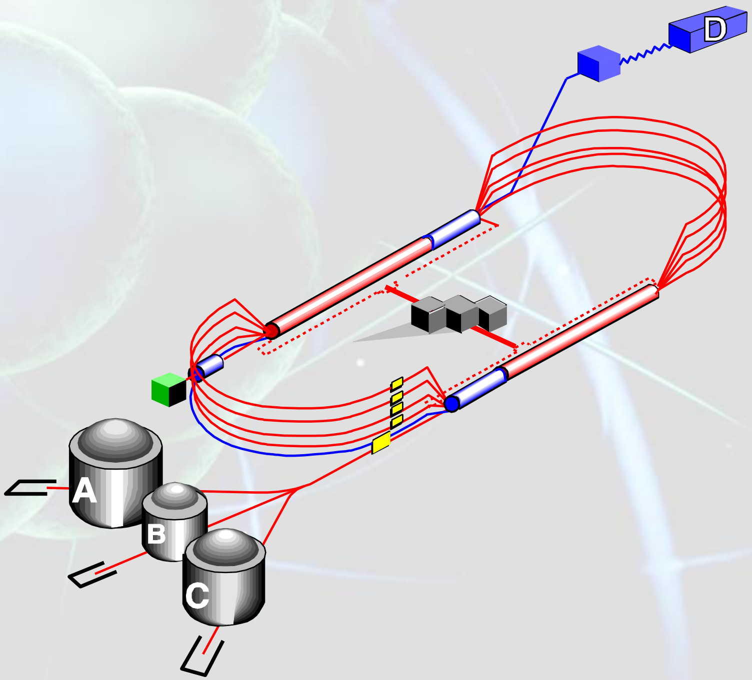
TMDs from unpolarised SIDIS data

Experimental Overview



Rolf Ent
Jefferson Lab

TMDs from Unpolarised SIDIS data

- The TMDs/SIDIS experiments – the world scene

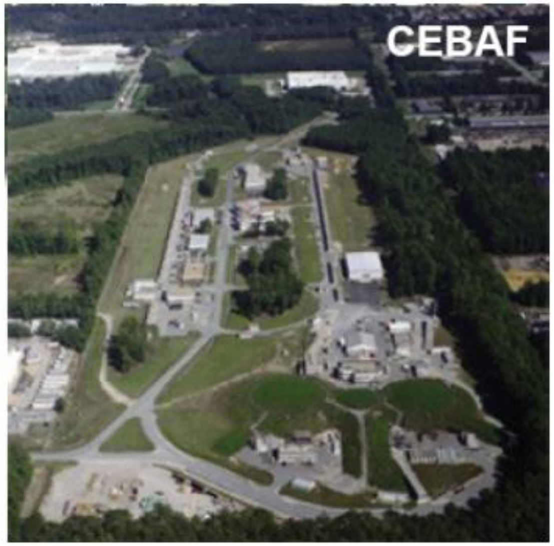
- What have we learned from unpolarised TMDs/SIDIS data?
  Unpol. TMDs = p_T distributions & azimuthal asymmetries

- What can we expect to learn within this framework?

- How much can we really project to know? Some issues…
  - The experimental verification of the SIDIS framework
  - The transition from photoproduction to perturbative QCD
  - How to make the most out of our data
  - 3D nucleon structure?

The SIDIS Factories

HERMES:
Polarized 27 GeV e+/e-
Polarized pure gaseous H&D targets
Excellent Particle ID



HALL-A, B , C:
Polarized 6 GeV e-
Polarized ^{3}He, NH_3 & HDice targets
High- Luminosity

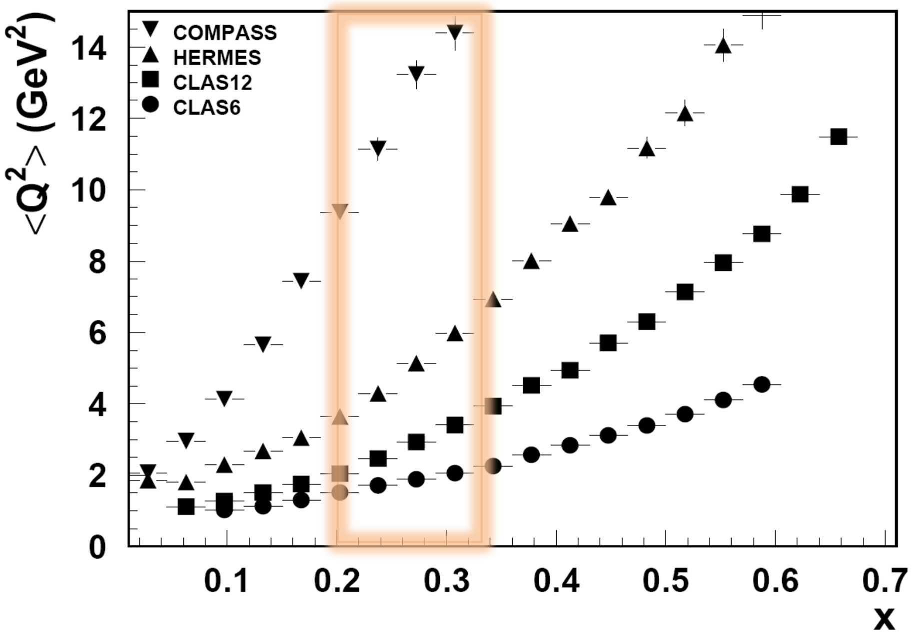
COMPASS:
Polarized 160 GeV μ
Polarized ^{6}LiD & NH_3 targets
High-Energy

From: Marco Contalbrigo

The SIDIS Landscape

$$\frac{d\sigma(ep \to e'hX)}{dxdy\ dzdP_{h\perp}} \propto \sum_q e_q^2 C\left[q(x,k_T)D_q^h(z,p_T)\right]$$

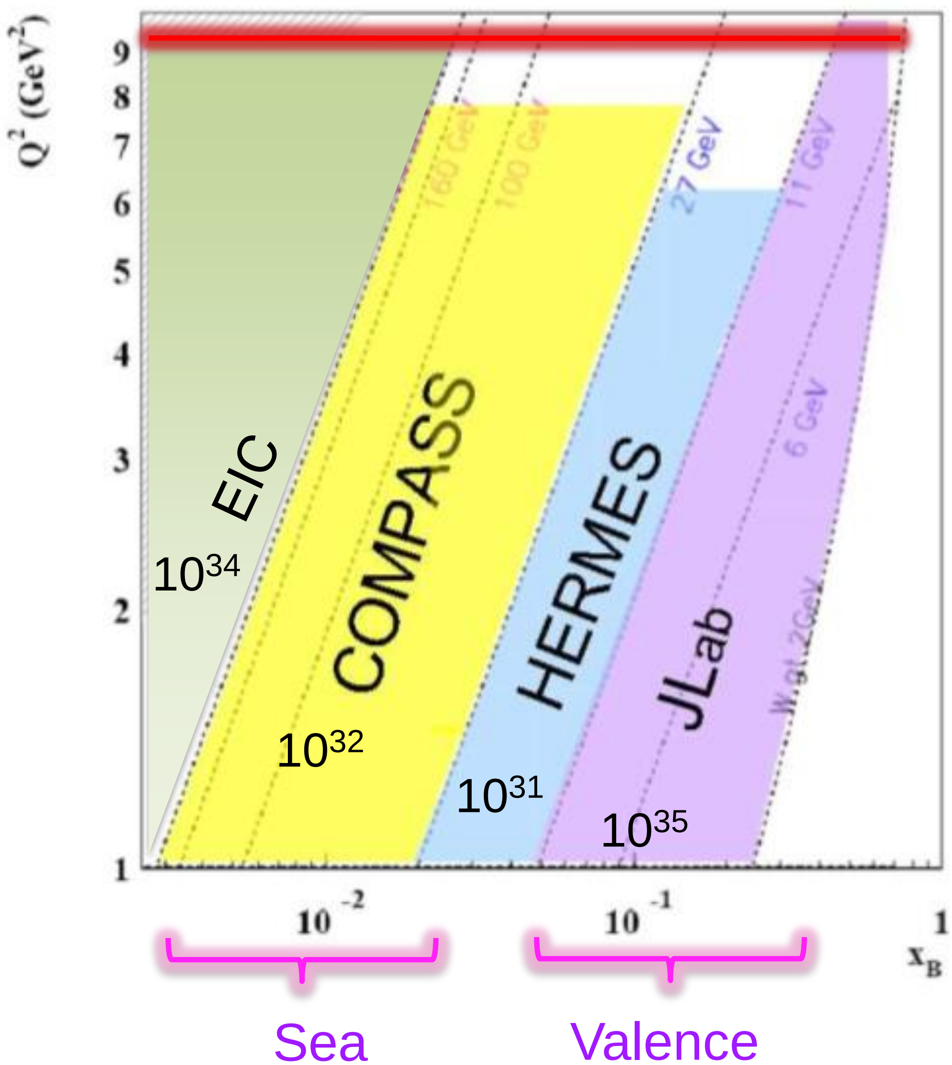
Different Q^2 for same x range



Complementary experiments

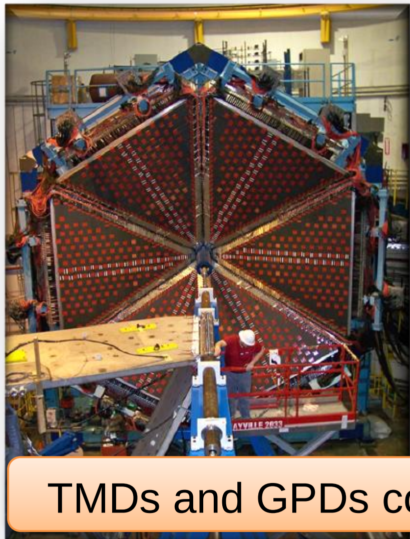
Adapted from Marco Contalbrigo

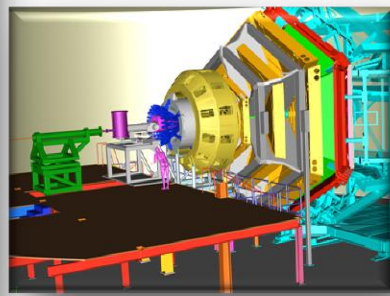
Limit defined by luminosity



12 GeV (TMD) Scientific Capabilities

Hall B **– understanding nucleon structure via generalized parton distributions**

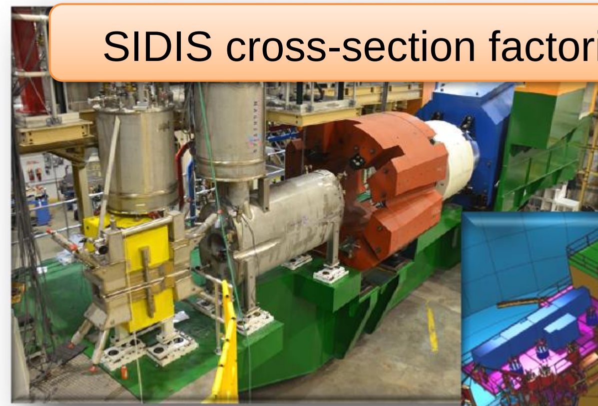


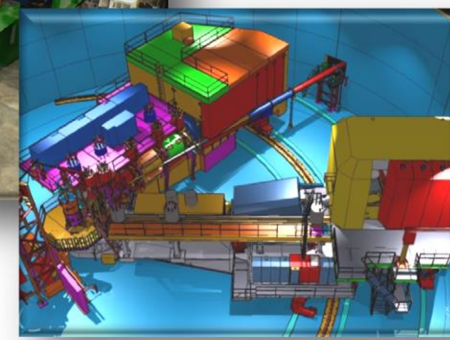


TMDs and GPDs comprehensive study

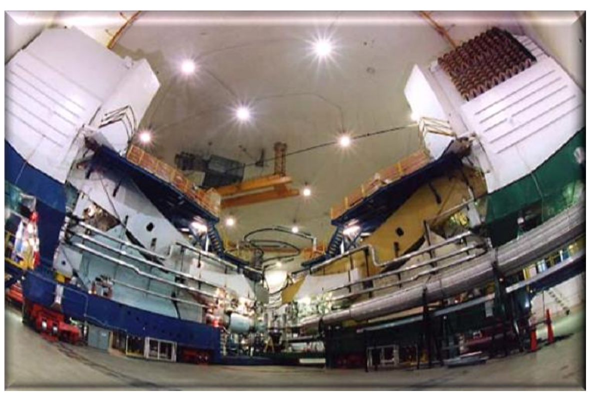
Hall C **– precision determination of valence quark properties in nucleons/nuclei**

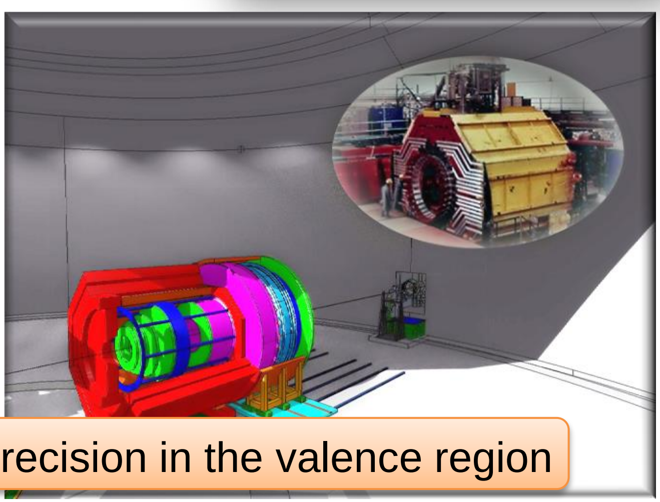
SIDIS cross-section factorization tests





Hall A **– polarized 3He, future new experiments (e.g., SBS, MOLLER and SoLID)**

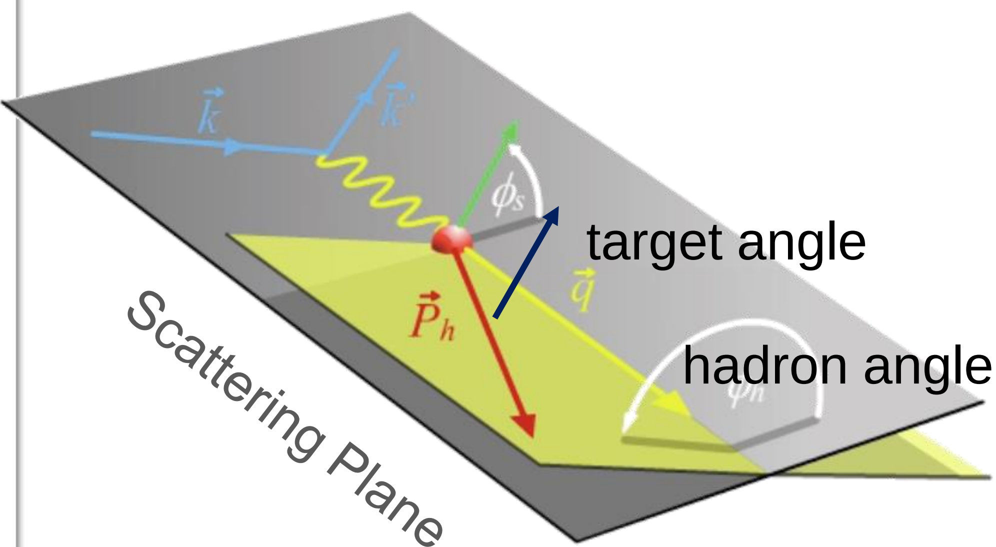




Ultimate statistical precision in the valence region

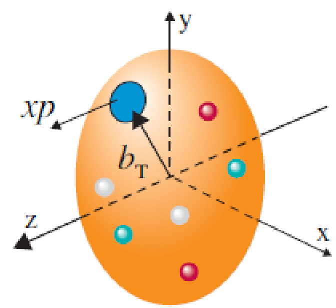
TMDs Accessible through Semi-Inclusive Physics

- Separate Sivers and Collins effects



Naturally, two scales:
- High Q: localized probe to "see" quarks and gluons
- Low P_T: sensitive to confining scale to "see" their confined motion

+ Theory input: TMD QCD factorization
TMD QCD evolution



- **Sivers** angle, effect in distribution function: $(\phi_h - \phi_s)$

  Or other combinations: Pretzelosity: $(3\phi_h - \phi_s)$
- **Collins** angle, effect in fragmentation function: $(\phi_h + \phi_s)$
- *Kaons enabled by Hall B RICH (INFN/DOE) and Hall C Aerogel (NSF)*

Features of partonic 3D non-perturbative distributions

$$f^a(x, k_T^2; Q^2)$$

Ex. TMD PDF for a given combination of parton and nucleon spins

Understanding of the 3D structure of nucleon requires studies of spin and flavor dependence of quark transverse momentum and space distributions

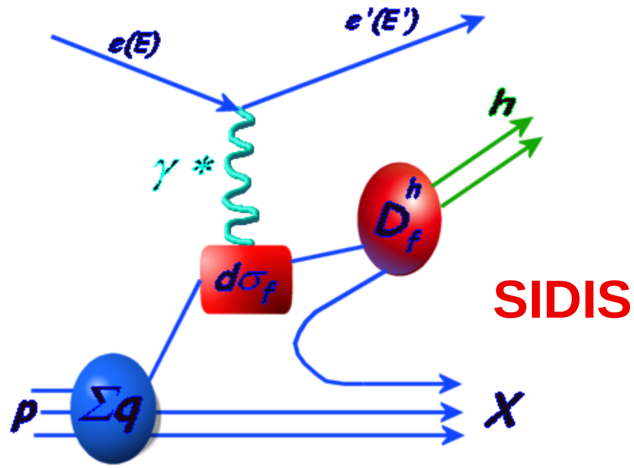
quark polarization

nucleon polarization	U	L	T
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 $h_{1T}^\perp$

transversity pretzelosity

- transverse position and momentum of partons are correlated with the spin orientations of the parent hadron and the spin of the parton itself
- transverse position and momentum of partons depend on their flavor
- transverse position and momentum of partons are correlated with their longitudinal momentum
- spin and momentum of struck quarks are correlated with remnant
- quark-gluon interaction play a crucial role in kinematical distributions of final state hadrons, both in semi-inclusive and exclusive processes

SIDIS – Flavor Decomposition



DIS probes only the sum of quarks and anti-quarks → requires assumptions on the role of sea quarks $\sum e_q^2(q+\bar{q})$

Solution: Detect a final state hadron in addition to scattered electron

→ Can 'tag' the flavor of the struck quark by measuring the hadrons produced: 'flavor tagging'

$M_x^2 = W'^2 \sim M^2 + Q^2\,(1/x - 1)(1 - z)$

$\boxed{Z = E_h/\nu}$

$$\frac{1}{\sigma_{(e,e')}}\frac{d\sigma}{dz}(ep \rightarrow hX) = \frac{\sum_q e_q^2 f_q(x) D_q^h(z)}{\sum_q e_q^2(x) f_q(x)}$$

$f_q(x)$: parton distribution function

$D_q^h(z)$: fragmentation function

Measure inclusive (e,e') at same time as (e,e'h)

- Leading-Order (LO) QCD
- after integration over p_T and ϕ
- NLO: gluon radiation mixes x and z dependences
- Target-Mass corrections at large z
- ln(1-z) corrections at large z

Overall Goal of SIDIS Program

validate basic reaction mechanism of SIDIS at "our" energies

and then

spin and flavor dependence of quark transverse momentum distributions

There are indications from both theory (lattice, chiral constituent quark model) and experimental data of different k_T dependences of quark flavor distributions

… but, keep in mind overall goal of 3D nucleon structure…

TMDs and SIDIS – General Formalism

General formalism for (e,e'h) coincidence reaction w. polarized beam: [A. Bacchetta et al., JHEP 0702 (2007) 093]

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\left\{\boxed{F_{UU,T}+\varepsilon F_{UU,L}}+\right.$$

