High-energy spin physics at fixed-target experiments

Fabienne KUNNE
CEA /IRFU Saclay, France

Highlights on measurements of:

- **Nucleon spin,** **Gluon and quark helicities: DIS**
- **Transverse spin: DIS and Drell-Yan**
- **Generalized parton distributions : DVCS, HEMP**

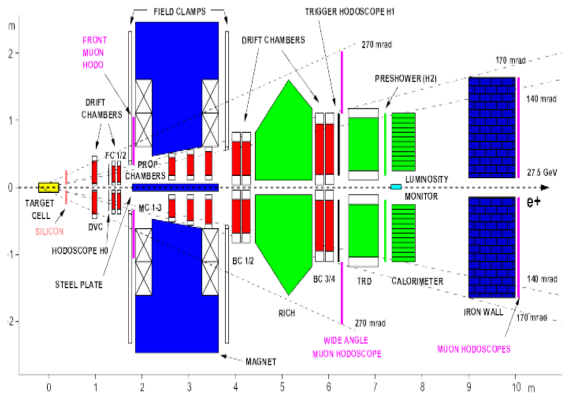
SPIN21, Matsue, Japan, Oct. 18-22, 2021

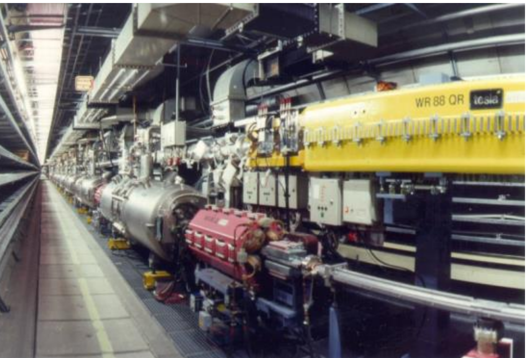
HERMES at DESY / COMPASS at CERN / JLab

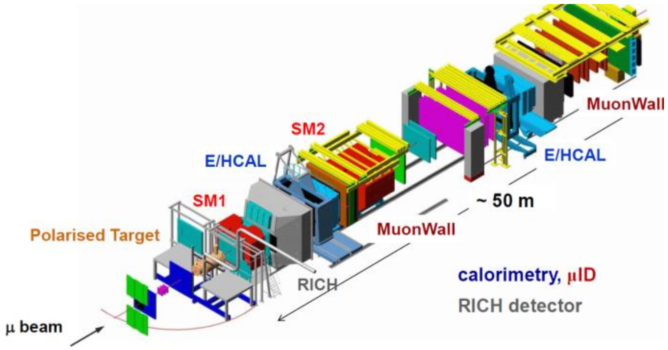
27 GeV e^+& e^-
Longit. polarized ~ 54%
Gaseous intern. polar target
1995 to 2007

160-200 GeV
polarized muon beam DIS
pion beam: Drell-Yan
Long solid polarized targets

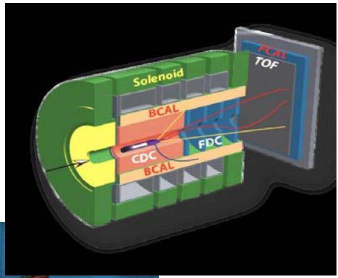
12 GeV
Polarized CW e^- beam
Pol=85%,
High luminosity

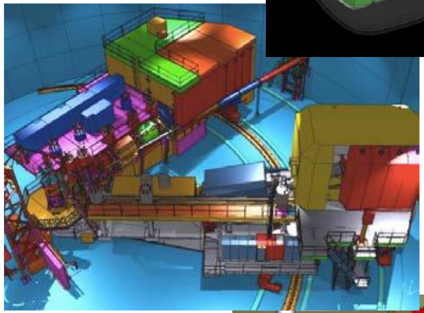






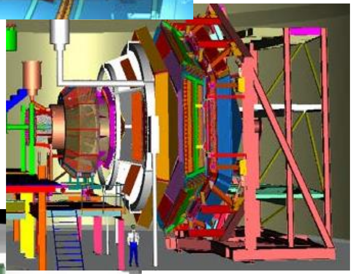
Hall D: hybrid mesons

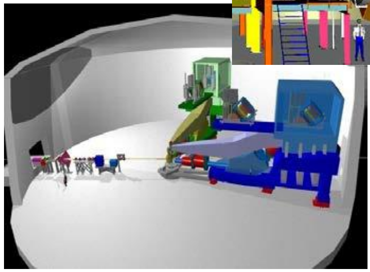




Hall C

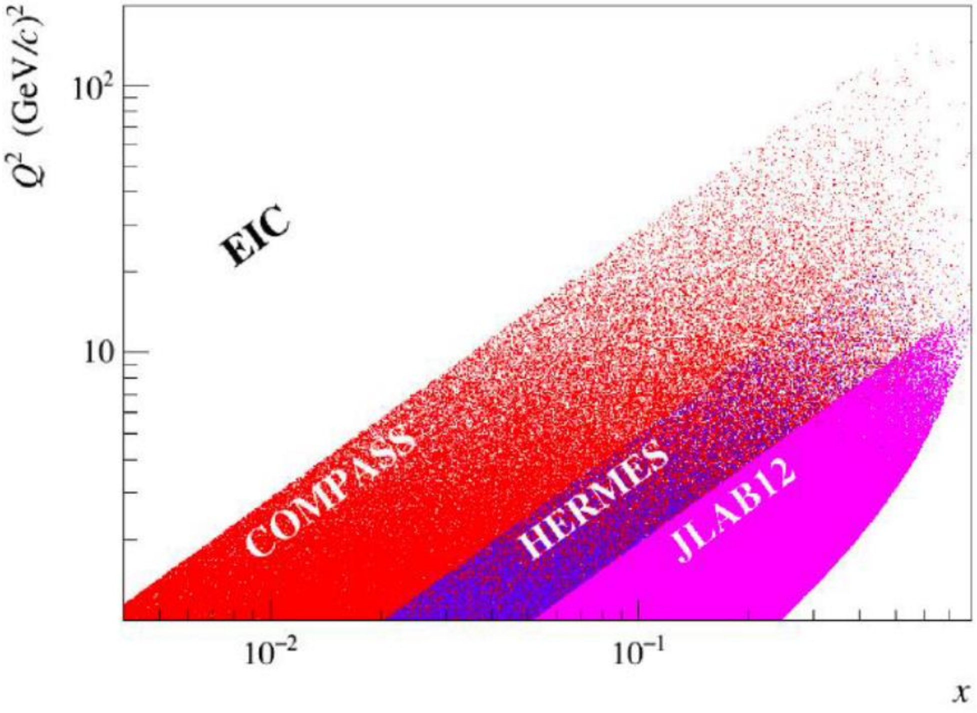
Hall B: GPDs





Hall A: form factors + Moller & SOLID…

Kinematical ranges



Nucleon spin - longitudinal

How is the nucleon spin distributed among its constituents?

Nucleon Spin $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$

quark gluon orbital momentum

$\Delta\Sigma$: sum over u, d, s, $\bar{u}$, $\bar{d}$, $\bar{s}$
can take non half-integer value:
superposition of several spin states

$\Delta q = \overrightarrow{q} - \overleftarrow{q}$
Parton spin parallel or anti parallel to nucleon spin

$\Delta\Sigma$ Today:
Precise world data on polarized DIS: g_1 + $SU_f(3)$ $a_0 = \Delta\Sigma \sim 0.3$
Quark spin contribution ~ 30%

Confirmed by first results from Lattice QCD on $\Delta\Sigma_{u,d,s}$

See talk of C. Alexandrou

Large experimental effort on :

- ΔG measurement

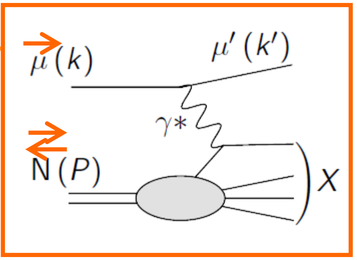
also because $a_0 = \Delta\Sigma - n_f\,(\alpha_s/2\pi)\,\Delta G$ (AB scheme)

