New experimental results on the (spin) structure of the nucleon

Catarina Quintans, LIP Lisbon
9th September 2021

LIP
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

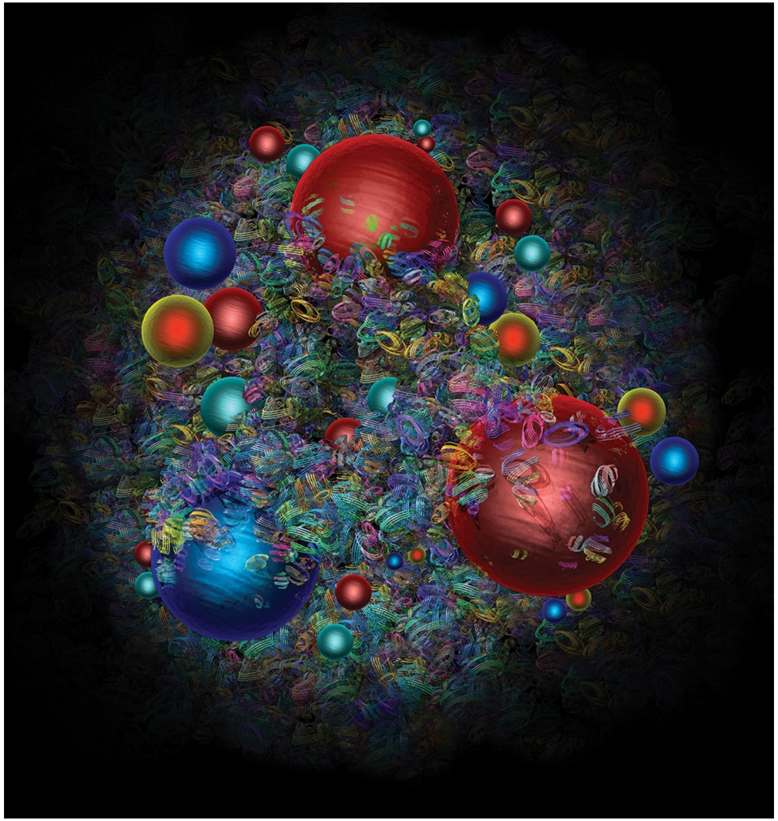
FCT Fundação para a Ciência e a Tecnologia

Disclaimer:

I did not try to be exhaustive in this talk. I made a (personal) selection of new/recent results, instead.

Most plots, graphs, diagrams, etc were taken from your talks (thank you)

Understanding the proton...



An artist's impression of the mayhem of quarks and gluons inside the proton. Credit: D Dominguez/CERN.

i.e. understanding the matter we are made of

...means (also) understanding the spin-momentum correlations in place

The spin crisis of the '80s (EMC@CERN result: $\Delta\Sigma \ll 1$) turned into a spin puzzle

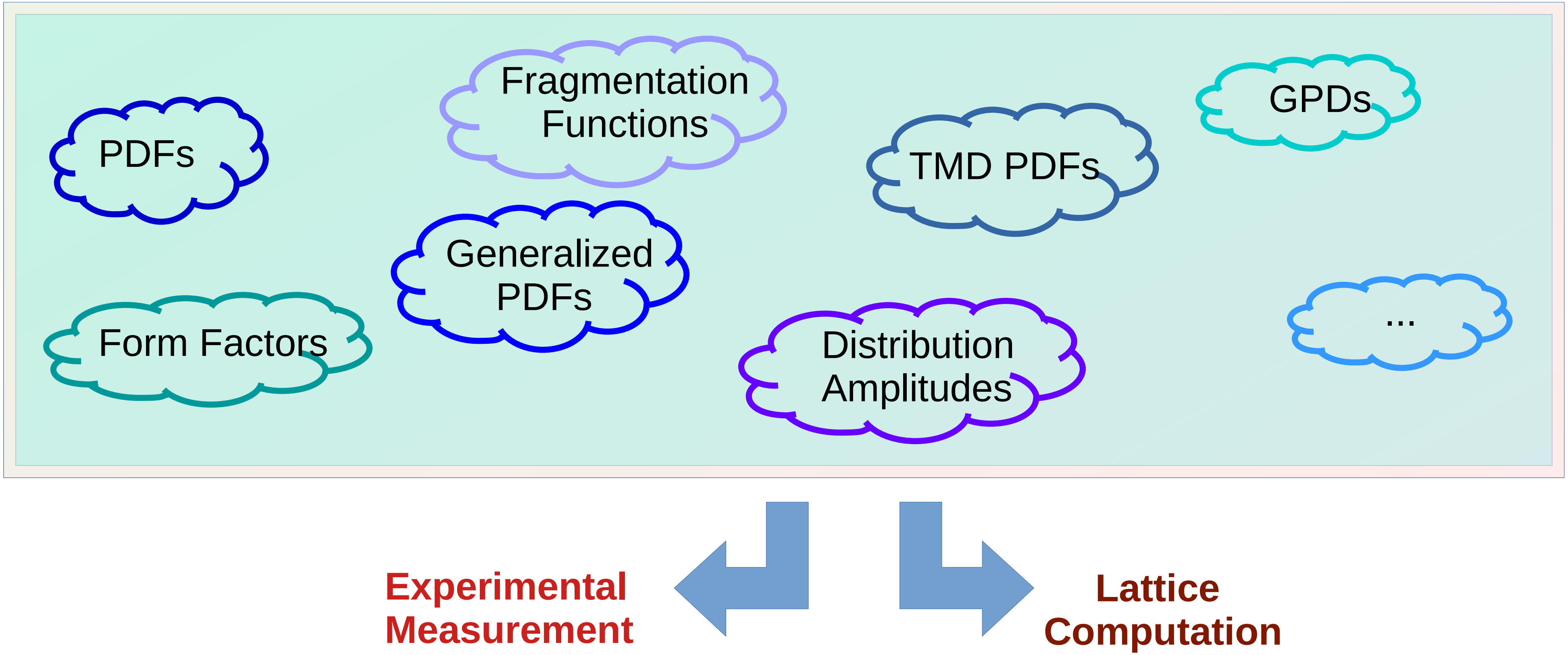
Proton spin: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q,g}$

- $\frac{1}{2}\Delta\Sigma$: quarks spin
- ΔG: gluons spin
- $L_{q,g}$: Orbital angular momentum

- 3 decades of experimental efforts to measure each
- Key to "solving" **QCD**

Non-perturbative QCD

A variety of **universal objects**, that relate to each other in a non-trivial way:

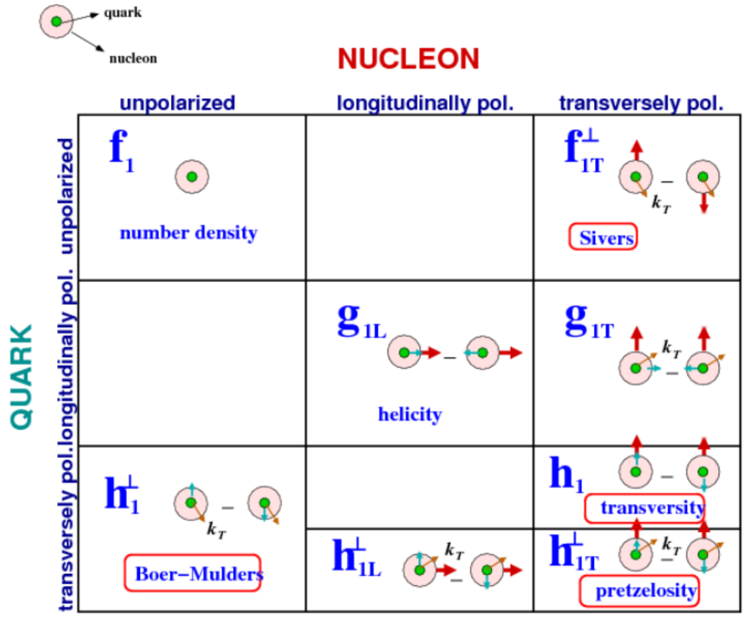


PDFs and TMD PDFs

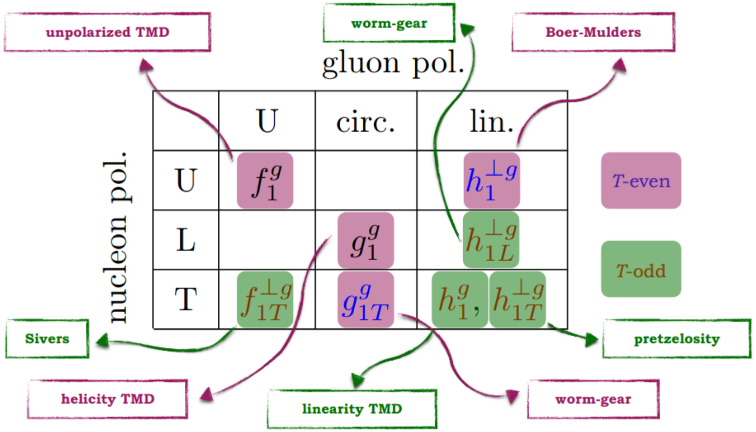
3 collinear quark PDFs used to describe the proton and its dependences (x, Q^2):

- Unpolarized
- Helicity
- Transversity

If considering also transverse motion, **8 quark TMD PDFs** are needed to describe the proton (x, k_T, Q^2):



Also 8 gluon TMD PDFs to be considered:

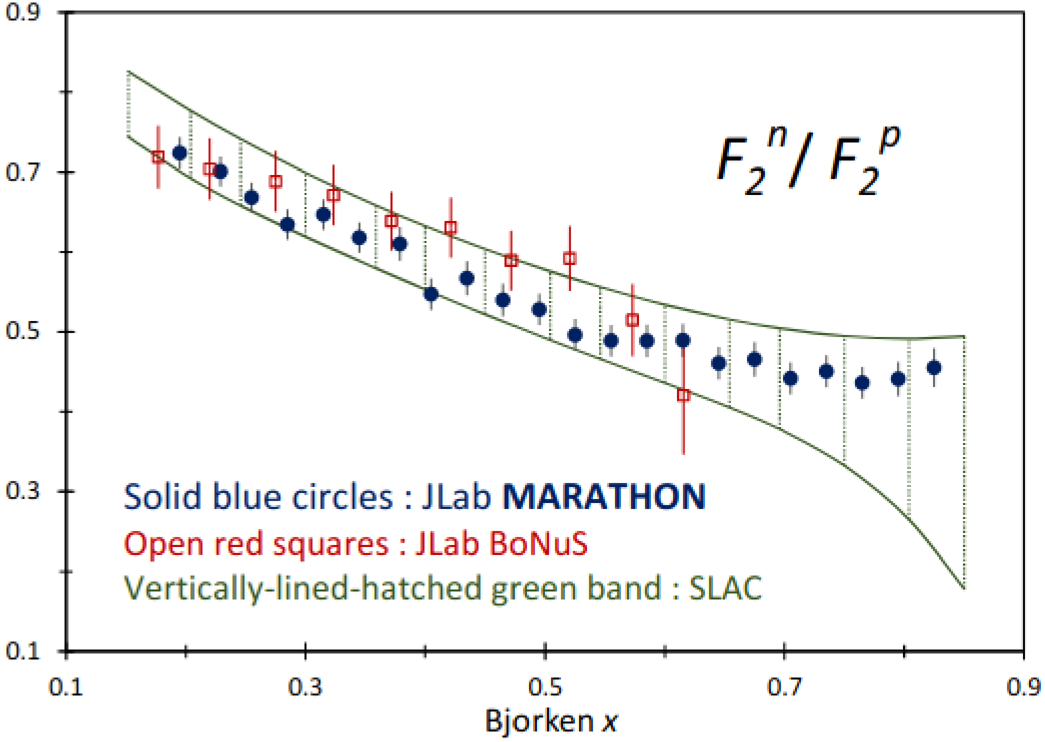


F. Celiberto talk,
Wednesday, QCD & Spin

Proton valence quarks ratio

MARATHON at JLab Hall-A

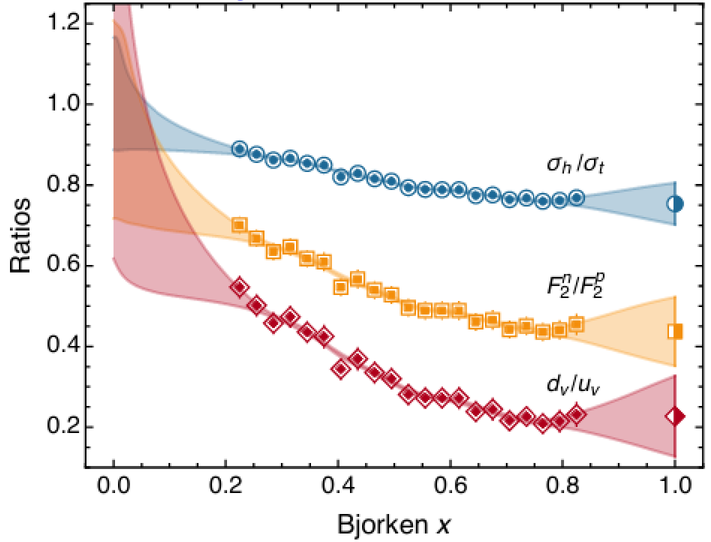
arXiv: 2104.05850



DIS experiment: 10 GeV electrons off ³He and ³H targets

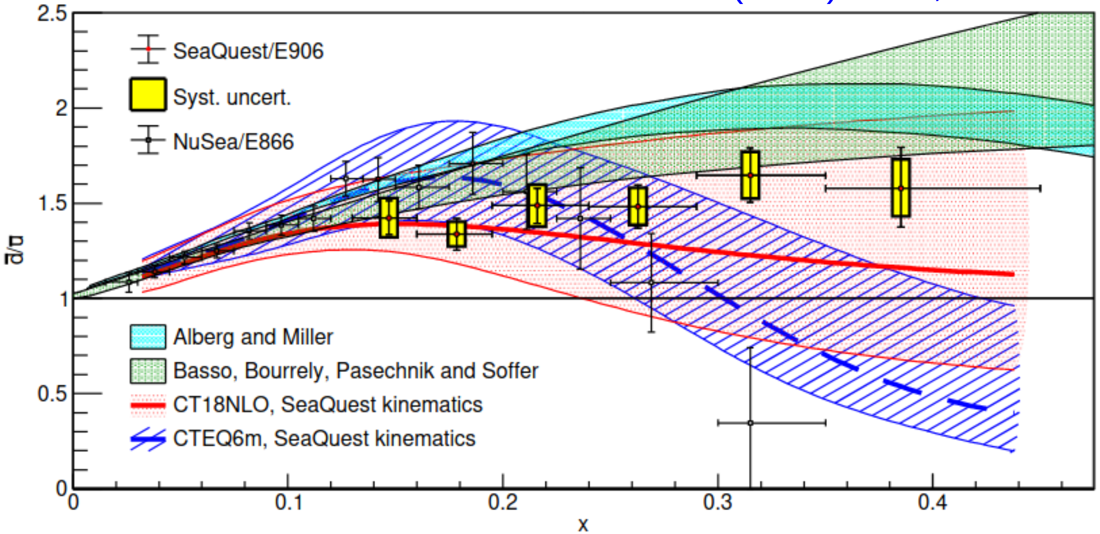
The nucleon structure functions ratio F_2^n/F_2^p is important input to access at large x-Bjorken to **d/u** ratio:

Zhu-Fang Cui et al, arXiv:2108.11493

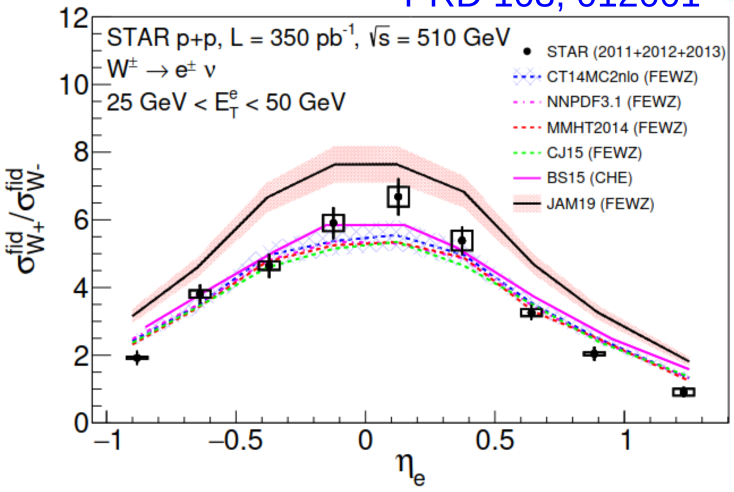


Light sea asymmetry in the proton

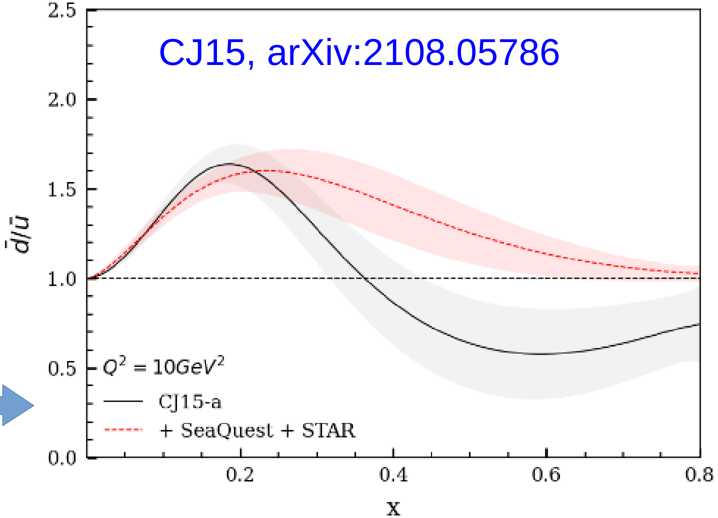
Nature 590 (2021) 7847, 561-565



PRD 103, 012001



SeaQuest: 120 GeV proton-induced Drell-Yan on H and D targets.

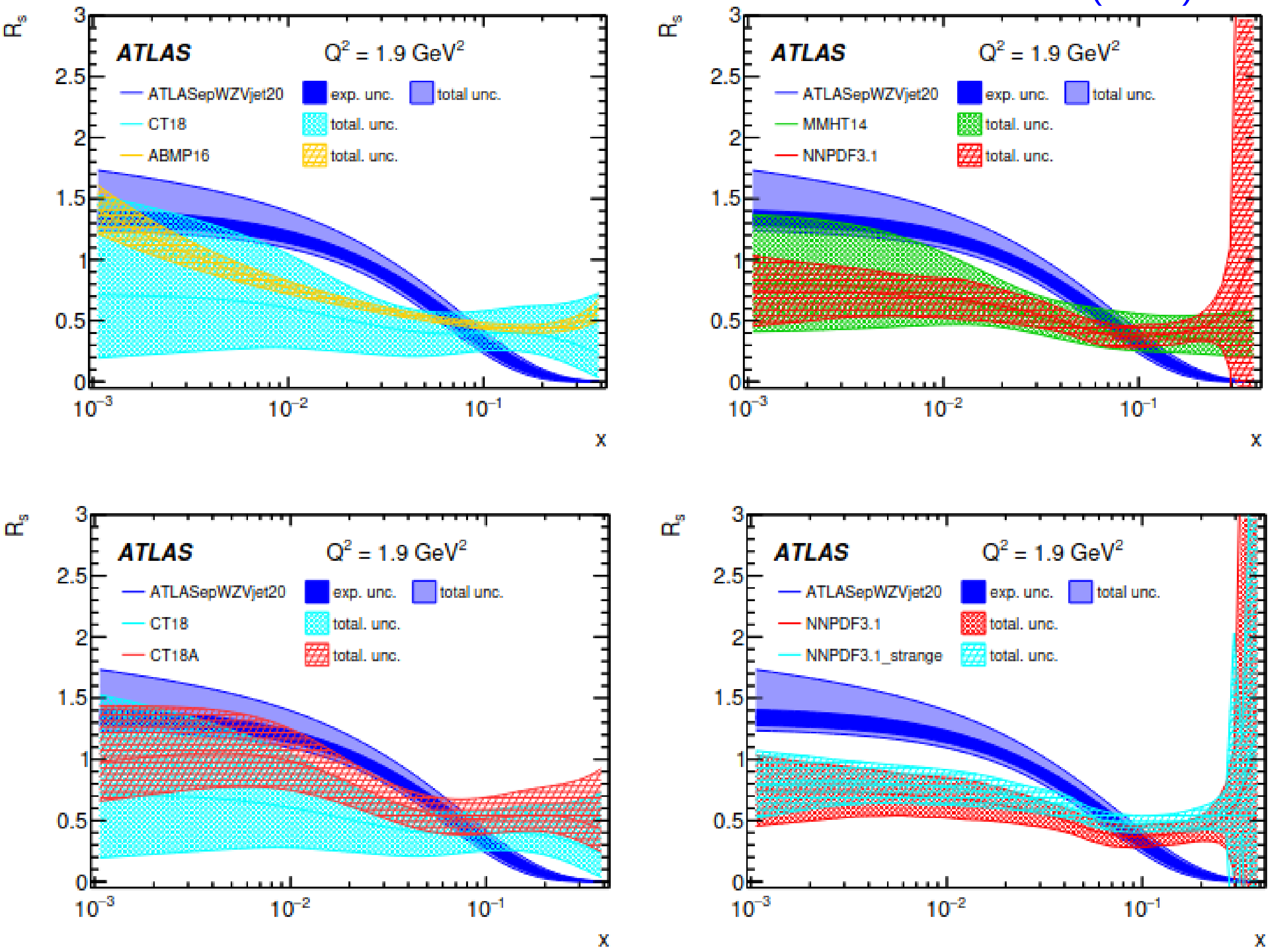


Including SeaQuest Drell-Yan and STAR data on W+/W- production ratio to the global fits significantly constrains the sea pdfs

$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

Strangeness content in the proton

JHEP07(2021)223



From $W^{\pm}$ and Z boson production in association with jets

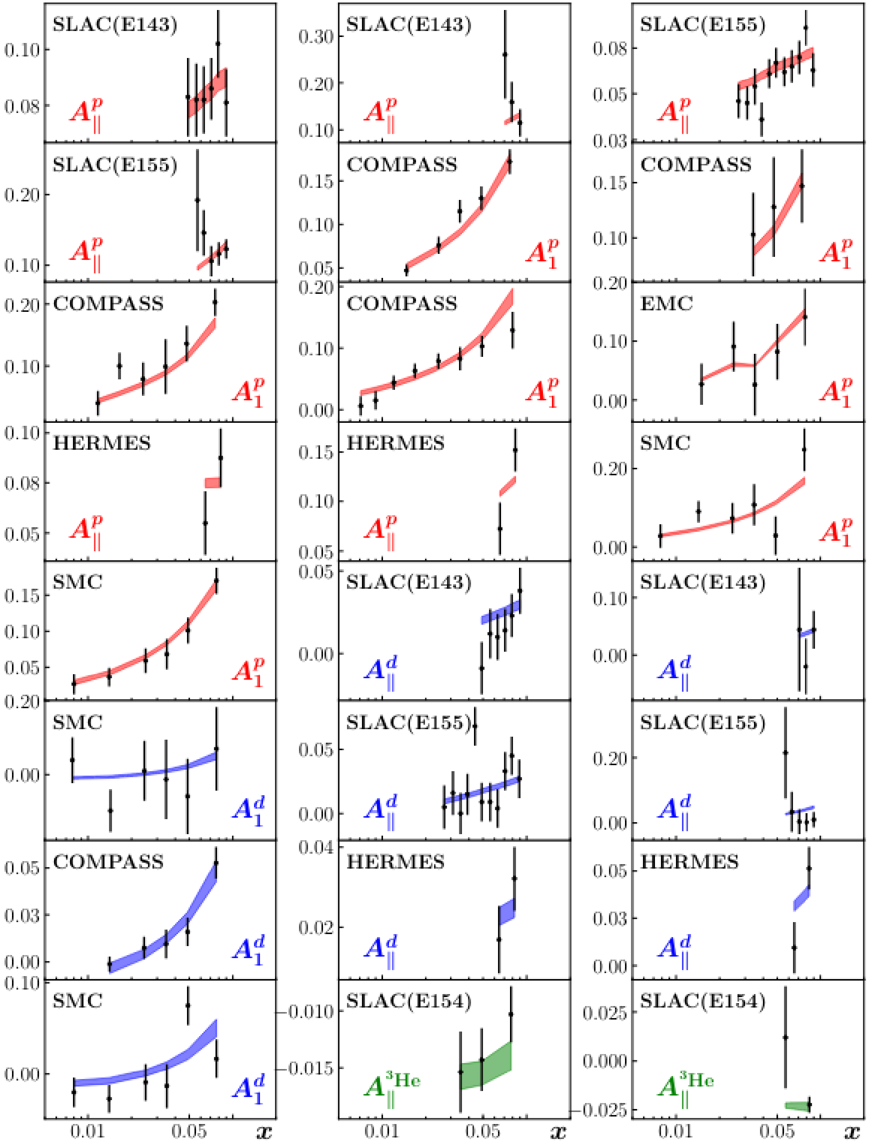
Strange-quark content similar in size to u- and d- sea quark ones at x < 0.02

contrary to expectations (driven by neutrino-induced DIS results)

ATLAS global fit results, including also HERA DIS data.

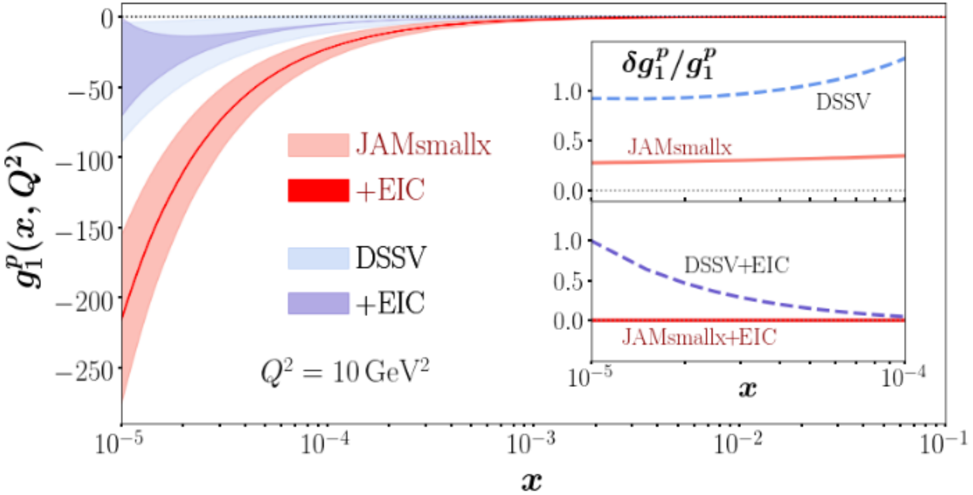
Longitudinal double spin asymmetries

Helicity



Small-x evolution equations allow to "predict" the behaviour of the g_1 structure function and the helicity PDFs of the proton in the $x \to 0$ limit.

With the future EIC data, this approach will greatly constrain g_1 and helicity distributions.

