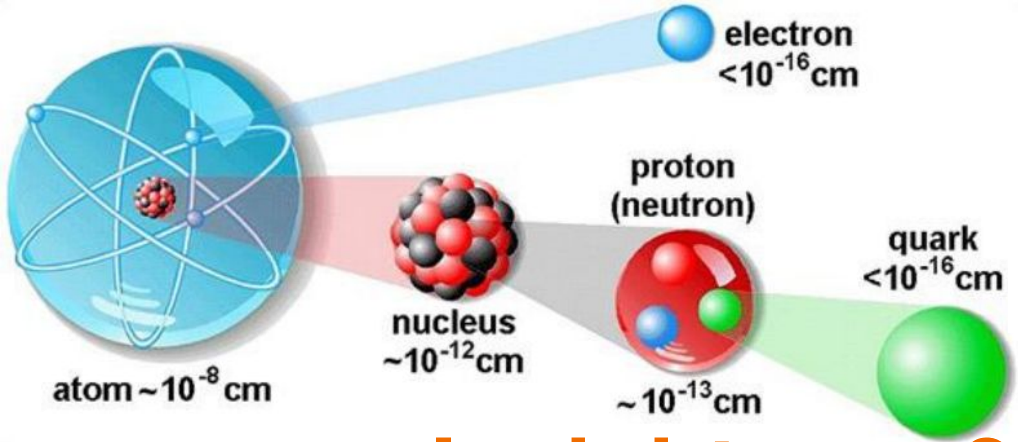
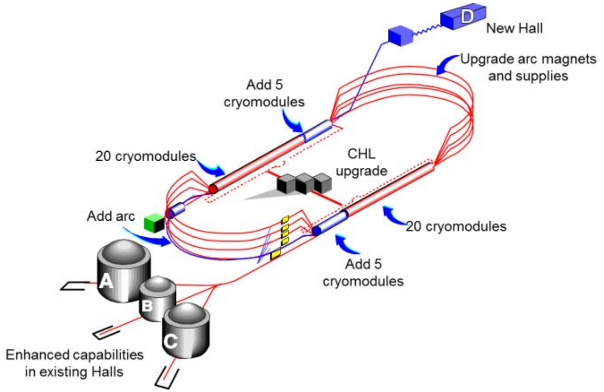



# Insights on 3D Nucleon Structure through Kaons

Richard Trotta
Spokespeople: Tanja Horn, Garth Huber, Pete Markowitz

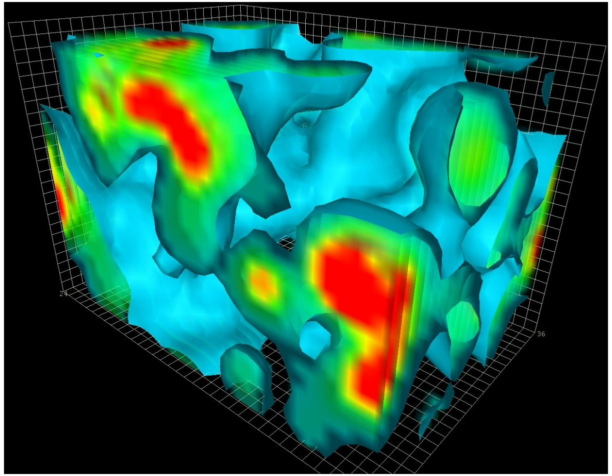
CUA

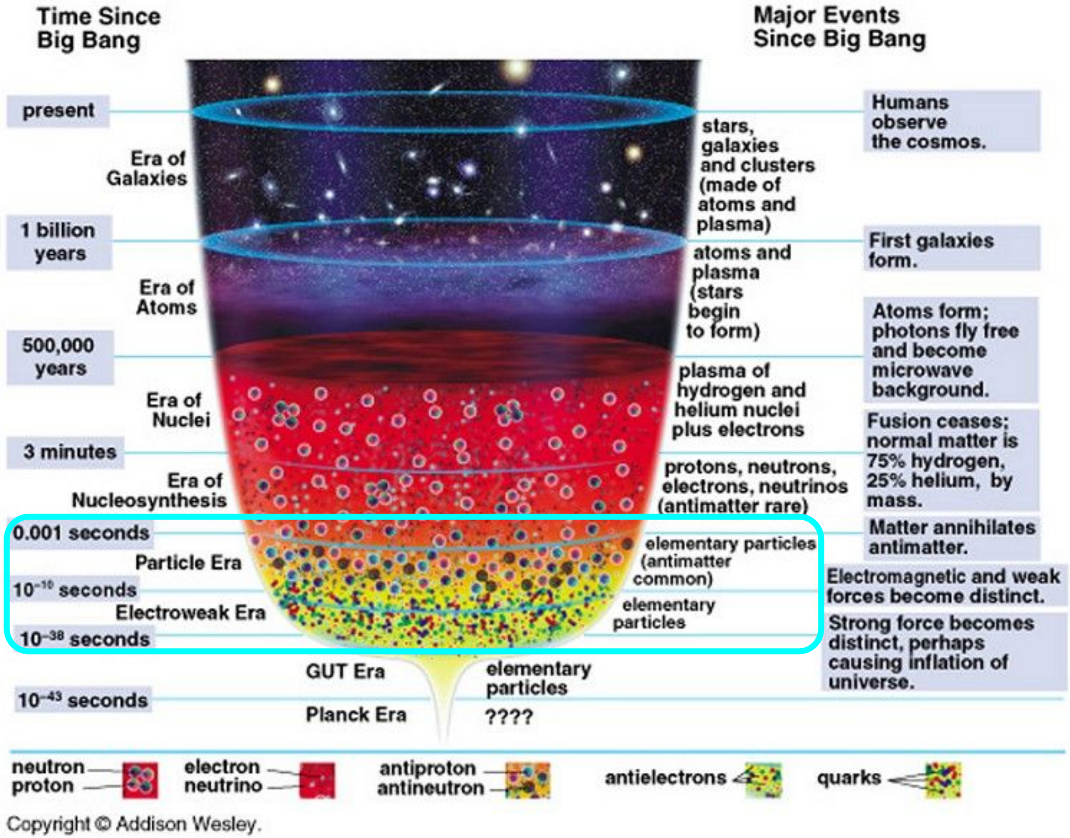
DEUS LUX MEA EST

Jefferson Lab

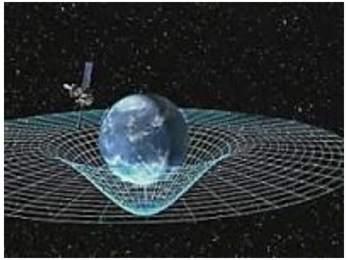
# Particle and Nuclear Physics

- Nuclear physics seeks to
  - Understand the fundamental structure of visible matter (i.e. quarks, gluons)
  - Understand how hadrons (i.e. mesons, nucleons) are formed



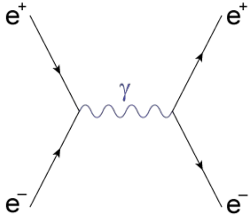


# Four Fundamental Forces



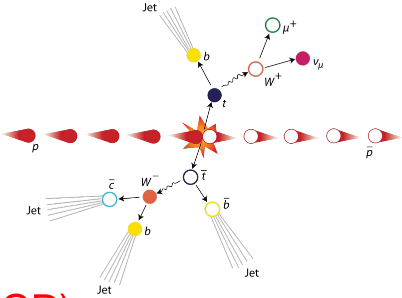
- Gravity, general relativity

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$




- Electromagnetism, quantum electrodynamics (QED)

$$\mathcal{L}_{QED} = i\bar{\psi}\gamma^{\mu}D_{\mu} - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

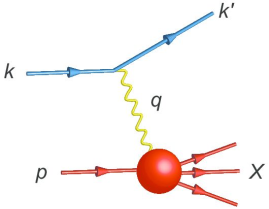



- Weak Force, electroweak theory (EW)

$$\mathcal{L}_{EW} = \mathcal{L}_g + \mathcal{L}_f + \mathcal{L}_h + \mathcal{L}_y$$

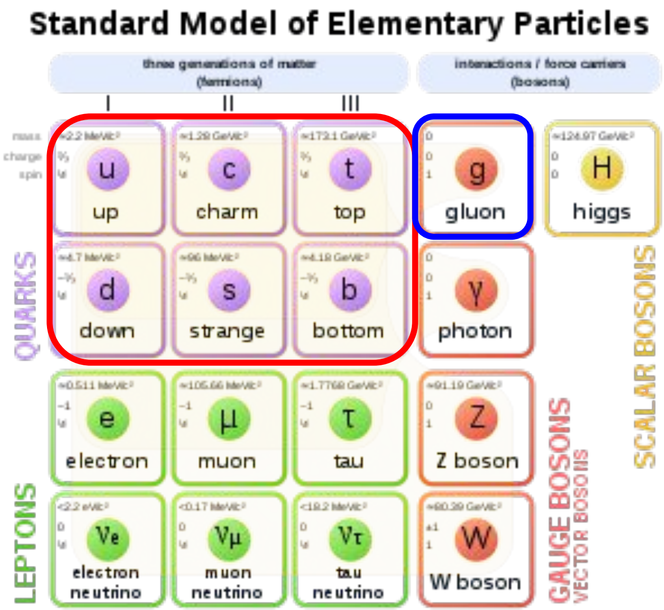
- Strong Force, quantum chromodynamics (QCD)

$$\mathcal{L}_{QCD} = \bar{q}_i[i\gamma^{\mu}[D_{\mu}]_{ij} - M\delta_{ij}]q_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$



