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

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University of Regina

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Regina is located in the northern Great Plains of North America

Regina, Saskatchewan CANADA

Regina is named after Queen Victoria, and is capital of the province of Saskatchewan

A2 Collaborator Dave Hornidge is 3900 km east

IT'S A BIG COUNTRY!

University of Regina

- Founded 1974.
- 14,300 students, incl. 1,750 Grad Students (2015).
- Physics Dept. offers B.Sc., M.Sc. and Ph.D. degrees.

Quantum Electrodynamics
Quantum Chromodynamics

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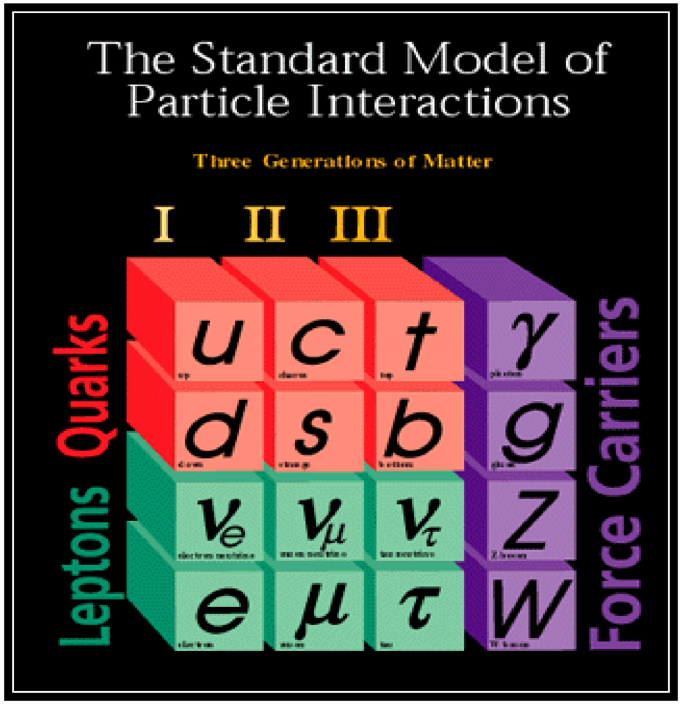
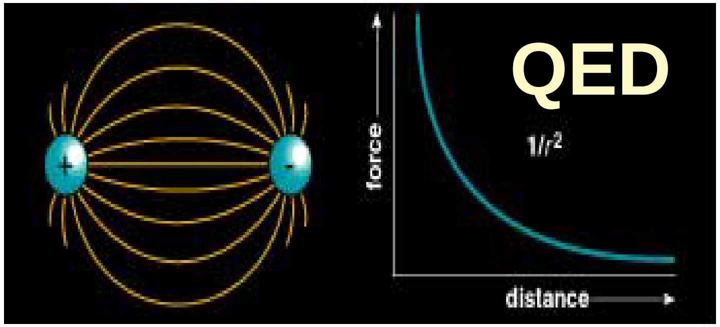
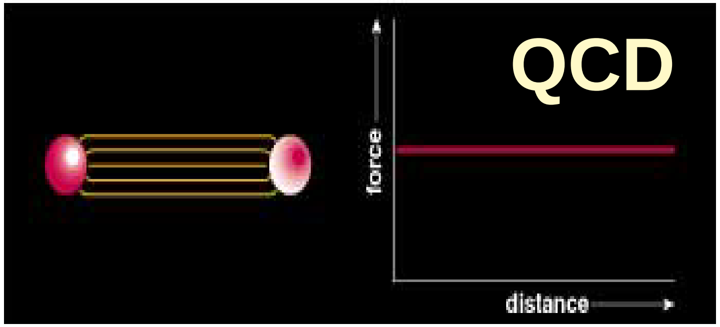
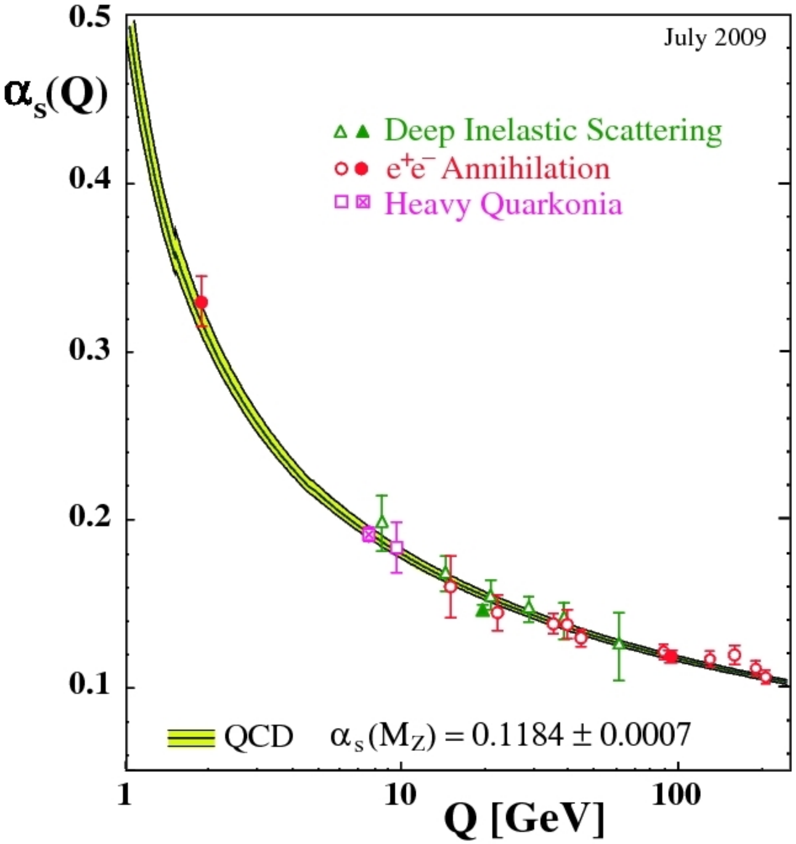






- Quarks are fractionally charged and interact via the electromagnetic (QED) and strong (QCD) interactions.
- Unlike the photons of QED, the gluons of QCD carry color charge and interact strongly, leading to the confinement of quarks inside hadrons.

QCD's Dual Nature



Short Distance Interaction:

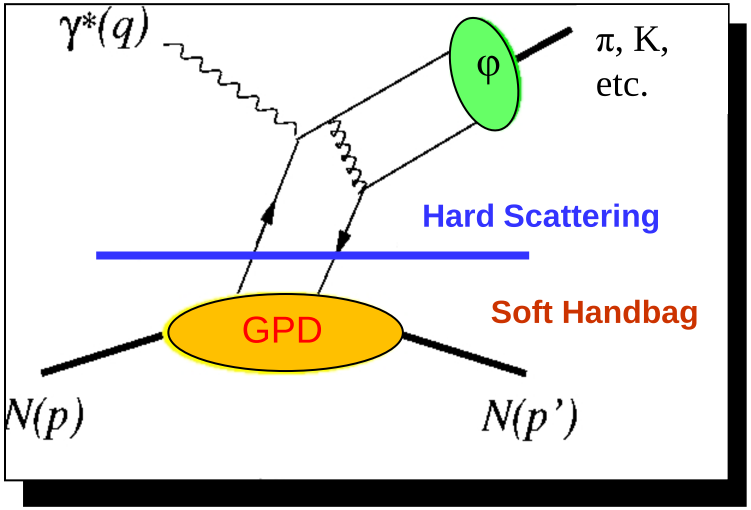
- Short distance quark-quark interaction is feeble.
  - Quarks inside protons behave as if they are nearly unbound.
  - Asymptotic Freedom.
- perturbative QCD (pQCD).

Long Distance Interaction:

- Quarks strongly bound within hadrons.
  - Color confinement (strong QCD).
- QCD calculations extremely difficult.
- **QCD-based models often used, but experimental data needed to validate approaches used.**
- **Studies are at the interface of particle and nuclear physics since the problems often require a "many body" approach.**

Deep Exclusive Meson Production (DEMP)

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



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

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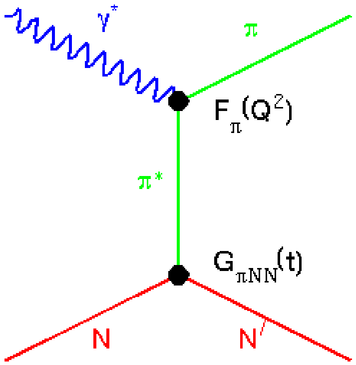
1) Determine the Pion Form Factor at Q^2>0.3 GeV^2:

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

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

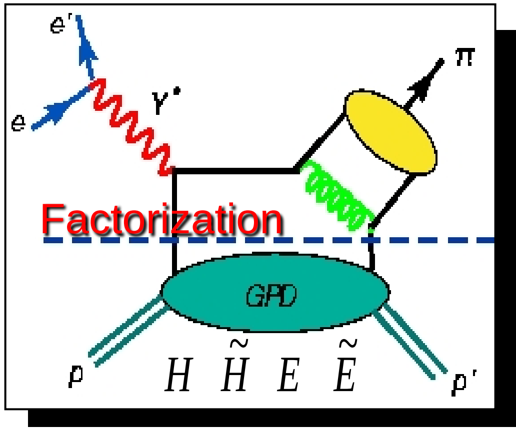
  - Pion pole process dominates σ_L in forward kinematics.



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.

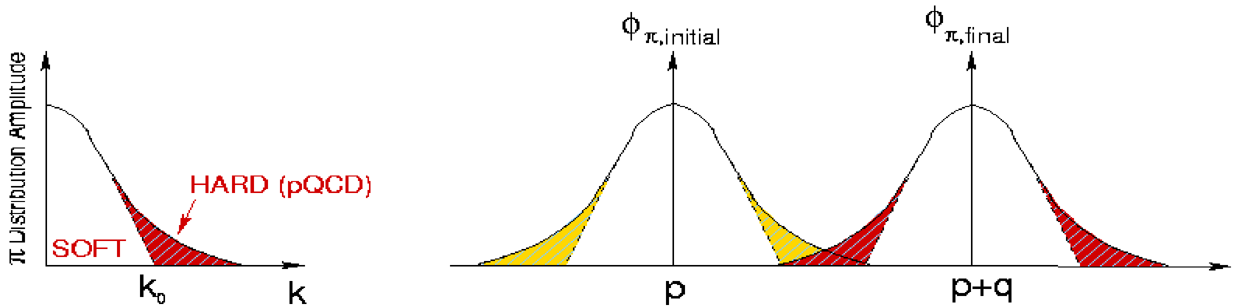


Meson Form Factors

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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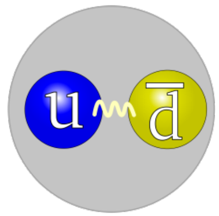
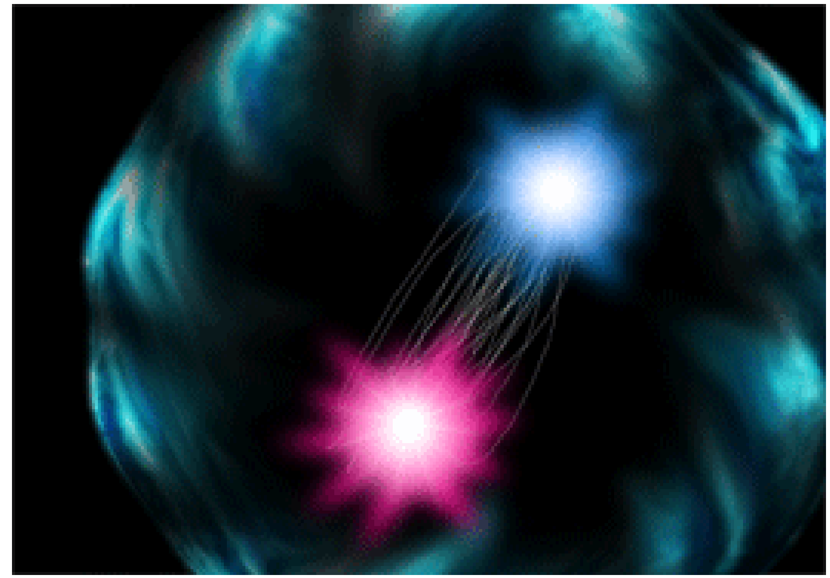
Charged Pion Form Factor

- **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:

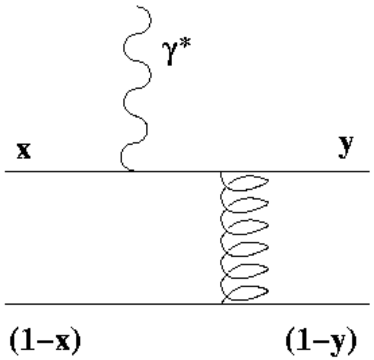
- No “free” pion targets.
- Measurements at large momentum transfer difficult.

