RESULTS FROM SEMI-INCLUSIVE DIS (AND FRIENDS)

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INFN Ferrara

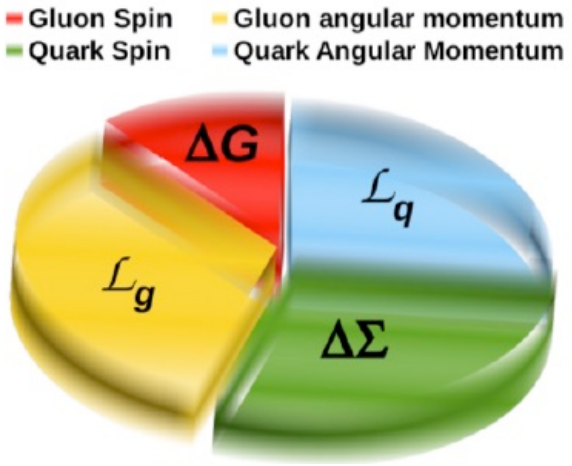
Hadron Physics and Non Perturbative QCD 2017
May 23, 2017 Pollenzo (CN)

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

Proton Spin Budget

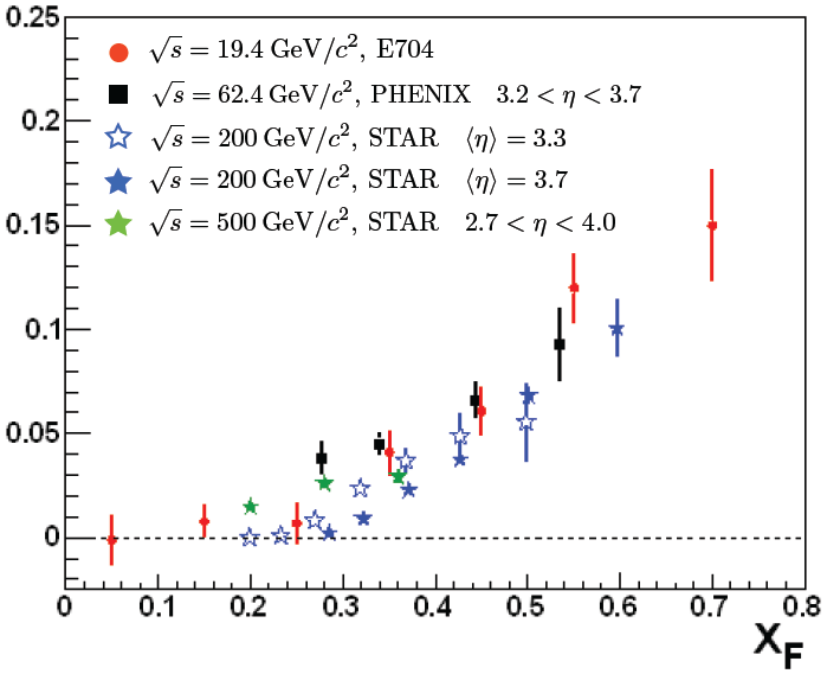


?

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

Single Spin Asymmetries

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



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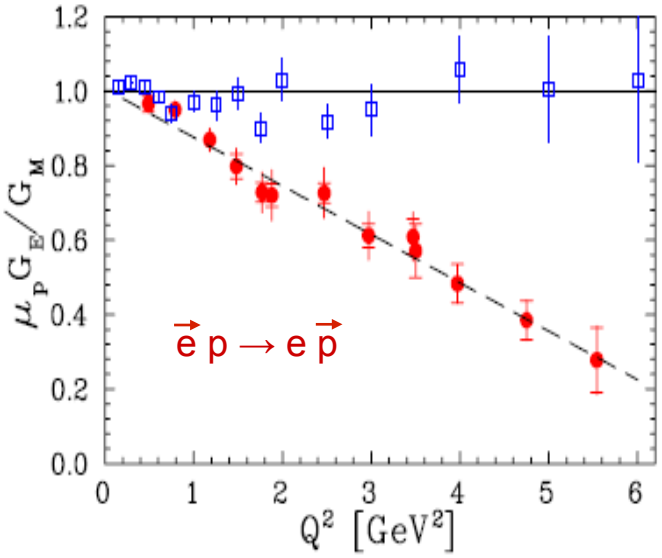
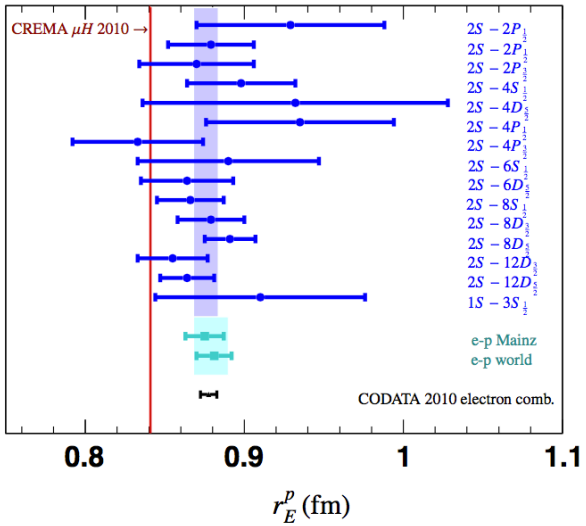
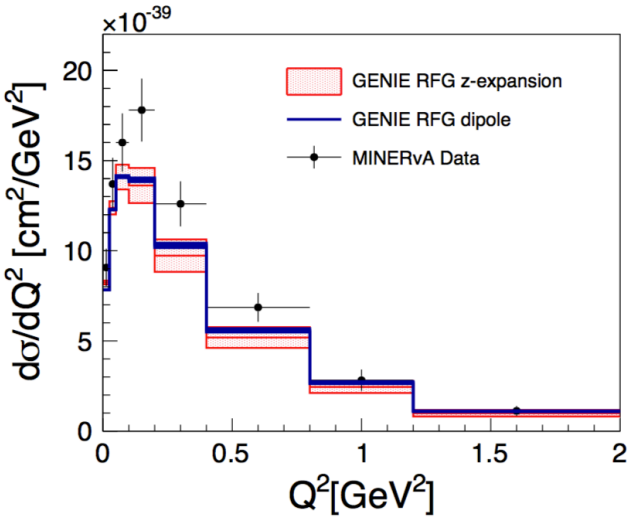
Proton form factors



Proton radius



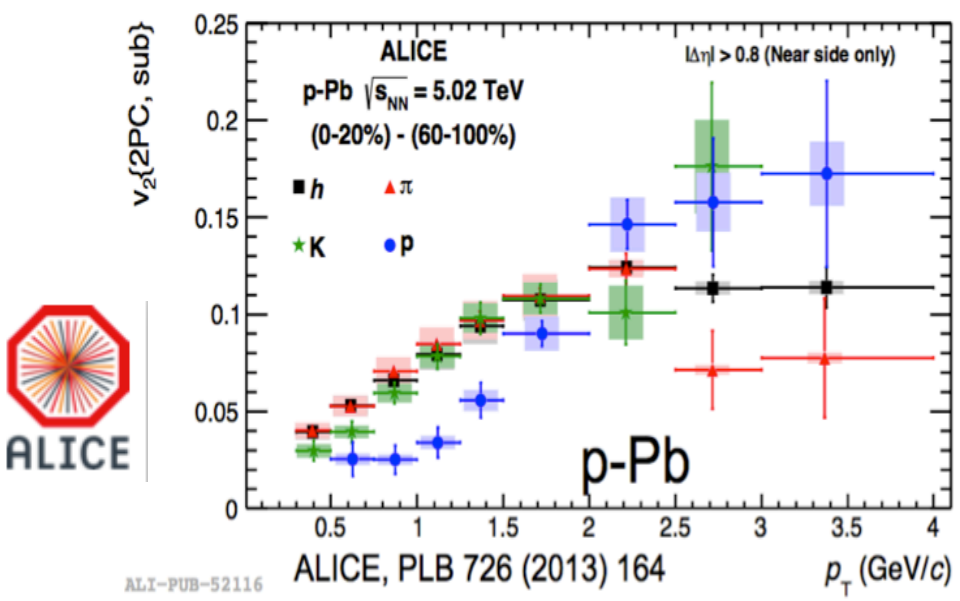
Neutrino anomalies

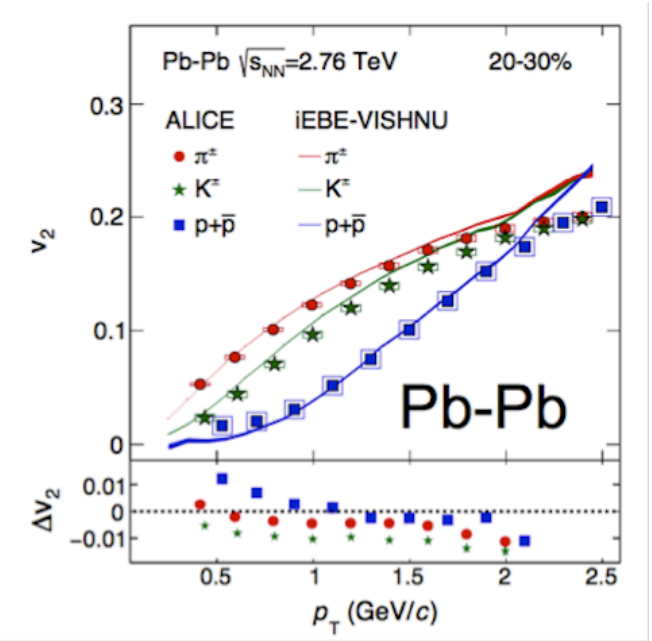


Elliptic Flow

Is there a collective motion in small systems ?

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

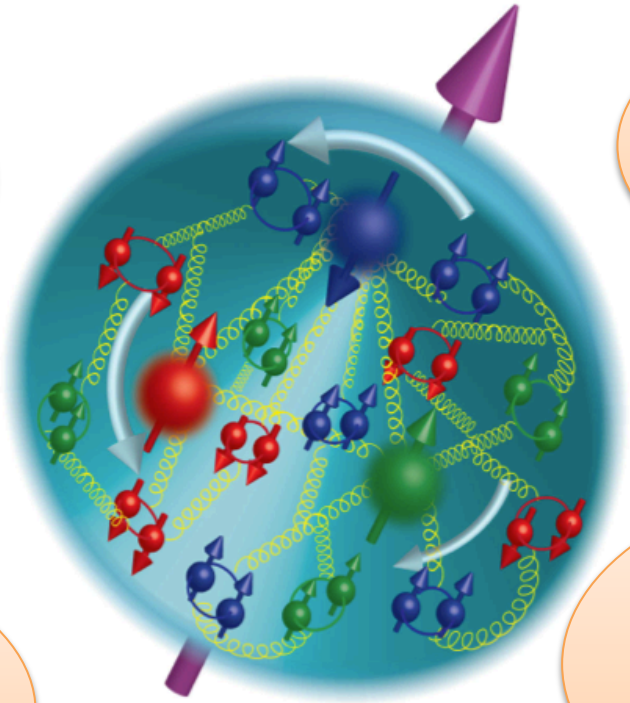




The Strong-Force Confined-Universe

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

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

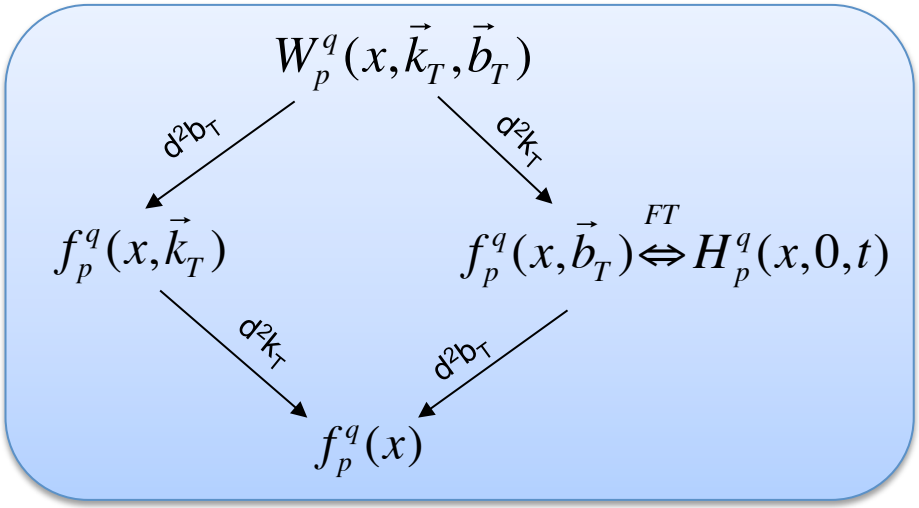


Parton Correlations
- dPDFs
- Short range
- MPI

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

Transverse momentum

$\vec{k}_T$

$\vec{b}_T$

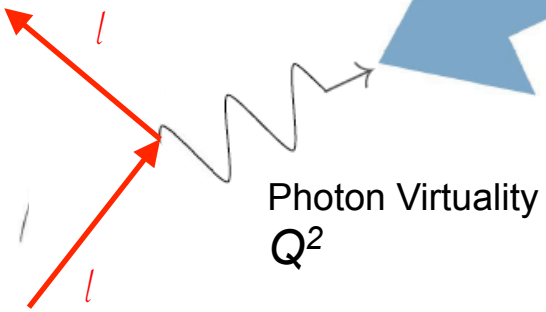
Transverse position

Spin

Transverse plane

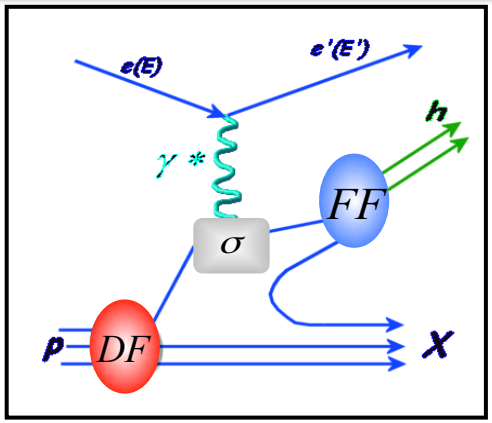
High Energy Probe
Hard Scale

Longitudinal momentum
$k^+ = xP^+$



Photon Virtuality
Q^2

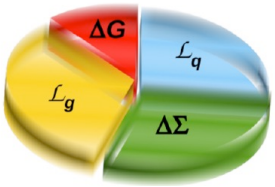
Physics reactions



SIDIS: rich phenomenology, the most explored so far

SIDIS $\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$

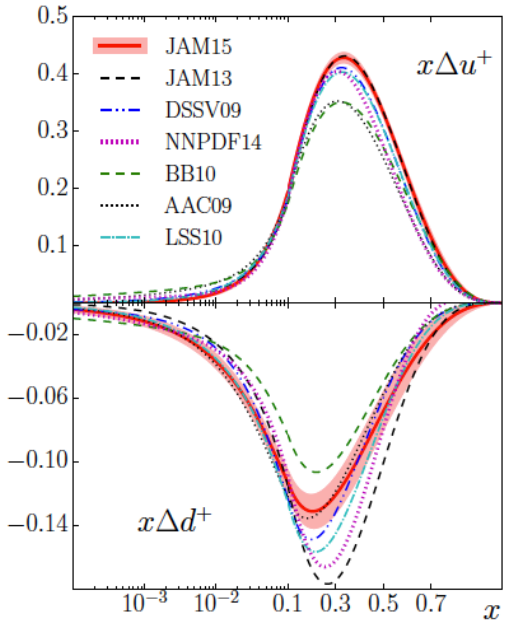
hermes COMPASS Jefferson Lab

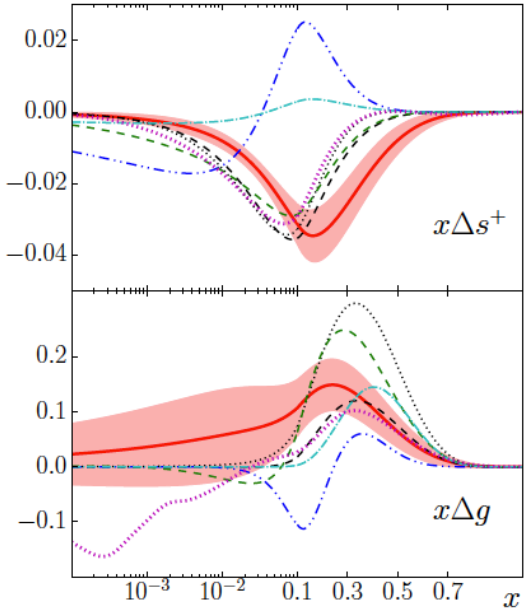


Parton helicity (proton spin budget)

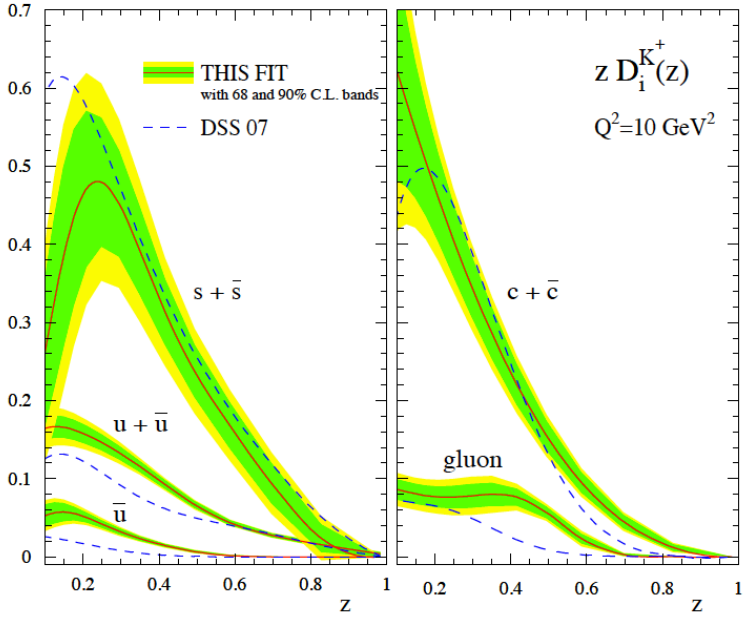
Kaon FF

JAM, N.Sato++ [arXiv 1601.07782]