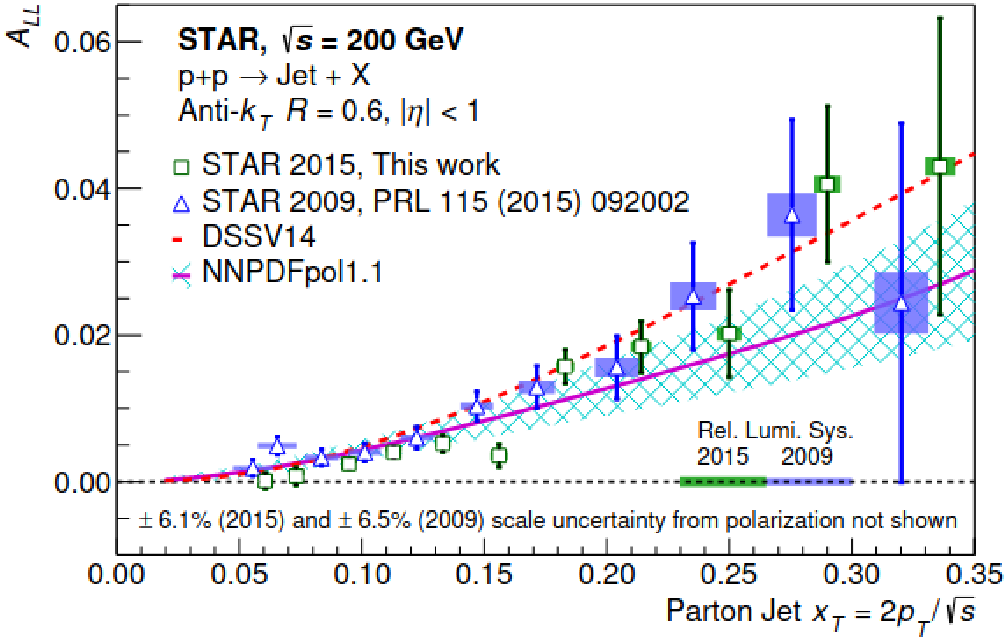


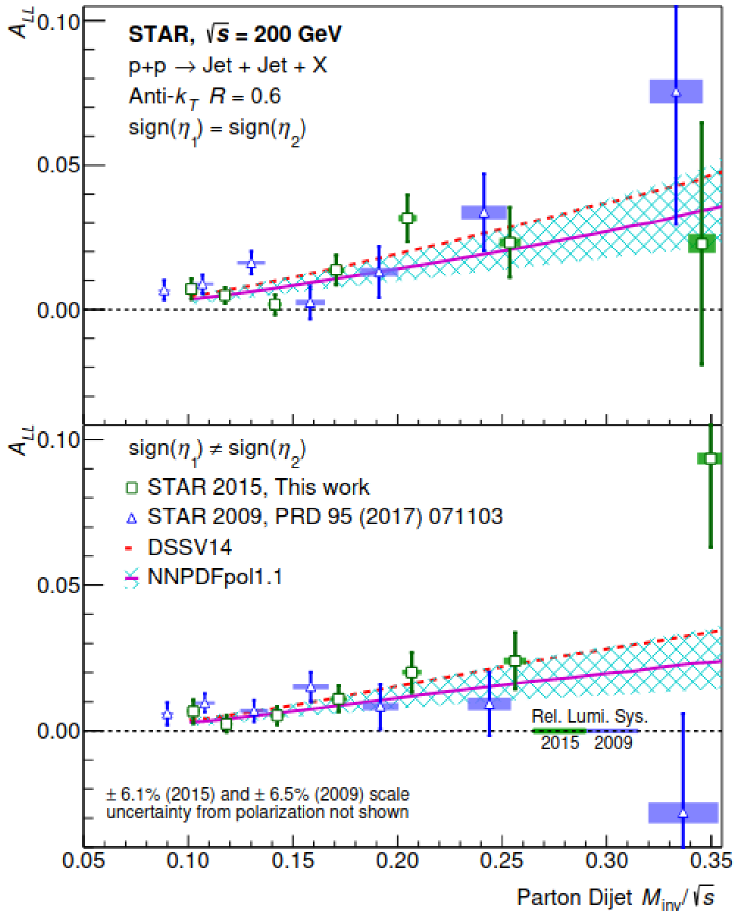
JAMsmallx, arXiv:2102.06159

Longitudinal double spin asymmetries

Inclusive jet and dijet data: sensitivity to the gluon helicity in $0.05 < x_g < 0.5$

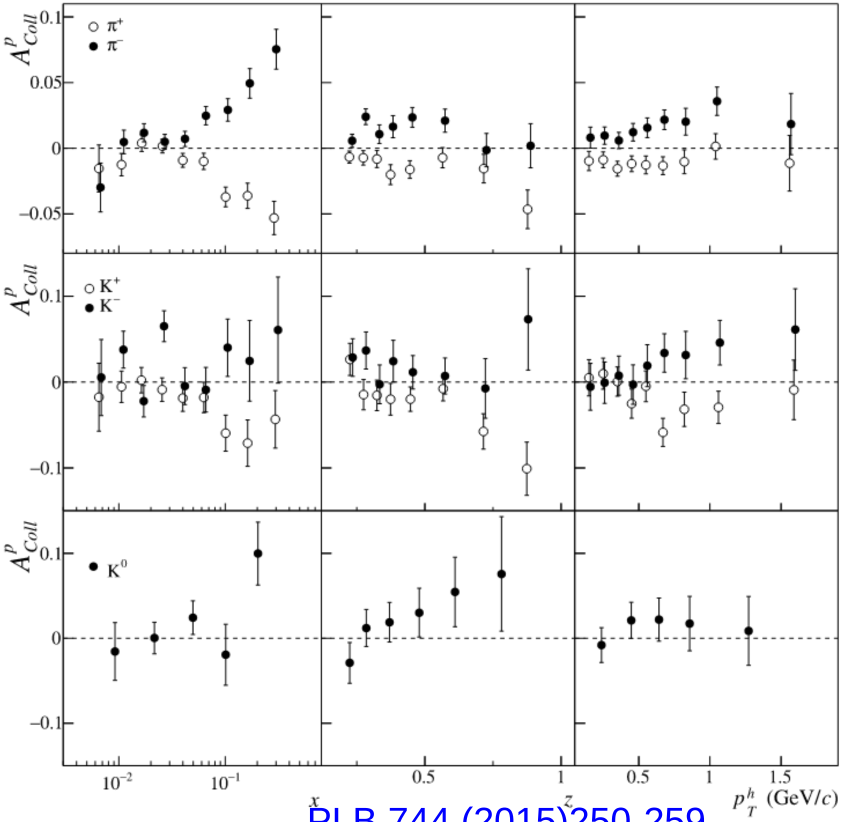
arXiv:2103.05571





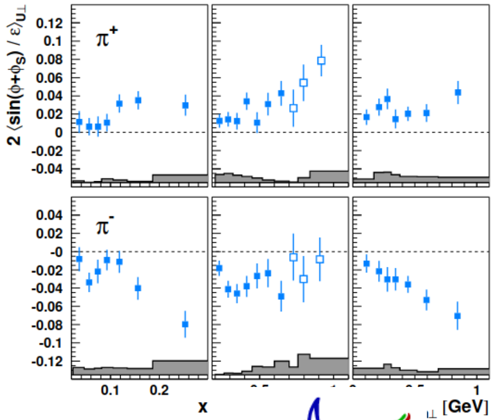
These results provide further evidence that
Δg(x,Q²) is positive for x_g > 0.05

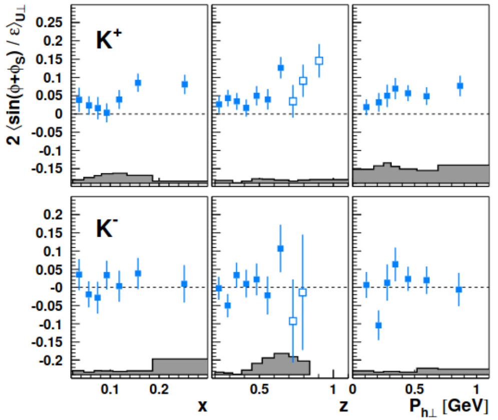
Collins asymmetry in SIDIS:
Transversity ⊗ Collins Fragmentation Function

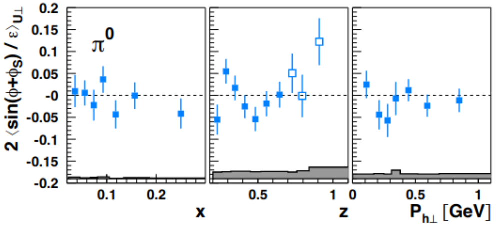


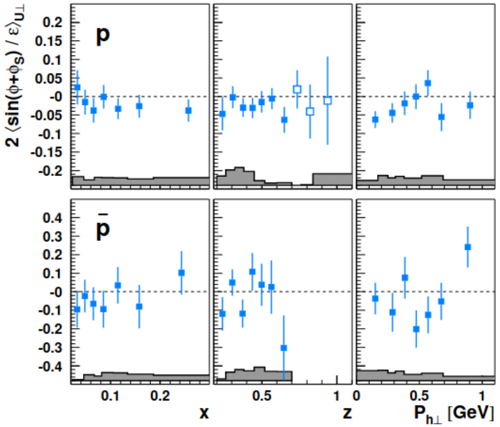
PLB 744 (2015)250-259

In COMPASS the Collins angle is: $\Phi_C = \varphi_h + \varphi_s - \pi$









arXiv:2007.07755

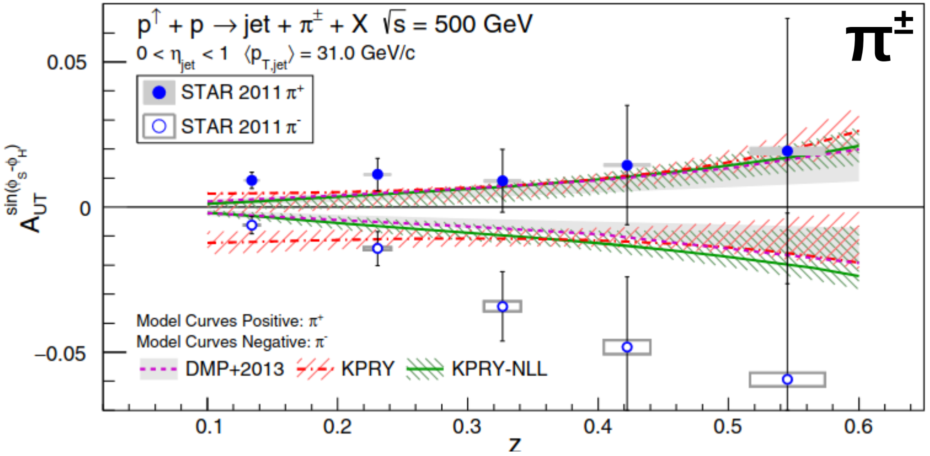
3D analysis newly available from HERMES.
Agreement between experiments, except for K^- (?)

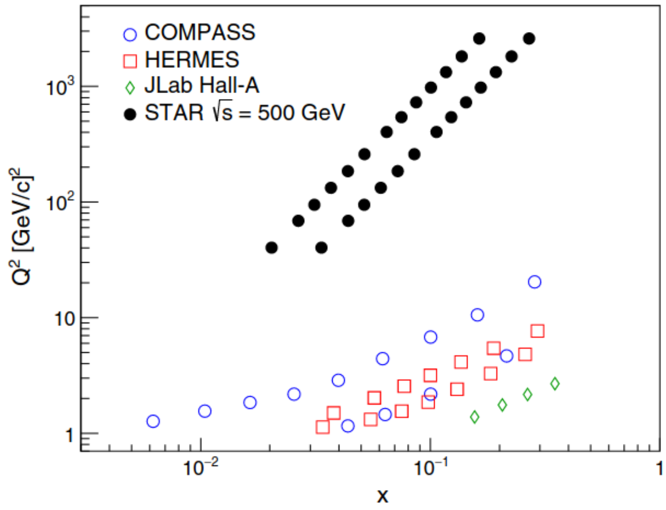
Markus Diefenthaler talk
Sunday, Spin&QCD

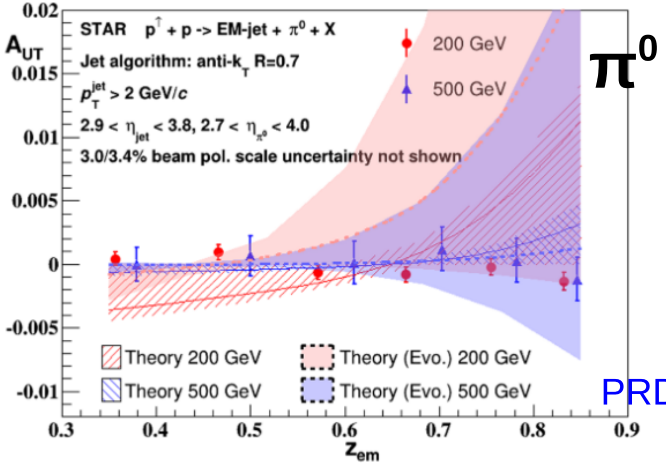
Collins asymmetry at RHIC: $p^{\uparrow} + p \rightarrow h + X$

Hard scale given by p_{Th} . Collinear twist-3 factorization applies. Spin effects arising from interference of multiparton states.

