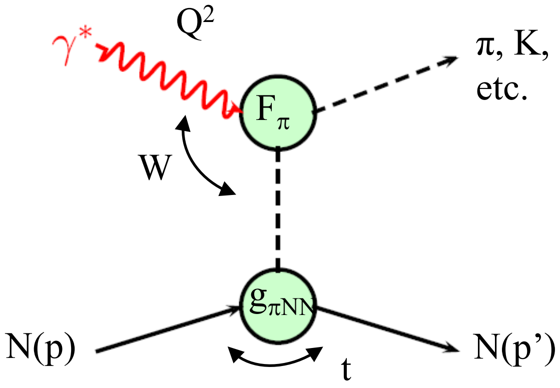
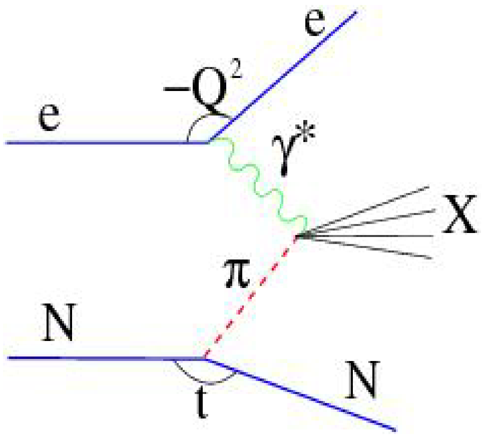
# Structure of Pion and Kaon and Emergence of Hadron Mass





Tanja Horn

THE CATHOLIC UNIVERSITY OF AMERICA

Jefferson Lab
Thomas Jefferson National Accelerator Facility



20th International Conference on Hadron Spectroscopy and Structure (HADRON 2023)

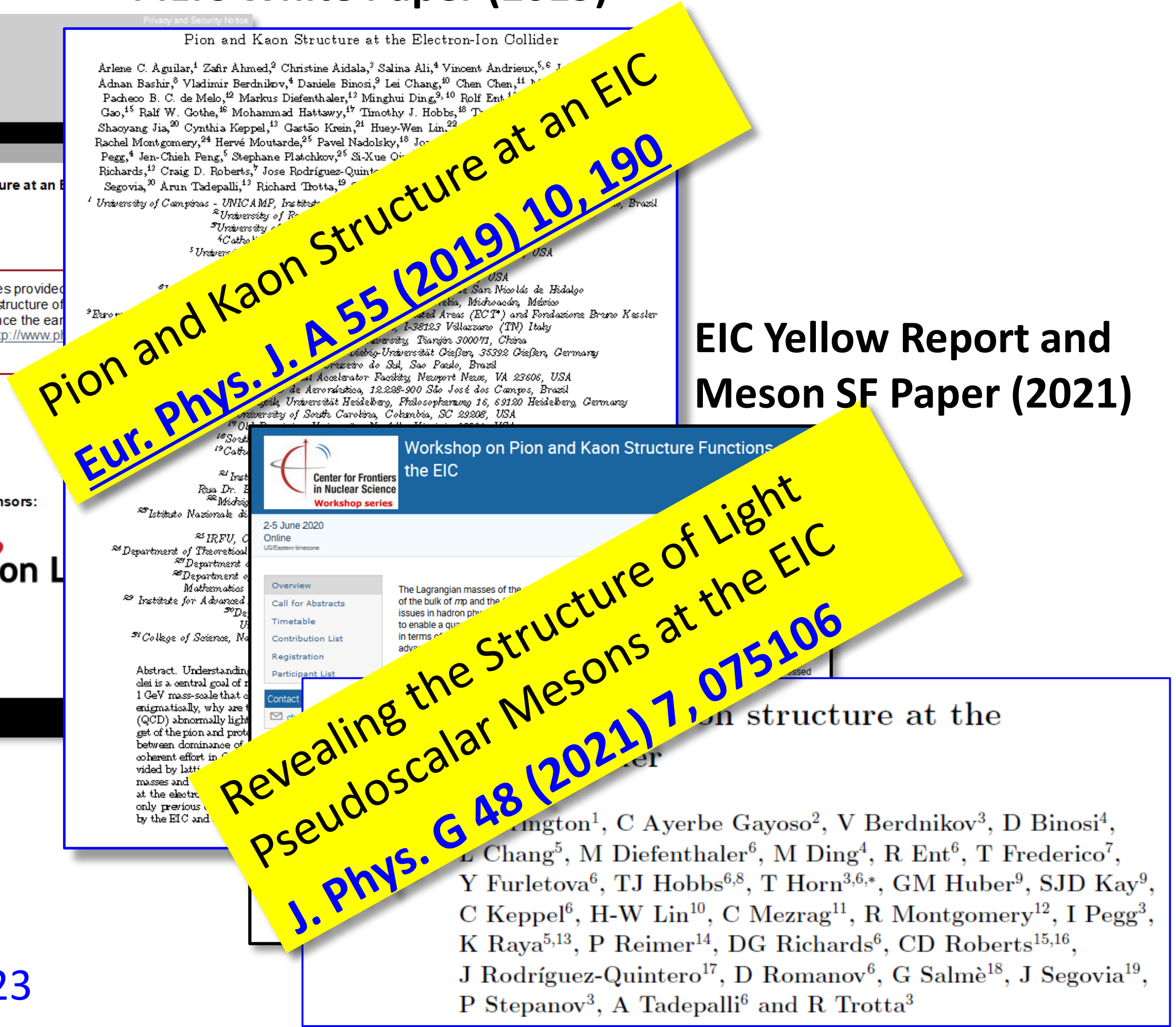
Genoa/Italy, 5-9 June 2023

# Pion and Kaon Structure at the EIC – History

- PIEIC Workshops hosted at ANL (2017) and CUA (2018)
- ECT* Workshop: Emergent Mass and its Consequences (2018)


PIEIC White Paper (2019)

EIC Yellow Report and Meson SF Paper (2021)

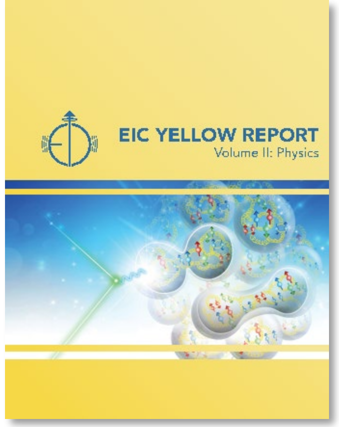


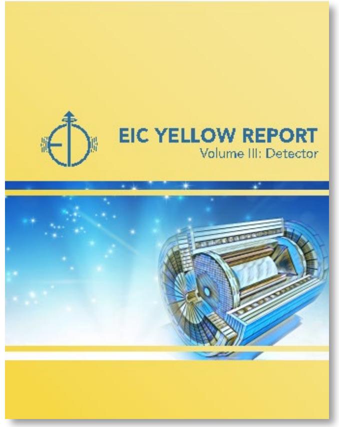

- AMBER/CERN Workshop (2020)
- CFNS Workshop (2020)
- EHM through AMBER@CERN (2020)
- ECT* Workshops in 2021 (remote) & 2022/23

# Meson Structure Functions Working Group

***Formed in 2019 in context of the EIC User Group Yellow Report Effort***

- Meson SF WG: 27 members, 18 institutions, 10 countries
- To join the Meson Structure Functions WG mailing list, contact T. Horn (hornt@cua.edu)
- Very successful effort, and lively discussions during YR effort, Meson SF WG is likely to continue existing.



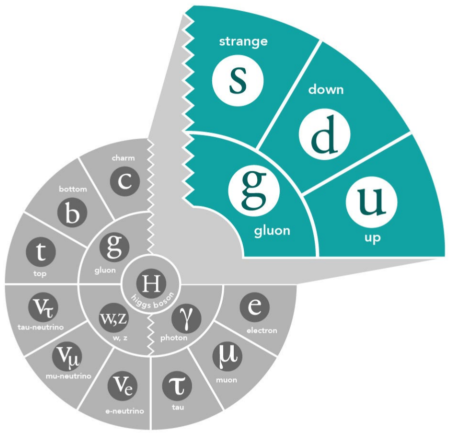




## 2022/23 Meson SF Meetings have been focused on Theory Progress and the next publication

- *Complementary of experimental and lattice QCD data on pion PDFs* by P. Barry - Link to the slides
- *Pion Structure explored in Minkowski Space* by T. Frederico - Link to the slides
- Pion GPD by C. Mezrag and M. Defurne - Link to the talk
- Pion and Kaons GPDs and gravitational form factors by Craig Roberts - Link to the talk
- Goals (experimental/theory) on the topic of TMDs

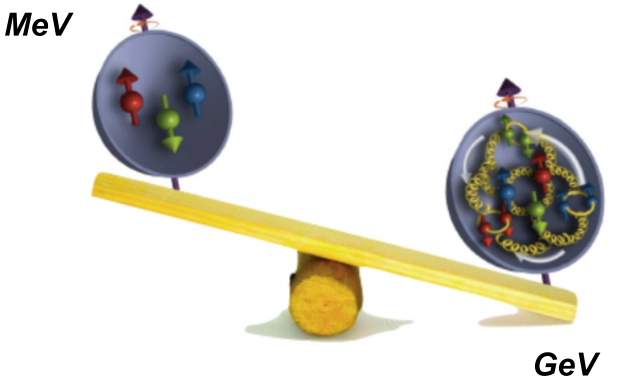
**Meson SF Working group members:**
John R. Arrington (LBNL), Carlos Ayerbe Gayoso (Mississippi State U), Patrick Barry (JLab), Adnan Bashir (U. Michoacán/Morelia, Mexico), Daniele Binosi (ECT*), Lei Chang (Nankai U.), Rolf Ent (Jlab), Tobias Frederico (Instituto Tecnologico de Aeronautica), Timothy Hobbs (FNAL), Tanja Horn (CUA), Garth Huber (U. Regina), Parada Hutauruk (Pukyong National University), Stephen Kay (U. Regina), Cynthia Keppel (Jlab), Bill Lee (W&M) ), Shuije Li (LBNL), Huey-Wen Lin (MSU), Cedric Mezrag (CEA), Rachel Montgomery (U. Glasgow), Ian L. Pegg (CUA), Paul Reimer (ANL), David Richards (Jlab), Craig Roberts (Nanjing U.), Jorge Segovia (Universidad Pablo de Olavide), Arun Tadepalli (JLab), Richard Trotta (CUA), Ali Usman (U. Regina)

# The incomplete Hadron: Mass Puzzle




*Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions.*

"Mass without mass!"



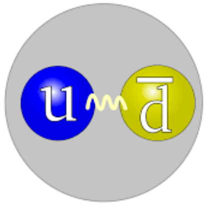

**Proton**

Quark structure: uud
Mass ~ 940 MeV (~1 GeV)
Most of mass generated by dynamics.

Gluon rise discovered by HERA e-p

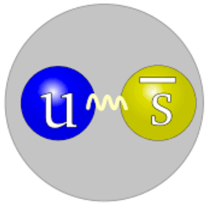
**Pion**

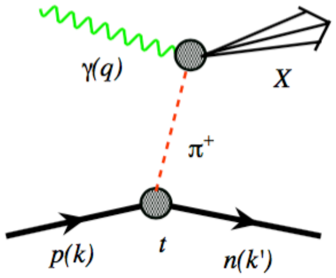
Quark structure: ud
Mass ~ 140 MeV
Exists only if mass is dynamically generated.
Empty or full of gluons?




**Kaon**

Quark structure: us
Mass ~ 490 MeV
Boundary between emergent- and Higgs-mass mechanisms.
More or less gluons than in pion?




***For the proton the EIC will allow determination of an important term contributing to the proton mass, the so-called "QCD trace anomaly"***

***For the pion and the kaon the EIC will allow determination of the quark and gluon contributions with the Sullivan process.***

*A.C. Aguilar et al., Pion and Kaon structure at the EIC, EPJA* ***55 (2019)*** *190.*
*J. Arrington et al., Revealing the structure of light pseudoscalar mesons at the EIC, J. Phys. G* ***48 (2021)*** *7 075106.*
*C.D. Roberts, D. Richards, T. Horn, L. Chang, Insights into Emergence of Mass, Prog. Part. NP* ***120 (2021)*** *103883*

# Origin of Mass in the EIC Yellow Report

## 2.3 Origin of Nucleon Mass

*Yellow Report, exec. summary, pages 9/10*

More than 99% of the mass of the visible universe resides in atomic nuclei, whose mass, in turn, is primarily determined by the masses of the proton and neutron. Therefore, it is of utmost importance to understand the origin of the proton (and neutron) mass, particularly how it emerges from the strong interaction dynamics. Interestingly, the proton mass is not even approximately given by summing the masses of its constituents, which can be attributed to the Higgs mechanism. Just adding the masses of the proton's valence quarks provides merely about 1% of the proton mass. While a QCD analysis leads to a more considerable quark mass contribution to the proton mass, the qualitative picture that the Higgs mechanism is responsible for only a small fraction of the proton mass is not altered. An essential role for a complete understanding of the proton mass is played by the trace anomaly of the QCD energy-momentum tensor [8–11]. It is precisely this essential ingredient for which the EIC can deliver crucial input through dedicated measurements of quarkonia's exclusive production ($J/\psi$ and $\Upsilon$) close to the production threshold.

Another way to address the emergence of mass is through the pion and kaon

The trace anomaly vanishes for the pion due to cancellations between competing effects in the chiral limit of vanishing quark masses. It is exact in the case of pions due to dynamical chiral symmetry breaking. For the kaon, the effect of the Higgs mechanism will play a more substantial role. This affects the shape and size of the pion (and kaon) wave function and has measurable implications for the various quark/gluon energy distributions and the form factor.

# 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 ($m_\pi = 0$):

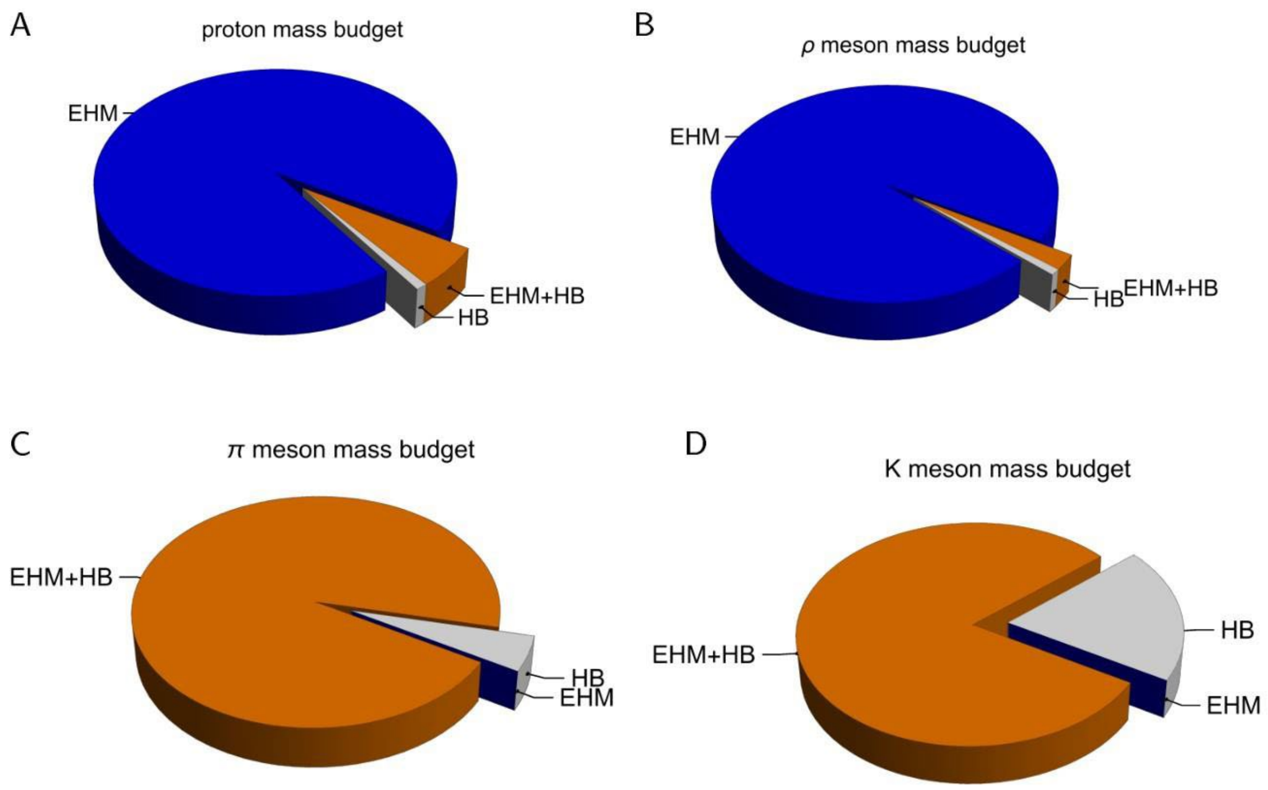
$$\langle \pi(q)|\Theta_0|\pi(q)\rangle = -q_\mu q_\mu = m_\pi^2 = 0$$

*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 budgets for the Proton, Kaon, and Pion




J. Arrington et al., J.Phys.G **48** (2021) 7, 075106

**Pion/Kaon are essential for understanding the Emergent Hadronic Mass (EHM)**

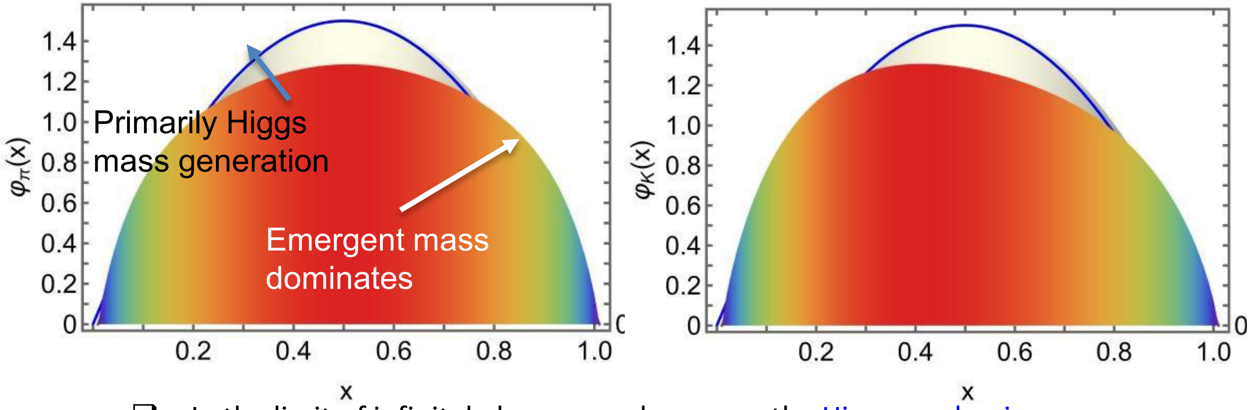
- Proton (and heavy meson) mass is large in the chiral limit – expression of emergent hadronic mass
- Pion/kaon: Nambu-Goldstone Boson of QCD: massless in the chiral limit
  - chiral symmetry of massless QCD dynamically broken by quark-gluon interactions and inclusion of light quark masses (DCSB, giving pion/kaon mass)
- Understanding pion/kaon is vital to understand the **dynamic** generation of hadron mass and offers unique insight into EHM and the role of the Higgs mechanism
  - Without Higgs mechanism of mass generation pion/kaon would be indistinguishable

# Light Mesons and EHM

Insights into the Emergence of Mass from Studies of Pion and Kaon Structure, C.D. Roberts, D.G. Richards, T. Horn, L. Chang, Prog. Part. Nucl. Phys. **120** (2021) 103883/1-65

**Pion and kaon distribution amplitudes (DA – $\phi_{\pi,K}$) are fundamental to our understanding of pion and kaon structure**

- EHM is expressed in the x-dependence of the pion and kaon DA
- Pion DA is a direct measure of the dressed-quark running mass in the chiral limit

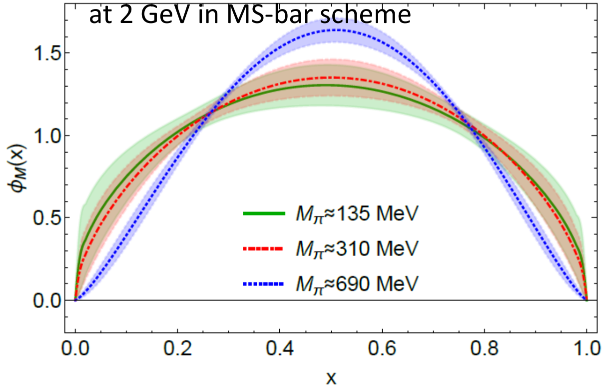



- In the limit of infinitely-heavy quark masses, the Higgs mechanism overwhelms every other mass generating force, and the PDA becomes a δ-function at x = ½.
- The DA for the light-quark pion is a broad, concave function, a feature of emergent mass generation.
- Kaon DA is asymmetric around the midpoint – signature of constructive interference between EHM and HB mass-generating mechanism

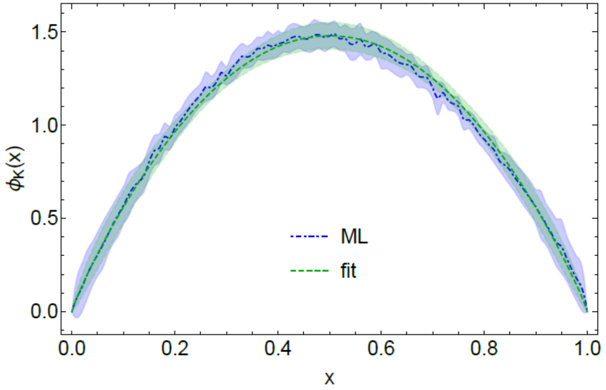
**Strong synergy with lattice QCD**

R. Zhang et al., Phys. Rev. D **102** (2022) 9, 094519

Calculations using meson-boosted momentum at $P_z$ = 1,.73 GeV and renormalized at 2 GeV in MS-bar scheme




*Pion at two different pion masses & extrapolated to the physical mass*

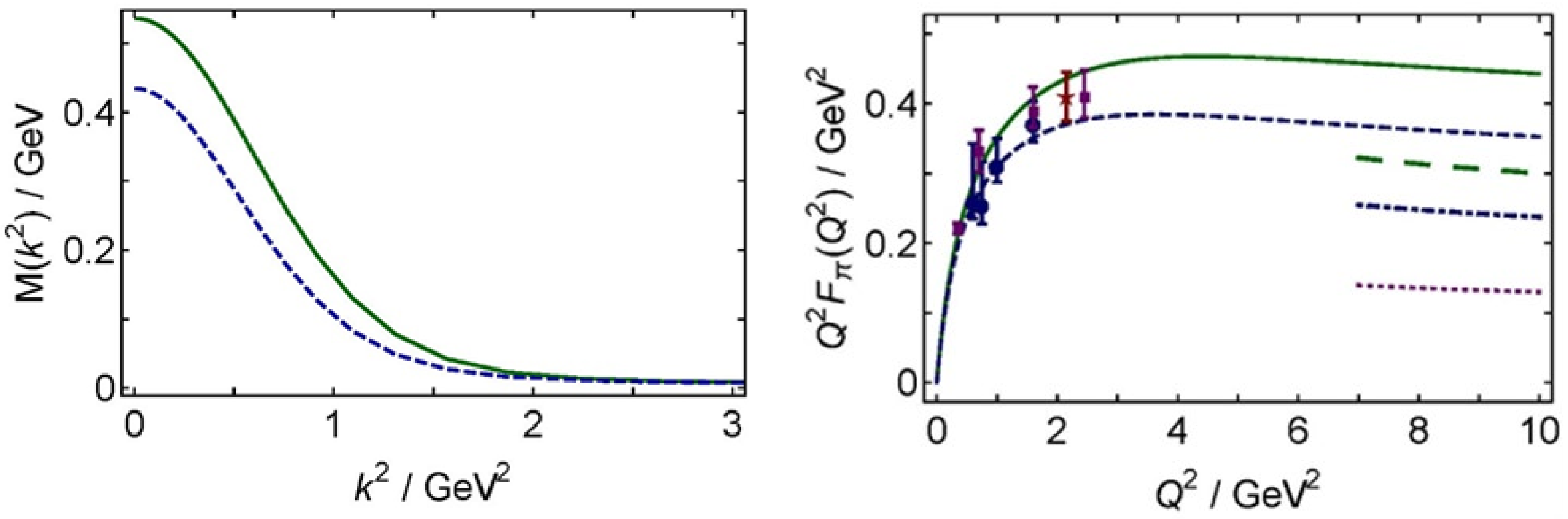



*Fit to lattice data for kaon, and using machine learning approach*

- Experimental signatures of the exact PDA form are, in general, difficult
- Understanding light meson structure requires collaboration of QCD phenomenology, continuum calculations, lattice, and experiment.

# Pion Form Factors and Emergent Mass

There are several measurement observables (e.g., hadron elastic/transition form factors)



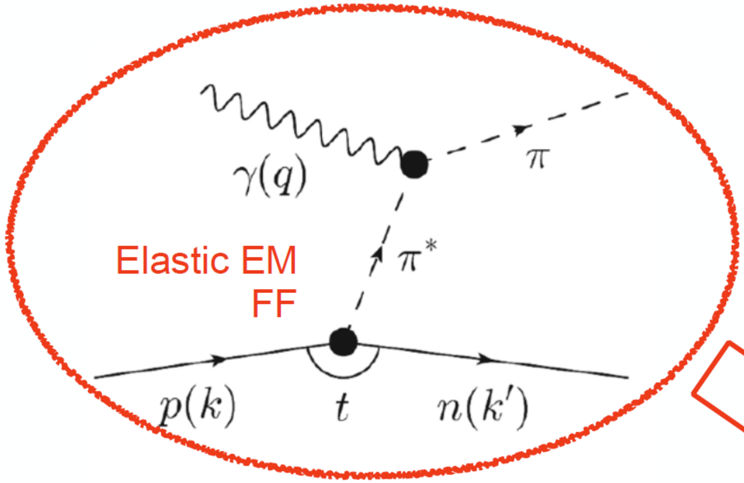

*A.C. Aguilar et al., Eur. Phys. J. A* ***55*** *(**2019**) 10, 190*

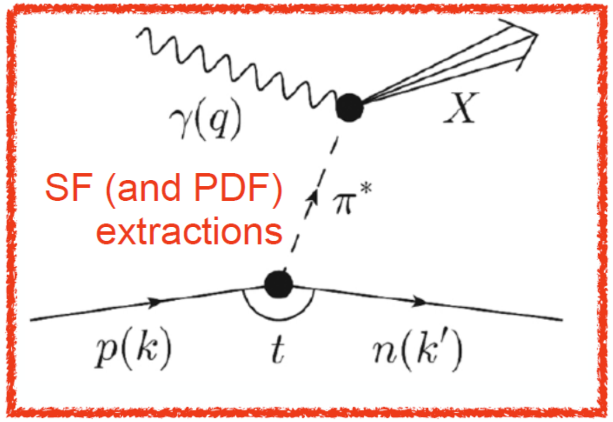
*Left panel. Two dressed-quark mass functions distinguished by the amount of DCSB: emergent mass generation is 20% stronger in the system characterized by the solid green curve, which describes the more realistic case. Right panel.* $F_\pi(Q^2)$ *obtained with the mass function in the left panel:* $r_\pi = 0.66$ *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,* $\phi(x)=6x(1-x)$.

# Accessing Pion/Kaon Structure Information

**Sullivan**

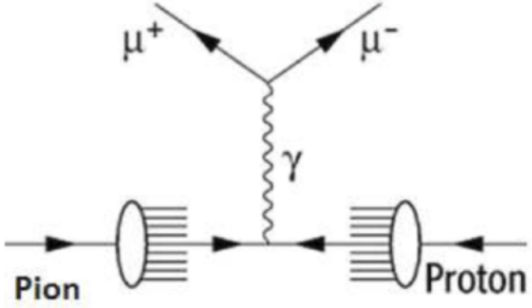
Hard scattering from virtual meson cloud of nucleon



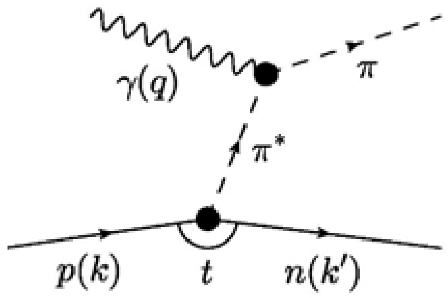

**Drell-Yan**

Quark of pion (e.g.) annihilates with anti-quark of proton (e.g.), virtual photon decays into lepton pair

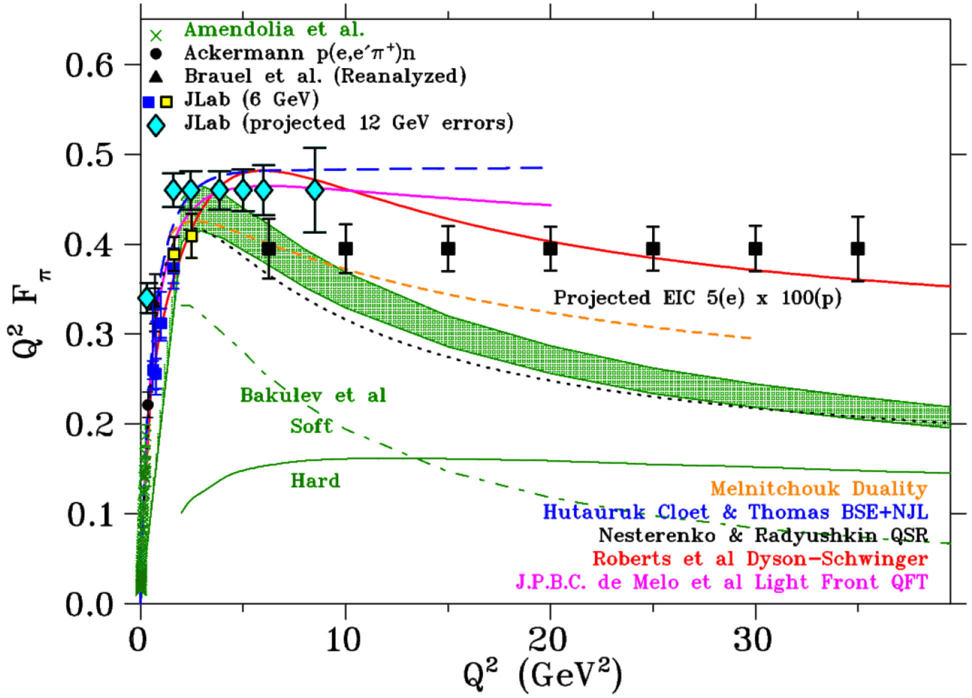



- **Pion/Kaon elastic EM Form Factor**
  - Informs how EHM manifests in the wave function
  - Decades of precision $F_\pi$ studies at JLab and recently completed measurement in Hall C for $F_\pi$ and also $F_K$
  - EIC offers exciting kinematic landscape for FF extractions
- **Pion/Kaon Structure Functions**
  - Informs about the quark-gluon momentum fractions

# Pion Form Factor Prospects @ EIC




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



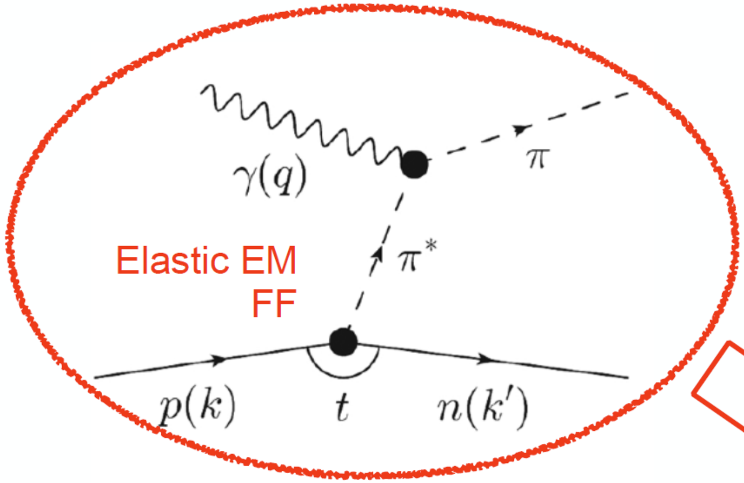

- Assumed 5 GeV($e^-$) x 100 GeV(p) with an integrated luminosity of 20 fb$^{-1}$/year, and similar luminosities for d beam data
- $R=\sigma_L/\sigma_T$ assumed from VR model and assume that $\pi$ pole dominance at small t confirmed in $^2H$ $\pi^-/\pi^+$ ratios
- Assumed a 2.5% pt-pt and 12% scale systematic uncertainty, and a 100% systematic uncertainty in the model subtraction to isolate $\sigma_L$

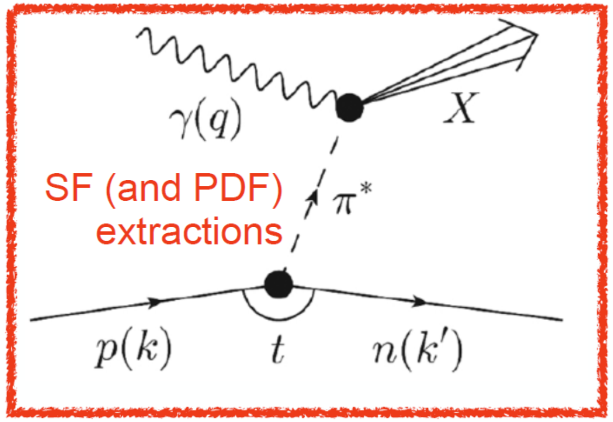
Can we measure the kaon form factor at EIC? Or only through L/T separations emphasizing lower energies? Not clear – needs guidance from JLab 12- GeV.

# Accessing Pion/Kaon Structure Information

## Sullivan

Hard scattering from virtual meson cloud of nucleon

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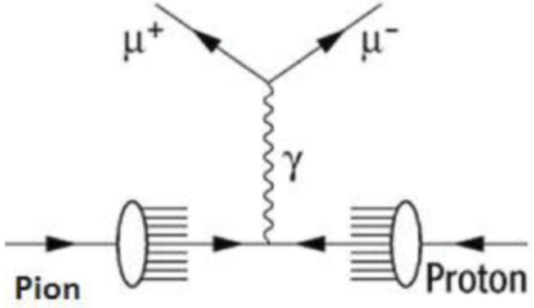


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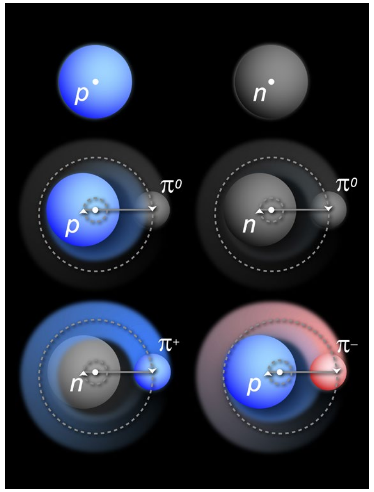
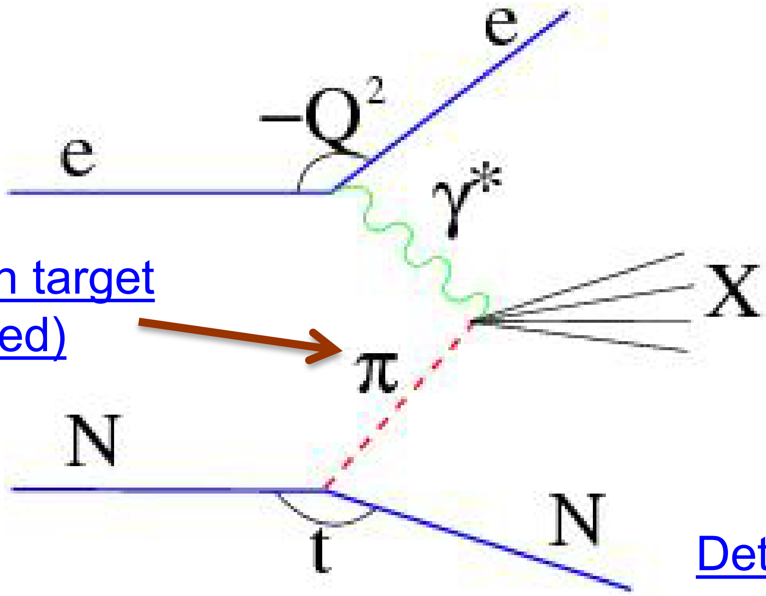
# Physics Objects for Pion/Kaon Structure Studies




**Sullivan process:**
scattering from nucleon-meson fluctuations

Detect scattered electron




Pion/Kaon target (undetected)

DIS event – reconstruct x, $Q^2$, $W^2$, also $M_X$ ($W_\pi$) of undetected recoiling hadronic system

Detect "tagged" neutron/lambda

**Tag nucleon's mesonic content via N(e,e'N')X**

- DIS cross section allows to access the partonic substructure via $F_2$ SF

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E_0^2 \sin^4\frac{\theta}{2}} \cos^2\frac{\theta}{2}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

- Exciting suite of upcoming SF measurements at JLab and EIC…

$$F_2^{LP(3)} = \sum_i \left[\int_{t_0}^{t_{min}} f_i(z,t)dt\right] F_2(x_i, Q^2)$$

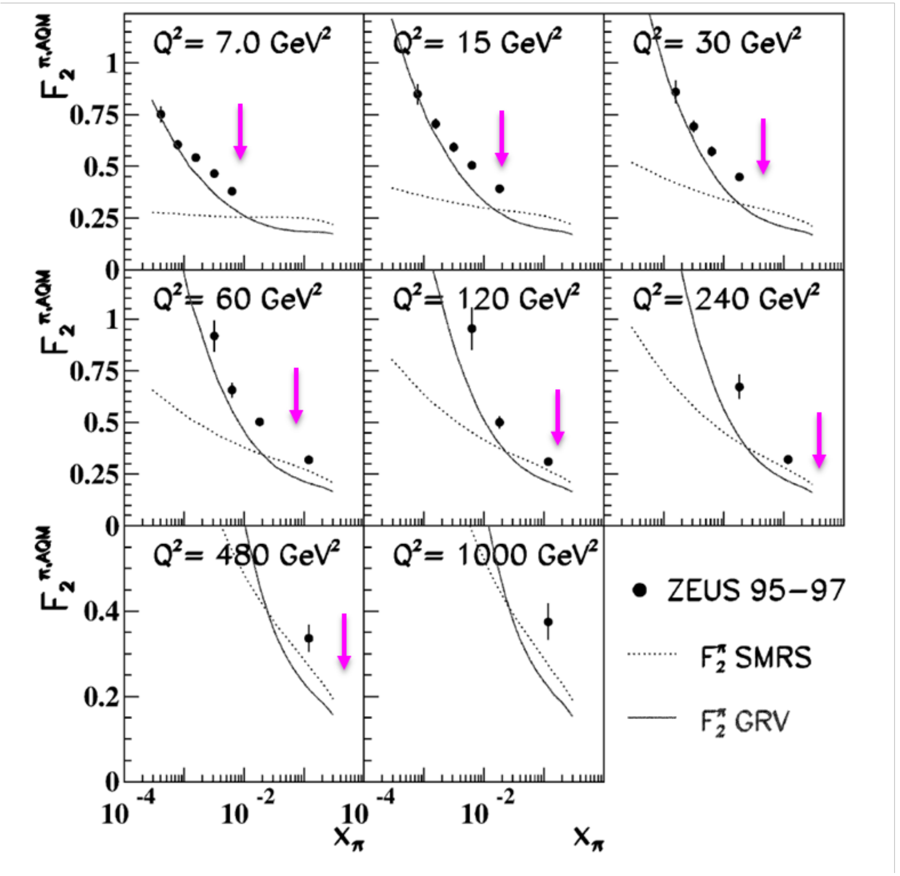
"Flux factor"

# World Data on Pion Structure Function

## HERA

Pion sea region, low Bjorken x, high $Q^2$
$6<Q^2<100\,\mathrm{GeV}^2$; $1.5e^{-4}<x<3.0e^{-2}$

$\downarrow$ ~$x_{min}$ for EIC



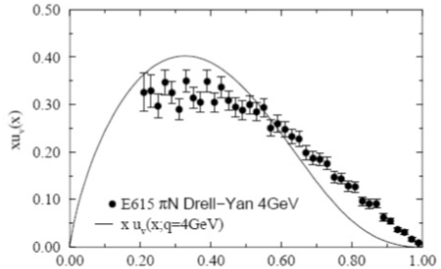

**EIC kinematic reach down to a x = few $10^{-3}$**
**Lowest x constrained by HERA**

DESY 08-176 JHEP06 (2009) 74

## DY: Large x Structure of the Pion

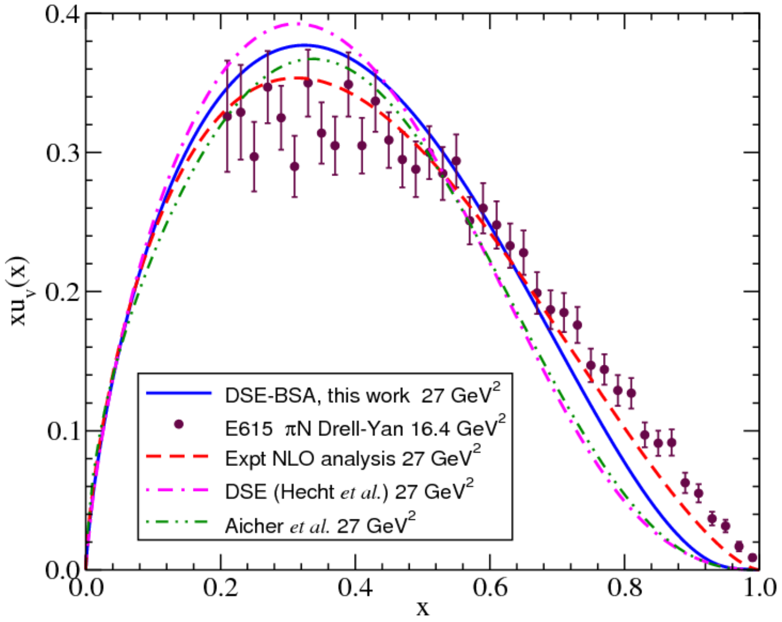
Initial observations:

- PDF ~ $(1-x_\pi)$ as $x_\pi$->1
- Agrees with structureless model
- Differs from pQCD prediction of $(1-x_\pi)^2$




$\pi^- W \to \mu^+\mu^- X$

$\sigma \propto \bar{u}(x_{\pi^-})u(x_N)$




*[C.D. Roberts, IRMA Lect. Math. Theor. Phys. 21 (2015) 355; arXiv:1203.5341 (2012)]*

- Model tensions, pQCD, Dyson-Schwinger, Light Front, Instanton,…
- NLO gluon resummation effects

*[Aicher, Schäfer, Vogelsang, Phys. Rev. Lett. 105, 252003 (2010)]; [L. Chang et al., Phys. Lett. B 737 (2014) 23]*

**Jefferson Lab TDIS can provide important verification**

# Projected JLab TDIS Results for π, K Structure Functions

*TDIS in Hall A with SBS:*

✓High luminosity,

50 μAmp,

$\mathcal{L}$ = 3x10$^{36}$/cm$^2$ s

✓Large acceptance

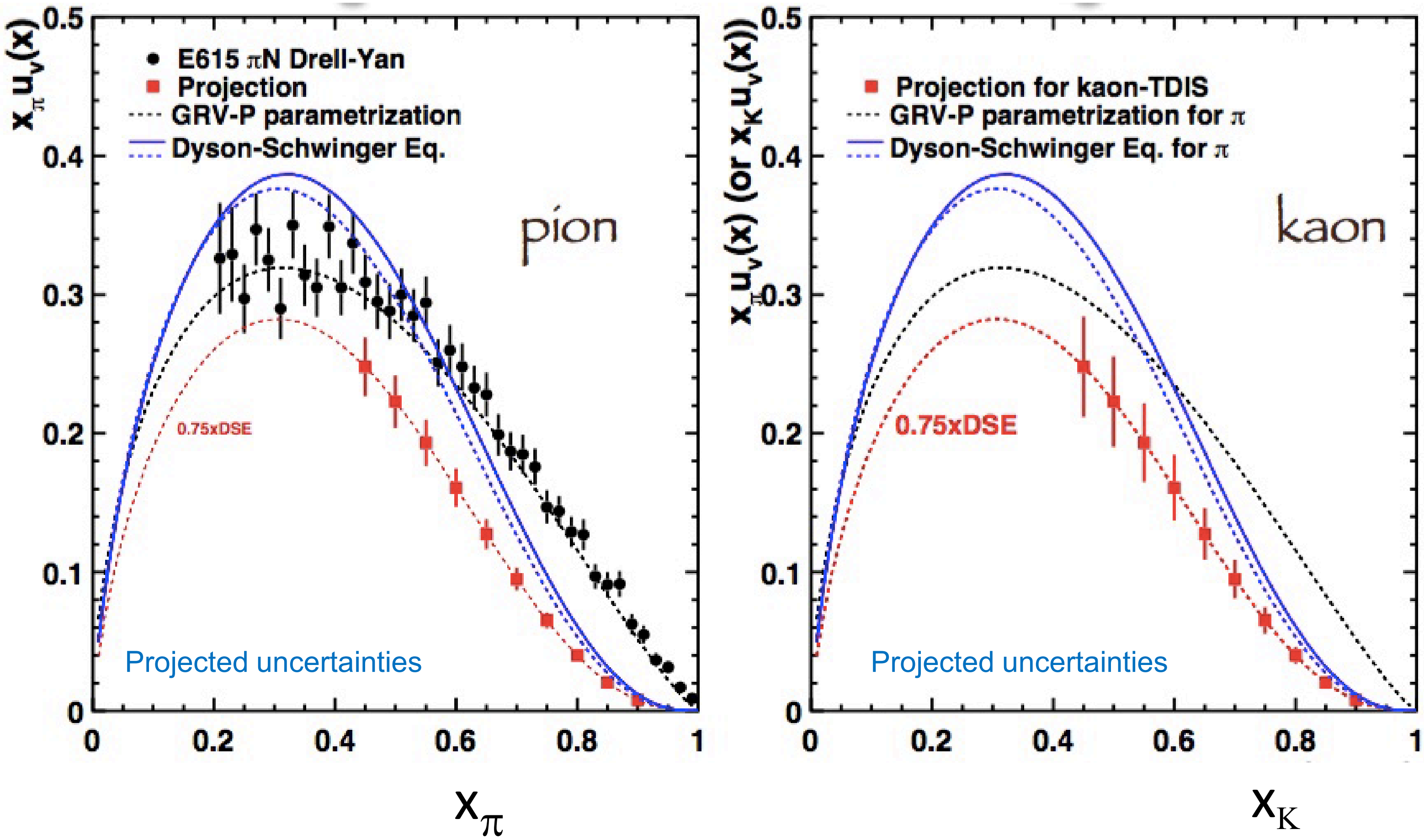
~70 msr

**Important for small cross sections**

**Pion and Kaon F2 SF extractions in valence regime**

- Independent charged pion SF
- First kaon SF
- First neutral pion SF

**Jefferson Lab 12 GeV – experiment C12-15-006/006A**




Projections based on phenomenological pion cloud model

T.J. Hobbs, Few Body Syst. 56 (2015) 6-9

J.R. McKenney et al., Phys. Rev. DD 93 (2016) 05011

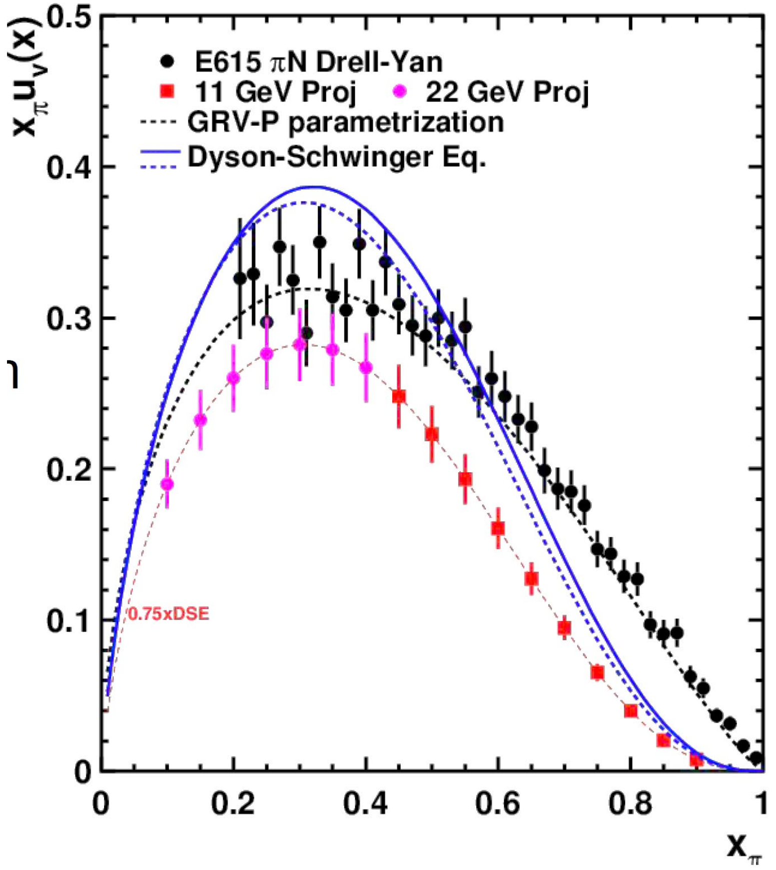
**Essentially no kaon data currently**

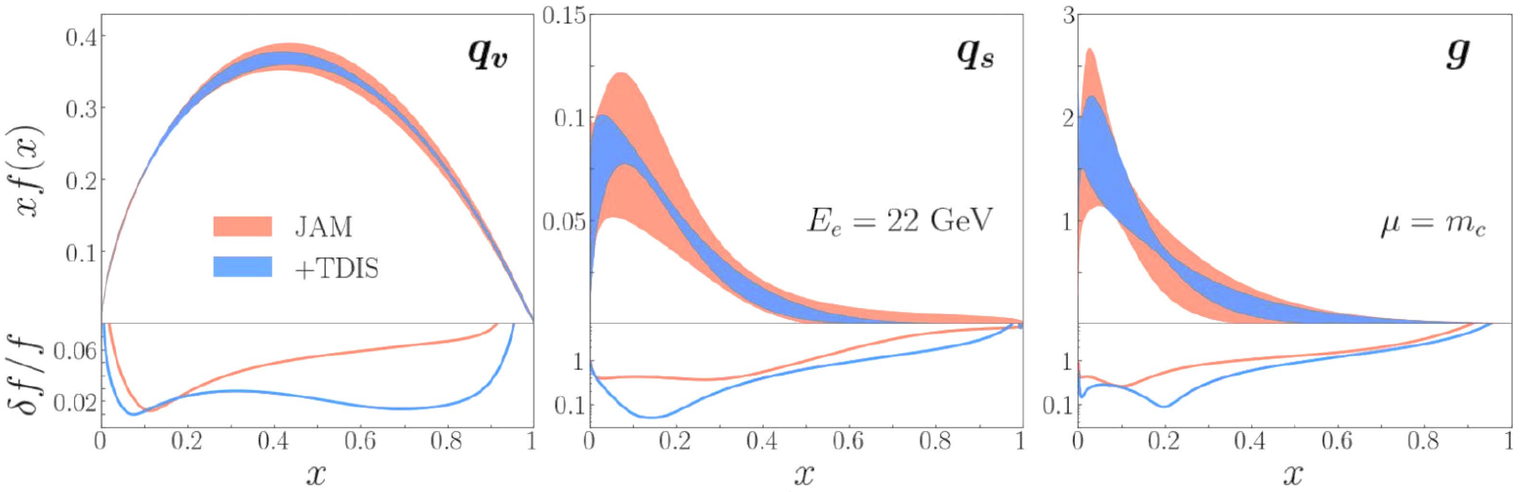
# JLab 22 GeV: Opportunities for TDIS π, K Structure

Tagged DIS in the JLab era study group: Dipangkar Dutta (MSU), Carlos Ayerbe-Gayoso, Rachel Montgomery (U. Glasgow), Tanja Horn (CUA), Thia Keppel (JLab), Paul King (OU), Rolf Ent (JLab), Patrick Barry (JLab)

→ Also see talk by P. Rossi for further information on JLab 22 GeV

Projections based on 50 days of beam time

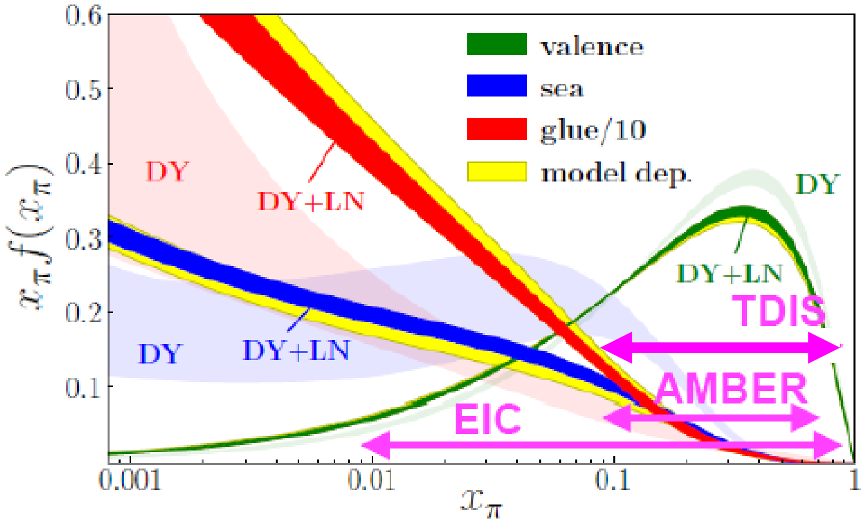


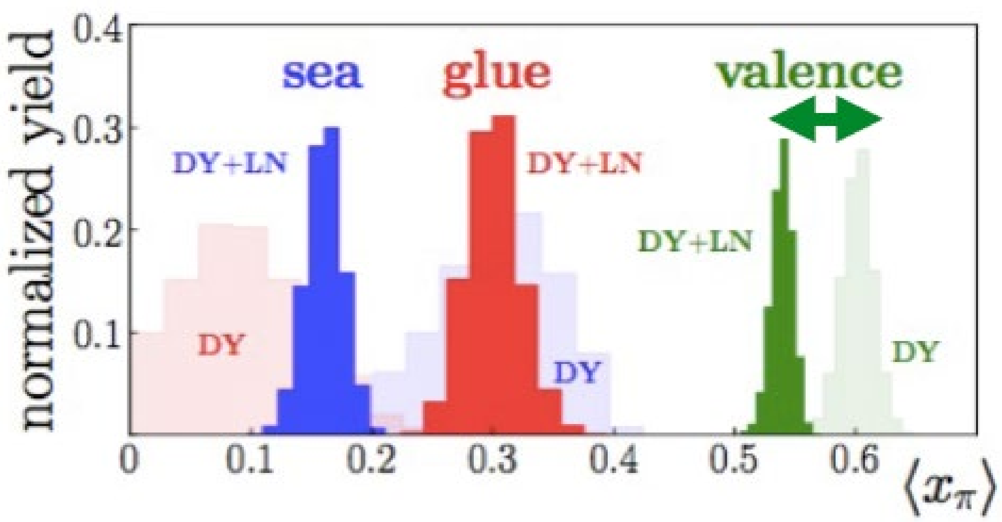

- ❑ Adding a new constraint in the kinematics enables the study of π resonances
  - The low-$W^2$ region was not measured at HERA – strength of resonances is unknown
  - Wide kinematic coverage in TDIS to measure the resonance region
- ❑ Measurement of SIDIS from a pion target – requires additional instrumentation for detection of an additional pion (ongoing effort)

# Global PDF Fits and Demand for more Data

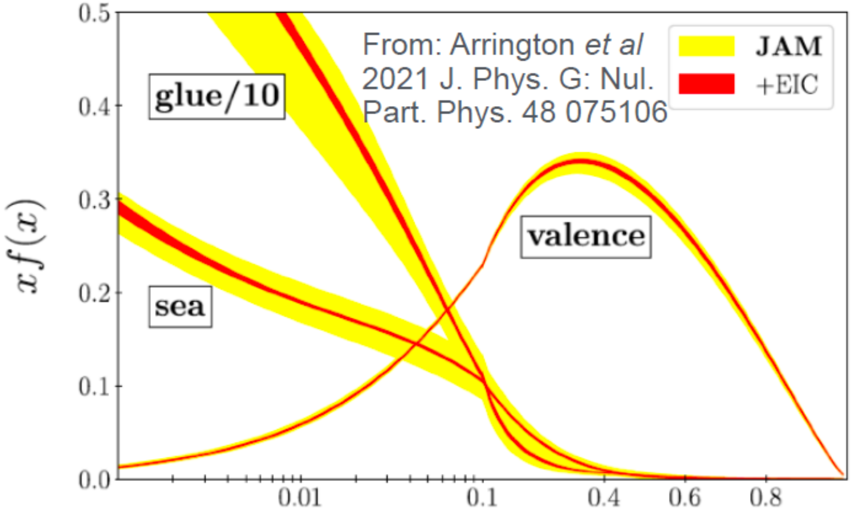
- ❑ Combined Leading Neutron/Drell-Yan analysis for PDF fitting, with novel MC techniques for uncertainties (JLab JAM)
- ❑ Non-overlapping uncertainties – tension at large x




Mom. Fraction carried by sea/glue/valence



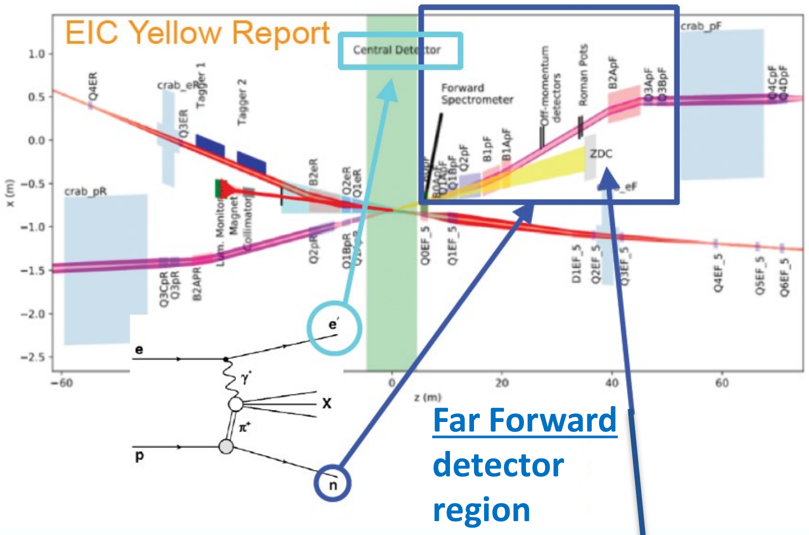

*P.C. Barry, N. Sato, W. Melnitchouk, C-R Ji (JAM Collaboration), PRL 121 (2018) 152001*



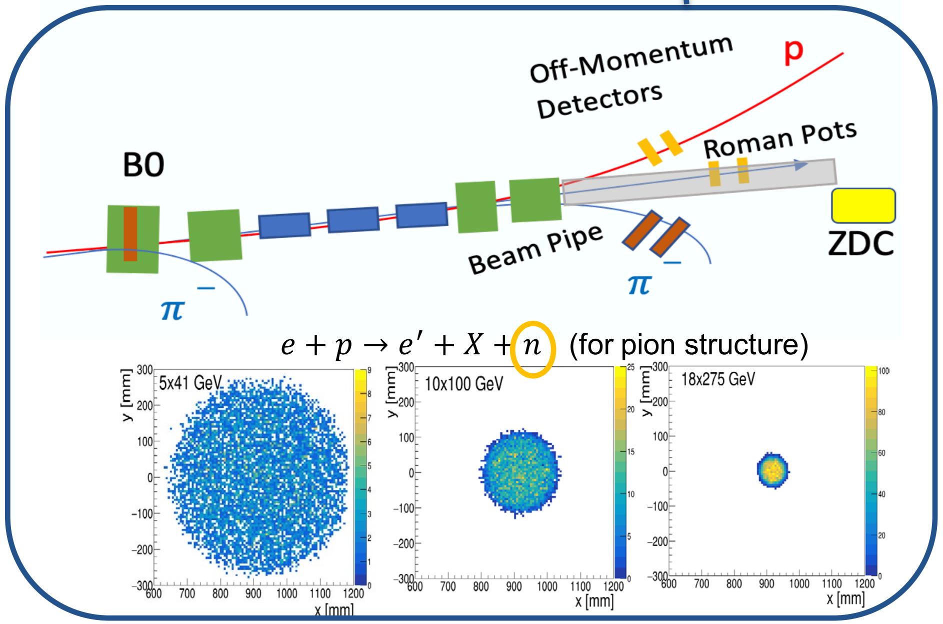

- ❑ Yet, different basis light front quantization (BFLQ) technique finds agreement in PDF evolution between DY and DIS
  J. Lan, C. Mondal, S. Jia, X. Zhao, J.P. Vary, arXiv:1907.01509 (2019)
  - ➢ More data needed
- ❑ **Excellent opportunity for more data with EIC**
  - ➢ Kinematic bridge between HERA and high-x with wide coverage in x

# EIC and Sullivan Process SF Measurements

Good Acceptance for TDIS-type Forward Physics! Low momentum nucleons ***easier*** to measure!

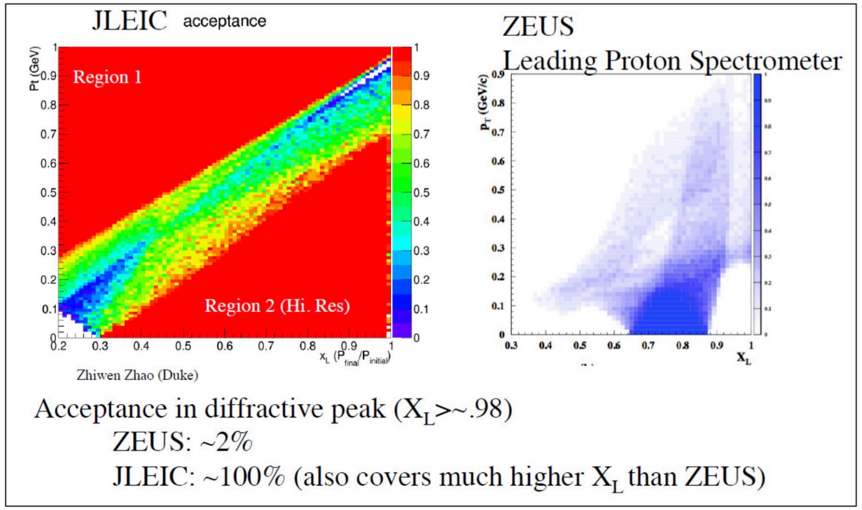



- EIC design well suited for HERA-style pion/kaon SF measurements
- Scattered electron detected in the central detector
- Leading hadrons → large fraction of initial beam energy → far forward detector region
    - ZDC particularly important (reaction kinematics and 4 momenta)

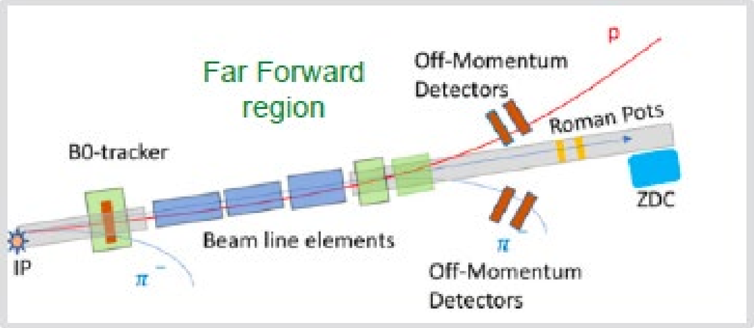


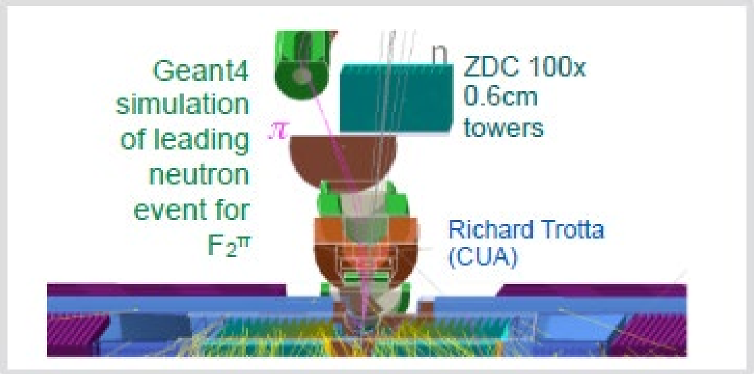

***Huge gain in acceptance for forward tagging….***

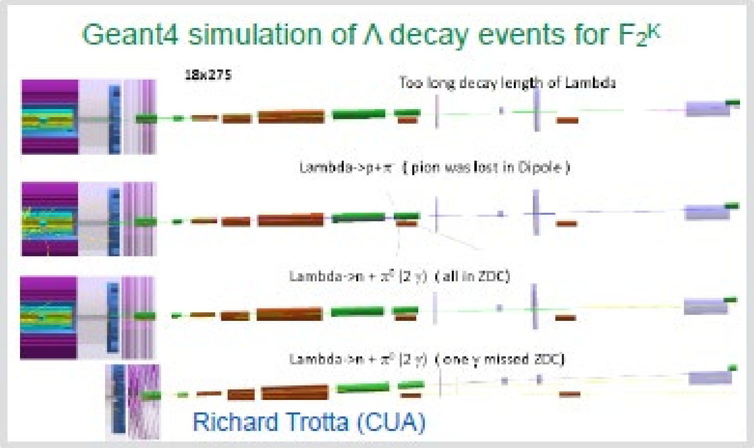
Example: acceptance for p' in e + p → e' + p' + X

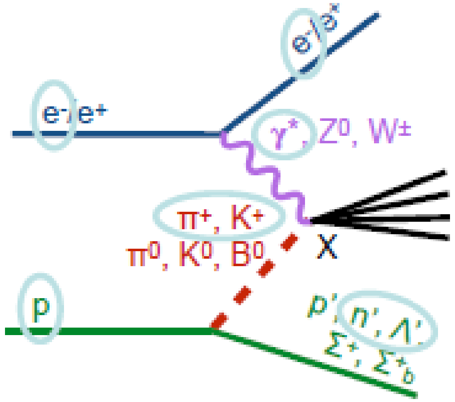


# EIC Pion/Kaon SF Measurements



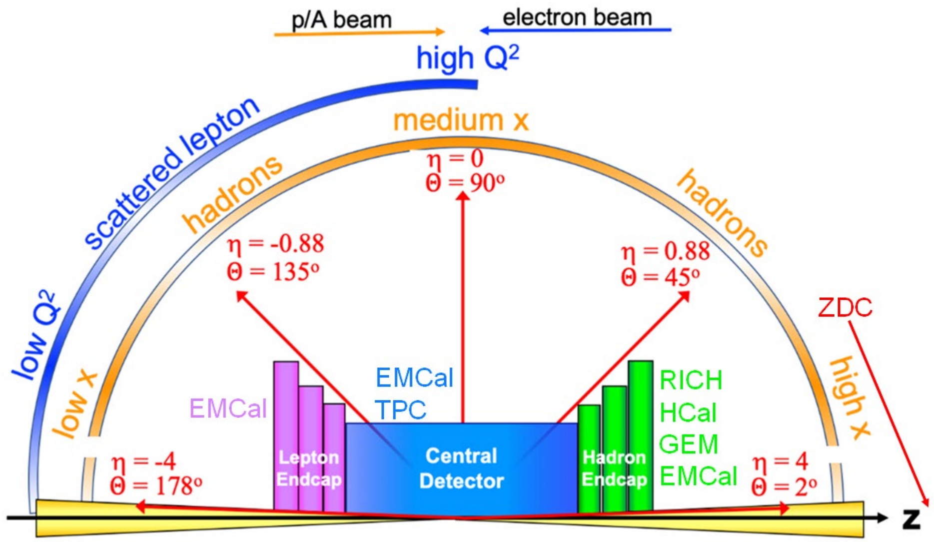
- Custom fast MC event generator (R. Trotta, CUA) and G4 for detector acceptance/response
- Focus so far: ep and measuring cross section at small-t for
  - $F_2^{\pi}$ ($\pi^+$) tagged by n
  - $F_2^{K}$ ($K^+$) tagged by $\Lambda^0$ decay
- Settings e x p(GeV): 5x41, 5x100, 10x100, 10x135, 18x275

**Detector requirements:**

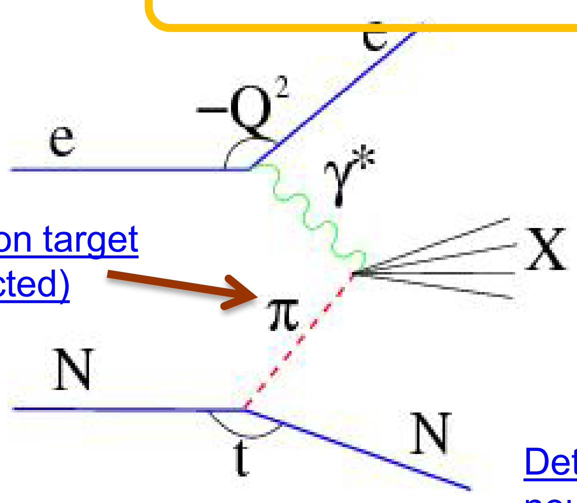
- **For $\pi$-n:**
  - Lower energies (5 on 41, 5 on 100) require at least 60 x 60 cm$^2$
  - For all energies, the neutron detection efficiency is 100% with the planned ZDC
- **For $\pi$-n and $K^+/\Lambda$:**
  - All energies need good ZDC angular resolution for the required -t resolution
  - High energies (10 on 100, 10 on 135, 18 on 275) require resolution of 1cm or better
- **$K^+/\Lambda$ benefits from low energies (5 on 41, 5 on 100) and also need:**
  - $\Lambda \rightarrow n+\pi^0$ : additional high-res/granularity EMCal+tracking before ZDC – seems doable
  - $\Lambda \rightarrow p + \pi^-$: additional trackers in opposite direction on path to ZDC – more challenging
- Standard electron detection requirements
- Good hadron calorimetry for good x resolution at large x

# EIC Detector and SF Measurements

## Scattered Electron



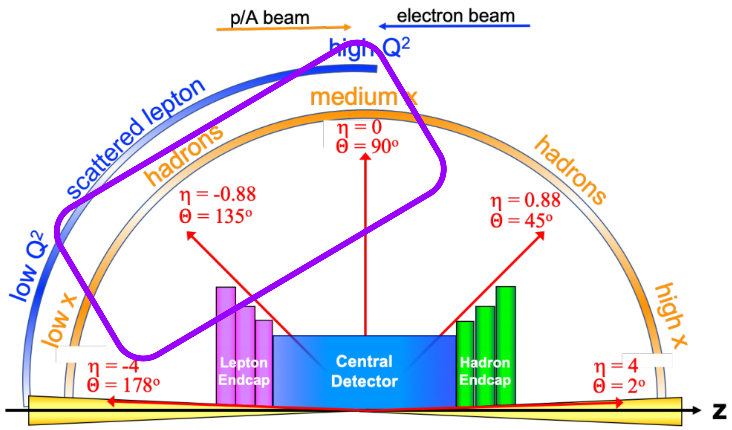

Detect scattered electron

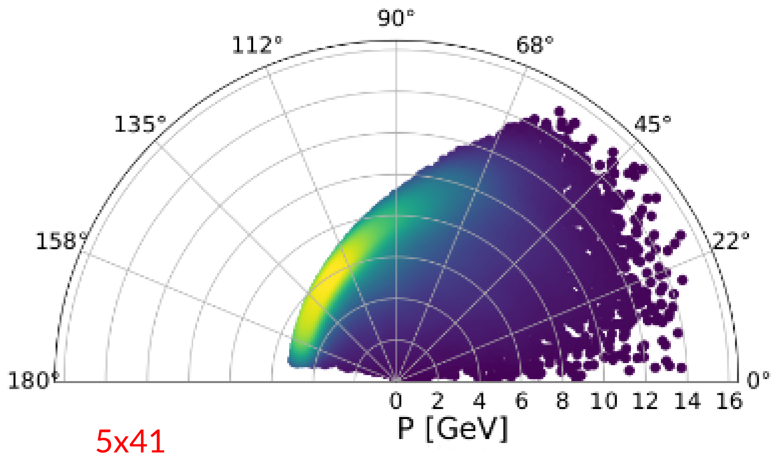



Pion/Kaon target (undetected)

DIS event – reconstruct x, $Q^2$, $W^2$, also $M_X$ ($W_\pi$) of undetected recoiling hadronic system

Detect "tagged" neutron/lambda

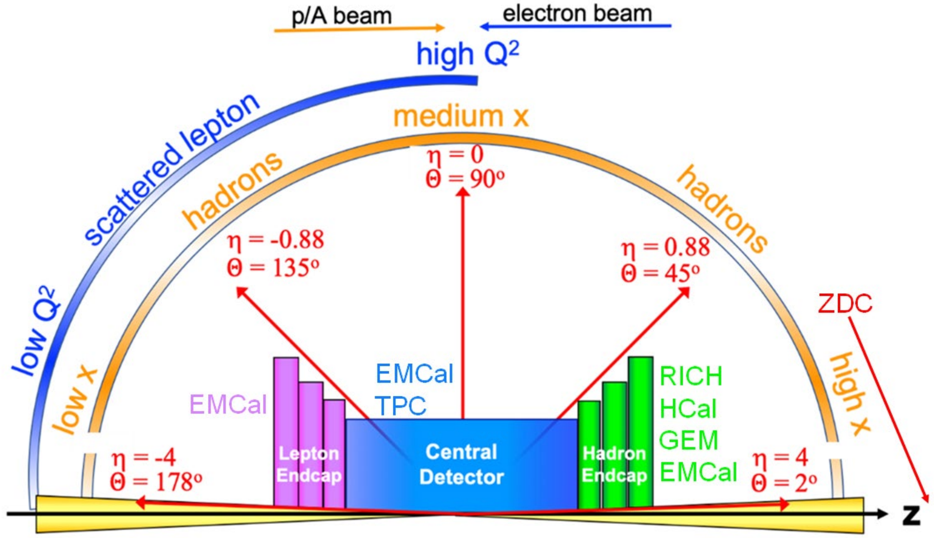


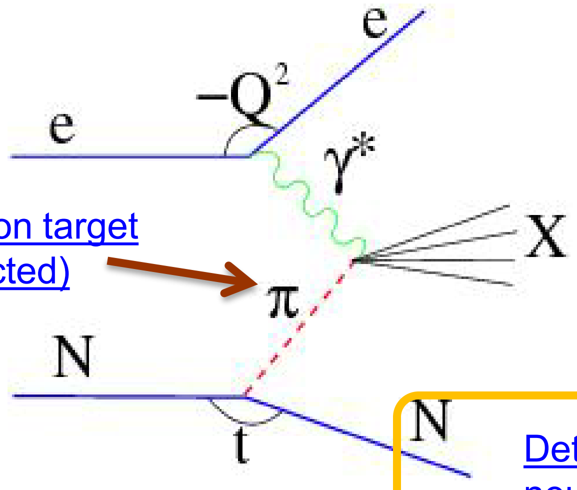

5x41

# EIC Detector and SF Measurements

## Leading Baryon



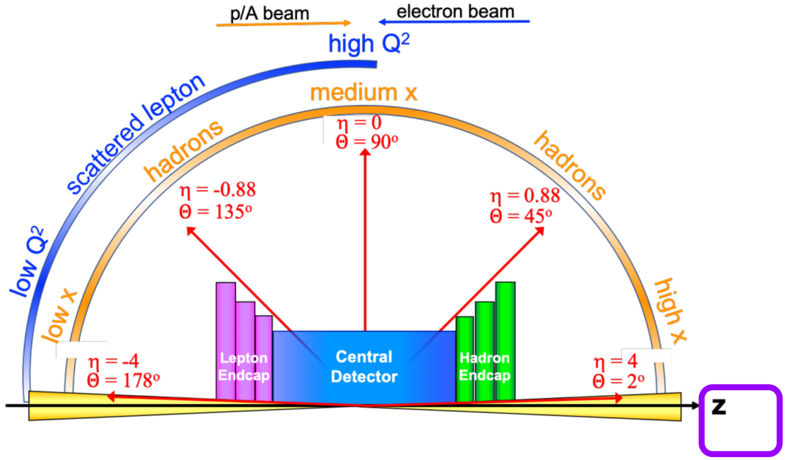

Detect scattered electron



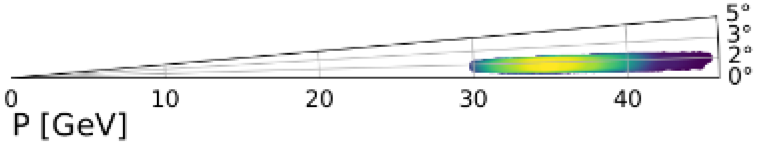

Pion/Kaon target (undetected)

DIS event – reconstruct x, $Q^2$, $W^2$, also $M_X$ ($W_\pi$) of undetected recoiling hadronic system

Detect "tagged" neutron/lambda



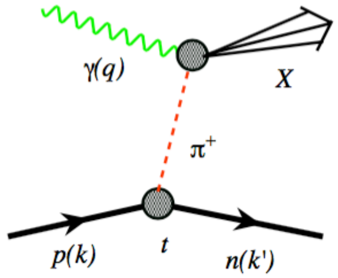

Baryon (neutron lambda) at very small forward angles and nearly the beam momentum



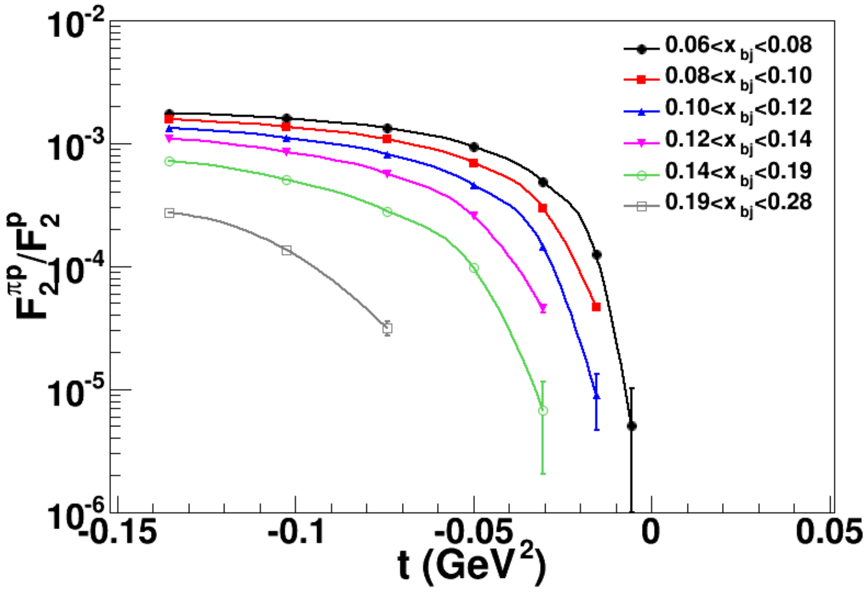

5x41

# EIC – Versatility and Luminosity for SF measurements

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

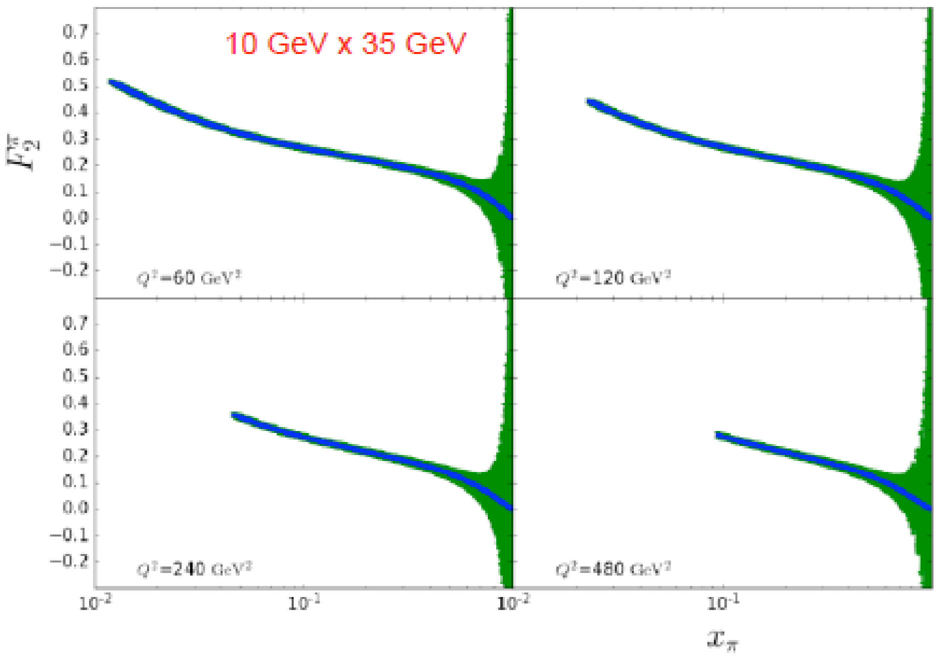



- $L_{EIC} = 10^{34} = 1000 \times L_{HERA}$
- Detection fraction @ EIC in general much higher than at HERA
- Fraction of proton wave function related to pion Sullivan process is roughly $10^{-3}$ for a small –t bin (0.02).
- Hence, pion data @ EIC should be comparable or better than the proton data @ 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) GeV$^2$, we gain at least a decade as compared to HERA/COMPASS.

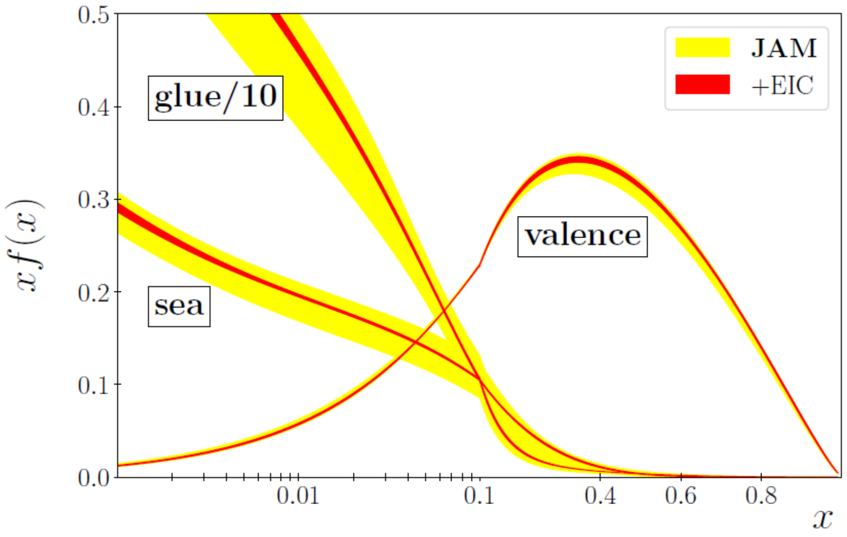


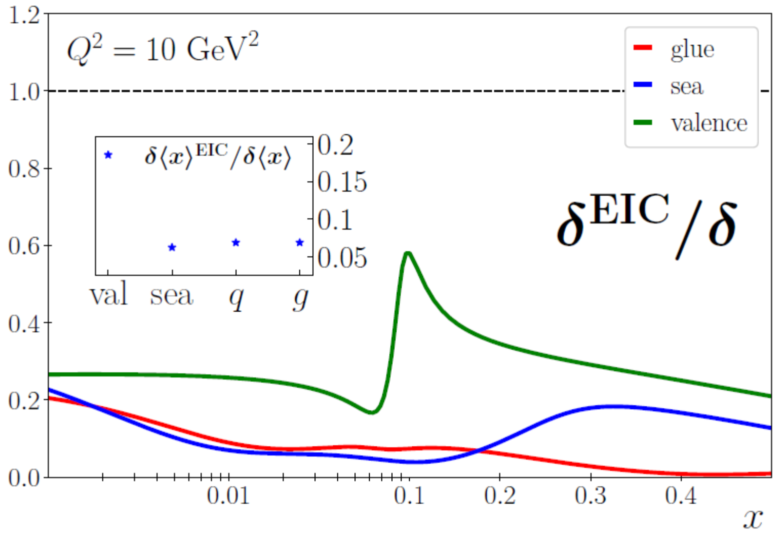

*Ratio of the $F_2$ structure function related to the pion Sullivan process as compared to the proton $F_2$ structure function in the low-t vicinity of the pion pole, as a function of Bjorken-x (Jefferson Lab TDIS Collaboration, JLab Experiment C12-15-005)*

# EIC Pion SF Projections




- SF shown calculated at NLO using pion PDFs
- Projected data binned in x(0.001) and $Q^2$ (10 $GeV^2$)
  - Blue = projections
  - Green = uncertainties for luminosity 100 $fb^{-1}$
  - x-coverage down to $10^{-2}$
  - Unprecedented mid-large x coverage, wide x/$Q^2$
- Similar SF analysis can be extended to the kaon (in progress) and expect similar quality
- Detailed comparison between pion/kaon and gluon contents possible with coverage and uncertainties
- Reduce uncertainties in global PDF fits



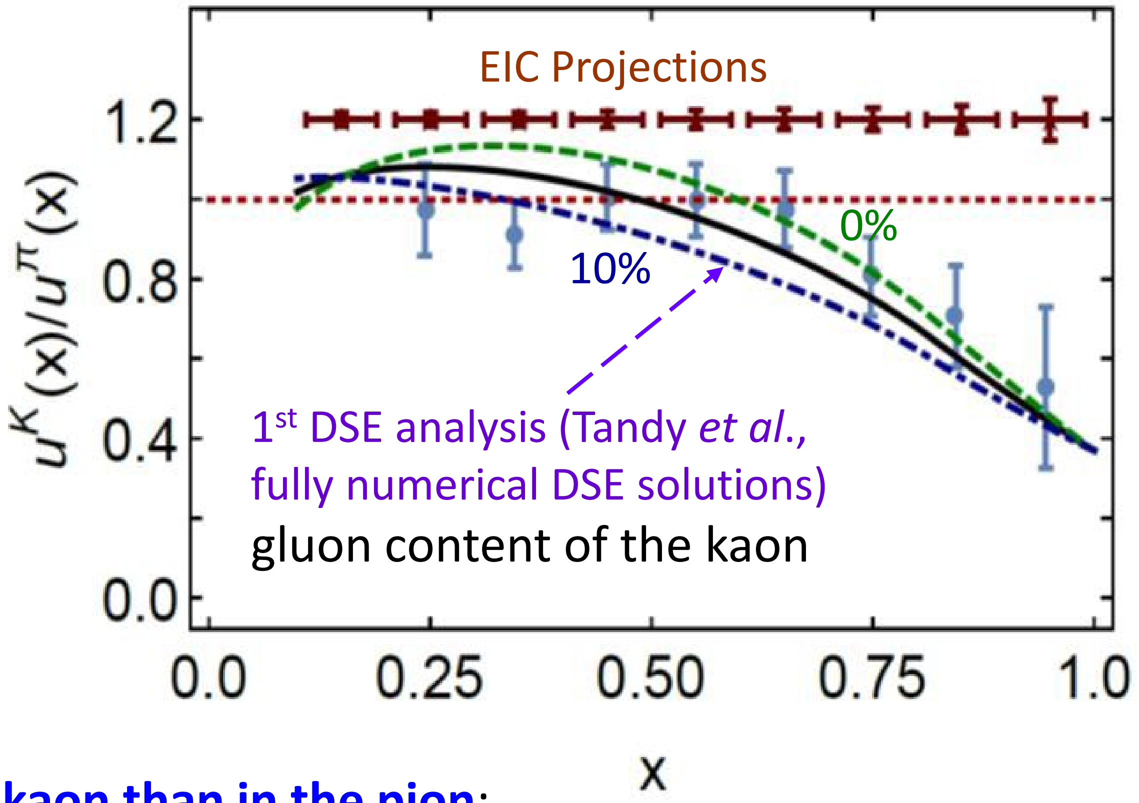



# Kaon structure functions – gluon pdfs

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

*A.C. Aguilar et al., Eur.Phys.J.A* ***55*** *(2019) 10, 190*




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.

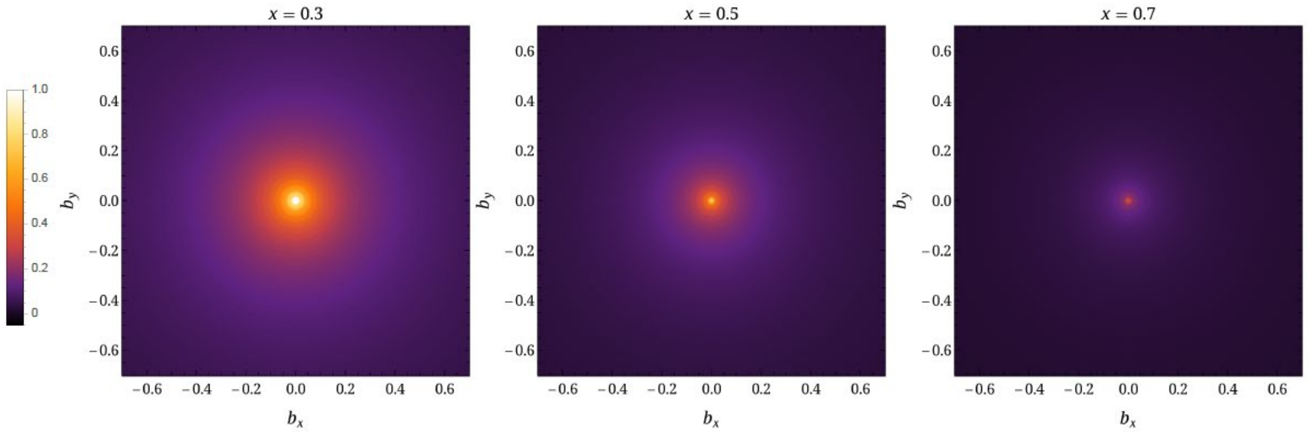
# EIC Meson Structure Functions Questions

| Science Question | Key Measurement[1] | Key Requirements[2] |
|---|---|---|
| What are the quark and gluon energy contributions to the pion mass? | Pion structure function data over a range of $x$ and $Q^2$. | • Need to uniquely determine $e + p \to e' + X + n$ (low $-t$)<br>• CM energy range ~10-100 GeV<br>• Charged and neutral currents desirable |
| Is the pion full or empty of gluons as viewed at large $Q^2$? | Pion structure function data at large $Q^2$. | • CM energy ~100 GeV<br>• Inclusive and open-charm detection |
| What are the quark and gluon energy contributions to the kaon mass? | Kaon structure function data over a range of $x$ and $Q^2$. | • Need to uniquely determine $e + p \to e' + X + \Lambda/\Sigma^0$ (low $-t$)<br>• CM energy range ~10-100 GeV |
| Are there more or less gluons in kaons than in pions as viewed at large $Q^2$? | Kaon structure function data at large $Q^2$. | • CM energy ~100 GeV<br>• Inclusive and open-charm detection |
| Can we get quantitative guidance on the emergent pion mass mechanism? | Pion form factor data for $Q^2$ = 10-40 $(\text{GeV}/c)^2$. | • Need to uniquely determine exclusive process $e + p \to e' + \pi^+ + n$ (low $-t$)<br>• $e + p$ and $e + D$ at similar energies<br>• CM energy ~10-75 GeV |
| What is the size and range of interference between emergent-mass and the Higgs-mass mechanism? | Kaon form factor data for $Q^2$ = 10-20 $(\text{GeV}/c)^2$. | • Need to uniquely determine exclusive process $e + p \to e' + K + \Lambda$ (low $-t$)<br>• L/T separation at CM energy ~10-20 GeV<br>• $\Lambda/\Sigma^0$ ratios at CM energy ~10-50 GeV |
| What is the difference between the impacts of emergent- and Higgs-mass mechanisms on light-quark behavior? | Behavior of (valence) up quarks in pion and kaon at large $x$. | • CM energy ~20 GeV (lowest CM energy to access large-x region)<br>• Higher CM energy for range in $Q^2$ desirable |
| What is the relationship between dynamically chiral symmetry breaking and confinement? | Transverse-momentum dependent Fragmentation Functions of quarks into pions and kaons. | • Collider kinematics desirable (as compared to fixed-target kinematics)<br>• CM energy range ~20-140 GeV |

J. Arrington et al., J.Phys.G 48 (2021) 7, 075106

# EIC Meson Structure Functions Questions

| Science Question | Key Measurement[1] | Key Requirements[2] |
|---|---|---|




Can we even do SIDIS or DES off meson target?

| More speculative observables | | |
|---|---|---|
| What is the trace anomaly contribution to the pion mass? | Elastic $J/\Psi$ production at low $W$ off the pion. | • Need to uniquely determine exclusive process $e + p \to e' + J/\Psi + \pi^+ + n$ (low $-t$)<br>• High luminosity ($10^{34+}$ cm$^{-2}$ sec$^{-1}$)<br>• CM energy ∼70 GeV |
| Can we obtain tomographic snapshots of the pion in the transverse plane? What is the pressure distribution in a pion? | Measurement of DVCS off pion target as defined with Sullivan process. | • Need to uniquely determine exclusive process $e + p \to e' + \gamma + \pi^+ + n$ (low $-t$)<br>• High luminosity ($10^{34+}$ cm$^{-2}$ sec$^{-1}$)<br>• CM energy ∼10-100 GeV |
| Are transverse momentum distributions universal in pions and protons? | Hadron multiplicities in SIDIS off a pion target as defined with Sullivan process. | • Need to uniquely determine SIDIS off pion $e + p \to e' + h + X + n$ (low $-t$)<br>• High luminosity ($10^{34}$ cm$^{-2}$ sec$^{-1}$)<br>• $e + p$ and $e + D$ at similar energies desirable<br>• CM energy ∼10-100 GeV |

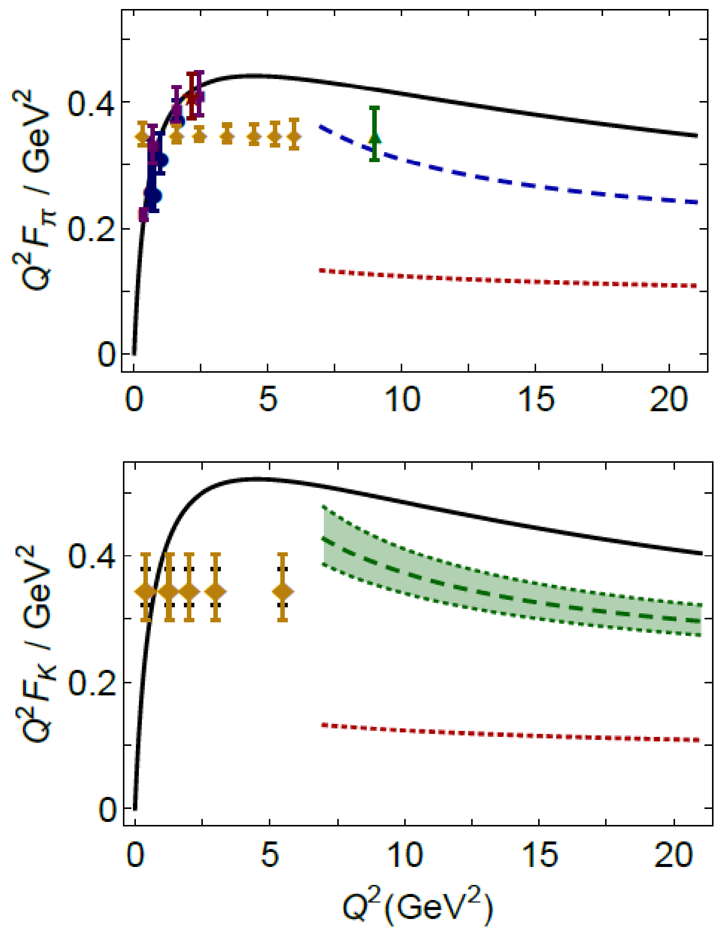
J. Arrington et al., J.Phys.G 48 (2021) 7, 075106

# Summary

- Meson structure is essential for understanding EHM and our visible Universe
  - Meson structure is non-trivial and experimental data for pion and kaon structure functions is extremely sparse
- A coherent effort is required among theory, phenomenology, computing, and experiment to complete our understanding of light meson structure
- There are very exciting imminent opportunities to collect additional data for light mesons
  - TDIS @ 11 GeV JLab - provides data for resolving and cross checking pion PDF issues at high-x and provides kaon SF extraction in an almost empty kaon structure world data set
  - EIC - Potential game-changer for this topic due to large CM range (20-140 GeV); Large x/Q2 langscape for pion/kaon SF; Potential to provide definite answers on different gluon distributions in pion/kaon
- Ongoing efforts extending into 3D light hadron structure – GPDs and TMDs – in theory/experiment
  - TDIS @ 22 GeV JLab could offer new opportunities including possible SIDIS from pion target measurements

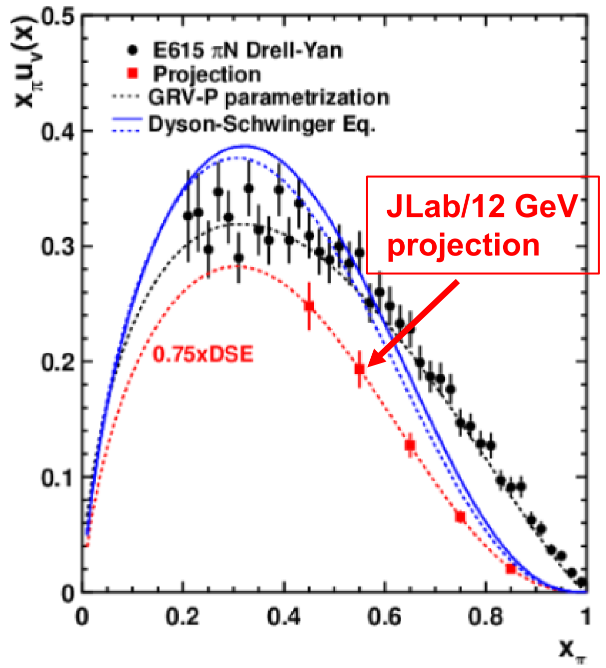
# Summary Pion and Kaon Structure at 12 GeV and beyond

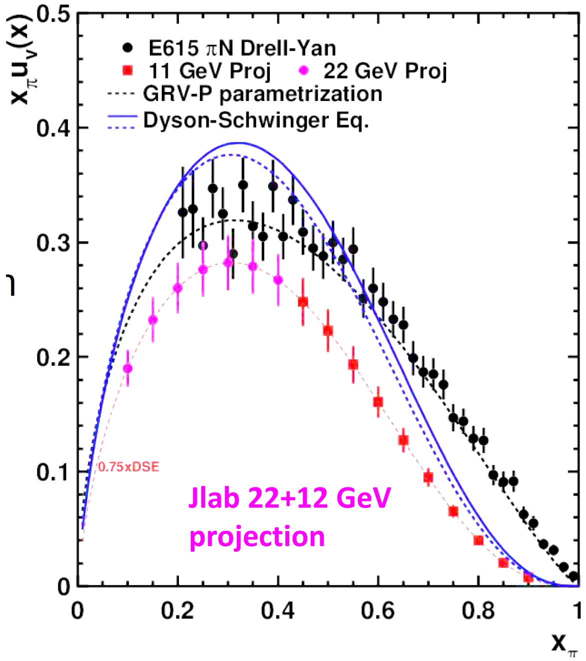
Jefferson Lab will provide, at its CM energy of 5 GeV, tantalizing data for the pion (kaon) form factor up to $Q^2 \sim 10$ (5) $GeV^2$, and measurements of the pion (kaon) structure functions at large-x (> 0.5) through the Sullivan process.




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

PR12-15-006



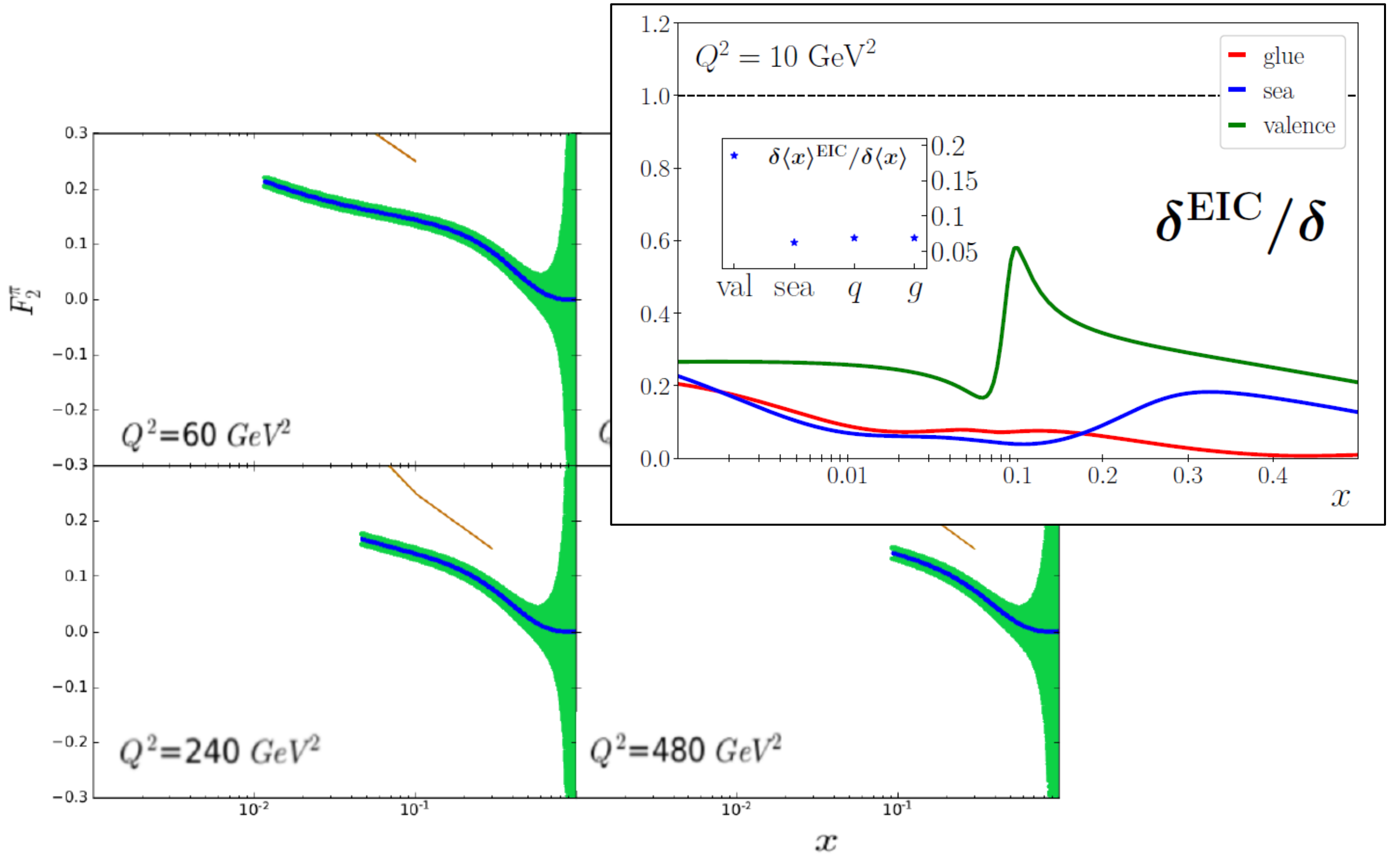



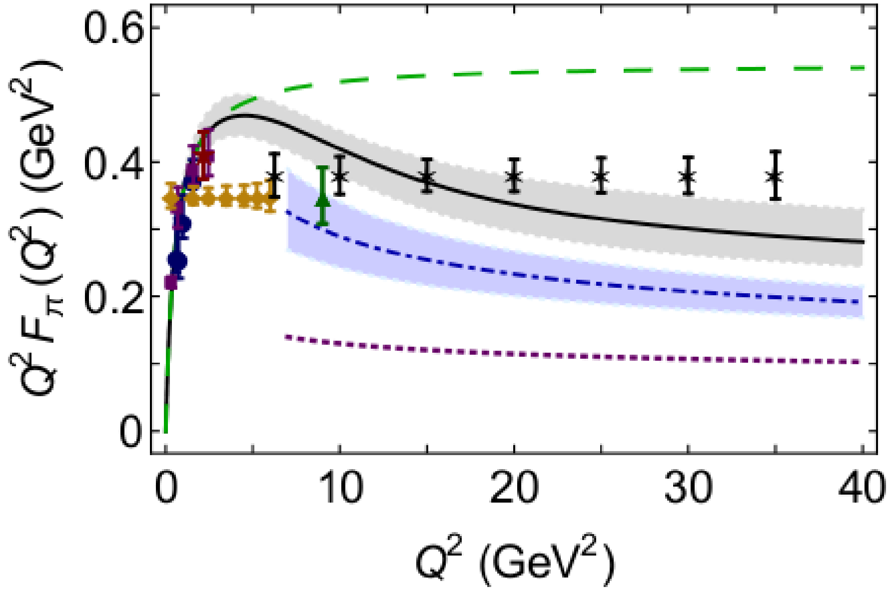

Pion SF – $(1-x)^1$ or $(1-x)^2$ dependence at large x?

and kaon

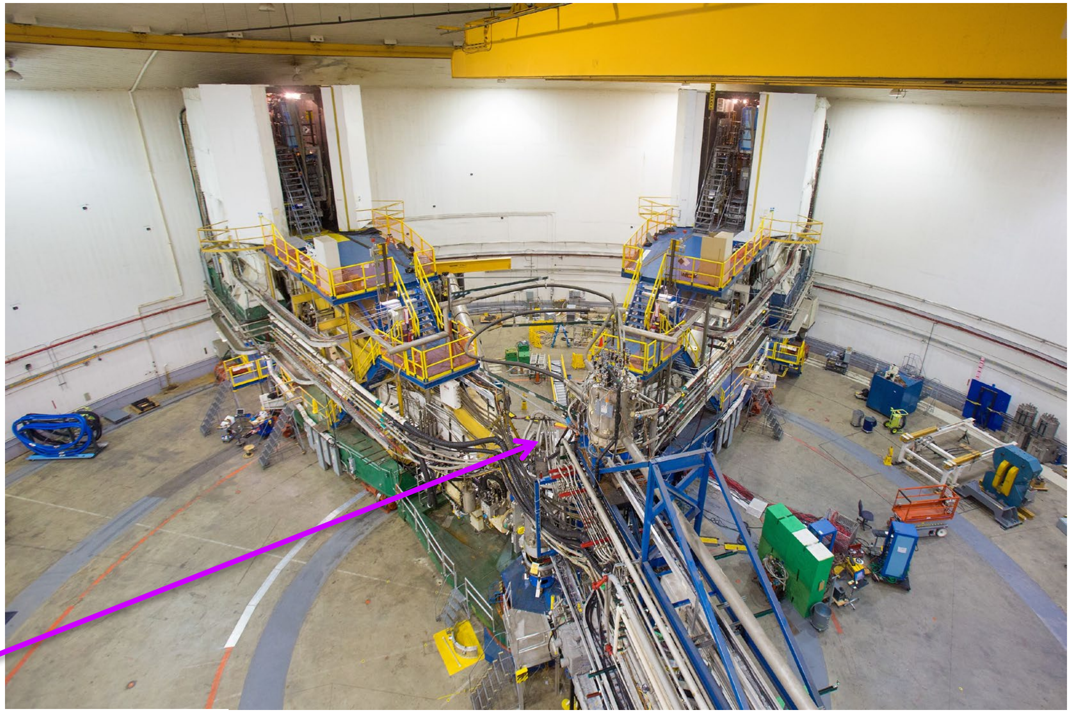
# Summary – Role of EIC

The unique role of EIC is its access to pion and kaon structure over a versatile large CM energy range, ~20-140 GeV. With its larger CM energy range, the EIC will have the final word on the contributions of gluons in pions and kaons as compared to protons, settle how many gluons persist as viewed with highest resolution, and vastly extend the x and $Q^2$ range of pion and kaon charts, and meson structure knowledge.



# JLab Hall A TDIS Experiment

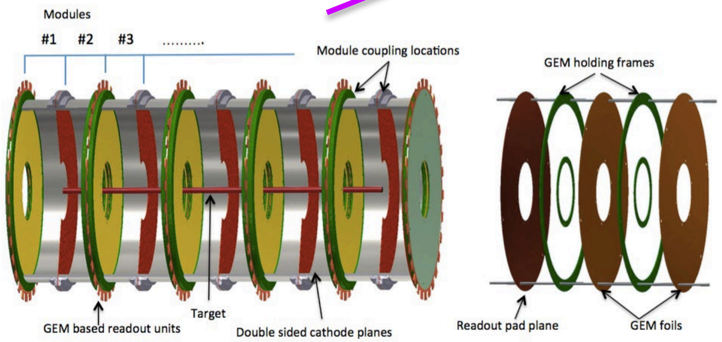


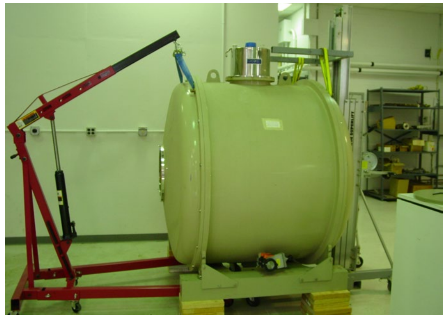
## *Hall A with SBS:*

- ✓High luminosity,
  50 μAmp,
  $\mathcal{L}$ = $3\text{x}10^{36}/\text{cm}^2$ s
- ✓Large acceptance
  ~70 msr

**Important for small cross sections**

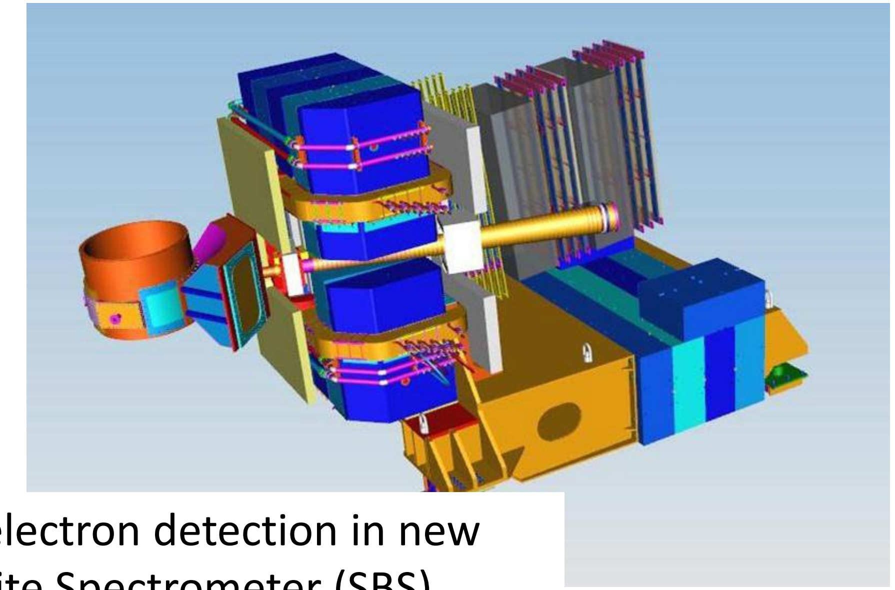
proton tag detection in GEM-based mTPC at pivot



multiple Time Projection Chamber (mTPC) inside superconducting solenoid

**e- beam**



Scattered electron detection in new Super Bigbite Spectrometer (SBS)