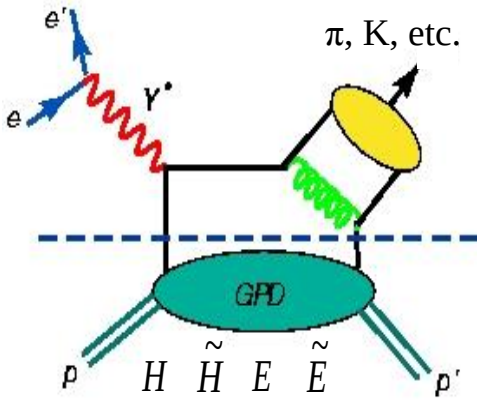
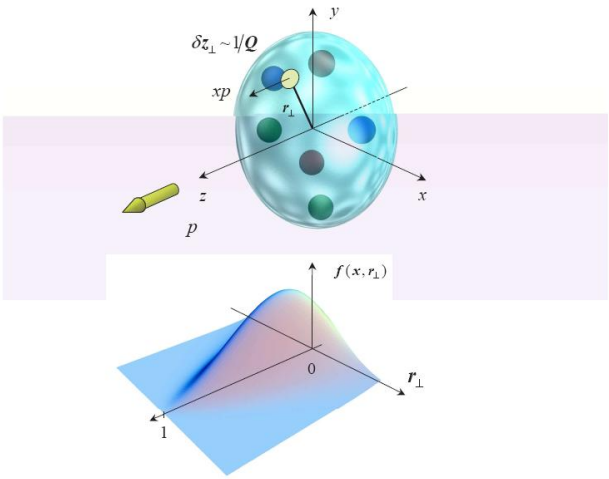
Quark Imaging at JLab 12 GeV and beyond (1)

Puzzles, Challenges, and Opportunities in meson production



Tanja Horn

Jefferson Lab



HUGS, Newport News, VA

9 June 2009

Outline

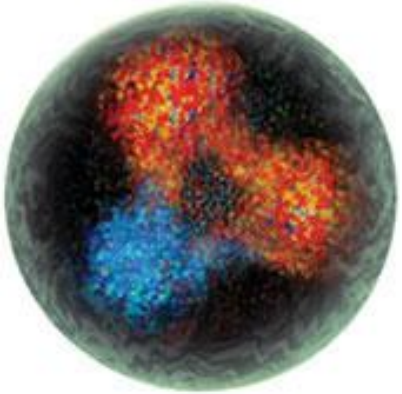
- The structure of the universe and the forces that bind it
- JLab Today
  - A first glimpse through the wall of confinement
- JLab 12 GeV
  - Imaging of bound nuclear matter
- Next-generation facility
  - A new spin on the strong force

Structure of the Universe

- Astronomy - a macroscopic view of the universe, including:
  - star birth and evolution
  - dark matter and energy
  - cosmology

Three pillars of creation

- Nuclear Physics - a microscopic view:
  - elementary forces
  - universal symmetries
  - fundamental structure of matter
  - the origin of mass
  - physics of the early universe

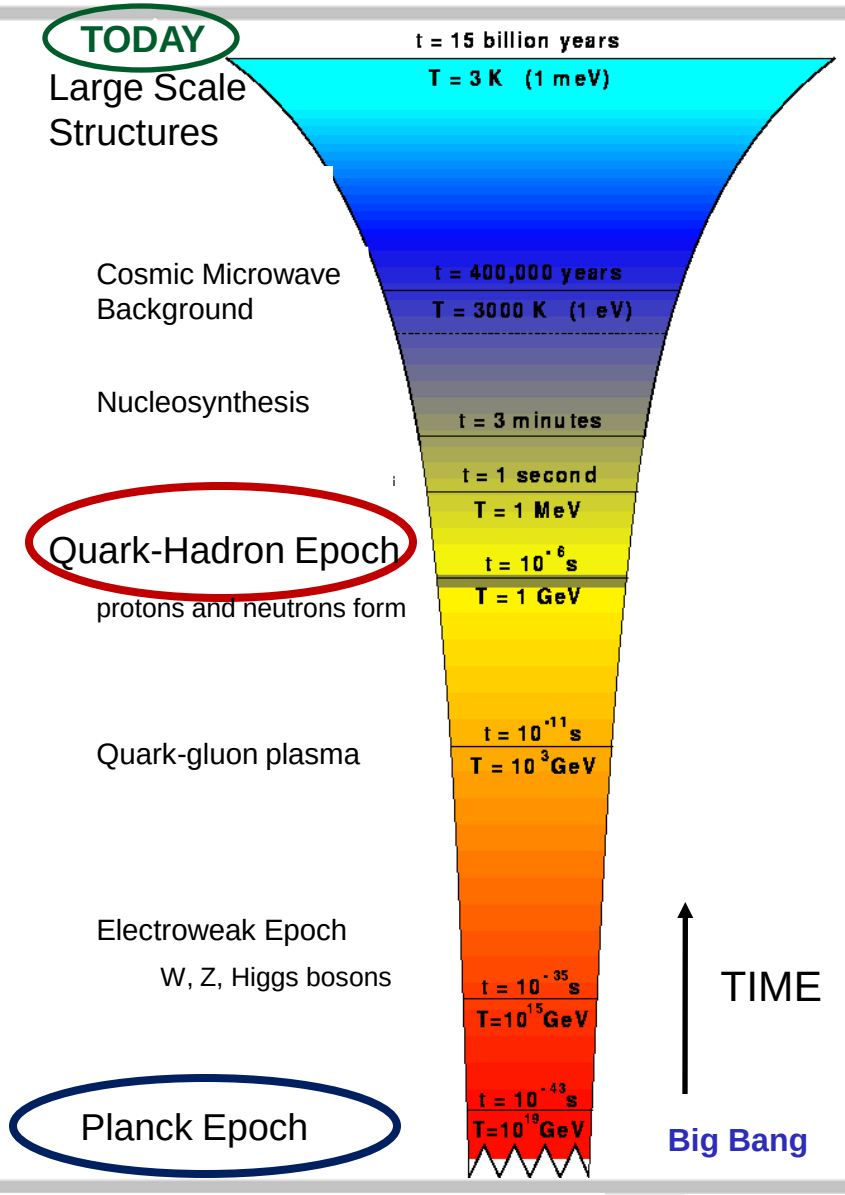


Cartoon picture of the nucleon

A Journey Back in Time

- To study the smallest building blocks of matter, one needs to recreate the very extreme conditions that existed shortly after the Big Bang.

- A journey into the center of the atom is also a journey back in time. It gives us a glimpse of the early universe beyond the reach of any telescope.



Unification and Confinement

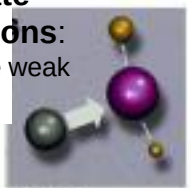
Gluons: carriers of the strong force between quarks

Binds all matter together

Photons: carriers of the electromagnetic force

Electricity and magnetism

Intermediate vector bosons: carriers of the weak force

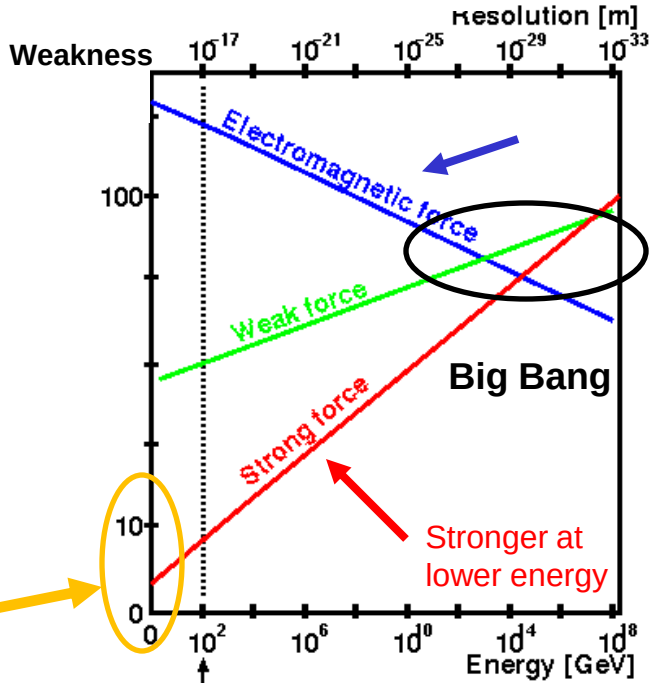


Radioactive decays

Gravitons: carriers of gravity

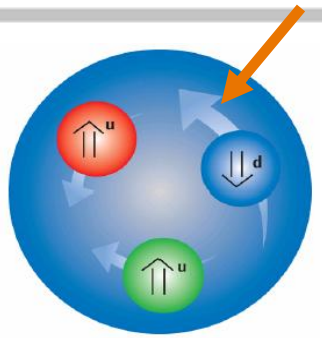
Weakest force

- During the Big Bang the four forces of nature were all equal (unified), and then "froze" apart.
- Photons do not carry electric charge
- Gluons carry their own strong charge (color).
- Vacuum screens electric, but enhances color charge.
- At small distances, or high energy, color charges are practically free, but if separated, the coupling becomes very strong, *confining* them to colorless objects.



Mysteries of the Strong Force

What about?



u + u – d = proton

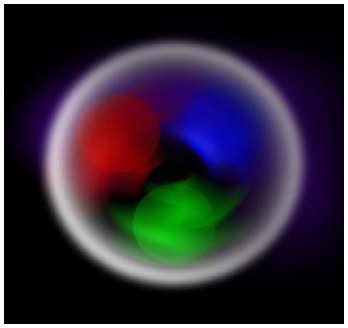
Spin: 1/2 + 1/2 – 1/2 = 1/2 √

u + u + d = proton

Mass: 0.003 + 0.003 +0.006 ≠ 0.938 GeV

- 98% of the mass of visible matter is dynamically generated by the motion of real and *virtual* quarks and gluons.
  - The proton mass arises from the strong interaction, described by Quantum Chromo Dynamics (QCD)
- QCD dynamics also determines proton spin.
- The strong coupling at low energy (Q^2) makes QCD very complicated (non-perturbative).

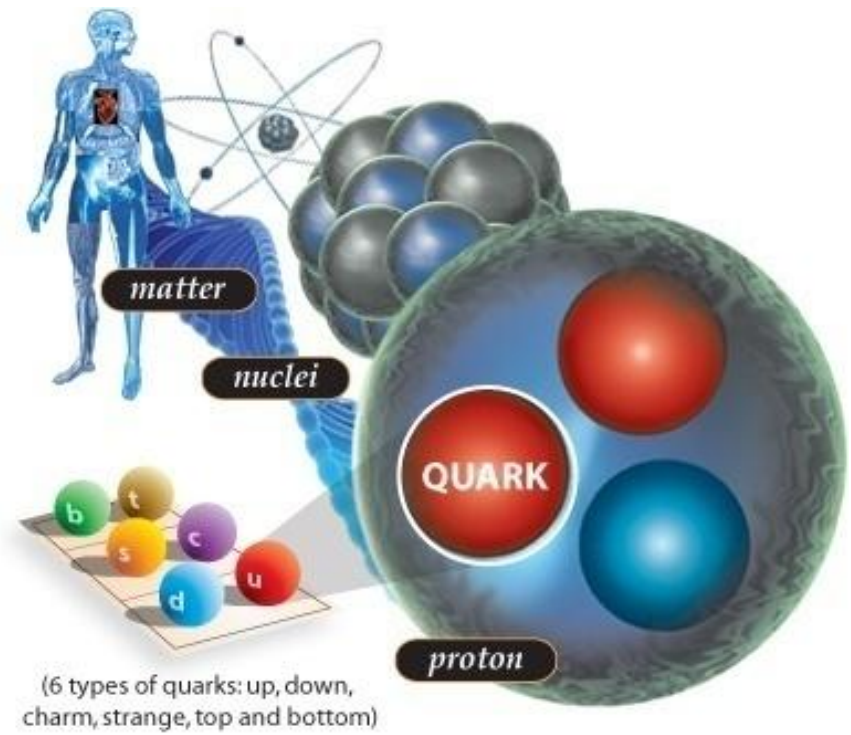
Is all mass dynamically generated?



We need to understand *confinement* to know how proton properties arise from its quark and gluon constituents

Models of Matter

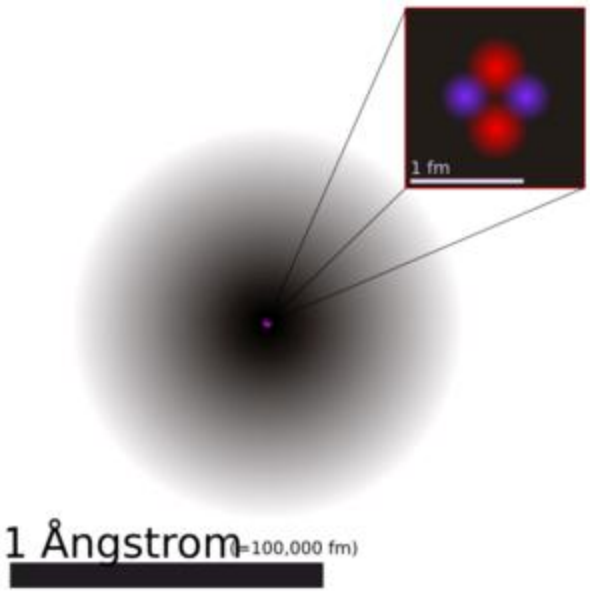
- Matter as we know it has many layers of structure.
- To understand each layer, we apply models that capture the most important features.
  - *Qualitative* models give us a picture of the concepts, but often cannot illustrate all of them at the same time
  - *Quantitative* models allow us to perform calculations and compare with measurements



Models of the Atom

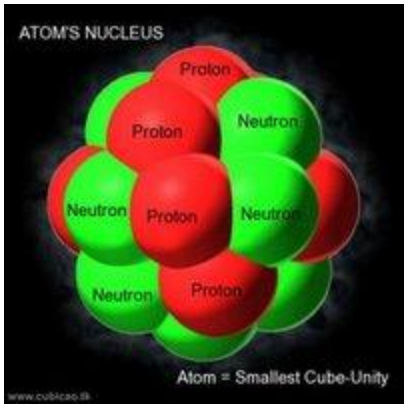
- The Rutherford model of the atom shows that solid matter consists of "empty" space.
  - The mass is concentrated in the nucleus orbited by tiny electrons at large distance
  - The electrons are held in place by electromagnetic interactions
  - Classical mechanics cannot explain the observed behavior of the electrons

