Constraining kaon structure at the EIC

B. Fraïsse*, A. Singh, T. Horn (CUA)

D. Romanov, Y. Furletova (JLab)

S. Kay, R. Montgomery, G. Penman (UGL)

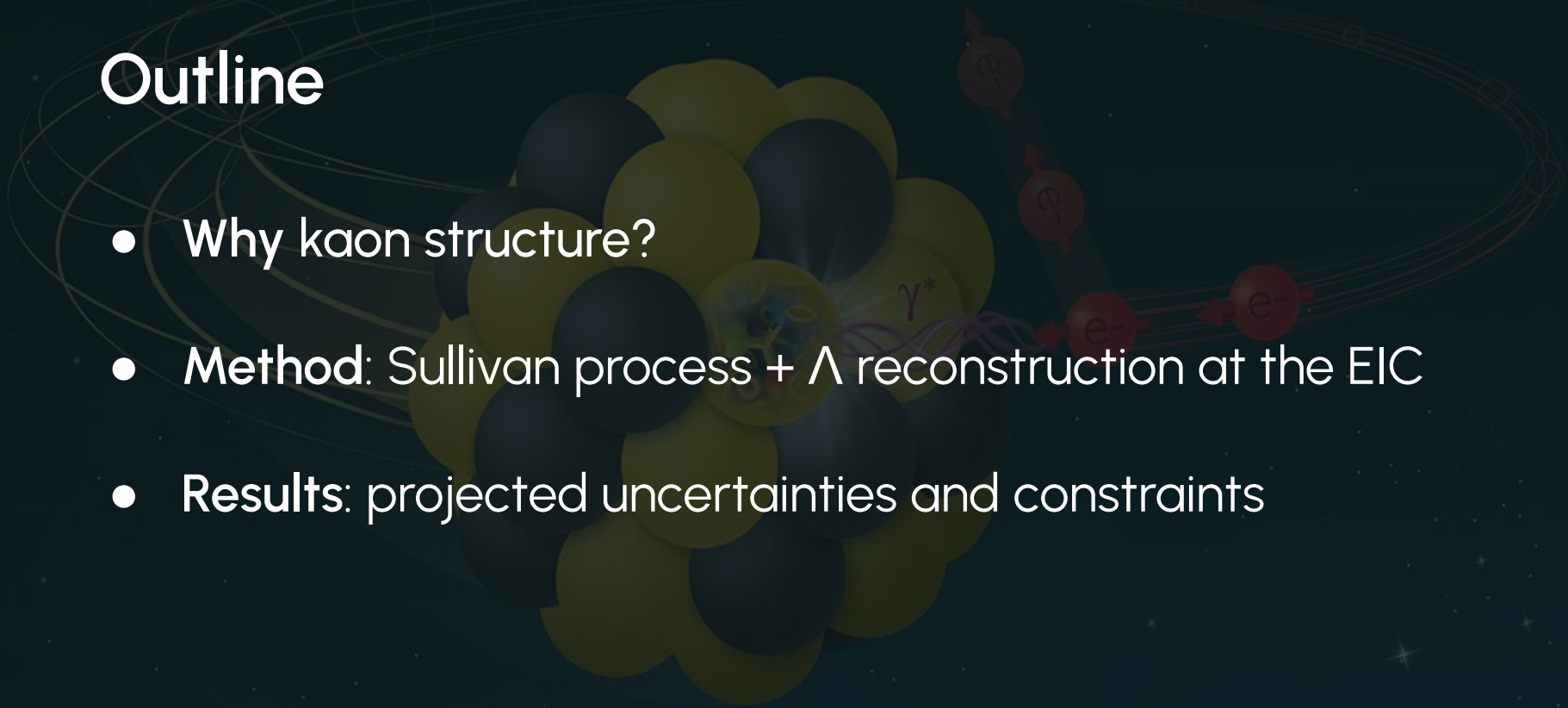
P.-J. Lin, W.-C. Chang (NCU)

P. Barry (ANL), C. Roberts (NJU)

*fraisse@cua.edu

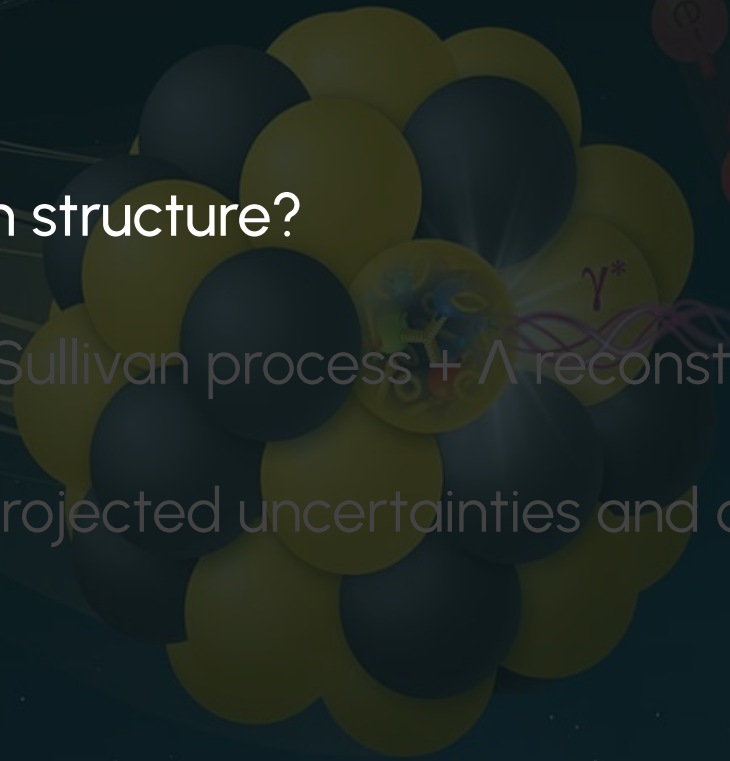
Outline

- **Why** kaon structure?
- **Method**: Sullivan process + Λ reconstruction at the EIC
- **Results**: projected uncertainties and constraints



Outline

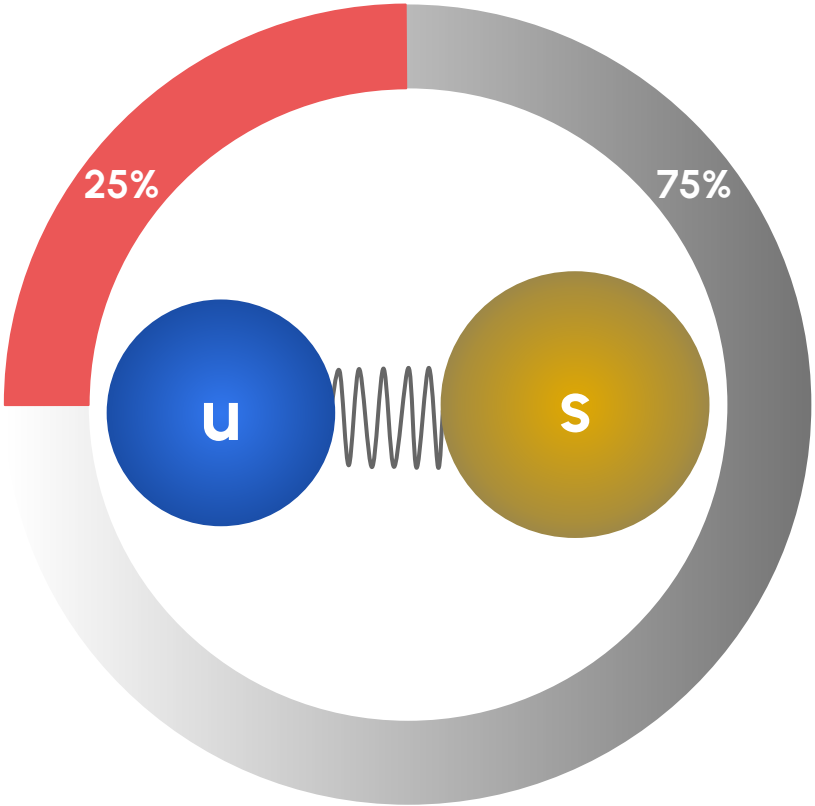
- Why kaon structure?
- **Method**: Sullivan process + Λ reconstruction at the EIC
- **Results**: projected uncertainties and constraints