PRD 97, 032004 (2018)

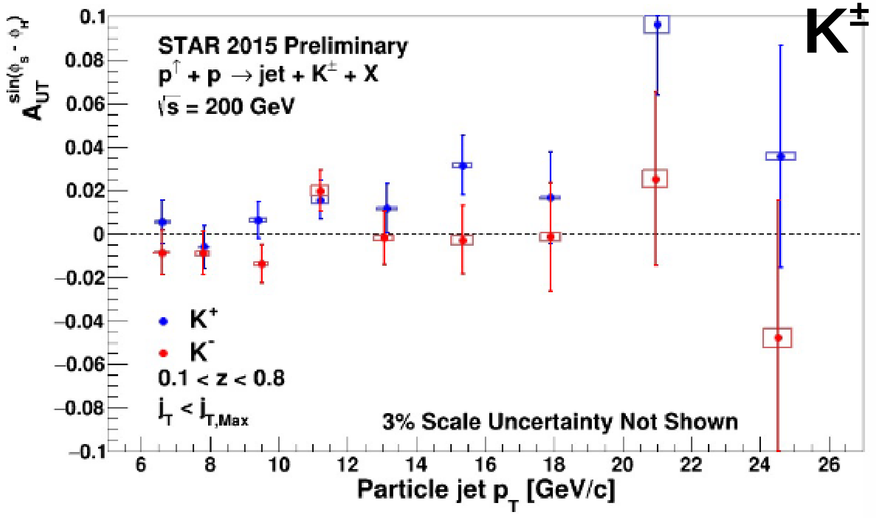






Only sensitive to final state effects – seen to be small

PRD 103, 092009 (2021)

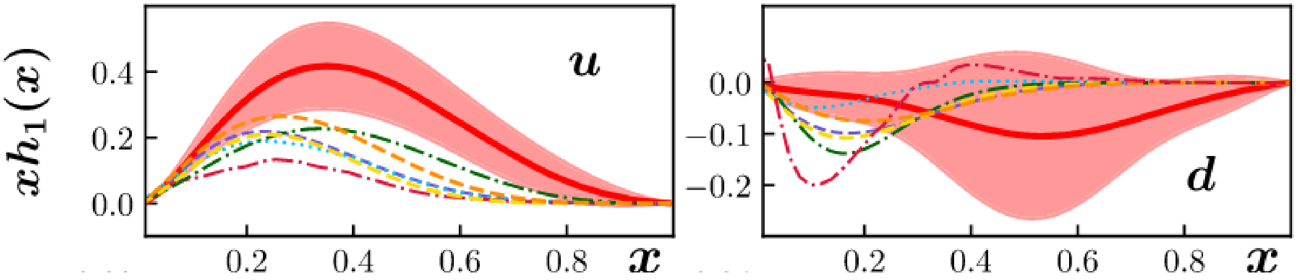


Ting Lin talk at QPT 2021

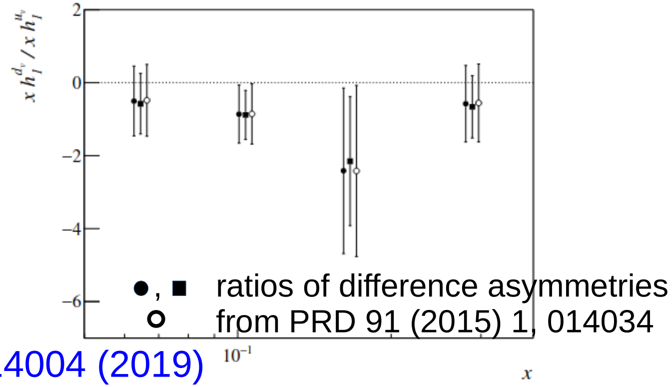
Extraction of the transversity function

In SIDIS it comes convoluted with the Collins FF.
Extraction from global analyses (SIDIS, DY, pp, e^+e^-)

JAM20, PRD 102, 054002 (2020)



From the ratio of difference Collins asymmetries between π^+ and π^- obtained from deuteron and proton targets one can access $h_1^{d_v}/h_1^{u_v}$ independently from the Collins FF.



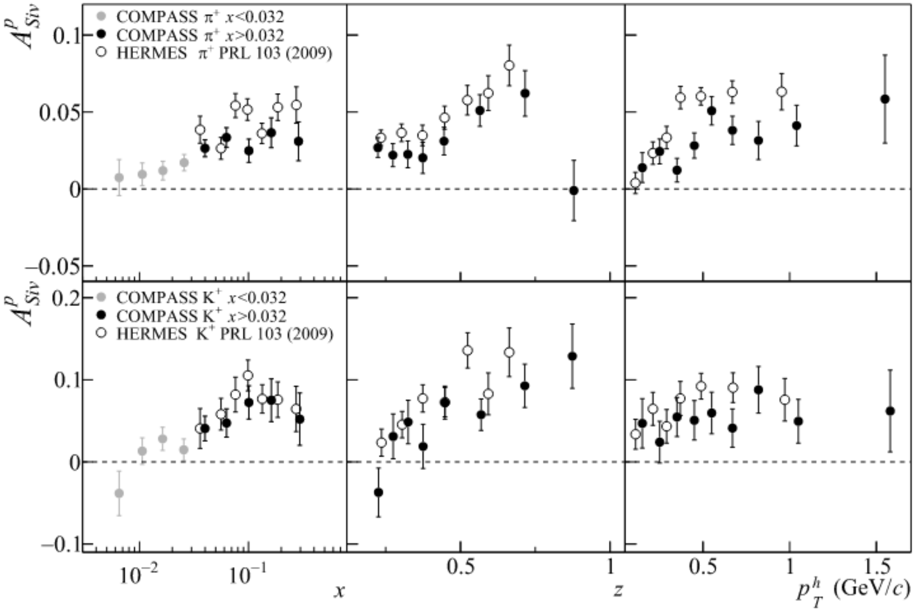
V. Barone et al, PRD 99, 114004 (2019)

The Collins-modulation in SIDIS cross-section for proton and deuteron targets and π^+ and π^- also allows to access a simple ratio of valence quark transversity functions:

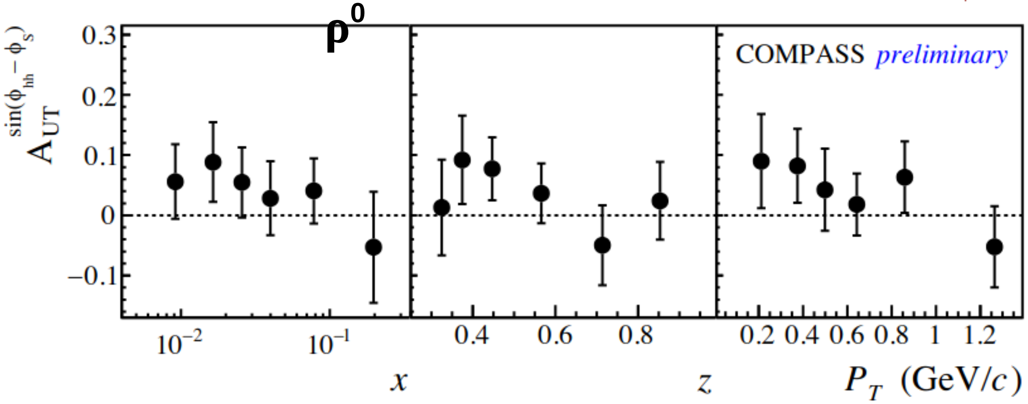
$$R_{C,d/p} \equiv \frac{\sigma^+_{C,d} - \sigma^-_{C,d}}{\sigma^+_{C,p} - \sigma^-_{C,p}} = 3\,\frac{h_1^{u_v} + h_1^{d_v}}{4h_1^{u_v} - h_1^{d_v}}$$

M. Anselmino et al, PRD 102,096012 (2020)

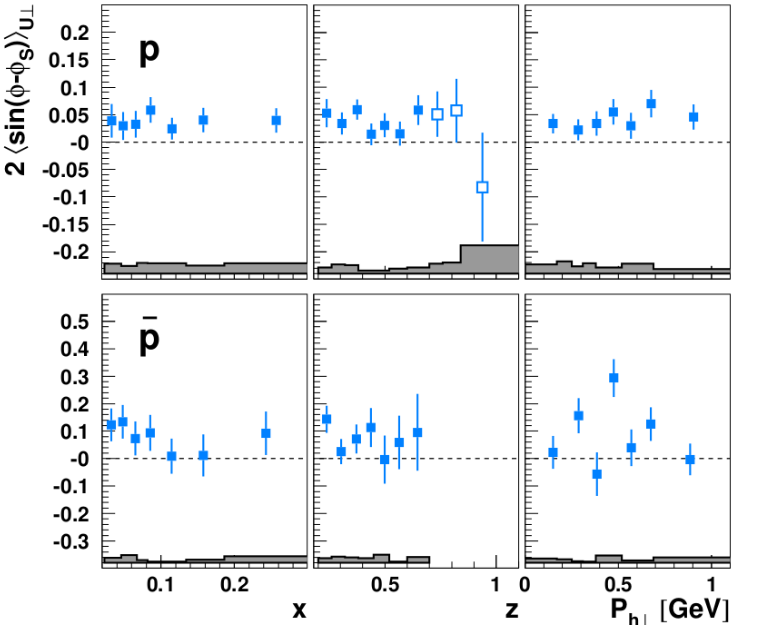
Sivers asymmetry in SIDIS

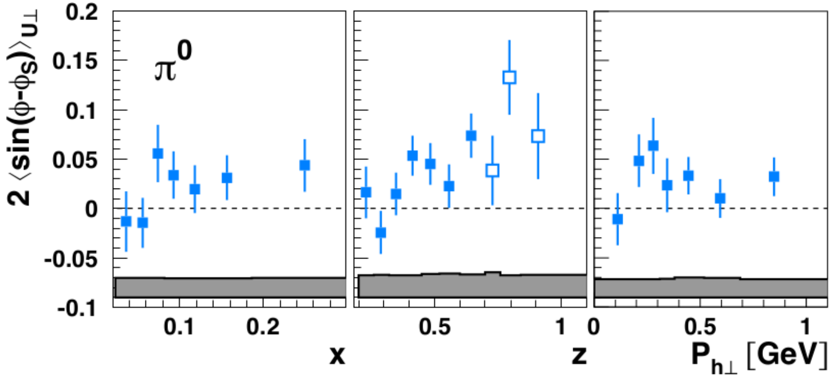


PLB 744 (2015) 250-259



arXiv:2107.10099



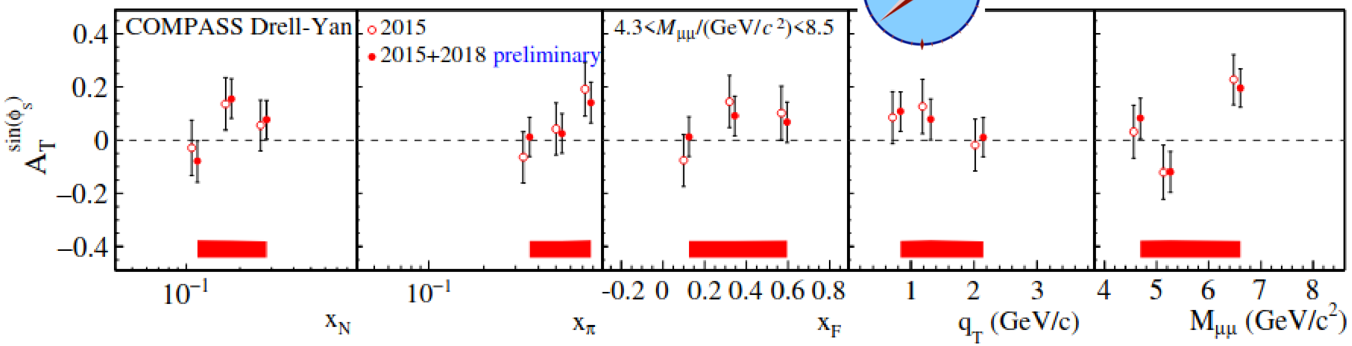


arXiv:2007.07755

Markus Diefenthaler talk
Sunday, Spin&QCD

Sivers asymmetry and A_N in polarized hadronic collisions

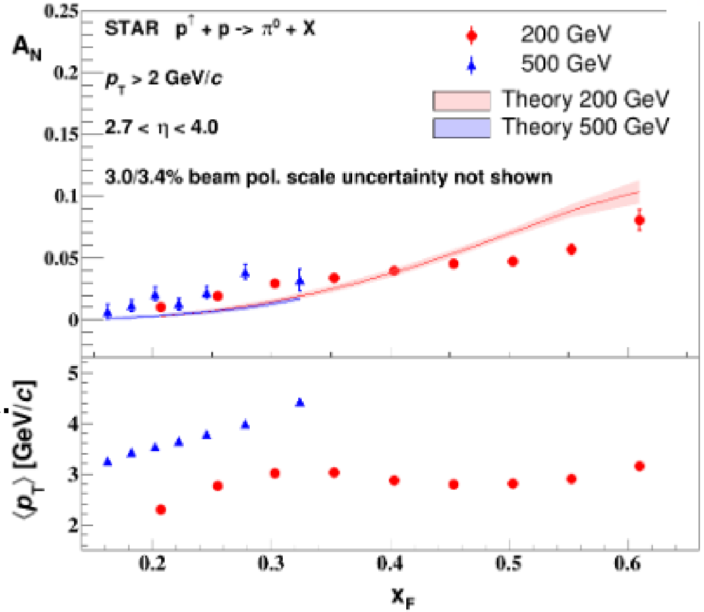
PoS (DIS 2019) 195

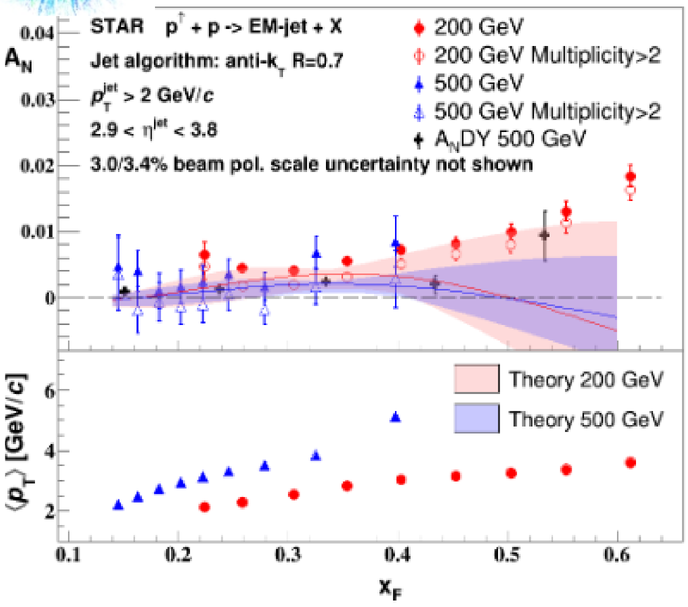


In π-induced Drell-Yan $A_T^{\sin(\phi_S)}$ is proportional to

$$f_1^{\pi} \otimes f_{1T}^{\perp p}$$

PRD 103 (2021) 9, 092009

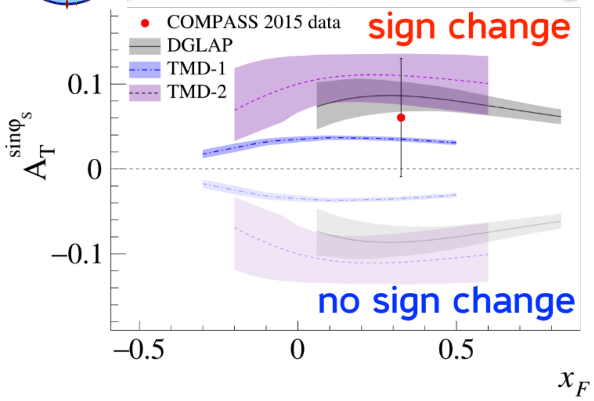




The small TSSA of EM-jets as compared to that of π^0 seems to indicate that the Sivers effect is not the dominant source of π^0 TSSA.