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



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

and F_π takes the very simple form

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

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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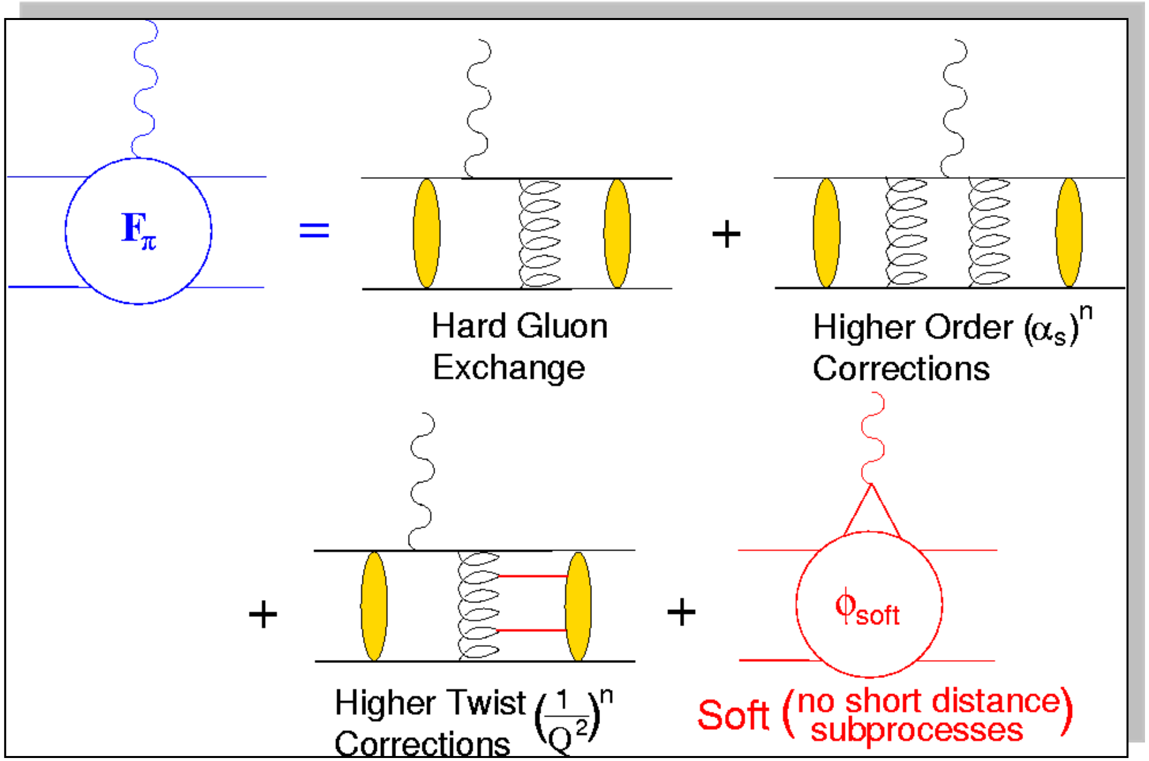
Pion Form Factor at Finite Q^2

- 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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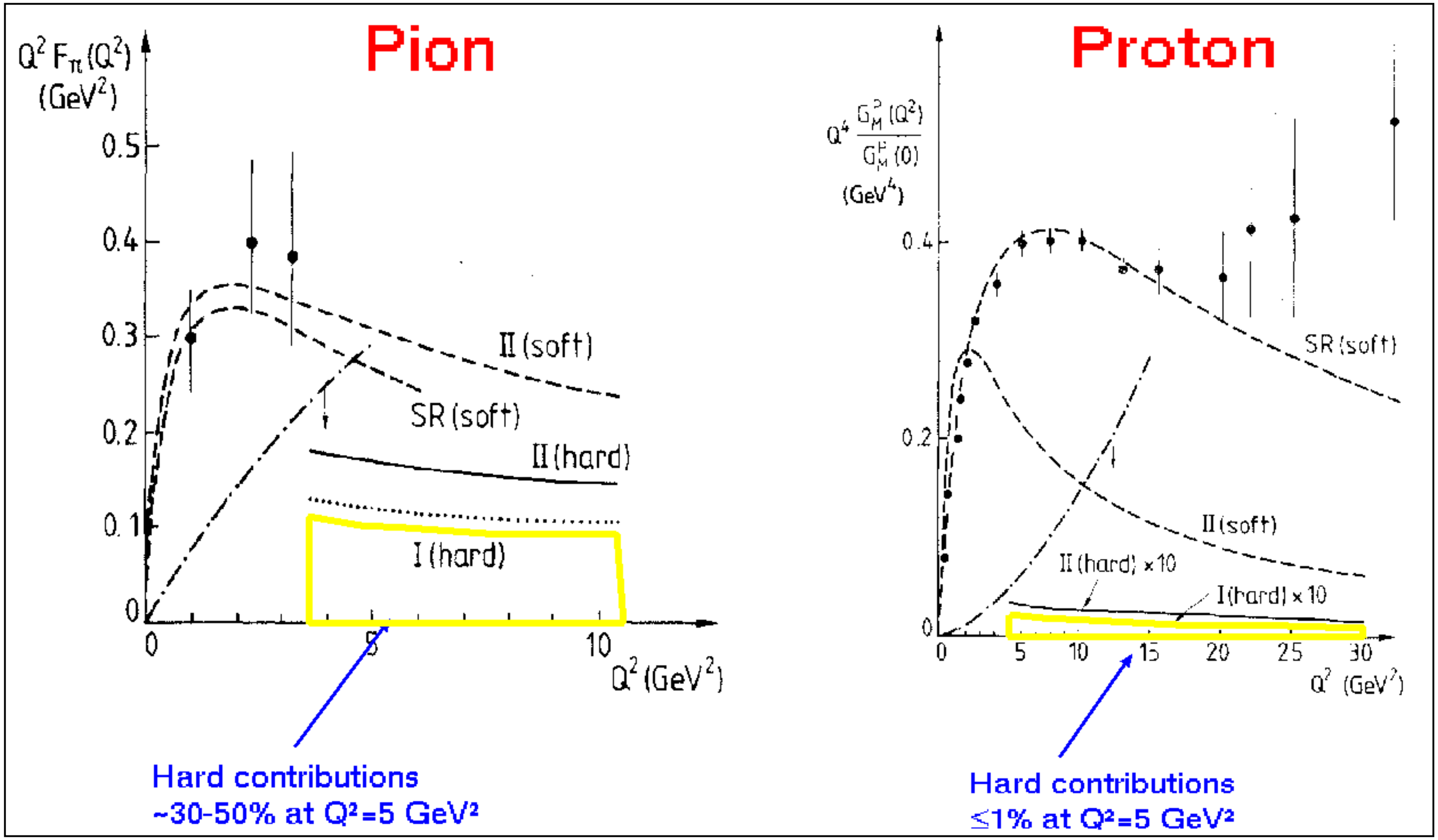
The Pion as a QCD Laboratory



Isgur & Llewellyn-Smith, PRL **52**(1984)1080

F_π is the clearest test case for study of QCD's transition between non-perturbative (confinement) and pQCD (asymptotic freedom) regions.

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

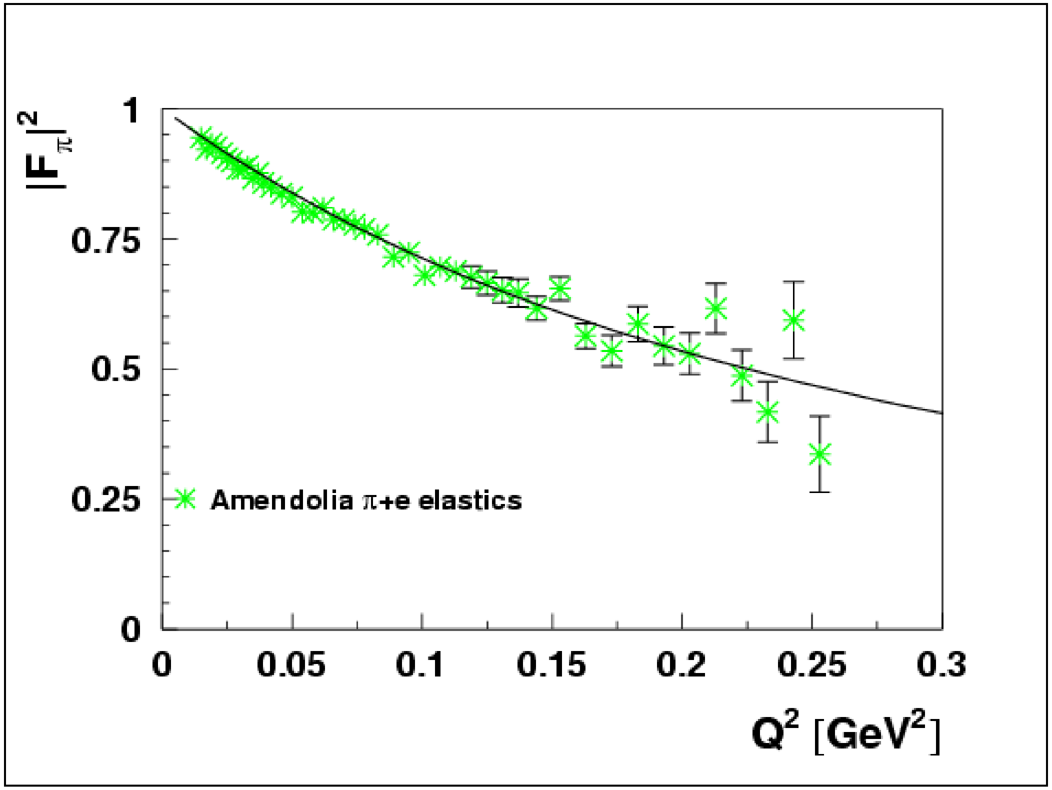
At low Q^2, F_π can be measured model-independently via high energy elastic π^- scattering from atomic electrons in Hydrogen

- 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



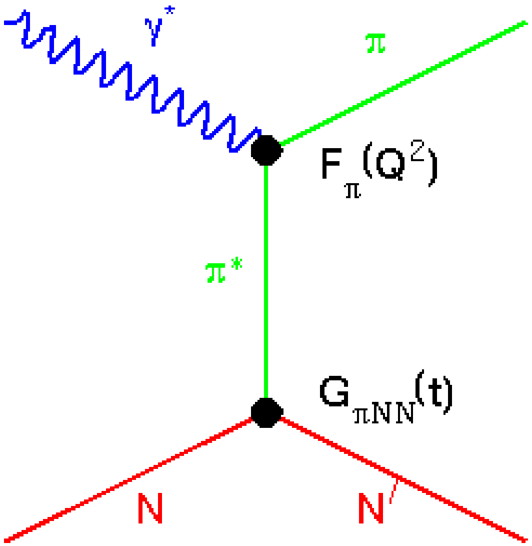
Measurement of π^+ Form Factor – Larger Q^2

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,

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



Drawbacks of this technique
1. Isolating σ_L experimentally challenging
2. Theoretical uncertainty in form factor extraction.

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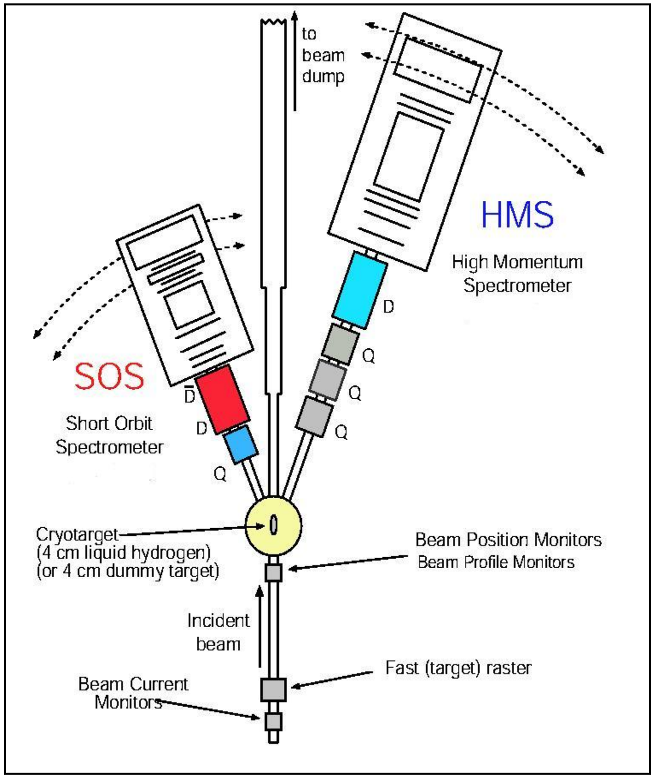
F_π Program at JLab Hall C



- 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.

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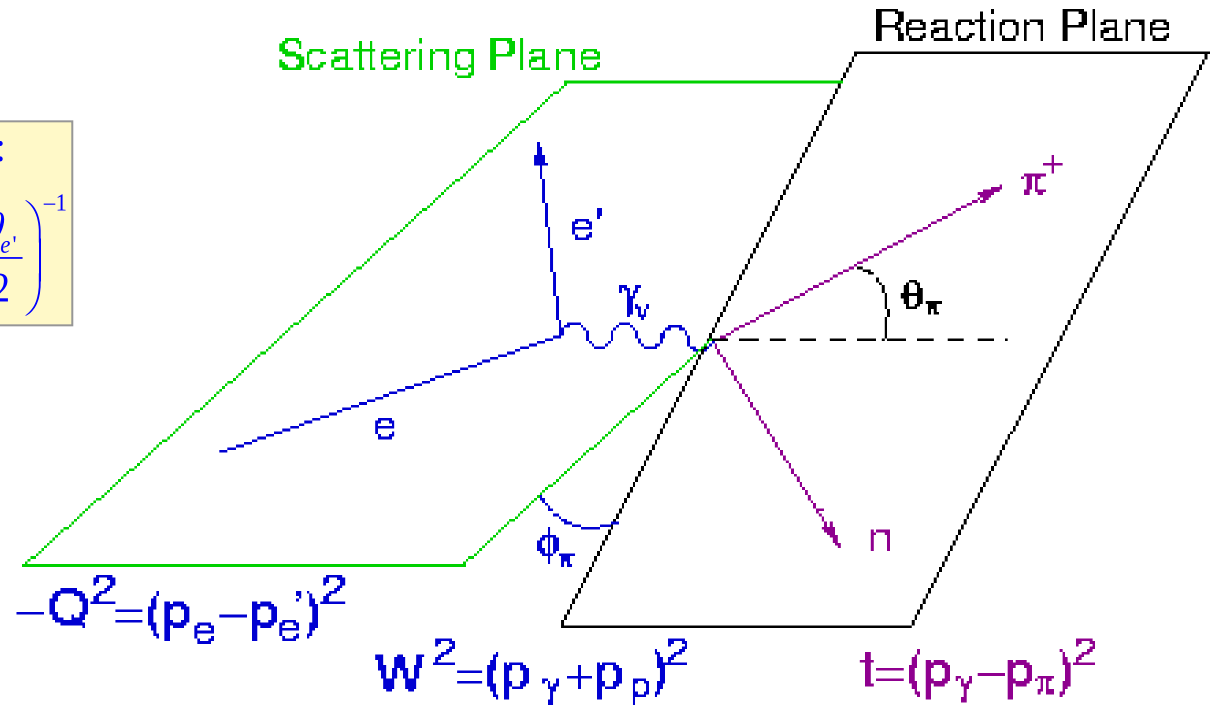
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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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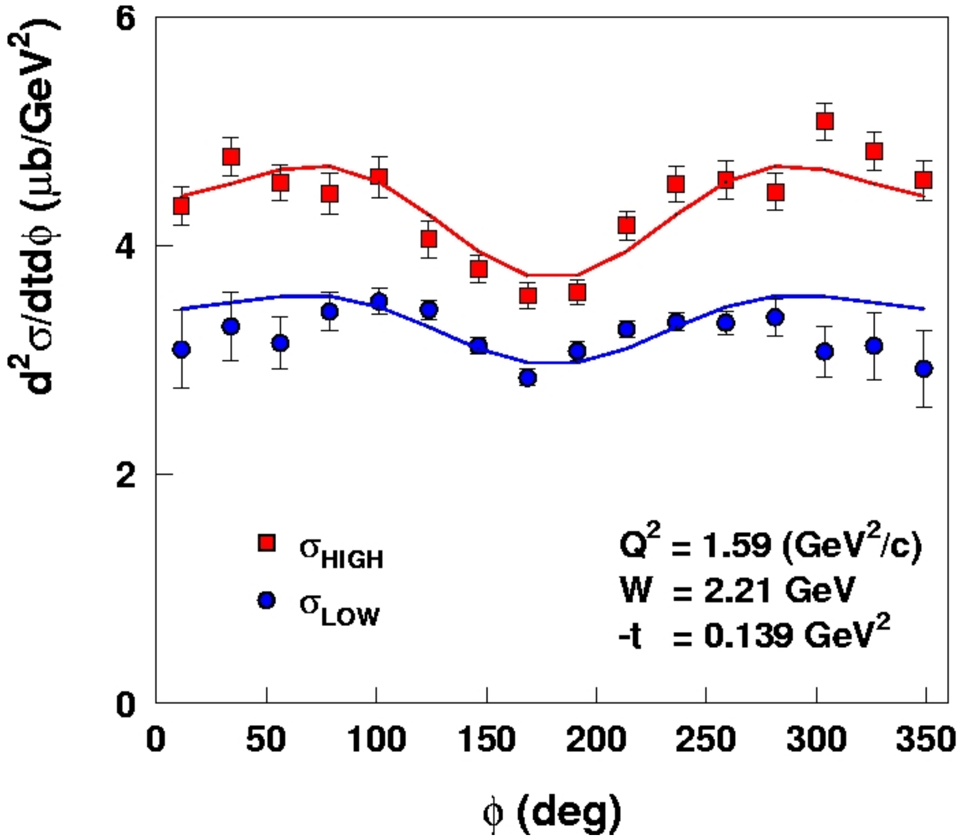
Measuring $d\sigma_L/dt$

