Meson Production

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INT 18-3: Probing Nucleons and Nuclei in High Energy Collisions

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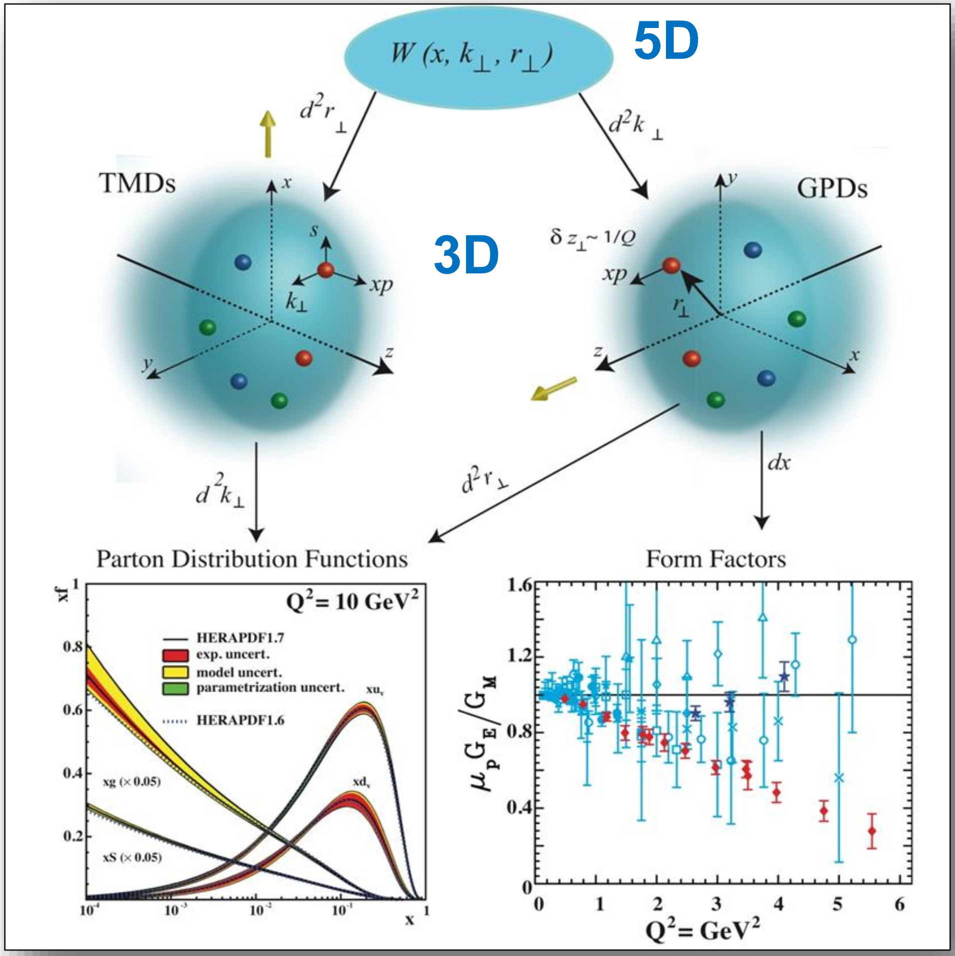
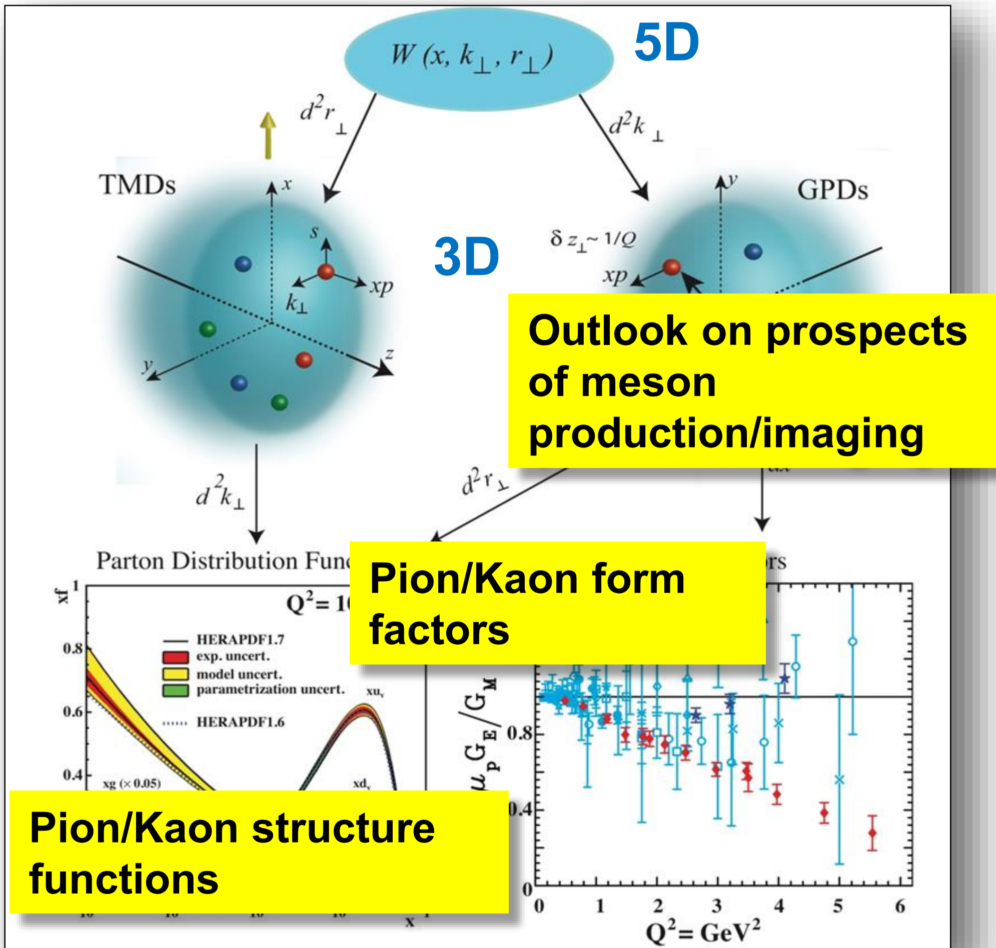
The 3D Hadron Structure



- Meson Form Factors
  - Most basic information about internal structure
- GPDs
  - Spatial imaging (exclusive DIS)
- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- Requires
  - High luminosity
  - Sophisticated detector systems
  - Polarized beams and targets

The 3D Hadron Structure – this talk



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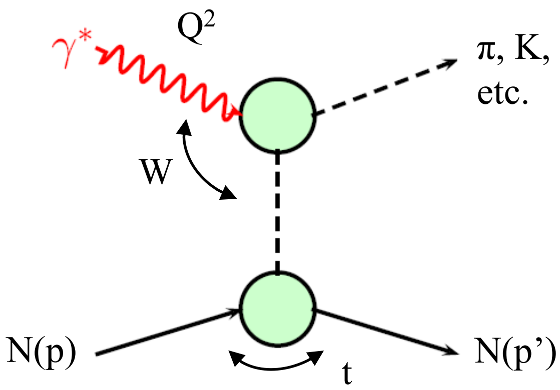
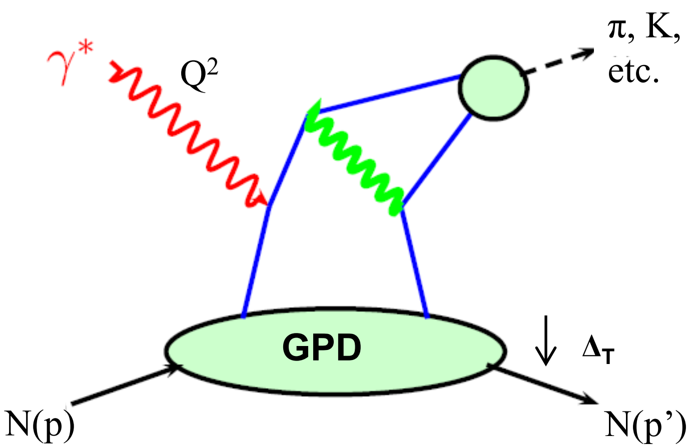
Deep Exclusive Meson Electroproduction



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]*

Overview Form Factors

- ***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

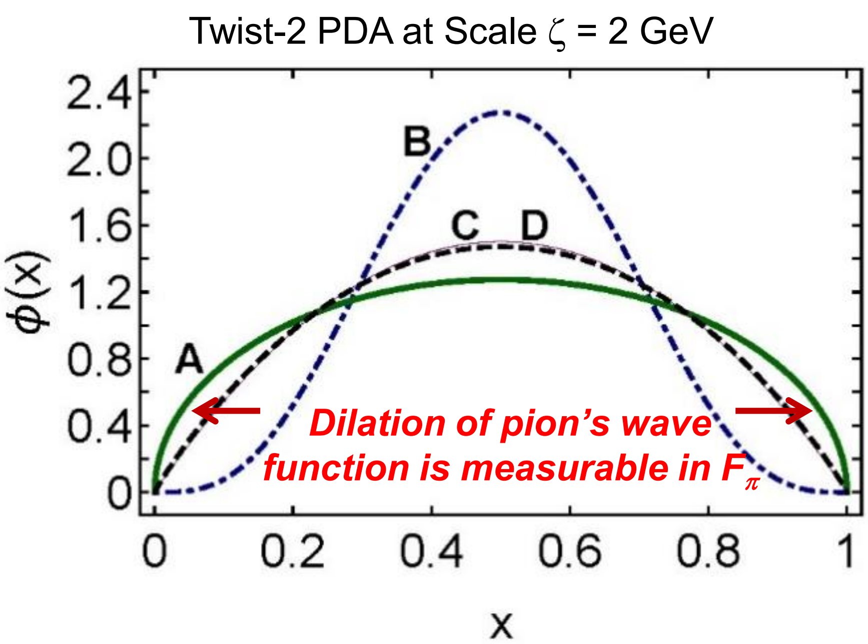
    - ***Clearest test case for studies of the transition from non-perturbative to perturbative regions***

- Recent advances and future prospects in experiments
  - Dramatically improved precision in F_π measurements

    - ***12 GeV JLab data have the potential to quantitatively reveal hard QCD's signatures***

    - ***EIC data have the potential to quantitatively reveal DCSB emergent mass generation***

Emergent- versus Higgs-Mass Generation



A solid (green) curve – pion ⇐ emergent mass is dominant;

B dot-dashed (blue) curve – η_c ⇐ primarily, Higgs mass generation;

C solid (thin, purple) curve – conformal limit result, 6x(1 - x); and

D dashed (black) curve – "heavy-pion", i.e., a pion-like pseudo-scalar meson (~η_s) in which the valence-quark current masses take values corresponding to a strange quark ⇐ the border, where emergent and Higgs mass generation are equally important.

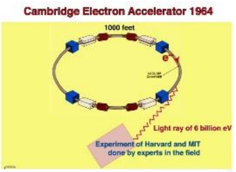
Unfortunately, experimental signatures of the exact PDA form are, in general, difficult.

- The PDA for the light-quark pion (**A**) is a broad, concave function, a feature of emergent mass generation.
- In the limit of infinitely-heavy quark masses, the Higgs mechanism overwhelms every other mass generating force, and the PDA becomes a δ-function at x = ½.
- The sufficiently heavy η_c meson (**B**), feels the Higgs mechanism strongly.

Meson Form Factor Data Evolution

Experiment

Capability to reliably access large Q^2 regime



DESY

Jefferson Lab

JLab 6 GeV

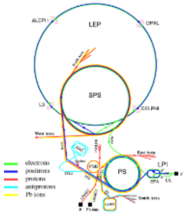
JLab 12 GeV

EIC

1959 1971 1976 1979 1981 1984 1986 1997 2003 2004 2017+ 2025+

Cornell University

Fermilab



Theory

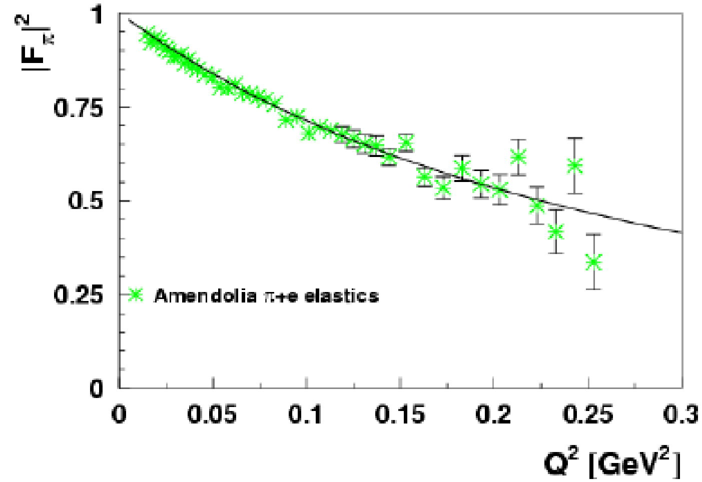
- Accessing the form factor through electroproduction
- Extraction of meson form factor from data
- Electroproduction formalism

Theory

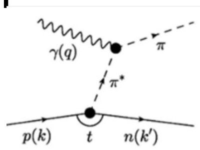
Major progress on large Q^2 behavior of meson form factor

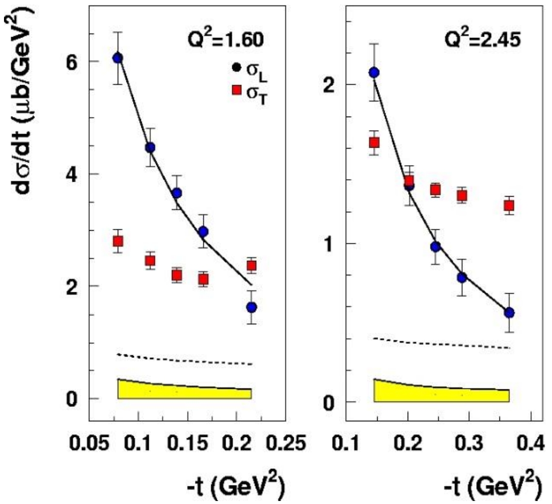
Measurement of π^+ Form Factor

- 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, NPB**277**,168 (1986)]*
  - These data used to constrain the pion charge radius: $r_\pi = 0.657 \pm 0.012$ fm



- At larger Q^2, $F_{\pi+}$ must be measured indirectly using the "pion cloud" of the proton in exclusive pion electroproduction: $p(e,e'\pi^+)n$ – ***L/T separations***





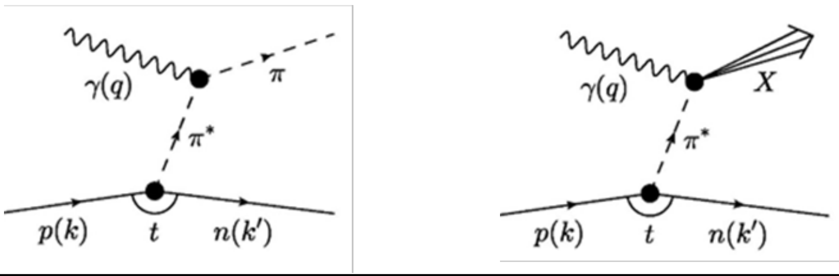
*[Horn et al., PRL **97**, (2006) 192001]*

