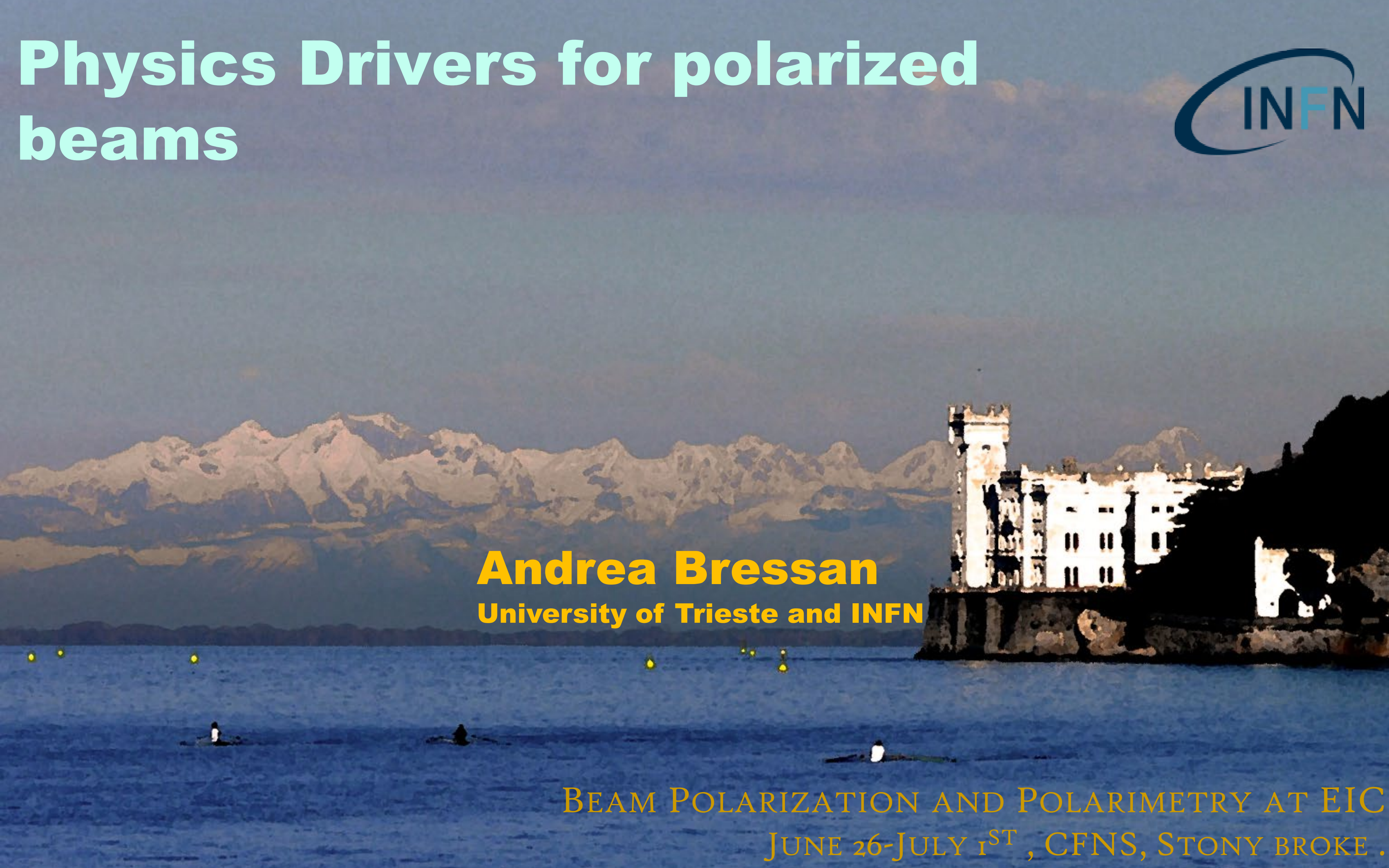
Physics Drivers for polarized beams



Andrea Bressan

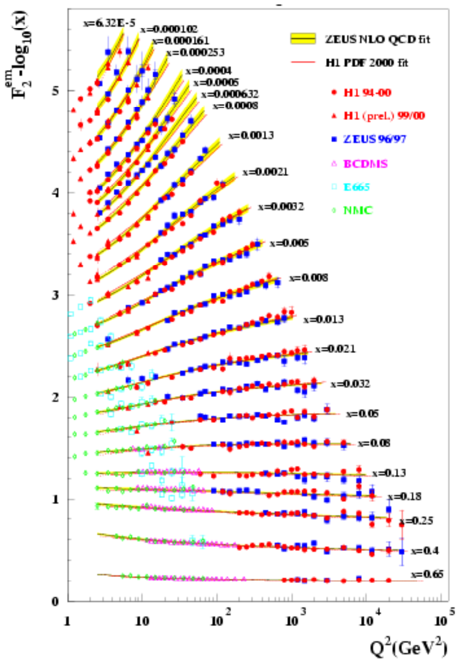
University of Trieste and INFN

Beam Polarization and Polarimetry at EIC

June 26-July 1st , CFNS, Stony broke .

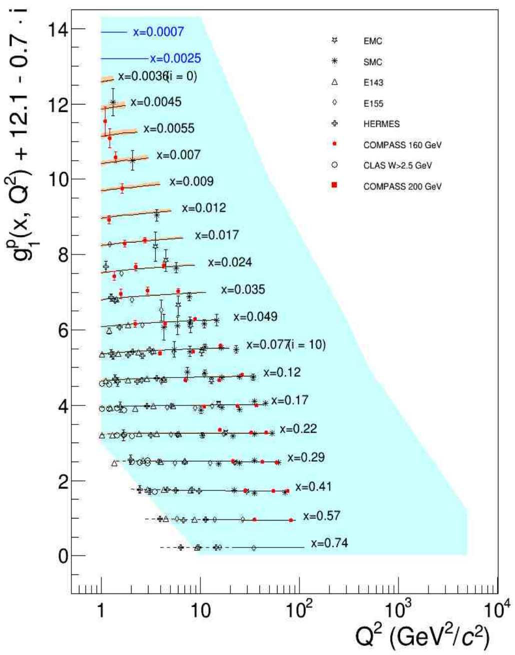
Why we need an EIC

World Data on F_2^p



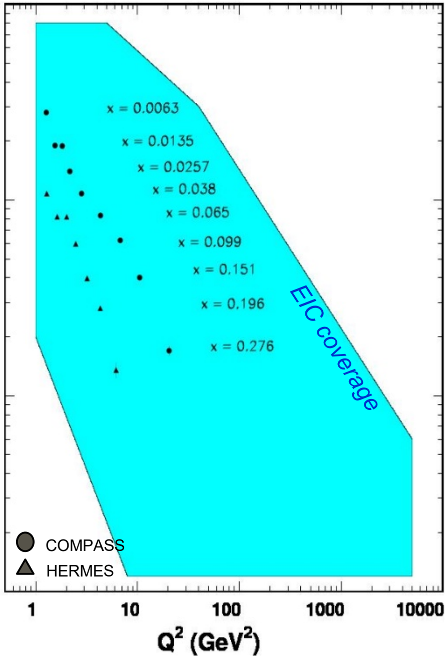
momentum

World Data on g_1^p



spin

World Data on h_1^p



transverse spin ~ angular momentum

Inclusive Deep Inelastic Scattering

- The inclusive deep inelastic scattering double differential cross section $\ell p \rightarrow \ell' X$ can be expressed using two structure functions F_2 and F_1, or, better, F_2 and F_L ($F_L = F_2 - 2xF_1$) which depend from x and mildly by Q^2.

$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{2xQ^4}\left[(1+(1-y)^2)F_2(x,Q^2) - y^2 F_L(x,Q^2)\right]$$

- Keeping in mind the transformations:

$$\frac{d^2\sigma}{dxdy} = \frac{2\pi M\nu}{E'}\frac{d^2\sigma}{d\Omega dE'} = x(s-M^2)\frac{d^2\sigma}{dxdQ^2} \simeq xs\frac{d^2\sigma}{dxdQ^2}$$

We are able to express the cross section in other variables.

Physics content of the structure functions

- In quark-parton model the structure functions can be written as:

$$F_2(x, Q^2) = x \sum_q e_q^2 f_1^q(x) \quad \text{and} \quad F_L(x, Q^2) = 0$$

where f_1^q is the probability that to find a parton of type $q = u, \bar{u} \cdots$ with momentum fraction $p_q = xP$ in the proton

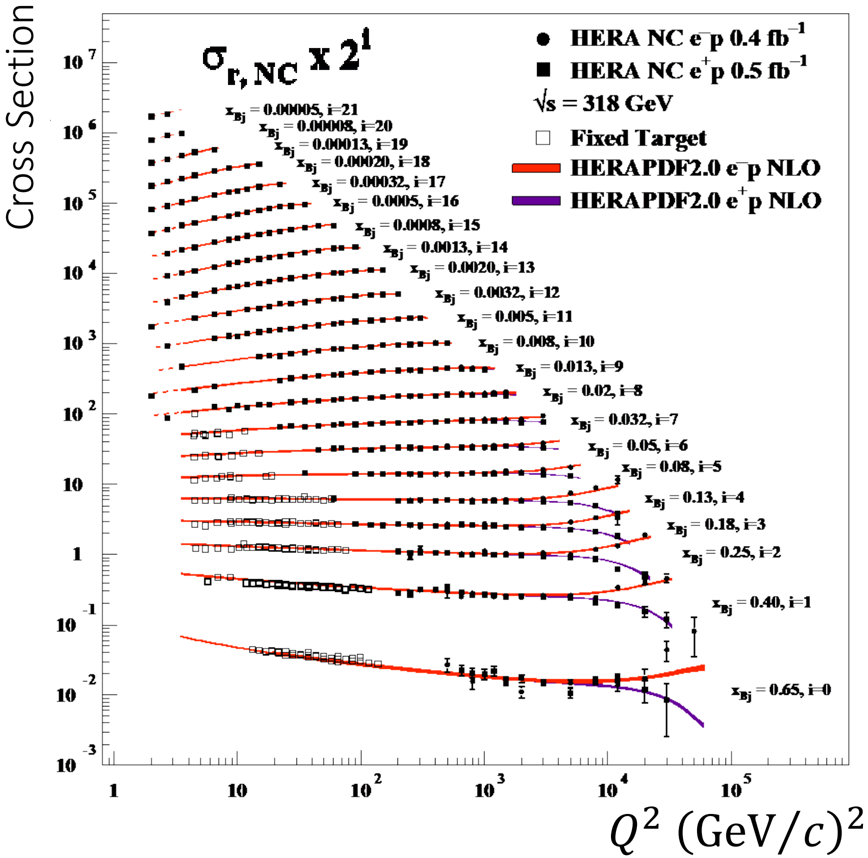
- When including higher orders the structure functions become:

$$F_2(x, Q^2) = x \sum_{n=0}^{\infty} \frac{\alpha_s^n}{(2\pi)^n} \sum_{i=q,g} \int_x^1 \frac{dz}{z} C_{2,i}^{(n)}(z, Q^2) f_1^i\left(\frac{x}{z}\right)$$

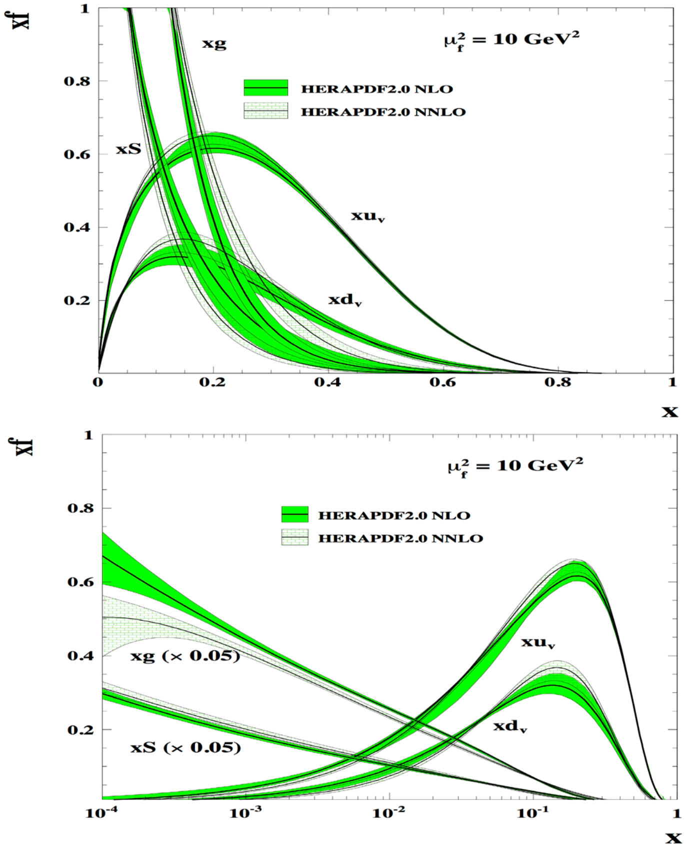
With the Wilson coefficients $C_{2,i}^{(n)}$ known up to $\mathrm{N}^3\mathrm{LO}$

$C_{2,q}^{(0)} = e_q^2 \delta(1 - z)$ and $C_{2,g}^{(0)} = 0$

Impact of the HERA *ep* Collider



arXiv:1506.06042



Polarized Cross Sections

- For longitudinally polarized beams (either parallel or antiparallel we can express the difference of the parallel to anti-parallel cross sections by mean of two structure functions g_1 and g_2,

$$\frac{d^2\sigma_{\rightrightarrows}}{dxdQ^2} - \frac{d^2\sigma_{\rightleftarrows}}{dxdQ^2} = \frac{d^2\Delta\sigma_{\parallel}}{dxdQ^2} = \frac{16\pi\alpha^2 y}{Q^4}\left[\left(1 - \frac{y}{2} - \frac{\gamma^2 y^2}{4}\right) g_1(x,Q^2) - \frac{\gamma^2 y}{2} g_2(x,Q^2)\right]$$

- And when the proton beam is transversely polarized we have:

$$\frac{d^3\sigma_{\uparrow\rightarrow}}{dxdQ^2d\phi} - \frac{d^3\sigma_{\downarrow\longrightarrow}}{dxdQ^2d\phi} = \frac{d^3\Delta\sigma_{\perp}}{dxdQ^2d\phi} = -\cos\phi\,\frac{8\alpha^2 y}{Q^4}\gamma\sqrt{1 - y - \frac{\gamma^2 y^2}{4}}\left[\frac{y}{2} g_1(x,Q^2) + g_2(x,Q^2)\right]$$