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

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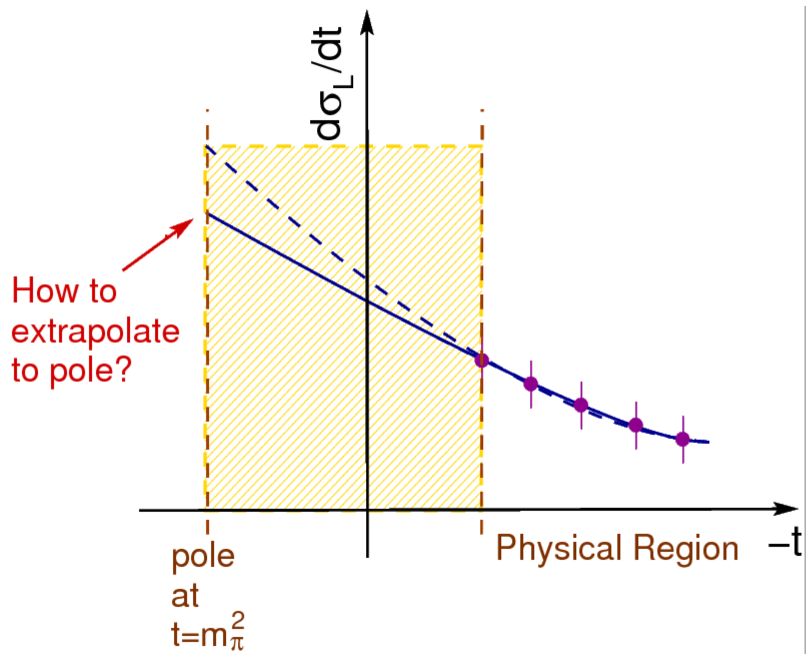
p(e,e'π^+)n **data are obtained some distance from the** $t=m_\pi^2$ **pole.**

→ **"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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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

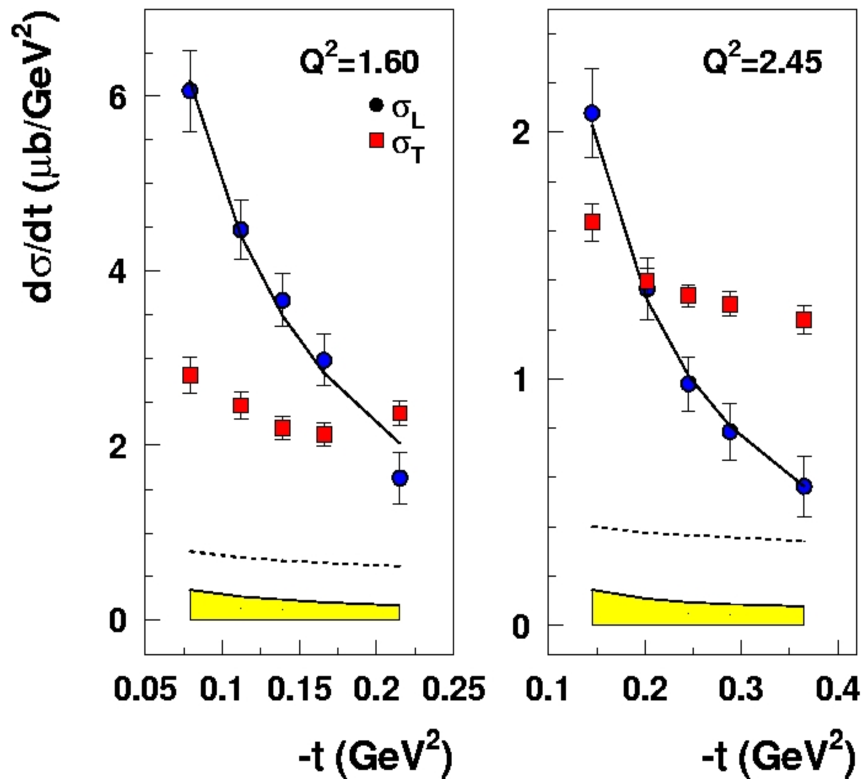
- Feynman propagator $\left(\dfrac{1}{t - m_\pi^{\ 2}}\right)$

  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



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

The JLab 6 GeV experiments were limited to Q^2=2.45 GeV² by $-t_{min}$<0.2 GeV² and Δε>0.25 needed for reliable L/T separation.

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 GeV², Λ_ρ^2=1.7 GeV².

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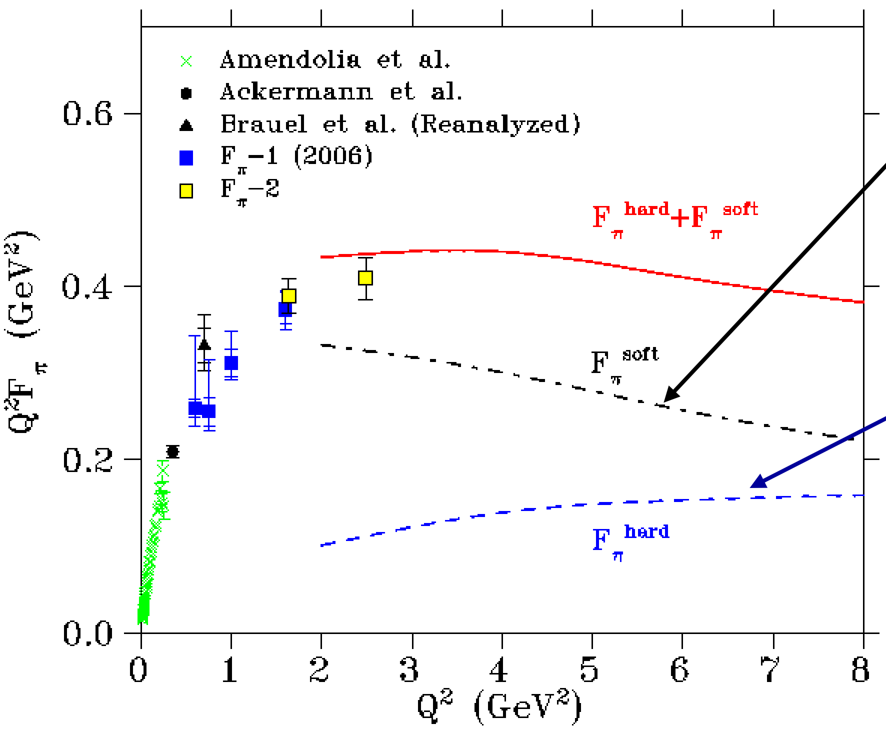
Current Experimental Status

pQCD LO+NLO Calculation:

Analytic perturbation theory at the parton amplitude level.

*A.P. Bakulev, K. Passek-Kumericki, W. Schroers, & N.G. Stefanis, PRD **70** (2004) 033014.*



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

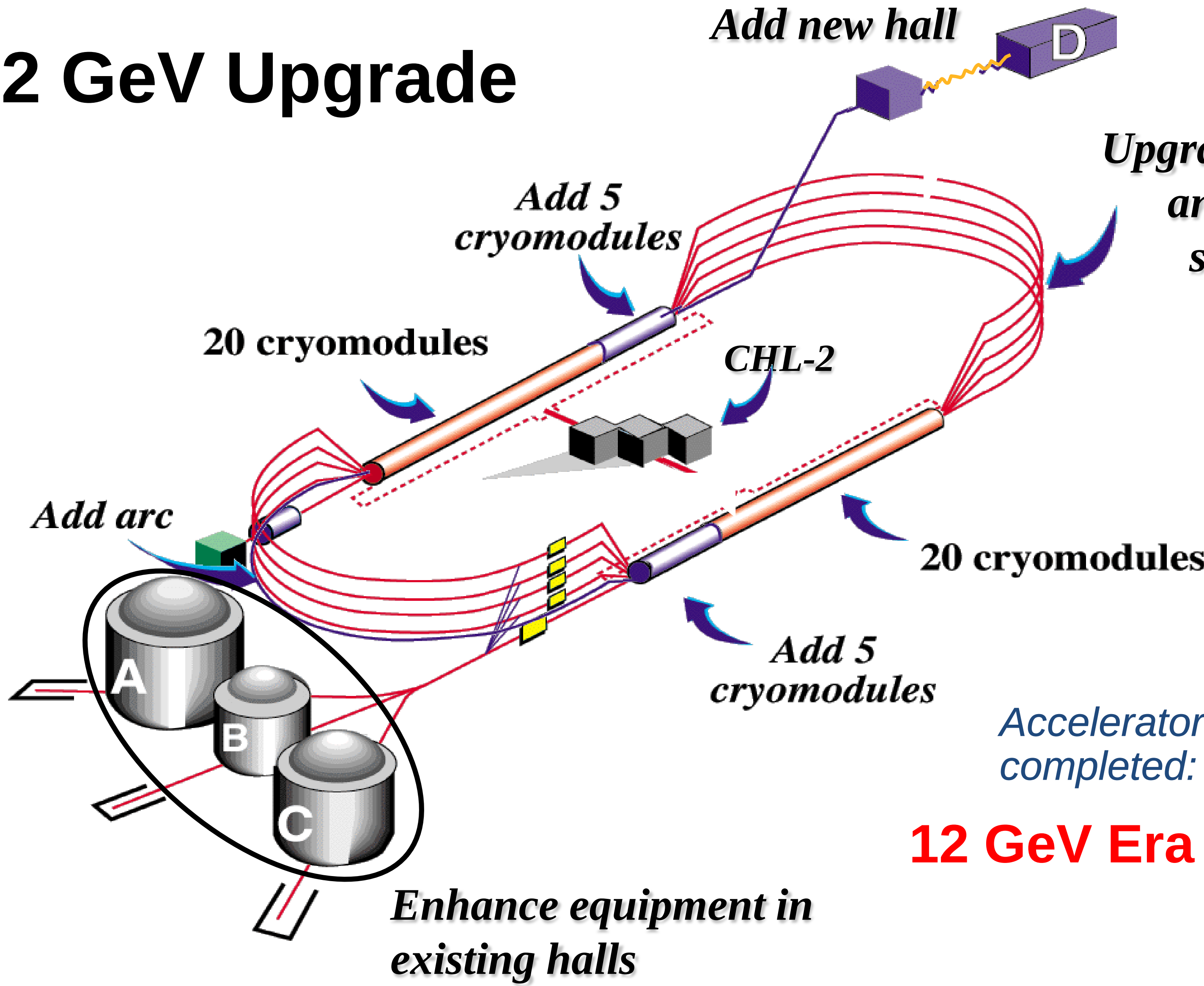
SOFT QCD:

- Extra piece needed to describe data.
- Model-dependent.
- Estimated from local quark-hadron duality model.

HARD QCD: pQCD LO+NLO

- JLab 6 GeV F_π results are far from the values predicted by pQCD.
- At the distance scales probed by the experiment (0.15<r<0.30 fm), the π^+ structure is not governed by the two valence quarks.
- Virtual quarks and gluons dominate.

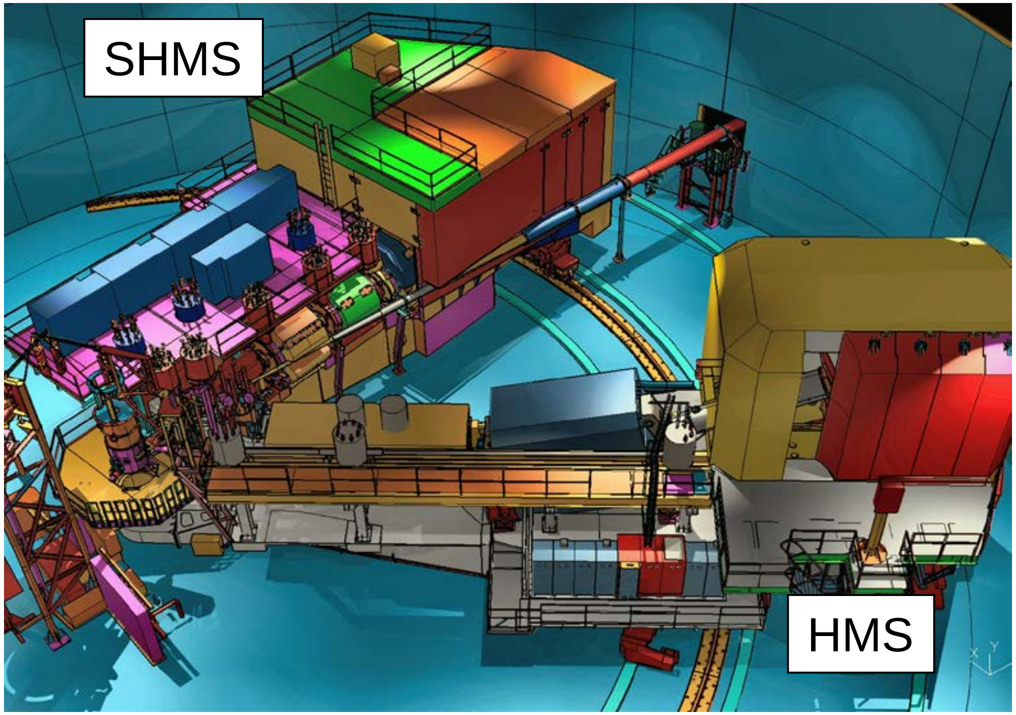
12 GeV Upgrade



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^2sec).