# Try All Six Flavors!

- Quarks, similar to leptons, have six flavors
- Everyday matter is made of protons and neutrons, which are made of the light up and down quarks
- The strong force mediates massless gluons between quarks, like how photons are the mediating force carrier between charged particles
- These gluons interact with the up and down quarks, rapidly changing colors to make what we see as protons and neutrons
    - Hadrons are color-neutral bound states of quarks
        - three valence quarks (baryons)
        - valence quark-antiquark pair (mesons)

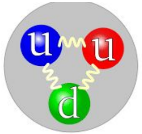


# Is the Proton Pointlike?

- A microscope uses photons to see tiny objects, can we do something similar to view the proton?
    - Very very very high momentum photons would be needed

$$\Delta x \geq \frac{\hbar}{2\Delta p}$$

    - Why not use a similar probe with easier to access momenta?
    - Let's use the de Broglie Wavelength for motivation

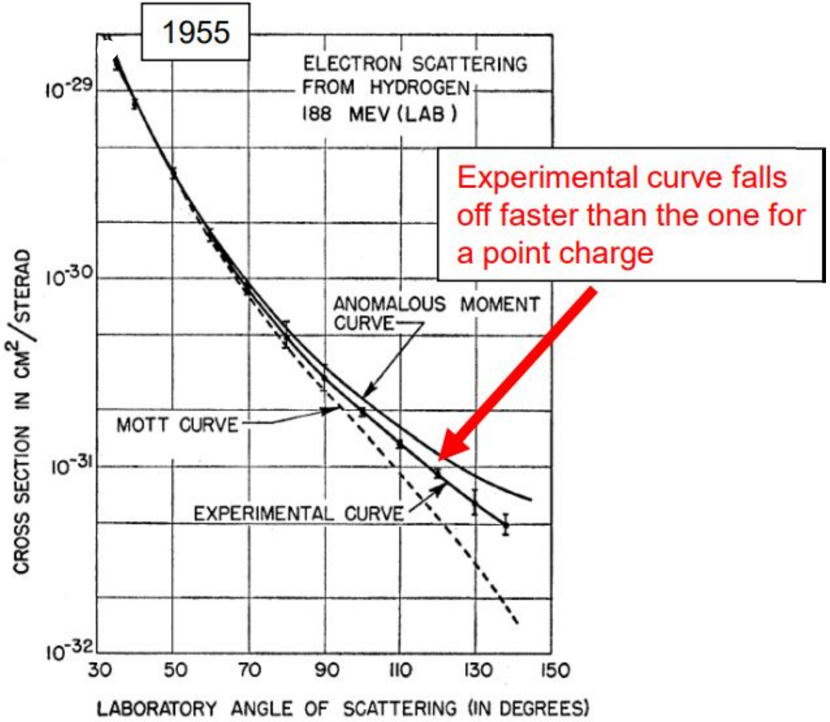



$$d_{probe} \propto \lambda = \frac{\hbar}{p}$$

- The proton interacts electromagnetically, so we use a lepton (e.g. electron) with a high momentum as a probe.

# Proton is Not Pointlike

- 1950's: The exploration of the internal structure of the proton began with Hofstadter's experiments




Point-like cross section

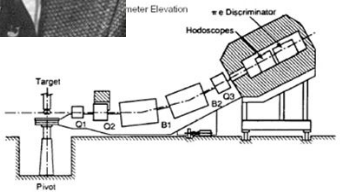
$$\frac{d\sigma}{d\Omega} = \boxed{\left(\frac{d\sigma}{d\Omega}\right)_{Mott}} \boxed{|F(Q^2)|^2}$$

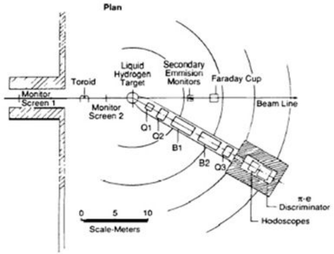
Form Factor

# Foundations of Proton's Internal Structure

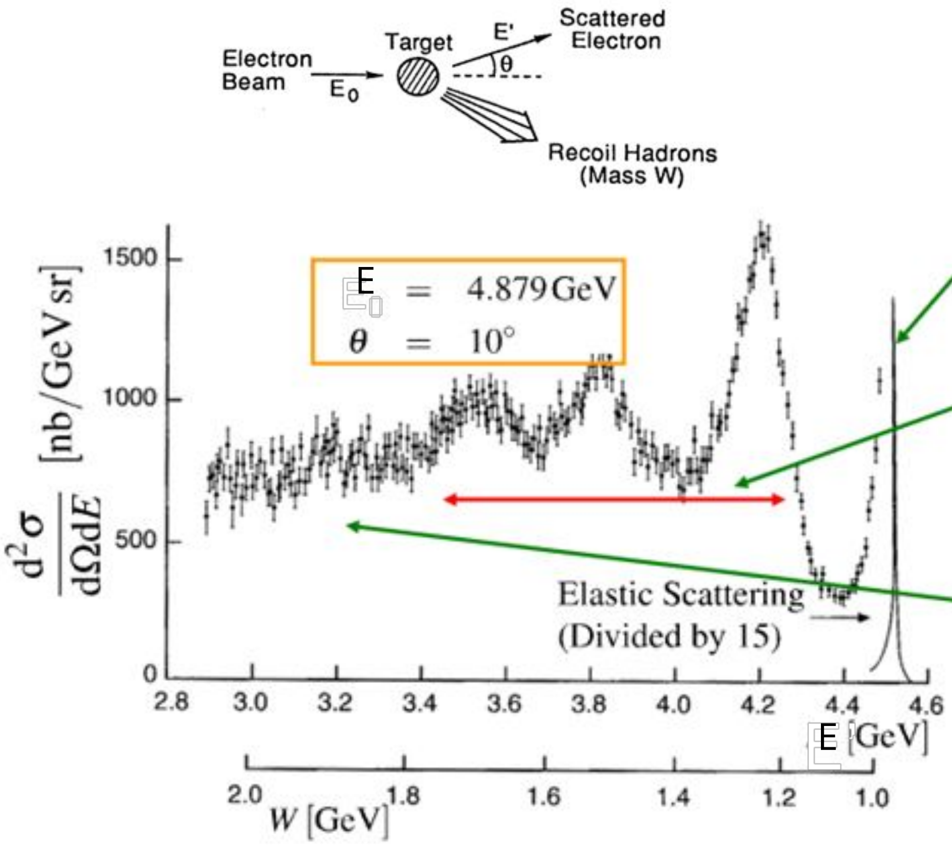
- 1960s: The proton's internal structure was described by the quark model
  - Proposed by Murray Gell-Mann and George Zweig
  - Point-like particles called quarks were what the proton was made of
- 1968: Deep Inelastic scattering (DIS) at SLAC which observed scaling. The proton's internal structure is composed of point-like charged particles.
- 1972: QCD is developed

Taylor, Friedman and Kendall



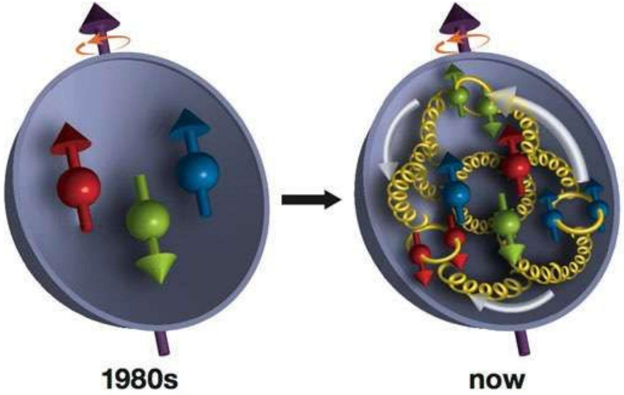
# Types of Scattering



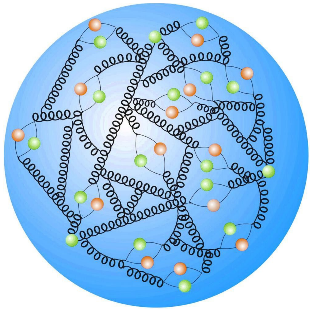

- Elastic Scattering: proton stays intact
  - The initial and final states are the same, only the momenta change.
  - **Static image!**
- Inelastic Scattering: proton gets excited, produces excited states or proton's resonances
- Deep Inelastic Scattering: proton breaks up and end up with a many particle final state
  - **Dynamical image!**

