COMPASS results on nucleon spin and structure

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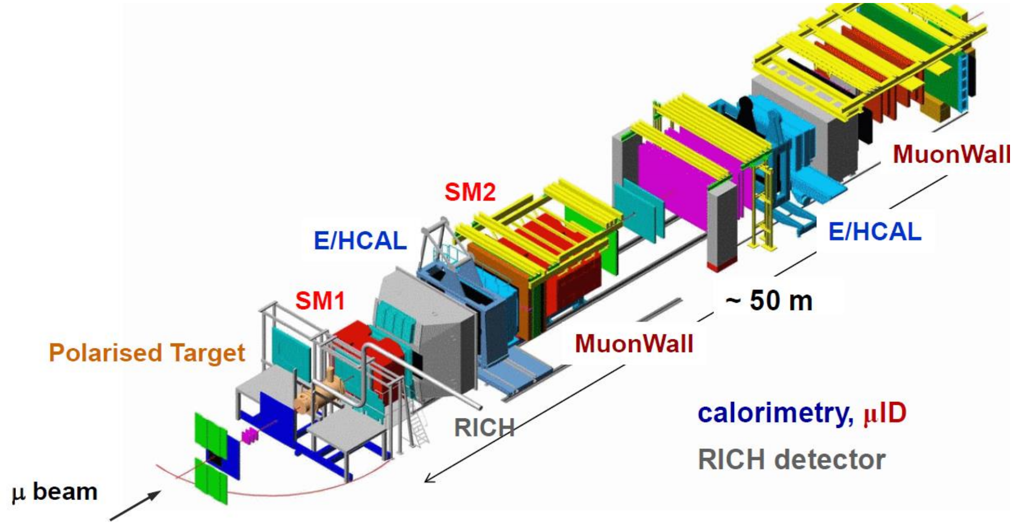
- **Nucleon longitudinal & transverse spin**
- **Quark Fragmentation functions**
- **Generalized parton distributions**
- **π induced Drell-Yan and J/Psi production**

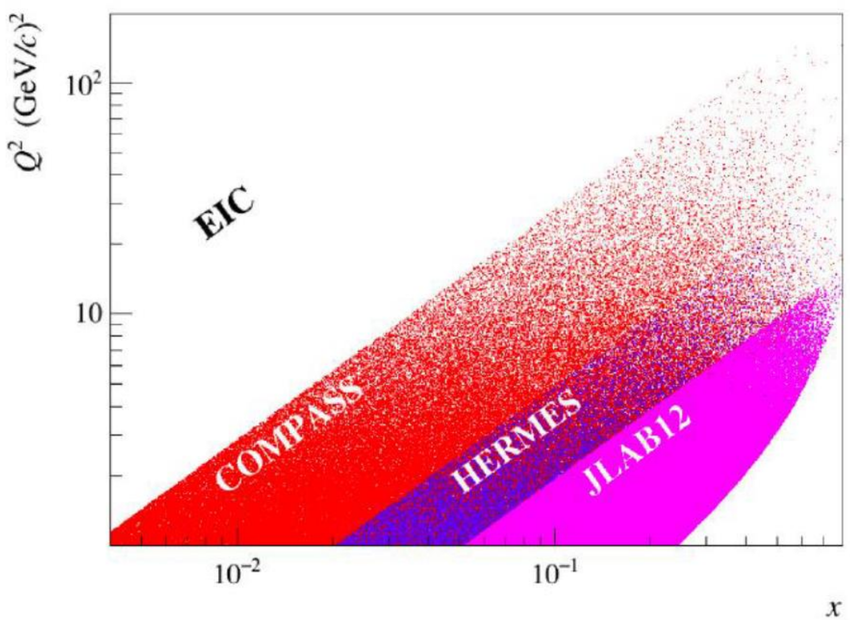
LC-2021, Jeju Island Korea and online, Nov 29-Dec 3, 2021

COMPASS at CERN

160-200 GeV
polarized muon beam DIS
pion beam: Drell-Yan
Long solid polarized targets,
LH2 target
& nuclear targets for DY



DIS kinematics



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

Large experimental effort on :

- ΔG measurement

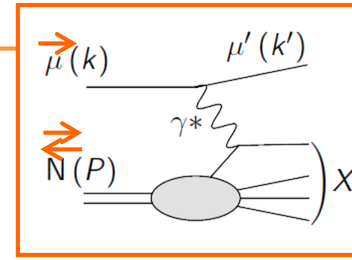
also because $a_0 = \Delta\Sigma - n_f (\alpha_s/2\pi) \Delta G$ (AB scheme)

- 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

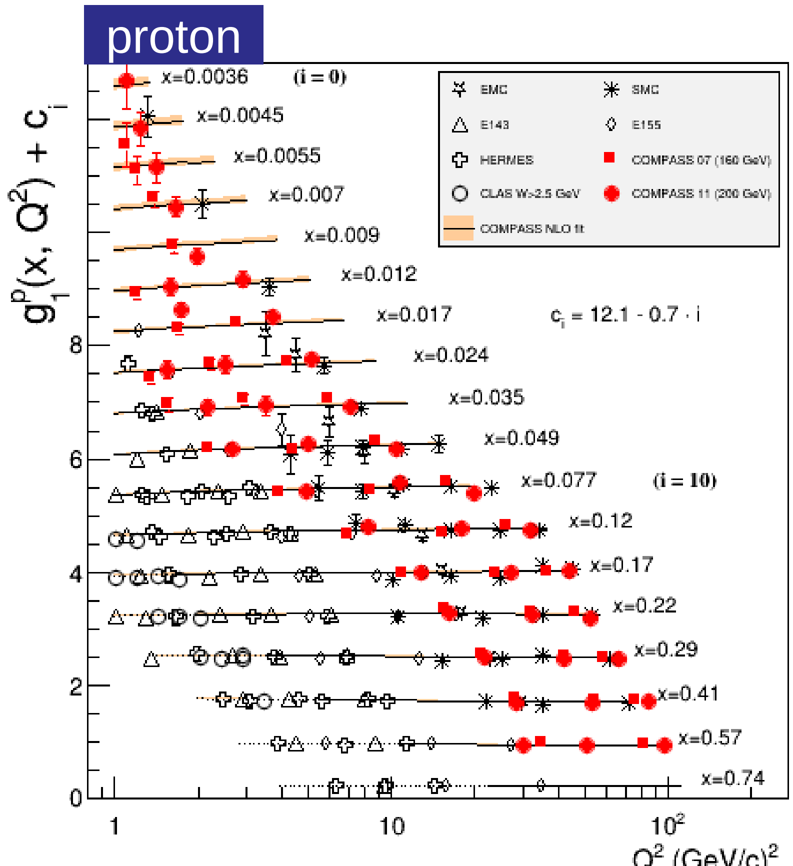
DIS

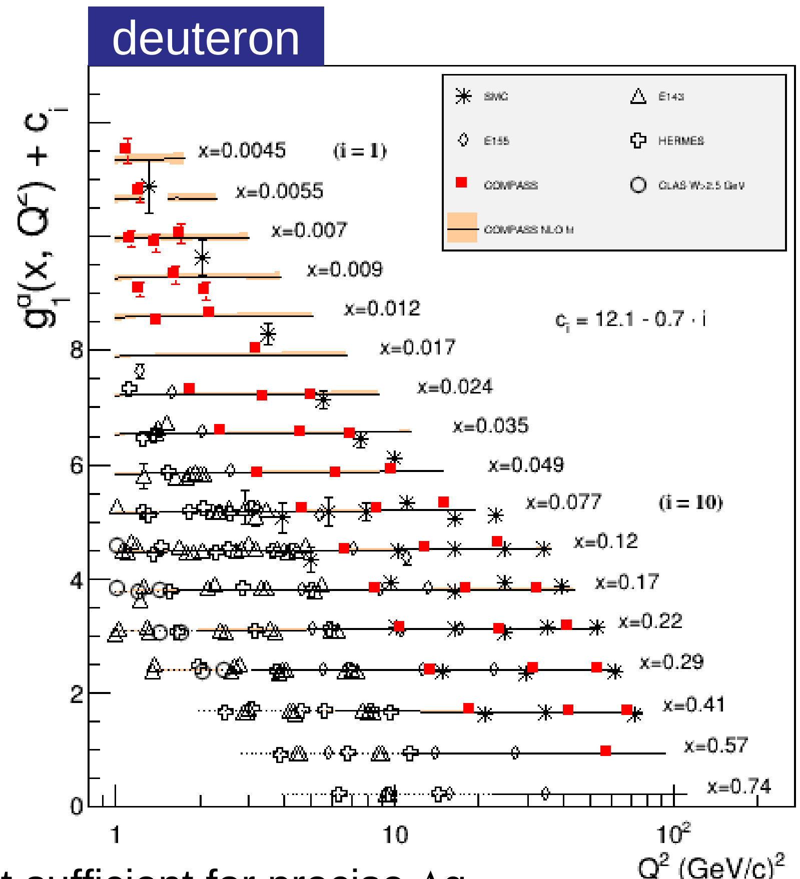


Polarized Deep Inelastic Scattering
➔ Nucleon spin structure functions g_1

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

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





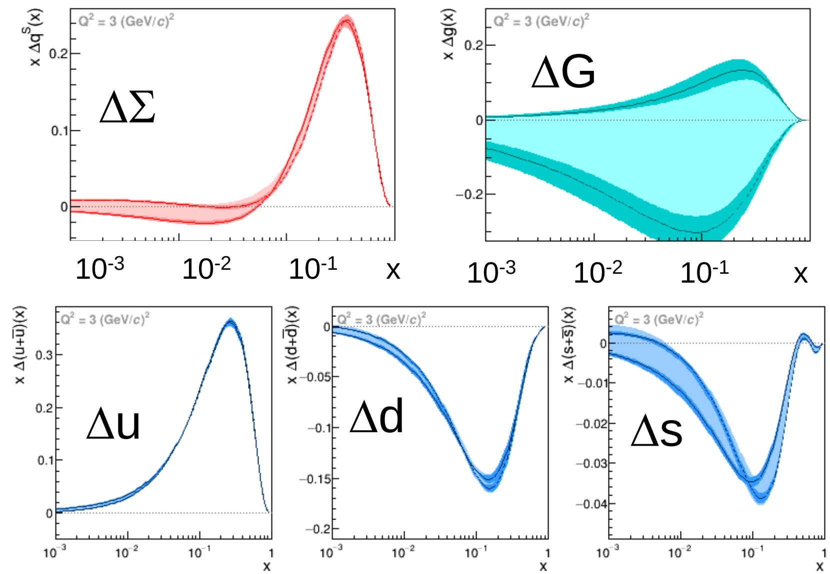
However x and Q^2 coverage in DIS not yet sufficient for precise Δg
Need to use constraint from pp data (as in DSSV, NNPDF… fits)

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)
- Extract $\Delta\Sigma$ Quarks ΔG Gluons

