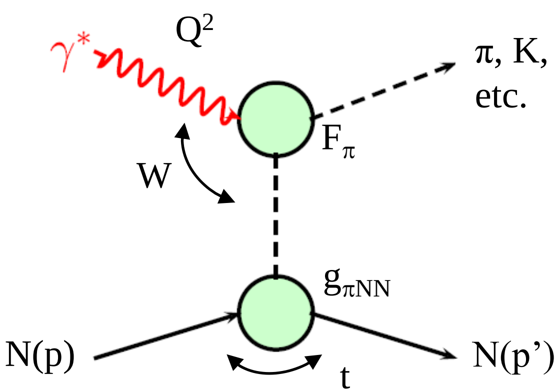
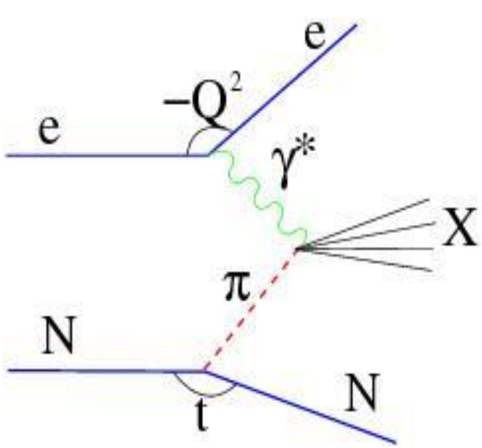
Studies of Meson Structure





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Thomas Jefferson National Accelerator Facility

Diquark Correlations in Hadron Physics

ECT*, Trento, Italy, 22-27 September 2019

Outline

- Accessing meson form factors through the Sullivan Process
  - Extraction from data and validation of the technique
  - $F_{\pi+}$ and F_{K+} up to Q^2 ~9 and ~6 GeV^2

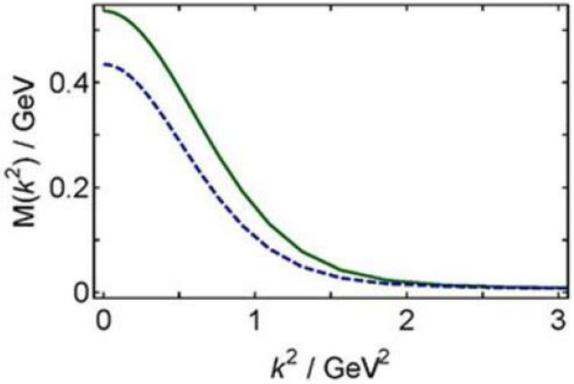
- Towards GPD flavor decomposition
  - Q^2 dependence of L/T separated π+/K+ cross sections
  - Opportunities with neutrals: L/T separated π^0 cross sections with the NPS

- Accessing meson structure functions through the Sullivan process
  - JLab TDIS experiments
  - Opportunities at the EIC

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

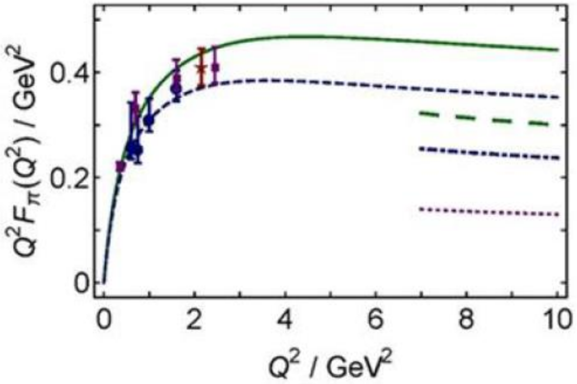
A.C. Aguilar et al., ***arXiv:1907.08218*** *(2019)*



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 data have the potential to quantitatively reveal hard QCD's signatures



- ❑ Form factor data and measurements go hand-in-hand with activities on theory side, e.g.

Distribution amplitudes – normalization fixed by pion wave function whose dilation from conformal limit is a signature of DCSB

(Pseudo)Meson Production Data Evolution

Experiment

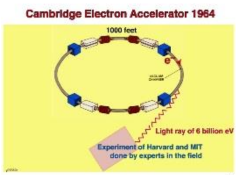
Capability to reliably access large Q^2 regime

Jefferson Lab

JLab 6 GeV

JLab 12 GeV

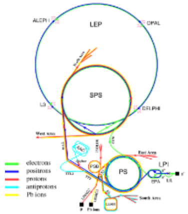
EIC



1959 1971 1976 1979 1981 1984 1986 1997 2003 2004 2017+ 2025+

Cornell University

Fermilab



Theory

- Accessing the form factor through electroproduction
- Extraction of meson form factor from data
- Electroproduction formalism

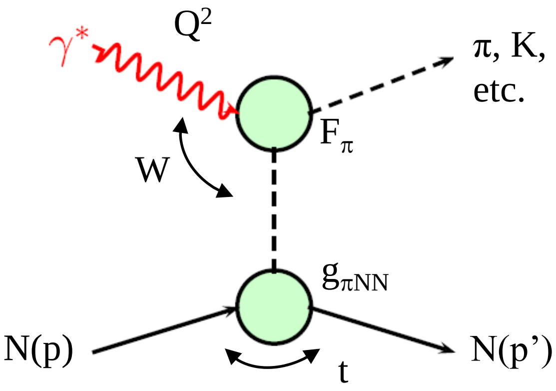
Theory/Lattice/Global Fitting

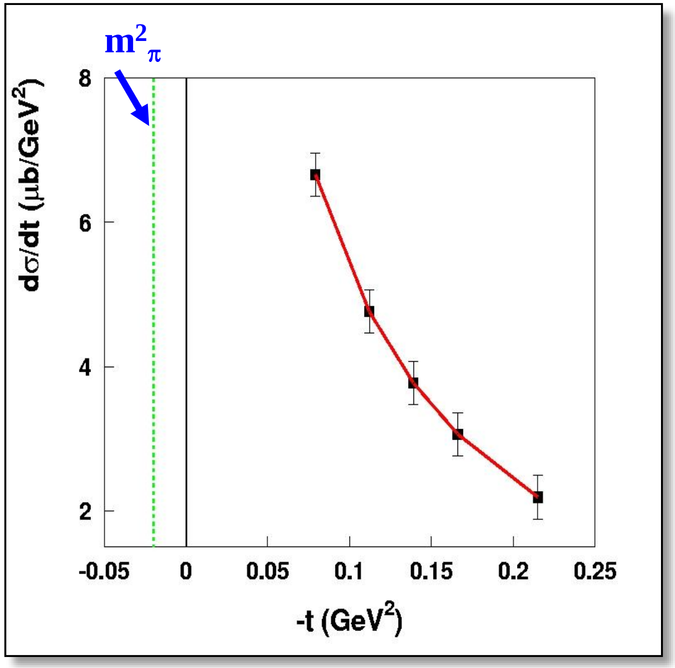
Major progress on hadron structure calculations (also lattice and global fitting), e.g. large Q^2 behavior of meson form factor

Accessing meson form factors through the Sullivan Process

- $F_{\pi+}$ must be measured indirectly using the "pion cloud" of the proton in exclusive pion electroproduction: *p(e,e'π^+)n* – ***L/T separations***

- *Select pion pole process:* at small –*t* pole process dominates the longitudinal cross section, σ_L





- *Isolate* σ_L - in the Born term model, F_π^2 appears as

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

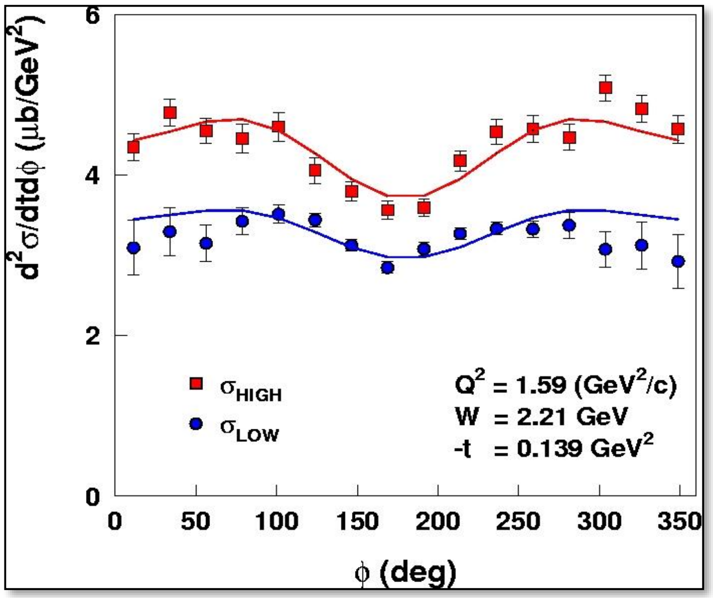
[In practice one uses a more sophisticated model]

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/ε amplification in the σ_L extraction
  - Spectrometer acceptance, kinematics, and efficiencies

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



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

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

Using a model to extract of F_π from σ_L JLab data

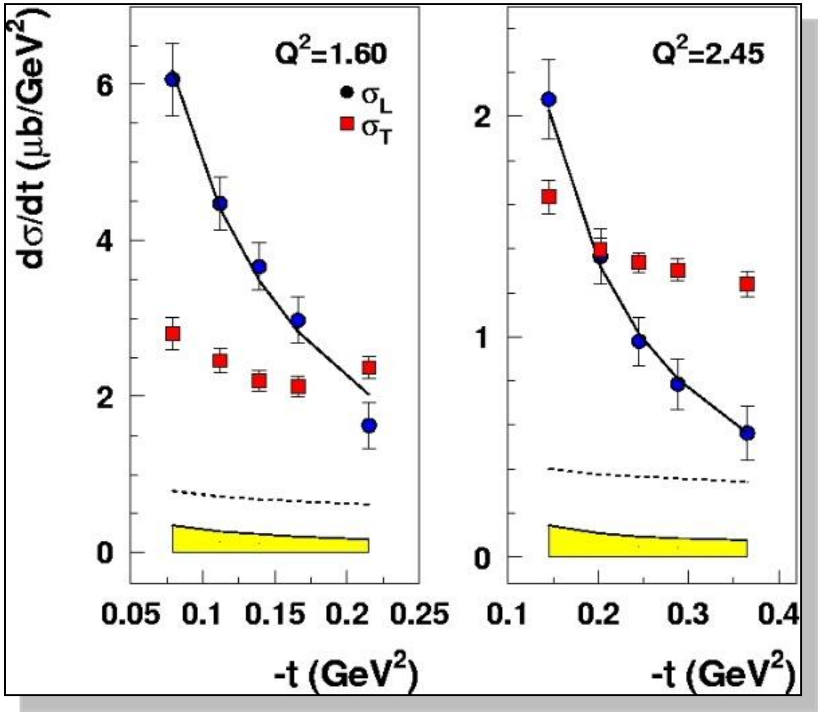
[Horn et al., PRL **97**, (2006) 192001]

- 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]

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

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



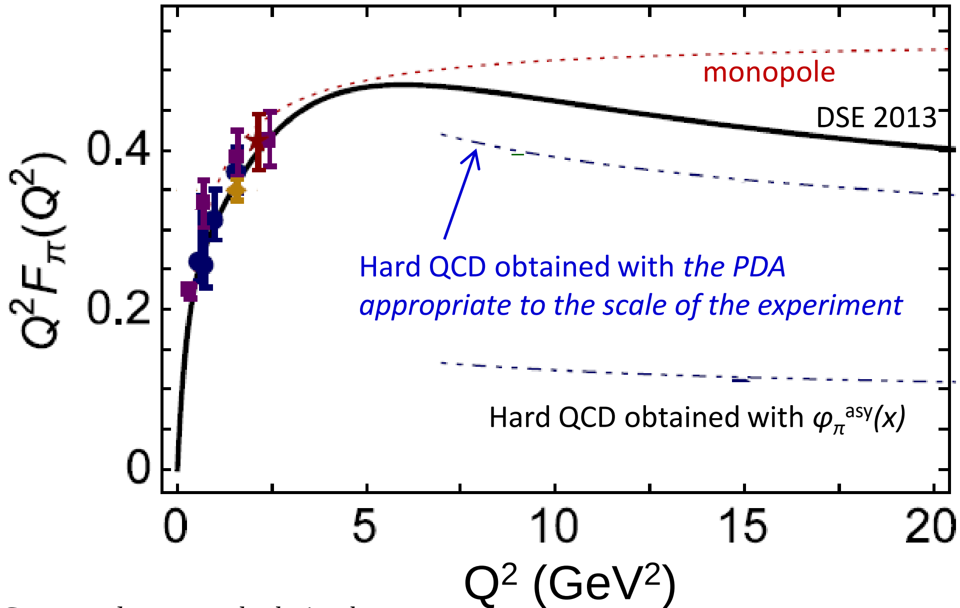
$$\Lambda_\pi^2 = 0.513,\ 0.491\ GeV^2$$

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

- Separated L/T cross sections will be published, so F_π can be extracted using other models as they become available, e.g. *R. J. Perry et al., Phys. Rev. C **100** (**2019**) no. 2, 025206*

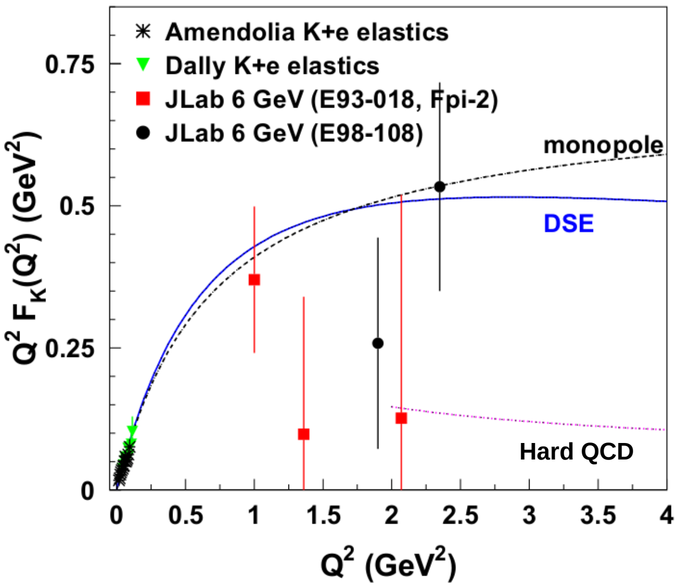
$F_{\pi^+}(Q^2)$ and $F_{K^+}(Q^2)$ in 2019

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



Compared to one calculation here – there are others, e.g.Braun et al.

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



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

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

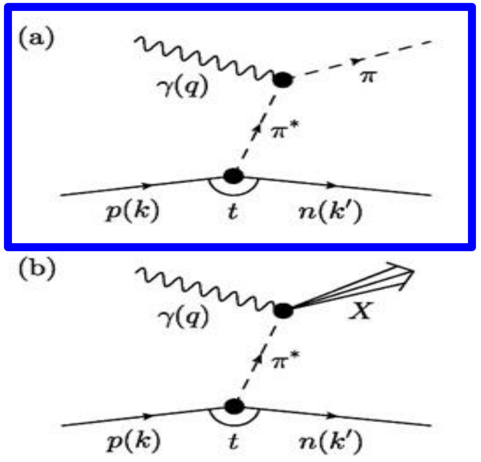
- F*actor ~3* from hard QCD calculation evaluated with asymptotic valence-quark Distribution Amplitude (DA) *[L. Chang, et al., PRL **111** (2013) 141802; PRL **110** (**2013**) 1322001]*
  - Trend consistent with time like meson form factor data up to Q^2=18 GeV^2

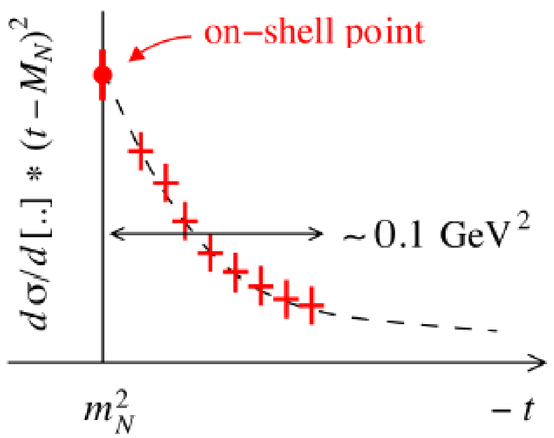
- Recent developments: when comparing the hard QCD prediction with a pion valence-quark DA of a form appropriate to the scale accessible in experiments, magnitude is in better agreement with the data

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

Accessing meson structure through the Sullivan Process

- The **Sullivan process can provide reliable access to a meson target** as *t* becomes space-like if the pole associated with the ground-state meson is the dominant feature of the process and the structure of the (off-shell) meson evolves slowly and smoothly with virtuality.