- 3D mapping of nucleon and constraining L

through DVCS and Hard Exclusive Meson Production

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

DIS

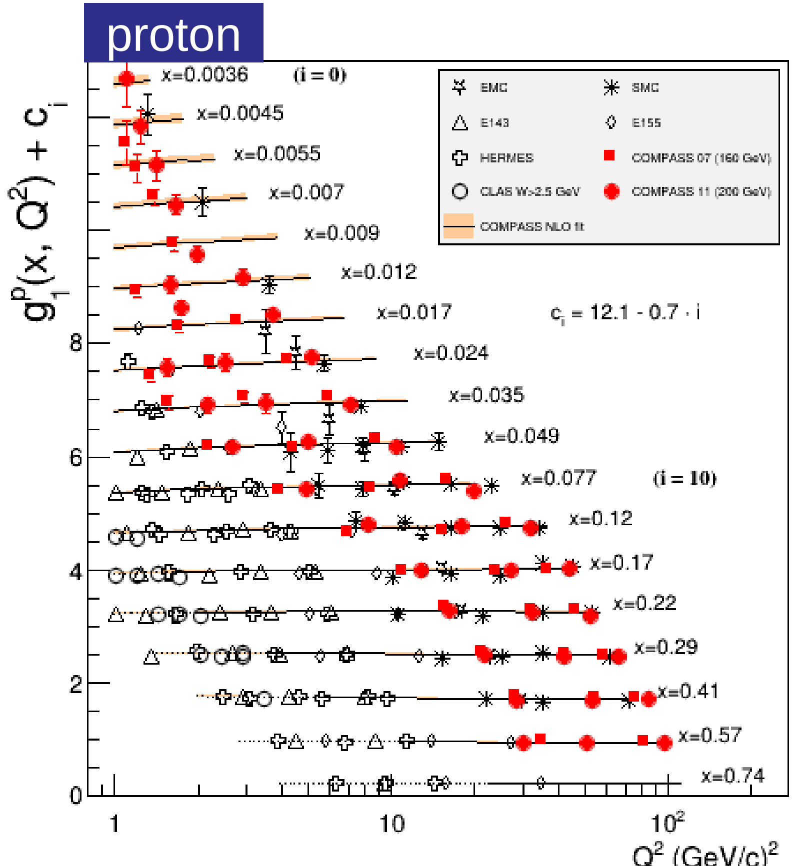


Polarized Deep Inelastic Scattering
➔ Nucleon spin structure functions g_1

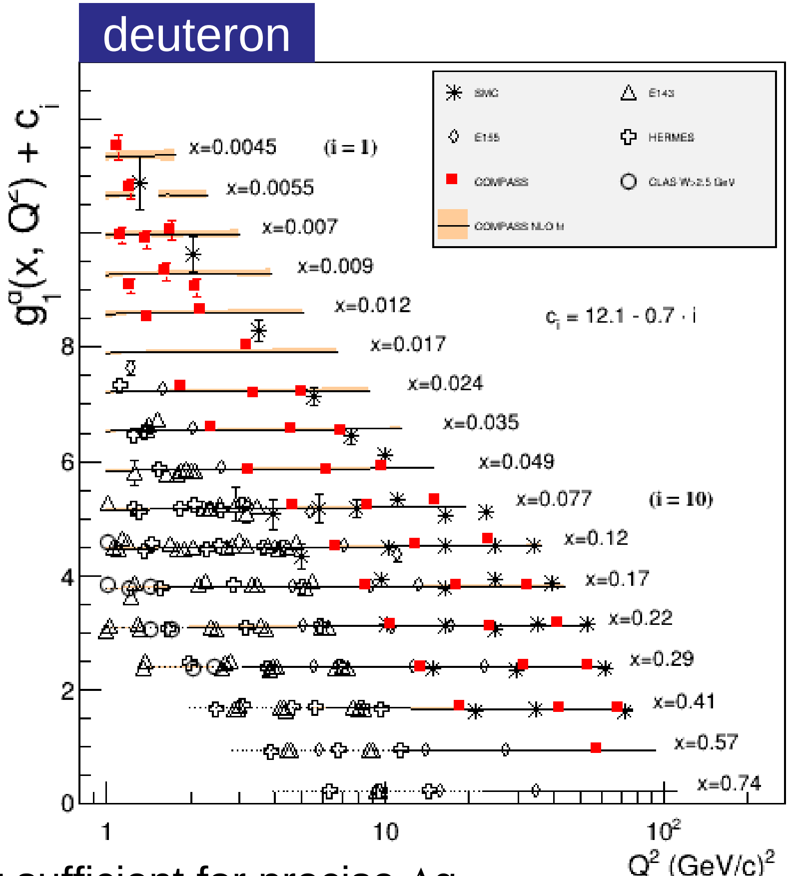
$$\frac{d\,g_1}{d\,Log(Q^2)} \propto -\Delta g(x,Q^2)$$

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

proton



deuteron



However x and Q^2 coverage in DIS not yet sufficient for precise Δg
Need to use constraint from pp data (as DSSV, NNPDF…)

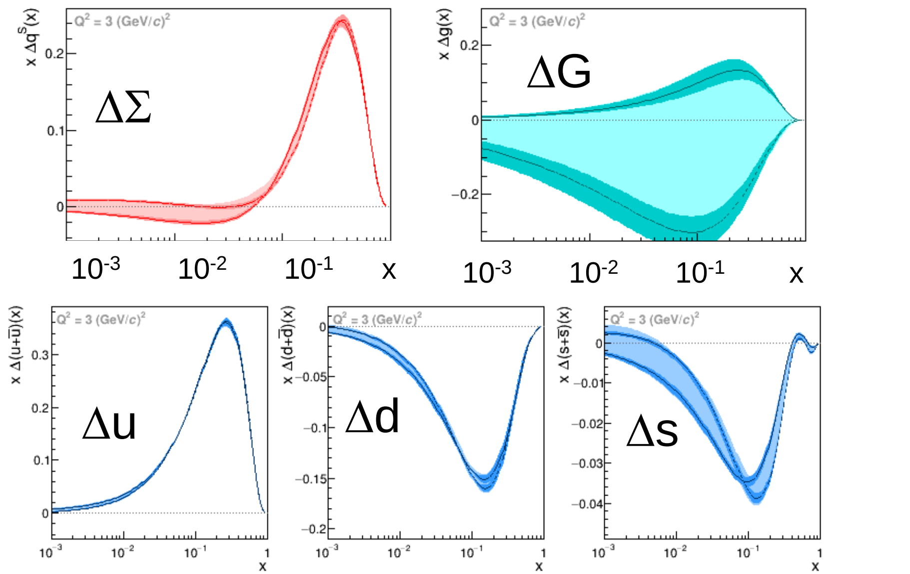
PLB753 (2016) 18

NLO pQCD fit to g_1 DIS world data

- Assume functional forms for $\Delta\Sigma$, ΔG and Δq^{NS}
- Use DGLAP equations, relating $\Delta\Sigma$, ΔG evolutions .
- Fit g_1^p, g_1^d, g_1^n DIS world data. (SU_3)

COMPASS, PLB 753 (2016) 18

- Extract $\Delta\Sigma$ Quarks ΔG Gluons



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

ΔG not well constrained using DIS only

Obtain solutions with $\Delta G>0$ and $\Delta G<0$

Solution with $\Delta G>0$ agrees with result from DSSV++ which uses RHIC pp data

$\Delta\Sigma$ well constrained in valence region

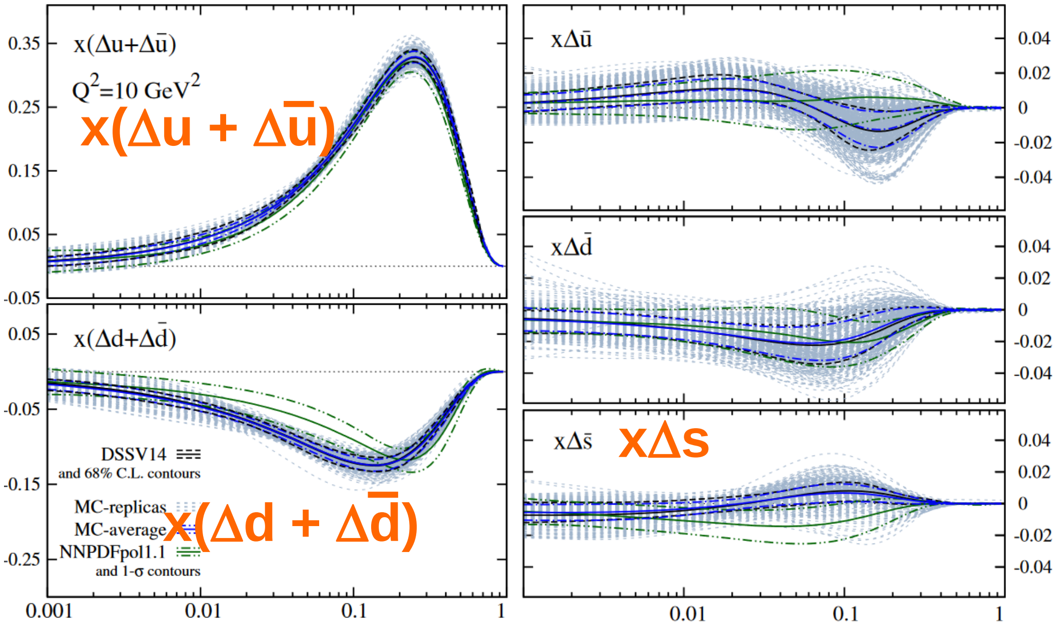
$\Delta\Sigma = 0.31\ (5)$ at $Q^2=3\ (GeV/c)^2$

Still large uncertainty coming from the bad knowledge of functional form

Global fits to polarized PDFs (I)

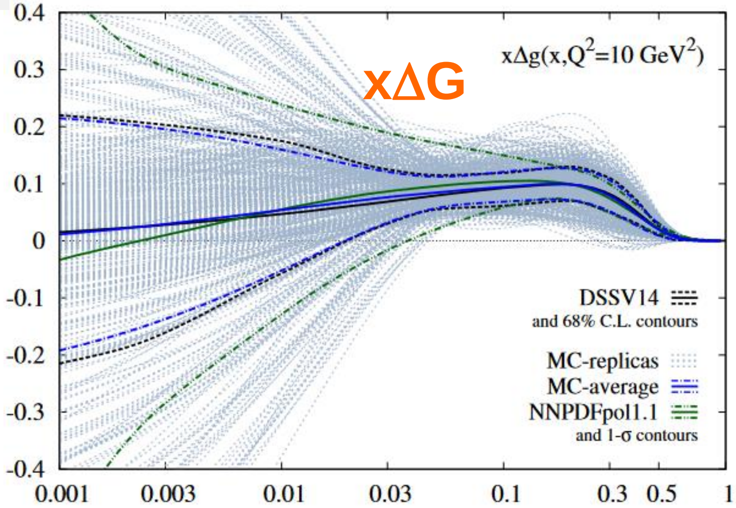
Fits to world data, including collider data. Many fitters. Some examples:

DLSSV: PRD100, 114027 (2019)



Blue: ***DSSLV***
from DSSV14 w. replicas and MC average

Green: ***NNPDFpol1.1***



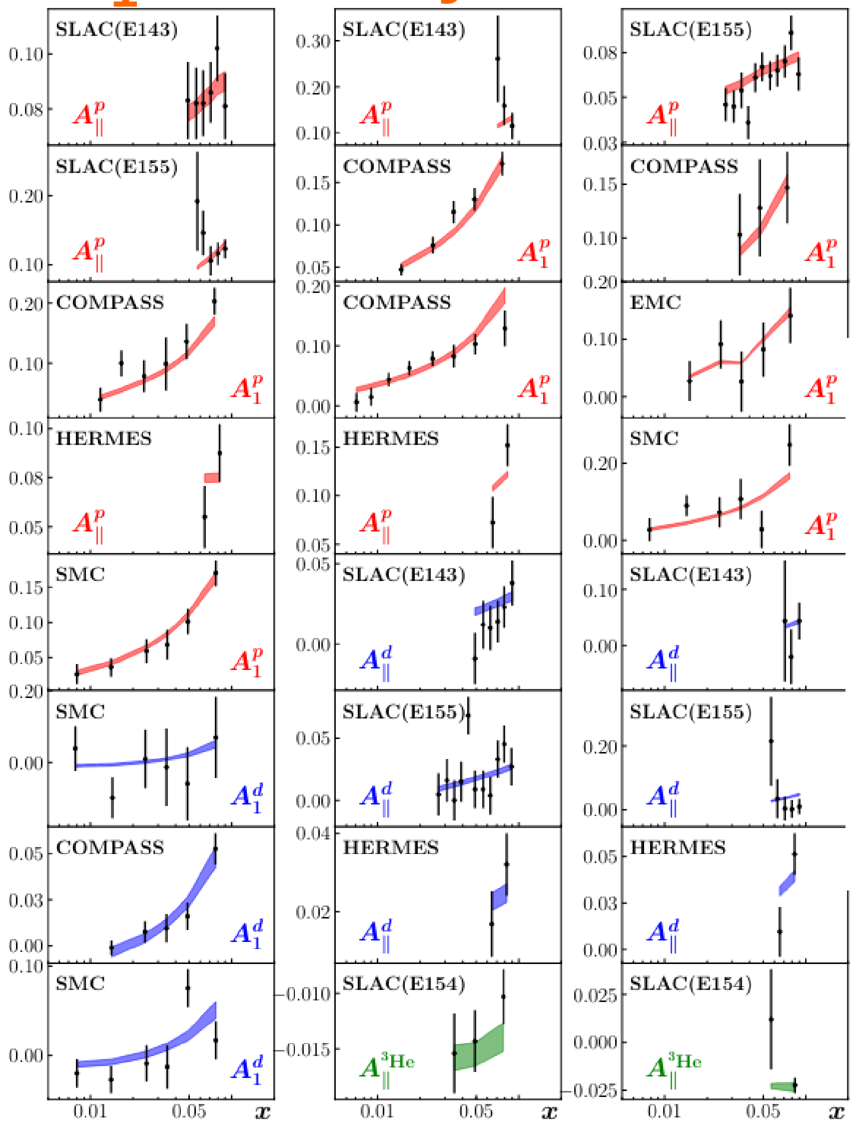
More realistic evaluation of uncertainties