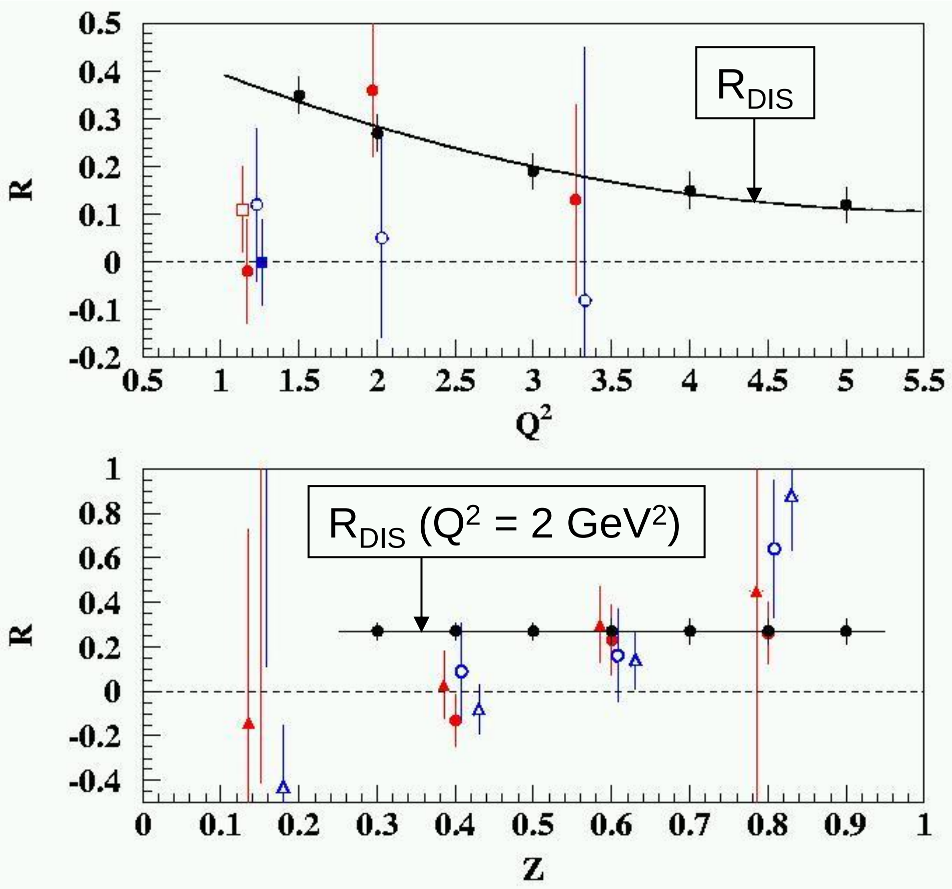
$$\left.\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)} + \lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\right\}$$

(Ψ = azimuthal angle of e' around the electron beam axis w.r.t. an arbitrary fixed direction)

If beam is unpolarized, and the (e,e'h) measurements are fully integrated over ϕ, only the $\mathbf{F_{UU,T}}$ and $\mathbf{F_{UU,L}}$ responses, or the usual transverse (σ_T) and longitudinal (σ_L) cross section pieces, survive.

Longitudinal Cross Section: $R = \sigma_L/\sigma_T$ in SIDIS

- R_{DIS} is in the naïve parton model related to the parton's transverse momentum:
  $R = 4(M^2x^2 + \langle k_T^2 \rangle)/(Q^2 + 2\langle k_T^2 \rangle)$.
- $R_{DIS} \rightarrow 0$ at $Q^2 \rightarrow \infty$ is a consequence of scattering from free spin-½ constituents



Only existing SIDIS data:
Cornell 70's (H and D, π^+ and π^-)

- Knowledge on R_{SIDIS} is non-existing
- R_{SIDIS} may (will!) vary with z, and with p_T
  (JLab E12-06-104 will scan versus p_T too)

- Knowledge on R_{SIDIS} needed for any TMD-related asymmetry

- Even if one can relate R_{SIDIS} to a flavor-dependent average transverse momentum in a naïve parton model (W. Melnitchouk *et al*, in progress), R_{SIDIS} can not easily be integrated in a global TMD analysis as it is sensitive to gluon and HT effects.

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$$\left.\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}+\varepsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)}+\lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\right\}$$

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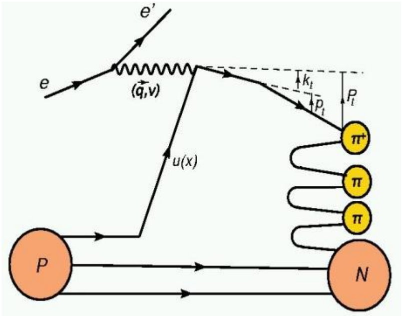
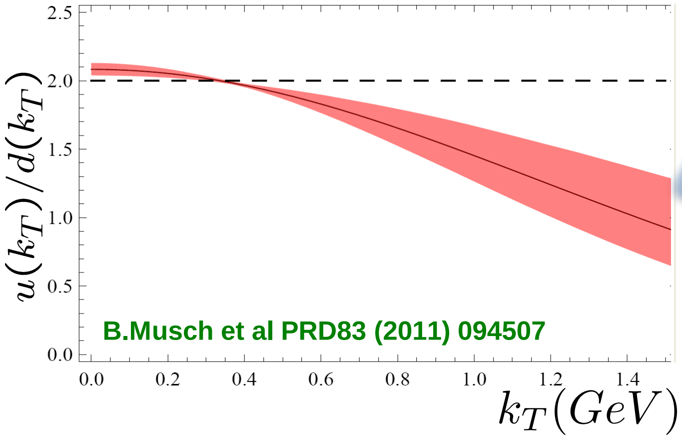
Unpolarized k_T-dependent SIDIS: $F_{UU}^{\cos(\phi)}$ and $F_{UU}^{\cos(2\phi)}$, in framework of Anselmino et al. described in terms of *convolution of quark distributions f and (one or more) fragmentation functions D*, each with own characteristic (Gaussian) width. Transverse momentum widths of quarks with **different flavor (and polarization)** can be different.



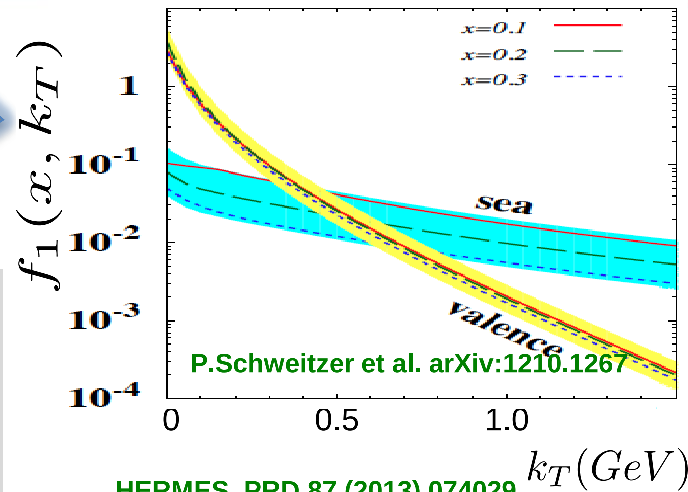
Final transverse momentum of the detected pion $\mathbf{P}_t$ arises from convolution of the struck quark transverse momentum $\mathbf{k}_t$ with the transverse momentum generated during the fragmentation $\mathbf{p}_t$.

$P_t = p_t + z\,k_t + O(k_t^2/Q^2)$

Probing the flavor-dependence of k_T-distributions

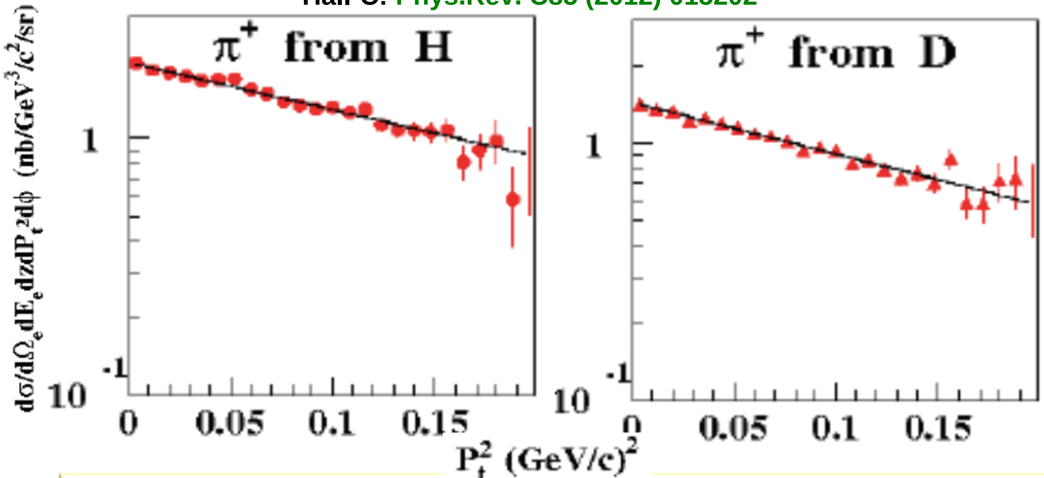


Higher probability to find more sea & d-quarks at **large k_T**

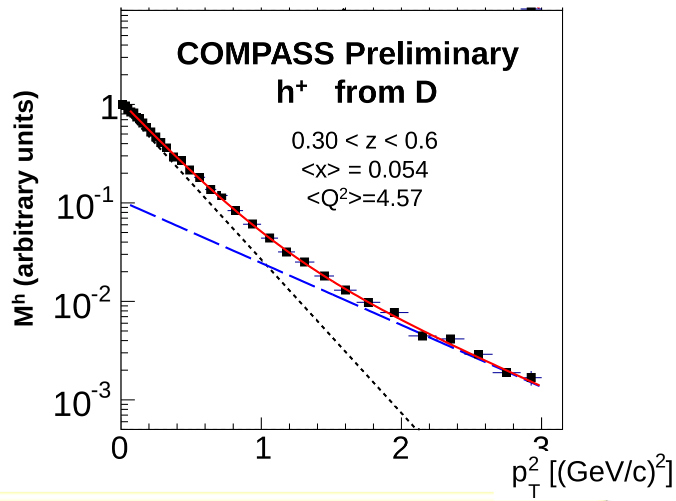


Measurements of hadronic multiplicities provide a crucial input for studies of k_T dependence of spin independent distributions

Hall-C: Phys.Rev. C85 (2012) 015202

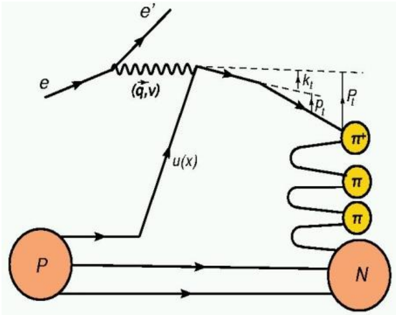


HERMES, PRD 87 (2013) 074029
COMPASS, EPJC 73 (2013) 2531



There are indications from both theory (lattice, chiral constituent quark model) and experimental data of the k_T dependence of quark flavor distribution.

Transverse momentum dependence of SIDIS



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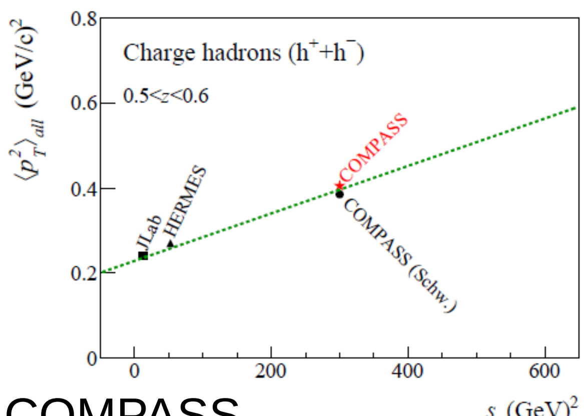
$P_t = p_t + z\, k_t + O(k_t^2/Q^2)$

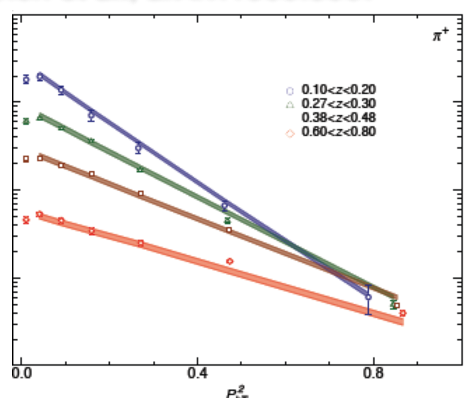
Intrinsic value of SIDIS to establish transverse momentum widths of quarks with different flavor and polarization now well established (and they can be different). Steps towards QCD evolution taken. <u>Need precision at large z to validate fragmentation process, verify target-mass correction and ln(1-z) re-summation, etc.</u> – To acquire precision data is the job of JLab-12!

Adolph et al., arXiv:1305.7317v1



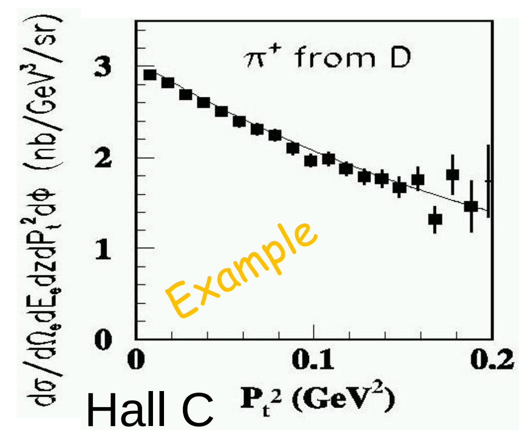
COMPASS

Airapetian et al., PRD 107 (2013) 074029; Signori et al., arXiv:1309.3507



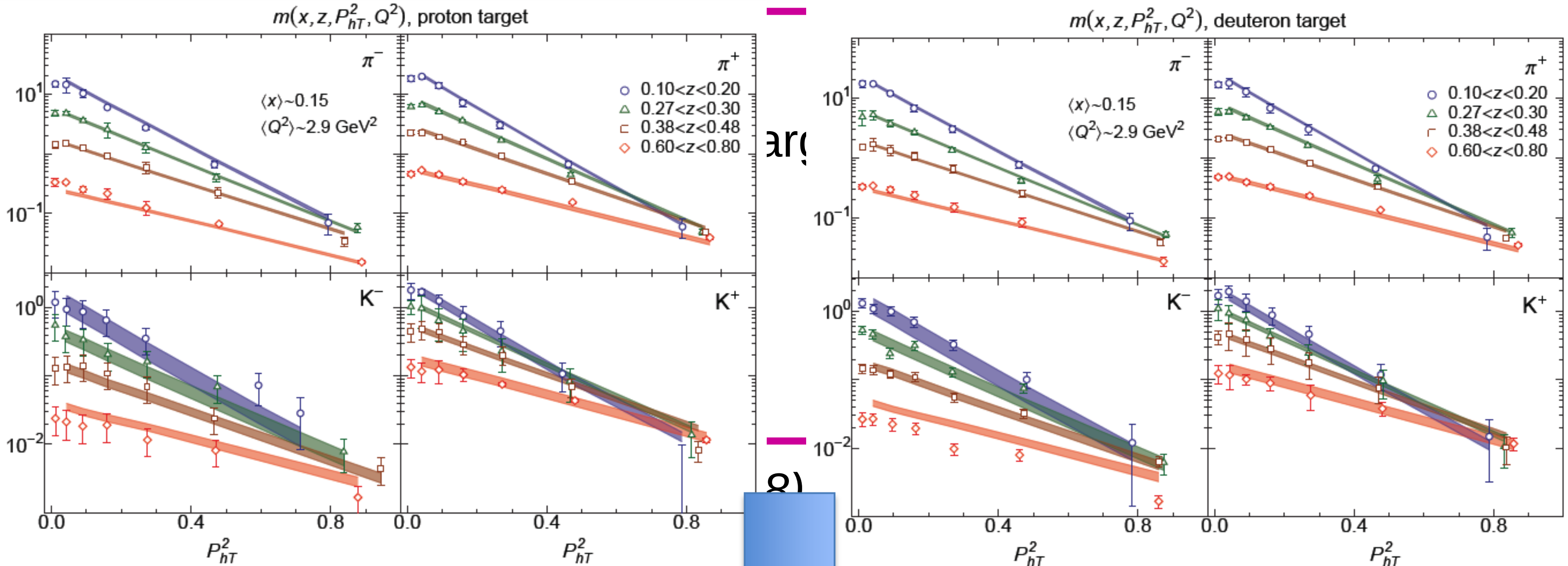
HERMES

Mkrtchyan et al., PL B665 (2008) 20; Asaturyan et al., PRC 105 (2012) 015202



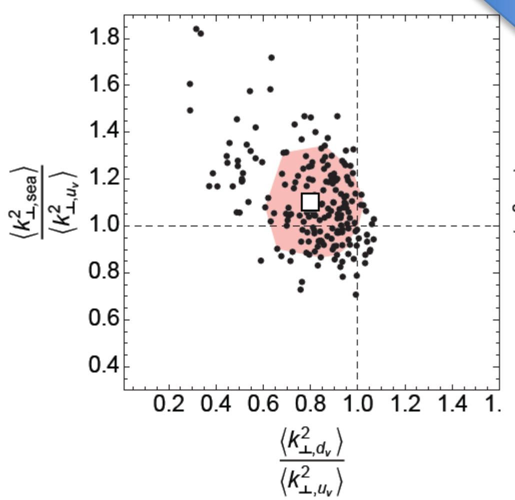
Hall C

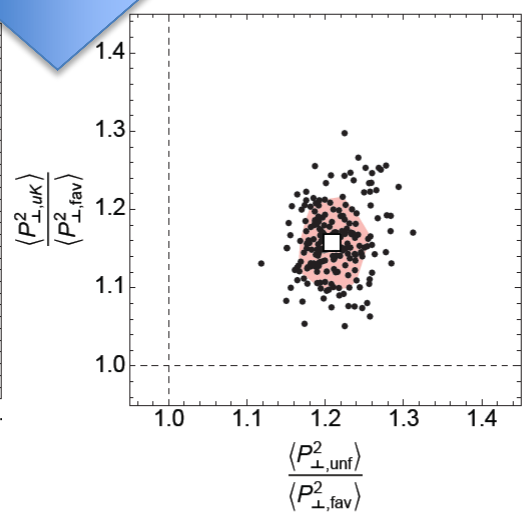
Investigations into the flavor dependence