- With $\gamma = \sqrt{Q^2}/\nu \ll 1$

Physics content of the structure functions

- At LO in quark-parton model the structure functions can be written as:

  $$g_1(x,Q^2) = \frac{1}{2}\sum_q [\Delta q(x) - \Delta\bar{q}(x)] \quad \text{and} \quad g_2(x,Q^2) = 0$$

  Where the helicity distribution $\Delta q(x) = q^+(x) - q^-(x)$ represents the difference between the number of quarks in the proton with the spin parallel q^+ and antiparallel q^- to the spin of the proton

- When including higher orders the structure functions content become, f.i.:

  $$g_1(x,Q^2) = \frac{1}{2}\frac{\sum_{k=1}^{n_f} e_f^2}{n_f}\left[C_q^S \otimes \Delta\Sigma + 2n_f C_g \otimes \Delta g + C_q^{NS} \otimes \Delta q^{NS}\right]$$

  The Wilson coefficients at LO are:

  $C_q^S = C_q^{NS} = \delta(1-x)$ and $C_g = 0$

The spin content of the proton: where we stand

Gluons PDF are accessed using DGLAP Equations

$$\frac{d}{dt}\Delta\Sigma(x,t) = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}^{S}\left(\frac{x}{y},\alpha_s(t)\right)\Delta\Sigma(y,t) + 2n_f P_{qg}\left(\frac{x}{y},\alpha_s(t)\right)\Delta g(y,t)\right]$$

$$\frac{d}{dt}\Delta g(x,t) = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{gq}\left(\frac{x}{y},\alpha_s(t)\right)\Delta\Sigma(y,t) + P_{gg}\left(\frac{x}{y},\alpha_s(t)\right)\Delta g(y,t)\right]$$

$$\frac{d}{dt}\Delta q_{NS}(x,t) = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y} P_{qq}^{NS}\left(\frac{x}{y},\alpha_s(t)\right)\Delta q_{NS}(x,t)$$

With $t = \ln Q^2/\Lambda^2$, $\Delta\Sigma(x,t) = \sum_{i=1}^{n_f}\Delta q_i$ and $\Delta q_{NS}(x,t) = \sum_{i=1}^{n_f}(e_i^2/\langle e^2\rangle - 1)\Delta q_i$,

where $\langle e^2\rangle = \frac{1}{n_f}\sum_{i=1}^{n_f} e_i^2$

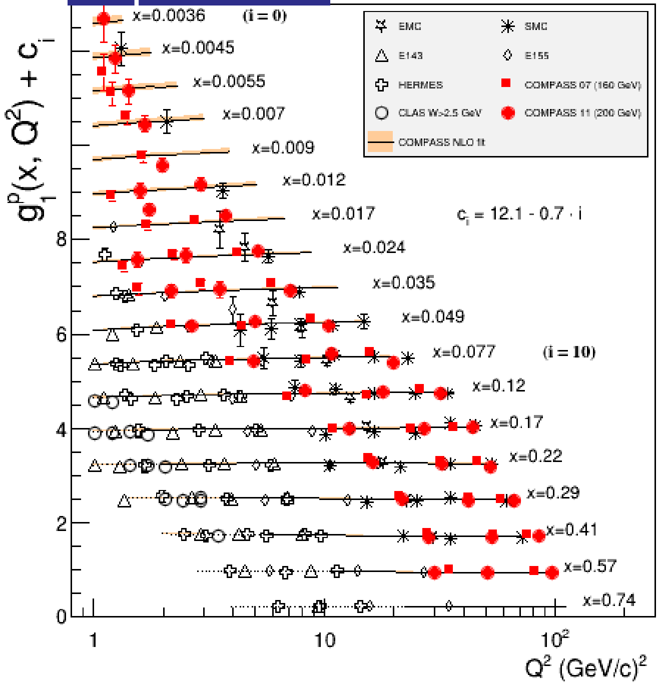
A very powerful tool access Δg, but limited by the present experimentally available phase space

QCD fits- World data on g_1^p and g_1^d

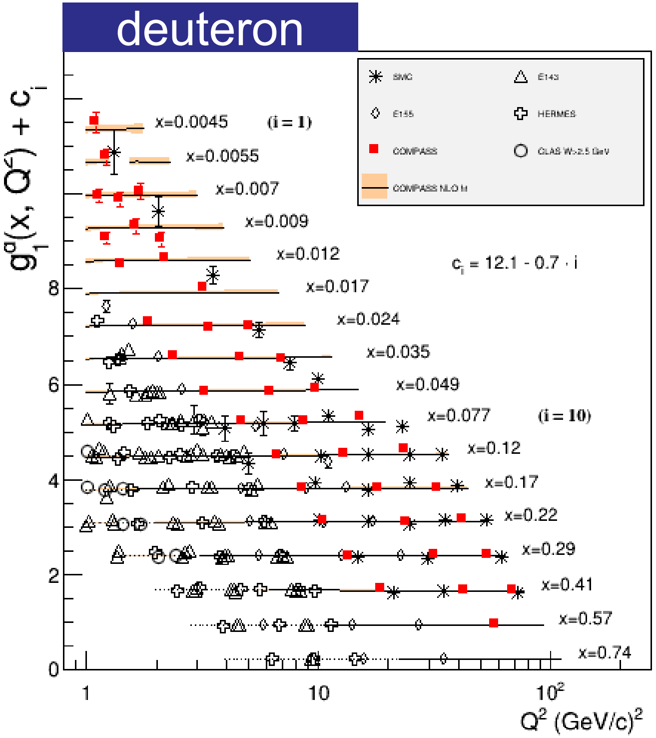
→ $g_1(x, Q^2)$ as input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta g(x)$

$$\boxed{\frac{dg_1}{d\ln Q^2} \propto -\Delta g(x, Q^2)}$$

proton



deuteron



x and Q^2 coverage not yet sufficient for precise Δg

Can be improved by constraining from pp data (as DSSV, NNPDF…)

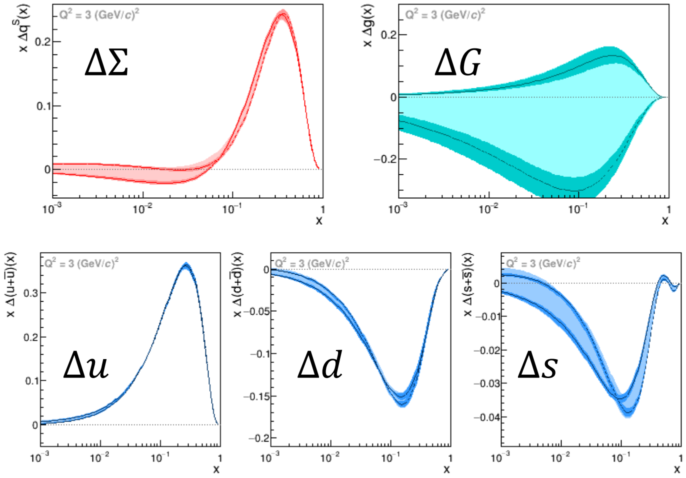
PLB753 (2016) 18

Another NLO pQCD fit to g_1 DIS world data

- Assumes functional forms for $\Delta\Sigma$, ΔG and Δq^{NS} and SU3 symmetry
- Use DGLAP equations.
- Fit g_1^p, g_1^d, g_1^n DIS world data

→ Quark spin contribution :

$\Delta\Sigma = 0.31 \pm 0.05$ at $Q^2 = 3\ (\mathrm{GeV}/c)^2$



$0.82 \leq \Delta U \leq 0.85$ $-0.45 \leq \Delta D \leq -0.42$ $-0.11 \leq \Delta S \leq -0.08$

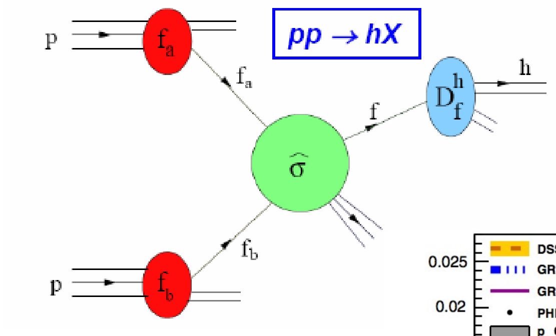
Uncertainties are dominated by the bad knowledge of the functional forms.

→ Gluon spin contribution: ΔG not well constrained, even the sign, using DIS only

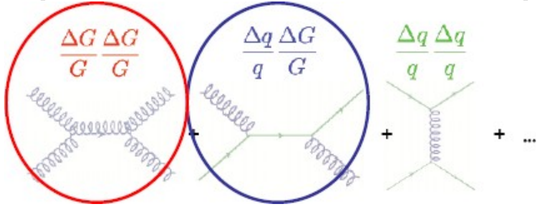
Solution with ΔG>0 agrees with result from DSSV++ using RHIC pp data

PLB 753 (2016) 18

Measurement of the ΔG at RHIC

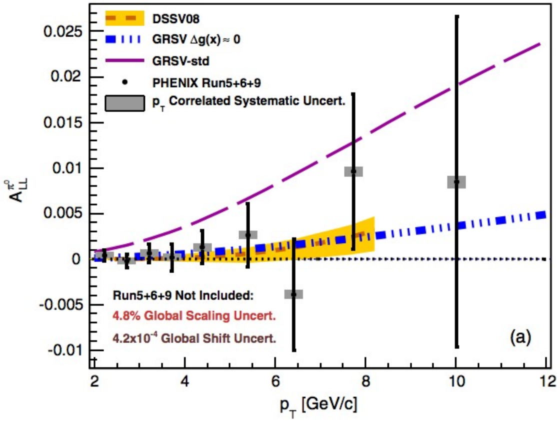


Dominates at low p_T Dominates at high p_T

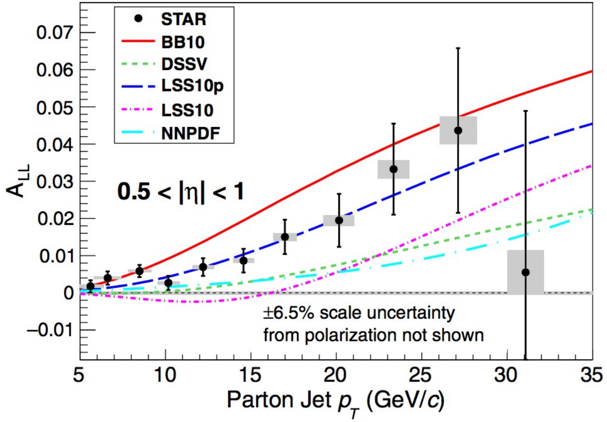


D. de Florian *et al*,
PRL 113 (2014) 012001

E. Nocera et al,
NPB 887 (2014) 276



Phys. Rev. D 90 (2014) 012007



Phys. Rev. Le]. 115 (2015) 092002

$$\int_{0.05}^{1} dx\, \Delta g(x, Q^2 = 10\ \mathrm{GeV}^2/c^2) = 0.20^{+0.6}_{-0.7}$$

DSSV++

$$\int_{0.05}^{0.2} dx\, \Delta g(x, Q^2 = 10\ \mathrm{GeV}^2/c^2) = 0.17 \pm 0.06$$

NNPDFpol1.1

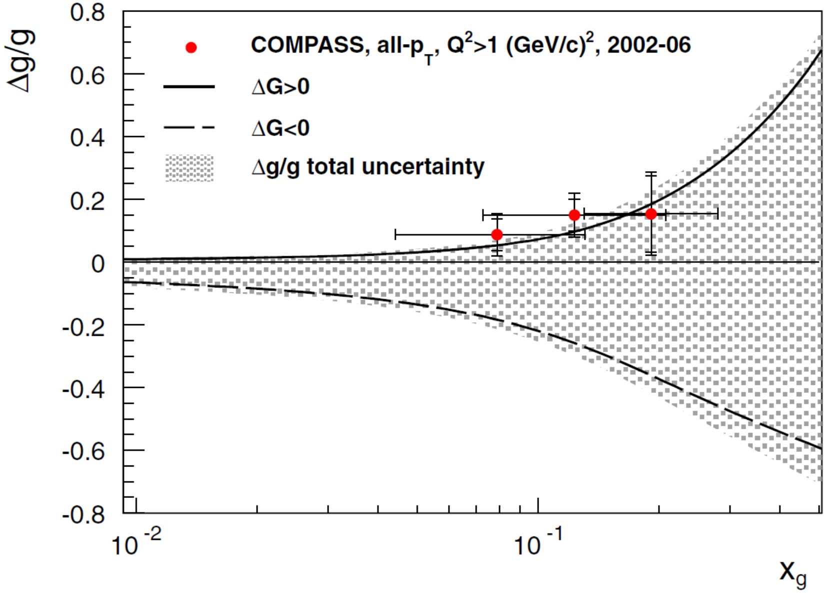
JAM15

$$\int_{0.001}^{0.8} dx\, \Delta g(x, Q^2 = 1\ \mathrm{GeV}^2/c^2) = 0.5 \pm 0.4$$

Gluon helicity $\Delta g/g$ from SIDIS

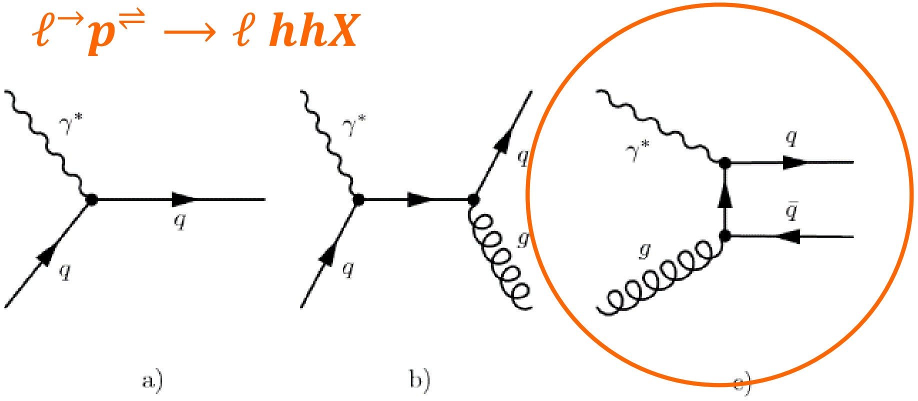
Extraction at LO:

$$\boxed{\Delta G/G\,(x=0.1) = 0.11 \pm 0.04 \pm 0.04}$$



EPJC 77 (2017) 209

$\ell^{\rightarrow} p^{\rightleftarrows} \longrightarrow \ell\, hhX$



Photon Gluon Fusion

Summary on nucleon SPIN

$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta u_v + \Delta q_s) + \Delta G + L_q + L_g$$

Quarks $\frac{1}{2}\Delta\Sigma \sim 0.15$ from $g_1$measurements and global analysis at NLO. Largest uncertainty on ΔΣ due to uncertainty on ΔG

Gluons $\Delta G \sim 0.2$ integrated between $0.05 < x < 0.2$: precise result from RHIC. ΔG/G positive at $x \sim 0.1$ (from data of γg fusion process, at LO). Low-x contribution to integral still unknown. Not enough constrain from g_1 global analysis at NLO.

