3D Distributions, Future

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INFN Ferrara

3D Parton Distributions: path to the LHC
December 2, 2016 LNF

Disclaimer

Many concepts already discussed this week

A lot of material grabbed from other talks

Personal (limited) perspective

The General Equations and Dynamics

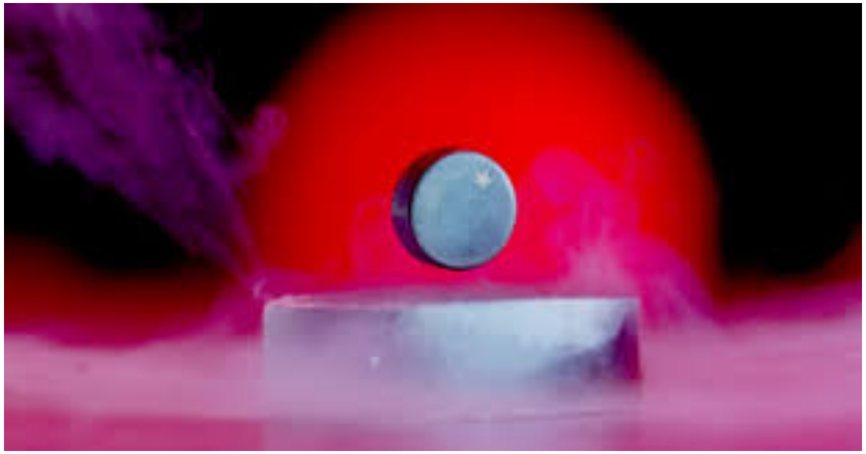
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

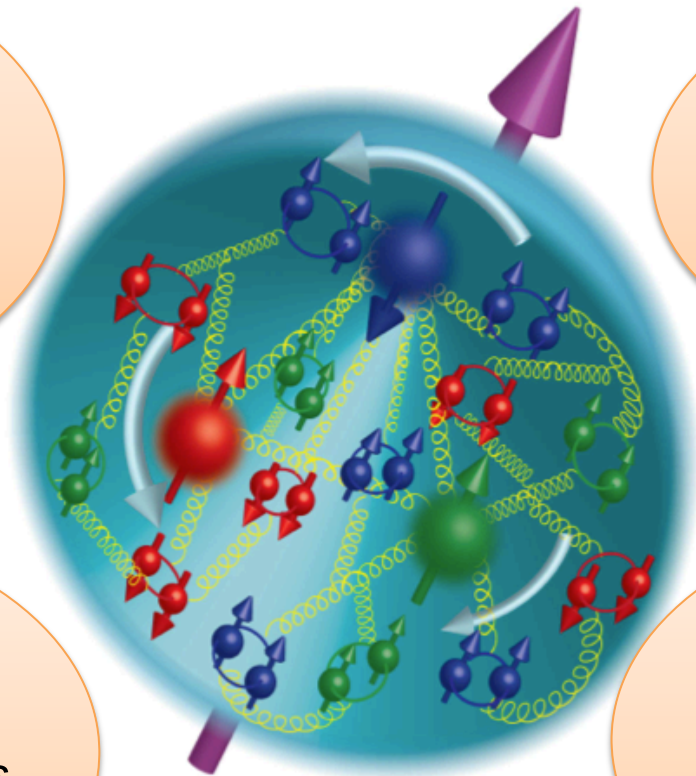


But superconductivity ?

But star dynamics ?

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

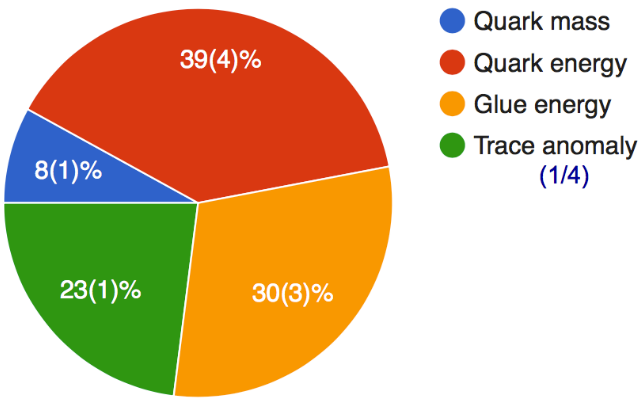
Hadronization
- Spin-orbit effects
- Parton energy loss
- Jet quenching

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

Lattice Achievements

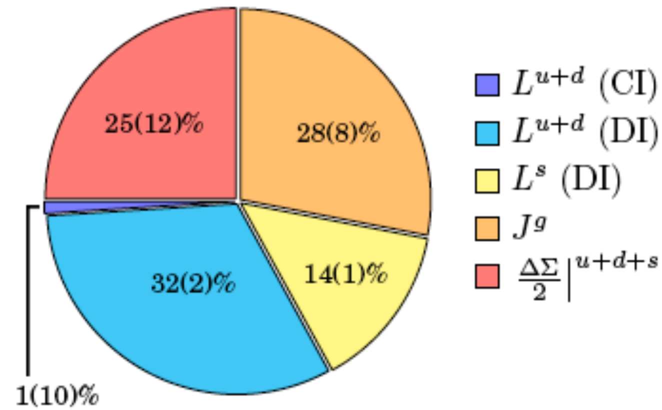
Nucleon mass components

K-F Liu @ this Conf.

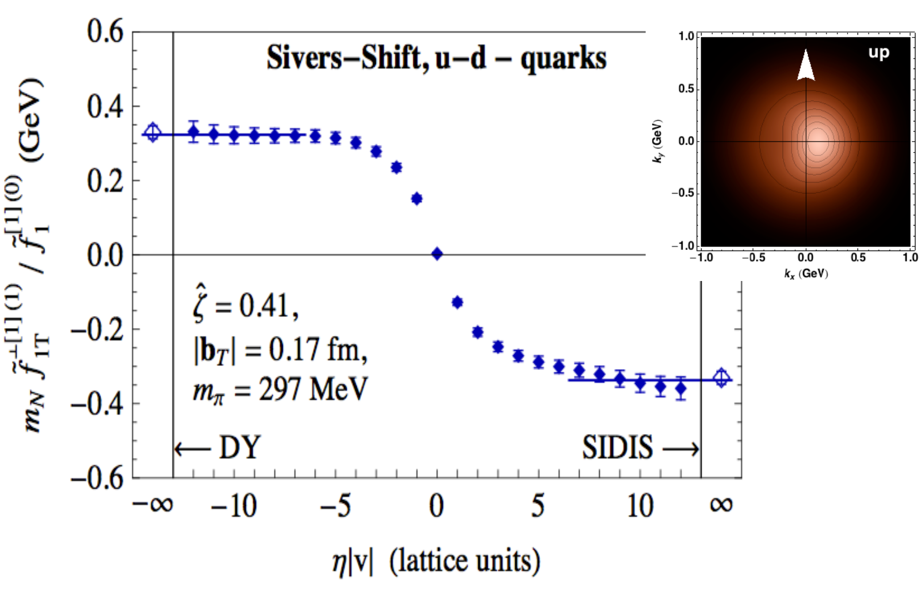


Spin dsecomposition

K-F Liu++ [arXiv 1203.6388]

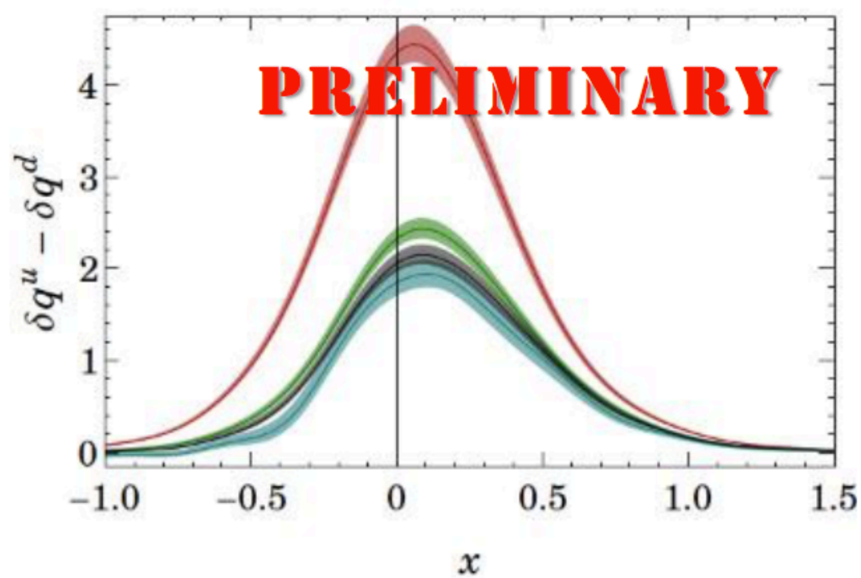


Sivers shifts



Transversity distribution

H-W Lin @ QCD-Evol 13

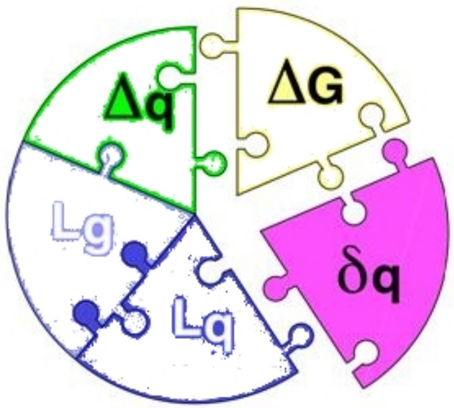


QCD vs pQCD

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

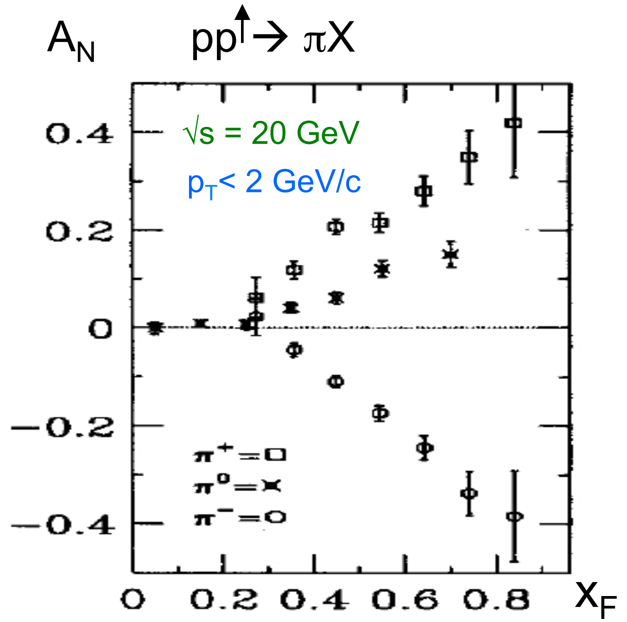
Proton Spin Budget



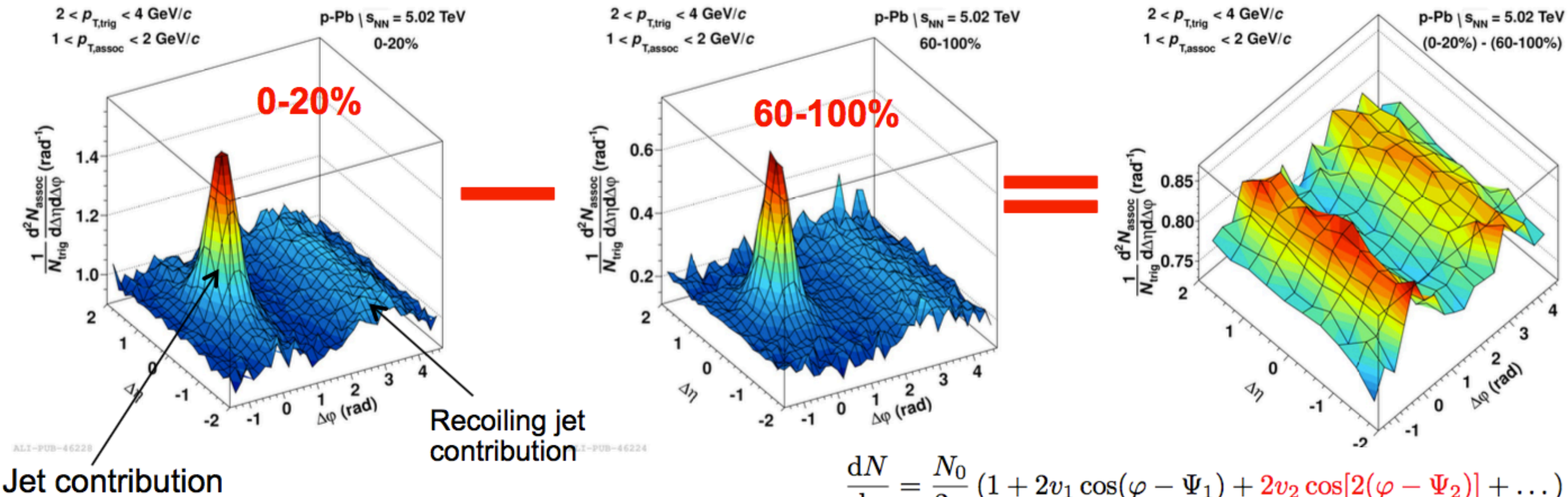
$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$

?

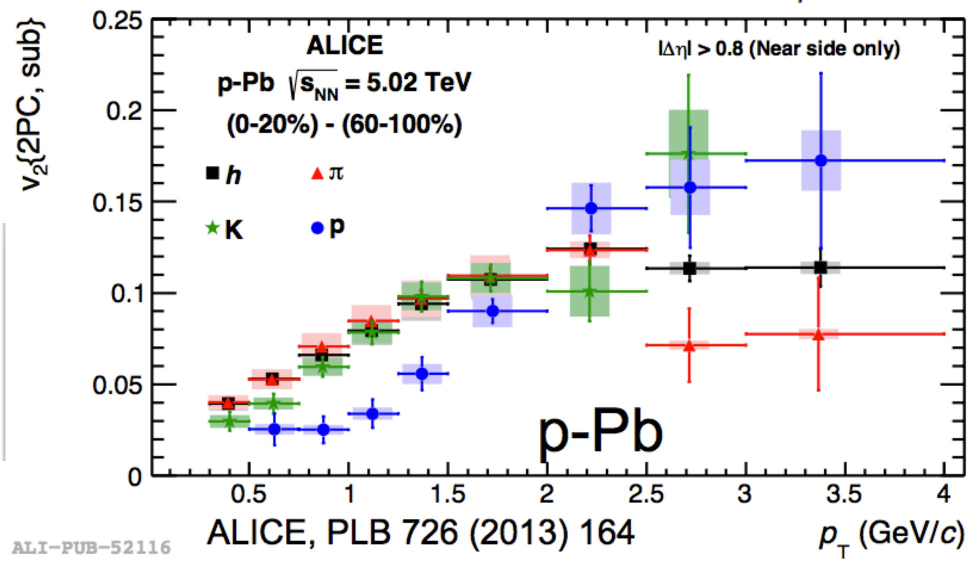
Single Spin Asymmetries



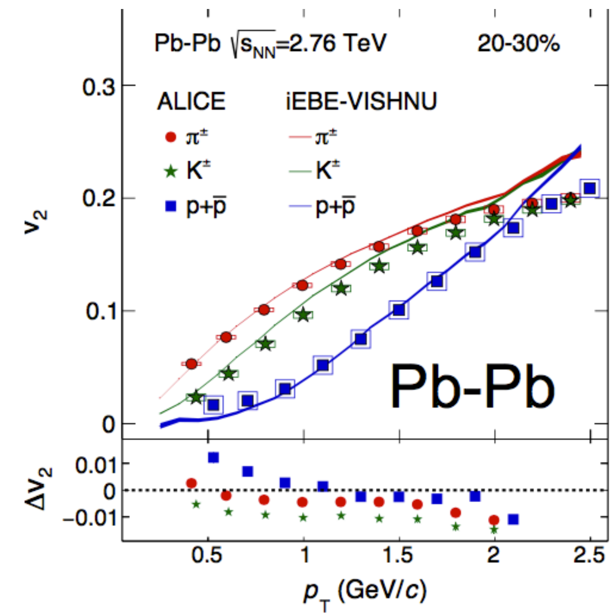
Elliptic Flow



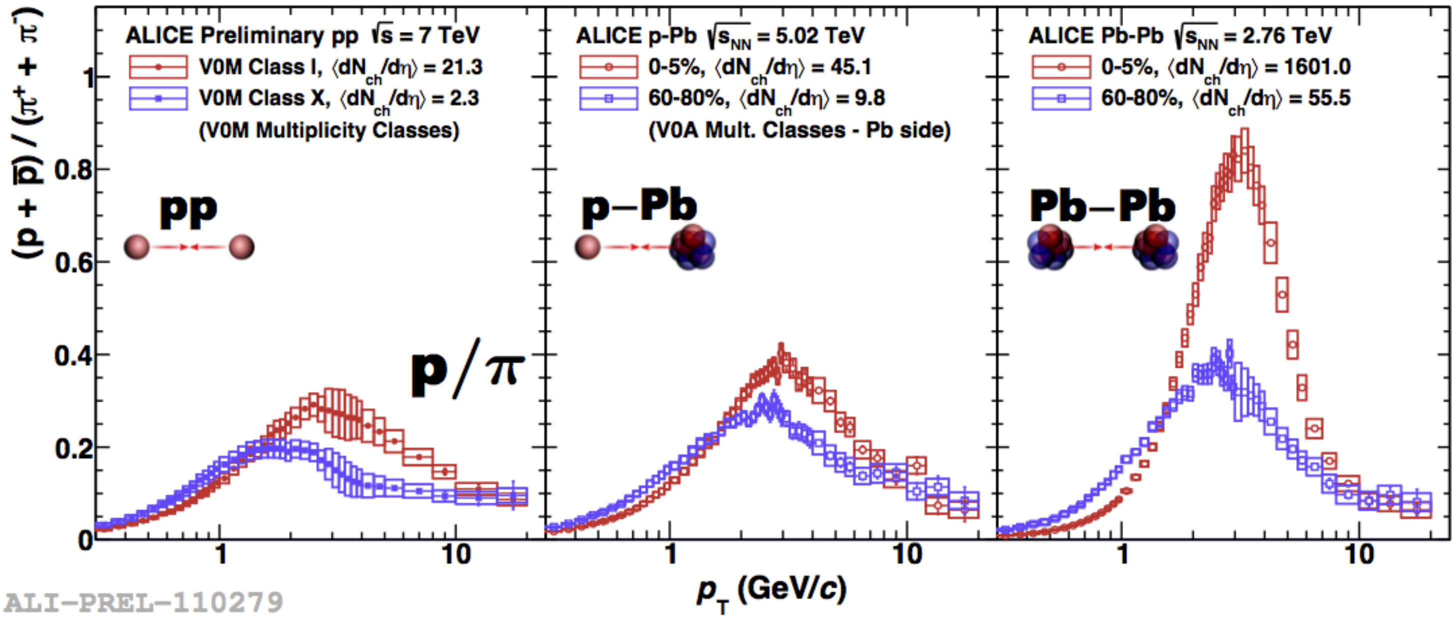
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \ldots\right)$$



ALICE, PLB 726 (2013) 164



Hadron Multiplicity Ratio



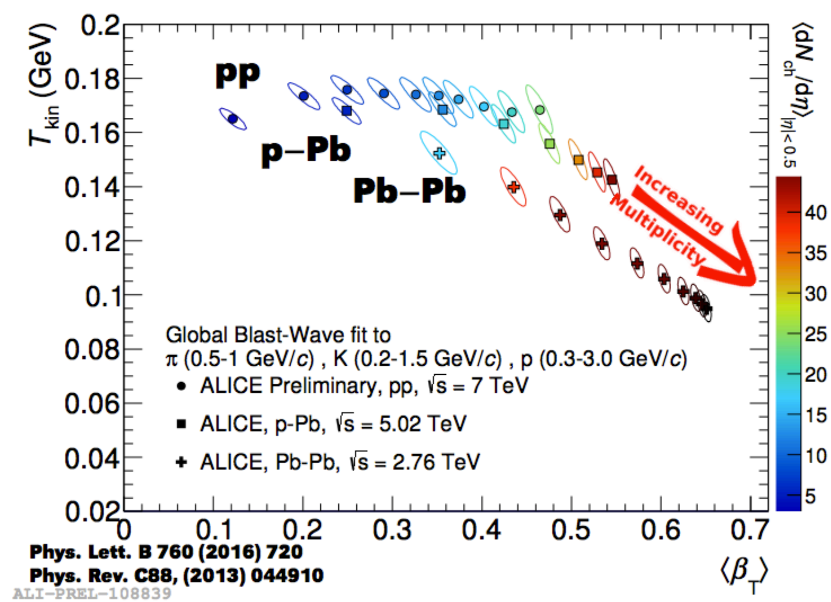
Similar features in Pb-Pb, p-Pb and even p-p at high multiplicity

Where QGP is really formed and manifest ?

Collective effects even for the “simple” proton ?

