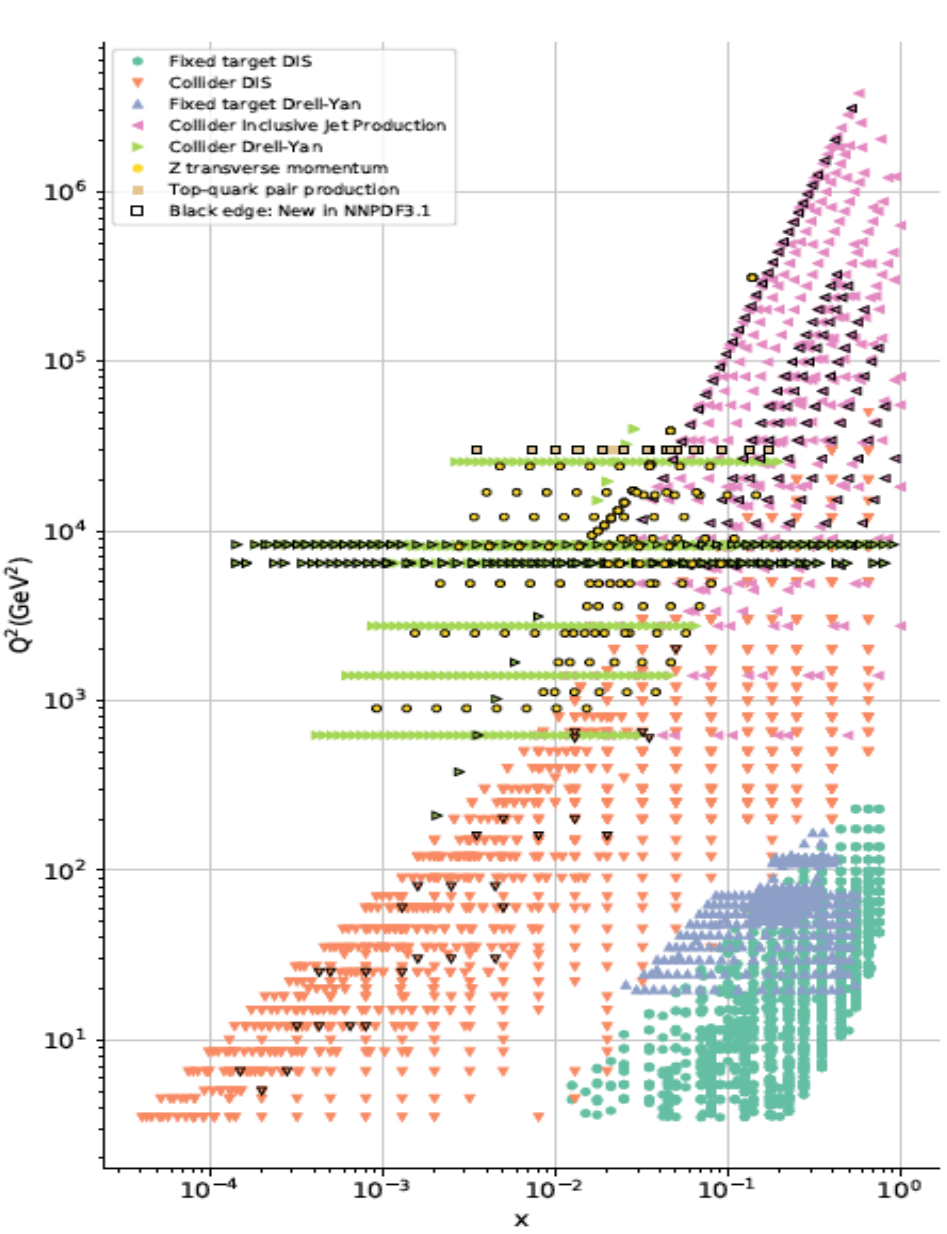
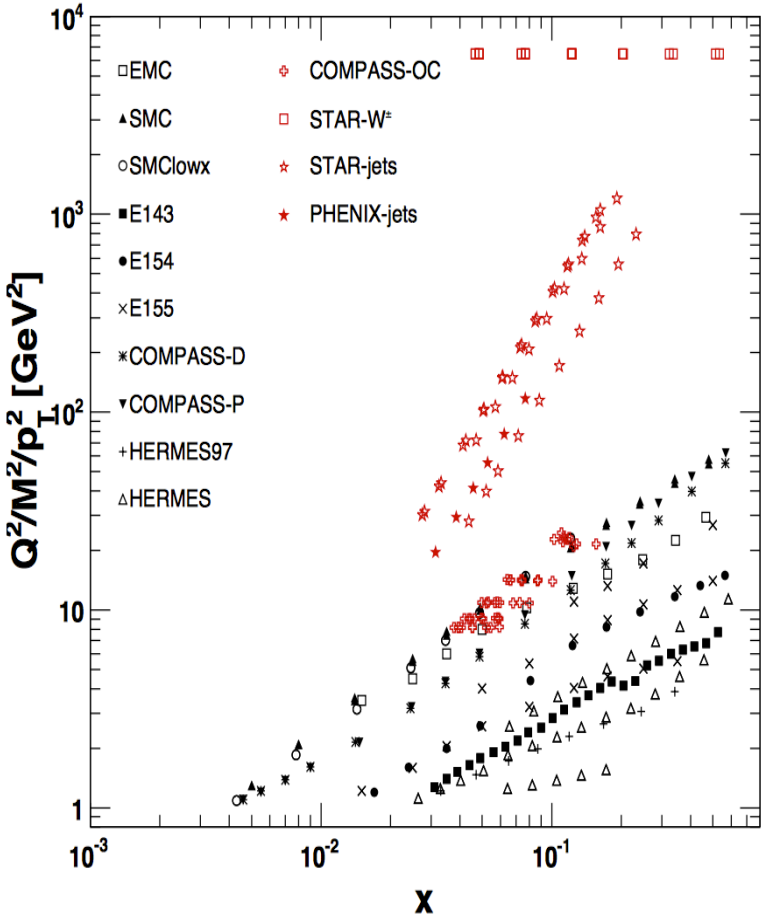
3D Nucleon Structure
Medium-term Program at JLab

Contalbrigo Marco
INFN Ferrara

Sar WorS 2019 – Sardinia Workshop on Spin studies
July 8, 2019 Cittadella dei Musei, Cagliari

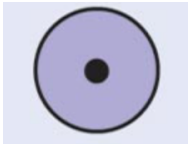
Kinematic Coverage



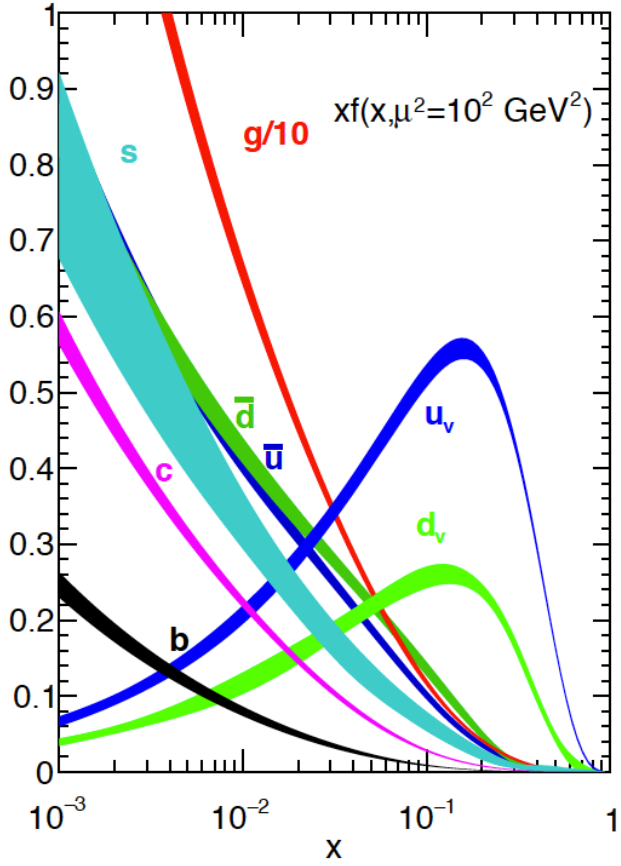


Parton Content

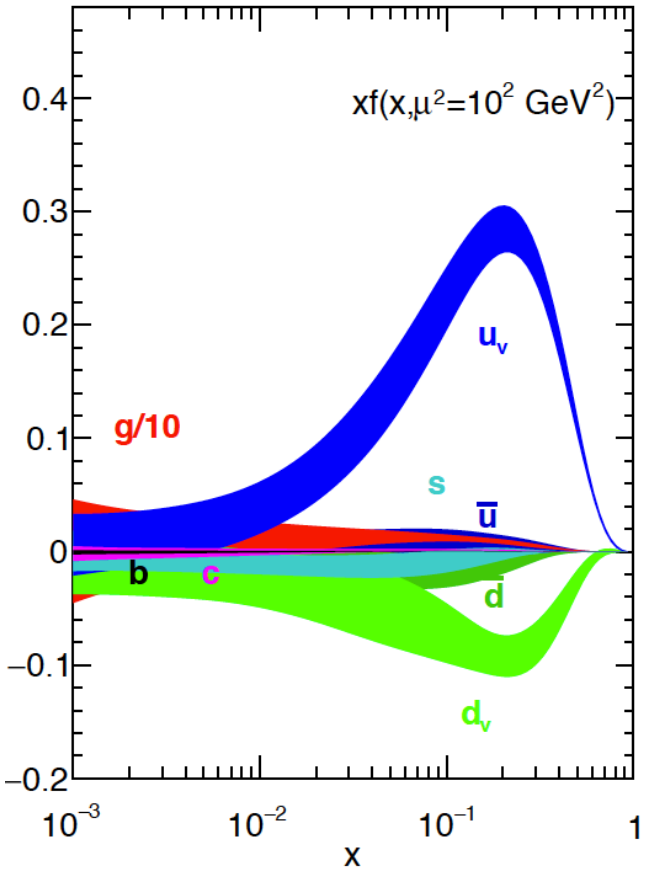
MMHT	[arXiv 1412.3989]
HERAPDF2.0	[arXiv 1506.06042]
CT14	[arXiv 1506.07443]
CJ15	[arXiv 1602.03154]
ABMP16	[arXiv 1701.05838]
NNPDF3.1	[arXiv 1706.00428]



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

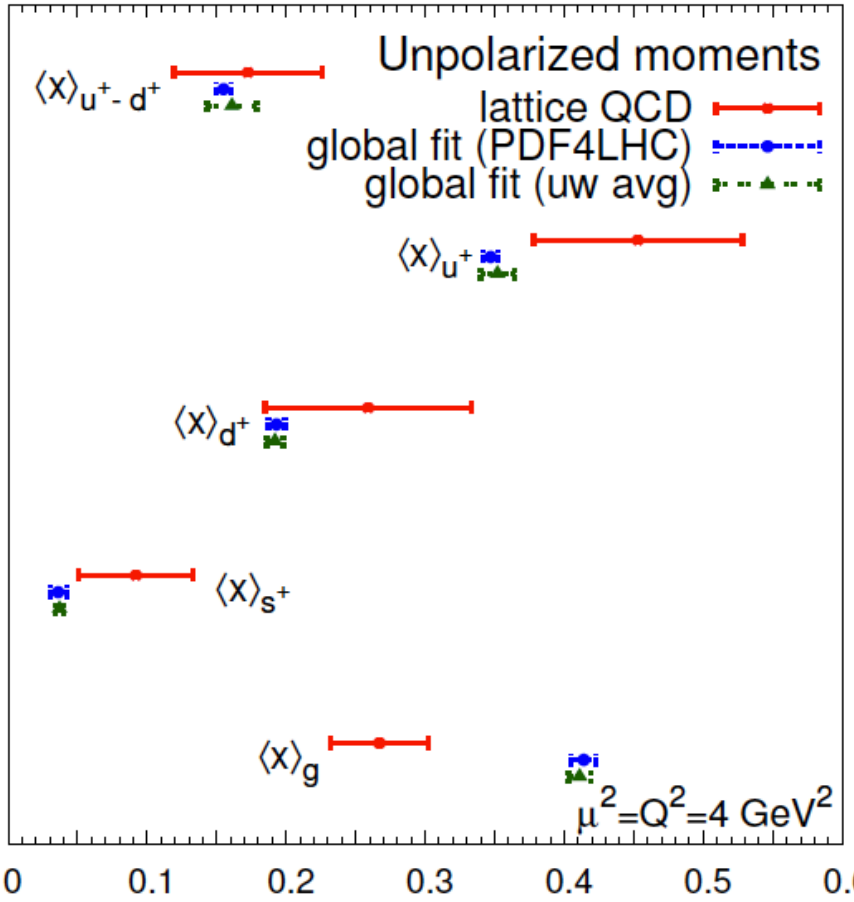


H-W Lin++ [1711.07916]



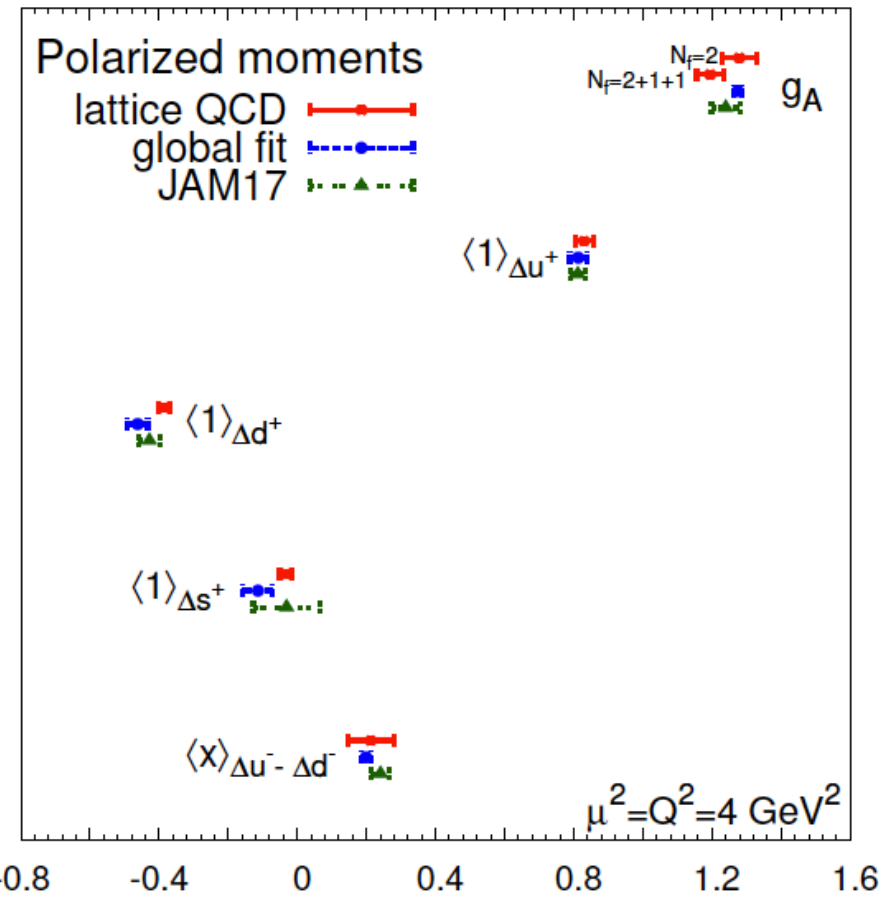
Parton Content

Unpolarized moments



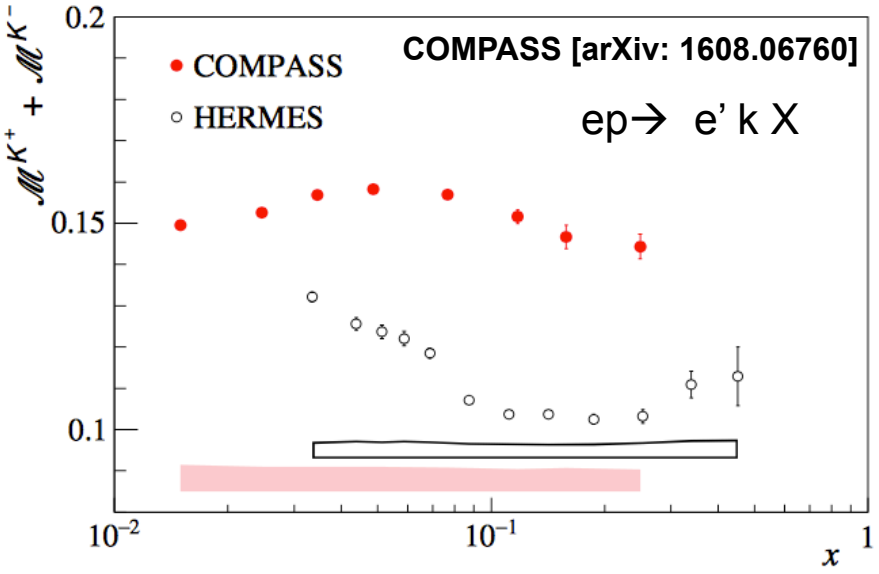
Polarized (helicity) moments

H-W Lin++ [1711.07916]

