# EIC Physics: Pion and Kaon Structure

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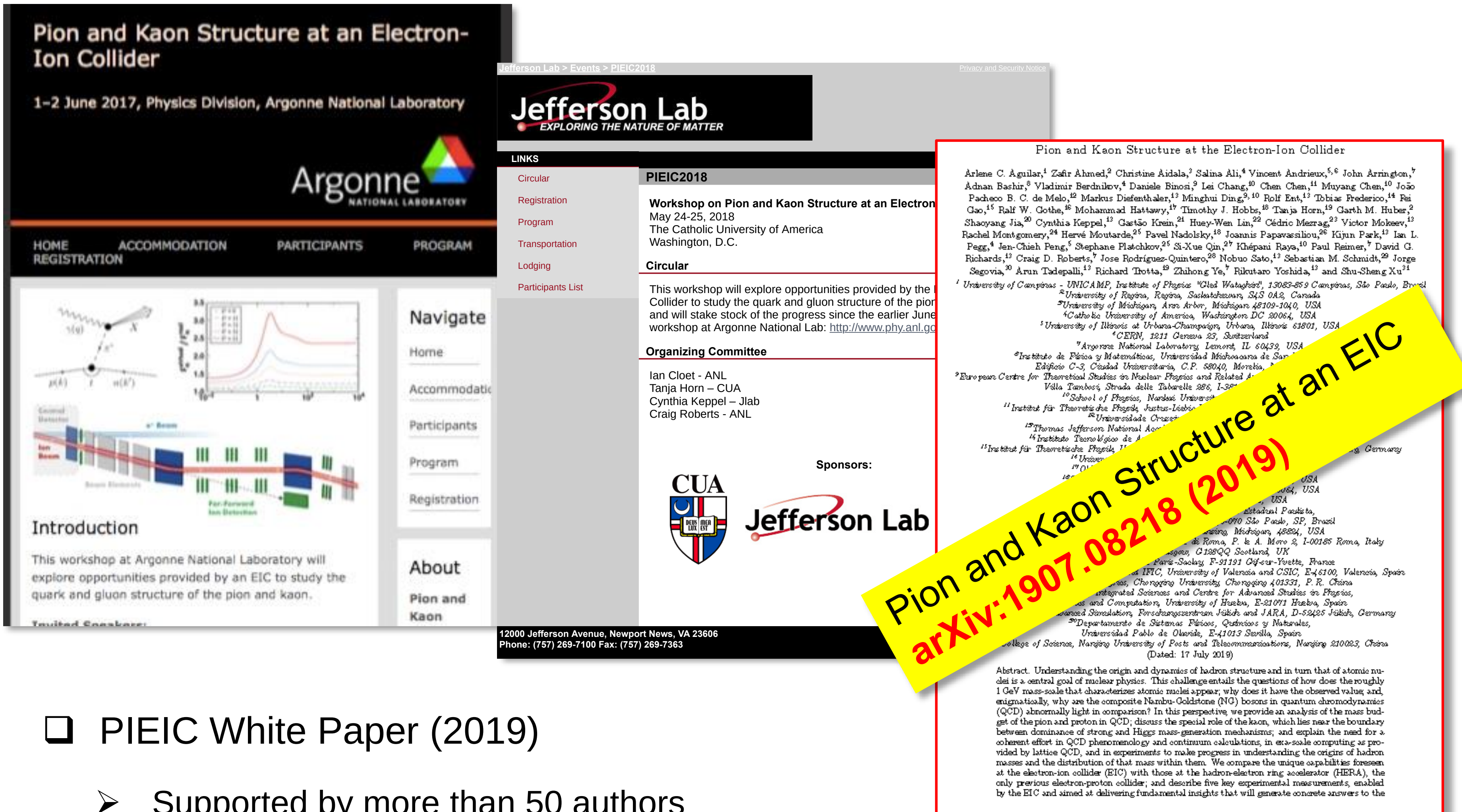
# Outline

- The Emergence of Mass
- $J/\Psi$ and Upsilon Threshold Production at an EIC
- Pion and Kaon PDFs – History
- Versatility and Detection Capabilities at an EIC
- Off-Shellness Considerations
- First Check of Impact of EIC on Pion PDFs
- Prospects for Kaon PDFs at an EIC
- EIC Measurement of Pion Form Factor at High $Q^2$

# Based on…

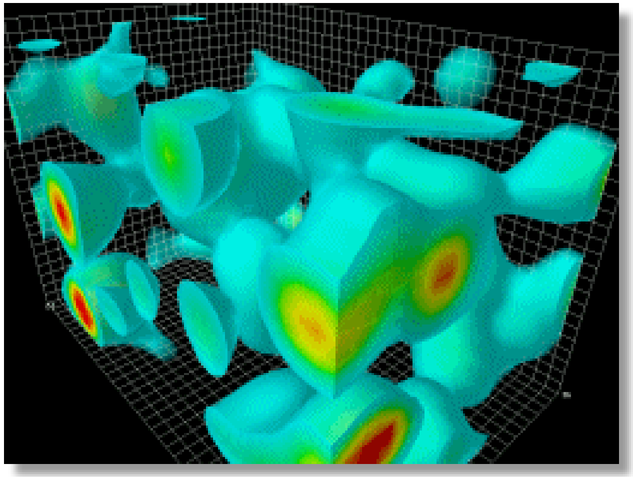
- ❑ PIEIC Workshops hosted at ANL (2017) and CUA (2018)




- ❑ PIEIC White Paper (2019)
  - ➢ Supported by more than 50 authors

# Gluons and QCD

- QCD is the fundamental theory that describes structure and interactions in nuclear matter.
- Without gluons there are no protons, no neutrons, and no atomic nuclei
- Gluons dominate the structure of the QCD vacuum



$$L_{QCD} = \sum_{j=u,d,s,\ldots} \bar{q}_j \left[ i\gamma^\mu D_\mu - m_j \right] q_j - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}$$

$$D_\mu = \partial_\mu + ig\tfrac{1}{2}\lambda^a A^a_\mu,\ G^a_{\mu\nu} = \partial_\mu A_\nu + \partial_\nu A_\mu \boxed{+ igf^{abc} A^b_\mu A^c_\nu}$$

- Facts:
  - Unique aspect of QCD is the self interaction of the gluons
  - The essential features of QCD - asymptotic freedom and (the emergent features) dynamical chiral symmetry breaking and color confinement - are all driven by gluons!
  - Mass from massless gluons and nearly massless quarks
    - Most of the mass of the visible universe emerges from quark-gluon interactions
    - The Higgs mechanism has almost no role here

# Origin of Mass of QCD's Pseudoscalar Goldstone Modes

- The pion is both the lightest bound quark system with a valence $\bar{q}q$ structure and a Nambu-Goldstone boson

- There are exact statements from QCD in terms of current quark masses due to PCAC *(Phys. Rep. 87 (1982) 77; Phys. Rev. C 56 (1997) 3369; Phys. Lett. B420 (1998) 267)*

$$f_\pi m_\pi^2 = \left(m_u^\zeta + m_d^\zeta\right) \rho_\pi^\zeta$$
$$f_K m_K^2 = \left(m_u^\zeta + m_s^\zeta\right) \rho_K^\zeta$$

- Pseudoscalar masses are generated **dynamically**
  - From these exact statements, it follows the mass of bound states increases as √m with the mass of the constituents.
  - In contrast, in, *e.g*. the CQM, bound state mass rises linearly with constituent mass, *e.g.*, with constituent quarks Q: in the nucleon $m_Q \sim ⅓ m_N \sim 310$ MeV, in the pion $m_Q \sim ½ m_\pi \sim 70$ MeV, in the kaon (with one s quark) $m_Q \sim 200$ MeV – **This is not real**.
  - In both DSE and LQCD, the mass function of quarks is the same, regardless what hadron the quarks reside in – **This is real**. It is the Dynamical Chiral Symmetry Breaking (D$\chi$SB) that makes the pion and kaon masses light.

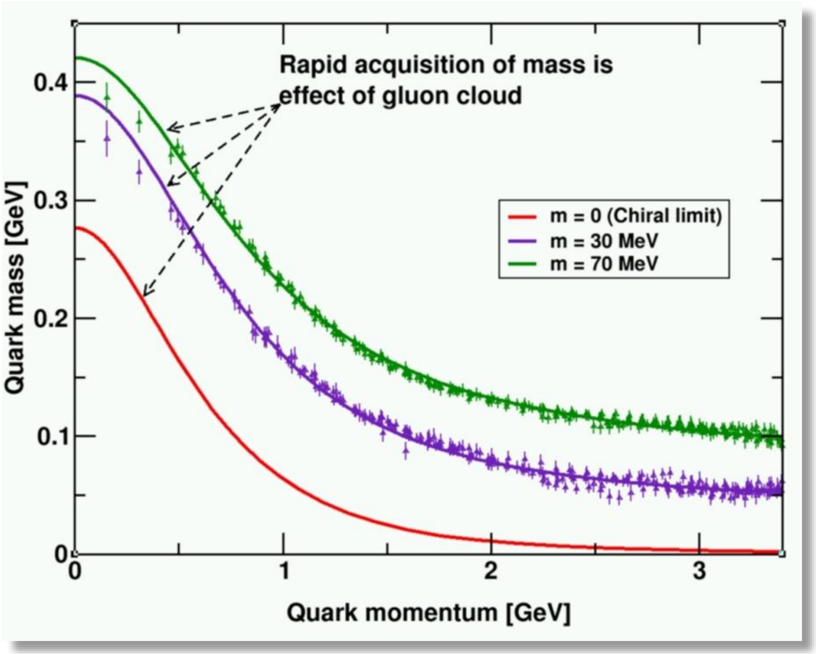
# The role of gluons in pions

## 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 $\rho$, 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 ($m_\pi = 0$):

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

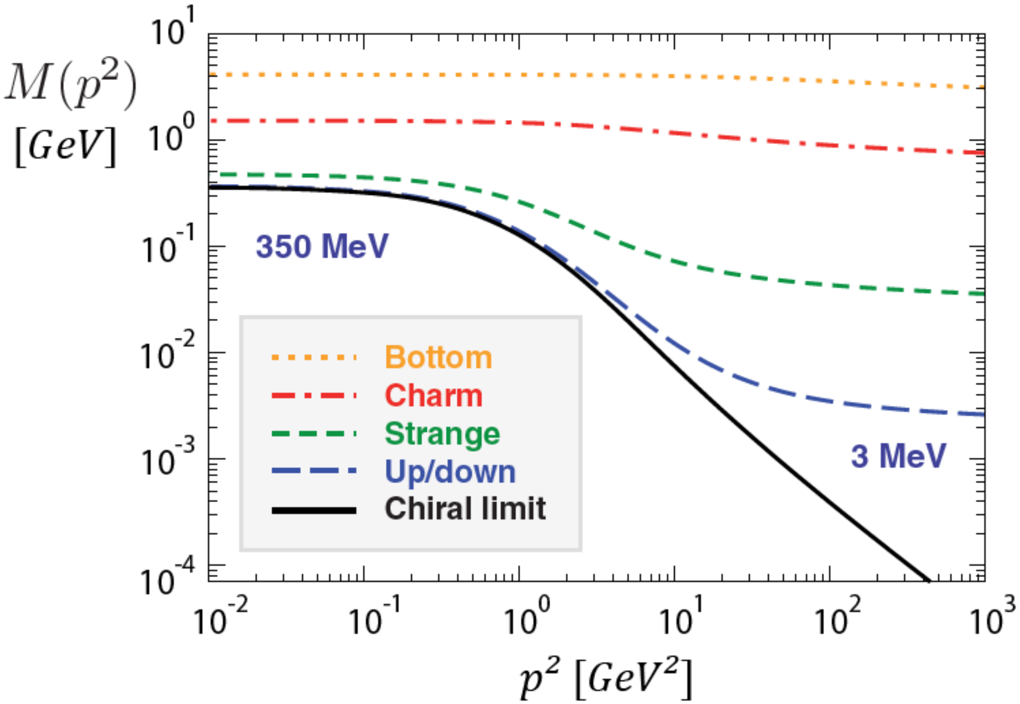
Sometimes interpreted as: *in the chiral limit the gluons disappear and thus contribute nothing to the pion mass*.

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"

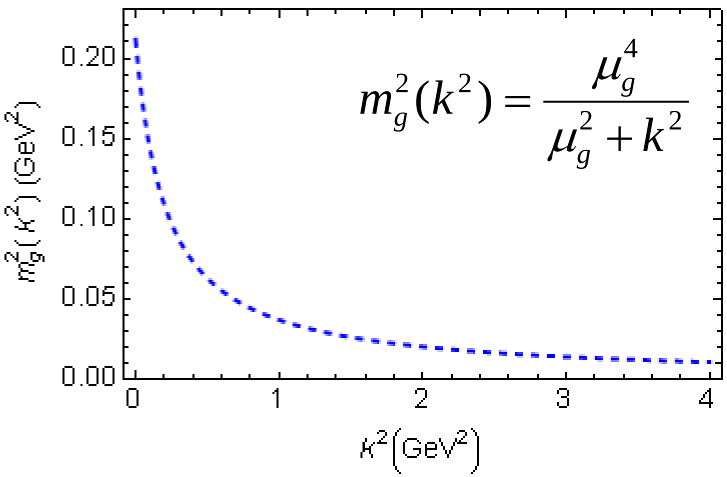
Nonetheless: are there gluons at large $Q^2$ in the pion or not?

# Mass of the Visible Universe

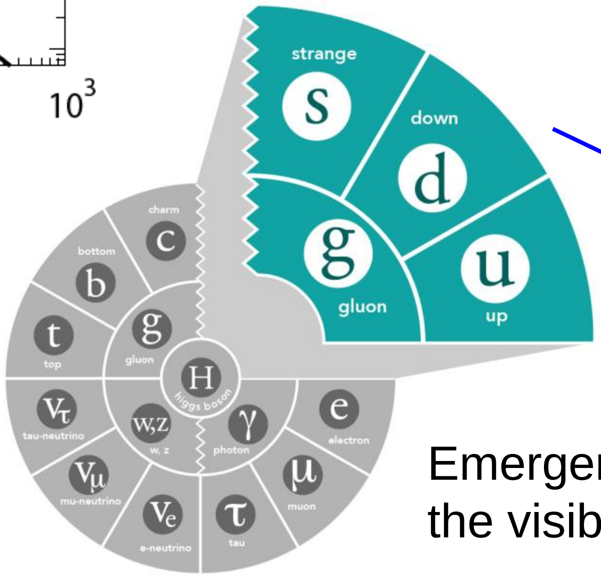
"Mass without mass!"




Gluon mass-squared function



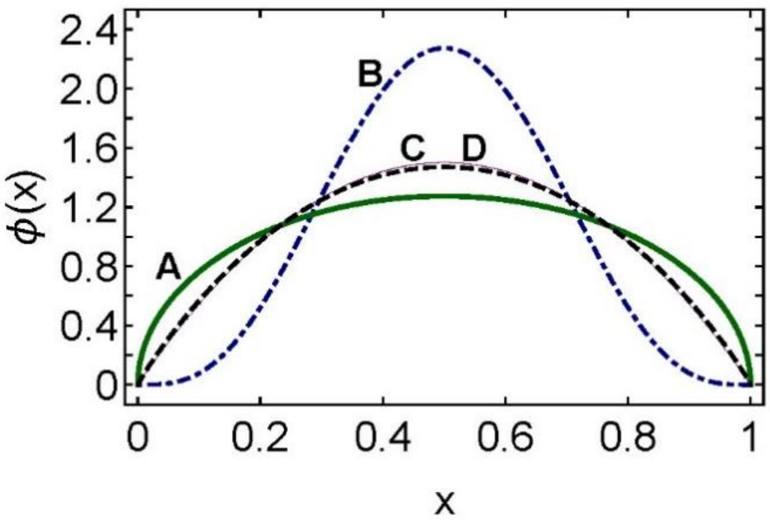

The strange quark is at the boundary - both emergent-mass and Higgs-mass generation mechanisms are important.




Emergent mass of the visible universe

# Emergent- versus Higgs-Mass Generation

Twist-2 PDA at Scale $\zeta$ = 2 GeV




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

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

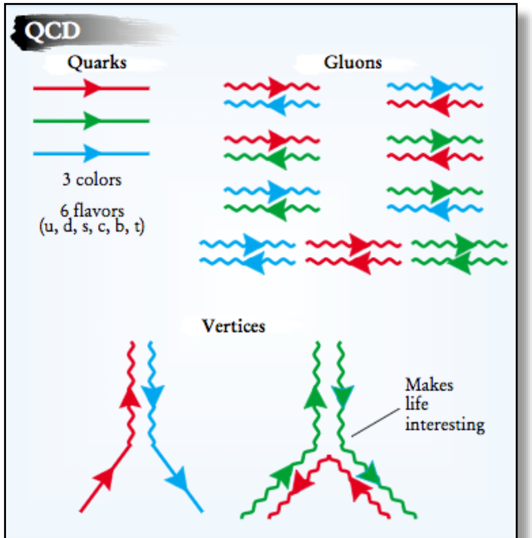
**B** dot-dashed (blue) curve – $\eta_c$ ⇐ primarily, Higgs mass generation;

**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 ($\sim\eta_s$) 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.

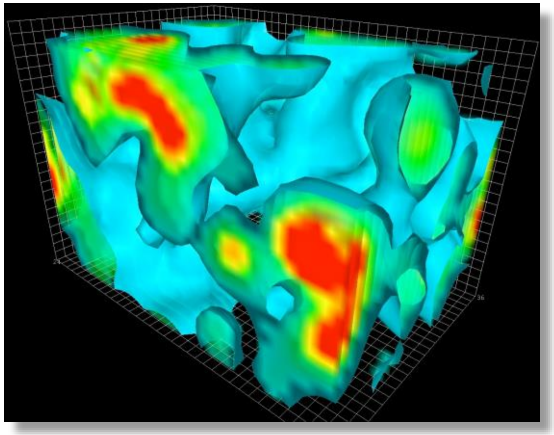
- In the limit of infinitely-heavy quark masses, the Higgs mechanism overwhelms every other mass generating force, and the PDA becomes a $\delta$-function at $x = ½$.
- The sufficiently heavy $\eta_c$ meson (**B**), feels the Higgs mechanism strongly.
- The PDA for the light-quark pion (**A**) is a broad,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

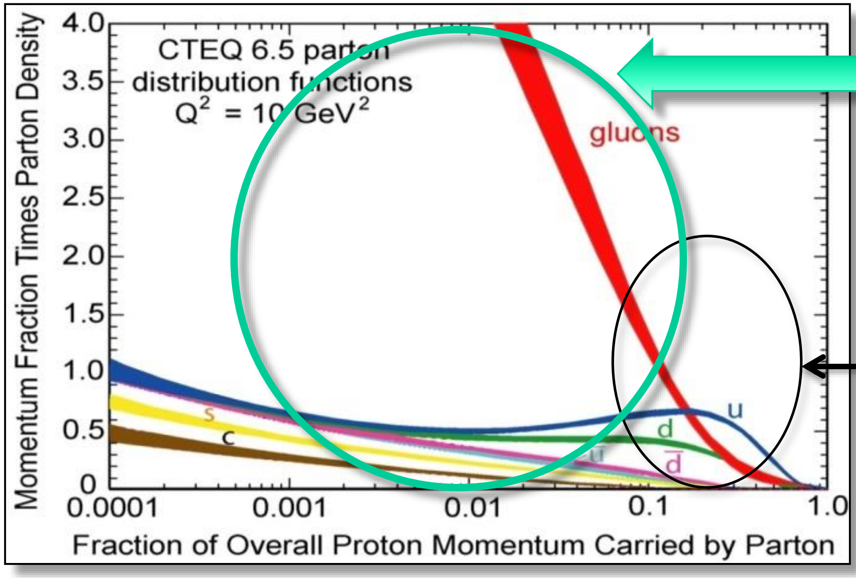
# Subatomic Matter is Unique




**Interactions and Structure are entangled**
because of gluon self-interaction.

**Observed properties such as mass and spin emerge from this complex system.**

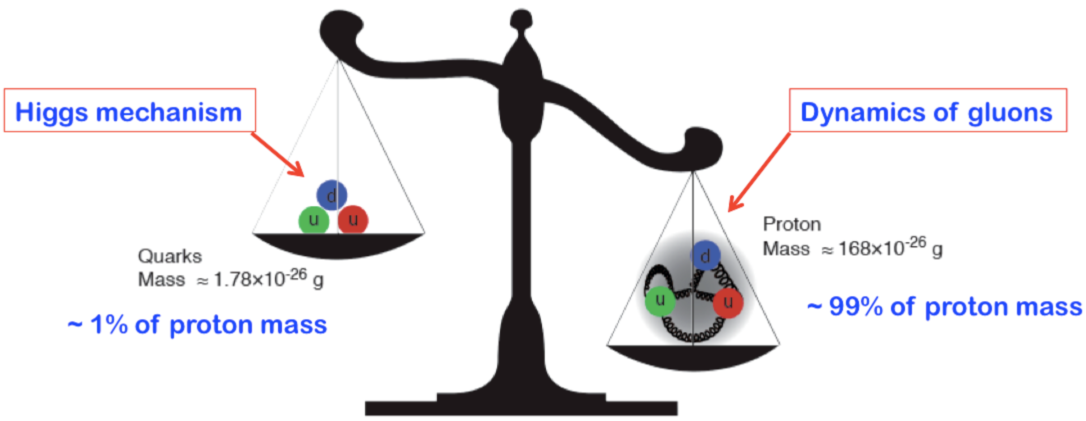


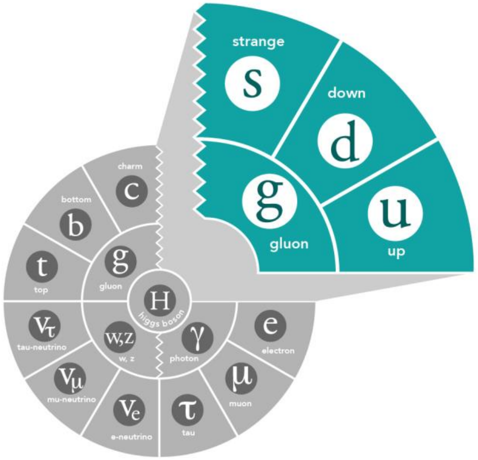



EIC needed to explore the gluon dominated region

JLAB 12 to explore the valence quark region

# The Incomplete Nucleon: Mass Puzzle




"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

- Proton mass:

$$M = \overbrace{\underbrace{E_q}_{\text{Quark Energy}} + \underbrace{E_g}_{\text{Gluon Energy}}}^{\text{Relativistic motion}} + \overbrace{\underbrace{\chi_{m_q}}_{\text{Quark Mass}} + \underbrace{T_g}_{\text{Trace Anomaly}}}^{\text{Quantum fluctuation}}$$