D de Florian++ [arXiv 1702.06353]



First evidences

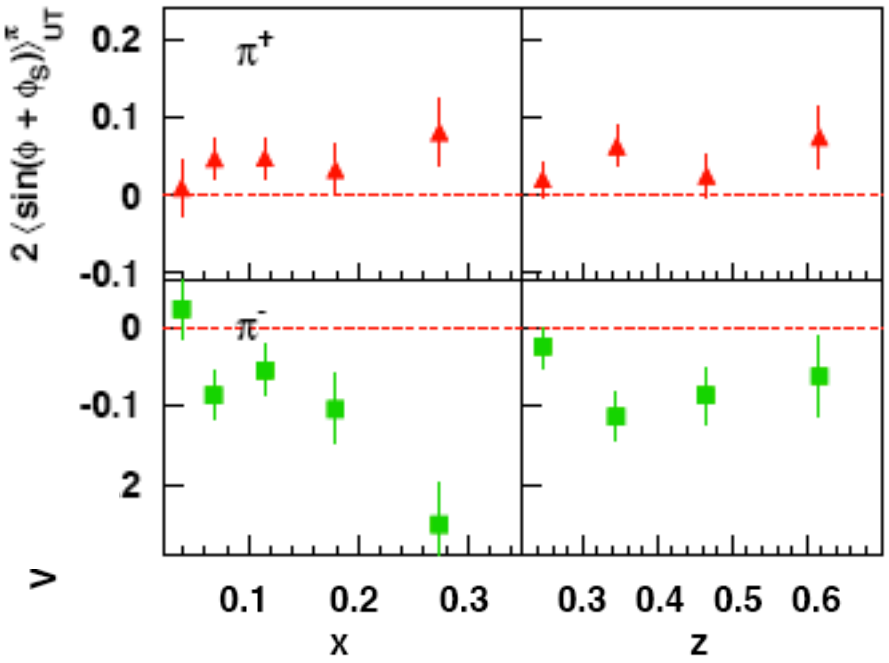
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^{\perp}$$

SIDIS:
ep → e'hX

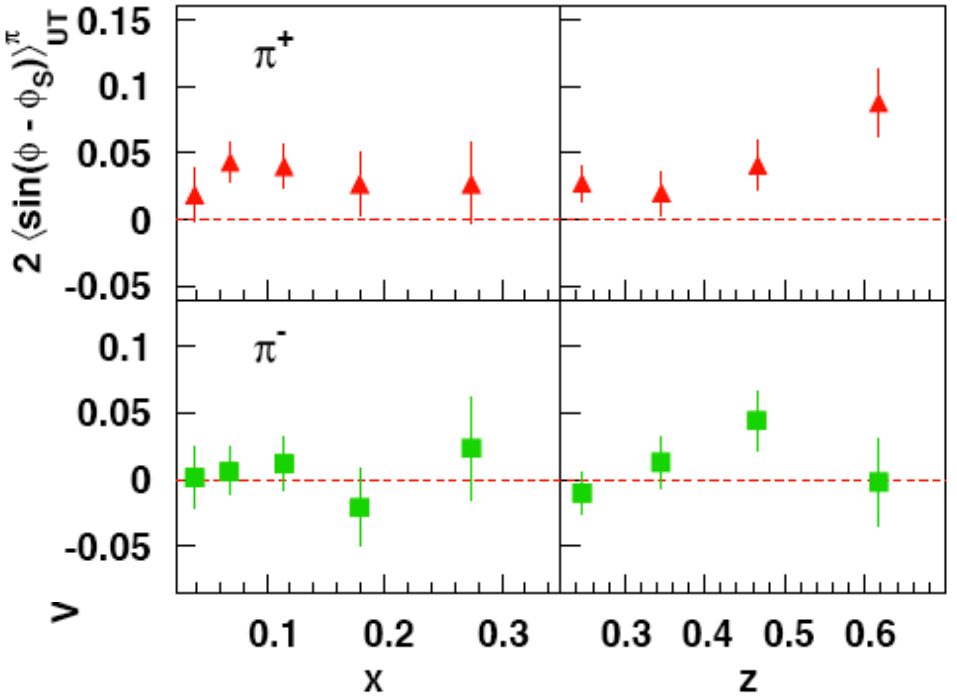
$$\sigma_{UT}^{\sin(\phi-\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$$

2005: First evidence from HERMES measuring SIDIS on proton

A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002



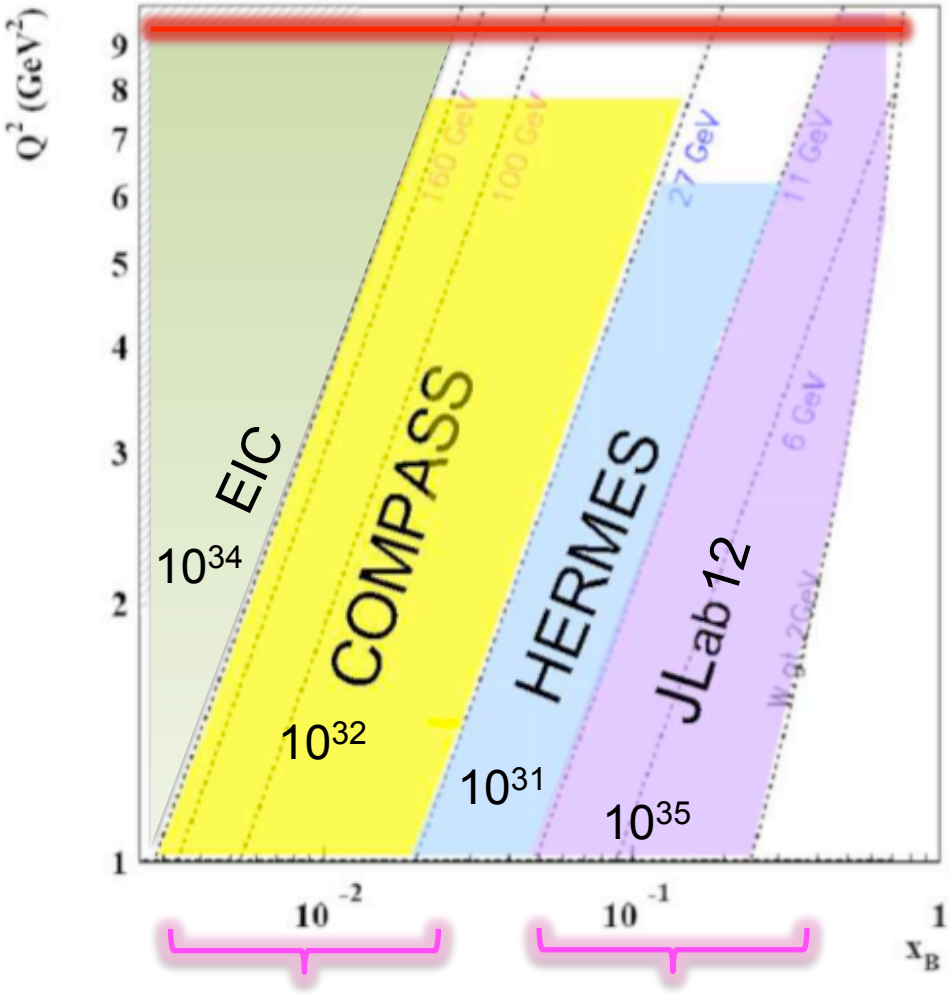
Non-zero transversity !!
Non-zero Collins function !!



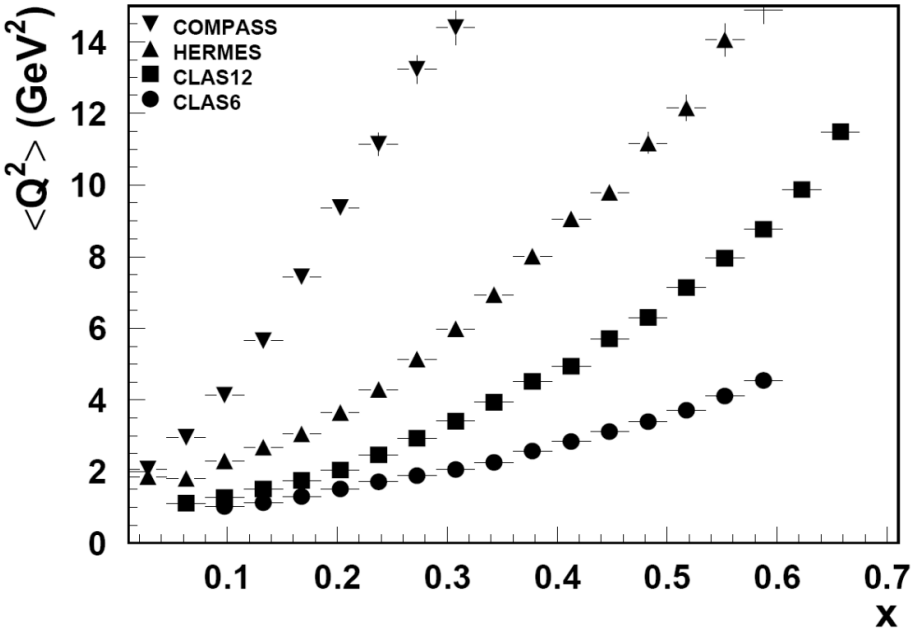
Non-zero Sivers function !!

The SIDIS Landscape

Limit defined by luminosity



Different Q^2 for same x range



HERMES: < 2007

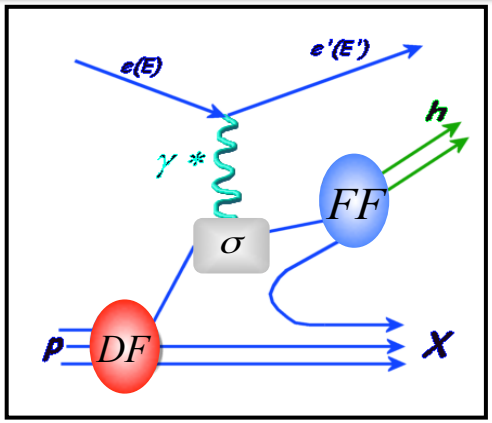
COMPASS: < 2017 (2021++)

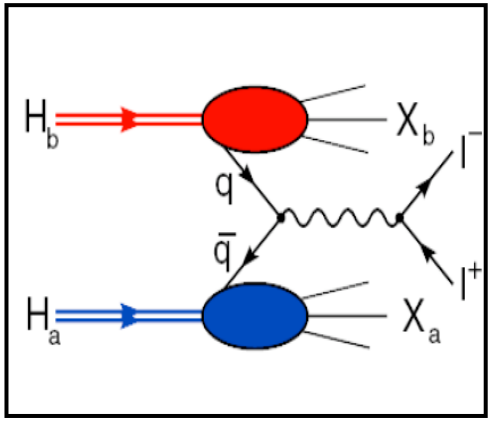
JLab6 < 2012

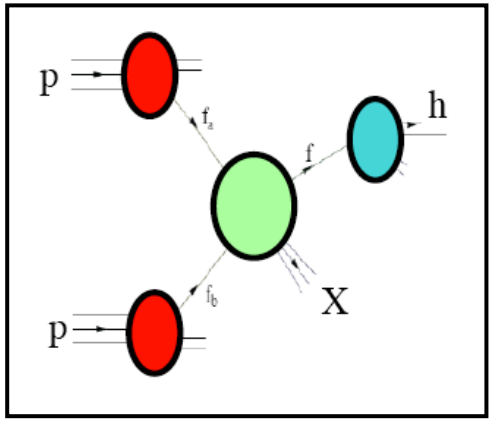
JLab12: 2017++

EIC: 2025++

Physics reactions







SIDIS: rich phenomenology, the most explored so far

SIDIS $\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$

hermes COMPASS Jefferson Lab

e^+e^- colliders: powerful fragmentation laboratories

e^+e^- $\sigma^{ee\to hhX} = \sum_q \sigma^{qq\to ee} \otimes FF \otimes FF$

BELLE BESIII

DY: challenging for experiments (only unpolarized so far)

DY $\sigma^{pp\to eeX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to ee}$

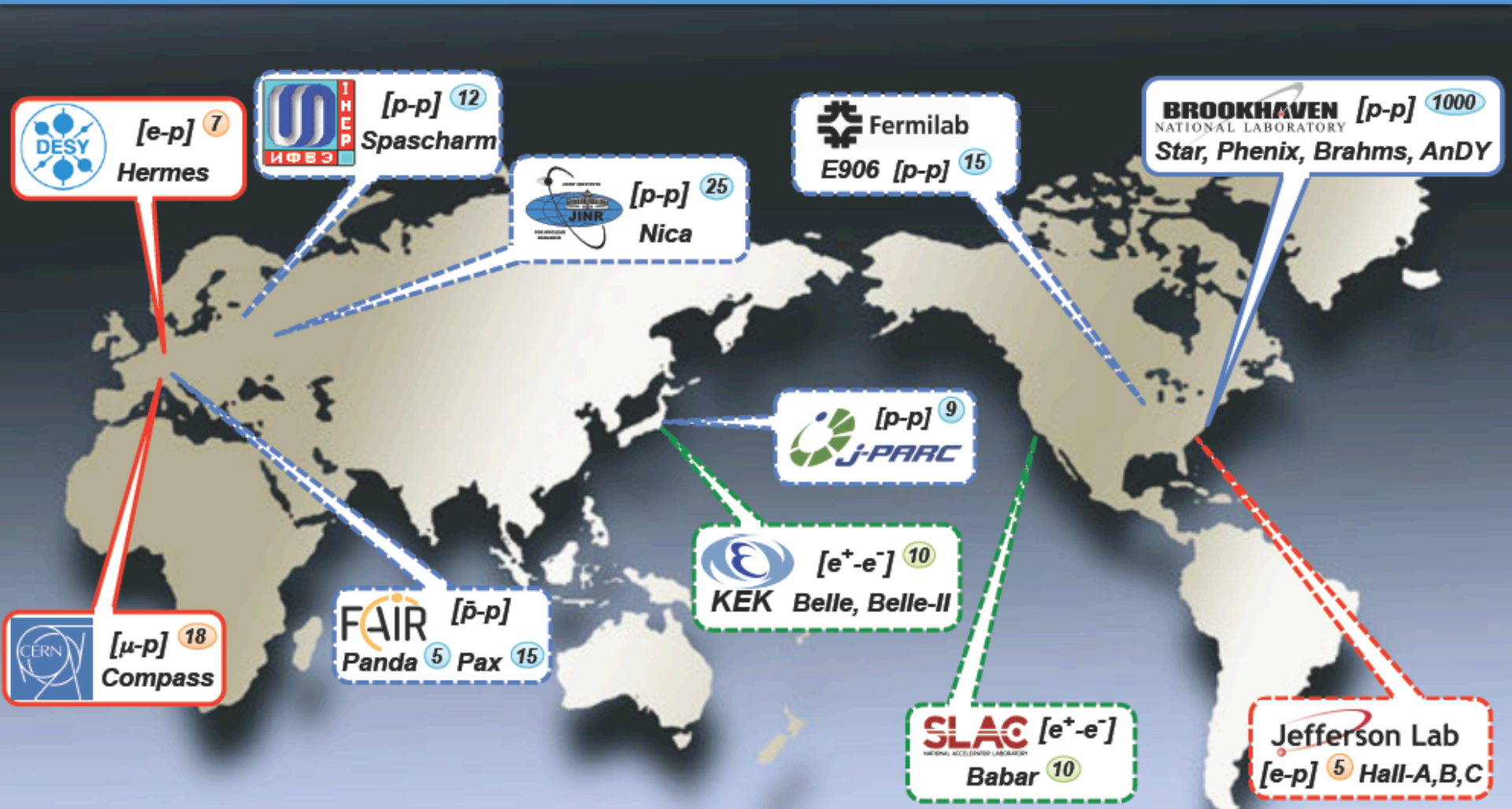
CERN Fermilab BROOKHAVEN NATIONAL LABORATORY

Hadron reactions: challenging for theory (ISI + FSI)

pp $\sigma^{pp\to hX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to qq} \otimes FF$

J-PARC FAIR NICA

A World-wide Challenge



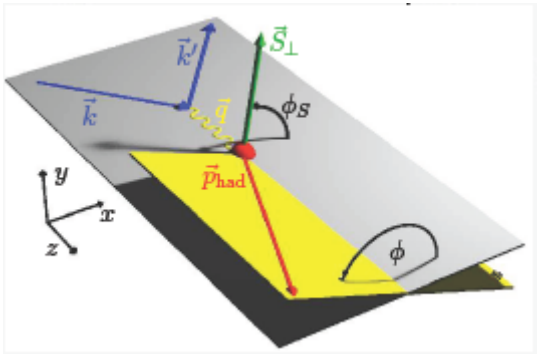
Babar (e+e-):	< 2007	SeaQuest (pp):	2012 - 2016	LHC (pp):	2008++	FAIR ($\bar{p}p$):	2020++
BELLE (e+e-):	< 2010	RHIC (pp):	2011, 2017++	LHCb (pp)	2018++	NICA (pp):	2020++
BELLEII (e+e-):	2017++	COMPASS (πp):	2016 – 2017	JPARC(pp):	2018++	AFTER (pp):	2020++