COMPASS, PLB 753 (2016) 18



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

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

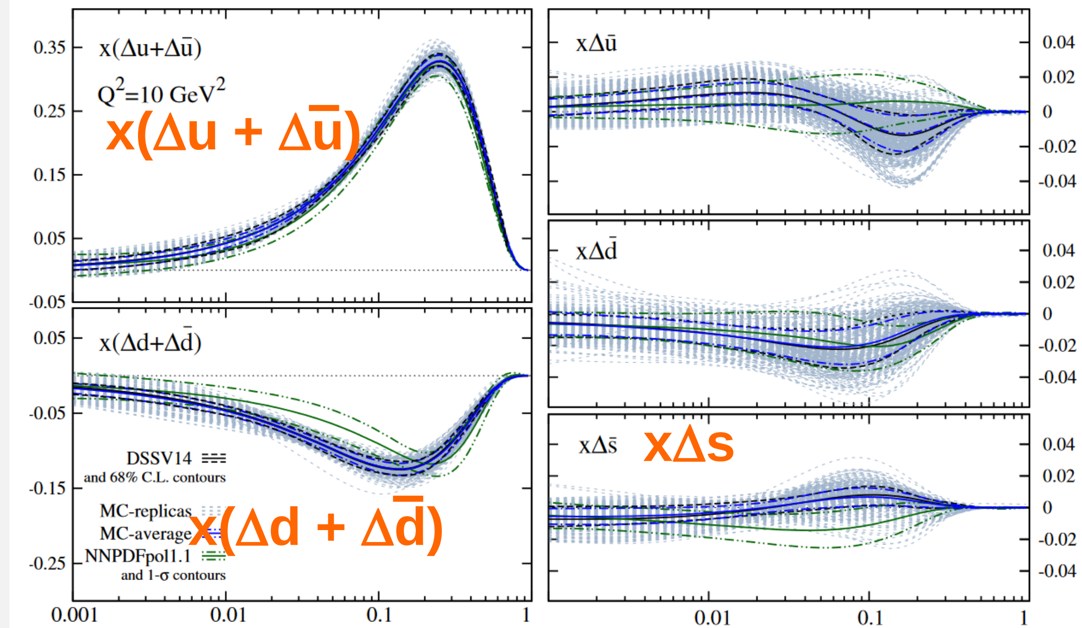
$\Delta\Sigma = 0.31\ (5)$ at $Q^2=3\ (GeV/c)^2$

Still large uncertainty coming from the bad knowledge of functional forms

Global fits to polarized PDFs (I)

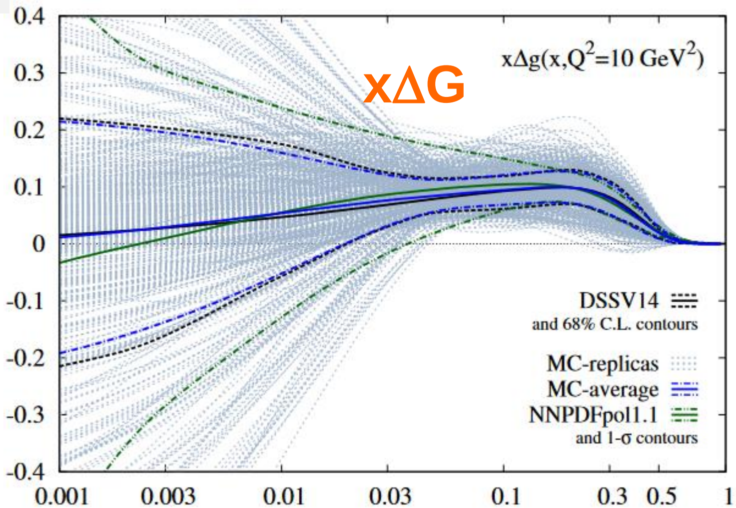
Fits to world data, including $\vec{p}\,\vec{p}$ collider data. Many fitters. Some examples:

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**

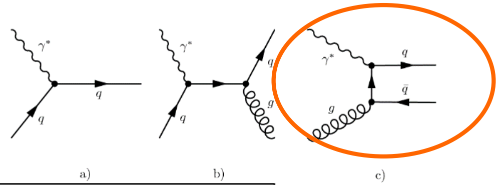
~ unknown **ΔG**, below x~0.05

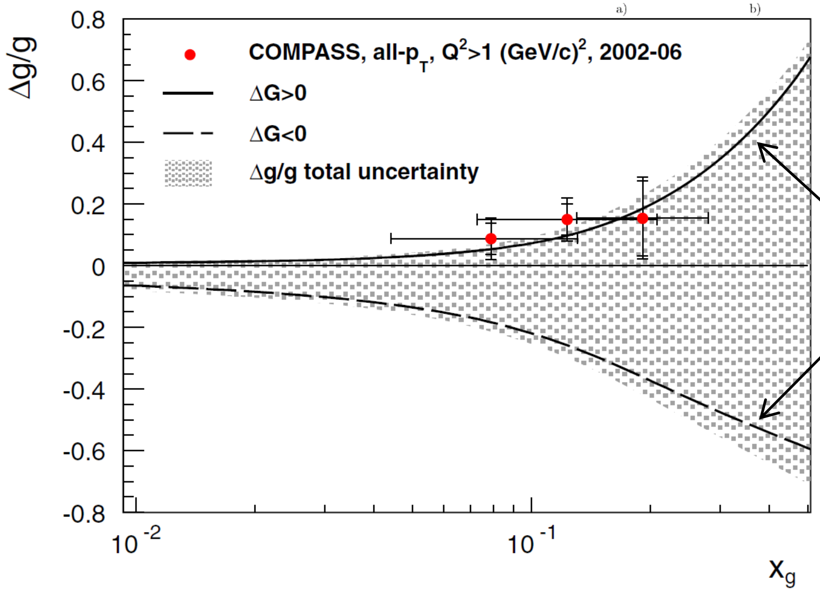
Gluon helicity ΔG/G direct measurement

Photon Gluon Fusion

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

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





Extraction at LO:

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

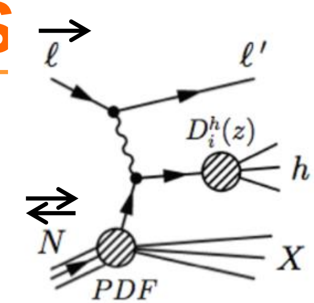
Solutions from COMPASS NLO QCD fit of g_1 world data (see before)

EPJC 77 (2017) 209

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

$$\int_{0.05}^{0.2} \Delta g(x)\mathrm{d}x \simeq 0.20$$

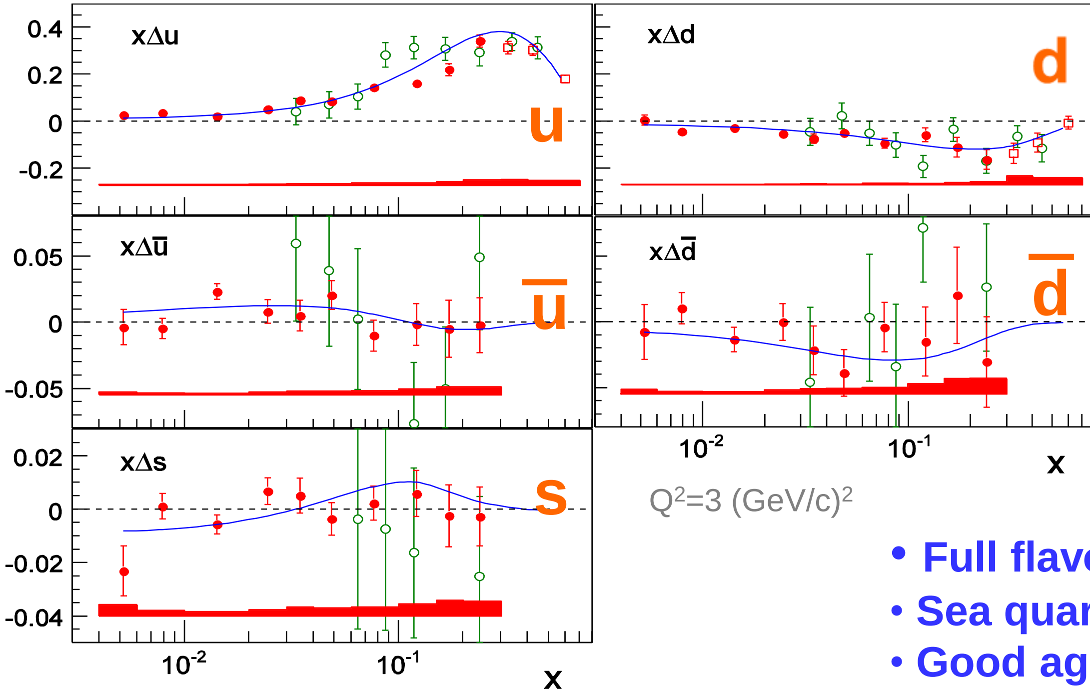
Quark helicities from semi-inclusive DIS



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

Outgoing hadron tags quark flavor
(via quark fragmentation functions)

Flavour separation of quark helicities:



o **HERMES**
PRD71(2005)012003

• **COMPASS**
PLB693(2010)227, using DSS-07 FFs

__ DSSV at NLO

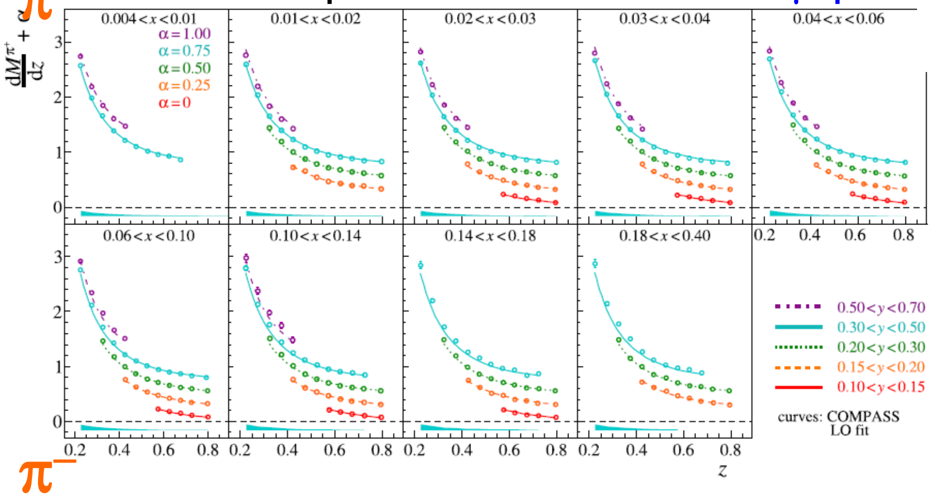
- **Full flavour separation → x~0.004**
- **Sea quark distributions ~ zero**
- **Good agreement with global fits**