*Not unambiguous: Physical interpretation of the proton mass decomposition also has to be done with care, as one seemingly treats gluons in the trace anomaly and in kinetic and potential energy as separate entities (C. Lorcé, Eur. Phys. J. C **78** (2018) 120).*

# The Incomplete Hadron: Mass Puzzle

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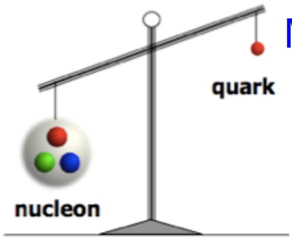
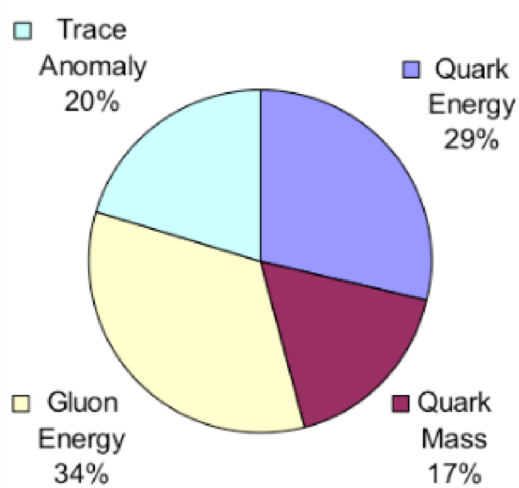
- ❑ Proton mass:




$$M = \overbrace{E_q + E_g}^{\text{Relativistic motion}} + \overbrace{\chi_{m_q} + T_g}^{\text{Quantum fluctuation}}$$

Quark Energy — Gluon Energy — Quark Mass — Trace Anomaly

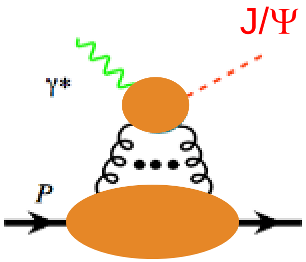
- ❑ Preliminary Lattice QCD results:



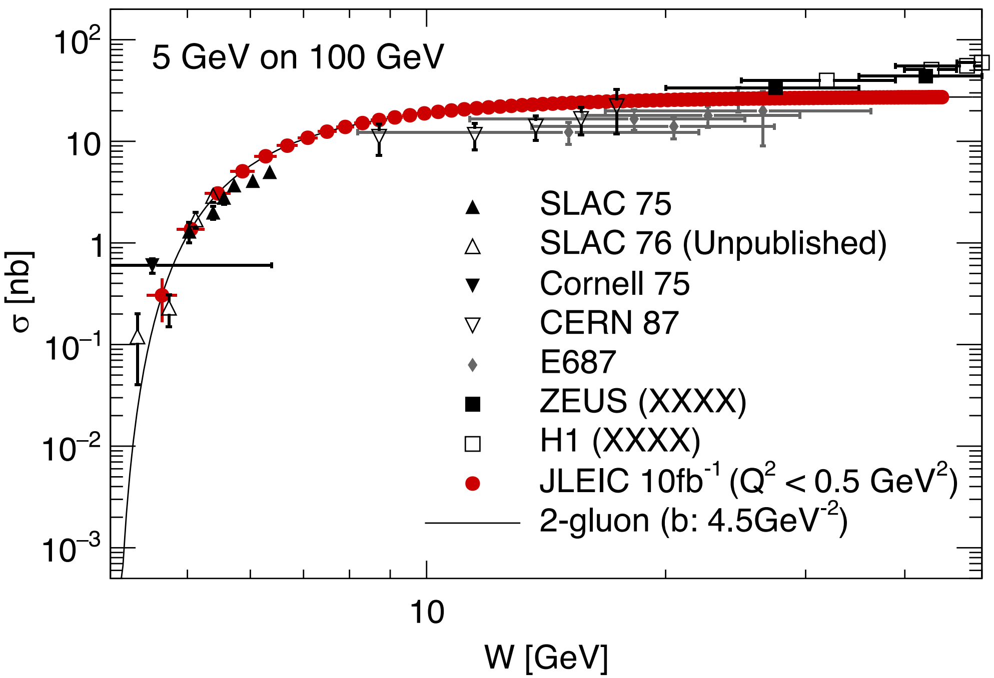

*Not unambiguous: Physical interpretation of the proton mass decomposition has to be done with care, as one seemingly treats gluons in the trace anomaly and in kinetic and potential energy as separate entities (C. Lorcé, Eur. Phys. J. C* ***78*** *(2018) 120).*

# Elastic J/Ψ production near threshold at an EIC

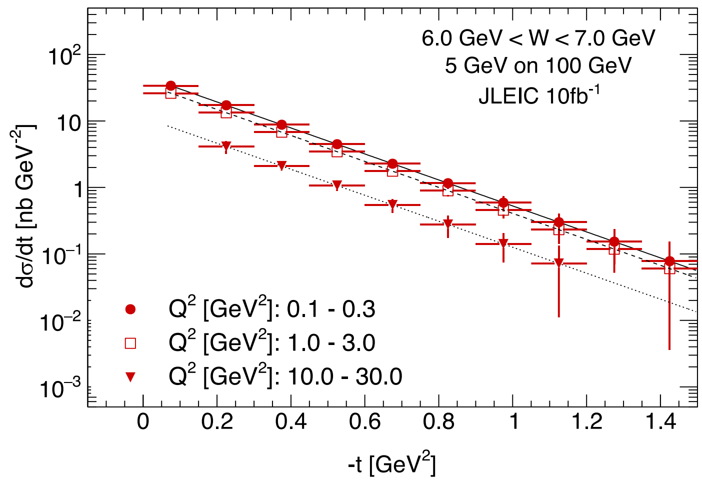
At an EIC a study of the $Q^2$ dependence in the threshold region is possible



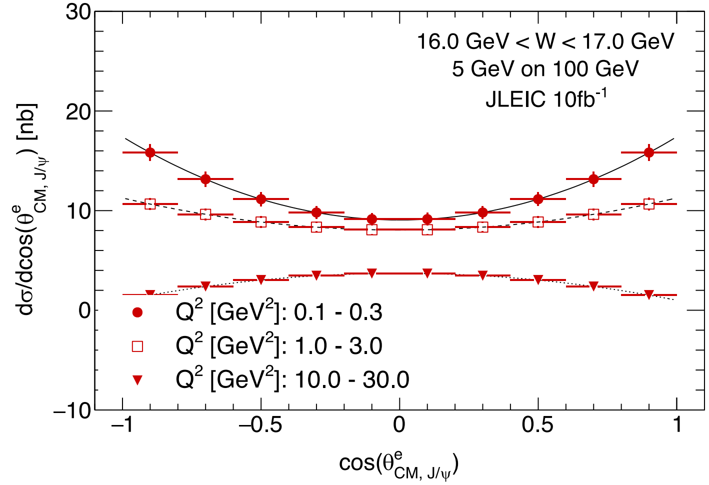

Total electroproduction cross section




*t* distribution



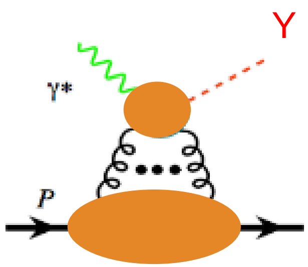

*angular* distribution of decay




*S. Joosten, Z-E. Meziani*

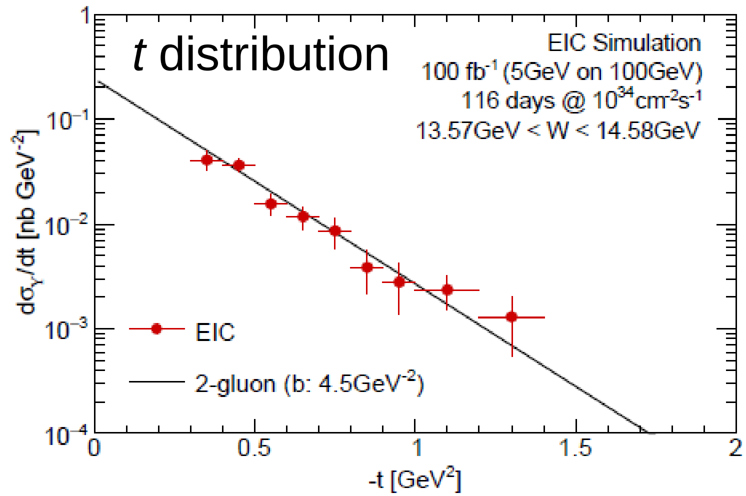
# Elastic Υ production near threshold at an EIC

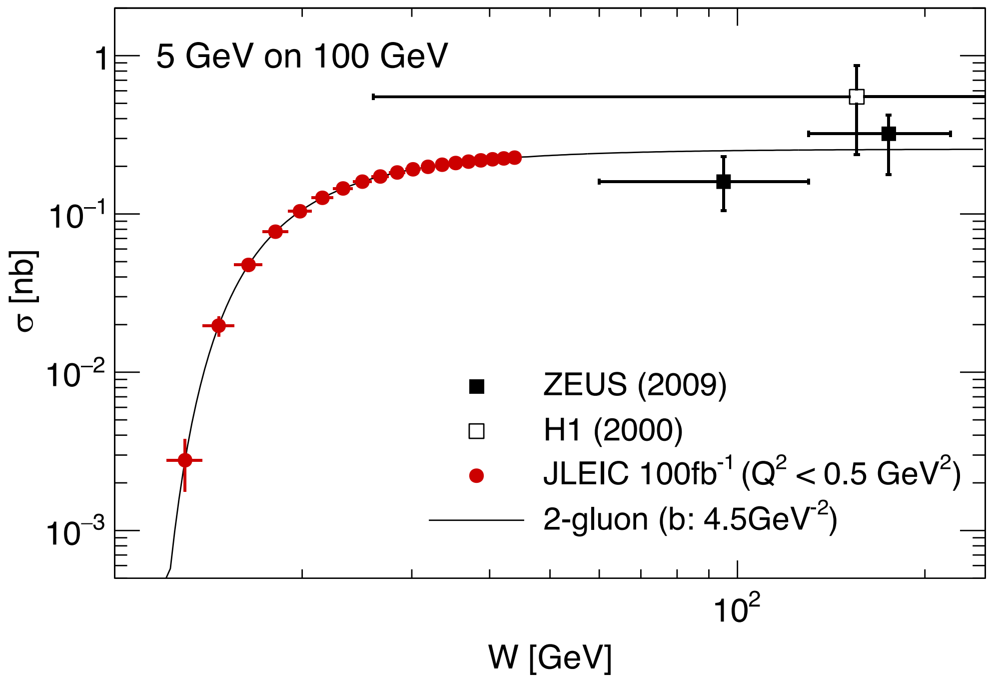
At an EIC a study of the $Q^2$ dependence in the threshold region is possible

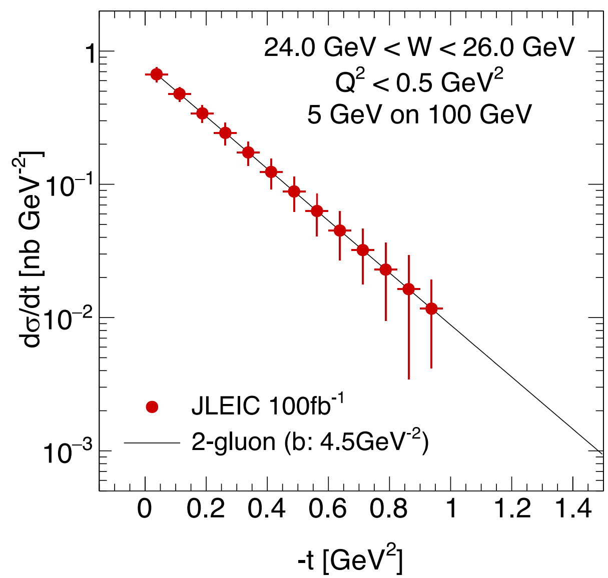



Low W → trace anomaly
Large W → Gluon GPDs

*(see arXiv:1802.02616)*




*S. Joosten, Z-E. Meziani*

# The Incomplete Hadron: Mass Puzzle

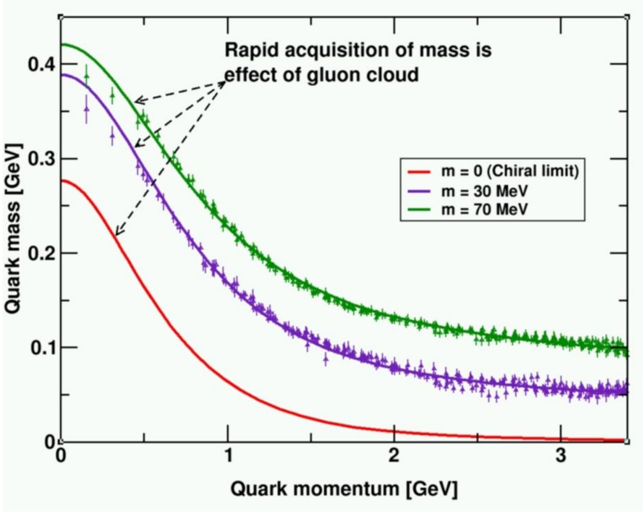
"Mass without mass!"

Bhagwat & Tandy/Roberts et al

Proton: Mass ~ 940 MeV
preliminary LQCD results on mass budget,
or view as mass acquisition by D$\chi$SB

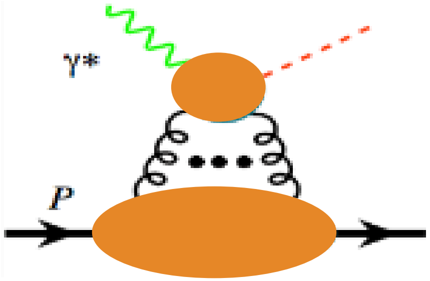
Kaon: Mass ~ 490 MeV
at a given scale, less gluons than in pion

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




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

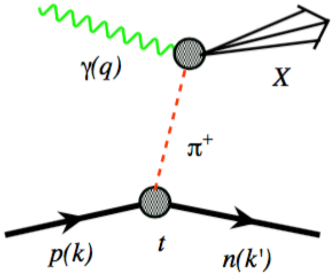
*Upsilon production near the threshold*




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

*In $\pi$, K and N with DIS and SIDIS*

***In $\pi$ and K with Sullivan process***



# WHY SHOULD YOU BE INTERESTED IN PIONS AND KAONS?

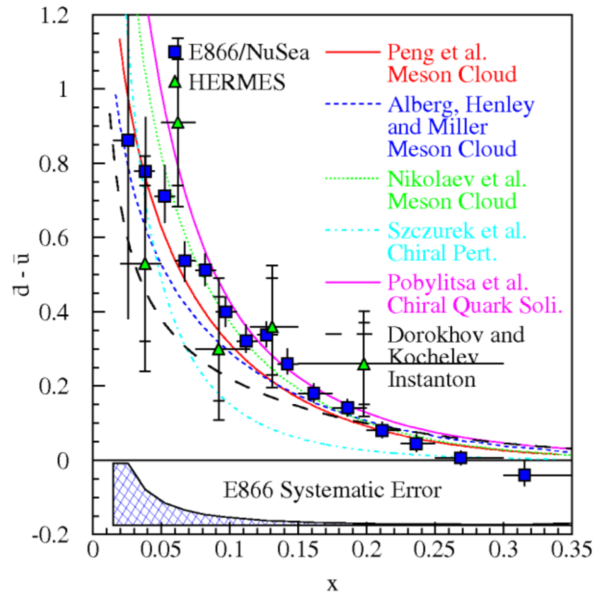
Protons, neutrons, pions and kaons are the main building blocks of nuclear matter

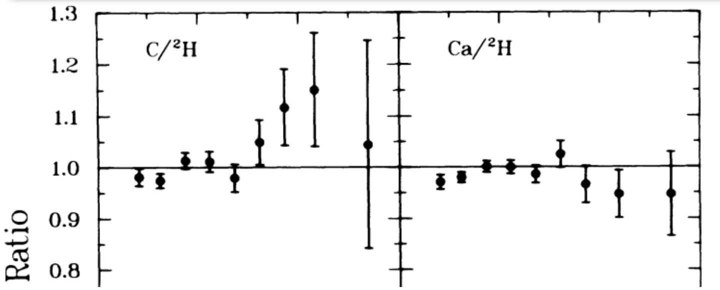
1) The pion, or a meson cloud, explains light-quark asymmetry in the nucleon sea

2) Pions are the Yukawa particles of the nuclear force – but no evidence for excess of nuclear pions or anti-quarks

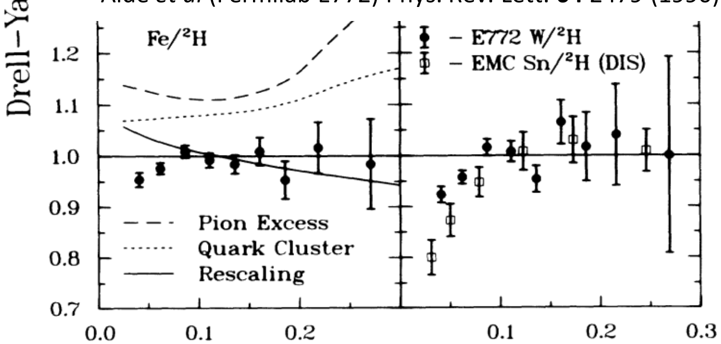
3) Kaon exchange is similarly related to the ΛN interaction – correlated with the Equation of State and astrophysical observations

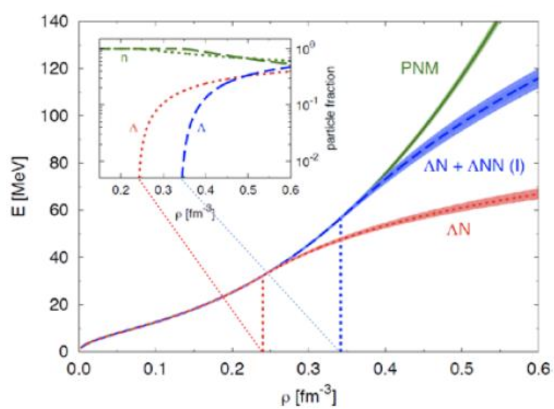
4) Mass is enigma – cannibalistic gluons vs massless Goldstone bosons

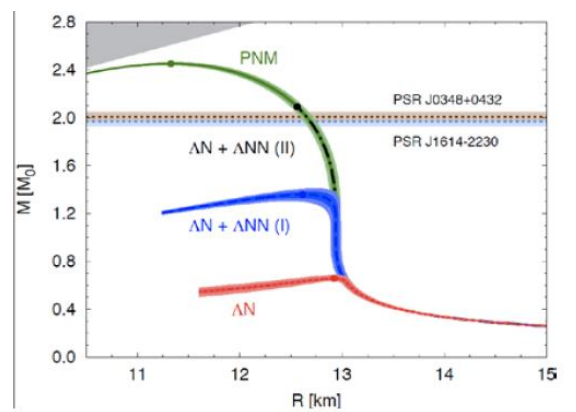


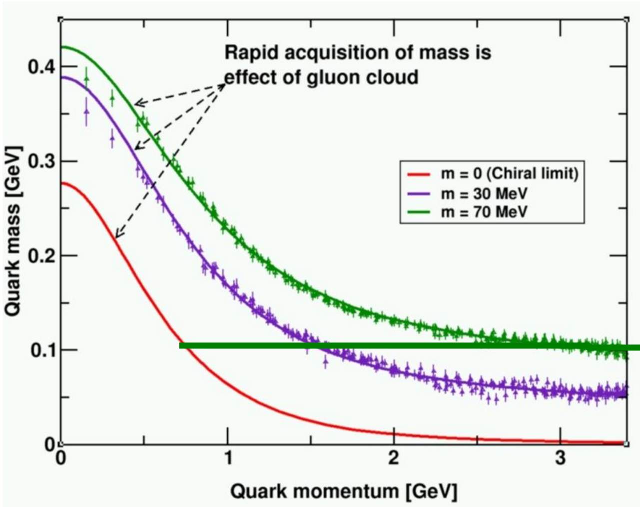

Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

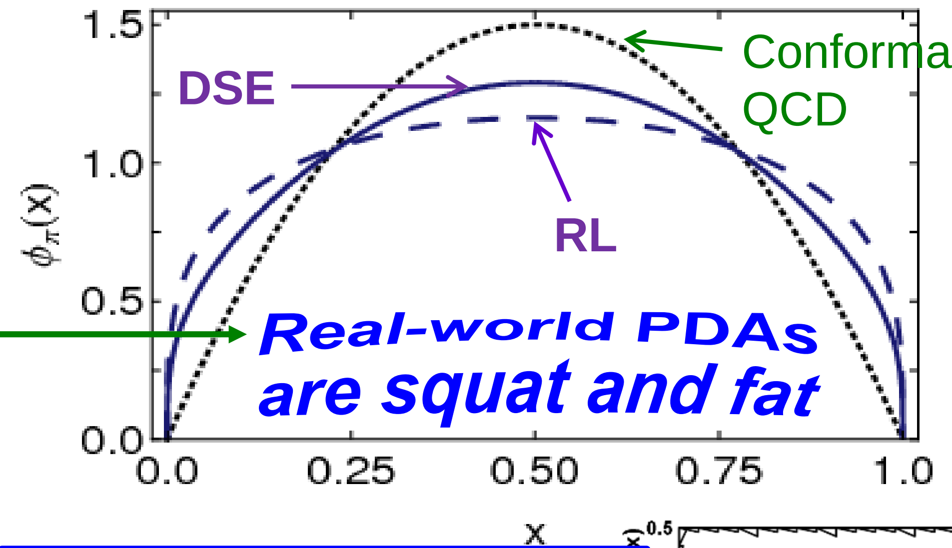


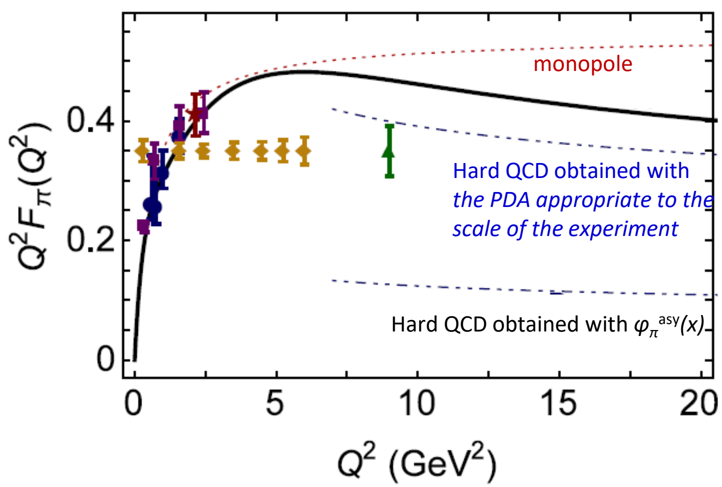



# Pion Form Factor and Structure Function



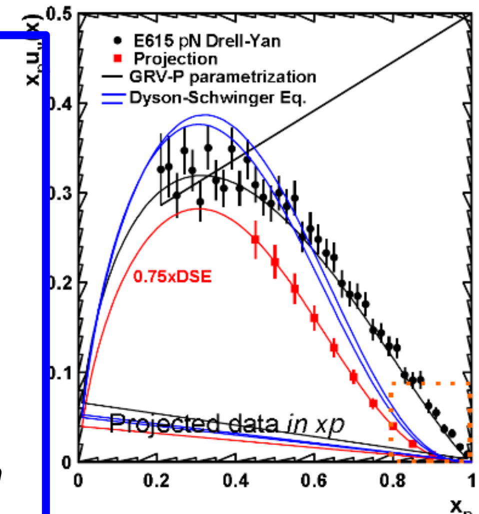




Implications if so: two long-standing puzzles could be solved

1. Magnitude of pion form factor in hard scaling regime
2. Power of pion parton behavior at large x

*Also implications for nucleon and N* form factor interpretation (not shown here).*




Pion FF – first quantitative access to hard scattering scaling regime?