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

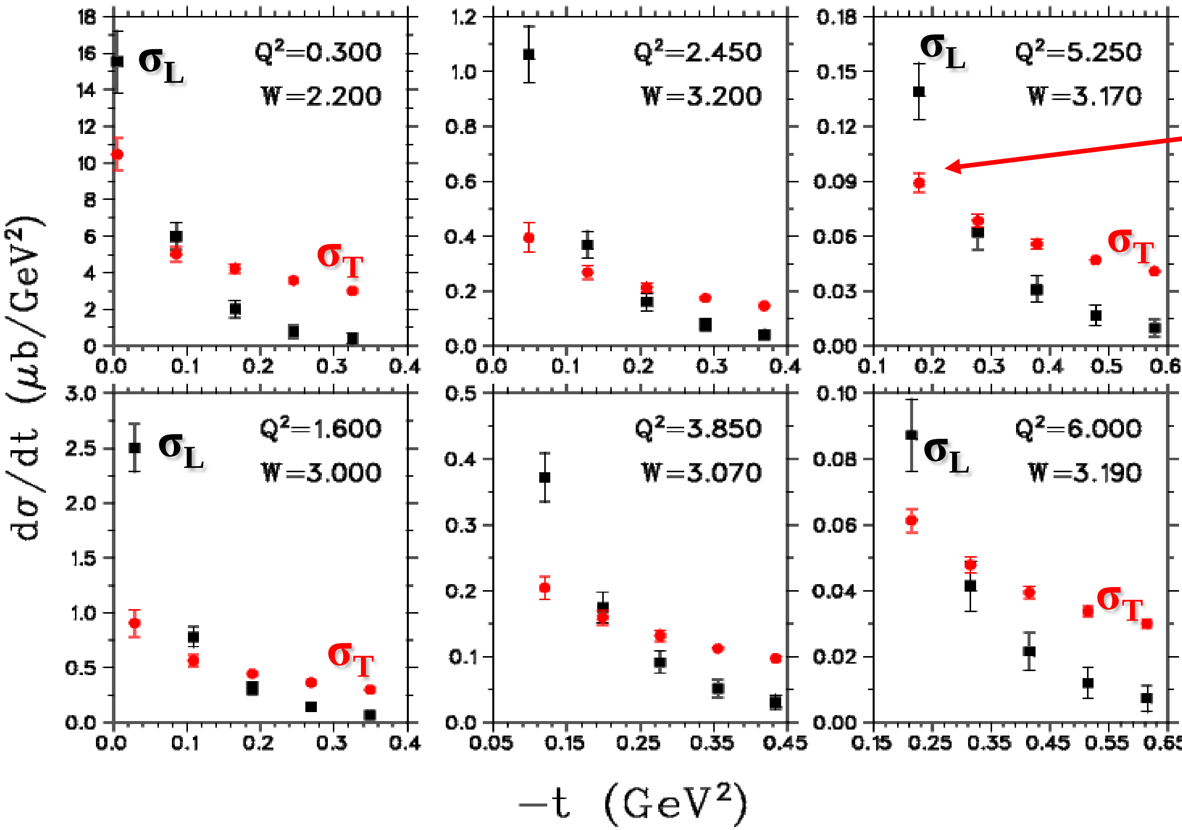
Achievable errors are limited by $R=\sigma_T/\sigma_L$ ratio and $1/\Delta\varepsilon$ error magnification.

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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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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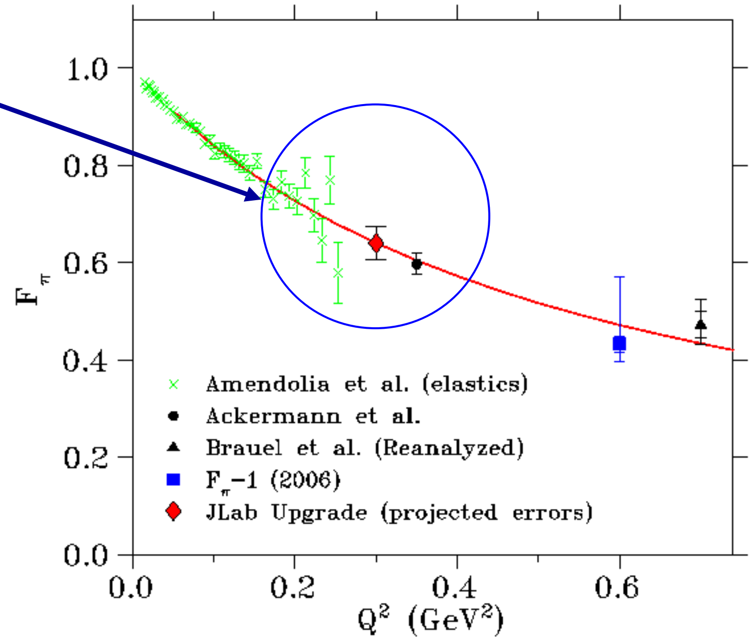
METHOD PASSES CHECKS:

- 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).



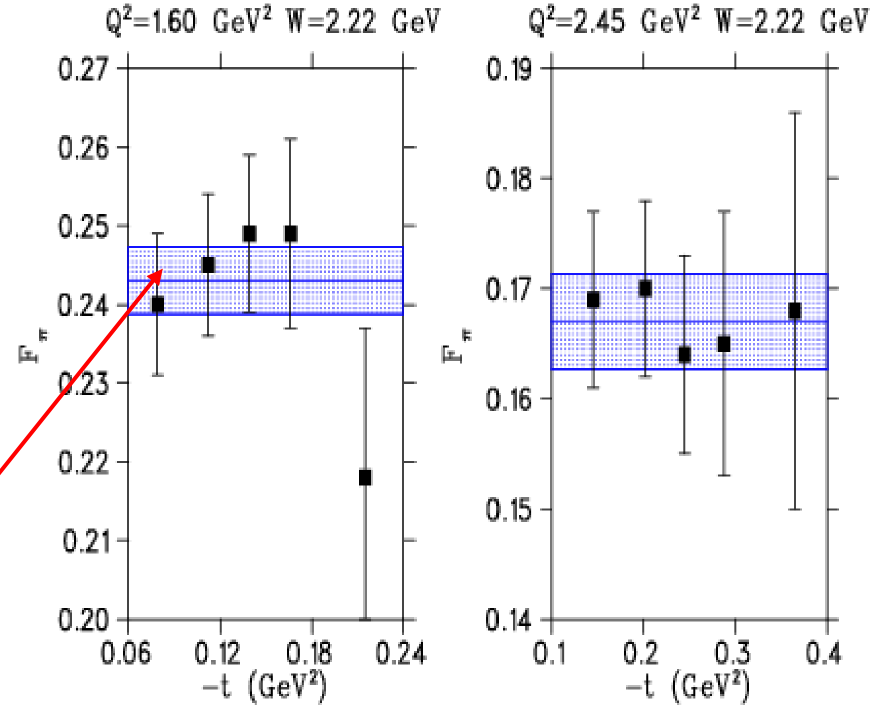
E12-06-101 Proposal:
G.M. Huber, D. Gaskell, spokespersons

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.

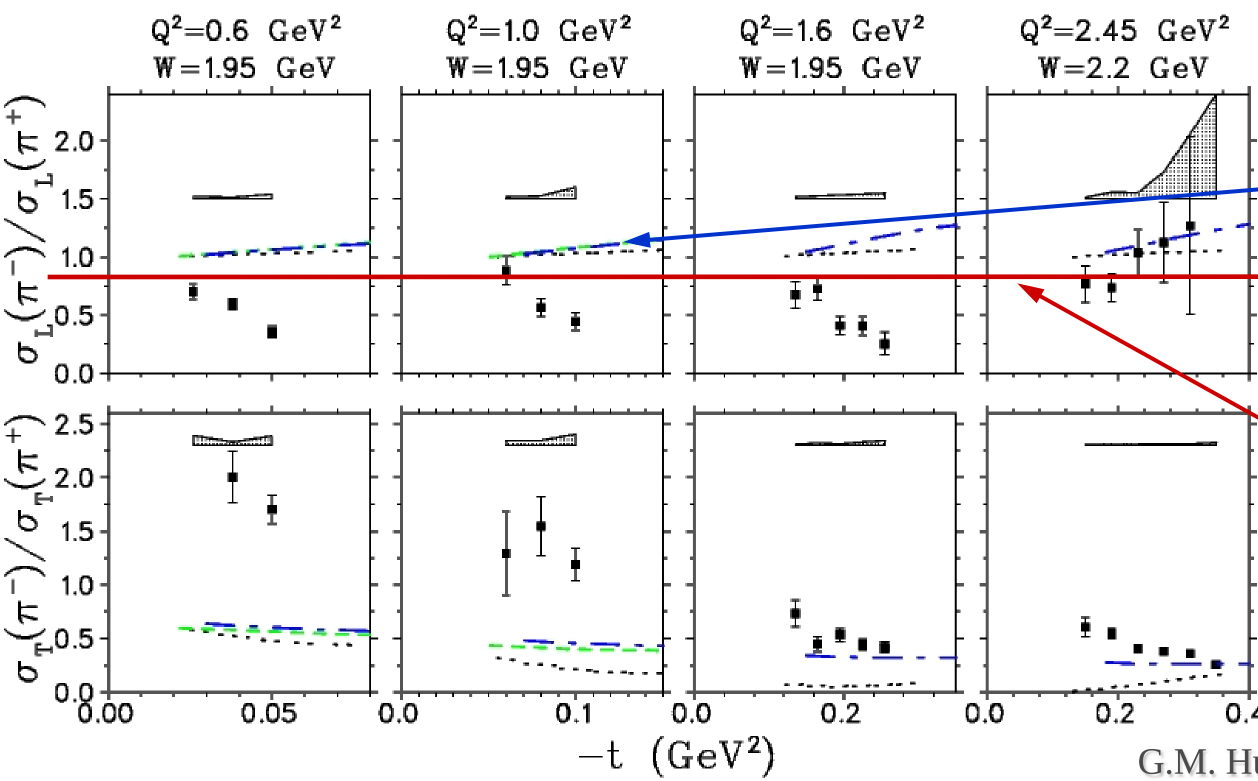
π^-/π^+ data to check *t*-channel dominance

- 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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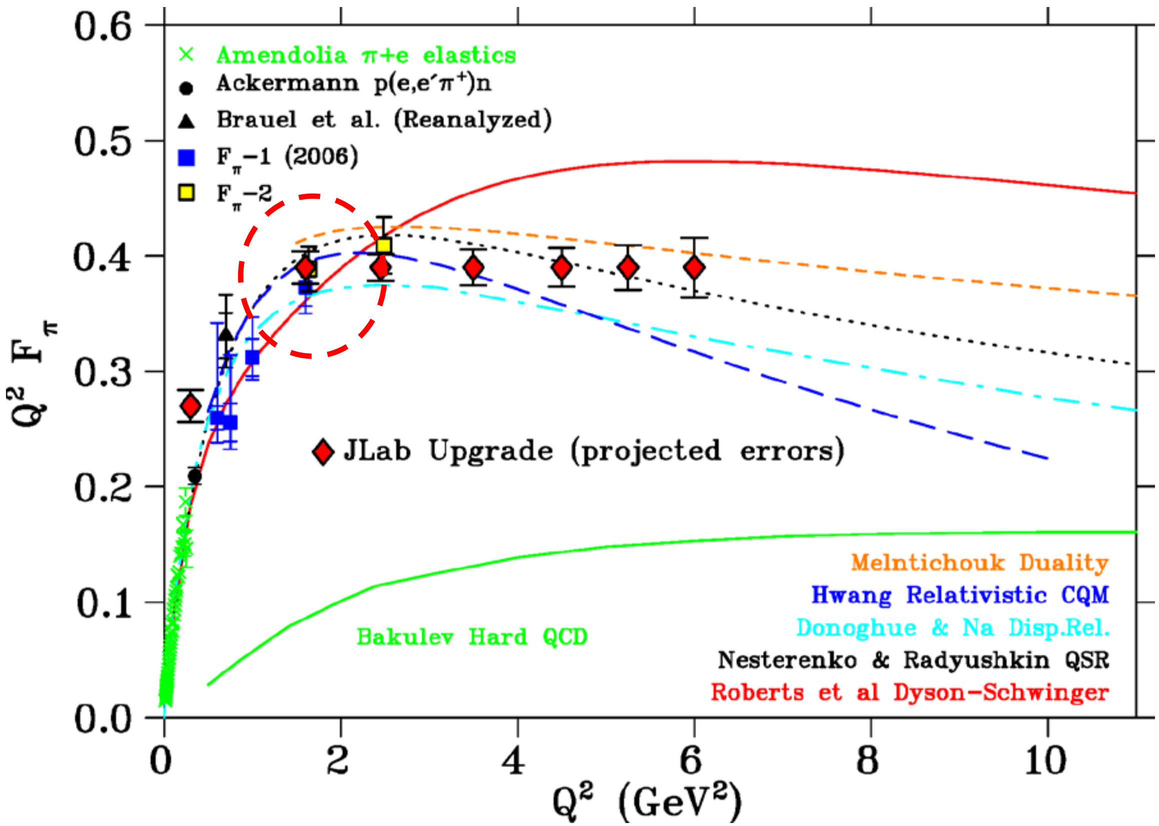
$F_\pi(Q^2)$ after JLab 12 GeV Upgrade

JLab 12 GeV upgrade will allow measurement of F_π up to $Q^2 = 6$.

No other facility worldwide can perform this measurement.

New overlap point at $Q^2=1.6$ 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.



