PARTONIC NUCLEON STRUCTURE IN LEPTON SCATTERING

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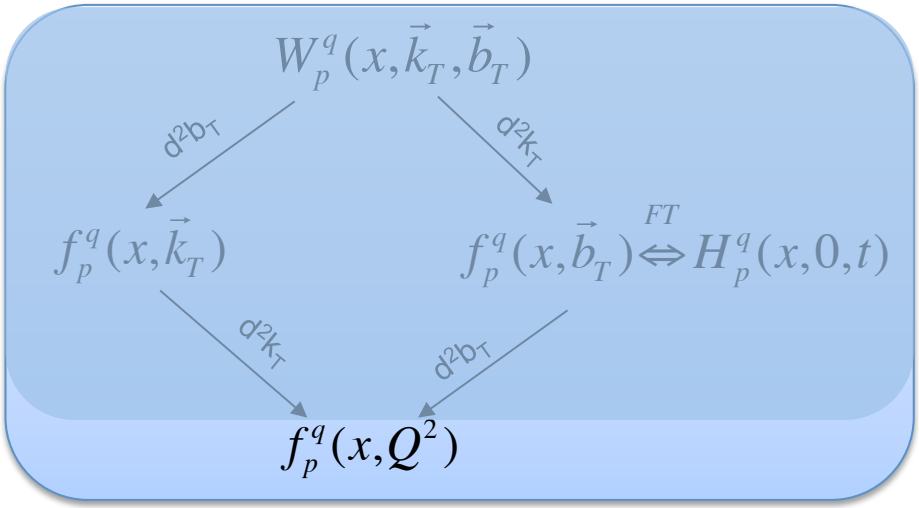
INFN Ferrara

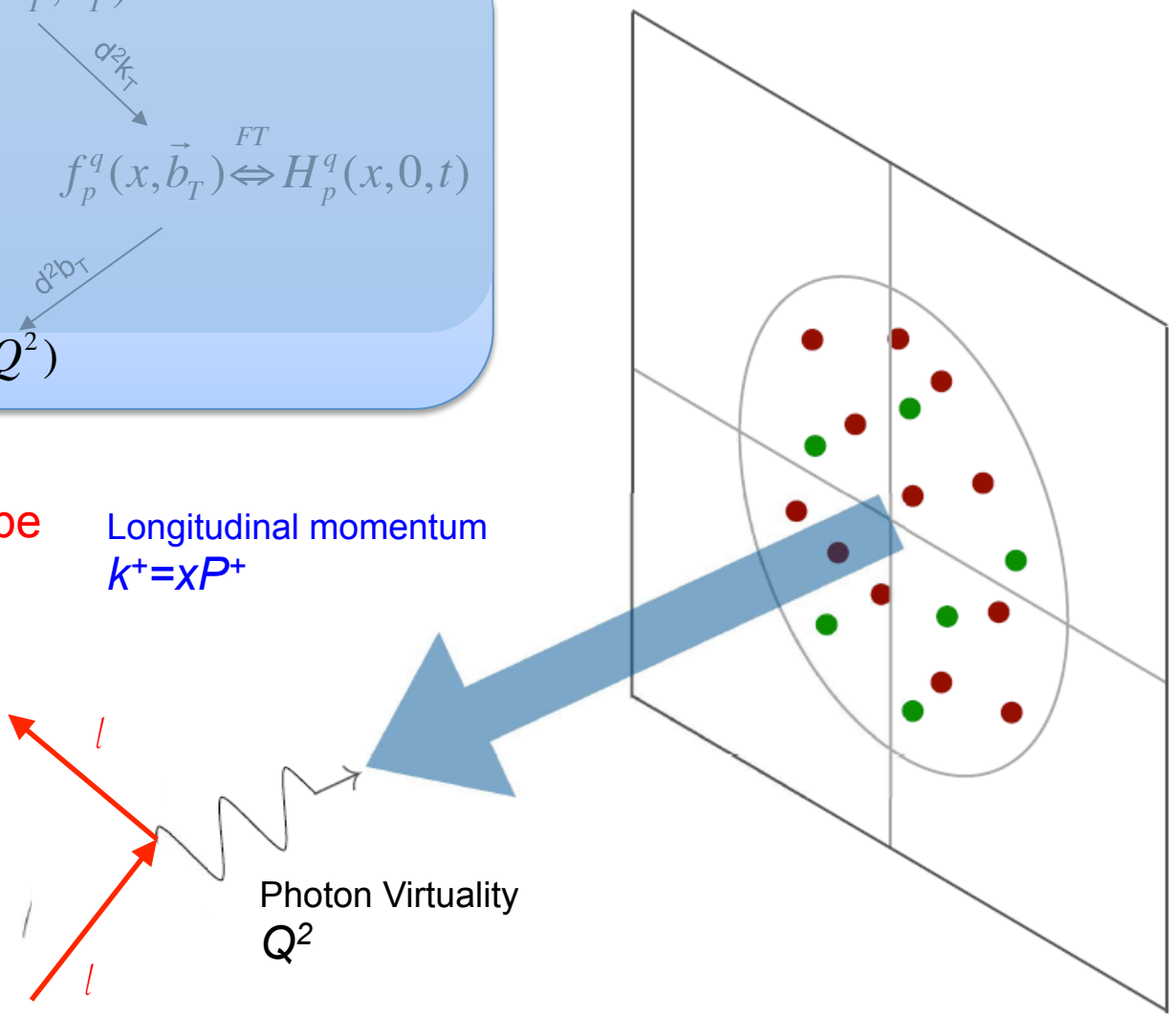
15th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon
December 2, 2016 Carnegie Mellon University, Pittsburg PA, USA

The Nucleon Structure

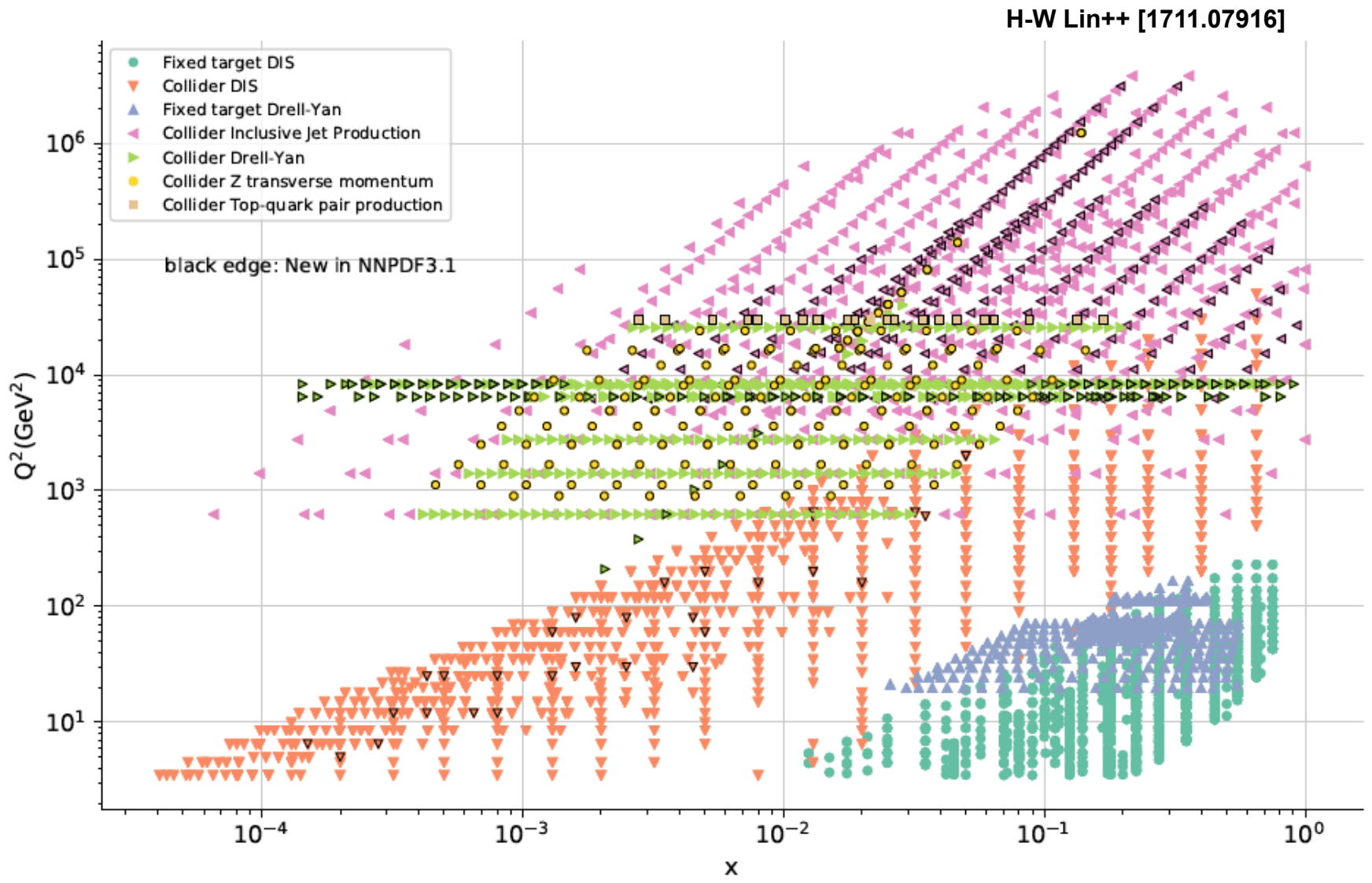


High Energy Probe
Hard Scale

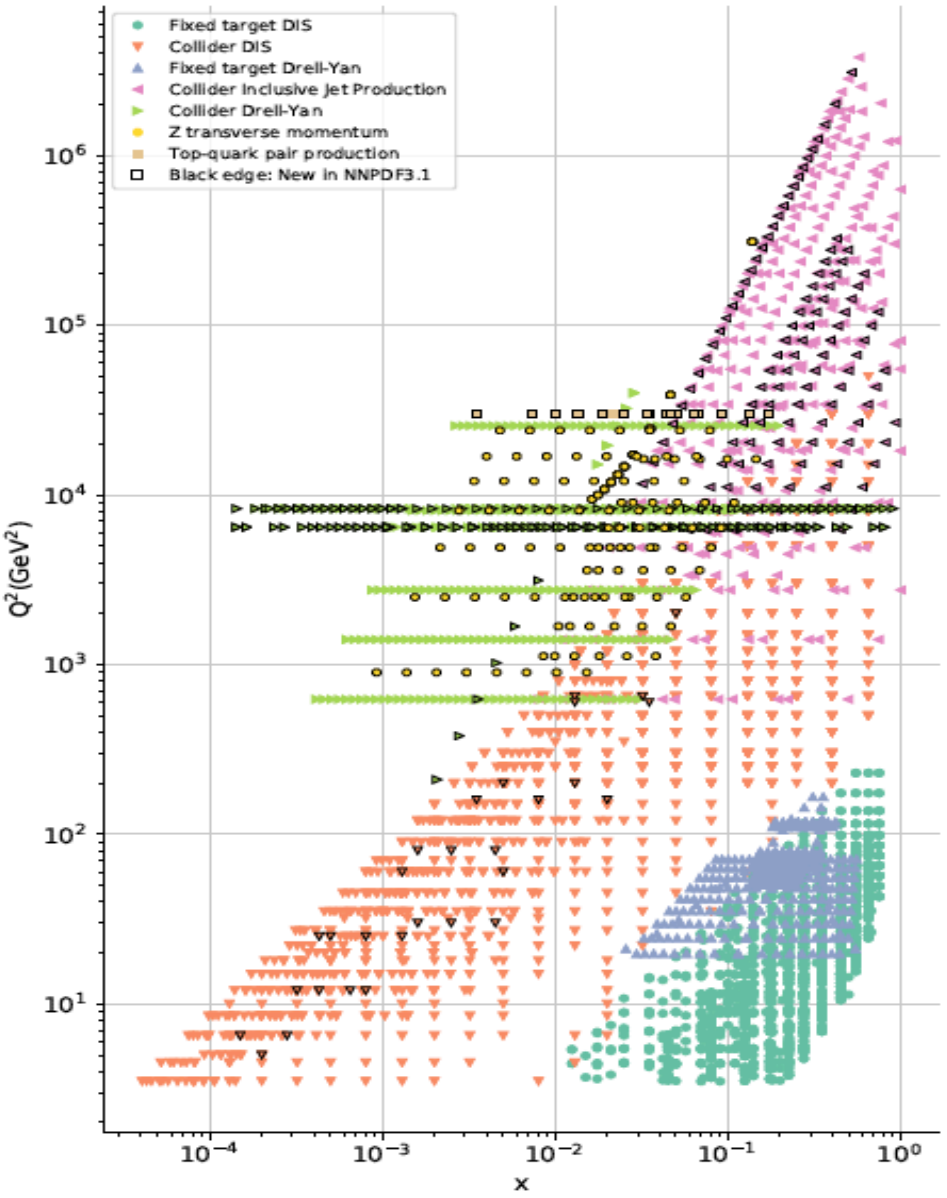
Longitudinal momentum
$k^+ = xP^+$

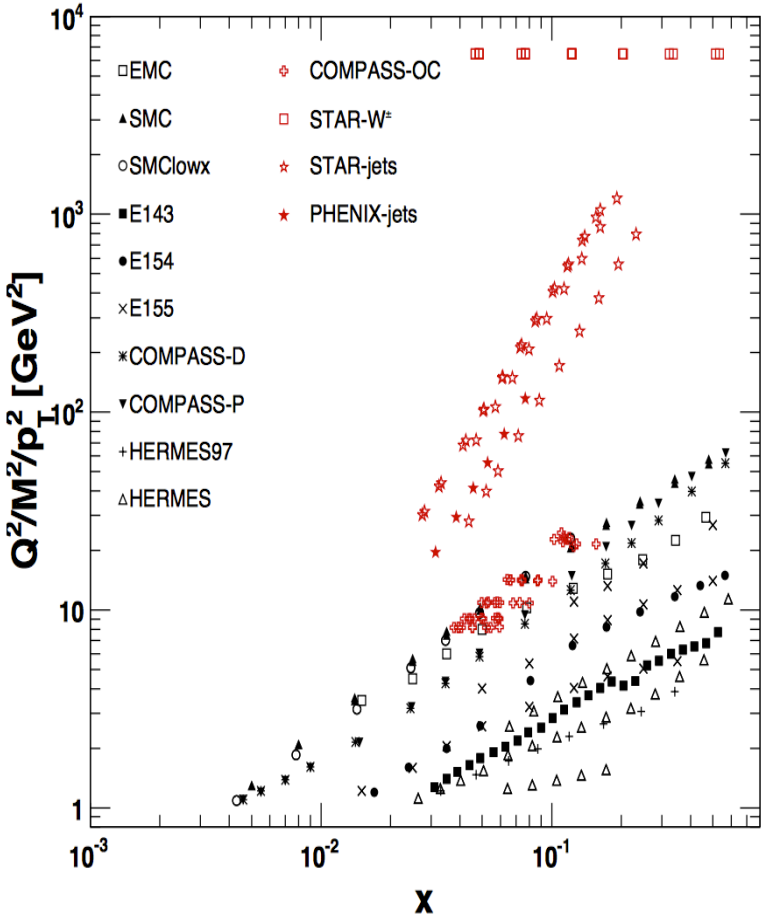


Kinematic Coverage



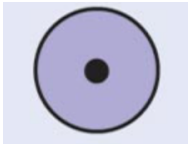
Kinematic Coverage



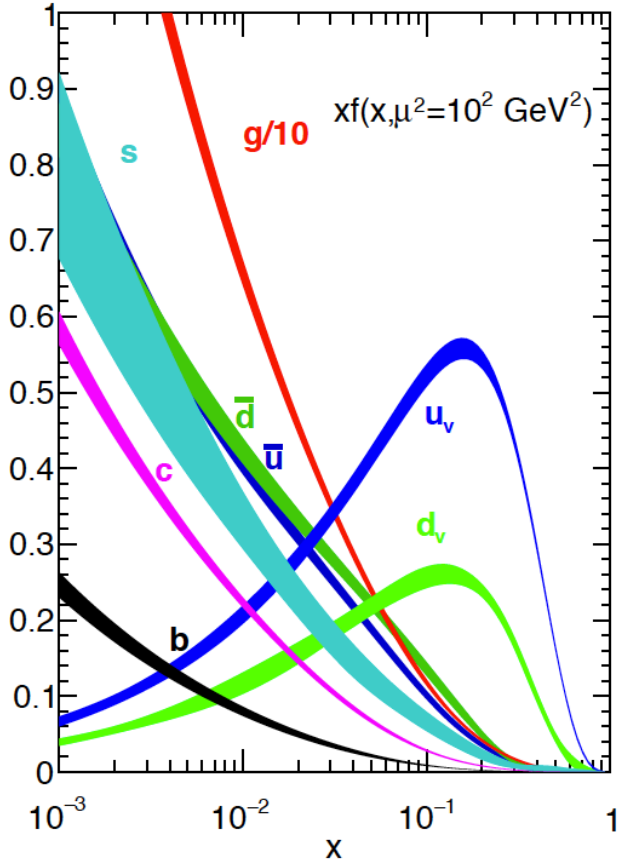


Parton Content

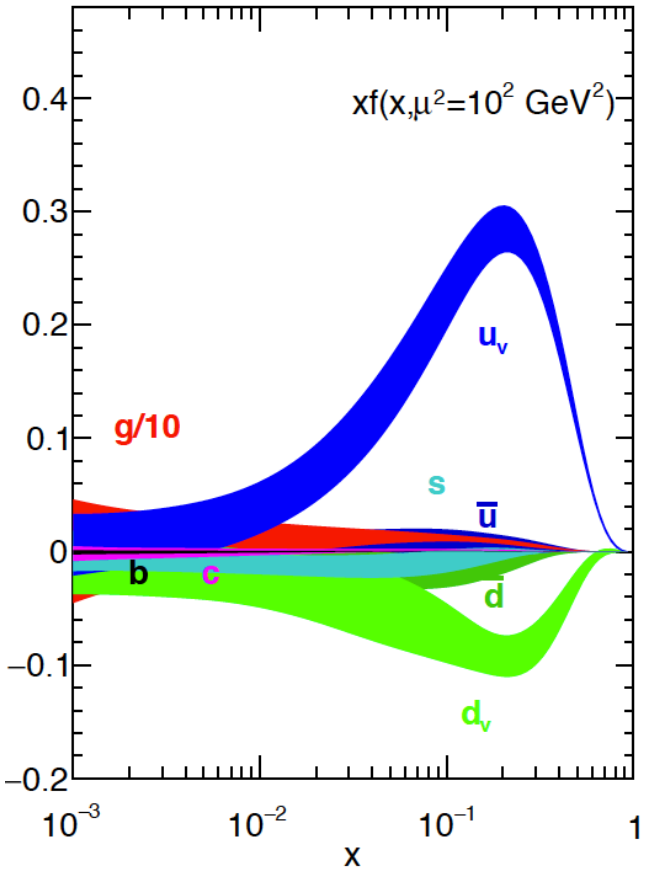
MMHT	[arXiv 1412.3989]
HERAPDF2.0	[arXiv 1506.06042]
CT14	[arXiv 1506.07443]
CJ15	[arXiv 1602.03154]
ABMP16	[arXiv 1701.05838]
NNPDF3.1	[arXiv 1706.00428]



BB	[arXiv 1005.3113]
LSS	[arXiv 1010.0574]
DSSV	[arXiv 1404.4293]
BS	[arXiv 1408.7057]
NNPDF	[arXiv 1406.5539]
JLAM	[arXiv 1601.07782]

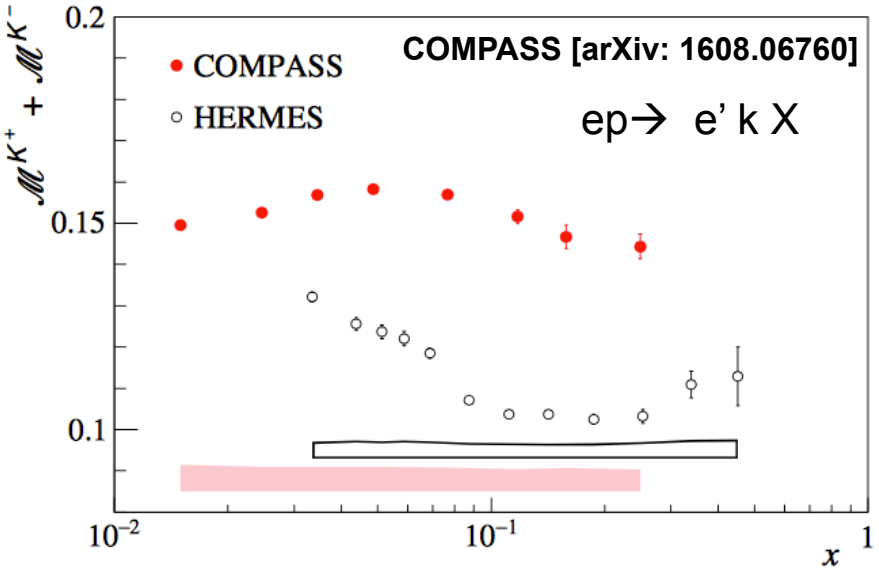


H-W Lin++ [1711.07916]

