Deep Exclusive Meson Production:
- Studies of Underlying Quark-Gluon Structure at Jefferson Lab's Hall C

Garth Huber

UNIVERSITY OF REGINA

Prairie Universities Physics Seminar Series, Winter 2015.

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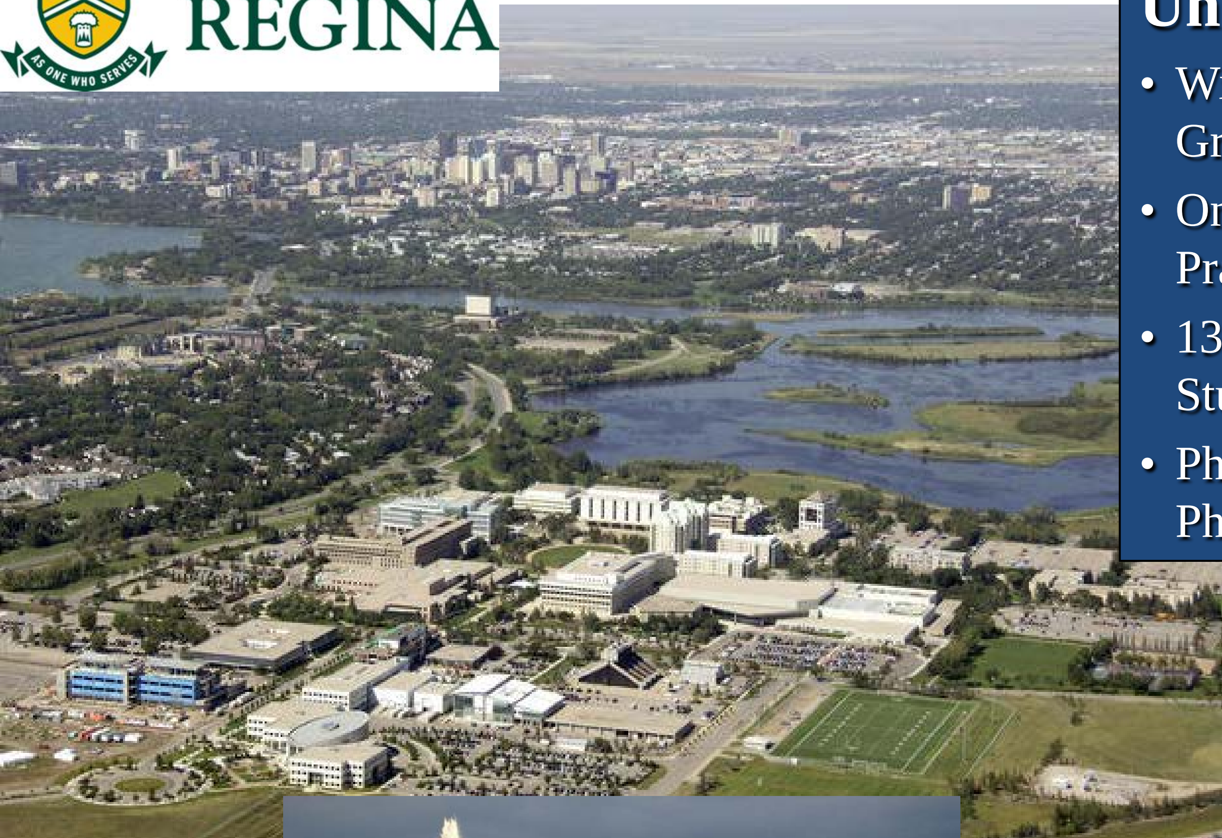
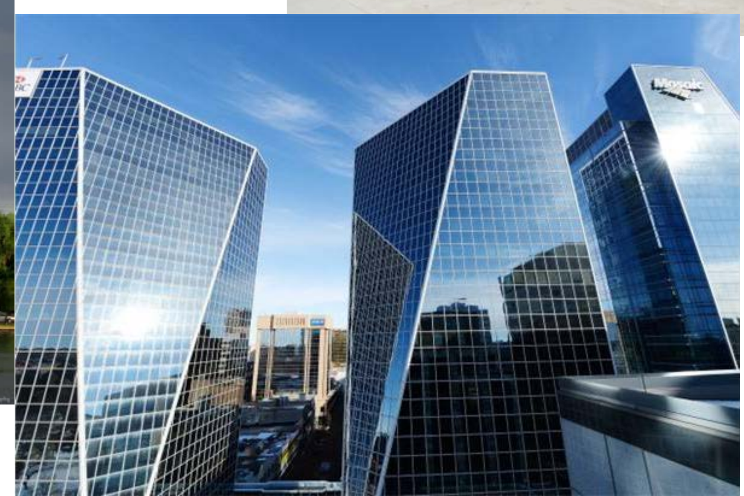
AS ONE WHO SERVES



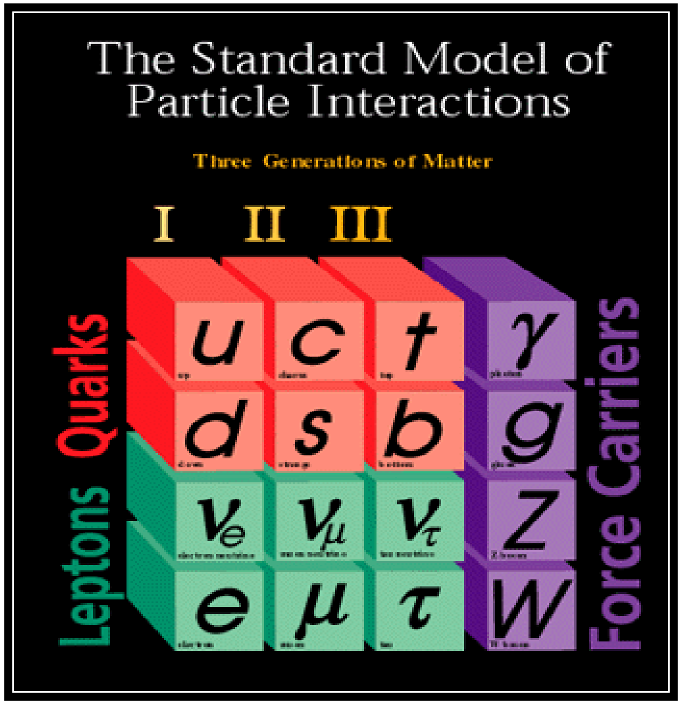
University of Regina:

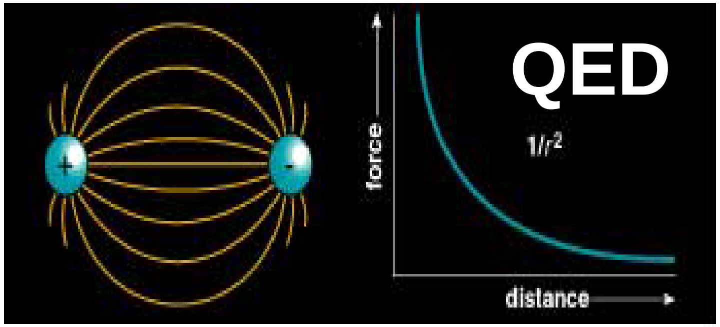
- Wide range of Undergraduate and Graduate programs and research.
- Only Comprehensive University on Prairies.
- 13,900 students, incl. 1,660 Grad Students (2014).
- Physics Dept. offers B.Sc., M.Sc. and Ph.D.

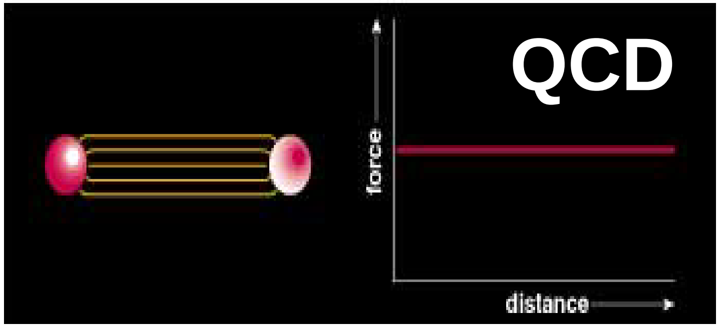


Dr. G.M Huber, Univ. of Regina, Regina, SK S4S0A2, Canada.

Quantum Electrodynamics
Quantum Chromodynamics

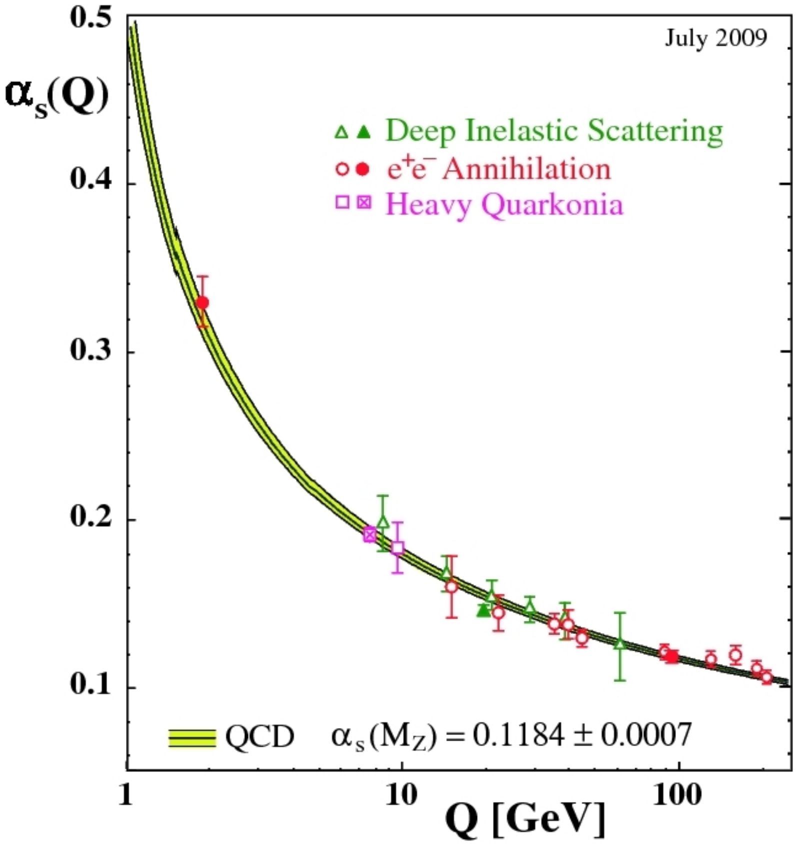






- Quarks are fractionally charged and interact via the electromagnetic (QED) and strong (QCD) interactions.
- Unlike the photons of QED, the gluons of QCD carry color charge and interact strongly, leading to the confinement of quarks inside hadrons.

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.**

Physics Problems for the Next Millennium

Selected by:

Michael Duff, David Gross, Edward Witten

Strings 2000

1. Size of dimensionless parameters.
2. Origin of the Universe.
3. Lifetime of the Proton.
4. Is Nature Supersymmetric?
5. Why is there 3+1 Space-time dimensions?
6. Cosmological Constant problem.
7. Is M-theory fundamental?
8. Black Hole Information Paradox.
9. The weakness of gravity.
10. Quark confinement and the strong force.

The Fundamental Issue

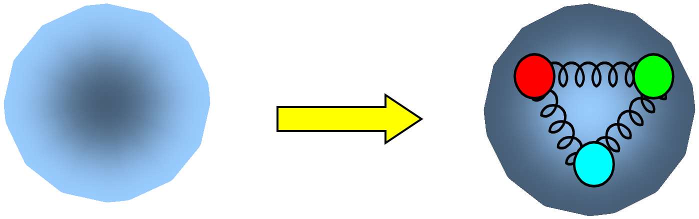
Quantum Chromodynamics (QCD) in the confinement regime:
How does it work?

What do we know?

QCD works in the perturbative (weak) regime

Many experimental tests led to this conclusion, example:

- Proton is not point-like; Elastic electron scattering (Nobel Prize: Hofstadter, 1961).
- Quarks and gluons/Partons are the constituents; Deep Inelastic electron Scattering (Nobel prize: Friedman, Kendall and Taylor, 1990).



Theory celebrated recently

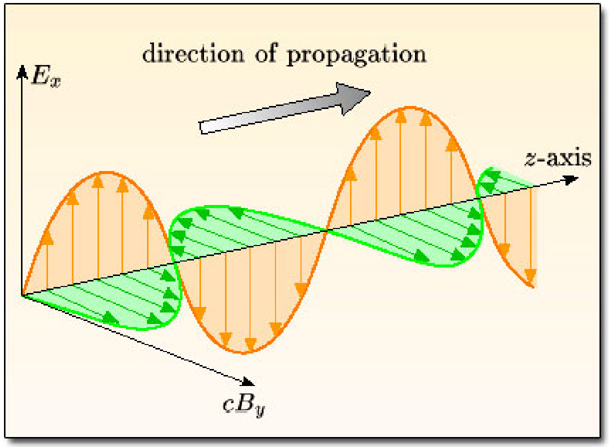
Asymptotic freedom (Nobel prize: Gross, Politzer and Wilczek, 2004), **but**

Quantitative QCD description of the nucleon's properties
(i.e. understanding of the confinement regime) remains a puzzle!

