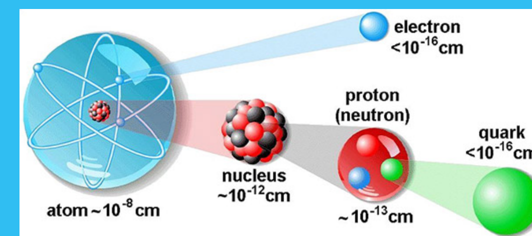
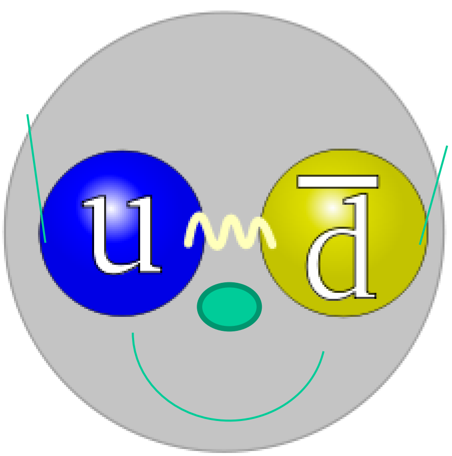
Nucleon Structure – 3D!

Tanja Horn





Paul the Pion

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Lecture 4 of 6

Intro and Overview

- **Lecture 1 & 2: General Overview of QCD and imaging**
  - Introduction and importance of nucleon structure
  - From form factors to GPDs in electron scattering

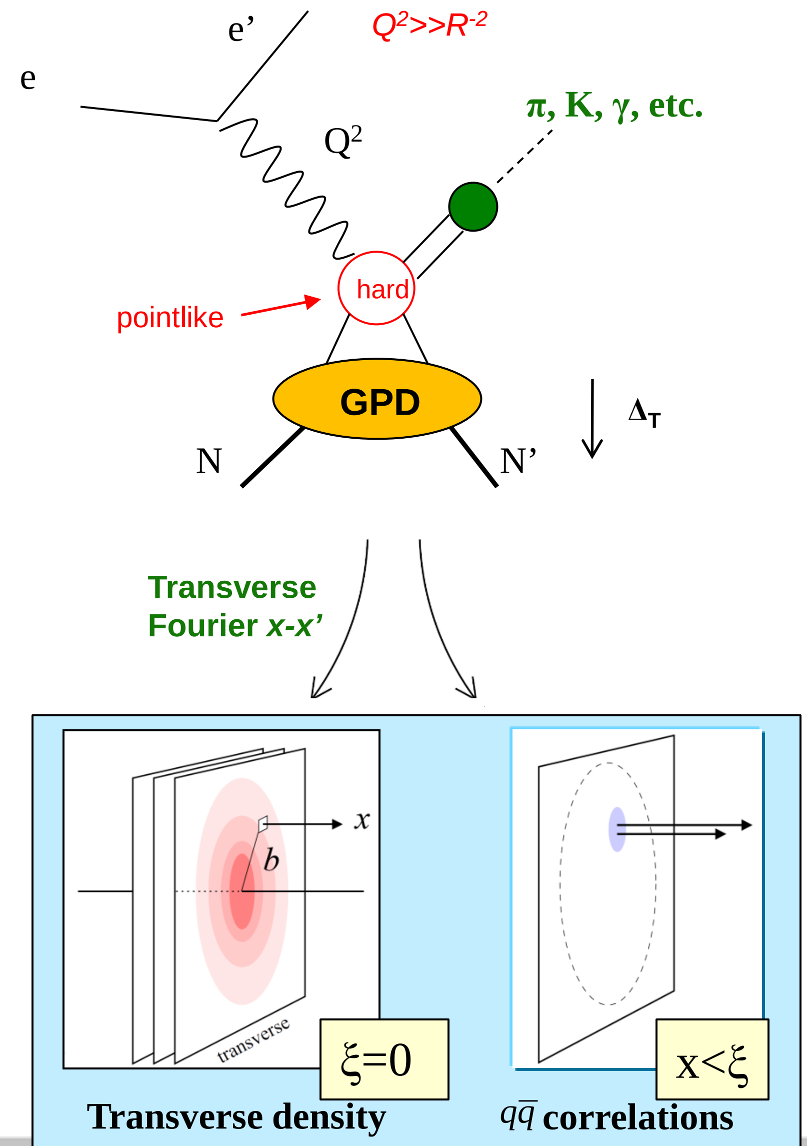
- **Lecture 3 & Lecture 4: Valence quark imaging at JLab** ⟵
  - Jefferson Lab – the place to study nucleon structure
  - Comments on experimental techniques, e.g., Compton Scattering and Deeply Virtual Meson Production
  - Review of results and future prospects

- **Lecture 5: Future of imaging studies**
  - Opportunities at future facilities

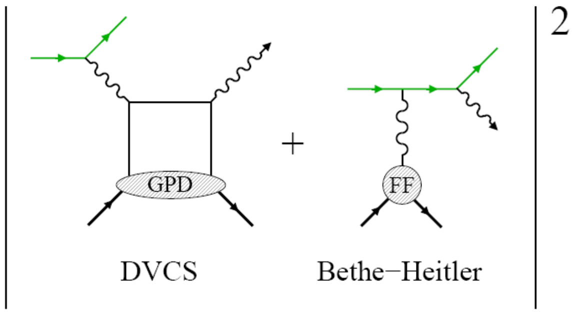
Nucleon Structure through Exclusive Processes

Exclusive Reactions: $\gamma^* N \rightarrow M + B$

- Exclusive processes at sufficiently high Q^2 allow access to Generalized Parton Distributions (GPDs)
  - Factorization theorem: non-perturbative physics factorizes from perturbative QCD processes for longitudinal photons *[Collins , Frankfurt, Strikman 97]*
- GPDs are *a tool for transverse imaging of the nucleon*
  - **Encode information on correlations and distribution of partons in transverse space** *[Burkardt 00]*
  - Moments, Form factor of local twist-2 spin-n operators: EM tensor, angular momentum *[Ji 96, Polyakov 02]*
- Tests of reaction mechanism
  - Model-independent features of small-size regime
  - Finite-size corrections



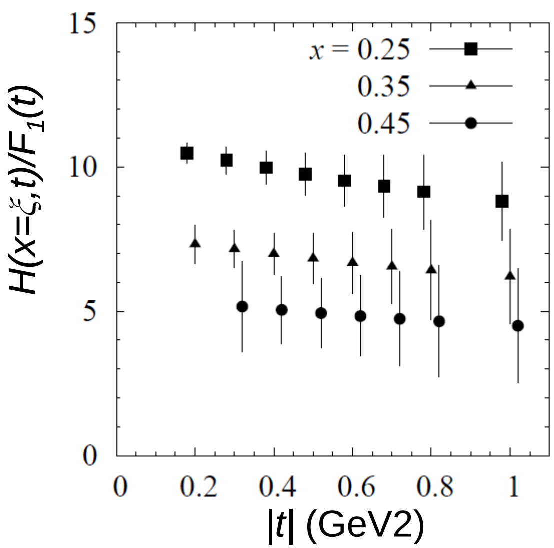
Valence Quark Imaging Example



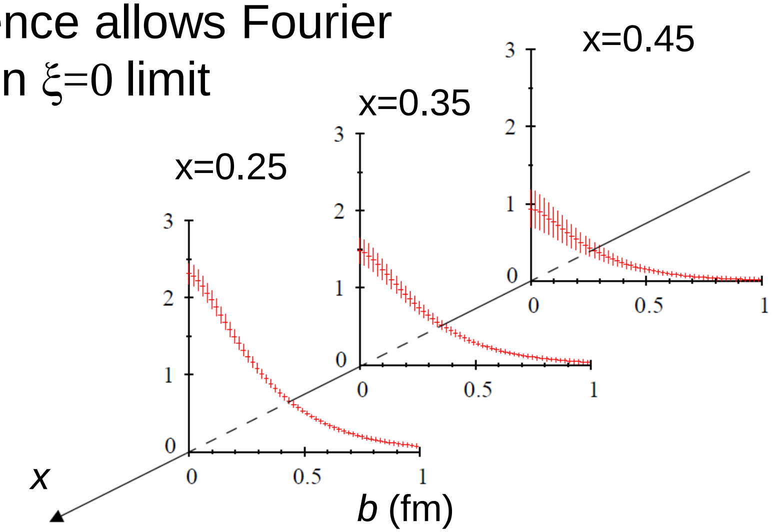
Interference with BH gives access to DVCS amplitude

$$\mathrm{Im(DVCS)} \overset{\mathrm{LT}}{\sim} H(x=\xi,\xi;t)$$

$$\mathrm{Re(DVCS)} \sim \int dx \frac{H(x,\xi;t)}{x-\xi}$$



t- dependence allows Fourier transform in ξ=0 limit



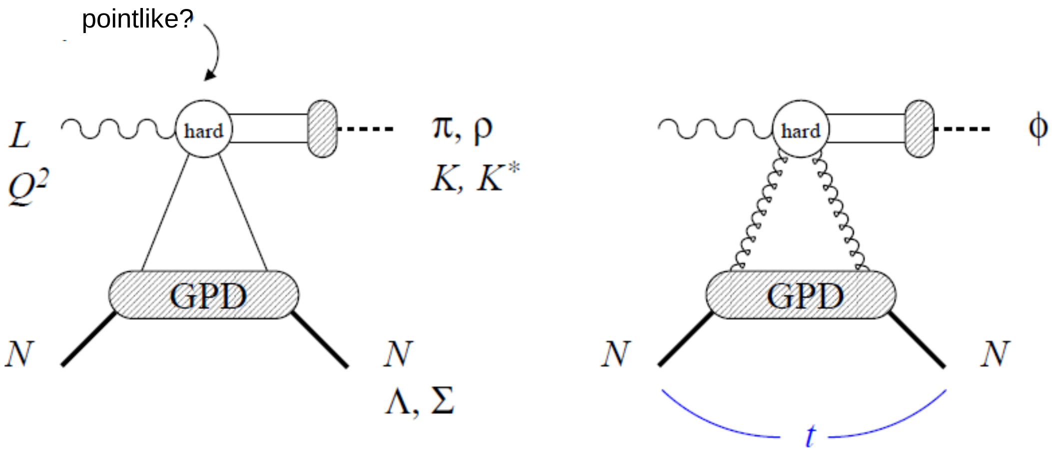
Projected results for GPD H(ξ,x=ξ,t) extracted from beam spin asymmetry

Transverse spatial image of proton obtained by Fourier transforming the measured GPD

