Deep Exclusive $p(e,e'\pi^+)n$ Studies at Jefferson Lab

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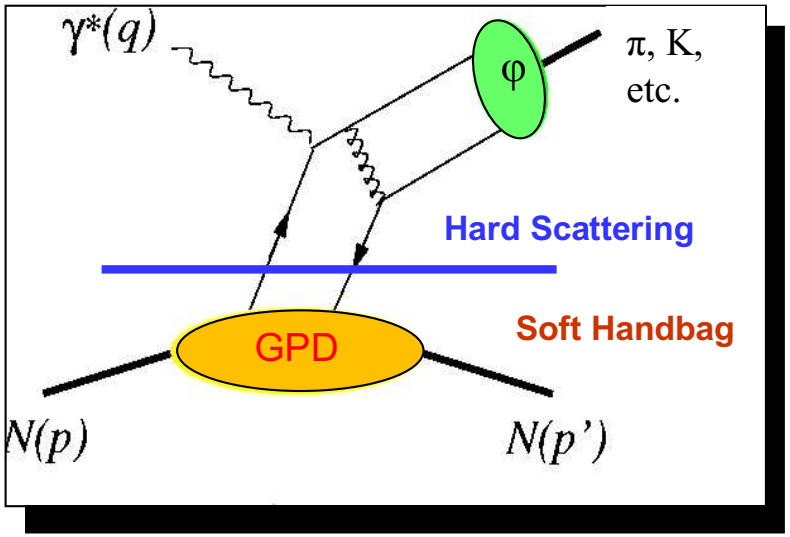
Argonne National Laboratory Physics Division Seminar, May 9, 2016

NSERC CRSNG

FRN: SAPIN-2016-00031

Deep Exclusive Meson Production (DEMP)

- In Deep Exclusive Scattering, <u>all final state particles</u> are either detected or inferred via missing mass.
- **Experiments are demanding, since exclusive cross sections are <u>small</u>, and multiple particles must be detected in coincidence with <u>sufficient resolution to ensure exclusivity</u>.**



Deep Exclusive Scattering allows some simplifications at sufficiently high Q^2, where the Soft-Hard factorization theorem applies.

[Collins, Frankfurt, Strikman, 1997]

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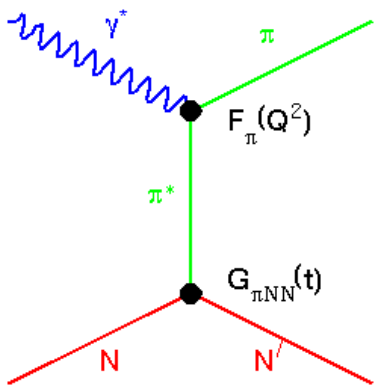
Two Motivations for Studying DEMP

1) Determine the Pion Form Factor at Q^2>0.3 GeV^2:

- Indirectly measure F_π using the "pion cloud" of the proton via p(e,e'π$^+$)n

$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots$$

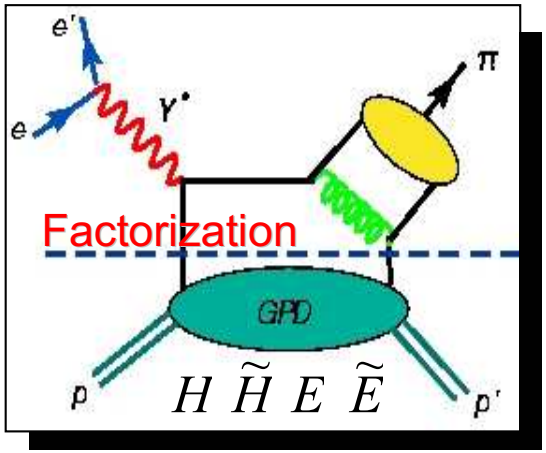
  - Pion pole process dominates σ_L in forward kinematics.



2) Study the Hard-Soft Factorization Regime:

Implications for GPD studies, as they can only be extracted from hard exclusive data where hard-soft factorization applies.

- Investigate if the p(e,e'π^+)n cross section at fixed *x* behaves according to the Q^{-n} expectations of hard QCD.
- Form $\dfrac{\sigma_T[n(e,e'\pi^-)p]}{\sigma_T[p(e,e'\pi^+)n]}$ ratios where soft contributions may cancel, yielding insight to factorization at modest Q^2.



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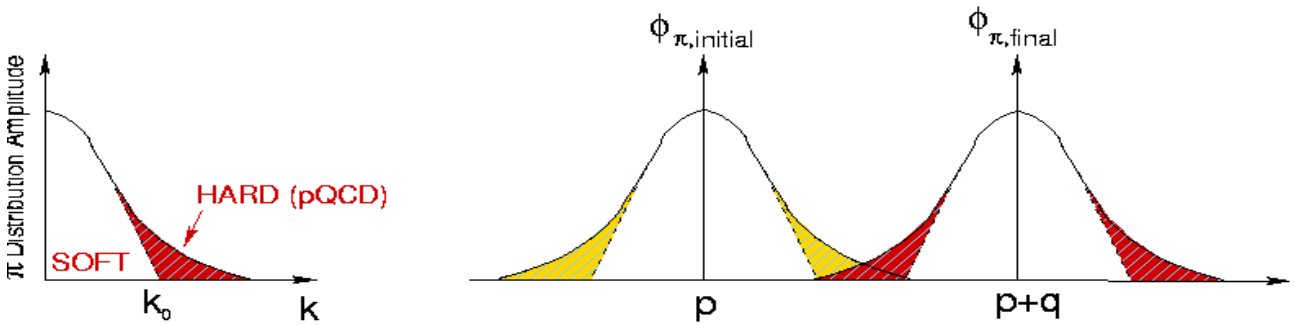
Meson Form Factors

Simple $q\bar{q}$ valence structure of mesons presents the ideal testing ground for our understanding of bound quark systems.

In quantum field theory, the form factor is the overlap integral:

$$F_\pi(Q^2) = \int \phi_\pi^*(p)\phi_\pi(p+q)dp$$



The meson wave function can be separated into φ_π^{soft} with only low momentum contributions ($k<k_0$) and a hard tail φ_π^{hard}.

While φ_π^{hard} can be treated in pQCD, φ_π^{soft} cannot.

From a theoretical standpoint, the study of the Q^2-dependence of the form factor focuses on finding a description for the hard and soft contributions of the meson wave-function.

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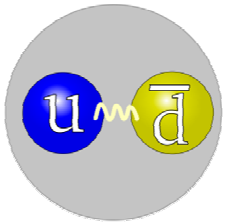
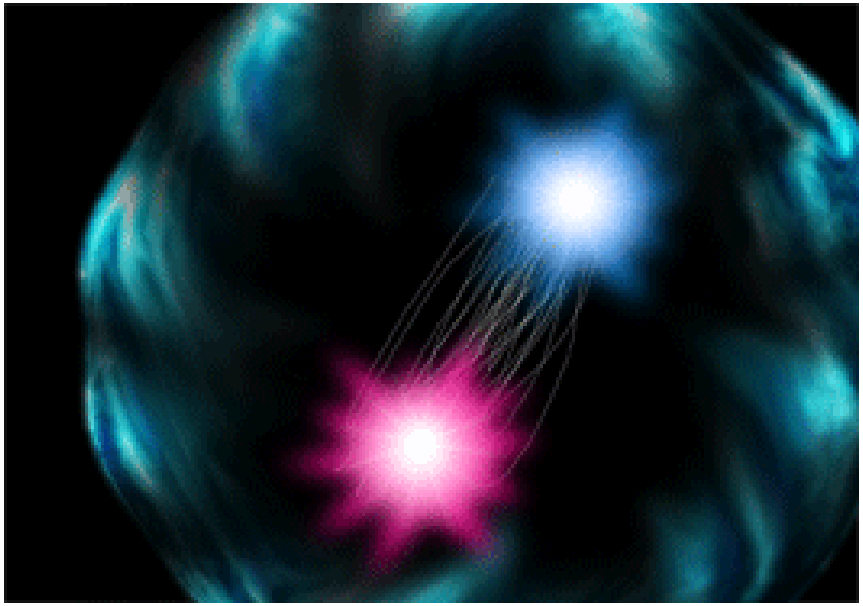
Charged Pion Form Factor

- **The pion is attractive as a QCD laboratory:**
- Simple, 2 quark system



- Electromagnetic form factor can be calculated exactly at very large momentum transfer (small distances).
- For moderate Q^2, it remains a theoretical challenge.
  - "the positronium atom of QCD"



Pion's structure is determined by two valence quarks, and the quark-gluon sea.

Downside for experimentalists:

- No "free" pion targets.
- Measurements at large momentum transfer difficult.

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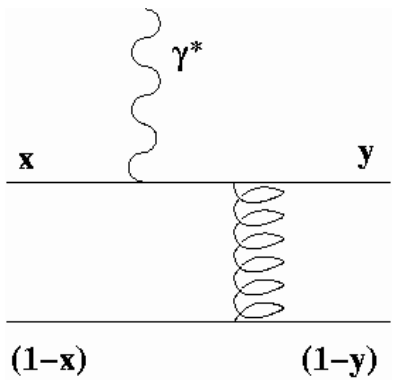
pQCD and the Charged Pion Form Factor

At large Q^2, perturbative QCD (pQCD) can be used

$$F_\pi(Q^2) = \frac{4\pi C_F \alpha_S(Q^2)}{Q^2} \left| \sum_{n=0}^{\infty} a_n \left(\log\left(\frac{Q^2}{\Lambda^2} \right) \right)^{-\gamma_n} \right|^2 \left[1 + O\left(\alpha_s(Q^2), \frac{m}{Q} \right) \right]$$

at asymptotically high Q^2, only the hardest portion of the wave function remains



$$\phi_\pi(x) \underset{Q^2 \to \infty}{\to} \frac{3 f_\pi}{\sqrt{n_c}} x(1-x)$$

and F_π takes the very simple form

$$F_\pi(Q^2) \underset{Q^2 \to \infty}{\to} \frac{16\pi \alpha_s(Q^2) f_\pi^2}{Q^2}$$

where f_π=92.4 MeV is the $\pi^+ \to \mu^+ \nu$ decay constant.

G.P. Lepage, S.J. Brodsky, Phys.Lett. **87B**(1979)359.

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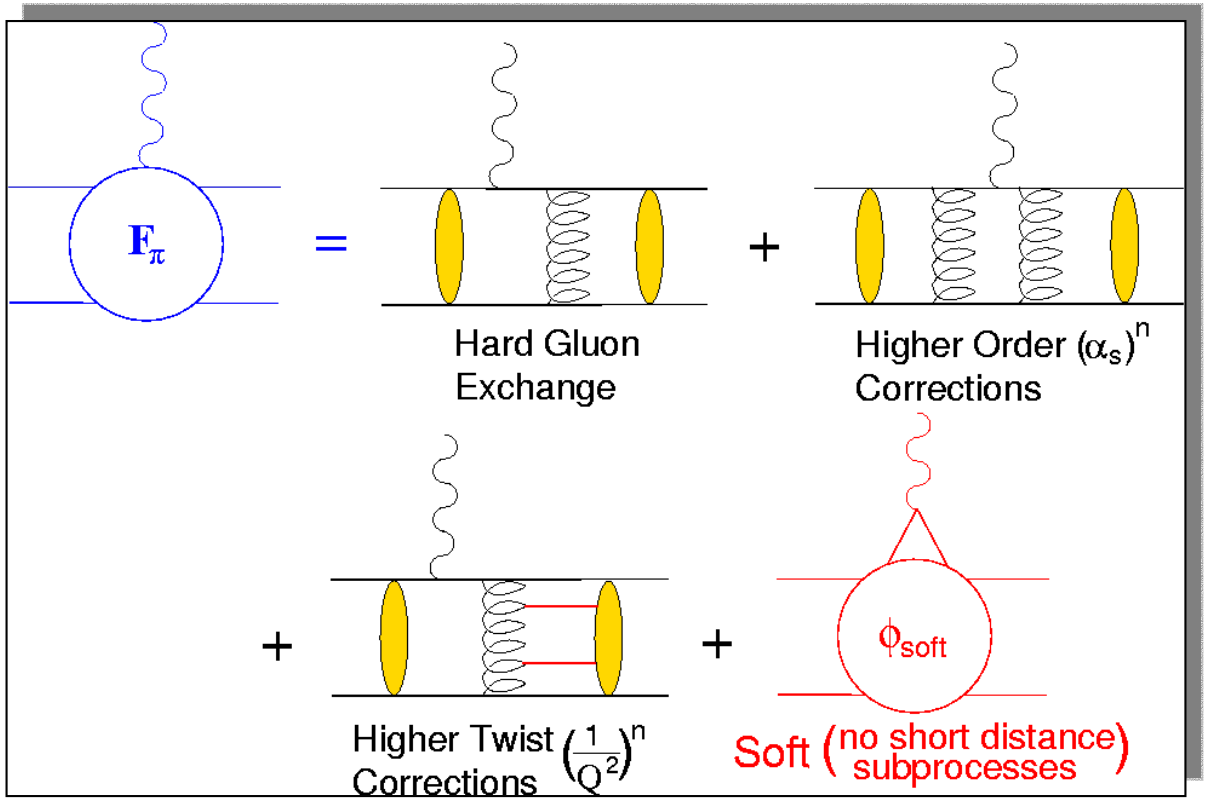
Pion Form Factor at Finite Q^2

- At finite momentum transfer, higher order terms contribute
- Calculation of higher order, "hard" (short distance) processes difficult, but tractable



- There are "soft" (long distance) contributions that cannot be calculated in the perturbative expansion
- **Understanding the interplay of these hard and soft processes is a key goal**

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Measurement of π^+ Form Factor – Low Q^2

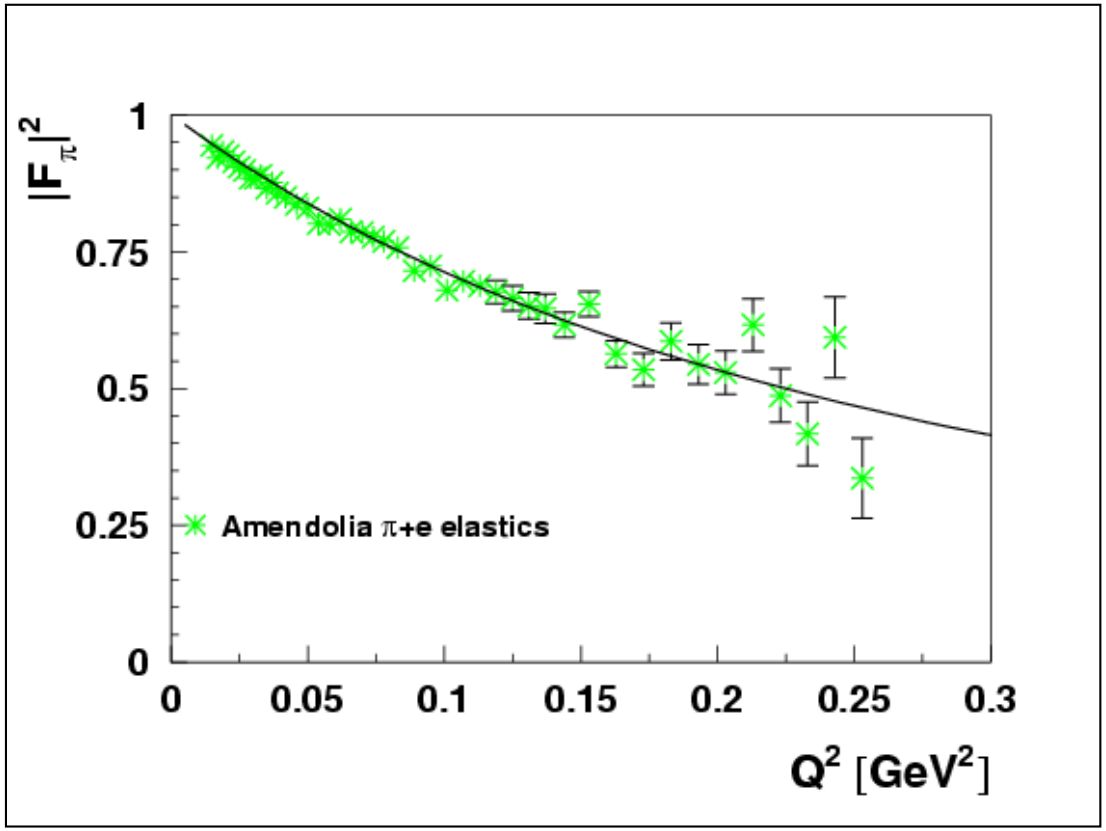
At low Q^2, F_π can be measured <u>model-independently</u> via high energy elastic π^- scattering from atomic electrons in Hydrogen

- CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2 *[Amendolia et al, NPB277, 168 (1986)]*

