

Feasibility of pion and kaon structure function measurements at the EIC using the Sullivan process

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Outline

- Pion and kaon structure: interest and background
- Simulation chain: from event generation to reconstruction
- Results: Projected uncertainties and model constraints

Outline

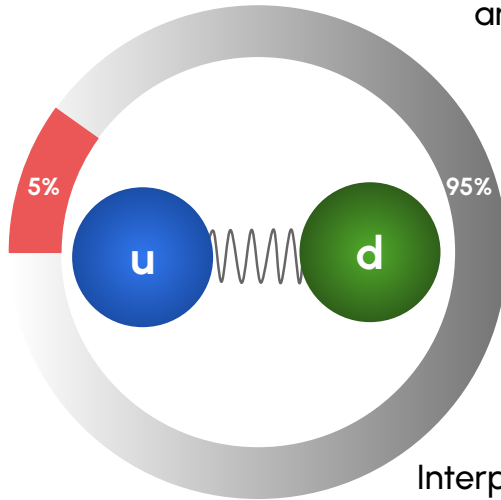
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Physics Background: Pions and Kaons are vital to understand Hadron Structure

Pions and kaons allow us to understand the interplay between different mass generation mechanisms

Pion (π^+)

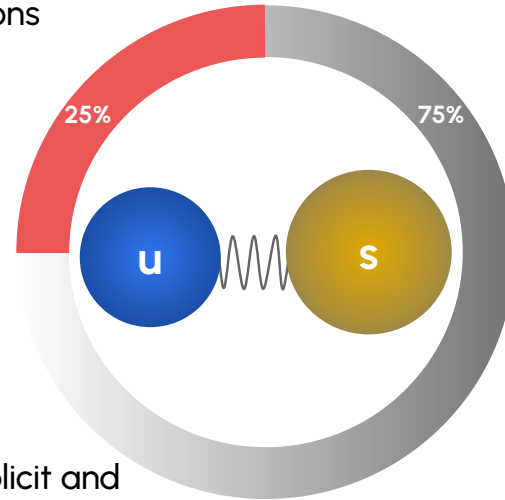
Higgs mechanism
Quark masses are insufficient to explain the mass



Pseudo-Goldstone bosons
and simplest hadrons

Kaon (K^+)

Emergent mass
and interference
with Higgs



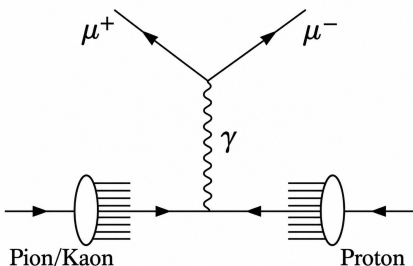
Interplay between explicit and
dynamical **symmetry breaking**

Probing the meson structure: experimental considerations

Drell-Yan process [1]

Sensitive to valence quarks
Nuclear effects (target)

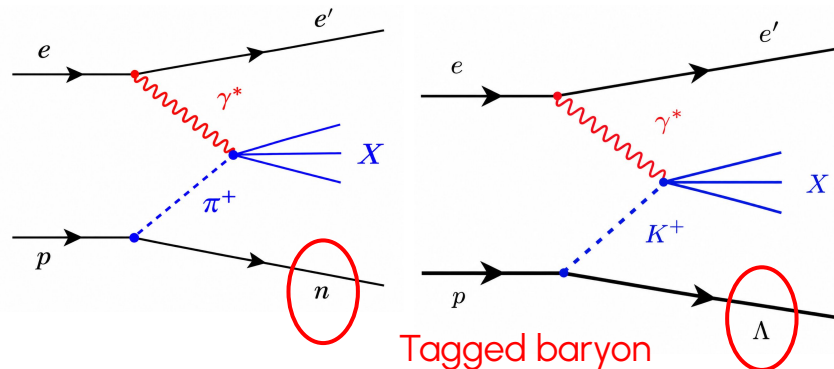
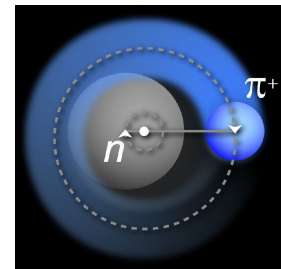
Meson quark annihilates with
proton quark from target nuclei
Lepton pair detection



[1] Drell, Yan, Phys. Rev. Lett. **25** (1970)

Sullivan process [2]

Diffusion off meson cloud
Demonstrated @ HERA
Reliable surrogate: small- t [3]



[2] J. D. Sullivan, Phys. Rev. D **5**, 1732–1737 (1972)

[3] S. X. Qin, Phys. Rev. C **97** (2018)

Available and future experimental data

Pions experiments

Drell-Yan: NA3, NA10 (CERN), E615 (Fermilab)

Sullivan process: H1, ZEUS (HERA/DESY)

Experiment	Target	Beam	DY events
NA3	Pt	$\pi^\pm$, 200 GeV	6700
NA3	Pt	$K^\pm$, 200 GeV	700
NA10	W	π^- , 140–286 GeV	200000
NA10	D ₂	π^- , 286 GeV	7800
E615	W	$\pi^\pm$, 252 GeV	35000
COMPASS	NH ₃	π^- , 190 GeV	87000

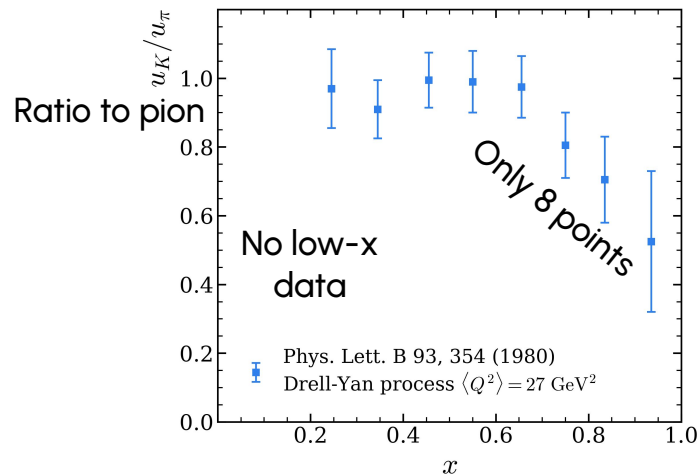
Contradictory results NA3 vs NA10

Kaon is a ratio to pion (additional uncertainty)

Need for more data !