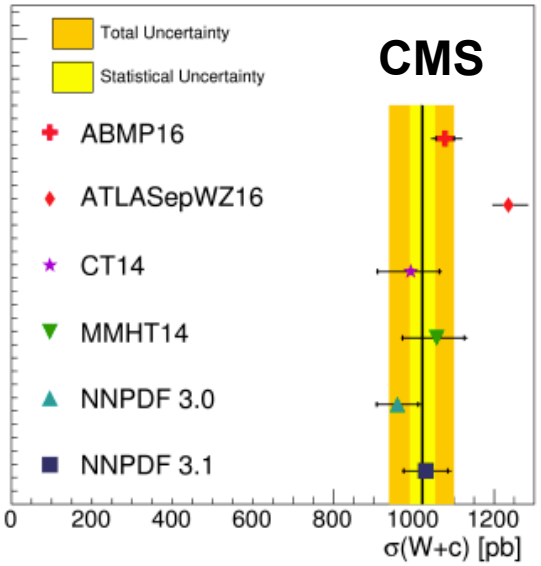


Strange Content

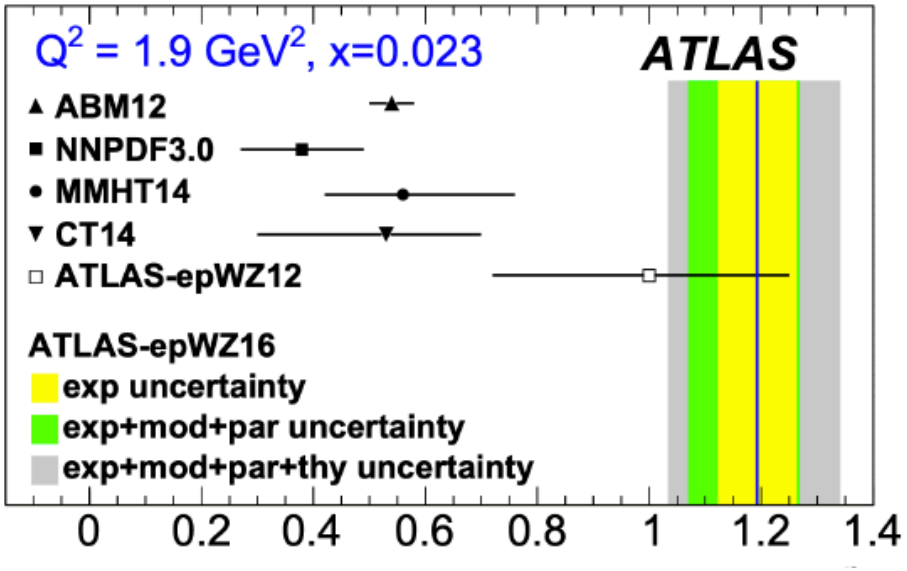
Still contradictory experimental results



pp→ W c X **CMS [arXiv: 1310.1138]**



pp→ W X **ATLAS [arXiv: 1612.03016]**

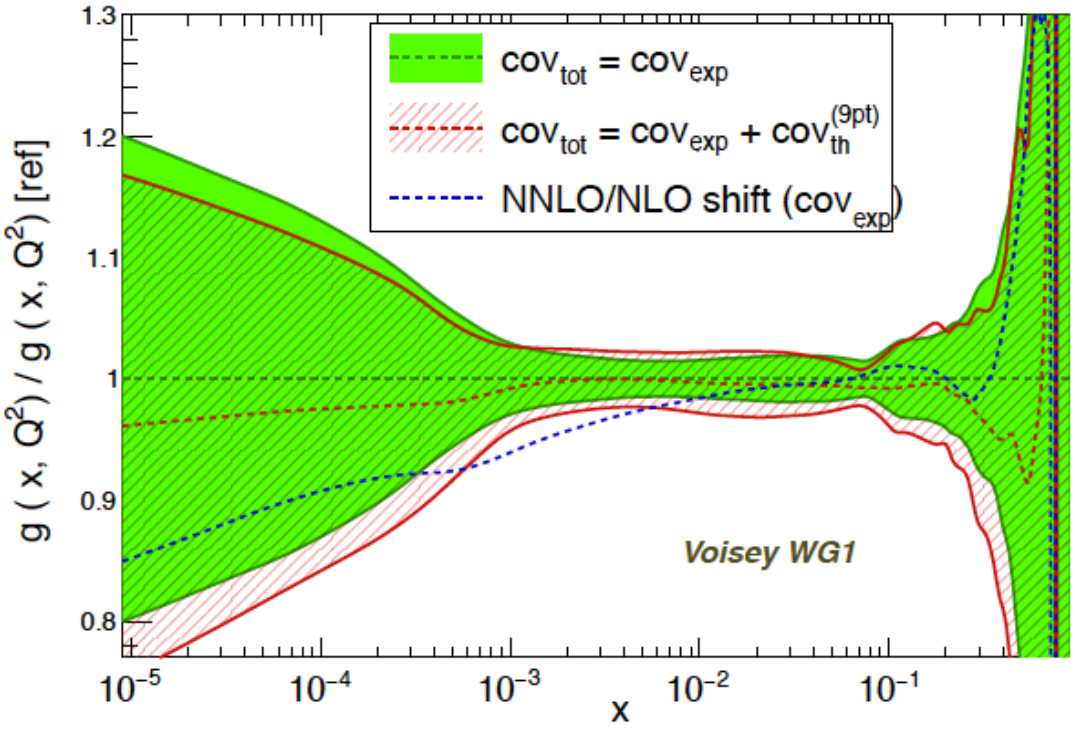


$$r_s = \frac{s + \bar{s}}{2\bar{d}}$$

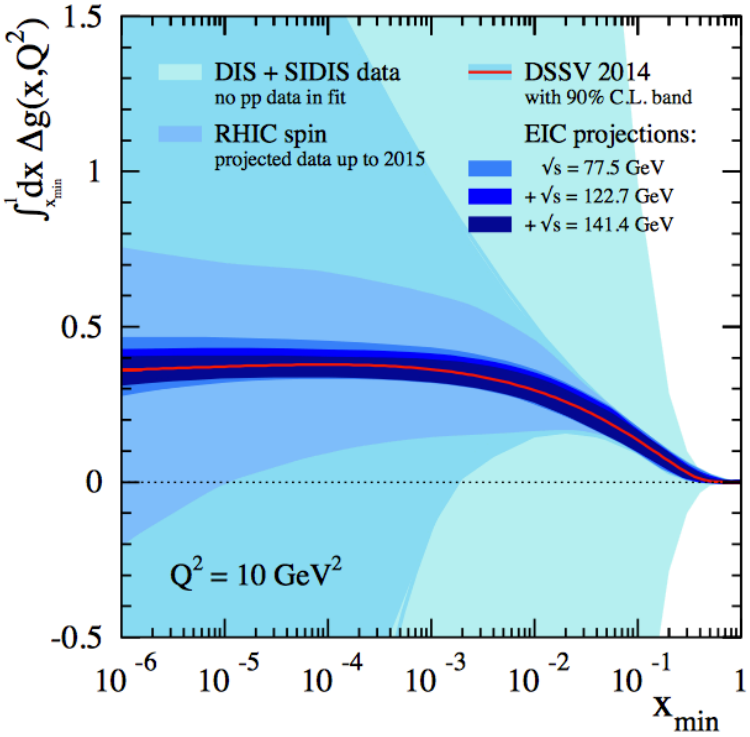
Gluon Content

Awaiting the advent of a dedicated electron−ion collider

NNPDF3.1++ [1706.00428]



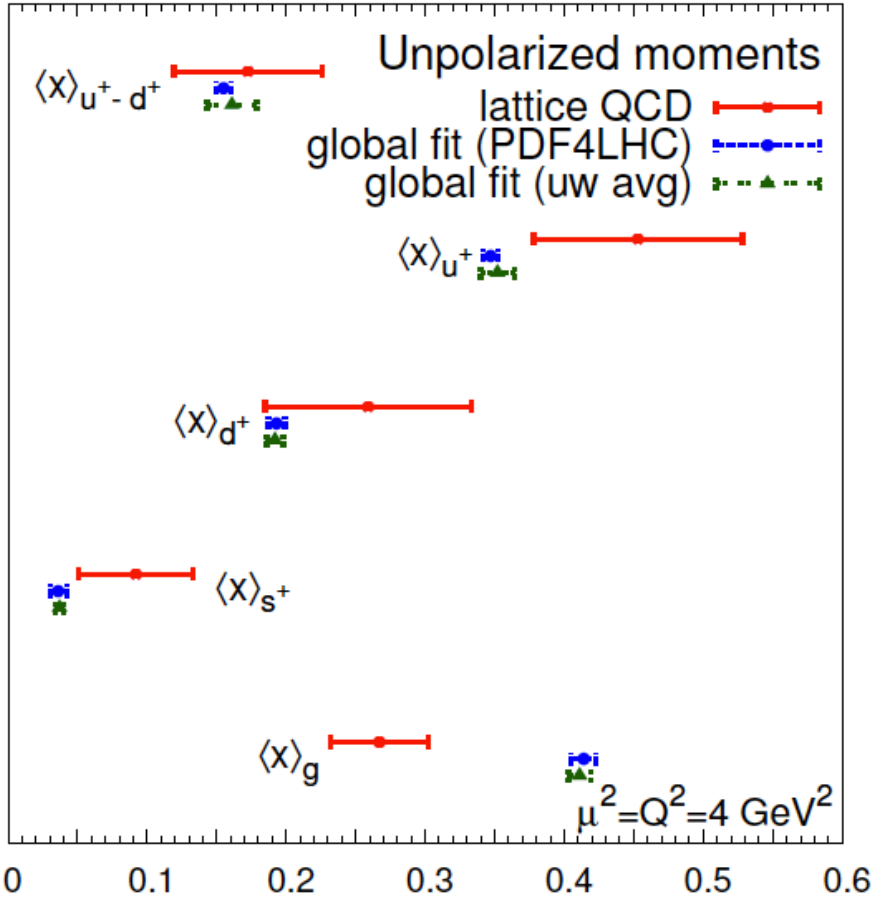
E.C. Ashenauer++ [1509.06489]



R. Seidl, C. Weiss talks

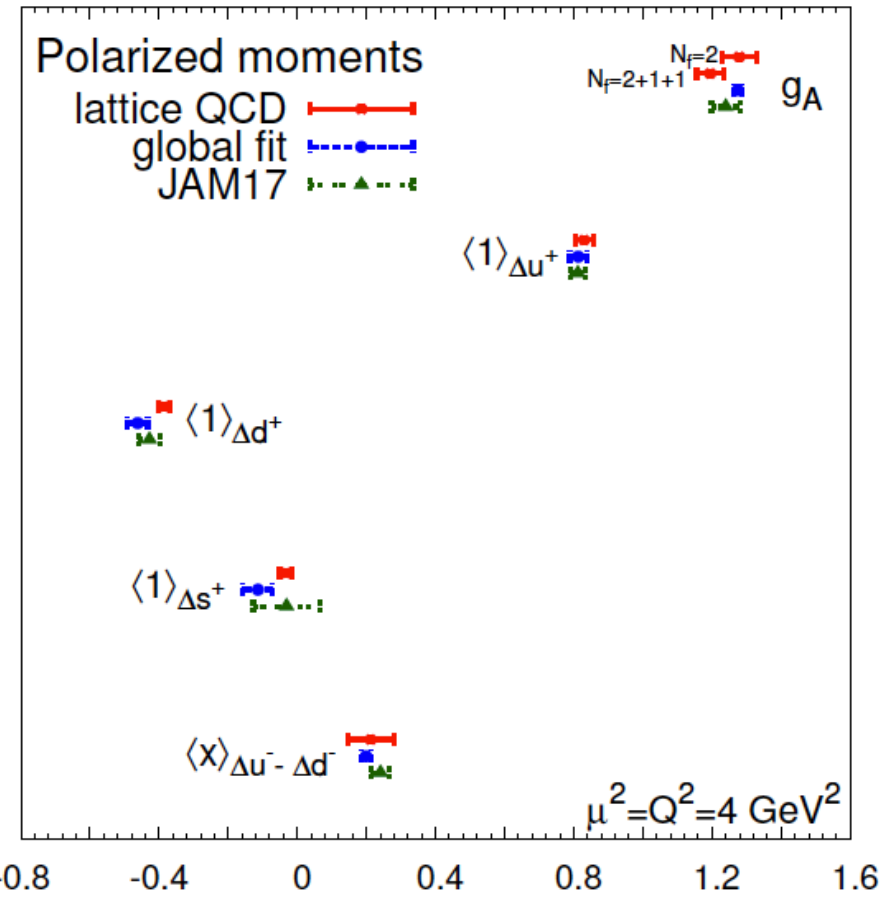
Parton Content

Unpolarized moments



Polarized (helicity) moments

H-W Lin++ [1711.07916]



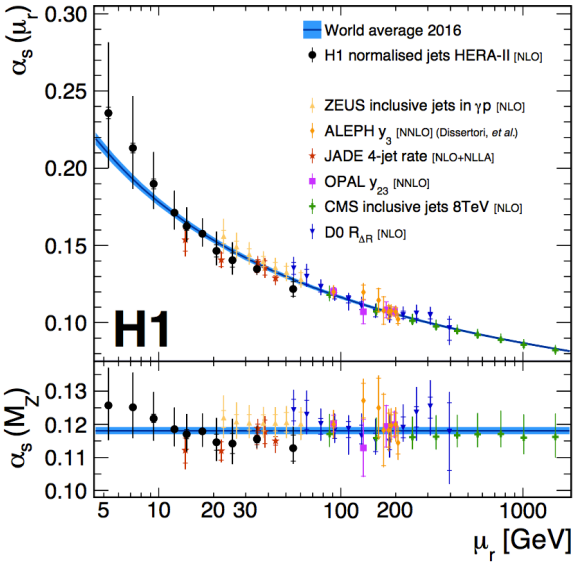
Inclusive Jets @ HERA

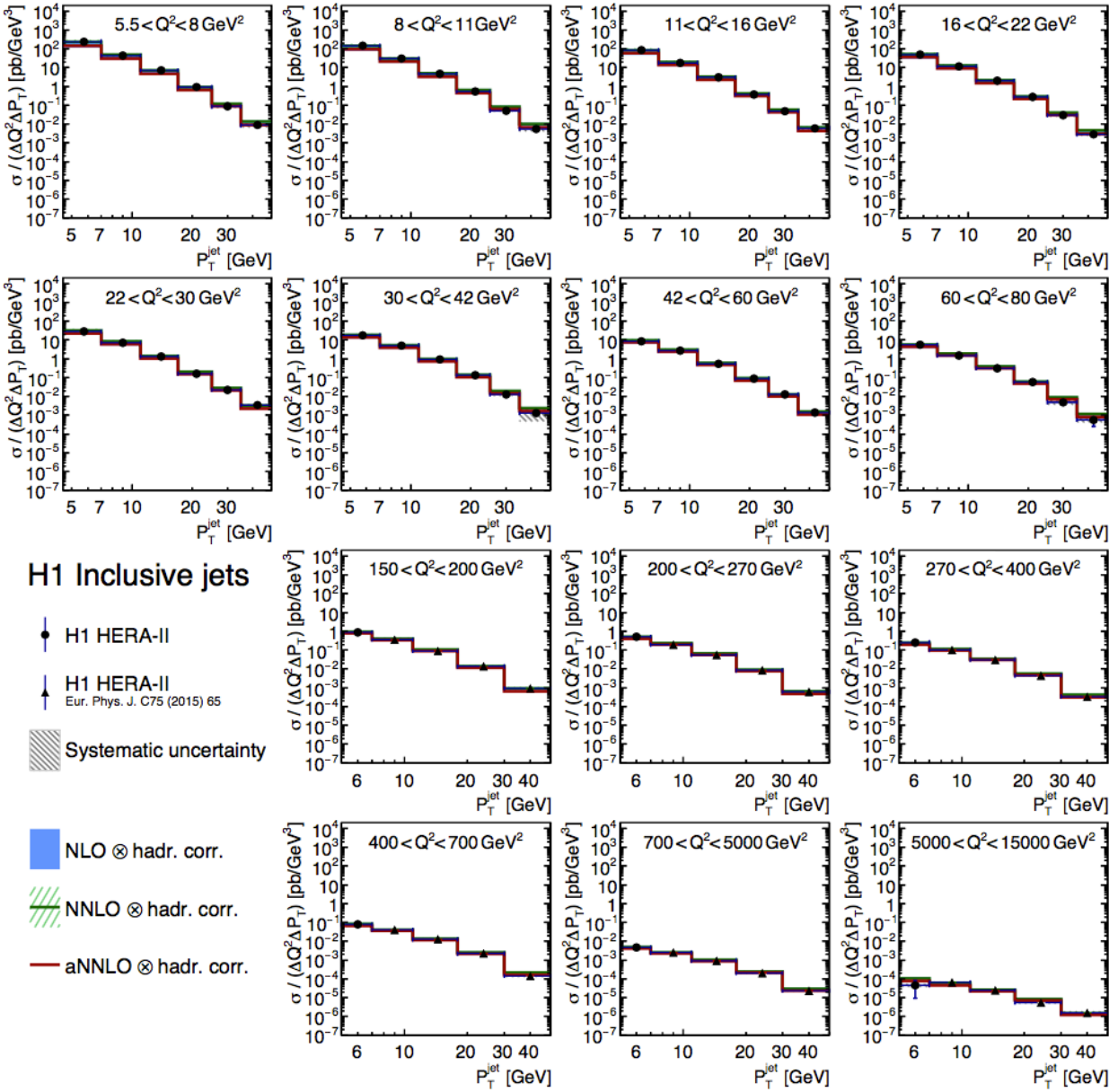
Good perturbative description (hard gluon emission)

p_T>5 GeV Q^2>5 GeV^2

Part in a p_T<<Q TMD regime

H1 [arXiv: 1611.03421]

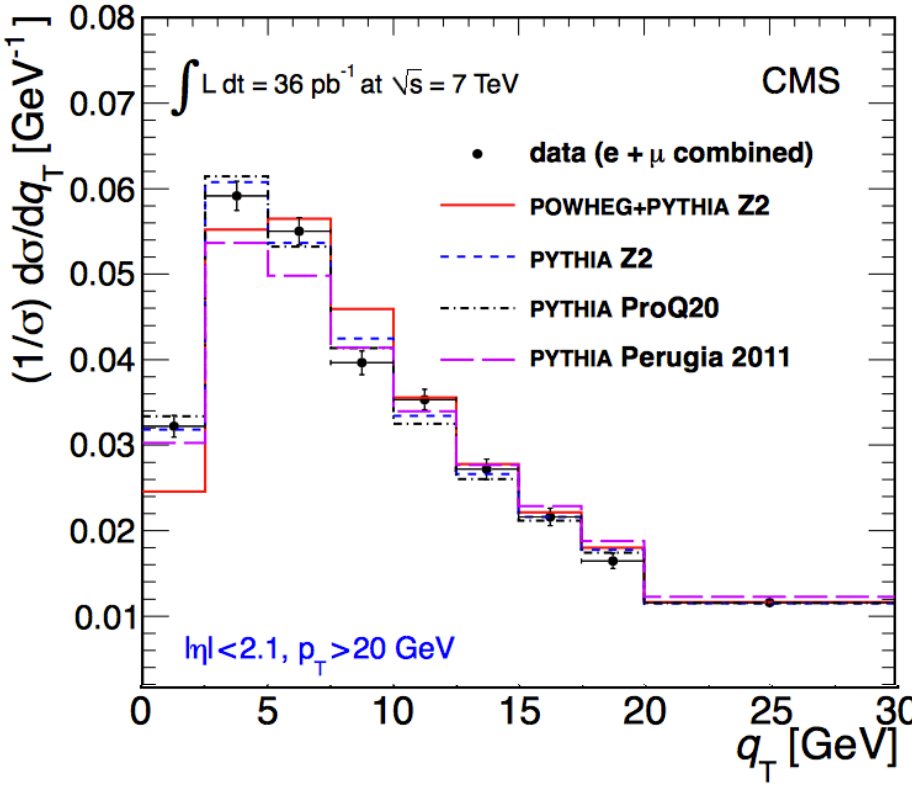




Non Perturbative QCD signals

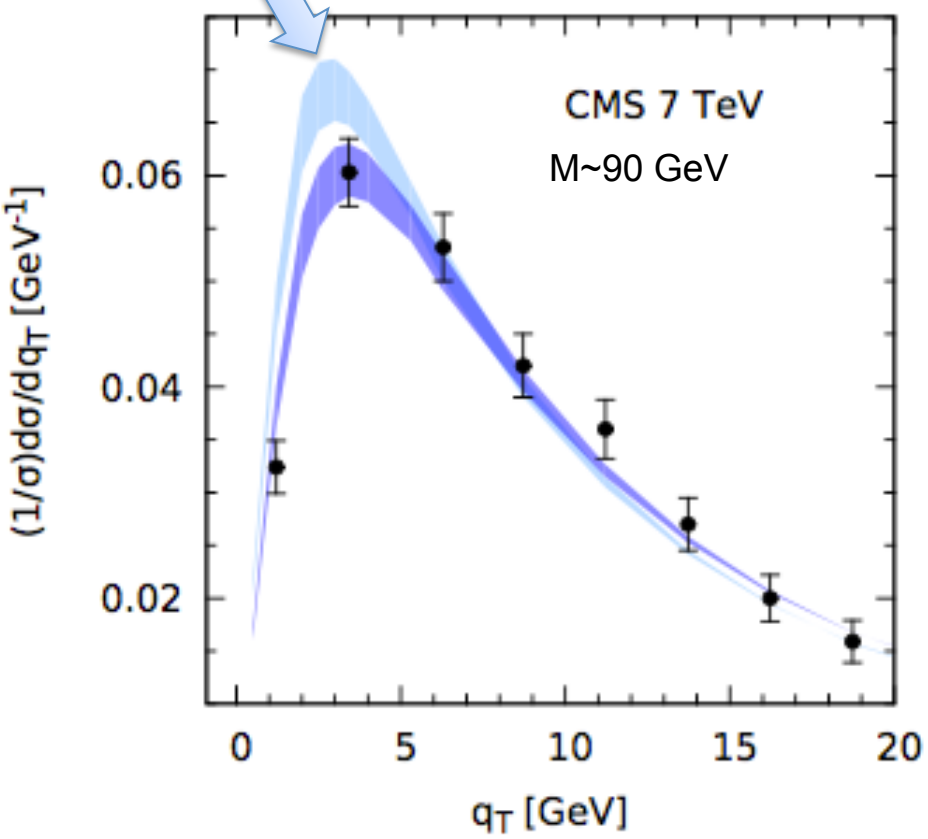
Non perturbative PDF component shows effects up to vector boson production at LHC

CMS [arXiv: 1110.4973]



$f_p^q(x,k_\perp^2)$

D'Alesio++ [arXiv: 1407.3311]