- Data used to extract pion charge radius $r_\pi = 0.657 \pm 0.012$ fm

Maximum accessible Q^2 roughly proportional to pion beam energy

Q^2=1 GeV^2 requires 1 TeV pion beam



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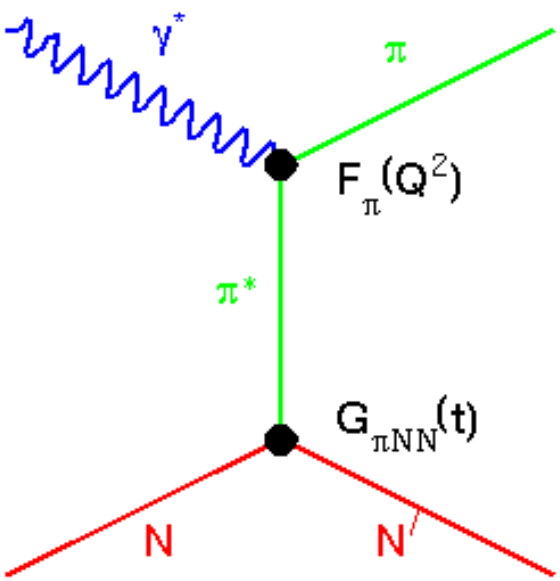
Measurement of π^+ Form Factor – Larger Q^2

At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots$$

- At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
- In Born term model, F_π^2 appears as,

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



Drawbacks of this technique

1. Isolating σ_L experimentally challenging
2. Theoretical uncertainty in form factor extraction.

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F_π Program at JLab Hall C

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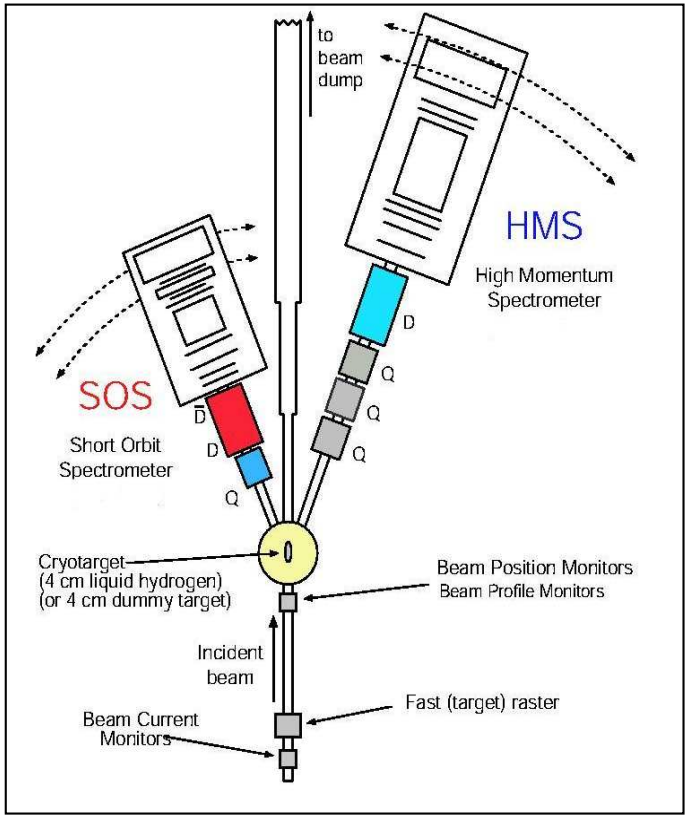
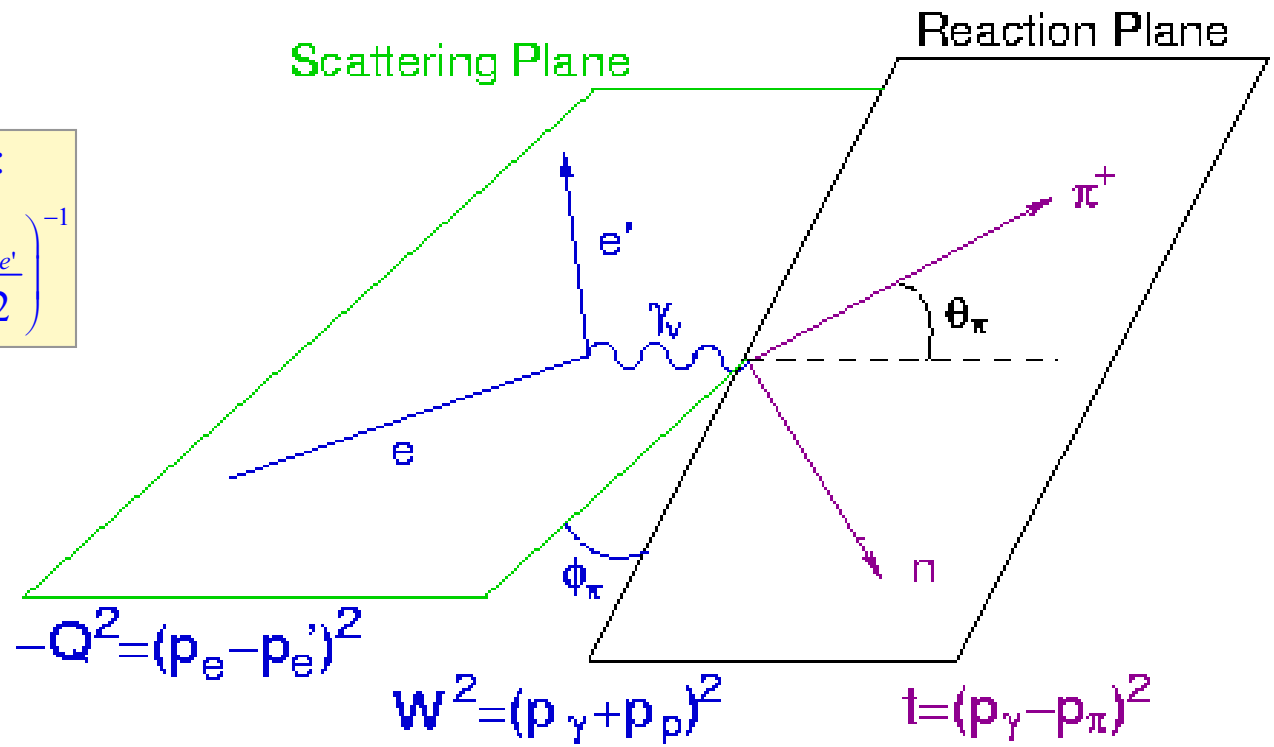


- 2 F_π experiments have been carried out at JLab
  (spokespersons H. Blok, G. Huber, D.Mack)
  - F_π-1: Q^2=*0.6-1.6* GeV^2 with 4 GeV beam, 1997-2001.
  - F_π-2: Q^2=*1.6, 2.45* GeV^2 with 6 GeV beam, 2003-2008.

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

Virtual-photon polarization:

$$\varepsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$



- **L-T separation required to separate σ_L from σ_T.**
- **Need to take data at smallest available $-t$, so σ_L has maximum contribution from the π^+ pole.**

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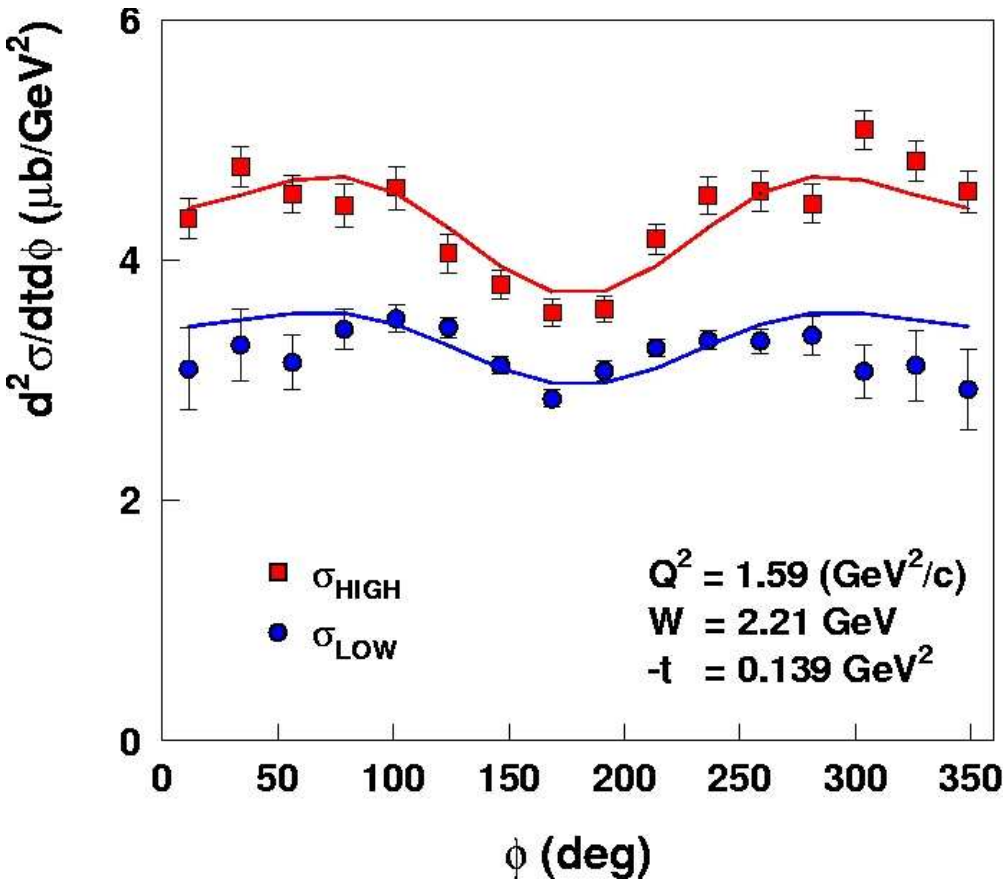
Measuring $d\sigma_L/dt$

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

- Rosenbluth separation required to isolate σ_L
  - Measure cross section at fixed ($W, Q^2, -t$) at 2 beam energies
  - Simultaneous fit at 2 ε values to determine σ_L, σ_T, and interference terms

- Control of point-to-point systematic uncertainties crucial due to $1/\Delta\varepsilon$ error amplification in σ_L
- Careful attention must be paid to spectrometer acceptance, kinematics, efficiencies, …



Horn et al, PRL97, 192001,2006

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Chew–Low Method to determine Pion Form Factor

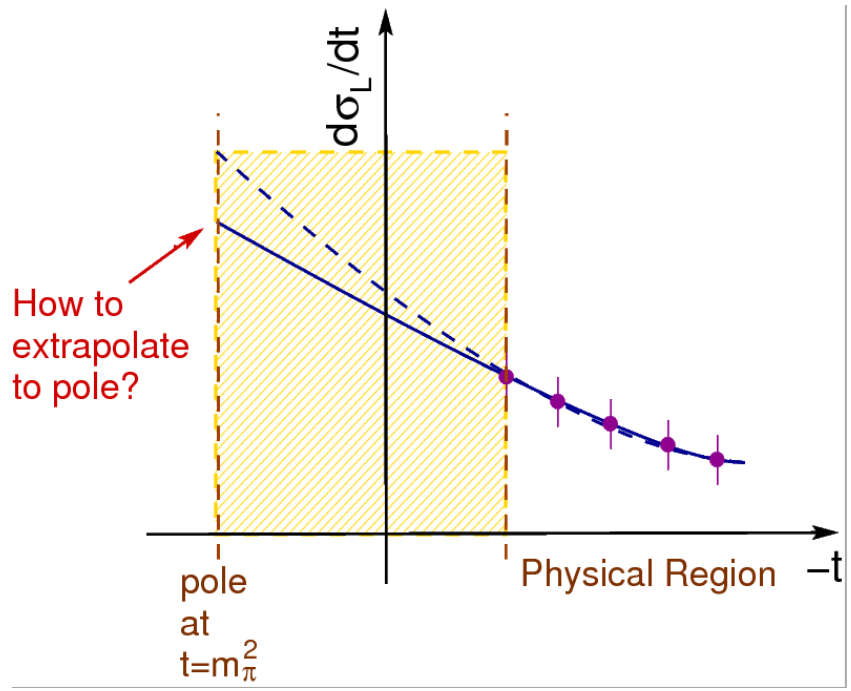
***p(e,e'π⁺)n* data are obtained some distance from the $t=m_\pi^2$ pole.**

→ "Chew Low" extrapolation method requires knowing the analytic dependence of $d\sigma_L/dt$ through the unphysical region.

Extrapolation method last used in 1972 by Devnish & Lyth

- Very large systematic uncertainties.
- Failed to produce reliable result.

  → Different polynomial fits equally likely in physical region gave divergent form factor values when extrapolated to $t=m_\pi^2$.



The Chew-Low Method was subsequently abandoned.

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Chew-Low Method Check with PseudoData

Plot $F^2 = \frac{N}{4\hbar c(eg_{\pi NN})^2} \frac{(t-m_\pi^2)^2}{-Q^2 m_\pi^2} \frac{d\sigma_L}{dt}$ **vs. –*t*.**

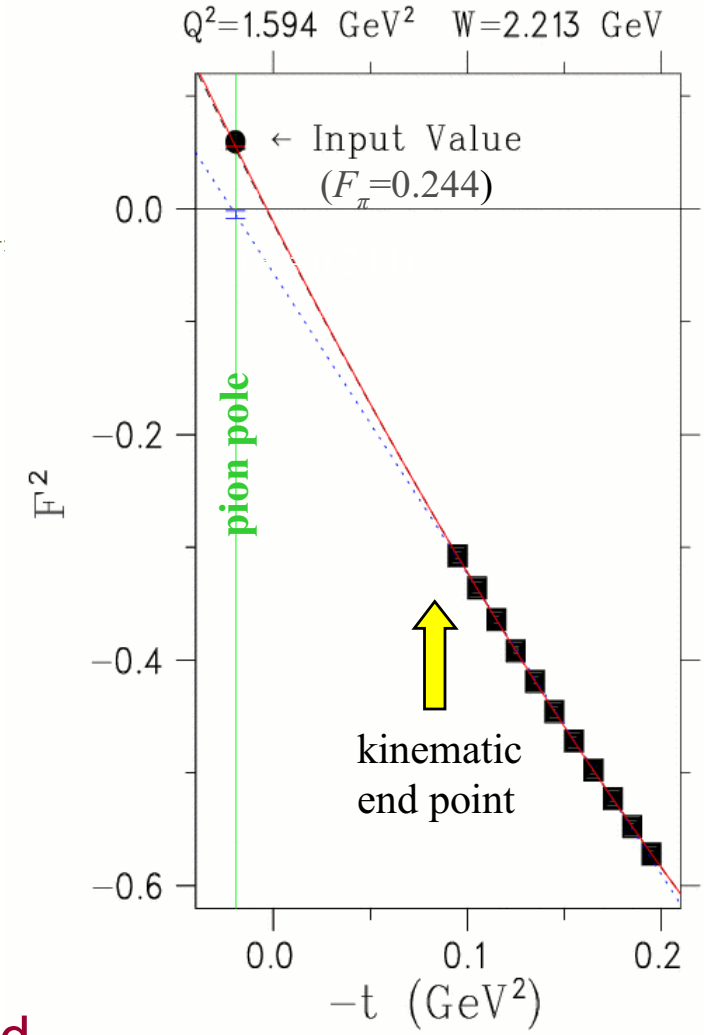
- Pure pole cross section gives straight line through origin with value $F_\pi^2(Q^2)$ at pole.
- **Other contributions introduce non-linearities since don't contain $(t-m_\pi)^2$ factor, but don't influence F^2 value at pole.**
  - → Do not know if behavior of F^2 with –t is linear, quadratic, or higher order.

All fits missed the input F_π.

→ no consistent trend on order of polynomial best able to reproduce input value

(6-15% deviation, Q^2=0.6-2.45 GeV^2).

- Experimental σ_L data have only 4-6 *t*-bins and statistical and systematic uncertainties of 5-10%.
  - → Extrapolation with real data will be even more uncertain.



For details see: G.M. Huber et al., PRC 78(2008)045203.

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Only reliable approach is to use a model incorporating the π^+ production mechanism and the `spectator' nucleon to **extract** F_π from σ_L.

- JLab F_π experiments use the Vanderhaeghen-Guidal-Laget (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*
- More models would allow a better understanding of the model dependence of the F_π result. There has been considerable recent interest:
  - *T.K. Choi, K.J. Kong, B.G. Yu, arXiv: 1508.00969.*
  - *T. Vrancx, J. Ryckebusch, PRC **89**(2014)025203.*
  - *M.M. Kaskulov, U. Mosel, PRD **81**(2010)045202.*
  - *S.V. Goloskokov, P. Kroll, Eur.Phys.J. **C65**(2010)137.*

Our philosophy remains to publish our experimentally measured $d\sigma_L/dt$, so that updated values of $F_\pi(Q^2)$ can be extracted as better models become available.

