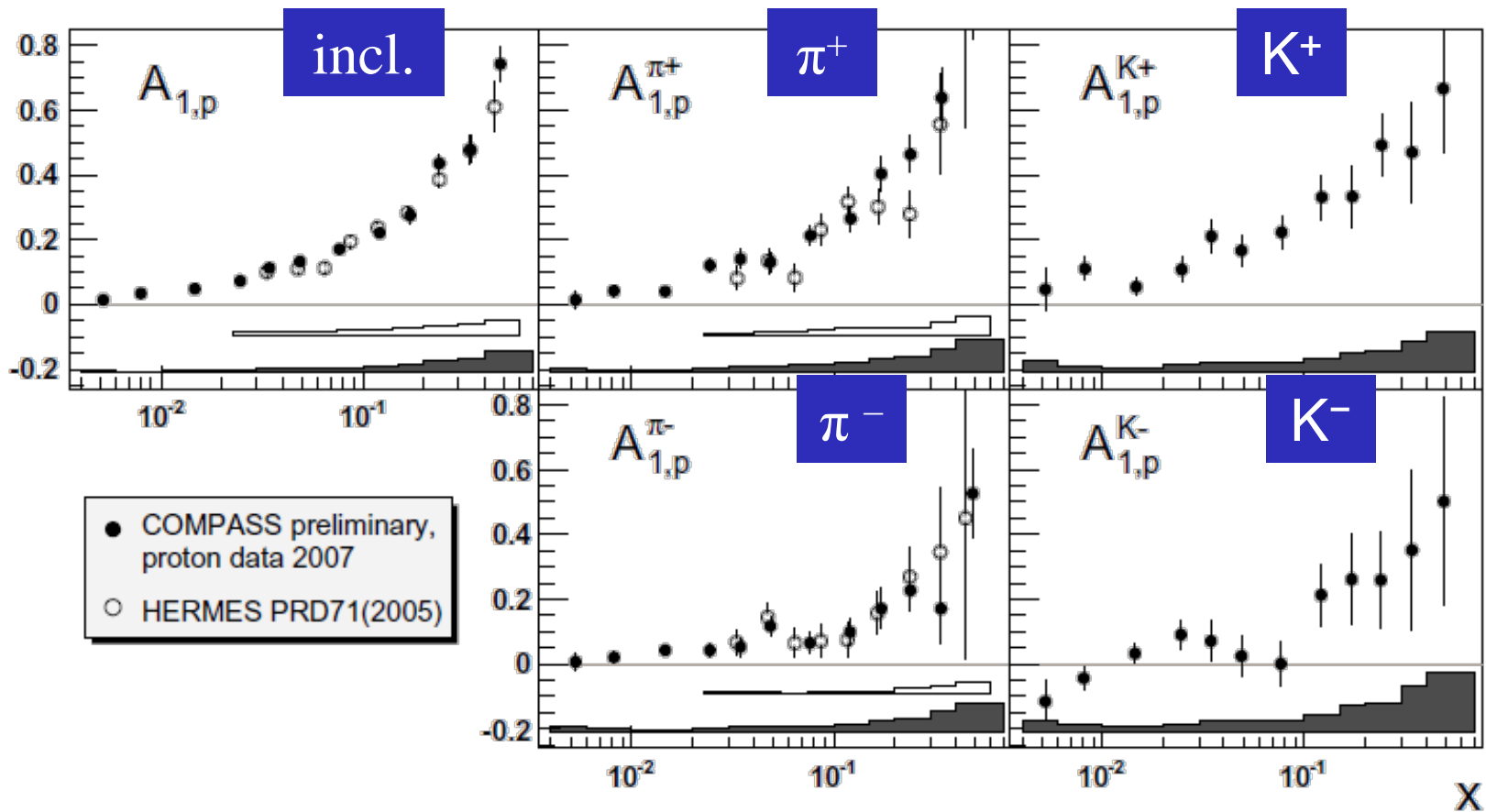
Helicity structure



Proton asymmetries



- incl. & semi-incl. asymmetries,
- similar data for deuteron



Structure function $g_1(x, Q^2)$



- very precise data
- only COMPASS for $x < 0.01$ ($Q^2 > 1$)

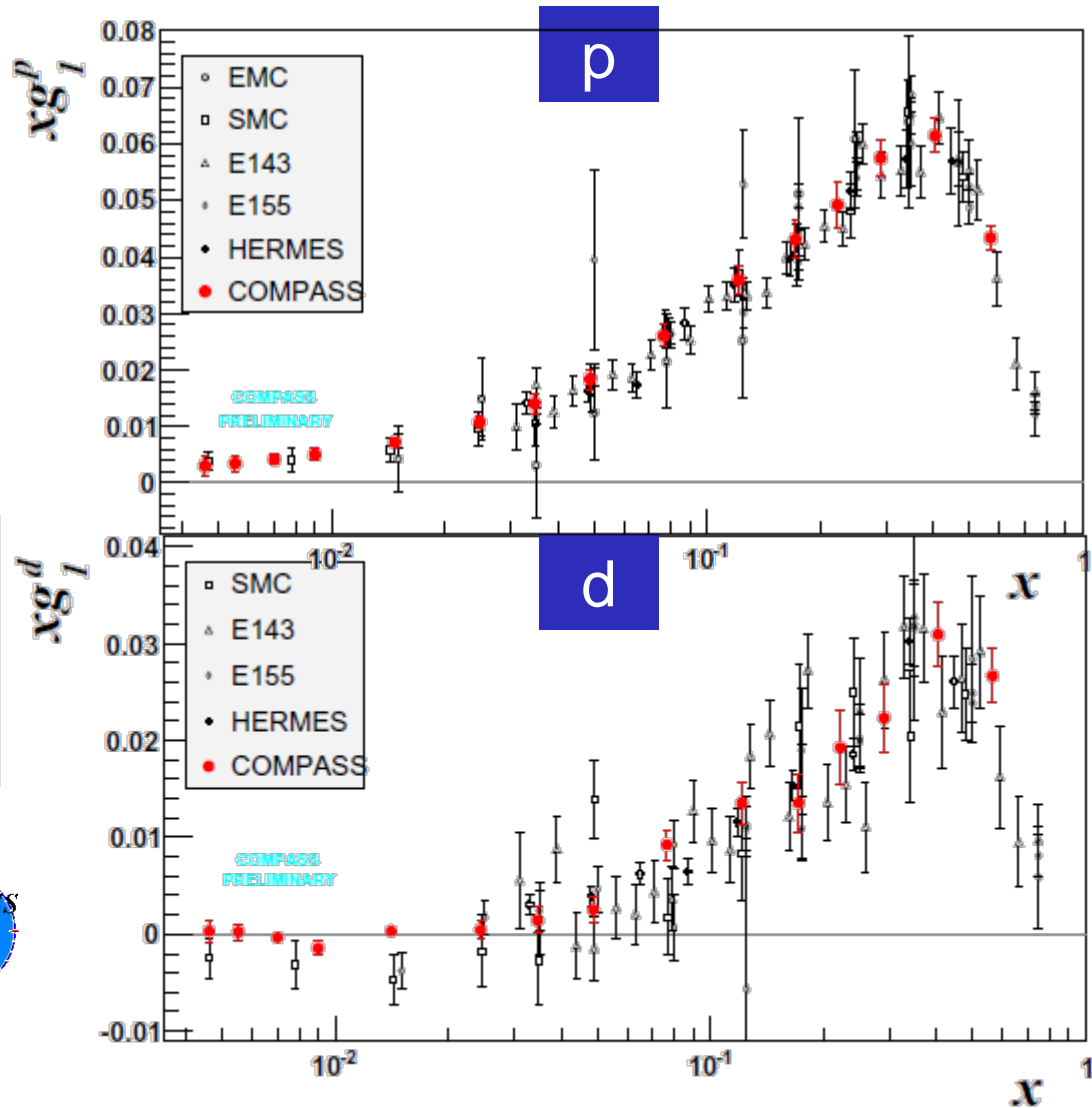
- deuteron data:

$$\Delta\Sigma = 0.33 \pm 0.03 \pm 0.05$$

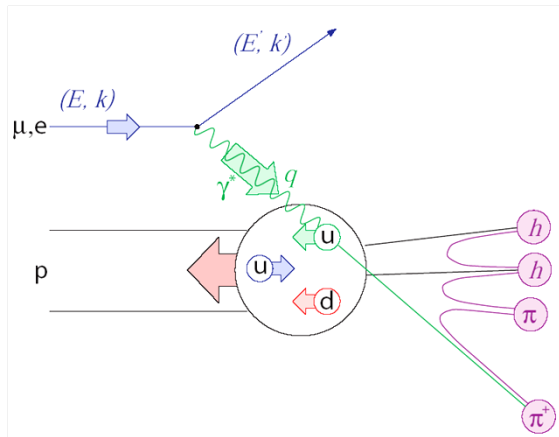
$$\Delta s + \Delta\bar{s}$$

$$= -0.08 \pm 0.01 \pm 0.02$$

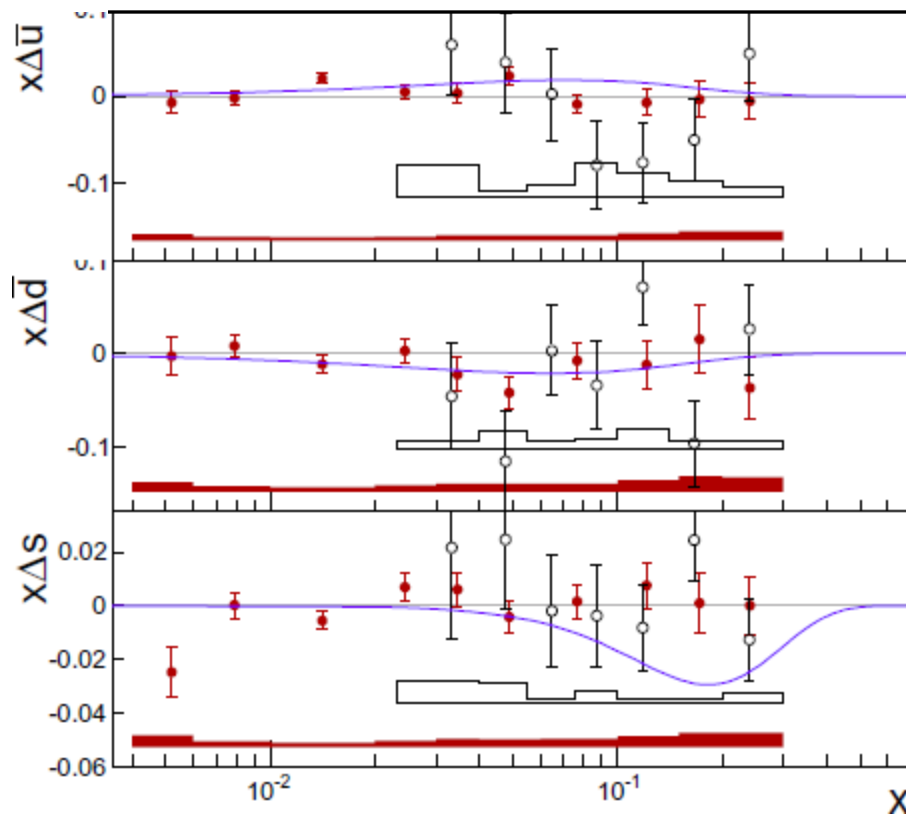
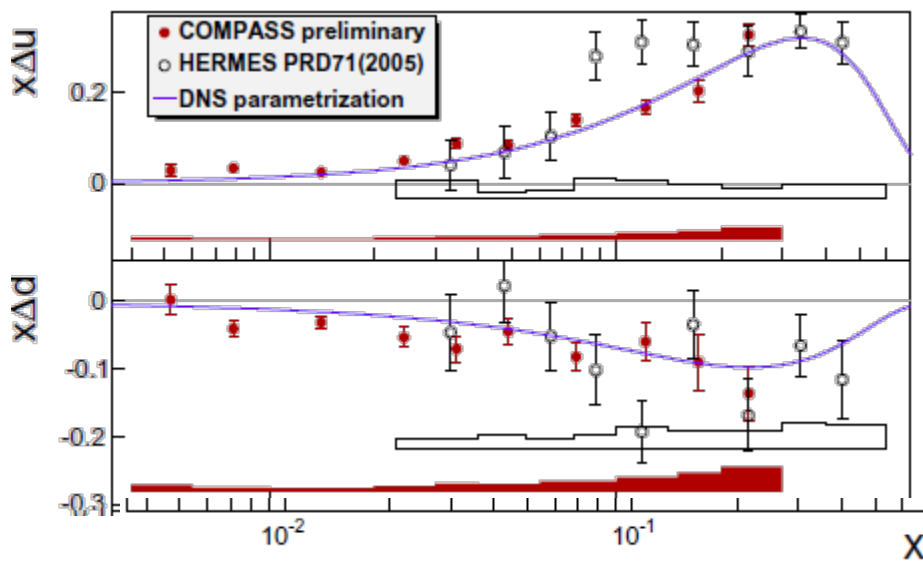
$$(\Delta\Sigma = a_0, \text{ evol. to } Q^2 = \infty)$$