$\beta_T \rightarrow$ **radial velocity**

$T_{kin} \rightarrow$ **kinetic freeze-out temperature (particle decoupling)**

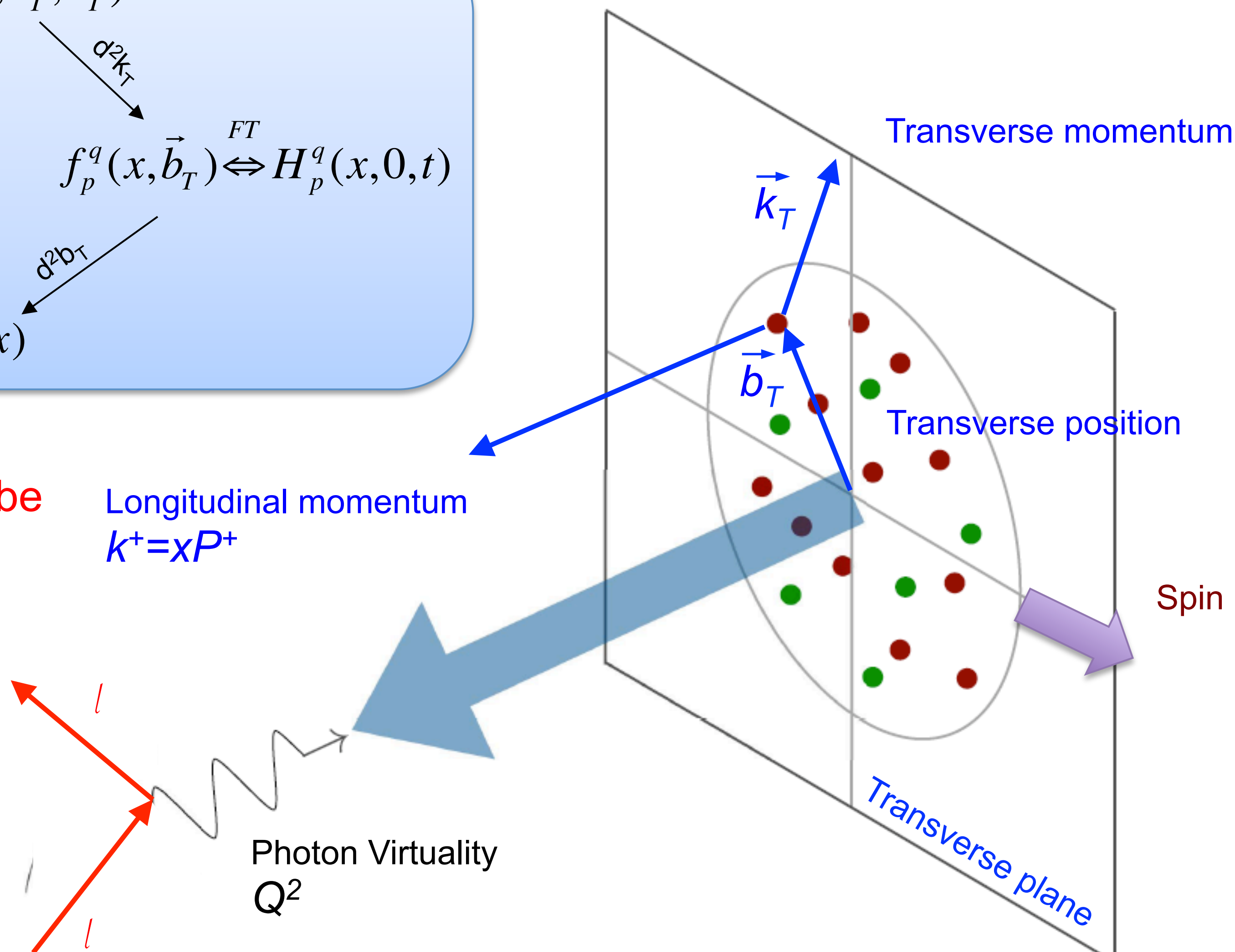


The 3D Nucleon Structure

$$
\begin{tikzcd}
 & W_p^q(x,\vec{k}_T,\vec{b}_T) \arrow[dl, "d^2b_T"'] \arrow[dr, "d^2k_T"] & & \\
f_p^q(x,\vec{k}_T) \arrow[dr, "d^2k_T"'] & & f_p^q(x,\vec{b}_T) \arrow[dl, "d^2b_T"] \arrow[r, phantom, "\overset{FT}{\Leftrightarrow}"] & H_p^q(x,0,t) \\
 & f_p^q(x) & &
\end{tikzcd}
$$

Confinement Scale

High Energy Probe
Hard Scale

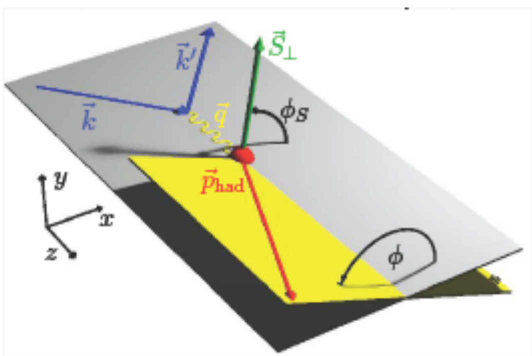


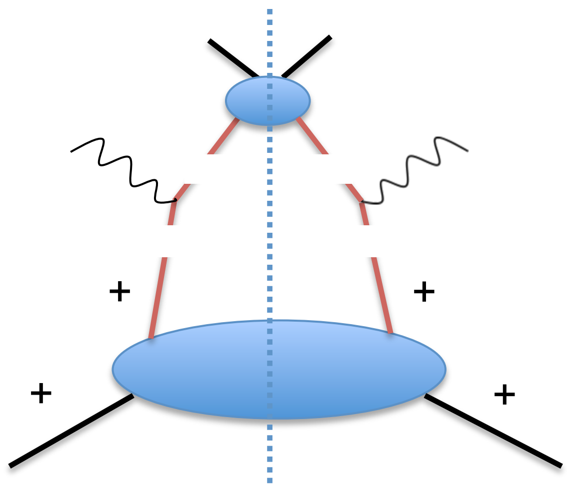
SIDIS Cross-Section & TMDs

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

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

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





Quark fragmentation

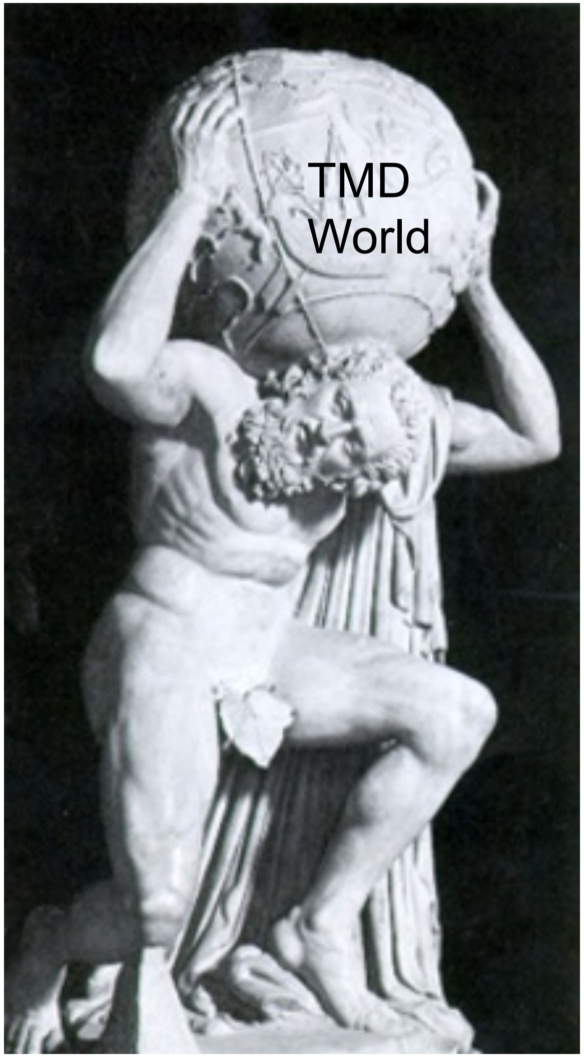
TMD Factorization holds for p_T<<Q

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



quark polarisation

hadron polarisation

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

quark polarisation

nucleon polarisation

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

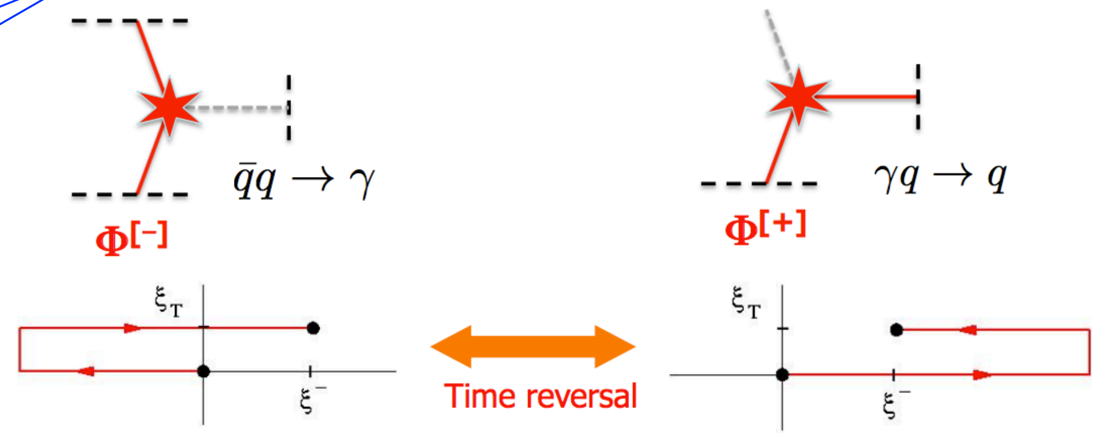
+ Quark correlators at sub-leading twist
+ Gluon correlators (x 2 gauge links)
+ Di-hadron fragmentations

Beauty and complexity of the unique strong-interacting world

Gauge Invariance

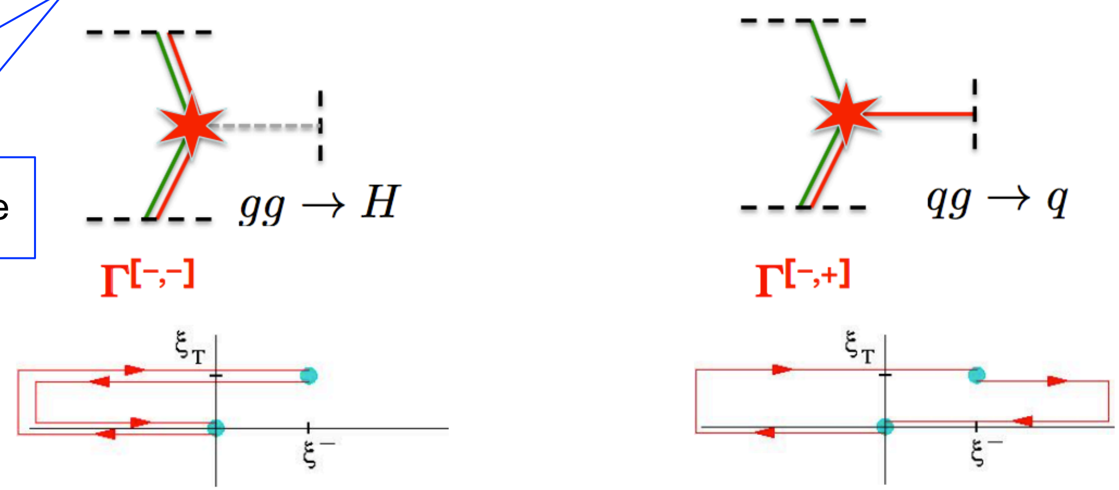
$$\Phi_{ij}^{q[C]}(x,p_T;n)=\int\frac{d(\xi.P)d^2\xi_T}{(2\pi)^3}e^{ip.\xi}\langle P|\bar{\psi}_j(0)U^{[C]}_{[0,\xi]}\psi_i(\xi)|P\rangle_{\xi.n=0}$$

Path dependent gauge link



$$\Gamma^{\alpha\beta[C,C']}(x,p_T;n)=\int\frac{d(\xi.P)d^2\xi_T}{(2\pi)^3}e^{ip.\xi}\langle P|U^{[C]}_{[\xi,0]}F^{n\alpha}(0)U^{[C']}_{[0,\xi]}F^{n\beta}(\xi)|P\rangle_{\xi.n=0}$$

Color flow and process dependence



A way to access gauge effects as color flow

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

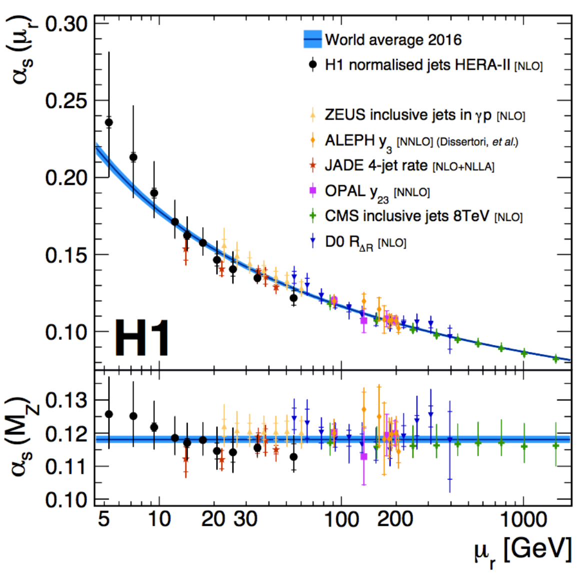
Inclusive Jets @ HERA

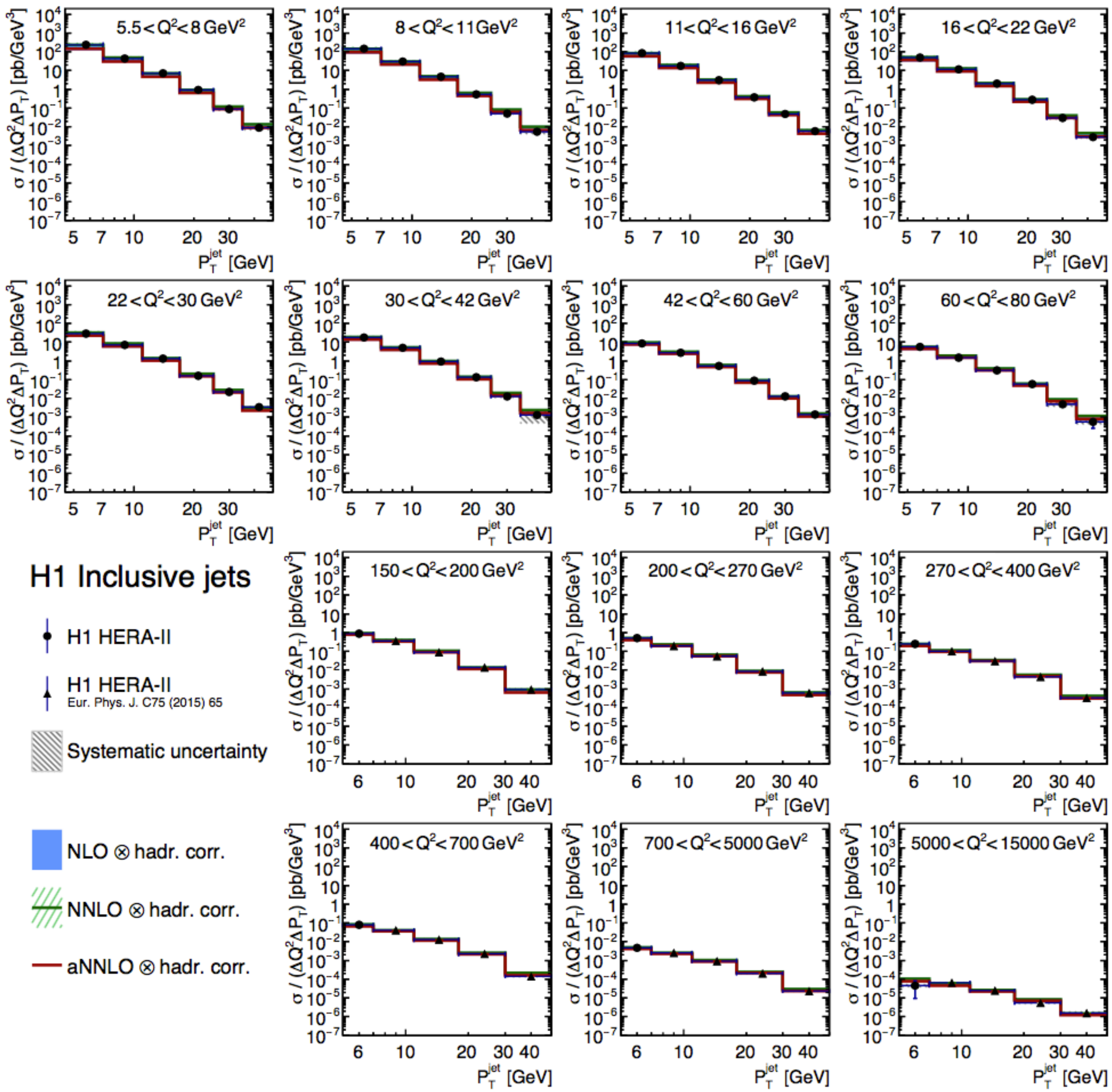
Good perturbative description (hard gluon emission)

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

Part in a $p_T << Q$ TMD regime

H1 [arXiv: 1611.03421]

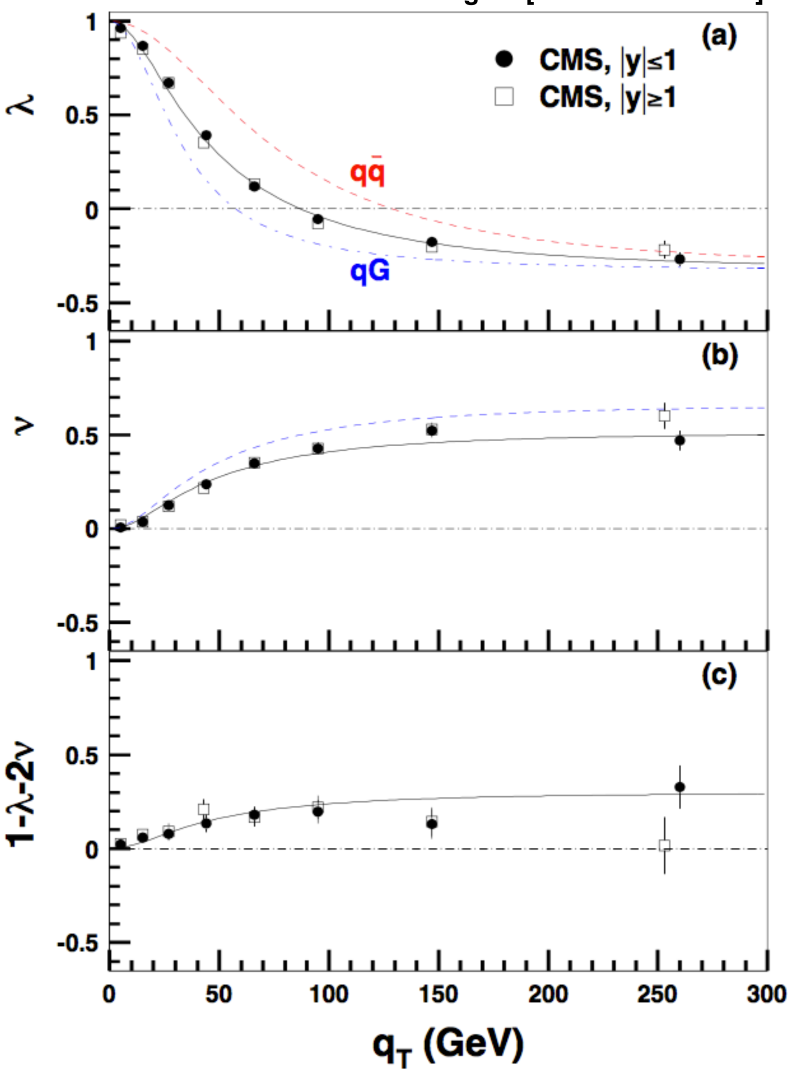




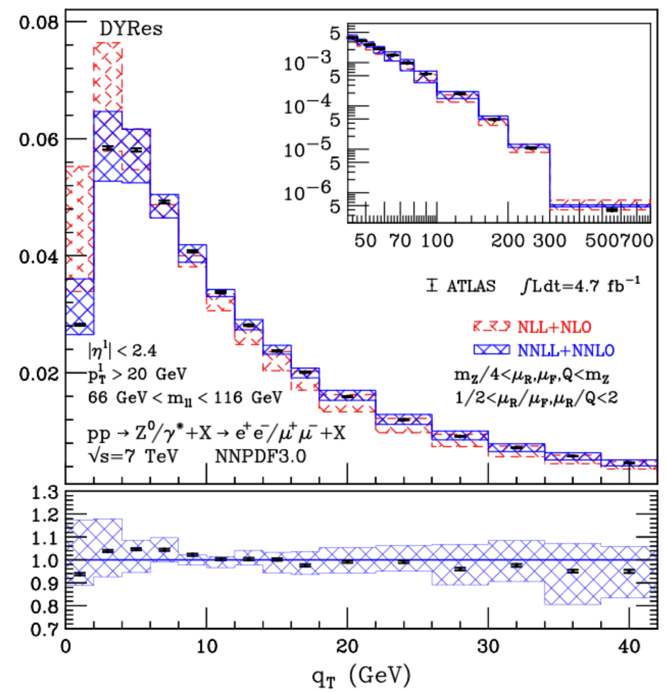
Non Perturbative QCD Signals

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

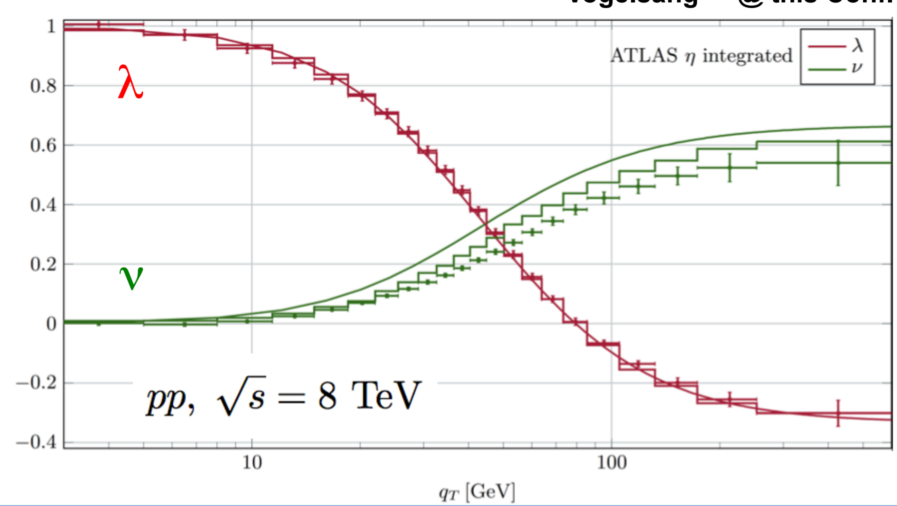
Peng++ [arXiv: 1511.08932]



Catani++ [arXiv: 1507.06937]



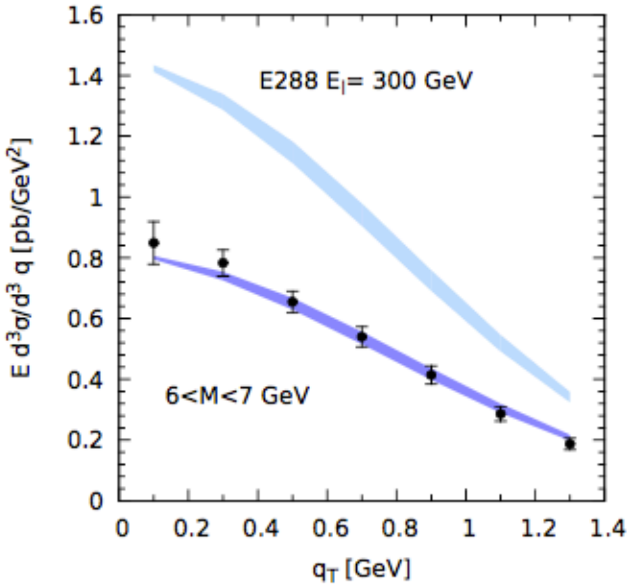
Vogelsang++ @ this Conf.