Kaons experiments

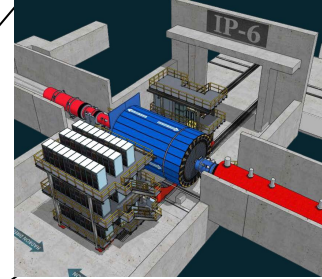
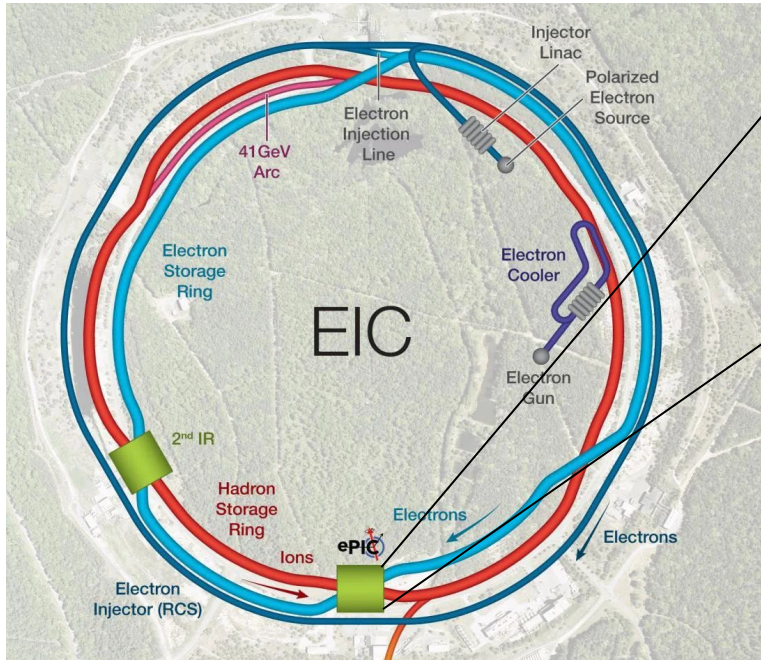
Drell-Yan: NA3 (CERN)



Future experiments

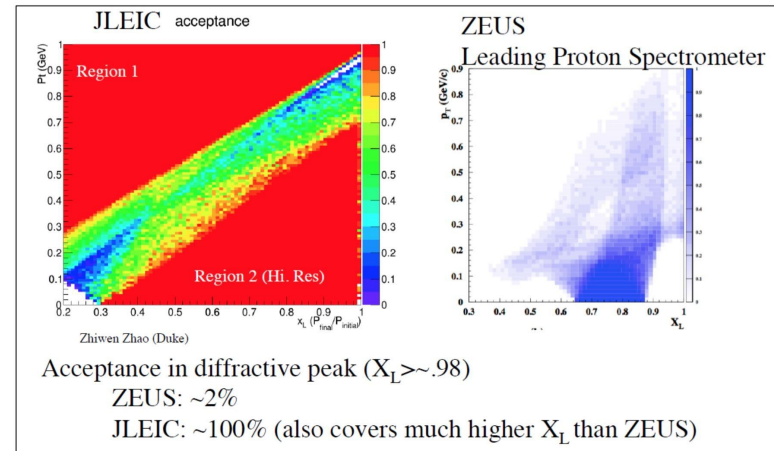
- AMBER @ CERN (Drell-Yan process)
- TDIS @ JLab (Sullivan process, feasibility test)
- **EIC/ePIC (Sullivan process)**

The Electron-Ion Collider (EIC) and ePIC detector*



Early science program ($1\text{--}10\text{ fb}^{-1}$)
 Full design luminosity (100 fb^{-1})
 Huge acceptance gain vs. HERA
Suited for Sullivan process!

Example: acceptance for p' in $e + p \rightarrow e' + p' + X$



*Science Requirements and Detector Concepts for the EIC:
 Yellow Report, *Nuclear Physics A* **1026**, 122447 (2022).

Outline

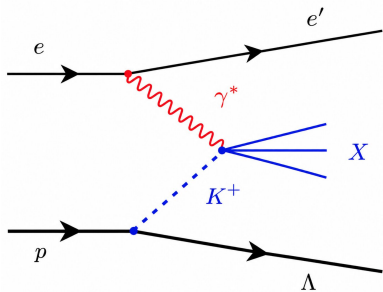
- Pion and kaon structure: interest and background
- **Simulation chain: from event generation to reconstruction**
- Results: Projected uncertainties and model constraints

Meson structure function WG : a full simulation chain implemented for future measurements at the EIC [1]



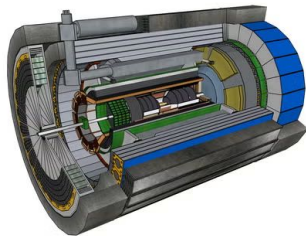
Generator

SURGE : a dedicated event generator for the Sullivan process at the EIC beam energies [2]



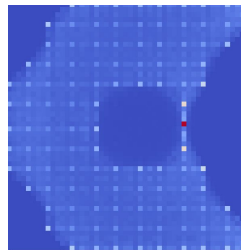
Simulation

HPC simulation campaigns using Geant4 transport for EIC/ePIC



Reconstruction

Specific forward baryon tagging and reconstruction using EICrecon [3]