The role of quark flavours



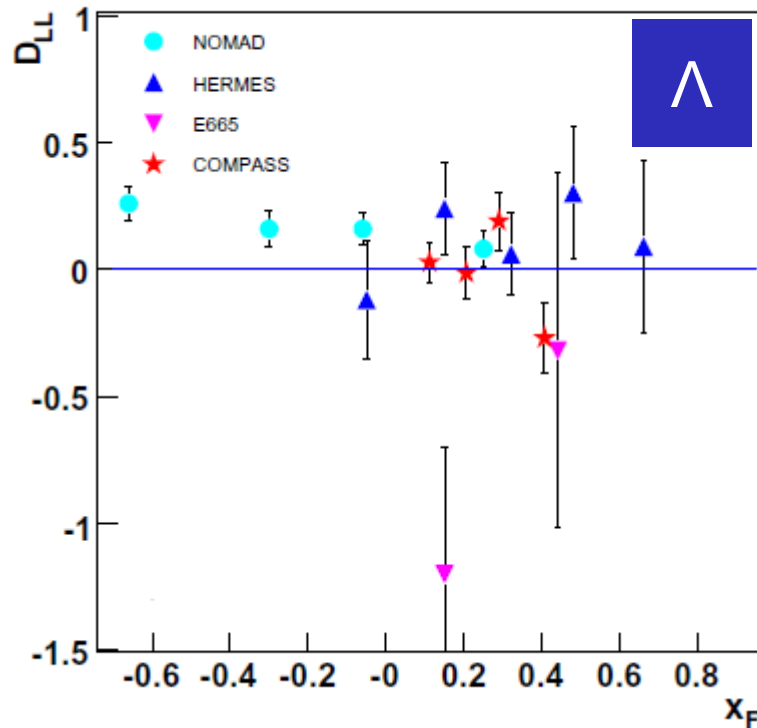
LO semi-inclusive data analysis



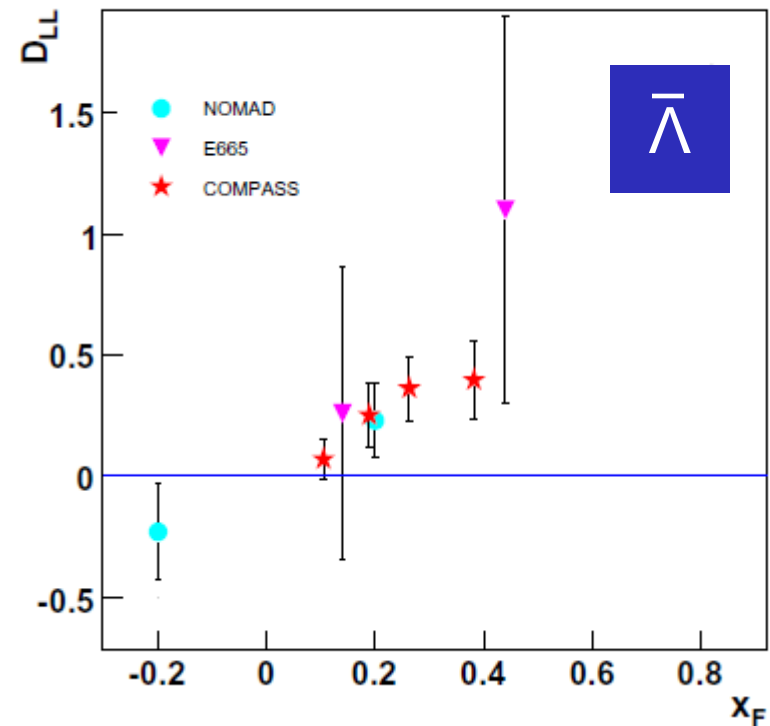
Longitudinal spin transfer to Λ & $\bar{\Lambda}$



2003/2004 data 69500 Λ



41600 $\bar{\Lambda}$

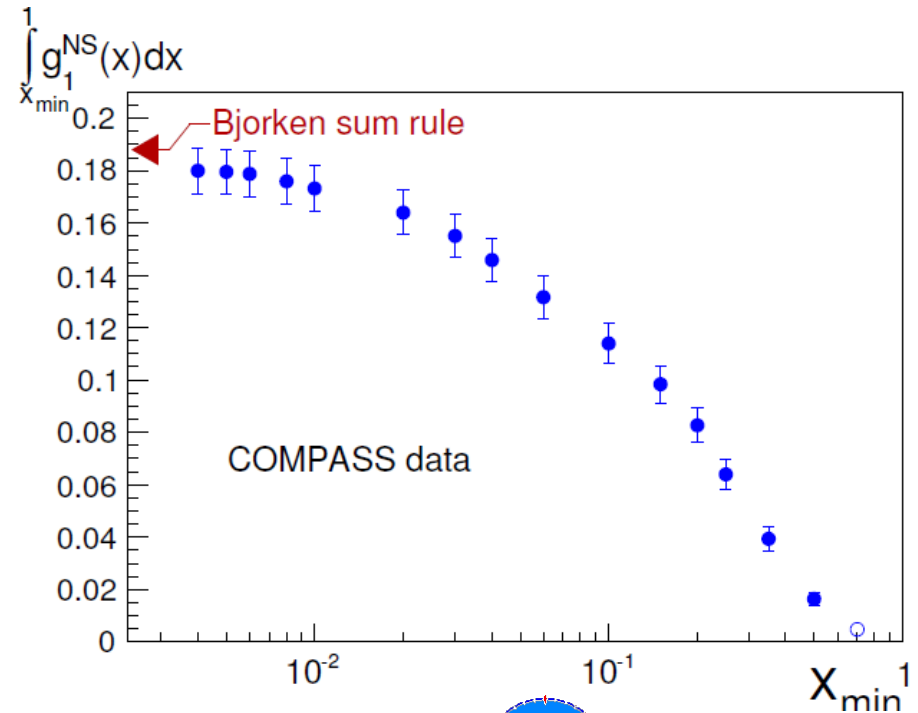
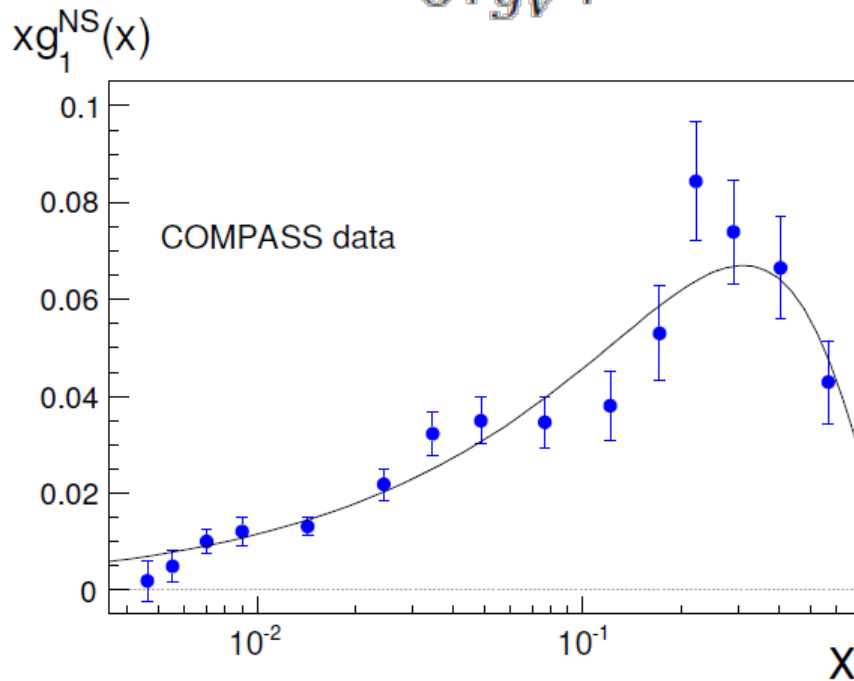


- Large (!) D_{LL} for $\bar{\Lambda}$ related to antistrange quark distribution

Bjorken sum rule

$$\Gamma_1^{NS}(Q^2) = \frac{1}{6} \left| \frac{g_A}{g_V} \right| C_1^{NS}(Q^2)$$

$$g_1^{NS}(x, Q^2) = g_1^p(x, Q^2) - g_1^n(x, Q^2)$$



$$\left| \frac{g_A}{g_V} \right| = 1.28 \pm 0.07(\text{stat.}) \pm 0.10(\text{syst.})$$

$$\left| \frac{g_A}{g_V} \right| = 1.269 \quad \text{from neutron } \beta \text{ decay}$$



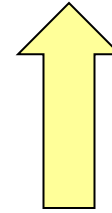
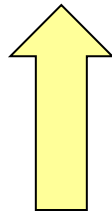
Angular momentum of the nucleon