Probing Hadrons via well-known Electromagnetic Interaction

Real Photons (γ):

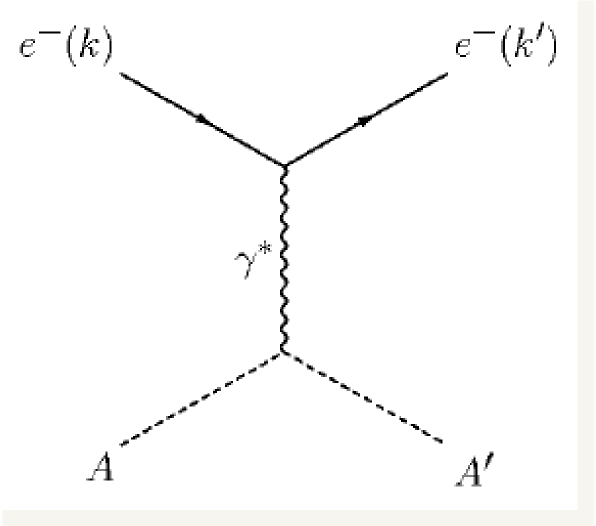
- *Created in hard electron deceleration (Bremsstrahlung).*
- *Zero Rest Mass: $E=pc$*
- *Equivalently: $Q^2=p^2c^2-E^2=0$*
- *Observation Scale: $R \approx h/p$.*
- *Electric Polarization Transverse to Propagation.*



Virtual (Spacelike) Photons (γ*):

- ***Created in larger θ electron scattering.***
- ***$E \neq pc$: Heisenberg Principle: $\Delta E \Delta t \geq \hbar/2$***
- ***$Q^2=p^2c^2-E^2>0$***

  If we define $m^2c^4=E^2-p^2c^2$, then $Q^2>0$ implies imaginary virtual photon mass.
- ***Observation Scale: $R \approx (\hbar c)/Q$.***
- ***Transverse and Longitudinal Electric Polarizations permitted.***



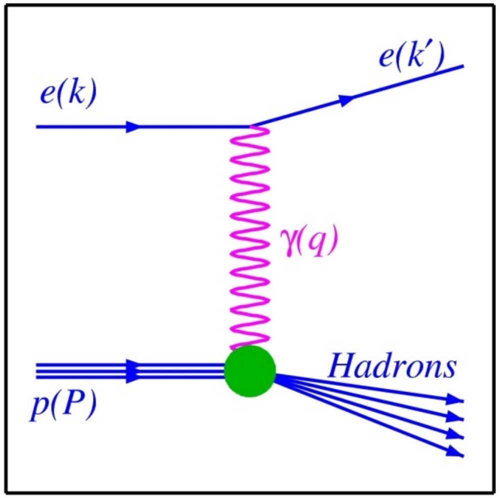
Virtual Photon Energy $= E - E'$
Virtual Photon Momentum $= \vec{k} - \vec{k}'$

(Inclusive) Deep Inelastic Scattering

- In an electron-proton scattering, there are many inelastic final states.
- It is traditional to define a quantity called the inclusive cross section

$$ep \rightarrow e'X$$

- **Called an inclusive reaction because the properties of "X" are not measured, hence including all available final states.**

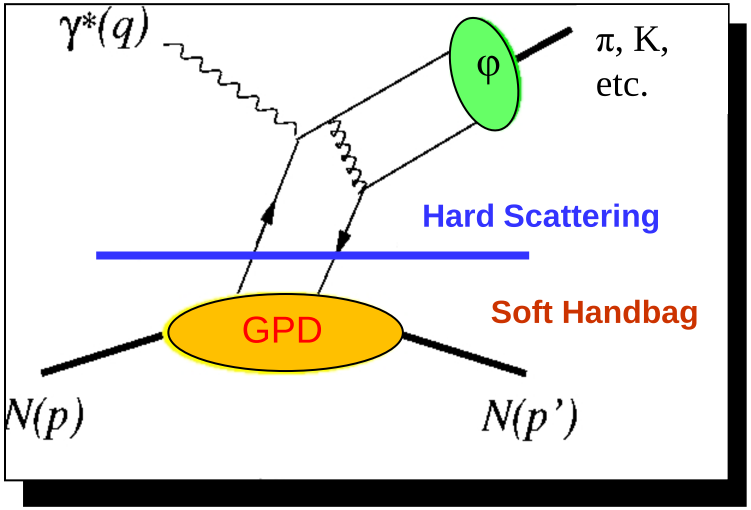


- **Experimental requirements are modest, since inclusive cross sections are large and only the scattered electron is detected.**
- **Much valuable information about QCD was obtained in this way in the 1970-90's, but DIS can access only partial hadronic structure information.**

Deep Exclusive Scattering

- 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.

Luminosity:
(SLAC, 1978) ~ 8 x 10^{31} cm^{-2}-s^{-1}
(JLab, 2000) ~ 4 x 10^{38} cm^{-2}-s^{-1}



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

[Collins, Frankfurt, Strikman, 1997]

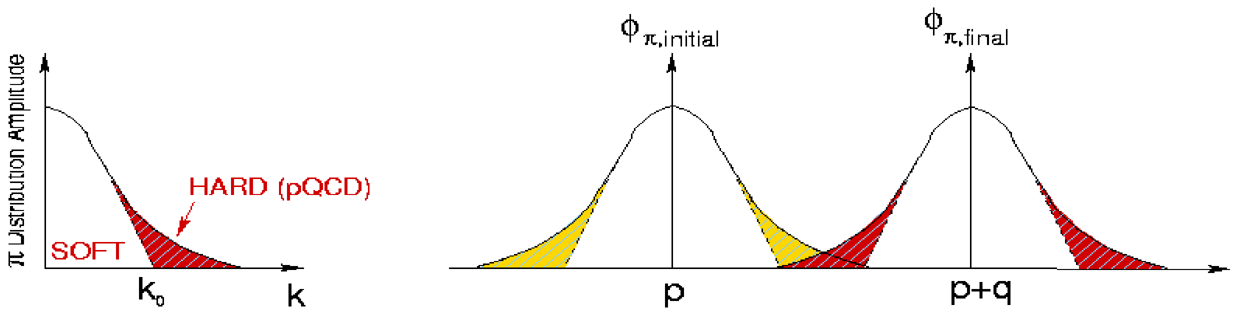
Hadron Form Factors

In general, the elastic scattering cross section from an extended target is

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\substack{\text{point}\\ \text{object}}} \left|F(Q^2)\right|^2$$

In quantum field theory, $F(Q^2)$ is the overlap integral:

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



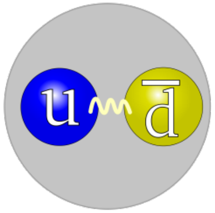
The hadron wave function can be separated into φ_π^{soft} with only low momentum contributions ($k<k_0$) and a hard tail φ_π^{hard}.

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

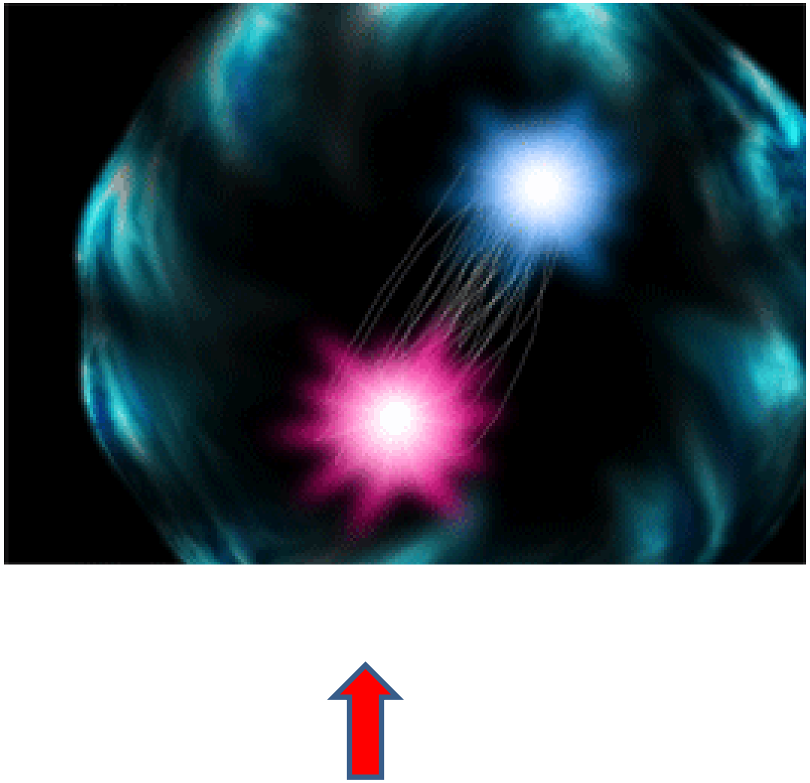
From a theoretical standpoint, the study of the Q^2-dependence of the form factor focuses on finding a description for the hard and soft contributions of the hadron wave-function.

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 Pion Form Factor

At very large Q^2, pion form factor (F_π) can be calculated using perturbative QCD (pQCD)

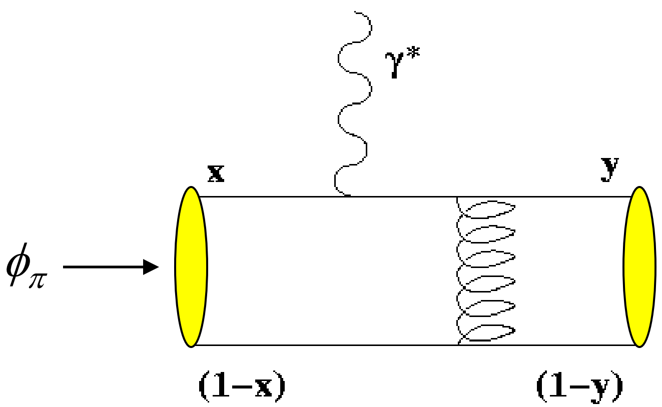
$$F_\pi(Q^2) = \frac{4}{3}\pi\alpha_s \int_0^1 dxdy \frac{2}{3}\frac{1}{xyQ^2}\phi(x)\phi(y)$$

at asymptotically high Q^2,
the pion wave function becomes

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

and F_π takes the very simple form

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

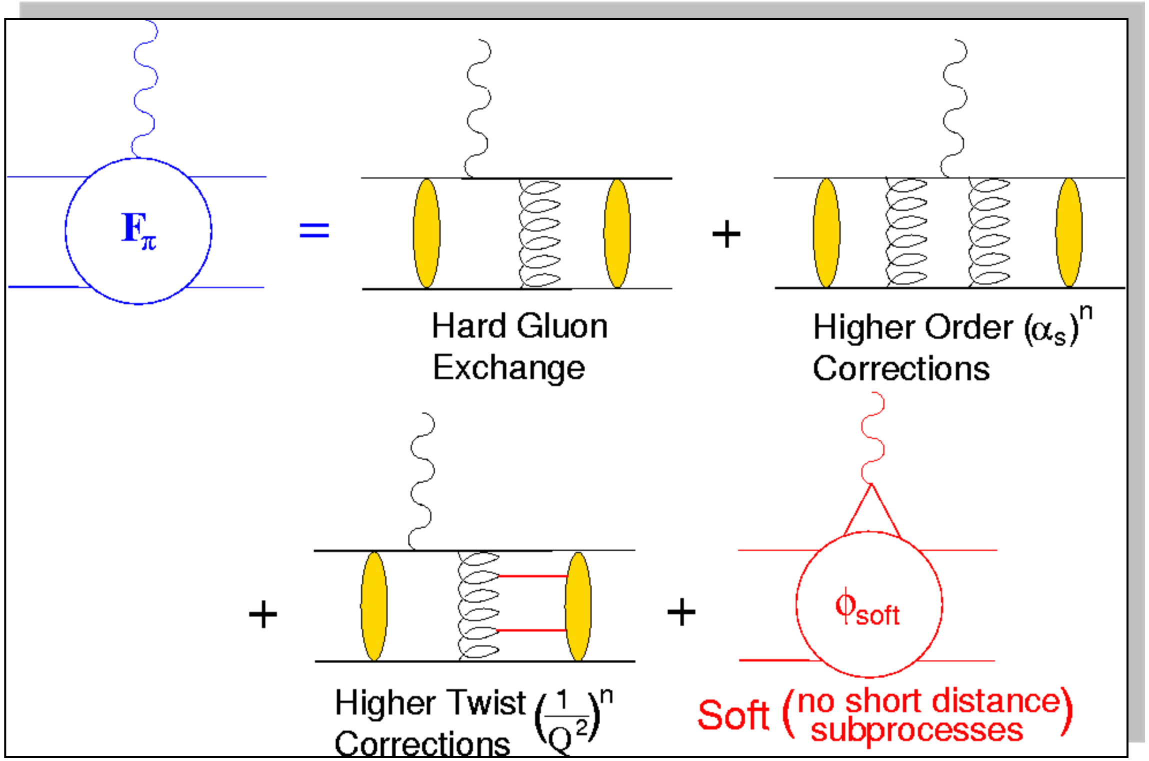


f_π=93 MeV is the $\pi^+\to\mu^+\nu$ decay constant.

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

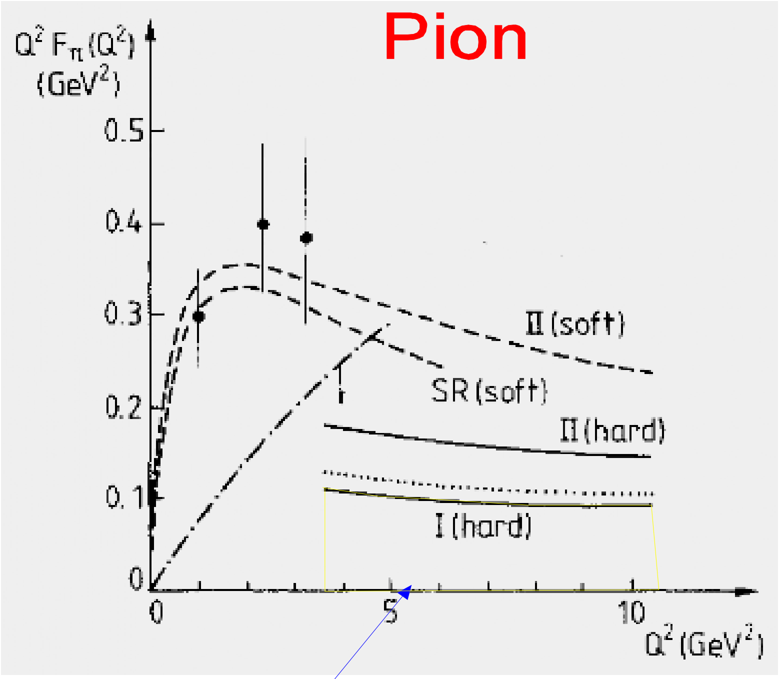
Pion Form Factor at Finite Q^2

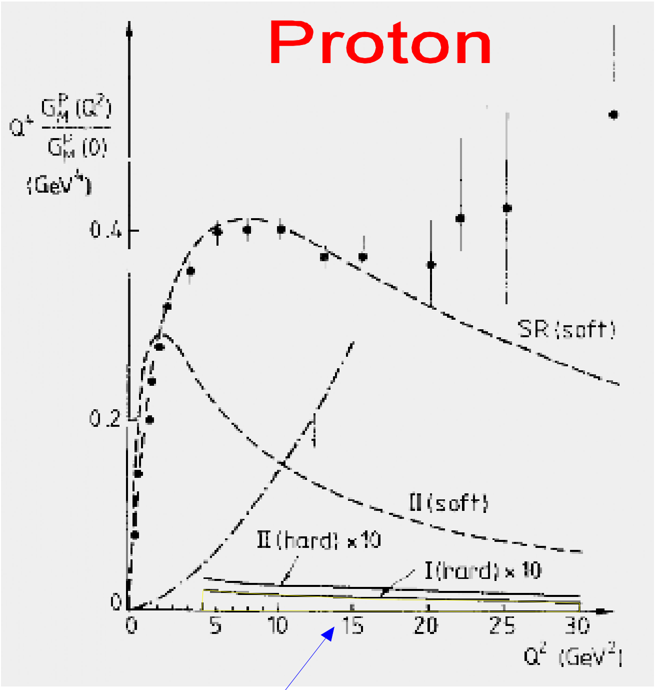
- At finite momentum transfer, higher order terms contribute
- Calculation of higher order, "hard" (short distance) processes difficult, but tractable