Approved with "A" scientific rating and identified by JLab PAC41 as "high impact". (E12-06-101: G. Huber and D. Gaskell, spokespersons)

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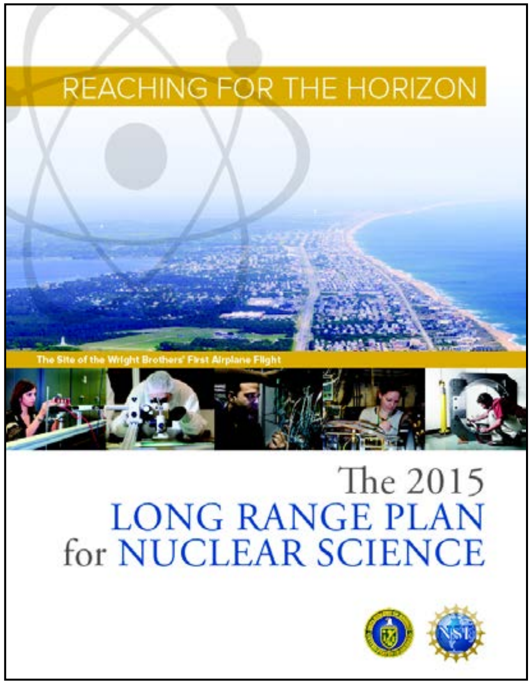
Endorsement in USA Long Range Plan

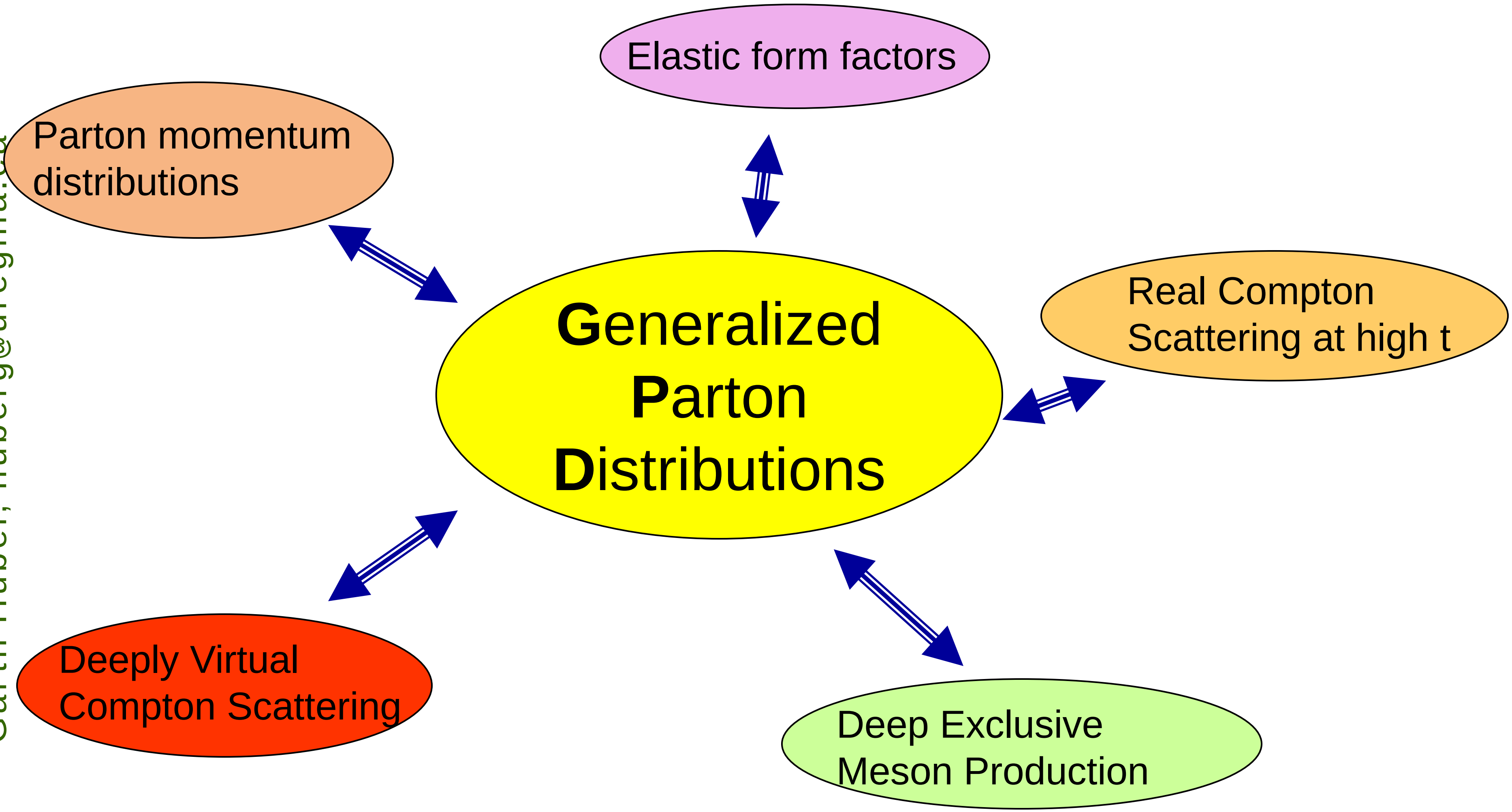
Section 2.1.1: The Quark Structure of Hadrons

- The pion plays a unique role in nature. It is the lightest quark system… It is also the particle responsible for the long range character of the strong interaction that binds the atomic nucleus together.
- If [chiral symmetry] were completely true, the pion would have no mass.
- 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.**

GPDs – A Unified View of Hadron Structure



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.

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

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

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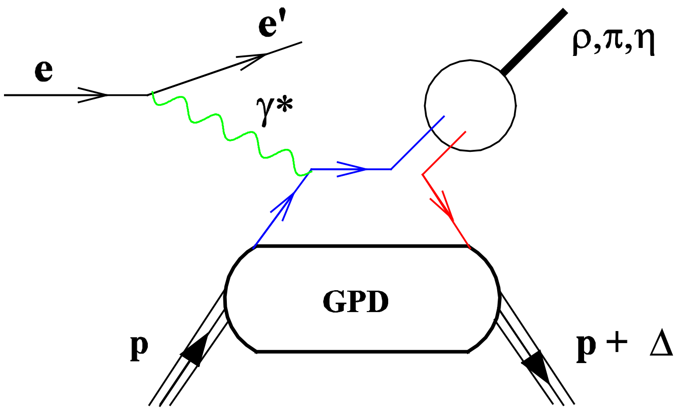
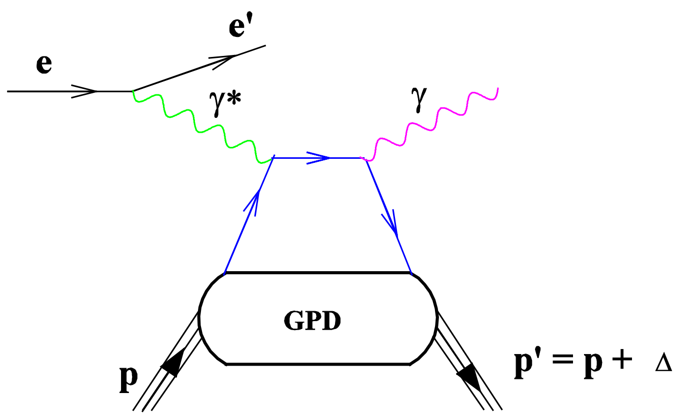
Deep Exclusive Meson Production:

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





Deeply Virtual Compton Scattering:

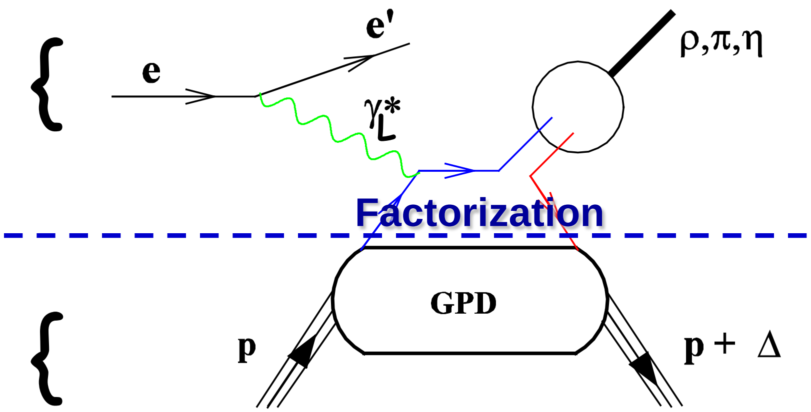
- Sensitive to all four GPDs.

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

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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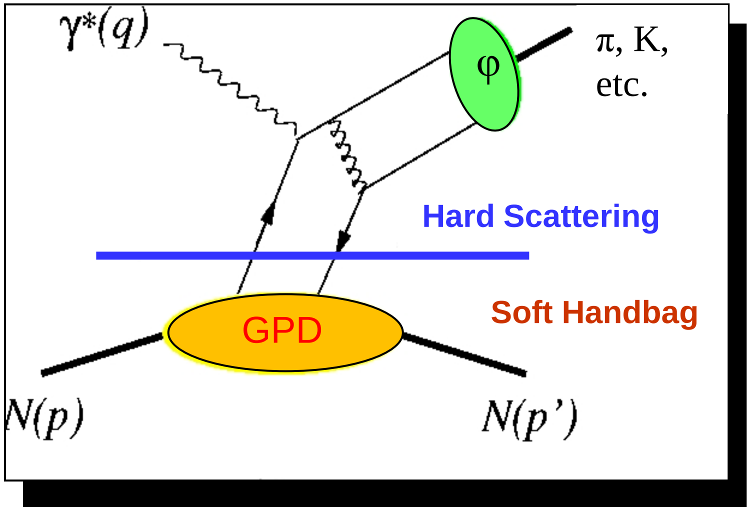
Investigations of QCD Factorization Regime

- **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

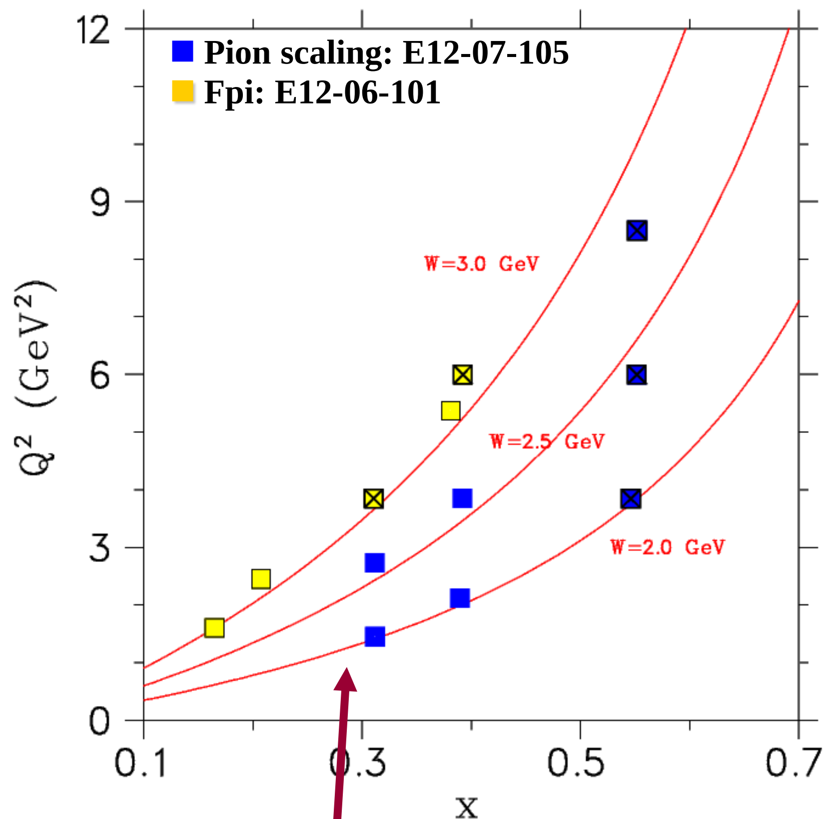
- **Measure the Q^2 dependence of the $p(e,e'\pi^+)n$, $p(e,e'K^+)\Lambda$, $p(e,e'K^+)\Sigma$ cross sections at fixed x_B and $-t$ to search for evidence of hard-soft factorization**
  - Separate the cross section components: L, T, LT, TT
  - Highest Q^2 for any L/T separation in π^+,K^+ electroproduction
  - 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: $\sigma_L >> \sigma_T$.

$p(e,e'\pi^+)n$ 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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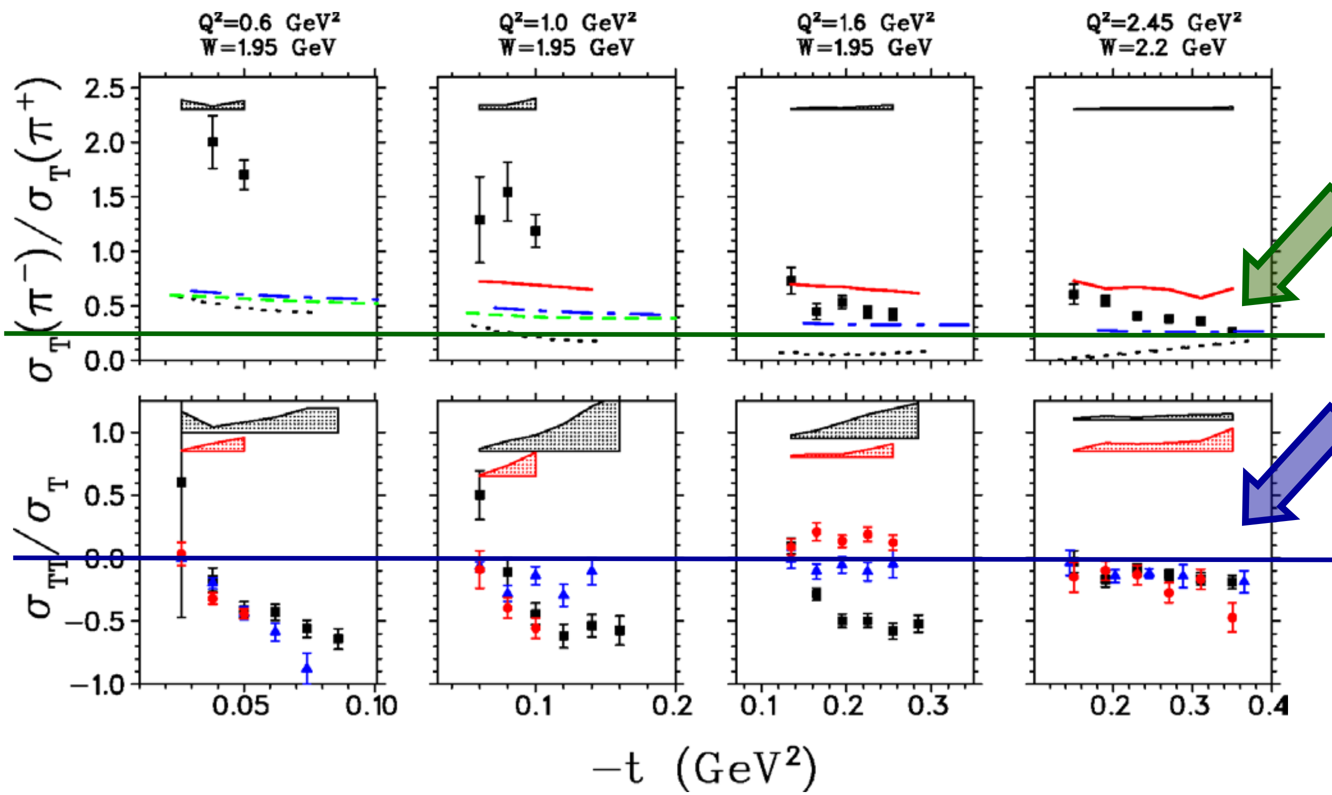
π^-/π^+ Separated Response Function Ratios

- **Transverse Ratios tend to ¼ as –t increases:**
  → Is this an indication of Nachtmann's quark charge scaling?
- **-t=0.3 GeV^2 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.