- To **check these conditions** are satisfied empirically, one can **take data covering a range in *t*** and compare with phenomenological and theoretical expectations.

- Recent **theoretical calculations found that for -t ≤ 0.6 GeV^2**, **changes in pion structure do evolve slowly** so that a well-constrained experimental analysis should be reliable, and the Sullivan processes can provide a valid pion target.
- Also **progress with elastic form factors – experimental validation**

Off-shellness considerations

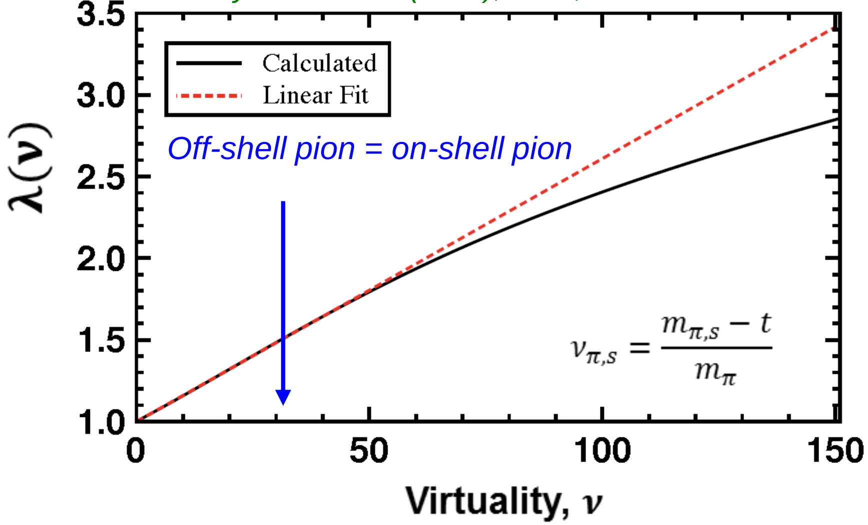
In the Sullivan process, the mesons in the nucleon cloud are virtual (off-shell) particles

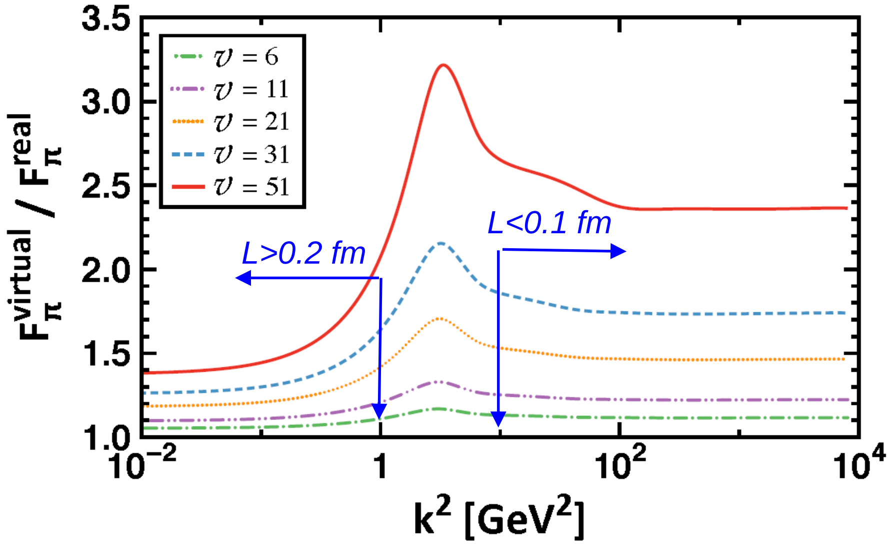
- ❑ Recent calculations estimate the effect in the BSE/DSE framework – **as long as $\lambda(\nu)$ is linear in ν the meson pole dominates**
  - ○ Within the linearity domain, alterations of the meson internal structure can be analyzed through the amplitude ratio

- ❑ ***Off-shell meson = On-shell meson*** **for t<0.6 GeV^2 (ν =30) for pions and t<0.9 GeV^2 (ν_s~3) for kaons**

This means that pion and kaon structure can be accessed through the Sullivan process

*S-X Qin, C.Chen, C. Mezrag, C.D. Roberts, Phys. Rev. C**97** (2018), no. 1, 015203*





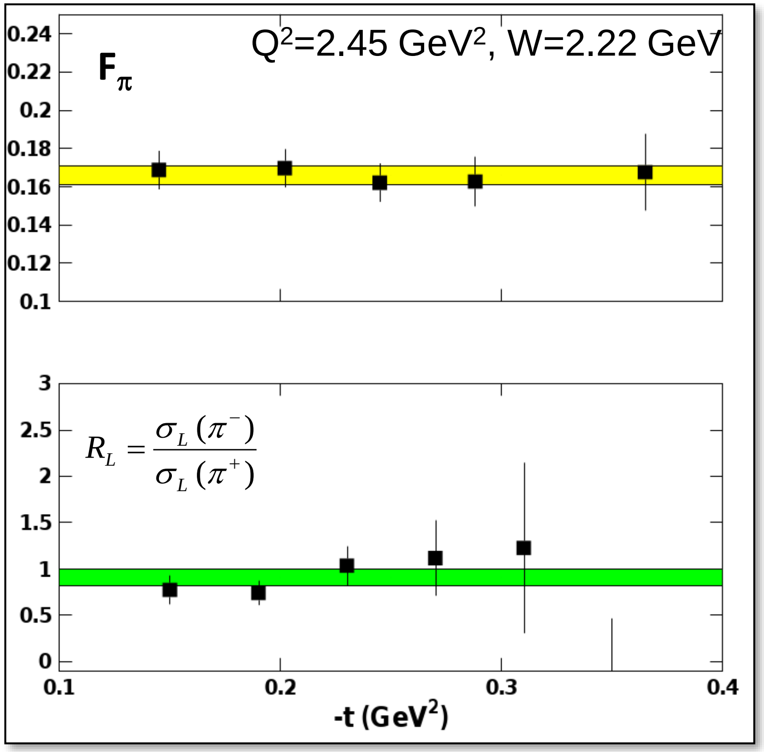
Experimental Validation (Pion Form Factor example)

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

Experimental studies include:

- **Check F_π extraction for a range of t**
  - F_π values seem robust at larger -t (>0.2) – increased 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 (= $\sigma_L(\pi^-)/\sigma_L(\pi^+)$) approaches the pion charge ratio, consistent with pion pole dominance
- Extract F_π at several values of t_{min} for fixed Q^2 (not shown here)

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

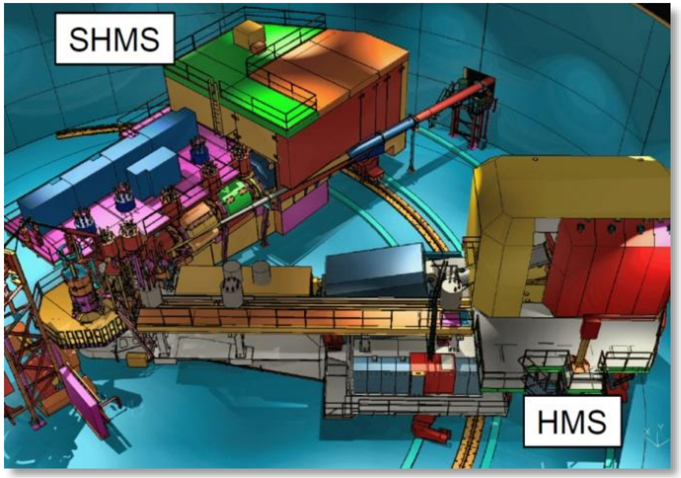


$$R_L = \frac{\sigma(n(e,e'\pi^-)p)}{\sigma(p(e,e'\pi^+)n))} = \frac{|A_v - A_s|^2}{|A_v + A_s|^2}$$

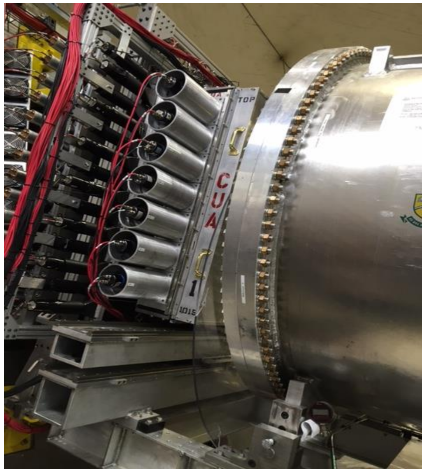
Exclusive Meson Experiments in Hall C @ 12 GeV

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

- New SHMS fulfills the meson experiments L/T separation requirements
  - Small forward-angle capabilities
  - Good angular reproducibilty
  - Missing mass resolution

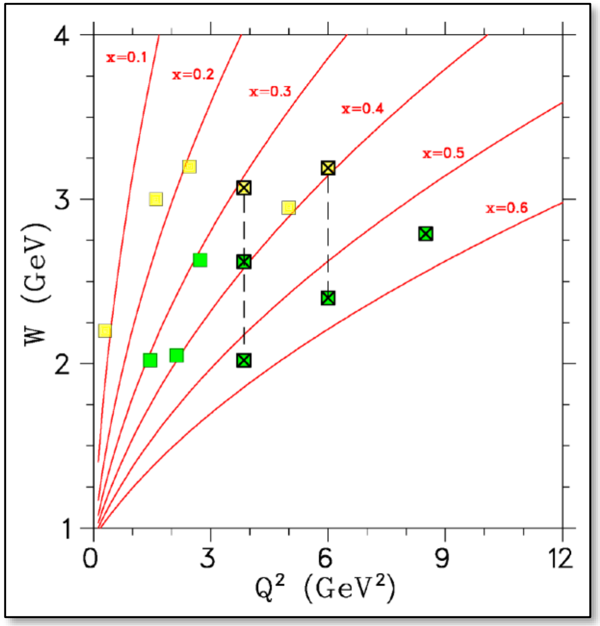


- Dedicated key SHMS Particle Identification detectors for the experiments
  - Aerogel Cherenkov – funded by NSF MRI (CUA)
  - Heavy gas Cherenkov – partially funded by NSERC (U Regina)



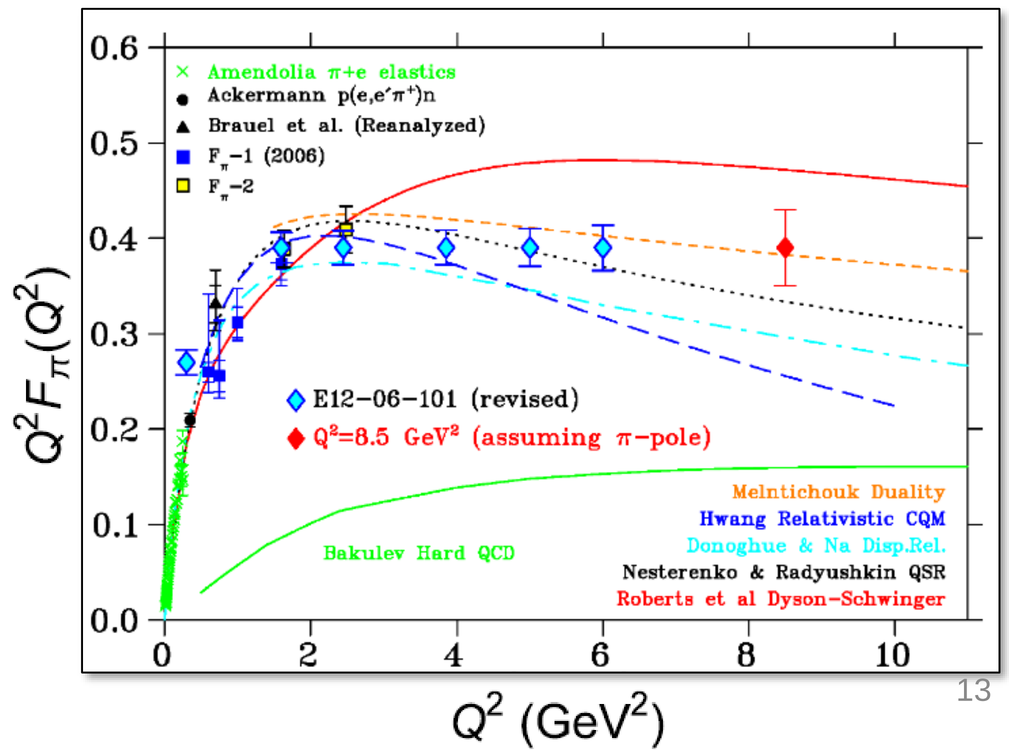
PionLT (E12-19-006): Kinematic Reach

*E12-**19**-006 spokespersons: T. Horn, G. Huber, D. Gaskell*



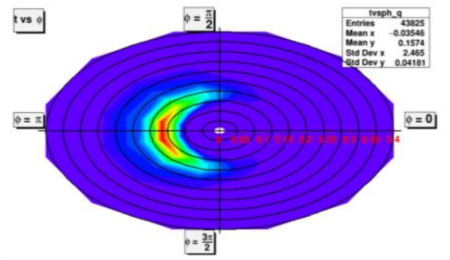
- PionLT experiment features:
  - L/T separated cross sections at fixed x=0.3, 0.4, 0.55 up to Q^2=8.5 GeV^2
  - Pion form factor at Q^2 values up to 6 GeV^2
  - Enables pion form factor extraction at Q^2 =8.5 GeV^2, highest achievable at 12 GeV JLab

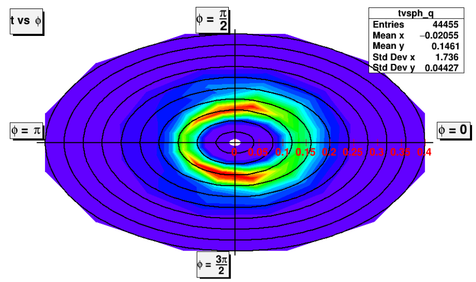
JLab 12 GeV experiments have the potential to access the perturbative scaling regime quantitatively – may also provide info on log corrections.

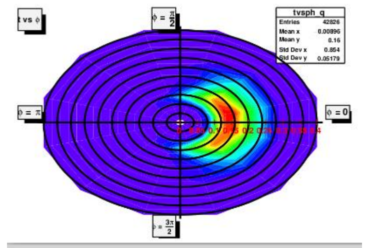


PionLT: Low energy kinematic run summer 2019

Completed 2 L/T separations at low Q^2 and took data for the low epsilon points for two more settings, which also required these beam energies







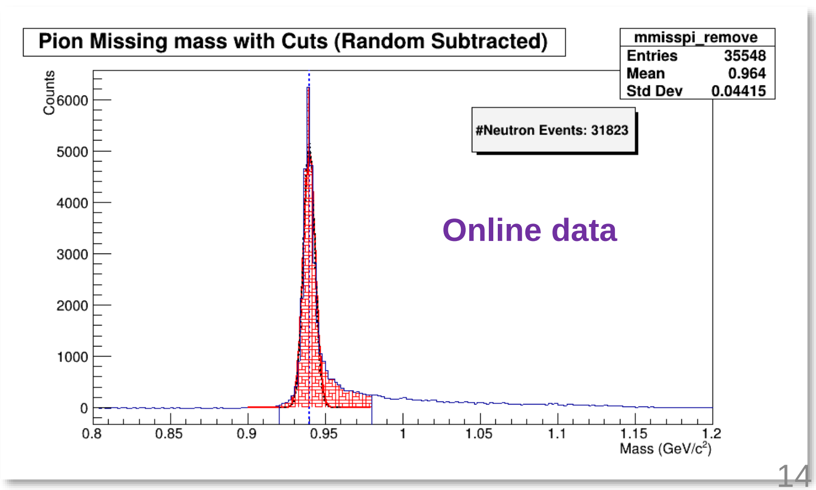
Three SHMS angles

Physics cross section

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

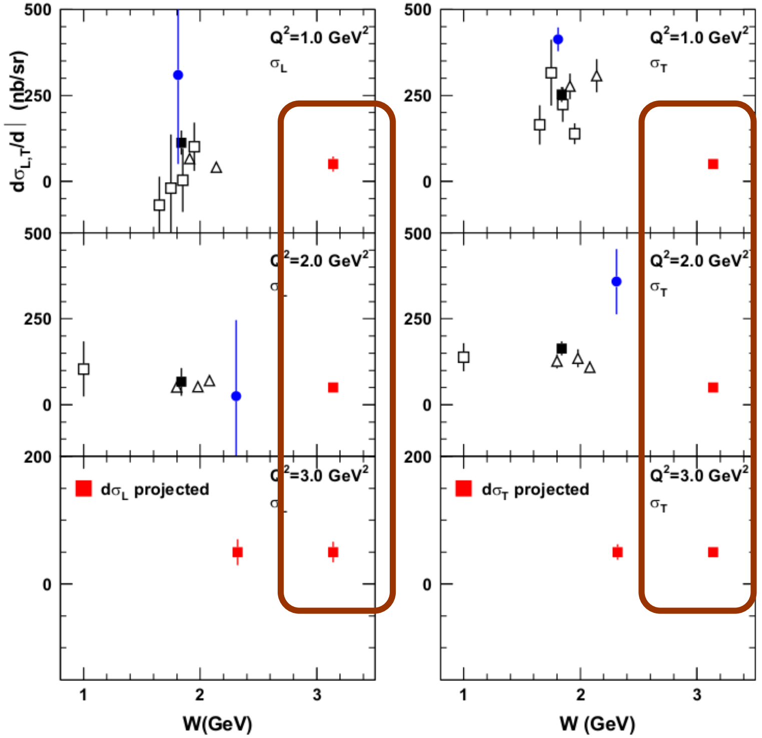
Two/three beam energies

Q^2 (GeV^2)	x_B	L/T complete	Purpose
0.375	0.09	Yes	Form Factor
0.425	0.1	Yes	Form Factor
1.45	0.3	No	Reaction mechanism
2.12	0.4	No	Reaction mechanism



