Studies of TMDs at JLab

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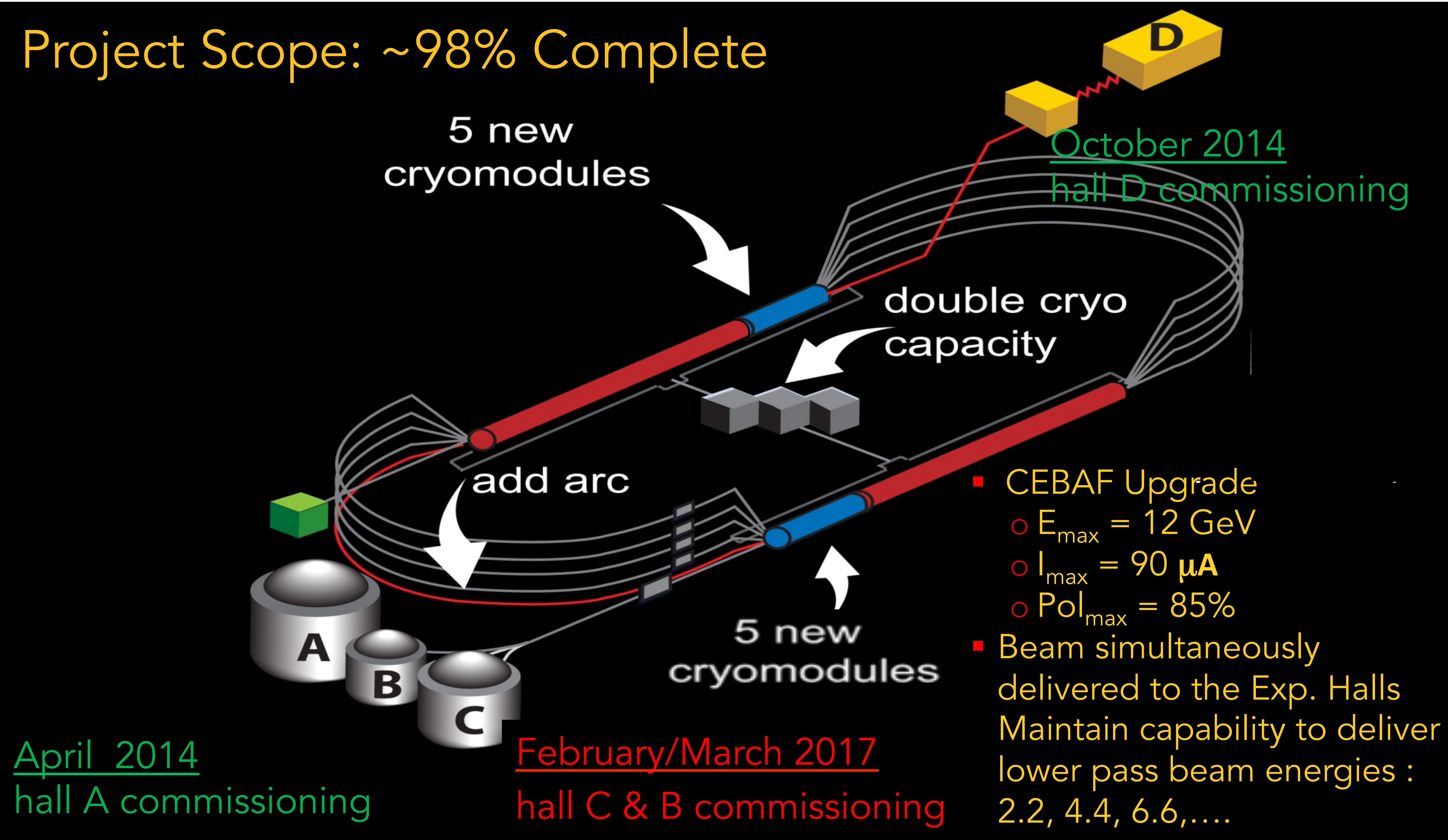
3D PARTON DISTRIBUTIONS: PATH TO THE LHC
29/11-2/12 2016, INFN-Laboratori Nazionali di Frascati (Italy)

Outline

- CEBAF: from 6 to 12 GeV
- The JLab TMD program: the 6 GeV legacy and highlights of future measurements with the 12 GeV upgrade
- TMD extraction effort @ JLab
- Conclusions

CEBAF: from 6 to 12 GeV

Project Scope: ~98% Complete



- CEBAF Upgrade
  - E_{max} = 12 GeV
  - I_{max} = 90 μA
  - Pol_{max} = 85%
- Beam simultaneously delivered to the Exp. Halls

Maintain capability to deliver lower pass beam energies : 2.2, 4.4, 6.6,….

Quark-parton Model Interpretation of SIDIS: Transverse Momentum Dependent PDFs (TMDs)

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Trasversely Polarized (T)
Nucleon Polarization	U	f_1		$h_1^{\perp}$ -
	L		g_1 -	$h_{1L}^{\perp}$ -
	T	$f_{1T}^{\perp}$ -	$g_{1T}^{\perp}$ -	h_1 - $h_{1T}^{\perp}$ -

- All explored @ 6 GeV
- All will be measured at 12 GeV
- \+ Higher twist TMDs
- \+ Medium Modification of TMDs @ 12 GeV

12 GeV Approved Experiments by PAC Days

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD		219	11	540		**770**
The transverse structure of the hadrons	145.5	185	110	25		**465.5**
The longitudinal structure of the hadrons	65	230	165			**460**
The 3D structure of the hadrons	409	972	212			**1593**
Hadrons and cold nuclear matter	208	175	201		14	**598**
Low-energy tests of the Standard Model and Fundamental Symmetries	547	180		79	60	**866**
Total Days	**1374.5**	**1961**	**699**	**644**	**74**	**4752.5**
Total Days – Without MIE Days	**556.5**	**1961**	**699**	**644**	**28**	**4057.5**
Total Approved Run Group Days (includes MIE)	**1374.5**	**926**	**656**	**424**	**74**	**3454.5**
Total Approved Run Group Days (without MIE)	**556.5**	**926**	**656**	**424**	**28**	**2590.5**
Total Days Completed	**20**	**30**	**0**	**25**	**0**	**75**
Total Days Remaining	**536.5**	**896**	**656**	**399**	**28**	**2515.5**

Milestones for future measurements

Evolution

Factorization

Universality
& QCD
gauge-formalism

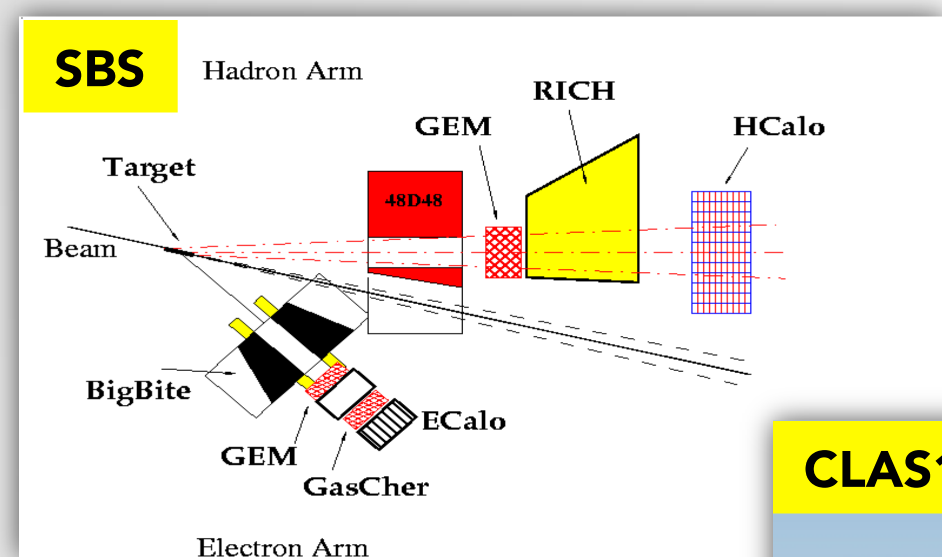
Large variety of reactions is essential in order to meet the goals

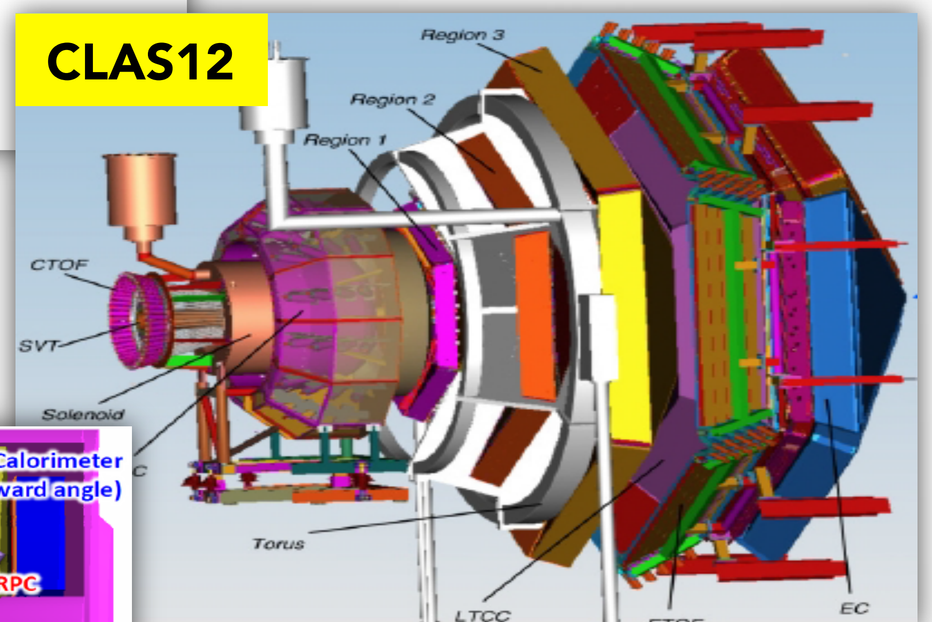
Flavor separation

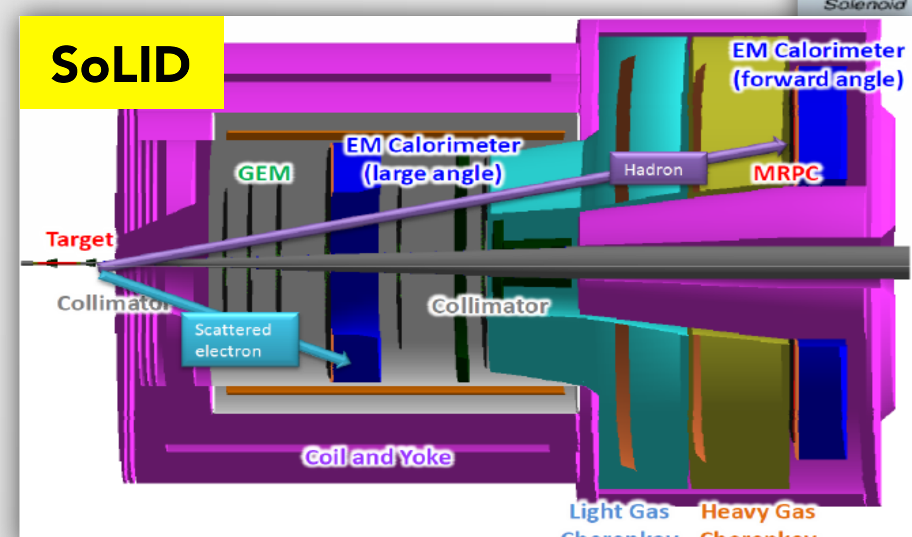
Robust procedure for TMD extractions and validation

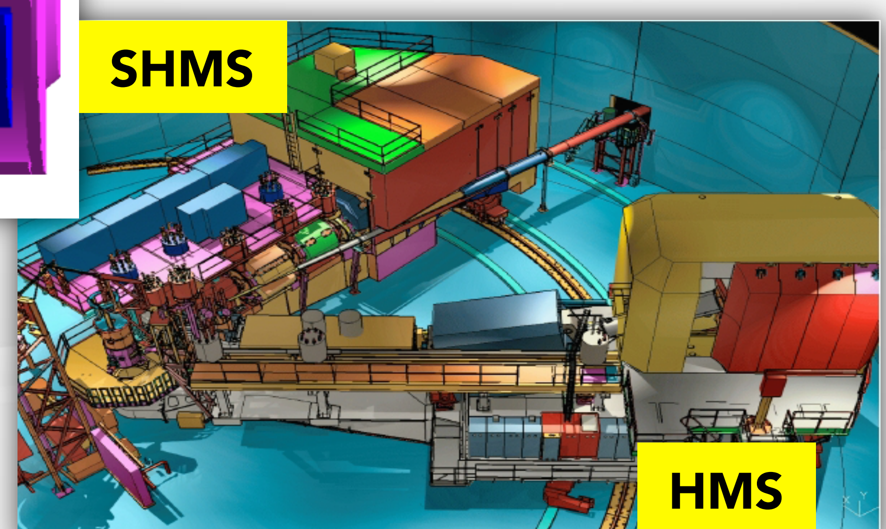
How will Jlab @ 12 GeV contribute?

A Multi-Hall SIDIS Program









Use advantages of multi-hall approach!

Hall B: Large acceptance (CLAS12)
Unpolarized and polarized H & D targets
→ azimuthal distributions of final-state particles
→ cross sections, single & double-spin asymmetries
→ start kaon SIDIS program with RICH detector

Hall C: SHMS + HMS
Precision magnetic-spectrometer setup, π and K, high luminosity, unpolarized target
→ L/T separations in SIDIS
→ precision cross sections and ratios of π^+ and π^- (and K^+, K^-)

Hall A: Forward Large acceptance (SoLID)
polarized ^{3}He target
→ longitudinal & transversely polarized ^{3}He
→ pion & kaon run with BigBite and **SBS**
→ Access to n structure at high-x and high-Q^2

First Measurements Rolling in @ 12 GeV : Unpolarized SIDIS

◆ Hall B: proton target (**Nov 2017**)

- E12-06-112:
  Proton's quark dynamics in SIDIS pion production
- E12-06-112A:
  Semi-inclusive Λ production in target fragmentation region
- E12-06-112B:
  Collinear nucleon structure at twist-3

◆ Hall C: proton and deuteron targets

E12-09-002: π^+/π^- ratios on H/D targets (**Feb 2018**)

E12-09-017: p_T dependence studies in SIDIS (**Nov 2018**)

Unpolarized SIDIS

$$\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h}\Big\},$$

$F_{UU,T}$: $f_1 \otimes D_1$; $F_{UU,L}$: HT; $F_{UU}^{\cos\phi_h}$: HT; $F_{UU}^{\cos 2\phi_h}$: $h_1^\perp \otimes H_1^\perp$; $F_{LU}^{\sin\phi_h}$: HT

- BM TMD describes correlation between the transverse momentum and transverse spin of quarks, requires FSI or ISI

$F_{UU}^{cos\phi_h} cos\phi_h$ → **Cahn + BM**

$F_{UU}^{cos2\phi_h} cos2\phi_h$ → **BM + h.t. Cahn**

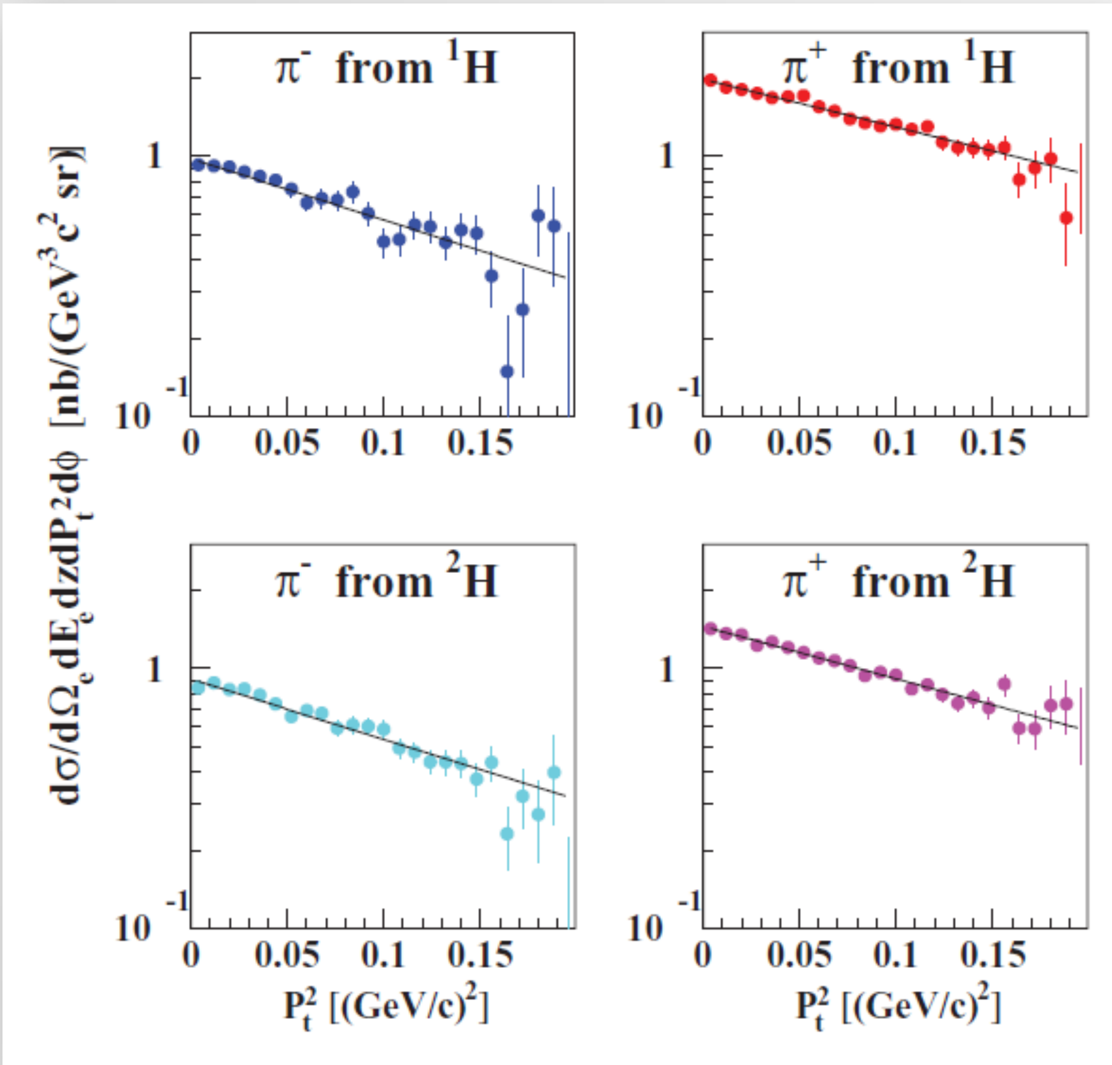
- Nontrivial modulations from the Cahn and Boer-Mulders effects

➔ under intensive studies worldwide, including experiments, model calculations, lattice simulations

Flavor dependence of k_T-distributions

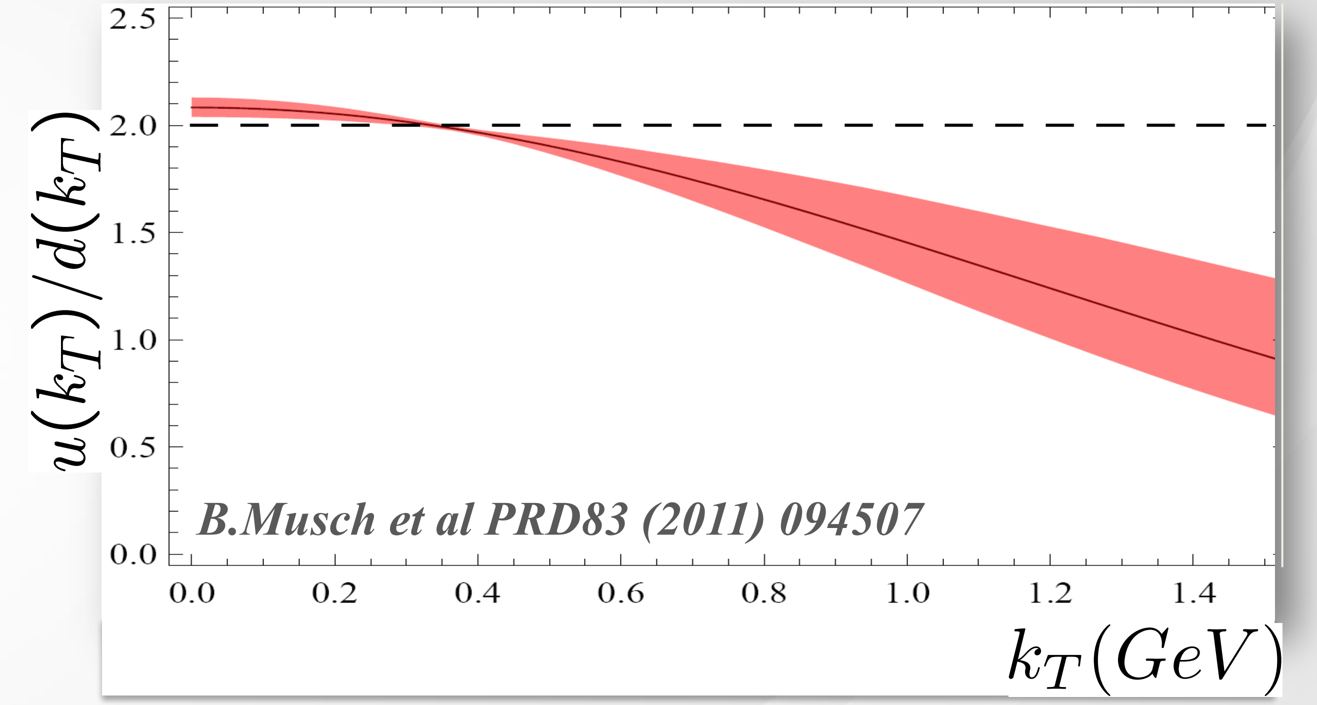
$$\langle P_{hT}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$$

JLab 6 GeV Hall C



R. Asaturyan et al. PRC 85, 015202 (2012)

From the transverse hadron momentum P_{hT} ➔ information on the intrinsic k_T and the p_T generated during fragmentation

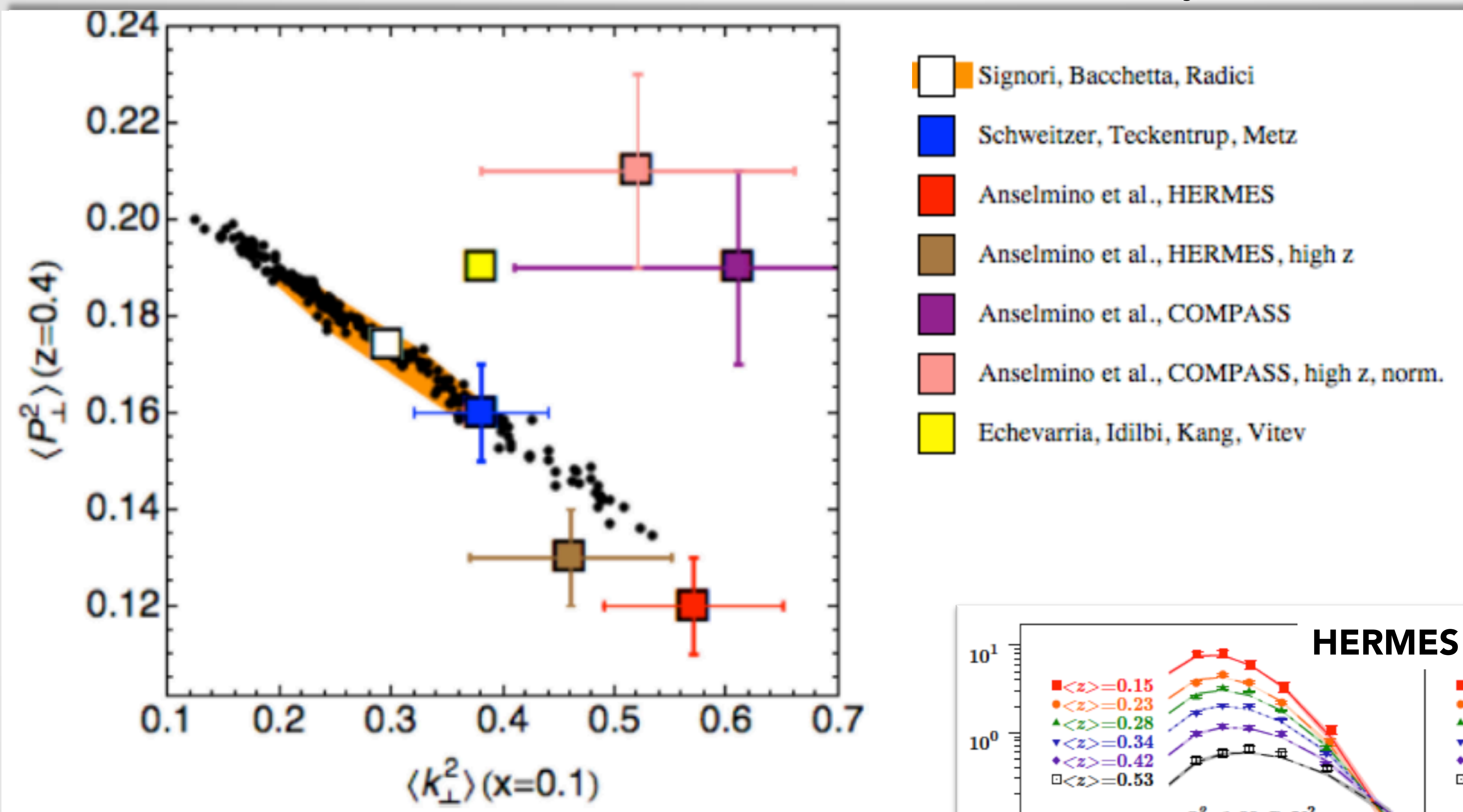


- Higher probability to find more d-quarks at large k_T
- Data (assuming only valence quarks) indicate that k_T-width of u-quarks is larger than for d-quarks

- Indications from both experimental data and theory (lattice, χCQM) of the k_T dependence of quark flavor distribution

Global analysis fitting

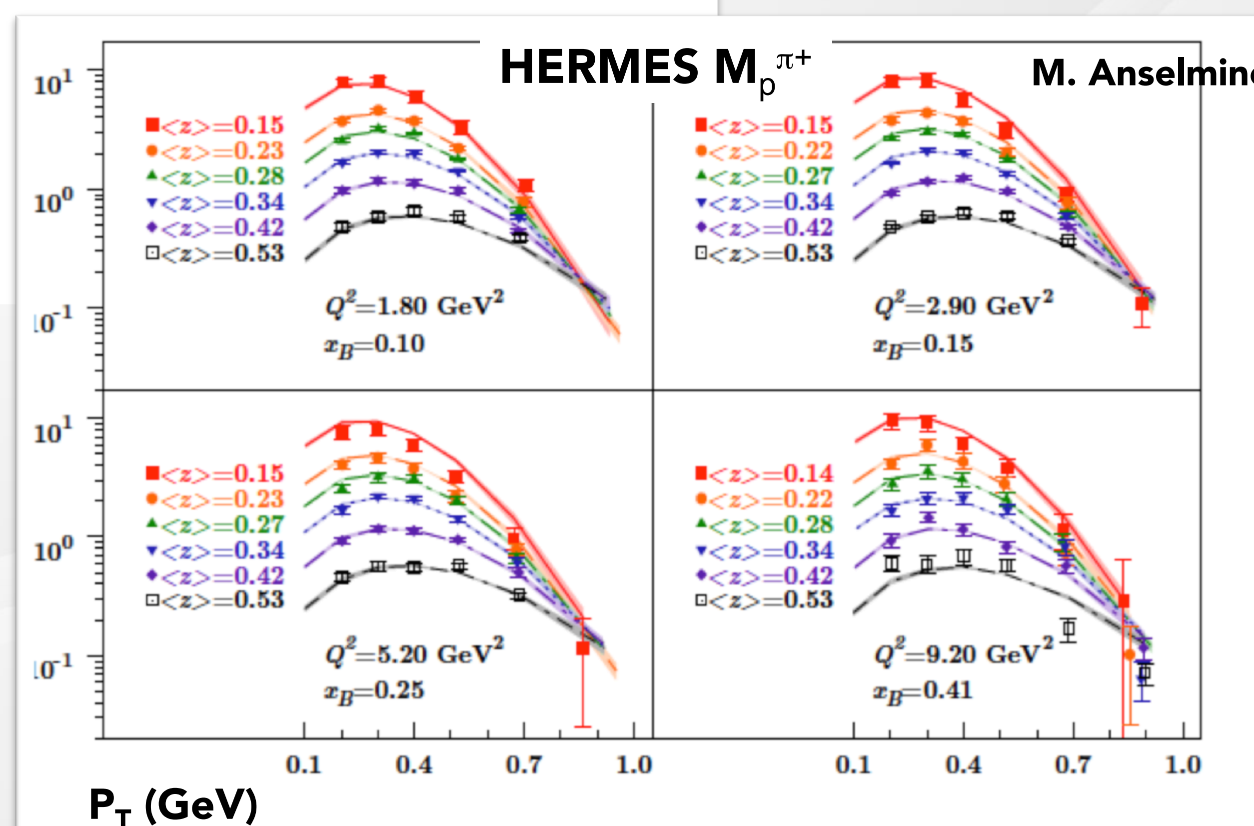
Radici et al., Int. J. Mod. Phys. Conf. Ser. 2015.37



- Factorised functional form with **Gaussian dependence** on the intrinsic transverse momentum
- Global analyses fitting of **multiplicities and/or asymmetries**
  ➔ different values for <k^2_T>

- Stong anti-correlation between the widths of the distribution and fragmentation Gaussians
- The flavor-dependent Gaussian ansatz performs better

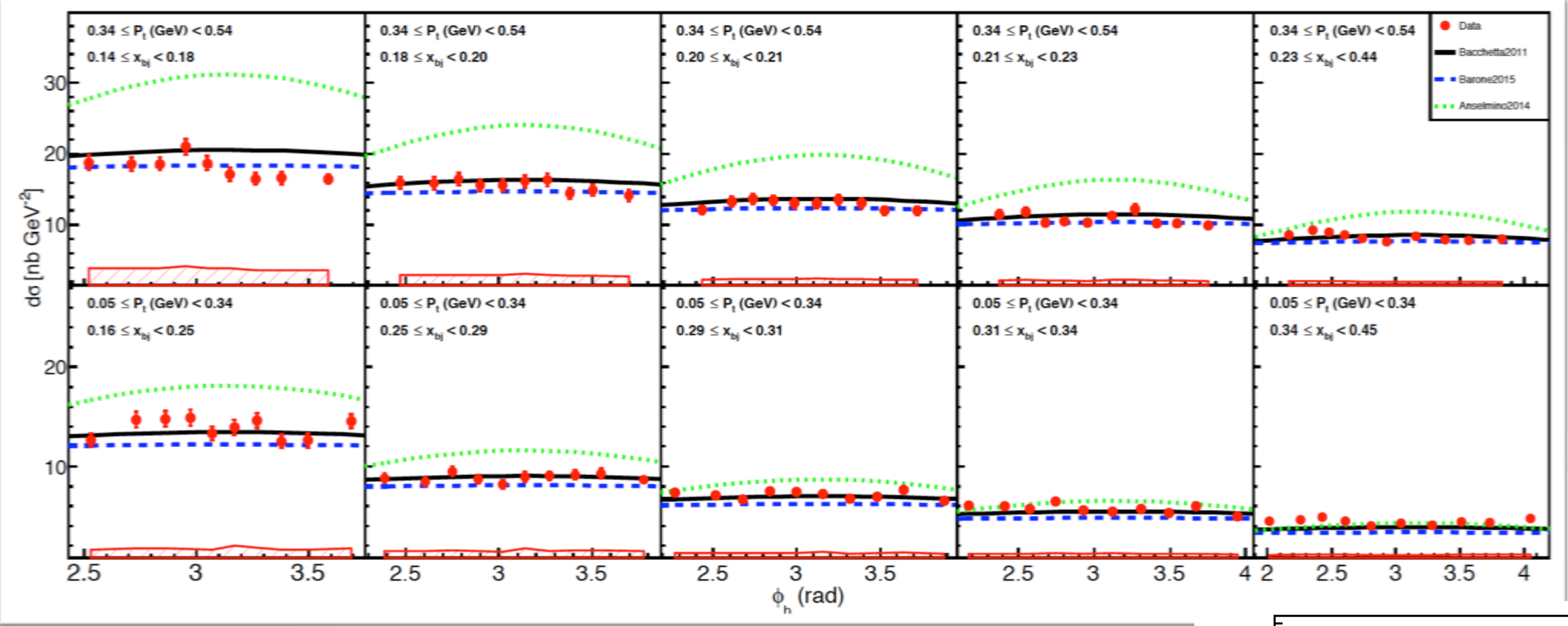
M. Anselmino, et al., JHEP 1404 (2014) 005



Unpolarized SIDIS x-section from a ^{3}He target

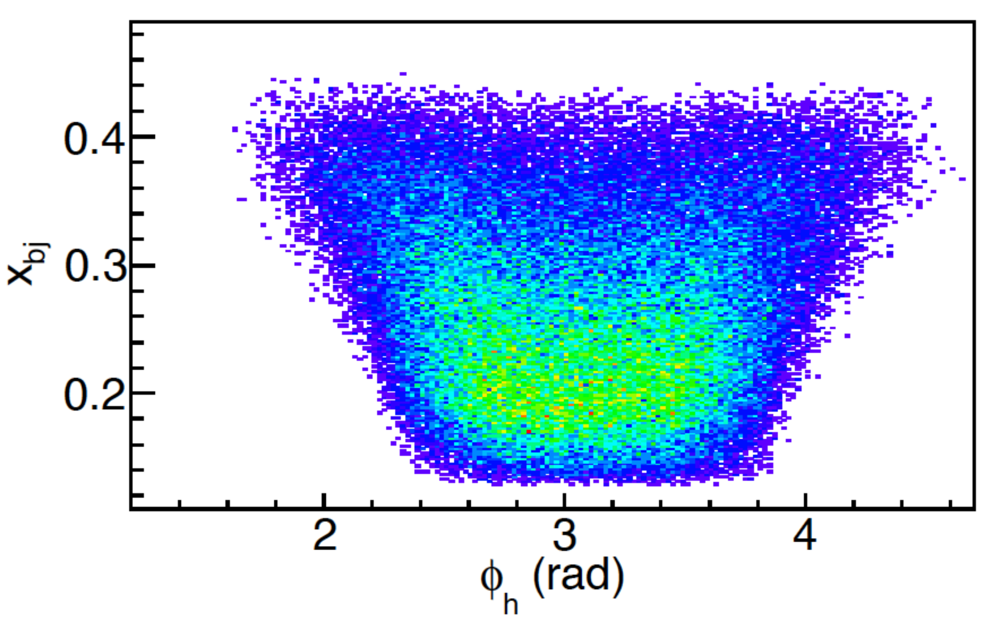
π^+

Hall A : ArXiv:1610.02350v2



- New JLab data on ^{3}He @ 6 GeV in 3D binnings

$0.12 < x_{bj} < 0.45$; $1 < Q^2 < 4$ (GeV/c)^2
$0.45 < z_h < 0.65$; $0.05 < P_t < 0.55$ GeV/c

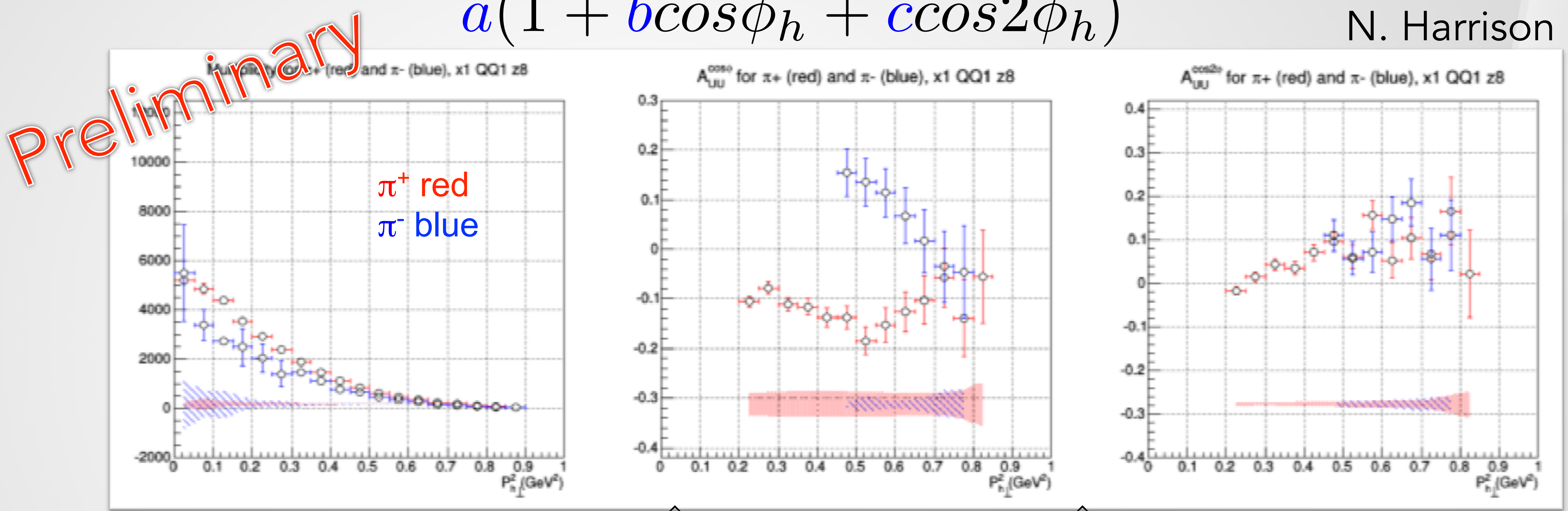


- Even if with limited ϕ coverage they can be used in global analysis

Unpolarized SIDIS x-section from CLAS @ 6 GeV

$$a(1 + b cos\phi_h + c cos2\phi_h)$$

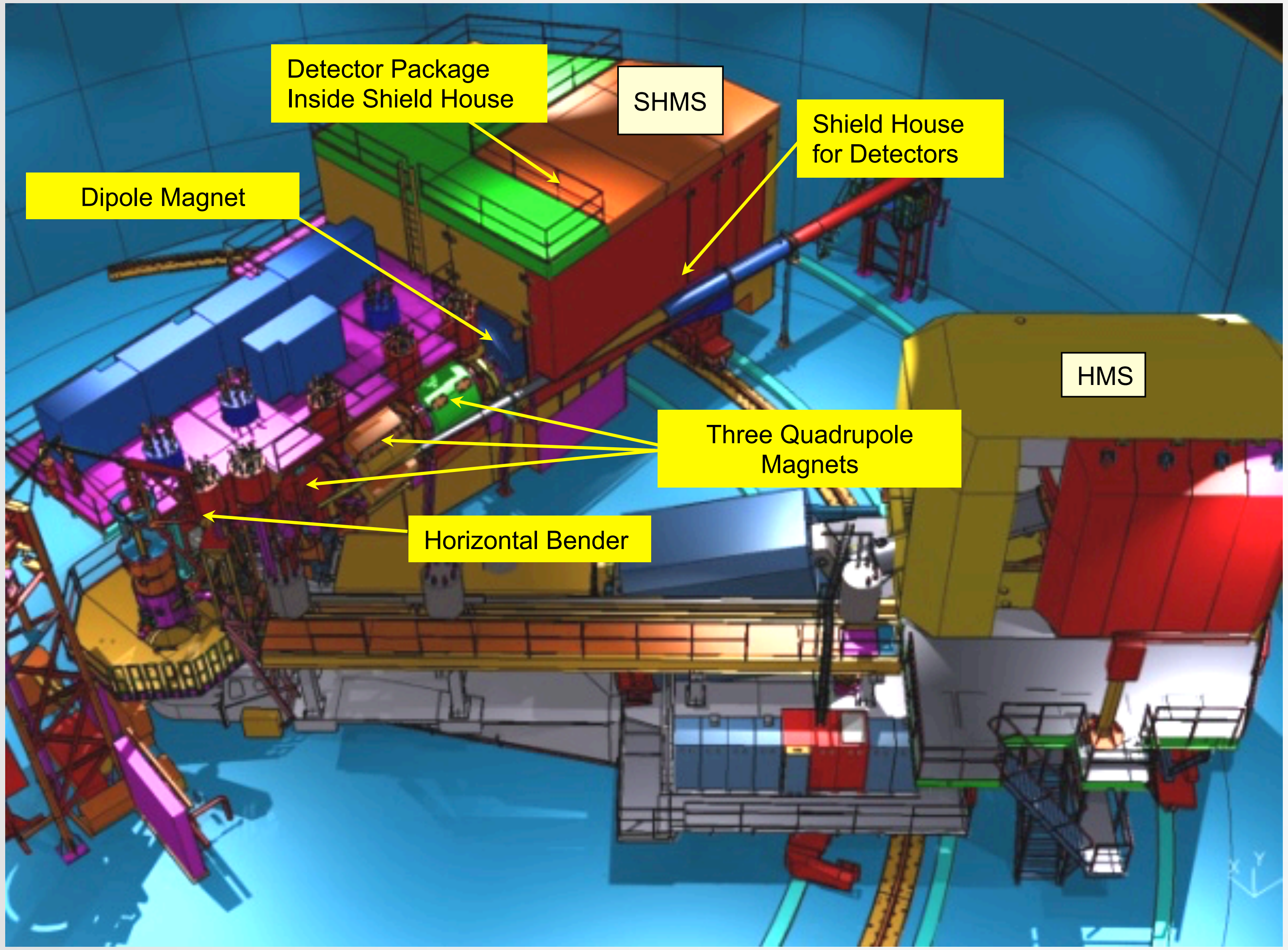
N. Harrison



$$F_{UU}^{cos\phi_h} = \frac{2M}{Q} C\left[\frac{\hat{h}\cdot p_T}{zM_h}\frac{k_T^2}{M^2} h_1^\perp H_1^\perp - \frac{\hat{h}\cdot k_T}{M} z f_1 D_1\right]$$

- <cos ϕ> is more sensitive to the intrinsic k_T
- Symmetric behaviour indicates large BM contribution
- Approved experiments @ 12 GeV [E12-06-112 H_2 (e,e'π) & E12-09-007 D_2(e,e'π/K)] will continue these studies in a wider Q^2 and P_T range.

Hall C: SHMS + HMS



- High momentum capability & resolution
- Full PID
- High luminosity polarized ^{3}He target

SIDIS program

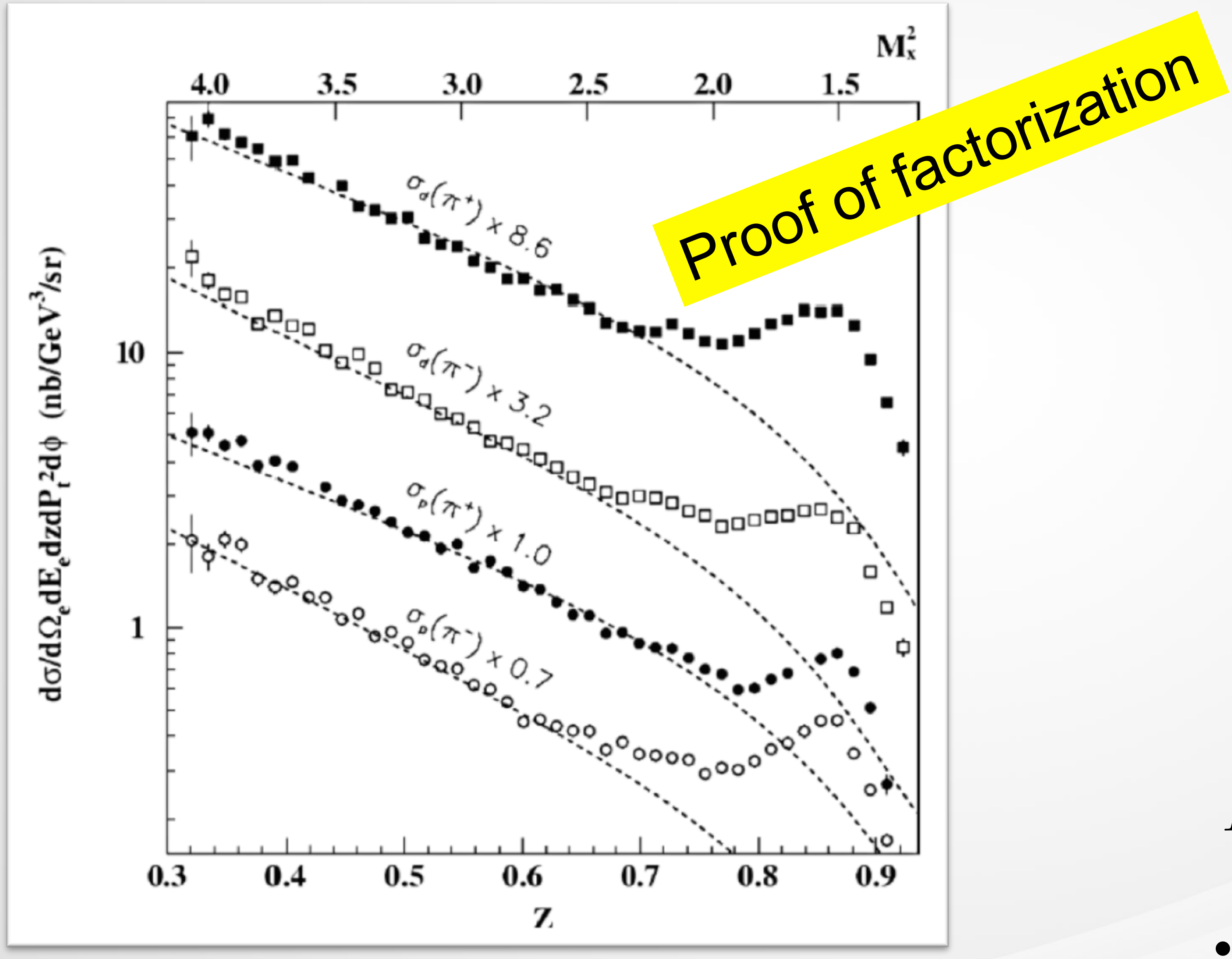
- Precise measurements of absolute cross-sections (1% level) and p_T dependence $\pi^{+/-}$ and $K^{+/-}$ on proton and deuteron
- Setup optimal for longitudinal-transverse separations and ratios of charged-meson cross sections (unique amongst the Hall experimental setups)
- Disadvantage of the setup: lack of full azimuthal coverage at larger p_T.

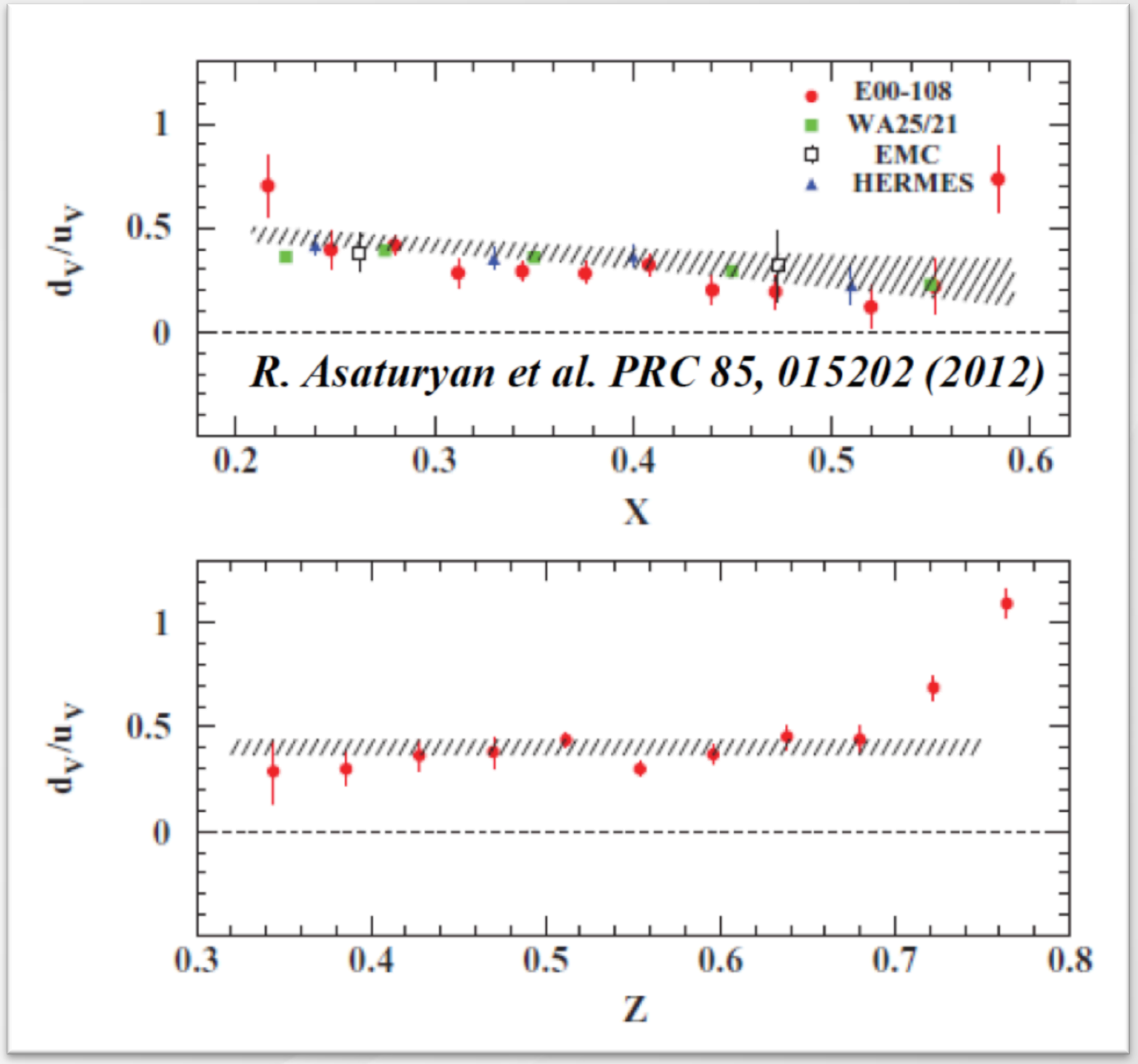
→ limited ability to constrain azimuthal moments of the SIDIS cross-sections

→ analysis will often need to go hand-in-hand with that of the large-acceptance setups.

Hall C Cross Section data at 6 GeV

T. Navasardyan et al. PRL 98, 022001 (2007)
R. Asaturyan et al. PRC 85, 015202 (2012)





$$R_{pd}(x) = \frac{\sigma_p^{\pi^+(x,z)} - \sigma_p^{\pi^-(x,z)}}{\sigma_d^{\pi^+(x,z)} - \sigma_d^{\pi^-(x,z)}} = \frac{4u_v(x) - d_v(x)}{3[u_v(x) + d_v(x)}$$

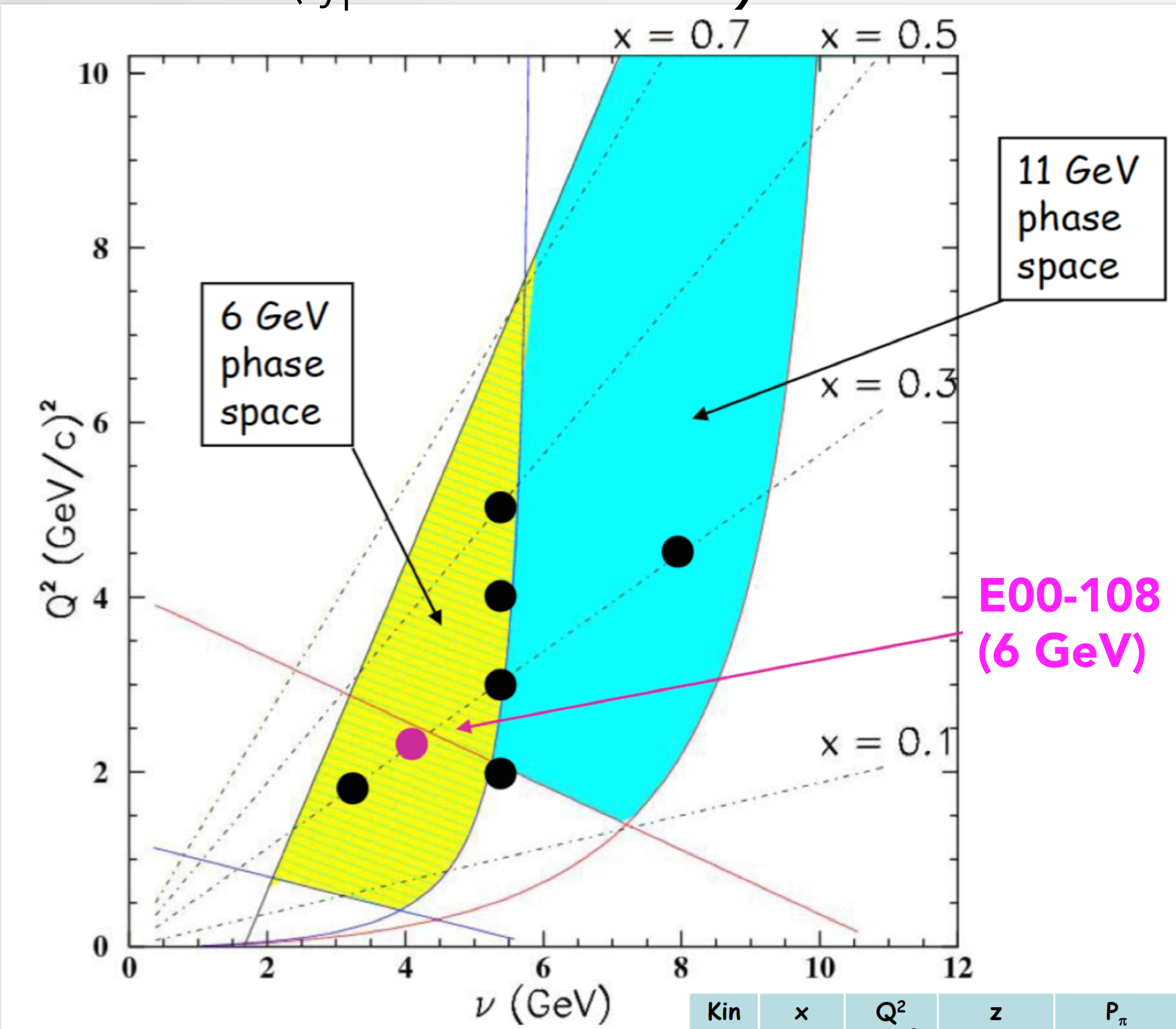
- Hall C SIDIS cross section data are in reasonable agreement with LO, naive partonic picture, provided M_X^2>~ 2.5 GeV^2

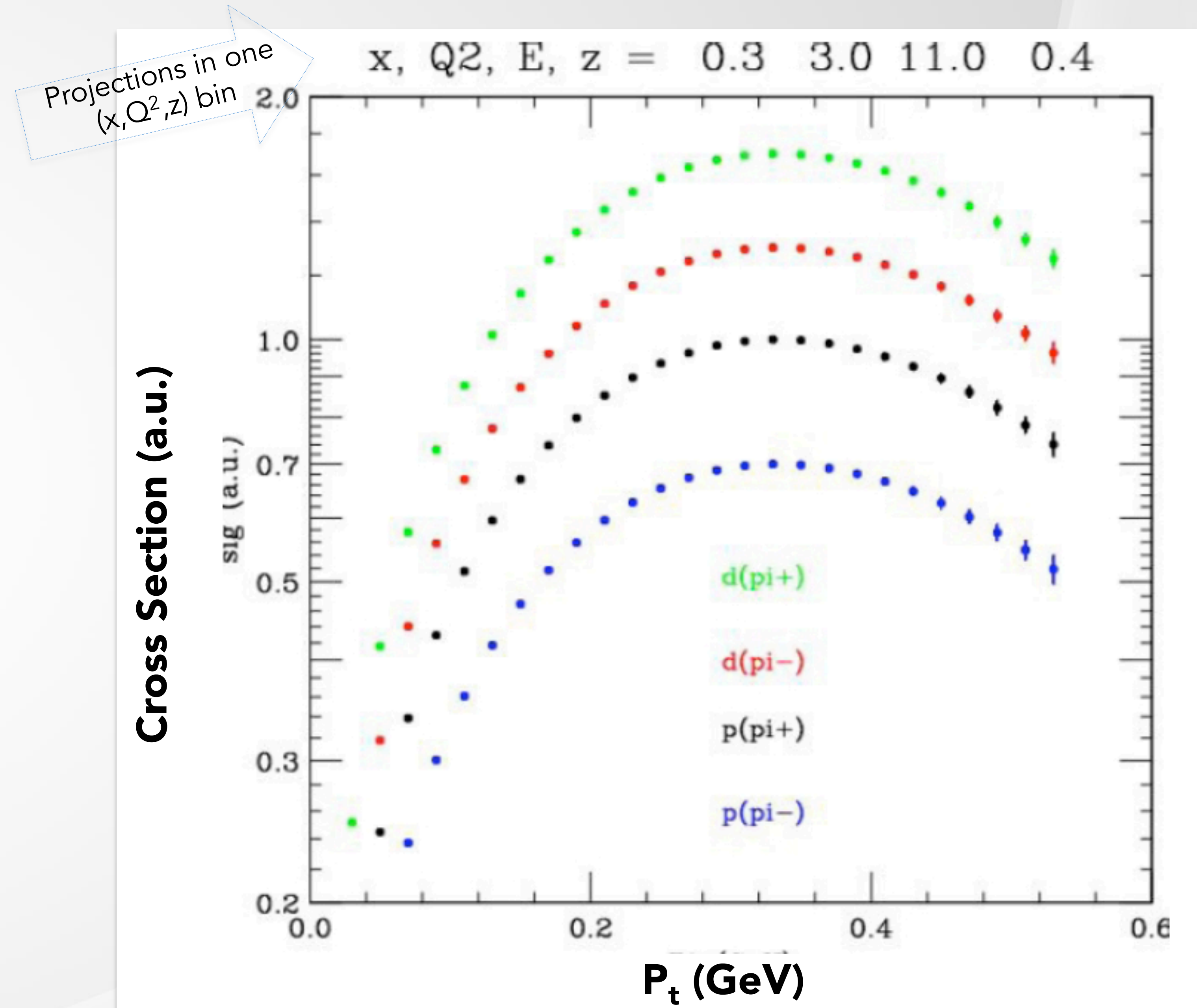
- p/d ratios of π^+-π^- cross section difference depends only on d_v/u_v at leading order
- Data for z < 0.7 in reasonable agreement with CTEQ6 LO PDFs

P_T Dependence of SIDIS π/k production @ 11 GeV

(E12-09-017)

Kinematics (typ. x/Q^2 ~ constant)





Kin	x (GeV)	Q^2 (GeV^2)	z	P_π (GeV)	Θ_π (deg)
I	0.2	2.0	0.3 -0.6	1.7 - 3.3	8.0 - 23.0
II	0.3	3.0	0.3 -0.6	1.7 - 3.4	5.5 - 25.5
III	0.4	4.0	0.3 -0.6	1.7 - 3.4	5.5 - 25.5
IV	0.5	5.0	0.3 -0.6	1.7 - 3.5	8.0 - 28.0
V	0.3	1.8	0.3 -0.6	1.1 - 2.1	8.0 - 30.5
VI	0.3	4.5	0.3 -0.6	2.5 - 5.0	5.5 - 20.5

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

- Can cover low P_T (up to 0.05 GeV) with very good angle and momentum resolution

P_T Dependence of SIDIS π/k production @ 11 GeV

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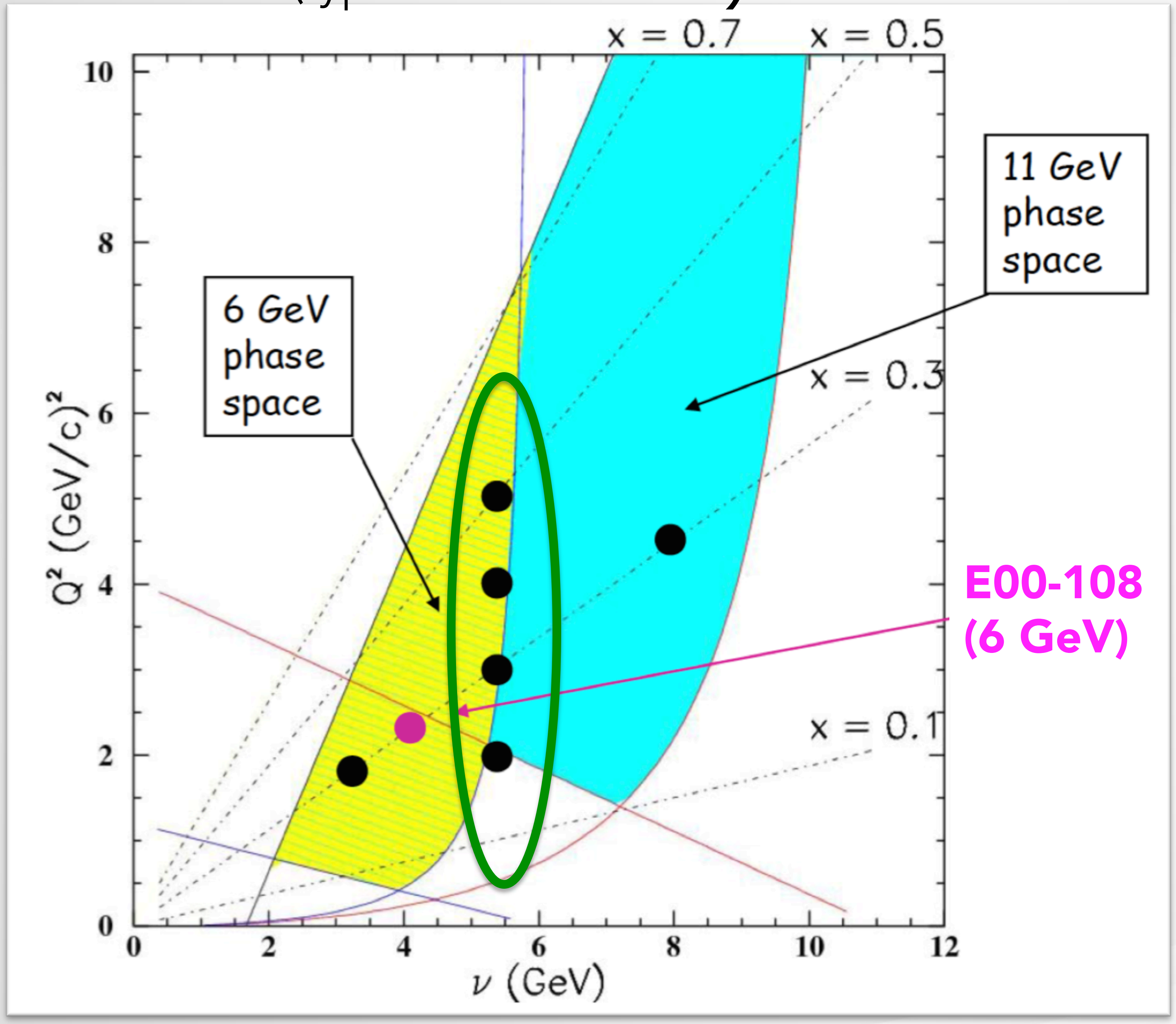
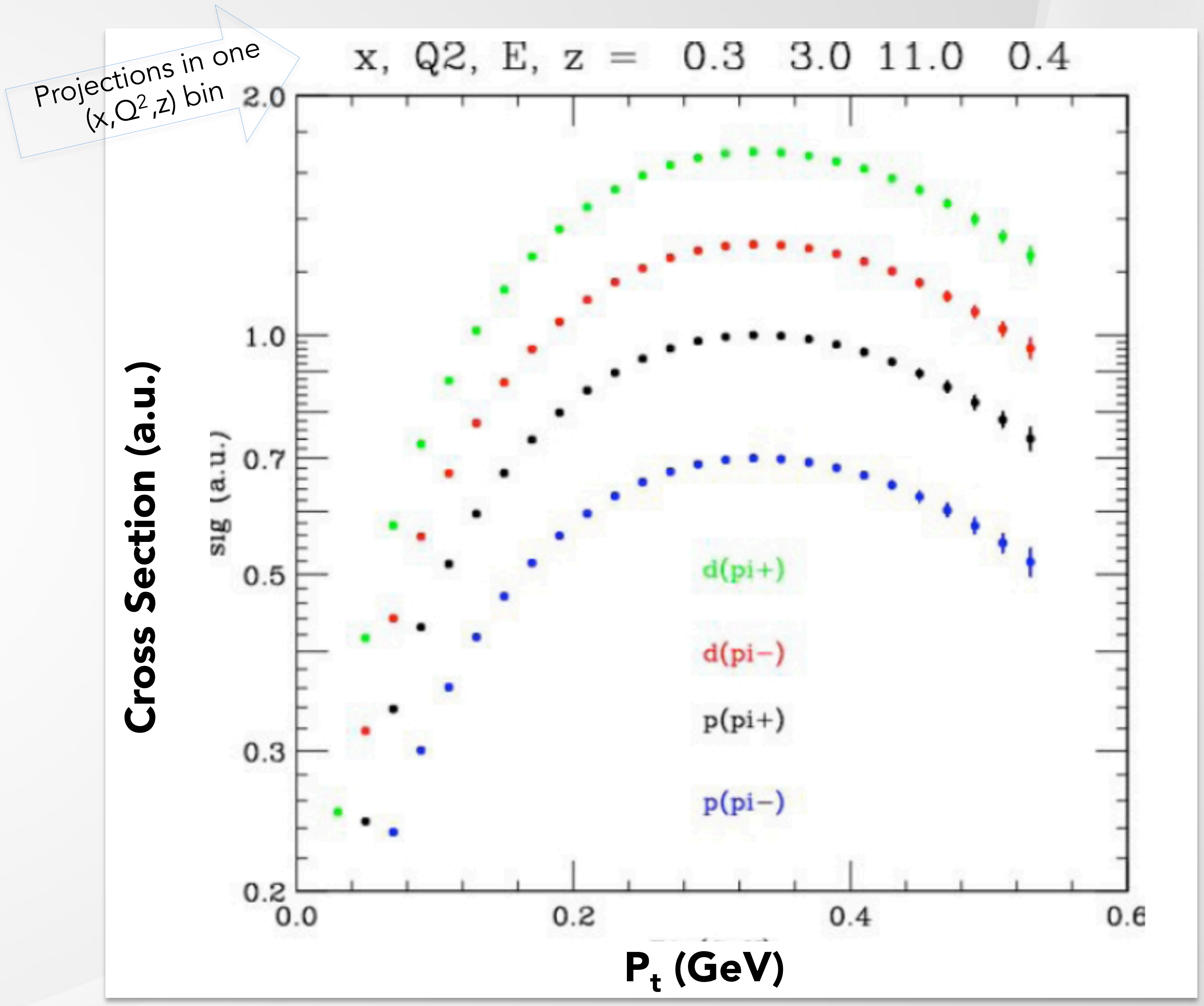


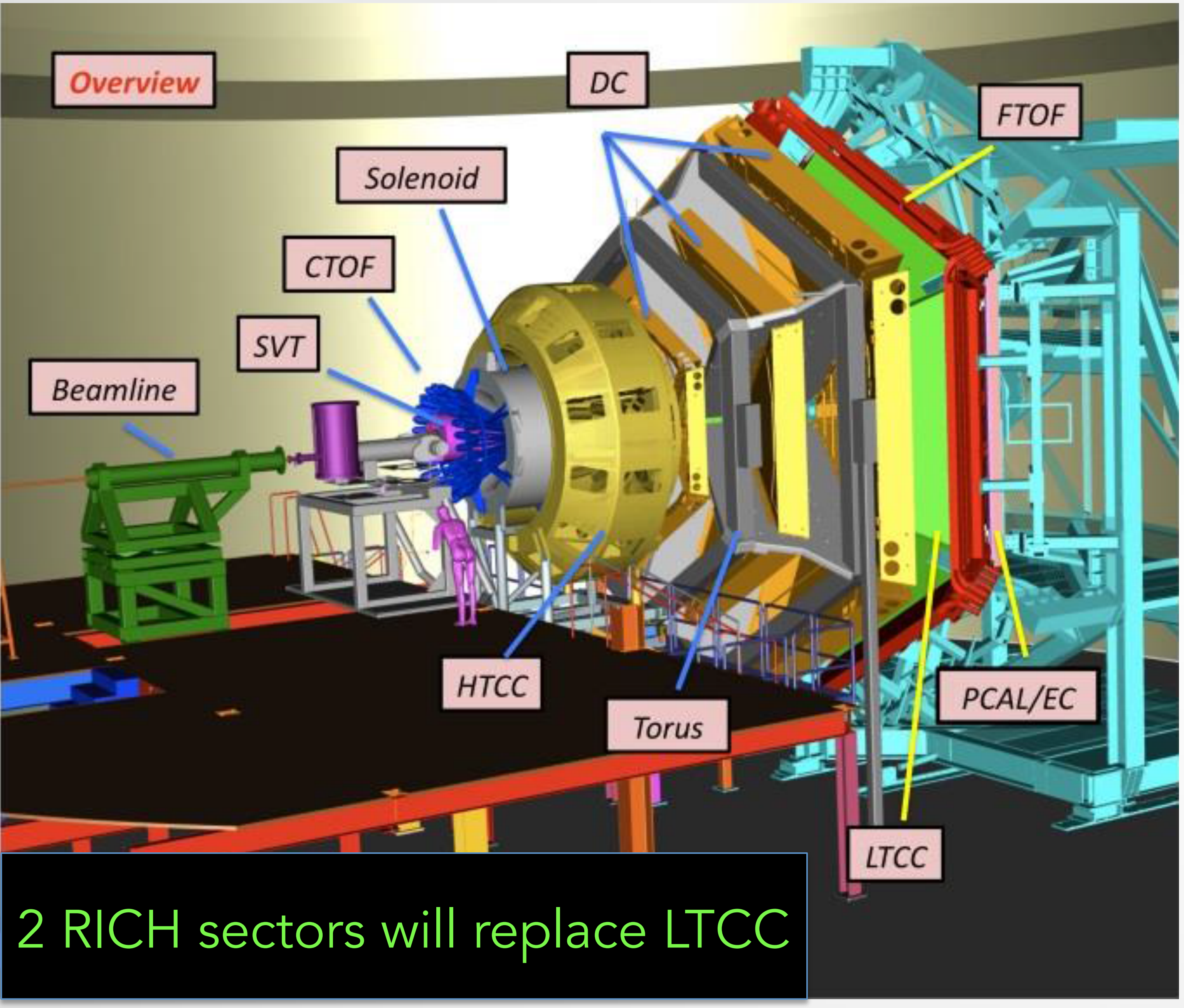


- **E12-09-017** Scan in (x,z,P_T) + scan in Q^2 at fixed x

Map of R (= σ_L/σ_T) in SIDIS in E12-06-104.

- Can cover low P_T (up to 0.05 GeV) with very good angle and momentum resolution

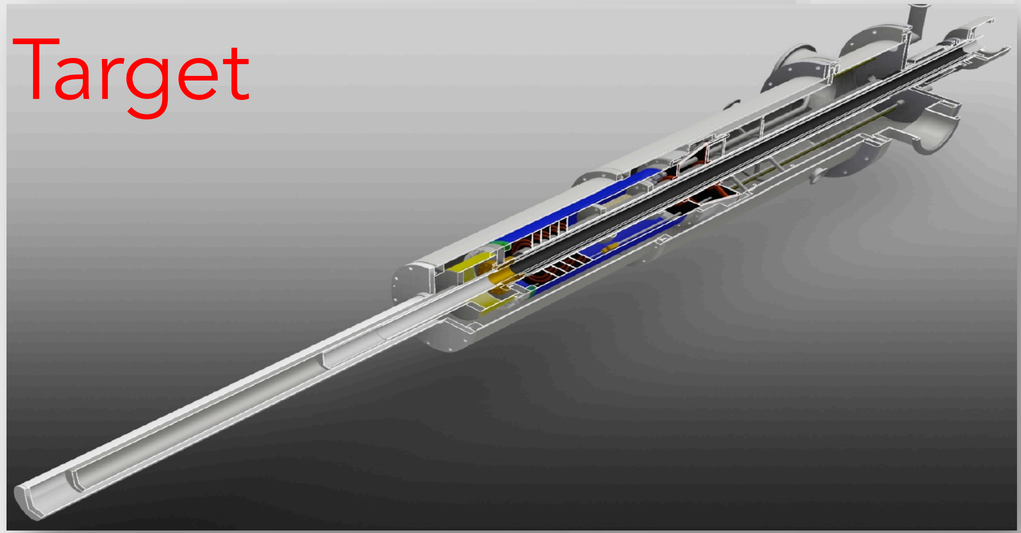
Hall B: CLAS12



- Very Large Acceptance
- Full PID
- Moderately high luminosity ($10^{35} cm^{-2} s^{-1}$)

Long. Polarized Target

- Expected polarization: ≥ 90% (p); ≥ 40% (d)
- Electron beam current operation up to 30 nA.



- DNP polarized NH_3 /ND_3 using the 5T magnetic field of the CLAS12 solenoid as a holding field

HDice for transverse config.

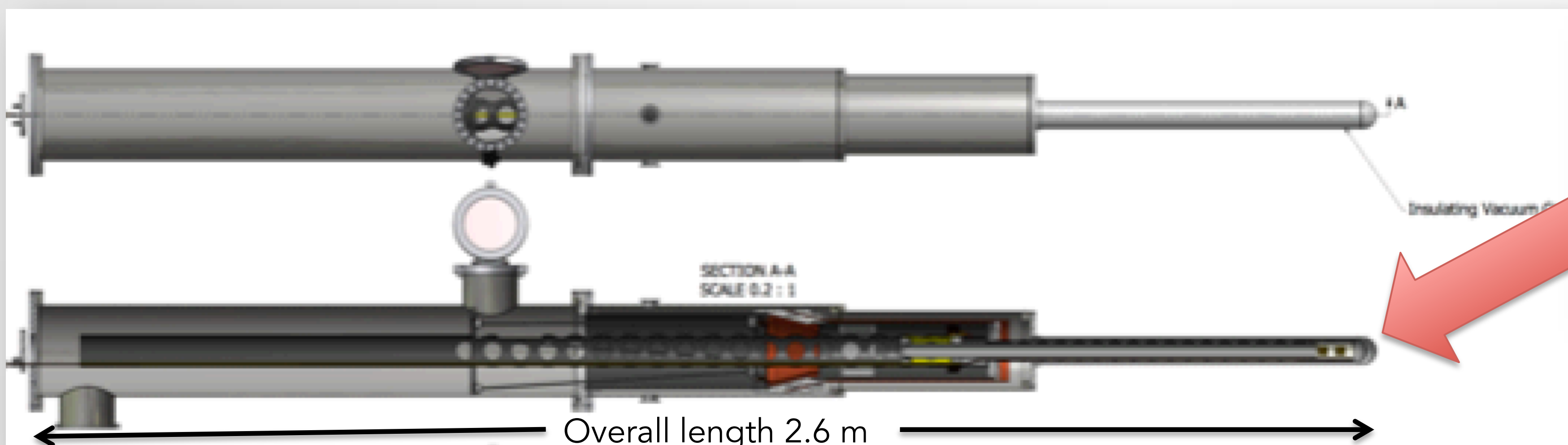
- Frozen HD material placed into a frozen spin state to allow polarization for long time periods.
- Operating performance with electrons beams requires further beam tests

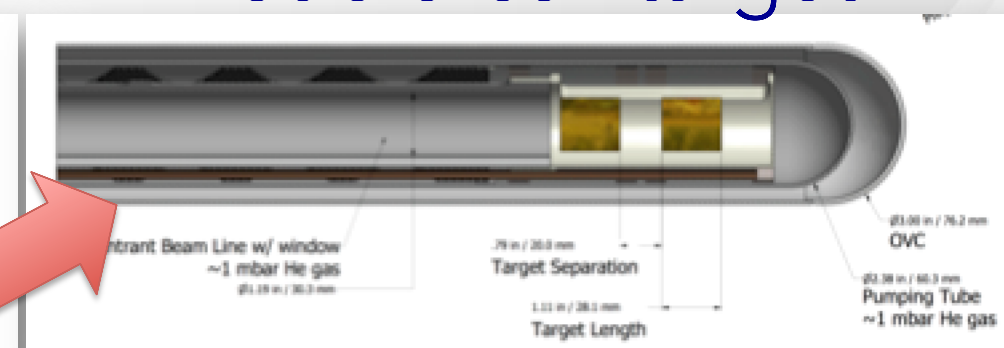
Polarized NH_3/ND_3 target

Approved CLAS12 Exps. Using Longitudinally Polarized Targets

Proposal	Contact Person	Physics	Energy (GeV)	PAC days	Parallel Running	Run Group
E12-06-119(b)	Sabatie	DVCS pol. target	11	120	120	
E12-06- 109	Kuhn	Long. Spin Str.	11	80	50	
E12-07-107	Avakian	TMD SSA	11	103	5	175
PR-09-007(b)	Hafidi	Partonic SIDIS	11	103		
PR-09-009	Avakian	Spin-Orbit Corr.	11	103		

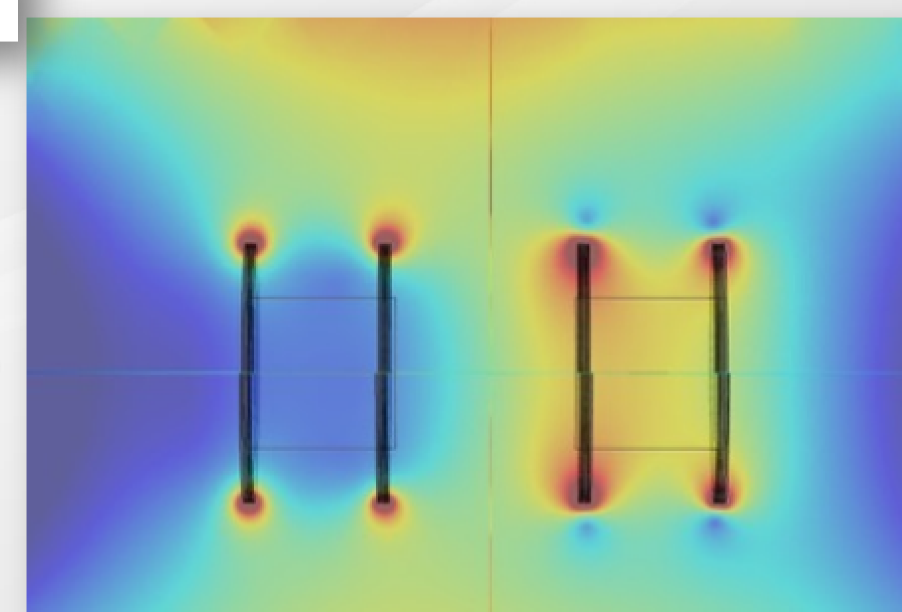
Double-cell target





Current Status:

- Cryostat design for double-cell target is in progress
- Construction complete 2018
- First experiments 2019

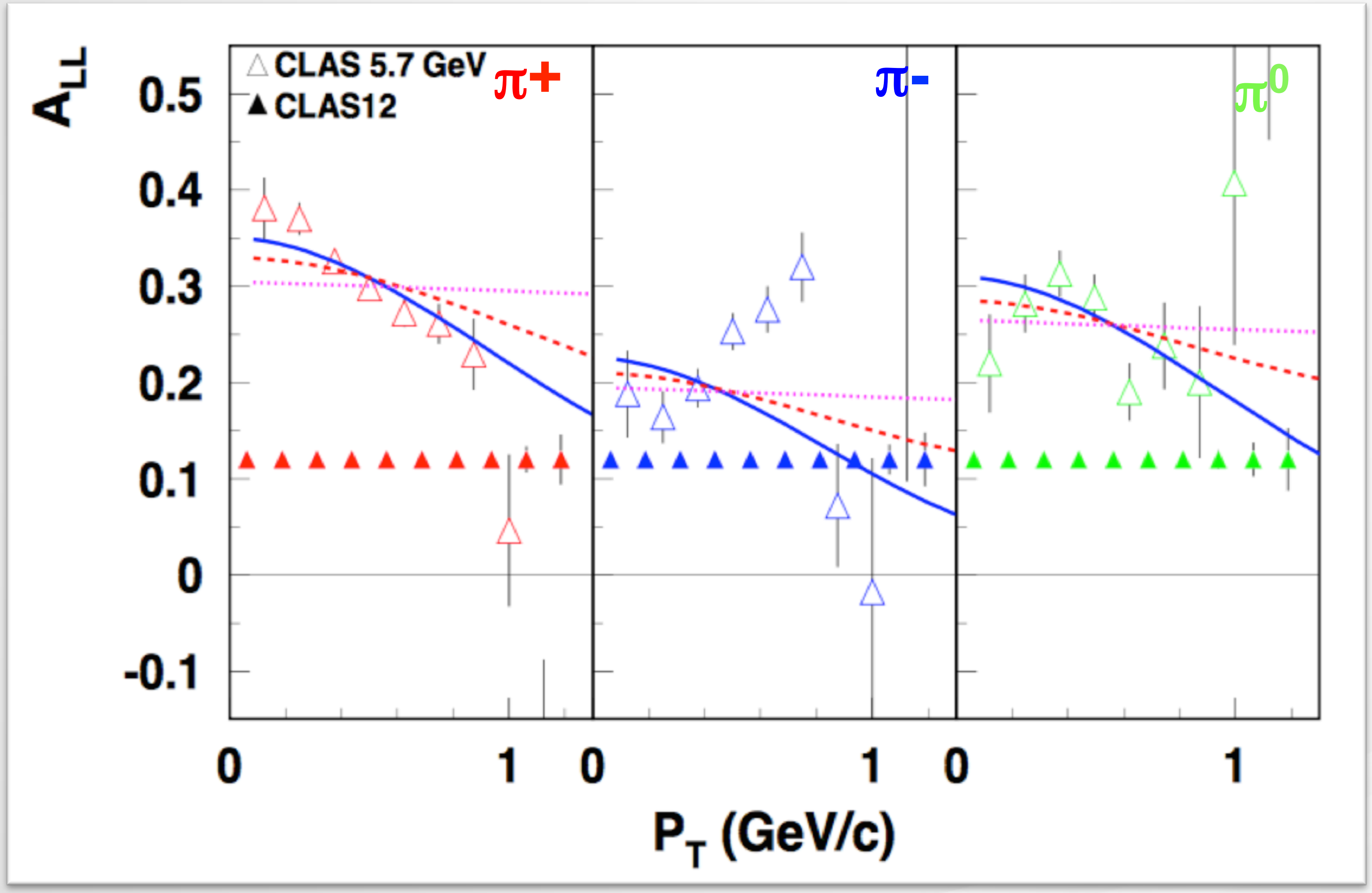


Superconducting shim coils will shift the polarizing field of each sample by ~ ±80 G to allow opposite dynamic polarization with a single microwave frequency

Expected polarization: ≥ 90% (p); ≥ 40% (d)
Electron beam current operation up to 30 nA.

CLAS12: K_T Helicity Dependence

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



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

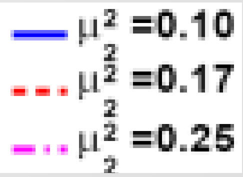
$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}e^{-\frac{k_T^2}{\mu_2^2}}$$

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

μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2

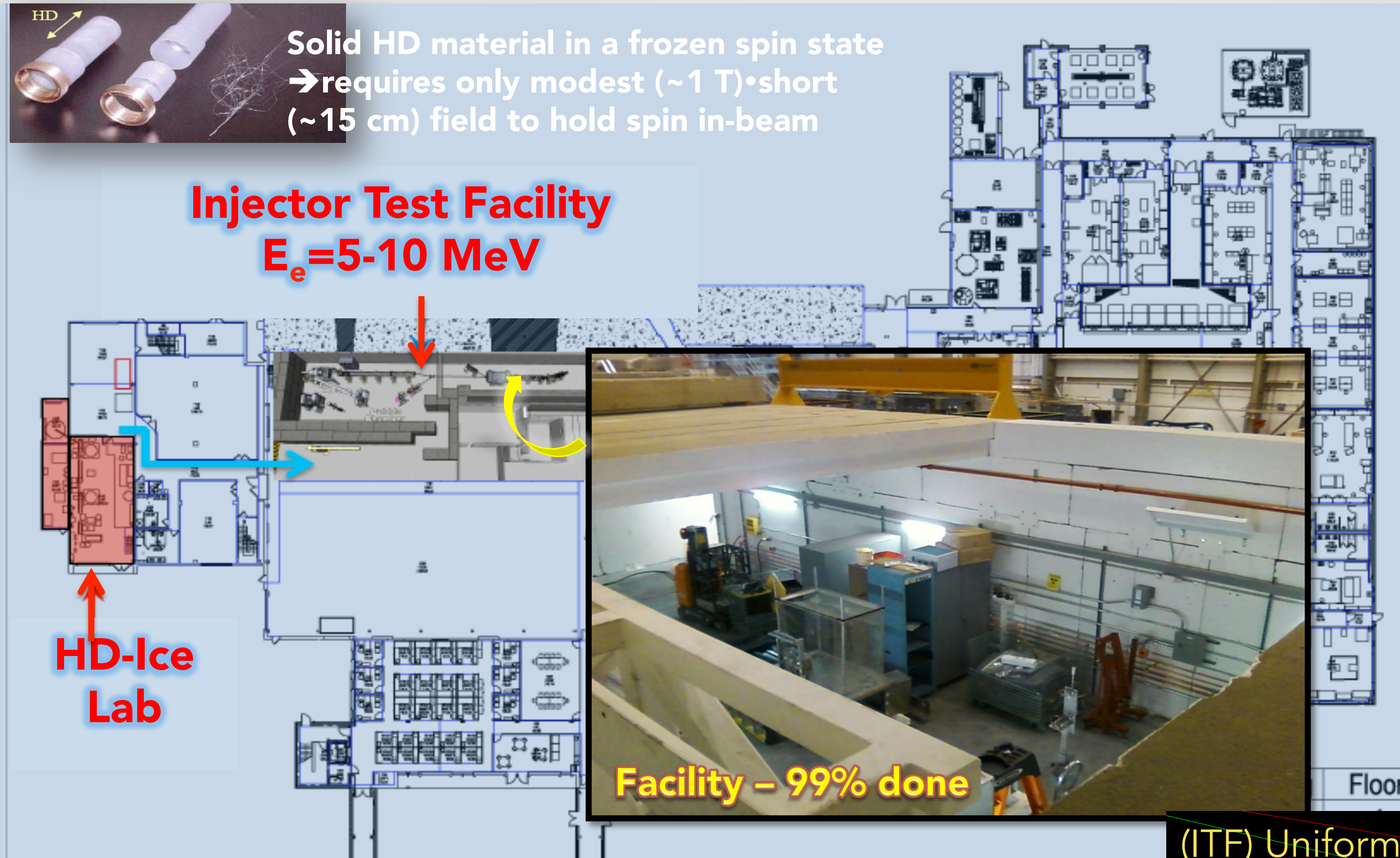
M.Anselmino et al hep-ph/0608048

Curves are calculated using different k_T widths for helicity distributions



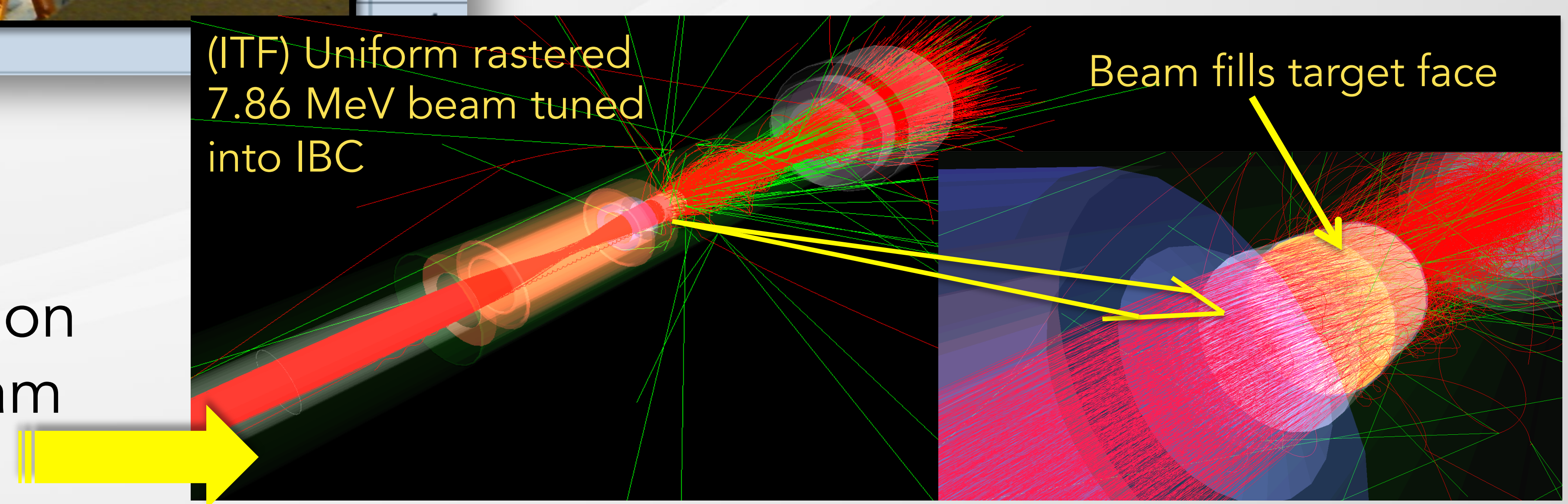
- A_{LL} (π) sensitive to difference in k_T distributions for f_1 and g_1
- Wide range in P_T allows studies of transition to perturbative approach

HDice Target for transverse configuration

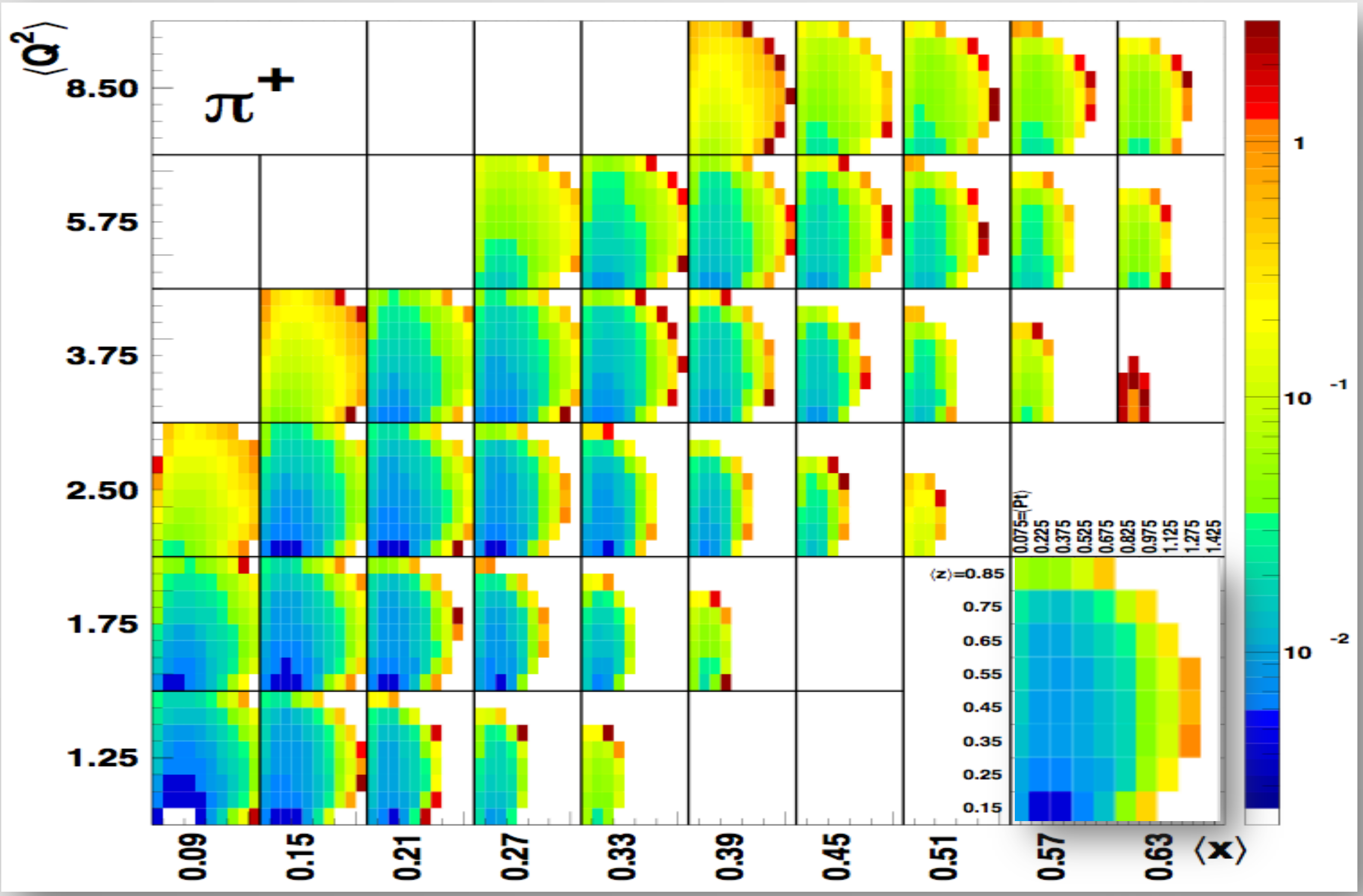


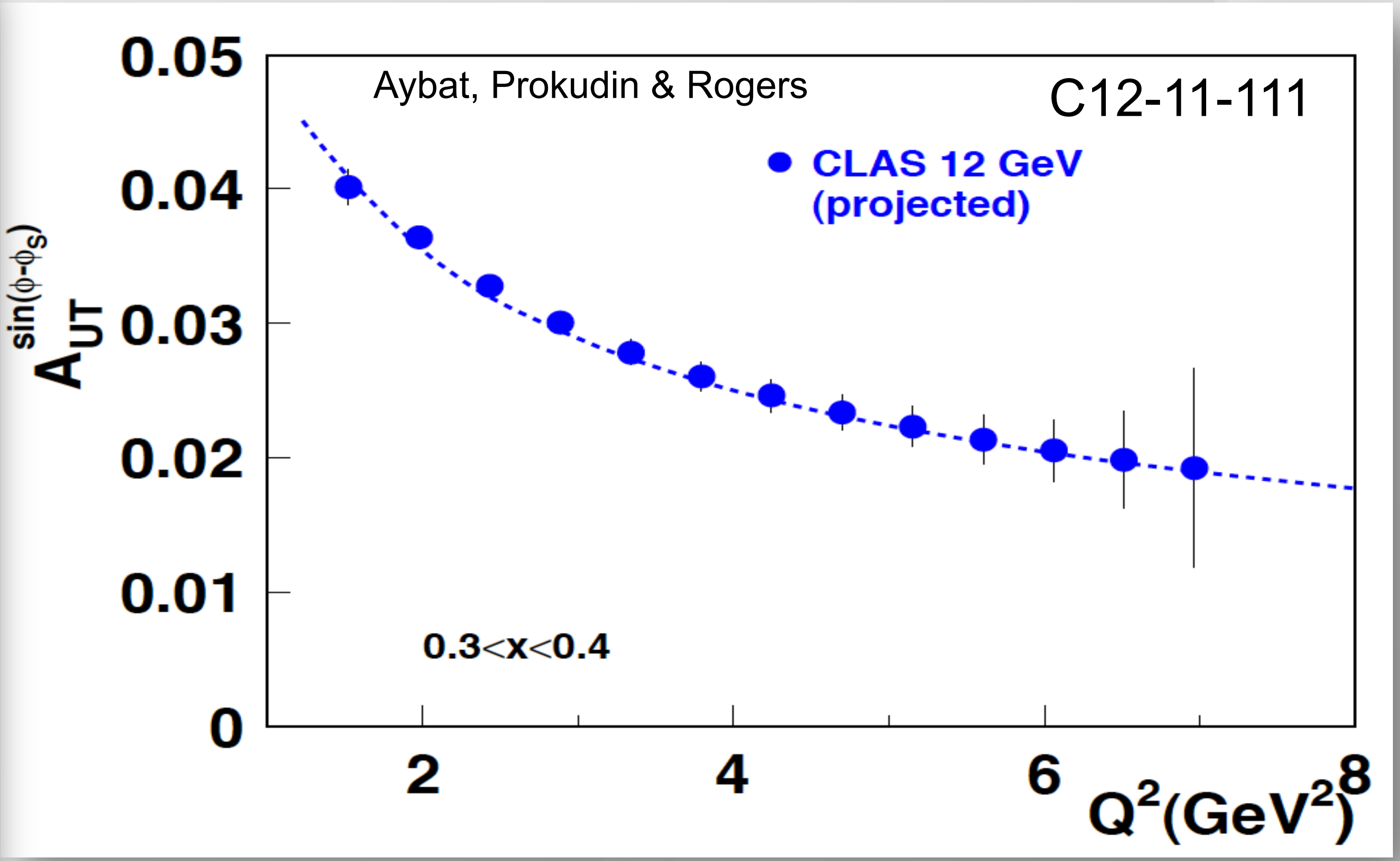
- Work in progress to operate the target with e^- beam in transverse polarization mode in the CLAS12 Solenoid.
- Test foreseen earliest summer 2017 at the Upgraded Injector Test Facility

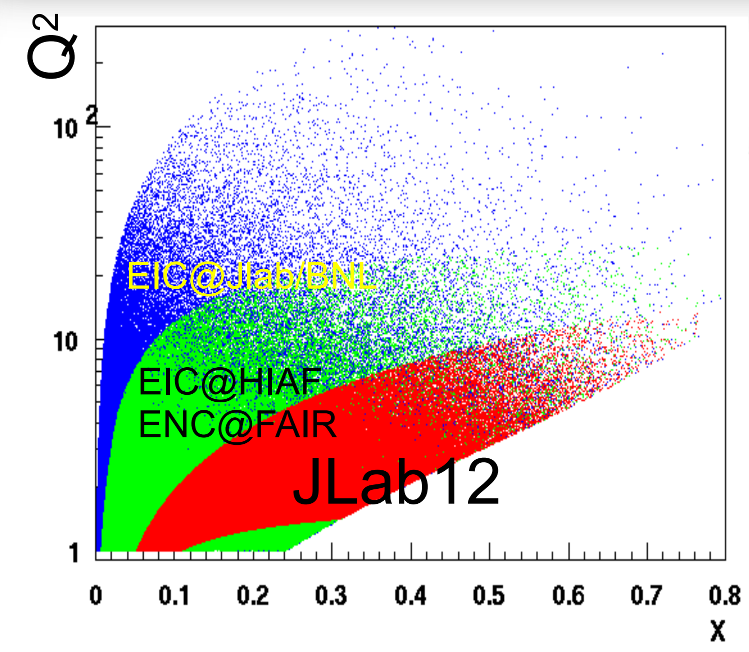
Transport design and simulation for 10 MeV rastered UITF beam

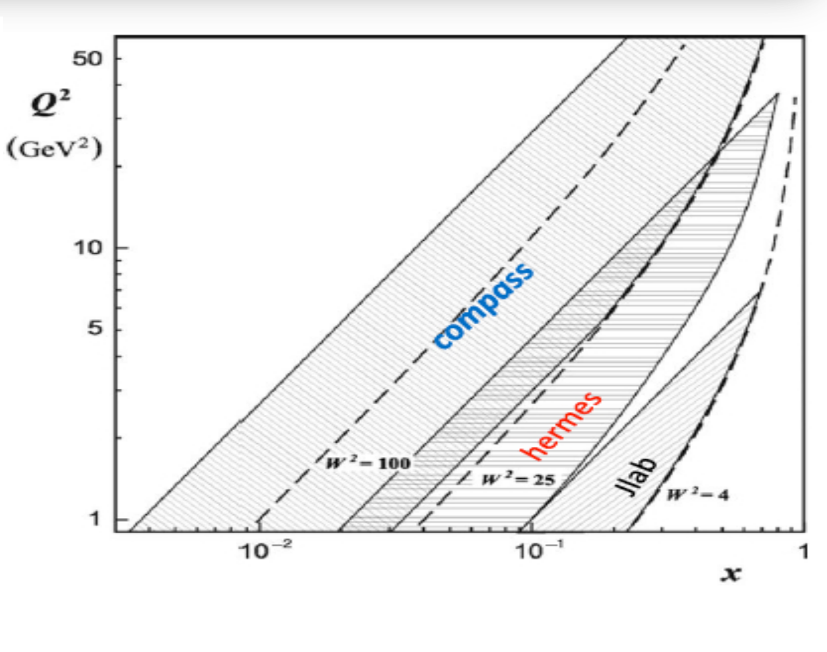


CLAS12: A_{UT} with Transverse Proton Target





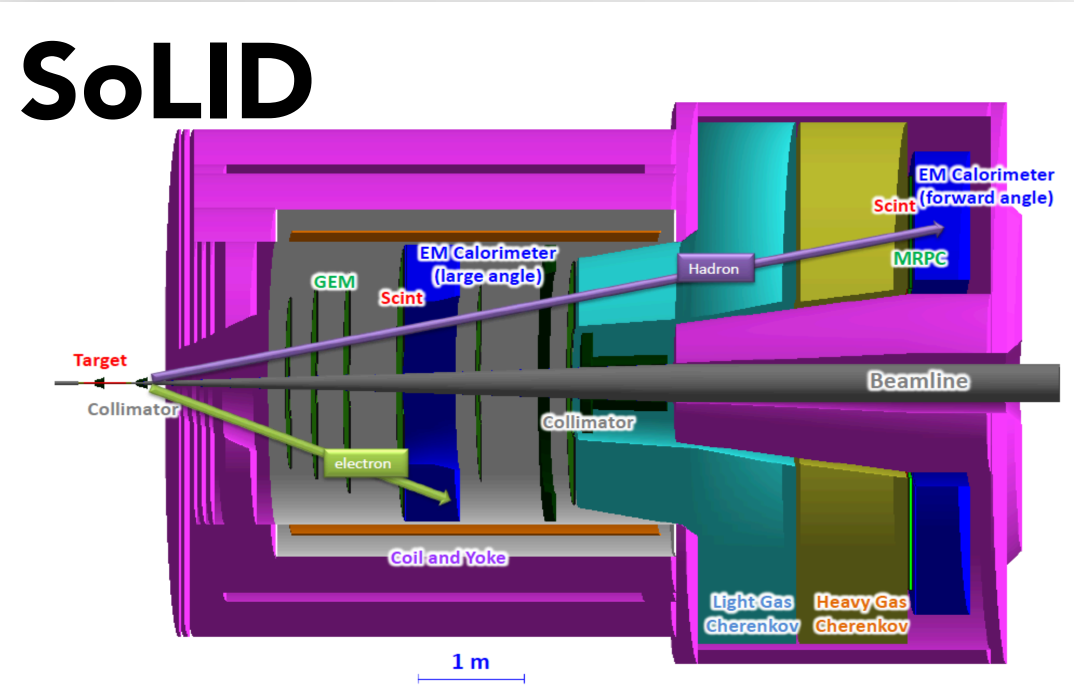




- Large acceptance of CLAS12 allows studies of P_T and Q^2-dependence of SSAs in a wide kinematic range
- Comparison of JLab12 data with HERMES, COMPASS and EIC will pin down the Q^2 evolution of Sivers asymmetry

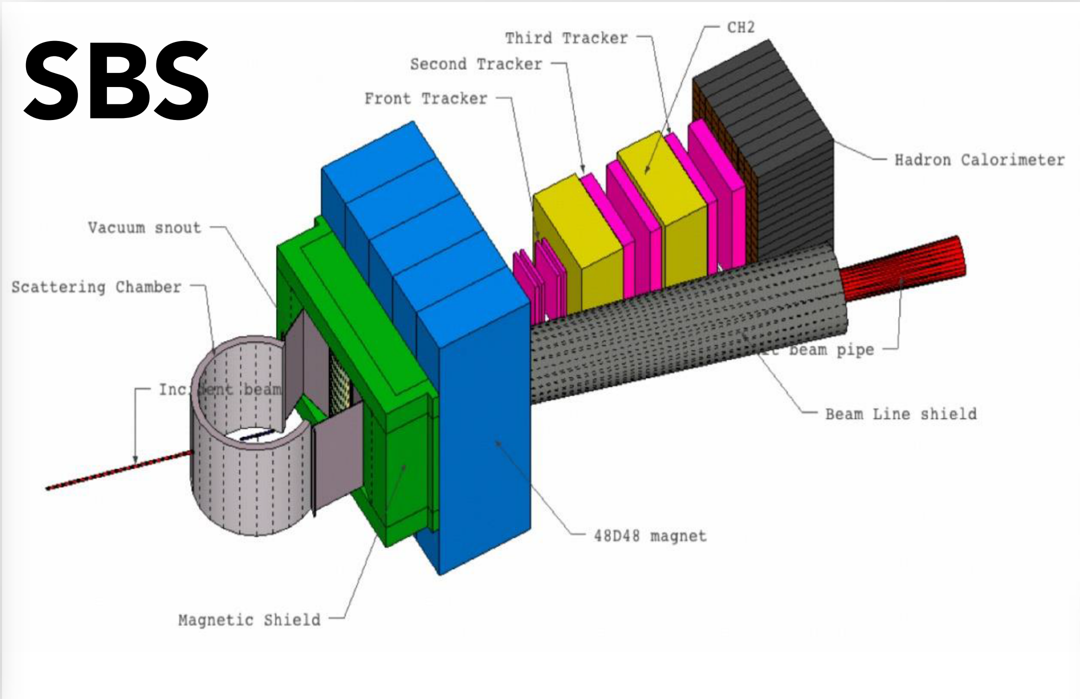
Hall A: SoLID & SBS

TMD program based on 2 new detectors not in the 12 GeV baseline upgrade



- Large acceptance (2π)
- Kinematic coverage out to moderately large P_T
- Capable of quite high luminosity (10^{36} cm^{-2}s^{-1})

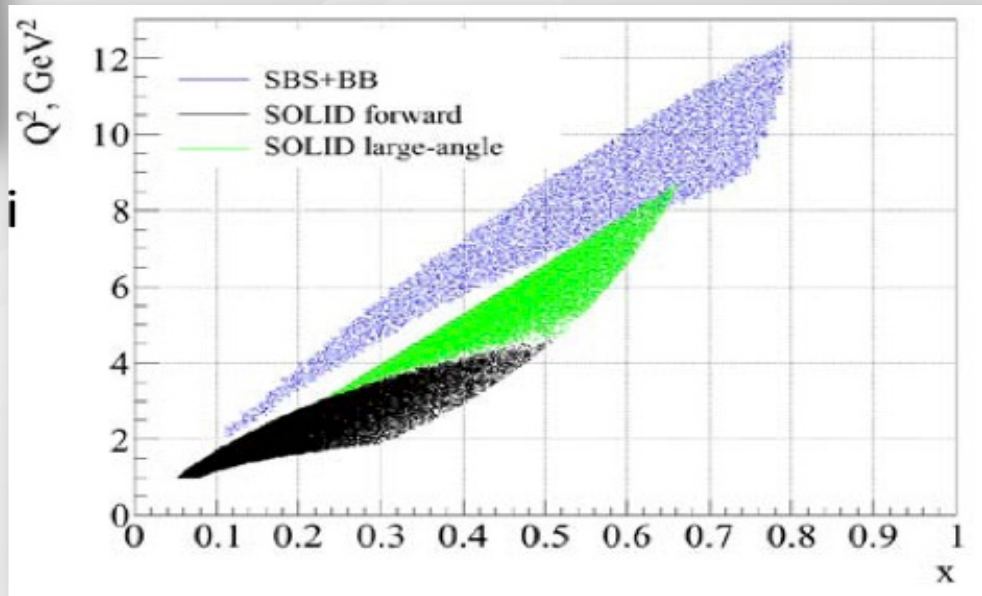
- CLEO Solenoid being arrived at Jlab
- Director's review (Feb. 2015)
- Collaboration briefing to DOE-NP (Nov. 2015)



- Moderately large acceptance
- Full PID (p and k)
- Well matched to high luminosity ^{3}He target

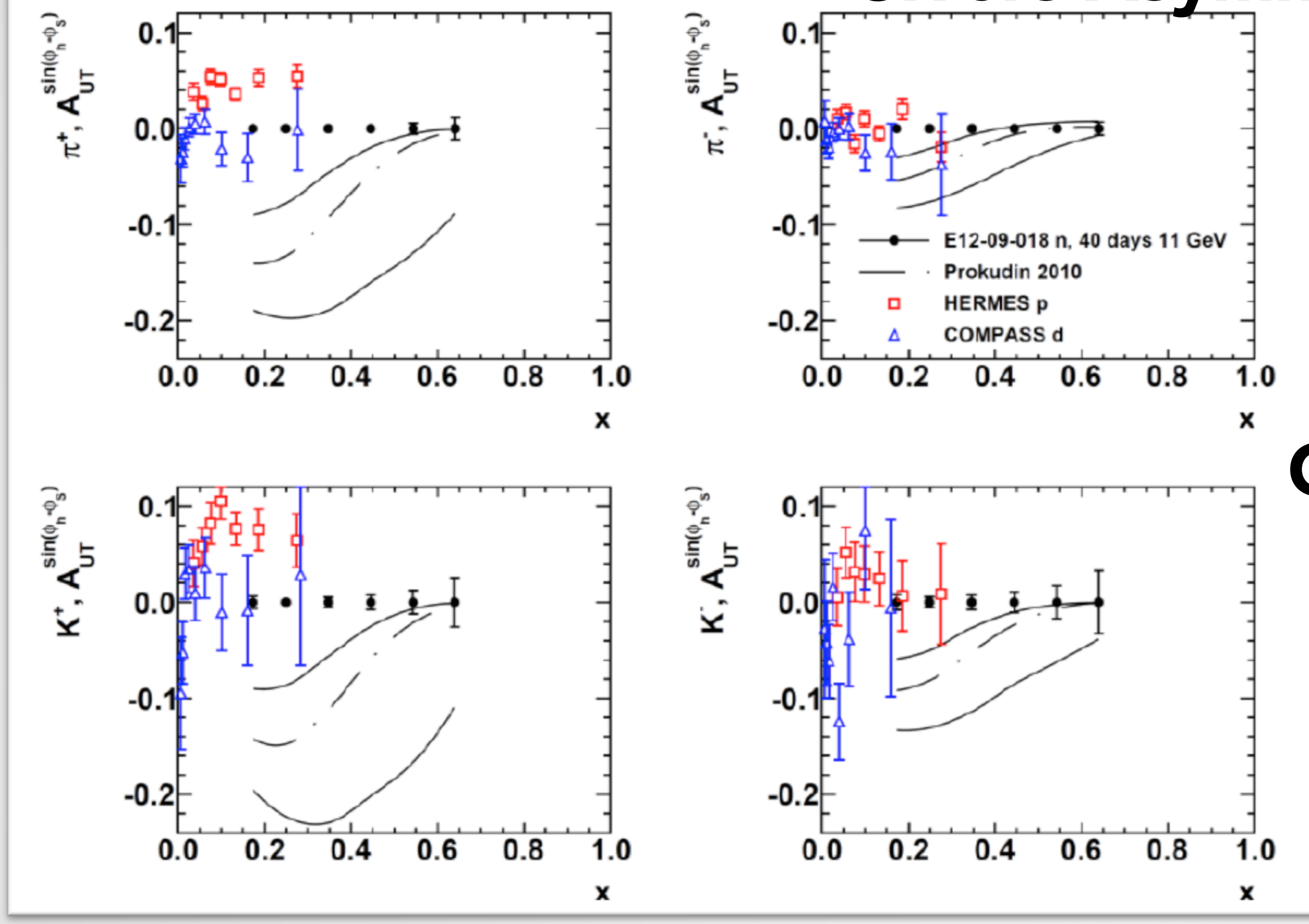
- Experiments start in Spring 2019

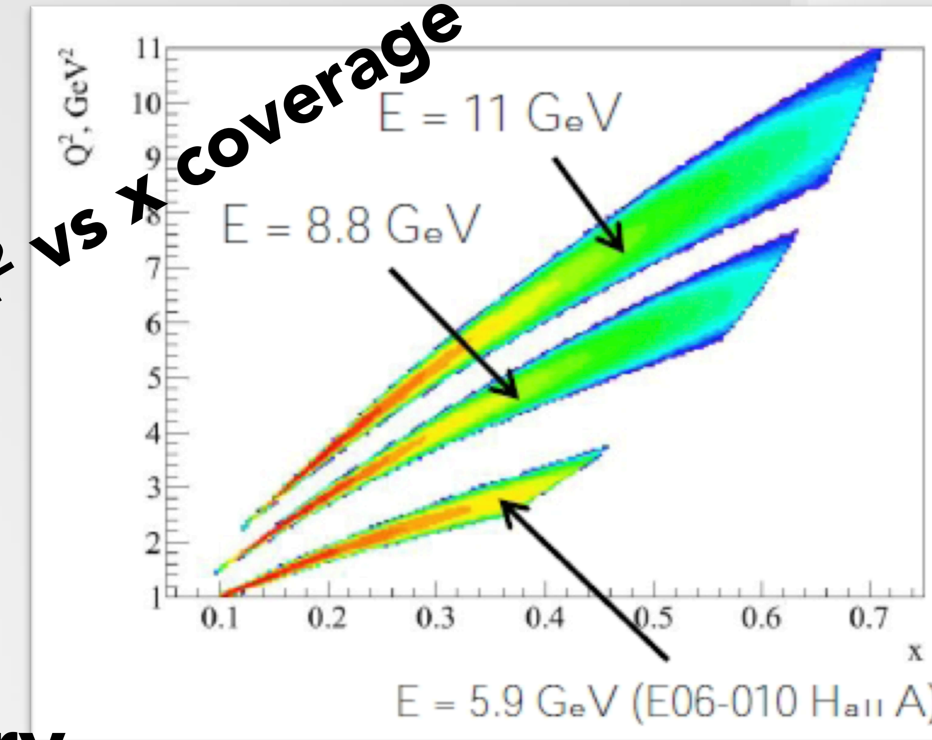
SoLID & SBS:
Complementary Kinematics



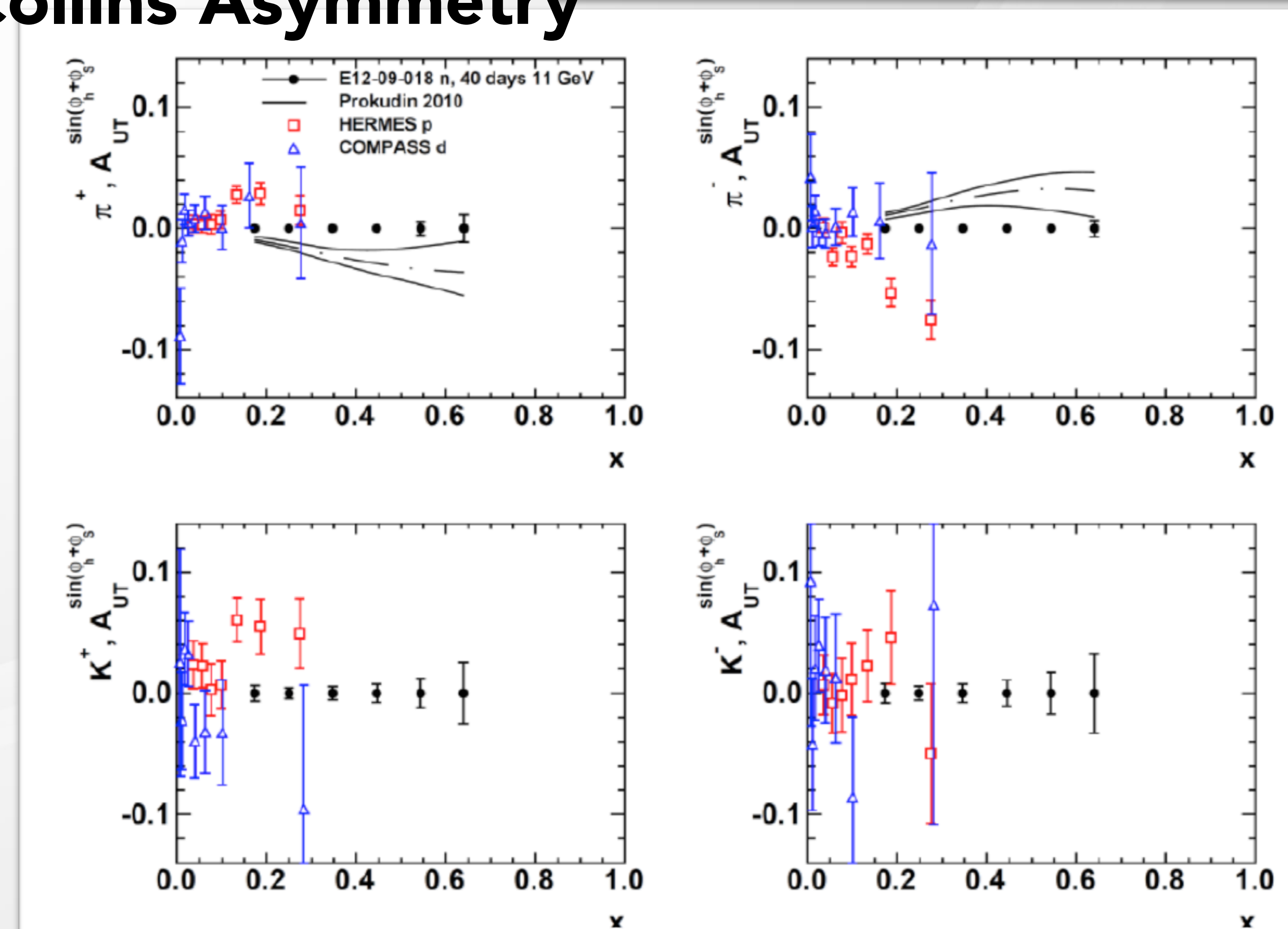
Neutron Structure with SBS

Sivers Asymmetry



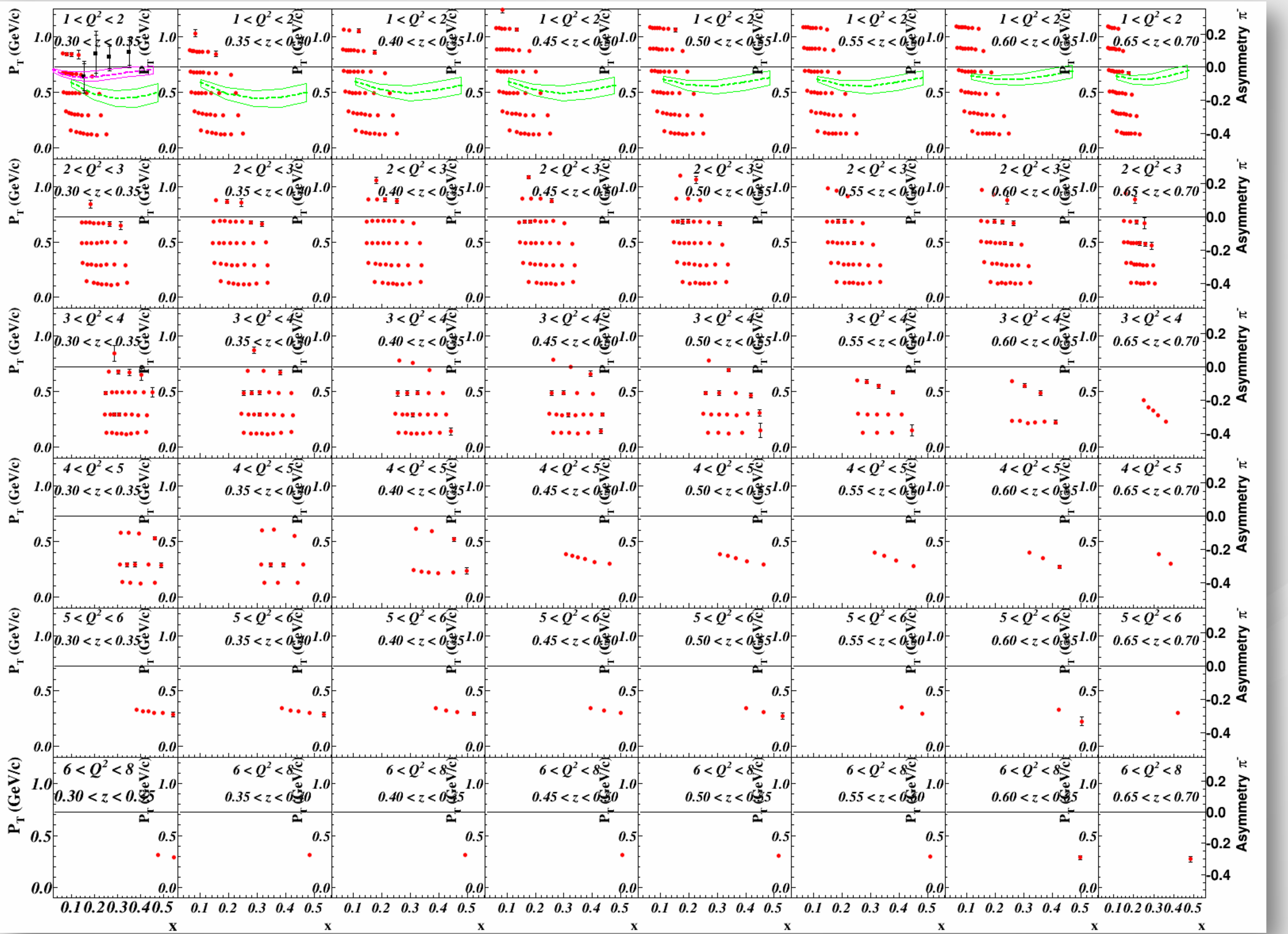


Collins Asymmetry



- E12-09-018 will achieve statistical FOM for the neutron ~100X better than HERMES proton data and ~1000X better than E06-010 neutron data.
- Kaon and neutral pion data will aid flavor decomposition, and understanding of reaction-mechanism effects.

Power of SoLID



Sivers π^- projected results

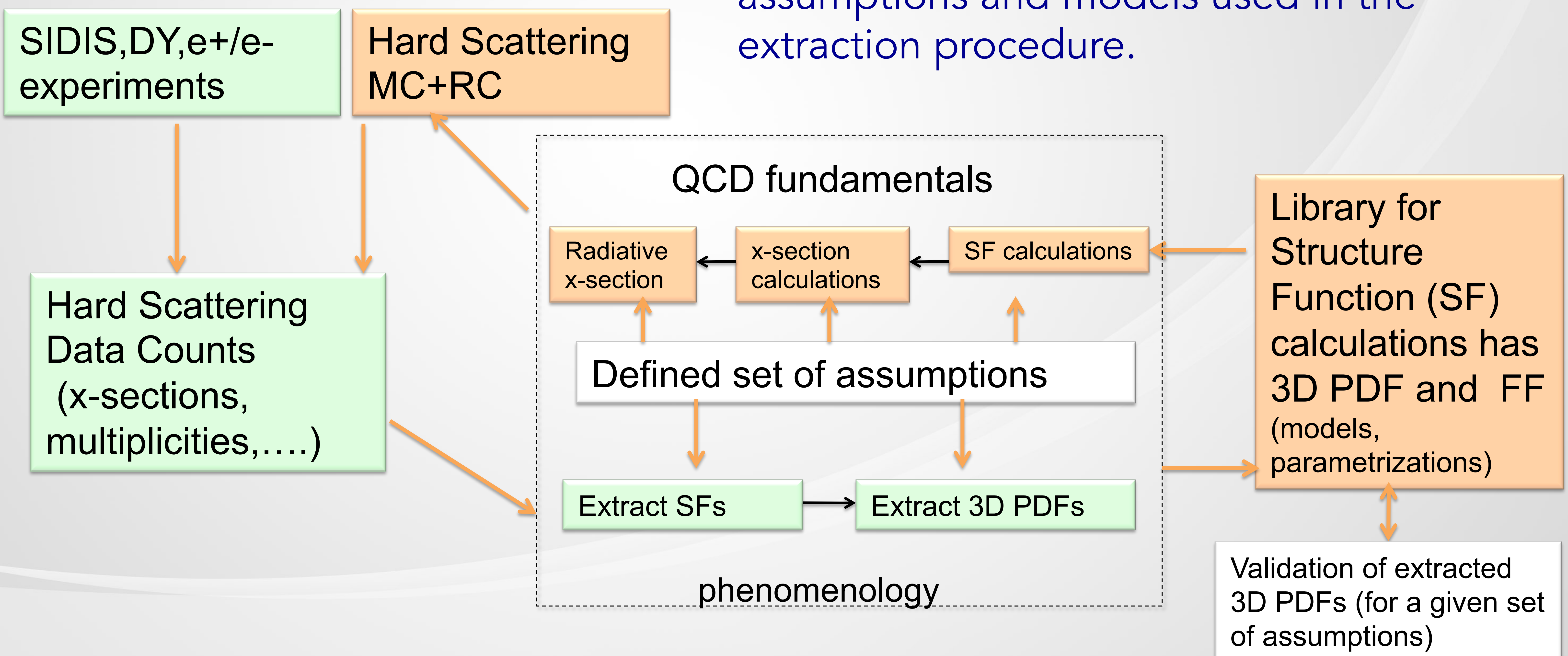
Huge amount of data will be collected

we urgently need a model independent procedure to extract TMDs from data and validate the process

ExtractionVAlidation framework (EVA)

H. Avakian et al.

Main goal: assist extraction of 3D PDFs, by testing different extraction procedures and estimating systematics related to different assumptions and models used in the extraction procedure.



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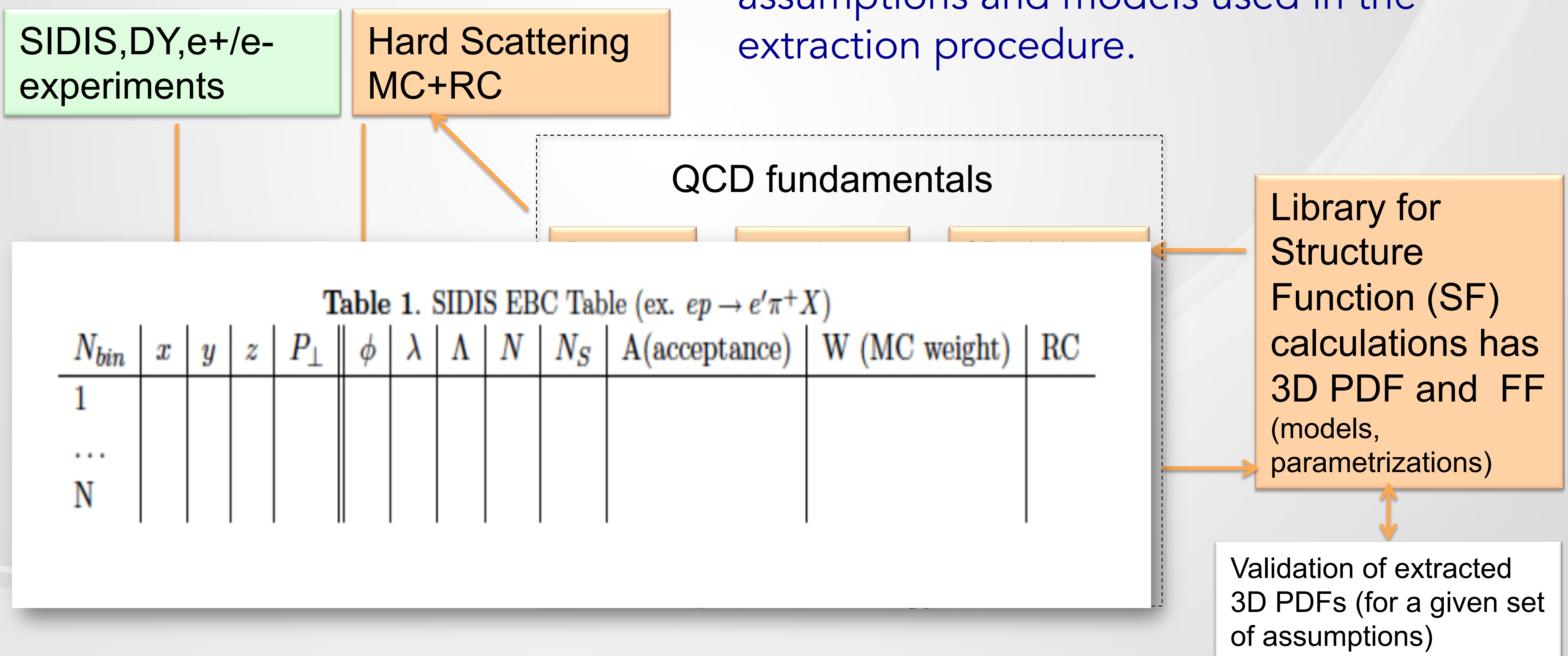

Table 1. SIDIS EBC Table (ex. $ep \to e'\pi^+ X$)

N_{bin}	x	y	z	$P_\perp$	ϕ	λ	Λ	N	N_S	A(acceptance)	W (MC weight)	RC
1												
...												
N												

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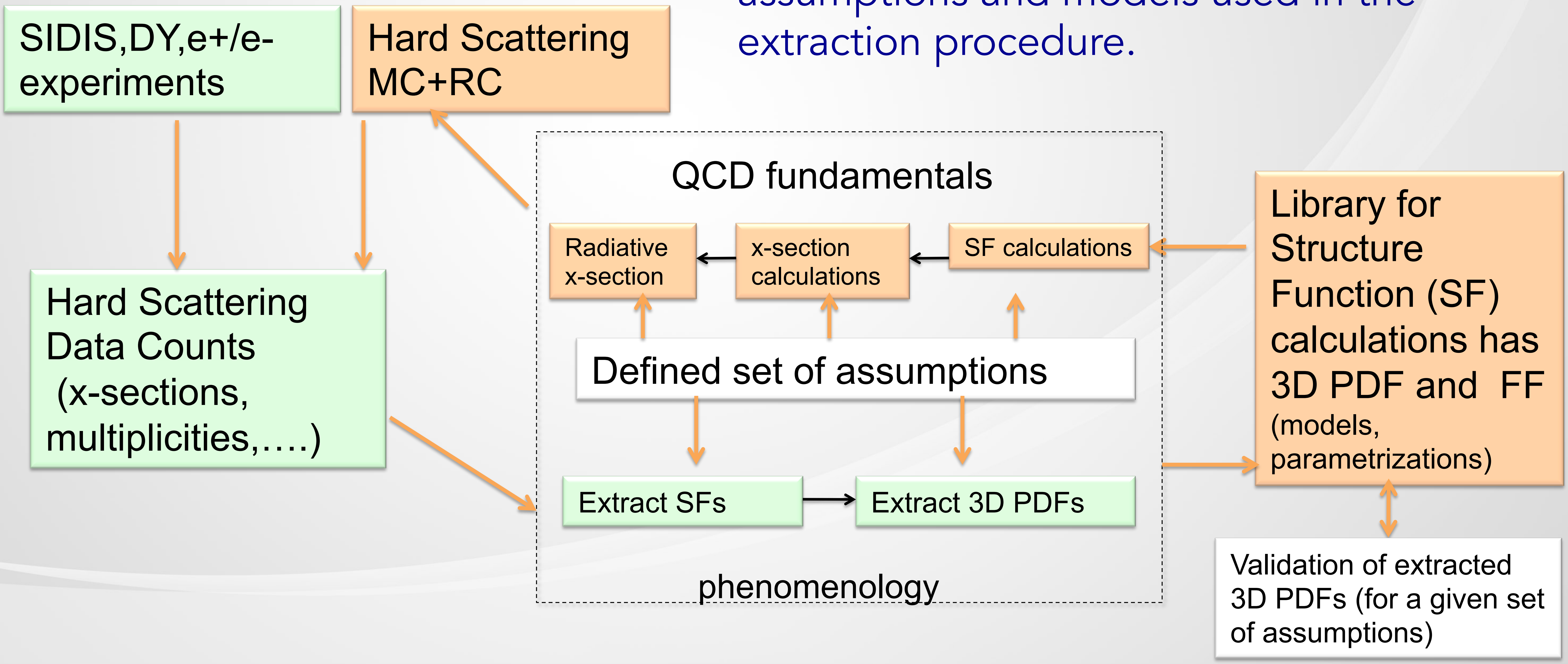


ExtractionVAlidation framework (EVA)

1) Structure for the data input defined

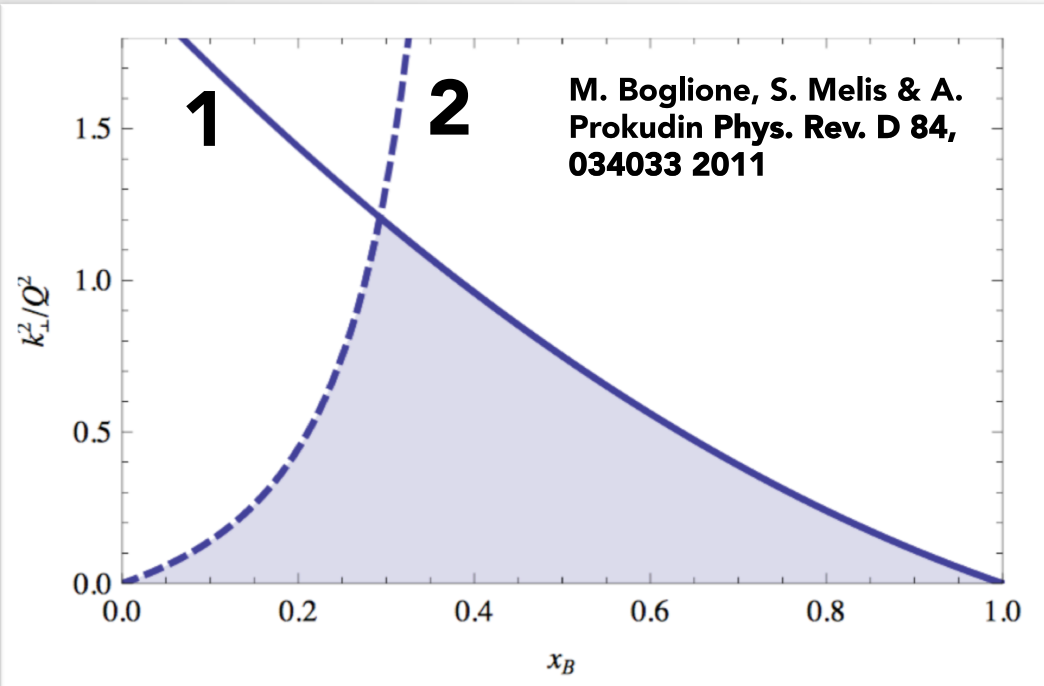
Data Grids:
- Experimental data is stored in a sparse grid.
- Theoretical model calculation stored in a grid
- Only bins with values are stored
- Grid contains binning and limits of phase space.

Grid interface allows:
- integration over selected dimensions
- extraction of slices
- generation of random numbers (grid weighted)
- functional interpolation

Grid Visualization:
- displays data for chosen ranges of bins
- allows integration and slicing
- mathematical operations with grids

ExtractionVAlidation framework (EVA)

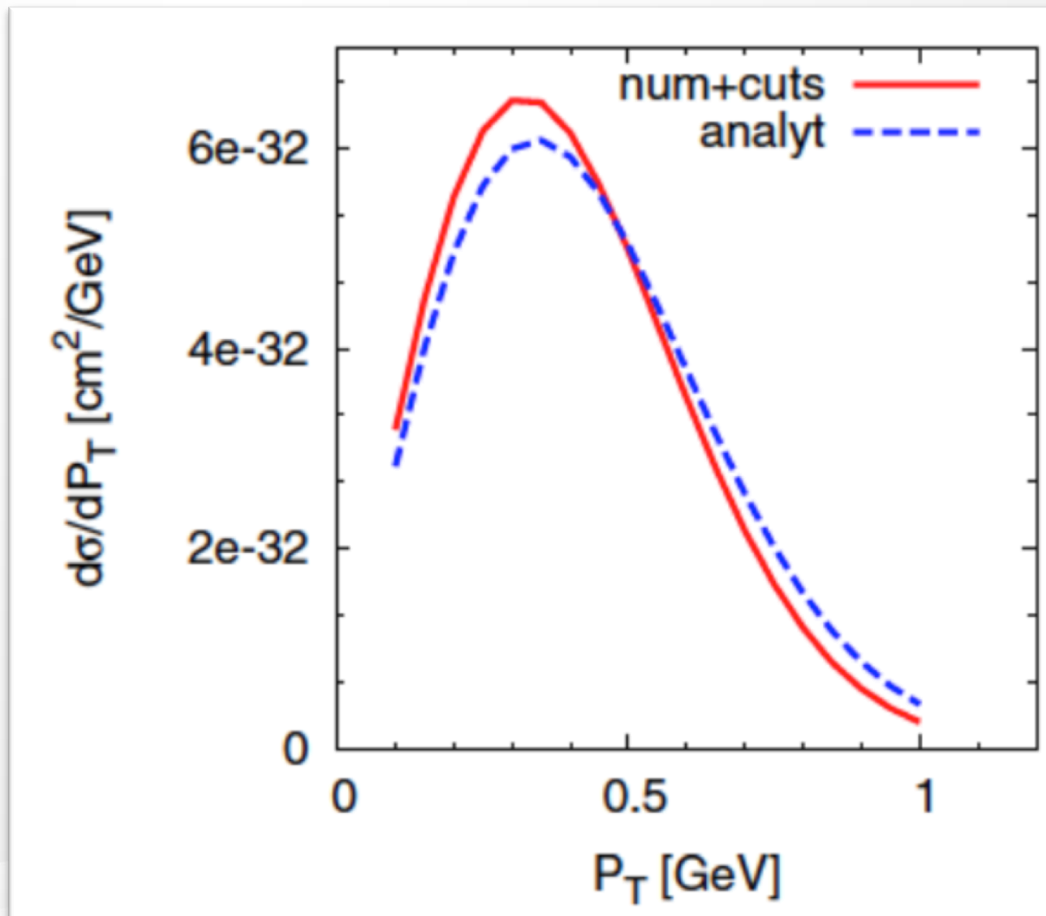
2) We will use unpolarized moments for EVA tests.

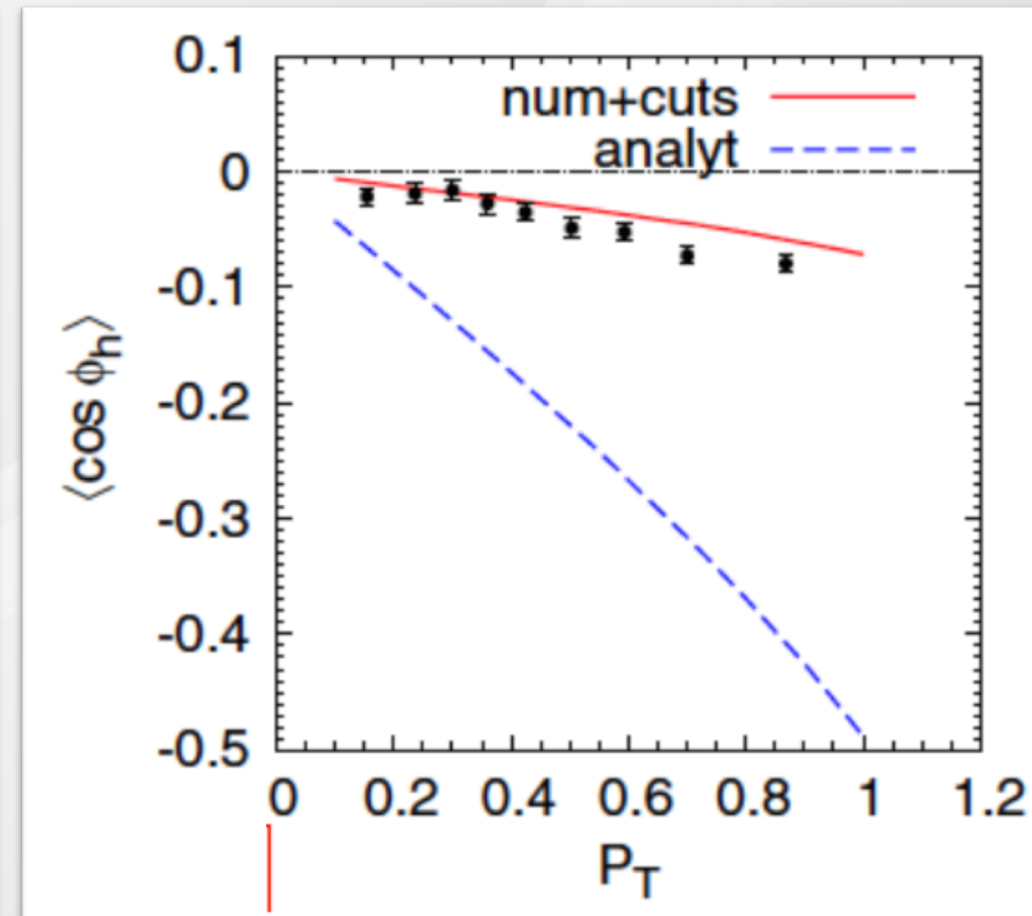


1. Energy of the parton less than the energy of the parent hadron
2. Parton moves forward with respect to the parent hadron direction

x and k_T are not independent at low Q^2 even in factorized Gaussian approach!

COMPASS Deuteron π^+





<cos ϕ> more sensitive to kinematic limitations than multiplicities

ExtractionVAlidation framework (EVA)

Next:

- Use MC to test the program for x-section calculations
- Use CLAS data to choose reasonable constants for MC
- Analyze <cosϕ> and extract Cahn and BM contributions from MC and data.
- A self consistent procedure for extraction of TMDs with validation will be used to test the sensitivity of different observables to k_T structure of nucleon

Conclusions

- The 6 GeV SIDIS program has laid a strong foundation for precision TMDs studies at JLab 12 GeV

- A comprehensive SIDIS program at 12 GeV is in place:
  - Wide kinematic coverage and large acceptance
  - Precise un-polarized cross-sections and their kinematic dependence
  - Study leading and sub-leading twist TMDs
  - Many modulations will be extracted in more than one experimental hall, equipped with complementary performing detectors

- Flavor separation will be performed analyzing asymmetries with different target/beam polarization combinations on both neutron and proton targets

- A consistent procedure for extraction of TMDs from data with controlled systematic errors has started.

Support Slides

Hall C SIDIS Program

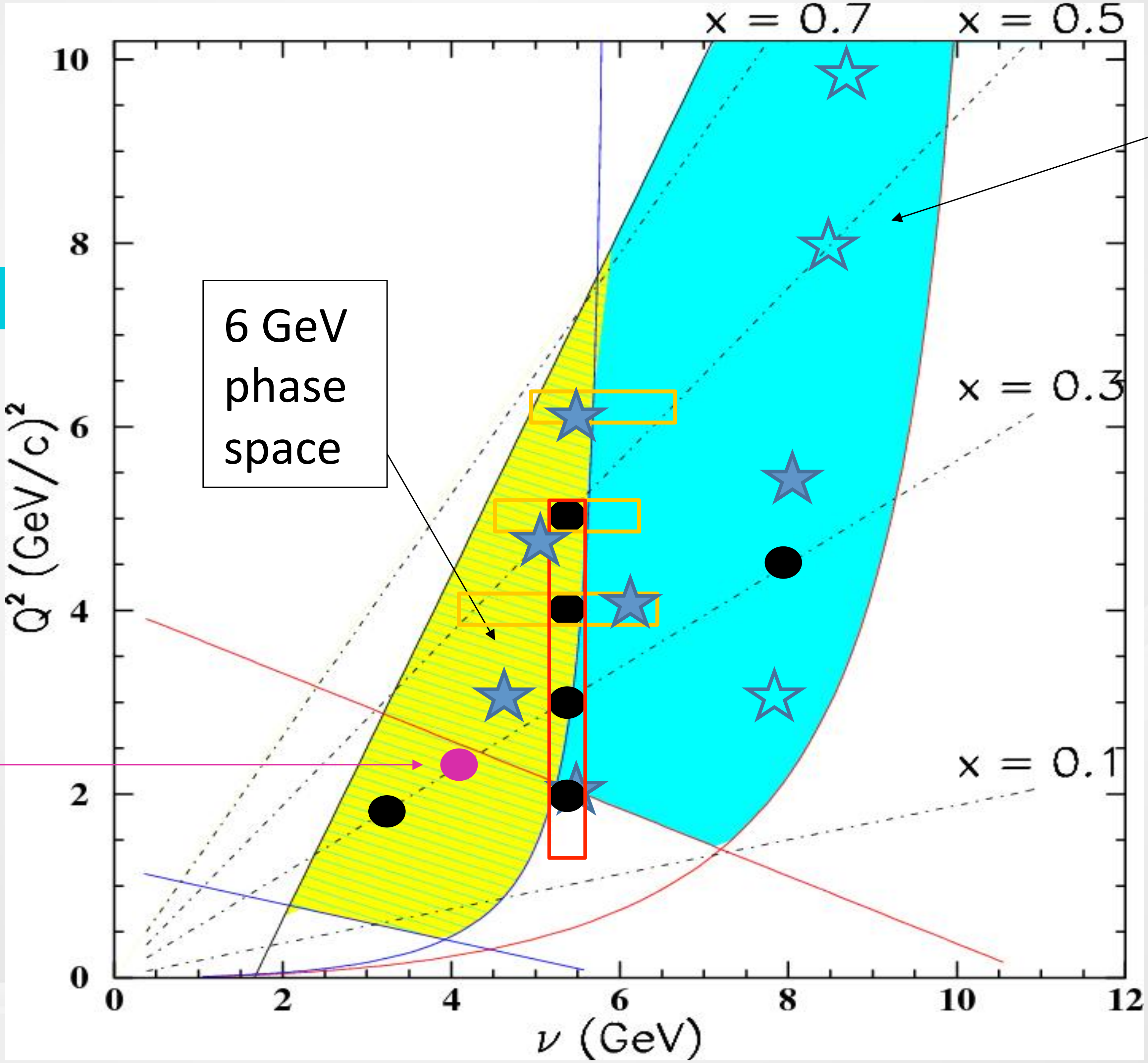
Kinematics (typ. $x/Q^2 \sim$ constant)

PR12-13-007

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

Parasitic with
PR12-13-010

E00-108



Charged pions:

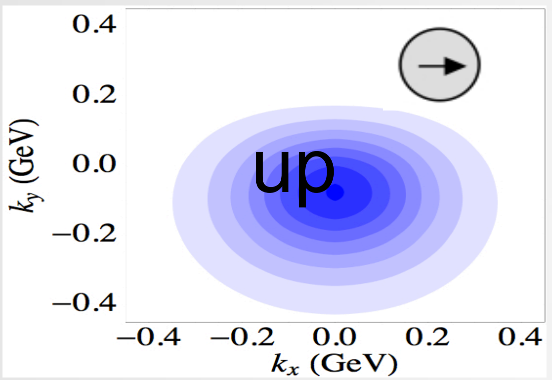
E12-06-104
L/T scan in (z,P_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

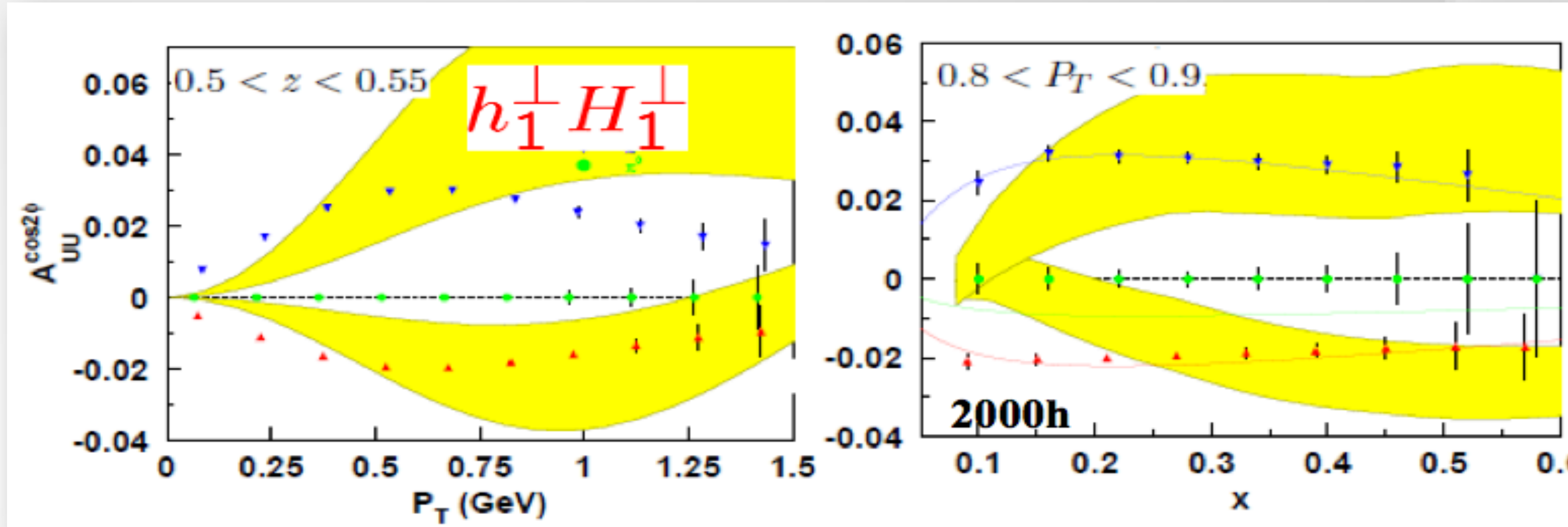
E12-09-017
Scan in (x,z,P_T)
+ scan in Q^2 at fixed x

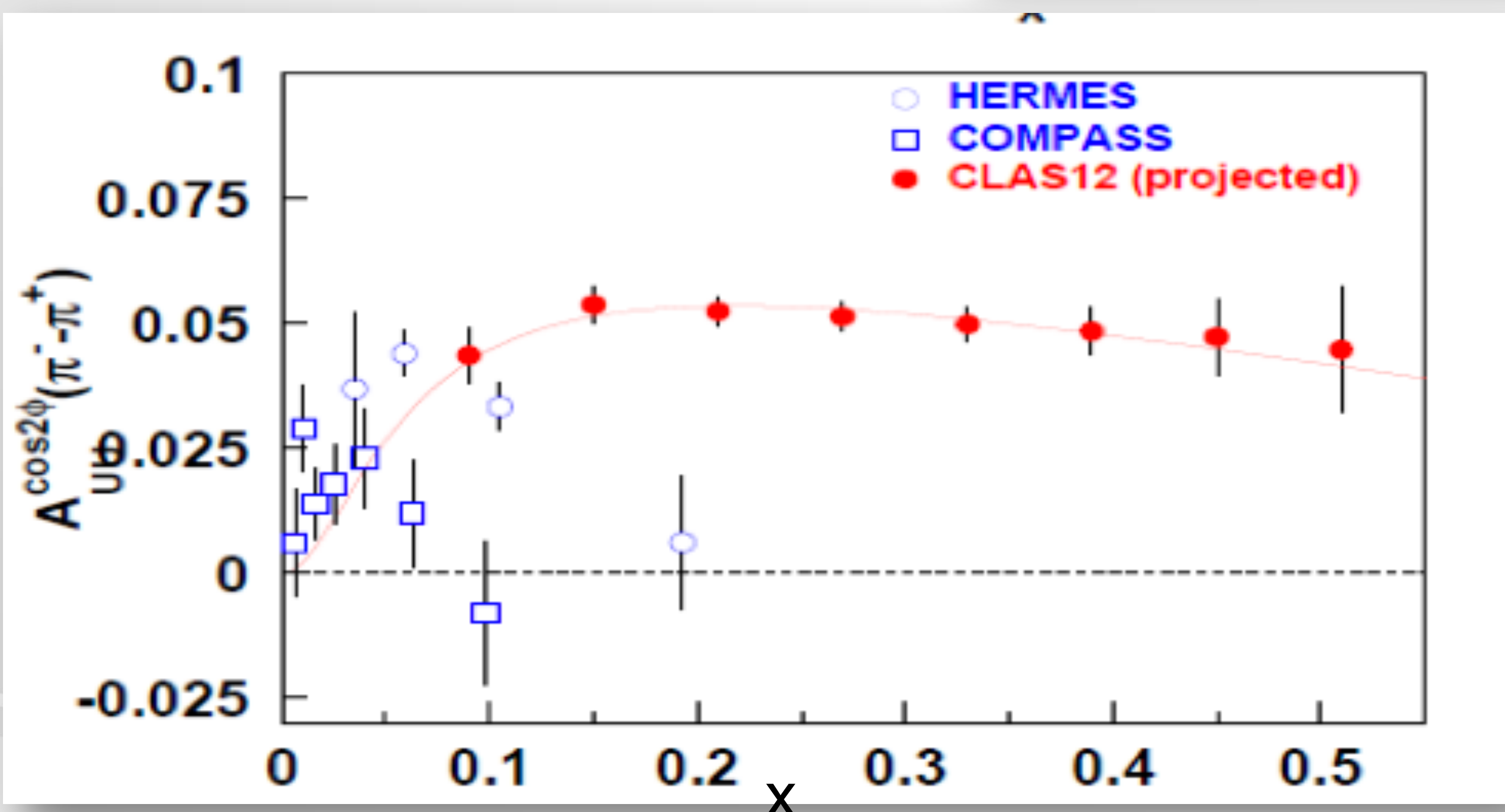
E12-09-002
+ scans in z

CLAS12: Boer-Mulders Asymmmetries

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 $h_{1T}^\perp$







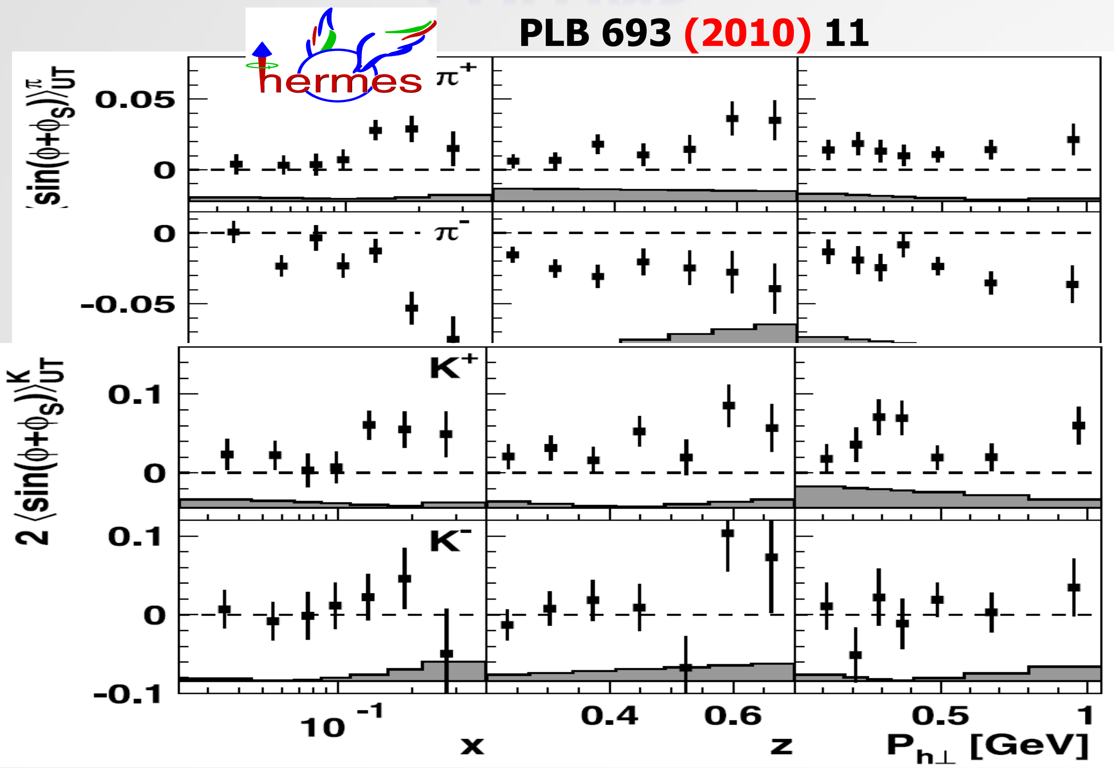
- Wide range in Q^2 and P_T accessible with CLAS12 are important for cos2φ studies

(all background contributions are HT)

- **Background contributions:**
  - Higher twist azimuthal moments
    - kinematical HT (Cahn)
    - dynamical HT (Berger-Brodsky)
  - Radiative corrections
  - Acceptance

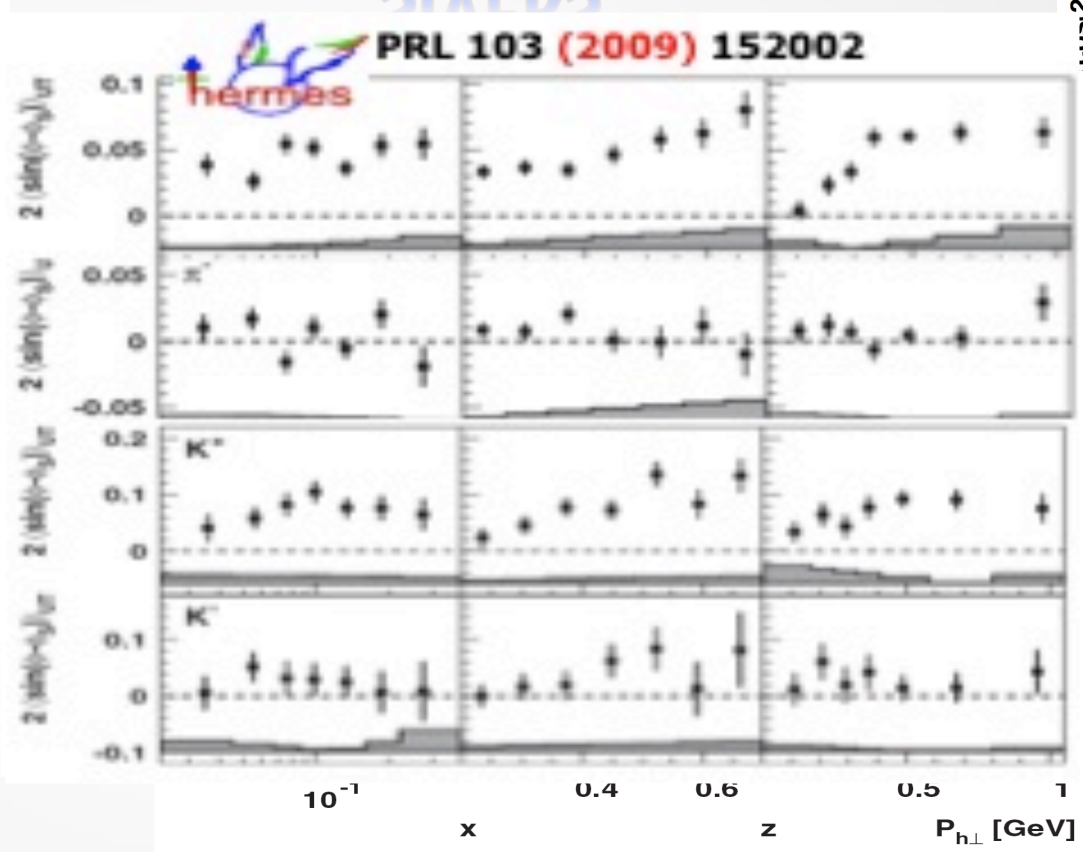
The Kaon Puzzle

COLLINS



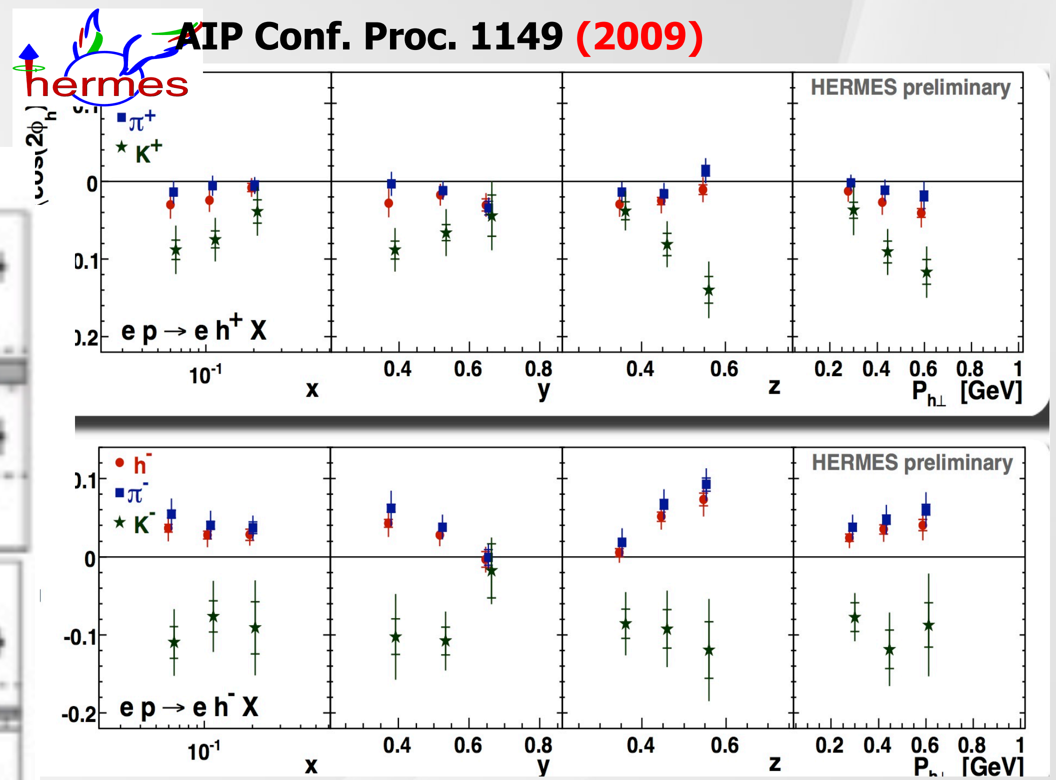
- K^+ amplitude ≅ π^+ amplitude
- K^- ~0 (still contr.) π^- large <0

SIVERS



- K^+ amplitude > π^+ amplitude
- K^- no conclusive results-limited stat.