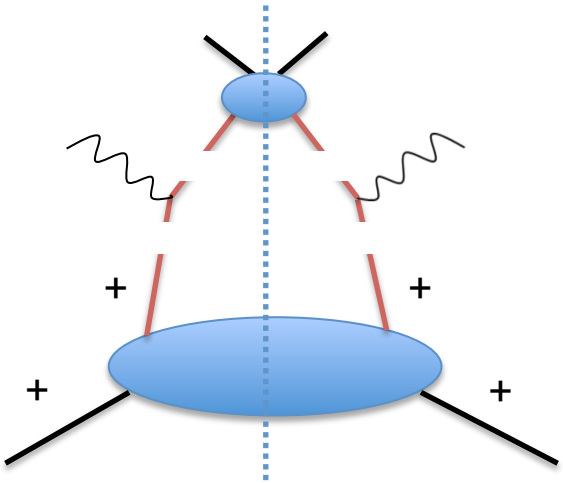
SIDIS Cross-Section & TMDs

$$\frac{d^6\sigma}{dxdQ^2dzdP_hd\phi d\phi_S} \overset{LT}{\propto} \left[F_{UU} + \varepsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\right] + S_L\left[\varepsilon\sin(2\phi)F_{UL}^{\sin(2\phi)}\right]$$

$$+ S_T\left[\sin(\phi-\phi_S)F_{UT}^{\sin(\phi-\phi_S)} + \varepsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\right]$$

$$+ S_L\lambda_e\left[\sqrt{1-\varepsilon^2}F_{LL}\right] + S_T\lambda_e\left[\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right] + O\left(\frac{1}{Q}\right)$$





Quark fragmentation

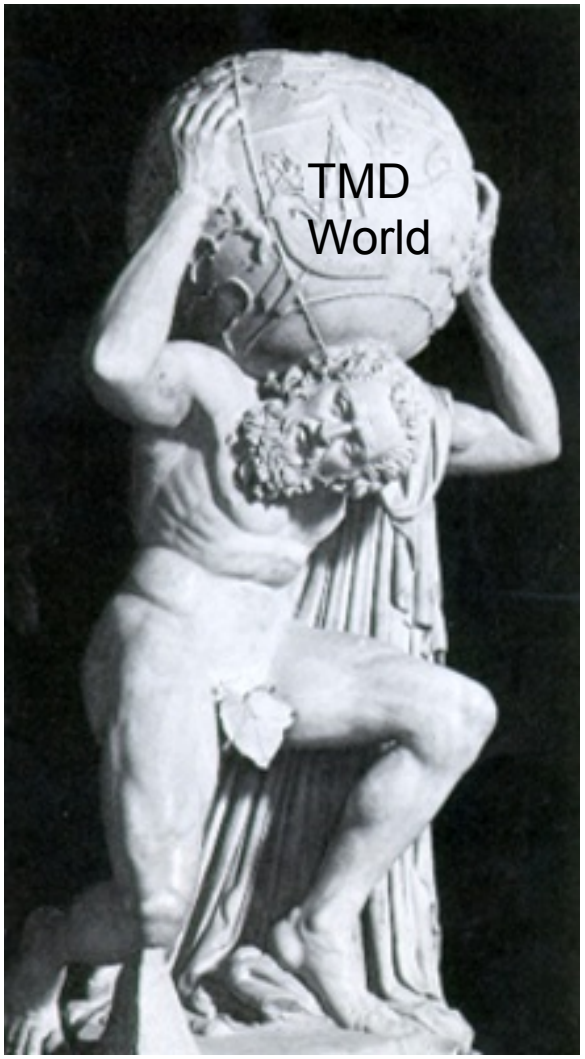
TMD Factorization holds for p_T<<Q
Two scales

Quark parton distribution

Wide kinematic coverage is needed to resolve the convolution

$$F_{UU} = f \otimes D = x\sum_q e_q^2 \int d^2p_T d^2k_T \;\; \delta^{(2)}(\mathbf{P}_{h\perp} - z\mathbf{k}_T - \mathbf{p}_T) \;\; w(\mathbf{k}_T, \mathbf{p}_T) \;\; f^q(x, k_T^2) \;\; D^q(z, p_T^2)$$

Parton Correlators



hadron polarisation

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

nucleon polarisation

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

+ Quark correlators at sub-leading twist
+ Gluon correlators (x 2 gauge links)
+ Di-hadron fragmentations

Beauty and complexity of the unique strong-interacting world

Transverse Momentum Dependent Distr.

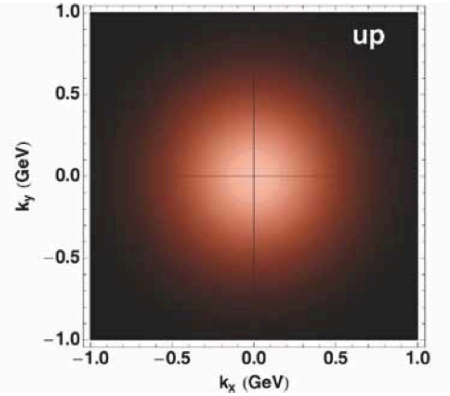
quark polarisation

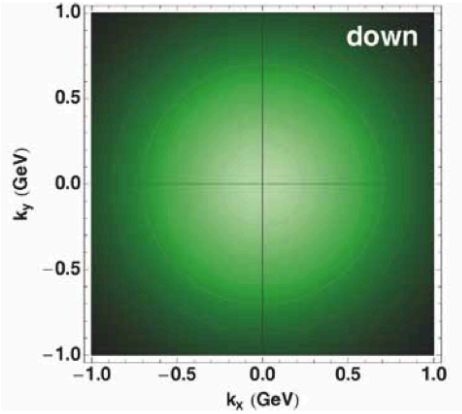
nucleon polarisation: N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h, h_{1T}^\perp$

$\otimes$

quark polarisation

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





Related to:

- ✓ Low-pT regime: precise xsec measurements
- ✓ Parton correlations: short range, MPI
- ✓ Low-x physics: color glass condensate
- ✓ Hadronization: parton dynamic in medium

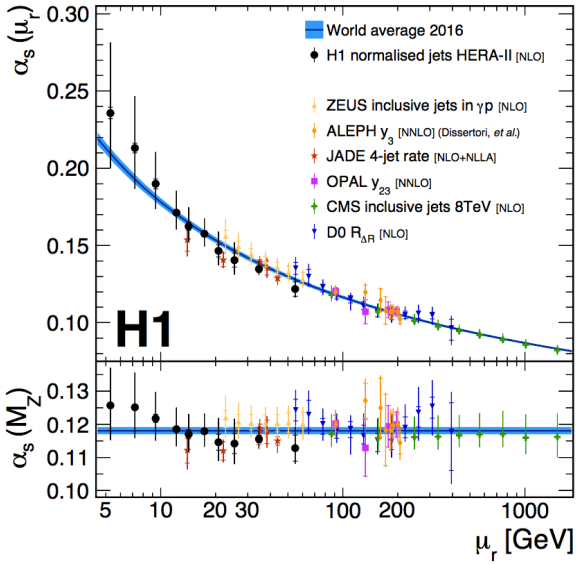
Inclusive Jets @ HERA

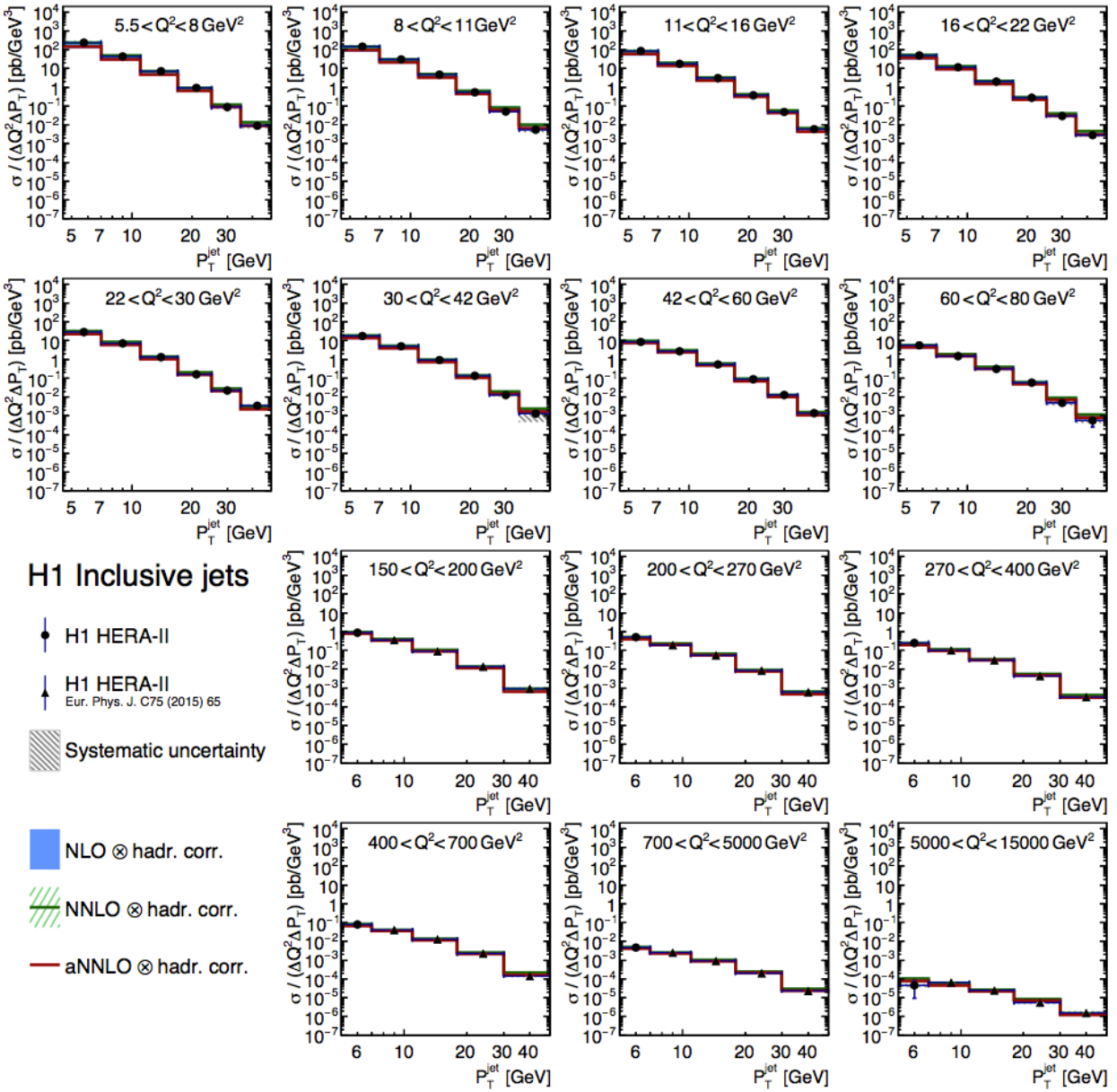
Good perturbative description (hard gluon emission)

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

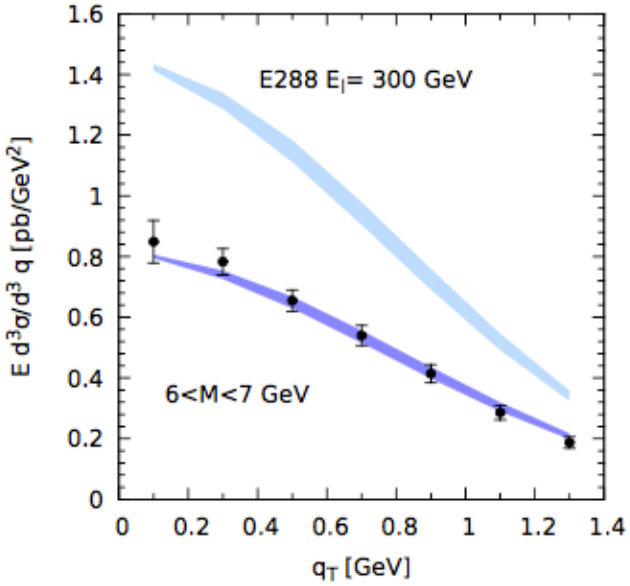
Part in a p_T<<Q TMD regime

H1 [arXiv: 1611.03421]





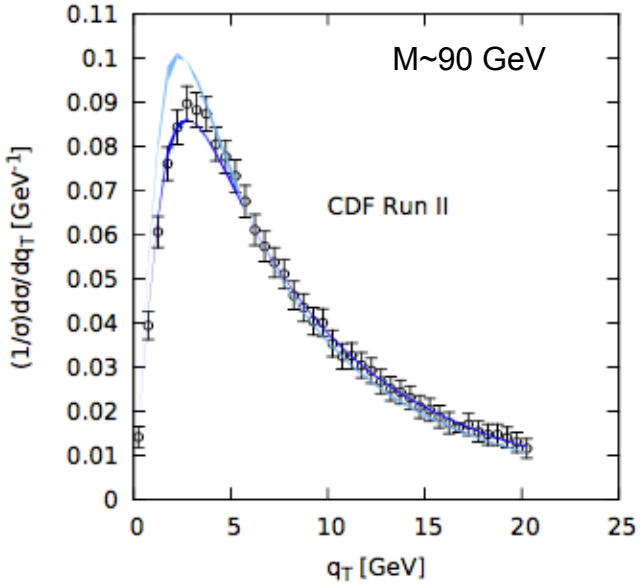
Non Perturbative QCD Signals



$q_T/Q \sim 1/10$

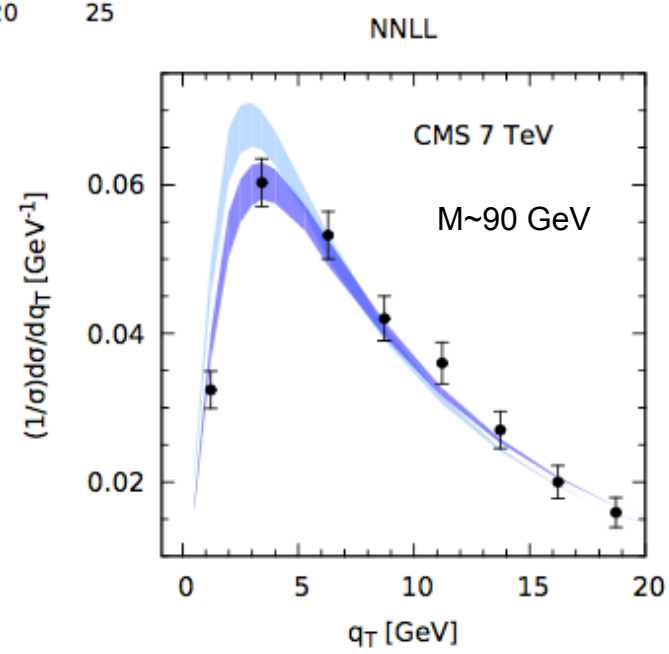
$q_T \sim \Lambda_{QCD}$

D'Alesio++ [arXiv: 1407.3311]



$q_T/Q \sim 1/20$

$q_T >> \Lambda_{QCD}$

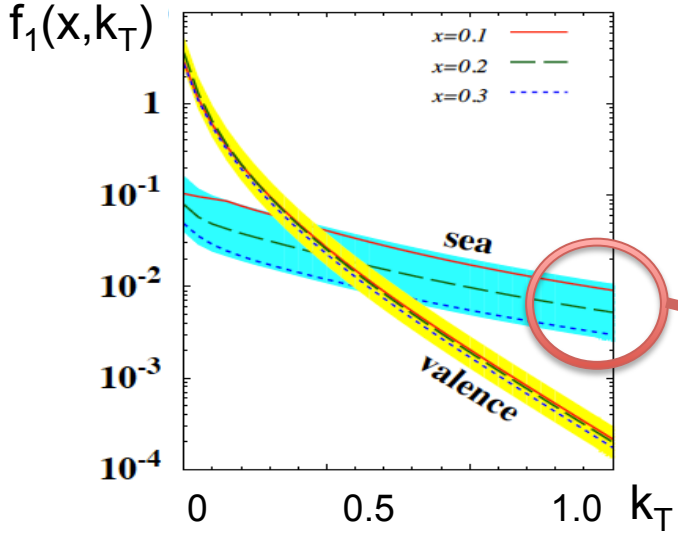


Non perturbative PDF component shows effects up to vector boson production at LHC

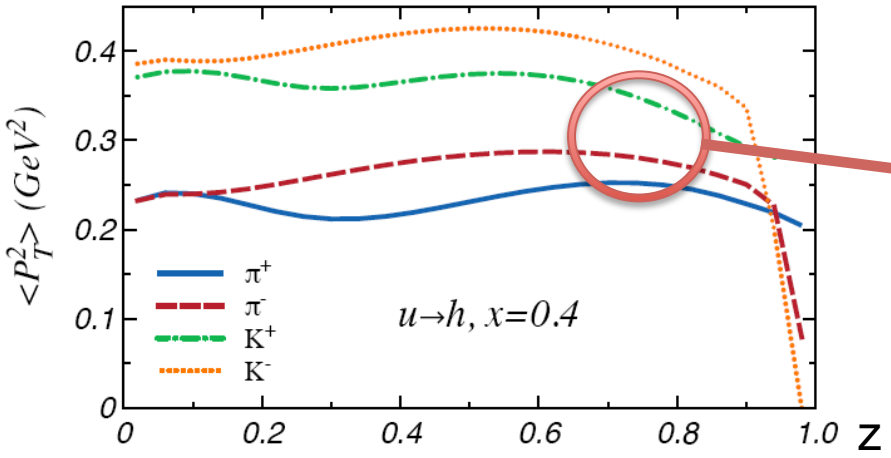
Unpolarized TMDs

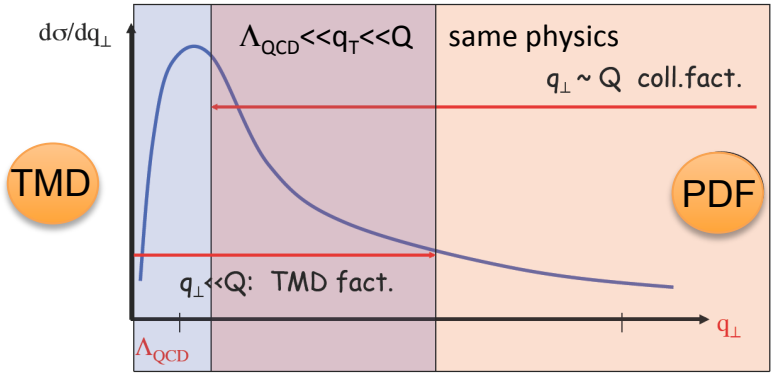
$$\sigma_{UU} \propto f_1(k_T \ldots) \otimes D_1(p_T \ldots)$$

P. Schweitzer++ [arXiv:1210.1267]



Matevosyan++ [arXiv:1111.1740]





Large tiles extending up to the inverse of the gauge field fluctuation scale $\rho<<M$

May short range parton correlations manifest also in pp MPI ?