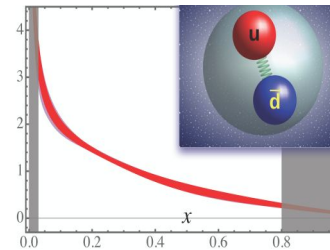
Uncertainties

Statistical ΔN
Detectors $\Delta \epsilon$
Machine background
Physics background

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

Physics

Constraining power on global fit approaches and discriminating theoretical calculations



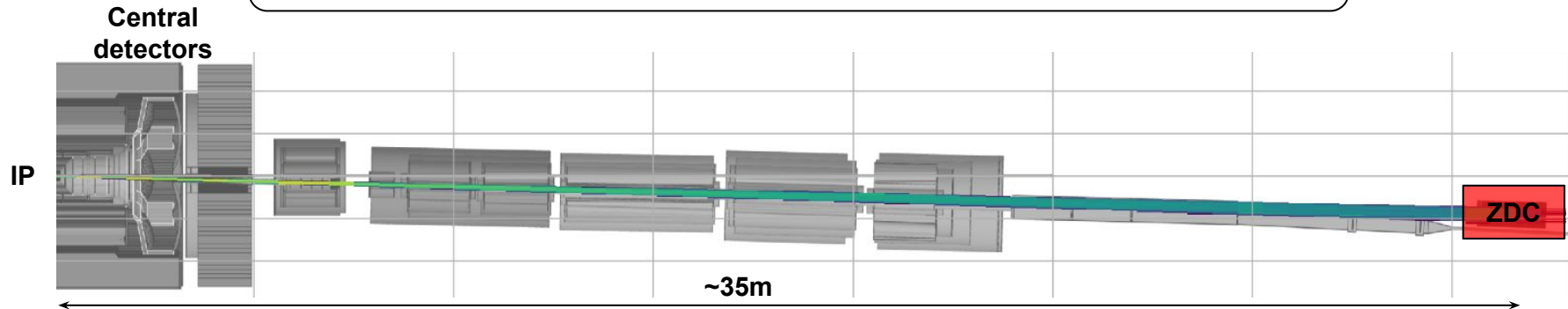
Pion Sullivan tagging : neutron reconstruction in ePIC

Reconstruction strategy

Far-forward neutron tagging using the ZDC

Kinematic reconstruction from the scattered electron and tagged neutron

Realistic yields including machine and physics backgrounds



Results @ 9x275 GeV | ePIC simulation campaign image 26.07

Total cross-section

~0.2 nb

Reconstructed neutrons

$7 \times 10^4 / \text{fb}^{-1}$

Angle resolution

0.5%

Energy resolution

6%

Kaon Sullivan tagging : Λ reconstruction in ePIC

Challenge #1

Small cross-section
 ~ 0.0005 nb

Challenge #2

Instable, displaced
decay vertex

Challenge #3

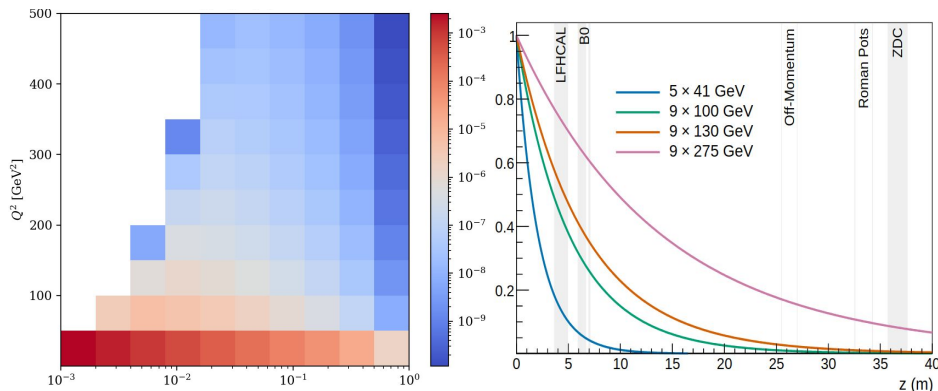
$\Lambda^0 \rightarrow p + \pi^-$ (65 %)

$\Lambda^0 \rightarrow n + \pi^0$ (35 %)

Challenge #4

Triple coincidence

$n + \pi^0 \rightarrow n + \gamma + \gamma$



Neutral channel reconstruction strategy

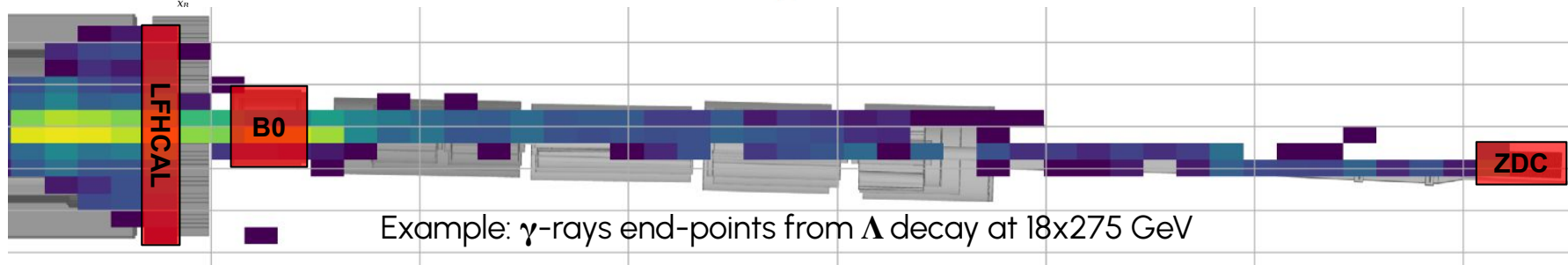
Combine ZDC, B0, LFHCAL to maximize acceptance

