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

Garth Huber

University of Regina

On behalf of the PionLT and KaonLT Collaborations

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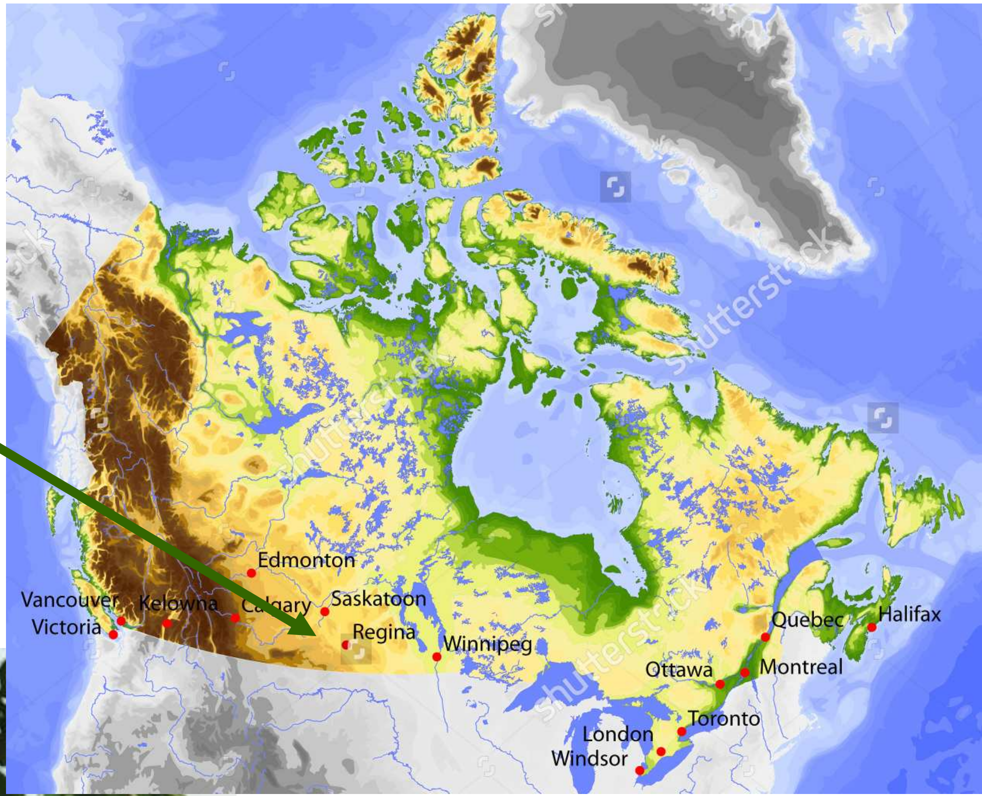
Regina, Saskatchewan CANADA



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

Population: 300,000

University of Regina

- **Founded 1974.**
- **16,650 students, incl. 2,240 Grad Students (Oct 2025).**
- **Physics Dept. offers B.Sc., M.Sc. and Ph.D. degrees.**

Quantum Electrodynamics
Quantum Chromodynamics

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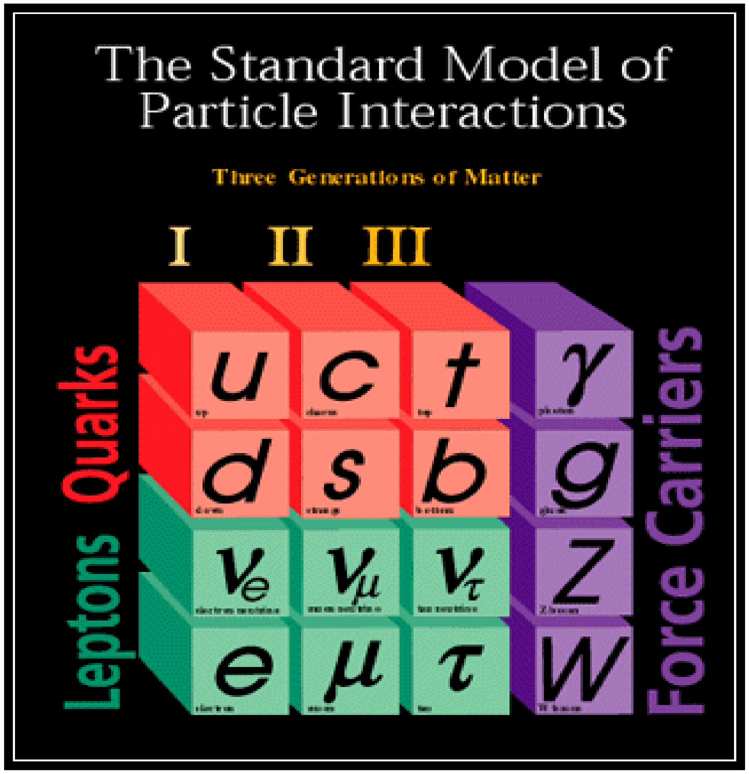
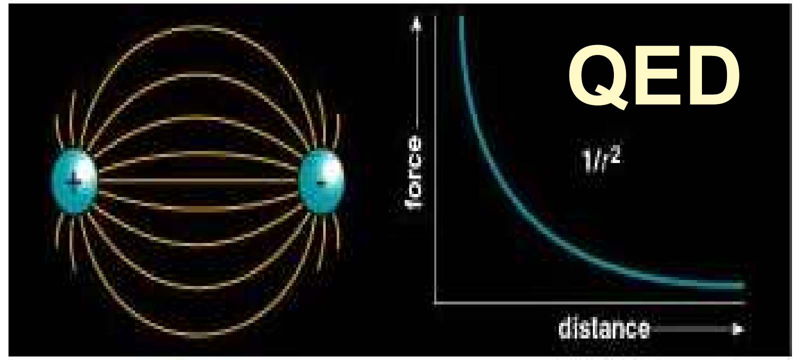
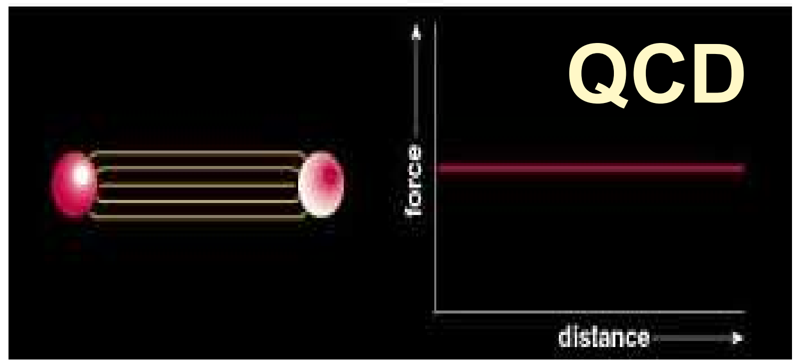
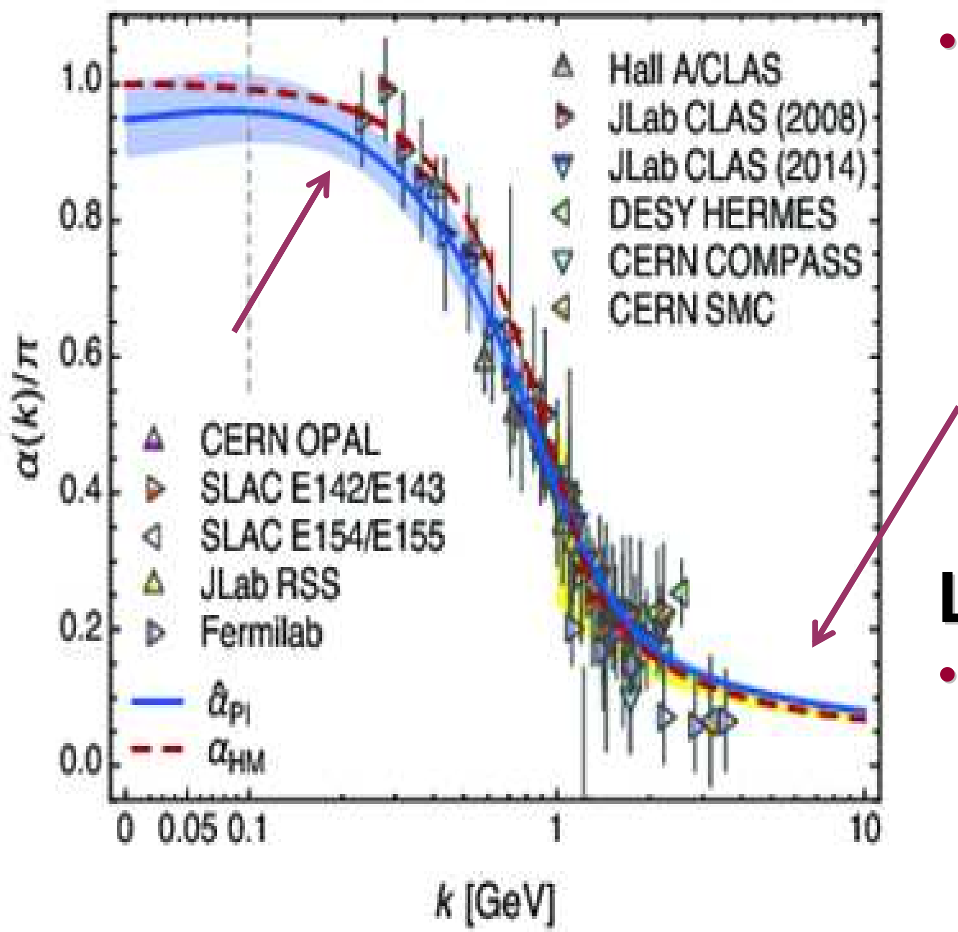






- Quarks are fractionally charged and interact via the electromagnetic (QED) and strong (QCD) interactions.
- Unlike the photons of QED, the gluons of QCD carry color charge and interact strongly, leading to the confinement of quarks inside hadrons.

QCD's Dual Nature



Binosi, Mezrag, Papavassiliou, C.D. Roberts, Rodriguez-Quintero, PRD 96 (2017) 054026. arXiv:1612.04835

Short Distance Interaction:

- Short distance quark-quark interaction is feeble.
  - Quarks inside protons behave as if they are nearly unbound, pQCD.
  - Asymptotic Freedom.
  - Nobel prize: Friedman, Kendall and Taylor, 1990.

Long Distance Interaction:

- Quarks strongly bound within hadrons.
  - Color confinement (strong QCD).
  - Quantitative QCD description of nucleon's properties (i.e. understanding of the confinement regime) remains a puzzle!

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The Fundamental Issue

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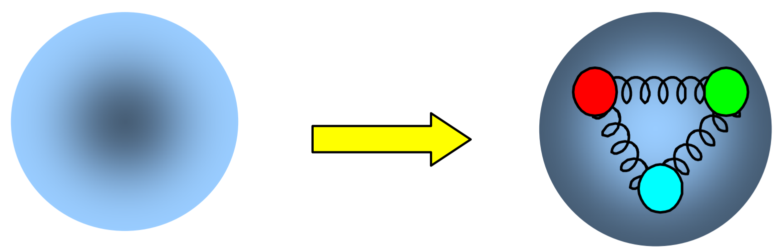
Quantum Chromodynamics (QCD) in the confinement regime: How does it work?

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

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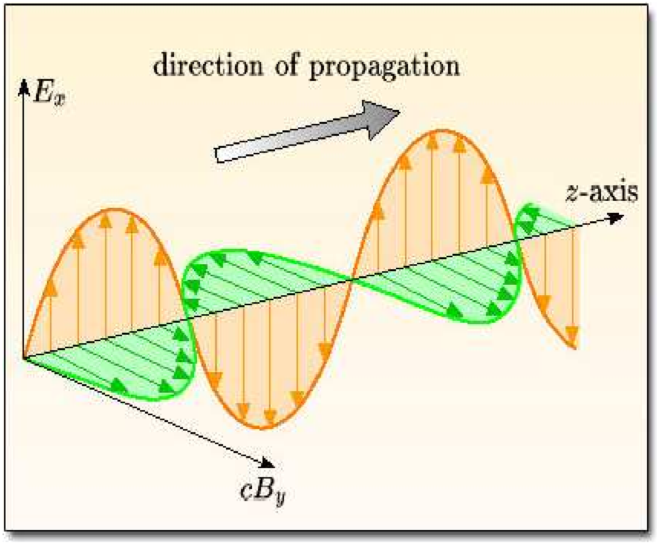
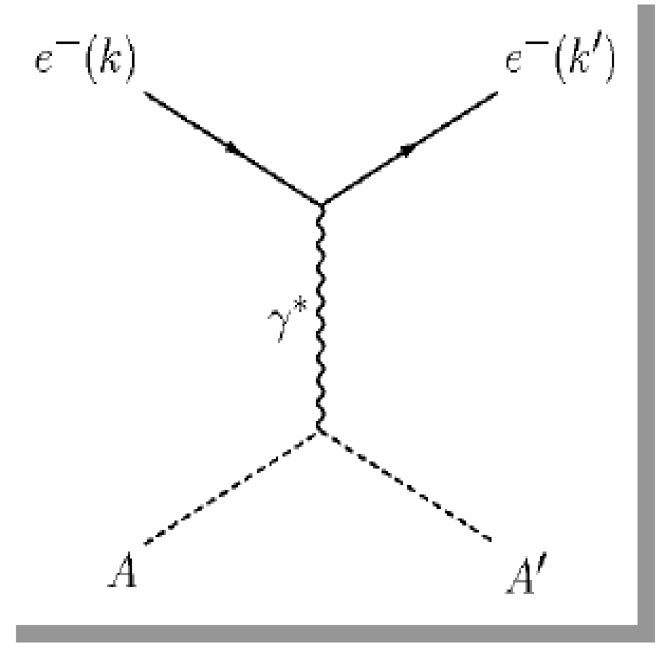
Real Photons (γ):



- *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*

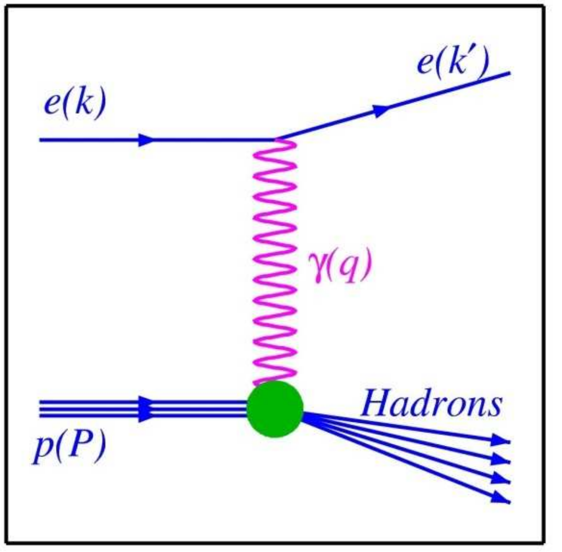
$$\text{Virtual Photon Energy} = E - E'$$
$$\text{Virtual Photon Momentum} = \vec{k} - \vec{k}'$$

(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.**

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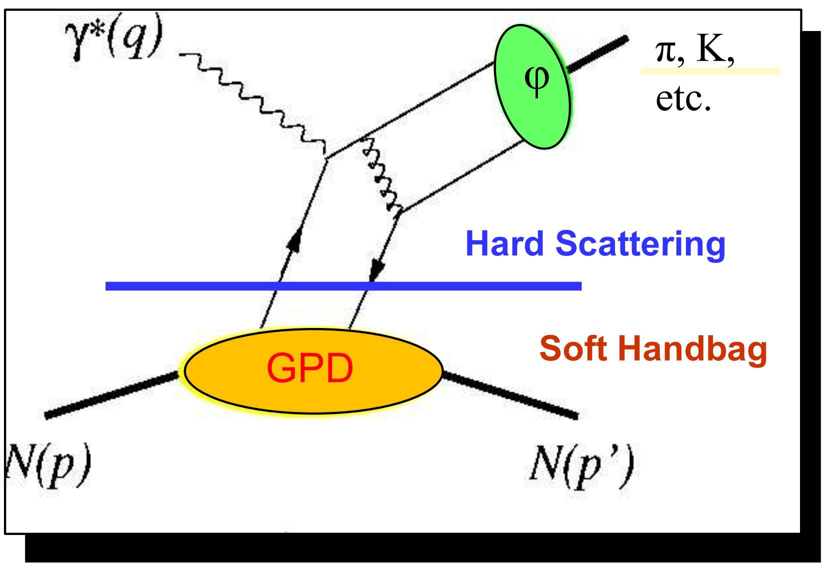
Deep Exclusive Meson Production (DEMP)

- 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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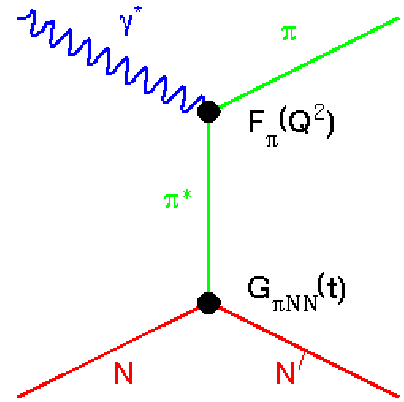
Two Motivations for Studying DEMP

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



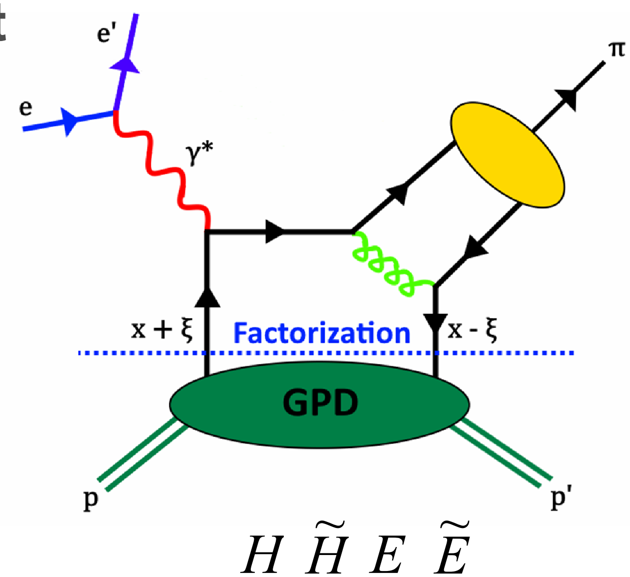
- Indirectly measure F_π using the "pion cloud" of the proton via p(e,e'π$^+$)n

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

  - Pion pole process dominates σ_L in forward kinematics.
  - Can a similar method be used to determine the kaon form factor?

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 p(e,e'π$^+$)n and p(e,e'K$^+$)Λ cross sections at fixed *x* behave according to the Q^{-n} scaling expectations of hard QCD.
- Form $\frac{\sigma_T[n(e,e'\pi^-)p]}{\sigma_T[p(e,e'\pi^+)n]}$ ratios where soft contributions may cancel, yielding insight to factorization at modest Q^2.

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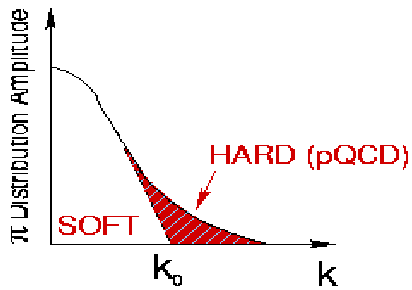
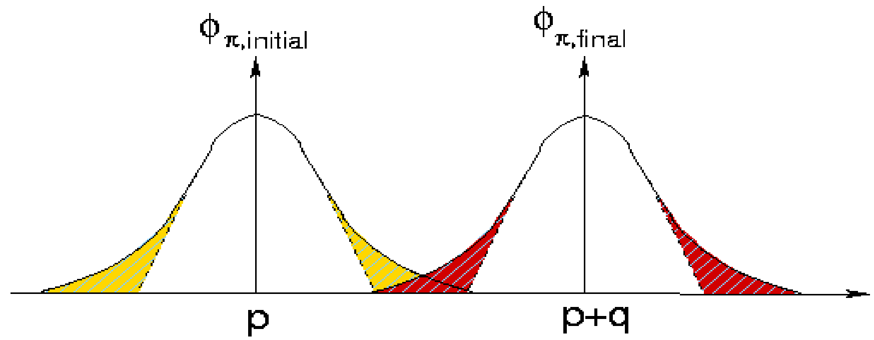
Charged Meson Form Factors

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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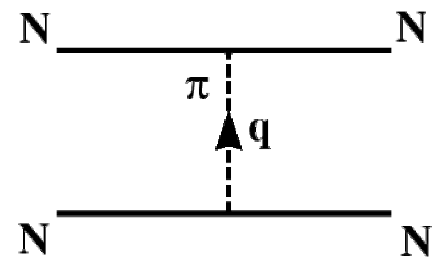
The Pion has Particular Importance

- The pion is responsible for the long-range part of the nuclear force, acting as the basis for meson exchange forces, and playing a critical role as an elementary field in nuclear structure Hamiltonians.



- As the lightest meson, it must be a valence $q\bar{q}$ bound state, but understanding its structure through QCD has been exceptionally challenging.
  - e.g. Constitutent Quark Models that describe a nucleon with m_N=940 MeV as a qqq bound state, are able to describe the ρ-meson under similar assumptions, yielding a constituent quark mass of about

$$m_Q \approx \frac{m_N}{3} \approx \frac{m_\rho}{2} \approx 350 \text{ MeV}$$

- The pion mass $m_\pi \approx 140$ MeV seems "too light".

- **We exist because nature has supplied two light quarks and these quarks combine to form the pion, which is unnaturally light and hence very easily produced.**

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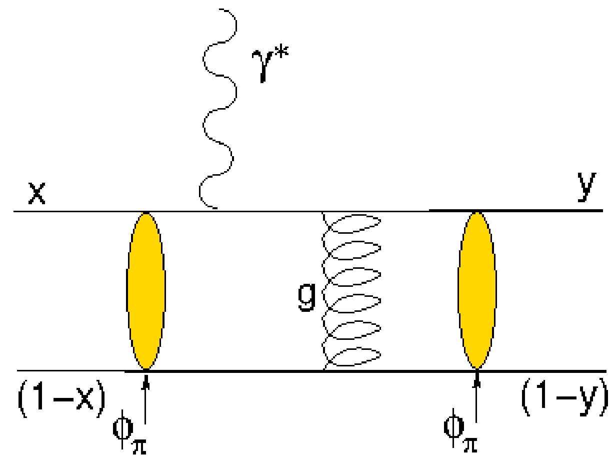
The Pion in perturbative QCD

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

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

at asymptotically high Q^2, the pion distribution amplitude becomes

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



and F_π takes the very simple form

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

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

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

This only relies on asymptotic freedom in QCD, *i.e.* $(\partial\alpha_S/\partial\mu)<0$ as $\mu\to\infty$.

***$Q^2 F_\pi$* should behave like *$\alpha_s(Q^2)$* even for moderately large *Q^2*.**

→ Pion form factor seems to be best tool for experimental study of nature of the quark-gluon coupling constant renormalization.

[A.V. Radyushkin, JINR 1977, arXiv:hep–ph/0410276]

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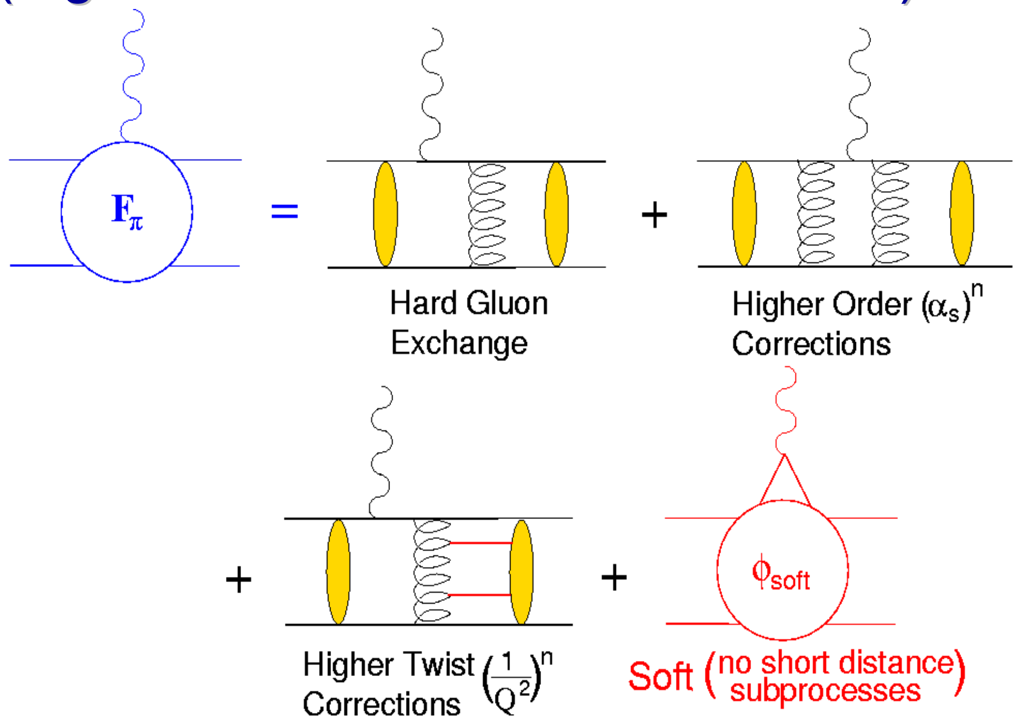
Pion Form Factor at Intermediate Q^2

At experimentally–accessible Q^2, both the "hard" and "soft" components (e.g. transverse momentum effects) contribute.



- **The interplay of hard and soft contributions is poorly understood.**

  → Different theoretical viewpoints on whether higher–twist mechanisms dominate until very large momentum transfer or not.

- **The pion elastic and transition form factors experimentally accessible over a wide kinematic range.**

  → A laboratory to study the **transition** from the soft to hard regime.