- 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**

The Pion as a QCD Laboratory





Isgur & Llewellyn-Smith, PRL **52**(84)1080

Hard contributions
~30-50% at Q^2=5 GeV^2

Hard contributions
≤1% at Q^2=5 GeV^2

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

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

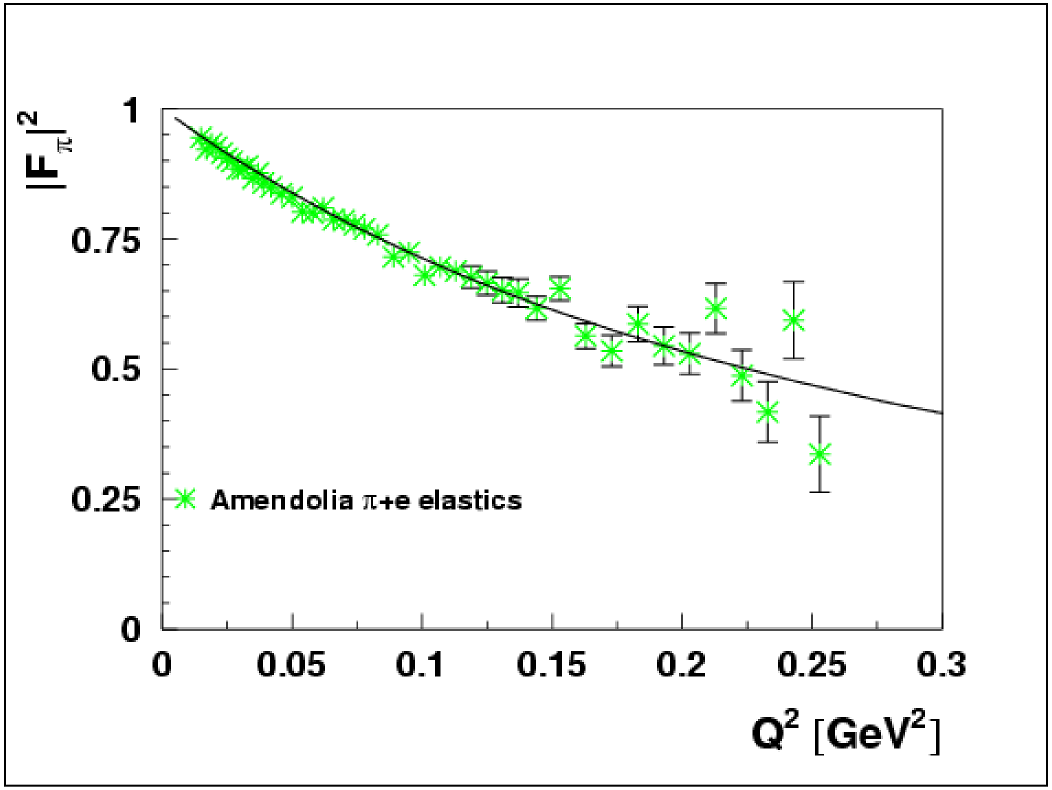
- CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2 *[Amendolia et al, NPB277, 168 (1986)]*

- 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



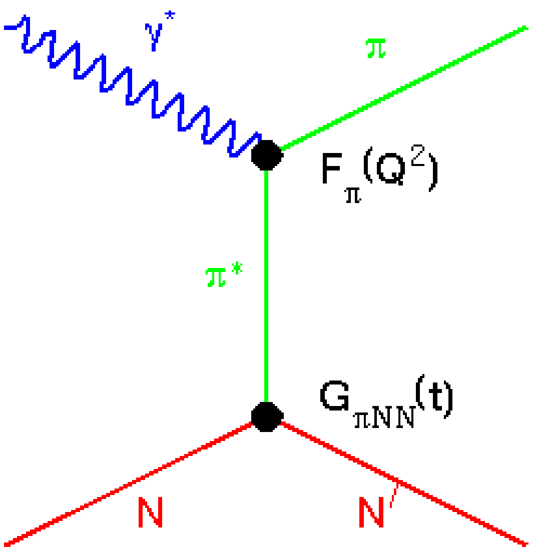
Measurement of π^+ Form Factor – Larger Q^2

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

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

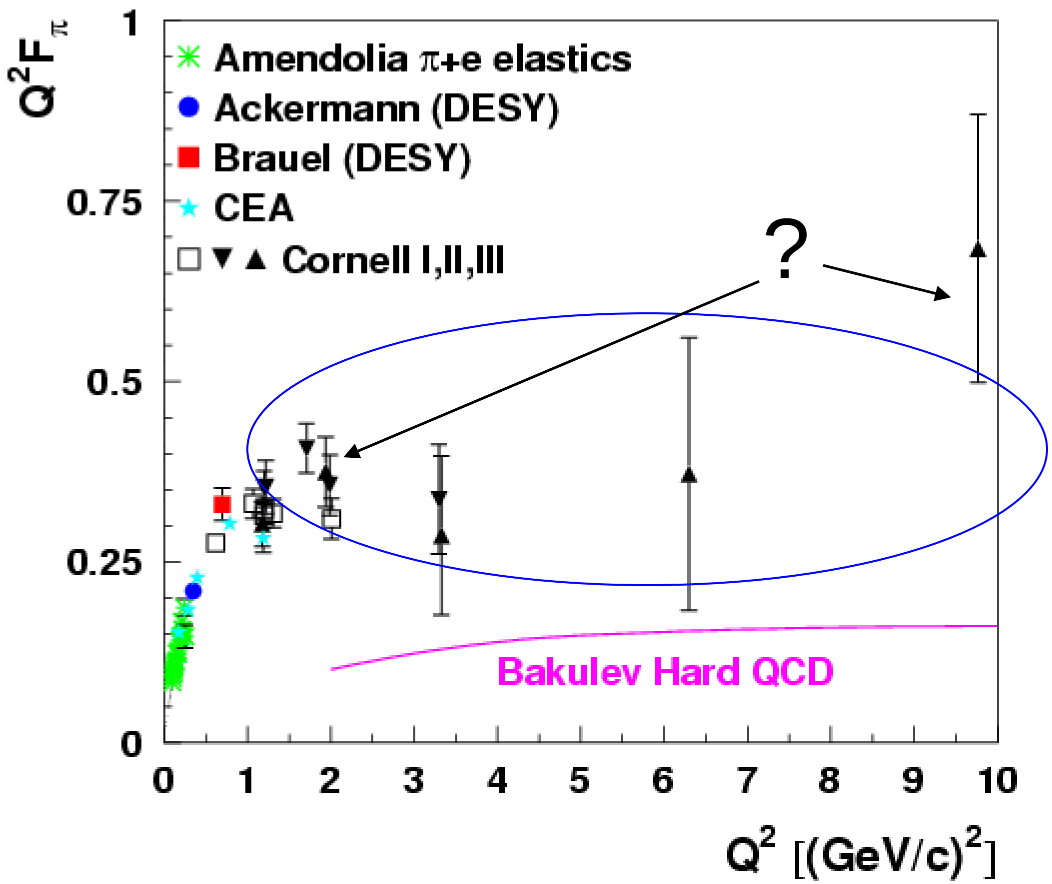
- At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
- In Born term model, F_π^2 appears as,

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



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

World π^+ Data Set, 1997



Problematic L/T separation.

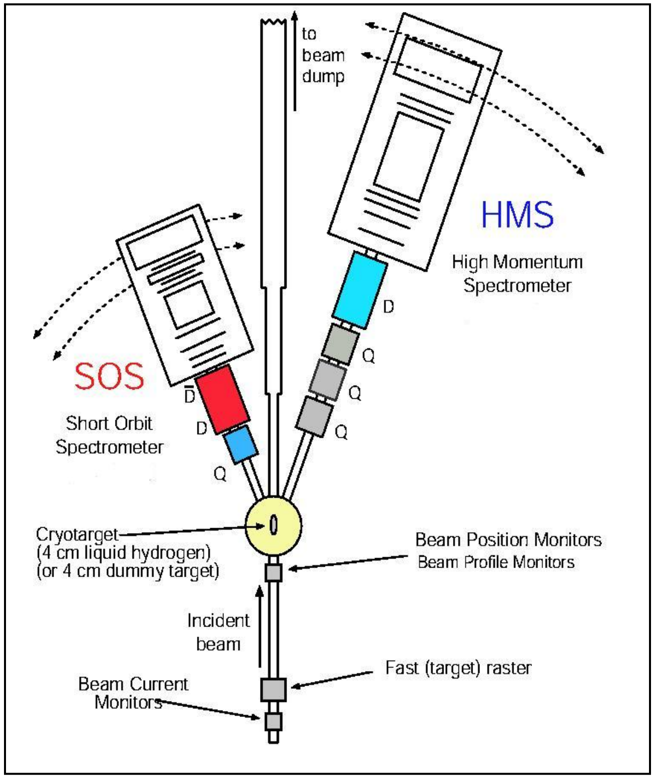
- Older data at larger Q^2 (> *1* GeV^2) extracted F_π from unseparated cross sections.
- Used extrapolation of σ_T fit at low Q^2 to isolate σ_L.

Analysis based on assumptions with systematic errors that are difficult to quantify.

- Data taken far from pole, with $-t_{min}$ *as high as 40* m_π^2.

"[we] question whether F_π has been truly determined for large Q^2." - C.E. Carlson, J. Milana, PRL **65**(1990)1717.

F_π Program at JLab Hall C



- 2 F_π experiments have been carried out at JLab

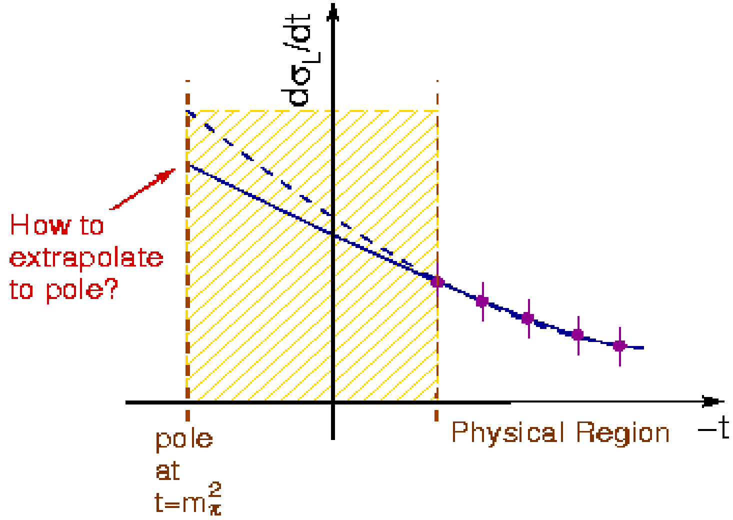
  (spokespersons H. Blok, G. Huber, D.Mack)
  - F_π-1: $Q^2=0.6\text{-}1.6$ GeV^2 with 4 GeV beam, 1997-2001.
  - F_π-2: $Q^2=1.6, 2.45$ GeV^2 with 6 GeV beam, 2003-2008.

Extraction of form factor from σ_L data

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

- No reliable phenomenological extrapolation possible.

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



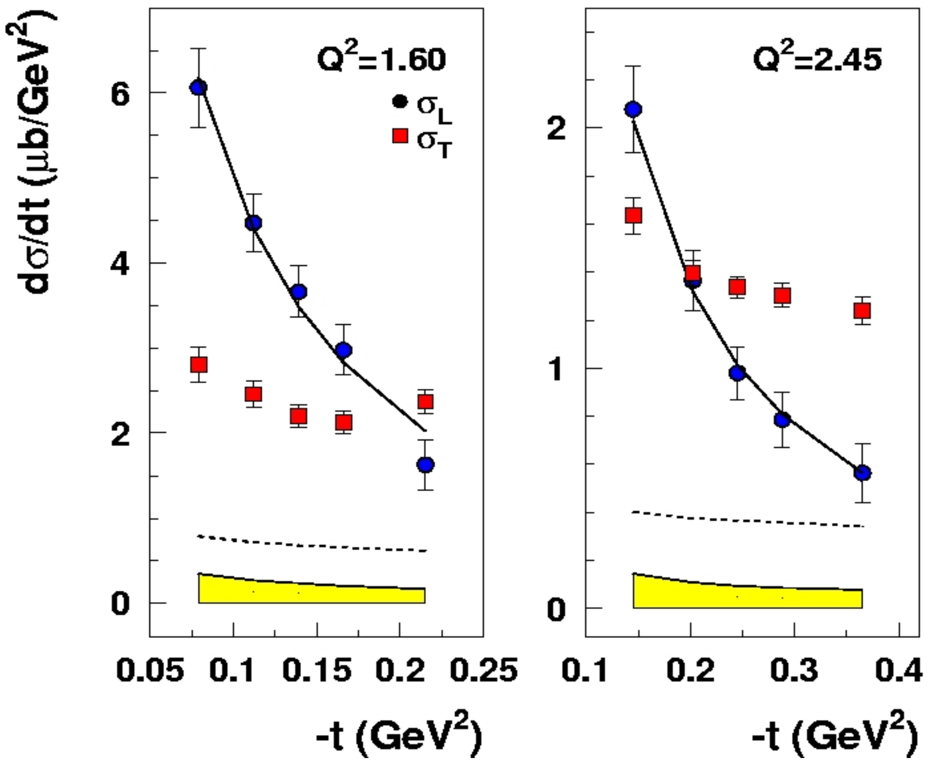
Our philosophy is to publish our experimentally measured $d\sigma_L/dt$, so that updated values of $F_\pi(Q^2)$ can be extracted as better models become available.

F_π Extraction from JLab data

- **Model is required to extract F_π from σ_L**
- **JLab F_π experiments used the VGL Regge model**
  [Vanderhaeghen, Guidal, Laget, PRC 57, 1454 (1998)]
  - Propagator replaced by π and ρ Regge trajectories
  - Most parameters fixed by photoproduction data
  - 2 free parameters: Λ_π, Λ_ρ
  - At small $-t$, σ_L only sensitive to Λ_π

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

Horn et al, PRL ***97****, 192001,2006*



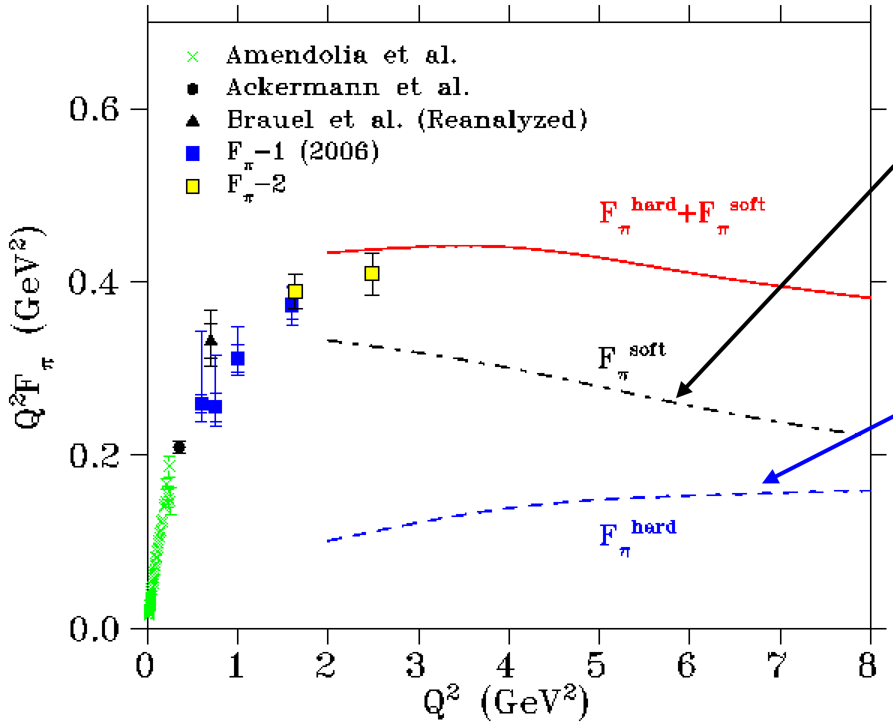
Dr. G.M Huber, Univ. of Regina, Regina, SK S4S0A2, Canada.