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Extract $F_\pi(Q^2)$ from σ_L data via VGL Regge Model

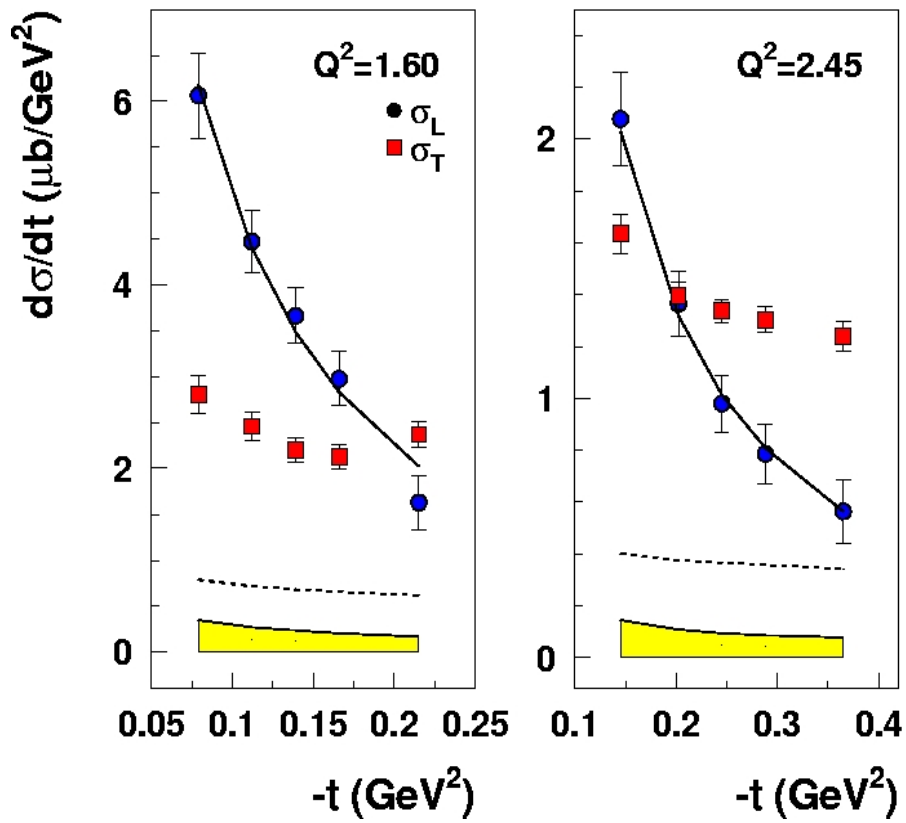
- Feynman propagator $\left(\frac{1}{t - m_\pi^2}\right)$ replaced by π and ρ Regge propagators.
- Free parameters: Λ_π, Λ_ρ (trajectory cutoff).

  [Vanderhaeghen, Guidal, Laget, PRC **57**(1998)1454]
- At small $-t$, σ_L only sensitive to F_π

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

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

The JLab 6 GeV experiments were limited to Q^2=2.45 GeV^2 by $-t_{min}$<0.2 GeV^2 and $\Delta\varepsilon$>0.25 needed for reliable L/T separation.



Fπ-2 data: T. Horn et al., PRL **97**(2006)192001.

Error bars indicate statistical and random (pt-pt) systematic uncertainties in quadrature.
Yellow band indicates the correlated (scale) and partly correlated (t-corr) systematic uncertainties.

Λ_π^2=0.513, 0.491 GeV^2, Λ_ρ^2=1.7 GeV^2.

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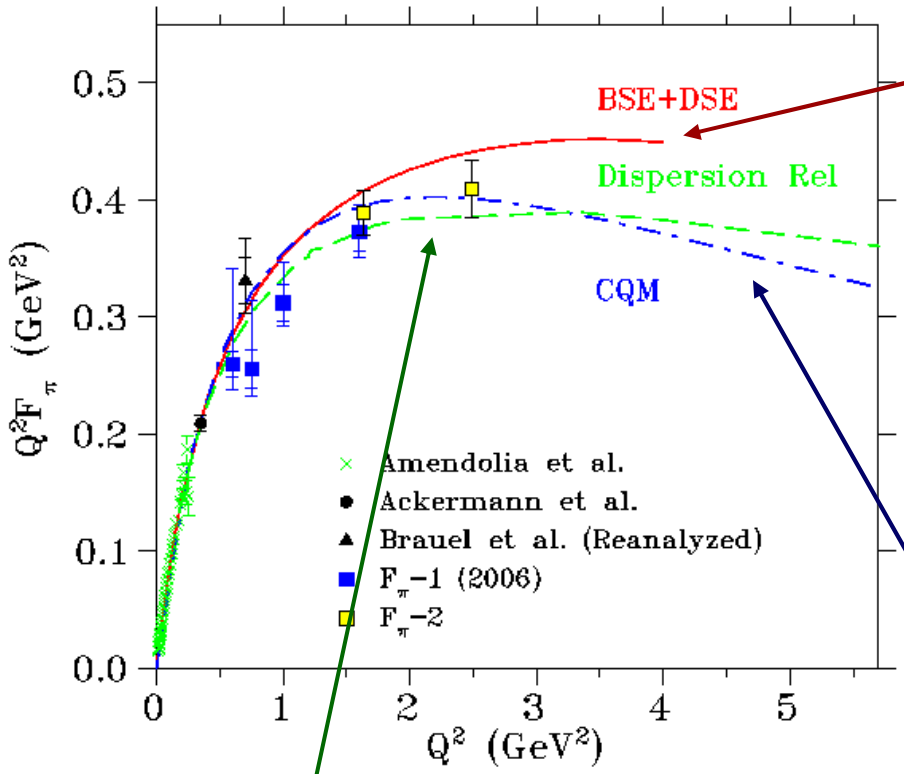
Current Experimental Status

JLab results in a region of Q^2 where model calculations begin to diverge.



Bethe-Salpeter/Dyson-Schwinger:

*[P. Maris and P. Tandy, Phys.Rev.C **62**(2000)055204]*

- B-S equation is conventional formalism for relativistic bound states.
- D-S expansion in terms of dressed quark propagators, consistent w/ confinement.
- Model parameters fixed from f_π and m_π, then r_π and F_π predicted.

Constituent Quark Model:

*[C-W. Hwang, Phys.Rev.D **64**(2001)034001]*

- Relativistic constituent quarks and effective interaction on the light front
- Consistent treatment of quark spins.
- Wave function parameters determined from f_π and $\pi^0 \rightarrow \gamma\gamma$ decay width, then charge and transition FF's and π^0 branching ratios predicted.

Disperson Relation with QCD Constraint:

*[B.V. Geshkenbein, Phys.Rev.D **61**(2000)033009]*

- Uses constraints posed by **causality** and **analyticity** to relate the timelike and spacelike domains of the pion form factor on the complex plane.
- Additional constraints, such as behavior of F_π in asymptotic region, imposed.

For details see: G.M. Huber et al., PRC 78(2008)045203.

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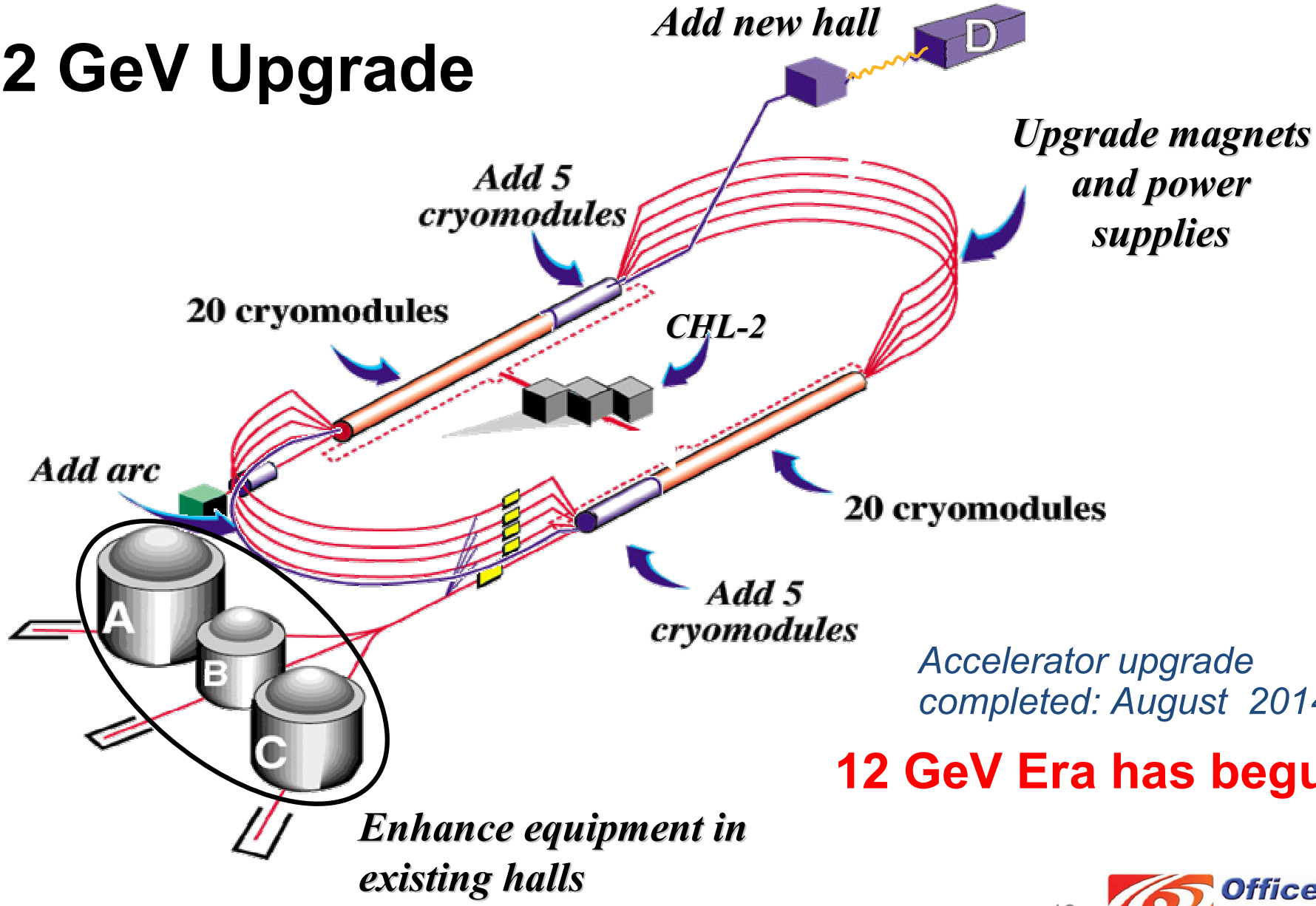
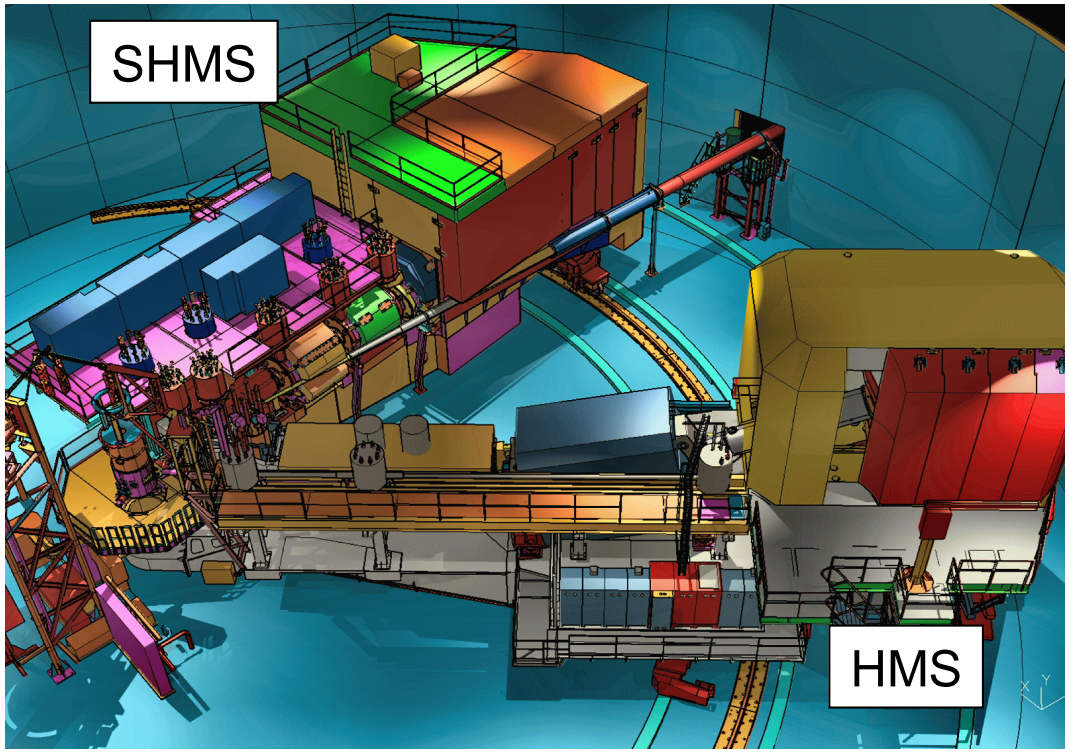
12 GeV Upgrade



Accelerator upgrade completed: August 2014

12 GeV Era has begun!

Jefferson Lab 12 GeV Era – Hall C Configuration



Hall C will provide 2 moderate acceptance, magnetic focusing spectrometers:

High Momentum Spectrometer:
$d\Omega \sim 6$ msr, $P_{max} = 7$ *GeV/c*
$\Theta = 10.5$ *to 80 degrees*

Super-HMS :
$d\Omega \sim 4$ msr, $P_{max} = 11$ *GeV/c*
$\Theta = 5.5$ *to 40 degrees*

- Both spectrometers provide excellent control of systematic uncertainties
- Kinematic reproducibility, well-understood acceptance

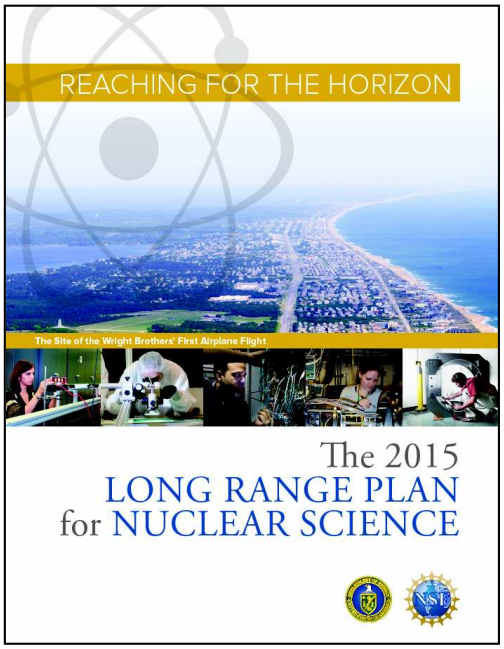
Ideal for:

- precision cross section measurements and response function separations,
  - in single arm or coincidence,
  - at high luminosity (>10^{38}/cm^{2}sec).

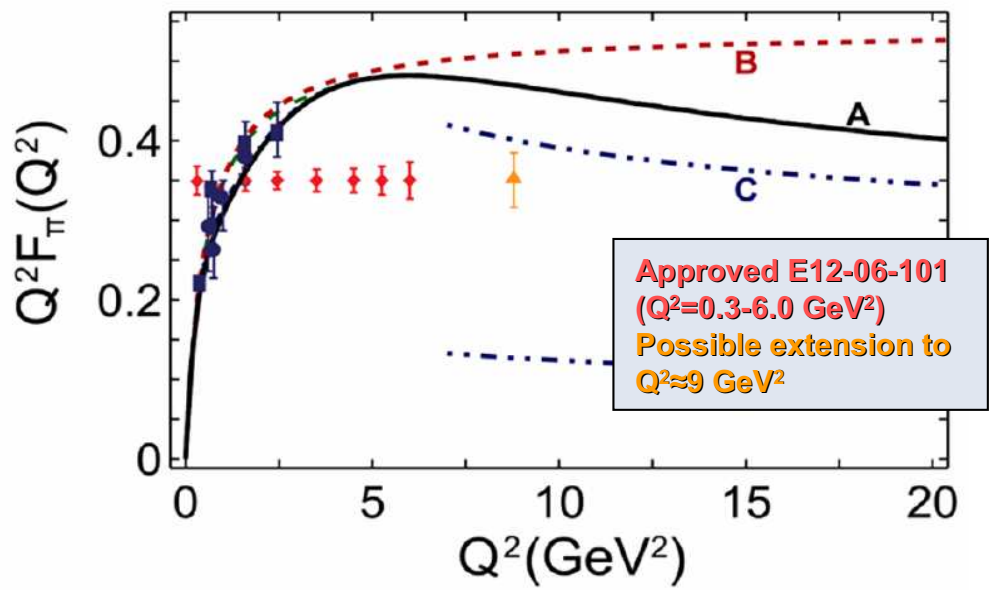
Interest in Higher Q^2 Measurements

Section 2.1.1: The Quark Structure of Hadrons

- The pion is seen as key to confirm the mechanisms that dynamically generate nearly all of the mass of hadrons and central to the effort to understand hadron structure.
- With such strong theoretical motivation, the study of the pion form factor is one of the flagship goals of the JLab 12-GeV Upgrade.
- The SHMS (in Hall C) will nearly quadruple the momentum transfer over which the pion form factor is known.
- These measurements will probe a broad regime in which the phenomenology of QCD begins to transition from large- to small-distance-scale behavior.