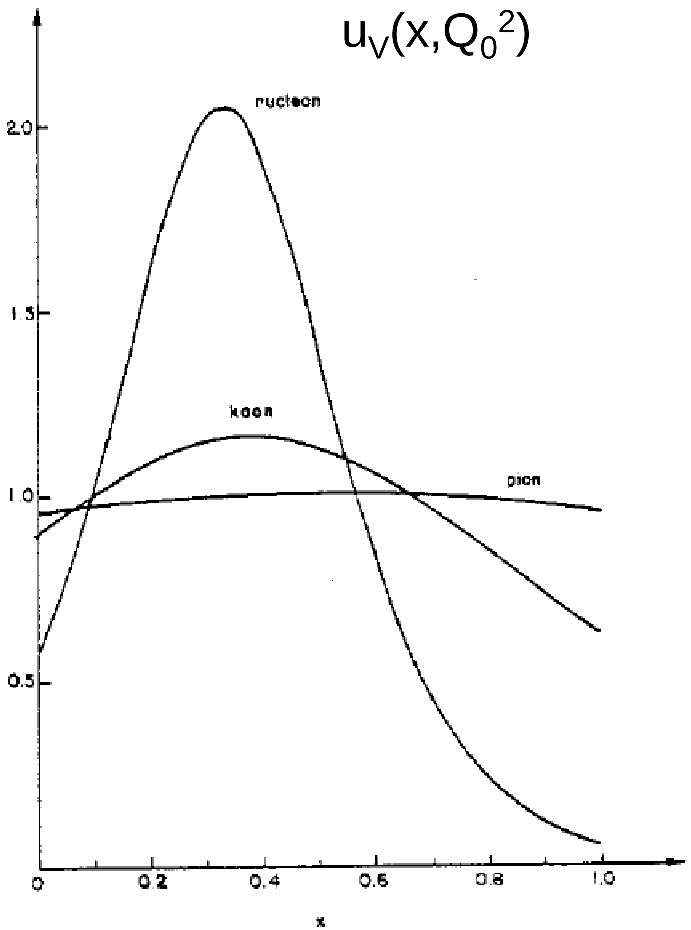
and kaon

Pion SF – $(1-x)^1$ or $(1-x)^2$ dependence at large x?

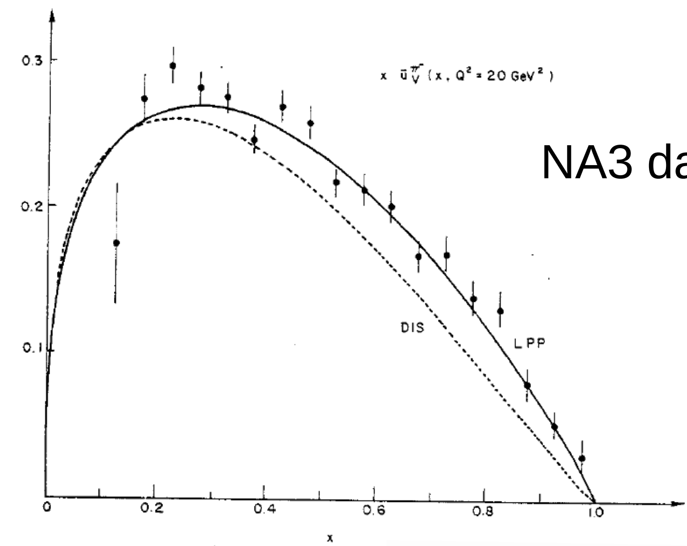
# At some level an old story…

## A model for nucleon, pion and kaon structure functions
## F. Martin, CERN-TH 2845 (1980)

$u_V(x,Q_0^2)$

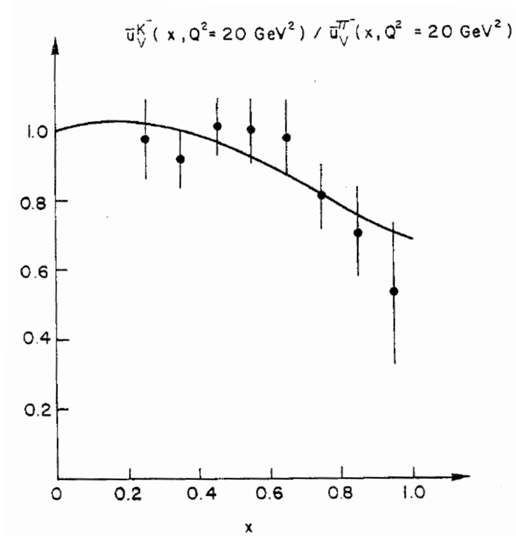



NA3 data



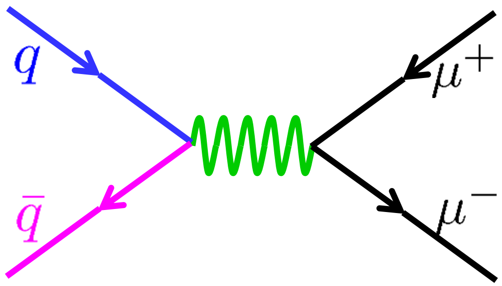

Predictions based on non-relativistic model with valence quarks only →

1) pion/kaon differs from proton: 2q vs. 3q system
2) kaon differs from pion as it owns one heavy quark



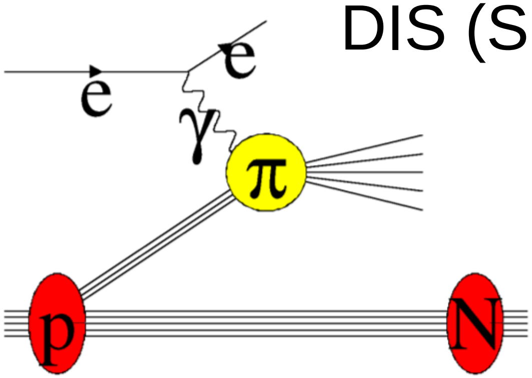
# World Data on pion structure function $F_2^{\pi}$

## Pion Drell-Yan

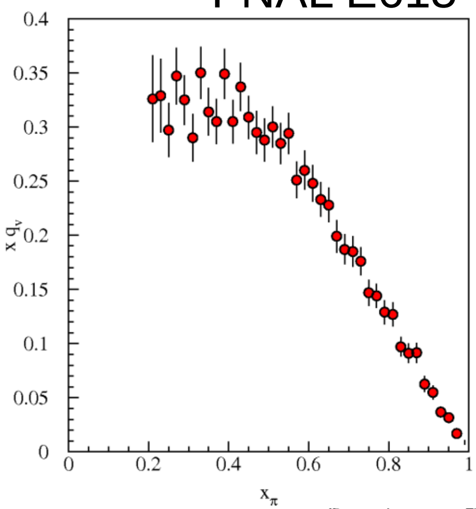



Data much more limited…

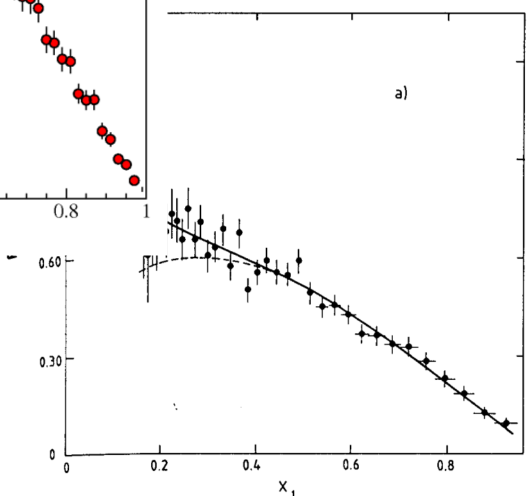
## DIS (Sullivan Process)

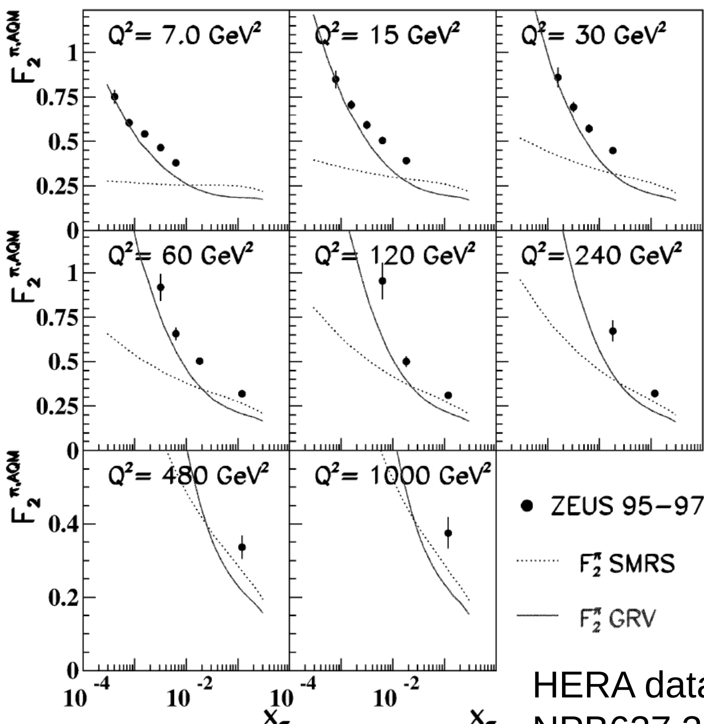



FNAL E615



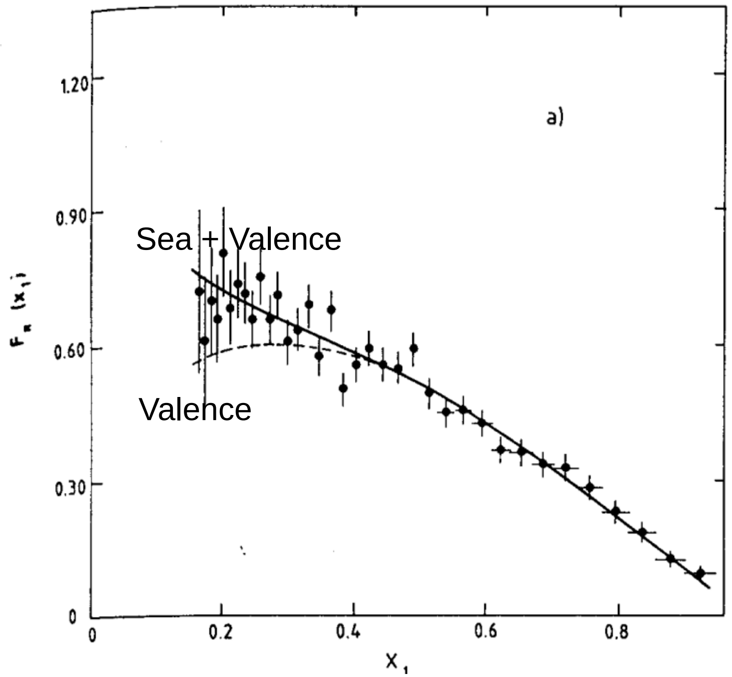

CERN NA3



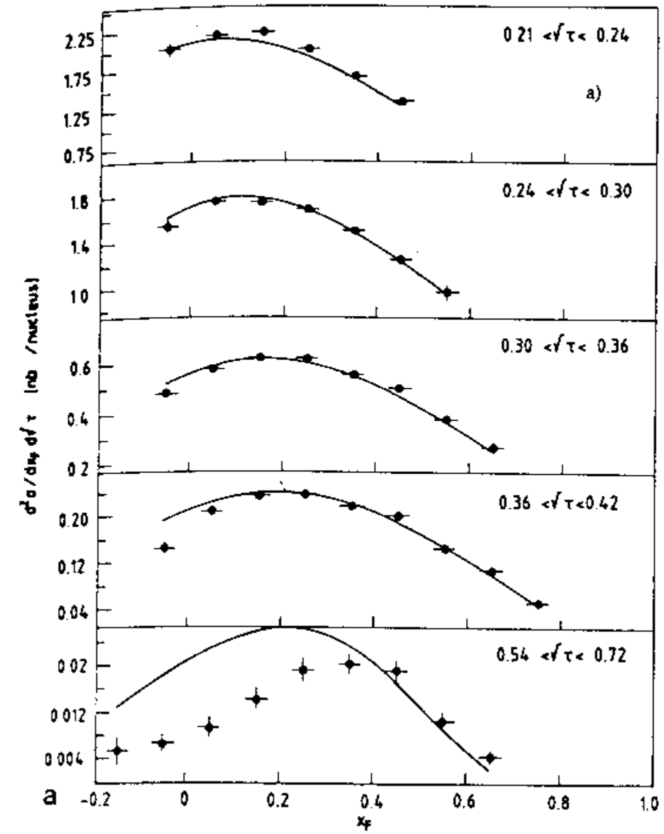

HERA data [ZEUS, NPB637 3 (2002)]

# Pion Drell-Yan Data:  CERN NA3 ($\pi^{+/-}$) NA10 ($\pi^-$)




NA3 200 GeV $\pi^-$ data (also have 150 and 180 GeV $\pi^-$ and 200 GeV $\pi^+$ data).  *Can determine pion sea*!

$$\boxed{Q_\pi^{\rm sea} \equiv \int_0^1 x q_\pi^{\rm sea}(x)dx = 0.01}$$



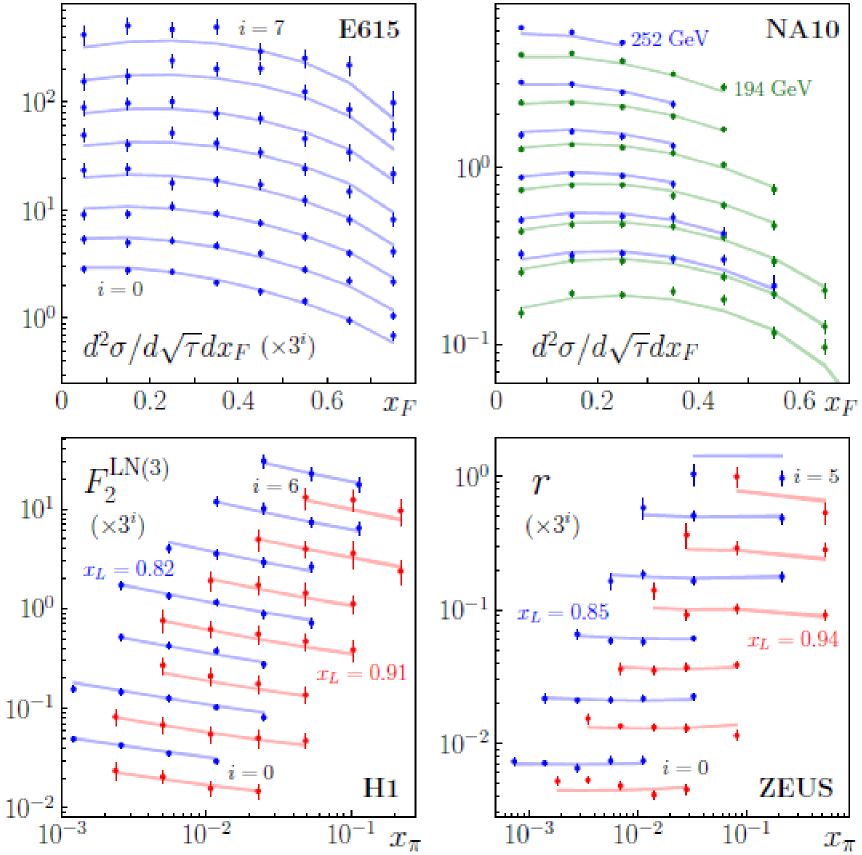

NA10 194 GeV $\pi^-$ data

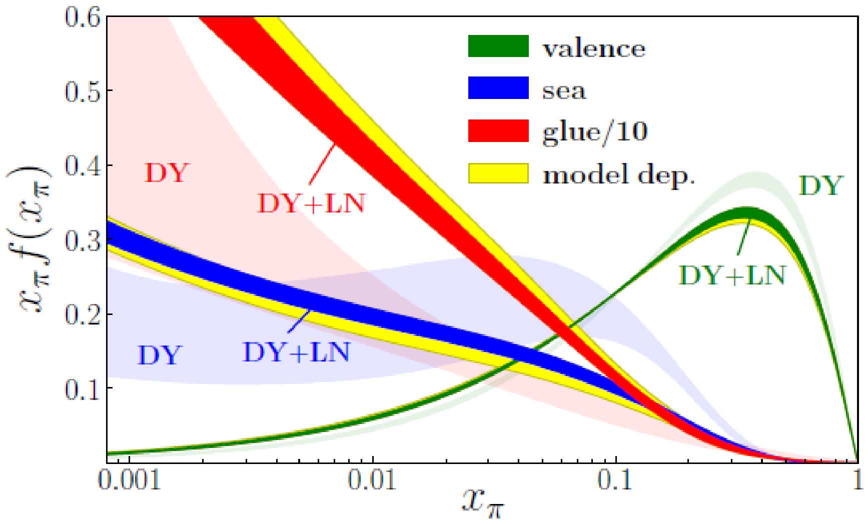
*quark sea in pion is small – few %*

# First Monte Carlo global analysis of pion pdfs

From combined Leading-Neutron (LN) and Drell-Yan (DY) analysis

P.C. Barry, N. Sato, W. Melnitchouk, C.-R. Ji, Phys. Rev. Lett. 121 (2018) no. 15, 152001, [arXiv:1804.01965]



# Quark and gluon pdfs in pions and kaons

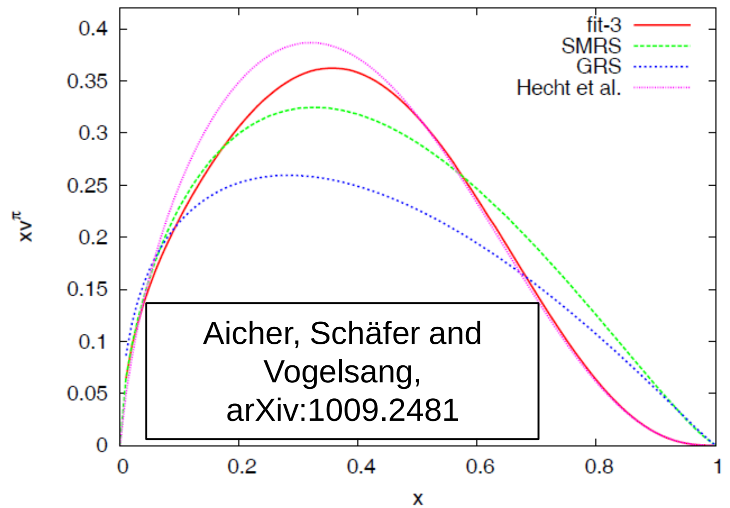
- ***At low x to moderate x***, both the quark sea and the gluons are very interesting.
  - Are the sea in pions and kaons the same in magnitude and shape?
  - Is the origin of mass encoded in differences of gluons in pions, kaons and protons, or do they in the end all become universal?

- ***At moderate x***, compare pionic Drell-Yan to DIS from the pion cloud,
  - test of the assumptions used in the extraction of the structure function (and similar assumptions in the pion and kaon form factors).

- ***At high x***, the shapes of valence u quark distributions in pion, kaon and proton are different, and so are their asymptotic x → 1 limits.
  - Some of these effects are due to the comparison of a two- versus three-quark system, and a meson with a heavier s quark embedded versus a lighter quark.
  - However, also effects of gluons come in. To measure this would be fantastic.
  - At high x, a long-standing issue has been the shape of the pion structure function as given by Drell-Yan data versus QCD expectations. However, this may be a solved case based on gluon resummation, and this may be confirmed with 12-GeV Jefferson Lab data. Nonetheless, soft gluon resummation is a sizable effect for Drell Yan, but expected to be a small effect for DIS, so additional data are welcome.