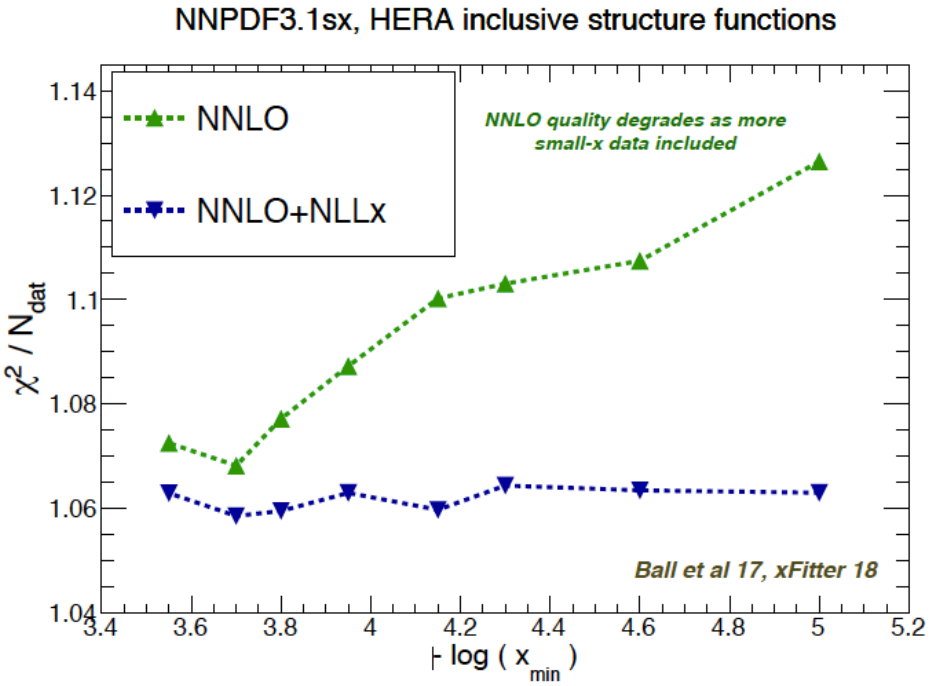
Gluon uPDF @ low-x

Starting distribution for gluons at q_0

$\sigma^2 = q_0^2 / 2$

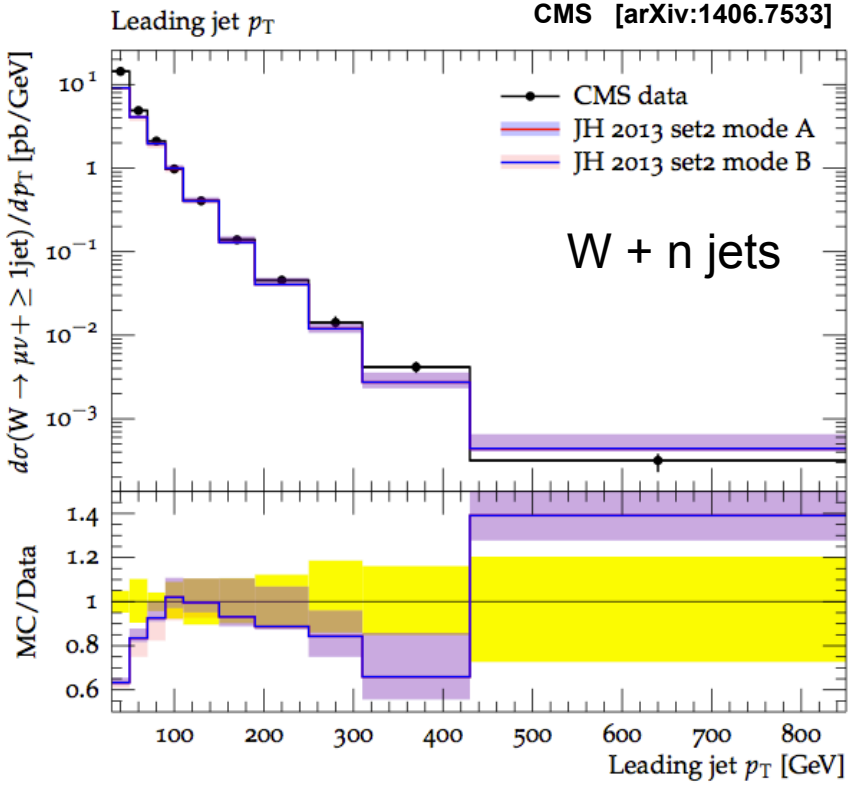
$$x\mathcal{A}_0(x, k_\perp) = Nx^{-B} \cdot (1-x)^C \left(1 - Dx + E\sqrt{x}\right) \exp[-k_t^2/\sigma^2]$$

with CCFM (BFKL like) evolution



S. Dooling ++ [arXiv 1406.2994]

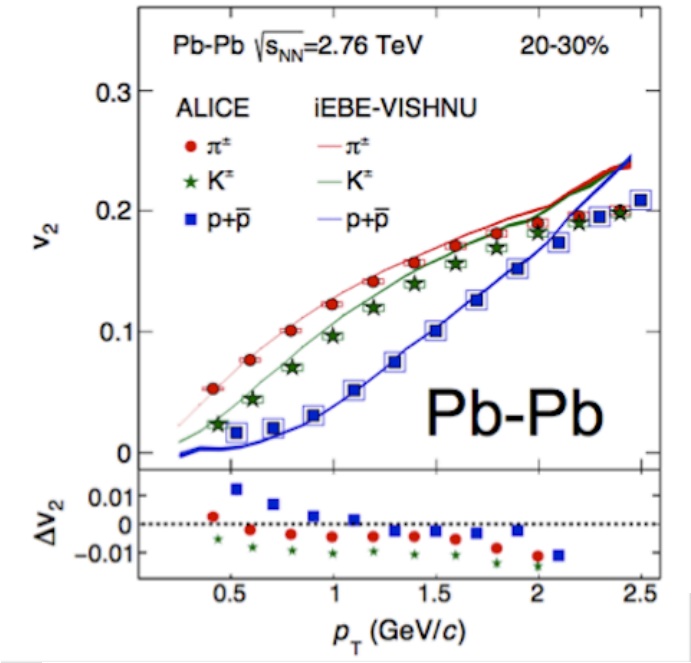
CMS [arXiv:1406.7533]



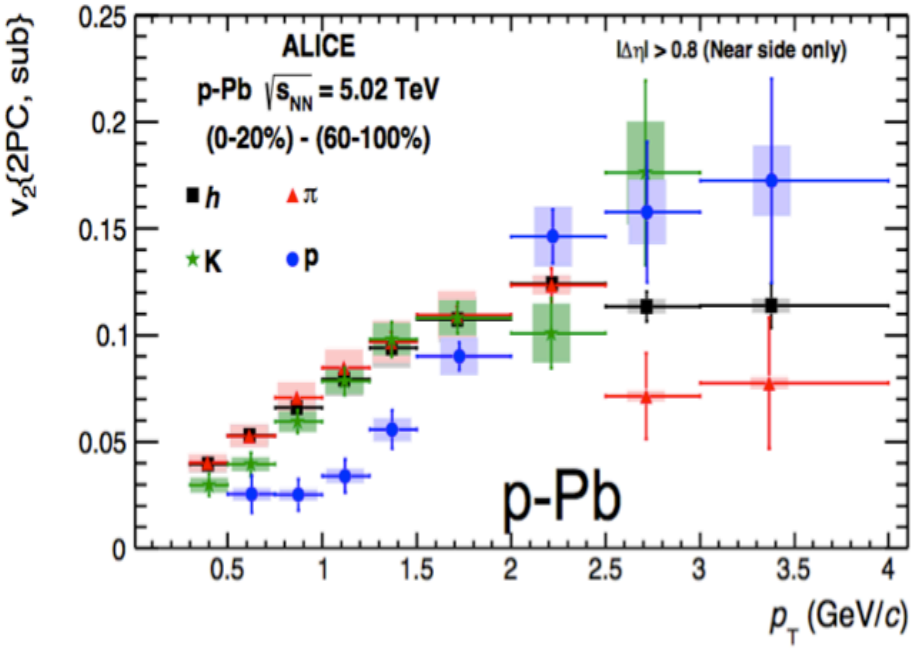
Elliptic Flow

Is there a collective motion in small systems ?

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \dots\right)$$



ALICE [PLB 726 (2013) 164]



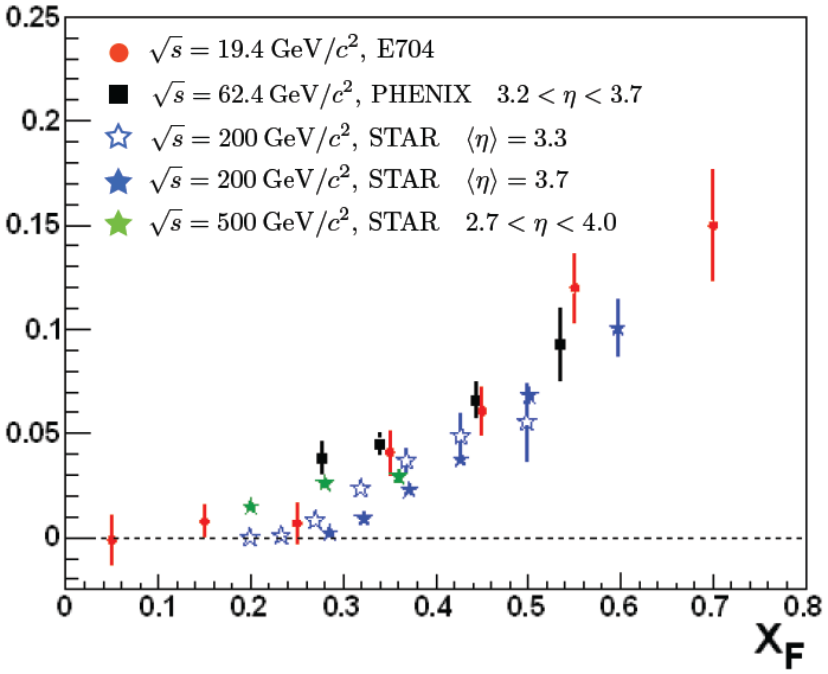
QCD vs pQCD

QCD can not be a precision science

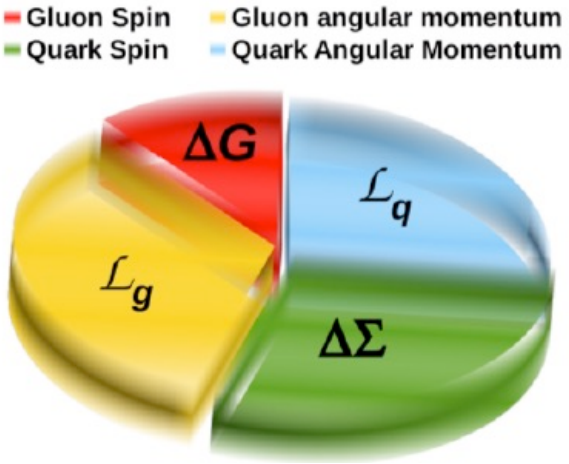
Should not be confused with pQCD, which can,
but is not touching the intimate nature of the strong interaction

Single Spin Asymmetries

A_N $pp^{\uparrow} \rightarrow \pi X$



Proton Spin Budget

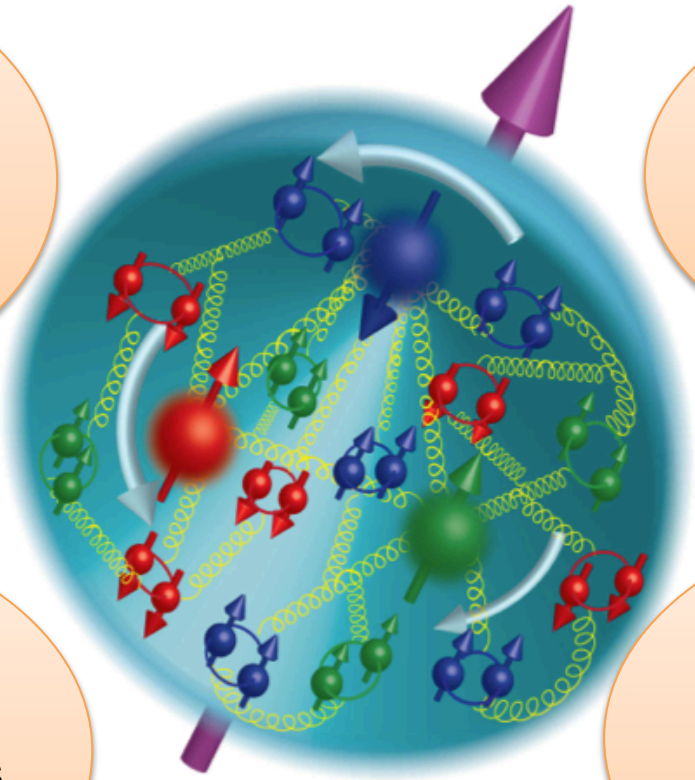


$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$

The Strong Force Confined Universe

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q}\left[i\gamma^{\mu}(\partial_{\mu} - igA_{\mu}) - m_q\right]q$$

Dynamic Spin
- Parton polarization
- Orbital motion
- Form Factors
- Magnetic Moment

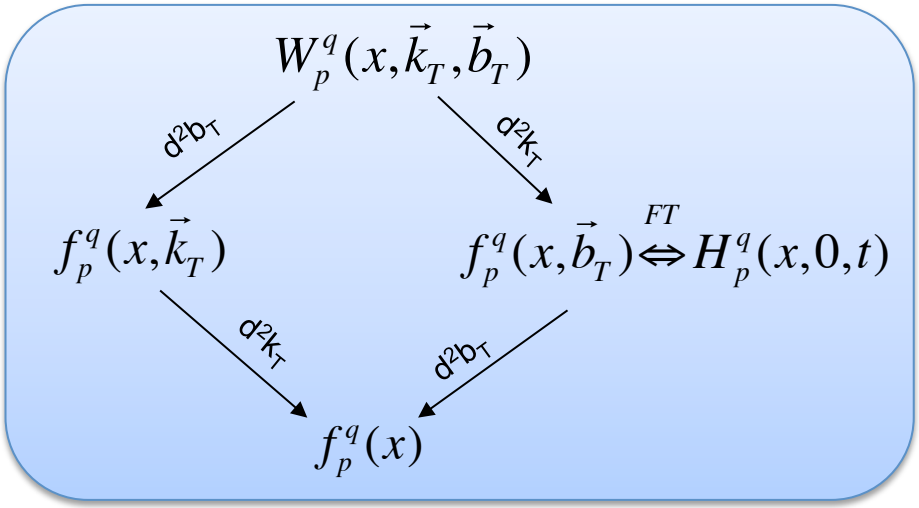


Parton Correlations
- dPDFs
- Short range
- MPI

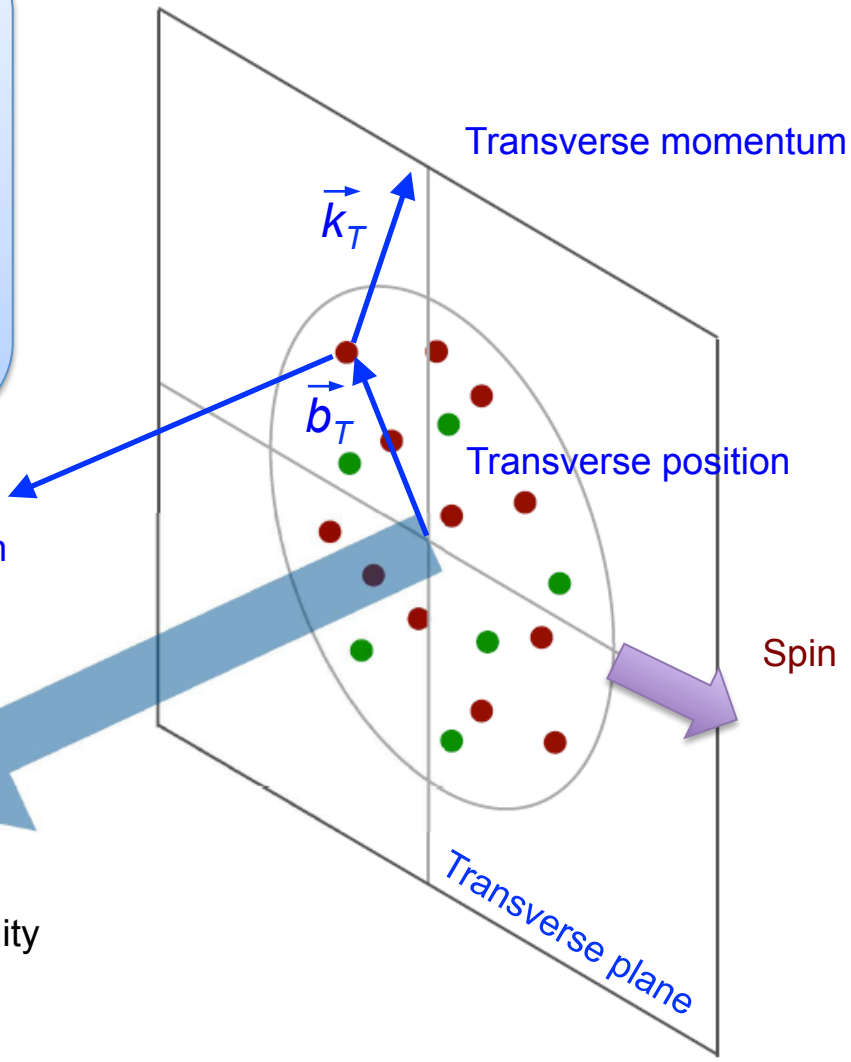
Hadronization
- Spin-orbit effects
- Parton energy loss
- Jet quenching

Color charge density
- Nucleon tomography
- Diffractive physics
- Gluon saturation
- Color force

The 3D Nucleon Structure

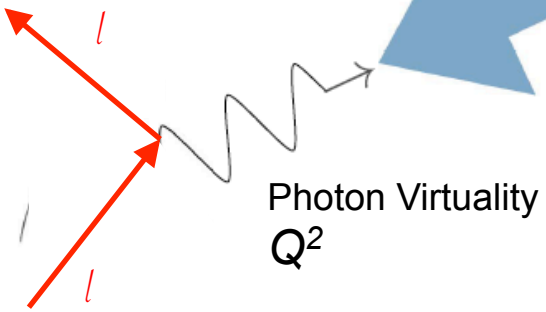


Confinement Scale



High Energy Probe
Hard Scale

Longitudinal momentum
$k^+ = xP^+$

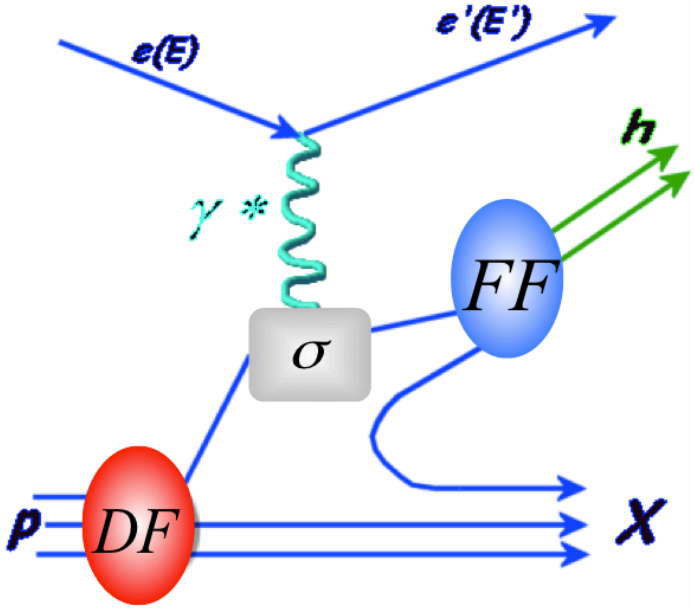


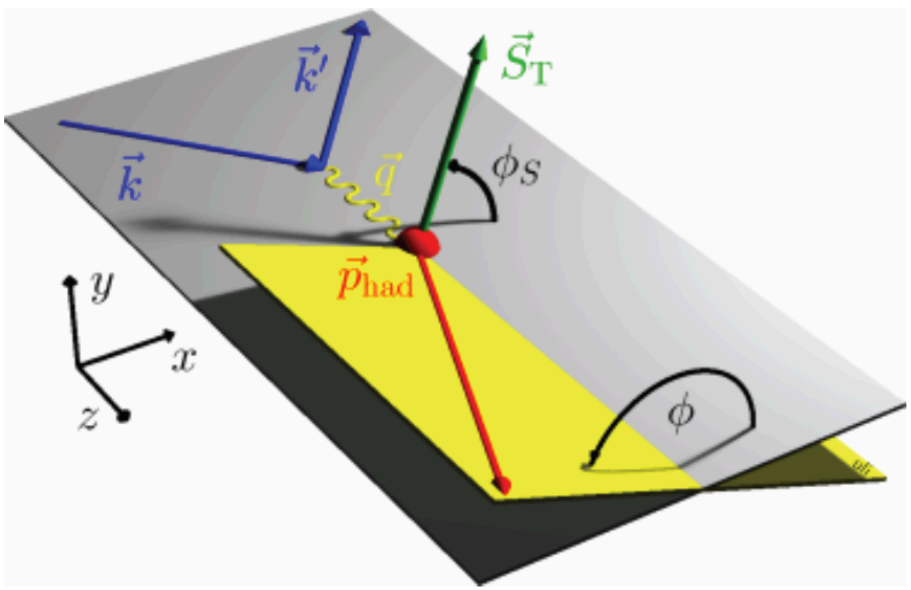
SIDIS & TMDs

3D momentum and spin-orbit effect:
Parton kinematics and flavor from observed hadron kinematics and type

Distribution and fragmentation convoluted:

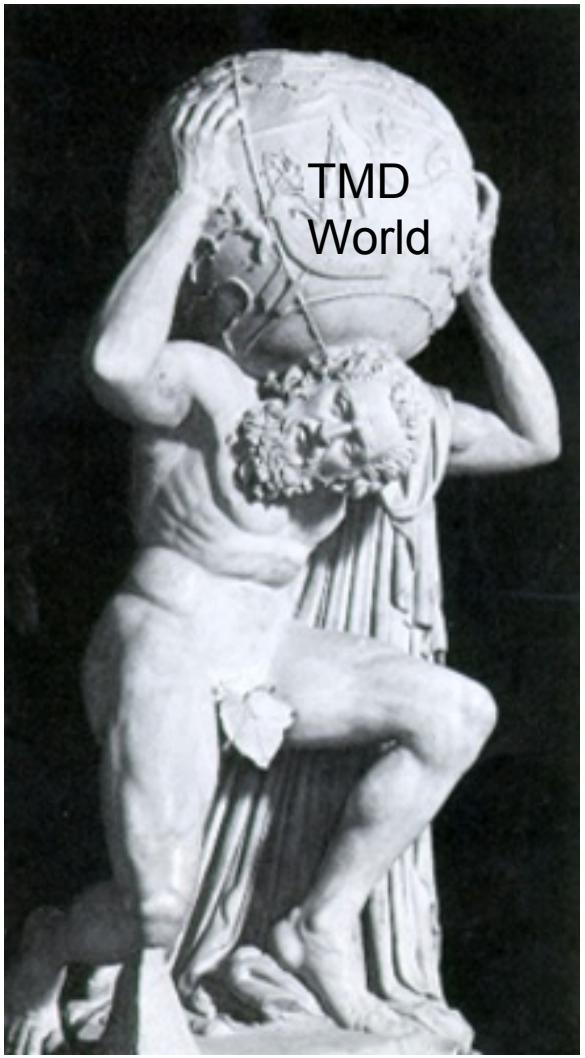
$$d^6\sigma^h \propto \sum_q e_q^2 q(x,k_T) \otimes D_q^h(z,p_T)$$

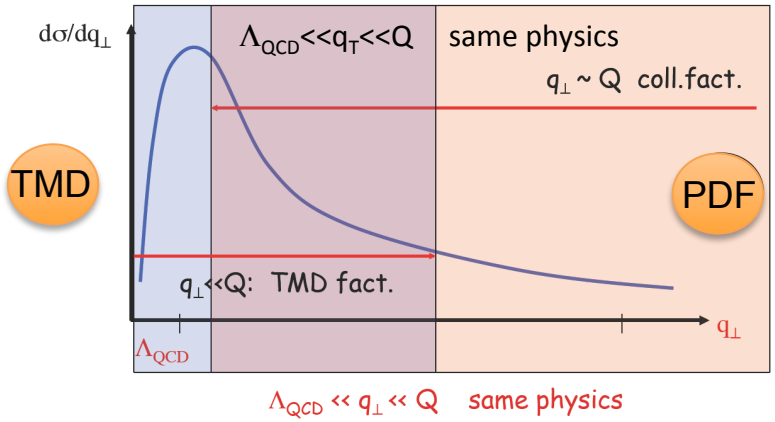




Parton Correlators

Beauty and complexity of the unique strong-interacting world





quark polarisation

nucleon polarisation

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1, h_{1T}^\perp$

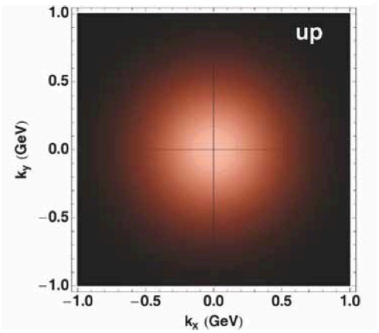
hadron polarisation

quark polarisation

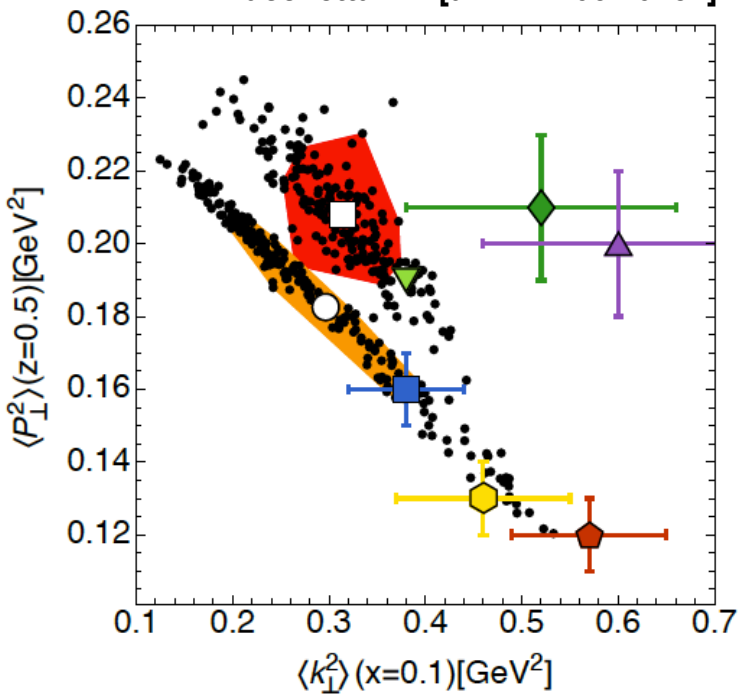
N/q	U	L	T
U	D_1		$H_1^\perp$

Unpolarised TMDs

$$\left\langle P_{h\perp}^2 \right\rangle = z^2 \left\langle k_T^2 \right\rangle + \left\langle p_T^2 \right\rangle$$



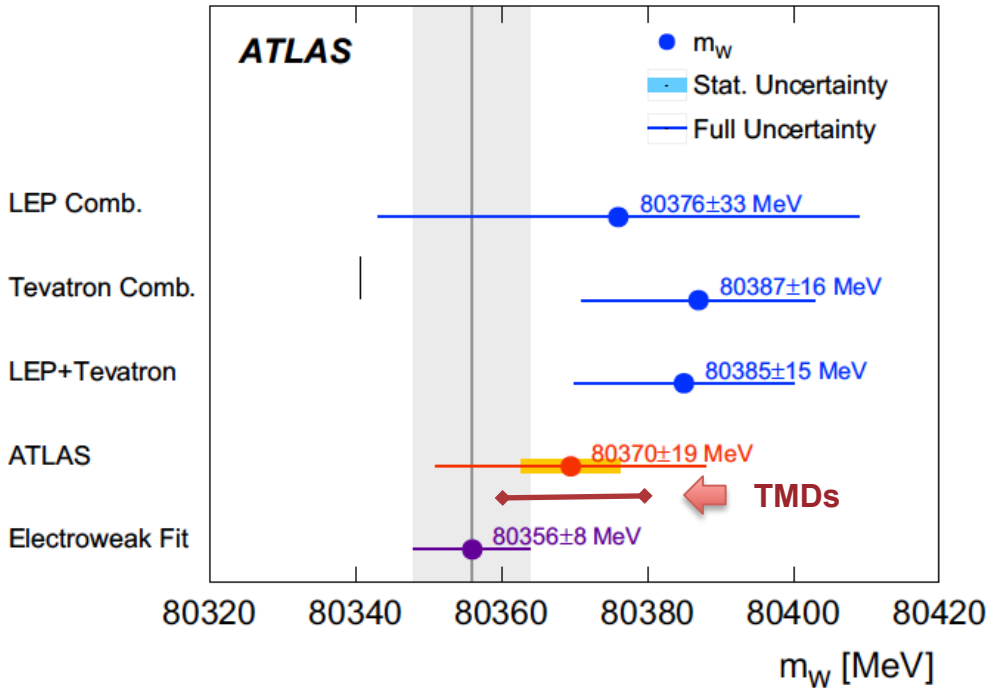
A. Bacchetta++ [arXiv:1703.10157]



$$m_W = 80370 \pm 7\ (\text{stat.}) \pm 11\ (\text{exp. syst.}) \pm 14\ (\text{mod. syst.})\ \text{MeV}$$

+9 / -6 (TMDs)

ATLAS++ [arXiv:1701.07240]

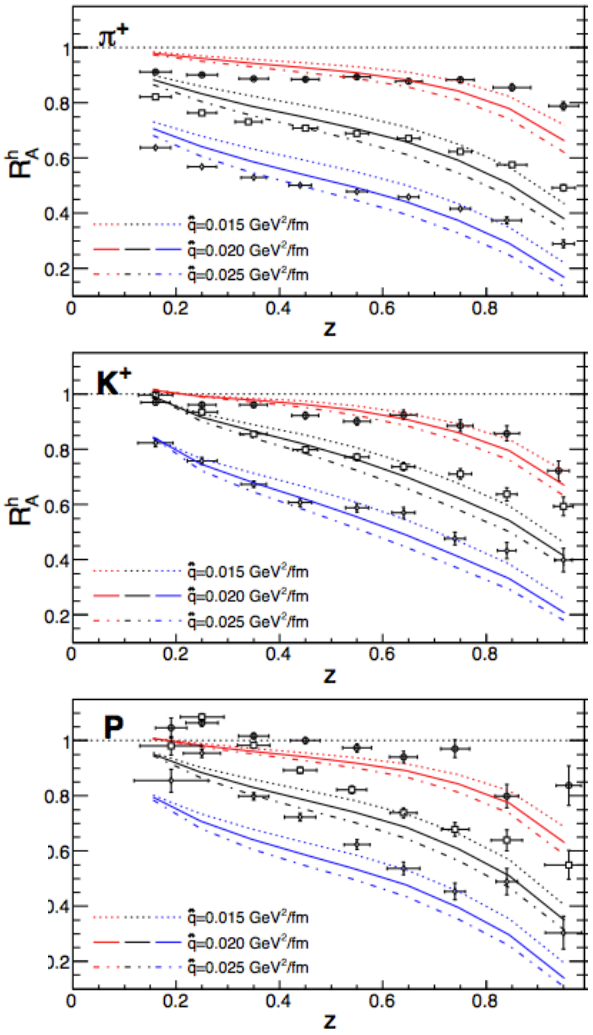


Medium Modifications

DIS

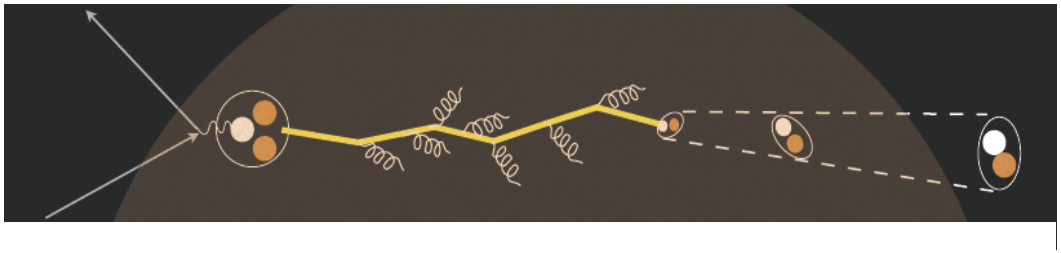
$$\hat{q}_0 \approx 0.020 \pm 0.005 \ \mathrm{GeV}^2/\mathrm{fm}$$

N-B Chang ++ [arXiv:1401.5109]



Parton propagation in nuclear matter

In DIS: kinematic control via scattered electron and target nuclei



RHIC

$$\hat{q} \approx 1.2 \pm 0.3 \ \mathrm{GeV}^2/\mathrm{fm}$$

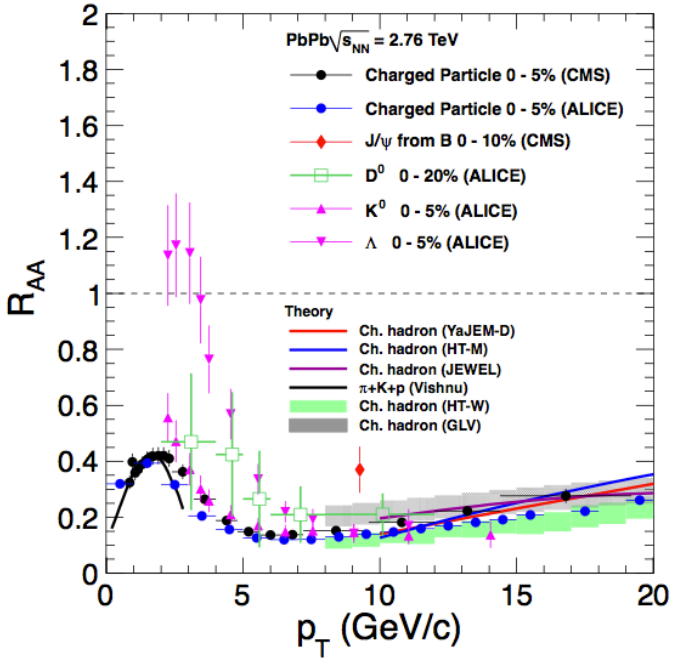
Au+Au $\quad \sqrt{s} = 200 \ \mathrm{GeV/n}$

JET Coll. [arXiv:1312.5003]

LHC

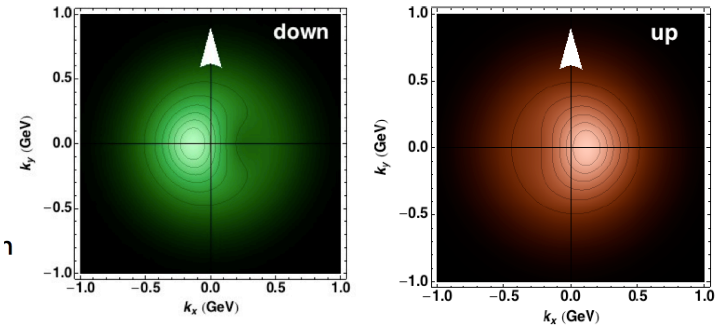
$$\hat{q} \approx 1.9 \pm 0.7 \ \mathrm{GeV}^2/\mathrm{fm}$$

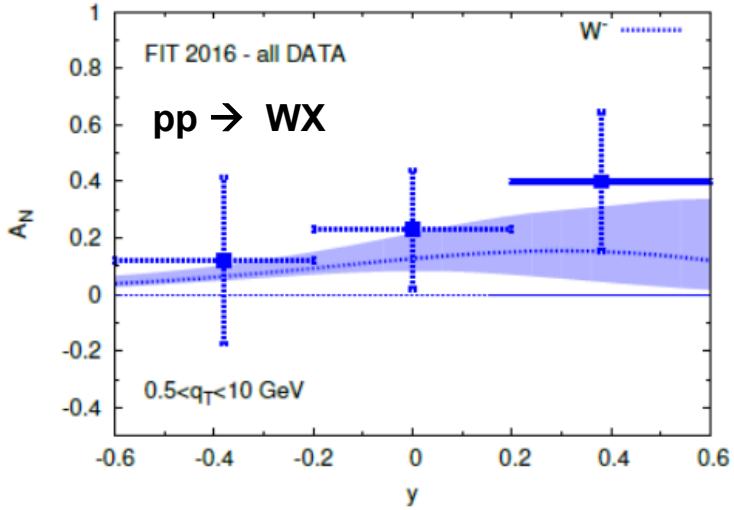
Pb+Pb $\quad \sqrt{s} = 2.76 \ \mathrm{TeV/n}$



Spin-Orbit Effects: Sivers

$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$$



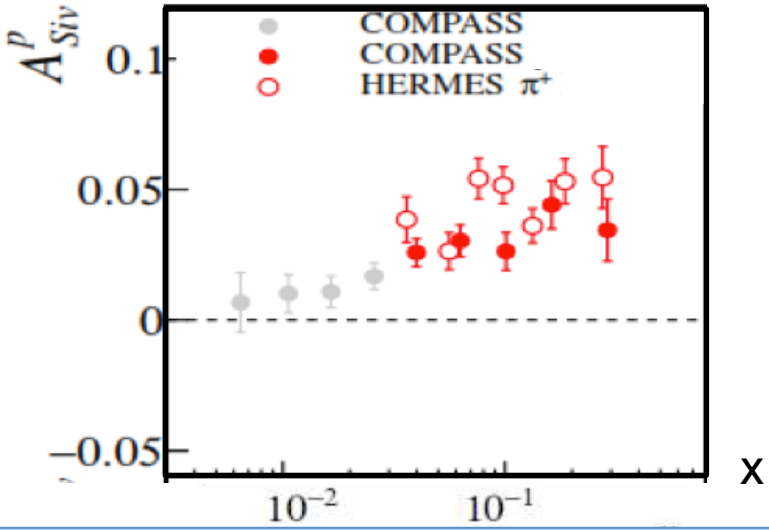


x (-1)

Sivers from polarized SIDIS

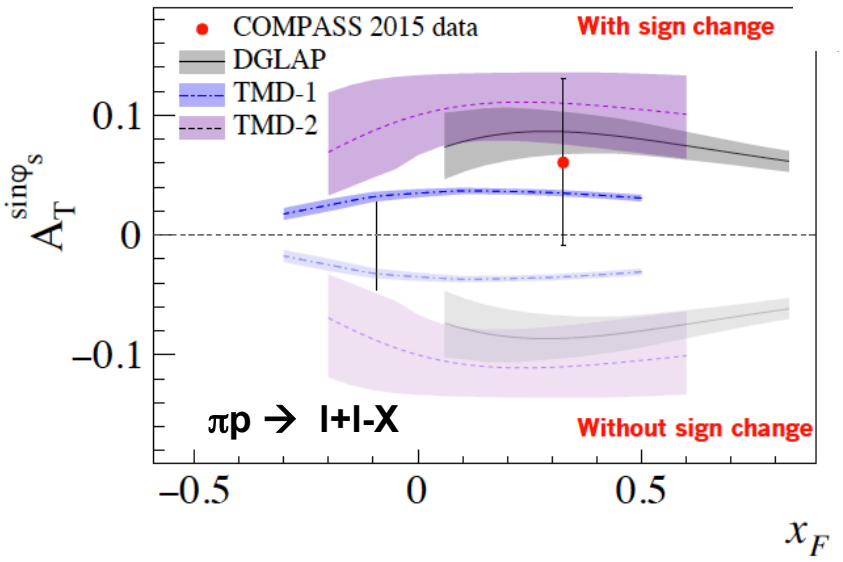
HERMES [arXiv:0906.3918]

COMPASS [arXiv:1205.5122]

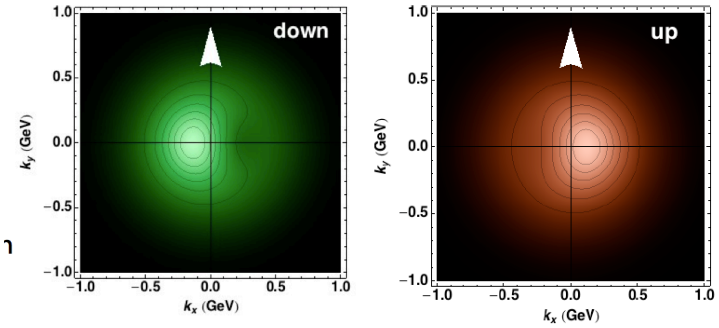


Sivers from hadronic reactions

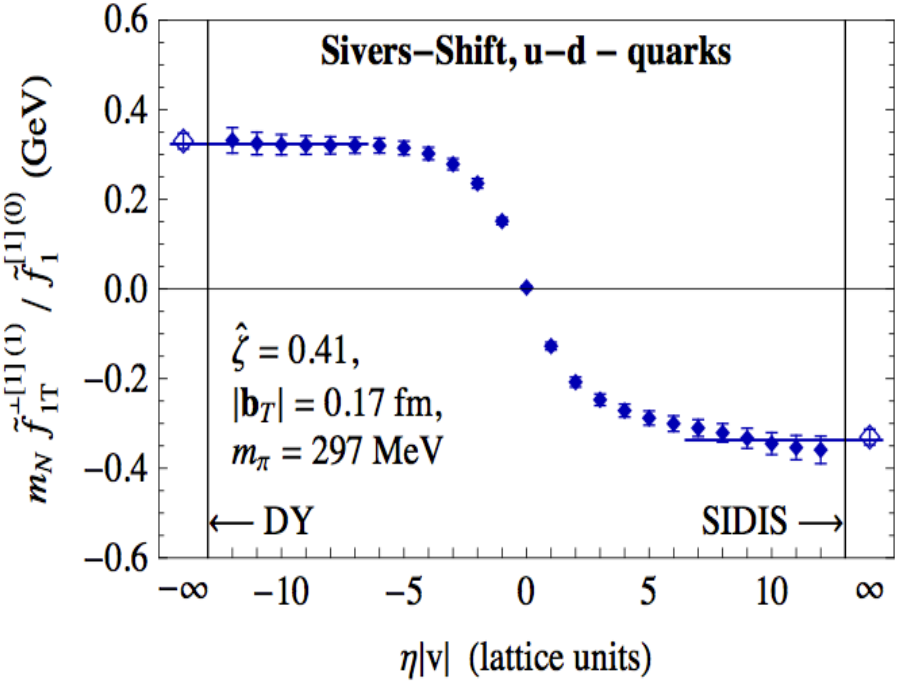
COMPASS [arXiv: 1704.00488]

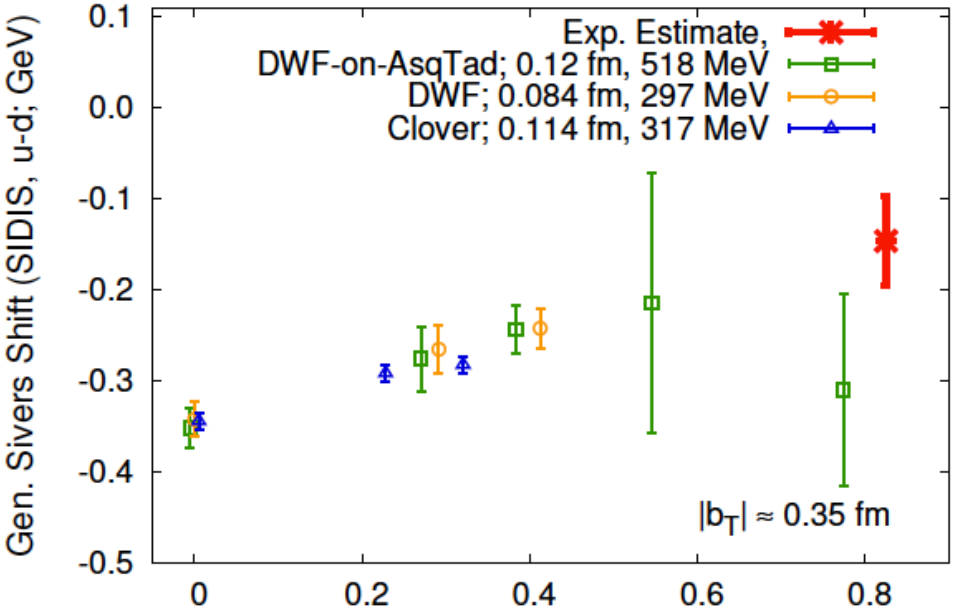


Sivers Shifts on Lattice

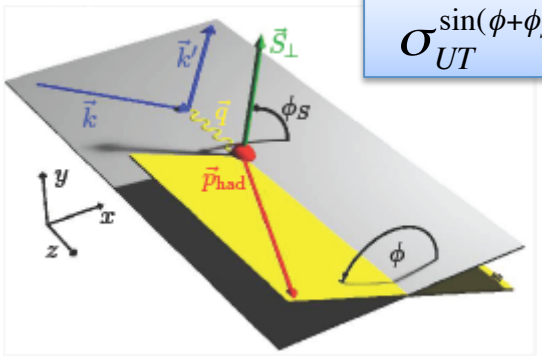


Yoon++ [arXiv: 1706.03406]