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

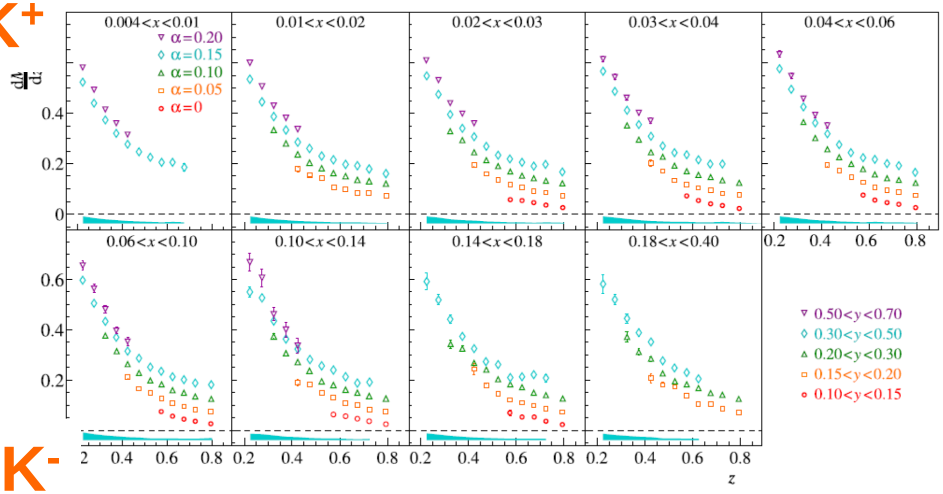
COMPASS π and K multiplicities vs z in (x,y) bins

from unpolarized SIDIS data: μ p → μ' π/K X

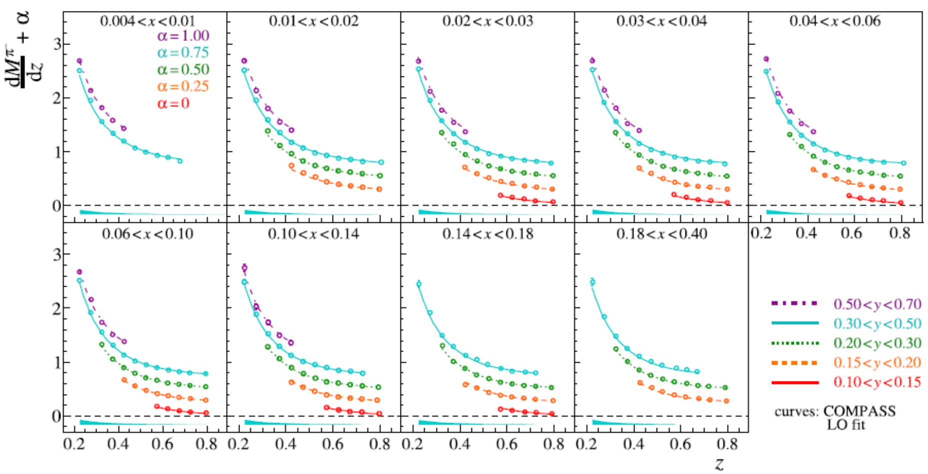
π+



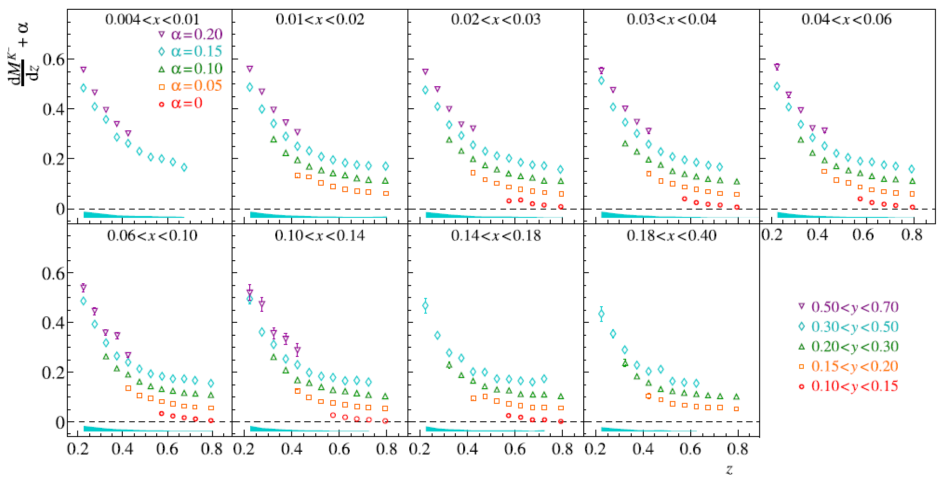
K+



π−



K-



- More than 1200 points in total, various Q^2 staggered vertically for clarity
- Strong z dependance
- $M(\pi^+) \sim M(\pi^-)$ and $M(K^+) > M(K^-)$

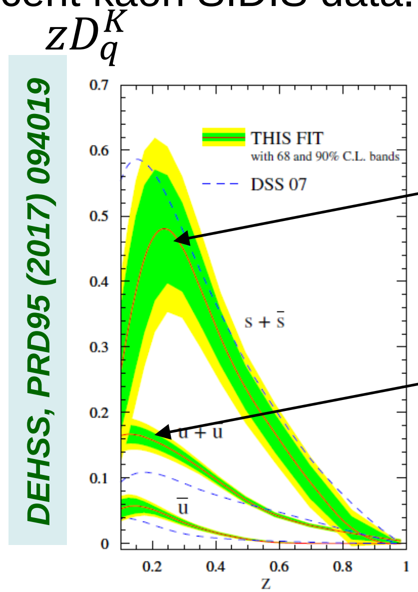
PLB 764 (2017) 001
PLB 767 (2017) 133

Kaons- Quark fragmentation functions from NLO fits

Extensive sets of SIDIS kaon data change significantly flavor decomposition of FFs (& PDFs)

COMPASS PLB 767 (2017) 133

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

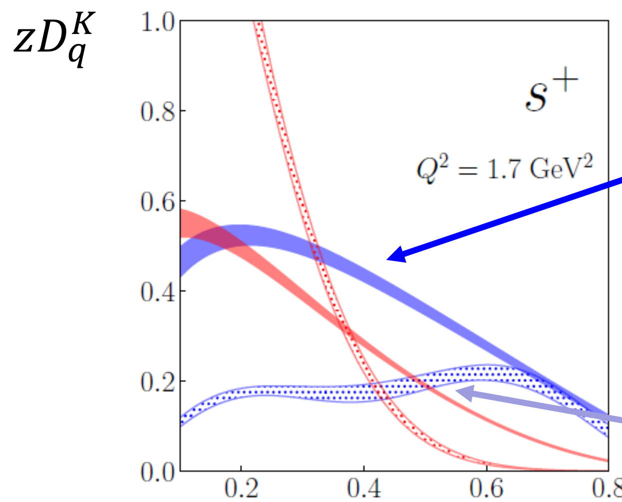


D_S^K smaller than in DSS-07

D_U^K larger than in DSS-07

z

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



D_S^K w SIDIS agrees with DEHSS

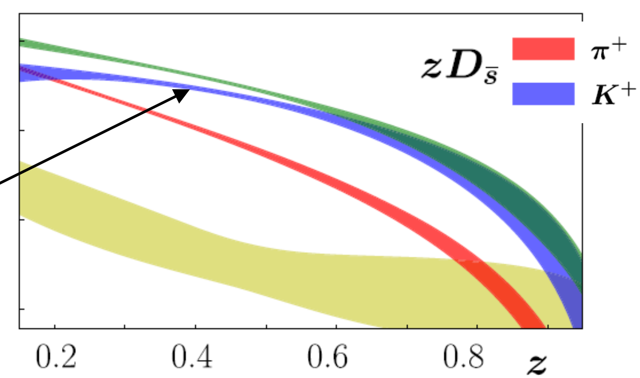
D_S^K w/o SIDIS

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'



→worth revisiting Δs(x) extraction from SIDIS data

R_K= M(K$^-$)/ M(K$^+$) kaon muliplicity ratio at high z

$\mu\, p \rightarrow \mu'\ K\ X$

Motivation: High *z* region not studied so far
Most experimental and theoretical uncertainties cancel in ratio

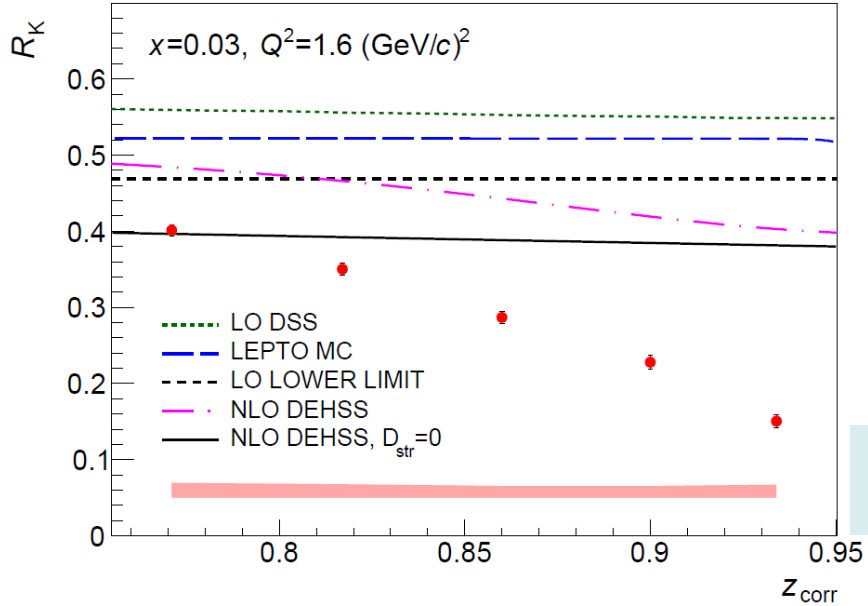
Simple estimation at LO, proton target
with assumptions (D_{unf} neglected…) :
and assuming $s = \bar{s}$,
→ **R_K lower bound** driven by light quarks :

$$R_K = \frac{4\bar{u}D_{fav} + sD_{str}}{4uD_{fav} + \bar{s}D_{str}}.$$

$$R_K > \frac{\bar{u}}{u}$$ for a proton target

$$R_K > \frac{\bar{u}+\bar{d}}{u+d}$$ for a deuteron target

In contradiction with data:



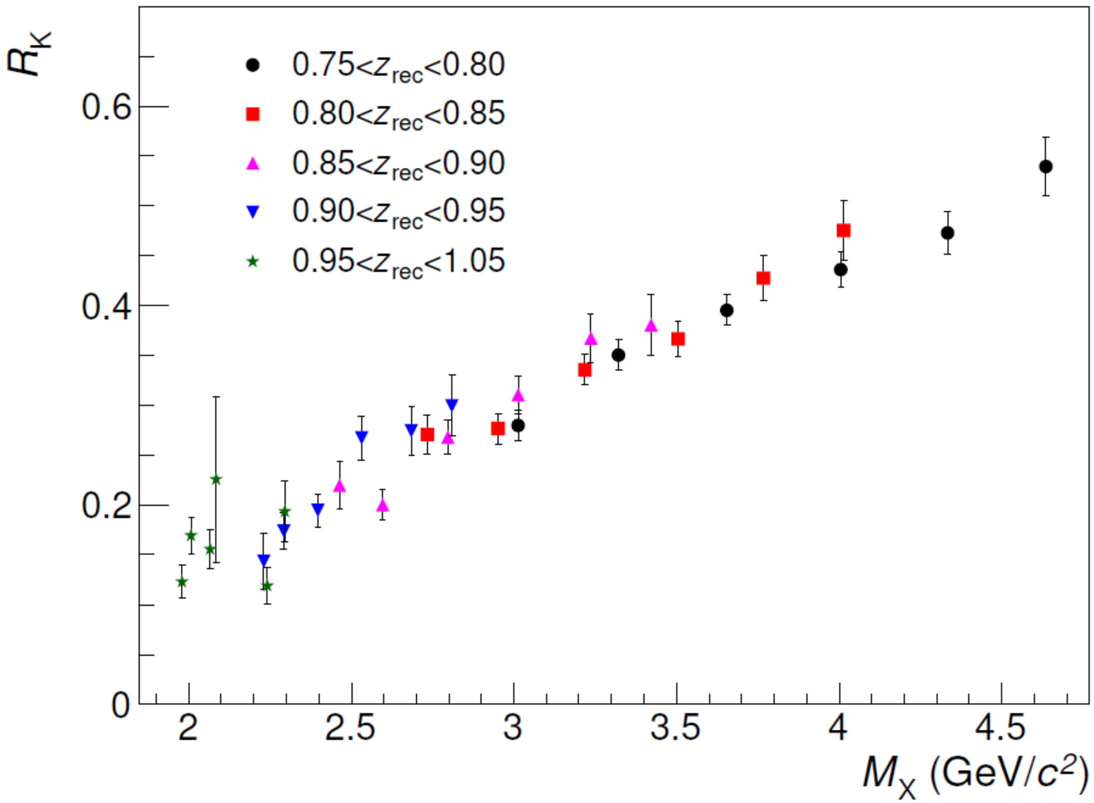
COMPASS, PLB 786 (2018) 390

M(K$^-$) / M(K$^+$) ratio well below expectations at high *z*

M(K⁻)/ M(K⁺)   Results vs missing mass M_X

High z kaon → reduced phase space for other particles
Study missing mass behaviour

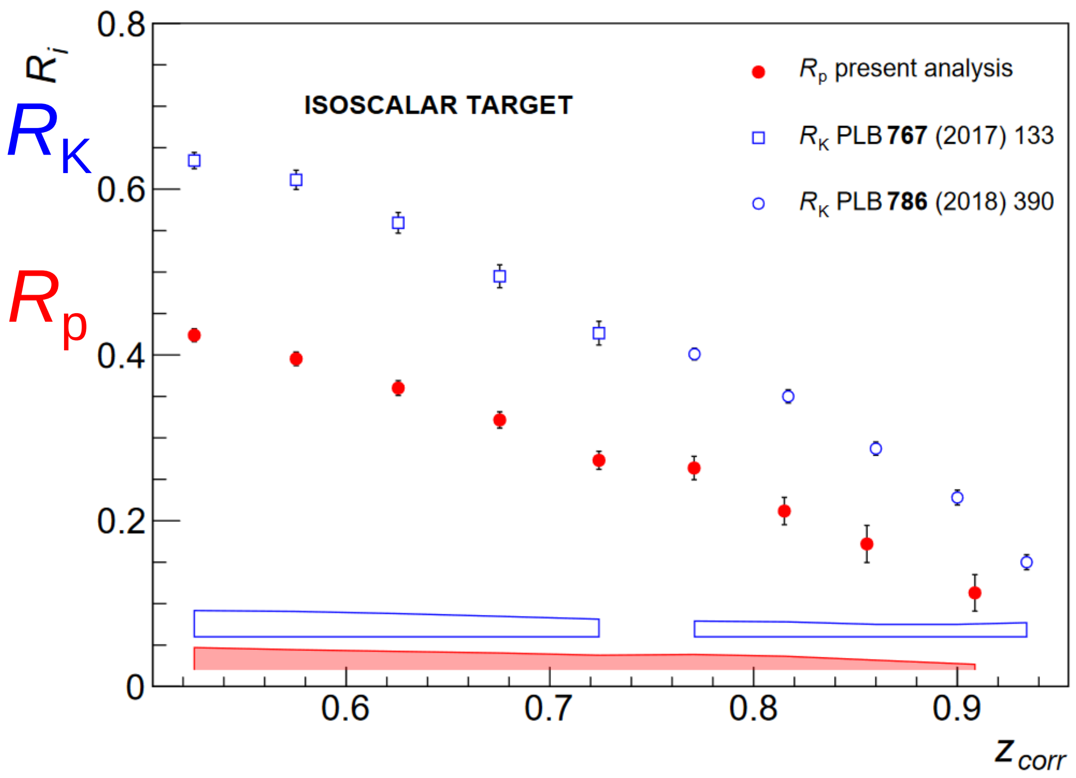
$$M_X = \sqrt{M_p^2 + 2M_p\nu(1-z) - Q^2(1-z)^2}$$



- **M(K⁻)/ M(K⁺) shows unexpected strong rise with M_X**
- **Suggests to take into account the available phase space for hadronisation, in the formalism**

$R_p = M(\bar{p}) / M(p)$

Stronger suppression of $\bar{p}$ vs p,
compared to K^- vs K^+.



PLB 807 (2020) 135600

Transverse Momentum Dependent distributions

TMDs

- spin of the nucleon
- spin of the parton
- k_T of the parton

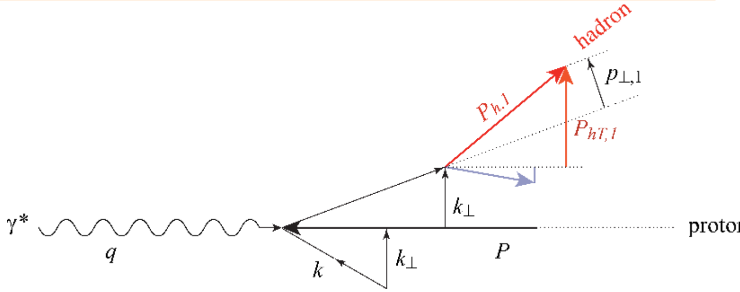
Quark / Nucleon	U	L	T
U	number density $f_1^{q,g}(x, k_T^2)$		Boer-Mulders $h_1^{\perp q,g}(x, k_T^2)$
L		Helicity $g_{1L}^{q,g}(x, k_T^2)$	worm-gear L $h_{1L}^{\perp q,g}(x, k_T^2)$
T	Sivers $f_{1T}^{\perp q,g}(x, k_T^2)$	Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x, k_T^2)$	Transversity $h_1^{q,g}(x, k_T^2)$ Pretzelosity $h_{1T}^{\perp q,g}(x, k_T^2)$

Transverse Momentum Dependent distr. : TMDs

Importance of hadron transverse momentum p_T :

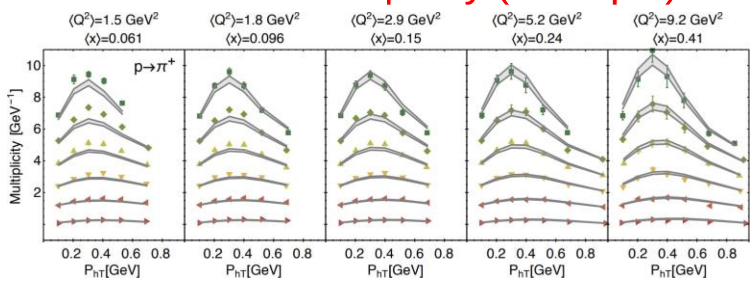
P_T dependence results from:

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

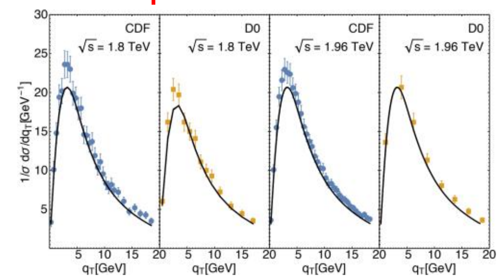


Global analyses of SIDIS, Drell-Yan and Z production data with TMD Q^2 evolution

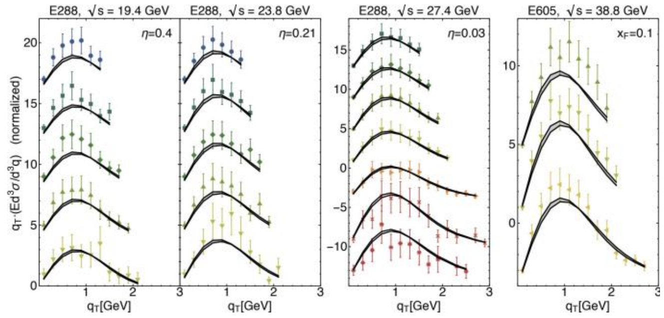
SIDIS multiplicity (example)



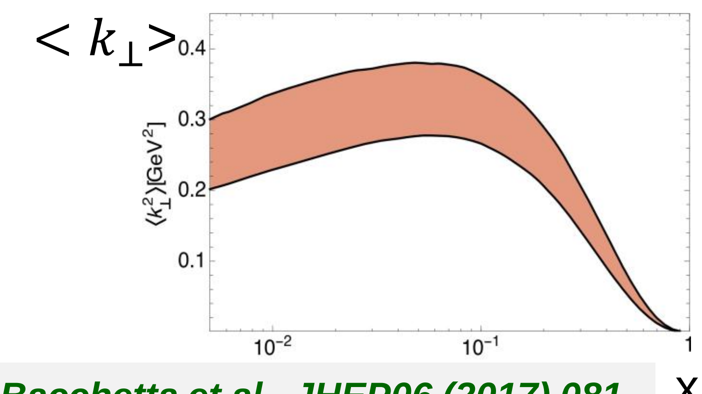
Z production



Drell-Yan cross section



Transverse momentum distribution



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

TMDs- Collins and Sivers functions (SIDIS)

- Access via **SIDIS**, transversely polarized target

$$\mu\, p^{\uparrow} \rightarrow \mu\, h^{+/-}\, X$$

- 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.