Nucleon GPDs: spin-flavor

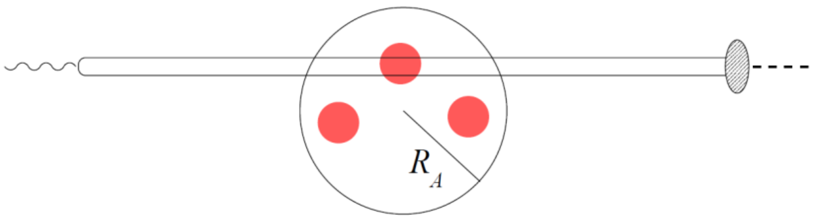
Deep Virtual Meson Production (DVMP)

Exclusive Reactions: $\gamma^* N \to M + B$



- Nucleon structure described by 4 (helicity non-flip) GPDs:
  - *H, E* (unpolarized), $\tilde{H}, \tilde{E}$ (polarized)
- Quantum numbers in DVMP probe individual GPD components selectively
  - Vector : ρ°/ρ+/*K** select *H, E*
  - Pseudoscalar: π,η,*K* select the polarized GPDs, $\tilde{H}$ and $\tilde{E}$
- Need good understanding of reaction mechanism
  - QCD factorization for mesons is complex (additional interaction of the produced meson)

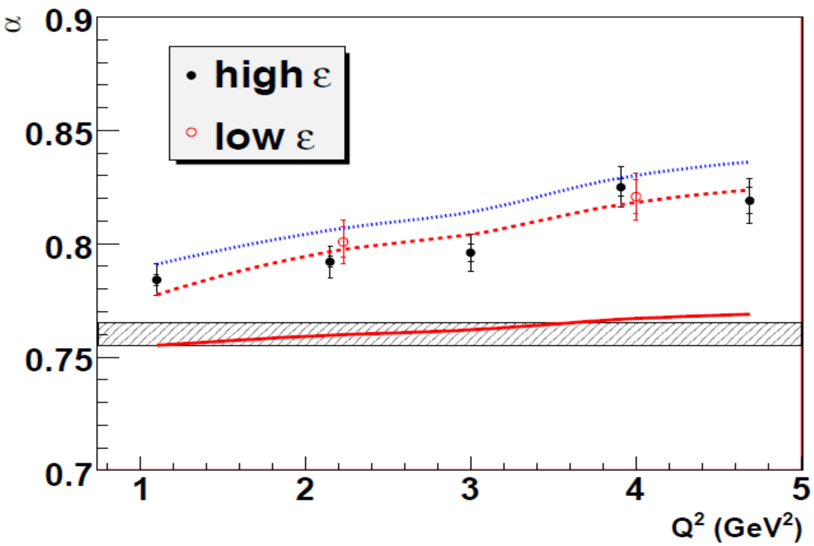
Factorization and Color Transparency



$l_{coh}, l_{form} >> R_A$

$\sigma(A) = \sigma_0 \, A^{\alpha}$

$\therefore T = A^{\alpha-1}$



Consistently larger than 0.76 found from π-N scattering cross sections

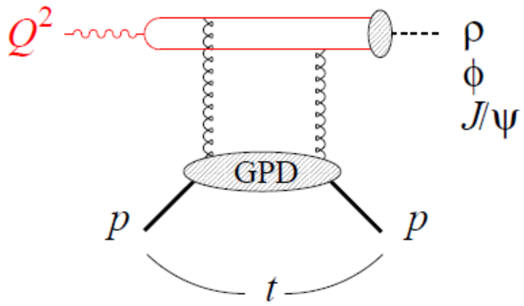
- Color transparency (CT) is a phenomenon predicted by QCD in which hadrons produced at large Q^2 can pass through nuclear matter with little or no interaction *[A.H.Mueller, Proc. 17th rec. de Moriond, Moriond, p13 (1982), S.J.Brodsky, Proc. 13th intl. Symp. on Multip. Dyn., p963 (1982)]*
  - At high Q^2, hadron can be created with a small transverse size (PLC)
  - Hadron can propagate through the nucleus before assuming its equilibrium size

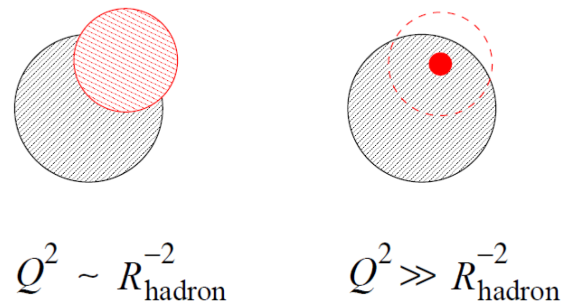
- CT is a signature of the approach of the factorization regime

CUA

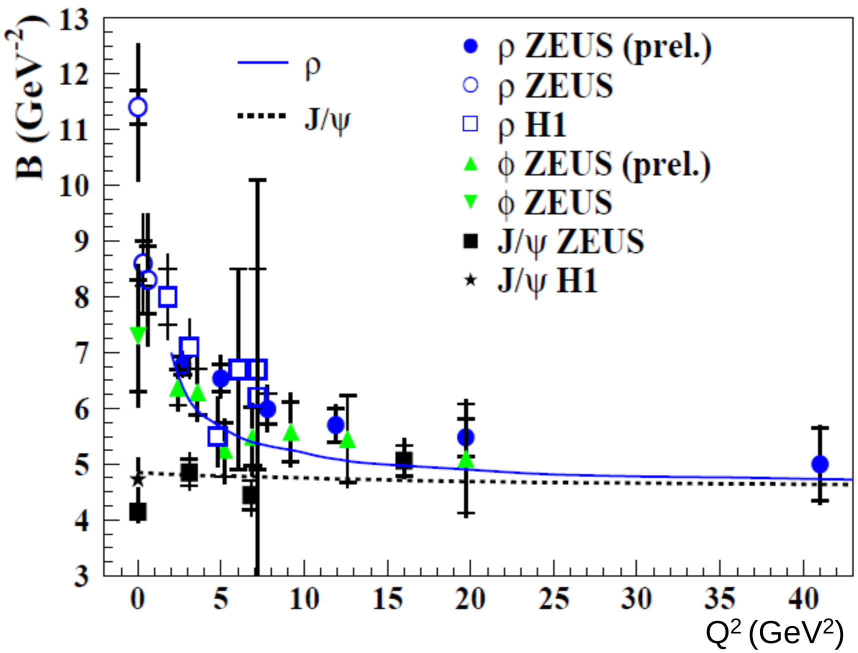
Recent CT results are suggestive but not conclusive for mesons

Vector Mesons and the Small Size Regime





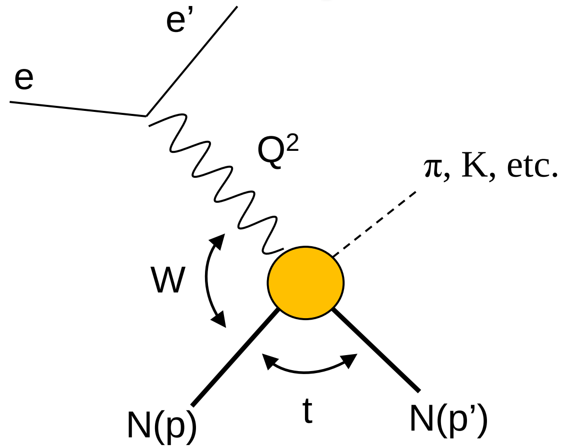
HERA Vector Meson Data



- t-slope of cross section measures the transverse area of the interaction region
  - Reflects size of target and that of dominant configurations of produced meson
- t-slope decreases with increasing Q^2 and stabilizes when small-size configurations dominate
- In small size regime t-slope can be associated with t-dependence of GPD

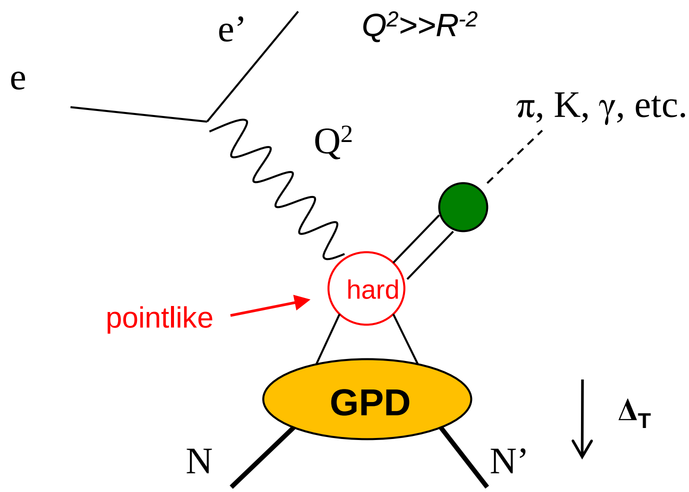
Data show that factorization sets in, but precision in mapping its onset is not sufficient for the needs of JLab experiments

Meson Reaction Dynamics



t-channel process

- Meson production can be described by the t-channel exchange meson pole term in the limit of small –t and large W
  - Pole term is dominated by longitudinally polarized photons
  - Spatial distribution described by form factor



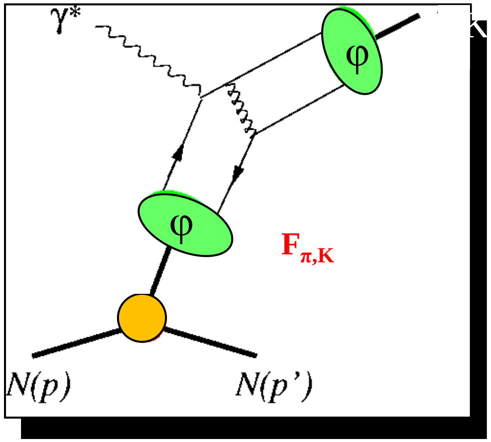
handbag

- At sufficiently high Q^2, the process should be understandable in terms of the "handbag" diagram
  - The non-perturbative (soft) physics is represented by the GPDs
    - Shown to factorize from QCD perturbative processes for longitudinal photons *[Collins, Frankfurt, Strikman, 1997]*

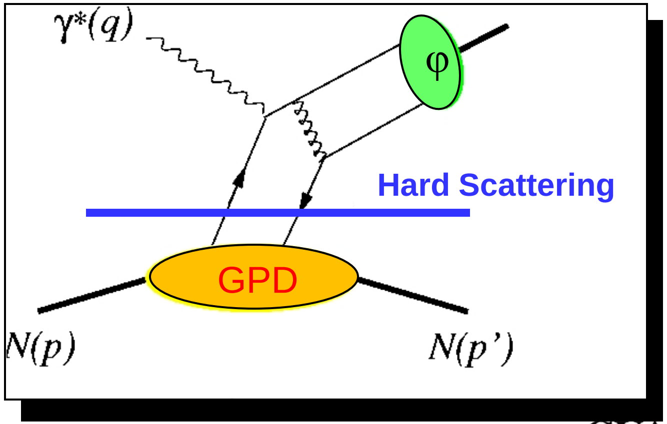
Transverse Spatial Distributions: Form Factors and GPDs