Still some discrepancies in **Δs sign** (and in **Δd position of minimum**)

Large uncertainties in **ΔG**, below x~0.1

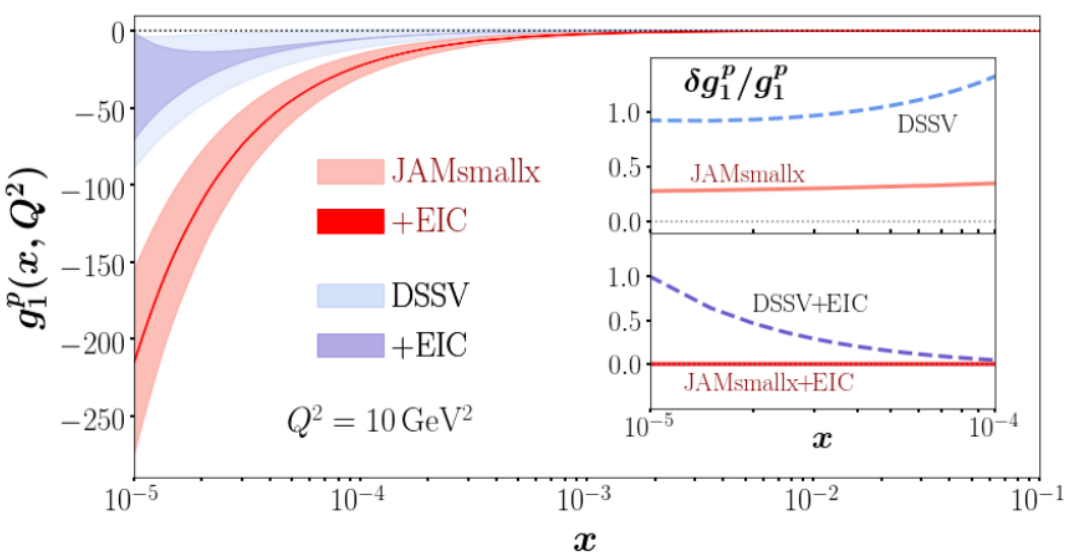
Global fits to polarized PDFs (II)

A_1 – helicity low x



Small-x evolution equations for **g_1**
Data from SLAC, CERN, DESY.

- Present projections toward low x
- Expected impact of EIC future data



JAM smallx, arXiv:2102.06159

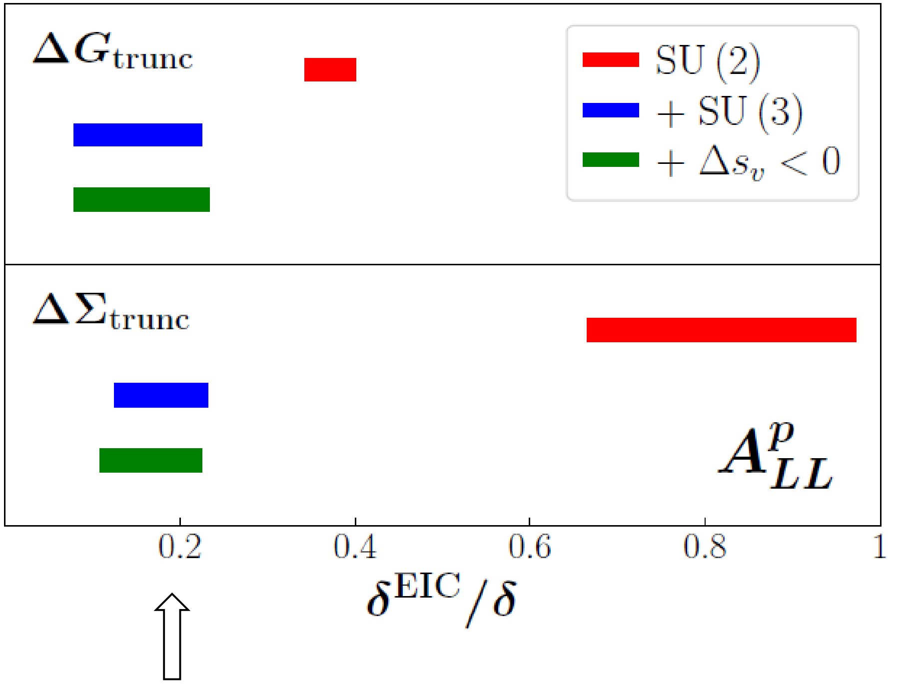
Global fits to polarized PDFs (III)

JAM hep-ph 2105.04434

See also talk C. Cocuzza

$\Delta\Sigma$ and ΔG

Expected impact of EIC future data on integrals truncated to x ~ 10^{-4}



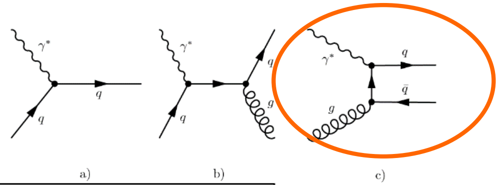
Huge reduction of uncertainties but need to use SU3

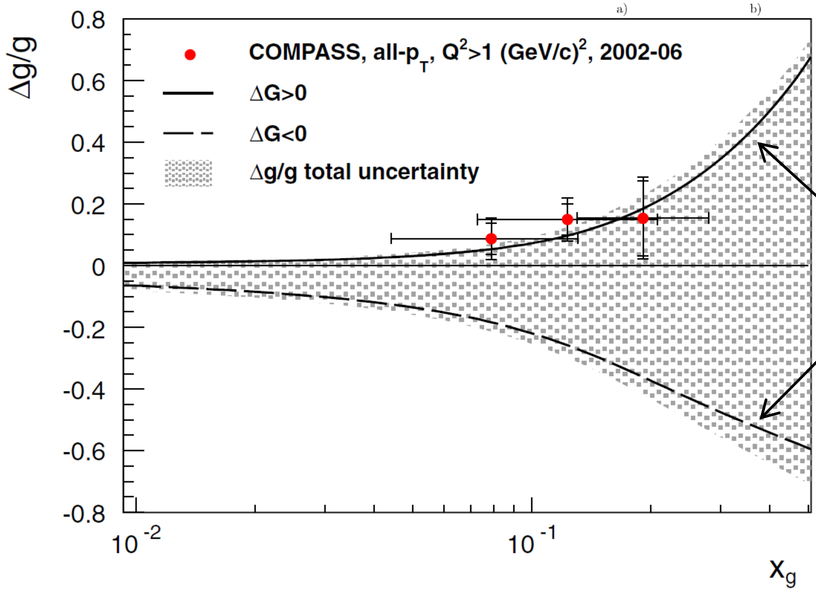
Gluon helicity ΔG/G direct measurement

Photon Gluon Fusion

$Q^2 > 1 (GeV/c)^2$

$\vec{\mu}\ \overleftarrow{\vec{p}} \rightarrow \mu'\ h + h\ + X$





Extraction at LO:

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

Solutions from COMPASS NLO QCD fit of g_1 world data (see before)

EPJC 77 (2017) 209

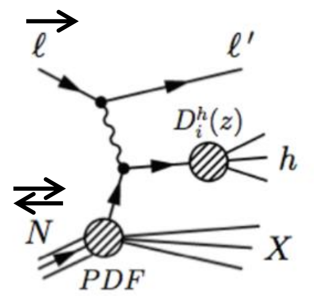
Results are in agreement with fits from NNPDF and DSSV++ using RHIC $\vec{p}\vec{p}$ data, which give

$$\int_{0.05}^{0.2} \Delta g(x)\,dx \simeq 0.20$$

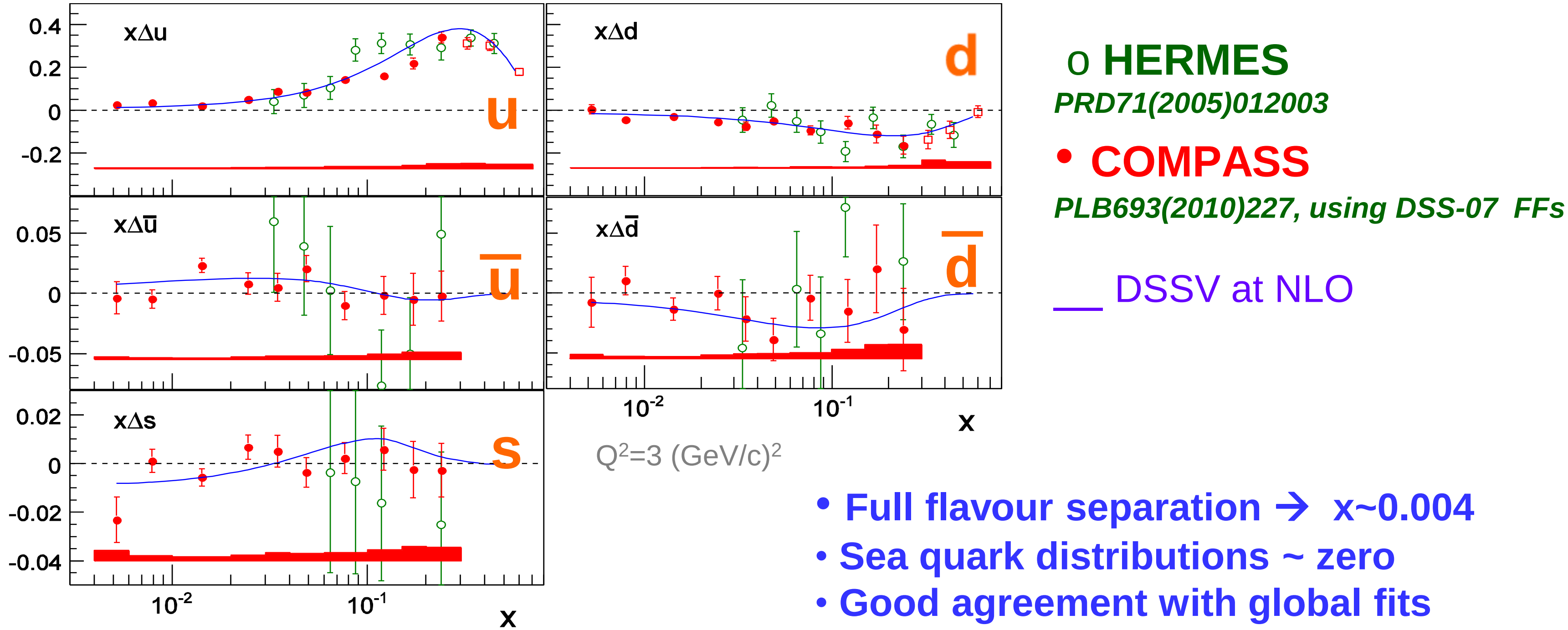
Quark helicities from semi-inclusive DIS