HERMES data

Phenomenology:
A. Signori,
A. Bacchetta,
M. Radici
ArXiv:1407.2445v1





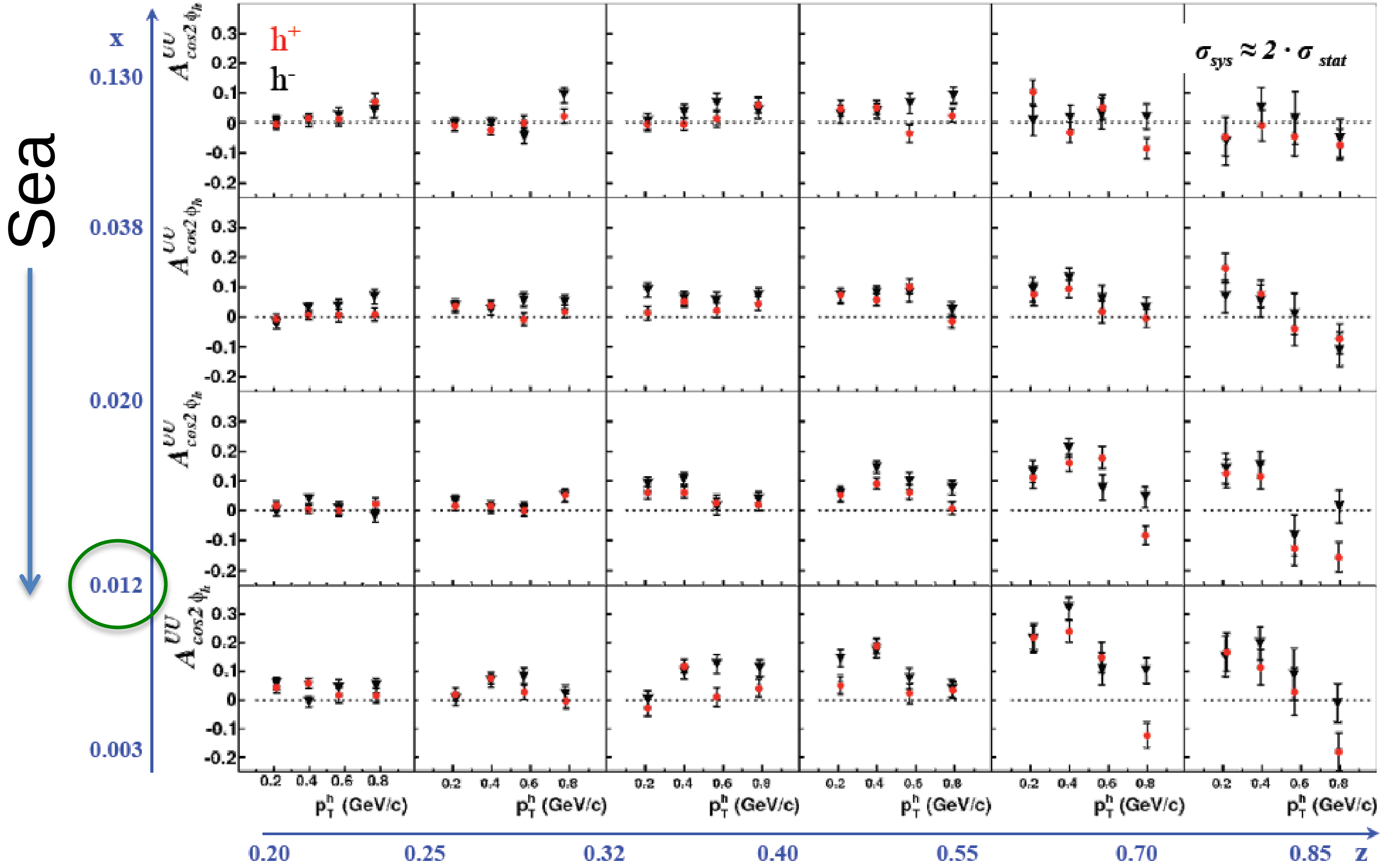
Many next steps:
1. COMPASS data
2. Evolution
3. Include e^+e^-, DY
4. Non-gaussian Ansatz

As long as we deal with Gaussians and they are o.k., we are in our infancy

Investigations into the sea

COMPASS: P_T dependence of $A^{UU}_{\cos(2\phi)}$ asymmetry

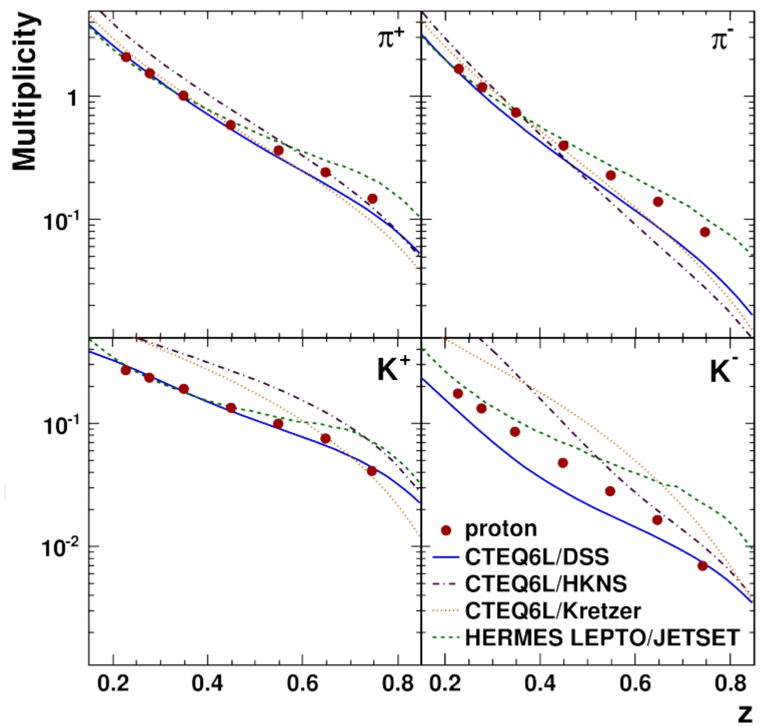
CERN-PH-EP-2014-009



Investigations into the hadron dependence

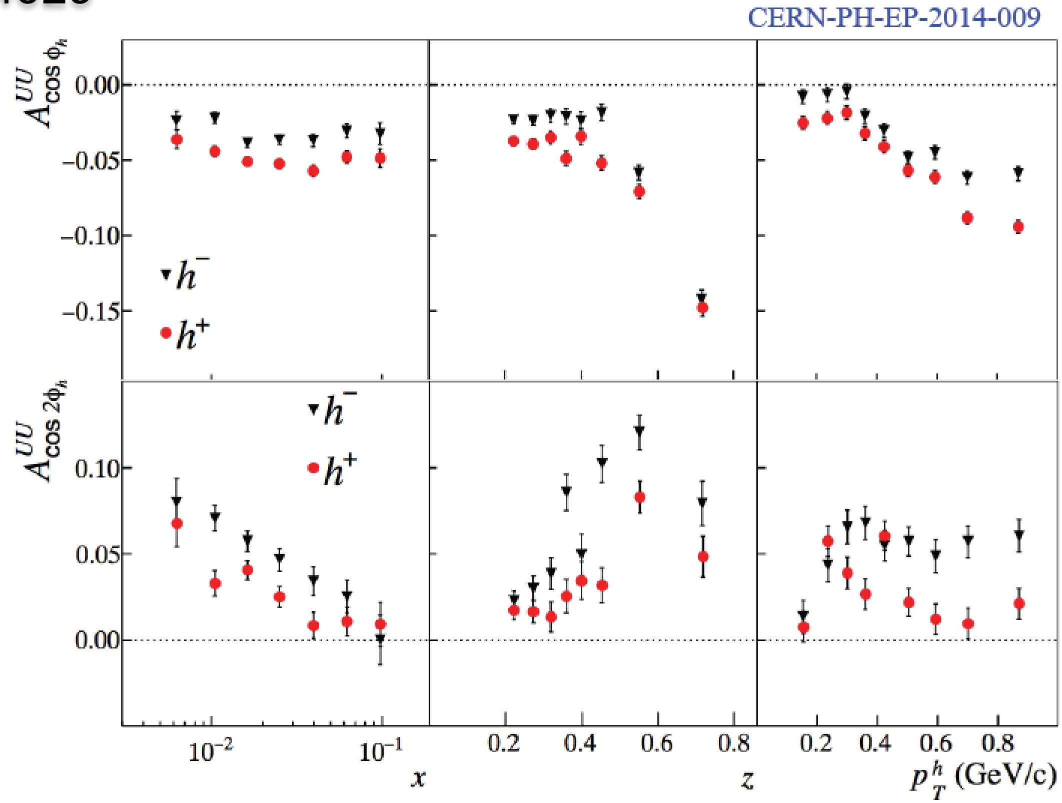
HERMES

Airapetian et al., PRD 107 (2013) 074029



COMPASS

CERN-PH-EP-2014-009



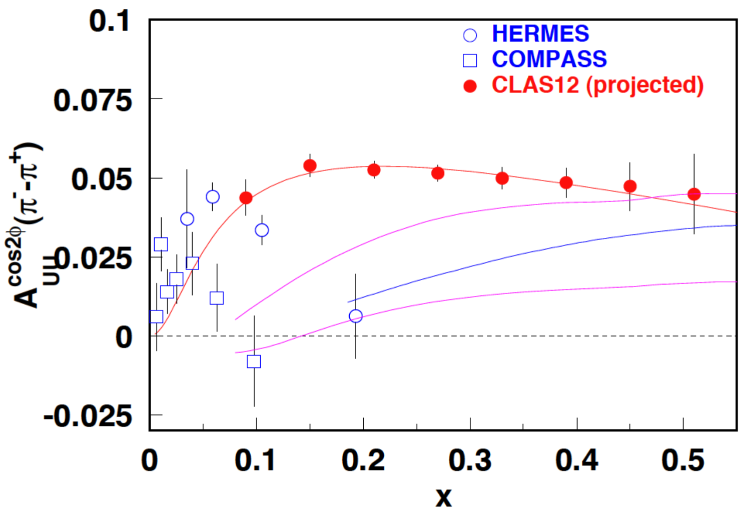
DSS and CTEQ6 (LO?) seems to give good description for π^+ and K^+, worse for π^-, and even worse for K^-.

Clear differences between h^+ and h^- in these azimuthal asymmetries, and clear dependencies as function of x, z, P_T

→ *Calls for multi-dimensional analysis (and NLO)*

Investigations into the hadron dependence

One example that this
will become possible:



Hall C SIDIS Program – basic (e,e'π) cross sections

Why need for (e,e'π) cross sections?

PAC37 Report: "the **cross sections** are **such basic tests of the understanding of SIDIS** at 11 GeV kinematics that they will play a **critical role** in establishing the entire SIDIS program of studying the partonic structure of the nucleon. In particular they complement the CLAS12 measurements in areas where the precision of spectrometer experiments is essential, being able to separate P_T and ϕ-dependence for small P_T."

$$\boxed{\sigma = \sum_q e_q^2 f(x) \otimes D(z)}$$

Basic precision cross section measurements:

- Crucial information to validate theoretical understanding
  - Convolution framework requires validation for most future SIDIS experiments and their interpretation
  - Can constrain TMD evolution
  - Questions on target-mass corrections and ln(1-z) re-summations require precision large-z data

Goal: Measure the basic SIDIS cross sections of **π^+, π^-, π^0 (and K^+)** production off the proton (and deuteron), including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate$^{(*)}$ a flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

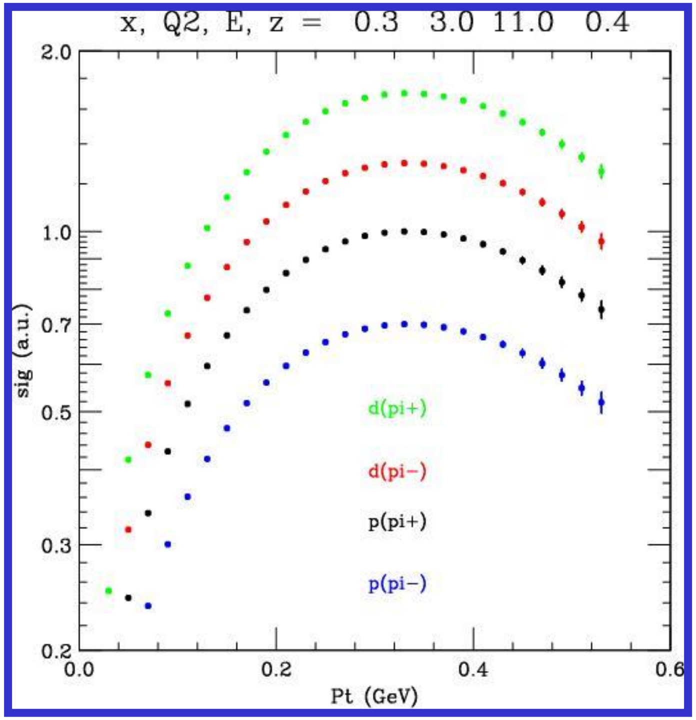
(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

Hall C SIDIS Program – basic (e,e'π) cross sections

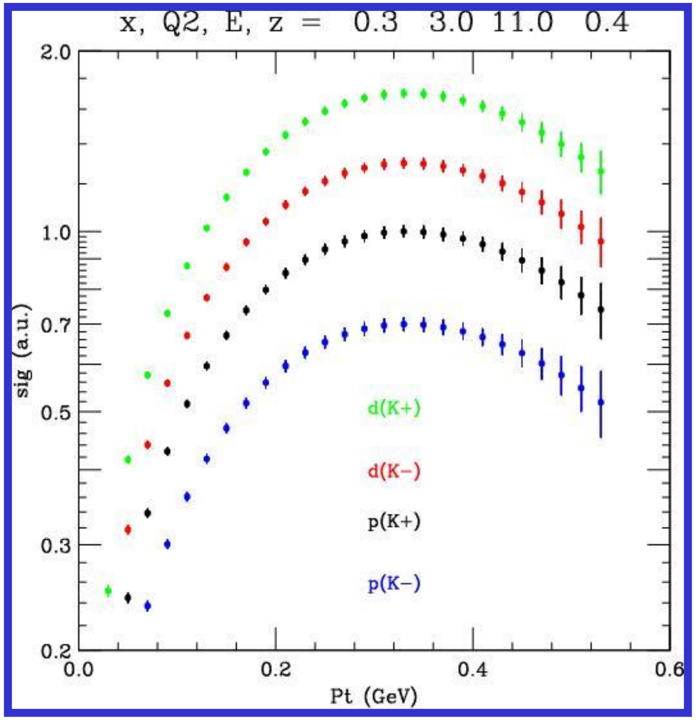
Goal: Measure the basic SIDIS cross sections of **π^+, π^-, π^0 (and K^+)** production off the proton (and deuteron), including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) a flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

Pions

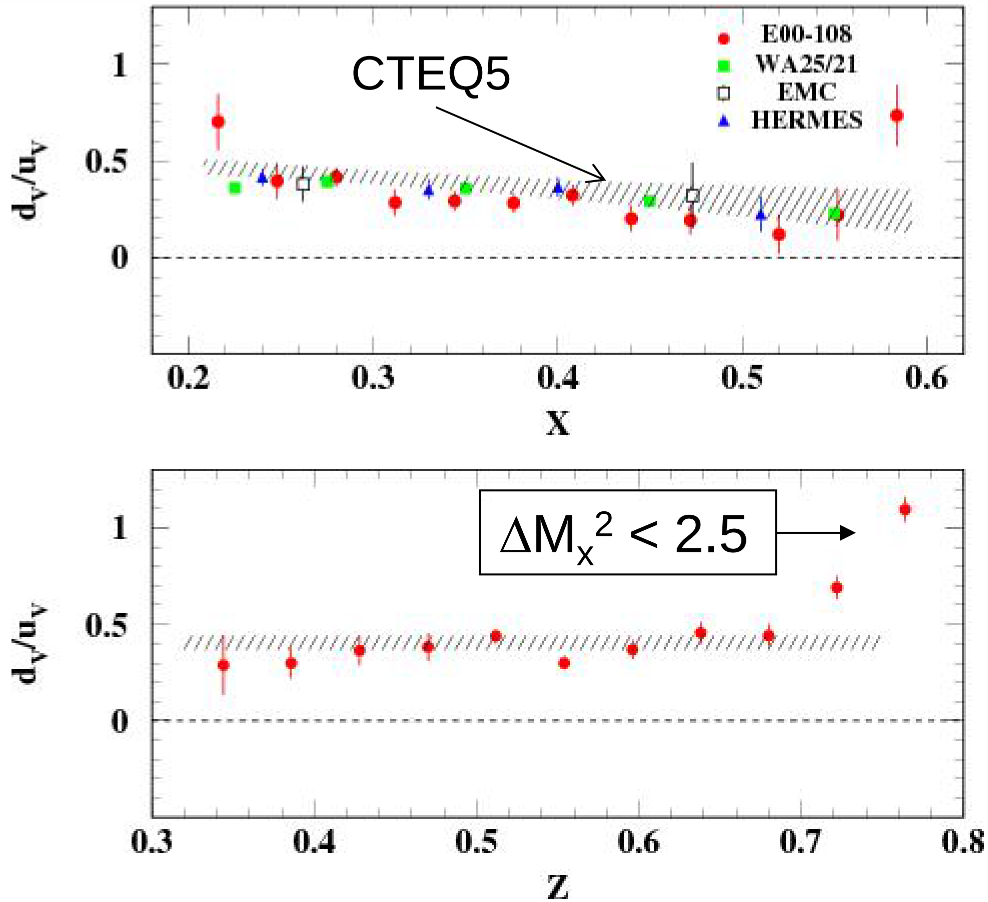


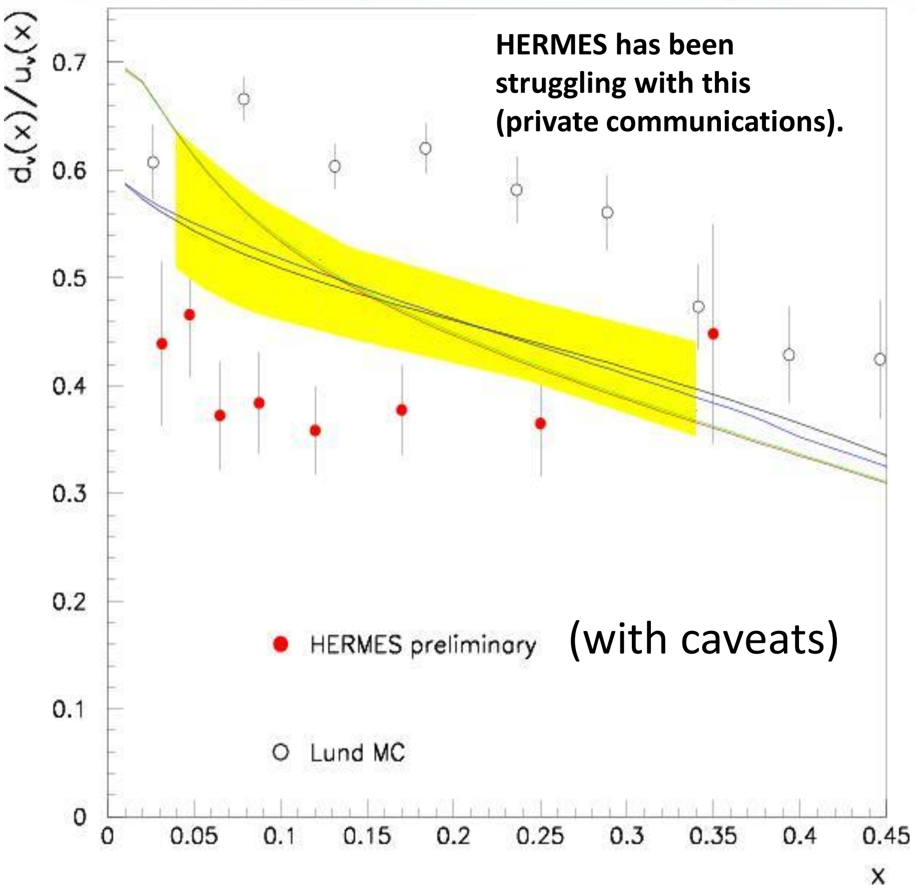
Kaons



(Kinematics II, z = 0.4 bin only)

Example - The Problem Child: d_v/u_v





As long as we do not quantitatively understand the extraction of a basic and known quantity like d_v/u_v (at intermediate x) from SIDIS data, we should question the SIDIS analysis, and leave no stone unturned to reach final quantitative understanding.