Universality of the Sivers TMD PDF
A test of the TMD approach

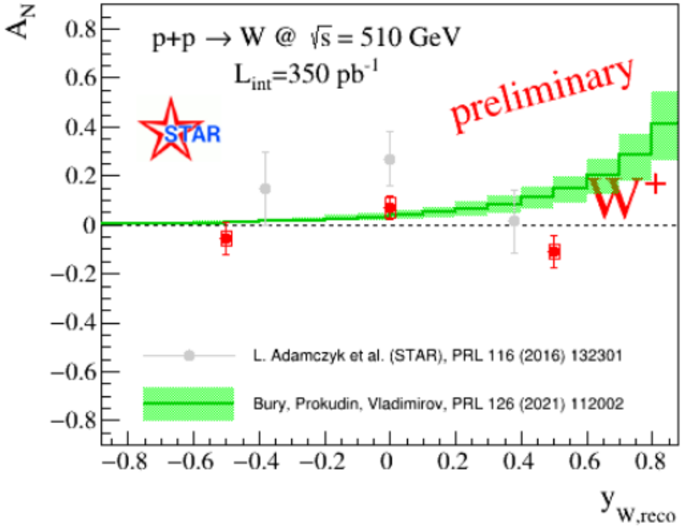
PRL 119 (2017) 112002

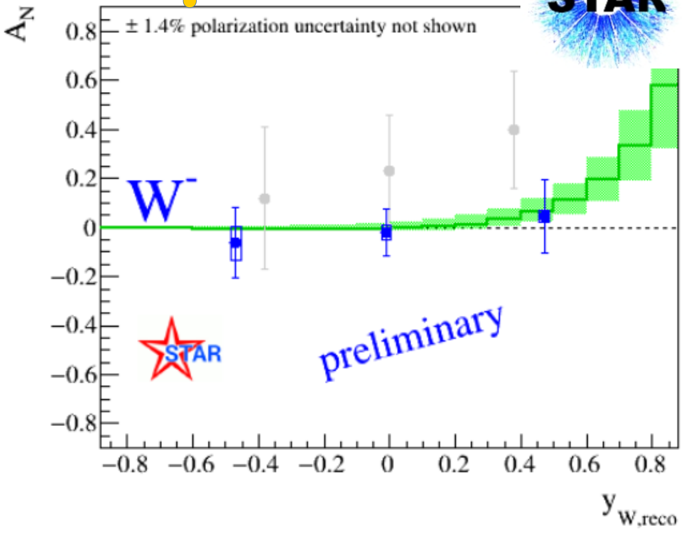


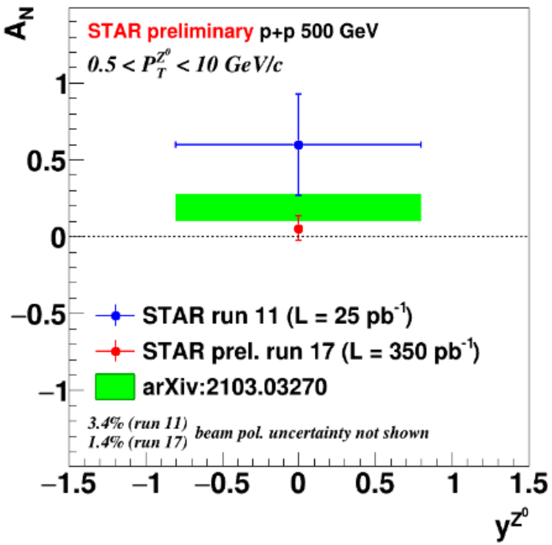
- Sivers function: non-vanishing orbital angular momentum
- Process dependence: $f_{1T}^{\perp}(\text{SIDIS}) = -\ f_{1T}^{\perp}(\text{DY})$

NEW

Oleg Eyser talk
Sunday, Spin&QCD





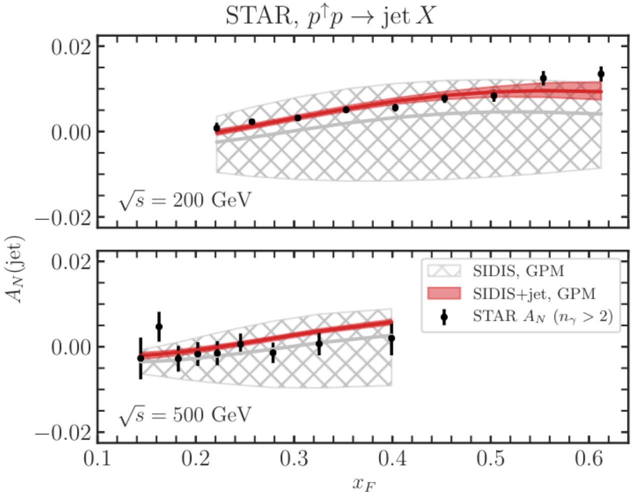


M. Bury et al, PRL 126 (2021) 112002 : only slight preference for Sivers sign-change (new STAR data not yet included).

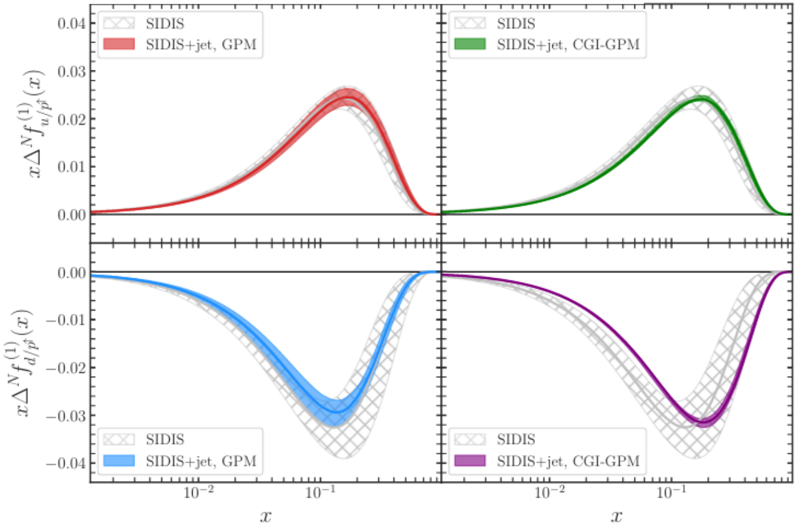
Extraction of the quark Sivers functions

M. Boglione et al, arXiv:2101.03955

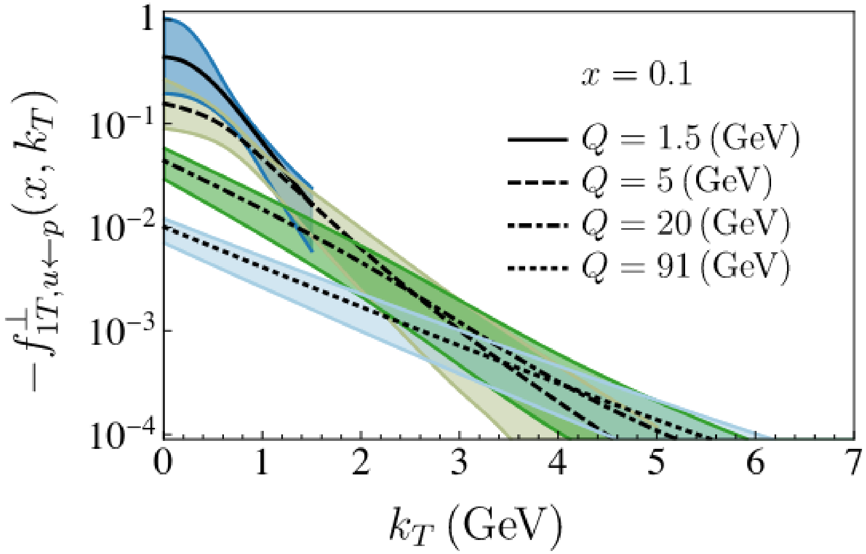
SIDIS + Drell-Yan + $W^{\pm}/Z$ and inclusive jet data in $pp^{\uparrow}$



Impact of inclusive jet data from STAR in constraining the first k_T moment of quark Sivers.



M. Bury et al, PRL 126 (2021) 112002 :

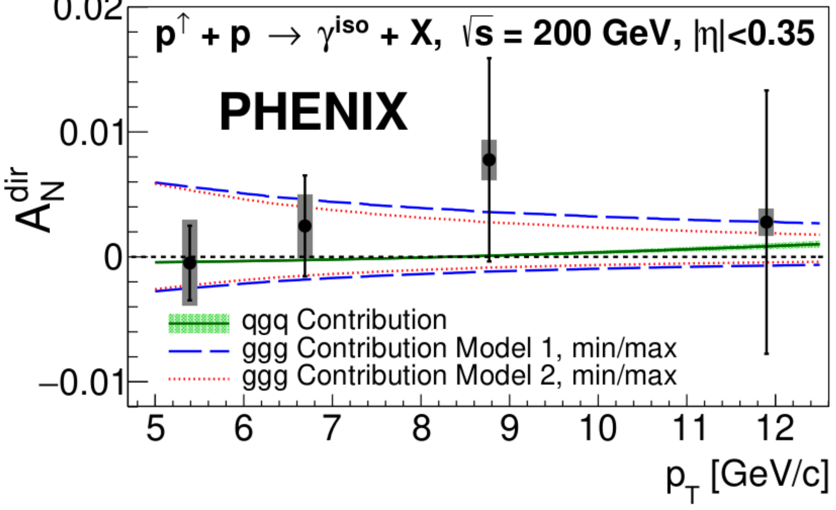


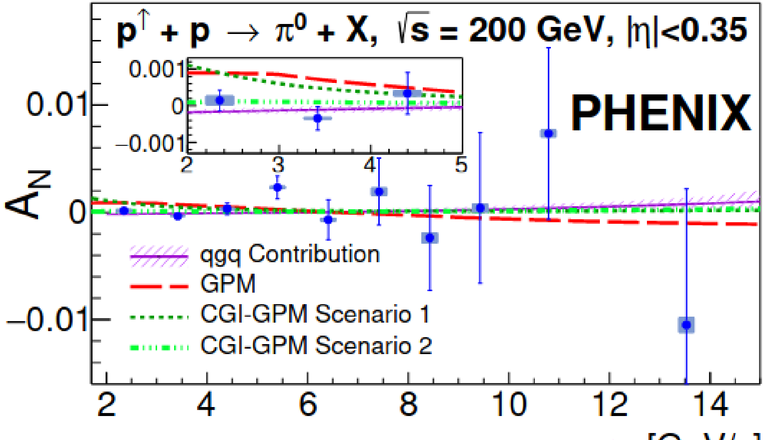
- QCD evolution modifies the shape and size of the Sivers function.
- Sivers function is 4-5 times smaller than the unpolarized TMD.

RHIC: direct photons and J/psi

Sensitivity to gluon Sivers

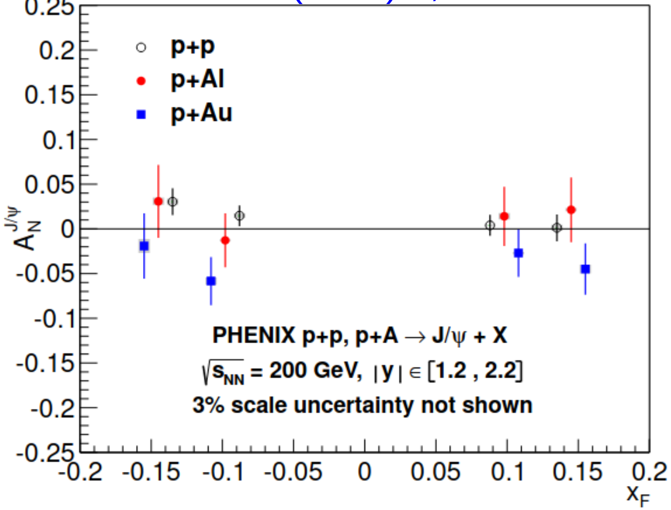
arXiv:2102.13585





PRD 103 (2021) 052009

PRD 98 (2018) 1, 012006

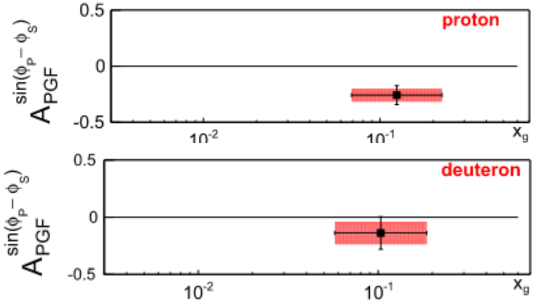


Milap Patel talk
Sunday, Spin&QCD

At midrapidities and low p_T, also π^0 production is believed to be mainly sensitive to gluon Sivers

and from SIDIS

Sivers two-hadron asymmetry from a PGF-enriched sample



PLB 772 (2017) 854

Hint for non-zero gluon Sivers, and thus gluon orbital angular momentum

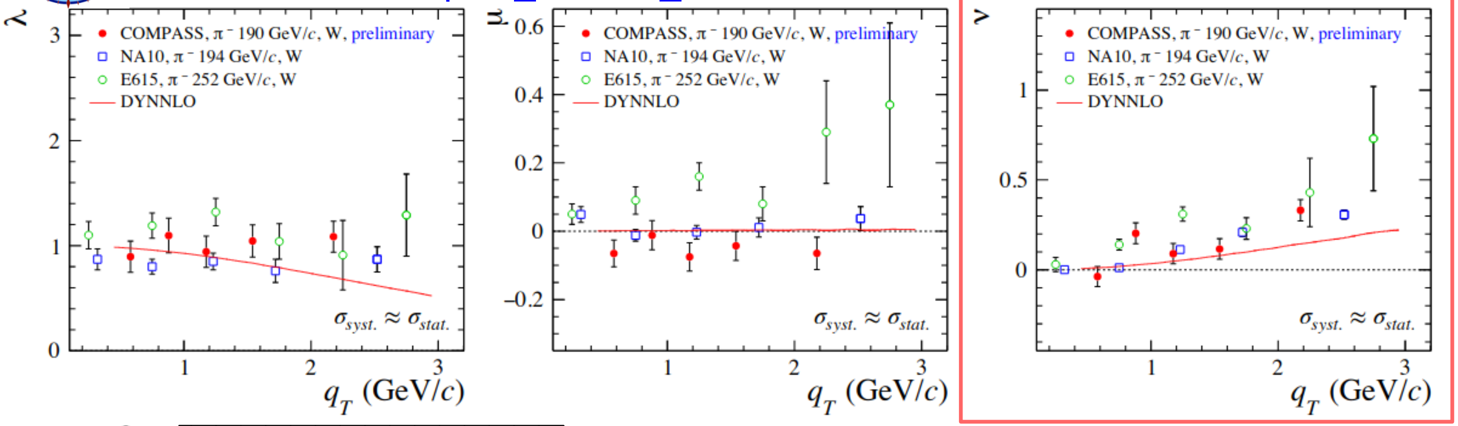
Sensitivity to the Boer-Mulders function

$$A_U^{\cos 2\varphi_{CS}} = \frac{\nu}{2} \propto h_1^{\perp}(N)\bar{h}_1^{\perp}(\pi)$$