The role of Soft and Hard QCD in F_π

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.*



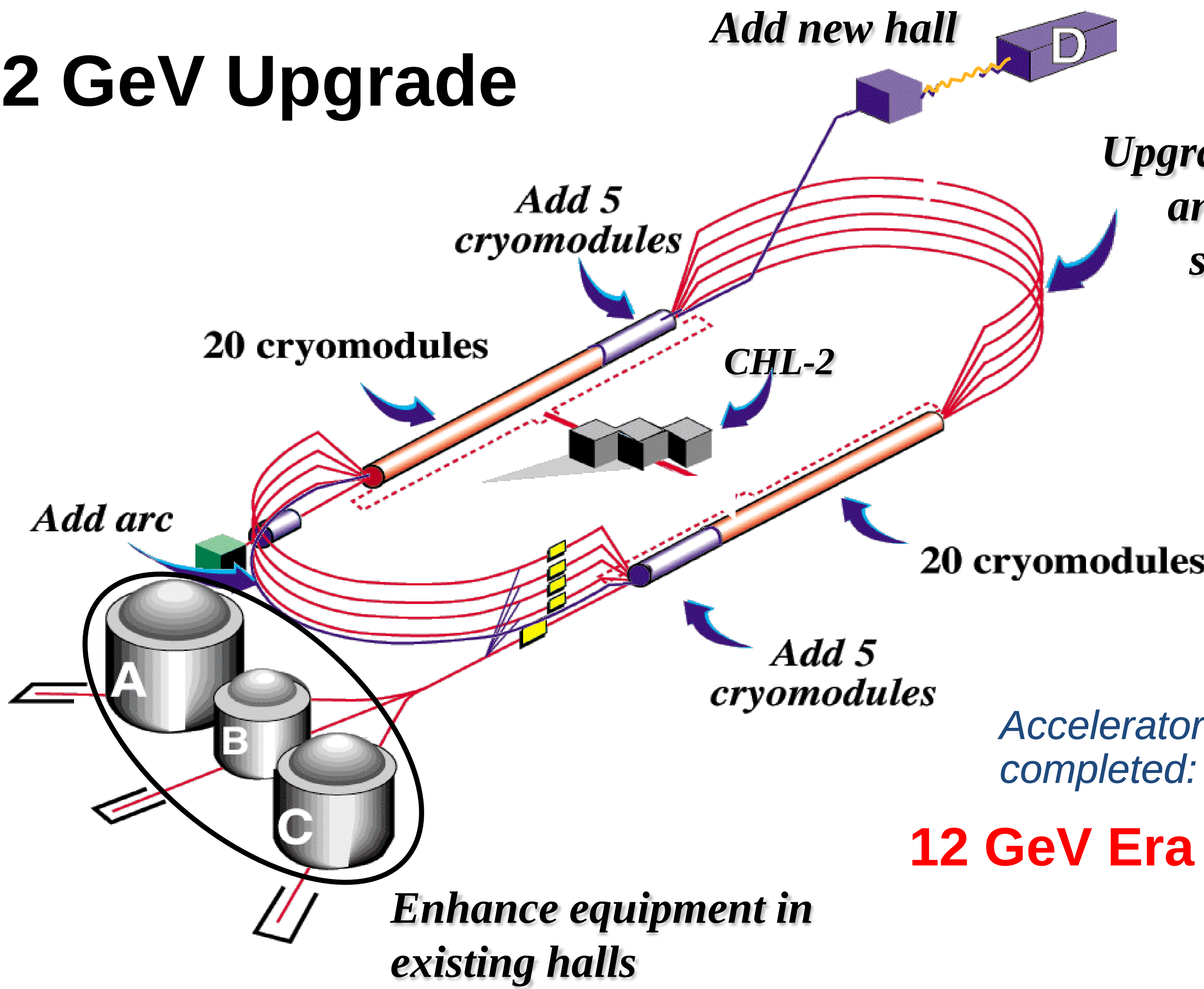
SOFT QCD:

- 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.

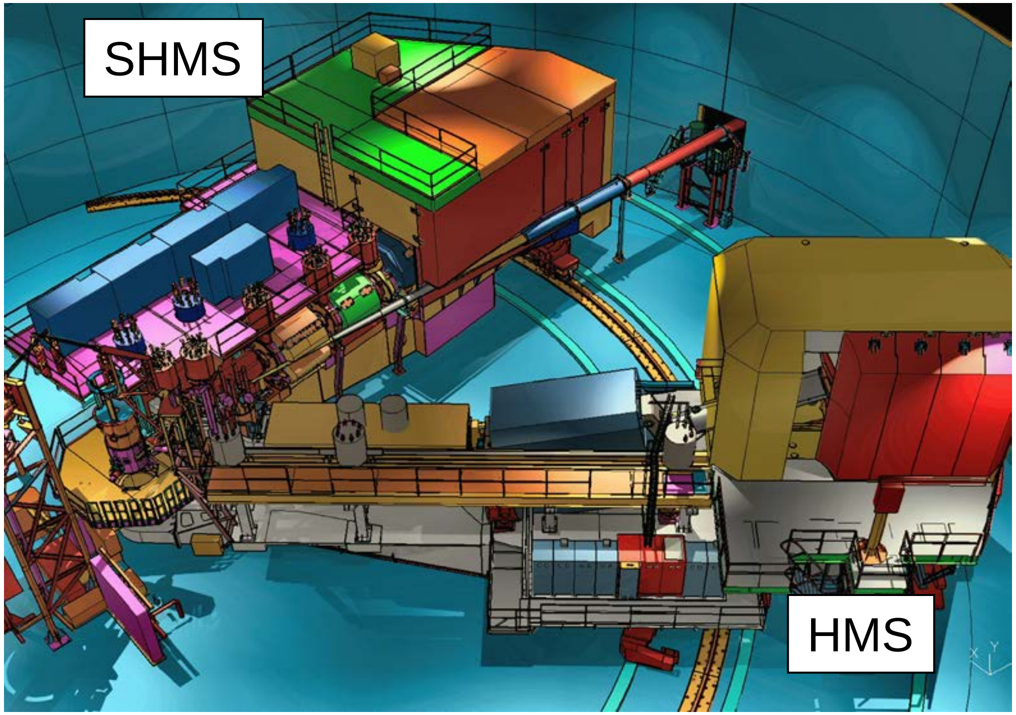
12 GeV Upgrade



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*

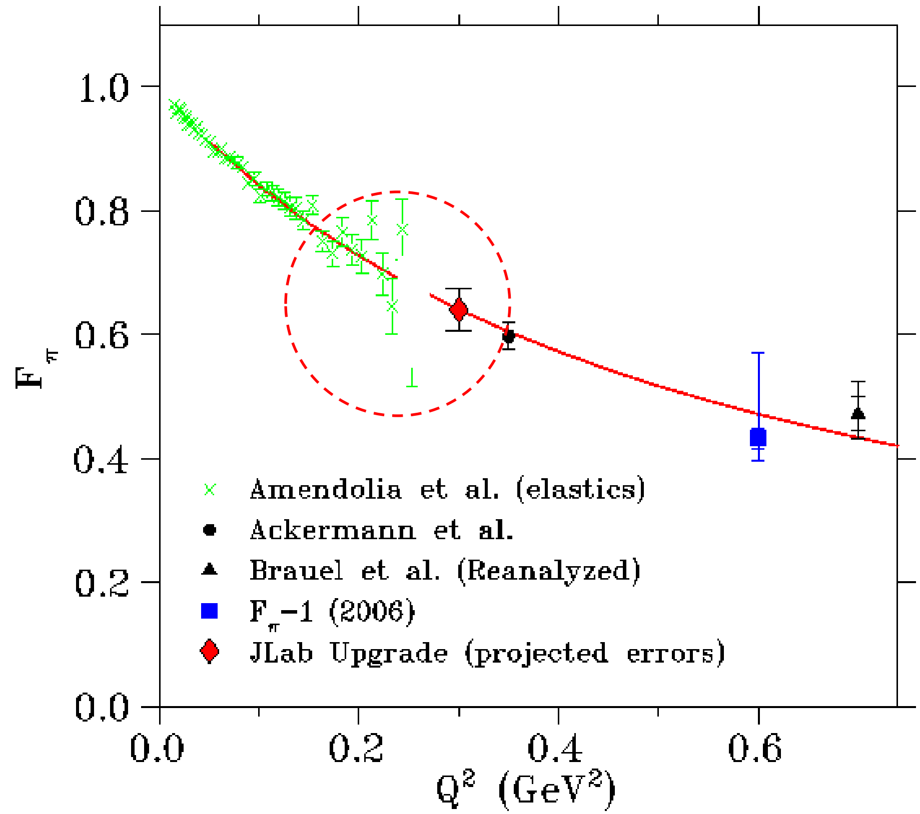
- Both spectrometers provide excellent control of systematic uncertainties
- Kinematic reproducibility, well-understood acceptance

Ideal for:

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

Check of Pion Electroproduction Technique

- Does electroproduction really measure the on-shell form-factor?
- Test by making *p(e,e'π^+)* measurements at same kinematics as π+e elastics.
- ***Can't quite reach the same Q^2, but electro-production appears consistent with extrapolated elastic data.***



We will do an improved test after the JLab 12 GeV upgrade

- **smaller Q^2 (=0.30 GeV^2)**
- **$-t$ closer to pole (=0.005 GeV^2)**

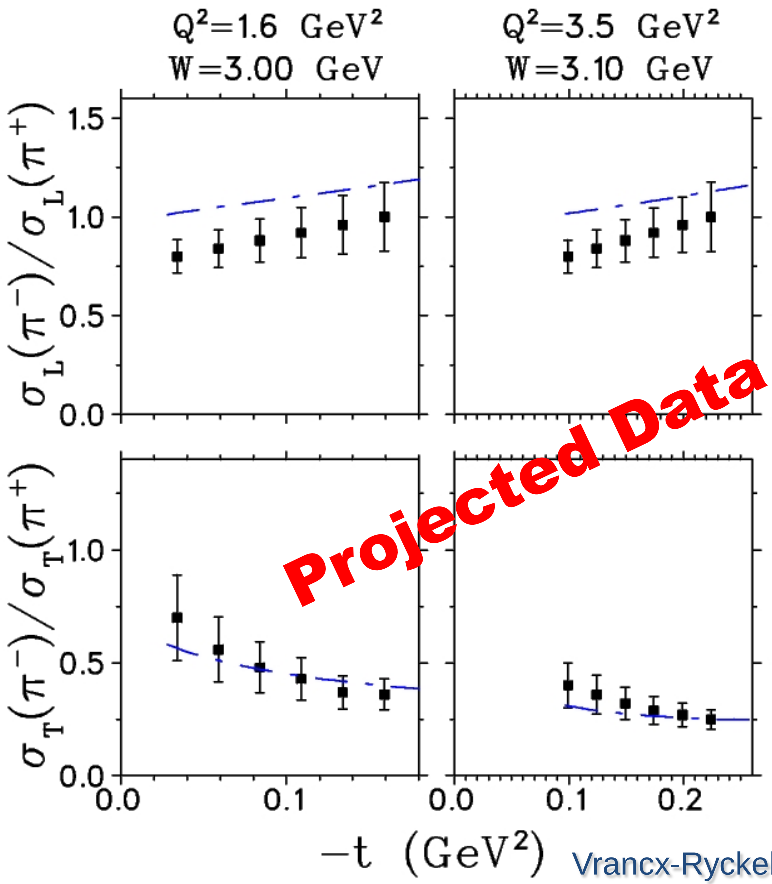
Verify that σ_L is dominated by t-channel process

- π^+ t-channel diagram is purely isovector.
- Measure

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

using a deuterium target.

- Isoscalar backgrounds (such as $b_1(1235)$ contributions to the t-channel) will dilute the ratio.
- We will do the same tests at Q^2=1.60 and 3.50 GeV^2.



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

Because one of the many problems encountered by the historical data was isoscalar contamination, this test will increase the confidence in the extraction of $F_\pi(Q^2)$ from our σ_L data.

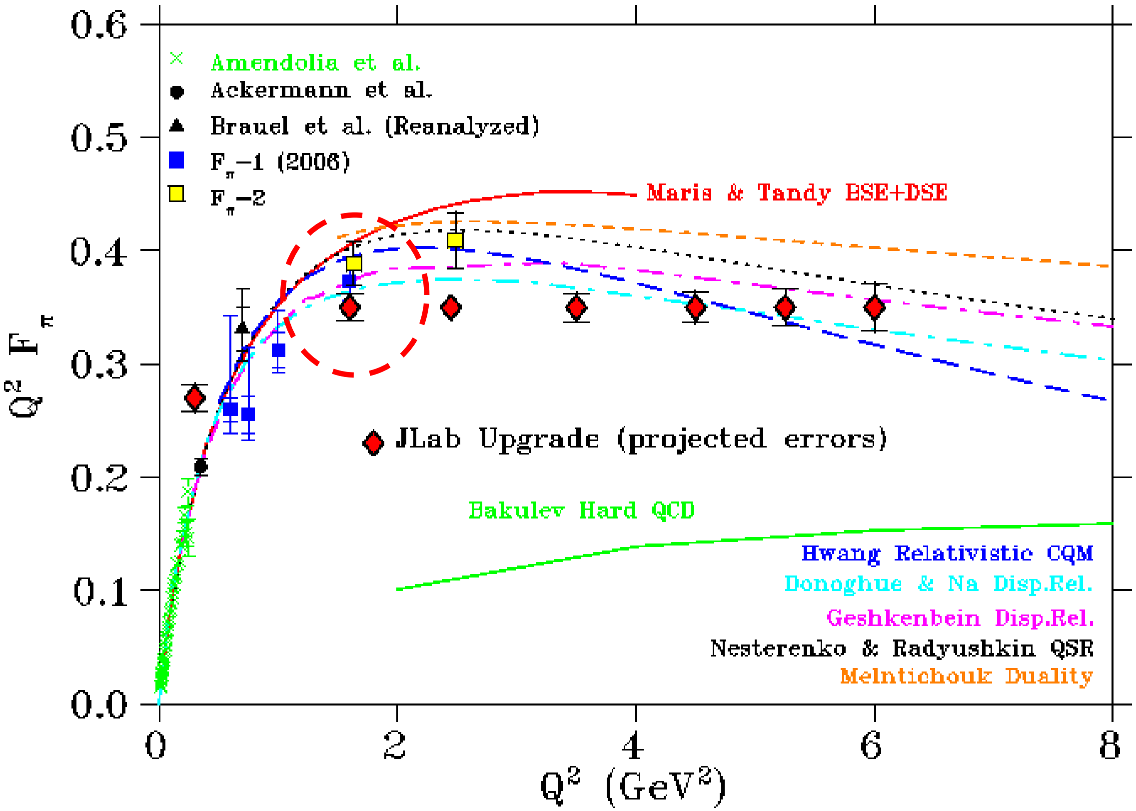
$F_\pi(Q^2)$ after JLab 12 GeV Upgrade

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

No other facility worldwide can perform this measurement.