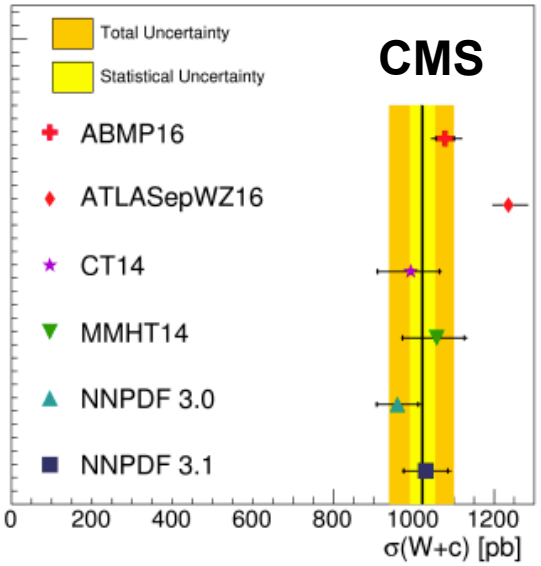


Strange Content

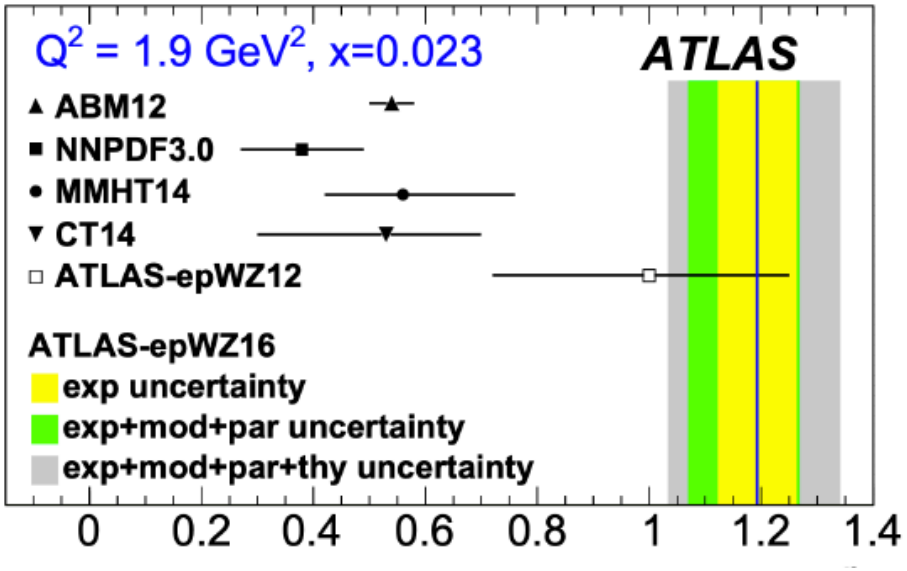
Still contradictory experimental results



pp→ W c X **CMS [arXiv: 1310.1138]**



pp→ W X **ATLAS [arXiv: 1612.03016]**



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

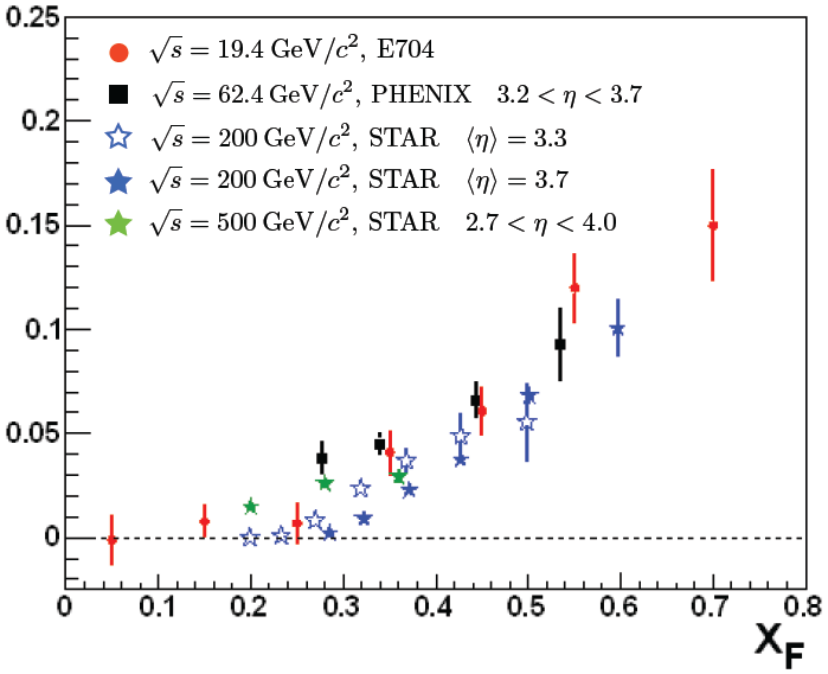
QCD vs pQCD

Can QCD be a precision science ?

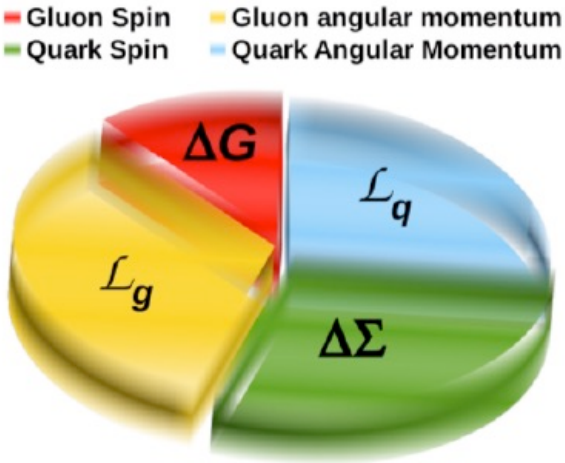
Should not be confused with pQCD, which can,
but is not touching the intimate nature of the strong interaction

Single Spin Asymmetries

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



Proton Spin Budget



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

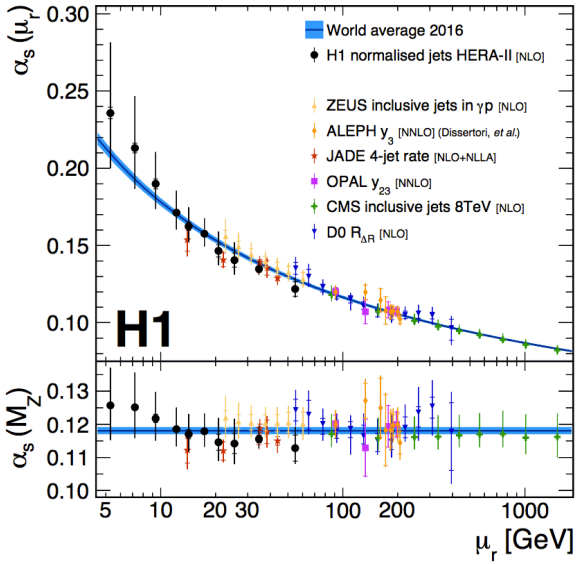
Inclusive Jets @ HERA

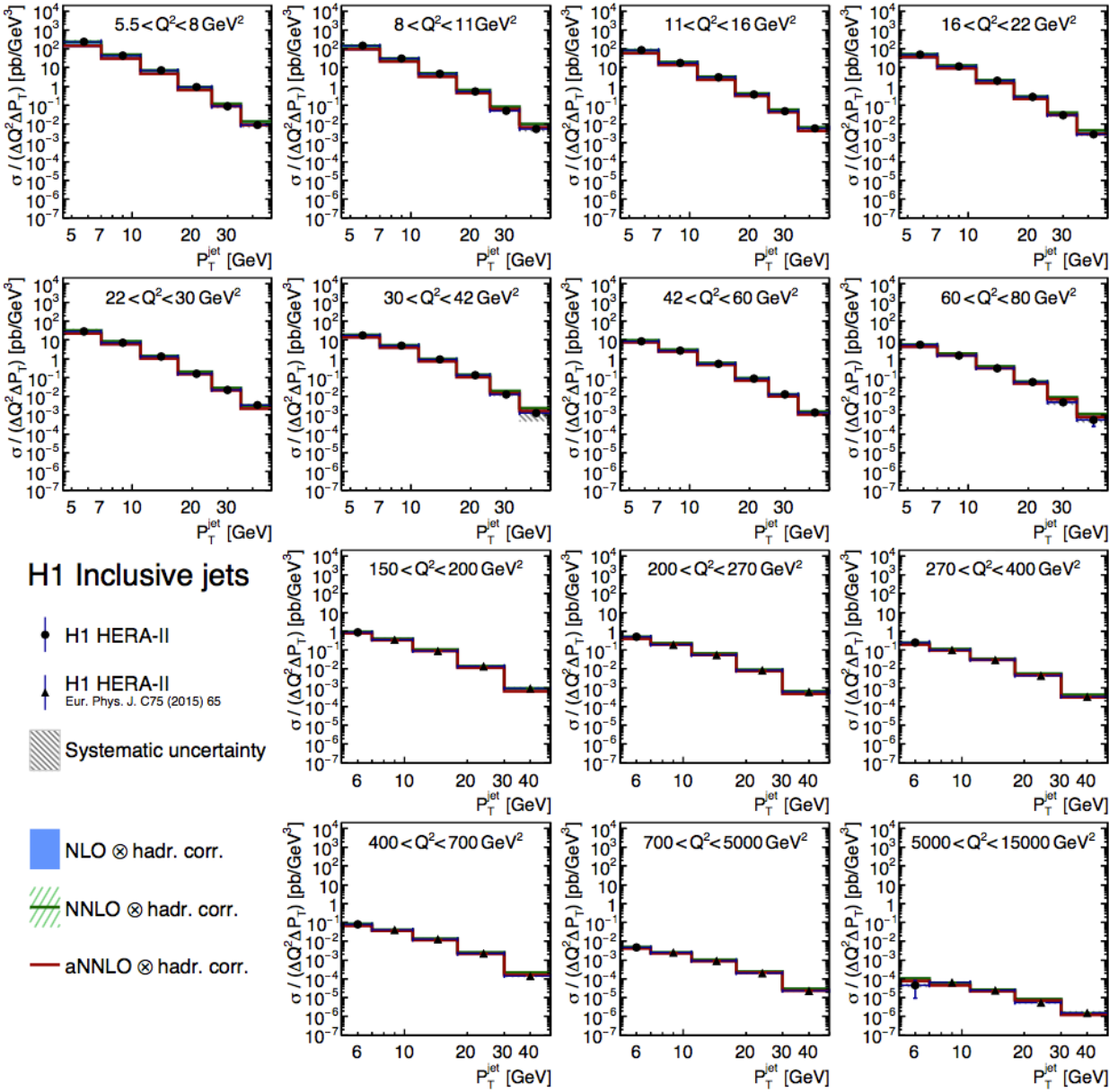
Good perturbative description (hard gluon emission)

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

Part in a p_T<<Q TMD regime

H1 [arXiv: 1611.03421]

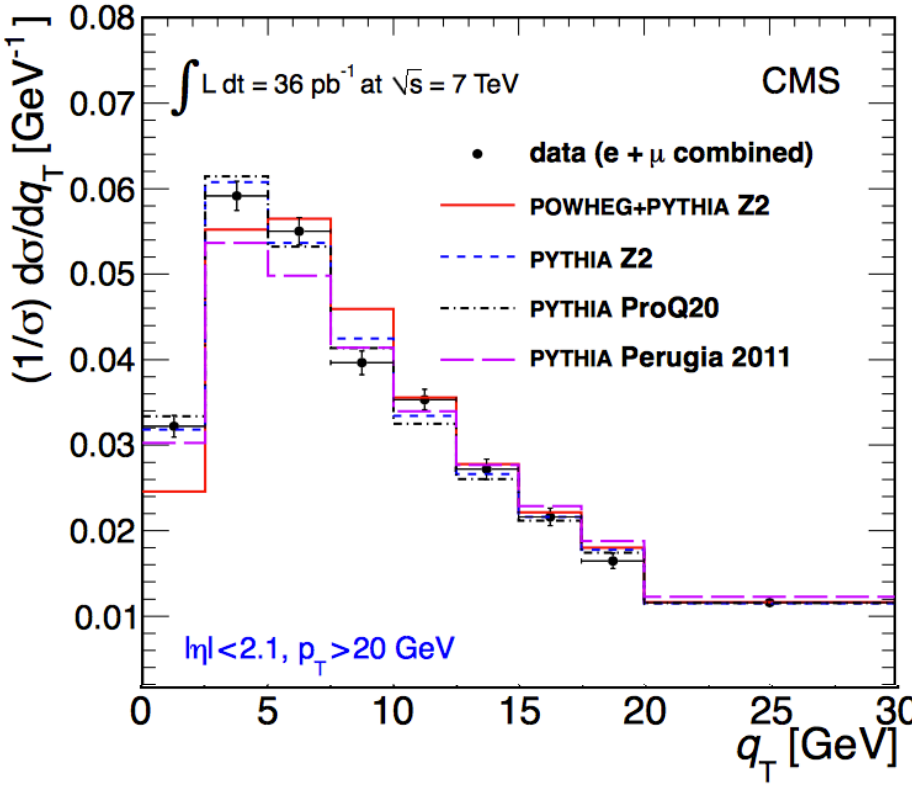




Non Perturbative QCD signals

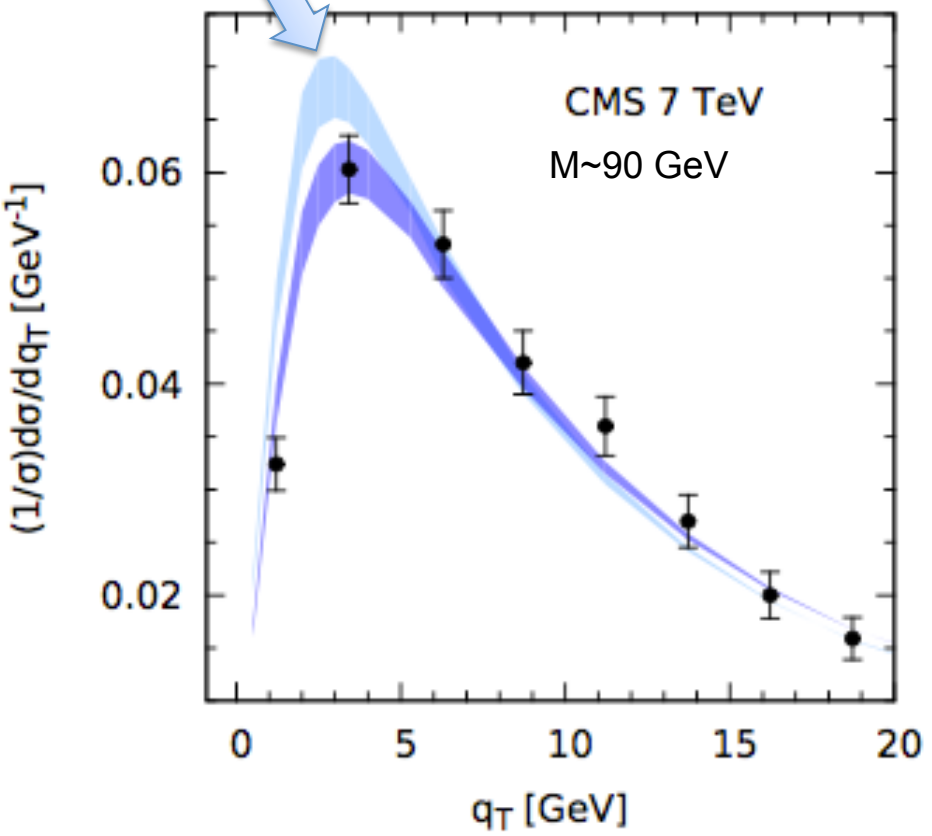
Non perturbative PDF component shows effects up to vector boson production at LHC

CMS [arXiv: 1110.4973]

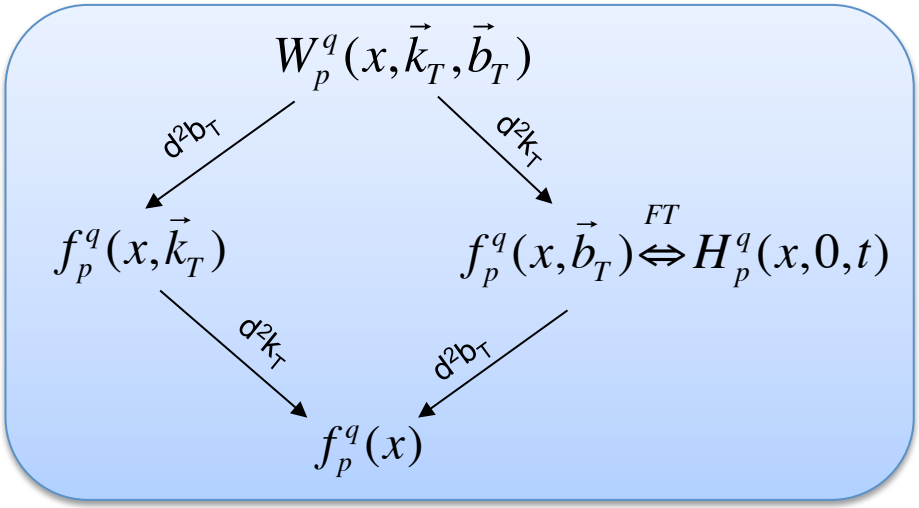


$f_p^q(x,k_\perp^2)$

D'Alesio++ [arXiv: 1407.3311]



The 3D Nucleon Structure



Confinement Scale

Transverse momentum

$\vec{k}_T$

$\vec{b}_T$

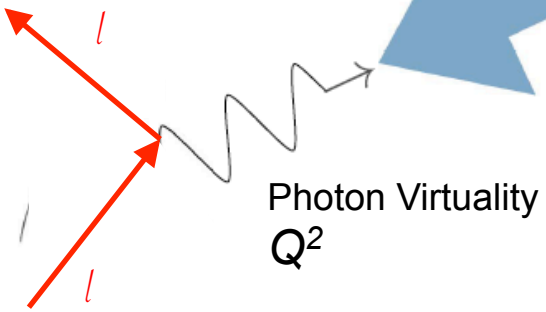
Transverse position

Spin

Transverse plane

High Energy Probe
Hard Scale

Longitudinal momentum
$k^+ = xP^+$

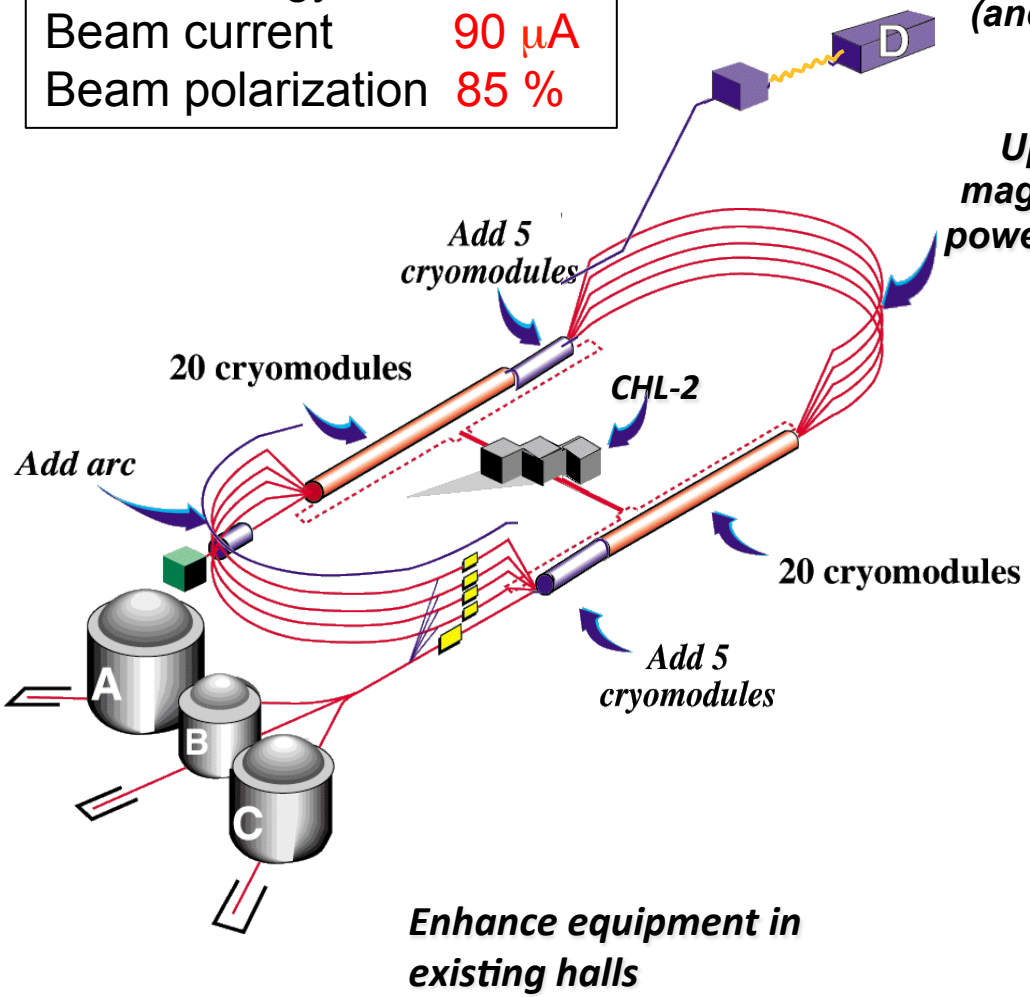


Photon Virtuality
Q^2

Courtesy of A. Bacchetta

CEBAF Upgrade at Jefferson Lab

Beam Energy	12 GeV
Beam current	90 μA
Beam polarization	85 %



Timeline (indicative)