What do we have to do to enable reliable F_π measurements at high Q^2?



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Model / Intepretation Issues

- A common criticism of the electroproduction technique is the difficulty to be certain one is measuring the "physical" form factor.

> "What is at best measured in electroproduction is the transition amplitude between a mesonic state with an effective space-like mass $m^2=t<0$ and the physical pion. It is theoretically possible that the off-shell form factor $F_\pi(Q^2,t)$ is significantly larger than the physical form factor because of its bias towards more point-like $q\bar{q}$ valence configurations within its Fock state structure." --S.J. Brodsky, Handbook of QCD, 2001.

- What tests/studies can we do to give confidence in the result?
  - Check consistency of model with data.
  - Extract form factor at several values of $-t_{min}$ for fixed Q^2.
  - Test that the pole diagram is really the dominant contribution to the reaction mechanism.
  - Verify that electroproduction technique yields results consistent with π-e elastic scattering at same Q^2.

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Check of Pion Electroproduction Technique

Directly compare $F_\pi(Q^2)$ values extracted from very low $-t$ electroproduction with the exact values measured in elastic e-π scattering.

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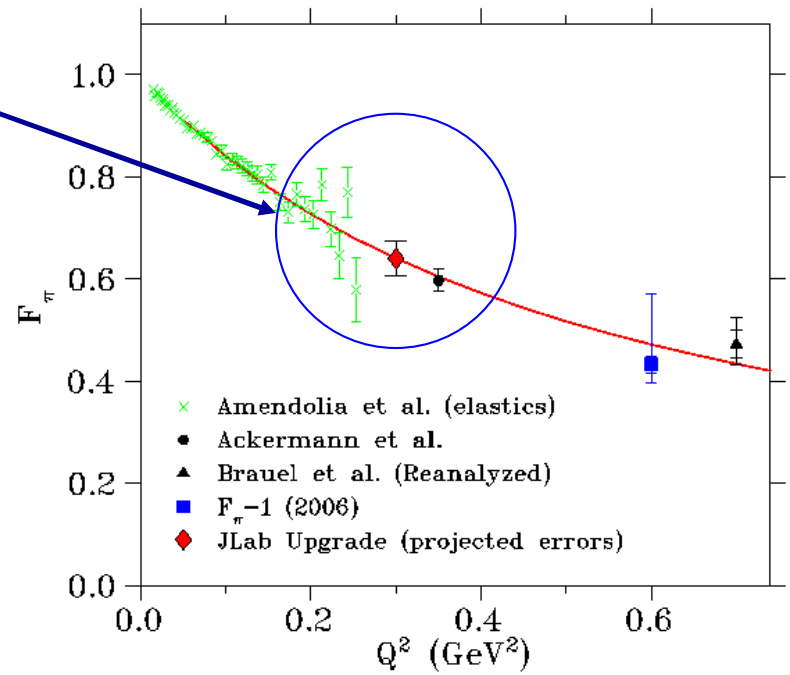
METHOD PASSES CHECKS:

- Q^2=0.35 GeV^2 data from DESY consistent with limit of elastic scattering data within uncertainties.
  *[H. Ackermann, et al., NP **B137**(1978)294]*
- A much better check is planned in E12–06–101 by taking Q^2=0.30 GeV^2 data at 50% lower $-t$ (0.005 GeV^2).



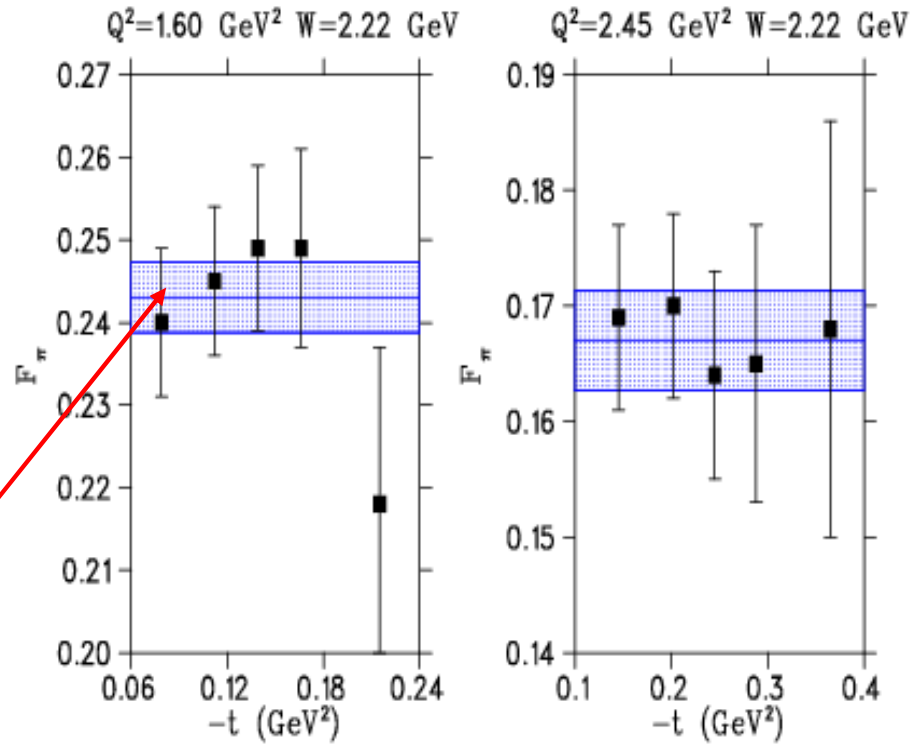
E12-06-101 Proposal:
G.M. Huber, D. Gaskell, spokespersons

Fπ-2 VGL $p(e,e'\pi^+)n$ model check

- To check whether VGL Regge model properly accounts for:
  - π^+ production mechanism.
  - spectator nucleon.
  - other off-shell (*t*-dependent) effects.

  extract F_π values for each *t*-bin separately, instead of one value from fit to all *t*-bins.

Error band based on fit to all *t*-bins.



G.M. Huber et al., PRC **78**(2008)045203.

Only statistical and t-uncorrelated systematic uncertainties shown.

- Deficiencies in model may show up as *t*-dependence in extracted $F_\pi(Q^2)$ values.
- Resulting F_π values are insensitive (<2%) to *t*-bin used.
- Lends confidence in applicability of VGL model to the kinematical regime of the JLab data, and the validity of the extracted $F_\pi(Q^2)$ values.

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Possible effect of resonances at W≈1.95 GeV

- Our earlier Fπ-1 data were obtained when only 4 GeV electron beam was available.
- Measurements limited to W≈1.95 GeV, which is above the region of most (but not all??) σ_L resonances.

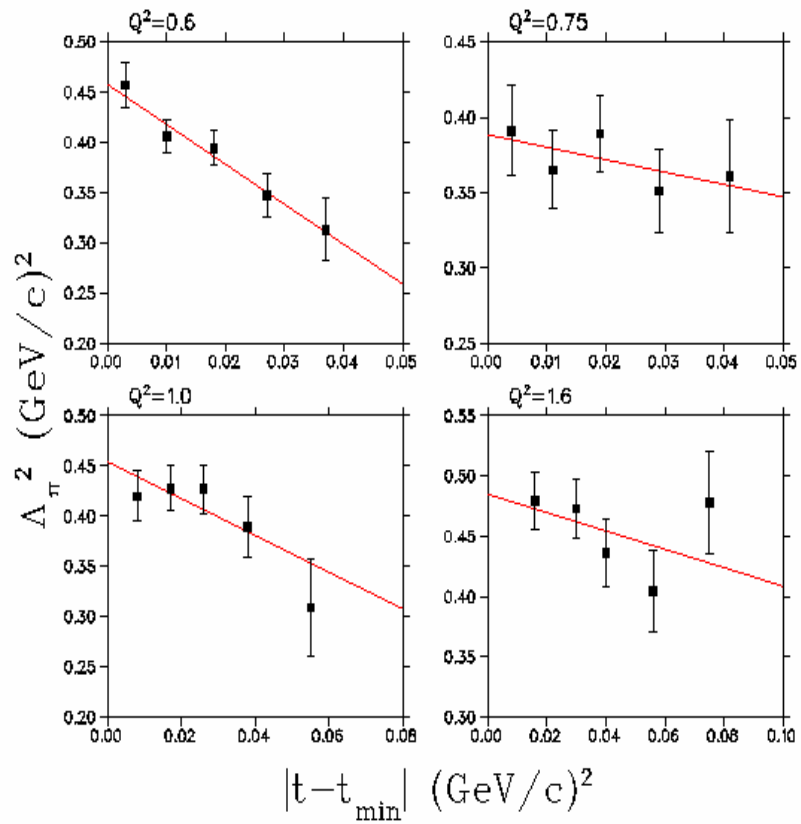
Expt	Q^2 $(GeV/c)^2$	W (GeV)	$\lvert t_{min}\rvert$ $(Gev/c)^2$	E_e (GeV)
Fπ-1	0.6-1.6	1.95	0.03-0.150	2.445-4.045
Fπ-2	1.6,2.5	2.22	0.093,0.189	3.779-5.246

We found some anomalies in the fit of the F_π-1 data by the VGL model

→ Likely due to contributions from resonances, which are not included in the Regge model

- The deficiency in the VGL fit is reflected in the non-constant Λ_π^2 fit to each –t bin
- Dependence strongest at the low Q^2
- At higher Q^2, the resonance form factor is expected to reduce resonance contributions

We needed to apply corrections to determine F_π from these data



For details see: G.M. Huber et al., PRC 78(2008)045203.

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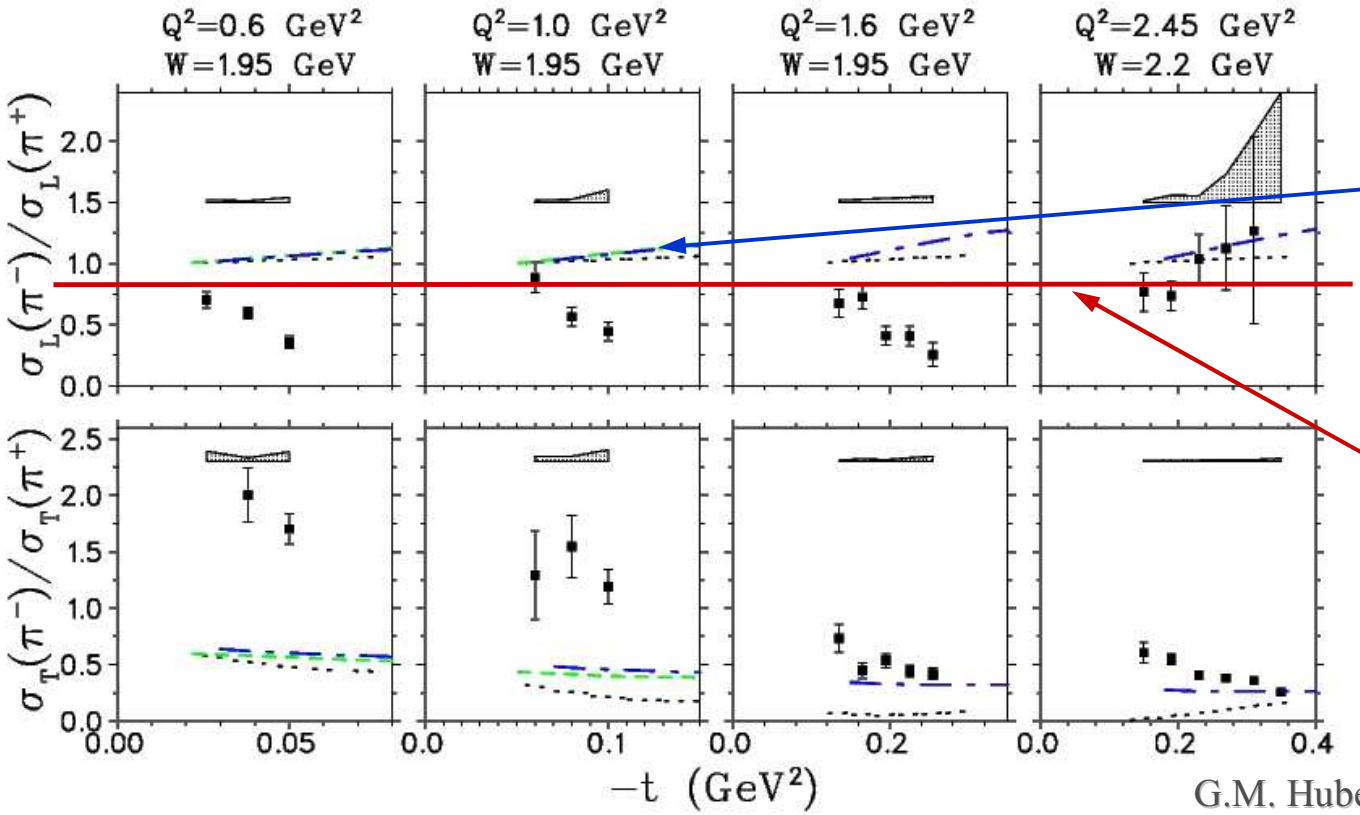
π^-/π^+ data to check *t*-channel dominance

- π^+ *t*-channel diagram is purely isovector (G-parity conservation).

$$R_L = \frac{\sigma_L[n(e,e'\pi^-)p]}{\sigma_L[p(e,e'\pi^+)n]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

- Isoscalar backgrounds (such as $b_1(1235)$ contributions to *t*-channel) will dilute ratio.

- **Qualitatively in agreement with our F_π-1 analysis:**
  - We found evidence for small additional contribution to σ_L at W=1.95 GeV not taken into account by the VGL model.
- We found no evidence for this contribution at W=2.2 GeV.



Vrancx-Ryckebusch Model:

- VR extend VGL with hard DIS process of virtual photons off nucleons.

[PRC **89**(2014)025203]

R_L=0.8 consistent with $|A_S/A_V|$<6%.

G.M. Huber, et al., PRL **112**, 182501 (2014)

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Anticipated E12-06-101 $d\sigma_L/dt$ Data

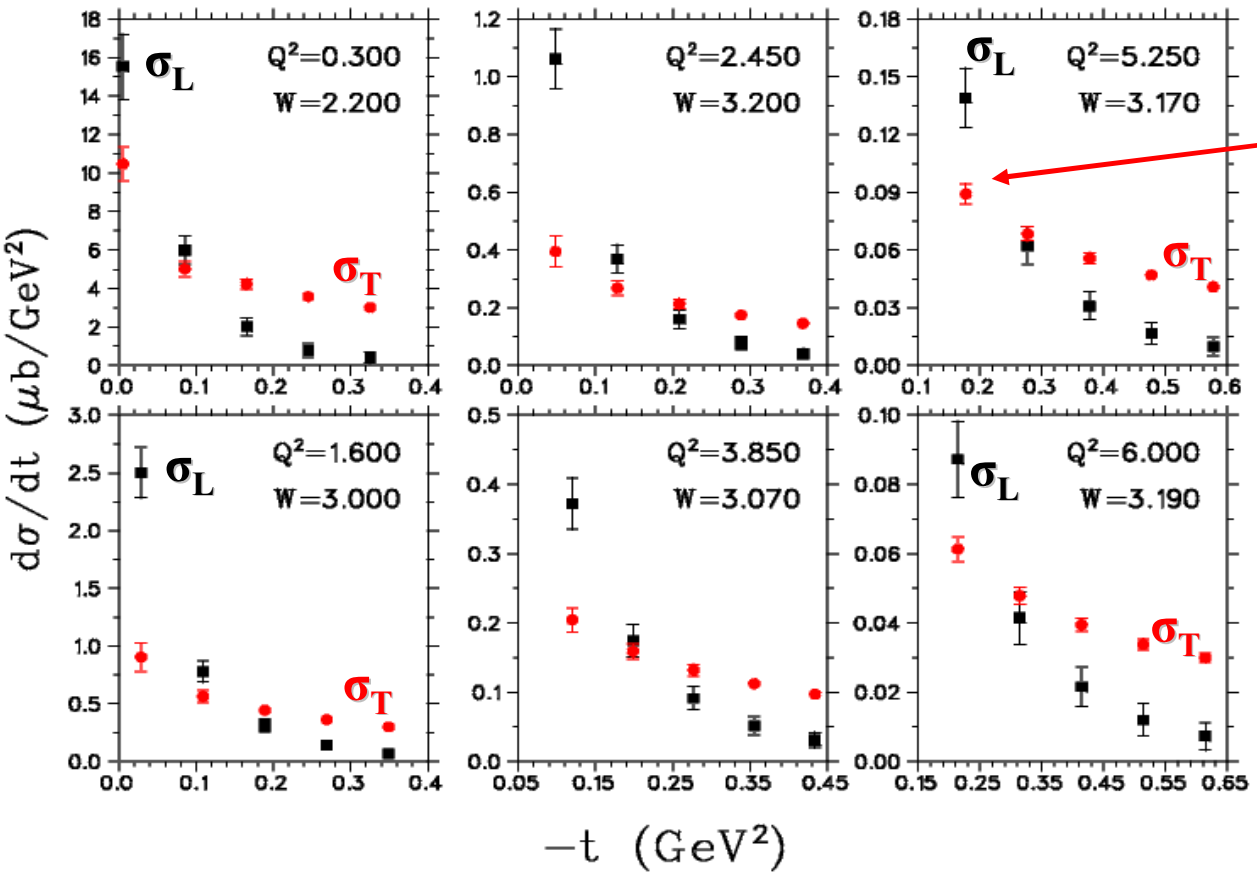
Achievable errors are limited by $R=\sigma_T/\sigma_L$ ratio and $1/\Delta\varepsilon$ error magnification.