KaonLT (E12-09-011): Opportunities with Kaons

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



- KaonLT experiment features:
  - L/T separated kaon cross sections at x=0.15, 0.25, 0.40 up to Q^2 =5.5 GeV^2
  - First L/T separated kaon cross sections above W=2.2 GeV
  - May enable F_K extraction up to Q^2=5.5 GeV^2

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

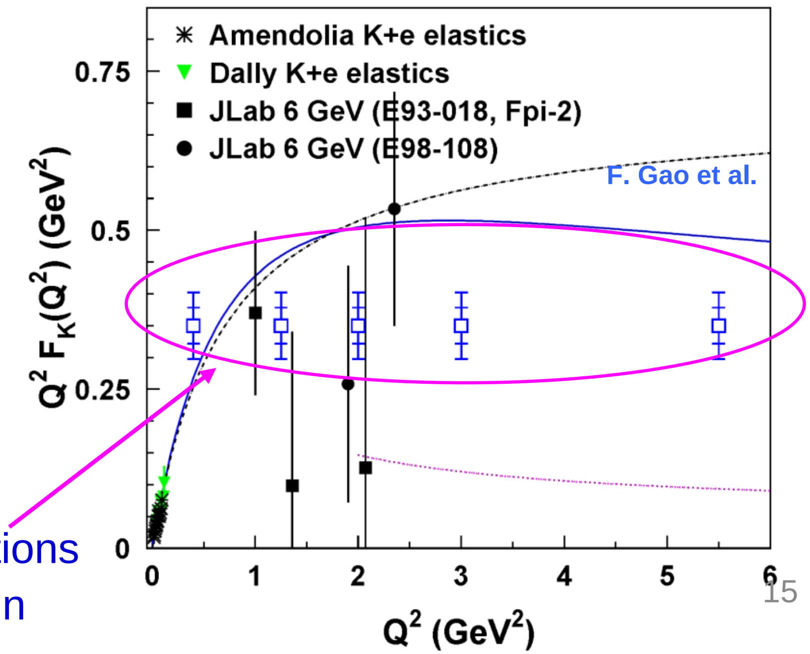
*[M. Carmignotto et al., Phys. Rev. C**97** (**2018**) no.2, 025204]*

- Recent theoretical efforts to understand role of the strange quark

*[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**)]*



Possible extractions from 2018/19 run

KaonLT: Completed data taking in 2018/2019

- Data taking completed end of Spring 2019 – in calibration phase of the analysis

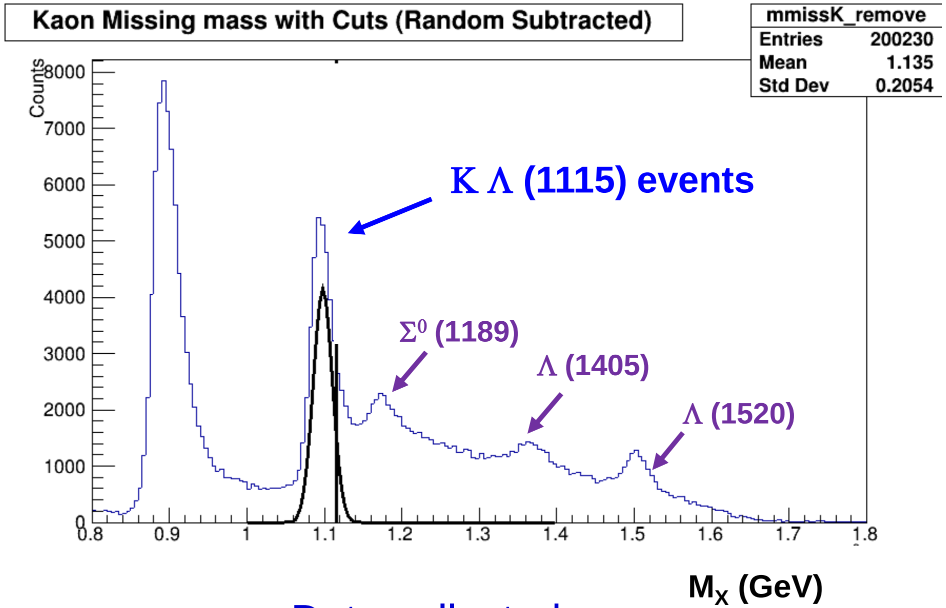
- Physics analyses may include:

  - **K^+ channel**: L/T separated Λ and Σ^0 cross sections, Q^{-n} dependence, coupling constants $g_{KN\Lambda}$, beam helicity asymmetry, $\Lambda(1405)$, $\Lambda(1115)$, $\Lambda(1520)$ cross sections

  - **π^+ channel**: L/T separated cross sections, beam helicity asymmetry, n/Δ^0 ratios, Q^{-n} dependence

  - **p channel**: $p(e,e'p)\rho/p(e,e'p)\omega$, $p(e,e'p)\phi$ ratios, as possible, cross sections and $p(e,e'p)\eta$ and $p(e,e'p)\eta'$, Q^{-n} dependence

Online data



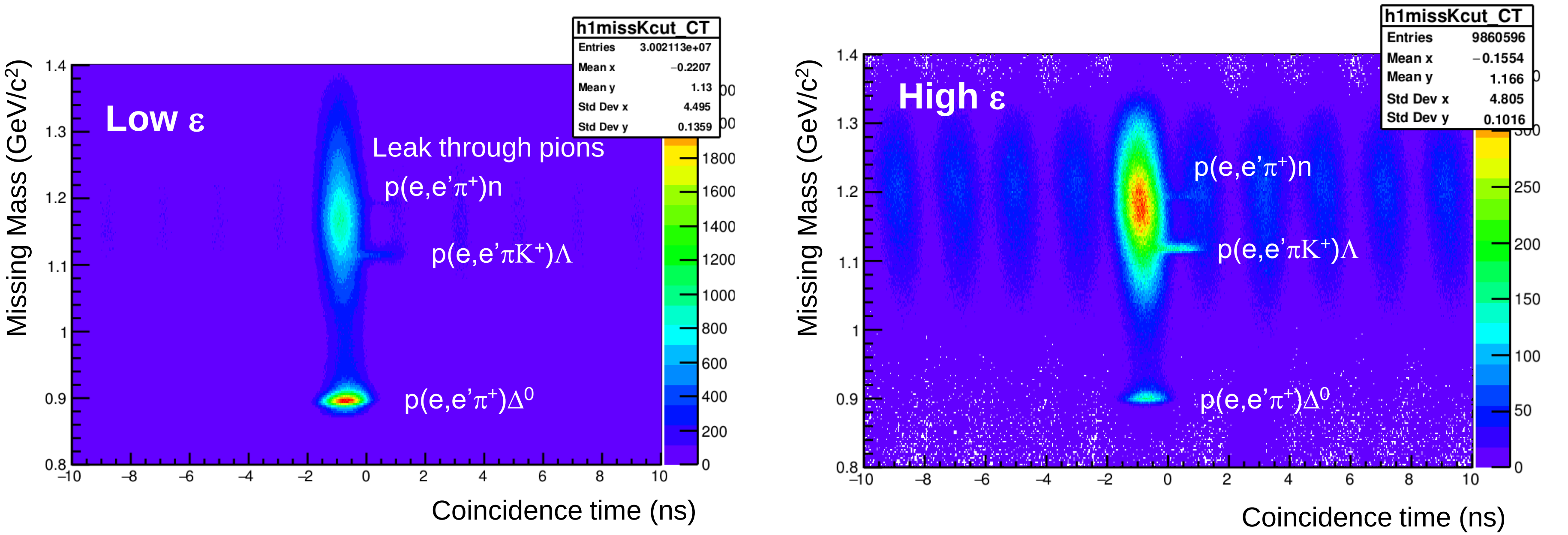
Data collected

Q^2 (GeV^2)	W (GeV)	LT complete
5.5	3.02	✓
4.4	2.74	✓
3.0	3.14	✓
3.0	2.32	✓
2.115	2.95	✓
0.5	2.40	✓

Interesting Physics in the other channels

- Large difference in L/T ratio between p(e.e'π^+)n and p(e,e'π^+)Δ^0 final states

Online data – L/T separation "by eye" at Q^2=0.50 GeV^2



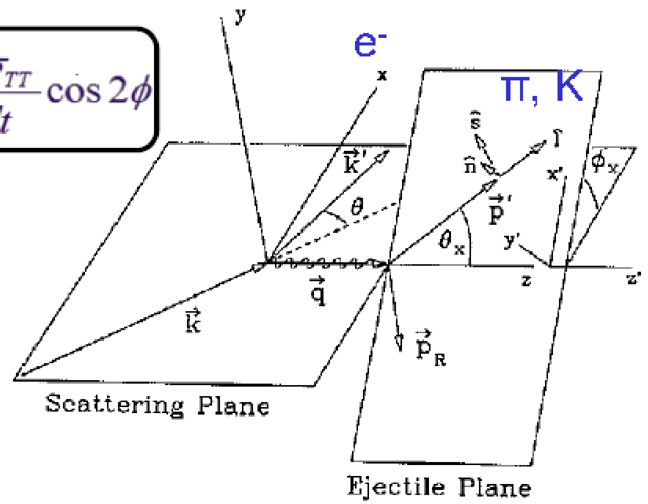
- Large increase in neutron missing mass at high epsilon is evidence of the pion-pole process at low Q^2 and small –t – suggests $\sigma_L >> \sigma_T$

- Δ^0 exclusive longitudinal cross section expected to be at best $\sigma_L \sim \sigma_T$

Physics Insight: Beam Single Spin Asymmetry

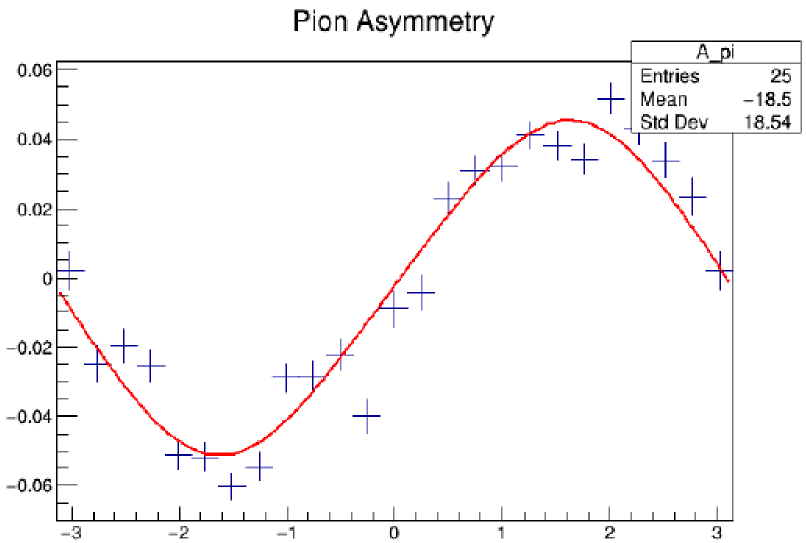
Analysis by S. Wood

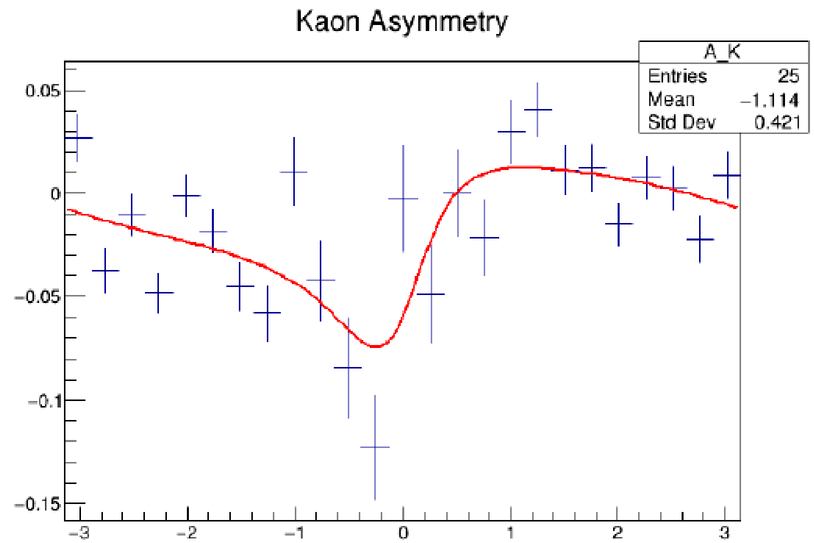
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$



Additional term if beam polarized $\quad h\,\frac{d\sigma_{LT'}}{dt}\sin\phi$

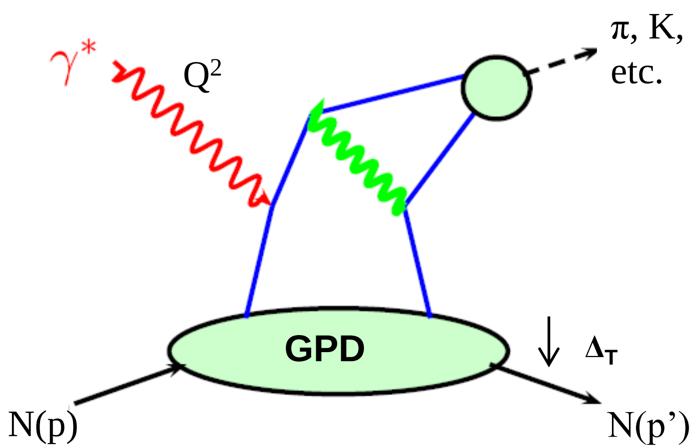
Measure $\quad A(\phi) = \frac{\sigma^+(\phi) - \sigma^-(\phi)}{\sigma^+(\phi) + \sigma^-(\phi)}$





Towards GPD flavor decomposition

- ❑ Meson data are also of great interest for nucleon structure studies



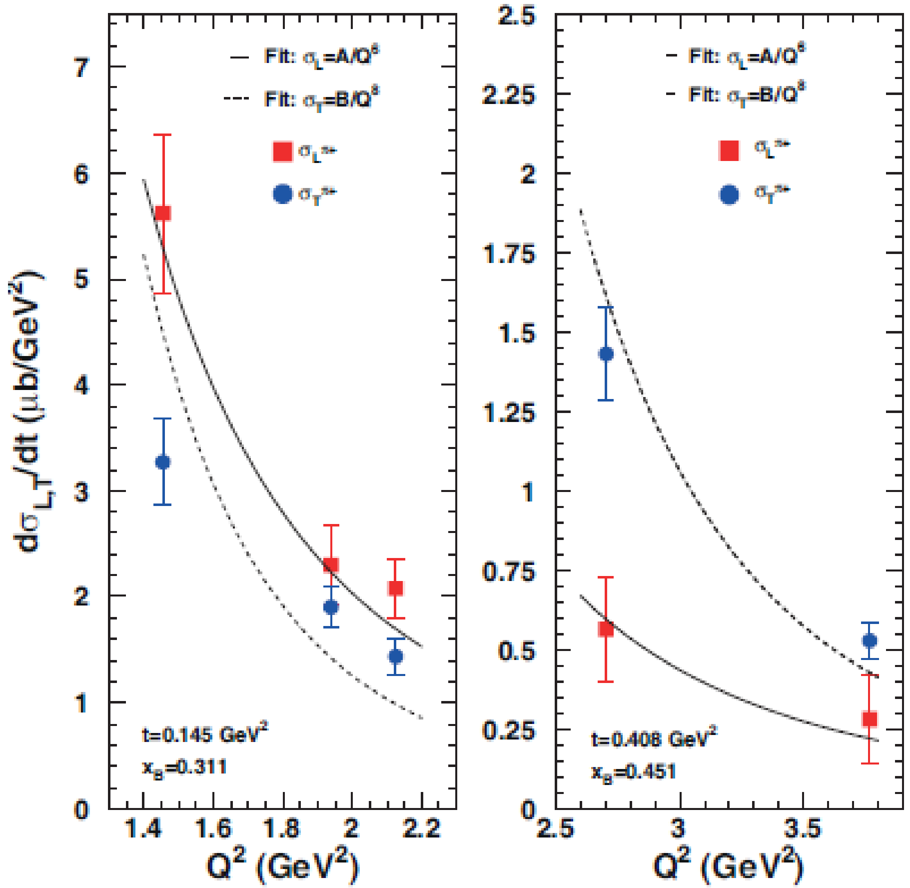
- ➢ described by 4 (helicity non-flip) GPDs:
  - *H, E* (unpolarized), $\tilde{H}$, $\tilde{E}$ (polarized)
- ➢ Quantum numbers in meson production probe individual GPD components selectively
  - Vector : $\rho^o/\rho+/K^*$ select *H, E*
  - **Pseudoscalar: π,η,*K* select the polarized GPDs, $\tilde{H}$ 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