Optimize ZDC clustering to resolve γ showers

Neutral channel results @ 9x275 GeV | 26.07

16% absolute efficiency (over 28%) $\rightarrow 100 \Lambda / \text{fb}^{-1}$

Mass resolution 8 MeV/c² (0.7%)



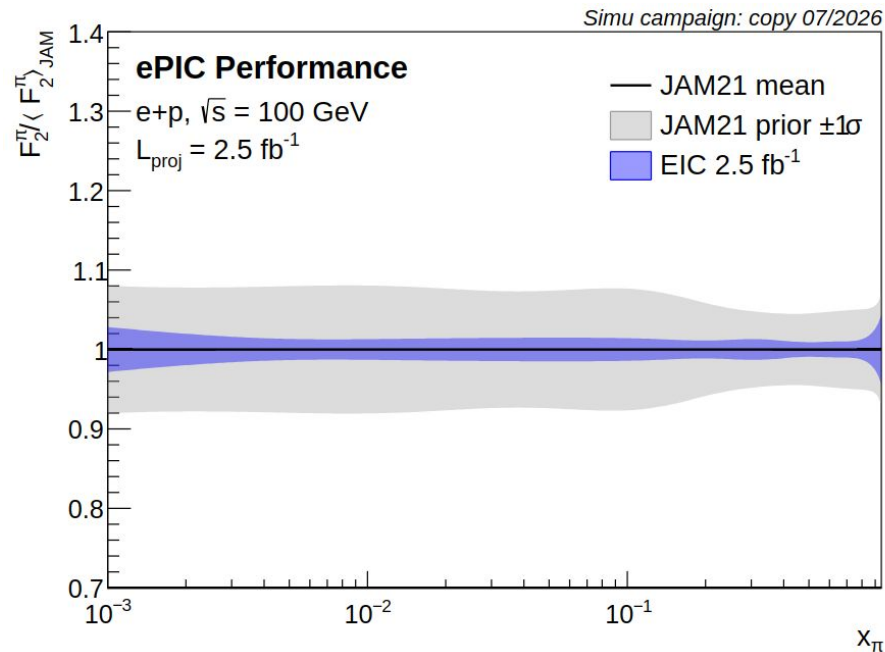
Example: γ -rays end-points from Λ decay at 18x275 GeV

Outline

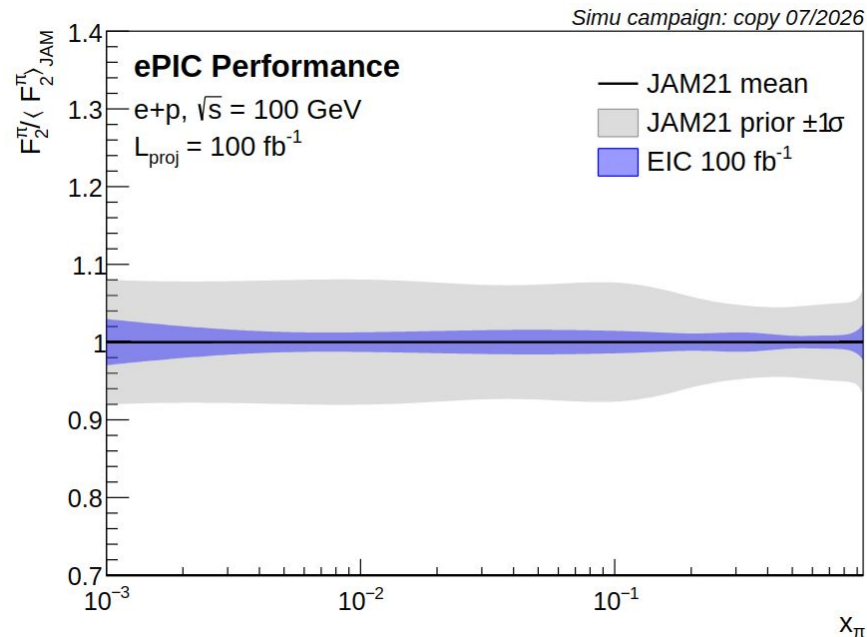
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Pion: constraining projections for JAM25*