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

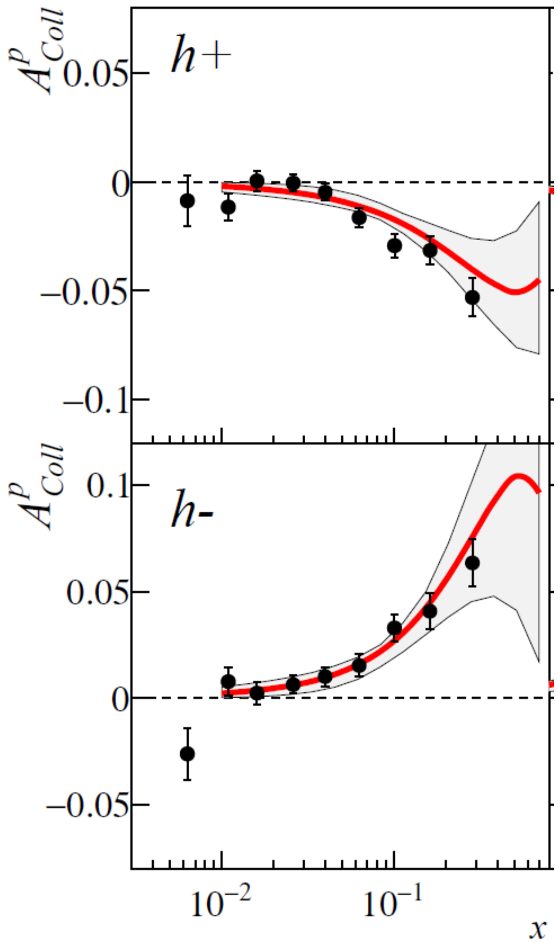
Collins TMD fragmentation function, depends on spin, and hadron p_T

Sivers

Unpolarized quark fragmentation function

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

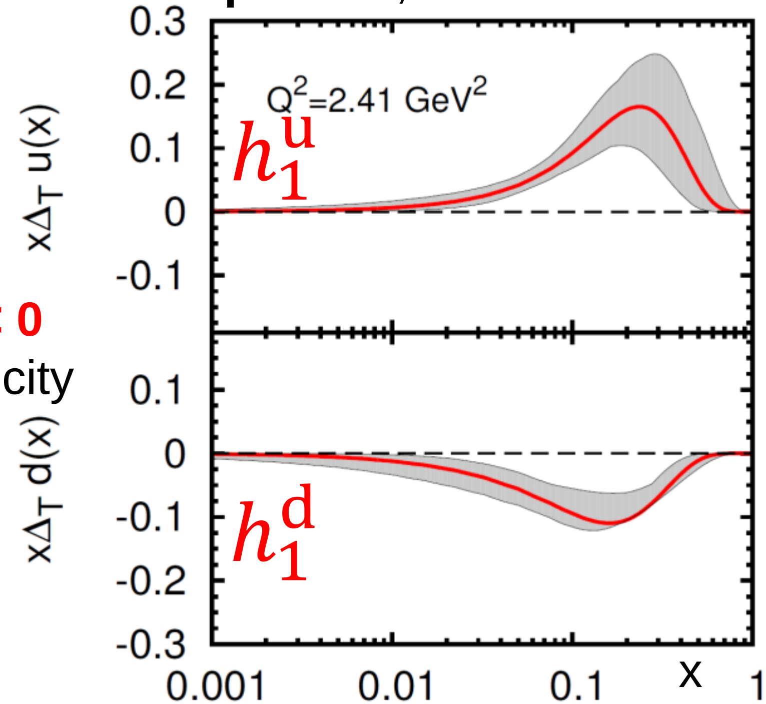
TMDs, Collins asymmetry → Transversity h_1



- **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

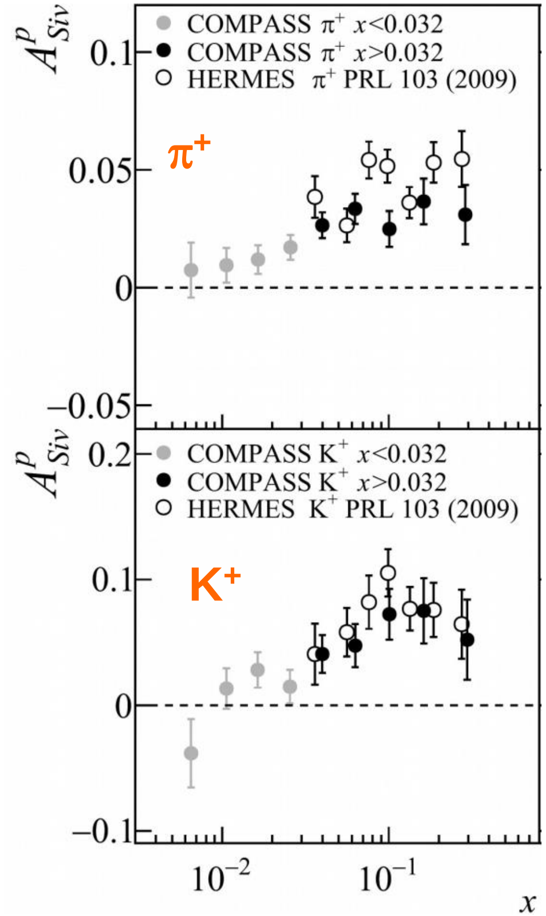
HERMES PLB 693(2010)
COMPASS PLB 744 (2015)

F. Kunne

Anselmino et al., PRD87(2013) 094019)

TMDs, Sivers asymmetry → Sivers function

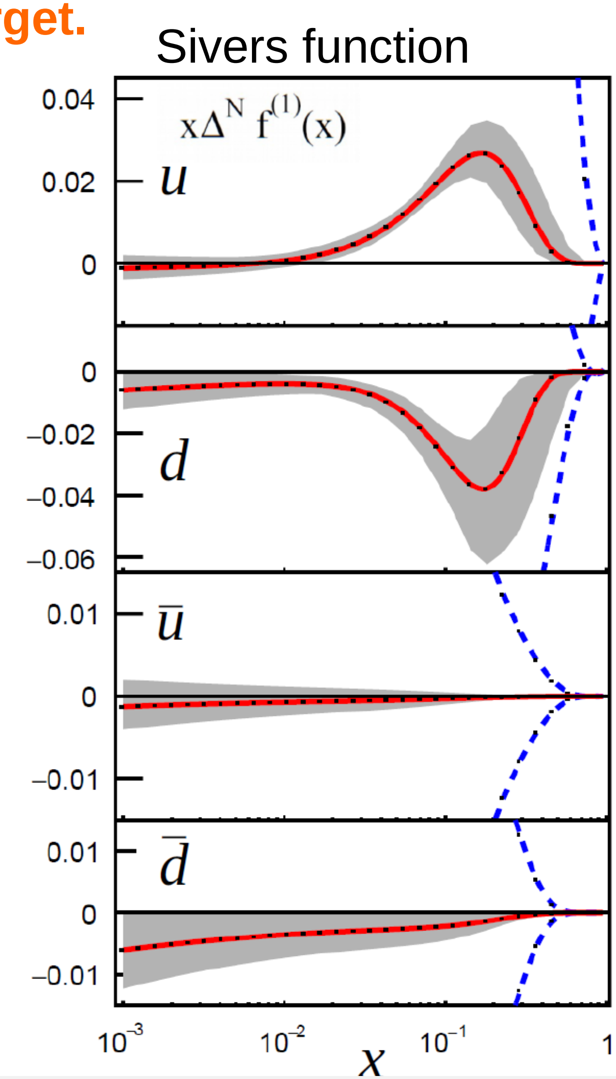
Correlation between Nucleon spin & quark transverse momentum k_T



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



Anselmino et al., JHEP04 (2017)046

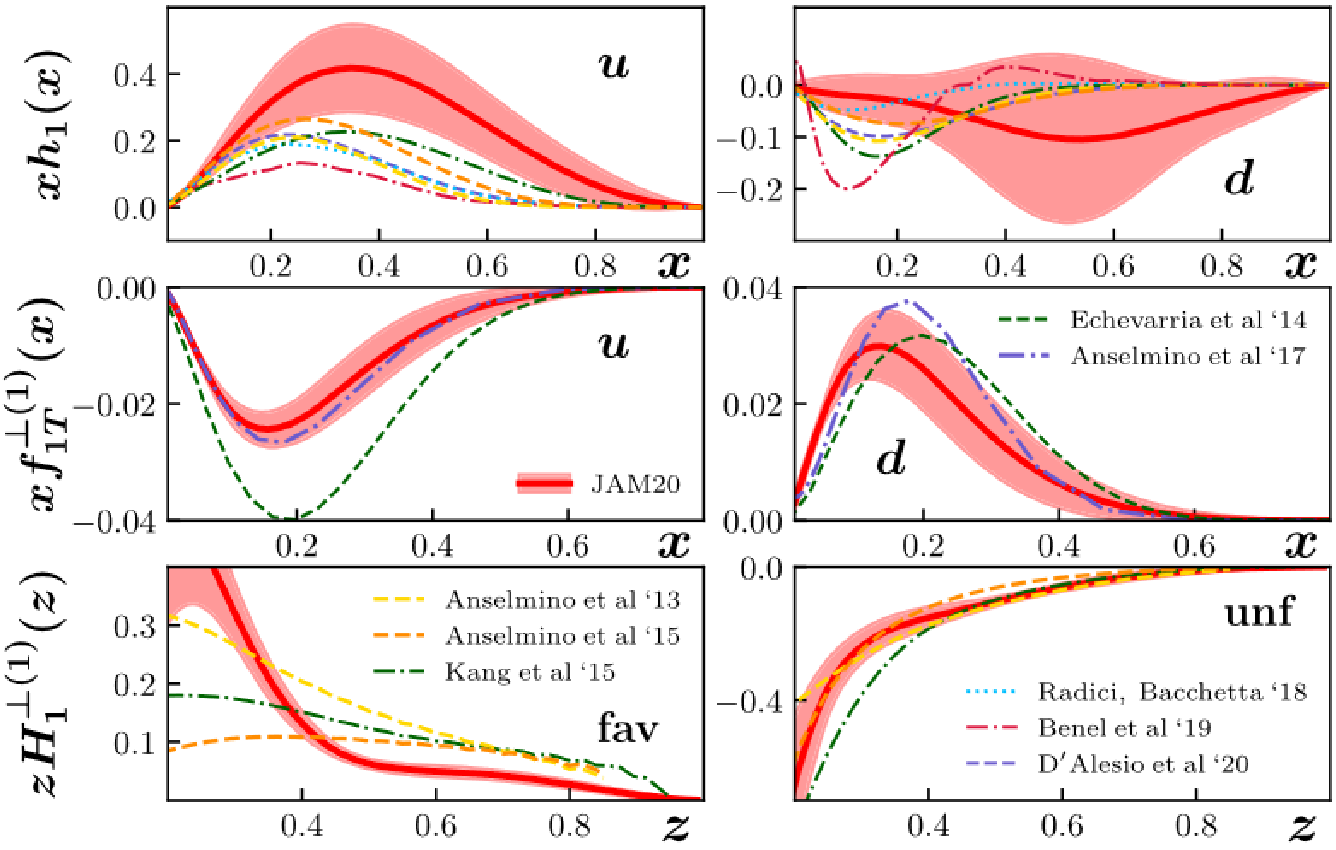
TMDs Collins & Sivers. Recent global fits

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)