- Quantum physics provides us with a more refined picture:
  - The nucleus is surrounded electrons not in planetary orbits, but a forming a "cloud"
  - We can calculate their interactions and distributions (wave functions)
  - The electrons are fundamental particles, but the nucleus has a rich substructure

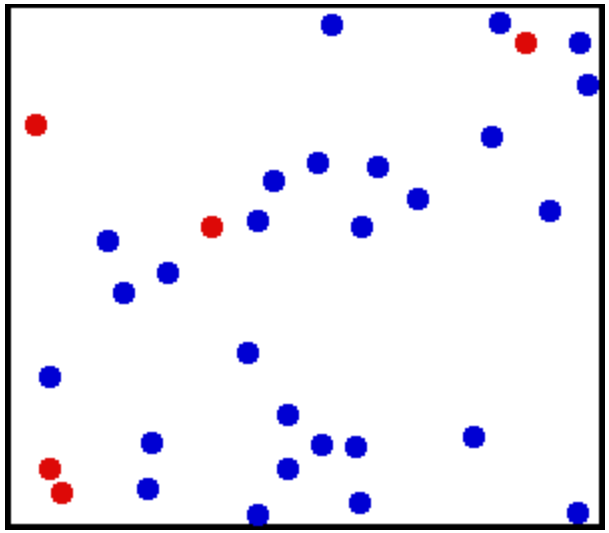


Models of the Nucleus

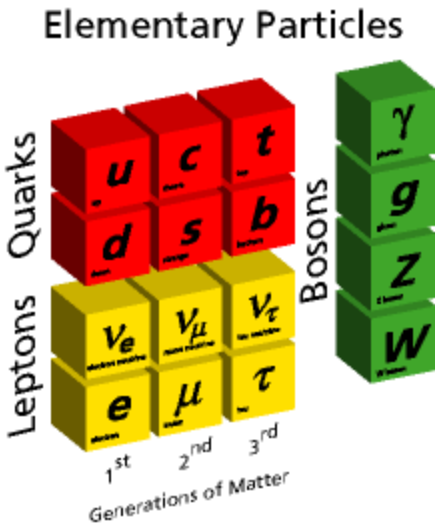
- The nucleus consists of protons and neutrons, commonly called nucleons.
  - The popular “molecule model” picture shows correctly that the nucleons fill the volume
  - But they are not at rest!

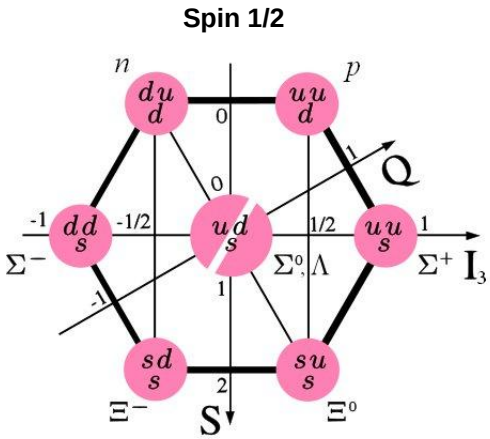


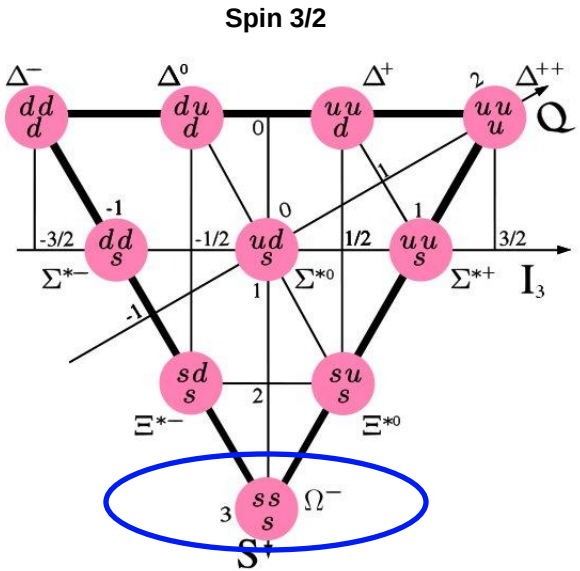
- The nucleus also has the properties of a Fermi gas
  - Particle velocities are a considerable fraction of the speed of light
  - Since there is no “empty” space, the traffic is really complicated!
  - Collisions that would eject a nucleon from its orbit are not energetically possible and do not occur



Flavor: A Periodic Table for Hadrons





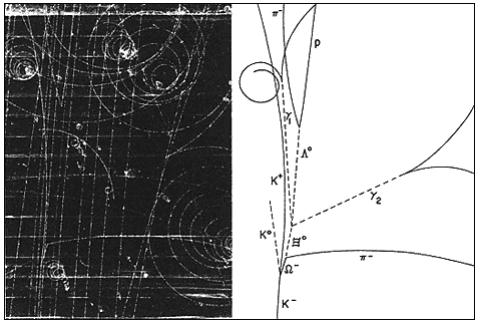


- Six quark "flavors" can be combined to form all observed particles (hadrons), including the proton and neutron, except the leptons (yellow) and the force particles (green).

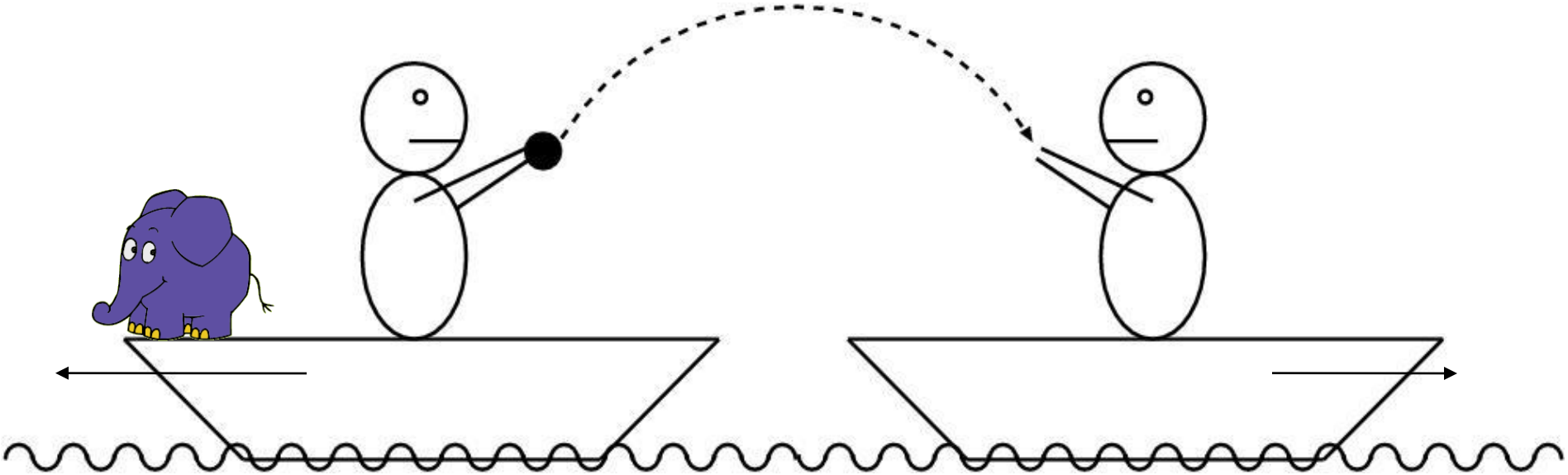
The mass of Ω^- predicted by Gell-Mann.

Its discovery in 1963, shown below, was a breakthrough for the $SU(3)_f$ quark model.

- The success of the quark model was also a puzzle
  - Ω^- was predicted to have 3 identical quarks (sss) in the same state spinning in the same direction
  - *Forbidden* by the Pauli principle, which requires fermions (non-integer spin particles) to have different quantum numbers
  - *Possible if each has a different "color".* In fact, color turns out to be the charge of the strong interaction

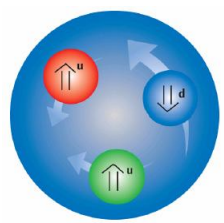


Virtual Particles as Force Carriers



- Exchanged (thrown) particles can create repulsive and attractive forces
  - for the latter, consider throwing a boomerang in the other direction!
- These particles are not real, but virtual, created from the vacuum
- The brief existence of virtual particles is allowed by the Heisenberg uncertainty principle: $\Delta E \Delta t \geq \frac{\hbar}{2}$
  - Even elephants may show up, if they disappear quickly enough!

Excited States and Nucleon Structure

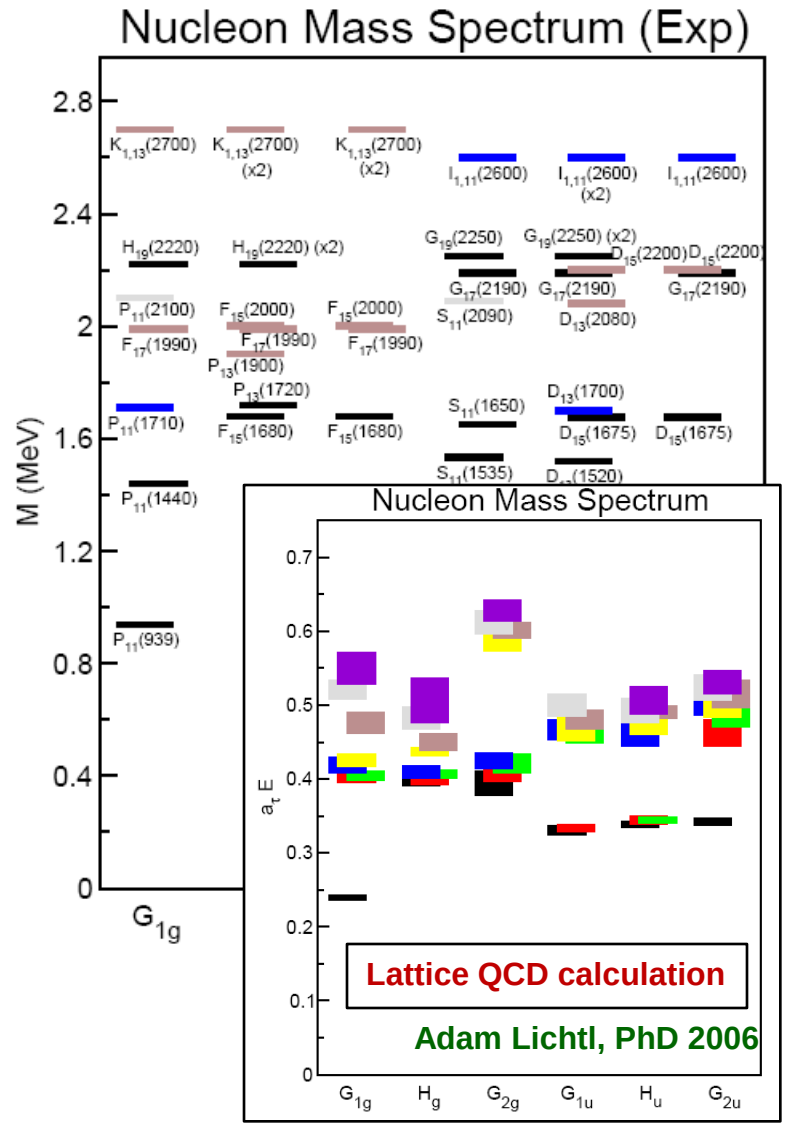


- By changing the orbital motion and spin orientation of the quarks, excited states can be created.

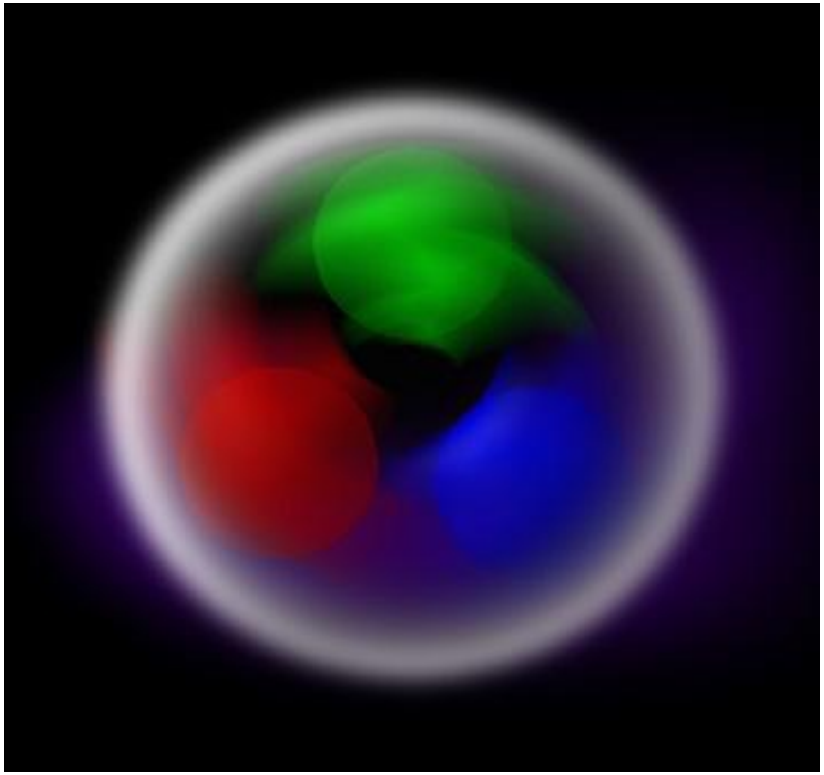
- Since perturbation theory cannot be applied, QCD calculations are performed on a lattice using powerful computers, but the results are still far from the data.

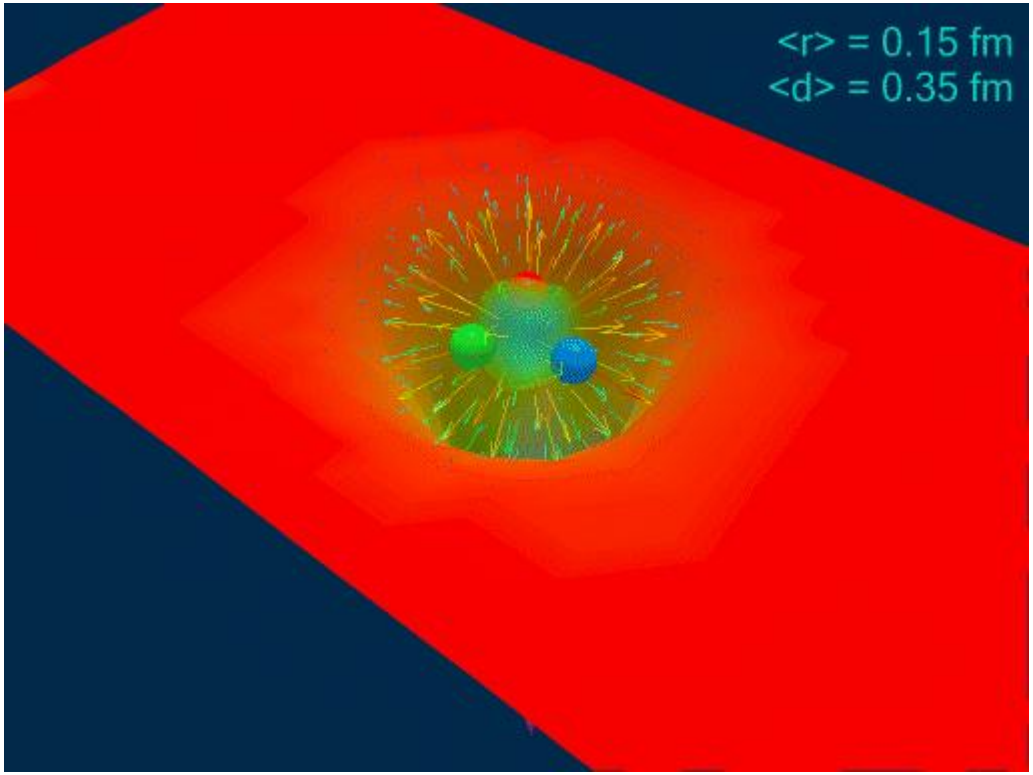
- Comparing the observed states with models using three constituent quarks one can learn about the quark interactions at low energy, and in particular about quark-quark correlations (diquarks).

- Spectroscopy may also reveal states where not only the quarks but also the gluons are excited.



Two Pictures of the Nucleon



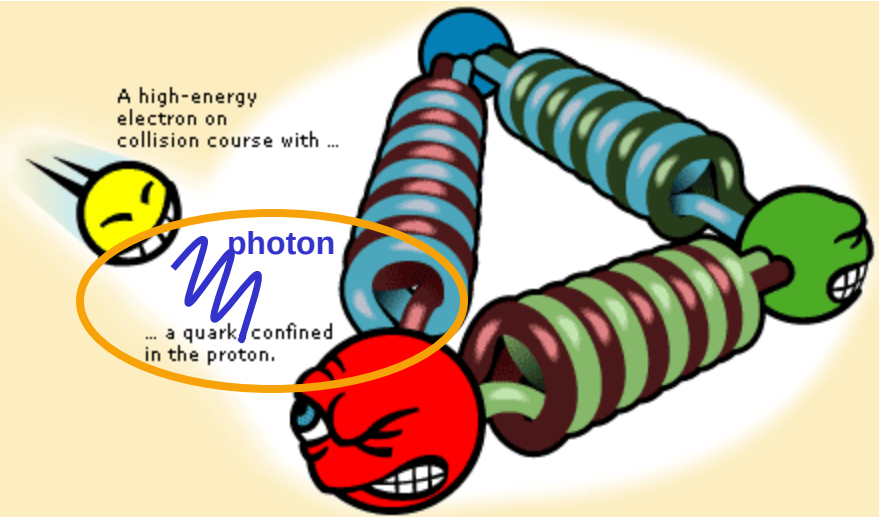


But does the nucleon really consist of *heavy quarks*, each with its own cloud of virtual particles, or *light quarks* in a common sea of virtual gluons and quark-antiquark pairs?

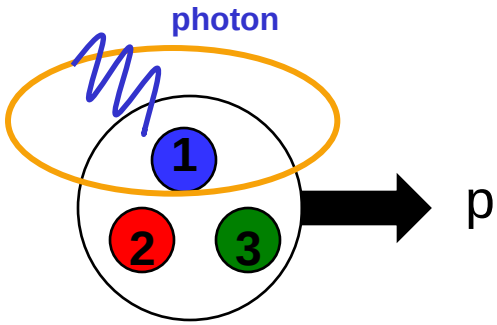
To answer this question we need to learn about Q^2 and x, which define the landscape of the nucleon.

Q^2 and x

- Real photons have no mass, but virtual ones do. The mass (with a minus sign) is called Q^2.
- Q^2 is a measure of the "size" of the probe. The larger the Q^2, the deeper the electron penetrated the cloud of virtual particles.
- Real photons ($Q^2 = 0$) cannot distinguish the quarks from the cloud around them.



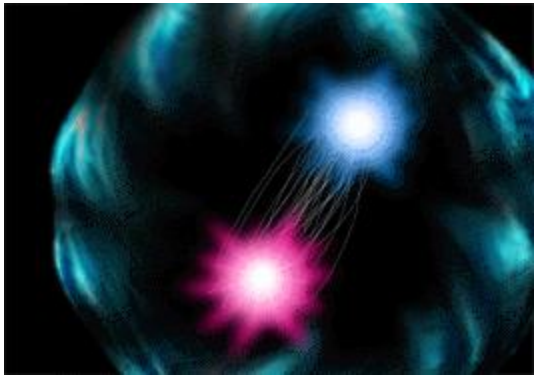
- x is the fraction of the nucleon momentum carried by the struck quark in a frame where the nucleon is moving quickly to the right. Naively, one would expect x = 1/3.
- Photons with high energy and low Q^2 do, however, probe small values of x. This rarely means that the struck quark does not follow the other two, but rather that most of the momentum is carried by the virtual particles.

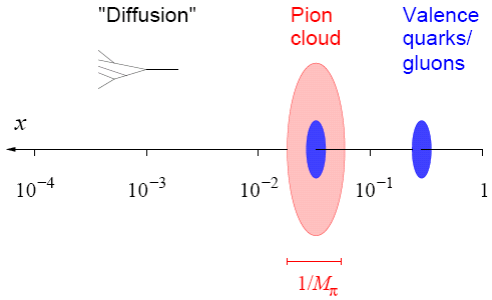


$$x = p_1 / p_{proton}$$

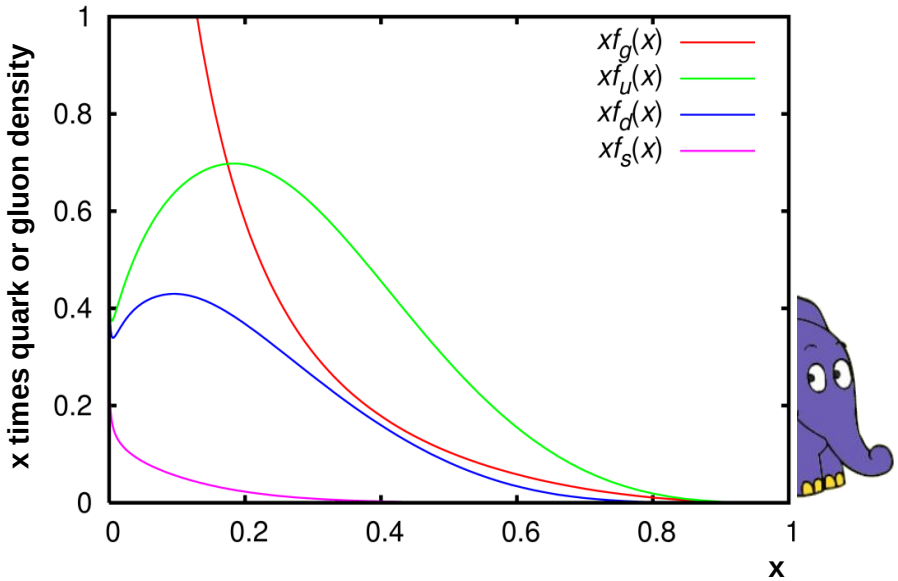
$$x = Q^2 / 2\, m_{proton}\, E_{photon}$$

The Nucleon Ground State





- The sea of virtual *gluons* and *quark-antiquark* pairs is an important part of the nucleon, carrying a significant part of the momentum and spin.



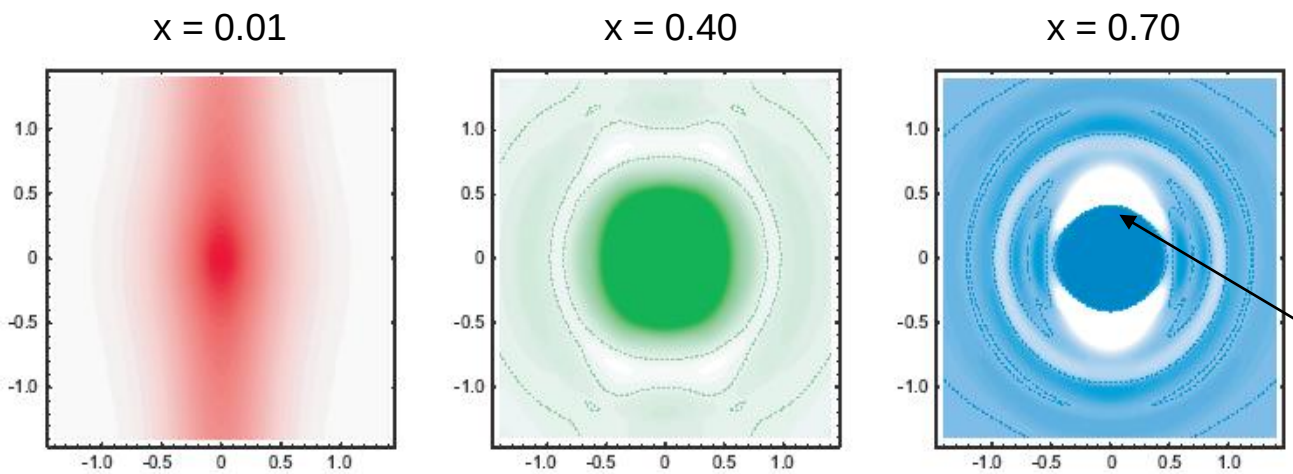
- To understand the *ground state*, we need to map the spatial and momentum distributions of the three "valence" quarks, and the sea surrounding them, over a large range in x and Q^2.

Only recently have advances in theory and experiment have made it possible to create such a tomographic picture.

Quark Imaging

- Wigner quantum phase space distributions provide a simultaneous, correlated, 3-dimensional description of both the position and momentum.

- They are the closest analogue to a classical phase space density allowed by the uncertainty principle.



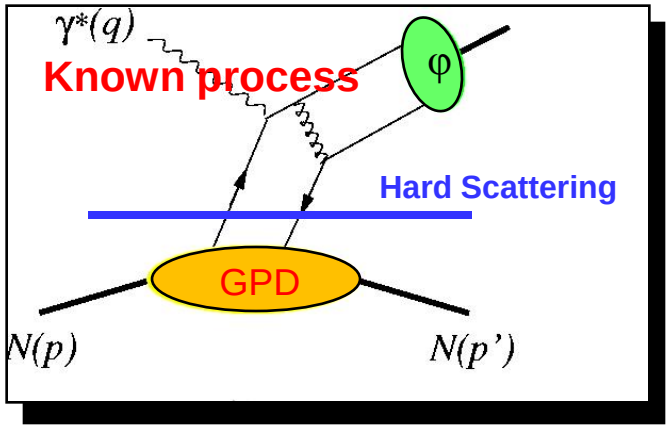
Pictures show transverse plane for different quark momentum fractions x

Interference pattern

Wigner distributions provide the language for the Generalized Parton Distributions (GPDs), which allow us to create a complete map of the behaviour of partons (quarks and gluons) inside of the nucleon.

How Do We Measure GPDs?

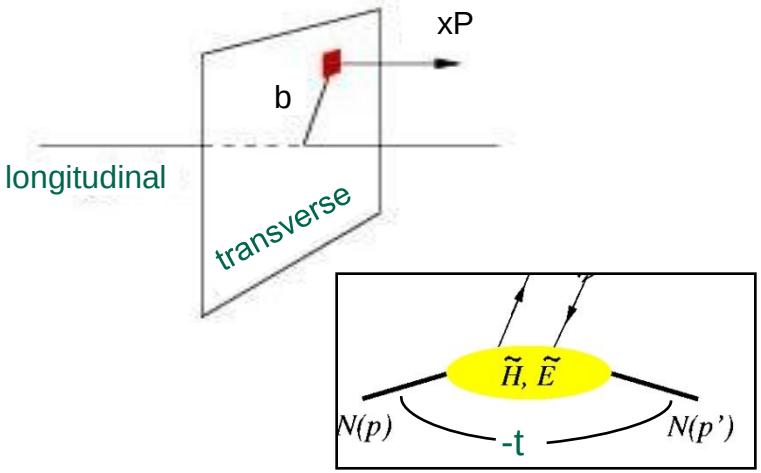
- Need processes that can be factorized into a part that we can calculate using perturbation theory, and one that contains the GPD information.
  - The former is a hard (high Q^2) scattering on a single quark
  - The latter reflects many soft interactions inside the nucleon as the quark returns.
- A theorem proves QCD factorization at large Q^2, but how large needs to be tested experimentally for each reaction.
- Meson production provides the flavor contents, but requires stringent tests of factorization
- Scattering of real and virtual photons off a quark is the cleanest reaction for measuring GPDs (no hard gluon in the diagram)

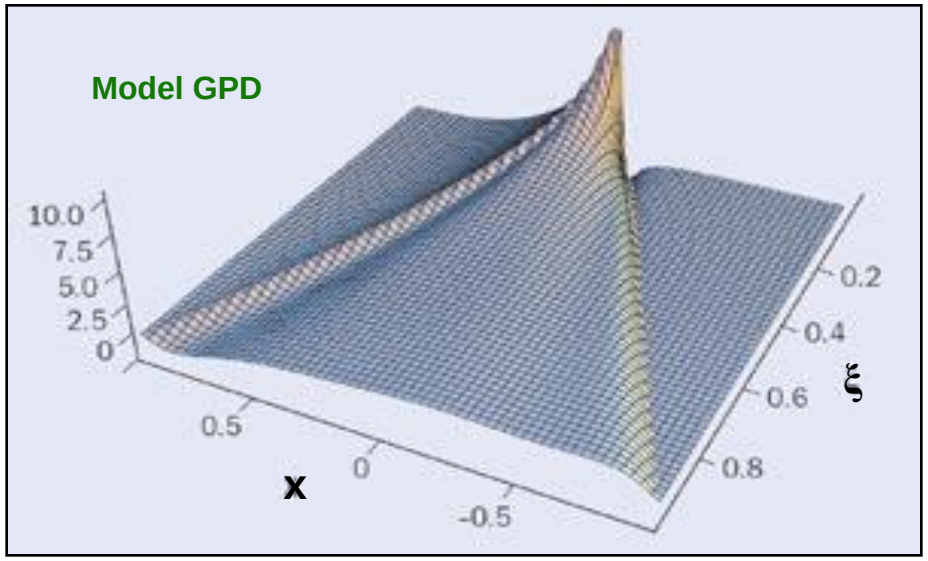


GPDs are a major emerging field in nuclear physics, driving the upgrades of current facilities and construction of future ones.

GPDs and Relativistic Form Factors

- For each quark flavor *q*, the form factors from *relativistic* quantum mechanics are moments of GPDs with a given value of ξ, which is related to the *transverse motion* of the struck quark.

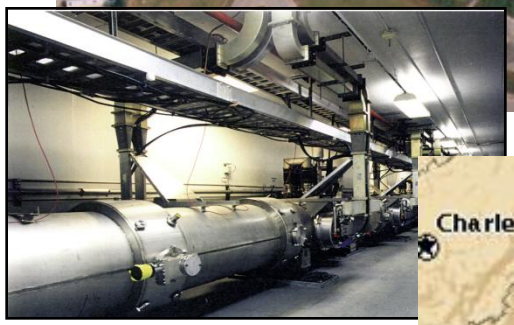




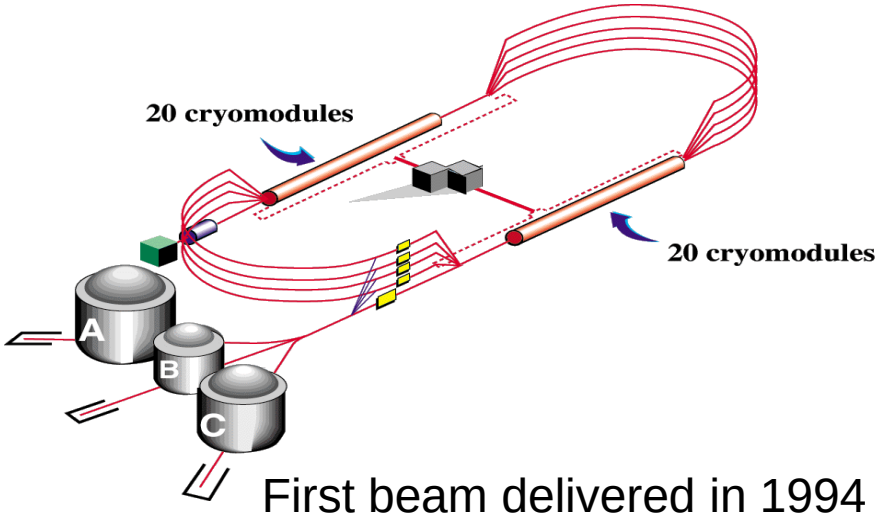
- A good determination of the form factors is essential for modeling GPDs; in particular their *t*-dependence (four-momentum transfer from photon to target).

Meson form factor measurements are important since they shed light on the quark-antiquark (color-anticolor) interaction in QCD.

Jefferson Lab Today

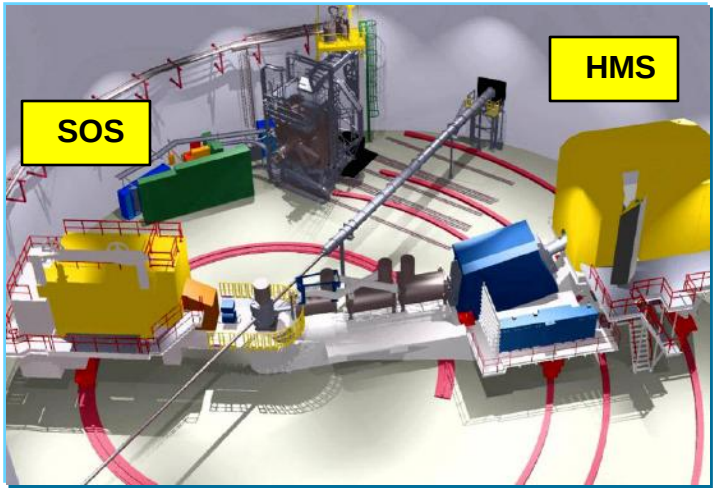


- 2000 member international user community
- Superconducting accelerator provides 100% duty factor beams with energies up to 6 GeV
- CEBAF's design allows delivery of beams with unique properties to all three experimental halls simultaneously

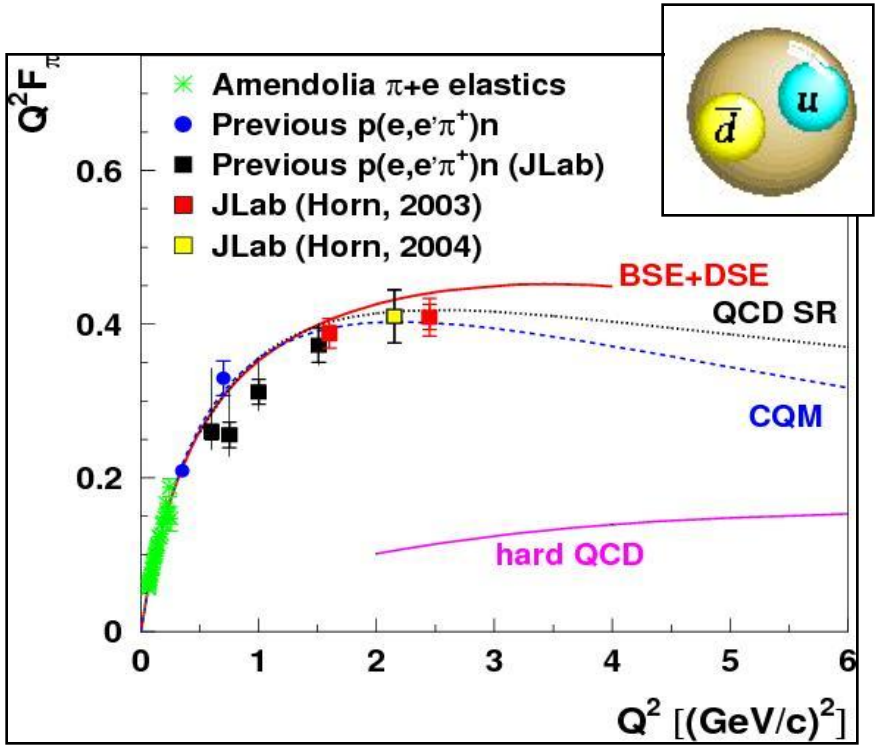


First beam delivered in 1994

Experimental Hall C

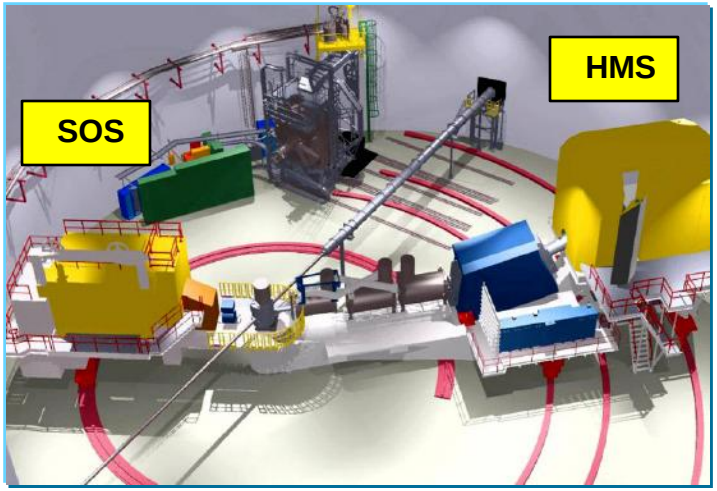


- Hall C has two magnetic spectrometers for particle detection
  - Short Orbit Spectrometer (SOS) for short lived particles
  - High Momentum Spectrometer (HMS) for high momentum particles

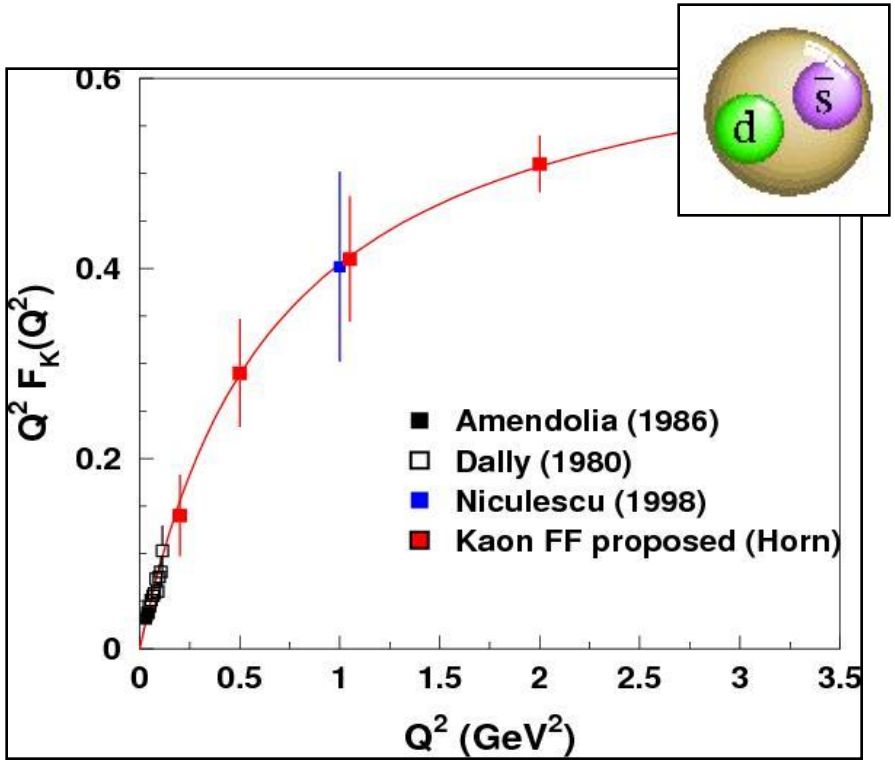


- Physics highlights:
  - The transition from hadrons to quarks
  - Strange quark content of the proton
  - Form factor of the pion and other simple quark systems

Experimental Hall C

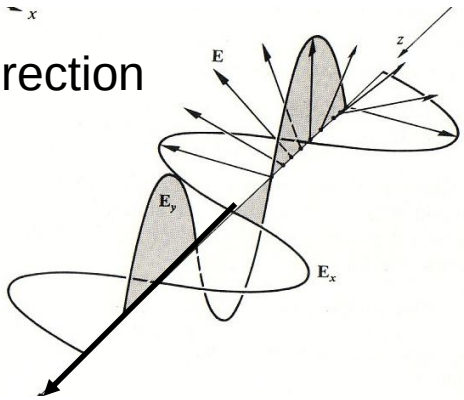


- Pion form factor measurements at high Q^2 show that calculations using perturbative QCD do not yet apply
- We can learn more about the reaction dynamics by substituting a light u quark with a heavy s quark



Virtual Photon Polarization

- The photon in the e p → e' π^+ n reaction can be in different polarization states, e.g., along or at 90 to the propagation direction



- The interaction probability includes all possible photon polarization states

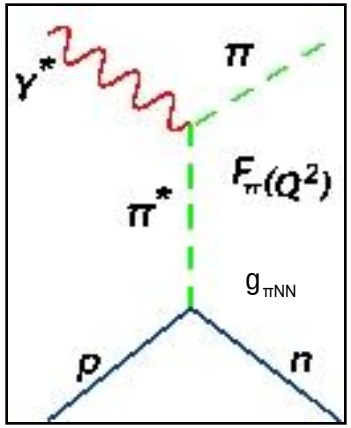
"Transverse Photons"

Interference terms

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

"Longitudinal Photons"

- Longitudinal photons have no classical analog (must be virtual)
  - Dominate at high Q^2 (virtuality)
- Interference terms are also allowed in this quantum mechanical system

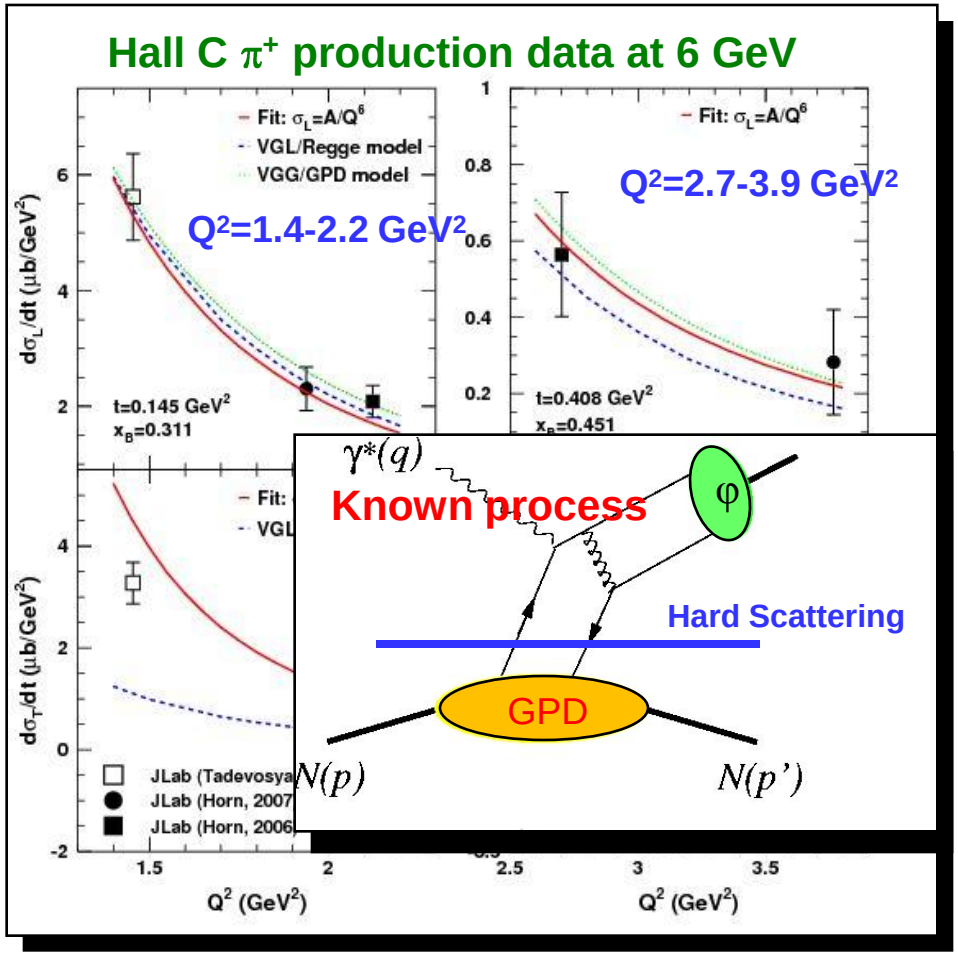


π^+ production with polarized photons

- Measurements of GPDs are limited to kinematics where *hard-soft factorization* applies
- A test is the Q^2 dependence of the polarized cross section:
  - $\sigma_L \sim Q^{-6}$
  - $\sigma_T \sim Q^{-8}$
  - For large Q^2: $\sigma_L >> \sigma_T$
- The QCD scaling prediction is reasonably consistent with recent 6 GeV JLab π^+ σ_L data, *but* σ_T does not follow the scaling expectation

σ_L →

σ_T →



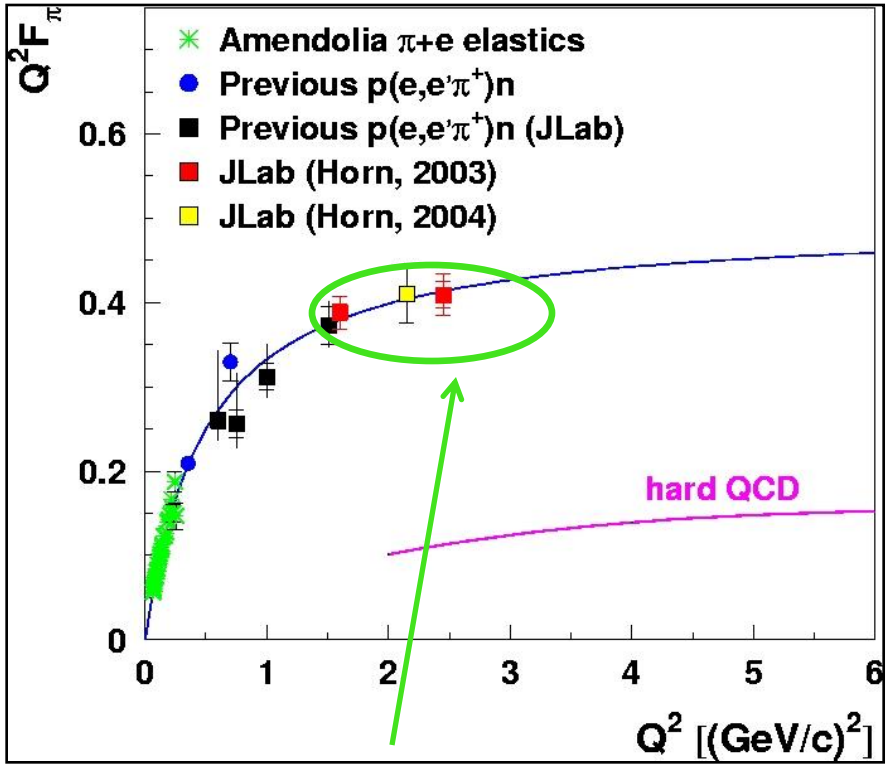
T. Horn et al., Phys. Rev. C78, 058201 (2008)

Full understanding of the onset of factorization requires an extension of the kinematic reach

Pion Form Factor – a similar puzzle?

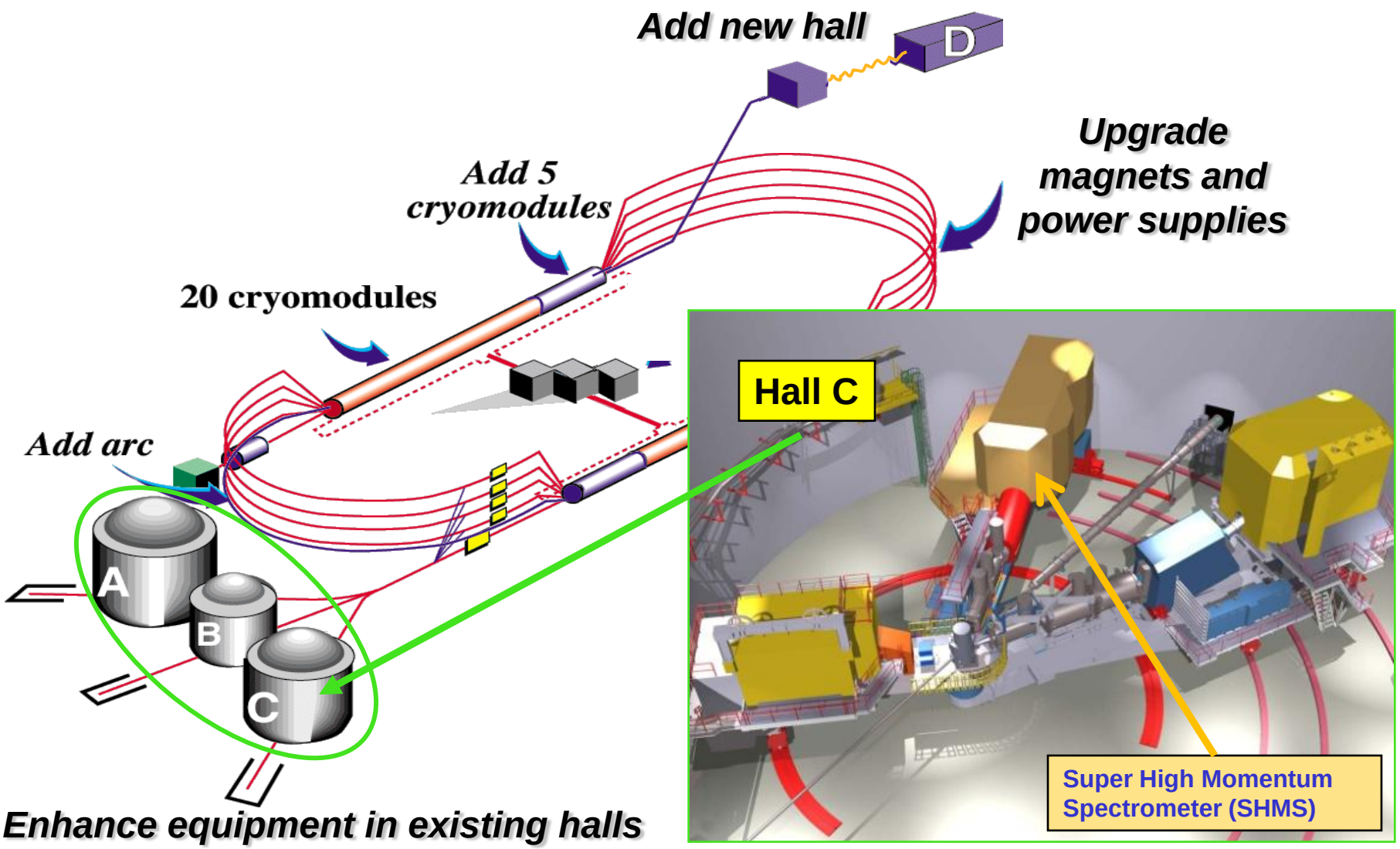
T. Horn et al., Phys. Rev. Lett. 97 (2006) 192001.
T. Horn et al., arXiv:0707.1794 (2007).

- A closer look at the pion form factor (F_π) shows a similar behavior
- The Q^2 dependence of F_π follows perturbative QCD
  - Factorization condition seems to hold
- BUT the magnitude does not
  - Factorization condition does not hold
  - Or something else is missing in the calculation



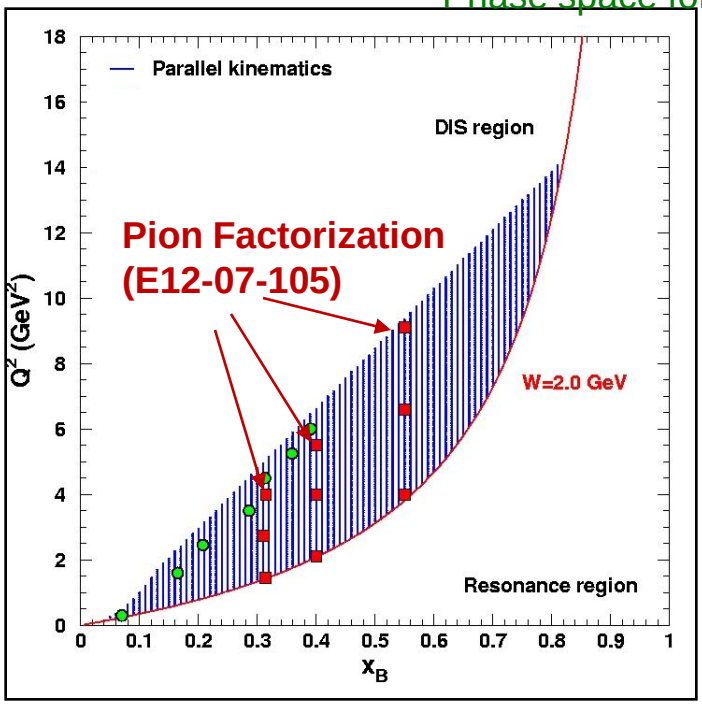
Highest Q^2 pion form factor data (my thesis experiment)

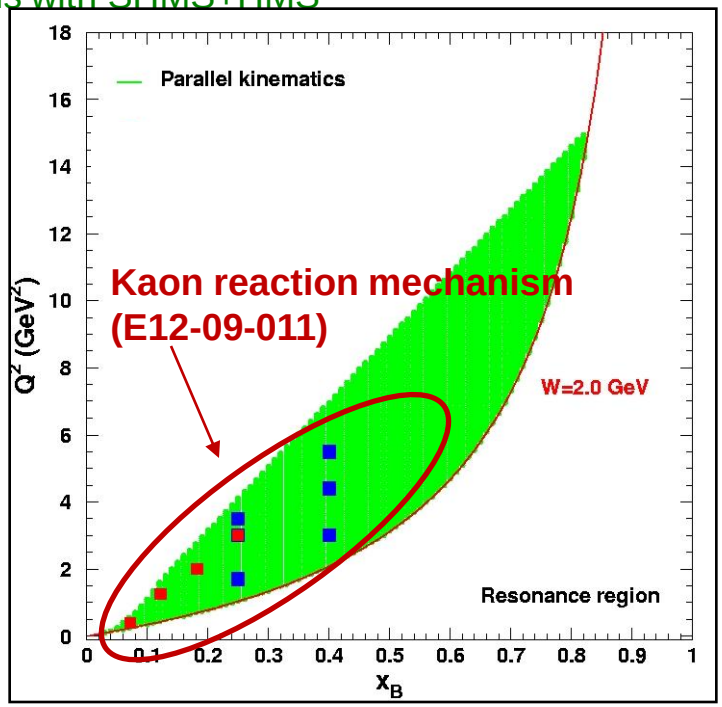
Jefferson Lab 12 GeV Upgrade



JLab 12 GeV pion and kaon experiments

Phase space for L/T separations with SHMS+HMS

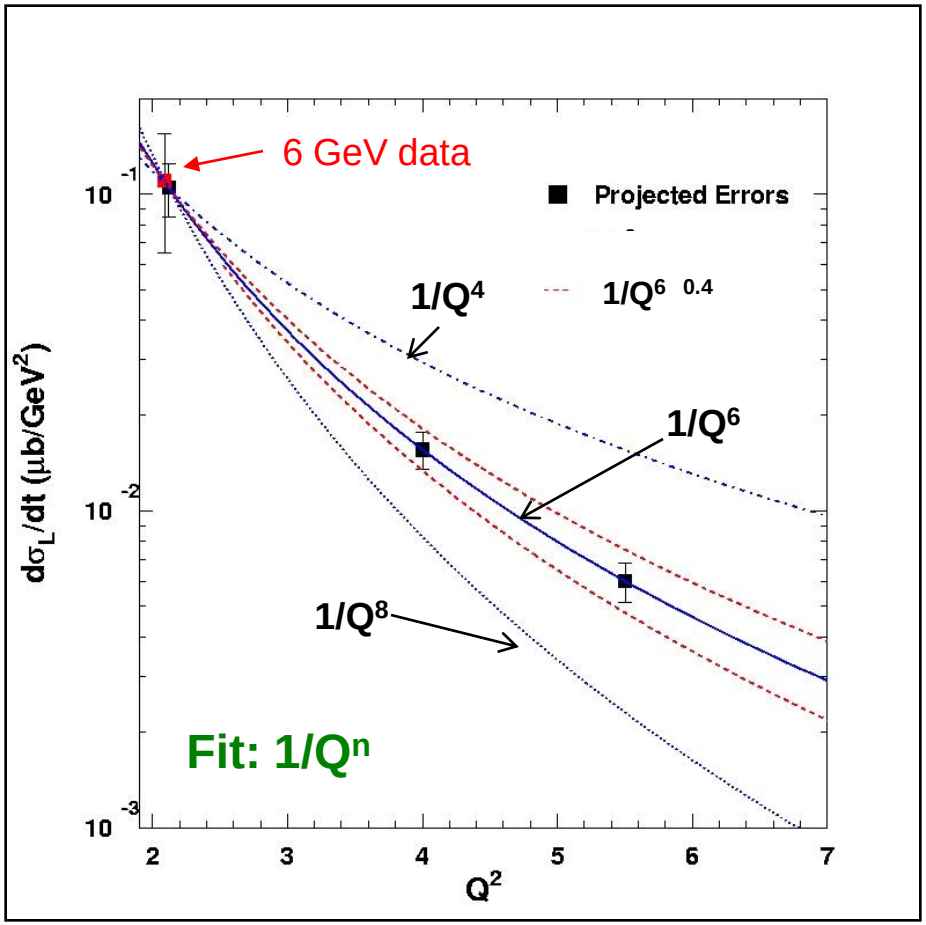




- *E12-07-105*: extends the kinematic reach of current data
  - To fully understand the onset of factorization
- *E12-09-011*: provides the first L/T separated kaon data above the resonance region
  - Quasi-model independent comparison of pions and kaons

Factorization Tests in π^+ Electroproduction

- JLab experiment E12-07-105 *[T. Horn et al.]* will search for the onset of factorization
- Q^2 coverage is 2-3 times larger than at 6 GeV at smaller t
- Factorization essential for reliable interpretation of results from the JLab GPD program at both 6 GeV and 12 GeV



Is the partonic description applicable in practice?

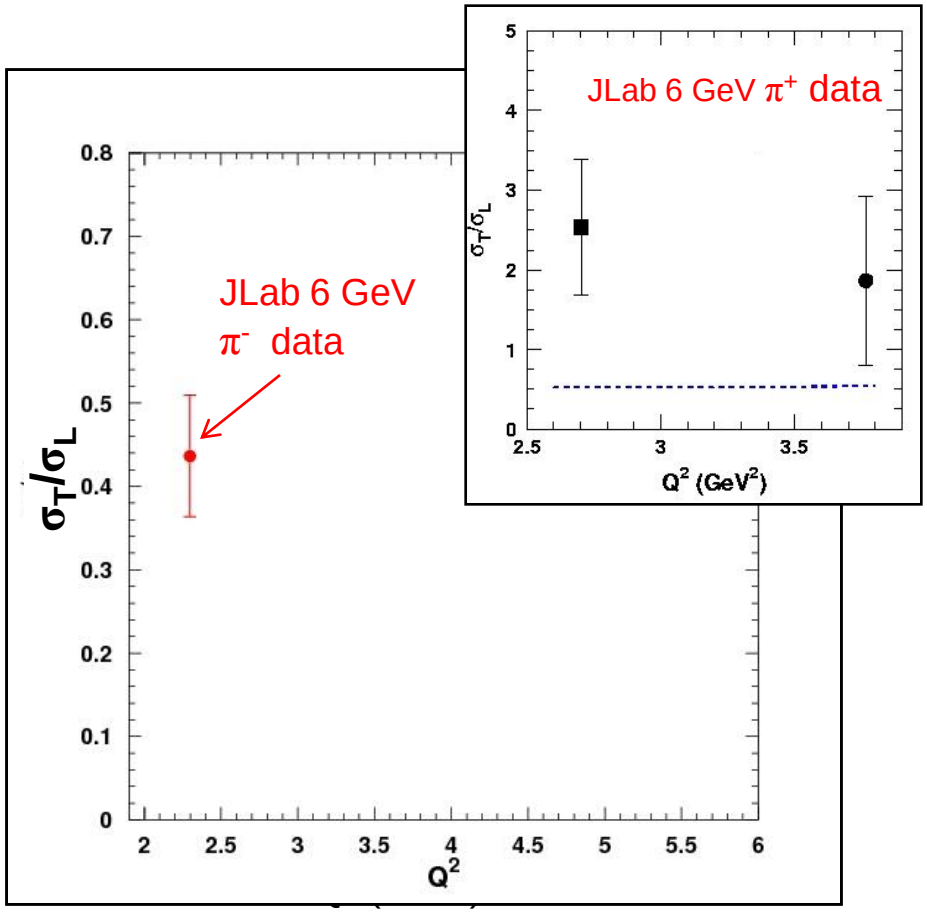
Can we extract GPDs from pion production?

σ_L without explicit L/T?

- If σ_L is small, GPD flavor studies may be limited to focusing spectrometers
  - L/T separations required

- But data suggest that σ_L is larger for π^- than for π^+ production
  - If this holds, one can extract σ_L from unseparated cross sections

$$\sigma = \sigma_T + \varepsilon\,\sigma_L \xrightarrow{\sigma_T \to 0} \varepsilon\,\sigma_L$$



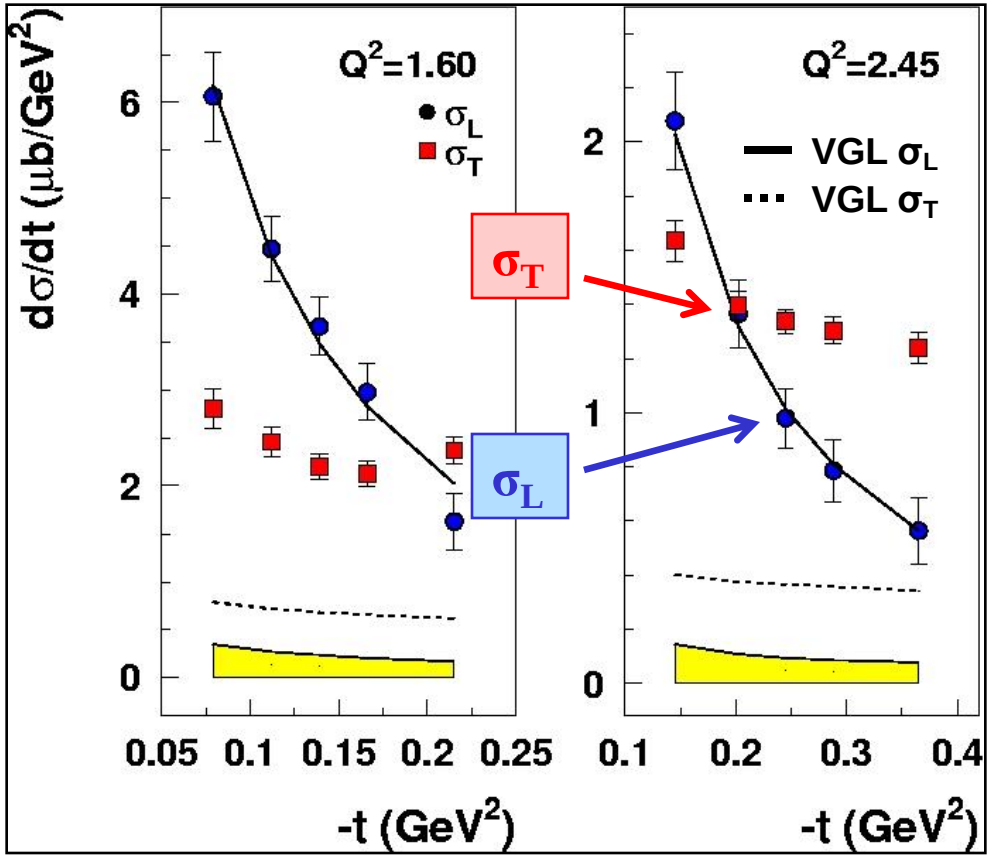
E12-07-105 will compare π^+ and π^- production to check possibilities of extracting GPDs without explicit L/T

Transverse Contributions: π^+

- In π^+ production, σ_T is much larger than predicted by the VGL/Regge model *[PRL**97**:192001 (2006)]*

- To understand the reaction mechanism, one should compare with a different yet similar system

Hall C 6 GeV π^+ data at W=2.2 GeV



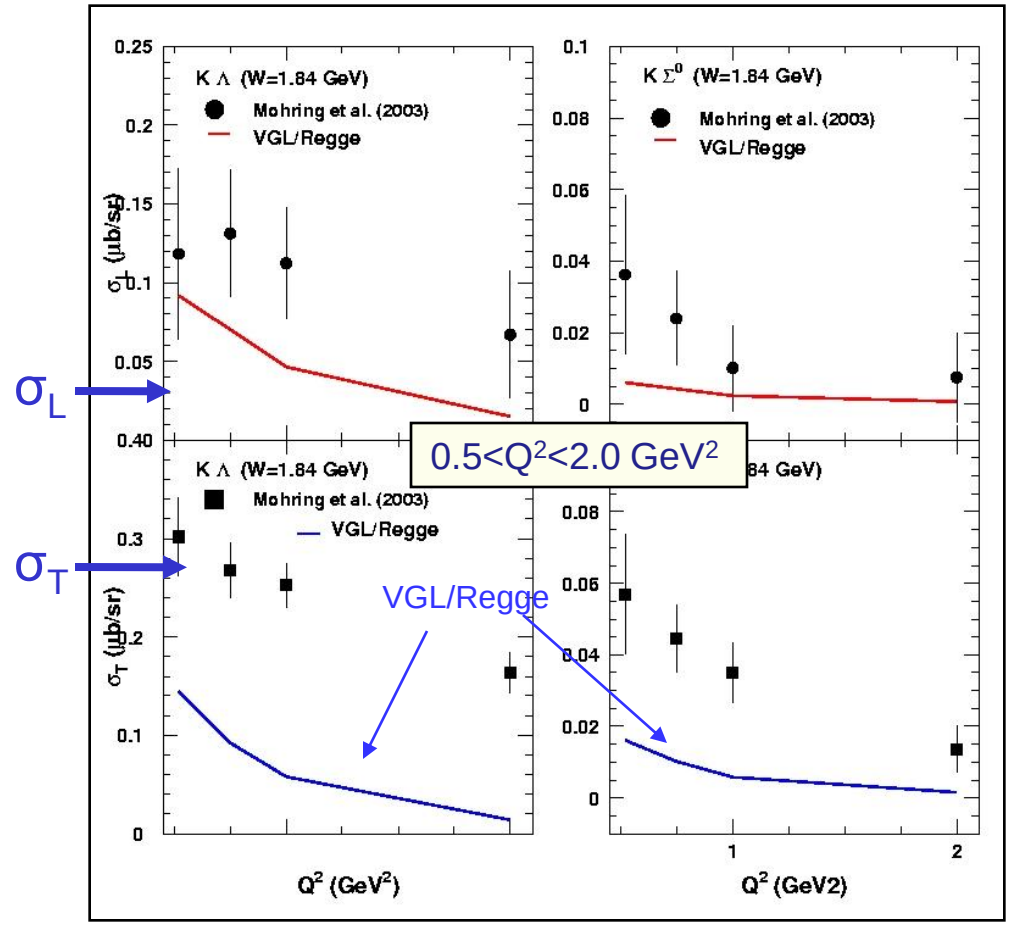
Horn *et al.*, Phys. Rev. Lett. 97, 192001 (2006)

Transverse Contributions: K^+

- For K^+ production in the *resonance region* σ_T is also not small at Q^2=2 GeV^2

- Unfortunately, available kaon data are limited
  - No separated data above the resonance region
  - Limited W and Q^2 range
  - Significant uncertainty due to scaling in x_B and –t

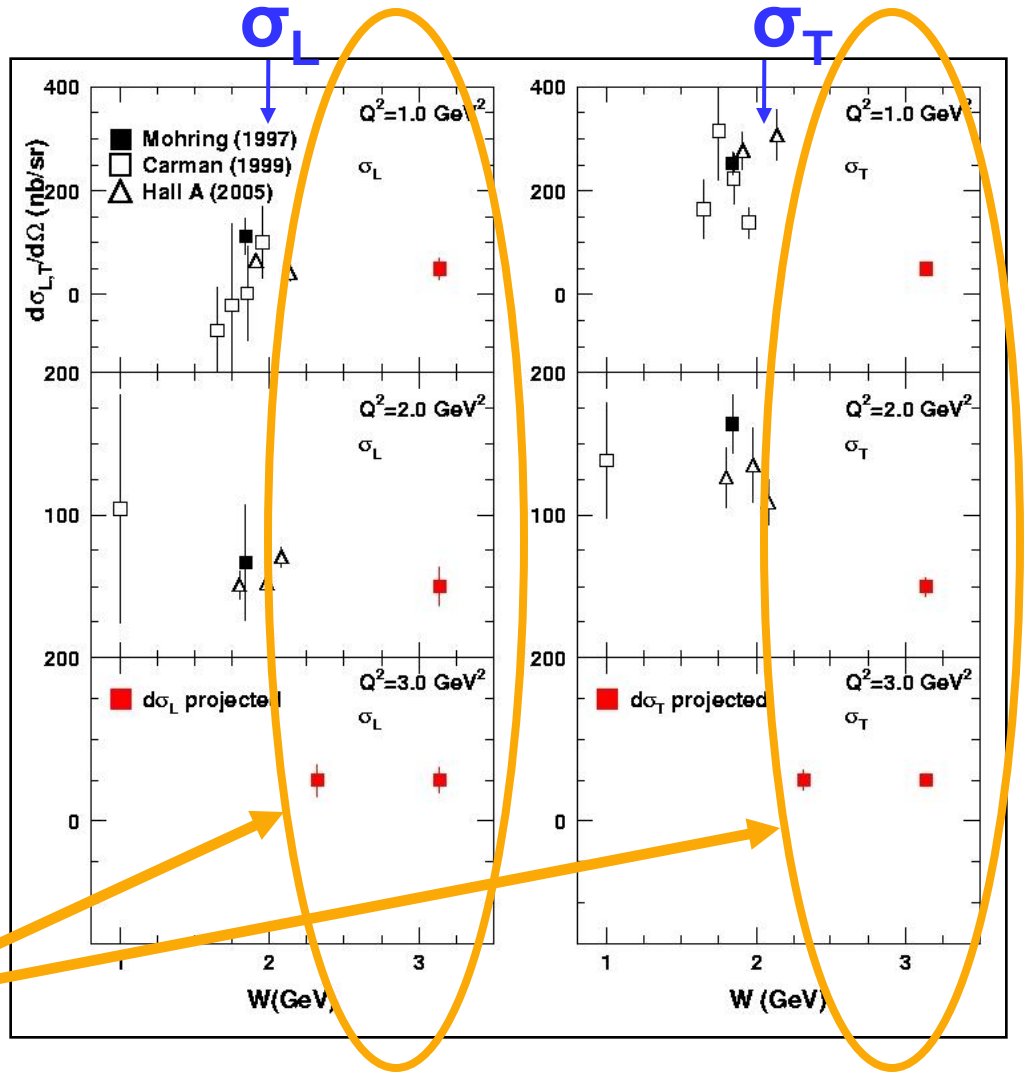
Hall C 6 GeV K^+ data (W=1.84 GeV)



Mohring *et al.*, Phys.Rev.C67:055205,2003

Kaon cross section: σ_L and σ_T

- Approved experiment E12-09-011 *[T. Horn et al.]* will provide first L/T separated **kaon** data above the resonance region
- Onset of factorization
- Understanding of hard exclusive reactions
  - QCD model building
  - Coupling constants

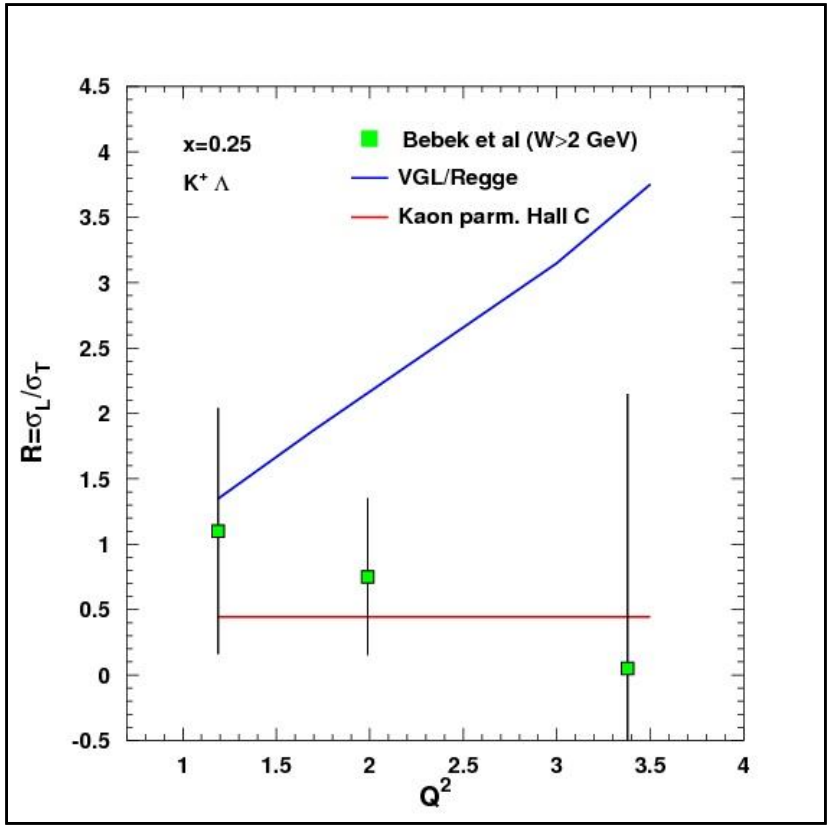


E12-09-011: Precision data for W > 2.5 GeV

$R=\sigma_L/\sigma_T$: Form Factor Prerequisite

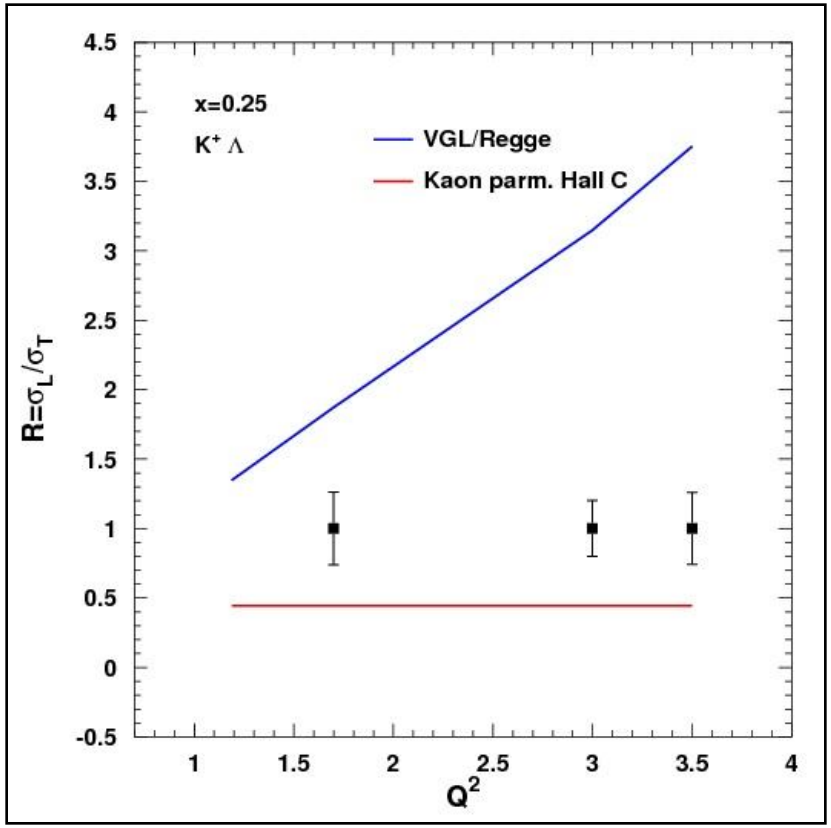
- To reliably extract meson ff, the influence of non-pole *t*-channel contributions must be modest in comparison to pole contributions

- For kaons, current knowledge of σ_L and σ_T above the resonance region is insufficient



$R=\sigma_L/\sigma_T$: Form Factor Prerequisite

- To reliably extract meson ff, the influence of non-pole *t*-channel contributions must be modest in comparison to pole contributions
- For kaons, current knowledge of σ_L and σ_T above the resonance region is insufficient
- Experiment E12-09-011 will provide a better understanding of the t-channel kaon exchange in the amplitude

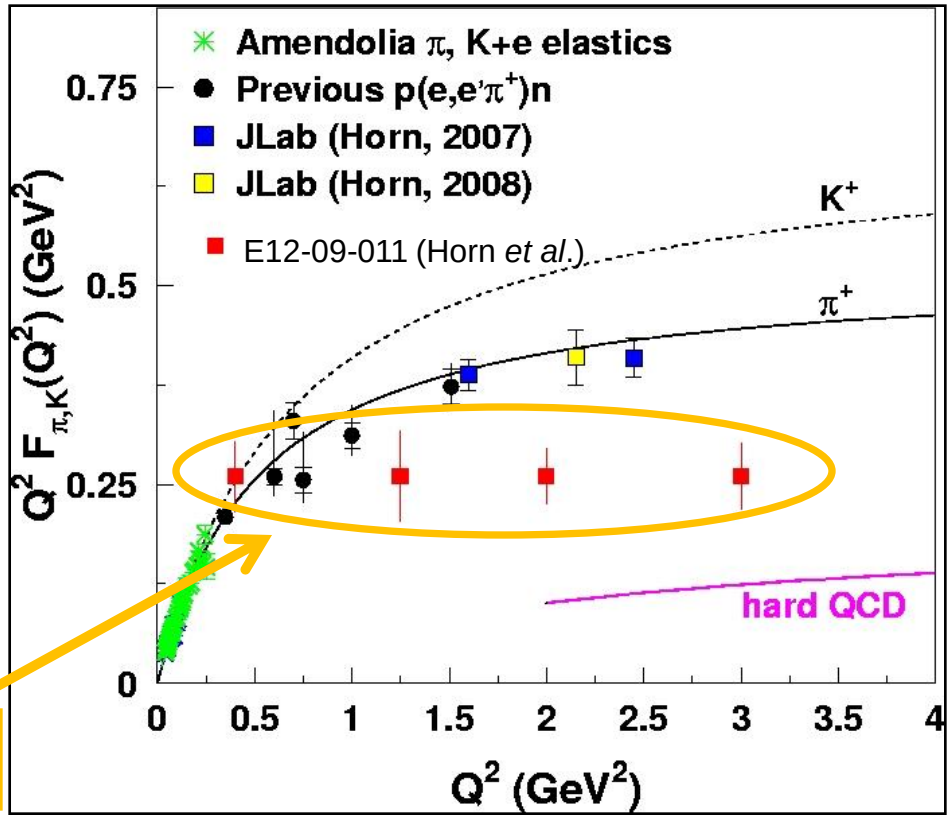


$F_{\pi,K}$ – can kaons shed light on the puzzle?

T. Horn et al., arXiv:0707.1794 (2007).

T. Horn et al., Phys. Rev. Lett. 97 (2006) 192001.

- Compare the observed Q^2 dependence and magnitude of π^+ and K^+ form factors
- Will the analogy between pion cross section and form factor also manifest itself for kaons?

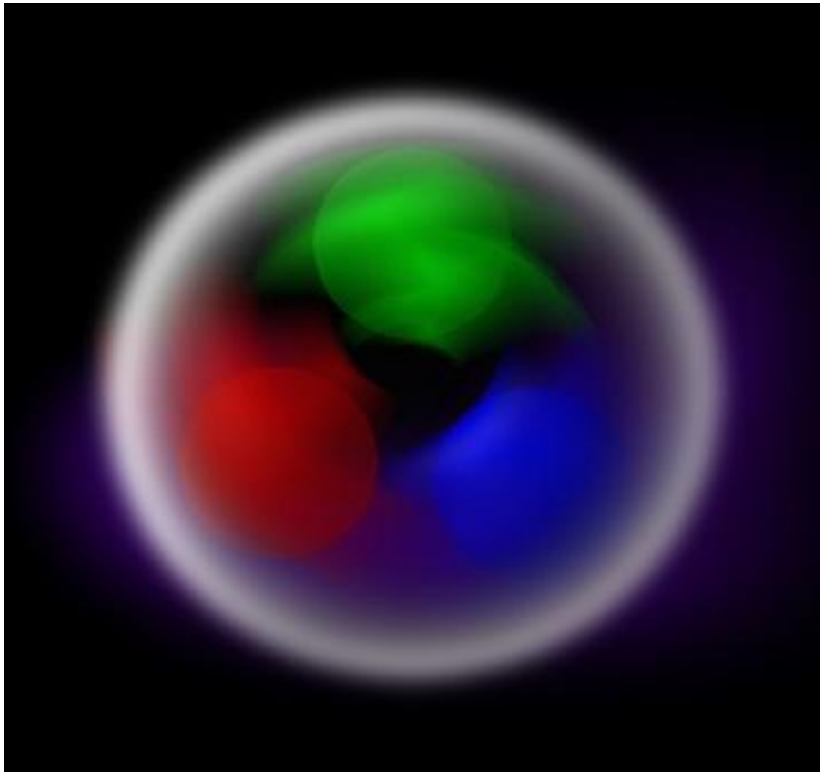


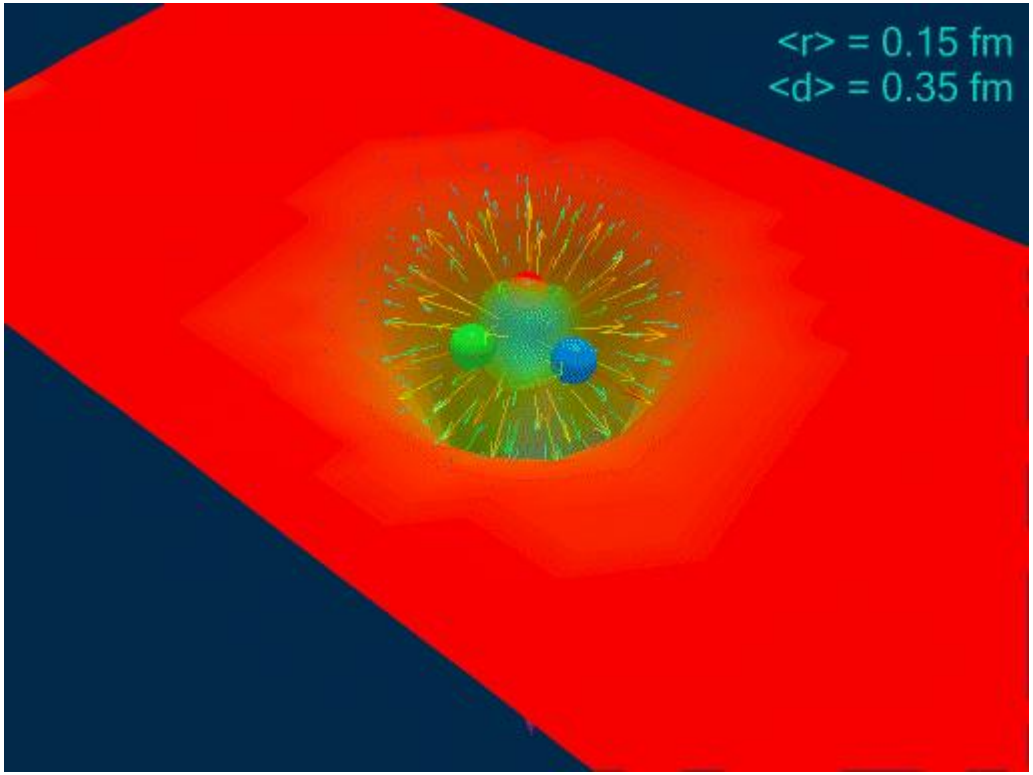
Projected uncertainties for kaon experiment at 12 GeV

Is onset of scaling different for kaons than pions?

Kaons and pions together provide quasi model-independent study

Jefferson Lab beyond 12 GeV





- At JLab 12 GeV we study the three “valence” quarks of the nucleon.
- The next step is to extend this to the sea of virtual quarks and gluons that surround them, and carry a large fraction of the momentum and spin.

Electron Ion Collider (EIC)

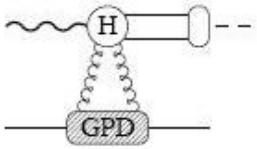
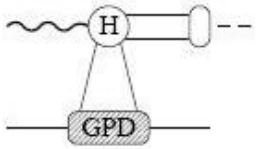
- A next-generation facility aimed at providing unprecedented access to gluon imaging in nucleons and nuclei

  We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron-Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton. [NSAC Long Range Plan 2007]

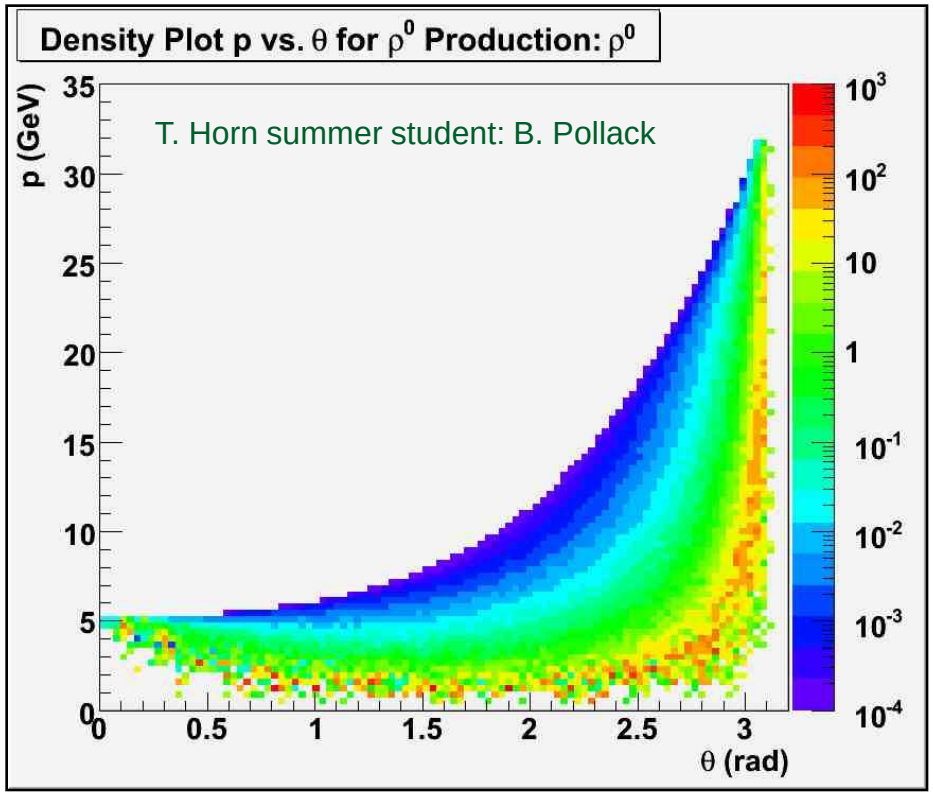
- Two possible physics goals:
  - QCD at high gluon densities
    - Related to the scientific program at LHC
  - Precision imaging of sea-quarks and gluons to determine spin, flavor, and spatial structure of the nucleon
    - Builds on 12 GeV JLab

- Candidates for the EIC are BNL and JLab

Mapping the Virtual Sea

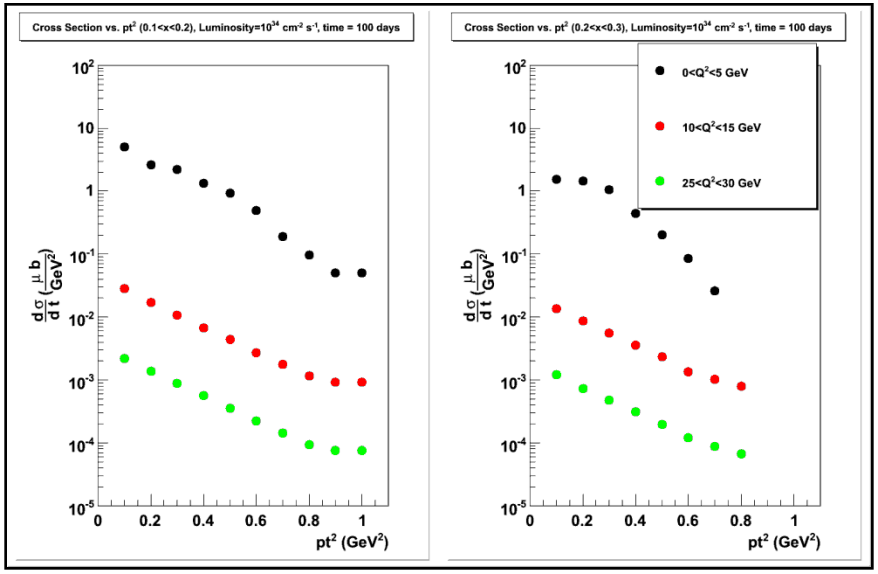
	"diffractive" (vacuum exchange)	"non-diffractive" (quantum number exchange)
Channel	$\gamma p,\ \rho^0 p,\ J/\psi\, p, \ldots$	$\pi^+ p,\ \pi^0 p,\ K\Lambda,\ \rho^+ n, \ldots$
GPDs	 gluon	 non-singlet quark
Cross section	rises with energy	drops with energy
Interest	gluon imaging of nucleon	spin/flavor structure of quark GPDs

Case study: ρ° production



- First figure out where particles go, and how much momentum they have
  - Need this information to know where to place detectors

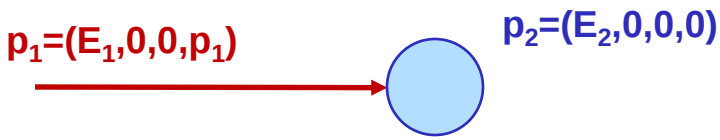
T. Horn summer students: D. Cooper, K. Henderson, B. Pollack, and E. van der Goetz



- Studies of how likely it is to find a particle show how feasible the experiment is

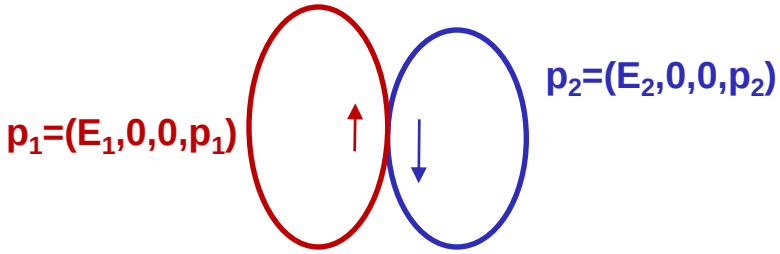
Why a Collider ?

- Fixed target experiments
  - Increase electron beam energy beyond 12 GeV



$$s = (E_1 + E_2)^2 - (p_1 + p_2)^2$$

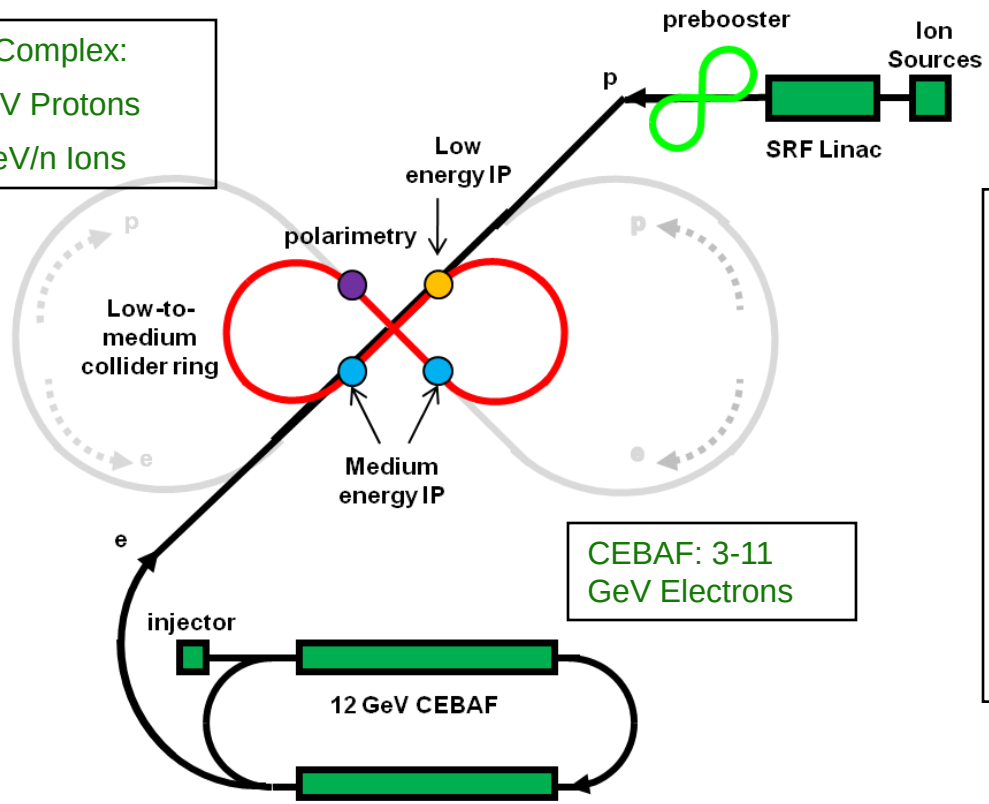
- Collider experiments
  - By colliding two beams of particles, one can achieve even higher energies
  - Facilitates work with beams of particles with particular spin orientation



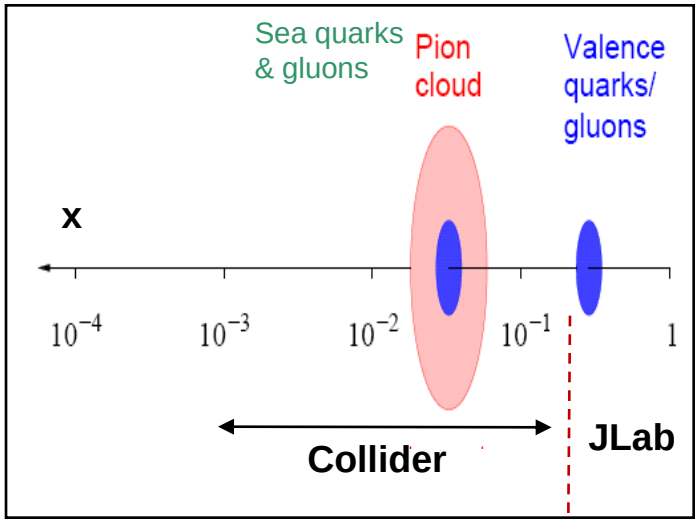
Collider configuration best suited for high energy experiments needed for imaging of sea quarks and gluons

EIC: a new path for JLab

New Ion Complex:
30-60 GeV Protons
15 -30 GeV/n Ions



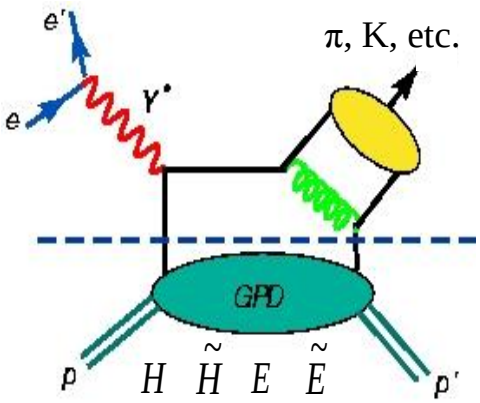
CEBAF: 3-11 GeV Electrons



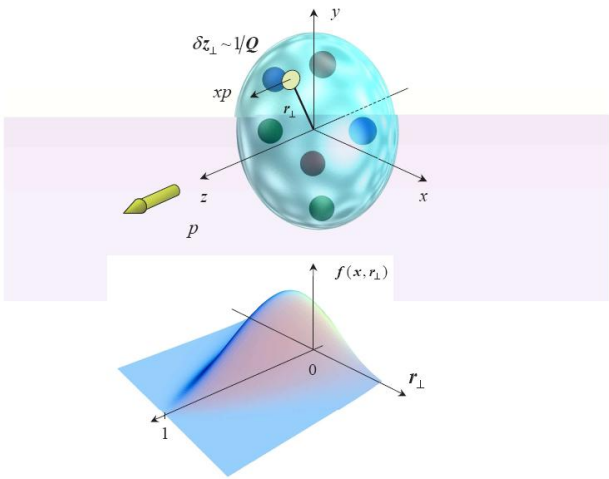
- Combines JLab's electron beam with ions in a new collider ring
- The next big US nuclear physics facility?
- Current plans are based on our proposal *[JLAB-TN-08-070]* http://tnweb.jlab.org/tn/2008/08-070.pdf

Feasibility ↔ Measurement

- *Exclusive meson production* adds flavor to quark imaging studies
  - But one needs to test various pre-requisites
  - Demonstrate that, e.g., *QCD factorization* applies



- What about other exclusive processes like *Compton scattering?*
  - Factorization easier to achieve



Summary

- Meson production data play an important role in our understanding of nucleon structure

- JLab 12 GeV will allow rigorous tests of factorization in meson production
  - Extended kinematic reach and studies of additional systems
  - Essential prerequisite for studies of valence quark spin/flavor/spatial distributions

- Beyond JLab 12 GeV: meson production at an electron-ion collider allows for imaging of sea quarks and gluons
  - Consistent description of kinematic dependences of all channels?

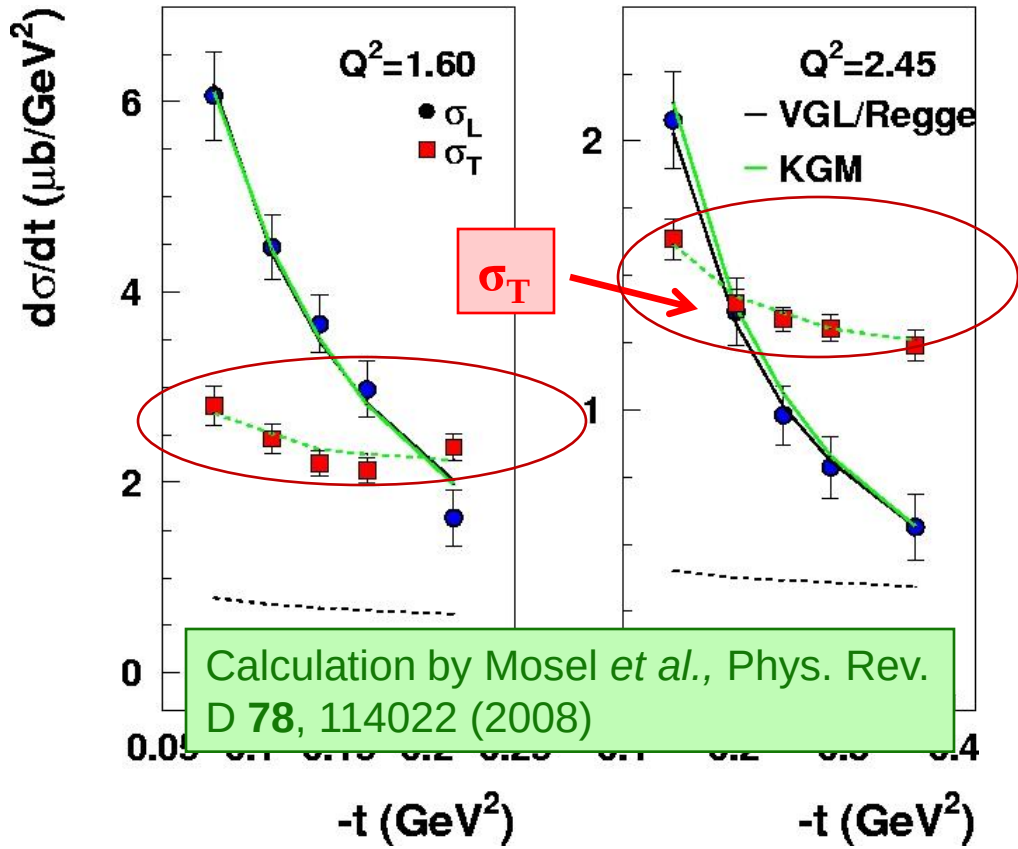
Backup

Transverse Contributions: π^+

- Recent calculation by Mosel *et al.* shows better agreement *[Phys. Rev.* ***D78****: 114022 (2008)]*

- Is σ_T in exclusive π^+ production above the resonance region the limit of SIDIS via the fragmentation mechanism?

Hall C 6 GeV π^+ data at W=2.2 GeV



Horn et al., Phys. Rev. Lett. 97, 192001 (2006)