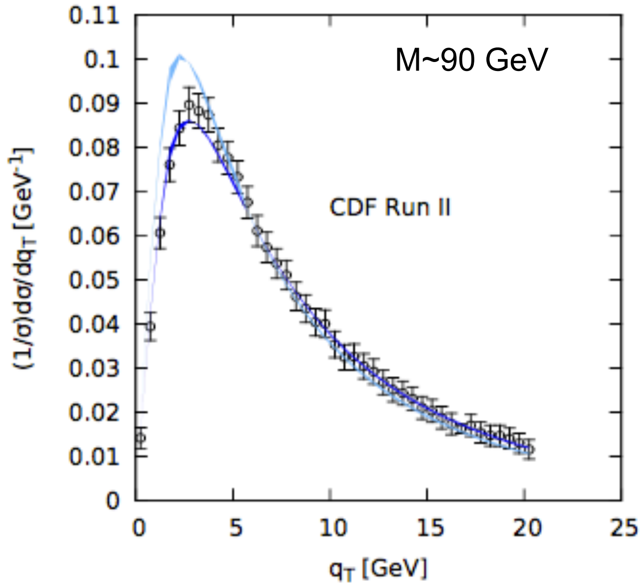
LO

NLO

Non Perturbative QCD Signals



D'Alesio++ [arXiv: 1407.3311]



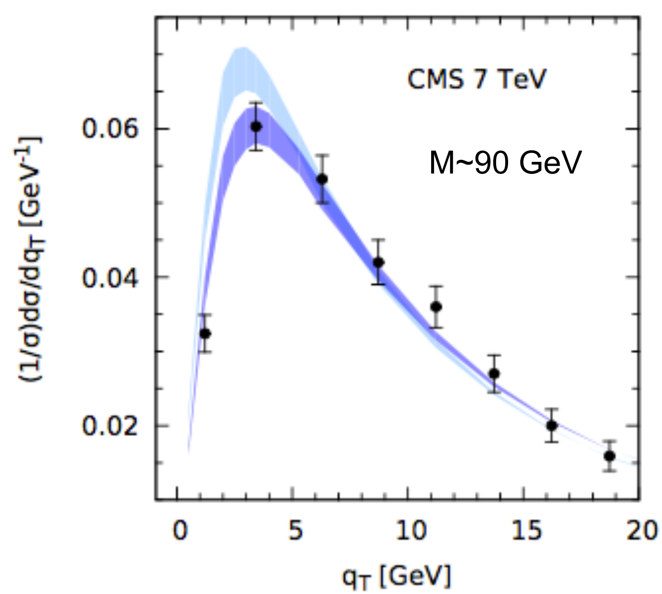
$q_T/Q \sim 1/10$

$q_T \sim \Lambda_{QCD}$

$q_T/Q \sim 1/20$

$q_T >> \Lambda_{QCD}$

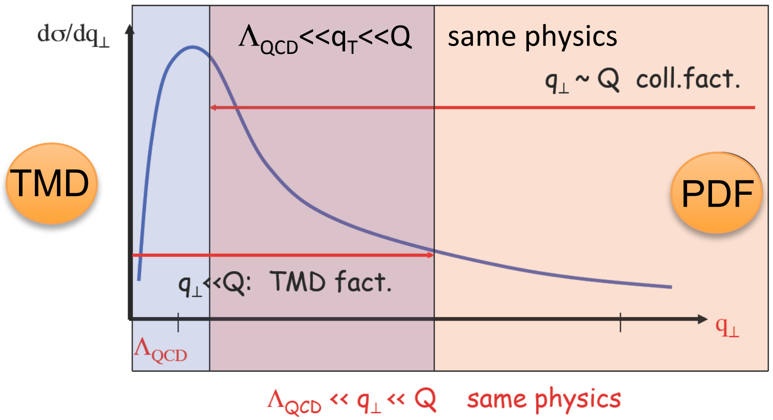
NNLL

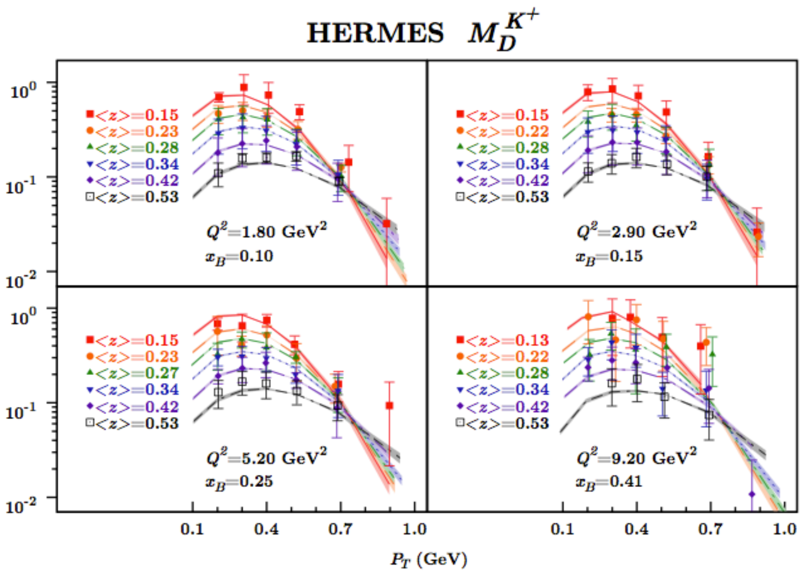


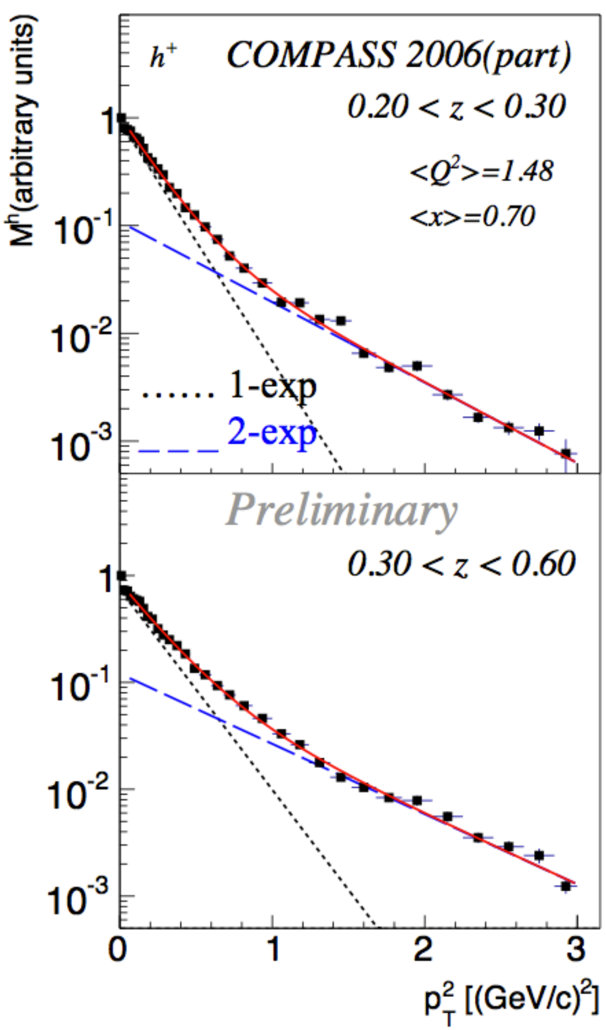
Non perturbative PDF component shows effects
up to vector boson production at LHC
No evidence for a strong NP contribution in evolution

Matching Issue

Within the limited phase−space of fixed target SIDIS experiments, easy to reach p_T~Q





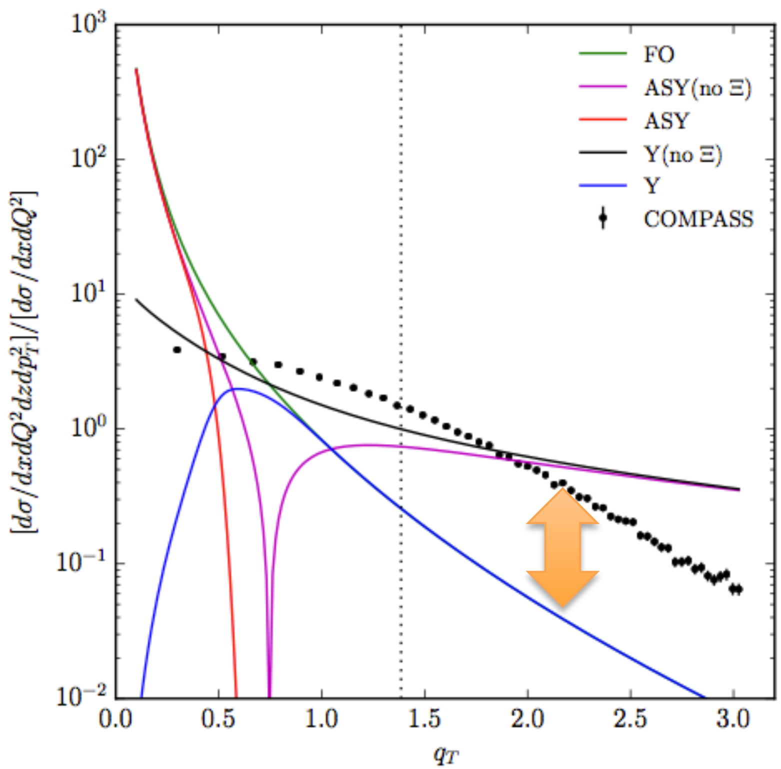


Matching Issue

Y term required to match the high q_T region

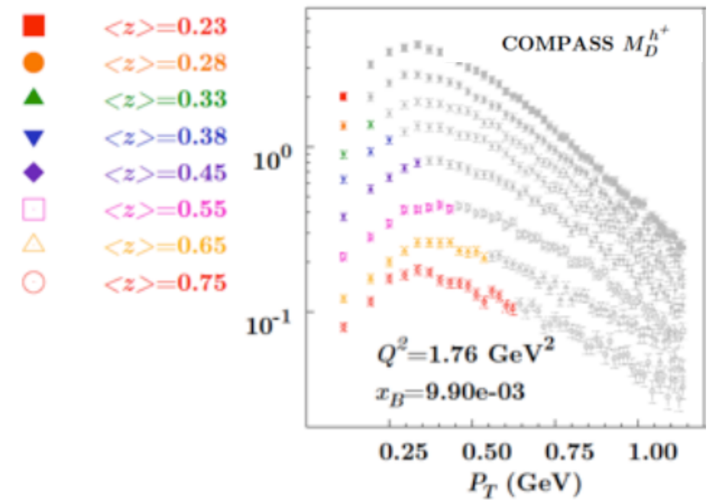
Dominated by un-constrained non-perturbative contribution at fixed target experiments

Collins++ [arXiv: 1605.00671]

