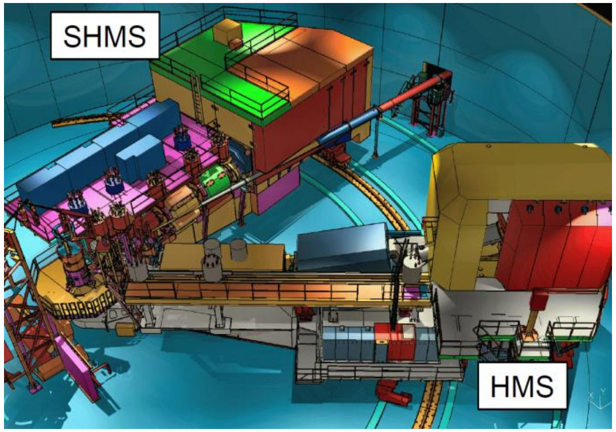
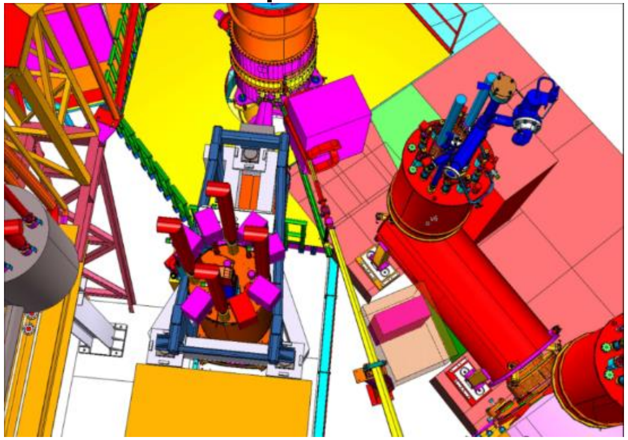
Deep Exclusive Meson Production and Form Factors

Hall C focusing spectrometers



Neutral Particle Spectrometer



The experimental Program in Hall C at 12 GeV JLab… and beyond

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The Catholic University of America

Jefferson Lab
Thomas Jefferson National Accelerator Facility

INT 17-3: Spatial and Momentum Tomography of Hadrons and Nuclei

University of Washington, Seattle, 29 August 2017

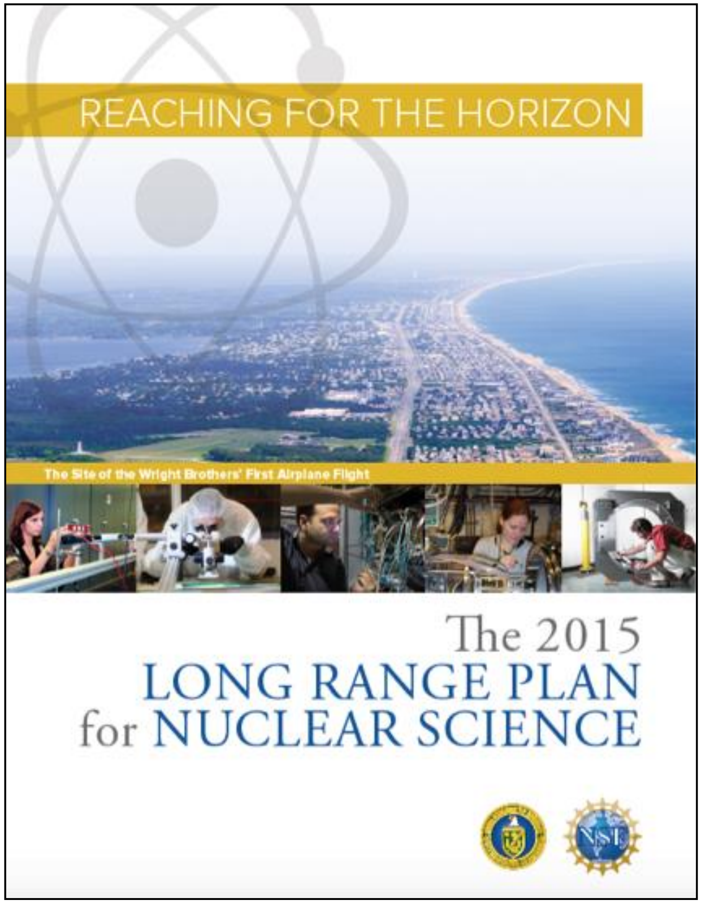
NSAC 2015 Long Range Plan

- "A suite of DVCS and DVMP experiments is planned in Hall B with CLAS12; in Hall A with HRS and existing calorimeters; and in Hall C with HMS, the new SHMS, and the Neutral Particle Spectrometer (NPS). These new data will transform the current picture of hadronic structure."

- "Multiple instruments bring essential elements to this campaign: … HMS-SHMS and the … NPS"

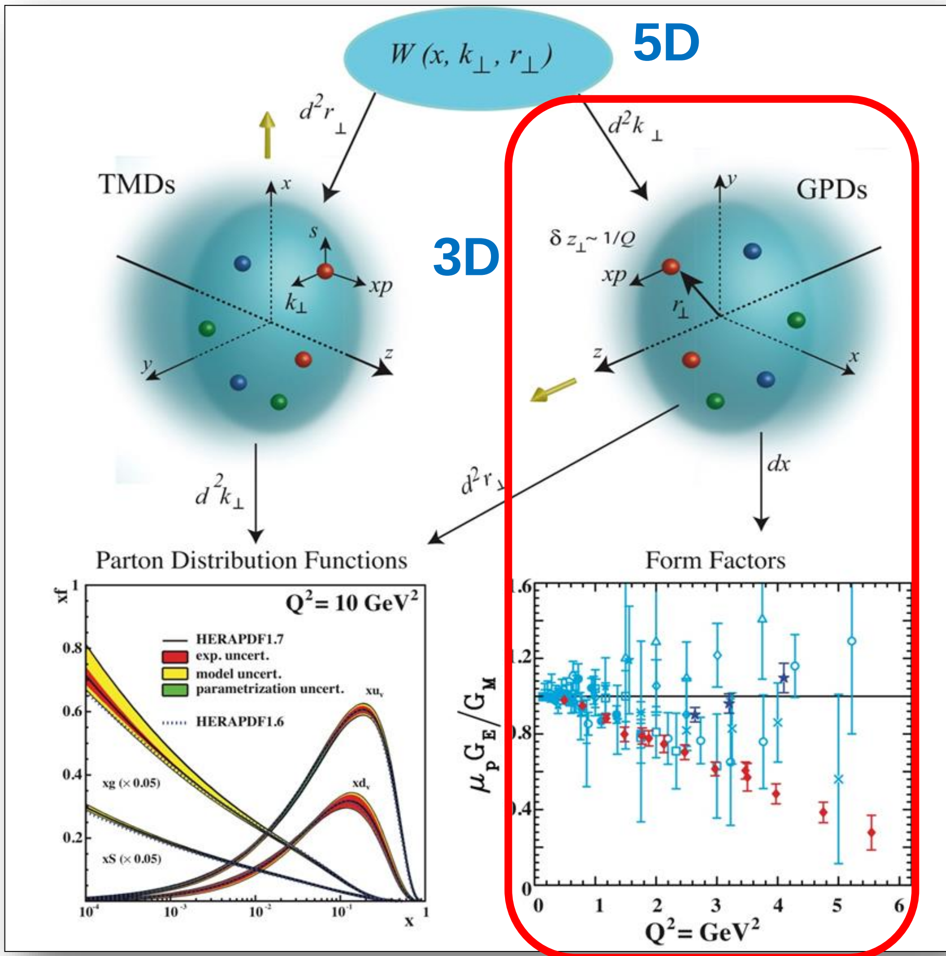
- "Some of the most important tools for describing hadrons are Generalized Parton Distributions, [which] can be investigated through the analysis of hard exclusive processes"

- "The HMS-SHMS …[and] the NPS will allow …refined high resolution imaging of the nucleon's internal landscape…"



The 3D Nucleon Structure

Generalized Parton and Transverse Momentum Distributions are essential for our understanding of internal hadron structure and the dynamics that bind the most basic elements of Nuclear Physics



- TMDs
  – Confined motion in a nucleon (semi-inclusive DIS)
- GPDs
  – Spatial imaging (exclusive DIS)

- Requires
  – High luminosity
  – Polarized beams and targets

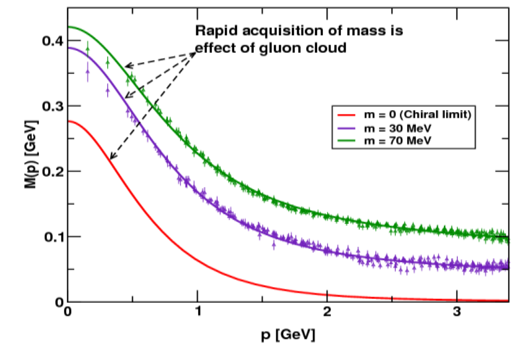
Major new capability with JLab12

Overview Form Factors

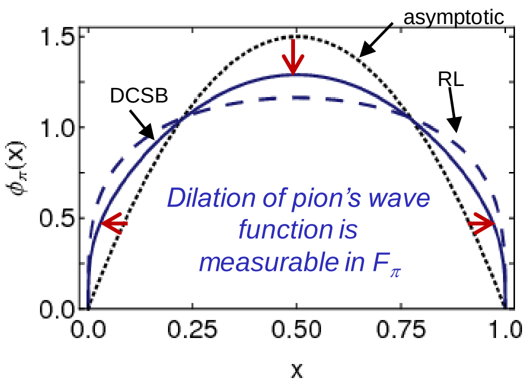
Form factors are essential for our understanding of internal hadron structure and the dynamics that bind the most basic elements of nuclear physics

- ❑ ***Pion and kaon form factors*** are of special interest in hadron structure studies
  - ➢ The *pion* is the lightest QCD quark system and also has a central role in our understanding of the dynamic generation of mass - *kaon* is the next simplest system containing strangeness

    Clearest test case for studies of the transition from non-perturbative to perturbative regions



- ❑ Recent advances and future prospects in experiments
  - ➢ Dramatically improved precision in F_π measurements
  - ➢ 12 GeV JLab: F_π and exclusive meson studies up to highest possible Q^2 and possible F_{K+} extractions



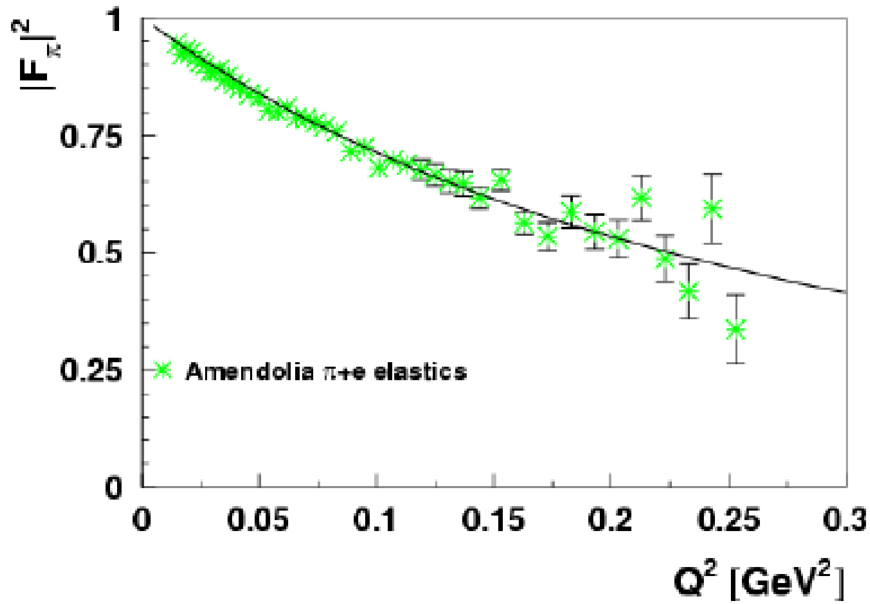
- ❑ Form factor data drive renewed activity on theory side
  - ➢ Distribution amplitudes – signatures of dynamical chiral symmetry breaking

    12 GeV JLab data have the potential to reach the regime in which hard QCD's signatures will be quantitatively revealed

Experimental Determination of the π^+ Form Factor

Through π-e elastic scattering

- At low Q^2, $F_{\pi+}$ can be measured directly via high energy elastic π^+ scattering from atomic electrons
  - CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2
    [Amendolia et al, NPB277,168 (1986)]
  - These data used to constrain the pion charge radius: $r_\pi = 0.657 \pm 0.012$ fm



- The maximum accessible Q^2 is roughly proportional to the pion beam energy
  - $Q^2 = 1$ GeV^2 requires 1000 GeV pion beam

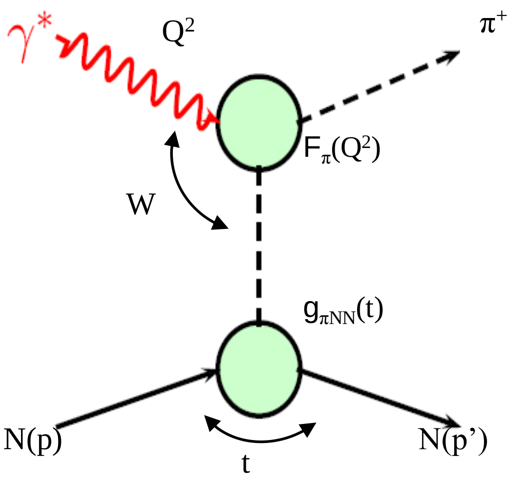
Experimental Determination of the π^+ Form Factor

Through pion electroproduction

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

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

[In practice one uses a more sophisticated model]



- ❑ Requirements:
  - Full L/T separation of the cross section – isolation of σ_L
  - Selection of the pion pole process
  - Extraction of the form factor using a model
  - Validation of the technique - model dependent checks

Pion and Kaon Form Factor Program at 6 GeV JLab

Jefferson Lab

- Precision pion electroproduction data and form factor: three experiments at JLab 6 GeV
  - Full separation of the L/T/TT/LT terms of cross section
  - Experimental validation of reaction mechanism through, e.g., π^-/π^+ (separated) ratio

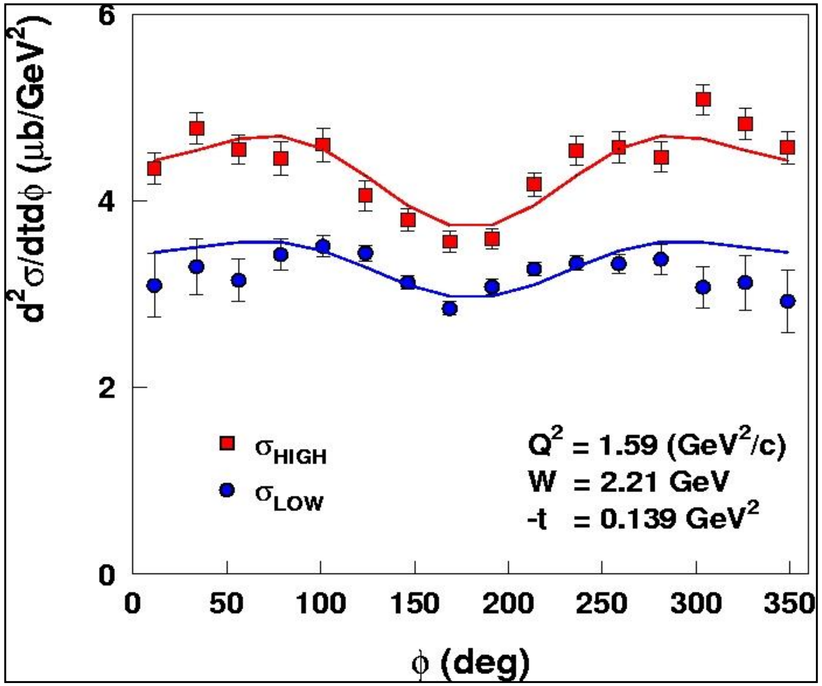
Expt	Q^2 (GeV^2)	W (GeV)	$\|t_{min}\|$ (GeV^2)
Fpi1	0.6-1.6	1.95	0.03-0.15
Fpi2	1.6-2.45	2.22	0.09-0.19
pionCT	2.15, 4.0	2.2	0.1-0.7

- Kaon electroproduction data and form factor: two dedicated experiments
  - L/T separated cross sections, but no form factor extractions (yet)
    - An ongoing analysis using methods used in pion form factor extraction
  - Additional data from pion experiments with kaons in acceptance
    - Experiments: Fpi2, SIDIS

Expt	Q^2 (GeV^2)	W (GeV)	$\|t_{min}\|$ (GeV^2)
E93-018	0.5-2.0	1.85	0.2-0.95
E98-108	1.9, 2.35	1.8-2.1	0.41-0.95
Fpi2	1.35, 2.05	2.3	0.3-0.7

L/T Separation Example

- σ_L is isolated using the Rosenbluth separation technique
  - Measure the cross section at two beam energies and fixed W, Q^2, -t
  - Simultaneous fit using the measured azimuthal angle (ϕ_π) allows for extracting L, T, LT, and TT
- Careful evaluation of the systematic uncertainties is important due to the 1/ε amplification in the σ_L extraction
  - Spectrometer acceptance, kinematics, and efficiencies
- Magnetic spectrometers a must for such precision cross section measurements
  - This is only possible in Hall C at JLab



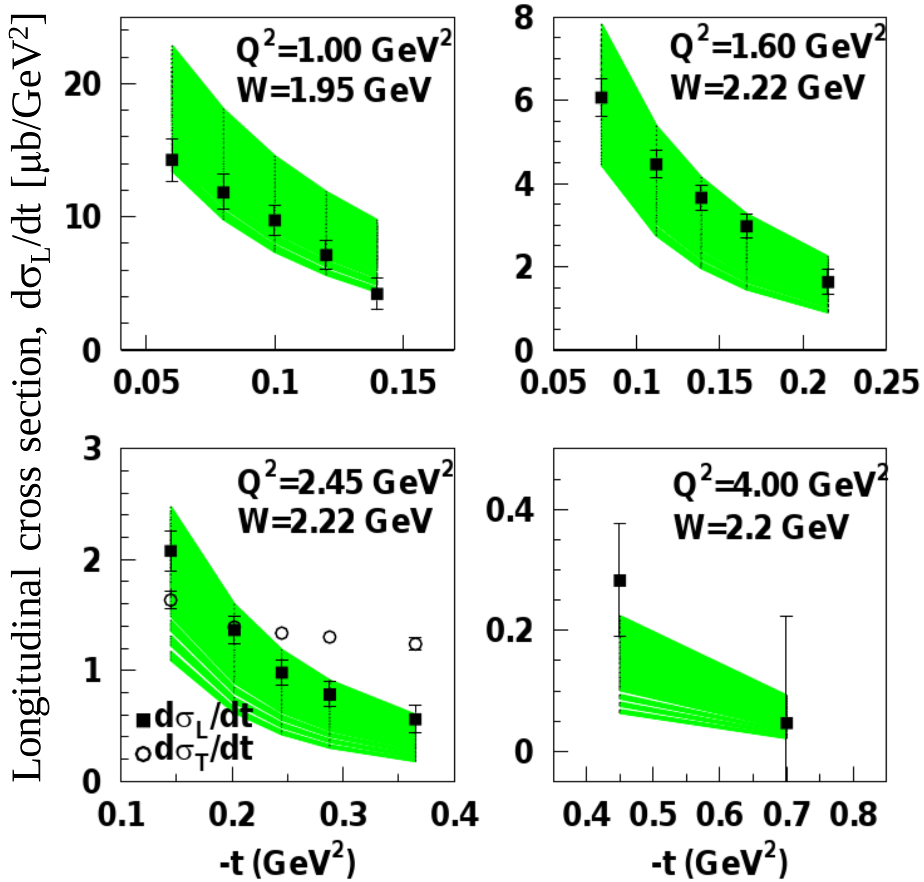
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$

σ_L will give us F_π

Pion pole process in pion electroproduction data at low *t*

L/T separated data from JLab 6 GeV (Hall C)

*[Horn et al., PRL **97**, (2006) 192001]*



$$\frac{d\sigma^{pole}}{dt}\left(\gamma_L^* \to \pi^+\right) = \frac{1}{\kappa}\frac{-t}{\left(t-m_\pi^2\right)^2} Q^2 \rho_{\pi\pi}^2$$

$$\rho_{\pi\pi} = \sqrt{2} e_0 F_\pi(Q^2) g_{\pi NN} F_{\pi NN}(t)$$

$$F_{\pi NN} = \frac{\Lambda_N^2 - m_\pi^2}{\Lambda_N^2 - t} \qquad F_\pi = \frac{1}{1+Q^2/\Lambda_\pi^2} \qquad [\Lambda_\pi^2=0.53\ \mathrm{GeV}^2]$$

Band indicates calculated range of values for:
Λ_N=0.4-0.6 GeV $g_{\pi NN}$=13.1-13.5

- Longitudinal cross section at W=2.2 GeV in good agreement with the pion pole calculation
- At W=1.95 GeV the pole calculation seems to predict a different Q^2 dependence than the data

Note: the values of W and Q2 listed are the overall *central* values. Each t-bin has actually its own bin-centered W and Q2 values

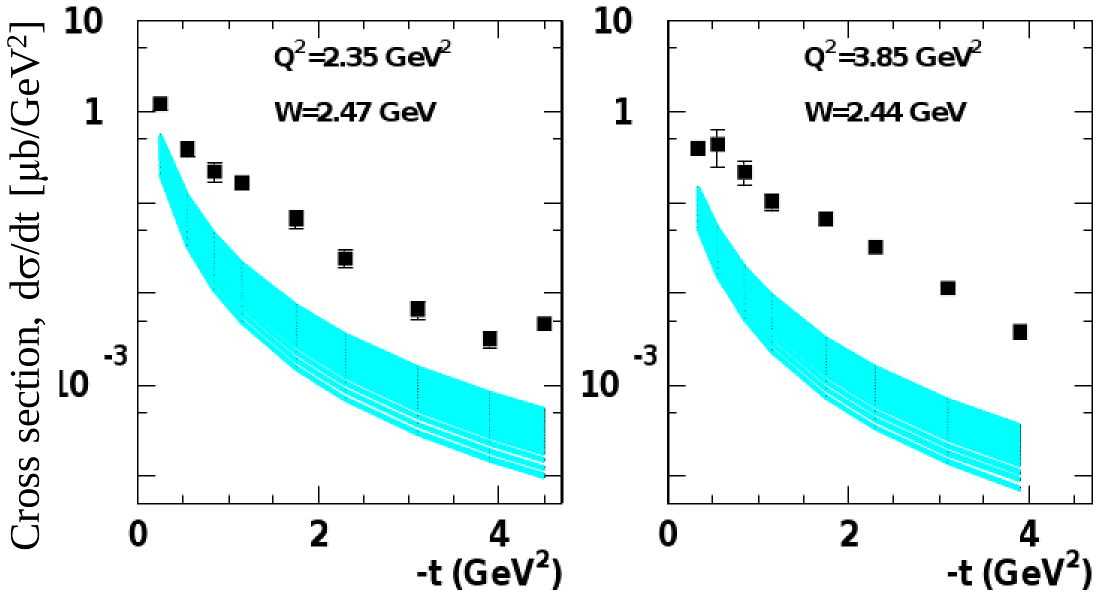
Overall, σ_L data demonstrate the important contribution from the pion pole at small t

[Favart, Guidal, Horn, Kroll, EPJA (2016)]

Pion pole process in pion electroproduction data at larger t

Unseparated data from JLab 6 GeV (Hall B)

*[K. Park et al., EPJA **49** (2013)]*



Band indicates calculated range of values for:
Λ_N=0.4-0.6 GeV $g_{\pi NN}$=13.1-13.5

- ❑ At larger t the pole contribution does not give a good description of the data

[Favart, Guidal, Horn, Kroll, EPJA (2016)]

- ❑ In the unseparated cross section one cannot quantify the contribution of longitudinal and transverse photons
  - ➢ For F_π extraction must fully separate cross section into longitudinal and transverse contributions

- ❑ Need to experimentally determine that F_π extraction does not depend on the t-value of the data

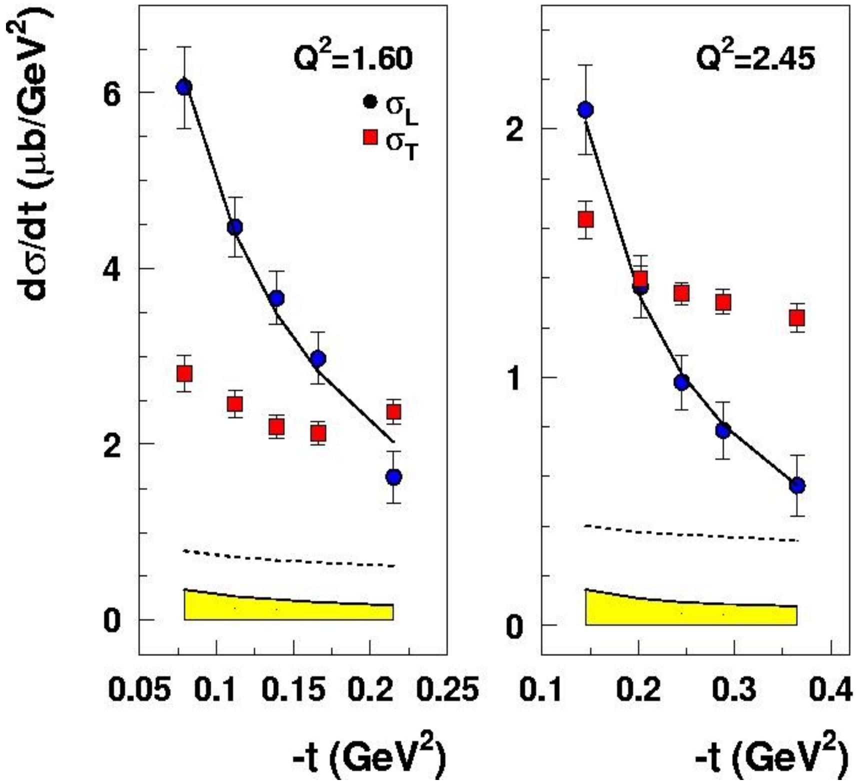
Extraction of F_π from σ_L Jlab data

*[Horn et al., PRL **97**, (2006) 192001]*

- JLab 6 GeV F_π experiments used the VGL/Regge model as it has proven to give a reliable description of σ_L across a wide kinematic domain

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

  - Feynman propagator replaced by π and ρ trajectories
  - Model parameters fixed by pion photoproduction data
  - Free parameters: $\Lambda_\pi^2, \Lambda_\rho^2$



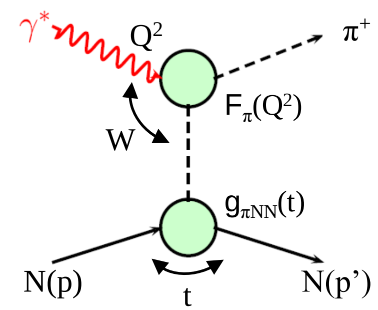
$$F_\pi(Q^2) = \frac{1}{1+Q^2/\Lambda_\pi^2}$$

$$\Lambda_\pi^2 = 0.513,\ 0.491\ GeV^2$$

$$\Lambda_\rho^2 = 1.7\ GeV^2$$

Fit of σ_L to model gives F_π at each Q^2

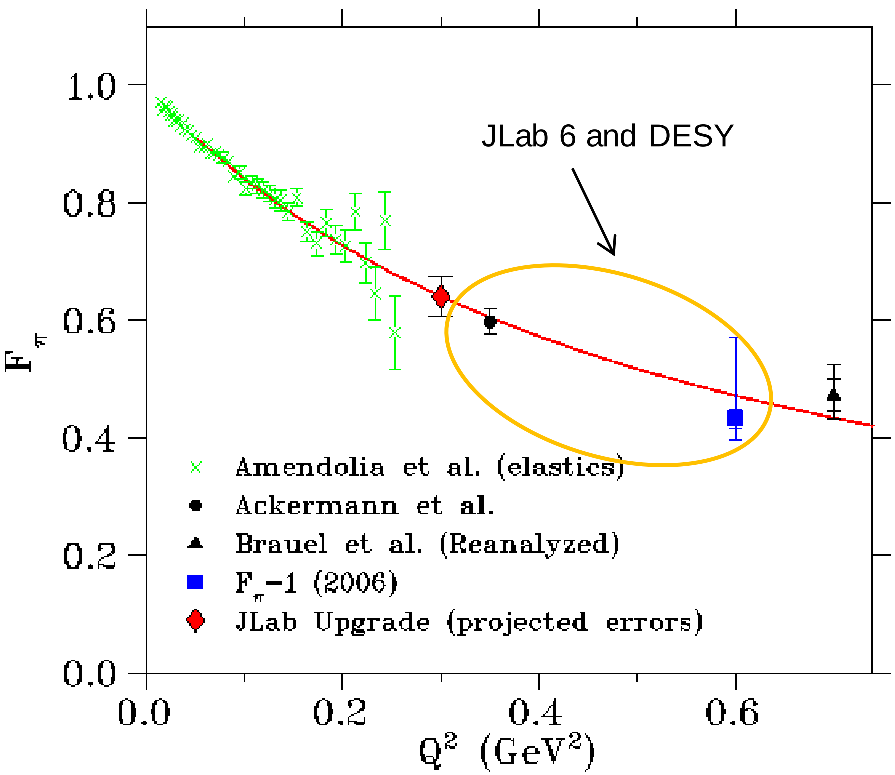
Validation: Electroproduction method consistency check



- Directly compare $F_\pi(Q^2)$ values extracted from very low $-t$ electroproduction with the exact values measured in elastic e-π scattering
  - JLab data: **blue**, re-analyzed DESY data: **black**

Method passes check: Q^2=0.35 GeV^2 data from DESY consistent with limit of elastic data within uncertainties

[H. Ackerman et al., NP B137 (1978) 294]

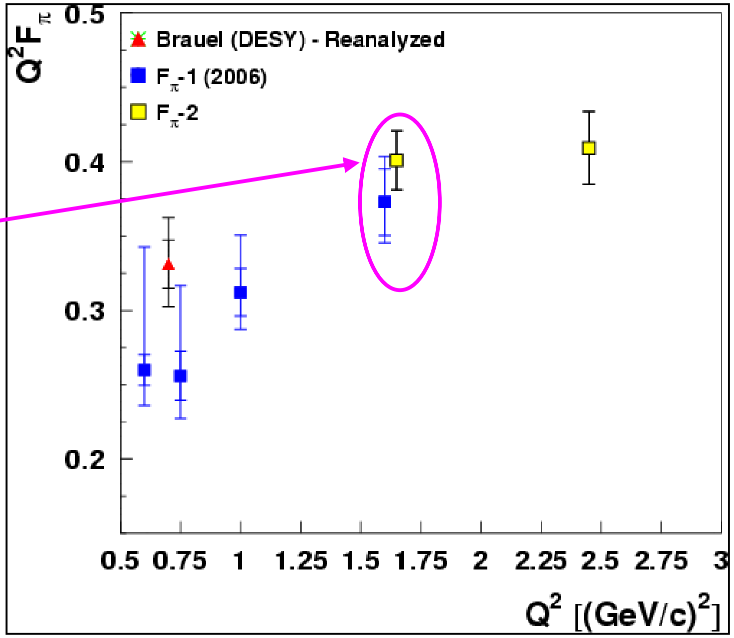


- More detailed tests planned with future 12 GeV experiment taking data at 50% lower $-t$ (0.005 GeV^2)

Validation: Model dependence

- Test by extracting the pion form factor at different distances from the –t pole

  - Data from JLab 6 GeV show good agreement for different t_{min} values
    - Fpi2: t_{min}=0.093 GeV^2
      Fpi1: t_{min}=0.150 GeV^2



- More detailed tests planned with future 12 GeV experiment taking data at even lower t_{min} (0.029 and 0.048 GeV^2 at Q^2=1.6 and 2.45 GeV^2)

Validation: Check of non-pole backgrounds in σ_L with charged pion ratios in deuterium

*[Huber et al, PRL **112** (**2014**)182501]*

- π^+ *t*-channel diagram is pure isovector (G-parity conservation)
- Measure (separated) π^-/π^+ *ratio to test pole dominance*

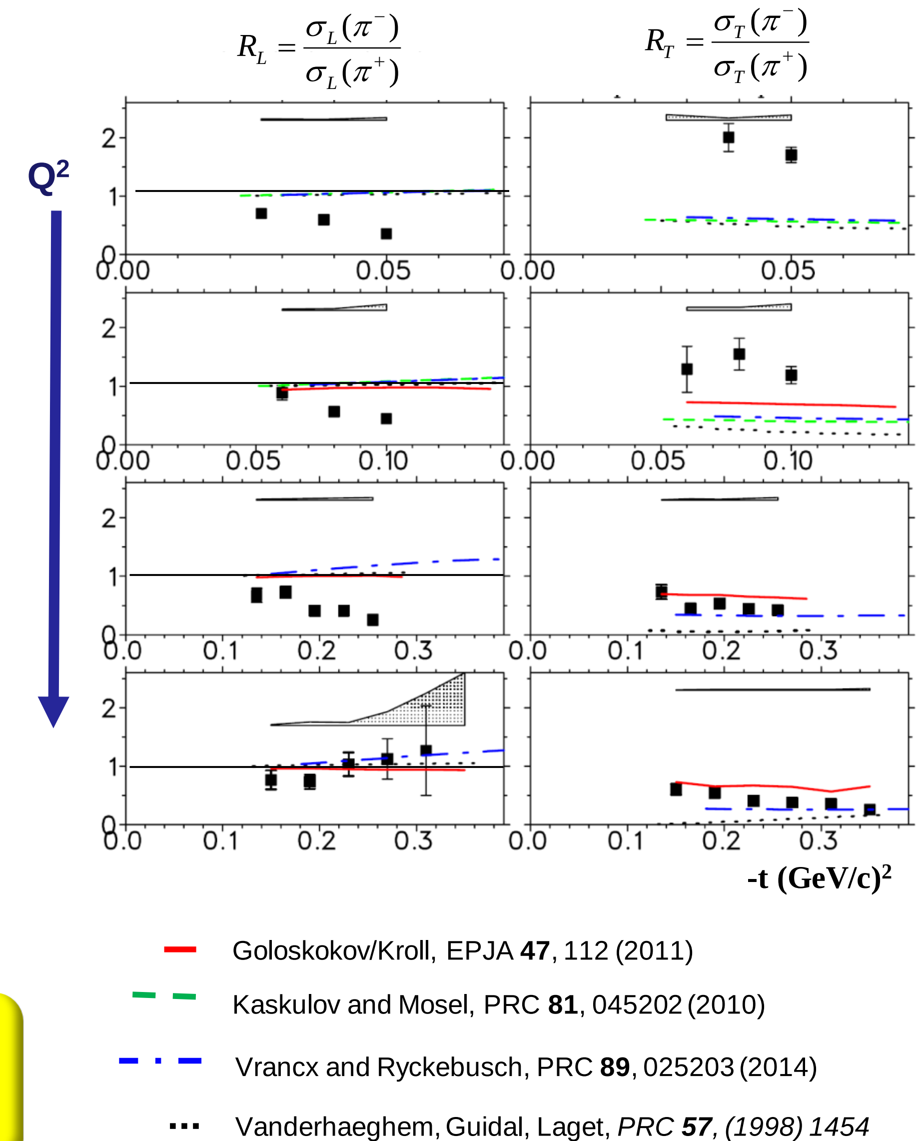
$$R_L = \frac{\sigma_L(\pi^-)}{\sigma_L(\pi^+)} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

  - Isoscalar backgrounds like $b_1(1235)$ contributions to *t*-channel will dilute the ratio from unity

- With increasing *t*, R_T is expected to approach the ratio of quark charges

  [O. Nachtman, NP B115 (1976) 61]

R



R_L approaches unity at large Q^2 - consistent with pion-pole dominance

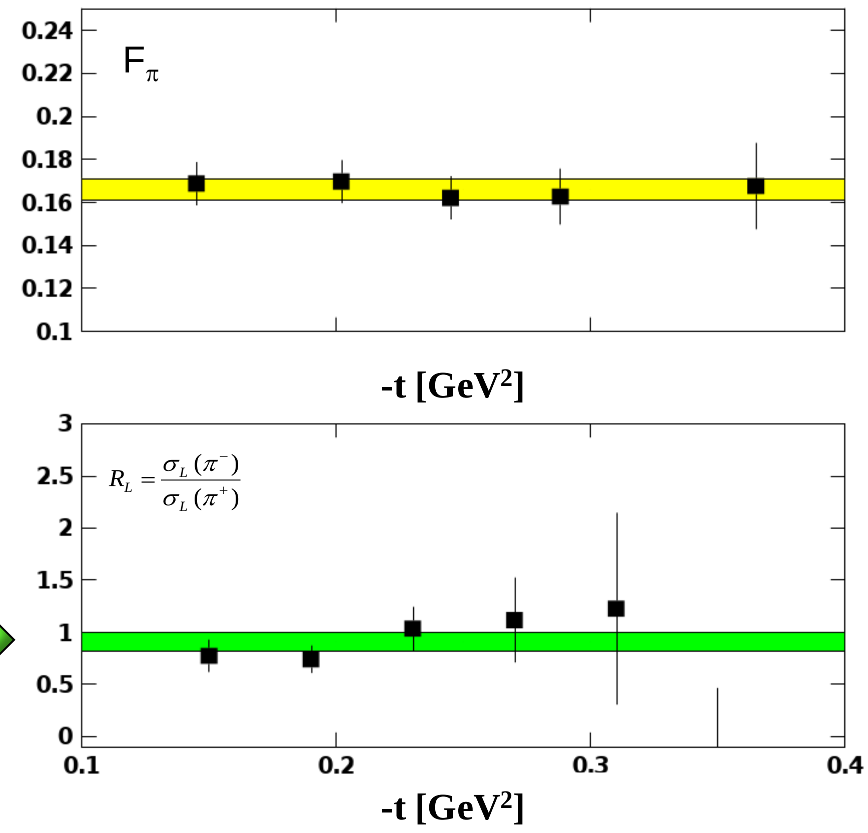
Validation: experimental considerations

Experimental studies over the last decade have given *confidence* in the electroproduction method yielding the physical pion form factor

*[T. Horn, C.D. Roberts, J. Phys. G**43** (2016) no.7, 073001]*

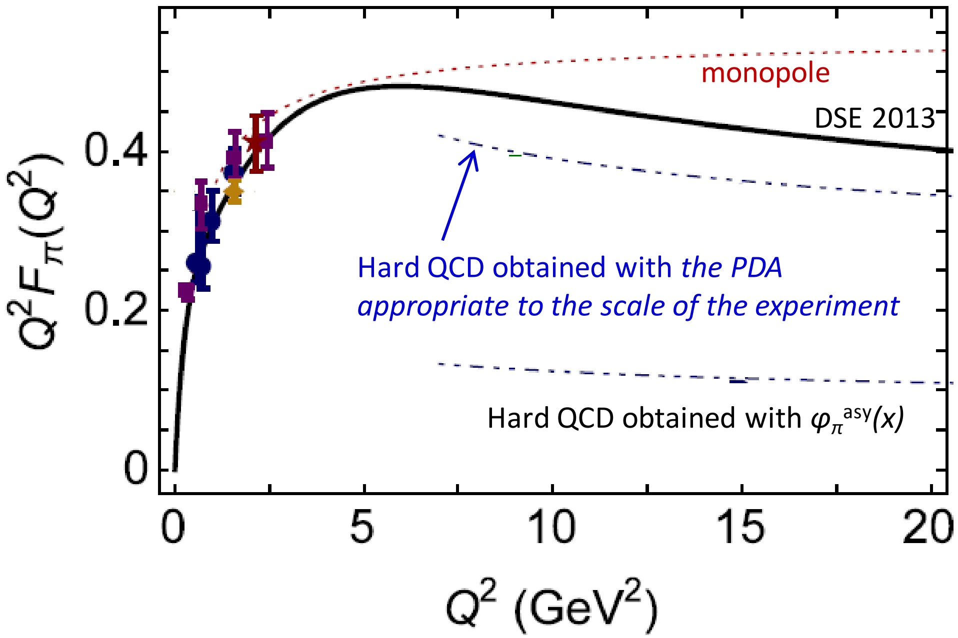
- Experimental studies include:
  - Check consistency of model with data
    - F_π values do not depend on the t-acceptance – confidence in applicability of model to the kinematic regime of the data
  - Verify that the pion pole diagram is the dominant contribution in the reaction mechanism
    - R_L approaches the pion charge ratio, consistent with pion pole dominance

      *[Huber et al, PRL**112 (2014)**182501]*
  - Extract F_π at several values of t_{min} for fixed Q^2



$$R_L = \frac{\sigma(n(e,e'\pi^-)p)}{\sigma(p(e,e'\pi^+)n))} = \frac{|A_v - A_s|^2}{|A_v + A_s|^2}$$

$F_{\pi^+}(Q^2)$ in 2017



- Factor ~3 from hard QCD calculation evaluated with asymptotic valence-quark Distribution Amplitude (DA)
  - Trend consistent with time like meson form factor data up to Q^2=18 GeV^2

  *[Seth et al, PRL **110** (2013) 022002]*

- <u>Recent developments</u>: when comparing the hard QCD prediction with a pion valence-quark DA of a form appropriate to the scale accessible in experiments, magnitude is in better agreement with the data

*[L. Chang, et al., PRL **111** (2013) 141802; PRL **110** (2013) 1322001]*

*[I. Cloet, et al., PRL **111** (2013) 092001]*

- Closer agreement between the relevant hard QCD and DSE-2013 curves
- Monopole fit ~10% above DSE-2013 at Q^2~9 GeV^2

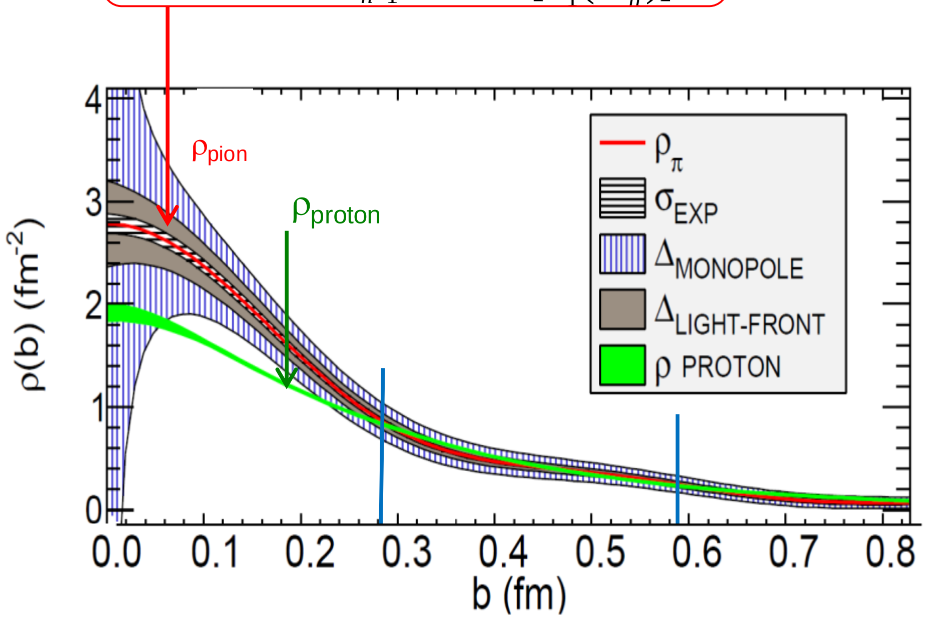
Insight from data: Pion Transverse Charge Density and the edge of hadrons

- Transverse charge densities allow interpretation of FFs in terms of physical charge density and are also related to the Generalized Parton Distributions

- First attempt of analysis with existing space like pion form factor data

*[M. Carmignotto et al., Phys. Rev. C**90** 025211 **(2014)**]*

$$\rho_\pi(b) = \frac{1}{\pi R^2} \sum_{n=1}^{\infty} F_\pi(Q_n^2) \frac{J_0(X_n \frac{b}{R})}{[J_1(X_n)]^2} \qquad Q_n \equiv \frac{X_n}{R}$$

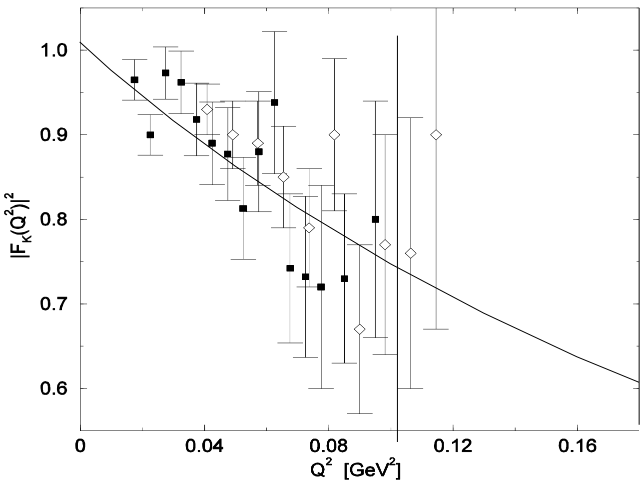


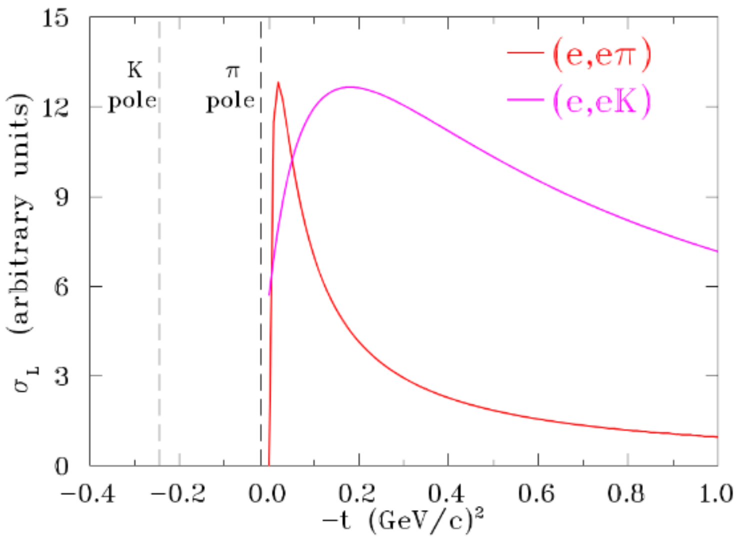
- Uncertainty in the analysis dominated by incompleteness error
  - Estimated using the monopole as upper bound and a light front model as lower bound

- ρ_π and ρ_p coalesce for *0.3 fm < b < 0.6 fm*
  - meson cloud dominating only at large impact parameter?

Extension to systems containing strangeness: the K^+ Form Factor

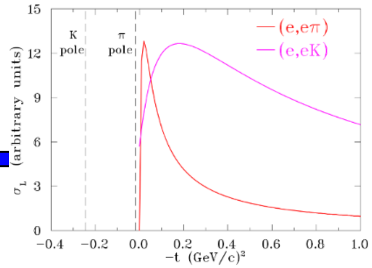
- Similar to π^+, elastic K^+ scattering from electrons used to measure charged kaon for factor at low Q^2
  - CERN SPS used 250 GeV kaons to measure form factor up to $Q^2 = 0.13$ GeV^2 *[Amendolia et al, PLB 178, 435 (1986)]*
  - These data used to constrain the kaon RMS radius: $r_K = 0.58 \pm 0.04$ fm





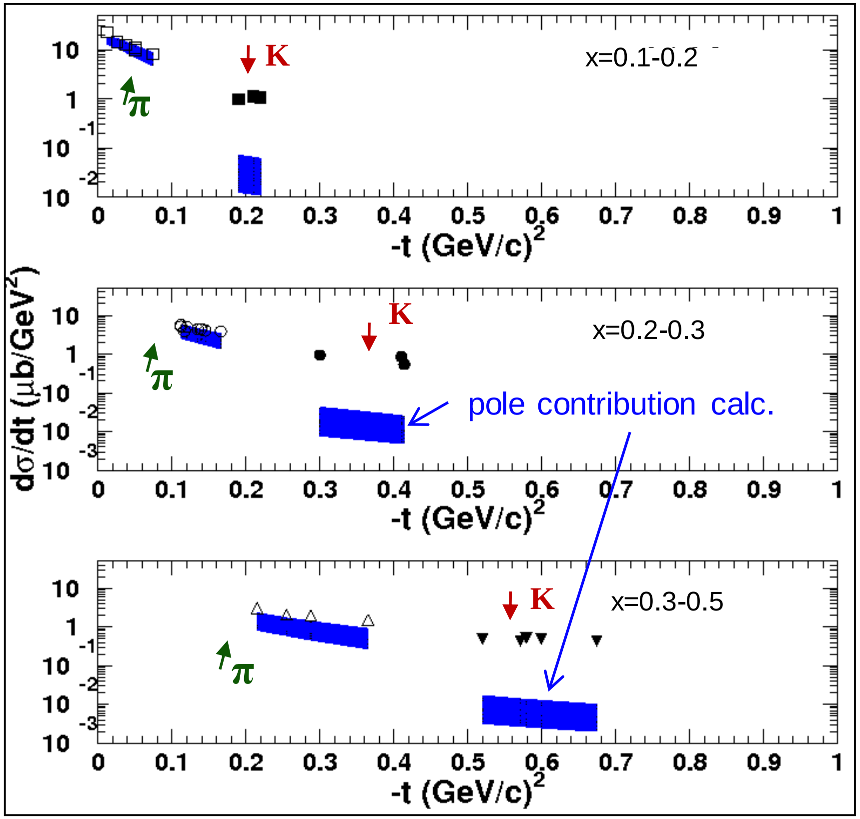
- Can "kaon cloud" of the proton be used in the same way as the pion to extract kaon form factor via ***p(e,e'K$^+$)Λ***?
  - *Need to quantify the role of the kaon pole*

Kaon pole process in kaon electroproduction



Unseparated data from JLab 6 GeV and HERMES

W=2.2 GeV, Q^2=1.6 GeV^2



[Favart, Guidal, Horn, Kroll , EPJA (2016)]

- ***At large t:***
  - *Unseparated* data: pion t-dependence is steeper than for kaons

    *[T. Horn, Phys. Rev. C **85 (2012)** 018202]*
  - Due to experimental constraints most of existing kaon data fall into this category

- ***At small t:***
  - *K*aon pole is *expected* to be strong enough to produce a maximum in σ_L

    [Kroll/Goloskokov EPJ A47 (2011), 112]
  - Ultimate experimental verification at 12 GeV JLab

$F_{K+}(Q^2)$ in 2017

- Extraction of F_{K+} from JLab 6 GeV electroproduction data
  - Kaon electroproduction – kinematic reach limited by experimental equipment
  - Pion electroproduction (parasitic) – limited in statistics and non-optimized kinematics

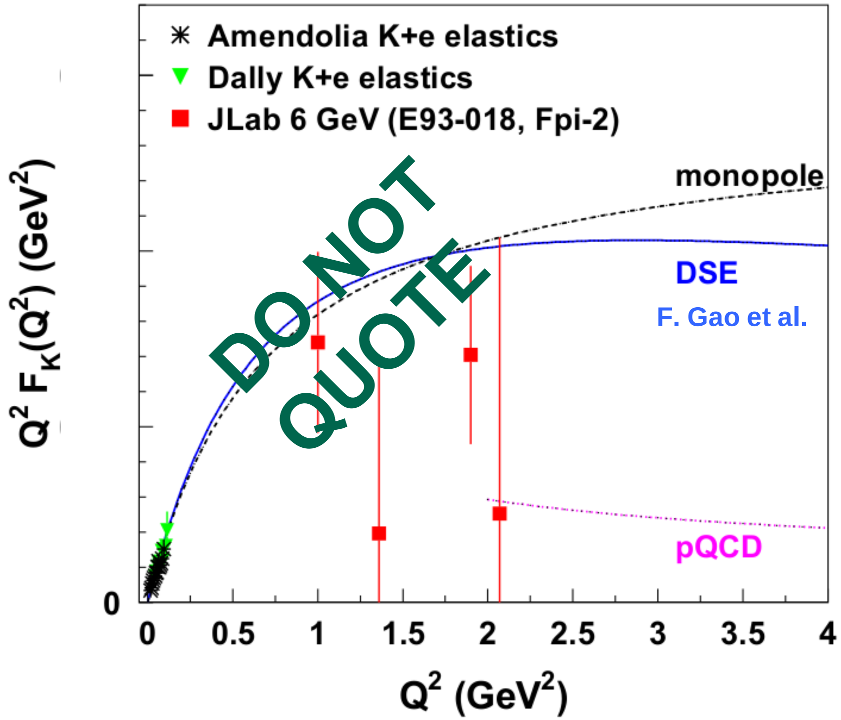
[Analysis by Marco Carmignotto, PhD2017]

- L/T separation: –*t* dependence of longitudinal cross section of K^+ data
- Extract form factor fitting the VGL-Regge model to the –*t* dependence of K^+ longitudinal cross section
- Recent theoretical efforts to understand role of the strange quark

*[P.T.P. Hutauruk et al., Phys. Rev. C **94 (2016)** 035201]*

*[C. Chen et al., Phys. Rev. D **93 (2016)** no. 7, 074021]*

*[F. Gao et al., arXiV:1703.04875 **(2017)**]*



Kaon Transverse Charge Distribution

- First extraction of kaon transverse charge density
  - Essentially no space-like data, so use dispersion representation of the time-like kaon form factor

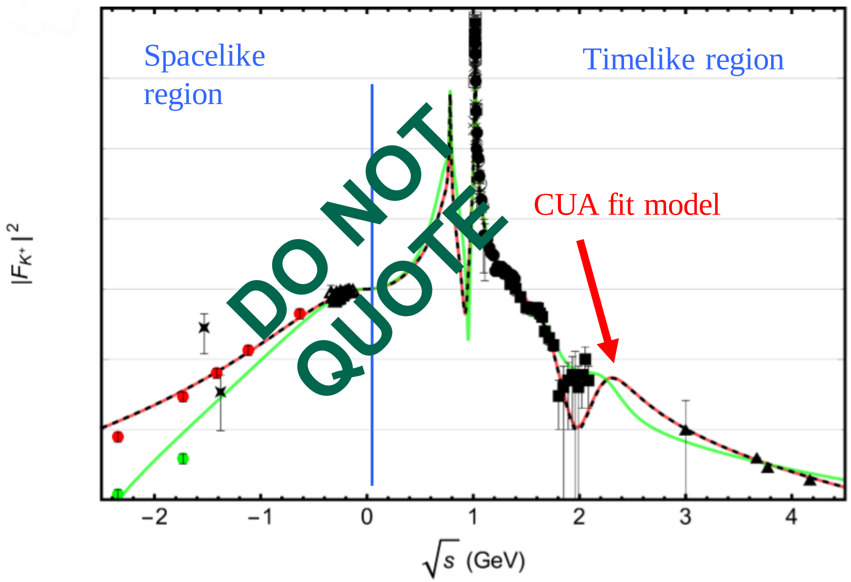
$$\rho(b) = \frac{1}{2\pi} \int_{4m_K^2}^{\infty} dt\, K_0(\sqrt{t}\, b)\, \frac{\mathrm{Im}\, F_K(t)}{\pi}$$

- Previous time-like kaon form factor parametrizations cannot describe high-s data from CLEO

- *CUA new fit model* including dominant resonances and a broad resonance providing a ~1/s behavior at high s *describes all data*

$$F_K(t) = \frac{1}{\pi} \int_{4m_K^2}^{\infty} dt' \frac{\mathrm{Im}\, F_K(t')}{t' - t + i\varepsilon}$$

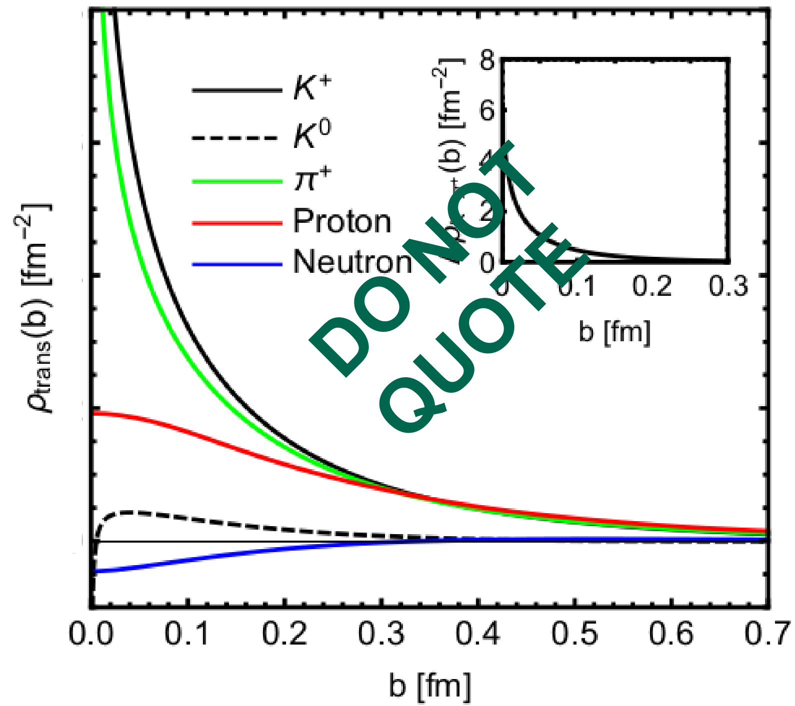
*[Fits based on a model from C. Bruch et al., EPJC **39]** 2005), 41]*



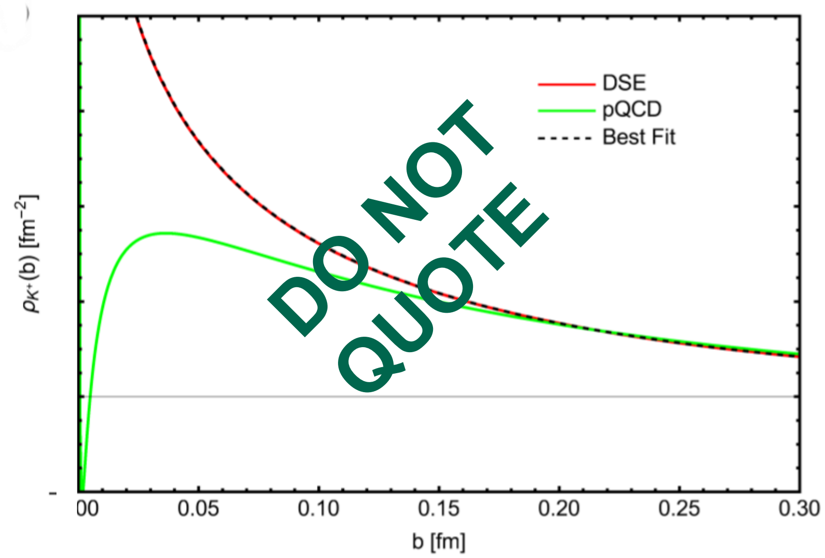
[N. Mecholsky, J. Meija-Ott, M. Carmignotto, T. Horn, G. Miller, I. Pegg – publication in preparation]

Kaon vs. pion transverse Charge Density and impact of future data

N. Mecholsky, J. Meija-Ott, M. Carmignotto, T. Horn, G. Miller, I. Pegg – publication in preparation



Transverse density assuming very different behavior of the form factor



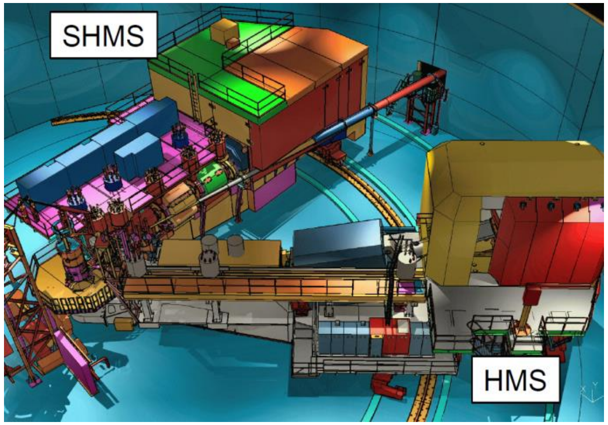
- New fit of kaon time-like form factor including high-t data mostly impacts the extracted transverse charge density at small b
- ρ_π and ρ_p coalesce for *0.3 fm < b < 0.6 fm; and so does* ρ_K+
- It would be interesting to extract the transverse charge density for different flavors

JLab12: F_π measurements

- CEBAF 10.9 GeV electron beam and SHMS small angle capability and controlled systematics are essential for extending precision measurements to higher Q^2

- The JLab 12 GeV π^+ experiments:
  - ***E12-06-101***: determine F_π up to Q^2=6 GeV^2 in a dedicated experiment
    - Require t_{min}<0.2 GeV^2 and $\Delta\varepsilon$>0.25 for L/T separation
    - Approved for 52 PAC days with "A" rating, high impact

    *E12-**06**-101 spokespersons: G. Huber, D. Gaskell*



  - ***E12-07-105***: probe conditions for factorization of deep exclusive measurements in π^+ data to highest possible Q^2~9 GeV^2 with SHMS/HMS
    - Potential to extract F_π to the highest Q^2~9GeV^2 achievable at Jlab 12 GeV
    - Approved for 40 PAC days with "A-" rating

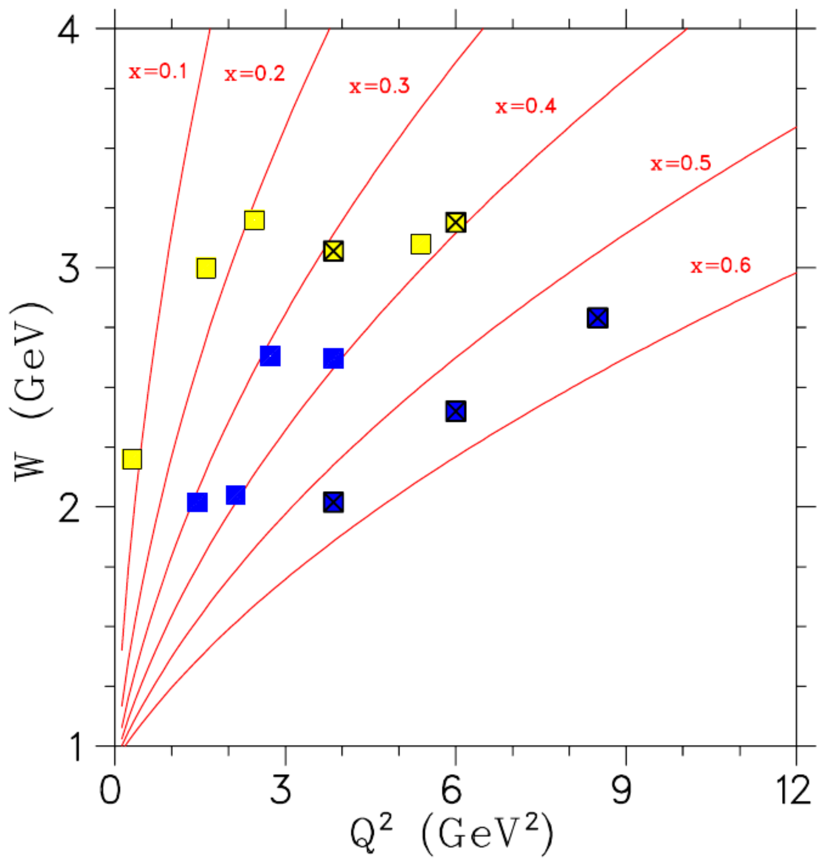
    *E12-**07**-105 spokespersons: T. Horn, G. Huber*

How to get there: Optimization of two experiments into one program

An optimization of the kinematics of these two experiments now allows to extend pion form factor data to the highest possible Q^2 achievable at 12 GeV JLab

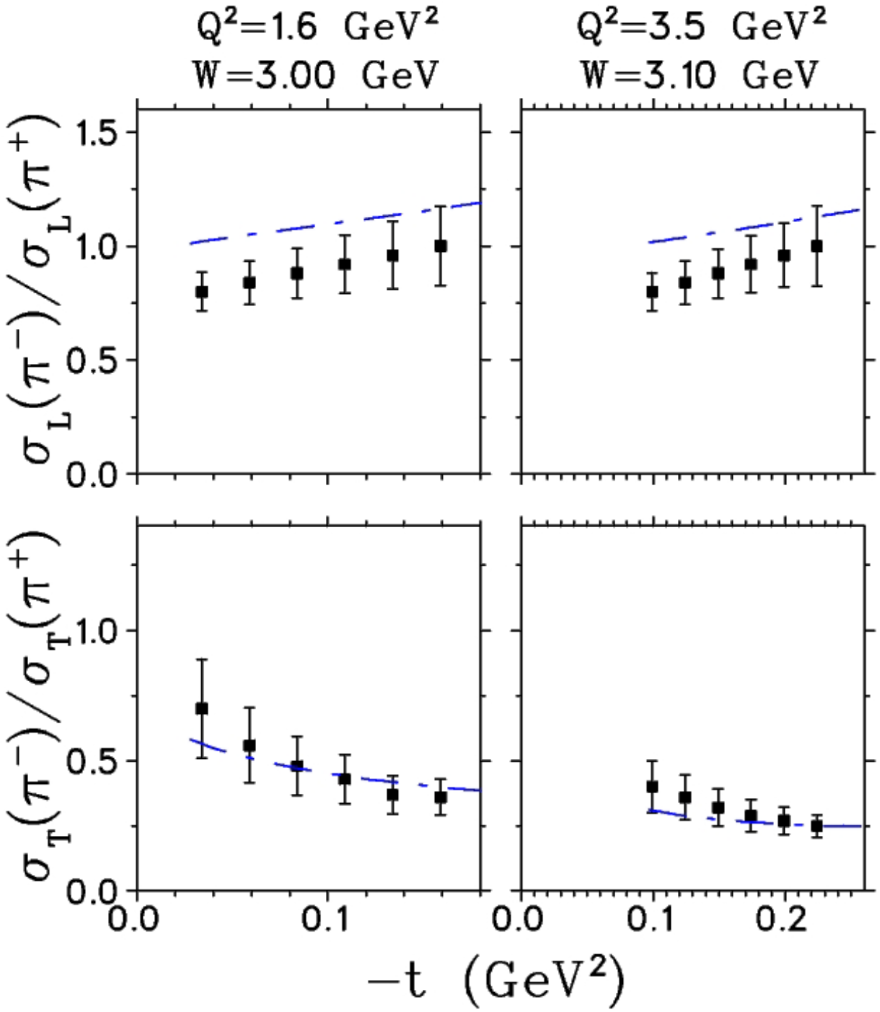
JLab 12 GeV F_π Program features:

- Reliable F_π extractions from existing data to the highest possible Q^2
- Validation of F_π extraction at highest Q^2
- Separated cross sections as function of Q^2 at fixed x=0.3, 0.4, 0.5



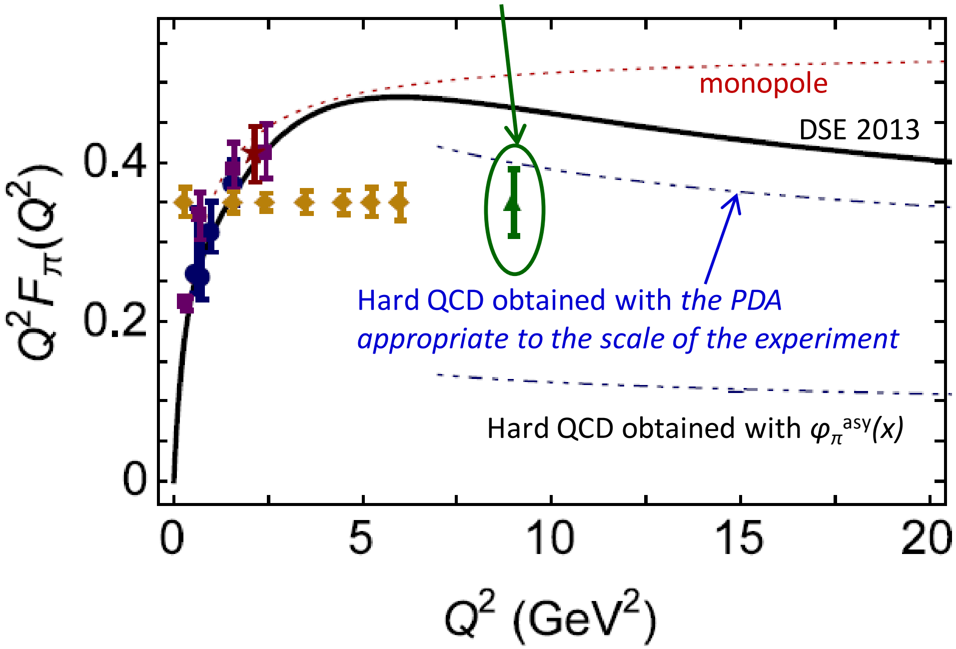
How to get there: include validation of the F_π extraction

- Check consistency of model with data
- Extract F_π at several values of t_{min} for fixed Q^2
  - data at t_{min} 0.029 and 0.048 GeV^2 at Q^2=1.6 and 2.45 GeV^2
- Verify that the pole diagram is the dominant contribution in the reaction mechanism
  - π-/π+ ratios to validate form factor extraction at Q^2=1.6, 3.85, 5.5 and 6.0 GeV^2



JLab 12 GeV: F_π measurements

Measurement at Q^2=8.5 GeV^2 and t_{min}~0.5 GeV^2



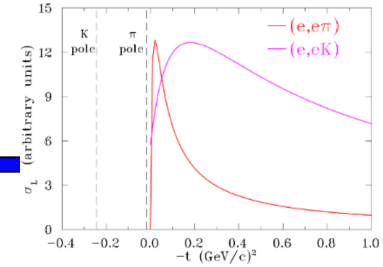
- JLab 12 GeV and HMS+SHMS in Hall C allow for:
  - Measurements of σ_L up to Q^2=8-9 GeV^2
  - Reliable F_π extractions from existing data to the highest possible Q^2
  - Validation of F_π extraction at highest Q^2

Projected precision using $R=\sigma_L/\sigma_T$ from VR model and assumes pole dominance – uncertainties are very sensitive to that value

JLab 12 GeV experiments have the potential to access the hard scattering scaling regime quantitatively for the first time – may also provide info on log corrections.

- These results would also have implications for nucleon structure interpretation

JLab12: Kaon electroproduction and form factor measurements



- **E12-09-011**: primary goal L/T separated kaon cross sections to investigate hard-soft factorization and non-pole contributions

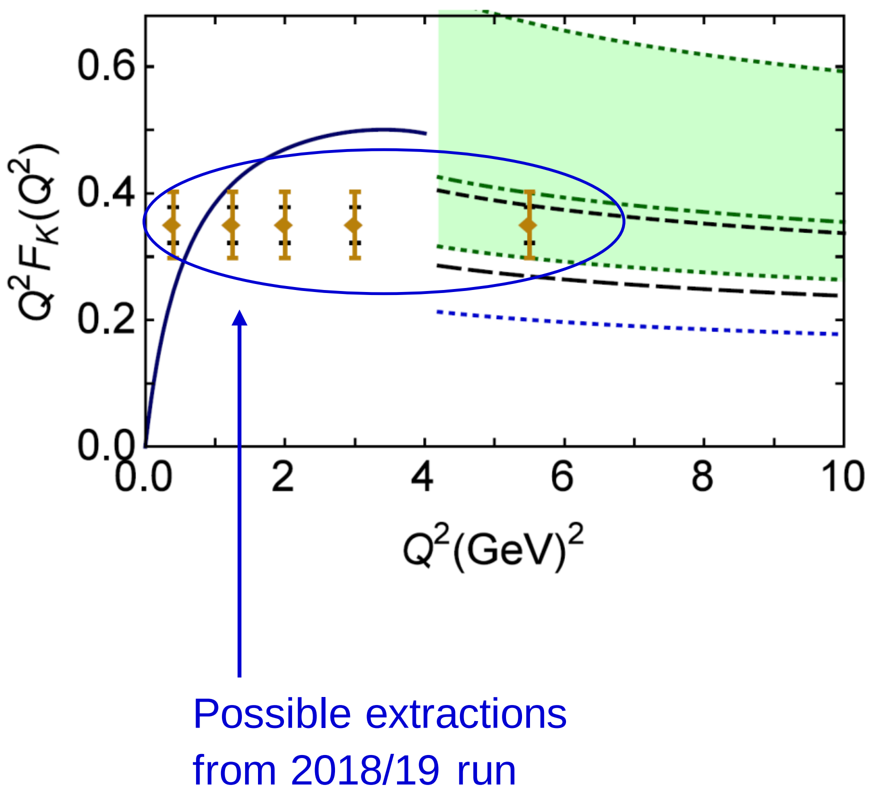
*E12-**09**-011spokespersons: T. Horn, G. Huber, P. Markowitz*

- **scheduled to run in 2018/19**

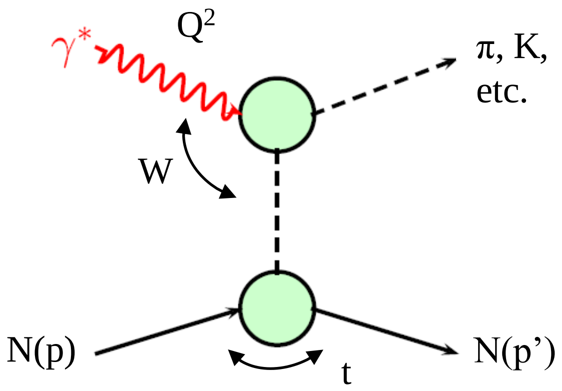
- Possible K^+ form factor extraction to highest possible Q^2 achievable at JLab

  - Extraction like in the pion case by studying the model dependence at small t
  - Comparative extractions of F_π at small and larger t show only modest model dependence
    - larger t data lie at a similar distance from pole as kaon data

*[T. Horn, C.D. Roberts, J. Phys. G**43** (2016) no.7, 073001]*

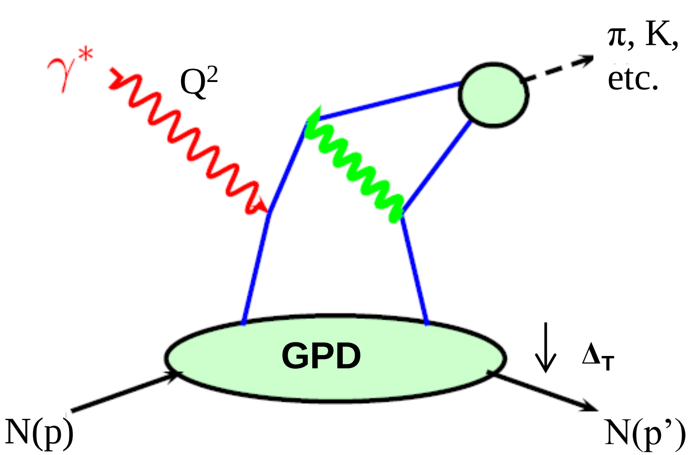


Transition to Deep Exclusive Meson Electroproduction



t-channel process

- In the limit of small $-t$, meson production can be described by the t-channel meson exchange (pole term)
  - Spatial distribution described by form factor

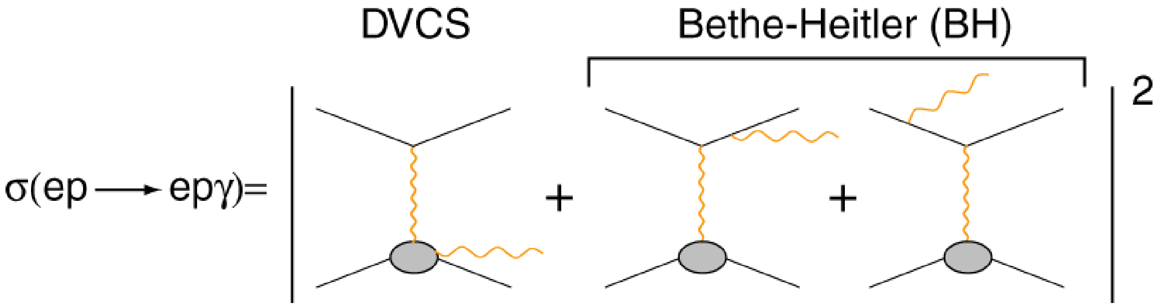


Handbag diagram

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

Experimental Access to GPDs: DVCS

See also talks by, e.g. R. Dupre, S. Niccolai, M. Defurne



Cleanest way to probe GPDs

- As the DVCS process interferes with BH one can access the DVCS amplitudes

At leading twist:

$$d^5 \overrightarrow{\sigma} - d^5 \overleftarrow{\sigma} = \Im m \left(T^{BH} \cdot T^{DVCS}\right)$$

$$d^5 \overrightarrow{\sigma} + d^5 \overleftarrow{\sigma} = |BH|^2 + \Re e \left(T^{BH} \cdot T^{DVCS}\right) + |DVCS|^2$$

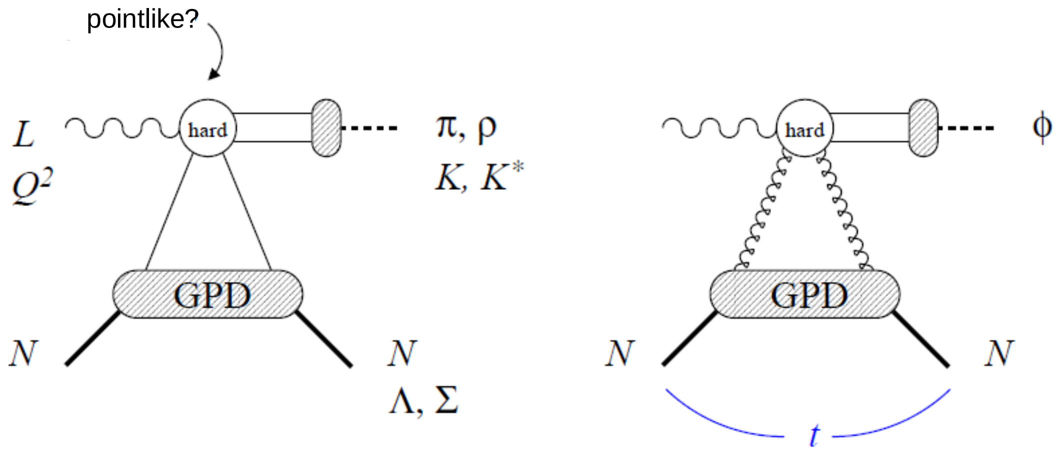
$$\mathcal{T}^{DVCS} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x - \xi + i\epsilon} + \cdots =$$

$$\underbrace{\mathcal{P} \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}}_{\text{Access in helicity-independent cross section}} - \underbrace{i\pi\, H(x=\xi,\xi,t)}_{\text{Access in helicity-dependent cross-section}} + \ldots$$

Towards spin-flavor separation: DVMP

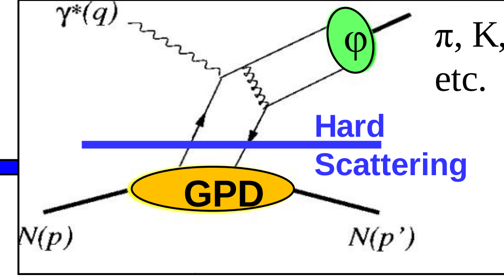
Deep Virtual Meson Production (DVMP)

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



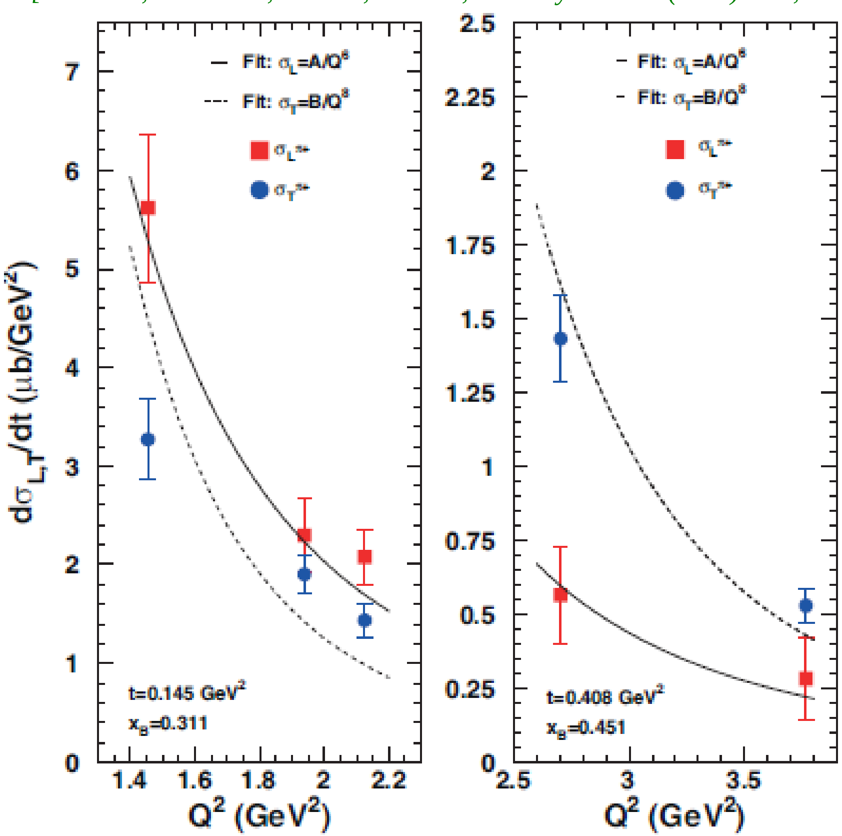
- Nucleon structure described by 4 (helicity non-flip) GPDs:
  - *H, E* (unpolarized), $\tilde{H}, \tilde{E}$ (polarized)
- Quantum numbers in DVMP probe individual GPD components selectively
  - Vector : ρ°/ρ+/*K** select *H, E*
  - **Pseudoscalar: π,η,*K* select the polarized GPDs, $\tilde{H}$ and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

Relative L/T contribution to the pion cross section



Important for nucleon structure studies

[L. Favart, M. Guidal, T. Horn, P. Kroll, Eur. Phys. J A 52 (2016) no.6, 158]

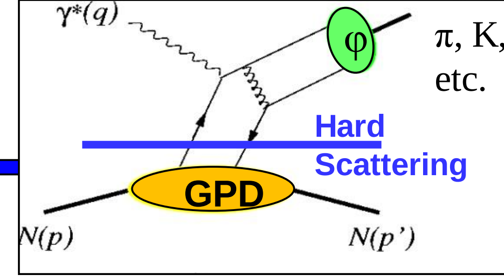


- ❑ Data from JLab 6 GeV demonstrated the technique of measuring the Q^2 dependence of L/T separated cross sections at fixed x/t
  [T. Horn et al., Phys. Rev. C ***78****, 058201* ***(2008)****]*

- ❑ Separated cross sections over a large range in Q^2 are essential for:
  - ➢ testing factorization required for studies of transverse spatial structure
  - ➢ understanding dynamical effects in both Q^2 and $-t$ kinematics
  - ➢ interpretation of non-perturbative contributions in experimentally accessible kinematics

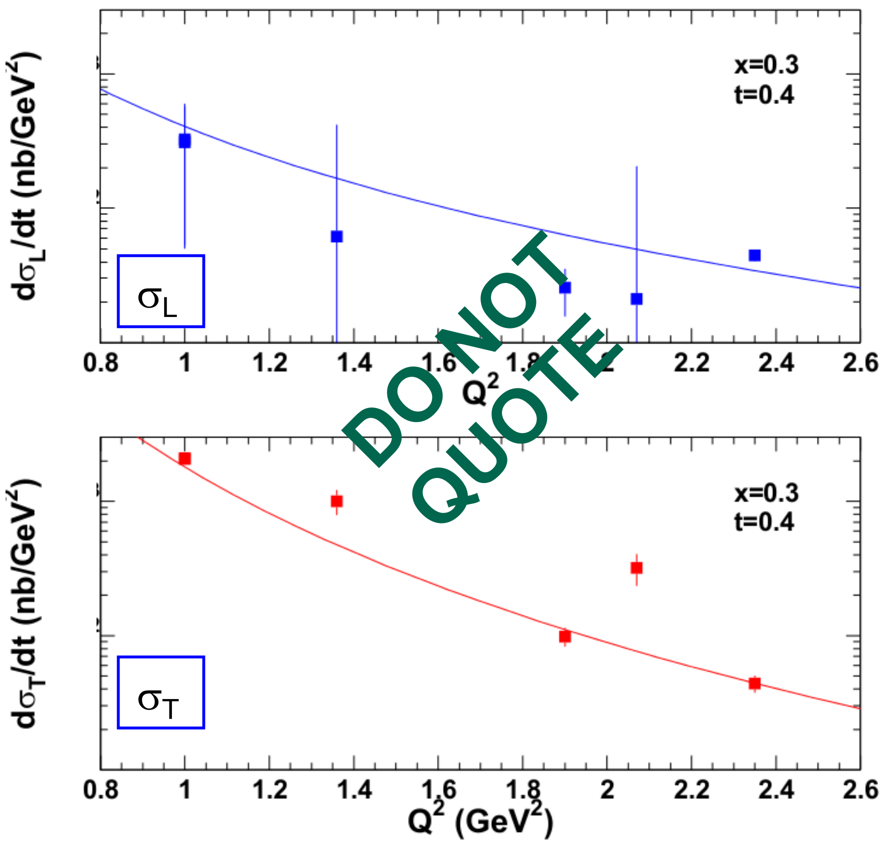
Q^2 dependence of σ_L relevant towards an interpretation in a GPD-based framework

Relative L/T contribution to the Kaon cross section



Important for nucleon structure studies

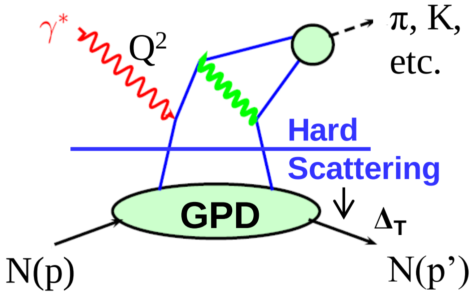
$$Fit = \frac{A}{Q^b}$$

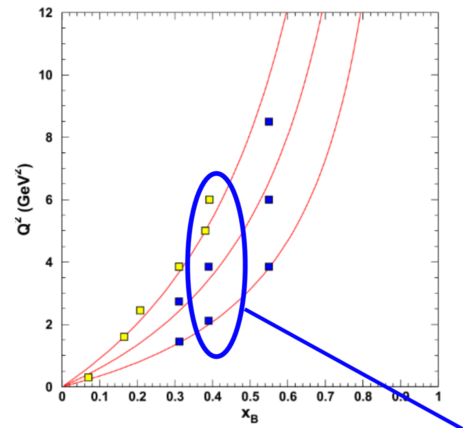


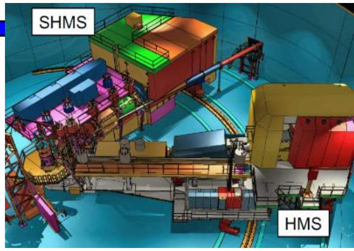
- Q^2 dependence of the K electro production cross section at fixed x and -t
  - Factorisation theorem predicts σ_L scales to leading order as Q^{-6}
  - In that regime expect σ_T to go as Q^{-8} and consequently $\sigma_L >> \sigma_T$

- 6 GeV JLab cross section data appear to be consistent with expected scaling, but small Q^2 lever arm and relatively large uncertainties

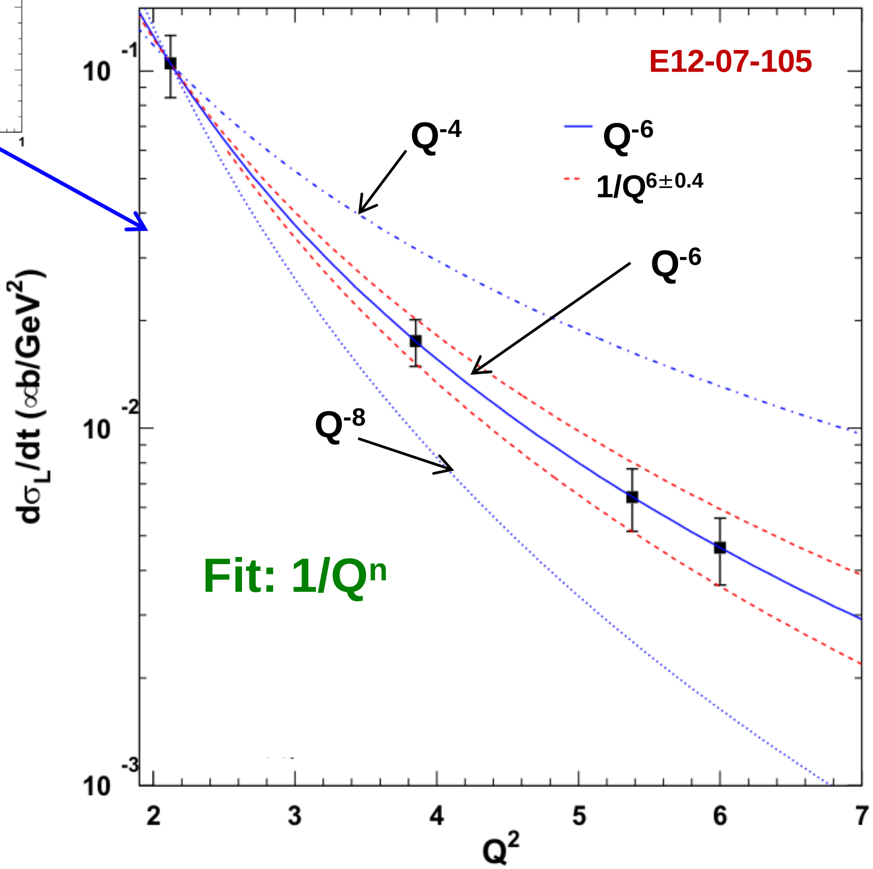
JLab12: confirming potential for nucleon structure studies with pion production







*E12-**07**-105 spokespersons: T. Horn, G. Huber*



- **E12-07-105 (P12):** Measure the Q^2 dependence of the π electro production cross section at fixed x and -t
  - Factorisation theorem predicts σ_L scales to leading order as Q^{-6}

x	Q^2 (GeV²)	W (GeV)	-t (GeV/c)²
0.3	1.5-2.7	2.0-2.6	0.1
0.4	2.1-6.0	2.0-3.2	0.2
0.5	3.9-8.5	2.0-2.8	0.5

Considered for running **in 2019**

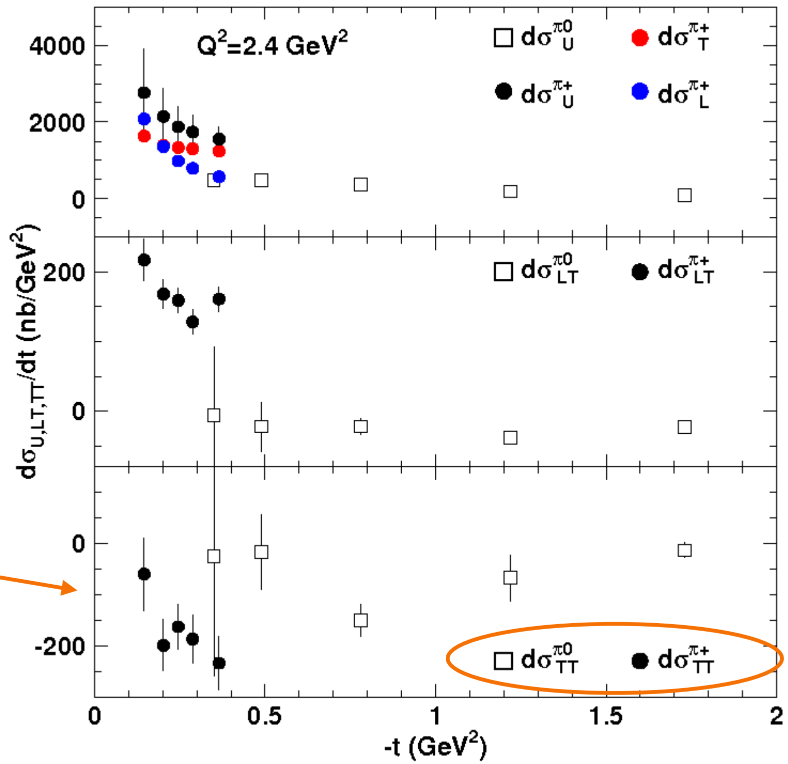
Transverse Contributions in pion production

*[Favart, Guidal, Horn, Kroll , EPJA (**2016**)]*

- Recent data suggest that transversely polarized photons play an important role in charged and neutral pion electroproduction
  - *π^+:* σ_T magnitude is large even at Q^2=2.5 GeV^2
  - π^o: σ_T is large even at Q^2=2 Gev^2

    *[M. Defurne et al, PRL **117 (2016)** no.26, 262001]*
  - substantial fraction of σ_{TT} in the *unseparated* cross section for t > 0.2 GeV^2

    [Bedlinskiy et al, PRL**109**, ***(2012)*** *109; arXiv:1405.0988* ***(2014)****]*



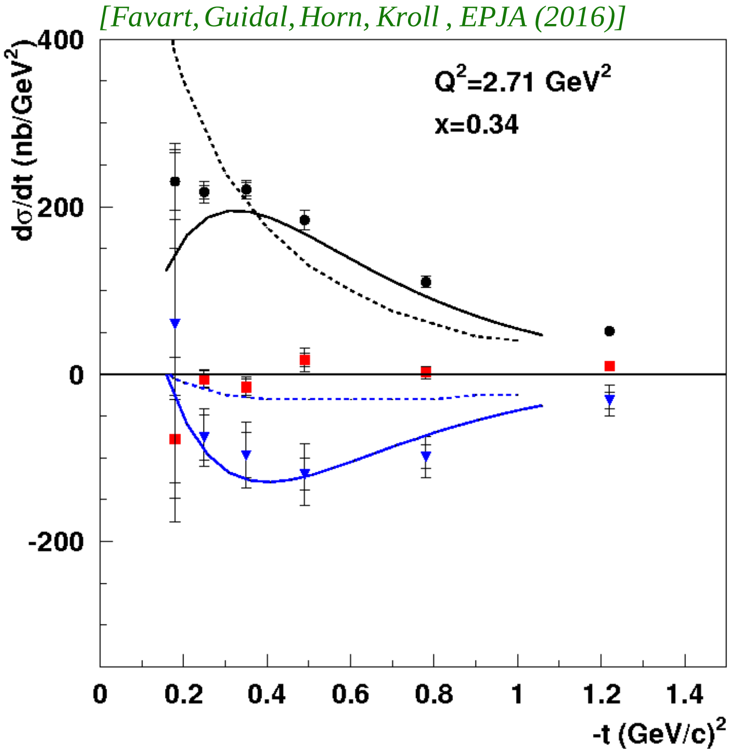
Measurements of relative σ_L and σ_T contributions to the π cross section to higher Q^2 planned for JLab 12 may shed light on this

- Exclusive π^o data may also be helpful for constraining non-pole contributions in F_π extraction

*E12-**07**-105 spokespersons: T. Horn, G. Huber*

*E12-**13**-010 spokespersons: C. Munoz-Camacho, T. Horn, C. Hyde, R. Paremuzyan, J. Roche; E12-**06**-101: K. Joo et al.*

Transverse Contributions may allow for probing a new set of GPDs



Goloskokov, Kroll, EPJ C65, 137 (2010); EPJ A45, 112 (2011)

*[Ahmad, Goldstein, Liuti, PRD **79 (2009)**]*

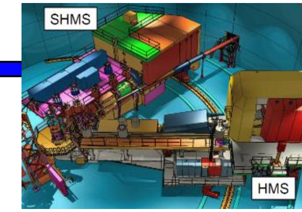
*[Goldstein, Gonzalez Hernandez, Liuti, J. Phys. G **39 (2012)** 115001]*

- Recent data suggest that transversely polarized photons play an important role in charged and neutral pion electroproduction
  - Model predictions based on handbag in good agreement with data
- For pion and kaon production the relative contribution of longitudinal and transverse photons in JLab 12 GeV kinematics this has to be verified
- A large transverse cross section in meson production may allow for accessing helicity flip GPDs

JLab 12 GeV will provide relative σ_L and σ_T contributions to the π^0 cross section up Q^2~6 GeV^2

– Exclusive π^o data may also be helpful for constraining non-pole contributions in F_π extraction

JLab12: confirming potential for nucleon structure studies with kaon production



- **E12-09-011**: Separated L/T/LT/TT cross section over a wide range of Q^2 and t

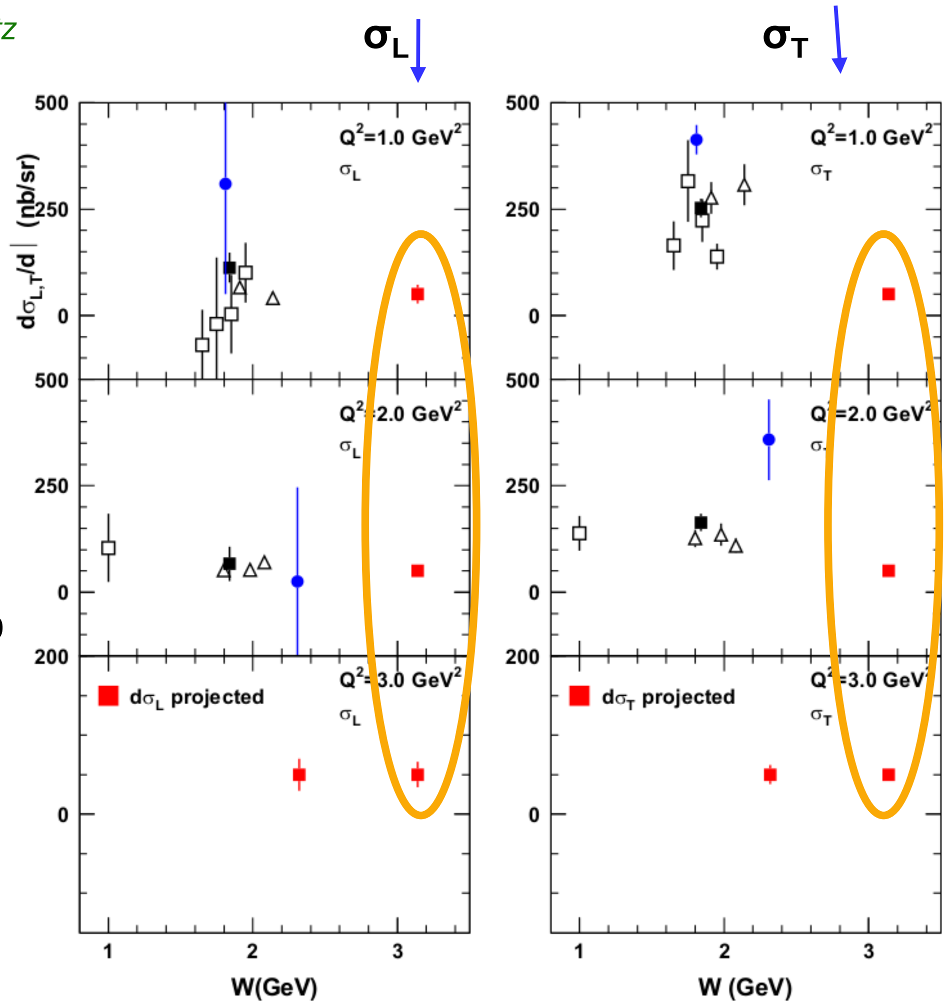
*E12-**09**-011 spokespersons: T. Horn, G. Huber, P. Markowitz*

JLab 12 GeV Kaon Program features:

- First cross section data for Q^2 scaling tests with kaons
- Highest Q^2 for L/T separated kaon electroproduction cross section
- First separated kaon cross section measurement above W=2.2 GeV

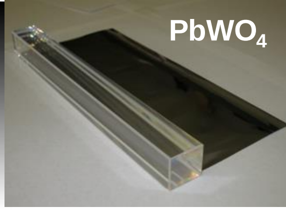
approved for 40 PAC days and **scheduled to run in 2018/19**

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



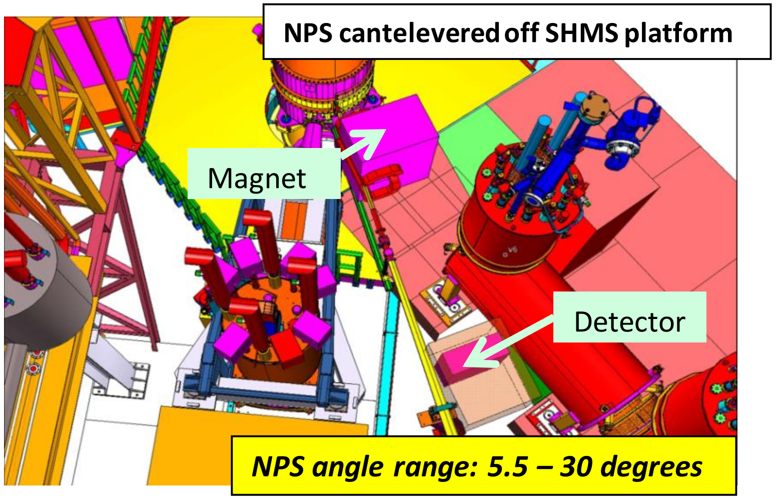
*[blue points from M. Carmignotto, PhD thesis **(2017)**]*

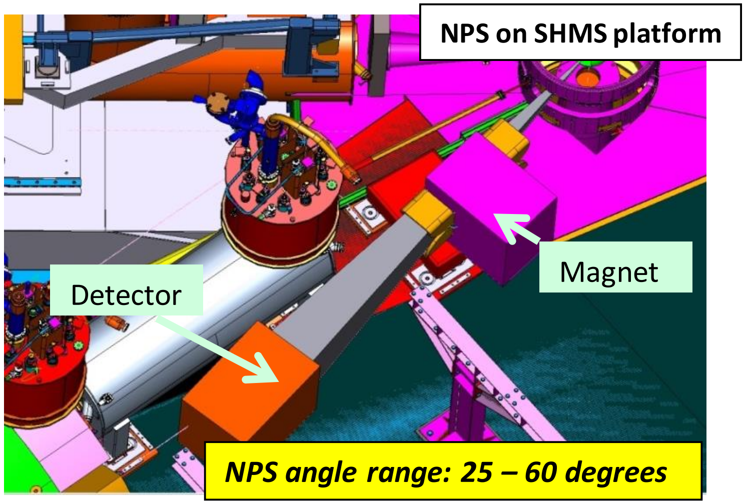
New Opportunities with the Neutral Particle Spectrometer (NPS)



NSF MRI PHY-1530874

- ❑ The NPS is envisioned as a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ and π^0).



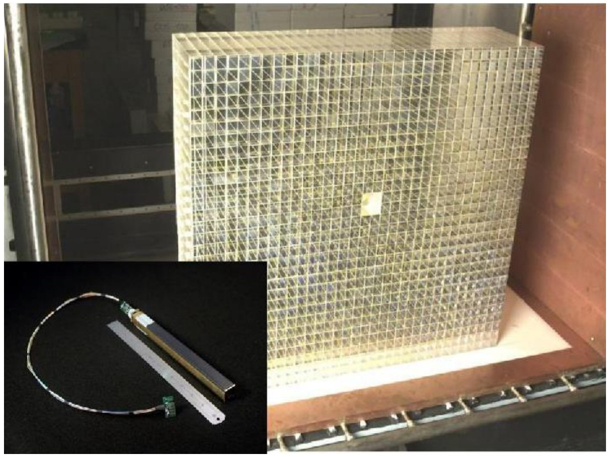


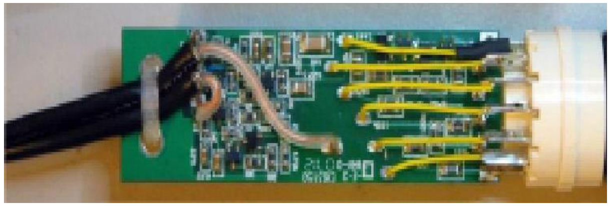
- ❑ Global design of a neutral-particle spectrometer between 5.5 and 60 degrees consists of a highly segmented EM calorimeter preceded by a sweeping magnet

NPS General Design Concept

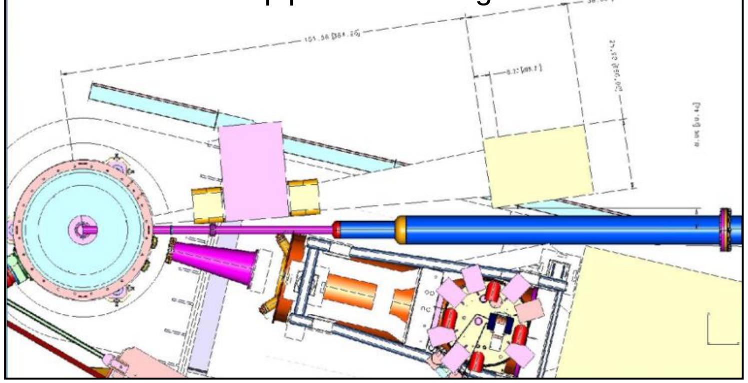
NSF MRI PHY-1530874

- a ~25 msr neutral particle detector consisting of up to 1116 **$PbWO_4$ crystals** in a temperature-controlled frame including gain monitoring and curing systems
- HV distribution bases with built-in amplifiers for operation in a high-rate environment
- Essentially deadtime-less digitizing electronics to independently sample the entire pulse form for each crystal – JLab-developed Flash ADCs
- A new 0.3Tm sweeping magnet allowing for small-angle and large angle operation at 0.6 TM. The magnet is compatible with existing JLab power supplies.
- Cantelevered platforms off the SHMS carriage to allow for remote rotation (in the small angle range), and platforms to be on the SHMS carriage (in the large angle range) – new
- A beam pipe with as large critical angle as possible to reduce beamline-associated backgrounds – further study showed only a small section needs modification (JLab/Hall C)





Modified beam pipe: critical angle 13.5 mr



NPS Project Status

The Catholic University of America

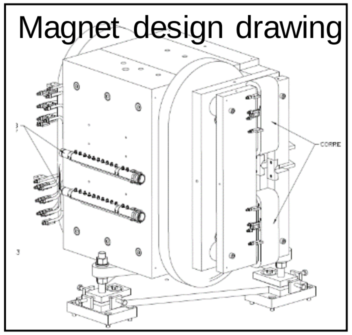
NSF MRI PHY-1530874

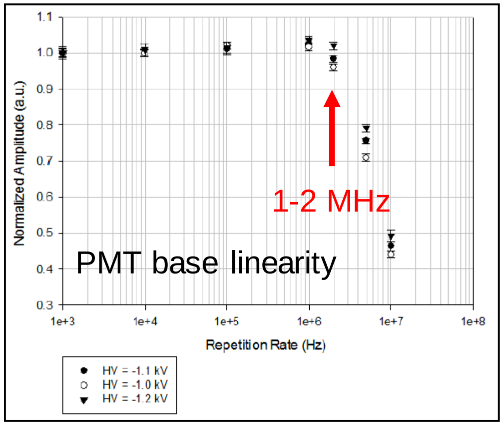
- Magnet: design drawings finalized, procurement of main coil awarded, corrector coil delivered, magnet assembly and mapping plans underway

- PMT and HV bases: design drawings final, vendor selection ongoing, linearity test complete, magnetic shielding concept selected

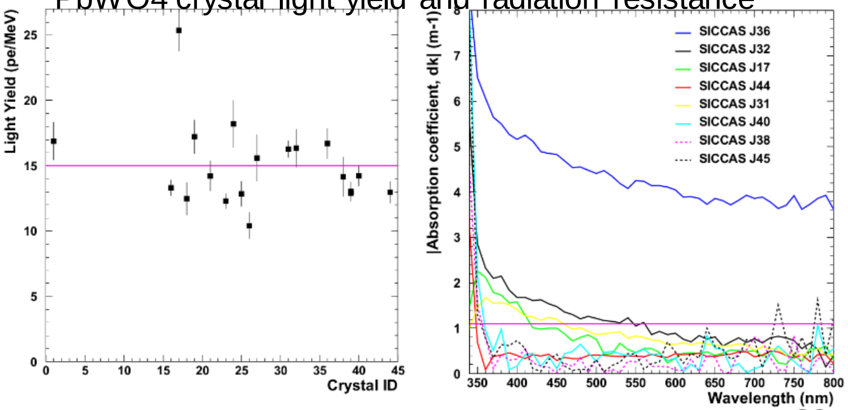
- Frame and integrated systems: initial design drawings completed, specifications for Light Monitoring System and curing system ongoing

- Crystals: characterization of systematic dependencies, irradiation studies, chemical analysis and crystal growing in collaboration with the Vitreous State Laboratory (VSL), synergy with EIC crystal calorimeter R&D





PbWO4 crystal light yield and radiation resistance



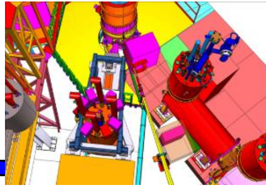
Overview Scientific Program

- 4 experiments fully approved by PAC to date
  - E12-13-007: Measurement of Semi-inclusive π^0 production as Validation of Factorization
  - E12-13-010 – Exclusive Deeply Virtual Compton and π^0 Cross Section Measurements in Hall C
  - E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
  - E12-14-005 – Wide Angle Exclusive Photoproduction of π^0 Mesons

- Ideas exist for future experiments and new scientific directions taking advantage of the compatibility of NPS with Hall infrastructure
  - Experiments with polarized targets
  - High-Intensity Photon Source
  - Exploring possibilities for correlation experiments

- 1 LOI and one conditionally approved proposal
  - LOI12-15-007 – Timelike Compton Scattering with transverse target
  - C12-17-008 – Polarization Observables in Wide Angle Compton Scattering

E12-13-010: precision DVCS cross sections



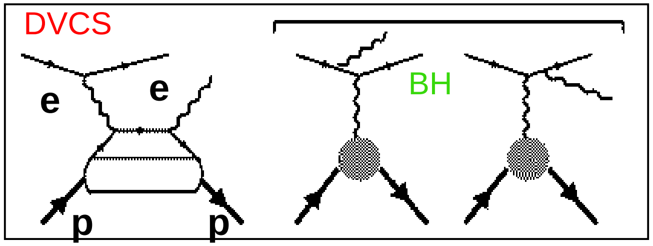
Simplest process **e + p → e' + p + γ (DVCS)**

E12-13-010 DVCS measurements follow up on measurements in Hall A:

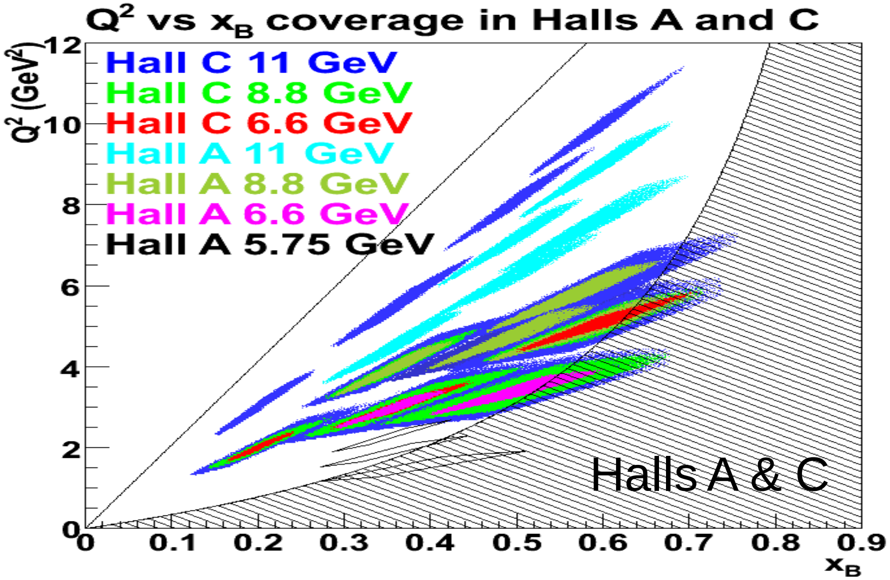
- Scaling of the Compton Form Factor
- Rosenbluth-like separation of DVCS:

$$\sigma = |BH|^2 + \mathrm{Re}\left[\underbrace{DVCS^{\perp}\,BH}_{\sim E_{beam}^2}\right] + \underbrace{|DVCS|^2}_{\sim E_{beam}^3}$$

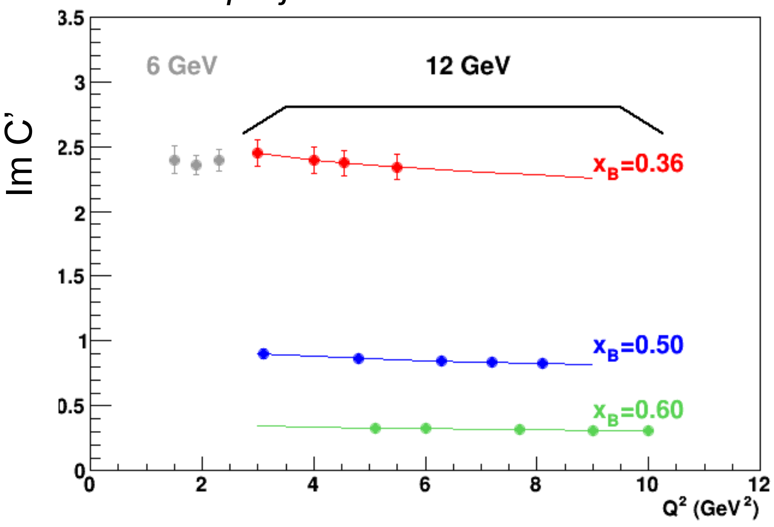
- L/T separation of π^0 production



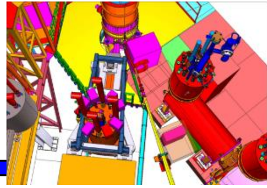
Hall A data for Compton form factor (over *limited* Q^2 range) agree with hard-scattering



12 GeV projections: confirm formalism

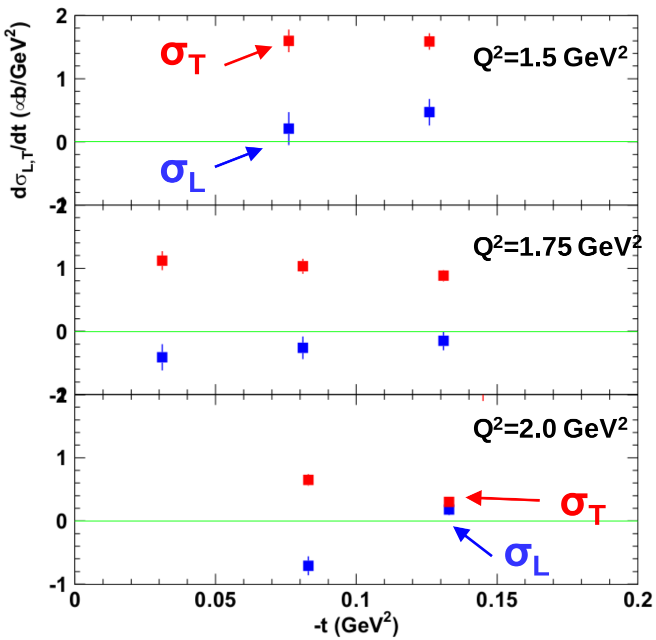


Extracting the real part of CFFs from DVCS requires measuring the cross section at multiple beam energies (DVCS^2−Interference separation)



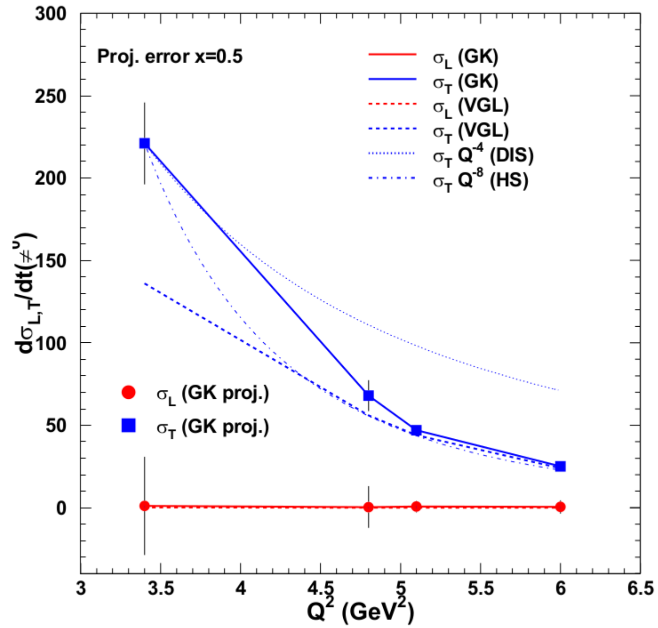
E12-13-010: exclusive π^0 cross section

- Relative L/T contribution to π^0 cross section important in probing transversity
  - If σ_T large: access to transversity GPDs
- Results from Hall A at 6 GeV Jlab suggest that the longitudinal cross section in π^0 production is non-zero up to Q^2=2 GeV^2
- Need to understand Q^2/t dependence for final conclusion on dominance of σ_T



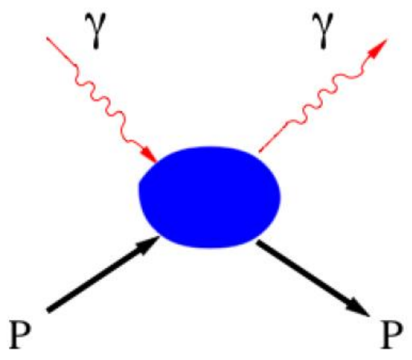
*M. Defurne et al, PRL **117** (**2016**) no.26, 262001*

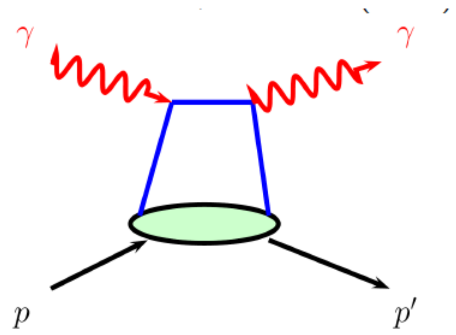
E12-13-010 projections



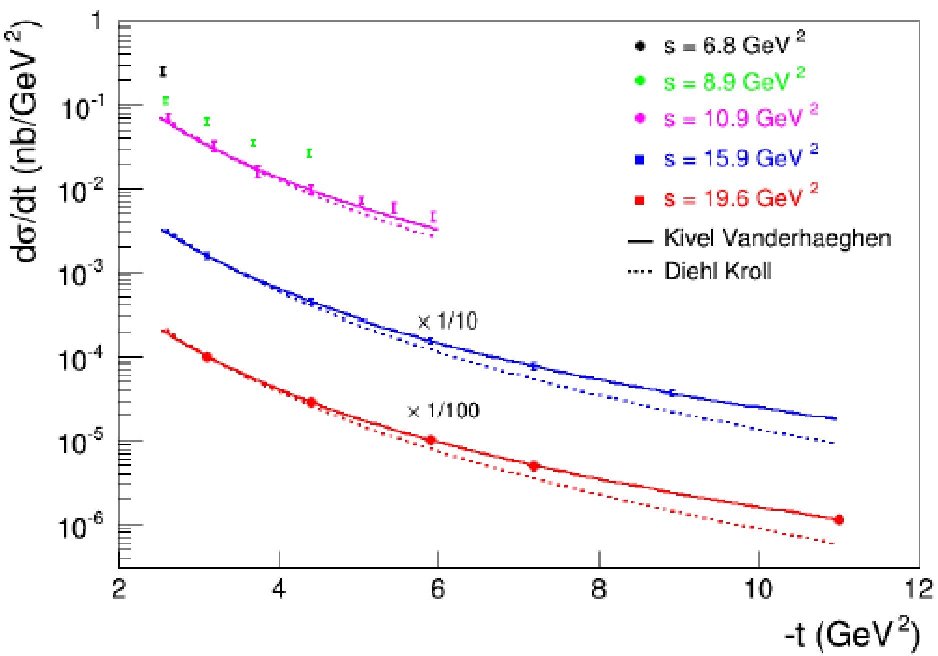
E12-13-010 will provide essential data on σ_T and σ_L at higher Q^2 for reliable interpretation of 12 GeV GPD data

E12-14-003: Wide Angle Compton Scattering





- Arguably the least understood of the fundamental reactions in the several-GeV regime
- Wide-Angle Compton Scattering cross section behavior was a foundation leading to the GPD formalism
- Reaction mechanism intrinsically intertwined with basics of hard scattering process (handbag diagram), yet also sensitivity to transverse structure like high-Q^2 form factors



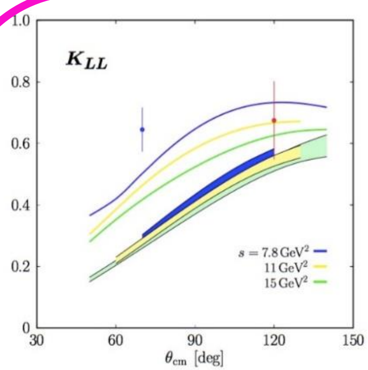
- Perhaps (6-GeV data) factorization valid for *s, -t, -u > 2.5 GeV²*
- 12-GeV data for *–u > 2.5* and *–t* up to *~ 10, s* up to *~ 20* GeV²

New Opportunities with NPS and a Compact Photon Source (CPS)

THE CATHOLIC UNIVERSITY of AMERICA

6-7 February 2017 High-Intensity Photon Sources Workshop (CUA)

https://www.jlab.org/conferences/HIPS2017/

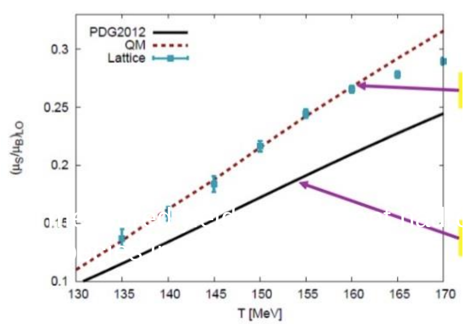


Polarization observables Wide Angle Compton Scattering

K_{LL}, A_{LL}, K_{LS}, $A_{LS,..}$)

Hadron Spectroscopy with secondary K_L beam

- Cross sections and polarization of Λ, Σ, Ξ, Ω hyperons
- Strange meson spectroscopy
- Connections to heavy ion physics
- Possibly link to doubly charged baryons?



Additional Science Topics under study

- ❑ WACS exclusive photoproduction
- ❑ Timelike Compton Scattering
- ❑ Short Range Correlations
- ❑ Photoproduction of Few Body Systems
- ❑ *Also: Missing mesons, Phi production,…*

Science Gain with a Compact Photon Source

Impact of a high intensity photon source for hadron physics at JLab:

- WACS must reach several GeV^2 in s, t, and u, but since the WACS rates drop with ~1/s$^{7.5}$ this science needs a luminosity boost.
- The K_L project is based on a 5 kW photon intensity (>100 times above the 15 W design level for the Hall D beam line) to do "prime physics with a secondary beam".

Impact of the photon source for WACS:

- The heat/radiation load is a limiting factor for luminosity with the polarized target.
  The target can take 20 times more photons than electrons.
- **The experiment productivity is improved even more (30 times)** due to higher target polarization averaged over the experiment, and reduced overhead time for the target annealing procedure.

Impact of the photon source for the K_L project:

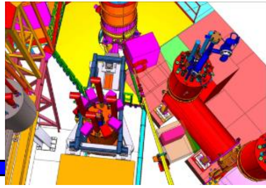
- The hermetic CPS concept allows **2 decades increase** of the beam intensity in
  the existing photon Tagger Area without major rebuilding of the facility.

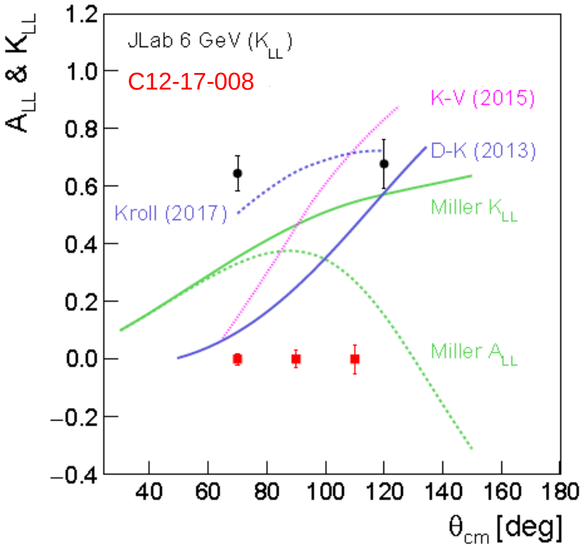
Compact Photon Source (CPS) – Concept

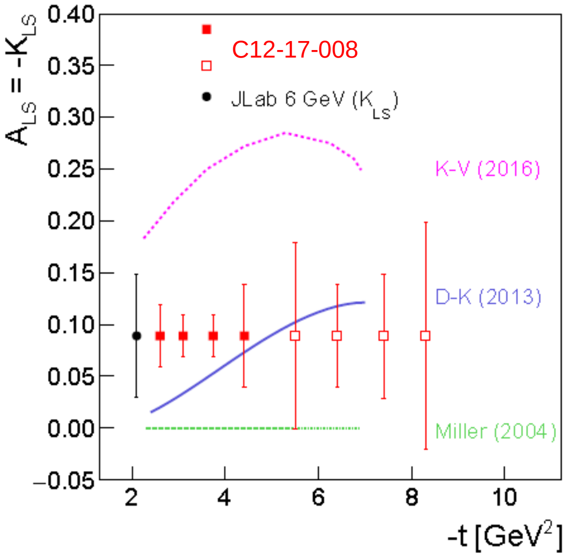
- Strong magnet after radiator deflects exiting electrons
- Long-bore collimator lets photon beam through
- No need in tagging photons, so the design could be compact as opposed to a Tagger Magnet concept
- The magnet itself is the electron beam dump
- Water-cooled W-Cu core for better heat dissipation
- Hermetic shielding all around and close to the source to limit prompt radiation and activation
- High Z and high density material for bulk shielding
- Boron outer layer for slowing, thermalizing, and absorbing fast neutrons still exiting the bulk shielding

CPS is a novel concept allowing for ***high photon intensity*** (equivalent photon flux: ~10^{12} photons/s) and ***low radiation*** (low activation: <1mrem/h after one hour) in the hall

C12-17-008: Polarization Observables in Wide-Angle Compton Scattering

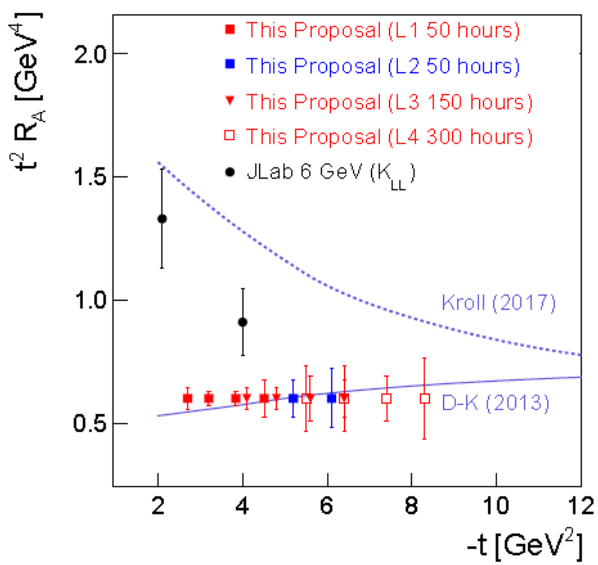


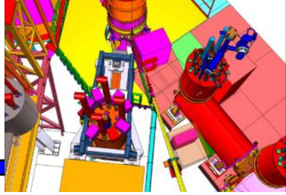




Kin	E_{Beam} [GeV]	E_{in} [GeV]	θ_γ [°]	E_γ [GeV]	D_{NPS} [m]	θ_p [°]	p_p [GeV/c]	D_{BB} [m]	θ^{cm} [°]
L1	8.8	6.0	21.5	4.16	3.0	35.5	2.62	1.5	70.0
S1	8.8	6.0	21.5	4.16	3.0	35.5	2.62	1.5	70.0
L2	11.0	9.5	17.4	6.49	3.0	30.5	3.82	1.5	70.0
L3	8.8	6.0	30.2	3.22	3.0	26.5	3.63	2.5	90.0
L4	8.8	6.0	42.3	2.25	1.0	19.4	4.55	3.5	110.0
S4	8.8	6.0	42.3	2.25	1.0	19.4	4.55	3.5	110.0

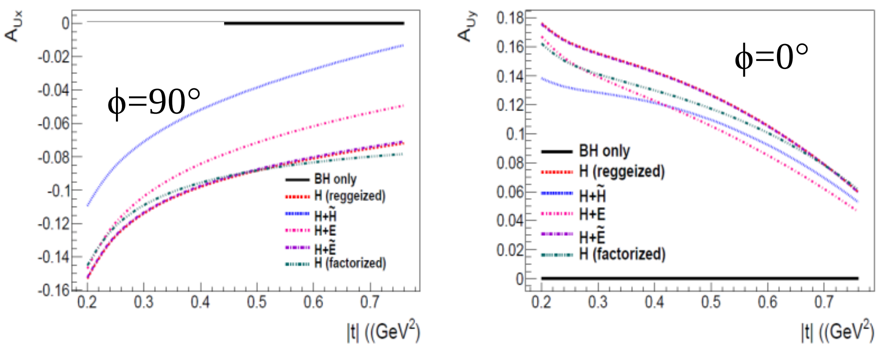
- ❑ Explicit, model-independent test of factorization by measuring the s-dependence of the polarization observables at fixed centre of mass angle
- ❑ Measurement of A_{LL} at large angles allowed for tests of relevant degrees of freedom in hard exclusive reactions
- ❑ Also extract the Axial and Pauli form factors - constrain GPDs $\tilde{H}$ and E at high –t



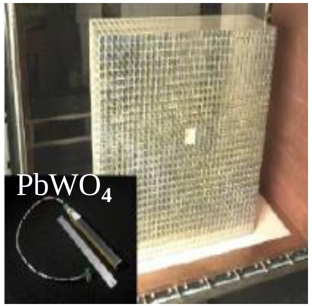


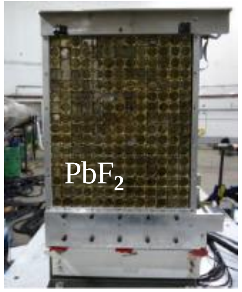
LOI12-15-007: Timelike Compton Scattering with Transverse targets

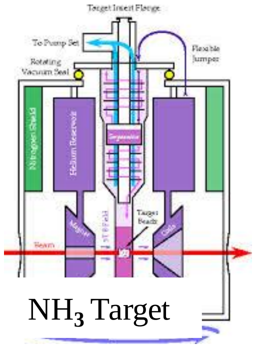
- Features of TCS measurements with transversely polarized target
  - Theoretical calculations show that transverse asymmetries are very sensitive to GPDs
    [M. Boer, M. Guidal, arXiv:1412.2036]
  - Asymmetries for the BH the main background for TCS is zero!
  - Predictions for asymmetries with different assumption of GPDs vary up to 20%

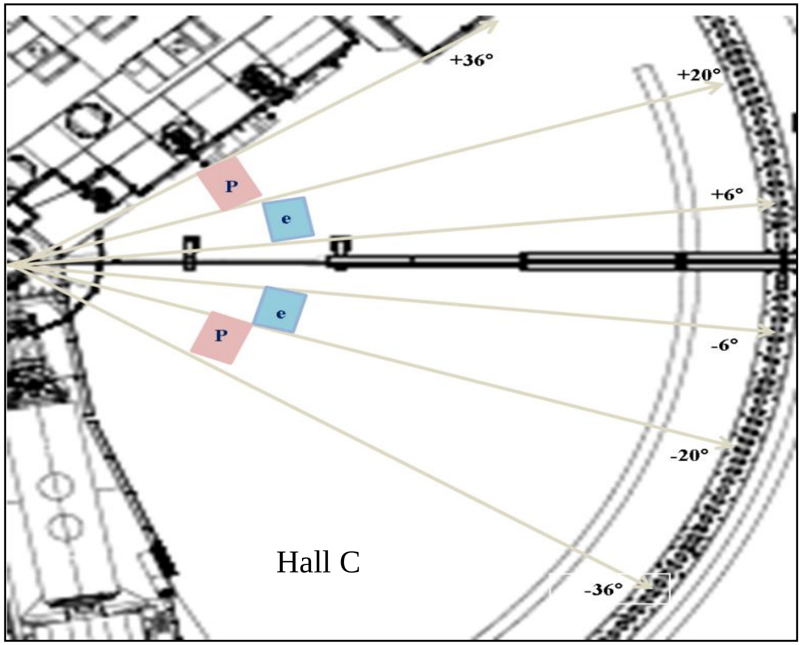


- TCS event detection with NPS
  - Lepton pair will be detected by pair of NPS
  - Recoil detection by combination of tracking and TOF









TCS measurements with transversally polarized target open interesting opportunities for probing GPD E

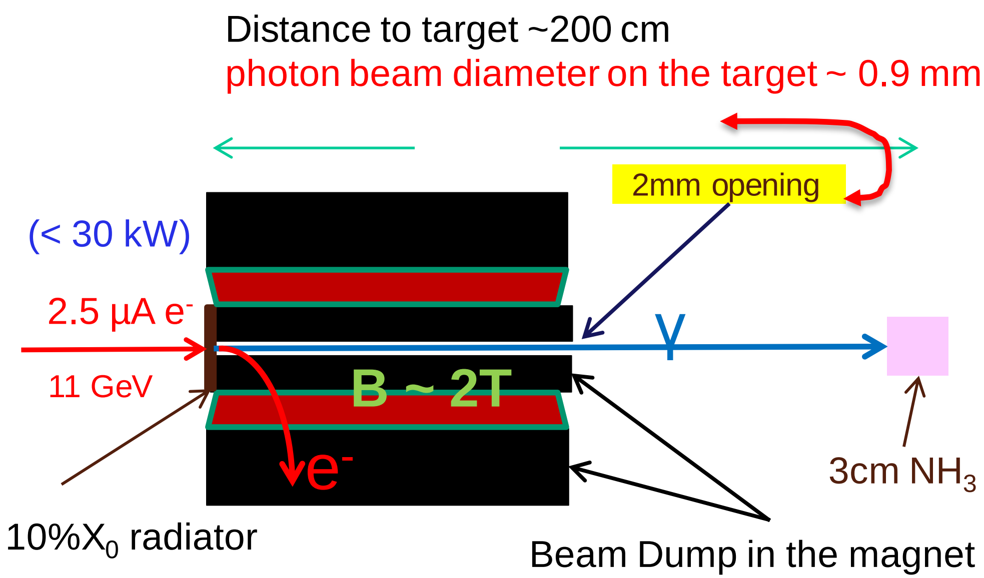
Summary and Outlook

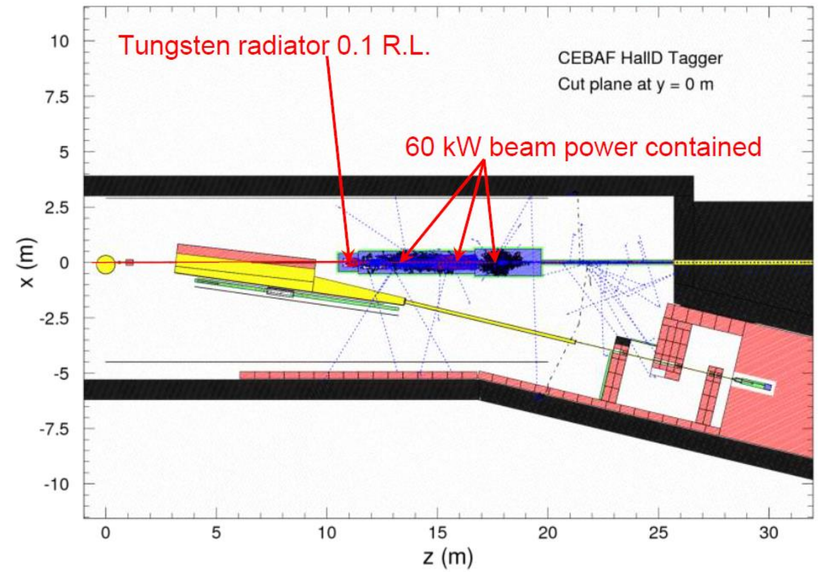
- Precision cross section measurements are essential for the GPD/TMD program at 12 GeV JLab
  - Validate applicability of hard-soft factorization in exclusive processes required for accessing GPDs
- The charged pion/kaon and neutral particle physics program in Hall C plays an important role in the GPD/TMD program
- The Neutral Particle Spectrometer gives unique opportunity for coincidence precision cross section measurements with neutral particles
  - NPS design/construction underway
- The combination of NPS and a Compact Photon Source opens new avenues for hadron structure studies
  - Work towards finalization of CPS design underway

Supported by NSF grants PHY-1306227/PHY-1714133, PHY1530874

CPS implementations in Halls A/C & K_L/Hall D

Basic CPS design concept for Halls A/C



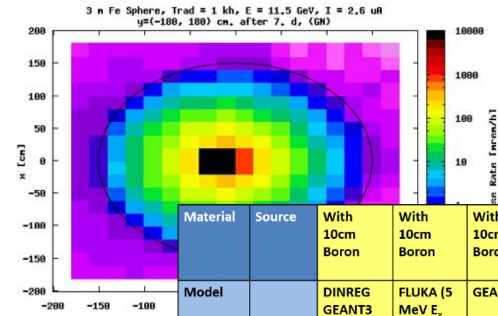


- If one uses a 2nd raster system for Hall D to compensate for the initial 1 mm raster, this can be an equivalent essential design

- Some differences…
  - Hall D alcove has more space, so simpler positioning and shielding placement
  - Hall D up to 60 kW (<5 µA @12 GeV), Halls A/C up to 30 kW (2.6 µA @ 11 GeV)
  - Different length/field magnet for Hall D
  - Shielding may differ

CPS Status

- Science at Jefferson Lab benefits from an optimized high intensity photon source



Material	Source	With 10cm Boron	With 10cm Boron	With 10cm Boron
Model		DINREG GEANT3	FLUKA (5 MeV E_γ cut)	GEANT4
Iron	neutron	0.8	0.11+- 3.4%	0.28
Iron	γ	2.8	0.063+- 0.7%	0.56
Tungsten Powder	neutron	2.7	0.52+- 15.3%	1.76
Tungsten Powder	γ	0.003	0.0052+- 8.3%	1.28

- CPS is a novel concept allowing for ***high photon intensity*** (equivalent photon flux: ~10^{12} photons/s) and ***low radiation*** (low activation: <1mrem/h after one hour) in the hall

- CPS implementations in Hall A/C and Hall D/K_L can be equivalent essential design (i.e., similar materials and shielding strategy), with some differences due to the locations (like more space in Hall D, perhaps longer magnet, ..)

- Strong interest by Hall A/C and Hall D/K_L to jointly further develop an as common as possible CPS design and seek funding for CPS