# The issue at large-x: solved by resummation?

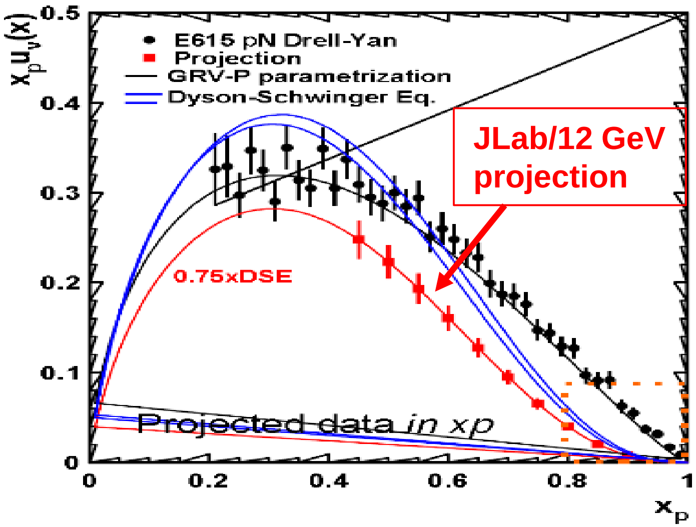
- Large $x_{Bj}$ structure of the pion is interesting and relevant
  - Pion cloud & antiquark flavor asymmetry
  - Nuclear Binding
  - Simple QCD state & Goldstone Boson




- Even with NLO fit and modern parton distributions, pion did not agree with pQCD and Dyson-Schwinger

Pion SF:
$(1-x)^1$ or $(1-x)^2$ dependence at large x?

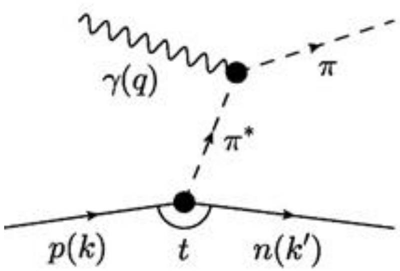
- **Soft Gluon Resummation saves the day! (or ?)**
  - JLab 12 GeV experiment can check at high-x
  - Resummation effects less prominent at DIS → EIC's role here may be more consistency checks of assumptions made in extraction

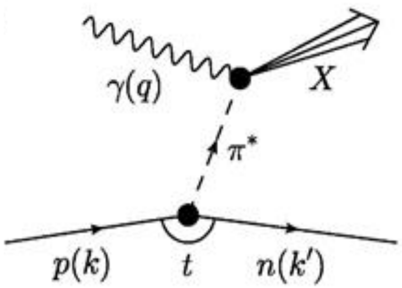



- Additional Bethe-Salpeter predictions to check in π/K Drell-Yan ratio

# Towards Pion Structure Functions

- Similar as process used to measure the pion elastic form factors, isolate the One Pion Exchange Contribution also to measure pion structure functions




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

- Sullivan was the first to consider the "Drell" process, with $\pi$+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

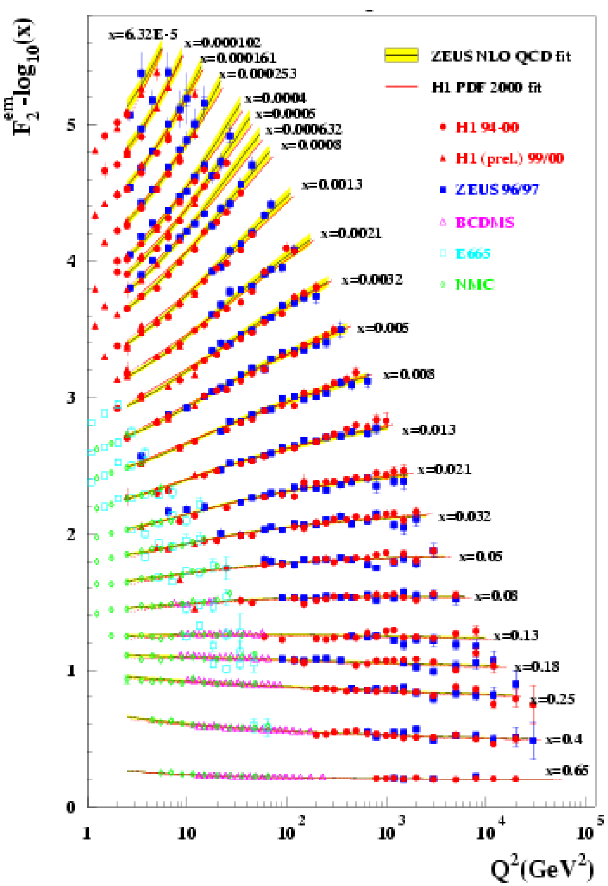
- Similar consideration for offshellness as for meson FF – a well-constrained experimental analysis should be reliable in regions of -t

# Landscape for p, π, K structure function after EIC

***Proton:*** much existing from HERA

EIC will add:

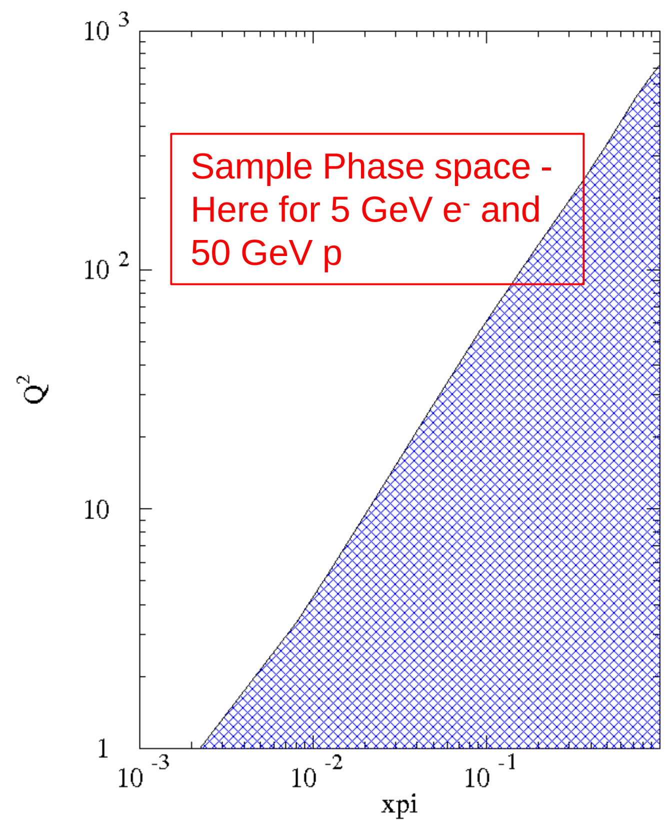
- Better constraints at large-x
- Precise $F_2^n$ neutron SF data




***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!



# World Data on pion structure function $F_2^{\pi}$

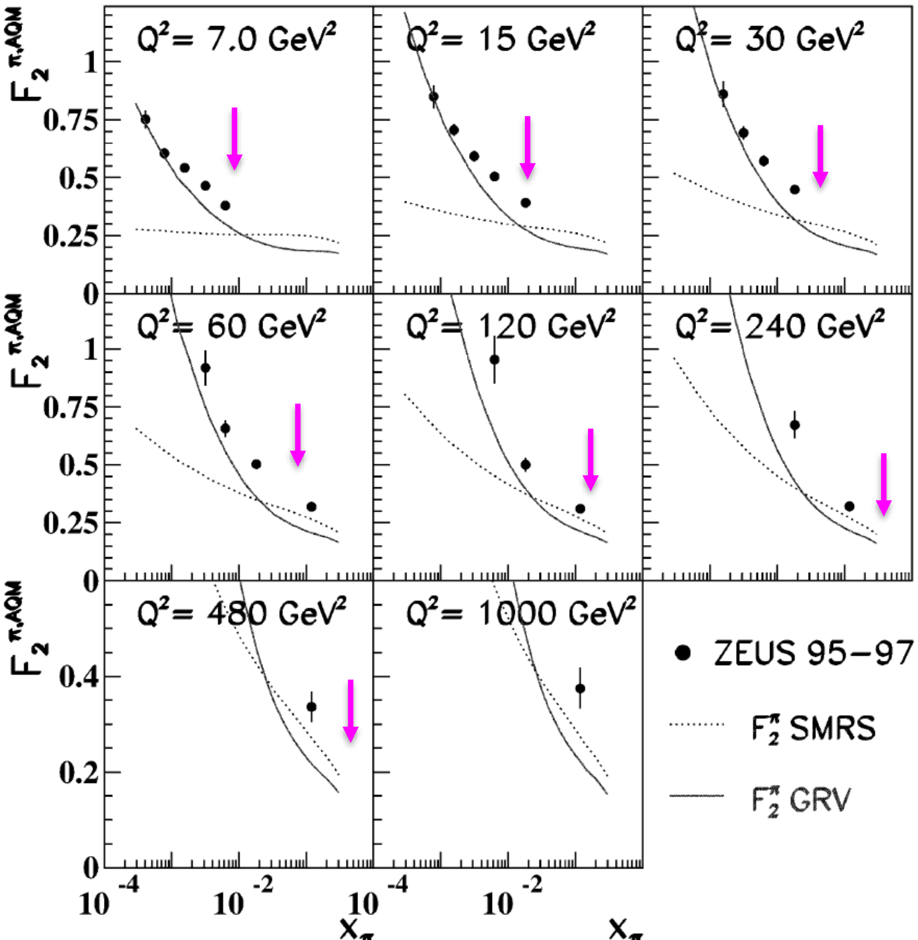
HERA

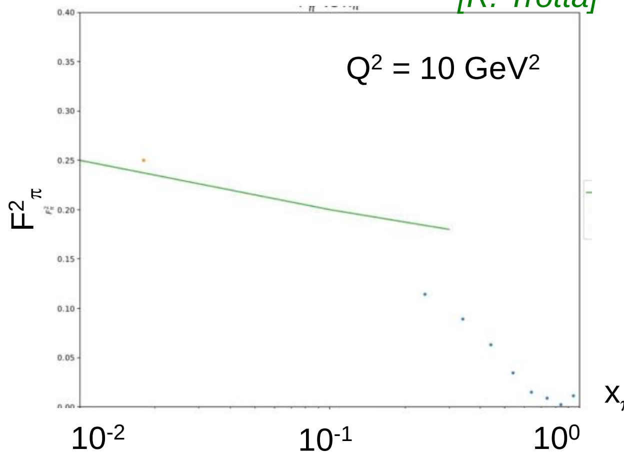
~$x_{min}$ for EIC

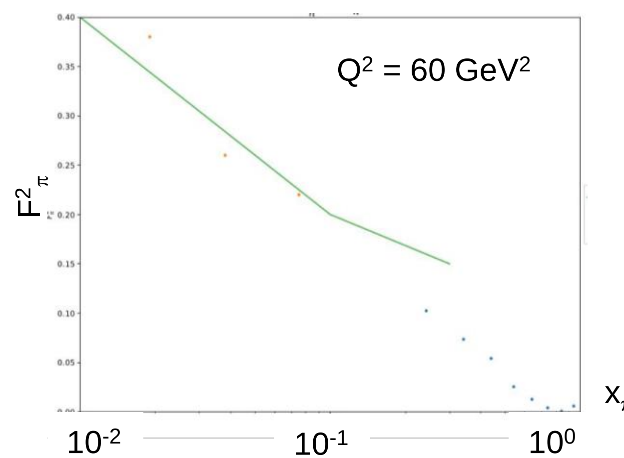
EIC

*Here example for 5 GeV e⁻ and 100 GeV p*

*[R. Trotta]*

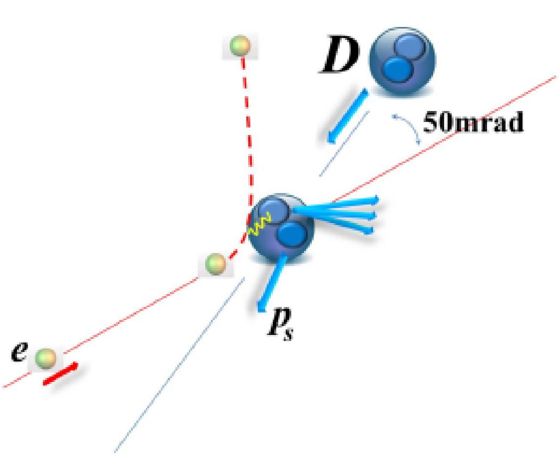


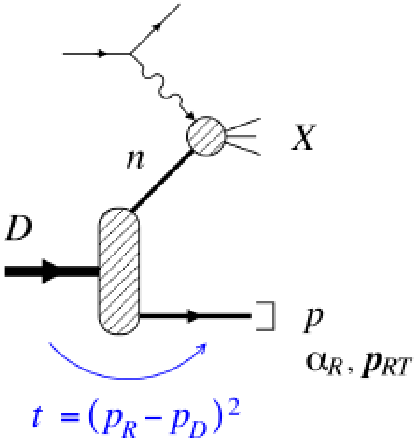



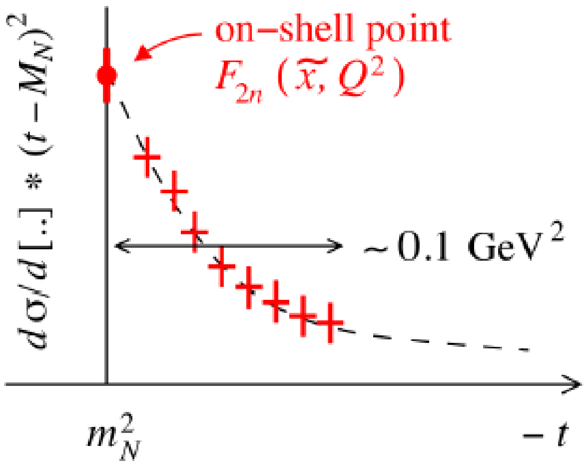



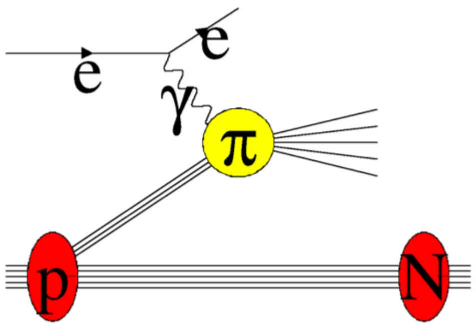

- ❑ **EIC kinematic reach down to a x = few $10^{-3}$**
- ❑ **Lowest x constrained by HERA**

# EIC – Versatility is Key



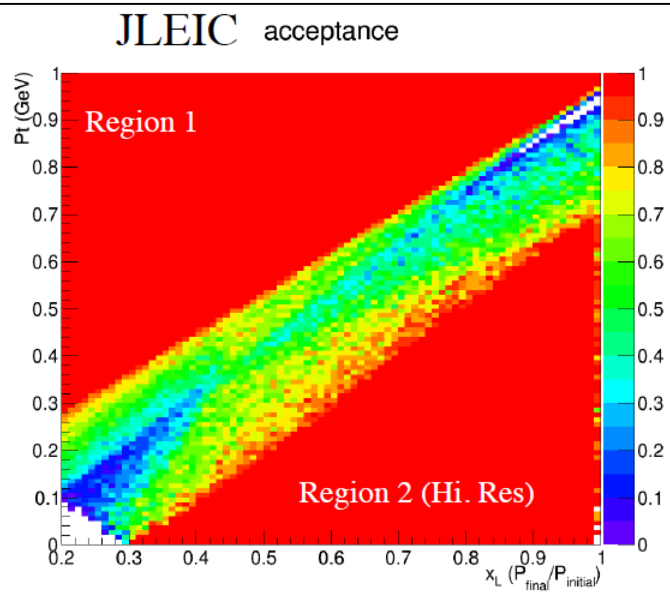




- ❑ Obtain $F_2^n$ by tagging spectator proton from e-d, and extrapolate to on-shell neutron to correct for binding and motion effects.
- ❑ Obtain $F_2^\pi$ and $F_2^K$ by Sullivan process and extrapolate the measured t-dependence as compared to DSE-based models.

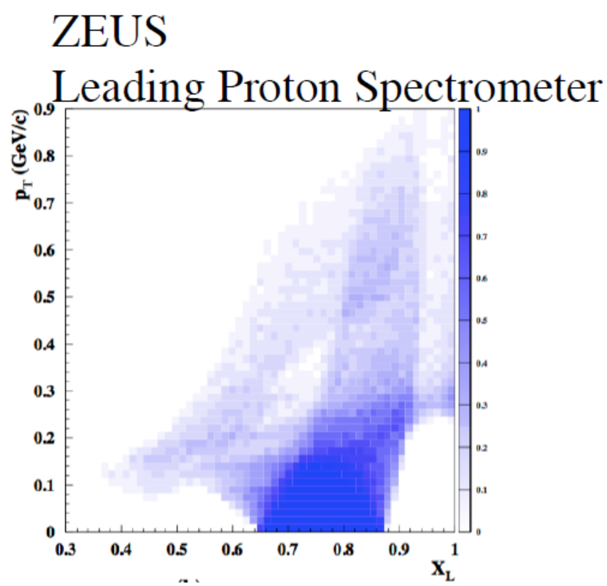
➢**Need excellent detection capabilities, and good resolution in –t**

# Full Acceptance for Forward Physics!

Example: acceptance for p’ in e + p → e’ + p’ + X




Zhiwen Zhao (Duke)

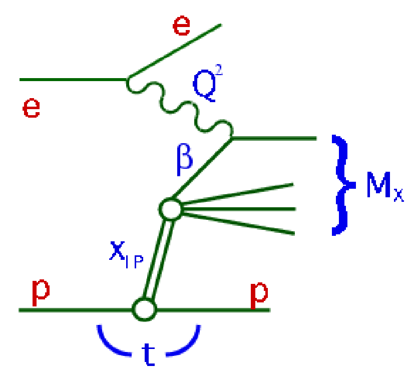


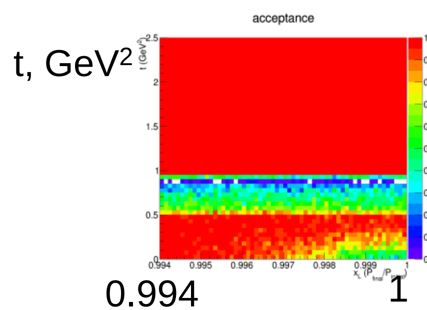

Acceptance in diffractive peak ($X_L$>~.98)

ZEUS: ~2%

JLEIC: ~100% (also covers much higher $X_L$ than ZEUS)

Diffraction

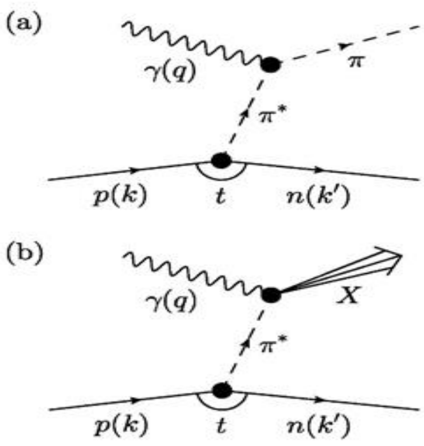


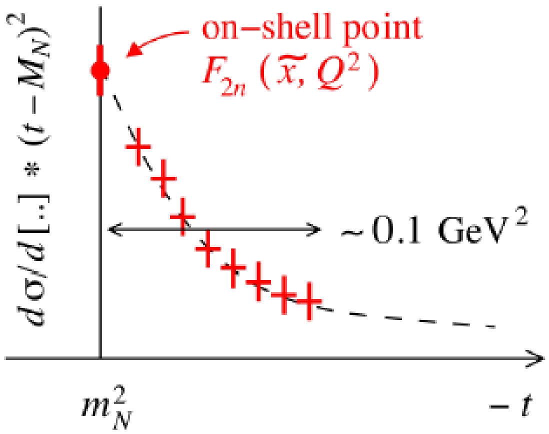




Huge gain in acceptance for diffractive physics and forward tagging to measure $F_2^n$!!!

# Pion and Kaon Sullivan Process

- The **Sullivan process can provide reliable access to a meson target** as *t* becomes space-like if the pole associated with the ground-state meson remains the dominant feature of the process and the structure of the related correlation evolves slowly and smoothly with virtuality.



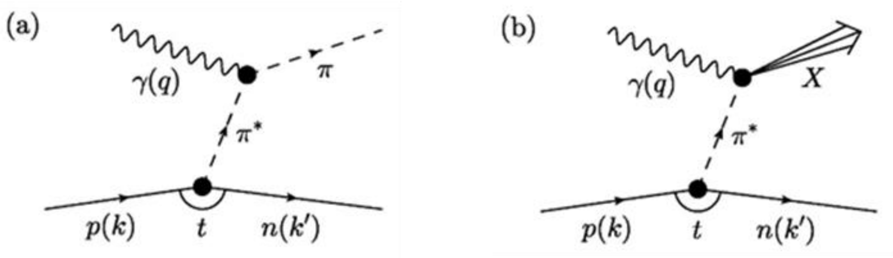




- To **check these conditions** are satisfied empirically, one can **take data covering a range in *t*** and compare with phenomenological and theoretical expectations.