# Mysteries of the Proton

- Proton spin puzzle
  - 1980s: experiments performed by the European Muon Collaboration
  - They showed that the contribution of quark spin to the total spin of the proton was between 4-24%
  - This was later confirmed by other experiments to be around 30%

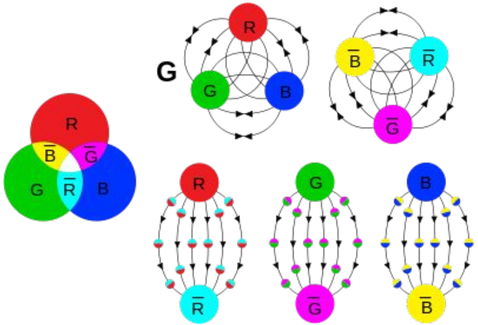


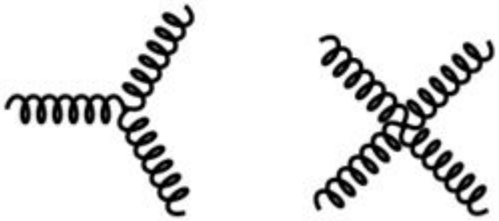

- Origin of hadron mass
  - The total is more than the sum of the parts, there's more than quarks making up the substructure
  - As we will see this is due to a quark-gluon sea and gluon dynamical interactions



# What is Quantum ChromoDynamics (QCD)?

- QCD is the theory describing strong force interactions through color-charged particles (quarks)
  - The strong force holds together protons and neutrons
  - Color is a quantum number
    - Quarks come in three colors; red, blue, green
    - Antiquarks come in three anticolors; antired, antiblue, antigreen

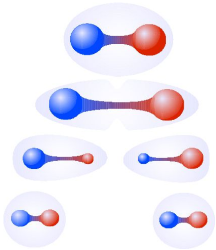


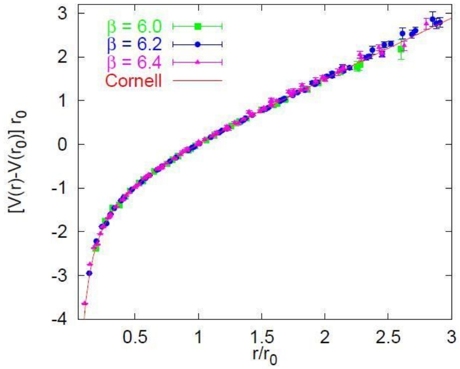



  - Gluons generate a color change for quarks (for the more advanced $SU_c(3)$), but they also can self interact (unlike photons in E&M)

# Solitary Confinement...plus a friend or two

- Unlike photons in QED, the strong force does not get weaker the further apart two quarks are. It gets stronger!
- This property means an infinite amount of energy would be required to remove a quark from a proton
  - This has led to the confinement hypothesis, which states that color-charged particles cannot be isolated (i.e. no singlet states). They must only exist in color-neutral bound states.
- Coupling with the gluon field is ~$5 \times 10^5$ times larger than coupling with the photon field...





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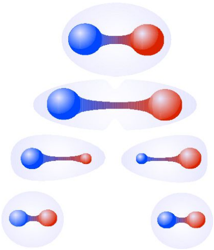
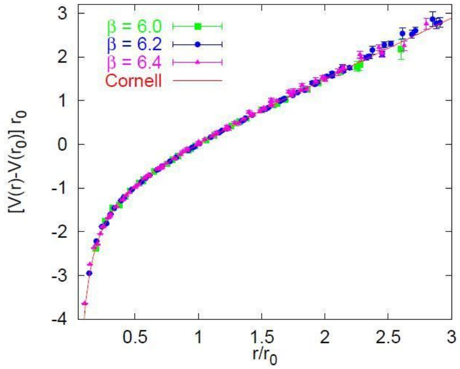
- Coupling with the gluon field is ~$5 \times 10^5$ times larger than coupling with the photon field...**well sometimes**

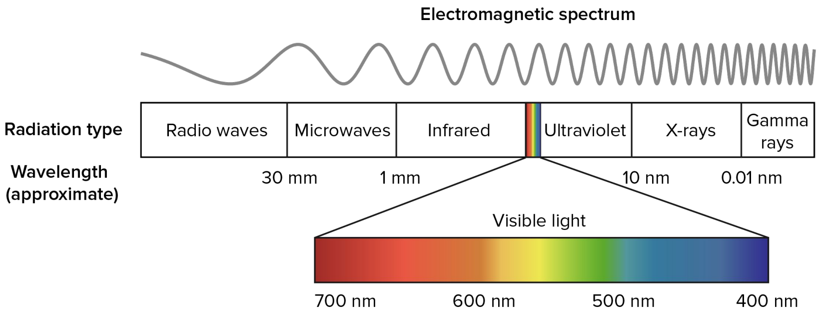




# Coming to a finer resolution

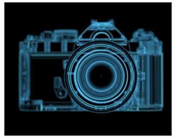
- QCD and QED are both relativistic quantum gauge-field theories which have the property that nothing is constant
  - Beloved quantum mechanical cornerstones are now dynamic, including charge distribution, mass, and even the number of particles

- This means that what you see depends on the wavelength of the probe used
  - Think about the wavelength of light for a photo vs. a xray



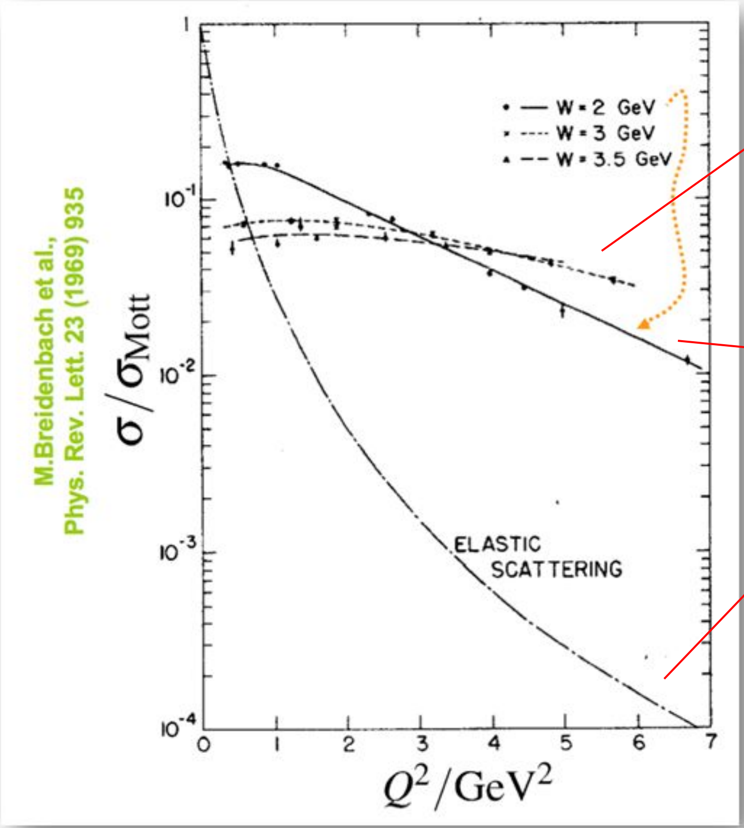

$$\lambda \simeq \frac{1}{\sqrt{Q^2}}$$

Momentum transfer

- This also means the strength of the force depends on the resolution, a so called mass-scale

# Exploring the Inner Proton




- Deep Inelastic Scattering: cross sections almost independent of transferred momentum, $Q^2$
  - i.e. "Form factors" -> unity
  - Scattering off point-like objects within proton
- Inelastic Scattering: cross sections weakly dependent on $Q^2$
- Elastic Scattering: falls off rapidly with $Q^2$ due to proton not being point-like

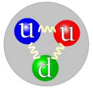
$$\frac{\sigma}{\sigma_{Mott}} = \left(\frac{1}{(1+\frac{Q^2}{0.71})^2}\right)^2 \propto Q^{-8}$$

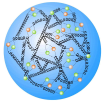
# Dynamical Nature of QCD

- The dynamical nature of QCD also affects what we know as a “quark”
- The uncertainty principle can be viewed as an inequality of energy and time
  - Nearly infinite energies can exist as long as they disappear incredibly fast

$$\Delta x \Delta p \geq \frac{\hbar}{2} \quad \Rightarrow \quad \Delta E \Delta t \geq \frac{\hbar}{2}$$

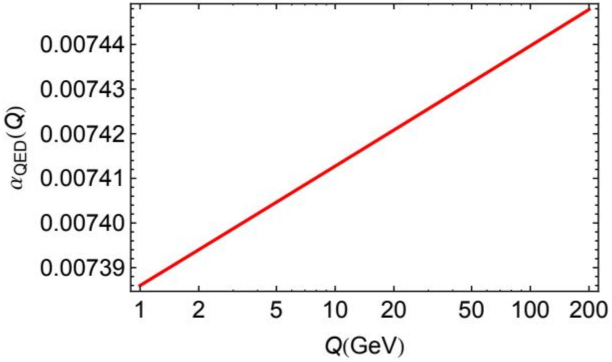
  - This is how virtual particles arise in quantum field theories
- But now in QCD these virtual particles (virtual quarks and gluons) interact with the valence quarks that make up a proton
- Probing at different scales we can see three distinct “quark” types
  - At ~30% the longitudinal momentum of the proton (a variable called x) we see the valence quarks
  - At ~10% we see a cloud of pions where the valence quarks are hidden in. (Partons we call them)
  - At ~1% we see the singlet quarks and gluons