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The Charged Kaon – a 2nd QCD test case

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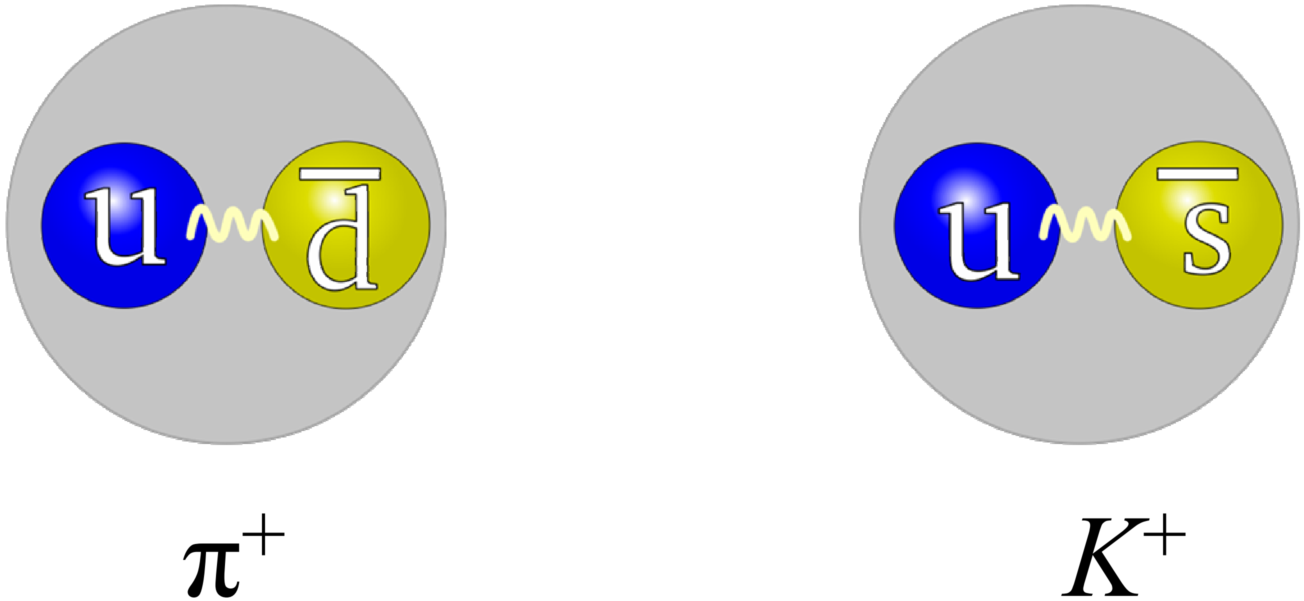

- In the hard scattering limit, pQCD predicts that the π^+ and K^+ form factors will behave similarly

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

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

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

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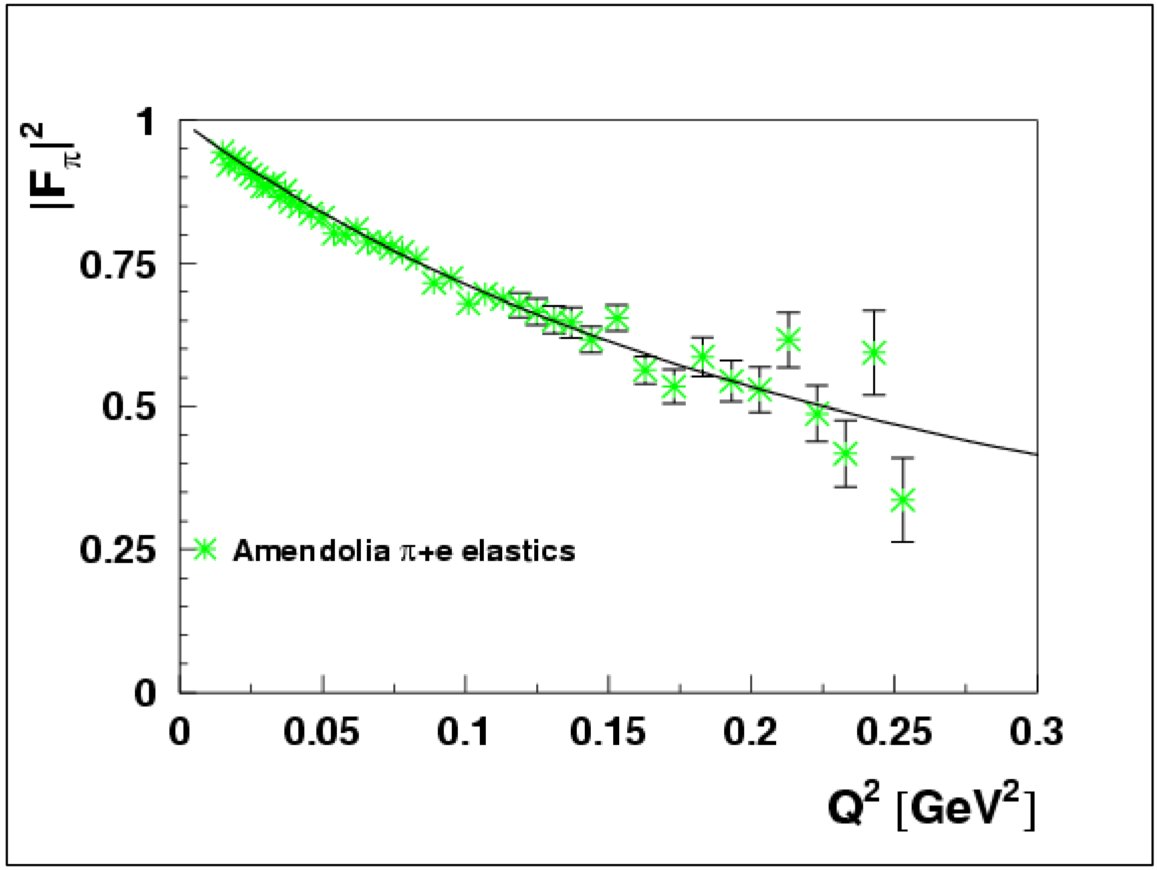
At low Q^2, F_π can be measured <u>model-independently</u> via high energy elastic π^- scattering from atomic electrons in Hydrogen

- CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2 *[Amendolia, et al., NP **B277** (1986) 168]*

- 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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Timelike vs Spacelike Pion Form Factors

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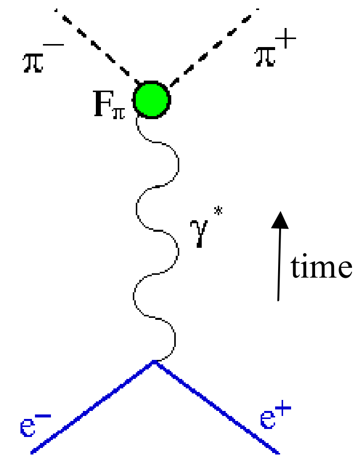
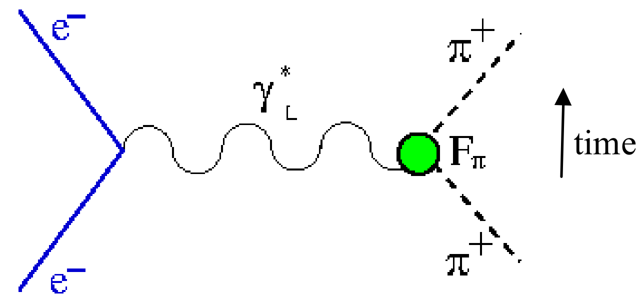
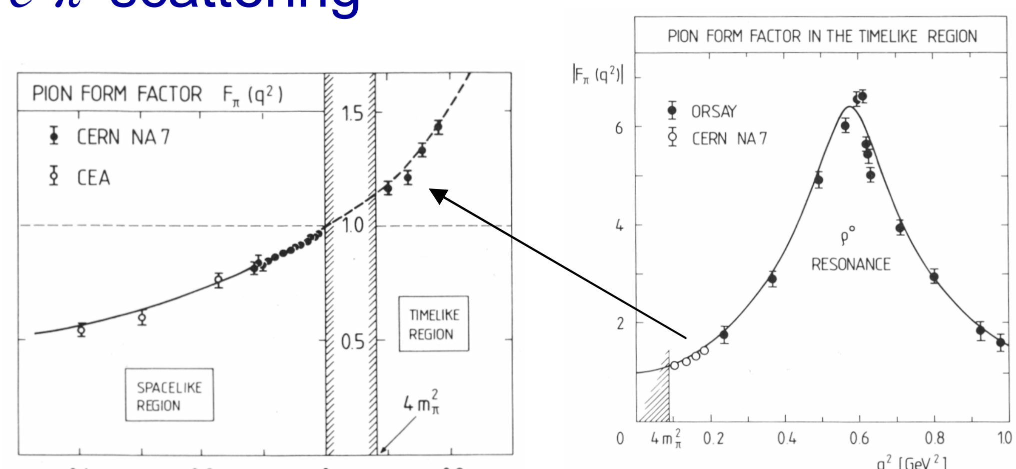
- **Timelike Region:**
  - Accessed in e^+e^- collisions
  - Virtual γ^* Energy>Momentum
  - $q^2 = E^2 - p^2 > 0$
  - $F_\pi(q^2>0)$ measured via $e^+e^- \rightarrow \pi^+\pi^-$ reaction



- **Spacelike Region:**
  - Accessed in e^- scattering
  - Virtual γ^* Momentum>Energy
  - $q^2 = E^2 - p^2 < 0$ *For convenience:* $Q^2 = -q^2$
  - $F_\pi(Q^2>0)$ measured via $e^-\pi^+ \rightarrow e^-\pi^+$ scattering



- **Pion Form Factor is analytically continuous between the Timelike and Spacelike regions**



Pions and Nuclei, Ericson & Weise

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

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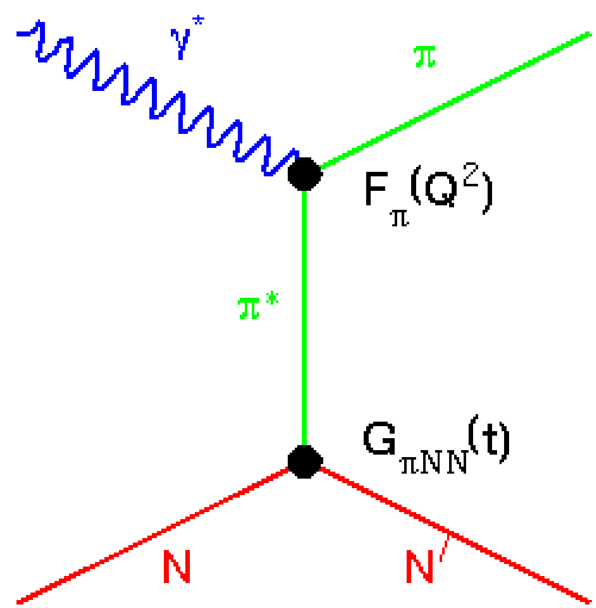
At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

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

- 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.

***K^+* pole is further in the unphysical region, uncertainties will be larger**

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Chew–Low Method to determine Pion Form Factor

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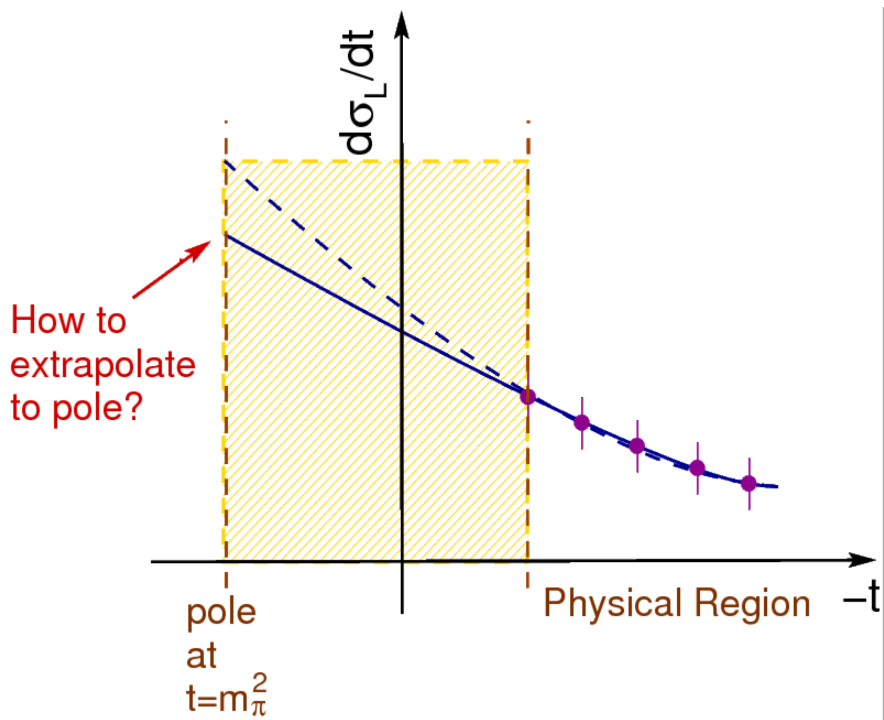
***p(e,e'π^+)n* data are obtained some distance from the *t*=m_π^2 pole.**

→ "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 Devenish & 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_π^2



The Chew–Low Method was subsequently abandoned

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

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- JLab F_π experiments have used 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.**
- Some recent model developments, more are welcome!
  - *R.J. Perry, A. Kizilersu, A.W. Thomas, PLB **807**(2020)135581*
  - *T.K. Choi, K.J. Kong, B.G. Yu, J.Kor.Phy.Soc. **67**(2015) L1089; arXiv: 1508.00969*
  - *T. Vrancx, J. Ryckebusch, PRC **89**(2014)025203*
  - *M.M. Kaskulov, U. Mosel, PRD **81**(2010)045202.*

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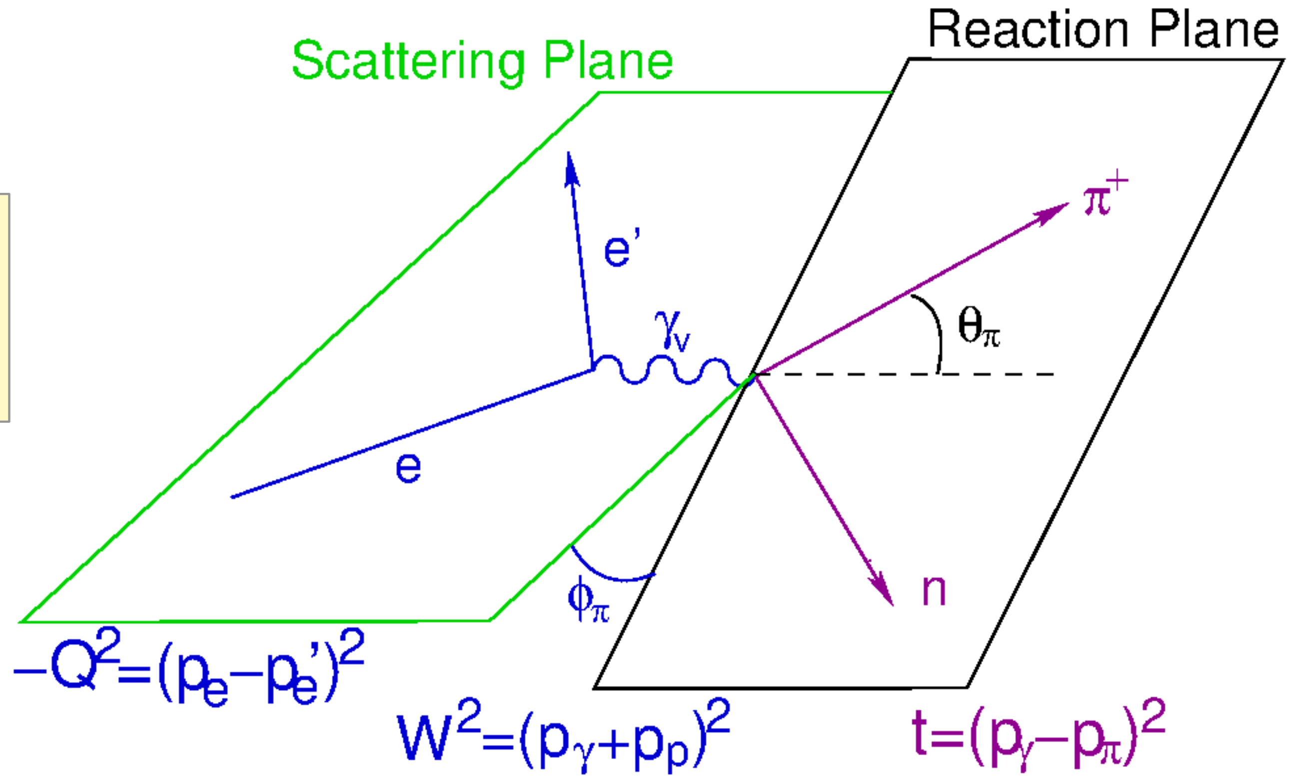
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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**
- **Need to measure t–dependence of σ_L at fixed Q^2,W**

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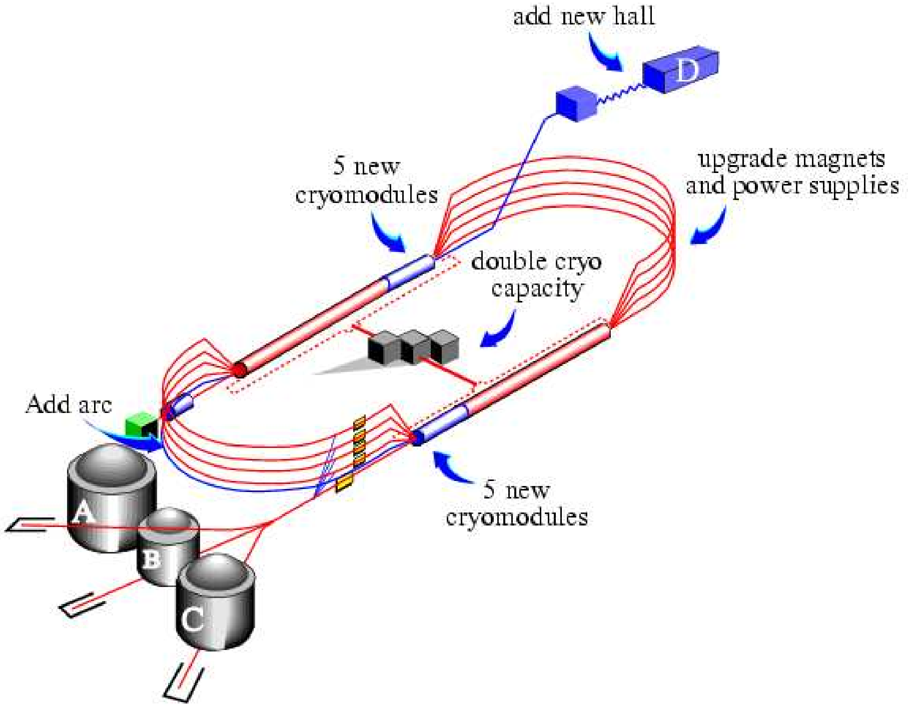
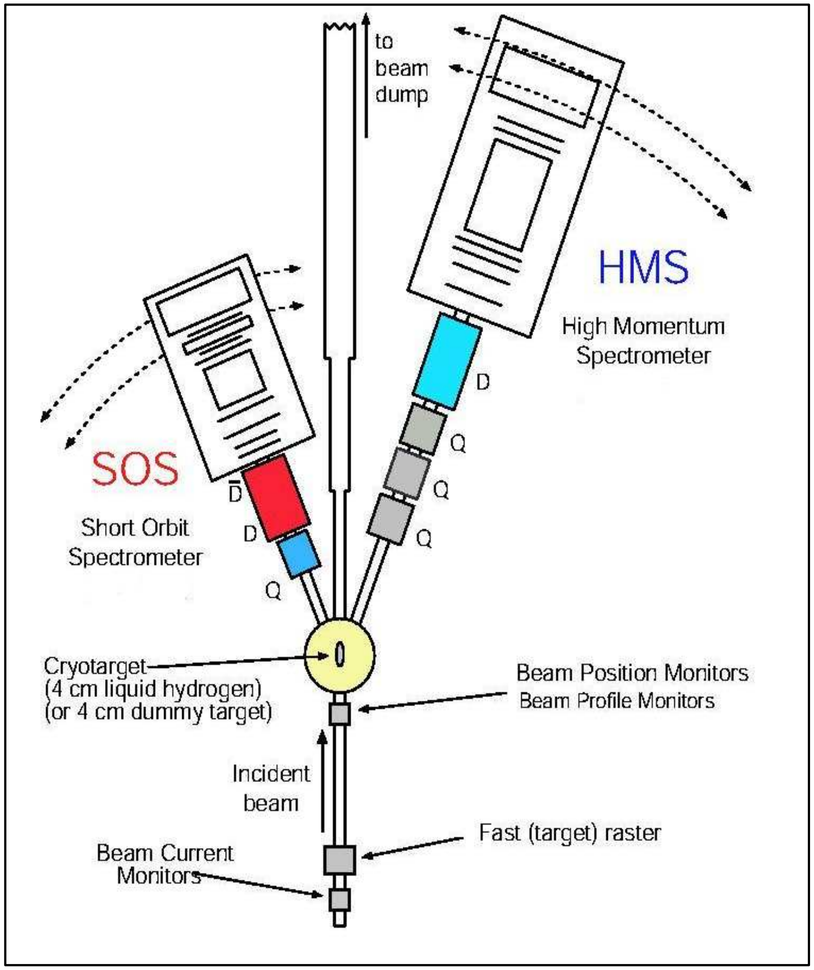
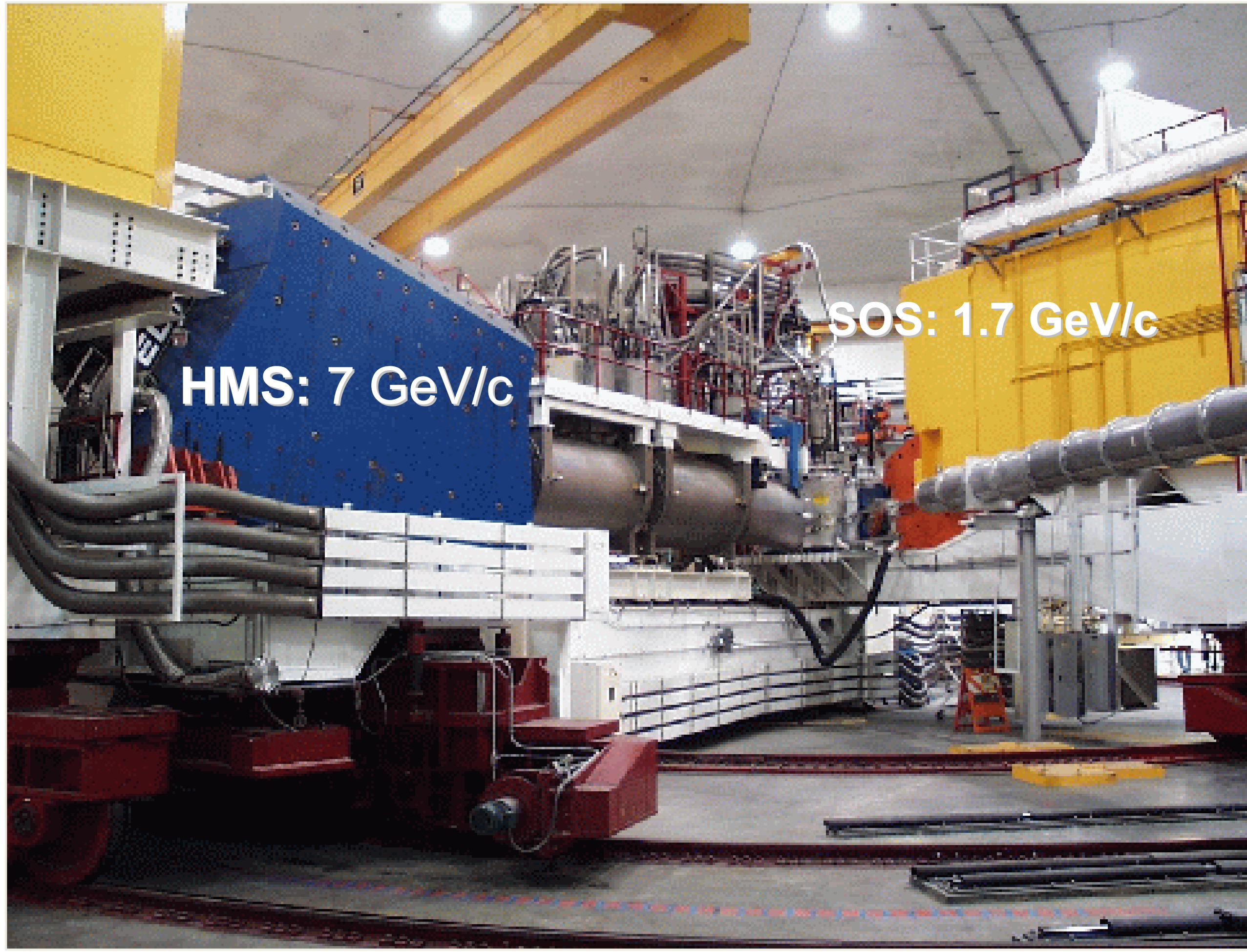


Two 1.5 GHz Superconducting Linear Accelerators provide electron beam for Nucleon & Nuclear structure studies.

- **Beam energy E → 12 GeV.**
- **Beam current >100 μA.**
- **Duty factor 100%, 85% polarization.**
- Experiments in all 4 Halls can receive beam simultaneously.

F_π Program at JLab Hall C – 6 GeV Era





- 2 F_π experiments have been carried out at JLab so far:
  (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.