Limits experimental kinematics.

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

$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{(R+\varepsilon_1)^2+(R+\varepsilon_2)^2} \qquad \text{where } R=\frac{\sigma_T}{\sigma_L}$$

$$\frac{\Delta\sigma_T}{\sigma_T} = \frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{\varepsilon_1^2\left(1+\frac{\varepsilon_2}{R}\right)^2+\varepsilon_2^2\left(1+\frac{\varepsilon_1}{R}\right)^2}$$



Note: $\sigma_T<\sigma_L$ at small *-t*

$R=\sigma_T/\sigma_L$ values taken from best available model:

Vrancx & Ryckebusch, Phys.Rev. C **89**, 025203 (2014)

Error Assumptions from PAC proposal:

- 1.3% stat. unc. per un-sep. t-bin
- 1.7% t-correl. & pt-pt syst. unc. which are magnified by $\Delta\varepsilon>0.25$

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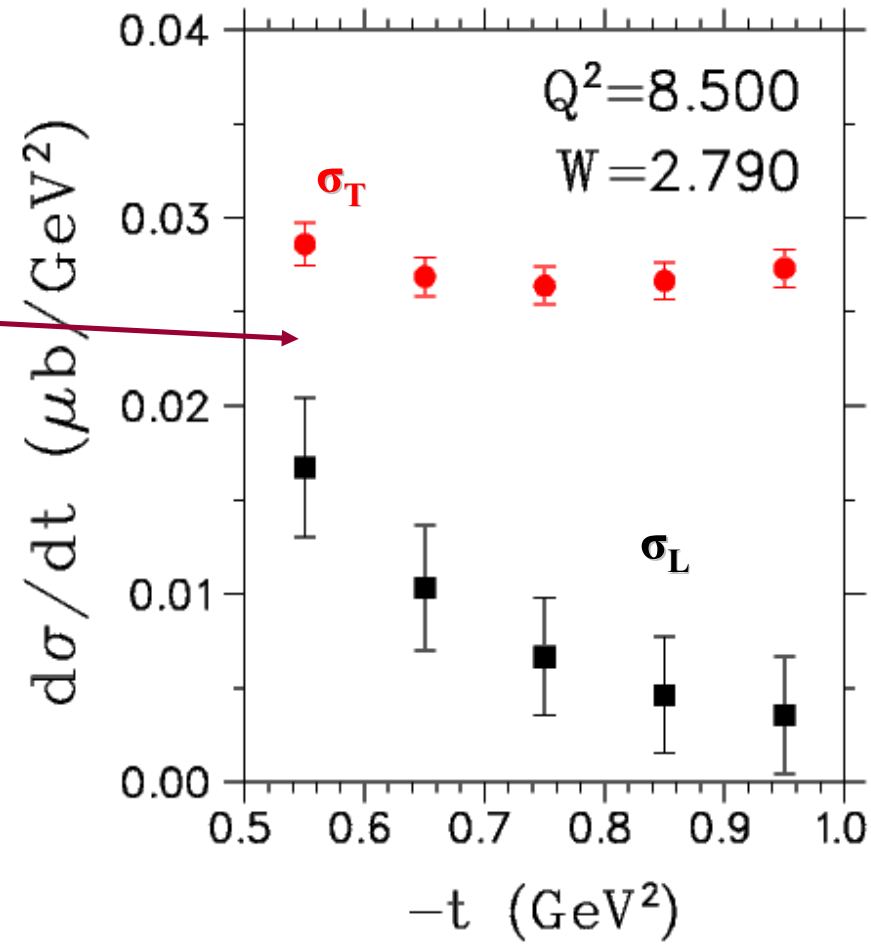
Extending $F_\pi(Q^2)$ to Q^2=8.5 GeV^2 in Hall C

- E_{beam}=10.9 GeV and $\Delta\varepsilon$>0.25 with the SHMS+HMS spectrometers allows L/T separations up to $Q^2 \approx 8.5$ GeV^2.
- **Note the less favorable $R=\sigma_T/\sigma_L$ predicted by VR model for these kinematics.**
- **For these Q^2, $-t_{min}$>0.5 GeV^2, and the pion pole contributions to σ_L will be significantly smaller.**

- **Will need to understand non–pole background to reliably extract F_π from these σ_L data.**



Assumptions same as E12-06-101:
- 1.3% stat. unc. per un-sep. t-bin
- 1.7% t-correl. & pt-pt syst. unc.

Magnified by $\Delta\varepsilon$>0.25

$R=\sigma_T/\sigma_L$ values from:
Vrancx & Ryckebusch, PRC 89, 025203 (2014)

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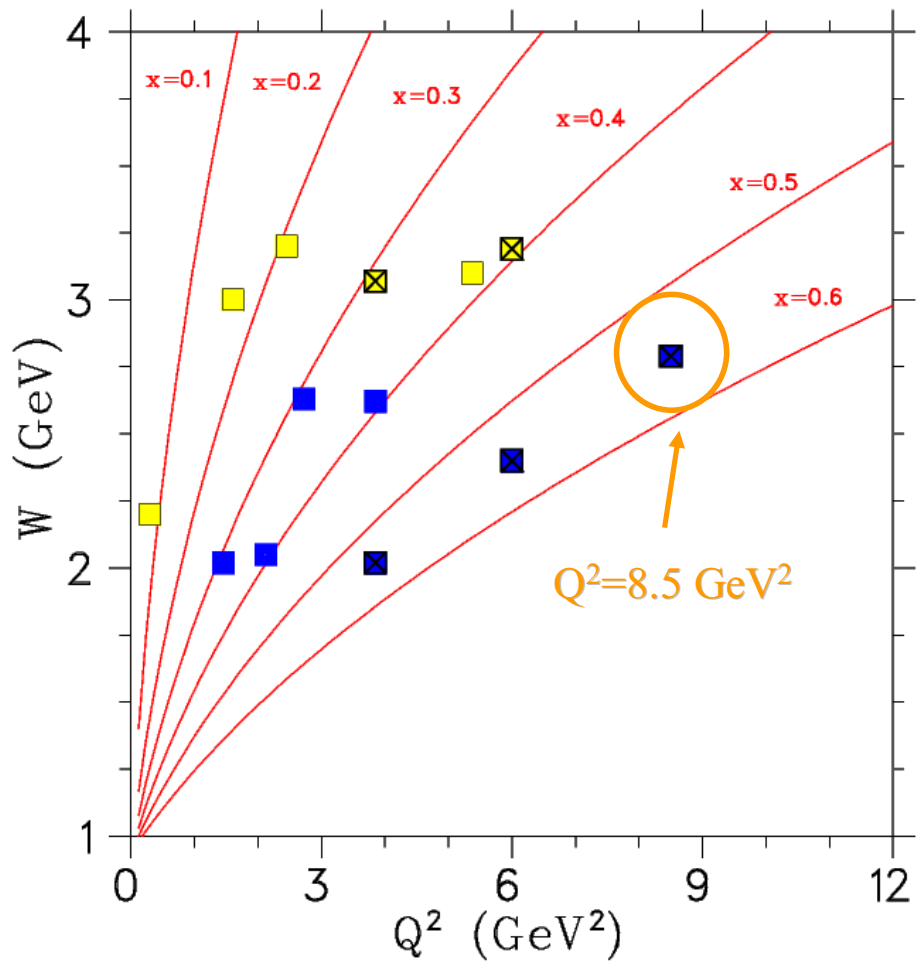
Extending $F_\pi(Q^2)$ to Q^2=8.5 GeV^2 in Hall C

- Efficiently combine settings from both p(e,e'π^+)n experiments so extra information can be obtained on non-pole backgrounds contributing to Q^2=8.5 GeV^2.
- Data-driven approach to better ensure a reliable extraction of the pion form factor value from these data.



■ Pion scaling: E12-07-105
■ Fpi: E12-06-101
X High Q^2 studies

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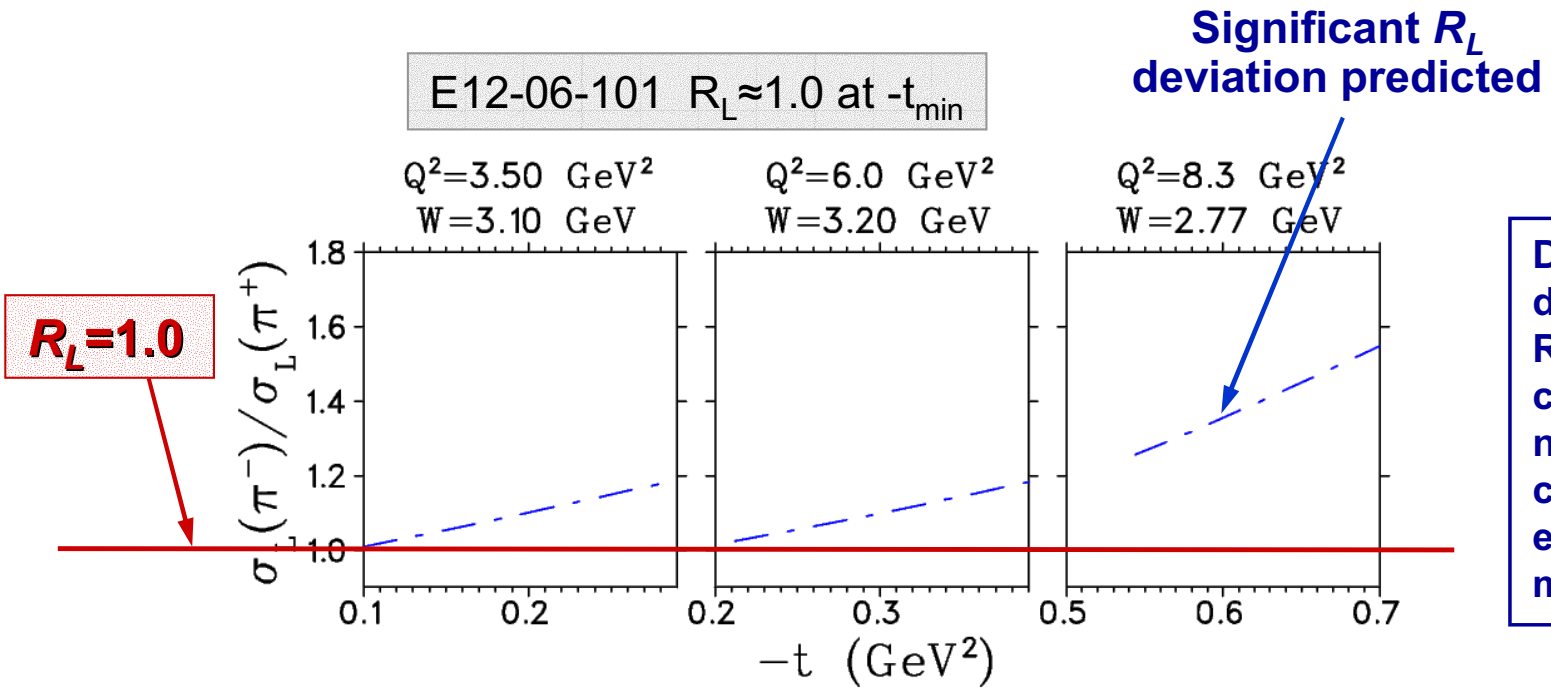
One way to understand non-pole to σ_L

Data–driven approach to better understand non–pole backgrounds at higher –*t*.

- Exclusive $^2H(e,e'\pi^+)nn$ and $^2H(e,e'\pi^-)pp$ L/T-separations.
- π^+ *t*–channel diagram is purely isovector (G-parity conservation).

$$R_L = \frac{\sigma_L[n(e,e'\pi^-)p]}{\sigma_L[p(e,e'\pi^+)n]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

- Isoscalar backgrounds would distort ratio (e.g. $b_1(1235)$ in *t*–channel).



Deviation of data from R_L=1.0 could confirm large non-pole contributions estimated by model.

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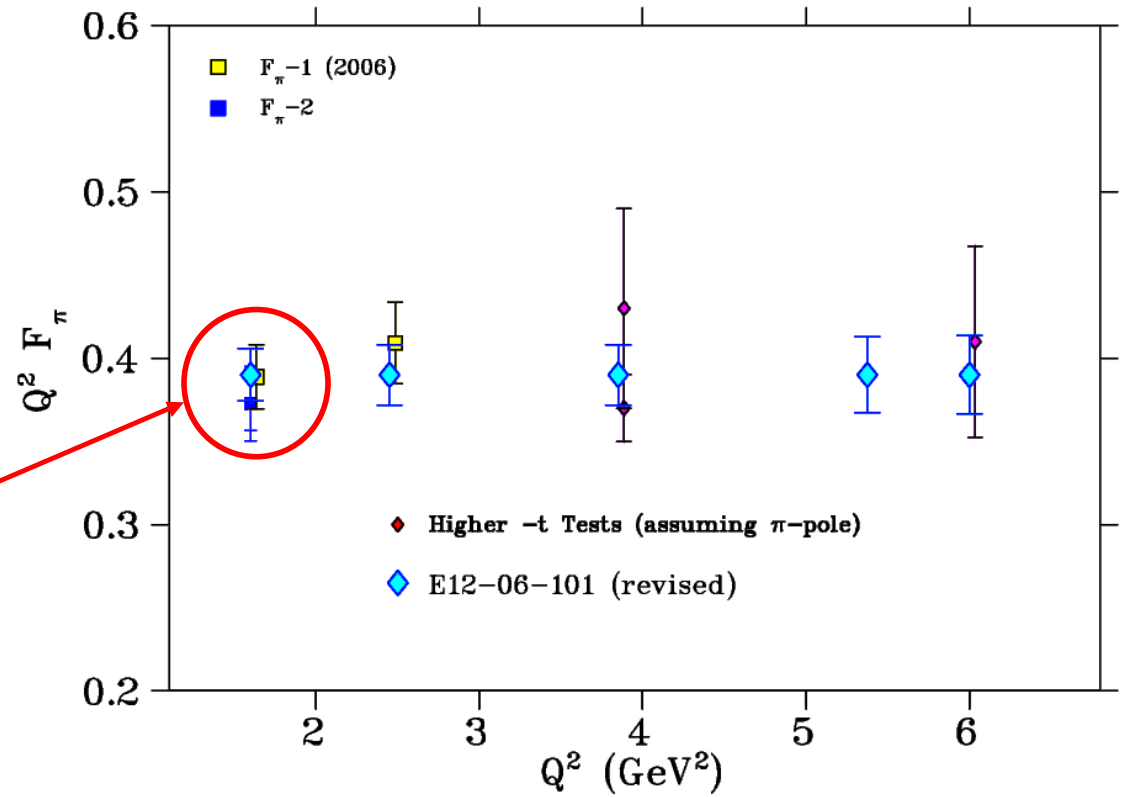
Another way to understand non-pole to σ_L

Test by extracting F_π at different distances from pole.

Expt: F_π-2, $-t_{min}=0.093\ GeV^2$
$W=2.22\ GeV.$
F_π-1, $-t_{min}=0.15\ GeV^2$
$W=1.95\ GeV.$

***W=2.22* point 30% closer to pole.**

→ Agreement ~4%.



