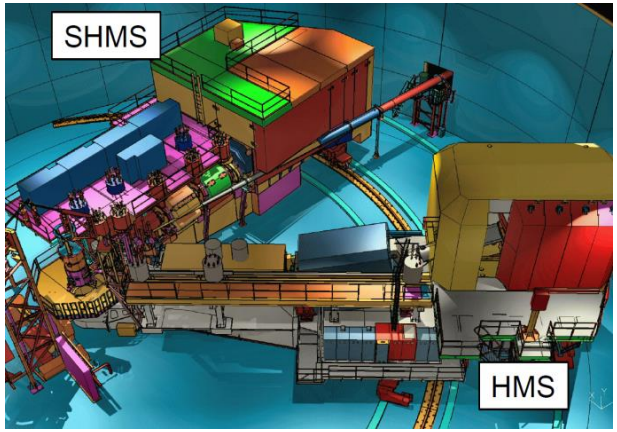
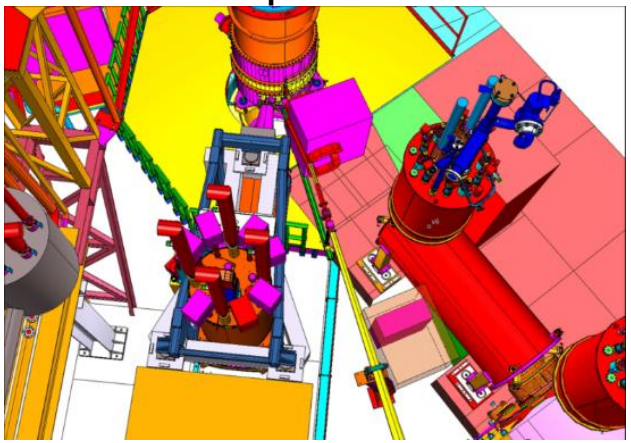
Exploring Meson Structure using Hard Electromagnetic Probes

Hall C focusing spectrometers



Neutral Particle Spectrometer



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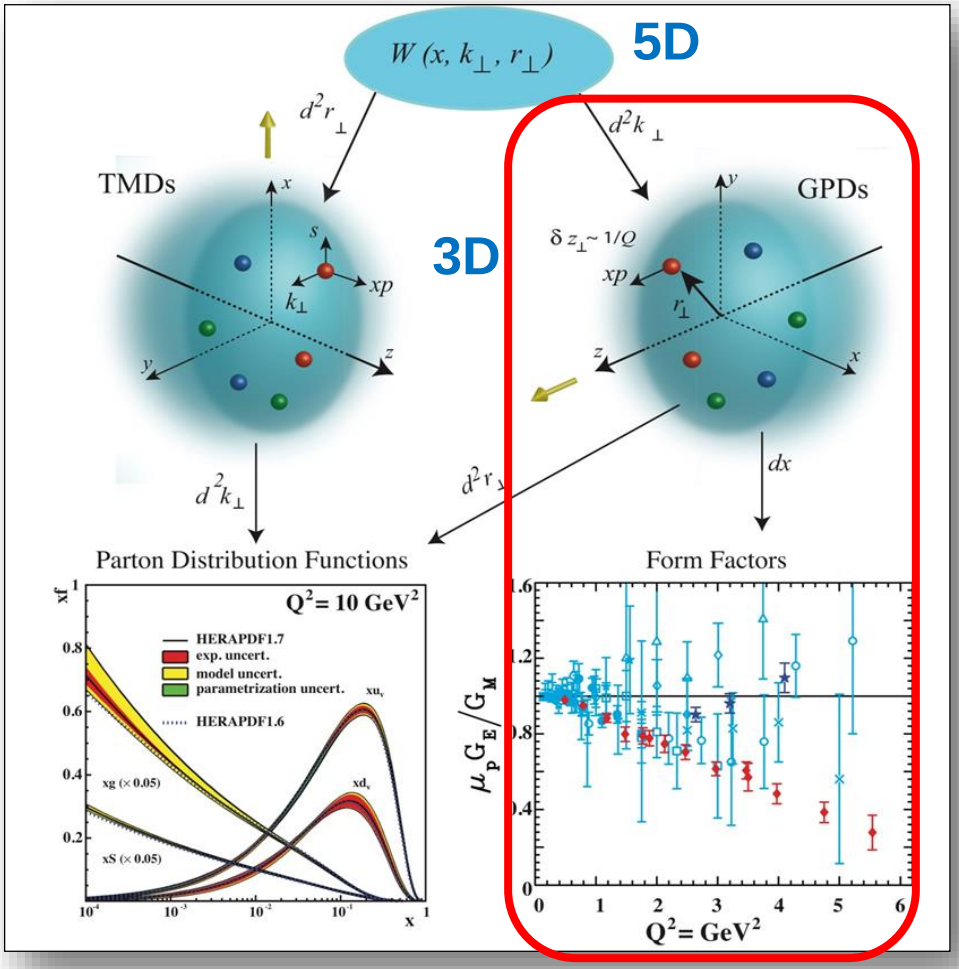
IWHSS 2018 – International Workshop on Hadron Structure and Spectroscopy

University of Bonn, Campus Poppelsdorf, 19-21 March 2018

The 3D Hadron Structure

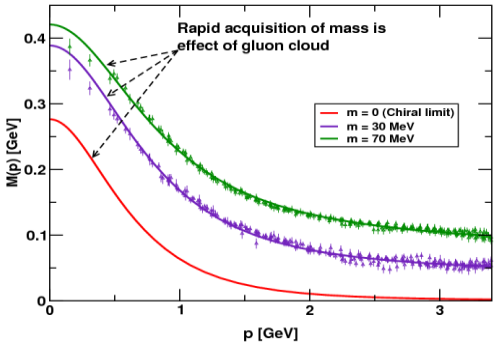


- Meson Form Factors
  - Most basic information about internal structure
- GPDs
  - Spatial imaging (exclusive DIS)
- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets

Major new capabilities with JLab12

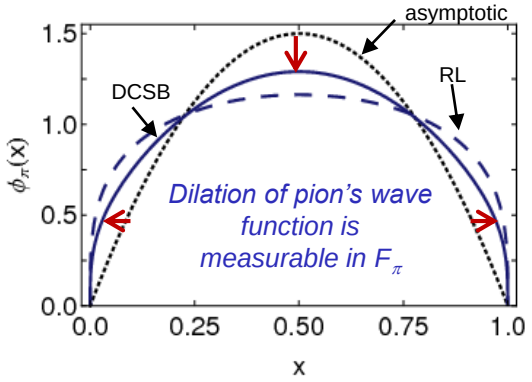
Overview Form Factors

- ***Pion and kaon form factors*** are of special interest in hadron structure studies
  - The *pion* is the lightest QCD quark system and also has a central role in our understanding of the dynamic generation of mass - *kaon* is the next simplest system containing strangeness



Clearest test case for studies of the transition from non-perturbative to perturbative regions

- Recent advances and future prospects in experiments
  - Dramatically improved precision in F_π measurements
  - 12 GeV JLab: F_π and exclusive meson studies up to highest possible Q^2 and possible F_{K+} extractions



- Form factor data drive renewed activity on theory side
  - Distribution amplitudes – signatures of dynamical chiral symmetry breaking

12 GeV JLab data have the potential to reach the regime in which hard QCD's signatures will be quantitatively revealed

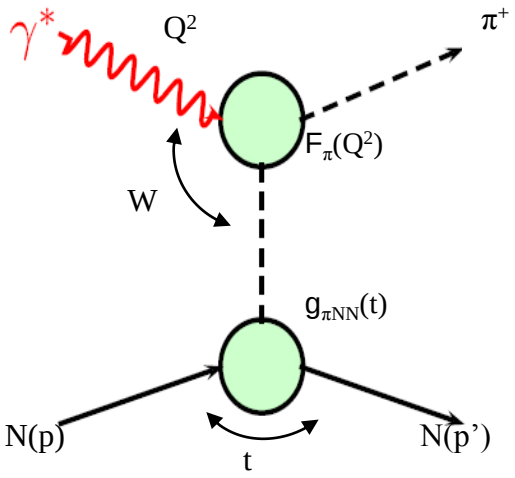
Experimental Determination of the π^+ Form Factor

Through pion electroproduction

- $F_{\pi+}$ measured indirectly using the "pion cloud" of the proton via the *p(e,e'π^+)n process*
  - At small –*t*, the pion pole process dominates the longitudinal cross section, σ_L
  - In the Born term model, F_π^2 appears as

$$\frac{d\sigma_L}{dt} \propto \frac{-t}{(t-m_\pi^2)}\, g_{\pi NN}^2(t)\, Q^2 F_\pi^2(Q^2,t)$$

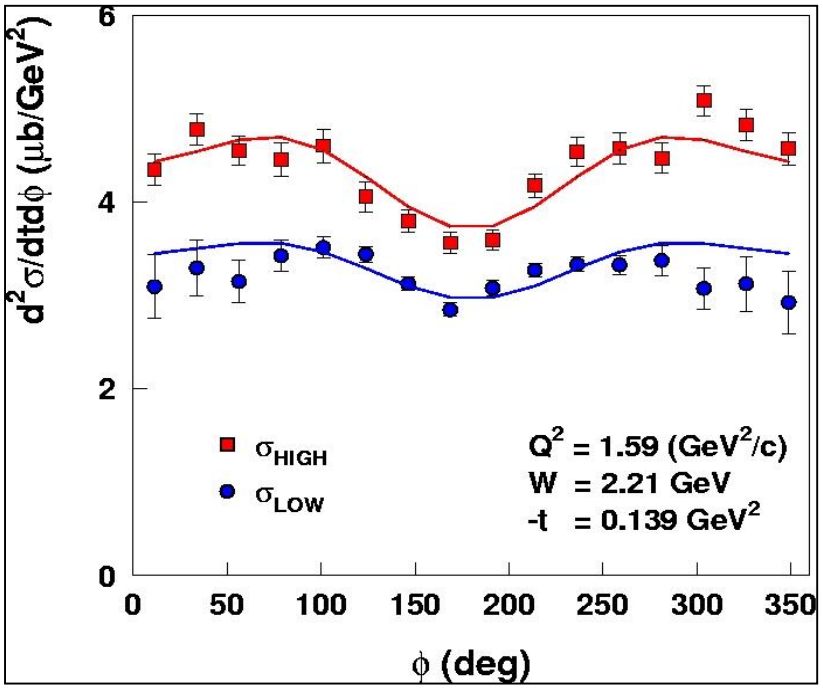
[In practice one uses a more sophisticated model]



- Requirements:
  - Full L/T separation of the cross section – isolation of σ_L
  - Selection of the pion pole process
  - Extraction of the form factor using a model
  - Validation of the technique - model dependent checks

L/T Separation Example

- σ_L is isolated using the Rosenbluth separation technique
  - Measure the cross section at two beam energies and fixed W, Q^2, -t
  - Simultaneous fit using the measured azimuthal angle (ϕ_π) allows for extracting L, T, LT, and TT
- Careful evaluation of the systematic uncertainties is important due to the $1/\varepsilon$ amplification in the σ_L extraction
  - Spectrometer acceptance, kinematics, and efficiencies



$$2\pi\frac{d^2\sigma}{dtd\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

σ_L will give us F_π

- Magnetic spectrometers a must for such precision cross section measurements
  - This is only possible in Hall C at JLab

Extraction of F_π from σ_L JLab data

- JLab 6 GeV F_π experiments used the VGL/Regge model as it has proven to give a reliable description of σ_L across a wide kinematic domain

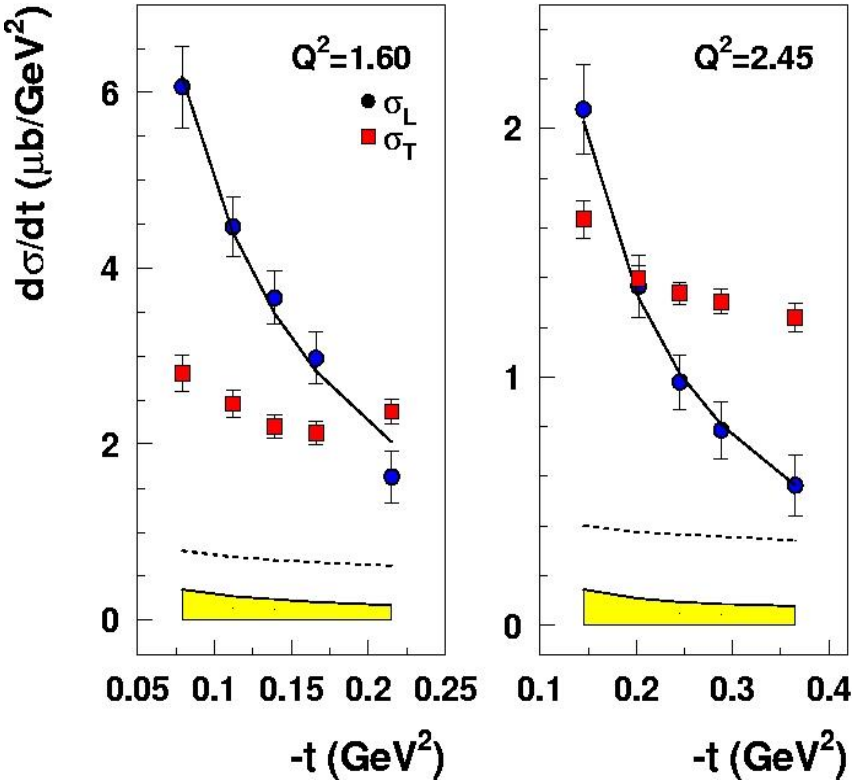
  *[Vanderhaeghen, Guidal, Laget, PRC **57**, (1998) 1454]*

  - Feynman propagator replaced by π and ρ trajectories
  - Model parameters fixed by pion photoproduction data
  - Free parameters: $\Lambda_\pi^2, \Lambda_\rho^2$

$$F_\pi(Q^2) = \frac{1}{1+Q^2/\Lambda_\pi^2}$$

Fit of σ_L to model gives F_π at each Q^2

*[Horn et al., PRL **97**, (2006) 192001]*



$$\Lambda_\pi^2 = 0.513,\ 0.491\ GeV^2$$

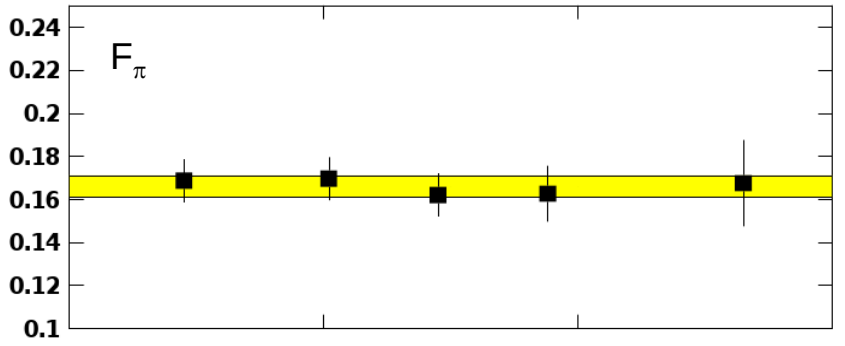
$$\Lambda_\rho^2 = 1.7\ GeV^2$$

Validation: Experimental Considerations

Experimental studies over the last decade have given *confidence* in the electroproduction method yielding the physical pion form factor

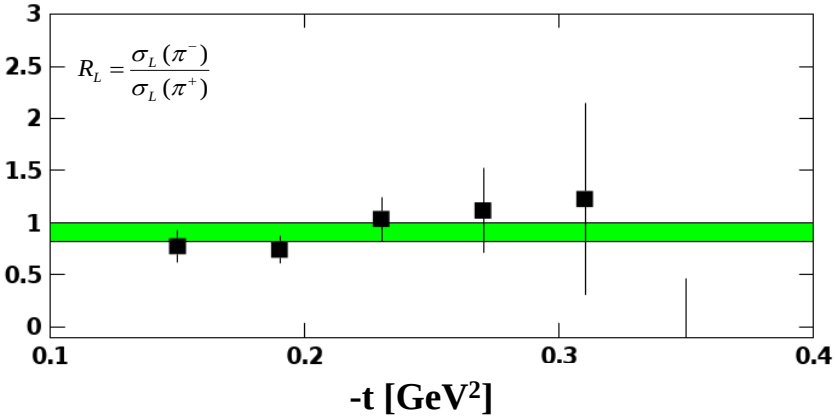
*[T. Horn, C.D. Roberts, J. Phys. G**43** (**2016**) no.7, 073001]*

- Experimental studies include:
  - Check consistency of model with data
    - F_π values do not depend on the t-acceptance – confidence in applicability of model to the kinematic regime of the data



  - Verify that the pion pole diagram is the dominant contribution in the reaction mechanism
    - R_L approaches the pion charge ratio, consistent with pion pole dominance

*[Huber et al, PRL**112** (**2014**)182501]*

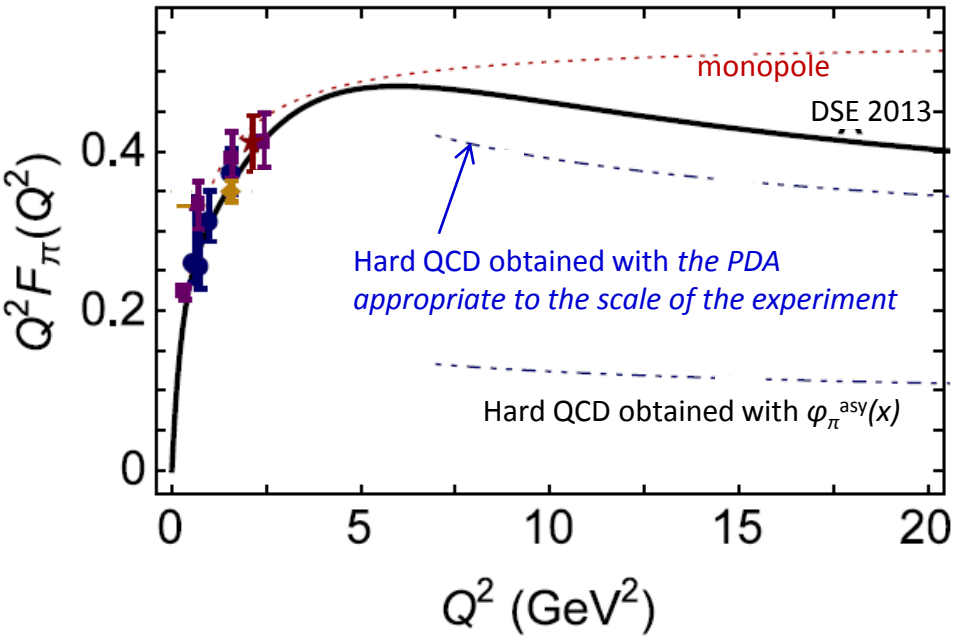


  - Extract F_π at several values of t_{min} for fixed Q^2

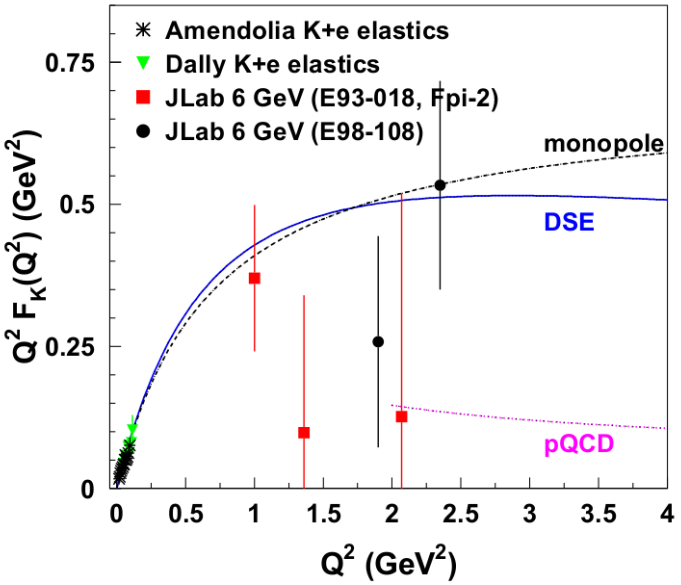
$$R_L = \frac{\sigma(n(e,e'\pi^-)p)}{\sigma(p(e,e'\pi^+)n))} = \frac{|A_v - A_s|^2}{|A_v + A_s|^2}$$

$F_{\pi+}(Q^2)$ and $F_{K+}(Q^2)$ in 2018

$F_{\pi+}(Q^2)$



$F_{K+}(Q^2)$



*[M. Carmignotto et al., Phys. Rev. C**97** (**2018**) no.2, 025204]*

- F*actor ~3* from hard QCD calculation evaluated with asymptotic valence-quark Distribution Amplitude (DA) *[L. Chang, et al., PRL **111** (2013) 141802; PRL **110** (**2013**) 1322001]*
  - Trend consistent with time like meson form factor data up to Q^2=18 GeV^2 *[Seth et al, PRL **110** (2013) 022002]*

- <u>Recent developments</u>: when comparing the hard QCD prediction with a pion valence-quark DA of a form appropriate to the scale accessible in experiments, magnitude is in better agreement with the data

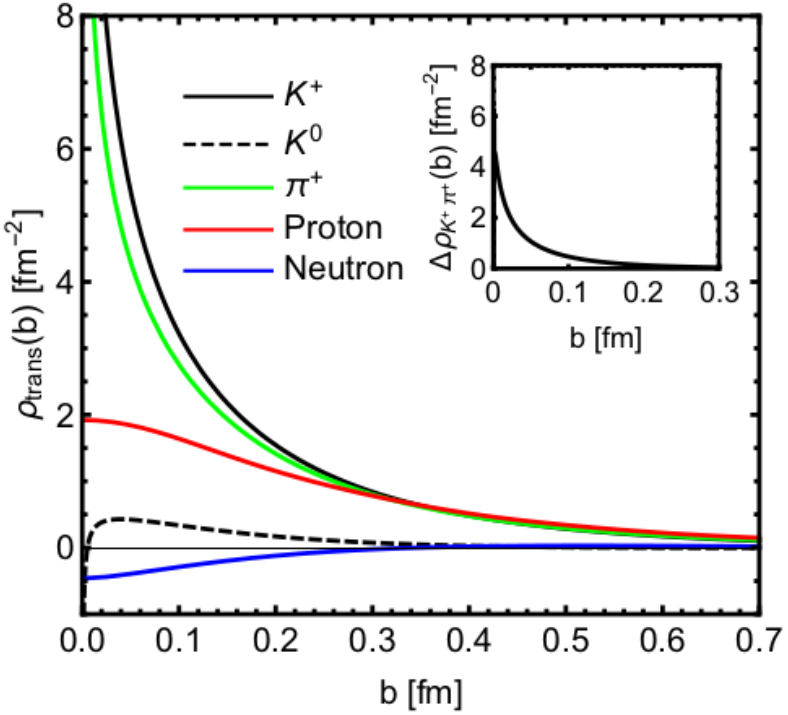
*[I. Cloet, et al., PRL **111** (2013) 092001]*

Pion and Kaon transverse Charge Density

- Transverse charge densities allow interpretation of FFs in terms of physical charge density and are also related to the Generalized Parton Distributions

*[M. Carmignotto et al., Phys. Rev. C**90** 025211 **(2014)**]*

*[N.A. Mecholsky et al., Phys. Rev. C**96** 065207 **(2017)**]*

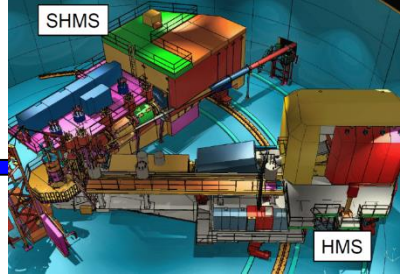


$$\rho_\pi(b) = \frac{1}{\pi R^2}\sum_{n=1}^{\infty} F_\pi(Q_n^2)\frac{J_0(X_n\frac{b}{R})}{[J_1(X_n)]^2} \qquad Q_n \equiv \frac{X_n}{R}$$

- Uncertainty in the analysis dominated by incompleteness error
  - Estimated using the monopole as upper bound and a light front model as lower bound

- ρ_π and ρ_p coalesce for *0.3 fm < b < 0.6 fm; and so does* ρ_K+
- It would be interesting to extract the transverse charge density for different flavors

JLab12: $F_{\pi^+}(Q^2)$ measurements

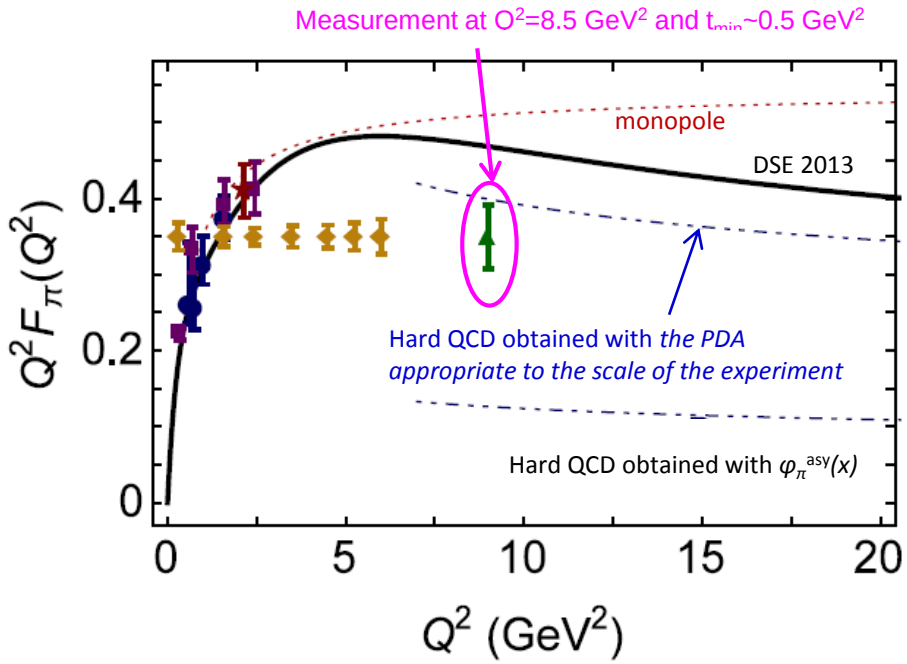


- CEBAF 10.9 GeV electron beam and SHMS small angle capability and controlled systematics are essential for extending precision measurements to higher Q^2

- The JLab 12 GeV π^+ experiments:

  - ***E12-06-101***: determine F_π up to Q^2=6 GeV^2 in a dedicated experiment
    - Approved for 52 PAC days with "A" rating, high impact

    *E12-**06**-101 spokespersons: G. Huber, D. Gaskell*



  - ***E12-07-105***: probe conditions for factorization of deep exclusive measurements in π^+ data to highest possible Q^2~9 GeV^2 with SHMS/HMS
    - Potential to extract F_π to the highest Q^2~9 GeV^2 achievable at Jlab 12 GeV
    - Approved for 40 PAC days with "A-" rating

    *E12-**07**-105 spokespersons: T. Horn, G. Huber*

JLab12: Opportunities for $F_{K^+}(Q^2)$ Measurements

- Possible K^+ form factor extraction to highest possible Q^2 achievable at JLab

- Extraction like in the pion case by studying the model dependence at small t
- Comparative extractions of F_π at small and larger t show only modest model dependence
  - larger t data lie at a similar distance from pole as kaon data

- Recent theoretical efforts to understand role of the strange quark

*[F. Gao et al., Phys. Rev. D 96 (**2017**) no. 3, 034024]*

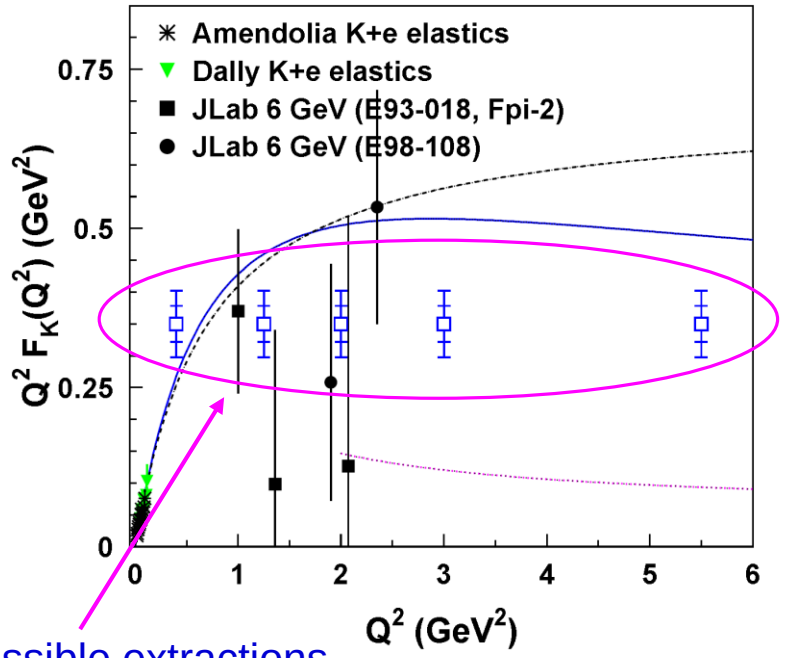
*[P.T.P. Hutauruk et al., Phys. Rev. C **94 (2016)** 035201]*

*[C. Chen et al., Phys. Rev. D **93 (2016)** no. 7, 074021]*

*[S-S Xu et al., arXiv:1802.09552 (**2018**)]*

*[T. Horn, C.D. Roberts, J. Phys. G**43 (2016)** no.7, 073001]*

*[M. Carmignotto et al., Phys. Rev. C**97 (2018)** no.2, 025204]*



Possible extractions from 2018/19 run

Exploring the 3D Nucleon Structure

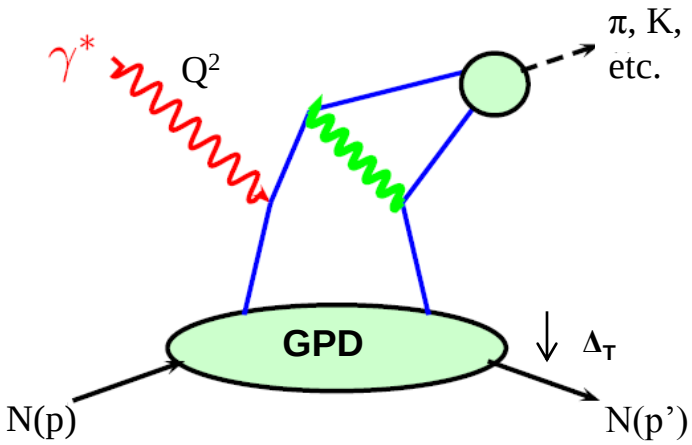
- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction (x_{Bj}) picture of the nucleon.
    - High luminosity, large acceptance experiments with polarized beams and targets.
    - Theoretical description of the nucleon in terms of a 5D Wigner distribution that can be used to encode both 3D momentum and transverse spatial distributions.

- Deep Exclusive Scattering (DES) cross sections give sensitivity to electron-quark scattering off quarks with longitudinal momentum fraction (Bjorken) x at a transverse location b.

- Semi-Inclusive Deep Inelastic Scattering (SIDIS) cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum (k_T) of a parton and transverse momentum (p_T) created during the [parton → hadron] fragmentation process.

Towards GPD spin-flavor separation: DVMP

- Relative contribution of σ_L and σ_T to cross section are of great interest for nucleon structure studies



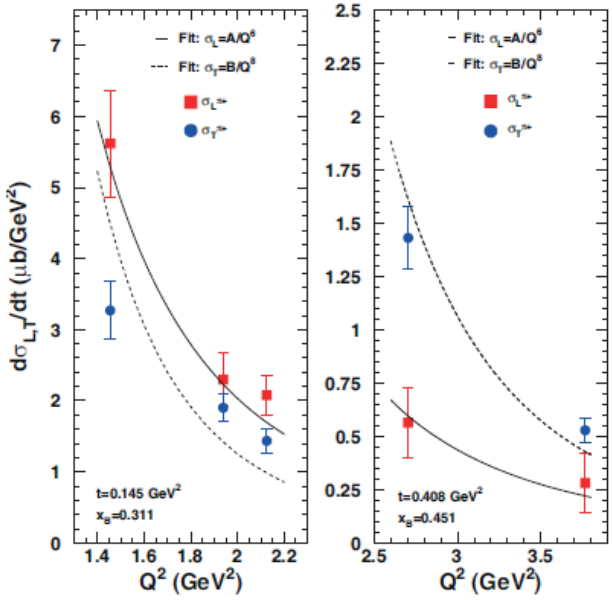
- described by 4 (helicity non-flip) GPDs:
  - *H, E* (unpolarized), $\tilde{H}, \tilde{E}$ (polarized)
- Quantum numbers in DVMP probe individual GPD components selectively
  - Vector : $\rho^o/\rho+/K^*$ select *H, E*
  - **Pseudoscalar: π,η,K select the polarized GPDs, $\tilde{H}$ and $\tilde{E}$**
- Reaction mechanism can be verified experimentally - **L/T separated cross sections to test QCD Factorization**

- Recent calculations suggest that leading-twist behavior for light mesons may be reached at Q^2=5-10 GeV^2
- JLab 12 GeV can provide experimental confirmation in the few GeV regime

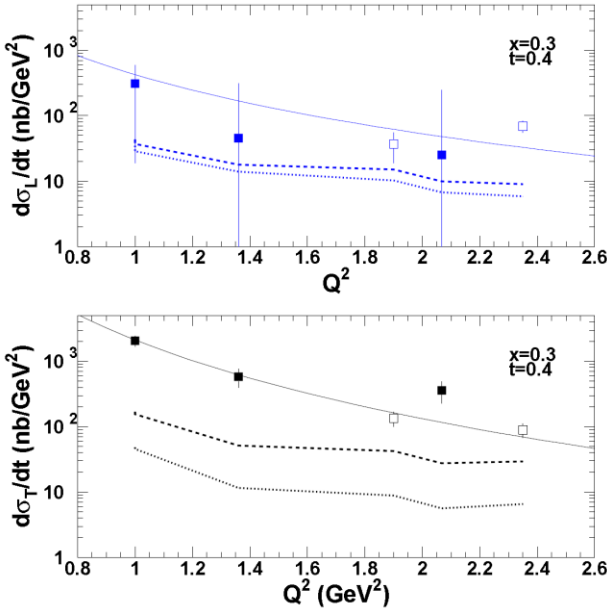
Results from 6 GeV JLab

- Data demonstrate the technique of measuring the Q^2 dependence of L/T separated cross sections at fixed x/t to test QCD Factorization
  - Consistent with expected factorization, but small lever arm and relatively large uncertainties
  - GPD models cannot reproduce ρ^0 data at small W

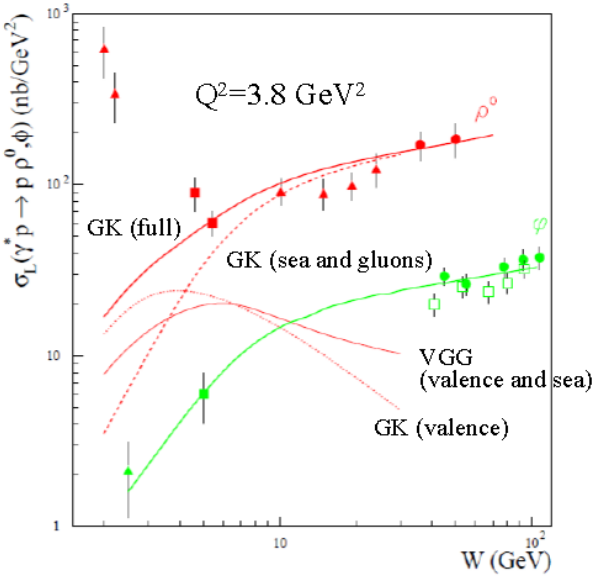
π^+ *[T. Horn et al., Phys. Rev. C **78**, 058201 **(2008)**]*



K^+ *[M. Carmignotto et al., Phys. Rev. C**97** (2018) no.2, 025204]*



ρ^0

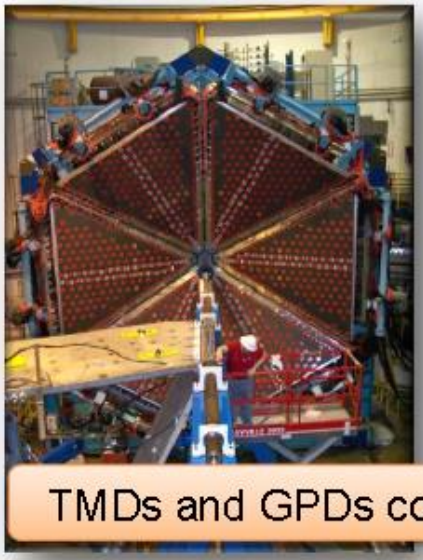


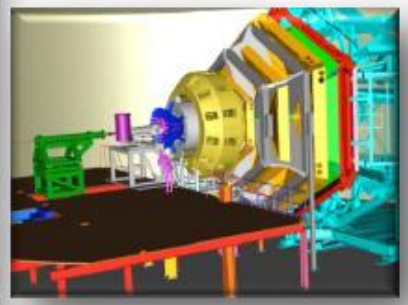
[L. Favart, M. Guidal, T. Horn, P. Kroll, Eur. Phys. J A 52 (2016) no.6, 158]

- Separated cross sections over a large range in Q^2 are essential for:
  - Testing factorization and understanding dynamical effects in both Q^2 and –t kinematics
  - Interpretation of non-perturbative contributions in experimentally accessible kinematics

12 GeV (GPD/TMD) Scientific Capabilities

Hall B – understanding nucleon structure via generalized parton distributions

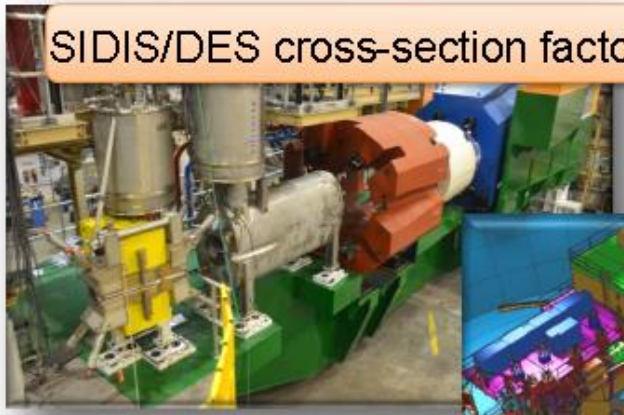


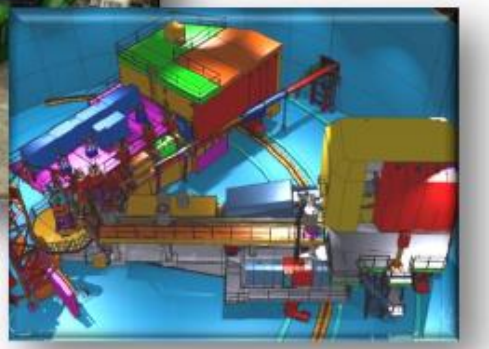


TMDs and GPDs comprehensive study

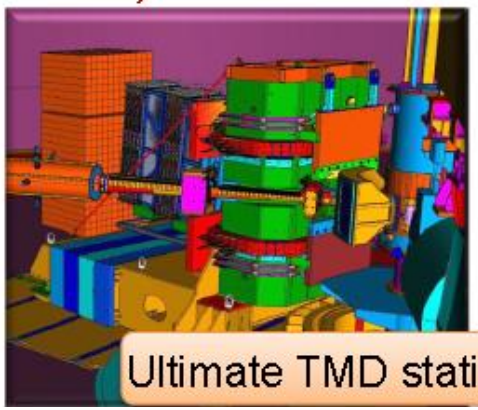
Hall C – precision determination of valence quark properties in nucleons/nuclei

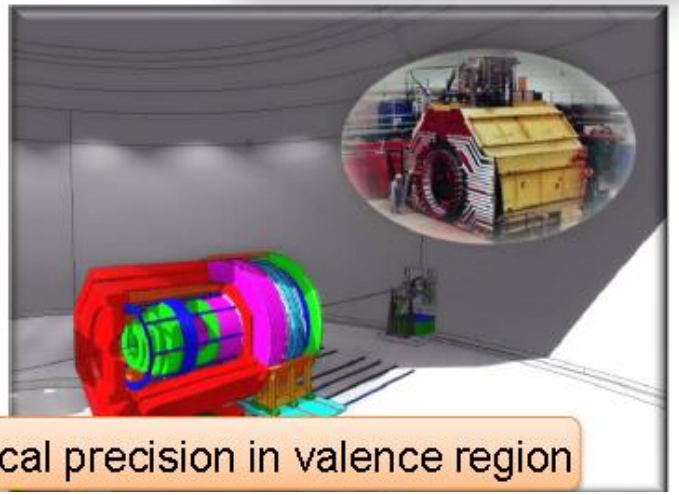
SIDIS/DES cross-section factorization tests





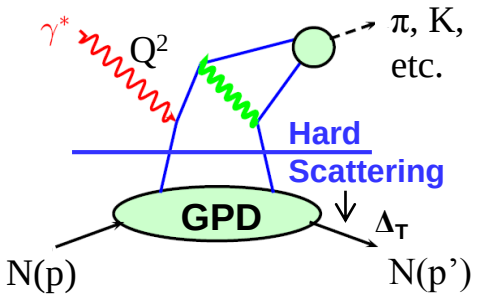
Hall A – polarized 3He, future new experiments (e.g., SBS, MOLLER and SoLID)

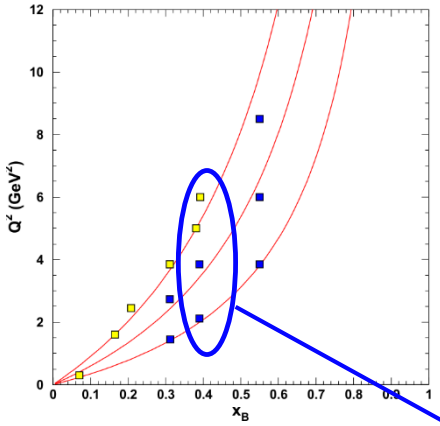


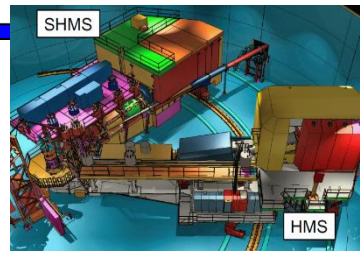


Ultimate TMD statistical precision in valence region

JLab12: confirming potential for nucleon structure studies with pion production





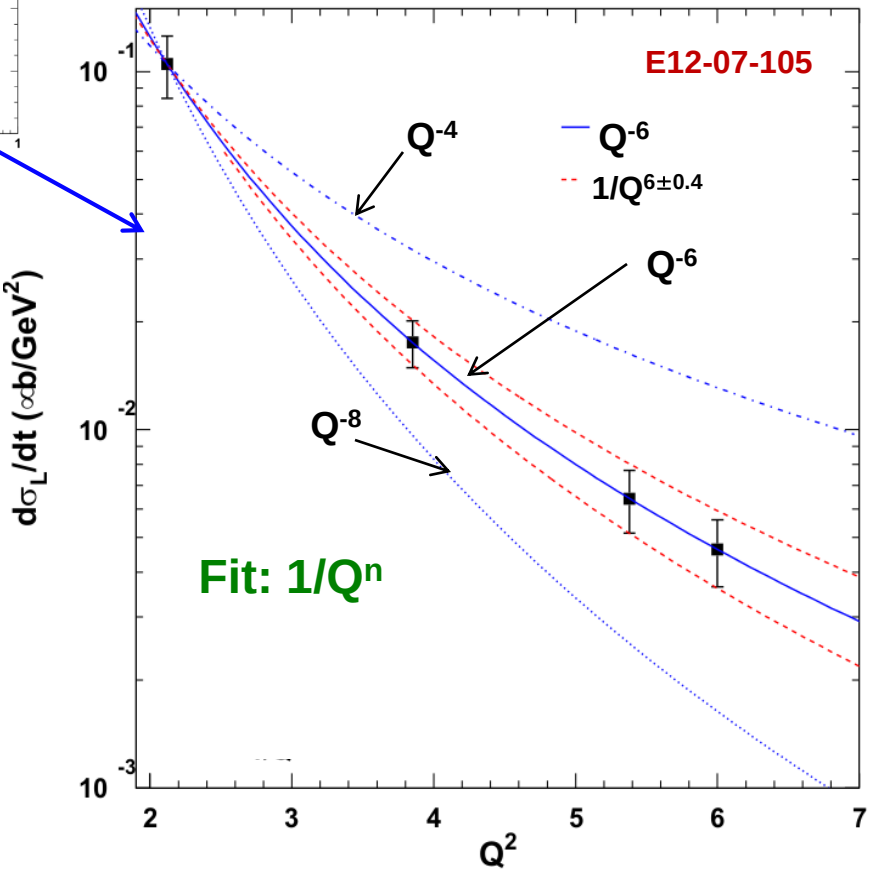


*E12-**07**-105 spokespersons: T. Horn, G. Huber*

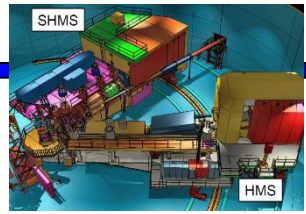
- **E12-07-105 (P12):** Measure the Q^2 dependence of the π electro production cross section at fixed x and -t
  - Factorisation theorem predicts σ_L scales to leading order as Q^{-6}

x	Q^2 (GeV^2)	W (GeV)	-t $(GeV/c)^2$
0.3	1.5-2.7	2.0-2.6	0.1
0.4	2.1-6.0	2.0-3.2	0.2
0.5	3.9-8.5	2.0-2.8	0.5

Considered for running **in 2019**



JLab12: confirming potential for nucleon structure studies with kaon production



- **E12-09-011**: Separated L/T/LT/TT cross section over a wide range of Q^2 and t

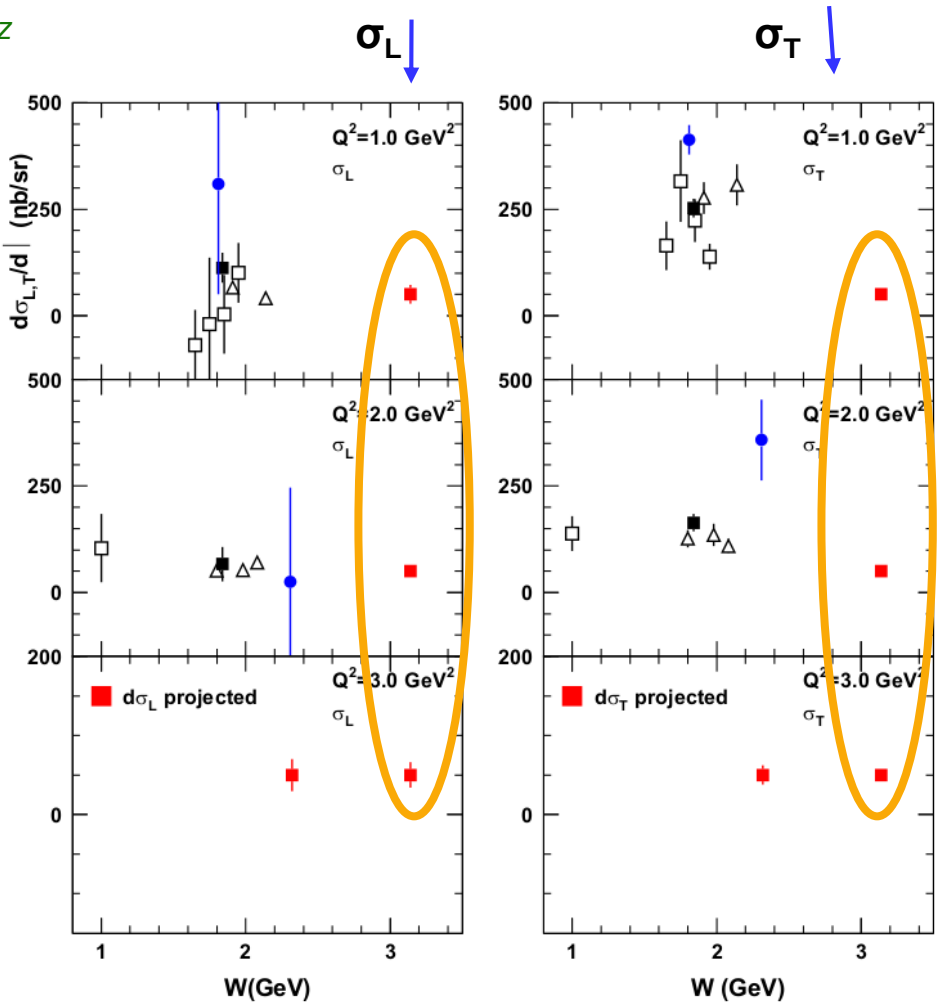
*E12-**09**-011 spokespersons: T. Horn, G. Huber, P. Markowitz*

JLab 12 GeV Kaon Program features:

- First cross section data for Q^2 scaling tests with kaons
- Highest Q^2 for L/T separated kaon electroproduction cross section
- First separated kaon cross section measurement above W=2.2 GeV

approved for 40 PAC days and **scheduled to run in 2018/19**

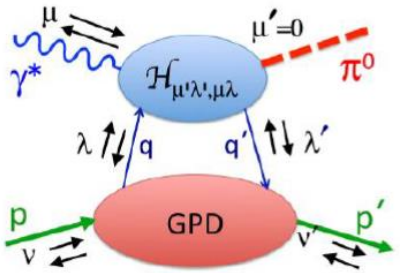
x	Q^2 (GeV^2)	W (GeV)	-t $(GeV/c)^2$
0.1-0.2	0.4-3.0	2.5-3.1	0.06-0.2
0.25	1.7-3.5	2.5-3.4	0.2
0.40	3.0-5.5	2.3-3.0	0.5



*[blue points from M. Carmignotto, PhD thesis **(2017)**]*

Transverse Contributions may allow for probing a new set of GPDs

- 4 Chiral-odd GPDs (parton helicity flip)



$$\tilde{H}^{\pi} = \frac{1}{3\sqrt{2}}\left[2\tilde{H}^{u} + \tilde{H}^{d}\right]$$

- A large transverse cross section in meson production may allow for accessing helicity flip GPDs

$$\sigma_T = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}\left[(1-\xi^2)|< HT >|^2 - \frac{t'}{8m^2}|< \overline{E_T} >|^2\right]$$

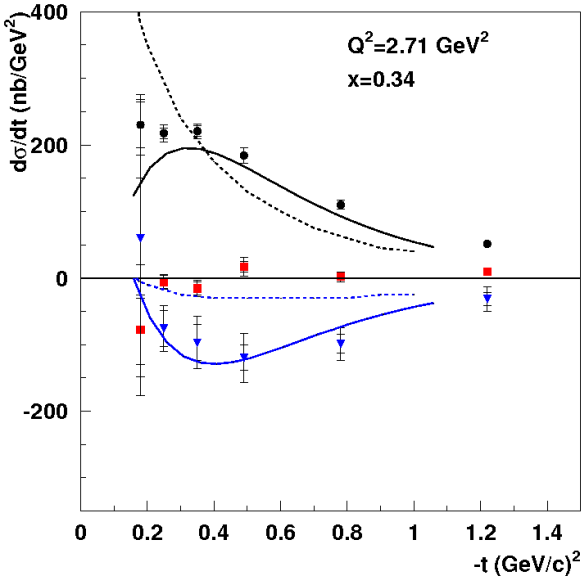
- Model predictions based on handbag in good agreement with 6 GeV data

  *[Goloskokov, Kroll, EPJ C65, 137 (2010); EPJ A**45**, 112 (**2011**)]*

  *[Goldstein, Gonzalez Hernandez, Liuti, J. Phys. G **39 (2012)** 115001]*

  *[Ahmad, Goldstein, Liuti, PRD **79 (2009)**]*

- JLab 12 GeV will provide relative σ_L and σ_T contributions to the π^0 cross section up Q^2~6 GeV^2 to verify reaction mechanism

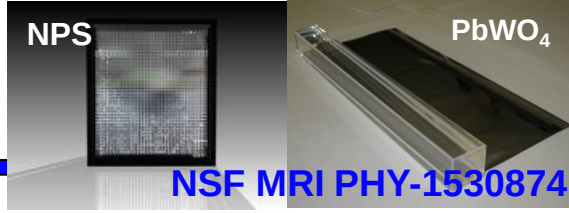


*[Favart, Guidal, Horn, Kroll , EPJA (**2016**)]*

*[Bedlinskiy et al. PRL 109 (**2012**) 112001]*

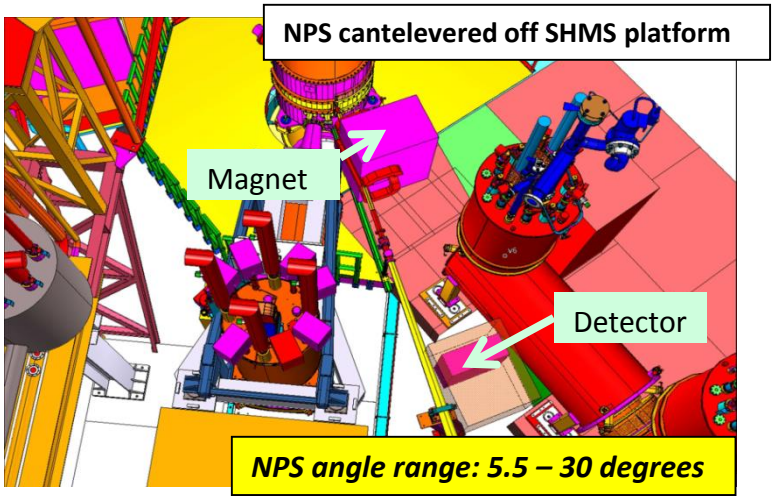
- Exclusive π^o data may also be helpful for constraining non-pole contributions in F_π extraction

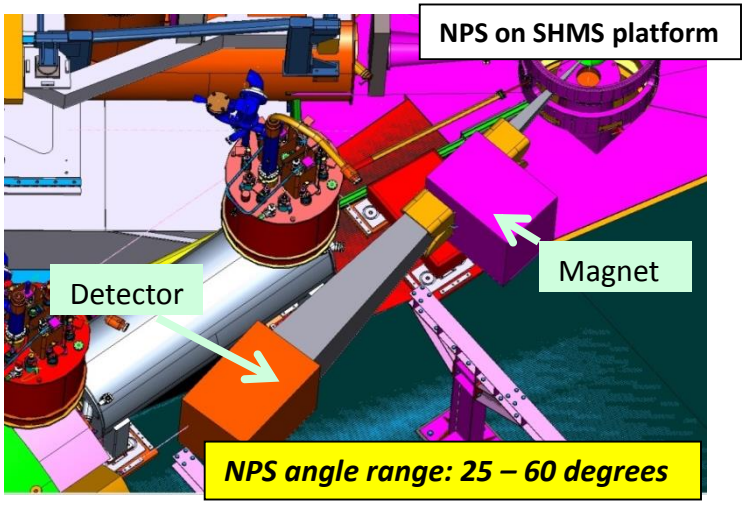
New Opportunities with the Neutral Particle Spectrometer (NPS)



NSF MRI PHY-1530874

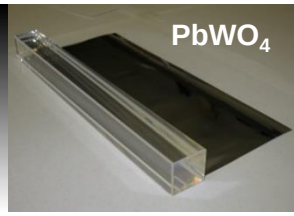
- The NPS is envisioned as a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ and π^0).





- Approved experiments to date
  - E12-13-010 – Exclusive Deeply Virtual Compton and π^0 Cross Section Measurements in Hall C
  - E12-13-007: Measurement of Semi-inclusive π^0 production as Validation of Factorization
  - 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
  - E12-17-008 – Polarization Observables in Wide-Angle Compton Scattering (cond. approved)
- Ideas exist for future experiments (e.g., TCS with transverse target)

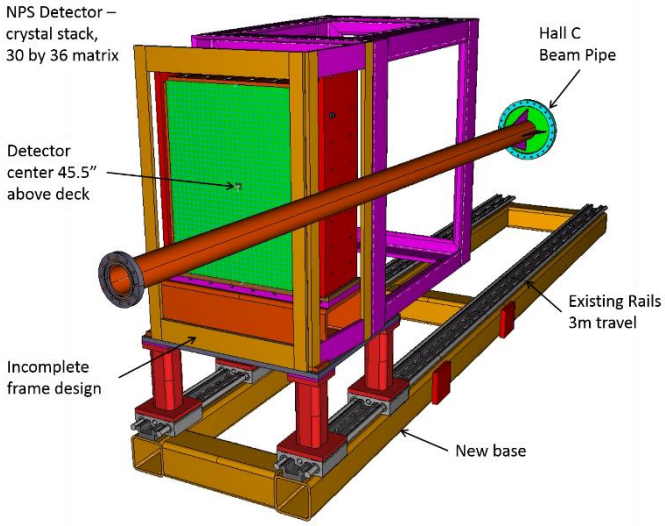
NPS Project Status



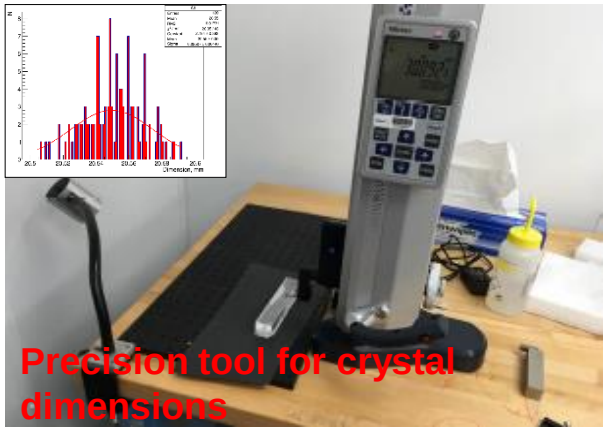
Four fully approved experiments, supported by NSF MRI PHY-1530874 (CUA, OU, ODU), international (IPN-Orsay, Glasgow, Yerevan), and JLab

Main coil before shipping

- Magnet: corrector and main coil construction complete, corrector coil is in test lab, yoke steel cutting nearly final, setting up space in test lab for assembly

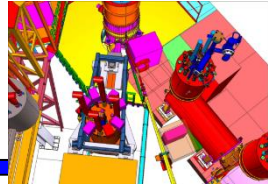


- PMT and HV bases: design drawings final, prototyping, procurement started, first articles received
- Frame and integrated systems: concepts and initial design complete, detailed drawings to be presented later this year, prototype tests ongoing

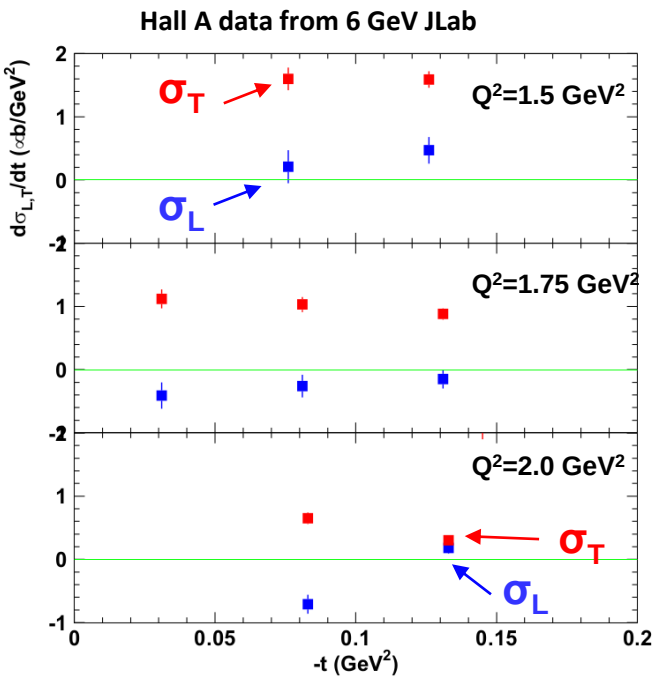

Precision tool for crystal dimensions

- Crystals: 460 crystals procured from SICCAS, plan to procure few 100 from Crytur, full crystal testing facilities at CUA and IPN-Orsay, chemical analysis and crystal growth in collaboration with the Vitreous State Laboratory (VSL), synergy with EIC crystal calorimeter R&D

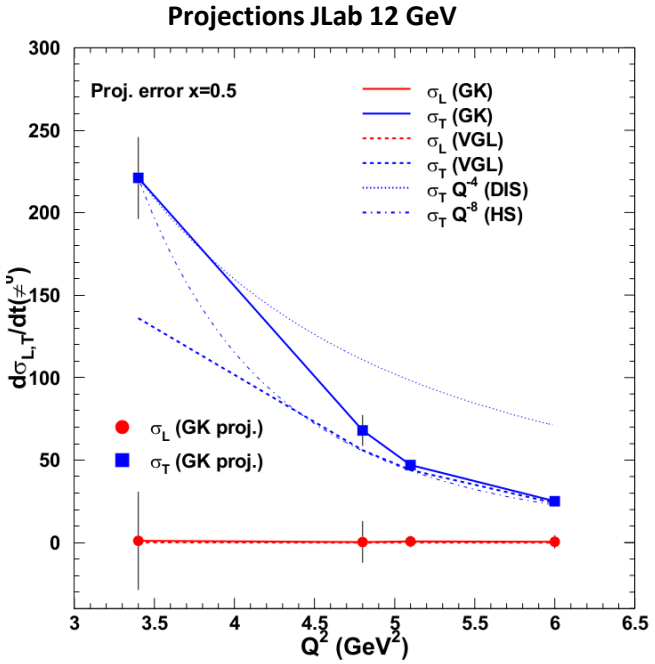
E12-13-010: Exclusive π^0 cross section



- Relative L/T contribution to π^0 cross section important in probing transversity
  - If σ_T large: access to transversity GPDs
- Results from Hall A suggest that σ_L in π^0 production is non-zero up to Q^2=2 GeV^2
- Need to understand Q^2/t dependence for final conclusion on dominance of σ_T



E12-13-010 projections

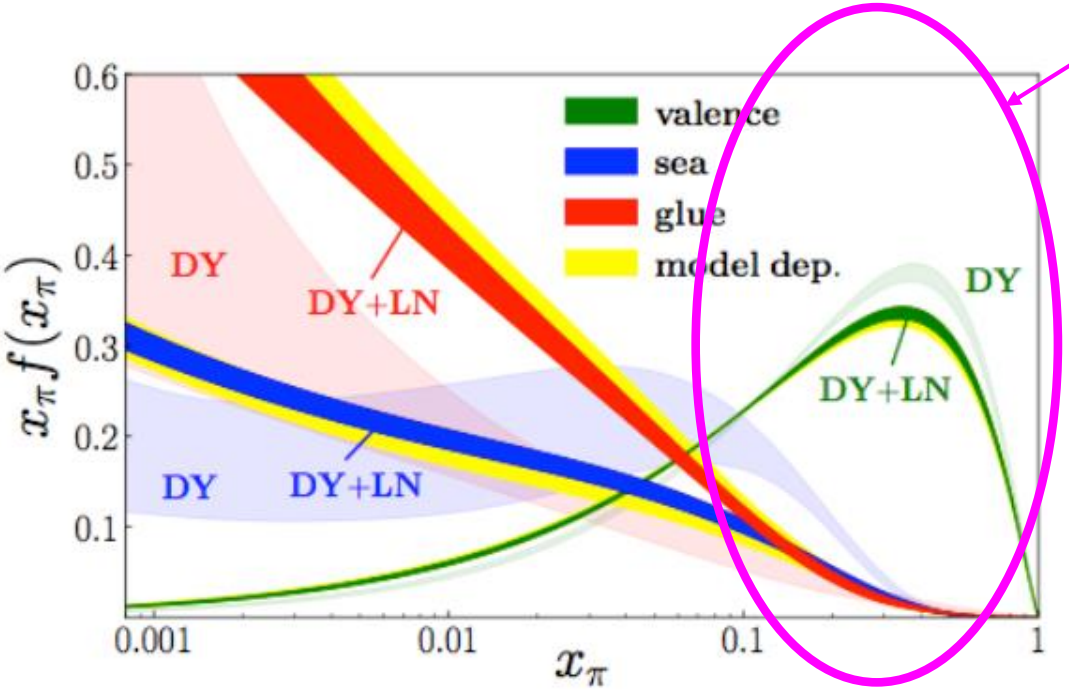


*M. Defurne et al, PRL **117** (**2016**) no.26, 262001*

E12-13-010 will provide essential data on σ_T and σ_L at higher Q^2 for reliable interpretation of 12 GeV GPD data

Meson Structure Functions

- First MC global QCD analysis of pion PDFs
  - Using Fermilab DY and HERA Leading Neutron data



- JLab 12 GeV: Tagged Pion and Kaon TDIS
- Also prospects for kaon DY at COMPASS and pion and kaon LN at EIC

DY = πN Drell-Yan

LN = Leading Neutron

Barry, Sato, Melnitchouk, Ji (2018, to appear)

- Significant reduction of uncertainties on sea quark and gluon distributions in the pion with inclusion of HERA leading neutron data
- Implications for "TDIS" (Tagged DIS) experiments at JLab

Summary and Outlook

- Meson form factors and structure functions play an important role in our understanding of hadrons

- JLab 12 GeV will dramatically improve the light meson data set
  - Pion and kaon form factor extractions up to high Q^2 possible (~9 and ~6 GeV^2)
  - L/T separated cross sections to validate applicability of hard-soft factorization – may allow for accessing new type of GPDs
  - The Neutral Particle Spectrometer gives unique opportunity for coincidence precision cross section measurements with neutral particles
  - Pion and kaon large-x structure functions through Tagged DIS – beyond 12 GeV, also prospects for kaon DY at COMPASS and pion and kaon structure function measurements at EIC

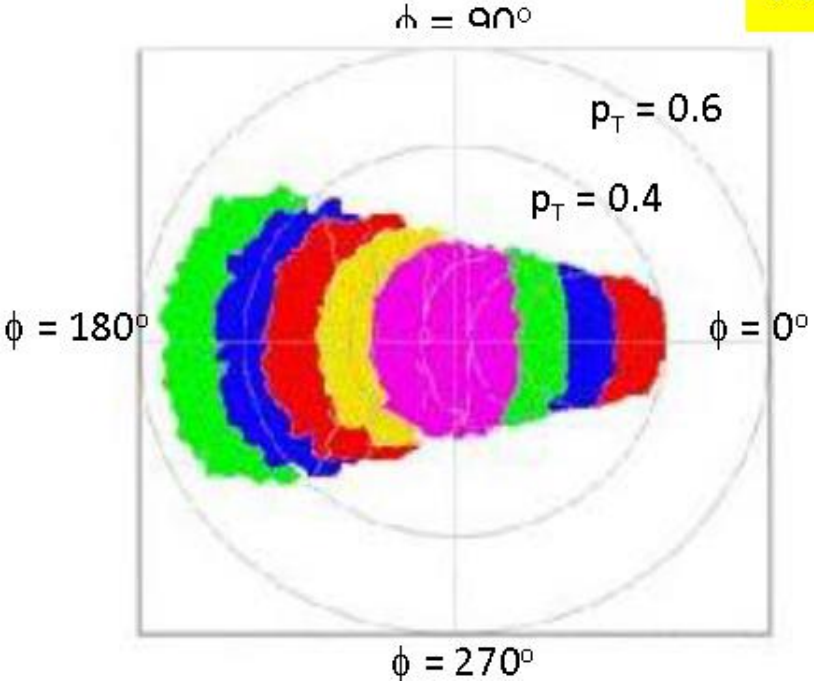
HMS + SHMS: P_T coverage

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

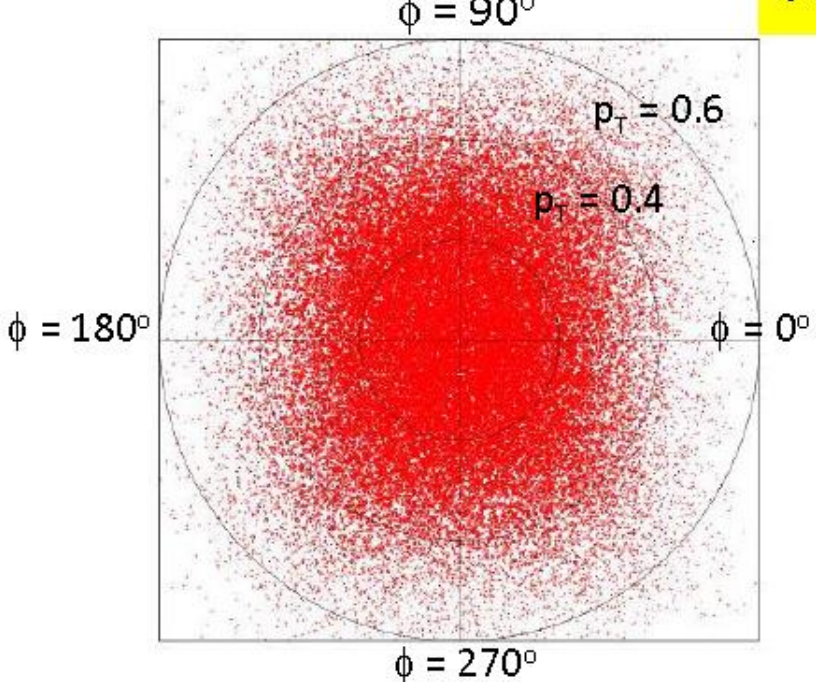
E12-13-007

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



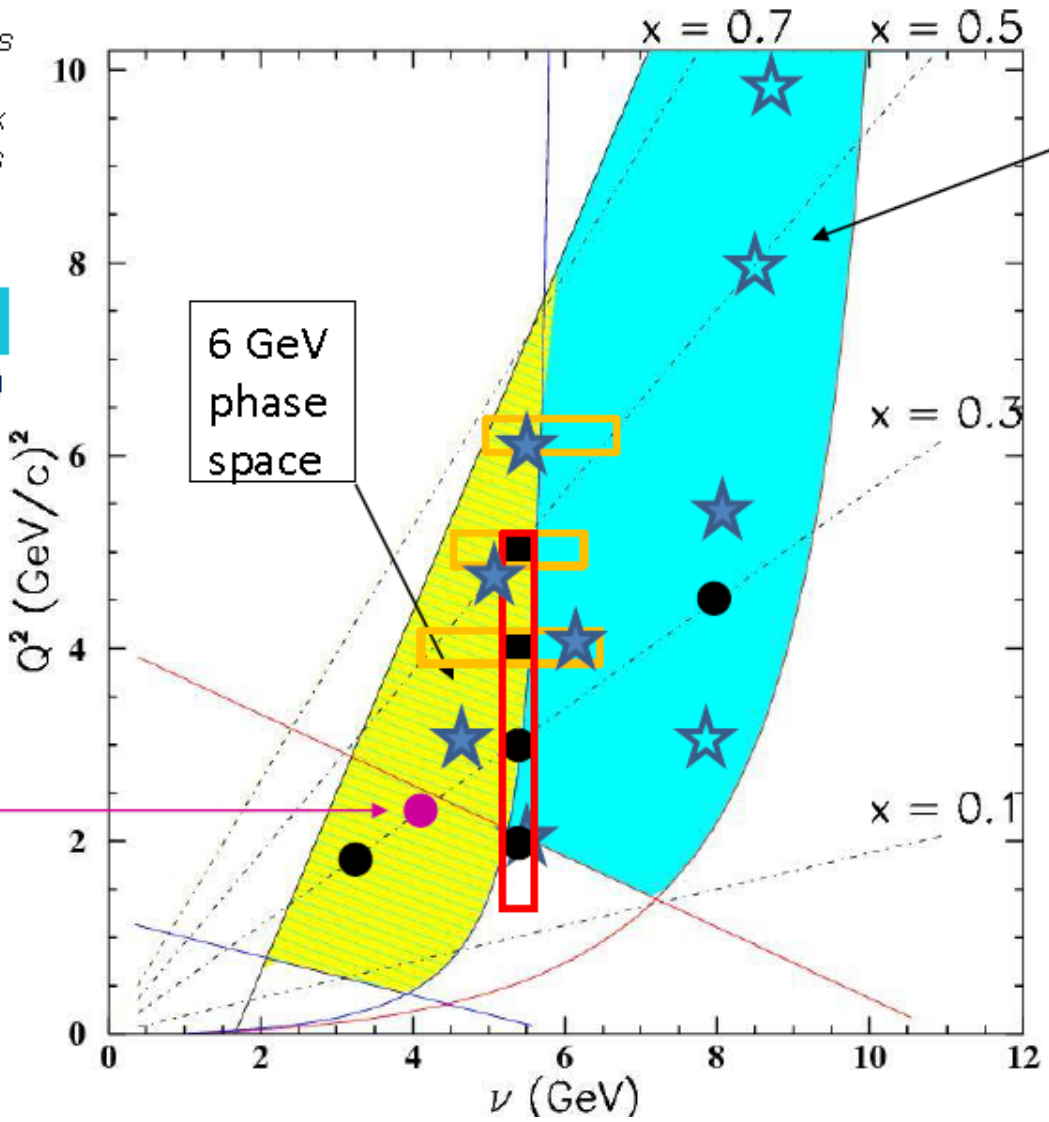
Hall C SIDIS Program (typ. x/Q^2 ~ constant)

HMS + SHMS (or NPS) Accessible Phase Space for SIDIS; w. typical z range 0.3-0.65

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)



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