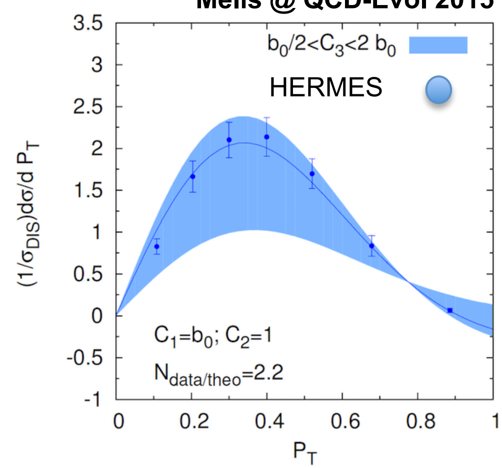


$$Q^2 = 1.92\mathrm{GeV}^2, x = 0.0318, z = 0.375$$

Gonzales @ POETIC2016

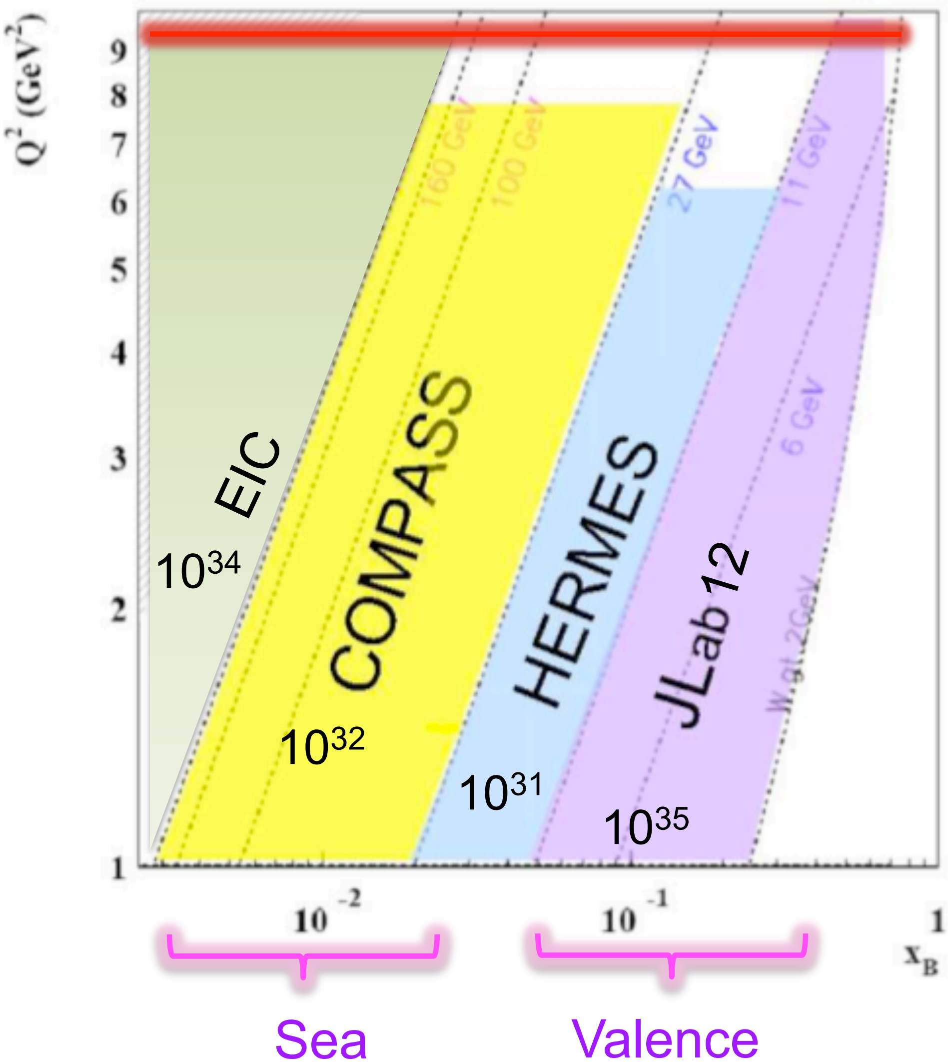


Melis @ QCD-Evol 2015

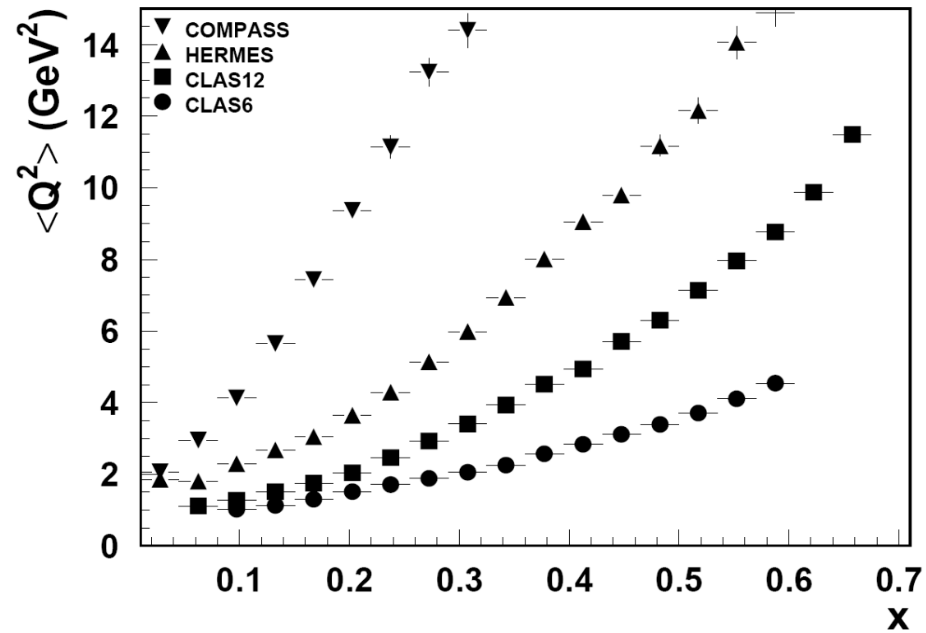


The SIDIS Landscape

Limit defined by luminosity



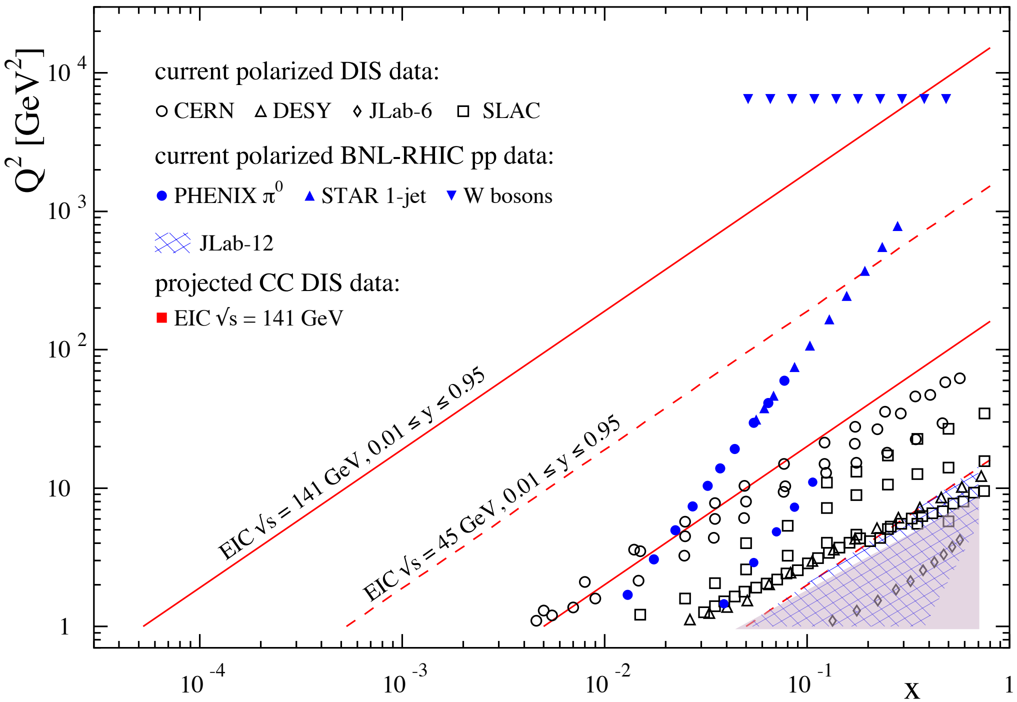
Different Q^2 for same x range

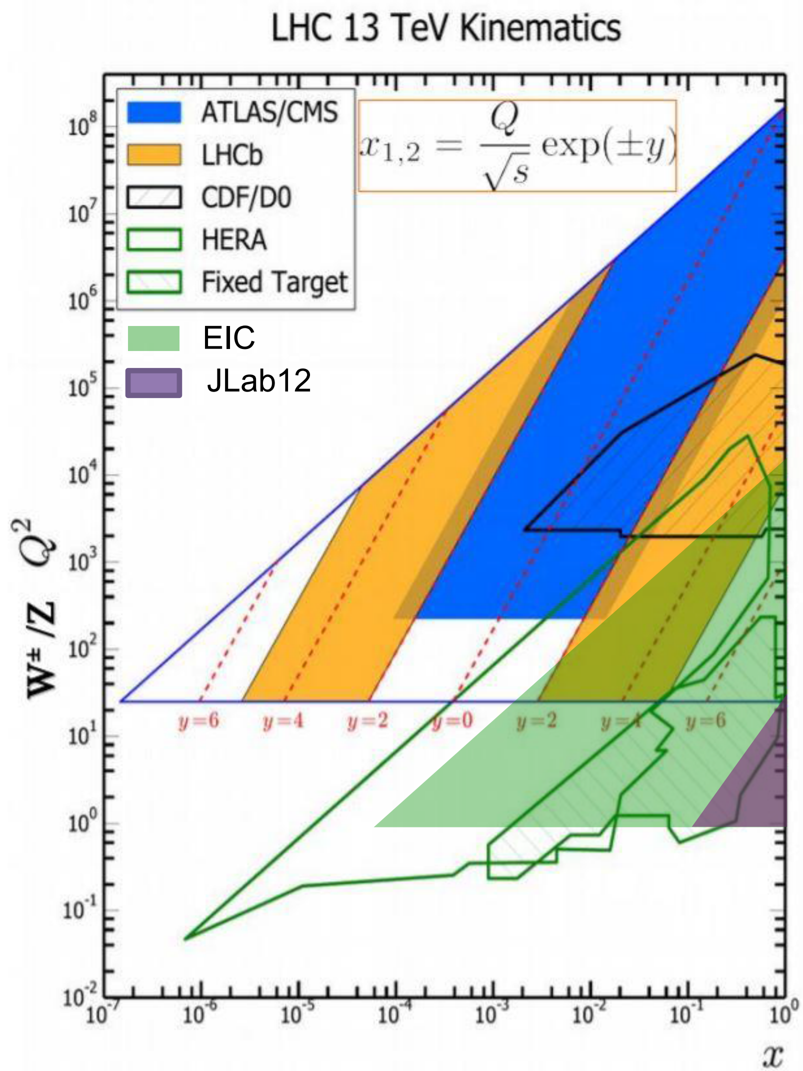


HERMES:	< 2007
COMPASS:	< 2017 (2021++)
JLab6	< 2012
JLab12:	2017++
EIC:	2025++

Kinematical Plane

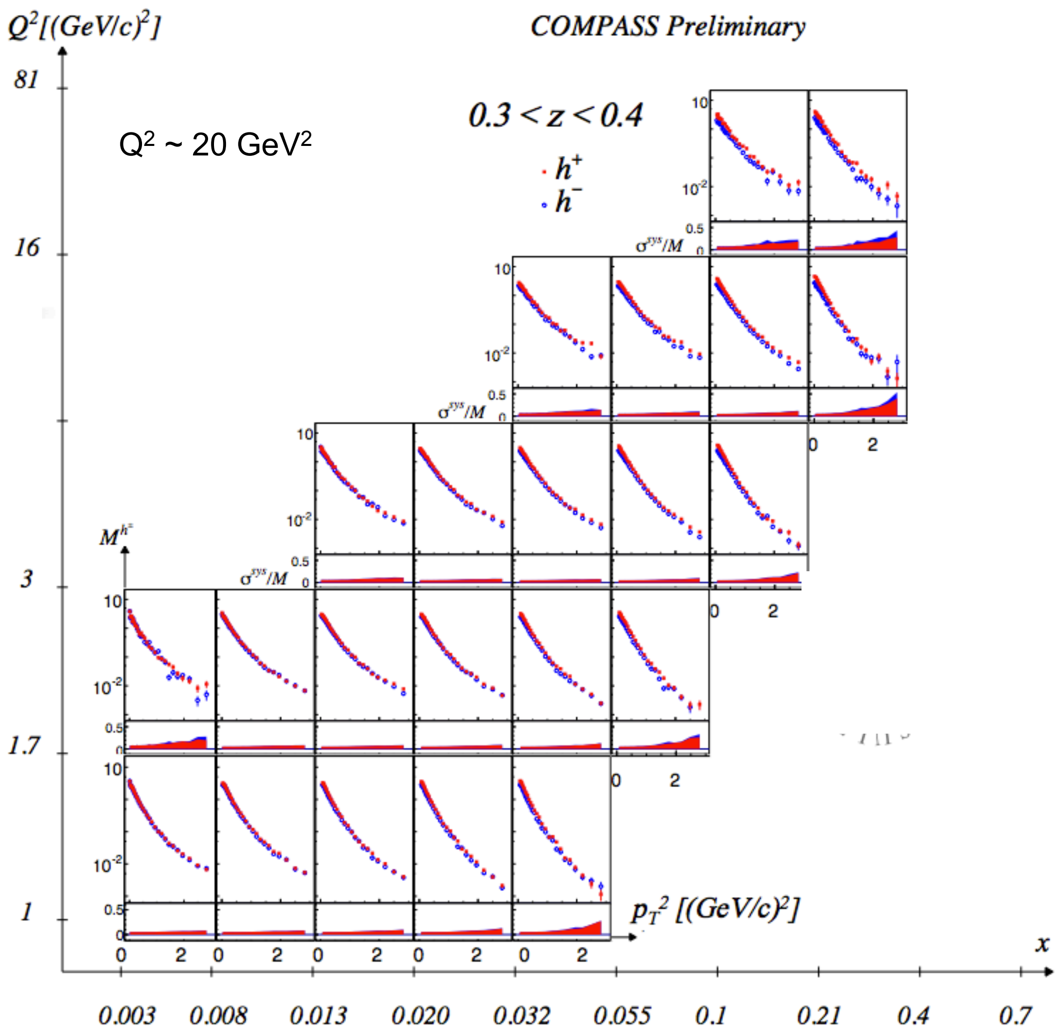
EIC will provide data in the much needed “intermediate” energy region matching “pure” pQCD with “pure” TMD regime.





The Multi-D Approach

Umpolarized Multiplicities



Disentangle all the kinematic dependences

Asymmetries so far used to suppress systematics effects

$$A_{LL} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$A_{LL} = \frac{1}{fP_T P_B} \frac{N^+ - N^-}{N^+ + N^-}$$

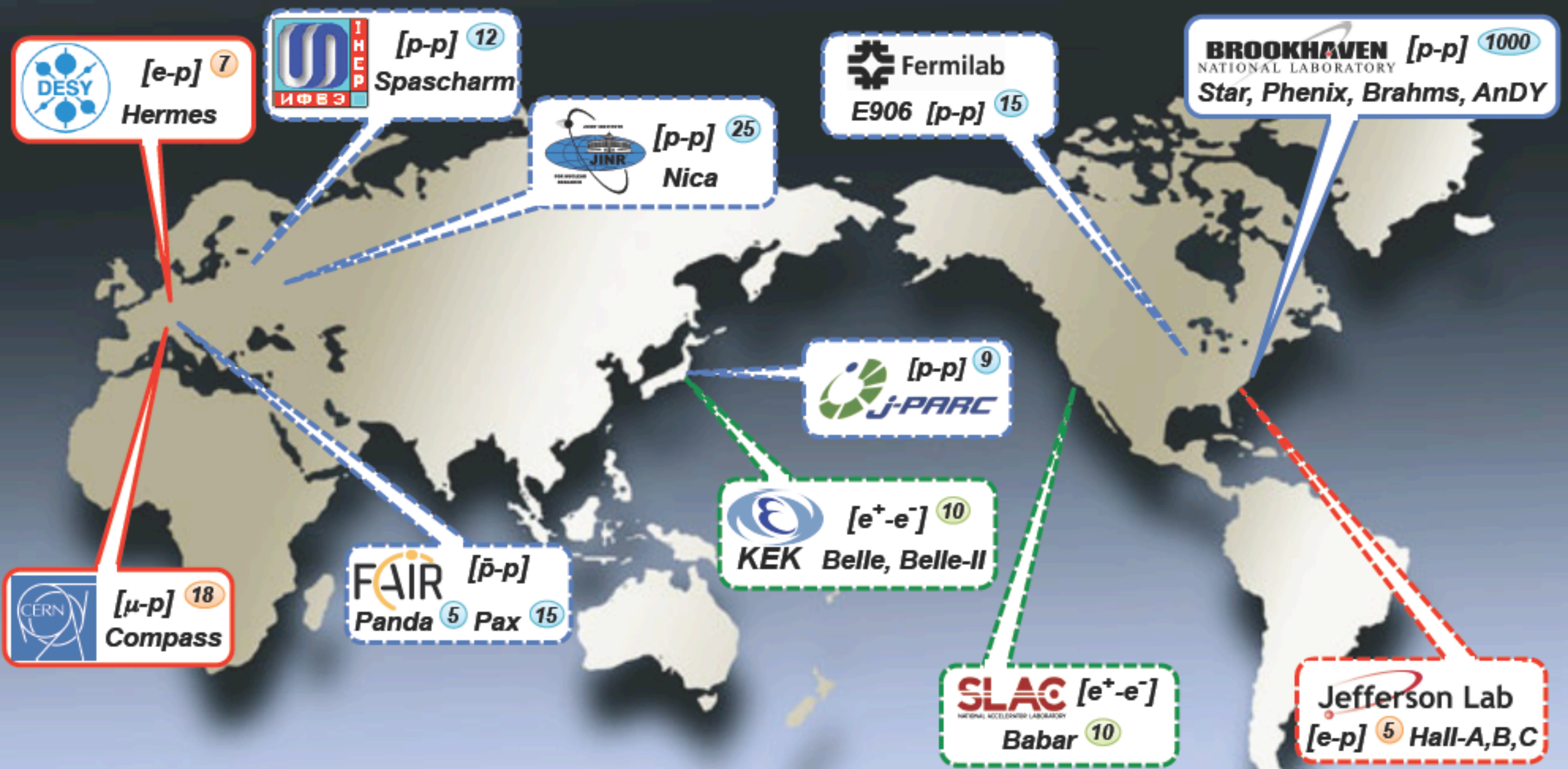
They suppress also physics (i.e. evolution)

Multi-D:

- naturally reduces some source of systematics
- blows up the statistical error also due to smearing and acceptance

Requires high-luminosity for next DIS

A World-wide Challenge



Babar (e+e-): < 2007

BELLE (e+e-): < 2010

BELLEII (e+e-): 2017++

SeaQuest (pp): 2012 - 2016

RHIC (pp): 2011, 2017++

COMPASS (πp): 2016 – 2017

JPARC(pp): 2018++

FAIR (p̄p): 2018++

NICA (pp): 2018++

AFTER (pp): 2020++

Transverse Momentum Dependent Distr.

quark polarisation

nucleon polarisation

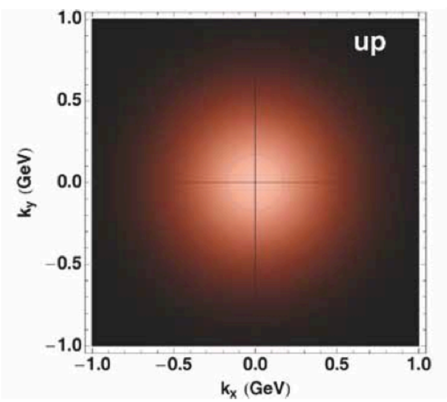
N/q	U	L	T
U	f_1		$\boldsymbol{h_1^\perp}$
L		g_1	$\boldsymbol{h_{1L}^\perp}$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h, h_{1T}^\perp$

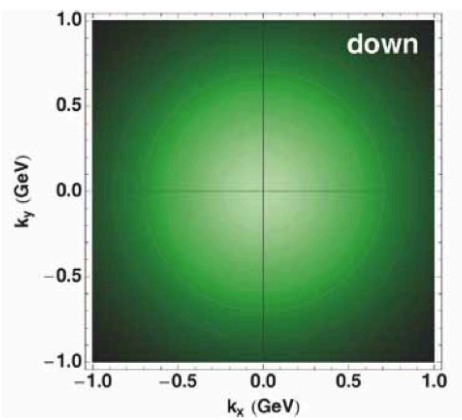
$\otimes$

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

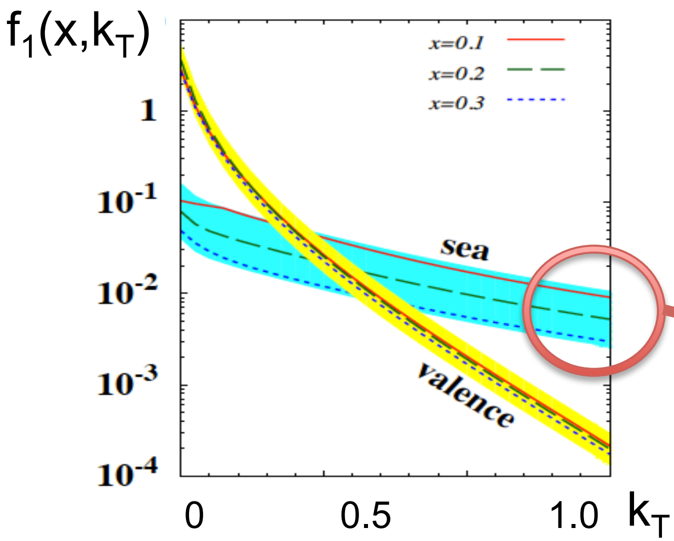
✓ Low-x physics:
color glass condensate

✓ Hadronization:
parton dynamic in medium

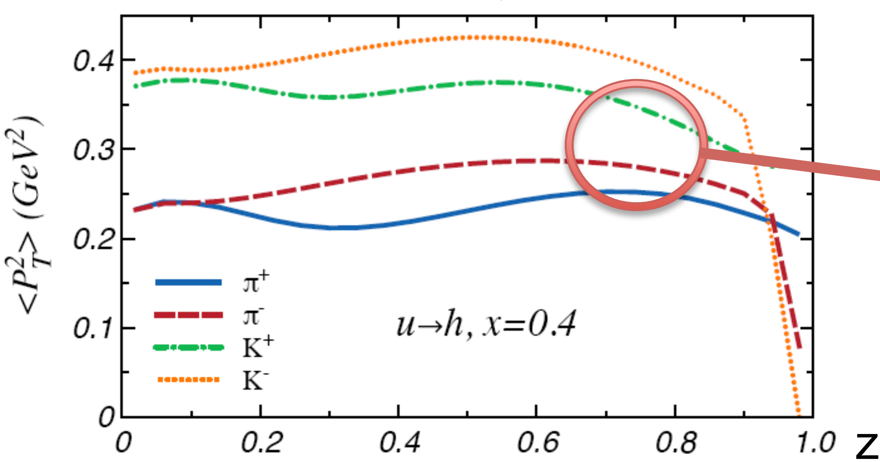
Unpolarized TMDs

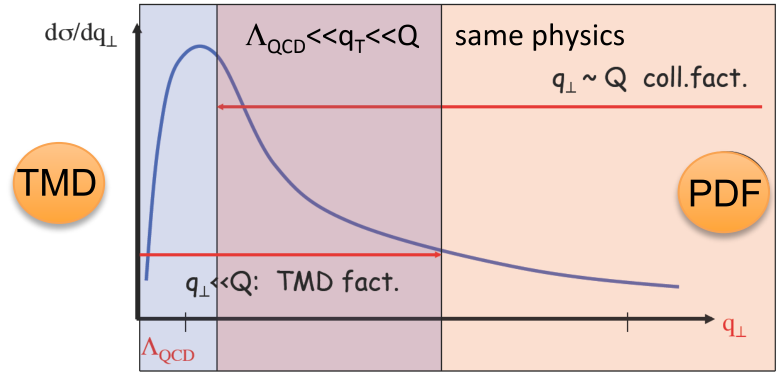
$$\sigma_{UU} \propto f_1\,(k_T\ldots)\otimes D_1\,(p_T\ldots)$$

P. Schweitzer++ [arXiv:1210.1267]



Matevosyan++ [arXiv:1111.1740]





Large tiles extending up to the inverse of the gauge field fluctuation scale ρ<<M

May short range parton correlations manifest also in pp MPI ?

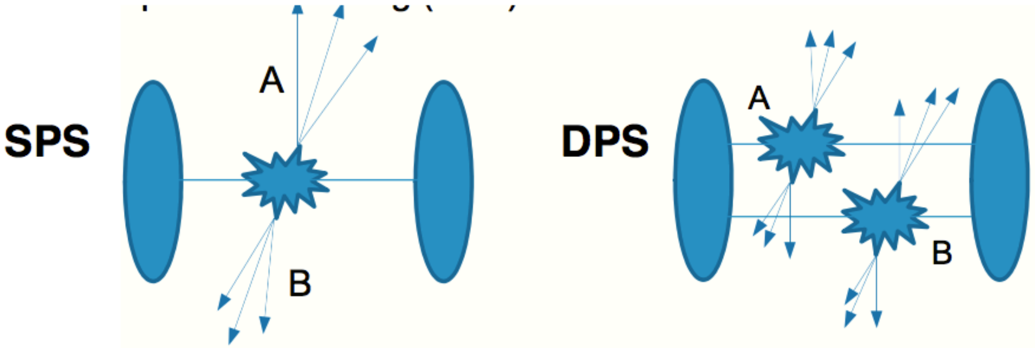
Reflect different fragmentation

May be enhanced in medium.

Parton propagation in cold matter as complementary study to QGP

Space-Momentum Parton Correlations

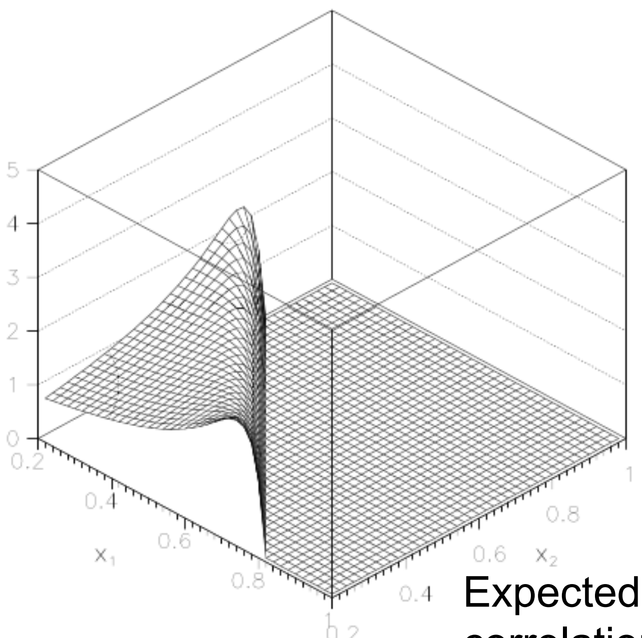
May manifest in multi-particle interactions



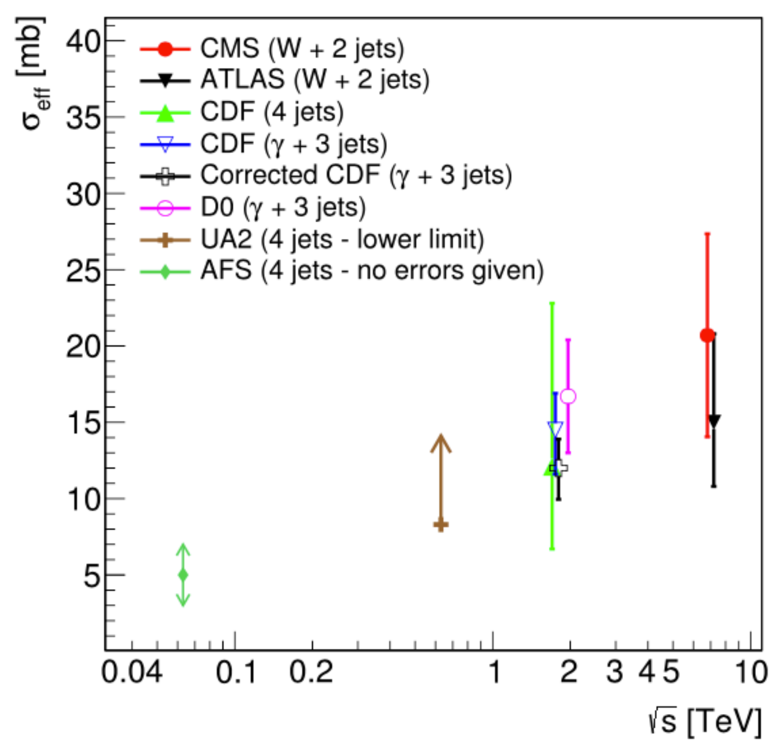
$$\sigma^{pp}_{double} = \frac{m}{2} \frac{\sigma^{pp'}_{A}\, \sigma^{pp'}_{B}}{\sigma_{eff}}$$

Scopetta++ @ this Conf.