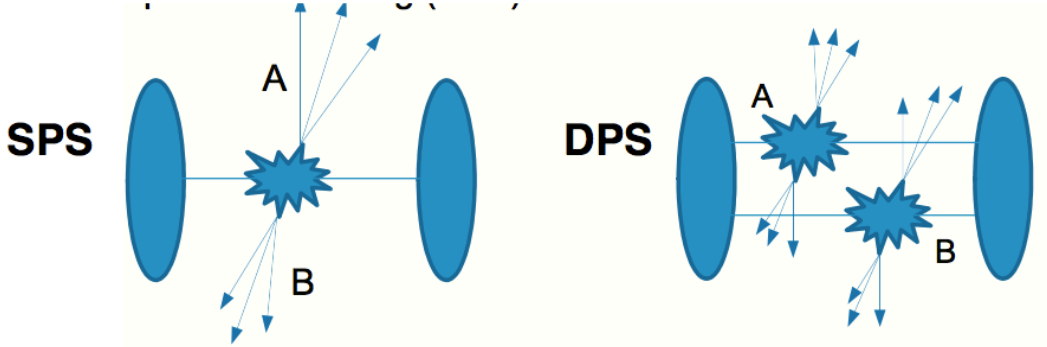
Reflect different fragmentation

May be enhanced in medium.

Parton propagation in cold matter as complementary study to QGP

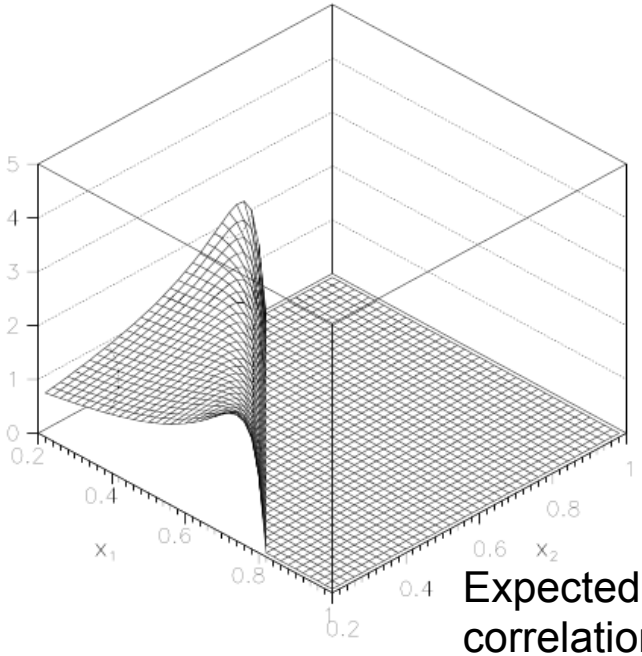
Space-Momentum Parton Correlations

May manifest in multi-particle interactions



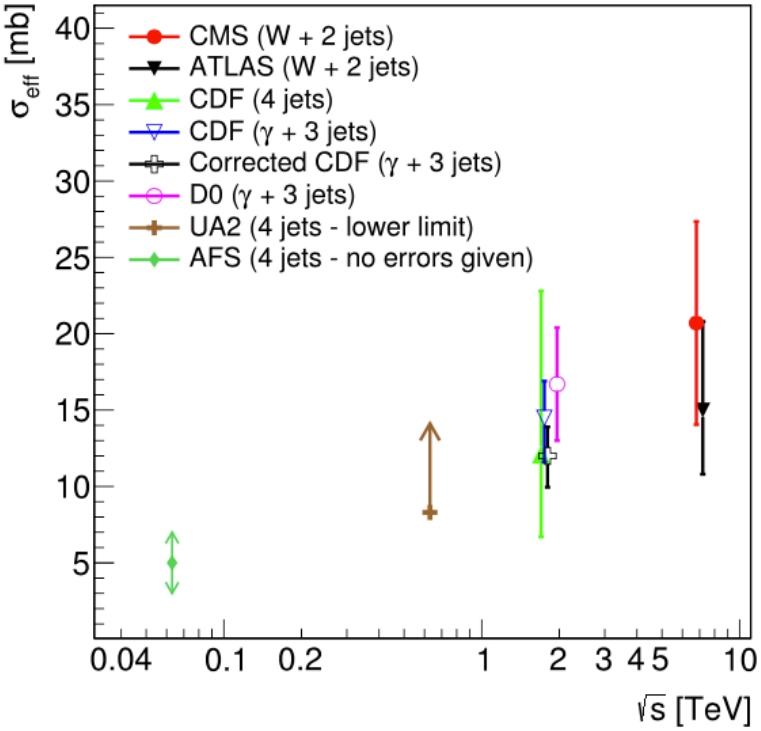
$$\sigma^{pp}_{double} = \frac{m}{2}\frac{\sigma^{pp'}_{A}\,\sigma^{pp'}_{B}}{\sigma_{eff}}$$

Light-front dPDF: $uu(x_1, x_2, k_\perp = 0)/u(x_2)$



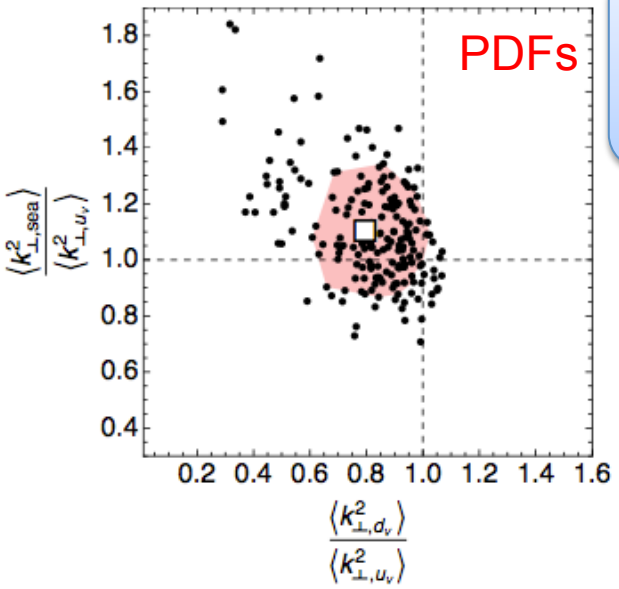
Expected model-independent correlation from $x_1+x_2<1$

Scopetta++ @ this Conf.



Flavor Dependence

A. Signori++ [arXiv:1309.3507]



TMD Q^2 evolution ≠ DGLAP

Very interesting non perturbative part of evolution taken from data

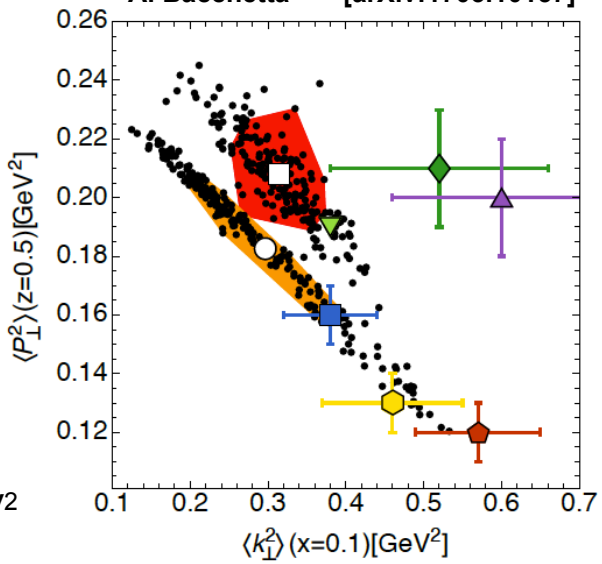
Fixed target SIDIS

Q^2 ~ few GeV^2

B-factories

Q^2 ~ 100 GeV^2

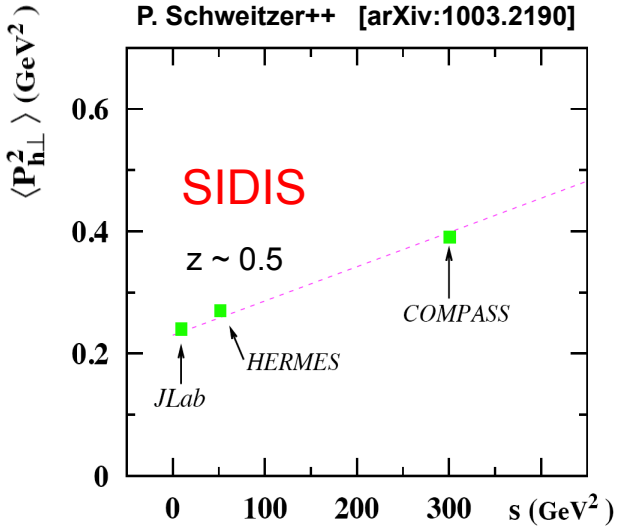
A. Bacchetta++ [arXiv:1703.10157]



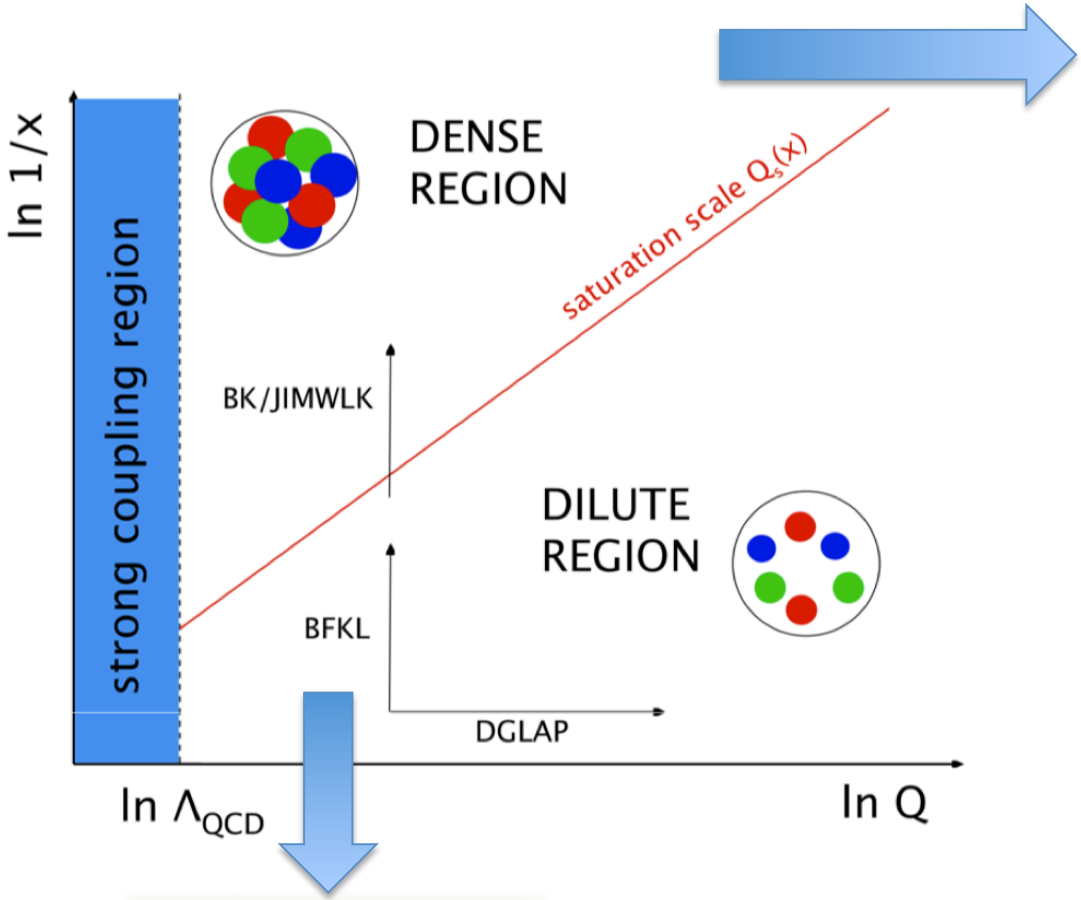
Indication of a k_T and p_T broadening with c.m. energy: TMD evolution

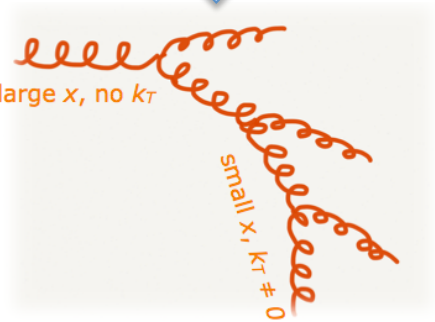
Energy scan at EIC in conjunction with B-factory data is crucial for effective progresses

P. Schweitzer++ [arXiv:1003.2190]

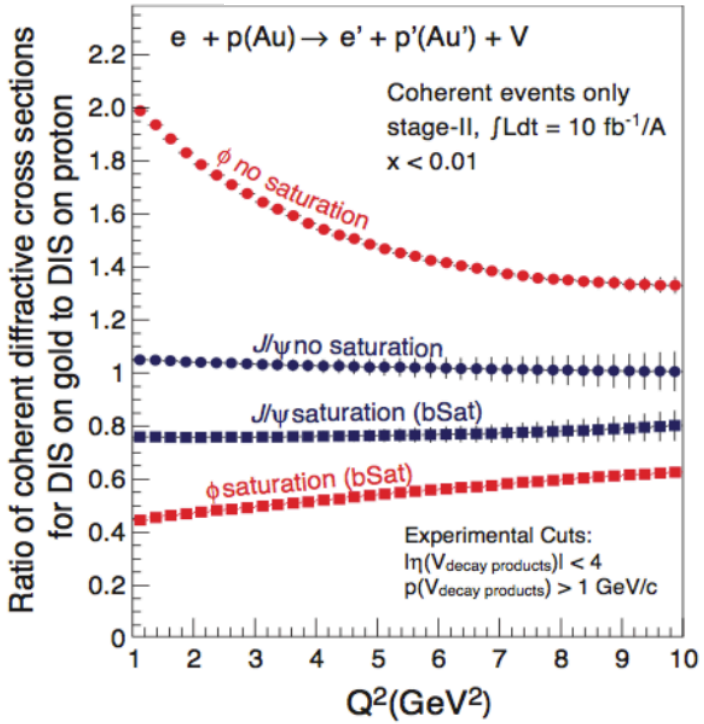


Low-x Physics





A. Accardi et al. [arXiv 1212.1701]



See M. Radici talk

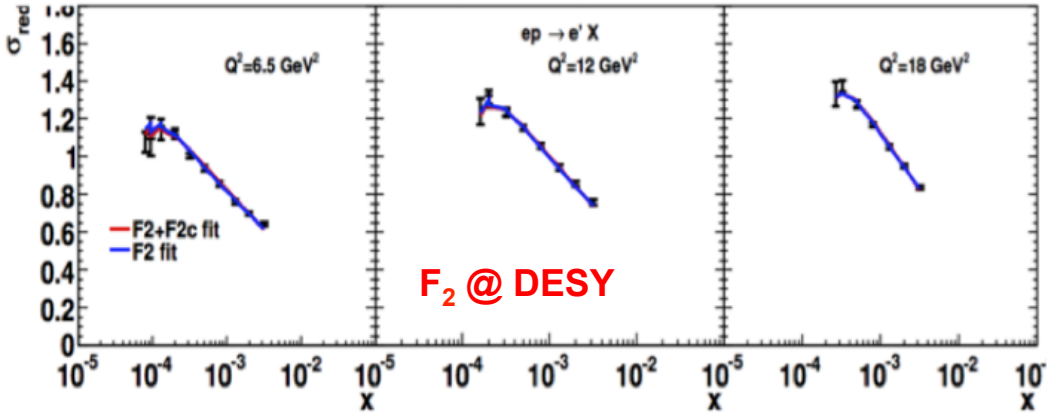
***x* low, Q^2 not too high:**

- **partonic k_T** may become important!