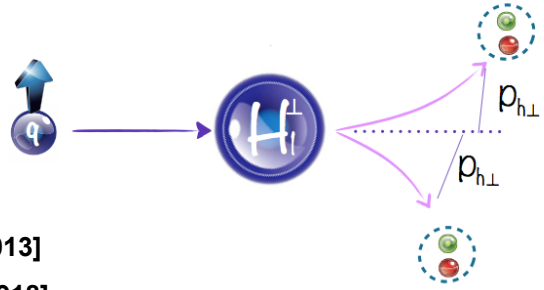


Spin-Orbit Effects: Collins



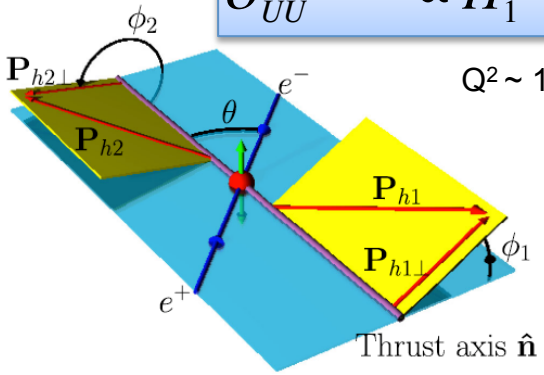
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^\perp$$

$Q^2 \sim 5\text{-}7\ GeV^2$

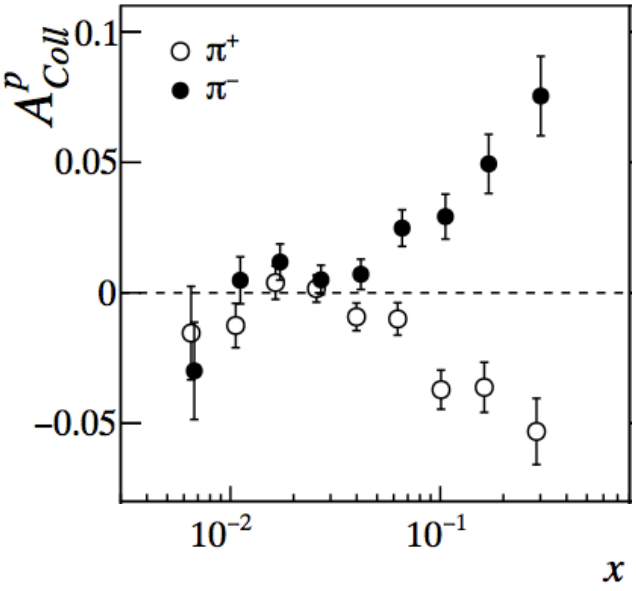


$$\sigma_{UU}^{\sin(\phi_1+\phi_2)} \propto H_1^\perp \otimes H_1^\perp$$

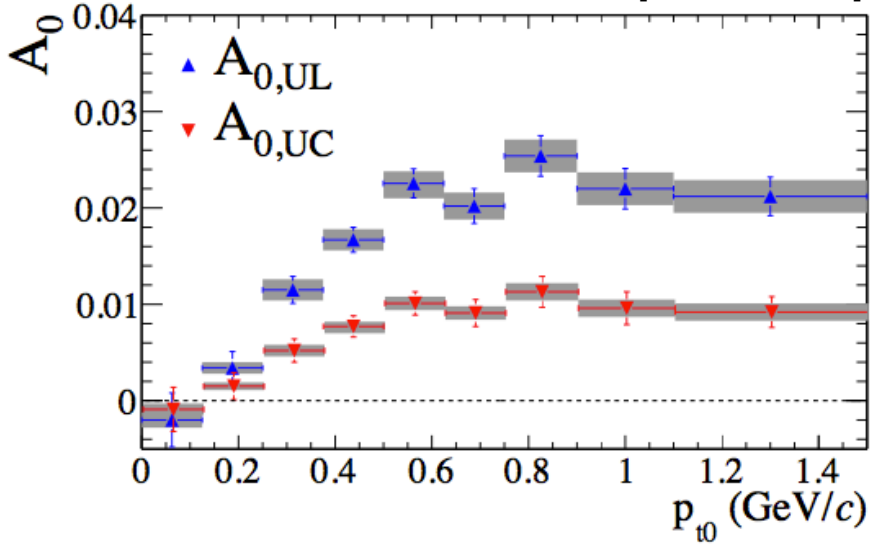
$Q^2 \sim 110\ GeV^2$



HERMES	[arXiv 0408013]
HERMES	[arXiv 0906.3918]
COMPASS	[arXiv 1005.5609]
COMPASS	[arXiv 1408.4405]

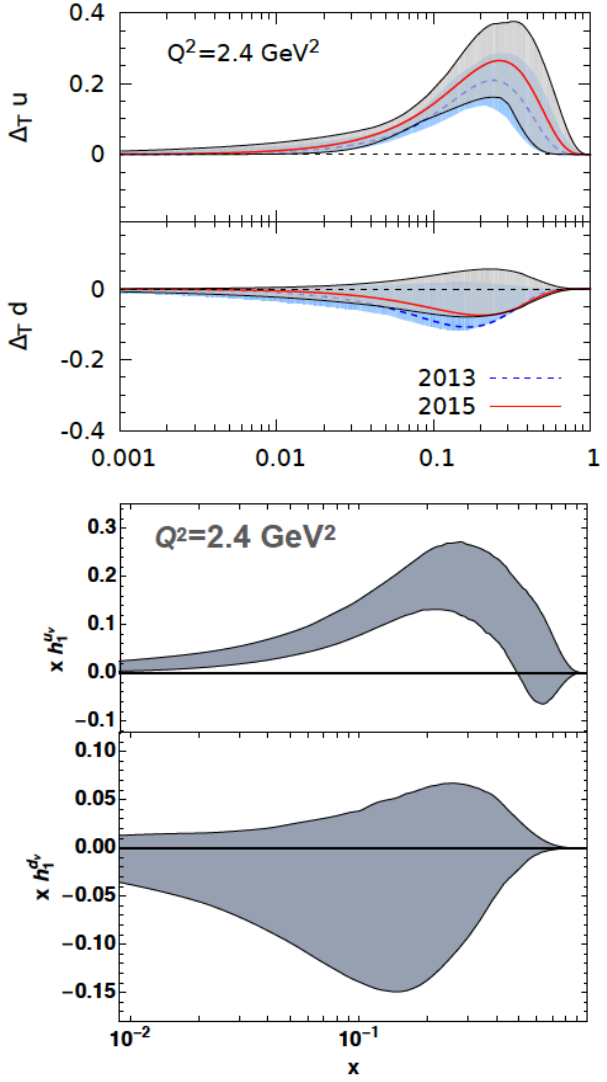


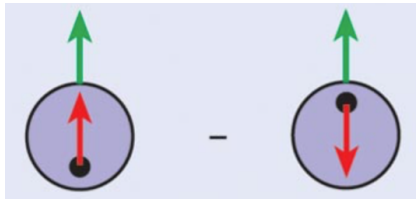
Belle	[talk at DIS2014]
BESIII	[arXiv 1507.06824]
Babar	[arXiv 1309.5278]



Transversity & Tensor Charge

Distributions:





Helicity

Alexandrou et al., arXiv:1703.0878

Gupta et al., arXiv:1806.09006

Anselmino et al., arXiv:1303.3822

Kang et al., arXiv:1505.05589

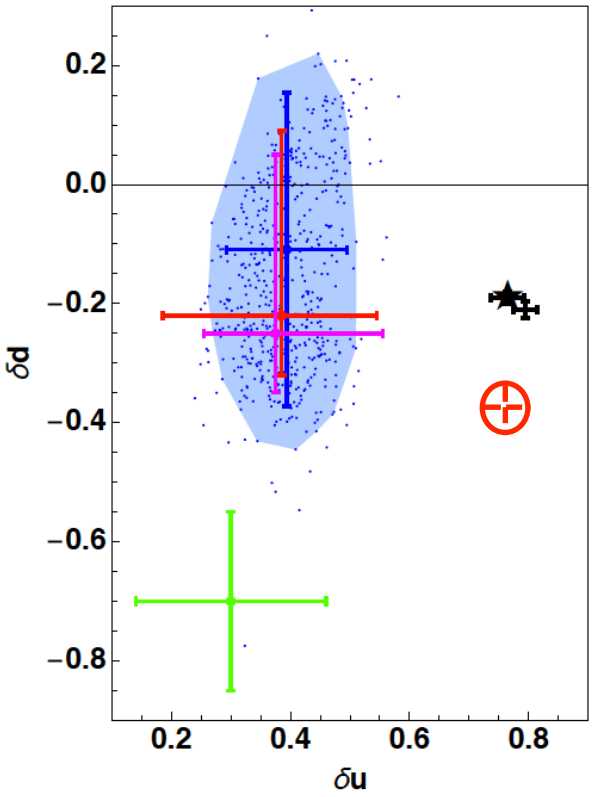
Lin et al., arXiv:1710.09858

Radici et al., arXiv:1802.05212

Charges:

$$\delta q \equiv \int_0^1 dx \, [\Delta_T q(x) - \Delta_T \bar{q}(x)]$$

A. Bacchetta @ DIS219



Tensor Charge & BSM Physics

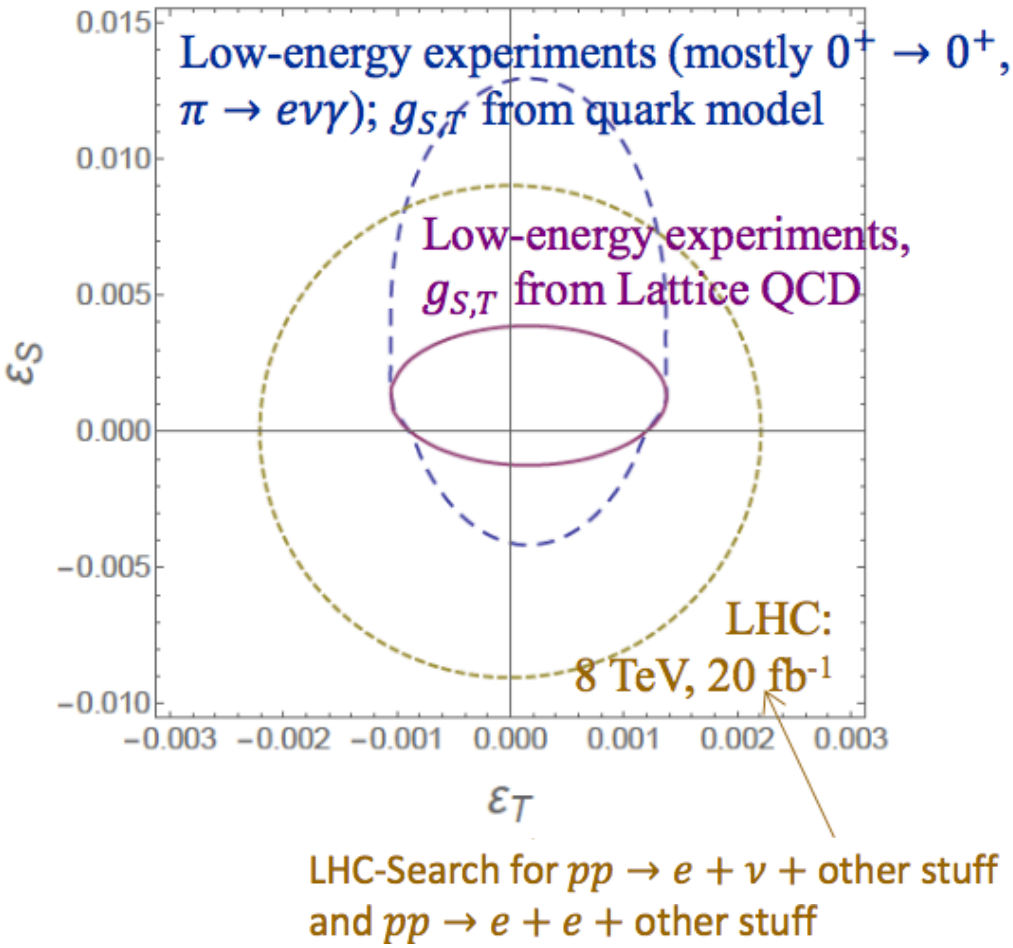
$$\varepsilon_T \, g_T \approx M_W^2 \, / \, M_{BSM}^2$$

current most stringent constraints on BSM tensor coupling from $\pi^+ \to e^+ \nu_e \gamma$ and neutron β-decay is

$$| \varepsilon_T \, g_T | \lesssim 5 \times 10^{-4}$$

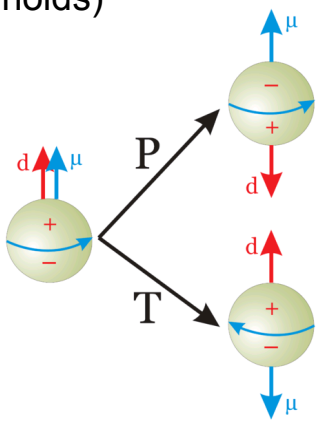
A. Bychkov++ [arXiv:0804.1815]
B. Pattie++ [arXiv:1309.2499]

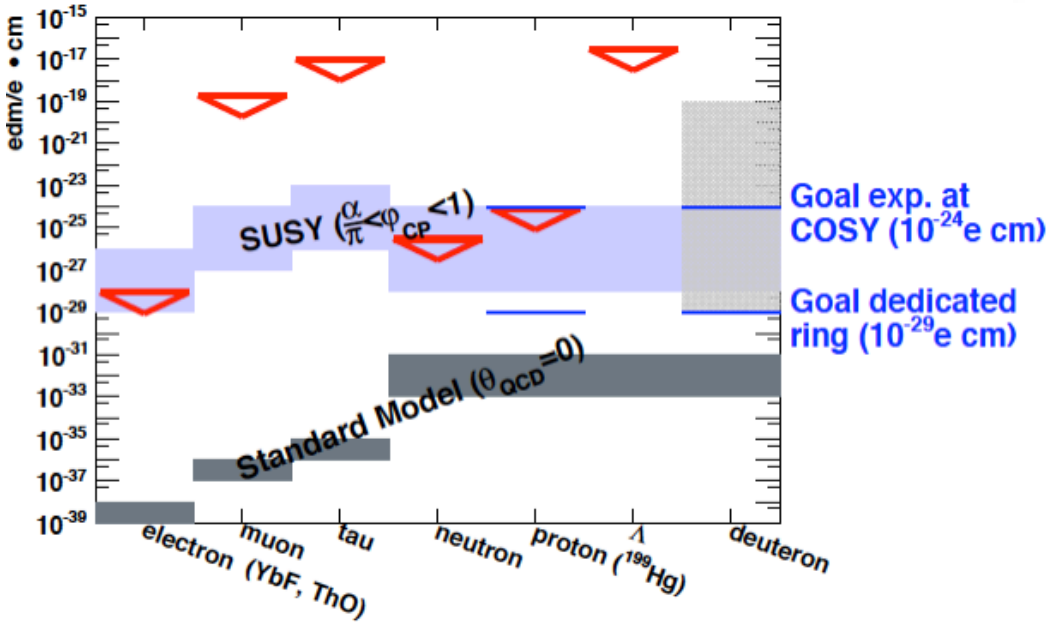
Baessler++ @ this Conf.



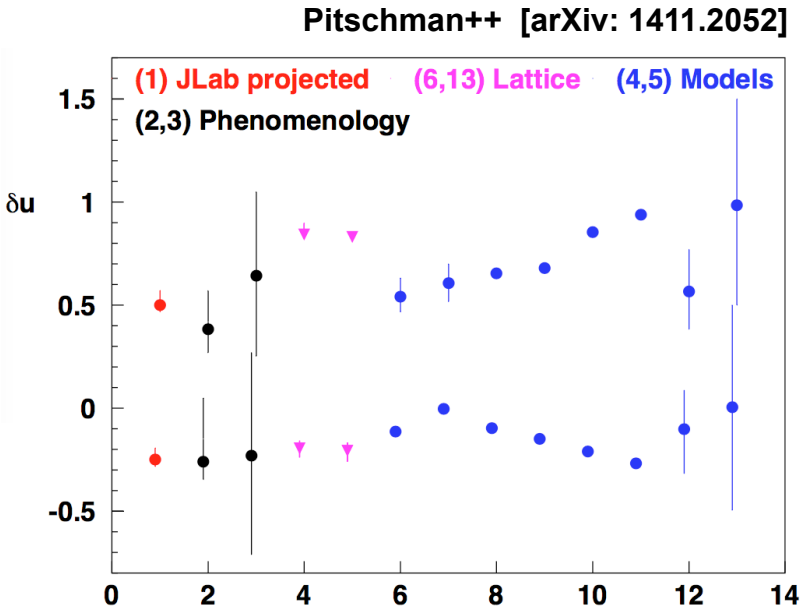
Tensor Charge & EDM

EDM violates P and T and CP (if CPT holds)





Tensor Charge measures transverse quark polarization in a transversely polarized nucleon



Proton *EDM*: $d_p = d_u\,\delta_T u + d_d\,\delta_T d$

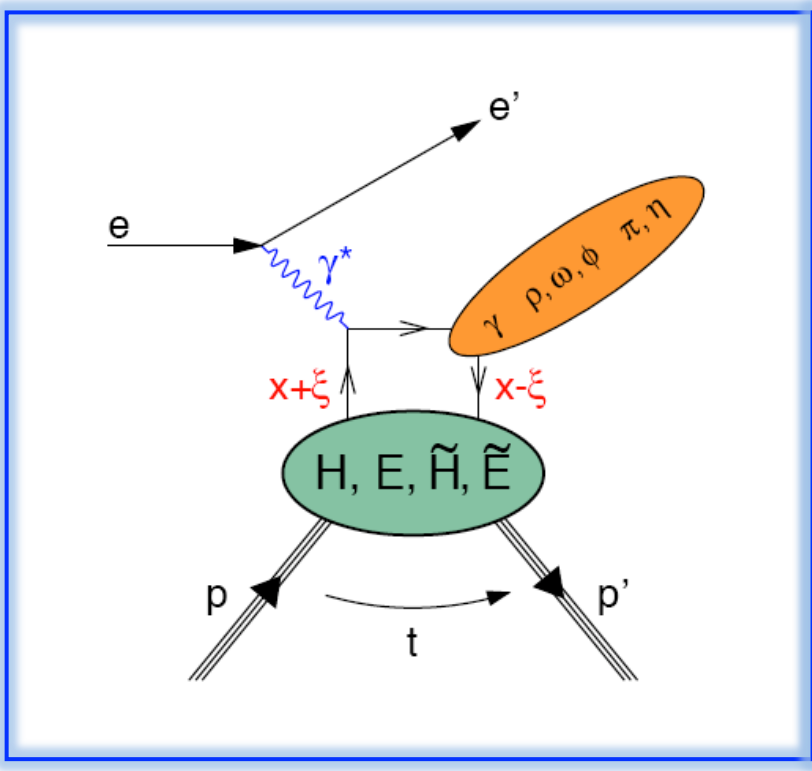
Neutron *EDM*: $d_n = d_u\,\delta_T d + d_d\,\delta_T u$

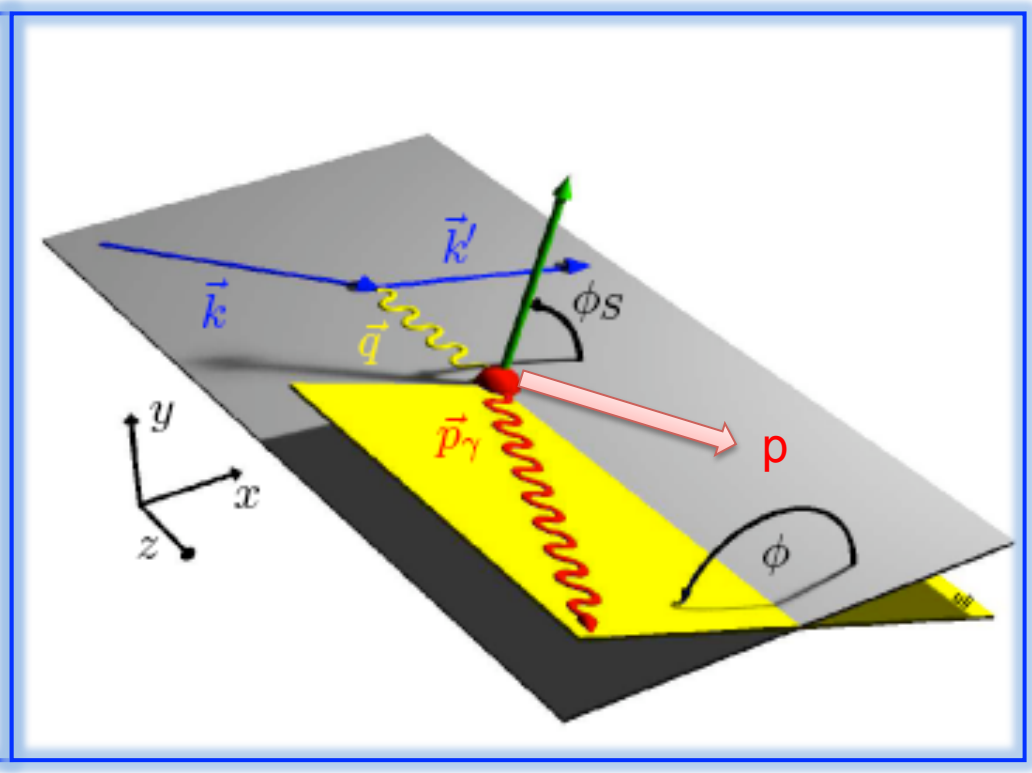
Hard Exclusive & GPDs

Transverse size & nucleon tomography:
Impact parameter derived from the transverse momentum transferred to nucleon