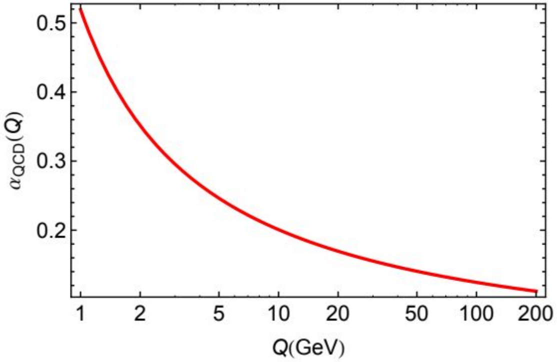


# Asymptotic Freedom

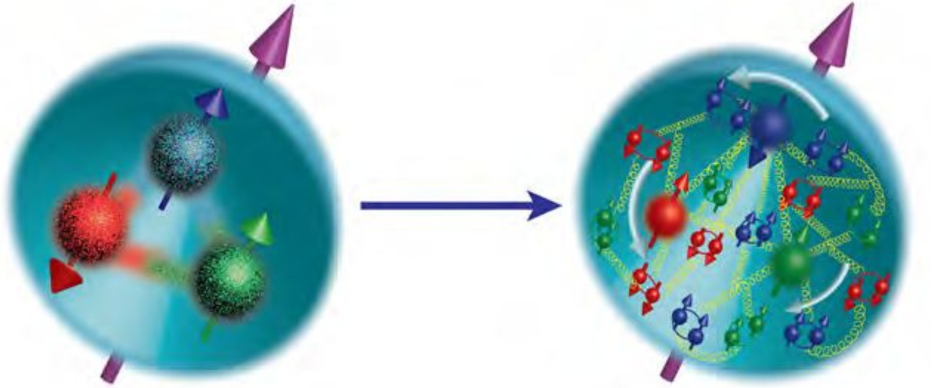
- At a higher mass-scale, the strong force asymptotically falls off. A feature known as asymptotic freedom.
- This allows QCD to be studied perturbatively at high energies
- Finding the onset of hard (perturbative QCD, pQCD) and soft (non-perturbative QCD) factorization is of critical importance in medium to high-energy physics
  - A scaling behavior in the parton model should show a dependence on transferred momentum ($Q^2$) at higher order corrections



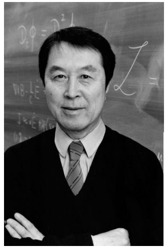




# Summary of QCD

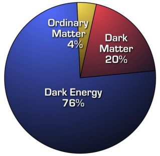
- QCD is characterized by two emergent phenomena:
  - confinement
  - dynamical chiral symmetry breaking (DCSB)
- The bound state degrees of freedom can be viewed through two lenses
  - Hadrons at large distance scales
  - Partons at small distance scales
- This transition from hadronic to partonic degrees of freedom is required to characterize hadrons ab initio
- The flavor degrees of freedom of the produced meson selectively probe aspects of the reaction mechanism



# Dynamical Chiral Symmetry Breaking



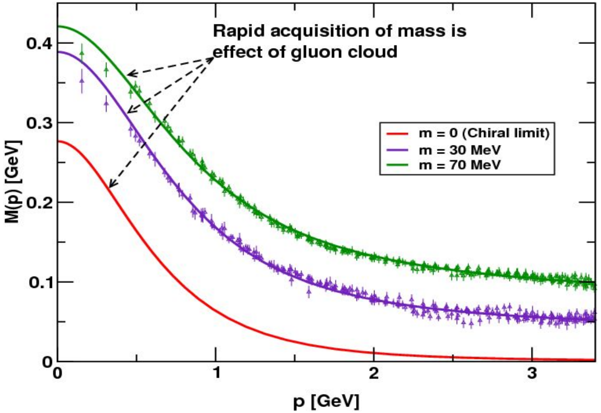
- But what is Dynamical Chiral Symmetry Breaking (DCSB)???
- Higgs boson gives valence quarks mass
    - This only contributes <1% the proton mass
    - Where does the rest of the mass come from? Well, DCSB!
    - This means that 98% of all visible matter comes from DCSB!




- This is because of a spontaneously broken symmetry, chirality (left and right “handedness”)
- The best way to study DCSB is primarily through the pion (and as we will subsequently the kaon)
- Chiral symmetry requires the pion to be partnered with a scalar meson of equal mass
    - There is no evidence for the existence of such a particle
    - No other properties of chiral symmetry are apparent in nature so the symmetry must be broken

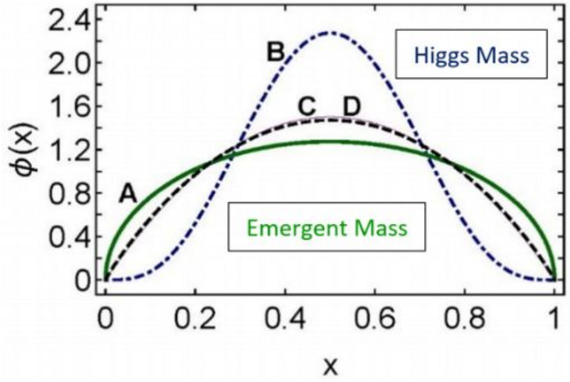
# Pion Mysteries

- The pion consists of an up quark and down antiquark so it is the simplest system to study light quarks, but also has many other unique properties
- The pion's mass is just a fifth what is expected in quantum mechanics
    - This can be contributed to symmetry constraints imposed by DCSB
    - These constraints lead to cancellations by (negative) gluon binding effects
    - This makes the pion a pseudo Nambu-Goldstone boson
- All this means that finding the origin of the proton's mass is the same as asking why the pion is so light, which is the connection between confinement and DCSB



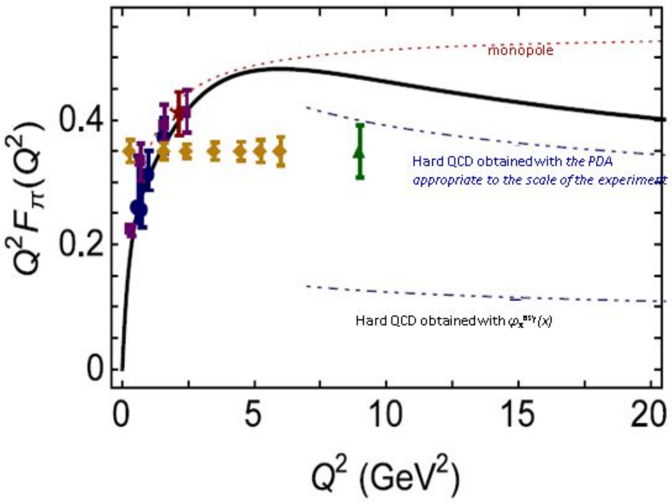
# What a Strange World!

- What about heavier quark bound states?
- The data suggests that heavier flavor quark mass is primarily generated through the Higgs mechanism
- The kaon sits in a unique position because its quark composition is both light and heavy
  - The kaon consists of an up quark and a strange antiquark
  - A competition seems to arise between DCSB and the Higgs mechanism
- The kaon is also a pseudo Nambu-Goldstone boson which makes it a prime candidate for deeper DCSB studies



# Meson Form Factors at Jlab

- Pion and kaon form factors are of special interest in hadron structure studies
  - Pion - lightest QCD quark system and crucial in understanding dynamic generation of mass
  - Kaon - next simplest system containing strangeness
- Clearest case for studying transition from non-perturbative to perturbative regions
- Jlab 6 GeV data showed form factor differs from harc QCD calculation
  - Evaluated with asymptotic valence-quark Distribution Amplitude (DA), but large uncertainties
- 12 GeV form factor extraction data require:
  - measurements over a range of t, which allow for interpretation of kaon pole contribution



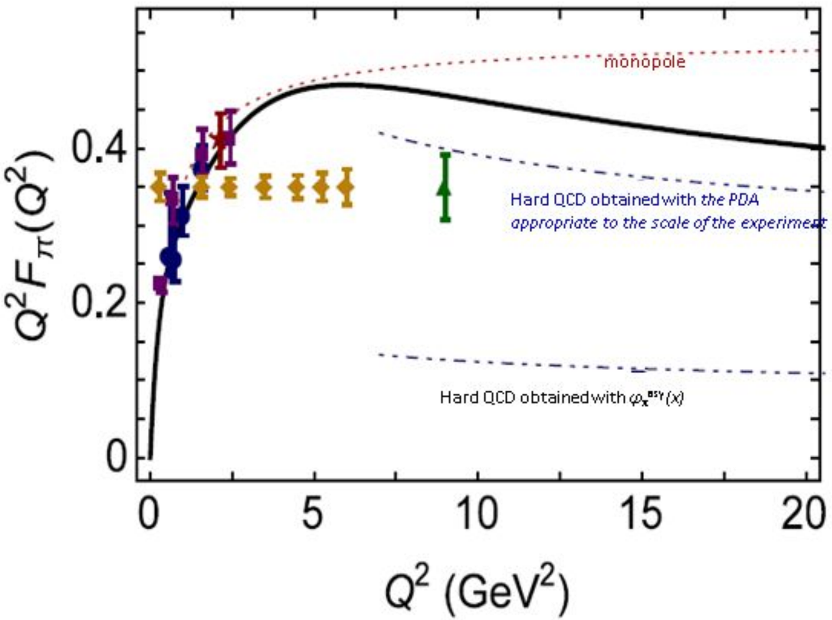
# What is the Form Factor?