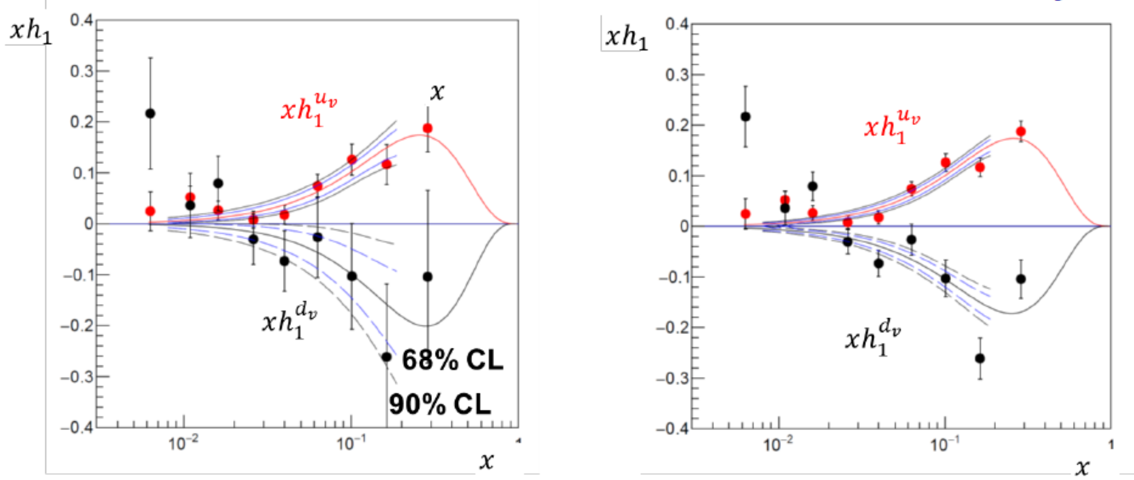
TMDs, Transversity h_1 / tensor charge

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

With 2022 data, expect improvement on uncertainties by factors of : ~2 (u), ~ 3 (d)

TMDs, new approach: weighted asymmetries

SIDIS, target transverse spin

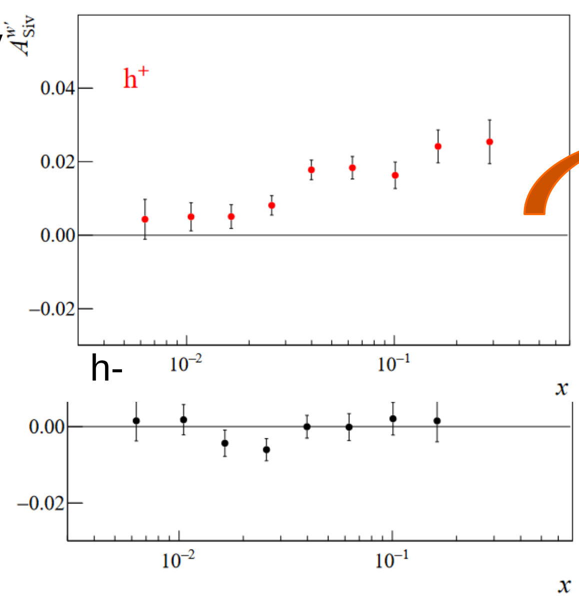
$$A_{Siv}^{(p_T^h/zM)}(x,z) = 2\frac{\sum_q e_q^2 f_{1T}^{\perp(1)\,q}(x)\cdot D_1^q(z)}{\sum_q e_q^2 f_1^q(x)\cdot D_1^q(z)},$$

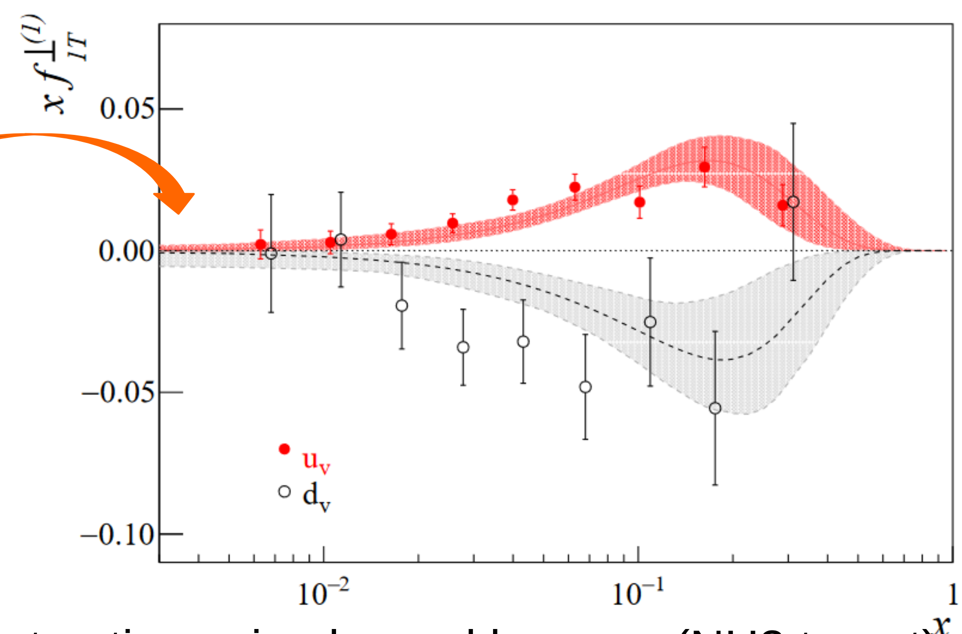
$$f_{1T}^{\perp(1)}(x,Q^2) = \int d^2k_T \frac{k_T^2}{2M^2} f_{1T}^{\perp}(x,k_T,Q^2).$$

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)

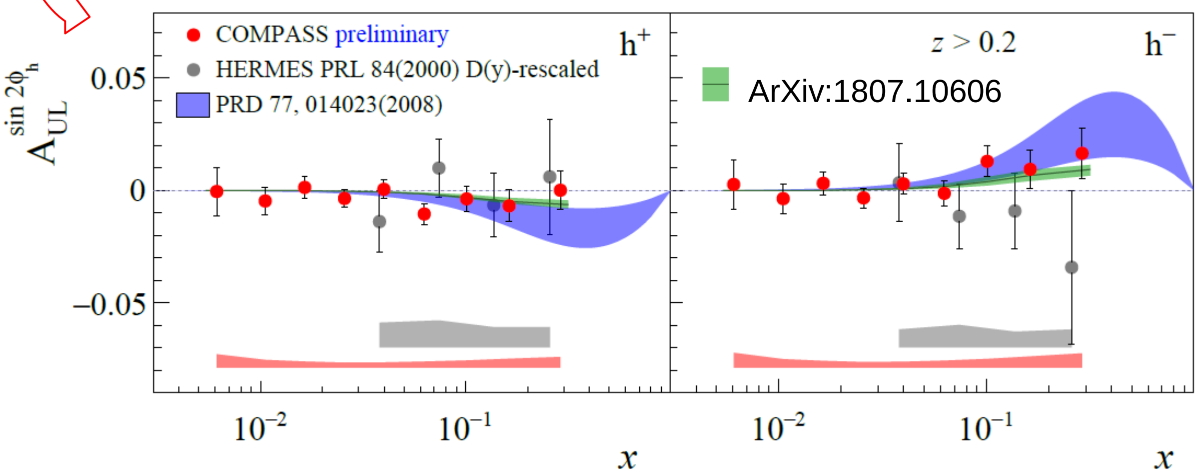
TMDs, Target spi-dnependent azimuthal asymmetries

Leading twist asymmetries

LO LSA/TSA	twist-2: PDF $\otimes$ FF	
$A_{UL}^{\sin(2\phi_h)}$	$h_{1L}^{\perp q} \otimes H_{1q}^{\perp h}$	
A_{LL}	$g_{1L}^{q} \otimes D_{1q}^{h}$	*g1*
$A_{UT}^{\sin(\phi_h-\phi_S)}$	$f_{1T}^{\perp q} \otimes D_{1q}^{h}$	*Sivers*
$A_{UT}^{\sin(\phi_h+\phi_S-\pi)}$	$h_{1}^{q} \otimes H_{1q}^{\perp h}$	*Collins*
$A_{UT}^{\sin(3\phi_h-\phi_S)}$	$h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	*Pretzelosity: (deviation of spin density from spherical shape)*
$A_{LT}^{\cos(\phi_h-\phi_S)}$	$g_{1T}^{q} \otimes D_{1q}^{h}$	

Results on TMDs are characterised by an unprecedented precision, covering a wider kinematic range and many observables.

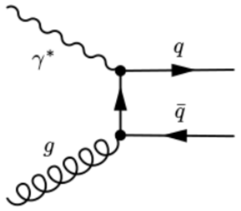
Example $A_{UL}(x)$

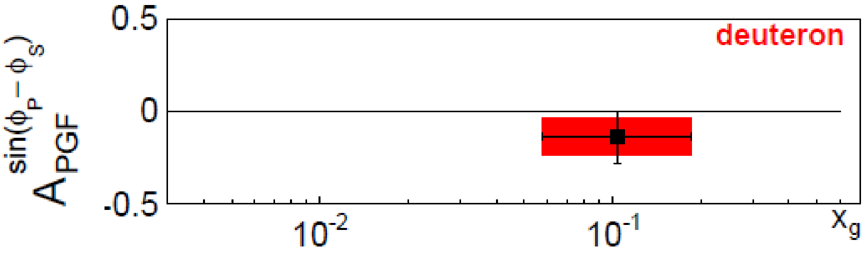


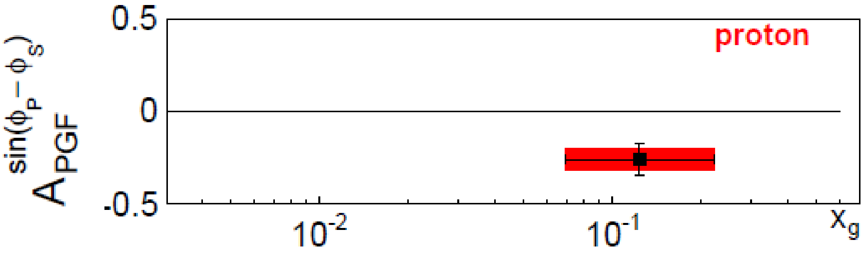
TMDs, Sivers gluon

Sivers asymmetry:
correlation between nucleon transverse spin
& **parton transverse momentum**.

Measured in SIDIS with transversely polarized target, (already done for quarks), now for **gluons** from azimuthal asymmetry for **PGF process**







$$A_{PGF}^{Siv,d} = -0.14 \pm 0.15(\text{stat.}) \pm 0.10(\text{syst.})$$
$$\langle x_g \rangle = 0.13$$

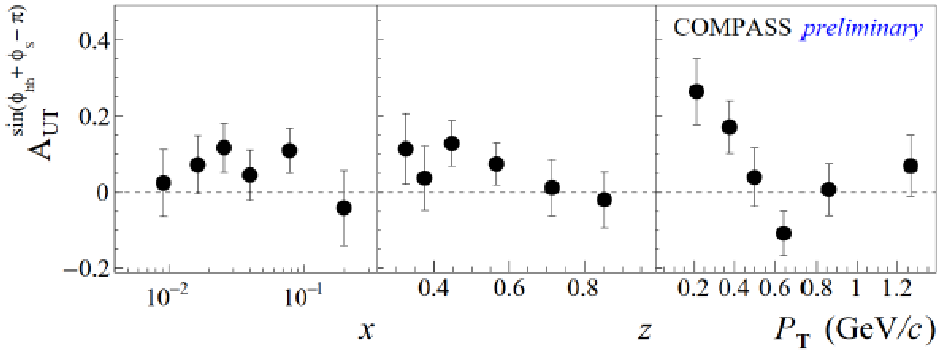
$$A_{PGF}^{Siv,p} = -0.26 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.})$$
$$\langle x_g \rangle = 0.15$$

COMPASS Phys. Lett. B 772, 854 (2017).