  - *Select pion pole process:* at small $-t$ pole process dominates the longitudinal cross section, σ_L
    *[L. Favart, M. Guidal, T. Horn, P. Kroll, Eur. Phys. J A **52** (2016) no.6, 158]*
  - *Isolate 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]

Theoretical Off-Shellness Considerations

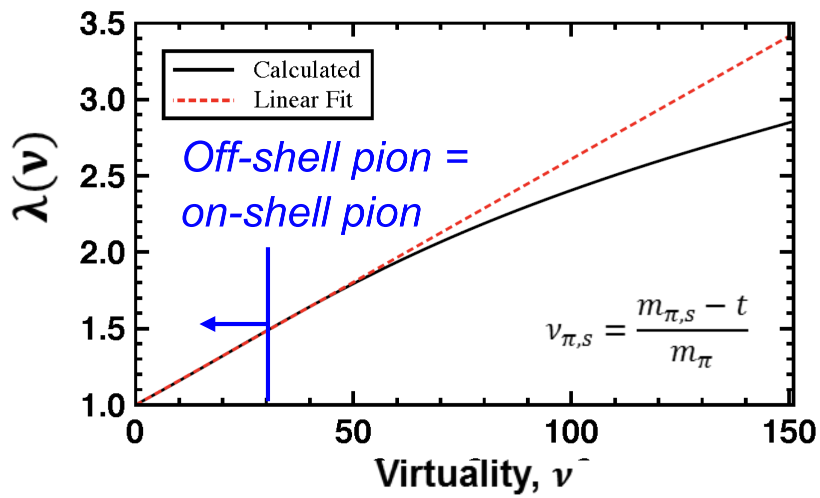


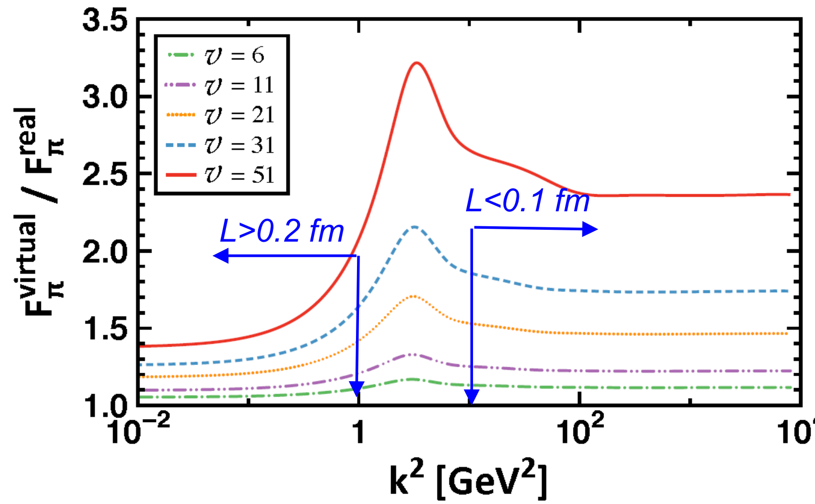
In the Sullivan process, the mesons in the nucleon cloud are virtual (off-shell) particles

- Recent calculations estimate the effect in the BSE/DSE framework – as long as $\lambda(\nu)$ is linear in ν the meson pole dominates
  - Within the linearity domain, alterations of the meson internal structure can be analyzed through the amplitude ratio
- *Off-shell meson* = *On-shell meson* for t<0.6 GeV^2 (ν =31) for pions and t<0.9 GeV^2(ν_s~3) for kaons

This means that pion and kaon structure functions can be accessed through the Sullivan process

S-X Qin, C. Chen, C. Mezrag, C.D. Roberts, Phys. Rev. C 97 (2017) 015203



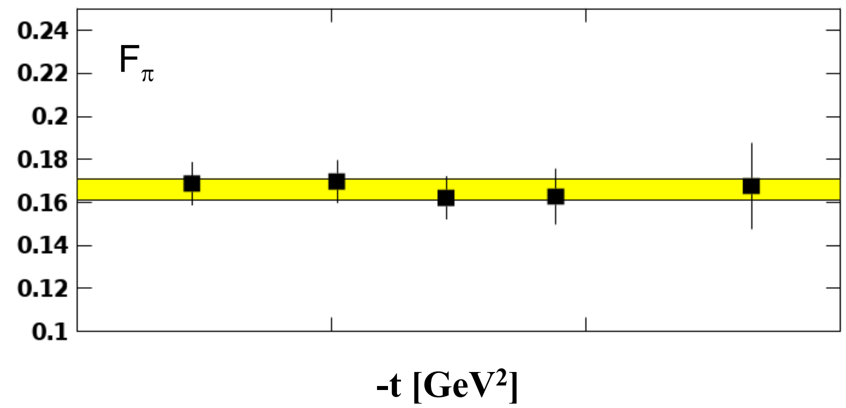


Experimental Validation

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

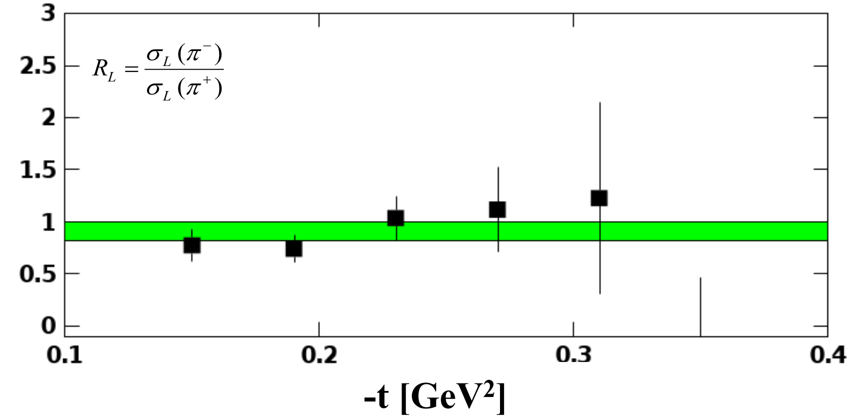
*[T. Horn, C.D. Roberts, J. Phys. **G43** (**2016**) no.7, 073001]*

- Experimental studies include:
  - Take data covering a range in –t and compare with theoretical expectation
    - F_π values do not depend on -t – 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]*

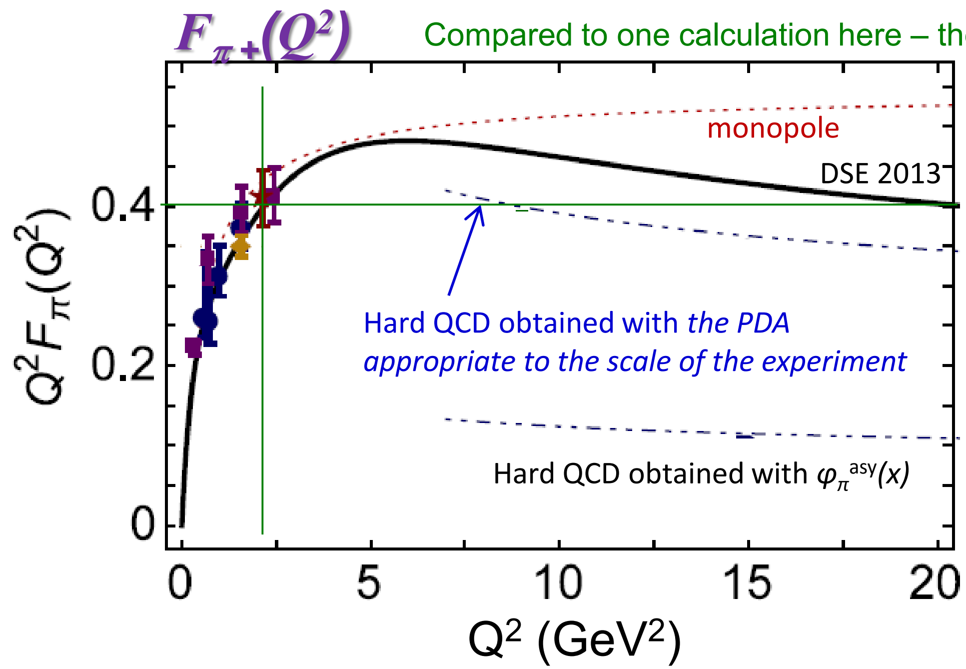


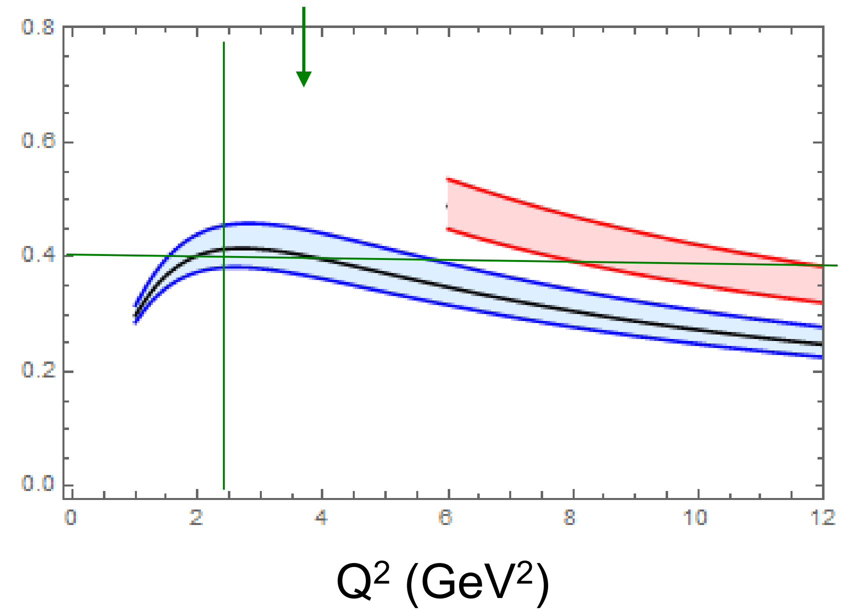
  - Extract F_π at several values of t_{min} for fixed Q^2

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

$F_{\pi^+}(Q^2)$ and $F_{K^+}(Q^2)$ in 2018

Compared to one calculation here – there are others, like: V. Braun et al.



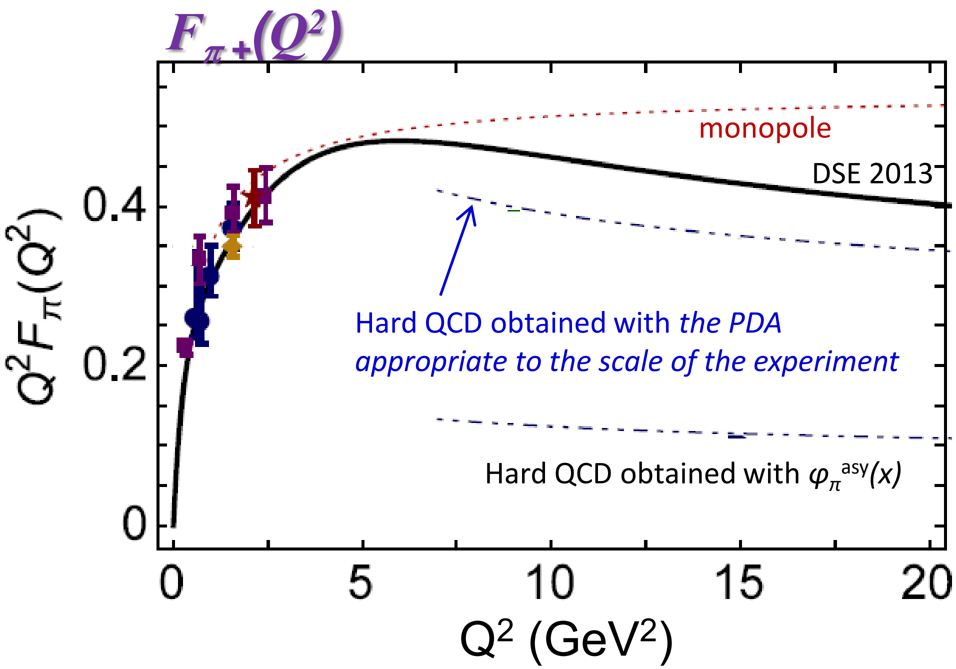


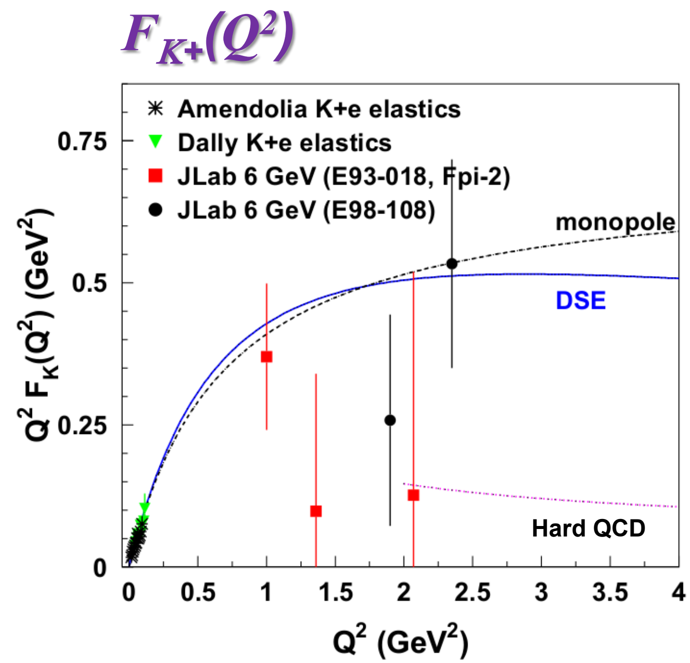
- ❑ F*actor ~3* from hard QCD calculation evaluated with asymptotic valence-quark Distribution Amplitude (DA) *[L. Chang, et al., PRL **111** (2013) 141802; PRL **110** (**2013**) 1322001]*
  - – Trend consistent with time like meson form factor data up to Q^2=18 GeV^2 *[Seth et al, PRL **110** (2013) 022002]*