Point-like cross section

$$\frac{d\sigma}{d\Omega} = \boxed{\left(\frac{d\sigma}{d\Omega}\right)_{Mott}}\boxed{|F(Q^2)|^2}$$

Form Factor

- We want a way to see how quarks are distributed in the pion/kaon
- QED is well understood so we exploit the charge of quarks
- There are two types of form factors used
  - Electric form factor ($G_E$), charge
  - Magnetic form factor ($G_M$), current
- The form factor is the fourier transform of the transverse spatial charge density
  - **1D function** dependent on the transferred momentum ($Q^2$)
- We can get the form factor from the cross-section



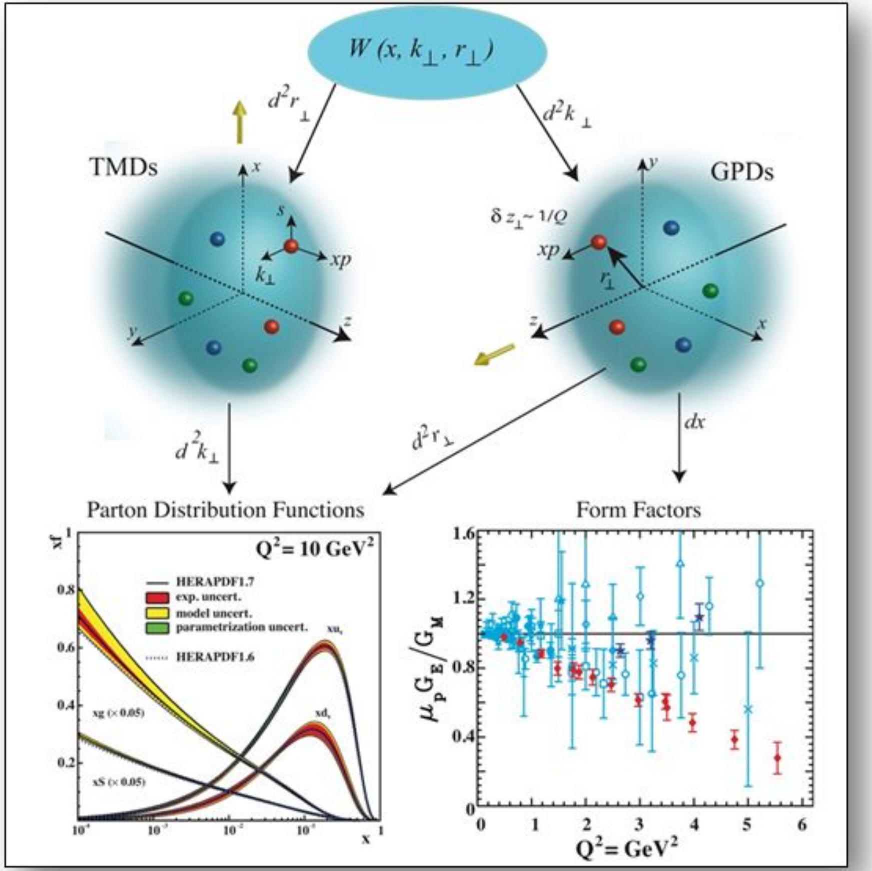
# Bringing it All Together

- ✅ We discovered that (nearly) massless quarks and gluons make up the nucleon and that QCD governs their interactions.
- ☐ We had hoped to find out how quarks and gluons and their interactions give rise to the characteristics of the nucleons.
  - Spin
  - Mass
- ☐ We also hoped that we would be able to find out how nucleon-nucleon interactions work in terms of QCD.
  - How nuclear forces arise?
  - How do nuclear characteristics come about?

- We were able to figure these out with E&M and atoms.
- Need something beyond a 1D form factor description...

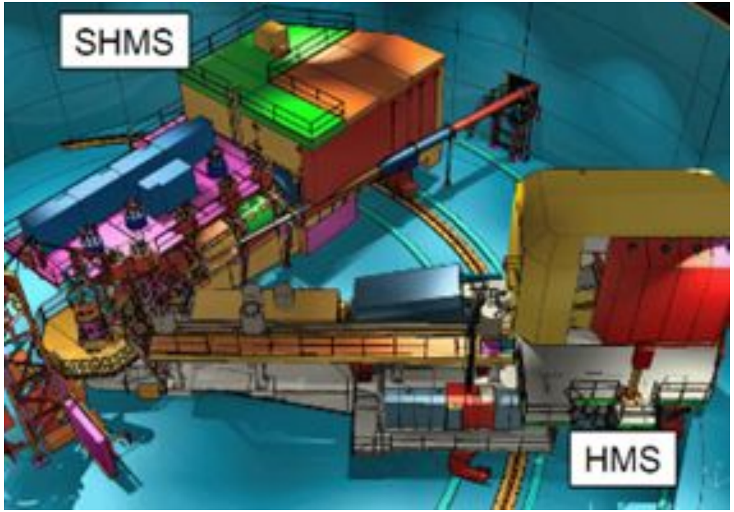
# Meson Structure in 3D

- Form factors are vital in understanding internal hadronic structure and dynamics
- The 3D imaging of a nuclei uses Generalized Parton Distributions (GPDs) and Transverse Momentum-dependent parton Distributions (TMDs)
- TMDs: Confined motion in nucleon (semi-inclusive DIS)
- GPDs: Spatial imaging (exclusive DIS)
- Requires…
    - High luminosity
    - Polarized beams and targets



# Review E12-09-011 (KaonLT) Goals

- First kaon experiment at high enough energies for non-perturbative studies
  - Need very high precision, which only focusing spectrometers can do
  - SHMS in Hall C was built for this purpose
- $Q^2$ dependence will allow studying the scaling behavior of the separated cross sections
- t-dependence allows for detailed studies of the reaction mechanism
  - Contributes to understanding of the non-pole contributions, which should reduce the model dependence
  - If warranted by data, extract the kaon form factor

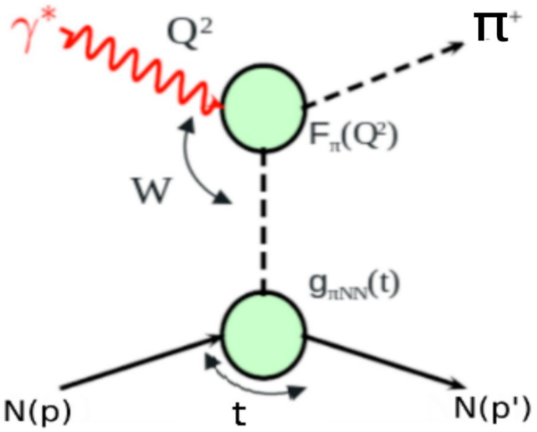


# Experimental Determination of the π/K$^+$ Form Factor

- At larger $Q^2$, $F_{\pi+}^2$ must be measured indirectly using the "pion cloud" of the proton via the p(e,e'$\pi^+$)n process
  - At small –t, the pion pole process dominates $\sigma_L$
  - In the Born term model, $F_{\pi+}^2$ appears as

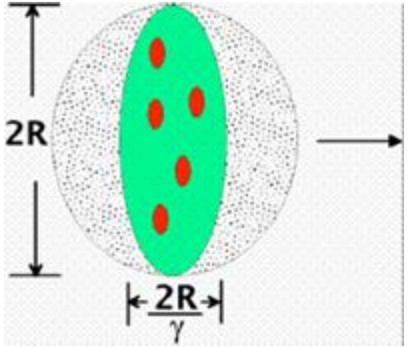
$$\frac{d\sigma_L}{dt} \propto \frac{-t}{(t-m_\pi^2)} g_{\pi NN}^2(t) Q^2 F_\pi^2(Q^2,t)$$

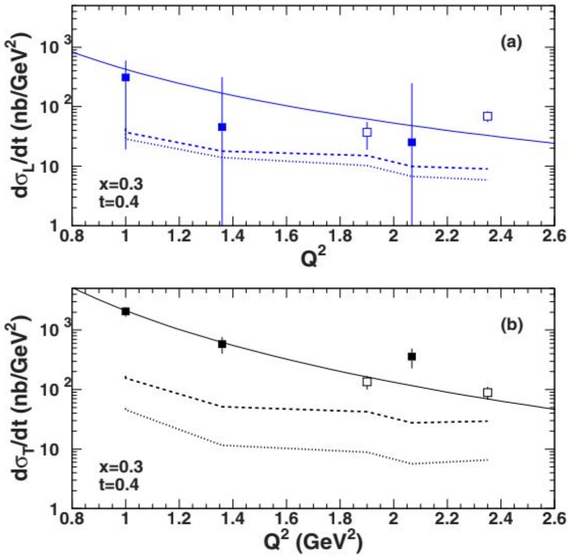
- Pole comes from the fact that π/K$^+$ are not real (i.e. pion cloud), but can be treated as real if the pole dominates $\sigma_L$ at small t
  - This is needed for validation that the form factor can be extracted
- For the same $Q^2$ values, one can fit several $\sigma_L$ values for different virtual photon polarizations (ε).