TMDs, ρ^0

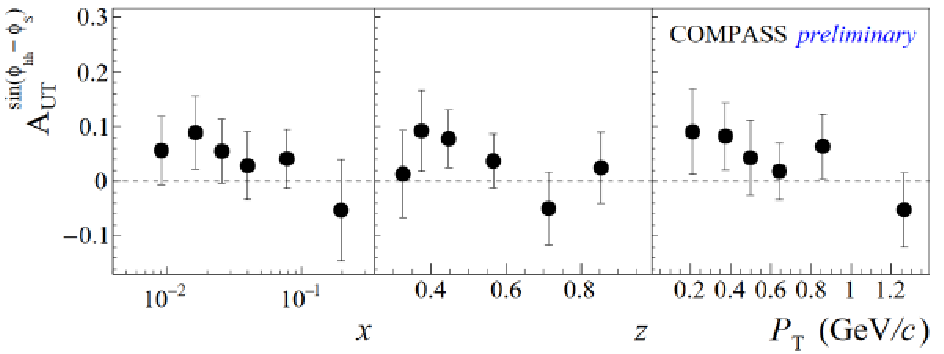
ρ^0 COMPASS first Collins and Sivers measurement

A.Moretti SPIN21



ρ^0 Collins

positive asymmetry
opposite to π+, as expected from models
large at small p_T



ρ^0 Sivers

positive asymmetry,
similarly to π+, as expected

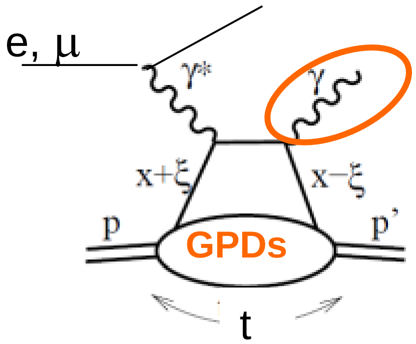
GPDs - Generalized Parton Distributions

Physics goals:

160 GeV μ beam

$\mu\ p \rightarrow \mu'\ p\ \gamma$

- **3D mapping of nucleon**
- **access to Orbital Angular Momentum**



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

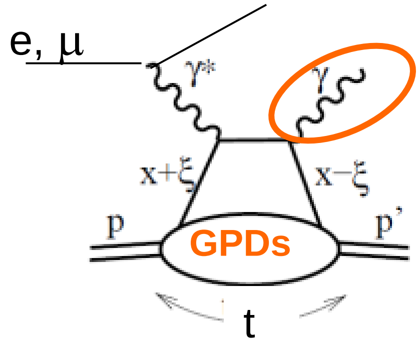
DVCS interferes with Bethe-Heitler process
→ Can use interference terms or pure DVCS production
with appropriate combinations of beam sign and polarization.

Way to it:

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

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

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



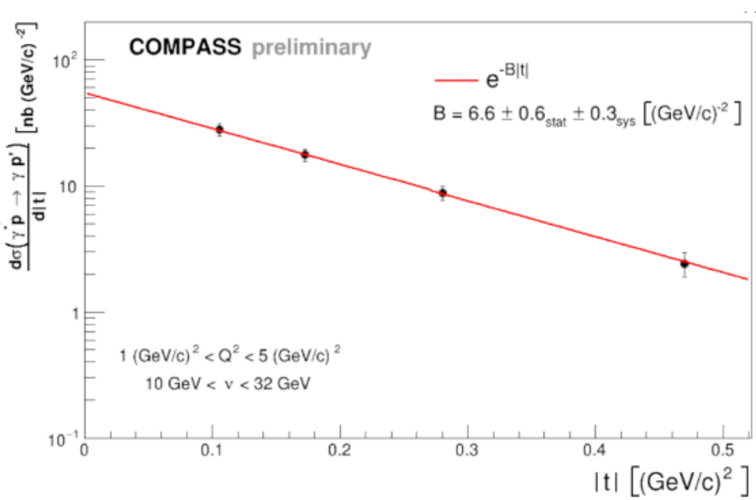
Measurement of proton transverse size vs x_B

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

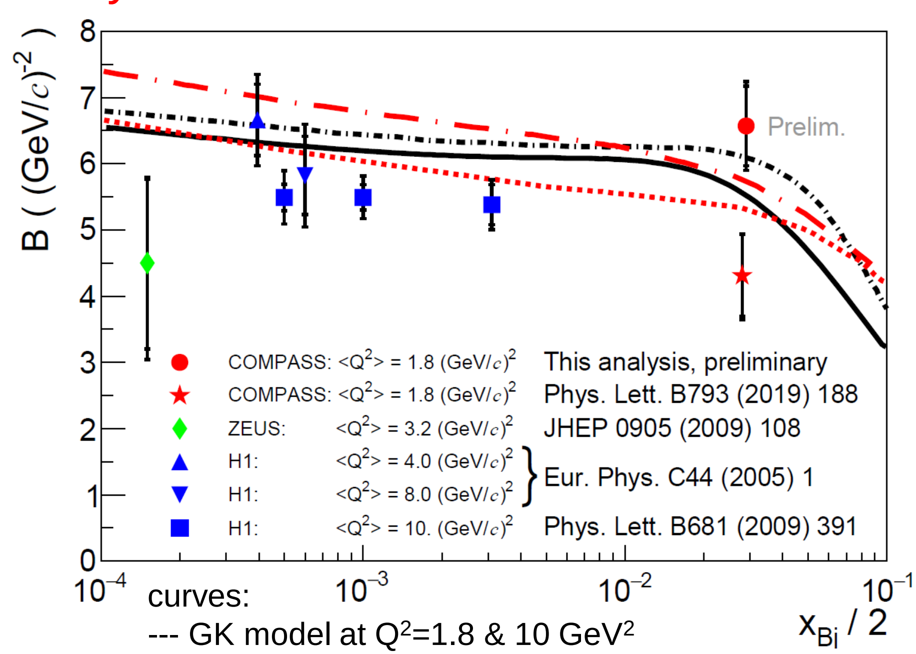
$$B(x_B) = ½ \langle r_\perp^{\,2}(x_B)\rangle$$

Combining data from μ+ and μ- beams
measure t-slope of DVCS cross section
→ x dependence of transverse size of the nucleon

New preliminary COMPASS result:



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



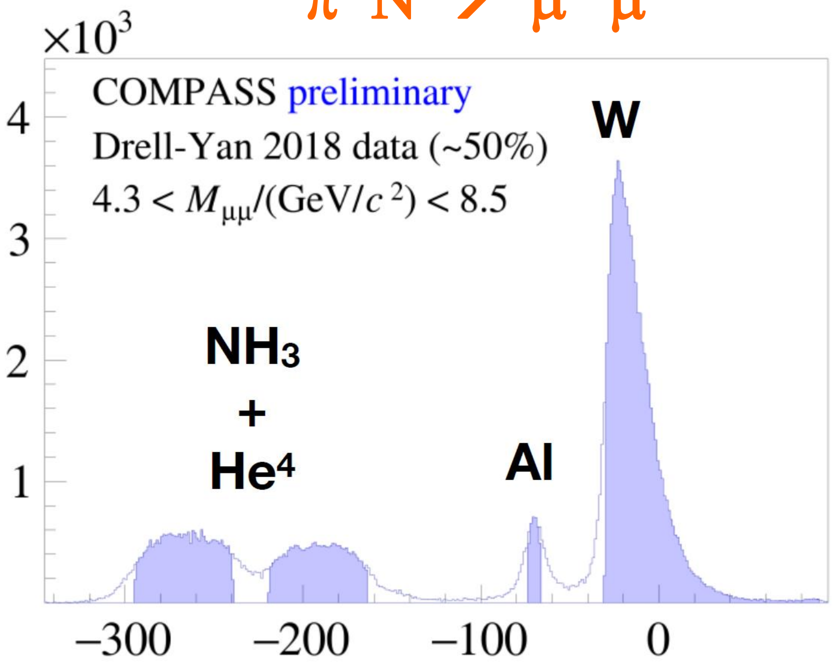
curves:
--- GK model at Q^2=1.8 & 10 GeV^2
--- KM15 at Q^2=1.8 & 10 GeV^2