BOER-MULDERS

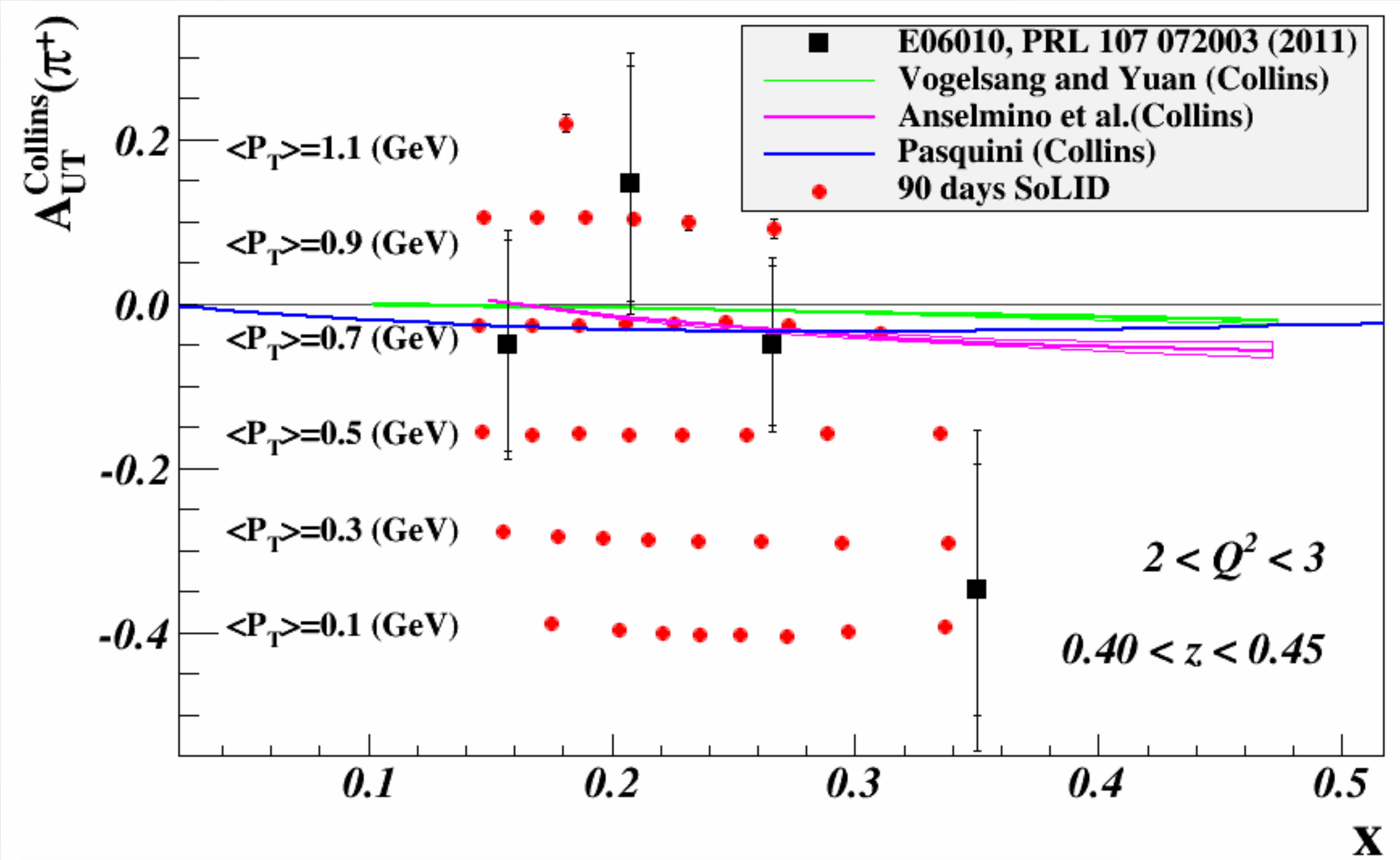


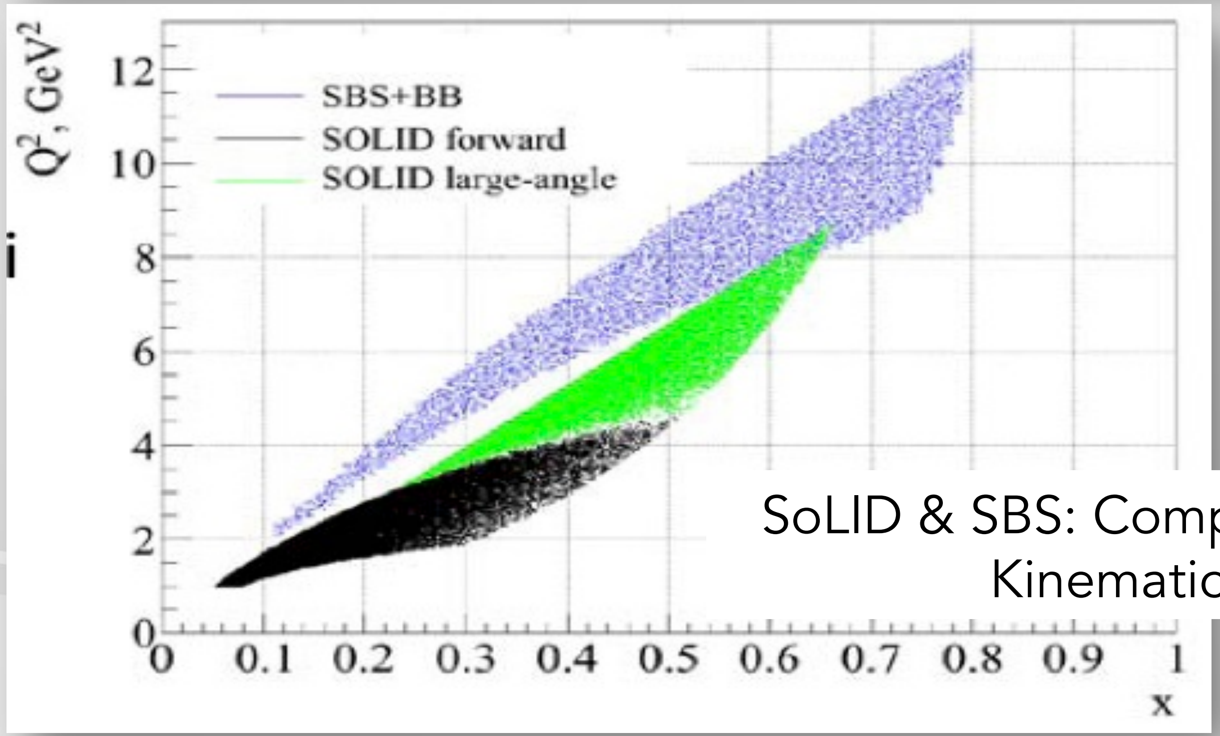
- relative sign $H_1^{\perp\,fav}$ / $H_1^{\perp\,unfav}$ for π and K incons.

CONTROVERSIAL pattern of SSA for K!!

- non trivial role of the sea quarks in the nucleon or/and
- peculiar behaviour of the fragmentation mechanism in the presence of s quark

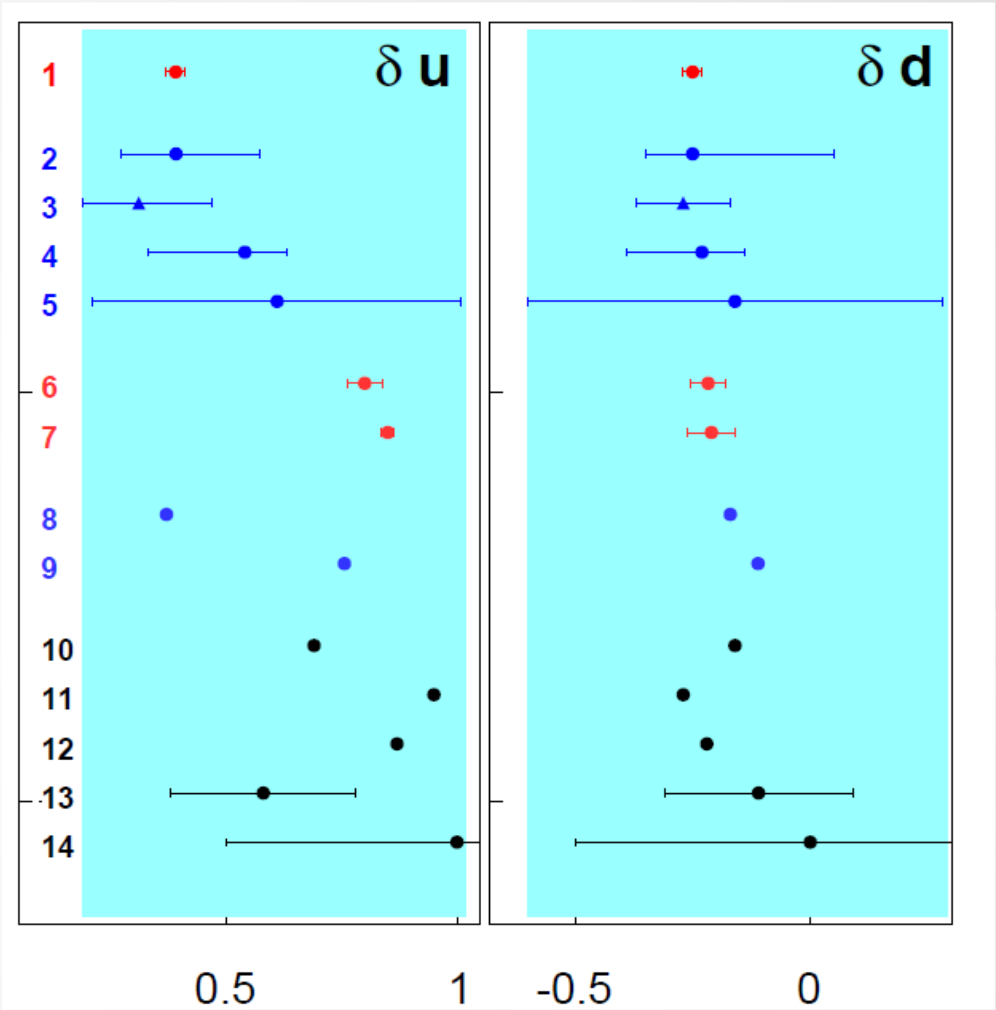
Nucleon Structure with SoLID & SBS





SoLID & SBS: Complementary Kinematics

Tensor Charges

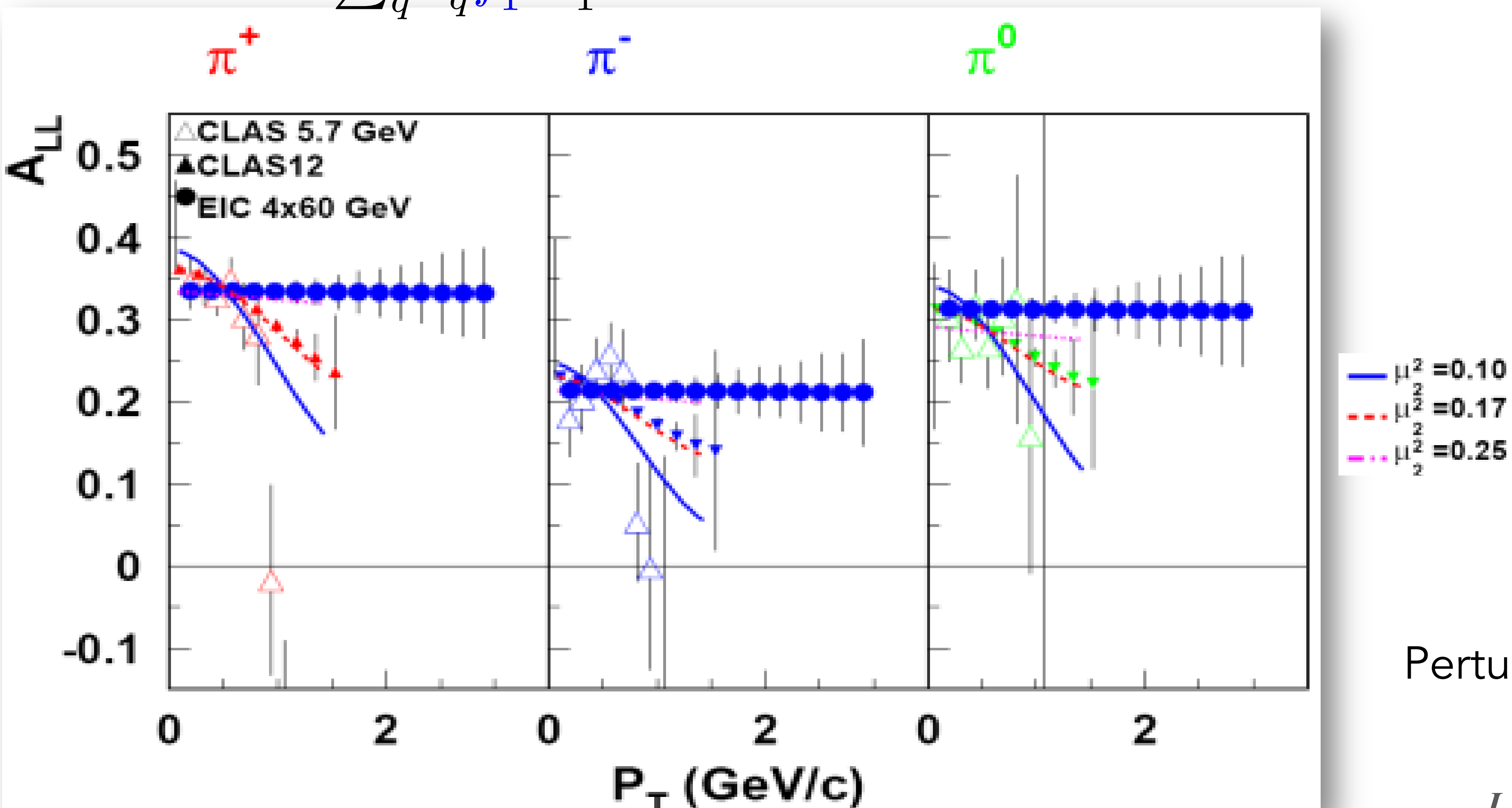


SoLID projection extraction by A. Prokudin using only statistical errors and based on:

- 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

CLAS12: K_T Helicity Dependence

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



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

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

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

μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2

M.Anselmino et al hep-ph/0608048

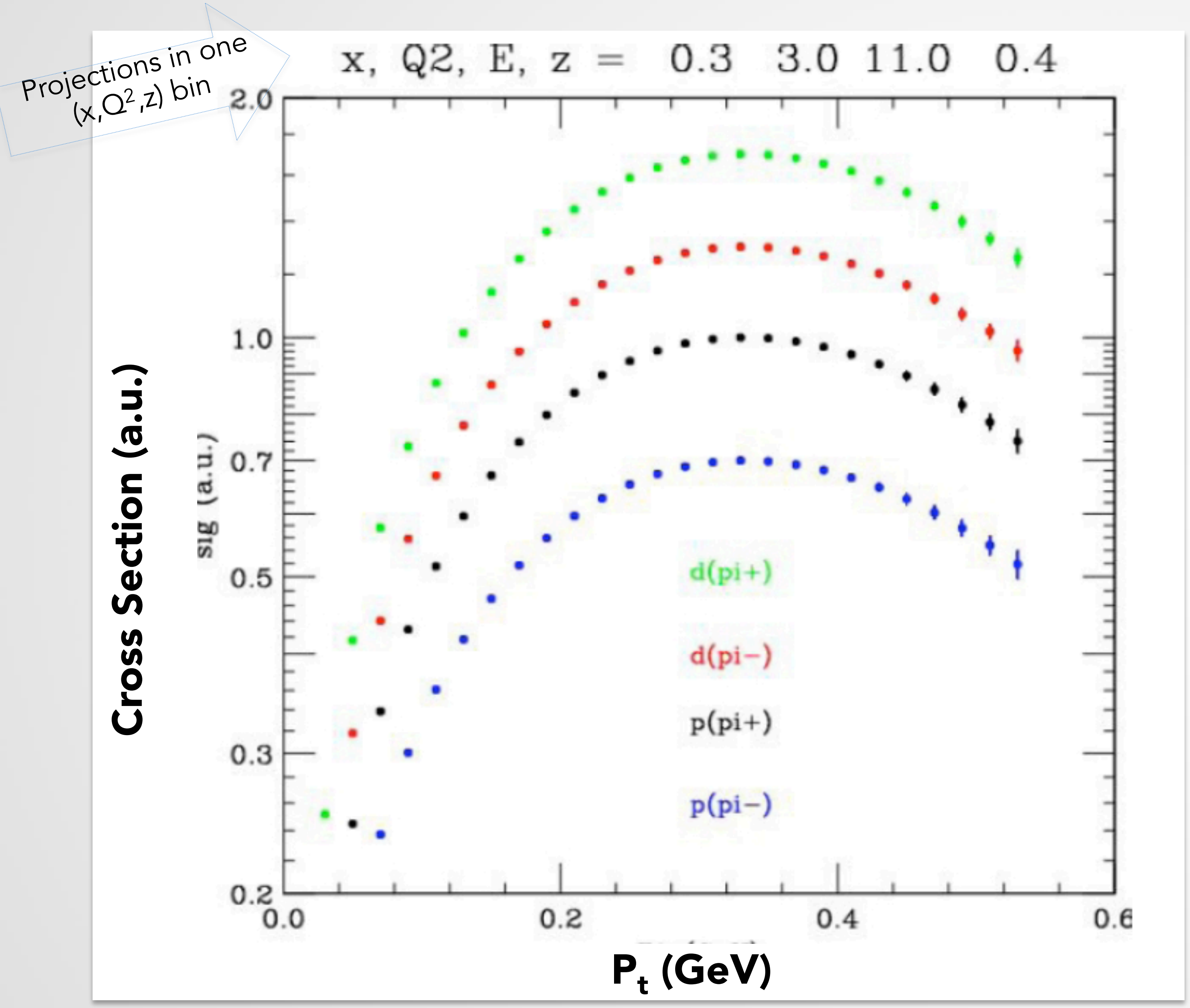
Perturbative limit calculations available for

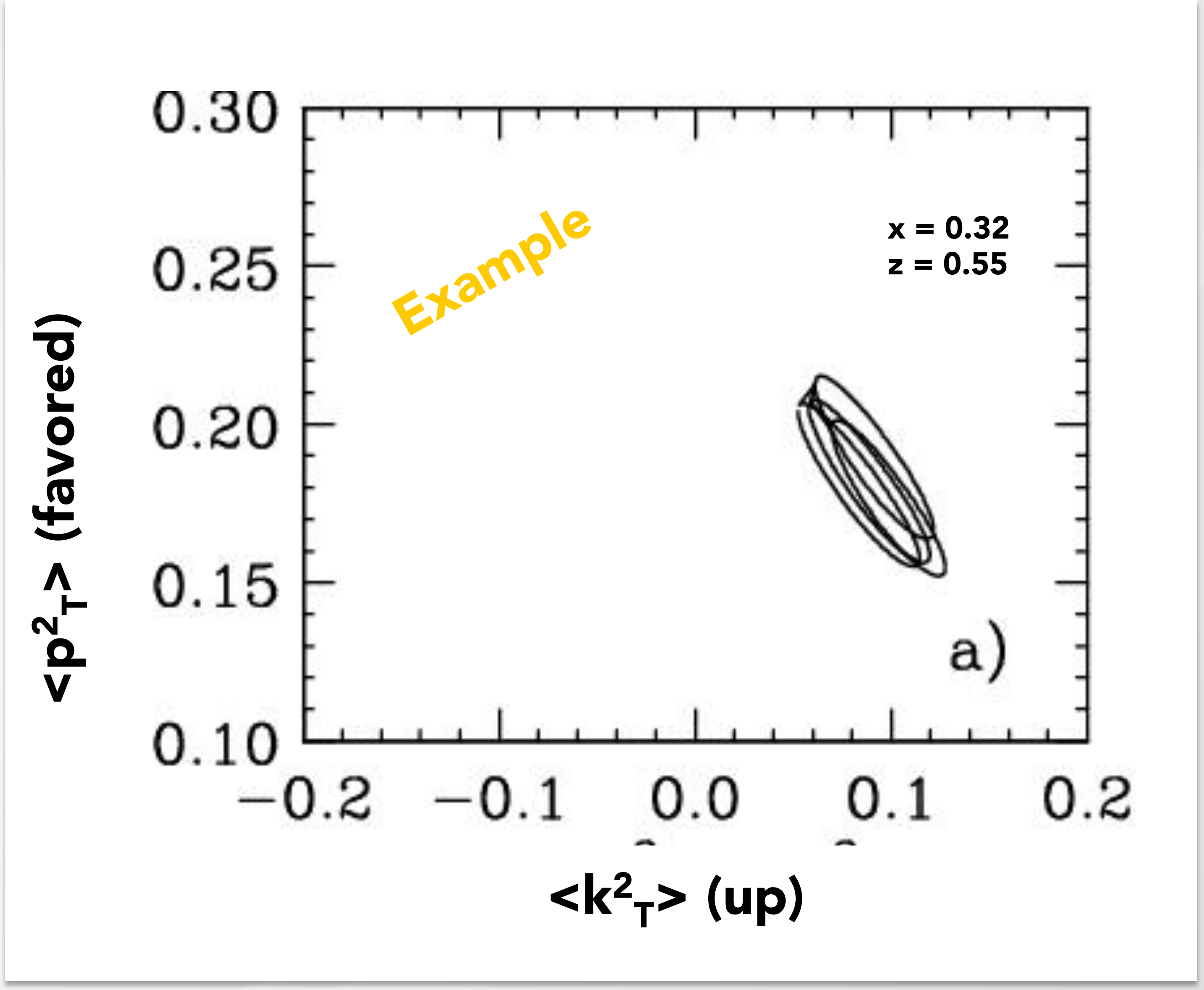
$$g_1^q(x,k_T), f_1^q(x,k_T)$$

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 to perturbative approach

P_T Dependence of SIDIS π/k production (E12-09-017)





- Can cover low P_T (up to 0.05 GeV) with very good angle and momentum resolution
- Constrain k_T dependence of u and d-quarks separately by combining π^+ and π^- yields, proton and deuteron targets