We plan further tests:

Q^2=1.6 GeV^2	$-t_{min}$=0.029 GeV^2	W=3.00 GeV
Q^2=2.45 GeV^2	$-t_{min}$=0.048 GeV^2	W=3.20 GeV
Q^2=3.85 GeV^2	$-t_{min}$=0.12, 0.21, 0.49 GeV^2	W=3.07, 2.62, 2.02 GeV
Q^2=6.0 GeV^2	$-t_{min}$=0.21, 0.53 GeV^2	W=3.19, 2.40 GeV

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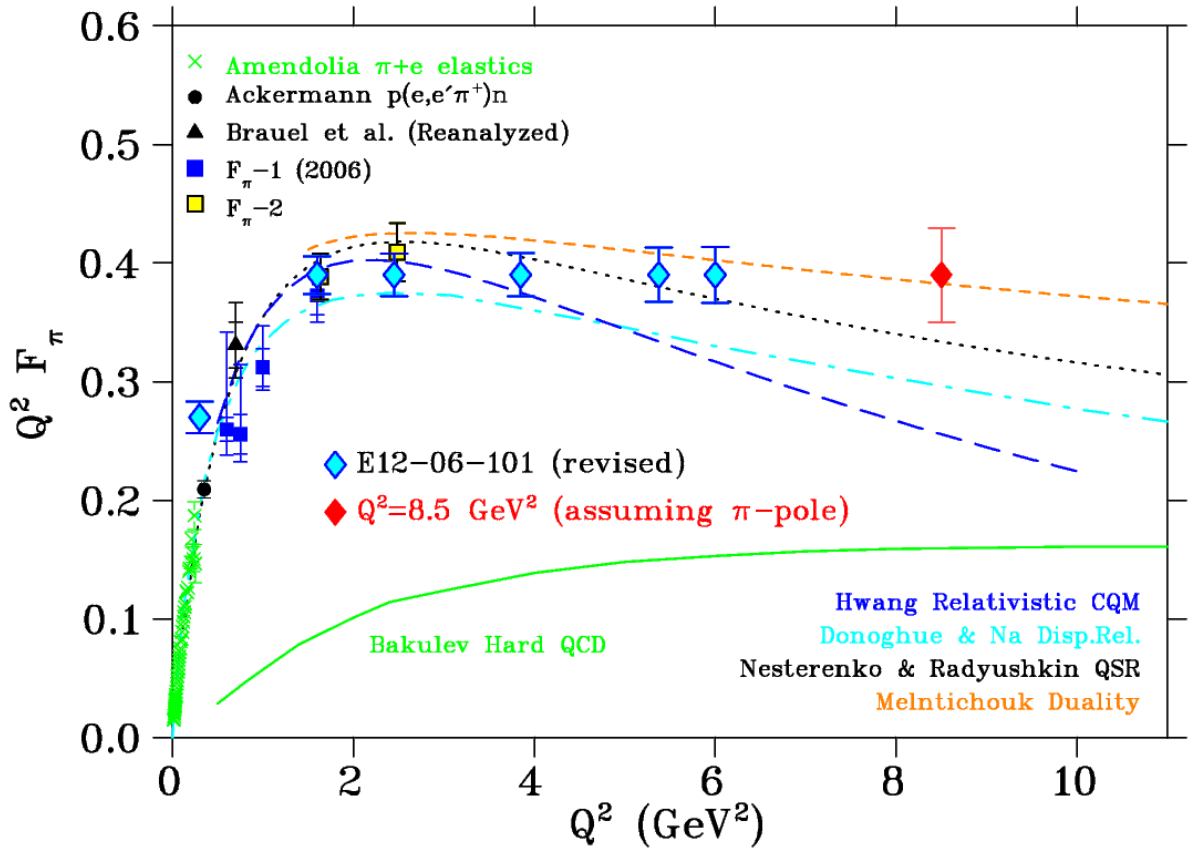
Projected Pion Form Factor Results

JLab 12 GeV upgrade will allow measurement of F_π to much higher Q^2.

No other facility worldwide can perform this measurement.

New overlap points at $Q^2=1.6, 2.45$ will be closer to pole to constrain $-t_{min}$ dependence.

New low Q^2 point will provide best comparison of the electroproduction extraction of F_π vs elastic π+e data.



- If the π-pole contribution to σ_L can be cleanly identified, a ~10% measurement of F_π at Q^2=8.5 GeV^2 would require about 6 days of additional beam. → $\Delta\varepsilon$=0.27, Expected $R=\sigma_T/\sigma_L$=1.7 at $-t_{min}$=0.544 GeV^2.

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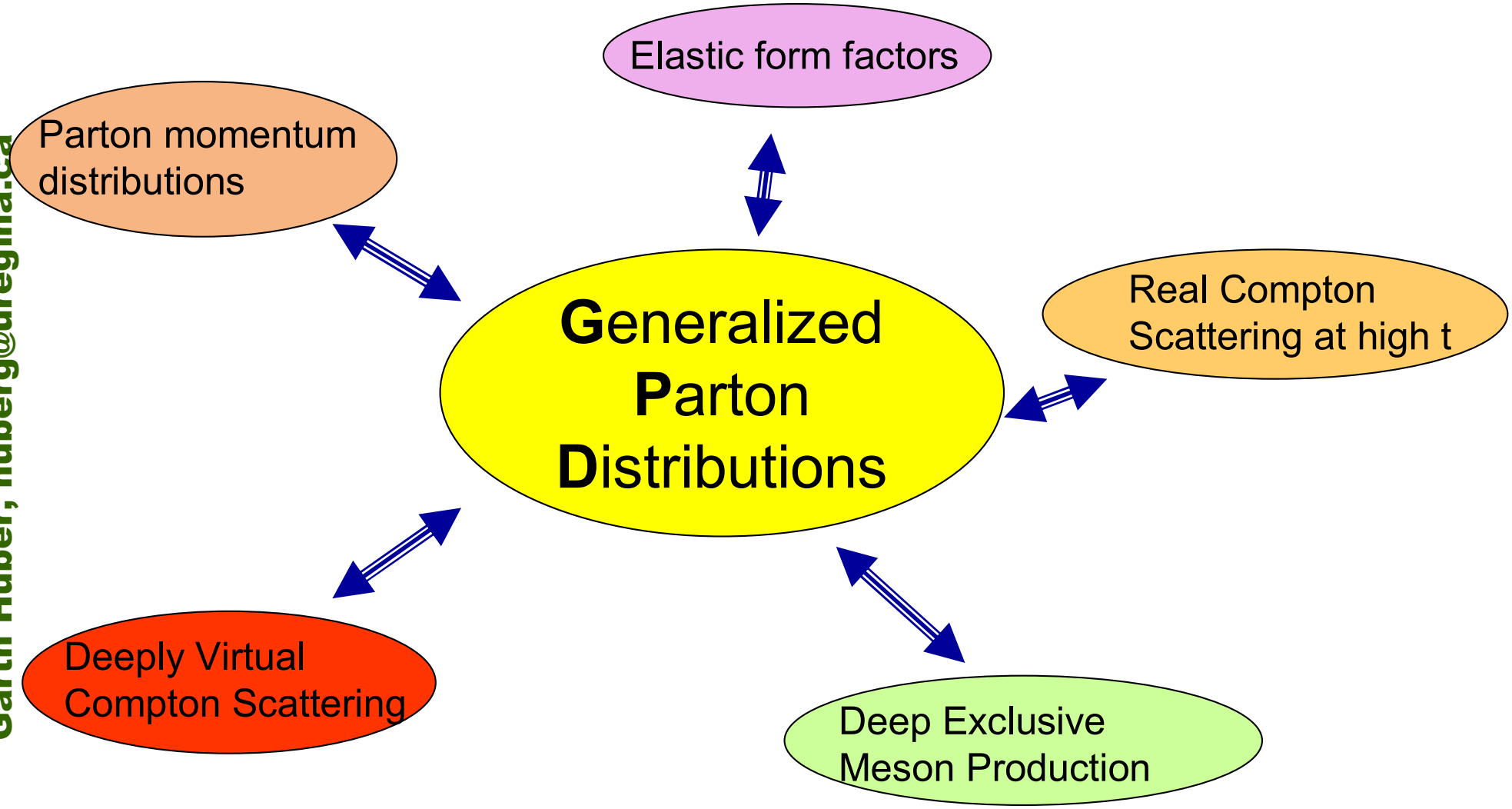
GPDs – A Unified View of Hadron Structure



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Leading Twist GPD Parameterization

- **GPDs are universal quantities and reflect nucleon structure independently of the probing reaction.**
  - GPDs provide 3D spatial information on the distributions of quarks and gluons in a nucleon.
  - GPDs inter-relate the longitudinal and transverse momentum structure of partons within a fast moving hadron.

- **At leading twist-2, four quark chirality conserving GPDs for each quark, gluon type.**

- **Because quark helicity is conserved in the hard scattering regime, the produced meson acts as a helicity filter.**

$H^{q,g}(x,\xi,t)$ spin avg no hel. flip	$E^{q,g}(x,\xi,t)$ spin avg helicity flip
$\tilde{H}^{q,g}(x,\xi,t)$ spin diff no hel. flip	$\tilde{E}^{q,g}(x,\xi,t)$ spin diff helicity flip

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Relation between GPDs and Form Factors

- First moments of GPDs are related to nucleon elastic form factors through model-independent sum rules:

Dirac and Pauli elastic form factors.
t -dependence fairly well known.

$$\begin{cases} \sum_q e_q \int_{-1}^{+1} dx\, H^q(x,\xi,t) = F_1(t) \\ \sum_q e_q \int_{-1}^{+1} dx\, E^q(x,\xi,t) = F_2(t) \end{cases}$$

Isovector axial form factor.
t –dep. poorly known.

$$\longrightarrow \quad \sum_q e_q \int_{-1}^{+1} dx\, \tilde{H}^q(x,\xi,t) = G_A(t)$$

Pseudoscalar form factor.
Very poorly known.

$$\longrightarrow \quad \sum_q e_q \int_{-1}^{+1} dx\, \tilde{E}^q(x,\xi,t) = G_P(t)$$

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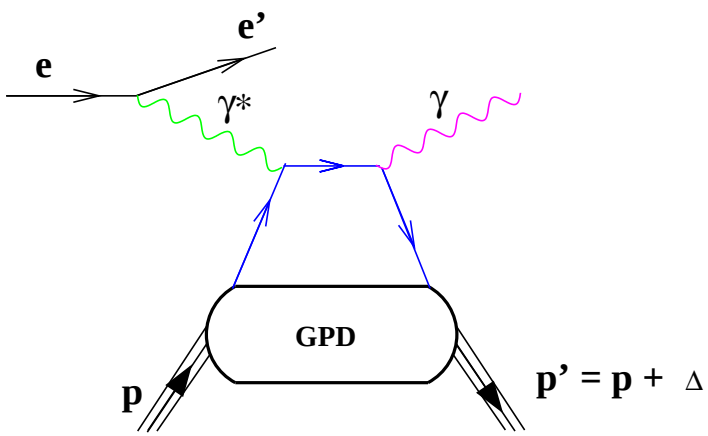
Complementarity of Different Reactions

Deep Exclusive Meson Production:

- Vector mesons sensitive to spin-average H, E.
- Pseudoscalar mesons sensitive to spin-difference $\tilde{H}$, $\tilde{E}$.



Deeply Virtual Compton Scattering:

- Sensitive to all four GPDs.

- **Need a variety of Hard Exclusive Measurements to disentangle the different GPDs.**

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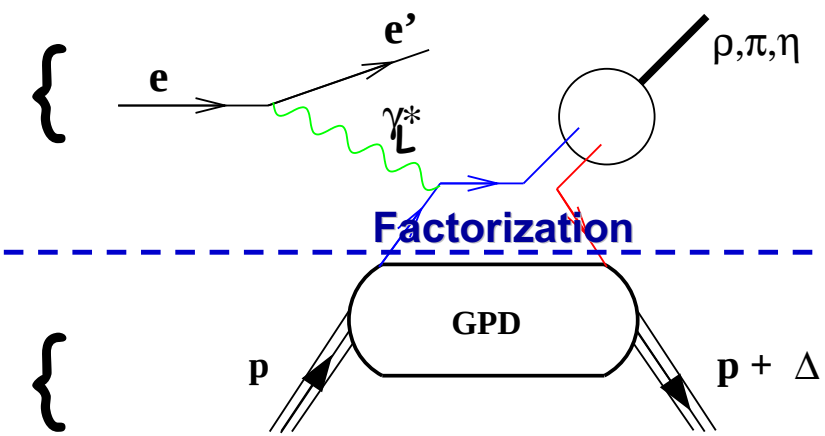
GPDs require Hard Exclusive Reactions

- **In order to access the physics contained in GPDs, one is restricted to the hard scattering regime.**

- **Factorization property of hard reactions:**
  - Hard probe creates a small size $q\bar{q}$ and gluon configuration,
    - interactions can be described by pQCD.
  - Non-perturbative part describes how hadron reacts to this configuration, or how the probe is transformed into hadrons (parameterized by GPDs).



- Hard Exclusive Meson Electroproduction first shown to be factorizable by Collins, Frankfurt & Strikman [PRD **56**(1997)2982].
- Factorization applies when the γ^* is longitudinally polarized.
  - corresponds to small size configuration compared to transversely polarized γ^*.

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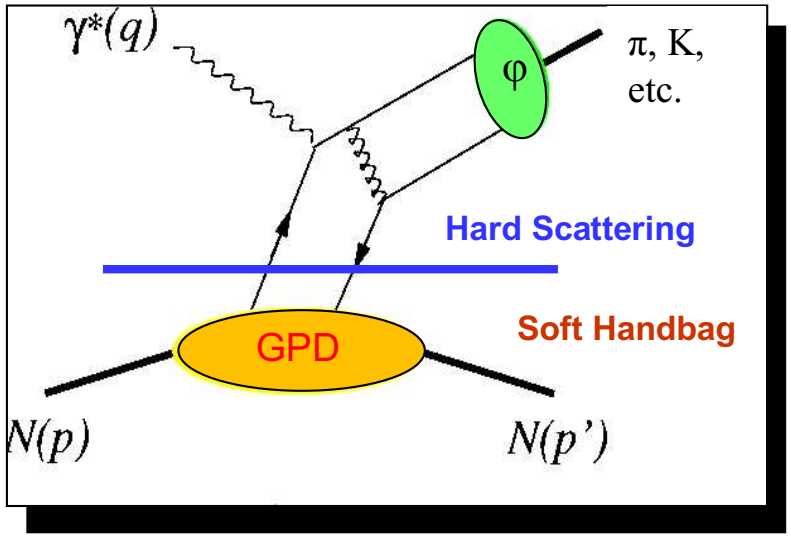
Investigations of QCD Factorization Regime

- **We will perform the most detailed study to determine whether or not meson electroproduction can provide information on GPDs.**

- As it is not known how high Q^2 is needed for the factorization theorem to apply, it is necessary to first test that the regime of validity has been reached.
- This can be done by comparing the Q^2 variation of the cross section against the prediction of Hard QCD.



- We will study both π^+ and K^+ electroproduction. Virtually nothing is known concerning QCD factorization when strangeness is in play.

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Scaling Experiment Goals

- **Measure the Q^2 dependence of the $p(e,e'\pi^+)n$, $p(e,e'K^+)\Lambda$, $p(e,e'K^+)\Sigma$ cross sections at fixed x_B and $-t$ to search for evidence of hard-soft factorization**
  - Separate the cross section components: L, T, LT, TT
  - Highest Q^2 for any L/T separation in π^+,K^+ electroproduction
  - Can only learn about GPDs if soft-hard factorization applies
  - If transverse contributions are large, the accessible phase space may be limited

- A stringent test is the Q^2-dependence of the $p(e,e'\pi^+)n$, $p(e,e'K^+)\Lambda$ cross sections:
  - σ_L scales to leading order as Q^{-6}.
  - σ_T scales as Q^{-8}.
  - As Q^2 becomes large: $\sigma_L >> \sigma_T$.