Early science program



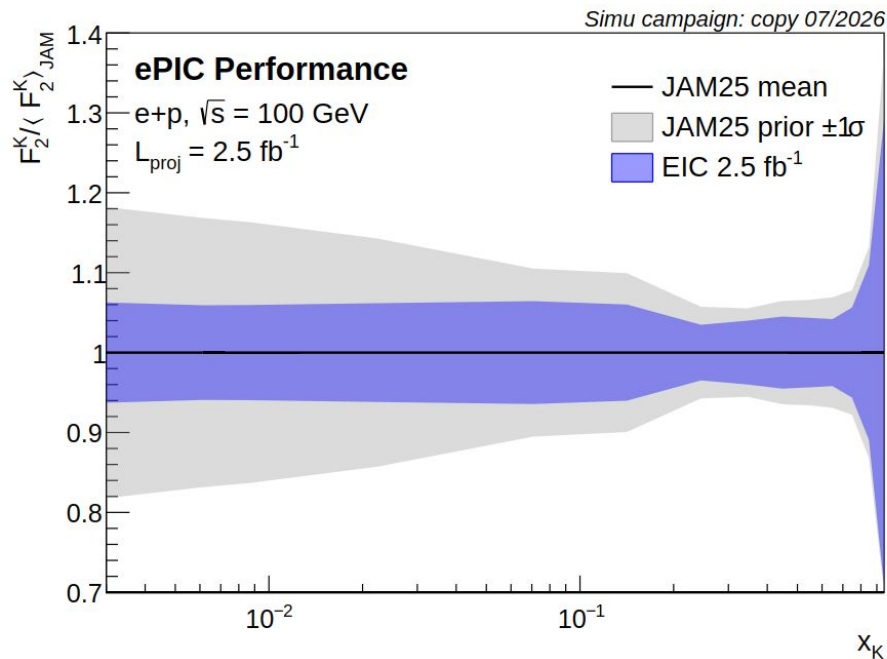
Design luminosity



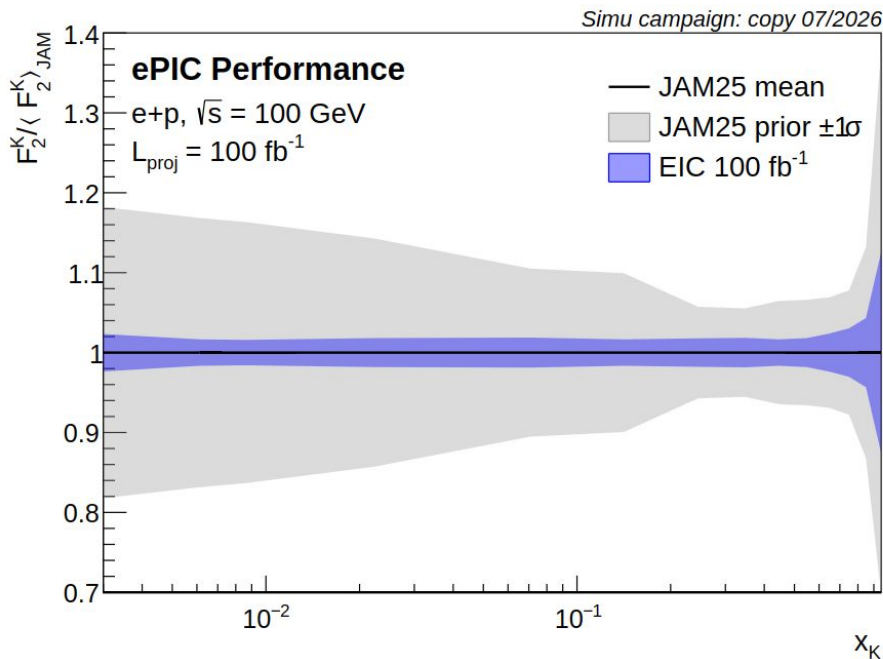
Projected early+design EIC data significantly reduce JAM pion PDF uncertainties

Kaon: constraining projections for JAM25*

Early science program



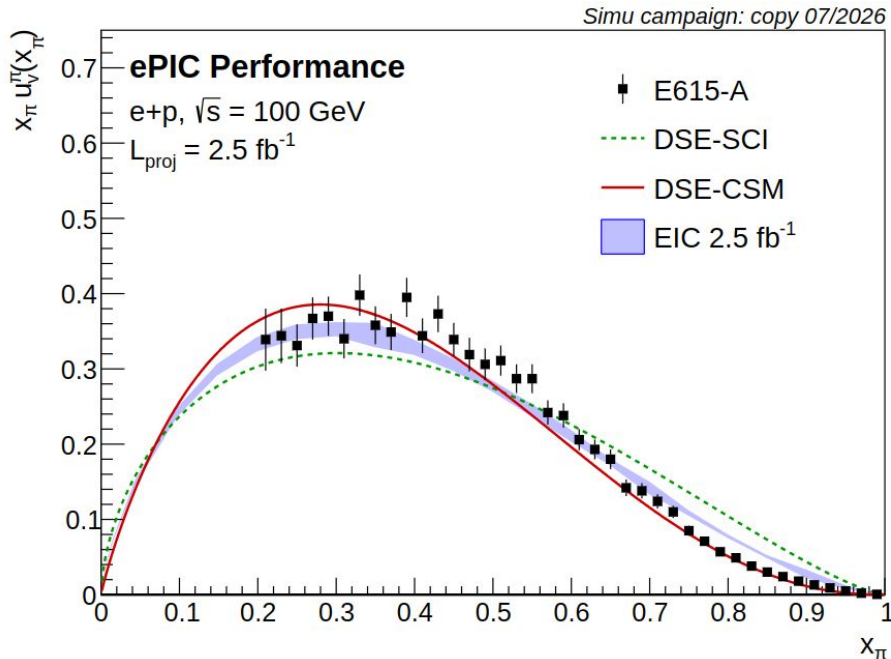
Design luminosity



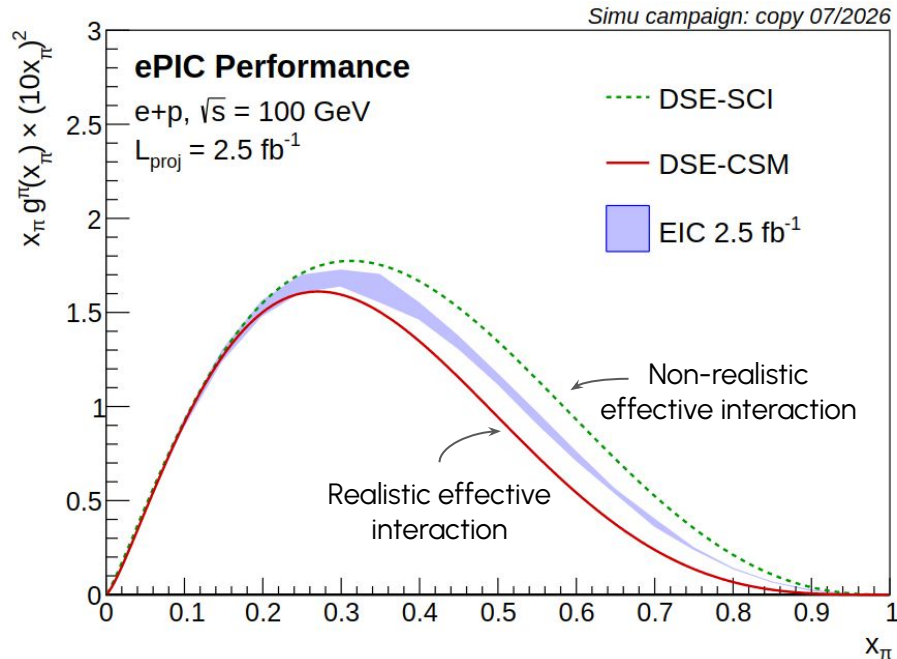
Projected early+design EIC data significantly reduce JAM kaon PDF uncertainties