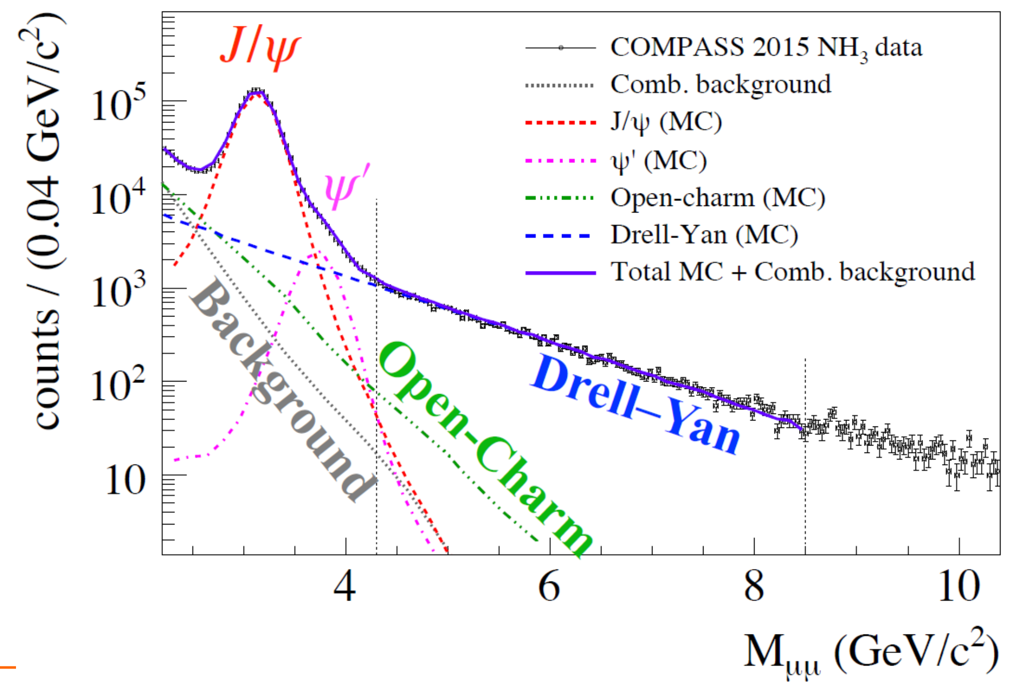
See SPIN 2021, J.Giarra talk

Drell-Yan and J/ψ from π induced dimuon production

$\pi\ N \rightarrow \mu^+ \mu^-$

190 GeV π beam





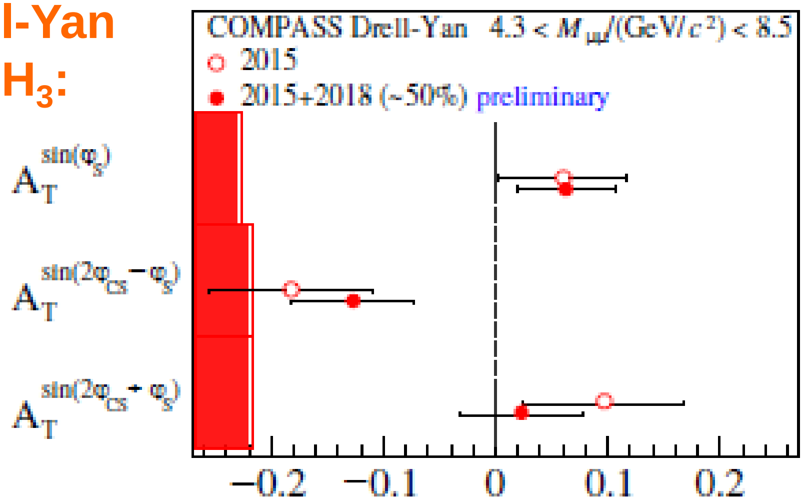
Drell-Yan : - polarized NH_3 target → results on TMDs (SIDIS/DY sign change)
- W target → Lam-Tung relation study

J/ψ production high statistics data:
- **J/ψ** TSA and cross-section analysis in progress
- study production mechanism, two processes:
  - q-qbar annihilation → quark TMDs
  - g g fusion → gluon TMDs
- search for **J/ψ** pairs

TMDs in polarized Drell-Yan

π induced Drell-Yan on polarized NH_3:

$\pi\ N \rightarrow \mu^+ \mu^-$



Sivers $\sim 1\sigma$ above zero

Transversity $\sim 2\sigma$ below zero

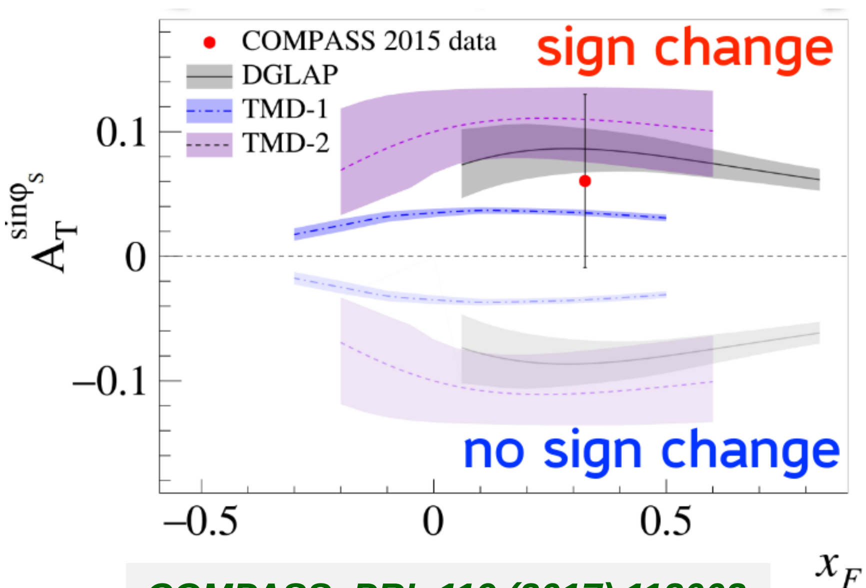
Pretzelosity $\sim 1\sigma$ above zero

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

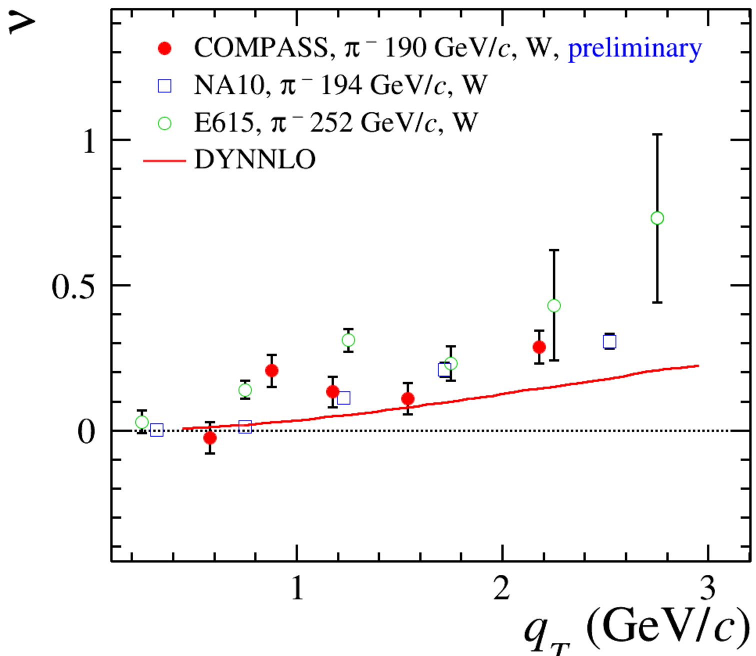


COMPASS, PRL 119 (2017) 112002

Preliminary results on Lam-Tung relation

π induced Drell-Yan, W target. $\pi W \rightarrow \mu^+ \mu^-$

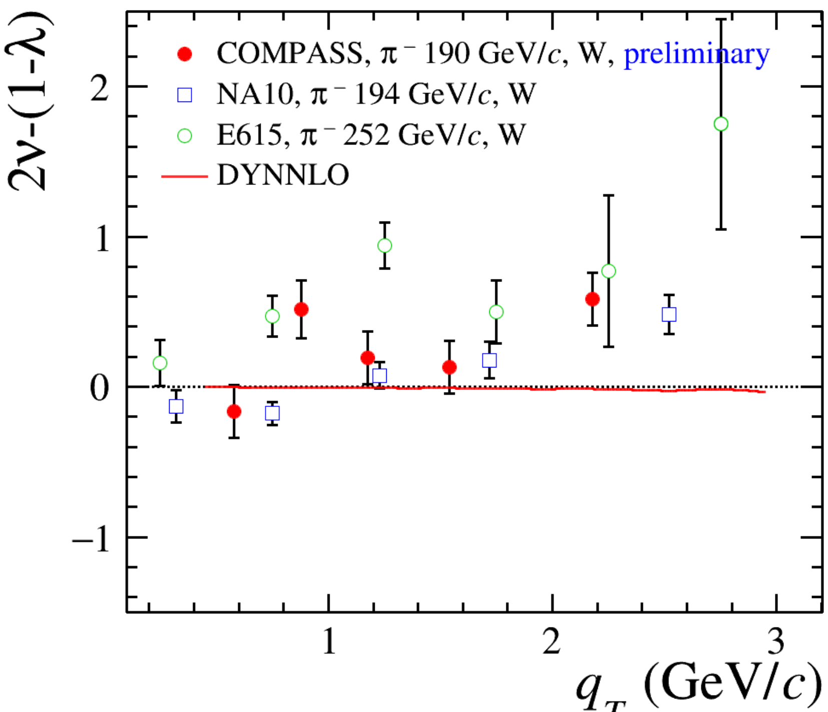
$$\frac{d\sigma}{d\Omega} \propto \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1+\lambda\cos^2\theta_{CS}+\mu\sin 2\theta_{CS}\cos\varphi_{CS}+\frac{\nu}{2}\sin^2\theta_{CS}\cos 2\varphi_{CS}\right]$$ at LO



Data deviate from pQCD calculation
→ Presence of non-zero TMD Boer-Mulders contribution

Lam-Tung violation quantity $2\nu - (1-\lambda)$

Non zero cos 2φ dependence



- Possible violation of Lam-Tung relation
- cos 2φ dependence
- Results compatible with previous data

J/ψ pair production in π –N collisions

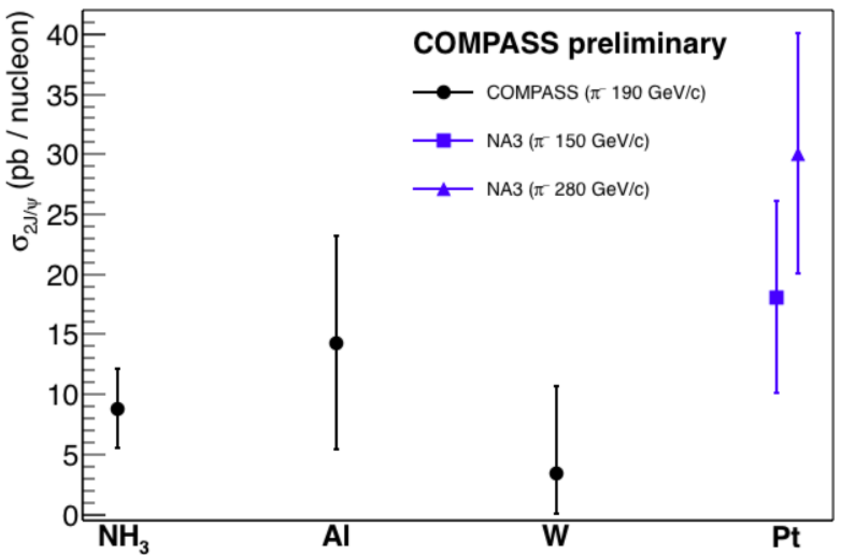
Search for J/ψ pairs

Goals:

- investigate possible intrinsic charm
- search for T_{4c} states

2-J/ψ cross-section estimation for NH_3, Al and W targets:

(25, 4 and 21 events)



See Qat 2021, A.Gridin talk

Result consistent with single parton scattering (SPS) mechanism:

$q\bar{q} \rightarrow 2\,J/\psi$

$g\,g \rightarrow 2\,J/\psi$

No sign of intrinsic charm d u c c̄ c c̄

Summary –

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; agrees with Lattice QCD
Flavor decomposition from SIDIS, down to x ~0.004.

Quark Fragmentation functions:

High *z* data for K^-/K^+ and pbar/p hadron multiplicity ratios
- Data disagree with current NLO QCD calculations **at high *z* and low ν**
- Unexpected rise of ratio $M(K^+) / M(K^-)$ with missing mass, suggesting to take into account the available phase space for hadronisation in formlism.

Transverse Momentum Dependent parton distributions

Extensive and precise results on all azimuthal asymmetries
Global analyses

GPDs via DVCS: b slope prelim. result
Many data coming and promising framework for global analyses.

Polarized Drell-Yan First ever measurement → Sivers asymmetry (sign change vs SIDIS)
Angular distributions: TMDs, Lam-Tung relation…