Most of the kaon mass arises from QCD

Higgs mechanism
Quark masses

Kaon is the simplest
system with s-quark

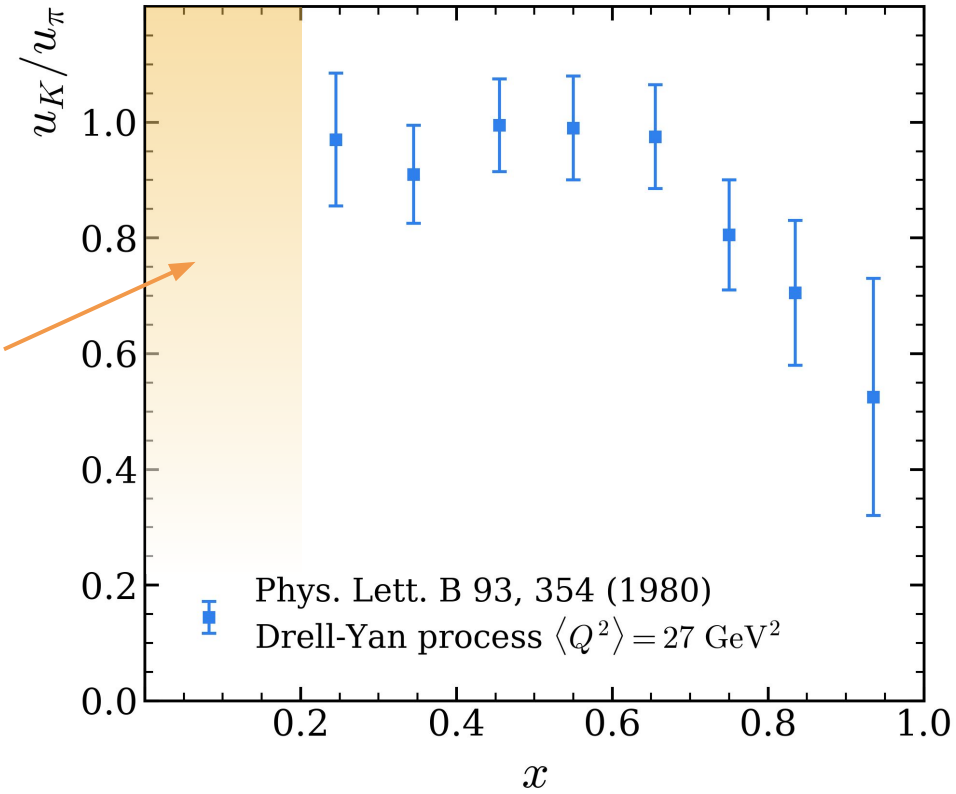


Emergent mass QCD
Quark motion, sea pairs

Crucial need for
structure function data

Current limited data on kaon structure

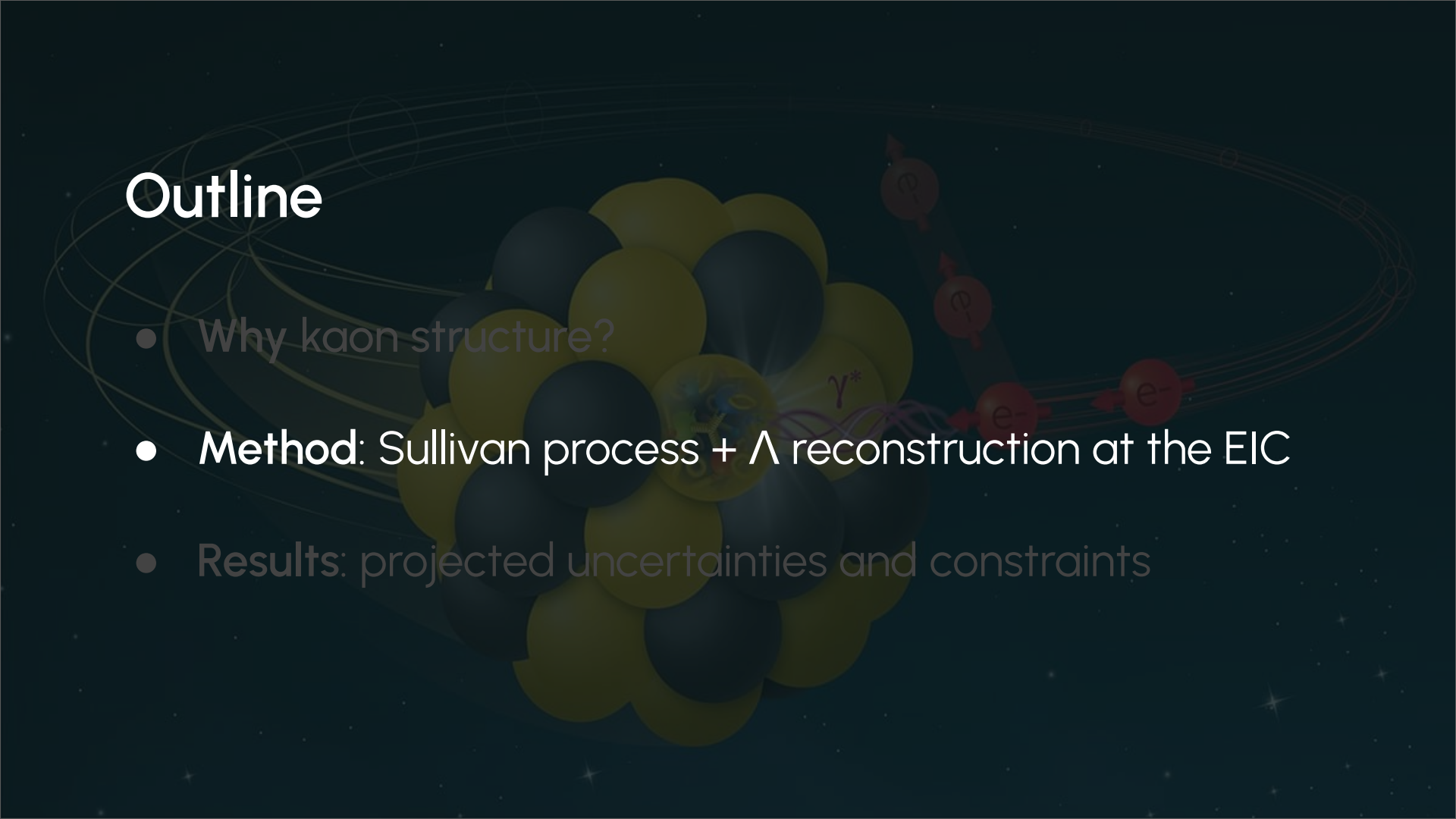
No coverage at low-x, where sea pairs dominate



Only a handful of data points, single Q^2, large uncertainties

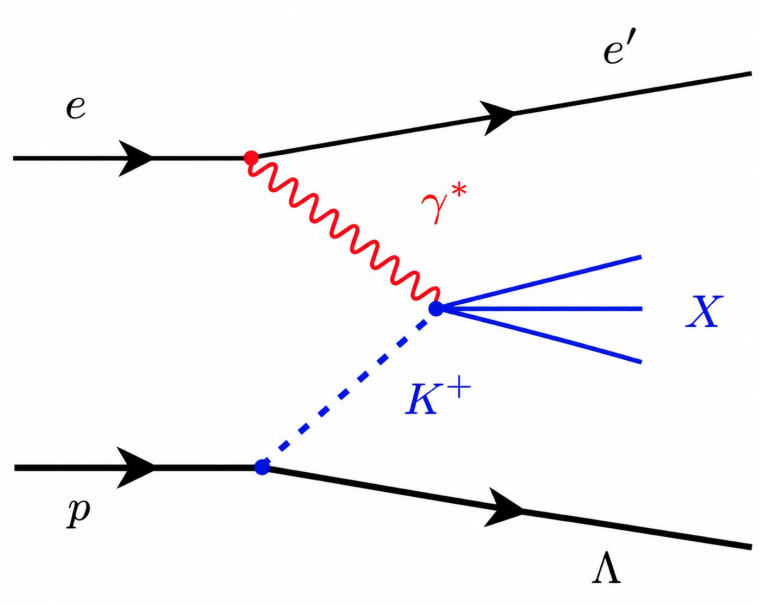
Outline

- Why kaon structure?
- **Method**: Sullivan process + Λ reconstruction at the EIC
- **Results**: projected uncertainties and constraints



Sullivan process as a probe for kaon

Electron-proton collision cross-section presents meson-pole for spacelike |-t|
Phys. Rev. C ***97*** *(2018)*



Backward electron for kinematics reconstruction

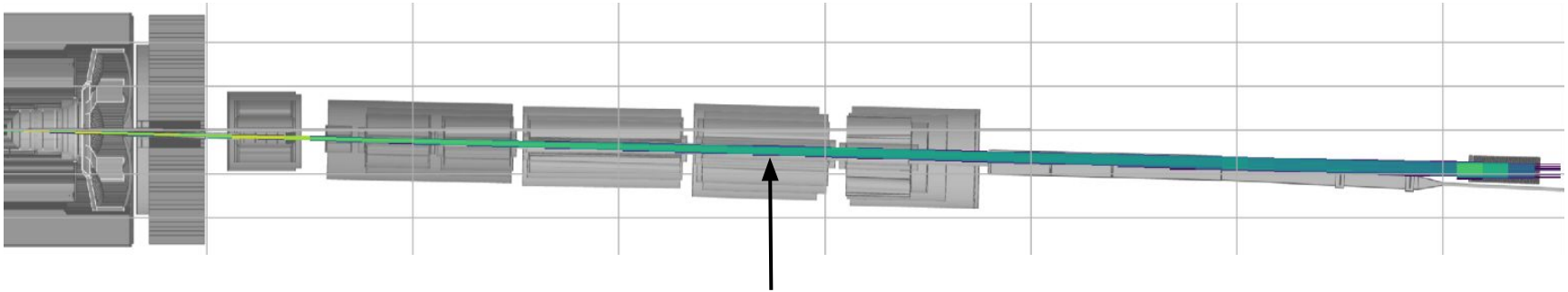
Recoil Λ hyperon for kaon structure inference

Reconstruction of Λ is challenging

Recoil Λ^0 is neutral:
looks like a neutron

Two decay channels
Charged: p + π^- (65 %)
Neutral: n + $\gamma\gamma$ (35 %)

Magnetic field distorts
charged tracks
focus on neutral channel

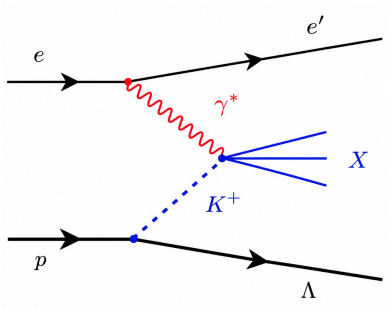


Λ decay points along ePIC setup at 18x275 GeV (tens of meters!)

Workflow for kaon structure projections at the EIC

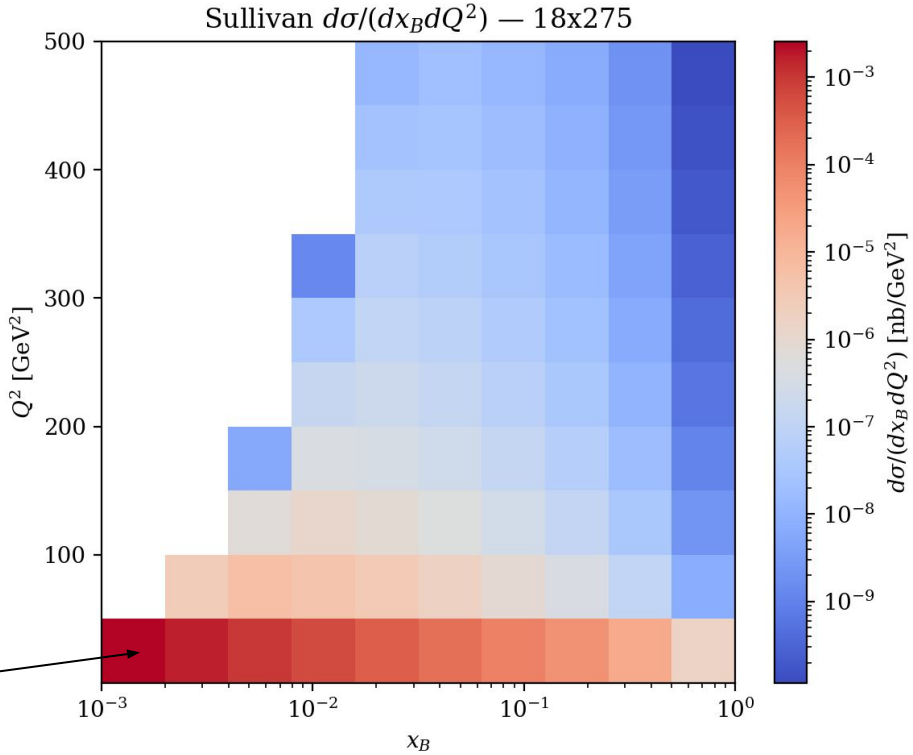
Generator

Event generator
Sullivan process



Event generator

Sullivan process
realistic model
$e + p \rightarrow e' + \Lambda^0 + K^+$



Kinematics
$0 < Q^2 < 500$ GeV^2
$0 < x_B < 1$
$|-t| < 0.4$ GeV

Higher at low x
and low Q^2

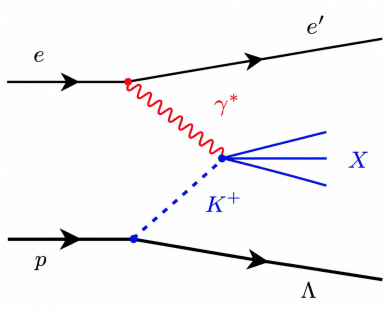
Total integrated
$\sigma \sim 0.002$ nb

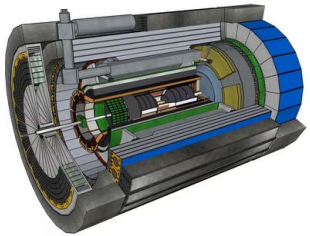
Workflow for kaon structure projections at the EIC

Generator → Simulation

Event generator
Sullivan process

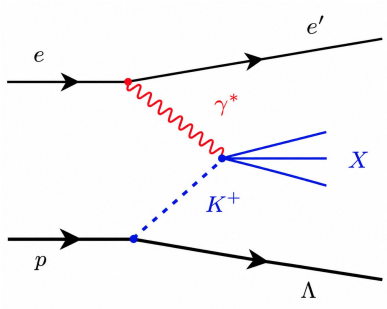
HPC campaigns
Geant4 transport ePIC

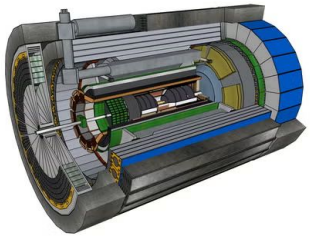


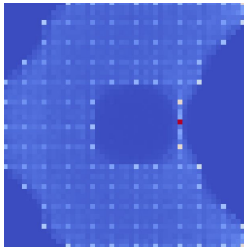


Workflow for kaon structure projections at the EIC

Generator	Simulation	Reconstruction
Event generator Sullivan process	HPC campaigns Geant4 transport ePIC	Multi-detector Λ (SIDIS) Kinematics (electron, JB)