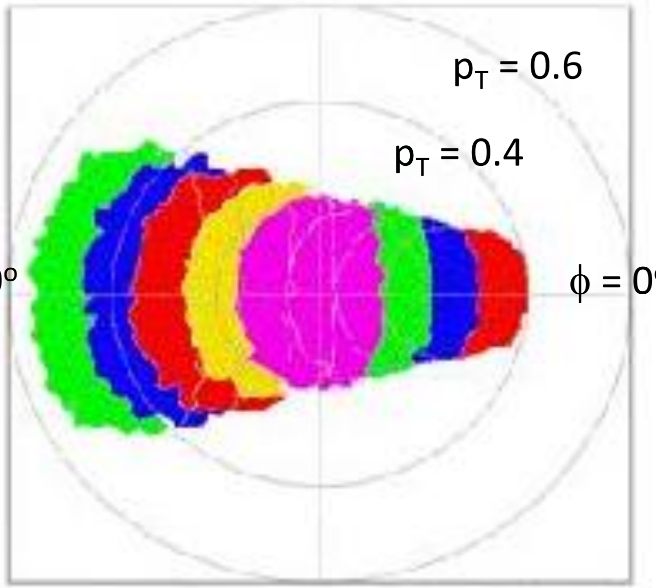
HMS + SHMS: P_T coverage

E12-09-017

Can do meaningful $\pi^{+/-}$ measurements at low p_T (down to 0.05 GeV) due to excellent momentum and angle resolutions!

- Excellent ϕ coverage up to P_T = 0.2 GeV
- Sufficient up to P_T = 0.4 GeV
  → coverage at ϕ = 0, π
- Limited up to P_T = 0.5 GeV
  → use f(ϕ) from CLAS12

$\pi^{+/-}$



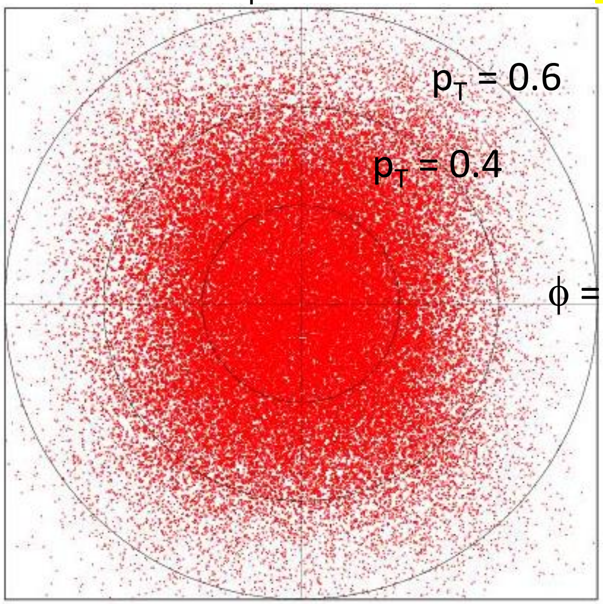
HMS + NPS: P_T coverage

E12-13-007

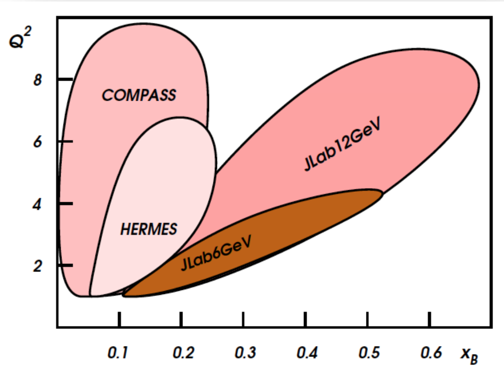
Basic π^0 SIDIS cross sections with excellent precision, and very good momentum and angle resolutions!

- Excellent ϕ coverage up to P_T = 0.3 GeV
- Good up to P_T = 0.4 GeV
- Limited up to P_T = 0.5 GeV
  → use f(ϕ) from CLAS12

π^0

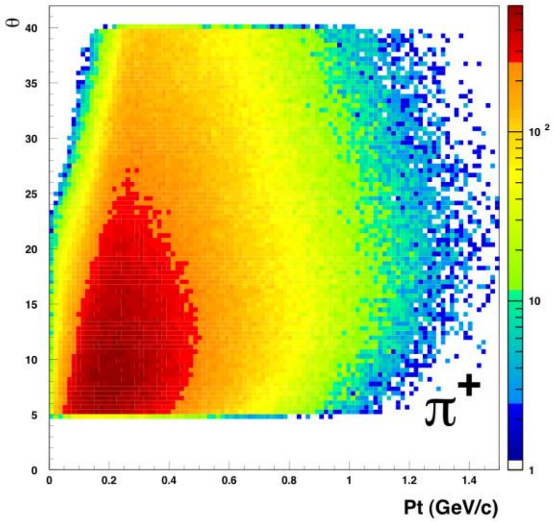


Towards the 3D Structure of the Proton



- **CLAS12** is expected to measure all the TMD observables accessible with a polarized beam, with a longitudinally polarized target, and (hopefully) a transversely polarized target.

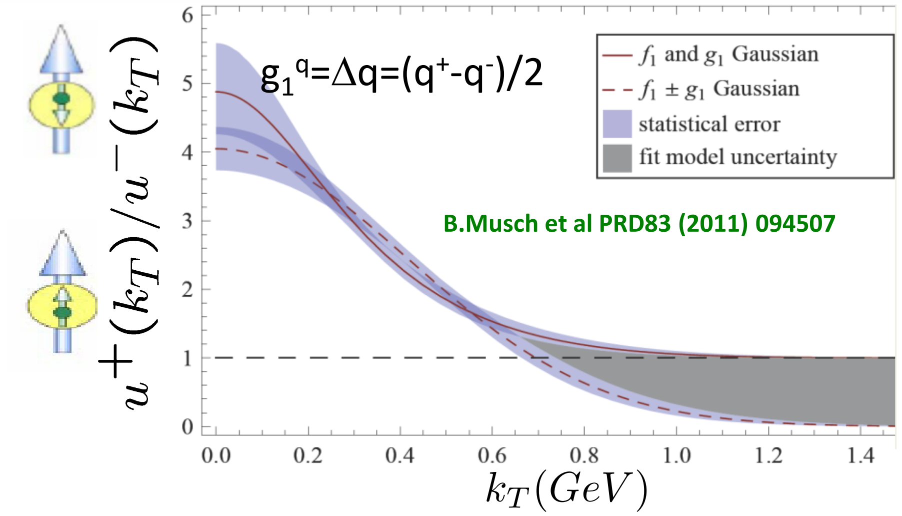
CLAS12 lacks the precision of Hall C for basic cross section measurements, but does boast a (very) good coverage in (p_T,ϕ) relevant to access the general TMD observables.



spin and flavor dependence of quark transverse momentum distributions

Distributions of PDFs may depend on flavor and spin
(lower fraction aligned with proton spin, and less u-quarks at large k_T,b_T)

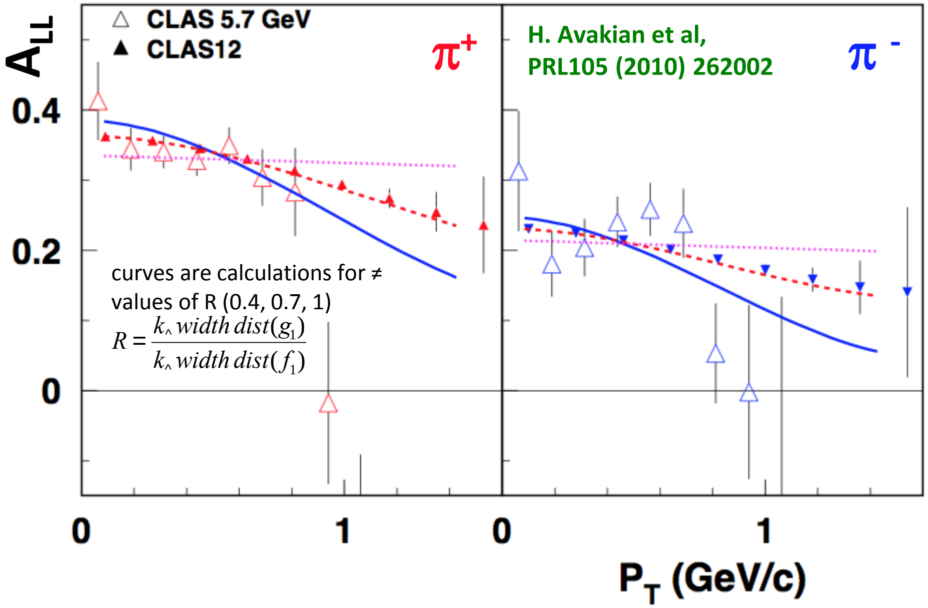
CLAS12: K_T Helicity Dependence



- Higher probability to find a quark anti-aligned with proton spin at **large k_T**
- Important to have q^+ and q^- k_T -dependent distribution separately
- q^- sensitive to orbital motion:

$$q^-_{L=1} \sim (1-x)^5 log^2(1-x)$$

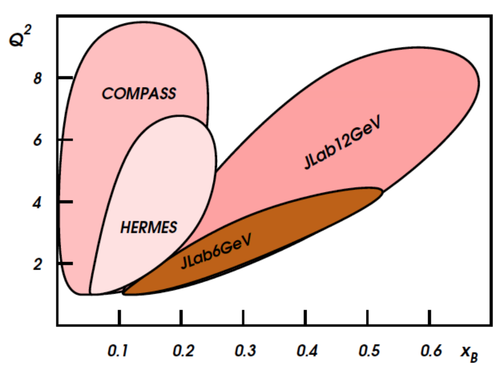
H. Avakian et al. PRL 99 (2007) 082001



- Double spin asymmetries from CLAS@JLab consistent with wider k_T distributions for f_1 than for g_1
- **Wider range in P_T from CLAS12 is crucial !**

Measurements of the P_T-dependence of A_{LL} ($\propto g_1/f_1$) provide access to transverse momentum distributions of quarks anti-aligned with the proton spin.

Towards the 3D Structure of the Proton



- **CLAS12** **is expected to measure all the TMD observables accessible with a polarized beam, with a longitudinally polarized target, and (hopefully) a transversely polarized target.**

TMDs from unpolarised SIDIS data → p_T dependence of f_1, azimuthal aymmetries

$$\frac{d\sigma}{dxdyd\psi dzd\phi_h dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{\boxed{F_{UU,T}+\varepsilon F_{UU,L}}+$$

$$\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)} + \lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\Big\}$$

and Boer-Mulders $\boxed{F_{UU}^{\cos 2\varphi} \propto h_1^\perp H_1^\perp + [\,f_1 D_1 + \ldots]/Q^2}$

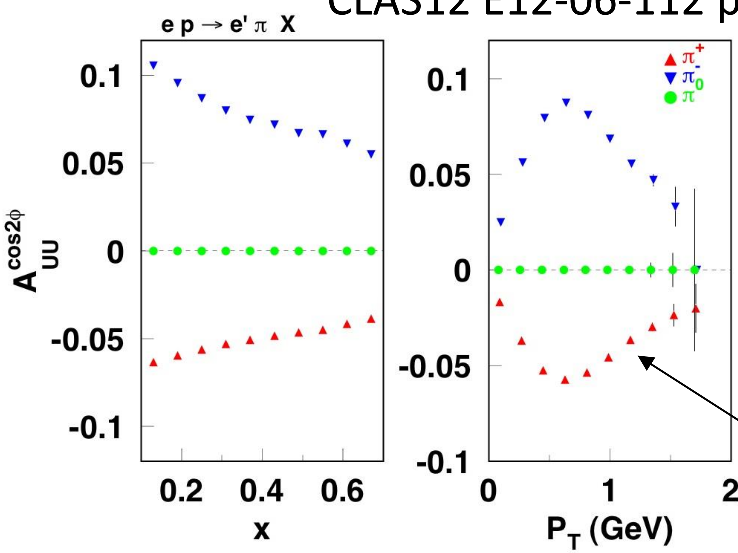
Towards the 3D Structure of the Proton

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2}=\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\left\{\boxed{F_{UU,T}+\varepsilon F_{UU,L}}+\right.$$

$$\left.\underline{\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}}+\underline{\varepsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)}}+\lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\,\underline{\sin\phi_h F_{LU}^{\sin\phi_h}}\right\}$$

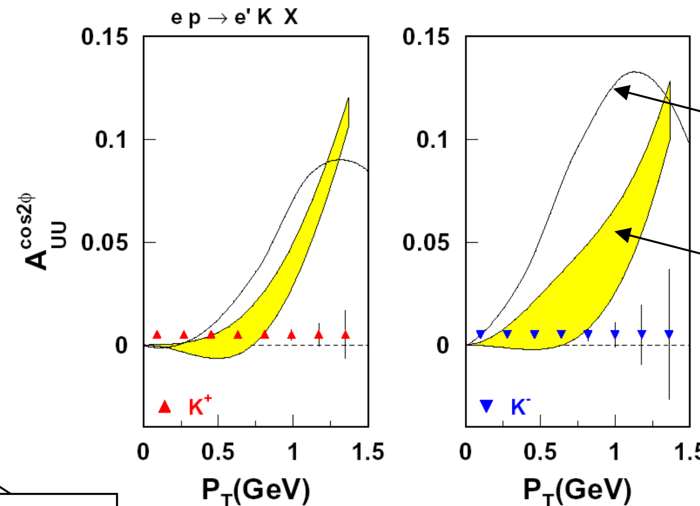
$$\boxed{F_{UU}^{\cos 2\varphi}\propto h_1^{\perp}H_1^{\perp}+[f_1D_1+\ldots]/Q^2}$$

CLAS12 E12-06-112 projections



Vanish like $1/p_T$ (Yuan)

CLAS12 E12-09-008 projections



Line: PRD78 045022
Boer-Mulders from Sivers
Collins from e+e- data

Band: PRD78 034035
Boer-Mulders from DY data
Collins from chiral limit

Overall Goal of SIDIS Program

validate basic reaction mechanism of SIDIS at "our" energies

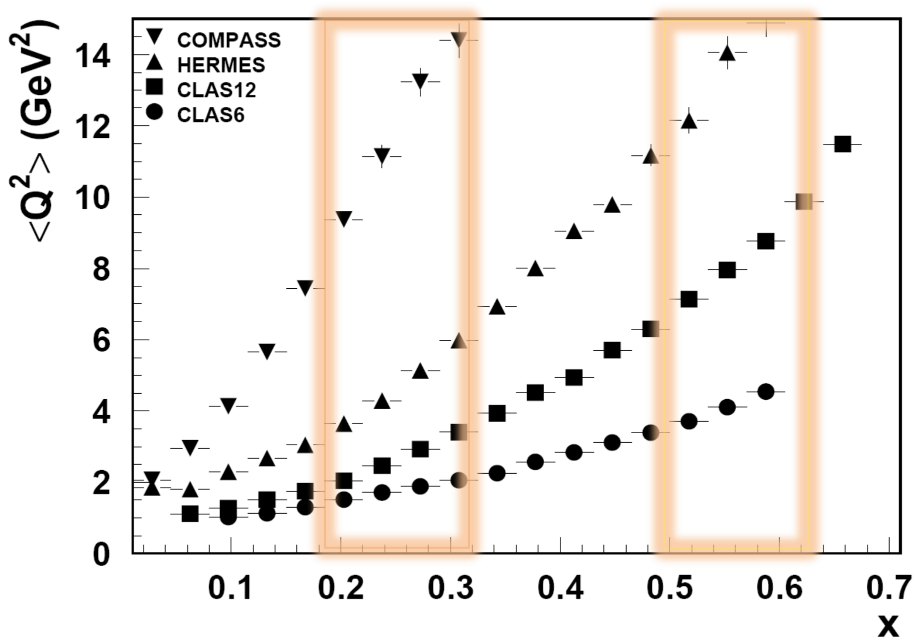
and then

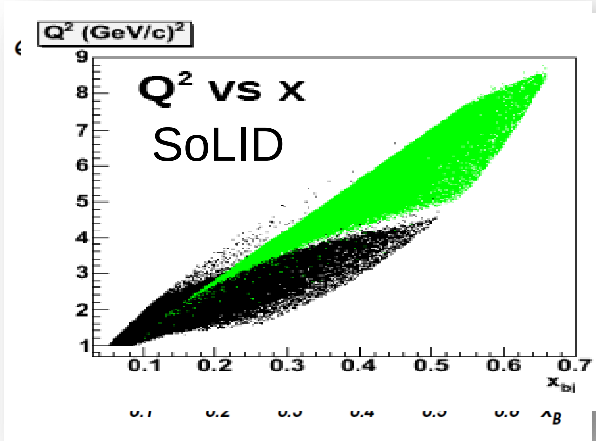
spin and flavor dependence of quark transverse momentum distributions

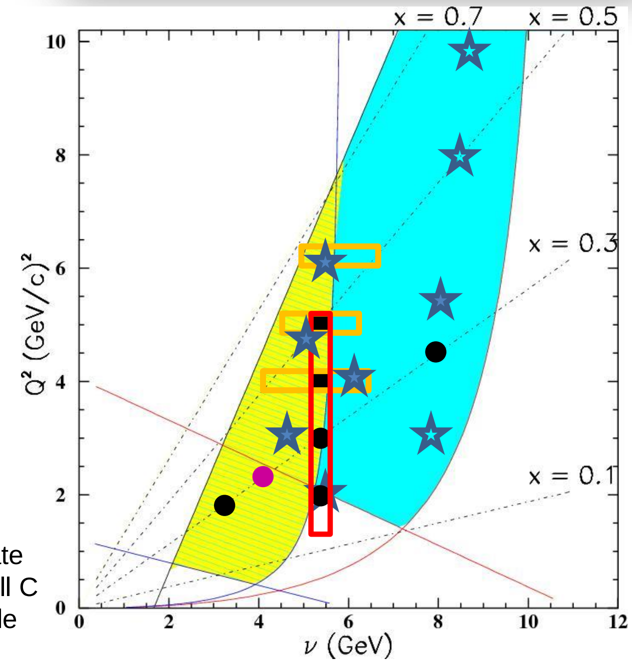
There are indications from both theory (lattice, chiral constituent quark model) and experimental data of different k_T dependences of quark flavor distributions

… but, keep in mind overall goal of 3D nucleon structure…

Need precision over range in Q^2 @ fixed x







Still many complications:

- Description valid? At what energies?
- TMD evolution
- Target-Mass effects
- ln(1-z) resummation

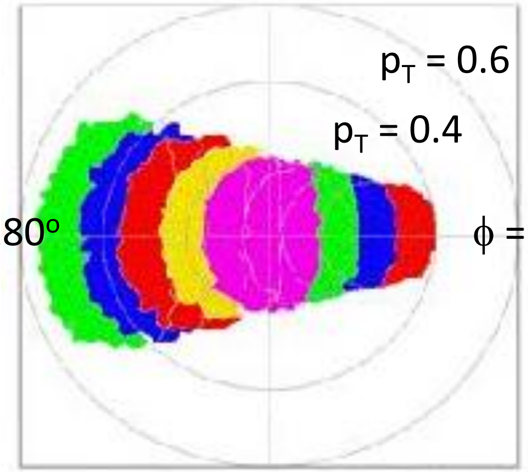
Symbols and rectangles indicate the kinematics of approved Hall C experiments within the available phase space

TMDs from SIDIS Analysis framework

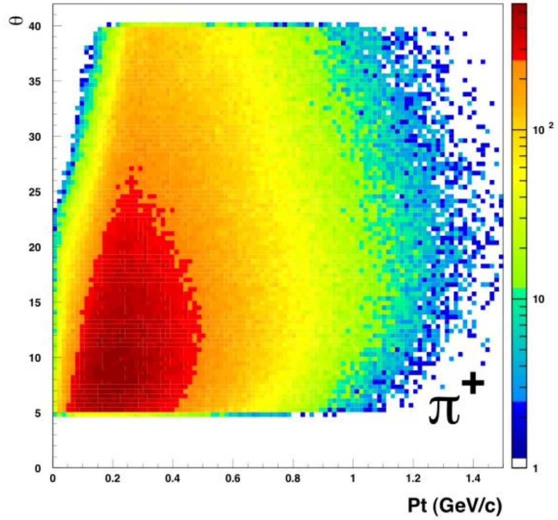
- Differential input (SIDIS):

M. Aghasyan et al arXiv:1409.0487 (JHEP)

bin#	x	Q^2	y	W	M_X	ϕ	z	P_T	λ	Λ	N(counts)	RC
1 ... N												



Need to combine precision experiments with more limited acceptance to broad-survey experiments with excellent acceptance

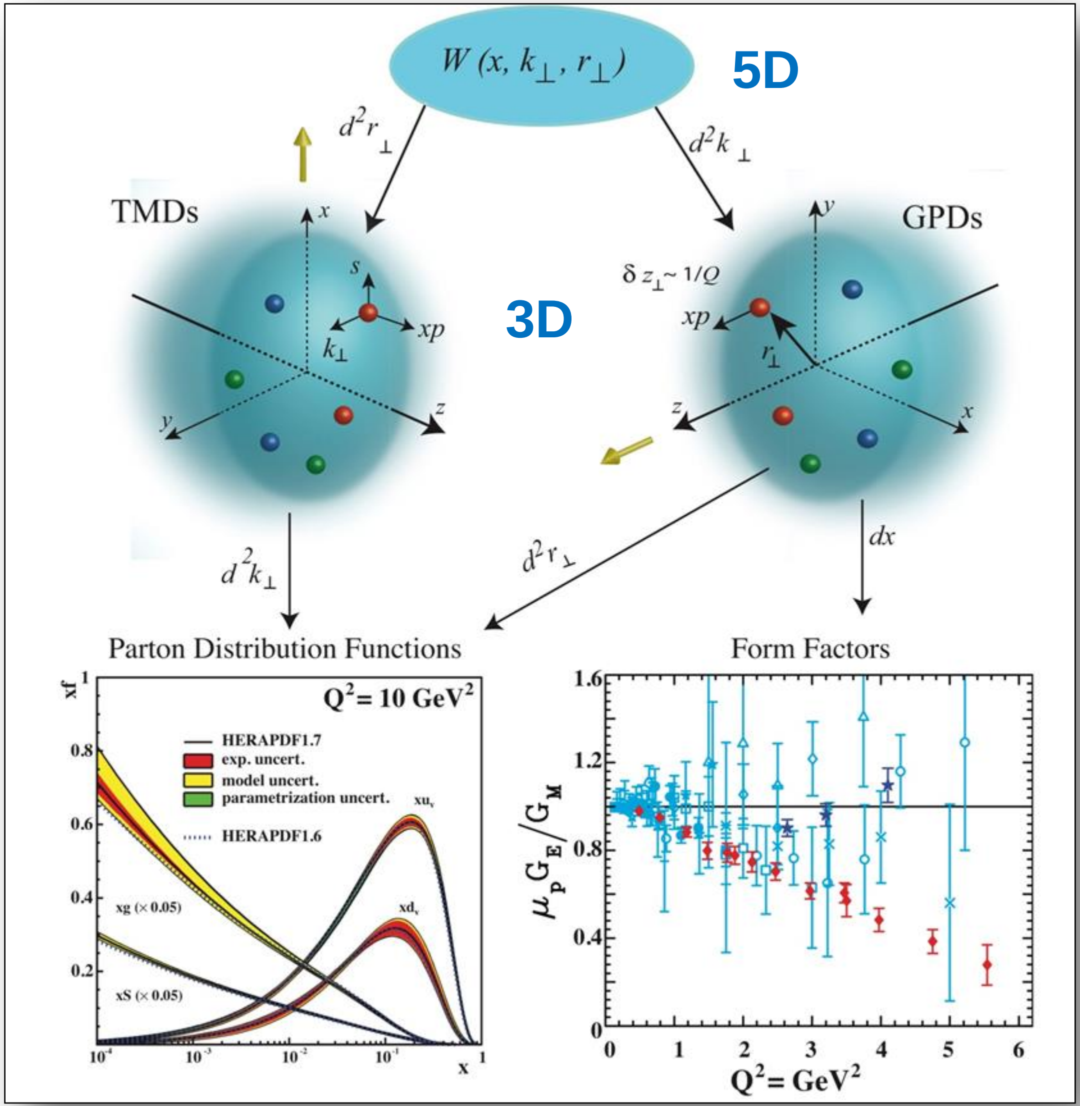


•Need a TMD extraction framework to define the input data info needed
•Define all the data from other experiments which may be needed (data preservation)

JLab: 21st Century Science Questions

- What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?
- Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?
- **Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?**
- What is the relation between short-range N-N correlations , the partonic structure of nuclei, and the nature of the nuclear force?
- Can we discover evidence for physics beyond the standard model of particle physics?

New Paradigm for Nucleon Structure



- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- GPDs
  - Spatial imaging (exclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets

Major new capability with JLab12

“3D” Analysis framework

- Differential input (SIDIS):

Adapted from Harut Avakian

bin#	x	Q^2	y	W	M_X	ϕ	z	P_T	λ	Λ	N(counts)	RC
1 … N												

M. Aghasyan et al arXiv:1409.0487 (JHEP)

- Differential input (DVMP):

bin#	x	Q^2	y	W	M_X	ϕ	t		λ	Λ	N(counts)	RC
1 … N												

•Need a TMD/GPD extraction framework to define the input data info needed
•Define all the data from other experiments which may be needed (data preservation)

Summary (or random thoughts)

- It is crucial to measure a set of basic SIDIS cross sections to validate basic reaction mechanism of SIDIS at "our" energies to subsequently allow for a spin and flavor dependence of quark transverse momentum distributions.
- We have made good strides towards uncovering assumptions and have great confidence now that the quark transverse momentum distributions are helicity and flavor dependent – but this also complicates analysis!
- There are still many (and difficult) questions on the table, and measurable effects tend to be small. So, to make further progress we need to be able to seamlessly merge data from various labs and experiments to further our understanding, and merge theory insight, phenomenology and data.

… and, keep in mind the overall nuclear physics goal of 3D nucleon structure we need to convey to our colleagues…

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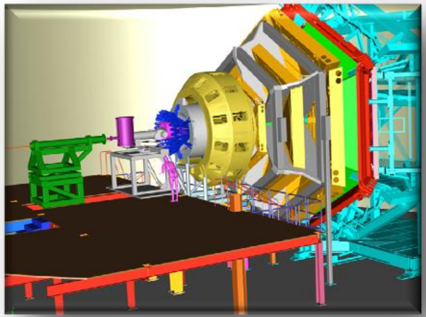
Together stronger: SIDIS Studies with 12 GeV

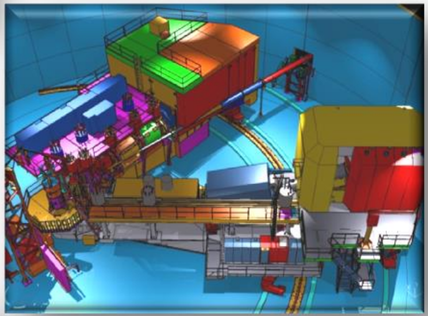
- **CLAS12 in Hall B**

  General survey, medium lumi



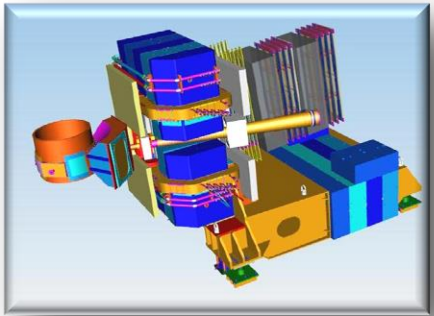
- **SHMS, HMS, NPS in Hall C**

  L-T studies, precise $\pi^+/\pi^-/\pi^0$ ratios



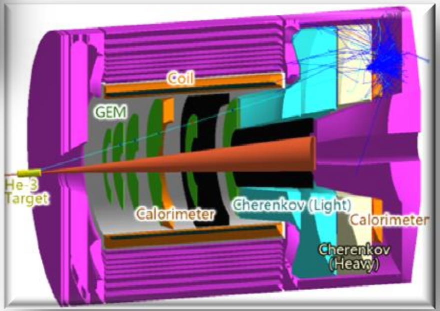
- **SBS in Hall A**

  High x, High Q^2, 2-3D



- **SOLID in Hall A**

  High lumi and acceptance – 4D



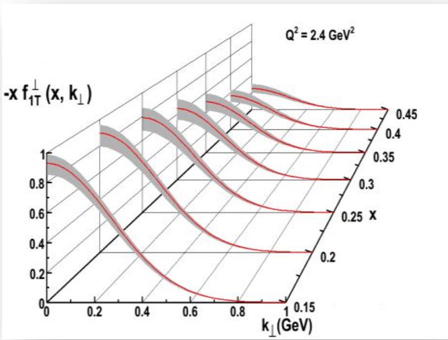
3D Mapping of the Nucleon

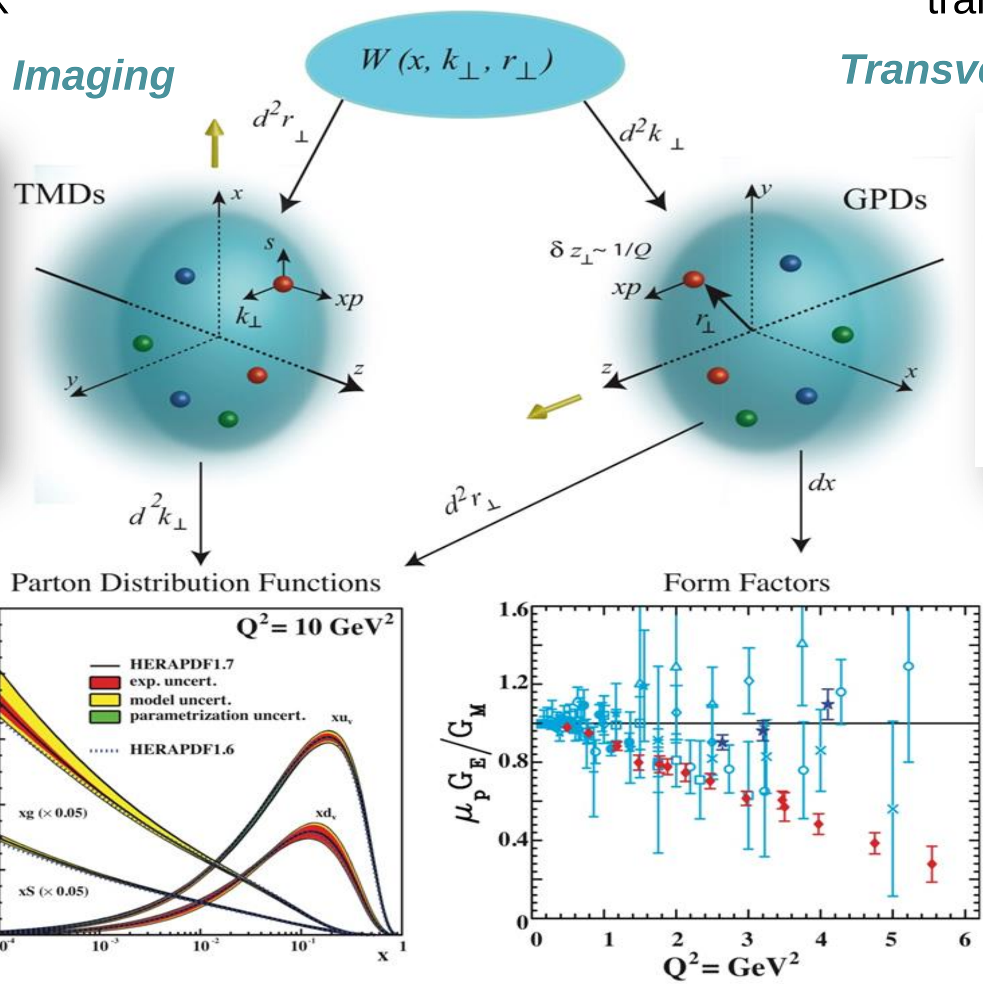
TMDs: Longitudinal momentum fraction x and transverse momentum k

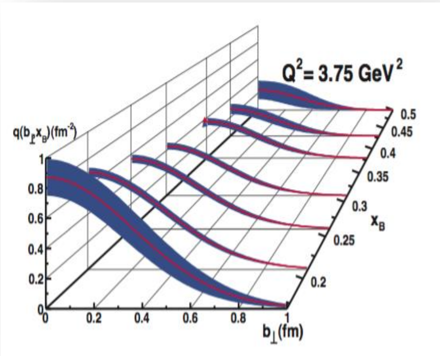
GPDs: Longitudinal momentum fraction x at transverse location b

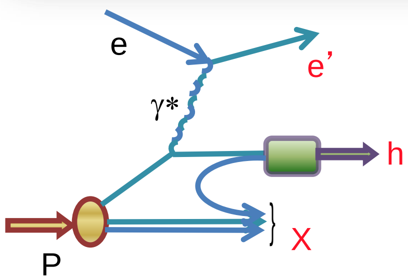
Transverse Momentum Imaging

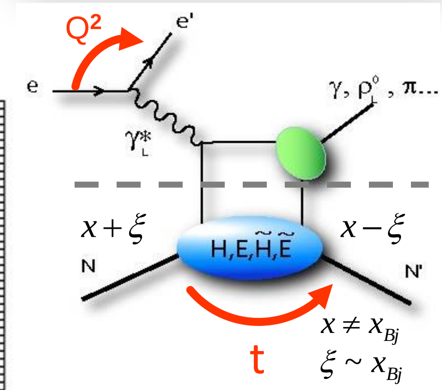
Transverse Spatial Imaging



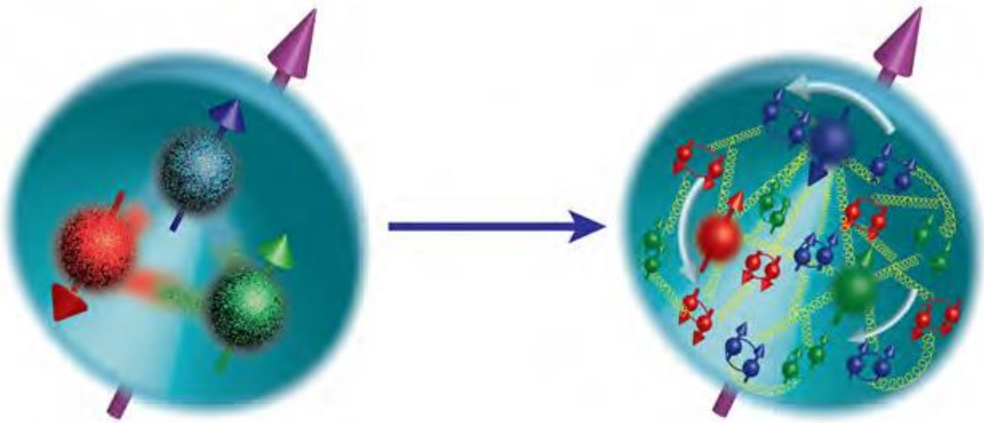








The Incomplete Nucleon: Spin Puzzle



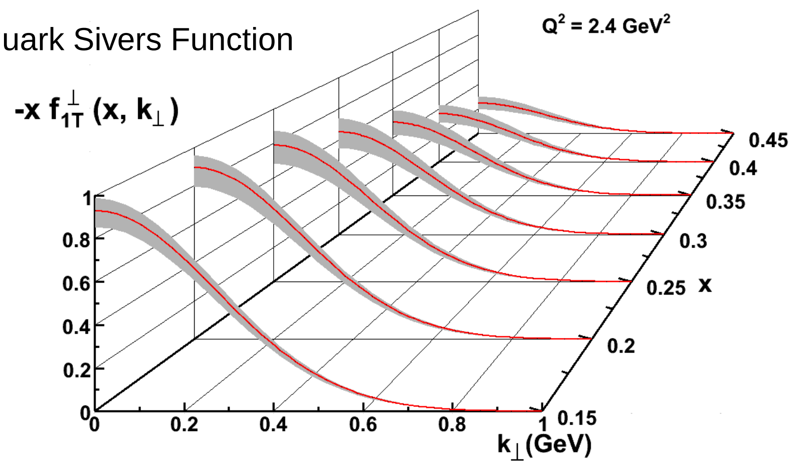
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

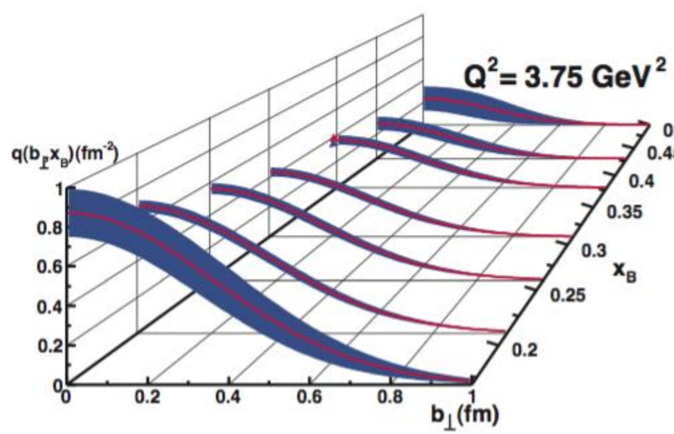
- $\Delta\Sigma$ ~ 0.25 (world DIS)
- ΔG ~ 0.2? (RHIC+DIS)
- L_q?

Longitudinal momentum fraction x and transverse momentum images

Longitudinal momentum fraction x and transverse spatial images

Up quark Sivers Function



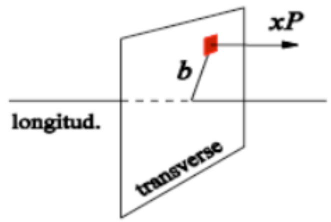


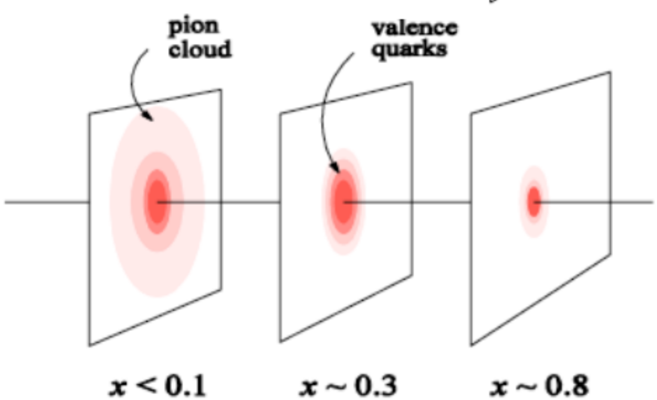
12 GeV projections: valence quarks well mapped

Hard Exclusive Processes → GPDs

Goal 1: Transverse Imaging of Nucleon

Fourier transform of t-dependence





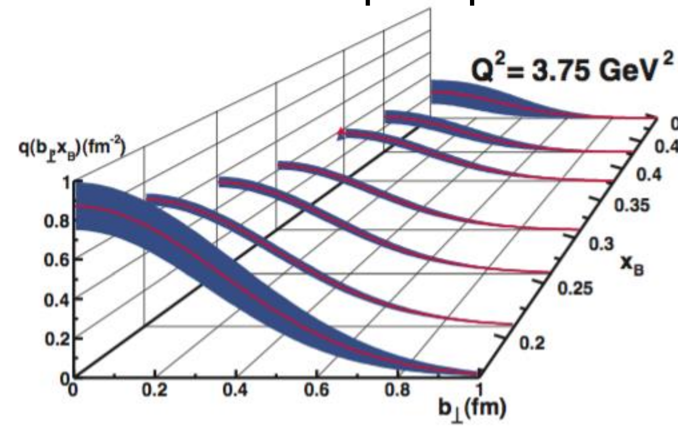
Goal 2: Orbital Angular Momentum

Ji's Sum Rule for $J^q = \frac{1}{2}\Delta\Sigma + L^q$

$$J^q = \frac{1}{2}\int_{-1}^{1} x\,dx\,[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$

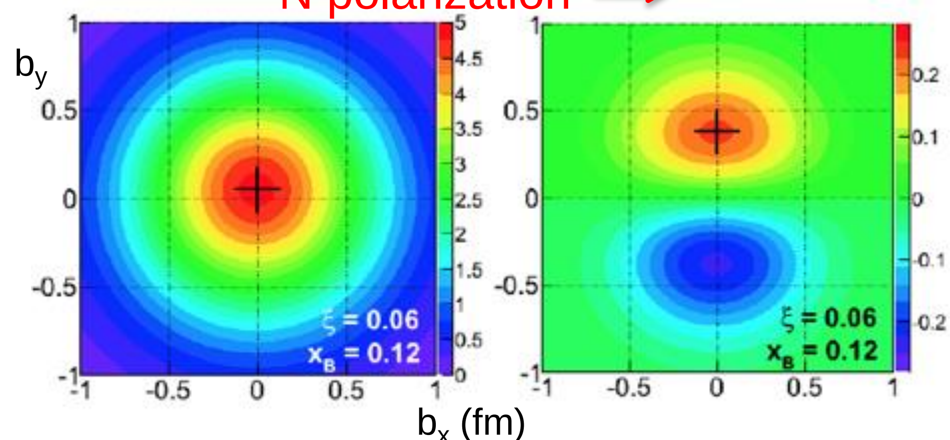
CLAS12 with help from Halls A & C

The proton's transverse profile as function of the impact parameter b



Distortions induced by spin direction

N polarization →

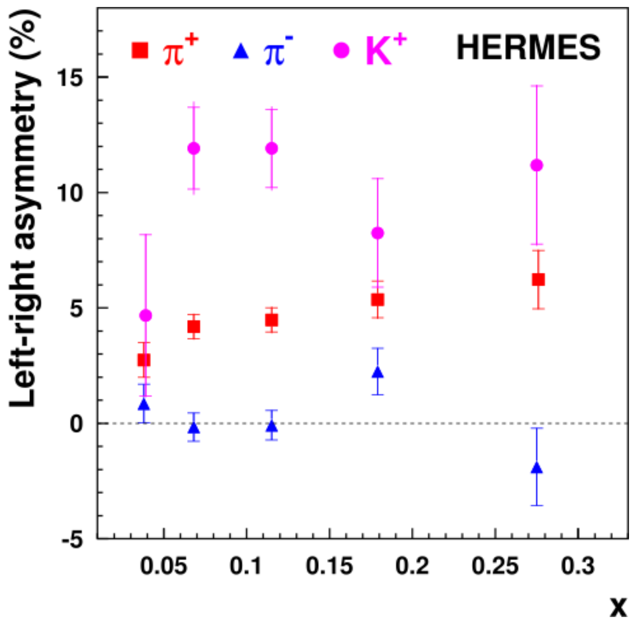


GPD H and E

GPD E only

3D Parton Distributions: TMDs

A surprise of transverse-spin experiments



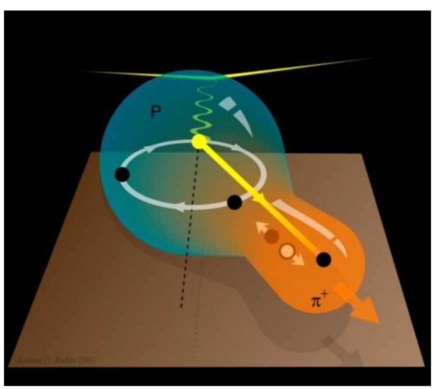
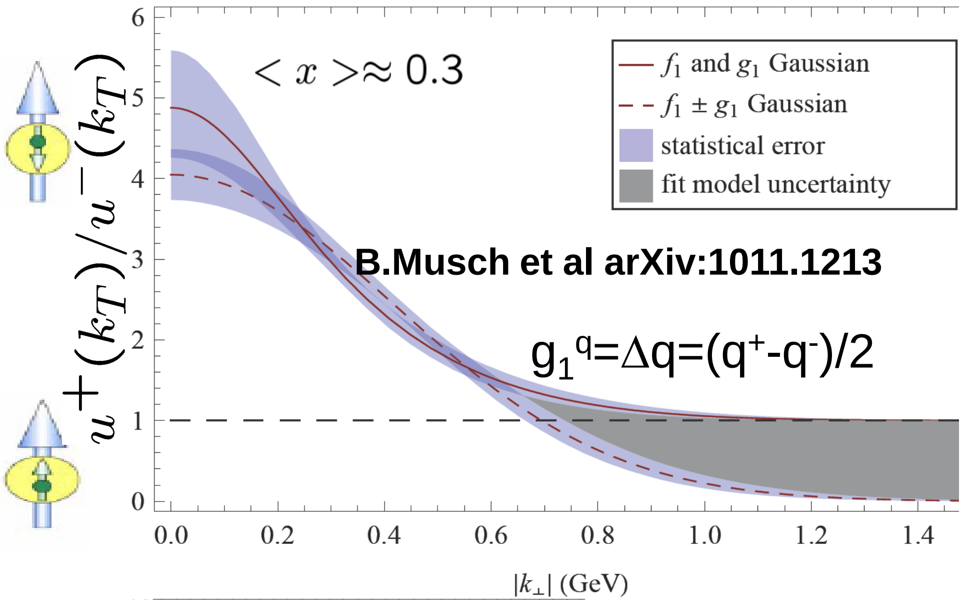


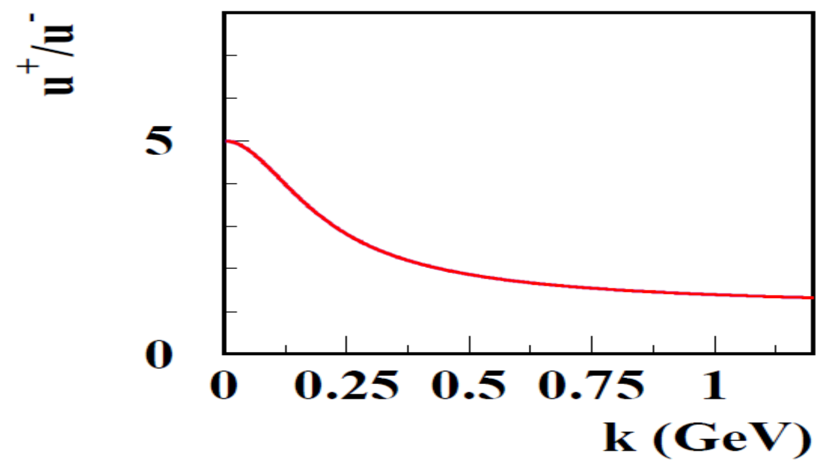
Illustration of the possible correlation between the internal motion of an up quark and the direction in which a positively-charged pion ($u\bar{d}$) flies off.

- **Access orbital motion of quarks**
  ➔ contribution to the proton's spin
- Observables: Azimuthal asymmetries due to correlations of spin q/n and transverse momentum of quarks

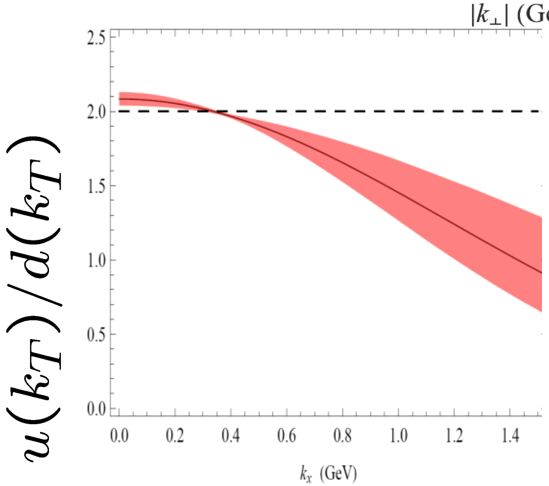
nucleon polarization \ quark polarization	U	L	T
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 transversity; $h_{1T}^\perp$ pretzelosity

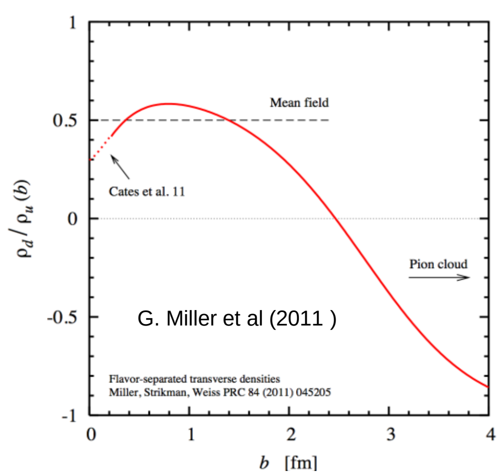
Correlations in quark distributions

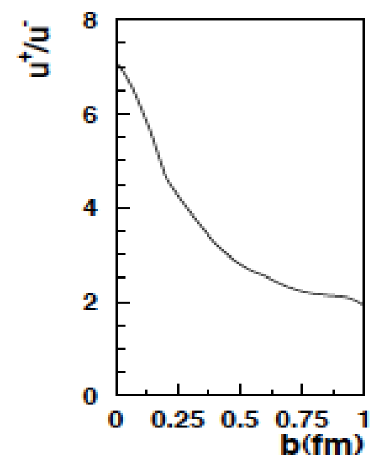


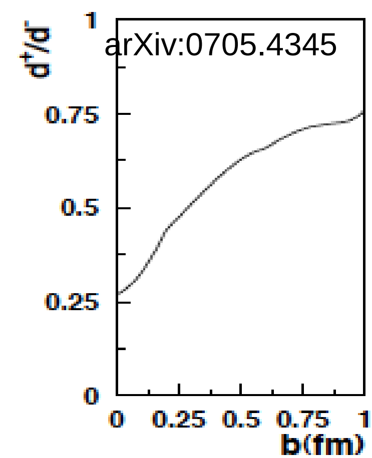


B.Pasquini et al









Distributions of PDFs may depend on flavor and spin (lower fraction aligned with proton spin, and less u-quarks at large k_T,b_T)

$R = \sigma_L/\sigma_T$ in DIS

- R_{DIS} is in the naïve parton model related to the parton's transverse momentum: $R = 4(M^2x^2 + \langle k_T^2\rangle)/(Q^2 + 2\langle k_T^2\rangle)$.
- $R_{DIS} \rightarrow 0$ at $Q^2 \rightarrow \infty$ is a consequence of scattering from free spin-½ constituents
- Of course, beyond this, at finite Q^2, R_{DIS} sensitive to gluon and higher-twist effects
- No distinction made up to now between diffractive and non-diffractive contributions in R_{DIS}
- $R_{DIS}^H = R_{DIS}^D$, to very good approximation (experimentally)
  - from formal point of view they should not be identical!

    (u not equal to d at large x + evolution in Q^2,
    H = spin-1/2 and D = spin-1, at low Q^2)

$R = \sigma_L/\sigma_T$ in $(e,e'\pi)$ SIDIS

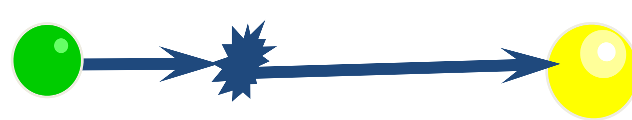
Knowledge on $R = \sigma_L/\sigma_T$ in SIDIS is essentially non-existing!

- If integrated over z (and p_T, ϕ, hadrons), $R_{SIDIS} = R_{DIS}$
- $R_{SIDIS} = R_{DIS}$ test of dominance of quark fragmentation
- R_{SIDIS} may vary with z
- At large z, there are known contributions from exclusive and diffractive channels: *e.g.*, pions from Δ and $\rho \rightarrow \pi^+\pi^-$
- R_{SIDIS} may vary with transverse momentum p_T
- Is $R_{SIDIS}^{\pi^+} = R_{SIDIS}^{\pi^-}$? Is $R_{SIDIS}^{H} = R_{SIDIS}^{D}$?
- Is $R_{SIDIS}^{K^+} = R_{SIDIS}^{\pi^+}$? Is $R_{SIDIS}^{K^+} = R_{SIDIS}^{K^-}$?

E12-06-104 measures kaons too! (with ~20% of pion statistics)

"A skeleton in our closet"

$$\boxed{\sigma = \sum_q e_q^2 f(x) \otimes D(z)}$$



So what about $R = \sigma_L/\sigma_T$ for pion electroproduction?

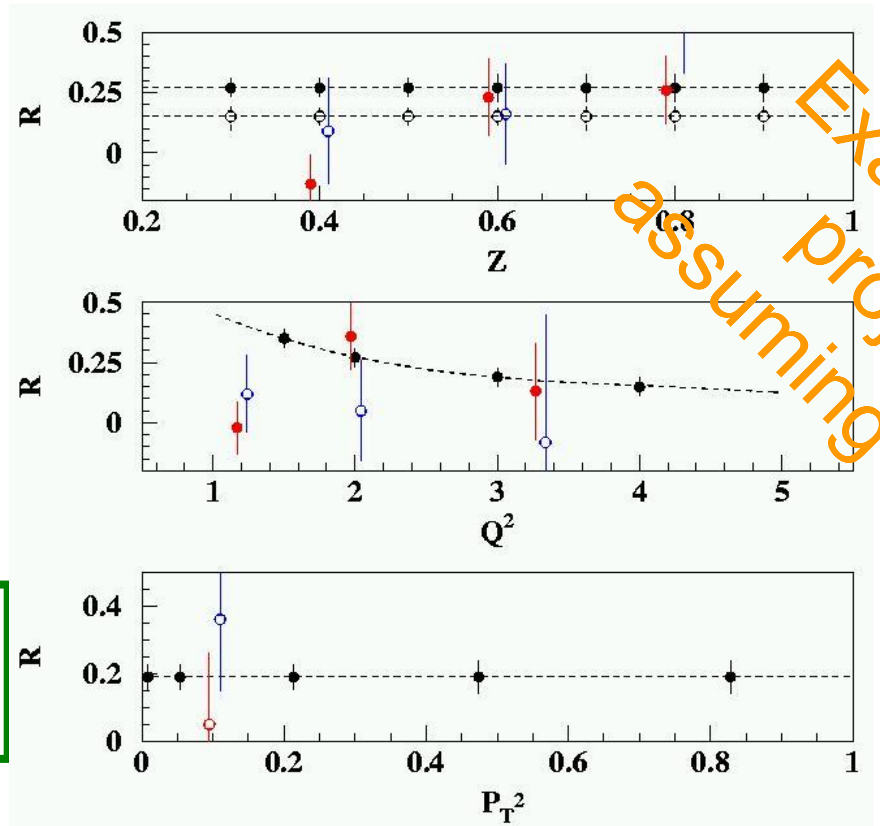
"Semi-inclusive DIS"

Here, $R_{SIDIS} \rightarrow R_{DIS}$ disappears with Q^2

"Deep exclusive scattering" is the z → 1 limit of this "semi-inclusive DIS" process

Here, $R = \sigma_L/\sigma_T \sim Q^2$ (at fixed x)

Not including a comparable systematic uncertainty: ~1.6%



Example of 12-GeV projected data assuming $R_{SIDIS} = R_{DIS}$

Have no idea at all how R will behave at large p_T

Planned scans in z at $Q^2 = 2.0$ ($x = 0.2$) and 4.0 GeV^2 ($x = 0.4$) → should settle the behavior of σ_L/σ_T for large z.

Planned data cover range $Q^2 = 1.5 – 5.0$ GeV^2, with data for both H and D at $Q^2 = 2$ GeV^2

Planned data cover range in P_T up to ~ 1 GeV. The coverage in ϕ is excellent (o.k.) up to $P_T = 0.2$ (0.4) GeV.

Hall C SIDIS Program (typ. $x/Q^2 \sim$ constant)

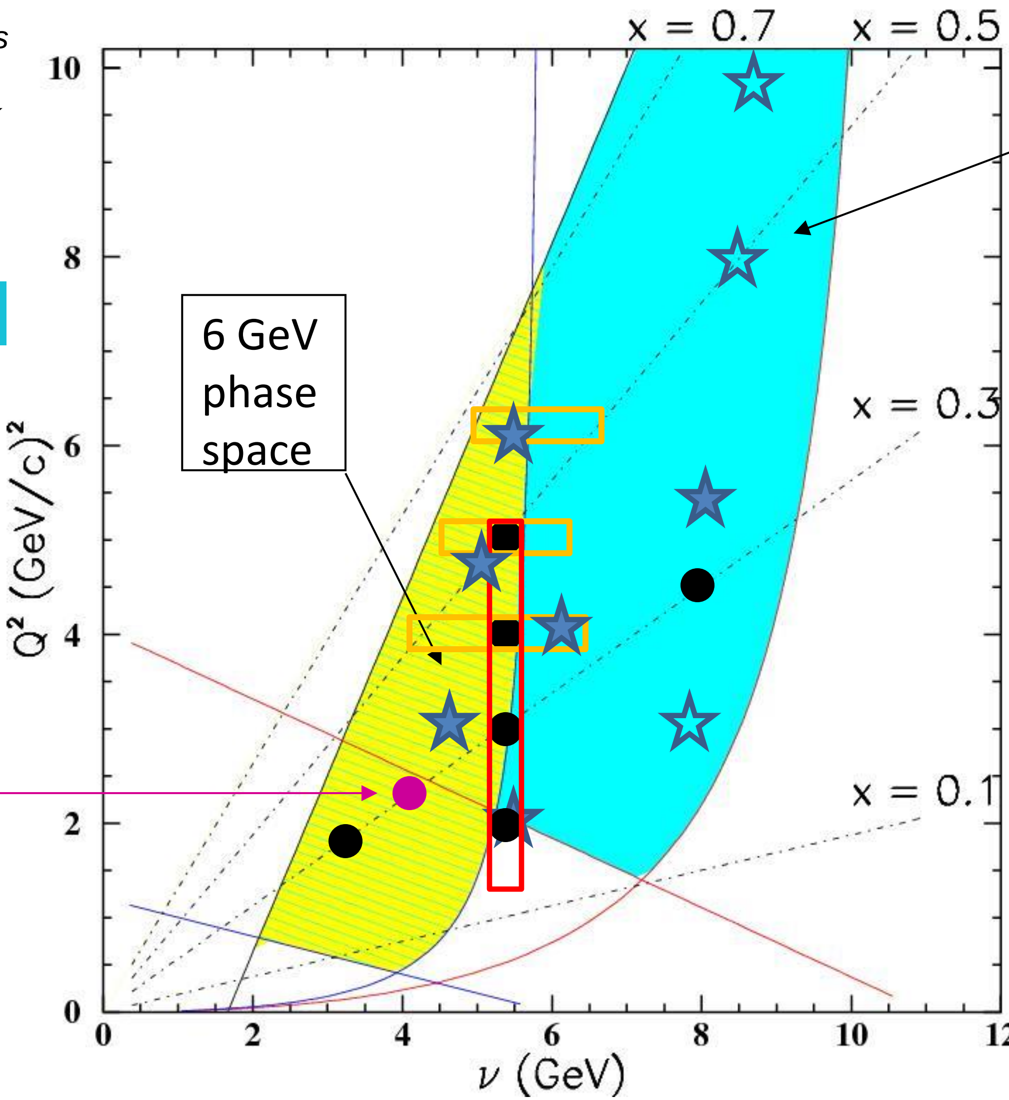
HMS + SHMS (or NPS) Accessible Phase Space for SIDIS

Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

E12-13-007
Neutral pions:
Scan in (x,z,P_T)
Overlap with E12-09-017 & E12-09-002

Parasitic with E12-13-010

E00-108
(6 GeV)



11 GeV phase space

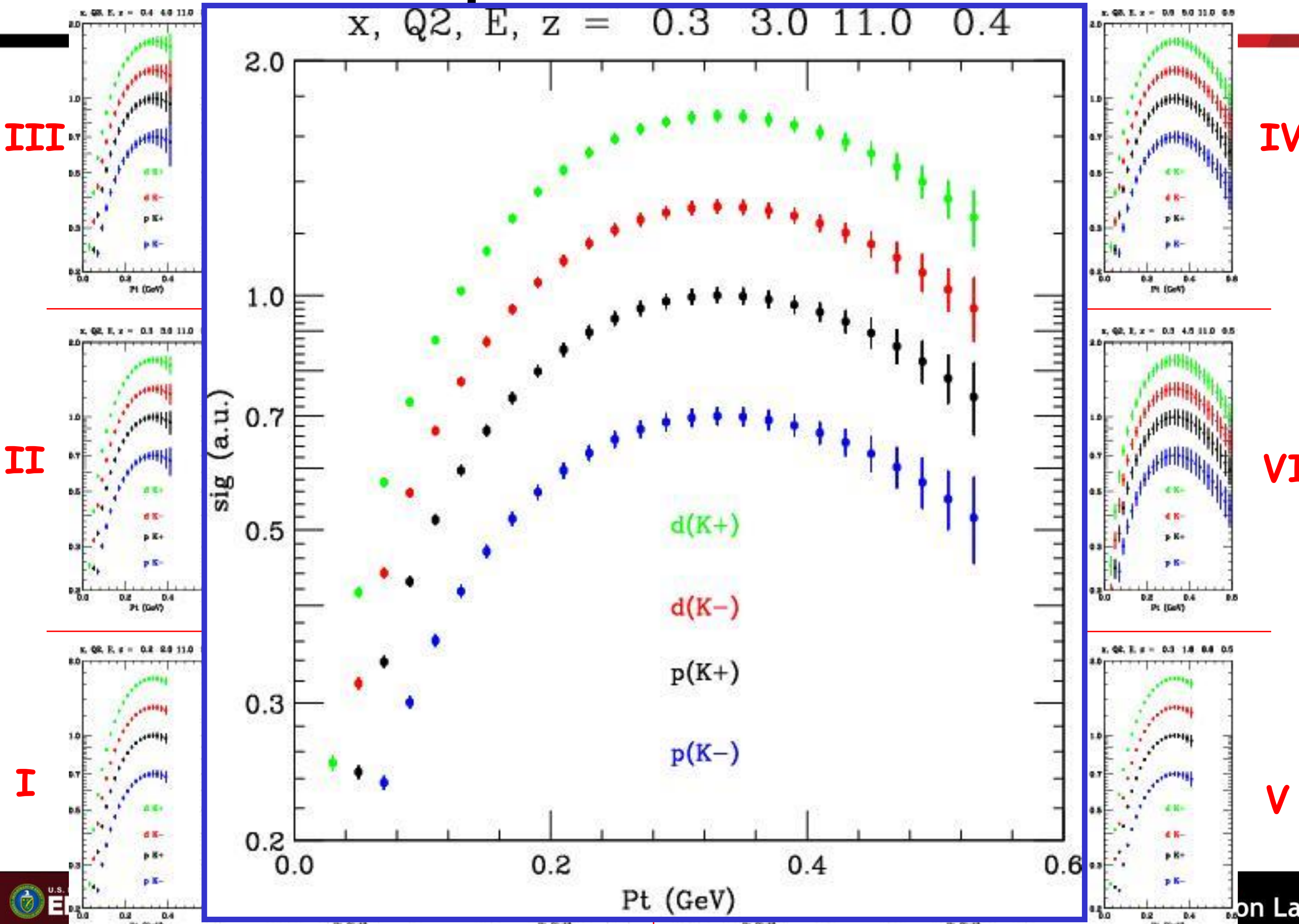
Charged pions:

E12-06-104
L/T scan in (z,P_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

E12-09-017
Scan in (x,z,P_T)
+ scan in Q^2 at fixed x

E12-09-002
+ scans in z

Hall C Projected Results – Kaons

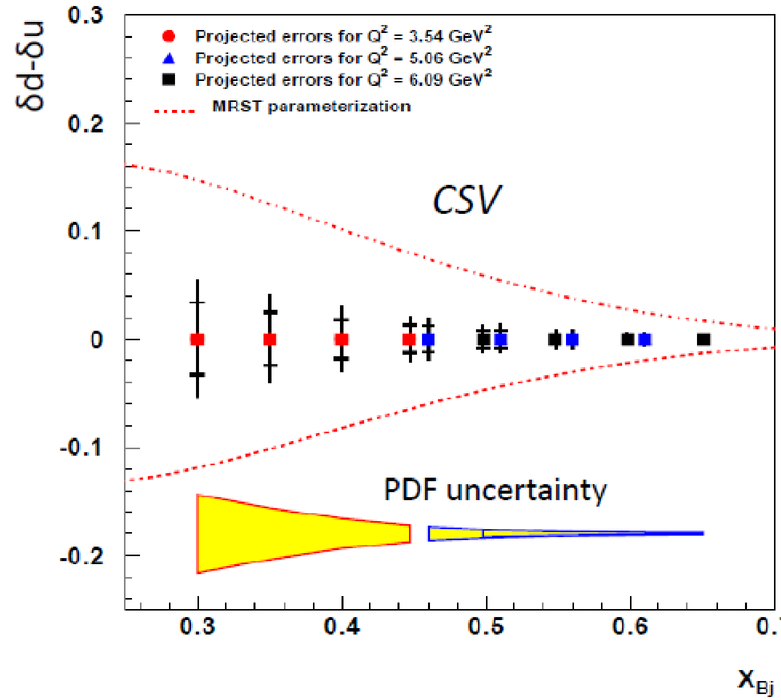


Hall C E12-09-002: The Hunt for CSV

- Charge symmetry (CS) is an approximate symmetry in the nuclear world, respected to better than 1%: $M_p \approx M_n$, energy levels in mirror nuclei (after Coulomb corrections), …
- At the quark level CS implies $u^p(x,Q^2) = d^n(x,Q^2)$, $d^p(x,Q^2) = u^n(x,Q^2)$. *This is widely assumed but never thoroughly checked by experiment!*
- In QCD charge symmetry violation (CSV) originates from EM interactions (small at high energies) and $\delta m = m_d - m_u$.
- Naively, CSV ~ $(m_d - m_u)/\langle M \rangle$, where $\langle M \rangle \sim 0.5 - 1$ GeV from the strong Hamiltonian → one expects an ~1% effect

$$R^D_{meas} = \frac{4Y^{D\pi-}(x,z) - Y^{D\pi+}(x,z)}{Y^{D\pi+}(x,z) - Y^{D\pi-}(x,z)}$$

Experiment aims, assuming a thorough understanding of the SIDIS reaction mechanism is validated, to extract CSV info from the charged-pion yield ratio on a D target.



Hall C SIDIS Program – basic (e,e'π) cross sections

(Hall C's basic SIDIS cross section data at a 6-GeV JLab showed agreement with partonic expectations laying the foundation for a vigorous 12-GeV SIDIS program. PRL 98 (2007) 022001; PL B665 (2008) 20; PRC 85 (2012) 015202. At a 12-GeV JLab, Hall C's role will be again to provide basis SIDIS cross sections, furthering our understanding.)

Low-energy (x,z) factorization, or possible *convolution in terms of quark distribution and fragmentation functions*, at JLab-12 GeV <u>must be</u> well validated to substantiate the SIDIS science output. Many questions remain at intermediate-large z (~0.2-1) and low-intermediate Q^2 (~2-10 GeV^2).

<u>Why need for (e,e'π^0) beyond (e,e'$\pi^{+/-}$)?</u>

(e,e'π^0) experimental advantages:

☺ no diffractive ρ contributions
☺ no exclusive pole contributions
☺ reduced resonance contributions
☺ proportional to average D

Further advantages:

- Can verify: $\sigma^{\pi^0}(x,z) = \frac{1}{2}\left(\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z)\right)$
- Confirms understanding of flavor decomposition & of k_T dependence

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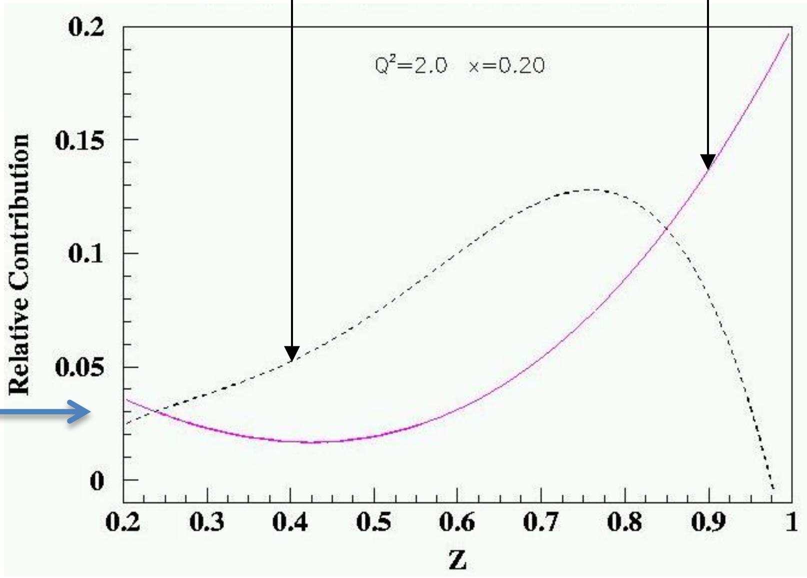
Further non-trivial contributions to (e,e'π^+) Cross Sections:

Contributions from ρ

Radiation contributions, including from exclusive



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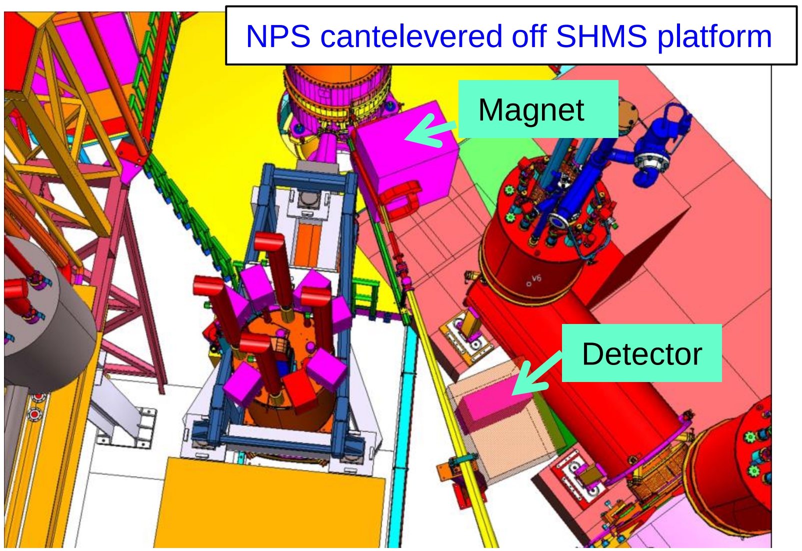
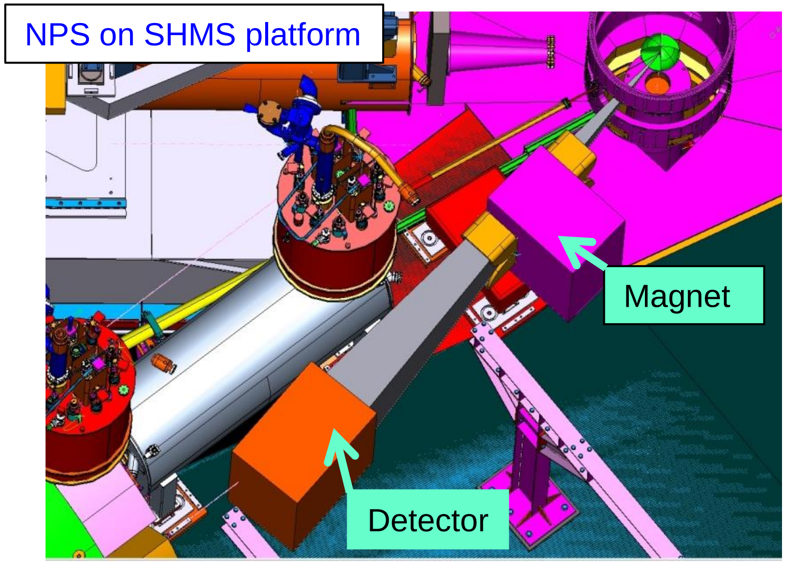
The Neutral-Particle Spectrometer (NPS)

The NPS is envisioned as a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ and π^0). The NPS will be remotely rotatable off the SHMS platform.



NPS angle range: 5.5 – 30 degrees



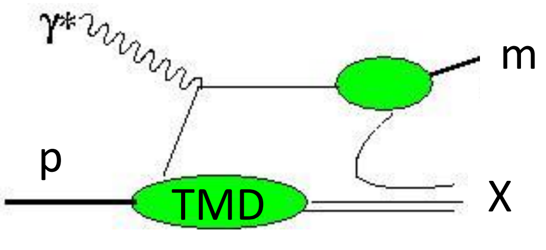
NPS angle range: 25 – 60 degrees

The large interest for such a device can be exemplified by the PAC-approved science program:
E12-13-007 – Measurement of Semi-inclusive π^0 production as Validation of Factorization
E12-13-010 – Exclusive Deeply Virtual Compton and
Neutral Pion Cross Section Measurements in Hall C
(E12-13-007 & E12-13-010 runs as one run group – first run group in Hall C)
E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
E12-14-005 – Wide Angle Exclusive Photoproduction of π^0 Mesons **(runs as run group with E12-14-003)**
E12-14-006 – Initial State Helicity Correlation in Wide-Angle Compton Scattering

Hall C SIDIS Program – basic (e,e'π) cross sections

Linked to framework of *Transverse Momentum Dependent Parton Distributions*

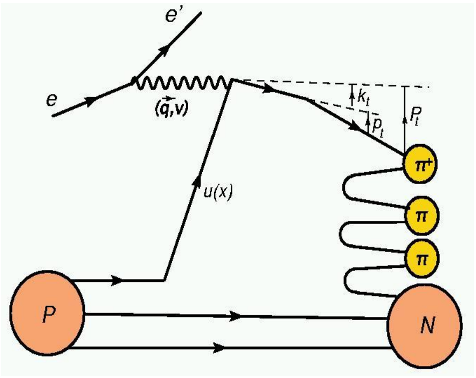
- Validation of factorization theorem needed for most future SIDIS experiments and their interpretation
- Need to constrain TMD evolution w. precision data
- Questions on target-mass corrections and ln(1-z) resummations require precision large-z data



$TMD^q(x,k_T)$

Transverse momentum widths of quarks with **different flavor (and polarization)** can be different

$P_T = p_t + z\,k_t + O(k_t^2/Q^2)$



Hall C goals: Measure the basic SIDIS cross sections of π^+, π^-, π^o production off the proton, including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

Requires SHMS and new ~25 msr Neutral-Particle Spectrometer

Advantages of (e,e'π^o) beyond (e,e'$\pi^{+/-}$)

- Many experimental and theoretical advantages to validate understanding of SIDIS with neutral pions
- Can verify: $\sigma^{\pi^0}(x,z) = ½\,(\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z))$
- Confirms understanding of flavor decomposition/k_T dependence

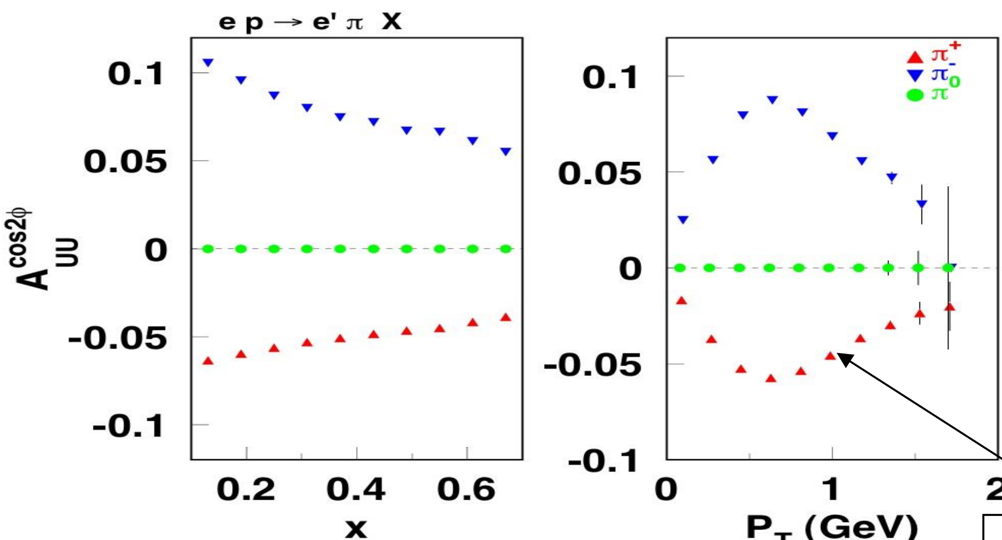
PAC: "the **cross sections** are **such basic tests of the understanding of SIDIS** at 11 GeV kinematics that they will play a **critical role** in establishing the entire SIDIS program of studying the partonic structure of the nucleon."

Towards the 3D Structure of the Proton

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{\boxed{F_{UU,T}+\varepsilon F_{UU,L}}+$$

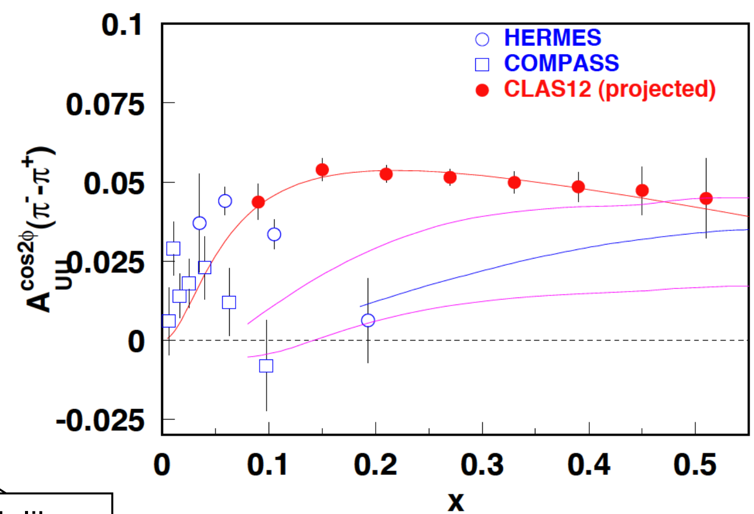
$$\sqrt{2\varepsilon(1+\varepsilon)}\,\underline{\cos\phi_h F_{UU}^{\cos\phi_h}} + \underline{\varepsilon\cos(2\phi_h) F_{UU}^{\cos(2\phi_h)}} + \lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_h \underline{F_{LU}^{\sin\phi_h}}\Big\}$$

$$\boxed{F_{UU}^{\cos 2\varphi} \propto h_1^{\perp} H_1^{\perp} + [f_1 D_1 + \ldots]/Q^2}$$



Vanish like $1/p_T$ (Yuan)