Pion: discriminating projections for DSE calculations*

Early science program: valence



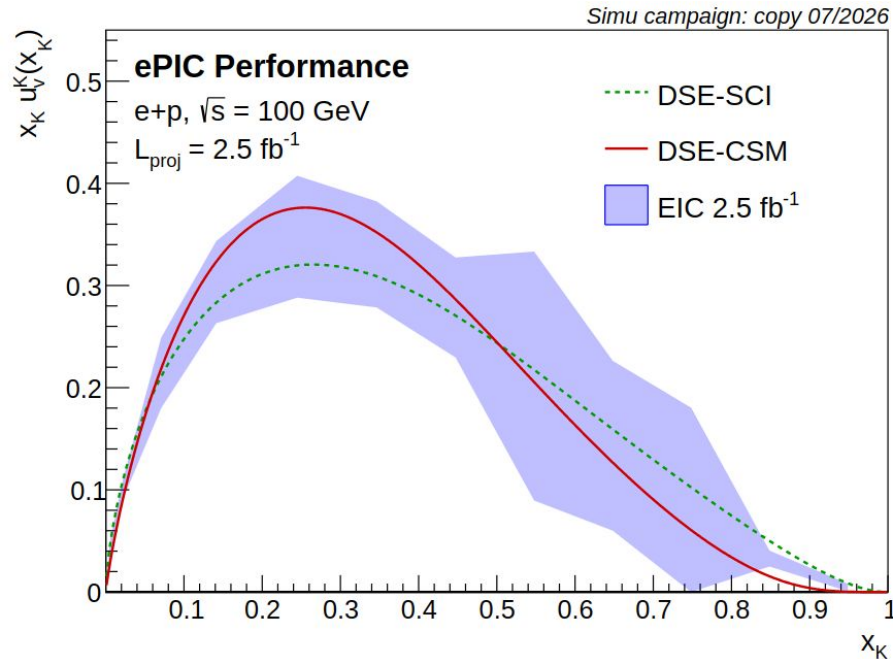
Early science program: glue



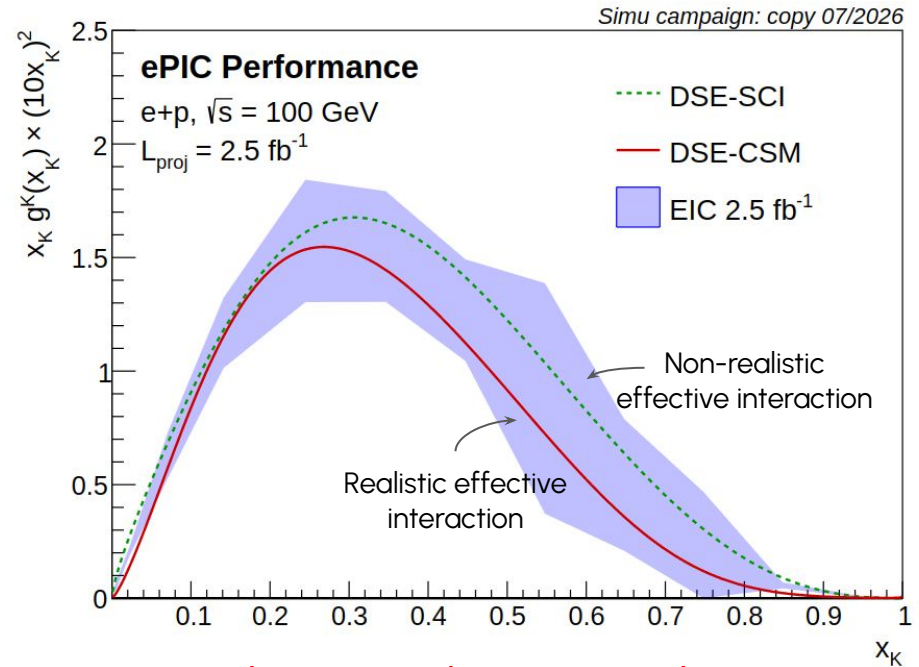
Projected early EIC data allow discrimination between pion DSE descriptions