$\boxed{l^{\rightarrow} p^{\rightarrow} \rightarrow l\, h^{+/-}\, x}$

Outgoing hadron tags quark flavor
(via quark fragmentation functions)



Flavour separation of quark helicities:



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

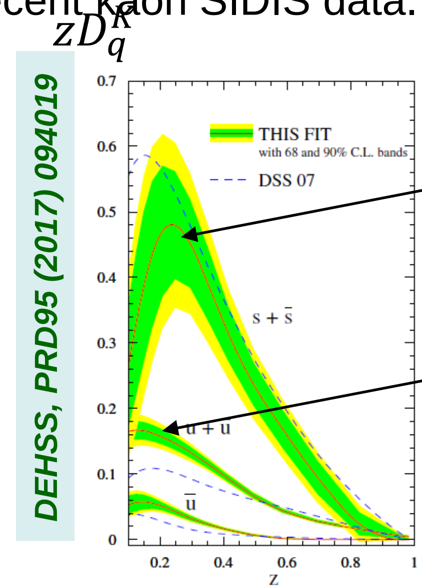
NB: The SIDIS extraction uses input of quark Fragmentation Functions, not that well determined yet, especially for the strange quark sector.

Kaons- Quark fragmentation functions from NLO fits

Extensive sets of SIDIS kaon data ***COMPASS PLB 767 (2017) 133***
change significantly flavor decomposition of FFs (& PDFs)

See plenary talk on FFs by F. Ringer

Ex1: **DEHSS-17** fit to quark FF, includes recent kaon SIDIS data.

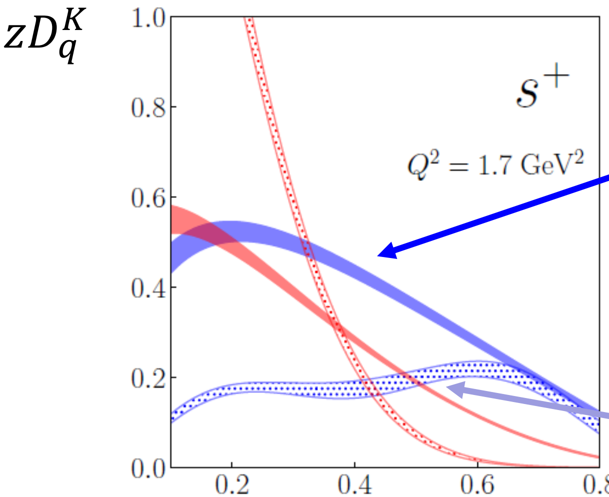


D_S^K smaller than in DSS-07

D_U^K larger than in DSS-07

z

Ex:2: **JAM18 w/wo SIDIS**
Combined fit of PDFs and FFs (prelim)



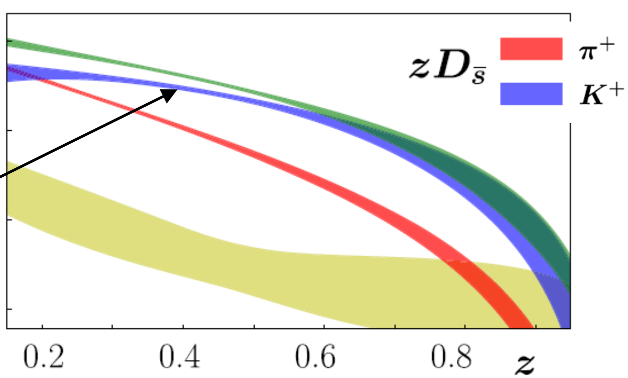
D_S^K w SIDIS agrees with DEHSS

D_S^K w/o SIDIS

Also **simultaneous/ iterative fits of PDFs & FFs:**

Ex: Borsa, Sasso, Stratmann, PRD96 (2017)
& JAM20-sidis, PRD104 (2021) 016015

'SIA + SIDIS data : strong preference for smaller strange to nonstrange PDF ratio, and enhanced DsK'



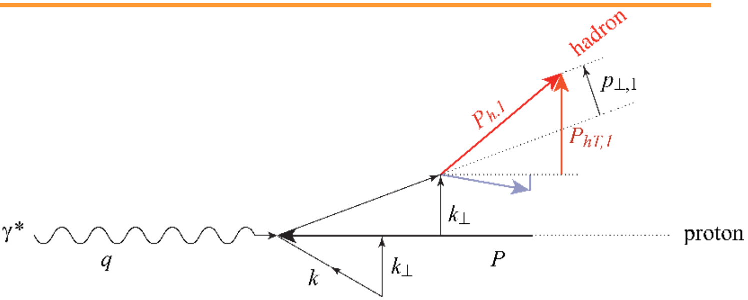
-> revisit $\Delta s(x)$ extraction from SIDIS data

Transverse Momentum Dependent distr. : TMDs

Importance of p_T :

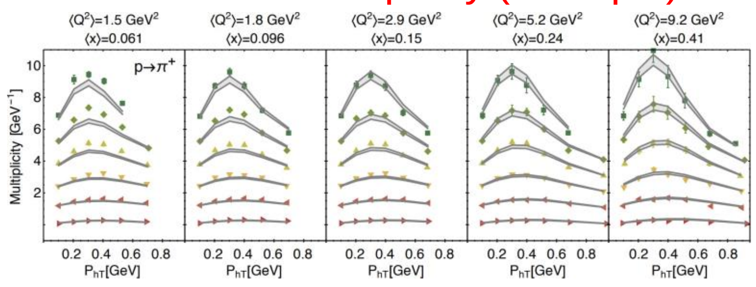
P_T dependence results from:

- intrinsic $k_\perp$ of the quarks
- $p_\perp$ generated in the quark fragmentation

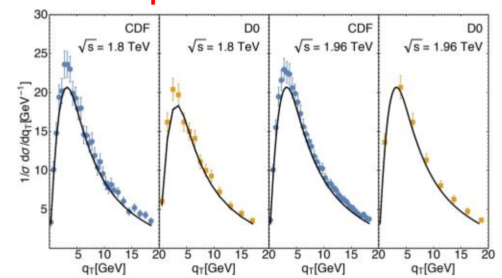


Global analyses of SIDIS, Drell-Yan and Z production data with TMD Q^2 evolution

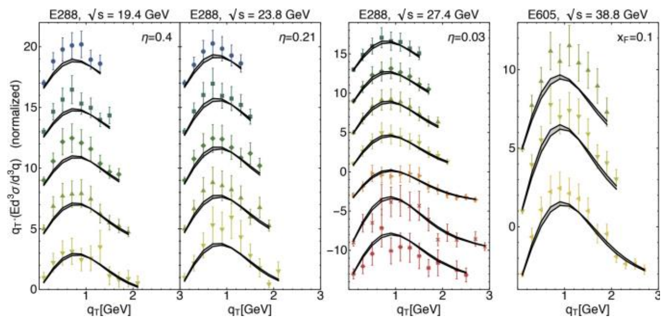
SIDIS multiplicity (example)



Z production

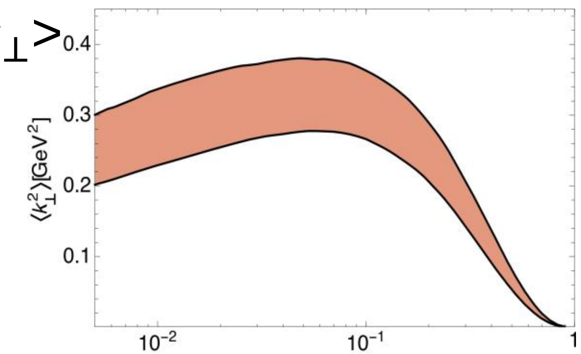


Drell-Yan cross section



Transverse momentum distribution

$< k_\perp >$



x

A. Bacchetta et al., JHEP06 (2017) 081

See also A. Martin talk

Transverse spin- Collins and Sivers functions (DIS)

- Access via **SIDIS**, transversely polarized target $\boxed{\mu\, p^{\uparrow} \rightarrow \mu\, h^{+/-}\, X}$

- Measure simultaneously several azimuthal asymmetries, out of which :

  Collins: Outgoing hadron direction & quark transverse spin

  Sivers: Nucleon spin & quark transverse momentum k_T

at LO: **Collins**

quark transverse spin distr.

$$\boxed{A_{Coll} = \frac{\sum_q e_q^2 \cdot x \cdot h_1^q \otimes H_{1q}^{\perp}}{\sum_q e_q^2 \cdot x \cdot q \otimes D_{1q}^{h}}}$$