2018: Hydrogen Target (Hall-B)

2019: Deuterium Target (Hall-B)

2020: Polarized ^{3}He (Hall-C inclusive)

2021++: Polarized NH_3, ND_3, HDice (Hall-A, Hall-B)

Beam is being delivered to all the Halls

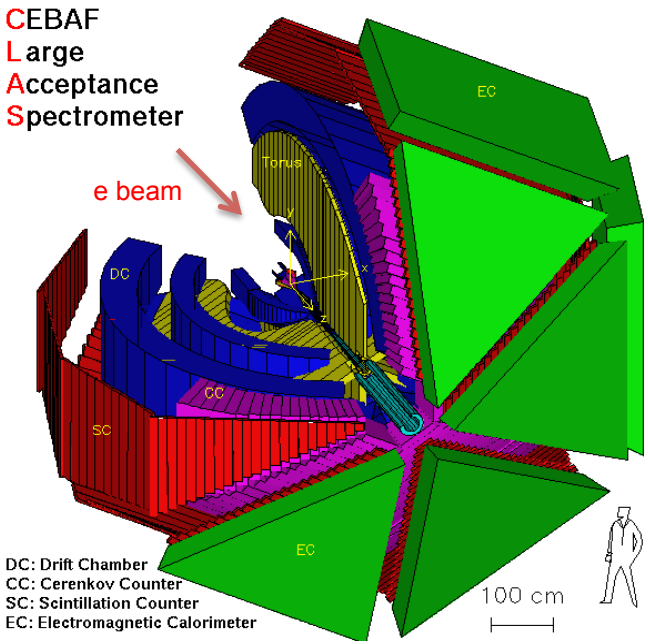
Hall-B Mission

Comprehensive measurements based on :

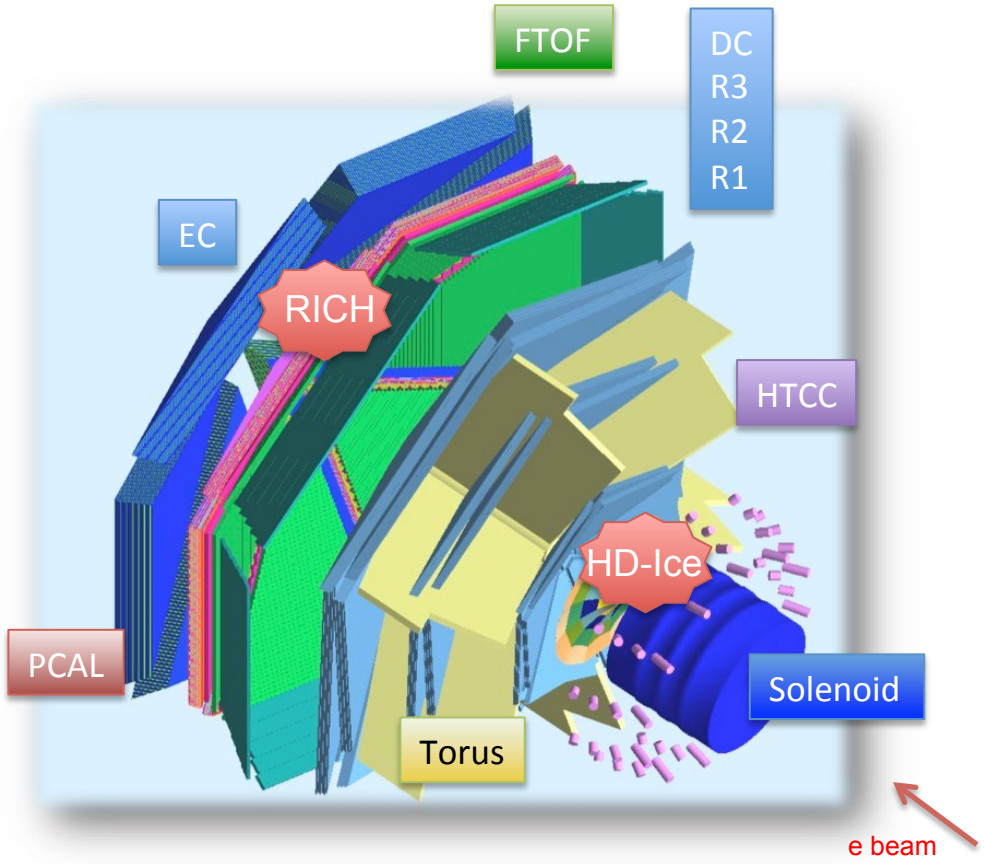
- High luminosity up to 10^{35} cm^{-2} s^{-1}
- Large acceptance (current & target fragmentation)
- Polarized beam and targets
- Multi-particle final state measurements

6 GeV

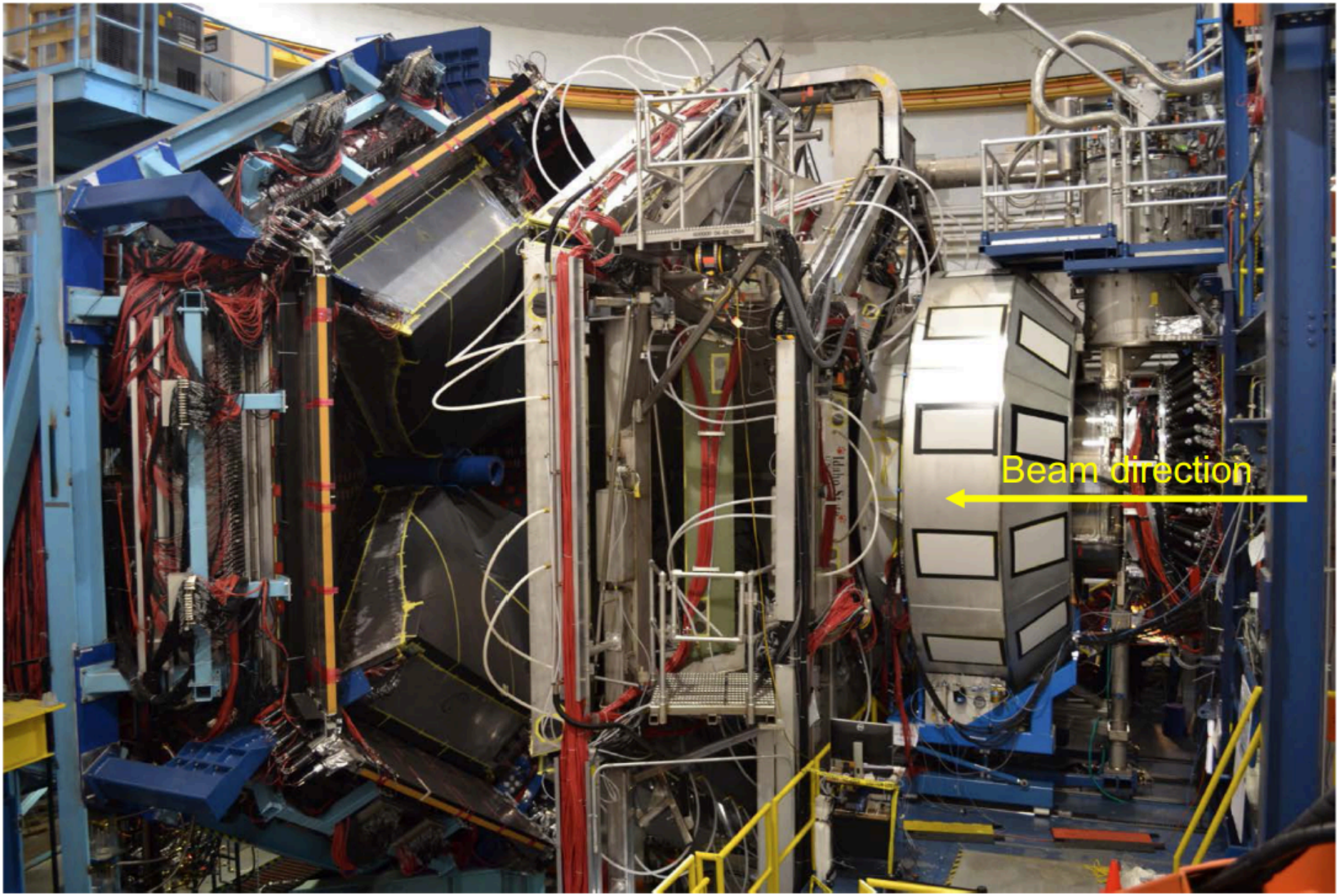
NIM A503, 513 (2003)



12 GeV

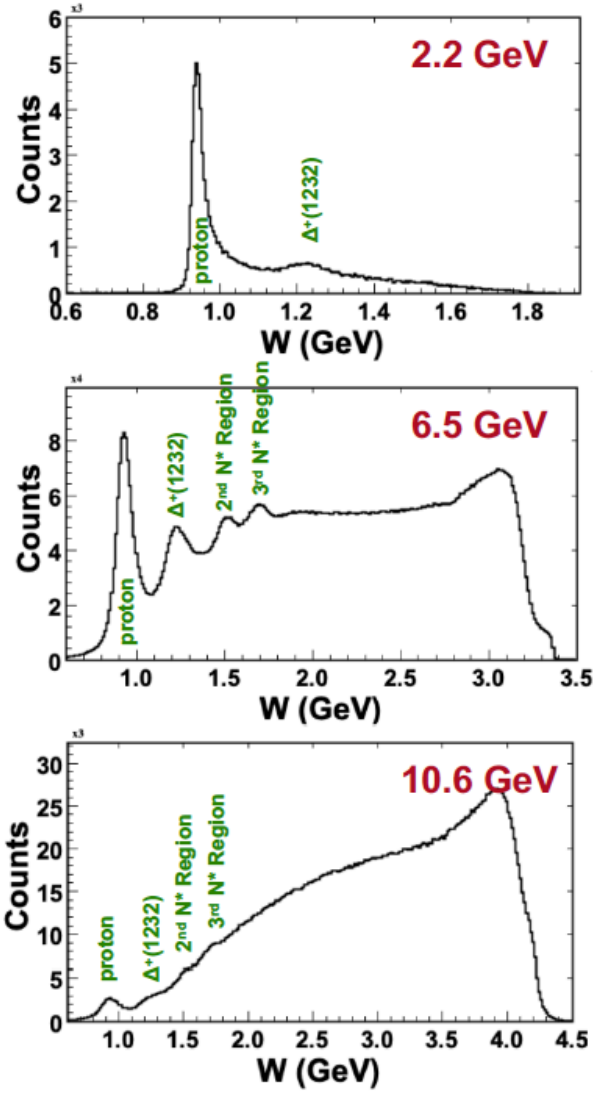


CLAS12 Experiment

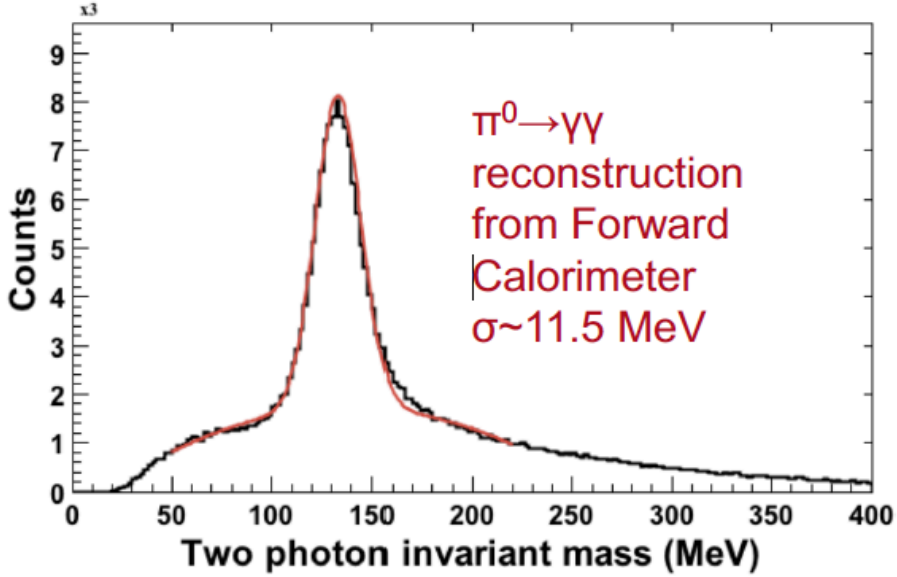


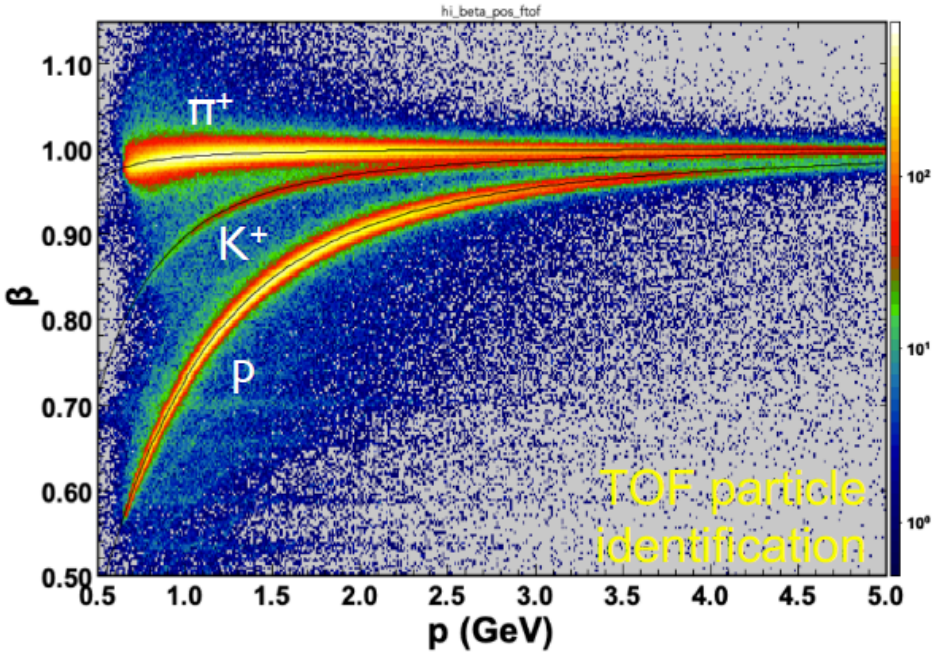
Hall-B Data-Taking

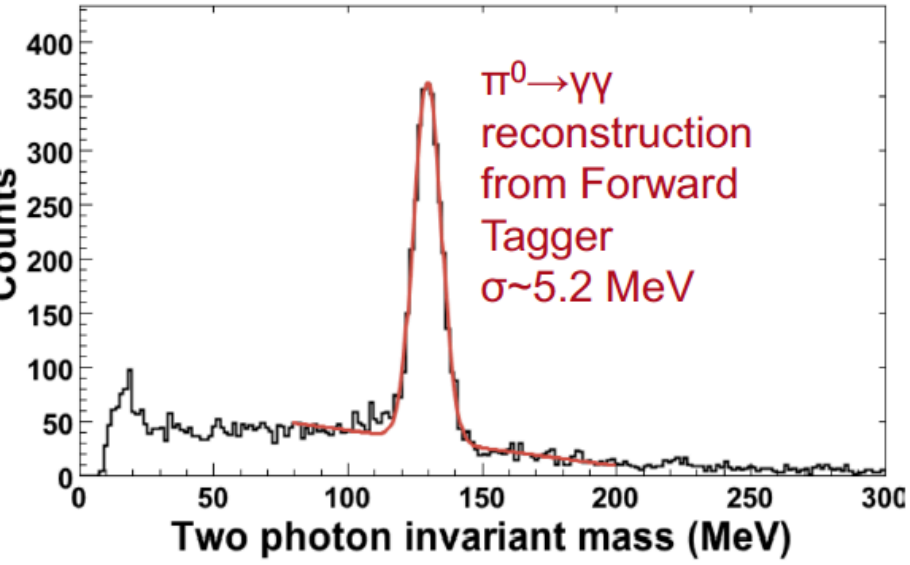
- **First commissioning run** (KPP) in February 2017
- **Engineering run** in December 2017-February 2018
- Physics data taking start in February 2018:
  - **Run Group A**: **Hydrogen**
    - 13 experiments
    - 10.2-10.6 GeV polarized electrons
    - Liquid-hydrogen target
    - ~300 mC, ~50% of approved beam time
  - **Run Group K**: **Energy**
    - 3 experiments
    - 6.5, 7.5 GeV polarized electrons
    - Liquid-hydrogen target
    - ~45 mC, ~12% of approved beam time
  - **Run Group B**: **Deuterium**
    - 7 experiments
    - 10.2-10.5 GeV polarized electrons
    - Liquid-deuterium target
    - ~84 mC, ~24% of approved beam time