- ❑ Recent developments: 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

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

$F_{\pi+}(Q^2)$ and $F_{K+}(Q^2)$ in 2018





*[M. Carmignotto et al., Phys. Rev. C97 (**2018**) no.2, 025204]*

*[F. Gao et al., Phys. Rev. D 96 (**2017**) no. 3, 034024]*

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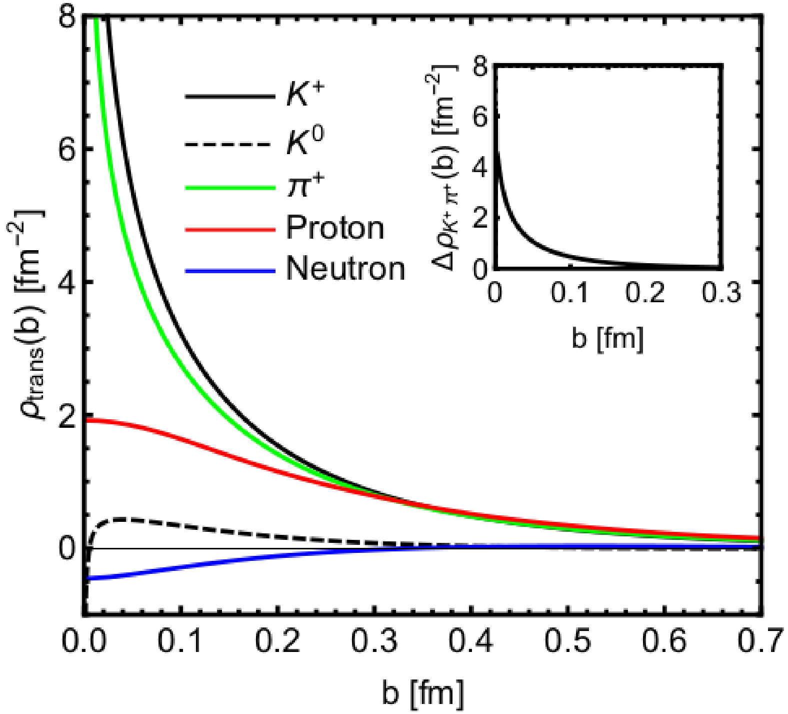
Pion and Kaon transverse Charge Density

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

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

*[N.A. Mecholsky et al., Phys. Rev. C**96** 065207 **(2017)**]*



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

See also talk by J. Miller

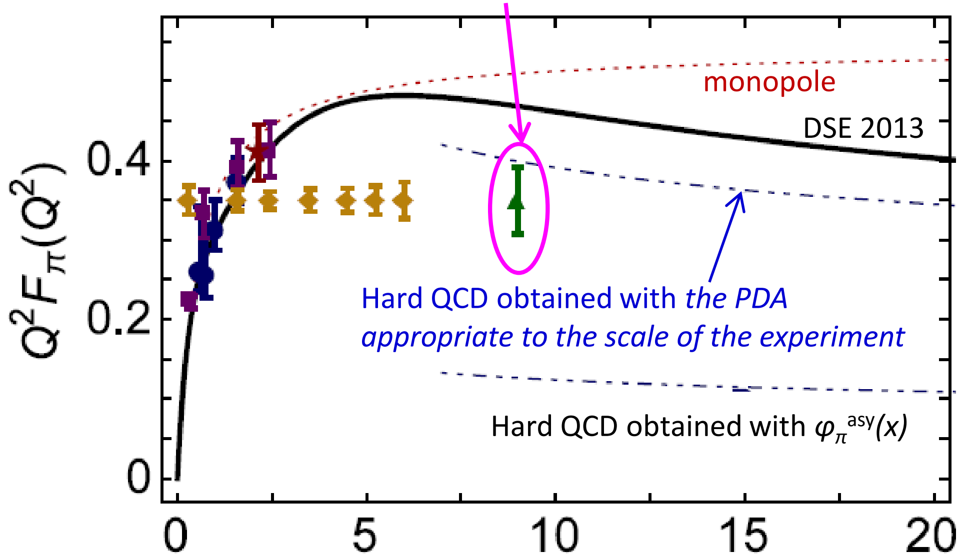
- ❑ Uncertainty in the analysis dominated by incompleteness error
  - ➢ Estimated using the monopole as upper bound and a light front model as lower bound

- ❑ ρ_π and ρ_p coalesce for *0.3 fm < b < 0.6 fm; and so does* ρ_{K^+}
- ❑ It would be interesting to extract the transverse charge density for different flavors

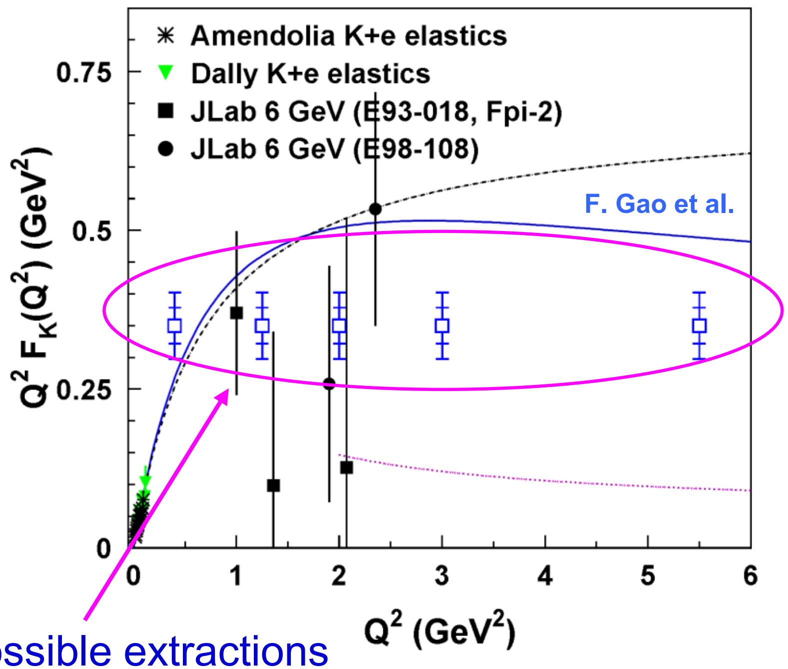
JLab 12 GeV: F_π and F_{K+} Measurements

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

E12-07-105: Q^2=8.5 GeV^2 and t_{min}~0.5 GeV^2



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



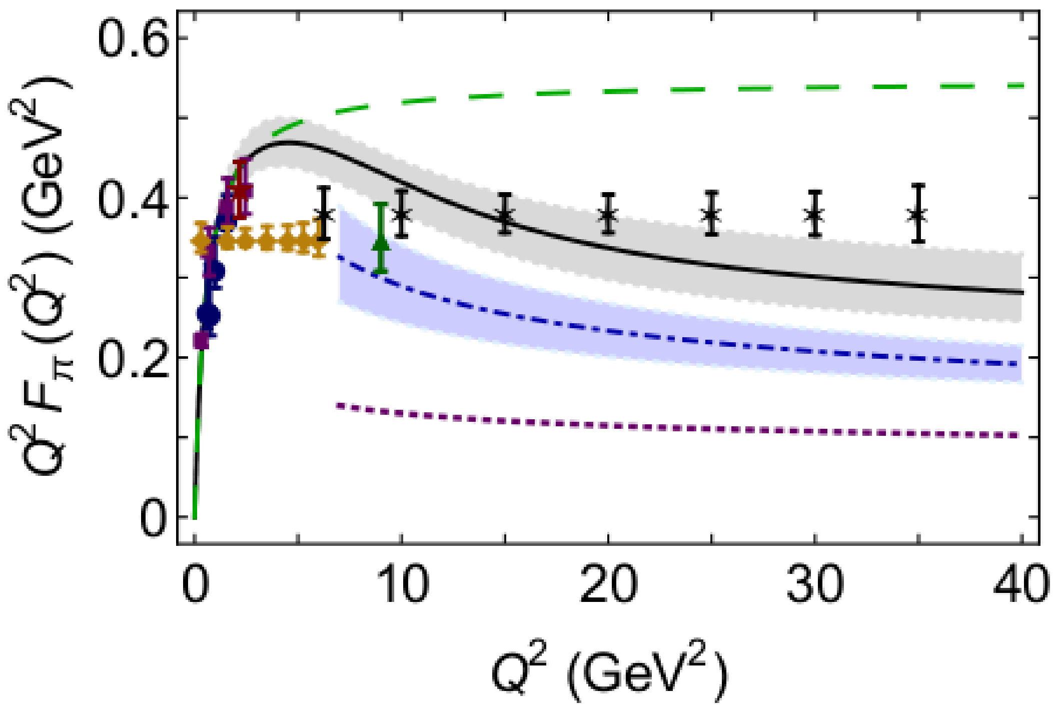
Possible extractions from 2018/19 run

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

EIC: F_π Measurements

1. Regge-based (VR) model shows strong dominance of σ_L at small –t at large Q^2.
2. Assume σ_L dominance
3. Measure the π^-/π^+ ratio to verify – it will be diluted (smaller than unity) if σ_T is not small, or if non-pole backgrounds are large



- 5 GeV(e$^-$) x 100 GeV(p)
- Integrated luminosity: L=20 fb^{-1}/yr
- Identification of exclusive p(e,e'π^+)n events
- 10% exp. syst. unc.
- R=σ_L/σ_T from VR model, and π pole dominance at small t confirmed in ^{2}H π^-/π^+ ratios
- 100% syst. unc. in model subtraction to isolate σ_L

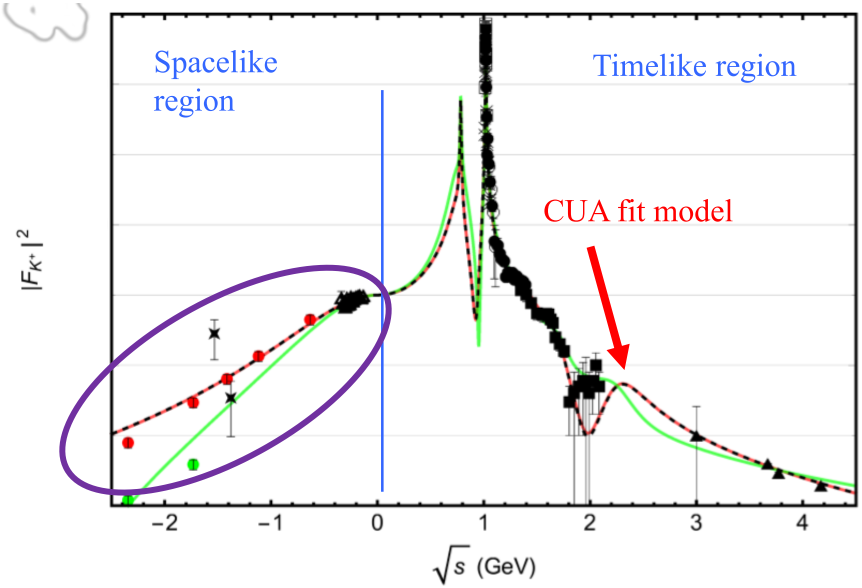
Looks promising for measuring F_π. Can we measure kaon form factor at EIC?

Adapted from Garth Huber slides (PIEIC2018)

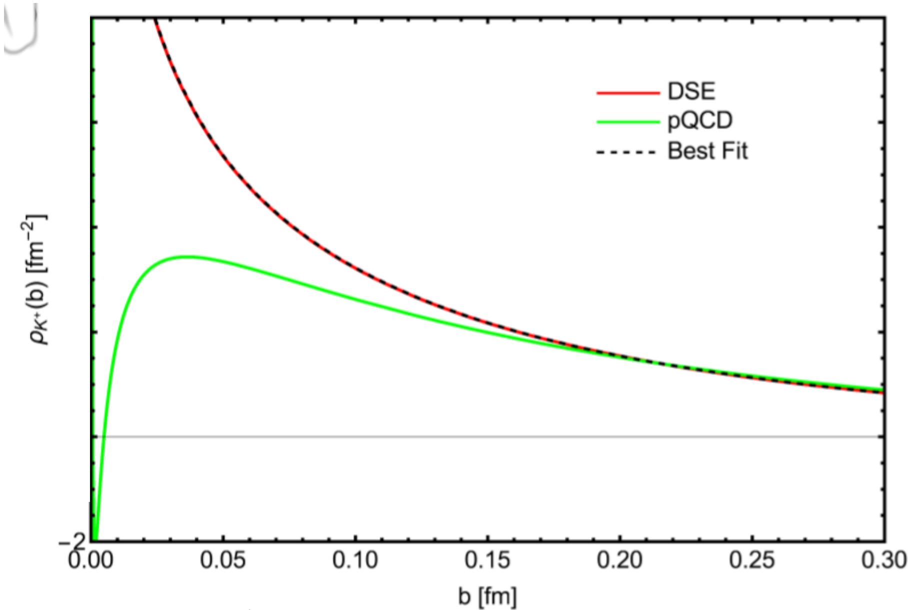
Impact of Future Data

*[N.A. Mecholsky et al., Phys. Rev. C**96** 065207 **(2017)**]*

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



Transverse density assuming very different behavior of the form factor

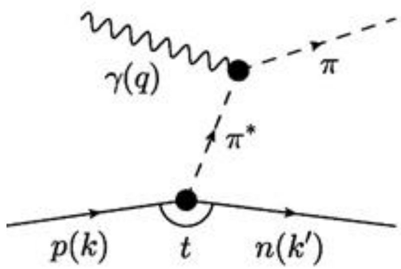


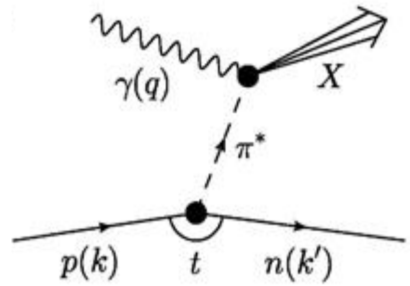
Ongoing: perhaps also interesting to see if any impact of mass-dependence of the meson form factor

*[M. Chen, M Ding, L. Chang, C.D. Roberts, arXiv:1808.09461 **(2018)**]*

Towards the Pion/Kaon Structure Function

- Is there anything besides the meson elastic form factors that can be learned by isolating the One Pion Exchange Contribution?





- Sullivan was the first to consider the "Drell" process, with π+X final states where m_X^2 grows linearly with Q^2

- A simple calculation gives the minimum momentum transfer squared $t_{min} = (q-k)^2_{min} \rightarrow \infty$ as $Q^2 \rightarrow \infty$
  - The requirement of being near the pion pole at $t = m_\pi^2$ can never be satisfied and processes of this type play no role in the scaling region

- Similar consideration for offshellness as for meson FF – a well-constrained experimental analysis should be reliable in regions of -t

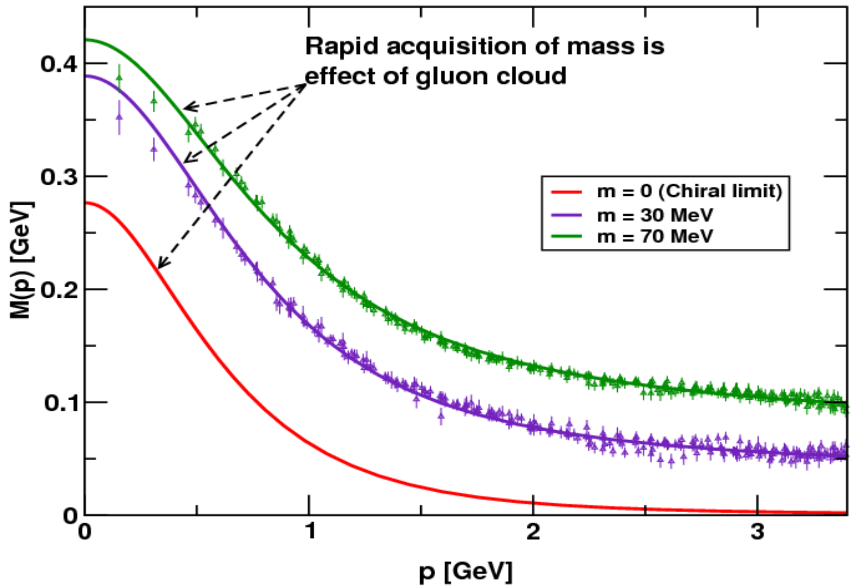
The role of gluons in pions

Pion mass is enigma – cannibalistic gluons vs massless Goldstone bosons

$$f_\pi E_\pi(p^2) = B(p^2)$$

Adapted from Craig Roberts:

- The most fundamental expression of Goldstone's Theorem and DCSB in the SM
- Pion exists if, and only if, mass is dynamically generated – "because of B, there is a pion"
- On the other hand, in absence of the Higgs mechanism, the pion mass $m_\pi = 0$ – the pion mass^2 is entirely driven by the current quark mass (for reference, for the ρ, only 6% of its mass^2 is driven by this).



