Pion and Kaon Structure Measurements at EIC and JLab

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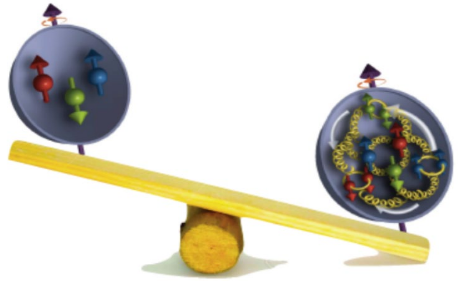
Outline

- Brief overview of the role of **meson structure** in understanding our visible Universe
- JLab 12 GeV and improving the $\pi^+/K^+/\pi^0$ electroproduction data set through the Sullivan process
  - Exclusive L/T separated cross sections and pion and kaon form factor – preliminary results
  - Tagged DIS to resolve and cross-check pion PDF issues at high-x; opportunity for kaon SFs measurement
- Exciting opportunities to collect additional data for light mesons beyond JLab 12 GeV
  - Electron-Ion Collider - far forward physics through the Sullivan process (pion and kaon SF projections)
  - JLab 22 GeV
- Ongoing efforts extending into 3D light hadron structure – GPDs and TMDs – in theory/experiment
  - Science program with the PWO-based Neutral Particle Spectrometer

What Do We Know: Mass of the Proton, Pion, Kaon

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

MeV

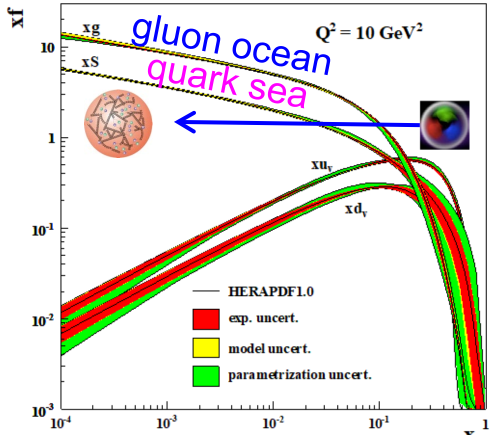


GeV

Proton

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

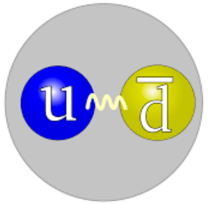
Gluon rise discovered by HERA e-p



Fraction of overall proton momentum carried by quark or gluons

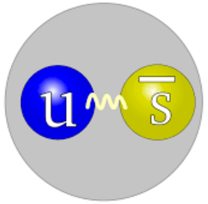
Pion

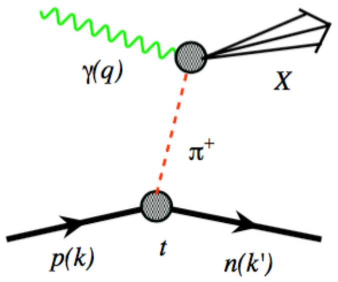
Quark structure: $u\bar{d}$
Mass ~ 140 MeV
Exists only if mass is dynamically generated.
Empty or full of gluons?



Kaon

Quark structure: $u\bar{s}$
Mass ~ 490 MeV
Boundary between emergent- and Higgs-mass mechanisms.
More or less gluons than in pion?



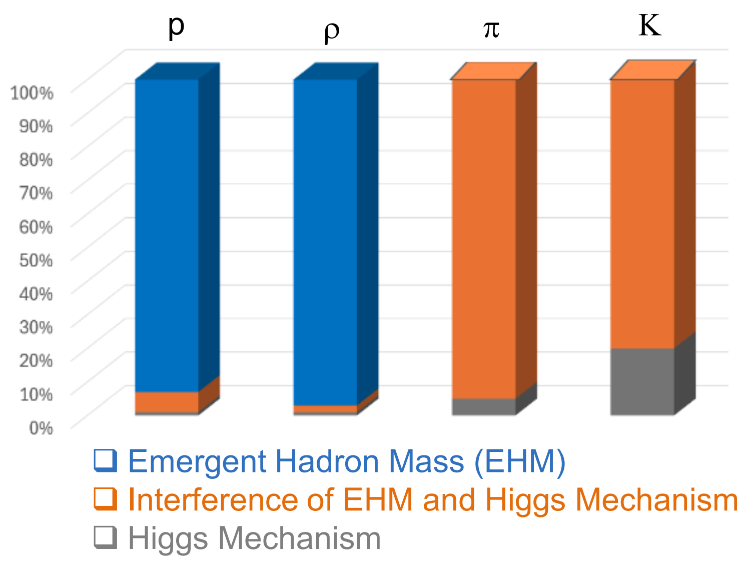


proton - determination of an important term contributing to the proton mass, the so-called "QCD trace anomaly"

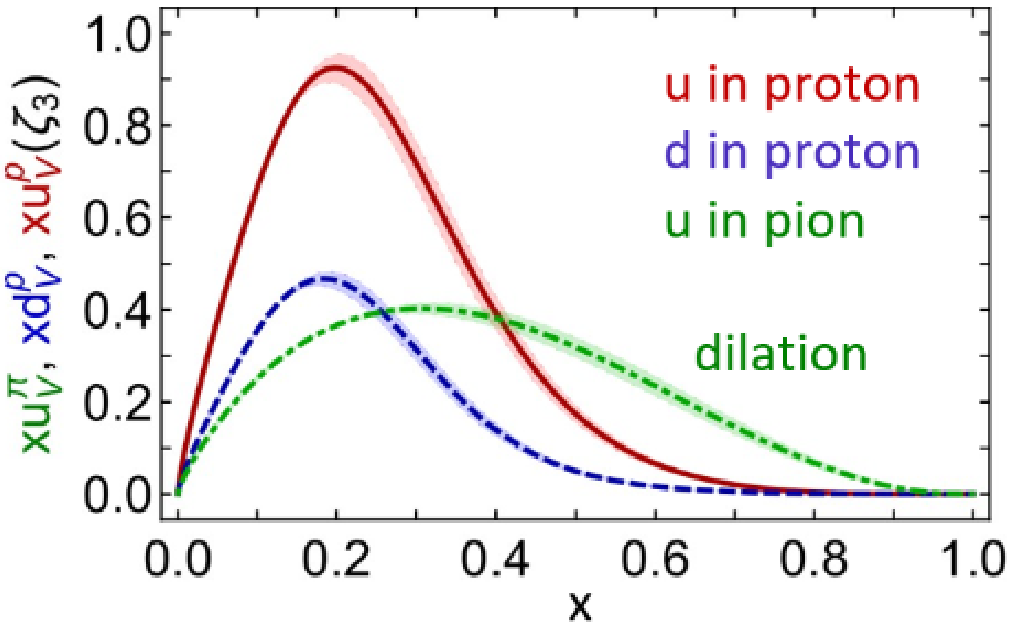
pion and the kaon - determination of the quark and gluon momentum contributions with the Sullivan process, e.g., at EIC

*C. Aguilar, …, T. Horn, et al., Pion and Kaon structure at the EIC, EPJA **55** (2019) 190.*
*J. Arrington, …, T. Horn, et al., Revealing the structure of light pseudoscalar mesons at the EIC, J. Phys. G **48** (2021) 7, 075106.*

Insights into Hadron Structure and Mass through Mesons



K. Raya, A. Bashir, D. Binosi, C.D. Roberts, J. Rodriguez-Quintero, Few Body Sust. ***65*** *(**2024**) 2, 60*
*D. Binosi, C.D. Roberts, Z.-Q. Yao, PoS QCHCC24 (**2025**) 001*



Mass budget for nucleons and mesons are vastly different

- Proton (and heavy meson) *mass is large in the chiral limit* – expression of Emergent hadronic mass (EHM)
- 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)
  - Without Higgs mechanism of mass generation pion/kaon would be indistinguishable

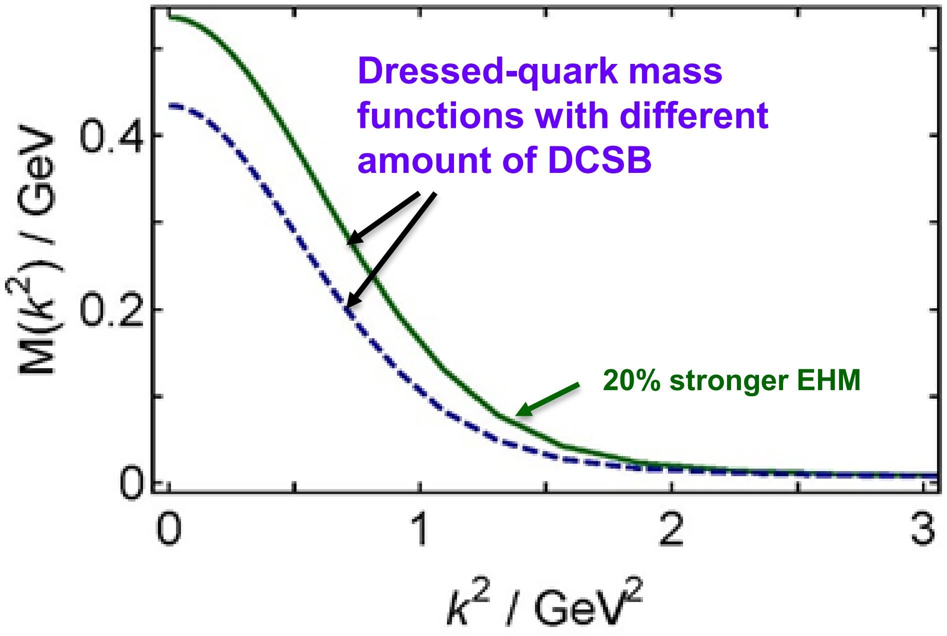
Valence quark distribution of proton/pion are also very different

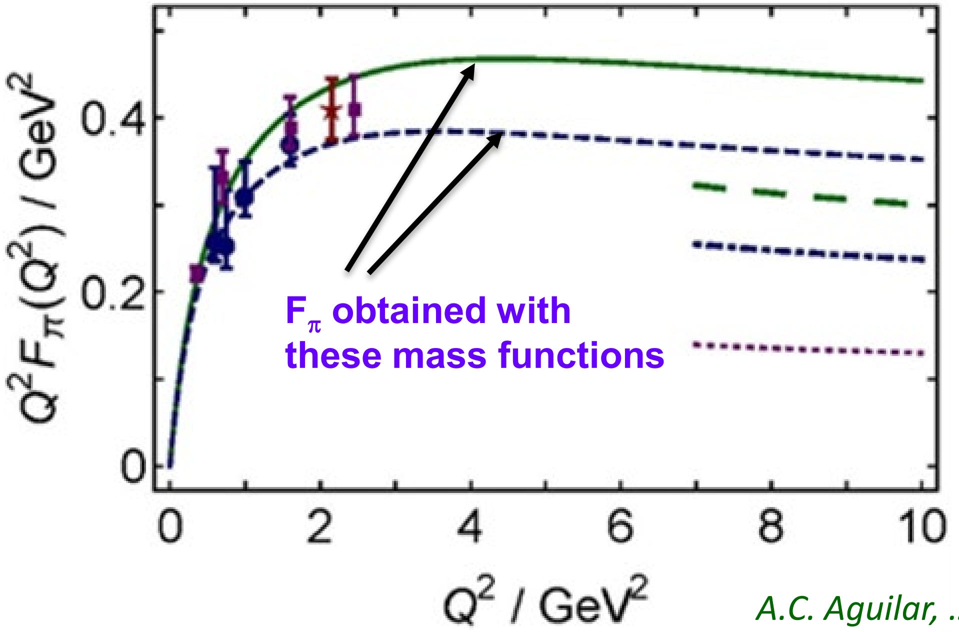
→ Difference between meson PDFs: direct information on emergent hadron mass (EHM)

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

Pion Form Factors and Emergent Hadron Mass

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





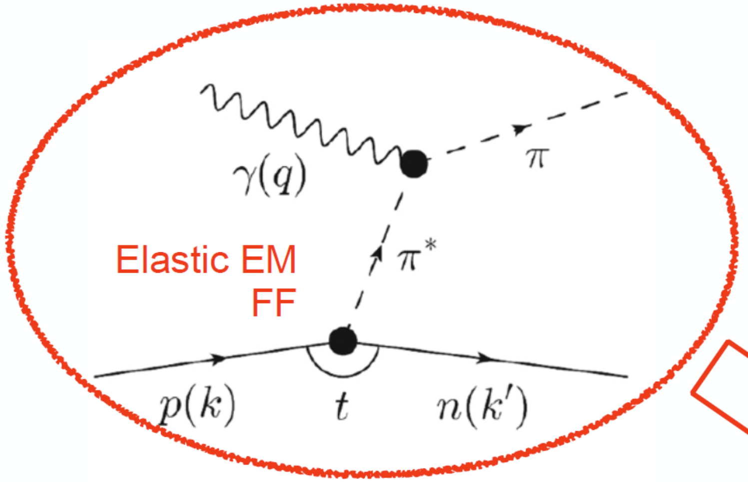
A.C. Aguilar, …, T. Horn, et al., Eur. Phys. J. A ***55*** ***(2019)*** *10, 190*

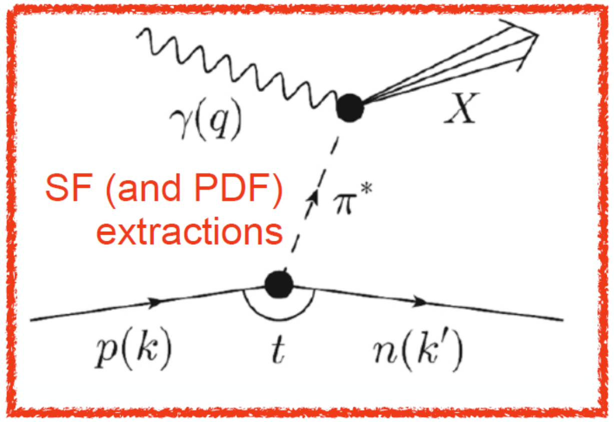
Left panel. Two dressed-quark mass functions distinguished by the amount of DCSB: emergent mass generation is 20% stronger in the system characterized by the solid green curve, which describes the more realistic case. Right panel. $F_\pi(Q^2)$ obtained with the mass function in the left panel: r_π =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

Accessing Pion/Kaon Structure Information

Sullivan

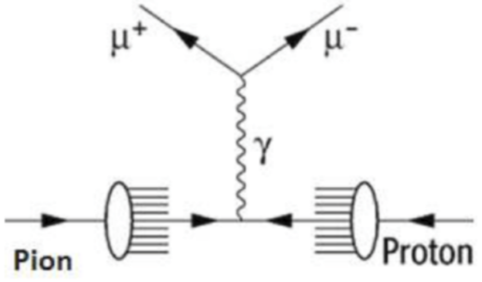
Hard scattering from virtual meson cloud of nucleon





Drell-Yan

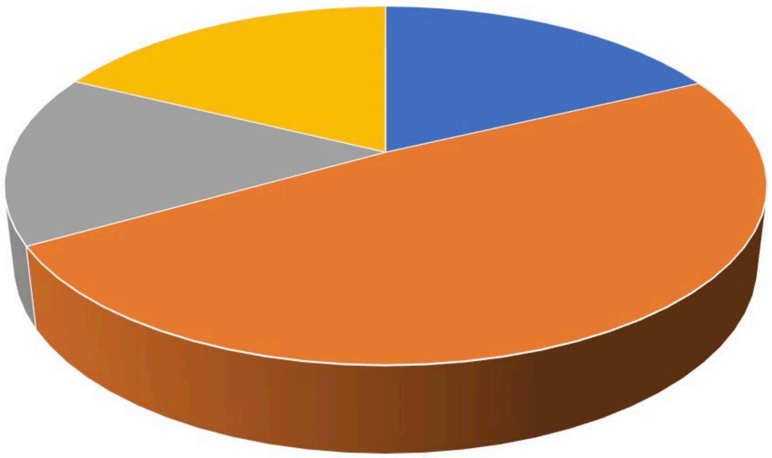
Quark of pion (e.g.) annihilates with anti-quark of proton (e.g.), virtual photon decays into lepton pair



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

Jefferson Lab and CEBAF

Approved 12 GeV program by PAC days



Hadron Spectra

1D-3D Nucleon Structure

Hadrons & Cold Nuclear Matter

Test of SM & Fundamental Sym.

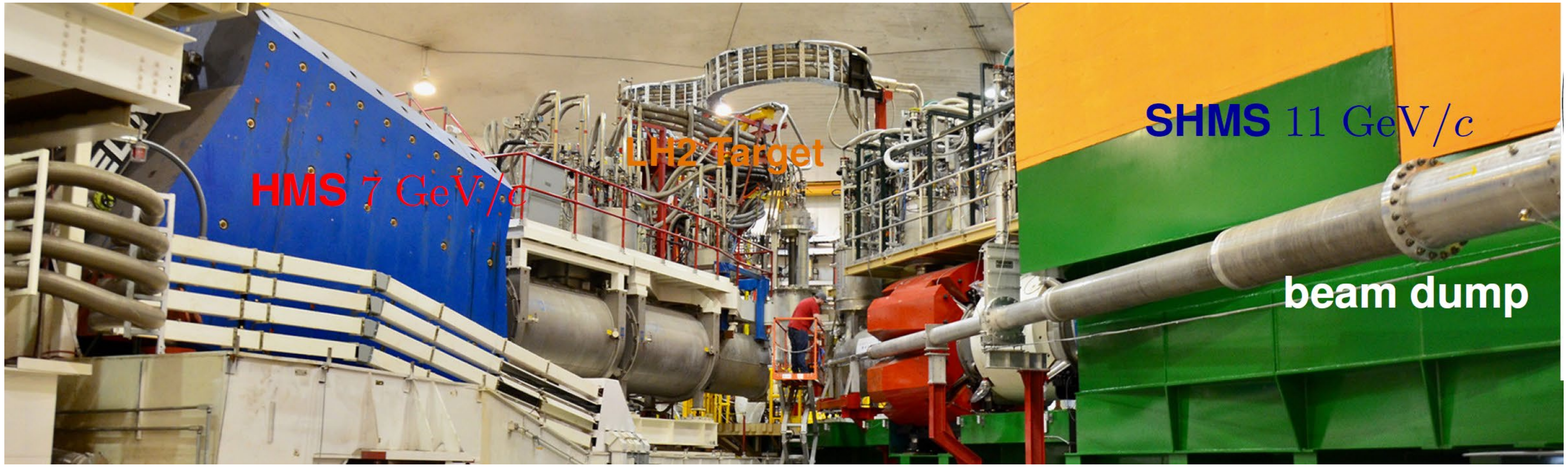
- Probe the structure of matter

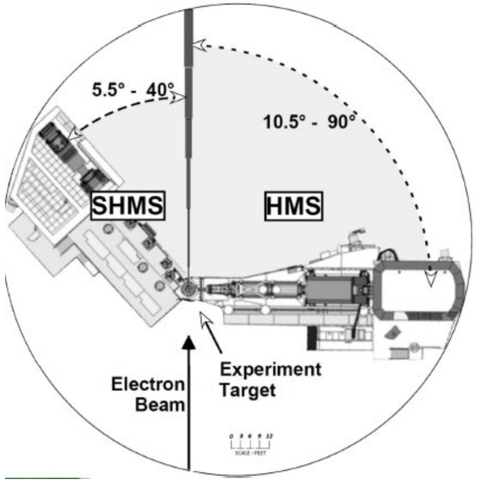
  Complex **non-pQCD** problem which demands different approaches and measurements to access multiple observables

- Discover evidence for physics beyond the standard model

Hall C: Precision Experiments with HMS + SHMS

Home of the precision cross section measurements through L/T and tagged DIS (TDIS)





S. Ali et al. Nucl.Instrum.Meth.A **1083** (**2026**) 171070

- CEBAF 10.9 GeV electron beam and SHMS small angle capability and controlled systematics are essential for precision measurements to higher Q^2
- Focusing spectrometers fulfill the L/T separation requirements
- Dedicated key SHMS Charged Particle Identification detectors
  - Aerogel Cherenkov – funded by NSF MRI (CUA)
  - Heavy gas Cherenkov – partially funded by NSERC (U Regina)

Two meson experiments
- **PionLT** (E12-19-006)
- **KaonLT** (E12-09-011)

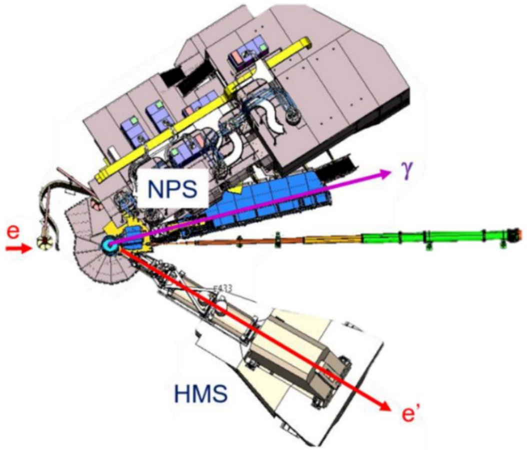
T. Horn, H. Mkrtchyan, et al., Nucl.Instrum.Meth.A **842** (**2017**) 28-47

Hall C: Neutral Particle Spectrometer (NPS) Program

Neutral pion: L/T separated cross sections
Relevant technologies for EIC (backward EMCal, B0 calorimeter, ZDC)

Neutral Particle Spectrometer (NPS) :
Sweeping magnet and calorimeter

- **1080 Lead-Tungstate blocks** in Calorimeter to detect γ and π^0
- fADC250 with **streaming triggers**
- NPS attached to SHMS carriage to allow easy angle change.



Extensive program of testing of PWO crystals completed

- QA procedure developed

T. Horn, et al. Nucl.Instrum.Meth.A **956** (2020) 163375

NPS data provide validation for ML SRO models - future runs and EIC

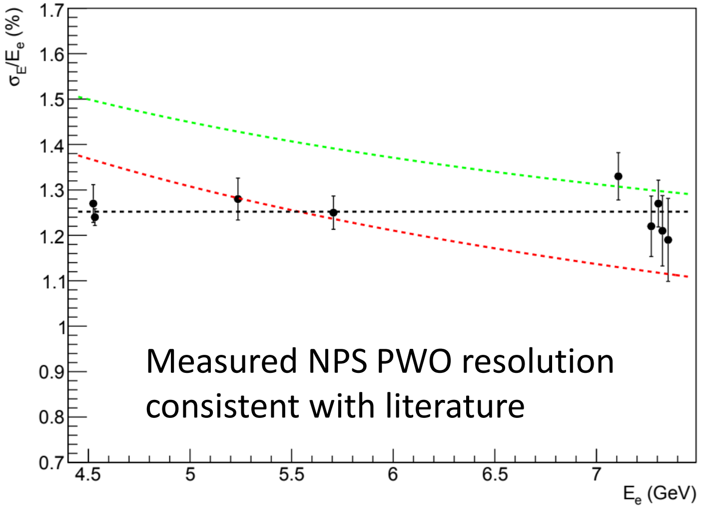
- leverage GNN architectures, using the VTP (VETROC Trigger Processor) trigger information as ground truth for training. More: NPS SRO Machine Learning Project

NPS Science Program

- RG1A: 4 experiments on DVCS and DES and SIDIS p(e,e',π^0) cross sections from proton and deuteron
- Five additional run groups with different configurations of the NPS (WACS, NPS+positron…) – planned ~2030+

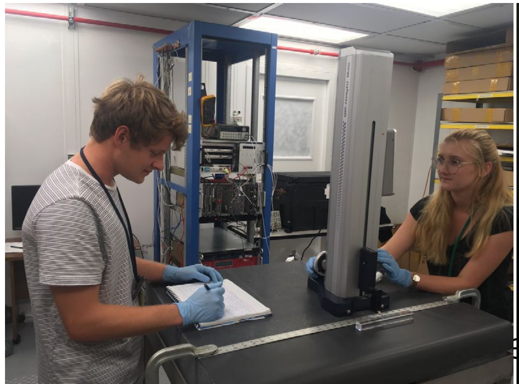
RG1A completed in 2024. Analysis ongoing.

First publication: W. Hamdi, et al., "*Intrinsic energy and time resolution of the Jefferson Lab Hall C Neutral Particle Spectrometer*" Nucl.Instrum.Meth.A **1086** (**2026**) 17132



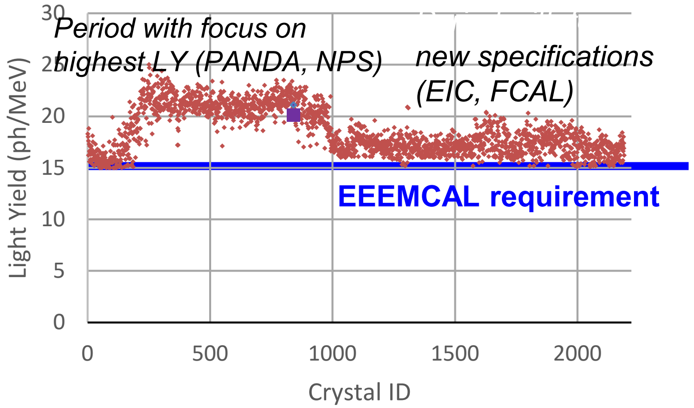
PWO Quality Assurance Protocol

- ❑ The QA builds on the process developed for NPS and consists of:
  - ➢ 2 step visual inspection
  - ➢ mechanical dimension measurement
  - ➢ light yield measurement
  - ➢ Kinetics
  - ➢ transmittance measurement
  - ➢ induced radiation absorption coefficient.
- ❑ **For NPS: all ~1100 PWO crystals passed QA**
- ❑ **For EIC: All ~1100 PWO crystals from CD3A passed QA**
- ❑ Additional batches of crystals (CD3B) expected to arrive at JLab as soon as May 2026 awaiting QA

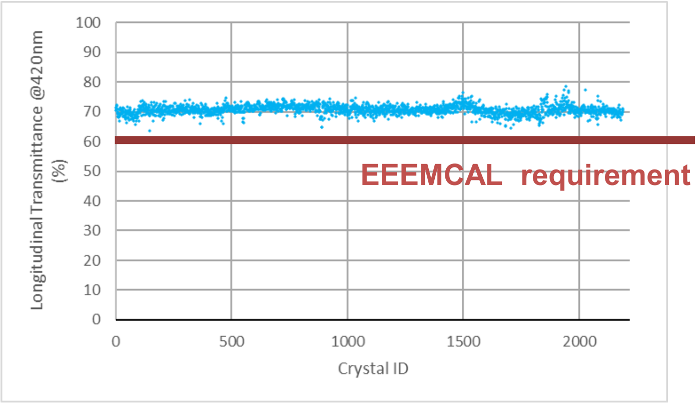



Characterization results of CRYTUR produced crystals (2017 – present)

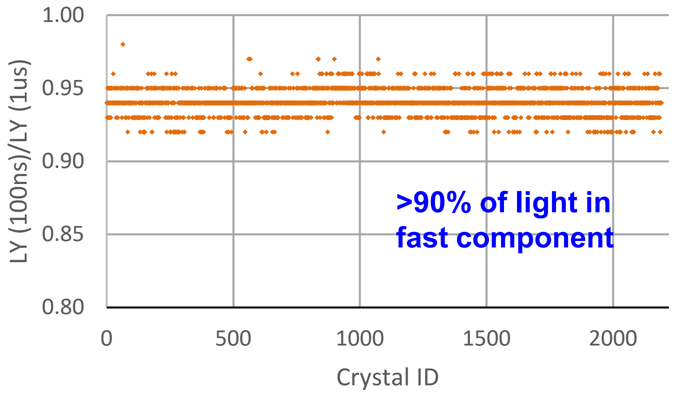
Light Yield (LY)

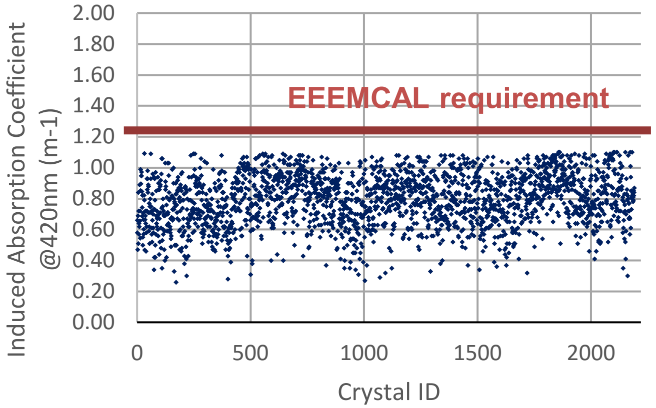


Longitudinal Transmittance



Kinetics

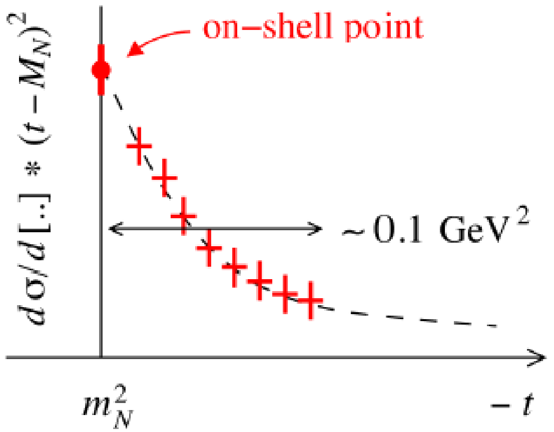




Accessing meson structure through the Sullivan Process

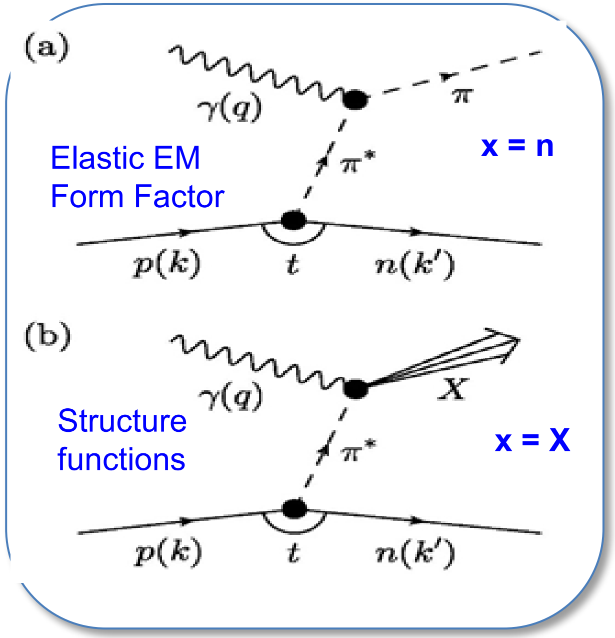
- The **Sullivan process can provide reliable access to a meson target** as t becomes space-like if the pole associated with the ground-state meson is the dominant feature of the process and the structure of the (off-shell) meson evolves slowly and smoothly with virtuality.

*S-X Qin, C. Chen, C. Mezrag, C.D. Roberts, Phys.Rev. C **97** (**2018**) 7, 015203*



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

Sullivan Process

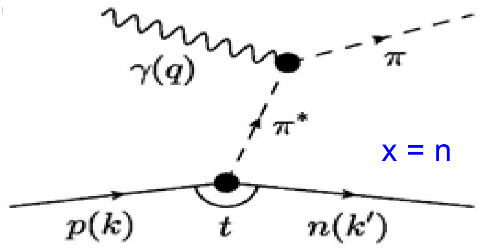


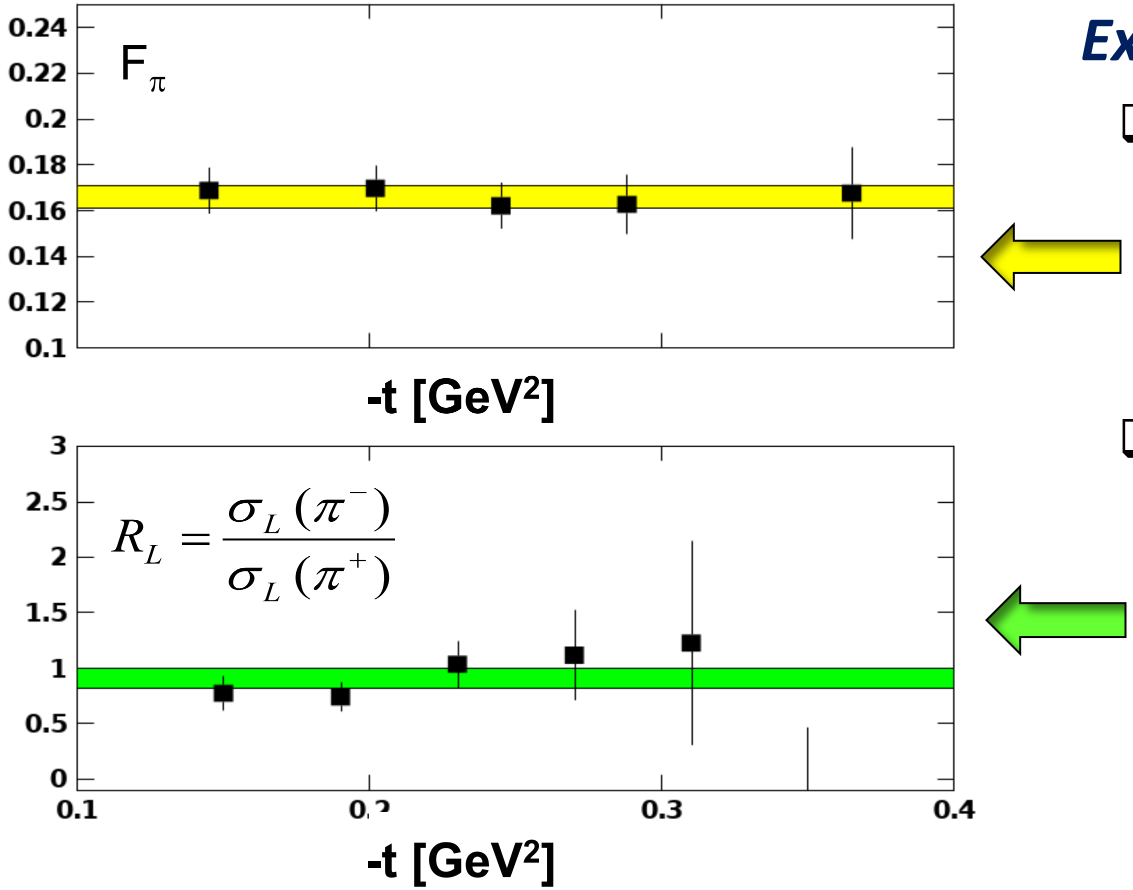
- **Theoretical calculations found that for $-t \leq 0.6$ (0.9) GeV^2**, changes in pion (kaon) structure evolve slowly so that a well-constrained experimental analysis should be reliable, and the **Sullivan processes can provide a valid pion (kaon) target**.

- Also **progress with elastic form factors – experimental validation (next page)**

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

*T. Horn, C.D. Roberts, J.Phys.G **43** (**2016**) 7, 073001*

*G. Huber, …, T. Horn, et al, PRL**112** (**2014**)182501*

*R. J. Perry et al., PRC**100** (**2019**) 2, 025206*

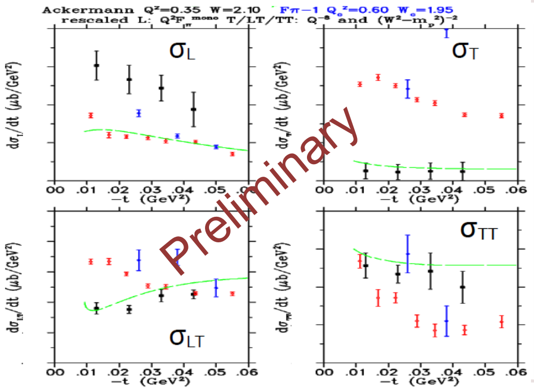
Hall C – **Preliminary** Results PionLT/KaonLT Program

Spokespersons: Dave Gaskell (JLab), Tanja Horn (CUA), Garth Huber (URegina)

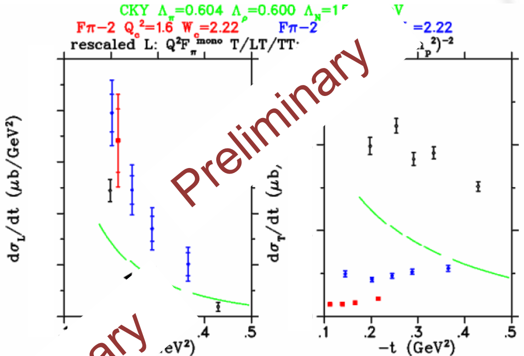
PionLT experiment (<u>completed in 2022</u>):

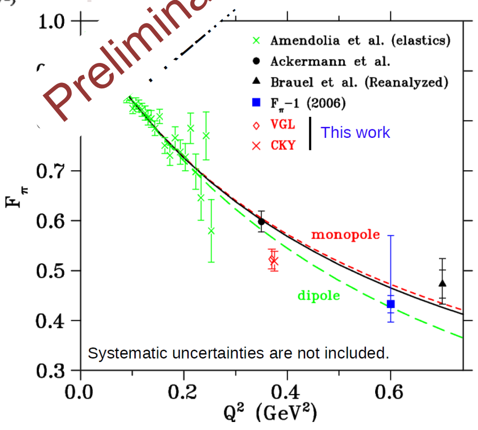
- L/T separated cross sections at fixed x=0.3, 0.4, 0.55 up to Q^2=8.5 GeV^2
- Pion form factor at Q^2 values up to 8.5 GeV^2

Q^2=0.425 GeV^2



Q^2=3.85 GeV^2





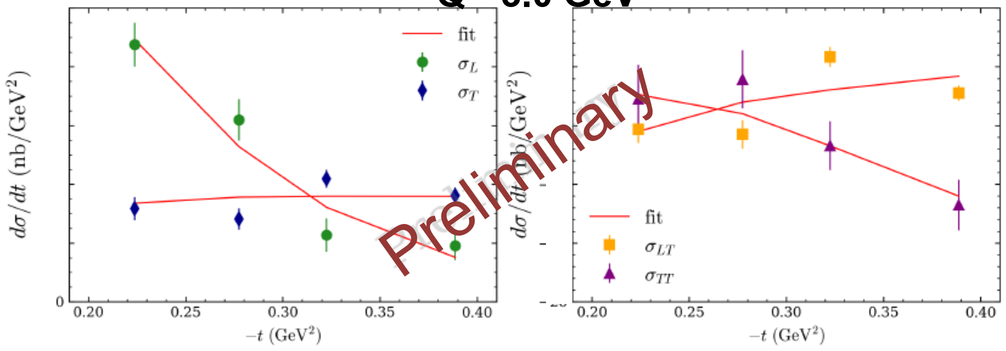
- Low Q^2 and Q^2=3.85 GeV^2 cross sections and F_π extractions (very preliminary) now availabl
- Publications in preparation
- High Q^2 data analysis ongoing (PhD thesis: Sameer Jain, CUA)

Spokespersons: Tanja Horn (CUA), Garth Huber (URegina), Pete Markowitz (FIU)

KaonLT experiment (<u>completed in 2018/19</u>):

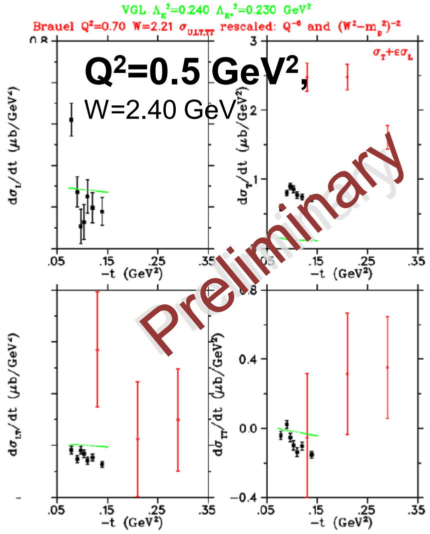
- Highest Q^2 for L/T separated kaon electroproduction cross section
- First separated kaon cross section measurement above W=2.2 GeV

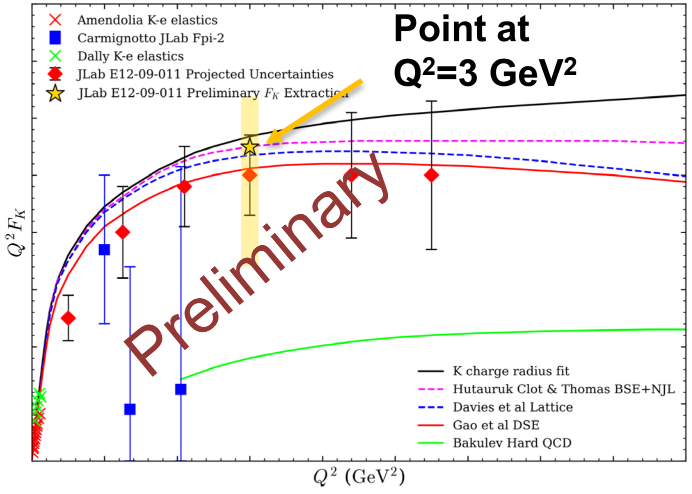
Q^2=3.0 GeV^2



- LT Separated KΛ and KΣ Cross Sections and F_K (preliminary) now available
- Publication expected later this year

High Q^2 plots by Chi Kin Tam (CUA)





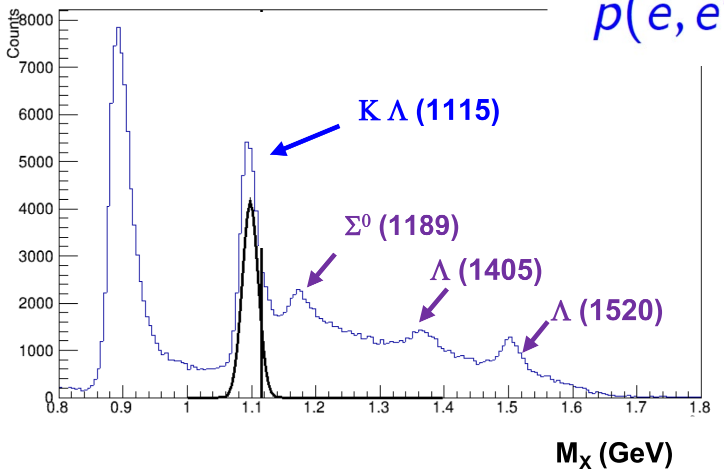
KaonLT (E12-09-011) Program – additional topics

Spokespersons: Tanja Horn (CUA), Garth Huber (URegina), Pete Markowitz (FIU)

Grad. Students: Vijay Kumar (Uregina, PhD 2025), Richard Trotta (CUA, Phd 2024), Ali Usman (URegina), A. Postuma (URegina)

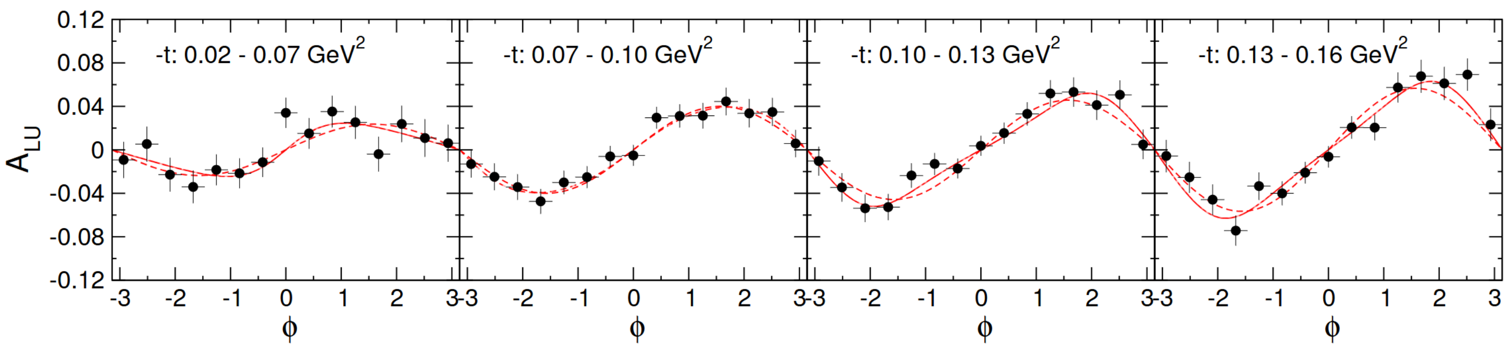
Additional Physics Channels/Topics

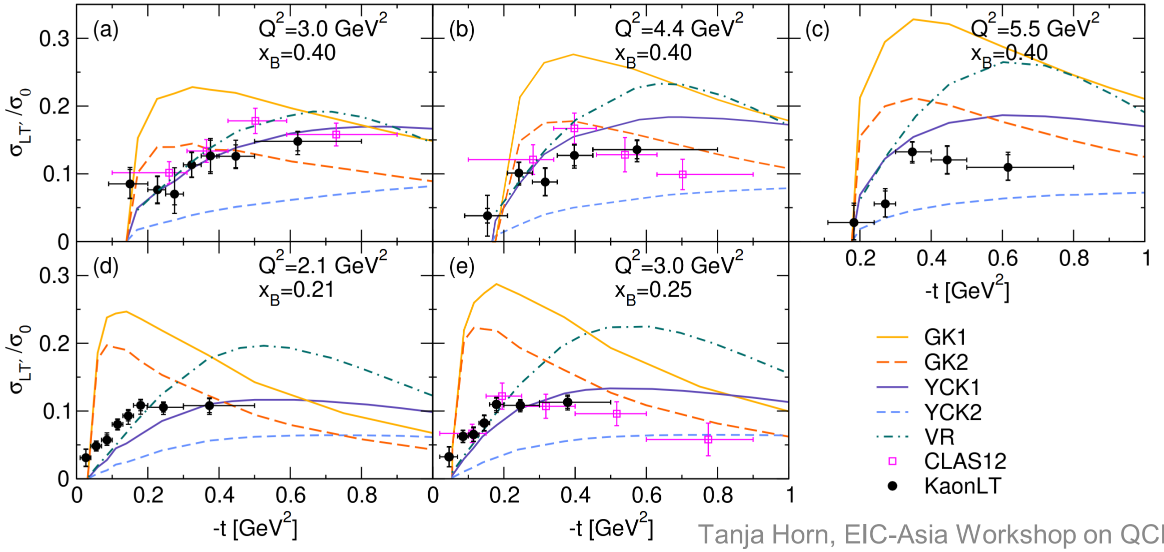
$p(e,e'\pi^+)n/\Delta^0$



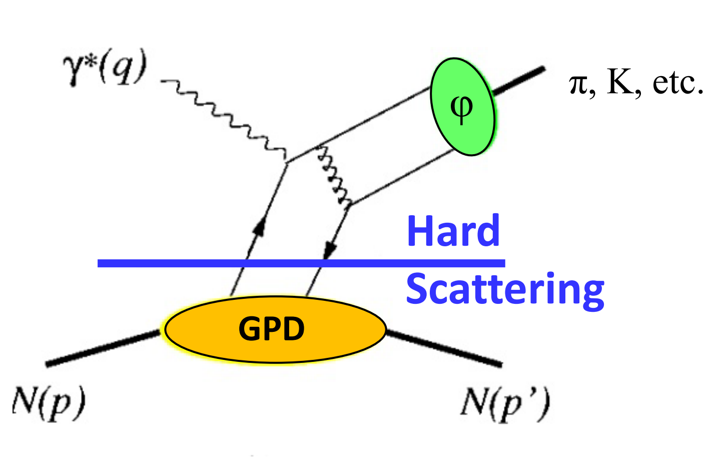
- ❑ KaonLT measured the beam spin asymmetry [(JLab news release 2026)]
- ❑ Finer binned at lower −t data (compared to CLAS12) suggest that have not yet reached hard/soft factorization
- ❑ Extraction of GPDs from these data should be delayed until a model-independent test can be performed, e.g., a Q^{-n} scaling study at fixed x_B for Rosenbluth separated cross-sections

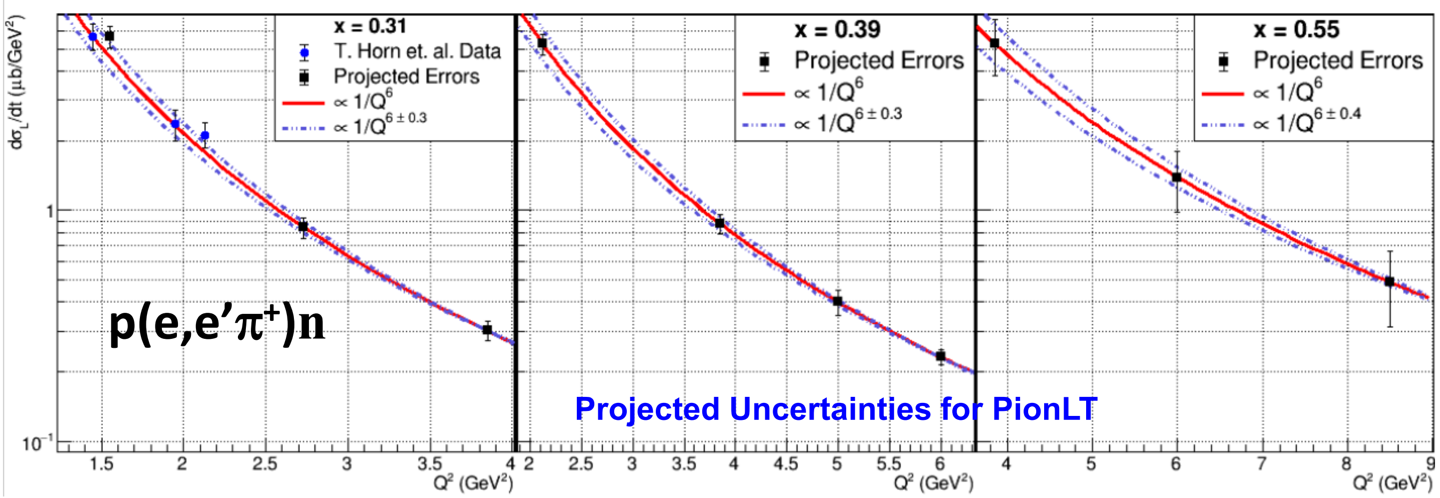
First publication from KaonLT: *A. Postuma, et al, "" Probing hard/soft factorization via beam-spin asymmetry in exclusive pion electroproduction from the proton, Phys.Lett.B* **872** (**2026**) 140094





L/T Separated π^+/K^+ Cross Sections with 12 GeV JLab





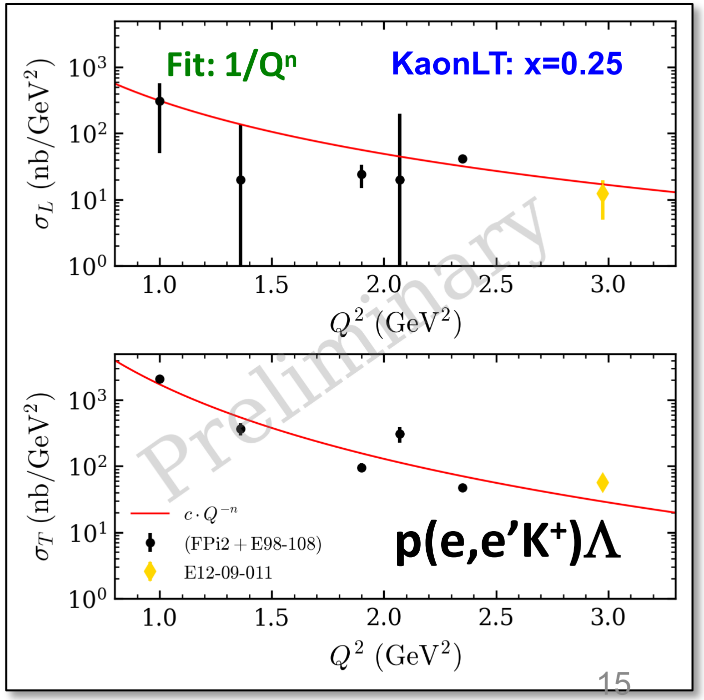
- One of the most stringent tests of the reaction mechanism is the Q^2 dependence of cross section
  - –σ_L scales to leading order as Q^{-6}
  - –σ_T does not

PionLT π^+: to Q^2~9 GeV^2
KaonLT K^+: to Q^2~6 GeV^2

- Need to validate the reaction mechanism for reliable interpretation of the GPD program – key are precision longitudinal-transverse (L/T) separated data over a range of Q^2 at fixed x/t

  - **If σ_T is confirmed to be large, it could allow for detailed investigations of transversity GPDs. If, on the other hand, σ_L is measured to be large, this would allow for probing the usual GPDs**

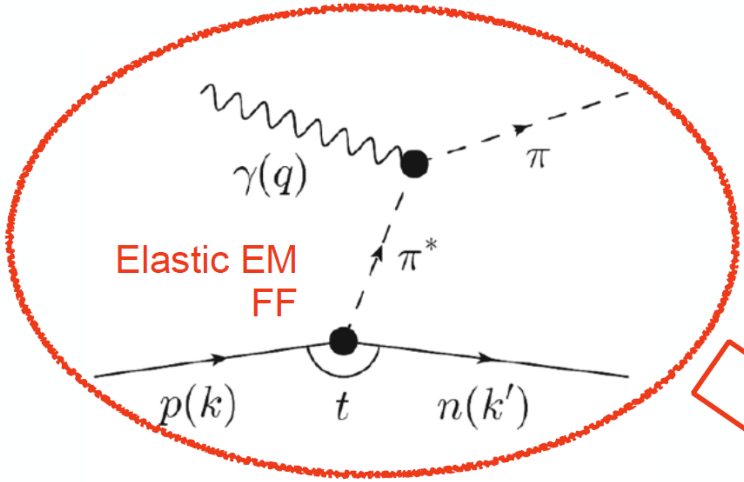
First scaling results with kaons

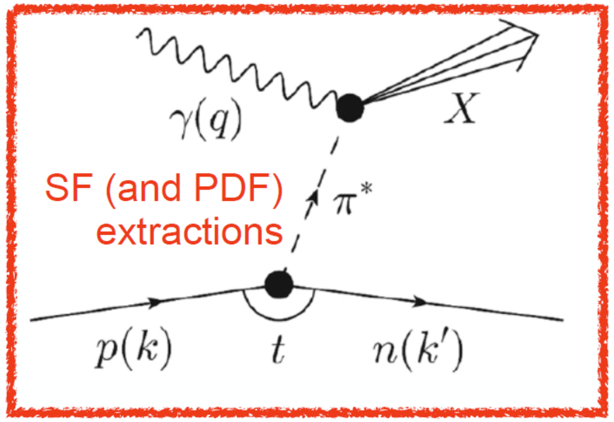


Accessing Pion/Kaon Structure Information

Sullivan

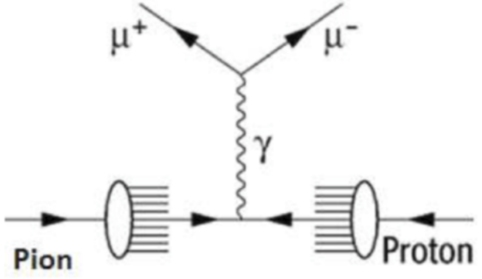
Hard scattering from virtual meson cloud of nucleon





Drell-Yan

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



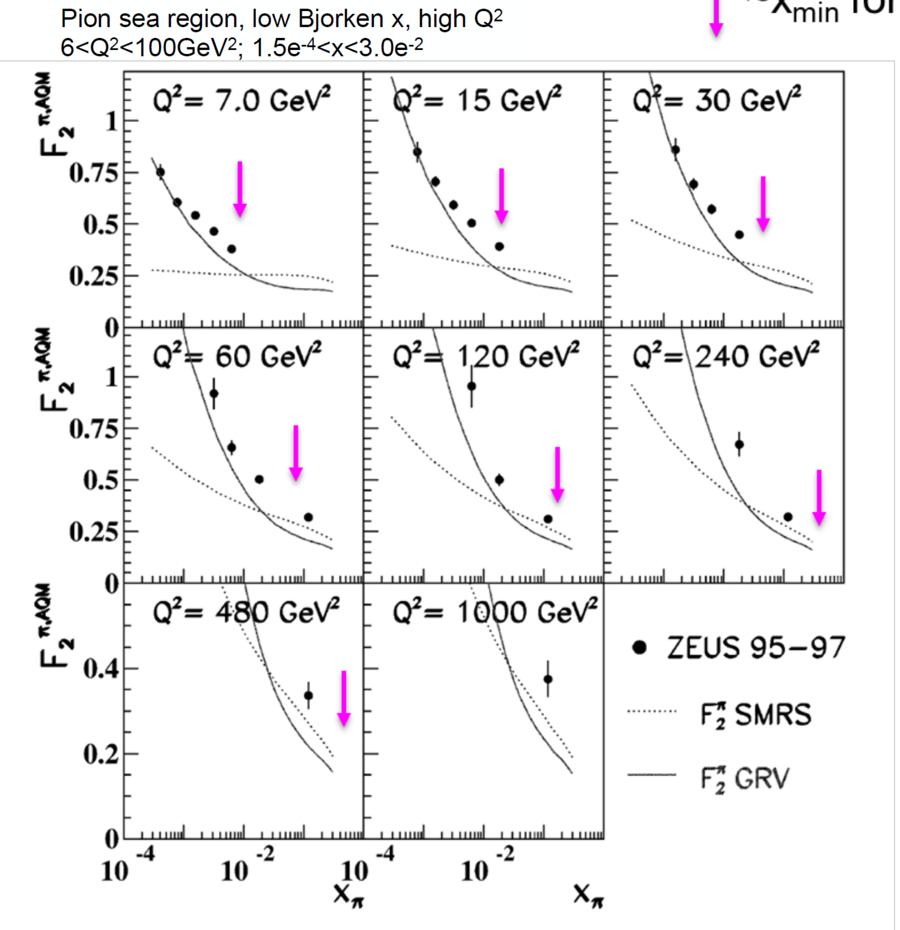
For FF measurements at EIC see talk by Stephen Kay

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

World Data on Pion Structure Function

HERA: showed Sullivan at low x

~x_{min} for EIC



EIC kinematic reach down to a x = few 10^{-3}

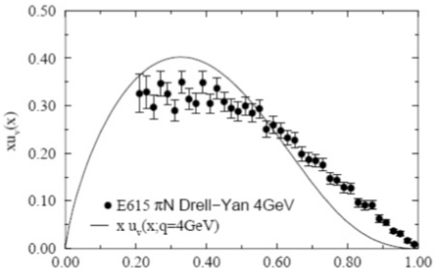
Lowest x constrained by HERA leading n

DESY 08-176 JHEP06 (2009) 74

DY: Large x Structure of the Pion

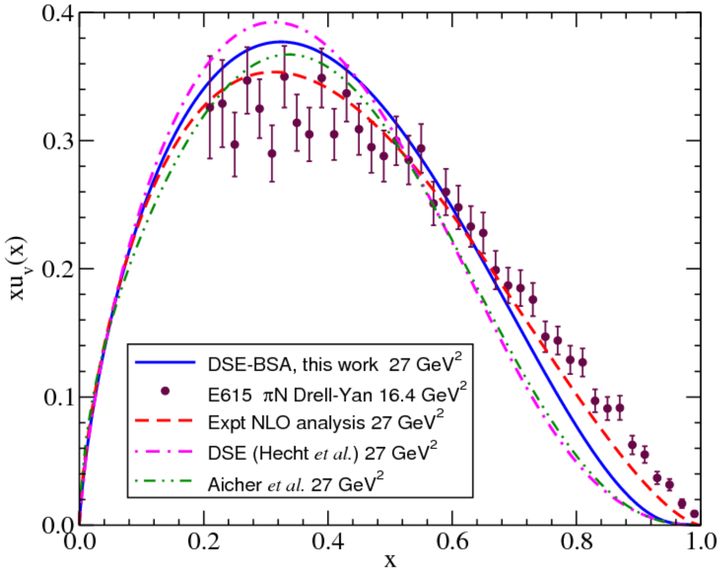
Initial observations:

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



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

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



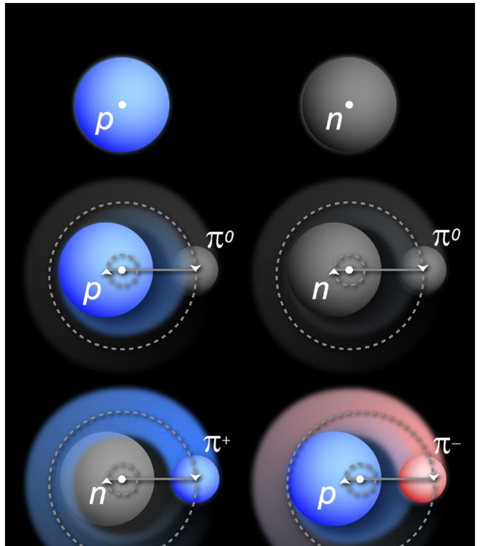
C.D. Roberts, IRMA Lect. Math. Theor. Phys. 21 (2015) 355; arXiv:1203.5341 (2012)

- 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

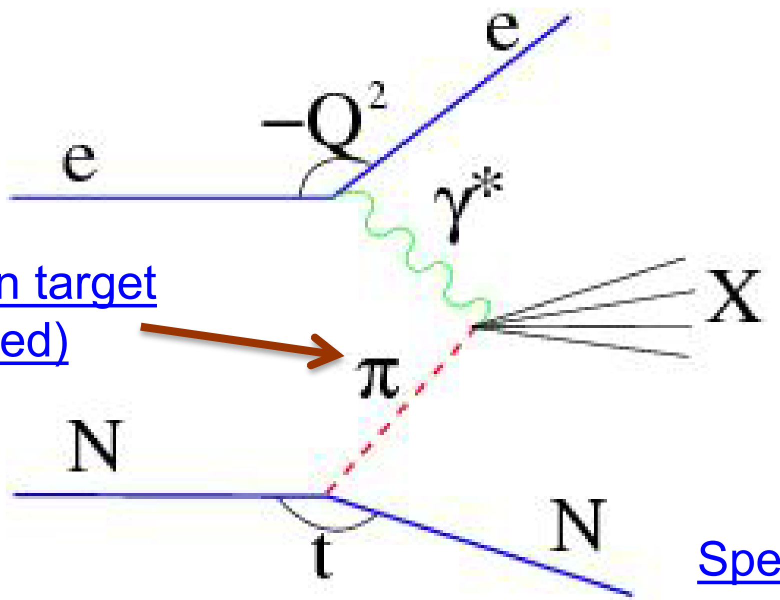
Jefferson Lab can provide important verification

Physics Objects for Pion/Kaon Structure Studies



Sullivan process: scattering from nucleon-meson fluctuations

Detect scattered electron



Pion/Kaon target (undetected)

DIS event – undetected recoiling hadronic system

Spectator "tagged" neutron/lambda

DIS event – reconstruct x, Q^2, W^2, also M_X of recoiling hadronic system

$$R^T = \frac{d^4\sigma(ep \to e'Xp')}{dxdQ^2dzdt} \Big/ \frac{d^2\sigma(ep \to e'X)}{dxdQ^2} \Delta z \Delta t \sim \frac{F_2^T(x,Q^2,z,t)}{F_2^p(x,Q^2)} \Delta z \Delta t.$$

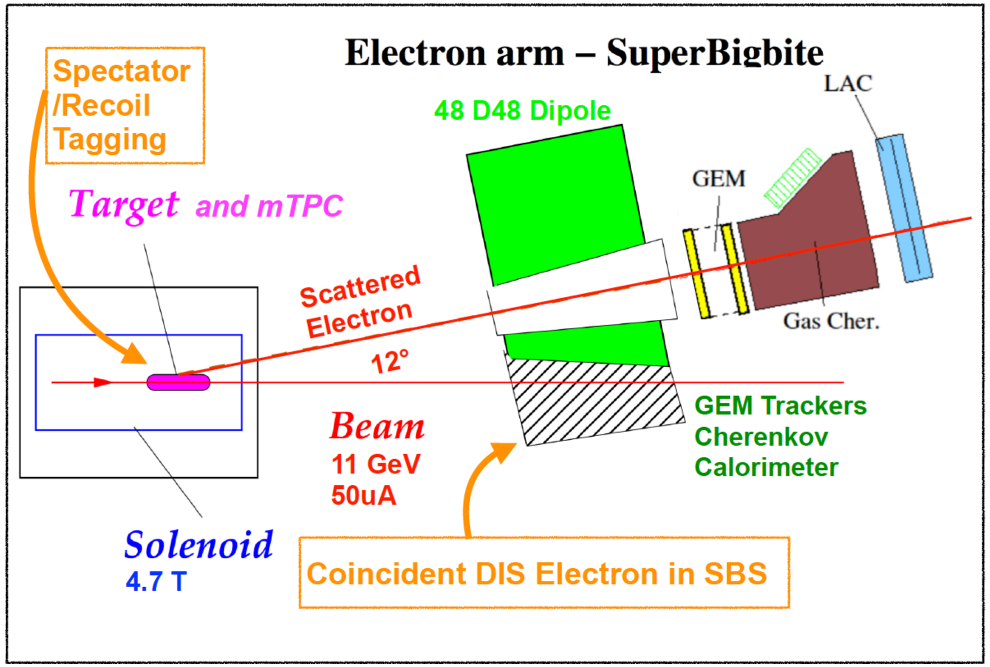
Tagged structure function
a direct measure of the mesonic content of nucleons

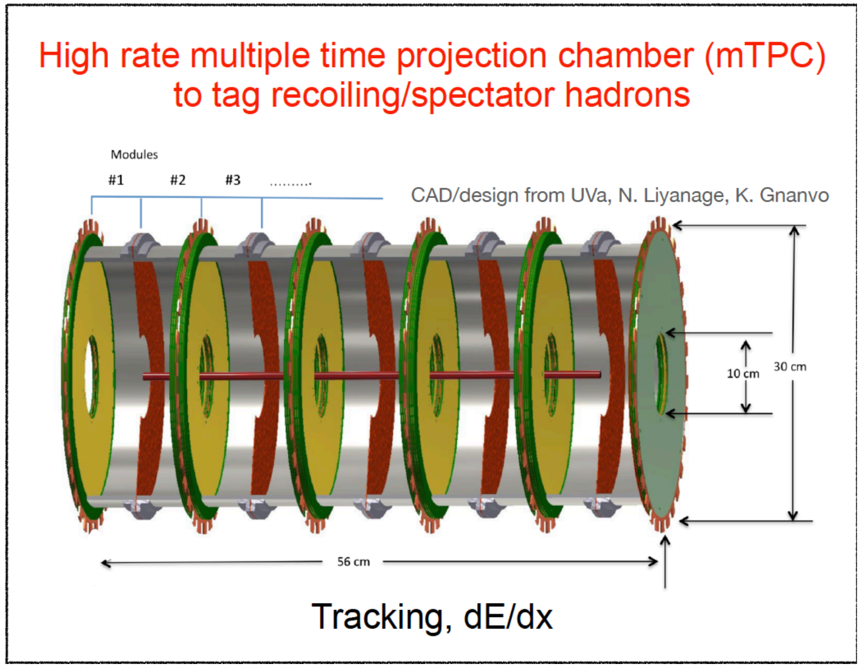
$$F_2^T(x,Q^2,z,t) = \frac{R^T}{\Delta z \Delta t} F_2^p(x,Q^2).$$

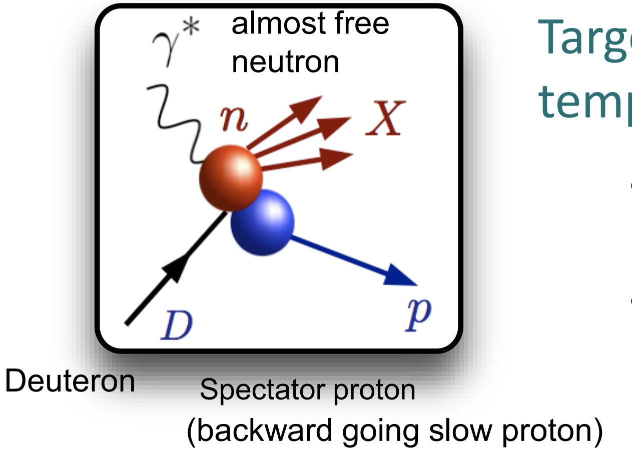
Tagged DIS can be used to tag the "meson cloud"

Spectator Tagging – well established technique at JLab

The TDIS experiment will use spectator tagging in a cylindrical recoil detector







Target: 40 cm long, 25 um wall thickness Kapton straw at room temperature and 3 atm. pressure.

- TDIS will be a pioneering experiment that will be the first direct measure of the mesonic content of nucleons.
- The techniques used to extract meson structure function will be a necessary first step for future experiments

Projected JLab TDIS Results for π, K Structure Functions

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

Spokespersons: D. Dutta, T. Horn, C. Keppel, P. King, N. Liyanage, R. Montgomery, K. Park, B. Wojtsekhowski,

TDIS with SBS:

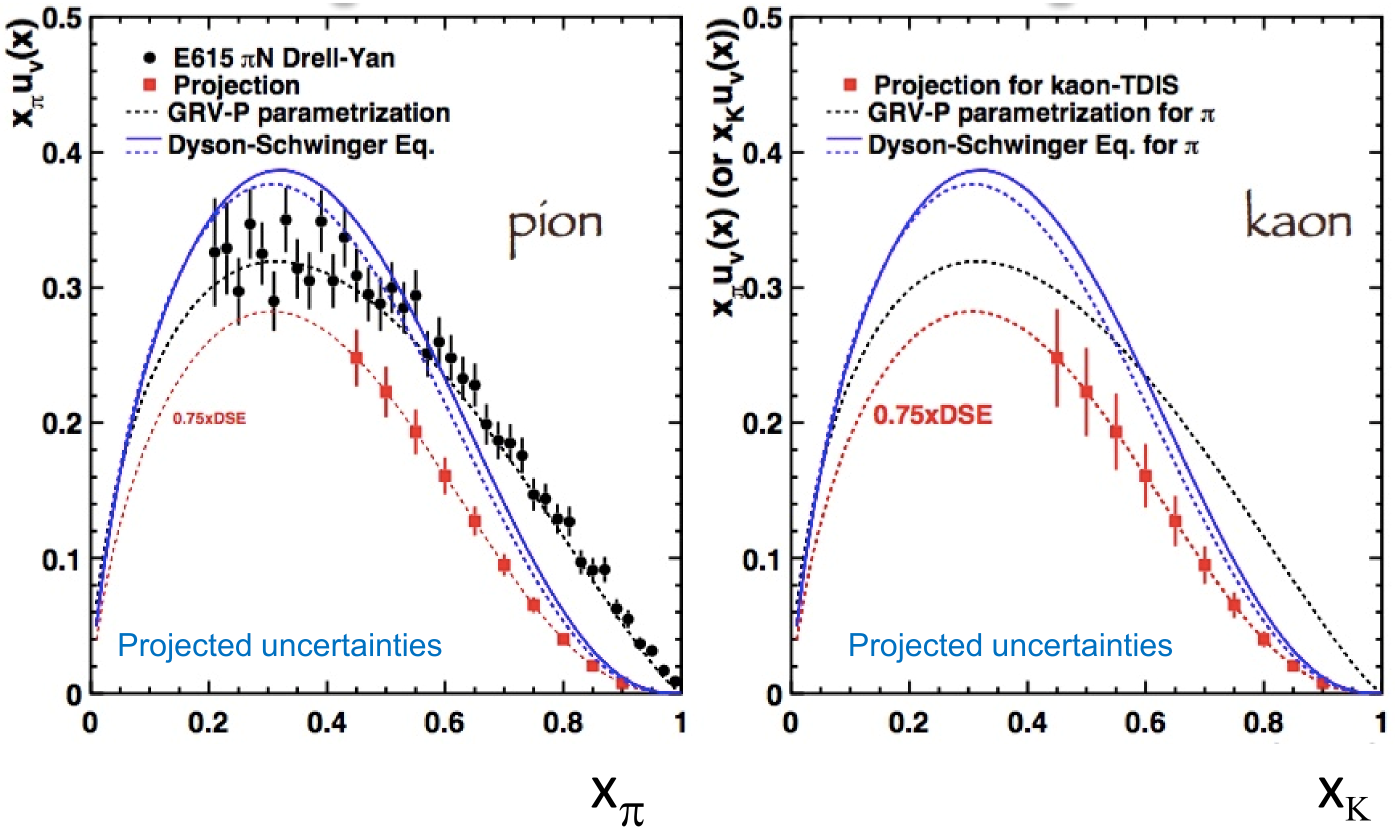
✓High luminosity,
50 μAmp,
$\mathcal{L} = 3\text{x}10^{36}/\text{cm}^2\ \text{s}$

✓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



Projections based on phenomenological pion cloud model

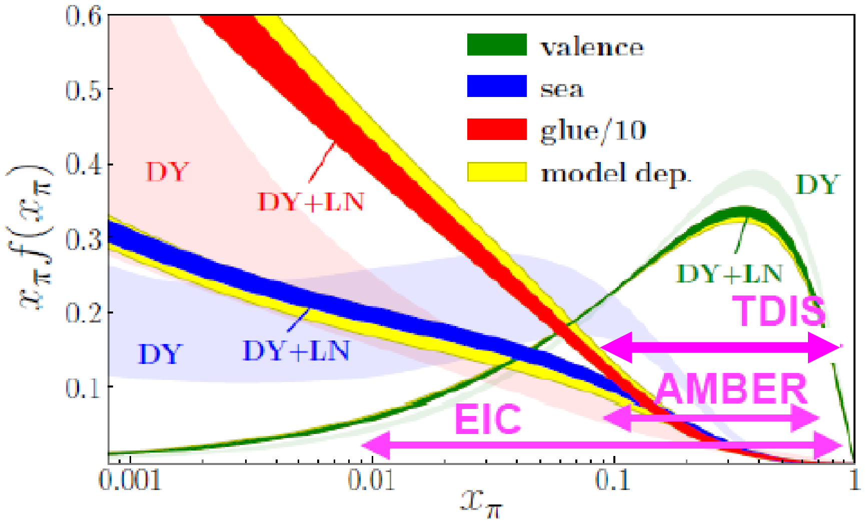
T.J. Hobbs, Few Body Syst. 56 (2015) 6-9

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

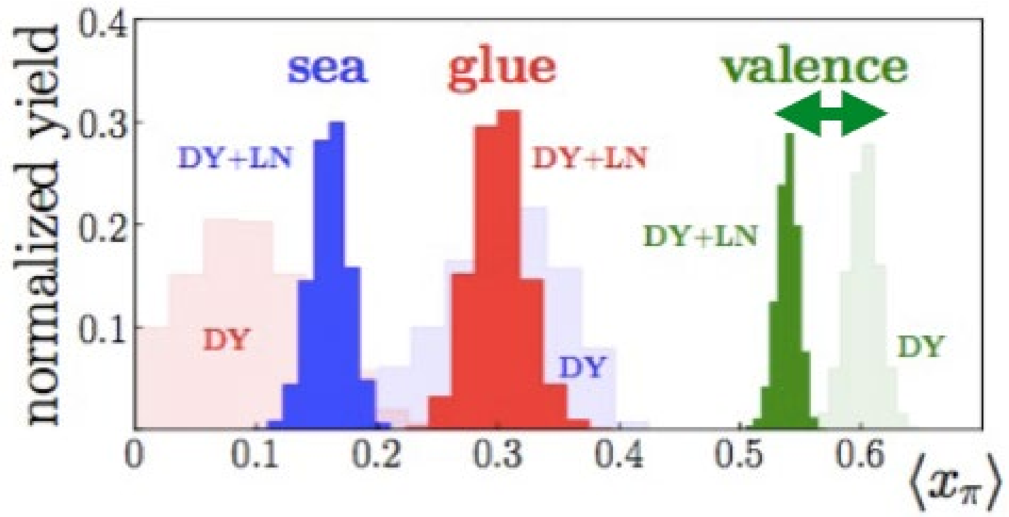
Essentially no kaon data currently

Global PDF Fits and Demand for more Data

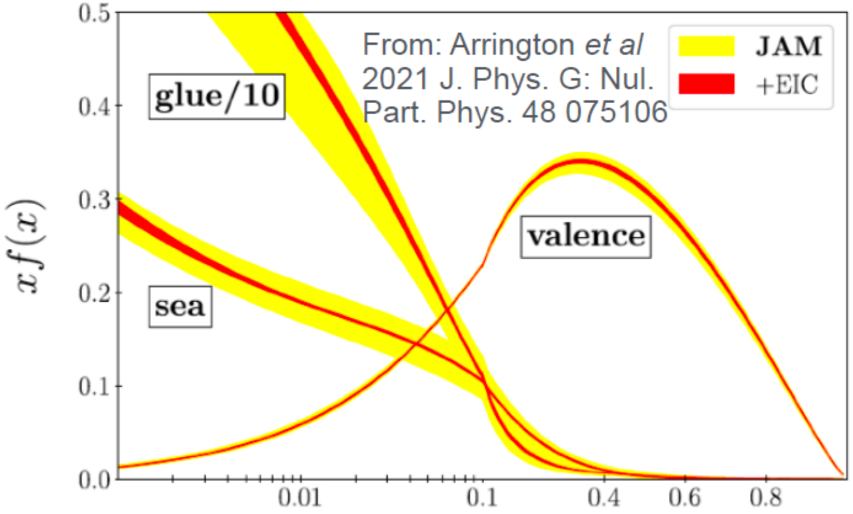
- ❑ Combined Leading Neutron/Drell-Yan analysis for PDF fitting, with novel MC techniques for uncertainties (JLab JAM)
- ❑ Non-overlapping uncertainties – tension at large x



Mom. Fraction carried by sea/glue/valence



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



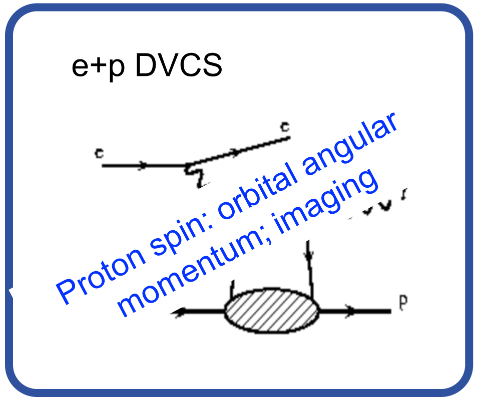
- ❑ Yet, different basis light front quantization (BFLQ) technique finds agreement in PDF evolution between DY and DIS

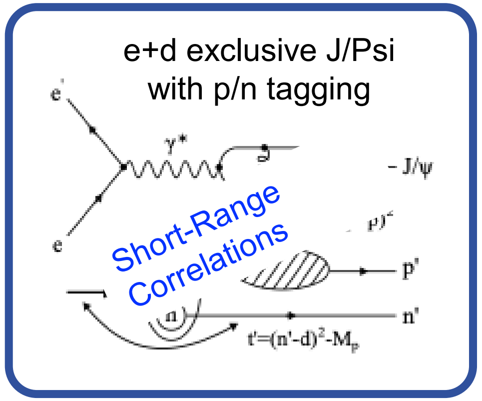
  J. Lan, C. Mondal, S. Jia, X. Zhao, J.P. Vary, Phys. Rev. D 101 (2020) 3, 034024

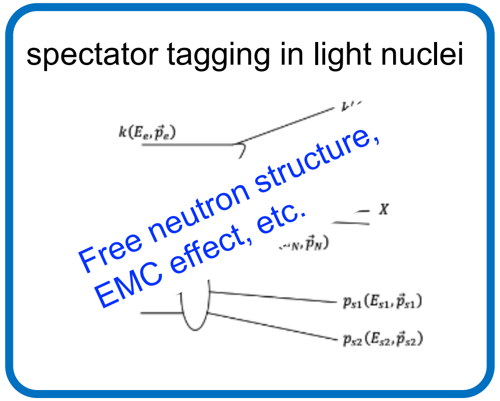
  - ➢ More data needed
- ❑ **Excellent opportunity for more data with EIC**
  - ➢ Kinematic bridge between HERA and high-x with wide coverage in x

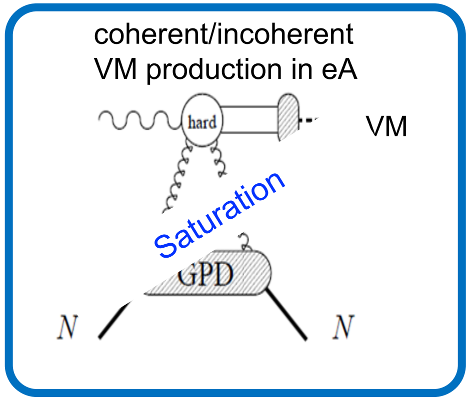
Far-Forward Physics at EIC

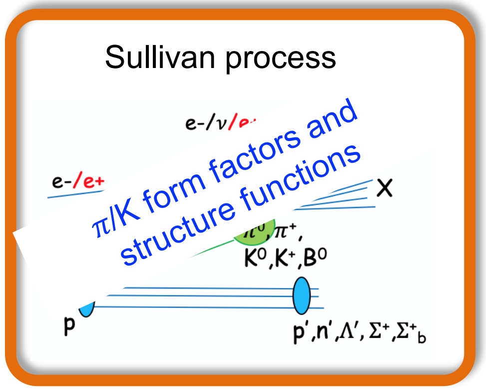
All these processes require the detection of protons, neutrons, photons and hadrons at small scattering angles → *MAJOR EIC science and detector emphasis*

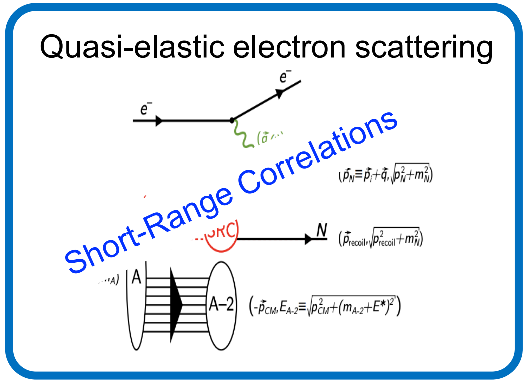


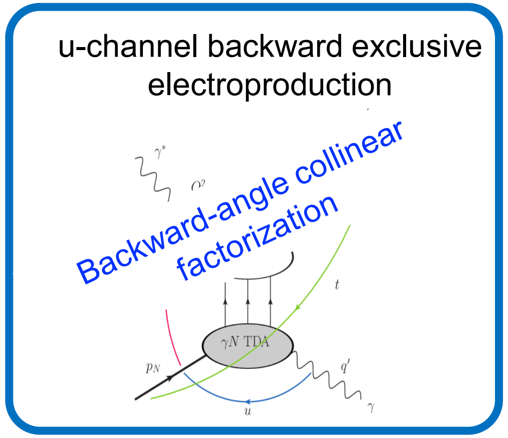


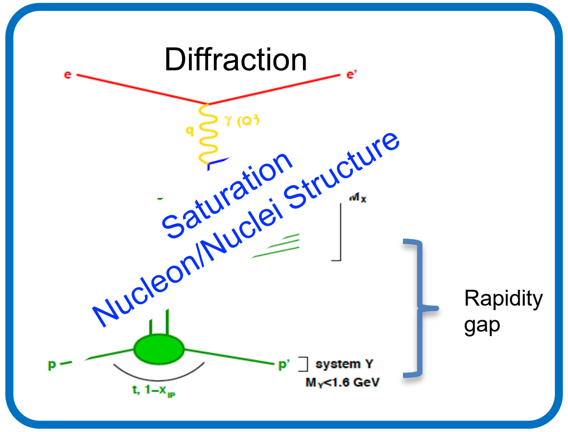






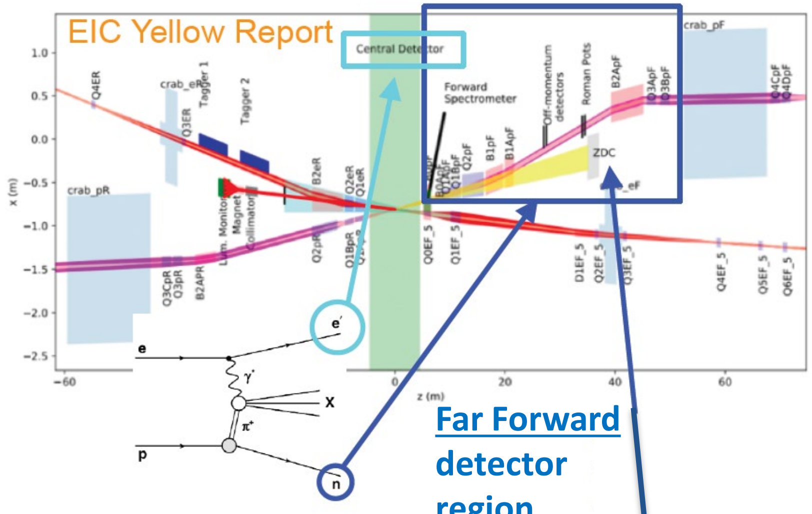


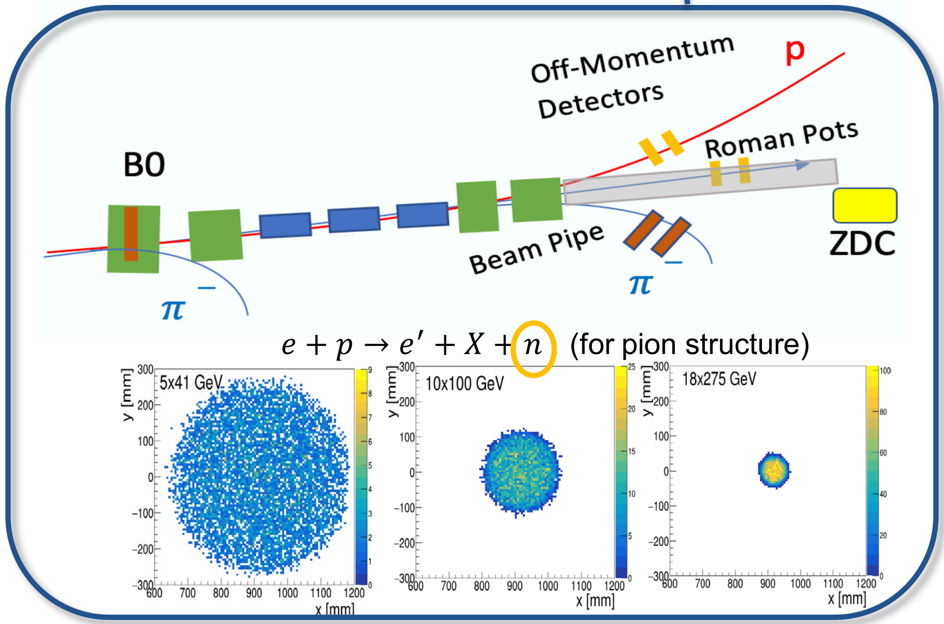




Look at this process in more detail

EIC Far Forward Region and Sullivan Process

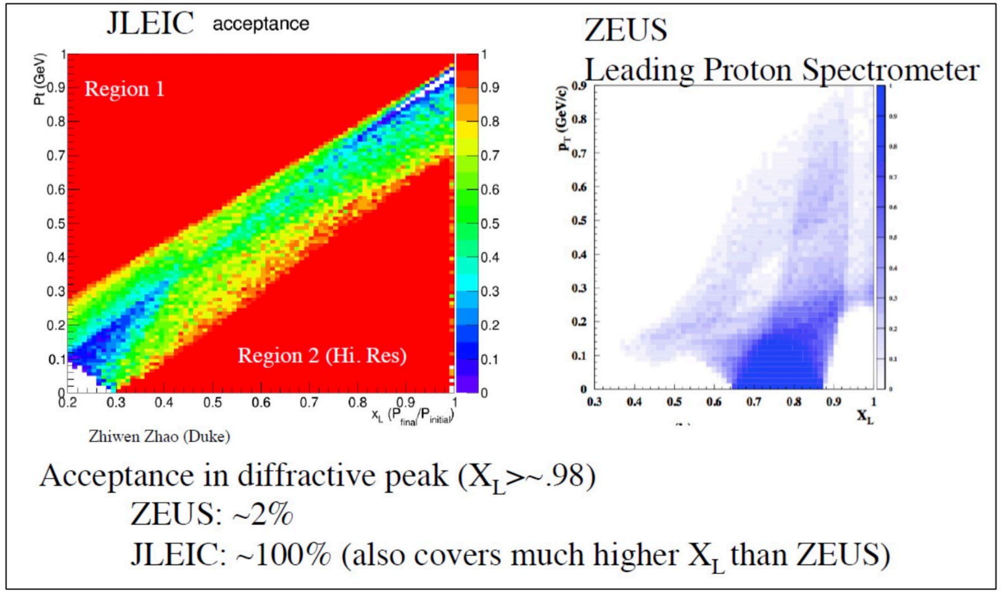




- EIC design well suited for Leading Neutron (HERA-style) pion/kaon SF measurements
- **ZDC particularly important (reaction kinematics and 4 momenta)**

Huge gain in acceptance for forward tagging….

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



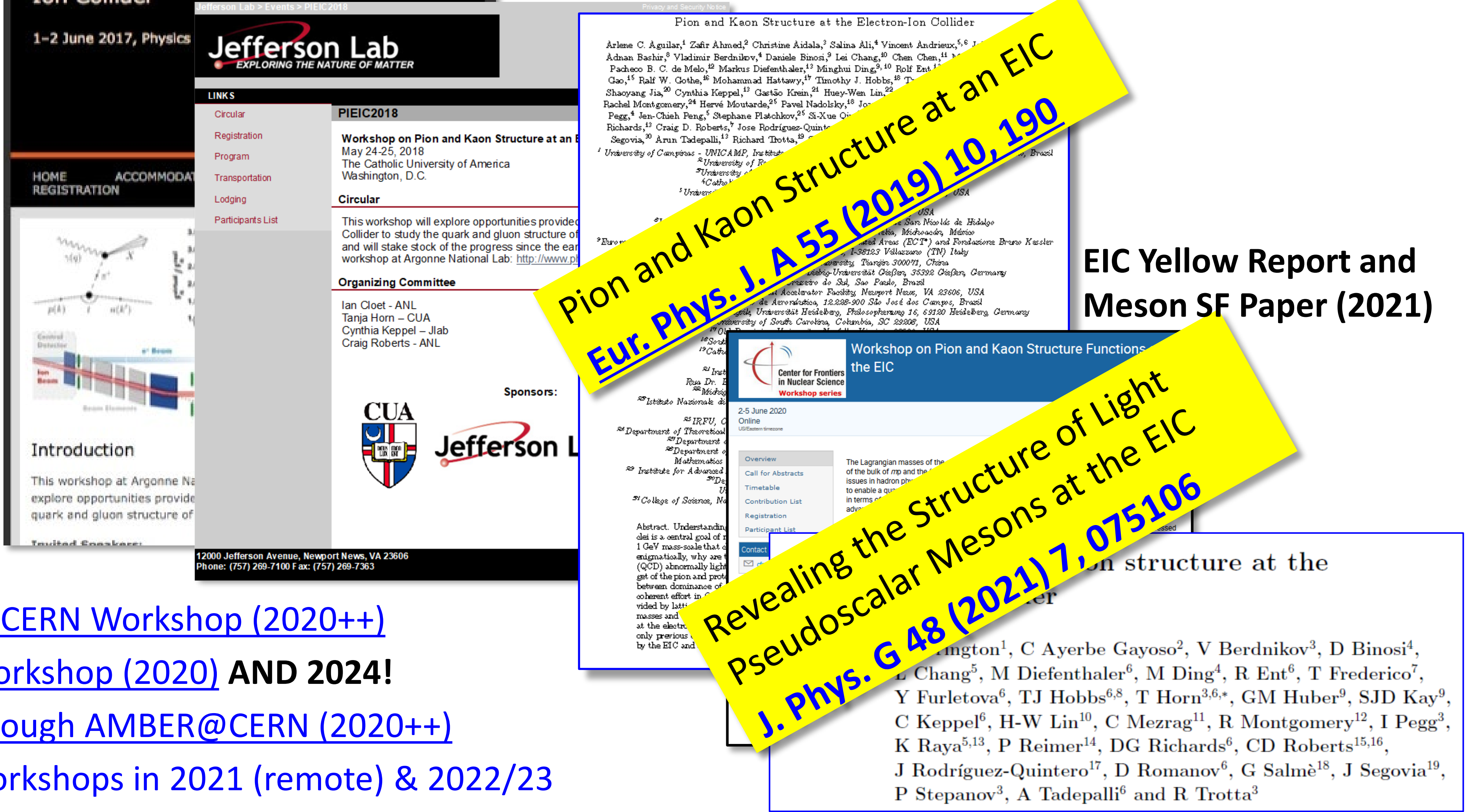
*R. Abdul Khalek, …, T. Horn, et al., Nucl. Phys. A **1026** (2022) 122447*

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)



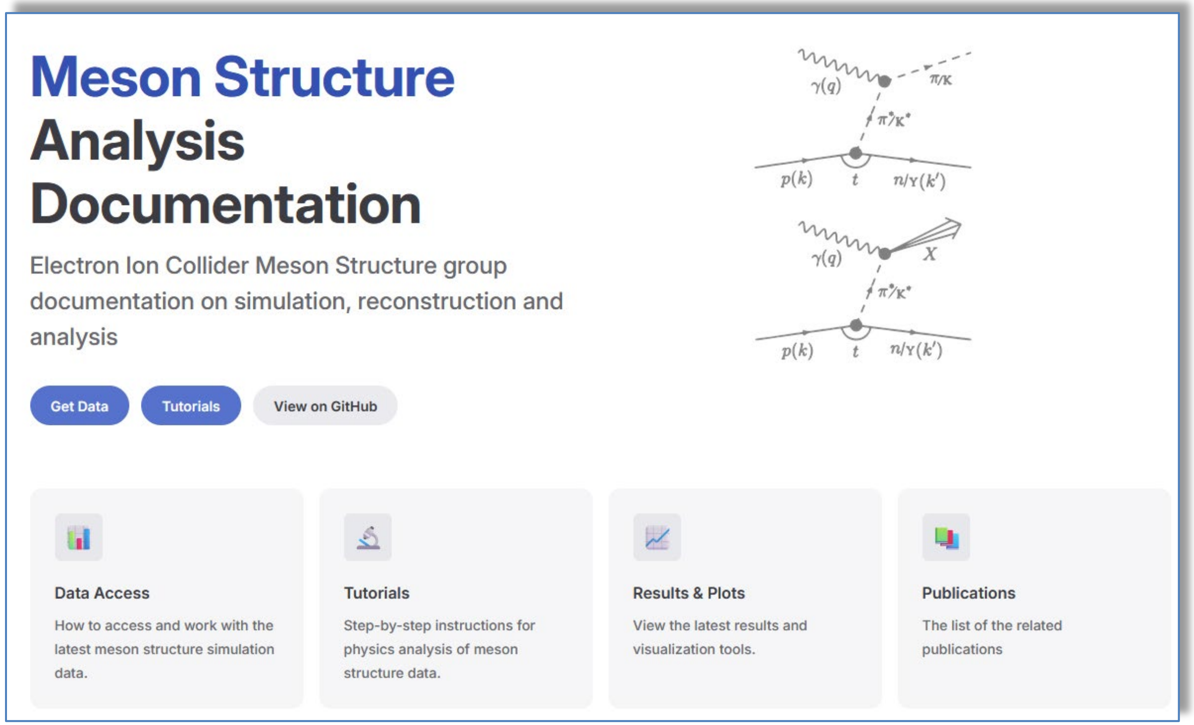
- AMBER/CERN Workshop (2020++)
- CFNS Workshop (2020) **AND 2024!**
- EHM through AMBER@CERN (2020++)
- ECT* Workshops in 2021 (remote) & 2022/23

Meson Structure Functions Working Group

Meson SF Working group members:

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

- Meson SF WG: 45 members, 27 institutions, 12 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 and continuing since then with new efforts and publications



Recent WG discussions and theory publications

- K. Raya Montana et al., "*Symmetry Constraints on Pion Valence Structure*", 2510.23950, (April 2026)
- A. Sturzu, et al., "*Accessing the gluon momentum fraction of nucleons through the gradient flow*", 2602.14260 (March 2026)
- Z-N. Xu et al., "*Kaon distribution functions from empirical information*", Phys. Lett. B **865** (2025) 13951
- W. Good et al., "*Towards the first gluon parton distribution from LaMET*", J. Phys. G **52** (2025) 3, 035105
- D-D. Cheng et al., "*Pion Boer Mulders function using a contact interaction*", Eur. Phys. J. C **85** (2025) 1, 115
- H-Y. Xing et al., "*Kaon and Pion Fragmentation functions*", 2504.08142 [hep-ph]

Recent experimental efforts focused on evaluating early science opportunities at EIC

Meson SF Analysis and Documentation

- Simulation Campaigns and Data Access for Analysis
- Developing analysis scripts to include in the analysis campaigns with all the standard plots (Chien-I An, Po-Ju Lin, Wen-Chen Chang)

Meson SF Working group members:

Simulation campaigns

This page documents the meson structure simulation campaigns.

> (!) For the list of files go to DATA PAGE

Campaign 2026-03

Campaign 2026-03 Link

Overview:

- Uses 2026-02 image - EIC software update
- Sets FF magnetic fields correctly
- Uses multiple forward calorimeters for lambda neutral channel identification
- On technical side: analysis automation

Campaign 2025-10

Campaign 2025-10 Link

Overview:

- Uses 2025-10 image that should be feature freeze before preTDR
- On technical side: better script jobs automation

Data

Location

The meson structure data is available from the following locations:

LATEST PROCESSED FILES
(last update of March 2026)

On JLab ifarm:

```bash
/volatile/eic/romanov/meson-structure-2026-03/reco

# CSV files
/volatile/eic/romanov/meson-structure-2026-03/csv_eicrecon

# priority queues (first 1'000'000 events == 200 files from each energy range):
/volatile/eic/romanov/meson-structure-2026-03/reco/5x41-priority
/volatile/eic/romanov/meson-structure-2026-03/reco/10x100-priority
/volatile/eic/romanov/meson-structure-2026-03/reco/10x130-priority
/volatile/eic/romanov/meson-structure-2026-03/reco/18x275-priority

#CSV files are located in csv_eicrecon and csv_dd4hep folders now:
/volatile/eic/romanov/meson-structure-2026-03/csv_eicrecon/5x41-priority
/volatile/eic/romanov/meson-structure-2026-03/csv_eicrecon/10x100-priority
/volatile/eic/romanov/meson-structure-2026-03/csv_eicrecon/10x130-priority
/volatile/eic/romanov/meson-structure-2026-03/csv_eicrecon/18x275-priority
```

On XRootD (open for universities and public)

```bash
xrdfs root://dtn-eic.jlab.org
ls /volatile/eic/romanov/meson-structure-2026-03/reco
```

Dynamic Histogram Plots

This page demonstrates interactive histogram visualization using Apache ECharts. You can select different histograms from the dropdown menu to explore the kinematics data.

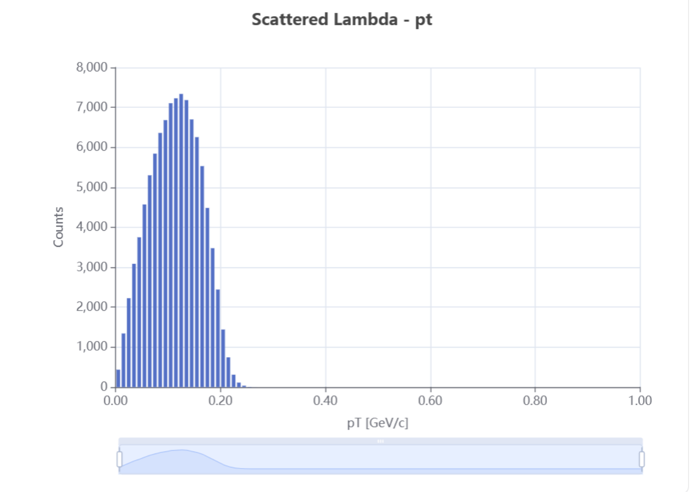
10×100 GeV Analysis

The following interactive viewer displays histograms from the 10×100 GeV beam configuration analysis. Select a histogram from the dropdown to view:

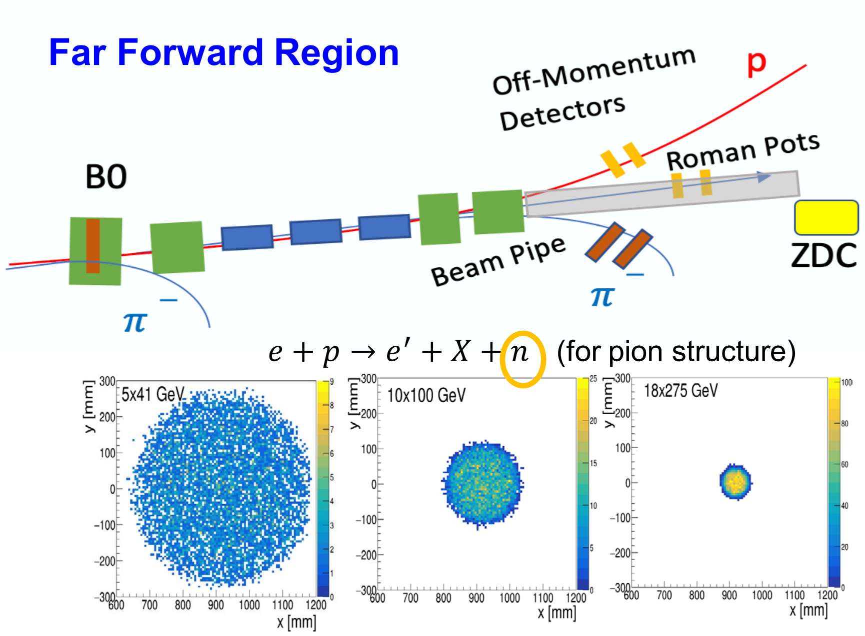
Select Histogram:

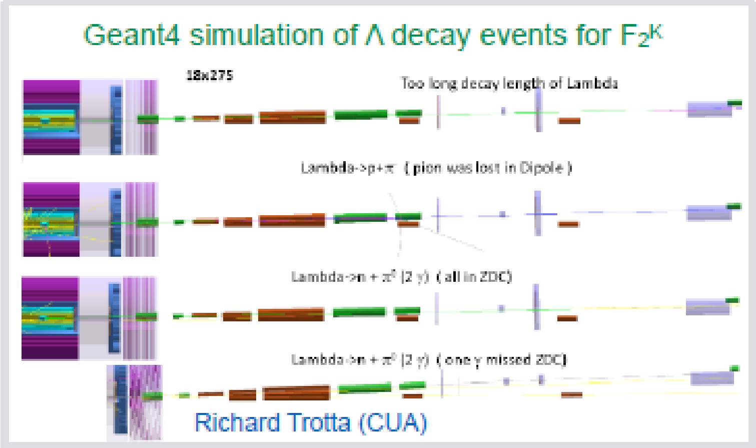
pt

Entries: 100,000 **Mean:** 0.114 **Std Dev:** 0.048

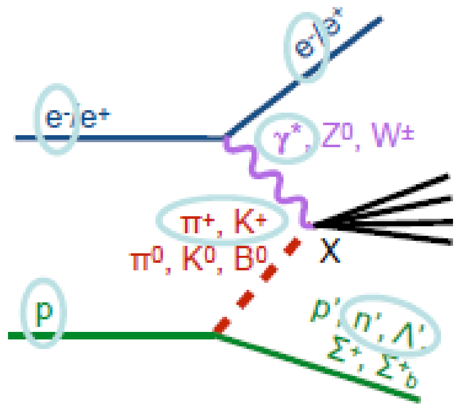


EIC Pion/Kaon SF – Experimental Considerations





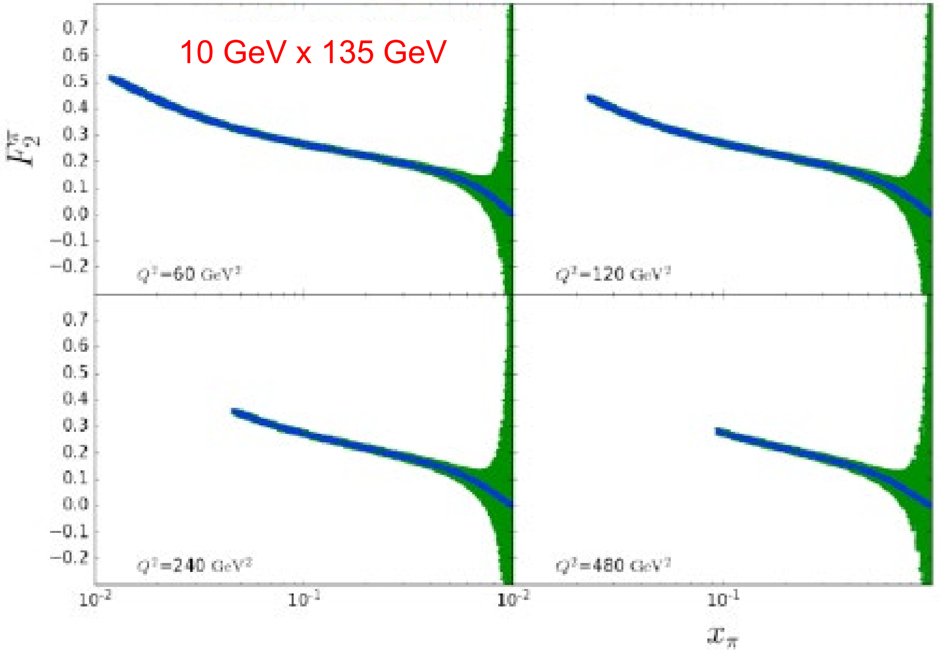
- Custom fast MC event generator (Avnish Singh, CUA) and G4 for detector acceptance/response
- Focus so far: ep and measuring cross section at small-t for
  - F_2^{π} (π^+) tagged by n
  - F_2^{K} (K^+) tagged by Λ^0 decay
- Settings e x p(GeV): 5x41, 10x100 (135), 18x275



Detector requirements:

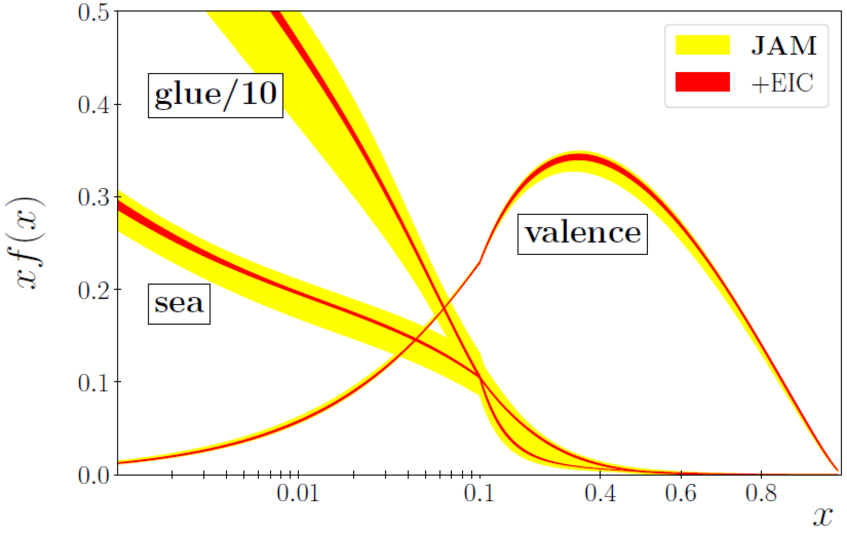
- **For π-n:**
  - Lower energies (5 on 41) require at least 60 x 60 cm^2 aperture
  - For all energies, the neutron detection efficiency is 100% with the planned ZDC
- **For π-n and K^+/Λ:**
  - All energies need good ZDC angular resolution for the required -t resolution
  - High energies (10 on 100,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

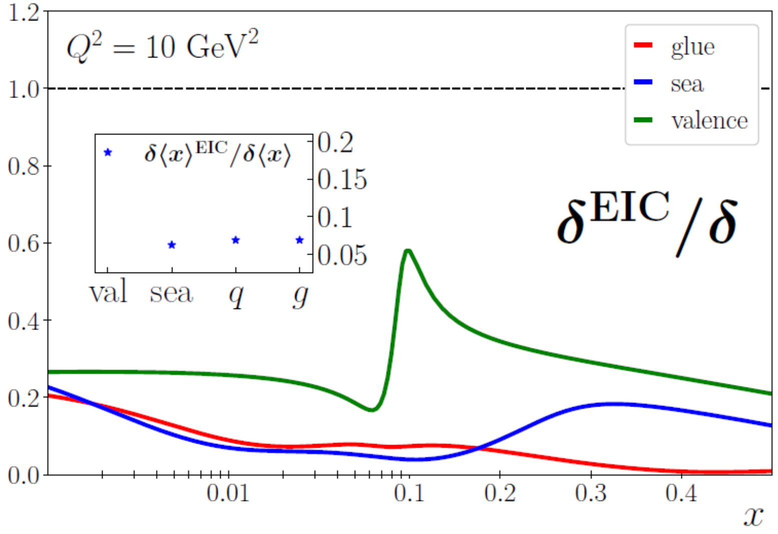
EIC Pion SF Projections



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

- 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)
- Detailed comparison between pion/kaon and gluon contents possible with coverage and uncertainties
- Reduce uncertainties in global PDF fits





*R. Abdul Khalek, …, T. Horn, et al., Nucl. Phys. A **1026** (2022) 122447*

Kaon Structure Functions at EIC

Team: Baptiste Fraïsse, Tanja Horn, Avnish Singh, Dmitry Romanov, Yulia Furletova, Rachel Montgomery, Po-Ju Lin, Wen-Chen Chang, Chien-I An

Detailed study including detector simulation and reconstruction

Meson Structure Analysis Code:
https://github.com/JeffersonLab/meson-structure
Documentation:
https://jeffersonlab.github.io/meson-structure/

Generator → Simulation → Reconstruction → Uncertainty → Physics

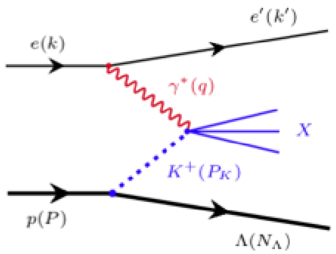
Event generator
strange Sullivan process

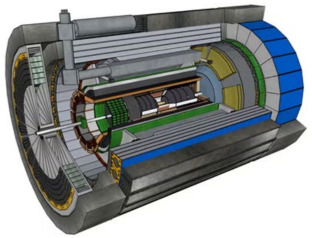
HPC campaigns
Geant4 transport
ePIC

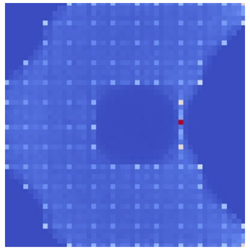
Multi-detector $\boldsymbol{\Lambda}$
(SIDIS)
Kinematics (electron, JB)

Statistical ΔN
Efficiency $\Delta\varepsilon$
Generator model Δσ
Physics background
x-uncertainty

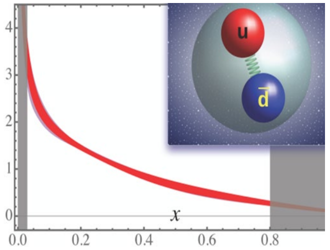
Models discrimination
Toy models
Theoretical models







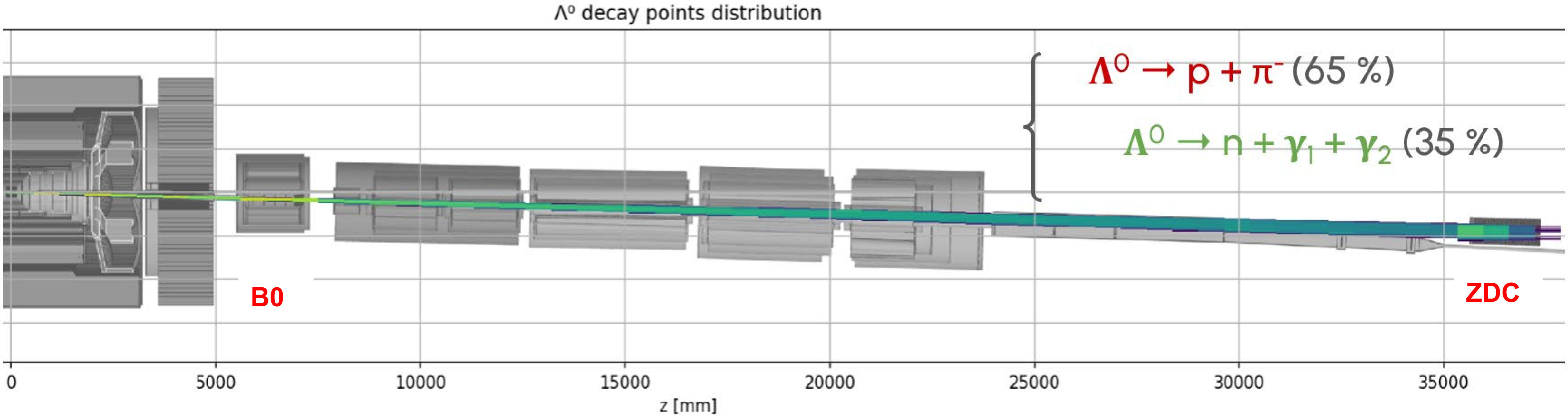
$$u_c(y_i) = \sqrt{\sum_{i=1}^{n}\left[\frac{\delta y_i}{\delta x_i}\cdot u(x_i)\right]^2}$$



Meson SF Event Generator (A. Singh, CUA):
https://github.com/JeffersonLab/eic_mesonsf_generator

Challenges of measuring Lambdas

- Kaon structure inferred from the measurements of the Lambda momenta
- Lambda is challenging to measure: unstable with two decay channels
  - Charged channel
  - Neutral decay channel

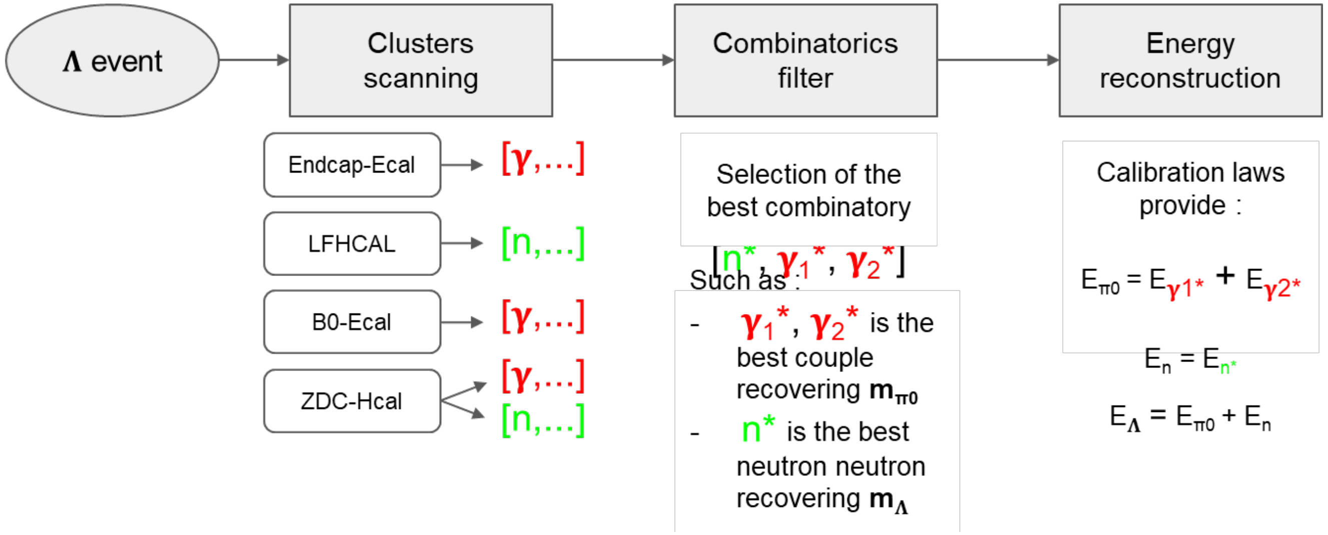


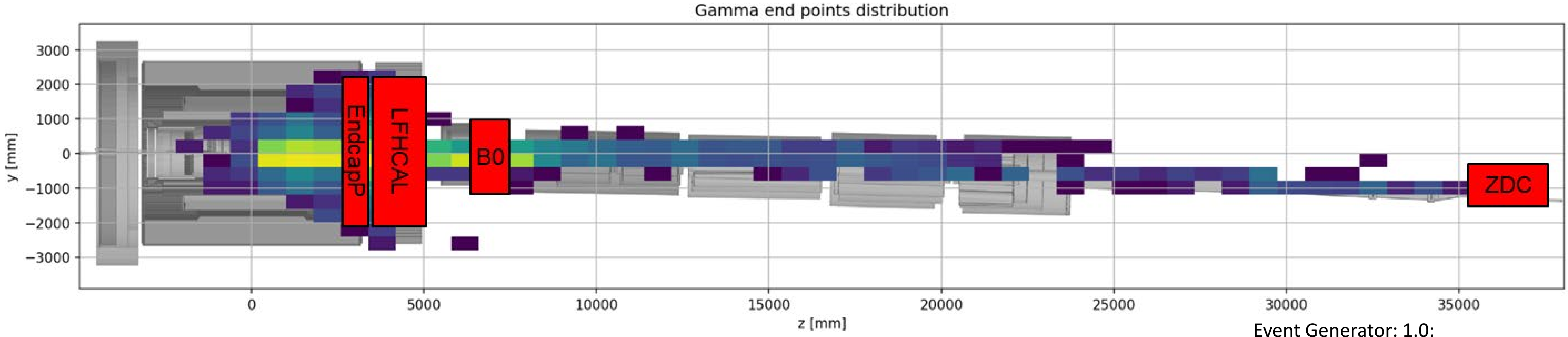
View of the Far Forward Region

Event Generator: 1.0;
Simulation campaign: 2025-07

NEW Lambda Reconstruction Algorithm

- An algorithm using a *single calorimeter* (ZDC) as presented in S.J. Paul et al. PRD 111 (2025) 9, 092013 is not sufficient to reconstruct lambdas
- New algorithm (B. Fraisse): search for triple coincidences (n+g1+g2) with **several calorimeters**
  - ZDC-HCAL and B0-Ecal in the Far-Forward region
  - EndcapP-Ecal and LFHCAL in the Forward region



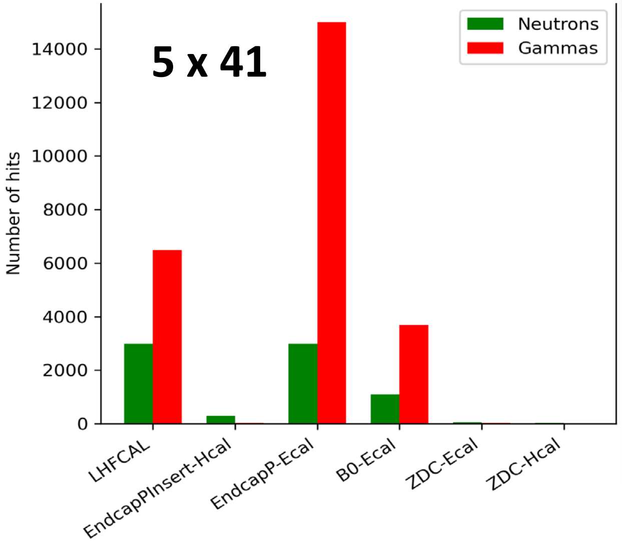


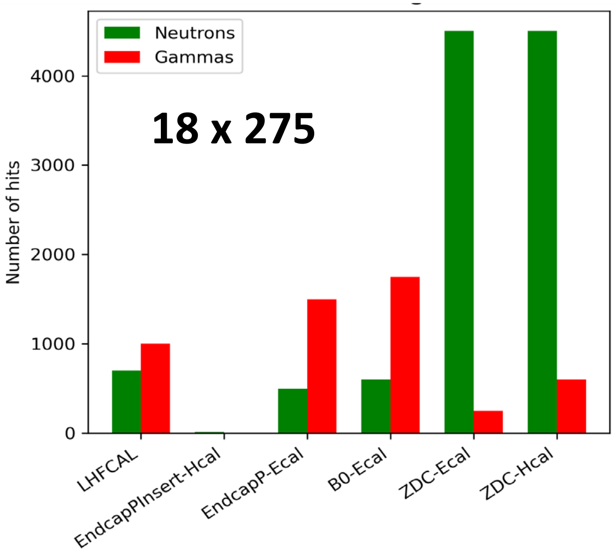
View of the Far Forward Region

Event Generator: 1.0;
Simulation campaign: 2025-07

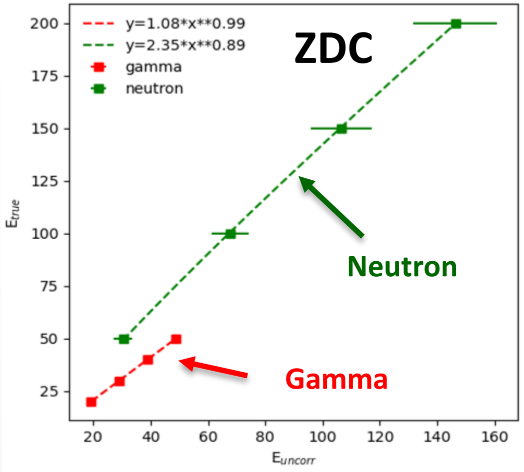
Results with the NEW algorithm

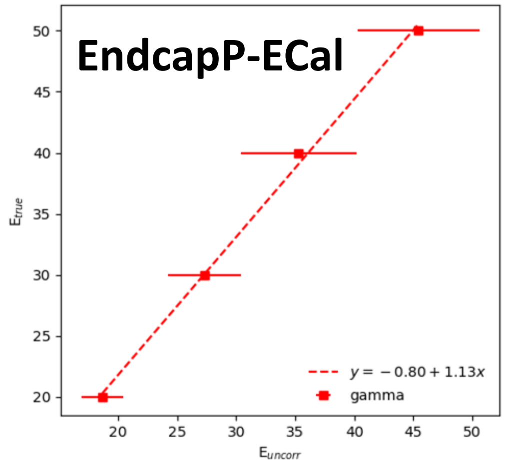
Λ hits in different detectors



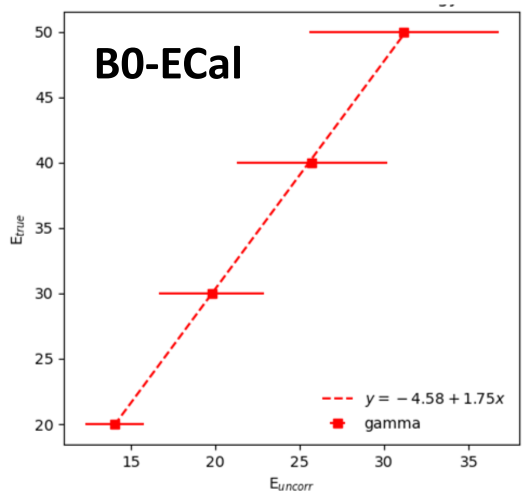


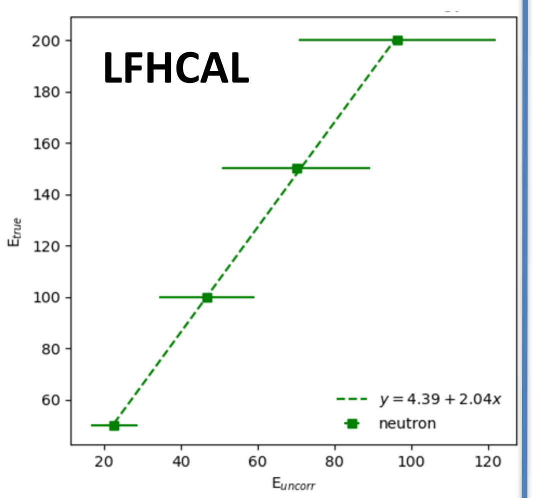
Reconstructed vs. true particle energy in calorimeters



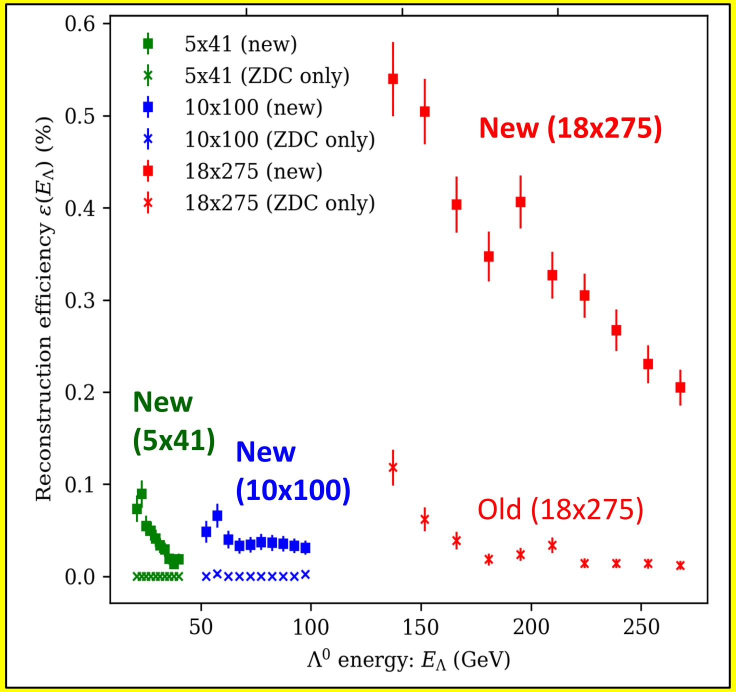


Linear responses as expected





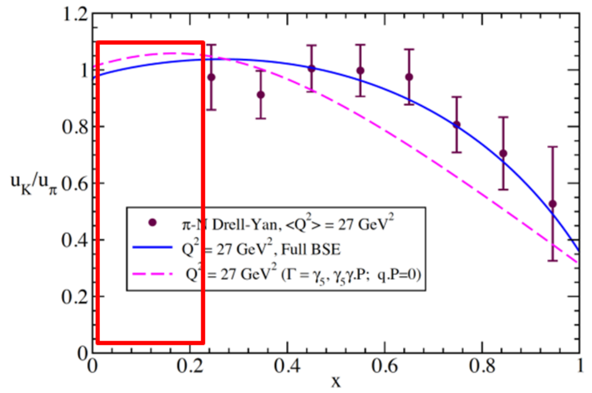
Λ Recon Efficiency Results



- New algorithm shows ***improved efficiency*** over the previous one
- The reconstruction efficiencies are ~0.1 – 0.5% but have ***high purity*** - tradeoff tunable into the combinatorics treatment (e.g., invariant mass window)

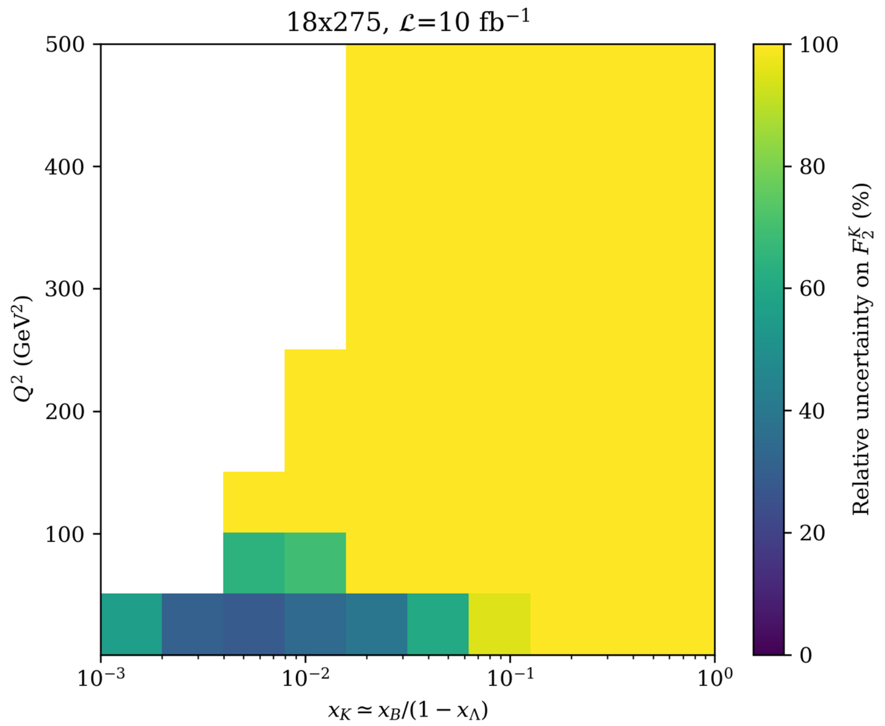
Kaon SF Projected Uncertainties

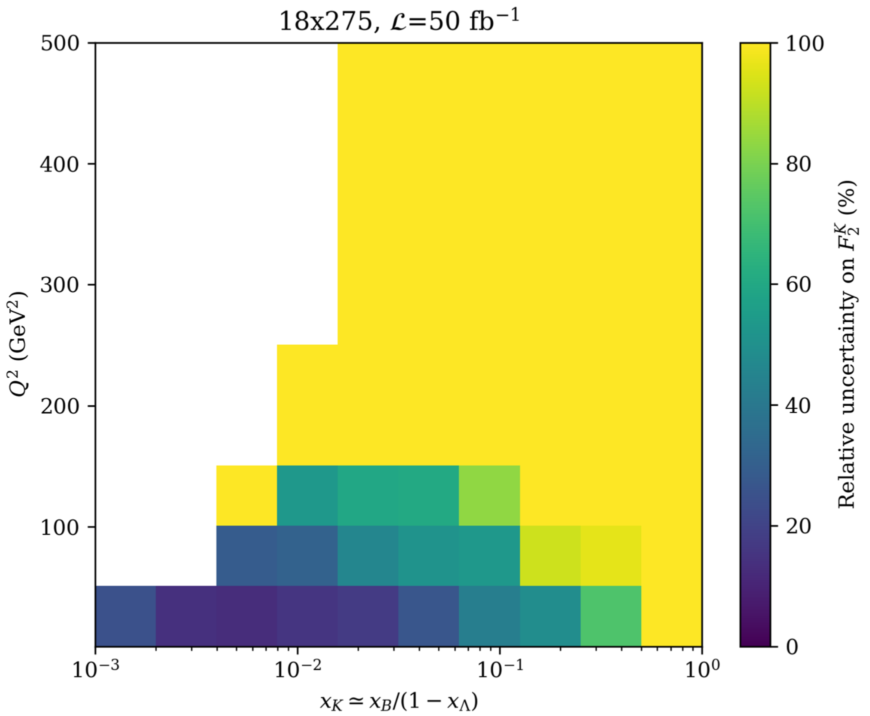
Using the new reconstruction algorithm



Small x is a region of interest

- Cross-section calculation : $\sigma = (\Sigma w_i)/N_{gen}$
- w_i = PhSpFct * Jac * tag_dis * k_int. Total cross-section : σ ~ 0.002 nb





Event Generator: 1.0;
Simulation campaign: 2026-03

- ➢ **Projections show that we have good sensitivity at small x**
- ➢ Statistics might improve with new simulation campaigns – issue with “missing Lambdas” (see GitHub issue)

Compare Theoretical Calculations (in progress)

Event Generator: 1.0;
Simulation campaign: 2026-03

Examples of types of different calculations

SMRS

Sutton–Martin–Roberts–Stirling

Phenomenological fit assuming SU(3) symmetry

Phys. Rev. D ***45*** *(1992)*

GRV-GRS

Gluck-Reya-Vogt
Gluck-Reya-Schienbein

Valence-like input at low-Q^2 and QCD evolution at higher-Q^2

Eur. Phys. J **10** (1999)

JAM-GRS

JAM Collaboration
Gluck-Reya-Schienbein

Modern fit using pion constraints and SU(3) asymmetry relations

Phys. Rev. Lett **121** (2018)
Phys. Rev. Lett. **127** (2021)

DSE

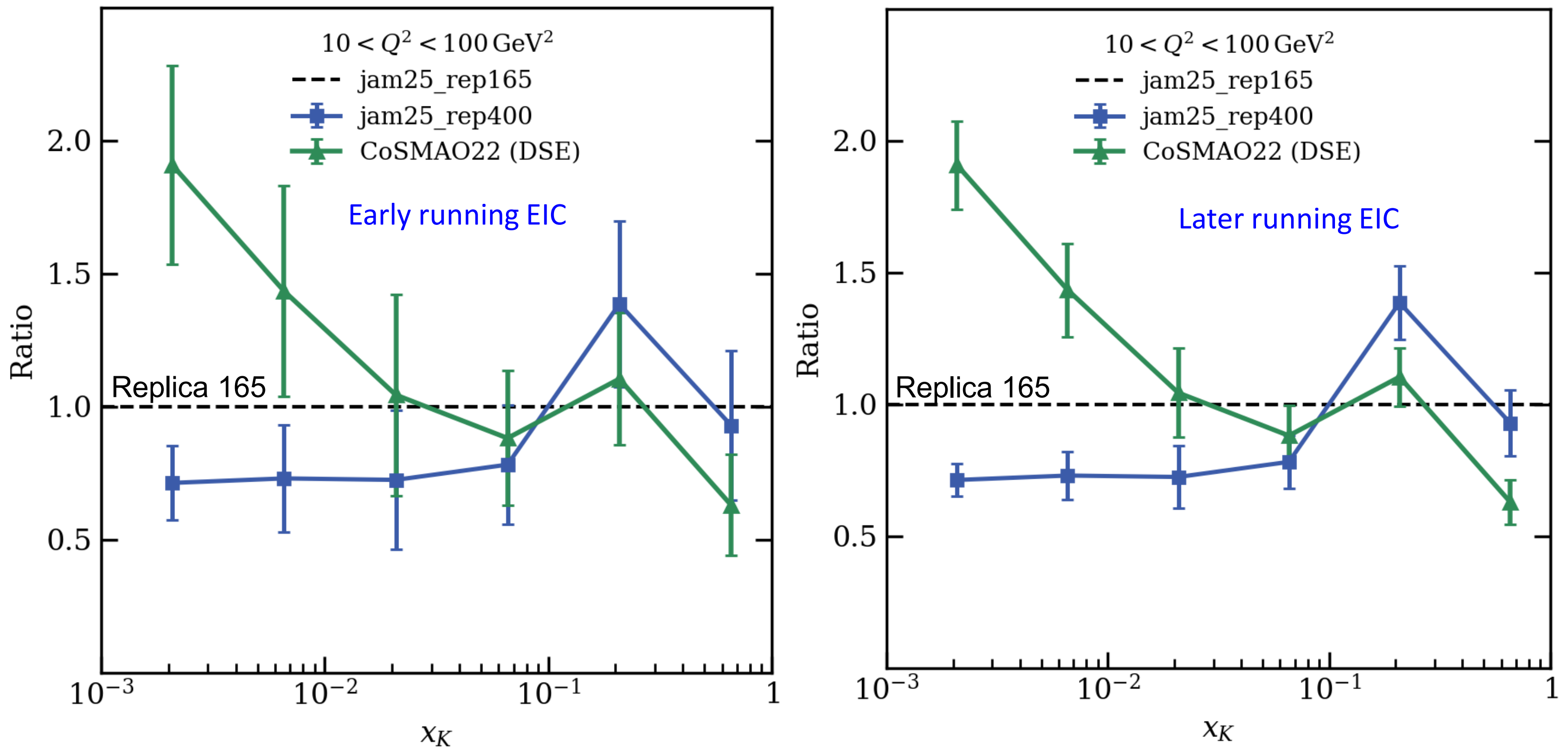
Dyson-Schwinger Equations

Non-perturbative fully microscopic theoretical predictions

Phys. Rev. D **93** (2016)

[Parton distribution functions at LHAPDF]

Initial study: **two JAM replicas and DSE and JAM replica with the projected uncertainties for one bin in Q^2**



In preparation: Meson SF group reference paper for kaon SF at EIC

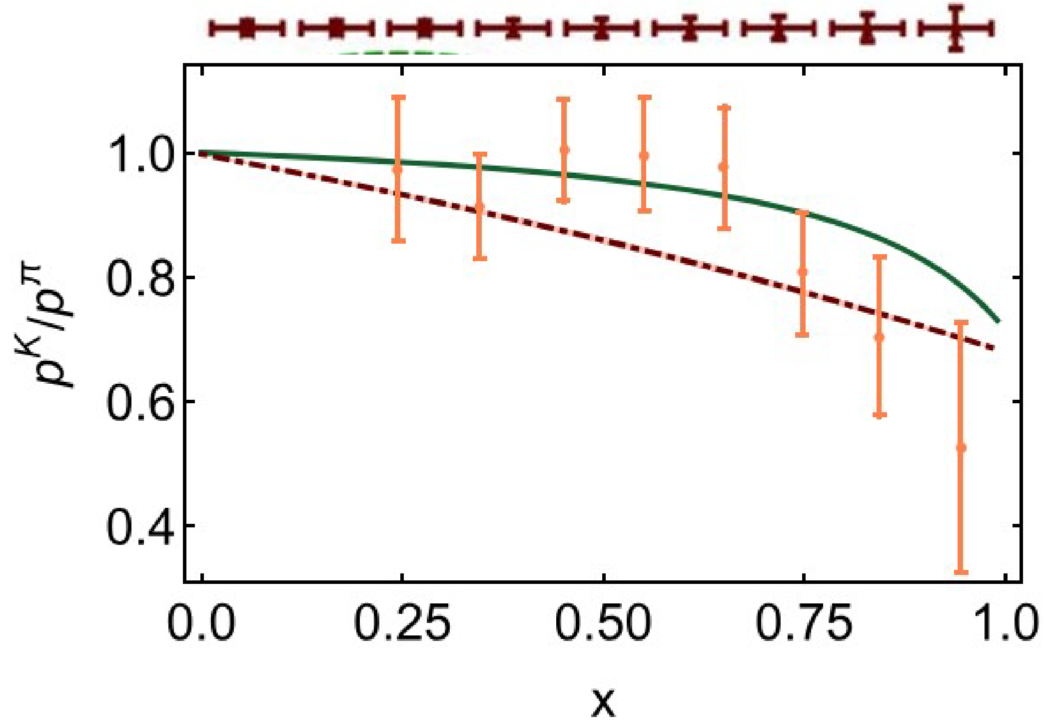
- Also ePIC is preparing an Early Science Report and NIM papers (see Stephen's talk for details)

Kaon structure functions projections – gluon pdfs

Projected Errors with Analytical approach

- Based on Lattice QCD and DSE calculations the kaon glue and sea distributions are similar to those in the pion at the scale of existing measurements.
  - A calculation predicts that the gluon light-front momentum fraction in the kaon is ~ 1% less than that in the pion and the sea fraction is ~ 2% less *Z-F Ciu et al., Eur.Phys.J.C* ***80*** *(2020) 1064, 1*
- Differences exist between pion and kaon glue and sea on the valence quark domain, where the current quark mass is playing a role.
- EIC could provide data to shed light on this – projected uncertainties for the ratio are shown

Analytical projected uncertainties for measurements at EIC



Z-F Ciu et al., Eur.Phys.J.C ***80*** *(2020) 1064, 1*

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

Summary

- Meson structure is essential for understanding EHM and our visible Universe
- The JLab 12 GeV era is going strong
  - Pion and kaon form factor extractions up to high Q^2 possible (~9 and ~6 GeV^2) – preliminary results becoming available
  - L/T separated cross sections important for transverse nucleon structure studies – may allow for accessing new type of GPDs
- JLab's approved program extends into 2030s - There are very exciting imminent opportunities to collect additional data for light mesons
  - TDIS experiments provide 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
- Example of science from JLab to EIC: Meson structure is one of the Far Forward processes with major EIC Science and Detector Emphasis and is essential for understanding EHM and our visible Universe
  - Meson structure is non-trivial and data for pion and kaon structure functions is extremely sparse
  - JLab 12 GeV will dramatically improve the $\pi^+/K^+/\pi^0$ electroproduction data set
  - EIC - Potential game-changer for this topic due to large CM range (20-140 GeV); Large x/Q^2 landscape for pion/kaon SF; Potential to provide definite answers on different gluon distributions in pion/kaon