The role of Soft and Hard QCD in F_π

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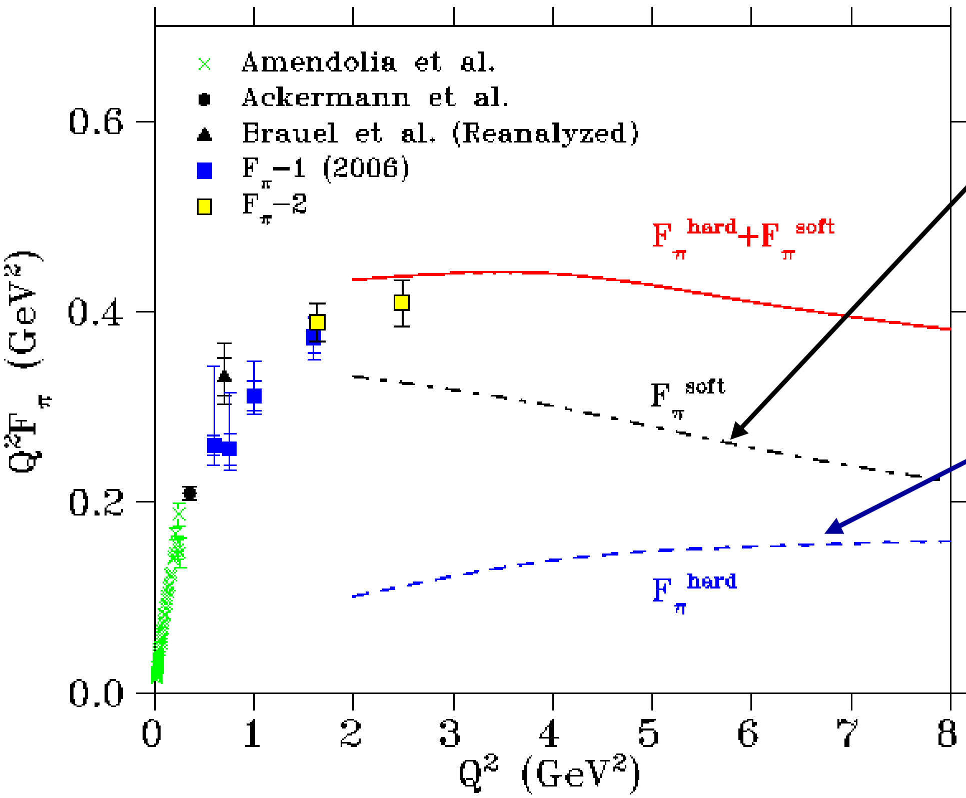
pQCD LO+NLO Calculation:

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.

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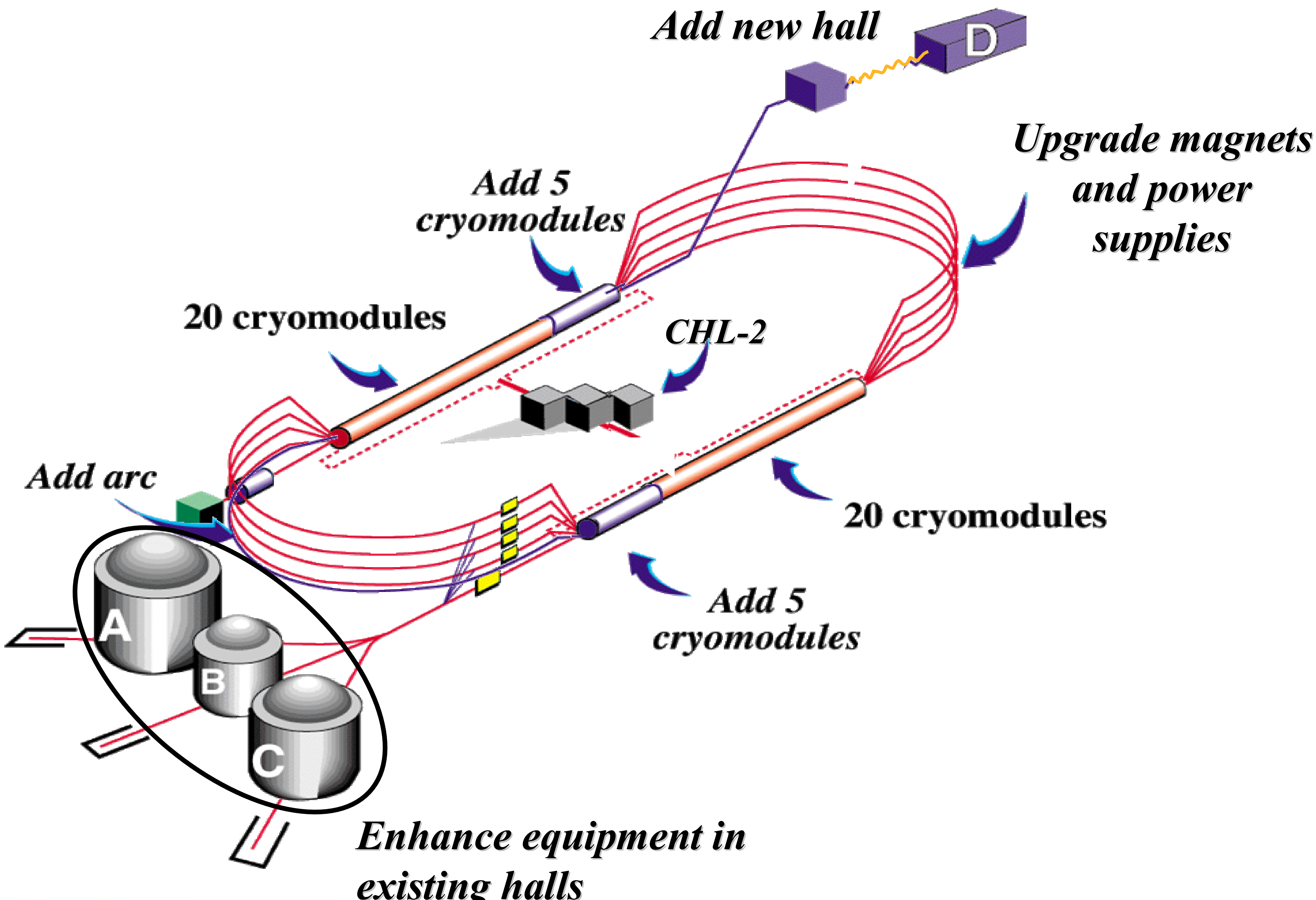
Jefferson Lab – 12 GeV Upgrade



JLab Hall C – 12 GeV Upgrade

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

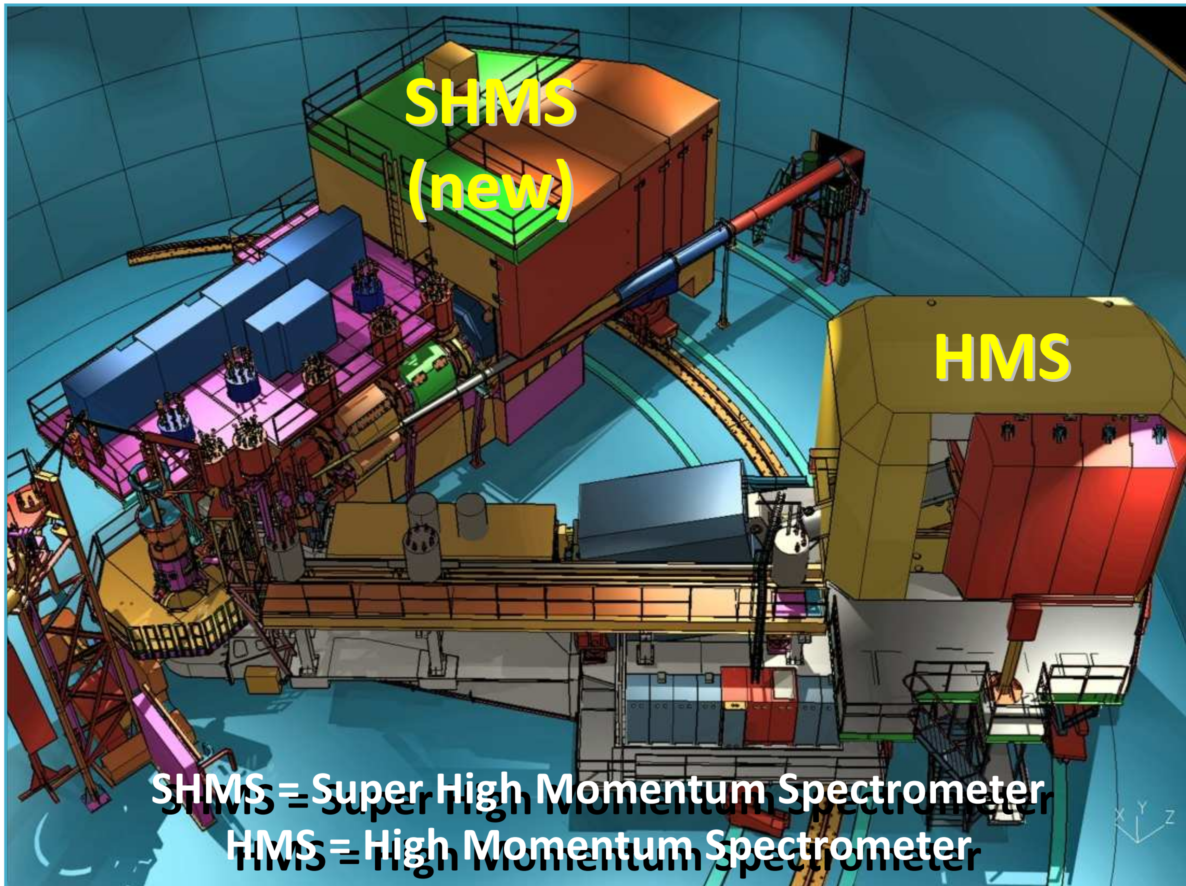
MAGNETIC OPTICS:
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

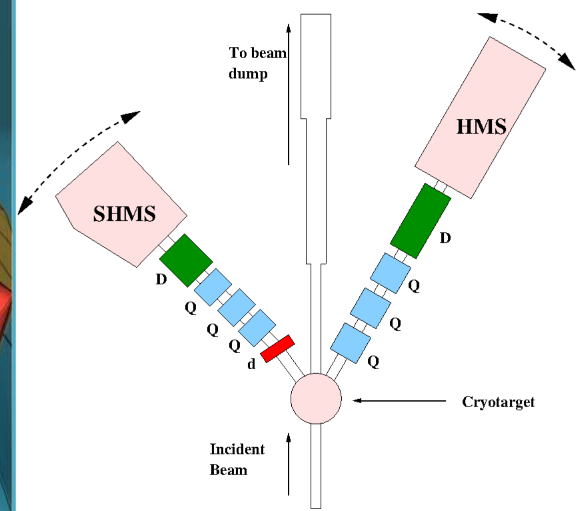
Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter

Well-Shielded Detector Enclosure

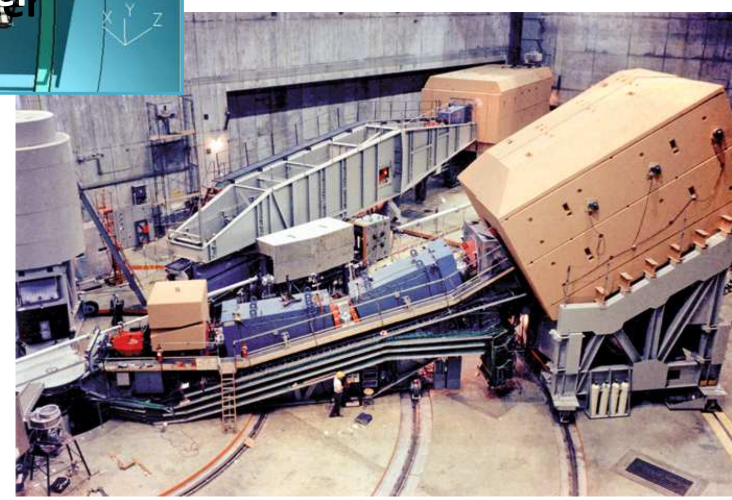
Rigid Support Structure
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS

Luminosity
- ~4x10^{38} cm^{-2} s^{-1}



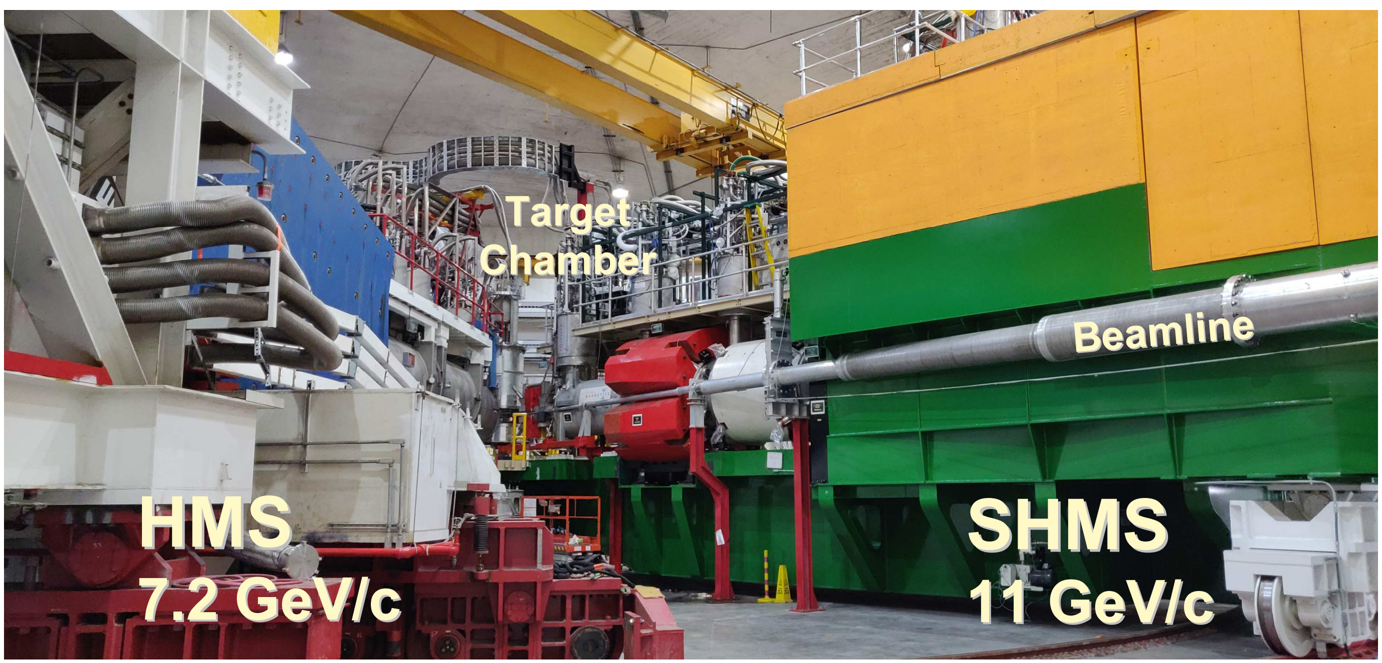


Upgraded Hall C has some similarity to SLAC End Station A, where the quark substructure of proton was discovered in 1968.



Hall C in 12 GeV Era

- Deep Exclusive Meson Production (DEMP) cross section is small, can exclusive *p(e,e'π^+)n* and *p(e,e'K$^+$)Λ* channels be cleanly identified?
  - High momentum, forward angle (5.5^o) meson detection is required, with good Particle ID to separate π^+, K^+, p
  - Good momentum resolution required to reconstruct crucial kinematics, such as M_{miss}, Q^2, W, t
- Need to measure the longitudinal cross section $d\sigma_L/dt$ needed for form factor extraction



Hall C of Jefferson Lab has been optimized for specifically such studies

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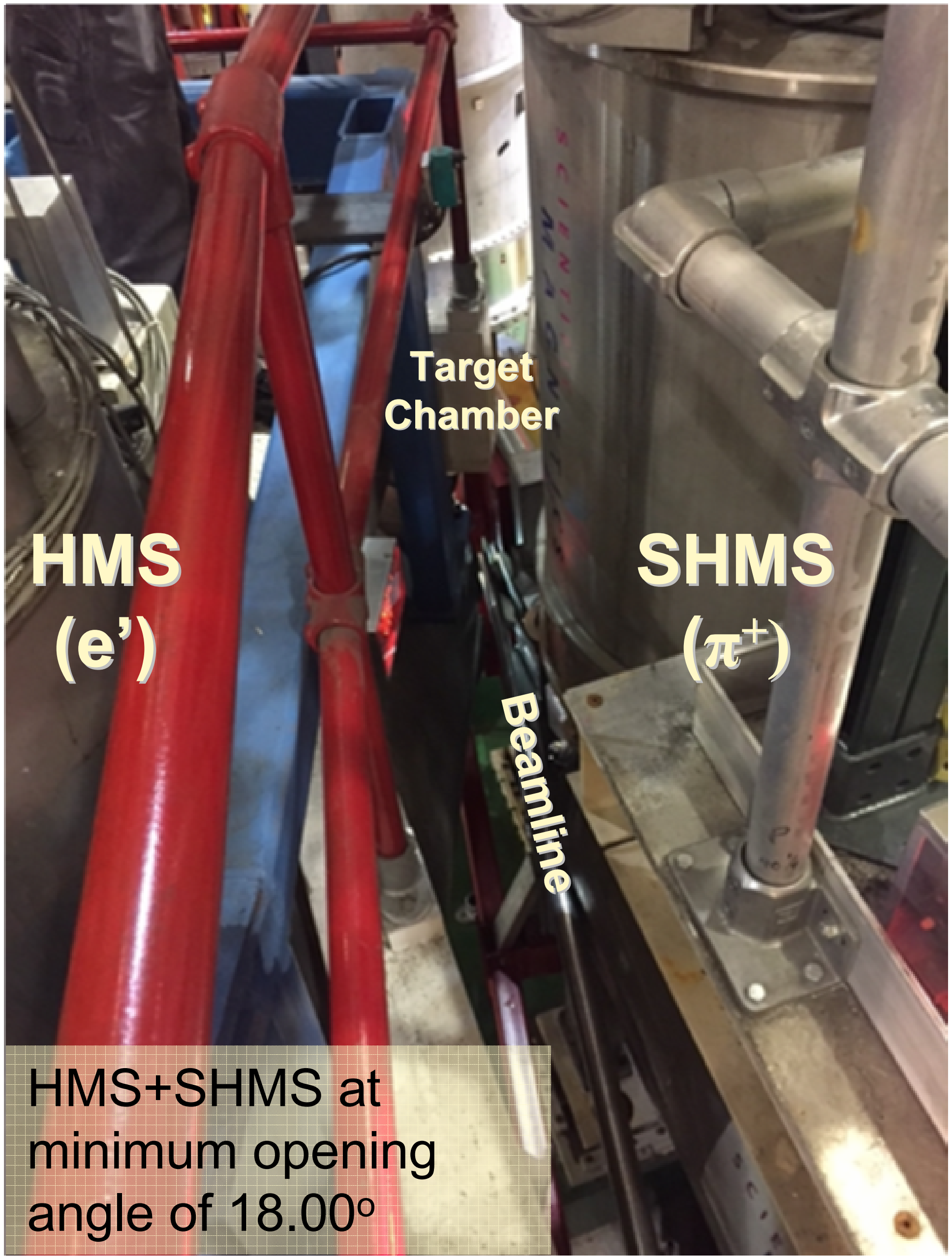
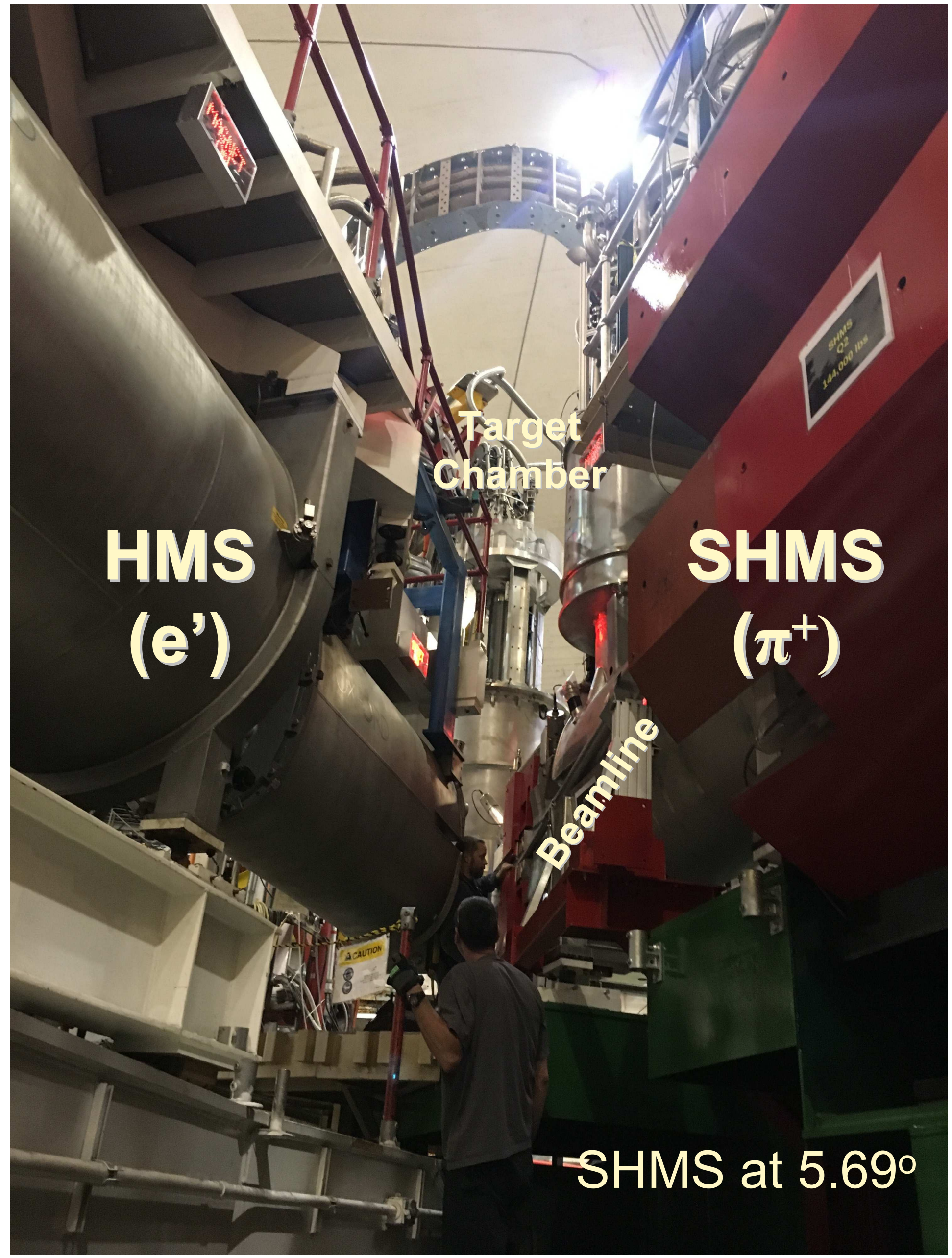
Hall C during Data Taking

π^+/K^+ FF experiments have challenging forward angle requirements





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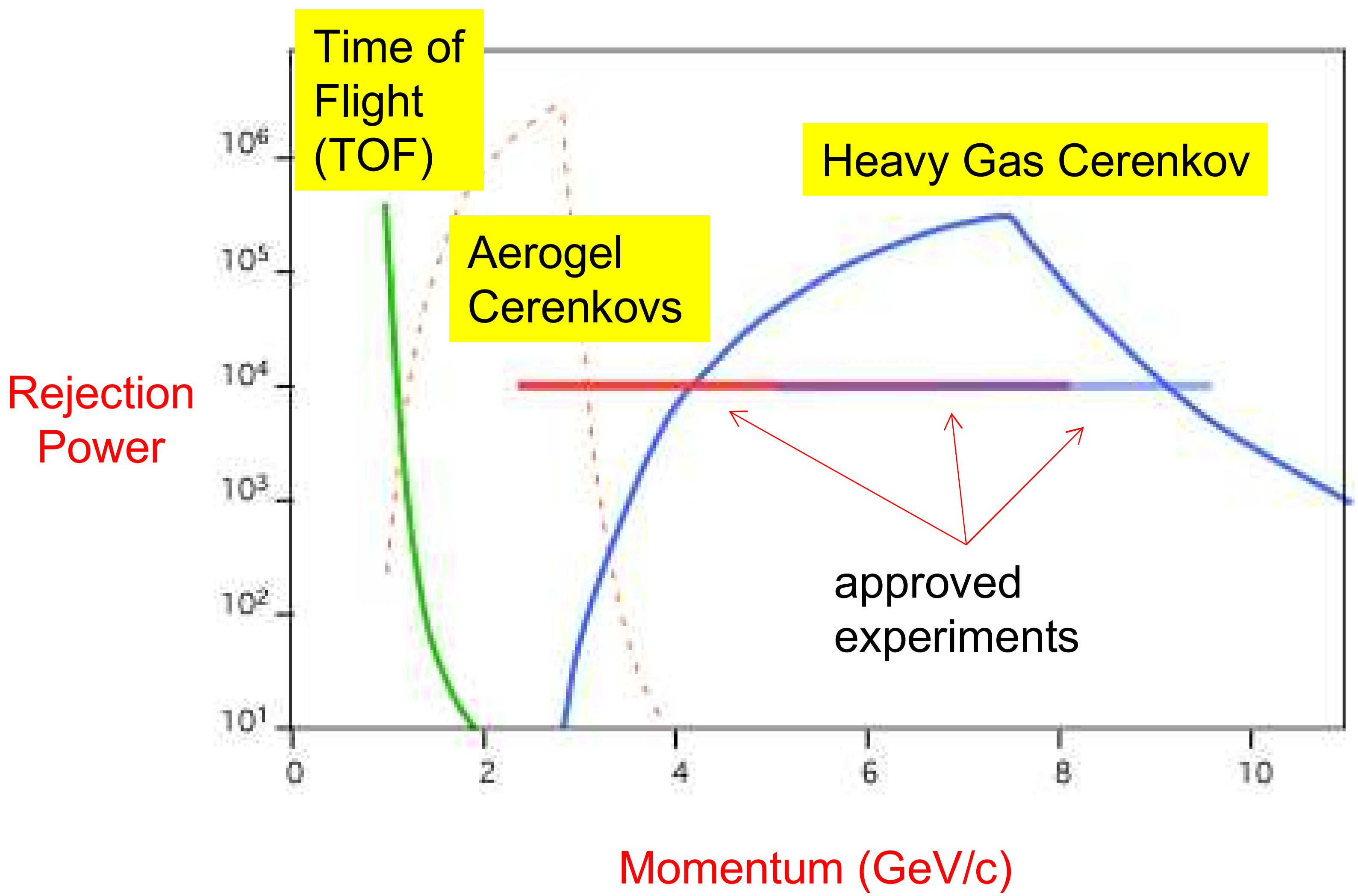
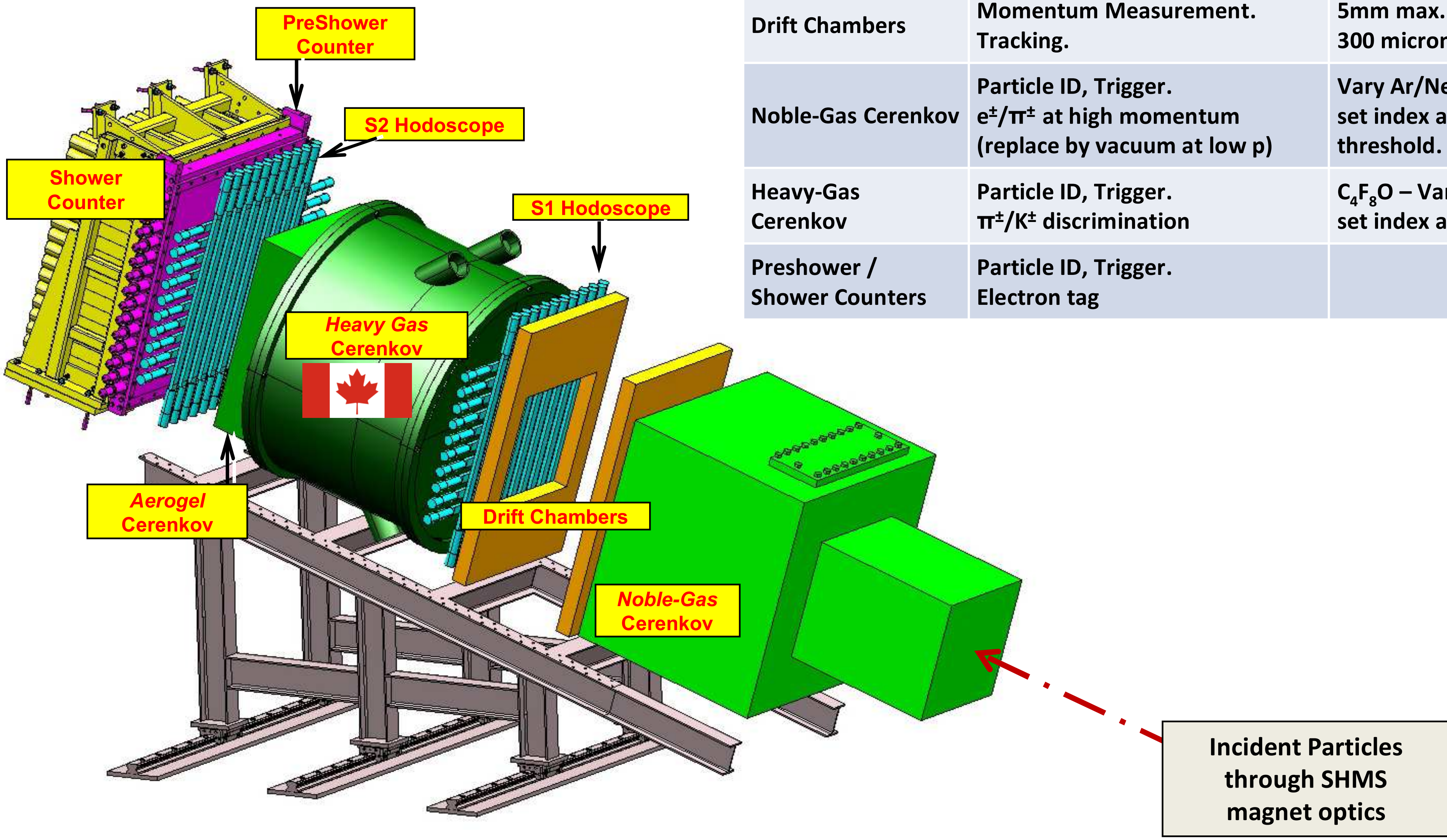
SHMS Particle Identification: +Hadrons