BFKL must be the correct theory of low-x QCD, it naturally incorporates k_T-unintegrated PDFs

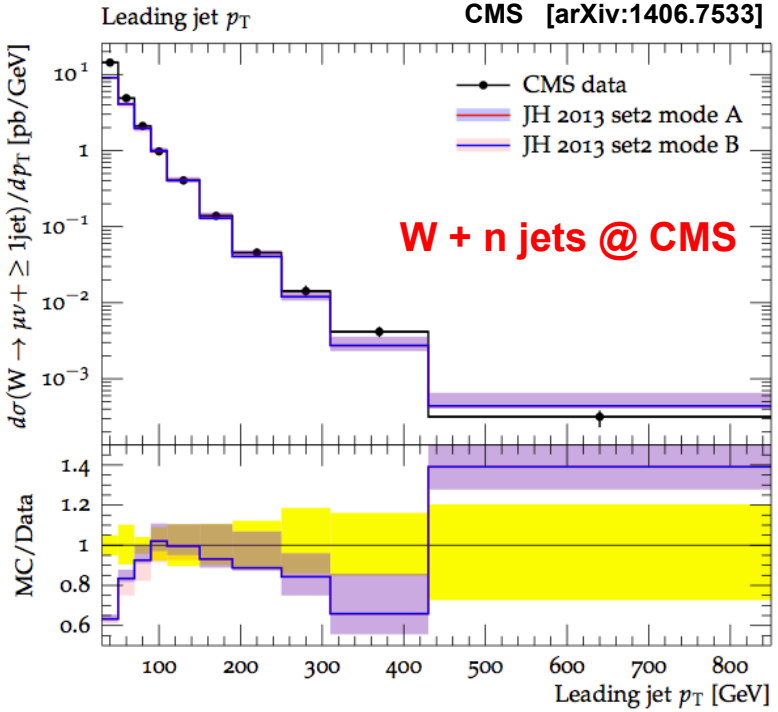
Gluon uPDFs

Starting distribution for gluons $f(x,k_T^2)$ from F_2 and inclusive hadron at LHC
+ CCFM (BFKL like) evolution

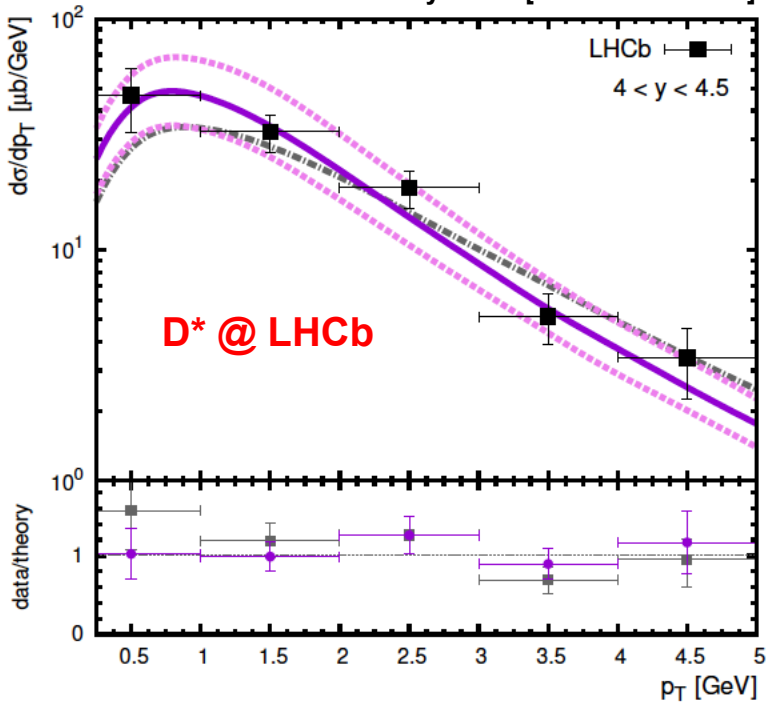


S. Dooling ++ [arXiv 1406.2994]

CMS [arXiv:1406.7533]



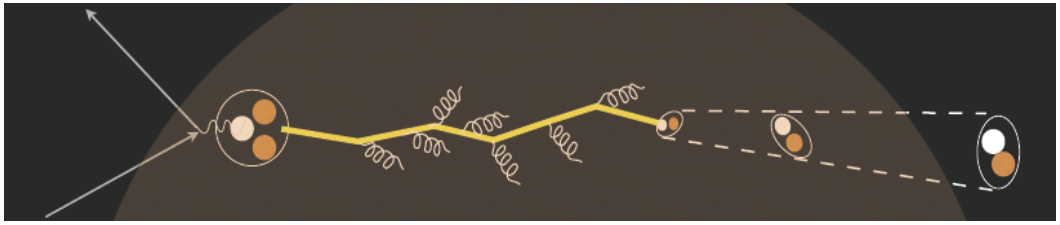
AA. Grinyuk ++ [arXiv 1510.07849]



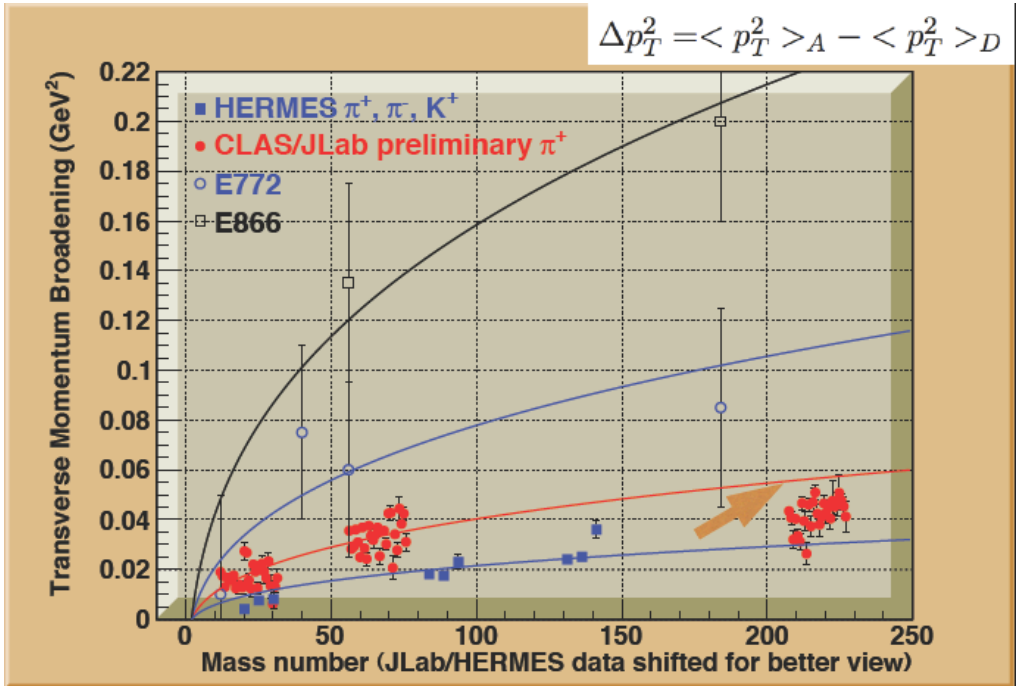
Medium modification

In terms of the QCD, there are several contributions to P_T distribution of hadrons produced in SIDIS:

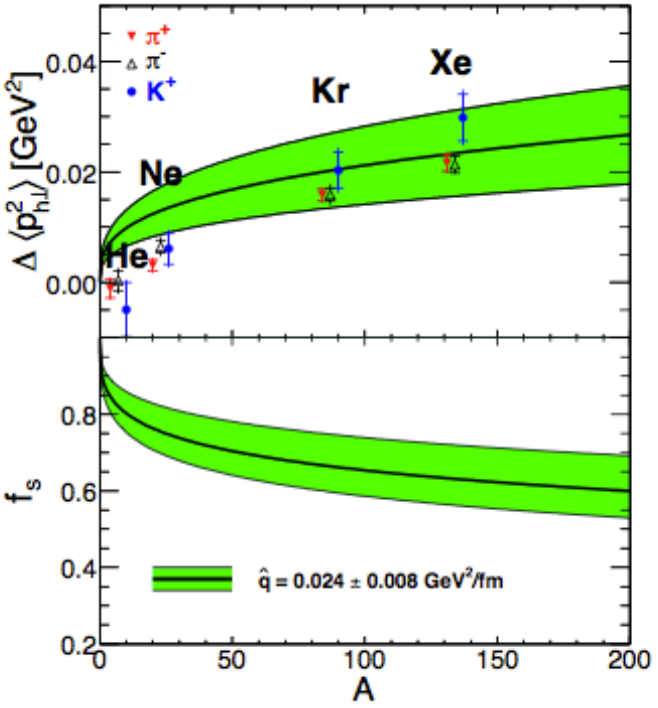
- primordial transverse momentum + gluon radiation of the struck quark
- the formation and soft multiple interactions of the "pre-hadron"
- the interaction of the formed hadrons with the surrounding hadronic medium



$\Delta p_T^2 = < p_T^2 >_A - < p_T^2 >_D$



HERMES [arXiv: 0906.2478]



N-B Chang ++ [arXiv:1402.3042]

$$\Delta_{2F} = 3\sqrt{2}\hat{q}_0 r_0 A^{1/3}/4$$

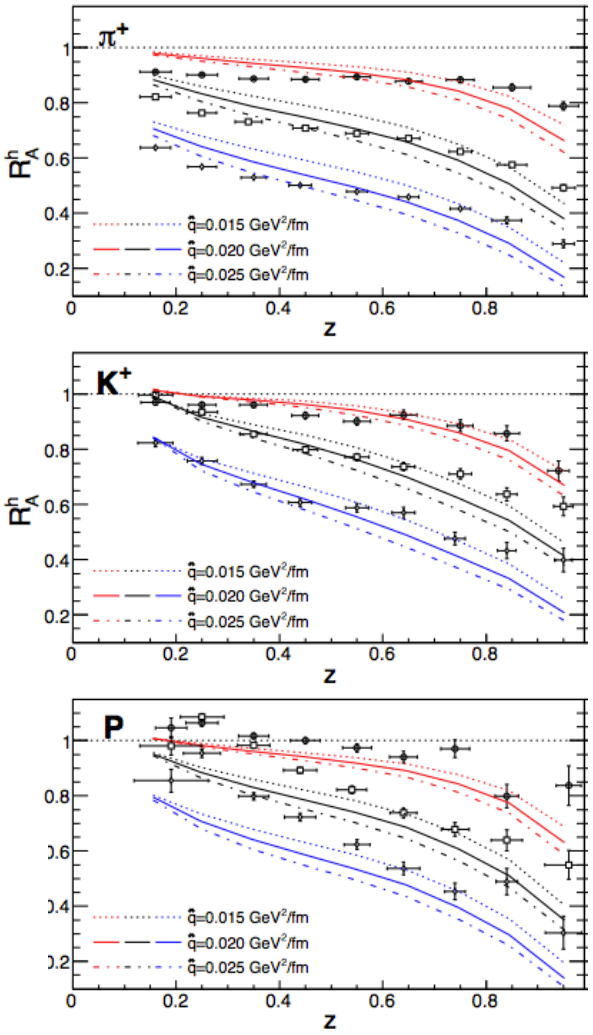
$$\frac{\langle \cos\phi \rangle_{UU}^{eA}}{\langle \cos\phi \rangle_{UU}^{eN}} \approx \frac{\langle \sin\phi \rangle_{LU}^{eA}}{\langle \sin\phi \rangle_{LU}^{eN}} \approx \frac{\alpha}{\alpha + \Delta_{2F}} = f_s$$

Medium modification

DIS

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

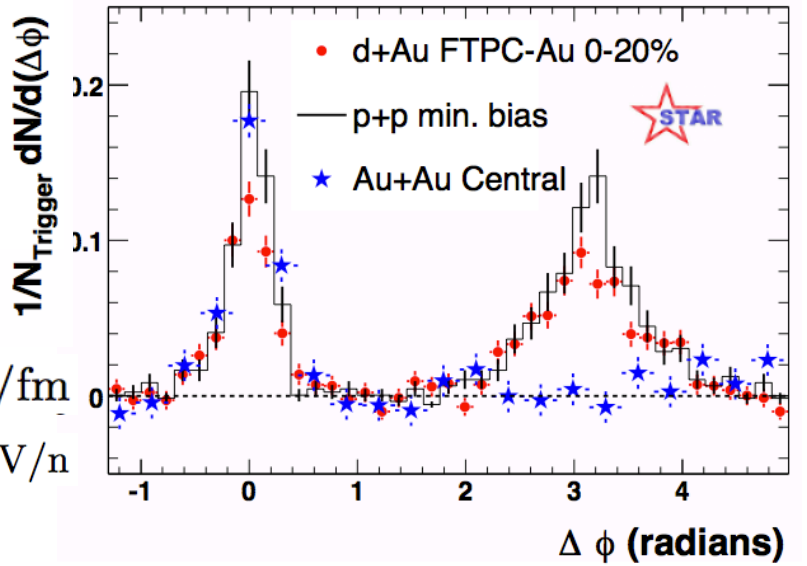
N-B Chang ++ [arXiv:1401.5109]



RHIC

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

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

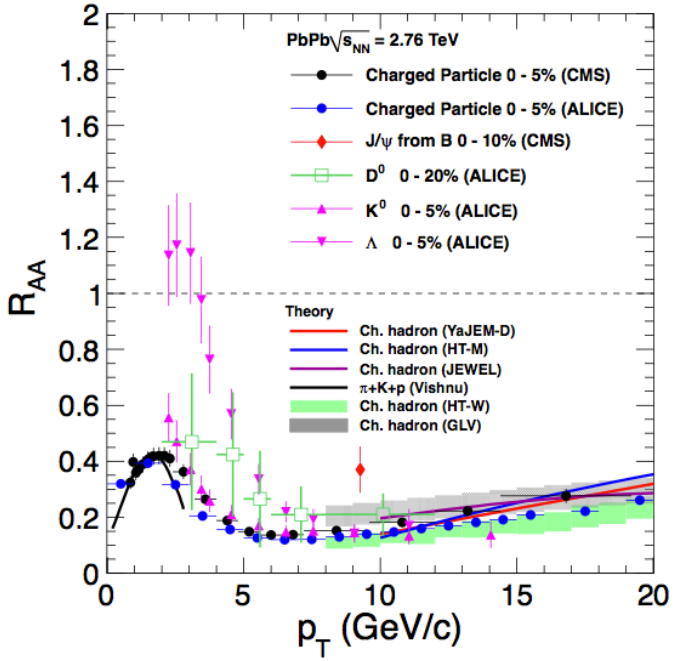


JET Coll. [arXiv:1312.5003]

LHC

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

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



Transverse Momentum Dependent Distr.

quark polarisation

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

$\otimes$

quark polarisation

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

Transversity:

different from helicity distribution as rotation and boost do not commute

- sensitive to the relativistic effects
- related to the tensor charge
- non-singlet type evolution
- chirally-odd

  it requires a chirally-odd fragmentation

Related to:

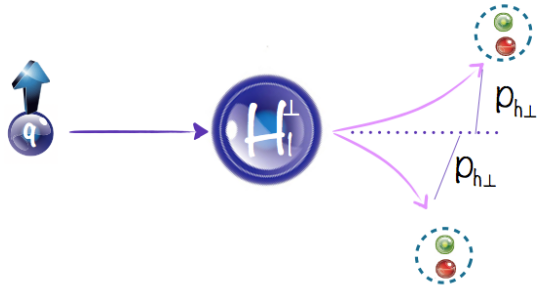
✓ Tensor Charge & Coupling

✓ SSA in hadron interactins

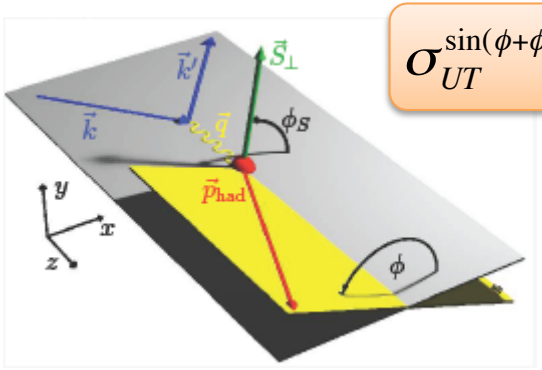
Collins function:

a spin-p_T correlator in fragmentation

$$D_{q/h}(z, \vec{p}_\perp, \vec{s}_q) = D_{q/h}(z, p_\perp^2) + \frac{1}{zM_h} H_1^{\perp q}(z, p_\perp^2) \vec{s}_q \cdot (\hat{k} \times \vec{p}_\perp)$$

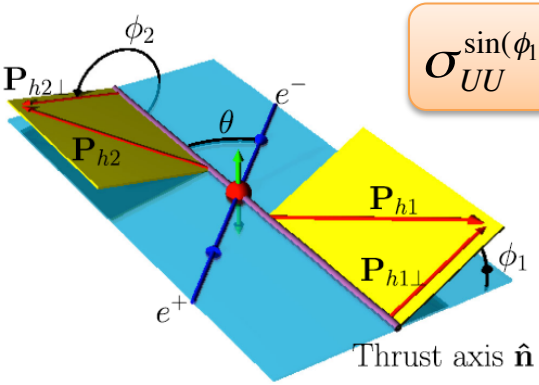


Transversity & Collins Evidences



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

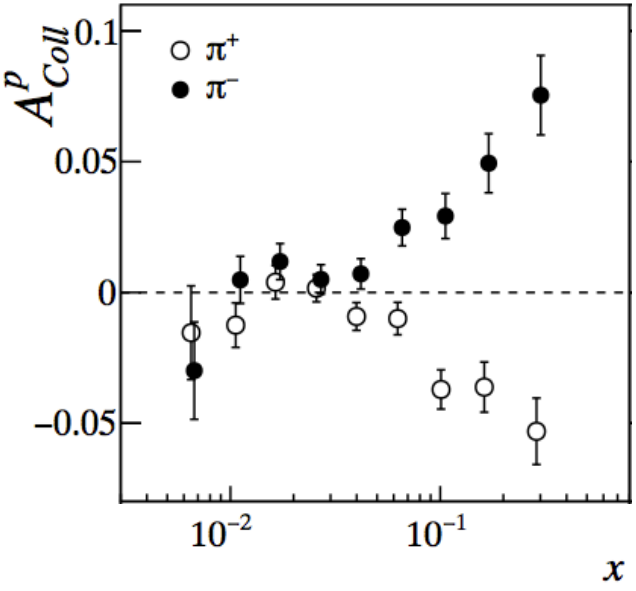
Q^2 ~ 5-7 GeV^2



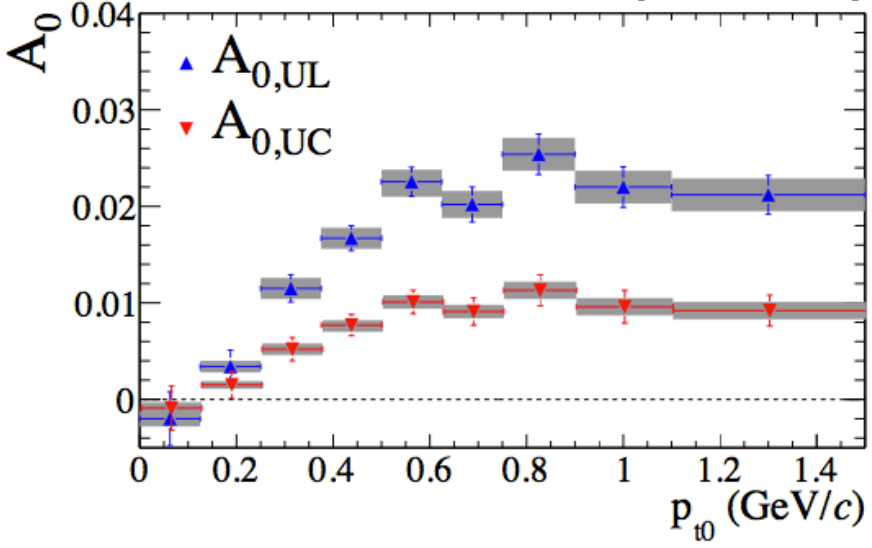
$$\sigma_{UU}^{\sin(\phi_1+\phi_2)} \propto H_1^\perp \otimes H_1^\perp$$