Orbital momenta: $L_q + L_q = ?$ Ongoing studies of GPDs.

Promising results from lattice QCD calculations:

→ The main question raised in 'Nucleon spin crisis' is resolved:

- Quark spin represents a non zero fraction (0.3) of nucleon spin
  (measurements and lattice QCD calculations)
- The hypothesis of very large ΔG $(2 \text{ to } 3$, associated to $L \sim -2 \div -3)$ rejected

→ Puzzle still pending: share between ΔG and L

Semi Inclusive Deep Inelastic Scattering

- The semi inclusive deep inelastic scattering cross section for a hadron of type h of a given energy fraction z_h is written as:

$$\frac{d^3\sigma}{dxdydz_h} = \frac{2\pi\alpha^2}{Q^2}\left[\frac{(1+(1-y)^2)}{xy}F_2^h(x,z_h,Q^2) + \frac{2(1-y)}{y}F_L^h(x,z_h,Q^2)\right]$$

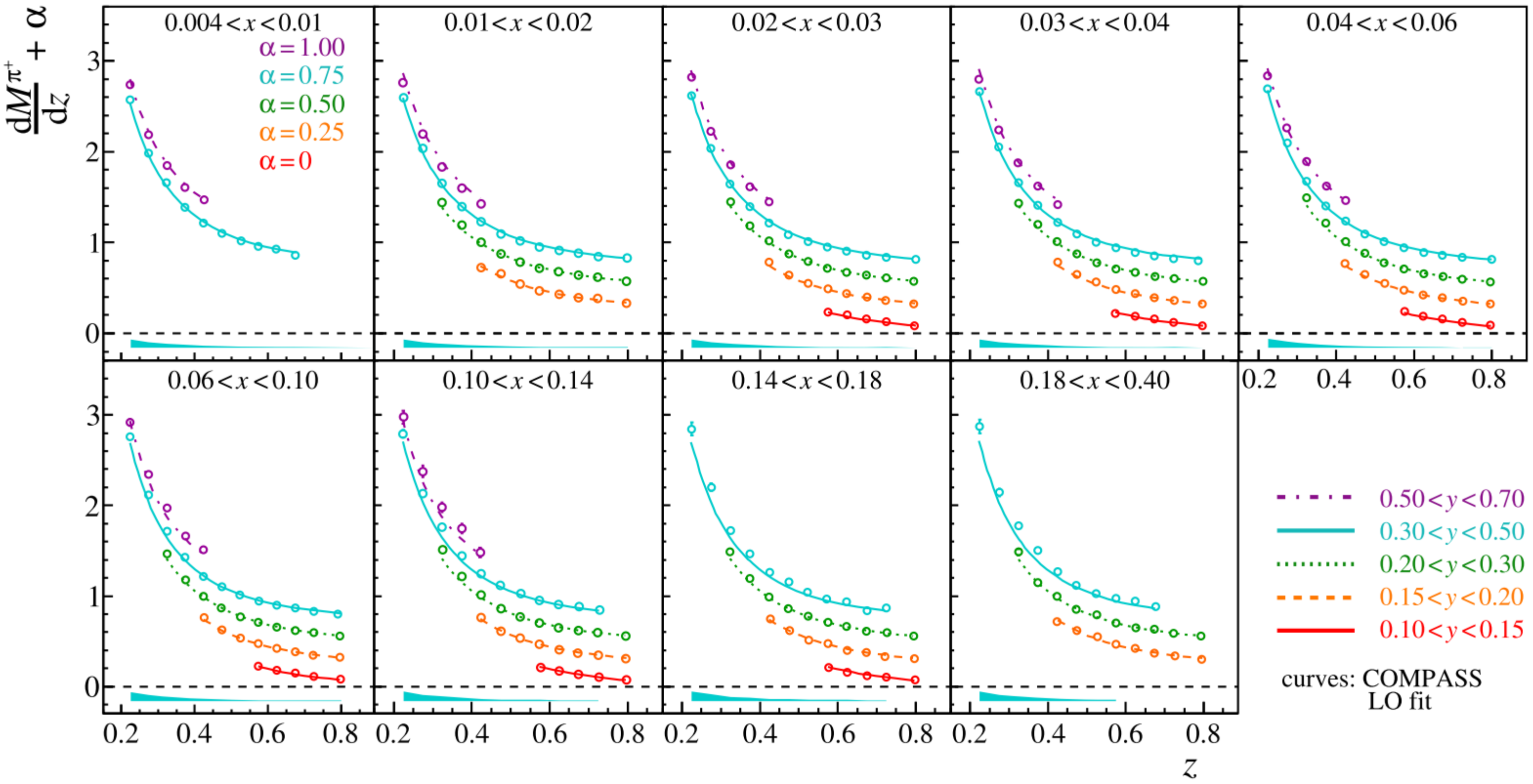
- Where the structure functions are:

$$\frac{F_2^h(x,z_h,Q^2)}{x} = \sum_{q,\bar{q}} e_q^2\left[f_1^q(x,Q^2)D_{h/q}(z;Q^2) + \frac{\alpha_s(Q^2)}{2\pi}(\text{QCD improved})\right]$$

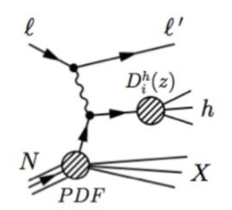
$$F_L^h(x,z_h,Q^2) = \sum_{q,\bar{q}} e_q^2\left[\frac{\alpha_s(Q^2)}{2\pi}(\text{QCD improved})\right]$$

Collinear Multiplicities

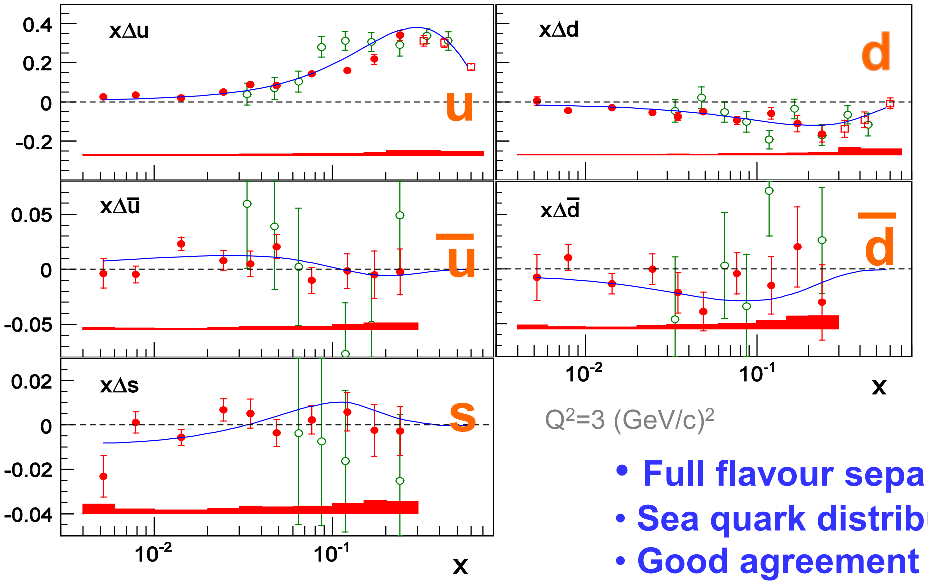
hep-ex/1604.02695



Quark helicities from semi-inclusive DIS



Leading order extraction of quark helicities from spin asymmetries:



- **COMPASS**

PLB693(2010)227, using DSS FFs

o **HERMES**

PRD71(2005)012003

___ DSSV at NLO

$$l^{\rightarrow} p^{\rightarrow} \rightarrow l\, h^{\pm} X$$

- **Full flavour separation → x~0.004**
- **Sea quark distributions ~ zero**
- **Good agreement with global fits**

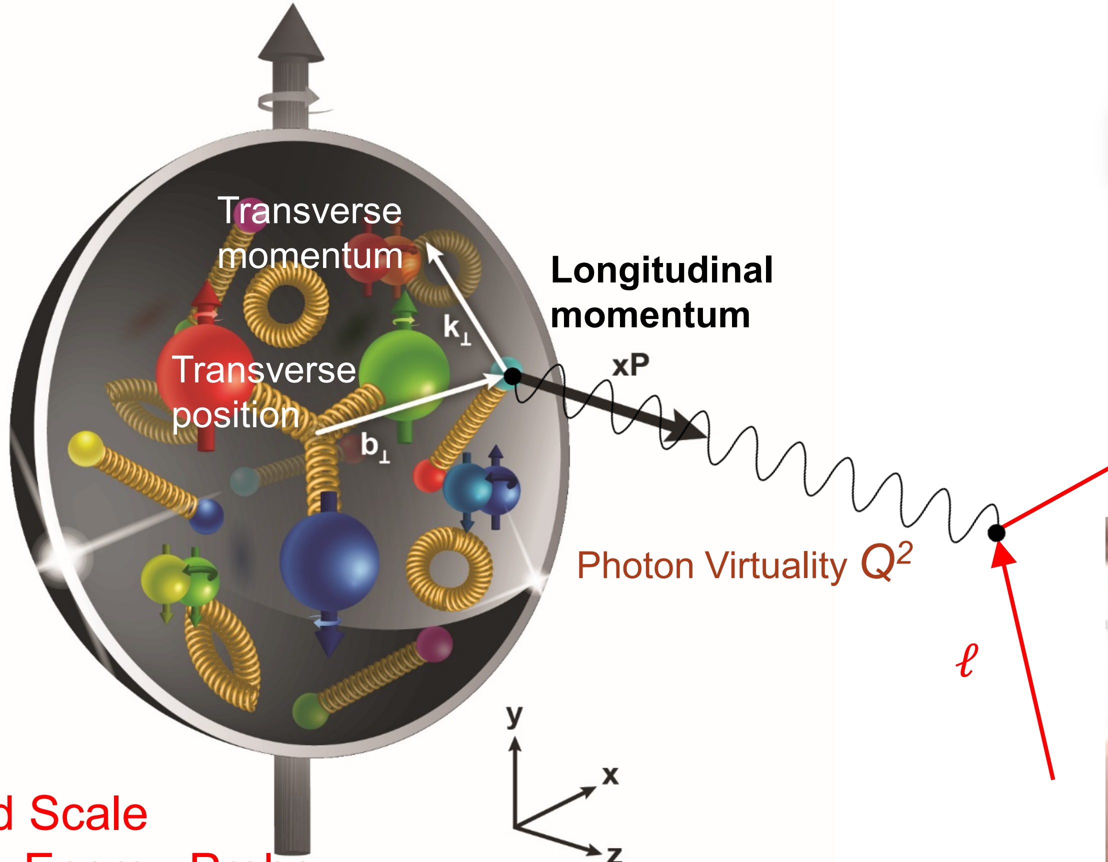
What about Δs? Integral is found negative from ***inclusive*** data, when imposing SU3 while here from ***semi-inclusive*** data, $x > \sim 0.005$ Δs is compatible with zero.

NB: - The extraction assumes quark Fragmentation Functions known (DSS here)

- No measurement at lower x

Transverse structure of the Nucleon

Confinement Scale

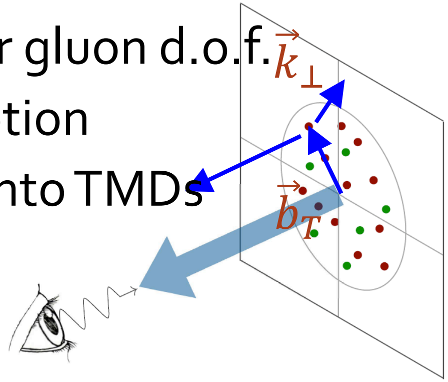


$$W_p^q\left(x,\vec{k}_\perp,\vec{b}_T\right)$$

Hard Scale
High Energy Probe

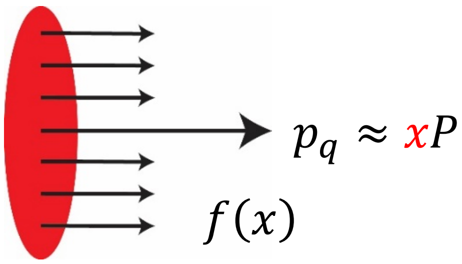
Confined parton motion in a hadron

- Scattering with a large momentum transfer
  - Momentum scale of the hard probe $Q \gg {}^{1}/_{R} \sim 1\ \mathrm{fm}^{-1} \sim \Lambda_{QCD}$
  - Combined motion $\sim {}^{1}/_{R}$ is too week to be sensitive to the hard probe
  - Collinear factorization – integrated into PDFs
- Scattering with multiple momentum scales observed
  - Two-scale observables (such as low P_{hT} SIDIS, low p_T Drell-Yan) $Q \gg q_T \sim {}^{1}/_{R} \sim \Lambda_{QCD} \sim 1\ \mathrm{fm}$
  - “Hard” scale Q localizes the probe to see the quark or gluon d.o.f.
  - “Soft” scale q_T could be sensitive to the confined motion
  - TMD factorization: the confined motion is encoded into TMDs

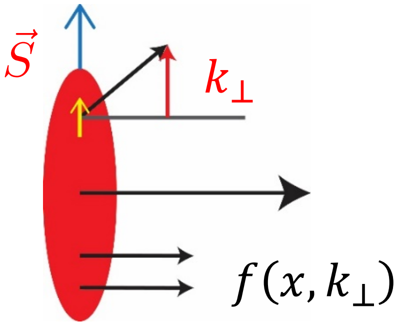


Unpolarised Transverse Momentum dependent PDFs

- When we consider the transverse momentum of the quark in the calculation of the cross section Transverse Momentum Dependent parton distribution (TMDs)



Longitudinal motion only



Longitudinal + transverse motion

- The unpolarised number density of the quarks gains a dependence from the intrinsic transverse momentum $k_\perp$