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	



$p(e,e'\pi^+)n$ Event Selection

Coincidence measurement between charged pions in SHMS and electrons in HMS

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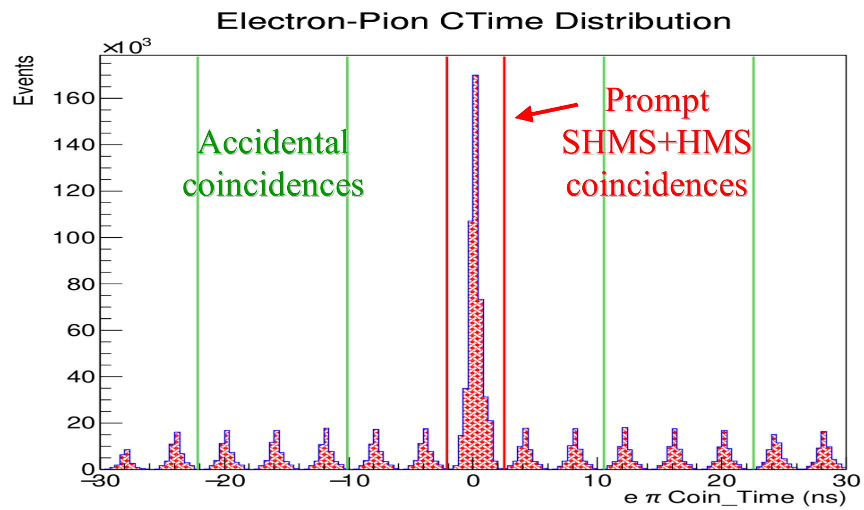
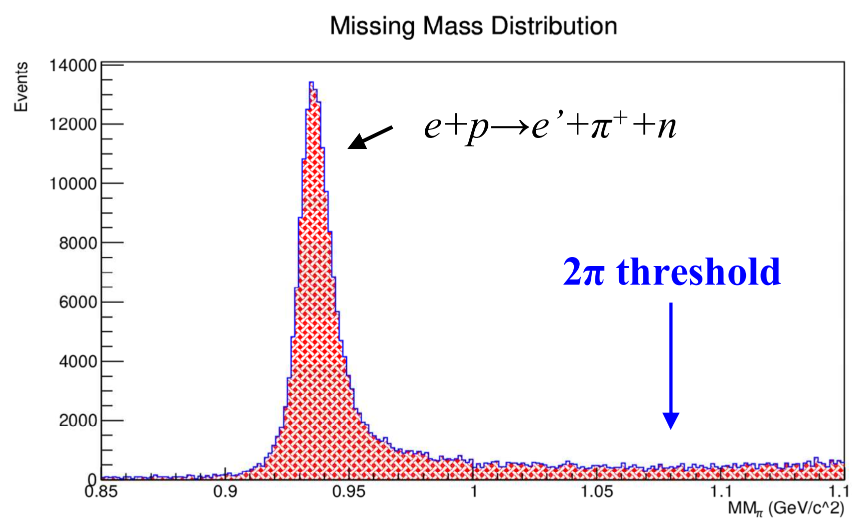
Easy to isolate exclusive channel

- Excellent particle identification
- CW beam minimizes "accidental" coincidences
- Missing mass resolution easily excludes 2–pion contributions





PionLT experiment E12–19–006 Data

Q^2=1.60, W=3.08, x= 0.157, ε=0.685

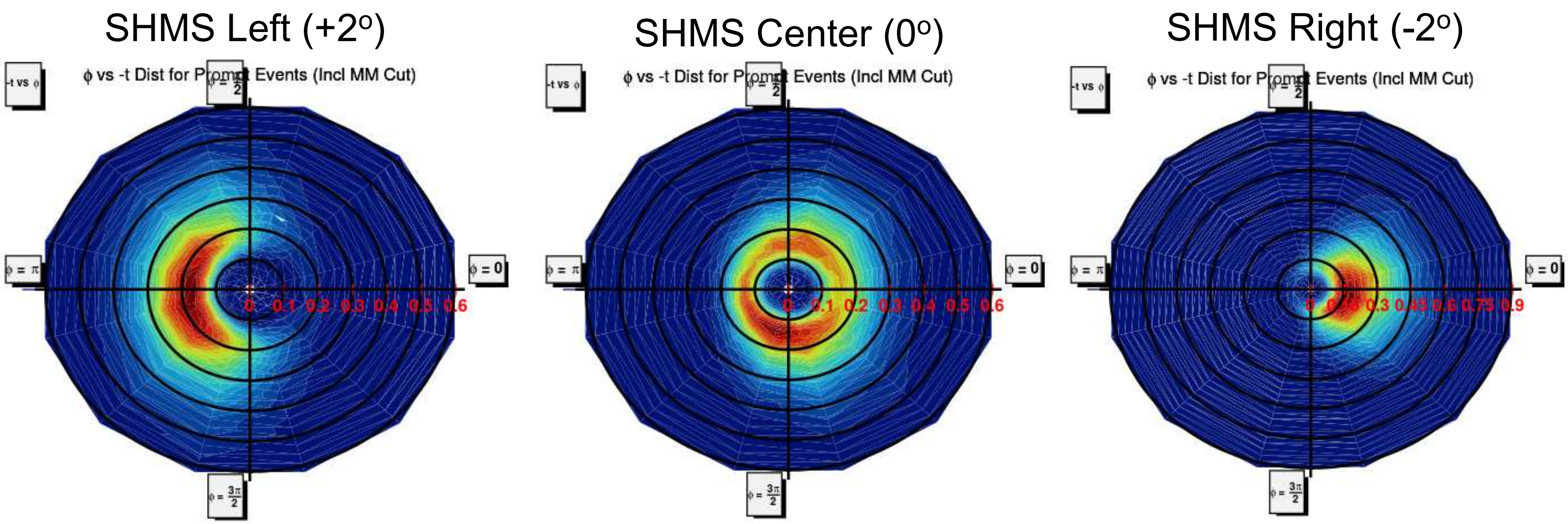
E_{beam}=9.177 GeV, P_{SHMS}=+5.422 GeV/c, θ_{SHMS}= 10.26° (left)

Plots by Muhammad Junaid (Regina PhD student)

PionLT (E12–19–006) t–φ Coverage

- Measure σ_{LT}, σ_{TT} by taking data at three pion spectrometer (SHMS) angles, +2°, 0°, -2°, with respect to *q*–vector

t–φ plots from: Q^2=3.85 W=3.07 High ε



Plots by Nathan Heinrich (Regina PhD student)

- To control systematics, an excellent understanding of spectrometer acceptances is required
  - Over–constrained *p(e,e'p)* reaction, and inelastic e+^{12}C, used to calibrated spectrometer acceptances, momenta, kinematic offsets, efficiencies.
  - Control of point–to–point systematic uncertainties crucial due to 1/Δε error amplification in σ_L

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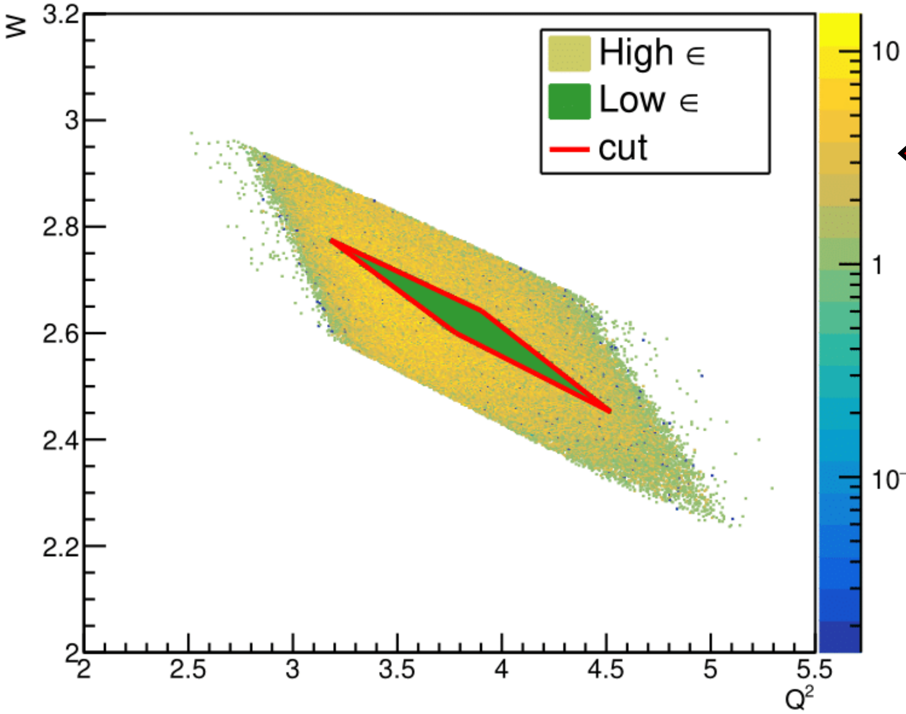
The different pion arm (SHMS) settings are combined to yield φ-distributions for each *t*-bin

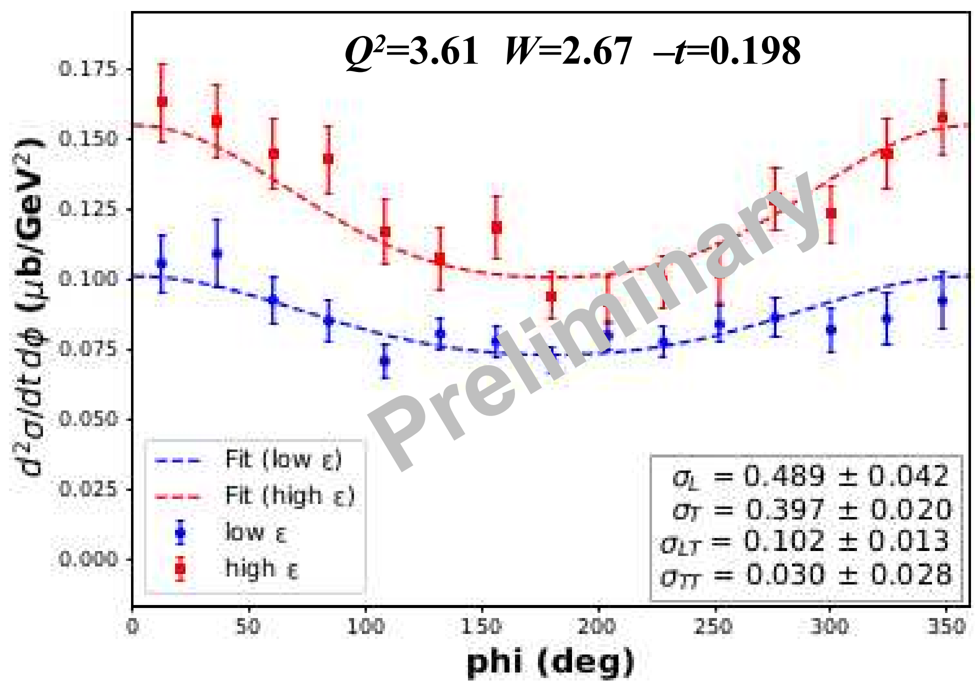
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$



Diamond cuts define common (W,Q^2) acceptance at both ε

SHMS+HMS data at Q^2=3.85, W=2.62
High ε=0.78 Low ε=0.29

- Extract σ_L by simultaneous fit of L,T,LT,TT using measured azimuthal angle (φ_π) and knowledge of photon polarization (ε)



Plots by Muhammad Junaid (Regina PhD student)

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F_π Extraction from JLab data

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- **A model is required to extract F_π from $d\sigma_L/dt$**
  - Fit of model to σ_L gives F_π at each Q^2

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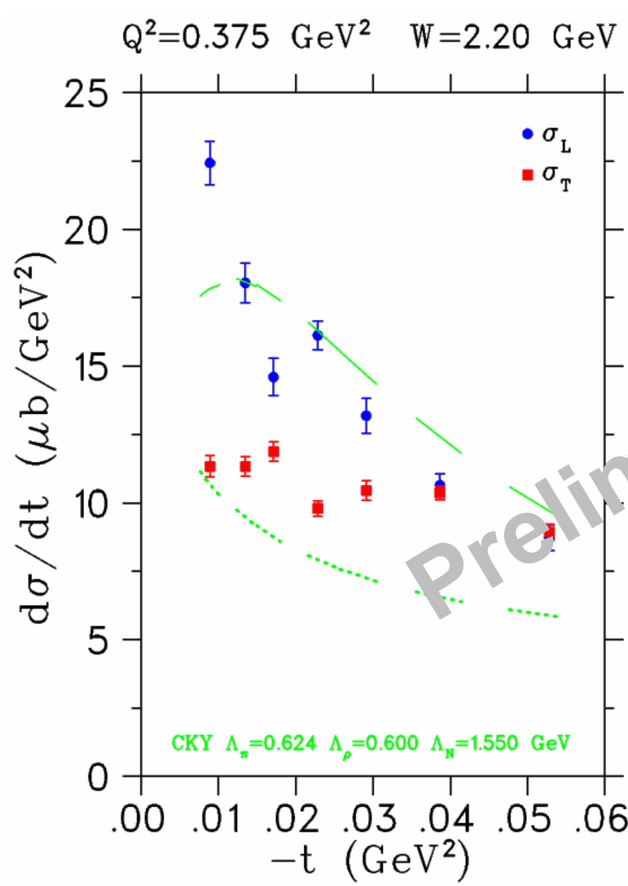
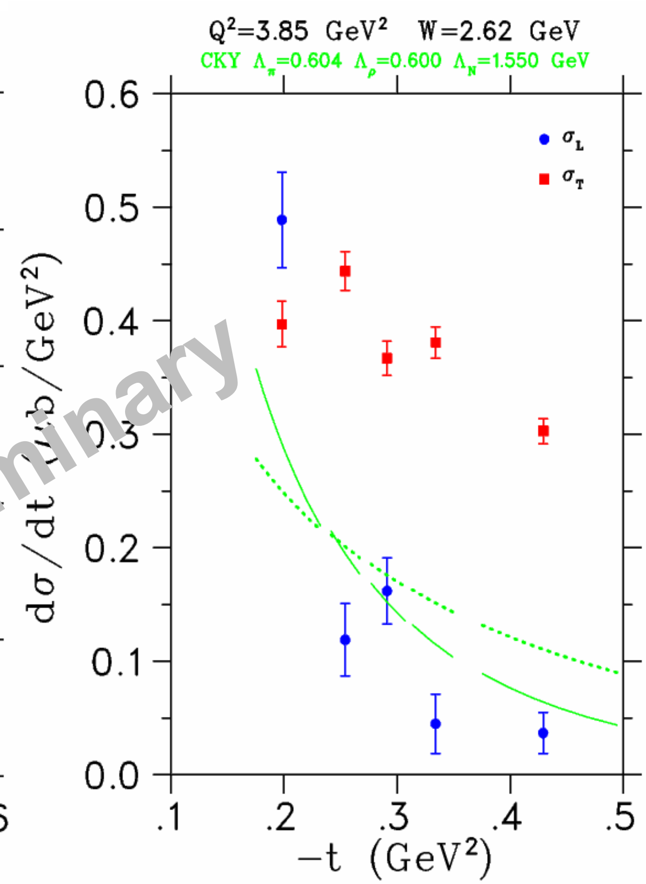
- **JLab 6 GeV F_π expts used VGL Regge model**
  [Vanderhaeghen, Guidal, Laget, PRC 57(1998)1454]
  - Most parameters fixed by photoproduction data
  - At small $-t$, σ_L only sensitive to π Regge trajectory cutoff Λ_π
- **Choi, Kong, Yu Regge model allows 2nd way to extract F_π from σ_L data**
  [JKorPhysSoc 67(2015)L1089, arXiv: 1508.00969]
- **Perry, Kizilersu, Thomas model also being considered** [PLB 807(2020)135581]



V.Kumar et al, publication in process



M. Junaid et al, publication in process

Addressing Model Concerns

- A concern with the electroproduction technique is if one is measuring the "physical" pion 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.

- **Our data-driven approach addresses this concern to the greatest extent possible:**
  - 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 p-e elastic scattering at same Q^2.

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One way to understand non-pole to σ_L

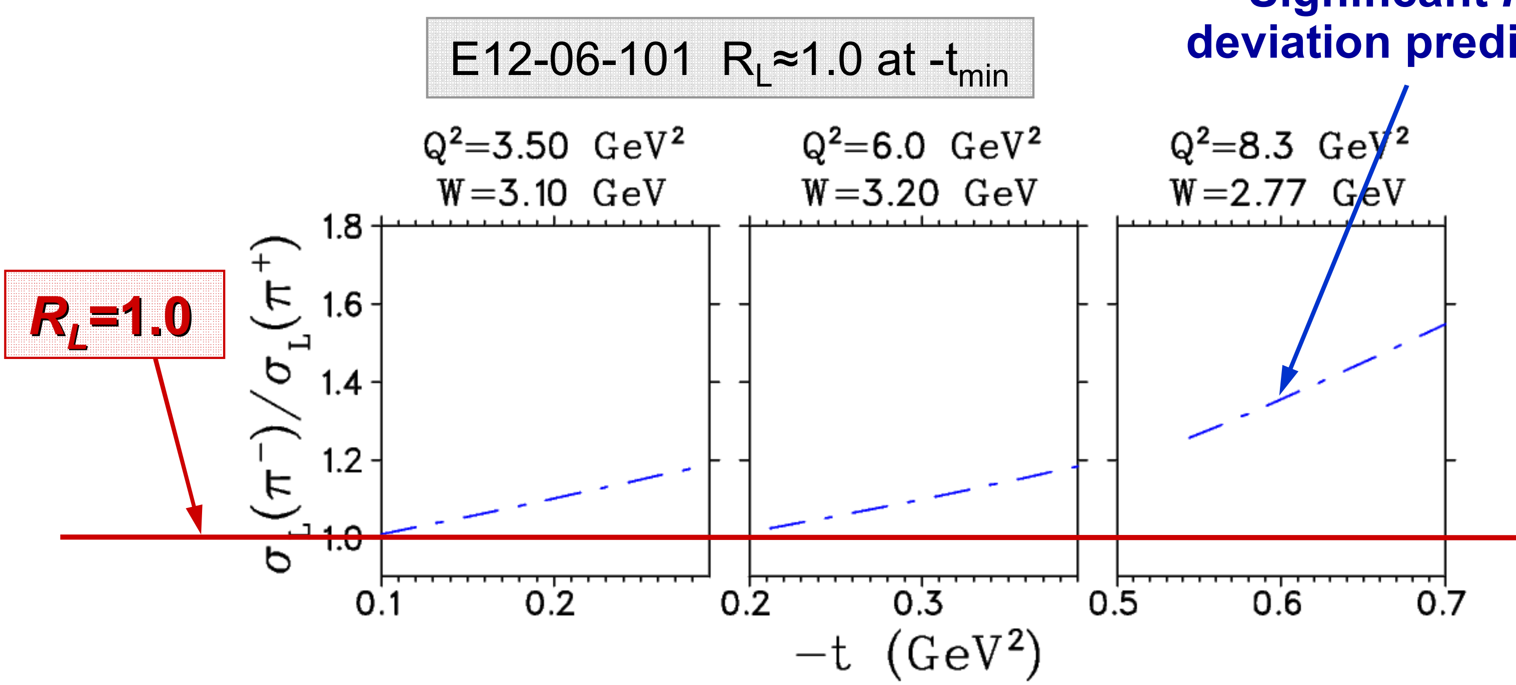
Data–driven approach to better understand non–pole backgrounds at higher –*t*.

- 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).

Significant R_L deviation predicted



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

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Test by extracting F_π at different distances from pole.

Expt: F_π-2, $-t_{min}=0.093\ GeV^2$

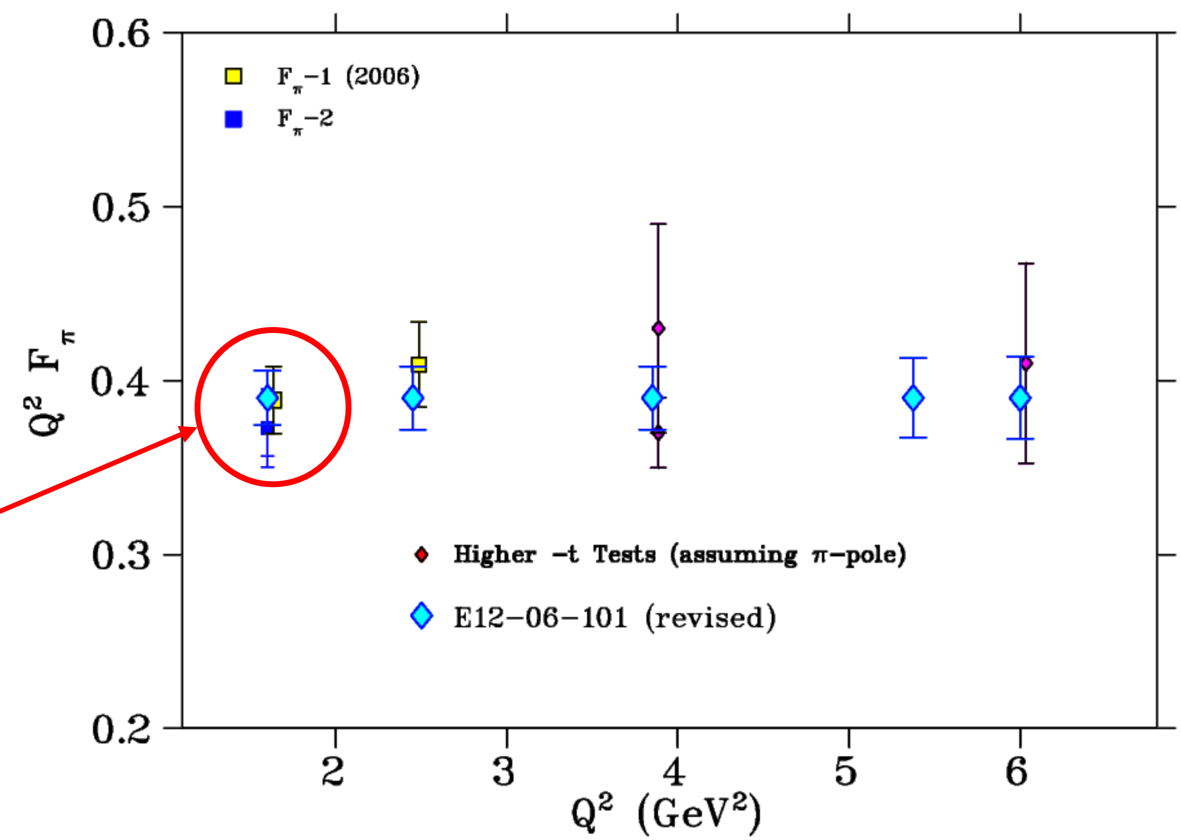
$W=2.22\ GeV$.

F_π-1, $-t_{min}=0.15\ GeV^2$

$W=1.95\ GeV$.

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

⟶ Agreement ~4%.



We have taken 12 GeV data for 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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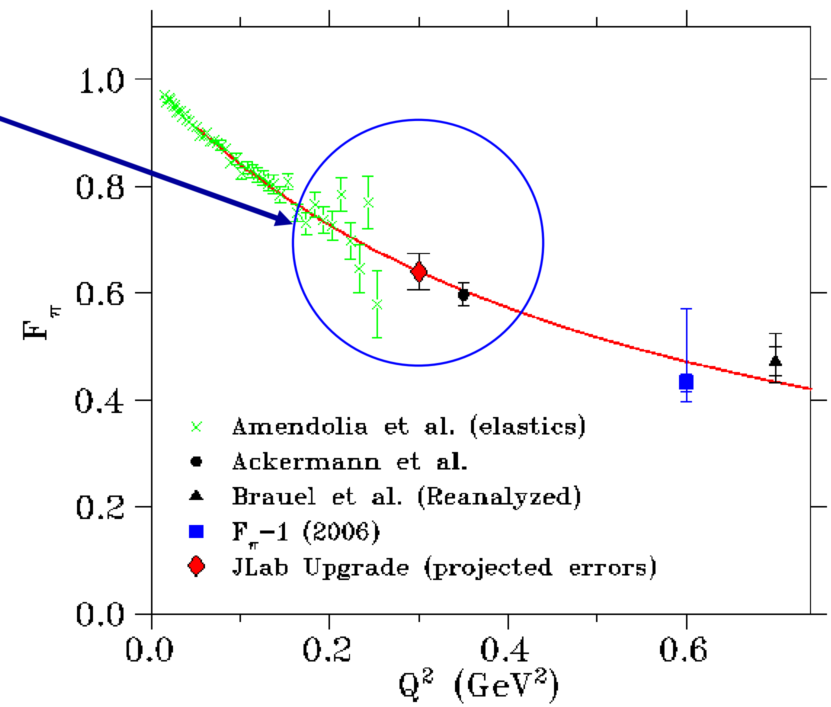
3rd Check of Electroproduction Technique

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

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]*
- **We have data for a better test at Q^2=0.375, 0.425 GeV^2 with much lower statistical and systematic uncertainties**



Data analysis in progress by V. Kumar (U.Regina)

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Current and Projected F_π Data

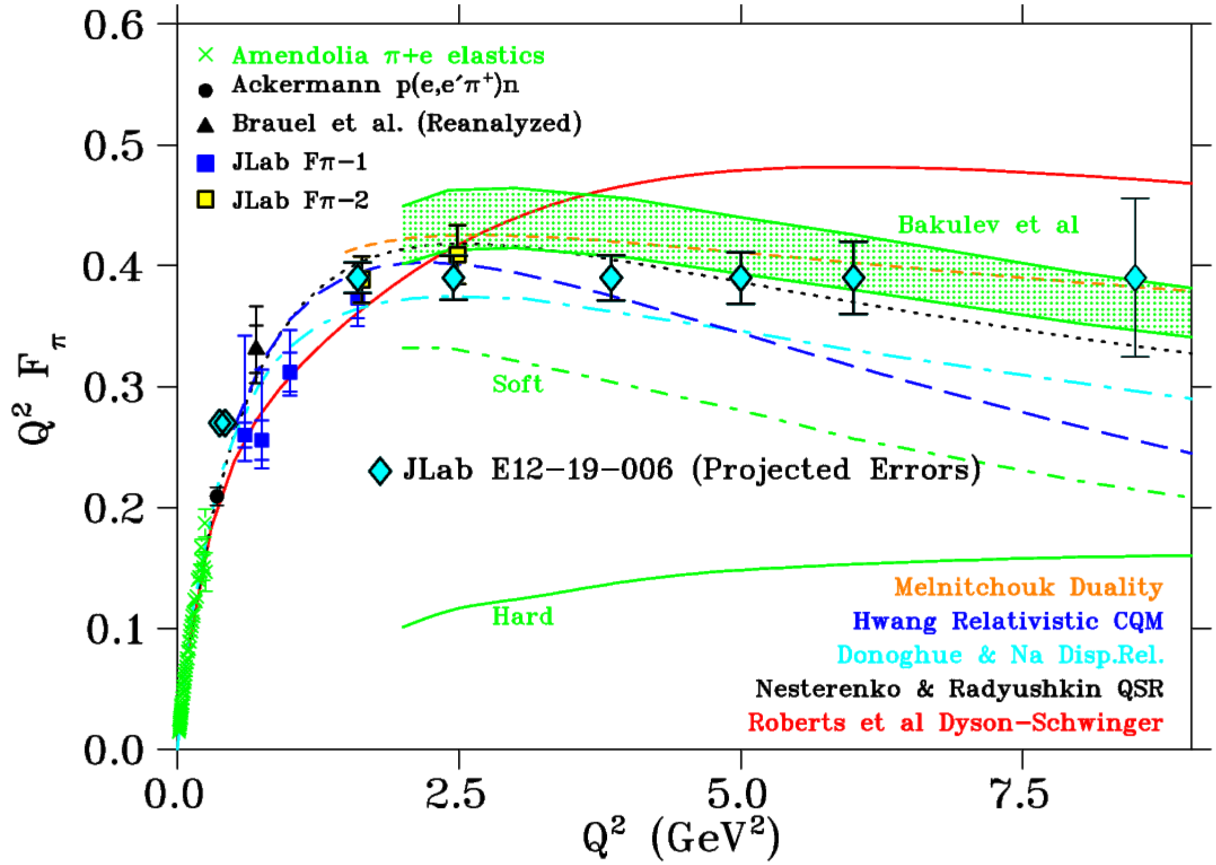
SHMS+HMS will allow measurement of F_π to much higher Q^2

No other facility worldwide can perform this measurement

Data taking completed September 2022 (E12–19–006: GMH, D. Gaskell and T. Horn, spokespersons)

y–positions of projected points are arbitrary

Error bars are calculated from obtained statistics and projected systematic uncertainties



The ~10% measurement of F_π at Q^2=8.5 GeV^2 is at higher $-t_{min}$=0.45 GeV^2

The pion form factor is the clearest test case for studies of QCD's transition from non–perturbative to perturbative regions

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$p(e,e'K^+)\Lambda(\Sigma^0)$ Experiment

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Isolate Exclusive Final States via Missing Mass

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

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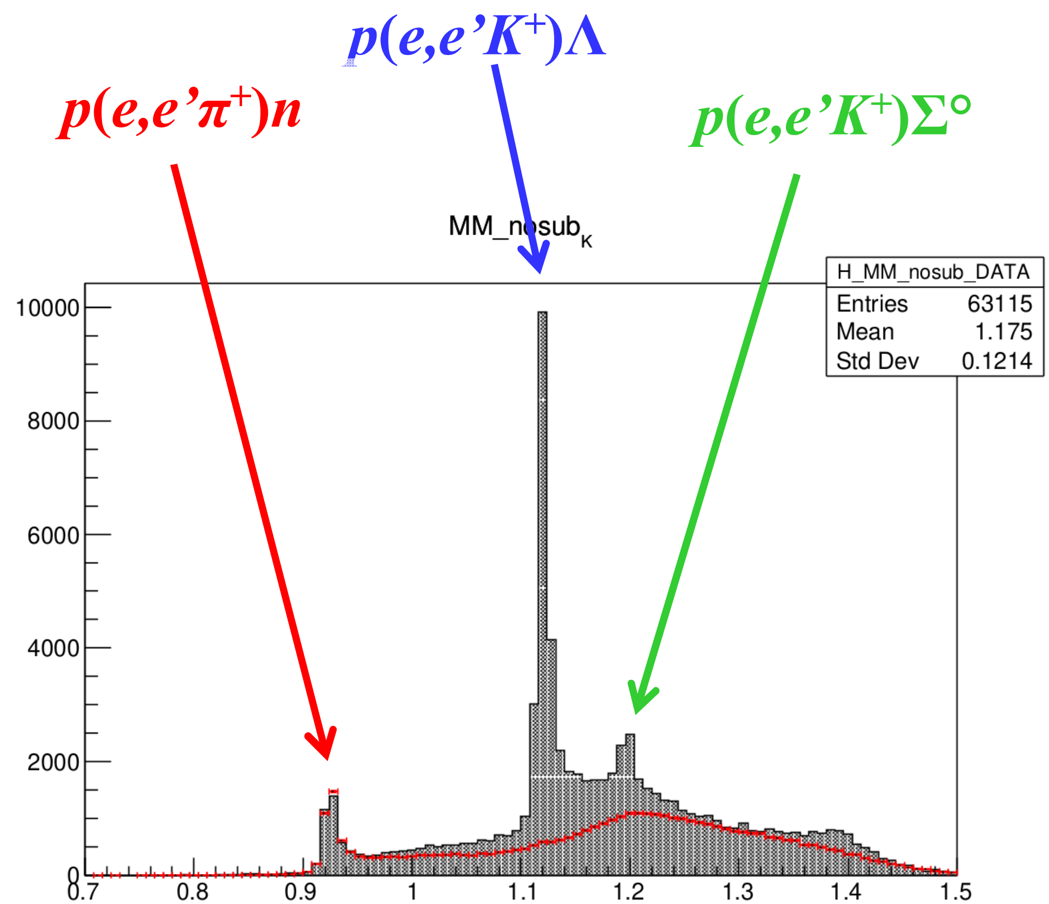
- Spectrometer coincidence acceptance allows for simultaneous studies of Λ and Σ° channels.
- Kaon-pole dominance test through

$$\frac{\sigma_L(\gamma^* p \rightarrow K^+\Sigma^0)}{\sigma_L(\gamma^* p \rightarrow K^+\Lambda^0)}$$

- Should be similar to ratio of $g^2_{pK\Lambda}/g^2_{pK\Sigma}$ coupling constants if t-channel exchange dominates.



Q^2=3.0 GeV^2 , W=3.14, low ε, θ_{Kq}=+0.0

Plot by Richard Trotta (CUA/Virginia)

Kaon Form Factor Experiment Goals

- **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

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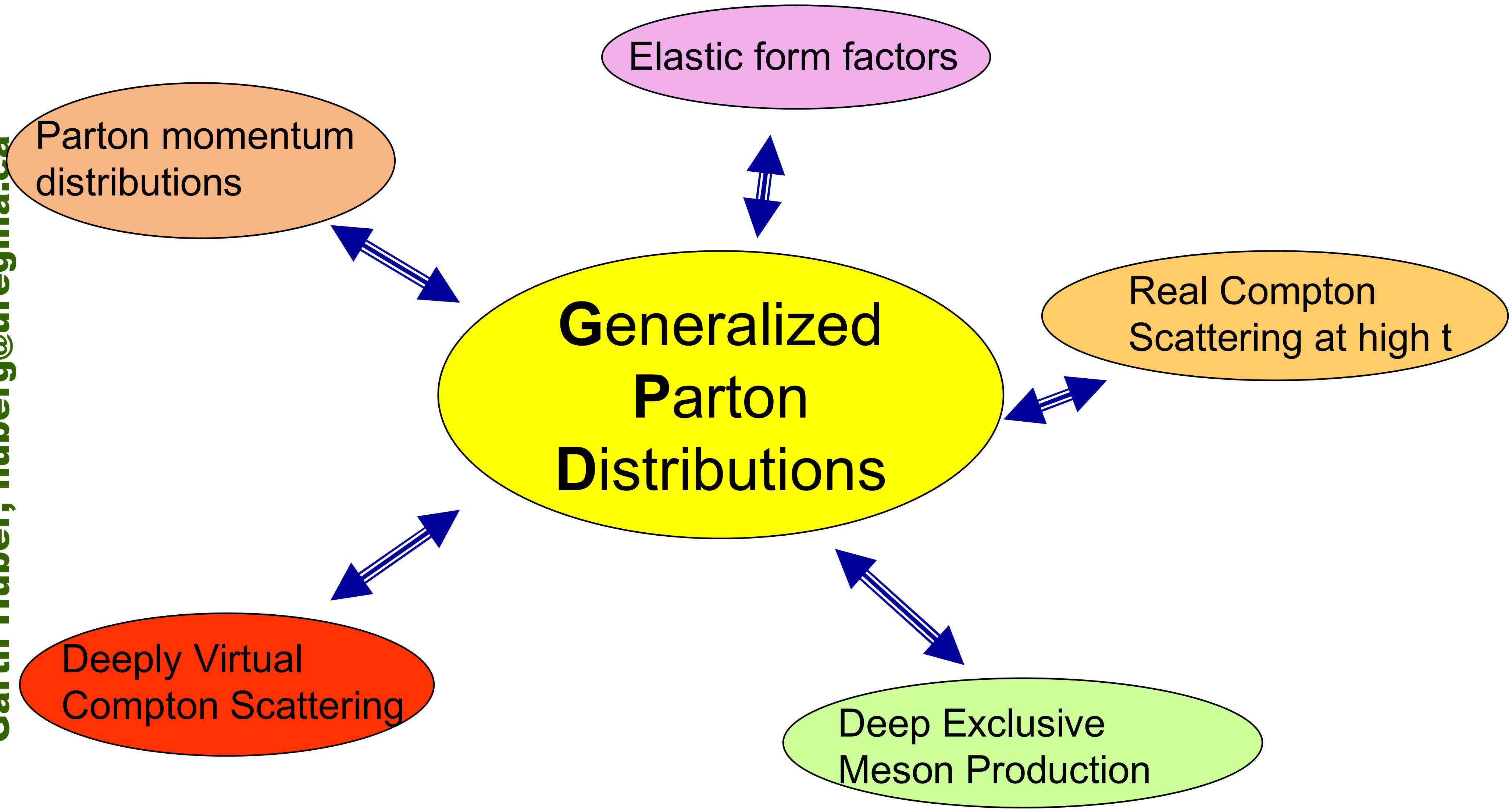
GPDs – A Unified View of Hadron Structure



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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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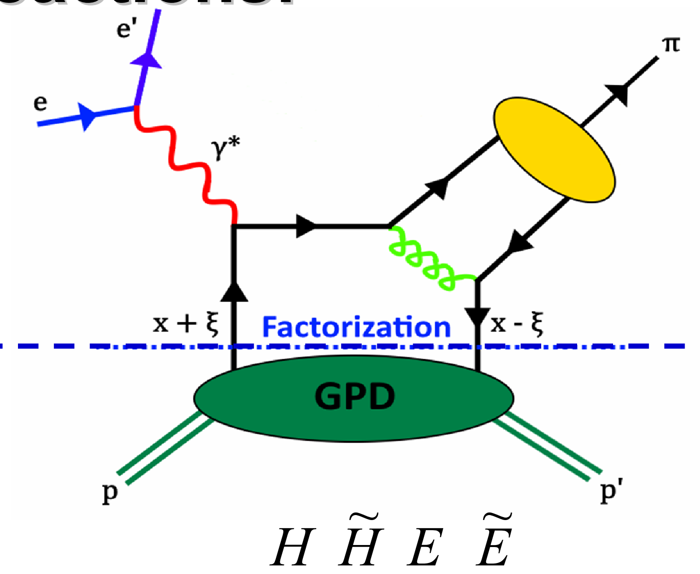
GPDs require Hard Exclusive Reactions

- **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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Scaling Experiment Goals

- **Measure the Q^2 dependence of the $p(e,e'\pi^+)n$, $p(e,e'K^+)\Lambda$ 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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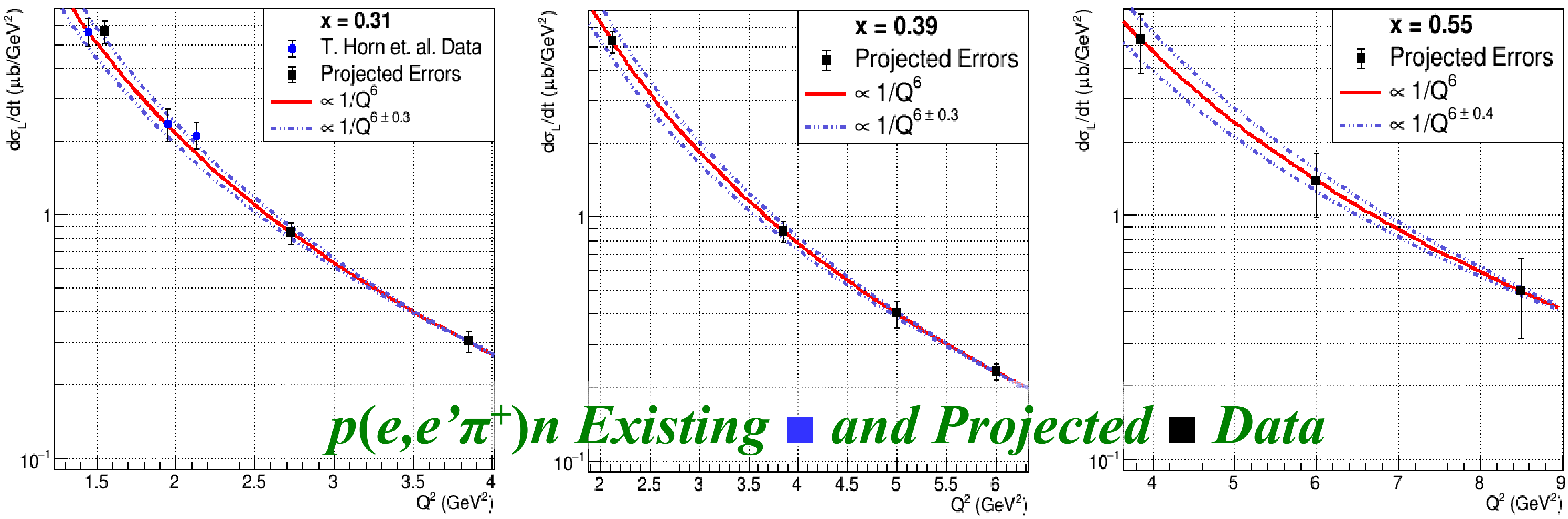
Testing Factorization: $p(e,e'\pi^+)n$

- **One of most stringent tests of factorization is Q^2 dependence of π/K electroproduction cross sections**
  - σ_L scales to leading order as Q^{-6}
  - As Q^2 becomes large: $\sigma_L \gg \sigma_T$
- **If we show factorization regime is not reached, it will have major implications for meson production GPD experiments in this Q^2 regime** (Some of these experiments are already taking data!)



$p(e,e'\pi^+)n$ Existing ■ and Projected ■ Data

- E12–19–006 data taking completed 2022
- PhD students: N. Heinrich, M. Junaid   Spokespersons: D. Gaskell, T. Horn, GMH

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Important 2nd Test: *p(e,e'K⁺)Λ*

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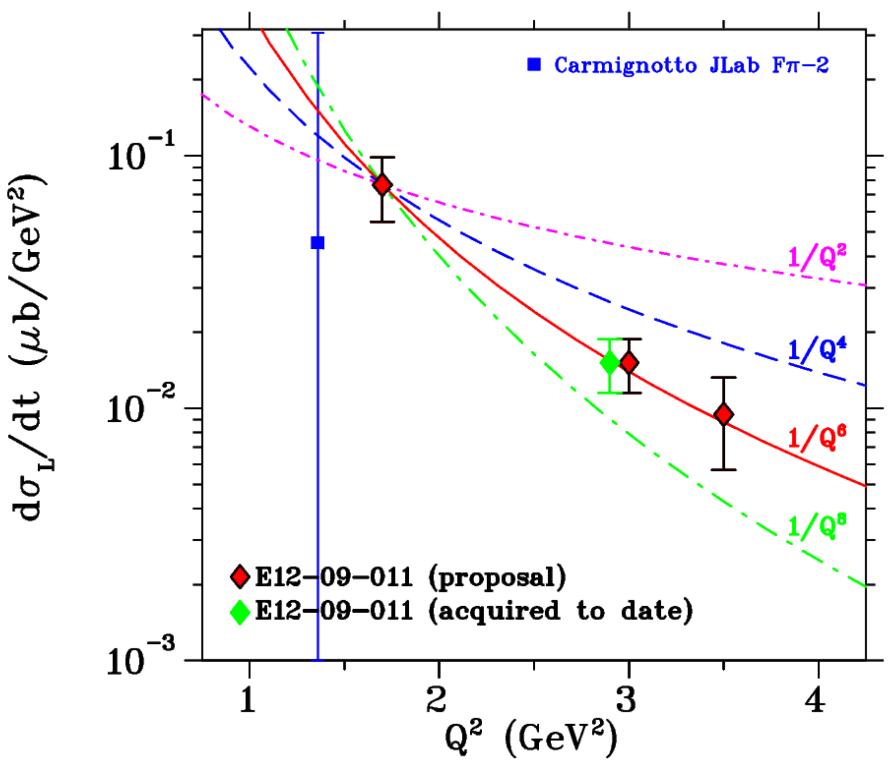
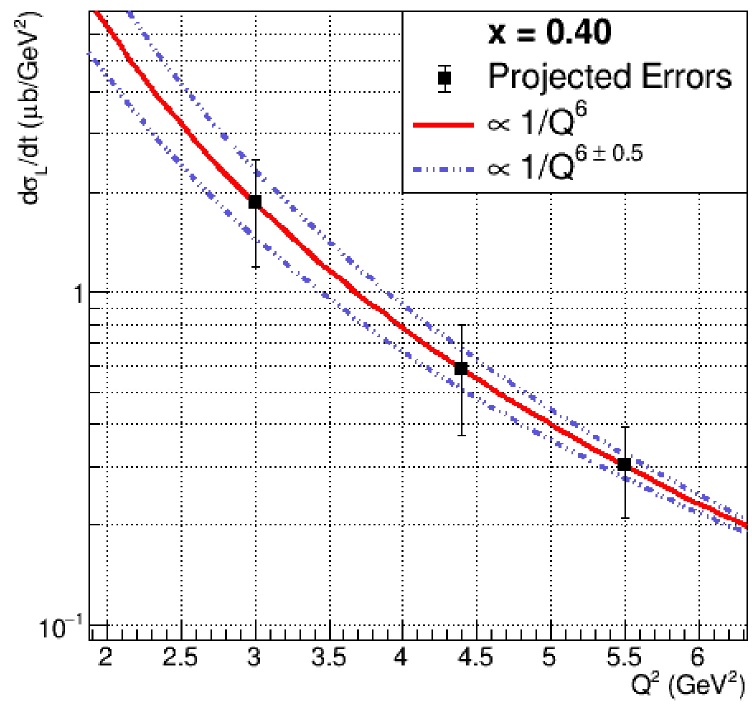
- **Experimental validation of onset of hard scattering regime is essential for reliable interpretation of JLab GPD program results**
- Is onset of scaling different for kaons than pions?
- K^+ and π^+ together provide quasi model-independent study





p(e,e'K⁺)Λ Existing ■ and Projected ♦♦■ Data

- E12-09-011 data taking partially completed in 2019
- Data for x_B=0.40 scan in hand. Data for x_B=0.25 scan only partly acquired.
  - Spokespersons: T. Horn, P. Markowitz, GMH

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Summary

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- Higher Q^2 data on π^+ and K^+ form factors are vital to our better understanding of hadronic physics
  - PionLT (E12–19–006) has for the first time, since the pioneering measurements at Cornell in 1970's, acquired the high quality data needed to test these theoretical developments with authority
  - KaonLT (E12–09–011) partially completed
  - First dσ/dt from both should be out later this year
- Factorization studies are crucial if the field is to fully utilize the information encoded in GPDs, as GPDs are only accessible experimentally in the hard–soft factorization regime
  - PionLT (E12–19–006) has acquired data for LT–separated $p(e,e'\pi^+)n$ Q^{-n} scans at x_B=0.31, 0.39, 0.55
  - KaonLT (E12–09–011) has acquired $p(e,e'K^+)\Lambda$ data for Q^{-n} scan at x_B=0.40, eventual extension to x_B=0.25

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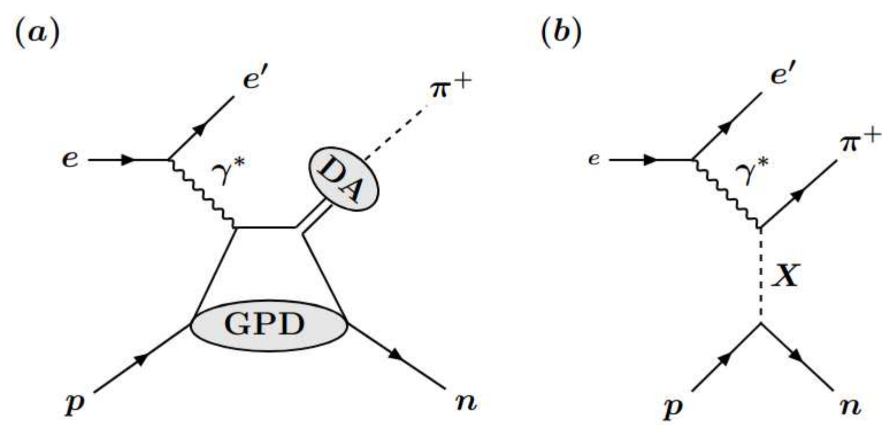
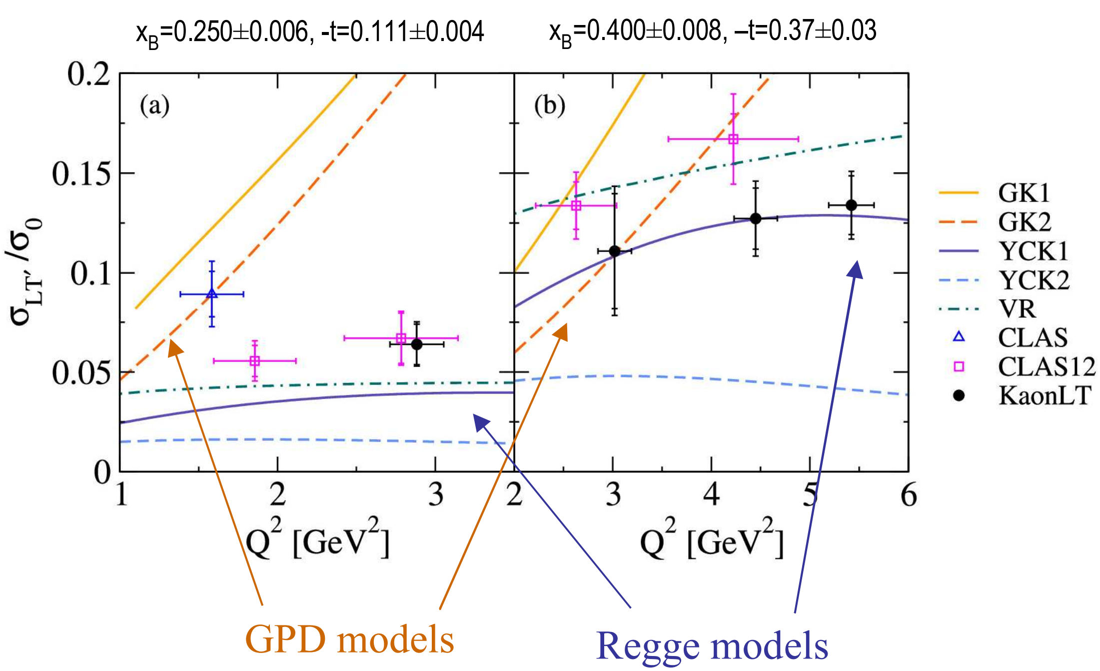
First publication from KaonLT using large $p(e,e'\pi^+)n$ data set

- Comparing data with **GPD** (a) and **Regge** (b) models
- Our data show better agreement with Regge models
- Implies **hard/soft factorization** is not valid for $Q^2 \leq 5.5$ GeV^2 in $p(e,e'\pi^+)n$
- **Improvement on previous CLAS12 results:** new model, finer kinematic binning
- First measurement of **Q^2 dependence** of $\sigma_{LT'}/\sigma_0$ at fixed (x_B,t): mostly flat





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Letter

Probing hard/soft factorization via beam-spin asymmetry in exclusive pion electroproduction from the proton

A.C. Postuma [a], G.M. Huber [a], D.J. Gaskell [b], N. Heinrich [a], T. Horn [c b], M. Junaid [a], S.J.D. Kay [a d], V. Kumar [a], P. Markowitz [e], J. Roche [f], R. Trotta [c], A. Usman [a], B.-G Yu [g], T.K. Choi [h], K.-J Kong [g], S. Ali [c], R. Ambrose [a], D. Androic [i], W. Armstrong [j k], A. Bandari [l], V. Berdnikov [c], H. Bhatt [m], D. Bhetuwal [m], D. Biswas [n], M. Boer [j], P. Bosted [l], E. Brash [o], A. Camsonne [b], J.-P. Chen [b], J. Chen [l], M. Chen [p], M.E. Christy [n], S. Covrig [b], M.M. Dalton [b], W. Deconinck [q], M. Diefenthaler [b], B. Duran [j], D. Dutta [m], M. Elaasar [r], R. Ent [b], H. Fenker [b], E. Fuchey [s], D. Hamilton [t], J.-O Hansen [b], F. Hauenstein [u], S. Jia [j], M.K. Jones [b], S. Joosten [k], M.L. Kabir [m], A. Karki [m], C. Keppel [b], E. Kinney [v], N. Lashley-Colthirst [n], W.B. Li [l w], D. Mack [b], S. Malace [b], M. McCaughan [b], Z.E. Meziani [k j], R. Michaels [b], R. Montgomery [t], M. Muhoza [c], C. Muñoz Camacho [x], G. Niculescu [y], I. Niculescu [y], Z. Papandreou [a], S. Park [w], E. Pooser [b], M. Rehfuss [j], B. Sawatzky [b], G.R. Smith [b], H. Szumila-Vance [b], A. Teymurazyan [a], H. Voskanyan [z], B. Wojtsekhowski [b], S.A. Wood [b], Z. Ye [k], C. Yero [e], J. Zhang [p], X. Zheng [p]

L/T–separation error propagation

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Error in $d\sigma_L/dt$ is magnified by $1/\Delta\varepsilon$, where $\Delta\varepsilon=(\varepsilon_{Hi}-\varepsilon_{Low})$

→ To keep magnification factor <5x, need $\Delta\varepsilon>0.2$, preferably more!

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

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

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

The relevant quantities for F_π extraction are R and $\Delta\varepsilon$

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

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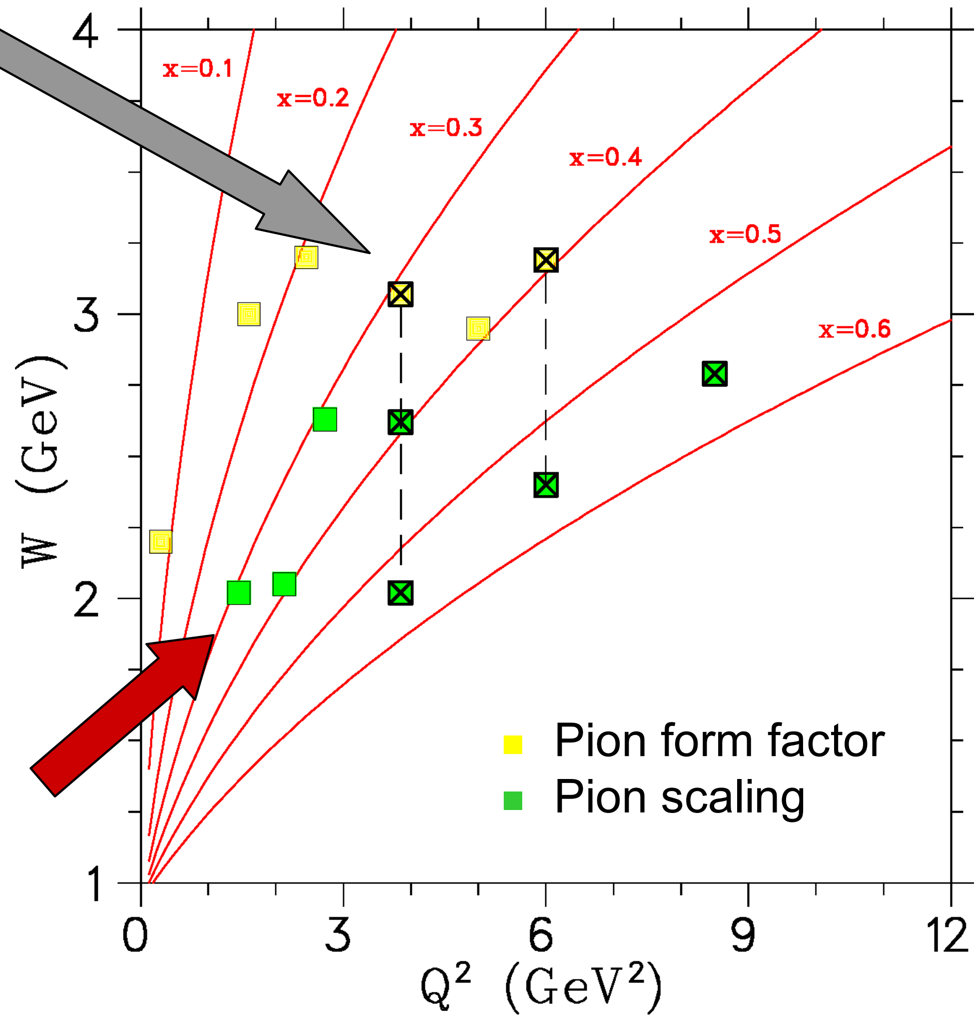
E12–19–006 Optimized Run Plan

Points along vertical lines allow F_π values at different distances from pion pole, to check model properly accounts for:

- **π^+ production mechanism**
- **spectator nucleon**
- **off-shell (*t*–dependent) effects**



Points along red curves allow $1/Q^n$ scaling tests at fixed x_B

For more details, visit Pion-LT RedMine: https://redmine.jlab.org/projects/hall-c/wiki/

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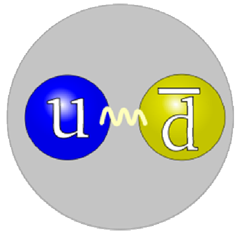
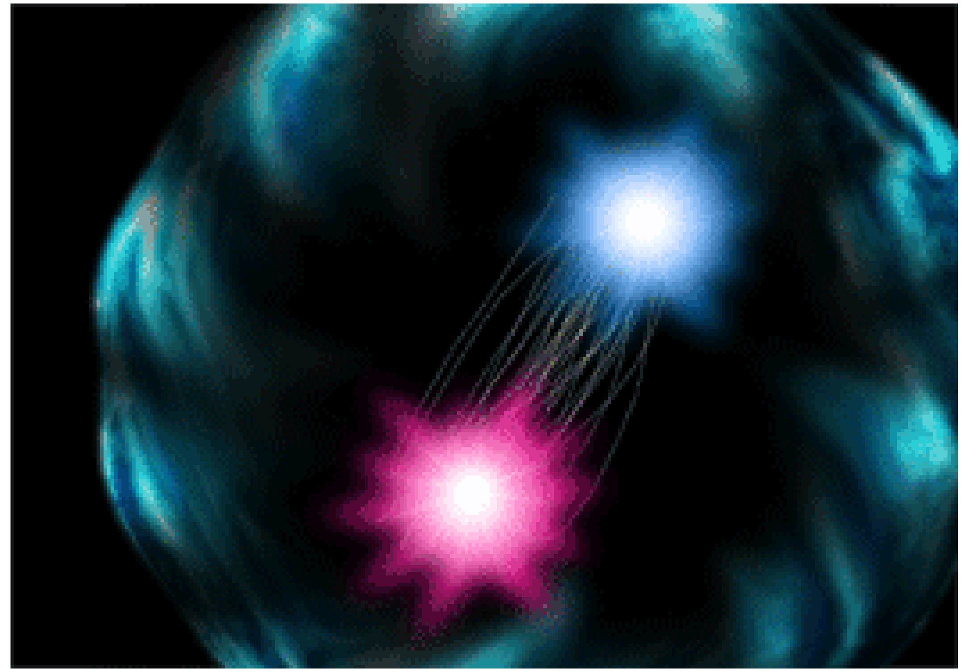
Charged Pion Form Factor

- **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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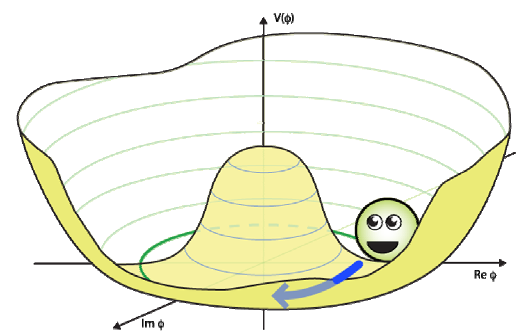
The Pion as a Goldstone Boson

- A remarkable feature of QCD is Dynamical Chiral Symmetry Breaking (DCSB) because it cannot be derived directly from the Lagrangian and is related to nontrivial nature of QCD vacuum.
  - Explicit symmetry breaking, which is put in "by hand" through finite quark masses, is quite different.
- DCSB is now understood to be one of the most important emergent phenomena in the Standard Model, responsible for generation of >98% baryonic mass.



- **Two important consequences of DCSB:**
  1. Valence quarks acquire a dynamical or constituent quark mass through their interactions with the QCD vacuum.
  2. The pion is the spin-0 boson that arises when Chiral Symmetry is broken, similar to how Higgs boson arises from Electroweak Symmetry Breaking.

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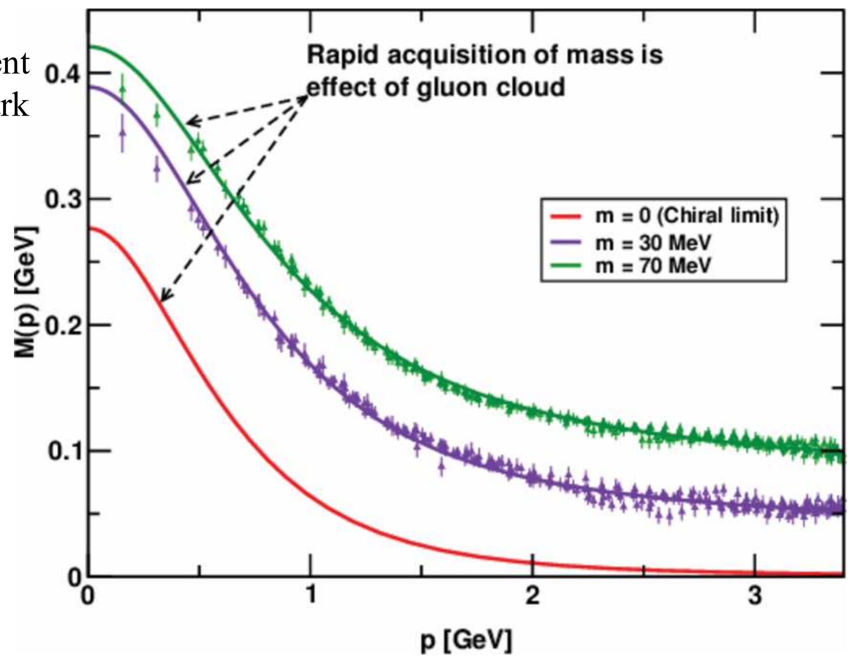
Recent Theoretical Advances

Amazing progress in the last few years.

- **We now have a much better understanding how Dynamical Chiral Symmetry Breaking (DCSB) generates hadron mass.**
- Quenched lattice-QCD data on the dressed-quark wave function were analyzed in a Bethe-Salpeter Equation framework by Bhagwat, et al.
- For the first time, the evolution of the current-quark of pQCD into constituent quark was observed as its momentum becomes smaller.

- The constituent-quark mass arises from a cloud of low-momentum gluons attaching themselves to the current quark.
- **This is DCSB:** an essentially non-perturbative effect that generates a quark *mass from nothing*: namely, it occurs even in the chiral (m=0) limit.

Constituent quark



Current quark

M.S. Bhagwat, et al., PRC **68** (2003) 015203.
L. Chang, et al., Chin.J.Phys. **49** (2011) 955.

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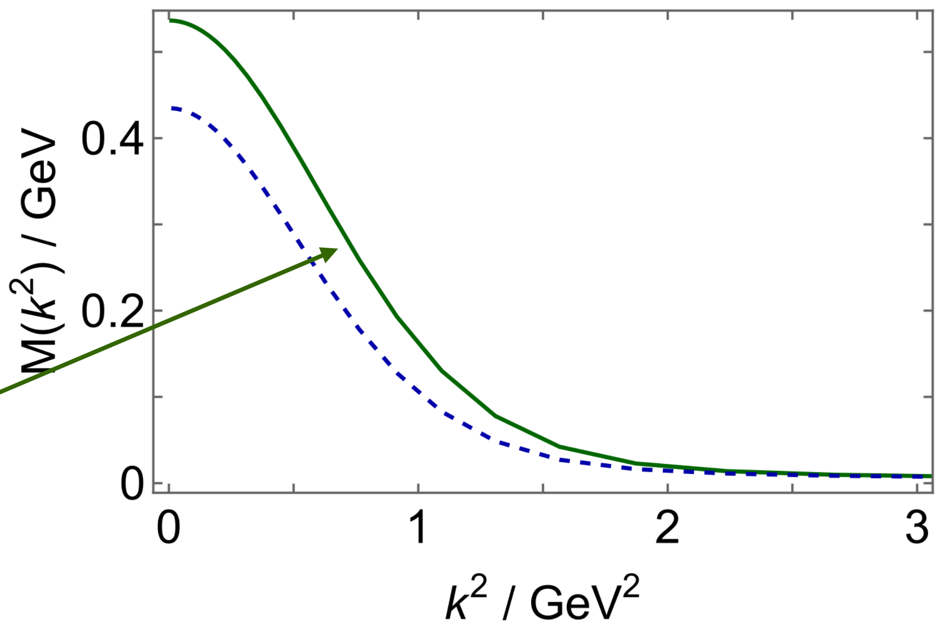
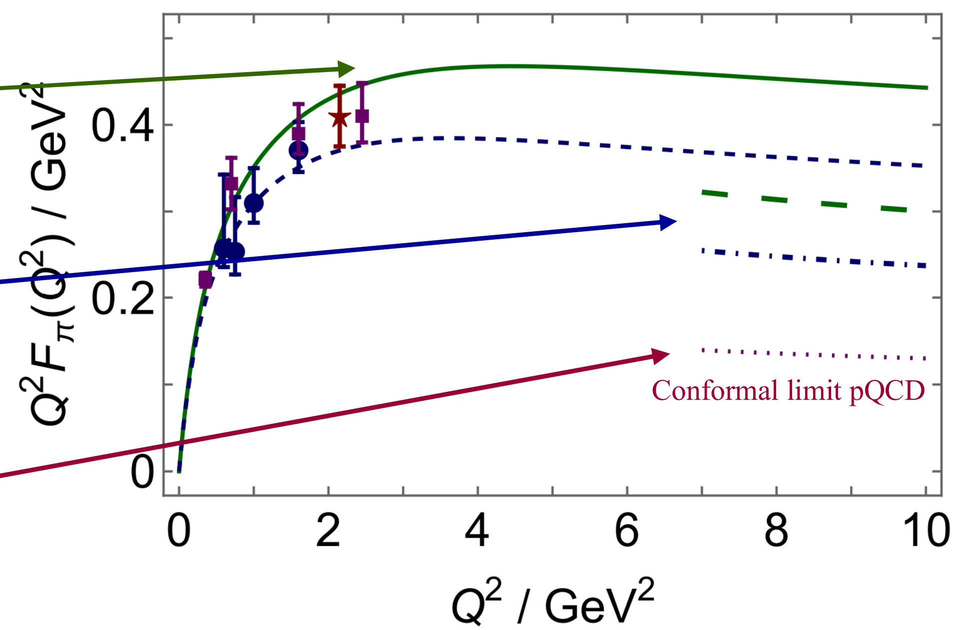
Synergy: Emergent Mass and π^+ Form Factor

At empirically accessible energy scales, π^+ form factor is sensitive to emergent mass scale in QCD

- **Two dressed–quark mass functions distinguished by amount of DCSB**
  - DCSB emergent mass generation is 20% stronger in system characterized by solid green curve, which is more realistic case
- **$F_\pi(Q^2)$ obtained with these mass functions**
  - r_π=0.66 fm with solid green curve
  - r_π=0.73 fm with solid dashed blue curve
- **$F_\pi(Q^2)$ predictions from QCD hard scattering formula, obtained with related, computed pion PDAs**
- **QCD hard scattering formula, using conformal limit of pion's twist–2 PDA**

$$\phi_\pi^{cl}(x) = 6x(1-x)$$





Chen, et al., PRD **98**(2018)091505(R); Aguilar et al, EPJA **55**(2019)190

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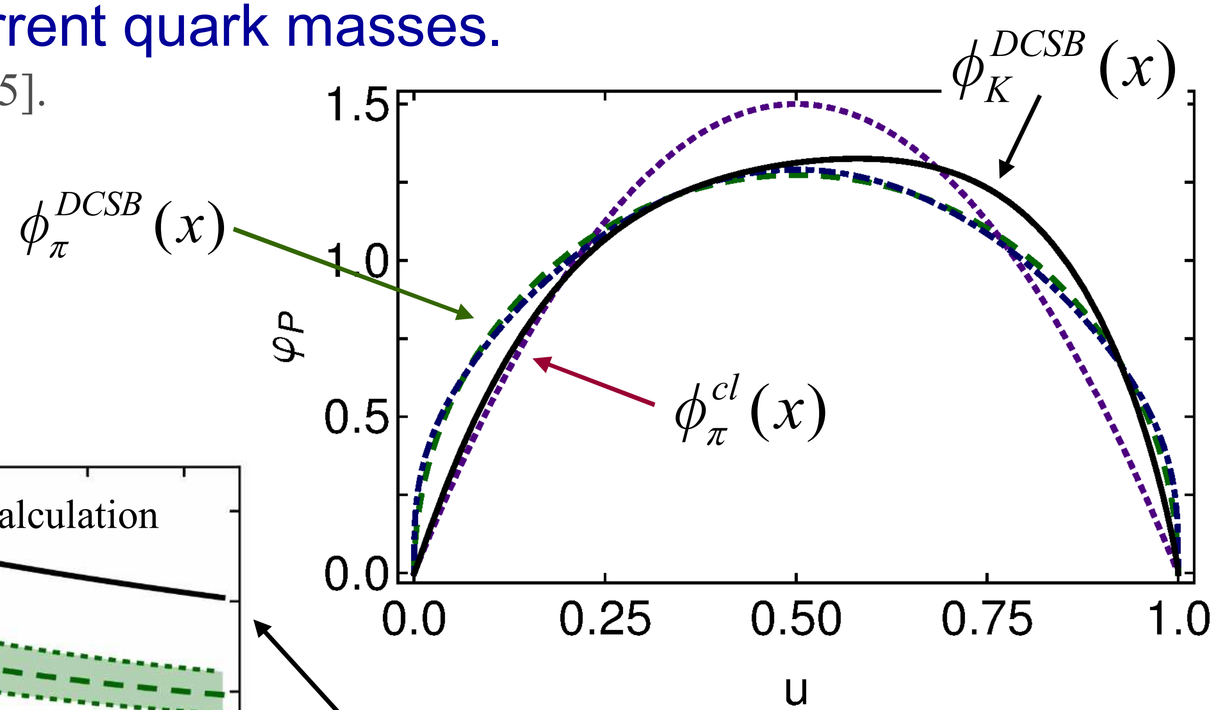
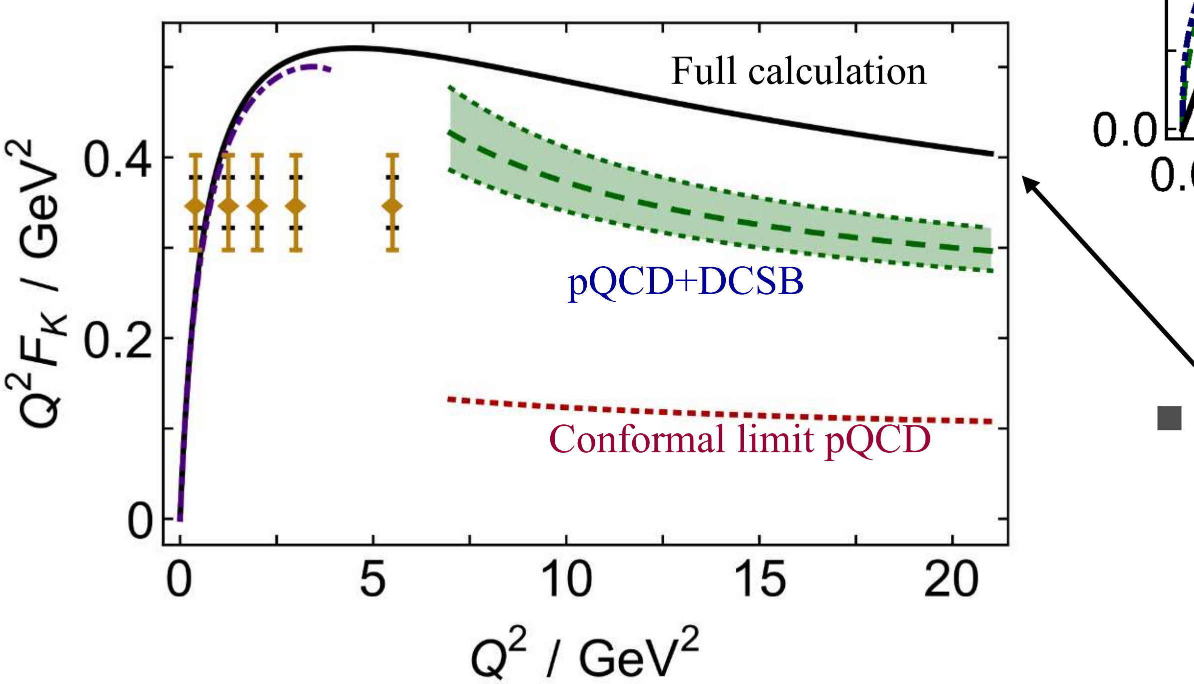
K^+ properties also strongly influenced by DCSB

- ***K^+* PDA also is broad, concave and asymmetric.**
- While the heavier s quark carries more bound state momentum than the u quark, the shift is markedly less than one might naively expect based on the difference of u, s current quark masses.
  [C. Shi, et al., PRD **92** (2015) 014035].





- **F_K DCSB model prediction for JLab kinematics**
  [F. Guo, et al., arXiv: 1703.04875].

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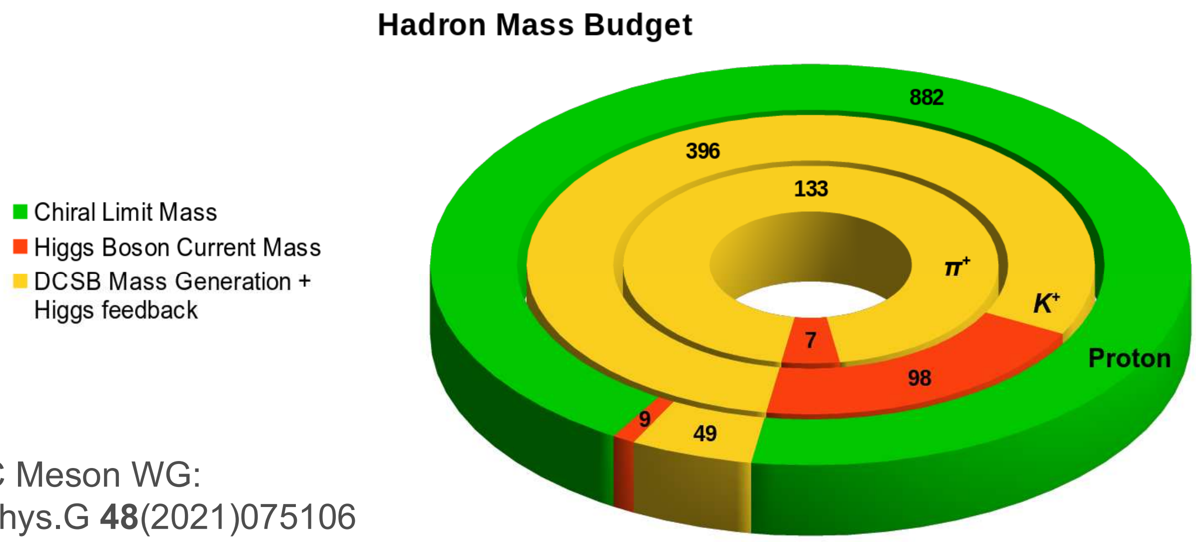
Contrasts in Hadron Mass Budgets



EIC Meson WG:
J.Phys.G **48**(2021)075106

Stark Differences between proton, K^+, π^+ mass budgets

- Due to Emergent Hadronic Mass (EHM), Proton mass large in absence of quark couplings to Higgs boson (chiral limit).
- Conversely, and yet still due to EHM and DCSB, *K* and π are massless in chiral limit (i.e. they are Goldstone bosons).
- The mass budgets of these crucially important particles demand interpretation.
- Equations of QCD stress that any explanation of the proton's mass is incomplete, unless it simultaneously explains the light masses of QCD's Goldstone bosons, the π and *K*.

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Measurement of K^+ Form Factor

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

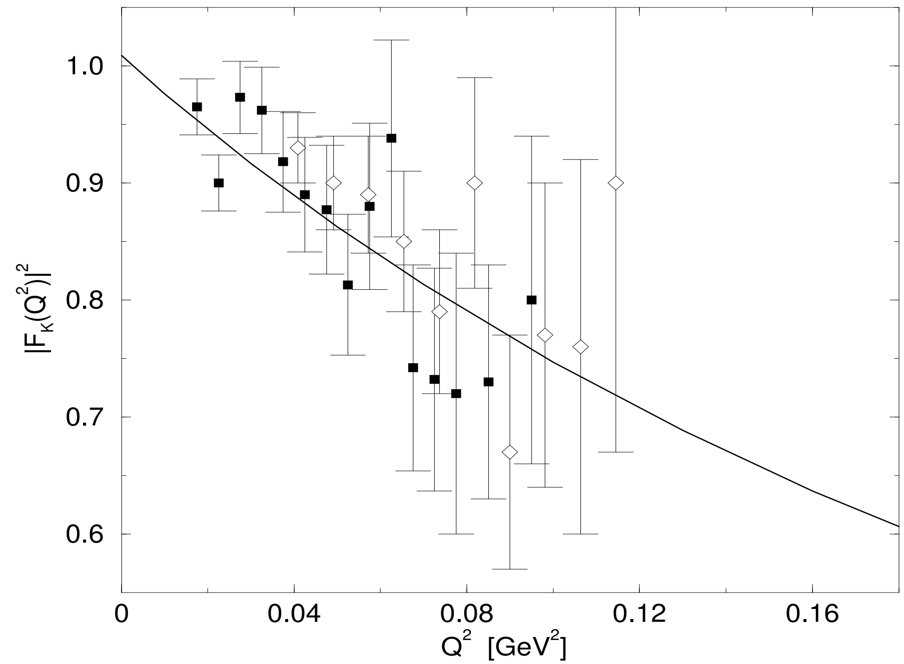
  [Amendolia, et al., PL **B178** (1986) 435]

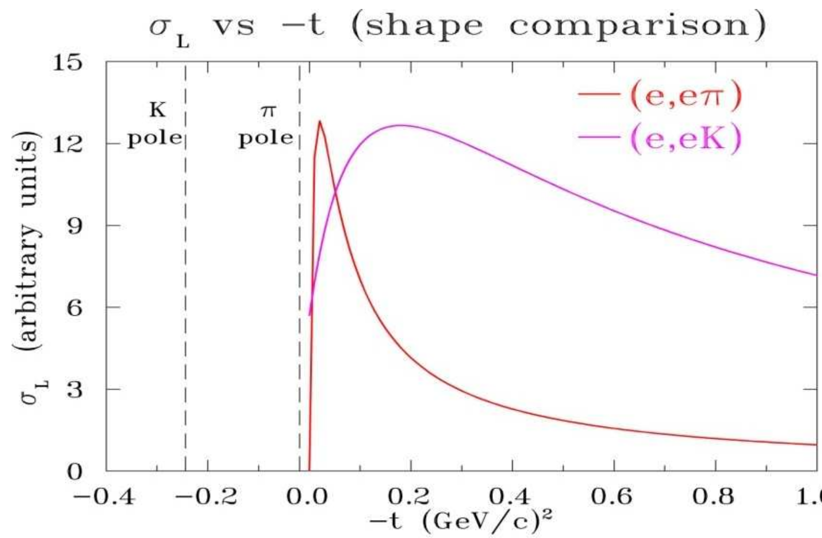
- Can "kaon cloud" of the proton be used in the same way as the pion to extract kaon form factor via ***p(e,e'K⁺)Λ*** ?

- Kaon pole further from kinematically allowed region.

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_K^2)} g^2_{K\Lambda N}(t) F_K^2(Q^2,t)$$

- Many of these issues will be explored in JLab E12-09-011.





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$p(e,e'K^+)\Lambda(\Sigma^0)$ Experiment Overview

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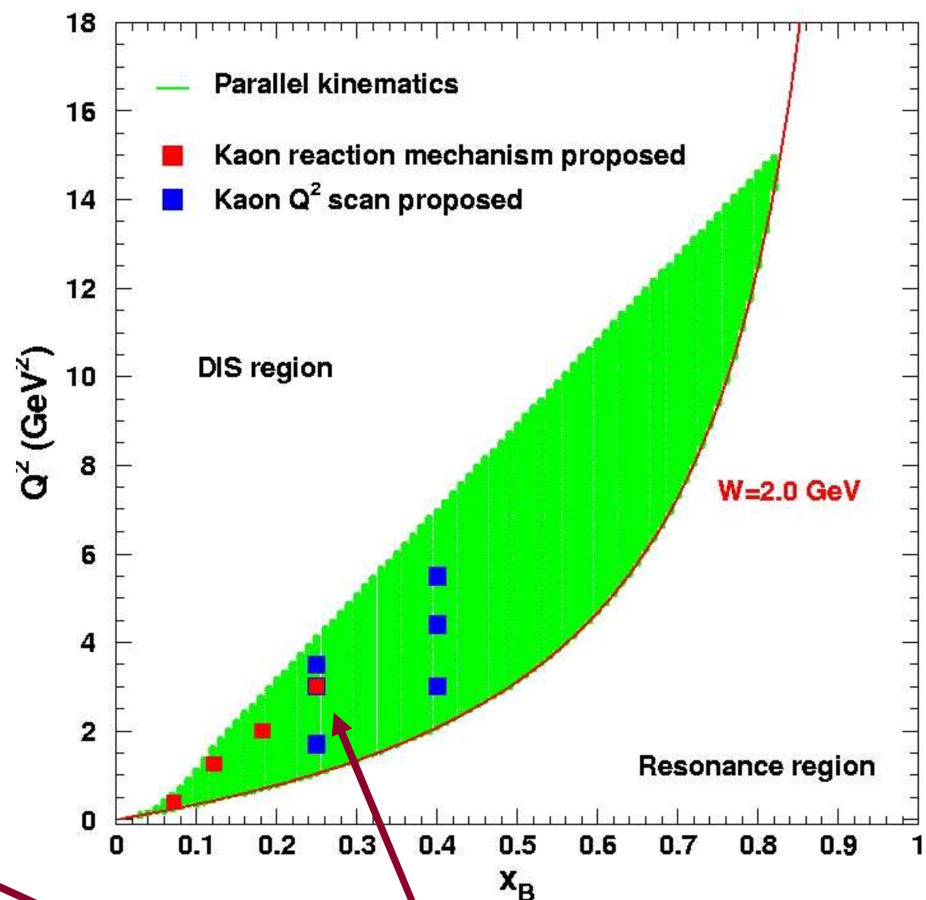
- Measure the separated cross sections at varying $-t$ and x_B
  - If K^+ pole dominates σ_L allows for extraction of the kaon ff (W>2.5 GeV)
- Measure separated cross sections for the $p(e,e'K^+)\Lambda(\Sigma^\circ)$ reaction at two fixed values of $-t$ and x_B
  - Q^2 coverage is a factor of 2-3 larger compared to 6 GeV at much smaller $-t$
  - Facilitates tests of Q^2 dependence even if L/T ratio less favorable than predicted



x	Q^2 (GeV^2)	W (GeV)	-t $(GeV/c)^2$
0.1-0.2	0.4-3.0	2.5-3.1	0.06-0.2
0.25	1.7-3.5	2.5-3.4	0.2
0.40	3.0-5.5	2.3-3.0	0.5

Q^2=3.0 GeV^2 was optimized to be used for both t-channel and Q^{-n} scaling tests

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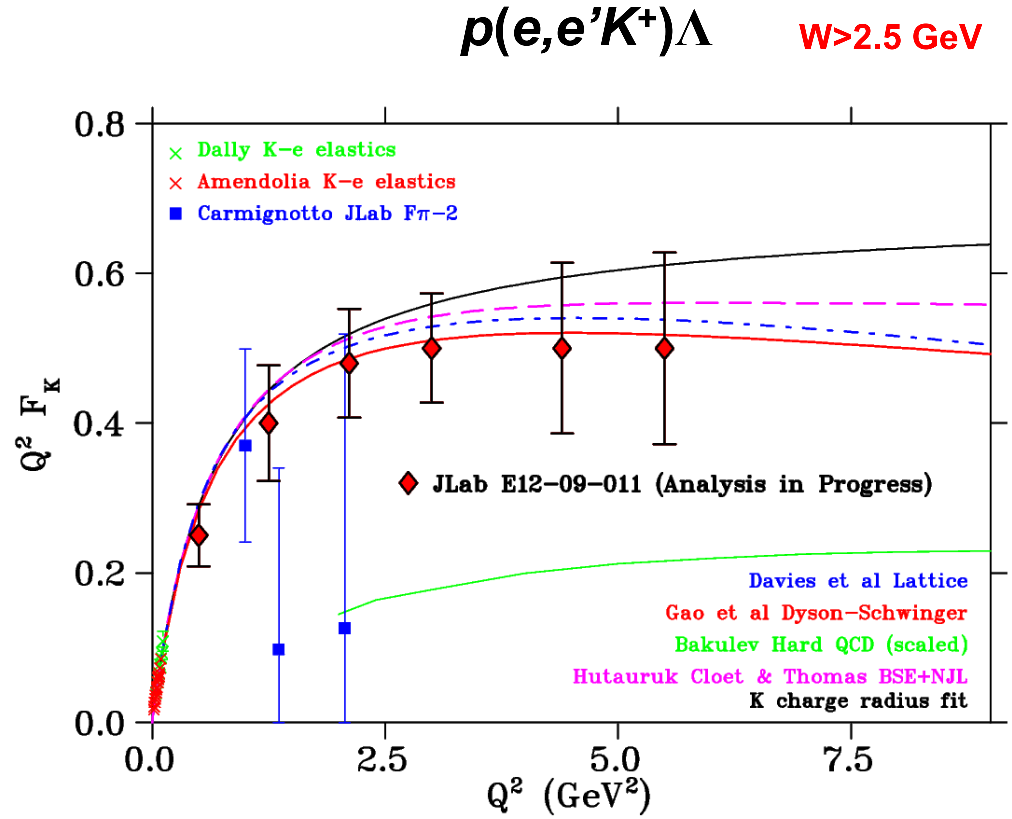
Projected Uncertainties for K^+ Form Factor

University of Regina

- 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.



Extraction of F_K from Q^2>4 GeV^2 data is more uncertain, due to higher $-t_{min}$

- ***Partially completed as an early SHMS commissioning experiment: LT–separation (E12–09–011: T. Horn, G. Huber and P. Markowitz, spokespersons)***
- ***Data under analysis, expecting final results next year***

— R. Trotta (CUA/Virginia)

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F_{π}–1,2 used VGL Model to extract F_{π} from σ_L

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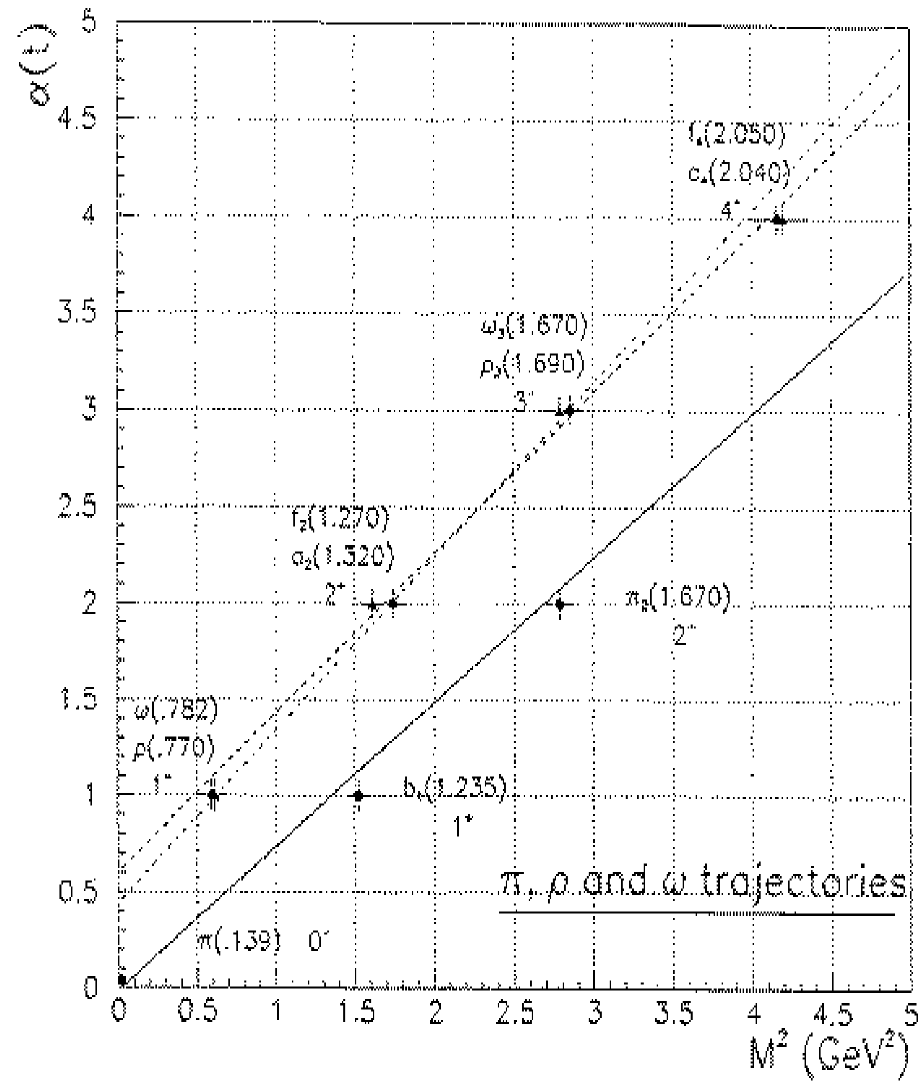
- Feynman propagator $\left(\frac{1}{t - m_{\pi}^{2}}\right)$ replaced by π and ρ Regge propagators.
  - Represents the exchange of a <u>series</u> of particles, compared to a <u>single</u> particle.
- Model parameters fixed from pion photoproduction.
- Free parameters: Λ_{π}, Λ_{ρ} (trajectory cutoffs).
- ρ exchange does not significantly influence σ_L at small $-t$.
- Pion form factor is a free parameter in the model, parameterized as:

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



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

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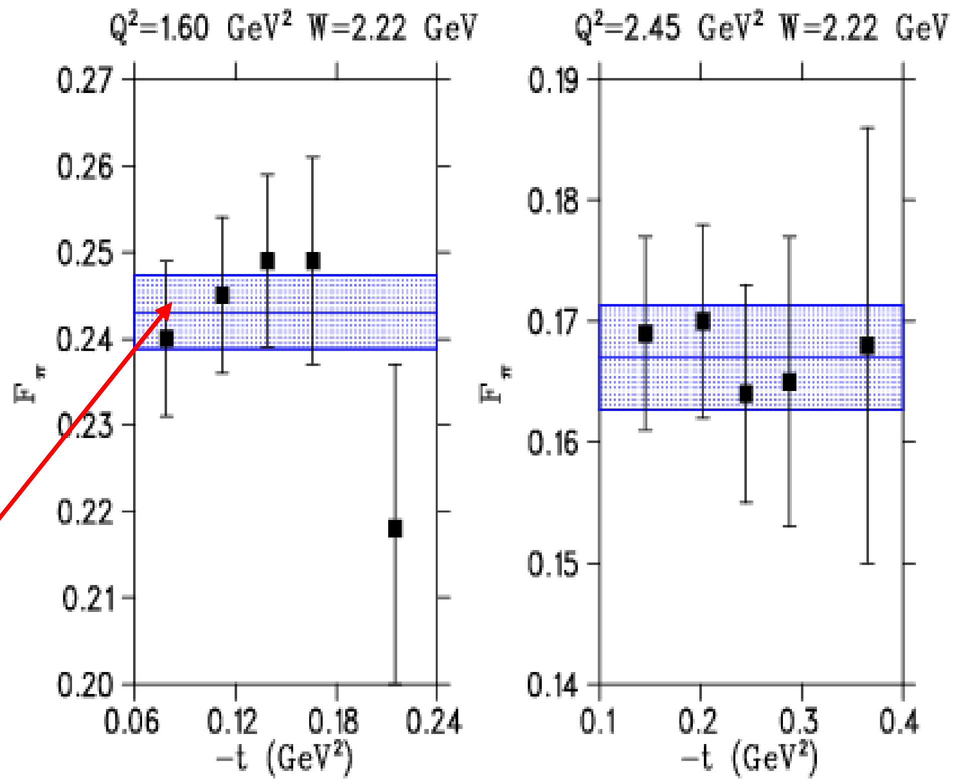
Fπ-2 VGL $p(e,e'\pi^+)n$ model check

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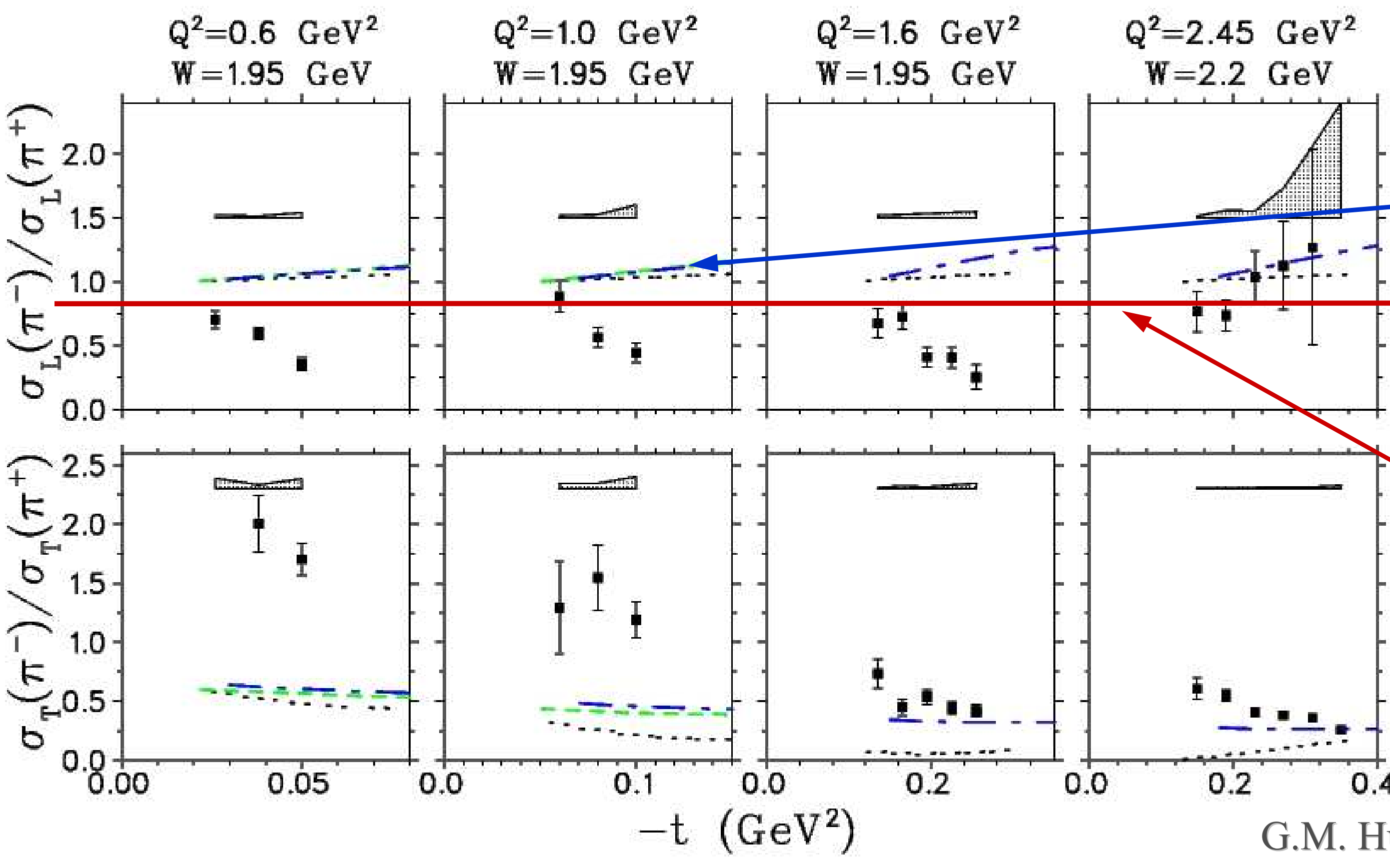
π^-/π^+ data to check *t*-channel dominance

- 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** (2014) 182501

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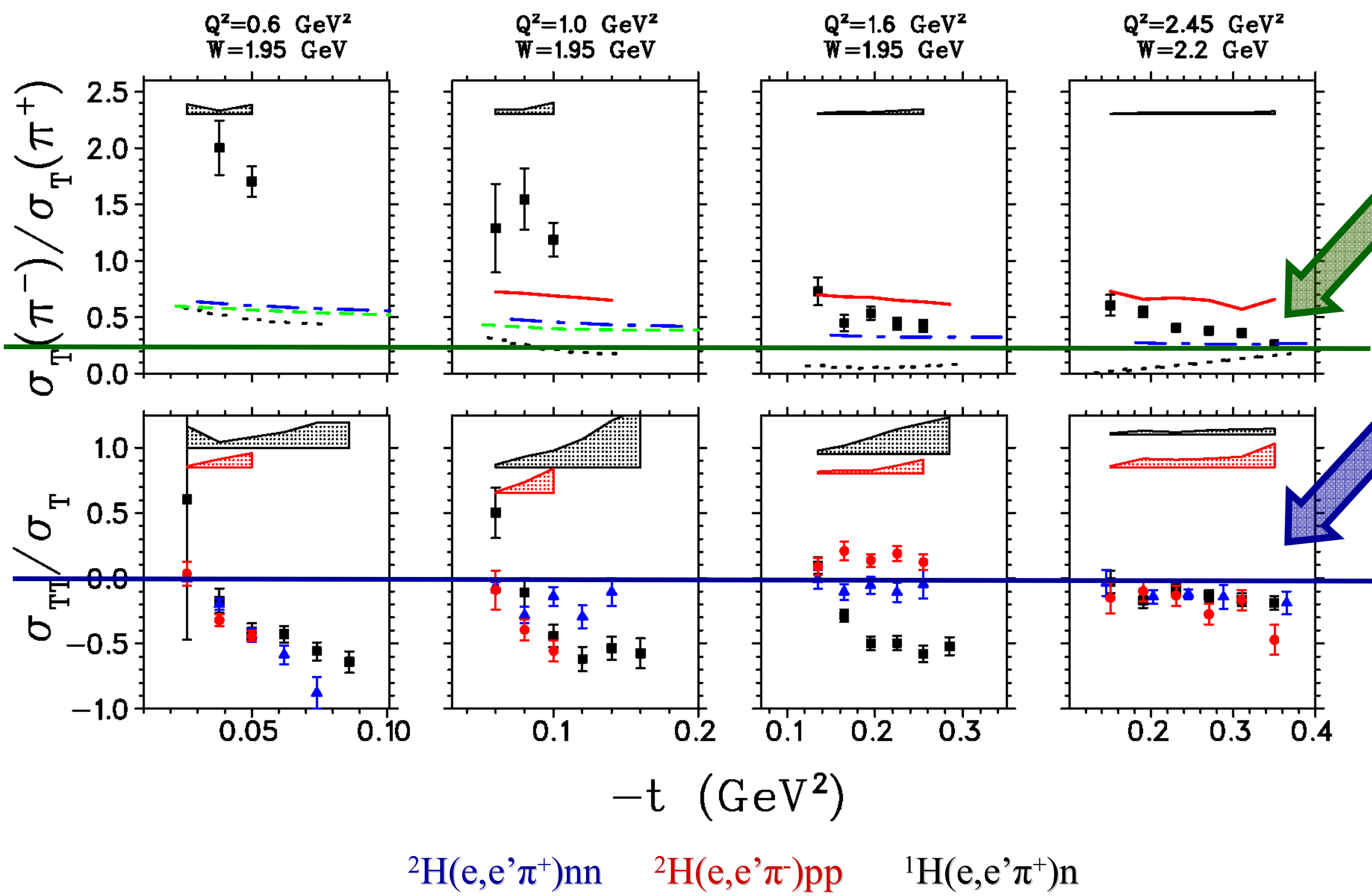
π^-/π^+ Hard–Soft Factorization Test

- **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 contributions 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.

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

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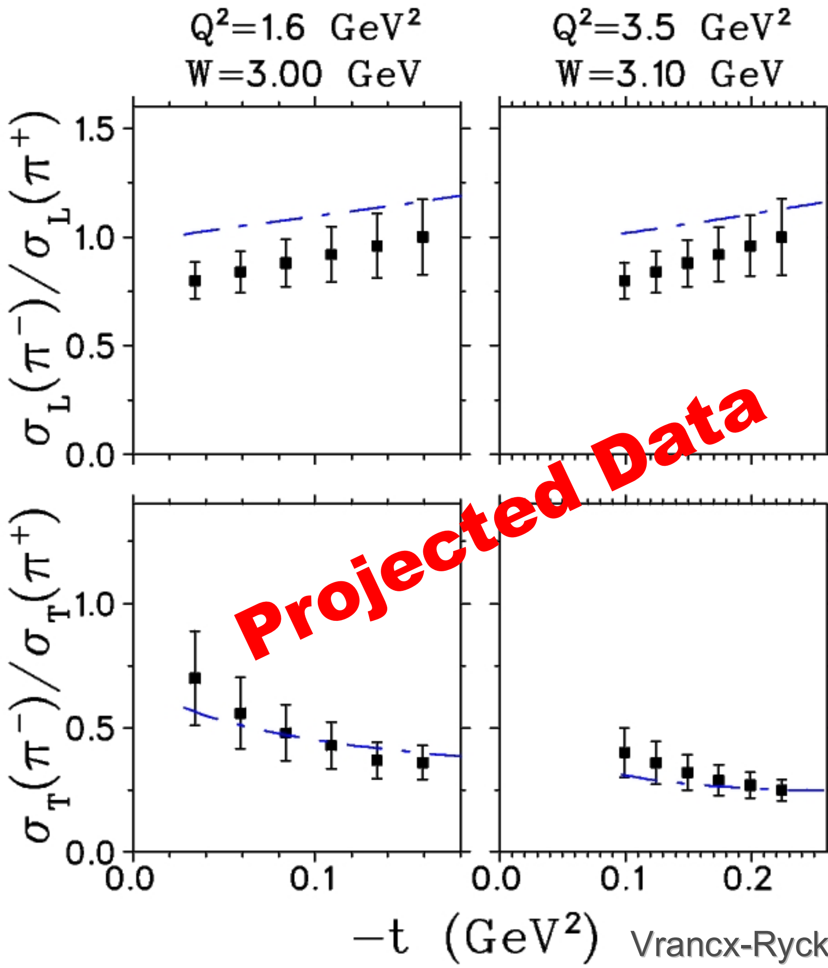
Verify that σ_L is dominated by *t*-channel process

- 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, 3.85, 6.0 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.

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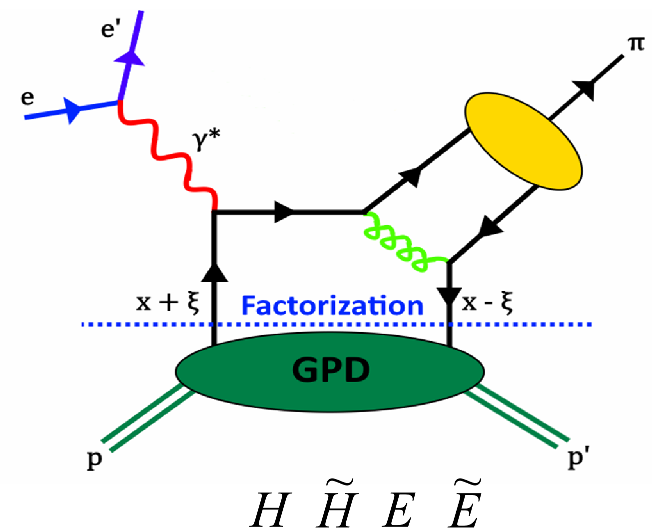
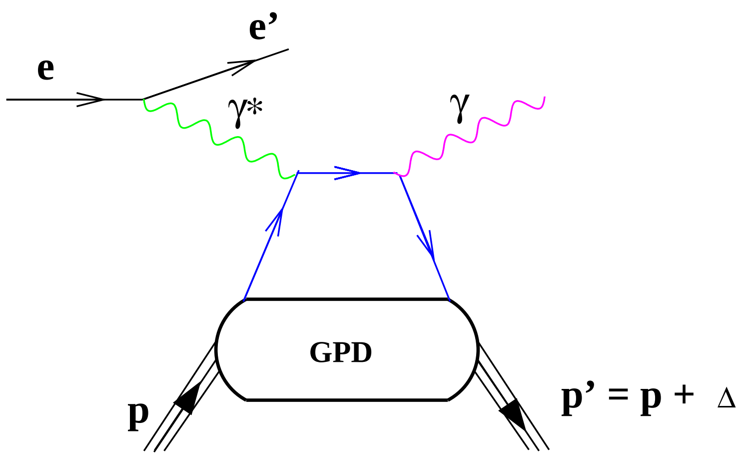
Complementarity of Different Reactions



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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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.

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

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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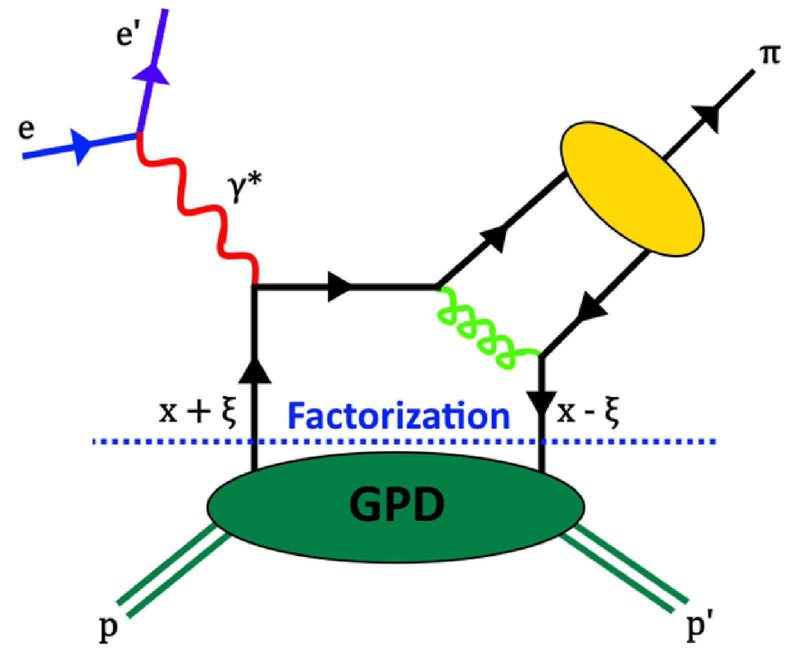
Verification of GPD Accessibility

- **At sufficiently high Q^2, the Hard–Soft Factorization Theorem separates the reaction amplitude into two parts:**
  - Hard scattering process, where perturbative QCD can be used
  - A non–perturbative (soft) part, where the response of the target nucleon to the virtual photon probe is encoded in GPDs



$H \quad \widetilde{H} \quad E \quad \widetilde{E}$

Collins, Frankfurt, Strikman PRD 56(1997)2982

- **To access physics contained in GPDs, one is limited to the kinematic regime where hard–soft factorization applies**
- No single criterion for applicability, but tests of necessary conditions can provide evidence that Q^2 scaling regime reached

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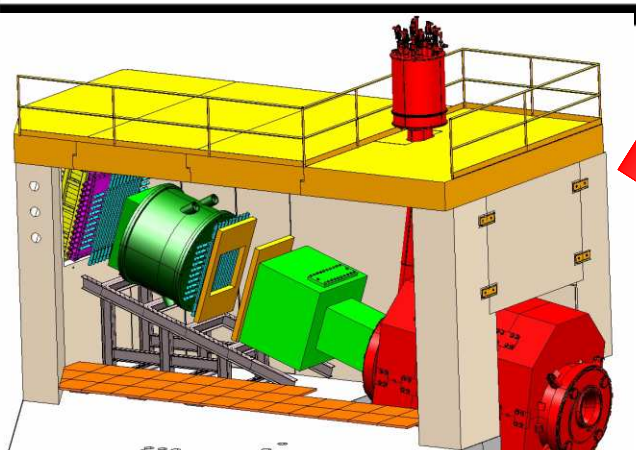
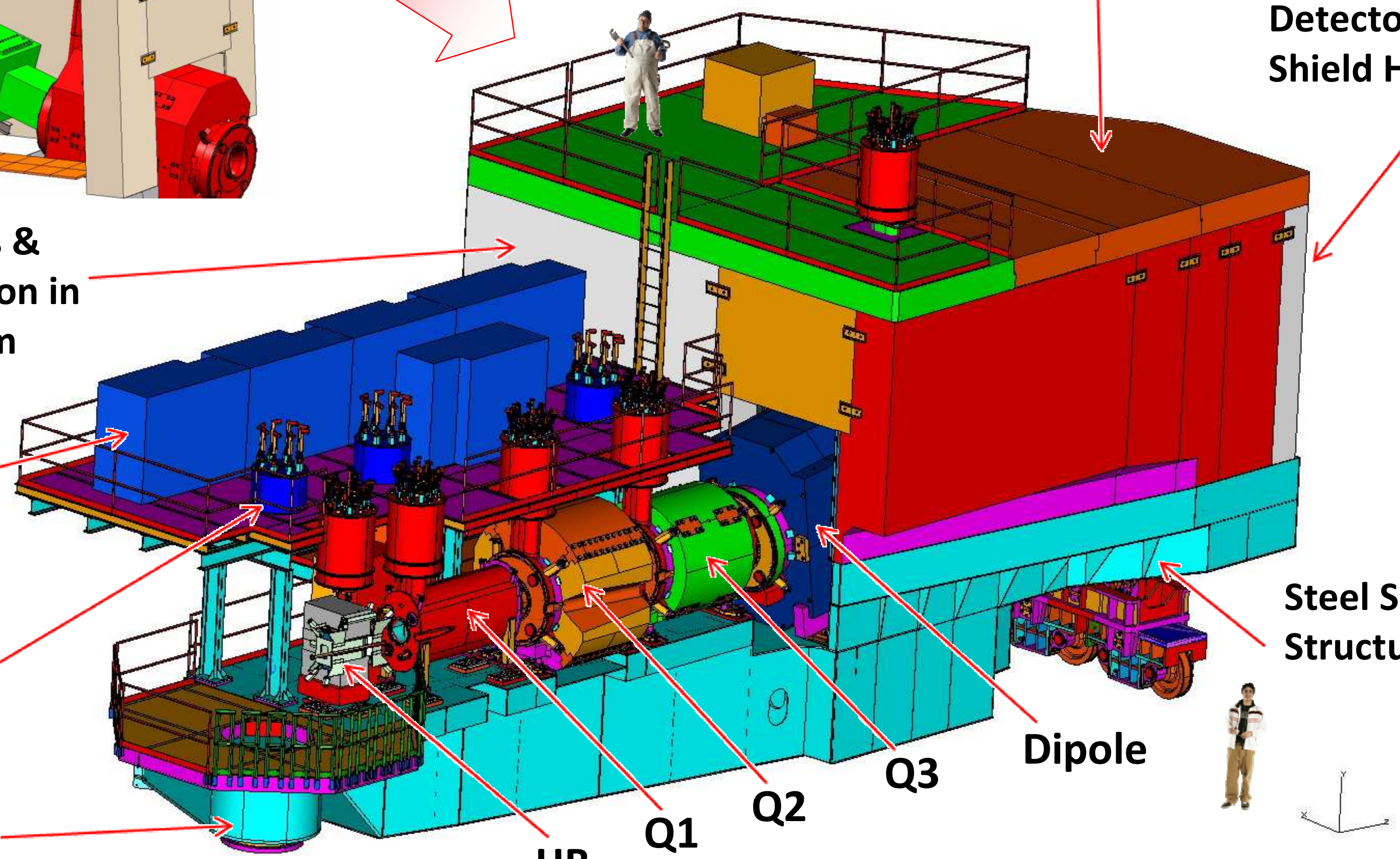
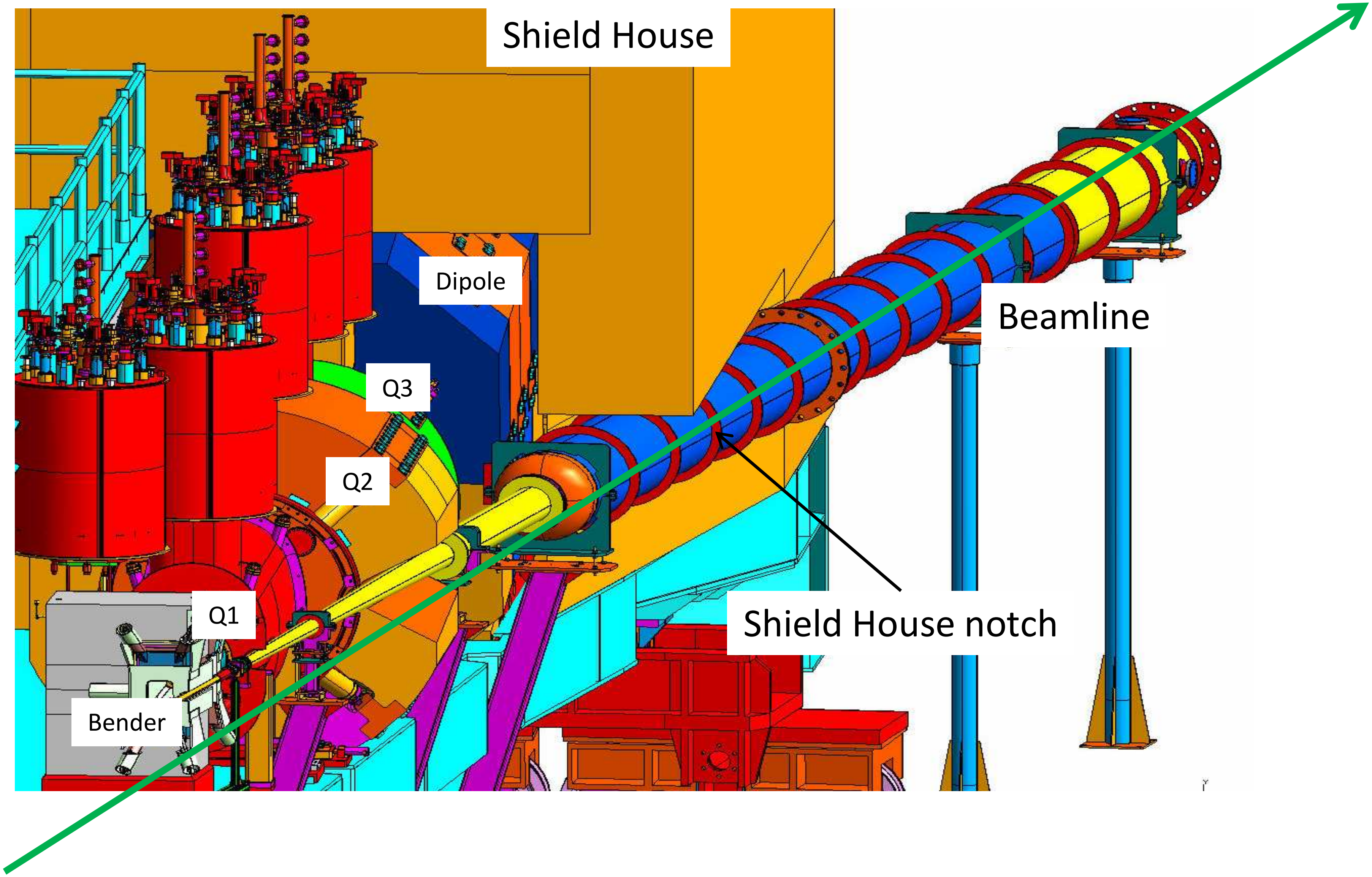
Super HMS Overview



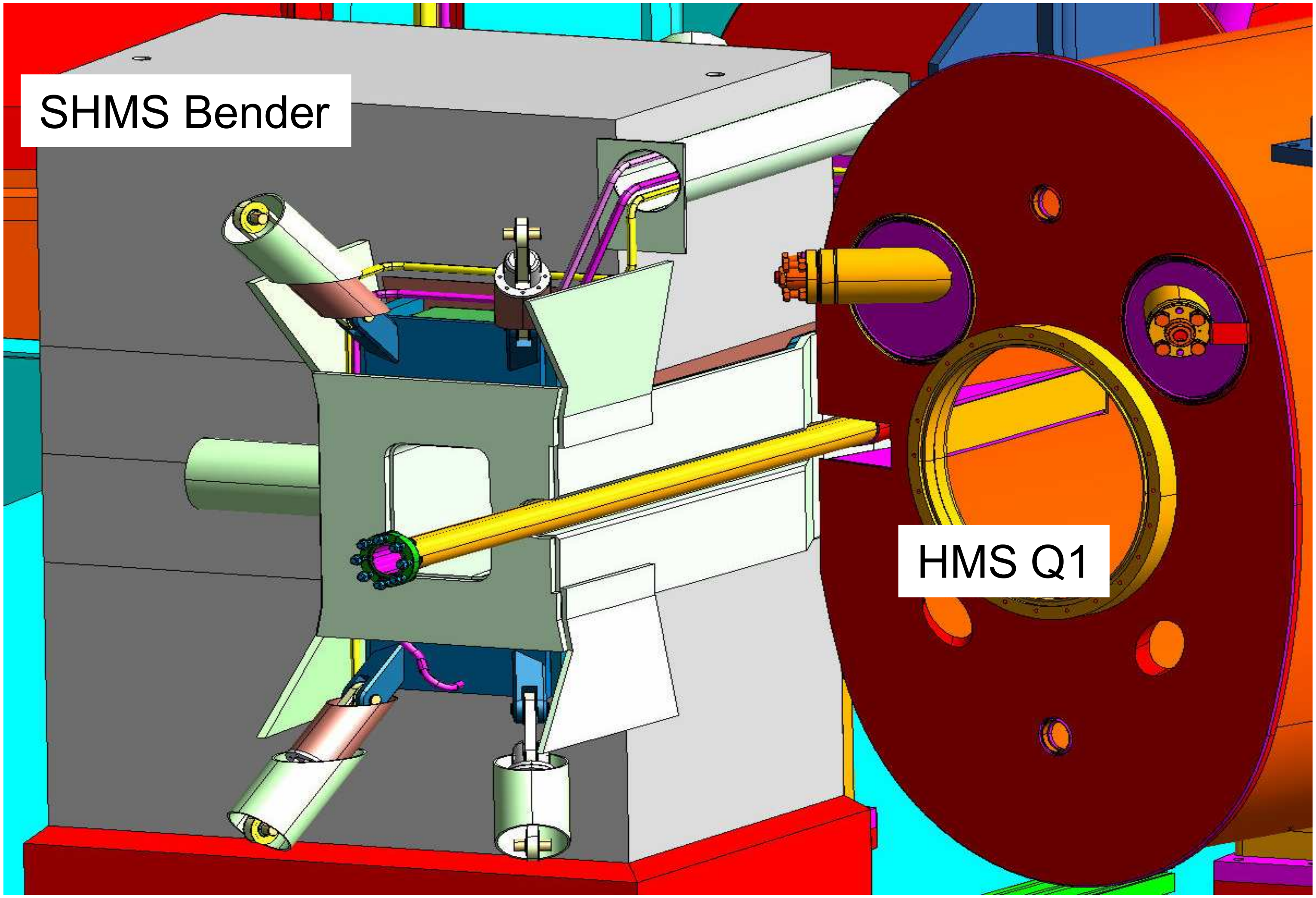


Also: Beamline Vacuum, Mods to Møller, Compton, Scattering Chamber

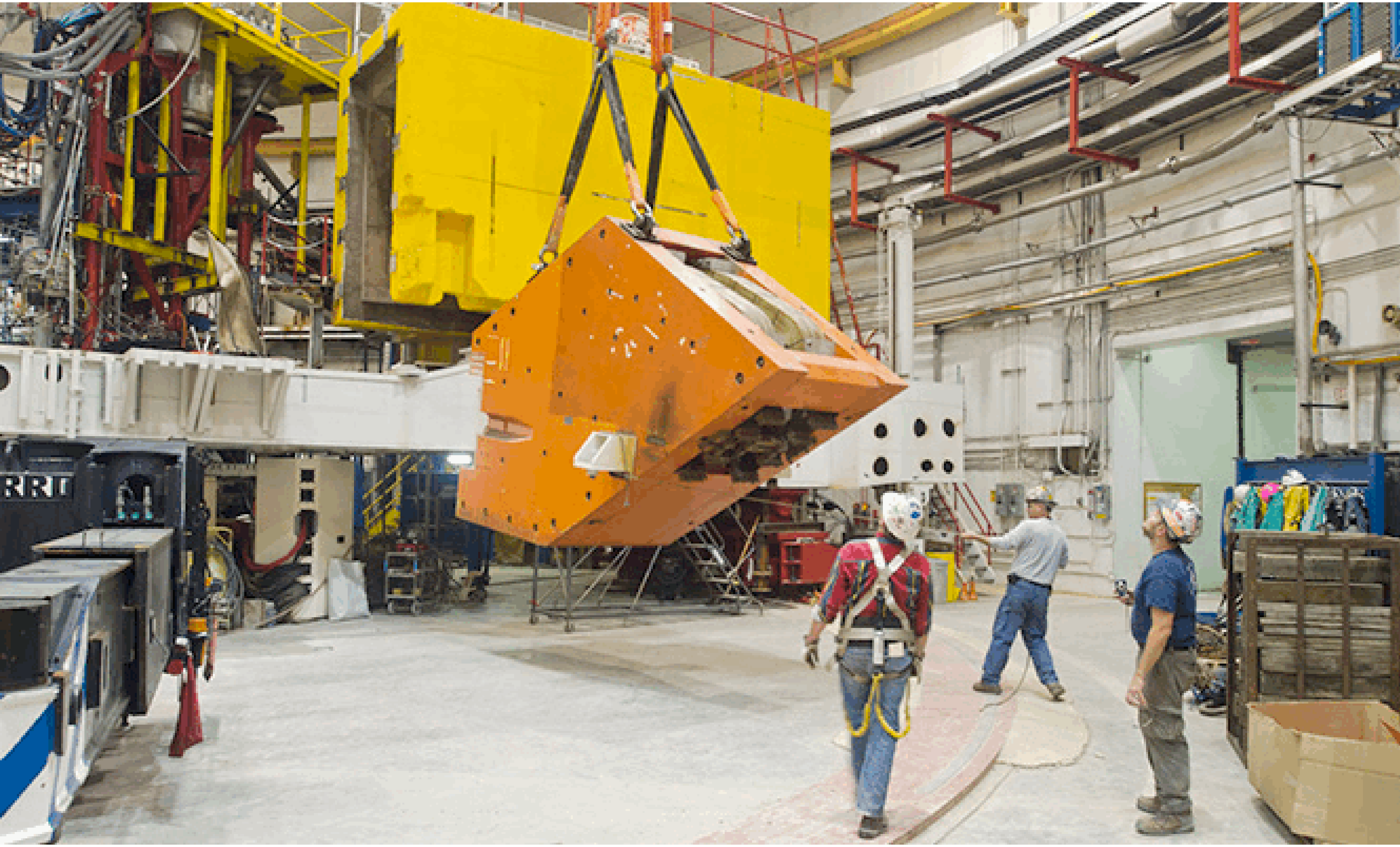
Engineering for SHMS Small Angle Operation



Bender Fit to HMS Q1

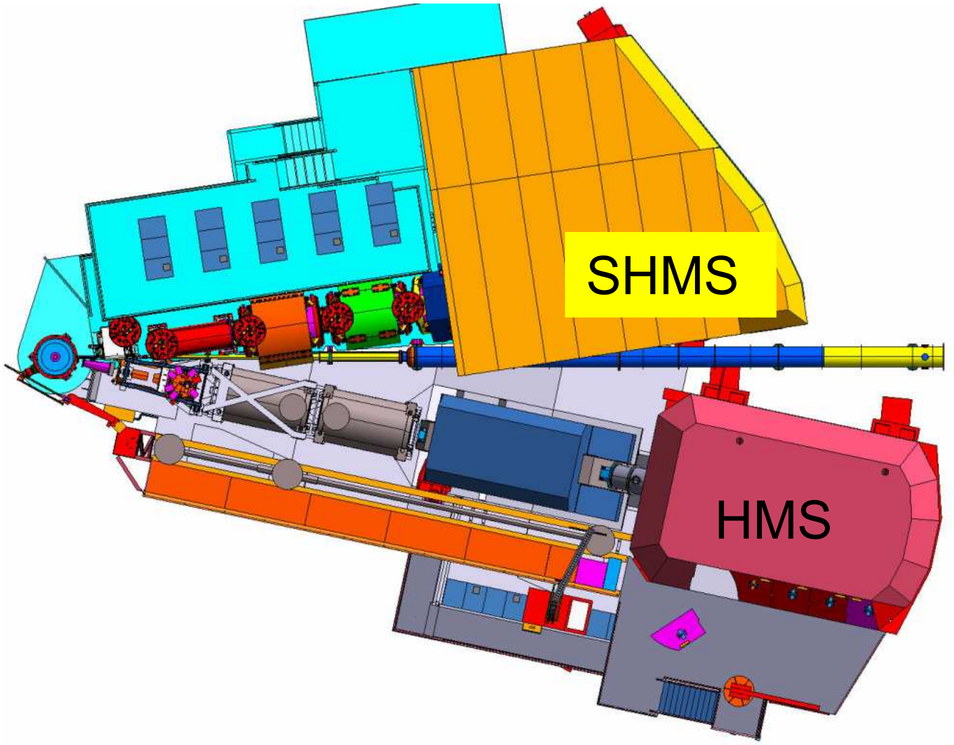


Dismantling the SOS in Early 2013

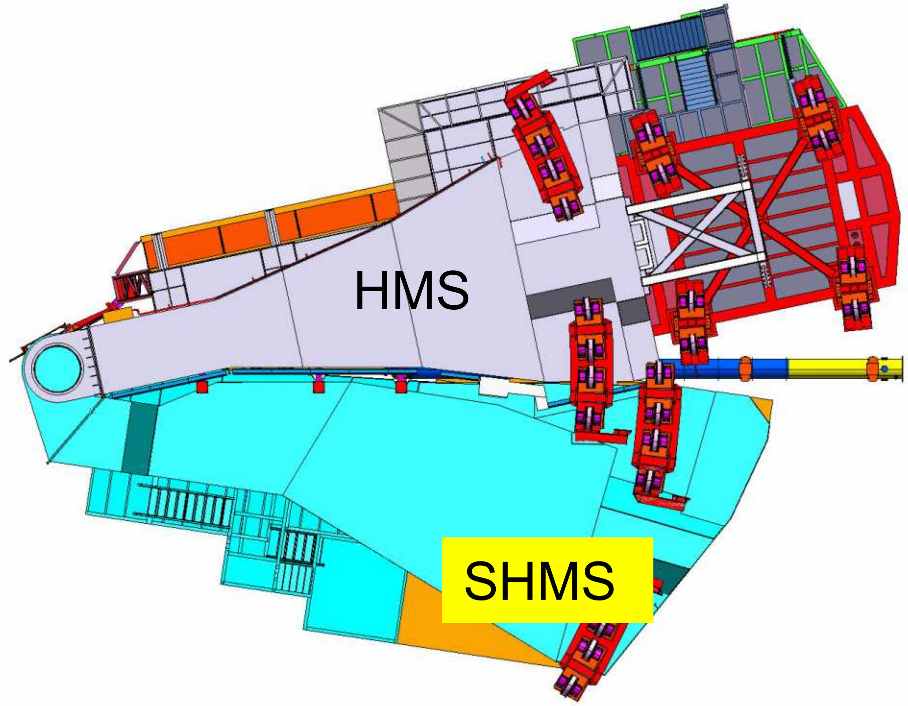


Getting Both Spectrometers to Small Angles

<u>Top View</u>



<u>Bottom View</u>



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

SHMS Nearing Completion - Feb 16, 2017