Pion cross section: 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 (or perhaps, a precocious description)

- Consistent with expected factorization, but small lever arm and relatively large uncertainties



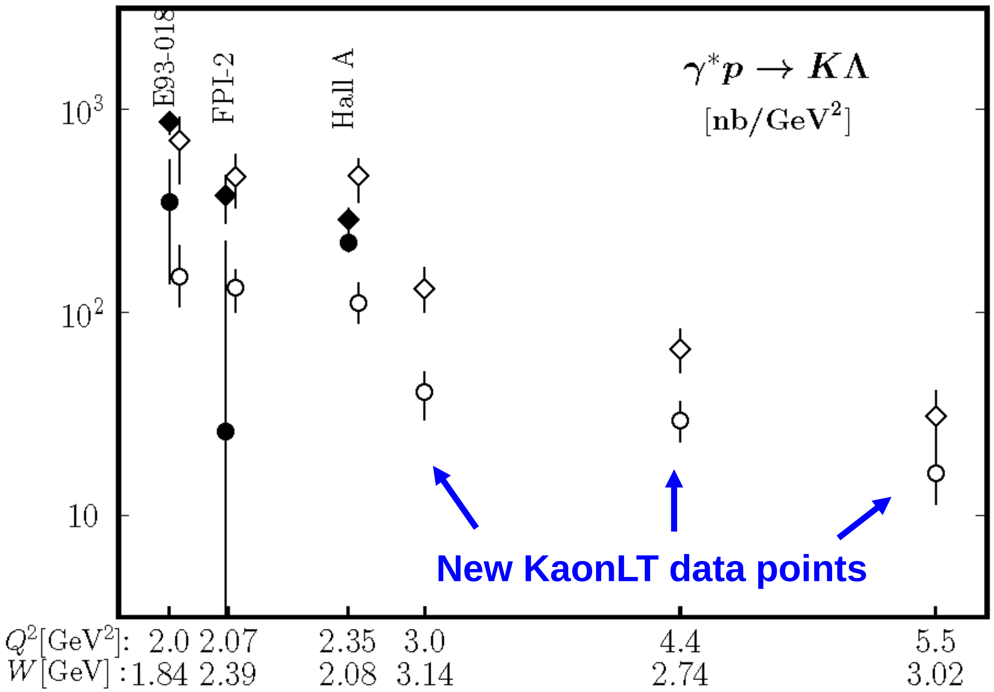
*[T. Horn et al., Phys. Rev. C **78**, 058201 **(2008)**]*

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

Kaon cross section: Results from 6 GeV JLab

Here, compare with P. Kroll's GPD model (circles=σ_L, diamonds=σ_T)

*[P. Kroll, EPJA **55**, (**2019**) no5, 76]*

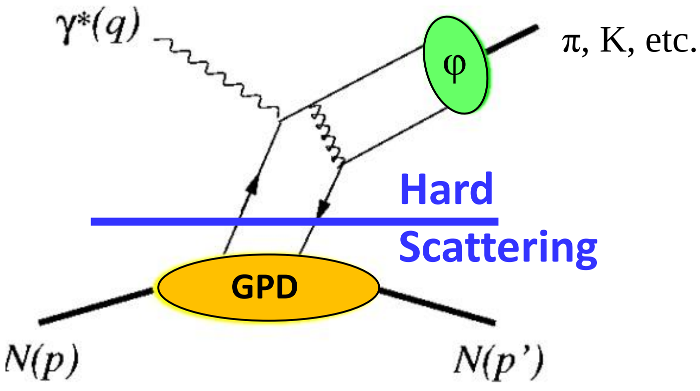


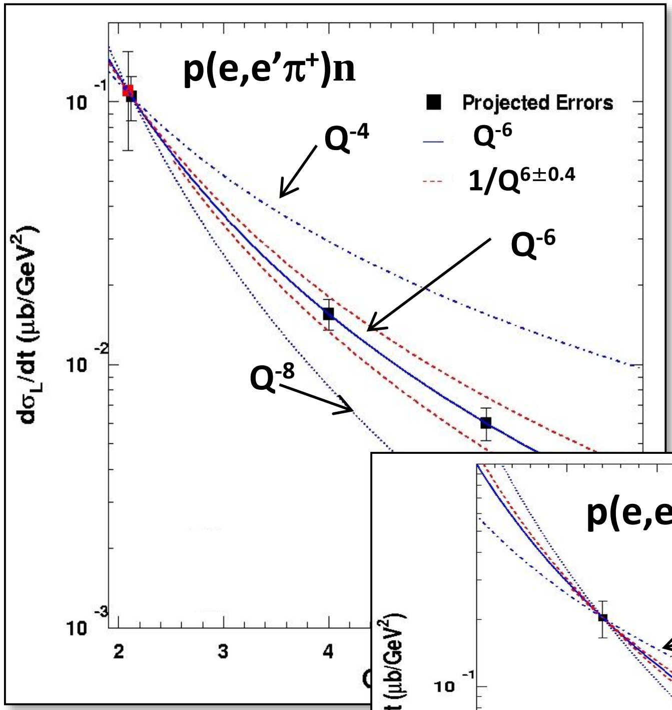
- Solid symbols are data
  - σ_L is comparable to σ_T at Q^2=2.4 GeV^2
- Open symbols model calculations
  - Model overpredicts σ_T
  - Model underpredicts σ_L

Separated cross section data 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

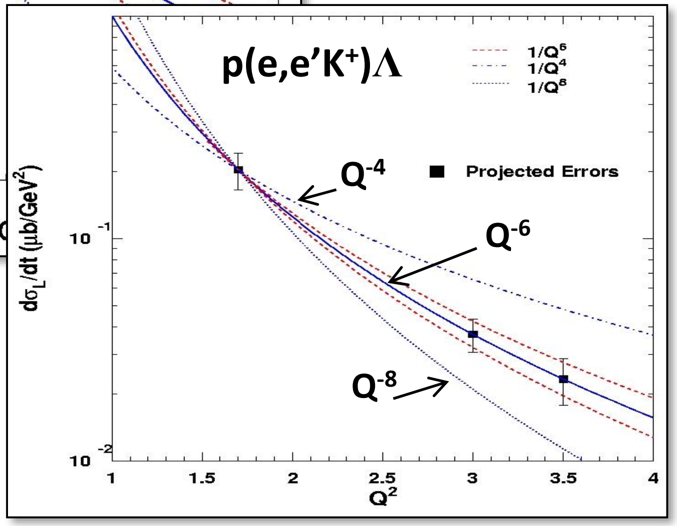
L/T Separated (e,e'π^+/K$^+$) Cross Sections with 12 GeV





π^+: to Q^2~9 GeV^2
K$^+$: to Q^2~6 GeV^2

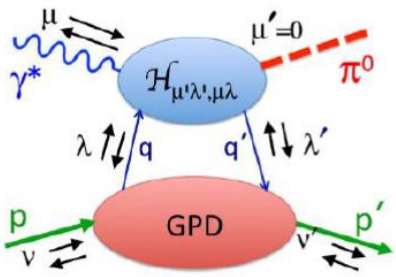
Fit: $1/Q^n$



- One of the most stringent tests of the reaction mechanism is the Q^2 dependence of cross section
  - σ_L scales to leading order as Q^{-6}
  - σ_T does not
- Need to validate the reaction mechanism for reliable interpretation of the GPD program – key are precision longitudinal-transverse (L/T) separated data over a range of Q^2 at fixed x/t

➢ **If σ_T is confirmed to be large, it could allow for detailed investigations of transversity GPDs. If, on the other hand, σ_L is measured to be large, this would allow for probing the usual GPDs**

Probing a new set of GPDs



- 4 Chiral-odd GPDs (parton helicity flip)

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

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

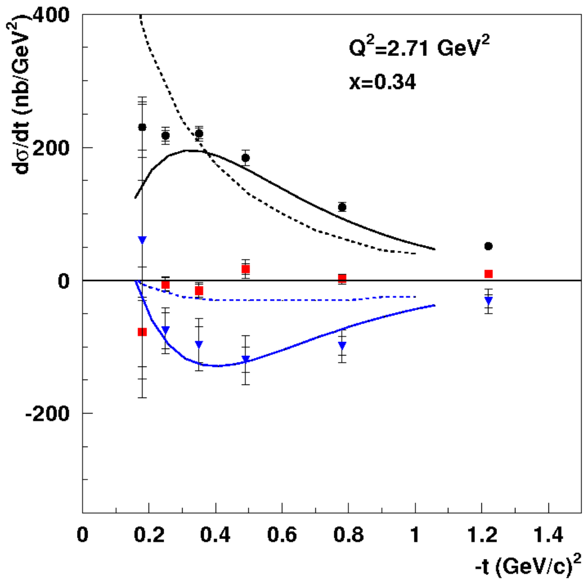
$$\sigma_T = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^{\,2}}{Q^4}\left[(1-\xi^2)|< H_T >|^2 - \frac{t'}{8m^2}|< \bar{E}_T >|^2\right]$$

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

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

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

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

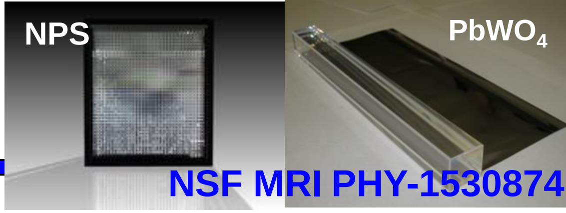


- Exclusive π^o data may also be helpful for constraining non-pole contributions in F_π extraction

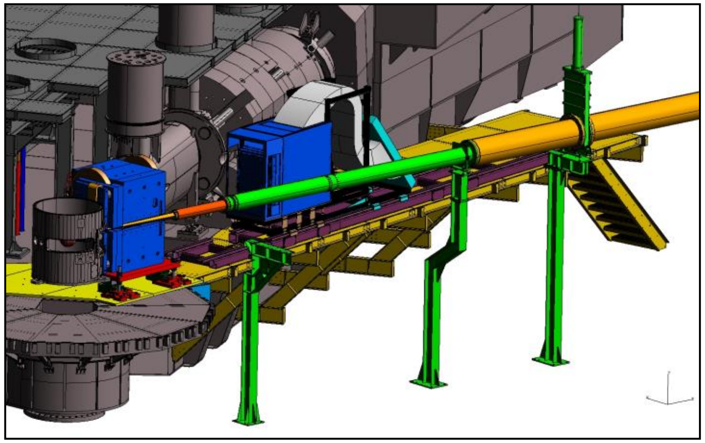
*[Favart, Guidal, Horn, Kroll , EPJA (**2016**)]*

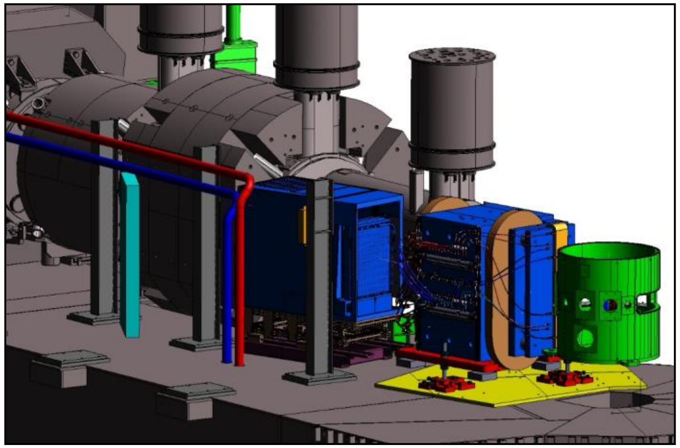
*[Bedlinskiy et al. PRL 109 (**2012**) 112001]*

New Opportunities with the Neutral Particle Spectrometer (NPS)



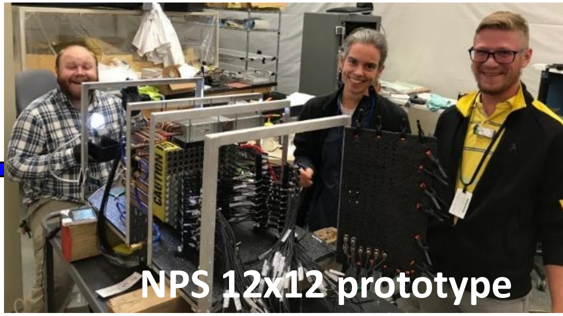
- The NPS is a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ and π^0).



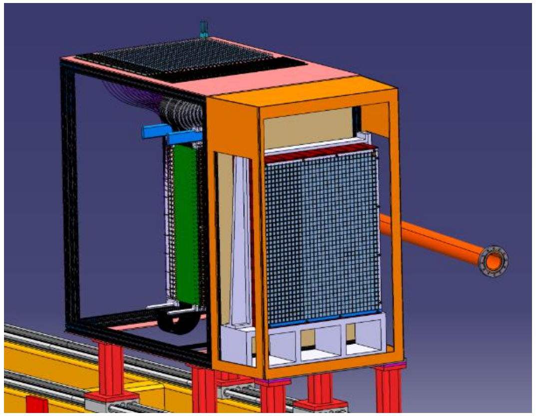


- Approved experiments to date
  - E12-13-010 – Exclusive Deeply Virtual Compton and π^0 Cross Section Measurements in Hall C
  - E12-13-007 - Measurement of Semi-inclusive π^0 production as Validation of Factorization
  - E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
  - E12-14-005 – Wide Angle Exclusive Photoproduction of π^0 Mesons
  - E12-17-008 – Polarization Observables in Wide-Angle Compton Scattering
- Conditionally approved experiments: TCS with transverse target

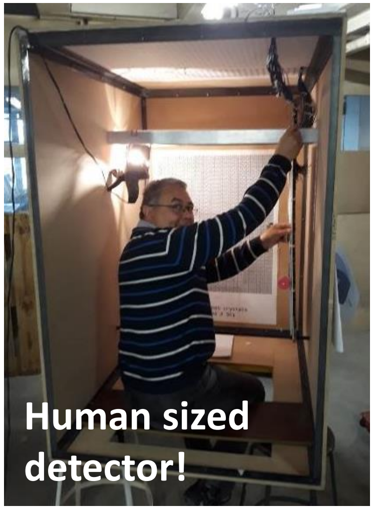
NPS Status



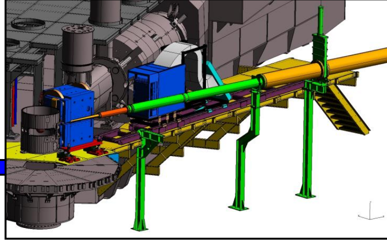
- ❑ NPS passed Experiment Readiness Review in 2019
  - ➢ Experiments: E12-13-010/007, E12-14-003/005
- ❑ NPS 12x12 prototype test successfully completed
- ❑ NPS subsystem status
  - ➢ Magnet provided by CUA and ODU (NSF MRI) - ready for mapping



  - ➢ Detector frame designed (IPN-Orsay)
  - ➢ Crystal testing ongoing (CUA), final procurement underway
  - ➢ PMTs on-site, HV base fabrication near completion (OU)
  - ➢ Software development ongoing (IPN-Orsay, JMU, U. Glasgow, JLab)
  - ➢ Trigger/Electronics/DAQ - (JLab)
  - ➢ Mechanical – systems identified, e.g. SHMS platform extension designed, installation plan being developed and tuned (Jlab)



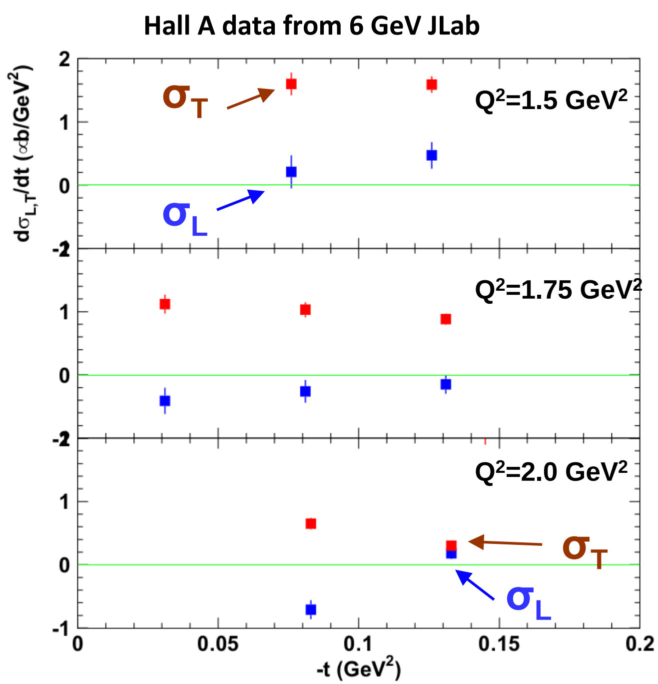
NPS/E12-13-010: Exclusive π^0 cross section



- Results from Hall A suggest that σ_L in π^0 production is non-zero up to Q^2=2 GeV^2

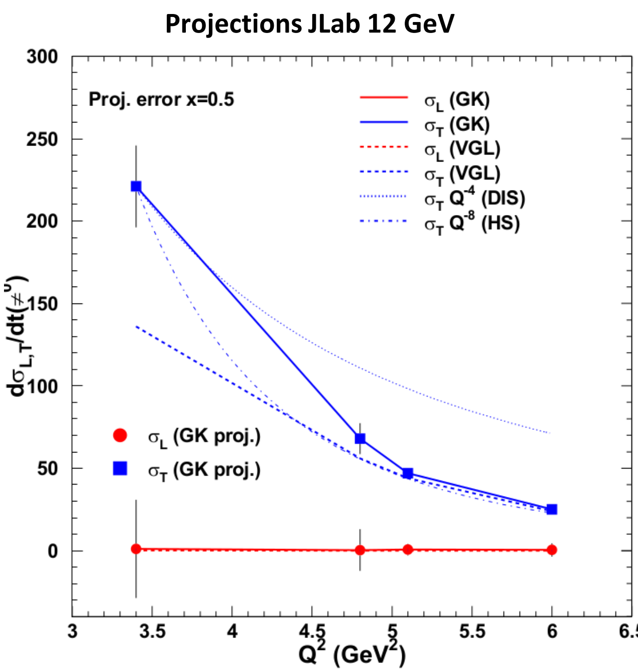
*E12-**13**-010 spokespersons: C. Munoz-Camacho, T. Horn, C. Hyde, R. Paremuzyan, J. Roche*

- Need to understand Q^2/t dependence for final conclusion on dominance of σ_T
  - If σ_T large: access to transversity GPDs



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

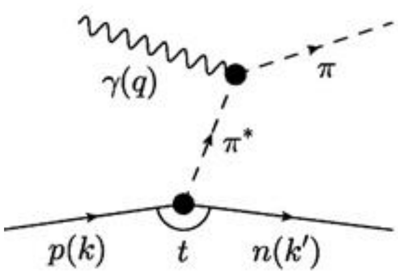
E12-13-010 projections



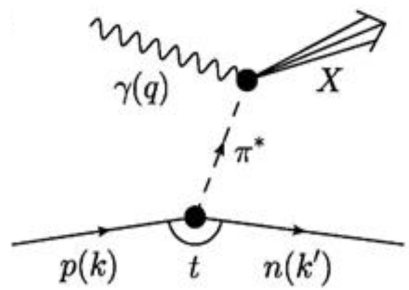
E12-13-010 will provide relative σ_L and σ_T contributions to the π^0 cross section up Q^2~6 GeV^2 to verify reaction mechanism

Towards the Pion/Kaon Structure Function

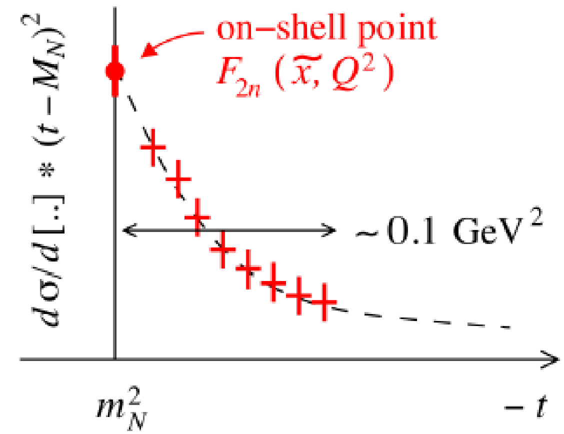
- The **Sullivan process can provide reliable access to a meson target** as *t* becomes space-like if the pole associated with the ground-state meson is the dominant feature of the process and the structure of the (off-shell) meson evolves slowly and smoothly with virtuality.



Elastic Form Factor



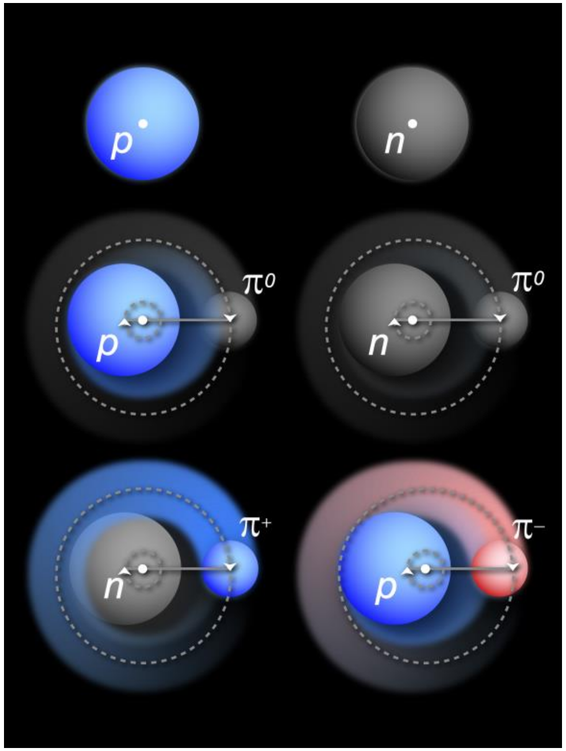
DIS



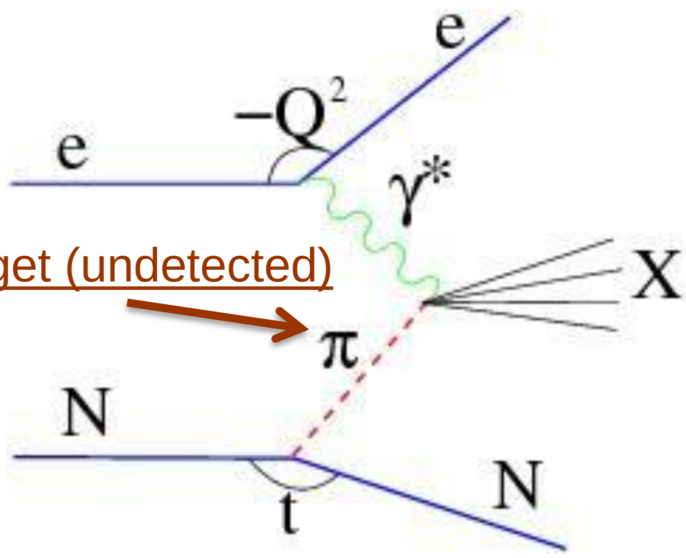
- Recent **theoretical calculations found that for -t ≤ 0.6 GeV², changes in pion structure do evolve slowly** so that a well-constrained experimental analysis should be reliable, and the Sullivan processes can provide a valid pion target.
- To **check these conditions** are satisfied empirically, one can **take data covering a range in *t*** and compare with phenomenological and theoretical expectations.

Tagged Deep Inelastic Scattering (TDIS)

- Use Sullivan process – scattering from nucleon-meson fluctuations



detect scattered electron



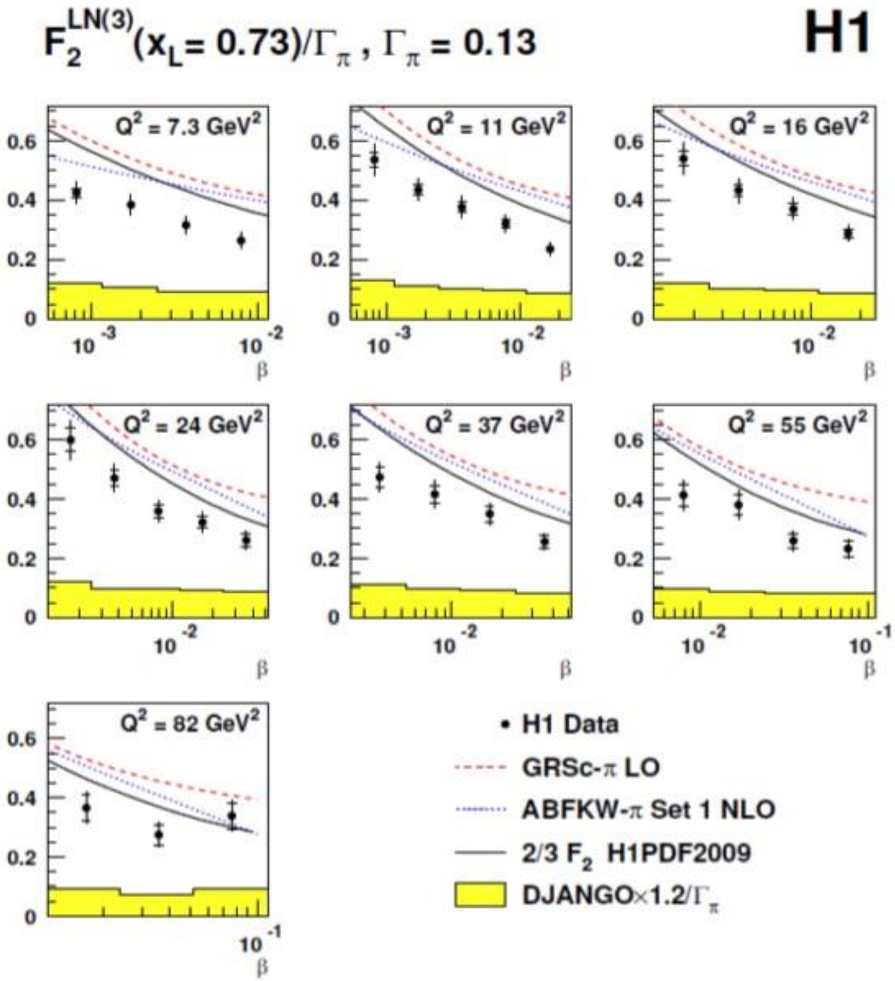
pion target (undetected)

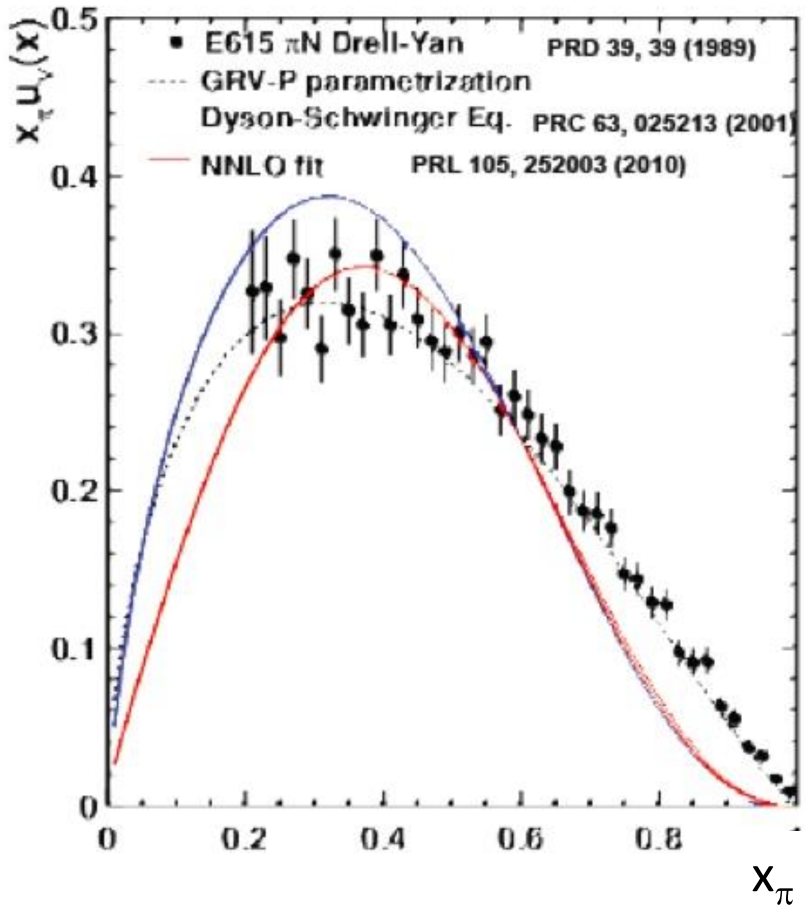
DIS event – reconstruct x, Q^2, W^2, also M_X (W_π) of undetected recoiling hadronic system

tagged outgoing target nucleon

Pion Structure Function Measurements

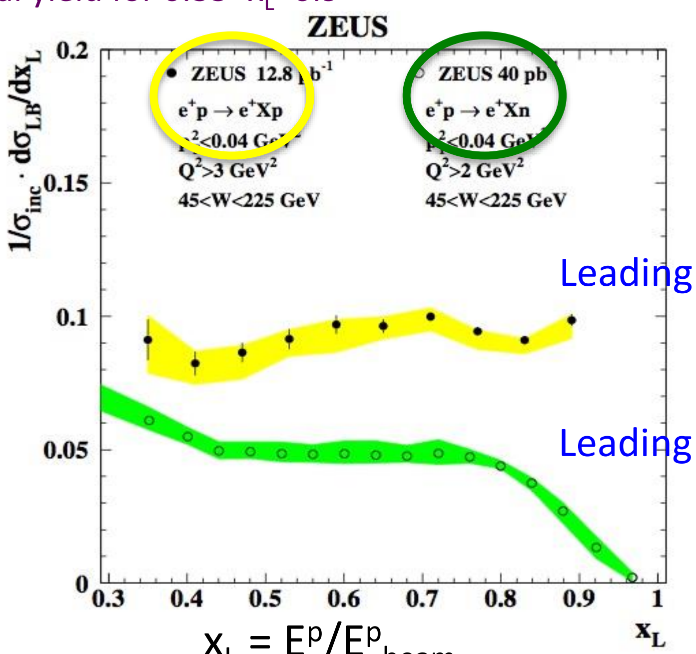
- Knowledge of the pion structure function is ***very limited:***
  - HERA TDIS data - at low x through Sullivan process (left)
  - Pionic Drell-Yan from nucleons in nuclei - at large x (right)



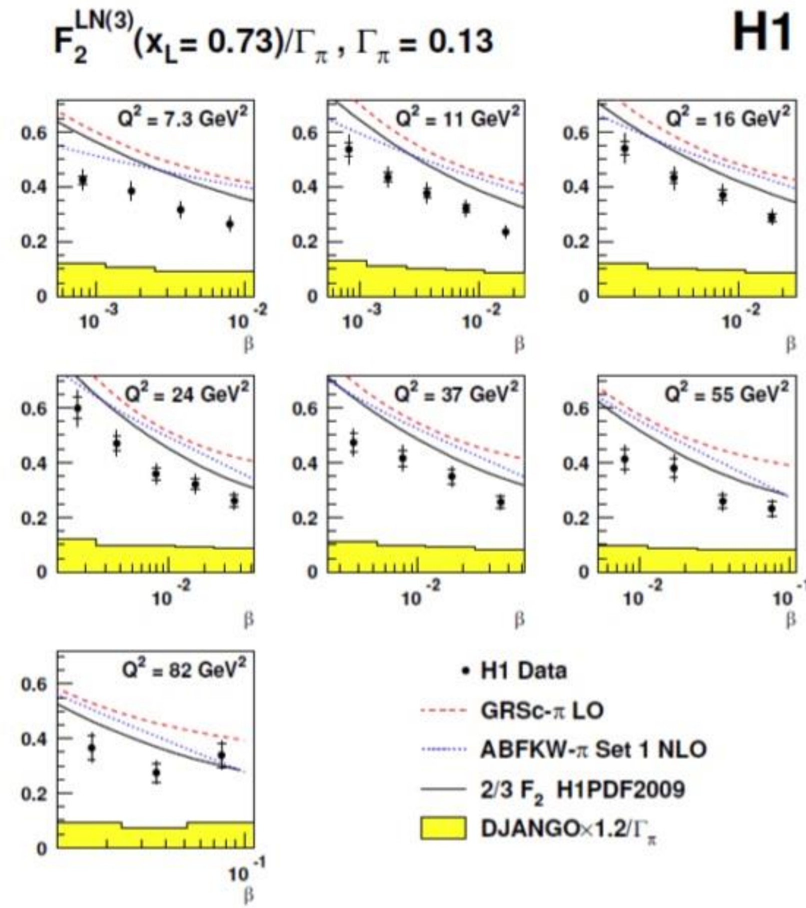


Pion Structure Function from TDIS Measurements at HERA

Total yield for $0.35<x_L<0.9$



$x_L = E^p/E^p_{beam}$



Pure isovector exchange

⇒ LP= ½ LN (isospin Clebsch-Gordon)

Data: LP ≈ 2LN

⇒ additional isoscalar exchanges for LP

Proton isoscalar events include diffractive scattering – *the neutral pion is buried*

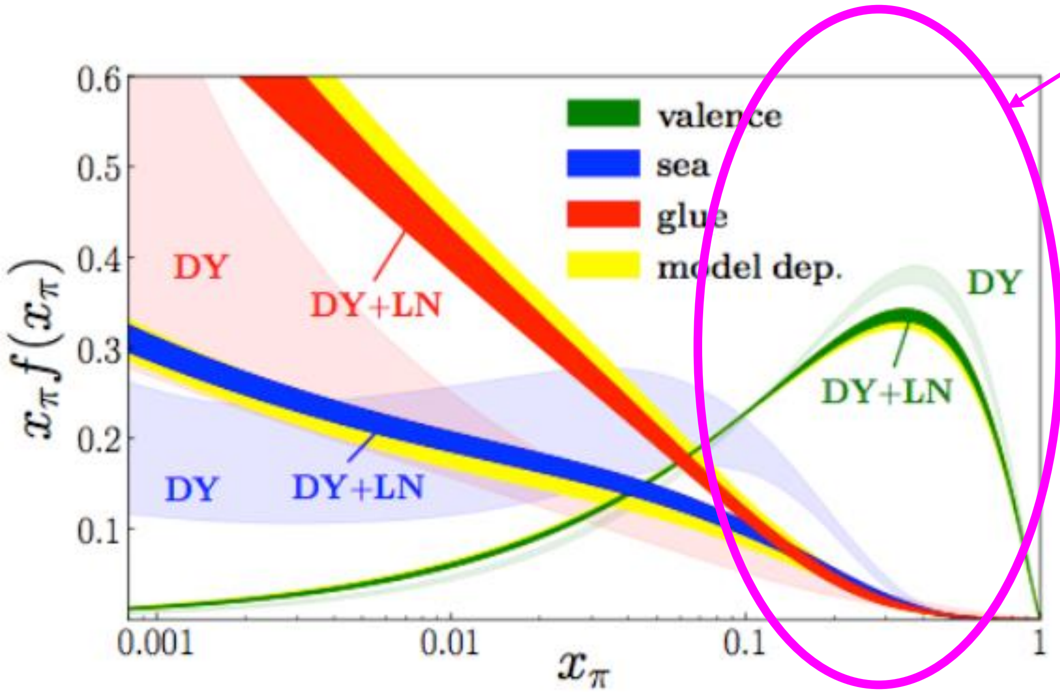
Neutron events isovector only, charged pions dominate

- *One pion exchange is the dominant mechanism*
  - *Can extract pion structure function*
  - *In practice use in-depth model and kinematic studies to include rescattering, absorption,…*

DESY 08-176 JHEP06 (2009) 74

Global Fits: Pion and Kaon 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, Phys. Rev. Lett. ***121*** *(****2018****) no.15, 152001]*

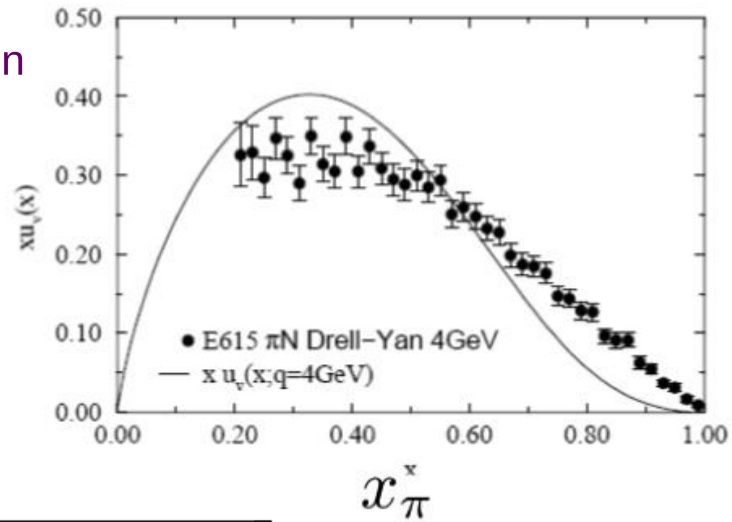
- Significant reduction of uncertainties on sea quark and gluon distributions in the pion with inclusion of HERA leading neutron data
- Implications for “TDIS” (Tagged DIS) experiments at JLab

Pion Structure Function from Drell-Yan: Large x

Large x Structure of the Pion

Initial observations:

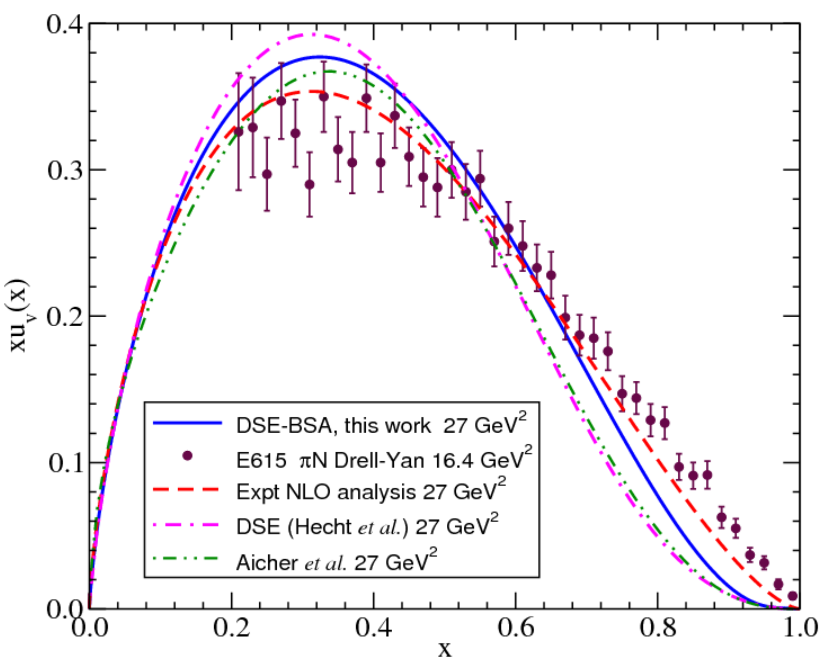
- PDF ~ $(1-x_\pi)$ as x_π->1
- Agrees with structureless model
- Differs from pQCD prediction of $(1-x_\pi)^2$



FNAL E615, CERN NA3,10

$$\pi^- W \to \mu^+ \mu^- X$$

$$\sigma \propto \bar{u}(x_{\pi^-}) u(x_N)$$

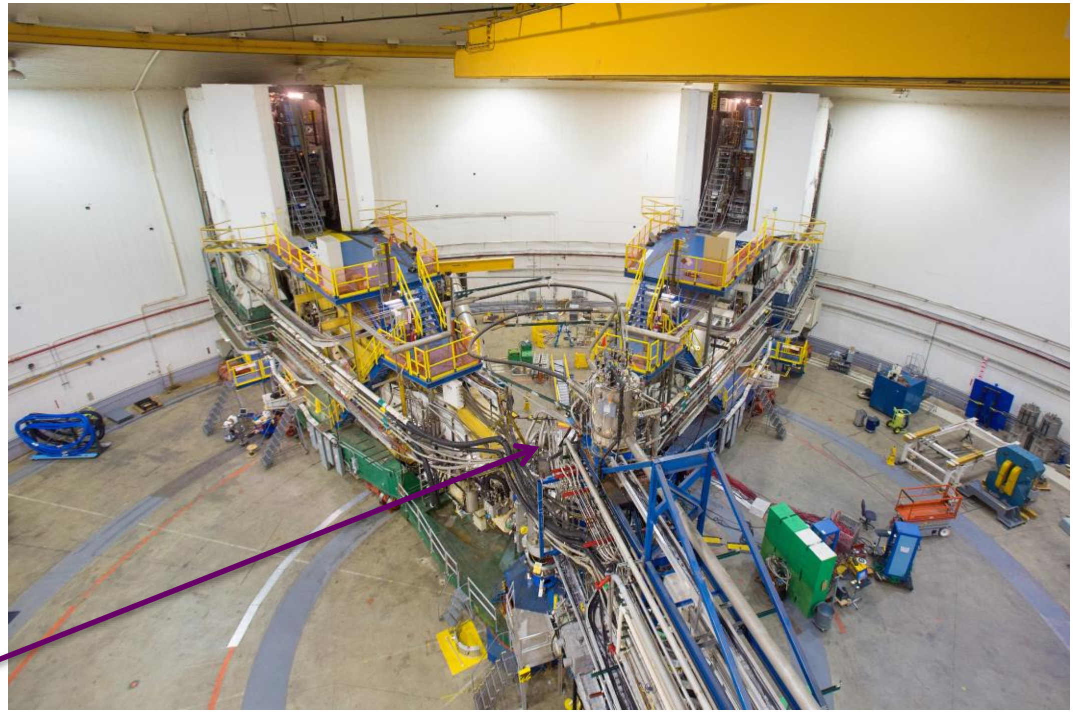


[C.D. Roberts, arXiv:1203.5341 (2012)]

- ❑ Data do not agree with pQCD, Dyson-Schwinger, Light Front, Instanton,….*numerous models!*
- ❑ Problems with data analysis?
  - NLO fit
  - Improved proton PDFs
  - Sea quark contribution
  - More flexible extractions of PDFs
- ❑ Nuclear corrections needed?
- ❑ Only soft gluon resummation shows "convex" shape [Aicher, Schäfer, Vogelsang, Phys. Rev. Lett. 105, 252003 (2010)]

Jefferson Lab TDIS can provide important verification

JLab Hall A TDIS Experiment



proton tag detection in GEM-based mTPC at pivot

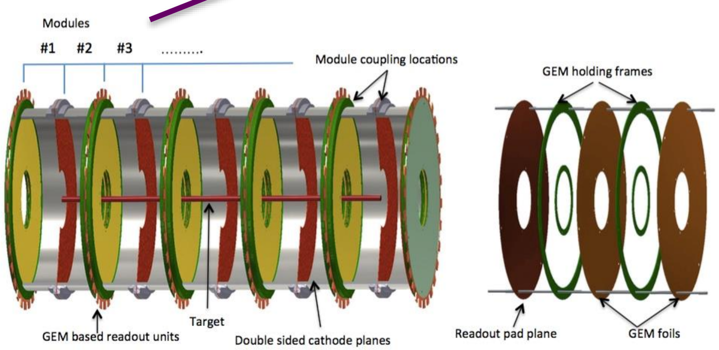
e- beam

Hall A with SBS:

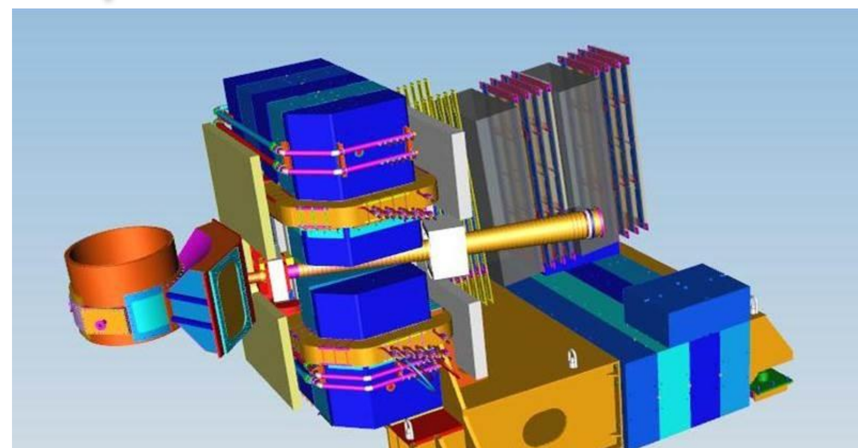
✓High luminosity,
50 μAmp,
$\mathcal{L}$ = 3x10^{36}/cm^2 s

✓Large acceptance
~70 msr

Important for small cross sections

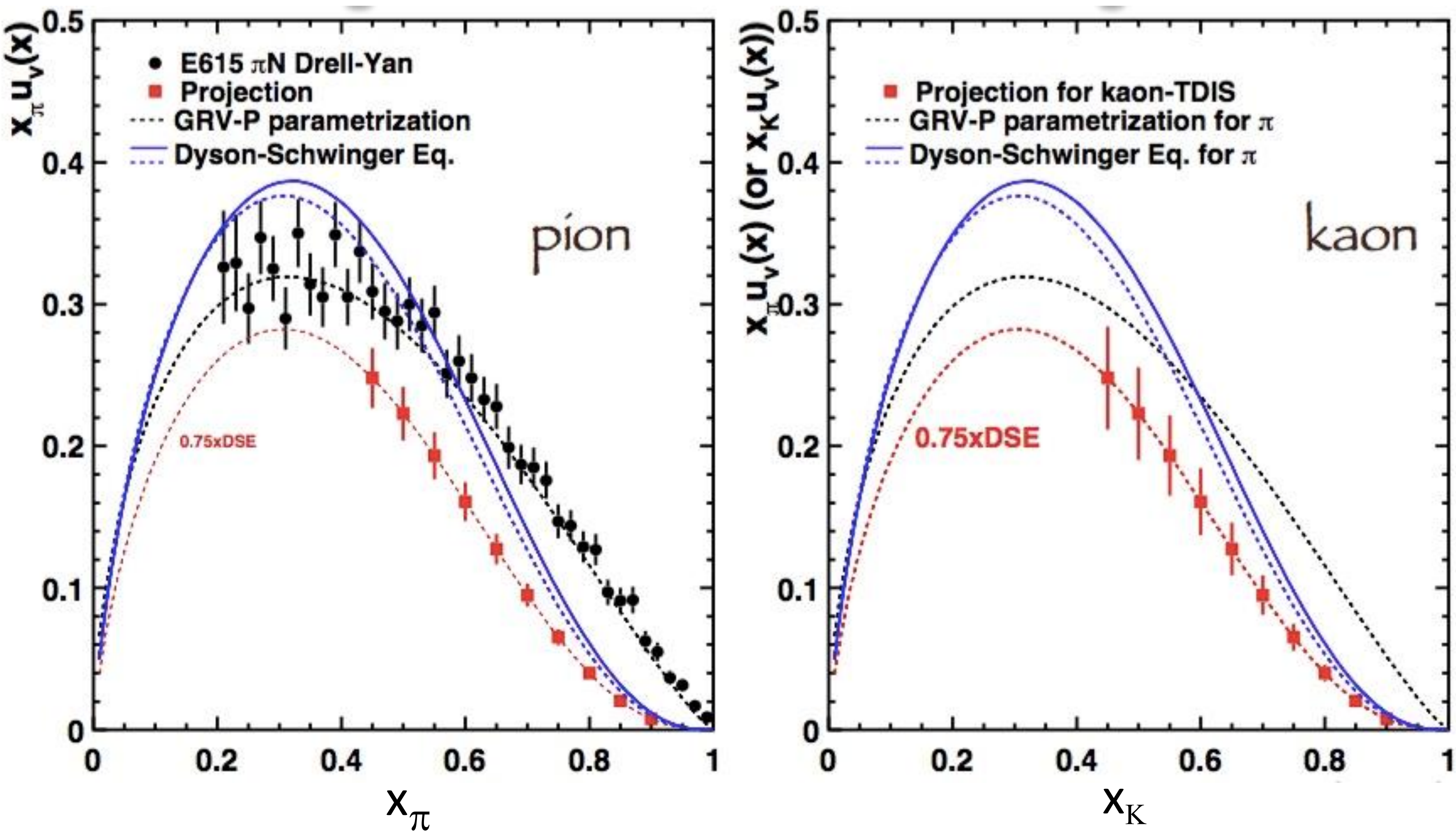


mTPC inside superconducting solenoid



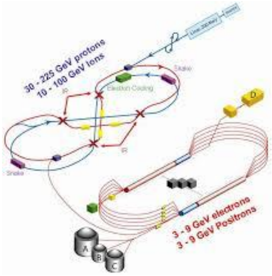
Scattered electron detection in new Super Bigbite Spectrometer (SBS)