- Meson form factors and nucleon GPDs are essential to understand the structure of hadrons

- But measurements of form factors and GPDs have certain prerequisites:
  - For form factors, must make sure that σ_L is dominated by the meson pole term at low -t
  - For GPDs, must demonstrate that factorization applies ($\sigma_L \sim Q^{-6}$ to leading order)

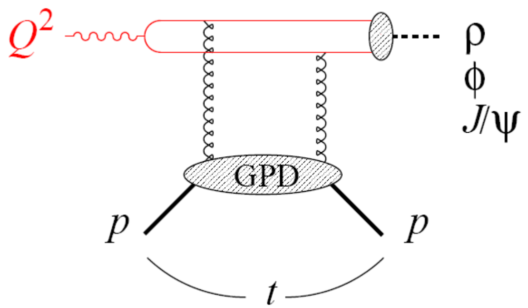


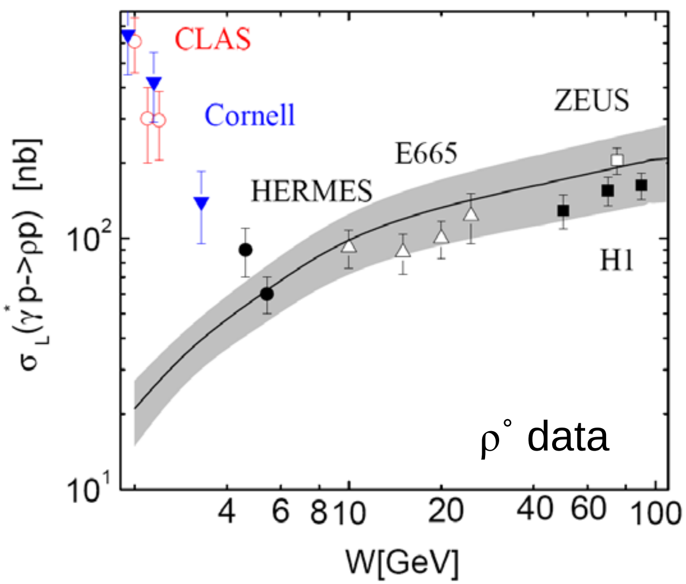
- A *comparison of pion and kaon production* data may shed further light on the reaction mechanism
  - quasi-model independent
  - more robust than calculations based on QCD factorization and present GPD models



Meson Reaction Mechanism

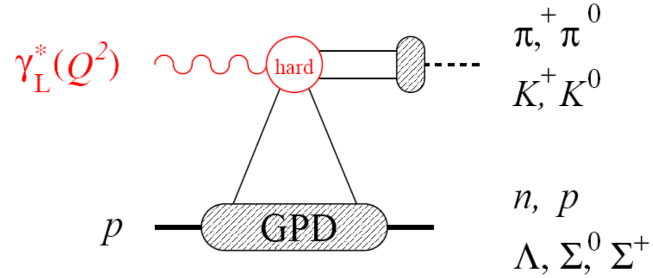
Vector Mesons

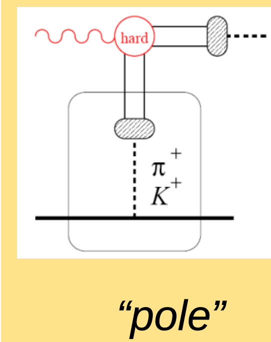


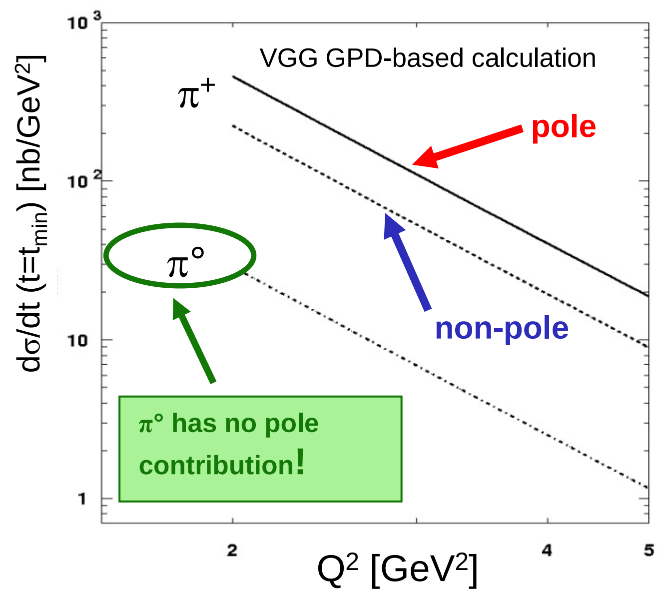


- Understanding of reaction mechanism
  - Role of qqbar pair knockout
  - Finite-size corrections

Pseudoscalar Mesons







- Feature: *pole term* in GPD
- Understand relative importance of "pole and "non-pole" contributions

Exclusive Pseudoscalar Data: Pions and Kaons

- Data used in this analysis
  - Used separated cross sections where possible

$$\boxed{e\,p \rightarrow \pi^{+} n}$$

- Cornell

  C.J. Bebek *et al*., Phys.Rev.D17 (1978) 1693.

- DESY

  P. Brauel *et al*., Z.Phys.C3 (1979) 101.

  A. Airapetian *et al*., Phys.Lett.B659 (2008) 486

- Jefferson Lab 6 GeV

  H.P. Blok, T. Horn *et al*., Phys.Rev.C78 (2008) 045202.

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

$$\boxed{e\,p \rightarrow K^{+} \Lambda}$$

- Cornell

  C.J. Bebek *et al.*, Phys.Rev.D15 (1977) 594.

- DESY

  P. Brauel *et al*., Z.Phys.C3 (1979) 101.

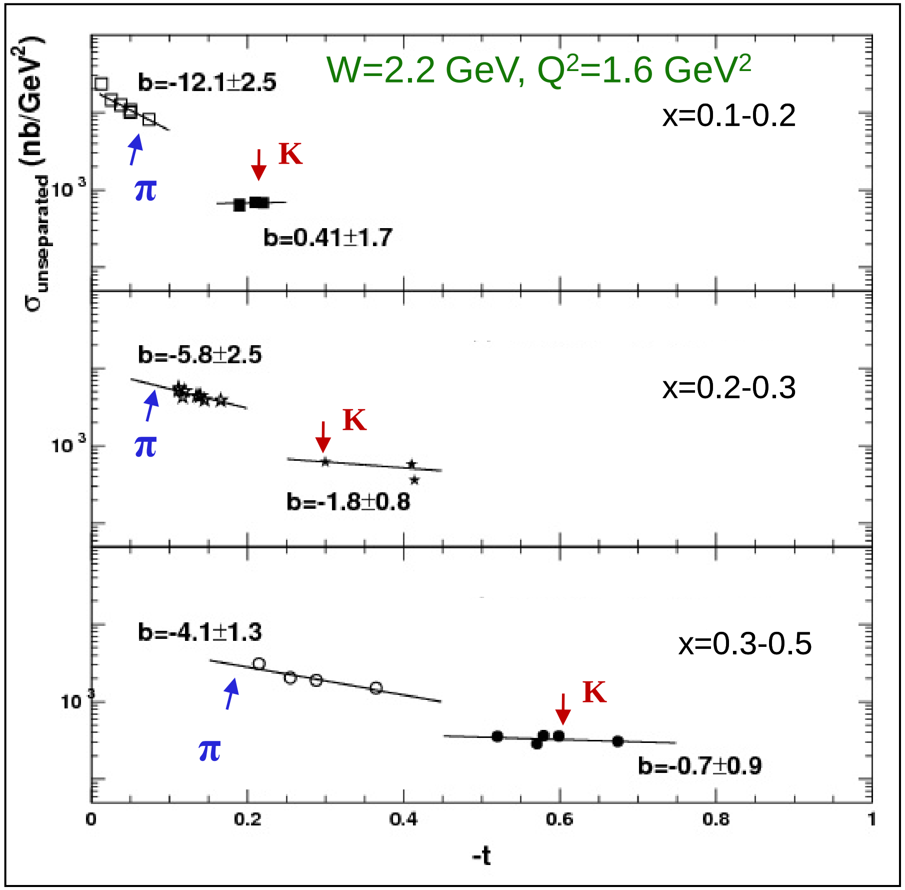
- Jefferson Lab 6 GeV

  M. Coman *et al*., arXiv:0911.3943.

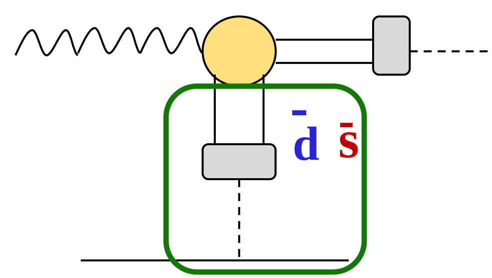
  R. Mohring *et al*., Phys.Rev.C67 (2003) 055205

Low Q^2: e^{-bt} scaling of σ_π and σ_K

Combines data from Cornell, DESY, and JLab 6 GeV



- Pion and kaon data follow an almost exponential t-dependence
  - Q^2 and t dependence does not factorize completely
- t-dependence flatter at larger x
- Pion t-dependence is steeper *at* low *t* than for kaons
  - pole factor $\left(m^2_{K,\pi} - t\right)^{-1}$ gives less enhancement for kaons than pions
  - Different from u-quark exchange



Pole factor enhances pion cross section – additional low t data would allow to interpret contribution for kaons

High Q^2: Q^{-n} scaling of σ_L and σ_T

- To access physics contained in GPDs, one is limited to the kinematic regime where hard-soft factorization applies

- A test is the Q^2 dependence of the cross section:
  - $\sigma_L \sim Q^{-6}$
  - $\sigma_T \sim Q^{-8}$
  - As Q^2 gets large: $\sigma_L >> \sigma_T$