Various final states to prove GPDs and flavors

$$f_p^q(x,\vec{b}_T) \overset{FT}{\Leftrightarrow} H_p^q(x,0,t)$$



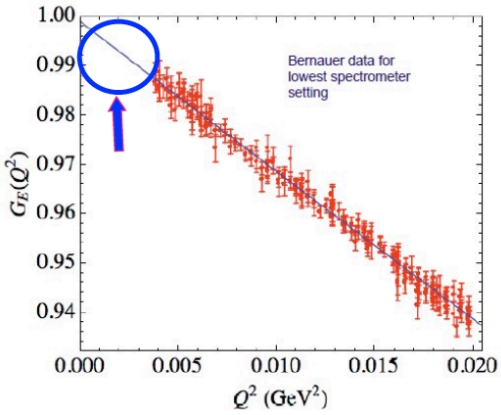


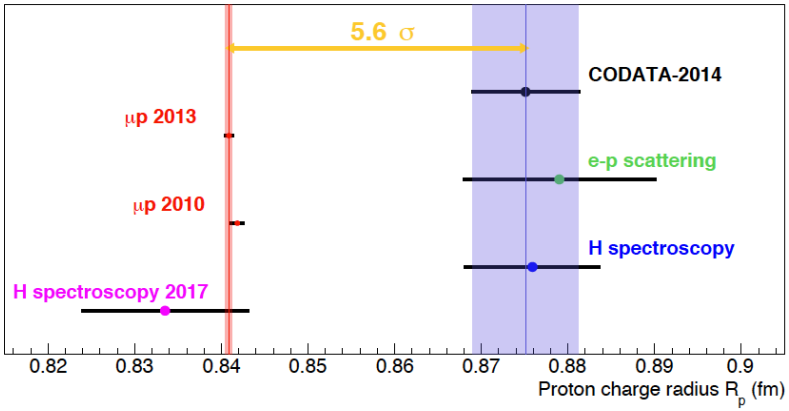
Elastic Scattering

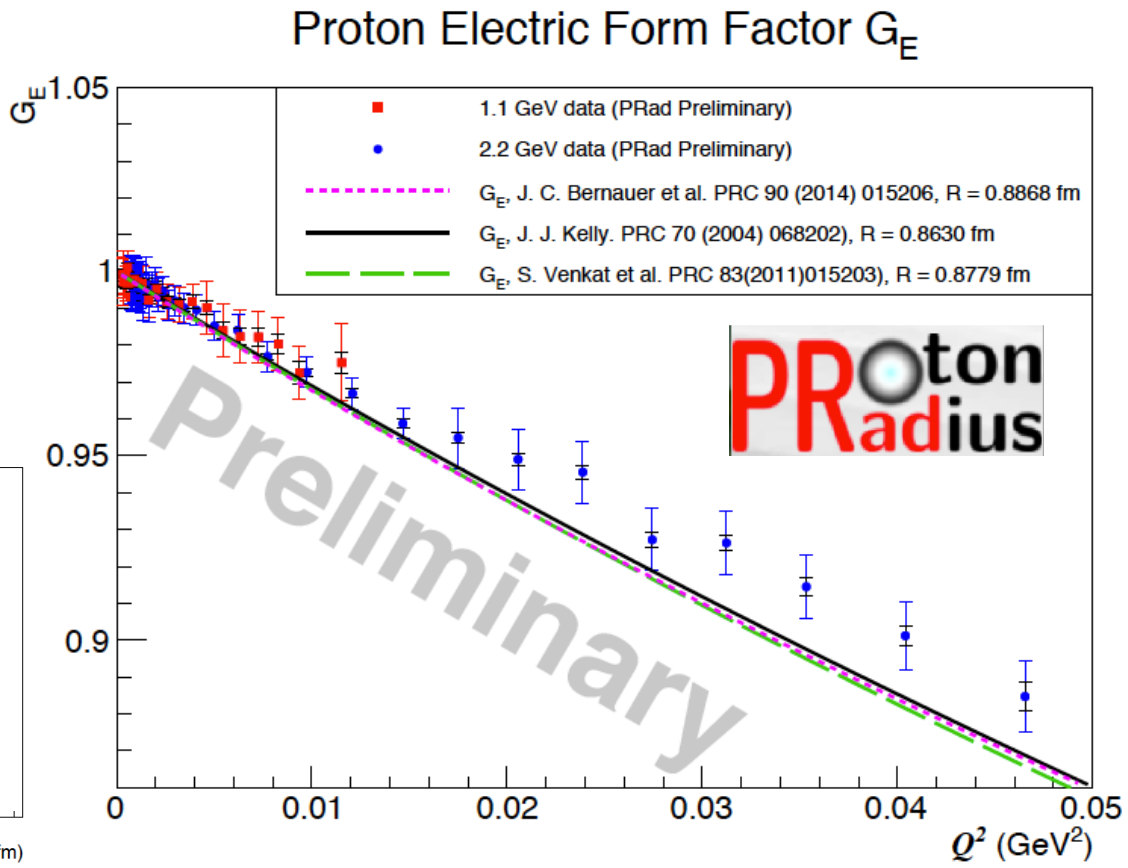
$$G_E^p(Q^2) = 1 - \frac{Q^2}{6}\langle r^2\rangle + \frac{Q^4}{120}\langle r^4\rangle + \ldots$$

$$\langle r^2\rangle = -6\,\frac{dG_E^p(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

A. Gasparian @ ECT* (2018)







Pseudoscalar Mesons Production

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \sigma_{LT})$$

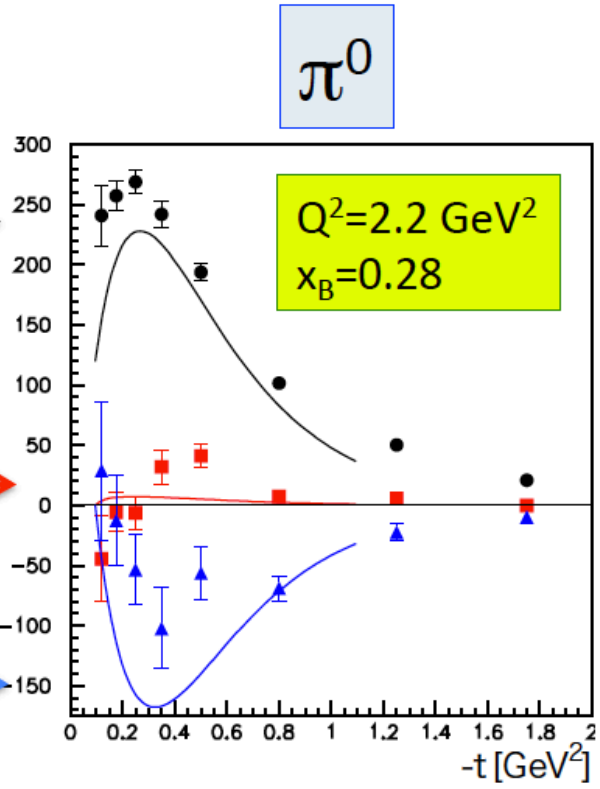
$$\sigma_{TT} = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}\frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2$$

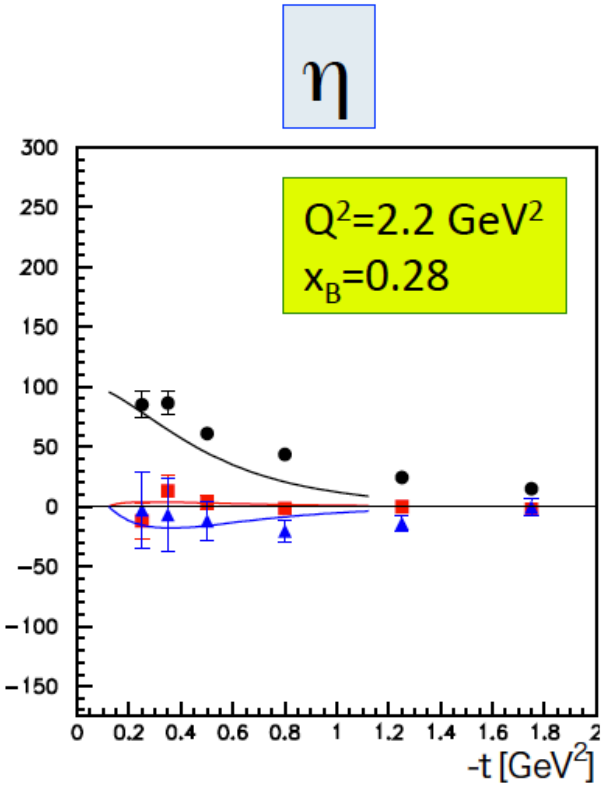
Surprising large contribution from
1/Q-suppressed transverse photon component

σ_u

σ_{LT}

σ_{TT}

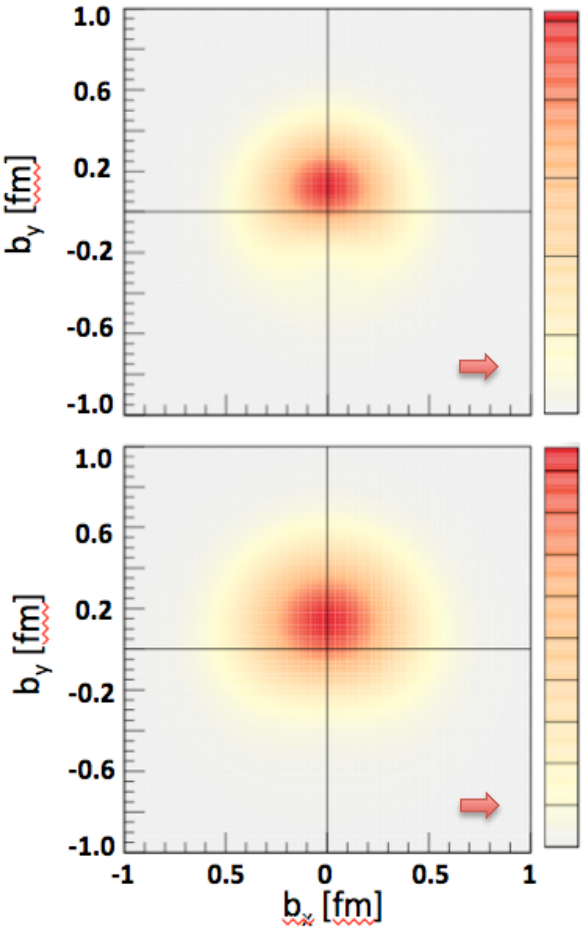




Polarized Quark Imaging

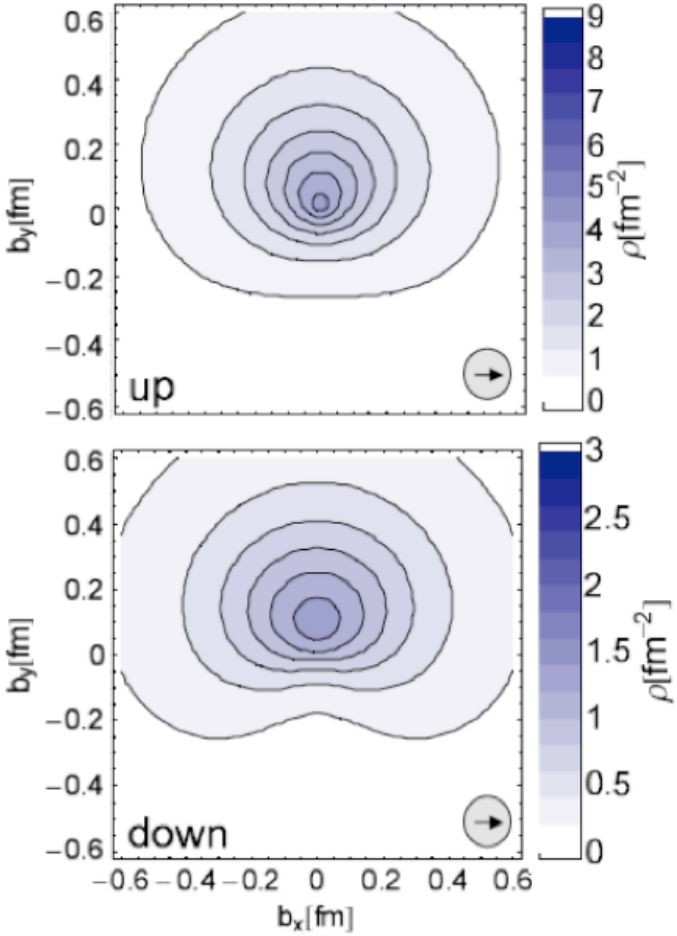
Phenomenological extractions

V.Kubarovsky [arXiv:1601.04367]



Lattice calculations

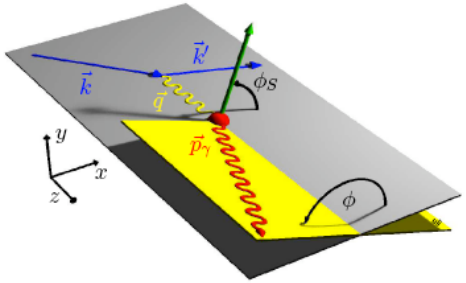
M.Gockeler++ [PRL 98 (2007) 222001]



DVCS Interference

Informations on the real and imaginary part of the QCD scattering amplitude

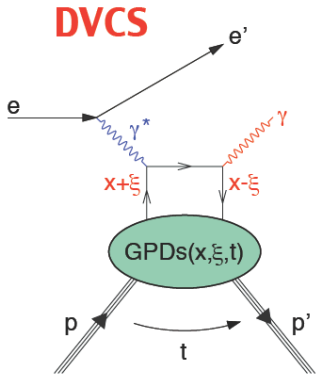
$$\frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\phi} \propto \left(|\mathcal{T}_{DVCS}|^2 + |\mathcal{T}_{BH}|^2 + \mathcal{I}\right)$$

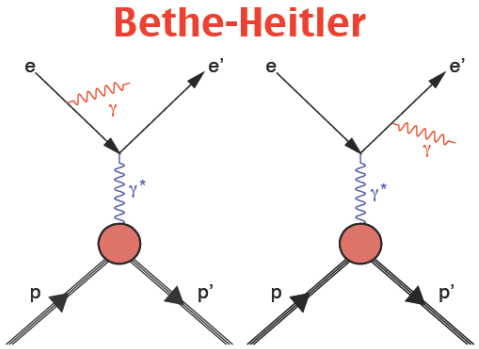


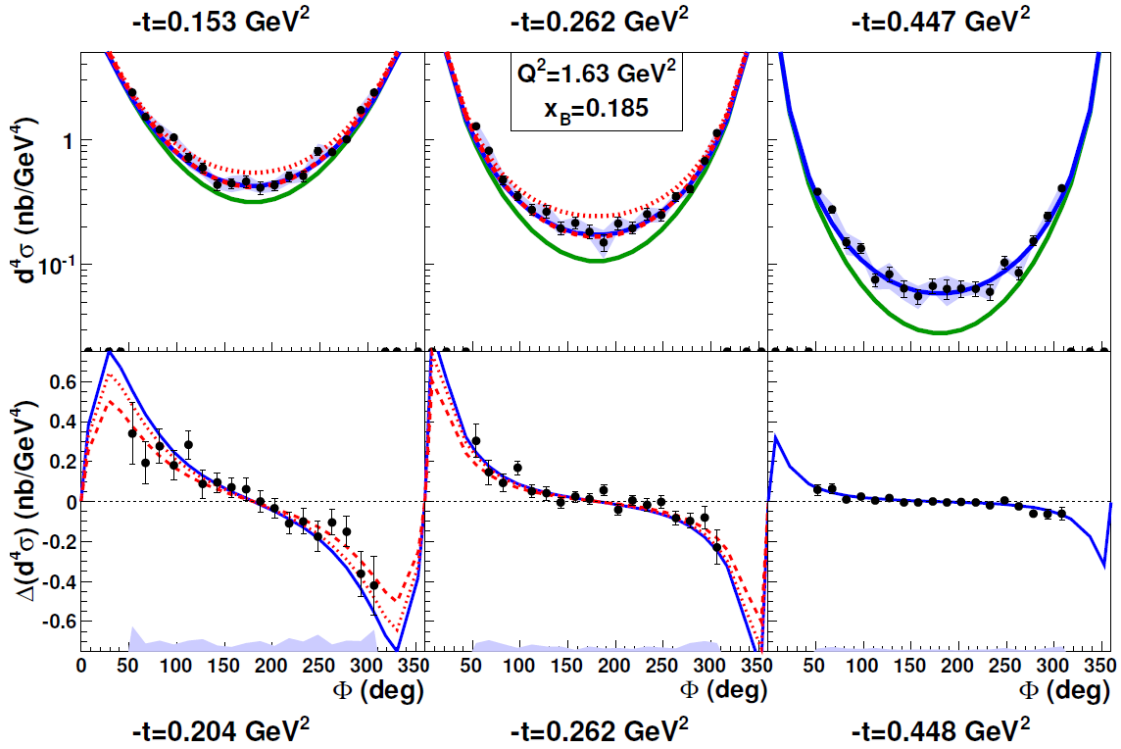
H. S. Jo et. al. [arXiv: 1504.02009]

$$\frac{d^4\sigma^{ep\to e'p\gamma}}{dx\, dQ^2 dt\, d\varphi}$$

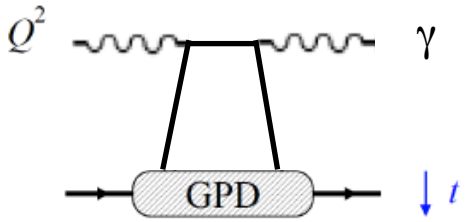
BH only
VGG (H only)
KM10 (Kumericki, Mueller)
KM10a

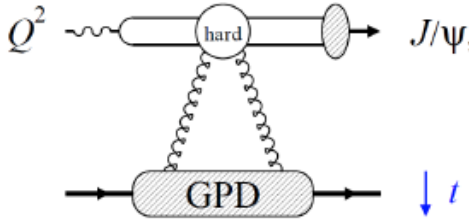




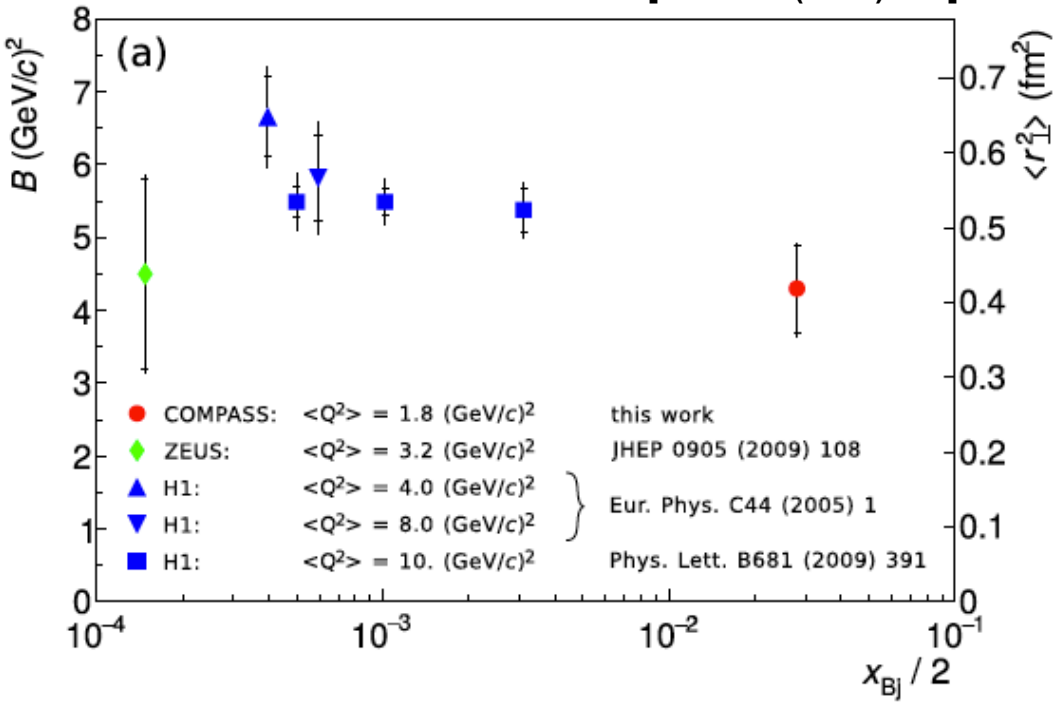


Parton Imaging

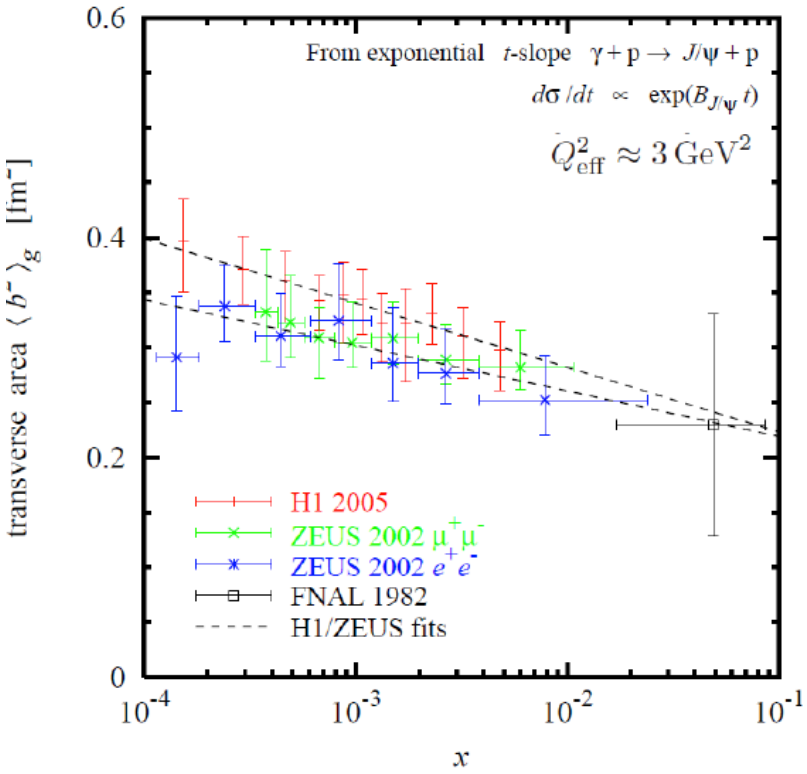




COMPASS++ [PLB 793 (2019) 188]