- Recent **theoretical calculations found that for $-t \leq 0.6\ \mathrm{GeV}^2$, all changes in pion structure are modest** so that a well-constrained experimental analysis should be reliable Similar analysis for the kaon indicates that Sullivan processes can provide a valid kaon target for $-t \leq 0.9\ \mathrm{GeV}^2$

*[S.-X. Qin, C. Chen, C. Mezrag and C. D. Roberts, Phys. Rev. C 97 (2018) 015203.]*

# Theoretical Off-Shellness Considerations

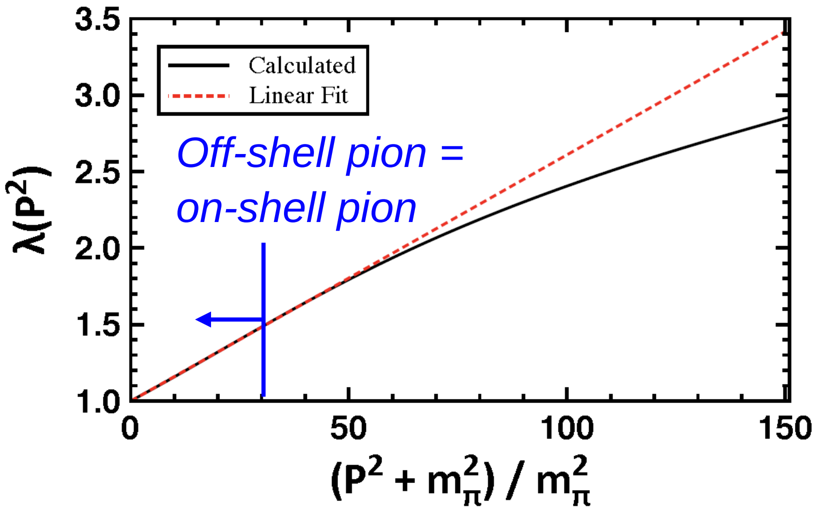


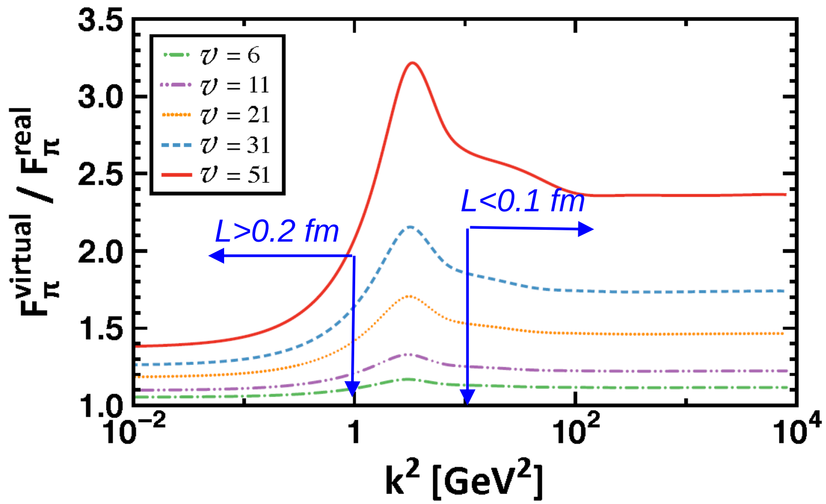

In the Sullivan process, the mesons in the nucleon cloud are virtual (off-shell) particles

- Recent calculations estimate the effect in the BSE/DSE framework – as long as $\lambda(\nu)$ is linear in $\nu$ 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$^2$ ($\nu$ =31) for pions and t<0.9 GeV$^2$($\nu_s$~3) for kaons

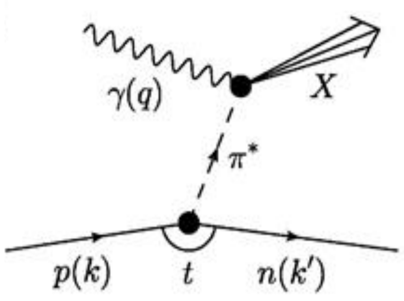
This means that pion and kaon structure functions can be accessed through the Sullivan process

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



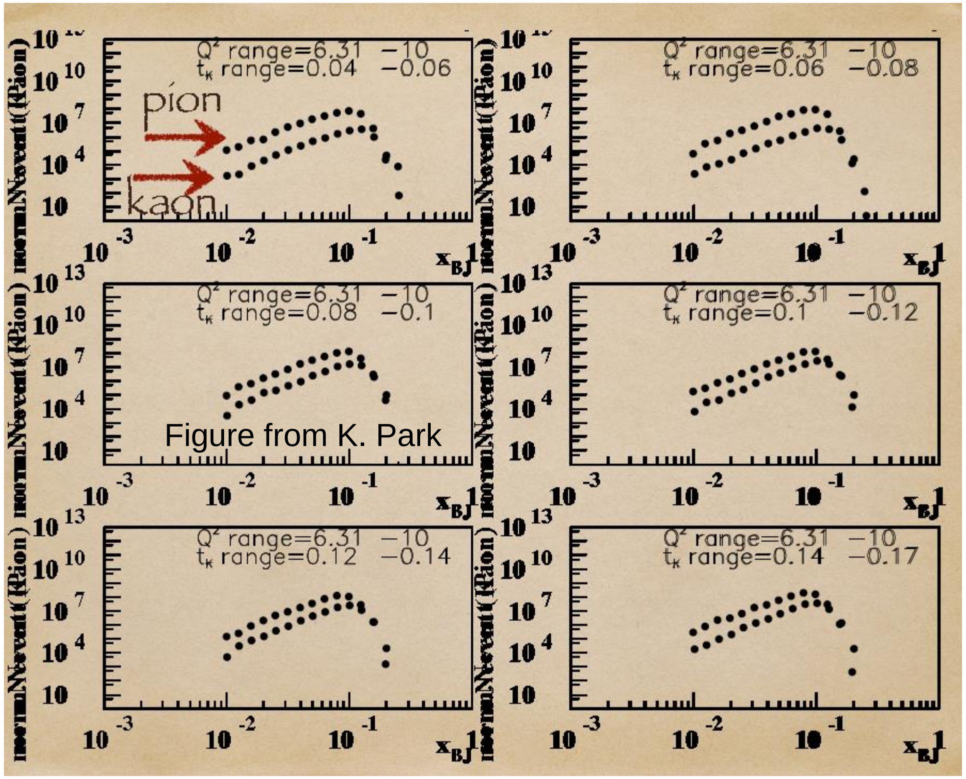
# Experimental Off-Shellness Considerations

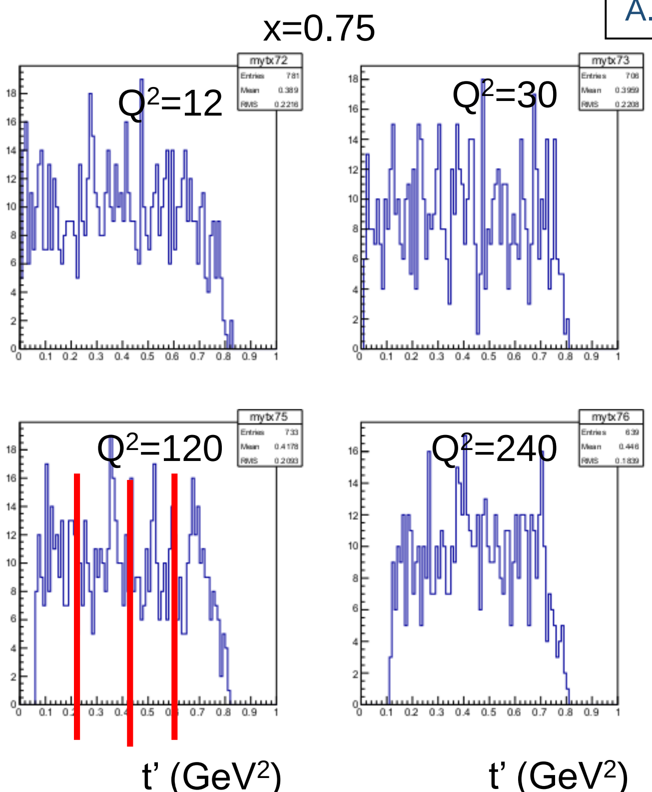



- Like nuclear binding corrections (neutron in deuterium)
- Bin in t to determine the off-shellness correction
- Compare with pion/kaon D-Y (→ pion/kaon flux factor!)

**EIC kinematic reach down to x=0.01 or a bit below**

T. Horn,
R. Trotta,
A. Vargas



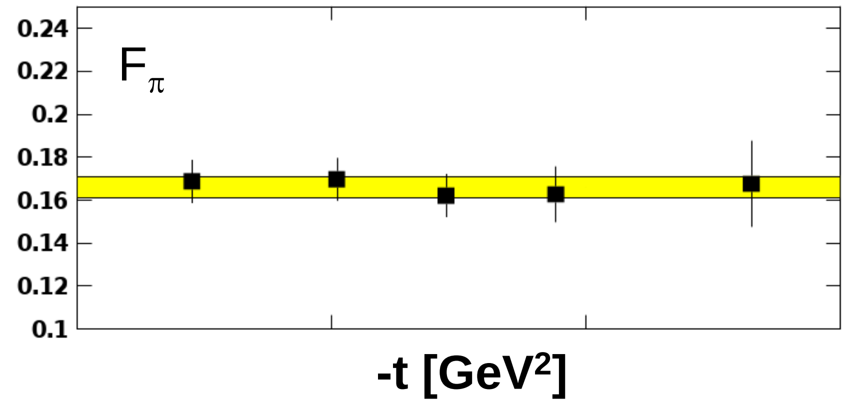

These are from initial trials and preliminary – we are redoing this now

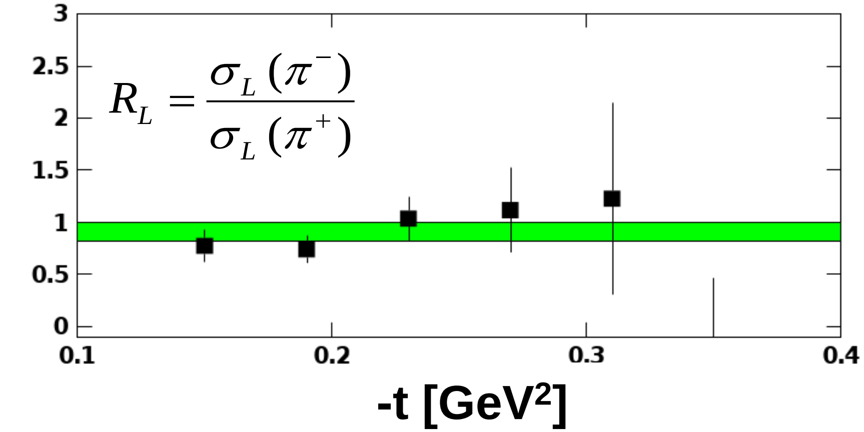
# Experimental Validation (Pion Form Factor example)

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

Experimental studies include:

- Take data covering a range in –t and compare with theoretical expectation
  - $F_\pi$ 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
  - $R_L$ (= $\sigma_L(\pi^-)/\sigma_L(\pi^+)$) approaches the pion charge ratio, consistent with pion pole dominance




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

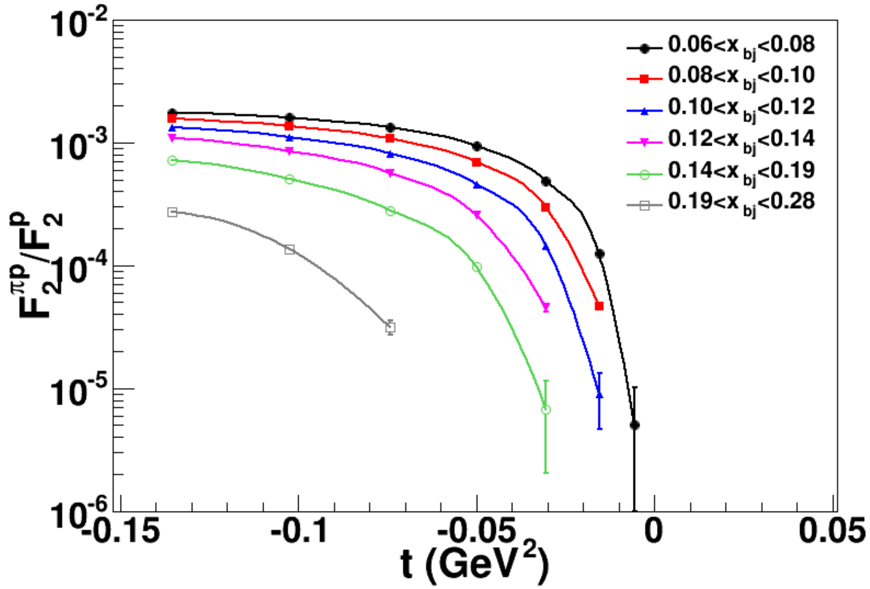
*[R. J. Perry et al., arXiV:1811.09356 (2019).]*

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

# 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?

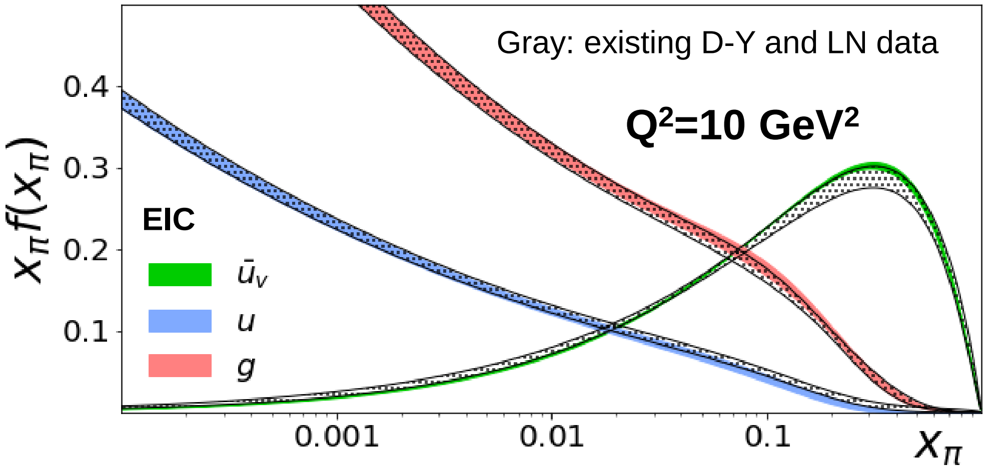
- $L_{EIC} = 10^{34} = 1000 \times L_{HERA}$
- Detection fraction @ EIC in general much higher than at HERA
- Fraction of proton wave function related to pion Sullivan process is roughly $10^{-3}$ for a small –t bin (0.02).
- Hence, pion data @ EIC should be comparable or better than the proton data @ 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.

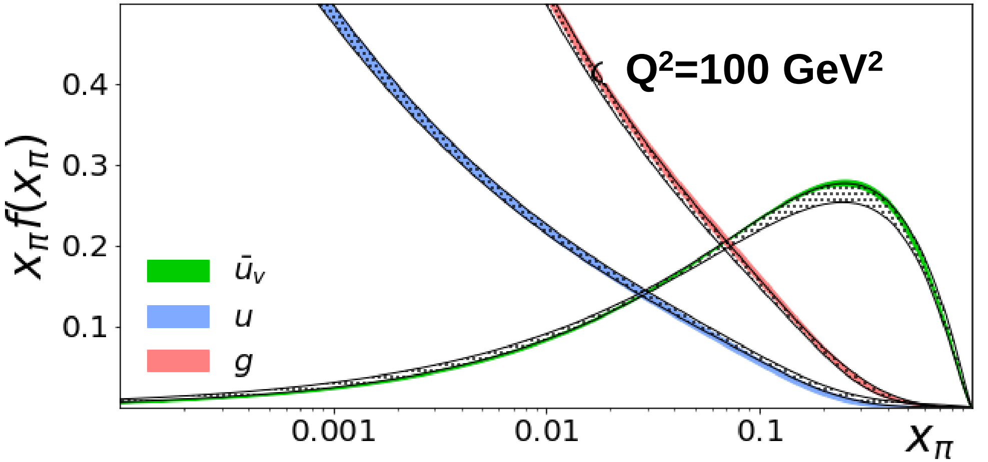



*Ratio of the $F_2$ structure function related to the pion Sullivan process as compared to the proton $F_2$ structure function in the low-t vicinity of the pion pole, as a function of Bjorken-x (for JLab kinematics)*

# Global pion PDF fit with EIC pseudodata

- ❑ 5 GeV (e-) on 50 GeV (p)
- ❑ 0.1 < y < 0.8
- ❑ EIC pseudodata fitted using self-serve pion PDF framework
- ❑ EIC will improve the PDFs, especially for kaons as will have similar-quality data.
- ❑ DY measurements by COMPASS++/AMBER could constrain x>02




**Precision gluon constraints of pion and kaon PDFs <u>are</u> possible.**

# Towards Kaon Structure Functions

- To determine projected kaon structure function data from pion structure function projections, we scaled the pion to the kaon case with the *coupling constants*

*S. Goloskokov and P. Kroll, Eur.Phys.J. A**47** (2011) 112:*

$g_{\pi NN}$=13.1 $g_{Kp\Lambda}$=-13.3 $g_{Kp\Sigma^0}$=-3.5

(these values can vary depending on what model one uses, so sometimes a range is used, *e.g.*, 13.1-13.5 for $g_{\pi NN}$)

- Good geometric detection efficiencies for n, $\Lambda$, $\Sigma$ detection at low -t

| **Process** | **Forward Particle** | **Geometric Detection Efficiency (at small –t)** |
|---|---|---|
| $^1H(e,e'\pi^+)n$ | N | > 20% |
| $^1H(e,e'K^+)\Lambda$ | $\Lambda$ | 50% |
| $^1H(e,e'K^+)\Sigma$ | $\Sigma$ | 17% |

- Folding this together: kaon projected structure function data will be roughly of similar quality as the projected pion structure function data for the small-t geometric forward particle detection acceptances at JLEIC.