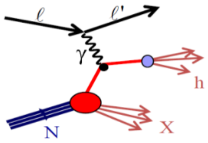
$$f_1^q(x, k_\perp)$$

- New parton densities arise: the Boer-Mulders functions $h_1^{\perp,q}(x, k_\perp)$, describing the correlation between the intrinsic quark transverse momentum and the spin of the quark in an unpolarised nucleon

$$f_{q\uparrow}(x, k_\perp, \vec{s}) = f_1^q(x, k_\perp) - \frac{1}{M} h_1^{\perp,q}(x, k_\perp) \vec{s} \cdot \left(\hat{p} \times \vec{k}_\perp\right)$$

Accessing TMD PDFs and FFs

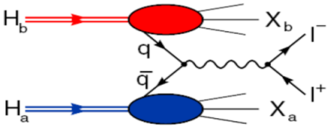
- TMD factorization works in the domain where there are two observed momenta in the process, such as SIDIS, DY, e^+e^-. $Q \gg q_T$: Q is large to ensure the use of pQCD, q_T is much smaller such that it is sensitive to parton's transverse momentum
- SIDIS off polarized p, d, n targets



HERMES
COMPASS
JLab
future: ***EIC***

$$\sigma^{\ell p\to\ell' hX} \sim q(x) \otimes \hat{\sigma}^{\gamma q\to q} \otimes D_q^h(z)$$

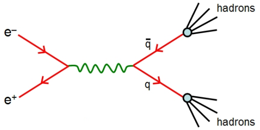
- polarised Drell-Yan



COMPASS
RHIC
FNAL
future: ***FAIR, JPark, NICA***

$$\sigma^{hp\to\mu\mu} \sim \bar{q}_h(x_1) \otimes q_p(x_2) \otimes \hat{\sigma}^{\bar{q}q\to\mu\mu}(\hat{s})$$

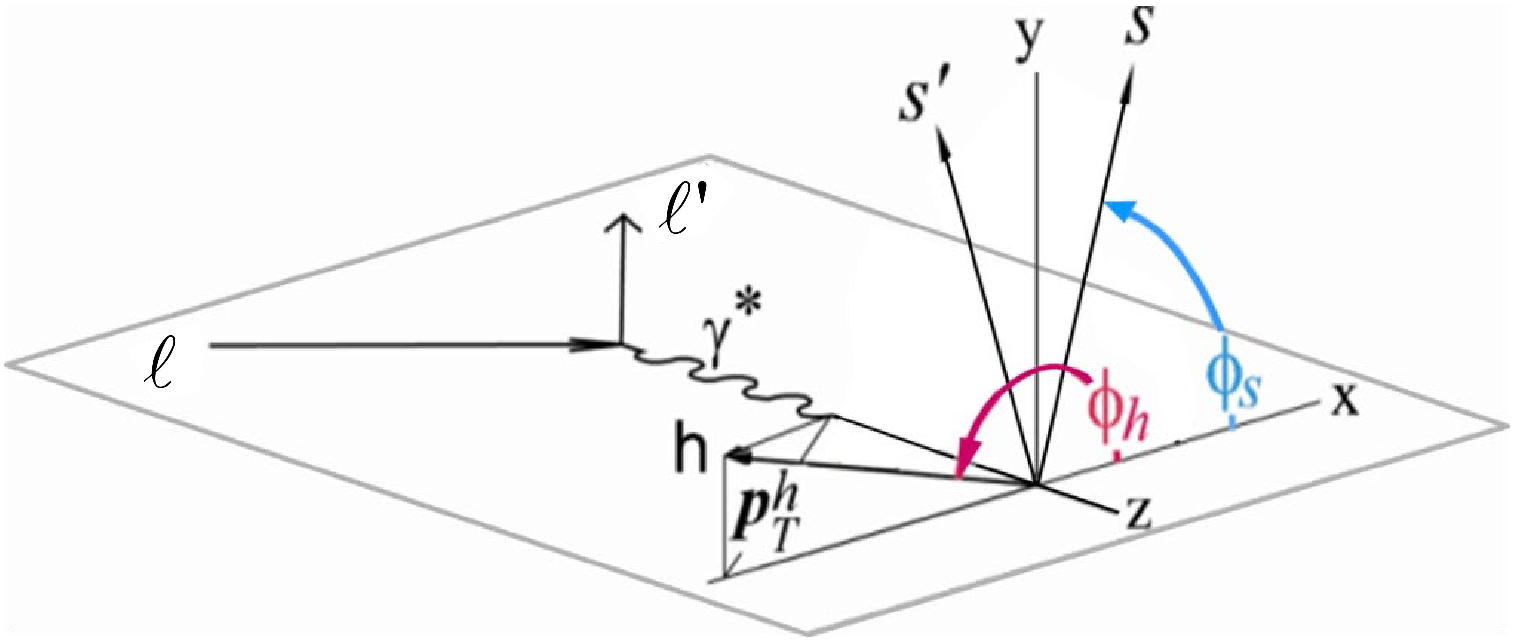
- $e^+e^- \to h_1h_2$



BaBar
Belle
Bes III

$$\sigma^{e^+e^-\to h_1h_2} \sim \hat{\sigma}^{\ell\ell\to\bar{q}q}(\hat{s}) \otimes D_q^{h_1}(z_1) \otimes D_q^{h_2}(z_2)$$

Azimuthal asymmetries in SIDIS



We look at our events in the Gamma Nucleon System (GNS), i.e. we need a perfectly reconstructed lepton kinematic.

Semi Inclusive DIS full Cross Section

14 independent azimuthal modulations

$$\frac{d^5\sigma}{dxdydzdP_{hT}^2d\phi_h}$$

$$= \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon\cos 2\phi_h\, F_{UU}^{\cos 2\phi_h}$$

$$+ \lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\, F_{LU}^{\sin\phi_h} + S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon\sin 2\phi_h\, F_{UL}^{\sin 2\phi_h}\right]$$

$$+ \lambda_e S_\parallel\left[\sqrt{1-\varepsilon^2}F_{LL} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\, F_{LL}^{\cos\phi_h}\right]$$

$$+ |\vec{S}_\perp|\left[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\right.$$

SIDIS Experiments

SIDIS Experiment must:

- Have large acceptances on all the relevant variables x, Q^2, z, P_{hT}, ϕ
- Use different targets (p, d, n) and identify hadrons to allow flavor separation
- Be ad different energies for to cover PDFs from the valence region down to small-x
- Large luminosity to allow multidimensional results needed by the complexity of TMDs

- **The polarized lepton-nucleon collider is a mandatory tool to reach the level of ordinary PDF**

SIDIS access to TMDs

Factorization (Collins & Soper, Ji, Ma, Yuan,
Qiu & Vogelsang, Collins & Metz...)

$$\sigma(\ell p \rightarrow \ell' h X) \sim \mathrm{TMDs} \otimes \hat{\sigma}^{\gamma q \rightarrow q} \otimes \mathrm{TMD-FFs}$$

TMDs $(x, \vec{k}_\perp)$

TMD-FFs $(x, \vec{p}_\perp)$

chiral odd

T odd

Nucleon polarization

Parton polarization	U	T	L
U	f_1	$f_{1T}^\perp$	
T	$h_1^\perp$	$h_1, h_{1T}^\perp$	$h_{1L}^\perp$
L		g_{1T}	g_{1L}

Hadron polarization

Parton polarization	U	T	L
U	D_1	$D_{1T}^\perp$	
T	$H_1^\perp$	H_1 , $H_{1T}^\perp$	$H_{1T}^\perp$
L		G_{1T}	G_{1L}

- NOT directly accessible
- Their extractions require measurements of x-sections and asymmetries in **a large kinematic domain of** x, Q^2, z, P_{hT}

TMD evolution:

- QCD evolution of TMDs in Fourier space (solution of equation)

$$F(x,b;Q) \approx C \otimes F(x,c/b^{*}) \exp\left\{-\int_{c/b^{*}}^{Q_f} \frac{d\mu}{d}\left(A \ln\frac{Q_f^2}{\mu^2} + B\right)\right\} \times \exp\left[-S_{\text{non-pert}}(b,Q)\right]$$

Evolution of longitudinal/ collinear part

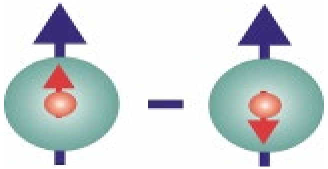
Evolution of transverse part (Sudakov form factor)

Non-perturbative part has to be fitted to experimental data
The key ingredient is spin-independent

- Polarized scattering data comes as ratio: e.g. $A_{UT}^{\sin(\phi_h-\phi_s)} = F_{UT}^{\sin(\phi_h-\phi_s)}/F_{UU}$
- Unpolarised data is very important to constrain/extract the key ingredient for the non-perturbative part

Transversity PDF

$h_1^q(x) = q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x)$ with $q = u_V, d_v$ and quarks/antiquarks of the sea



Describes quark with spin parallel to the nucleon spin in a transversely polarized nucleon

- is chiral-odd: decouples from inclusive DIS
- probes the relativistic nature of quark dynamics: in NR limit, boost and rotations commute and we should have $h_1^q(x) = g_1^q(x)$
- no contribution from the gluons → simple Q^2 evolution
- Positivity constrain, i.e.: Soffer bound [Soffer, PRL 74 (1995)] $2\left|h_1^q(x)\right| \leq f_1^q(x) + \Delta q(x)$
- first moments: tensor charge $g_T^q(Q^2) = \int_0^1 dx \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right]$

Transversity

is chiral-odd:

observable effects are given only by the product of h_1^q (x) and an other chiral-odd function

can be measured in SIDIS on a transversely polarized target via "quark polarimetry"

$\ell N^{\uparrow} \rightarrow \ell' \, h \, X$

"Collins" asymmetry

"Collins" Fragmentation Function

$\ell N^{\uparrow} \rightarrow \ell' \, h \, h \, X$

"two-hadron" asymmetry

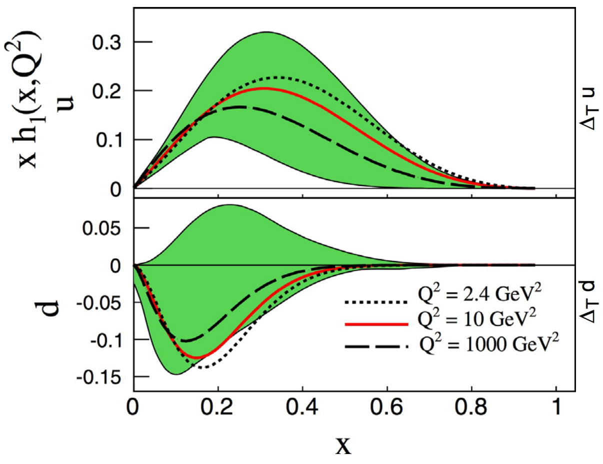
"Interference" Fragmentation Function

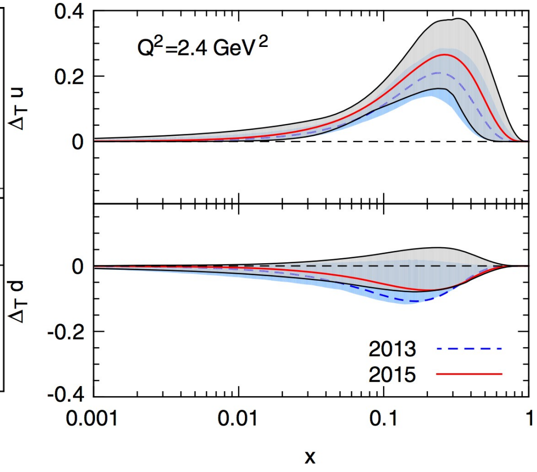
$\ell N^{\uparrow} \rightarrow \ell' \, \Lambda \, X$

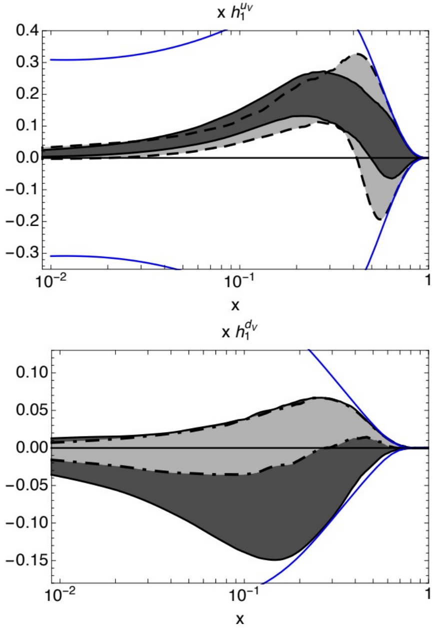
Λ polarization

Fragmentation Function of q↑→Λ

Global Analysis: Transversity







Z.-B. Kang et al., Phys. Rev. D 93, 014009 (2016).

M. Anselmino et al., Phys. Rev. D 92, 114023 (2015).

M. Radici and A. Bacchetta, arXiv: 1802.05212[hep-ph]

The Collins Fragmentation Function $H_1^\perp$

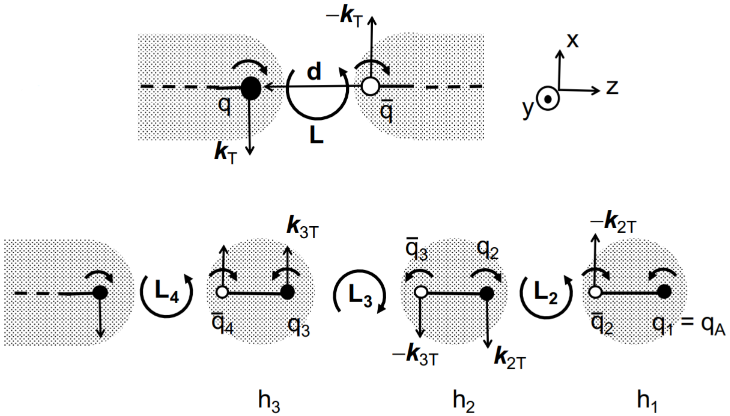
- Fragmentation (or hadronization) is the nonperturbative process that brings quarks and gluons to dress into observable hadrons. Fragmentation functions (FFs) describe the probability that a hadron h is produced in the fragmentation process of a quark q, taking away a fraction of the quark momentum.
- What about the quark spin? The fragmentation of a transversely polarized quark in an unpolarised hadron is described by:

$$D_{h/q^\uparrow}(z, p_\perp) = D_{h/q}(z, p_\perp) + \frac{\left(\hat{k} \times \vec{p}_\perp\right) \cdot \vec{S}_{qT}}{z m_h} H_1^\perp(z, p_\perp)$$

Where $\hat{k}$ is the direction of the fragmenting quark and $\vec{S}_{qT}$ is it's spin projection in the transverse plane.