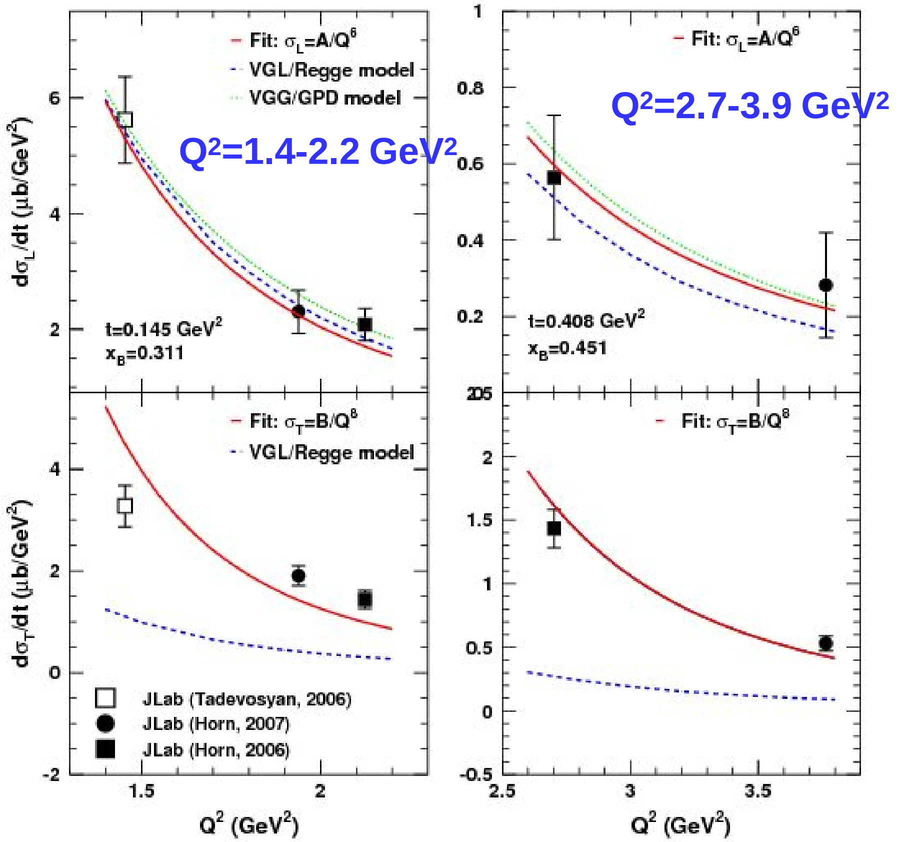
- The QCD scaling prediction is reasonably consistent with recent JLab π^+ σ_L data, *BUT* σ_T does not follow the scaling expectation

$ep \rightarrow e'\pi^+ n$

Hall C π^+ production data at 6 GeV

σ_L →

σ_T →



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

Kaon production data would allow for a quasi model-independent comparison that is more robust than calculations based on QCD factorization and present GPD models

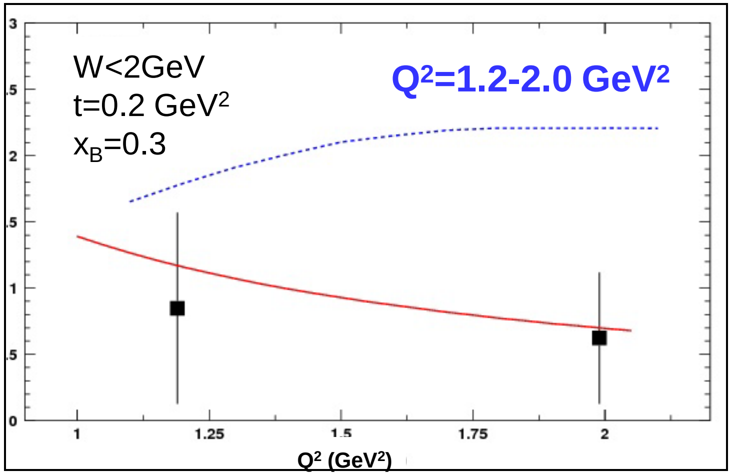
Kaons: Q^{-n} scaling of σ_L/σ_T in the resonance region

$ep \rightarrow e'K^+\Lambda$

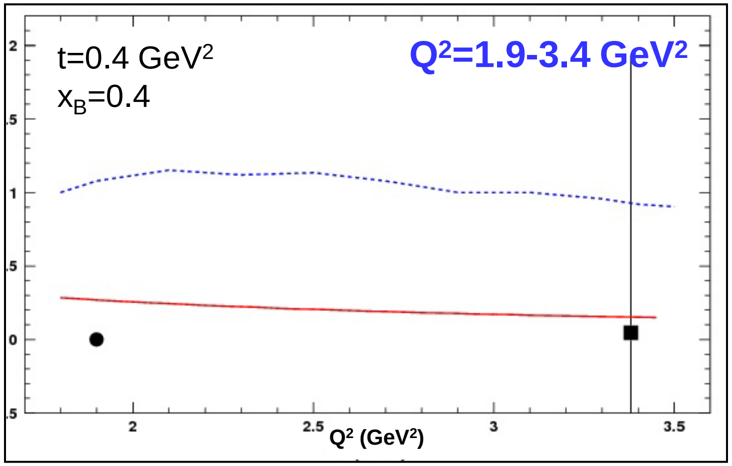
Cornell and JLab/Hall A data

- Q^{-n} scaling trough $R=\sigma_L/\sigma_T$ is not as rigorous as the scaling test of the individual cross sections
- Current knowledge of σ_L and σ_T *above* the resonance region is insufficient
- Current models not sufficient for understanding reaction mechanism
- Difficult to draw a conclusion from current K^+ σ_L/σ_T ratios
  - Limited W and Q^2 coverage
  - Uncertainties from scaling in x, t

$R=\sigma_L/\sigma_T \longrightarrow$



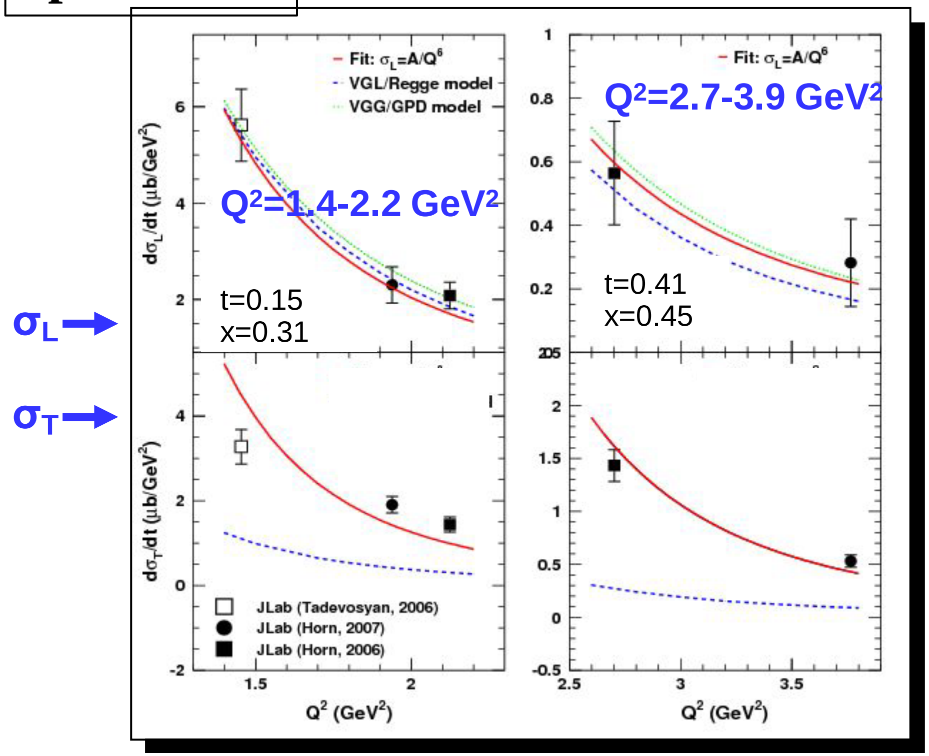
$R=\sigma_L/\sigma_T \longrightarrow$

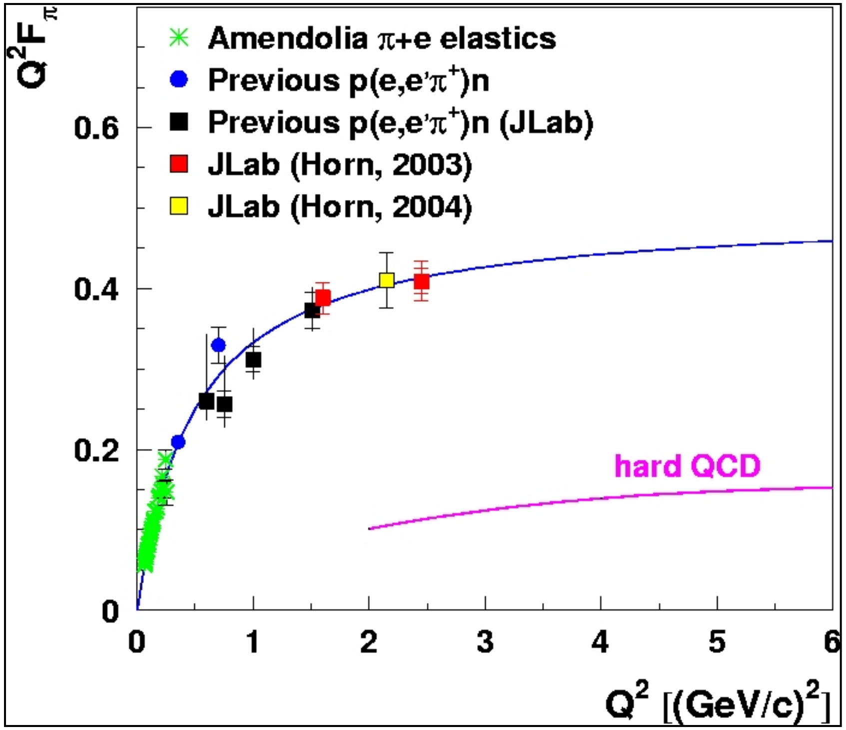


High quality σ_L and σ_T data for both kaon and pion would provide important information for understanding the meson reaction mechanism

Pion Form Factor – a puzzle?