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

quarks

gluons

orbital



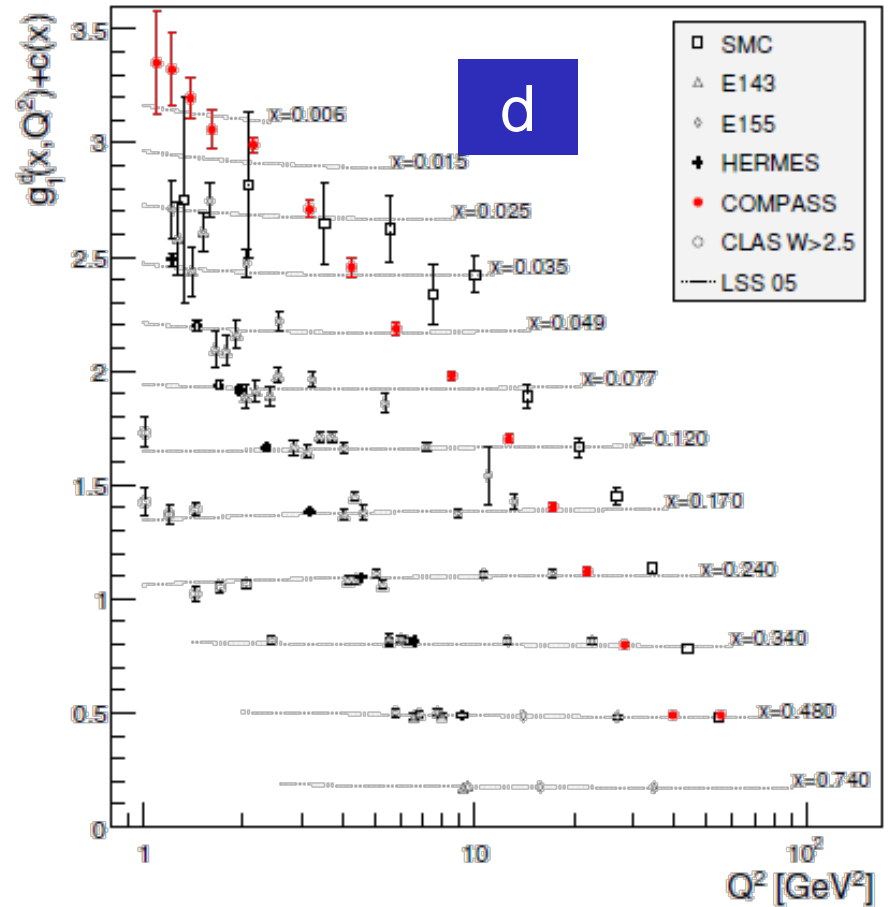
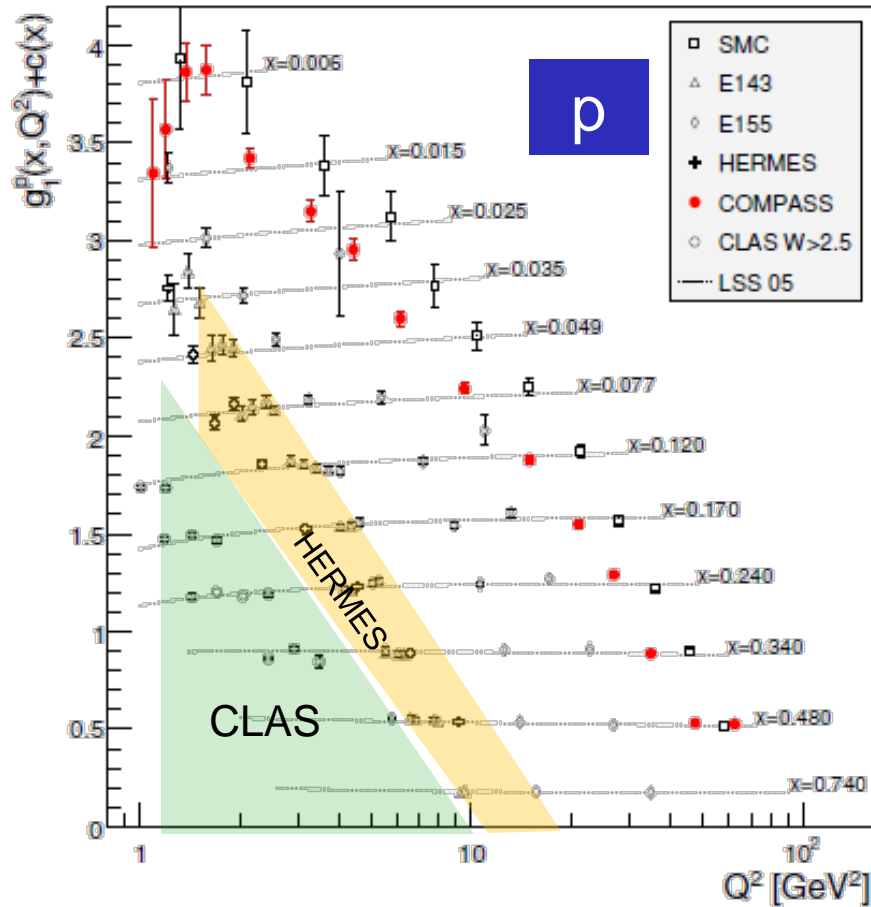
small ~ 0.15

unknown

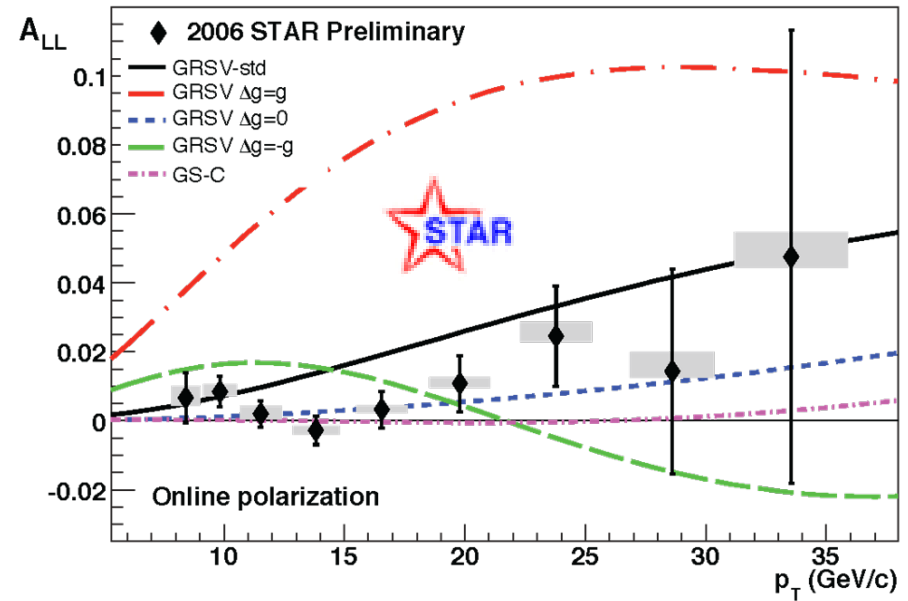
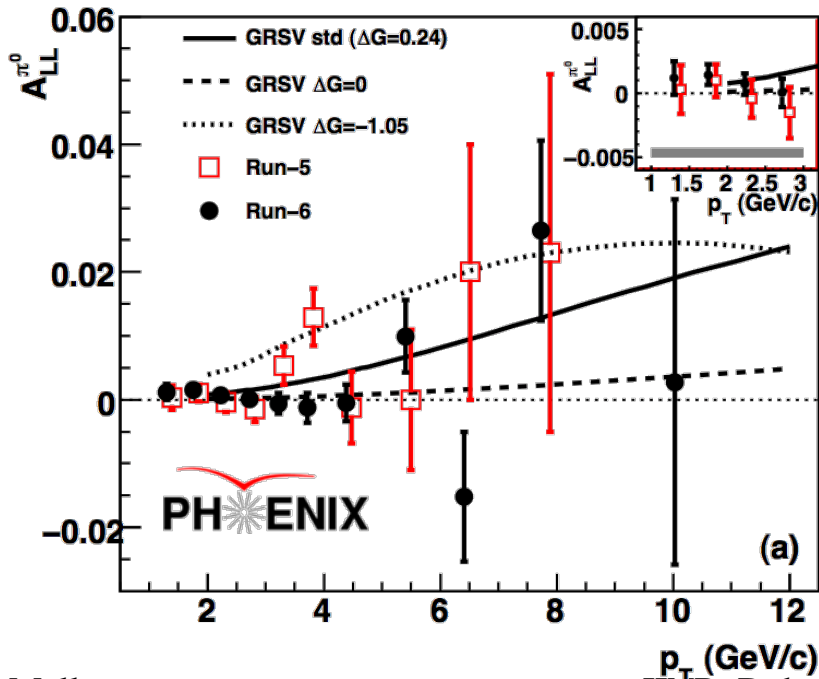
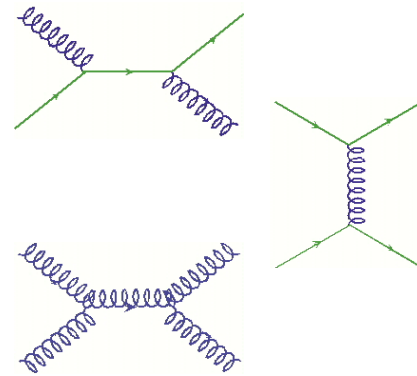
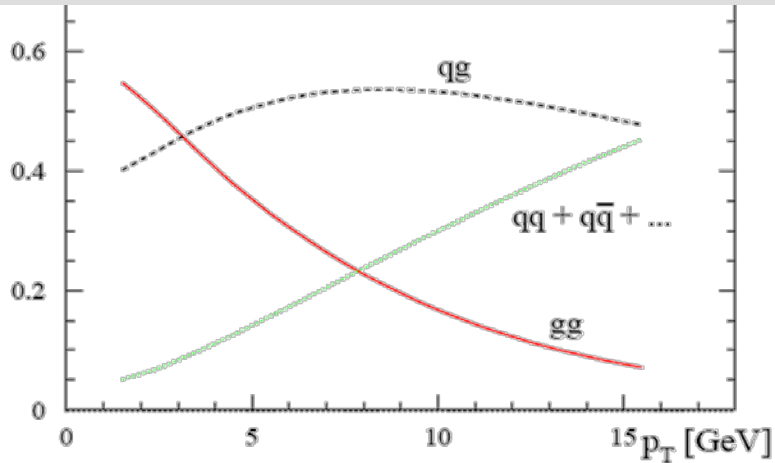
Still poorly known

Q^2 evolution and gluon polarization

- Q^2 dependence g_1 data related to gluon polarization (DGLAP)
- Limited kinematic range (c.f. unpol. HERA)