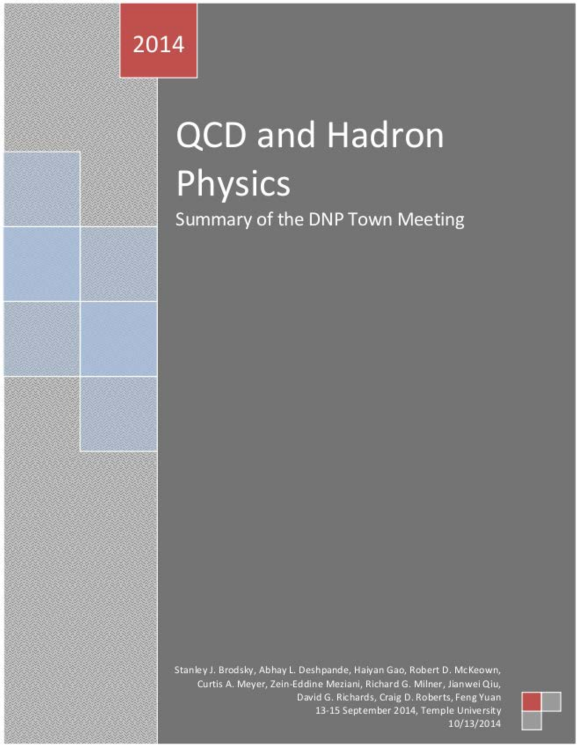
New overlap point at $Q^2=1.6$ will be closer to pole to constrain $-t_{min}$ dependence.

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



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

Recent Endorsement in QCD White Paper

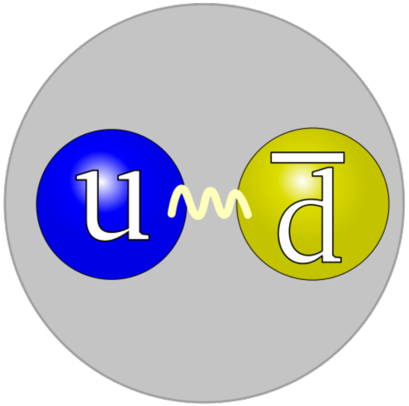


Section 2: Major steps toward understanding the pion, the long-range messenger in nuclear physics

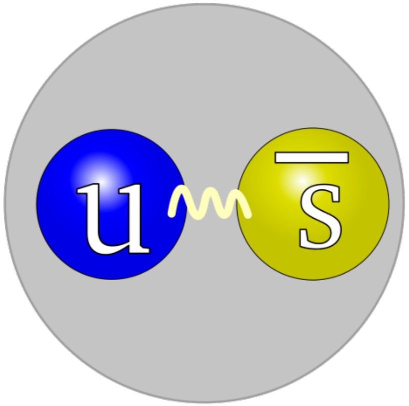
- Pion properties are intimately connected with dynamical chiral symmetry breaking (DCSB), which explains the origin of more than 98% of the mass of visible matter in the universe.
- measurement of the electromagnetic form factor of the pion, $F_\pi(Q^2)$, presents an extraordinary opportunity for charting the transition from confinement-dominated physics at large length-scales to the short-distance domain upon which aspects of perturbative QCD become apparent.

- Greater urgency is now attached to measurement of $F_\pi(Q^2)$ following recent theoretical progress.
- These measurements hold great promise: it is possible that they will be the first to sight parton model scaling in an elastic form factor.

The Charged Kaon – a second QCD test case



π^+



K^+

- In the hard scattering limit, pQCD predicts that the π^+ and K^+ form factors will behave similarly

$$\frac{F_K(Q^2)}{F_\pi(Q^2)} \xrightarrow[Q^2 \to \infty]{} \frac{f_K^{\,2}}{f_\pi^{\,2}}$$

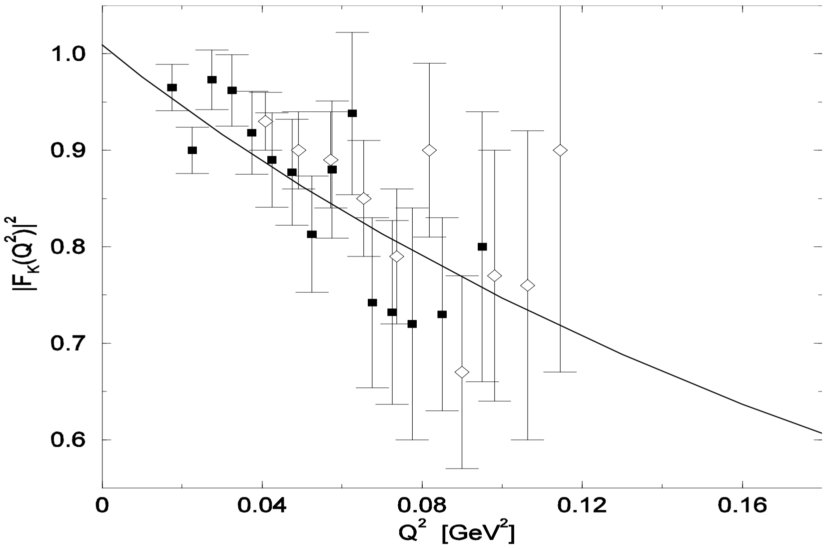
- It is important to compare the magnitudes and Q^2-dependences of both form factors.

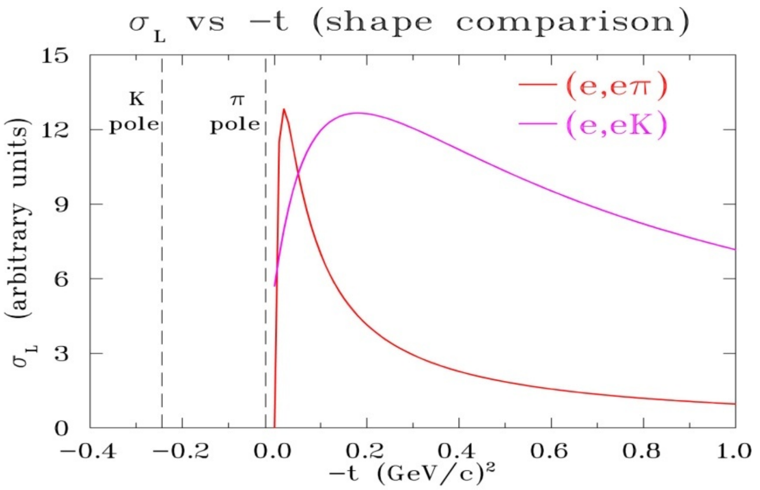
Measurement of K^+ Form Factor

- Similar to π^+ form factor, elastic K^+ scattering from electrons used to measure charged kaon for factor at low Q^2

  [Amendolia et al, PLB 178, 435 (1986)]

- Can "kaon cloud" of the proton be used in the same way as the pion to extract kaon form factor via ***p(e,e'K⁺)Λ*** ?
- Kaon pole further from kinematically allowed region.
- Can we demonstrate that the "pole" term dominates the reaction mechanism?



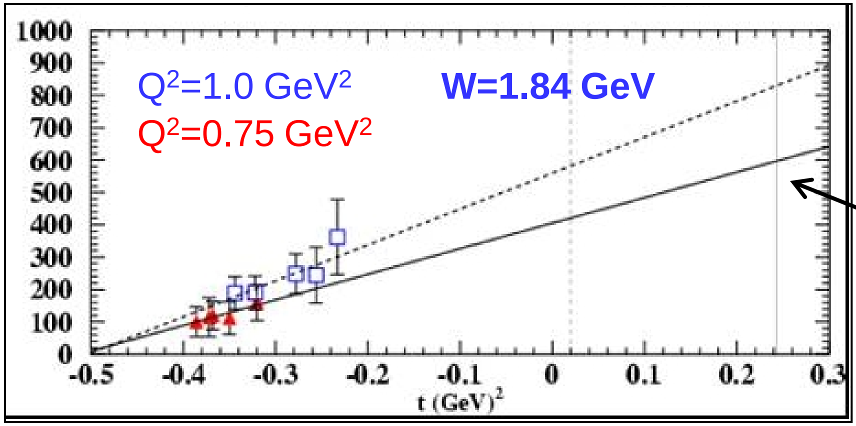


Test Extraction of K^+ Form Factor at JLab

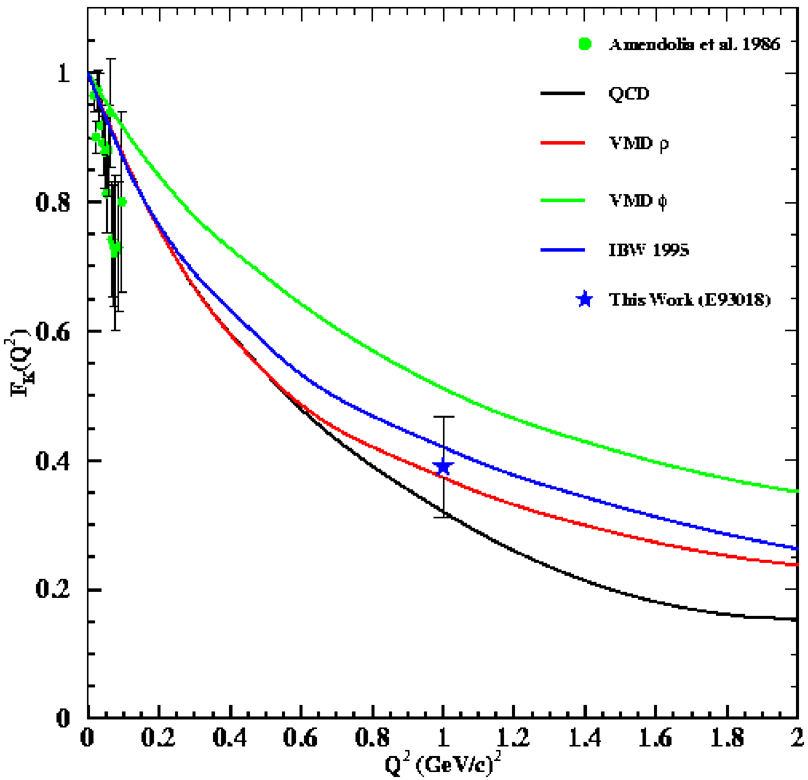
- JLab experiment E93-018 extracted $-t$ dependence of σ_L^{K+} near $Q^2=1$ GeV^2
  - Trial Kaon FF extraction was attempted using a simple Chew-Low extrapolation technique

$$\sigma_L \approx \frac{-2tQ^2}{(t-m_K^2)^2} k(eg_{K\Lambda N})^2 F_K^2(Q^2)$$

$g_{K\Lambda N}$ poorly known



G. Niculescu, Ph.D. Thesis, Hampton U.



$t=m_K^2$ (kaon pole)

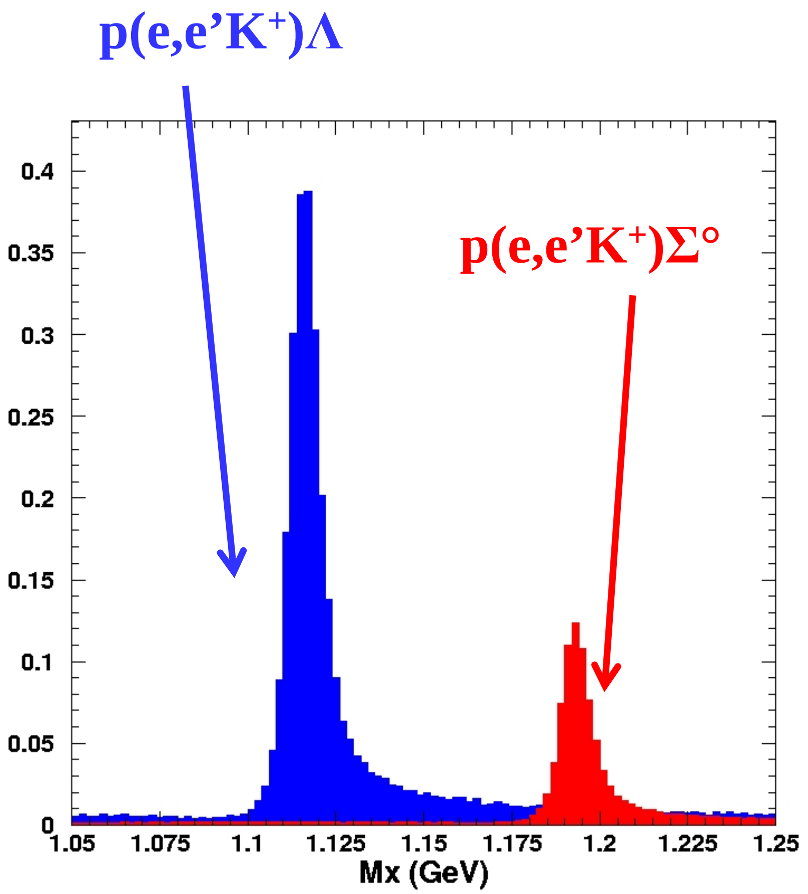
-t dependence shows some "pole-like" behavior

Isolate Exclusive Final States via Missing Mass

$$M_X = \sqrt{(E_{\det} - E_{init})^2 - (p_{\det} - p_{init})^2}$$

- SHMS+HMS missing mass resolution expected to be very good.
- Spectrometer coincidence acceptance allows for simultaneous studies of Λ and Σ° channels.

- Kaon-pole dominance test through
$$\frac{\sigma_L(\gamma^* p \rightarrow K^+\Sigma^0)}{\sigma_L(\gamma^* p \rightarrow K^+\Lambda^0)}$$
- Should be similar to ratio of $g^2_{pK\Lambda}/g^2_{pK\Sigma}$ coupling constants if t-channel exchange dominates.