$ep \to e'\pi^+n$ — T. Horn et al., Phys. Rev. C78, 058201 (2008)





- 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

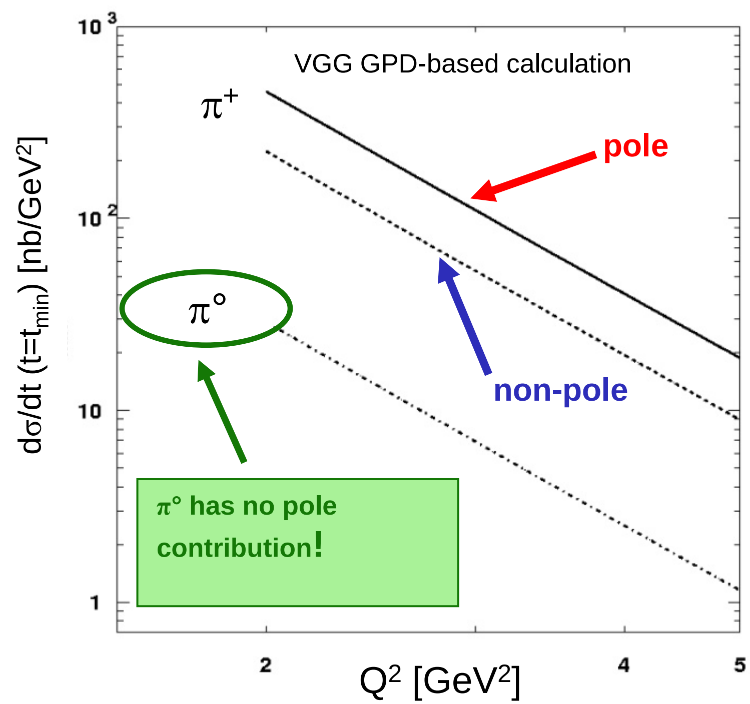
- Q^2 dependence of the pion form factor (F_π) follows prediction from perturbative QCD, suggests factorization holds
- Different magnitudes imply that factorization does not hold or something is missing in calculation

Further information on the pion puzzle through varying the system

Pole and Non-pole contributions

- Production of π^+ and K^+ feature a meson exchange contribution in the t-channel (pole term), whose impact on factorization has to be understood

- In π° production the pole term is suppressed
  - The t-dependence at small t can thus be associated with the structure of the nucleon rather than its pion cloud
    - A large $R=\sigma_L/\sigma_T$ would imply the realization of the factorization theorem
  - A large response in σ_L may indicate non-pole contributions in π^+ production



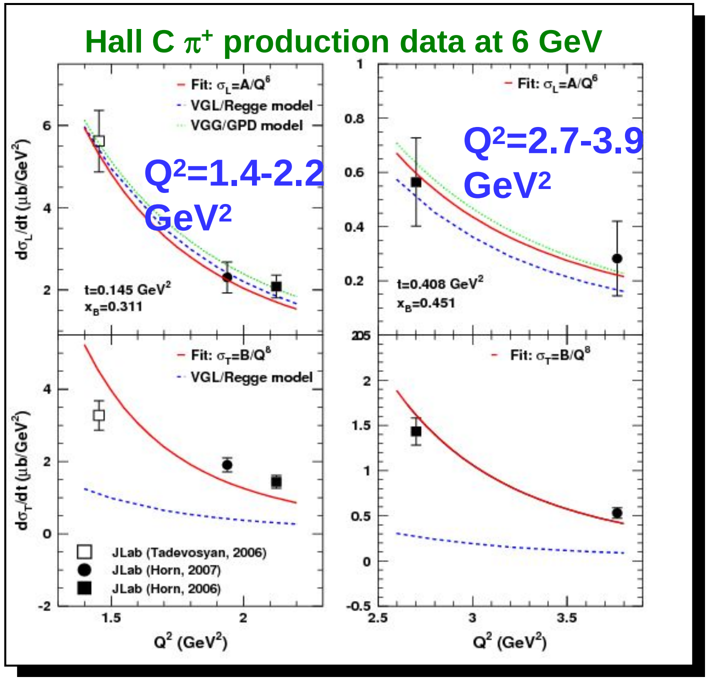
Comparison of R in π° and π^+ production important for understanding:
- Non-pole contributions in F_π extraction
- Relative importance of pole and non-pole contributions in nucleon spin structure studies

Transverse Contributions

- Recent data suggest that transversely polarized photons play an important role in pion electroproduction
  - *Hall C π^+:* σ_L follows scaling prediction, σ_T does not follow the corresponding expectation
  - HERMES π^+: sin ϕ_s modulation is large [Airapetian et al, Phys. Lett. B 682, 345 (2010)]
  - CLAS: π^0 data show substantial fraction of σ_{TT} in the *unseparated* cross section [Kubarovsky10+]

σ_L →

σ_T →

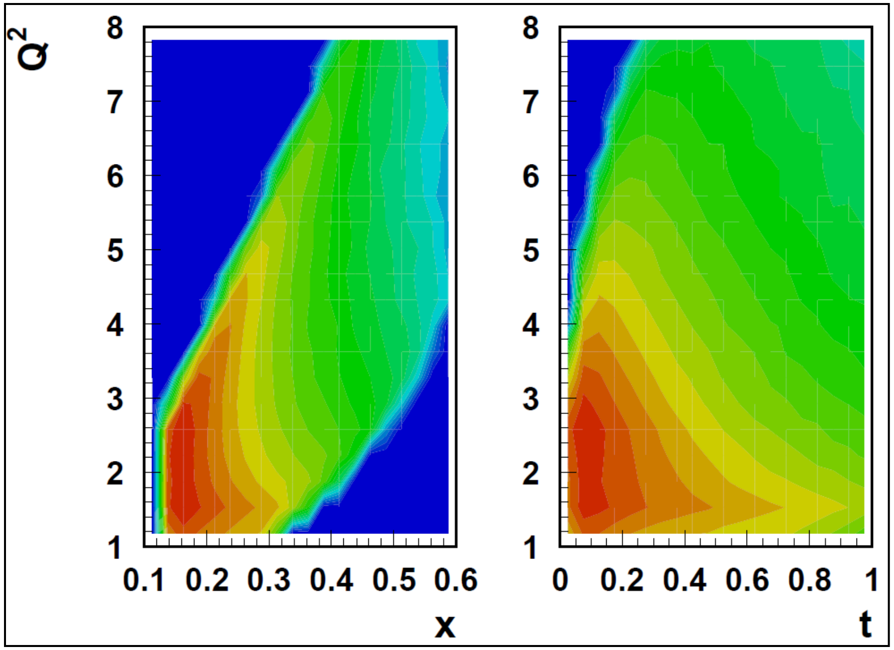


[Horn et al., Phys. Rev. C 78, 058201 (2008)]

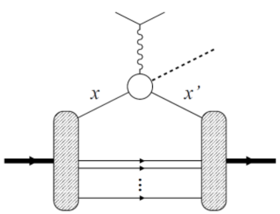
- Recent theoretical developments suggest no strong suppression of σ_T at experimentally accessible values of Q^2 [Goloskokov, Kroll Eur. Phys. J. C 65, 137 (2010); Eur. Phys. J. A 45, 112 (2011)]
  - Large σ_T in π^0 may allow access to helicity flip GPDs

Measurement of the relative σ_L and σ_T contributions to the π° cross section important for reliable interpretation of data from 12 GeV Jlab GPD program.

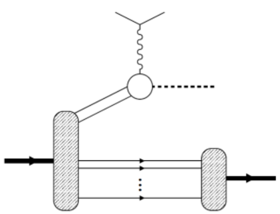
JLab 12 GeV: exclusive reactions



CLAS12 kinematic coverage $N(e,e'\gamma)N$



Scattering from q or $\bar{q}$



Knockout of $q\bar{q}$ pair

$s = 2E_e m_p$

- Unique features:
  - Center of mass energy, *s*=20.6 GeV^2
  - Luminosity 10^{37} cm^{-2}s^{-1} (Hall A,C), 10^{35} (CLAS12) for valence region, differential measurements, spin asymmetries
  - CLAS12 and magnetic spectrometers in Hall A, C are complementary

- Transverse imaging in valence region:
  - GPDs from DVCS $\gamma^* N \to \gamma + N$

    Transverse charge densities from elastic form factors $\int dx\, \rho(x,b)$
  - **Transverse flavor/spin distributions from exclusive meson production**

$$\gamma^* N \to N + \pi, K, \rho, K^*, \phi$$

- Limited kinematic coverage:
  - How to test the reaction mechanism?

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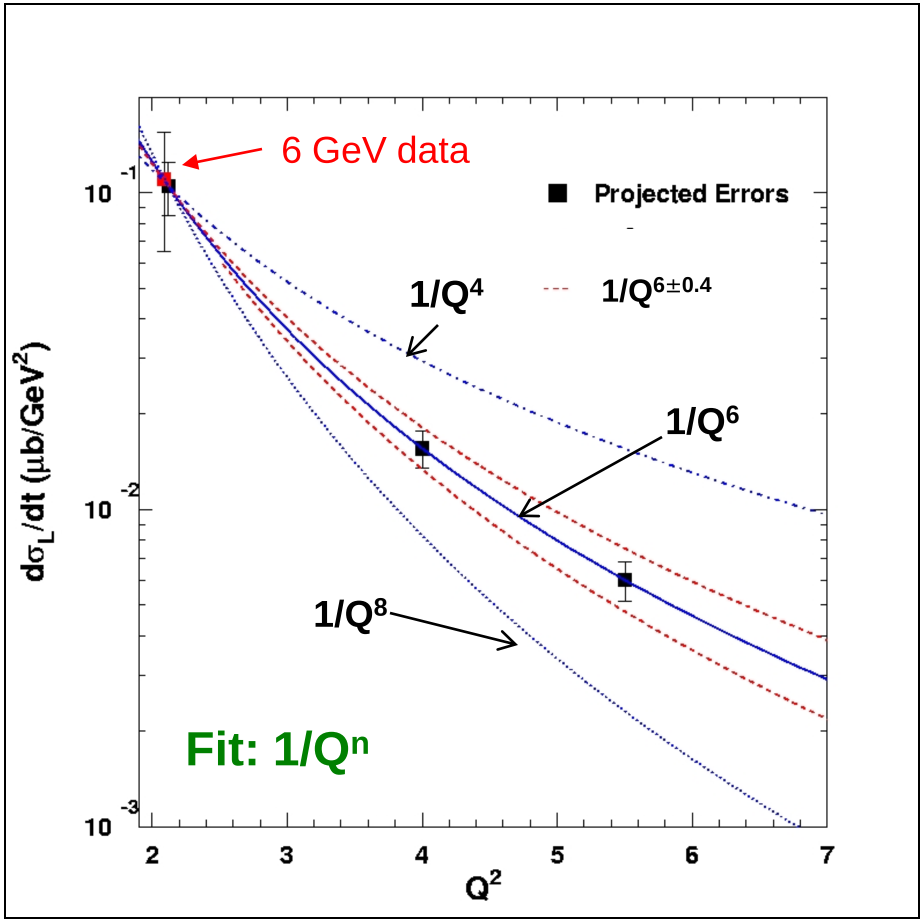
Factorization Tests in π^+ Electroproduction