# Plug event into GEMC: 5x100 GeV2, e/p beams

```
**************************************************************************************
 G4Track Information:   Particle = lambda,   Track ID = 4,   Parent ID = 0
**************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0        0        0        0  1.39e+05        0        0         0       root initStep
    1      -98     3.65 2.04e+03  1.39e+05        0 2.04e+03  2.04e+03 vac_det1_beamline_pipe_ionside_IonExtranceAperture Transportation
    2    -98.1     3.66 2.04e+03  1.39e+05        0        2  2.05e+03       root Transportation
    3     -240     8.94 4.99e+03  1.39e+05        0 2.95e+03     5e+03 det1_beamline_magnet_ion_downstream_dipole1_front Transportation
    4     -240     8.94 4.99e+03  1.39e+05        0    2e-07     5e+03 det1_beamline_magnet_ion_downstream_dipole1_inner Transportation
    5     -312     11.6 6.49e+03  1.39e+05        0  1.5e+03   6.5e+03 det1_beamline_magnet_ion_downstream_dipole1_back Transportation
    6     -312     11.6 6.49e+03  1.39e+05        0    2e-07   6.5e+03       root Transportation
    7     -336     12.5 6.99e+03  1.39e+05        0      500     7e+03 det1_beamline_magnet_ion_downstream_quadrupole1_front Transportation
    8     -336     12.5 6.99e+03  1.39e+05        0    2e-07     7e+03 det1_beamline_magnet_ion_downstream_quadrupole1_inner Transportation
    9     -393     14.7 8.19e+03  1.39e+05        0  1.2e+03   8.2e+03 det1_beamline_magnet_ion_downstream_quadrupole1_back Transportation
   10     -393     14.7 8.19e+03  1.39e+05        0    2e-07   8.2e+03       root Transportation
   11     -441     16.4 9.19e+03  1.39e+05        0    1e+03   9.2e+03 det1_beamline_magnet_ion_downstream_quadrupole2_front Transportation
   12     -441     16.4 9.19e+03  1.39e+05        0    2e-07   9.2e+03 det1_beamline_magnet_ion_downstream_quadrupole2_inner Transportation
   13     -556     20.7 1.16e+04  1.39e+05        0  2.4e+03  1.16e+04 det1_beamline_magnet_ion_downstream_quadrupole2_back Transportation
   14     -556     20.7 1.16e+04  1.39e+05        0    2e-07  1.16e+04       root Transportation
   15     -604     22.5 1.26e+04  1.39e+05        0    1e+03  1.26e+04 det1_beamline_magnet_ion_downstream_quadrupole3_front Transportation
   16     -604     22.5 1.26e+04  1.39e+05        0    2e-07  1.26e+04 det1_beamline_magnet_ion_downstream_quadrupole3_inner Transportation
   17     -662     24.7 1.38e+04  1.39e+05        0  1.2e+03  1.38e+04 det1_beamline_magnet_ion_downstream_quadrupole3_back Transportation
   18     -662     24.7 1.38e+04  1.39e+05        0    2e-07  1.38e+04       root Transportation
   19     -700     26.1 1.46e+04  1.39e+05        0      800  1.46e+04 det1_beamline_magnet_ion_downstream_solenoid1_front Transportation
   20     -700     26.1 1.46e+04  1.39e+05        0    2e-07  1.46e+04 det1_beamline_magnet_ion_downstream_solenoid1_inner Transportation
   21     -815     30.4  1.7e+04  1.39e+05        0  2.4e+03   1.7e+04 det1_beamline_magnet_ion_downstream_solenoid1_back Transportation
   22     -815     30.4  1.7e+04  1.39e+05        0    2e-07   1.7e+04       root Transportation
   23     -853     31.8 1.78e+04  1.39e+05        0      793  1.78e+04 det1_beamline_magnet_ion_downstream_dipole2_front Transportation
   24     -853     31.8 1.78e+04  1.39e+05        0    2e-07  1.78e+04 det1_beamline_magnet_ion_downstream_dipole2_inner Transportation
   25     -900     33.5 1.87e+04  1.39e+05        0      967  1.88e+04 det1_beamline_magnet_ion_downstream_dipole2_inner Decay

**************************************************************************************
 G4Track Information:   Particle = proton,   Track ID = 6,   Parent ID = 4
**************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0     -900     33.5 1.87e+04  1.15e+05        0        0         0 det1_beamline_magnet_ion_downstream_dipole2_inner initStep
    1     -992     37.5 2.18e+04  1.15e+05 1.07e-22 3.04e+03  3.04e+03 det1_beamline_magnet_ion_downstream_dipole2_back Transportation
    2     -992     37.5 2.18e+04  1.15e+05 7.07e-33    2e-07  3.04e+03       root Transportation
    3 -1.16e+03     56.7 3.63e+04  1.15e+05 5.15e-22 1.45e+04  1.76e+04 det1_beamline_magnet_ion_downstream_dipole3_front Transportation
    4 -1.16e+03     56.7 3.63e+04  1.15e+05 7.07e-33    2e-07  1.76e+04 det1_beamline_magnet_ion_downstream_dipole3_inner Transportation
    5 -1.31e+03     61.9 4.03e+04  1.15e+05 1.42e-22    4e+03  2.16e+04 det1_beamline_magnet_ion_downstream_dipole3_back Transportation
    6 -1.31e+03     61.9 4.03e+04  1.15e+05 7.09e-33    2e-07  2.16e+04       root Transportation
    7 -1.7e+04      404    3e+05  1.15e+05  9.2e-21  2.6e+05  2.82e+05  OutOfWorld Transportation

**************************************************************************************
 G4Track Information:   Particle = pi-,   Track ID = 5,   Parent ID = 4
**************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0     -900     33.5 1.87e+04  2.41e+04        0        0         0 det1_beamline_magnet_ion_downstream_dipole2_inner initStep
    1 -1.31e+03     45.9 2.18e+04  2.41e+04 1.11e-22 3.06e+03  3.06e+03 det1_beamline_magnet_ion_downstream_dipole2_back Transportation
    2 -1.31e+03     45.9 2.18e+04  2.41e+04 7.45e-33 2.05e-07  3.06e+03       root Transportation
    3 -6.39e+04  1.2e+03    3e+05  2.41e+04 1.04e-20 2.85e+05  2.88e+05  OutOfWorld Transportation

**************************************************************************************
* G4Track Information:   Particle = e-,   Track ID = 3,   Parent ID = 0
**************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
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    1     4.48     31.9    -5.87  6.89e+03 1.63e-24     32.8      32.8 vac_det1_beamline_pipe_eleside_VertexChamber Transportation
    2     4.62     32.9    -6.05  6.89e+03    0.298     1.02      33.8 vac_det1_beamline_pipe_ionside_VertexChamber Transportation
```
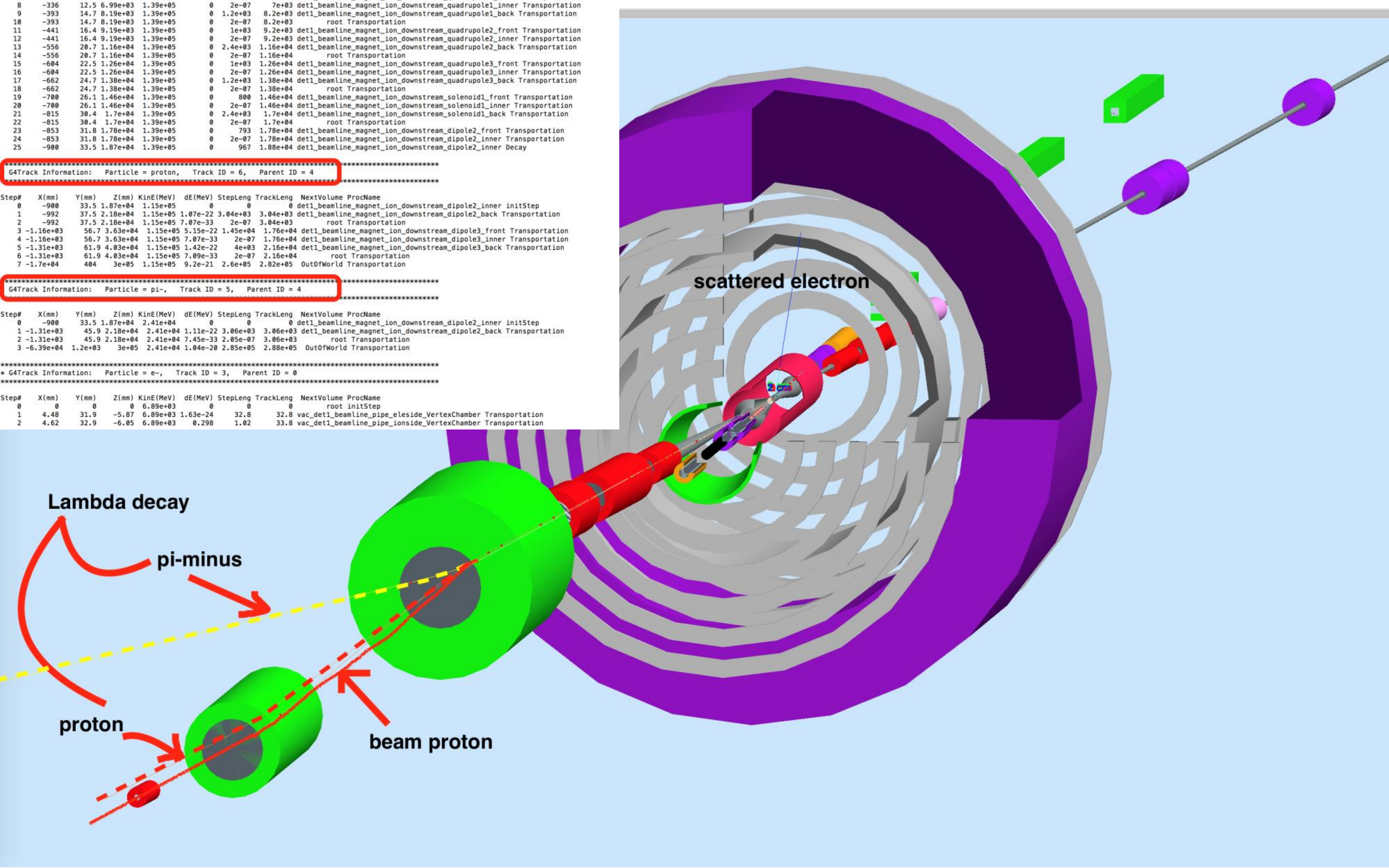
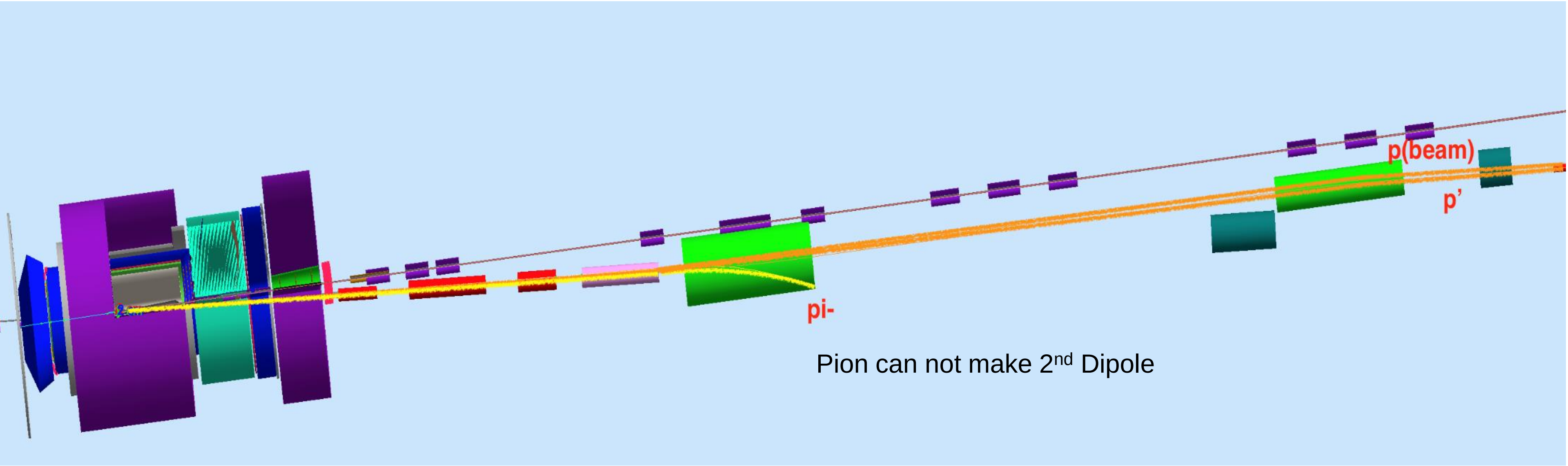



# Detection of $^1H(e,e'K^+)\Lambda$, $\Lambda$ decay to $p + \pi^-$



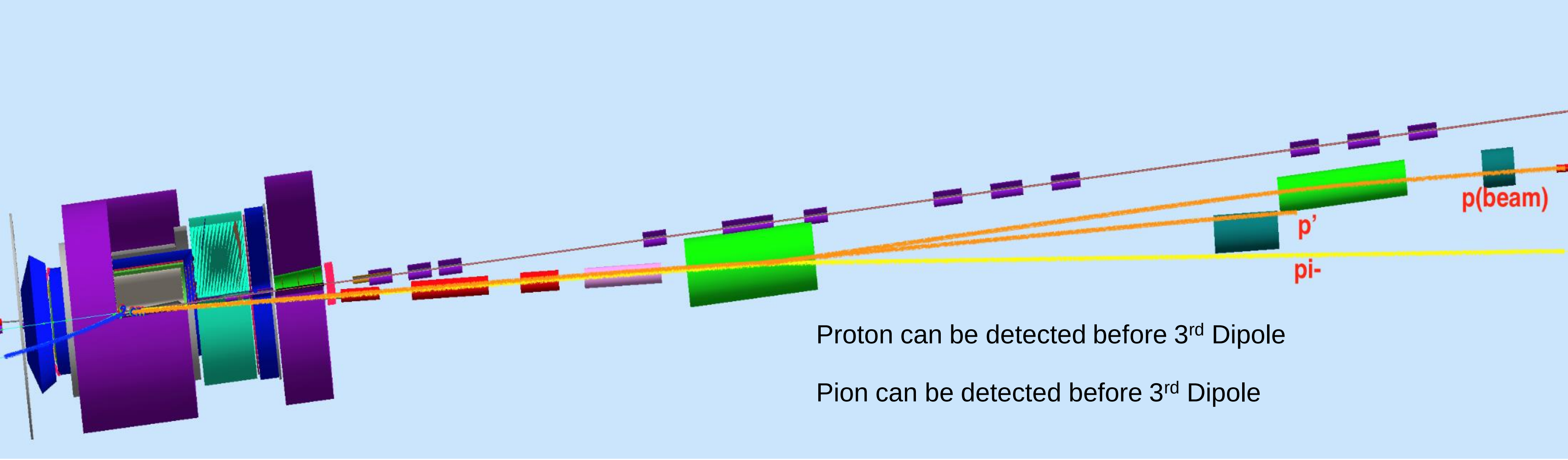



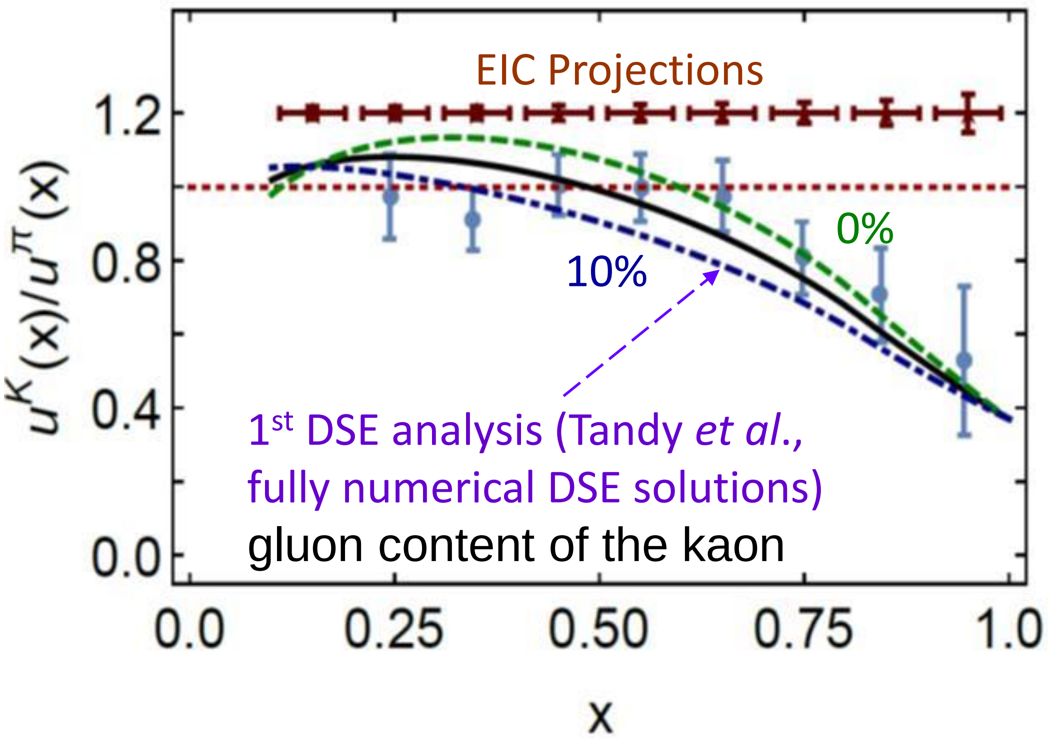

Figure from K.Park

# Kaon structure functions – gluon pdfs

T. Horn, C. Roberts, R. Ent

Based on Lattice QCD calculations and DSE calculations:

- Valence quarks carry 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




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.

# Calculable Limits for Parton Distributions

Calculable limits for ratios of PDFs at x = 1, same as predictive power of x → 1 limits for spin-averaged and spin-dependent proton structure functions (asymmetries)

$$\boxed{\left.\frac{u_V^K(x)}{u_V^\pi(x)}\right|_{x\to 1} = 0.37\,, \quad \left.\frac{u_V^\pi(x)}{\bar{s}_V^K(x)}\right|_{x\to 1} = 0.29}$$

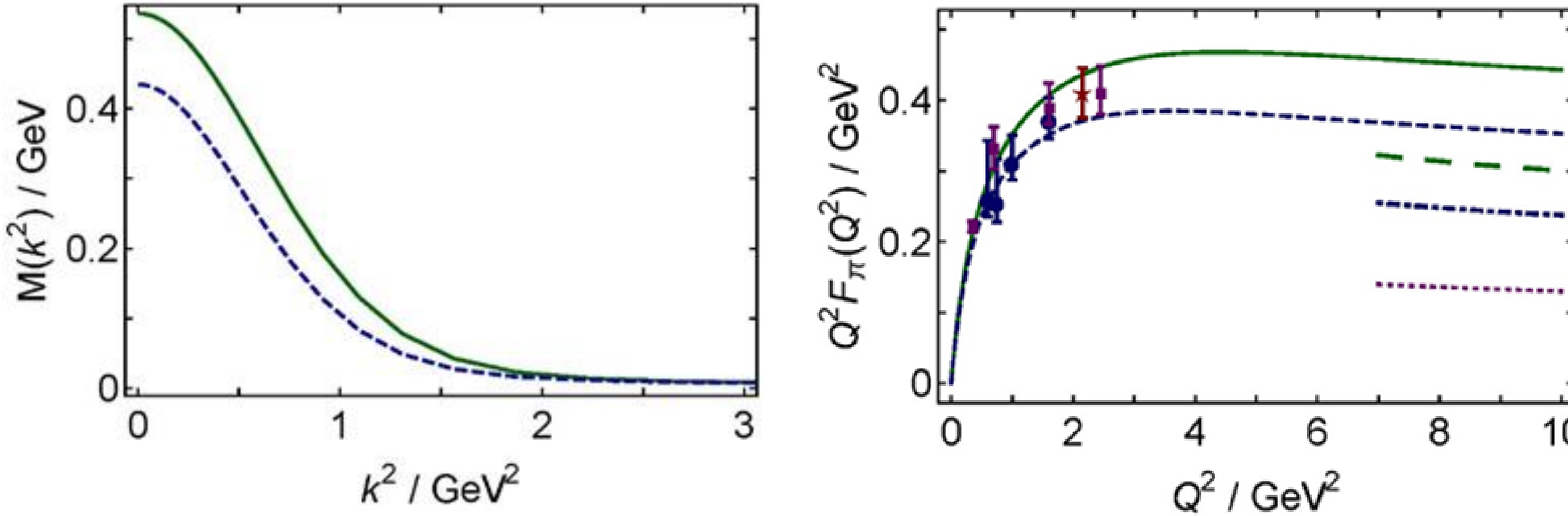
On the other hand, inexorable growth in both pions' and kaons' gluon and sea-quark content at asymptotic $Q^2$ should only be driven by pQCD splitting mechanisms. Hence, also calculable limits for ratios of PDFs at x = 0, *e.g.*,

$$\boxed{\lim_{x\to 0} \frac{u^K(x;\zeta)}{u^\pi(x;\zeta)} \overset{\Lambda_{\rm QCD}/\zeta\simeq 0}{\to} 1}$$

The inexorable growth in both pions' and kaons' gluon content at asymptotic $Q^2$ brings connection to gluon saturation.

# Pion Form Factor and Emergent Mass

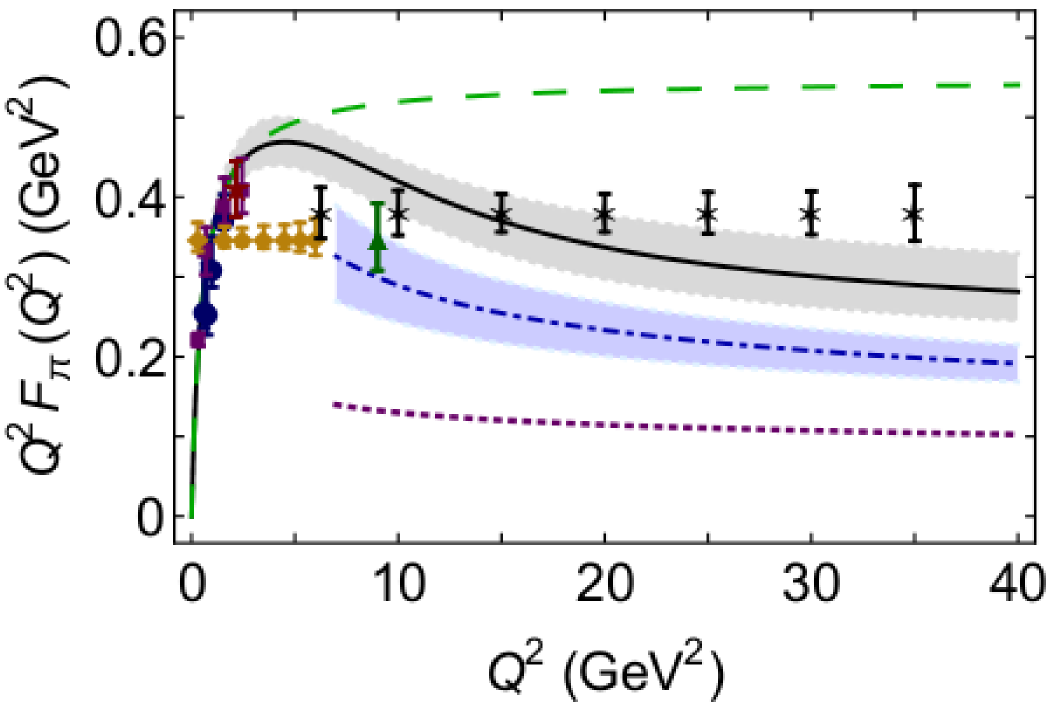
Muyang Chen, Craig Roberts




*Left panel. Two dressed-quark mass functions distinguished by the amount of DCSB: emergent mass generation is 20% stronger in the system characterized by the solid green curve, which describes the more realistic case. Right panel.* $F_\pi(Q^2)$ *obtained with the mass function in the left panel:* $r_\pi = 0.66$ *fm with the solid green curve and* $r_\pi = 0.73$ *fm with the dashed blue curve. The long-dashed green and dot-dashed blue curves are predictions from the QCD hard-scattering formula, obtained with the related, computed pion PDAs. The dotted purple curve is the result obtained from that formula if the conformal-limit PDA is used,* $\phi(x)=6x(1-x)$.

# Pion Form Factor Prospects

1. Models show a strong dominance of $\sigma_L$ at small –t at large $Q^2$.
2. Assume dominance of this longitudinal cross section
3. Measure the $\pi^-/\pi^+$ ratio to verify – it will be diluted (smaller than unity) if $\sigma_T$ is not small, or if non-pole backgrounds are large




- Assumed 5 GeV($e^-$) x 100 GeV(p) with an integrated luminosity of 20 $fb^{-1}$/year, and similar luminosities for d beam data
- $R=\sigma_L/\sigma_T$ assumed from VR model – and assume that $\pi$ pole dominance at small t confirmed in $^2H$ $\pi^-/\pi^+$ ratios
- Assumed a 10% experimental systematic uncertainty, and a 100% systematic uncertainty in the model subtraction to isolate $\sigma_L$

Can we measure the kaon form factor at EIC?

Not clear – needs guidance from JLab 12- GeV

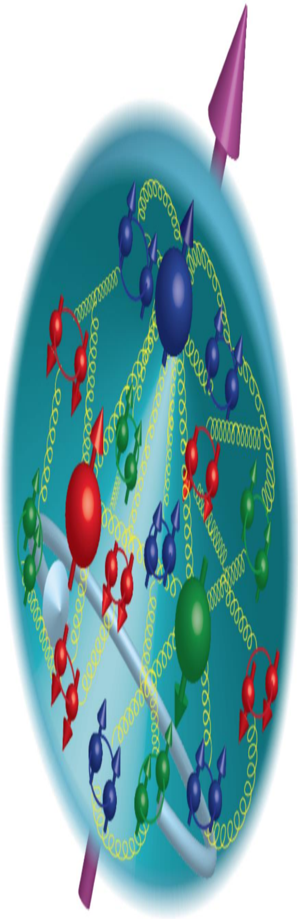
*[Garth Huber, Tanja Horn]*

# Conclusions – Pion and Kaon Structure

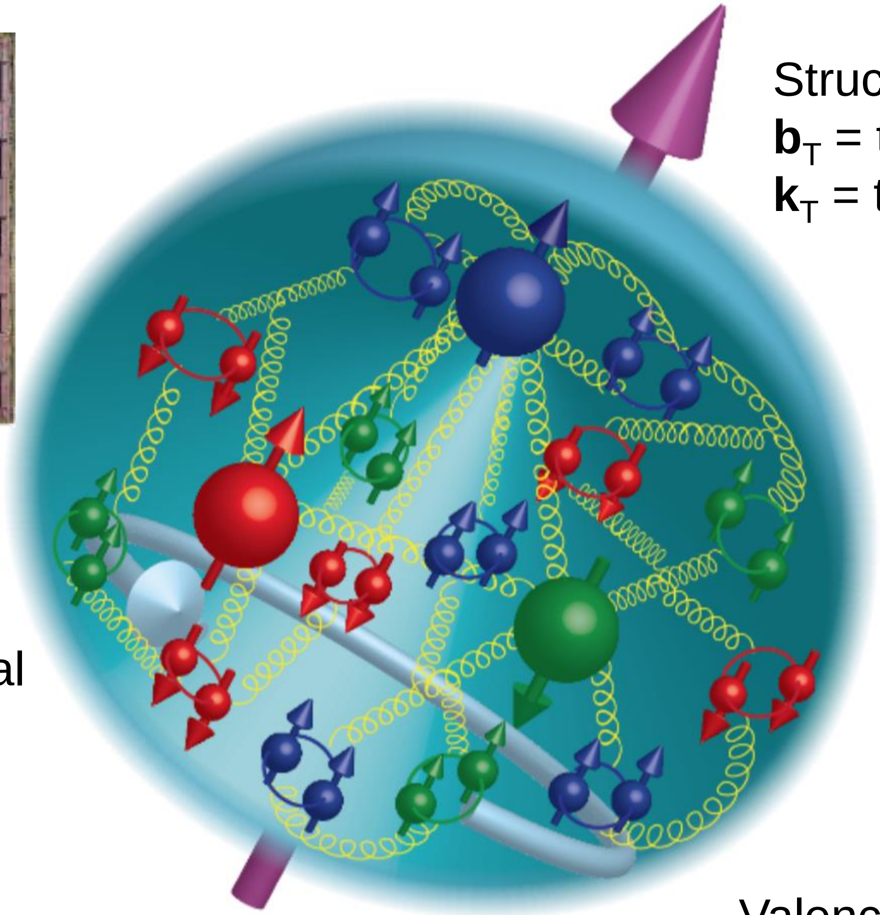
- Nucleons and the lightest mesons - pions and kaons, are the basic building blocks of nuclear matter. We **should** know their structure (functions).
- The distributions of quarks and gluons in pions, kaons, nucleons will differ.
  - Utilizing electroweak processes, be it through parity-violating processes or neutral vs charged-current interactions, some flavor dependence appears achievable.
  - If we can convince ourselves off-shellness considerations are under control, one could also access pion GPDs and TMDs.
- Is the origin of mass encoded in differences of gluons in pions, kaons and nucleons (at non-asymptotic $Q^2$)?
  - How much glue is in the pion?
- The pion form factor may be measured at an EIC up to $Q^2 = 35$ GeV$^2$, and could provide a direct connection to mass generation in the Standard Model.
- Some effects may appear trivial – the heavier-mass quark in the kaon “robs” more of the momentum, and the structure functions of pions, kaons and protons at large-x should be different, but confirming these would be **textbook material**.