Simulation at Q^2=2.0 GeV^2 , W=3.0 and high ε

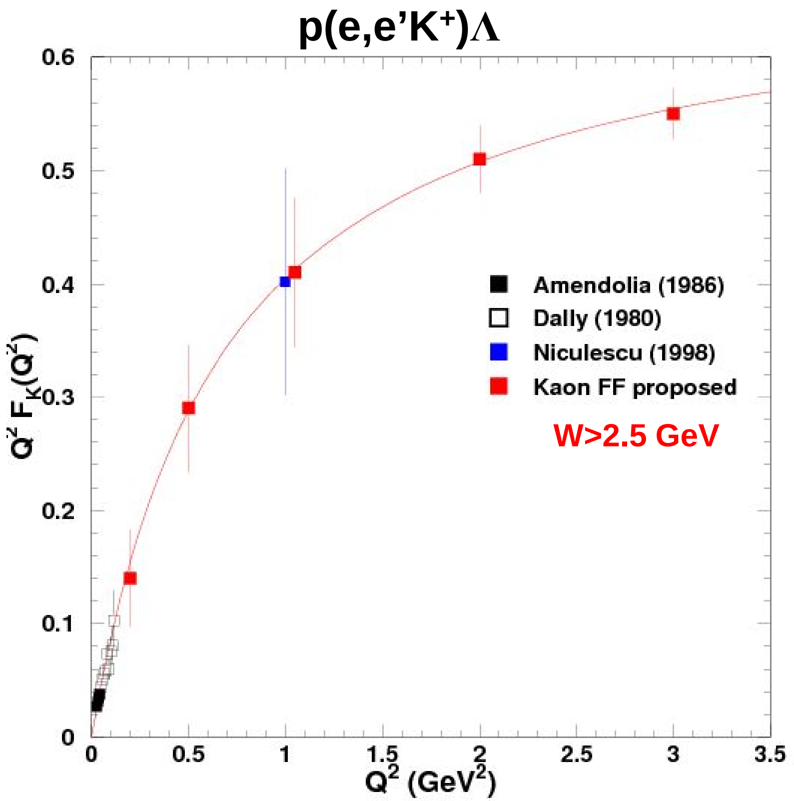
Kaon Form Factor

- **Measure the –t dependence of the *$p(e,e'K^+)\Lambda,\Sigma^\circ$* cross section at fixed Q^2 and W>2.5 GeV to search for evidence of K^+ pole dominance in σ_L**
  - Separate the cross section components: L, T, LT, TT
  - First L/T measurement above the resonance region in K^+ production
- **<u>If warranted by the data</u>, extract the Q^2 dependence of the kaon form factor to shed new light on QCD's transition to quark-gluon degrees of freedom.**

- **<u>Even if we cannot extract the kaon form factor</u>, the measurements are important.**
  - $K^+\Lambda$ and $K^+\Sigma^\circ$ reaction mechanisms provide valuable information in our study of hadron structure
  - Flavor degrees of freedom provide important information for QCD model building and understanding of basic coupling constants

Projected Uncertainties for K^+ Form Factor

- First measurement of F_K well above the resonance region.
- Measure form factor to Q^2=3 GeV^2 with good overlap with elastic scattering data.
  - Limited by $-t<0.2$ GeV^2 requirement to minimize non-pole contributions.
- Data will provide an important second $q\bar{q}$ system for theoretical models, this time involving a strange quark.

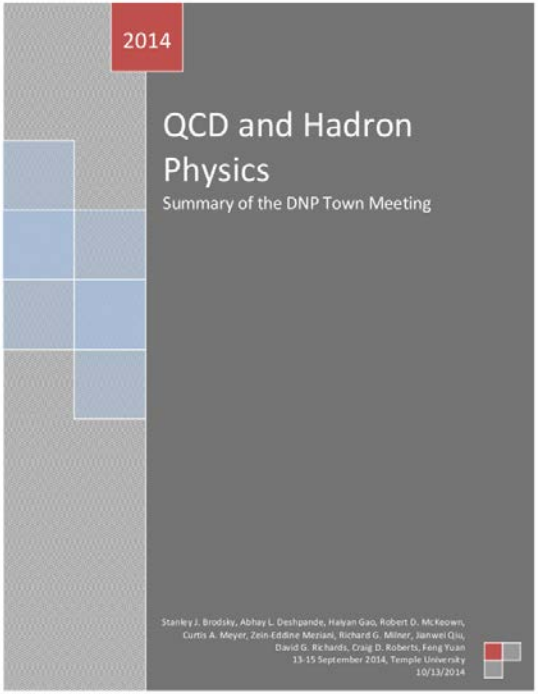


For VGL/Regge calculation, assume Λ^2_K=0.67 GeV^2, and Λ^2_{K*}=1.5 GeV^2.

Scheduled as an early SHMS commissioning experiment: LT-separation. (E12-09-011: T. Horn, G. Huber and P. Markowitz, spokespersons)

Second Endorsement from QCD White Paper

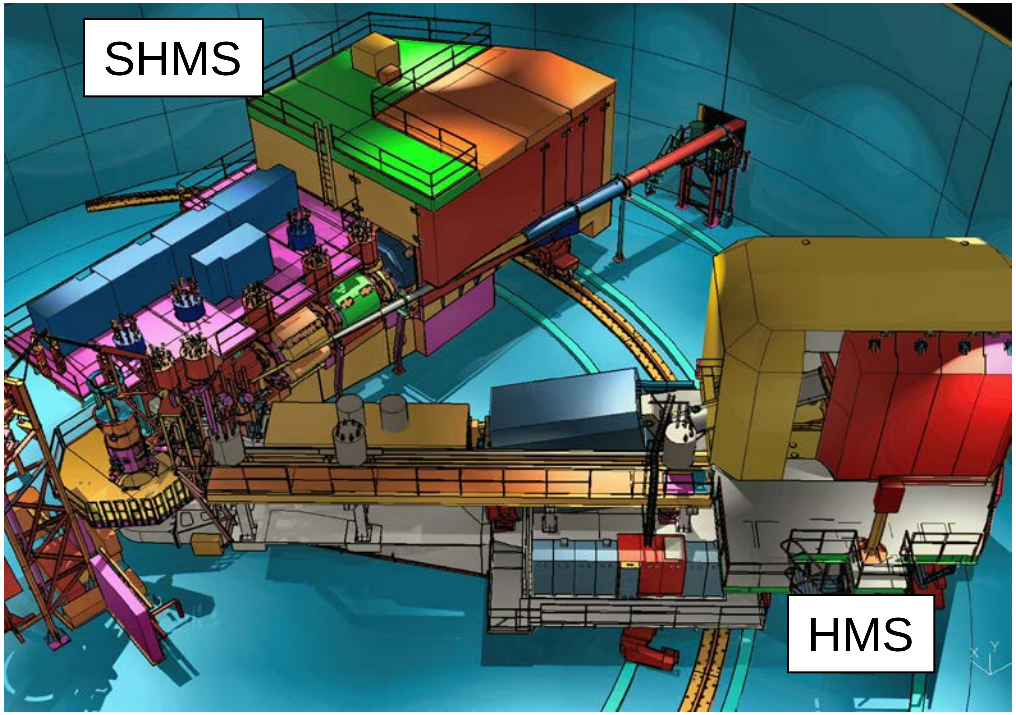
Section 3c: Meson Form Factors



- The form factors of pions and kaons are of special interest owing to the dichotomous nature of these mesons as both bound-states of strongly-dressed constituents and the pseudo-Goldstone modes through dynamical chiral symmetry breaking (DCSB) in QCD.

- Experimentally, pion elastic form factor measurements at JLab are made indirectly, using exclusive pion electroproduction, *p(e,e'π+)n*, to gain access to the proton's "pion cloud". This approach is reliable in forward kinematics.
- Analogously, in order to extract information on the kaon's elastic form factor it might be feasible to sample the proton's "kaon cloud" via $p(e,e'K^+)\Lambda$. In this instance, JLab at 12 GeV is essential for the measurements at low *t* that would allow for a clean interpretation of the kaon pole contribution.
- This data could allow for valuable comparisons between the Q^2 dependence and magnitude of the π^+ and K^+ form factors.

Jefferson Lab 12 GeV Era – Hall C Configuration



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

High Momentum Spectrometer:
dΩ ~ 6 msr, P_{max} = 7 GeV/c
Θ = 10.5 to 80 degrees

Super-HMS :
dΩ ~ 4 msr, P_{max} = 11 GeV/c
Θ = 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).

Super HMS Overview

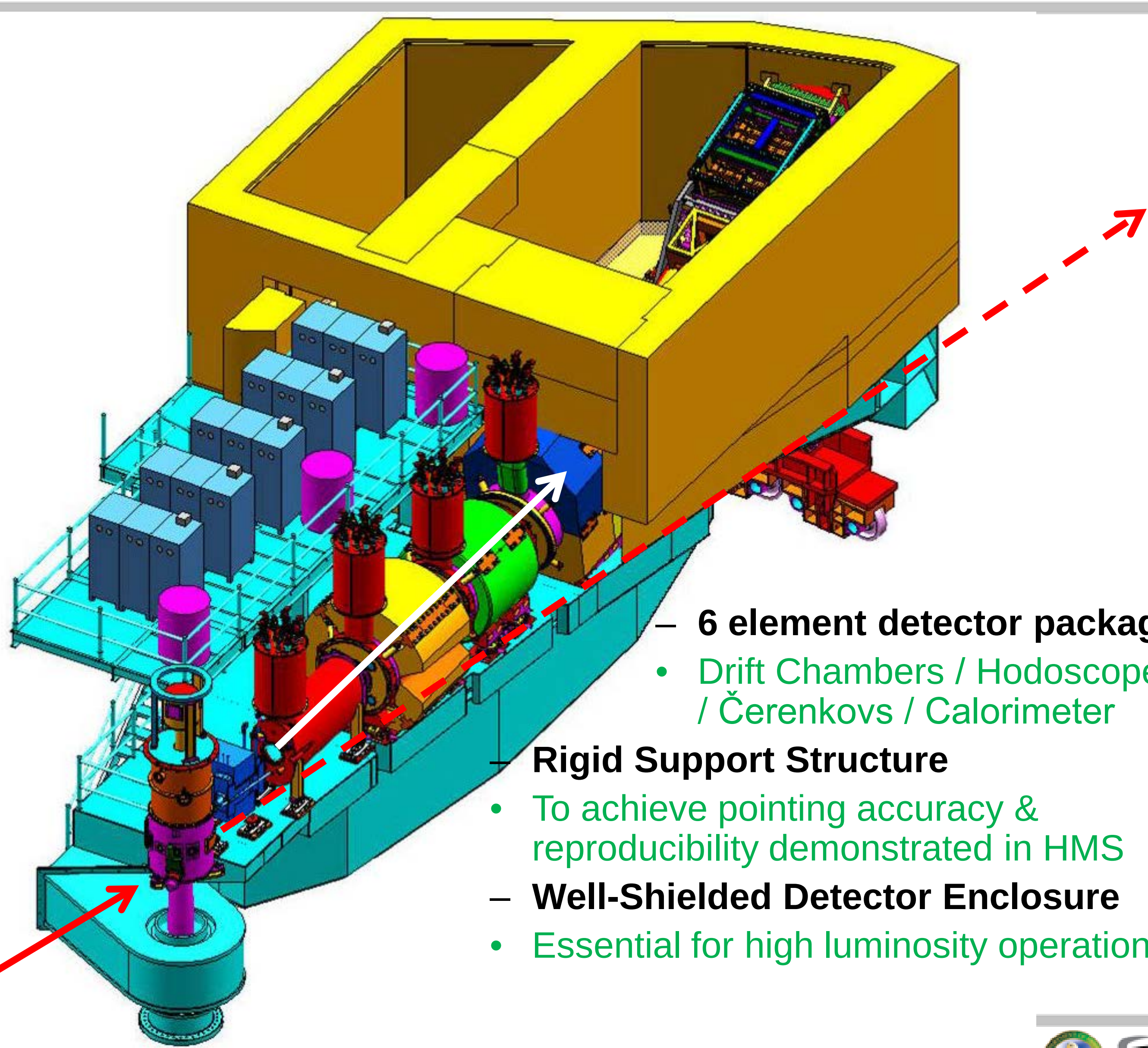
Key Features:

– **Horizontal bender magnet**

- Solution to reasonable acceptance at small angles.

– **QQQ-D**

- Provides easily calibrated optics and wide acceptance
- Uses SuperConducting magnets similar to existing HMS where possible