Q^2 ~ 110 GeV^2

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



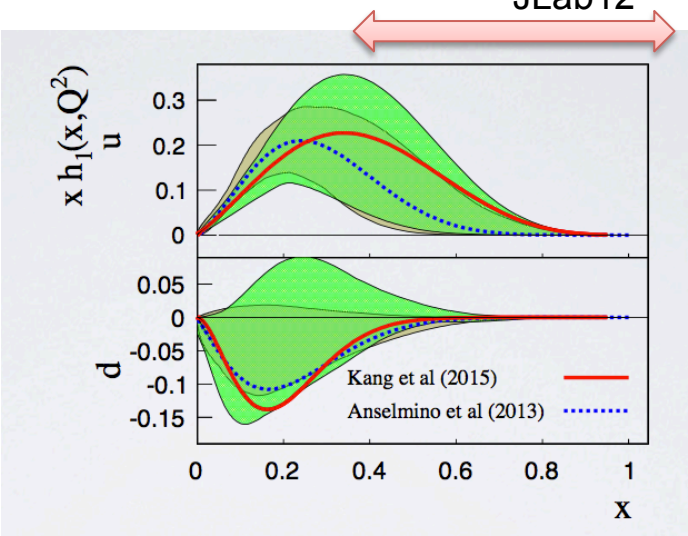
Belle [talk at DIS2014]
BESIII [arXiv 1507.06824]
Babar [arXiv 1309.5278]



Transversity & Tensor Charge

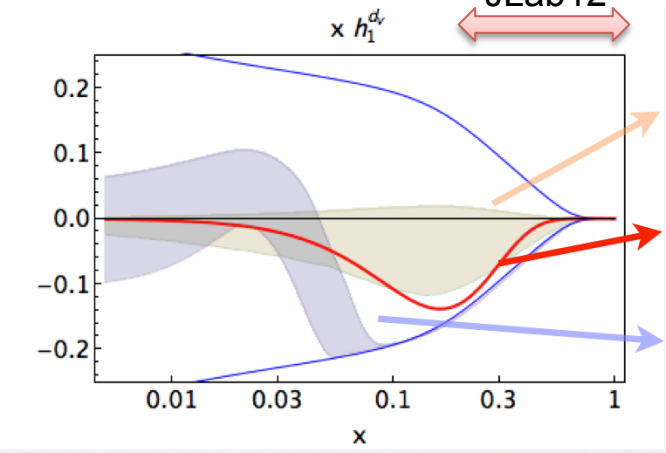
Distributions:

JLab12



x

JLab12



Torino 2013

Kang *et al.*

Pavia (DiFF)

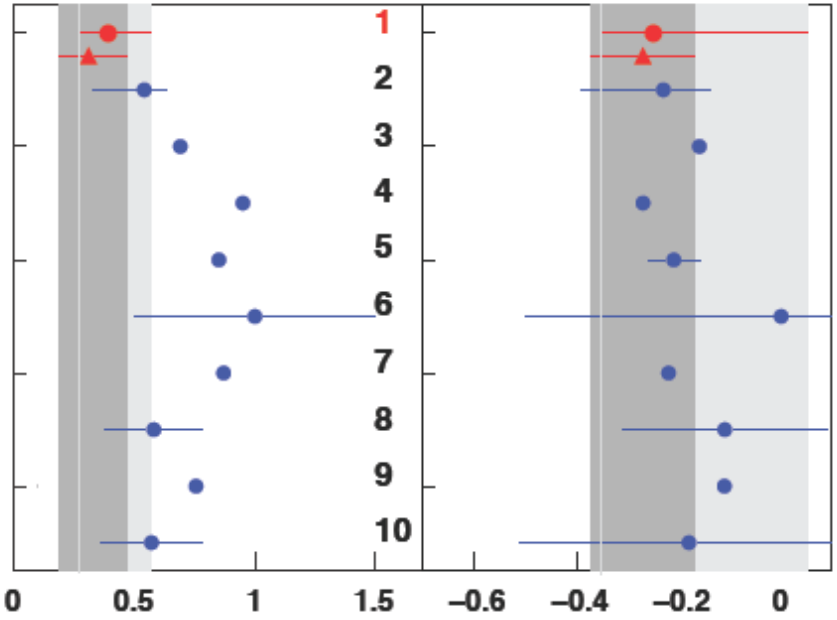
How well is Soffer bound know at large x ?

Charges:

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

Anselmino++ [arXiv 1303.3822]

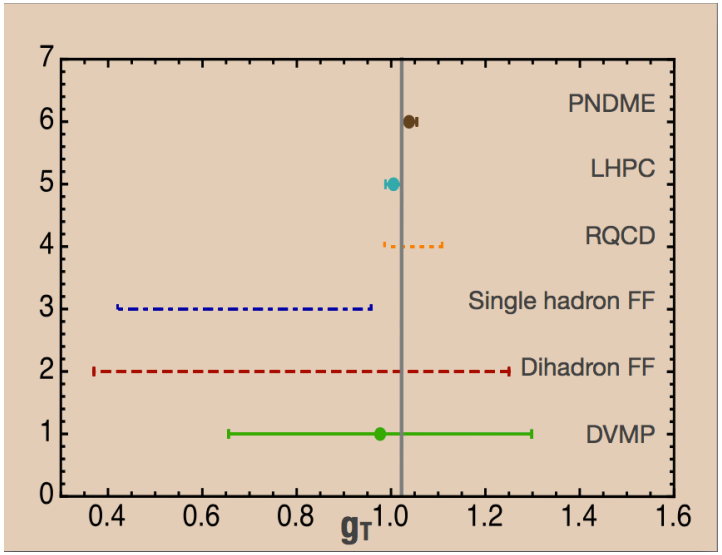
- $\delta u = 0.39^{+0.18}_{-0.12}$
- $\delta d = -0.25^{+0.30}_{-0.10}$
- $\delta u = 0.31^{+0.16}_{-0.12}$
- $\delta d = -0.27^{+0.10}_{-0.10}$



Δu = 0.787 **Δd = -0.319**

Tensor Charge & BSM Physics

A. Courtoy++ [arXiv 1503.06814]



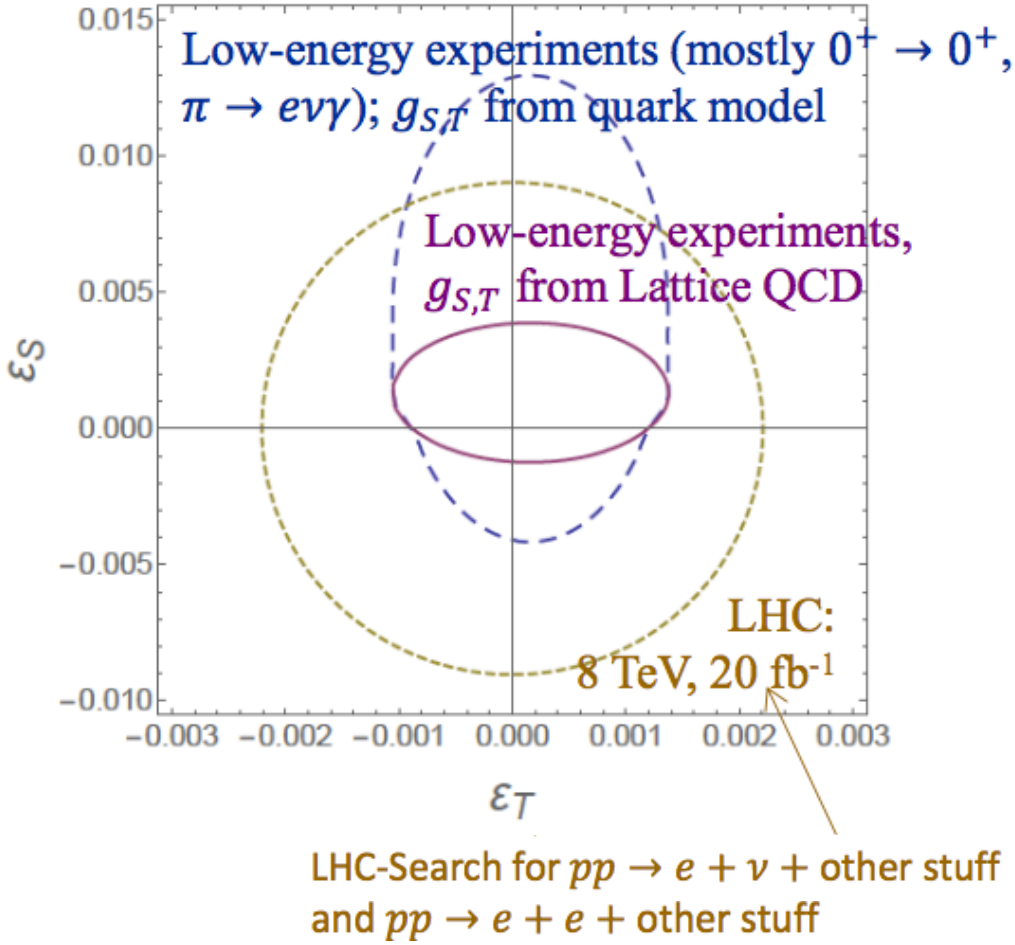
$g_T^{u-d} = \delta u - \delta d$ ($Q^2 = 4$ GeV^2)

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

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

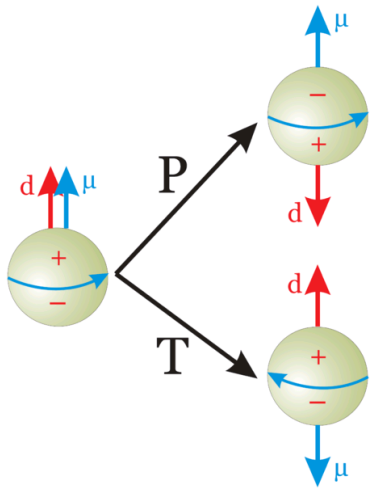
A. Bychkov++ [arXiv:0804.1815]
B. Pattie++ [arXiv:1309.2499]

Baessler++ @ SPIN2016

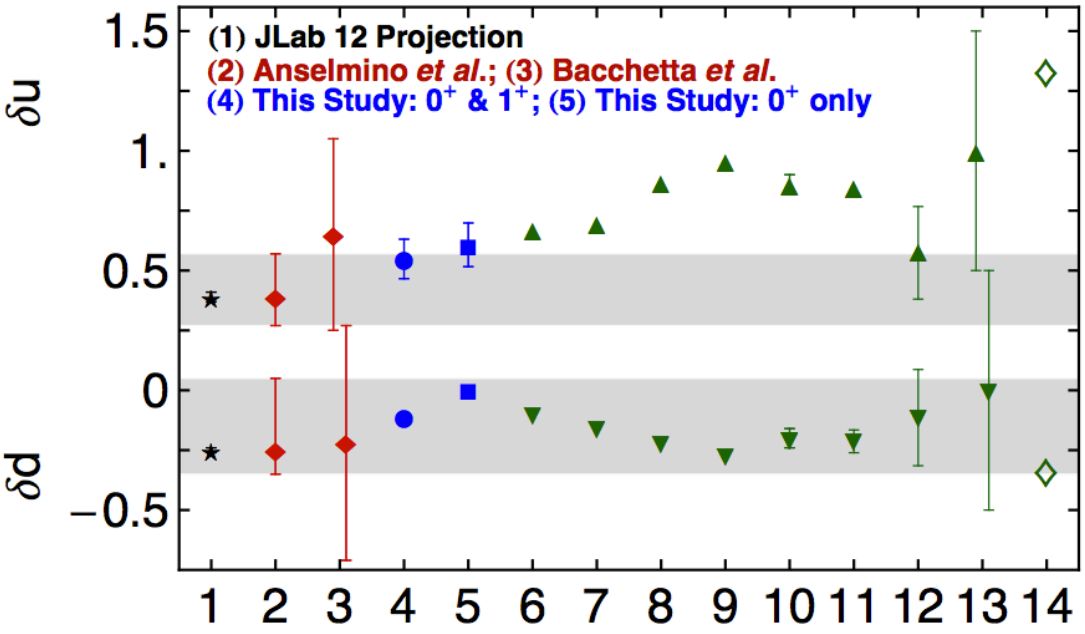


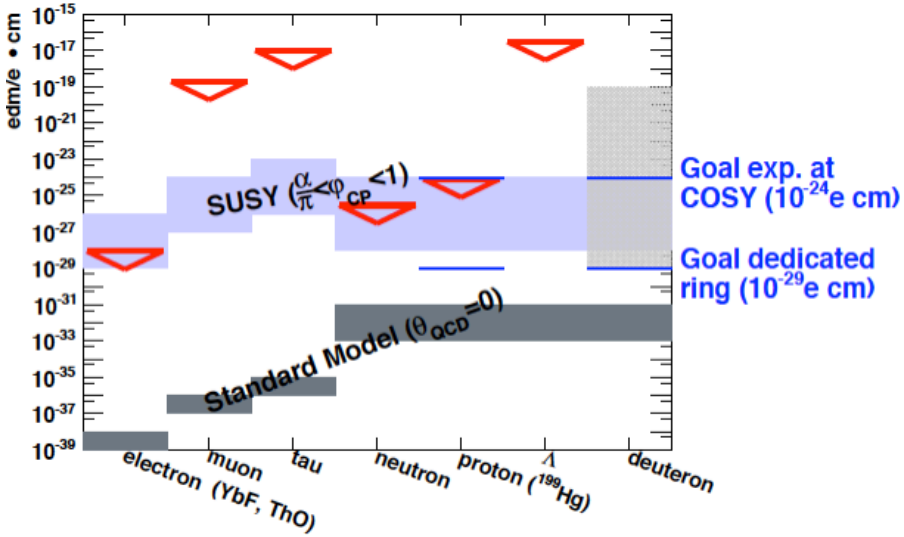
Tensor Charge and EDM

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



Pitschman++ [arXiv: 1411.2052]





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

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

Transverse Momentum Dependent Distr.

quark polarisation

nucleon polarisation

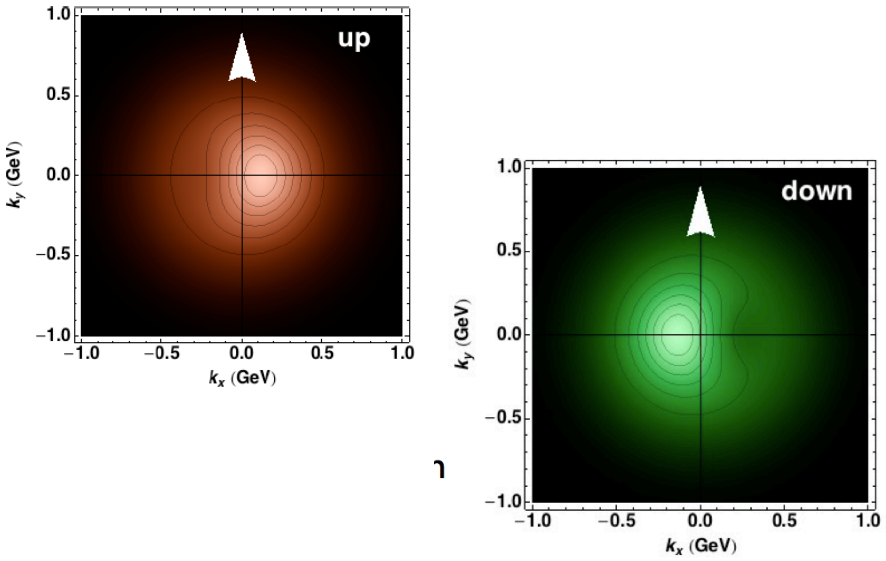
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h, h_{1T}^\perp$

$\otimes$

hadron polarisation

quark polarisation

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



Off-diagonal elements:

Interference between wave functions with different angular momenta: testing QCD at the amplitude level

T-odd elements:

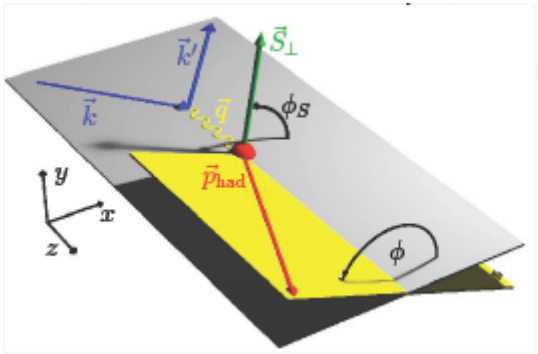
➜ Sign change between DY and SIDIS
Generalized universality of TMDs

Related to:

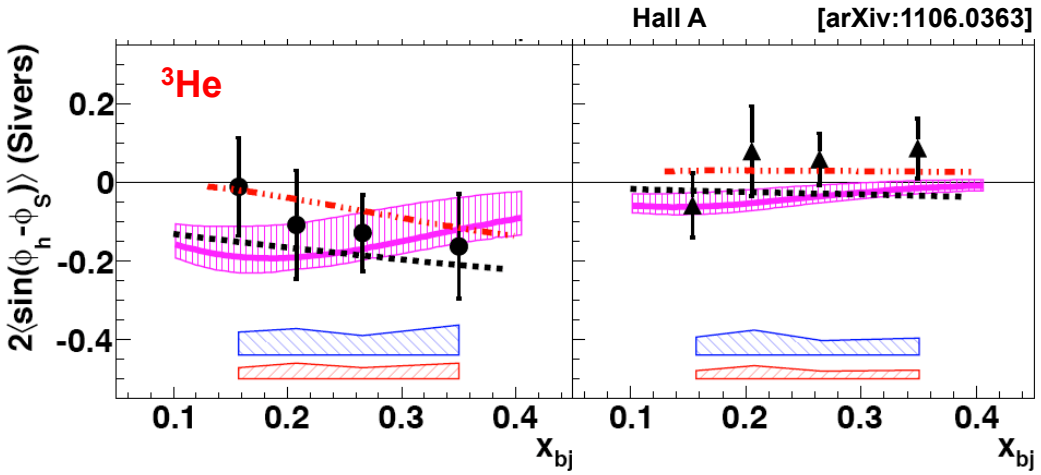
- ✓ SSA in hadronic interactions
- ✓ Parton Orbital motion
- ✓ Anomalous Magnetic Moment