${}^{3}P_{0}$; a model for the Collins FF $H_1^\perp$

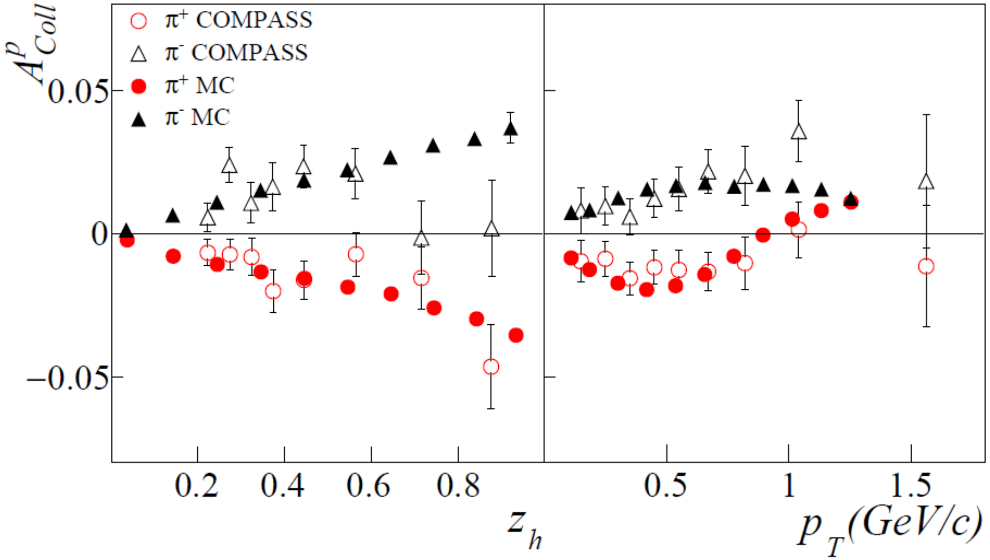
- A model by X. Artru for the Collins effect is based on the ${}^{3}P_{0}$ mechanism applied to the string fragmentation [Single spin asymmetry in inclusive pion production, Collins effect and the string model, X. Artru, J. Czyzewski, H. Yabuki, Z.Phys. C 73 (1997) 527].
- In this model, the $q\bar{q}$ pairs at each string breaking are produced in a state that has total orbital angular momentum $L = 1$ and total spin $S = 1$ opposite to the orbital angular momentum such that $J = L + S = 0$.
- For a struck quark q_A with spin along $\hat{y}$, the first $q_2\bar{q}_2$ at the string breaking will be polarized along $-\hat{y}$, while the angular momentum $\vec{L}_2$ is along $\hat{y}$**.** If the initial quark q_A is u then the ${}^{3}P_{0}$ mechanism produces opposite effects for positive and for negative pions



A^{p}_{Coll} on proton and ${}^{3}P_{0}$ model for FF

Albi Kerbizi @ DSPIN17 http://theor.jinr.ru/~spin/2017/

Phys. Rev. D 97, 074010 (2018)/**arXiv:1802.00962**



- The full points are Monte Carlo data, scaled by $\lambda \sim \langle h_1^u / f_1^u \rangle \sim 0.055$
- Agreement with the measured Collins asymmetry is quite satisfactory

Sivers Asymmetry

Sivers: correlates nucleon spin & quark transverse momentum k_T /T-ODD

at LO:

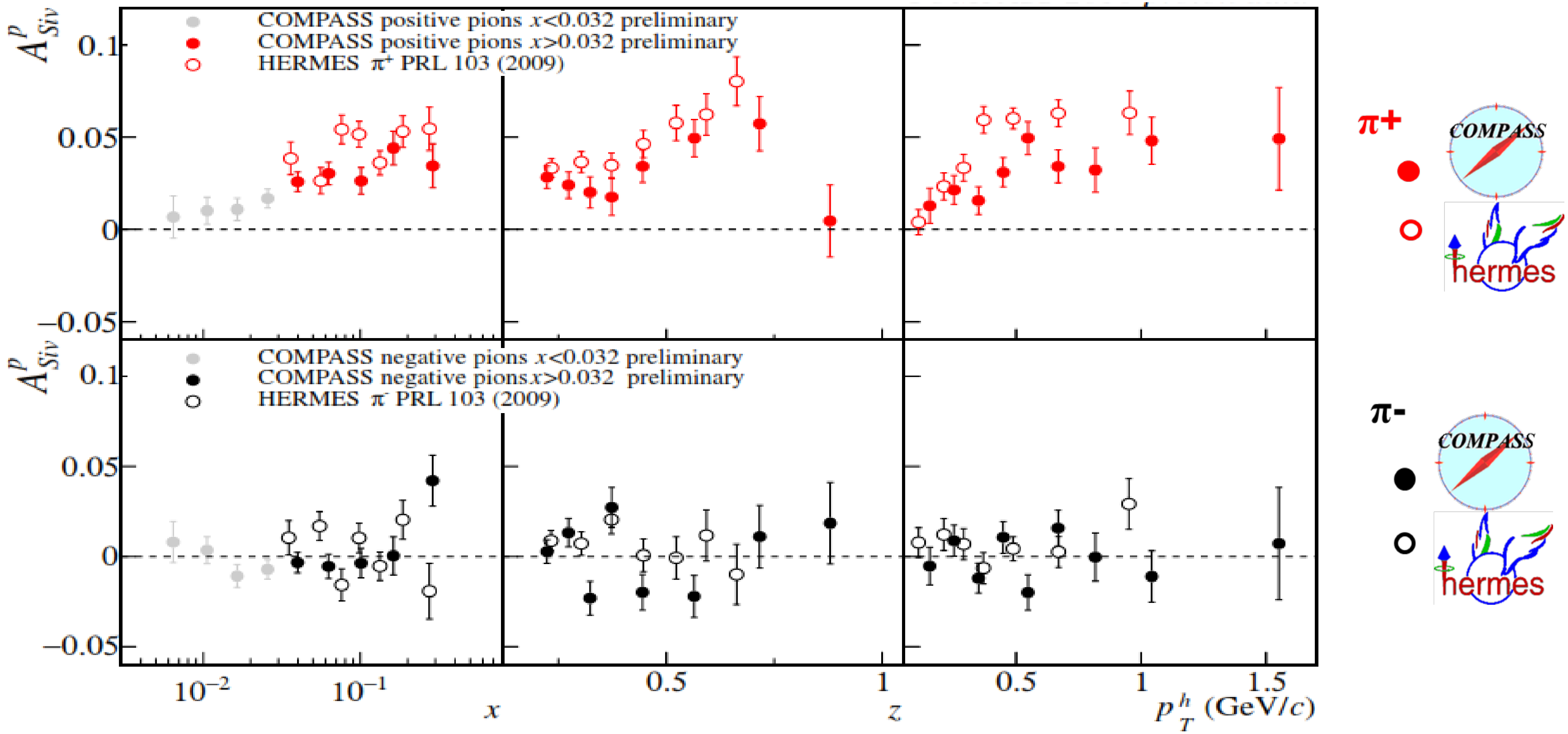
$$A_{Siv} = \frac{\sum_q e_q^2 f_{1Tq}^{\perp} \otimes D_q^h}{\sum_q e_q^2 q \otimes D_q^h}$$

$$\boxed{\mu p^{\uparrow} \rightarrow \mu X h^{\pm}}$$

The Sivers PDF	
1992	Sivers proposes $f_{1T}^{\perp}$
1993	J. Collins proofs $f_{1T}^{\perp} = 0$ for T invariance
2002	S. Brodsky, Hwang and Schmidt demonstrate that $f_{1Tq}^{\perp}$ may be $\neq 0$ due to FSI
2002	J. Collins shows that $(f_{1T}^{\perp})_{DY} = -(f_{1T}^{\perp})_{SIDIS}$
2004	HERMES on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$
2004	COMPASS on d: $A_{Siv}^{\pi^+} = 0$ and $A_{Siv}^{\pi^-} = 0$
2008	COMPASS on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$

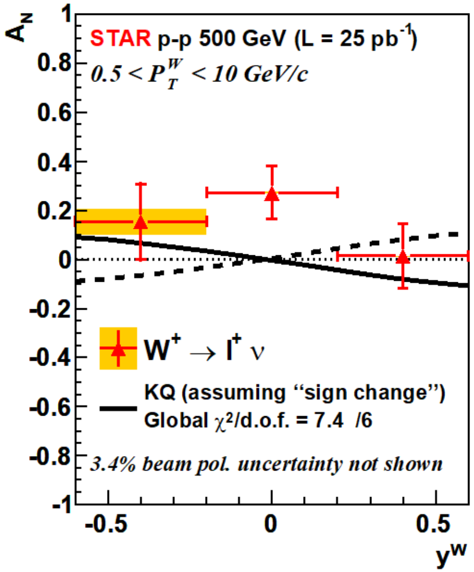
Sivers asymmetry on p

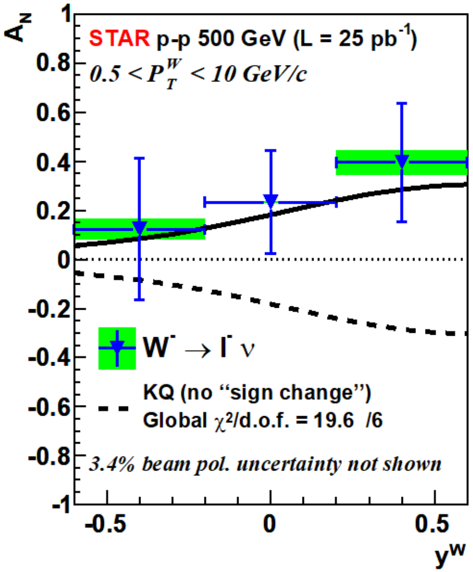
charged pions (and kaons), HERMES and COMPASS



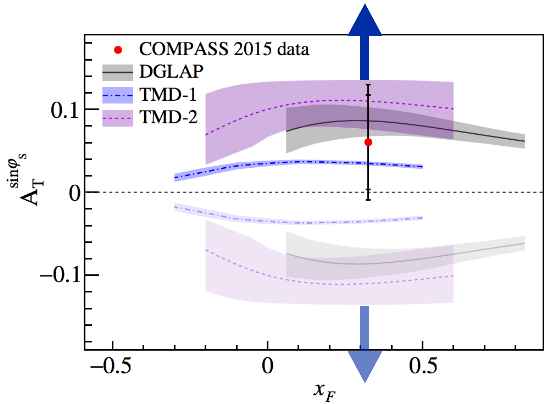
Transverse Spin Asymmetry in Drell-Yan

190 GeV/c π^- beam, transversely polarized NH_3 target





$$f_{1T,\,\mathrm{DY}}^{\perp} = -f_{1T,\,\mathrm{SIDIS}}^{\perp}$$



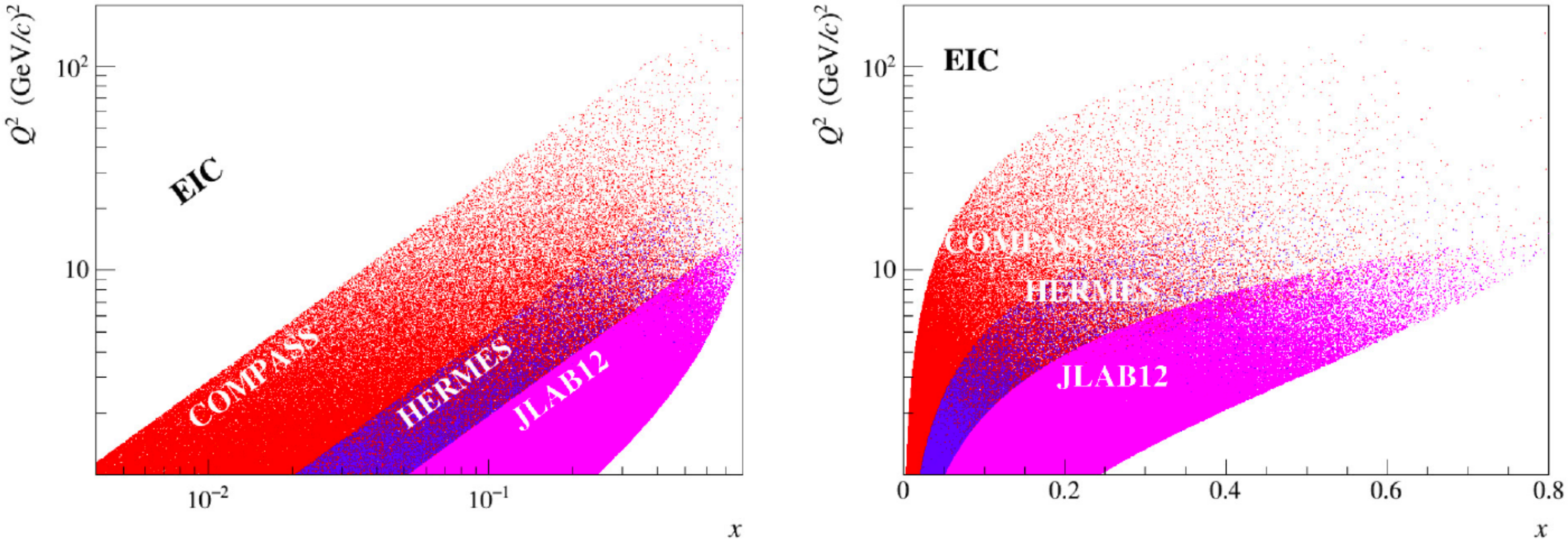
PRL119, 112002 (2017).