– **6 element detector package**

- Drift Chambers / Hodoscopes / Čerenkovs / Calorimeter

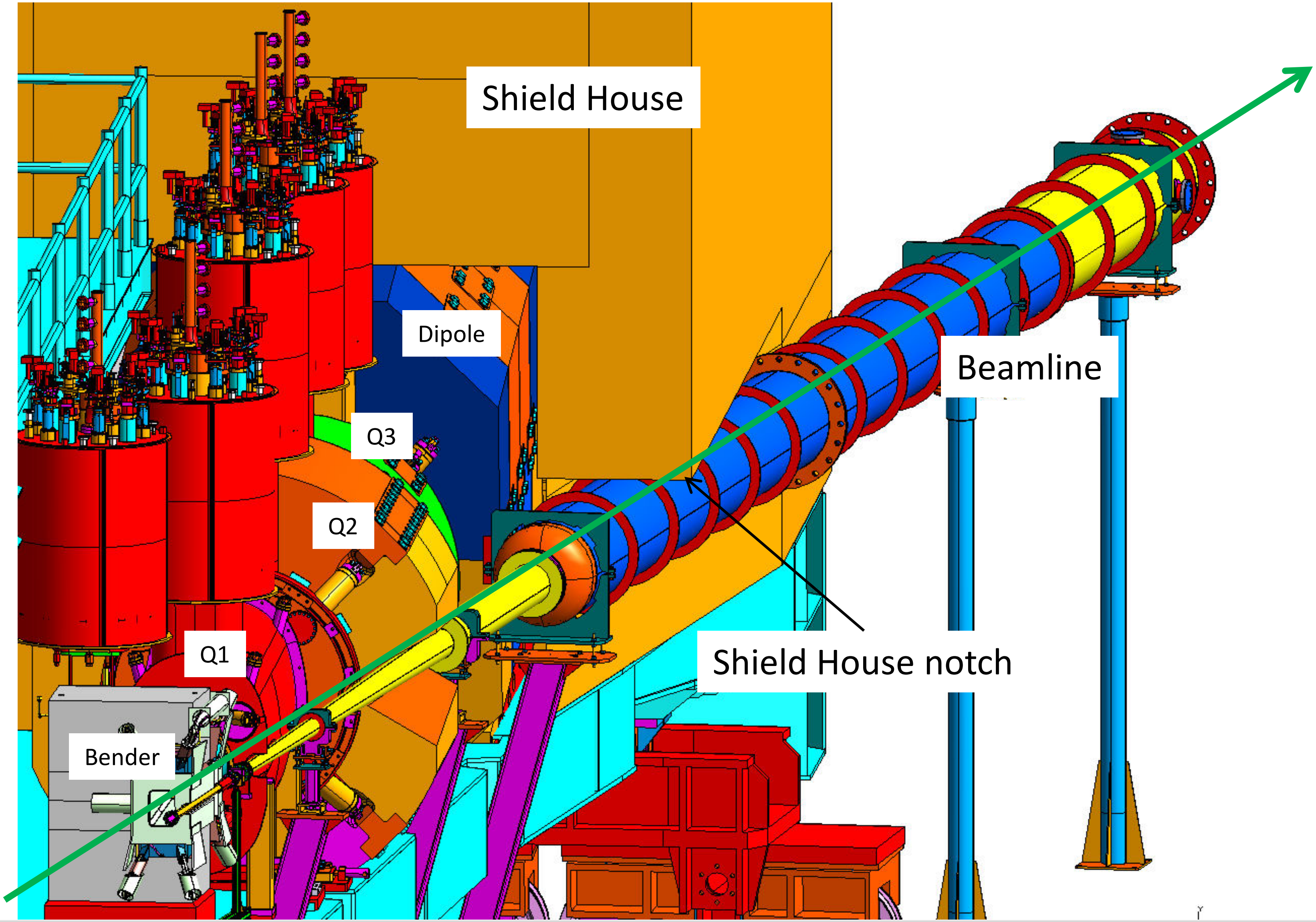
– **Rigid Support Structure**

- To achieve pointing accuracy & reproducibility demonstrated in HMS

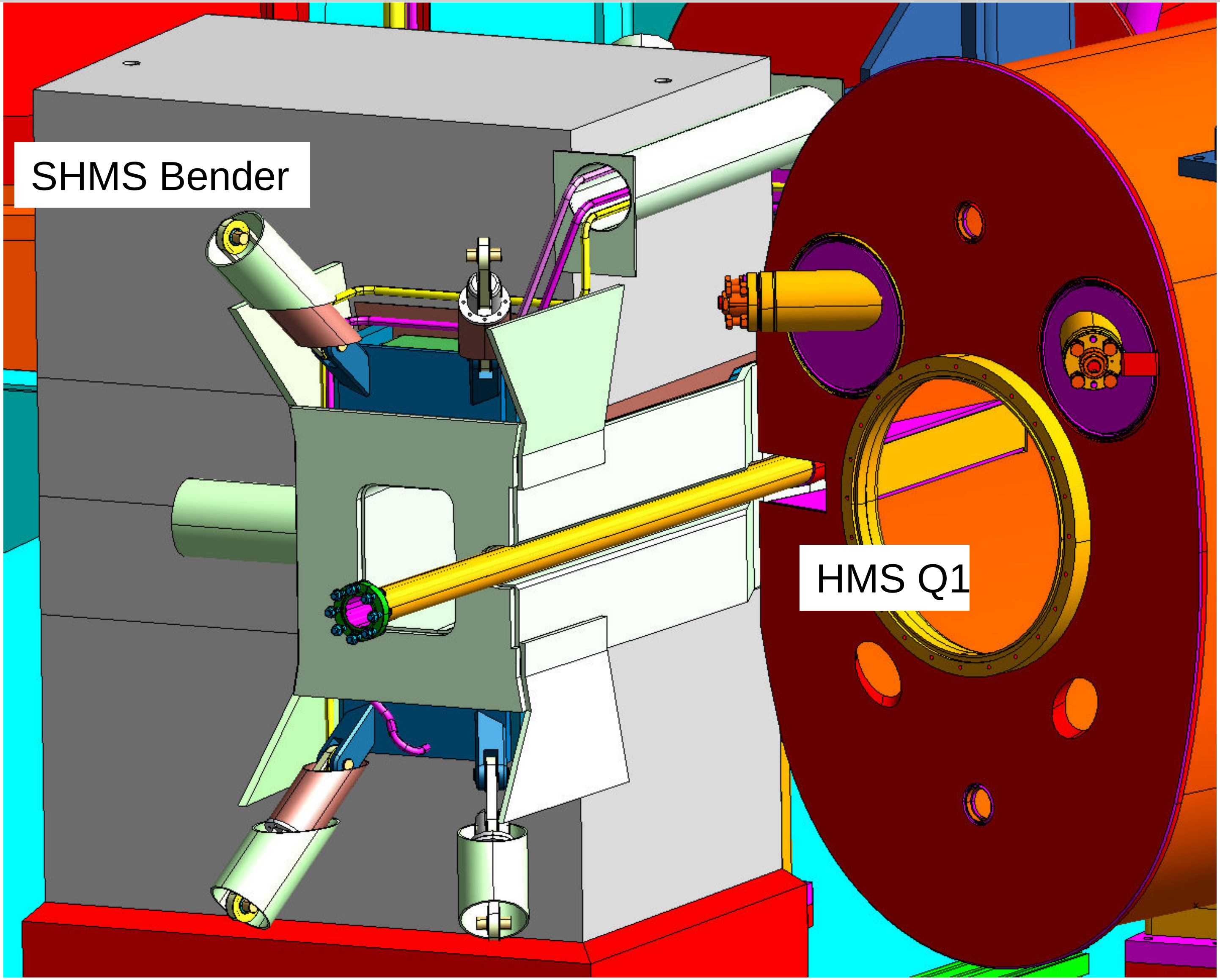
– **Well-Shielded Detector Enclosure**

- Essential for high luminosity operation

Engineering for SHMS Small Angle Operation

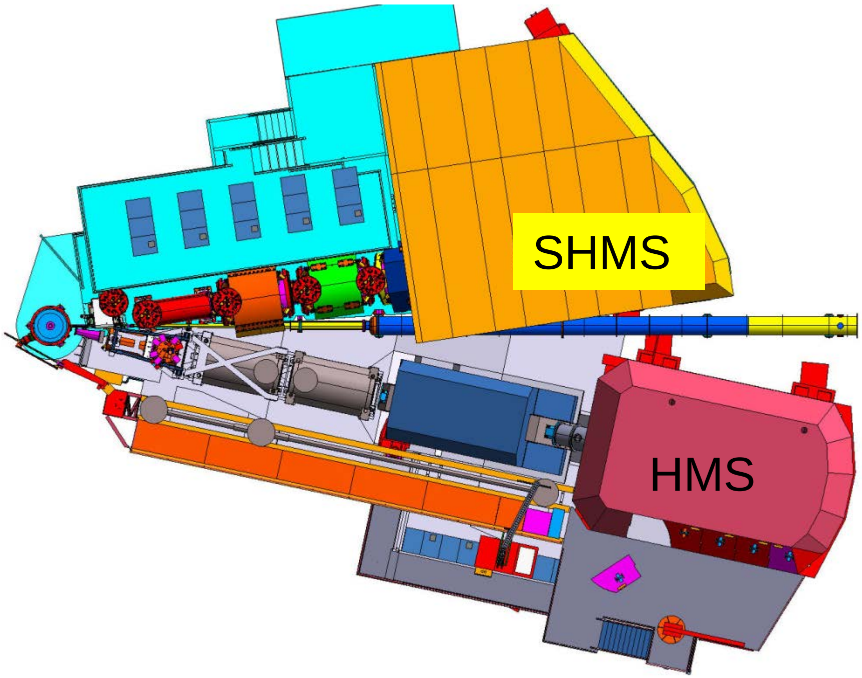


Bender Fit to HMS Q1

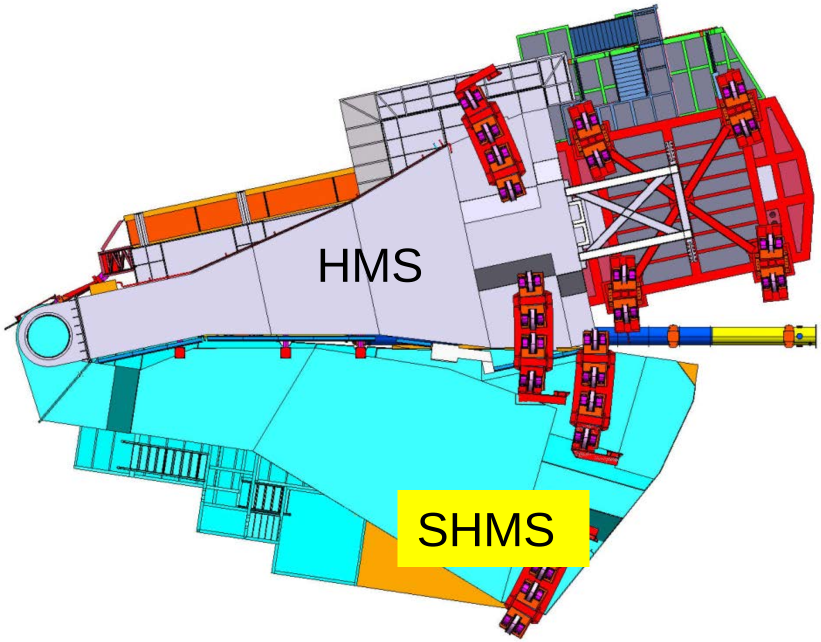


Getting Both Spectrometers to Small Angles

Top View

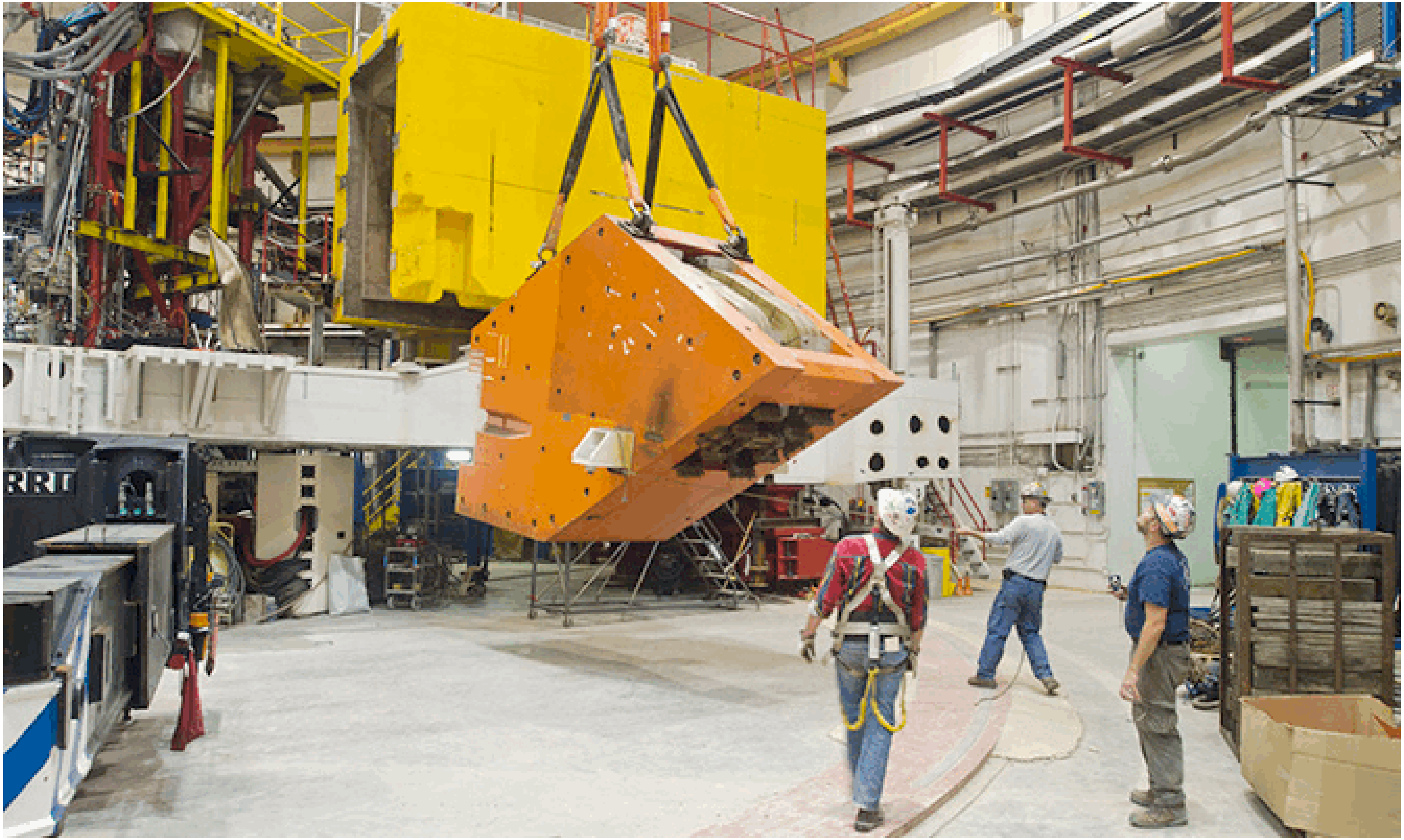


Bottom View



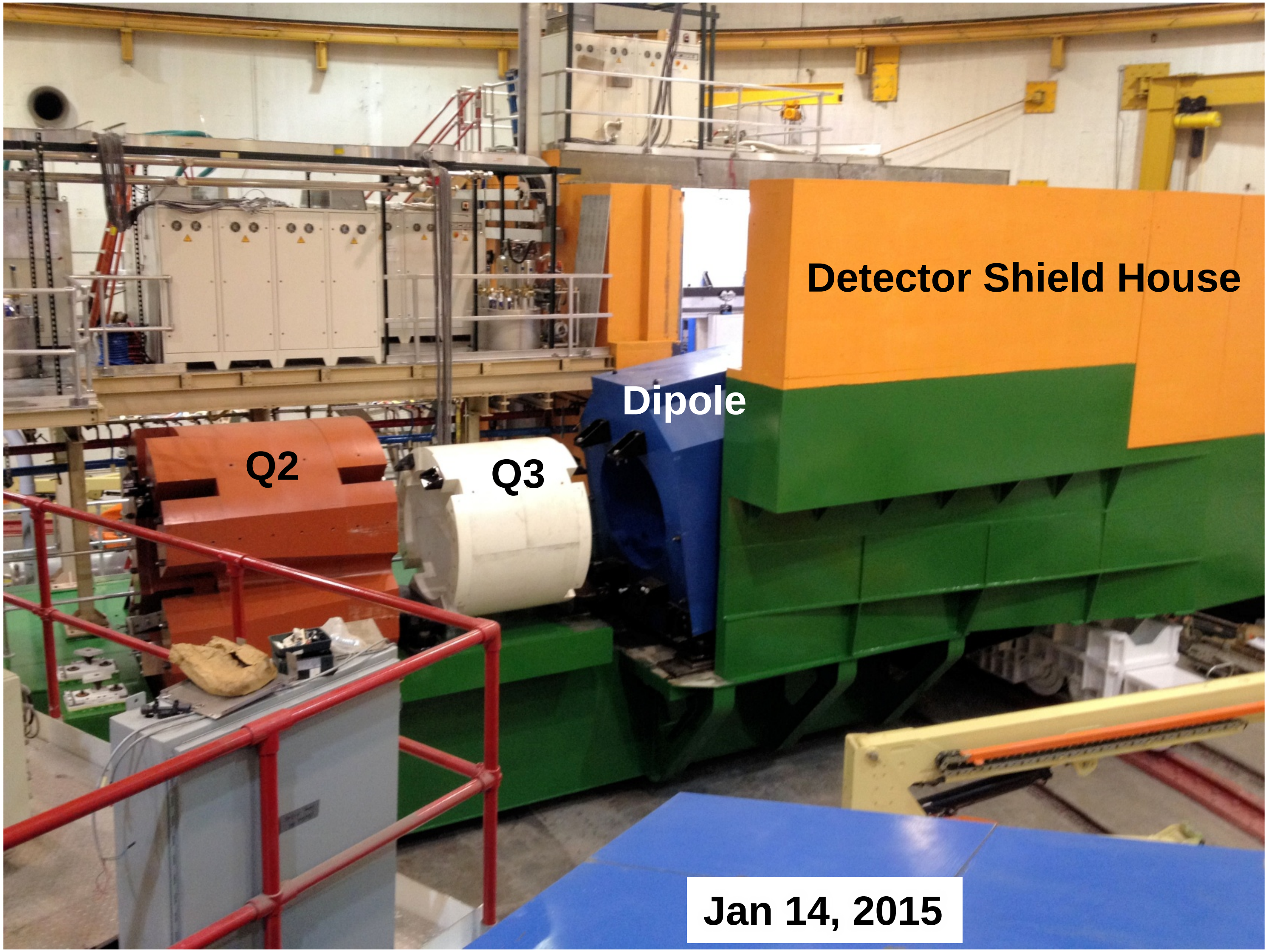
… an incredible 3-dimensional jigsaw puzzle for JLab engineers and designers

Dismantling the SOS in Early 2013



SHMS Installation Status

- SHMS Structure complete
- Services (Power, LCW, AC) installed
- signal, HV install in progress
- Magnet power supplies tested, DC cables ready for Q1 and HB
- Cryogenic system ready for Q1 and HB
- Steel for Q2, Q3, Dipole installed