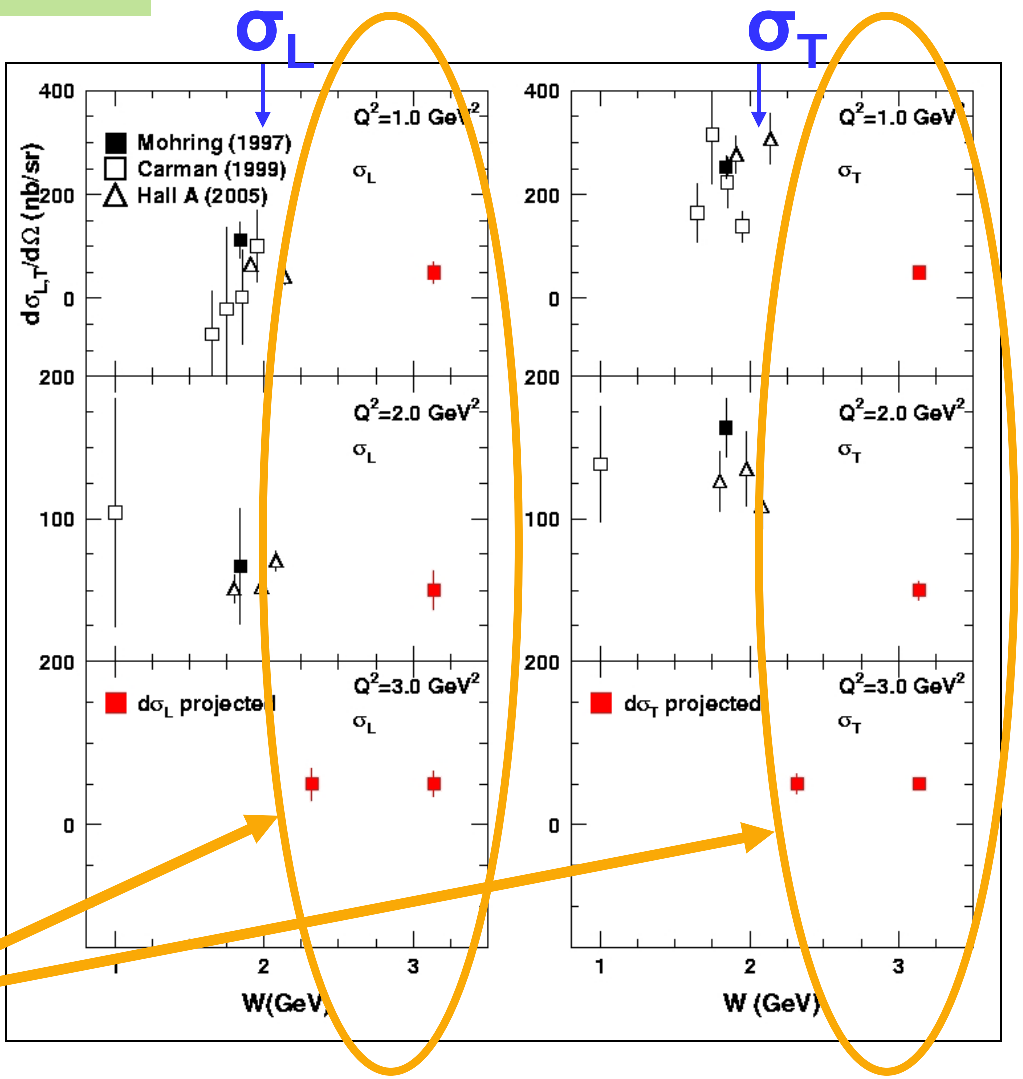
- JLab experiment E12-07-105 will search for the onset of factorization
- Q^2 coverage is 2-3 times larger than at 6 GeV at smaller t
- Factorization essential for reliable interpretation of results from the JLab GPD program at both 6 GeV and 12 GeV



Is the partonic description applicable in practice?
Can we extract GPDs from pion production?

Kaon cross section: σ_L and σ_T

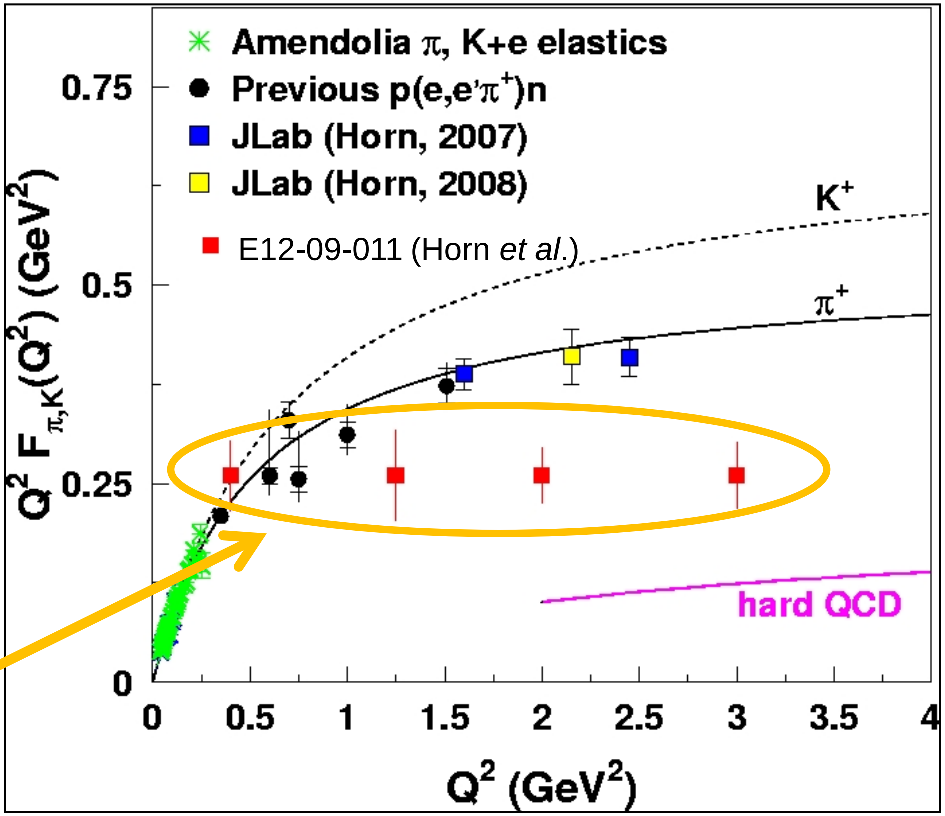
- Approved experiment E12-09-011 will provide first L/T separated **kaon** data above the resonance region
- Onset of factorization
- Understanding of hard exclusive reactions
  - QCD model building
  - Coupling constants



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

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

- 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?



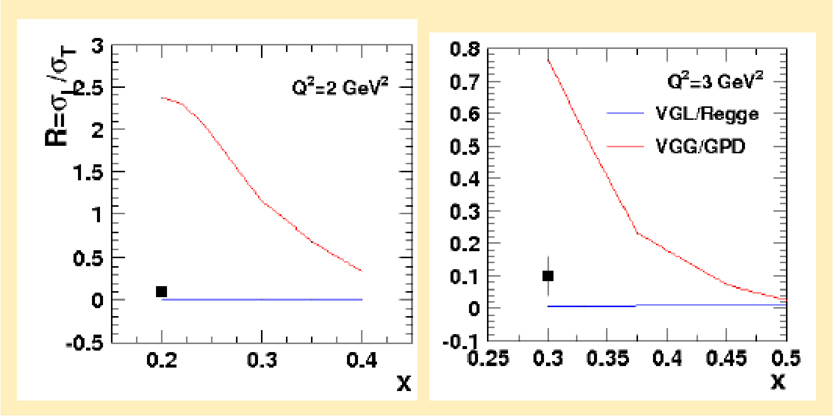
Projected uncertainties for kaon experiment at 12 GeV

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

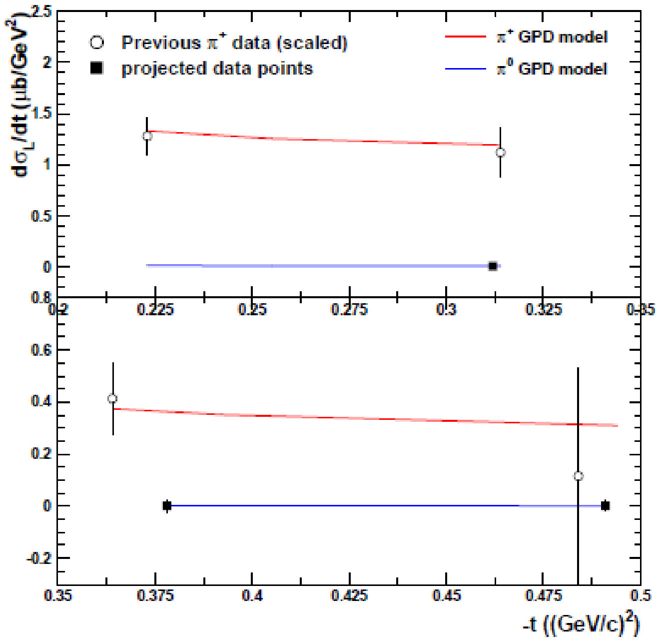
Is onset of scaling different for kaons than pions?
Kaons and pions together provide quasi model-independent study

Relative contribution of σ_L and σ_T in π^o production

- GPD studies with pions require understanding relative contributions of σ_L and σ_T



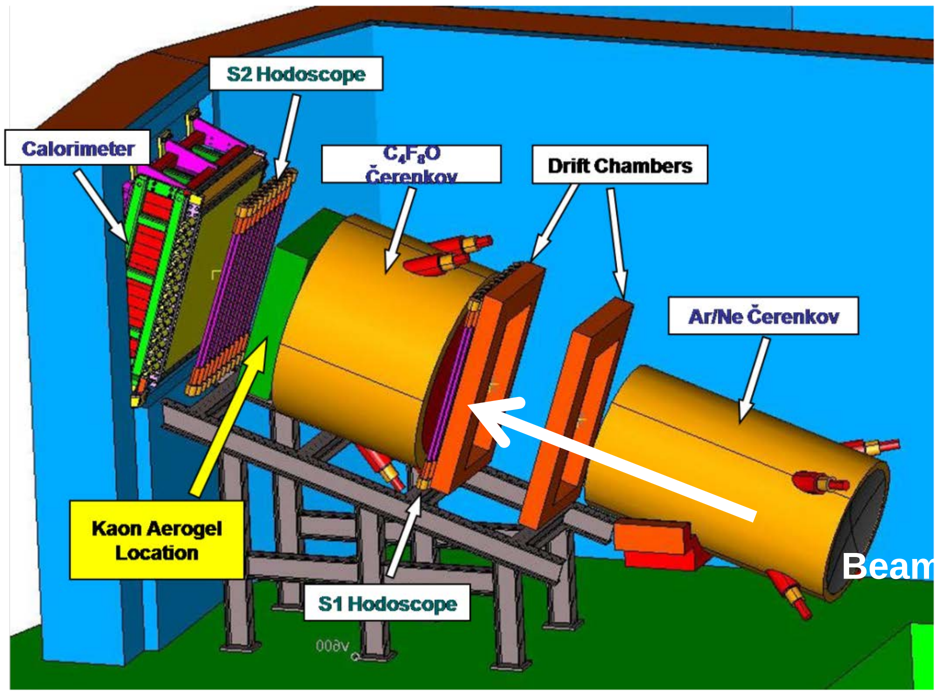
- Is the relative contribution of σ_L in π° production significant?
  - 12 GeV: Opportunity to compare to separated σ_L and σ_T in π^+ production (E12-07-105)
  - Constrain the size of non-pole contributions
    - If smaller than anticipated may extract F_π to higher Q^2