To conclude

- Many important results both for the spin structure and the internal 3D structure of the nucleon have been provided by experiments at HERA, CERN, RHIC and JLAB; very partial coverage here.
- Before the EIC, JLAB will map the valence region with high precision; COMPASS and RHIC will complete their programs
- THE EIC will allow us TO MOVE FROM EXPLORATION TO PRECISION in the KNOWLEDGE of the internal structure of the NUCLEON

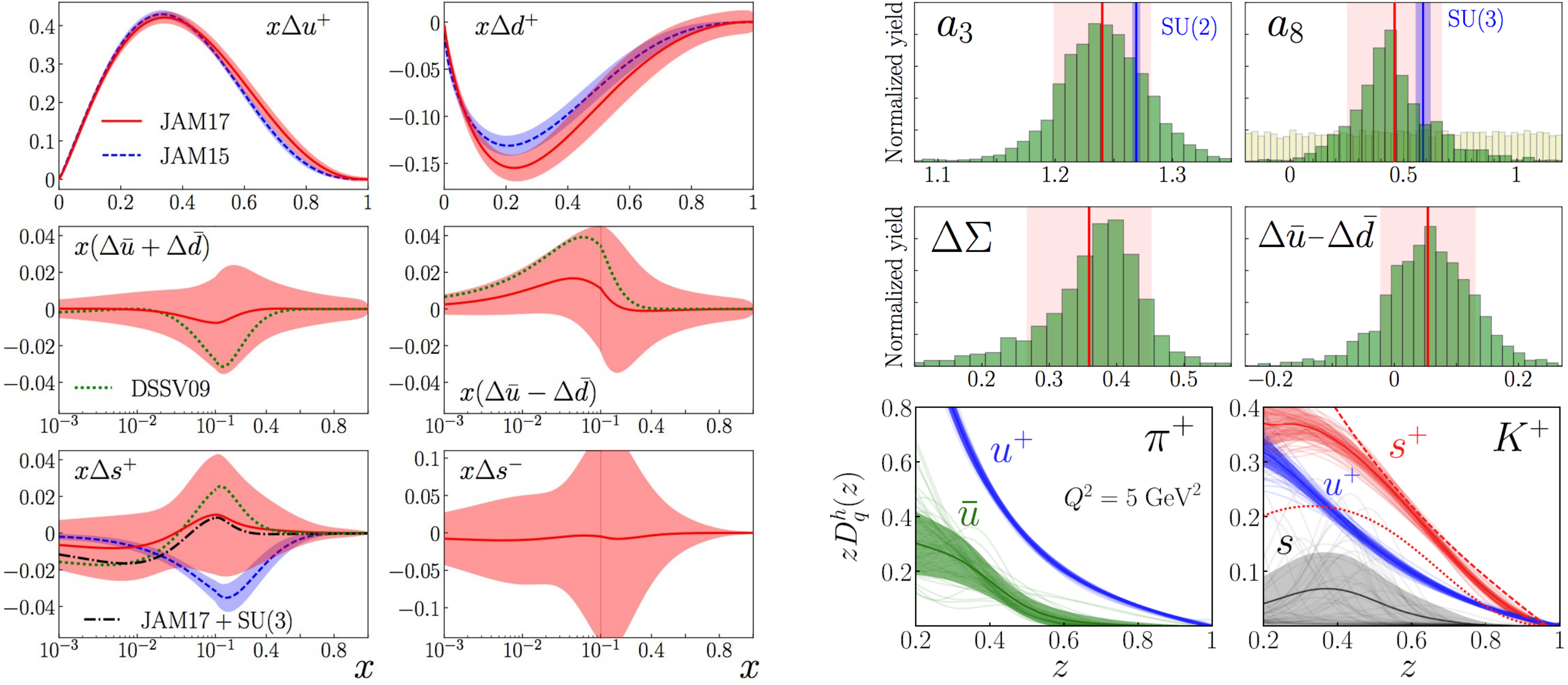
Thank you

Kinematic coverage



The spin content of the proton: where we stand

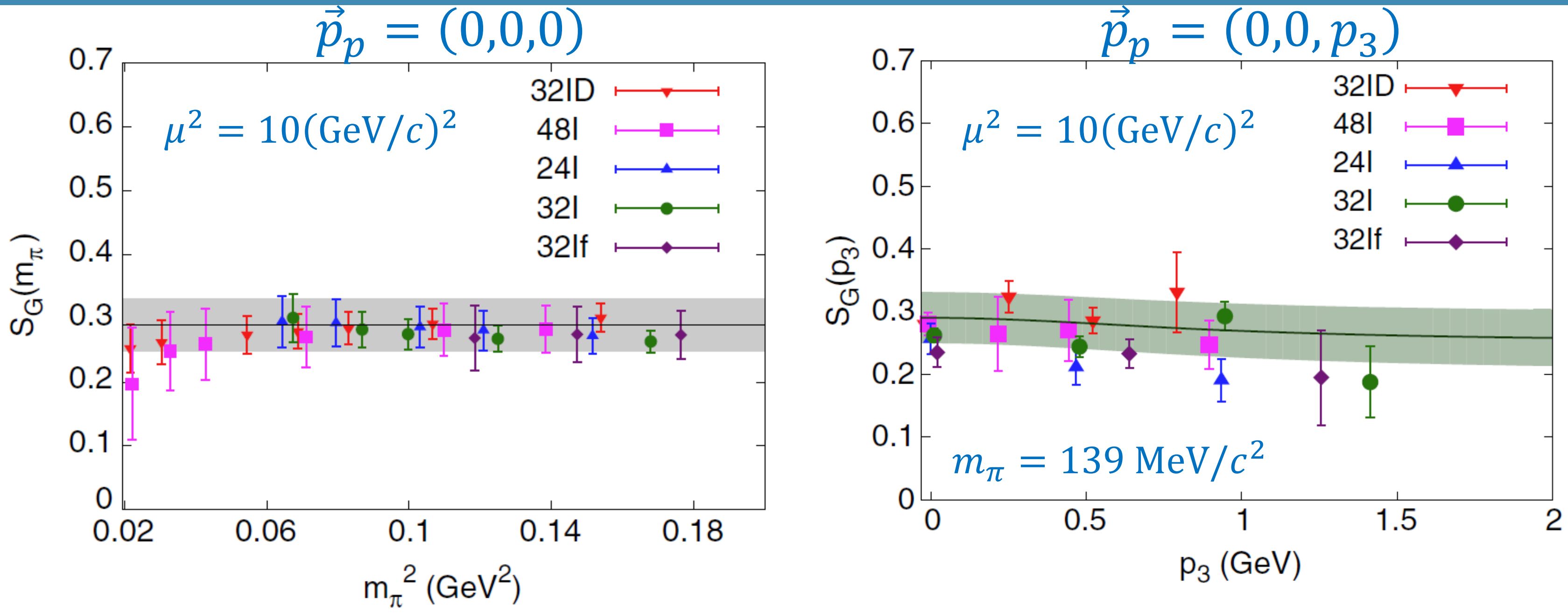
- Global analysis of the spin dependent distribution functions



J.J. Ethier et al. (JAM Collaboration), Phys. Rev. Lett. 119, 132001 (2017).

$$\Delta\Sigma = +0.36 \pm 0.09$$
$$\Delta s^+ = -0.03 \pm 0.10$$

Gluon Spin From Lattice QCD

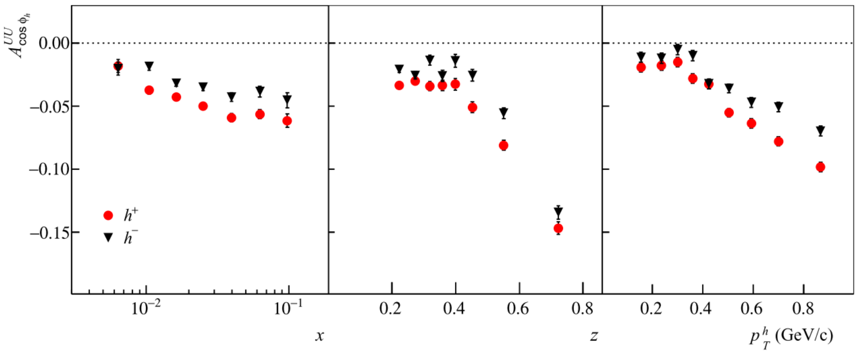


$$\Delta G(\mu^2 = 10(\text{GeV}/c)^2) \approx S_G(\mu^2 = 10(\text{GeV}/c)^2, |p| \to \infty) = 0.251 \pm 0.047 \pm 0.016$$

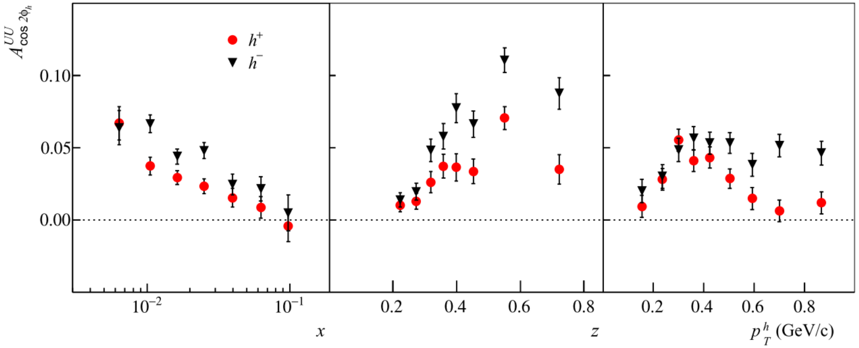
$\overline{\text{MS}}$ scheme

Y.-B. Yang et al. (χQCD Collaboration), Phys. Rev. Lett. 118, 102001 (2017).

Cahn $A_{UU}^{\cos\phi}$ and Boer-Mulders $A_{UU}^{\cos 2\phi}$ modulation



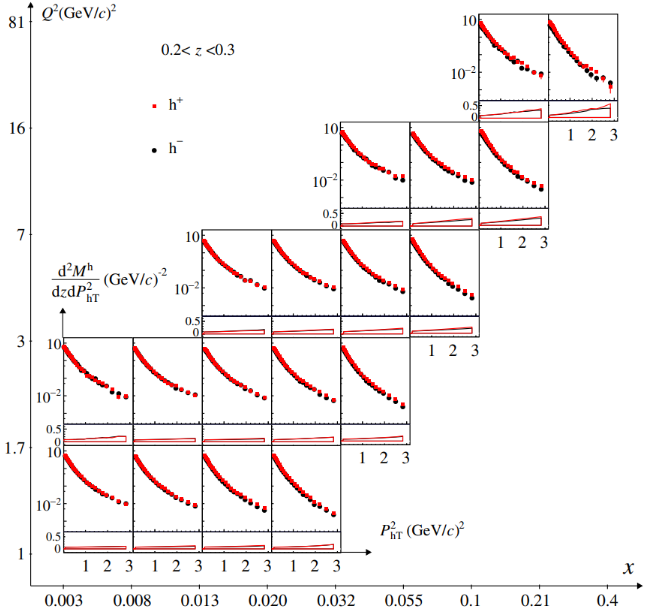
$$A_{UU}^{\cos\phi}(x,z,P_{hT}^2;\ Q^2) \propto \frac{1}{Q}\sum_q e_q^2\left[f_1^q \otimes D_1^{q\to h} - h_1^{\perp,q}\otimes H_1^{\perp,q\to h}\right]$$

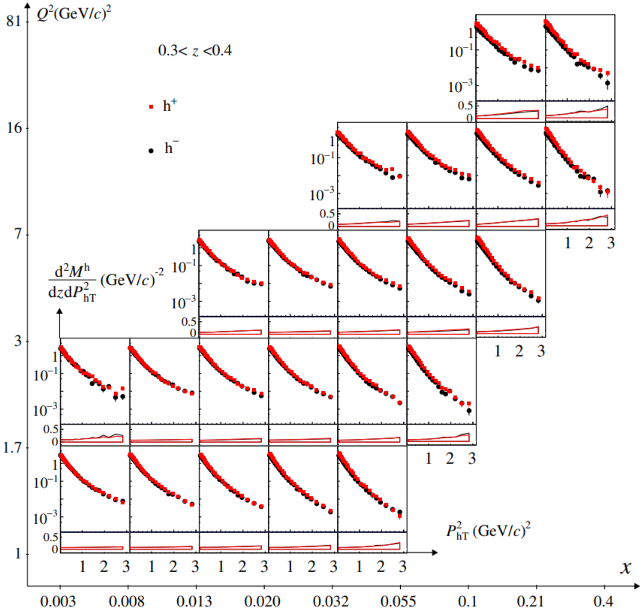


$$A_{UU}^{\cos 2\phi}(x,z,P_{hT}^2;\ Q^2) = -x\sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \frac{2\left(\hat{h}\cdot\vec{k}_\perp\right)\left(\hat{h}\cdot\vec{k}_\perp\right) - \vec{k}_\perp\cdot\vec{p}_\perp}{M m_h}\ h_1^{\perp,q}(x,k_\perp^2;Q^2)H_1^{\perp,q\to h}(z,p_\perp^2;Q^2)$$

P_{hT} dependent Multiplicities M_{UU}^{h}

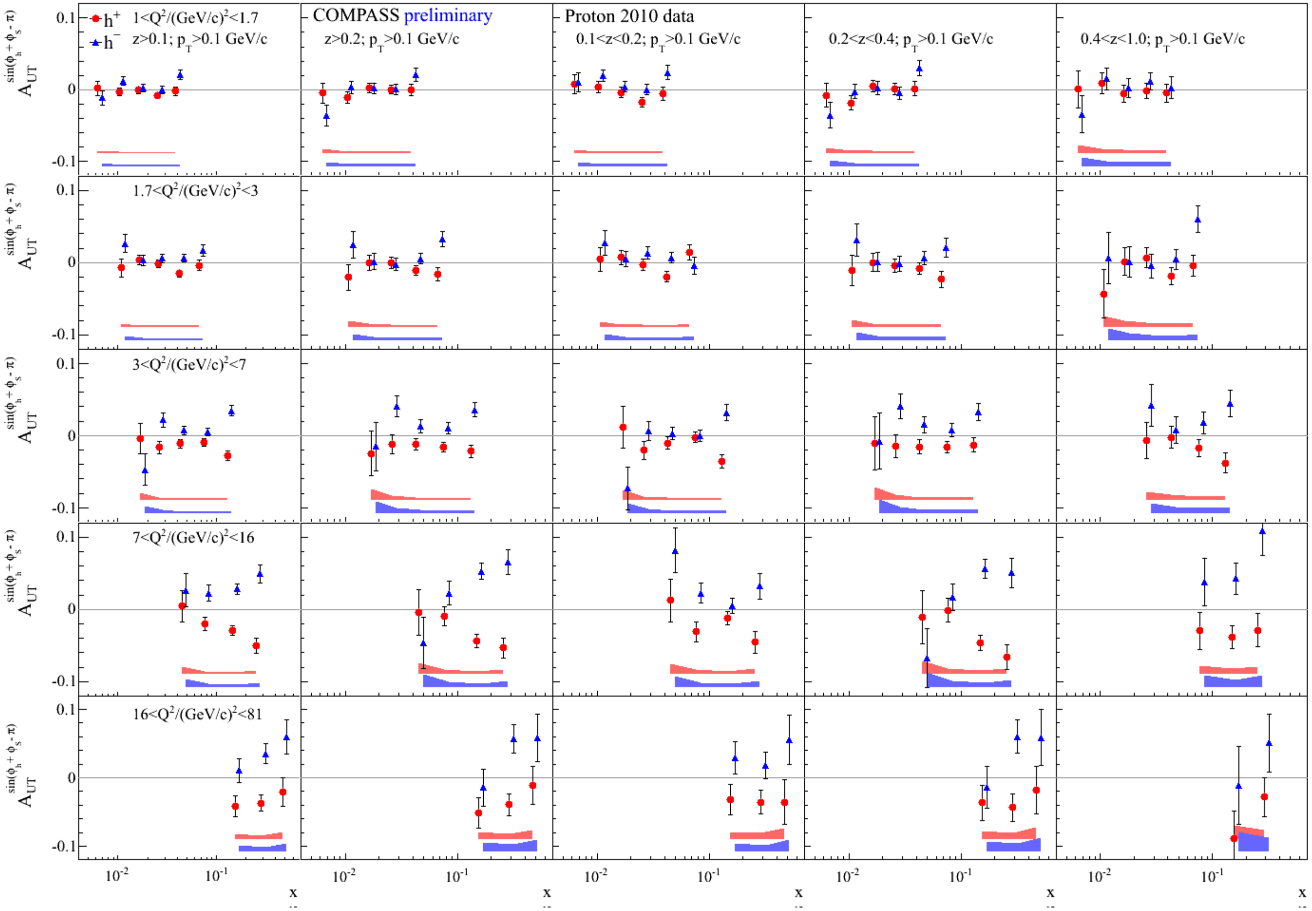
$$M^h(x,z,P_{hT}^2;Q^2) = \frac{d^5\sigma^h/dxdQ^2dzdP_{hT}^2}{d^2\sigma^{DIS}/dxdQ^2} \sim \underline{F_{UU}^h(x,z,P_{hT}^2;\ Q^2)}$$

