The 1D Meson and Ground Baryon Structure from JLab Experiments

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Hadron Structure from Strong QCD Workshop

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Electromagnetic Form Factors

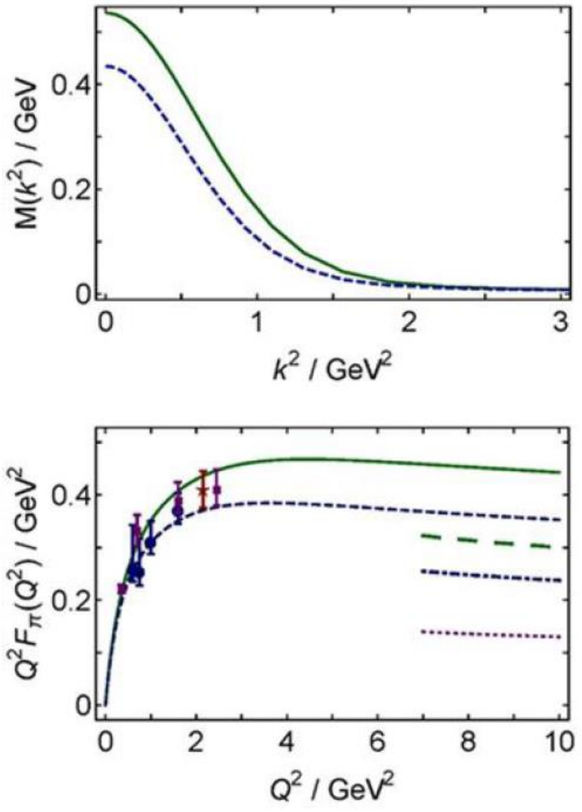
- ❑ Fundamental properties of mesons (pion, kaon,…), and nucleons
  - ➢ Contain information on charge, magnetization distributions
  - ➢ Connect to distributions, dynamics of quarks in hadrons

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

- ❑ Recent advances and future prospects
  - ➢ Dramatically improved precision of measurements

- ❑ Implications of new results
  - ➢ New information on basic hadron structure and dynamic generation of light hadron mass
  - ➢ Advances other programs relying on the same or similar experimental techniques
    - ○ Validation of the reaction mechanism for GPD studies
    - ○ Meson structure (PDF) measurements

A.C. Aguilar et al., Eur. Phys. J. ***A 55*** *(2019) 190*



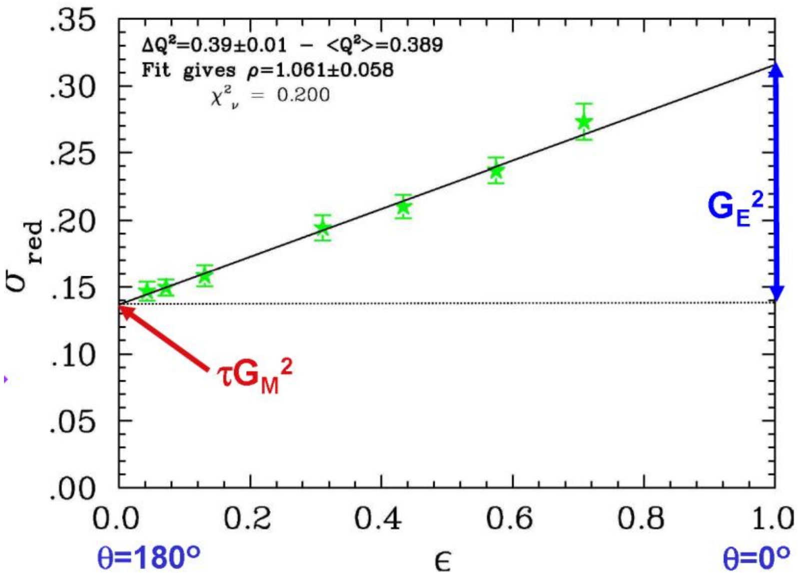
Unpolarized elastic e-N Scattering

- ☐ Rosenbluth separation:

$$\sigma_R = \frac{d\sigma}{d\Omega}(\varepsilon[1+\tau])\frac{1}{\sigma_{Mott}}$$

$$= \tau\, G_M^2 + \varepsilon\, G_E^2$$

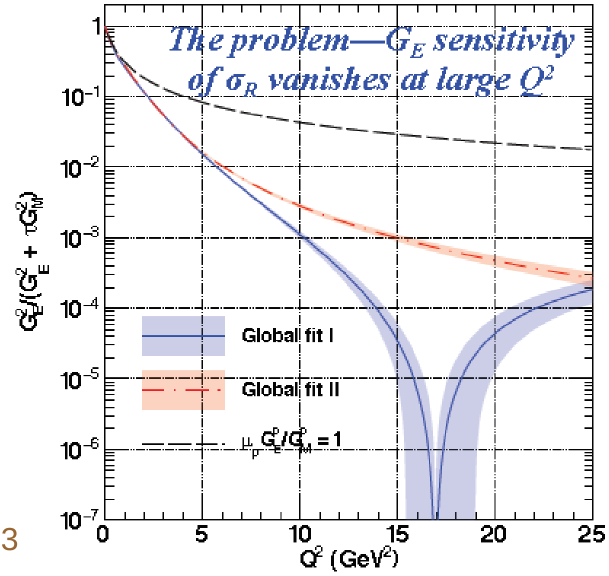
$$\varepsilon = [1 + 2(1+\tau)\tan(\theta/2)^2]^{-1}$$



- ☐ Reduced sensitivity when one term dominates
  - ➢ G_M if $\tau \ll 1$
  - ➢ G_E if $\tau \gg 1$

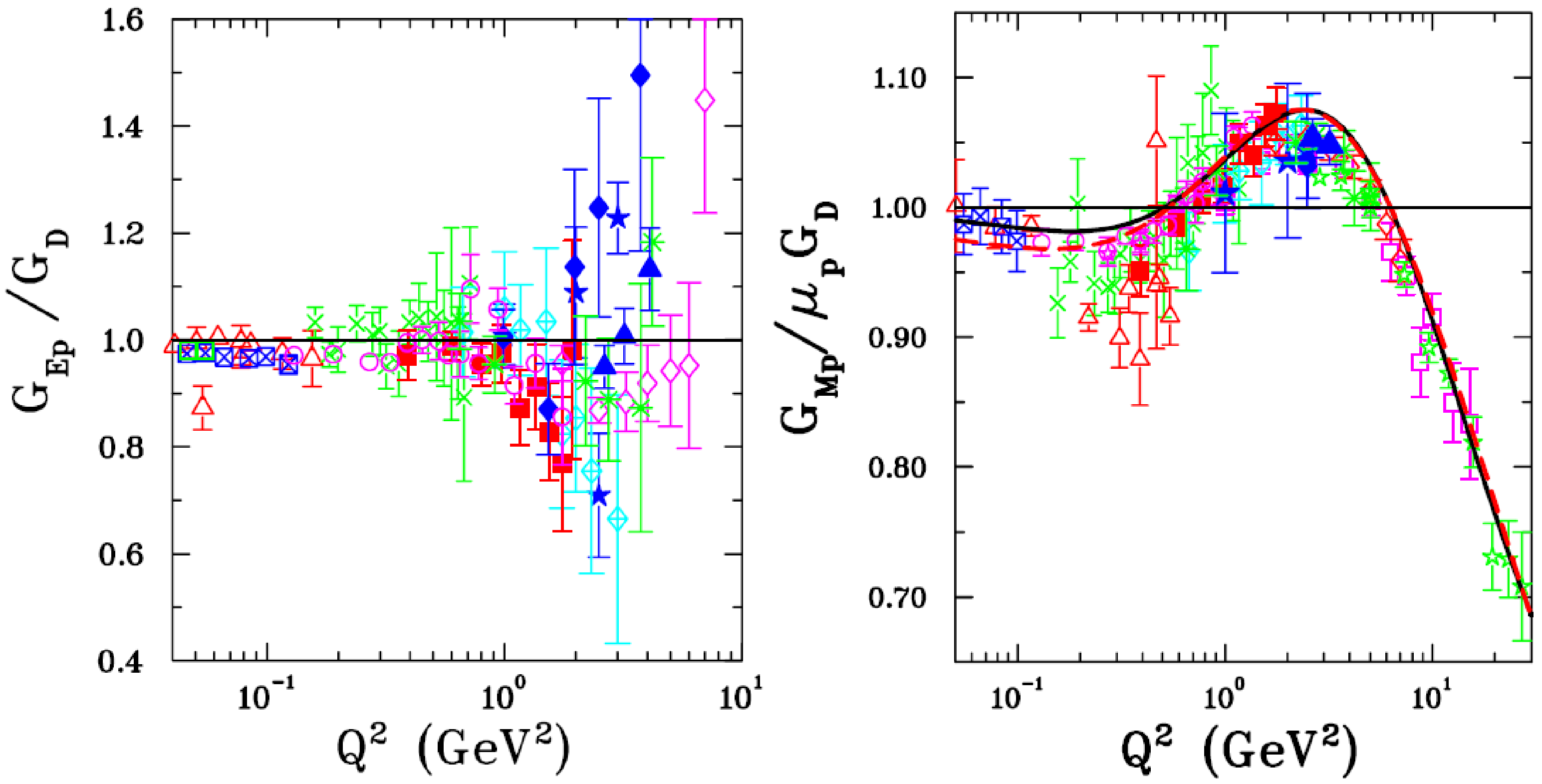
$$\tau = \frac{Q^2}{4M^2}$$

- ➢ In particular, maximum contribution of G_E^2 term to the cross section vanishes at large Q^2



Puckett et al., PR**C96** (2017) 055203

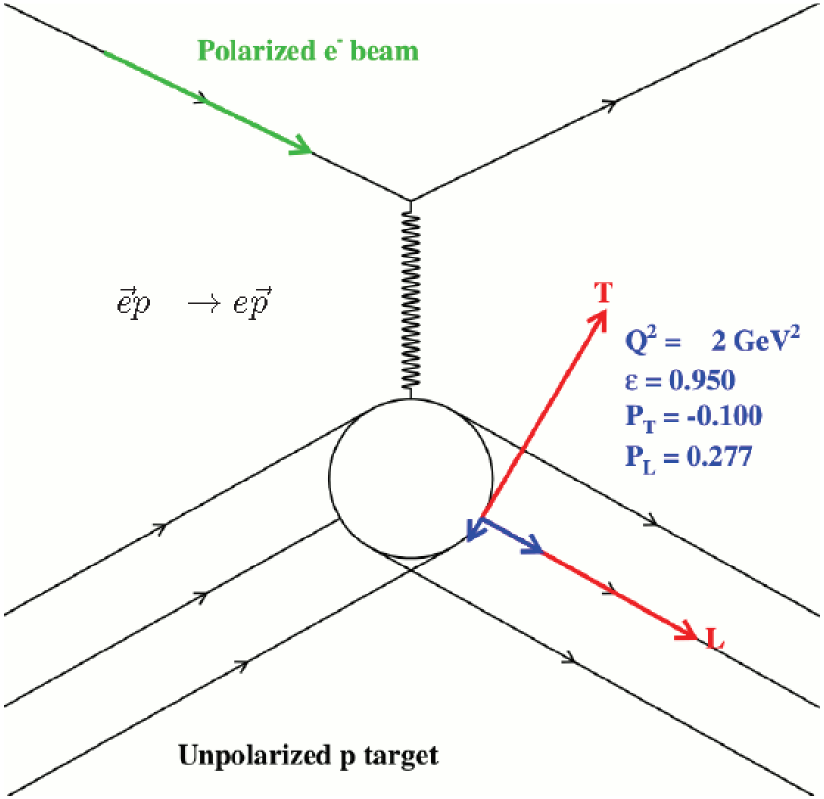
Proton Form Factor Rosenbluth Data



G_E^p and G_M^p Rosenbluth data: $G_E^p \approx \frac{1}{\mu} G_M^p \approx G_D$

- Elastic e-p cross sections have been measured for $0.003 \le Q^2 \le 31.2$ GeV^2
- Rosenbluth data are qualitatively described by the dipole form factor, the Fourier transform of a spherically symmetric, exponentially decreasing radial density

Alternate Technique: Polarization Transfer in Elastic e-N Scattering



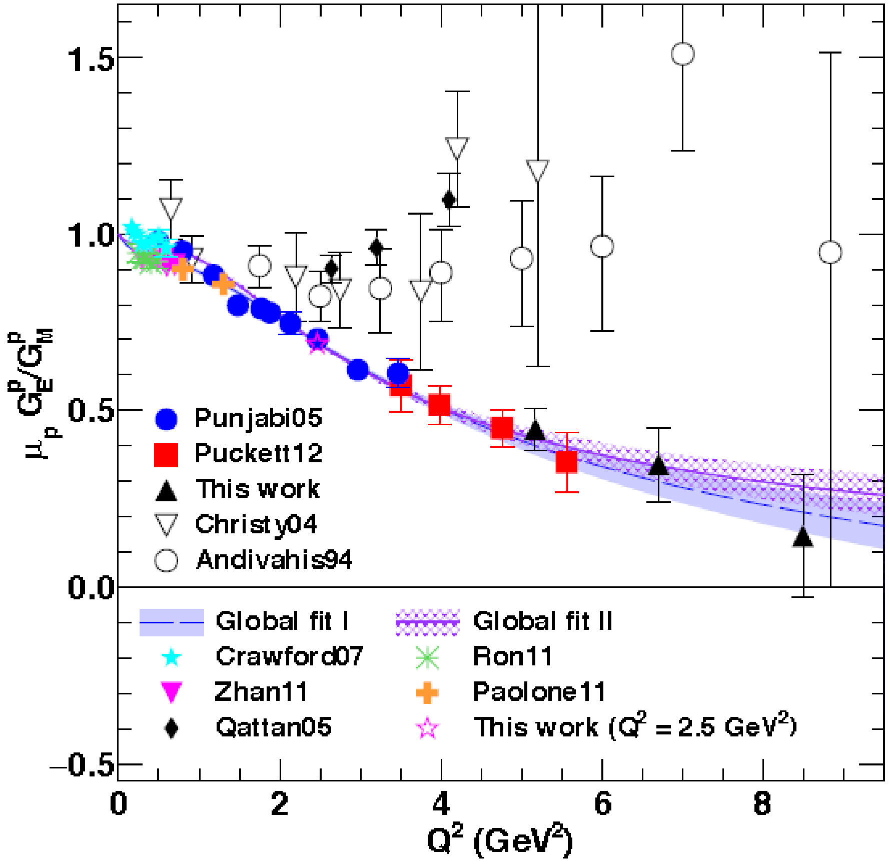
$$\begin{aligned} P_t &= -P_{beam}\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\,\frac{r}{1+\frac{\epsilon}{\tau}r^2} \\ P_\ell &= P_{beam}\frac{\sqrt{1-\epsilon^2}}{1+\frac{\epsilon}{\tau}r^2} \\ P_n &= 0 \\ r &\equiv \frac{G_E}{G_M} \end{aligned}$$

$$\Longrightarrow\ R_p \equiv \mu_p\frac{G_E^p}{G_M^p} = -\mu_p\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}}\,\frac{P_t}{P_\ell}$$

- Akhiezer and Rekalo (1968) derived relations between transferred polarization components in elastic e-N scattering and the ratio of EM FFs

- The ratio of transferred polarization components is directly proportional to G_E/G_M and thus more sensitive to G_E at large Q^2 than the cross section method

Proton Electric Form Factor (2019)



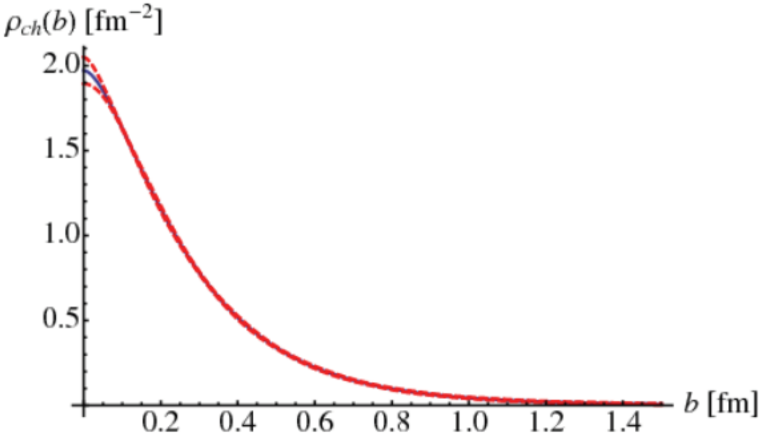
- GEp-I
  - Jones et al., PRL **84** (2000)1398
  - Punjabi et al., PRC **71** (2005) 055202
- GEp-II
  - Gayou et al., PRL **88** (2002) 092301
  - Puckett et al., PRC **85** (2012) 045203
- GEp-III
  - Puckett et al., PRL **104** (2010) 242301
  - Meziane et al., PRL **106** (2011) 132501
  - Puckett et al., PRC **96** (2017) 055203
- Low Q^2 data from JLab
  - Ron et al., PRL **99** (2007) 202002
  - Ron et al., PRC **84** (2011) 055204
  - Zhan et al., PLB **705** (2011) 59-64
  - Paolone et al., PRL **105** (2010) 072001

- GEp experiments have changed fundamental view on proton structure
- Discrepancy remains to be fully understood

Insights: Transverse Densities

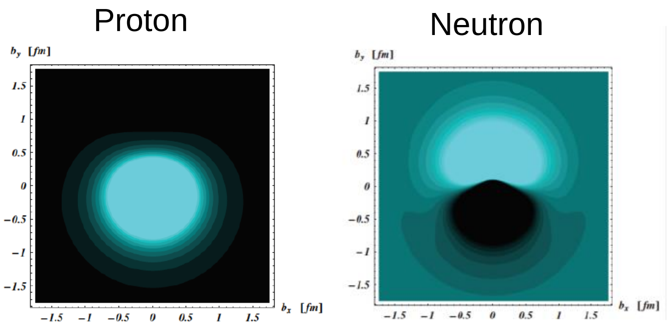
- ☐ Simple Picture: Fourier transform of the spatial distribution
  - ➢ Spatial distribution in Breit frame
  - ➢ Model dependent corrections in extracting rest frame distributions

Miller et al, PRC **83** (2011) 015203



- ☐ Model-independent relation between form factors and transverse spatial distribution
  - ➢ Impact parameter space densities in the infinite momentum frame derived from GPD-FF sum rules

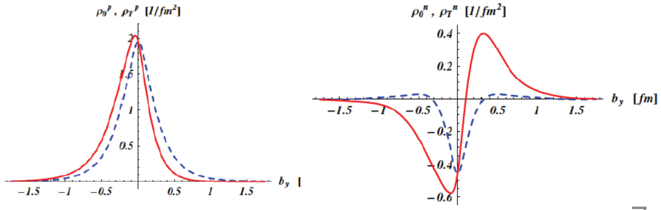
$$\rho_{ch}(b) = \frac{1}{2\pi}\int QdQJ_0(Qb)F_1(Q^2)$$



- ☐ Polarized transverse charge densities

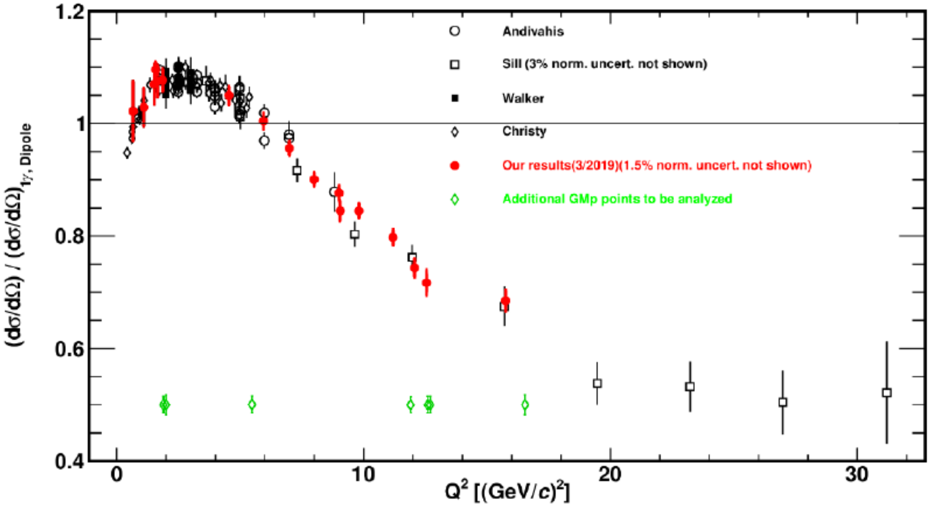
Carlson and Vanderhaeghen, PRL **100** (2008) 032004

→ Also see M. Vanderhaeghen’s talk at this workshop

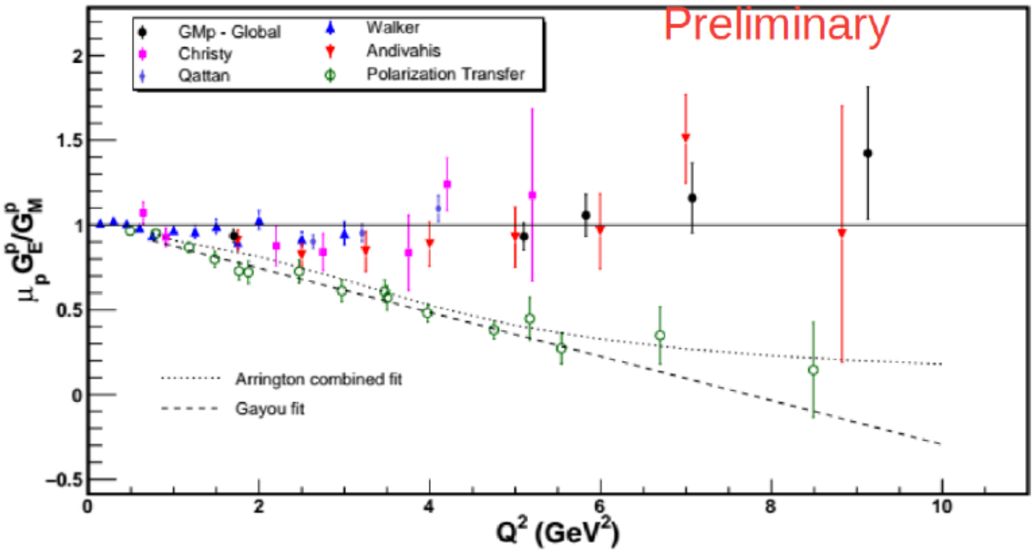


Proton Magnetic Form Factor

- ☐ Preliminary results from 2016
  - ➢ JLab experiment E12-07-108
  - ➢ Ran in Hall A – used the two identical HRSs



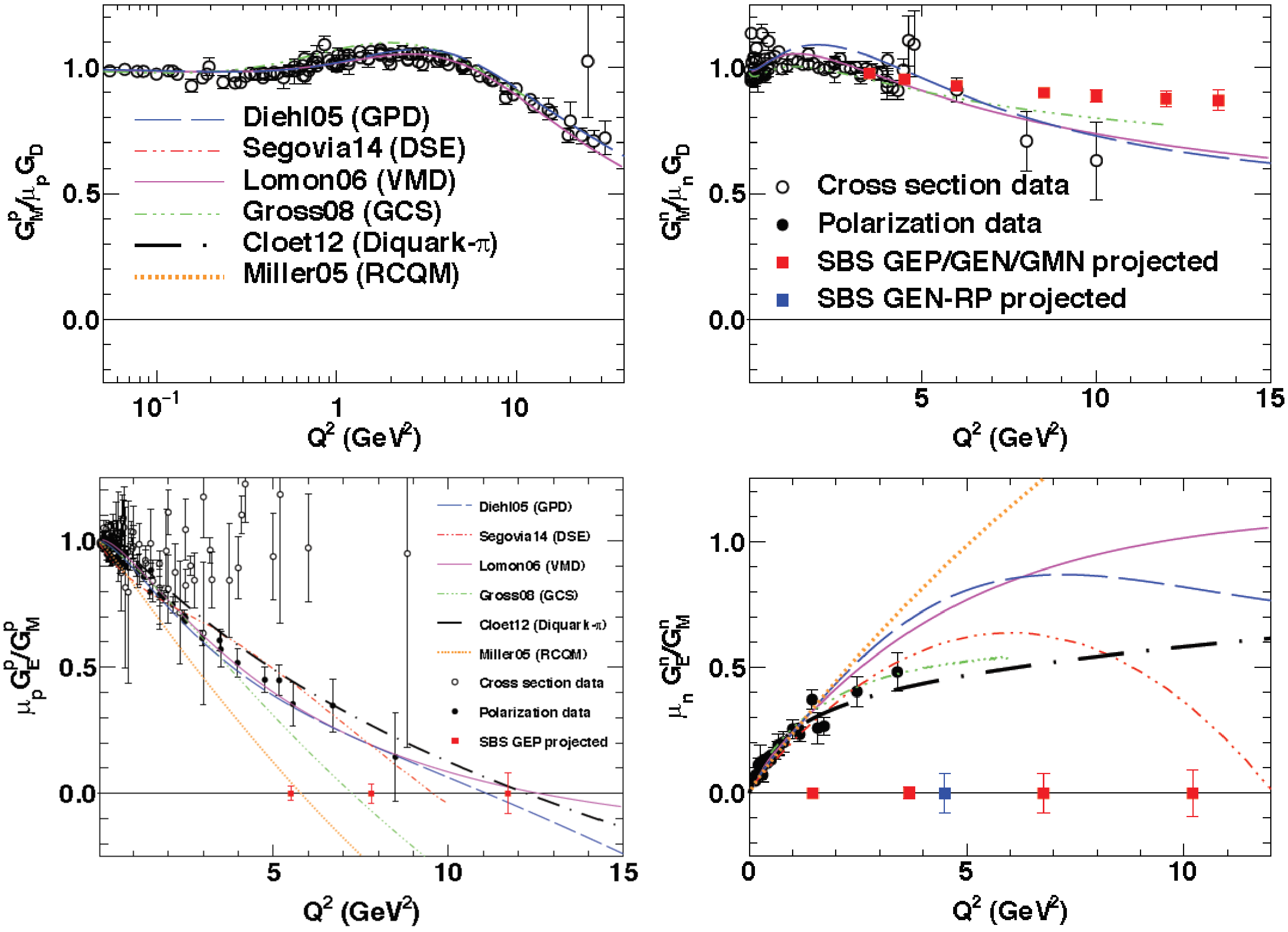
- ☐ Cross section – significant improvement in precision for $Q^2 > 6$ GeV^2



- ☐ GMp (E12-07-108) data significantly reduce uncertainty on the ratio at the largest Q^2
  - ➢ Further highlights discrepancy with polarization transfer data up to $Q^2 > 9$ GeV^2

*E12-**07**-108 spokespersons: B. Wojtsekhowski, J. Arrington, M. Christy, S. Gilad, V. Sulkosky*

Reaching Higher Q^2: The SBS Nucleon Form Factor Program



*E12-**07**-109 - G_E^p*

*E12-**09**-016 - G_M^p*

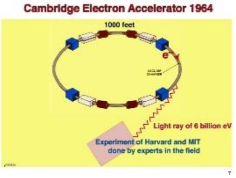
*E12-**07**-108 - G_E^n*

*E12-**09**-019 - G_M^n*

Meson Production and Form Factors

Experiment

Capability to reliably access large Q^2 regime



Jefferson Lab

JLab 6 GeV

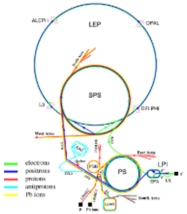
JLab 12 GeV

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

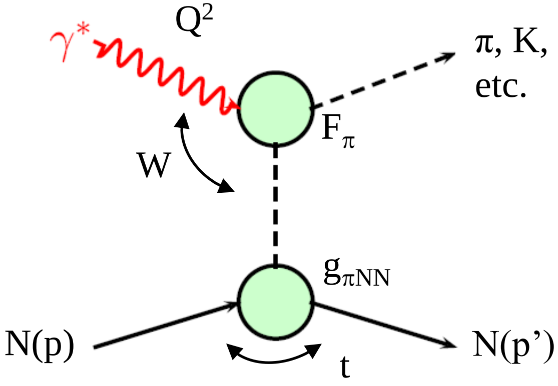
Major progress on hadron structure calculations (also lattice and global fitting), e.g. large Q^2 behavior of meson form factor

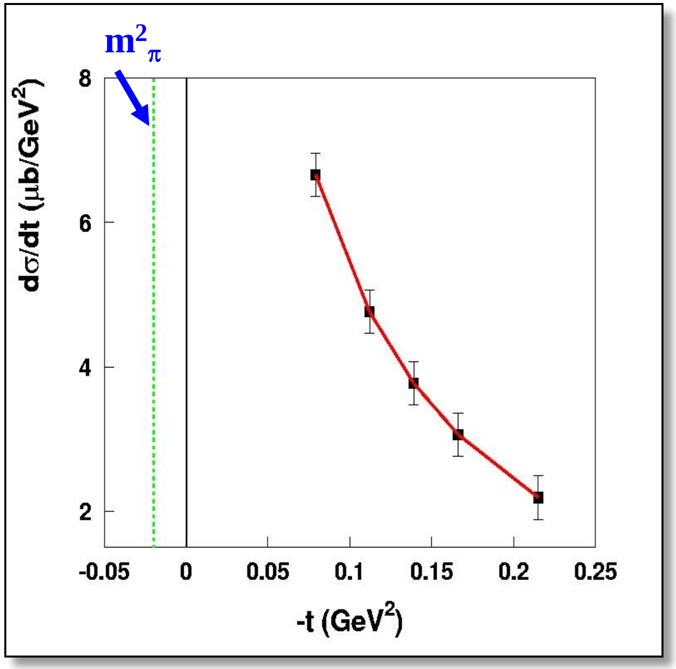
Accessing meson form factors through the Sullivan Process

- Sullivan Process allows accessing effective targets not readily found in nature

- $F_{\pi+}$ at $Q^2>0.3$ GeV^2 is measured 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

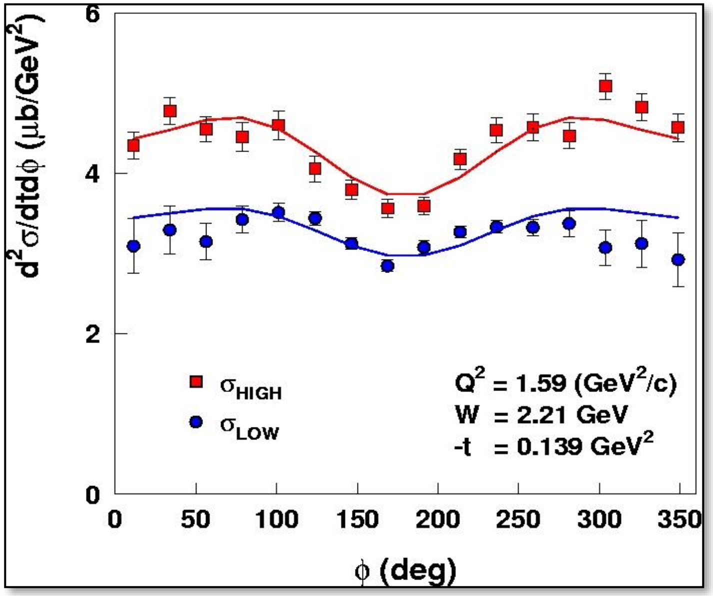
$$\frac{d\sigma_L}{dt} \propto \frac{-t}{(t-m_\pi^2)} g^2_{\pi NN}(t)\, Q^2 F_\pi^2(Q^2,t)$$

[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]*



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

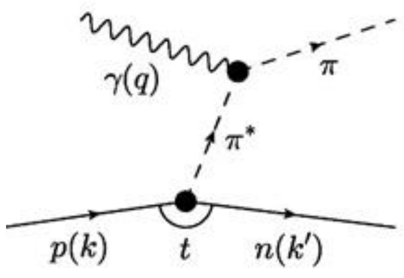
σ_L will give us F_π

Magnetic spectrometers a must for such precision cross section measurements

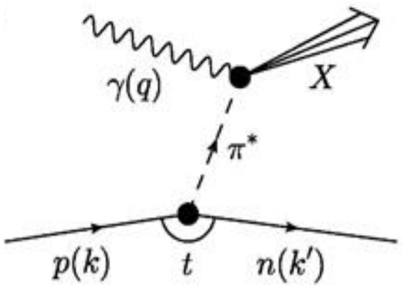
- This is only possible in Hall C at JLab

Experimental Considerations

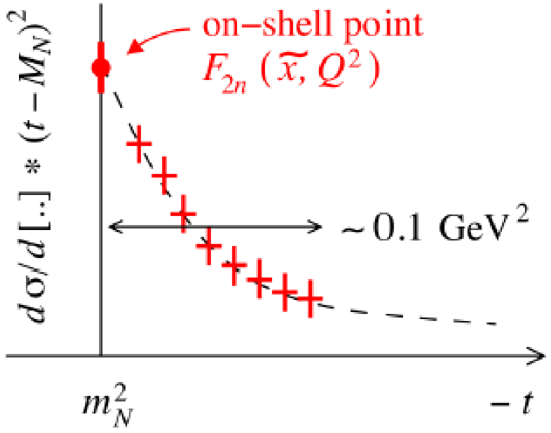
- The **Sullivan process can provide reliable access to a meson target** as *t* becomes space-like if the pole associated with the ground-state meson is the dominant feature of the process and the structure of the (off-shell) meson evolves slowly and smoothly with virtuality.



Elastic Form Factor



DIS



- Recent **theoretical calculations found that for -t ≤ 0.6 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**

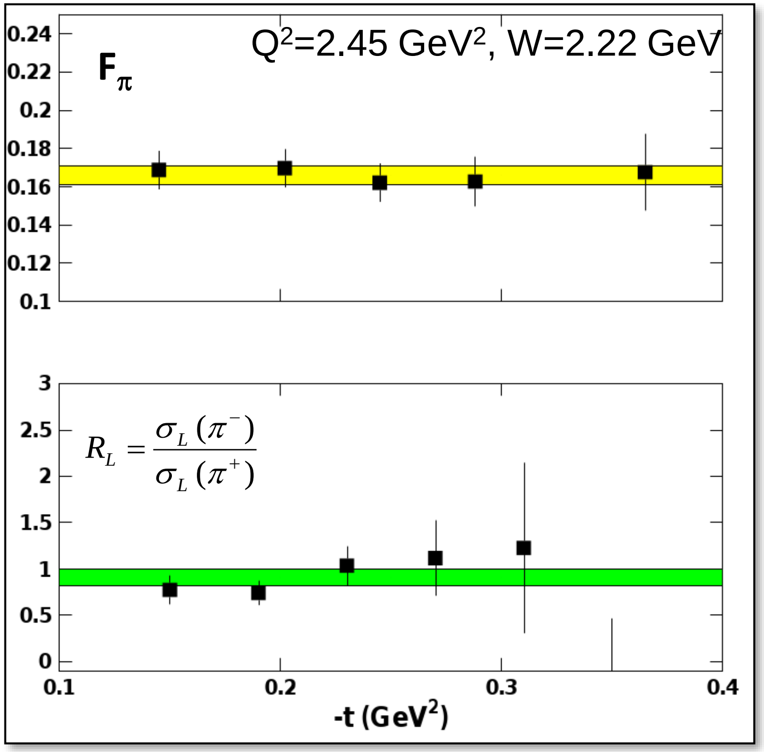
Experimental Validation (Pion Form Factor example)

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

Experimental studies include:

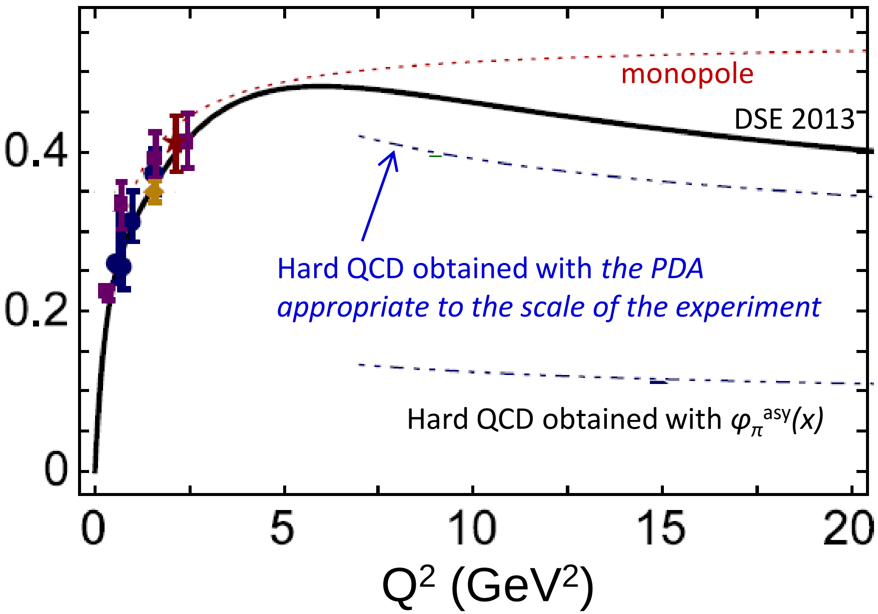
- **Check F_π extraction for a range of t**
  - ○ F_π values seem robust at larger -t (>0.2) – increased confidence in applicability of model to the kinematic regime of the data
- **Verify** that the **pion pole diagram** is the **dominant contribution** in the reaction mechanism
  - ○ R_L (= $\sigma_L(\pi^-)/\sigma_L(\pi^+)$) 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*



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

Pion Form Factor (2019)



*[L. Chang, et al., PRL **111** (2013) 141802; PRL **110** (**2013**) 1322001]*

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

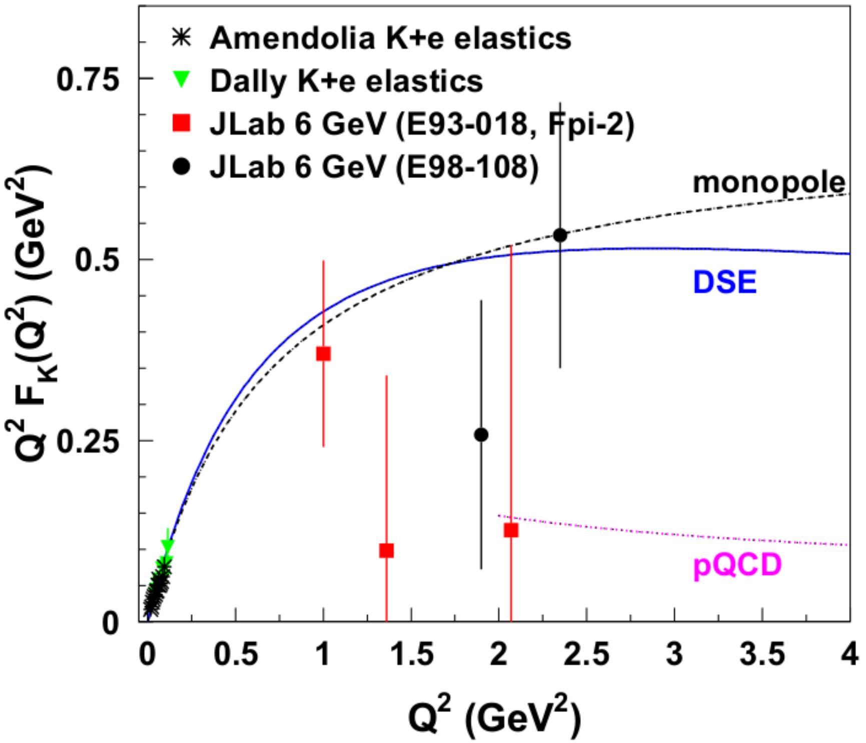
6 GeV Pion L/T and FF Program:

- **High precision** pion FF data up to **Q^2~2.5 GeV^2**

- J. Volmer et al., PRL **86** (2001) 1713 – **305 citations**
  - Precision F_π results between Q^2=0.60 and 1.60 GeV^2
- T. Horn et al., PRL **97** (2006) 192001 – **236 citations**
  - Precision F_π results at Q^2=1.60 and 2.45 GeV^2
- V. Tadevosyan, et al., PRC**75** (2007) 055205 – **200 ct's**
- G. Huber et al., PRC**78** (2008) 045203 – **175 citations**
  - Archival paper of precision F_π measurements 6 GeV
- H. P. Blok et al., PRC**78** (2008) 045202 – **101 citations**
  - Archival paper of precision LT separated cross sections
- T. Horn et al., PRC**78** (2008) 058201 – **62 citations**
  - L/T cross sections and F_π at Q^2=2.15 GeV^2 ,exploratory at Q^2~4.0 GeV^2
- Plus several spin-off papers on, e.g. L/T separations in π^- and ω production, high-t, transverse charge density (2012-present)

Kaon Form Factor (2019)

M. Carmignotto et al., PRC **97** (**2018**) no. 2, 025204



- First Kaon FF extraction from JLab 6 GeV data
- Using techniques from pion analysis
- Here, comparison to DSE calculation

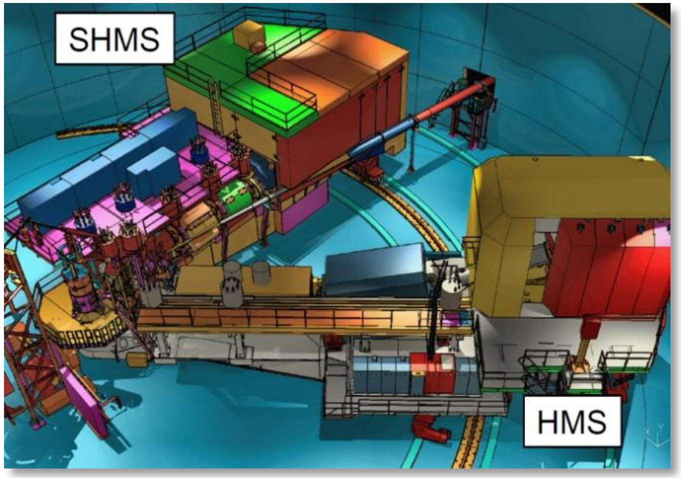
*F. Gao et al., Phys. Rev. D 96 (**2017**) no. 3, 034024*

Very limited data in region $Q^2 > 0.1$ GeV^2

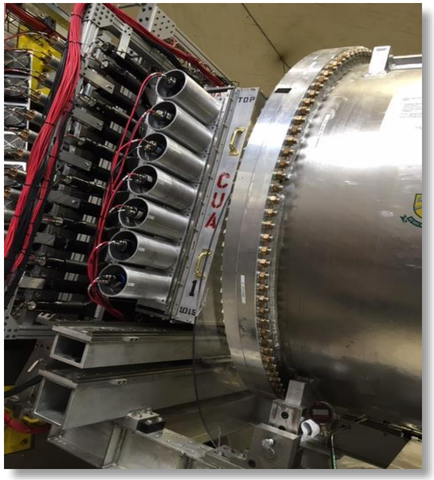
Exclusive Meson Experiments in Hall C @ 12 GeV

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

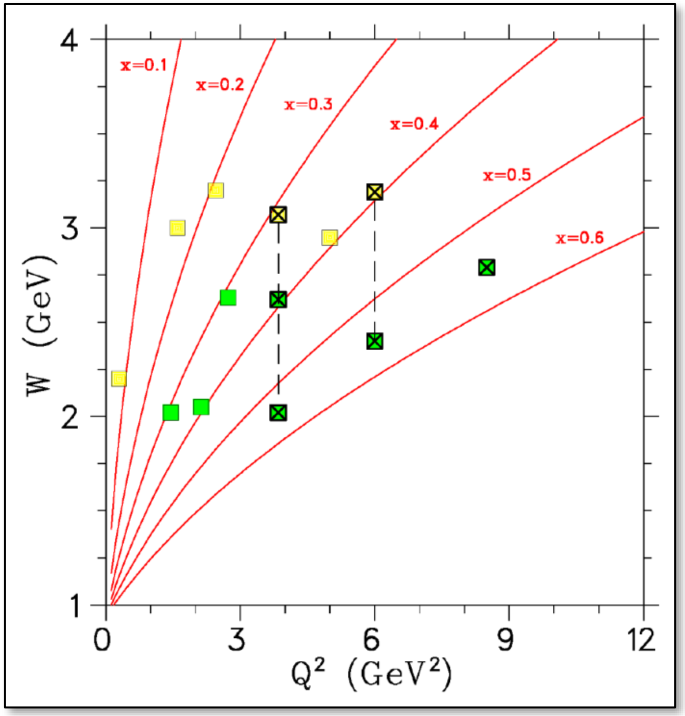
- ☐ New SHMS fulfills the meson experiments L/T separation requirements
  - ➢ Small forward-angle capabilities
  - ➢ Good angular reproducibilty
  - ➢ Missing mass resolution



- ☐ 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



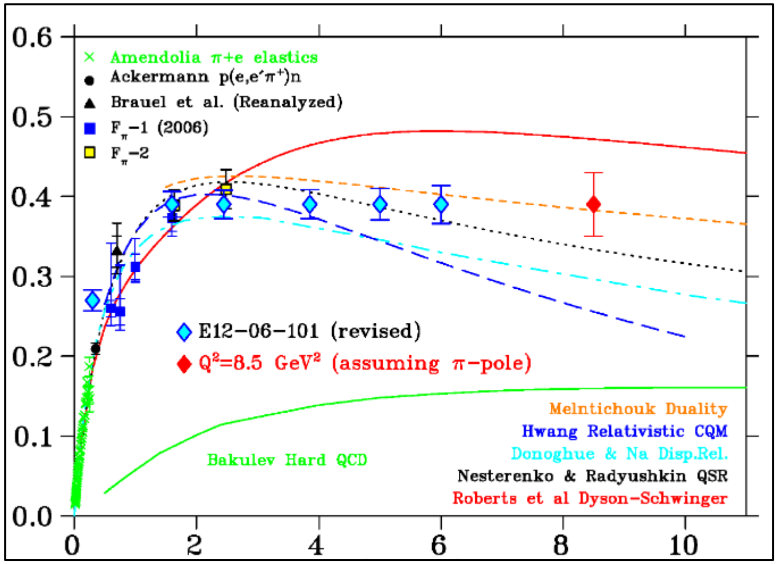
*E12-**19**-006 spokespersons: T. Horn, G. Huber, D. Gaskell*

❑ 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 – validate the reaction mechanism
- ➢ 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

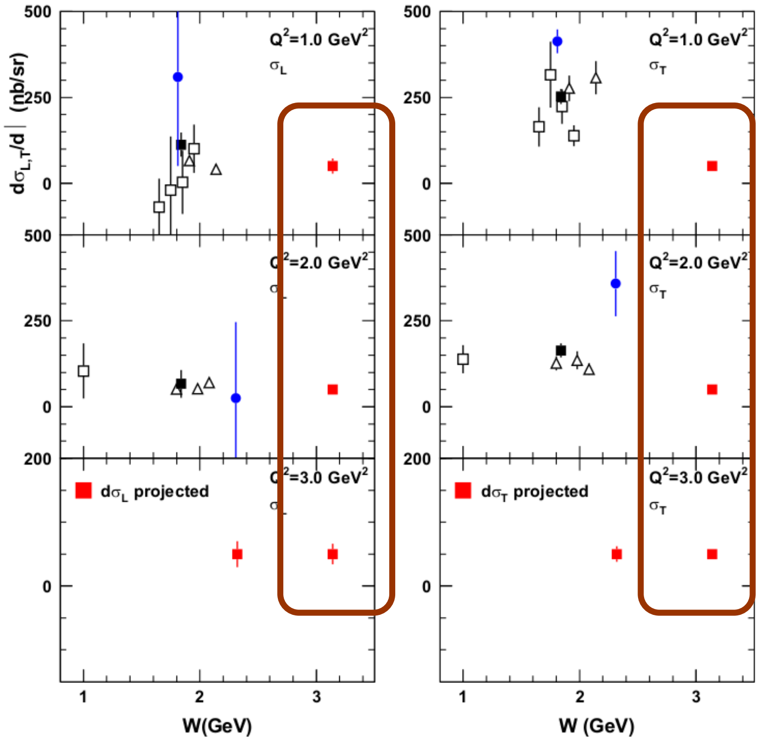
❑ **L/T separated cross sections are a cornerstone of the JLab GPD program** as they shed light on the mechanism that is most relevant for the reaction - *PAC47*

- ➢ Both L and T may provide information on GPDs; if T is large, access to transversity GPDs could become possible.



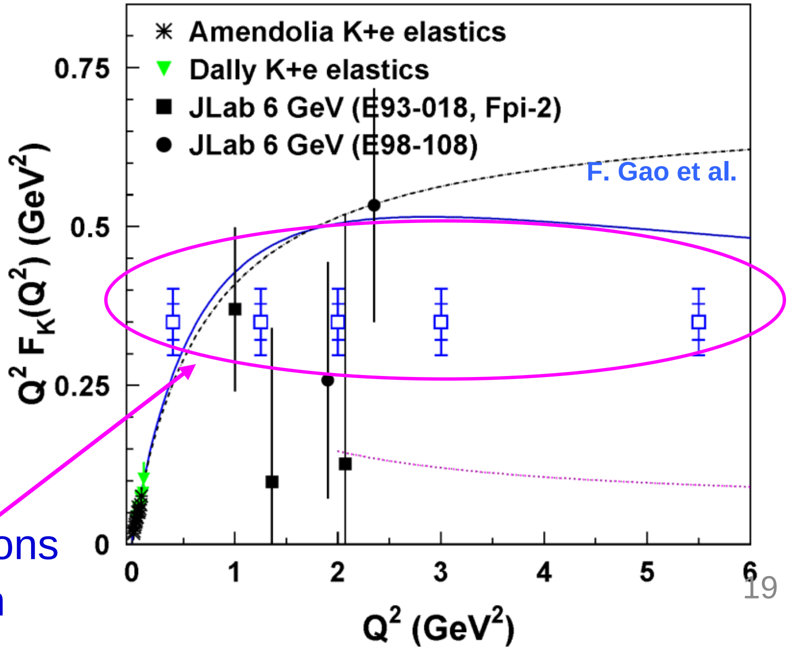
KaonLT (E12-09-011): Opportunities with Kaons

*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]



Possible extractions from 2018/19 run

- ☐ 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]

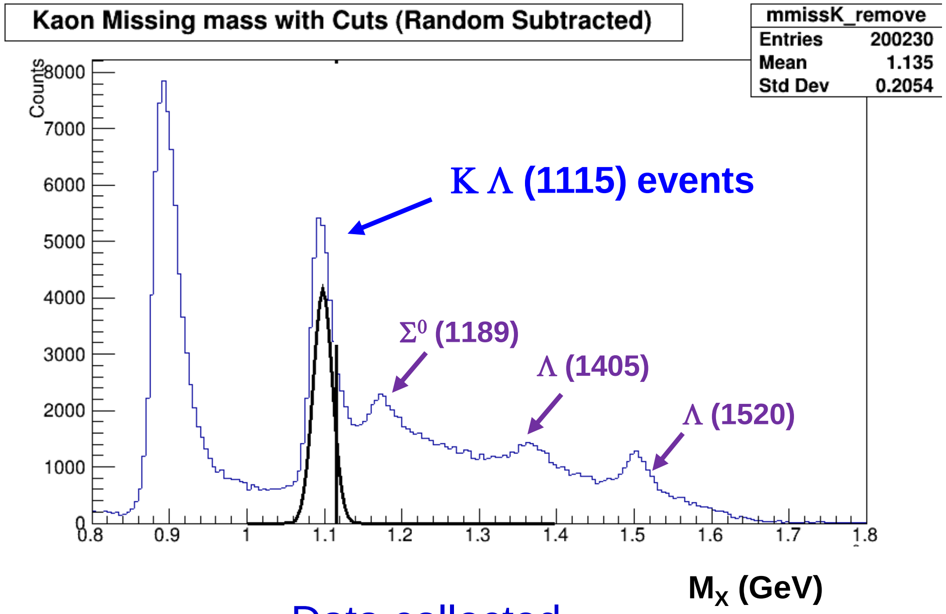
[S-S Xu et al., arXiv:1802.09552 (**2018**)]

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)ρ/p(e,e'p)ω, p(e,e'p)ϕ ratios, as possible, cross sections and p(e,e'p)η and p(e,e'p)η', Q^{-n} dependence

Online data

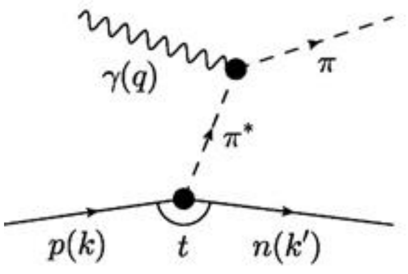


Data collected

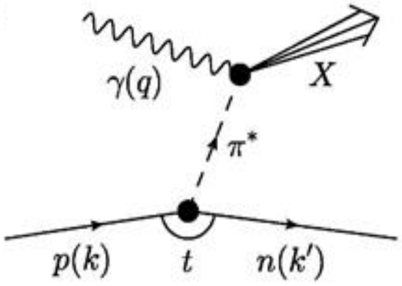
Q^2 (GeV^2)	W (GeV)	LT complete
5.5	3.02	✓
4.4	2.74	✓
3.0	3.14	✓
3.0	2.32	✓
2.115	2.95	✓
0.5	2.40	✓

Towards the Pion/Kaon Structure Function

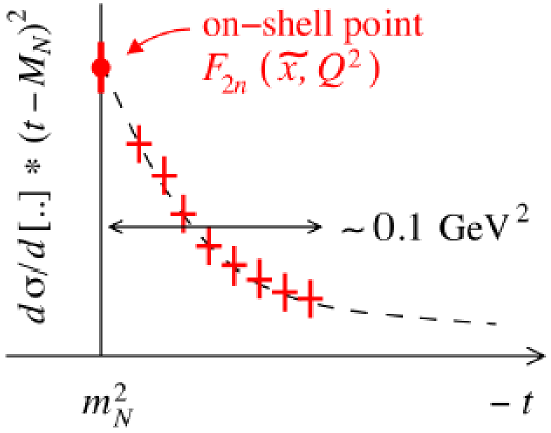
- The **Sullivan process can provide reliable access to a meson target** as *t* becomes space-like if the pole associated with the ground-state meson is the dominant feature of the process and the structure of the (off-shell) meson evolves slowly and smoothly with virtuality.



Elastic Form Factor



DIS



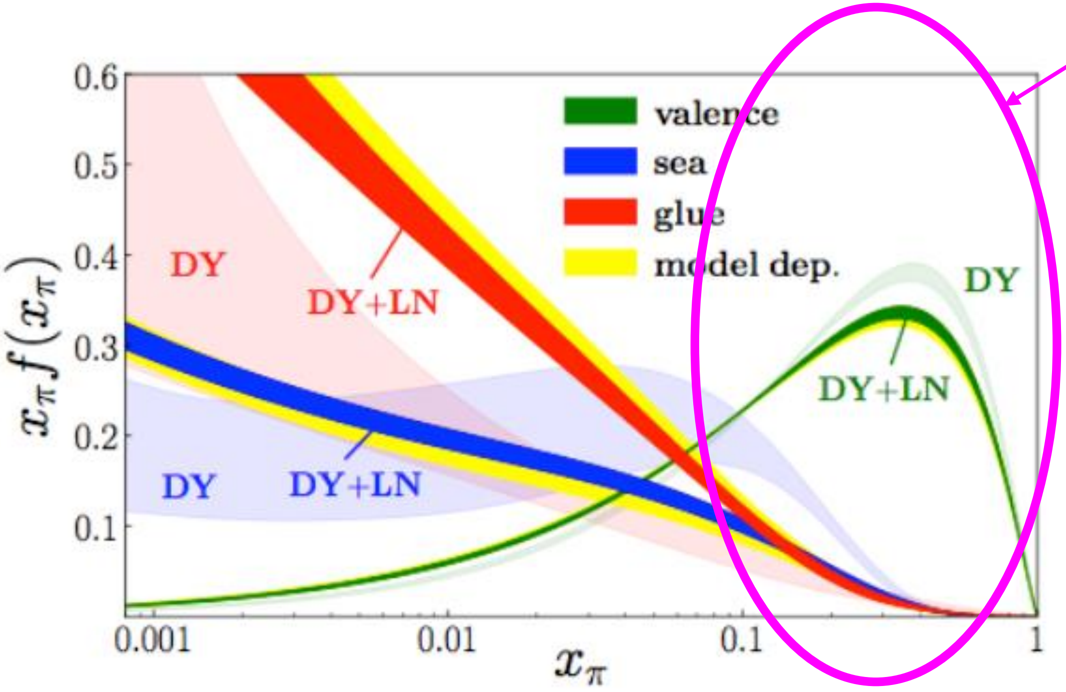
- Recent **theoretical calculations found that for -t ≤ 0.6 GeV^2**, **changes in pion structure do evolve slowly** so that a well-constrained experimental analysis should be reliable, and the Sullivan processes can provide a valid pion target.
- To **check these conditions** are satisfied empirically, one can **take data covering a range in *t*** and compare with phenomenological and theoretical expectations.

Global Fits: Pion and Kaon Structure Functions

*C12-**15**-006 **Pion** TDIS*

*C12-**15**-006A **Kaon** TDIS*

- ☐ 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]*

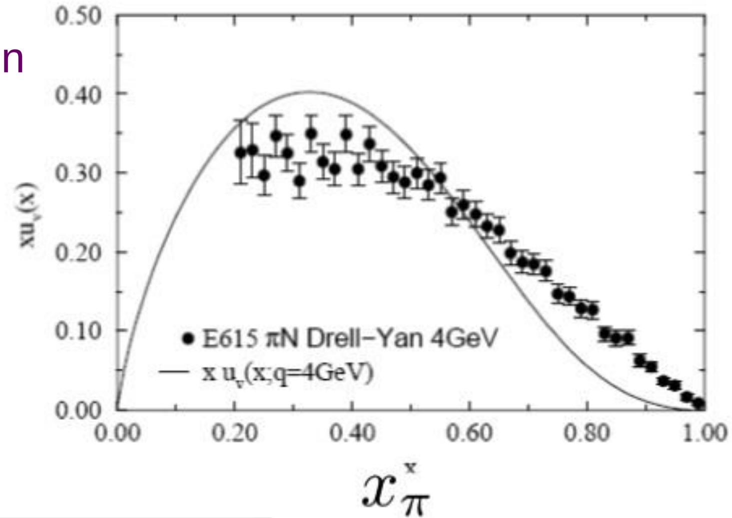
- ➢ Significant reduction of uncertainties on sea quark and gluon distributions in the pion with inclusion of HERA leading neutron data
- ➢ Implications for "TDIS" (Tagged DIS) experiments at JLab

Pion Structure Function from Drell-Yan: Large x

Large x Structure of the Pion

Initial observations:

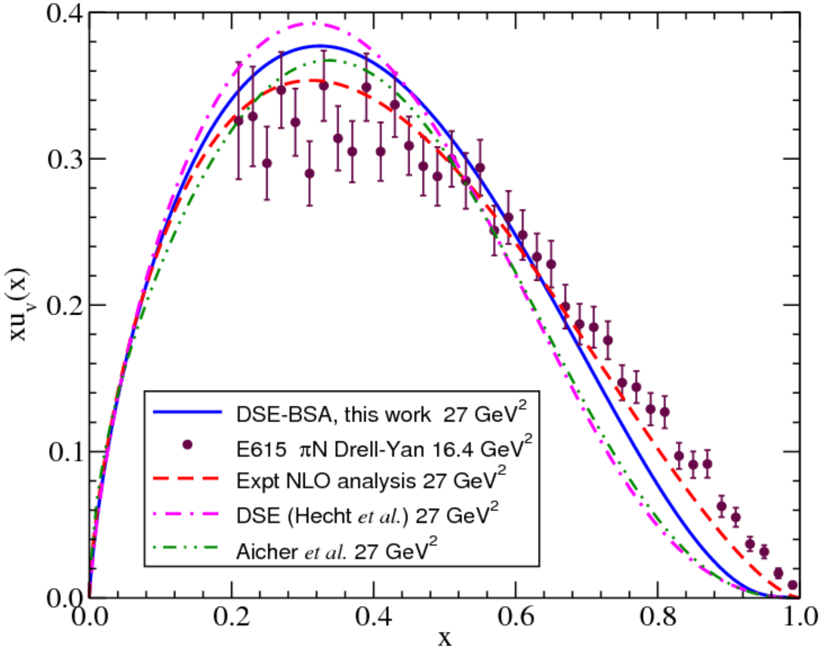
- PDF ~ (1-x_π) as x_π->1
- Agrees with structureless model
- Differs from pQCD prediction of (1-x_π)^2



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)]

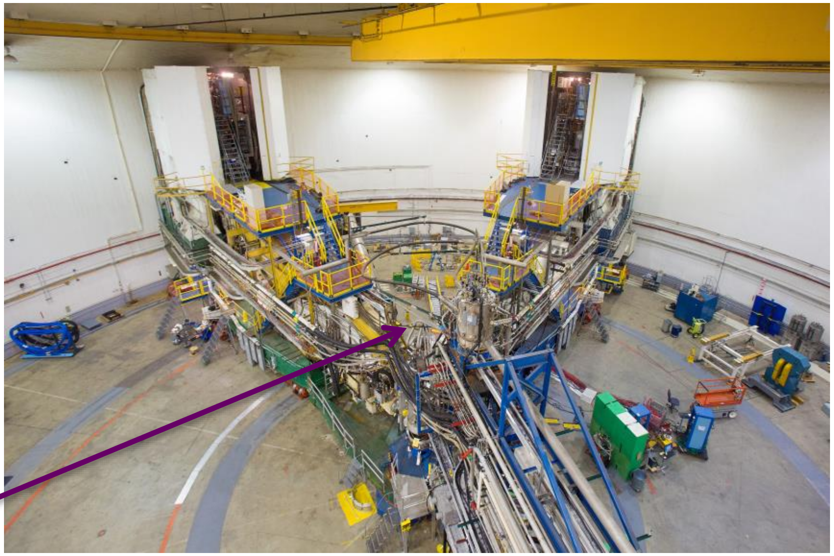
Jefferson Lab TDIS can provide important verification

JLab Hall A Tagged DIS (TDIS) Experiments

*C12-**15**-006 **Pion** TDIS*

*C12-**15**-006A **Kaon** TDIS*

proton tag detection in GEM-based mTPC at pivot

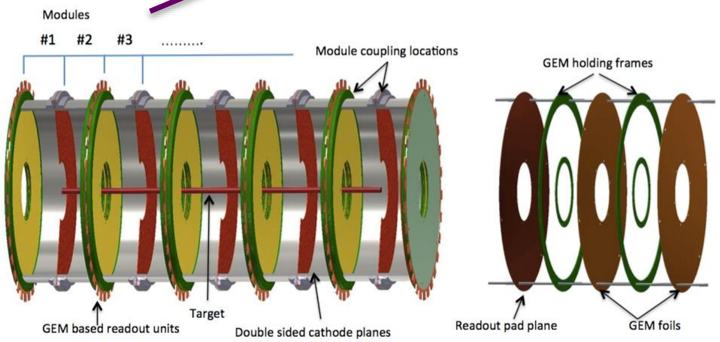


Hall A with SBS:

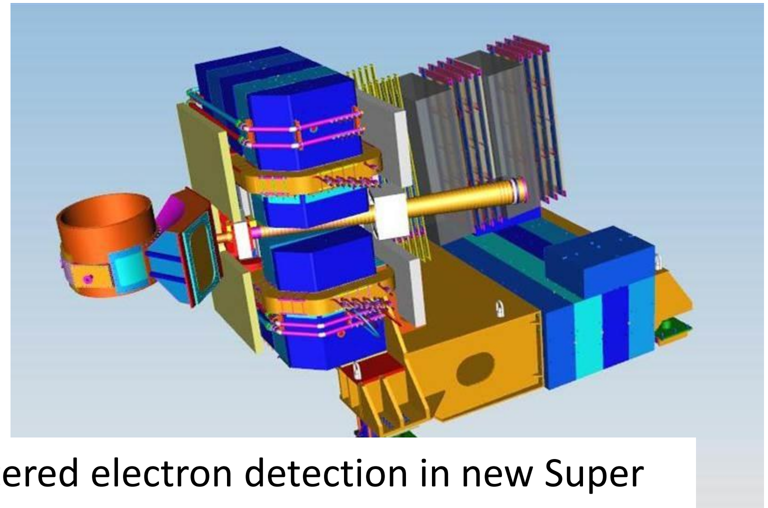
- ✓ High luminosity,
  50 μAmp,
  $\mathcal{L} = 3\text{x}10^{36}/\text{cm}^2\ \text{s}$
- ✓ Large acceptance
  ~70 msr

Important for small cross sections

e- beam

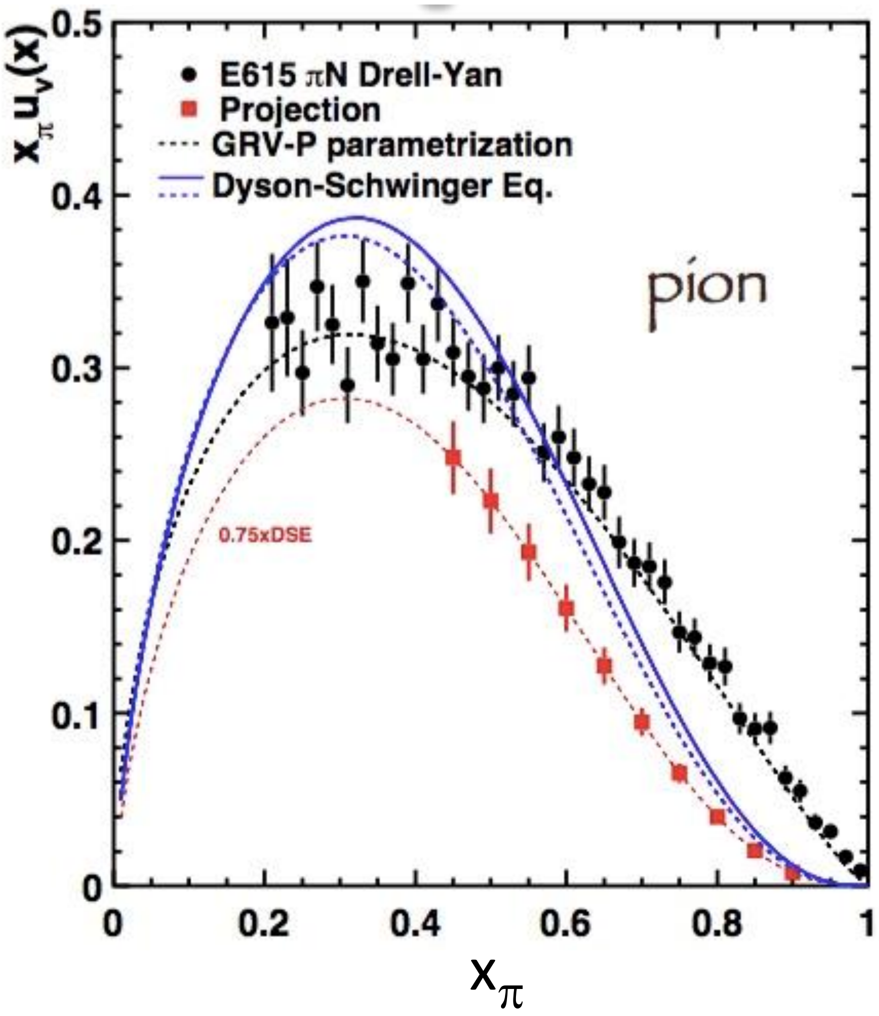


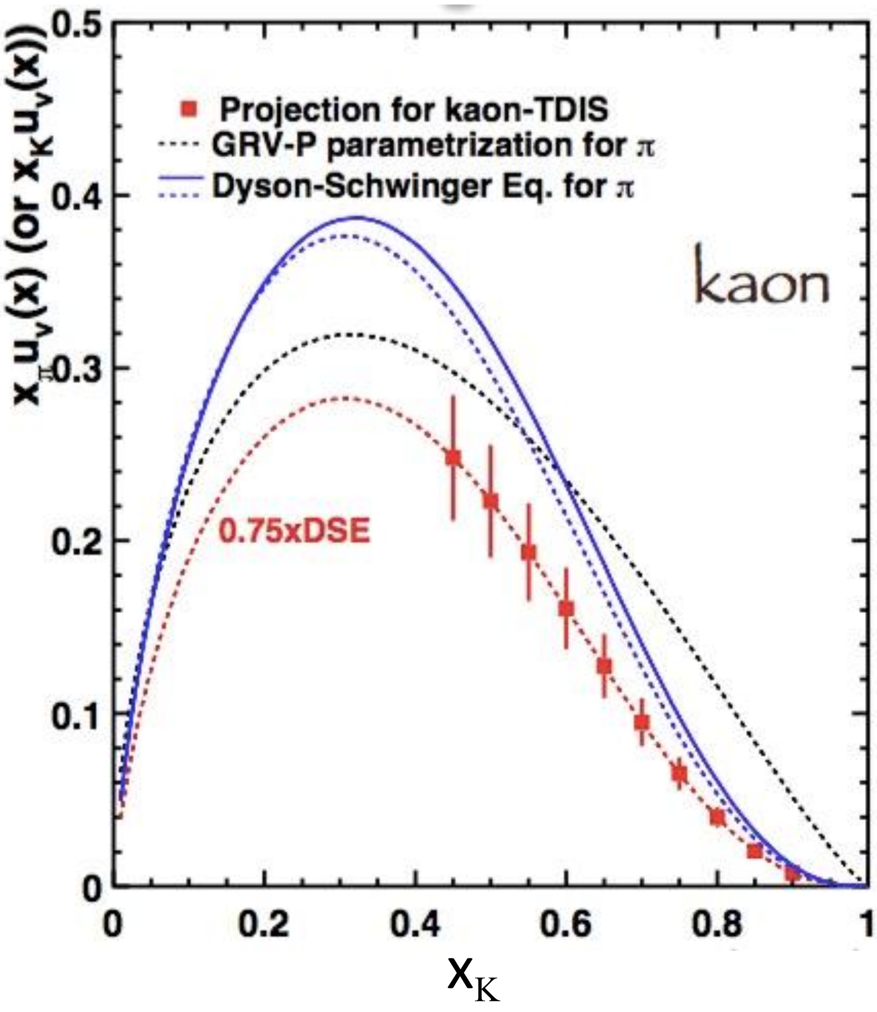
mTPC inside superconducting solenoid



Scattered electron detection in new Super Bigbite Spectrometer (SBS)

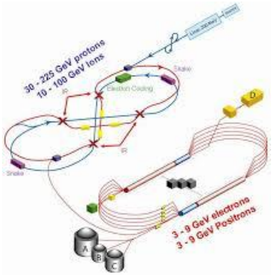
Projected JLab TDIS Results for π, K Structure Functions





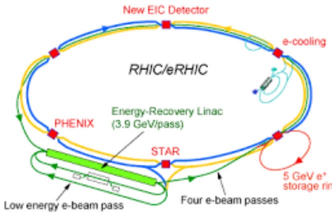
Essentially no data currently

Large Opportunity for Meson Structure Functions at the EIC

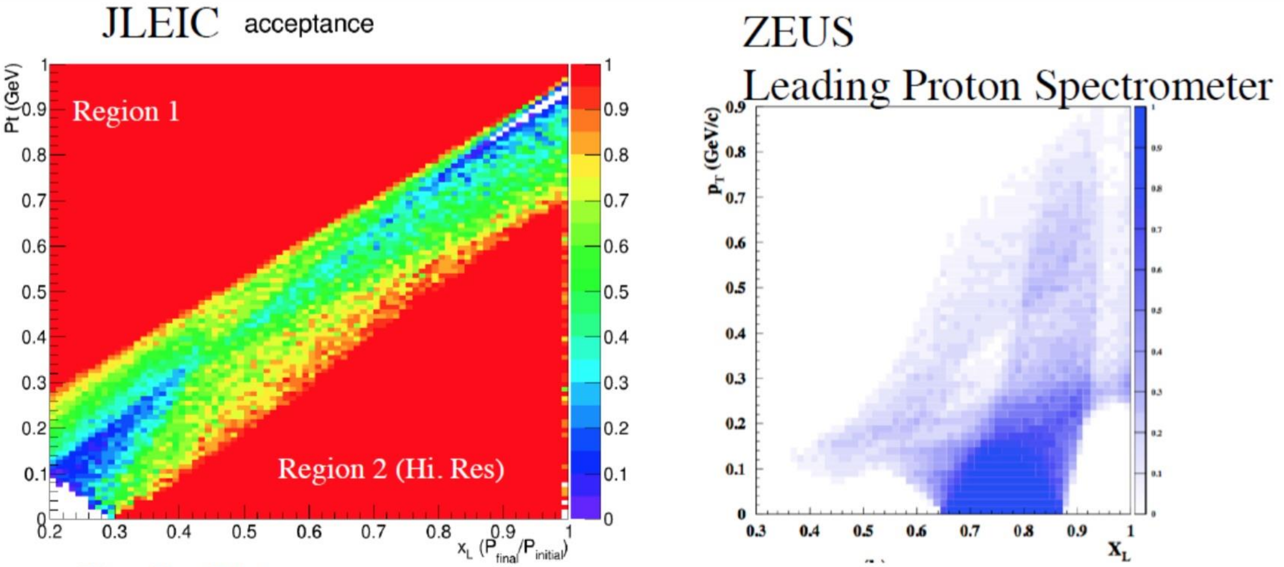


Good Acceptance for TDIS-type Forward Physics!

Low momentum nucleons ***easier*** to measure!



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



Zhiwen Zhao (Duke)

Acceptance in diffractive peak (X_L>~.98)

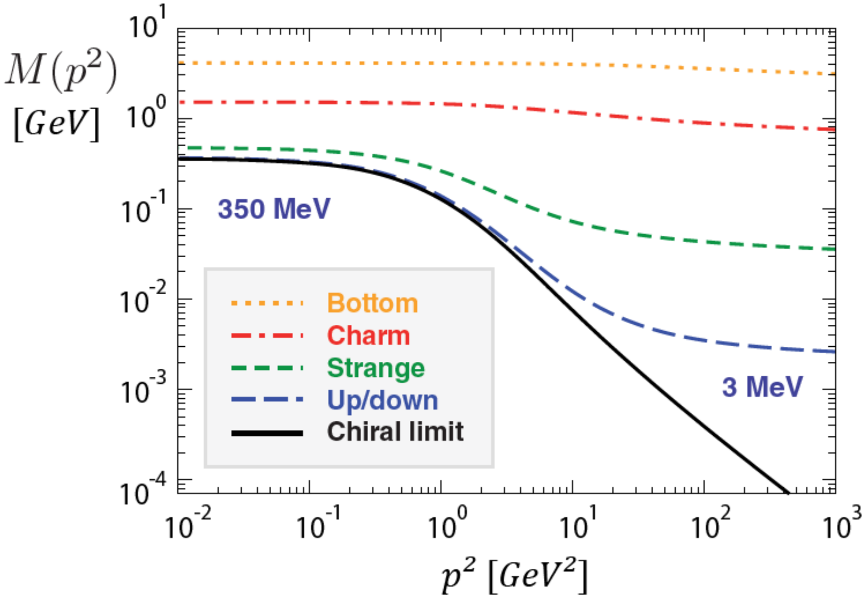
ZEUS: ~2%

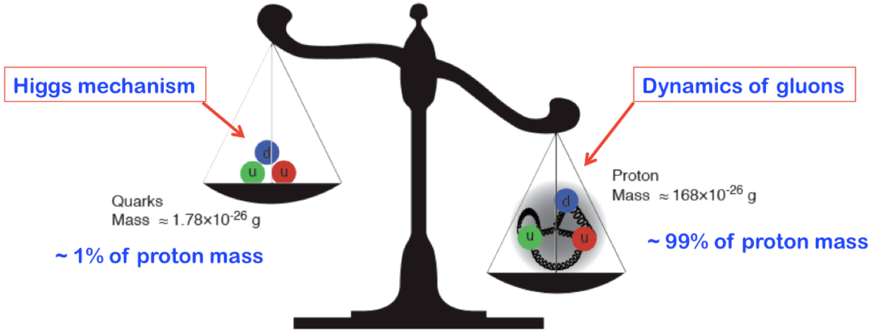
JLEIC: ~100% (also covers much higher X_L than ZEUS)

Huge gain in acceptance for forward tagging….

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

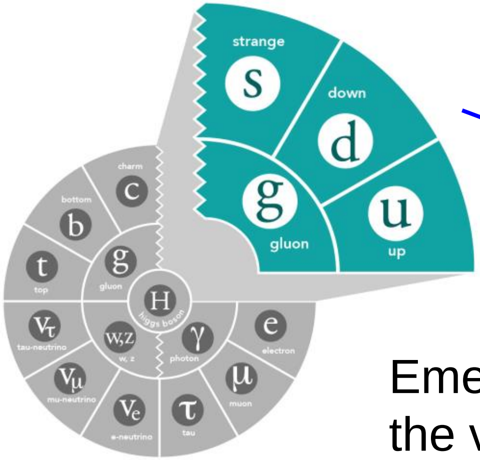
preliminary LQCD results on mass budget, or view as mass acquisition by DCSB

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

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?

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 S
  - Pion and kaon form factors
- Strong vs. Higgs mas
  - Valence quark dist at large momentum fraction x
- Timelike analog of mass on
  - Fragmentation of a quark into pions or kaons

Pion and Kaon Structure at an EIC

Eur. Phys. J. A 55 (2019) 190

Now available online!

Summary

- 1D meson and ground state baryon structure measurements play an important role in our understanding of the structure and interactions of hadrons based on the principles of QCD

- Spin-dependent techniques provide important information on the proton (and neutron) form factors - larger coverage and higher precision

- Meson form factors can be accessed through the Sullivan process
  - Technique validated experimentally – much progress with theoretical calculations
  - JLab12: Pion and kaon form factor extractions up to high Q^2 (~9 and ~6 GeV^2)

- 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

Using a model to extract of F_π from σ_L JLab data

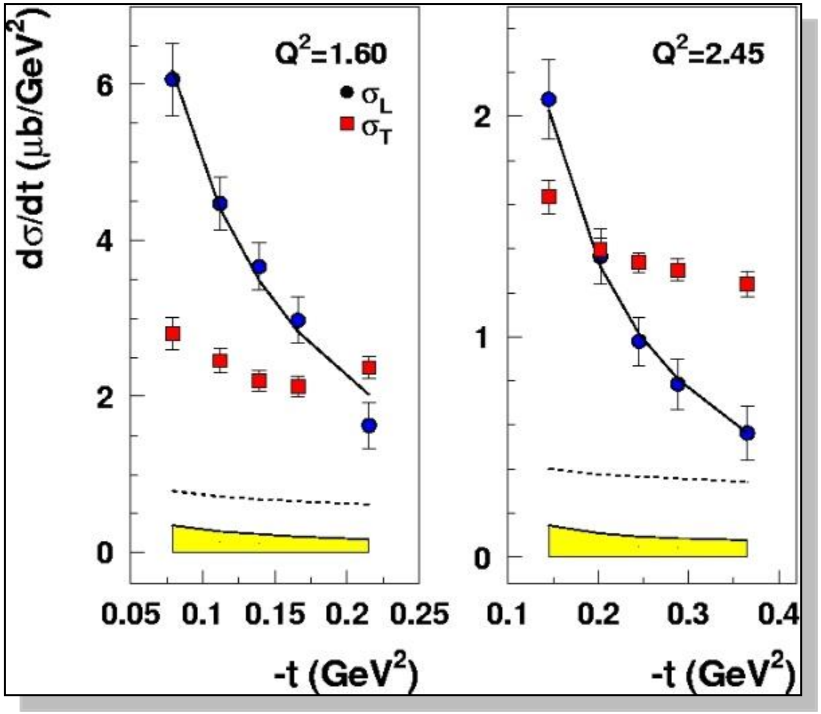
- ❑ JLab 6 GeV F_π experiments used the VGL/Regge model as it has proven to give a reliable description of σ_L across a wide kinematic domain

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

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

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

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



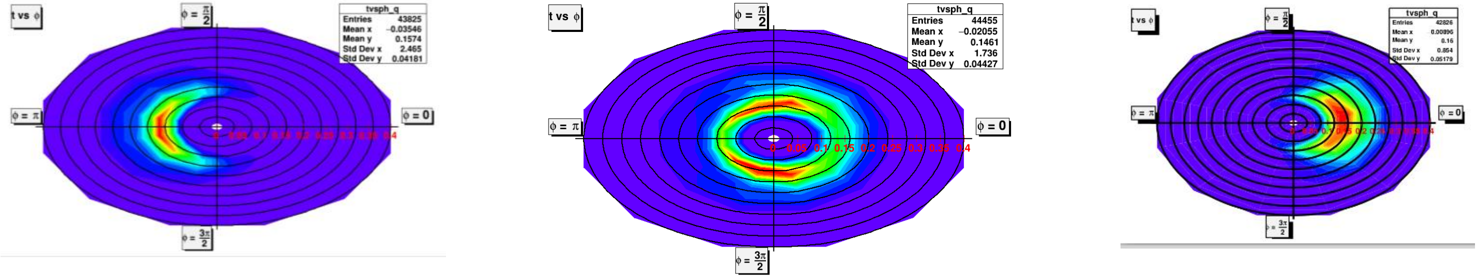
$$\Lambda_\pi^2 = 0.513,\ 0.491\ GeV^2$$

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

- ❑ 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*

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



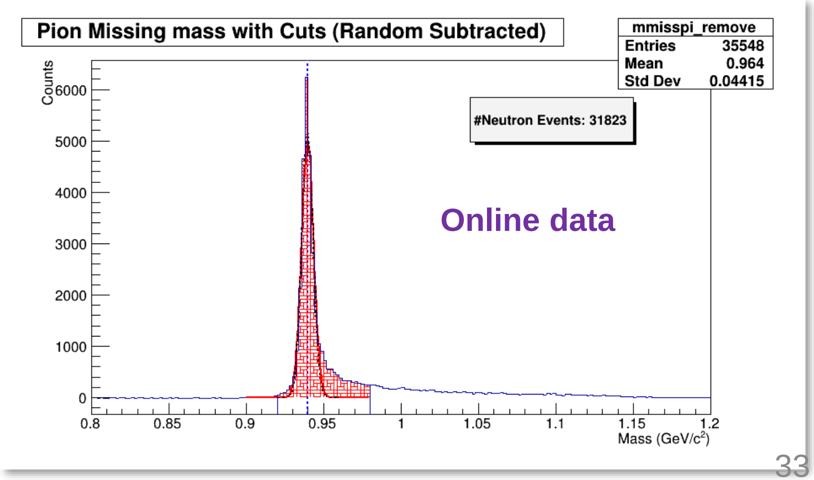
Three SHMS angles

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



Online data