Kaon: discriminating projections for DSE calculations*

Early science program: valence



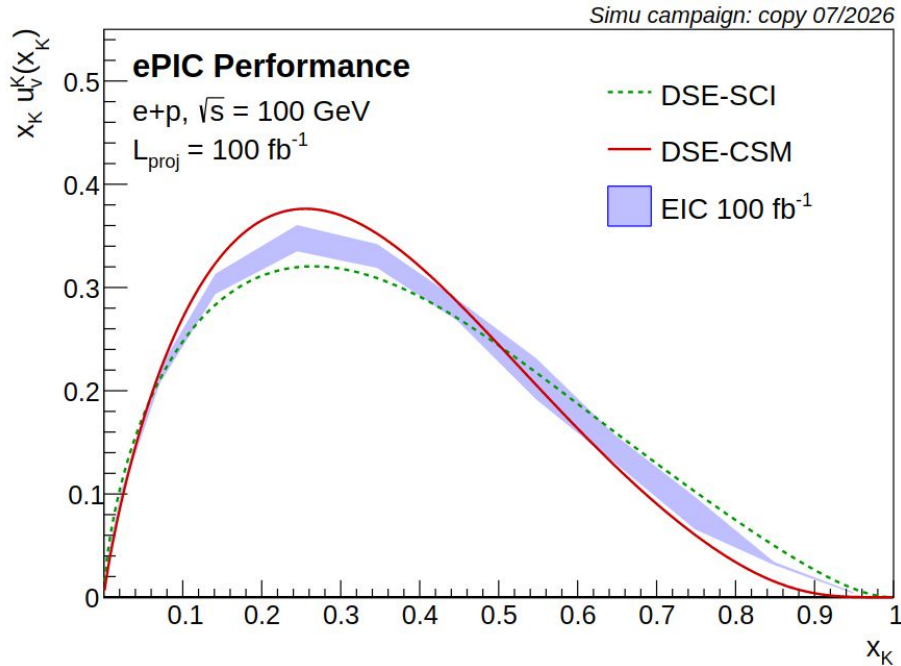
Early science program: glue



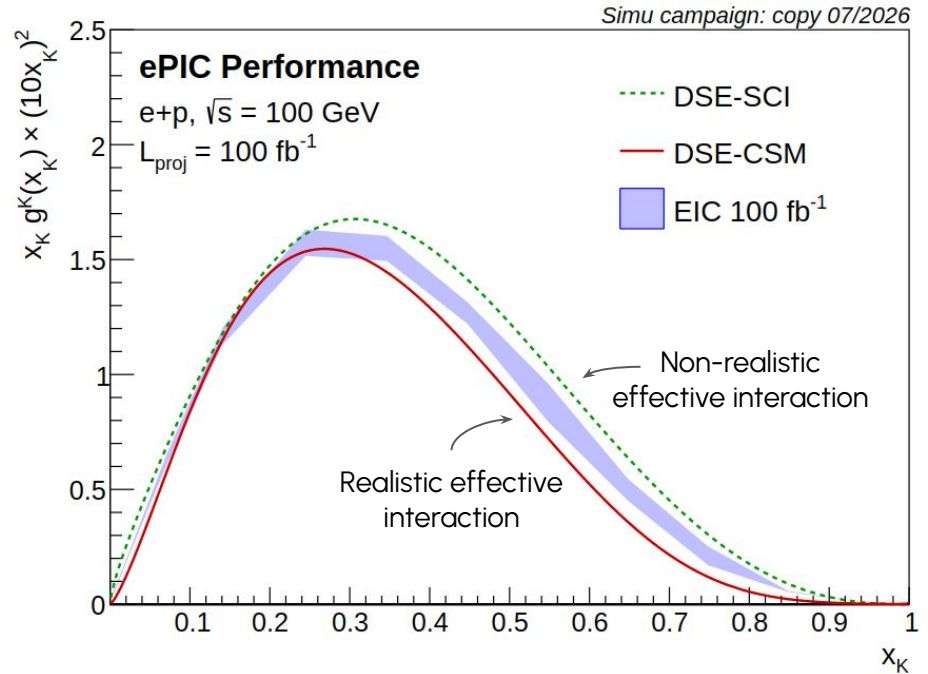
Projected early EIC data do **not** allow discrimination between kaon DSE descriptions