In π-induced Drell-Yan (unpolarized):

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

DIS2021, scipost_202107_00061v1

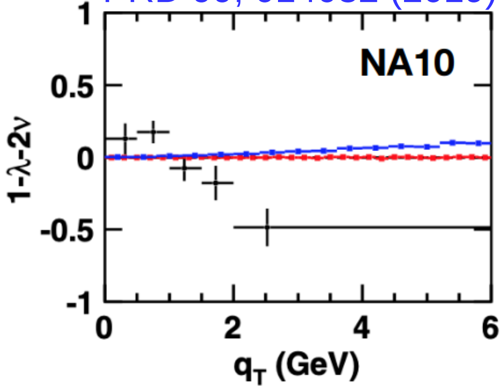


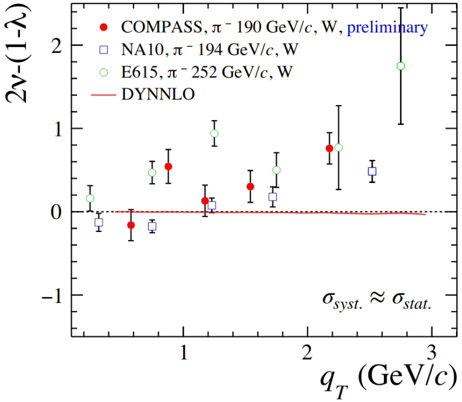
At LO: λ=1 and μ,ν=0

At NLO: Lam-Tung relation
1-λ=2ν

At NNLO: Lam-Tung violated, but 1-λ-2ν>0

W-C. Chang et al, PRD 99, 014032 (2019)



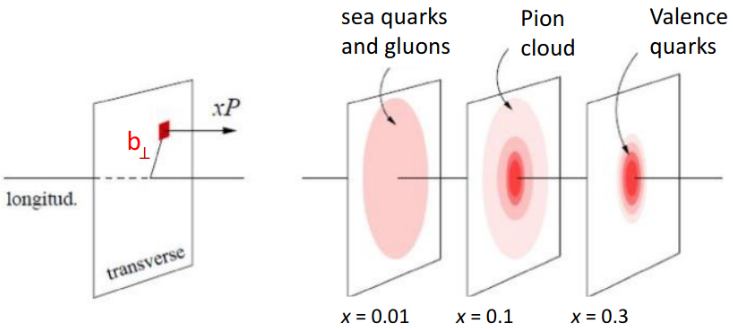


π-induced Drell-Yan indicates instead that 1-λ-2ν<0 !

Hint for Boer-Mulders

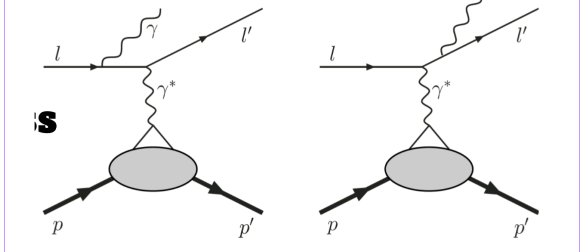
April Townsend talk
Sunday, Spin&QCD

GPDs: transverse imaging of the proton

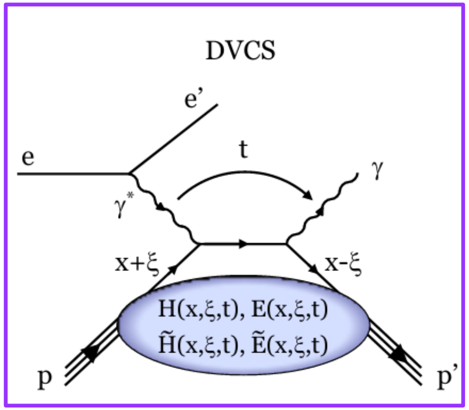


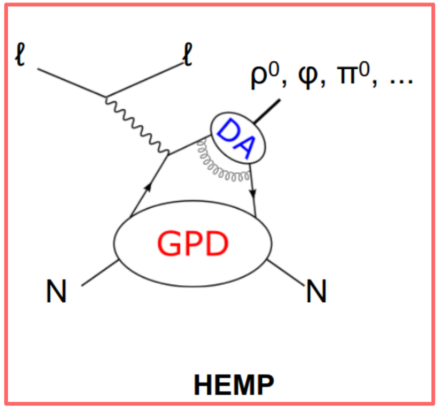
Exclusive measurements, like Deeply virtual Compton Scattering and Hard Exclusive Meson Production give access to the GPDs that describe quark and gluon dynamics inside the nucleon:

- 4 chiral-even GPDs (conserve parton helicity): H, E, $\tilde{H}$, $\tilde{E}$
- 4 chiral-odd GPDs (parton helicity flip): H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$



Background process to DVCS





Experimentally, one accesses GPDs via the **Compton Form Factors**:

CFF GPD

$$\mathcal{H} = \int_{-1}^{+1} dx \, \frac{\mathbf{H}(x,\xi,t)}{x - \xi + i\varepsilon}$$

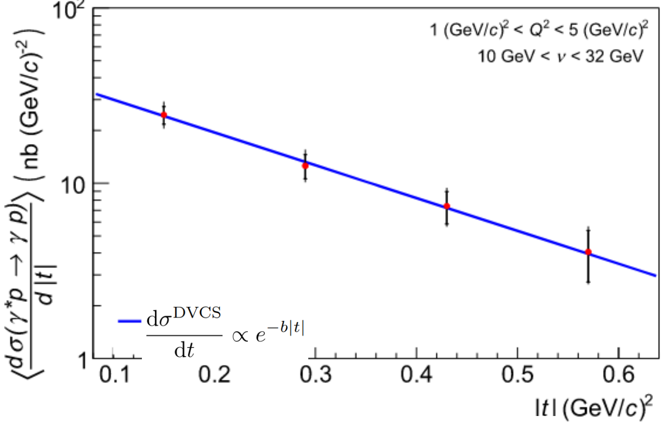
t, ξ fixed

From the azimuthal dependences/asymmetries in DVCS, having both beam charges and polarizations available, and (un)polarized targets, one can access the different GPDs

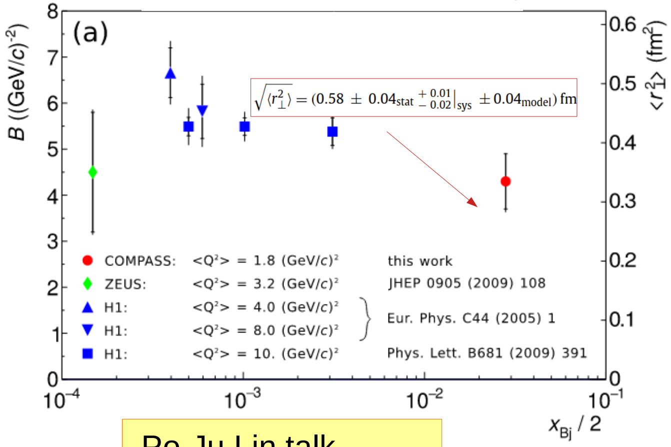
Transverse extension of partons in the proton

COMPASS

PLB 793 (2019) 188



$\langle r_\perp^2(x_{Bj}) \rangle \approx 2B(x_{Bj})$ At small x_{Bj}

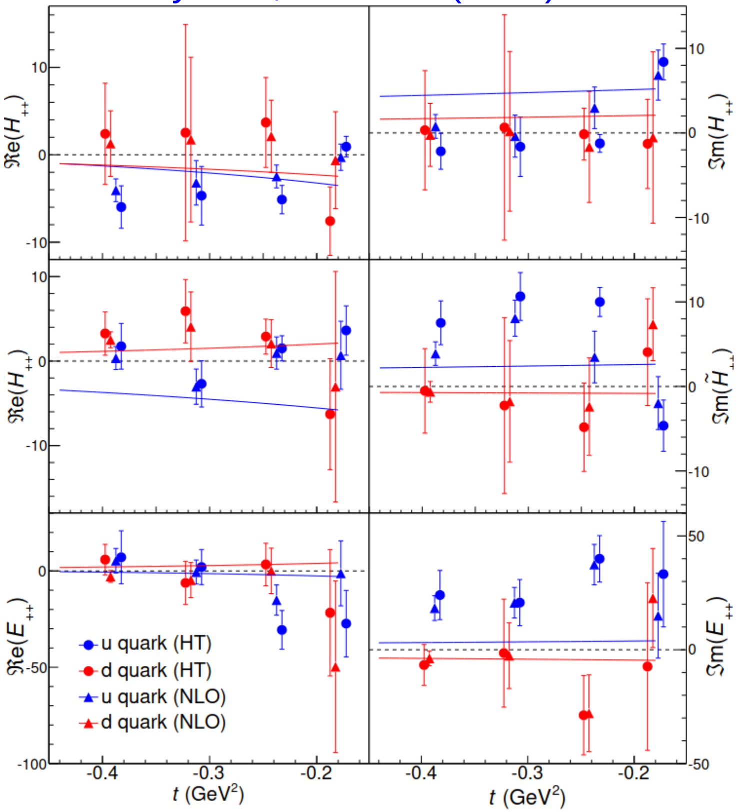


Po-Ju Lin talk
Sunday, Spin&QCD

Flavor separation of Helicity conserved CFFs

Jefferson Lab

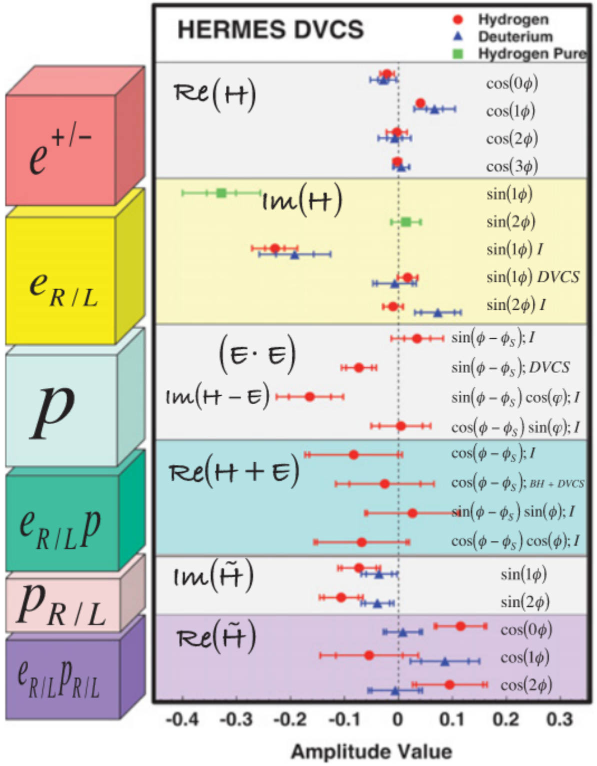
Nat. Phys. 16, 191–198 (2020)



JLab Hall-A n & p DVCS

hermes

DOI: 10.1051/epjconf/20147302014



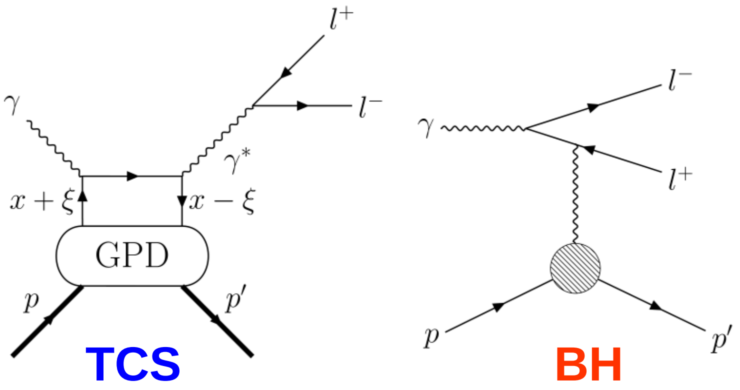
Pioneering measurements from HERMES

GPDs from TCS on the proton

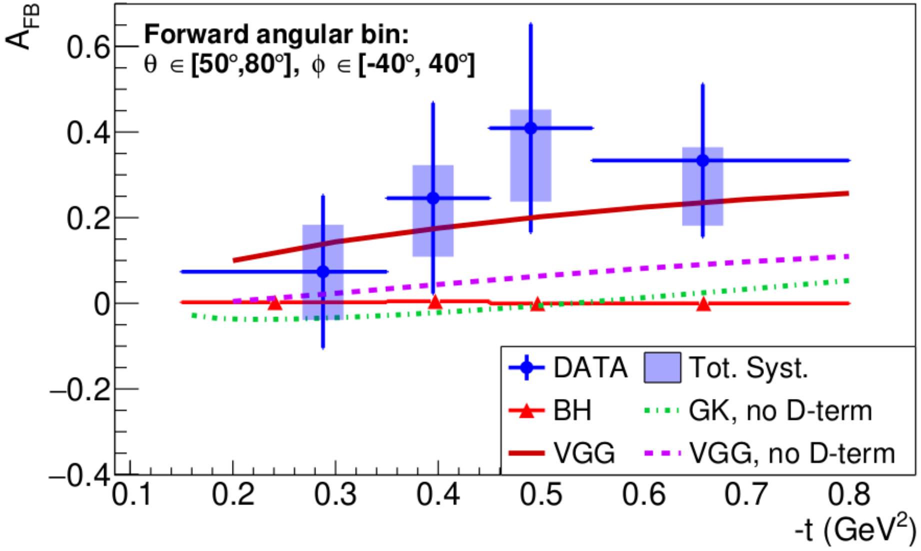
Jefferson Lab

Timelike Compton Scattering:
the time-reversal symmetric of DVCS.