# Hard-Soft Factorization

- The $K^+$ electroproduction cross section has a $Q^2$ dependence at fixed x and -t
  - Factorization of $\sigma_L$ scales to leading order $Q^{-6}$
  - In that regime expect $\sigma_T$ to go as $Q^{-8}$ and consequently $\sigma_L \gg \sigma_T$
  - Important because partons are "frozen" transversely in the reference frame of pQCD (i.e. infinite momentum frame)
- Separated cross sections over a large range in $Q^2$ are essential for:
  - Testing factorization and understanding dynamical effects in both $Q^2$ and –t kinematics
  - Interpreting non-perturbative contributions in experimentally accessible kinematics

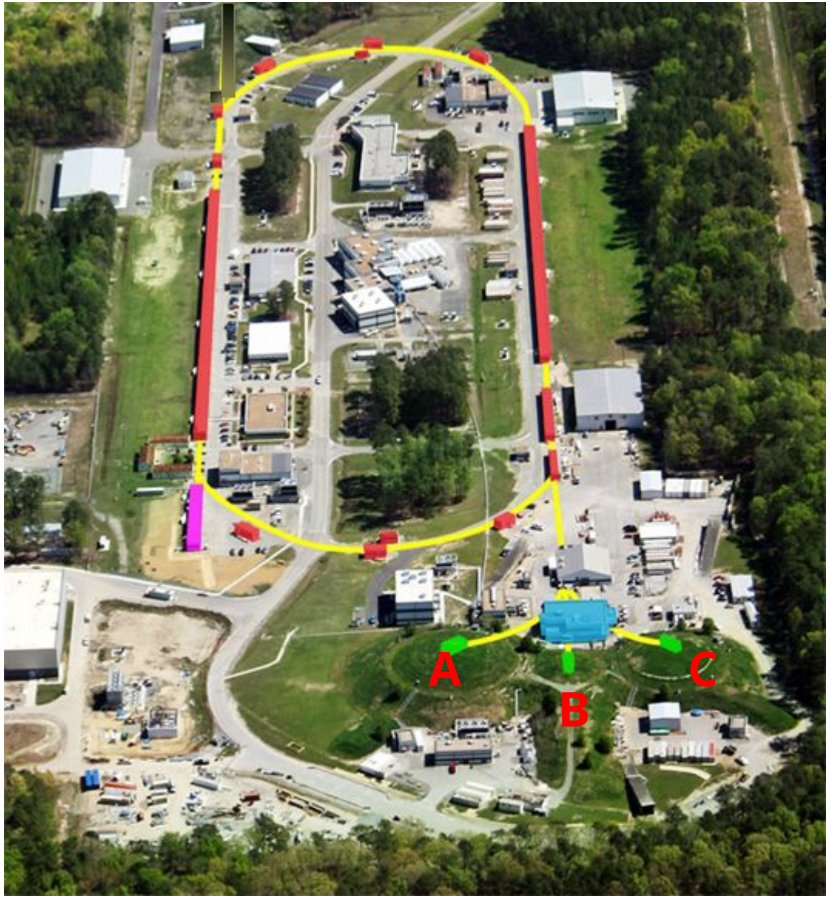



*M. Carmignotto et al., PhysRevC* ***97****(2018)025204*

# Jefferson Lab Continuous Electron Beam Accelerator Facility (Jlab CEBAF)

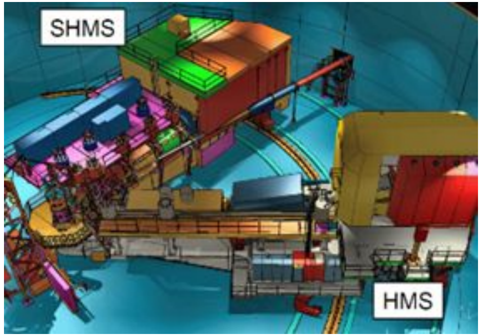
- 1995-2012:
  - Energies 0.4-6.0 GeV
  - 200 µA, 85% polarization
  - Simultaneous beam delivery to 3 halls

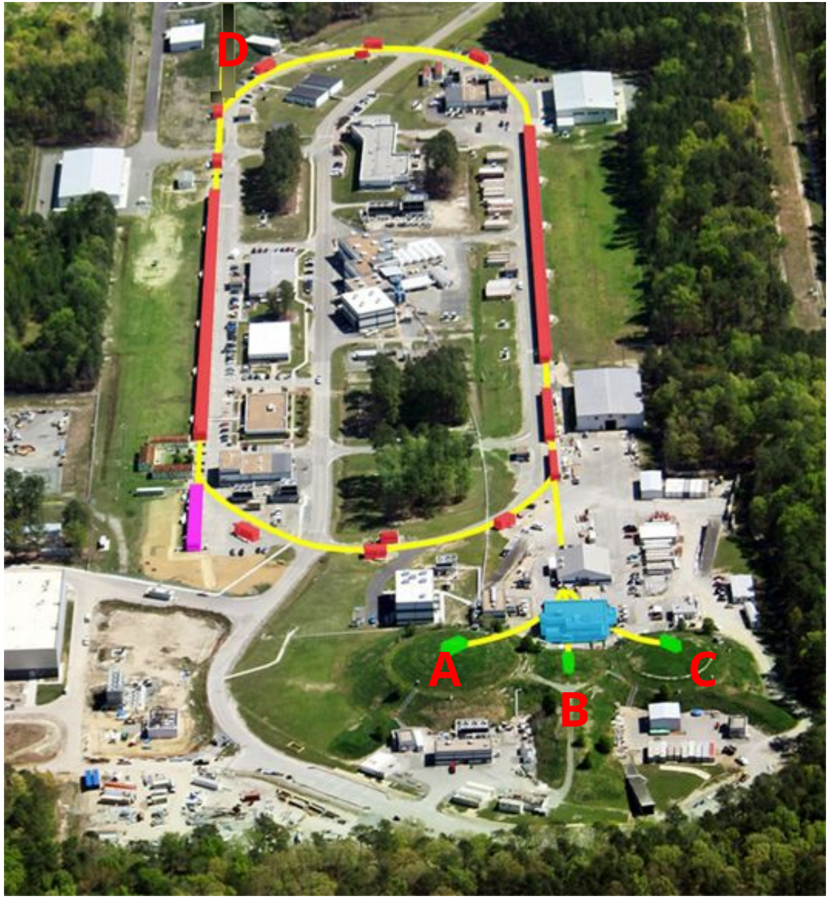


# Jefferson Lab Continuous Electron Beam Accelerator Facility (Jlab CEBAF)

- 1995-2012:
  - Energies 0.4-6.0 GeV
  - 200 µA, 85% polarization
  - Simultaneous beam delivery to 3 halls
- 2016-:
  - Energies 0.4-12.0 GeV
  - 150 µA, 85% polarization
  - Simultaneous beam delivery to 4 halls

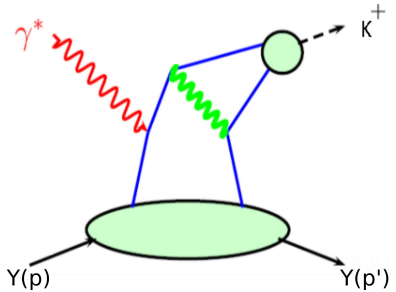
**Hall C**

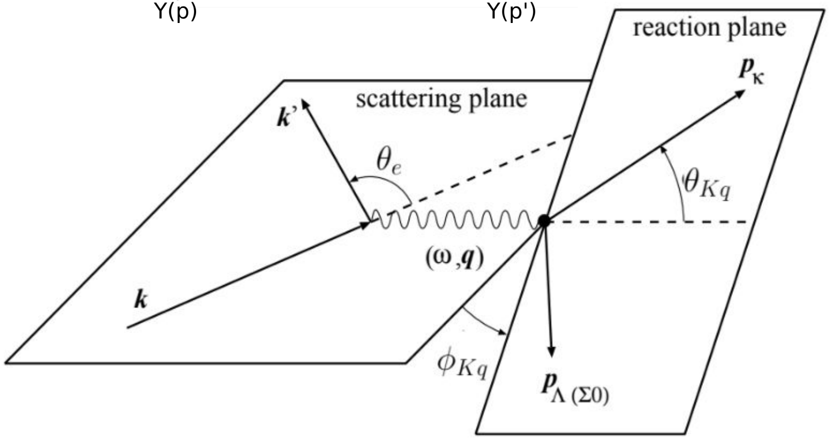


# Exclusive K⁺ Electroproduction

- $p(e, e'K^+)\Lambda(\Sigma^0)$
- Scattering Plane
  - Incident electron, k
  - Virtual photon, q
  - Scattered electron, k'
  - The incident electron scatters off the proton at an angle $\theta_e$.
- Reaction Plane
  - Kaon, $p_K$
  - The kaon ejectile scatters at angle $\theta_{Kq}$
  - The remaining proton energy (now a hyperon), $p_{\Lambda(\Sigma)}$
- $\phi_{Kq}$ is the azimuthal angle between the planes