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

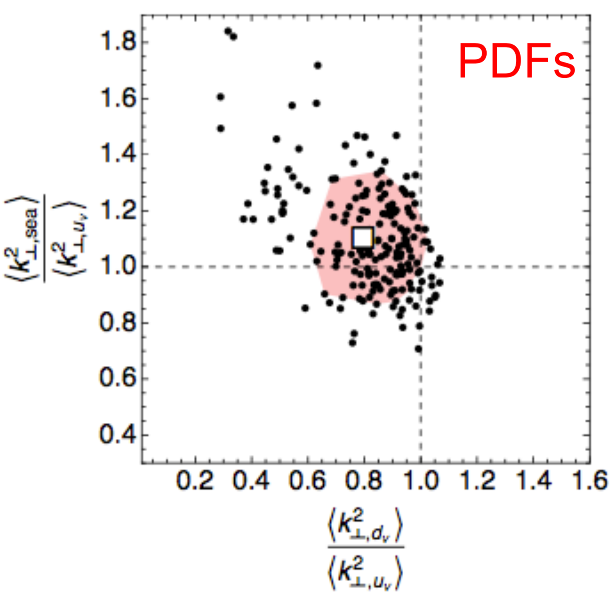


Expected model-independent correlation from $x_1+x_2<1$



Flavor Dependence

M. Anselmino++ [arXiv:1312.6261]



TMD Q^2 evolution ≠ DGLAP

Very interesting non perturbative part of evolution taken from data

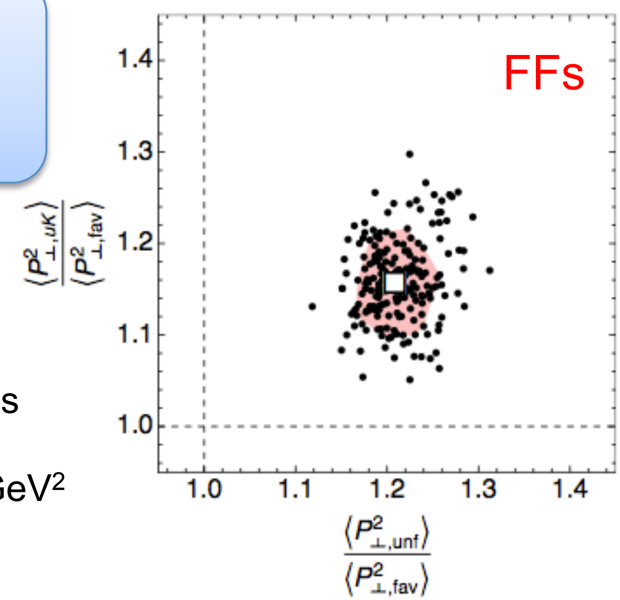
Fixed target SIDIS

Q^2 ~ few GeV^2

B-factories

Q^2 ~ 100 GeV^2

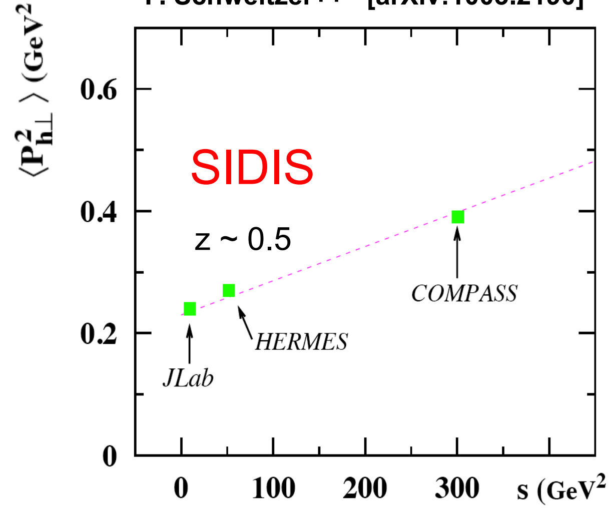
A. Signori++ [arXiv:1309.3507]



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]

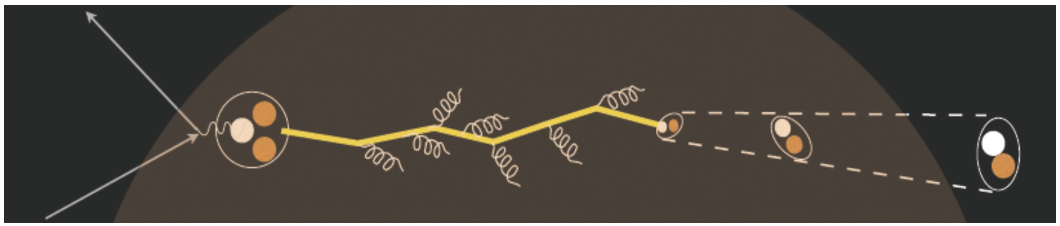


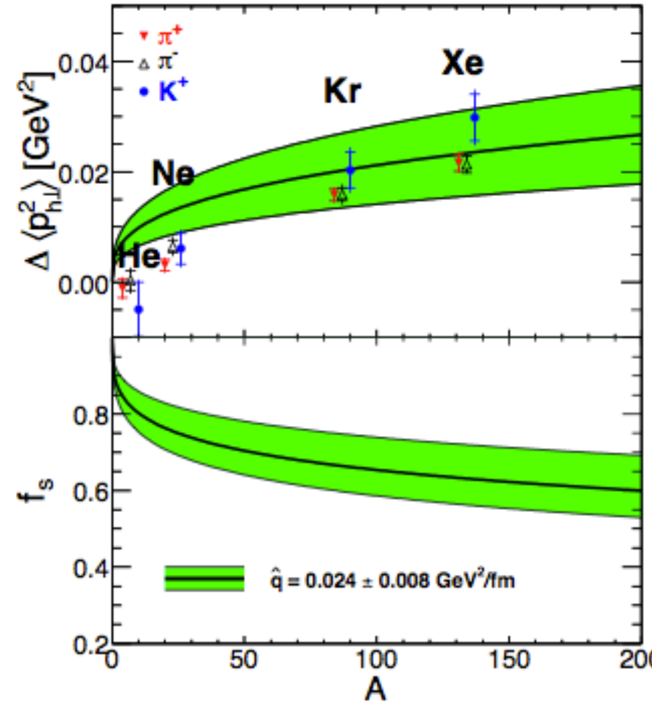
Medium modification

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

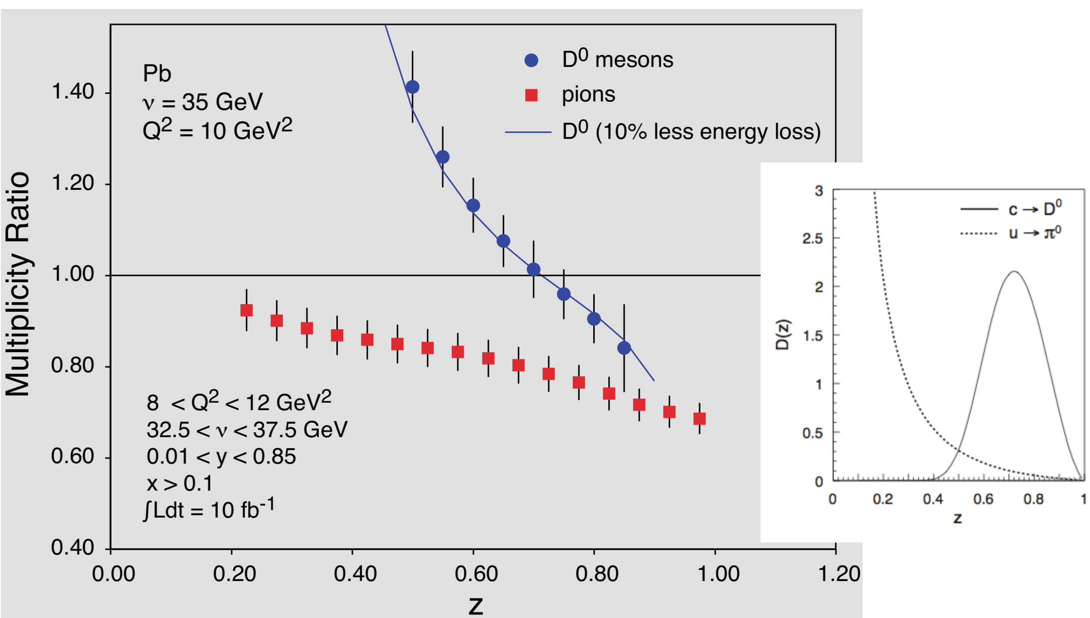
- primordial transverse momentum + gluon radiation of the struck quark
- the formation and soft multiple interactions of the "pre-hadron"
- the interaction of the formed hadrons with the surrounding hadronic medium

HERMES [arXiv: 0906.2478]





A. Accardi et al. [arXiv 1212.1701]



N-B Chang ++ [arXiv:1402.3042]

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

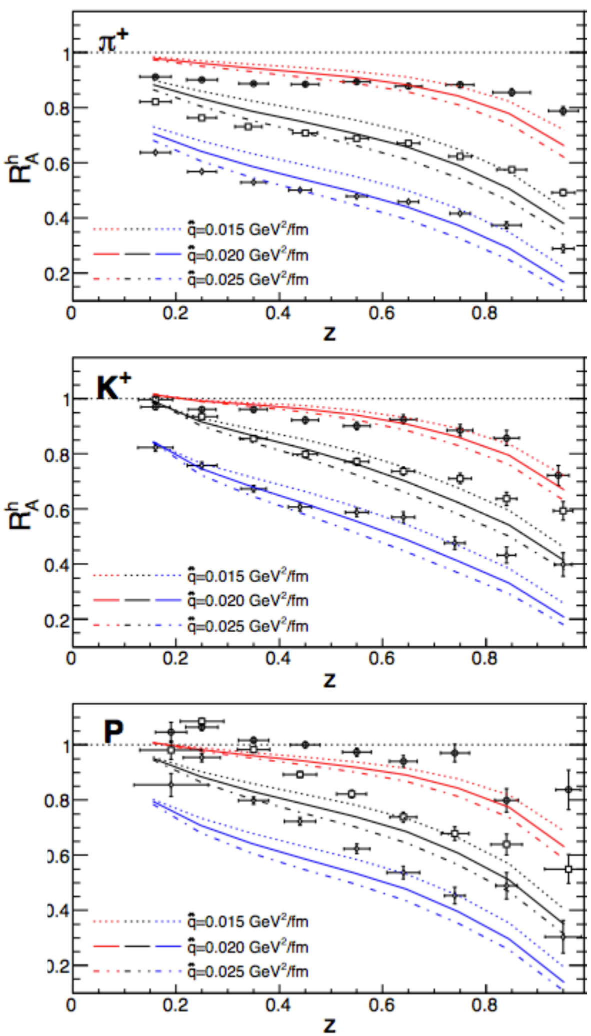
$$\frac{\langle\cos\phi\rangle^{eA}_{UU}}{\langle\cos\phi\rangle^{eN}_{UU}} \approx \frac{\langle\sin\phi\rangle^{eA}_{LU}}{\langle\sin\phi\rangle^{eN}_{LU}} \approx \frac{\alpha}{\alpha+\Delta_{2F}} = f_s$$

Medium modification

DIS

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

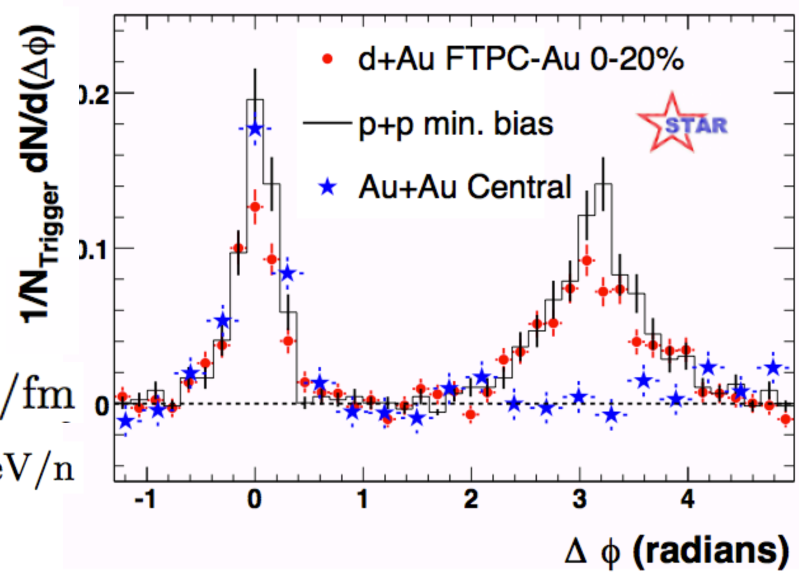
N-B Chang ++ [arXiv:1401.5109]



RHIC

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

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

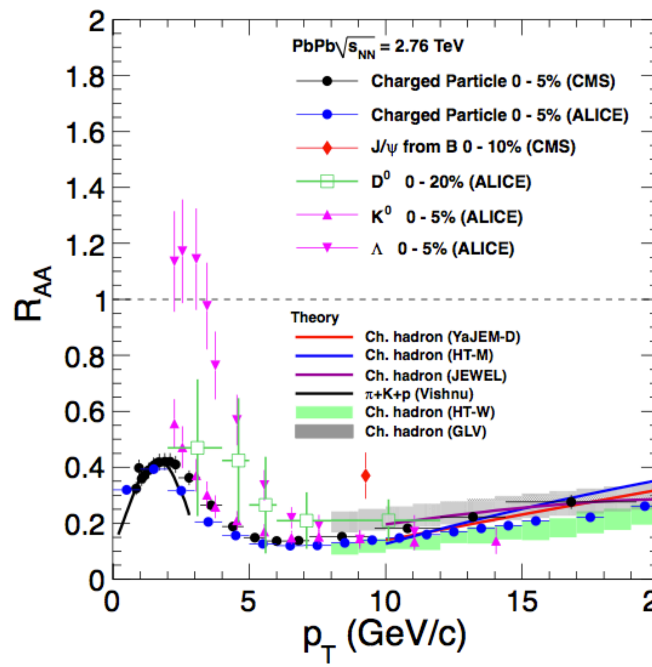


JET Coll. [arXiv:1312.5003]

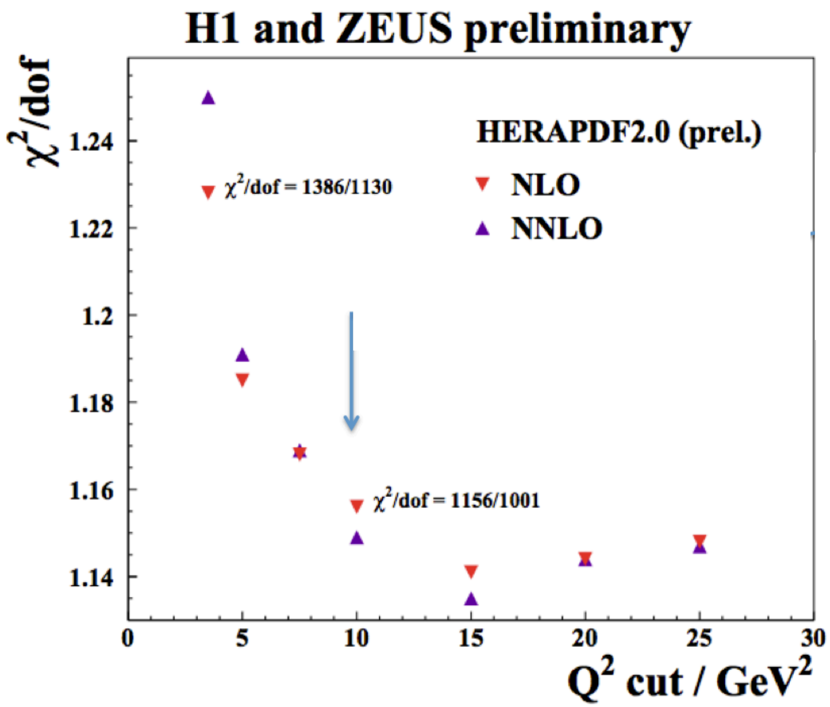
LHC

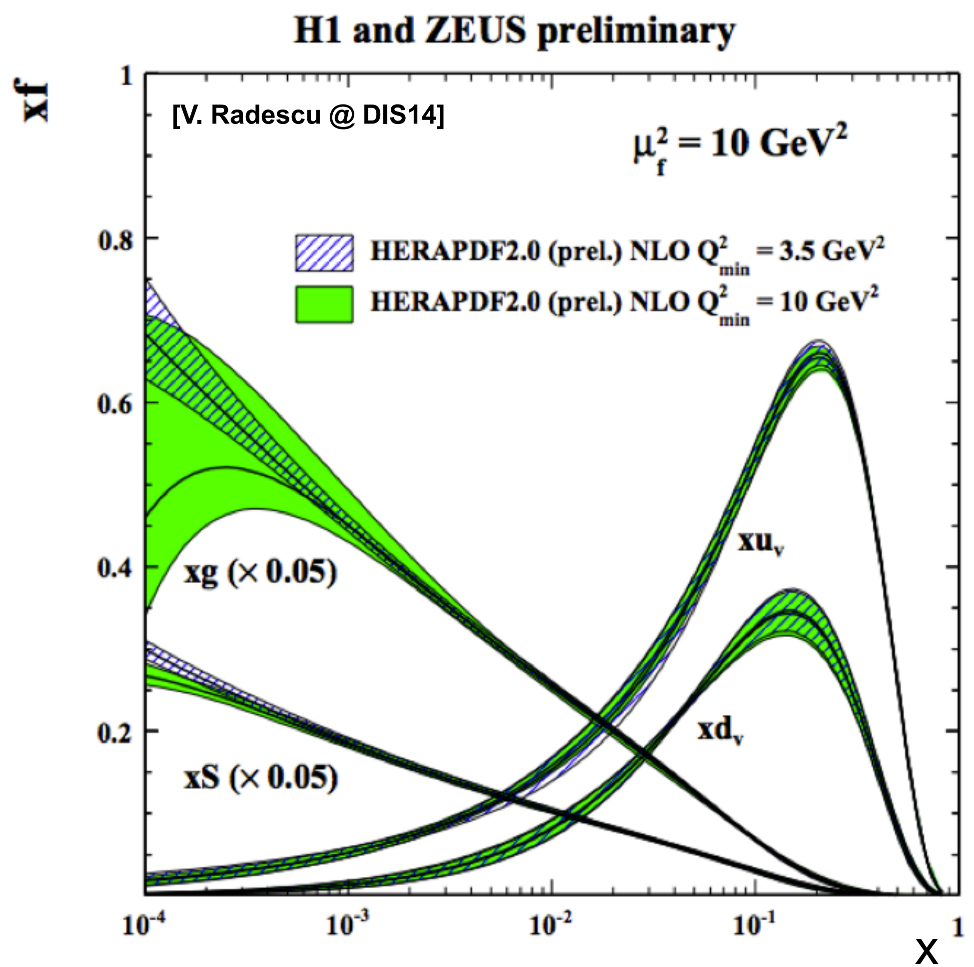
$\hat{q} \approx 1.9 \pm 0.7\ \mathrm{GeV}^2/\mathrm{fm}$

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



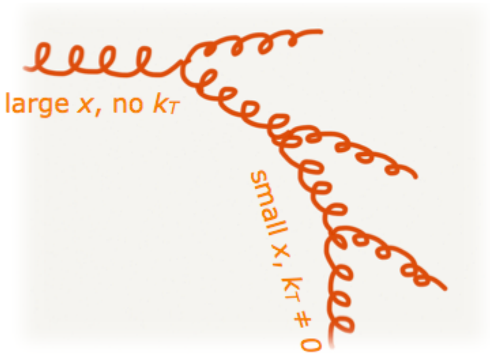
Low-x Physics





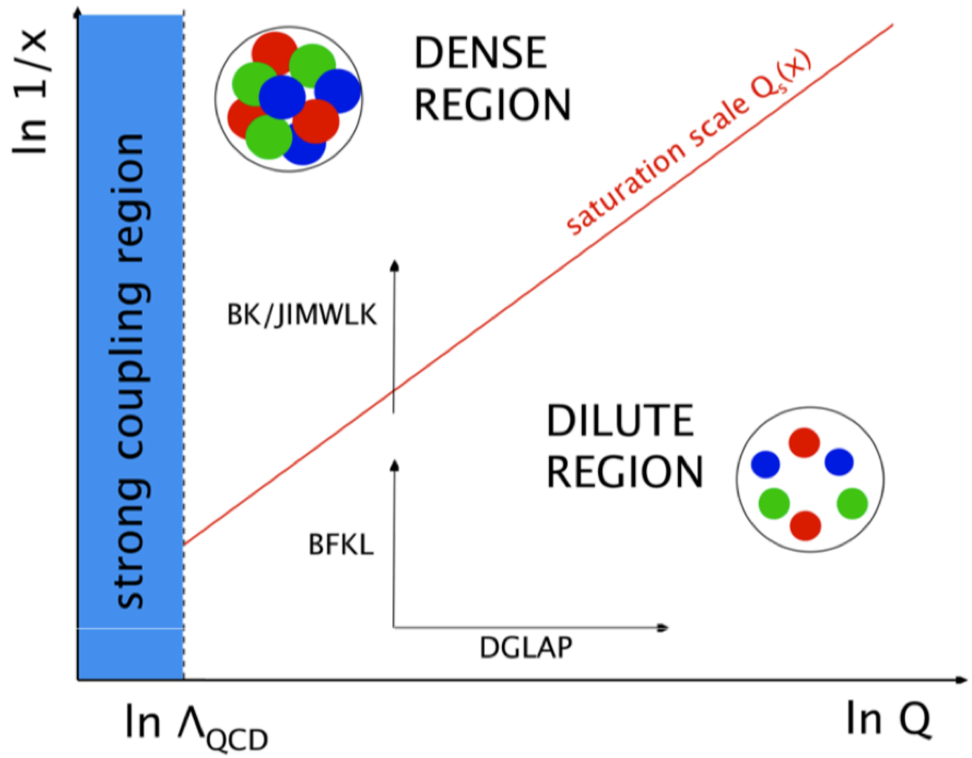
Interplay of the data cut at low Q^2 and impact on gluon at low x

QCD Phase Diagram



***x* low, *Q*² not too high:**

- **partonic k_T** may become important!
  - are (perturbative) parton showers enough to describe this?
  - or does one need something more? k_T-dependent parton densities?