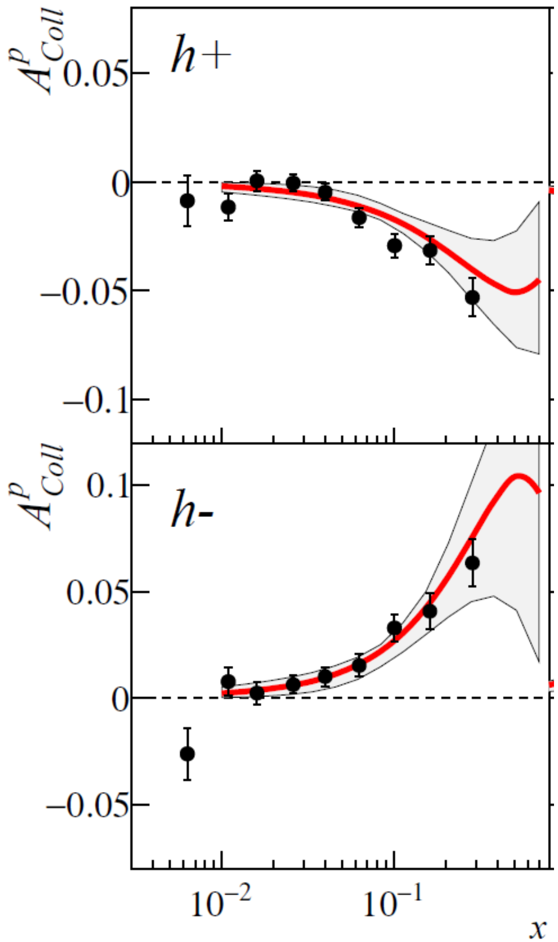
Collins TMD fragmentation function, depends on spin, and hadron p_T

Sivers

Unpolarized quark TMD fragmentation function

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

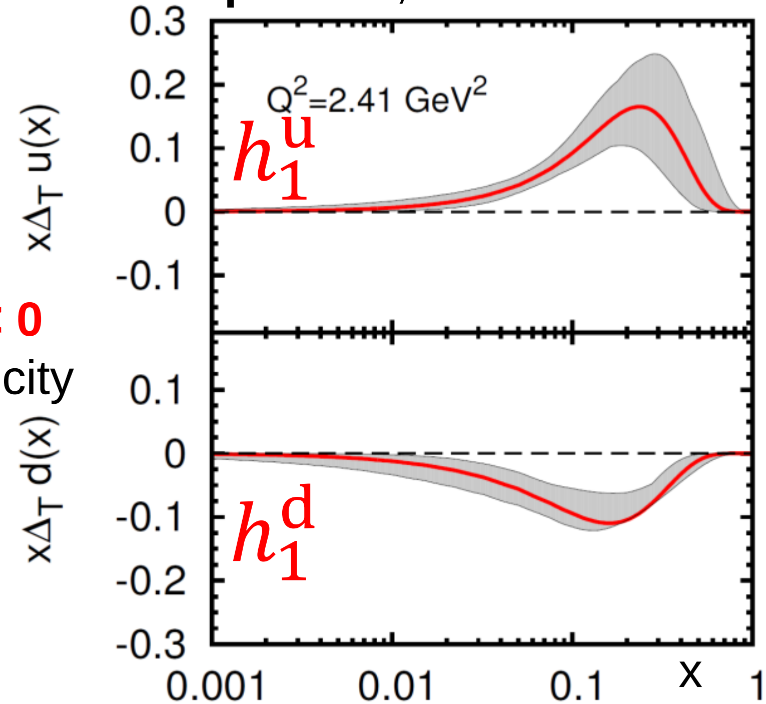
Collins asymmetry → Transversity h_1



- **Large signal for proton target.**
  (compatible with zero for deuteron target)
- **Same signal strength seen by HERMES and COMPASS, although different Q^2 (times 4)**

Several combined analyses of polarized SIDIS data
HERMES p, COMPASS p and d, and **BELLE FF**

$h_1^u > 0$ and $h_1^d < 0$
Smaller than helicity



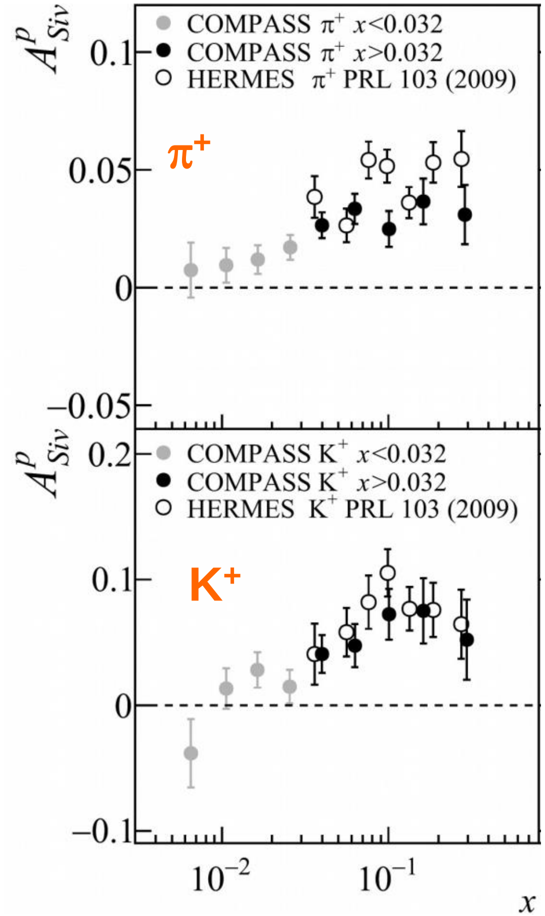
NB: asymmetries also measured for π and K

HERMES PLB 693(2010)
COMPASS PLB 744 (2015)

Anselmino et al., PRD87(2013) 094019)

Sivers asymmetry → Sivers function

Correlation between Nucleon spin & quark transverse momentum k_T

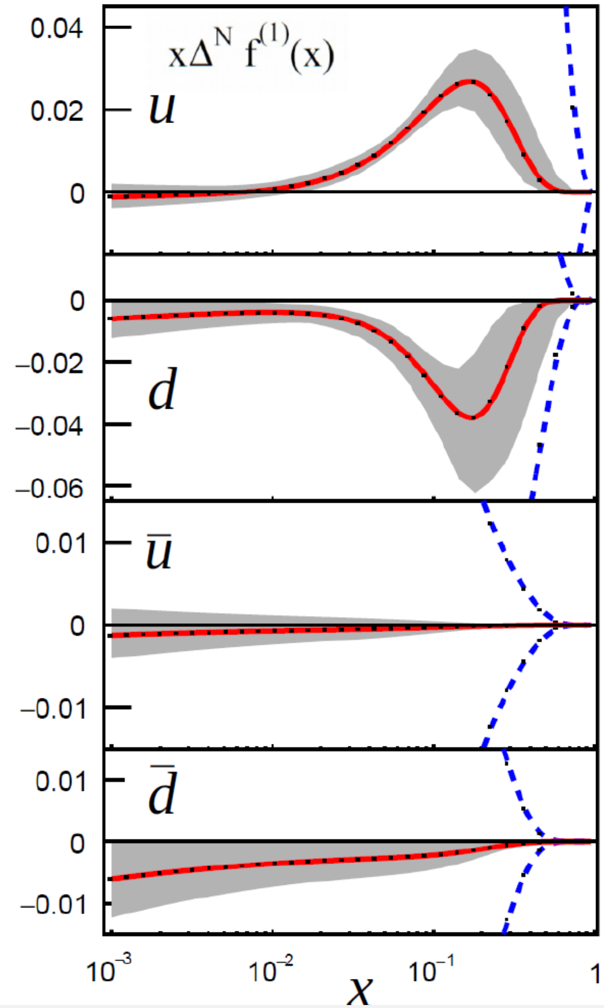


HERMES PRL 103 (2009)
COMPASS PLB 744 (2015)

Large signal with proton target.
Was measured compatible with zero on deuteron

Compared to COMPASS, HERMES (smaller Q^2) has larger signal

Sivers function



Anselmino et al., JHEP04 (2017)046

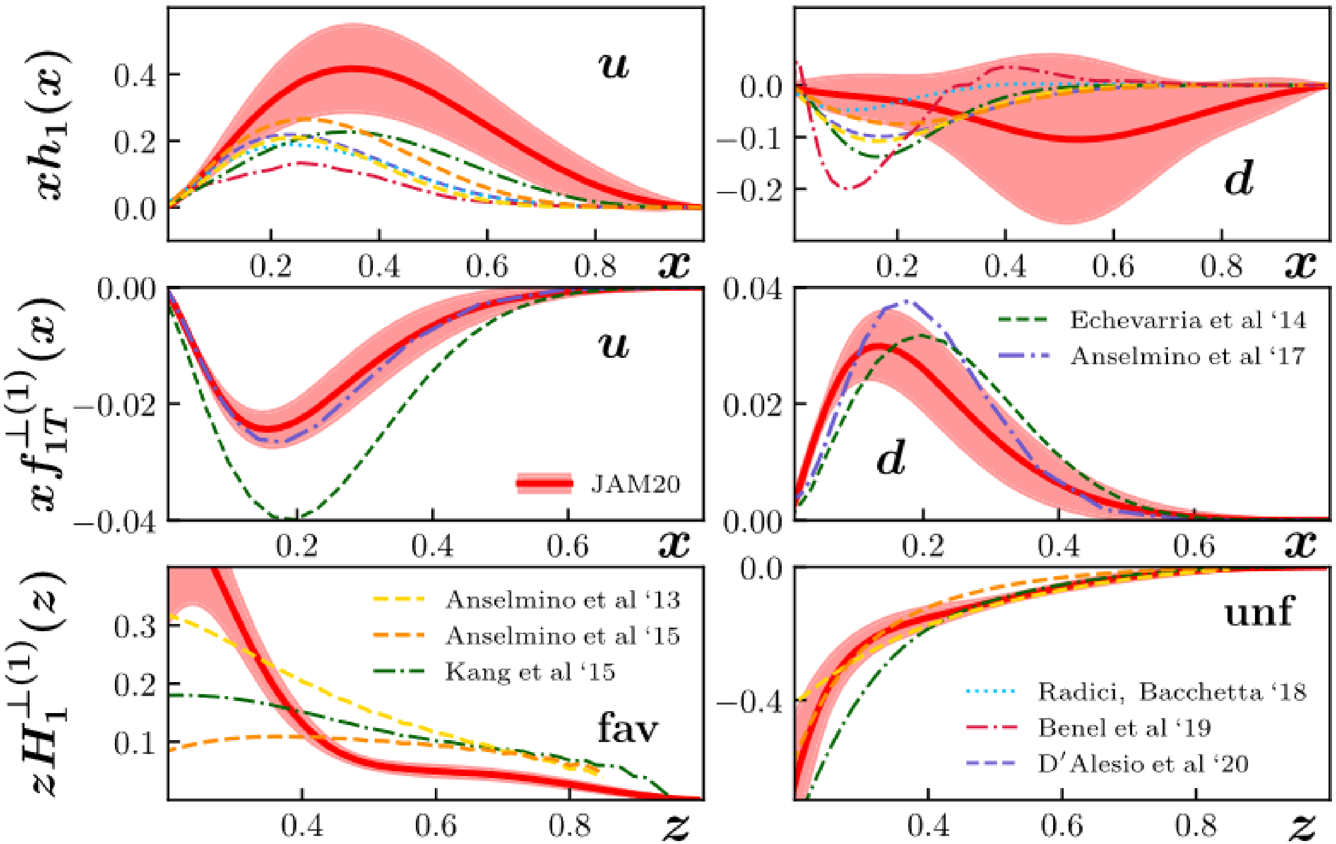
Collins & Sivers. Recent global fits

Many global analyses of SIDIS, Drell-Yan, pp and e+e- .