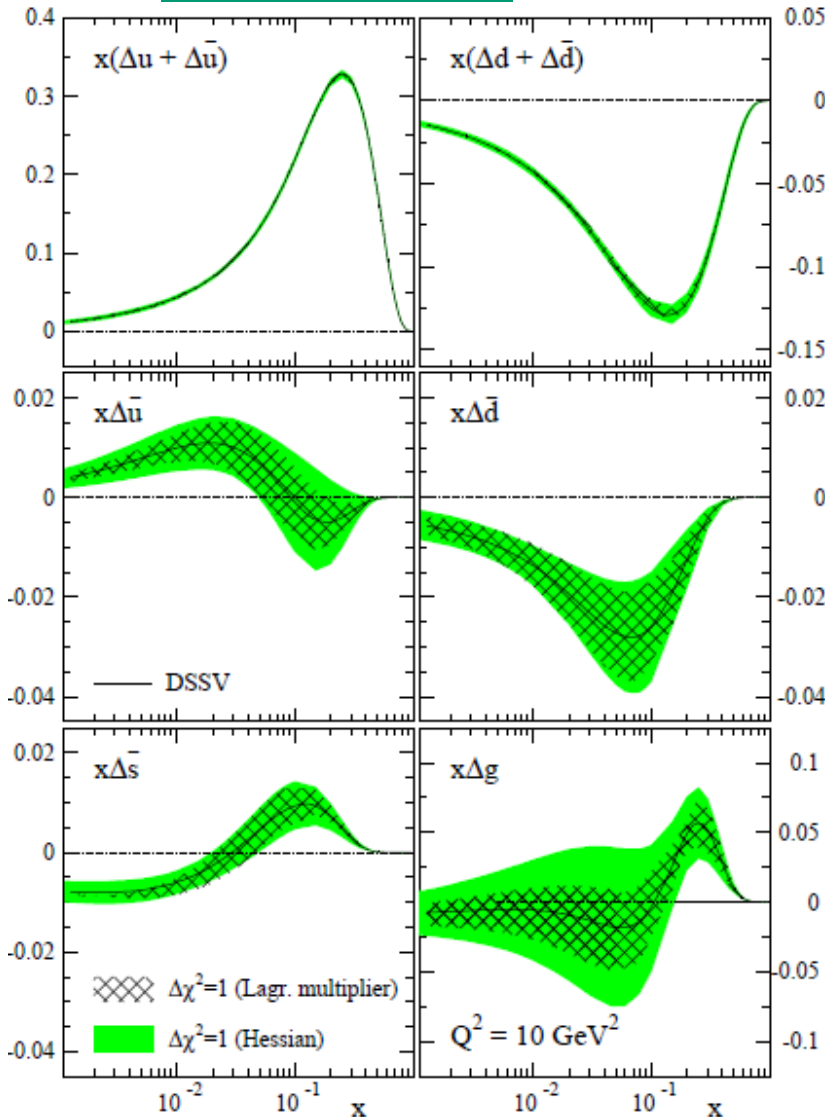


RHIC polarized pp

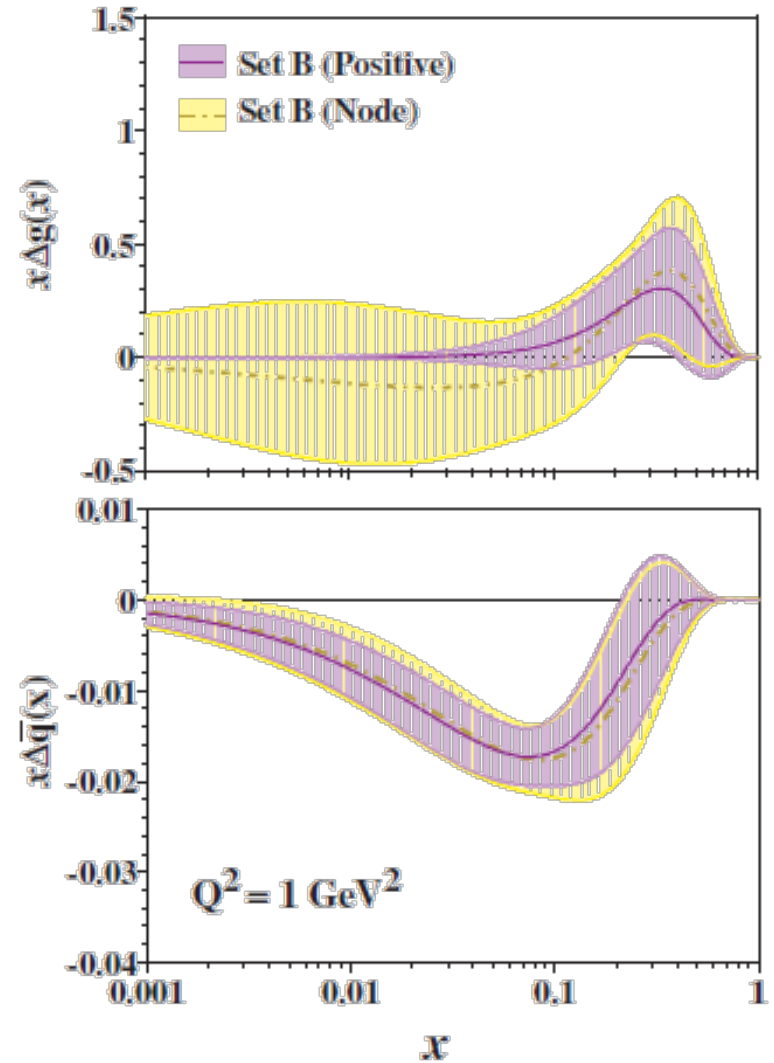


PDFs from global analyses

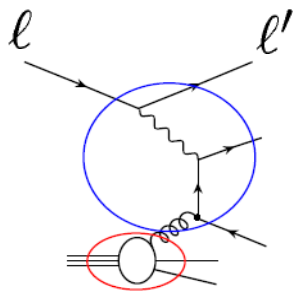
DSSV



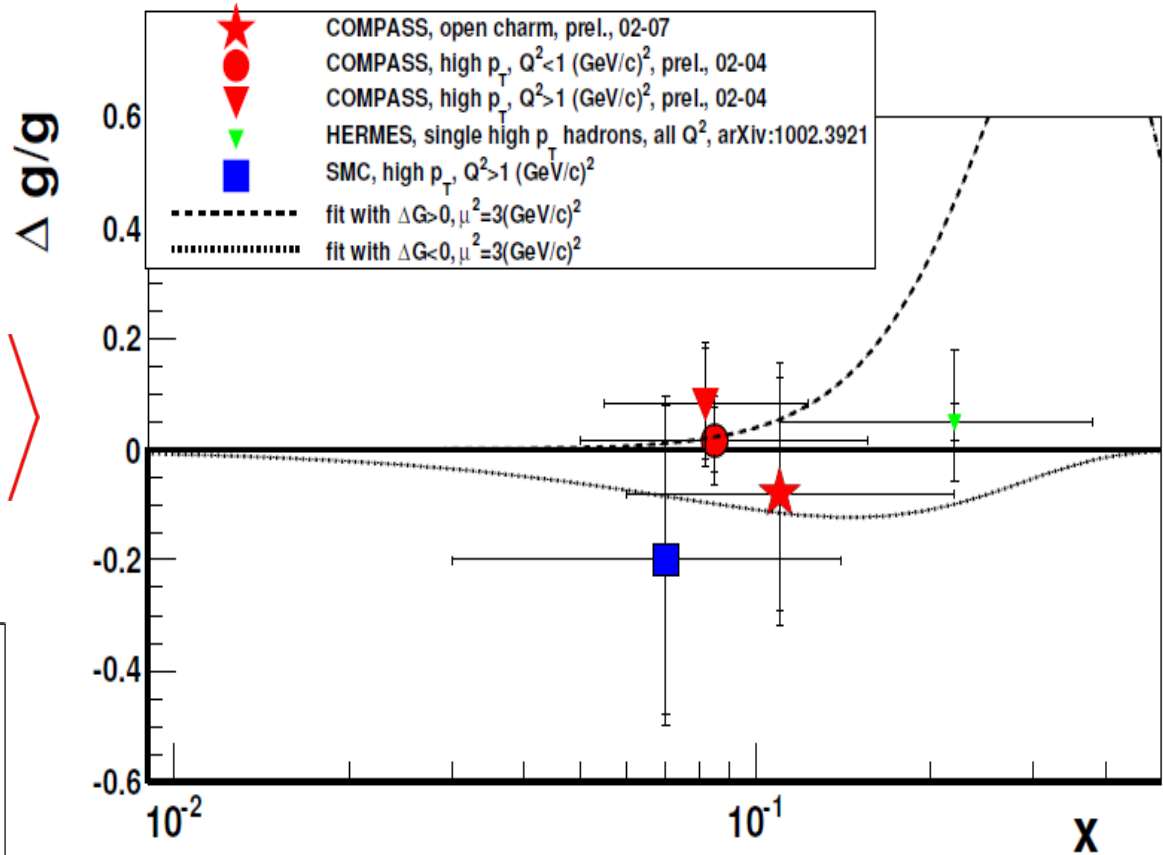
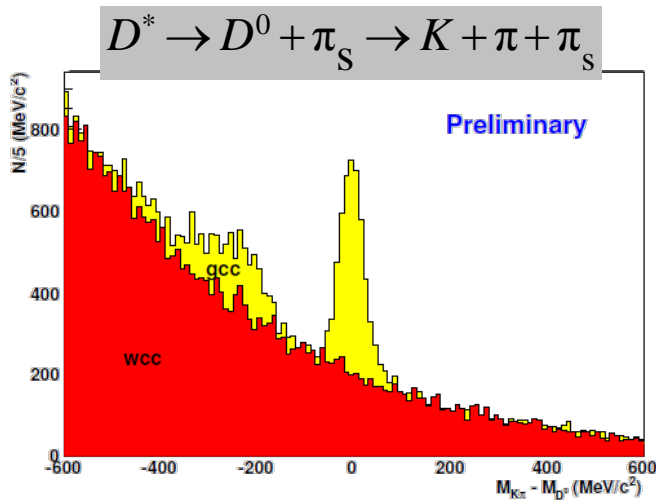
Hirai, Kumano



Gluon polarization from PGF



$$A_{||} = R_{pgf} \langle \hat{a}_{pdf} \rangle \left\langle \frac{\Delta g}{g} \right\rangle$$



Data not yet in global fits

Transverse spin structure



TMD parton distributions

- 8 intrinsic-transverse-momentum dependent PDFs at LO
- Azimuthal asymmetries with different angular modulations in the hadron and spin azimuthal angles, Φ_h and Φ_s

		nucleon polarization				
		U	L	T		aka
quark polarization	U	f_1 number density		f_{1T}^\perp	Sivers	$\Delta_0^T q$
	L		g_1 helicity	g_{1T}^\perp		
Boer–Mulders	T	h_1^\perp	h_{1L}^\perp	h_1 transversity h_{1T}^\perp	Transversity	$\Delta_T q$

Transversity PDF $\Delta_T q$ or h_1



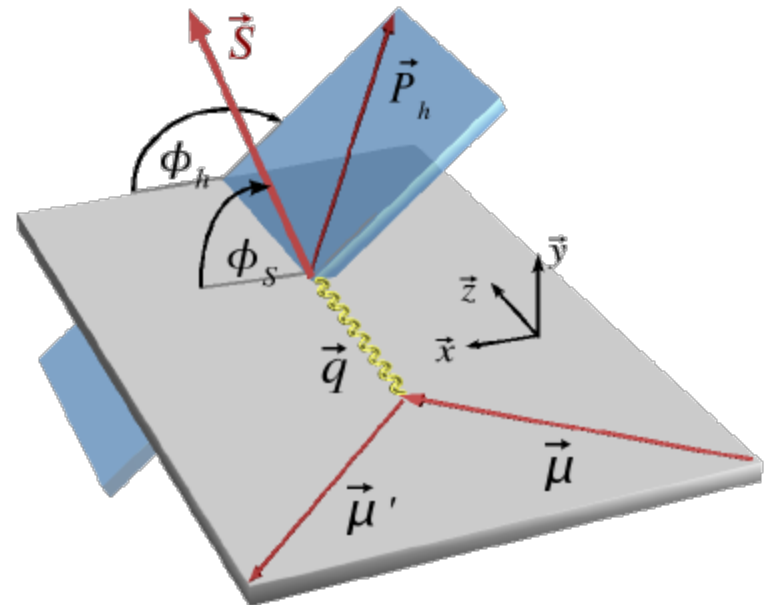
Couple $\Delta_T q$ to chiral odd Collins FF $\Delta_T^0 D_q^h$

$$A_{Coll} = \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 q(x) D_q^h(z, p_T^h)}$$