Sivers Signals

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



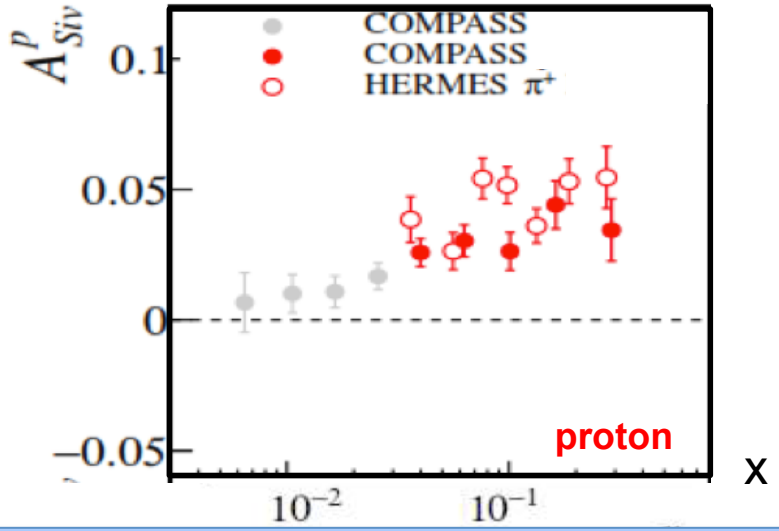
Hall A [arXiv:1106.0363]



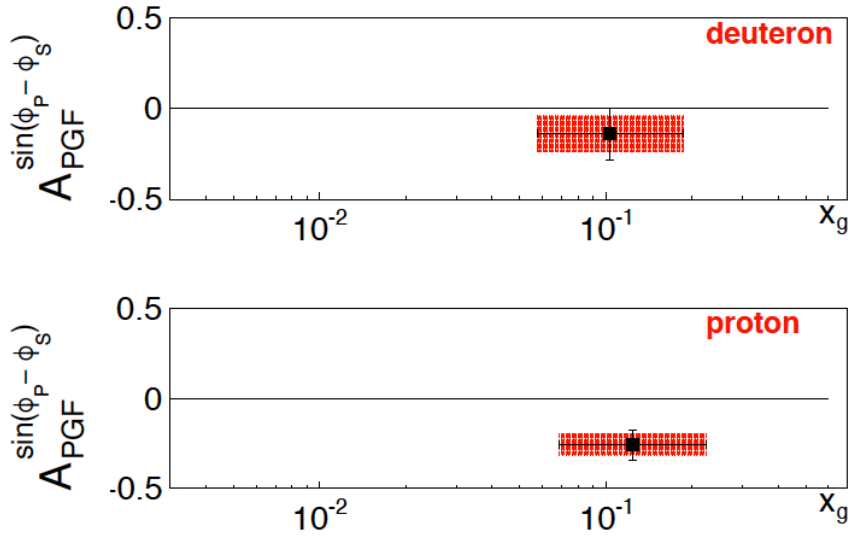
Sivers from polarized SIDIS

HERMES [arXiv:0906.3918]

COMPASS [arXiv:1205.5122]



COMPASS [arXiv:1701.02453]



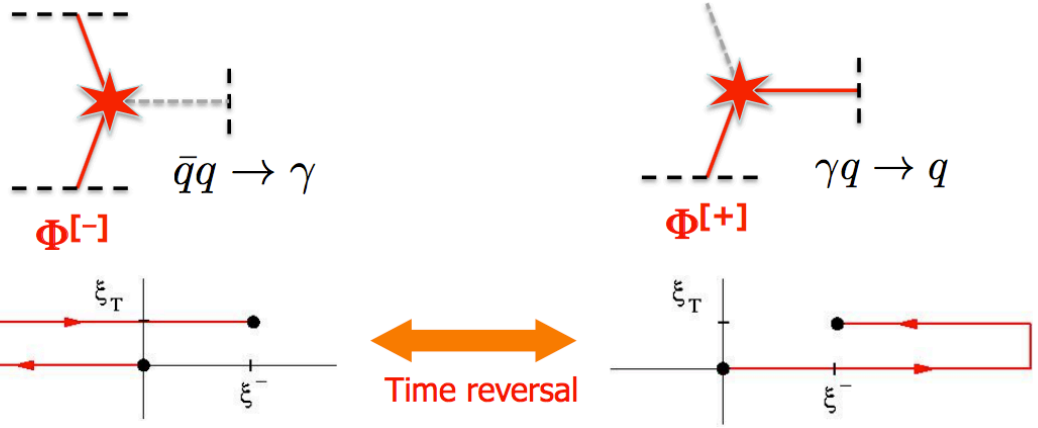
Gauge Invariance

$$\Phi_{ij}^{q[C]}(x,p_T;n)=\int\frac{d(\xi.P)d^2\xi_T}{(2\pi)^3}e^{ip.\xi}\left\langle P\left|\bar{\psi}_j(0)U_{[0,\xi]}^{[C]}\psi_i(\xi)\right|P\right\rangle_{\xi.n=0}$$

path dependent gauge link

Prediction: change of sign passing from FSI (SIDIS) to ISI (DY)

SIDIS

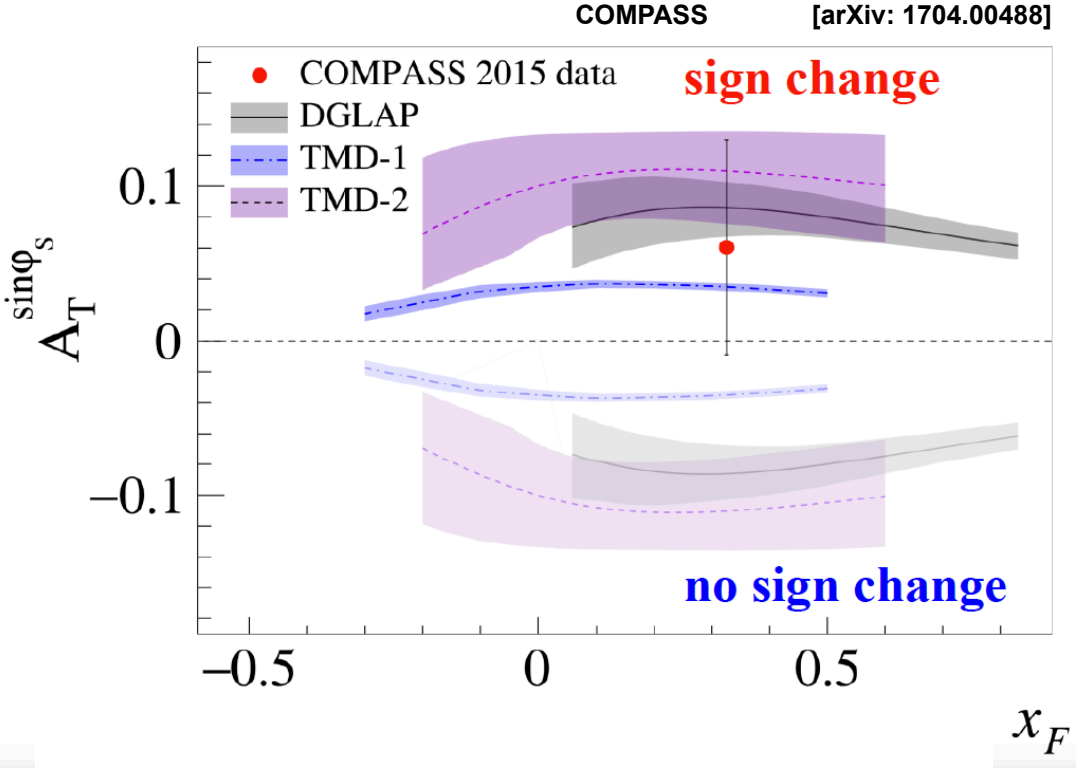


DY

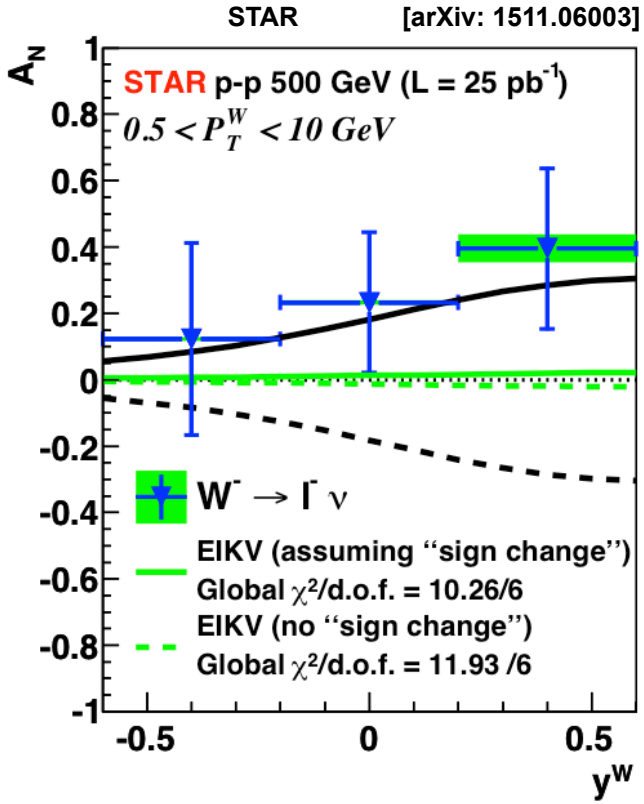
Process dependence: a way to access not-trivial gauge effects as color flow

Sivers Sign in Drell-Yan

Drell-Yan
p p → μμX @ COMPASS



Weak boson production
p p → WX @ STAR



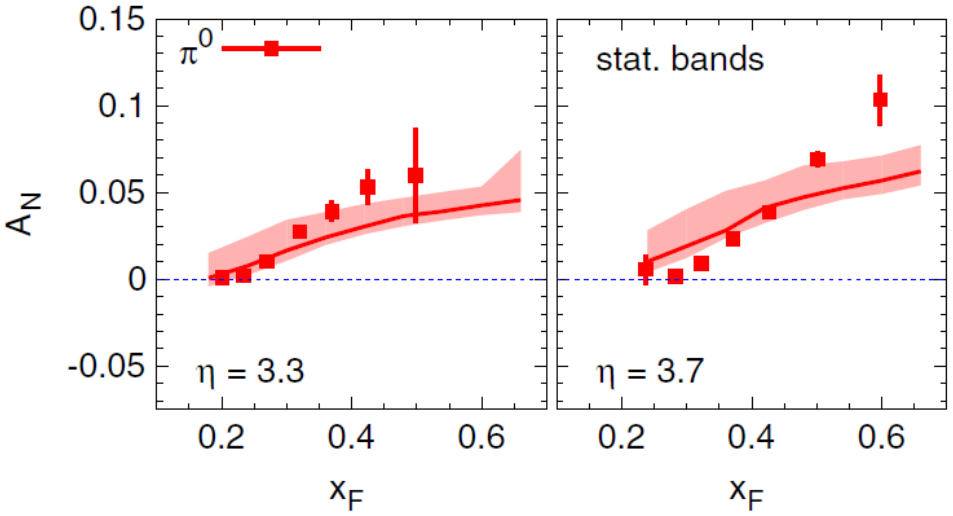
M. Anselmino++ [arXiv 1612.06413]
M.G. Echevarria++ [arXiv 1401.5078]
P.Sun++ [arXiv 1308.5005]

Kang and Qiu, [PRL 103 (2009) 172001]
Echevarria++, [PRD 89 (2014) 074013]

Parton Spin-Orbit Correlations

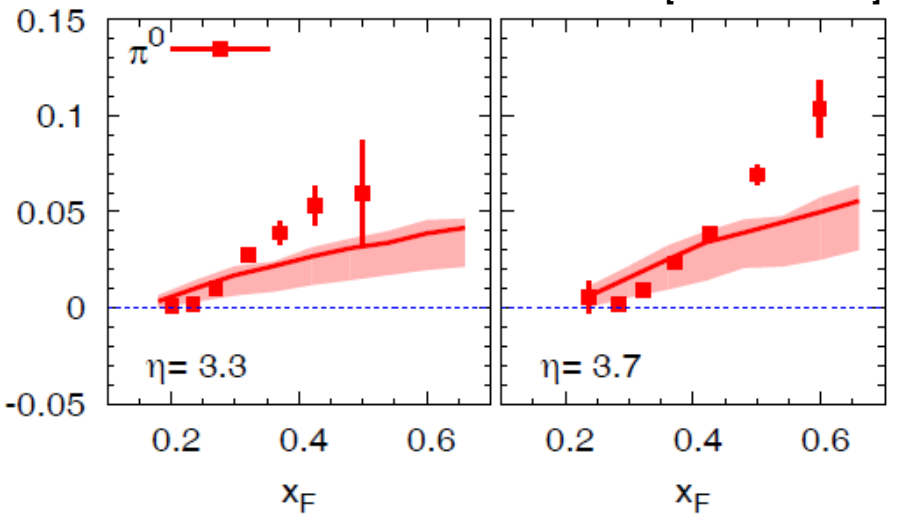
Possible mechanisms at the basis of mysterious hadronic SSA

Sivers effect alone



Collins effect alone

M. Anselmino et al. [arXiv 1304.7691]



TMDs Landscape

Phenomenology:

gather active dynamic mechanisms
spin-orbit, short range correlations, energy loss in matter, collective motion

make educated guesses on parton behavior
average transverse momentum, orbital motion

is the naïve interpretation of the observable sensible ?

Predictive Power (applicability as for collinear PDFs):

rigorous treatment, i.e. for tensor charge extraction, exploiting universality

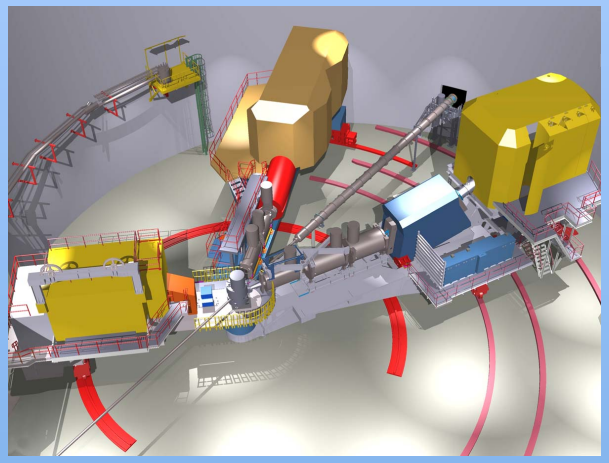
evolution well defined but not necessarily under control at medium-low energy

scale dependence should improve with next-to-leading orders, as for k-factor in DY

non perturbative parameters should be constrained by data

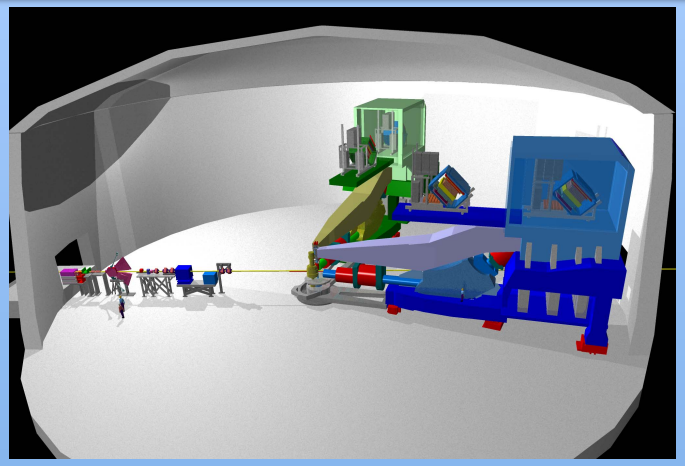
JLab12 Experimental Halls

Hall-C



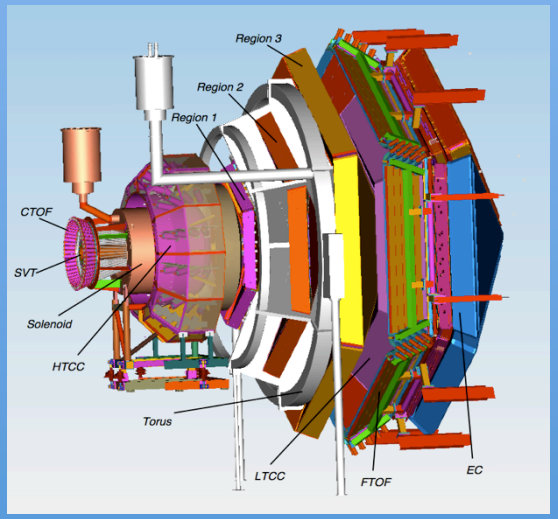
Super High Momentum Spectrometer (SHMS)
unpolarized SIDIS, hadron ID