# Nuclear Femtography

# Proton Viewed in High Energy Electron Scattering: 1 Longitudinal Dimension



# Proton Tomography: 2 New Dimensions Transverse to Longitudinal Momentum

Structure mapped in terms of
$\mathbf{b}_T$ = transverse position
$\mathbf{k}_T$ = transverse momentum

**Nuclei!**

**Goal:**
**Unprecedented**
**21st Century Imaging**
**of Hadronic Matter**

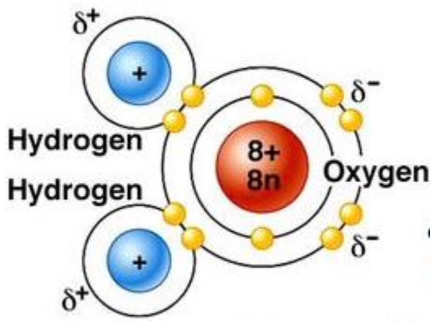
Direction of longitudinal momentum normal to plane of slide

Valence Quarks: JLab 12 GeV
Sea Quarks and Gluons: EIC

# Nuclear Femtography – Subatomic Matter is Unique

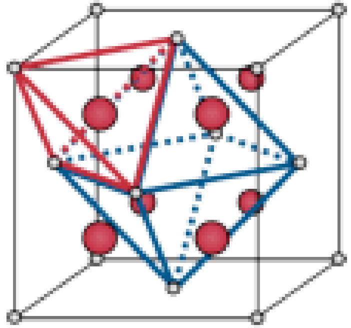
- Localized mass and charge centers – vast "open" space:

Molecule:



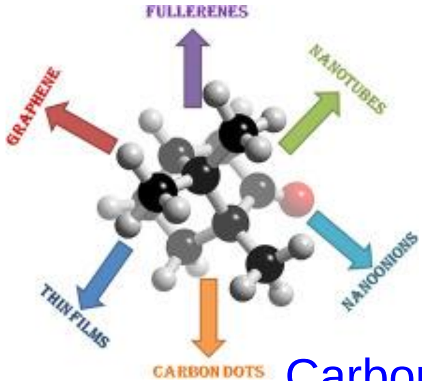

"Water"

Crystal:



Rare-Earth metal

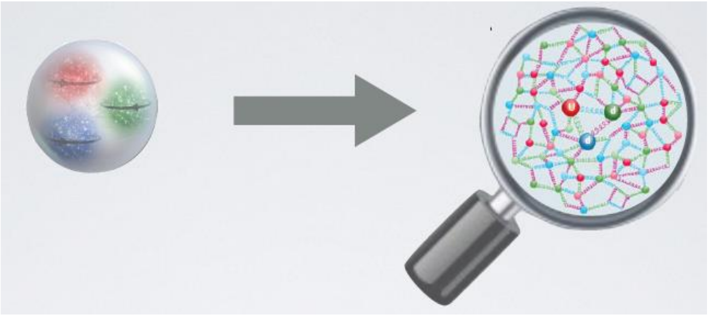
Nanomaterial:




Carbon-based

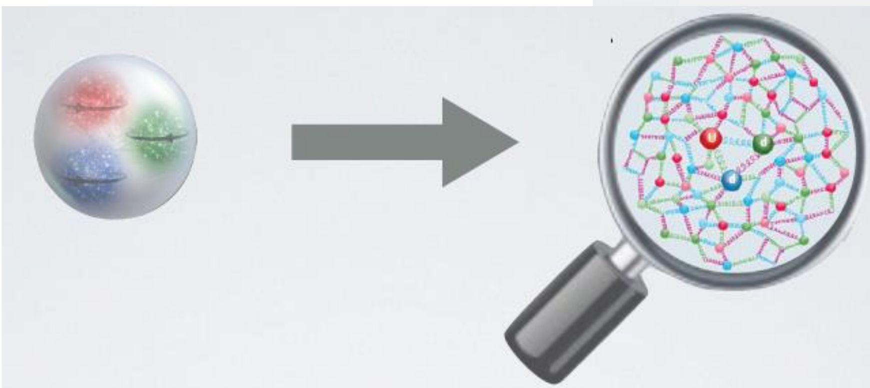
**Interactions and structure are mixed up in nuclear matter:** Nuclear matter is made of quarks that are bound by gluons that also bind themselves. Unlike with the more familiar atomic and molecular matter, the interactions and structures are inextricably mixed up, and the observed properties of nucleons and nuclei, such as mass & spin, emerge out of this complex system.

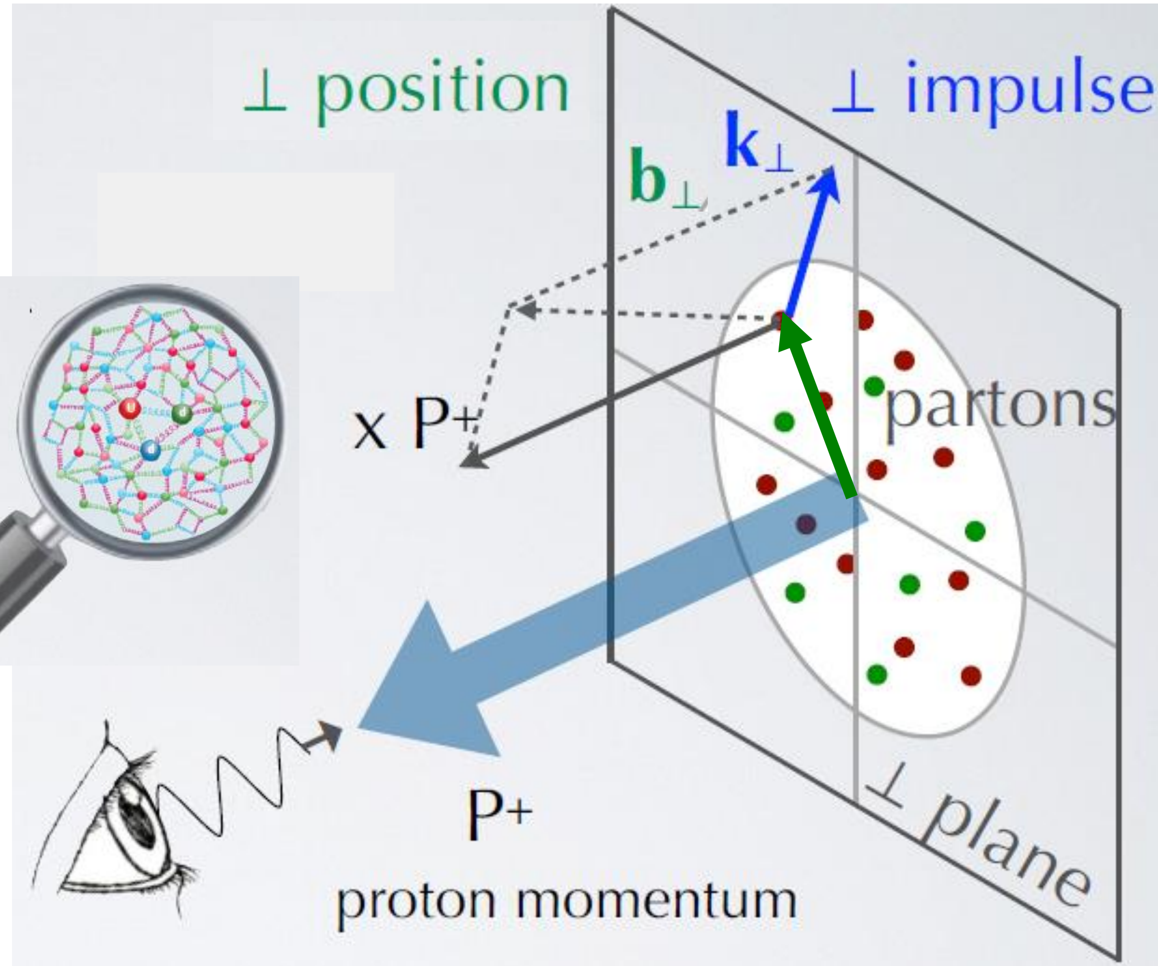
- Not so in proton structure!



# Nuclear Femtography - Imaging

In other sciences, imaging the physical systems under study has been key to gaining new understanding.






Structure mapped in terms of

$\mathbf{b}_T$ = transverse position

$\mathbf{k}_T$ = transverse momentum

# Exploring the 3D Nucleon 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.

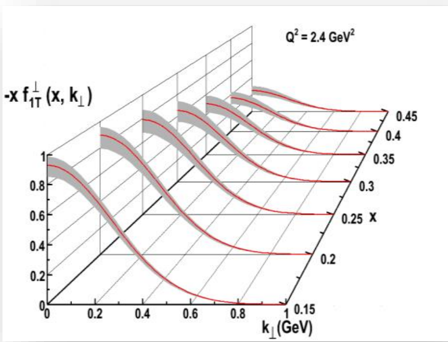
- **Semi-Inclusive Deep Inelastic Scattering (SIDIS)** cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum ($k_T$) of a parton and transverse momentum ($p_T$) created during the [parton → hadron] fragmentation process.

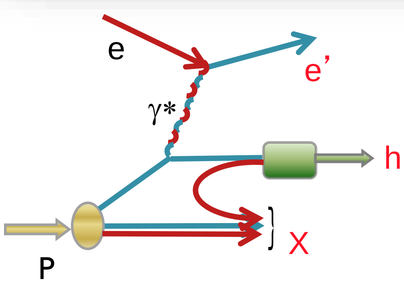
Nuclear Femtography

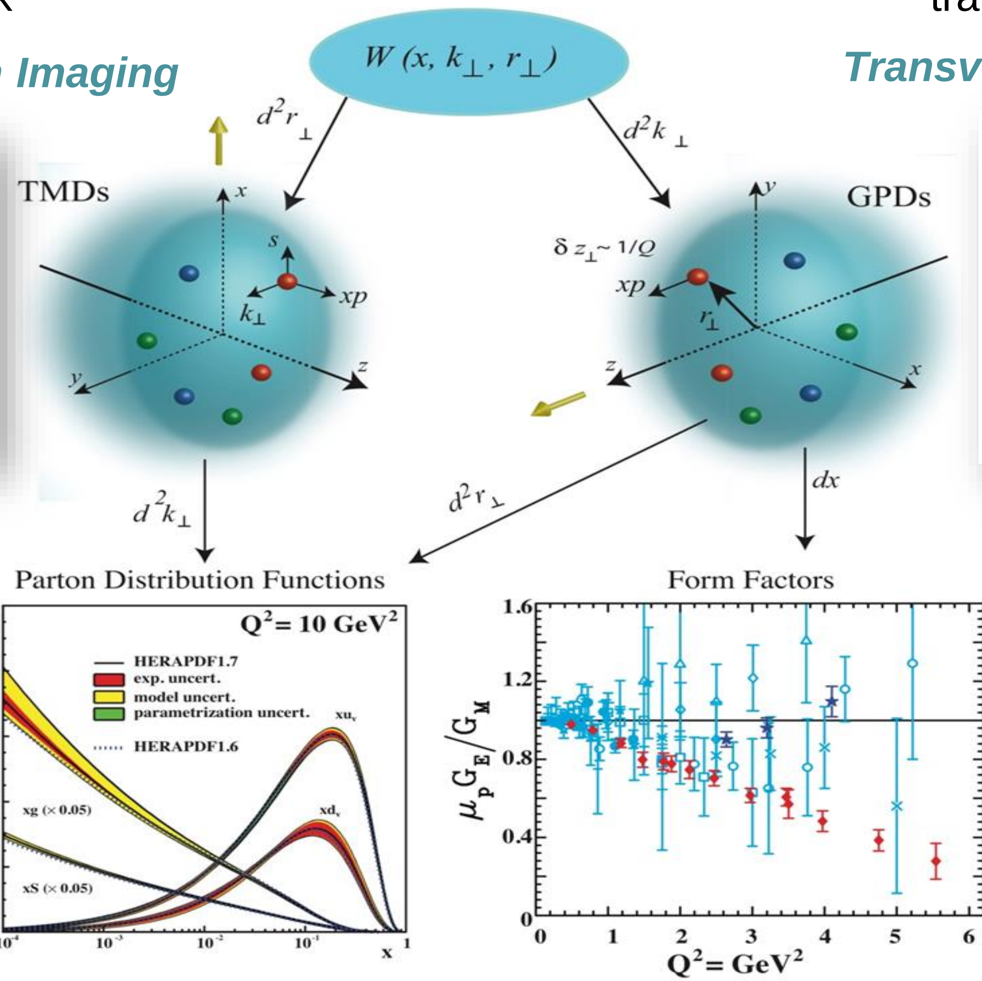
# 3D imaging of the Nucleon

**TMDs**: Longitudinal momentum fraction x and transverse momentum k

***Transverse Momentum Imaging***

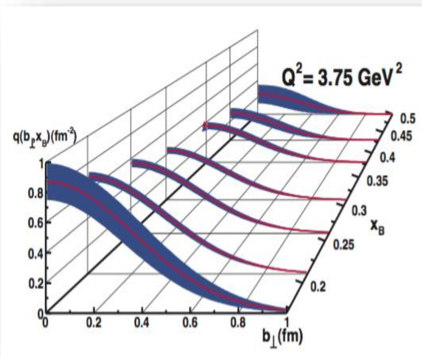


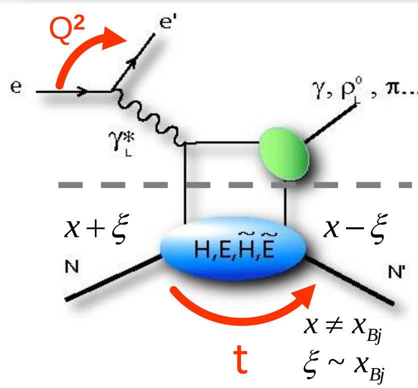




**GPDs**: Longitudinal momentum fraction x at transverse location b

***Transverse Spatial Imaging***

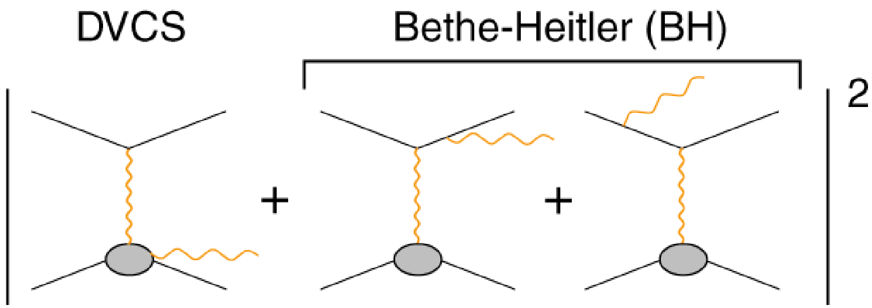


# Towards the 3D Structure of the Proton

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

σ(ep ⟶ epγ)=




Cleanest way to probe GPDs

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

At leading twist:

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

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

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

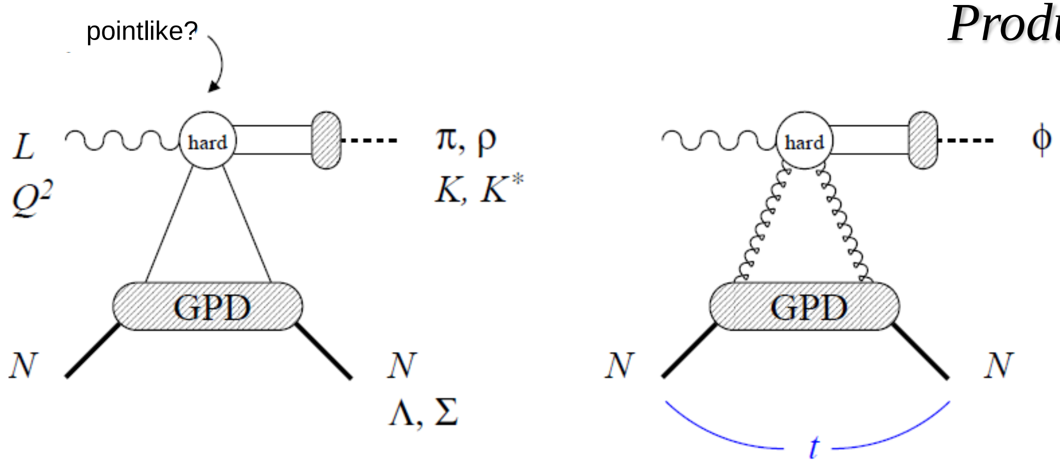
$$\underbrace{\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}}_{\text{Access in helicity-independent cross section}} - \underbrace{i\pi\, H(x=\xi,\xi,t)}_{\text{Access in helicity-dependent cross-section}} + \ldots$$


50

# Towards Spin/Flavor Separation

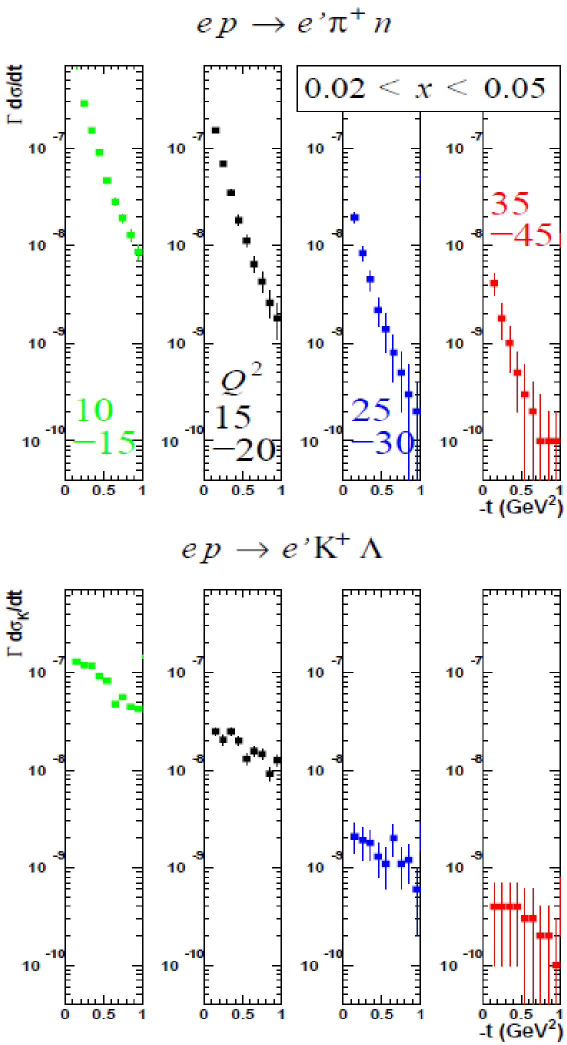
Exclusive Reactions: $\gamma^* N \rightarrow M + B$

*Deep Virtual Meson Production (DVMP)*

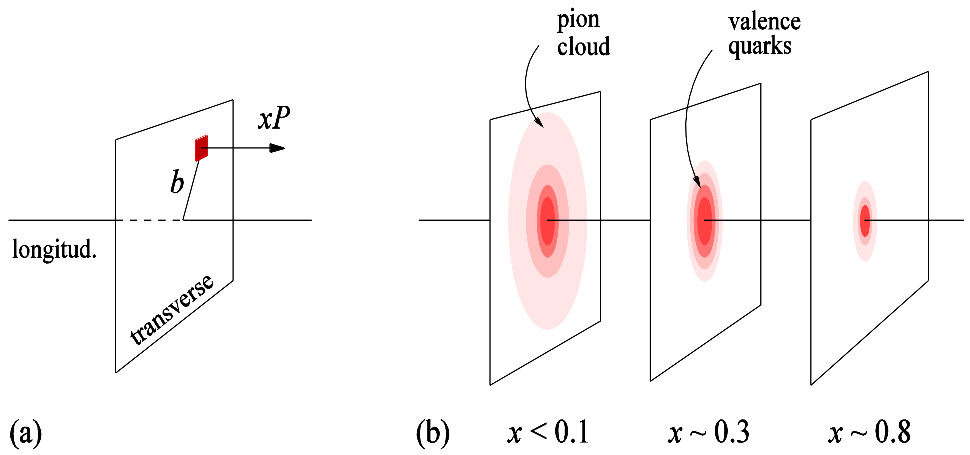


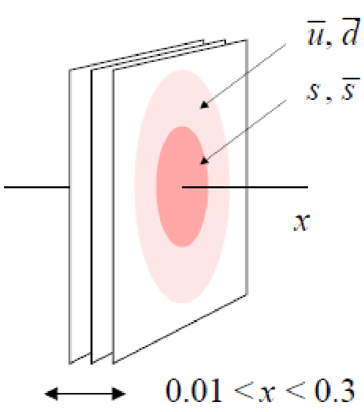

- ❑ Nucleon structure described by 4 (helicity non-flip) GPDs:
  - –*H, E* (unpolarized), $\tilde{H}$ $\tilde{E}$ (polarized)
- ❑ Quantum numbers in DVMP probe individual GPD components selectively
  - –Vector : ρ⁰/ρ+/*K** select *H, E*
  - –Pseudoscalar: π,η,*K* select the polarized GPDs, $\tilde{H}$ and $\tilde{E}$
- ❑ Need good understanding of reaction mechanism
  - –QCD factorization for mesons
  - –Can be verified experimentally through L/T separated cross sections