Frankfurt++ [PRD 83 (2011) 054012]



DVCS Interference

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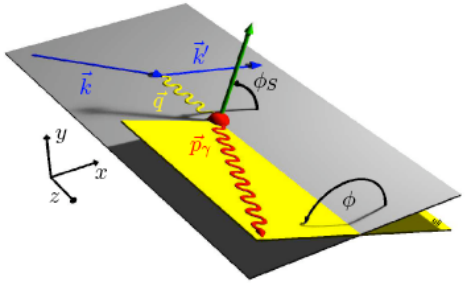
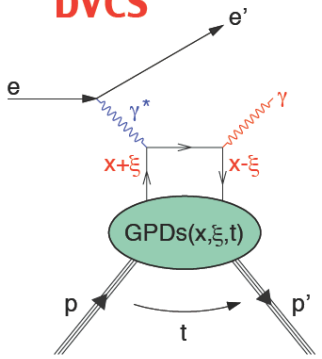


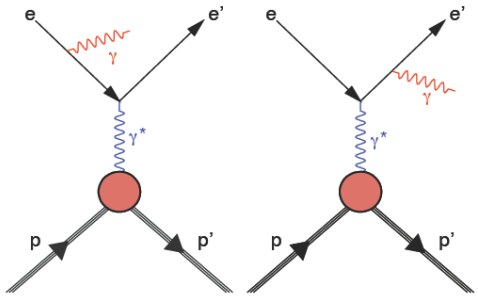
$$\begin{pmatrix} A_{LU,I}^{\sin(1\phi)} \\ A_{UL,+}^{\sin(1\phi)} \\ A_{UT,I}^{\sin(\varphi)\cos(1\phi)} \\ A_{UT,I}^{\cos(\varphi)\sin(1\phi)} \end{pmatrix} \Rightarrow \Im m \begin{pmatrix} \mathcal{H} \\ \tilde{\mathcal{H}} \\ \mathcal{E} \\ \tilde{\mathcal{E}} \end{pmatrix}$$

$$\begin{pmatrix} A_{C}^{\cos(1\phi)} \\ A_{LL,+}^{\cos(1\phi)} \\ A_{LT,I}^{\sin(\varphi)\sin(1\phi)} \\ A_{LT,I}^{\cos(\varphi)\cos(1\phi)} \end{pmatrix} \Rightarrow \Re e \begin{pmatrix} \mathcal{H} \\ \tilde{\mathcal{H}} \\ \mathcal{E} \\ \tilde{\mathcal{E}} \end{pmatrix}$$

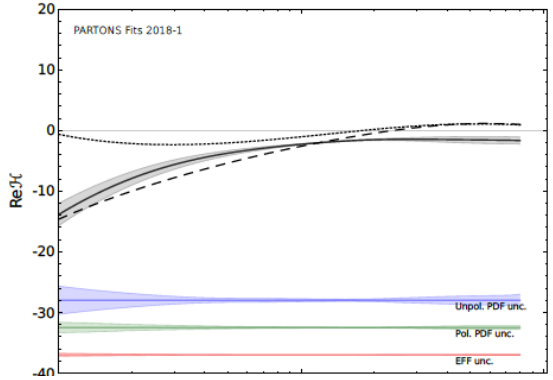
DVCS

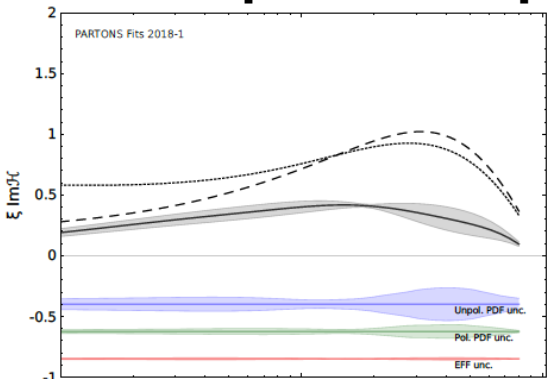


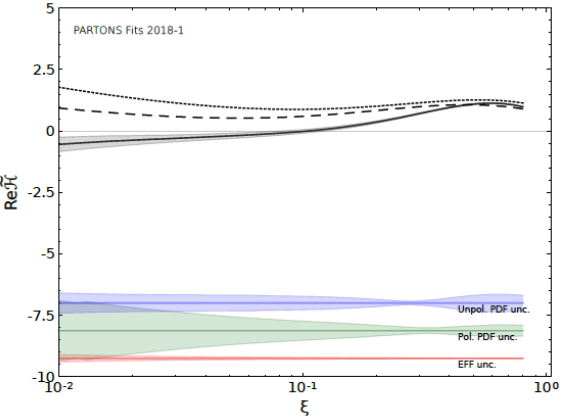
Bethe-Heitler

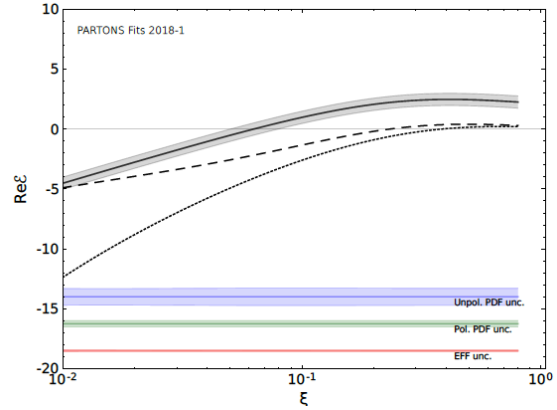


H.Moutarde++ [arXiv: 1807.07620]









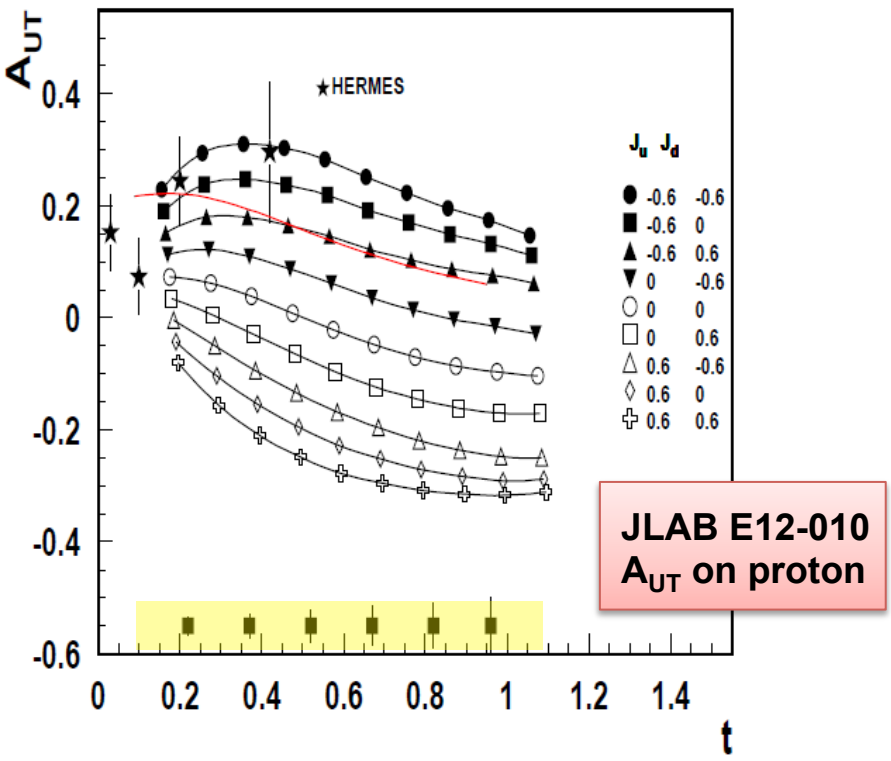
Quark Orbital Momentum

Access OAM $L_q = J_q - \frac{1}{2}\Delta\Sigma$ via Ji sum rule

$$J_q = \lim_{t\to 0}\int_{-1}^{1} dx\, x\left[H_q(x,\xi,t) + E_q(x,\xi,t)\right]$$

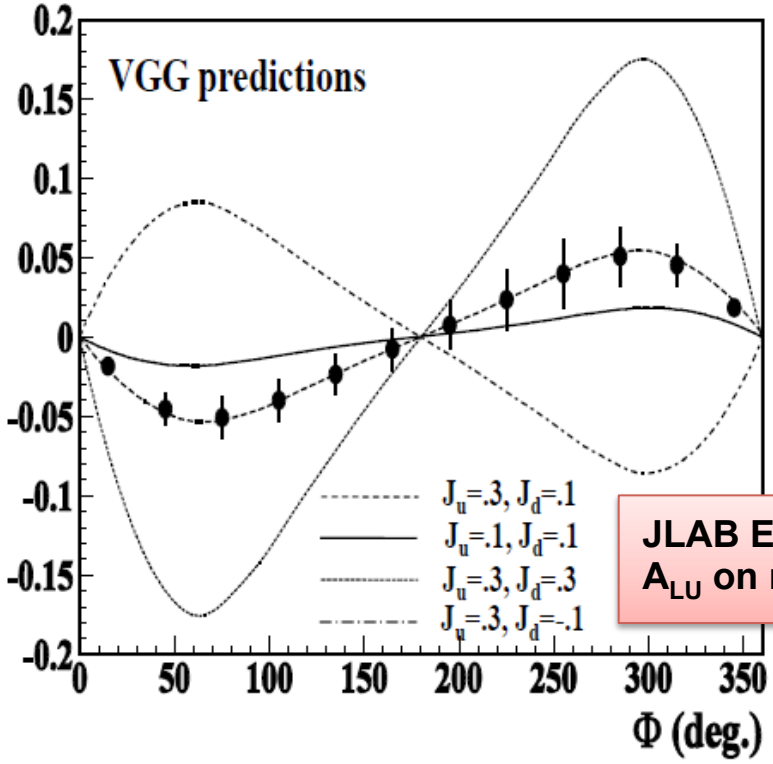
To access E_u & E_d both E_p & E_n are needed

Proton GPD



JLAB E12-010
A_{UT} on proton

Neutron GPD



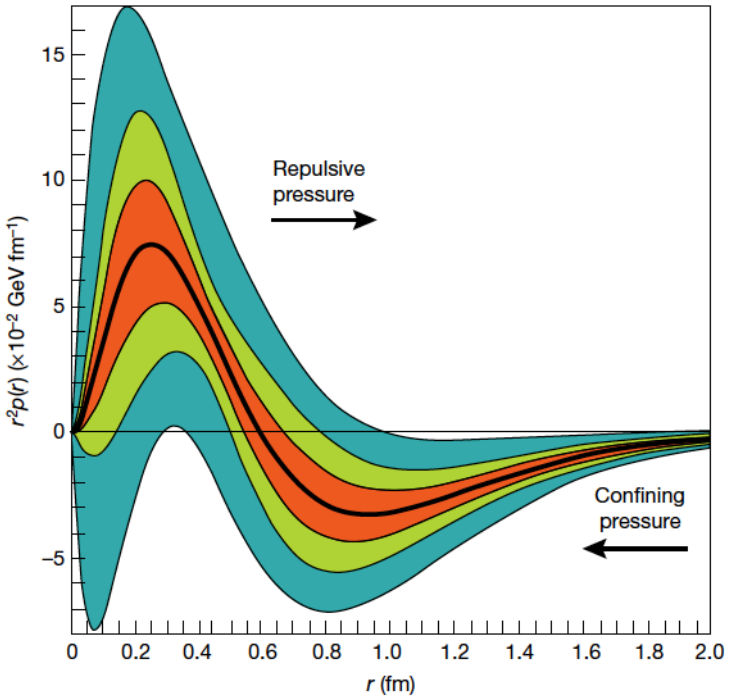
JLAB E11-003
A_{LU} on neutron

Extreme Matter Conditions

GPDs moments are related to the proton momentum-energy tensor,
e.g. how pressure and momentum are distributed within the nucleon

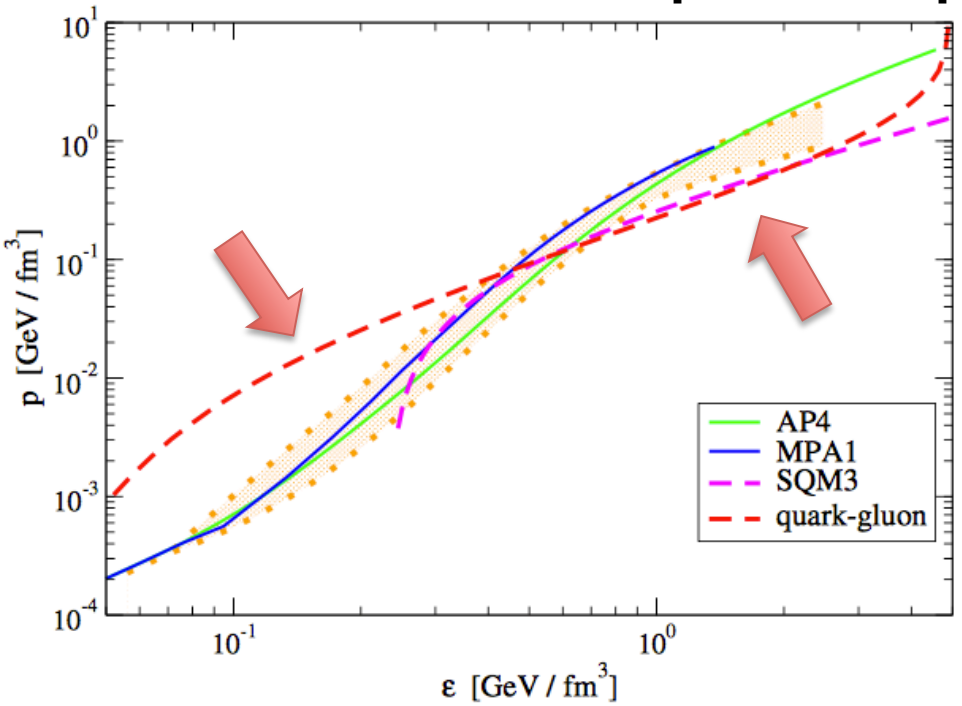
Pressure inside the nucleon

V.Burkert++ [Nature 577 (2018)]



Neutron star equation of state

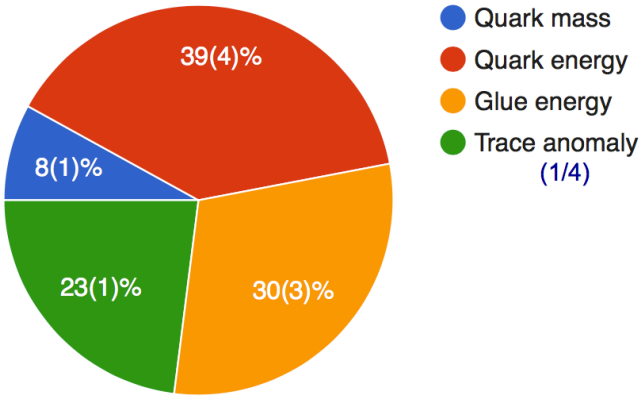
S.Liuti++ [arXiv 1812.01479]



Lattice Achievements

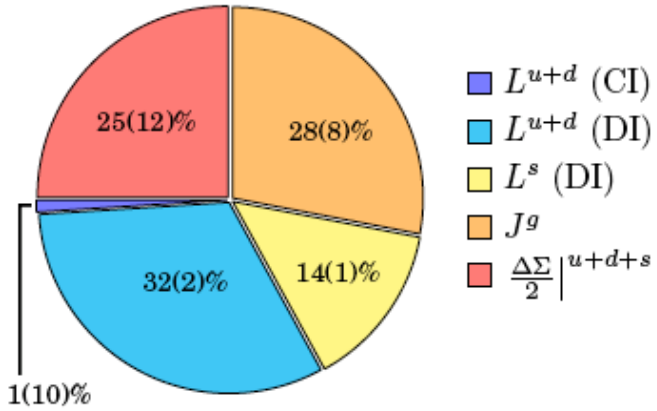
Nucleon mass components

K-F Liu @ this Conf.

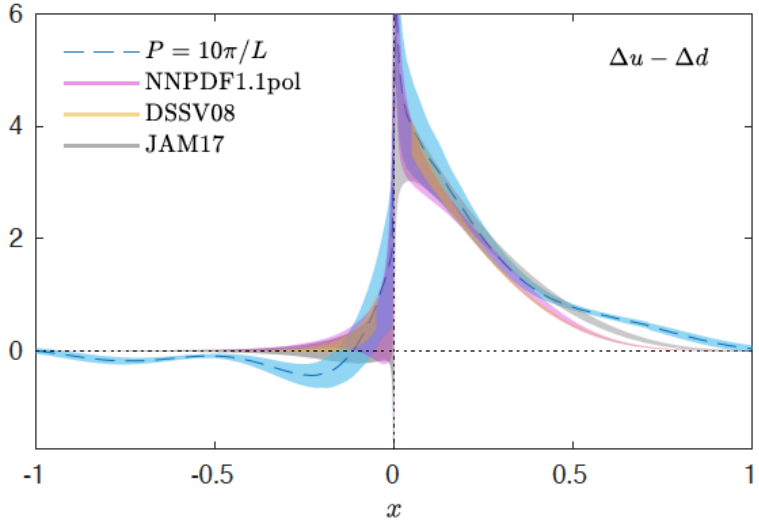


Spin decomposition

K-F Liu++ [arXiv 1203.6388]

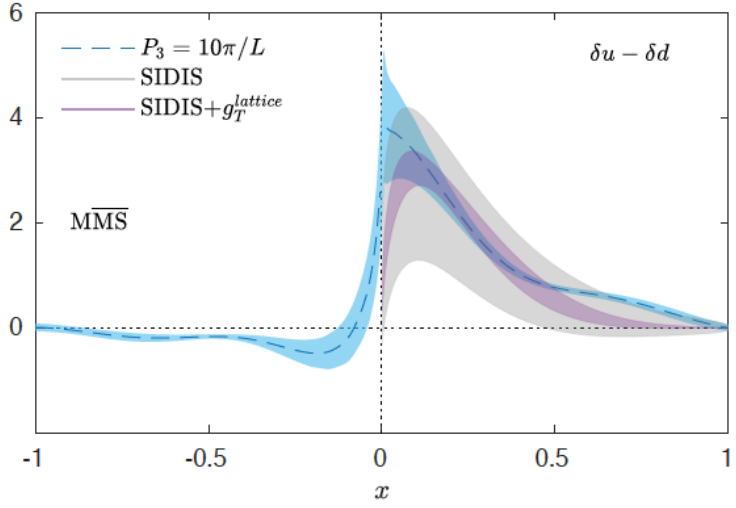


Helicity distribution

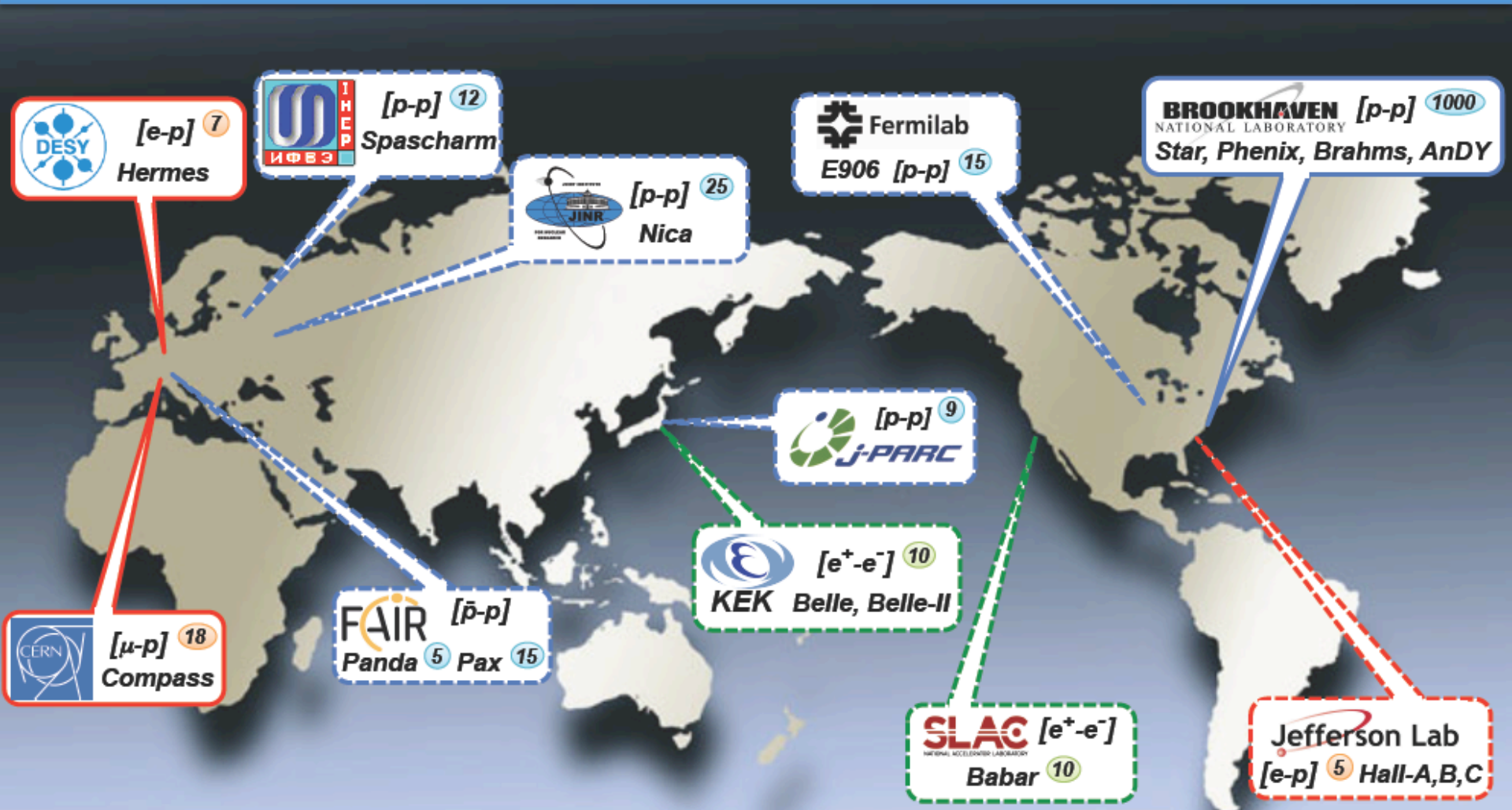


Transversity distribution

C. Alezandrous++ [arXiv 1902.00587]



A World-wide Challenge

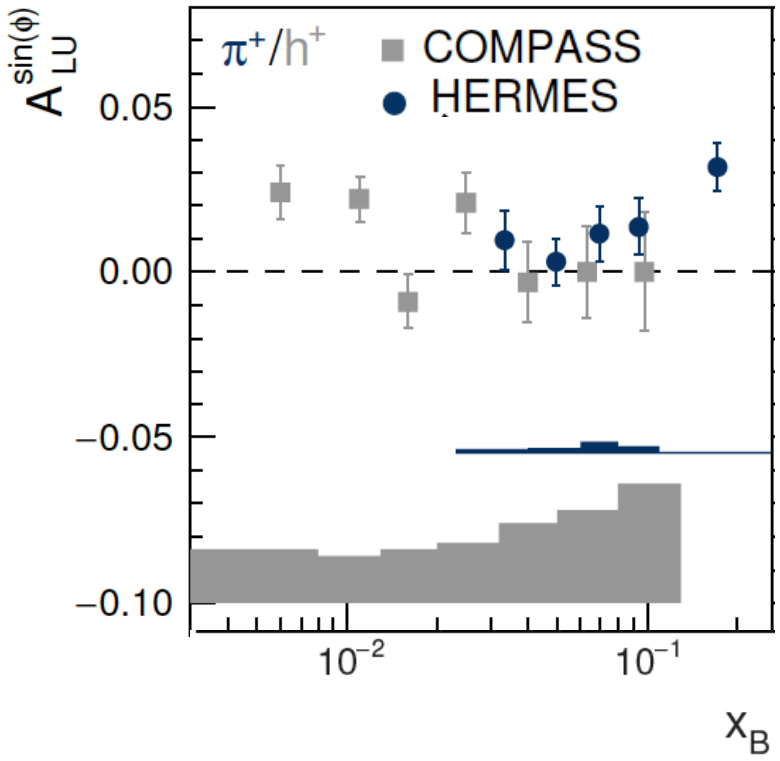


Babar (e+e-):	< 2007	SeaQuest (pp):	2012 - 2016	JPARC(pp):	2018++		
BELLE (e+e-):	< 2010	RHIC (pp):	2011, 2017++	FAIR ($\bar{p}$p):	2018++		
BELLEII (e+e-):	2017++	COMPASS (πp):	2016 – 2017	NICA (pp):	2018++	AFTER (pp):	2020++