Hall-A



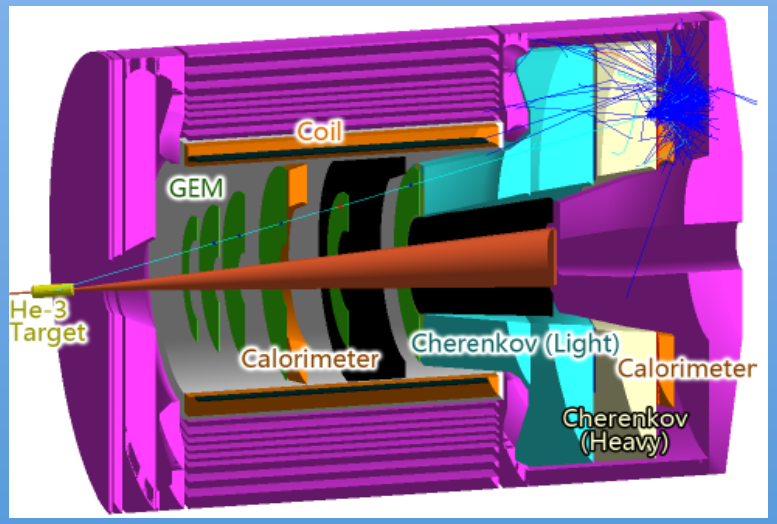
Spectrometer pair, polarized ^{3}He target
up to to 10^{38} cm^{-2} s^{-1}, hadron ID

Hall-B



CLAS12 HD-ice (H,D) polarized targets up to
10^{35} cm^{-2} s^{-1}, "complete" acceptance, hadron ID

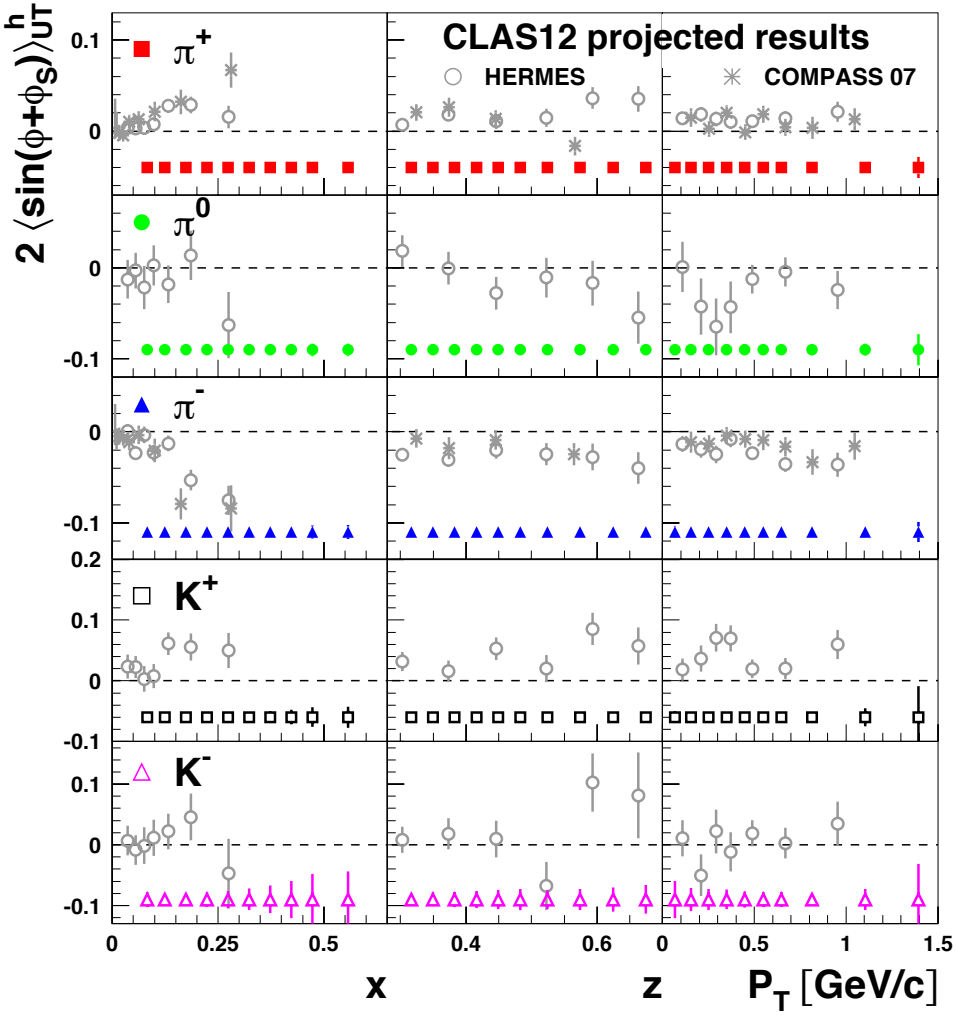
Hall-A



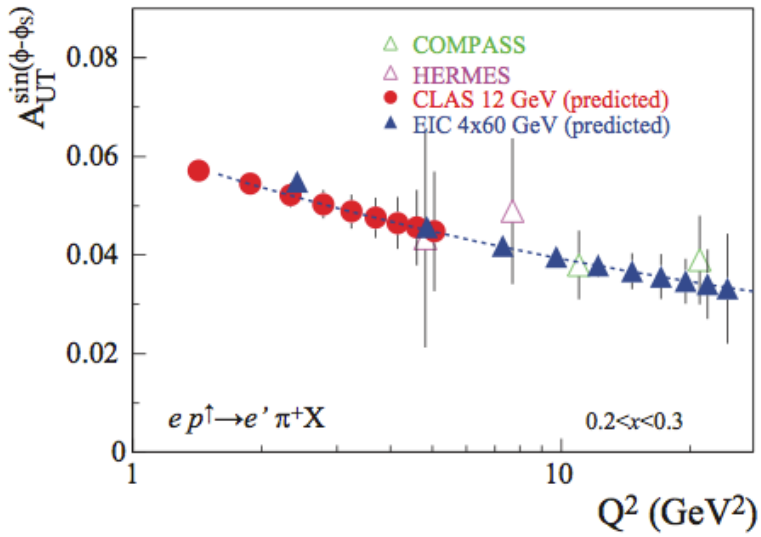
SOLID ^{3}He, NH_3 polarized targets up to
10^{36} cm^{-2} s^{-1}, large acceptance, pion ID

SIDIS @ JLAB12 (2017++)

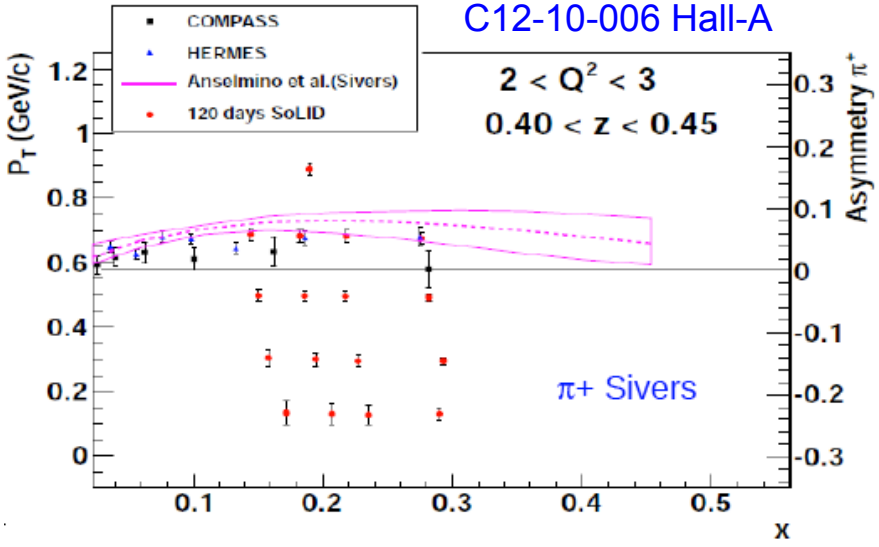
Collins asymmetry: C12-11-111 Hall-B



Sivers asymmetry:



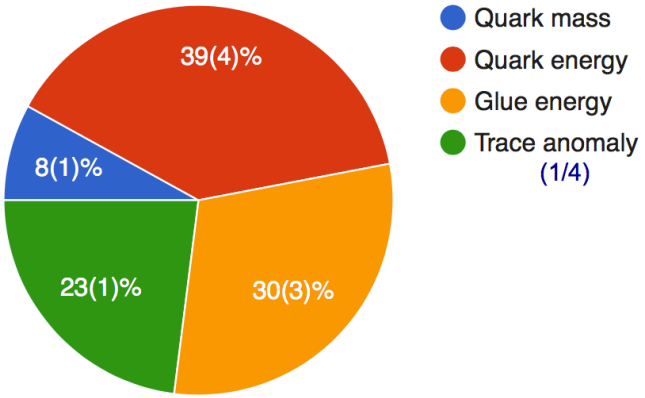
C12-10-006 Hall-A



Lattice Achievements

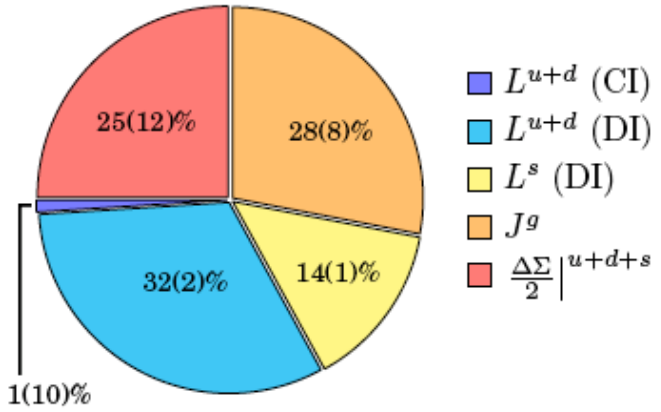
Nucleon mass components

K-F Liu @ this Conf.

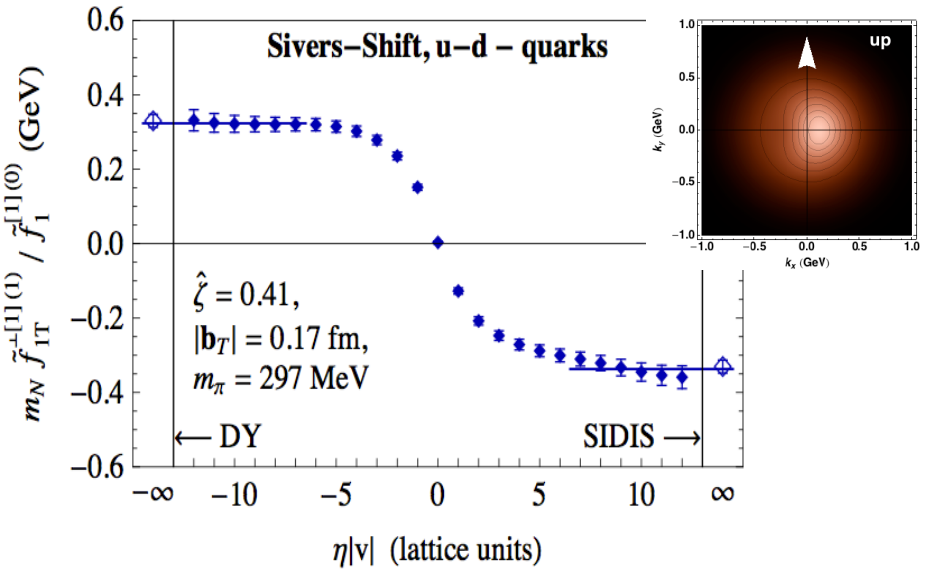


Spin dsecomposition

K-F Liu++ [arXiv 1203.6388]

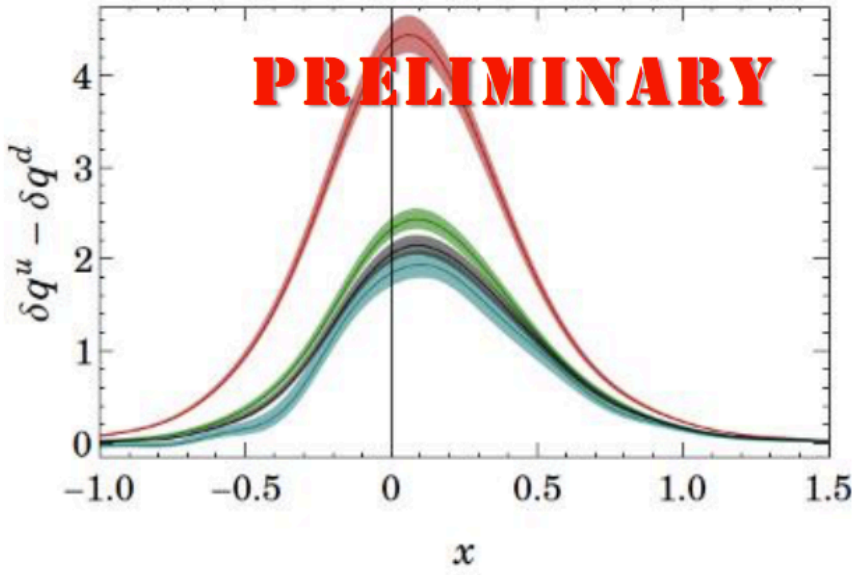


Sivers shifts



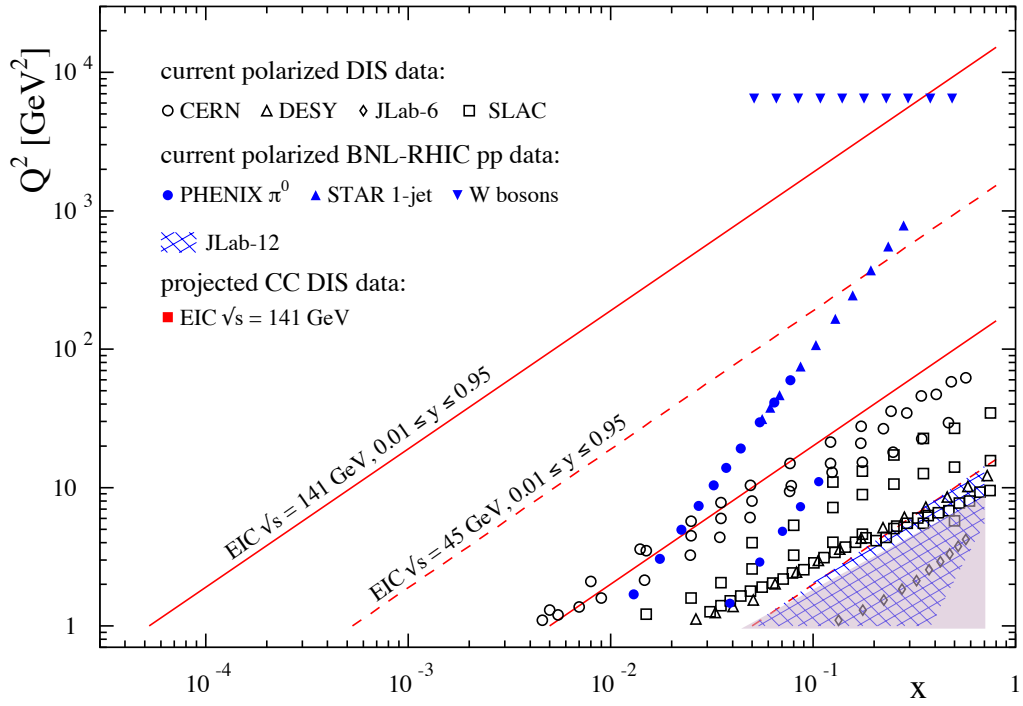
Transversity distribution

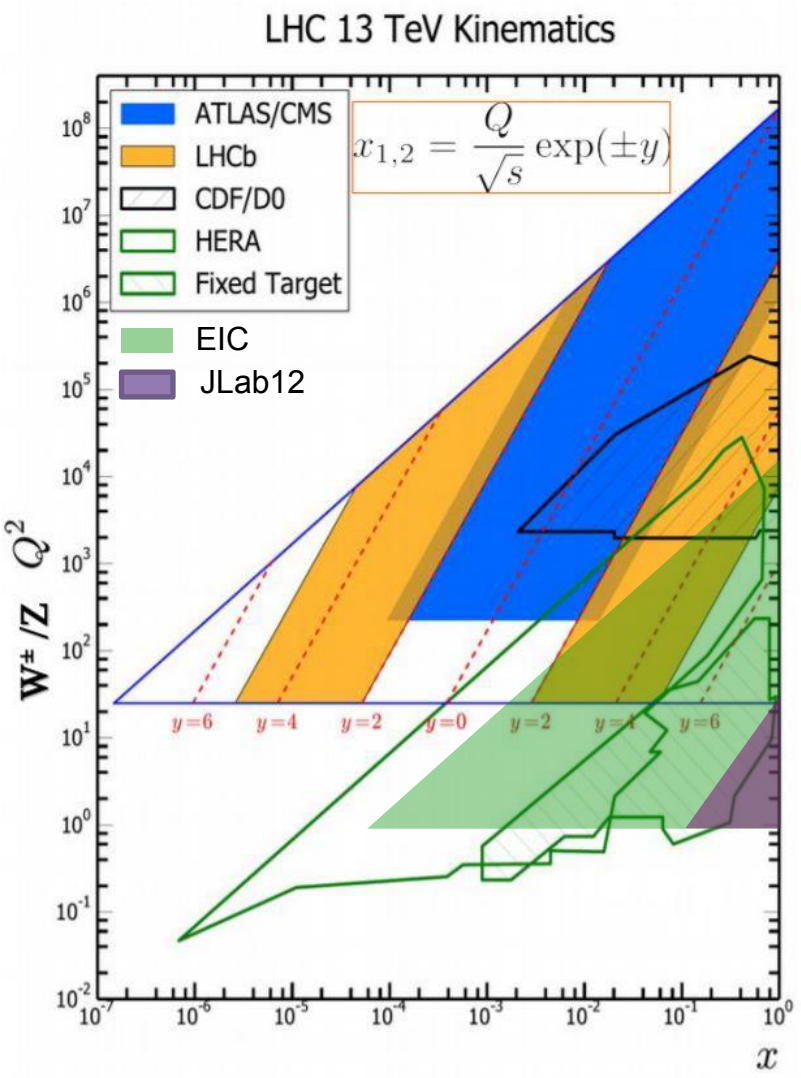
H-W Lin @ QCD-Evol 13



Future: EIC and LHC

EIC will provide data in the much needed "intermediate" energy region matching "pure" pQCD with "pure" TMD regime.





See L. Pappalaro and M. Radici talks

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 and sea 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