Rapid acquisition of mass is effect of gluon interactions

What is the impact of this for gluon parton distributions in pions vs nucleons? One would anticipate a different mass budget for the pion and the proton

The role of gluons in the chiral limit

In the chiral limit, using a parton model basis: *the entirety of the proton mass is produced by gluons and due to the trace anomaly*

$$\langle P(p)|\Theta_0|P(p)\rangle = -p_\mu p_\mu = m_N^2$$

In the chiral limit, for the pion ($m_\pi = 0$):

$$\langle \pi(q)|\Theta_0|\pi(q)\rangle = -q_\mu q_\mu = m_\pi^2 = 0$$

Sometimes interpreted as: *in the chiral limit the gluons disappear and thus contribute nothing to the pion mass*.

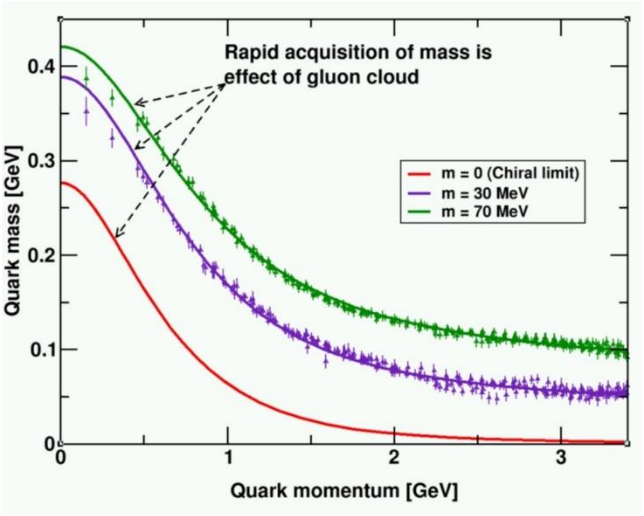
This is unlikely as quarks and gluons still dynamically acquire mass – this is a universal feature in hadrons – so more likely a cancellation of terms leads to “0”

Nonetheless: are there gluons at large Q^2 in the pion or not?

The Incomplete Hadron: Mass Puzzle

"Mass without mass!"

Bhagwat & Tandy/Roberts et al



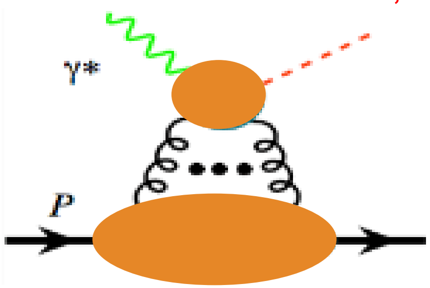
Proton: Mass ~ 940 MeV
preliminary LQCD results on mass budget,
or view as mass acquisition by DχSB

Kaon: Mass ~ 490 MeV
at a given scale, less gluons than in pion

Pion: Mass ~ 140 MeV
mass enigma – gluons vs Goldstone boson

- **EIC expected contributions in:**
  - ✧ trace anomaly:

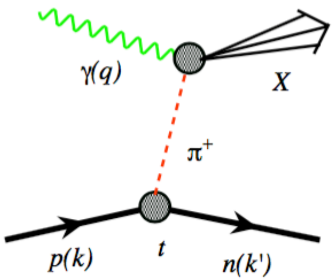
Upsilon production near the threshold



- **EIC's expected contribution in:**
  - ✧ Quark-gluon energy:
    ∝ *quark-gluon momentum fractions*

In π, K and N with DIS and SIDIS

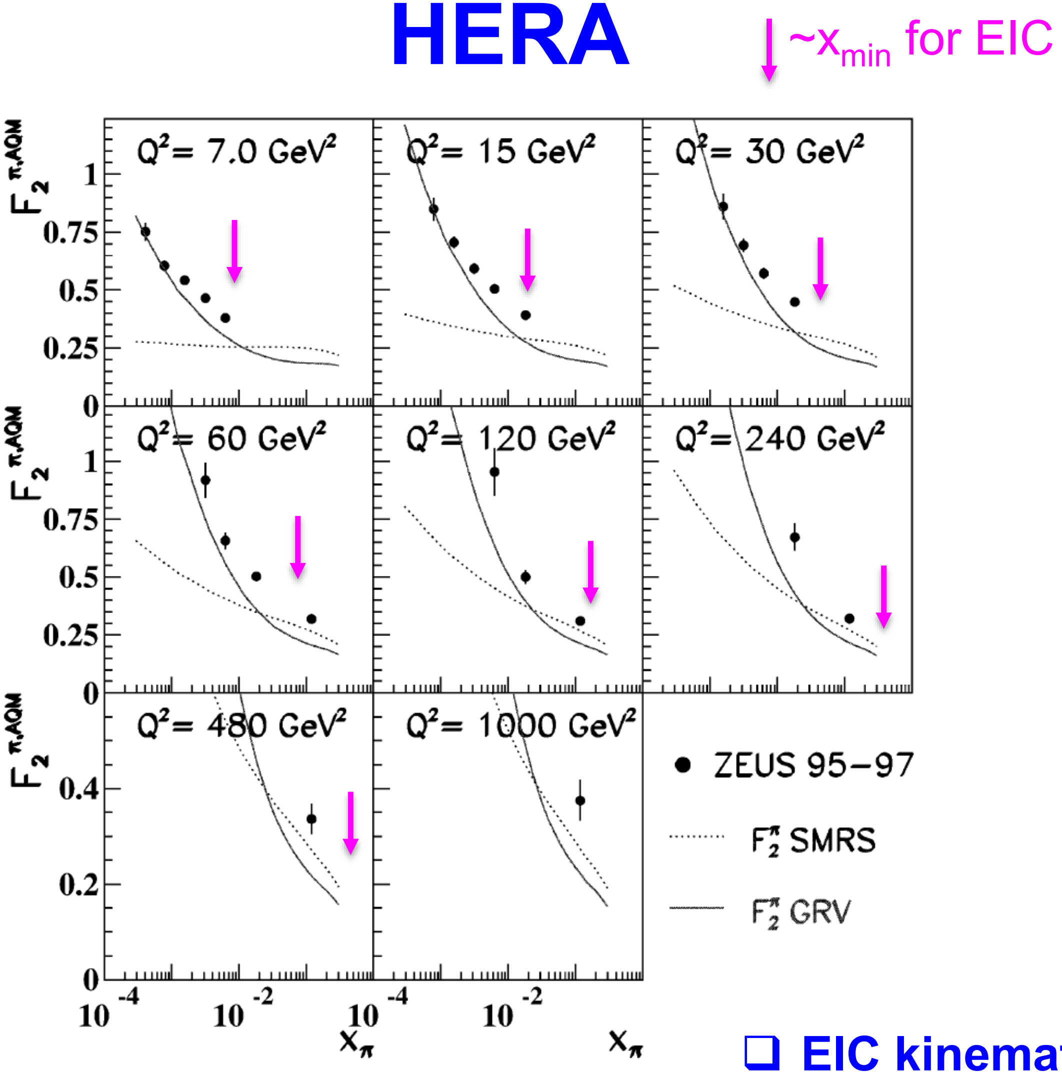
In π and K with Sullivan process



See talk by J. Qiu

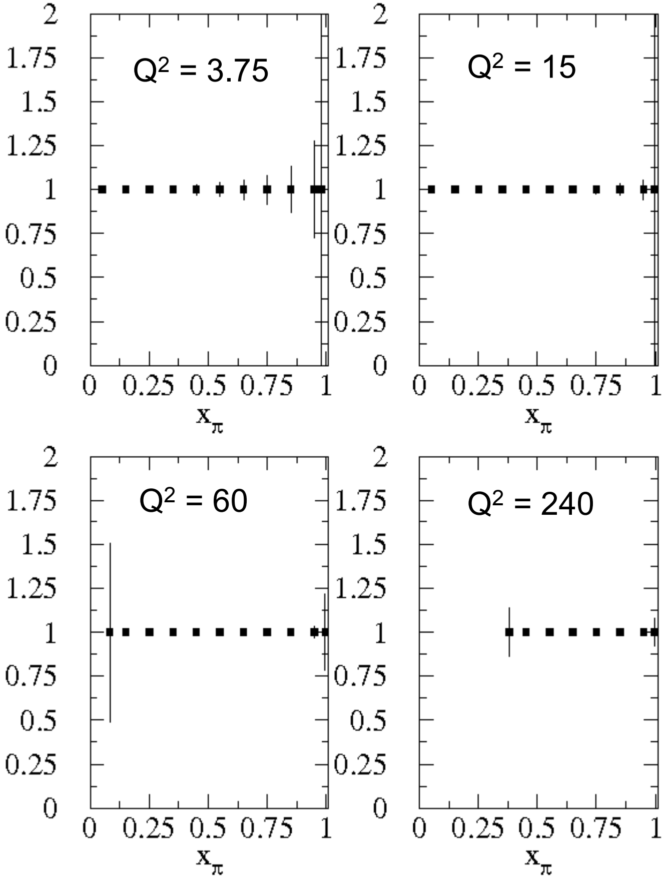
World Data on pion structure function F_2^π

HERA



EIC

Here example for 5 GeV e⁻ and 50 GeV p

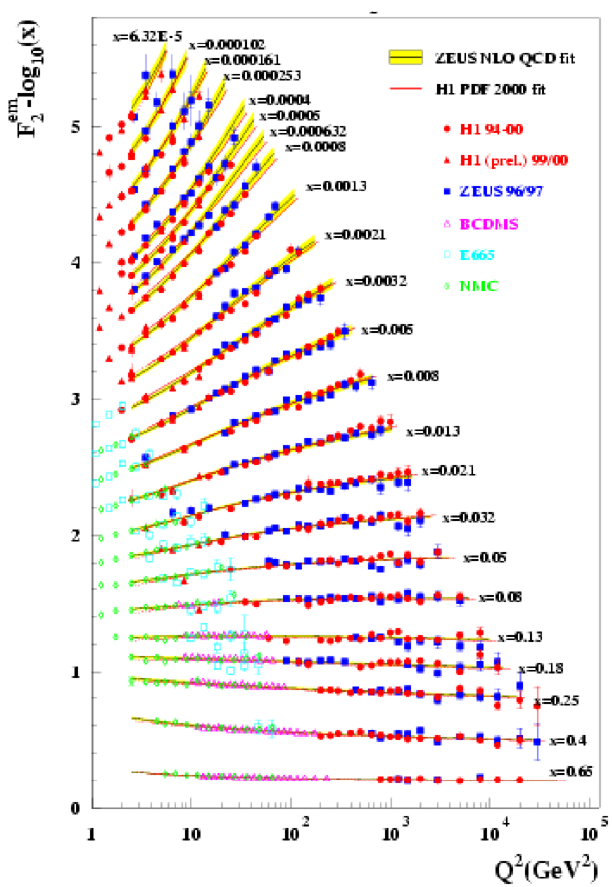


- EIC kinematic reach down to a x = few 10^{-3}
- Lowest x constrained by HERA

Landscape for p, π, K structure function after EIC

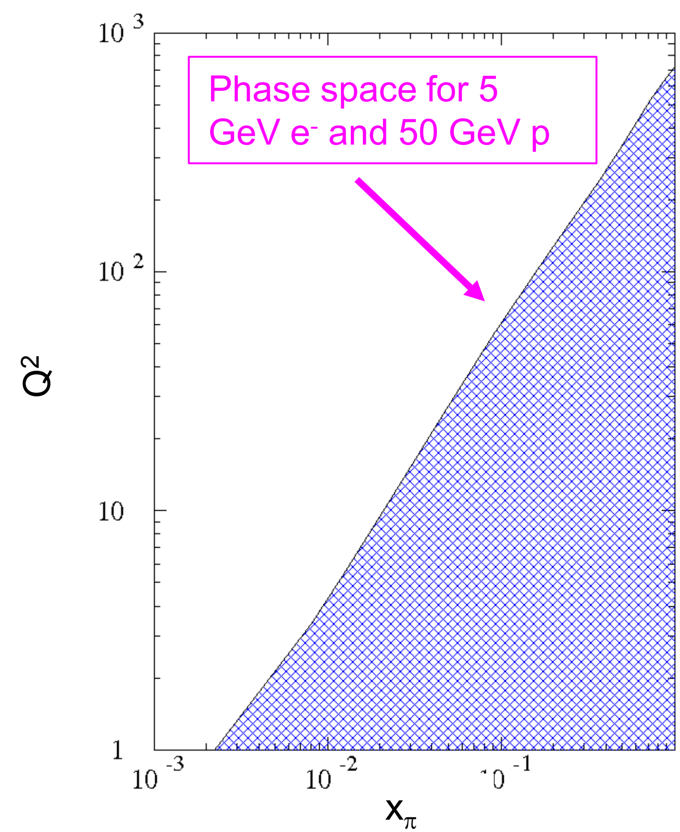
Proton: much existing from HERA

EIC will add:
- Better constraints at large-x
- Precise F_2^n neutron SF data



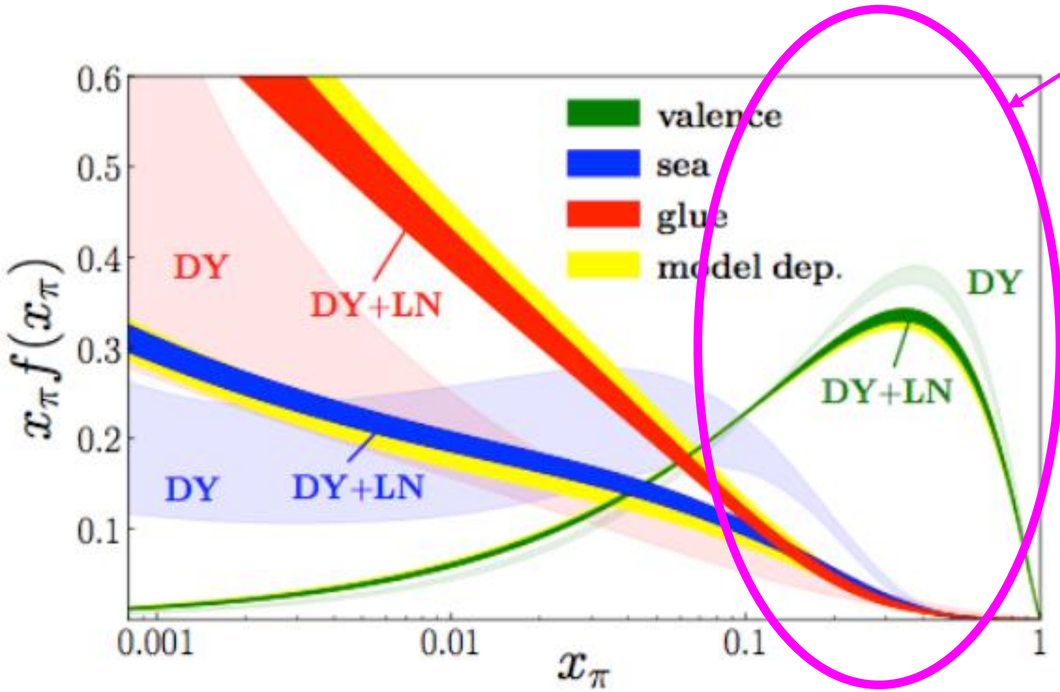
Pion and kaon: only limited data from:
- Pion and kaon Drell-Yan experiments
- Some pion SF data from HERA

EIC will add large (x,Q^2) landscape for both pion and kaon!