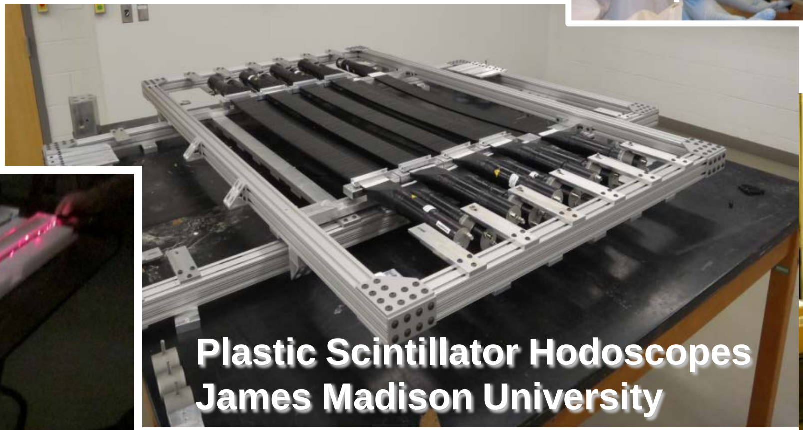
SHMS Platform & Detector House

- AC power complete
- LCW complete
- Cryogen system- complete & tested
- Magnet DC power supplies – installed & tested
- Controls & Instrumentation – complete & tested
- I&C cabling installed & tested
- Signal/HV cable pulls completed

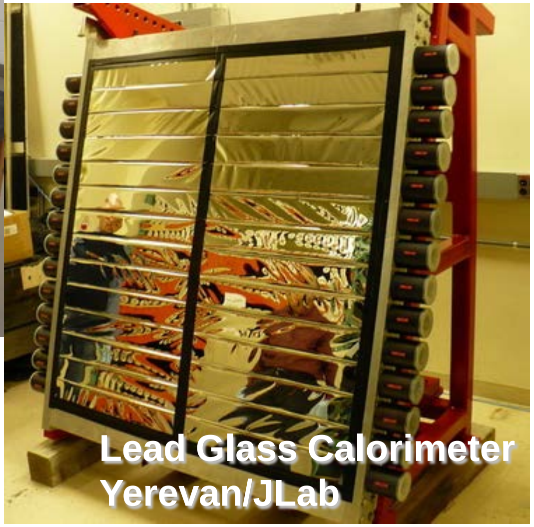
SHMS Detector Construction is Complete


Heavy Gas Čerenkov
University of Regina


Horizontal Drift Chambers
Hampton University


Plastic Scintillator Hodoscopes
James Madison University

Quartz Hodoscope
North Carolina A&T


Lead Glass Calorimeter
Yerevan/JLab

SHMS Magnet Progress

JLab Director (Hugh Montgomery), December 5, 2014:
"We expect the first Hall C magnet, Q1, to leave England by ship on December 18. The second magnet, coming from NSCL at Michigan State University, has had its vessel closed in the past week and should be here by spring 2015.


Quadrupole 1 Magnet

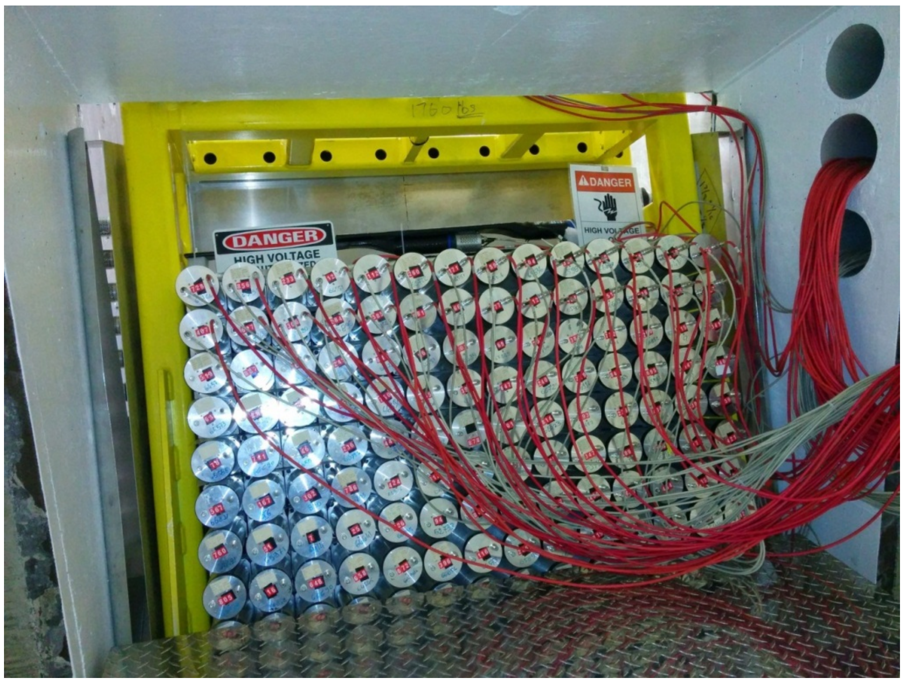
Bender Magnet

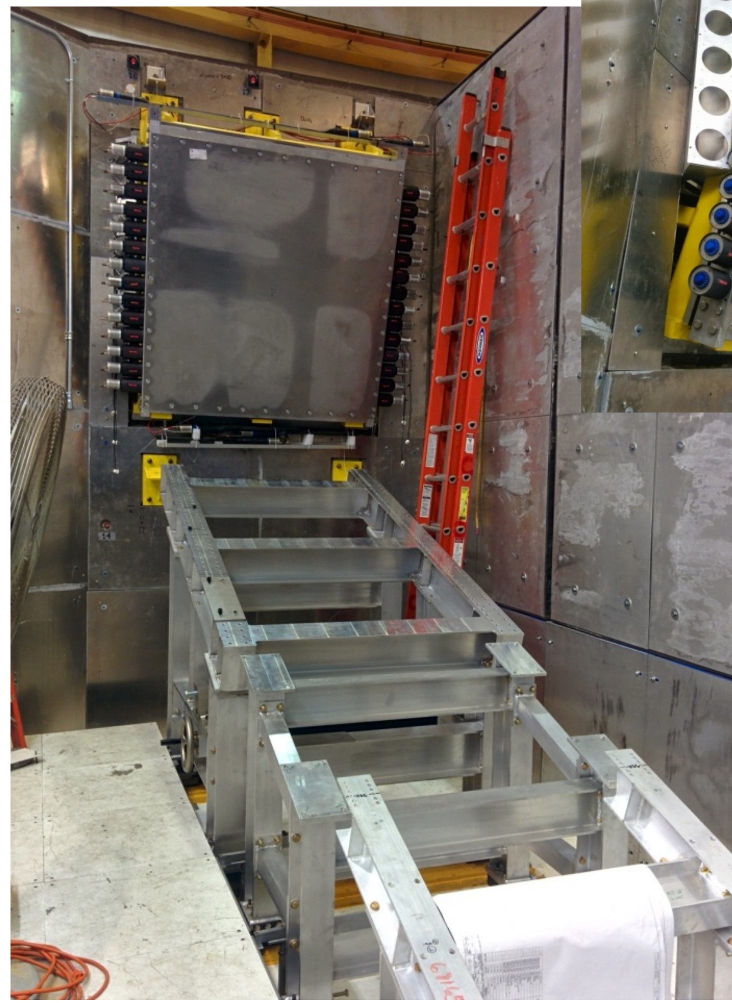
Superconducting Coil Fabrication

JLab Director (Hugh Montgomery), December 5, 2014:
“The large dipole coils being fabricated in France have completed winding and by the time you read this article, the Q2 quadrupole coil winding will also be complete. Potting of the dipole coils is in progress.”

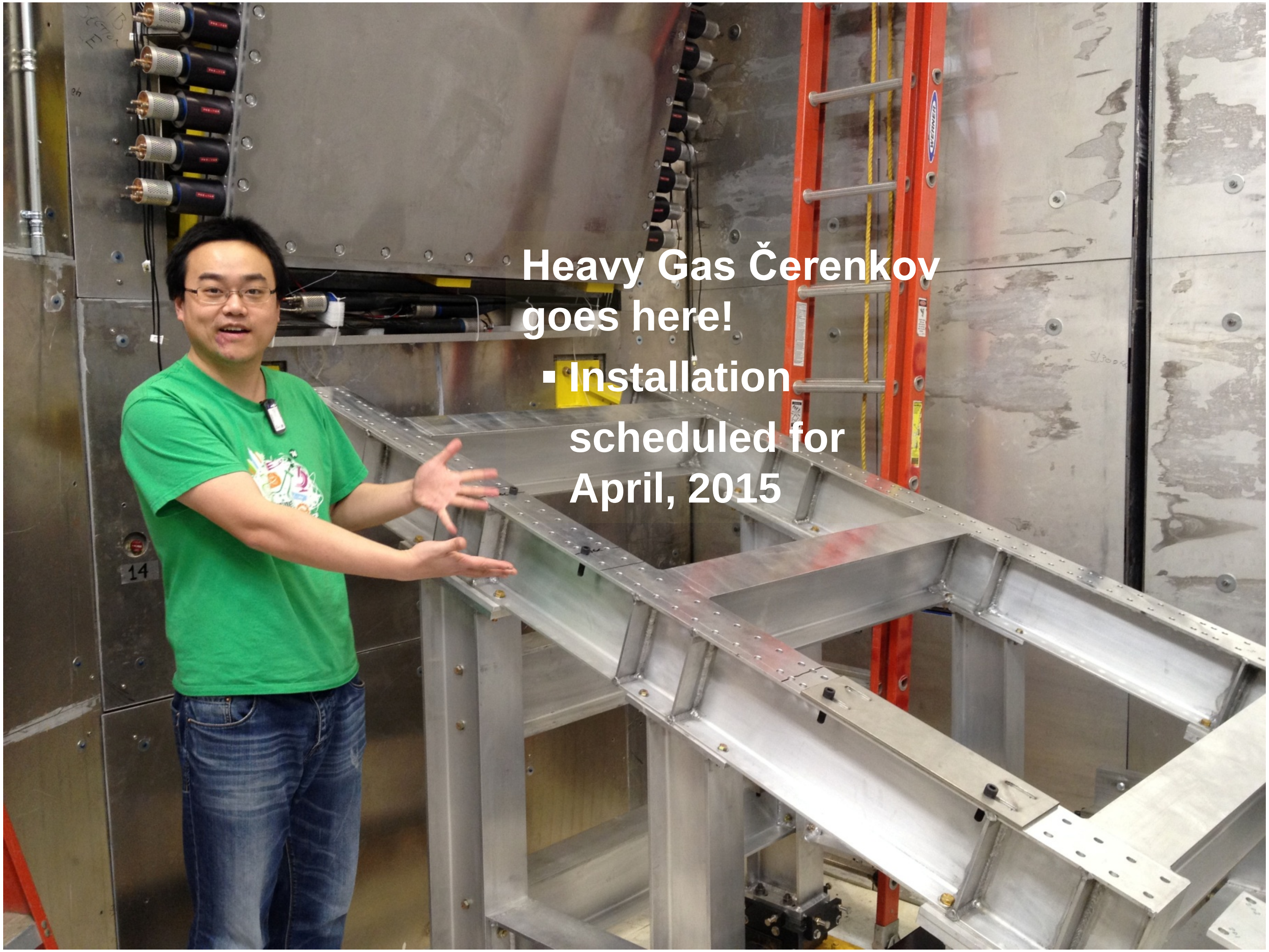
First Detectors Installed on SHMS

- SHMS Preshower and Shower Counter installed in Nov/Dec 2014
- Testing with Flash ADC DAQ





Our Detector is Next!

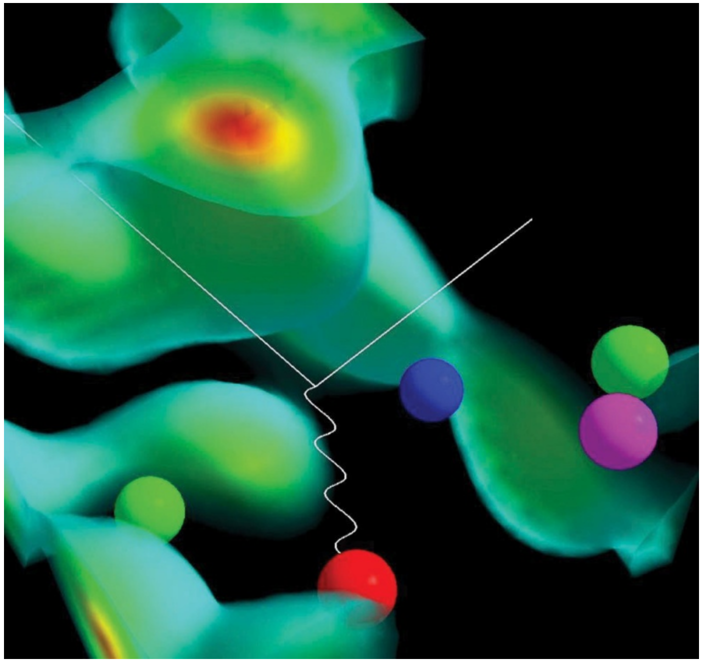


Heavy Gas Čerenkov goes here!

- Installation scheduled for April, 2015

Summary – The Big Problem

- **One of the top 10 unsolved problems in physics is our poor understanding of how quark and gluon interactions give rise to the observed properties of mesons and nucleons.**



Lattice QCD simulation of the quark and gluon "color field" inside the nucleon, being probed by a deep electron scattering.

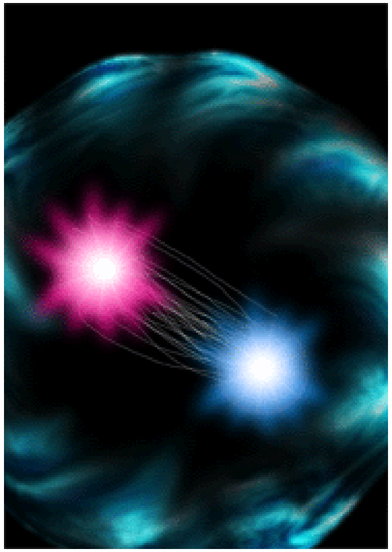
- Deep Exclusive electron scattering reactions provide a clearer picture of the inner workings of QCD (the theory of strong interactions in the Standard Model).
- This has motivated a new generation of DES experiments made possible by improvements in particle accelerator, detector, and computer technologies.

Probing the Physics of Quark Confinement

- Our measurements of the pion form factor have attracted great interest, especially at larger values of Q^2, as the pion has a unique role in our understanding of confinement.

"Another important issue in the physics of confinement is understanding the transition of the behavior of QCD from low Q^2 to high Q^2. The pion is one of the simplest QCD systems available for study, and the measurement of its elastic form factor is the best hope for seeing this transition experimentally."

- *U.S. Nuclear Science Advisory Committee (2002)*



- We also plan to perform the first systematic study of the K^+ form factor. The addition of the strange quark will provide an important comparison with the pion.

Stay tuned for many exciting results over the coming decade!