Great progress: theoretical developments, large data sets, uncertainty studies

JAM20, Etchevaria et al., Anselmino et al., Radici, Bacchetta, Kang et al., D'Alesio et al., Boglione et., Bury et al. ..

e.g.:



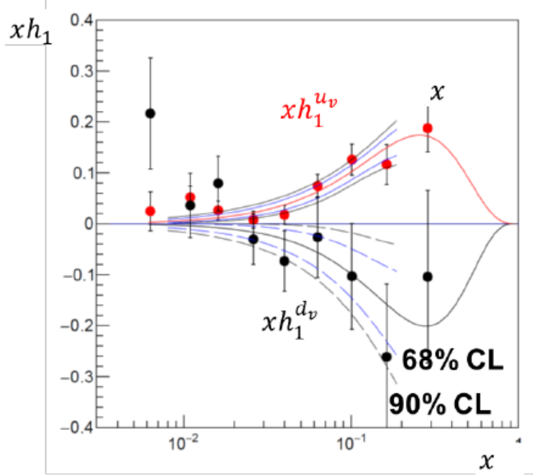
JAM20, PRD102, 054002 (2020)

Transversity h_1 / tensor charge

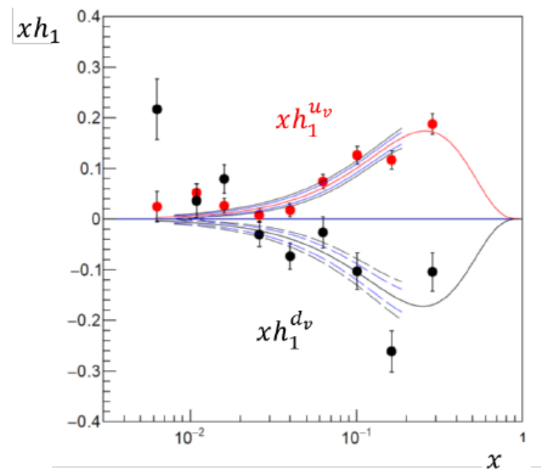
More data on deuteron needed

COMPASS projection for 2022 data, pol. 6LiD:

present
P all, **D 2002-2004**



projected
P all, **D 2021/22 only**



	$\delta_u = \int_{\Omega_x} dx\, h_1^{u_v}(x)$	$\delta_d = \int_{\Omega_x} dx\, h_1^{d_v}(x)$	$g_T = \delta_u - \delta_d$
Present	0.201 ± 0.032	-0.189 ± 0.108	0.390 ± 0.087
Projected	0.201 ± 0.019	-0.189 ± 0.040	0.390 ± 0.044

Expected improvement on uncertainties by factors of : ~2 (u), ~ 3 (d)

SIDIS transverse spin

TMDs, new approach: weighted asymmetries

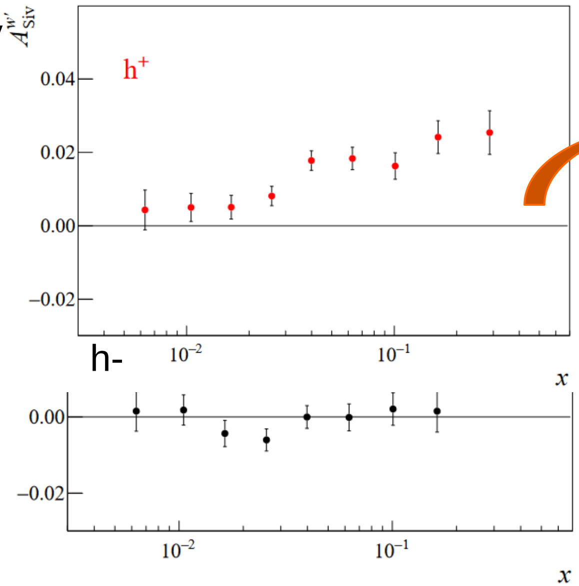
$$A_{Siv}^{(p_T^h/zM)}(x,z) = 2\frac{\sum_q e_q^2 f_{1T}^{\perp(1)\,q}(x)\cdot D_1^q(z)}{\sum_q e_q^2 f_1^q(x)\cdot D_1^q(z)},$$

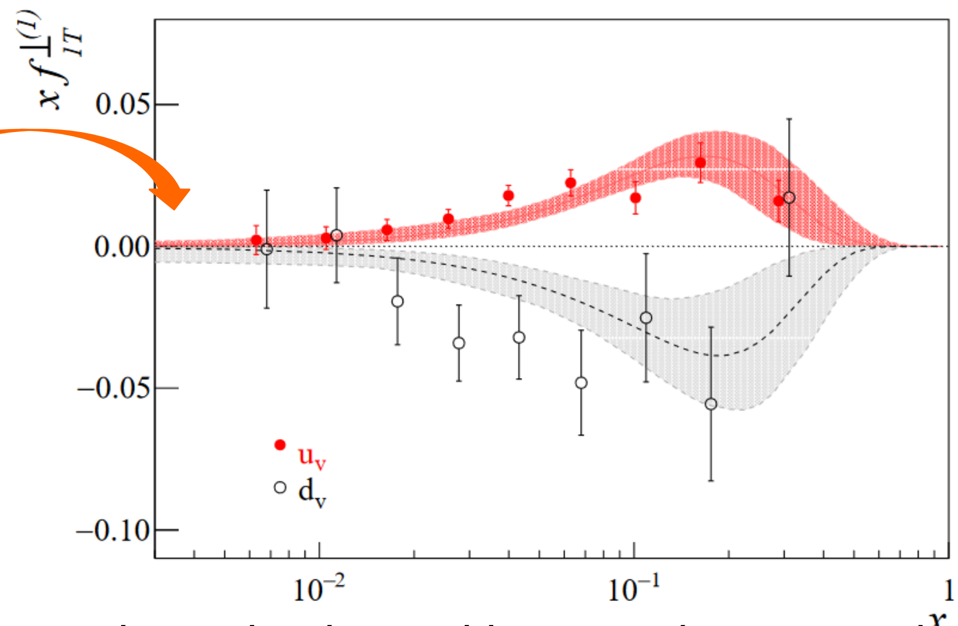
$$f_{1T}^{\perp(1)}(x,Q^2) = \int d^2k_T \frac{k_T^2}{2M^2} f_{1T}^{\perp}(x,k_T,Q^2).$$

Sivers asymmetry, with weight p_T/zM
No more convolution of TMDs and FFs but a product of integrals.

→ extract first moment of Sivers without assumption on k_T dependence

Asiv





COMPASS NPB 940 (2019)34

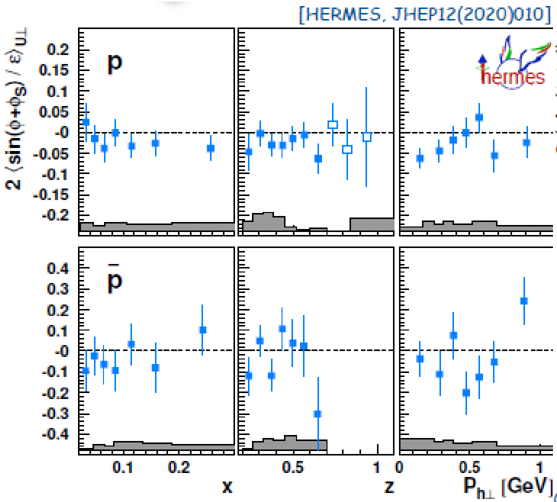
Point by point extraction using h+ and h- asym (NH3 target)

More on TMDs   Many other results, e.g.:

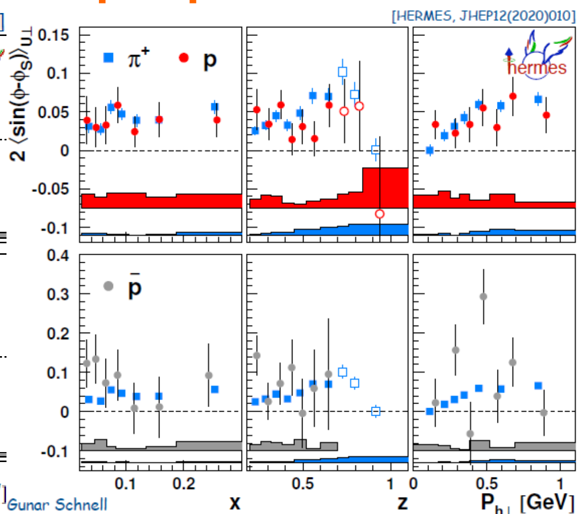
HERMES: extensive 3D analysis update

talks: G. Schnell (Transv.), H. Marukyan (Longit.)