Projected JLab TDIS Results for π, K Structure Functions

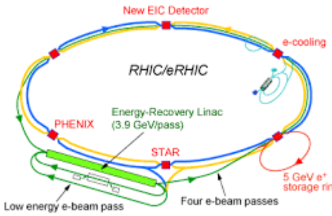


Essentially no data currently

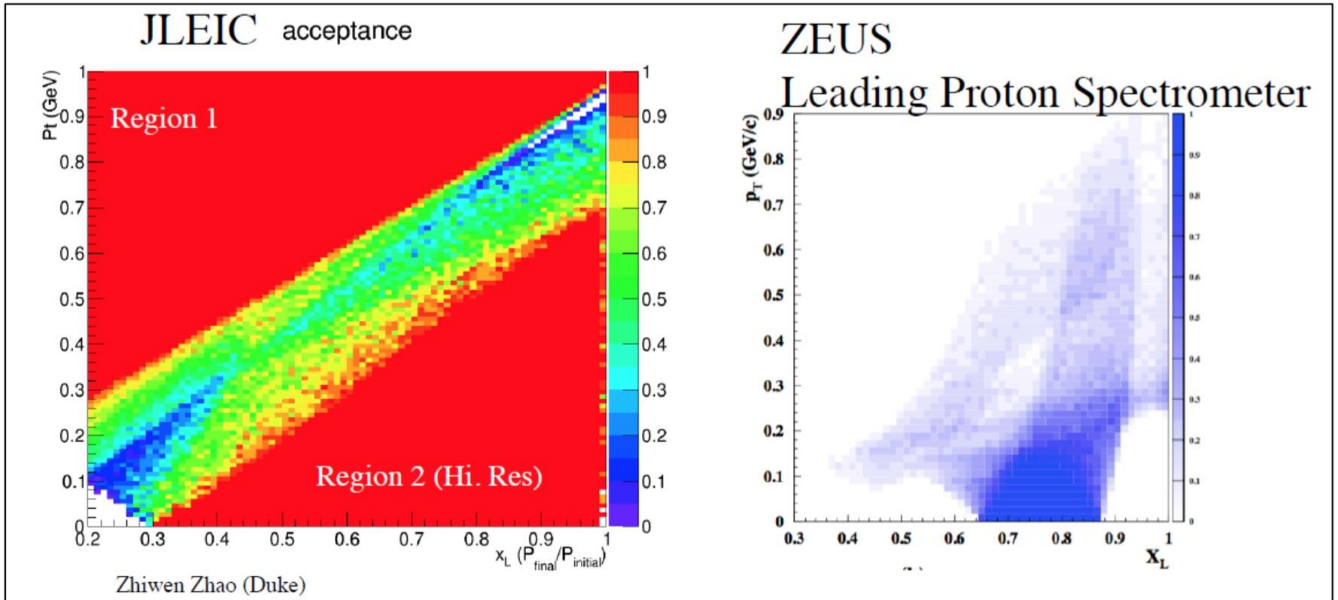
Large Opportunity for Meson Structure Functions at the EIC



Good Acceptance for TDIS-type Forward Physics!
Low momentum nucleons ***easier*** to measure!



Example: acceptance for p' in e + p → e' + p' + X



Acceptance in diffractive peak (X_L>~.98)

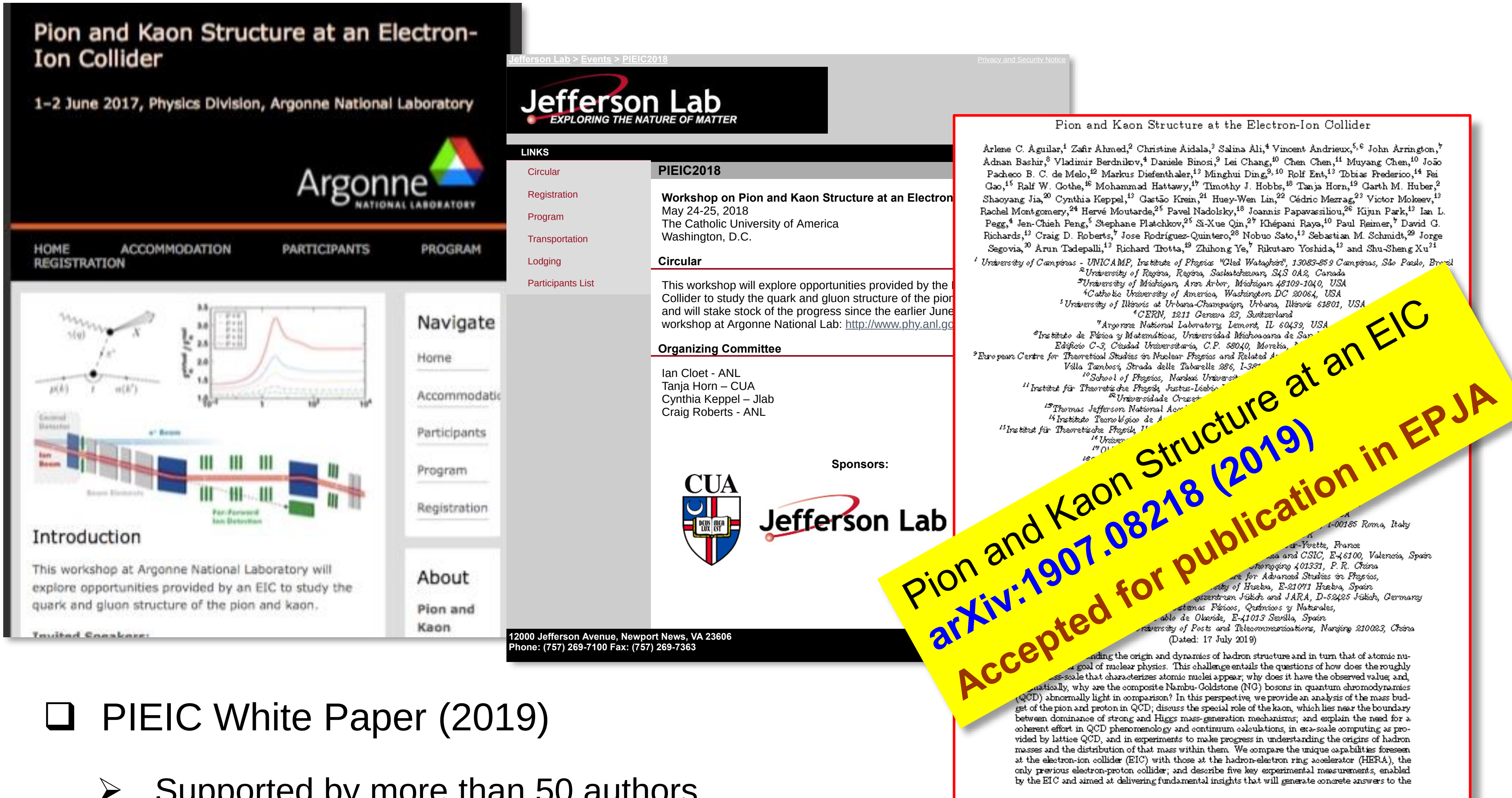
ZEUS: ~2%

JLEIC: ~100% (also covers much higher X_L than ZEUS)

Huge gain in acceptance for forward tagging….

Pion and Kaon Structure at an EIC and Understanding Mass

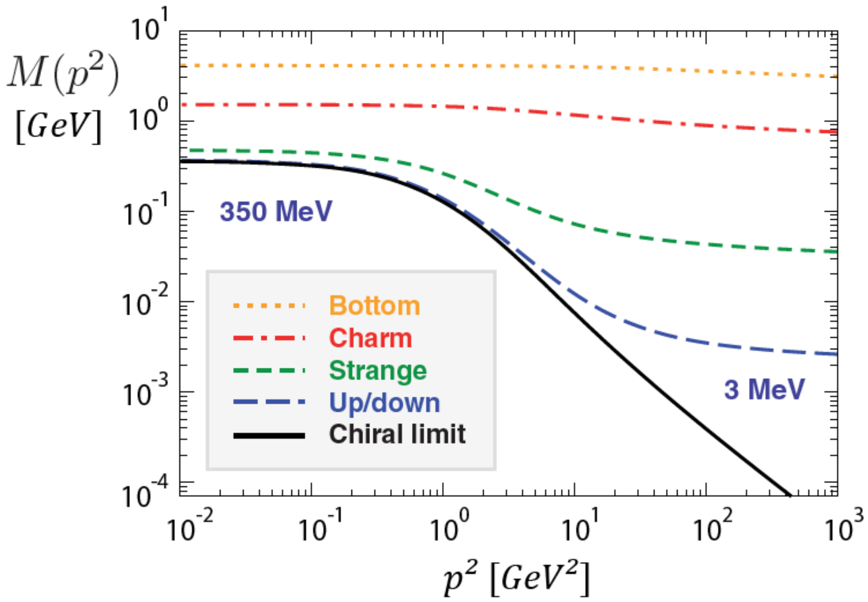
- PIEIC Workshops hosted at ANL (2017) and CUA (2018)
- Also ECT* workshop on Emergent Mass and its Consequences (2018)

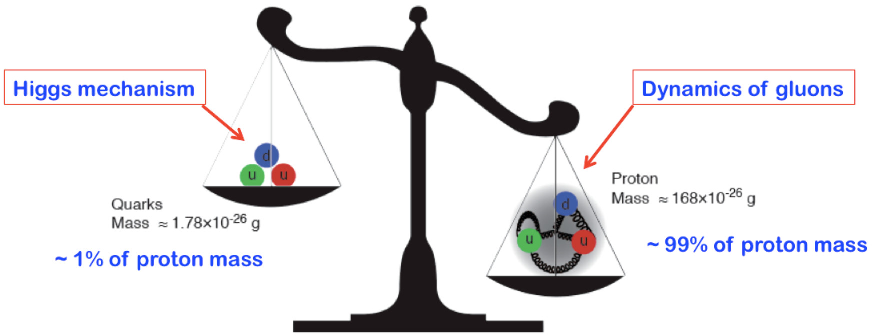


- PIEIC White Paper (2019)
  - Supported by more than 50 authors

The incomplete Hadron: Mass Puzzle

“Mass without mass!”





The light quarks acquire (most of) their masses as effect of the gluon cloud.

The strange quark is at the boundary - both emergent-mass and Higgs-mass generation mechanisms are important.

Proton: Mass ~ 940 MeV

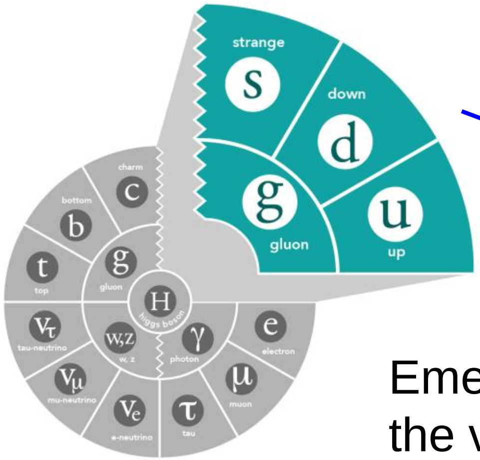
preliminary LQCD results on mass budget, or view as mass acquisition by DCSB

Kaon: Mass ~ 490 MeV

at a given scale, less gluons than in pion

Pion: Mass ~ 140 MeV

mass enigma – gluons vs Goldstone boson



Emergent mass of the visible universe

Origin of Mass of QCD's Pseudoscalar Goldstone Modes

- The pion is both the lightest bound quark system with a valence $\bar{q}q$ structure and a Nambu-Goldstone boson

- There are exact statements from QCD in terms of current quark masses due to PCAC *(Phys. Rep. 87 (1982) 77; Phys. Rev. C 56 (1997) 3369; Phys. Lett. B420 (1998) 267)*

$$f_\pi m_\pi^2 = \left(m_u^\zeta + m_d^\zeta\right)\rho_\pi^\zeta$$
$$f_K m_K^2 = \left(m_u^\zeta + m_s^\zeta\right)\rho_K^\zeta$$

- Pseudoscalar masses are generated **dynamically**
  - From these exact statements, it follows the mass of bound states increases as √m with the mass of the constituents.
  - In contrast, in, *e.g*. the CQM, bound state mass rises linearly with constituent mass, *e.g.*, with constituent quarks Q: in the nucleon $m_Q \sim ⅓m_N \sim 310$ MeV, in the pion $m_Q \sim ½m_\pi \sim 70$ MeV, in the kaon (with one s quark) $m_Q \sim 200$ MeV – **This is not real**.
  - In both DSE and LQCD, the mass function of quarks is the same, regardless what hadron the quarks reside in – **This is real**. It is the Dynamical Chiral Symmetry Breaking (DχSB) that makes the pion and kaon masses light.

The role of gluons in the chiral limit

In the chiral limit, using a parton model basis: *the entirety of the proton mass is produced by gluons and due to the trace anomaly*

$$\langle P(p)|\Theta_0|P(p)\rangle = -p_\mu p_\mu = m_N^2$$

In the chiral limit, for the pion ($m_\pi = 0$):

$$\langle \pi(q)|\Theta_0|\pi(q)\rangle = -q_\mu q_\mu = m_\pi^2 = 0$$

Sometimes interpreted as: *in the chiral limit the gluons disappear and thus contribute nothing to the pion mass*.

This is unlikely as quarks and gluons still dynamically acquire mass – this is a universal feature in hadrons – so more likely a cancellation of terms leads to “0”

Nonetheless: are there gluons at large Q^2 in the pion or not?

Fundamental Questions

For understanding the origin of hadron masses and distribution of that mass within

- How do hadron masses and radii emerge for light-quark systems from QCD?
- What is the origin and role of dynamical chiral symmetry breaking?
- What is the interplay of the strong-mass and Higgs generation mechanisms?
- What are the basic mechanisms that determine the distribution of mass, momentum, charge, spin, etc. within hadrons?

Requires coherent effort in QCD phenomenology and continuum calculations, exa-scale computing as provided by lattice QCD, and experiment

Key Experimental Efforts at an EIC

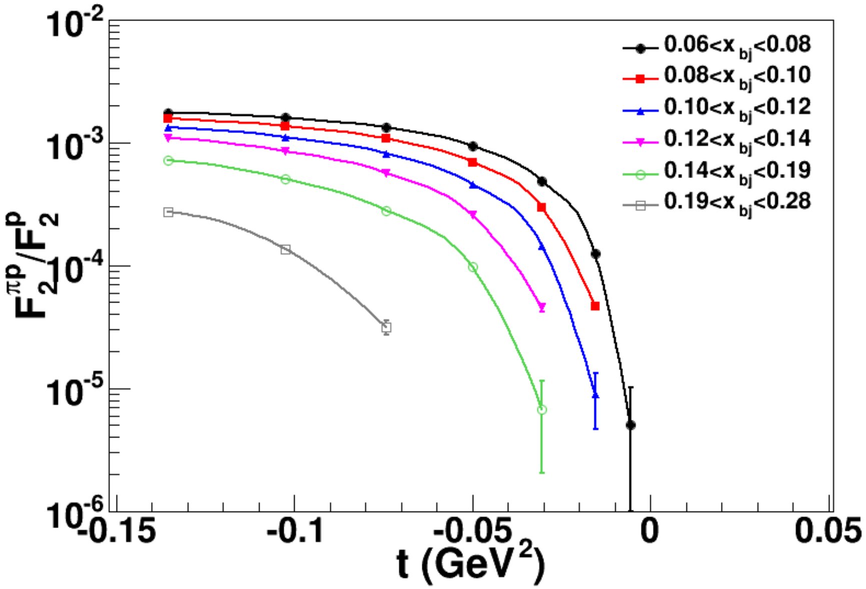
- Hadron masses in light quark systems
  - Pion and kaon parton distribution functions (PDFs) and generalized parton distributions (GPDs)
- Gluon (binding) energy in Nambu-Goldstone modes
  - Open charm production from pion and kaon
- Mass acquisition from Dynamical Chiral Symmetry Breaking (DCSB)
  - Pion and kaon form factors
- Strong vs. Higgs mass generating mechanisms
  - Valence quark distributions in pion and kaon at large momentum fraction x
- Timelike analog of mass acquisition
  - Fragmentation of a quark into pions or kaons

EIC – Versatility and Luminosity is Key

Why would pion and kaon structure functions, and even measurements of pion structure beyond (pion GPDs and TMDs) be feasible at an EIC?

- $L_{EIC} = 10^{34} = 1000 \times L_{HERA}$
  - Detection fraction @ EIC in general much higher than at HERA
- Fraction of proton wave function related to pion Sullivan process is roughly 10^{-3} for a small –t bin (0.02).
- Hence, pion data @ EIC should be comparable or better than the proton data @ HERA, or the 3D nucleon structure data @ COMPASS
- If we can convince ourselves we can map pion (kaon) structure for –t < 0.6 (0.9) GeV2, we gain at least a decade as compared to HERA/COMPASS.

A.C. Aguilar et al., ***arXiv:1907.08218*** *(**2019**); soon in EPJA*



Ratio of the F_2 structure function related to the pion Sullivan process as compared to the proton F_2 structure function in the low-t vicinity of the pion pole, as a function of Bjorken-x (for JLab kinematics)

World Data on pion structure function F_2^π

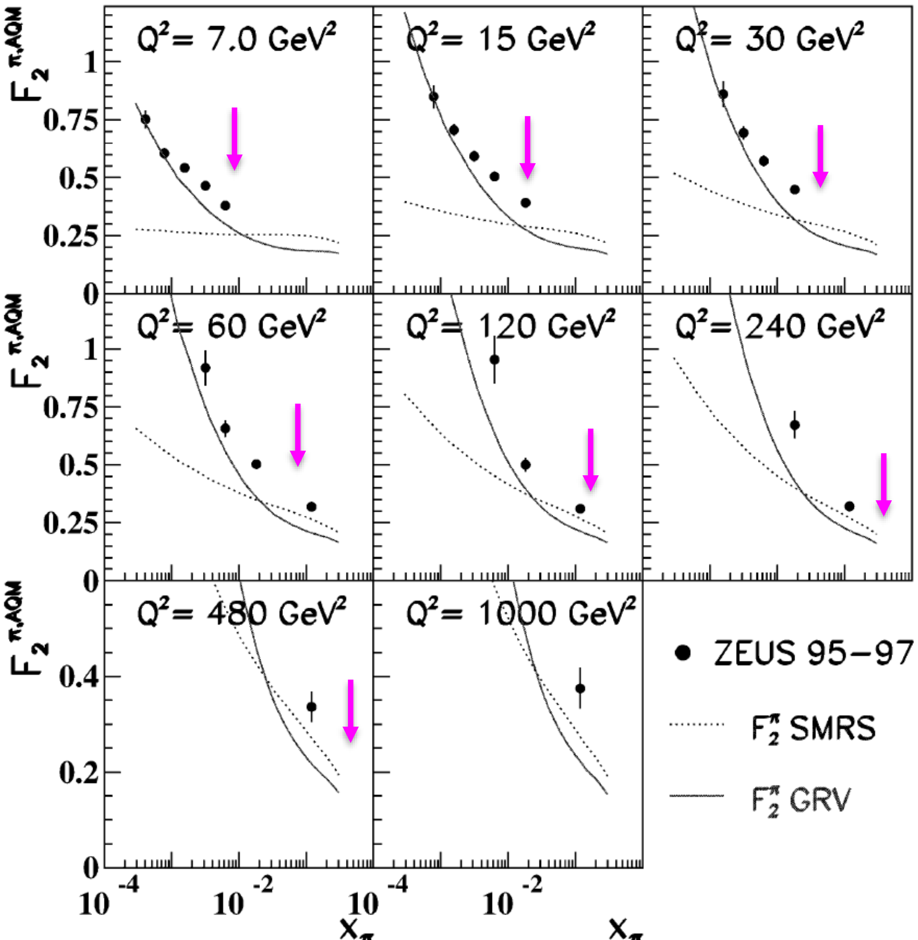
HERA

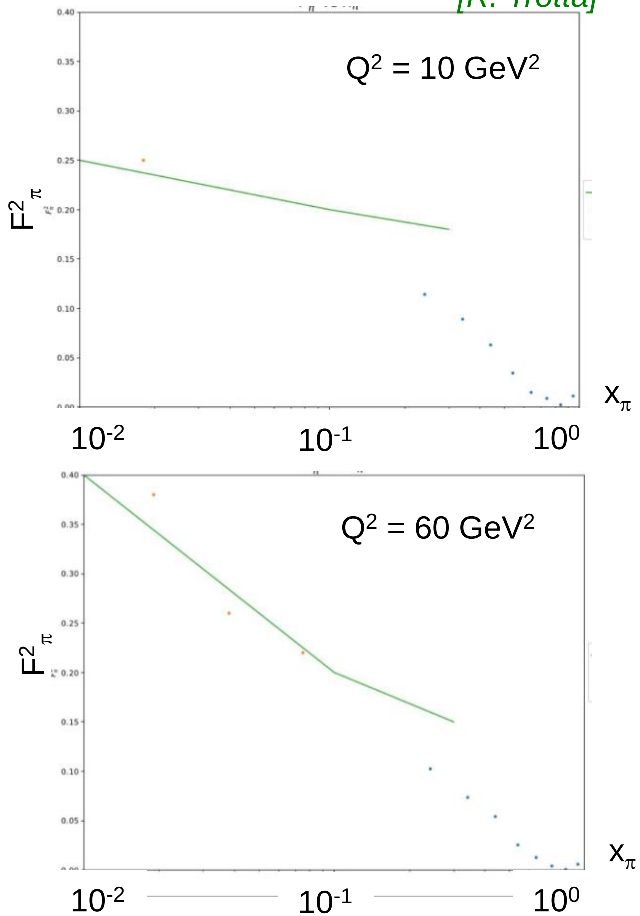
~x_{min} for EIC

EIC

Here example for 5 GeV e^- and 100 GeV p

[R. Trotta]



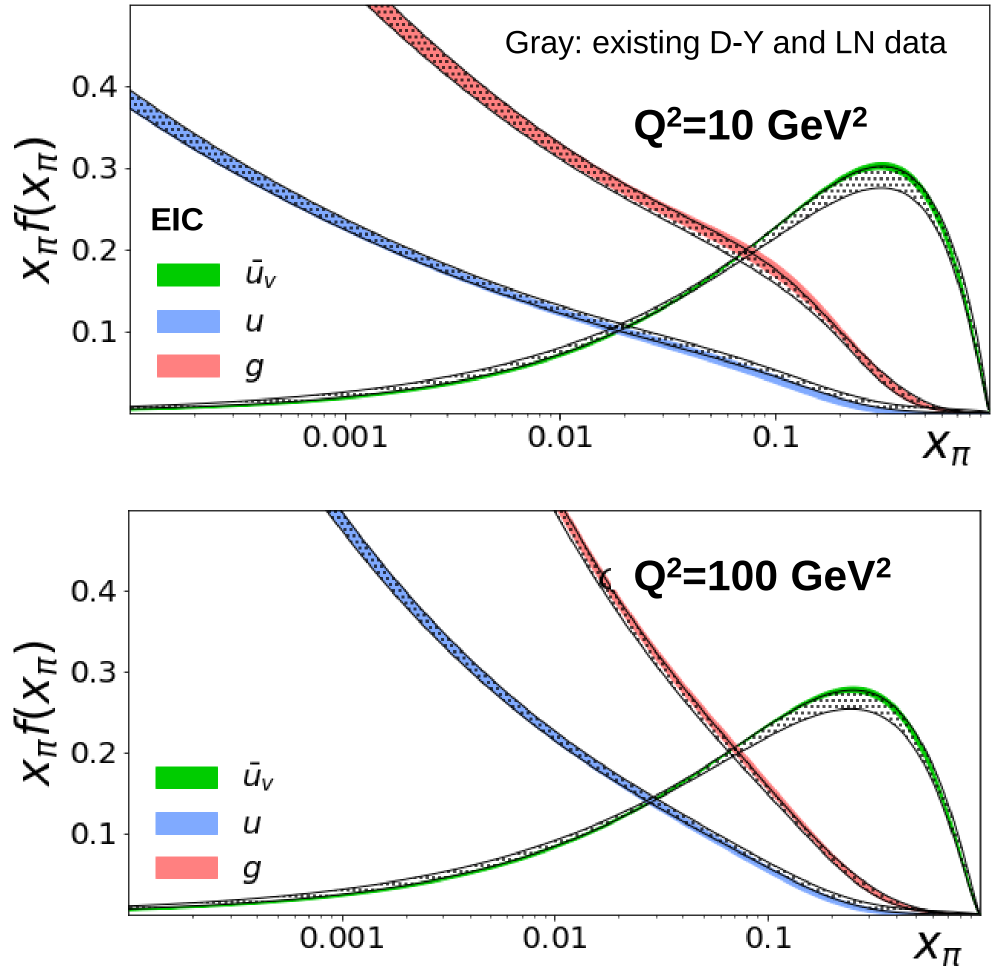


- ❑ **EIC kinematic reach down to a x = few 10^{-3}**
- ❑ **Lowest x constrained by HERA**

Global pion PDF fit with EIC pseudodata

*A.C. Aguilar et al., **arXiv:1907.08218** (**2019**); soon in EPJA*

- 5 GeV (e-) on 50 GeV (p)
- $0.1 < y < 0.8$
- EIC pseudodata fitted using self-serve pion PDF framework
- EIC will improve the PDFs, especially for kaons as will have similar-quality data.
- DY measurements by COMPASS++/AMBER could constrain $x>0.02$



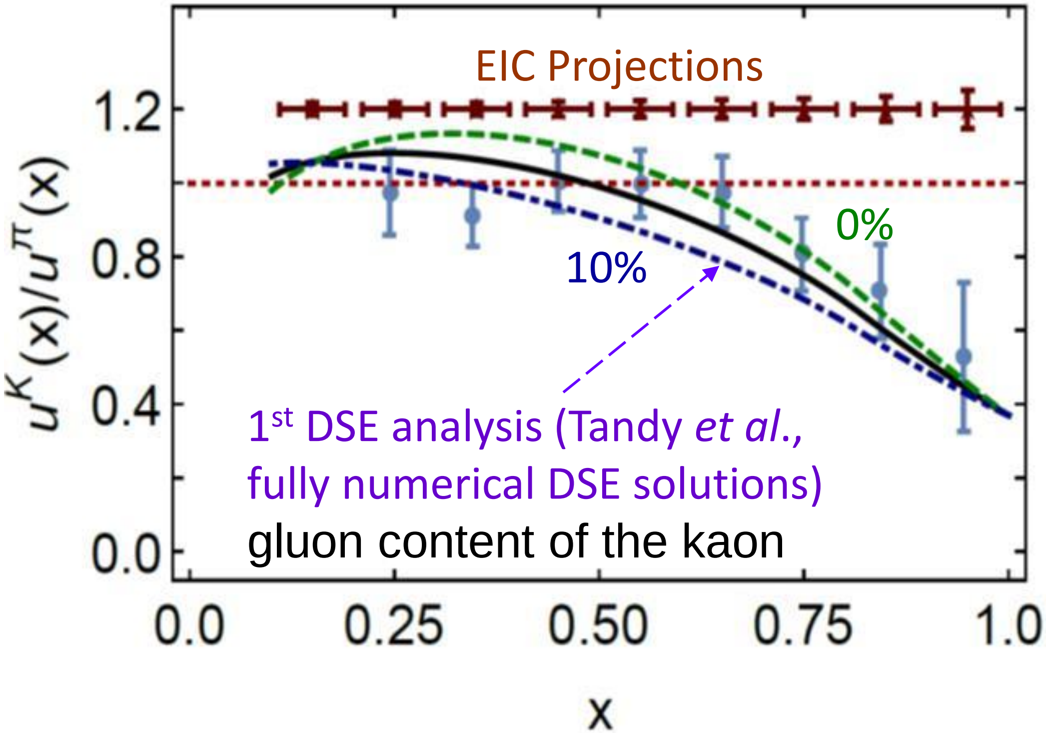
Precision gluon constraints of pion and kaon PDFs <u>are</u> possible.

Kaon structure functions – gluon pdfs

Based on Lattice QCD calculations and DSE calculations:

- Valence quarks carry 52% of the pion's momentum at the light front, at the scale used for Lattice QCD calculations, or ~65% at the perturbative hadronic scale
- At the same scale, valence-quarks carry ⅔ of the kaon's light-front momentum, or roughly 95% at the perturbative hadronic scale

*A.C. Aguilar et al., **arXiv:1907.08218** (**2019**); soon in EPJA*



Thus, at a given scale, there is far **less glue in the kaon than in the pion**:

- heavier quarks radiate less readily than lighter quarks
- heavier quarks radiate softer gluons than do lighter quarks
- Landau-Pomeranchuk effect: softer gluons have longer wavelength and multiple scatterings are suppressed by interference.
- Momentum conservation communicates these effects to the kaon's u-quark.

Pion Form Factor Prospects

1. Models show a strong dominance of σ_L at small –t at large Q^2.
2. Assume dominance of this longitudinal cross section
3. Measure the π^-/π^+ ratio to verify – it will be diluted (smaller than unity) if σ_T is not small, or if non-pole backgrounds are large

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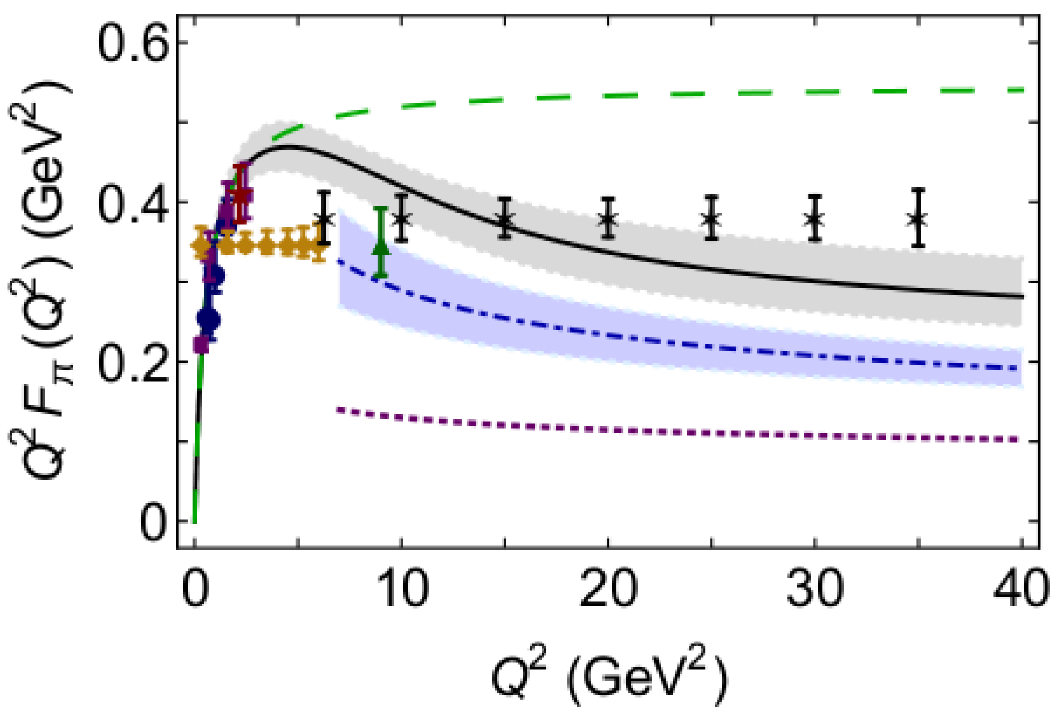

- ❑ Assumed 5 GeV(e$^-$) x 100 GeV(p) with an integrated luminosity of 20 fb^{-1}/year, and similar luminosities for d beam data
- ❑ R=σ_L/σ_T assumed from VR model – and assume that π pole dominance at small t confirmed in ^{2}H π^-/π^+ ratios
- ❑ Assumed a 10% experimental systematic uncertainty, and a 100% systematic uncertainty in the model subtraction to isolate σ_L

Can we measure the kaon form factor at EIC?

Not clear – needs guidance from JLab 12- GeV

Summary

- Meson structure measurements play an important role in our understanding of the structure and interactions of hadrons based on the principles of QCD

- Meson form factors can be accessed through the Sullivan process
  - Technique validated experimentally – also theoretical calculations
  - JLab: Pion and kaon form factor extractions up to high Q^2 (~9 and ~6 GeV^2)

- Towards GPD flavor decomposition with $\pi^+/K^+/\pi^0$ electroproduction
  - JLab: Q^2 dependence of L/T separated π^+/K^+ cross sections to Q^2 ~9/~6 GeV^2
  - JLab: NPS enables π^0 L/T separation – access to transversity GPDs

- Opportunities to map meson structure functions through the Sullivan process
  - JLab TDIS experiments – resolve large x issues
  - EIC: mapping pion and kaon structure functions over a large (x, Q^2) landscape