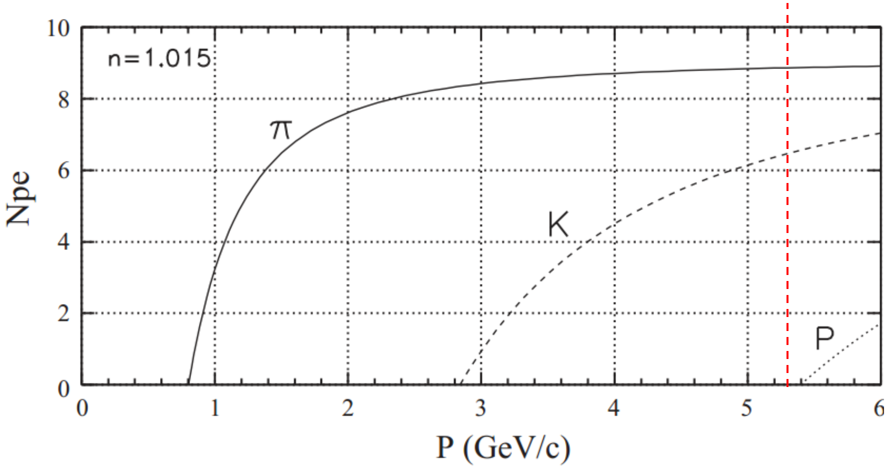
PR12-11-102: Separated σ_L, σ_T for studies of scaling in neutral systems and relative importance of pole and non-pole contributions

Kaon Particle Identification

- An aerogel Cerenkov detector is the simplest and most economical option to distinguish kaons from protons for momenta above 2.6 GeV/c
- Detector positioned in a space in the SHMS detector stack between the heavy gas Cerenkov and S2 hodoscope detectors
  - Support for multi-index aerogel Cerenkov for kaon physics program



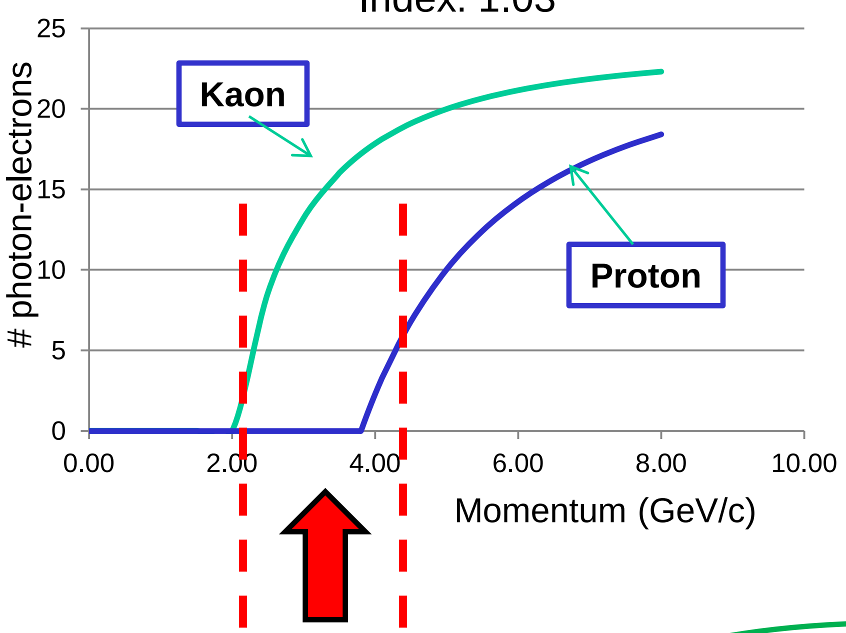
Aerogel detector installed in SHMS detector hut

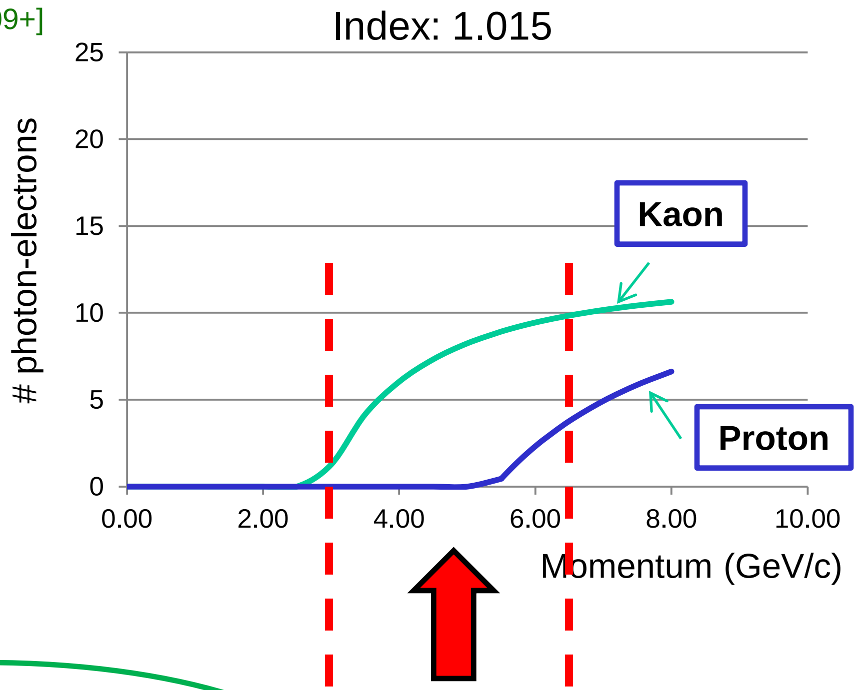


Aerogel refractive indexes

➢ Selecting the refractive index of the aerogel, one can select the range for Proton/Kaon distinguish

[Nathaniel Hlavin 09+]



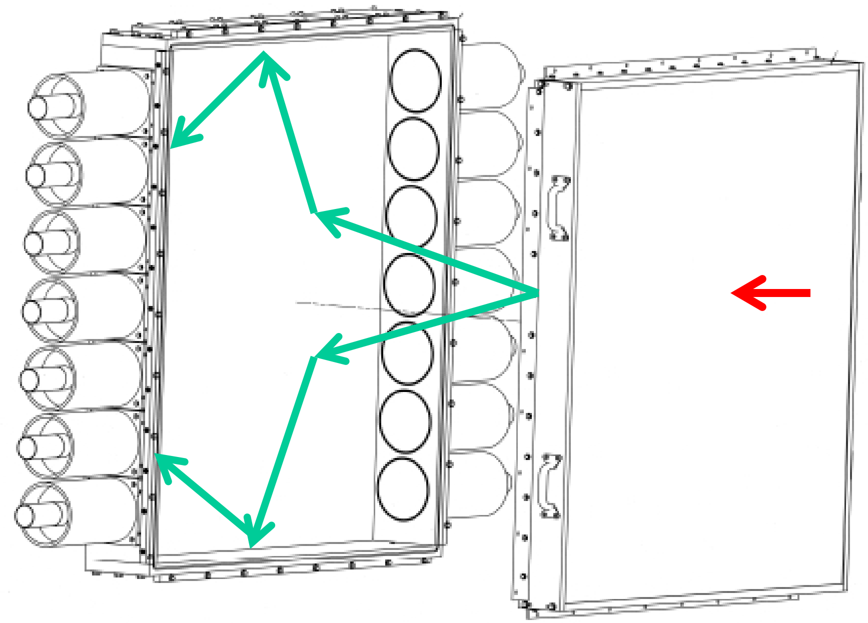


Cover the full Kaon momentum range: from 2.5 to 7.1 GeV/c

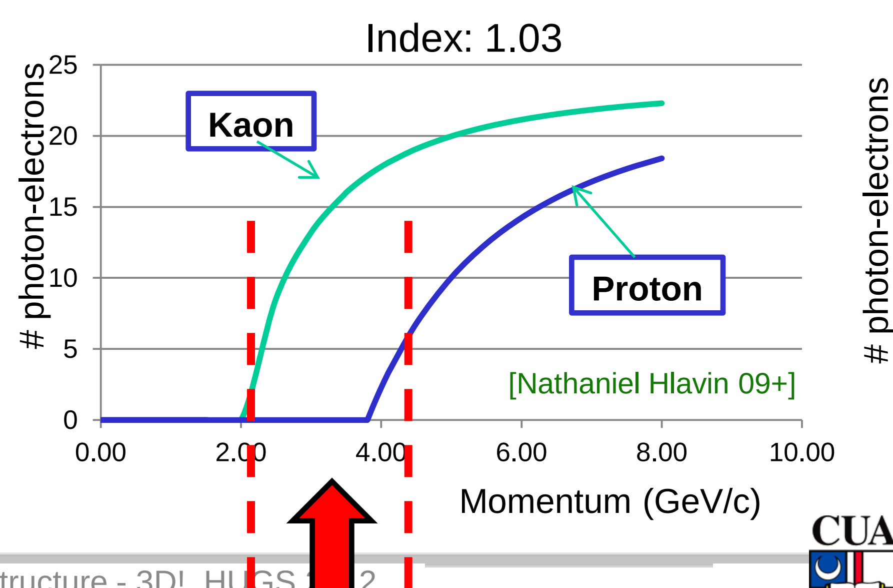
Slide from: Marco Carmignotto, CIPANP 2012

SHMS Aerogel Design Overview

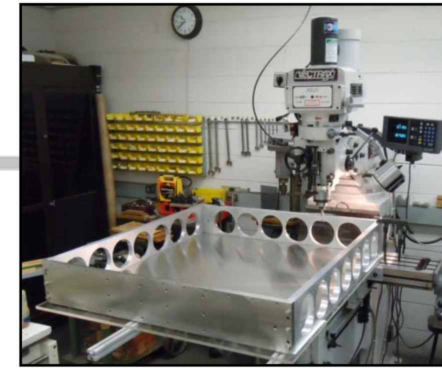
- Aerogel tray and diffusion lightbox with PMTs based on proven technology
  - Allows for simple detector assembly and easy replacement of the aerogel stack
- To cover momenta up to ~6 GeV/c aerogels will have different refractive indices, e.g., n=1.030 and n=1.015
- Diffusion box will be built as single unit with fourteen 5" PMTs, 7 on each long side of the detector
- Active area will be 90x60cm^2 with box size 110x100cm^2 for future upgrades
- Total depth ~ 30cm along the optical axis of the SHMS

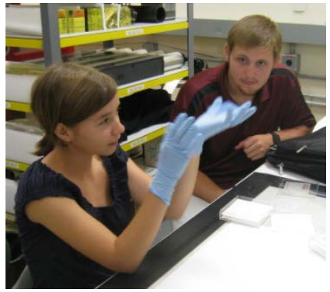


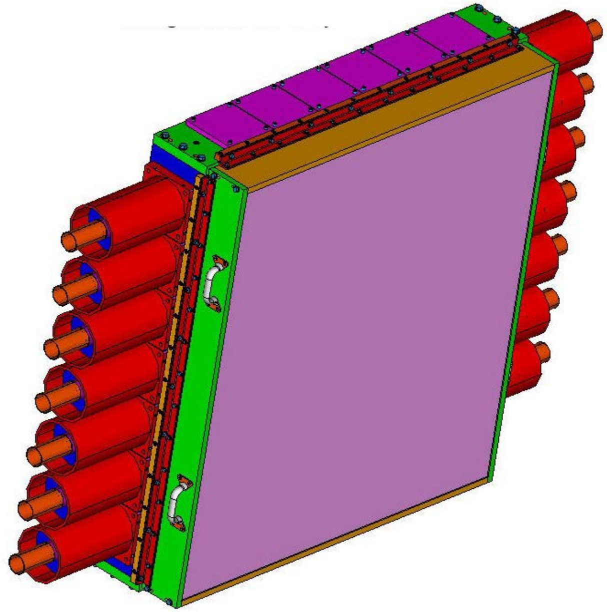
[Marco Carmignotto 11+]

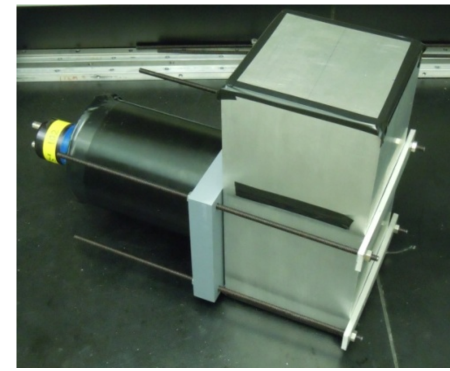


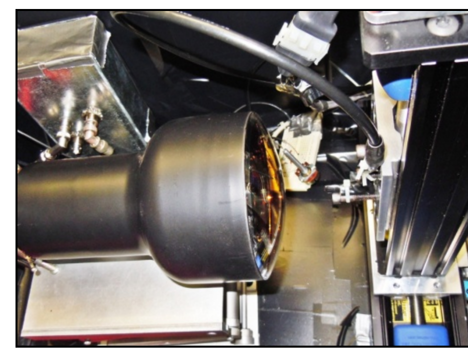
Kaon Aerogel Project





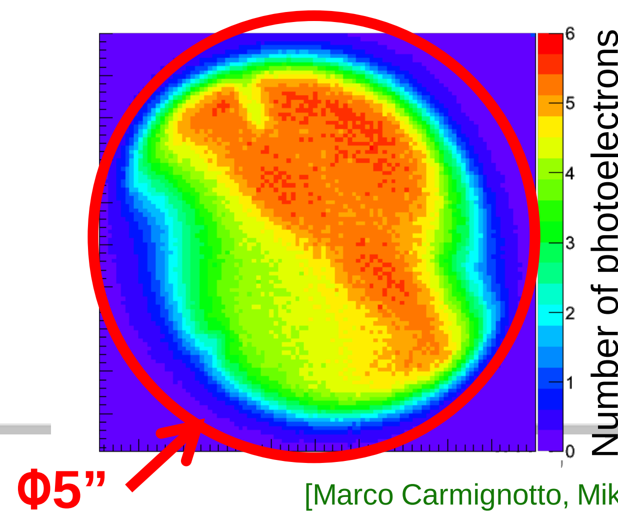




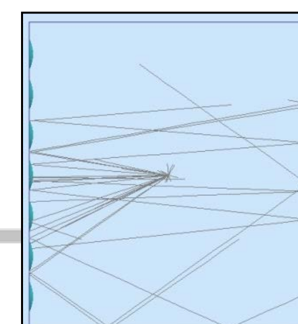


Detector design well underway

- Testing of detector components ongoing
- Final assembly and testing later this year

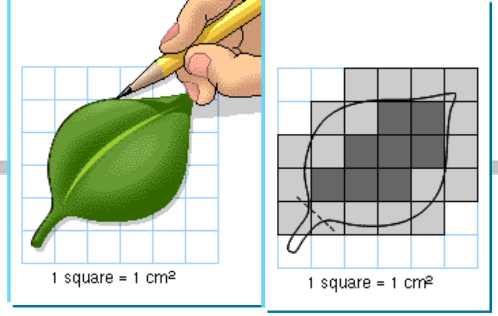


[Marco Carmignotto, Mike Metz 11+]

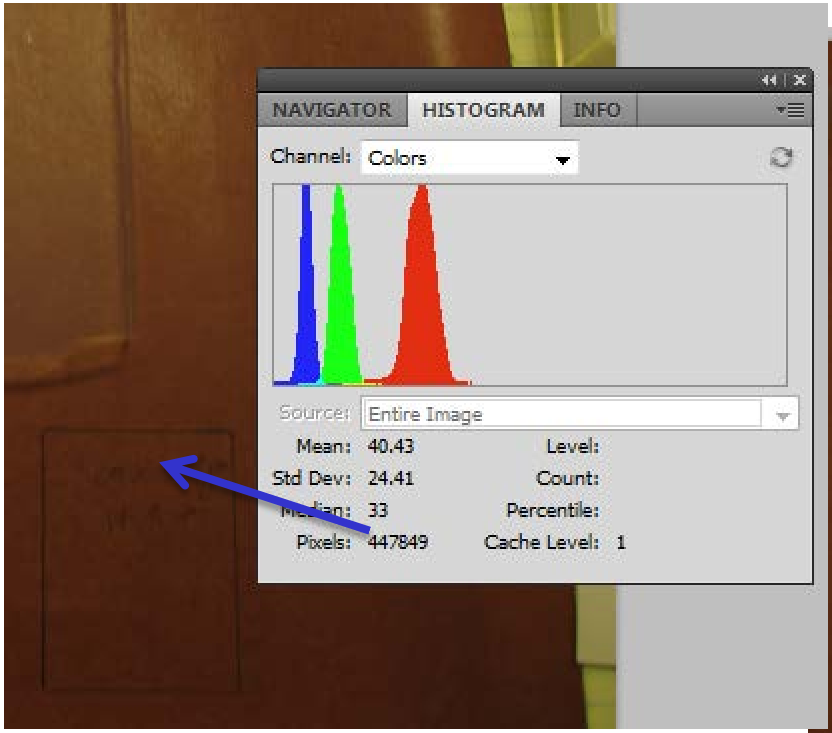


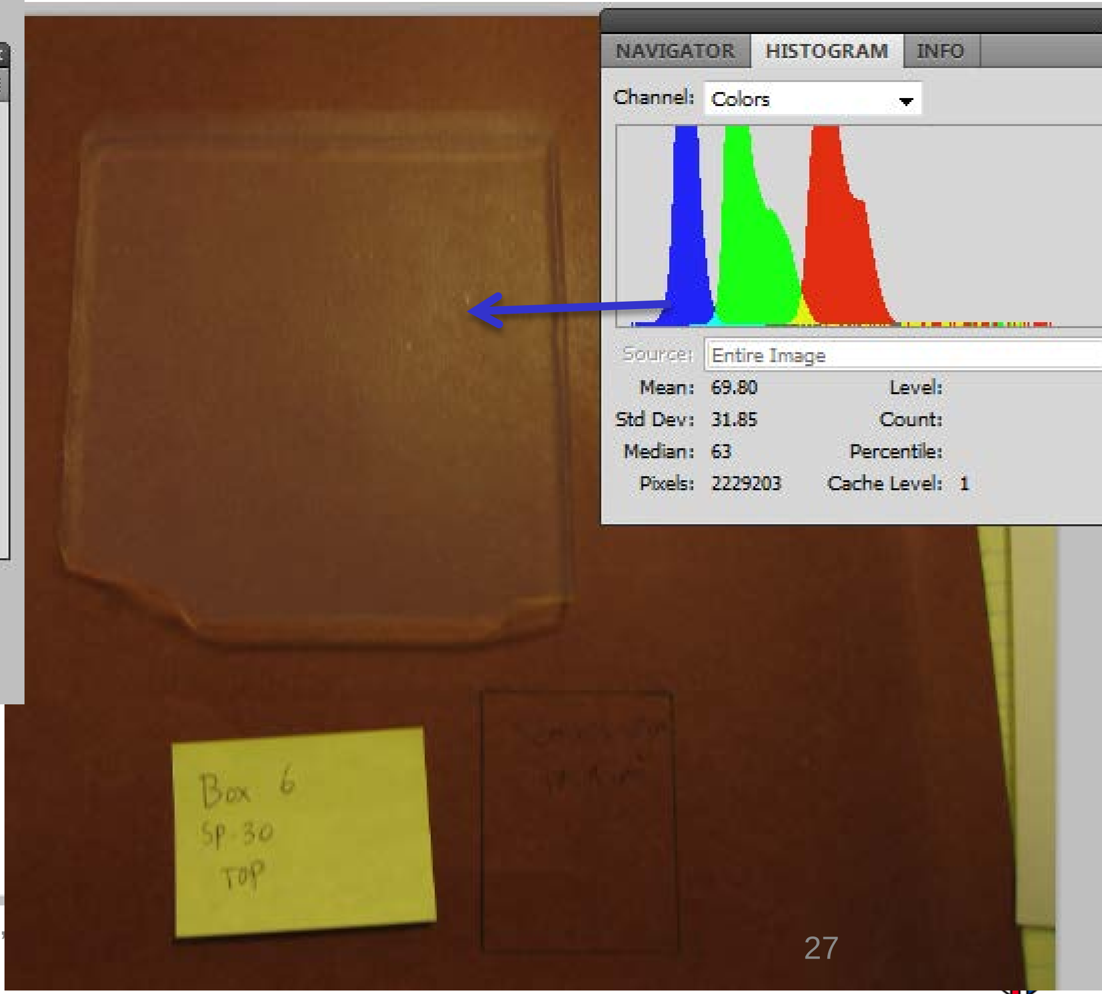
Amazing Aerogel

➢ Photoshop Statistic Application
For Accurate Volume Measurement
(applying a biological technique)



Katya Gilbo





n=1+0.21(p),
where n is the index, p is density

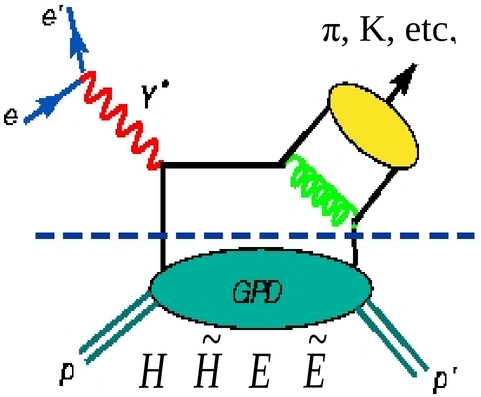
Neutral Pions

New project for 12 GeV Jlab we just started

Animation by: R. Macedo (2011)

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
  - But cannot learn about flavor