Azimuthal cross-section asymmetry:

$$\frac{\Delta\sigma}{\sigma} \propto A_{Coll} \sin \Phi_C$$

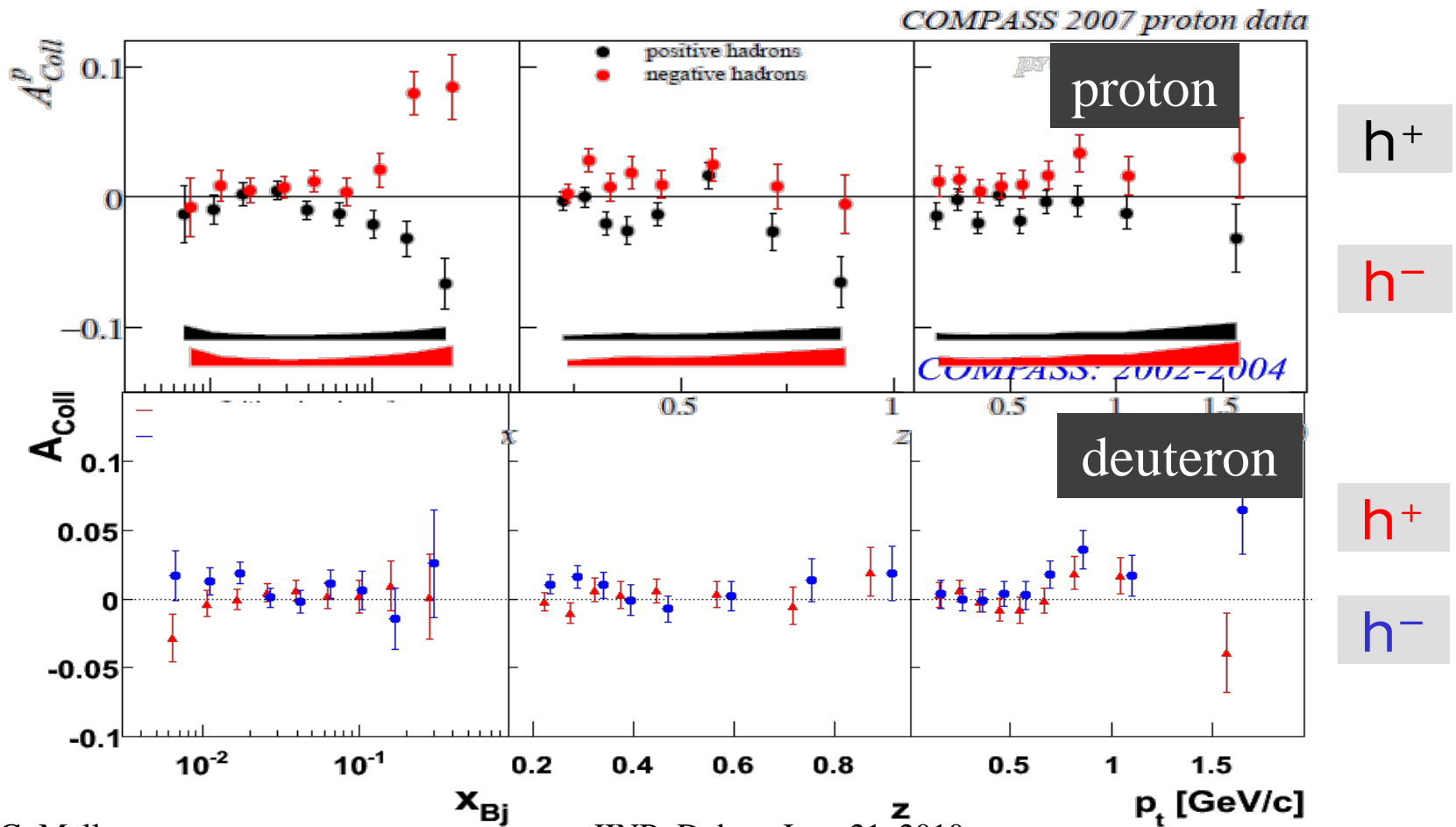
$$\Phi_C = \phi_h - \phi_s - \pi$$



Collins Asymmetries

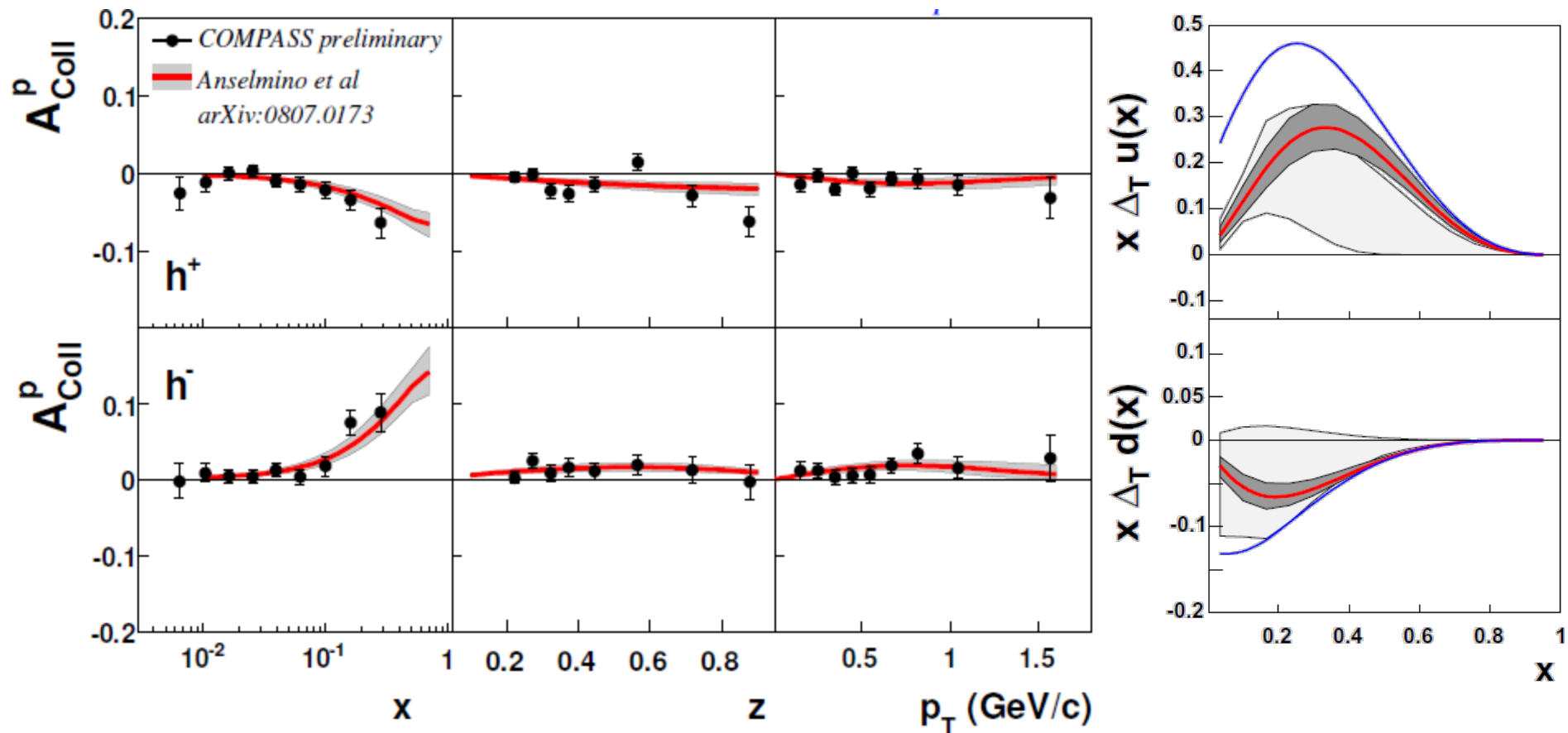


- large asymmetry for proton $\sim 10\%$
- zero deuteron result important \Rightarrow opposite sign of u and d

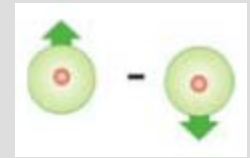


Global Fit

Fit to COMPASS d , HERMES, BELLE (Collins FF, e^+e^-)
in good agreement with new proton data



Sivers function $\Delta_0^T q$ or f_{1T}^\perp



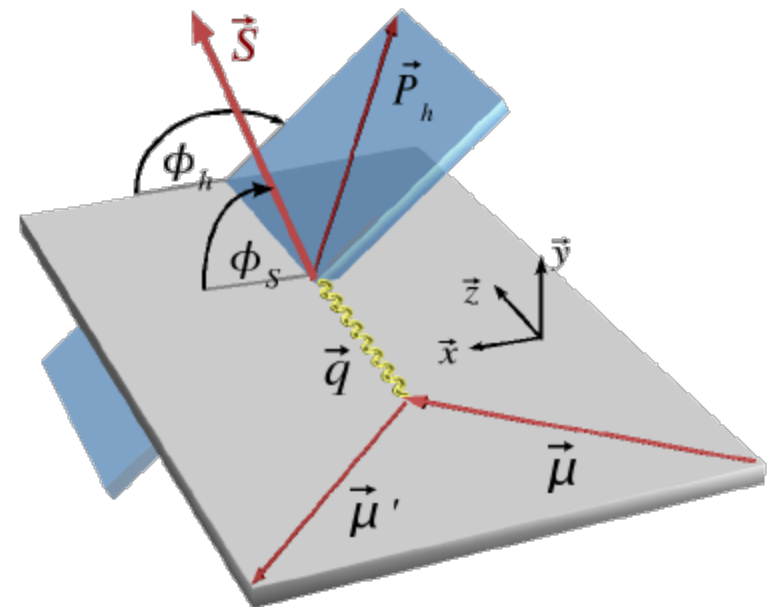
Sivers Asymmetry:

$$A_{Siv} = \frac{\sum_q e_q^2 \Delta_0^T q(x, p_T^h/z) D_q^h(z)}{\sum_q e_q^2 q(x, p_T^h/z) D_q^h(z)}$$

$$\frac{\Delta\sigma}{\sigma} \propto A_{Siv} \sin \Phi_S$$

$$\Phi_S = \phi_h - \phi_s$$

- proposed (1990, Sivers)
- thought to vanish (1993, Collins)
- resurrected (2002, Brodsky, Hwang, Schmitt)
- different sign in DY and SIDIS