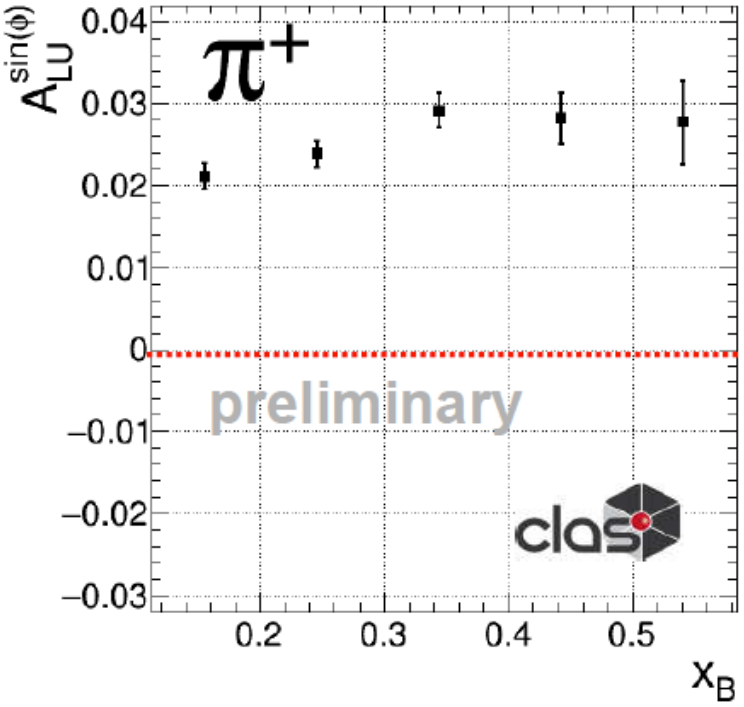
High-Luminosity @ JLab12

All 4 experimental hall in operation since February 2018

~ 1 year data taking

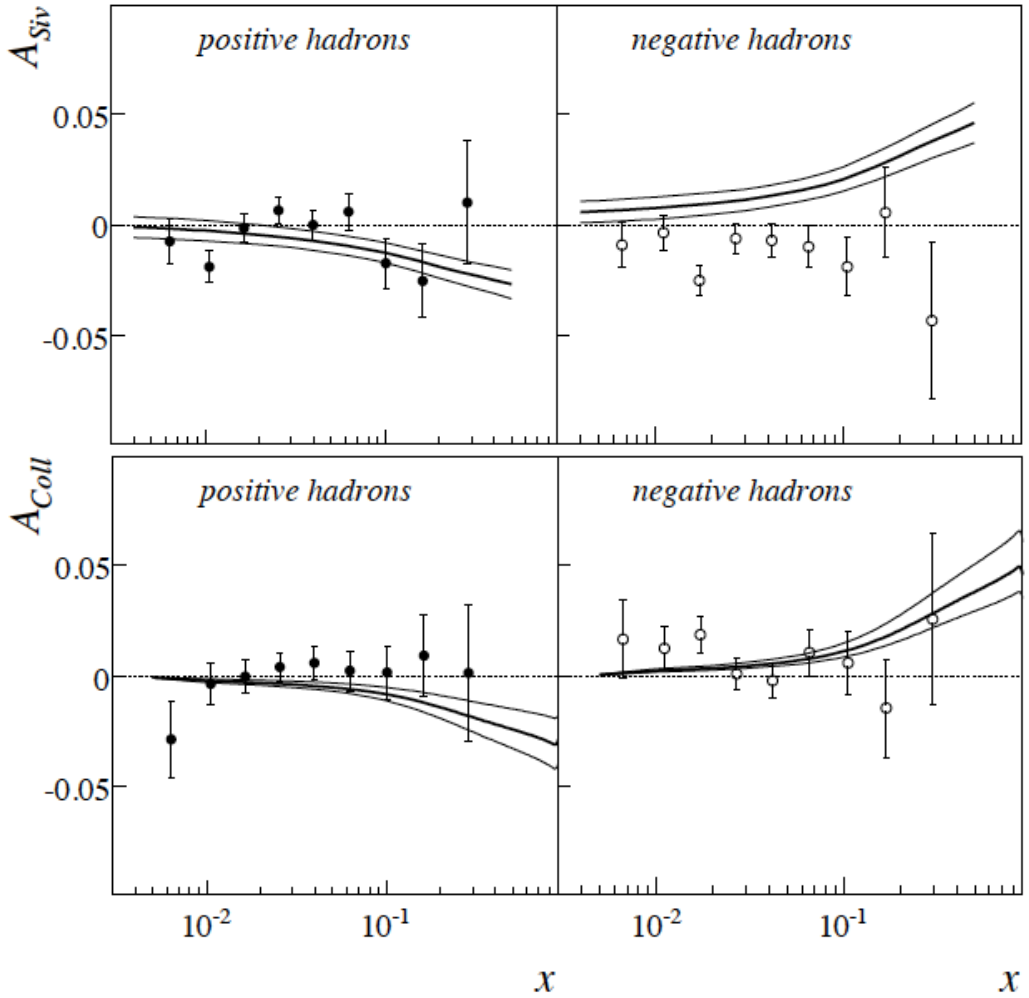


~ 1 day data taking



New data taking approved in 2021

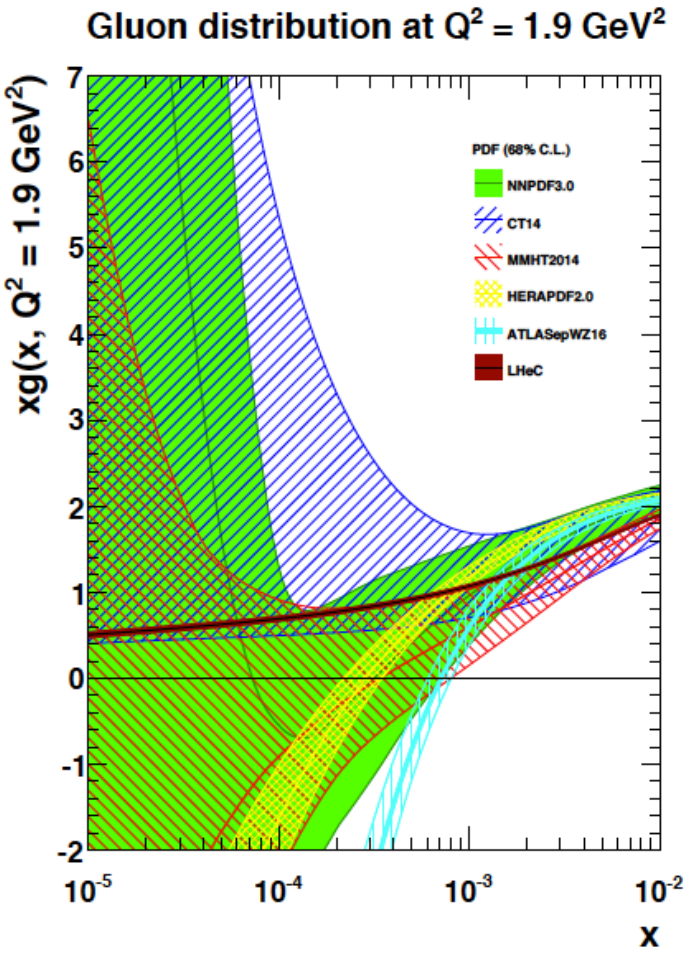
transversely polarized deuterium target for flavor separation

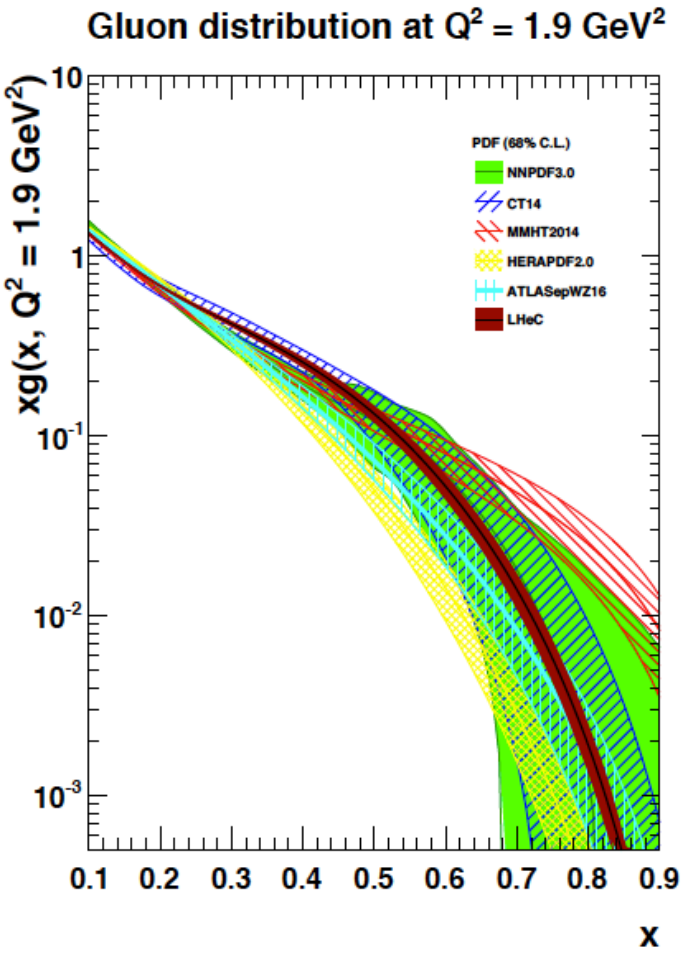


Under study

The ultimate collinear PDF determination

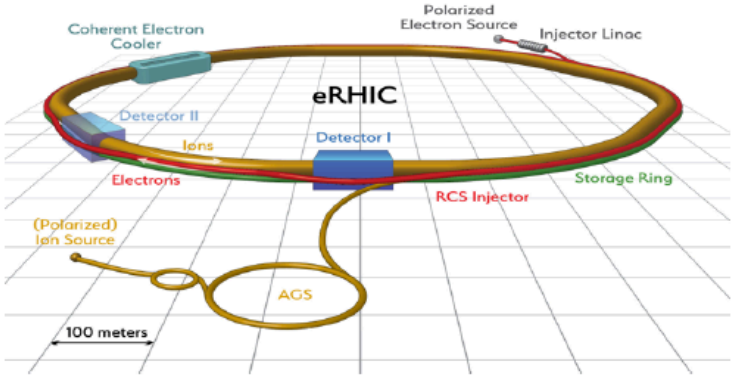
M.Klein++ [arXiv 1802.04317]



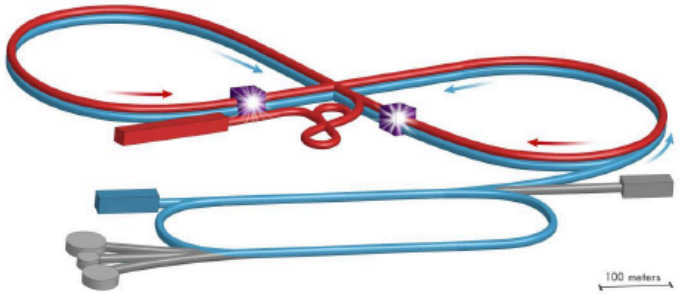


Electron-Ion Collider

BNL concept



JLab concept

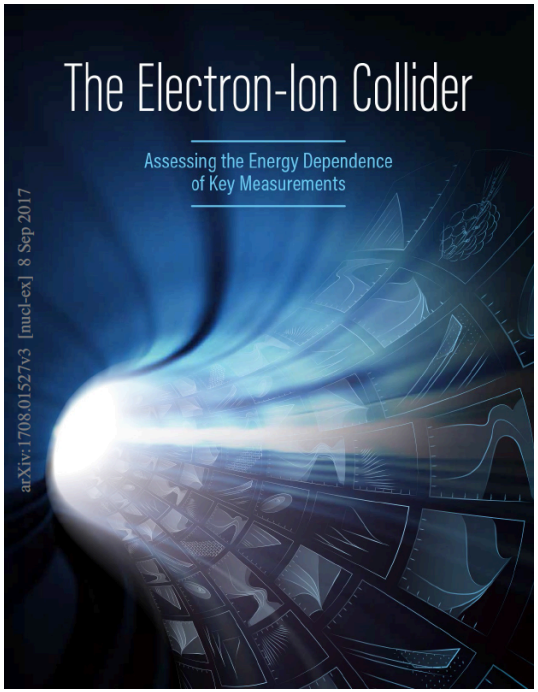


E.C.Aschenauer++ [arXiv: 17008.01527]

US NP priority

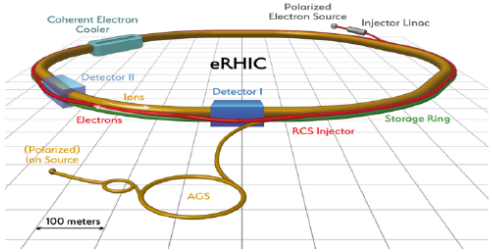
3D Nucleon and Gluon condensate

- ✔ High luminosity (10^{34} cm^{-2} s^{-1})
- ✔ Variable CM energy: 20 − 100 GeV
- ✔ Highly polarized beams
- ✔ Protons and other nuclei

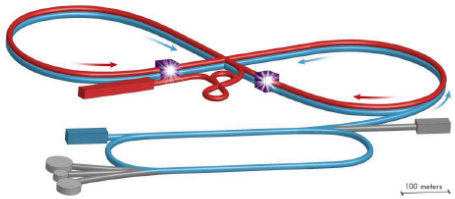


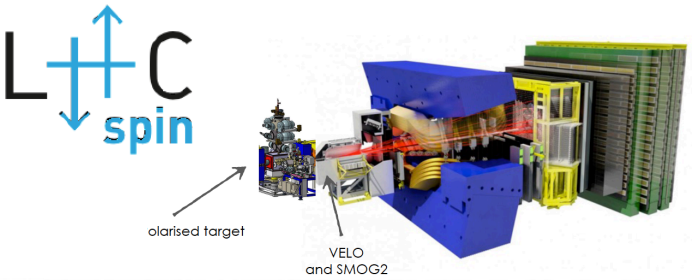
Nucleon Structure Landscape

BNL concept

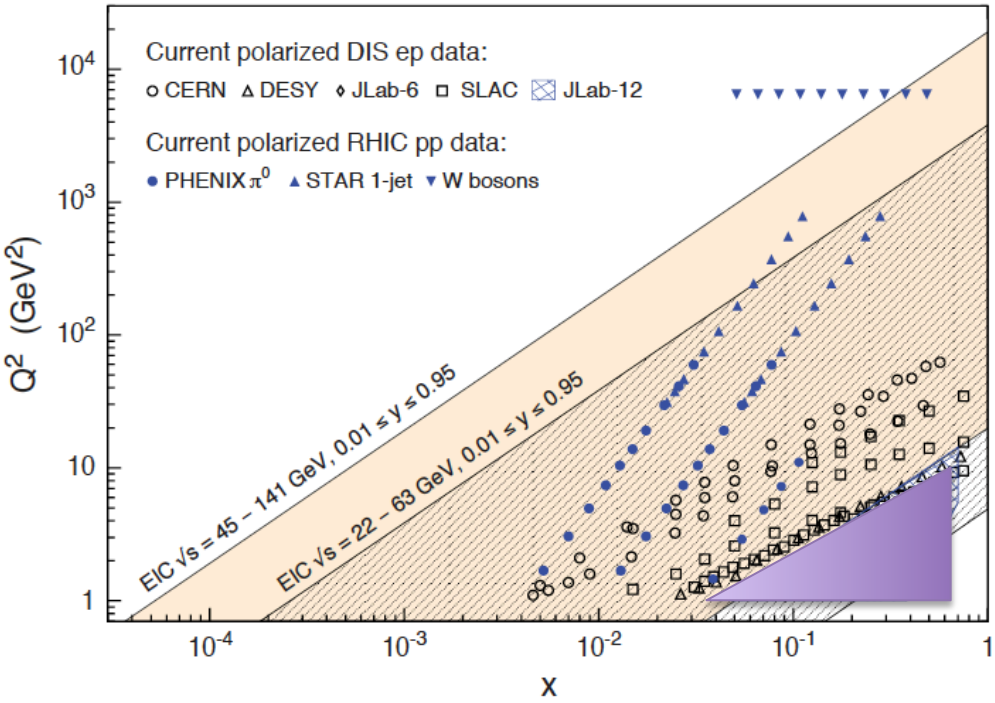


JLab concept

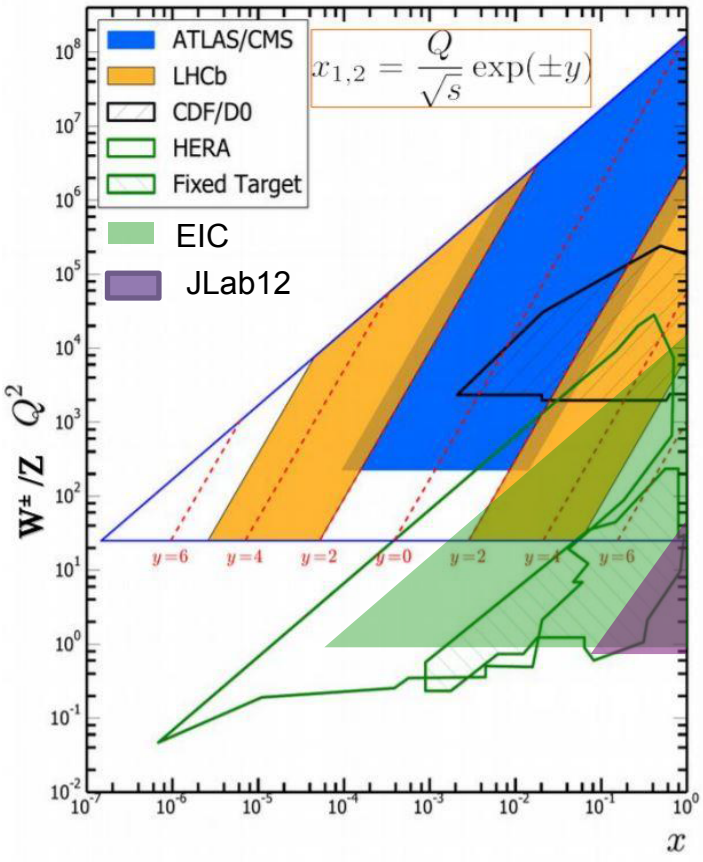




Data in the much needed “intermediate” energy region matching “pure” pQCD with “pure” TMD regime.



LHC 13 TeV Kinematics



Conclusions

The last decade provided many evidences that correlation of partonic transverse degrees of freedom in the nucleon do exist and manifest in hadronic interactions

Next step: Moving from phenomenology to rigorous treatment (predictive power)

New data coming from SIDIS, DY, e+e- and pp reactions should allow to:

- Constrain models in the valence region
- Test factorization, universality and evolution
- Study higher twist effects
- Investigate non-perturbative to perturbative transition (along P_T)
- Flavor separation via proton and deuteron targets and hadron ID
- Test of Lattice QCD calculations

A comprehensive study provides access to the peculiar dynamics of the QCD confined world