First Collins & Sivers for p & pbar

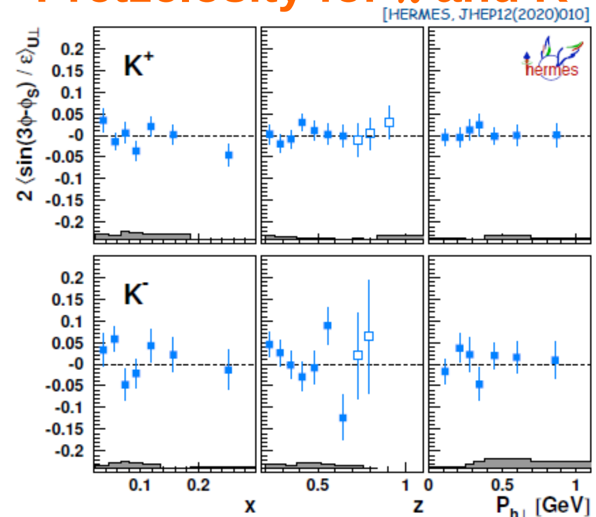


Collins: vanishing



Sivers: simil. magnitude as π+

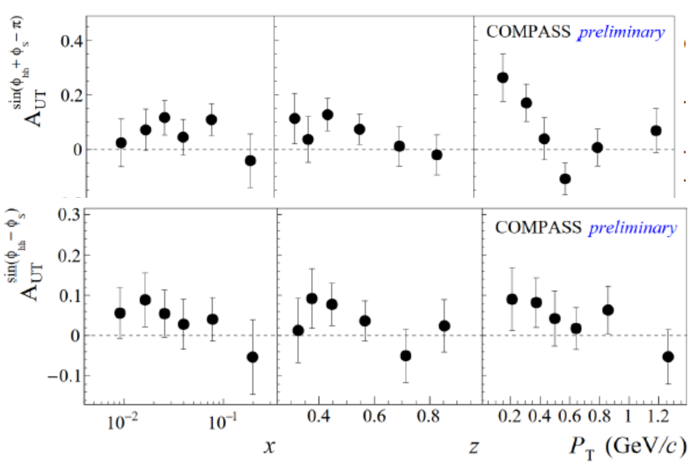
Pretzelosity for π and K



(quadrupole deformation): no sign

ρ^0 COMPASS first Collins and Sivers measurement

talk A.Moretti



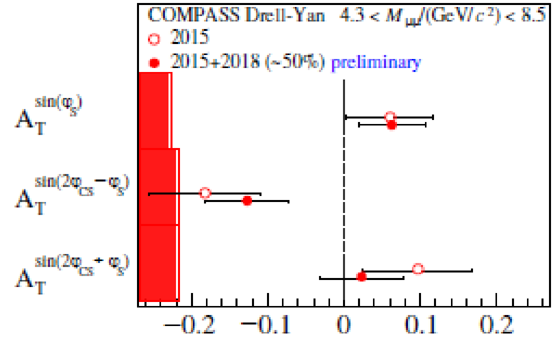
ρ^0 Collins asym: positive,
opposite to π+, as expected from models
large at small p_T

ρ^0 Sivers asym: positive,
similarly to π+, as expected

TMDs in polarized Drell-Yan

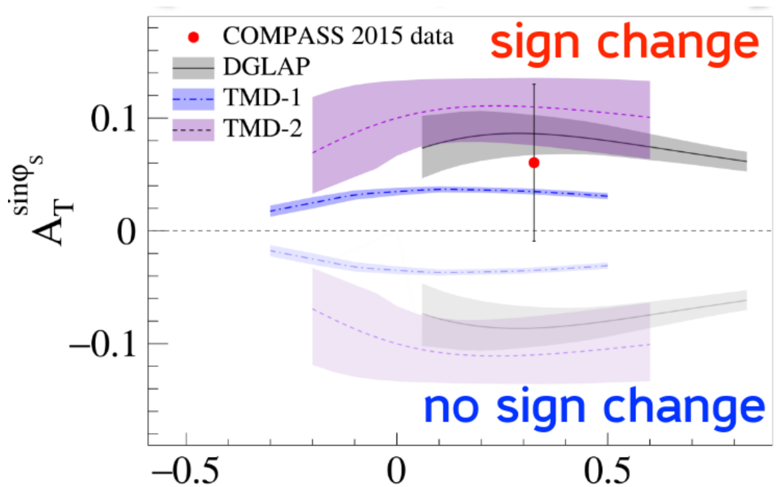
COMPASS,
π induced Drell-Yan
on pol. NH_3:

hep-ex 1908.01727,
& talk A. Chumakov



Sivers $\sim 1\sigma$ above zero
Transversity $\sim 2\sigma$ below zero
Pretzelosity $\sim 1\sigma$ above zero

Sivers function:
non-vanishing orbital angular momentum,
Process dependence expected :
sign change between SIDIS and Drell-Yan
Both measured in COMPASS
at similar hard scale



COMPASS, PRL 119 (2017) 112002

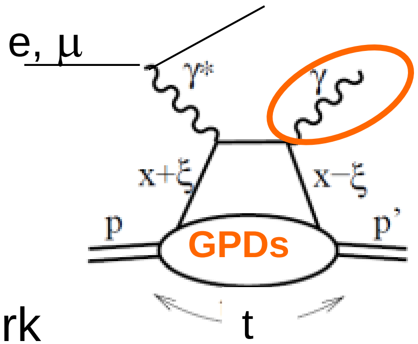
See also **Global analysis SIDIS+Star W, Z data** : ***M. Bury et al, PRL 126 (2021) 112002 :***
only slight preference for Sivers sign-change
(new STAR data not yet included).

GPDs generalized Parton Distributions

Physics goal: 3D mapping of nucleon and access to Orbital Angular Momentum

e p$\rightarrow$ e p γ

See theory talk by B. Pasquini



Determine 4 GPDs : **H, E, $\tilde{\text{H}}$, $\tilde{\text{E}}$** (Re and Im parts)
via 'exclusive' processes: DVCS (γ) and DVMP (ρ, ω, ϕ)

Measurements at Jlab, Compass, Hermes and pioneering work at H1 and Zeus

DVCS interferes with Bethe-Heitler process
→ Can use interference terms (e.g. at Jlab) or pure DVCS production with appropriate combinations of beam sign and polarization (COMPASS).

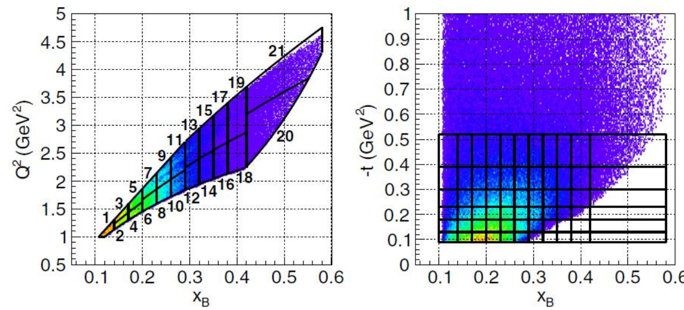
Way to it:

- Collect very large sample of data, various observables and several kinematic variables
- Global analyses to extract 4x2 Compton Form Factors **CFFs**
- Deconvolutions to finally access **GPDs**.

DVCS – Jlab CLAS proton target, e H → e'p γ

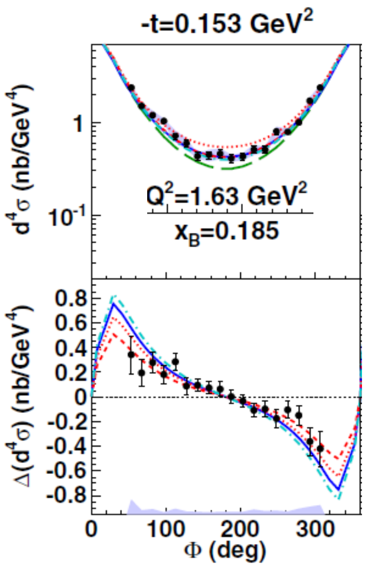
$d^4\sigma(x,Q^2,t,\phi)$ and $\Delta(d^4\sigma)$ beam spin difference, sensitive to *Im[H]* $\sim e^{-b(x)\,t}$

K. Jo et al., CLAS, PRL 115 (2015)

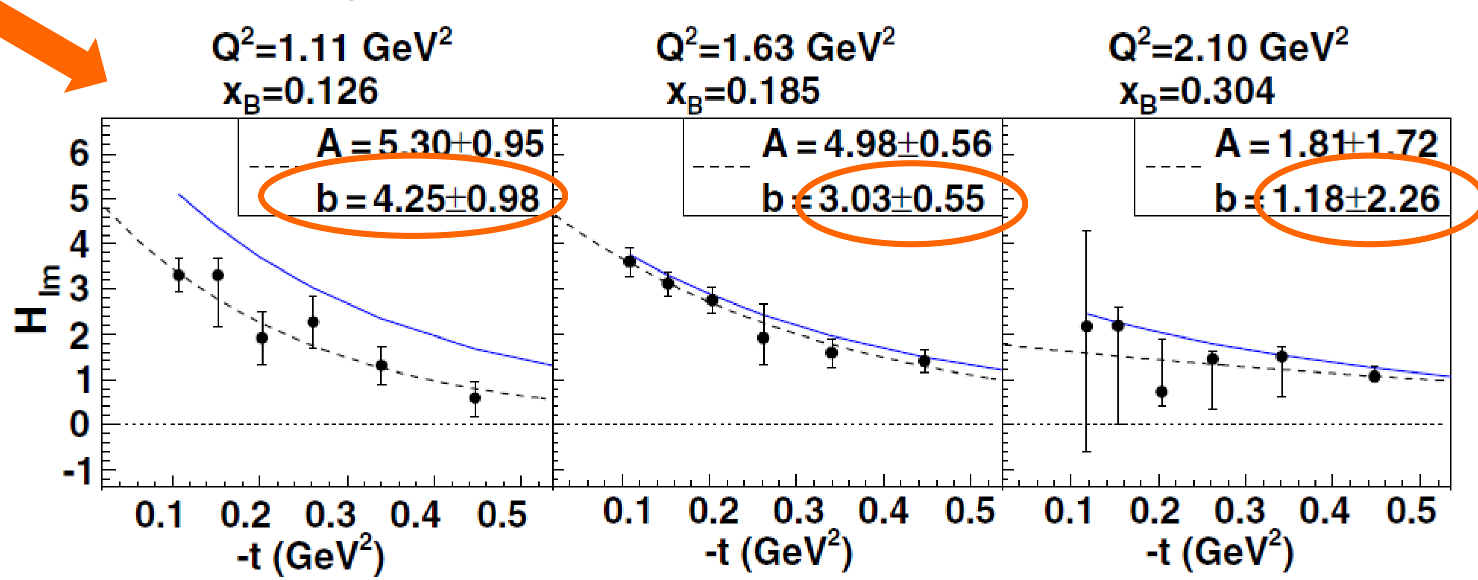


b **related to proton transverse size**

a sample:



Assuming one GPD, fit to CFF at 3 x values:

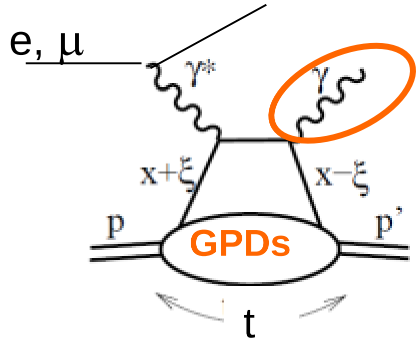


b **decreases as x_B increases**

→ proton shrinking with x_B

DVCS- t-slope of Cross-section (COMPASS)