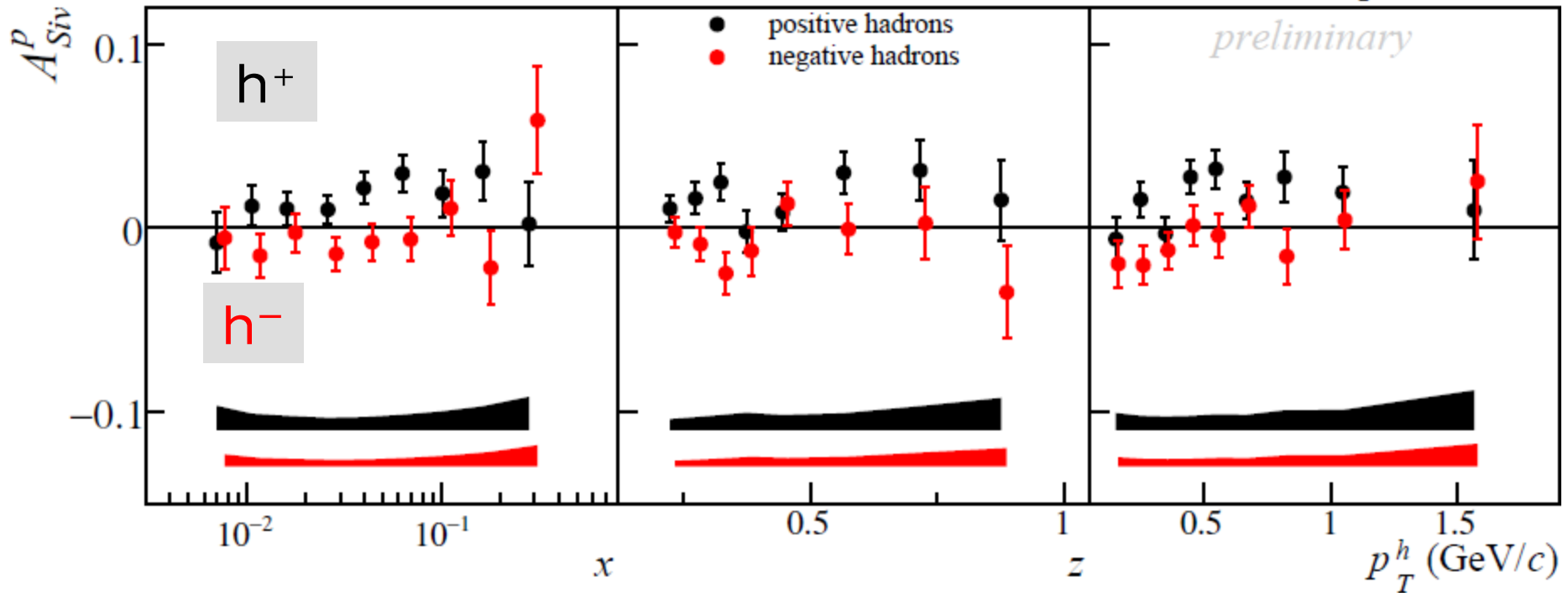


Proton Sivers Asymmetry

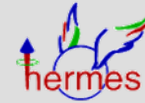


- compatible with zero for the deuteron
- non-zero asymmetry for pos. hadrons

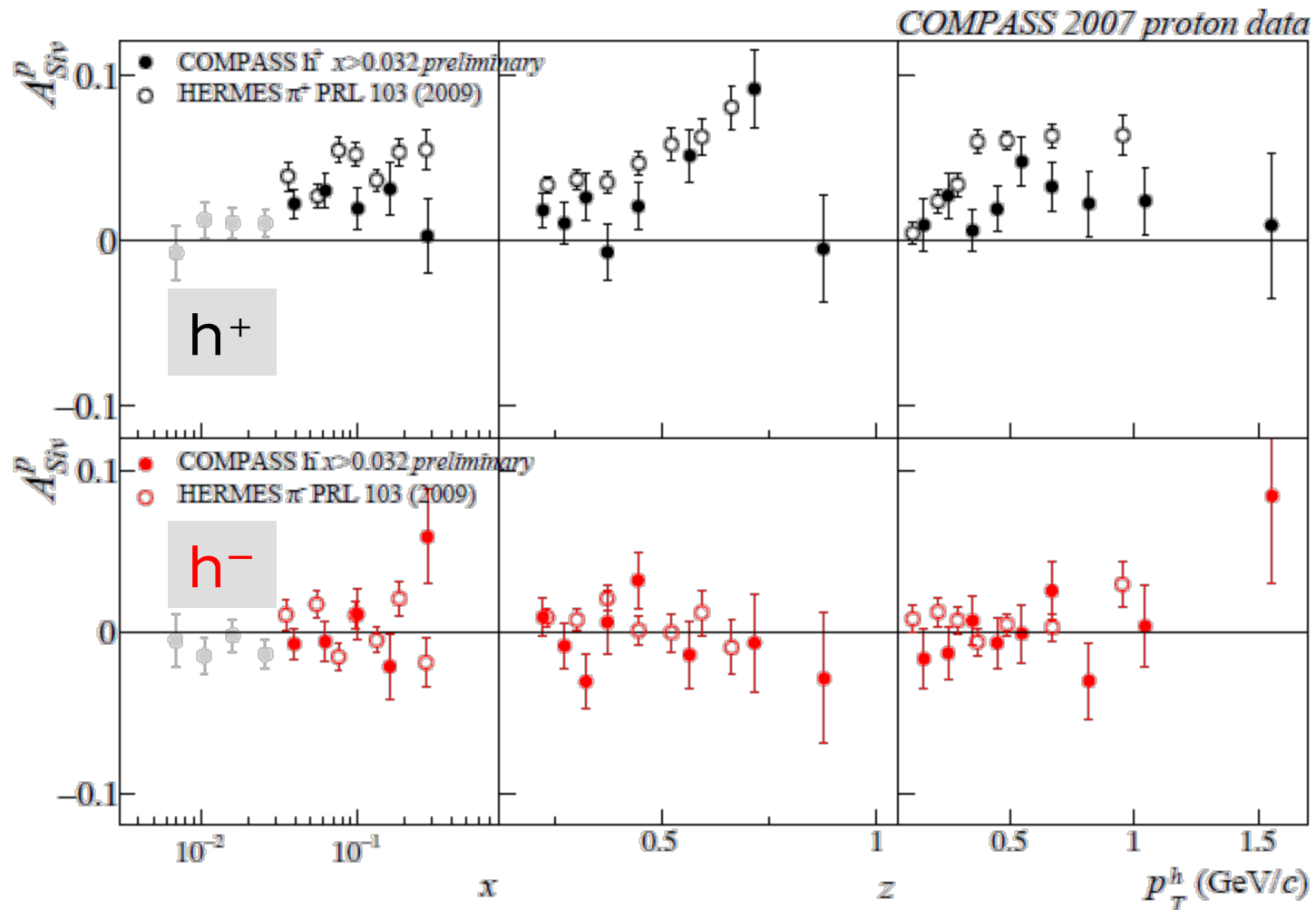
COMPASS 2007 proton data



Comparison Sivers

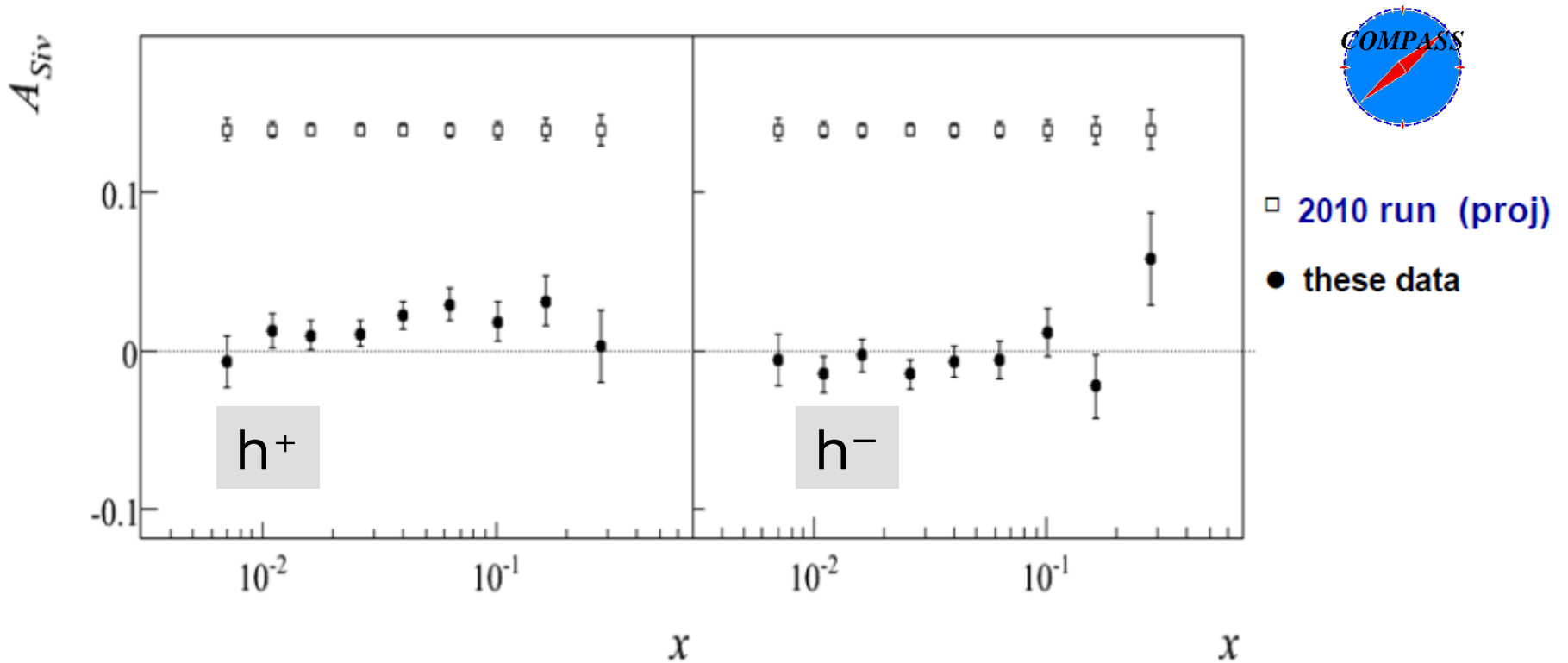


Compass data somewhat smaller for h^+



Proj. stat. precision for 2010 run

Clarification from 2010 data



What's next?