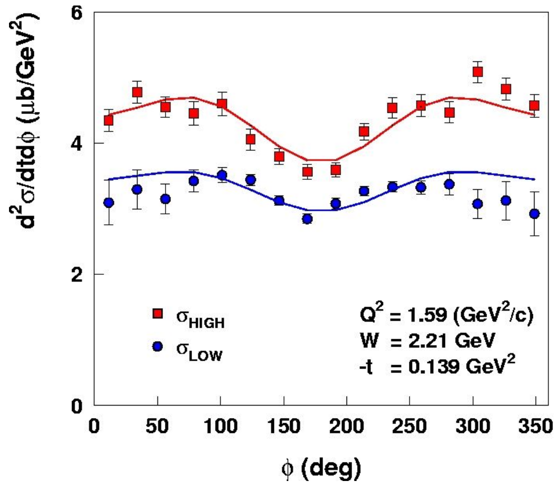




- The exclusive products are the scattered electron and Kaon, while the missing hyperon mass is calculated explicitly

# L/T Separation Basics

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

$\sigma_L$ will give us $F^2_{K+}$



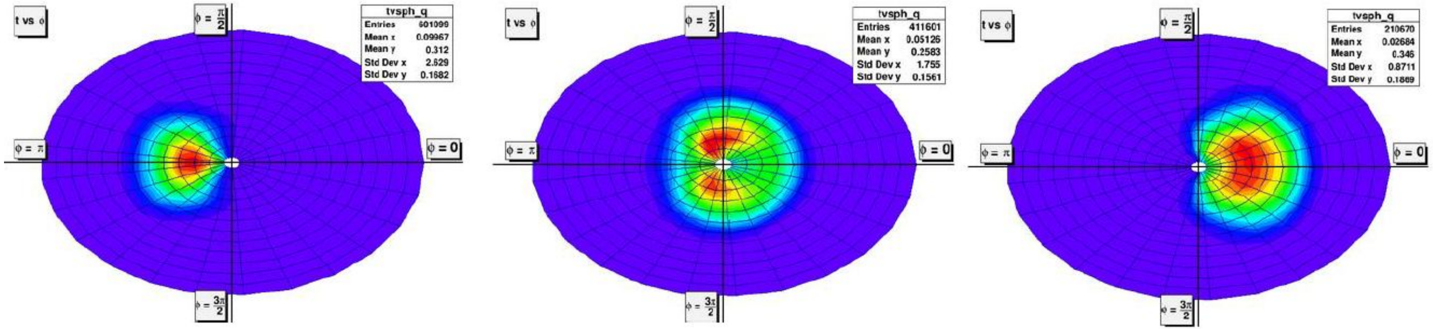

*T. Horn et al., PhysRevC* ***97****(2006)192001*

- $\sigma_L$ is isolated using the Rosenbluth separation technique
- Measure the cross section at two beam energies and fixed W, $Q^2$, -t
  - A high and low ε value
- Full azimuthal coverage, ϕ, will eliminate the interference terms
- Simultaneous fit using measured azimuthal angle (ϕ) allows for extracting L, T, LT, and TT
  - $\sigma_L$ -> slope
  - $\sigma_T$ -> y-intercept

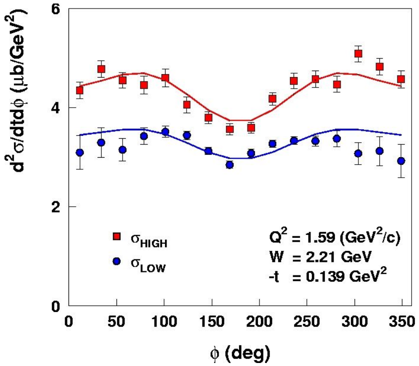
$$2\pi\frac{d^2\sigma}{dt\,d\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt}$$

# L/T Separation Example

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



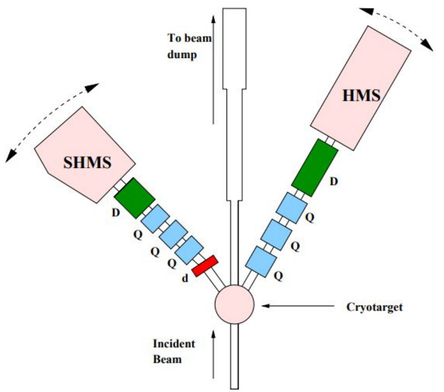

- Three SHMS angles for azimuthal (ϕ) coverage to determine the interference terms (LT, TT)
- Using the two beam energies (ε) to separate longitudinal (L) from transverse (T) cross section




Fit using measured ε and ϕ dependence

# Kaon LT - Data Collected

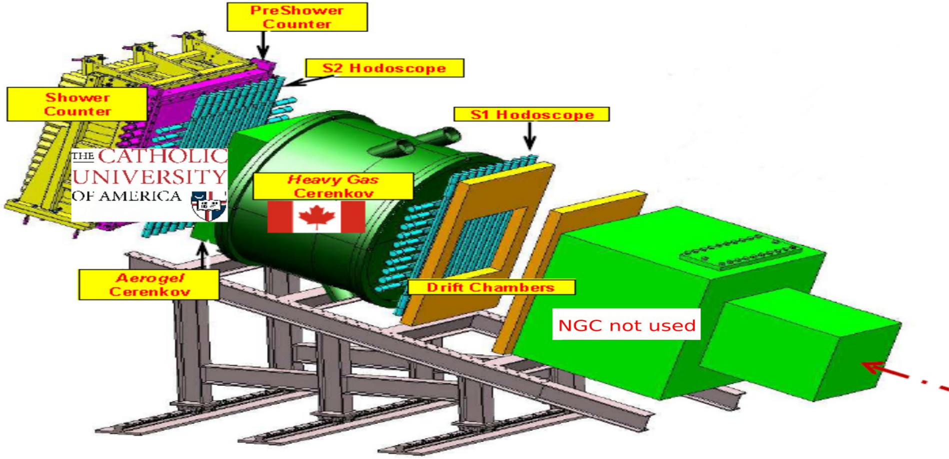
- The $p(e, e'K^+)\Lambda,\Sigma^0$ experiment ran in Hall C at Jefferson Lab over the fall and spring.

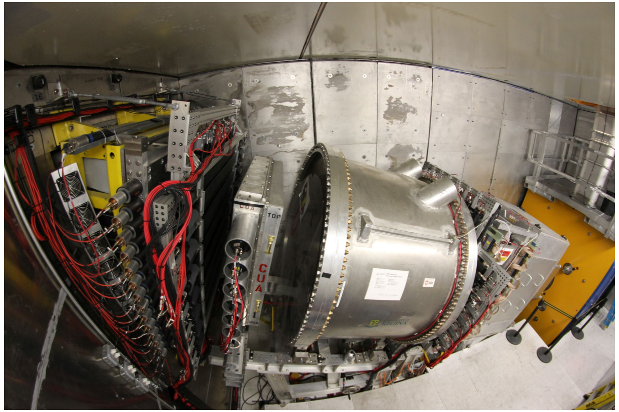



| E (GeV) | $Q^2$ ($GeV^2$) | W (GeV) | x | $\varepsilon_{high}/\varepsilon_{low}$ |
|---|---|---|---|---|
| 10.6/8.2 | 5.5 | 3.02 | 0.40 | 0.53/0.18 |
| 10.6/8.2 | 4.4 | 2.74 | 0.40 | 0.72/0.48 |
| 10.6/8.2 | 3.0 | 3.14 | 0.25 | 0.67/0.39 |
| 10.6/6.2 | 3.0 | 2.32 | 0.40 | 0.88/0.57 |
| 10.6/6.2 | 2.115 | 2.95 | 0.21 | 0.79/0.25 |
| 4.9/3.8 | 0.5 | 2.40 | 0.09 | 0.70/0.45 |

# Experimental Details

- Hall C: $k_e$=3.8, 4.9, 6.4, 8.5, 10.6 GeV
- SHMS for kaon detection :
  - angles, 6 – 30 deg
  - momenta, 2.7 – 6.8 GeV/c
- HMS for electron detection :
  - angles,10.7 – 31.7 deg
  - momenta, 0.86 – 5.1 GeV/c
- Particle identification:
  - Dedicated Aerogel Cherenkov detector for kaon/proton separation
    - Four refractive indices to cover the dynamic range required by experiments
  - Heavy gas Cherenkov detector for kaon/pion separation