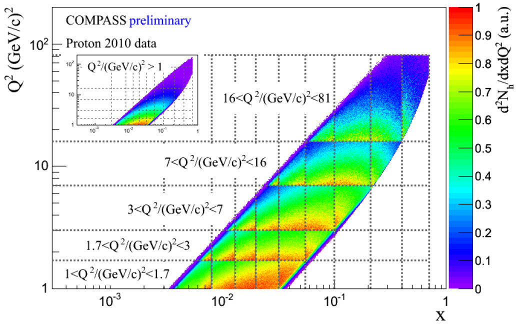




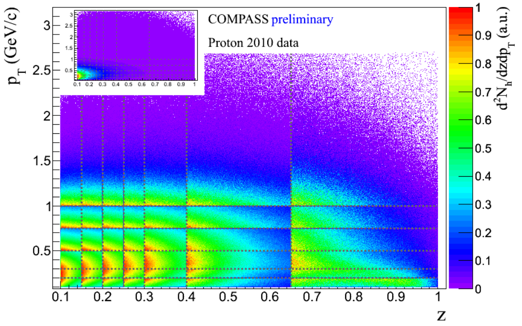
Collins asymmetry on proton. Multidimensional

Extraction of TSAs with a Multi-D $(x{:}\,Q^2{:}\,z{:}\,p_T)$ approach

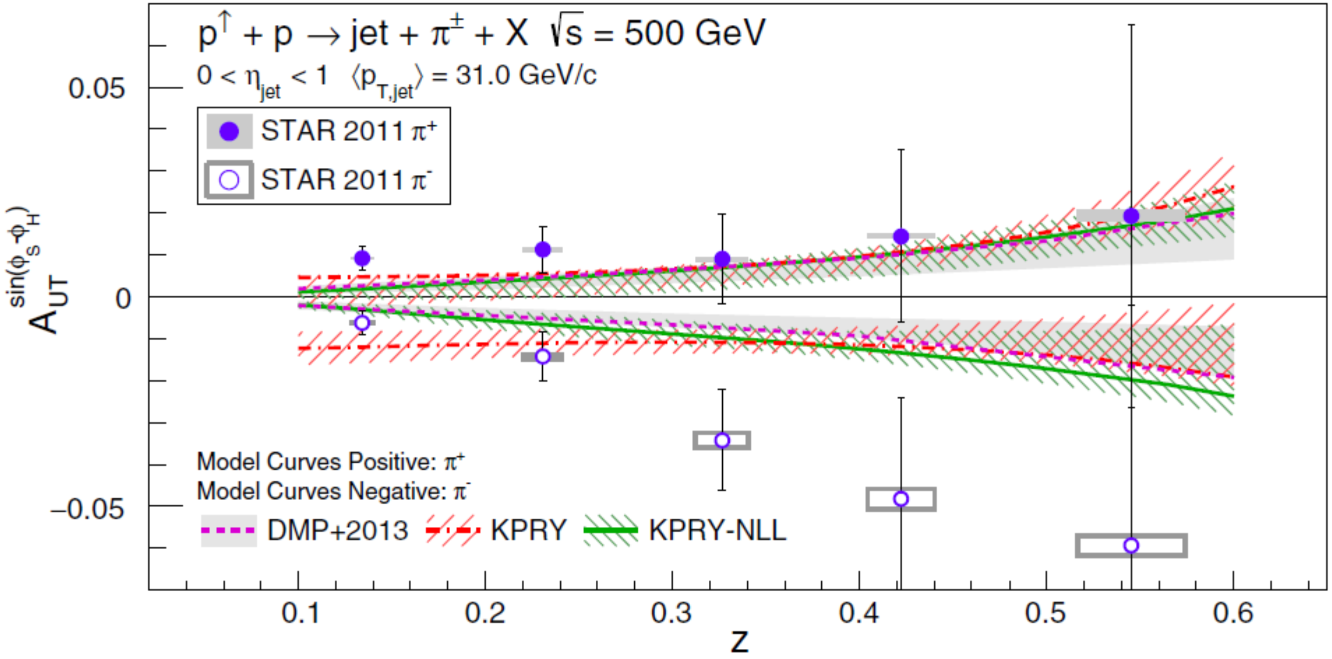




One dense plot out of many



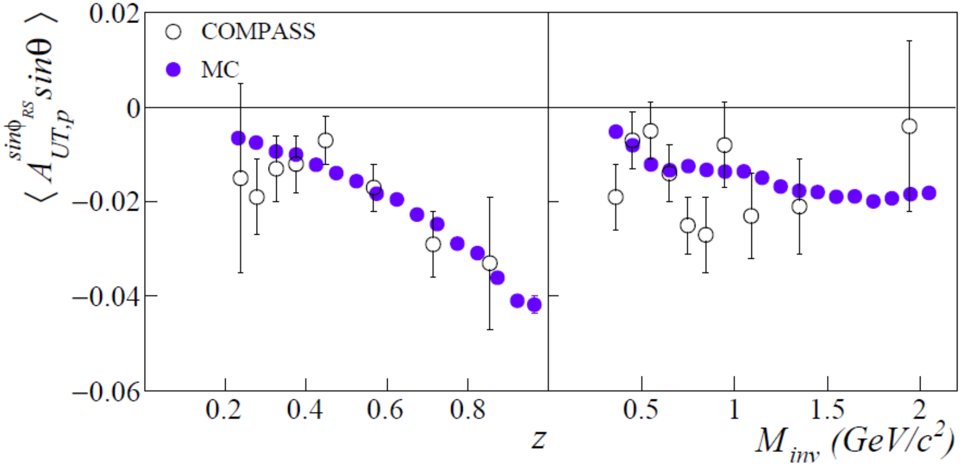
TSA of inclusive jets and $\pi^{\pm}$ within jets from STAR

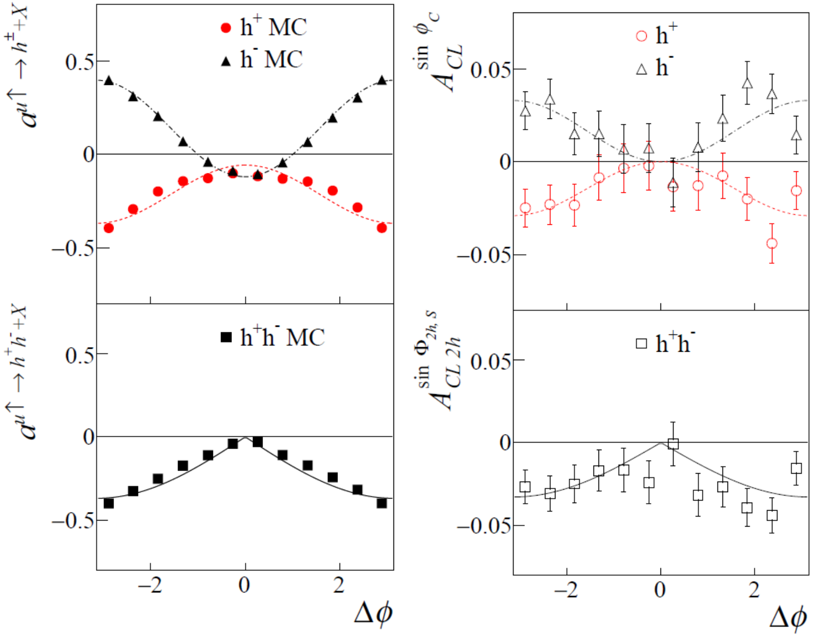


COLLINS asymmetries: general agreement between data and predictions from SIDIS consistent with TMD factorization and universality of the Collins function

2h asymmetries on p and $^3P_0$ model for FF

$$A_{UT}^{\sin(\phi_R+\phi_S-\pi)} = \frac{\sum_q e_q^2 h_1^q(x) H_{q\to h_1h_2}^{\measuredangle}\left(z,\mathcal{M}_{h_1h_2}^2\right)}{\sum_q e_q^2 q(x) D_q^{h_1h_2}\left(z,\mathcal{M}_{h_1h_2}^2\right)}$$





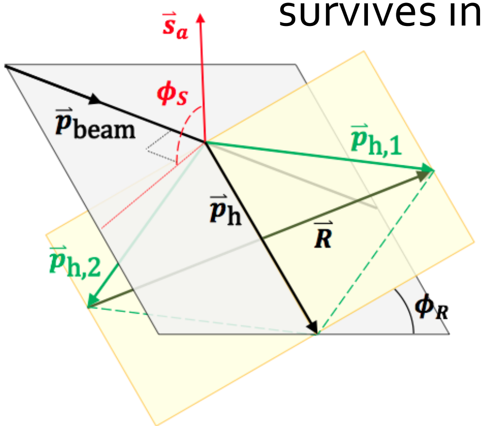
$a_P^{u\uparrow\longrightarrow h^+h^-X} = \langle\sin(\phi_R+\phi_S-\pi)\rangle$ and $\vec{R} = \frac{z_2\vec{P}_{h1}-z_1\vec{P}_{h2}}{z_1+z_2}$ and as before $\lambda\sim\langle h_1^u/f_1^u\rangle\sim 0.055$

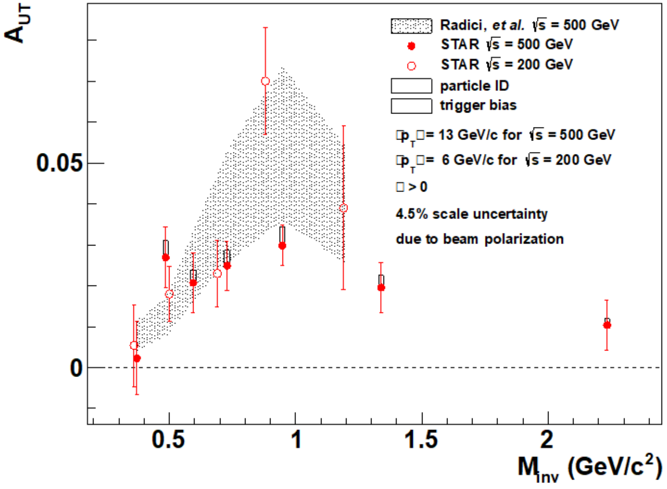
Interference fragmentation functions in pp

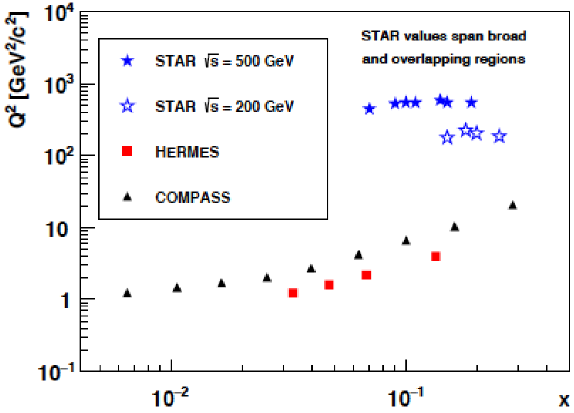
$p^{\uparrow}p \longrightarrow \pi^{+}\pi^{-}X \rightarrow h_1 \cdot H_1^{\sphericalangle}$

survives in collinear framework

$$A_{UT}\sin\left(\phi_{RS}\right) = \frac{1}{Pol}\,\frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

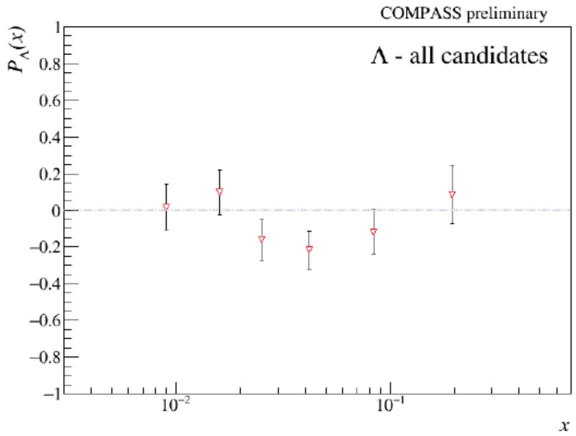


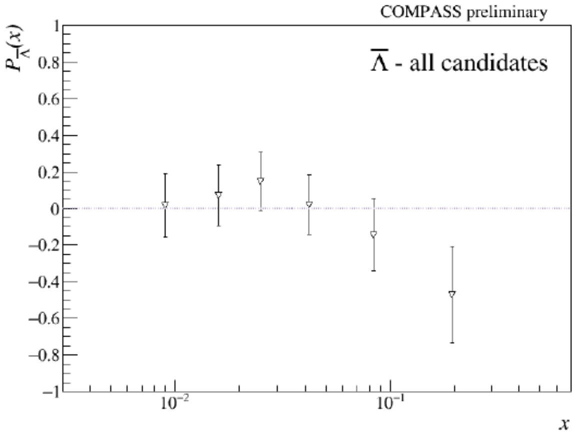




- ❑ Significant di-hadron asymmetries both at √s=200GeV and √s=500GeV (arXiv:1710.10215)
- ❑ Increasing with p_T
- ❑ Access to transversity with a collinear observable