Focus on transverse structure of the nucleon

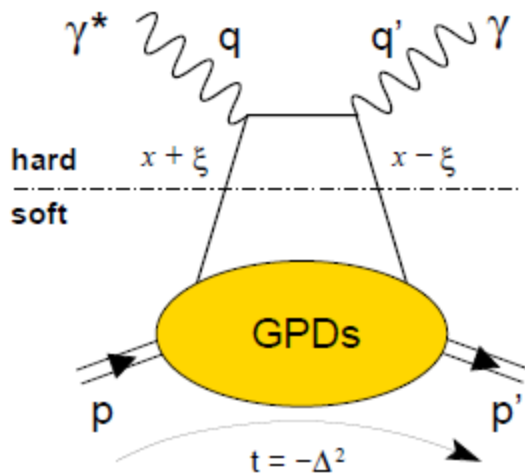
- Transverse size and orbital angular momentum (**GPDs**)
- Restricted universality of T-odd TMDs (Sivers, Boer-Mulders), sign change from SIDIS to **DY**
- Additional TMDs (pretzelosity, worm-gear)

- **COMPASS-II Proposal**
wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf

- **Other new facilities/experiments**
 - JLAB, RHIC, JLAB 11 GeV, **NICA/SPD**, eRHIC/ELIC

Generalized Parton Distribution Functions

- Novel concept, universal, $H, \tilde{H}, E, \tilde{E}$
- H (E) nucleon helicity (non)conservation
- Nucleon form factors and PDFs as limiting cases
- Correlating **transverse spatial** and **longitudinal momentum** degrees of freedom ('tomography')
- DVCS & DVMP



Total orbital momentum:

$$J^f(Q^2) = \frac{1}{2} \lim_{t \rightarrow 0} \int_{-1}^1 dx x [H^f(x, \xi, t, Q^2) + E^f(x, \xi, t, Q^2)]$$

X.-D. Ji, Phys. Rev. Lett. 78 (1997) 610

x is not x -Bjorken

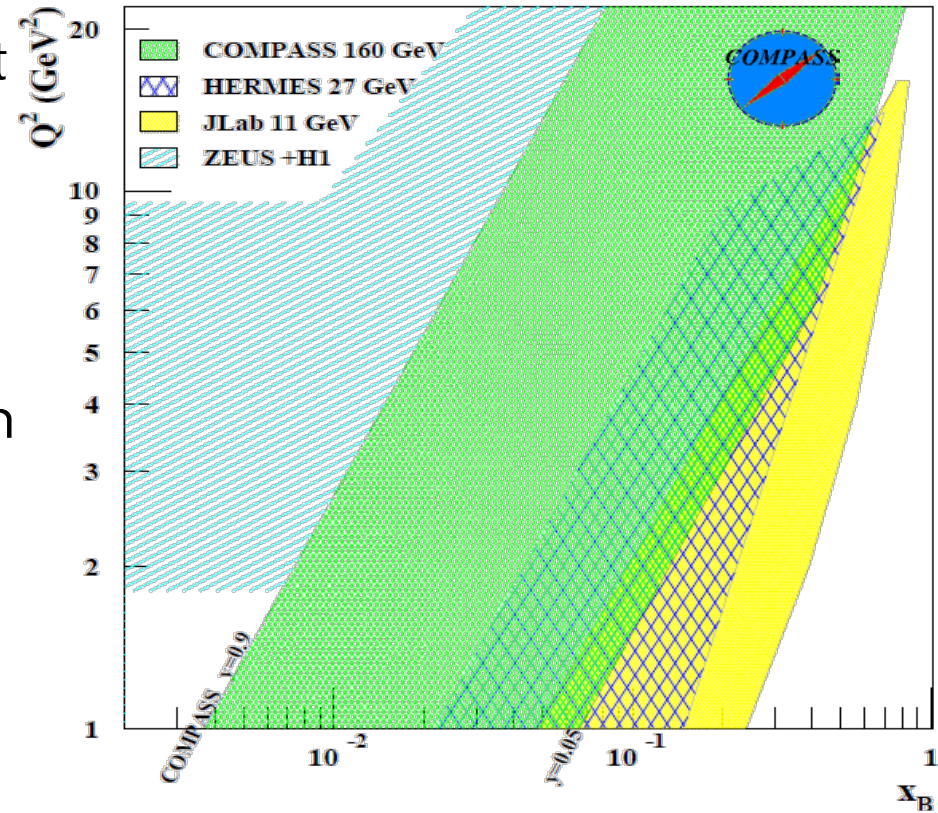
DVCS

- GPDs need a world-wide effort
- Global analysis over large kinematic range mandatory
- COMPASS-II: from HERA to JLAB 11 GeV kinematics
- H GPDs can be separated from BH and constrained by beam charge & spin ($\mu^+\mu^-$) combinations

$$\mathcal{D}_{CS,U} \equiv d\sigma^{\leftarrow+} - d\sigma^{\rightarrow-}$$

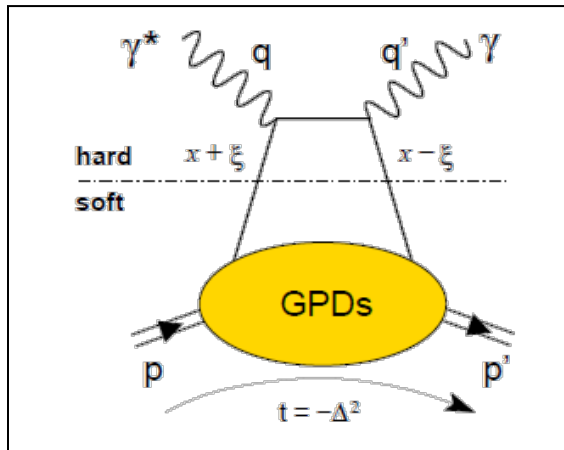
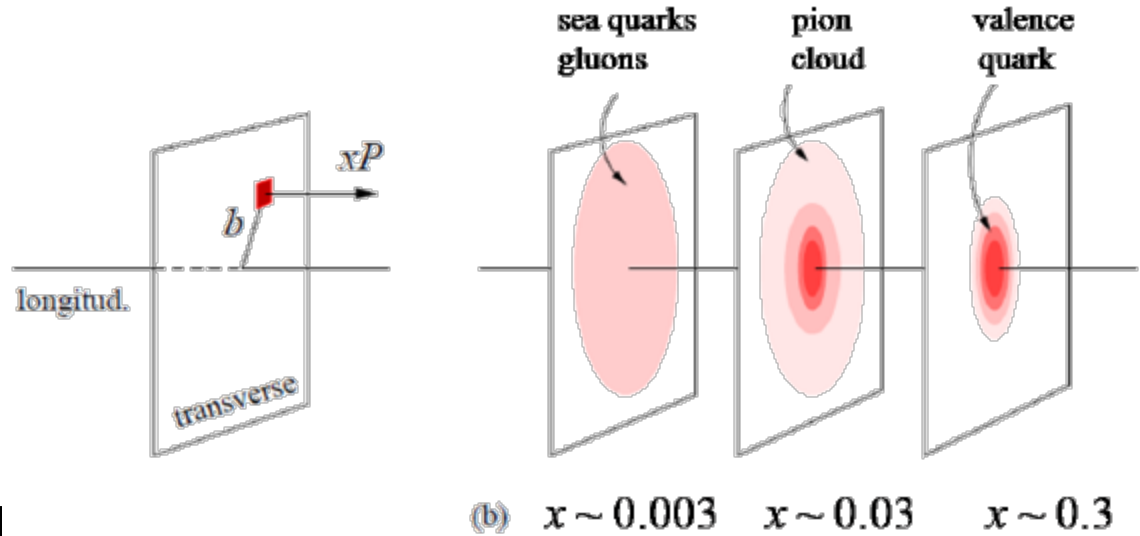
$$\mathcal{S}_{CS,U} \equiv d\sigma^{\leftarrow+} + d\sigma^{\rightarrow-}$$

- E GPDs require transversely pol. target (later)



Tomography-I' ($\xi=0$)

$$t = -\Delta_T^2$$

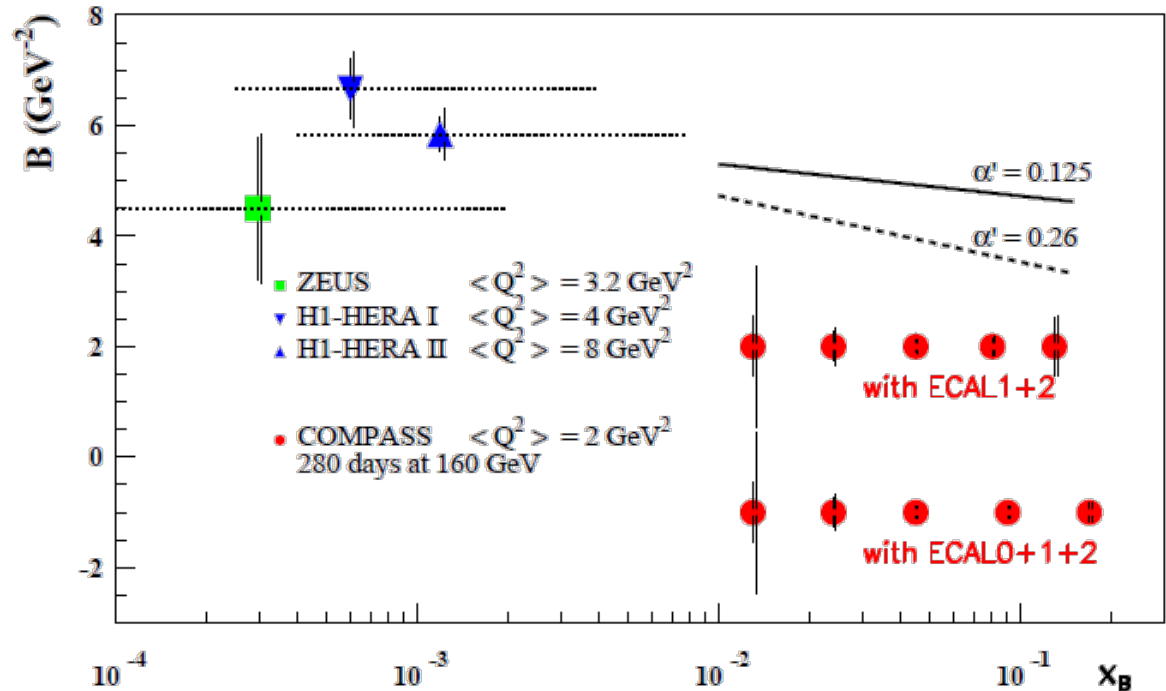


$$q^f(x, \mathbf{b}_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{-i\Delta_\perp \cdot \mathbf{b}_\perp} H^f(x, 0, -\Delta_\perp^2)$$

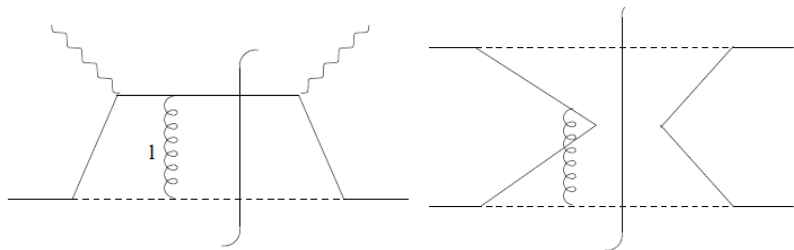
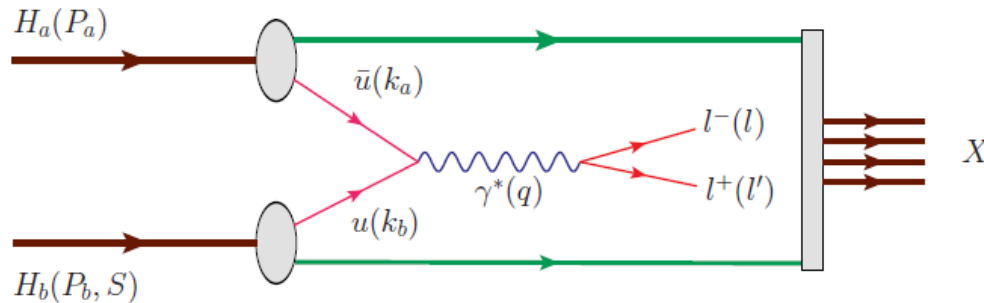
'Tomography-II' ($x = \xi$)