Measured now for the first time, at **CLAS12** (JLab Hall-B), with quasi-real photon beam on unpolarized proton target.



arXiv: 2108.11746



Forward-backward asymmetry:

$$A_{FB} \propto \mathrm{Re}(\mathcal{H})$$

Pierre Chatagnon talk
Sunday, Spin&QCD

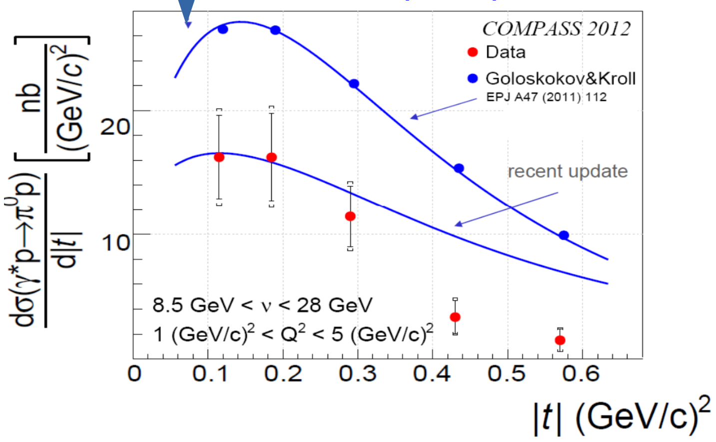
This A_{FB} arises from the interference between the 2 processes, and would be =0 if there was only BH.

GPDs and HEMP

$\mu\, p \rightarrow \mu\, \pi^0\, p$

Sensitivity to $\bar{E}_T = 2\tilde{H}_T + E_T$

PLB 805 (2020) 135454



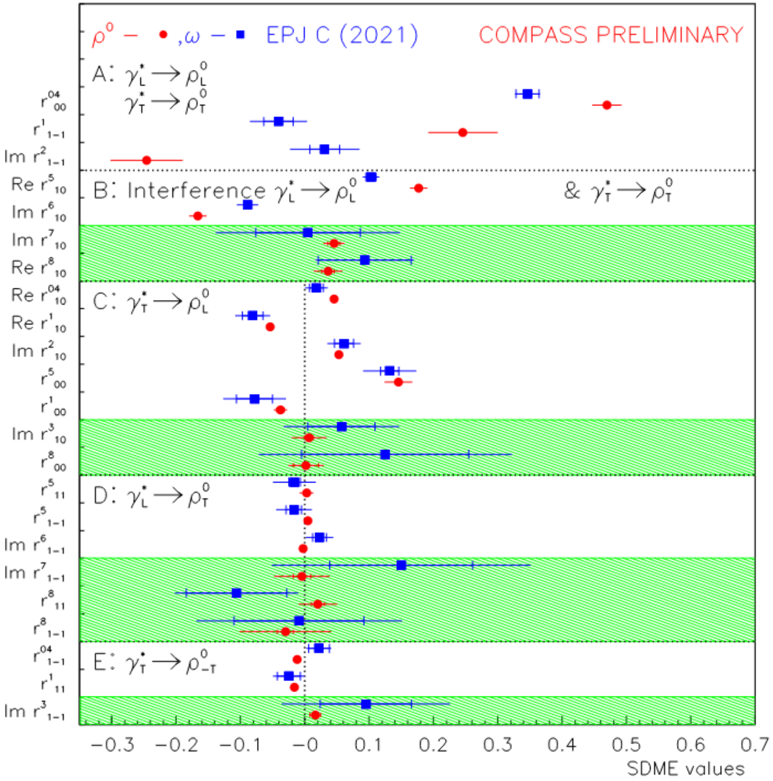
Full angular analysis of the exclusively produced **ρ** and **ω**

Po-Ju Lin talk
Sunday, Spin&QCD

Decomposition in terms of spin density matrix elements

- 15 unpolarized SDMEs
- 8 polarized SDMEs

In COMPASS unpolarized HEMP,
ρ: probing mostly GPDs E and H;
ω: probing also GPDs $\tilde{H}$ and $\tilde{E}$



EPJ C (2021) 81:126

DIS2021, scipost_202107_00046v1

Fragmentation functions

- **FF**s encode the probability that a quark or gluon converts to a hadron that carries a fraction z of the parton's momentum $D_q^h(z,Q^2)$
- Single-hadron FFs and di-hadron FFs
- **TMD FF**s are the counterpart of TMD PDFs, for the final state
- At hadron colliders we also talk about **jetFF**s
- TMD FFs can be measured in **(un)polarized SIDIS** and **e^+e^-** collisions
- **pp collisions** data to access gluon FF

hadron pol. \ quark pol.	U	L	T
U	D_1		$H_1^{\perp}$
L		G_{1L}	$H_{1L}^{\perp}$
T	$D_{1T}^{\perp}$	G_{1T}	H_1, $H_{1T}^{\perp}$

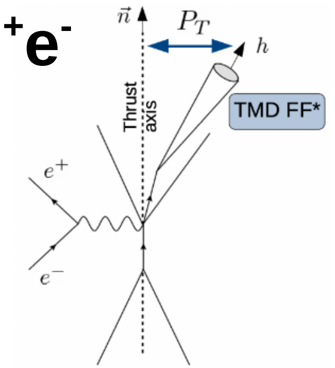
Collins FF ($H_1^{\perp}$)

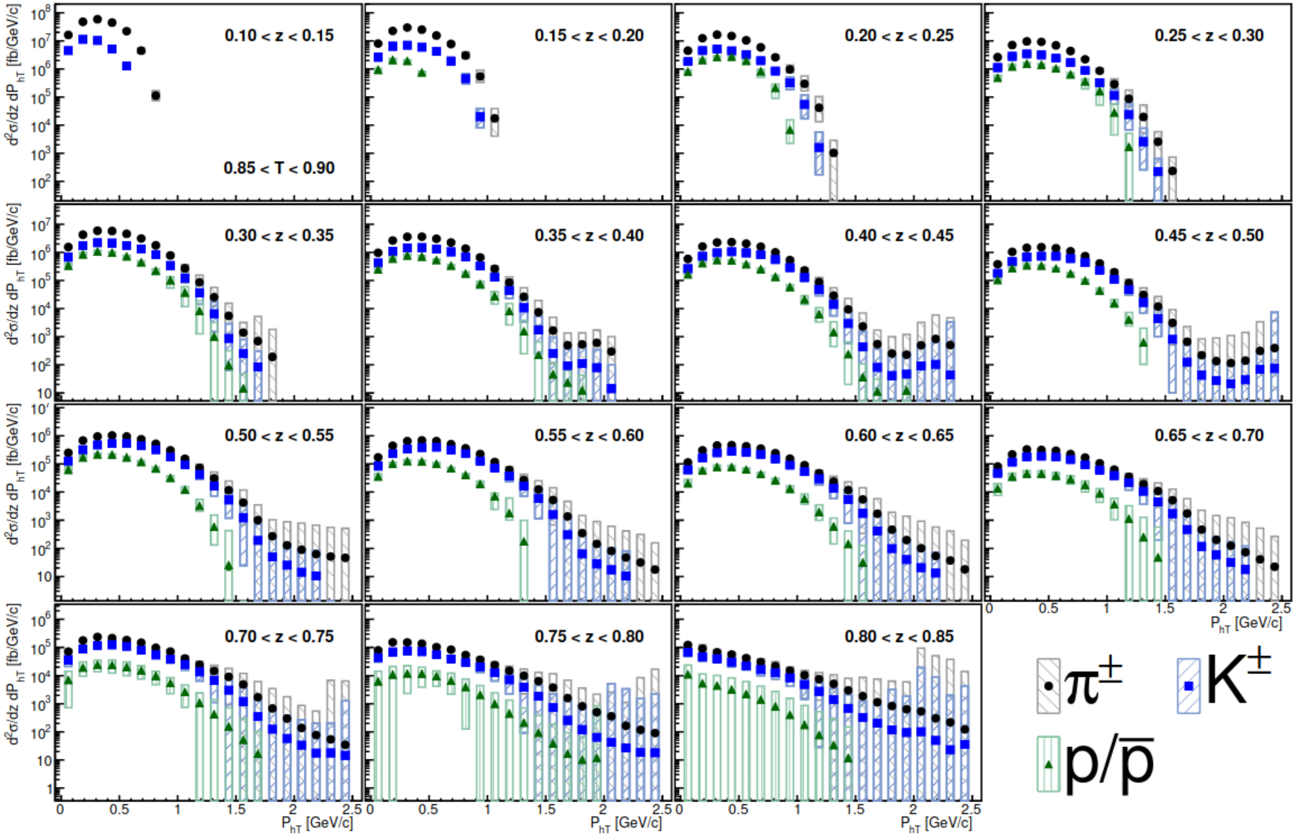
from Λ polarization ($D_{1T}^{\perp}$)

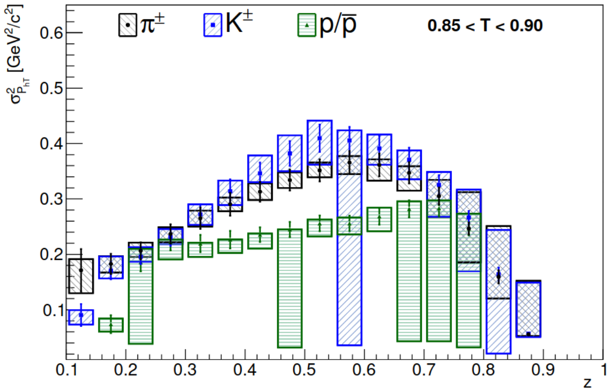
p_T dependent hadron production cross-sections in e^+e^-

Sensitivity to (TMD) fragmentation functions

PRD 99 (2019) 11, 112006







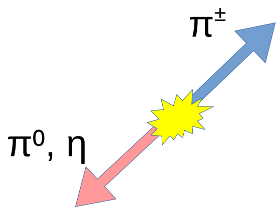
The low-pT part of cross-section is well described by Gaussian.

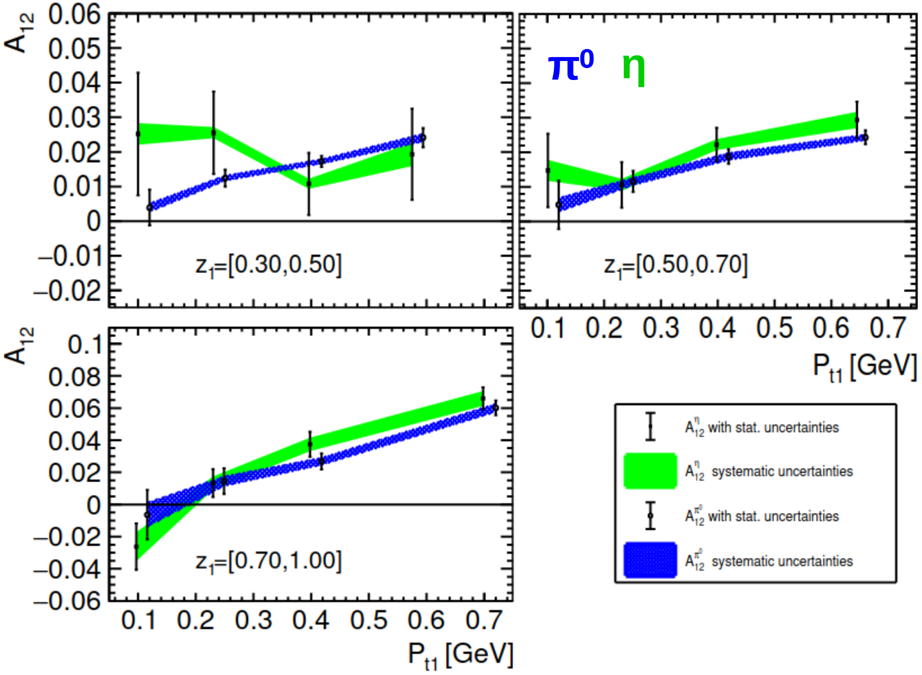
The Gaussian widths as function of fractional energy z are important Input for TMD FFs extraction.