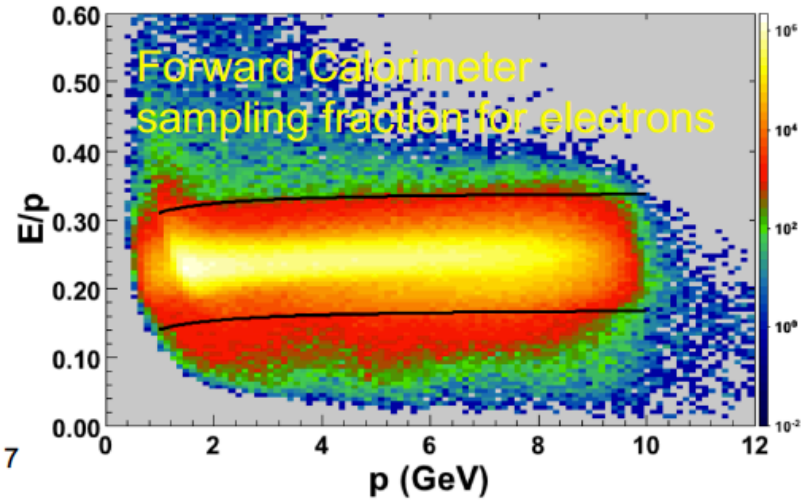


Event Reconstruction





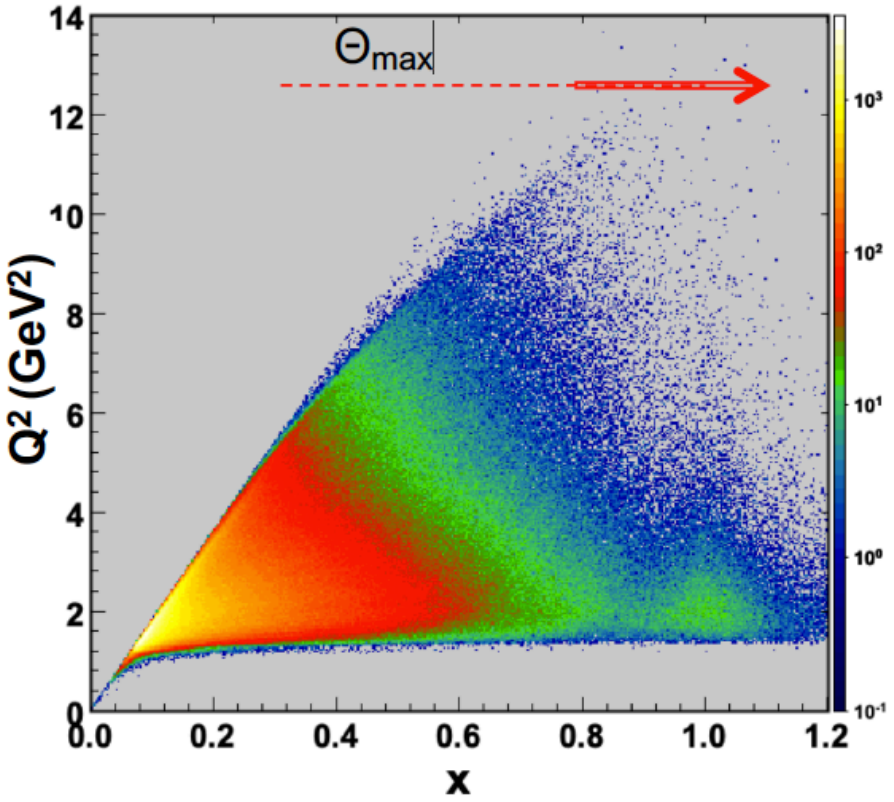


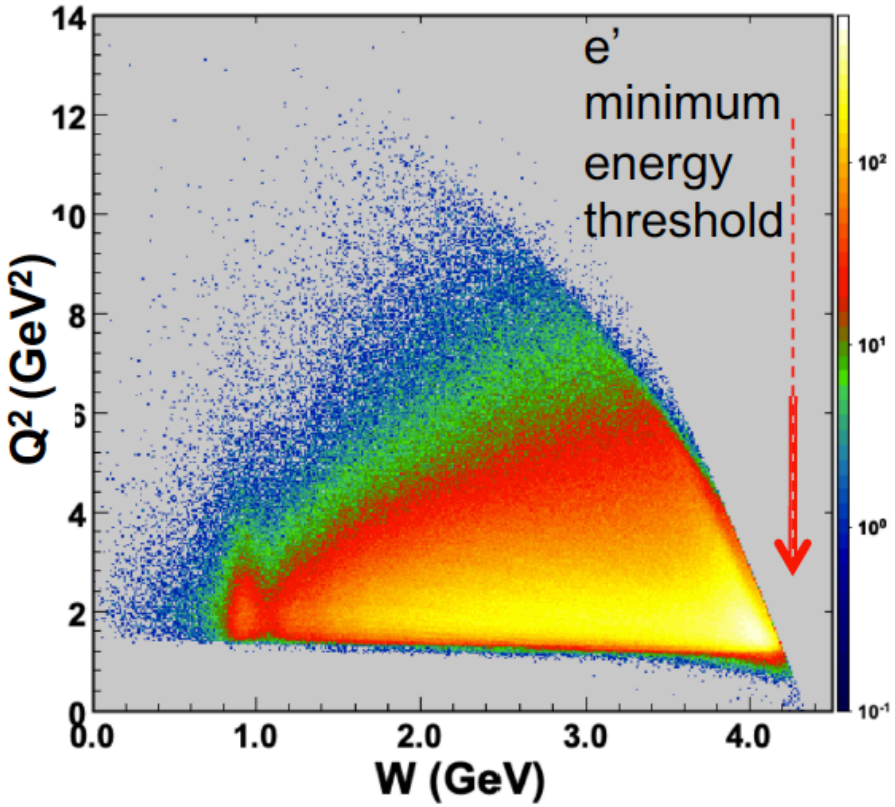


Kinematic Reach

Beam energy at 10.6 GeV Torus current 3770 A, electrons in-bending, Solenoid magnet at 2416 A.

p(e,e')X





Plots based on 100 min. of data taking

Polarized Targets

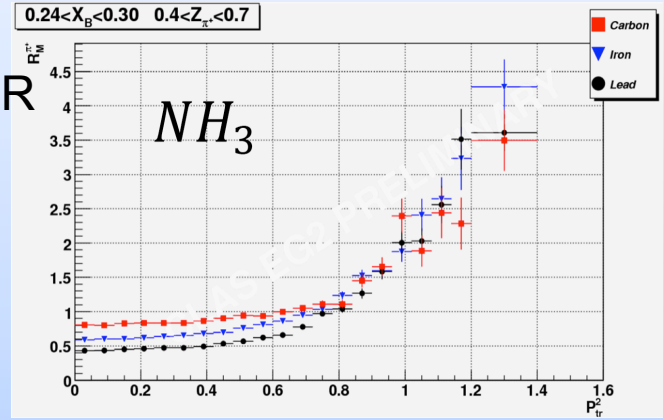
HD-Ice target vs standard nuclear targets (less luminosity for higher purity)

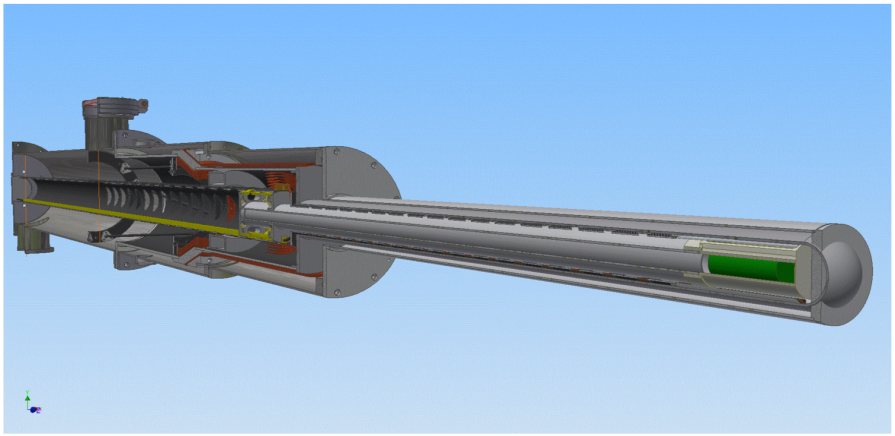
Advantages:

- **Minimize nuclear background**
  smaller dilution, no attenuation at large p_T
- **Weak holding field (BdL ~ 0.1 Tm)**
  wide acceptance, negligible beam deflection

Challenges:

- **Very long polarizing times (months)**
- **Sensitivity to local heating by charged beams**
- **Transverse holding field inside CLAS12**

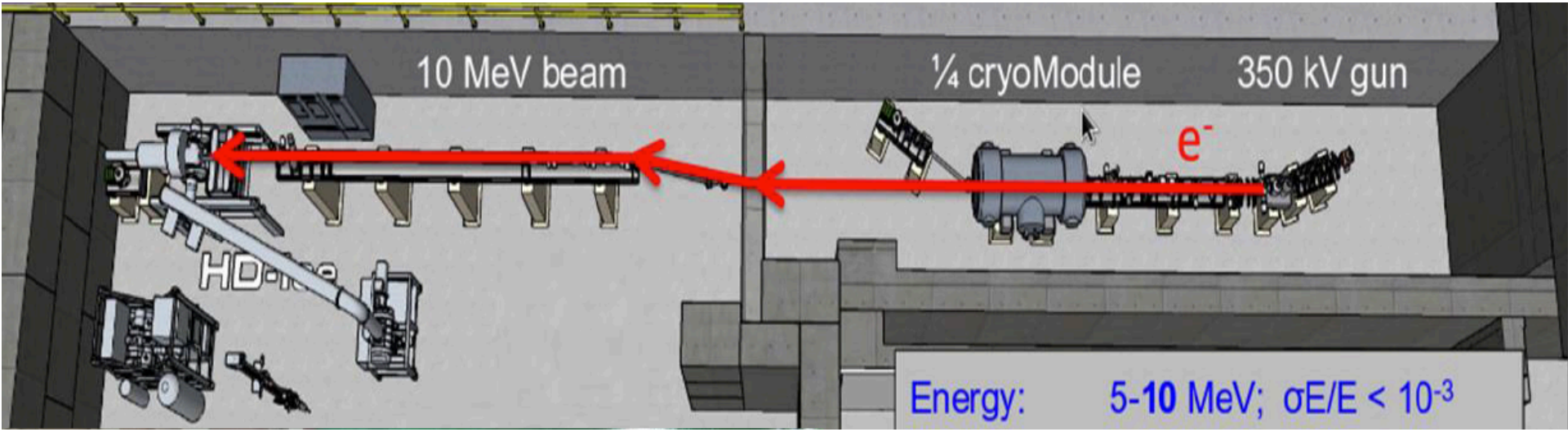




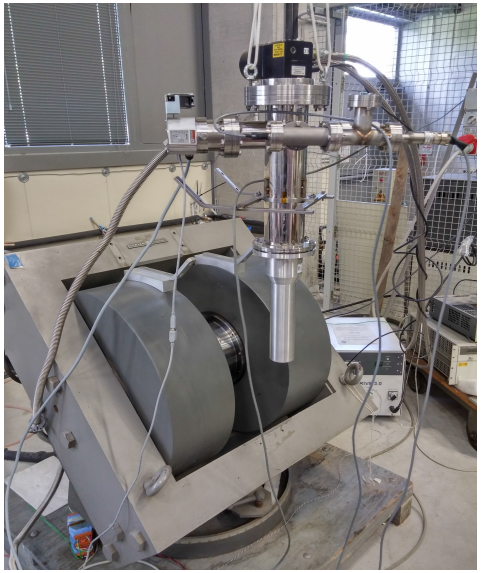
HDice Development

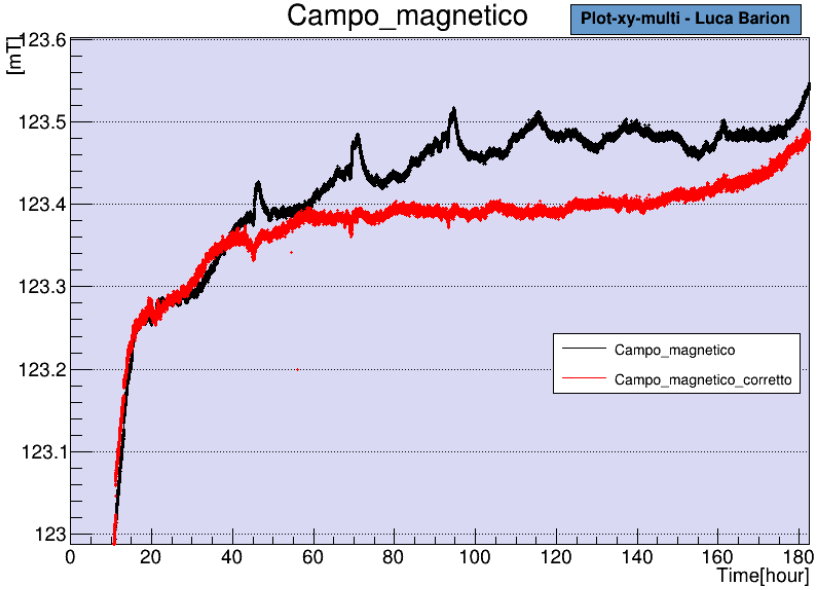
UITF: Electron beam to test polarization preservation

@ UITF in 2019 / 2020



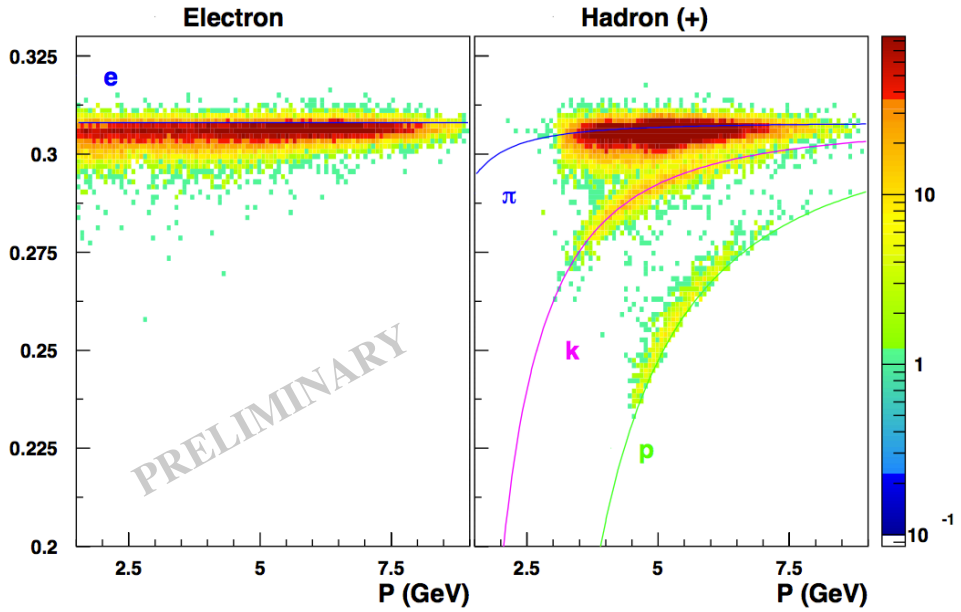
Frozen dipole-field in a MgB_2 cylinder





CLAS12 RICH

Hadron separation, direct photon, RGA data



Second Module Plan (FY)	19-1	19-2	19-3	19-4	20-1	20-2	20-3	20-4	21-1	21-2	21-3	21-4
Mechanics												
Aerogel												
Mirrors												
Electronics												
MAPMTS												
Services in Hall												
Assembling + Installation												