- Projection DVCS COMPASS-II
- Wealth of data to develop and check GPD models
- asymmetries in $6 \times 4, x_B \times Q^2$ bins

$$\langle r_{\perp}^2(x_B) \rangle \approx 2 \cdot B(x_B)$$



T-odd TMD in SIDIS and DY



SIDIS: FSI

DY: ISI

gauge link changes sign for T-odd TMD', restricted universality of T-odd TMDs

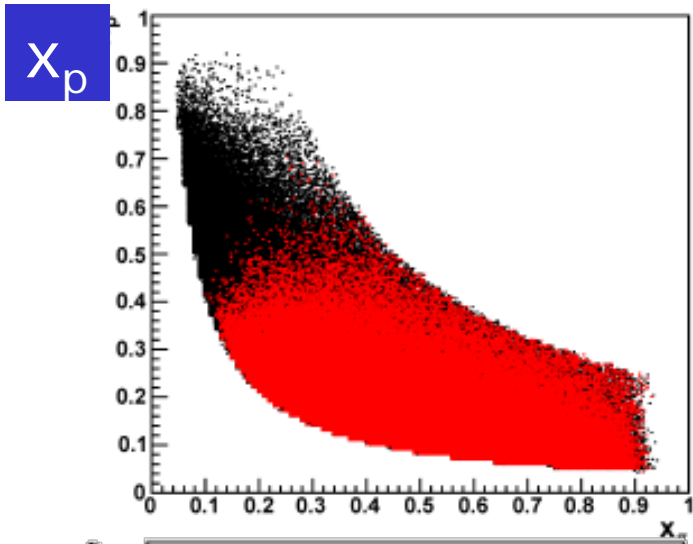
J.C. Collins, Phys. Lett. B536 (2002) 43

$$f_{1T}^\perp \Big|_{DY} = -f_{1T}^\perp \Big|_{DIS} \quad \text{and} \quad h_1^\perp \Big|_{DY} = -h_1^\perp \Big|_{DIS}$$

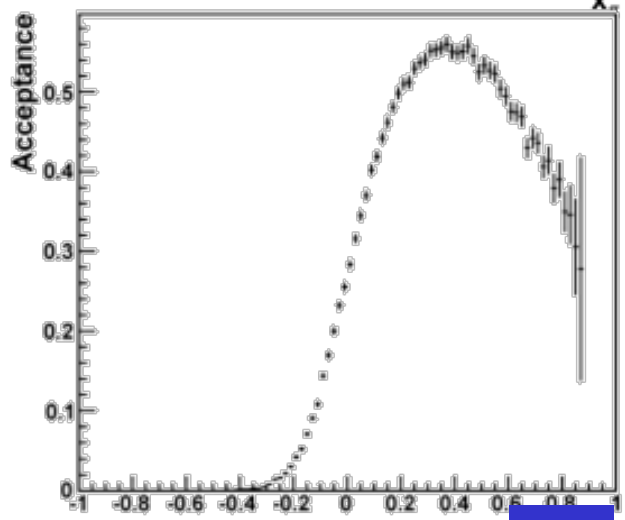
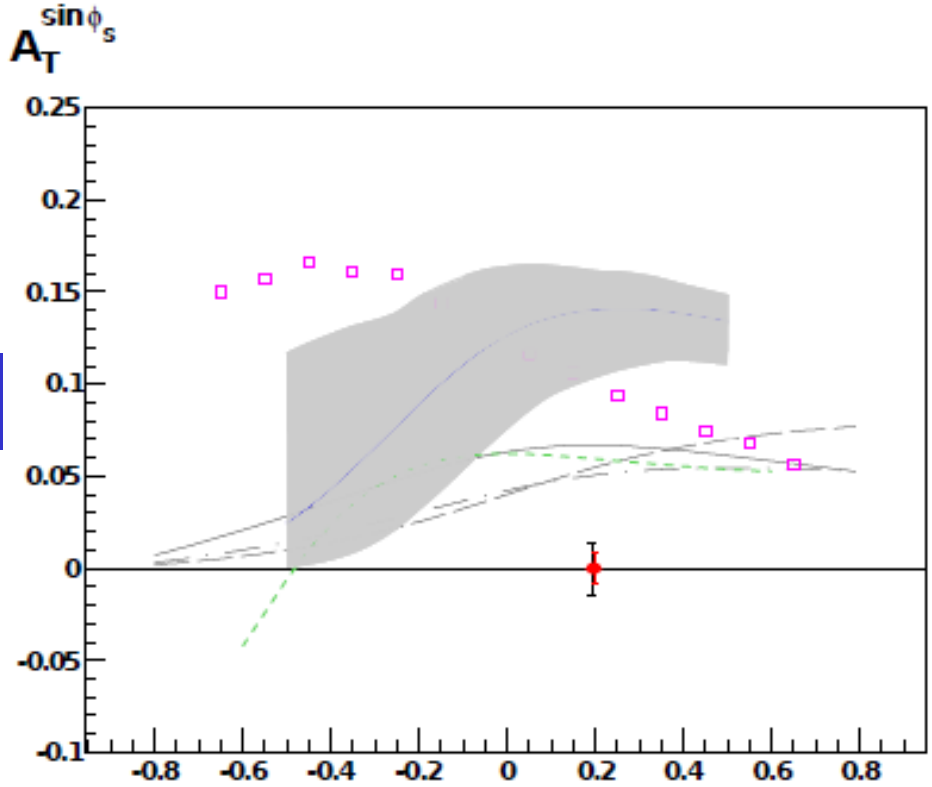
Polarised Drell-Yan

- COMPASS-II: 190 GeV/c π^- beam on transversely pol. proton target
- π^- valence u-antiquark picks nucleon's u quark in valence region (u-quark dominance)
- Access to transversity, the T-odd Sivers and Boer-Mulders TMDs and 'pretzelosity'

COMPASS polarized DY



X_π



X_F

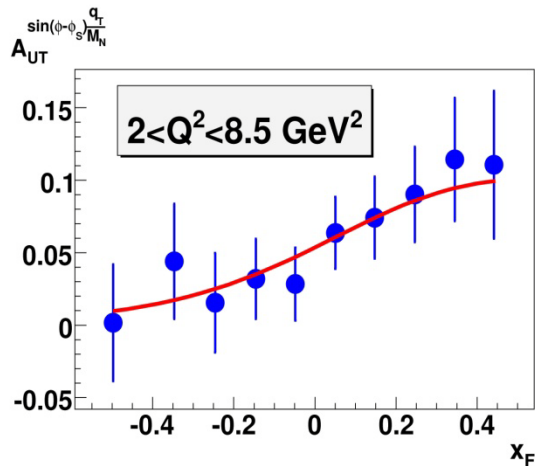
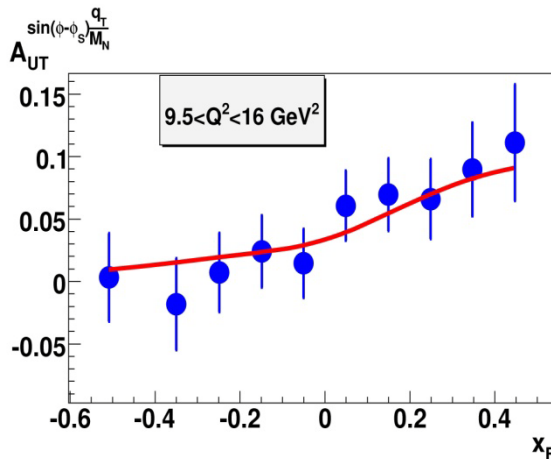
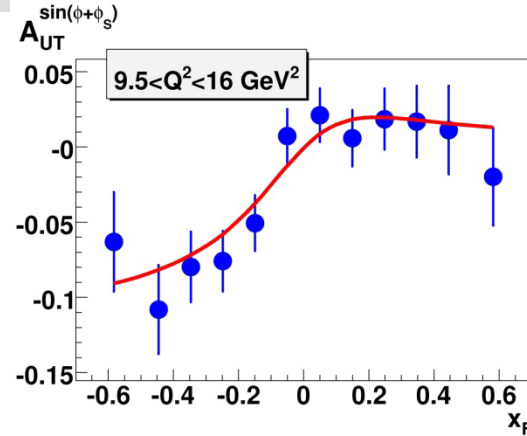
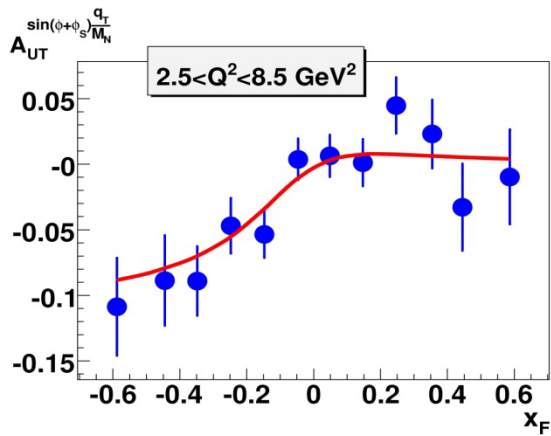
$$X_F = X_\pi - X_\rho$$

Future DY experiments

Facility	Type	s (GeV ²)	Time-line
RHIC (STAR, PHENIX) [147]	collider, $p^\uparrow p^\uparrow$	200 ² , 500 ²	> 2014
RHIC(internal target) [148]	fixed target, $p^\uparrow p^\uparrow$	500	> 2015
E906 (Fermilab) [149]	fixed target, pp ,	226	> 2010
J-PARC [150]	fixed target, pp^\uparrow	60 ÷ 100	> 2015
GSI(PAX) [151]	collider, $\bar{p}^\uparrow p^\uparrow$	200	> 2017
GSI (Panda) [152]	fixed target, $\bar{p}p$	30	> 2016
NICA [153]	collider, $p^\uparrow p^\uparrow, d^\uparrow d^\uparrow$	676	> 2014
COMPASS (this Paper)	fixed target, $\pi^- p^\uparrow$	300 ÷ 400	> 2012



Spin Physics at NICA. Polarized DY



The set of original software packages (MC simulation, generator etc.) were developed for the feasibility studies of DY polarized processes

The SSA asymmetries.
Top: access to transversity and Boer-Mulders PDFs.

(Sissakian, Shevchenko, Nagaytsev, PRD 72 (2005), EPJ C46 (2006))

Bottom: access to Sivers PDFs (Efremov, ... PLB 612(2005), PRD 73(2006));

Asymmetries are estimated for 100 K DY events

A. Nagaytsev, IWSS2010

(Nucleon) Spin is fun