Extraction Collins Fragmentation Function

PRD 100, 092008 (2019)

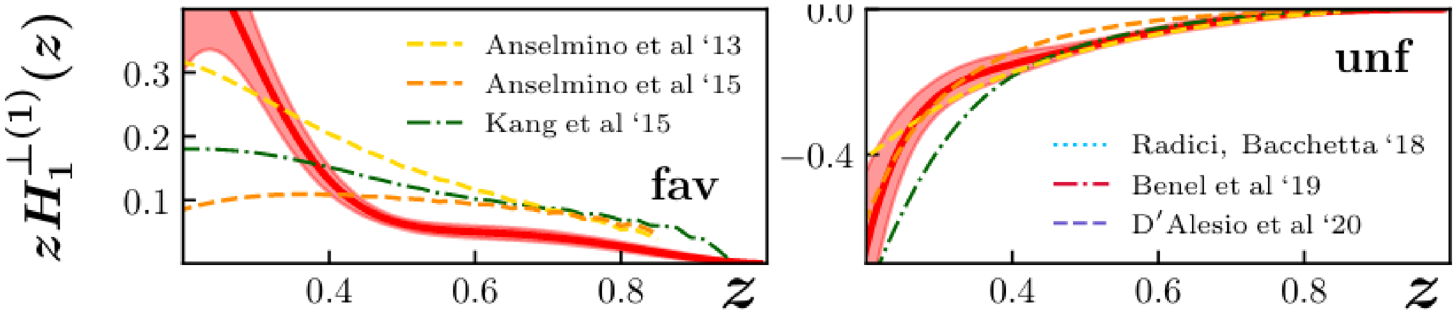
Azimuthal asymmetries of back-to-back hadron





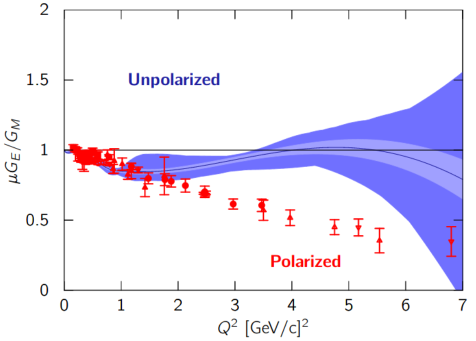
η: sensitivity also to the fragmentation of strange quarks

JAM20, PRD 102, 054002 (2020)



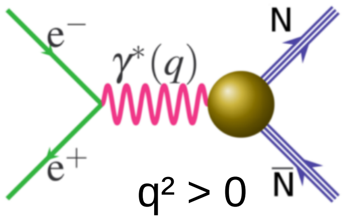
(does not include the above data)

Nucleon Electromagnetic Form Factors



Disagreement in pol. vs unpolarized techniques could be due to two photon exchange contributions

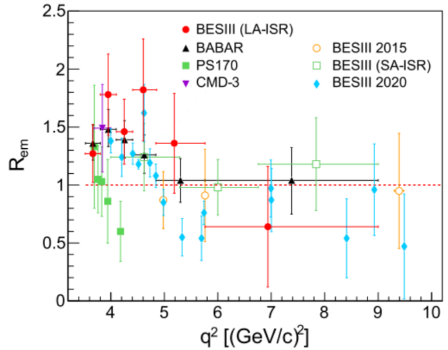
$$\sigma^{Born}_{B\bar{B}}(q^2) = \frac{4\pi\alpha^2\beta C}{3q^2}\left[|G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2\right]$$

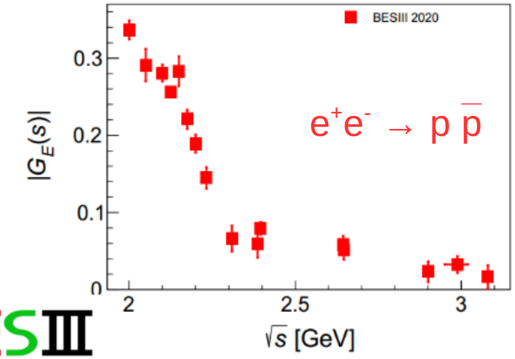


$q^2 > 0$

Yadi Wang talk
Wednesday, Spin&QCD

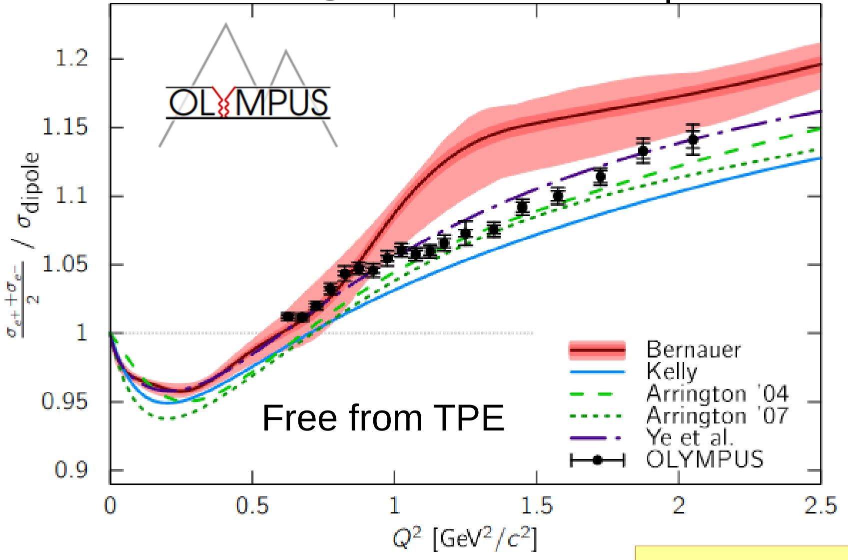
PRL 124. 042001 (2020)



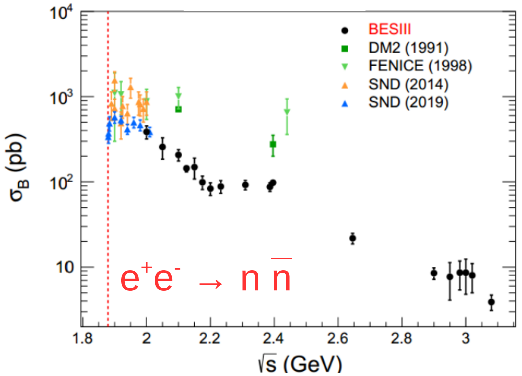


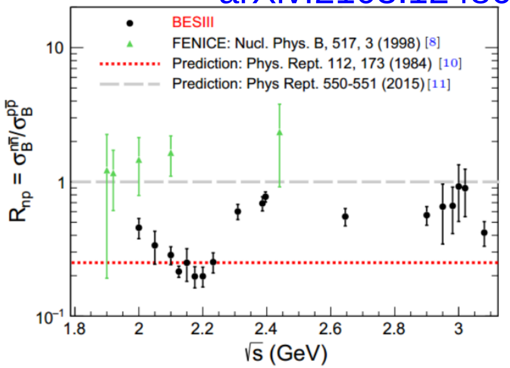
BESIII

OLYMPUS @ DESY: Elastic ep scattering



arXiv:2103.12486





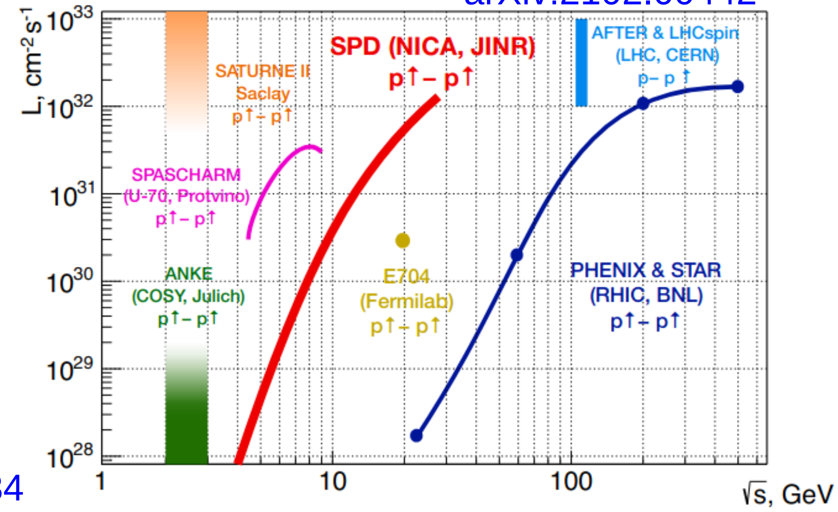
PRL 126, 162501 (2021)

Axel Schmidt talk
Sunday, Spin&QCD

Past, present and future Spin physics experiments

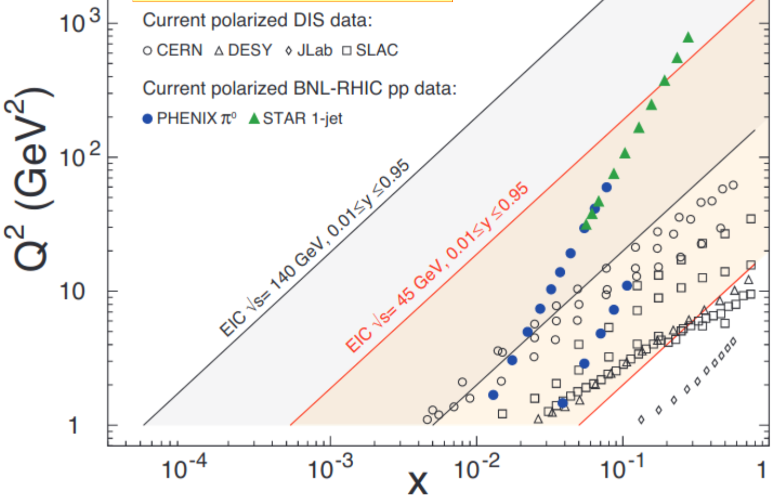
Alexey Guskov talk
Wednesday, Spin&QCD

arXiv:2102.00442

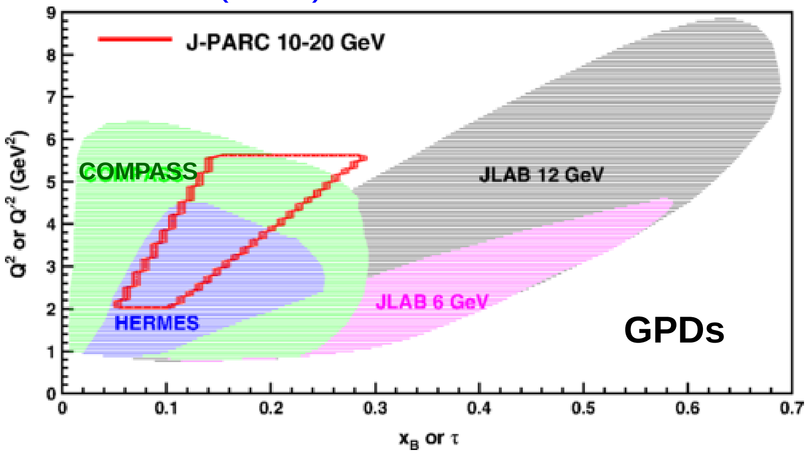


Bernd Surrow talk
Today, Plenary

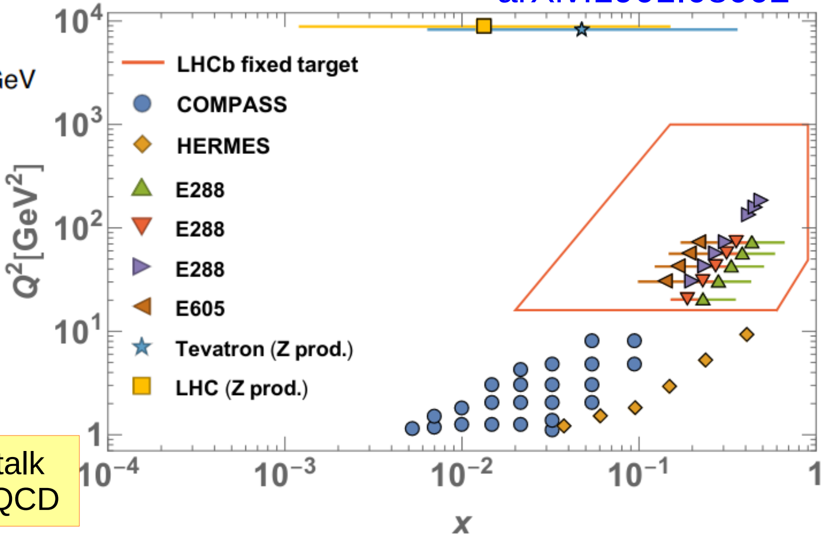
arXiv:1212.1701



PRD 93 (2016) 114034

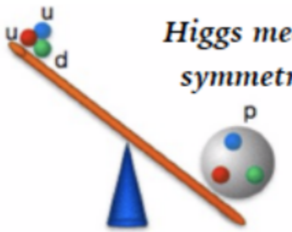


arXiv:1901.08002



Pasquale di Nezza talk
Wednesday, Spin&QCD

Other experimental trends



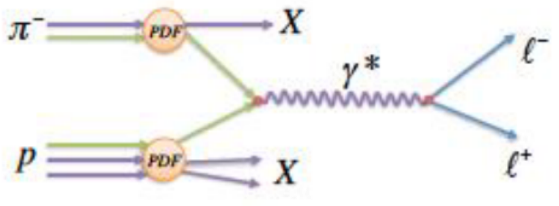
Higgs mechanism vs spontaneous symmetry breaking mechanism

Understanding the proton structure is closely related to understanding the mechanism by which protons (and hadrons in general) acquire mass

Dynamic Chiral Symmetry Breaking in QCD is key to understand the phenomenom of **Emergence of hadron mass**

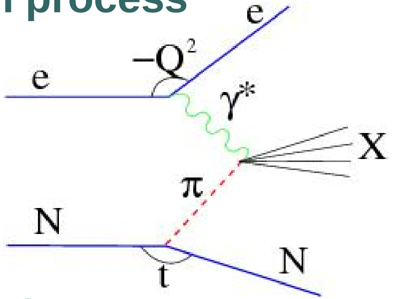
The high precision reached in our knowledge of proton structure needs to be followed by an improved knowledge on **meson structure**

π and K induced Drell-Yan



AMBER @ CERN

Sullivan process



JLab12 **EIC**

Thank you!