$\mu^{+/-}\ p \rightarrow \mu\ p\ \gamma$

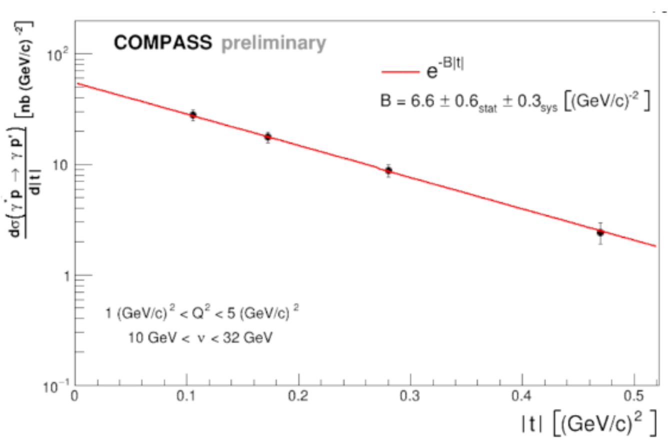


Combining data from $\overrightarrow{\mu+}$ and $\overleftarrow{\mu-}$ beams
(beam spin &charge sum),
measure t-slope of DVCS cross section
→ x dependence of transverse size of the nucleon

$$\sigma^{DVCS}/dt \sim \exp^{-B|t|}$$

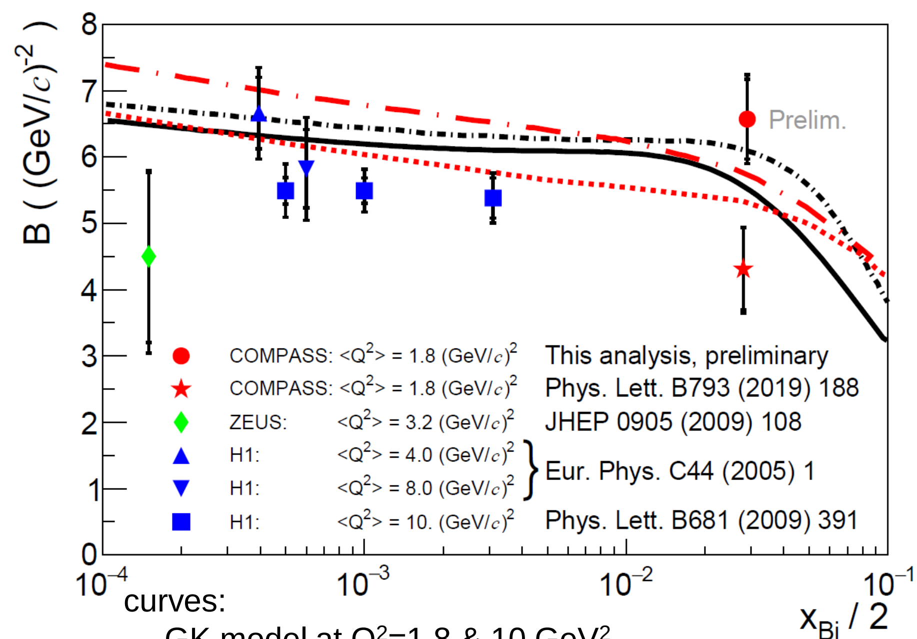
$$B(x_B) = ½ \langle r_\perp^2(x_B)\rangle$$

Measurement of proton transverse size vs x_B



2016 data :prelim. result
3 x more stat. expected from 2017 data

New prelim. COMPASS result: ***(J. Giarra talk)***

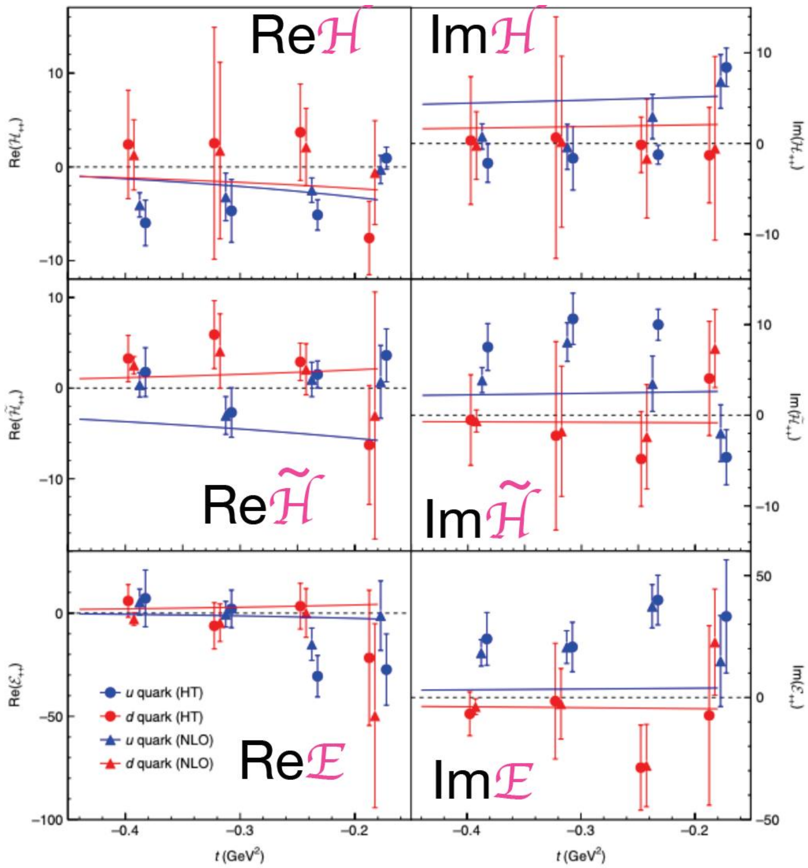


curves:
--- GK model at Q^2=1.8 & 10 GeV^2
--- KM15 at Q^2=1.8 & 10 GeV^2

Flavour separation of CFFs

JLab Hall-A neutron and proton DVCS

u quark
d quark



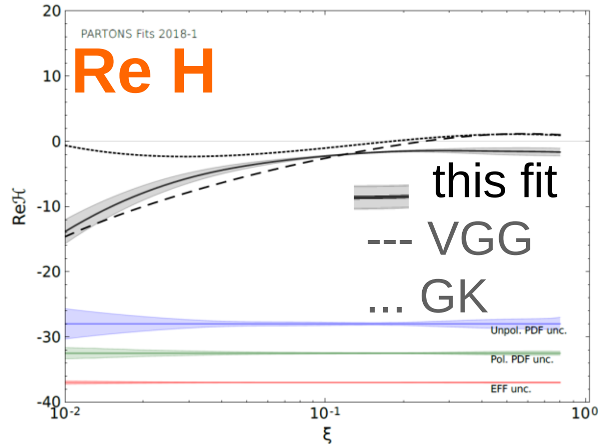
Benali, Desnault, Mazouz et al.,
Nature Physics 16 (2020) 191-198

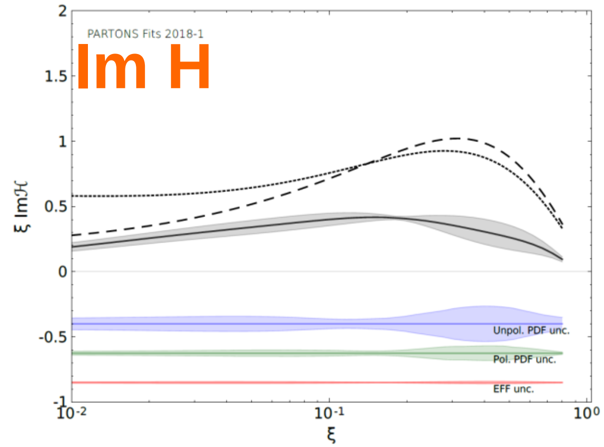
CFFs from globat fits of DVCS data

Example: 'PARTON' fit at LO/LT DVCS proton,
Including **Jlab, HERMES and COMPASS data**
2600 / 3970 points
with constraints on GPDs (PDFs, elastic Form Factors, limits at x→1...)

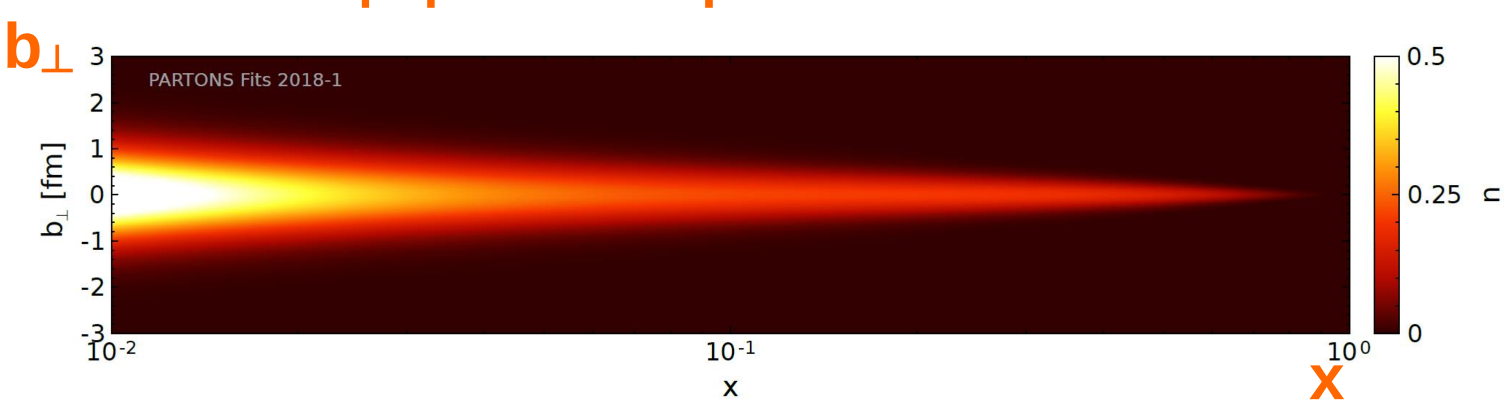
CFFs:

H. Moutarde, P.Sznajder, J. Wagner, arXiv:1807.07620





Position of up quarks in a proton:



Summary – Spin at fixed target experiments

Gluon and quark contribution to nucleon spin

Gluon $\Delta G/G=0.1$ at $x=0.1$ (photon gluon fusion process) agrees with RHIC $\int \Delta G \sim 0.2$
Unknown contribution at low x

Quarks : $\frac{1}{2}\,\Delta\Sigma \sim 0.15$ from global QCD fit of g_1 world data
Largest uncertainty comes from functional shape (of ΔG also)
Agreement with Lattice QCD
Flavor decomposition from SIDIS, down to x ~0.004.

Transverse Momentum Dependent parton distributions
Extensive and precise results on all azimuthal asymmetries
Global analyses

GPDs via DVCS: Many data coming and promising framework for global analyses.

Bright future See talks on EIC, SPD at NICA, pol. tagets at LHC…