# Transverse (sea) quark imaging



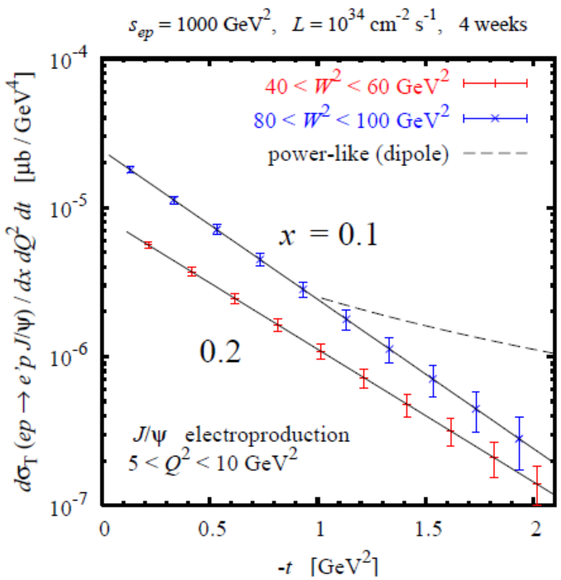

- GPDs as "$x$-dependent form factors"
  - Fourier transform of $t$-distribution provides transverse image

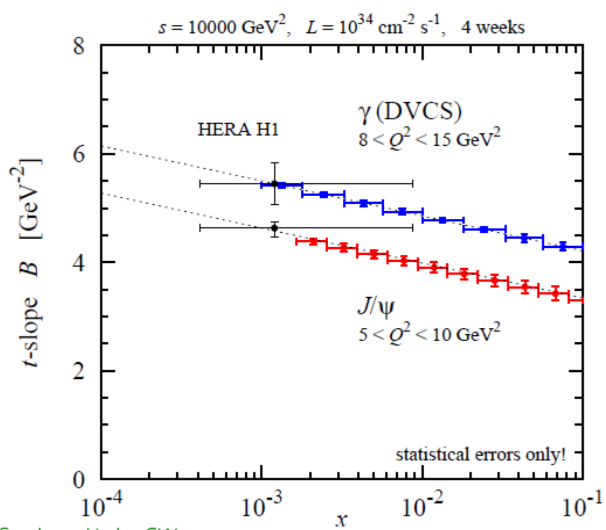


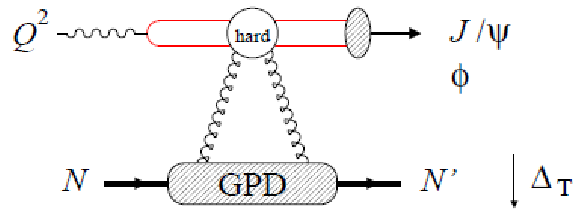

- Do strange and non-strange sea quark distributions have the same radius?
- $\pi$N or K$\Lambda$ components in nucleon?

# Transverse gluon imaging

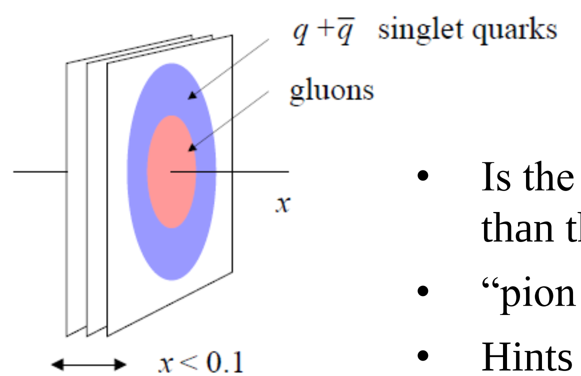



Sandacz, Hyde, CW




- Exclusive *J/Ψ* production a directly probe of gluons
- Hard scale given by mass, factorization ok even at low $Q^2$
- *t*-distribution powerlike for large -*t*?



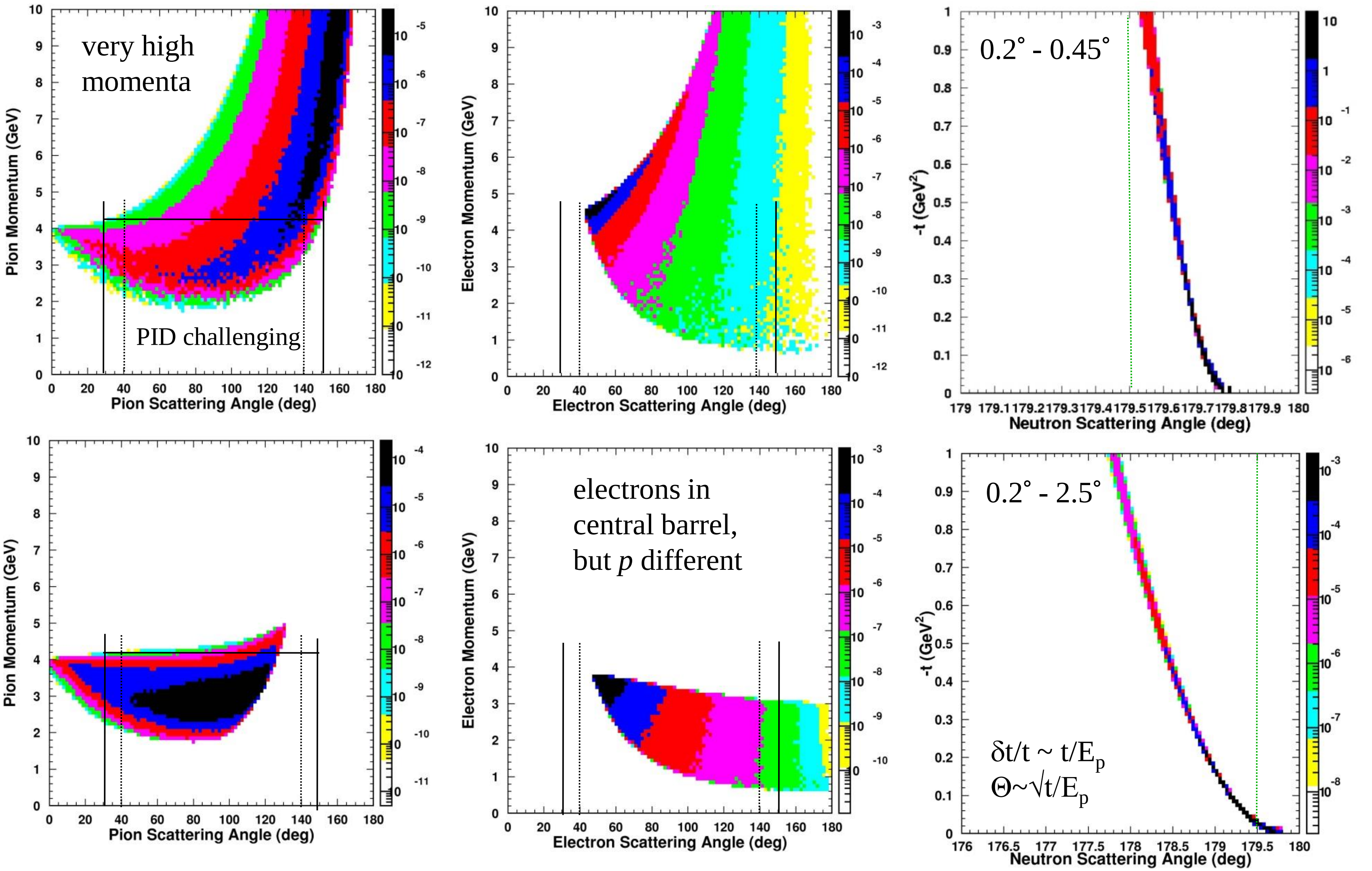

- Is the quark "radius" larger than the gluon radius?
- "pion cloud"
- Hints in HERA data

# Exclusive light meson kinematics

mesons | scattered electrons | recoil baryons

4 on 250 GeV

4 on 30 GeV



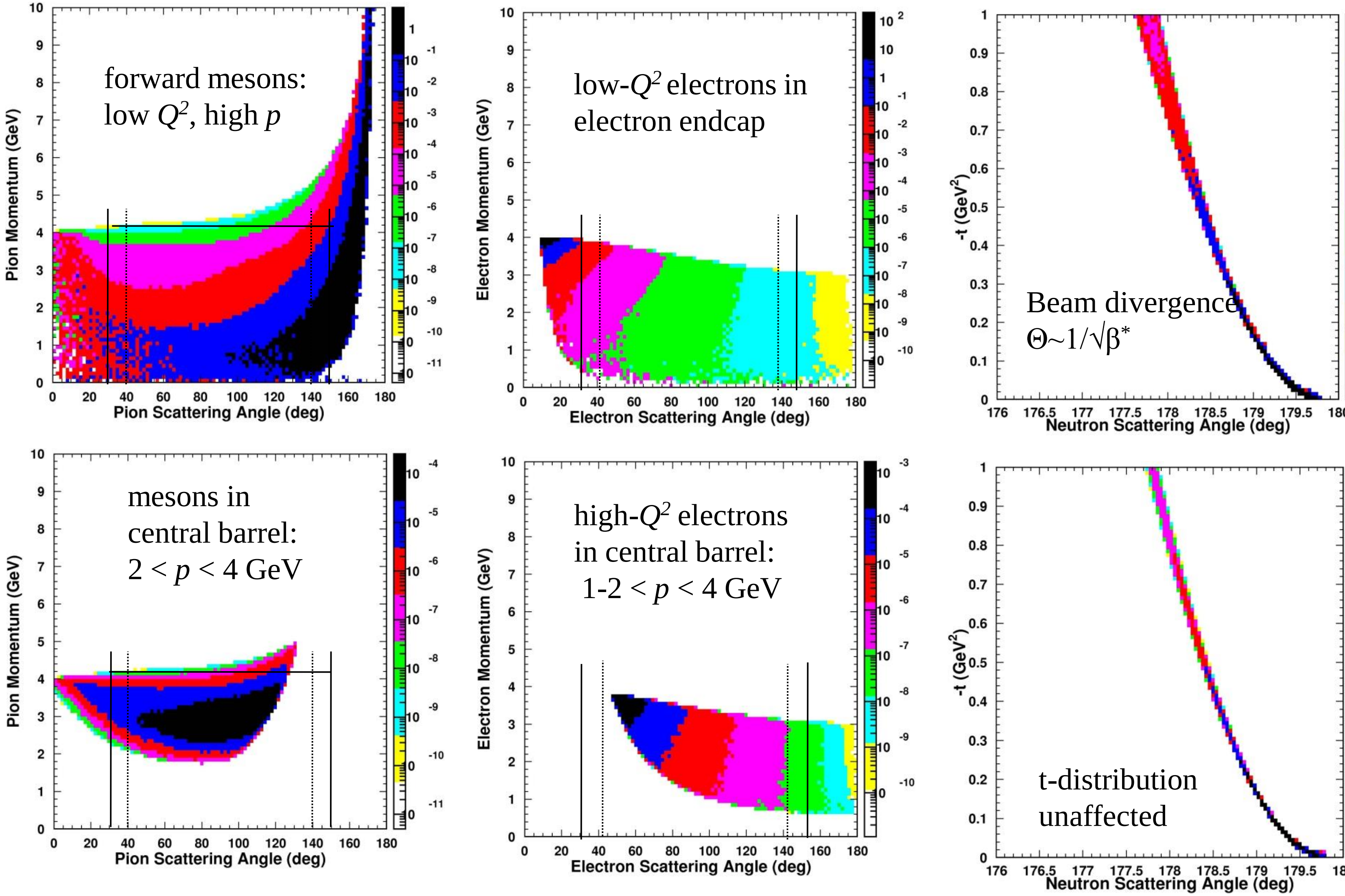

$ep \to e'\pi^+ n$

# Low (J/Psi) vs. high Q2 (light mesons)

mesons | scattered electrons | recoil baryons

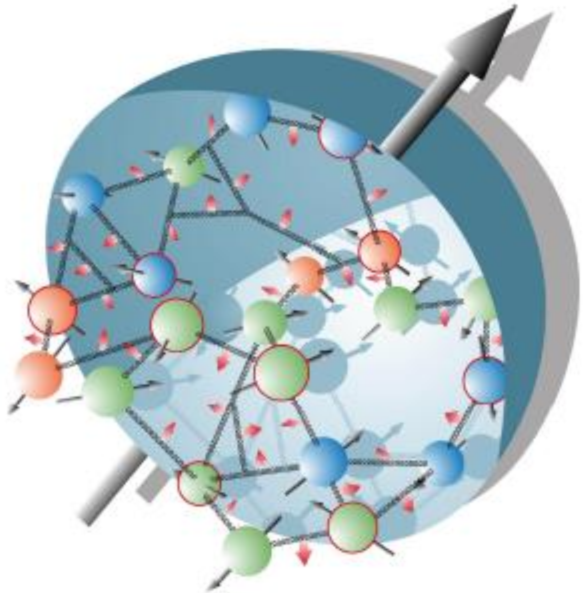
no $Q^2$ cut

$Q^2 > 10$ GeV$^2$




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

# The Incomplete Nucleon: Spin Puzzle



- Proton has spin-1/2
- Proton is a composite system consisting of spin-1/2 quarks and spin-1 gluons

This implies that the sum of angular momentum of quarks and gluons together must amount to 1/2. Can be due to:

| | |
|---|---|
| Quark spin ~0.25 | Quark orbital momentum |
| Gluon spin ~0.25 | Gluon orbital momentum |

Classical: ~ **r** x **p**

Needs a cross-product or something three-dimensional!

# Fundamental Questions

For understanding the origin of hadron masses and distribution of that mass within

- ❑ How do hadron masses and radii emerge for light-quark systems from QCD?
- ❑ What is the origin and role of dynamical chiral symmetry breaking?
- ❑ What is the interplay of the strong-mass and Higgs generation mechanisms?
- ❑ What are the basic mechanisms that determine the distribution of mass, momentum, charge, spin, etc. within hadrons?

Requires coherent effort in QCD phenomenology and continuum calculations, exa-scale computing as provided by lattice QCD, and experiment

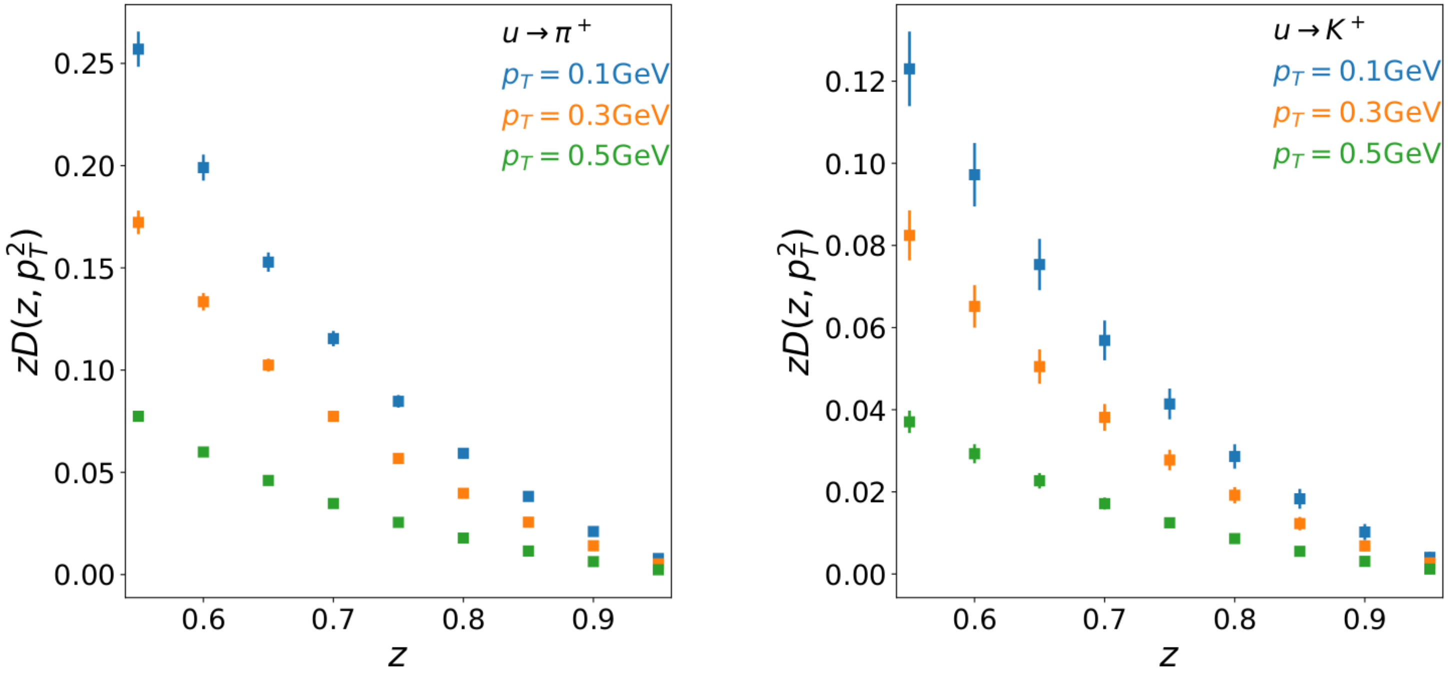
# Key Experimental Efforts

- Hadron masses in light quark systems
  - Pion and kaon parton distribution functions (PDFs) and generalized parton distributions (GPDs)
- Gluon (binding) energy in Nambu-Goldstone modes
  - Open charm production from pion and kaon
- Mass acquisition from Dynamical Chiral Symmetry Breaking (DCSB)
  - Pion and kaon form factors
- Strong vs. Higgs mass generating mechanisms
  - Valence quark distributions in pion and kaon at large momentum fraction x
- Timelike analog of mass acquisition
  - Fragmentation of a quark into pions or kaons

# Quark Fragmentation into Pions and Kaons

- Timelike analog of mass acquisition – measure fragmentation of quarks into pions and kaons

- Projections for integrated luminosity = 10 $fb^{-1}$




- EIC can provide precision data at large x (z>0.5) and transverse momentum (as picked up on the fragmentation process) of $k_T$=0.1, 0.3, 0.5

# The Structure of the Proton

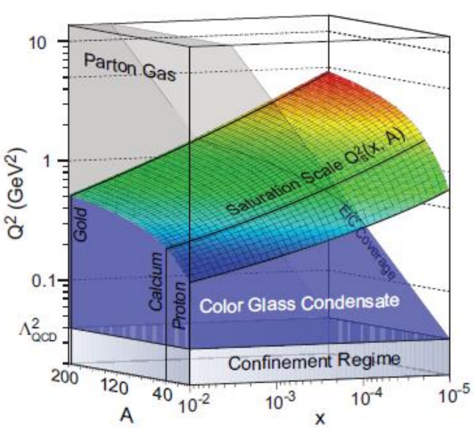
Naïve Quark Model: proton = uud (valence quarks)

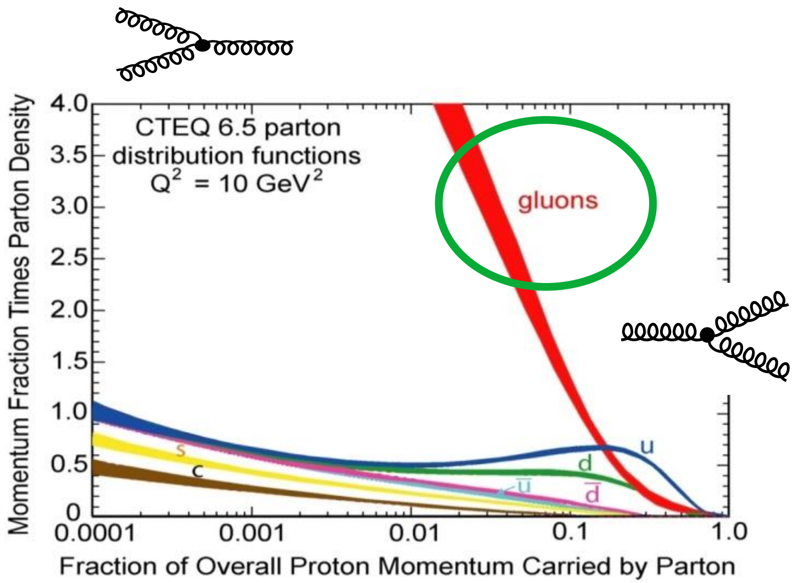
QCD: proton = $uud + u\bar{u} + d\bar{d} + s\bar{s} + \ldots$

The proton sea has a non-trivial structure: $\bar{u} \neq \bar{d}$

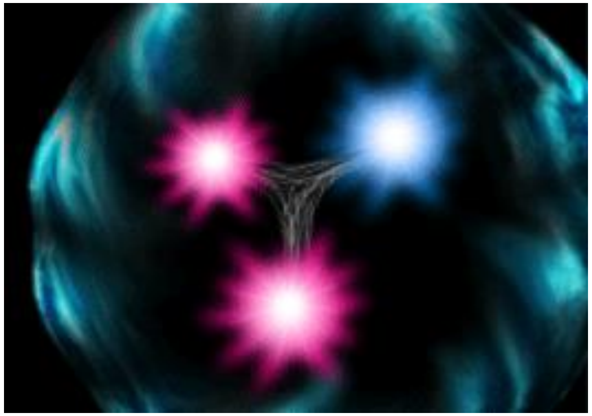
& gluons are abundant

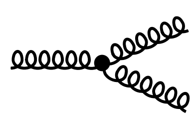
gluon dynamics




Non-trivial sea structure



- The proton is **far more** than just its up + up + down (valence) quark structure
- Gluon ≠ photon: Radiates  and recombines: