Prospects for Emergent Mass and Structure Studies at the EIC

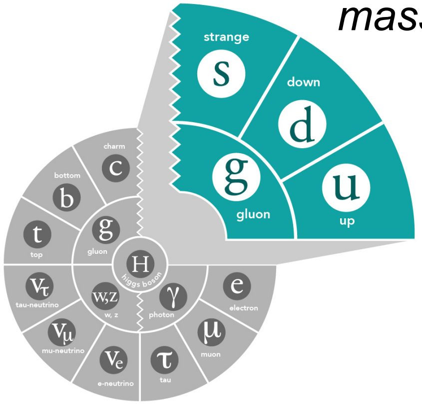
Rolf Ent (Jefferson Lab)

Mass in the Standard Model and Consequences of its Emergence

ECT* Trento

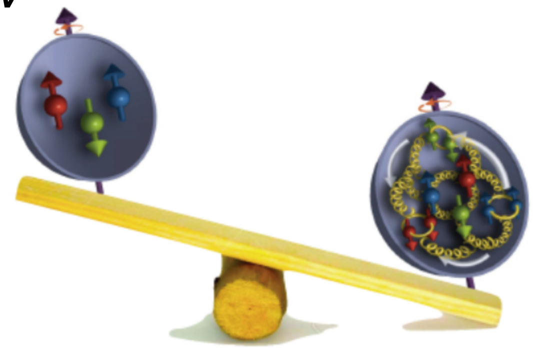
April 19-23, 2021

Mass of the Proton, Pion, Kaon



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

"Mass without mass!"



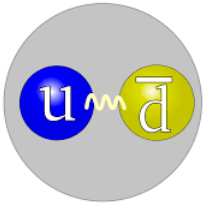
Proton

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

Gluon rise discovered by HERA e-p

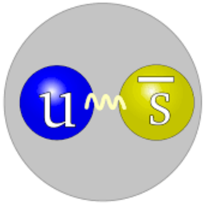
Pion

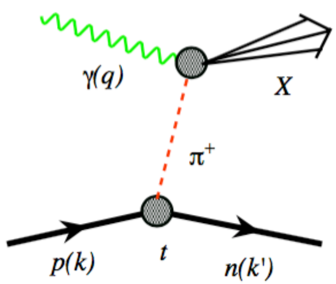
Quark structure: ud
Mass ~ 140 MeV
Exists only if mass is dynamically generated.
Empty or full of gluons?



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 to mass with the Sullivan process.

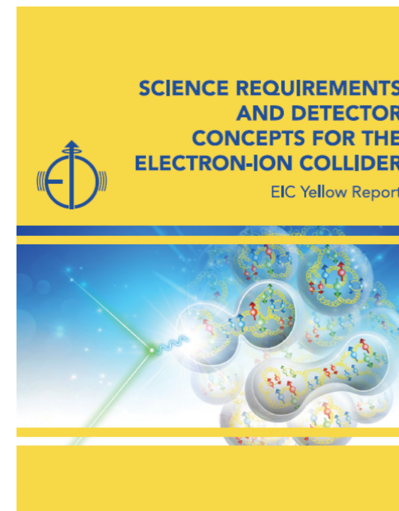
Origin of Mass in the EIC Yellow Report

Yellow Report, exec. summary, page 10

2.3 Origin of Nucleon Mass

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/ψ and Υ) close to the production threshold.

Another way to address the emergence of hadron mass is through chiral-symmetry features that manifest in the lightest mesons, the pion and kaon. In this picture, the properties of the nearly massless pion are the cleanest expressions of the mechanism that is responsible for the emergence of the mass and have measurable implications for the pion form factor and meson structure functions [12]. At variance with the pion, the effects of the Higgs mechanism, which gives a non-vanishing mass to the quarks, play a more substantial role for the kaon mass due to its strange quark content. Therefore, a comparison of the charged pion and charged kaon form factors over a wide range in Q^2 would provide unique information relevant to understanding the generation of hadronic mass. The EIC can also open a vast landscape of structure function measurements constraining quark and gluon energy distributions in pions and kaons.

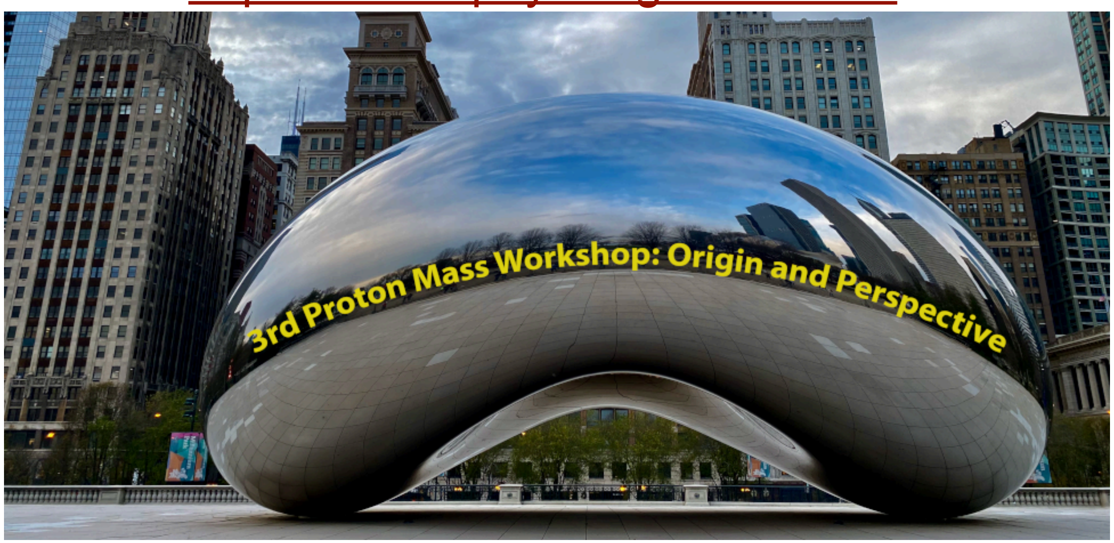


Proton Mass Workshops

https://phys.cst.temple.edu/~meziani/proton-mass-workshop-2016/

https://indico.jlab.org/event/194/overview

https://indico.phy.anl.gov/event/2/

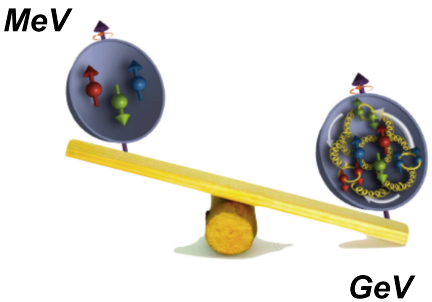


Next: https://www.int.washington.edu/PROGRAMS/20-77W/

The Incomplete Proton: 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:



Relativistic motion — Quantum fluctuation

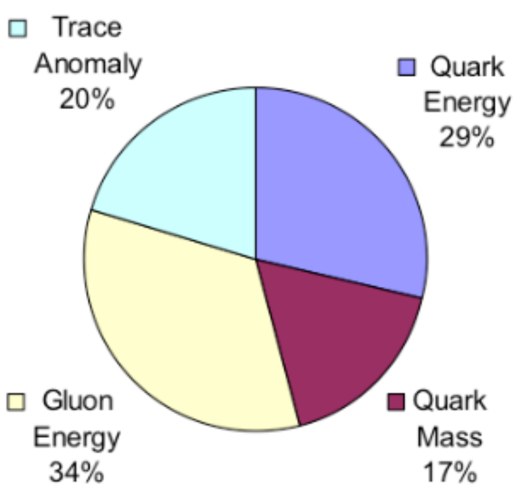
$$M = E_q + E_g + \chi_{m_q} + T_g$$

Quark Energy — Gluon Energy — Quark Mass — Trace Anomaly

Ji PRL 1995

Ji 1995 (proton): χ_{mq} = small, $E_q = ¾M <xq> (\mu)$, $E_g = ¾ M <xg> (\mu)$, $T_g = ¼ M$

Early Lattice:
(Keh-Fei Liu)

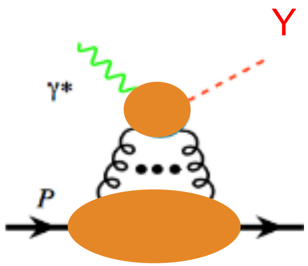


Present Lattice:
(C. Alexandrou)

χ_{mq} ~ 20%
Eq ~ 30% (MSbar, at 2 GeV)
Eg ~ 32% (MSbar), at 2 GeV)
Tg ~ 20%

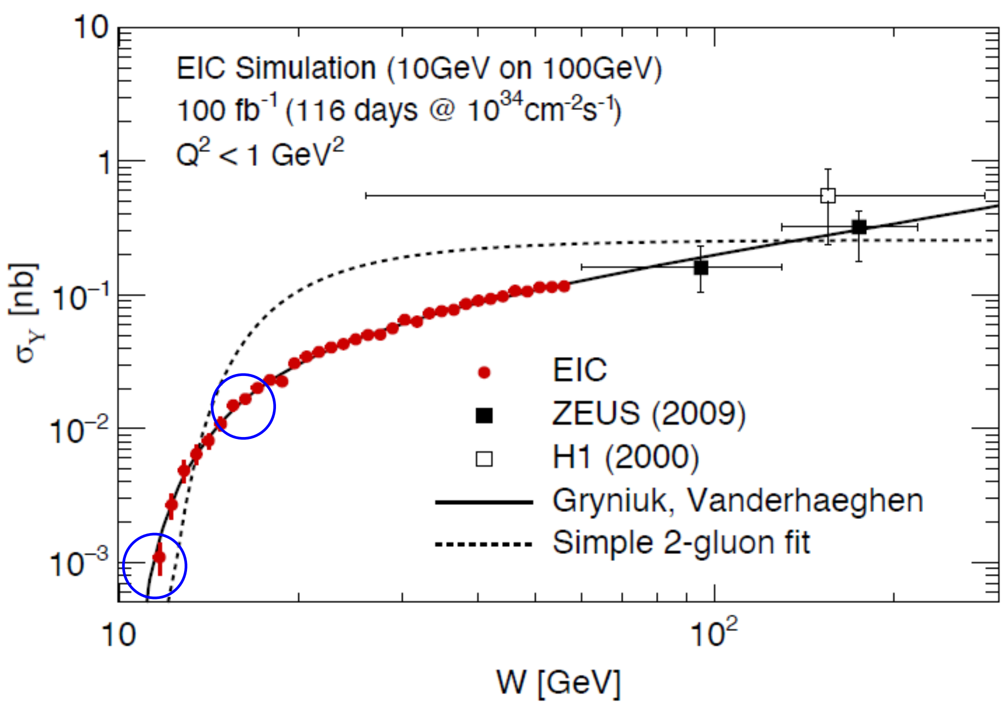
Elastic Υ production near threshold at an EIC

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

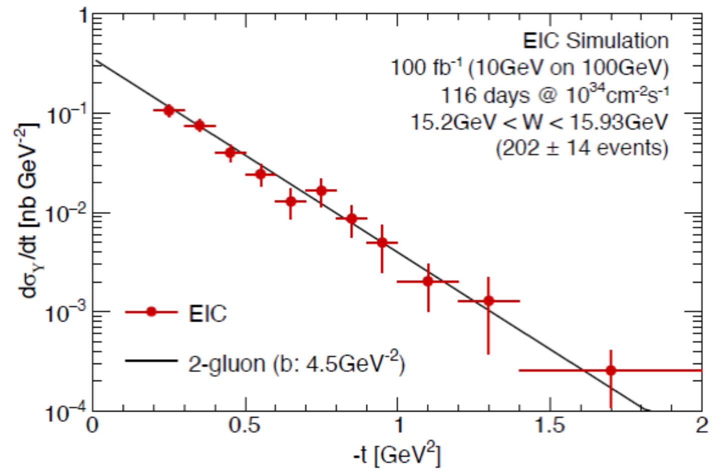


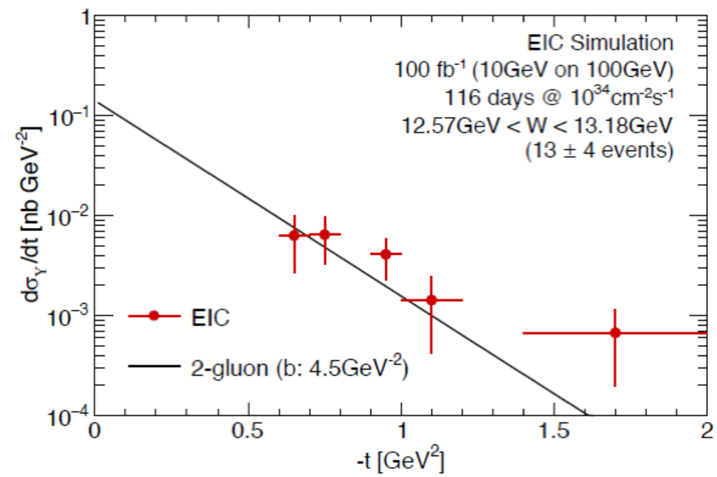
S. Joosten, Z-E. Meziani

Low W → trace anomaly
Large W → Gluon GPDs
(see arXiv:1802.02616)



t distribution





EIC – Origin of the Proton Mass

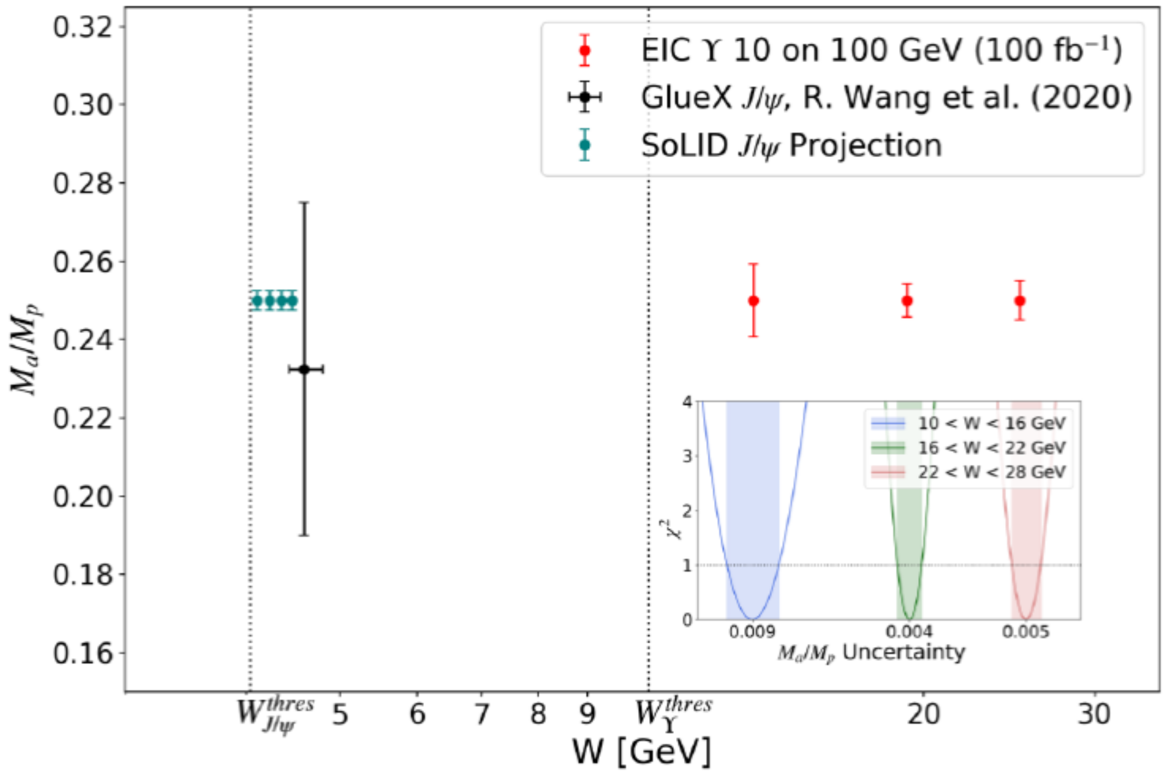
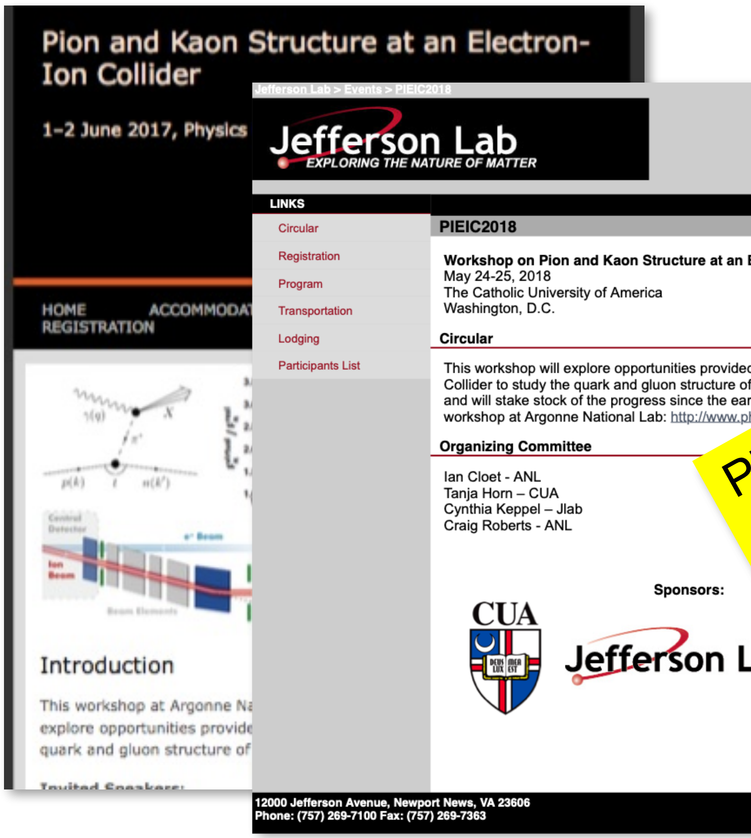


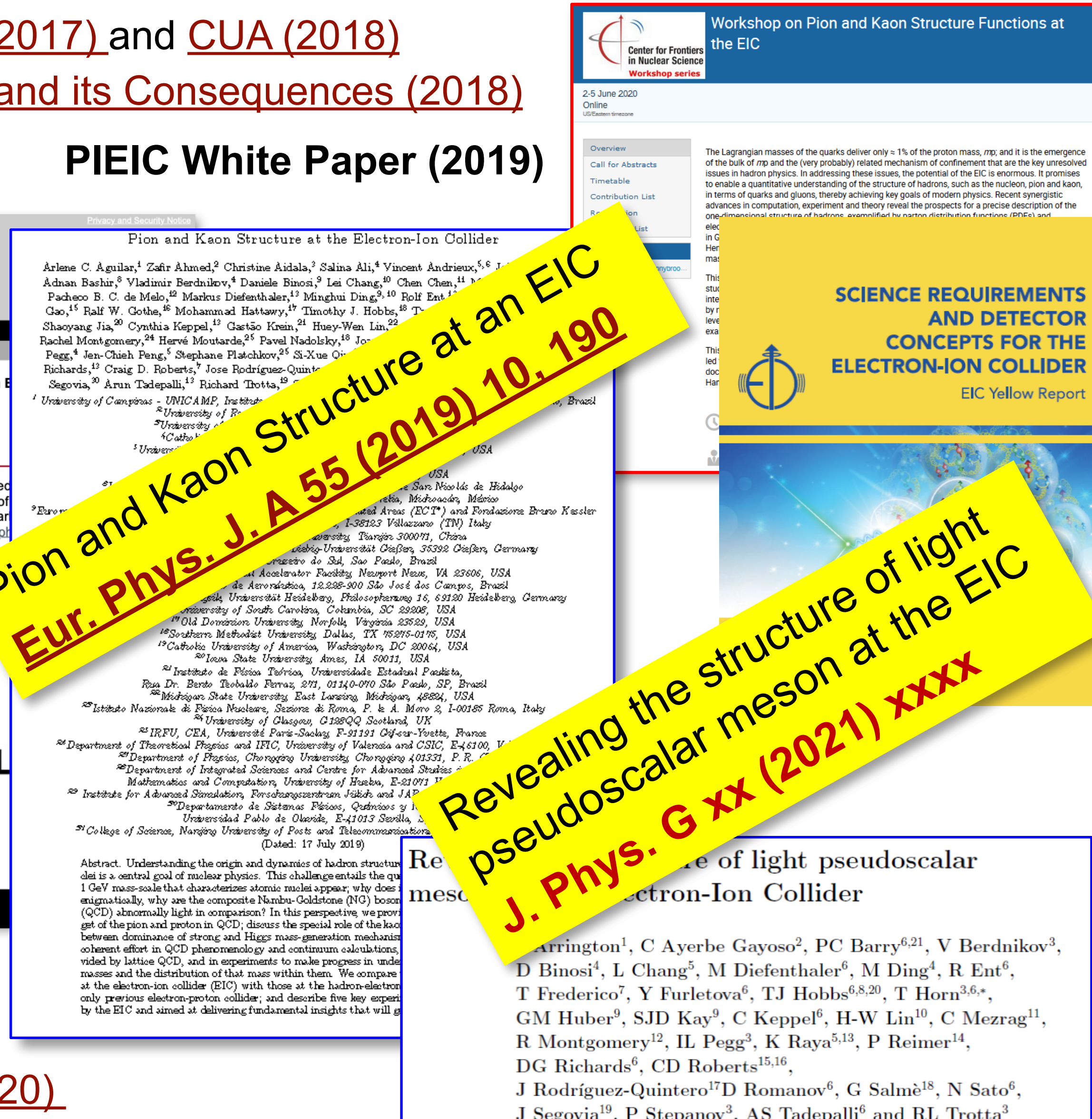
Figure 7.26: Projection of the trace anomaly contribution to the proton mass (M_a/M_p) with ϒ photoproduction on the proton at the EIC in 10 × 100 GeV electron/proton beam-energy configuration. The insert panel illustrates the minimization used to determine the uncertainty for each data point. The black circles are the results from the analysis of the GlueX J/ψ data [191], while the dark green circles correspond the JLab SoLID J/ψ projections. The ϒ projections were generated following the approach from Ref. [192] with the lAger Monte Carlo generator [193].

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)



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

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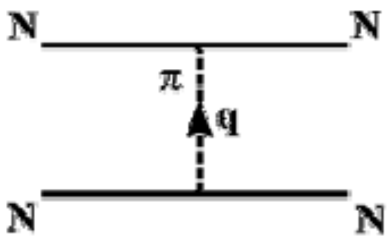
Origin of mass of QCD's pseudoscalar Goldstone modes

- The pion is responsible for the long-range part of the nuclear force, acting as the basis for meson exchange forces and playing a critical role as an elementary field in nuclear structure Hamiltonians



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

- 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)

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

- Pseudoscalar masses are generated dynamically – If $\rho_\pi \neq 0$, $m_\pi^2 \sim \sqrt{m_q}$
  - The mass of bound states increases as $\sqrt{m}$ with the mass of the constituents
  - In contrast, in quantum mechanical models, *e.g.*, constituent quark models, the mass of bound states rises linearly with the mass of the constituents
  - *E.g.*, with constituent quarks Q: in the nucleon $m_Q \sim ⅓m_N \sim 310$ MeV, in the pion $m_Q \sim ½m_\pi \sim 70$ 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 (DχSB) that makes the pion and kaon masses light.

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*

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

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

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

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 universal in hadrons

Also interpreted as: *in the chiral limit the pion's gluon structure becomes more like that of the vacuum.*

But M_π ~140 MeV $\neq 0$: what gluons are there in the pion?

The Role of the Chiral Limit

- The chiral limit gives us understanding and can act as consistency check
- But the pion mass is not zero, it is 140 MeV

[Jianwei Qiu:]

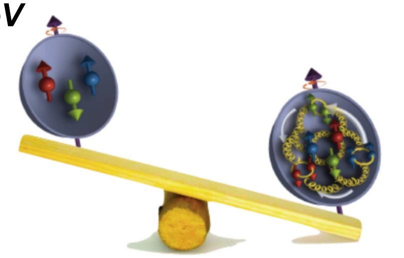
- Good mass decomposition should work for the proton, pion, (the kaon), …

$$\langle P(p)|T^{\mu}_{\mu}|P(p)\rangle = M_p^2 \sim (938\,\mathrm{MeV})^2$$
$$\langle \pi(p)|T^{\mu}_{\mu}|\pi(p)\rangle = M_\pi^2 \sim (139\,\mathrm{MeV})^2$$
$$\langle K(p)|T^{\mu}_{\mu}|K(p)\rangle = M_K^2 \sim (497\,\mathrm{MeV})^2$$

- A decomposition is valuable iff individual terms can be measured or calculated independently with controllable approximations

The Incomplete Hadron: Mass Puzzle

- Pion mass:



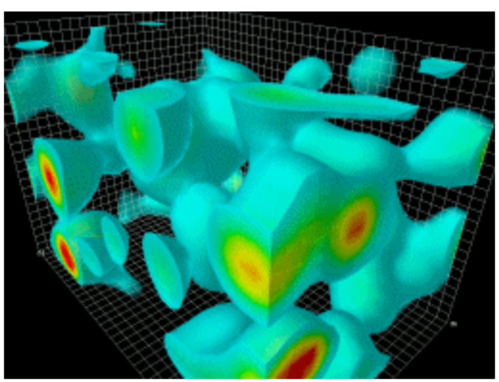
$$M = E_q + E_g + \chi_{m_q} + T_g$$

Relativistic motion ($E_q + E_g$) · Quantum fluctuation ($\chi_{m_q} + T_g$)

Quark Energy (E_q) · Gluon Energy (E_g) · Quark Mass (χ_{m_q}) · Trace Anomaly (T_g)

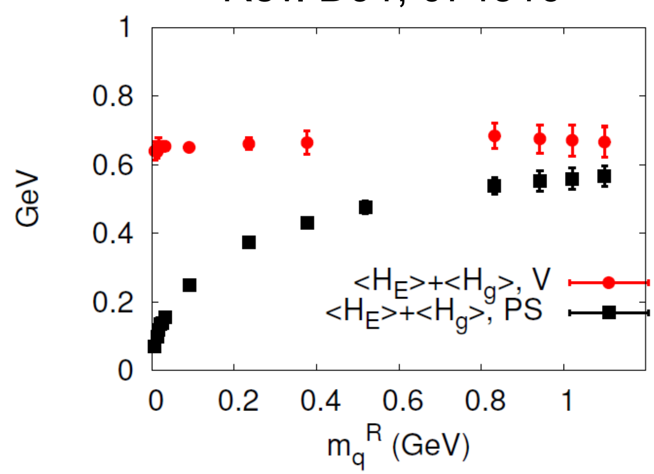
Ji 2021 (pion): χ_{mq} ~ 1/2 M, E_q = 3/8 M <xq> (μ), E_g = 3/8 M <xg> (μ), T_g = 1/8 M

Ji 1995



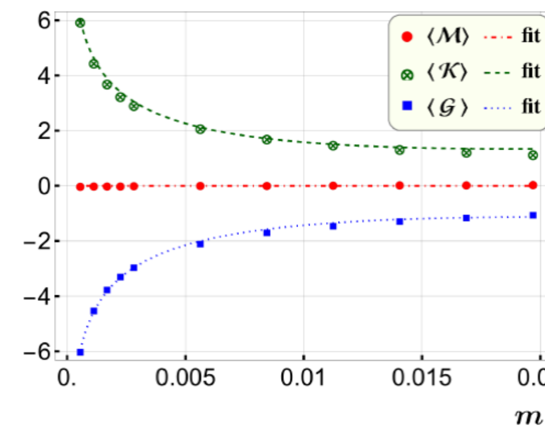
In chiral limit, all terms vanish, and pion's gluon structure becomes like vacuum

Yang et al, Phys. Rev. D91, 074516



The combined quark/glue energy contribution to the PS/V meson mass

Yu Jia et al., Phys. Rev. D98, 074024

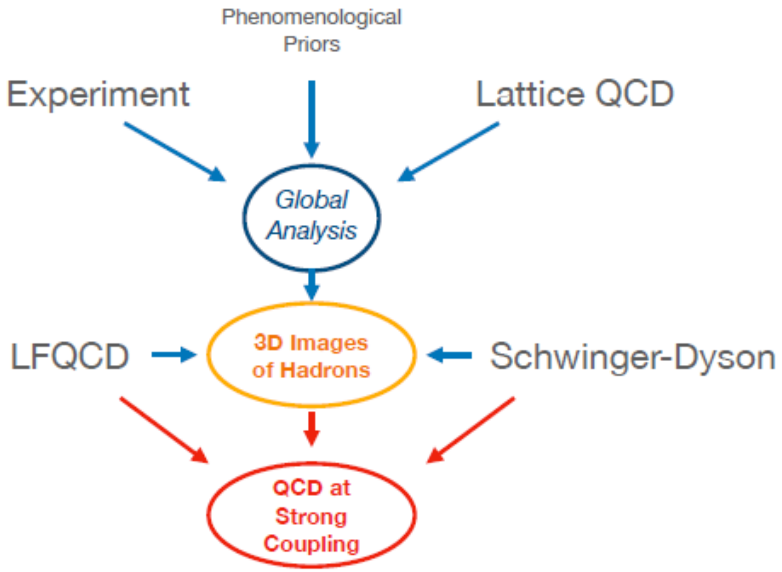


In 2D QCD the quark and gluon contributions diverge and bear opposite sign, upon summing the GOR relation holds

Pion and Kaon Structure and the Origin of Mass

Context: much work related to this by large group of theorists and experimentalists in context of EIC-related workshops ("Pion and Kaon Structure at the EIC"), an EIC white paper, and a sub-group on meson structure as part of the EICUG Yellow Report initiative.

Recently this resulted also in a 2nd EIC-related paper, emphasizing both synergy between experiment, theory and Lattice to understand emergent pion (kaon) mass and structure, and that access to such meson structure at EIC drives the forward-detection method and the full integration of the detector and Interaction Region.



Mass without Mass

Rapid acquisition of mass is effect of gluon interactions

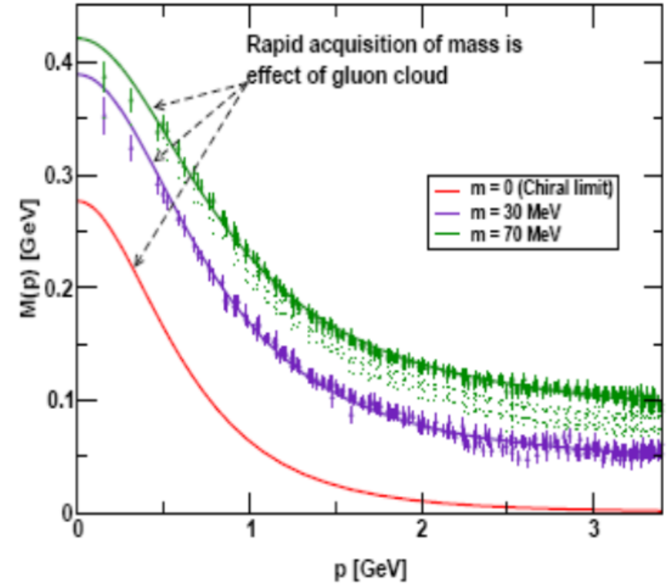
$$S_F(p) = \frac{\mathcal{F}(p)}{\not p - \mathcal{M}(p)}$$

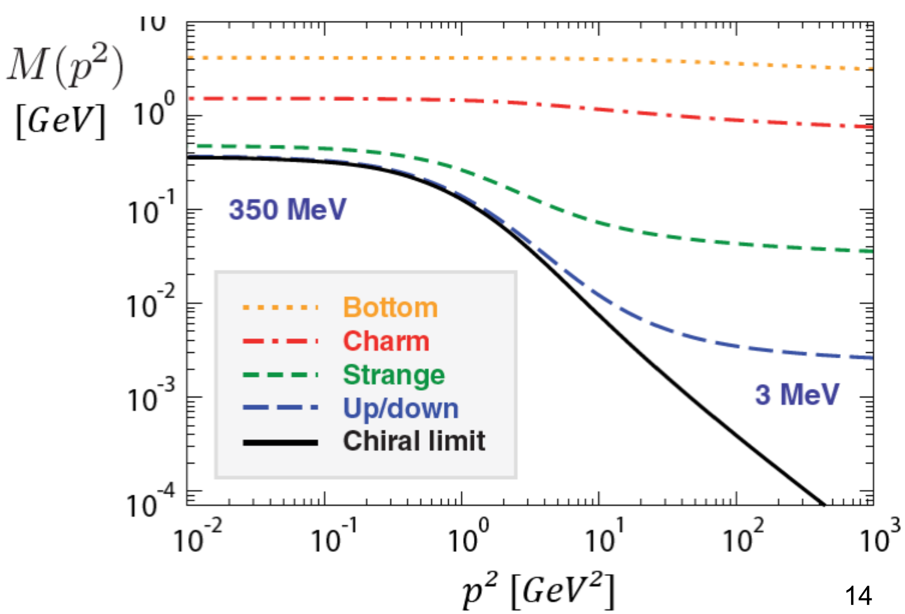
wavefunction renormalisation

mass function

$$S_F(p)^{-1} = \not p - m_0 - \frac{\alpha}{4\pi} \int d^4k \, \gamma_\mu S_F(k) \Gamma_\nu(k,p) \Delta^{\mu\nu}(q)$$

DSE and Lattice Results

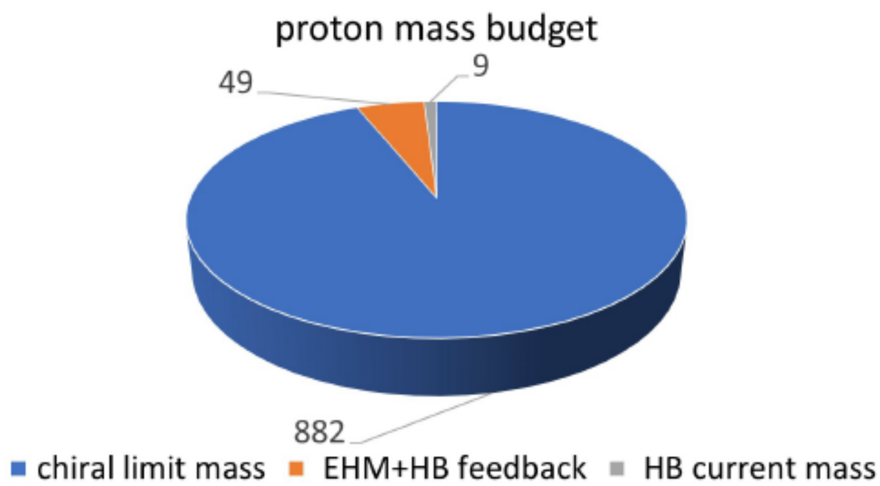


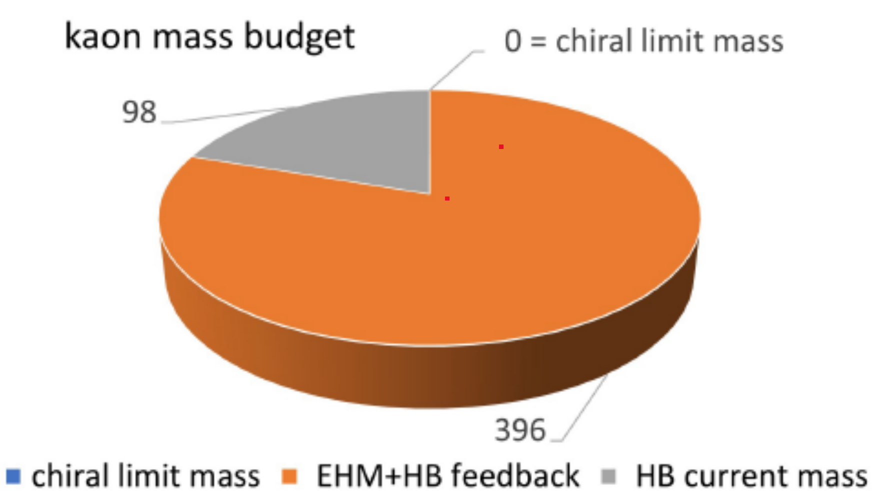


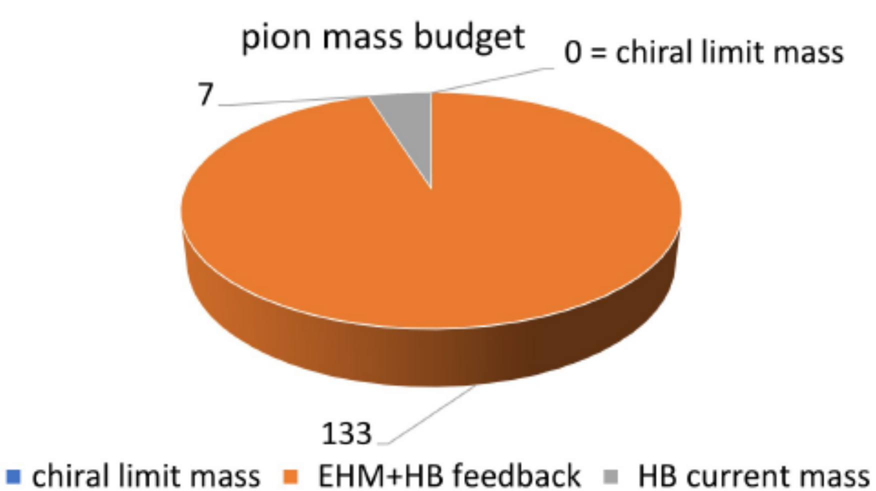
Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions. Higgs mechanism hardly plays a role.

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

Mass Budgets for the Proton, Kaon and Pion







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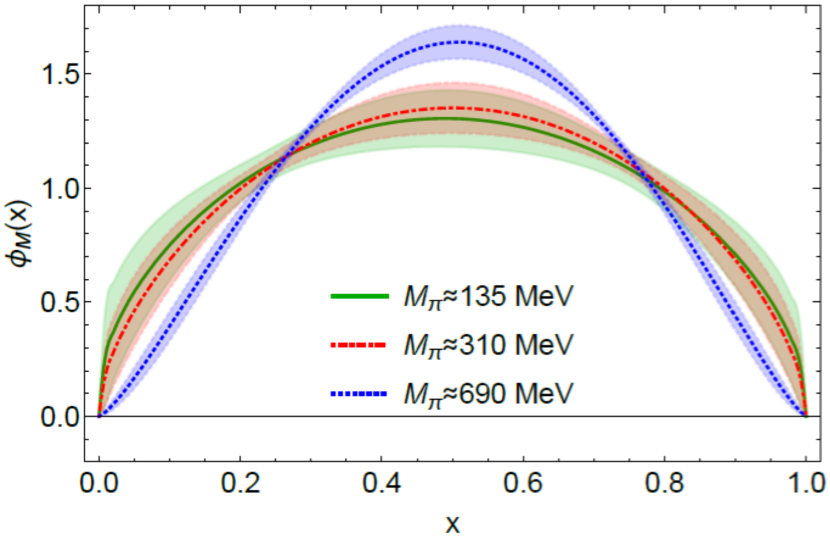
Strong Synergy with Lattice QCD

Huey-Wen Lin et al.

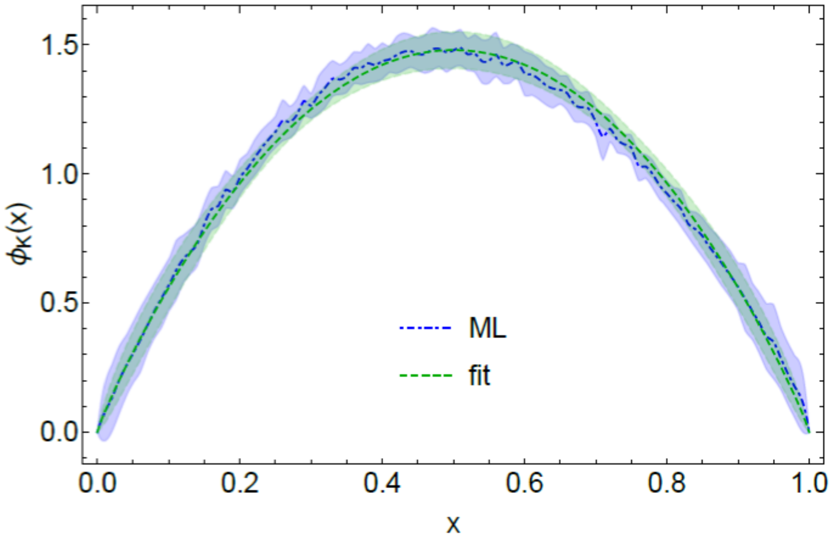
Parton distribution amplitudes

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



As the pion mass decreases, the distribution amplitude gets broader

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

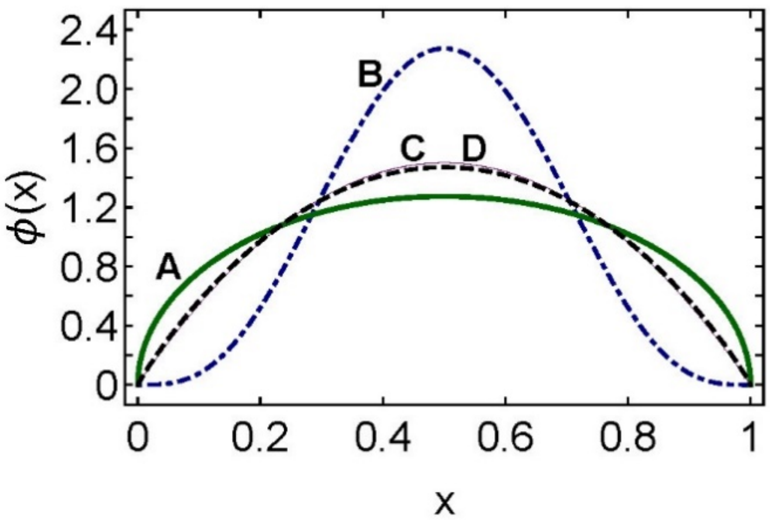


Note the slight asymmetry in the distribution amplitude around x = 0.5

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

Emergent- versus Higgs-Mass Generation

Twist-2 PDA at Scale ζ = 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 – η_c ⇐ primarily, Higgs mass generation;

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

D dashed (black) curve – “heavy-pion”, i.e., a pion-like pseudo-scalar meson ($\sim\eta_s$) 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 δ-function at x = ½.
- The sufficiently heavy η_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.

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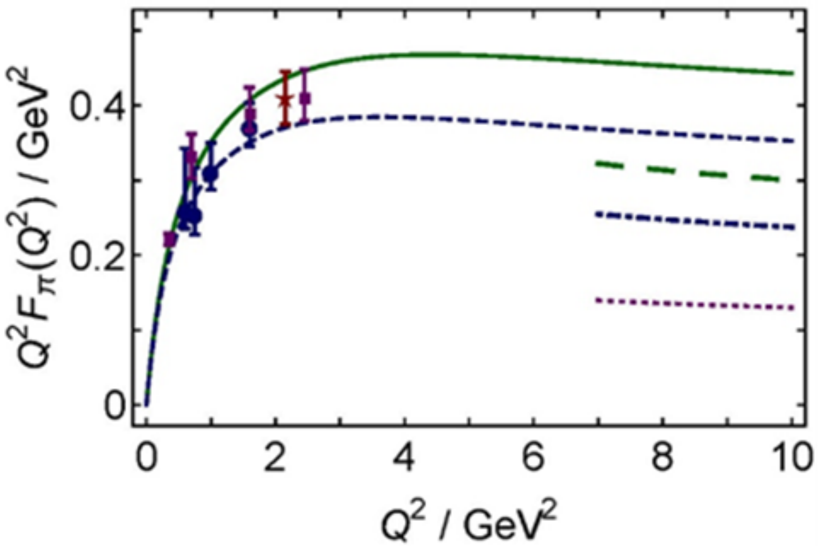
Pion Form Factor and Emergent Mass

Muyang Chen, Craig Roberts

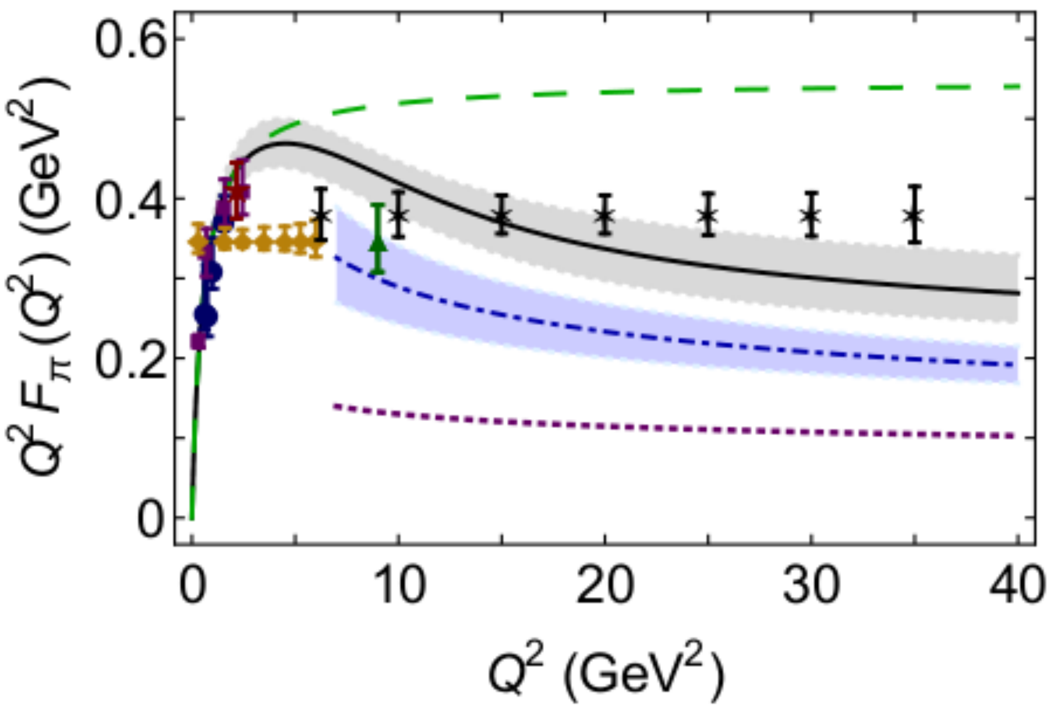


Left panel. Two dressed-quark mass functions distinguished by the amount of DCSB: emergent mass generation is 20% stronger in the system characterized by the solid green curve, which describes the more realistic case. Right panel. $F_\pi(Q^2)$ obtained with the mass function in the left panel: r_π =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

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

*A.C. Aguilar et al., EPJ A **55** (**2019**) 10, 190*



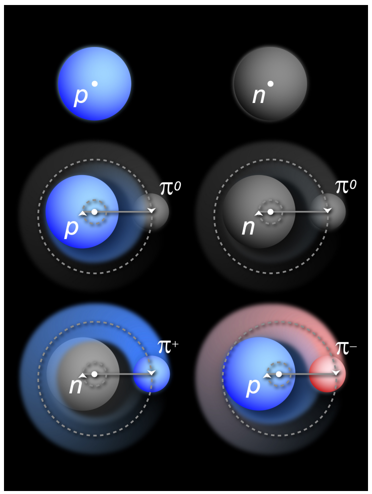
- Assumed 5 GeV(e⁻) x 100 GeV(p) with an integrated luminosity of 20 fb^{-1}/year, and similar luminosities for d beam data
- $R=\sigma_L/\sigma_T$ assumed from VR model – and assume that π pole dominance at small t confirmed in ^2H π^-/π^+ ratios
- Assumed a 10% experimental systematic uncertainty,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

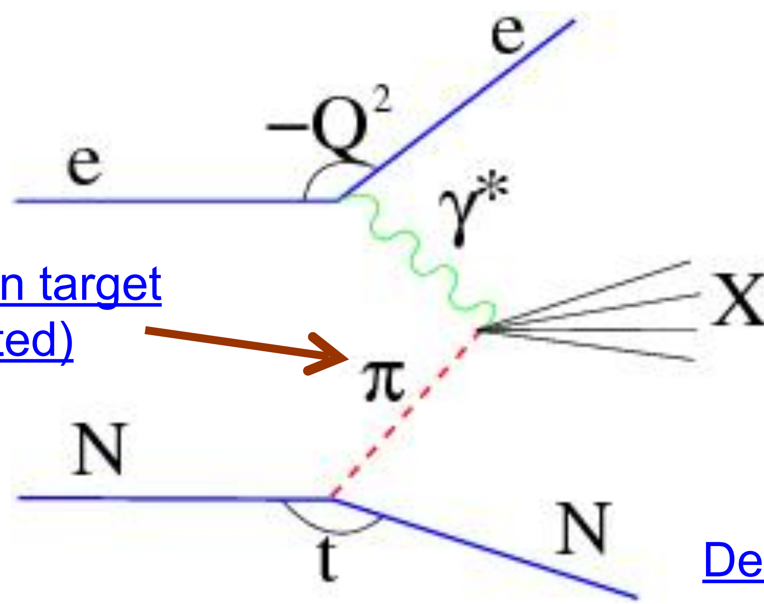
Physics Objects for Pion/Kaon Structure Studies

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_π) of undetected recoiling hadronic system

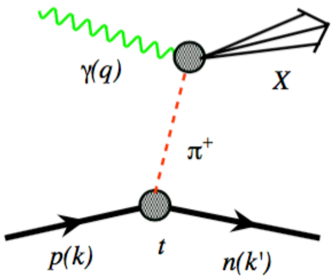
Detect "tagged" neutron/lambda

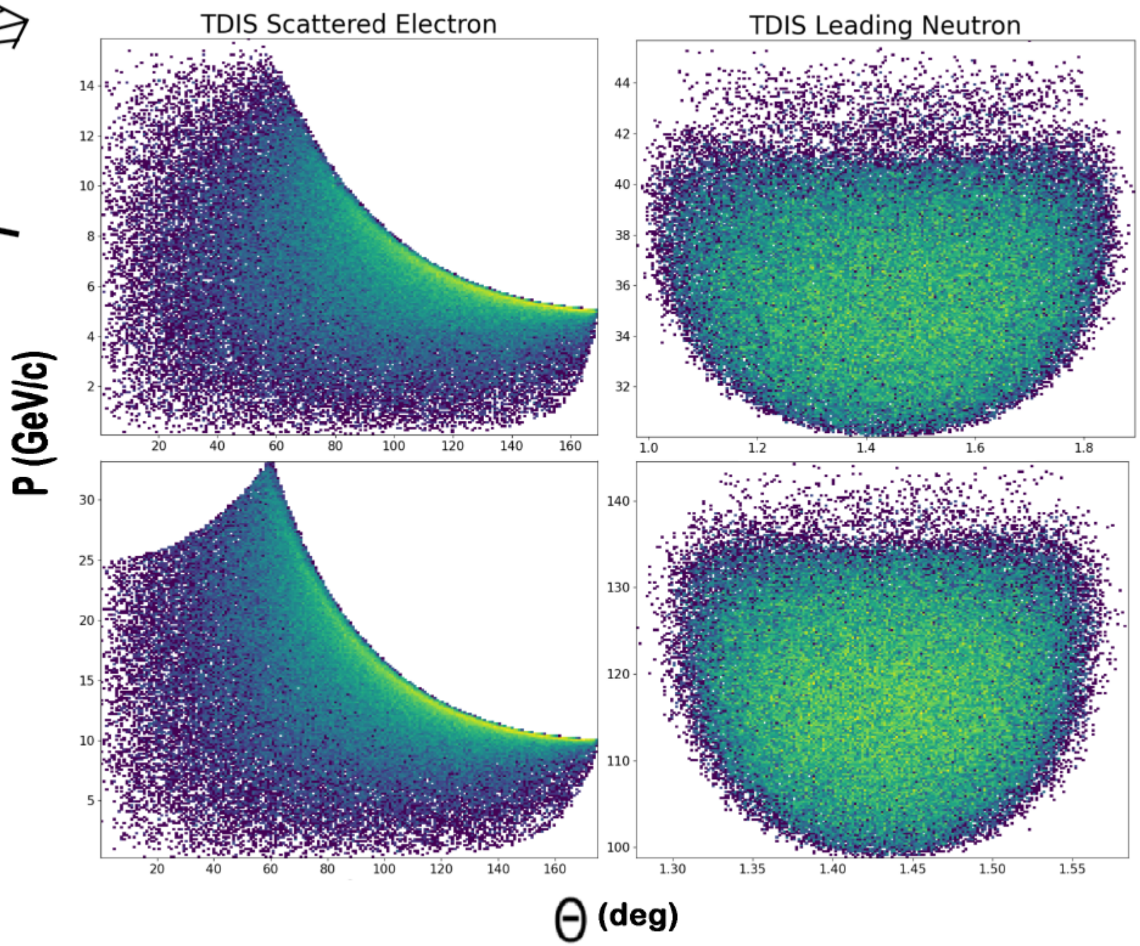
$$F_2^{LP(3)} = \sum_i \left[\int_{t_0}^{t_{min}} f_i(z,t)\,dt \right] F_2^i(x_i, Q^2)$$

$i = \pi, \rho, \ldots$

"Flux factor"

EIC Meson Structure Kinematics





Electron x Proton beam energies

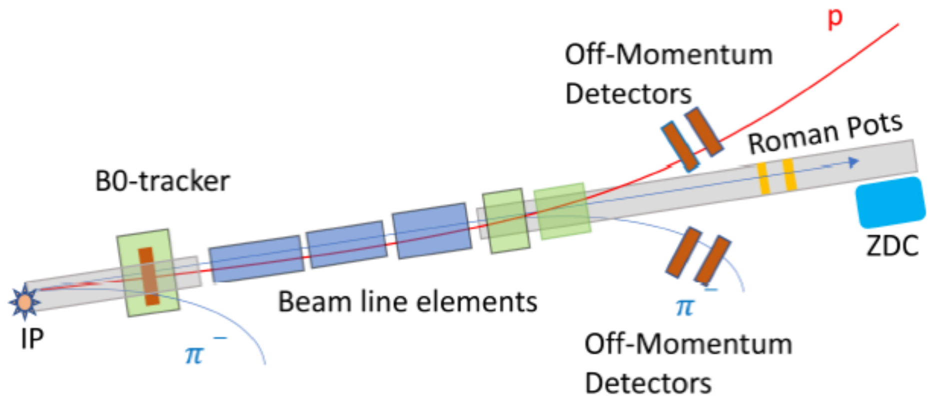
5 GeV x 41 GeV

10 GeV x 135 GeV

Scattered electron goes in EIC central detector region

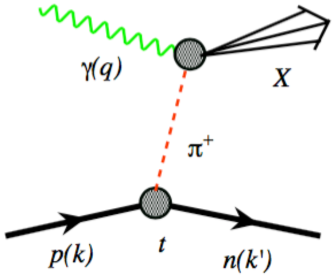
Leading neutron (or lambda) are at small forward angles and carry most of the proton beam momentum

Meson Structure: Summary of EIC Detector Requirements



- **For π-n:**
  - ➢ Lower energies (5 on 41, 5 on 100) require size of ZDC to be at least 60 x 60 cm^2
  - ➢ For all energies, the neutron detection efficiency is 100% with the planned ZDC
- **For π-n and K^+/Λ:**
  - ➢ 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^+/Λ 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 required for good x resolution at large x

EIC – Versatility and Luminosity is Key

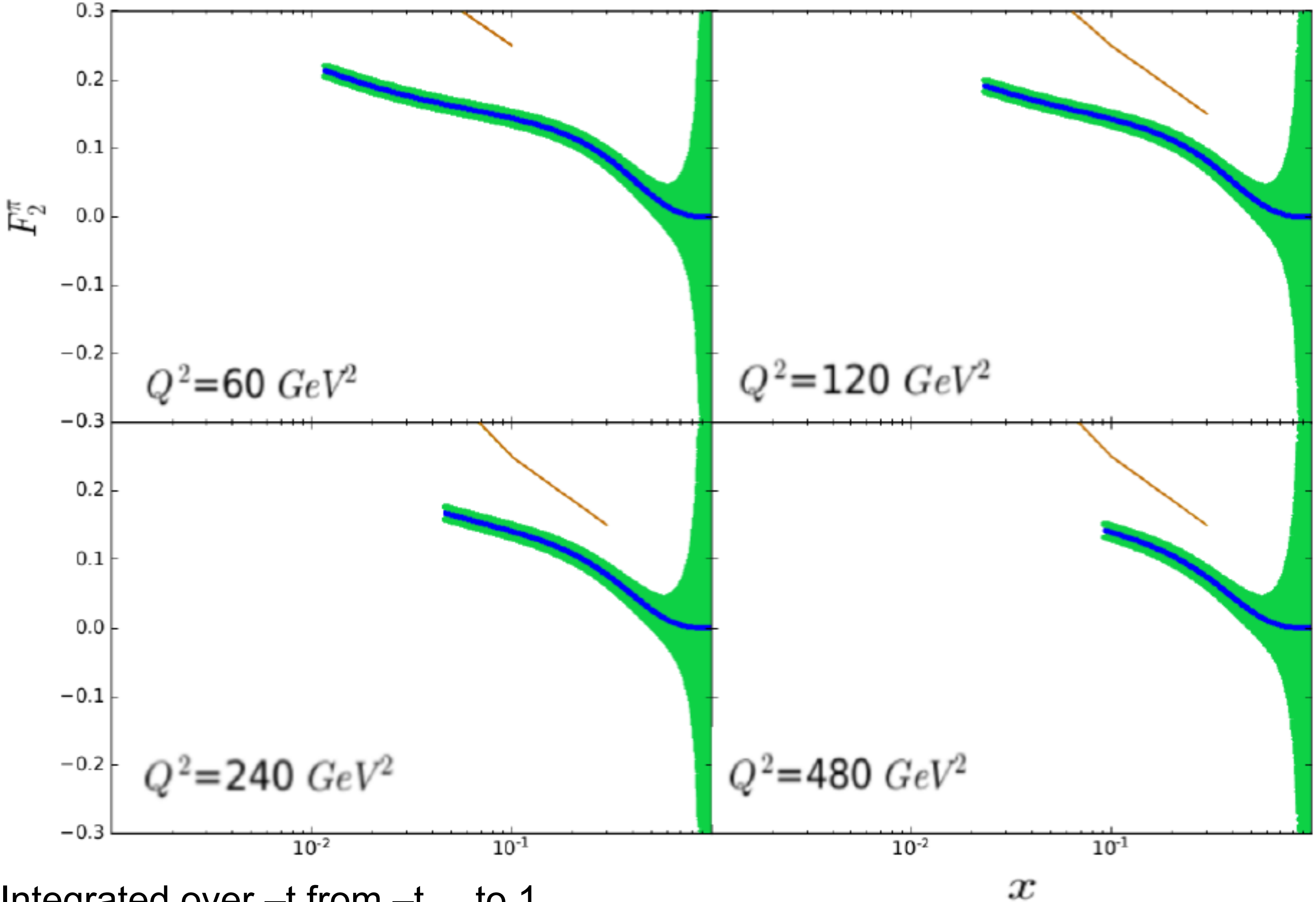


Why would pion and kaon structure functions, and even measurements of pion structure beyond (pion GPDs and TMDs) be feasible at an EIC?

- $L_{EIC} = 10^{34} = 1000 \times L_{HERA}$
- 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) 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)

Pion Structure Function Projections vs x



Integrated over –t from $-t_{min}$ to 1

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Reduction of Pion 1-D Structure Information by EIC

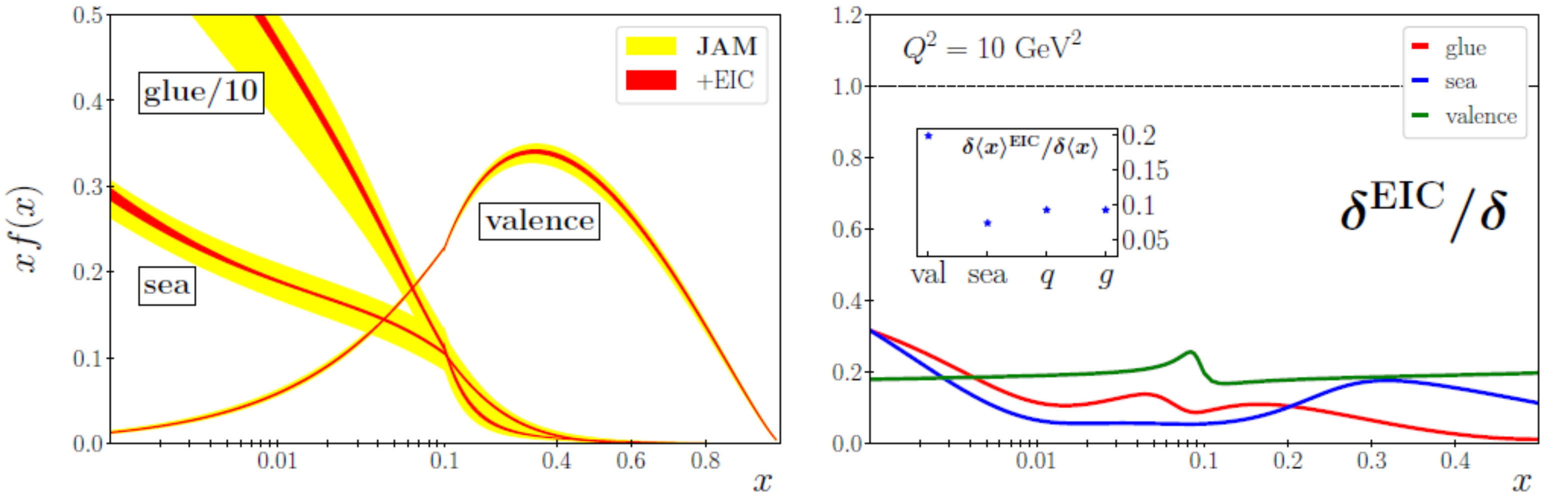

Figure 7.24: Left: Comparison of uncertainties on the pion valence, sea quark and gluon PDFs before (yellow bands) and after (red bands) inclusion of EIC data. Right: Ratio of uncertainties of the PDFs with EIC data to PDFs without EIC data, $\delta^{\rm EIC}/\delta$, for the valence (green line), sea quark (blue) and gluon (red) PDFs, assuming 1.2% systematic uncertainty, and (inset) the corresponding ratios of the momentum fraction uncertainties, $\delta\langle x\rangle^{\rm EIC}/\delta\langle x\rangle$, for valence, sea, total quark and gluon PDFs [149], at the scale $Q^2 = 10$ GeV^2. Fits were obtained using a Monte Carlo procedure, using DGLAP at NLL with VFNS, NLL α_s and both Drell-Yan and F_2 for leading neutrons at NLO.

From EIC Yellow Report,
P. Barry, W. Melnitchouk, N. Sato et al.

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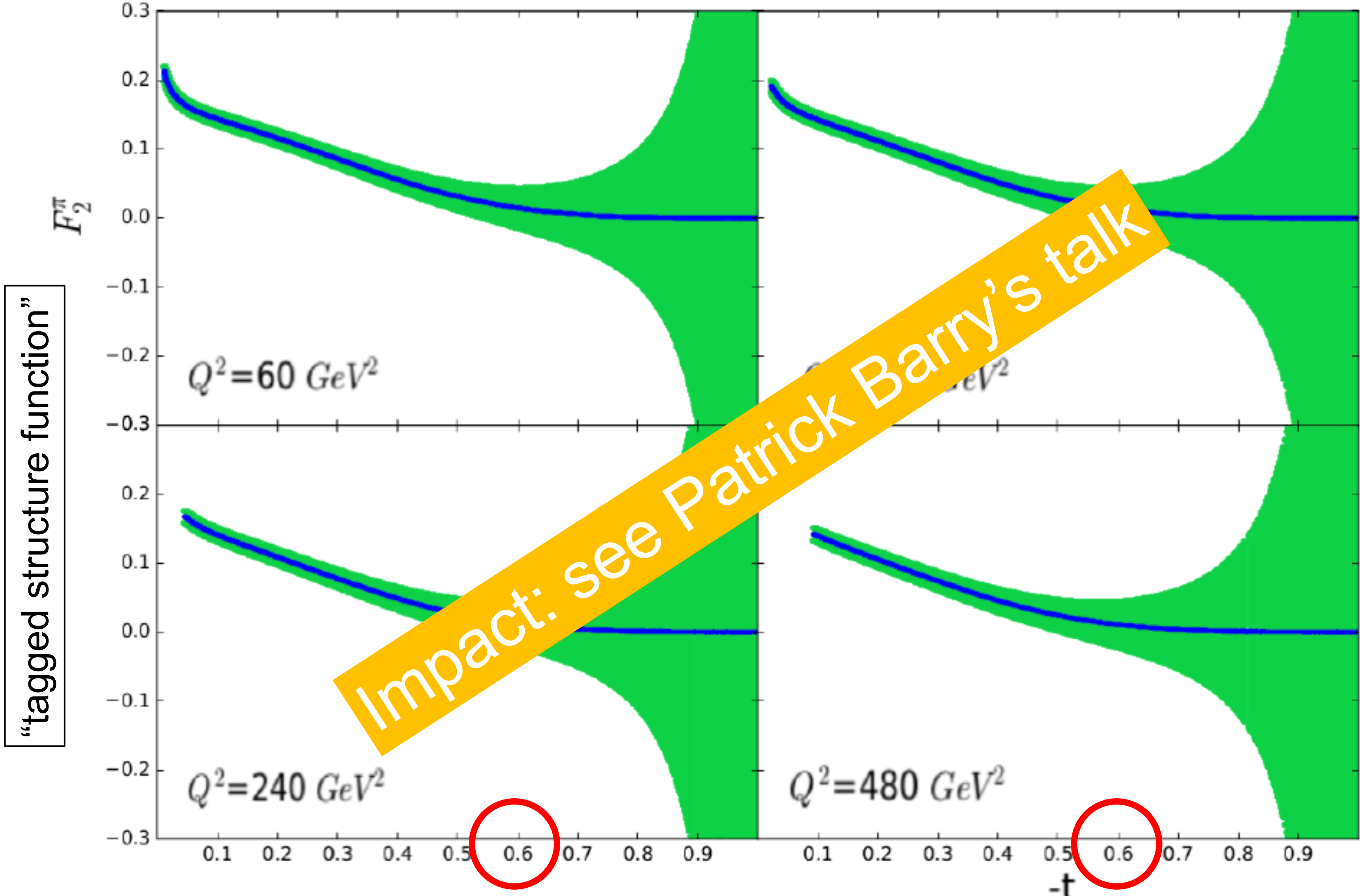
Pion Structure Function Projections vs -t



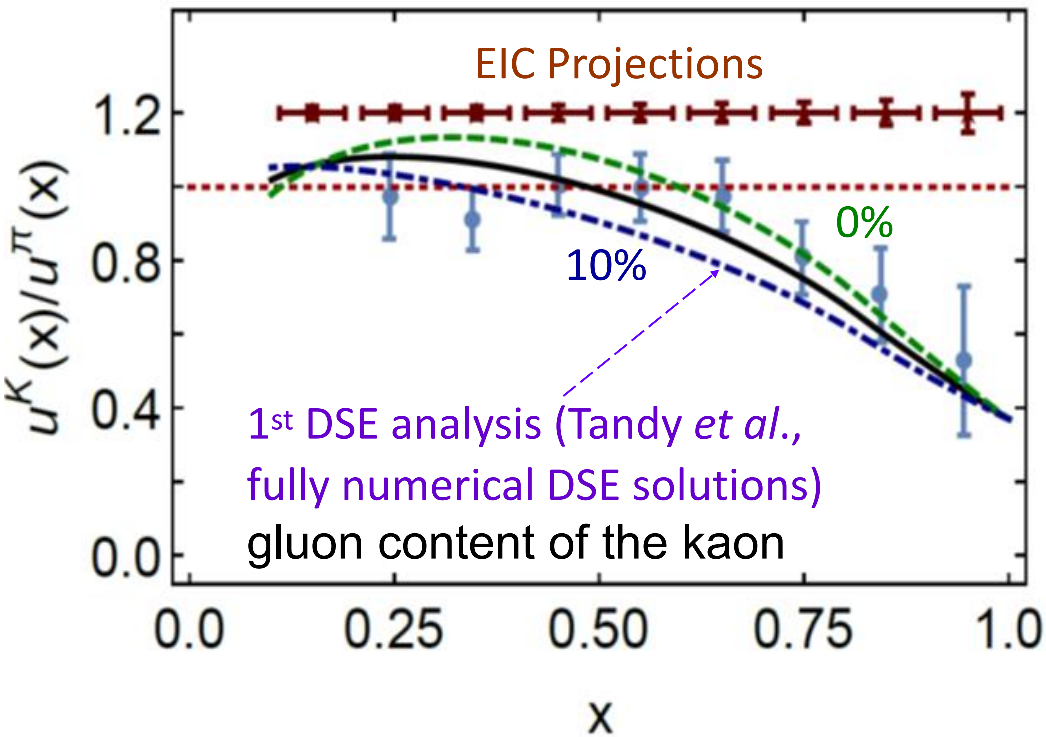
-t-dependence can verify robustness of data interpretation

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., EPJ A ***55*** *(****2019****) 10, 190*



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

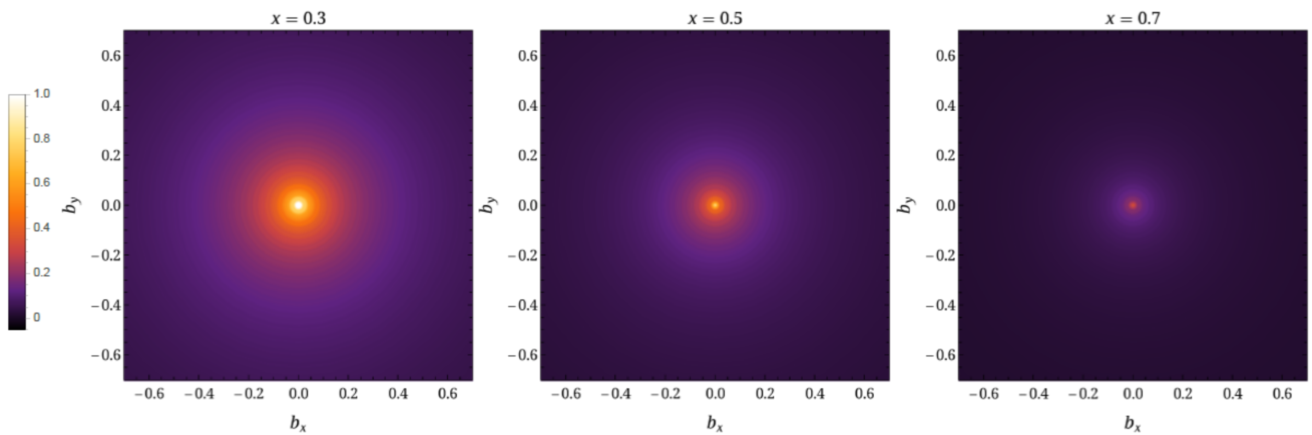
- ❑heavier quarks radiate less readily than lighter quarks
- ❑heavier quarks radiate softer gluons than do lighter quarks
- ❑Landau-Pomeranchuk effect: softer gluons have longer wavelength and multiple scatterings are suppressed by interference.
- ❑Momentum conservation communicates these effects to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

EIC – Meson Structure 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 $-t$) • CM energy range ~10-100 GeV • 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 • 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 $-t$) • 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 • 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 $-t$) • $e+p$ and $e+D$ at similar energies • 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 $-t$) • L/T separation at CM energy ~10-20 GeV • Λ/Σ^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) • 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) • CM energy range ~20-140 GeV

EIC – Meson Structure 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/Ψ production at low W off the pion.	• Need to uniquely determine exclusive process $e+p \rightarrow e' + J/\Psi + \pi^+ + n$ (low $-t$) • High luminosity (10^{34+} cm^{-2} sec^{-1}) • 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 $e+p \rightarrow e' + \gamma + \pi^+ + n$ (low $-t$) • High luminosity (10^{34+} cm^{-2} sec^{-1}) • 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 $e+p \rightarrow e' + h + X + n$ (low $-t$) • High luminosity (10^{34} cm^{-2} sec^{-1}) • $e+p$ and $e+D$ at similar energies desirable • CM energy ∼10-100 GeV

Summary – Emergent Mass and Structure Studies at the EIC

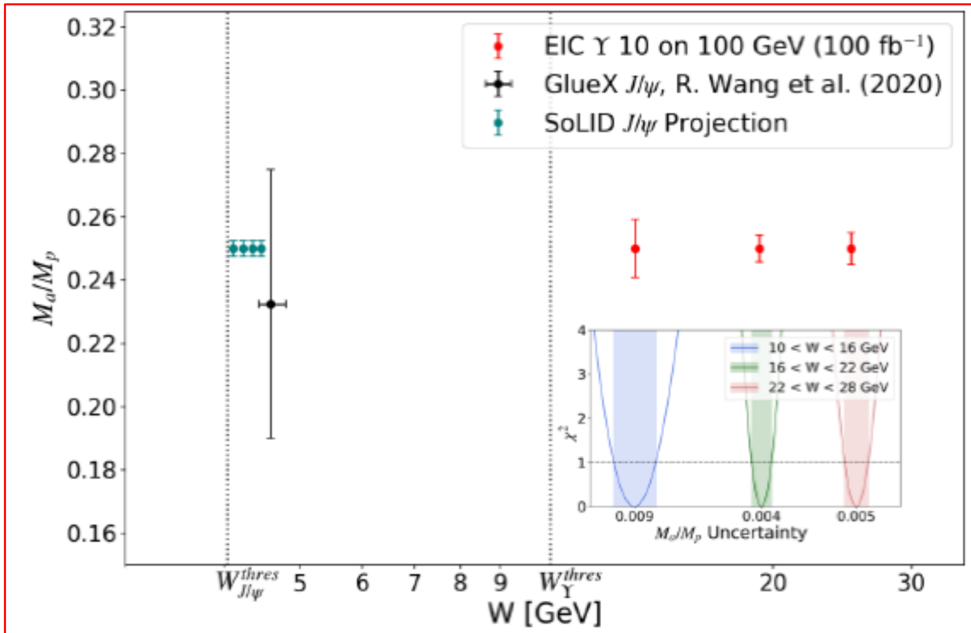
- Protons, neutrons, pions and kaons are the main building blocks of nuclear matter

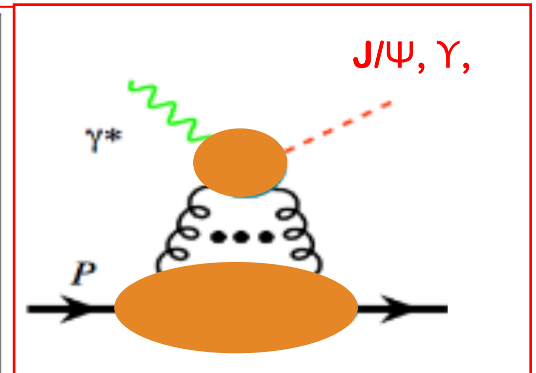
> If we really want to claim we understand hadron structure as relevant for the visible world, we HAVE to understand at least the pion, kaon, proton, neutron (and likely the Lambda) at the same level.

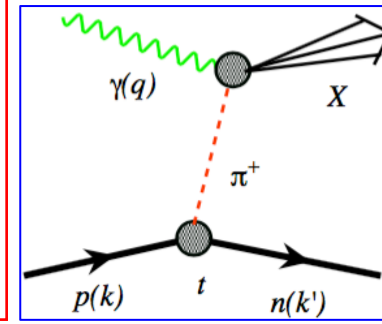
- Paradoxically, the lightest pseudoscalar mesons appear to be the key to the further understanding of the emergent mass and structure mechanisms.
  - These mesons, namely the pion and kaon, are the Nambu-Goldstone boson modes of QCD.
- Unraveling their exact partonic structure and interplay with the Higgs mass mechanism is a common goal of three independent methodologies – phenomenology with continuum QCD based approaches, Lattice QCD, and the global analysis of parton distributions – linked to experimental measurements of hadronic structure.

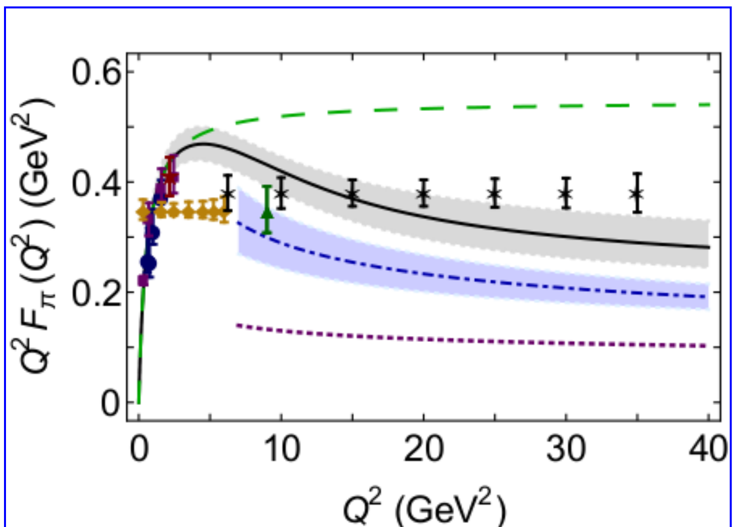
- The unique role of EIC is its access to pion and kaon structure over a versatile large CM energy range, ~20-140 GeV. With this, the EIC will have the final word on the contributions of gluons in pions and kaons as compared to protons, settle how many gluons persist as viewed with highest resolution,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

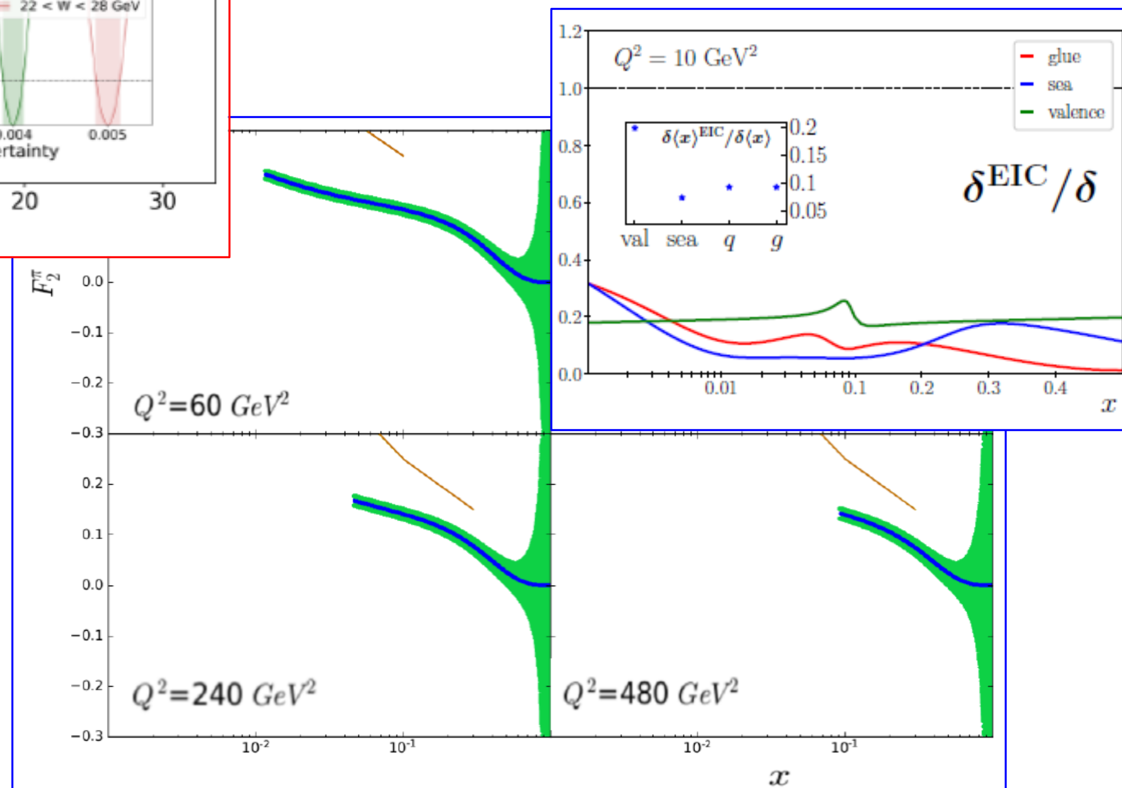
Summary – Role of EIC



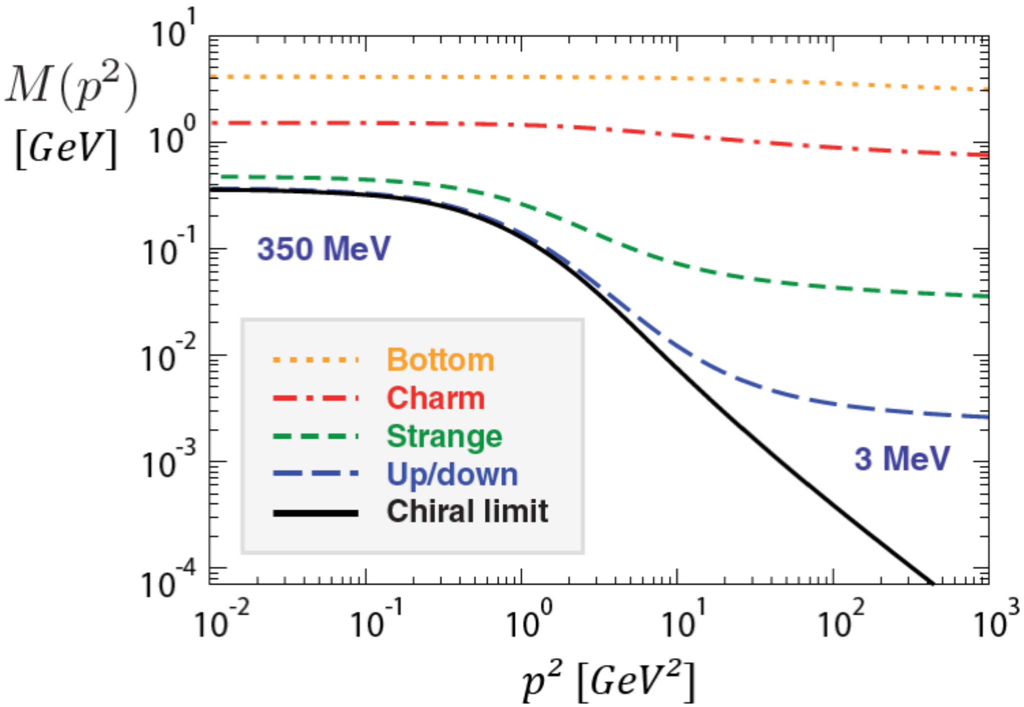




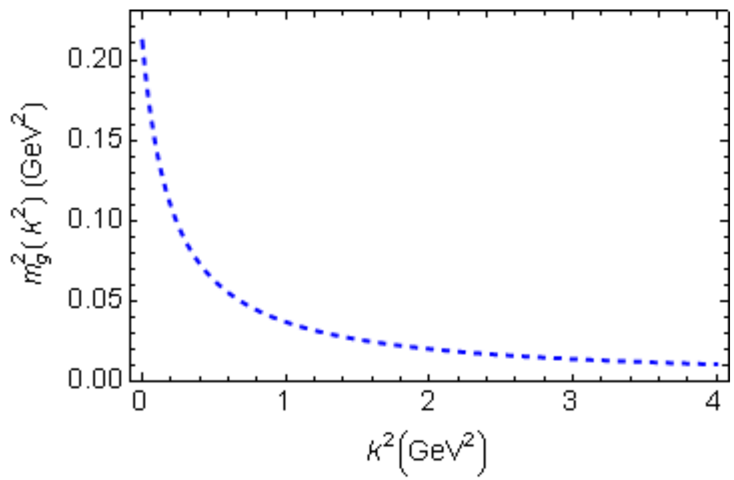




Mass of the Visible Universe

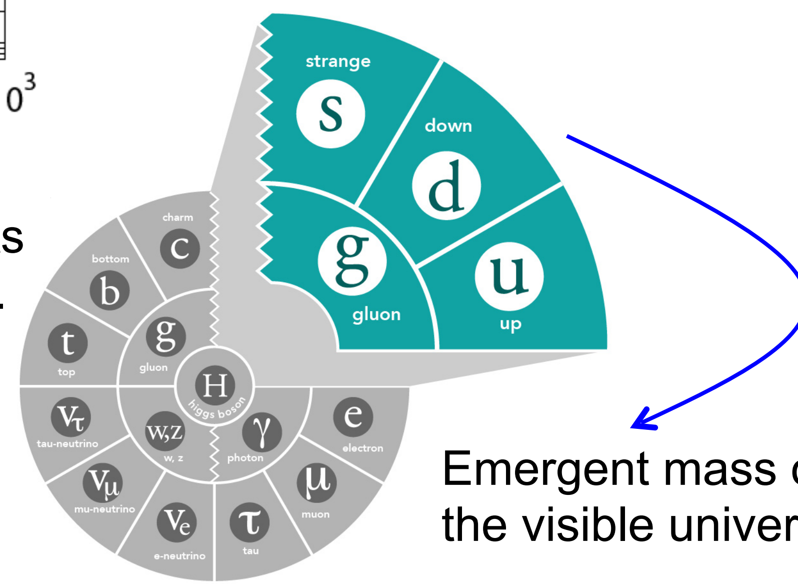


Gluon mass-squared function



Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions. Higgs mechanism hardly plays a role

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



Emergent mass of the visible universe

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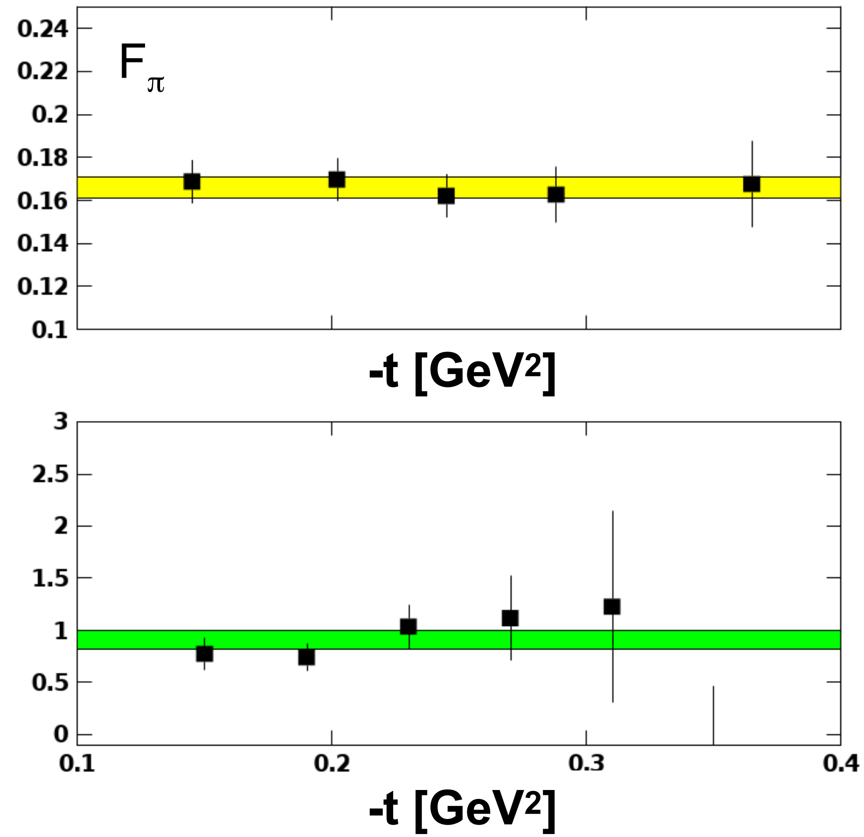
Experimental Validation (Pion Form Factor example)

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_π values do not depend on -t – confidence in applicability of model to the kinematic regime of the data
- Verify that the pion pole diagram is the dominant contribution in the reaction mechanism
  - R_L (= $\sigma_L(\pi^-)/\sigma_L(\pi^+)$) approaches the pion charge ratio, consistent with pion pole dominance

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

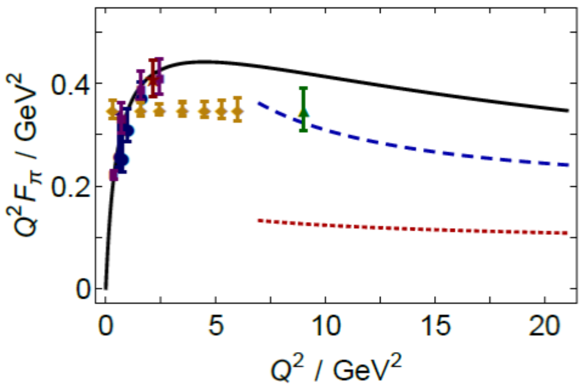


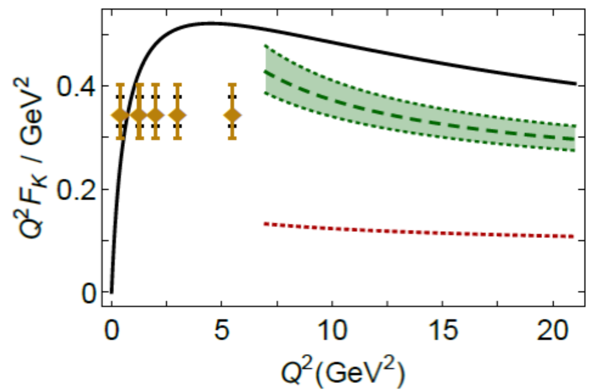
*[T. Horn, C.D. Roberts, J. Phys. G**43** (**2016**) no.7, 073001]*

Jefferson Lab

Pion and Kaon Structure - 12 GeV

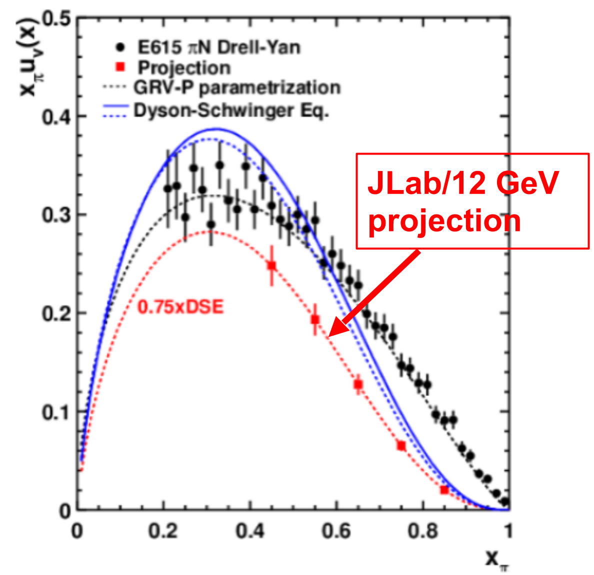
Jefferson Lab will provide, at its CM energy of 5 GeV, tantalizing data for the pion (kaon) form factor up to $Q^2 \sim 10$ (5) GeV^2, and measurements of the pion (kaon) structure functions at large-x (> 0.5) through the Sullivan process.





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

PR12-15-006

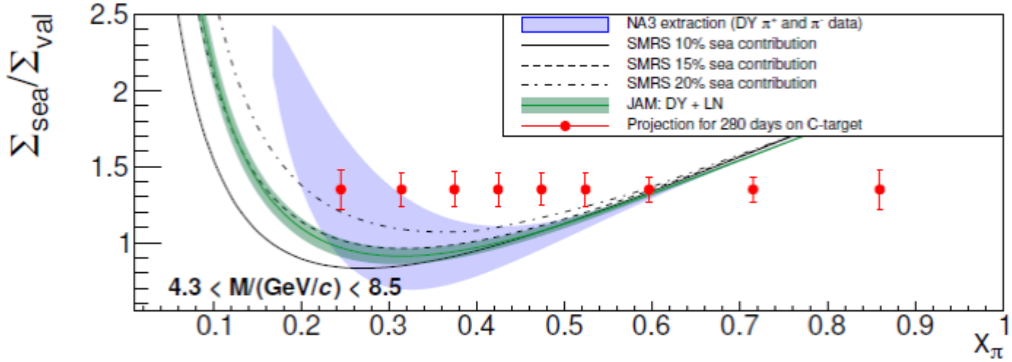


Pion SF – $(1-x)^1$ or $(1-x)^2$ dependence at large x?

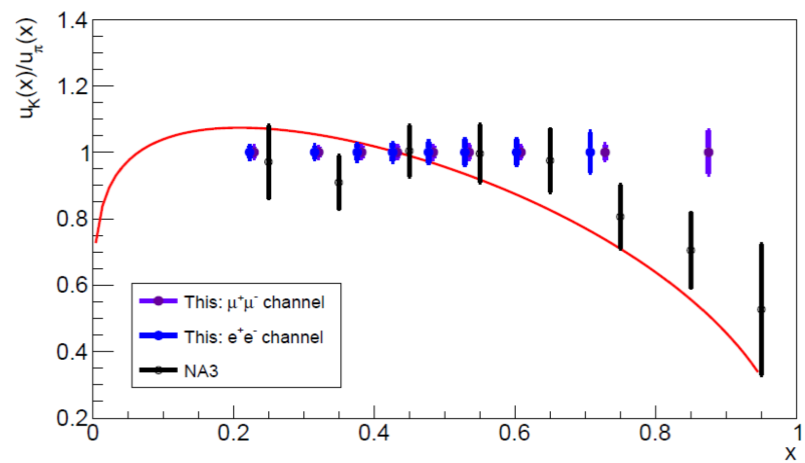
and kaon

12 GeV/EicC/AMBER/EIC Complementarity

COMPASS++/AMBER will play a crucial role as they can uniquely provide pion (kaon) Drell-Yan measurements in the CM energy region ~10-20 GeV. Some older pion and kaon Drell-Yan measurements exist, but for the kaon this is limited to less than 10 data points worldwide, so these measurements are absolutely important for a global effort of the pion structure function measurements (allowing a handle on determination of the so-called “pion flux" for the EIC Sullivan process measurements) and a *sinequanon* for any kaon structure function data map. The COMPASS++/AMBER data in themselves will already give new fundamental insights in the emergent-hadron mass mechanism.



Pionic Drell-Yan, 2 years: pionic sea!

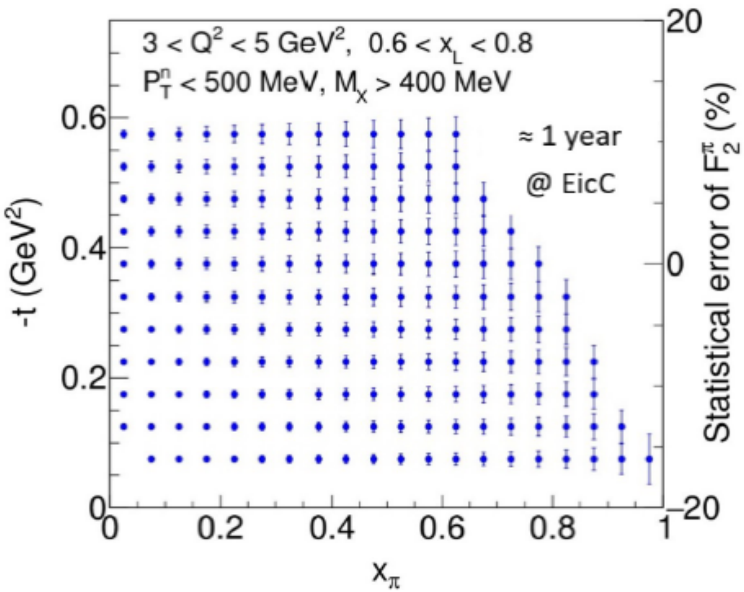


Kaonic Drell-Yan, 140 days: much-needed precise data!

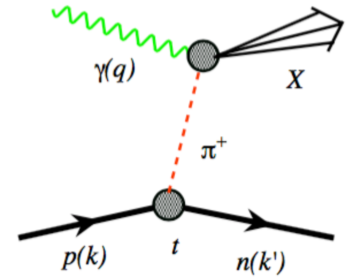
12 GeV/EicC/AMBER/EIC Complementarity

An Electron-Ion Collider in China (EicC) is under consideration with a similar CM energy range as COMPASS++/AMBER of 10-20 GeV and bridging the energy range from Jefferson Lab to EIC. EicC on its own, and even more in combination with COMPASS++/AMBER, can provide good access to the region of x > 0.01 for pion, and especially kaon, structure function determination and the impact on emergent-hadron mass mechanisms on valence quark and gluon structure. In addition, EicC can extend the Rosenbluth L/T-separated cross section technique beyond Jefferson Lab and access pion and kaon form factors to higher Q^2 values, roughly by a factor of 2-4.

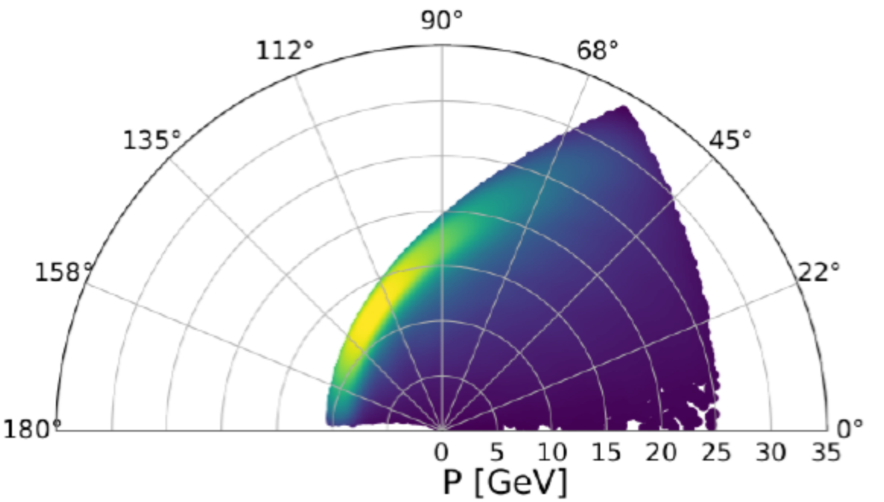
Pion structure function measurement projections at $Q^2 \sim 4$ GeV^2. Likely similar kaon structure function data possible at high x_π. *(arXiv:2008.00102)*

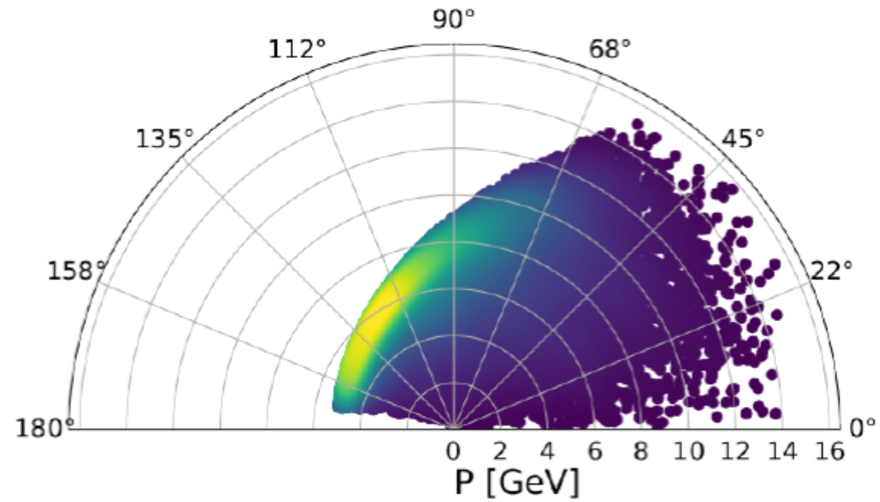


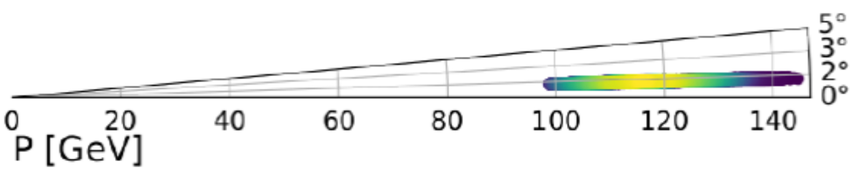
EIC Meson Structure Kinematics

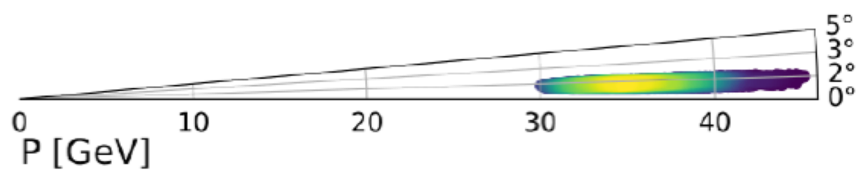


Scattered electron goes in EIC central detector region









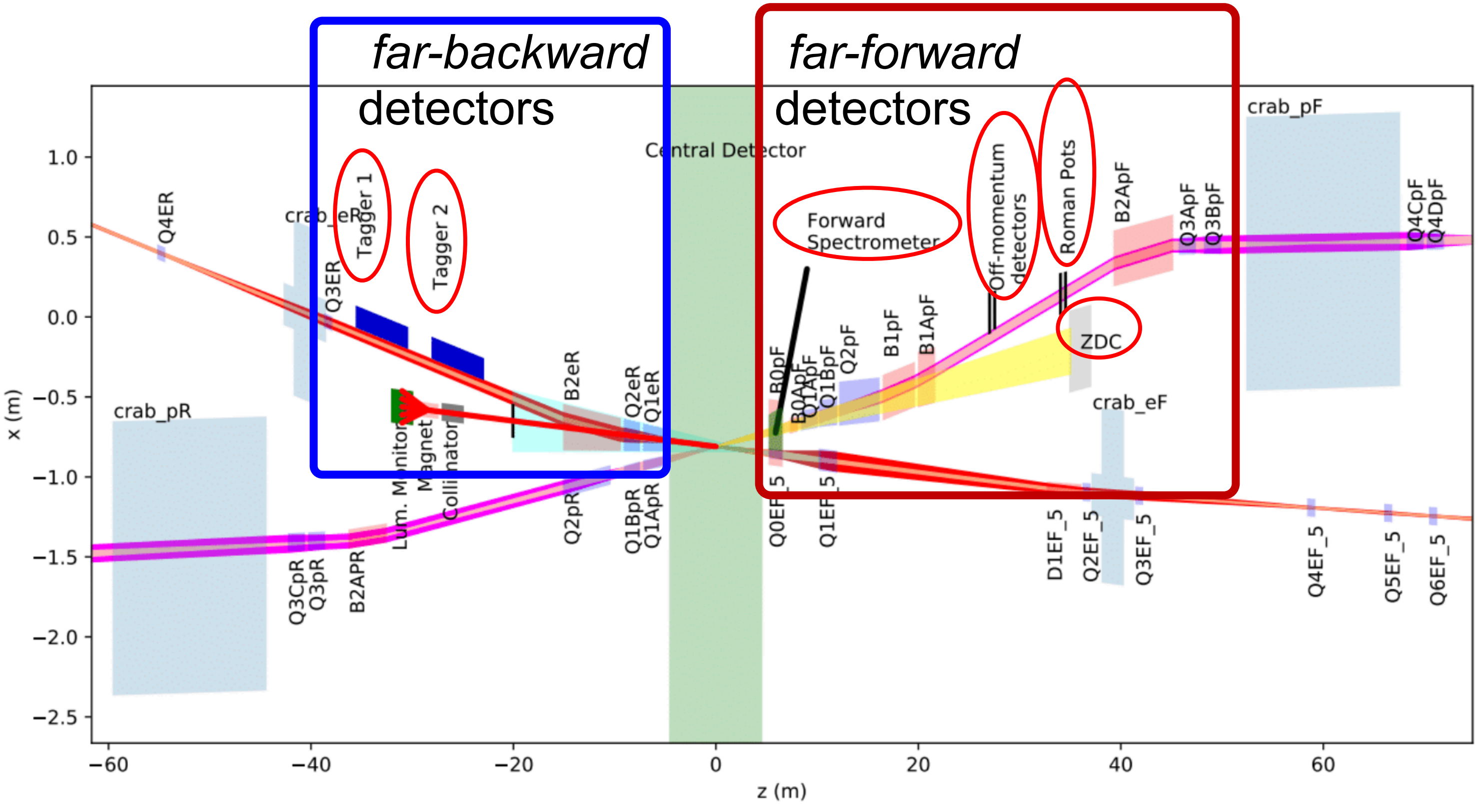
Leading neutron (or lambda) are at small forward angles
and carry most of the proton beam momentum

EIC Far-Forward Detector

Highly Integrated detector system: ~75m
1. Central detector: ~10m
2. Backward electron detection: ~35m
3. Forward hadron spectrometer: ~40m

Lesson learned from HERA – ensure low-Q^2 coverage

Various stage detector to capture forward-going protons and neutrons, and also decay products (Δ, Λ).



Meson Structure Functions Yellow Report Working Group

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

- ➢ Meson SF WG: 22 members, 13 institutions, 7 countries
- ➢ BlueJeans meetings every 2-3 weeks since January 2020
- ➢ To join the Meson Structure Functions WG mailing list, contact T. Horn (hornt@cua.edu)
- ➢ Within Yellow Report activities, part of the EIC Diffractive Reactions & Tagging PWG
- ➢ Very successful effort, and lively discussions, so Meson SF WG continues existing.

Meson SF Working group members:

John R. Arrington (LBNL), Carlos Ayerbe Gayoso (Mississippi State U), Daniele Binosi (ECT*), Lei Chang (Nankai U.), Rolf Ent (Jlab), Tobias Frederico (Instituto Tecnologico de Aeronautica), Timothy Hobbs (SMU), Tanja Horn (CUA), Garth Huber (U. Regina), Stephen Kay (U. Regina), Cynthia Keppel (Jlab), Bill Lee (W&M)), Huey-Wen Lin (MSU), Rachel Montgomery (U. Glasgow), Ian L. Pegg (CUA), Paul Reimer (ANL), David Richards (Jlab), Craig Roberts (Nanjng U.), Jorge Segovia (Universidad Pablo de Olavide), Arun Tadepalli (JLab), Richard Trotta (CUA), Rik Yoshida (ANL)

The Physics Working Group is divided in the following subgroups:

- **Inclusive Reactions:** to join this group and its mailing list, contact R. Fatemi
  - **Conveners:** Renee Fatemi (Kentucky), Nobuo Sato (JLab), Barak Schmookler (Stony Brook)
- **Semi-inclusive Reactions:** to join this group and its mailing list, contact R. Seidl
  - **Conveners:** Ralf Seidl (RIKEN), Justin Stevens (W&M), Alexey Vladimirov (Regensburg), Anselm Vossen (Duke), Bowen Xiao (CCNU, China)
- **Jets, Heavy Quarks:** to join this group and its mailing list, contact L. Mendez
  - **Conveners:** Leticia Mendez (ORNL), Brian Page (BNL), Frank Petriello (ANL & Northwestern U.), Ernst Sichtermann (LBL), Ivan Vitev (LANL)
- **Exclusive Reactions:** to join this group and its mailing list, contact S. Fazio
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- **Diffractive Reactions & Tagging:** to join this group and its mailing list, contact W. Cosyn
  - **Conveners:** Wim Cosyn (Florida), Or Hen (MIT), Doug Higinbotham (JLab), Spencer Klein (LBNL), Anna Stasto (PSU)