Pion and Kaon Structure Functions

- First MC global QCD analysis of pion PDFs
  - Using Fermilab DY and HERA Leading Neutron data



- JLab 12 GeV: Tagged Pion and Kaon TDIS
- Also prospects for kaon DY at COMPASS and pion and kaon LN at EIC

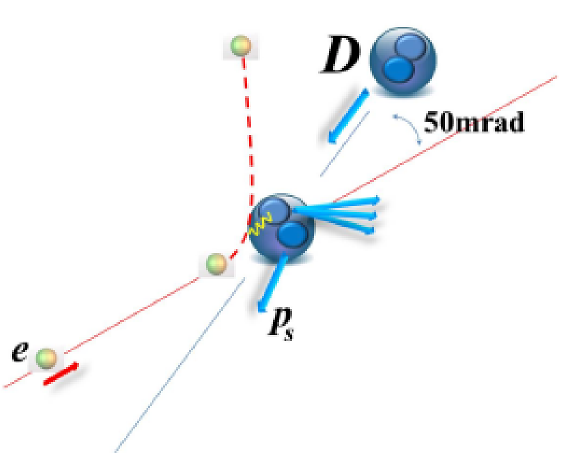
DY = πN Drell-Yan

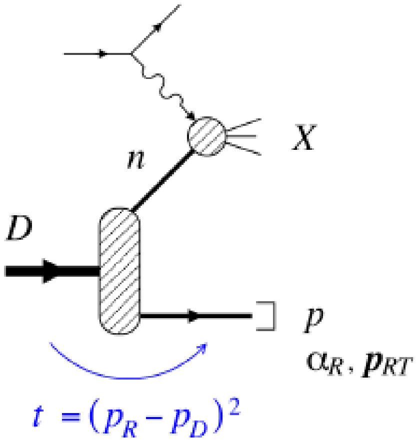
LN = Leading Neutron

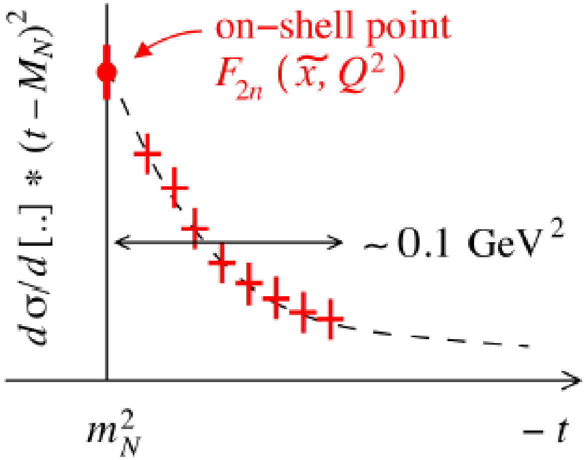
[Barry, Sato, Melnitchouk, Ji (2018, arXiv:1804.01965)]

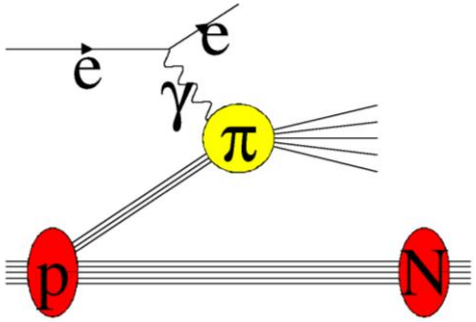
- Significant reduction of uncertainties on sea quark and gluon distributions in the pion with inclusion of HERA leading neutron data
- Implications for "TDIS" (Tagged DIS) experiments at JLab

Pion and Kaon Structure Functions at EIC – Versatility is Key







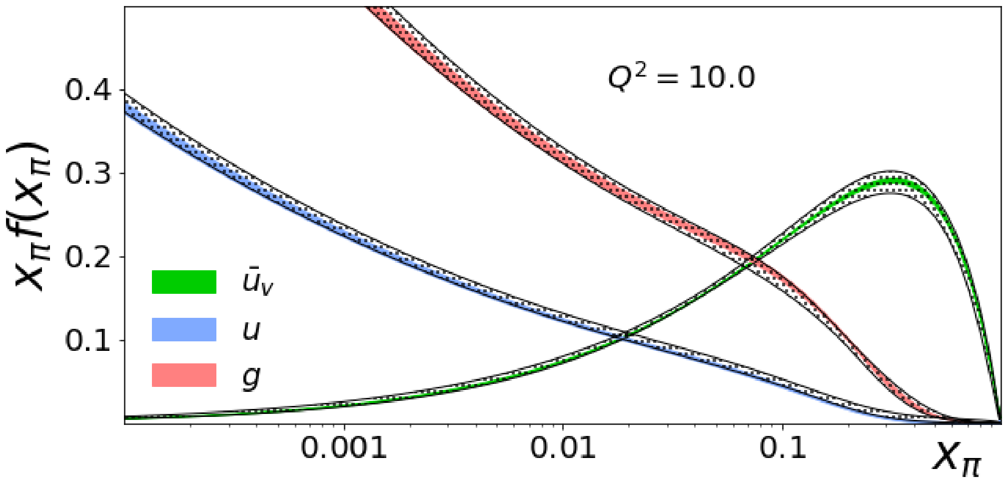


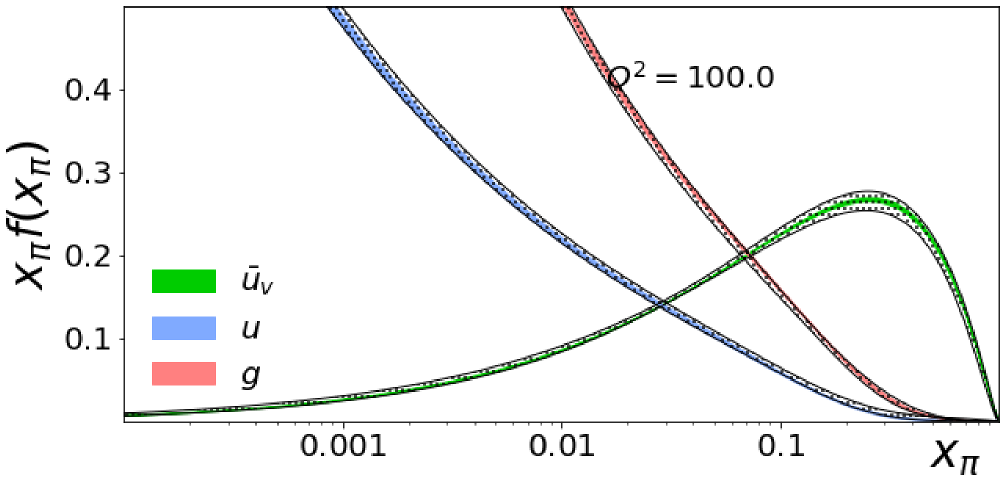
- Obtain F_2^n by tagging spectator proton from e-d, and extrapolate to on-shell neutron to correct for binding and motion effects.
- Obtain F_2^π and F_2^K by Sullivan process and extrapolate the measured t-dependence as compared to DSE-based models.

Need excellent detection capabilities, and good resolution in –t

Global Fits with Existing Data and EIC Projections

- ❑ 5 GeV(e$^-$) x 100 GeV(p)
- ❑ 0.1 < y < 0.8
- ❑ EIC pseudodata fitted with existing data
- ❑ Work ongoing:
  - Why did the curves shift?
  - The pion D-Y data, even if not many, already do constrain the curves surprisingly well – due to the various sum rules?
  - Curves to improve with the EIC projections, especially for kaon as will have similar-quality data.





Precision gluon constraints of pion and kaon pdfs are possible.

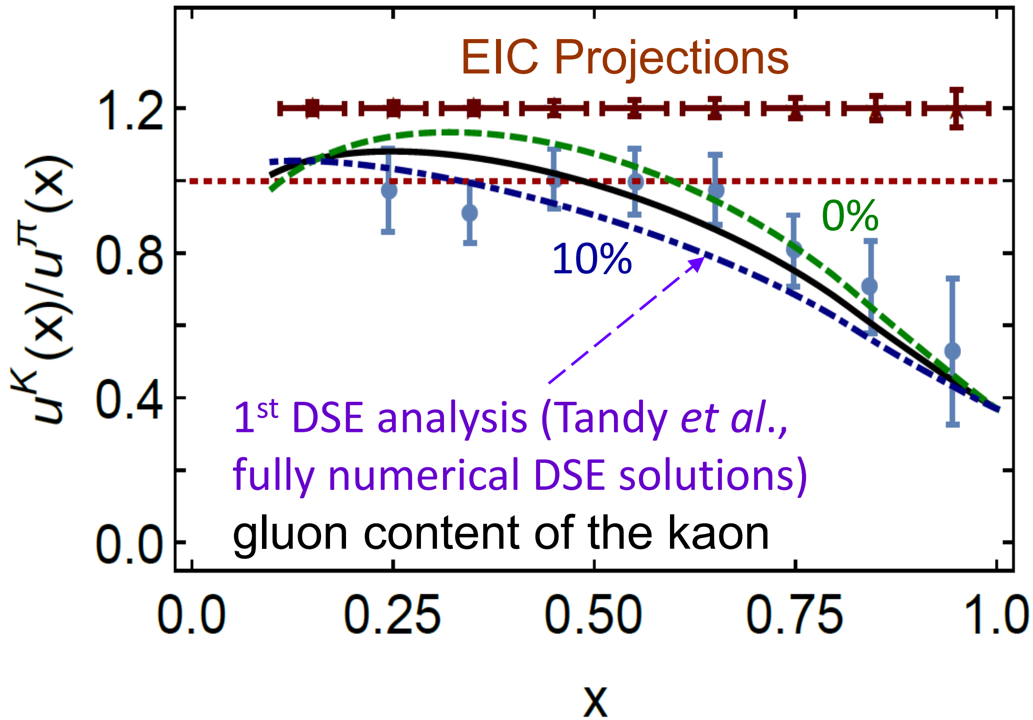
R. Trotta, V. Berdnikov, N. Mecholsky, T. Horn, I. Pegg, N. Sato et al., 2018+

Kaon structure functions – gluon pdfs

Based on Lattice QCD calculations and DSE calculations:

- ❑ Valence quarks carry some 52% of the pion's momentum at the light front, at the scale used for Lattice QCD calculations, or ~65% at the perturbative hadronic scale
- ❑ At the same scale, valence-quarks carry ⅔ of the kaon's light-front momentum, or roughly 95% at the perturbative hadronic scale

Projections: T. Horn, R. Ent, C. Roberts, R. Yoshida et al., 2018+



Thus, at a given scale, there is far **less glue in the kaon than in the pion**:

- heavier quarks radiate less readily than lighter quarks
- heavier quarks radiate softer gluons than do lighter quarks
- Landau-Pomeranchuk effect: softer gluons have longer wavelength and multiple scatterings are suppressed by interference.
- Momentum conservation communicates these effects to the kaon's u-quark.

Exploring the 3D Nucleon/Meson Structure

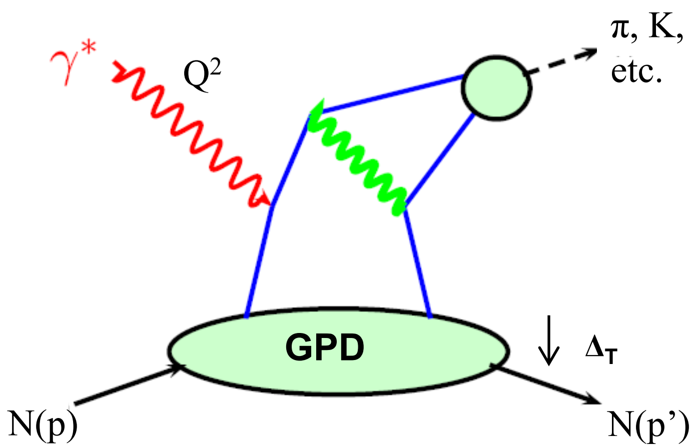
- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction (x_{Bj}) picture of the nucleon.
  - High luminosity, large acceptance experiments with polarized beams and targets.
  - Theoretical description of the nucleon in terms of a 5D Wigner distribution that can be used to encode both 3D momentum and transverse spatial distributions.

- Deep Exclusive Scattering (DES) cross sections give sensitivity to electron-quark scattering off quarks with longitudinal momentum fraction (Bjorken) x at a transverse location b.

- Semi-Inclusive Deep Inelastic Scattering (SIDIS) cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum (k_T) of a parton and transverse momentum (p_T) created during the [parton → hadron] fragmentation process.

Towards GPD flavor decomposition: DVMP

- Relative contribution of σ_L and σ_T to cross section are of great interest for nucleon structure studies



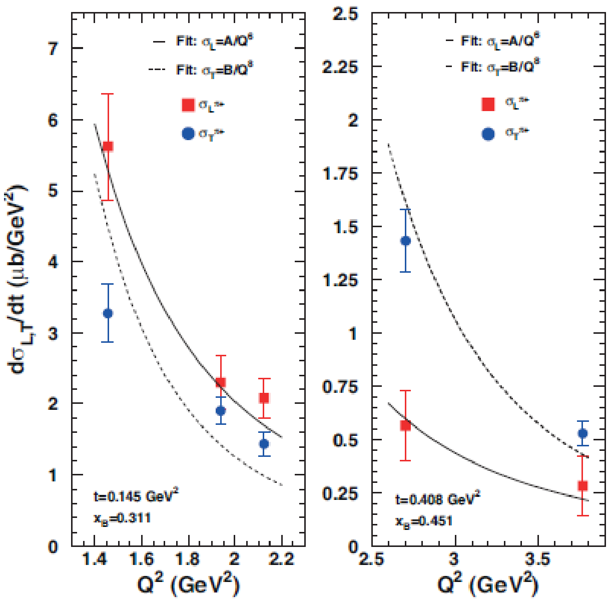
- described by 4 (helicity non-flip) GPDs:
  - *H, E* (unpolarized), $\tilde{H}, \tilde{E}$ (polarized)
- Quantum numbers in DVMP probe individual GPD components selectively
  - Vector : ρ^o/ρ+/*K** select *H, E*
  - Pseudoscalar: π,η,*K* select the polarized GPDs, $\tilde{H}$ and $\tilde{E}$
- Reaction mechanism can be verified experimentally - **L/T separated cross sections to test QCD Factorization**

- Recent calculations suggest that leading-twist behavior for light mesons may be reached at Q^2=5-10 GeV^2
- JLab 12 GeV can provide experimental confirmation in the few GeV regime

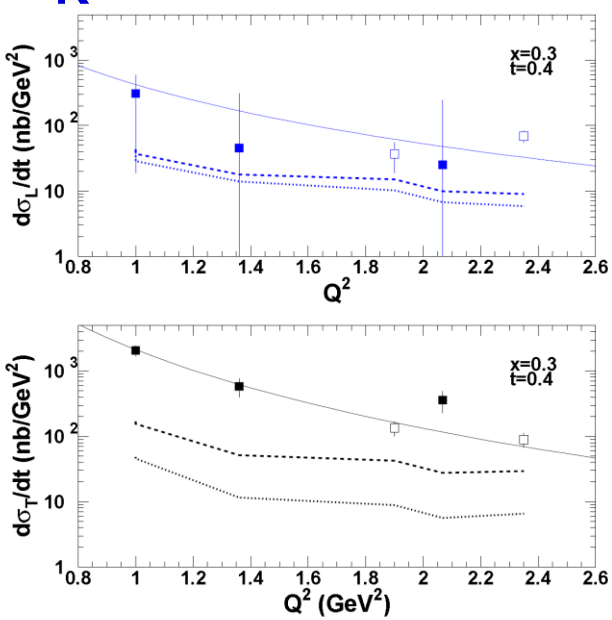
Results from 6 GeV JLab

- Data demonstrate the technique of measuring the Q^2 dependence of L/T separated cross sections at fixed x/t to test QCD Factorization
  - Consistent with expected factorization, but small lever arm and relatively large uncertainties
  - GPD models cannot reproduce ρ^0 data at small W

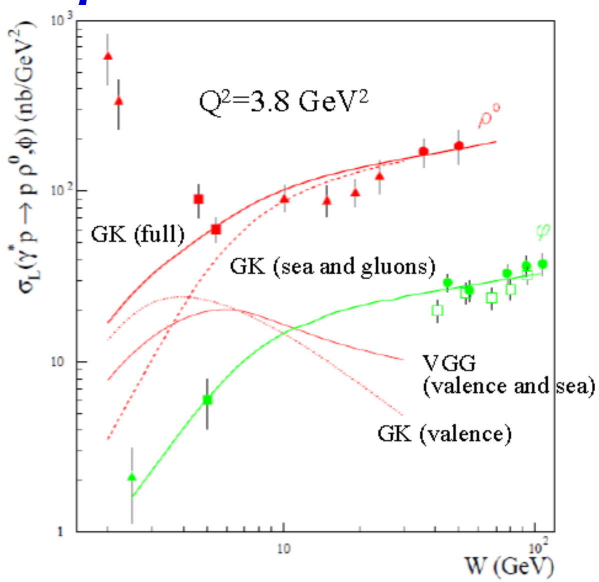
π^+ *[T. Horn et al., Phys. Rev. C **78**, 058201 **(2008)**]*



K+ *[M. Carmignotto et al., Phys. Rev. C97 (2018) no.2, 025204]*



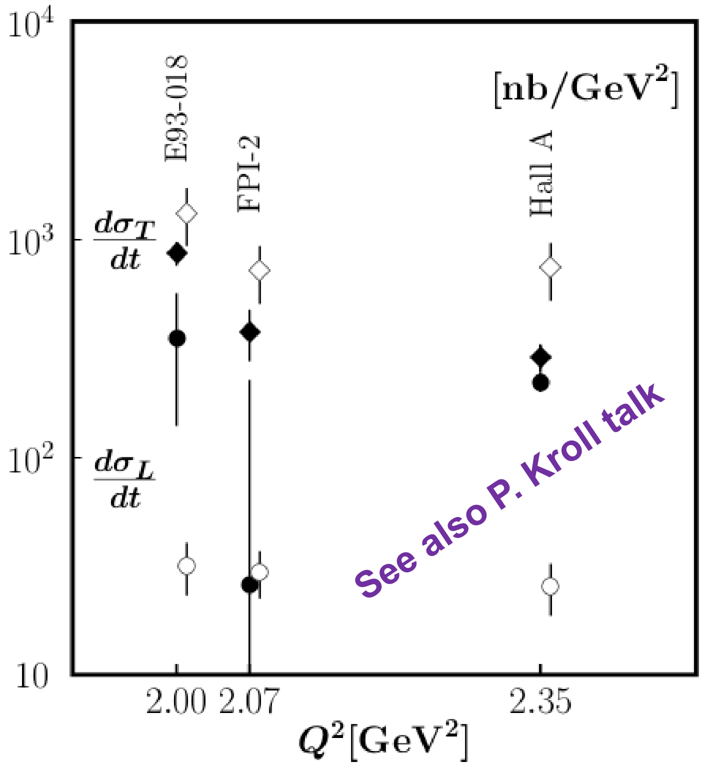
ρ^0



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

Results from 6 GeV JLab

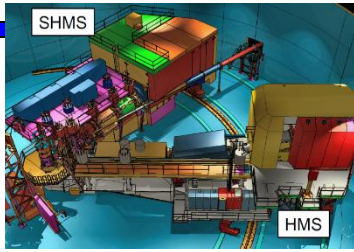
Here, compare with P. Kroll's GPD model (circles=σ_L, diamonds=σ_T)



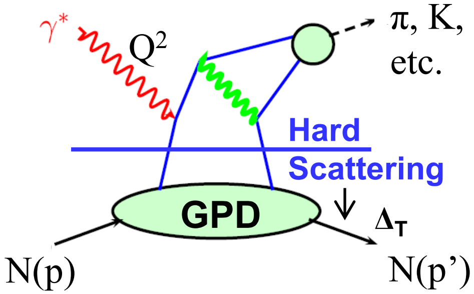
- Solid symbols are data
  - σ_L is comparable to σ_T at Q^2=2.4 GeV^2
- Open symbols model calculations
  - Model overpredicts σ_T
  - Model underpredicts σ_L

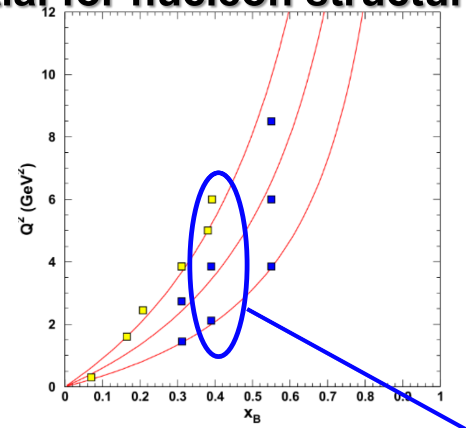
- Separated cross section data over a large range in Q^2 are essential for:
  - Testing factorization and understanding dynamical effects in both Q^2 and –t kinematics
  - Interpretation of non-perturbative contributions in experimentally accessible kinematics

Setting the stage for EIC – pion production

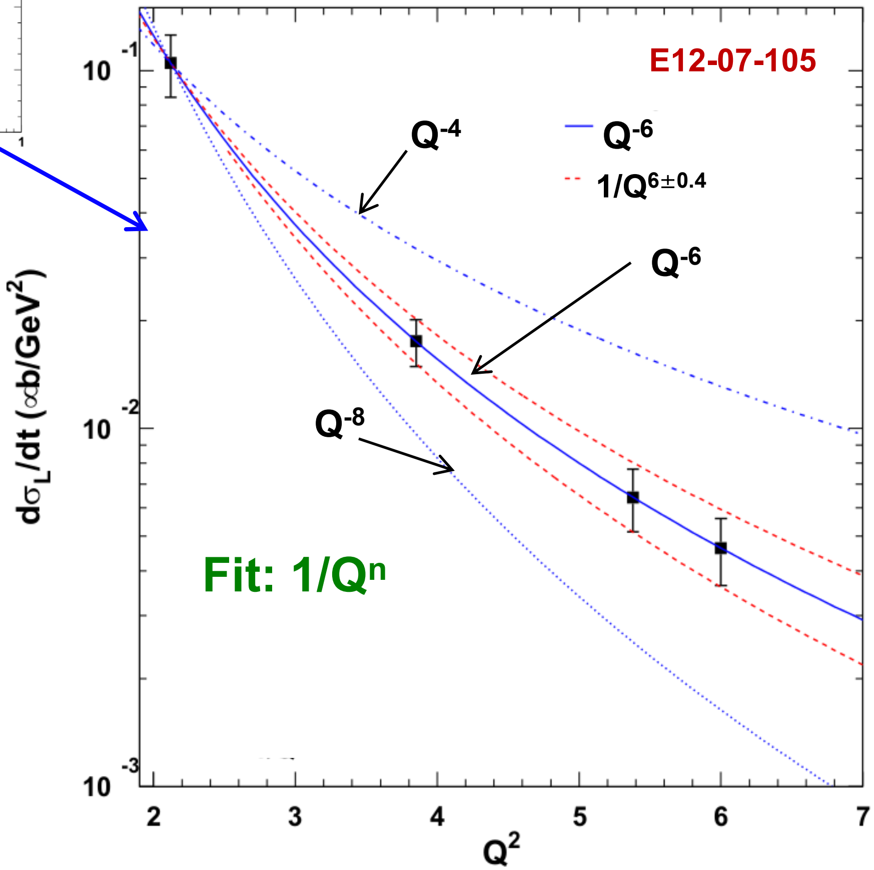


JLab12: confirming potential for nucleon structure studies





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

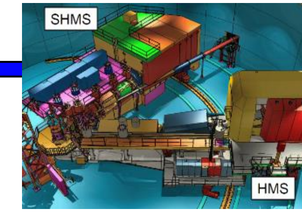


- **E12-07-105 (P12):** Measure the Q^2 dependence of the π electro production cross section at fixed x and -t
  - Factorisation theorem predicts σ_L scales to leading order as Q^{-6}

x	Q^2 (GeV^2)	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 2020+**

Setting the stage for EIC – kaon production



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

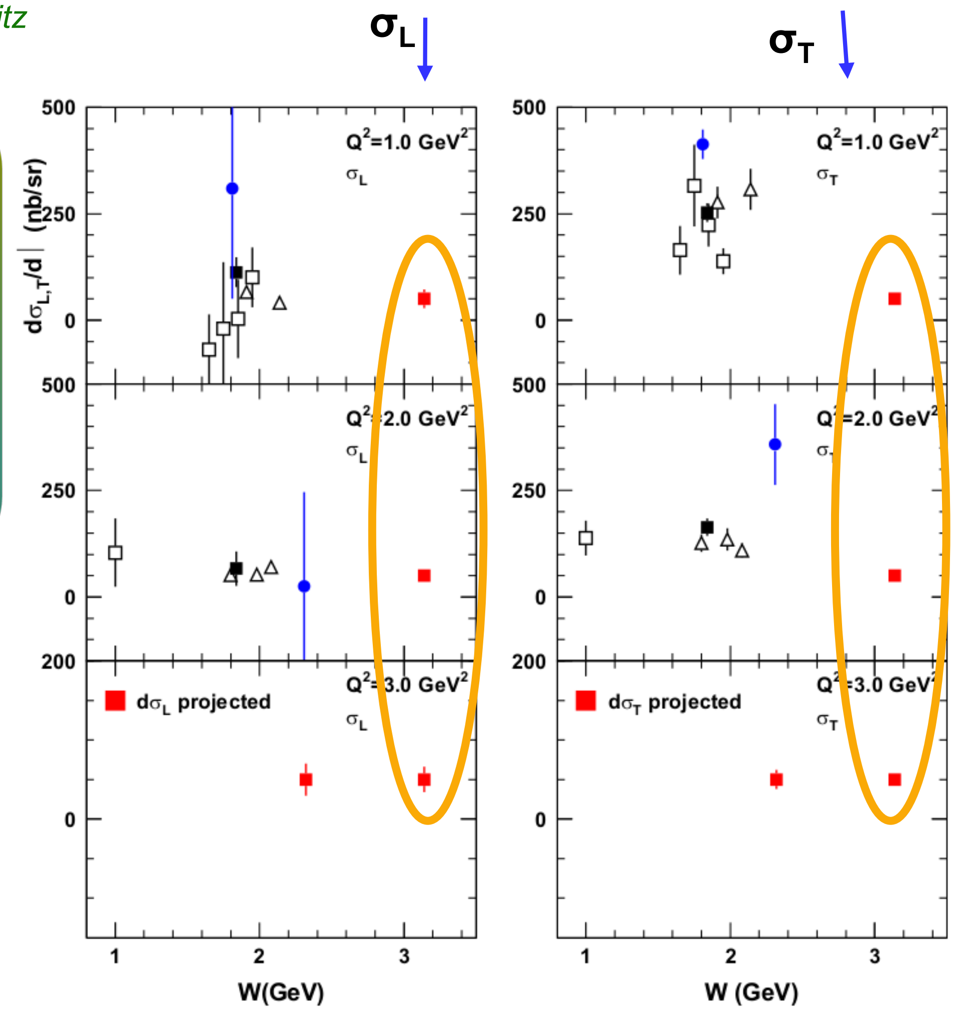
E12-09-011 spokespersons: T. Horn, G. Huber, P. Markowitz

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

Now running in Hall C at Jlab (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

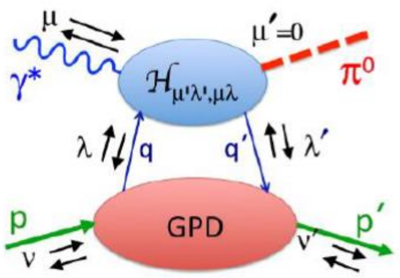


[blue points from M. Carmignotto, PhD thesis (2017)]

Transverse Contributions may allow for probing a new set of GPDs

See also P. Kroll's talk

- ❑ 4 Chiral-odd GPDs (parton helicity flip)



$$\widetilde{H}^{\pi} = \frac{1}{3\sqrt{2}}\left[2\widetilde{H}^{u} + \widetilde{H}^{d}\right]$$

- ❑ A large transverse cross section in meson production may allow for accessing helicity flip GPDs

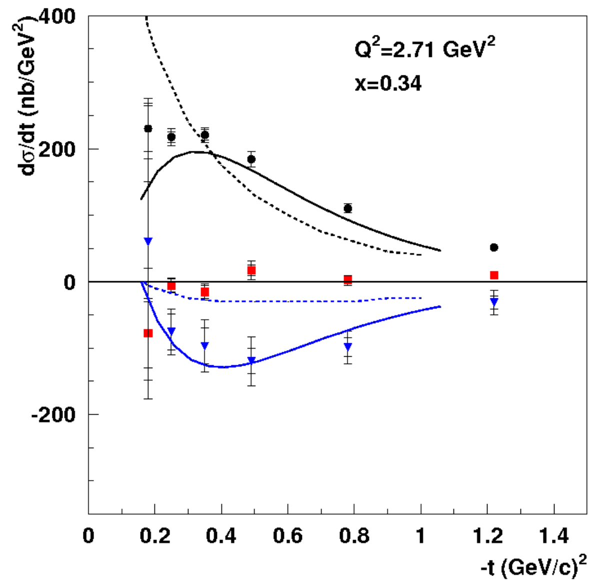
$$\sigma_T = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}\left[(1-\xi^2)|<HT>|^2 - \frac{t'}{8m^2}|<\overline{E}_T>|^2\right]$$

  - ➢ Model predictions based on handbag in good agreement with 6 GeV data

    *[Goloskokov, Kroll, EPJ C65, 137 (2010); EPJ A**45**, 112 (**2011**)]*

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

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

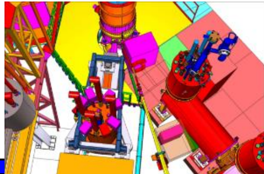


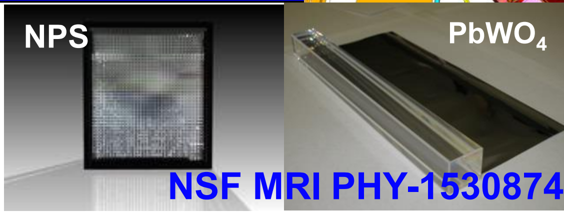
*[Favart, Guidal, Horn, Kroll , EPJA (**2016**)]*

*[Bedlinskiy et al. PRL 109 (**2012**) 112001]*

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

Setting the stage for EIC – π^0 production

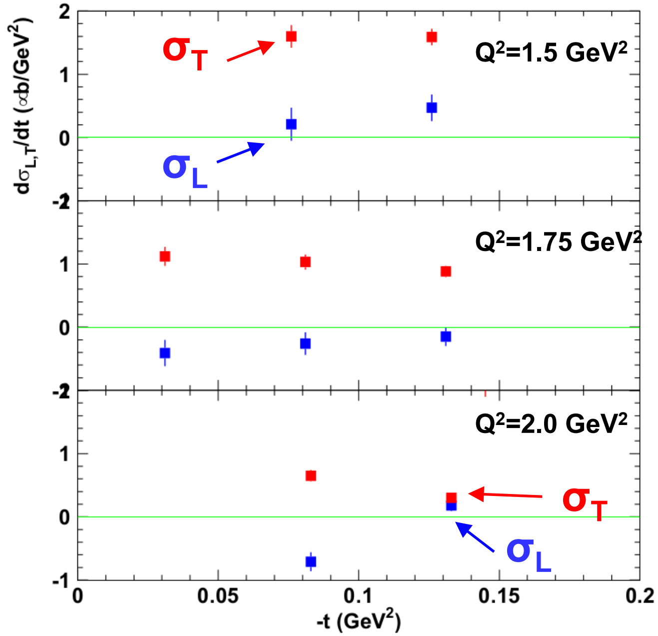




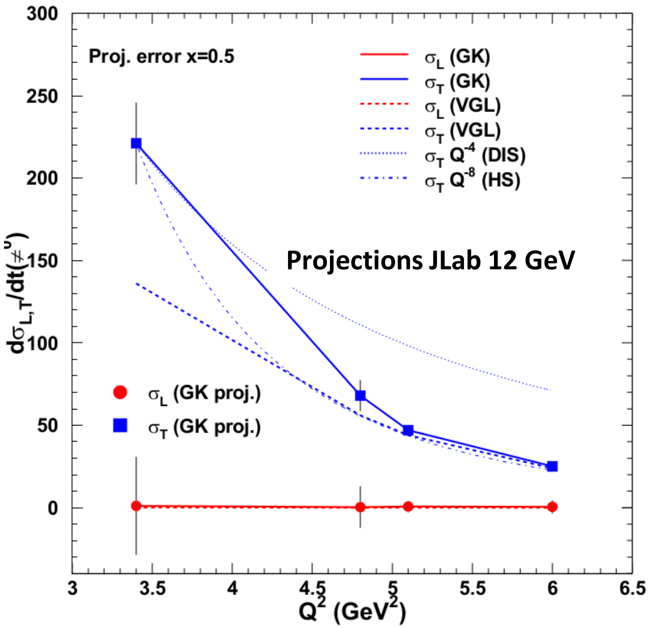
Neutral Particle Spectrometer currently under construction

- Relative L/T contribution to π^0 cross section important in probing transversity – verify reaction mechanism
  - If σ_T large: access to transversity GPDs

- Results from Hall A suggest that σ_L 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



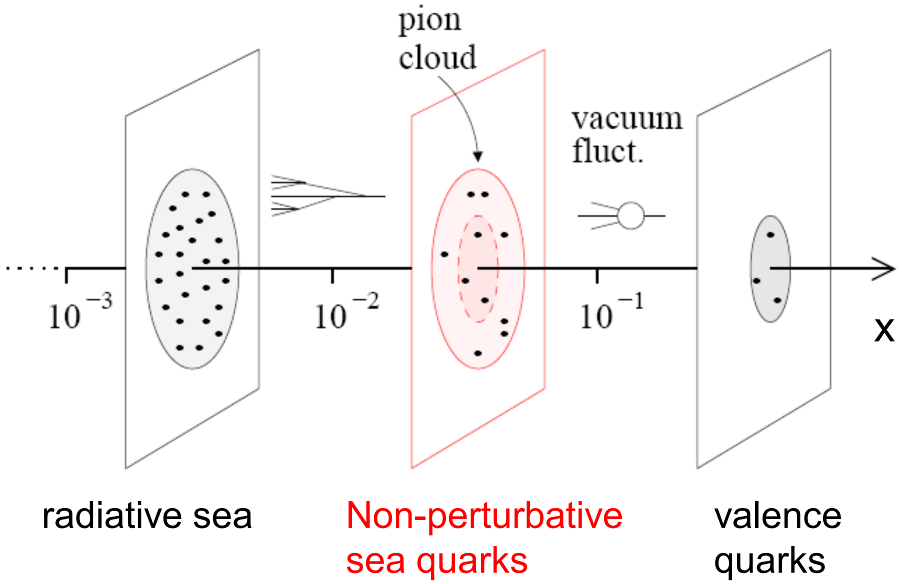
JLab 12 GeV projections

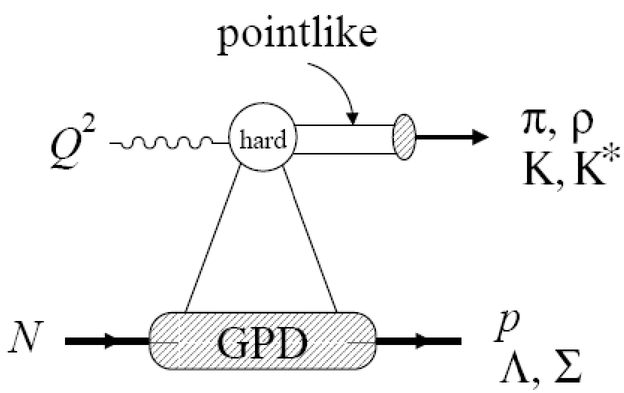


*M. Defurne et al, PRL **117** (**2016**) no.26, 262001*

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

EIC: Quark Imaging through Meson Production





- Physics interest
  - Transverse imaging of nonperturbative sea quarks and gluons
  - Information about meson wave function: spin/flavor structure
- Mesons select definite charge, spin, flavor component of GPD

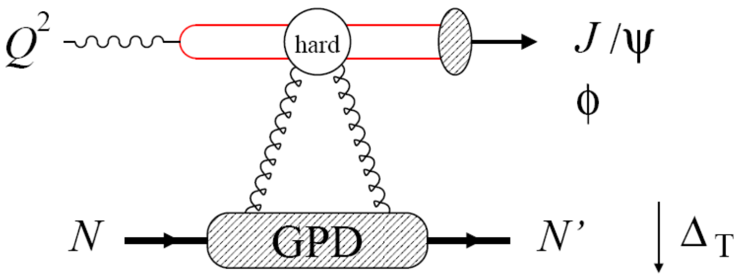
$J/\psi, \phi$	gluon
ρ^0	gluon + singlet q
ρ^+, K^*	non-singlet q
π, K, η	non-singlet Δq

- Exclusive meson production

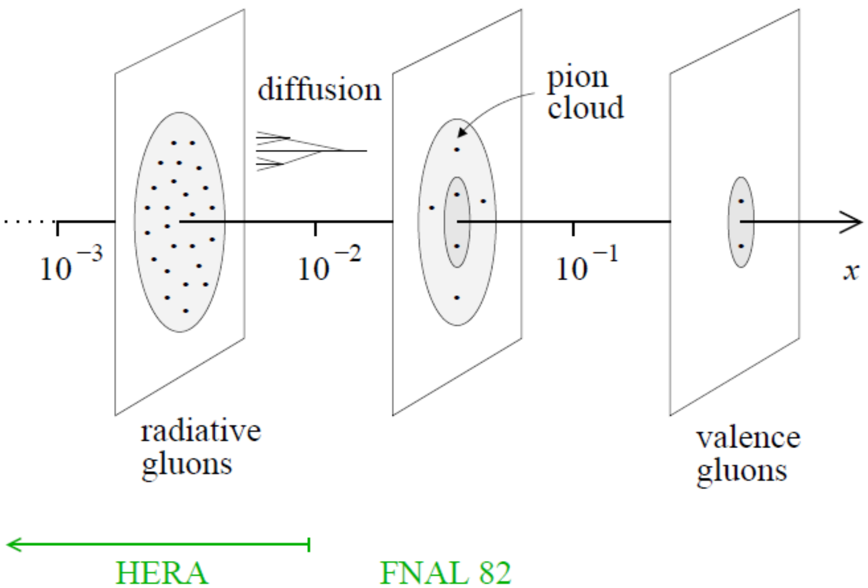
$$\gamma^* N \longrightarrow M + B$$

  - Requires Q^2~10GeV^2 for dominance of "pointlike" configurations $\rightarrow$ pQCD

EIC: Gluon Imaging with J/Ψ

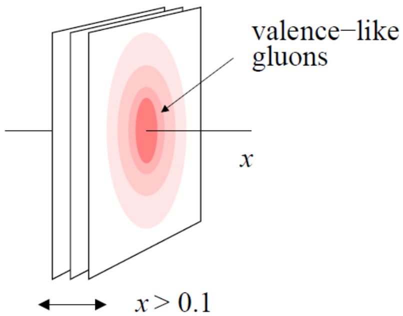


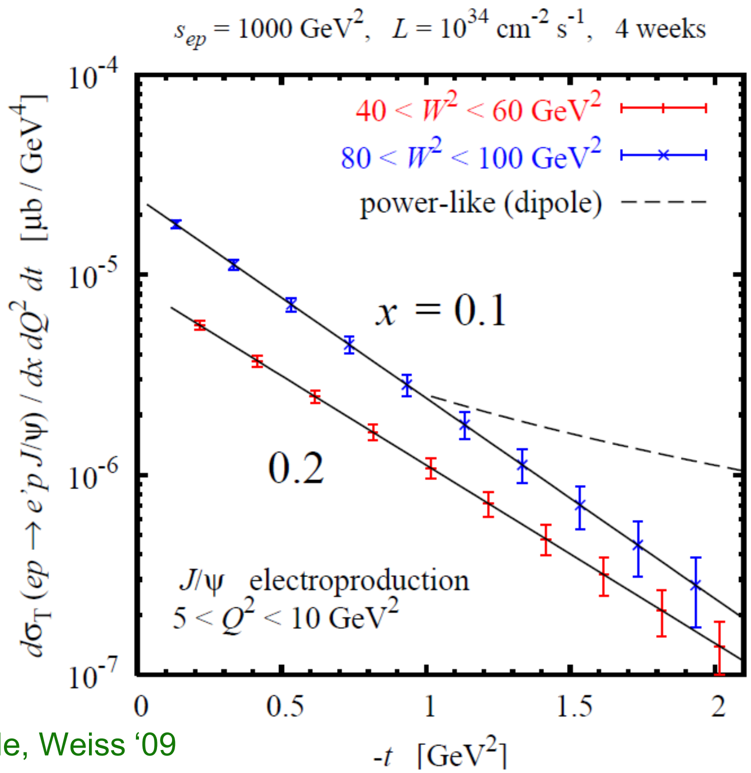
- Transverse spatial distributions from exclusive J/ψ, and φ at Q^2>10 GeV^2
  - Transverse distribution directly from Δ_T dependence
  - Reaction mechanism, QCD description studied at HERA



- Physics interest
  - Valence gluons, dynamical origin
  - Chiral dynamics at *b~1/M*$_\pi$
    [Strikman, Weiss 03/09, Miller 07]
  - Diffusion in QCD radiation
- Existing data
  - Transverse area x<0.01 *[HERA]*
  - Larger x poorly known *[FNAL]*

Gluon Imaging: Valence Gluons





Hyde, Weiss '09

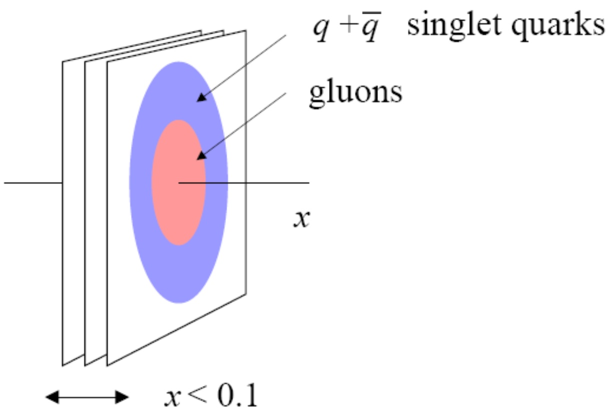
- Transverse imaging of valence gluons through exclusive J/ψ, φ

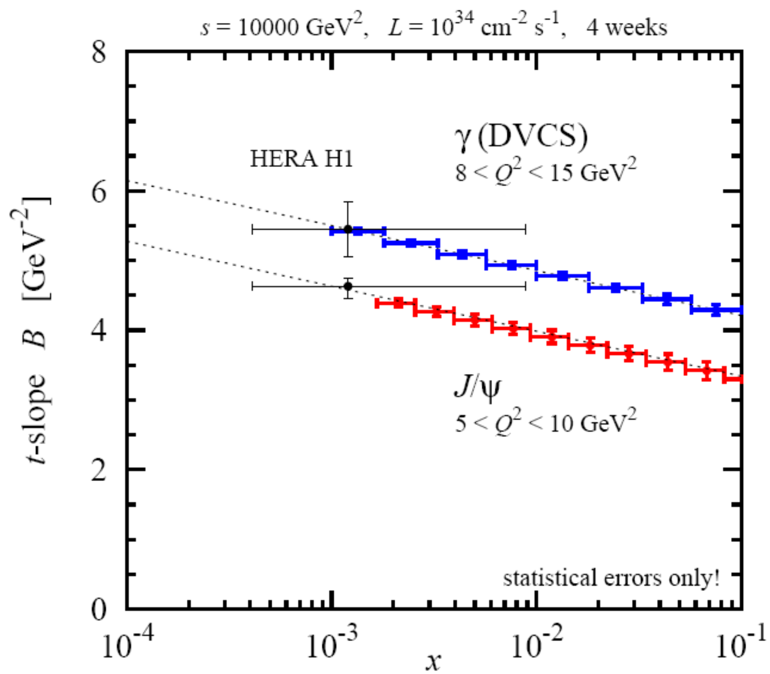
- Imaging requires
  - Full t-distribution for Fourier transform
  - Non-exponential? Power-like at $|t|>1$ GeV^2?
  - Electroproduction with $Q^2>10$ GeV^2: test reaction mechanism, compare different channels, control systematics

- Experimentally need:
  - Recoil detection for exclusivity, wide coverage in t with high resolution
  - Luminosity ~ 10^{34}, electroproduction, high-t

First gluon images of the nucleon at large x!

Gluon imaging: gluon vs. singlet quark size





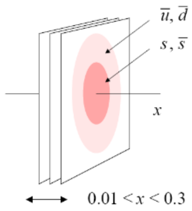
Sandacz, Hyde, Weiss

- Do singlet quarks and gluons have the same transverse distribution?
  - Hints from HERA: $Area(q+\bar{q}) > Area(g)$
  - Dynamical models predict difference: pion cloud, constituent quark picture *[Strikman, Weiss 09]*
  - No difference assumed in present pp MC generators for LHC!

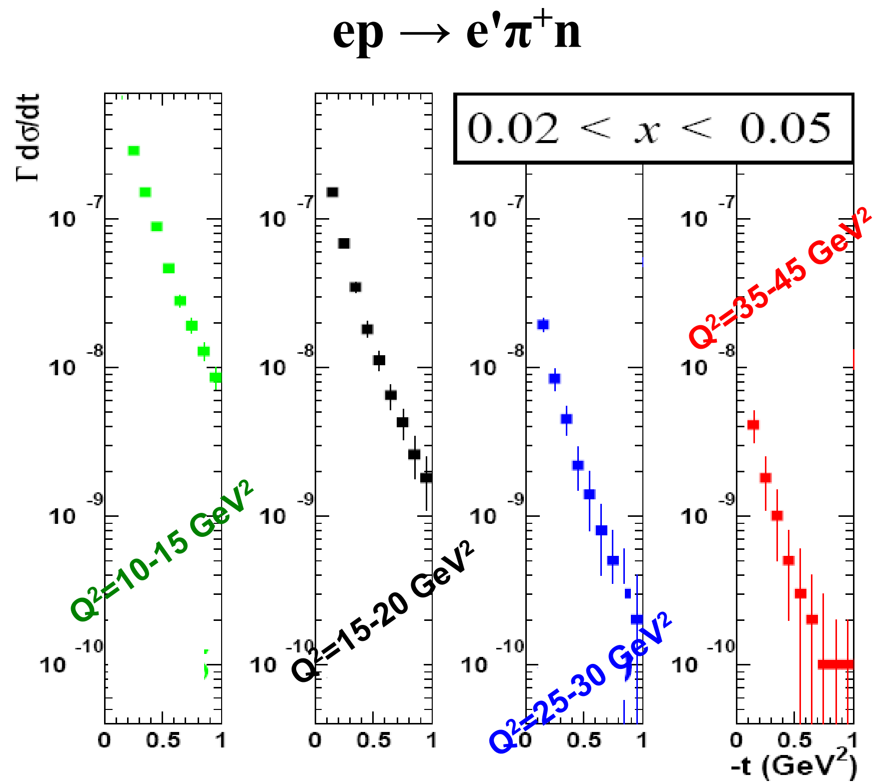
- EIC: gluon size from J/ψ, singlet quark size from DVCS
  - x-dependence: quark vs. gluon diffusion in wave function
  - Detailed analysis: LO → NLO *[Mueller et al.]*

Detailed differential image of nucleon's partonic structure

EIC: Transverse sea quark imaging



- Spatial structure of *non-perturbative sea*
  - Closely related to JLab 12 GeV
    - Quark spin/flavor separations
    - Nucleon/meson structure
- Simulation for π^+ production assuming 100 fb^{-1} of e-p with 5(e^-) on 50(p) GeV (s=1000 GeV^2)
  - V. Guzey, C. Weiss: Regge model
  - T. Horn: empirical π^+ parameterization
- Proton energies of 50-100 GeV have advantage to ensure exclusivity



[Tanja Horn, Antje Bruell, Christian Weiss, '08]

(Deep) exclusive pion electroproduction at EIC can reach up to Q^2~50 GeV^2 assuming 100 fb^{-1} of e-p (roughly one year of running at 10^{34} luminosity)

Transverse spatial structure of non-perturbative sea quarks!

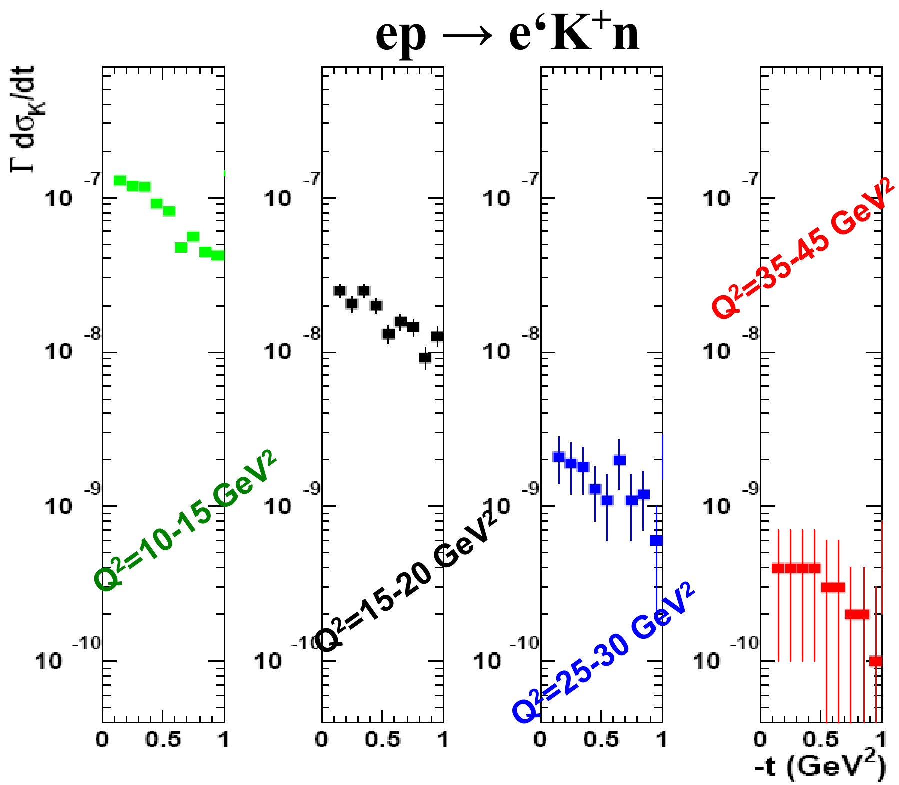
EIC: Transverse *strange* sea quark imaging

- Do strange and non-strange sea quarks have the same spatial distribution?
  - πN or $K\Lambda$ components in nucleon
  - QCD vacuum fluctuations
  - Nucleon/meson structure

- Rate estimate for KΛ using an empirical fit to kaon electroproduction data from DESY and JLab assuming 100 fb^{-1} of e-p with 5(e^-) on 50(p) GeV

- Proton energies of 50-100 GeV have advantage to ensure exclusivity

[Tanja Horn, David Cooper, '08]

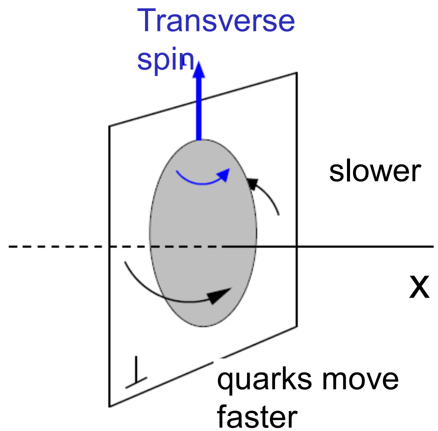


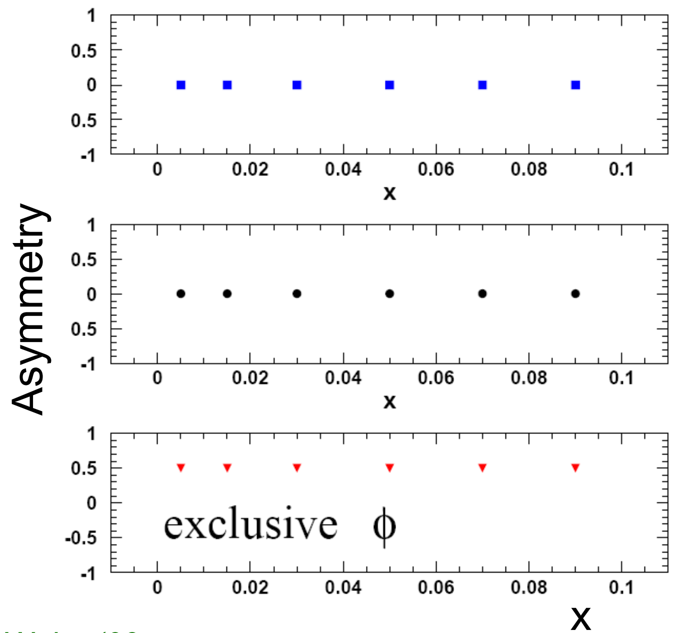
Imaging of strange sea quarks!

Exclusive kaon electroproduction at EIC can reach up to Q^2~30 GeV^2 (assuming 100 fb^{-1}, roughly one year running at 10^{34} luminosity)

Pushes **luminosity towards > 10^{34}, also at lower energy**

Transverse polarization example





Horn, Weiss '09

- Deformation of transverse distribution by transverse polarization of nucleon
  - Helicity flip GPD *E,* cf. Pauli ff
- EIC: exclusive ρ and φ production with transversely polarized beam
  - Excellent statistics at Q^2>10 GeV^2
  - Transverse polarization natural for collider

$$\frac{\sigma\uparrow - \sigma\downarrow}{\sigma\uparrow + \sigma\downarrow} \propto \frac{\mathrm{Im}(\mathcal{H}\mathcal{E}^*)}{|\mathcal{H}|^2 + \mathrm{corr.}}$$

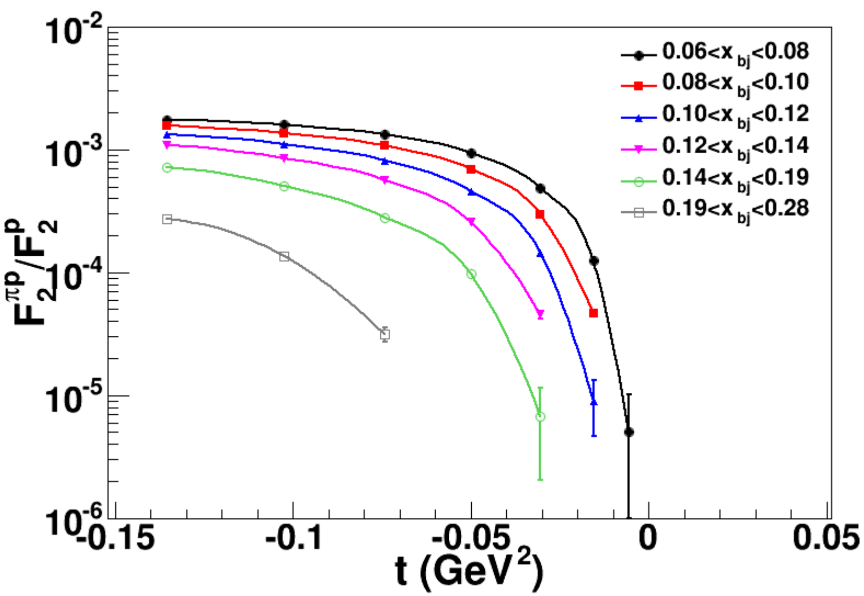
EIC – Versatility and Luminosity is Key

Why would pion and kaon structure functions, and even measurements of pion structure beyond (pion GPDs and TMDs) be feasible at an EIC?

C. Lorce, B. Pasquini, P. Schweitzer, Eur. Phys. J. **76** (2016) 415

L. Chang, I.C. Cloet, C.D. Roberts, S.M. Schmidt, P. C.Tandy, PRL **111** (2013) 092001

- $L_{EIC} = 10^{34} = 1000 \times L_{HERA}$
- Detection fraction @ EIC in general much higher than at HERA
- Fraction of proton wave function related to pion Sullivan process is roughly 10^{-3} for a small –t bin (0.02).
- Hence, pion data @ EIC should be comparable or better than the proton data @ HERA, or the 3D nucleon structure data @ COMPASS
- If we can convince ourselves we can map pion (kaon) structure for –t < 0.6 (0.9) GeV2, we gain at least a decade as compared to HERA/COMPASS.



Ratio of the F_2 structure function related to the pion Sullivan process as compared to the proton F_2 structure function in the low-t vicinity of the pion pole, as a function of Bjorken-x (for JLab kinematics)

Beyond transverse imaging

- Longitudinal correlations in nucleon
  - GPDs at *x'≠x:* correlated qqbar pairs in nucleon
    - QCD vacuum structure, relativistic nature of nucleon
  - EIC: reveal correlations through exclusive meson, γ at x>0.1, Q^2 dependence

…needs kinematic coverage way beyond JLab 12 GeV

- Orbital motion of quarks/gluons
  - TMD and orbital motion from SIDIS
    - Major component of the EIC program
  - Connection with GPDs
    - Unintegrated distributions, Ji sum rule

…should be discussed together

Summary

- Meson form factor measurements play an important role in our understanding of the structure and interactions of hadrons based on the principles of QCD
  - Pion and kaon form factor extractions up to high Q^2 possible (~9 and ~6 GeV^2)
  - Pion form factor measurement at EIC looks feasible, can one also measure the kaon form factor?

- Beyond 12 GeV, EIC provides interesting opportunities to map pion and kaon structure functions over a large (x, Q^2) landscape – White Paper in progress…
  - Access to pion/kaon structure functions at EIC looks feasible
  - Can one probe the pion GPD at EIC?

- Exclusive meson production data play an important role in quark and gluon imaging studies
  - L/T separated cross sections essential for transverse nucleon structure studies – may allow for accessing new type of GPDs
  - Synergy with theory/lattice essential for data interpretation – are we ready?

EIC: Exclusive Meson Production Perspectives

- Energies
  - More symmetric energies favorable, 5 on 50 seems to be a sweet spot for exclusive meson production
  - Lower energies essential for ε range in pseudoscalar L/T separations (pion form factor)
- Kinematic reach
  - Need Q^2>10 GeV^2 (pointlike configurations)
  - x range between 0.001 and 0.1 overlapping with HERA and JLab12 GeV
  - s-range between 200 and 1000 GeV^2
- Luminosity
  - Non-diffractive proceses (exclusive π and K production) require high luminosity for low rates, differential measurements in x, t, Q^2
  - Kaons push luminosity >10^{34}
- Detection
  - Recoil detection for exclusivity, t-range

JLab 12 GeV: Kaons from 2018 Data!