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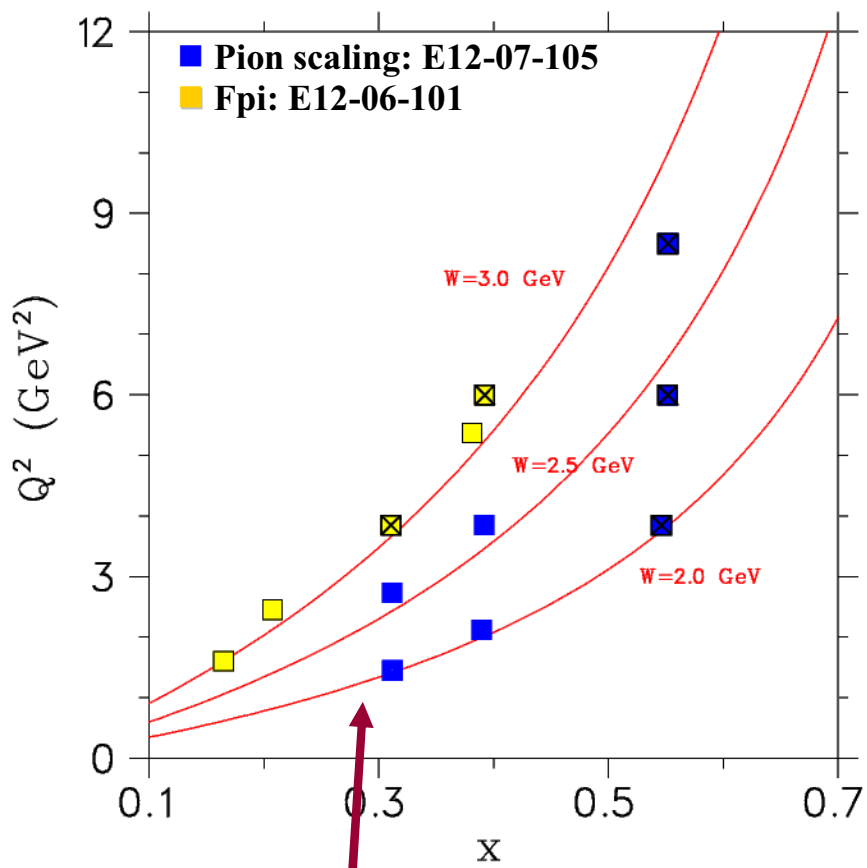
$p(e,e'\pi^+)n$ Scaling Experiment Overview

- Measure separated cross sections for the $p(e,e'\pi^+)n$, $p(e,e'K^+)\Lambda$, $p(e,e'K^+)\Sigma$ reactions at three values of x_B.
- **Q^2 coverage is a factor of 3-4 larger compared to 6 GeV.**
  - **Facilitates tests of the Q^2 dependence even if L/T is less favorable than predicted.**

Phase space for L/T separations with SHMS+HMS



x	Q^2 (GeV/c)^2	W (GeV)	-t (GeV/c)^2
0.31	1.5-4.0	2.0-3.1	0.1
0.40	2.1-5.5	2.0-3.0	0.2
0.55	4.0-9.1	2.0-2.9	0.5

Kinematics for π measurements

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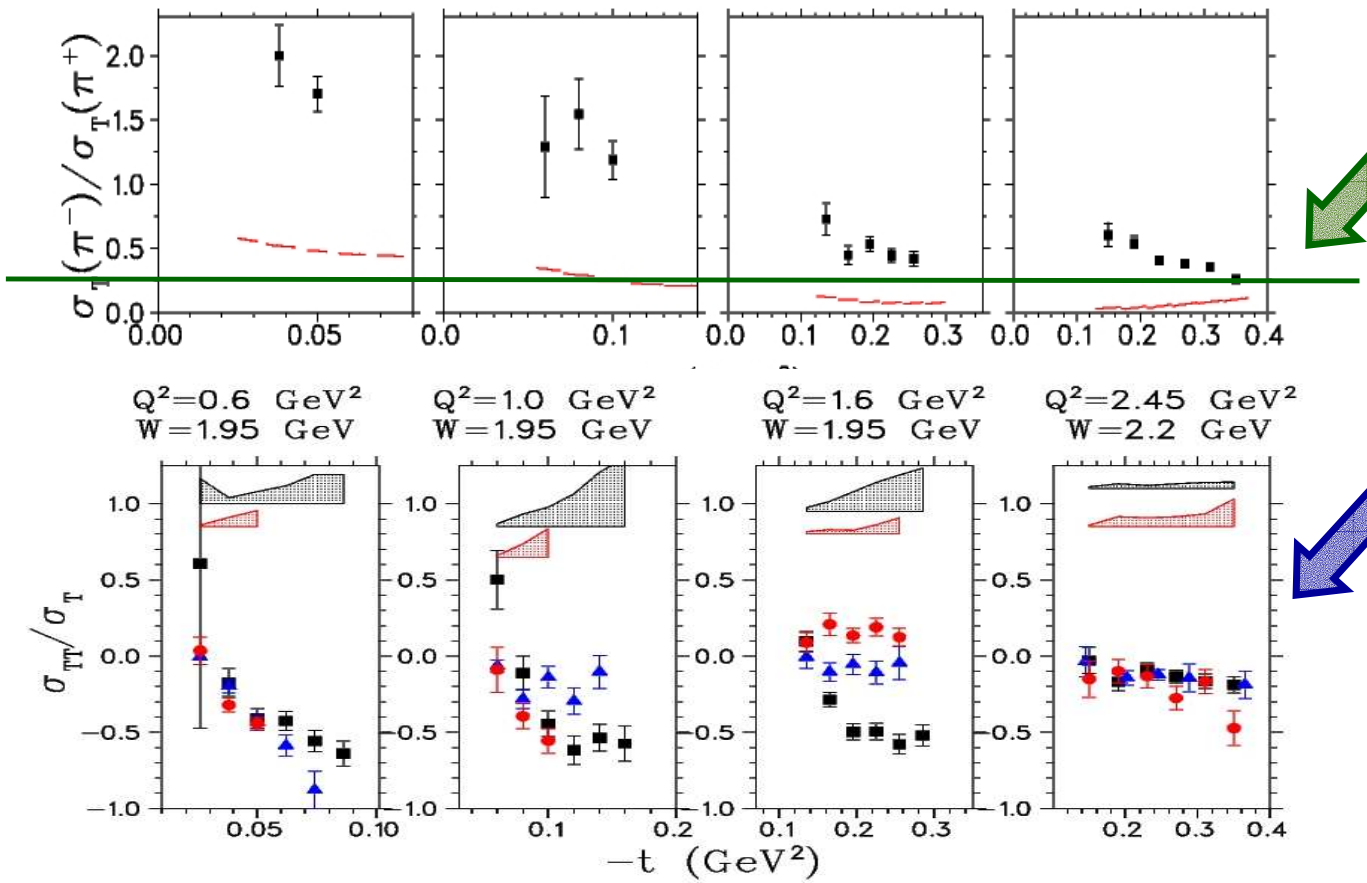
π^-/π^+ Separated Response Function Ratios

- **Transverse Ratios tend to ¼ as –t increases:**
  → Is this an indication of Nachtmann's quark charge scaling?
- **-t=0.3 GeV² seems too low for this to apply. Might indicate the partial cancellation of soft QCD corrections in the formation of the ratio.**

A. Nachtmann, Nucl.Phys.**B115** (1976) 61.



$$R_T \rightarrow \frac{2Q_d^2}{2Q_u^2} = \frac{1}{4}$$

- Another prediction of quark-parton mechanism is the suppression of σ_{TT}/σ_T due to *s*-channel helicity conservation.
- Data qualitatively consistent with this, since σ_{TT} decreases more rapidly than σ_T with increasing Q^2.

^{2}H(e,e'π^+)nn ^{2}H(e,e'π^-)pp ^{1}H(e,e'π^+)n

G.M. Huber, et al., PRC **92**, 015202 (2015)

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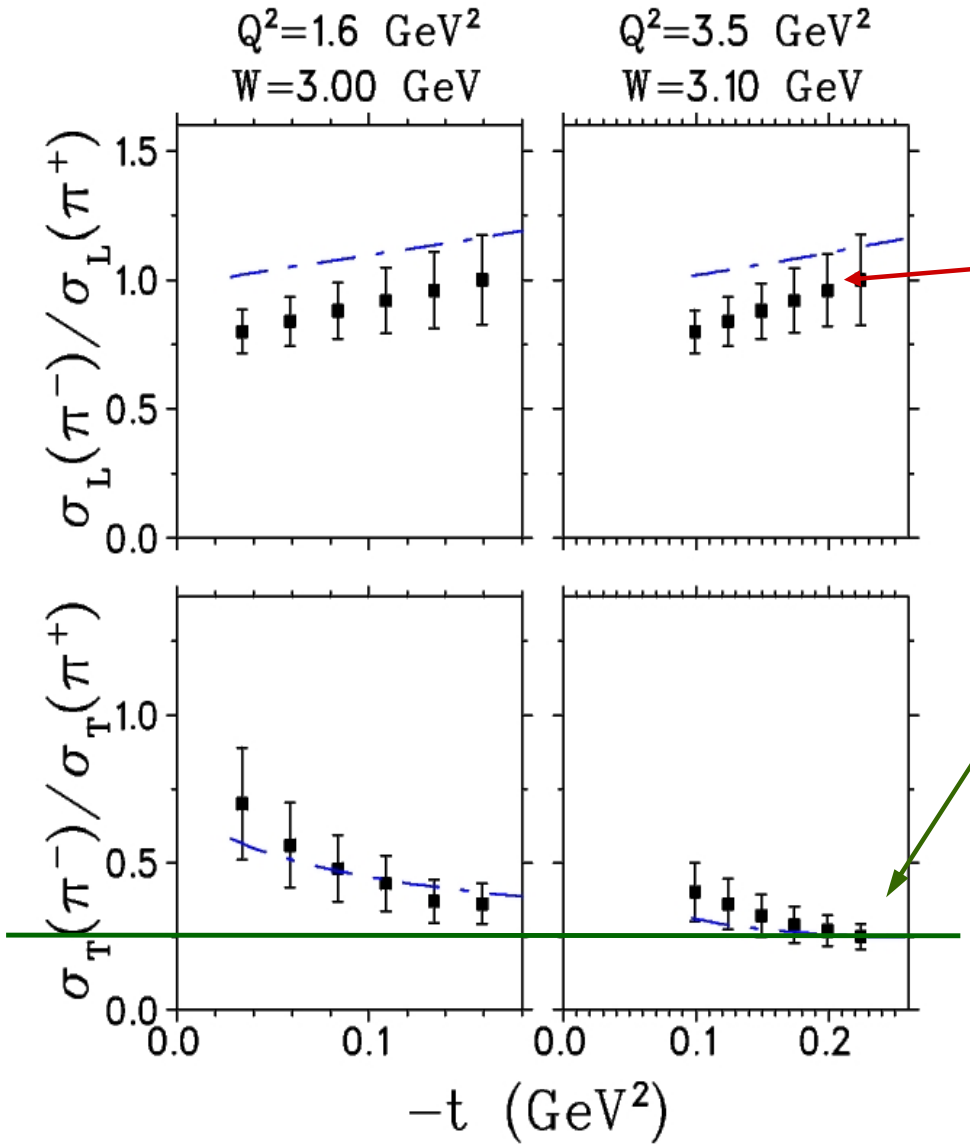
Projected π^-/π^+ Data from Fπ-12 Experiment



- ^{2}H data to determine R_L π^-/π^+ ratio to constrain modeling of non–pole backgrounds in σ_L, relevant for extraction of pion form factor
- If R_T is ~1/4 at higher Q^2 and similar x_B, the hypothesis of a quark knockout mechanism will be strengthened.

Predictions of Vrancx-Ryckebusch Regge+DIS Model
[PRC **89**(2014)025203]

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12 GeV era – Hall C with SHMS and HMS

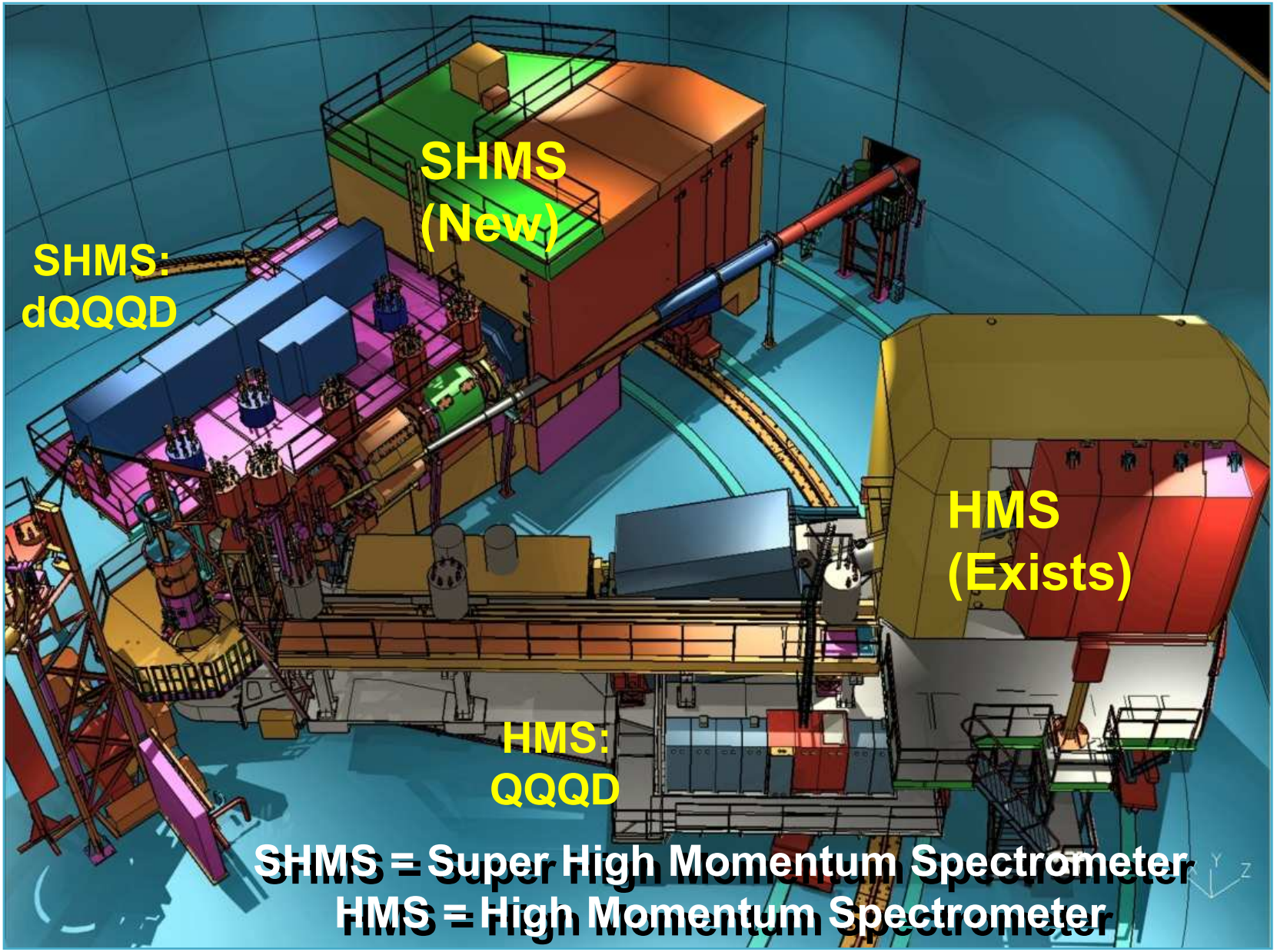
SHMS:
- 11 GeV/c Spectrometer
- Partner of existing 7 GeV/c **HMS**

MAGNETIC OPTICS:
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter
- All derived from existing HMS/SOS detector designs