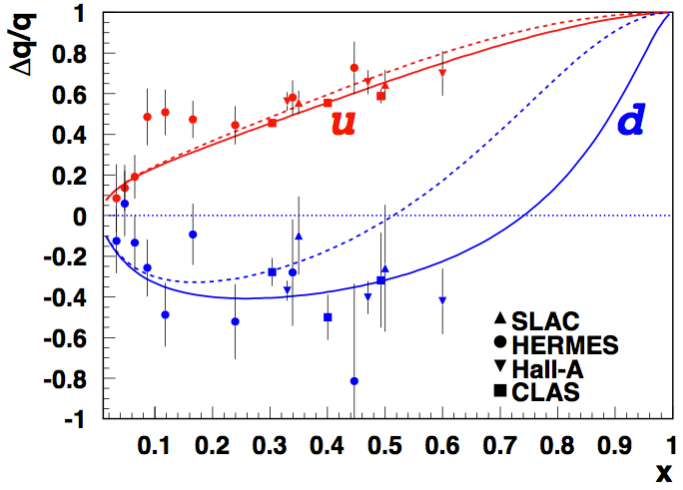
INFN JLab Shared

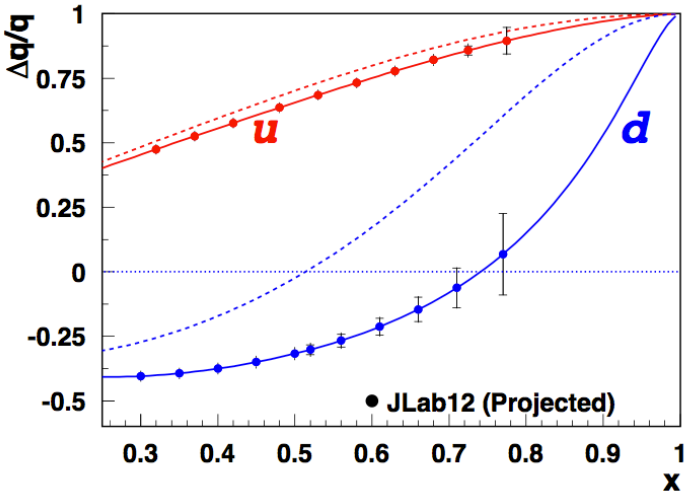
Polarized targets

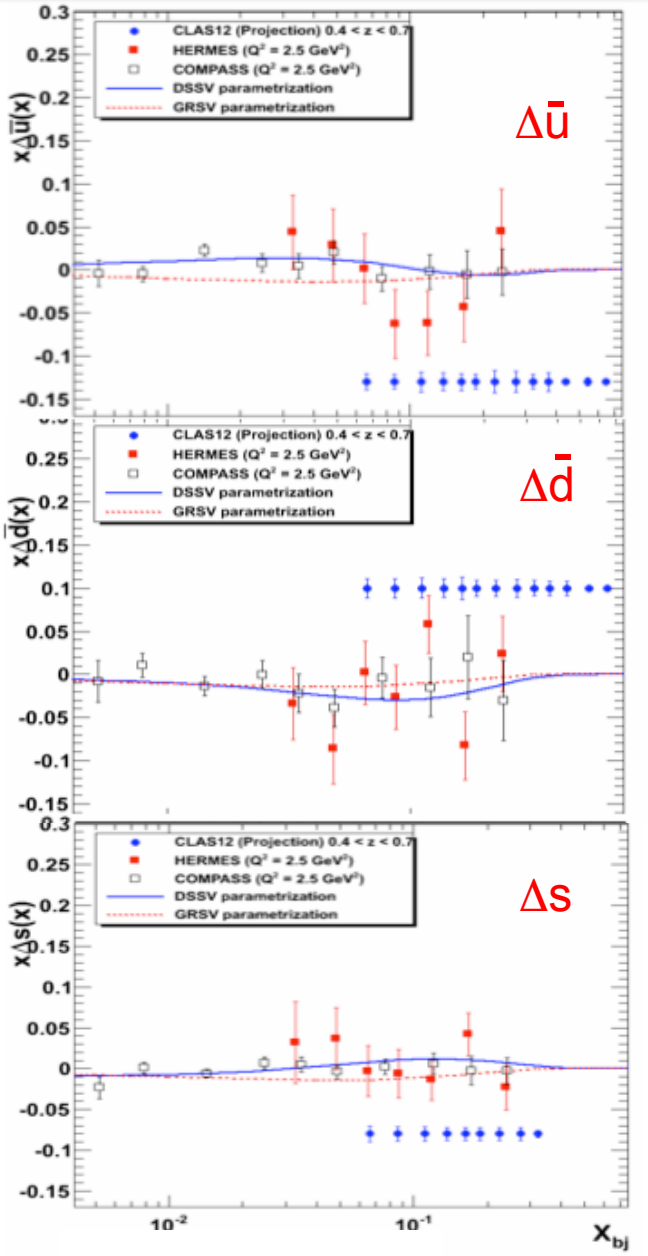
Quark Helicity

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

H. Avakian [arXiv: 0705.1553]



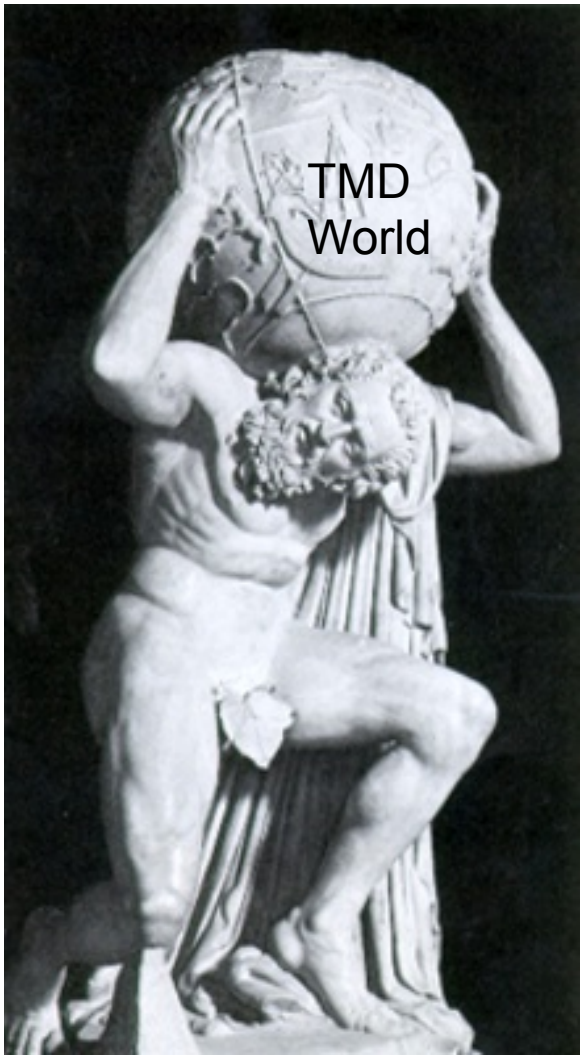


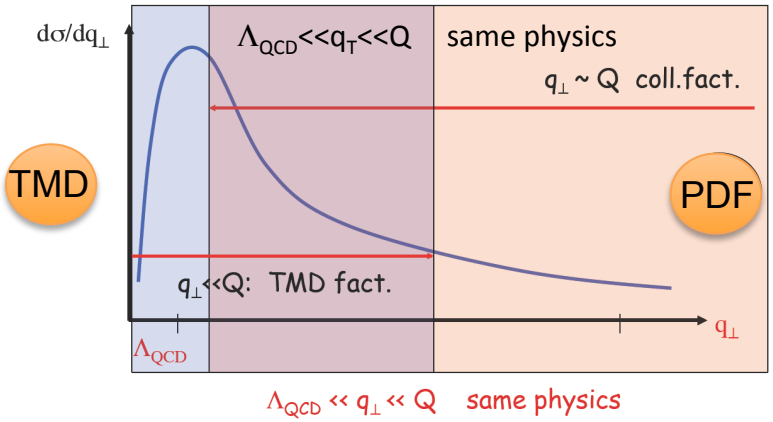


@ CLAS12 in 2021

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	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1, h_{1T}^\perp$

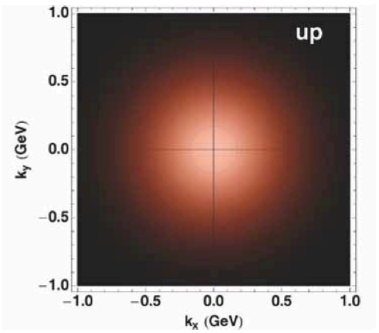
hadron polarisation

quark polarisation

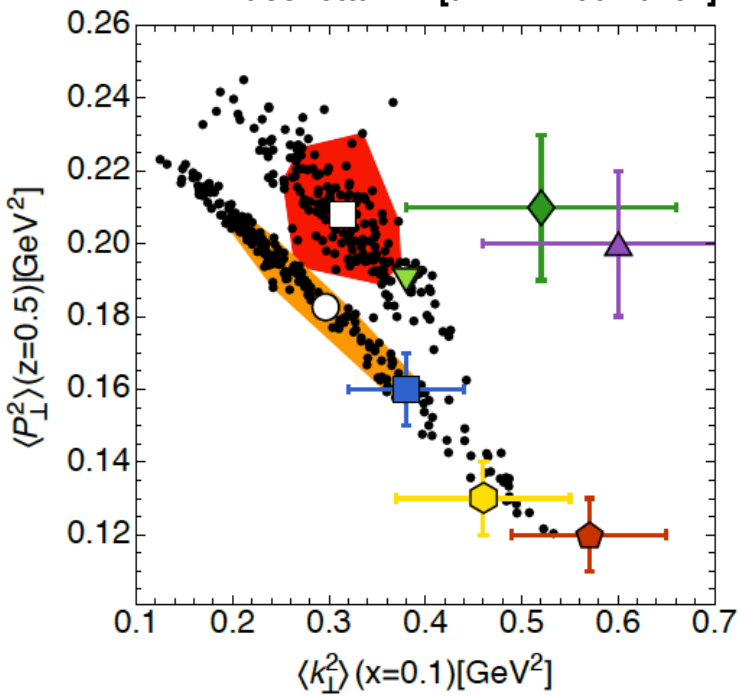
N/q	U	L	T
U	D_1		$H_1^\perp$

Unpolarised TMDs

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



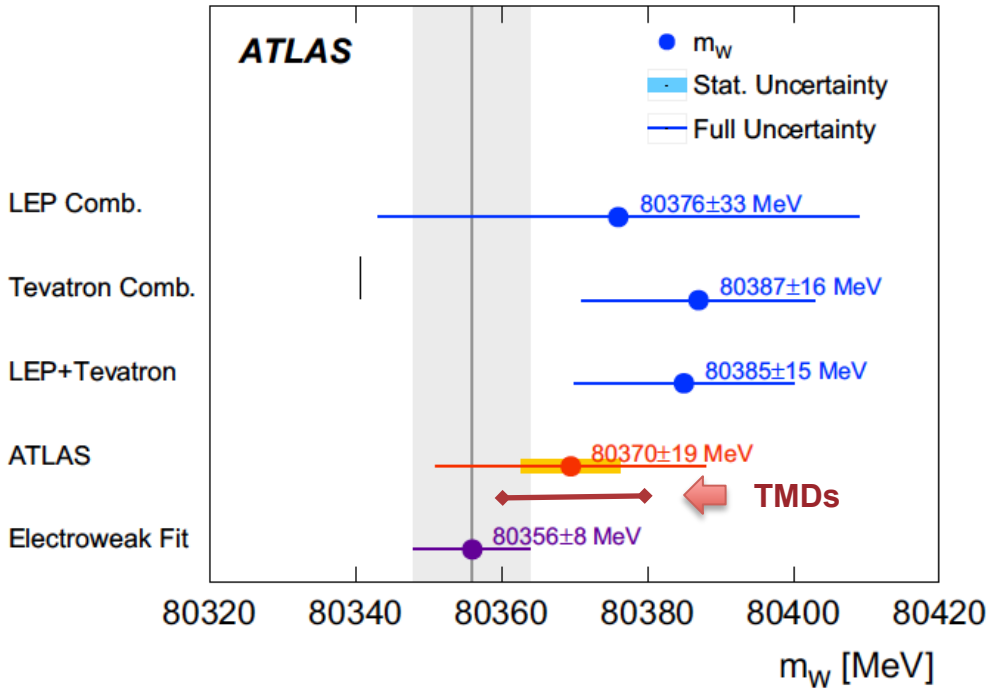
A. Bacchetta++ [arXiv:1703.10157]



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

+9 / -6 (TMDs)

ATLAS++ [arXiv:1701.07240]

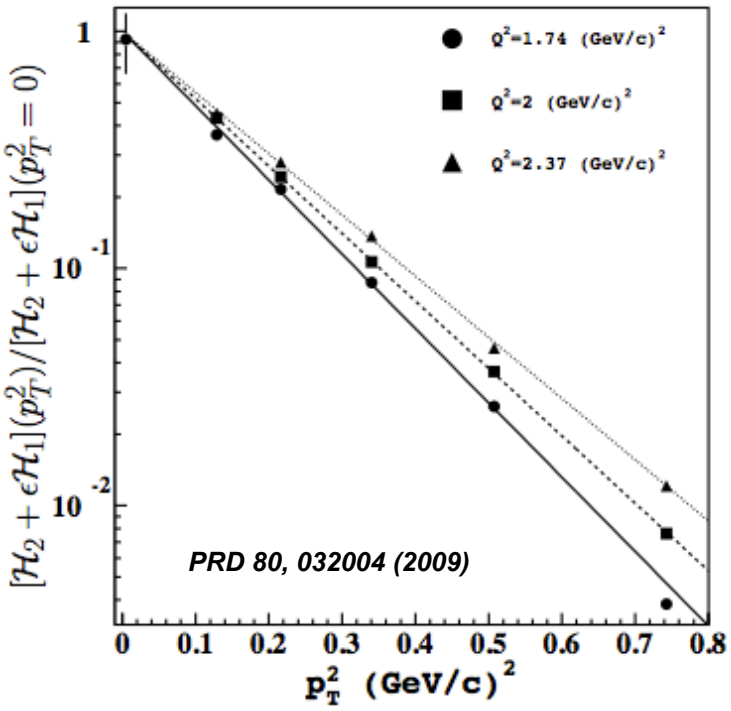


Unpolarized Targets

The baseline: hadron multiplicities

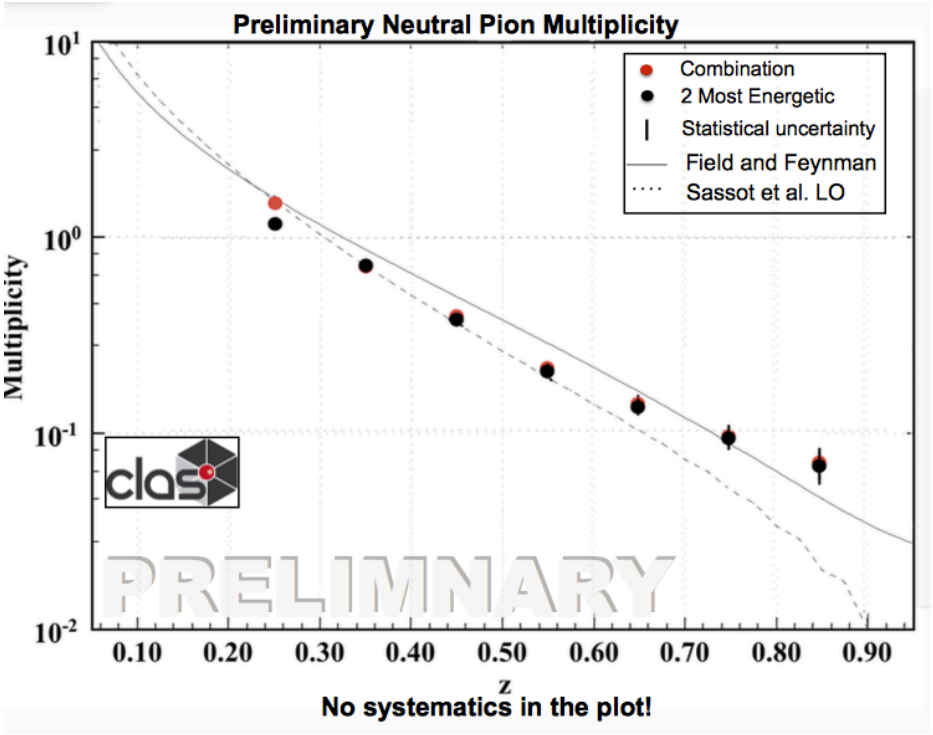
Extending the study to the transverse momentum

@ CLAS



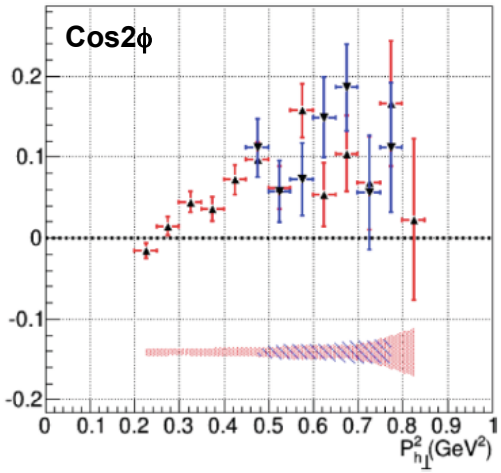
@ CLAS12 now

G. Angelini (DNP2018)

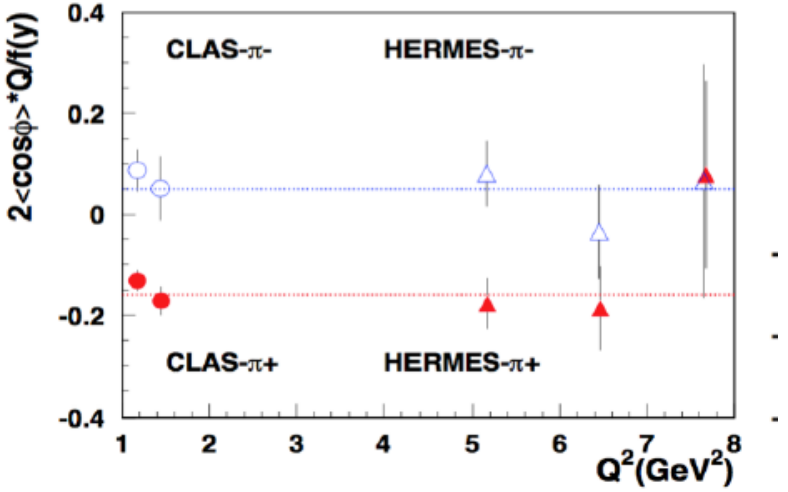


Unpolarized TMDs

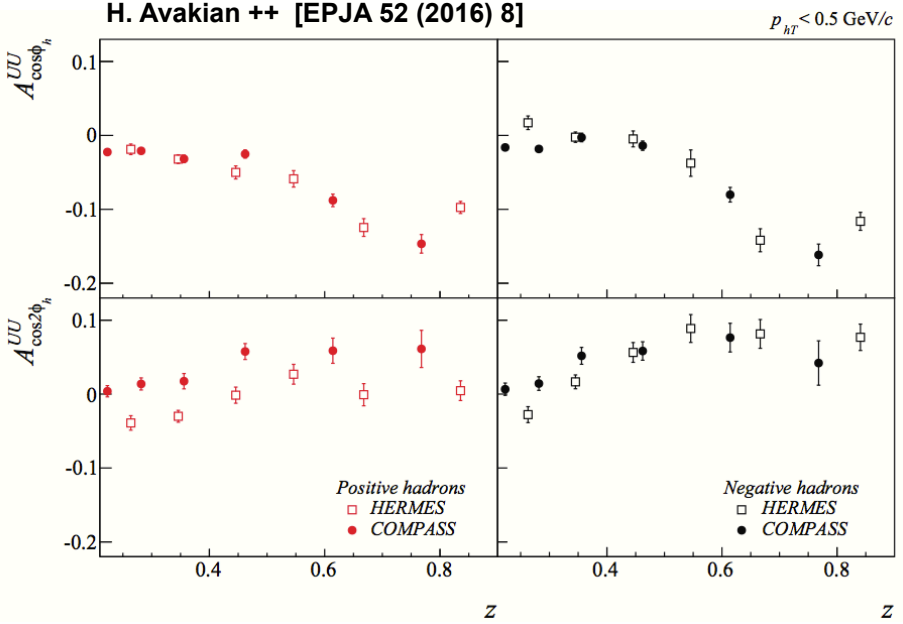
@ CLAS now



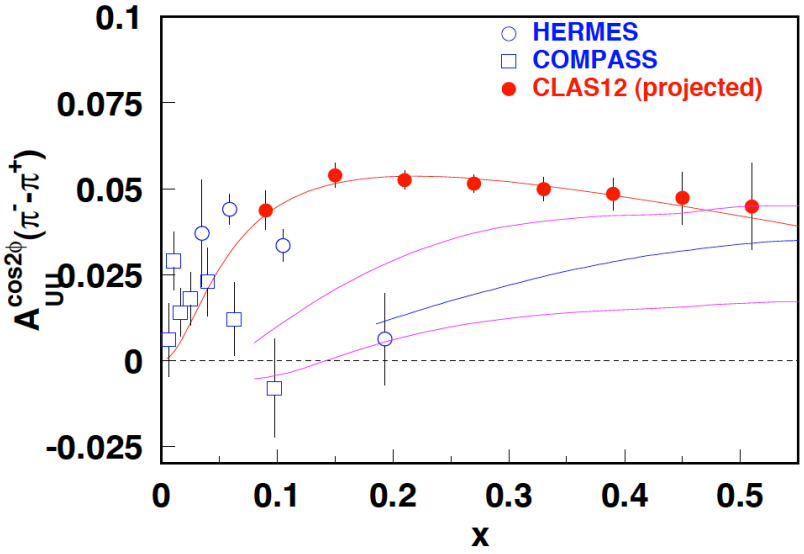
N. Harrison PoS (DIS2016) 215



H. Avakian ++ [EPJA 52 (2016) 8]



@ CLAS12 now

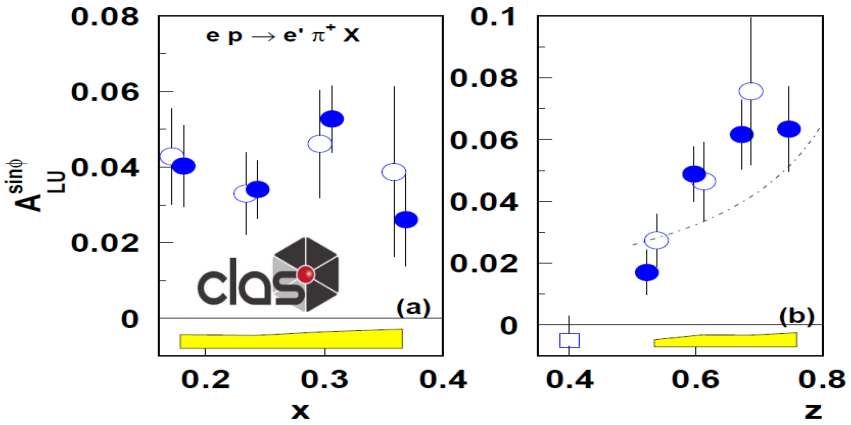


Quark-Gluon Correlations

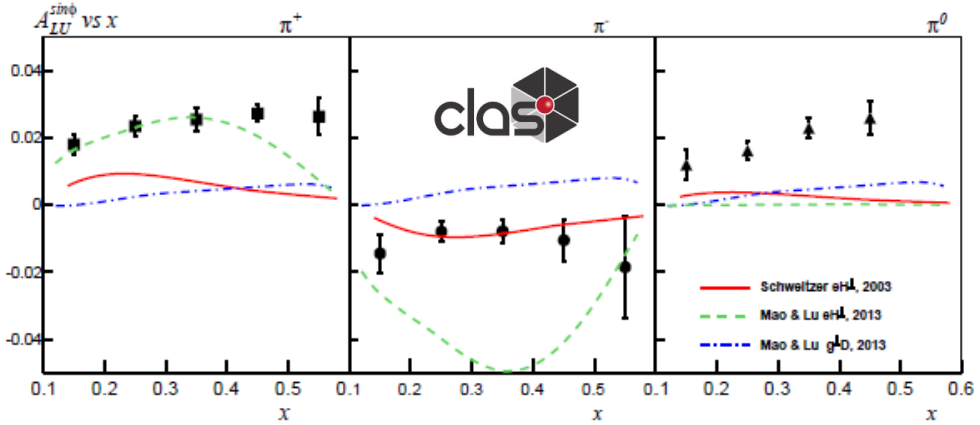
$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^{\perp}+\frac{M_h}{M}f_1\frac{\tilde{G}^{\perp}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^{\perp}D_1+\frac{M_h}{M}h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

e(x): twist-3 PDF sensitive to qGq correlations "transverse force"

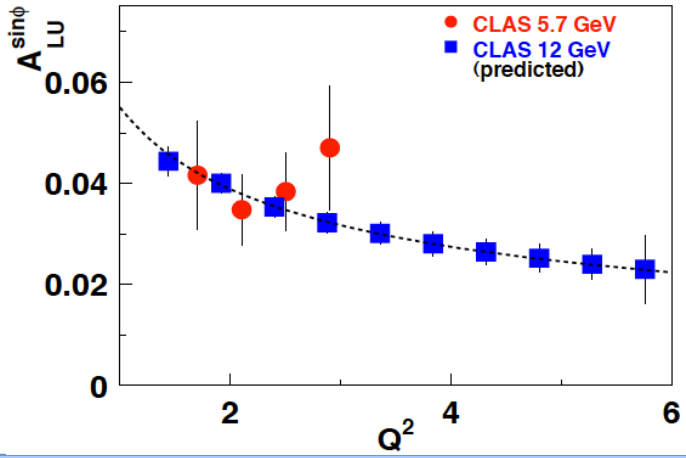
H. Avakian *et al.*, PRD69, 112004 (2004)@4.3 GeV



W. Gohn *et al.*, PRD89, 072011 (2014)@5.5 GeV



@ CLAS12 now

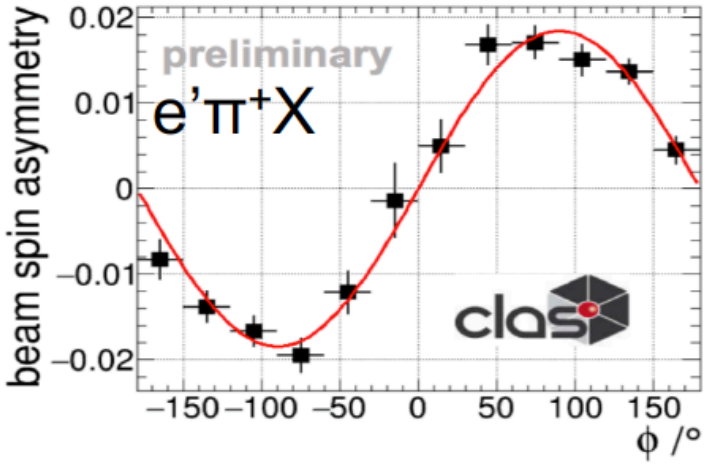


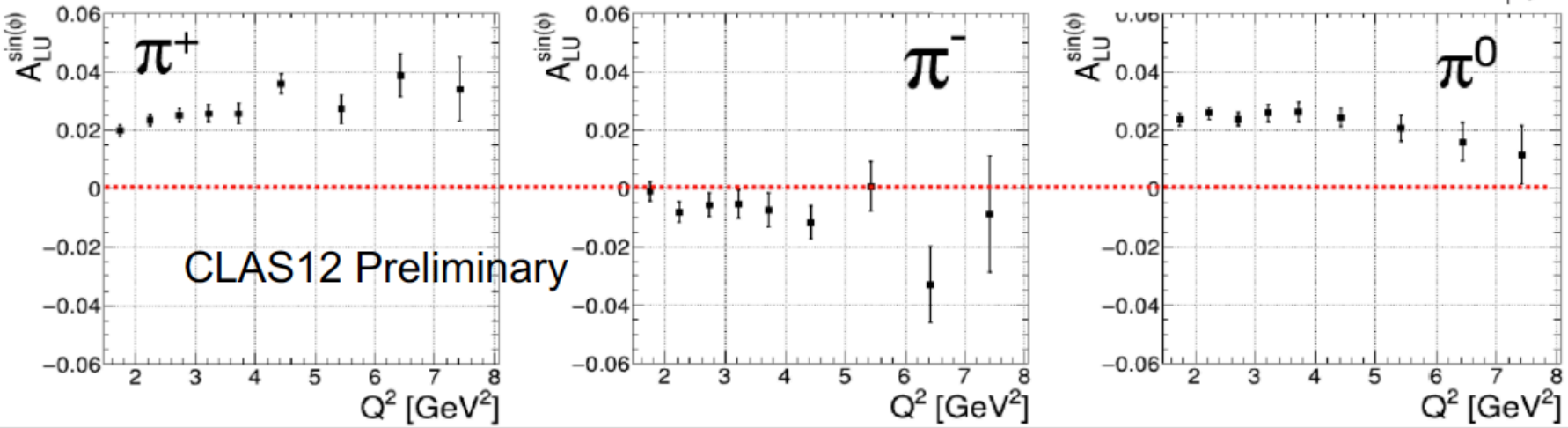
→ Entire structure function is twist-3, so in commonly used Wandzura-Wilczek approximation entire asymmetry = 0

Quark-Gluon Correlations

SSA in SIDIS sensitive to quark-gluon interactions and color forces

$$BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

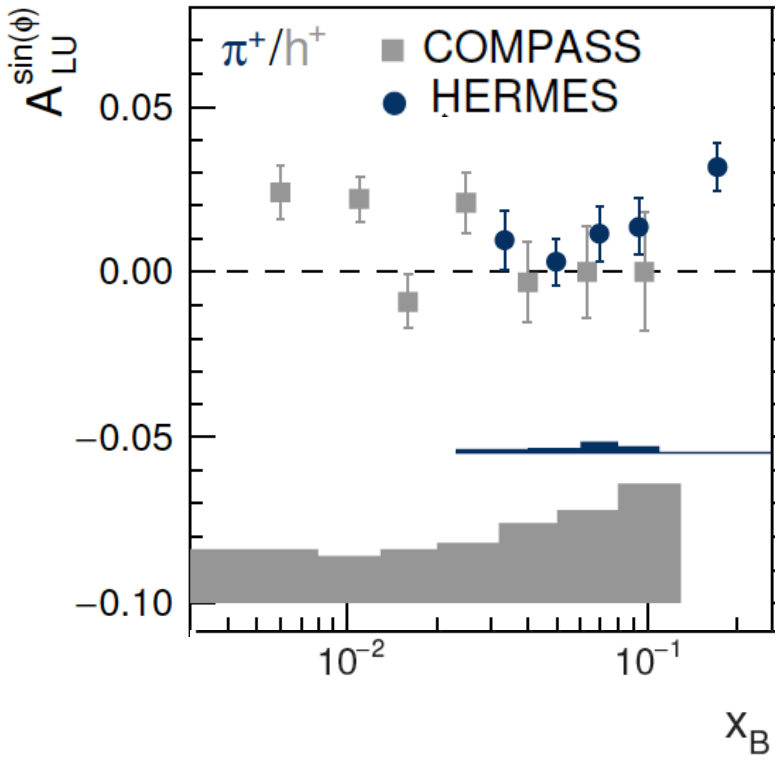




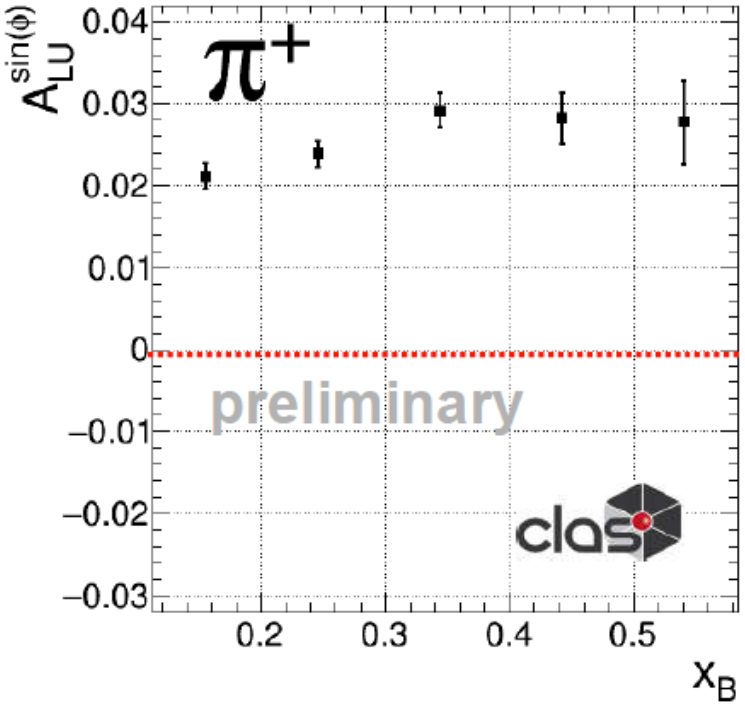
- With <2% of expected unpolarized target data, CLAS12 already provides a measurement comparable to previous experiments
- Will allow fine multidimensional binning to study the dependence on Q^2 and other variables

High-Luminosity @ JLab12

~ 1 year data taking

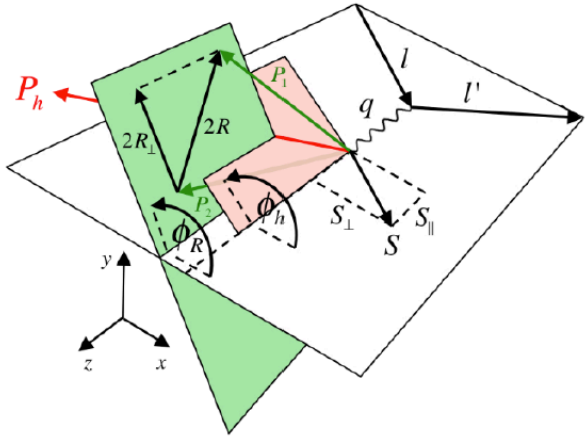


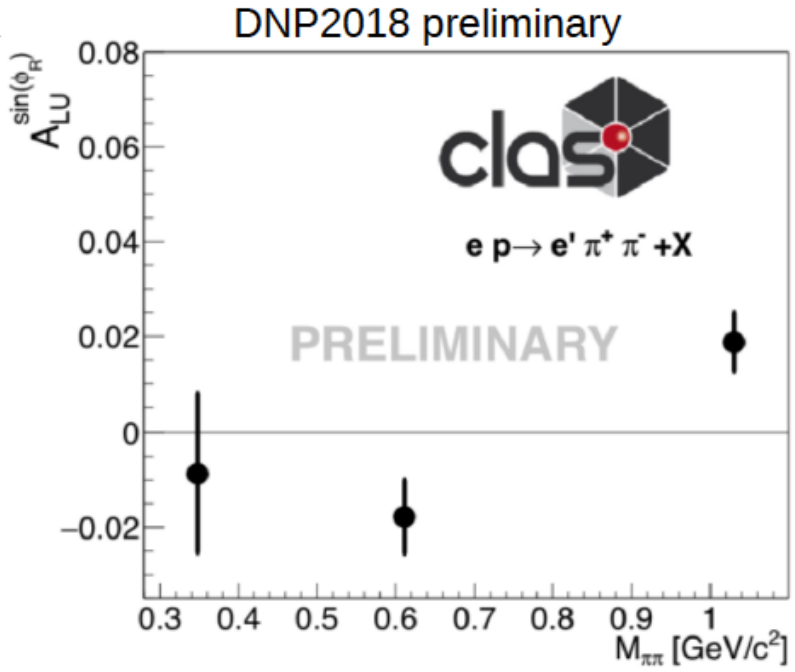
~ 1 day data taking

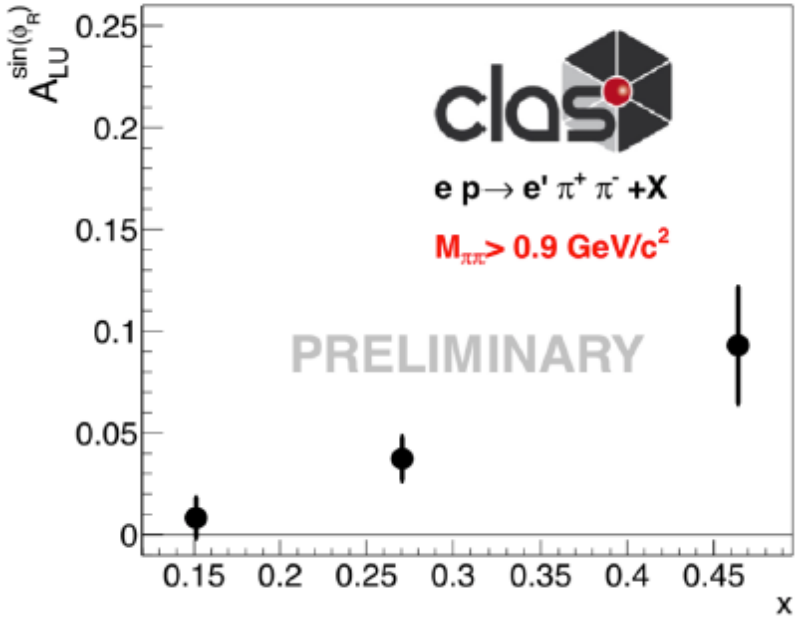


Di-hadron TMDs

$$A_{LU}\left[\sin\phi_R\right] \propto e\left(x\right) H_1^{\sphericalangle}\left(z, M_h, \cos\theta\right)$$

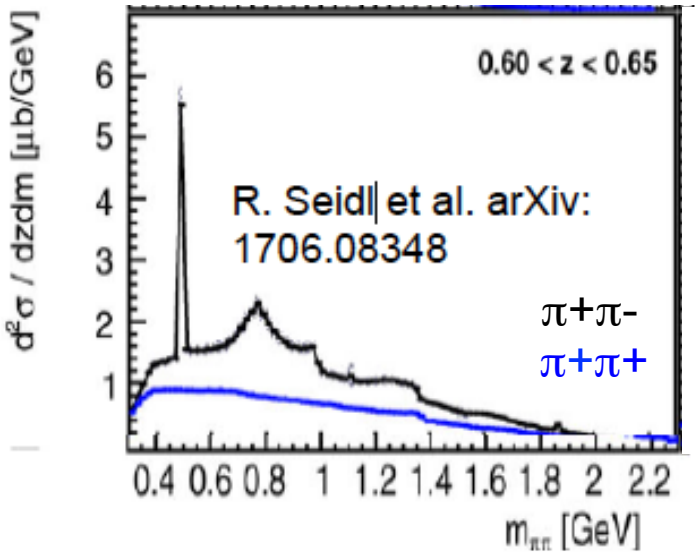




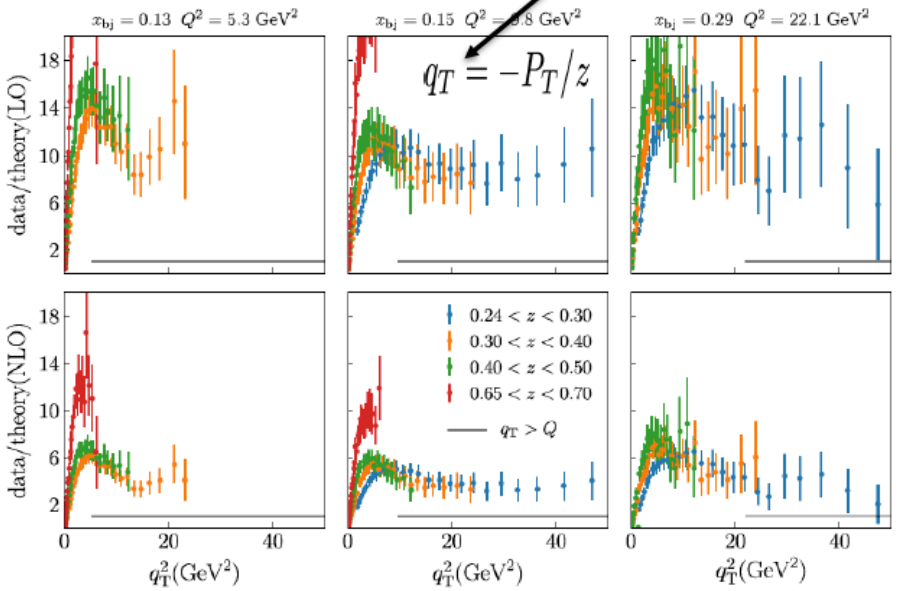


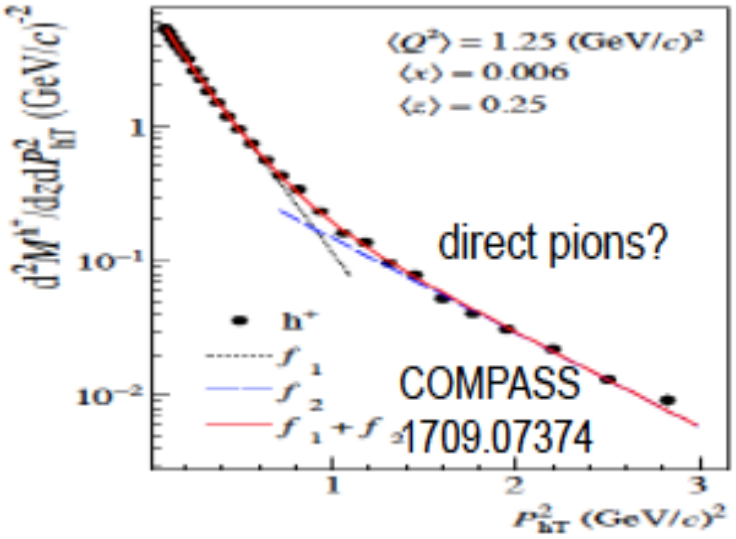
Resonances vs TMDs

Fragmentation Functions

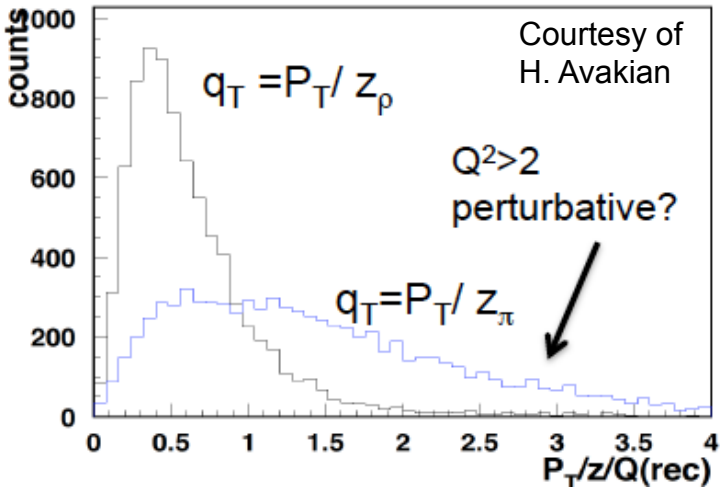


quark transverse momentum



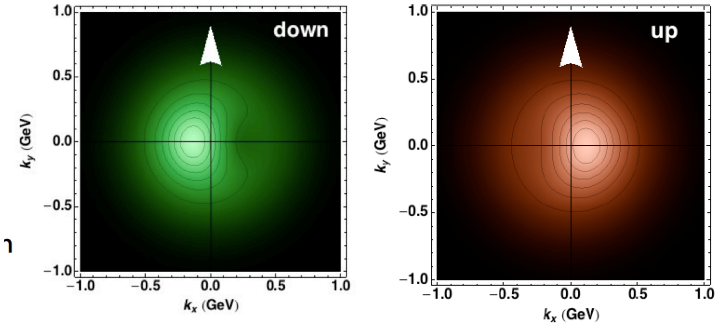


Matching with high pT (perturbative) regime



Spin-Orbit Effects: Sivers

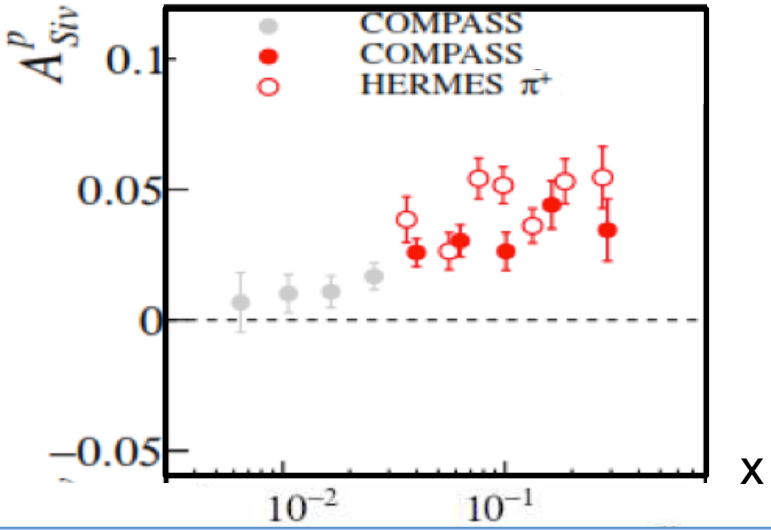
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$$



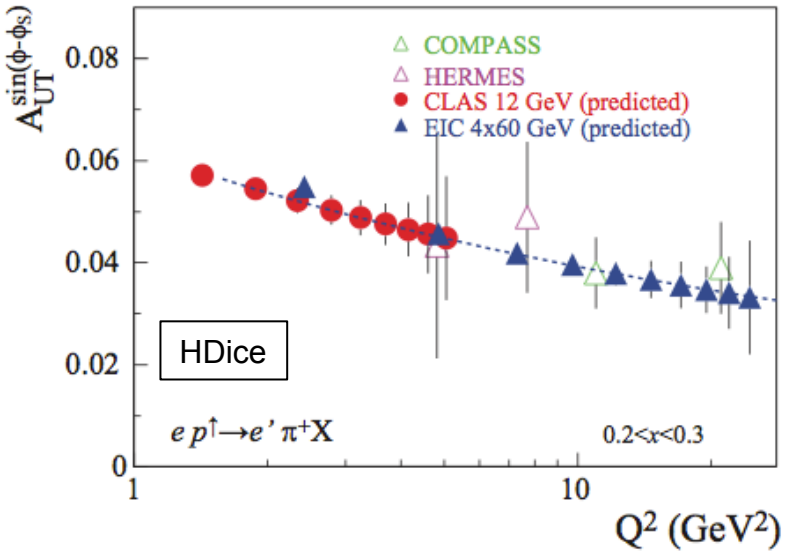
Sivers from polarized SIDIS

HERMES [arXiv:0906.3918]

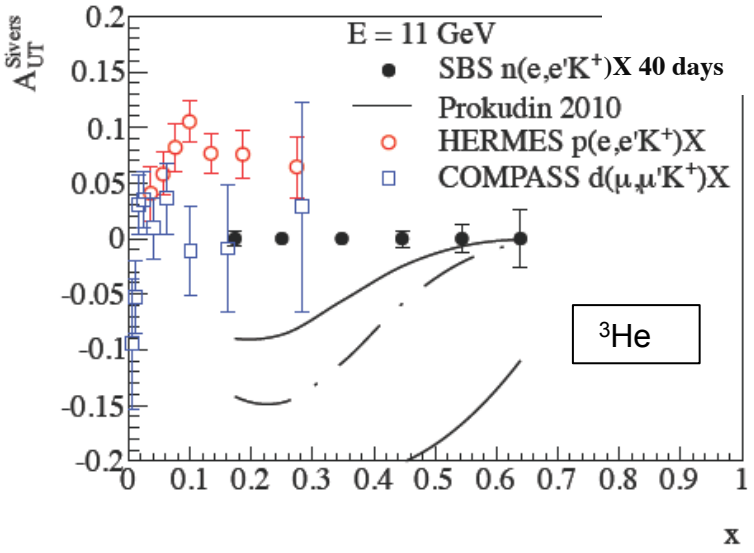
COMPASS [arXiv:1205.5122]



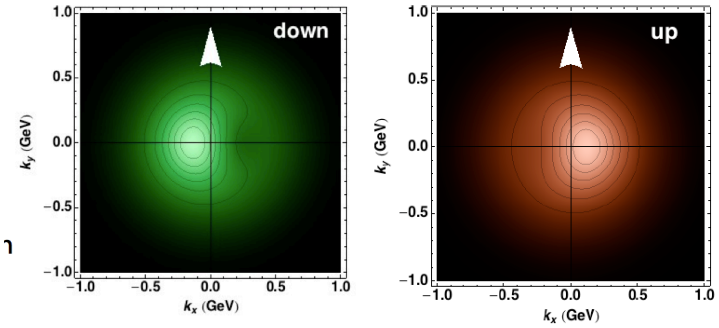
@ CLAS12 in 2022



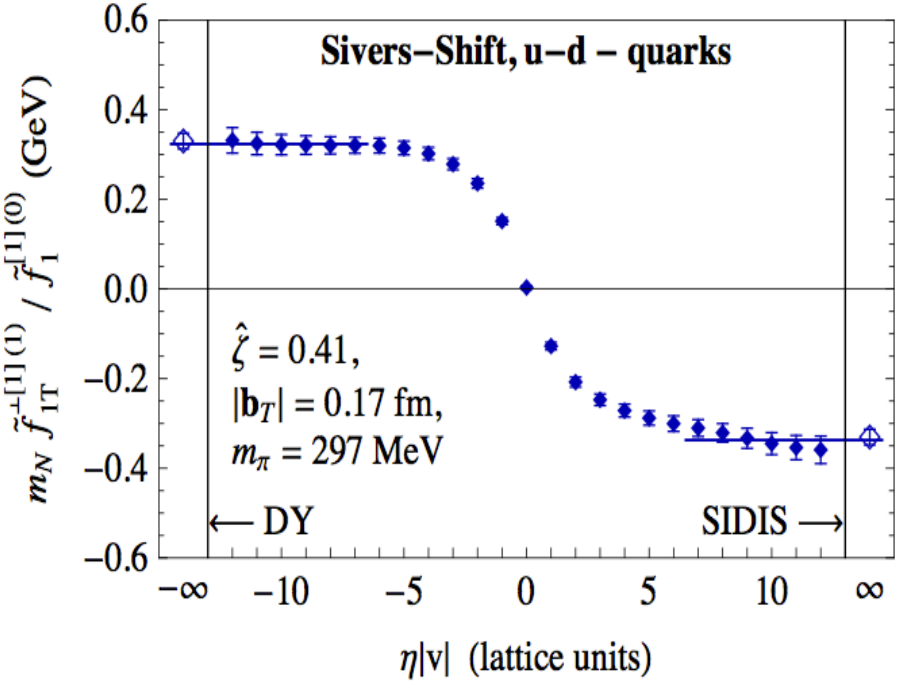
@ SBS in 2022

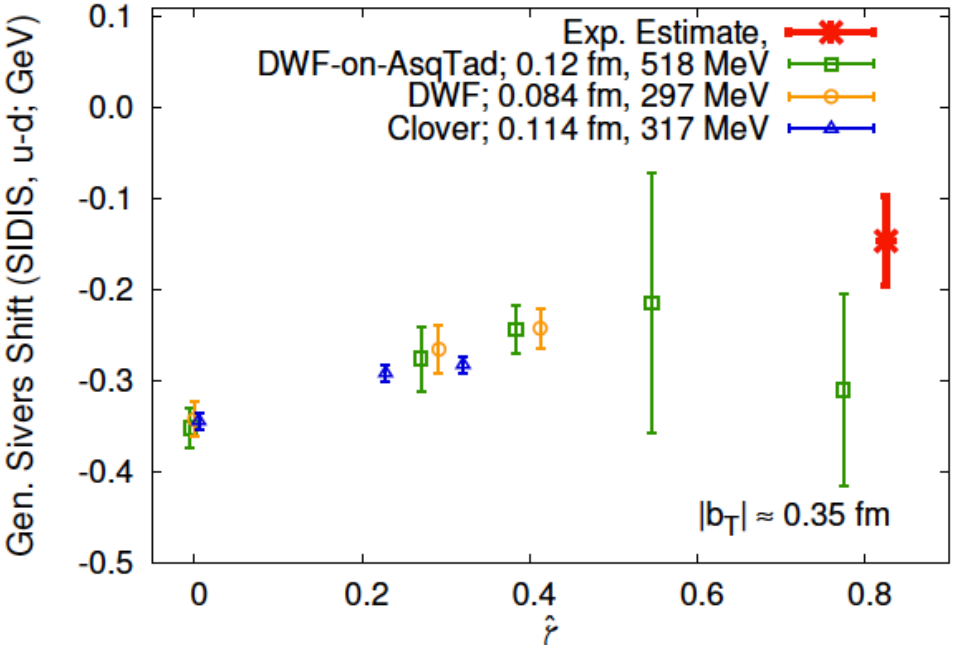


Sivers Shifts on Lattice

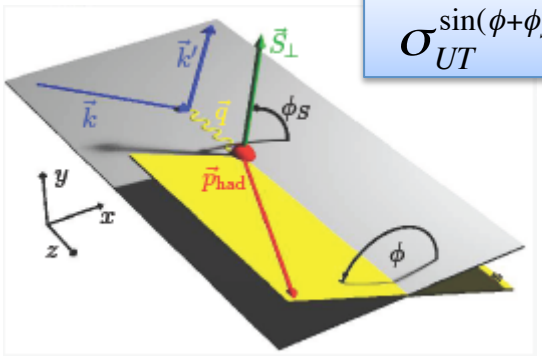


Yoon++ [arXiv: 1706.03406]



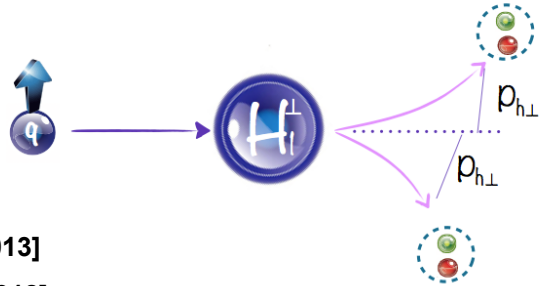


Spin-Orbit Effects: Collins



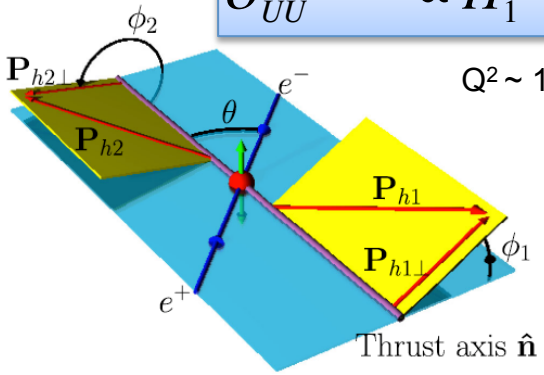
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^\perp$$

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

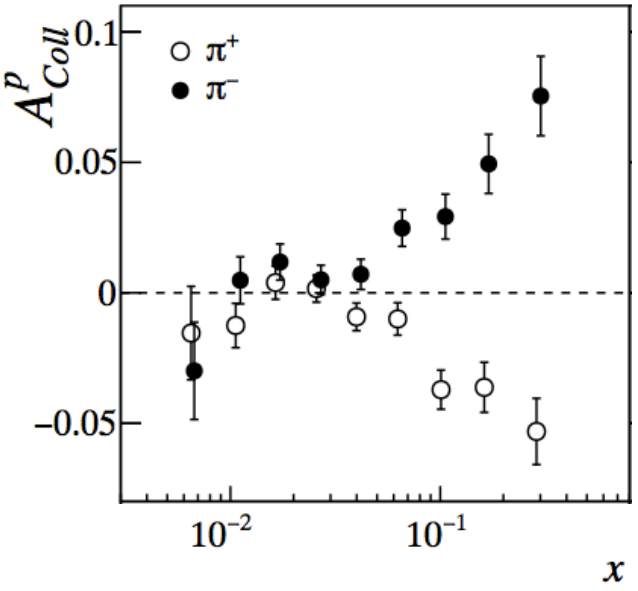


$$\sigma_{UU}^{\sin(\phi_1+\phi_2)} \propto H_1^\perp \otimes H_1^\perp$$

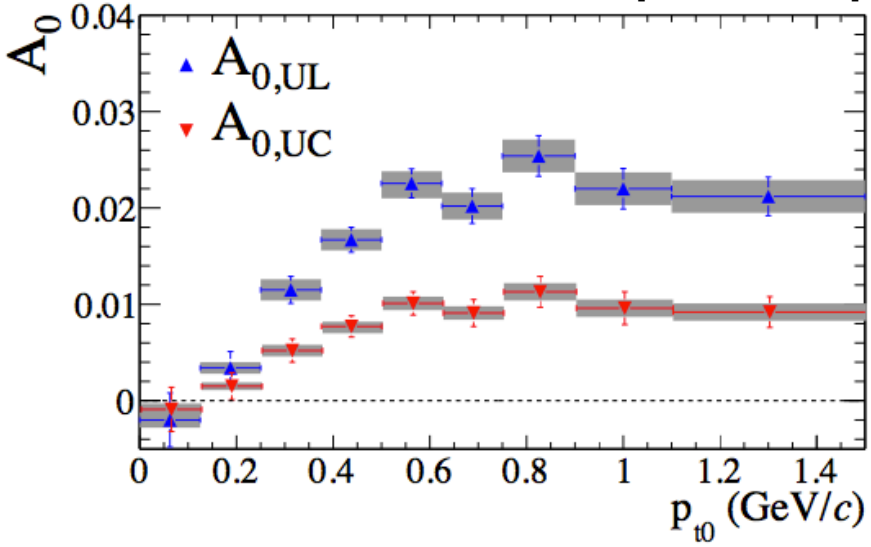
$Q^2 \sim 110\ GeV^2$



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



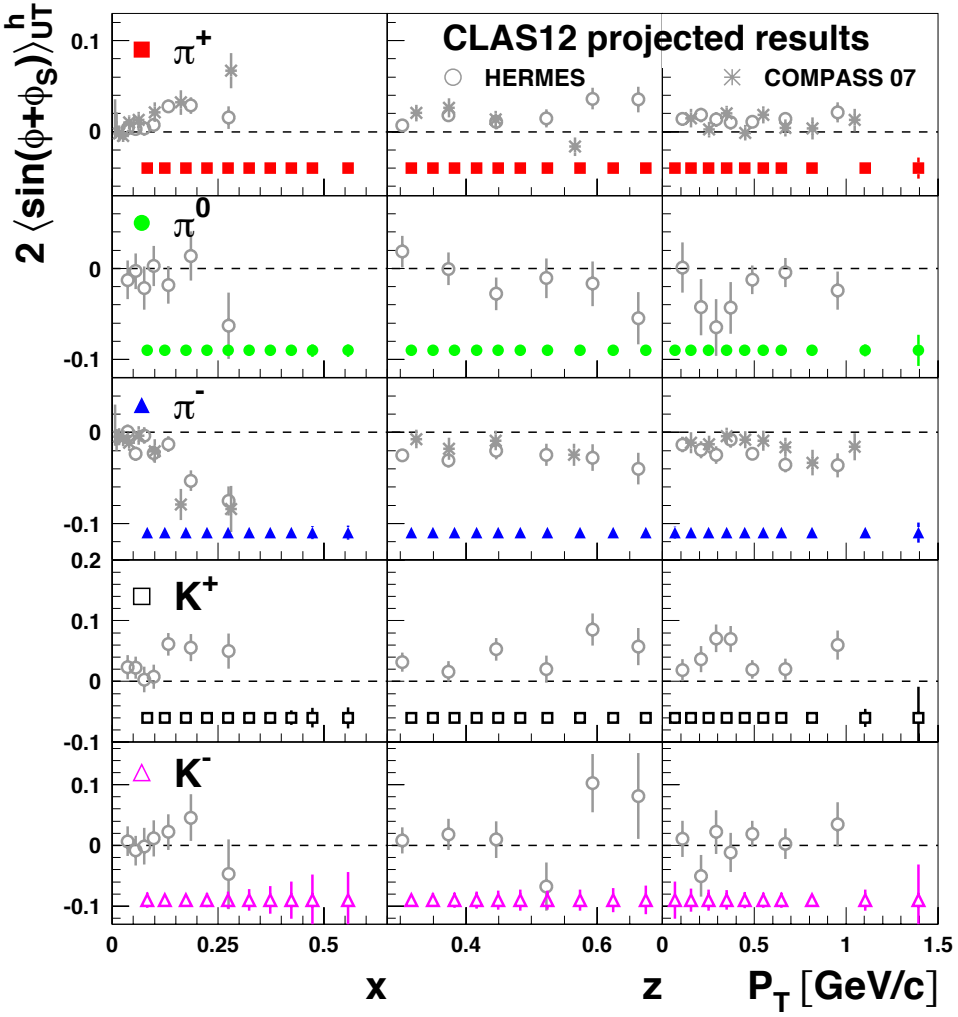
Belle [talk at DIS2014]
BESIII [arXiv 1507.06824]
Babar [arXiv 1309.5278]



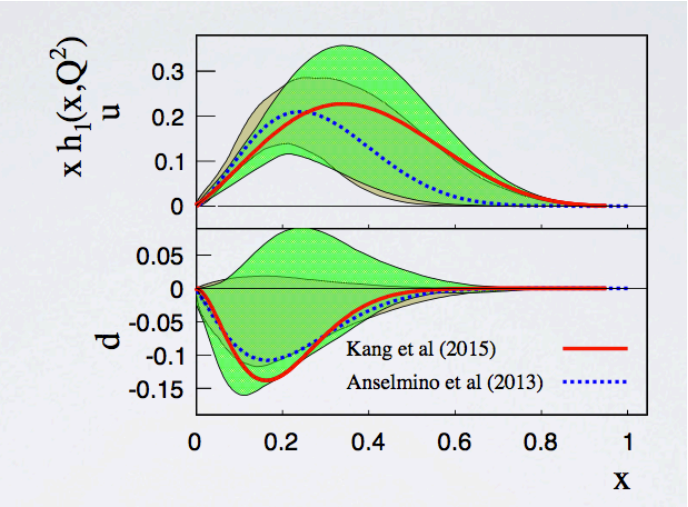
Transversity @ CLAS12

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

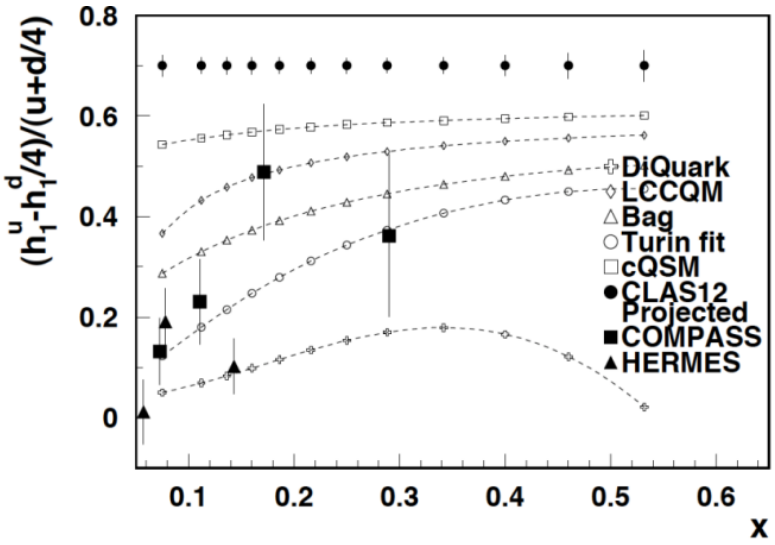
Single hadron channel: **@ CLAS12 in 2022**



Distributions:

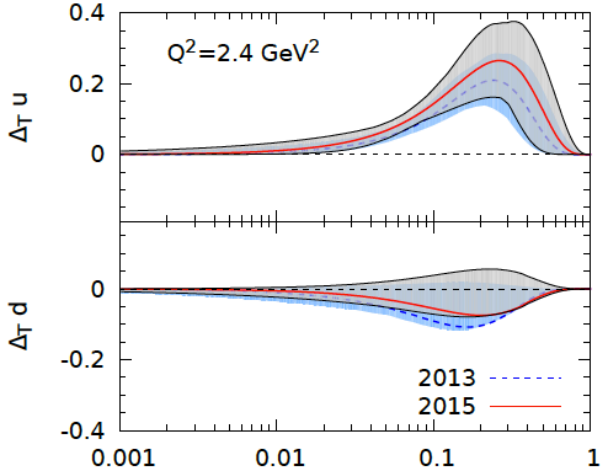


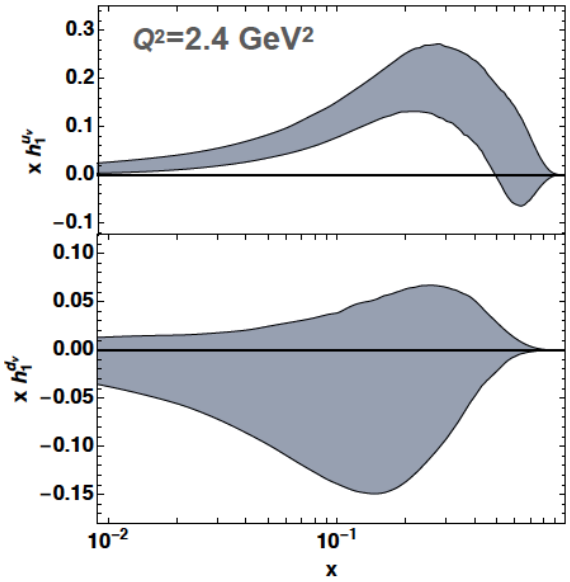
Di-hadron channel:

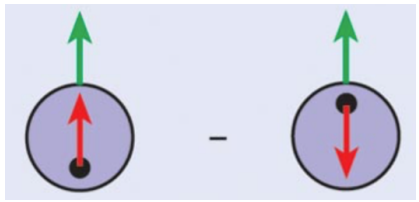


Transversity & Tensor Charge

Distributions:







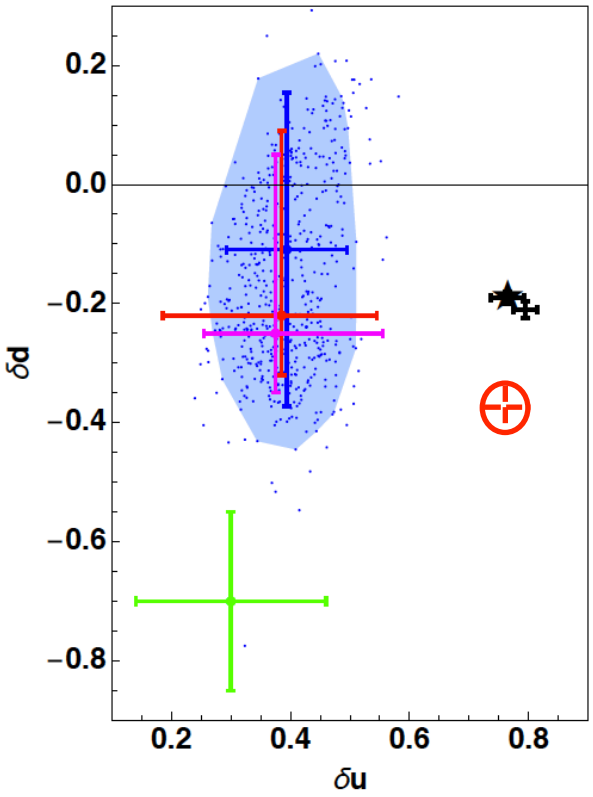
Charges:

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

Helicity

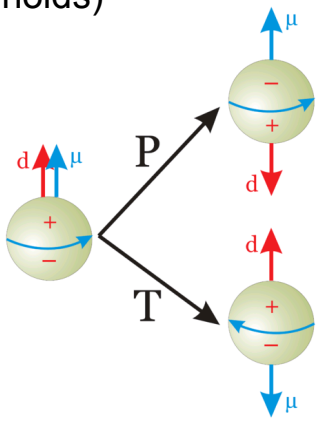
- Alexandrou et al., arXiv:1703.0878
- Gupta et al., arXiv:1806.09006
- Anselmino et al., arXiv:1303.3822
- Kang et al., arXiv:1505.05589
- Lin et al., arXiv:1710.09858
- Radici et al., arXiv:1802.05212

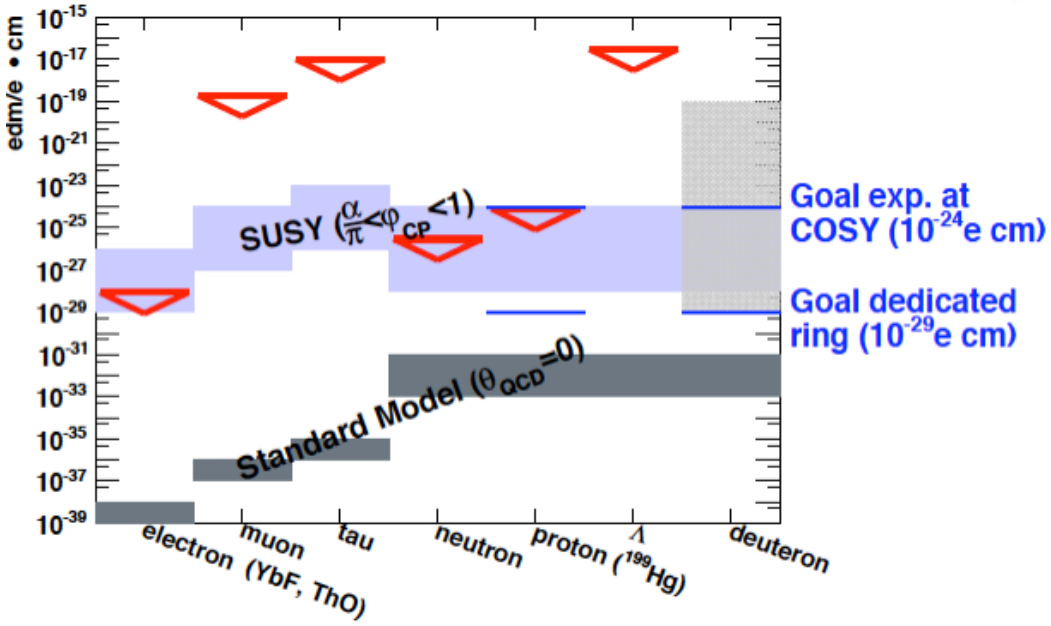
A. Bacchetta @ DIS219



Tensor Charge & EDM

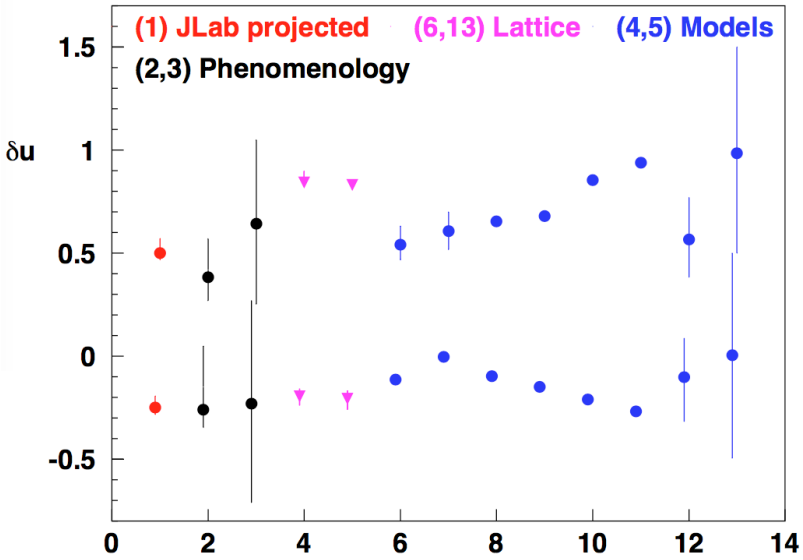
EDM violates P and T and CP (if CPT holds)





Tensor Charge measures transverse quark polarization in a transversely polarized nucleon

Pitschman++ [arXiv: 1411.2052]



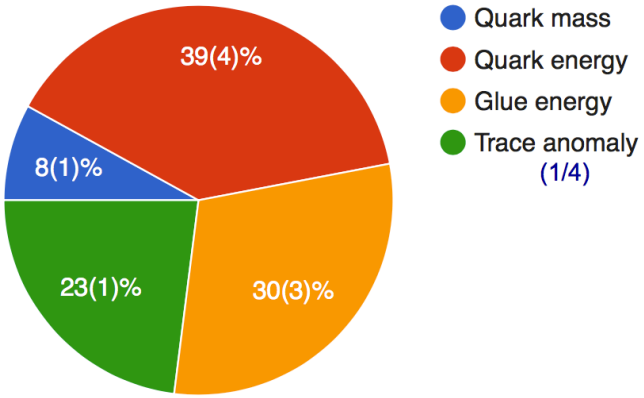
Proton *EDM*: $d_p = d_u\,\delta_T u + d_d\,\delta_T d$

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

Lattice Achievements

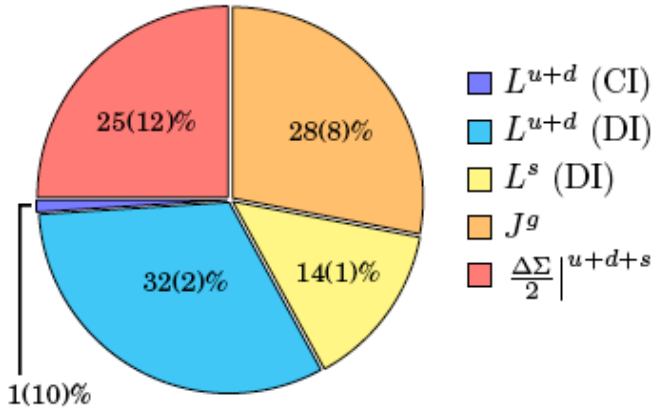
Nucleon mass components

K-F Liu @ this Conf.

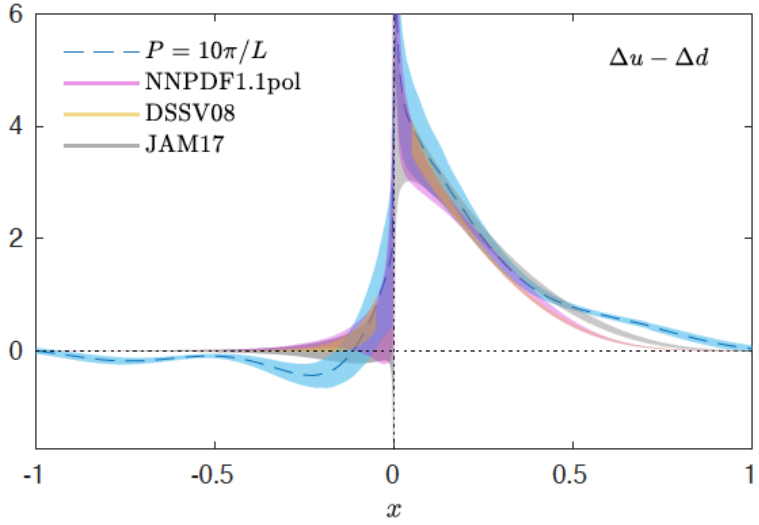


Spin decomposition

K-F Liu++ [arXiv 1203.6388]

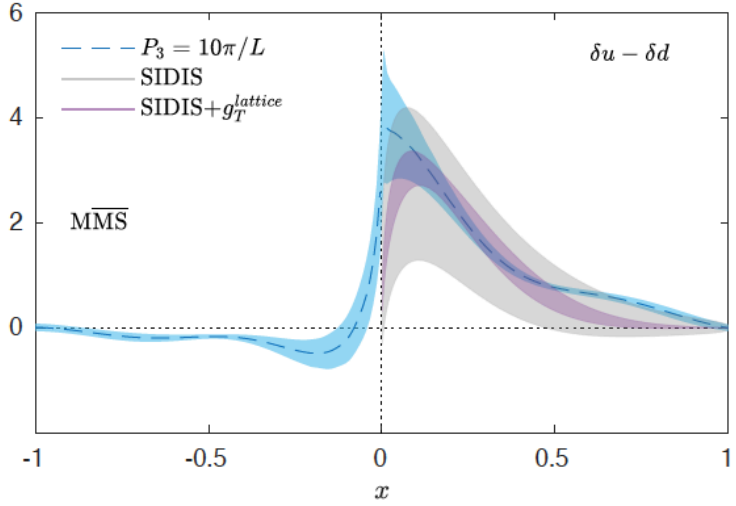


Helicity distribution



Transversity distribution

C. Alezandrous++ [arXiv 1902.00587]



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 JLab12 at high luminosity 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