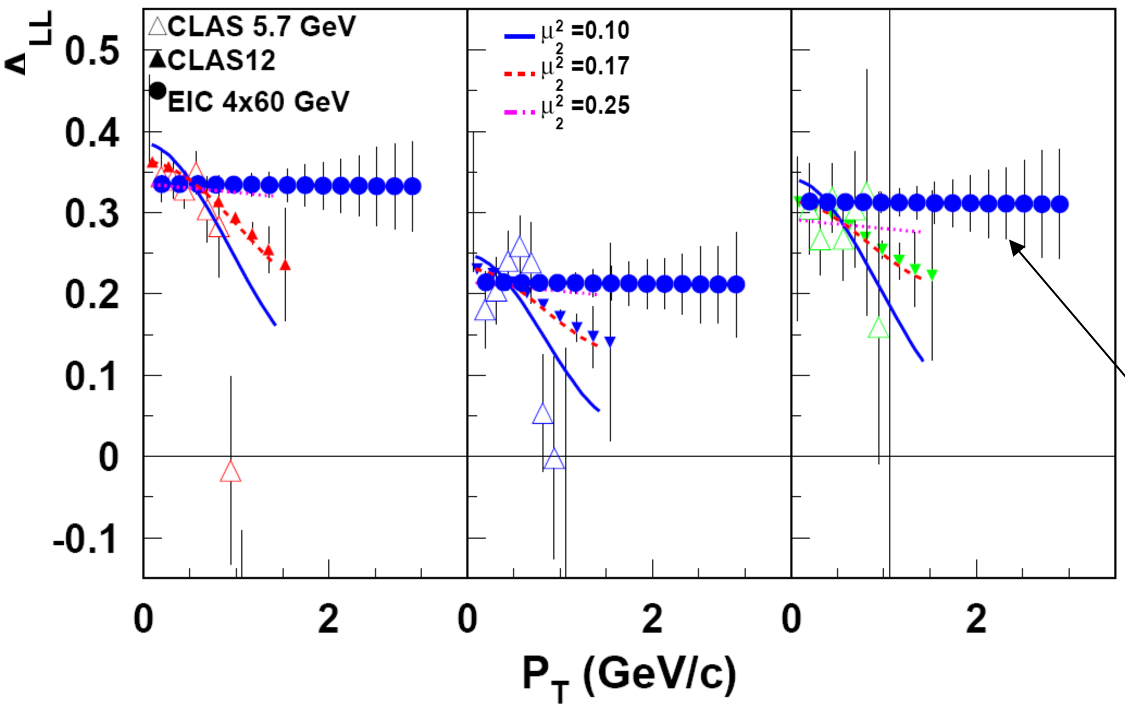
CLAS12 E12-06-112 projections



A_1 P_T-dependence in SIDIS

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)} \; e^{-z^2 P_T^2 \frac{(\mu_0^2-\mu_2^2)}{(\mu_D^2+z^2\mu_0^2)(\mu_D^2+z^2\mu_2^2)}}$$

M.Anselmino et al
hep-ph/0608048



$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

$$D_1^q(z,p_T) = D_1(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_T^2}{\mu_D^2}\right)$$

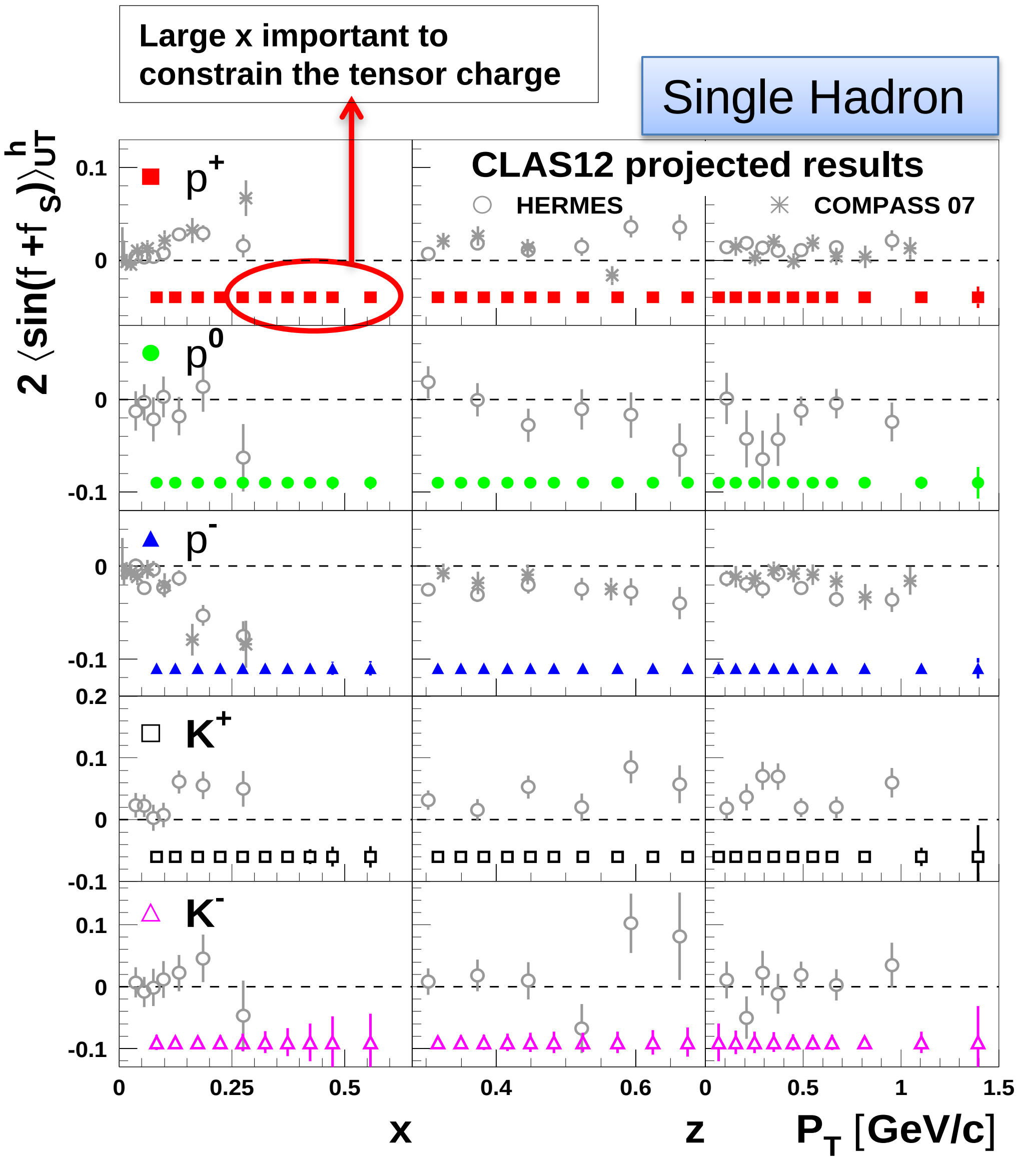
μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2

Perturbative limit calculations available for $g_1^q(x,k_T), f_1(x,k_T)$

J.Zhou, F.Yuan, Z Liang: arXiv:0909.2238

- A_{LL} (π) **sensitive to difference in k_T distributions for f_1 and g_1**
- **Wide range in P_T allows studies of transition from TMD to perturbative approach**

Transversity with CLAS12



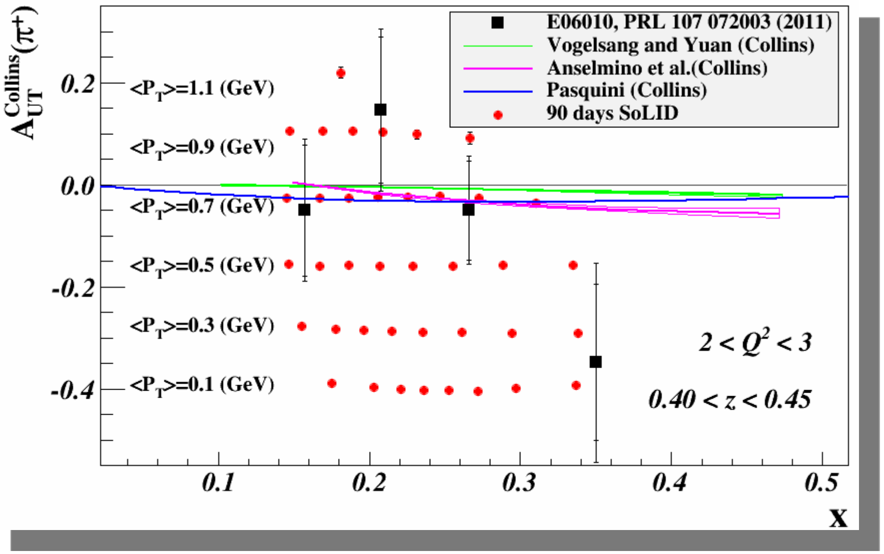
High Impact Exp. From PAC41 (C12-11-111 + C12-12-009)

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 $h_{1T}^\perp$

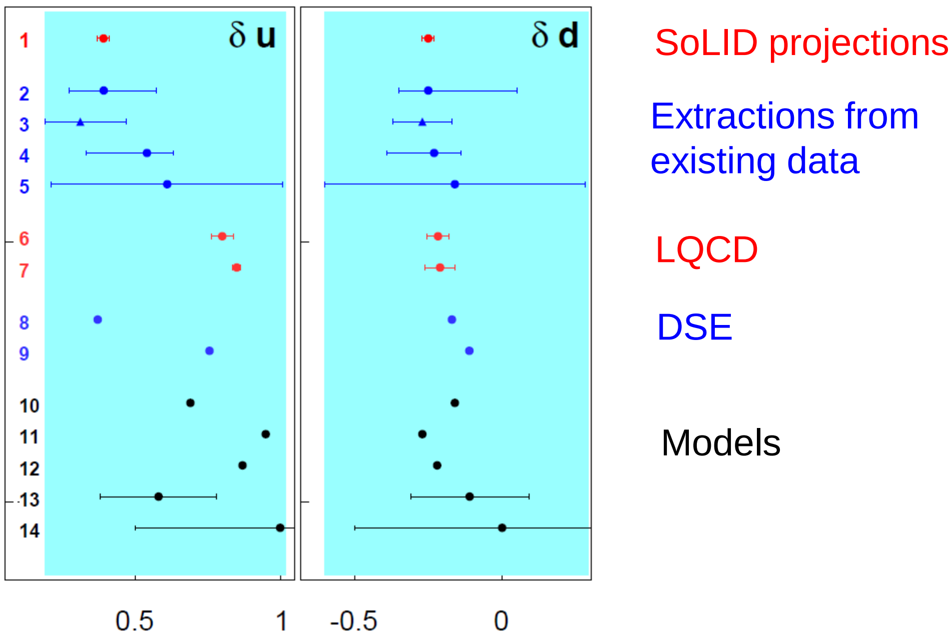
- HD-transversely polarized target and CLAS12

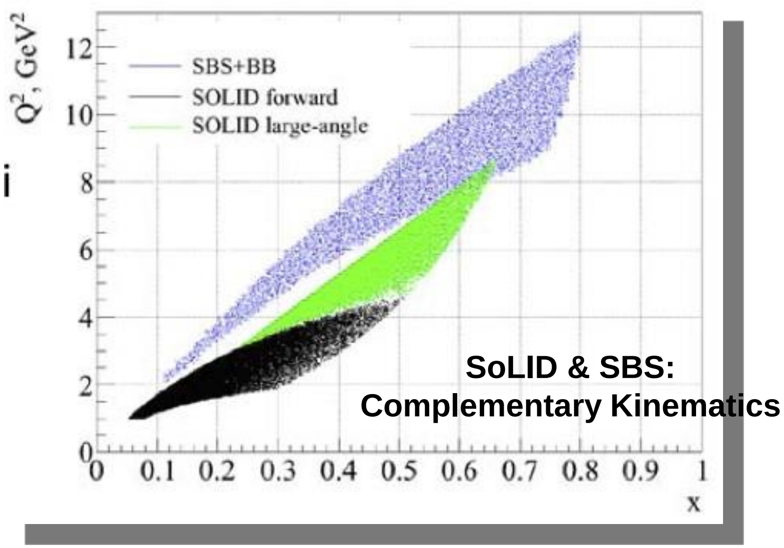
TMD Program in Hall A with SoLID & SBS

(match large acceptance devices at high luminosity to anticipated polarized 3He target performance)



Tensor Charges



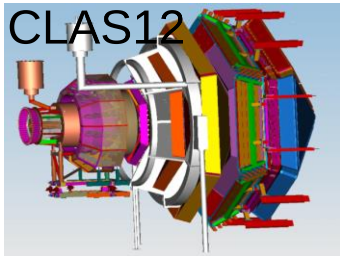


SoLID projection extraction by A. Prokudin using **only** statistical errors and based on:

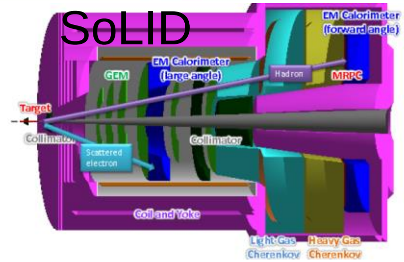
- a set of data with a limited range of x values
- the assumption of a negligible contribution from sea quarks
- assumption on Q^2 evolution
- model dependent assumptions on the shape of underlying TMD distributions

Accessing transversity in dihadron production

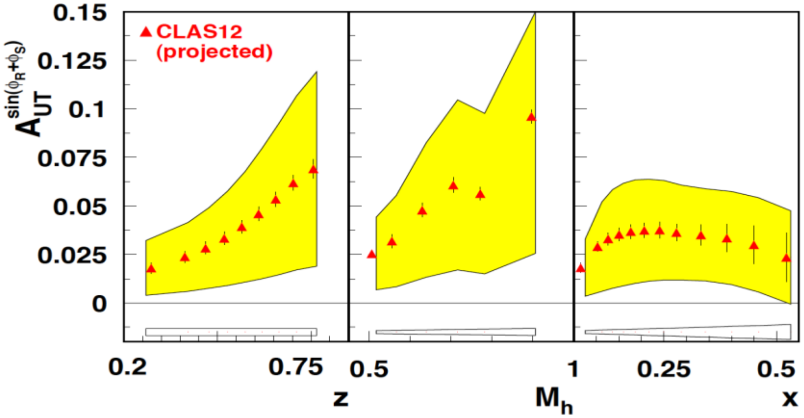
Measurements with polarized protons

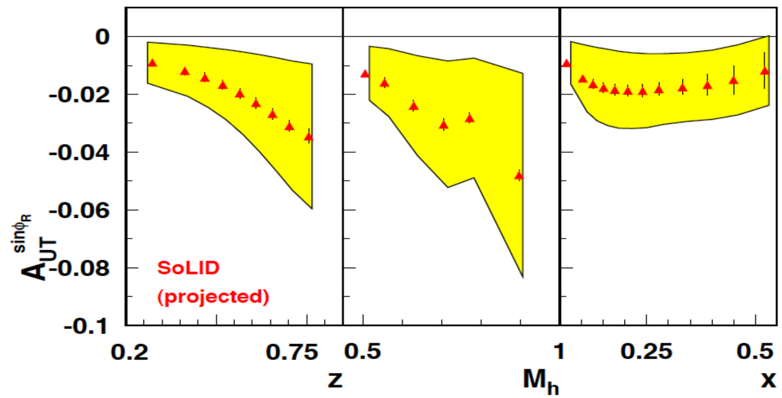


$$A_{UT}(\phi_R,\theta) = \frac{1}{fP_t}\frac{(N^+ - N^-)}{(N^+ + N^-)}$$



Measurements with polarized neutrons

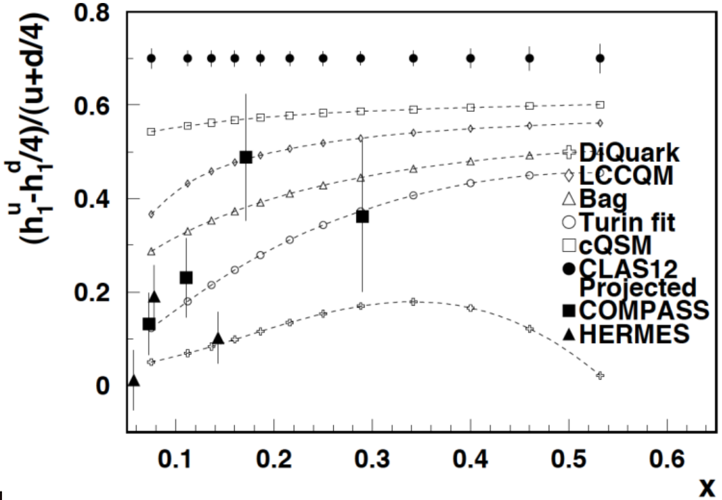




Di-hadron

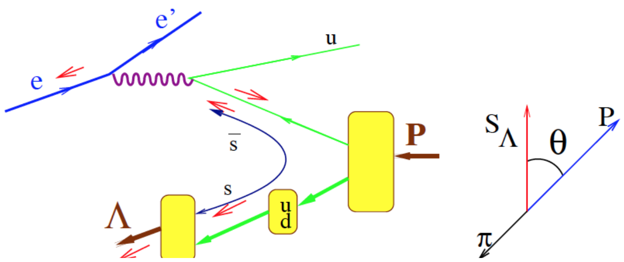
$$\frac{H_{1,sp}^{\sphericalangle,u}(z,M_h)[4h_1^u - h_1^d(x)]}{D_1^u(4f_1^u + f_1^d)}$$

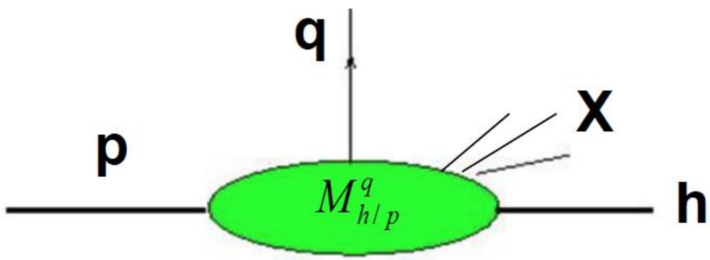
(Chiral-odd interference fragmentation function)



$$\frac{H_{1,sp}^{\sphericalangle,u}(z,M_{\pi\pi})\ \left(4h_1^d(x) - h_1^u(x)\right)}{D_1^u(z,M_{\pi\pi})\ \left(4f_1^d(x) + f_1^u(x)\right)}$$

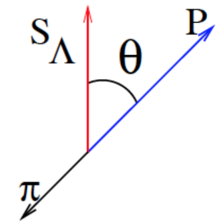
Target fragmentation region: Λ production



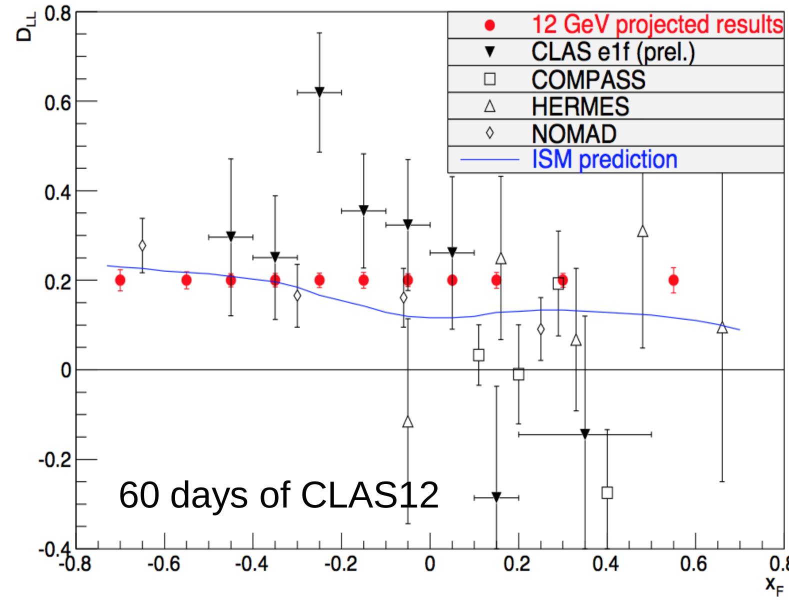


probability to produce the hadron h when a quark q is struck in a proton target

$$D^{LL} = \frac{\sum_a e_a^2 \Delta M^L}{\sum_a e_a^2 M}$$



polarization tranfer coefficient



Measurements of fracture functions opens a new avenue in studies of the structure of the nucleon in general and correlations between current and target fragmentation in particular

$$A_{LUL}^{TFR} = hS_{\parallel} \frac{y\left(1-\frac{y}{2}\right)\sum_a e_a^2 \Delta M^L}{\left(1-y+\frac{y^2}{2}\right)\sum_a e_a^2 M}$$

- Large acceptance of CLAS12 provides a unique possibility to study the nucleon structure in target fragmentation region and correlations of target and current fragmentation regions