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

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

- 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.

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

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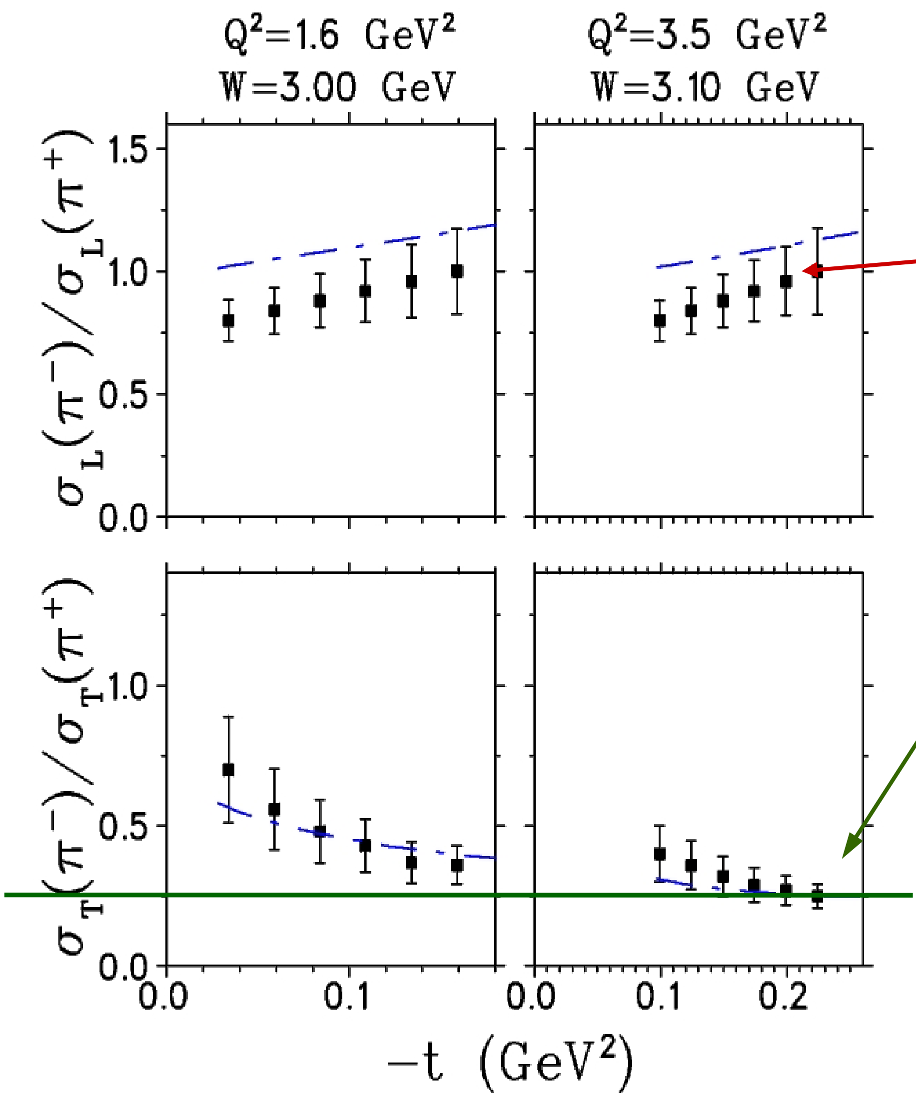
Projected π^-/π^+ Data from Fπ-12 Experiment



- ^{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

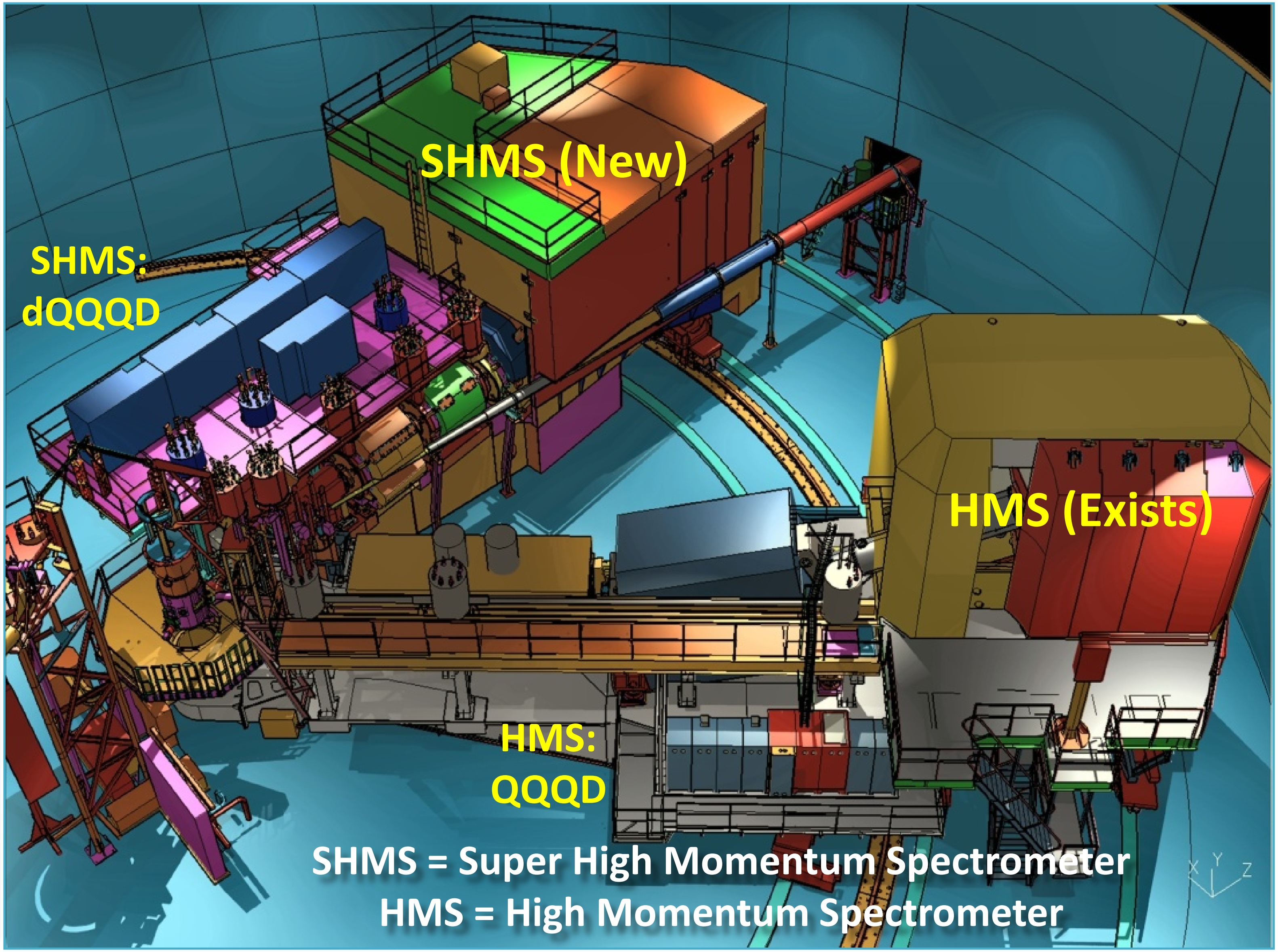
SHMS:
- 11 GeV/c Spectrometer
- Partner of existing 7 GeV/c **HMS**

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

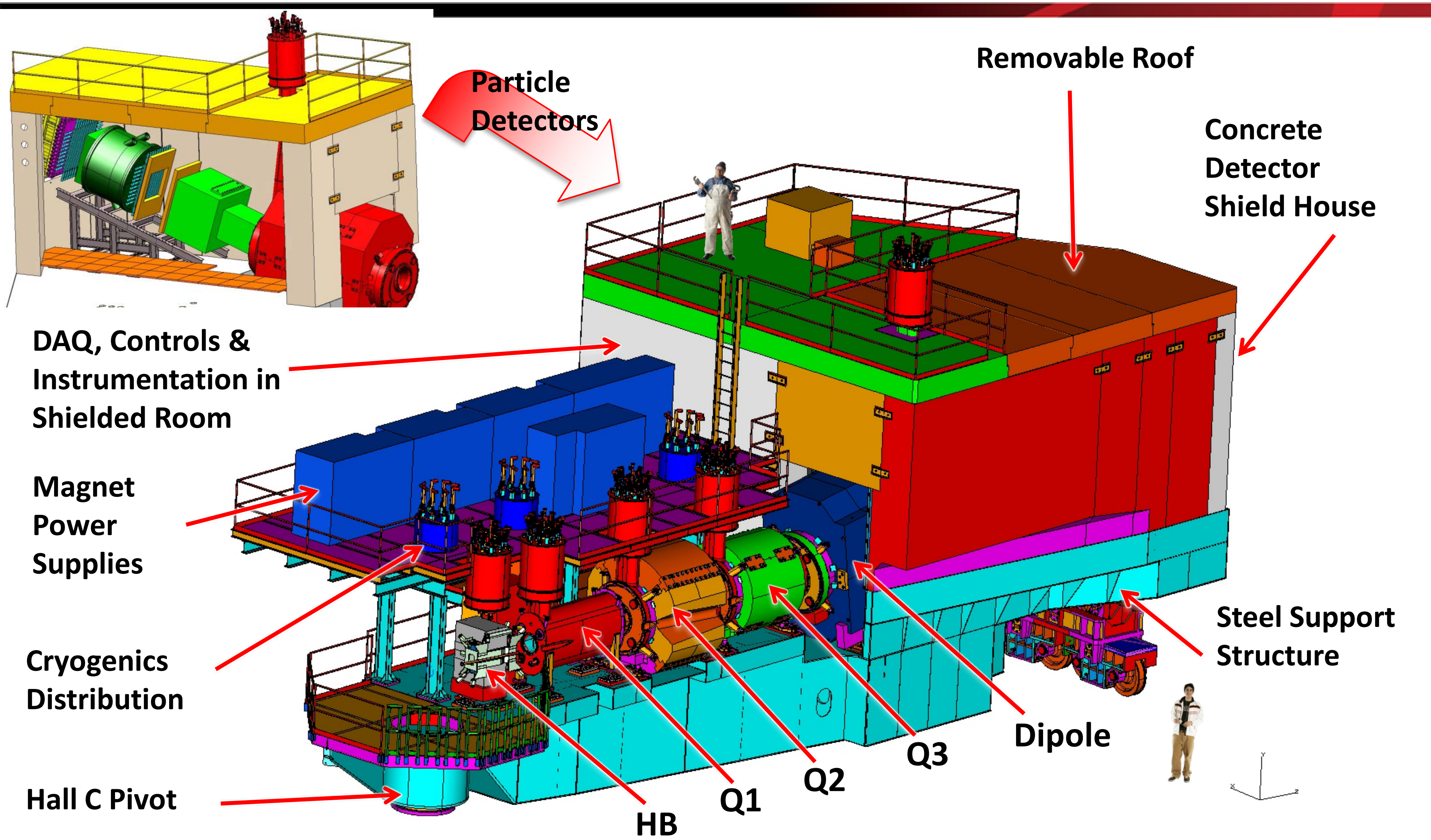
Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter
- All derived from existing HMS/SOS detector designs