BFKL must be the correct theory of low-x QCD

It naturally incorporates k_T-unintegrated PDFs

Mechelen at DIS2014: no clear evidence of BFKL in experimental data

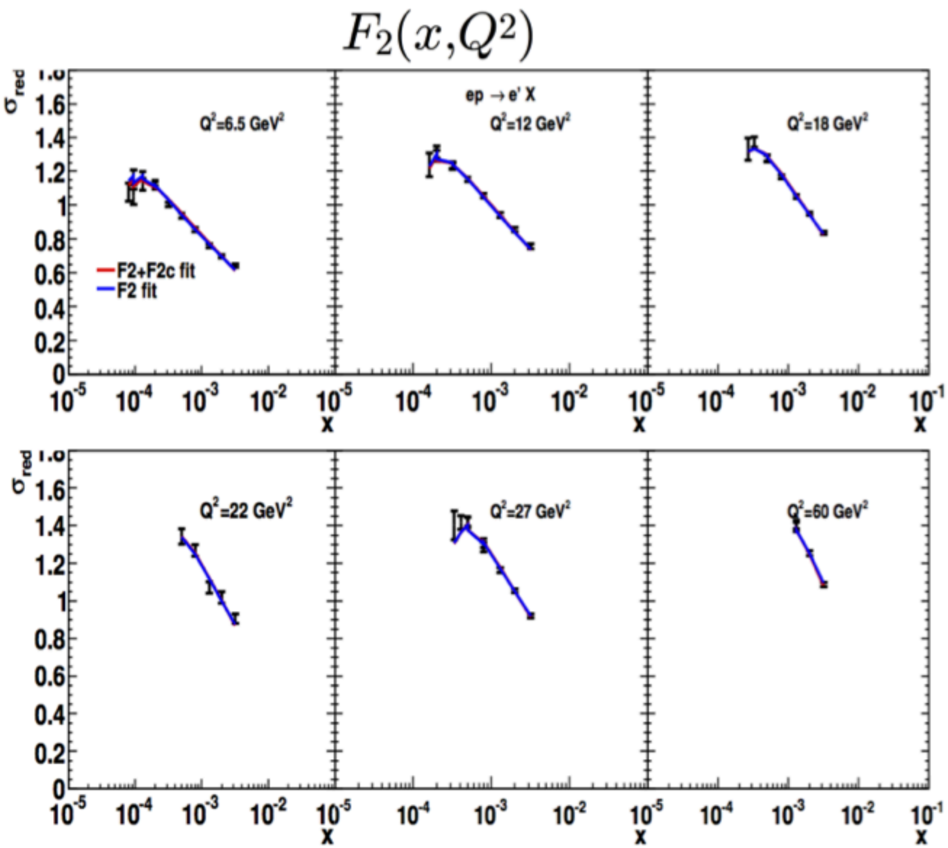
Gluon TMDs

Starting distribution for gluons at q_0

$$xA_0(x,k_\perp) = Nx^{-B}\cdot(1-x)^C\left(1-Dx+E\sqrt{x}\right)\exp[-k_t^2/\sigma^2]$$

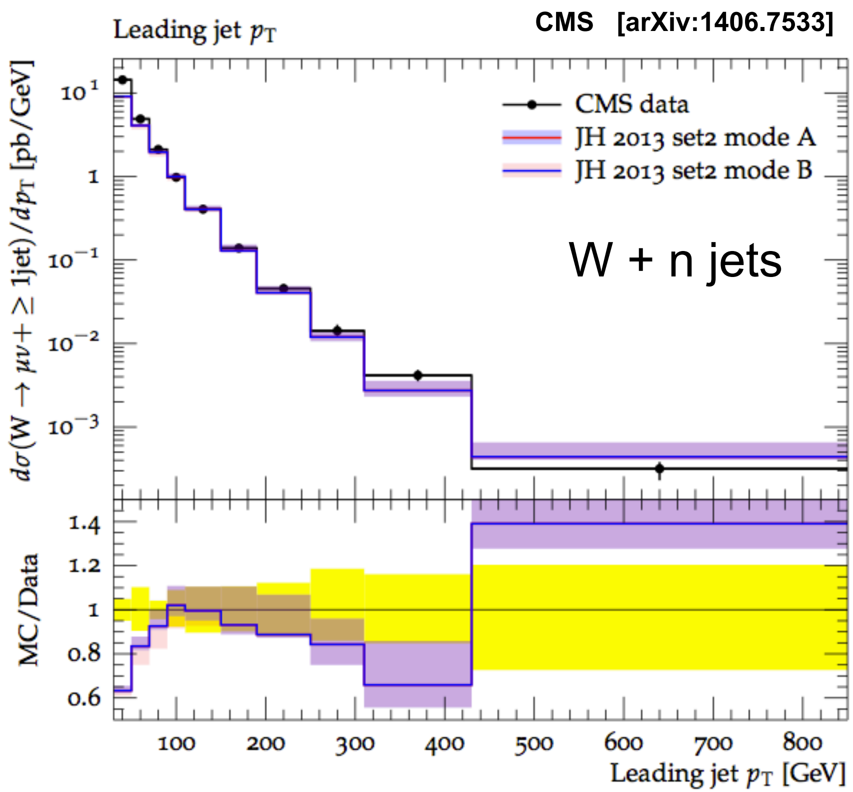
$\sigma^2 = q_0^2/2$

CCFM (BFKL like) evolution + Herafitter package



S. Dooling ++ [arXiv 1406.2994]

CMS [arXiv:1406.7533]



Transverse Momentum Dependent Distr.

quark polarisation (columns) / **nucleon polarisation** (rows)

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 (columns) / **hadron polarisation** (rows)

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:

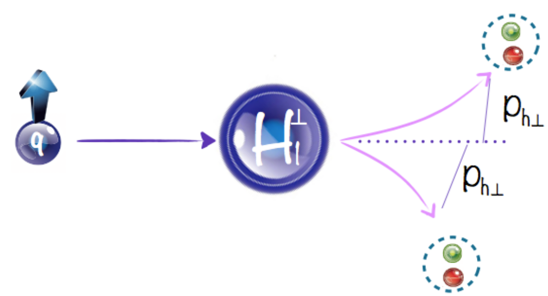
✓ Tensor Charge & Coupling

✓ SSA in hadron interactins

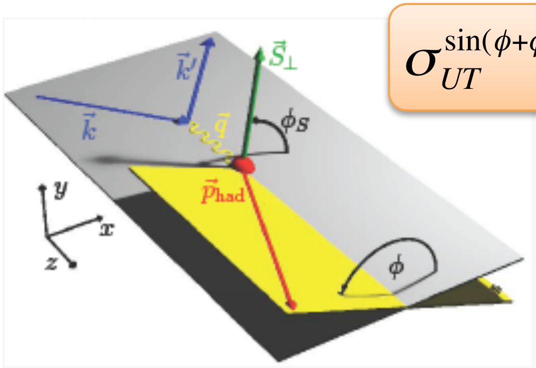
Collins function:

a spin-p_T correlator in fragmentation

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

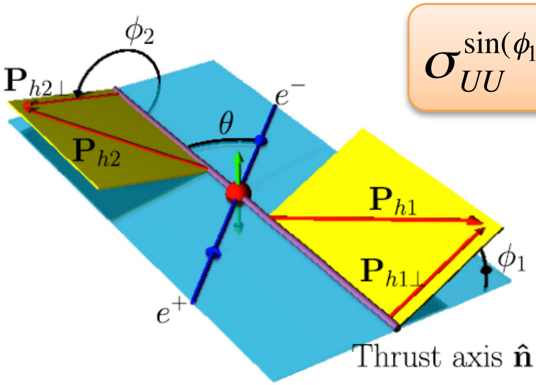


Transversity & Collins Evidences



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

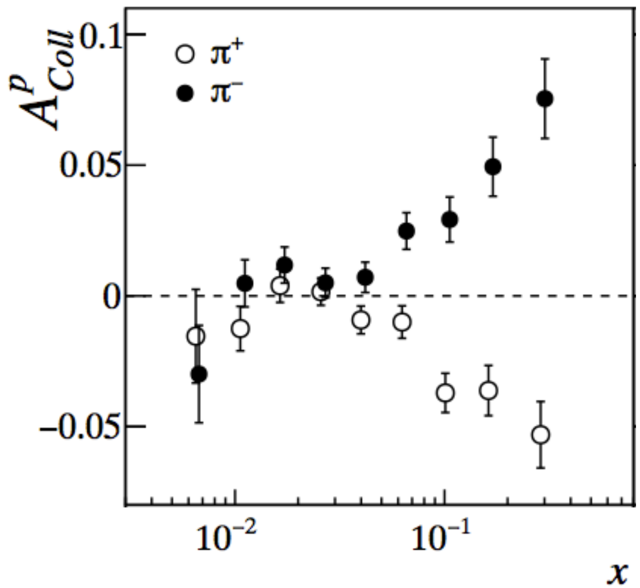
$Q^2 \sim$ 5-7 GeV^2



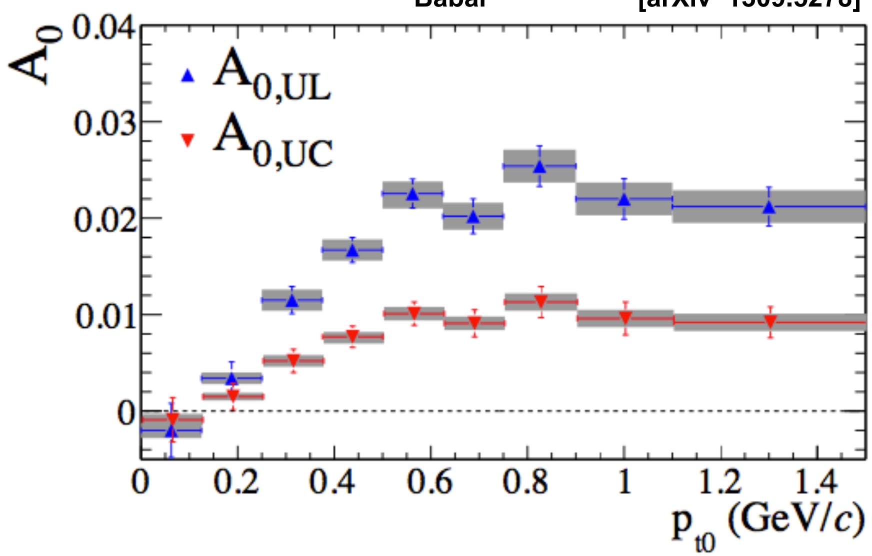
$$\sigma_{UU}^{\sin(\phi_1+\phi_2)} \propto H_1^{\perp} \otimes H_1^{\perp}$$

$Q^2 \sim$ 110 GeV^2

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

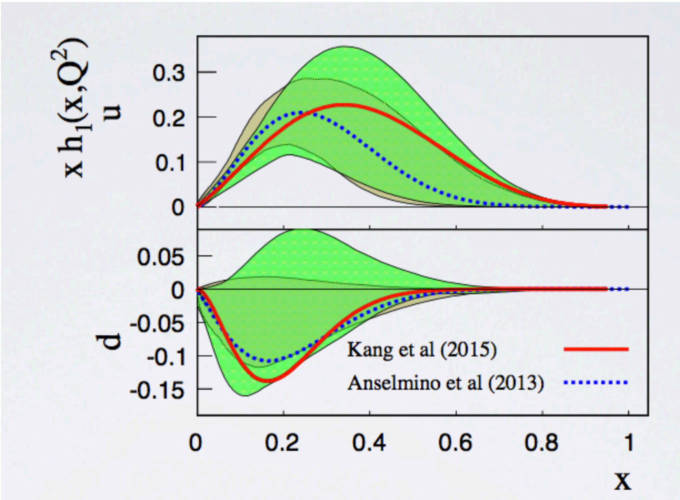


Belle	**[talk at DIS2014]**
BESIII	**[arXiv 1507.06824]**
Babar	**[arXiv 1309.5278]**

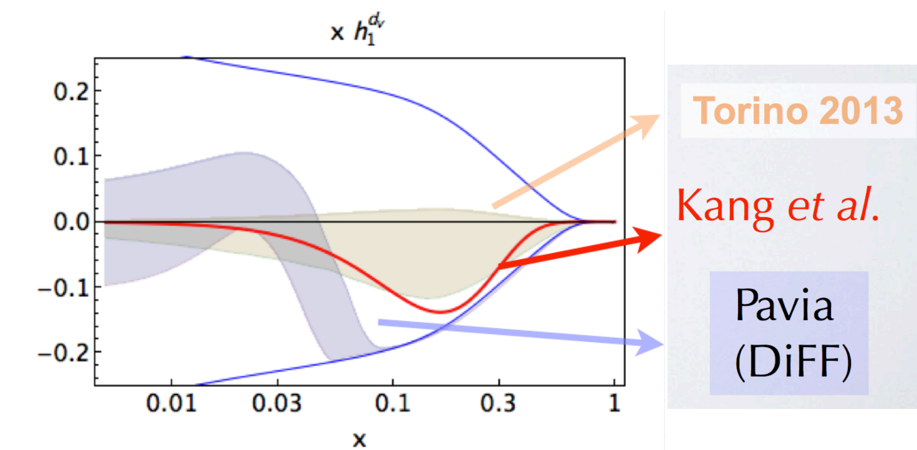


Transversity & Tensor Charge

Distributions:



x



How well is Soffer bound know at large x ?

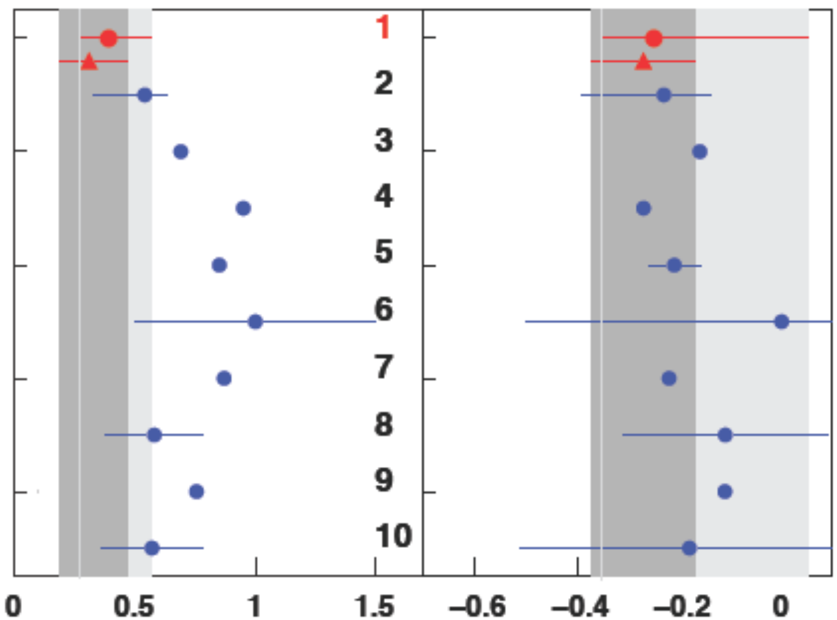
Charges:

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

Anselmino++ **[arXiv 1303.3822]**

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

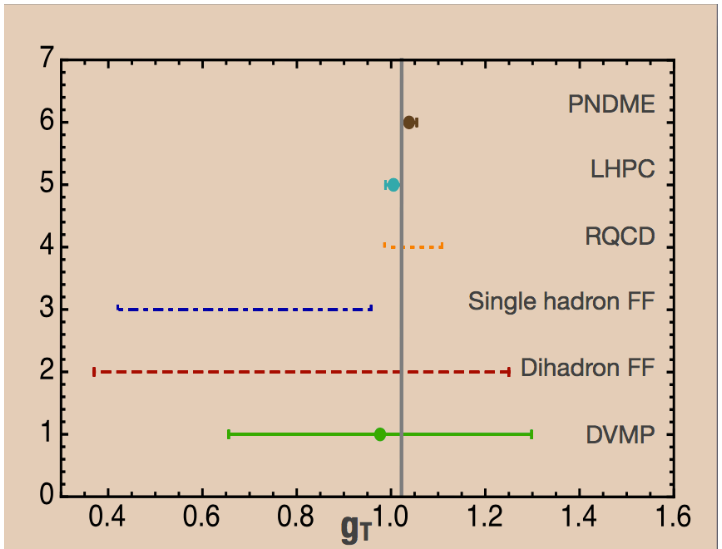
▲ $\delta u = 0.31^{+0.16}_{-0.12}$ ▲ $\delta d = -0.27^{+0.10}_{-0.10}$



Δu = 0.787 **Δd = -0.319**

Tensor Charge & BSM Physics

Courtoy++ @ this Conf.



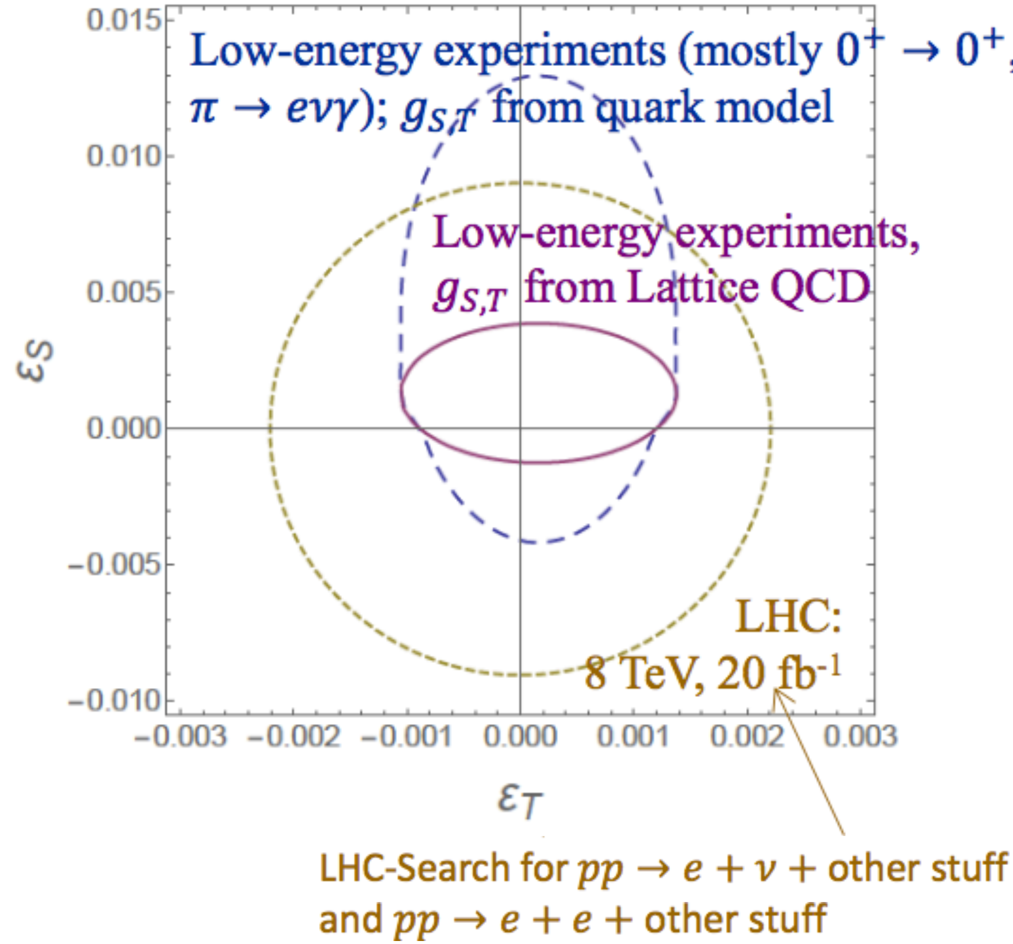
$g_T^{u-d} = \delta u - \delta d$ (Q^2 = 4 GeV^2)

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

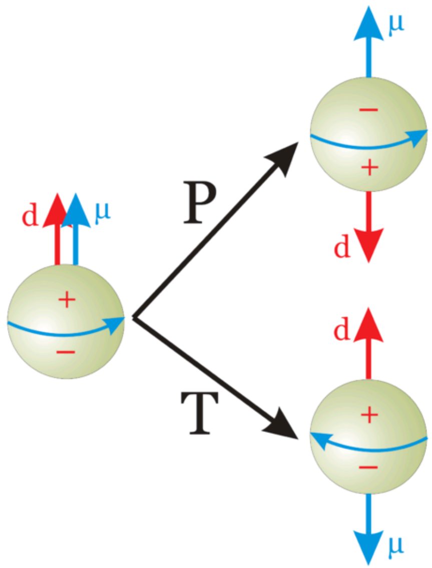
$| \varepsilon_T g_T | \lesssim 5 \times 10^{-4}$

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

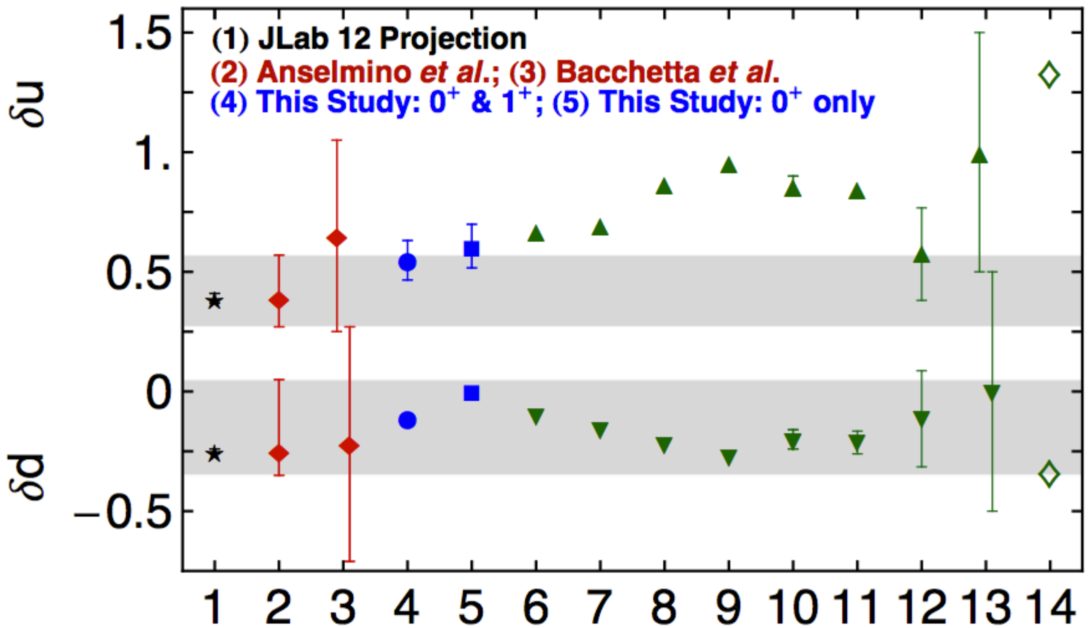
Baessler++ @ this Conf.

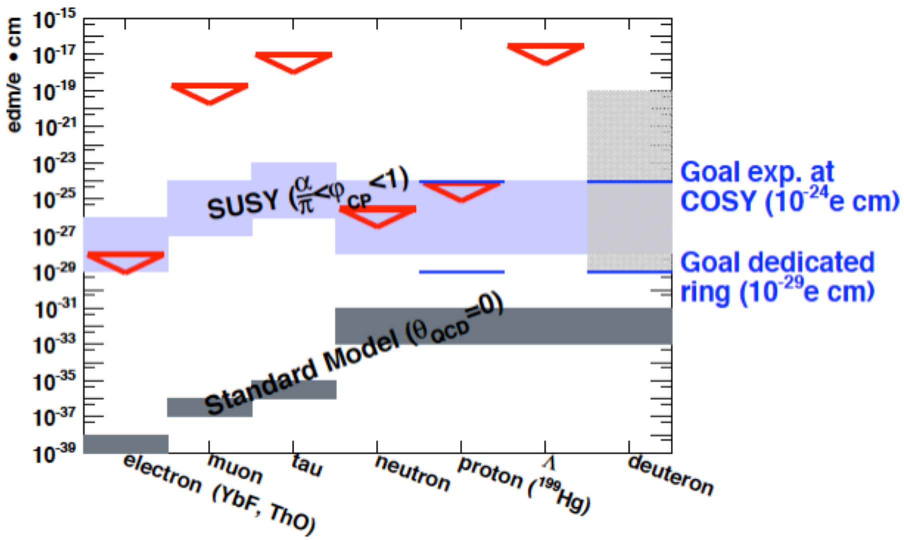


Tensor Charge and EDM



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.

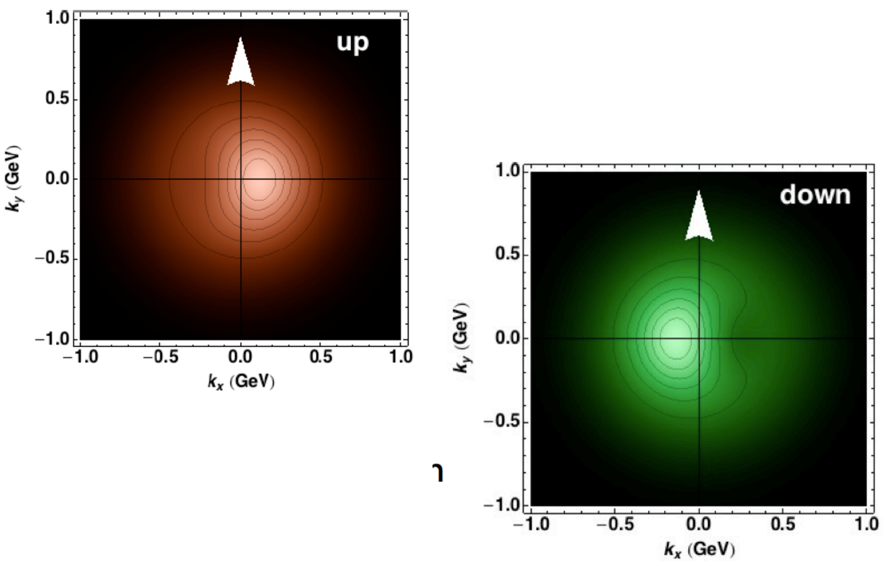
quark polarisation / **nucleon polarisation**

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

$\otimes$

quark polarisation / **hadron 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:

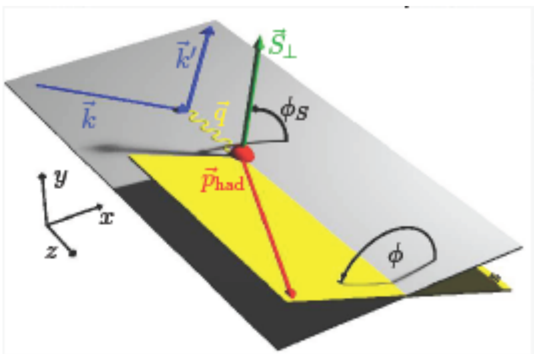
→ Sign change between DY and SIDIS
Generalized universality of TMDs

Related to:

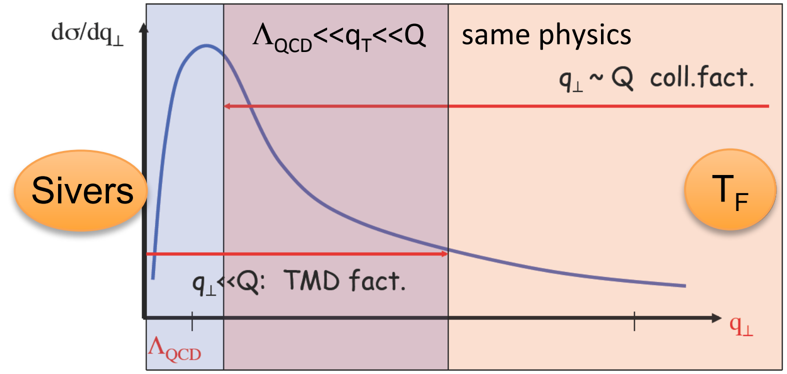
- ✓ SSA in adronic interactions
- ✓ Parton Orbital motion
- ✓ Anomalous Magnetic Moment

Sivers Signals

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



Sivers from polarized SIDIS

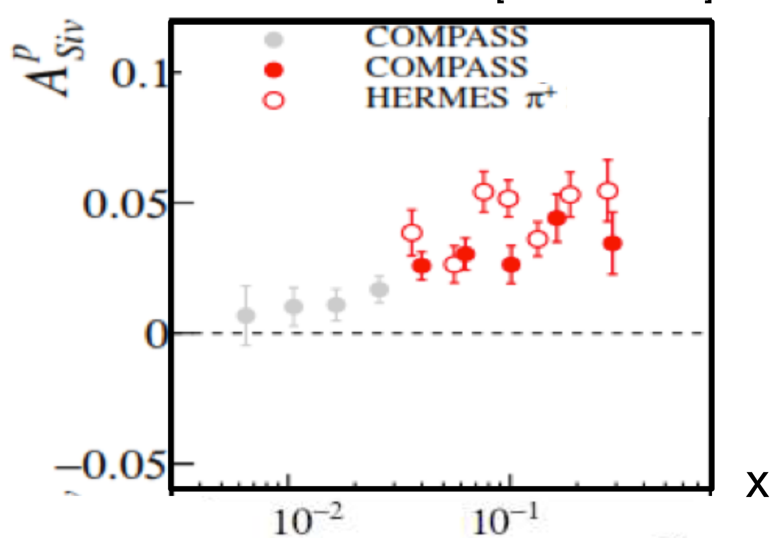


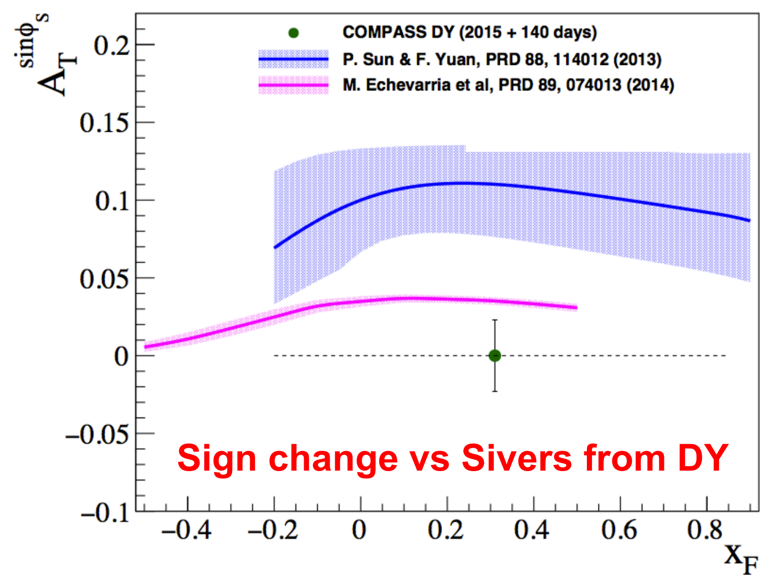
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\mathrm{SIDIS}}$$

May generate the misterious hadronic SSA

HERMES [arXiv:0906.3918]

COMPASS [arXiv:1205.5122]

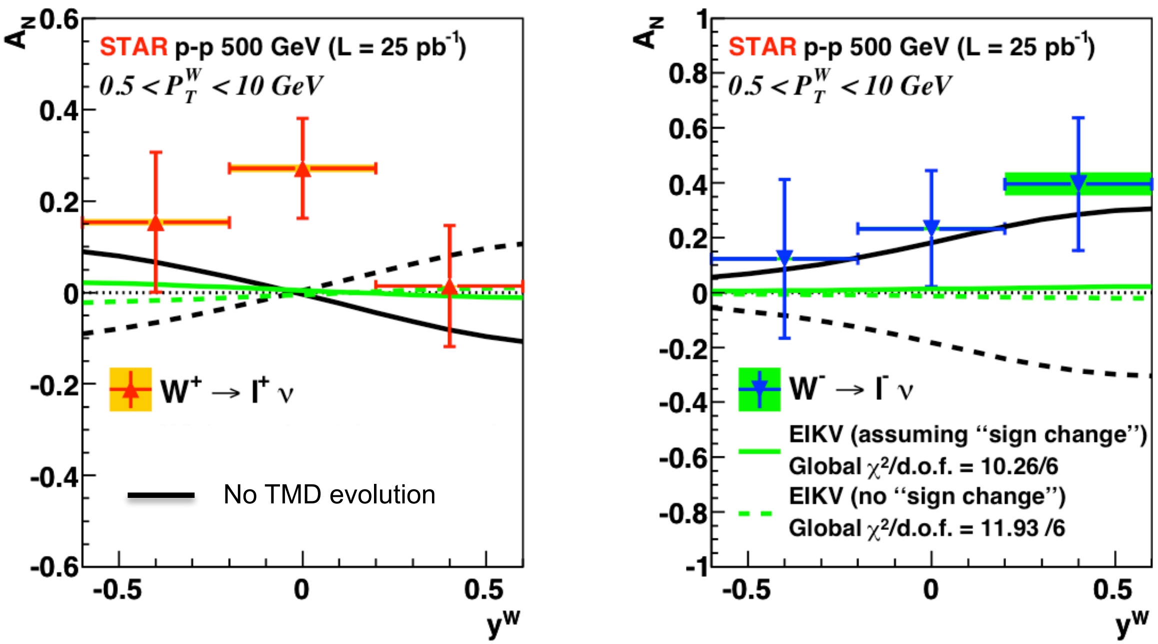




Sivers Sign in Drell-Yan

Weak boson production p p → WX @ STAR

STAR [arXiv: 1511.06003]



Solid line: assumption of sign change for Sivers

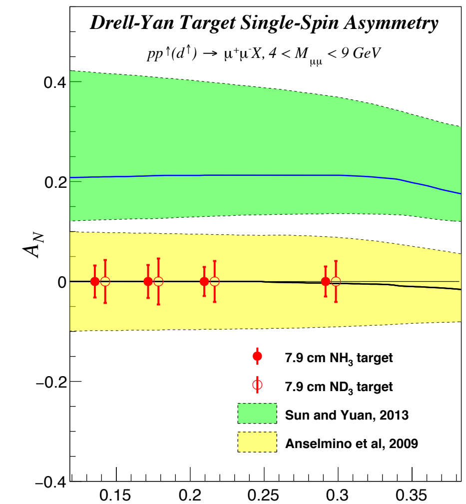
Dashed line: assumption of no sign change for Sivers

Kang and Qiu, [PRL 103 (2009) 172001]

Echevarria++, [PRD 89 (2014) 074013]

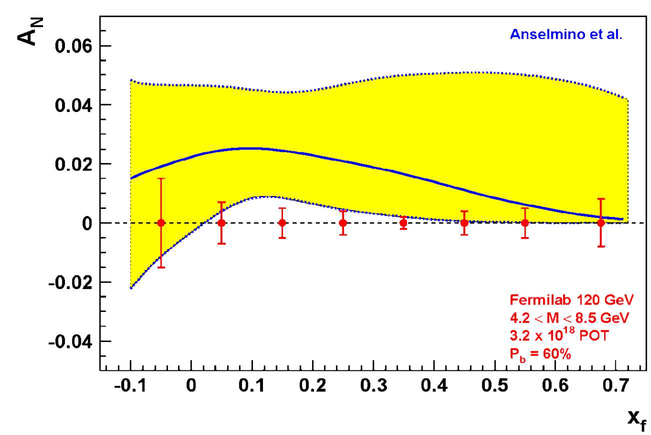
Fermilab E-1039

Sea quark Sivers asymmetry

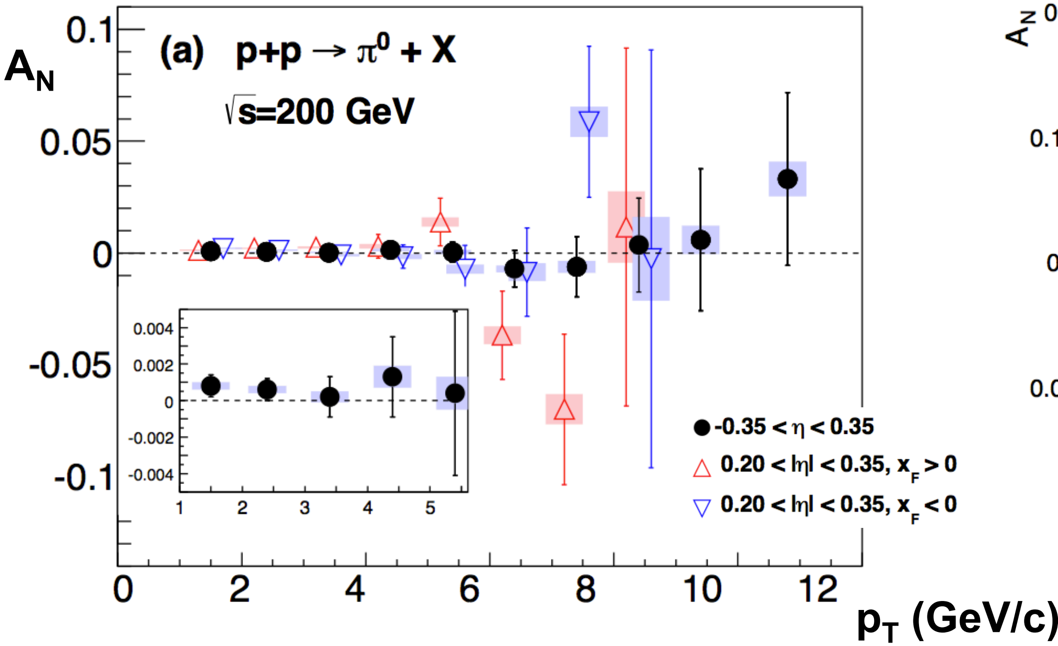


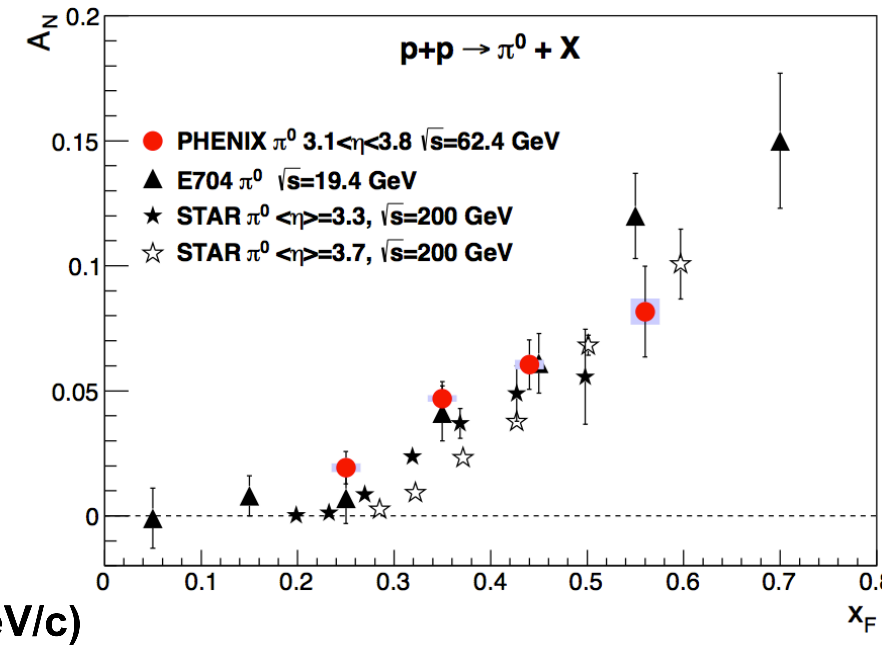
Fermilab E-1027

Valence quark Sivers asymmetry

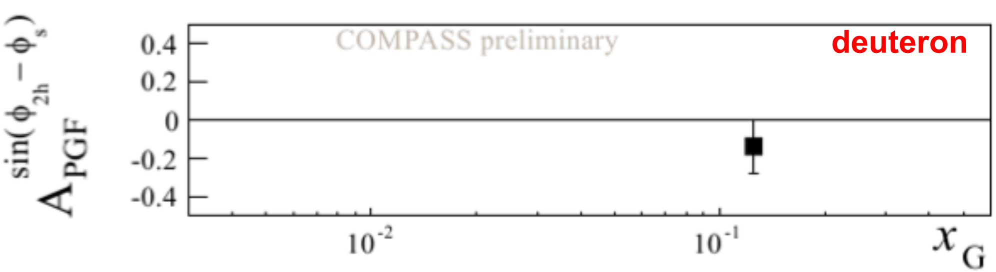


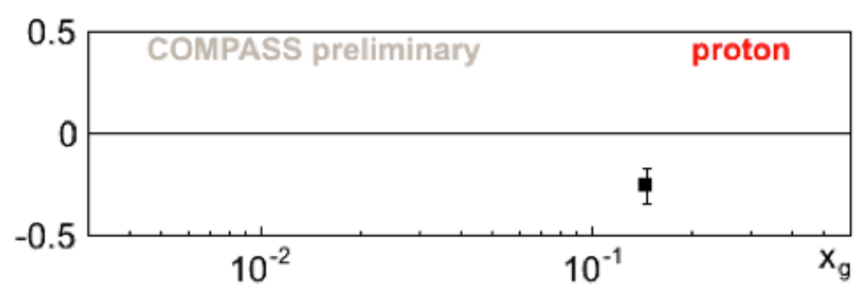
A_N @ RICH: mid rapidity (gluon+sea) and Forward (valence) rapidity PHENIX [arXiv: 1312.1995]





PGF @ COMPASS: gluon Sivers from deuterium and proton targets





Fixed Target Program @ LHC(b)

Since 2012: gas target internal to LHC for luminosity determination

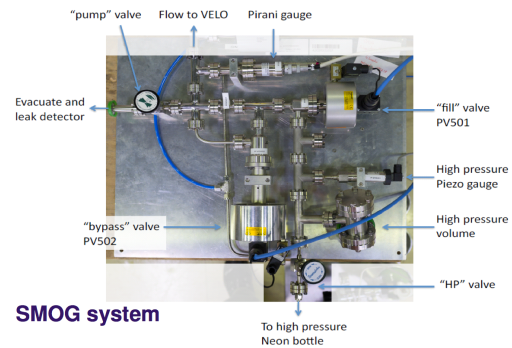
Polarized gaseous targets successfully used internal to HERA and COSY at FZJ

Requirements for LHC:

< 10 % beam half-life reduction

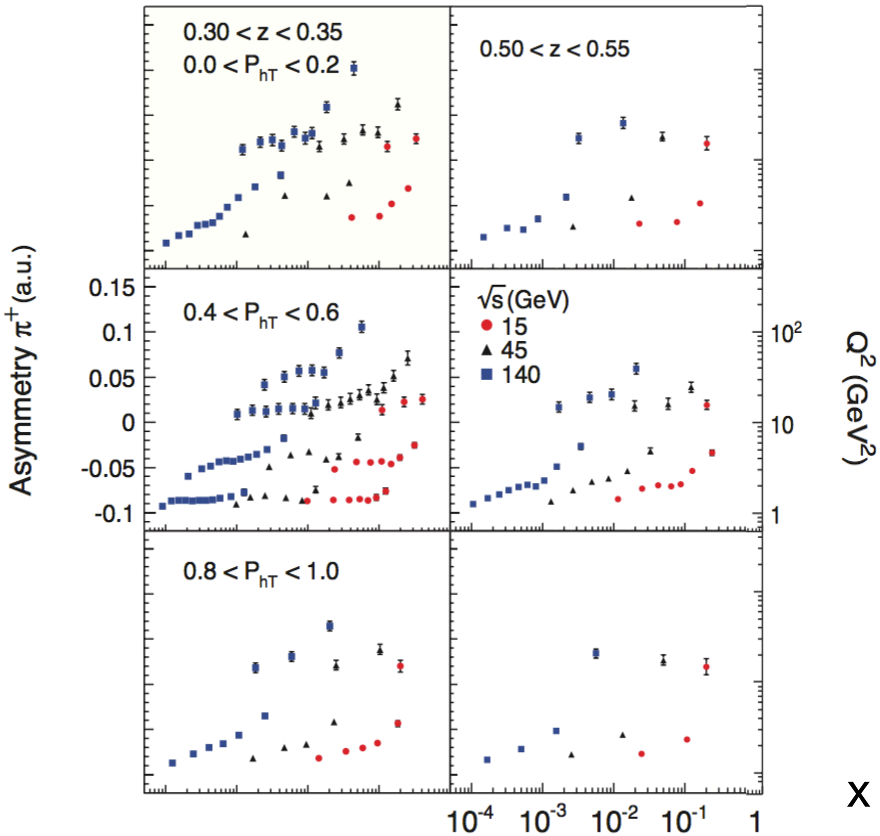
Cell openable (at injection) to access

$10^{33}/\text{cm}^2$ luminosity

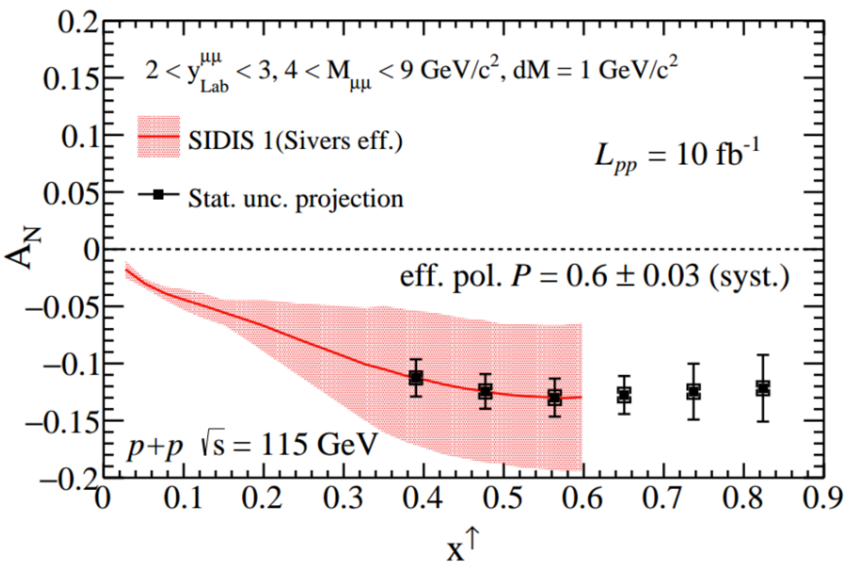


SMOG system

Sivers from SIDIS @ EIC A. Accardi++ [arXiv 1212.1701]



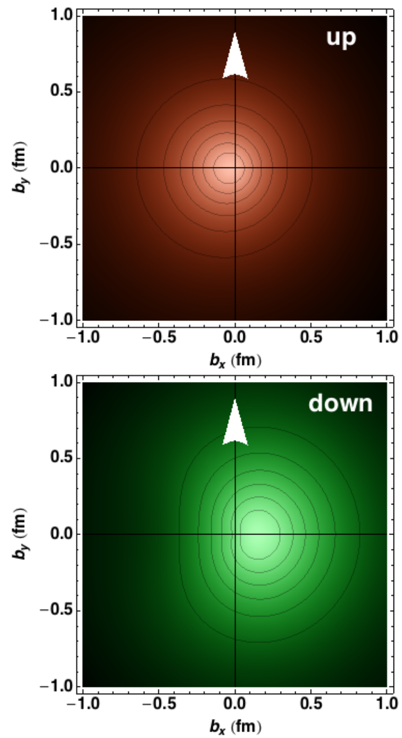
Sivers from DY J.P. Lansberg++ [arXiv 1602.06857]

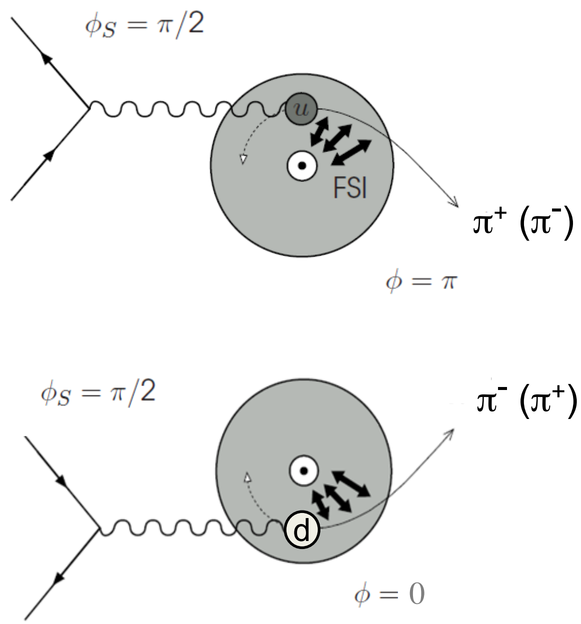


GPD E:

Imbalance in the probed parton spatial distribution

$$q_X(x, \mathbf{b}_\perp) = q(x, \mathbf{b}_\perp) - \frac{1}{2M}\frac{\partial}{\partial b_y}\mathcal{E}_q(x, \mathbf{b}_\perp)$$

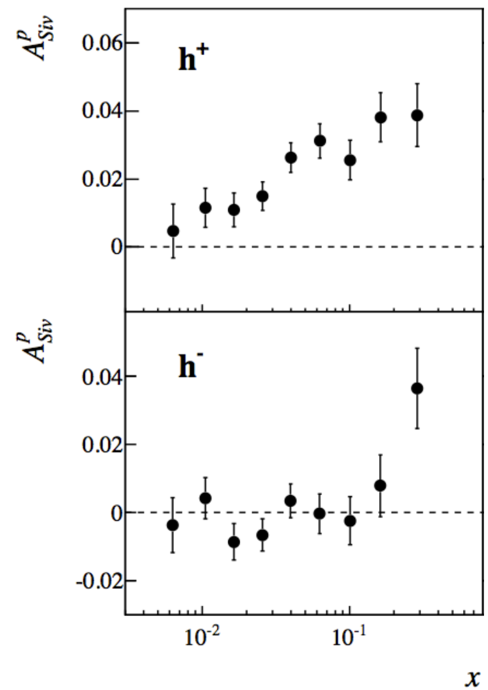




Sivers TMDs:

Imbalance in the observed hadron momentum distribution

$$f_{1T}^{\perp q} \sim -\kappa^q$$



Parton Orbital Motion

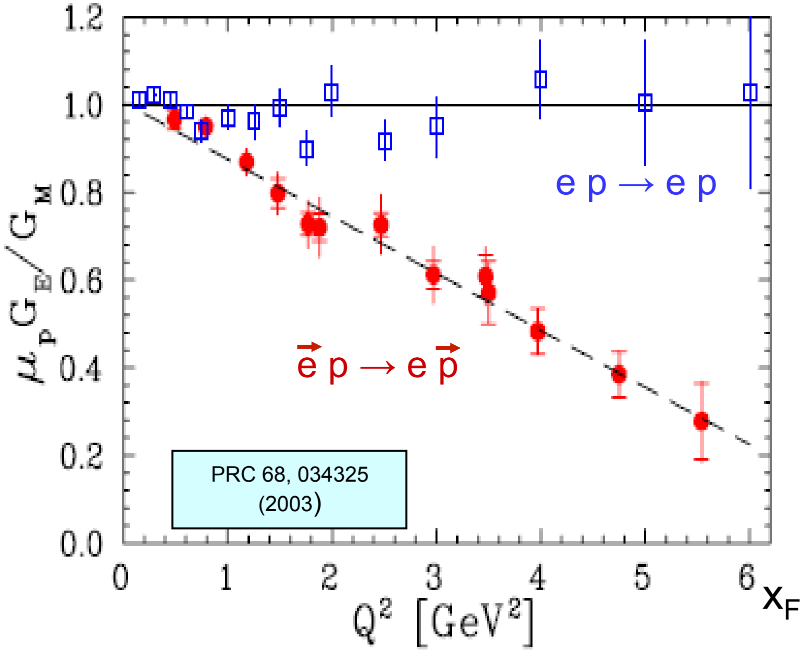
$$J_q = \frac{1}{2}\Delta\Sigma + L_q = \lim_{t\to 0}\int_{-1}^{1} dx\ x\ \left[H(x,\zeta,t) + E(x,\zeta,t)\right]$$

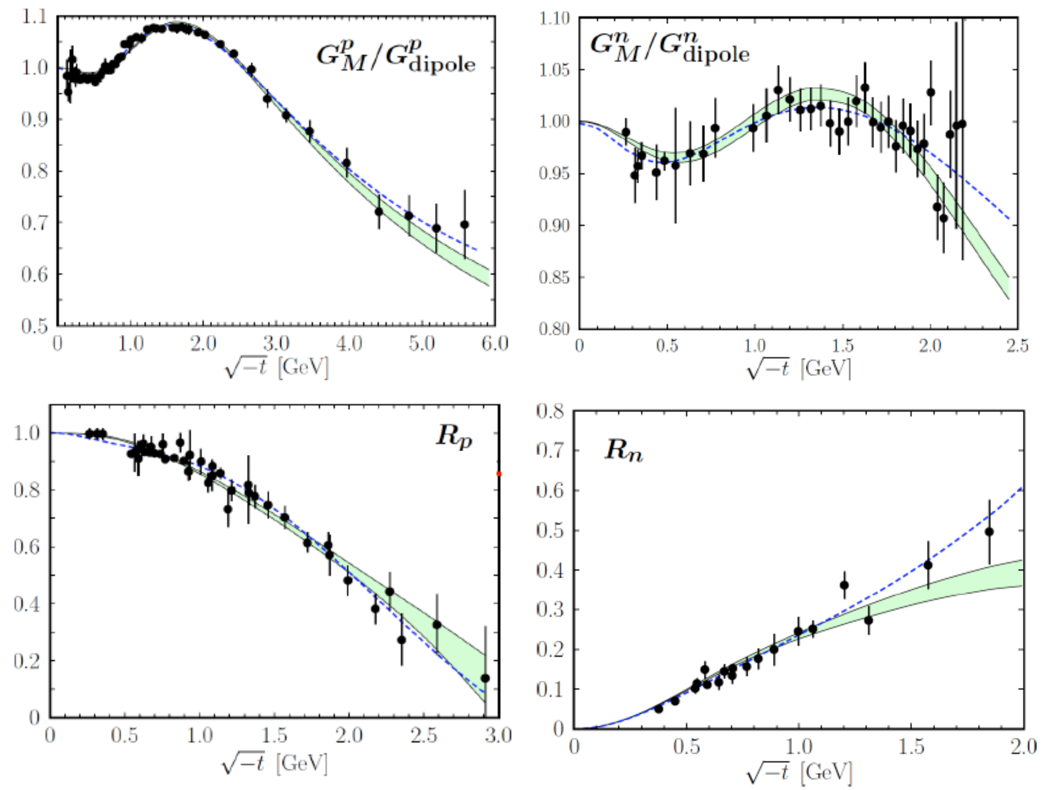
Anomalous Magnetic Moment

$$\int_{-1}^{1} dx \int d^2\mathbf{b}_\perp \mathcal{E}_q(x, \mathbf{b}_\perp) = F_{2,q}(0) = \kappa_q$$

GPDs from FFs

$$R^p = G_E^p / (G_M^p / \mu_p)$$





- obtain at μ = 2 GeV

$$J_v^u = 0.230^{+0.009}_{-0.024} \qquad J_v^d = -0.004^{+0.010}_{-0.016}$$

Diehl et al. arXiv: 1302.4604

- within errors consistent with determination from Sivers distrib. and model for chromodynamic lensing:

$$J_v^u = 0.214^{+0.009}_{-0.013} \qquad J_v^d = -0.029^{+0.021}_{-0.008}$$

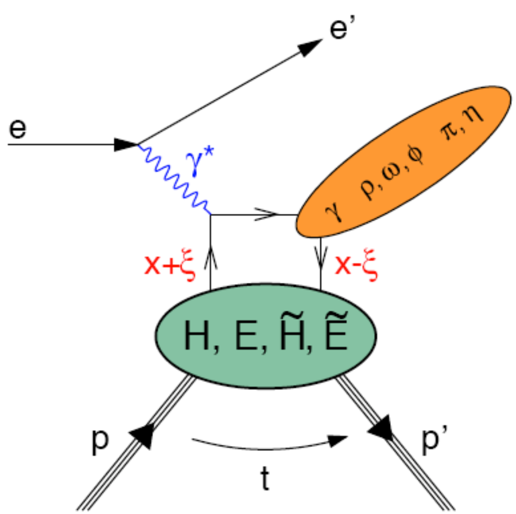
Bacchetta et al. arXiv: 1107.5755

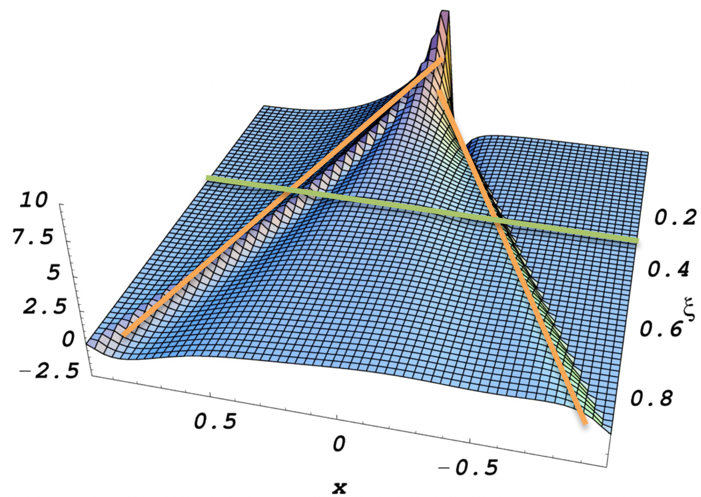
Hard Exclusive DIS & GPDs

$$
\begin{aligned}
H^{\mu\nu}_{LO} &= \frac{1}{2}\left[\tilde{p}^{\mu}n^{\nu}+\tilde{p}^{\nu}n^{\mu}-g^{\mu\nu}\right]\int_{-1}^{+1}dx\left[\frac{1}{x-\xi+i\epsilon}+\frac{1}{x+\xi-i\epsilon}\right]\\
&\quad\times\left[H^{p}_{DVCS}(x,\xi,t)\,\bar{N}(p')\gamma.nN(p)+\,E^{p}_{DVCS}(x,\xi,t)\,\bar{N}(p')i\sigma^{\kappa\lambda}\frac{n_{\kappa}\Delta_{\lambda}}{2m_N}N(p)\right]\\
&+\frac{1}{2}\left[-i\varepsilon^{\mu\nu\kappa\lambda}\tilde{p}_{\kappa}n_{\lambda}\right]\int_{-1}^{+1}dx\left[\frac{1}{x-\xi+i\epsilon}-\frac{1}{x+\xi-i\epsilon}\right]\\
&\quad\times\left[\tilde{H}^{p}_{DVCS}(x,\xi,t)\bar{N}(p')\gamma.n\gamma_5N(p)+\tilde{E}^{p}_{DVCS}(x,\xi,t)\bar{N}(p')\gamma_5\frac{\Delta\cdot n}{2m_N}N(p)\right]\ ,
\end{aligned}
$$

- DVCS (γ) → $H, E, \tilde{H}, \tilde{E}$
- Vector mesons (ρ, ω, ϕ) → H, E
- Pseudoscalar mesons (π, η) → $\tilde{H}, \tilde{E}$

For mesons
factorization proven for $\sigma_L \sim 1/Q^6$
suppression expected for $\sigma_T \sim 1/Q^8$





Only ξ and t are experimentally accessible

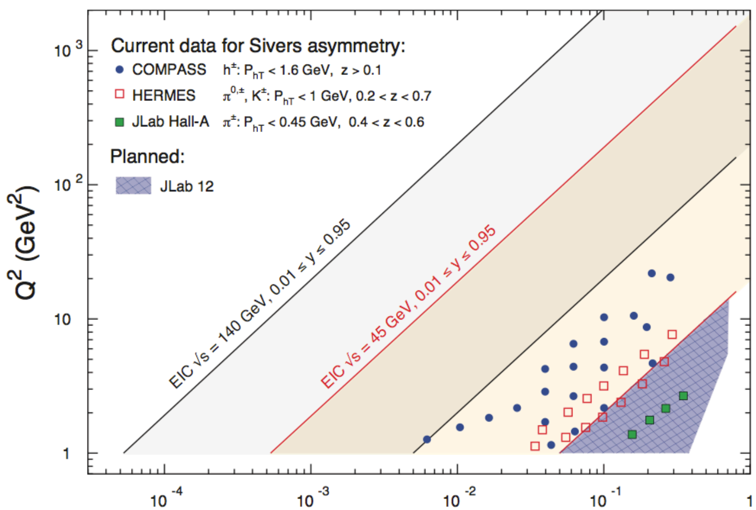
$$
T^{DVCS} \sim \int_{-1}^{+1}\frac{H(x,\xi,t)}{x\pm\xi+i\varepsilon}dx\ +\ldots\sim\quad P\int_{-1}^{+1}\frac{H(x,\xi,t)}{x\pm\xi}dx-i\pi H(\pm\xi,\xi,t)+\ldots
$$

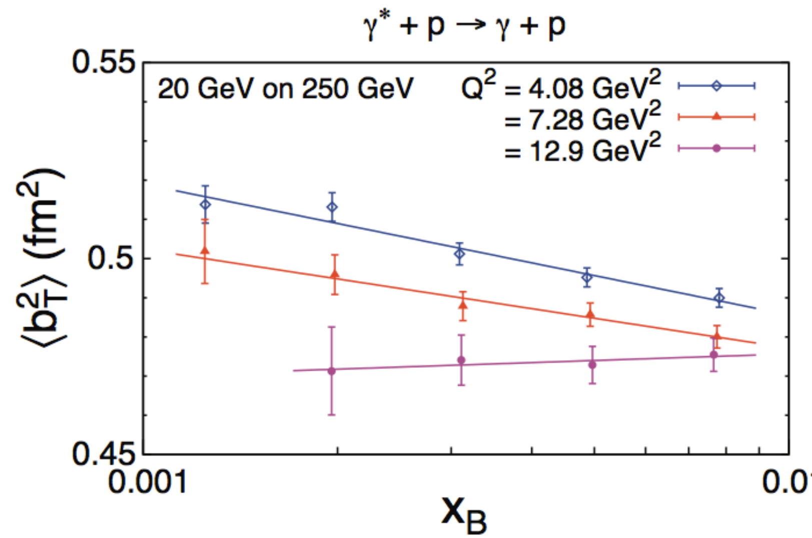
Nucleon Multi-D Mapping @ JLab +EIC

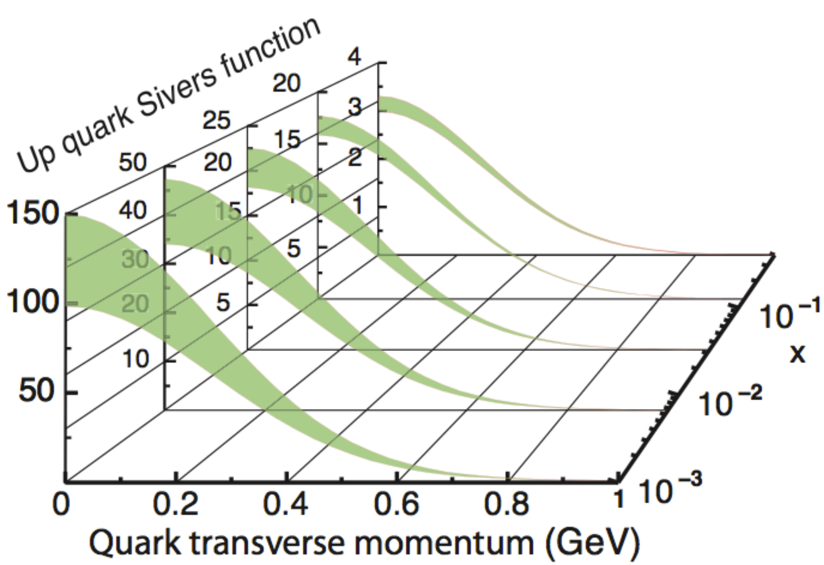
Transverse Momentum (TMDs)

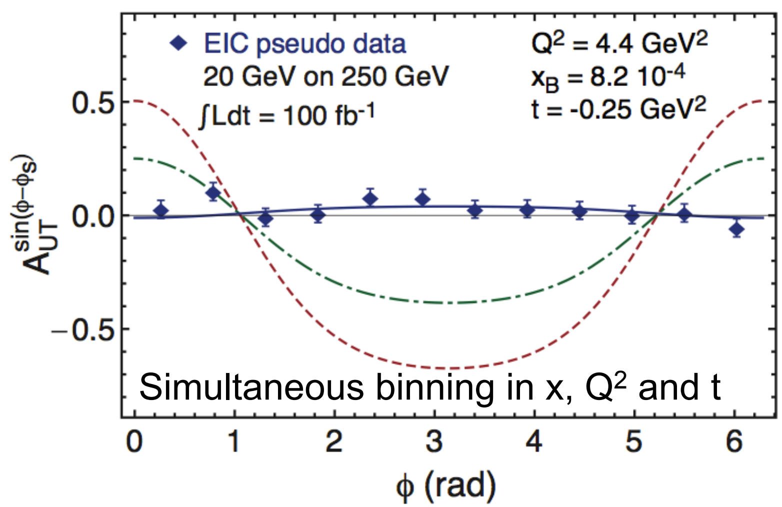
Impact parameter (GPDs)

A. Accardi et al. [arXiv 1212.1701]









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