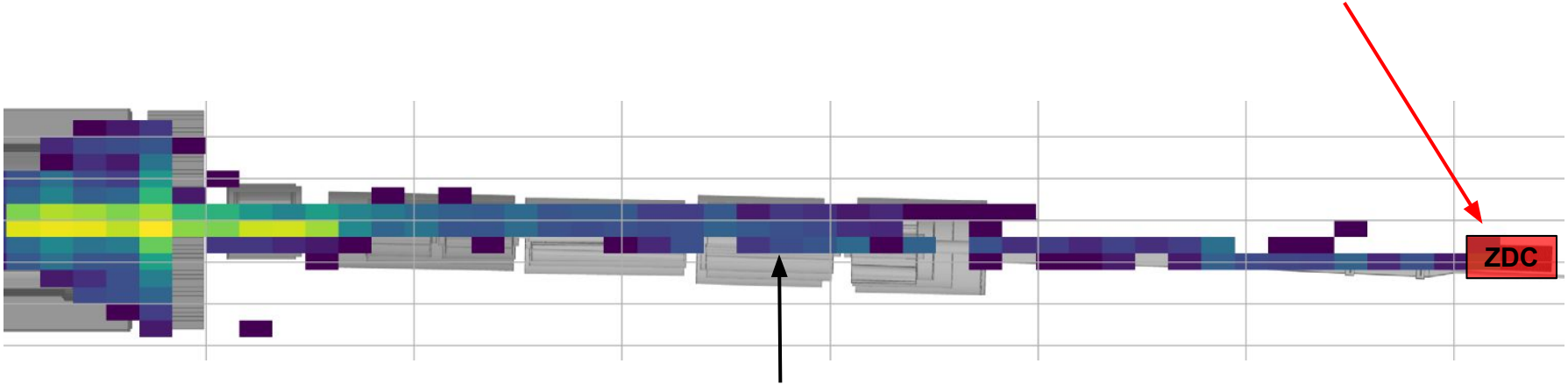


EICrecon status for Λ reconstruction

ZDC triple coincidence
n + γ + γ algorithm
S. Paul, Phys. Rev. B (2025)

Tested with Λ guns
mono-energy and
mono-angle

Near-zero acceptance
for realistic Λ (energy
angle event generator)



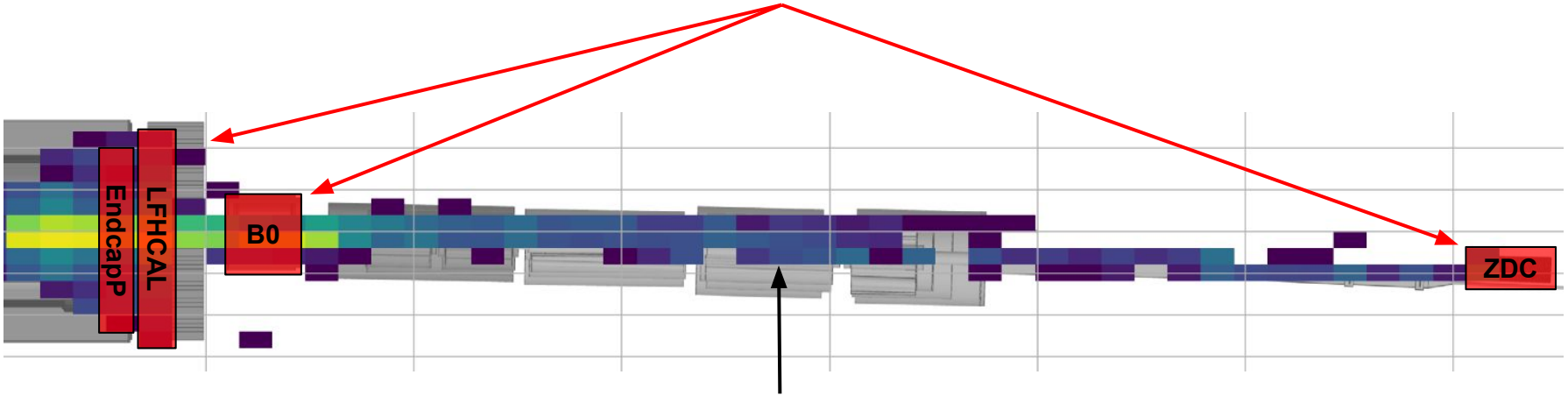
γ-rays end-points from Λ neutral decay at 18x275 GeV

EICrecon update for Λ reconstruction

Implemented algorithm
multi-detector triple coincidence n + γ + γ

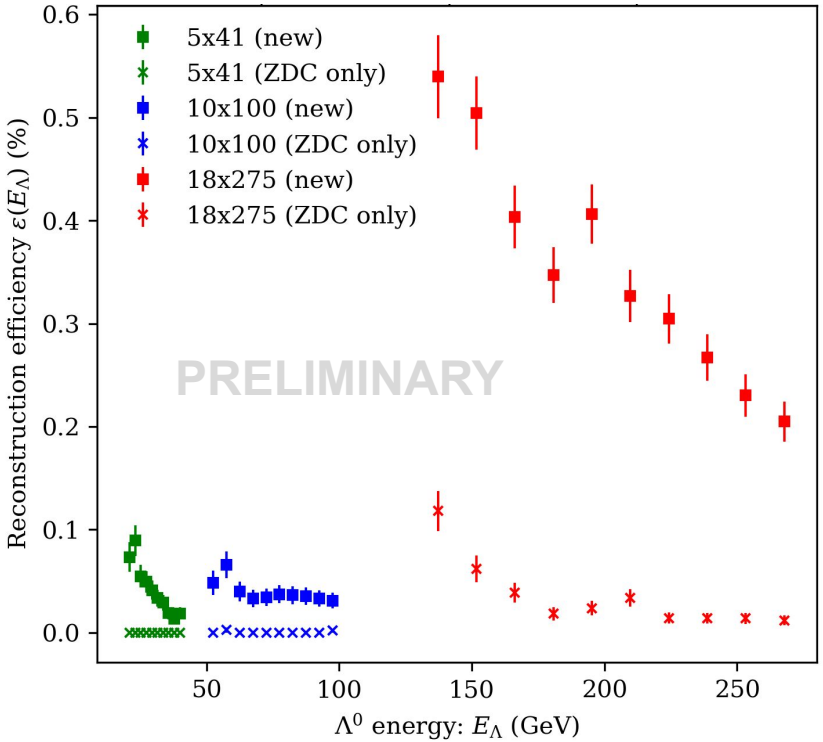
Involved detectors
EndcapP-Ecal, LFHCAL, B0-Ecal, ZDC-Hcal

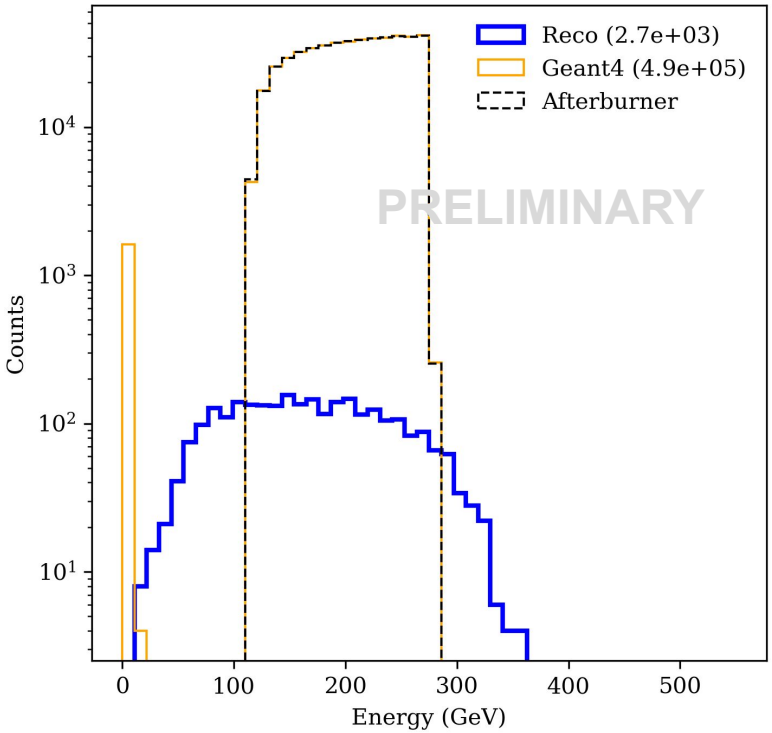
Improved acceptance for realistic Λ (energy angle event generator)



γ-rays end-points from Λ neutral decay at 18x275 GeV

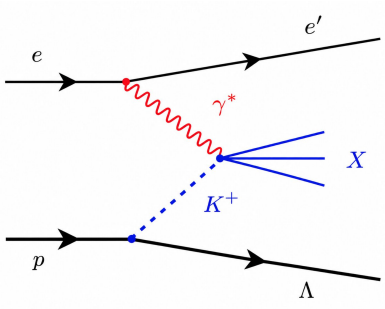
EICrecon results for Λ reconstruction

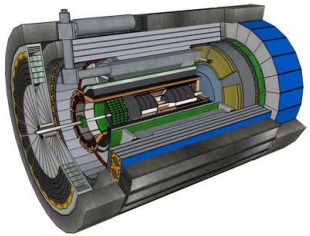


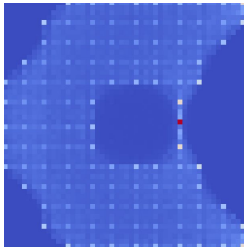


Workflow for kaon structure projections at the EIC

Generator	Simulation	Reconstruction	Uncertainty
Event generator Sullivan process	HPC campaigns Geant4 transport ePIC	Multi-detector Λ (SIDIS) Kinematics (electron, JB)	Statistical ΔN Detectors $\Delta\varepsilon$ Generator $\Delta\sigma$ Background Kinematics bias



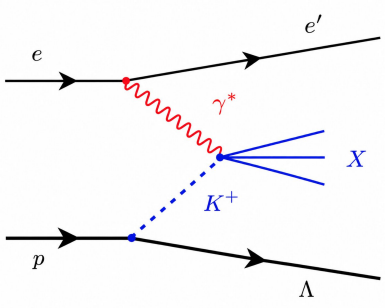


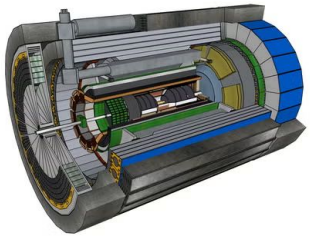


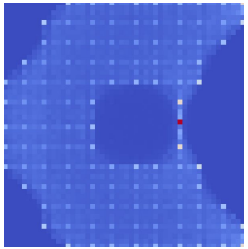
$$u_c(y_i) = \sqrt{\sum_{i=1}^{n} \left[\frac{\delta y_i}{\delta x_i} \cdot u(x_i)\right]^2}$$

Workflow for kaon structure projections at the EIC

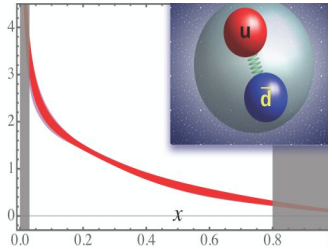
Generator	Simulation	Reconstruction	Uncertainty	Physics
Event generator Sullivan process	HPC campaigns Geant4 transport ePIC	Multi-detector Λ (SIDIS) Kinematics (electron, JB)	Statistical ΔN Detectors $\Delta\varepsilon$ Generator $\Delta\sigma$ Background Kinematics bias	Constraining power kaon structure models



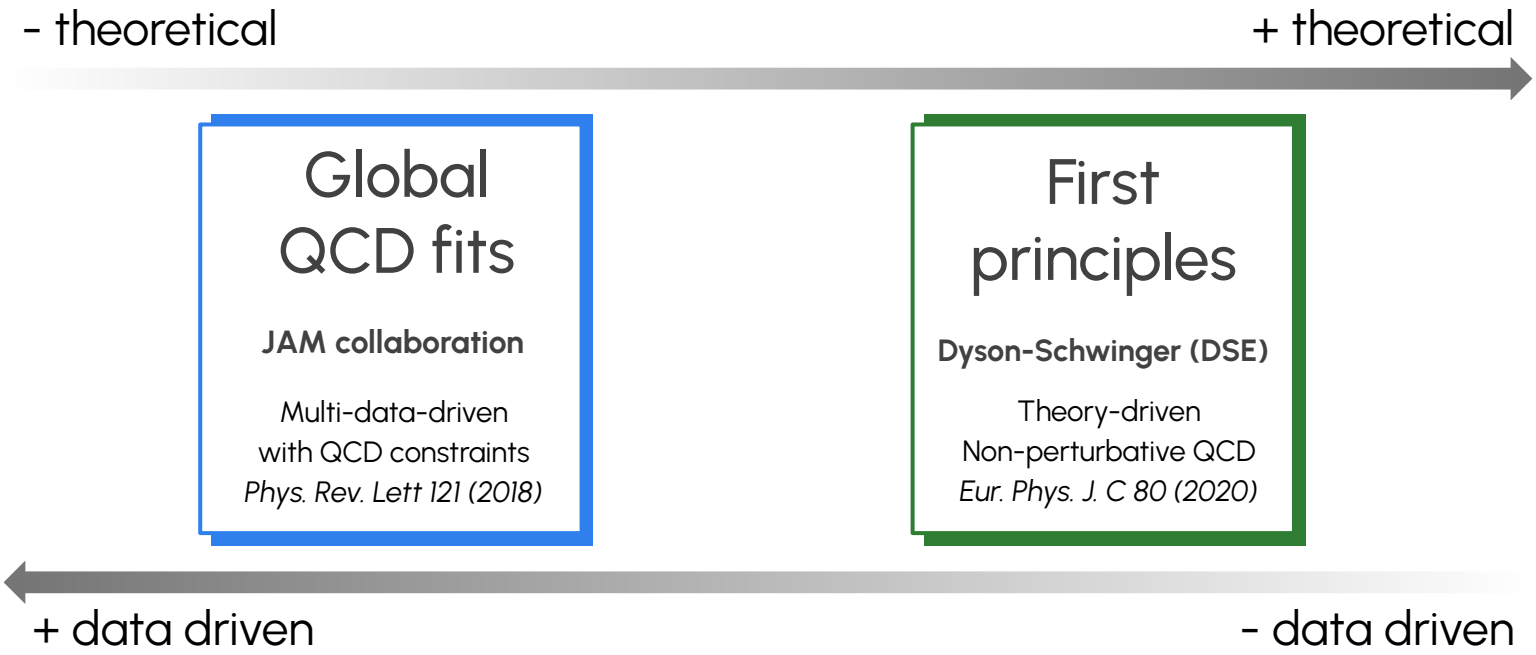




$$u_c(y_i) = \sqrt{\sum_{i=1}^{n} \left[\frac{\delta y_i}{\delta x_i} \cdot u(x_i)\right]^2}$$



Kaon structure models benchmark

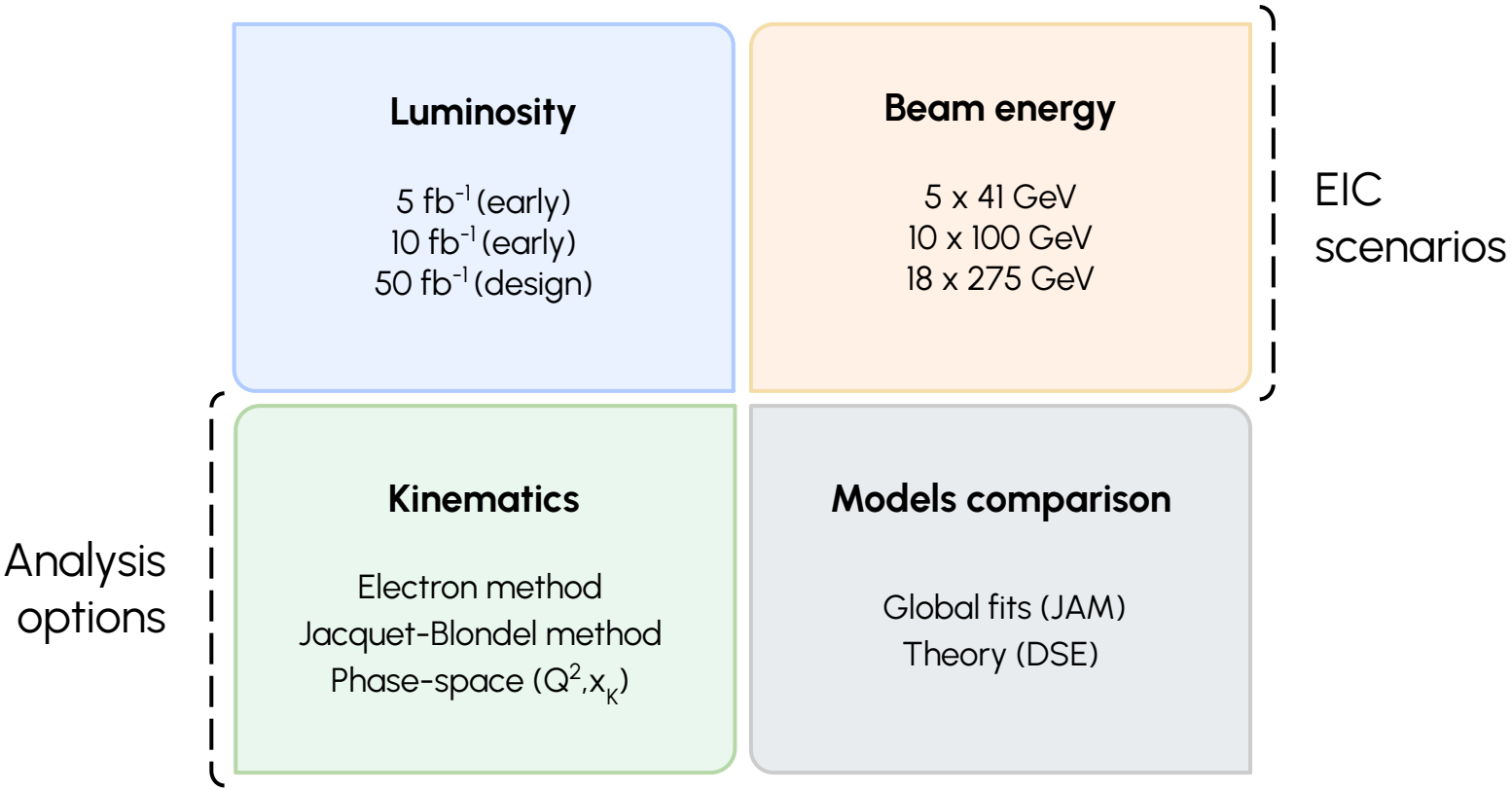


Different assumptions ⇨ different predictions for kaon structure

Outline

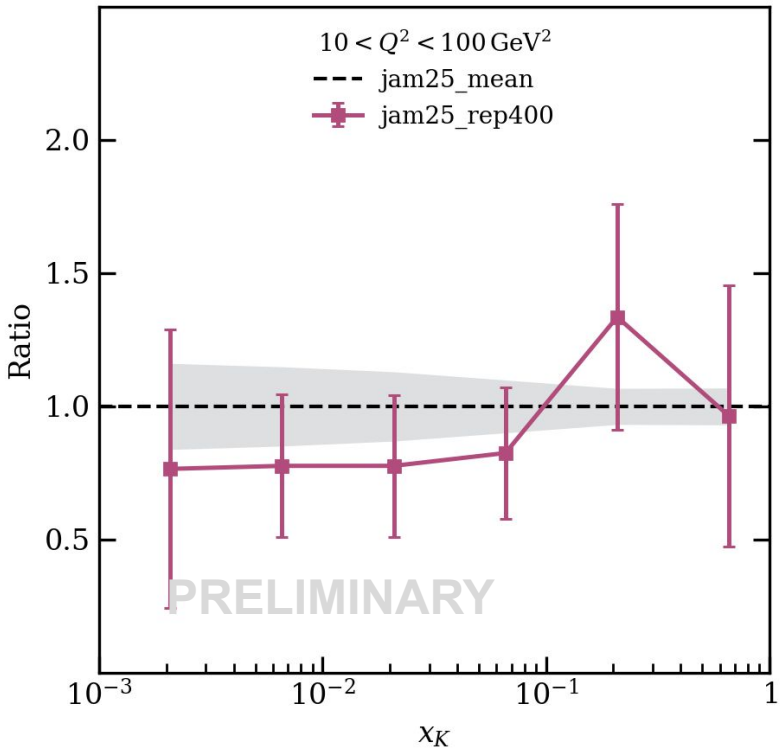
- **Why** kaon structure?
- **Method**: Sullivan process + Λ reconstruction
- **Results**: projected constraints at the EIC

Scope of the study

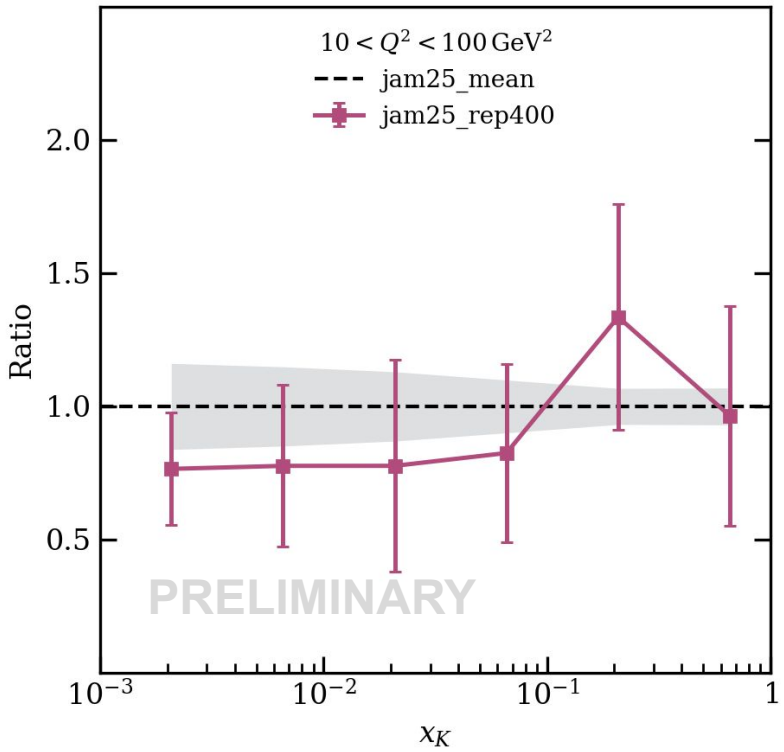


Constraining JAM global fit : example for one replica

18x275 GeV | 5.0 fb^{-1} | Electron kinematics

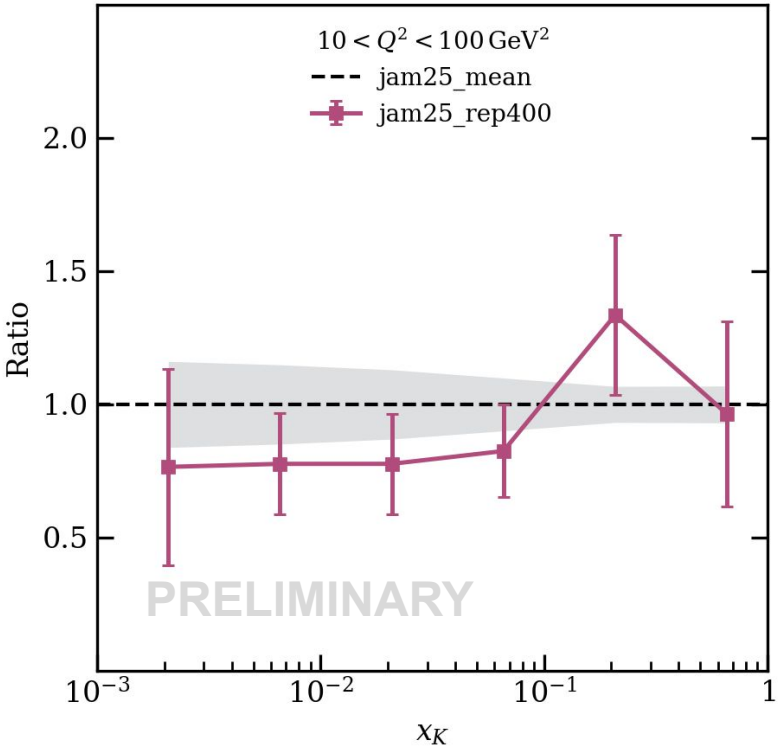


18x275 GeV | 5.0 fb^{-1} | JB kinematics

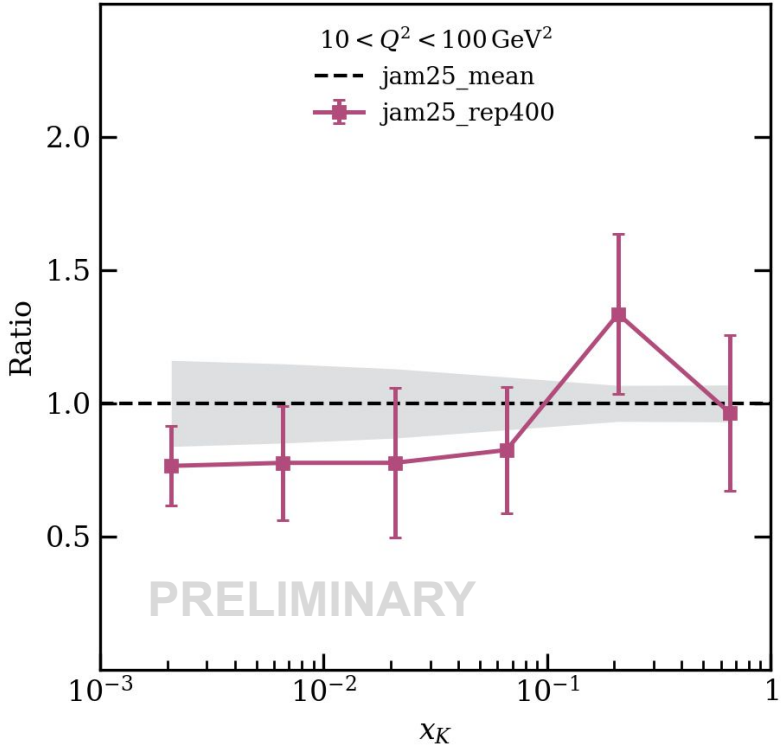


Constraining JAM global fit : example for one replica

18x275 GeV | 10.0 fb^{-1} | Electron kinematics

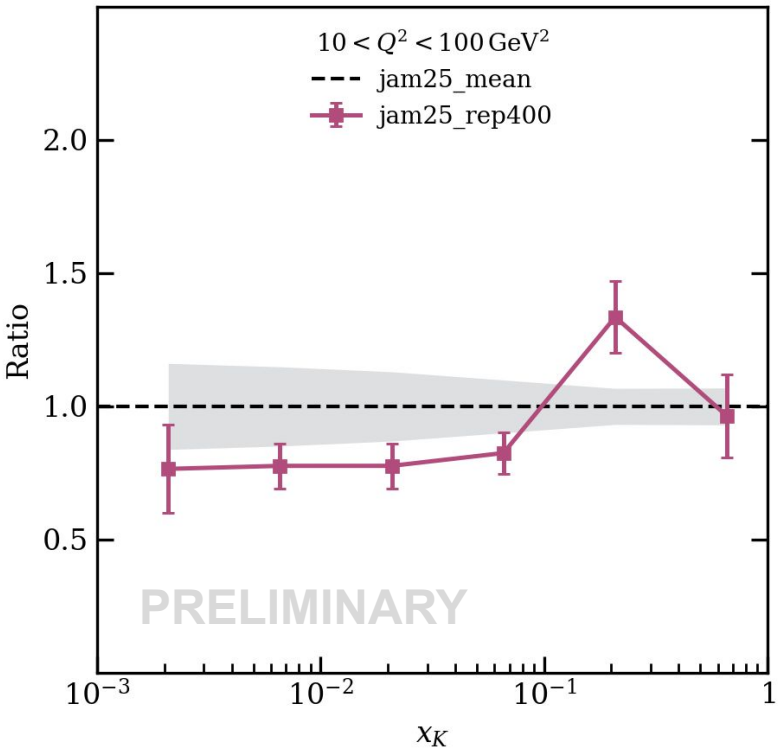


18x275 GeV | 10.0 fb^{-1} | JB kinematics

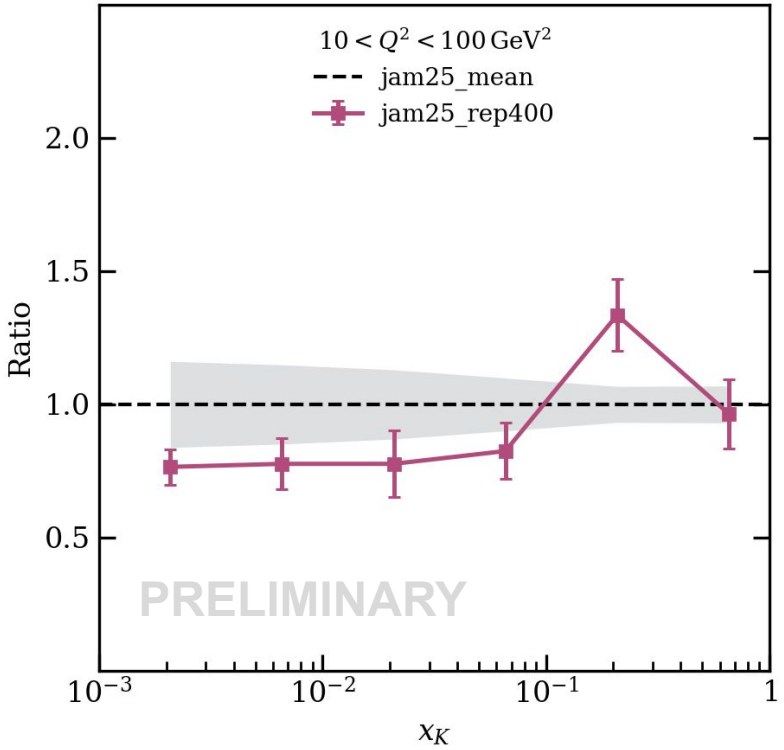


Constraining JAM global fit : example for one replica

18x275 GeV | 50.0 fb^{-1} | Electron kinematics

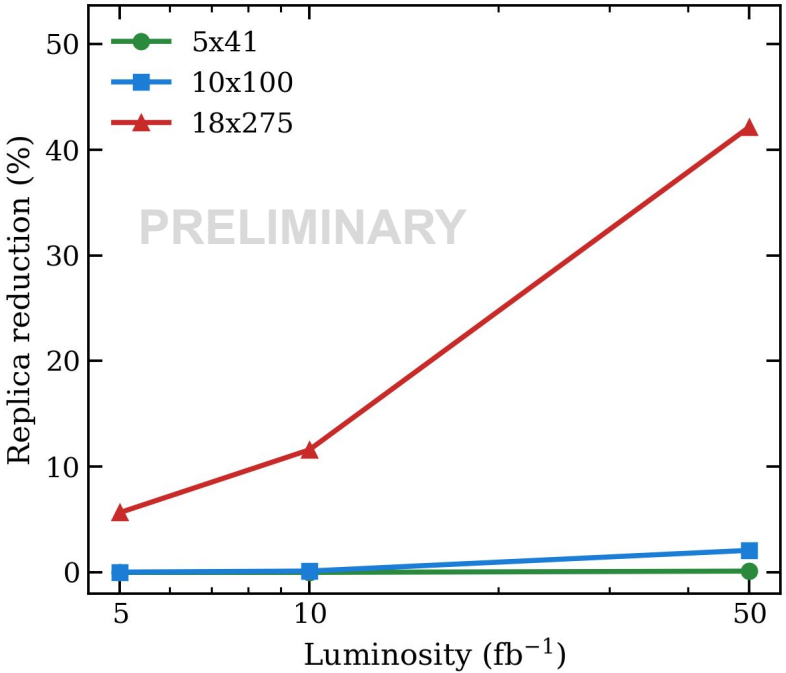


18x275 GeV | 50.0 fb^{-1} | JB kinematics

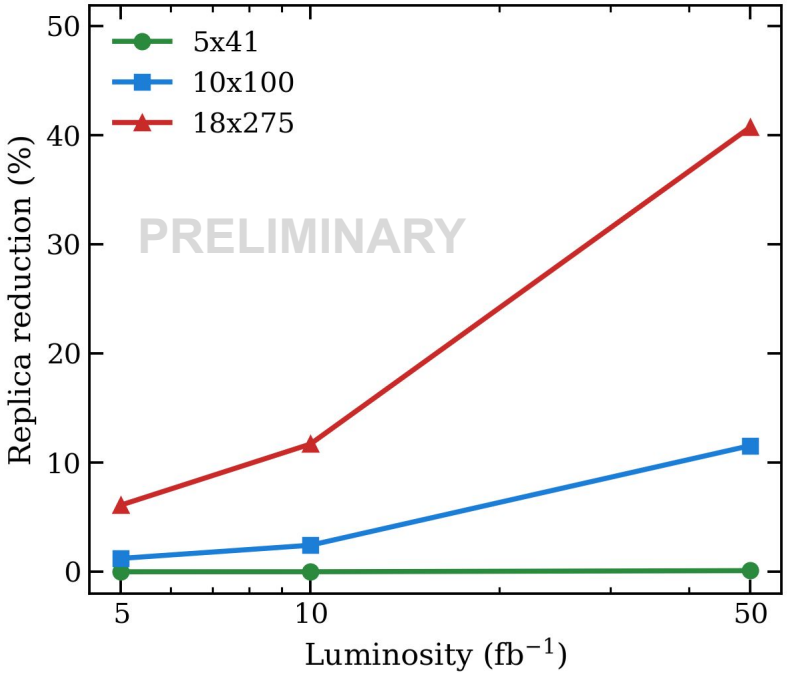


Constraining JAM fit : global study

Q^2 = 10–100 GeV^2 | Electron kinematics

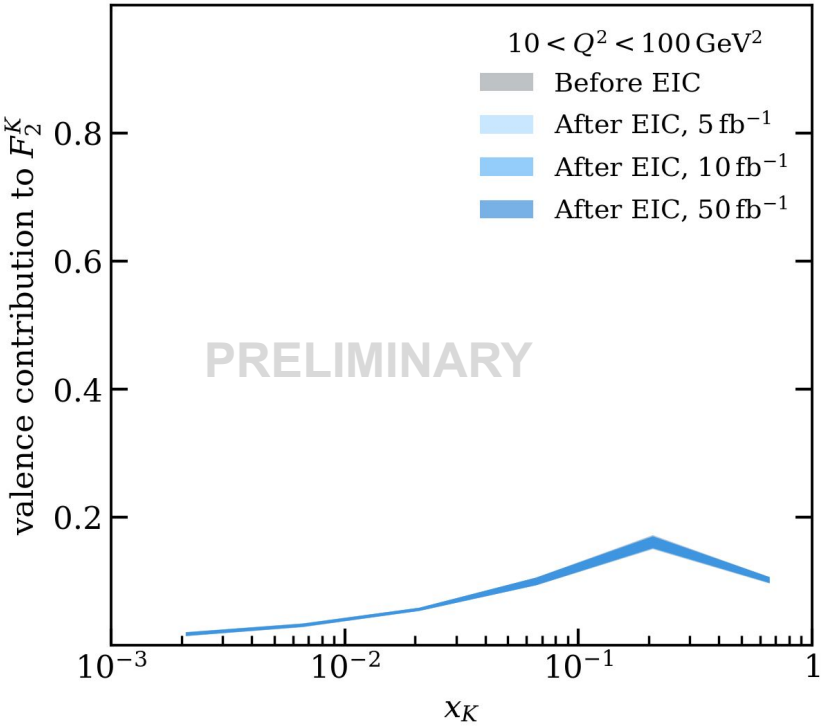


Q^2 = 10–100 GeV^2 | JB kinematics

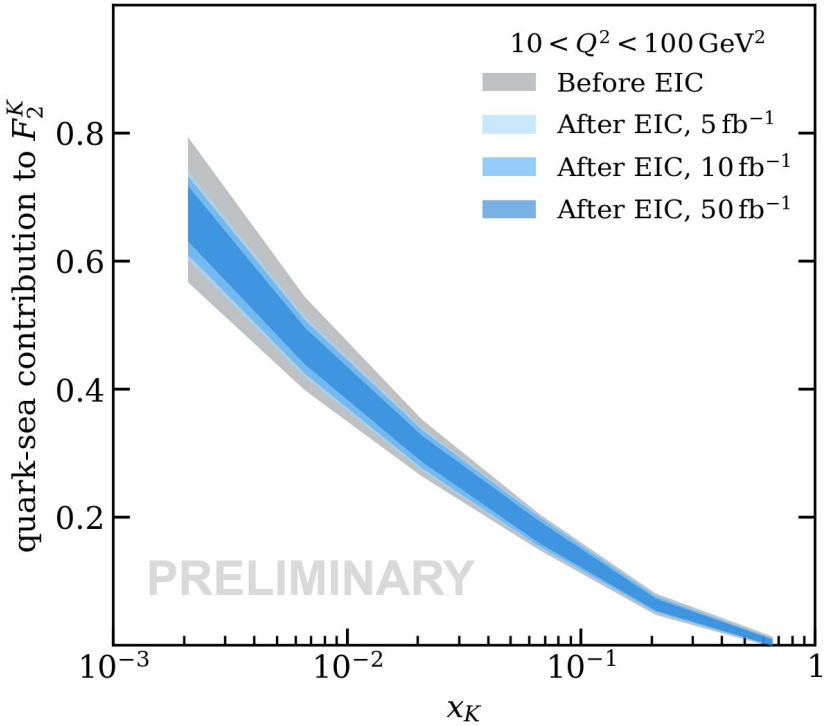


Constraining JAM global fit : global study

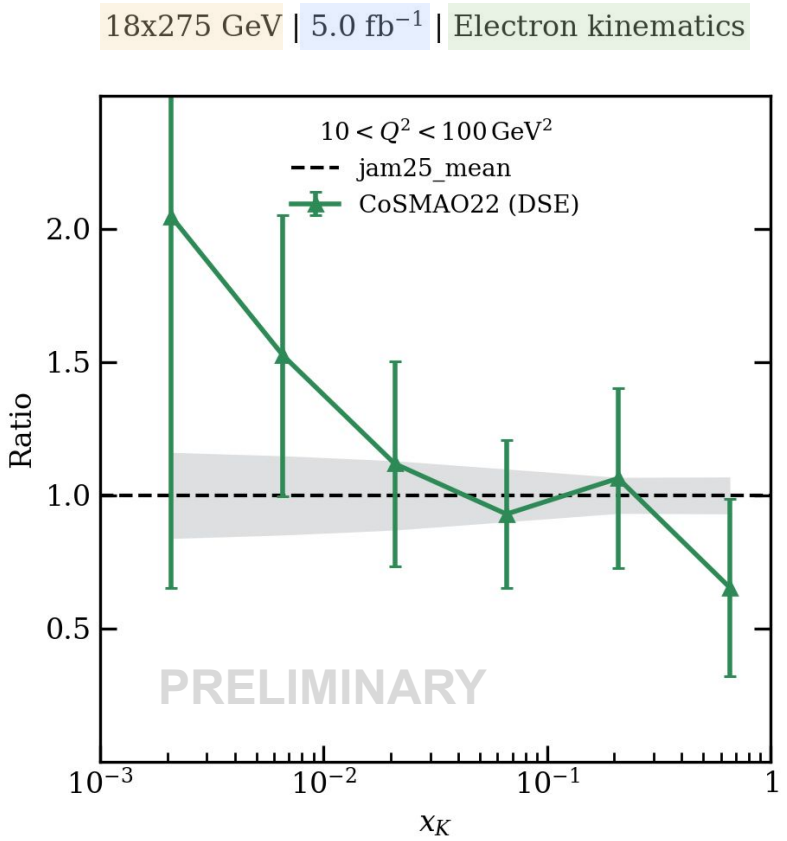
Valence F2K | 18x275 GeV | Electron kinematics

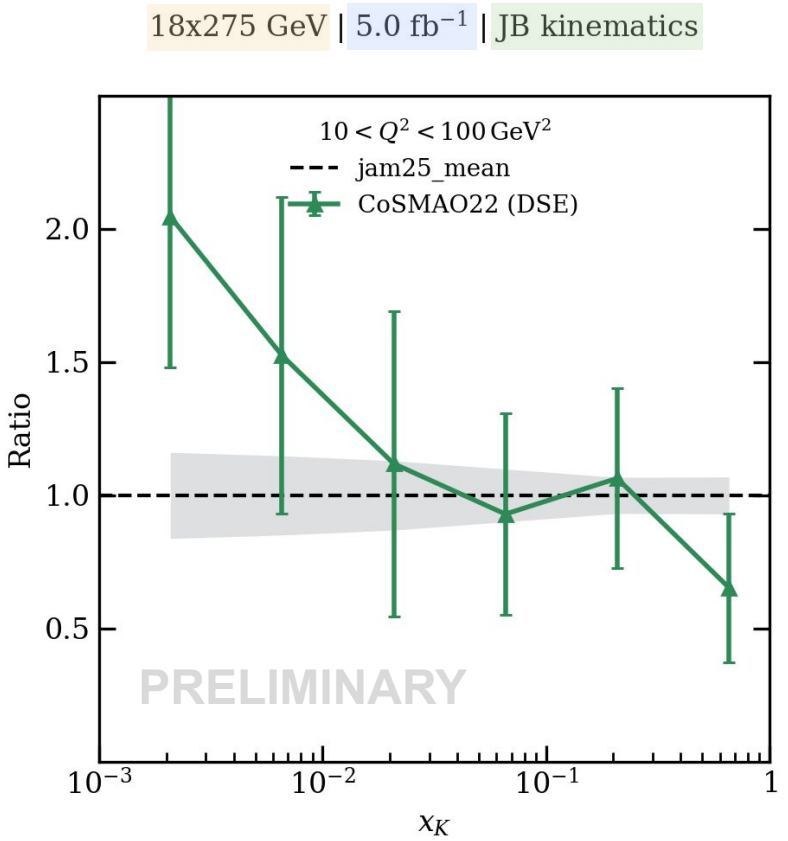


Quark-sea | 18x275 GeV | Electron kinematics

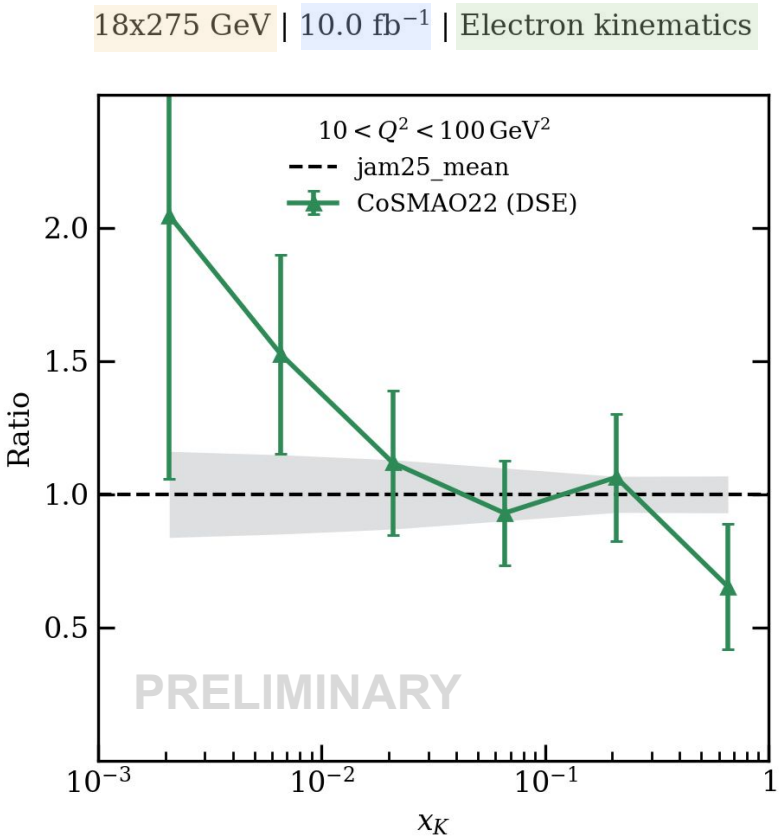


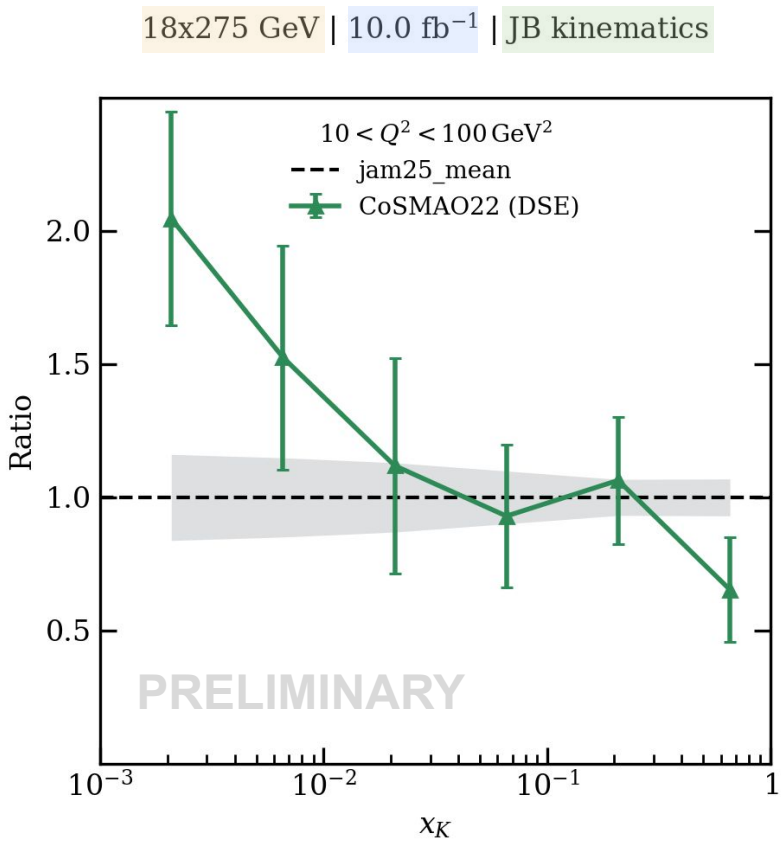
Discriminating JAM and theoretical calculations (DSE)



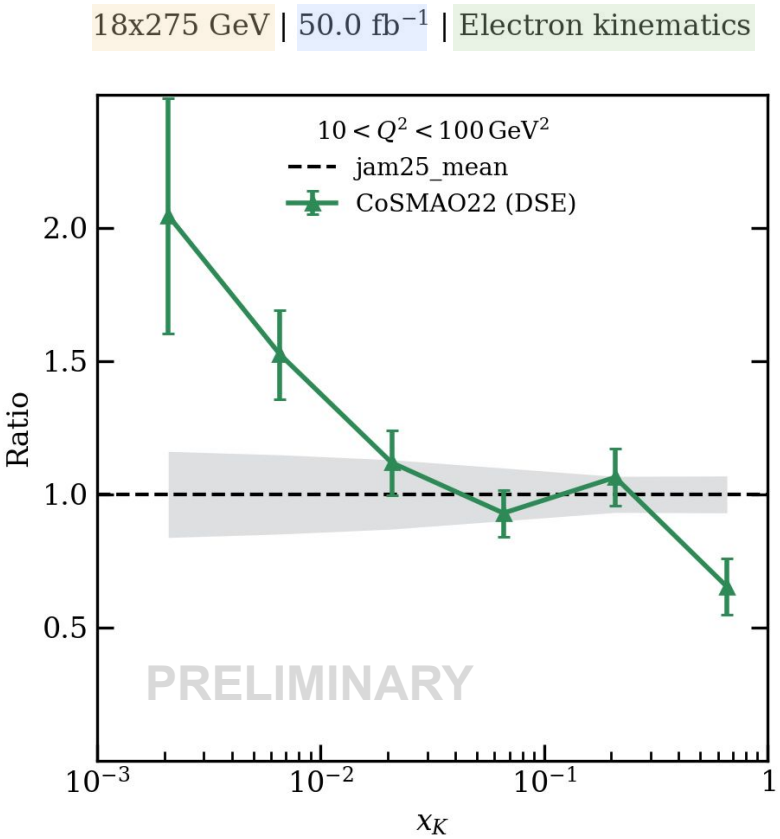


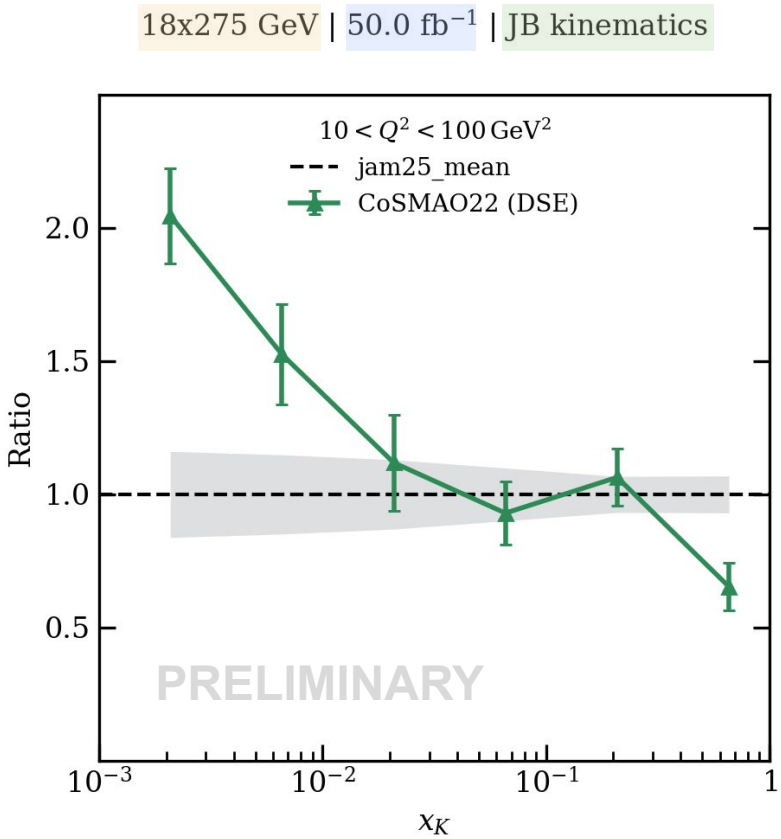
Discriminating JAM and theoretical calculations (DSE)





Discriminating JAM and theoretical calculations (DSE)





Conclusion

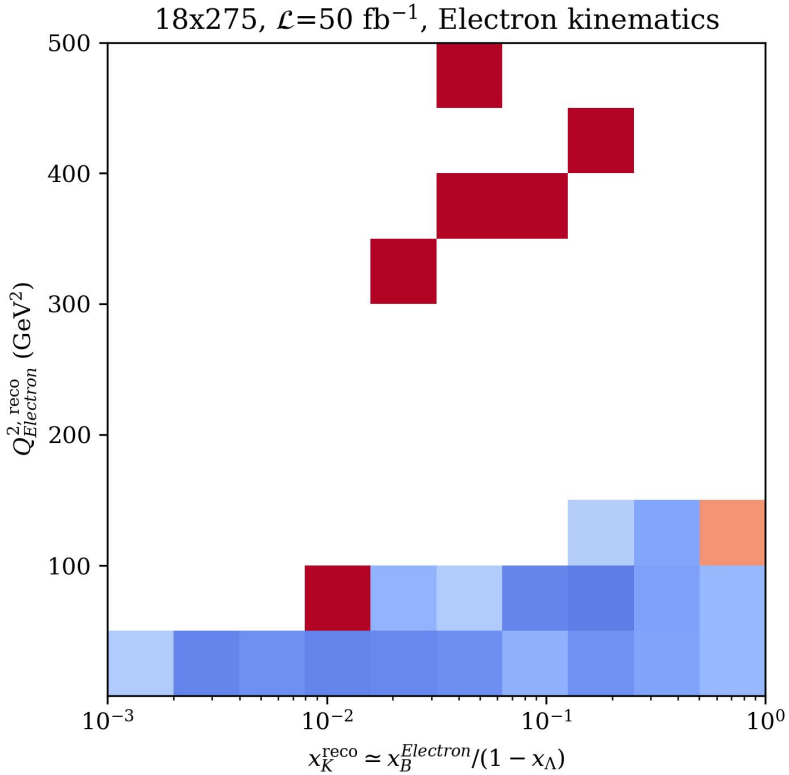
Kaon structure model constraints at the EIC

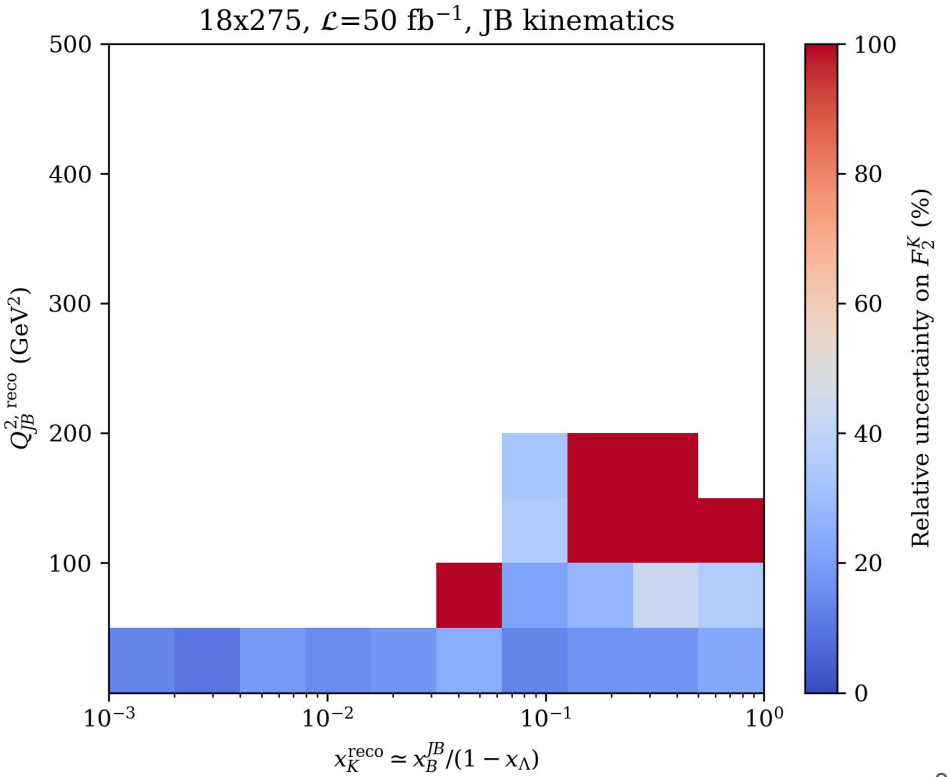
Scenarios	5 fb^{-1}	10 fb^{-1}	50 fb^{-1}
5x41 GeV	Limited	Limited	Limited
10x100 GeV	Limited	Limited	Moderate JAM-DSE discri: $x_K \sim 10^{-3}$-10^{-2} JAM replicas: ~5%
18x275 GeV	Limited	Strong JAM-DSE discri: $x_K \sim 10^{-2}$ JAM replicas: ~10%	Very strong JAM-DSE discri: $x_K \sim 10^{-3}$-10^{0} JAM replicas: ~40%

Early science

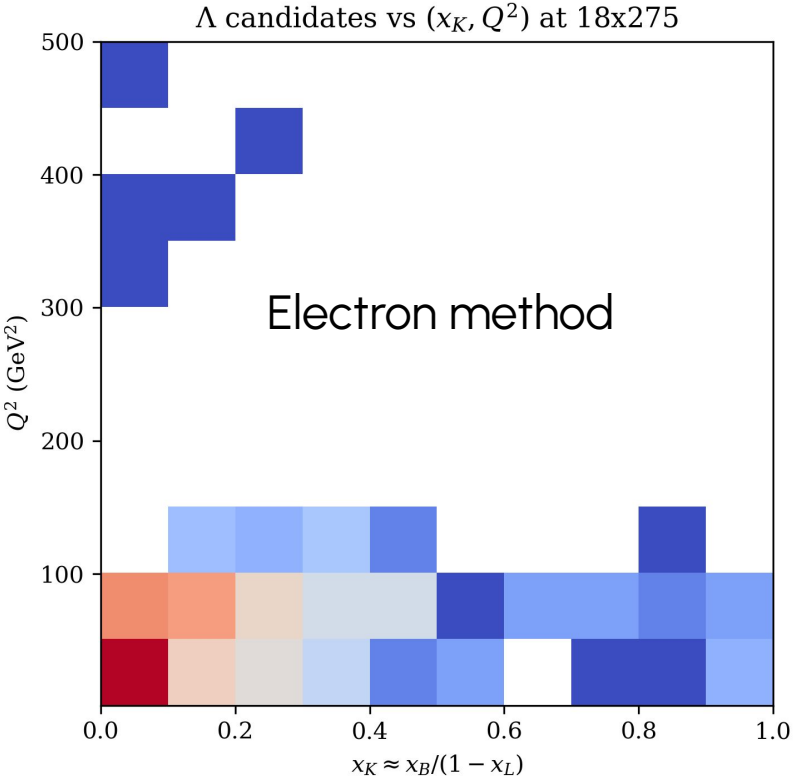
Backups

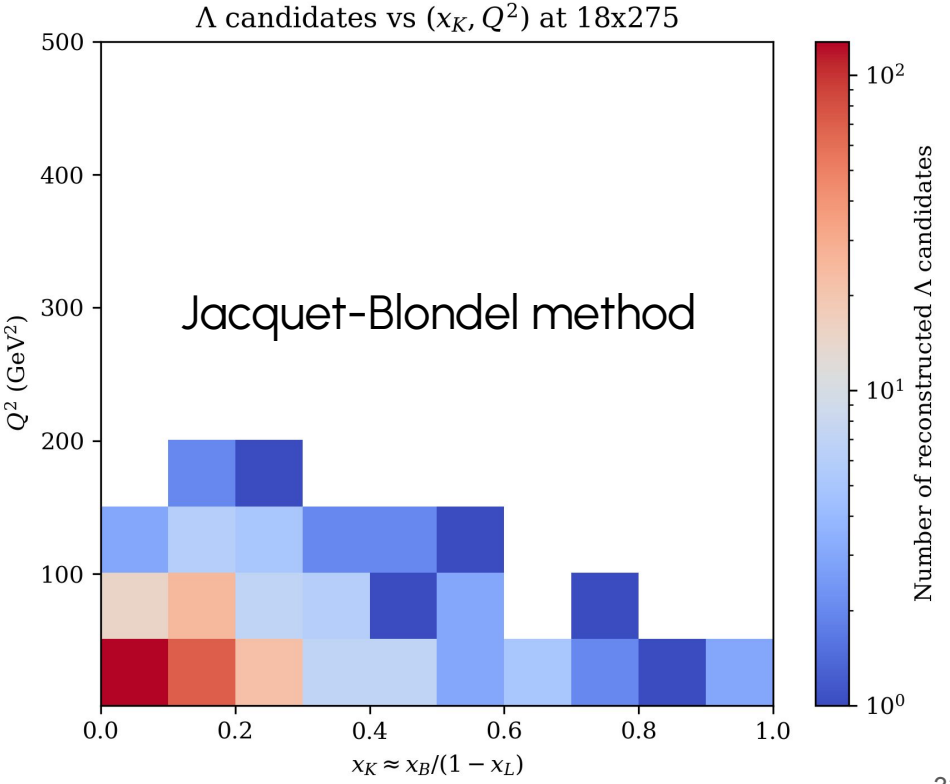
Uncertainty quantification



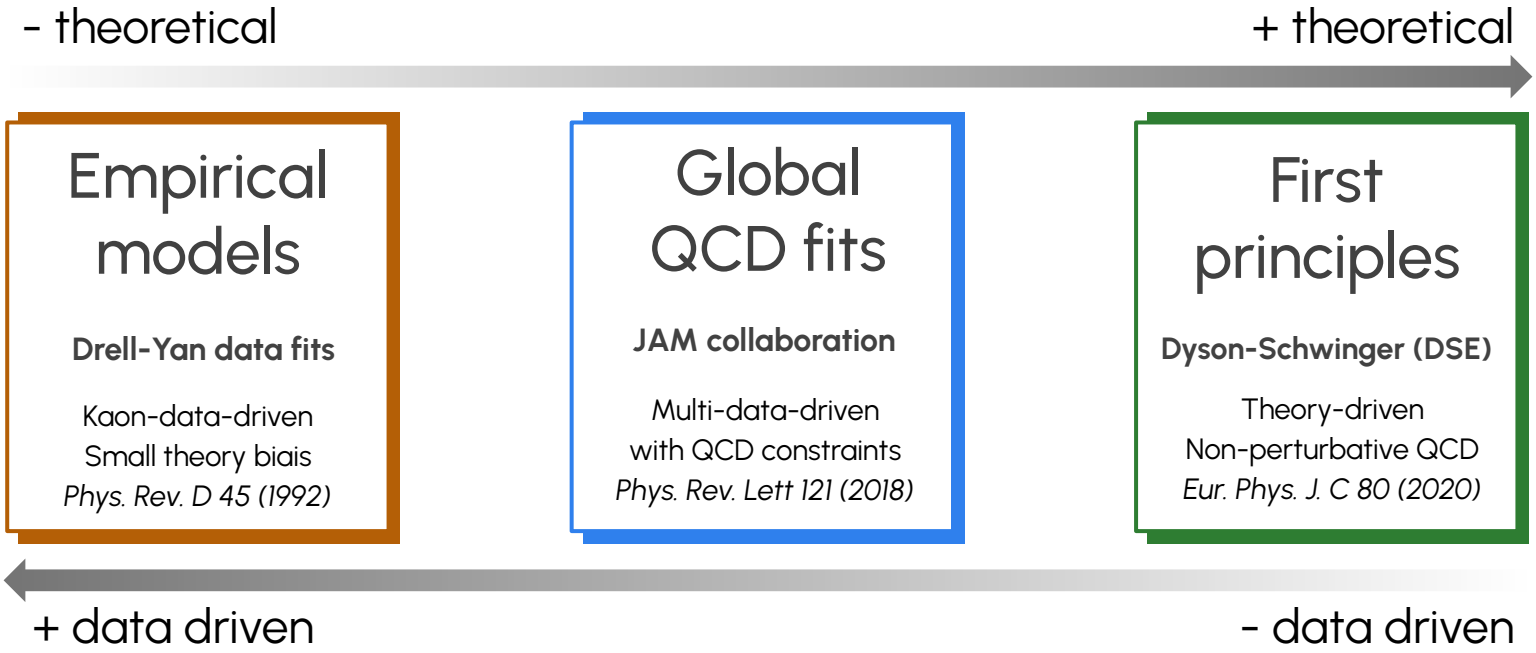


Kinematics reconstruction results





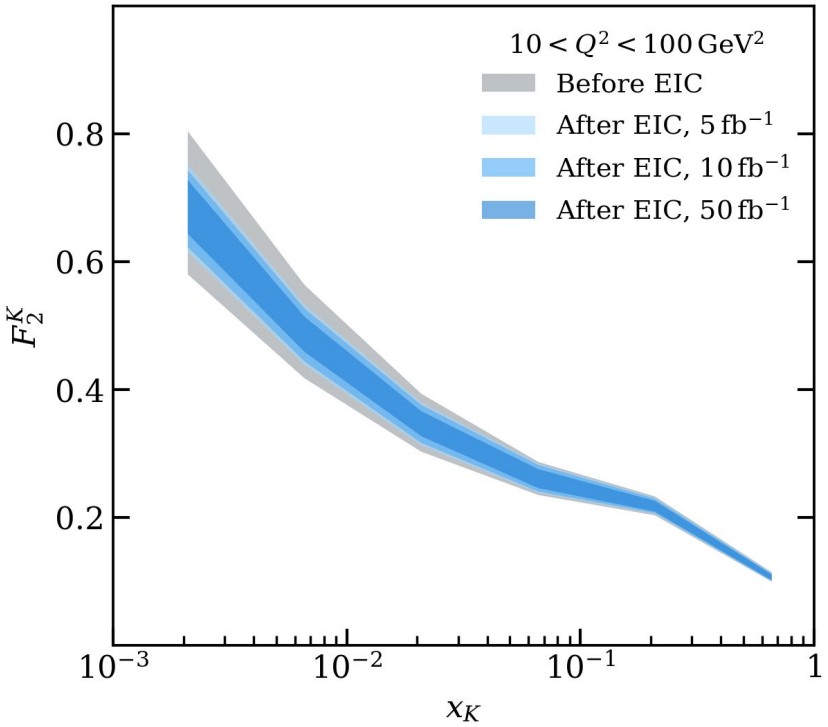
Kaon structure models benchmark



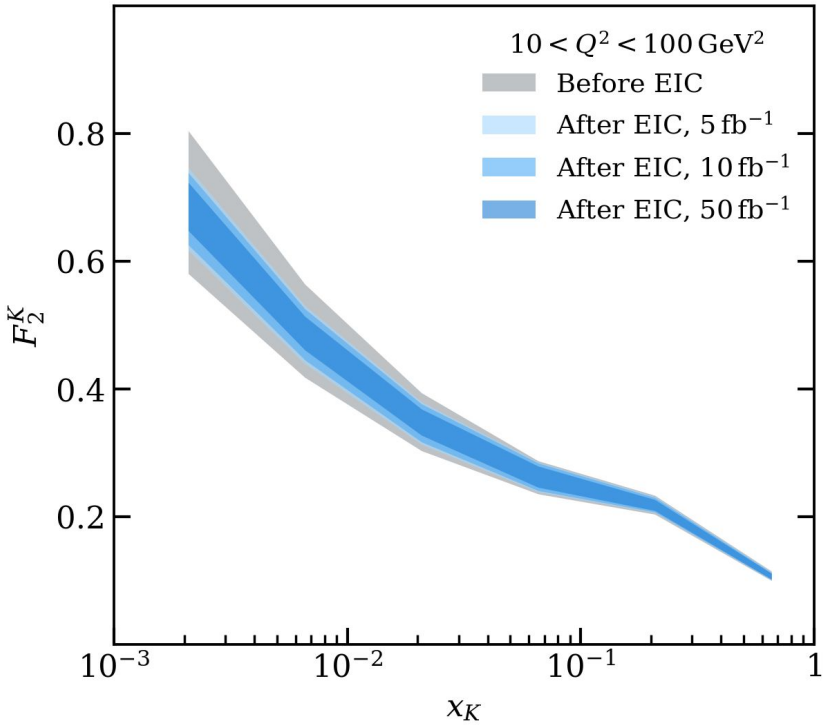
Different assumptions ⇨ different predictions for kaon structure

Constraining JAM global fit : global study

Total F2K | 18x275 GeV | Electron kinematics



Total F2K | 18x275 GeV | JB kinematics



Constraining JAM global fit : global study

Set of "*replicas*" : kaon structure functions compatible with experimental data

$$\mathrm{JAM} = \{F_i\}$$

Projected pseudo-data at the EIC for a given luminosity (L)

$$F_{truth} \pm \sigma_{EIC,L}$$

Reweighting the replicas (w_i) to reflect a global fit approach

$$w_i \propto \exp(-\chi_i^2/2) \text{ where } \chi_i^2 = \int (F_{truth}-F_i)^2/\sigma^2_{EIC,L}$$

New effective number of replicas

$$N_{eff} = \exp[-w_i \sum \log(w_i)]$$

Outlooks

- Boost Λ^0 reconstruction through charged decay channel ($p+\pi^-$)
- Improve predictions with more simulations (currently 500k events)
- Motivation for post-early-science EIC configurations ($L > 10\ fb^{-1}$)