Well-Shielded Detector Enclosure

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

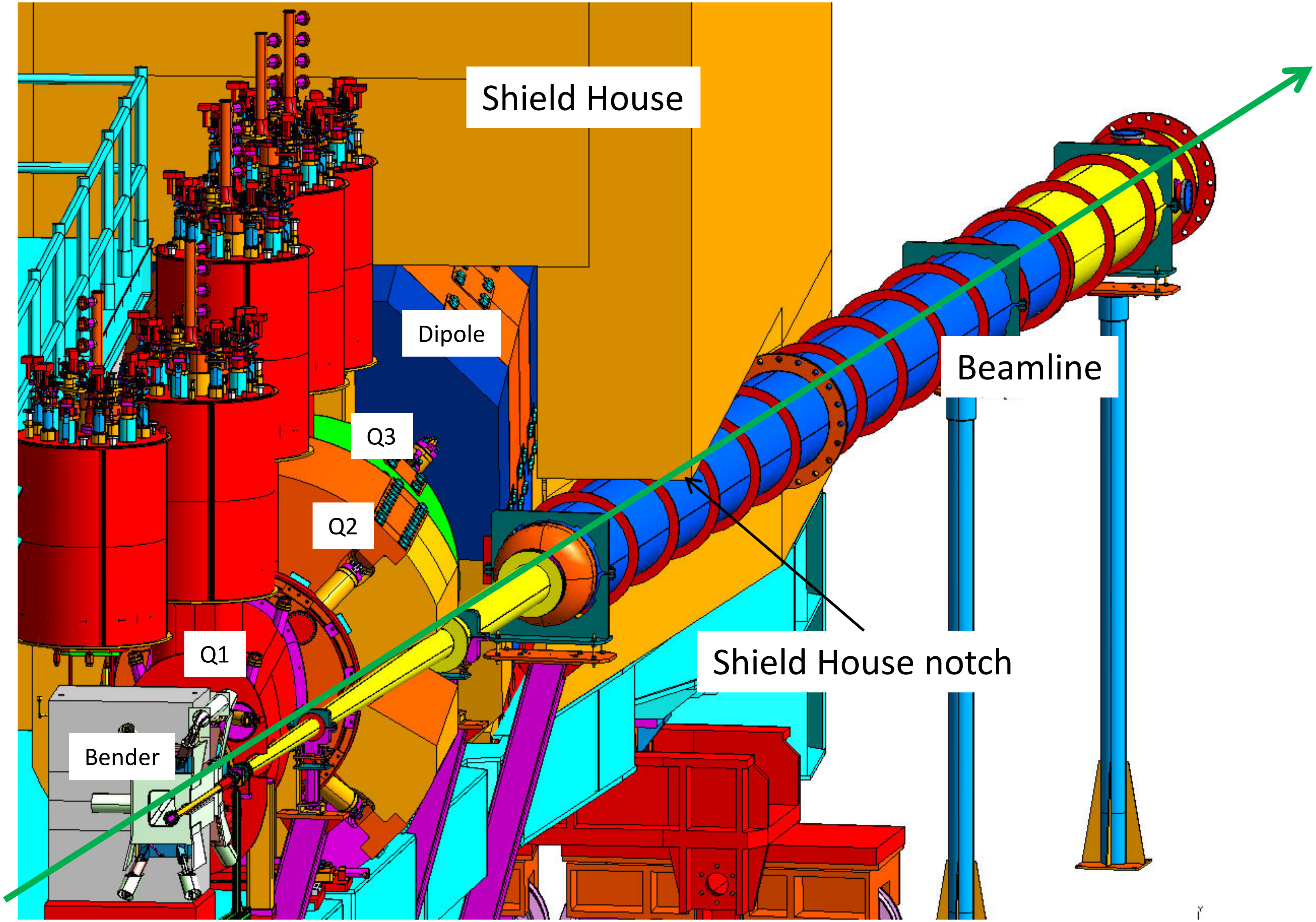


Super HMS Overview

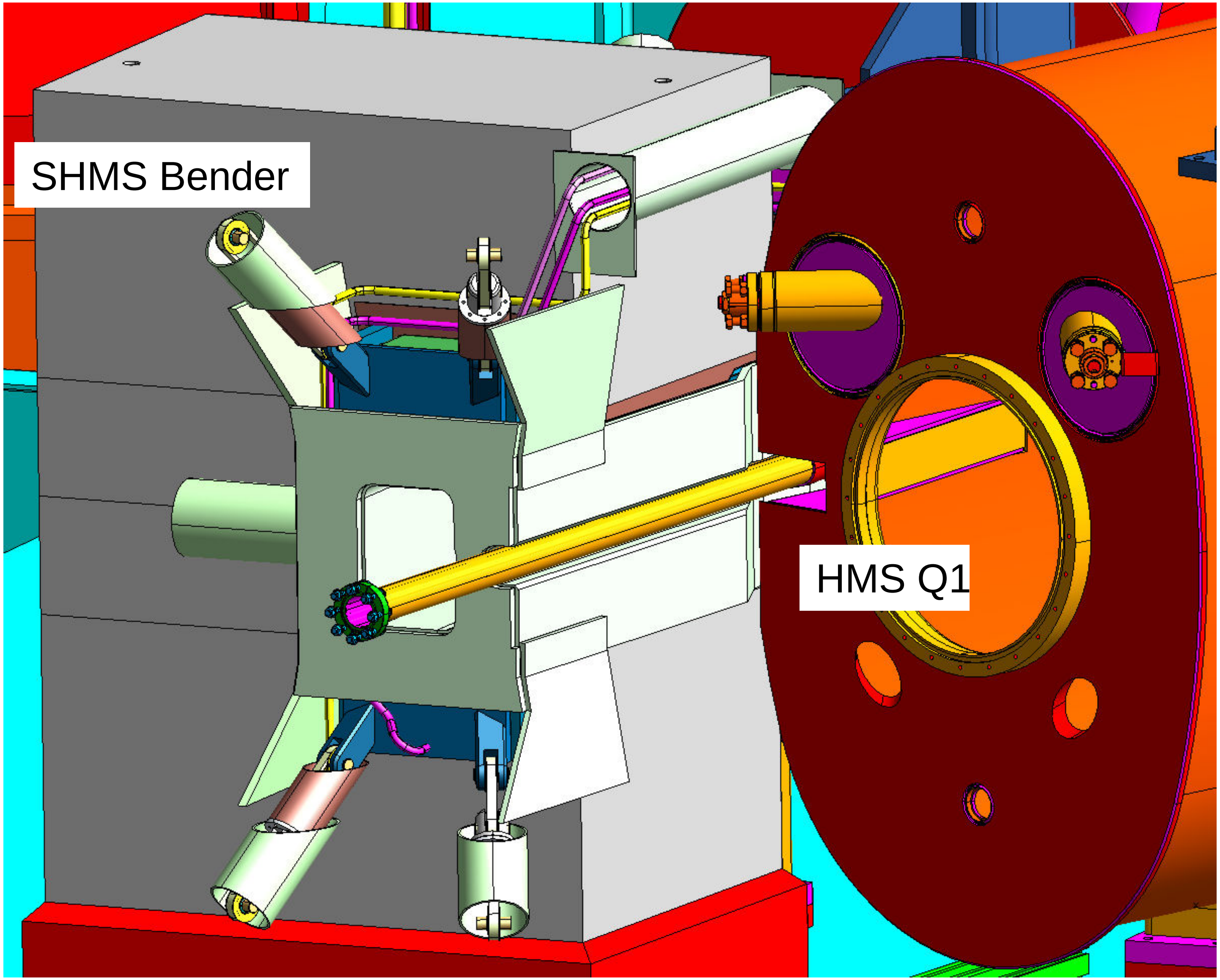


Also: Beamline Vacuum, Mods to Møller, Compton, Scattering Chamber

Engineering for SHMS Small Angle Operation

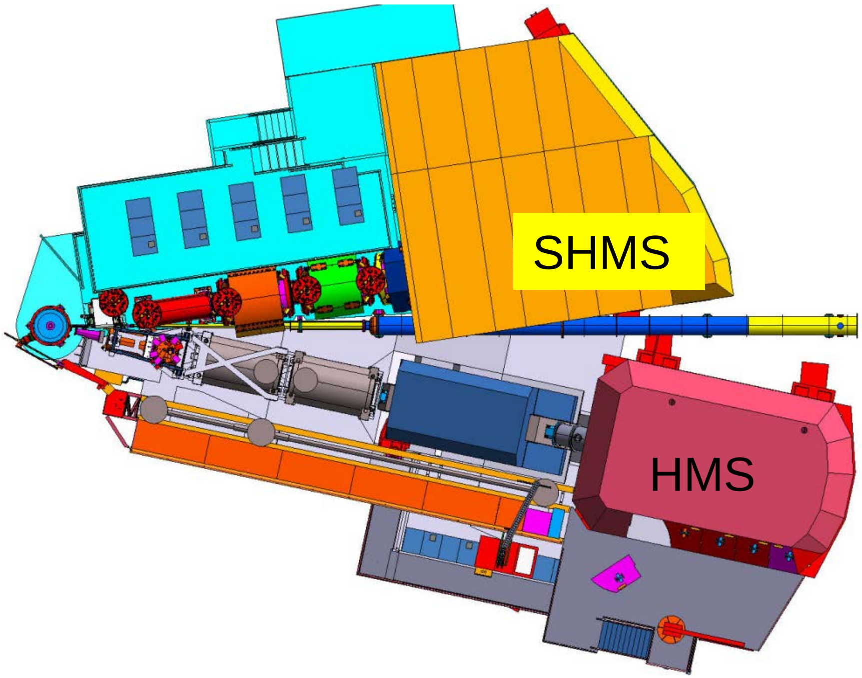


Bender Fit to HMS Q1

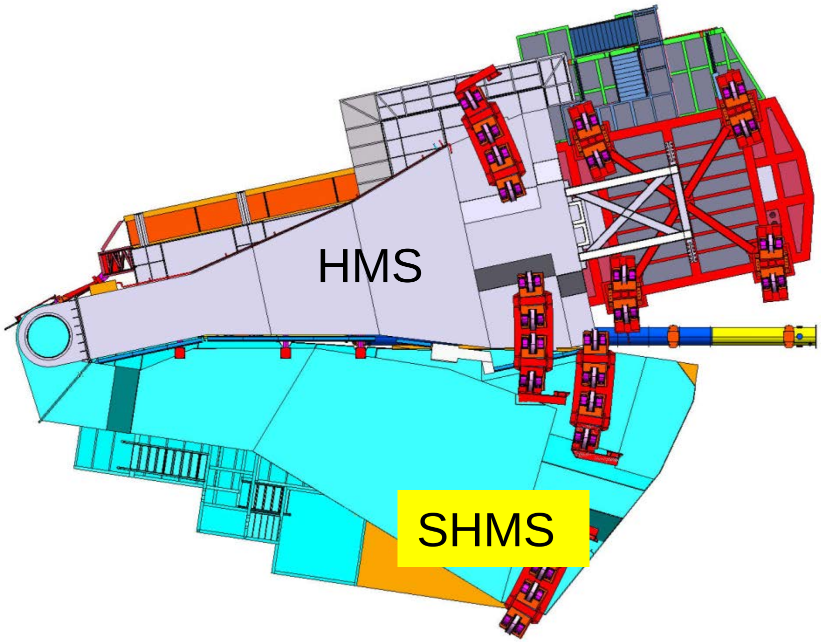


Getting Both Spectrometers to Small Angles

Top View

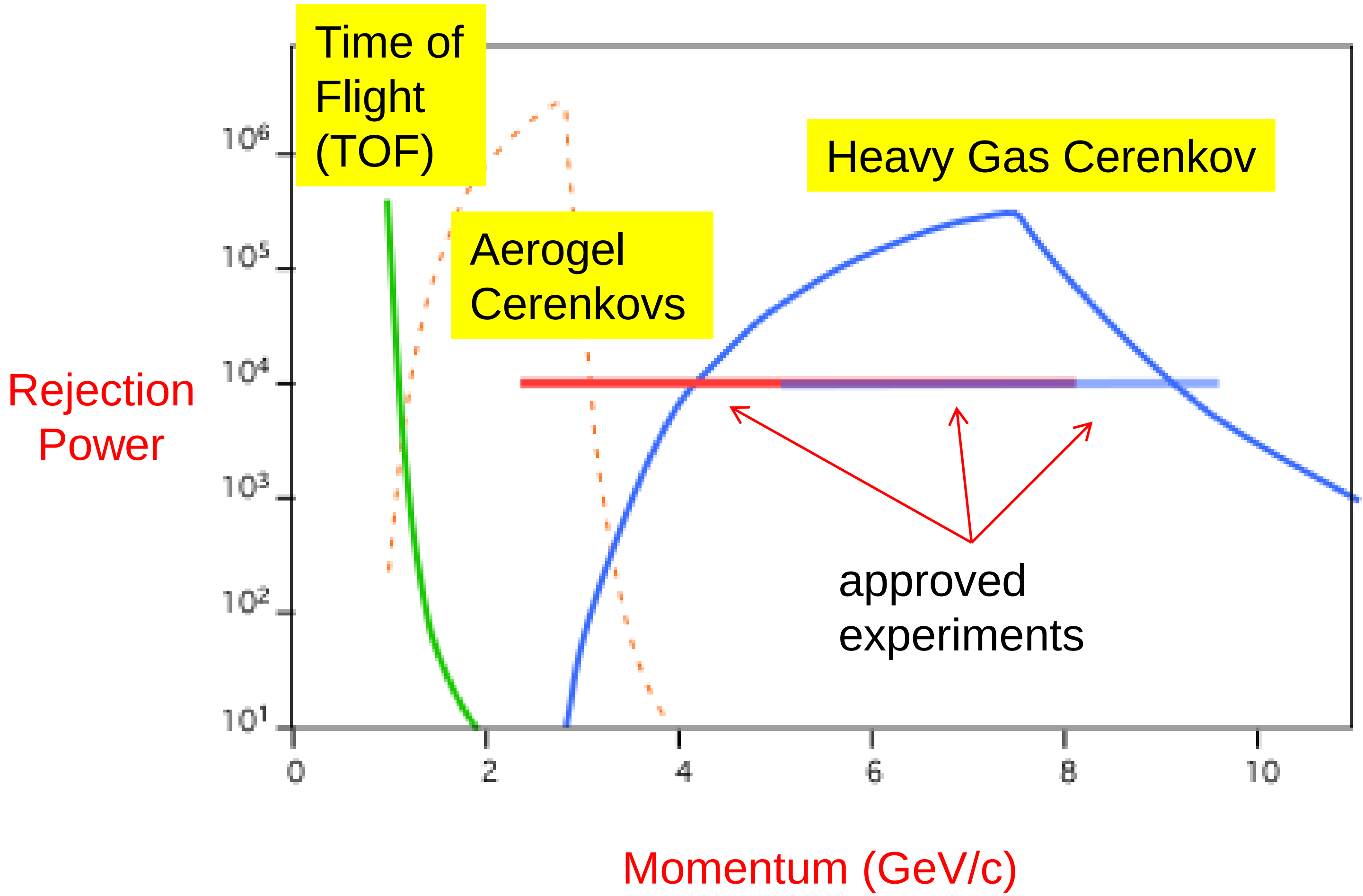


Bottom View

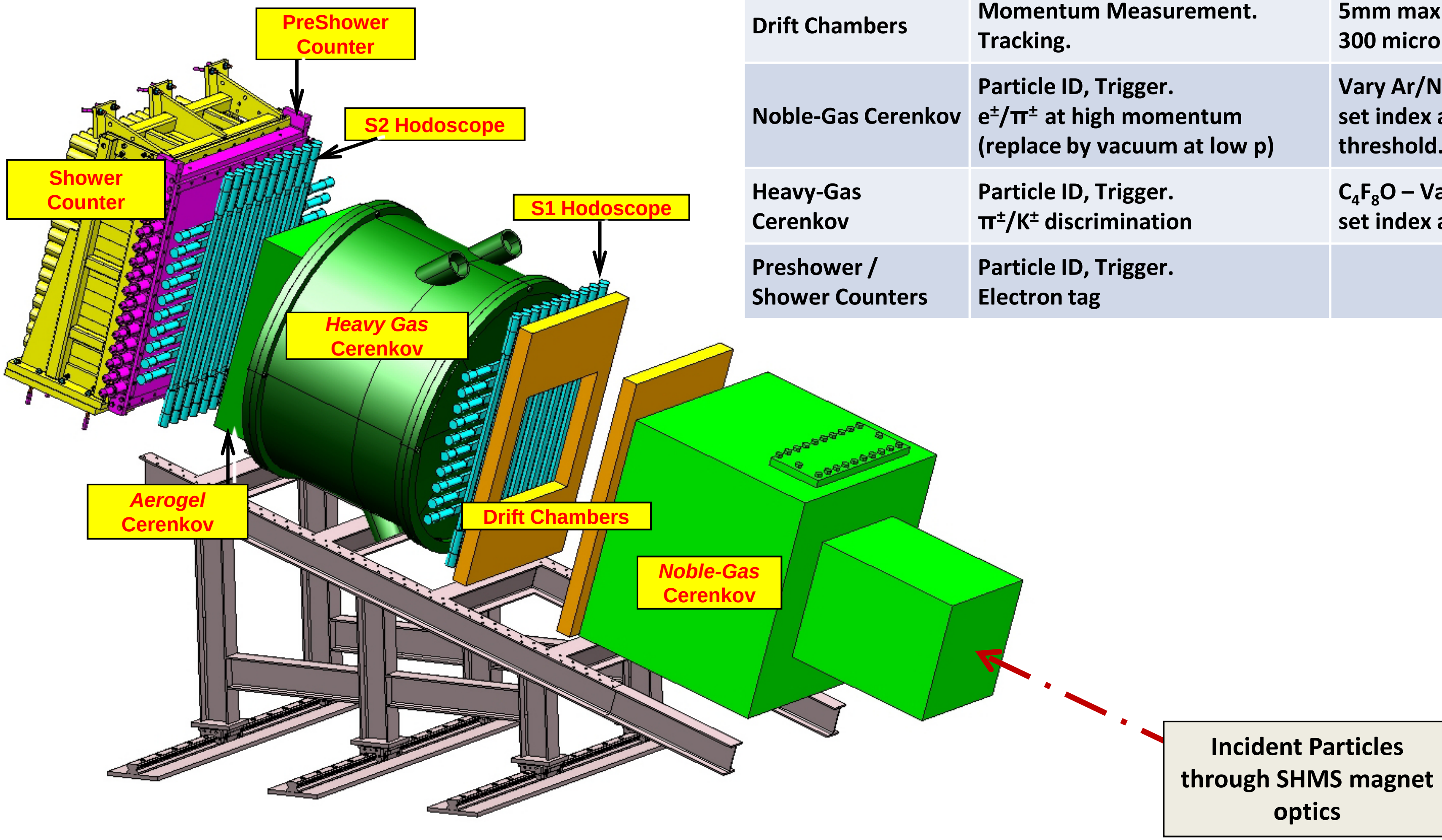


... an incredible 3-dimensional jigsaw puzzle for JLab engineers and designers

SHMS Particle Identification: +hadrons

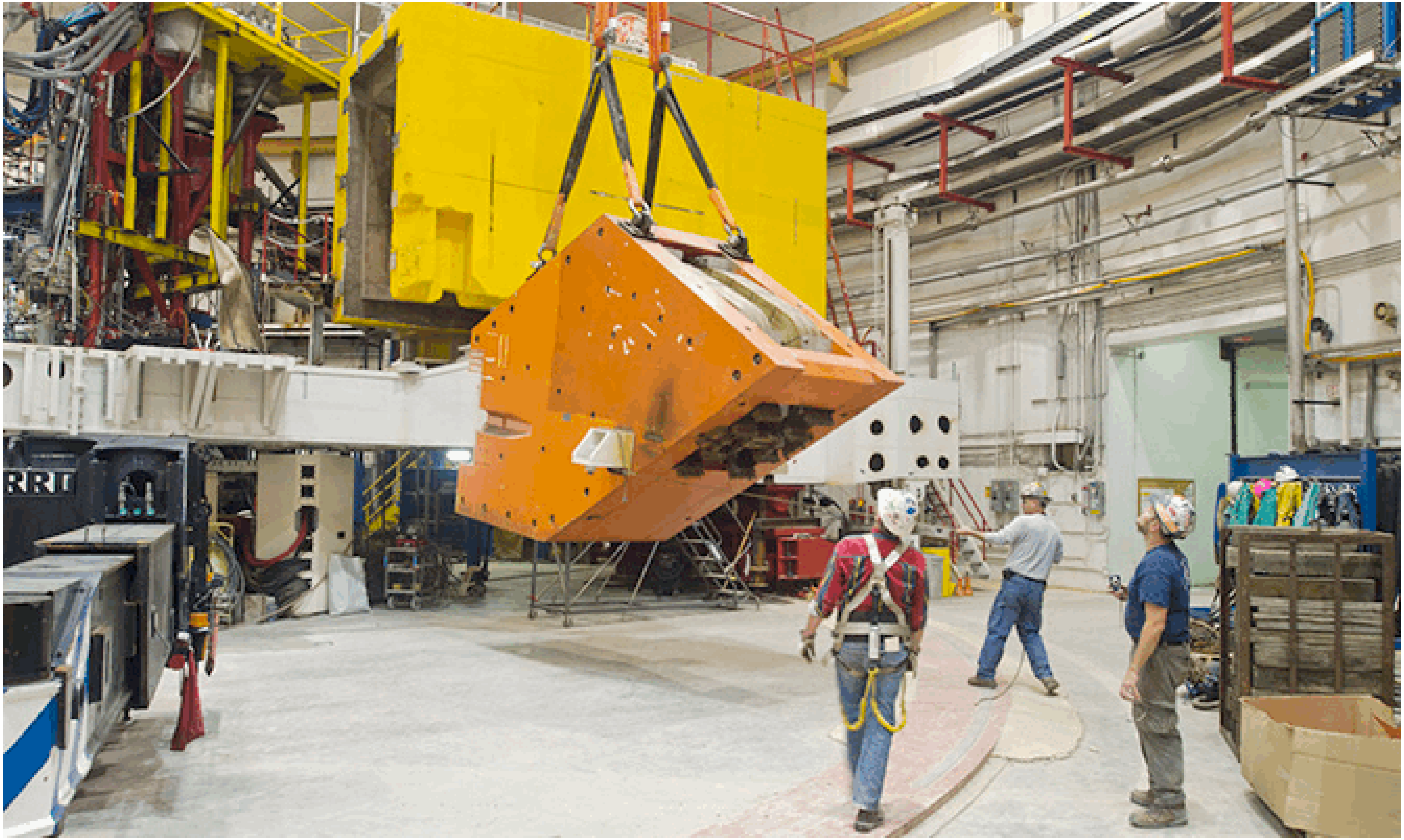


SHMS Detector System

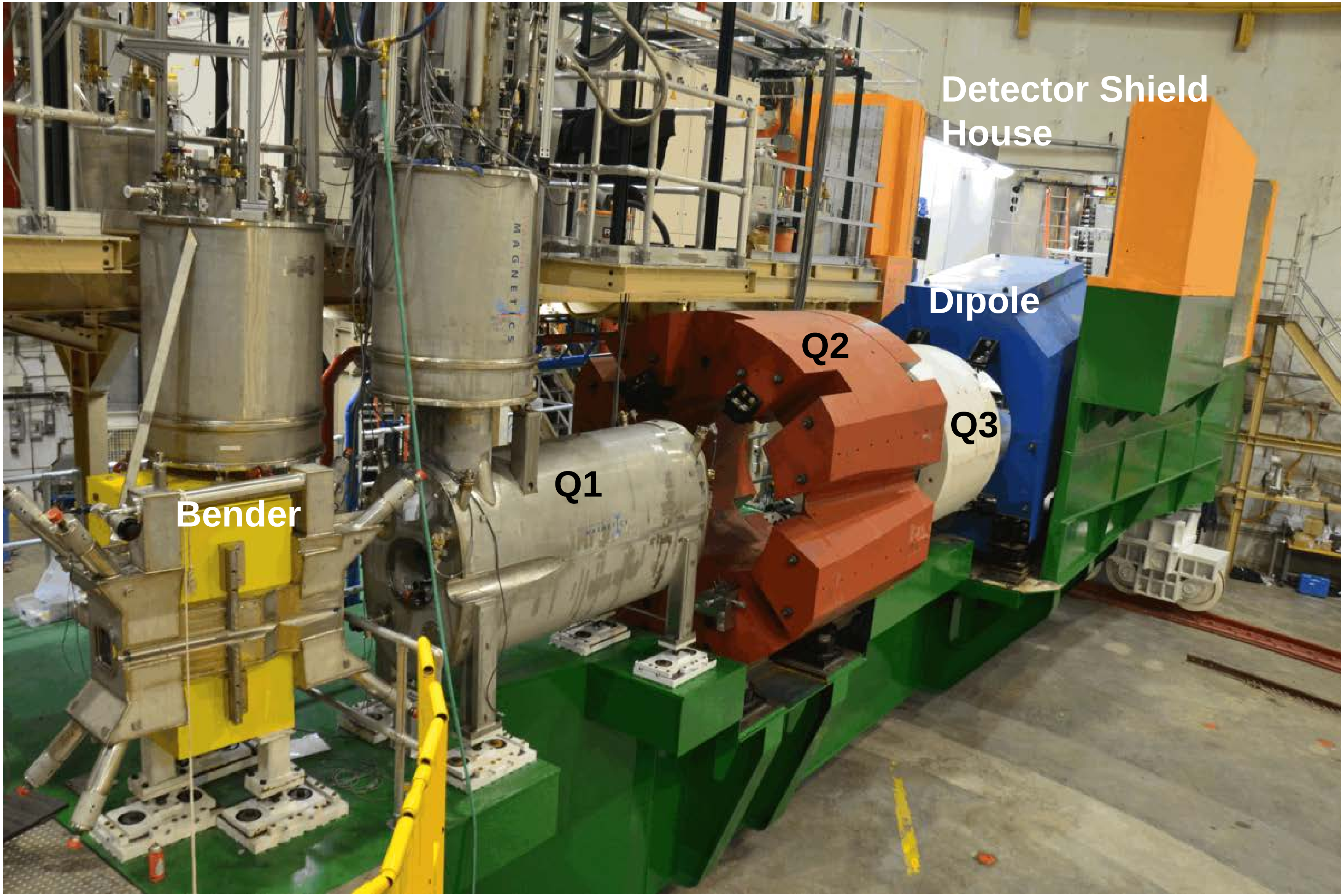


DETECTOR	PURPOSE	NOTES
S1XY, S2XY Hodoscopes	Lowest-level Trigger. Time reference	
Drift Chambers	Momentum Measurement. Tracking.	5mm max. drift 300 micron resolution
Noble-Gas Cerenkov	Particle ID, Trigger. $e^{\pm}/\pi^{\pm}$ at high momentum (replace by vacuum at low p)	Vary Ar/Ne mixture to set index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

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

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

SigmaPhi Vannes, France

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

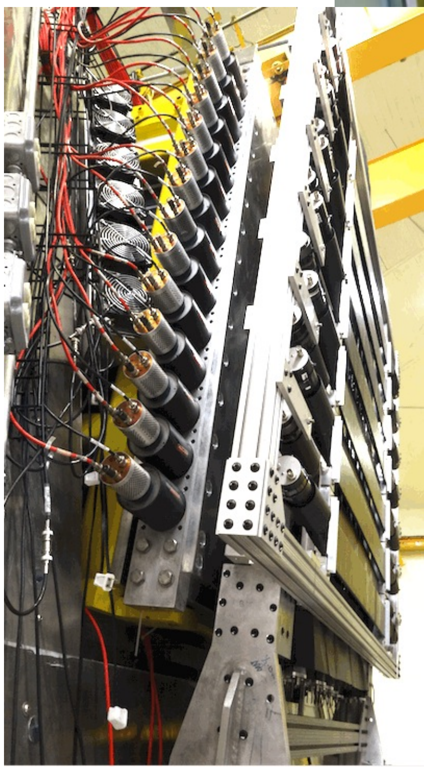
Fully-Potted Q3 Coils

Machined Q3 Coils

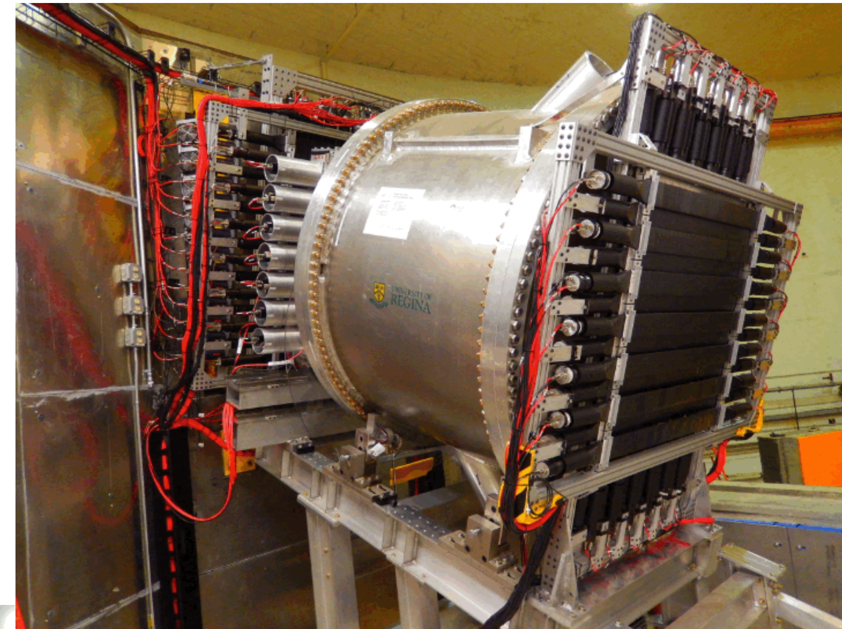
Q3 Coil Collaring 17-SEP-2015

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

Regina Efforts

Data Reconstruction Software (hcana)

- Z. Ahmed (PDF), completed

SHMS Detector Checkout & Commissioning

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

$p(e,e'K^+)\Lambda$ Kaon Form Factor

- L/T commissioning experiment (2017)

Pion Form Factor and π^+ QCD-Scaling Experiments

- Interleaved run-plans (2018 – 2020)

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Stay tuned for many exciting results over the coming decade!

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