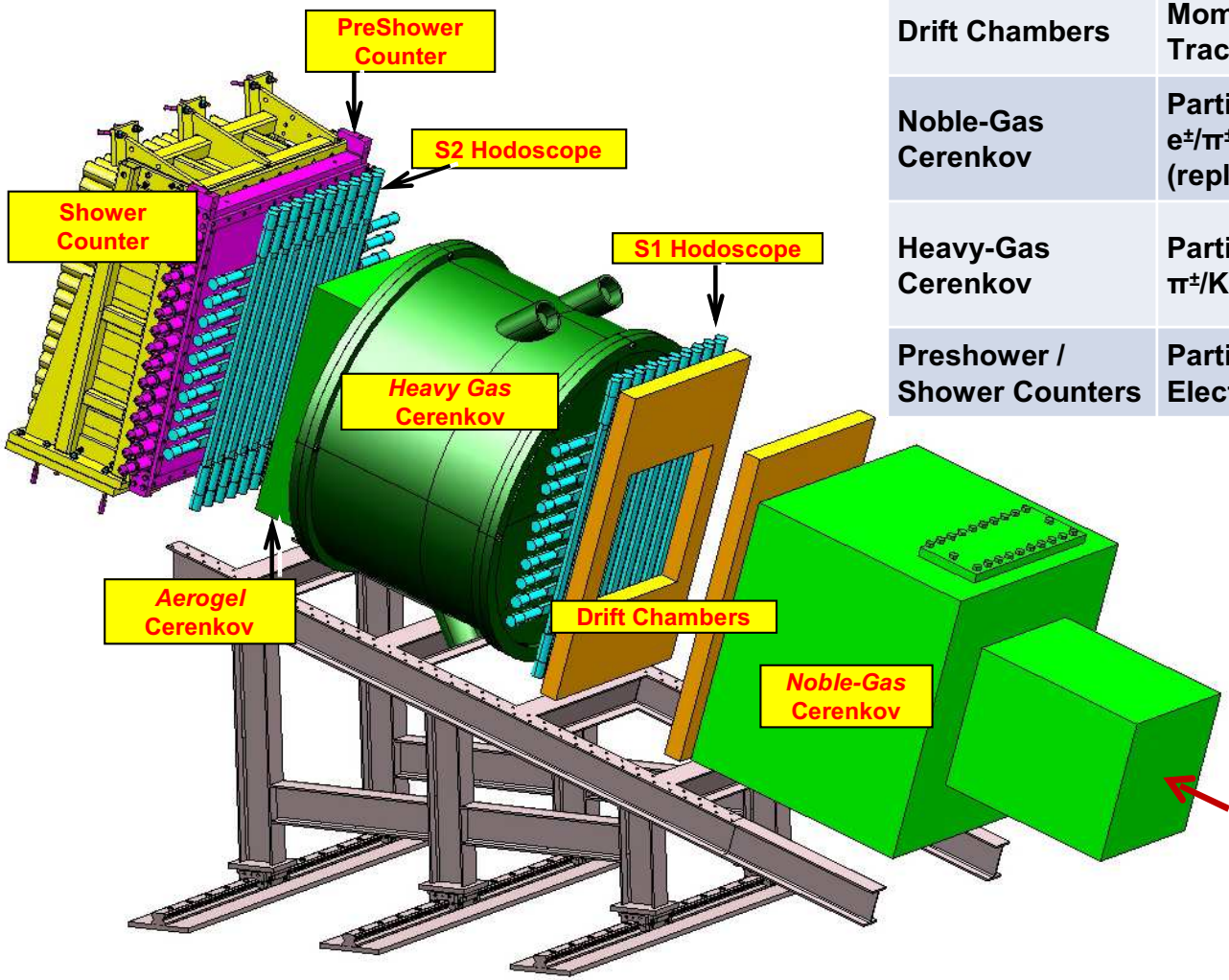
Well-Shielded Detector Enclosure

Rigid Support Structure
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS



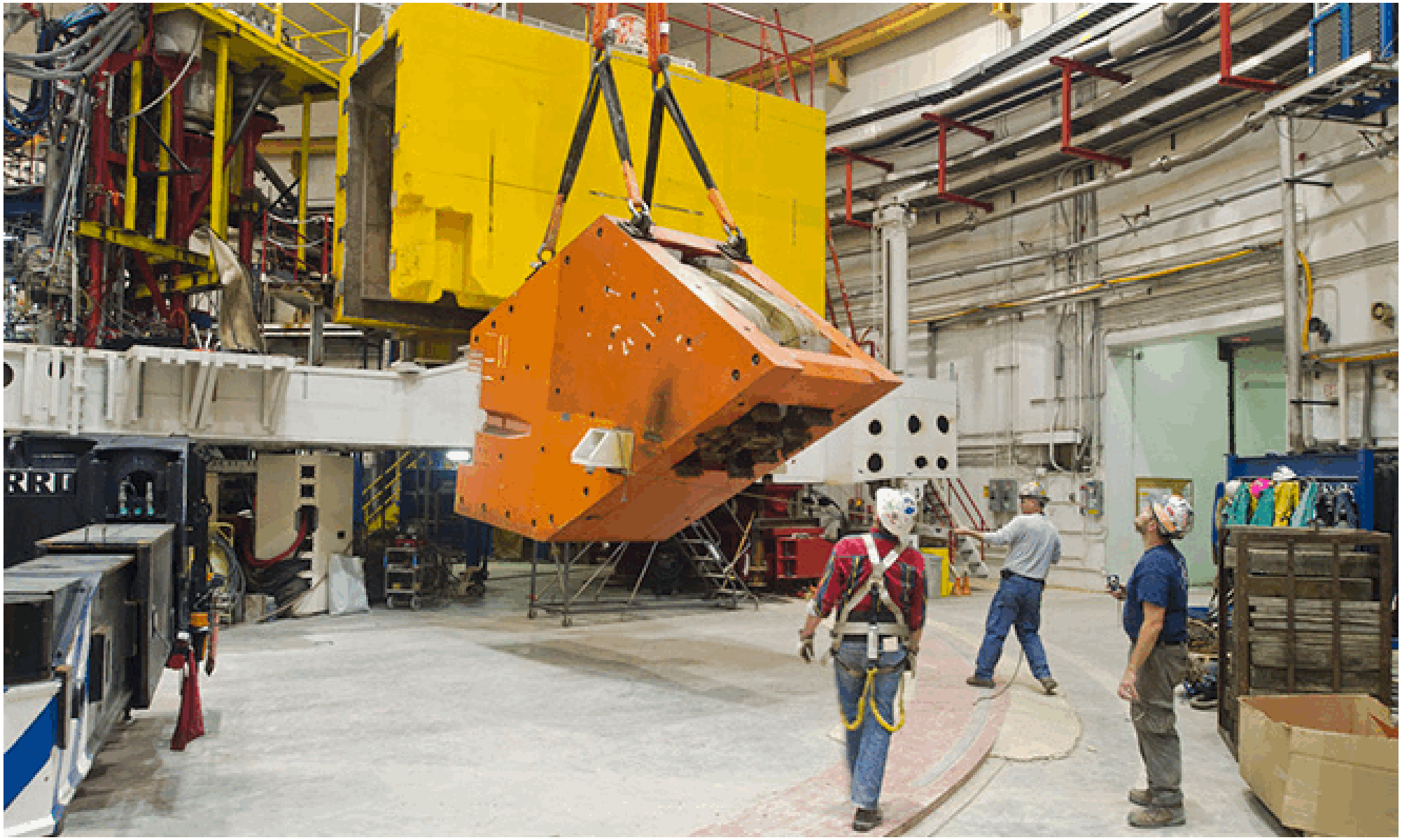
SHMS Detector System

DETECTOR	PURPOSE	NOTES
S1XY, S2XY Hodoscopes	Lowest-level Trigger. Time reference	
Drift Chambers	Momentum Measurement. Tracking.	5mm max. drift 300 micron resolution
Noble-Gas Cerenkov	Particle ID, Trigger. $e^{\pm}/\pi^{\pm}$ at high momentum (replace by vacuum at low p)	Vary Ar/Ne mixture to set index at $\pi^{\pm}$ threshold.
Heavy-Gas Cerenkov	Particle ID, Trigger. $\pi^{\pm}/K^{\pm}$ discrimination	C_4F_8O – Vary pressure to set index at $K^{\pm}$ threshold
Preshower / Shower Counters	Particle ID, Trigger. Electron tag	

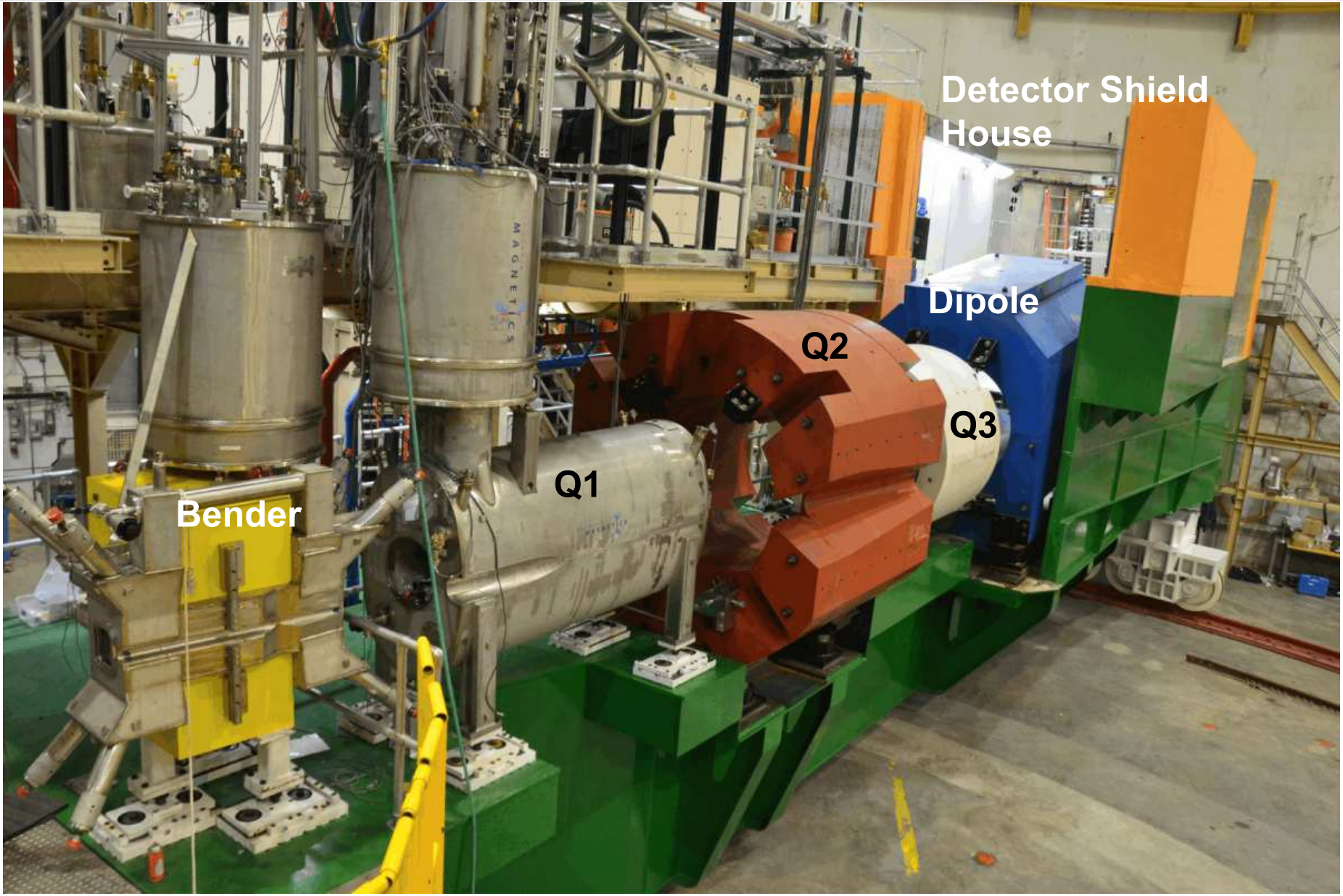


Incident Particles through SHMS magnet optics

Dismantling the SOS in Early 2013



SHMS Installation



SHMS Dipole Progress

- **Dipole**
  - Coils Joined Together and Entire Assembly Potted.
  - Coil Machined. Collars Machined.
  - Dipole Coil Collared 17-JUN-2015.
  - Coil sealed within its Helium Vessel.
  - Leak & Pressure tested successfully.
  - Thermal shields fabricated. Fitted around coil.
  - Vacuum Vessel Barrel Section is in Place.

Helium Vessel goes on

NOV-2014: Coil Potting

Collars going on Coil

SigmaPhi Vannes, France

14-JAN-2016: Coil Insulated and Surrounded by Thermal Screen and Vacuum Vessel Can

SHMS Q2 & Q3 Progress

SigmaPhi
Vannes, France

- **Q2 and Q3 Magnets**
  - Coil winding completed.
  - Coils Joined, Spliced, Wrapped & the Assemblies Potted.
  - Coils Machined. Collars Machined. Collaring complete.
  - Coils inserted in their Helium Vessels. Vessels welded closed.
  - All of the Q2 Parts are ready for shipment to SigmaPhi.
    - Waiting on dipole assembly so that floor space is available.
  - Q3 Parts are undergoing QA tests.

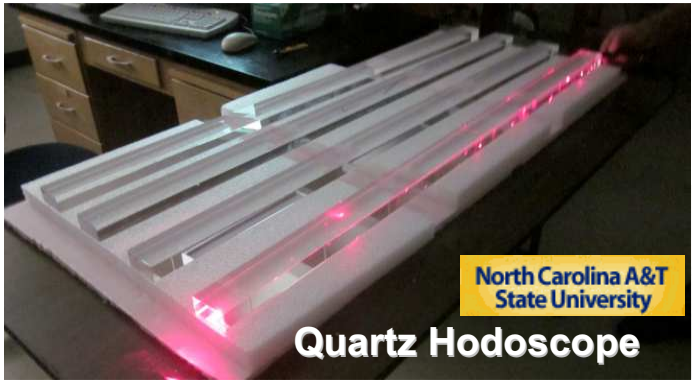
A partially wound Coil

Fully-Potted Q3 Coils

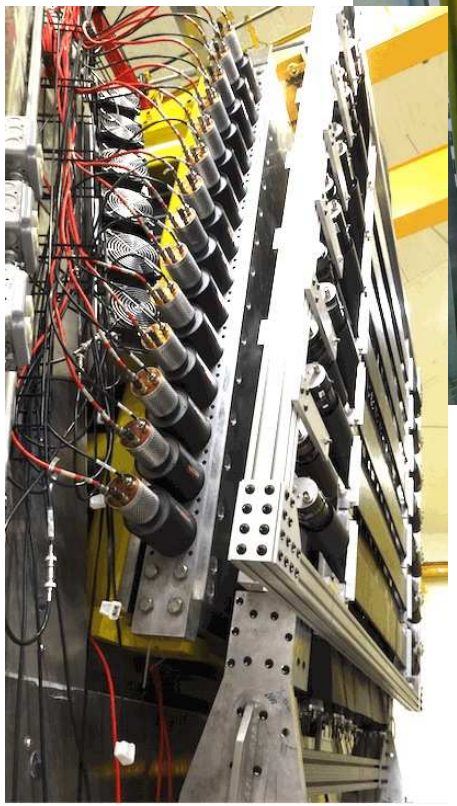
Machined Q3 Coils

Q3 Coil Collaring 17-SEP-2015

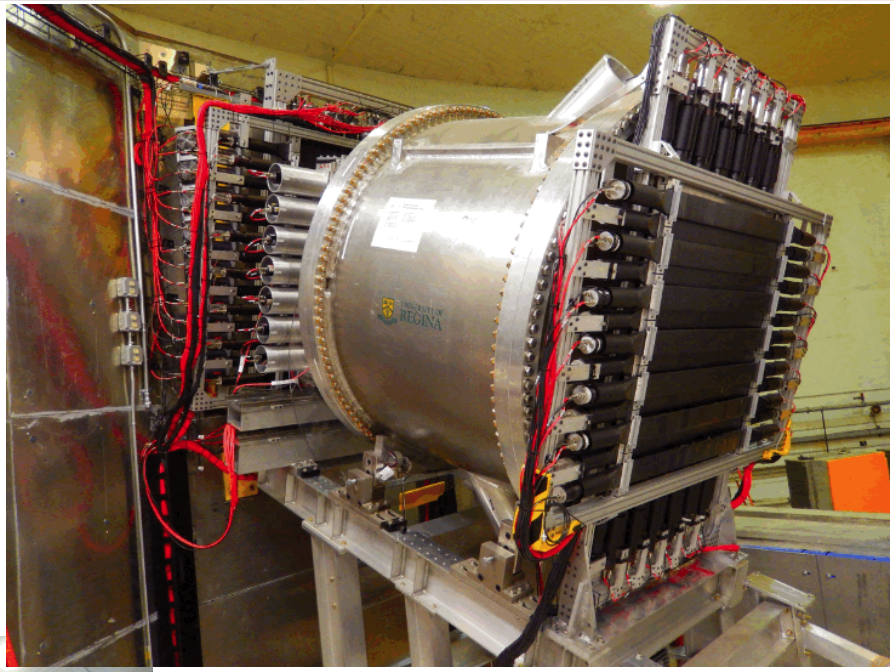
SHMS Detector Construction is Complete



SHMS Rear Detector Installation



SHMS Preshower and Shower Counter Testing with Flash ADC DAQ



Hall C Deep Exclusive Mesons Timeline

SHMS rear detector installation	Feb – Aug, 2015
SHMS superconducting magnet installation and testing	Until Sept, 2016
SHMS front detector installation	July – Aug, 2016
SHMS commissioning with beam	Dec, 2016
First physics-quality run in Hall C	Feb – June, 2017

Data Reconstruction Software (hcana)

- Z. Ahmed (PDF), completed

SHMS Detector Checkout & Commissioning

- W. Li (Ph.D.), S. Basnet (M.Sc.), work underway

p(e,e'K$^+$)Λ Kaon Form Factor

- L/T commissioning experiment (2017)

Pion Form Factor and π^+ QCD-Scaling Experiments

- Interleaved run-plans (2018 – 2019)

Regina Efforts

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