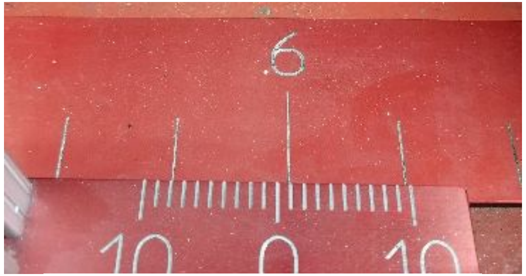


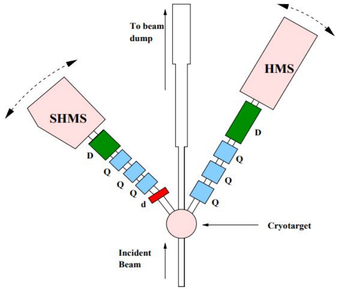



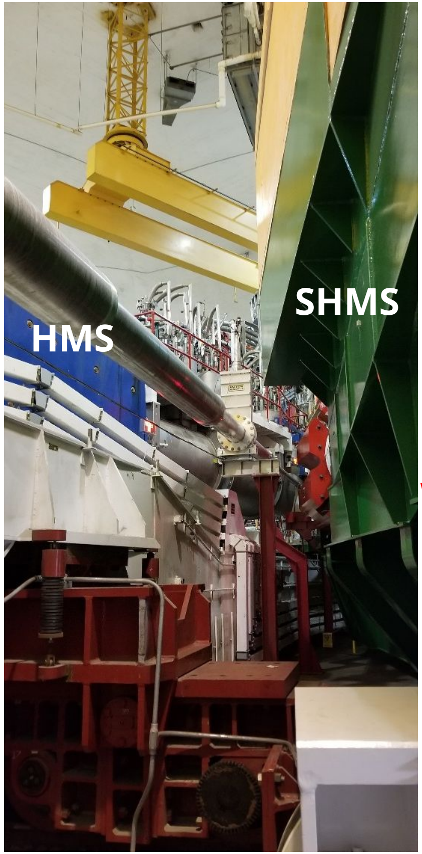
# SHMS small angle operation

- Some issues with opening and small angle settings at beginning of run
  - SHMS at 6.01°
  - HMS at 12.7°

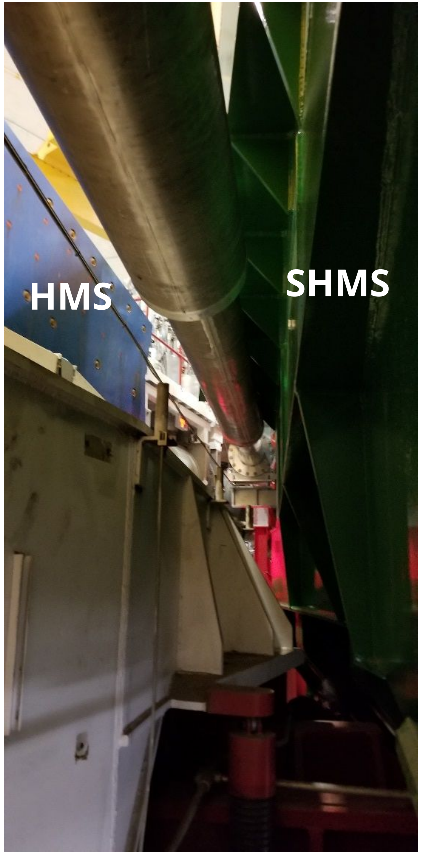
[12/17/18]




Work of many people ...



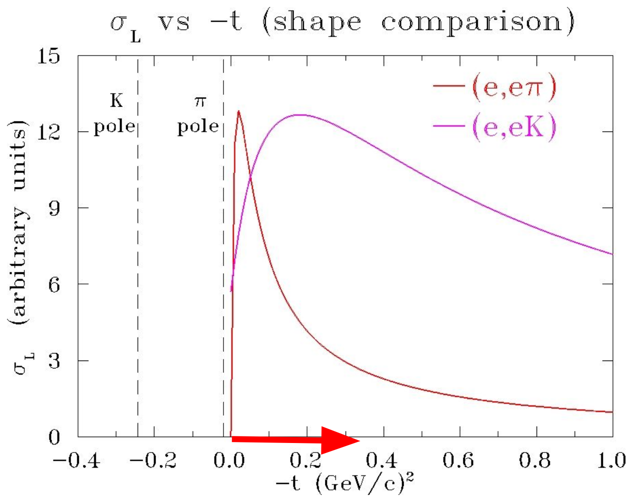
# Comparing π and K⁺ Form Factor

- Large pion t data lies a similar distance from the pole as kaon data
  - The Born term model should be approximately valid for kaon form factor

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

- The hard scattering limit in pQCD predicts a similar result

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




- Requirements:
  - Full L/T separation of the cross section – isolation of $\sigma_L$ (which requires $\sigma_L >> \sigma_T$)
  - Selection of the pion pole process
  - Extraction of the form factor using a model
  - Validation of the technique - model dependent checks

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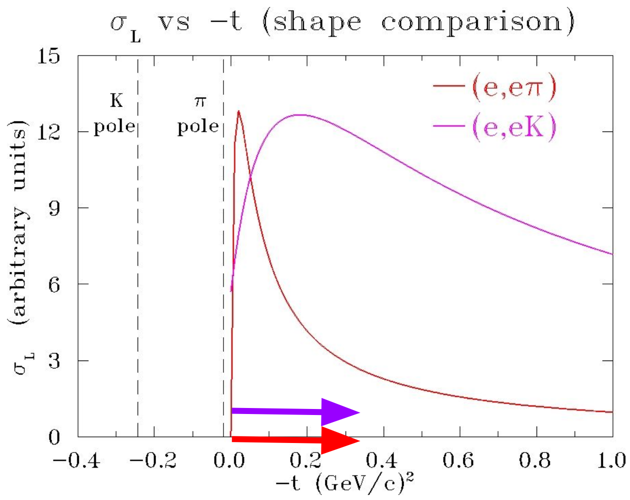

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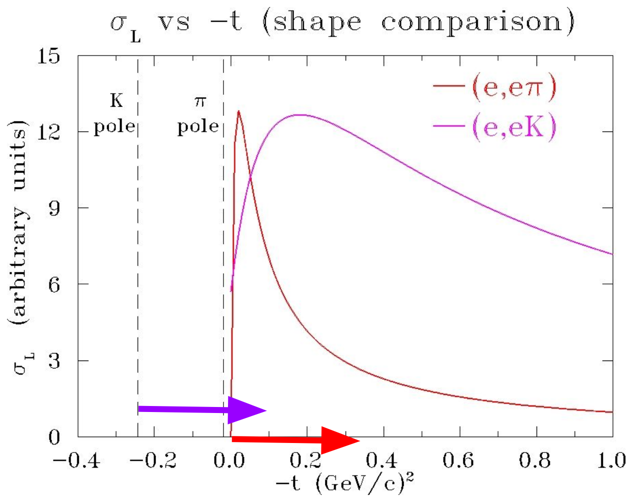


# KaonLT Event Selection

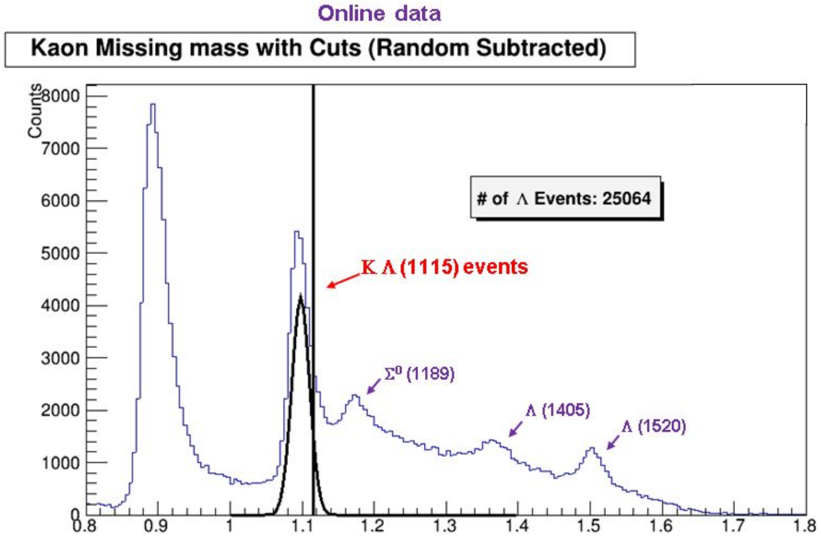
- Isolate exclusive final states through missing mass

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

- Coincidence measurement between kaons in SHMS and electrons in HMS
  - simultaneous studies of $K\Lambda$ and $K\Sigma^0$ channels…and a few others…
- Kaon pole dominance tests through

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

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




Plot by R. Ambrose, S. Kay, R. Trotta

# Extra Slides