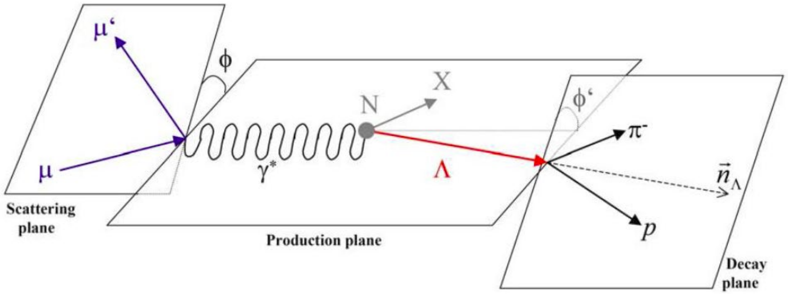
Λ transverse spin transfer from COMPASS



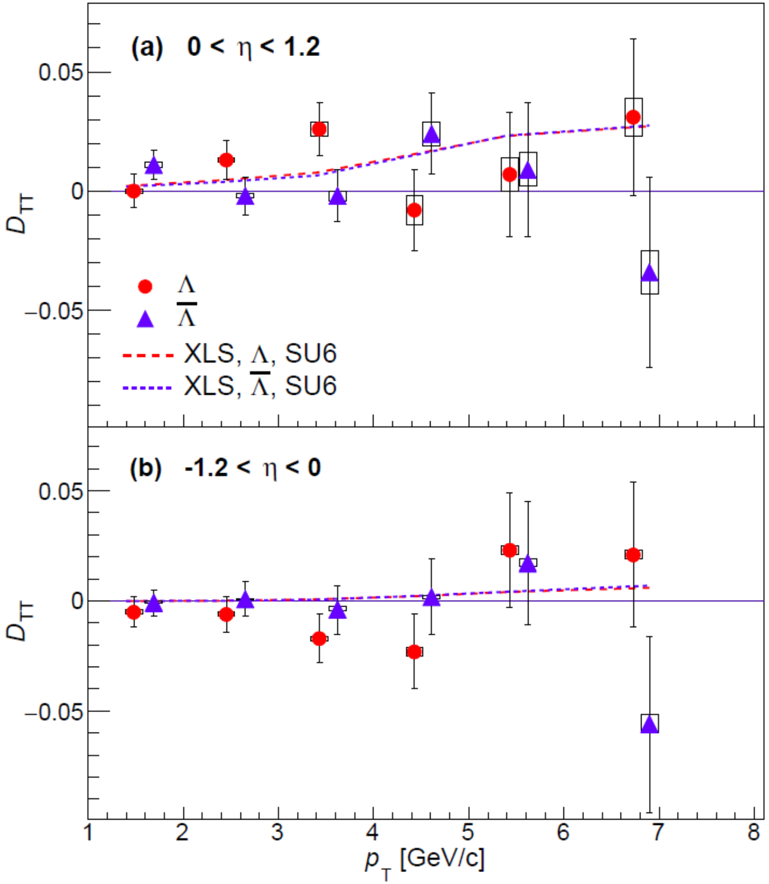


$$P_{\Lambda(\bar{\Lambda})}(x,z) = \frac{\sum_q e_q^2 h_1^q(x)\, H_1^{\Lambda(\bar{\Lambda})}(z)}{\sum_q e_q^2 f_1^q(x)\, D_1^{\Lambda(\bar{\Lambda})}(z)}$$

$$\frac{dN}{d\cos\theta^*} \propto A\left(1 + \alpha P_{\Lambda(\bar{\Lambda})} \cos\theta^*\right)$$



Λ transverse spin transfer from STAR



$$D_{TT} = \frac{d\sigma^{p^{\uparrow}p\to\Lambda^{\uparrow}X} - d\sigma^{p^{\uparrow}p\to\Lambda^{\downarrow}X}}{d\sigma^{p^{\uparrow}p\to\Lambda^{\uparrow}X} + d\sigma^{p^{\uparrow}p\to\Lambda^{\downarrow}X}}$$

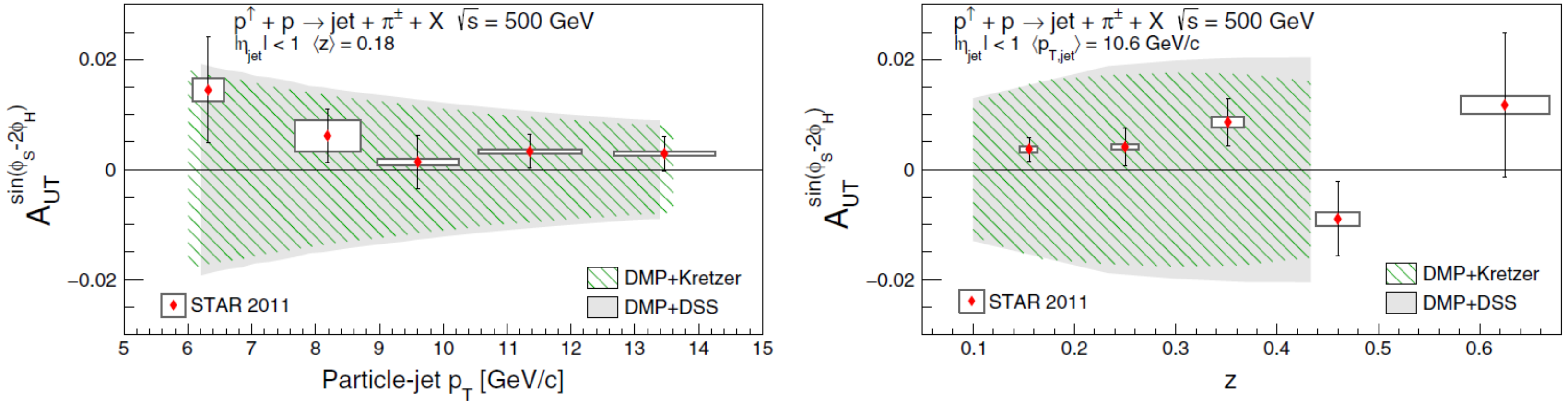
$$D_{TT} = -\frac{1}{\alpha P_B\langle\cos\theta^*\rangle}\frac{\sqrt{N^{\uparrow}_{\cos\theta^*}N^{\downarrow}_{-\cos\theta^*}} - \sqrt{N^{\downarrow}_{\cos\theta^*}N^{\uparrow}_{-\cos\theta^*}}}{\sqrt{N^{\uparrow}_{\cos\theta^*}N^{\downarrow}_{-\cos\theta^*}} + \sqrt{N^{\downarrow}_{\cos\theta^*}N^{\uparrow}_{-\cos\theta^*}}}$$

$$\frac{dN}{d\cos\theta^*} \propto A\left(1 + \alpha P_{\Lambda(\bar{\Lambda})}\cos\theta^*\right)$$

About 60% of Λ or $\bar{\Lambda}$ are not primary particles, but are from heavier hyperons decay.

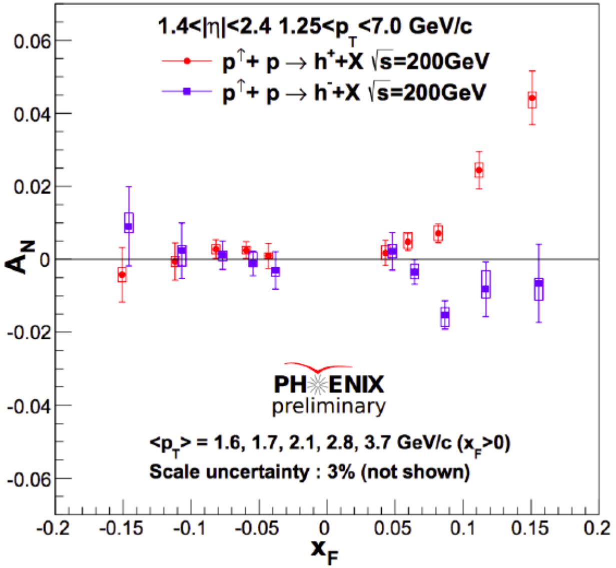
$$D_{TT}(\Lambda) = +0.031 \pm 0.033_{stat} \pm 0.008_{sys}$$
$$D_{TT}(\bar{\Lambda}) = -0.034 \pm 0.040_{stat} \pm 0.009_{sys}$$

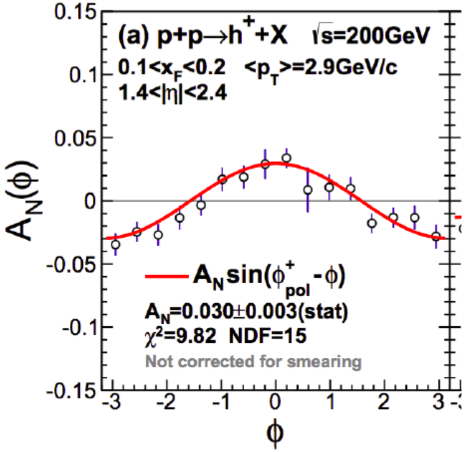
TSA of inclusive jets and $\pi^{\pm}$ within jets from STAR

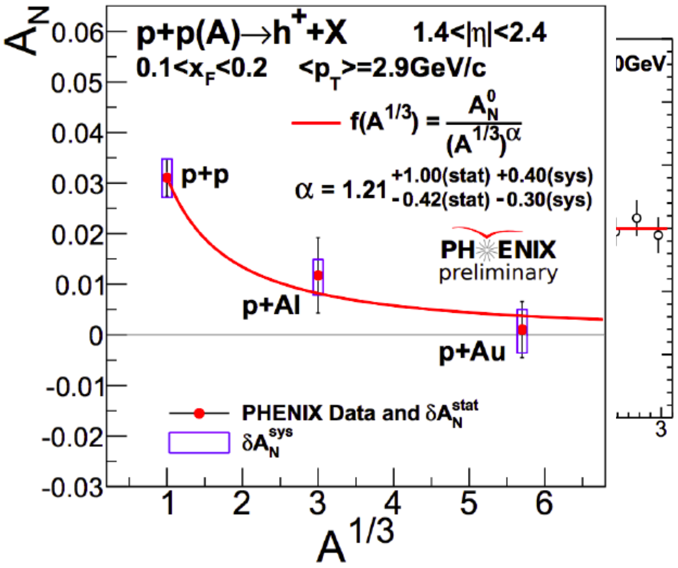


COLLINS LIKE asymmetries: sensitive to linearly polarized gluons in a polarized proton, are found to be small and provide the first constraints on model calculations.

TSSA A_N studies at PHENIX





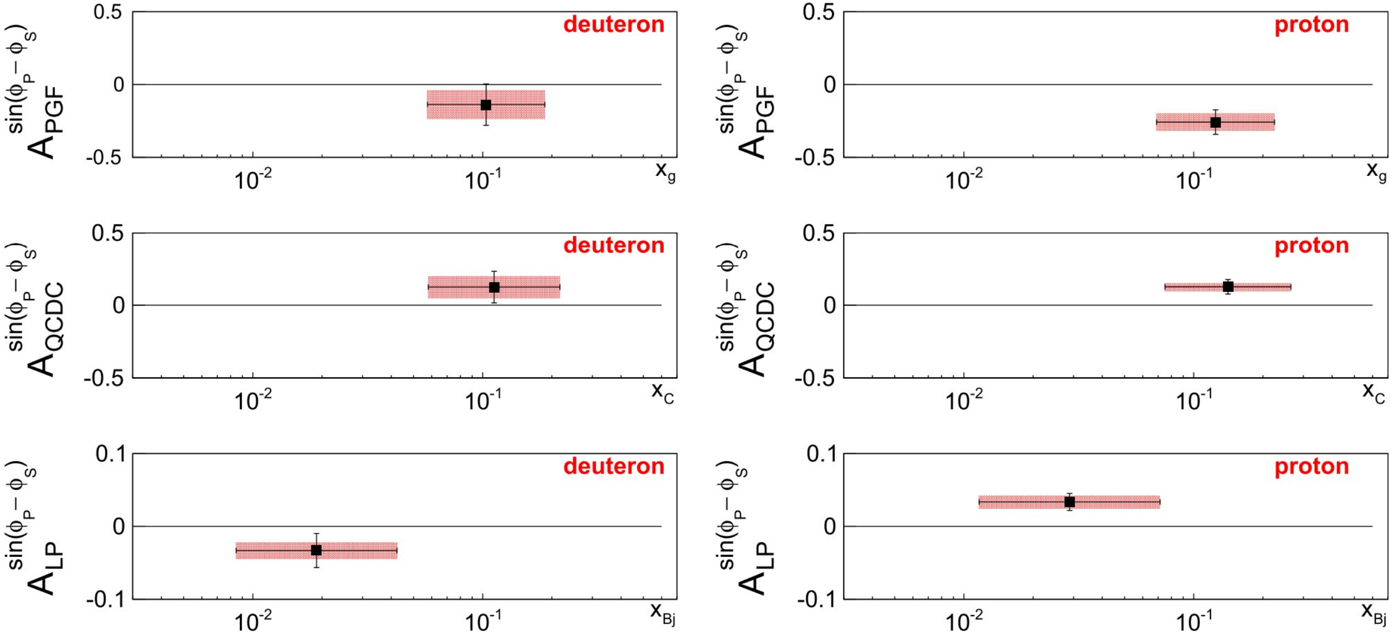


Described by twist 3 collinear approach (1 scale, high p_T)

Suppresion in $p^{\uparrow}A$ expected by gluon saturation ($\propto A^{1/3}$)

Hybrid approach: twist-3 and CGC

Sivers Asymmetry for Gluon from SIDIS



$$A_{PGF}^{Siv,d} = -0.14 \pm 0.15(\text{stat.}) \pm 0.10(\text{syst.})$$

$$\langle x_g \rangle = 0.13$$

$$A_{PGF}^{Siv,p} = -0.26 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.})$$

$$\langle x_g \rangle = 0.15$$

C. Adolph et al. (COMPASS Collaboration), Phys. Lett. B 772, 854 (2017).