Kaon: discriminating projections for DSE calculations*

Early science program: valence

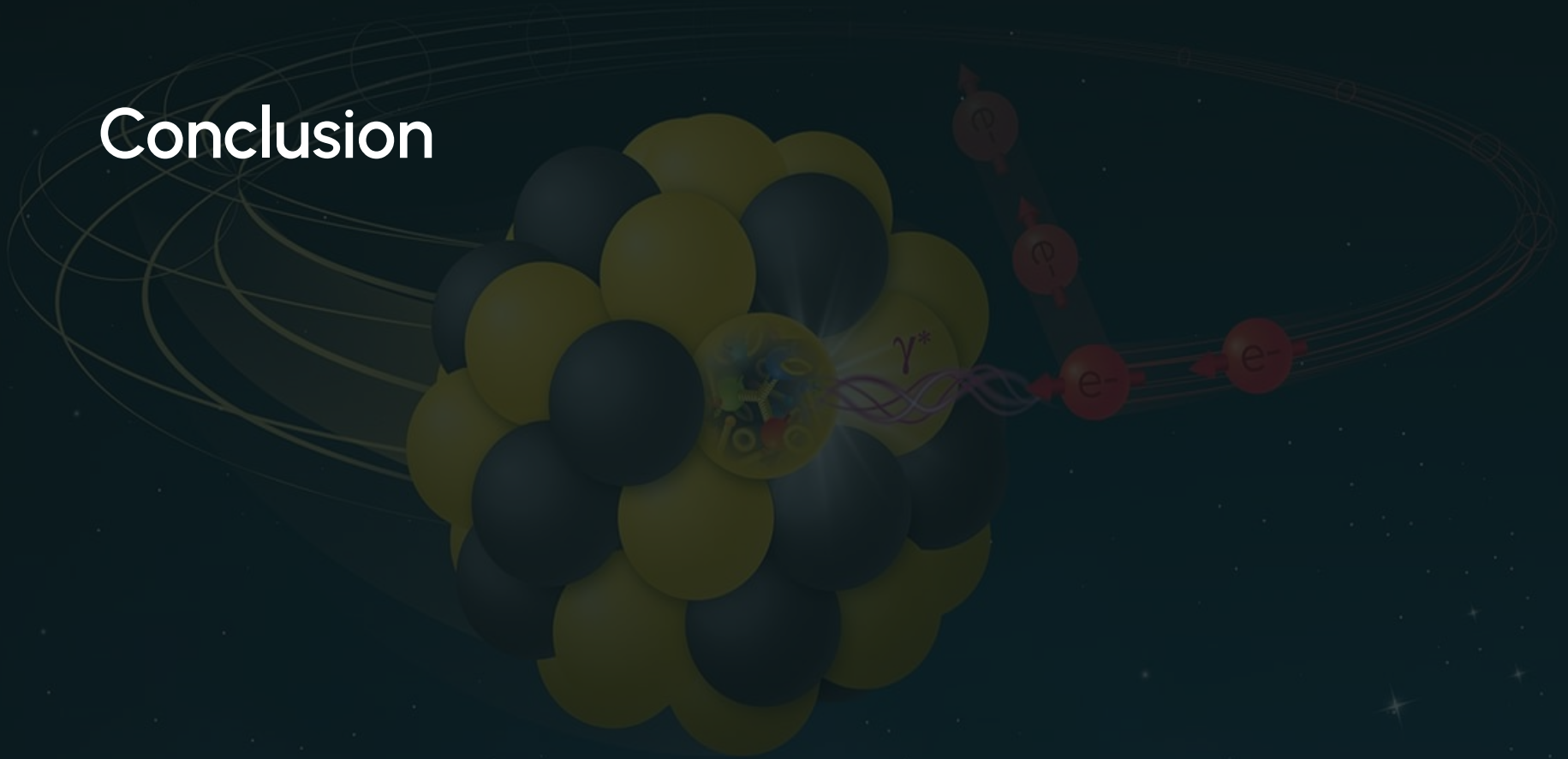


Early science program: glue



Projected design EIC data allow discrimination between kaon DSE descriptions

Conclusion



Projected impact of EIC on the Meson Structure

Energy 9 x 275 GeV		Early science luminosity: 2.5 fb ⁻¹	Design luminosity: 100 fb ⁻¹
Pion π^+		Strong impact	Very strong impact
		<i>JAM global fit</i> Replica spread -50% at low-x -70% at high-x <i>DSE calculations</i> Improved discrimination between interactions	<i>JAM global fit</i> Replica spread -60% at low-x -80% at high-x <i>DSE calculations</i> Improved discrimination between interactions
Kaon K^+ <i>Preliminary (neutral decay)</i>		Limited impact	Groundbreaking impact
		<i>JAM global fit</i> Replica spread -50% at low-x Nothing at high-x <i>DSE calculations</i> No discrimination power between interactions	<i>JAM global fit</i> Replica spread -90% at low-x -70% at high-x <i>DSE calculations</i> Discrimination between competing interactions

The EIC will provide new constraints on pion and kaon structure already during Early Science Program and advance our understanding of hadron mass!

Backups



Sullivan SIDIS kinematics variables

$$e + p \rightarrow e' + B + X$$

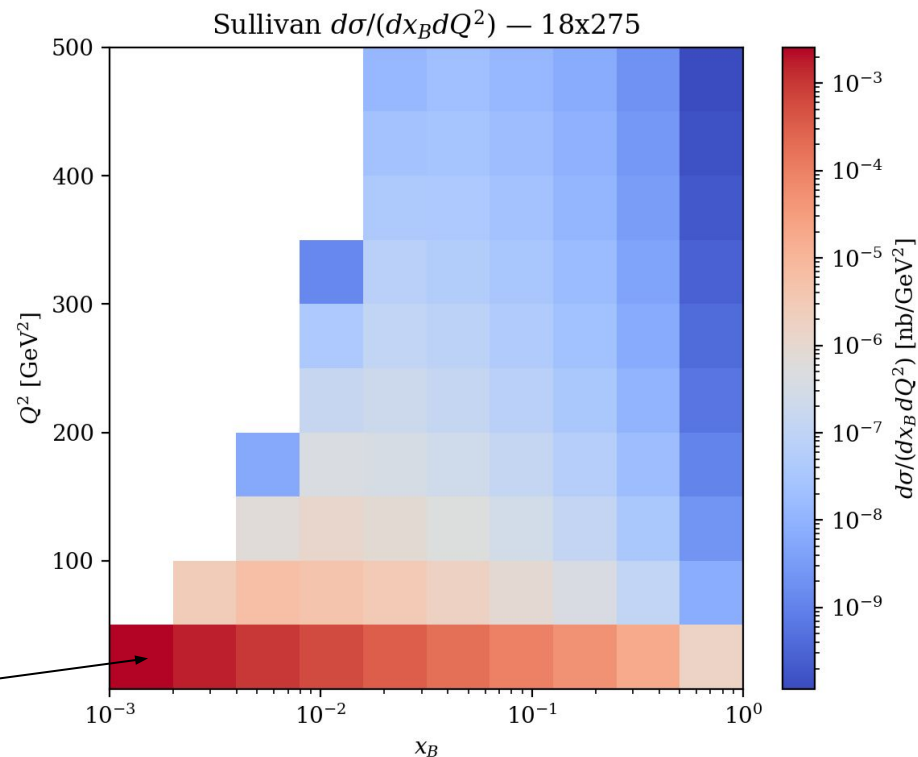
(p fluctuating as B + m, with $m = \pi, K$)

- Q^2 : photon virtuality (hard scattering scale)
- $x_B = Q^2 / (2p \cdot q)$: Bjorken scaling variable of the proton
- $y = (p \cdot q) / (p \cdot k)$: Inelasticity
- $x_L \approx E_B / E_p$: Fraction of proton energy carried by the tagged baryon
- $x_m \approx x_B / (1 - x_L)$: Bjorken scaling variable of the exchanged meson
- $t = (p - p_B)^2$: Four-momentum transfer squared (meson virtuality)
- $W_m^2 = (q + p - p_B)^2$: Photon-meson invariant mass squared

Sullivan SIDIS : Forward baryon tagging provides access to the meson's partonic structure as a function of x_m and Q^2 .

SURGE event generator (Kaon)

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



Kinematics
 $0 < Q^2 < 500$ GeV²
 $0 < x_B < 1$
 $|-t| < 0.4$ GeV

Higher at low x
and low Q^2

Total integrated
 $\sigma \sim 0.0005$ nb

Constraining power estimation method for JAM

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

$$\text{JAM} = \{F_i\}$$

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

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

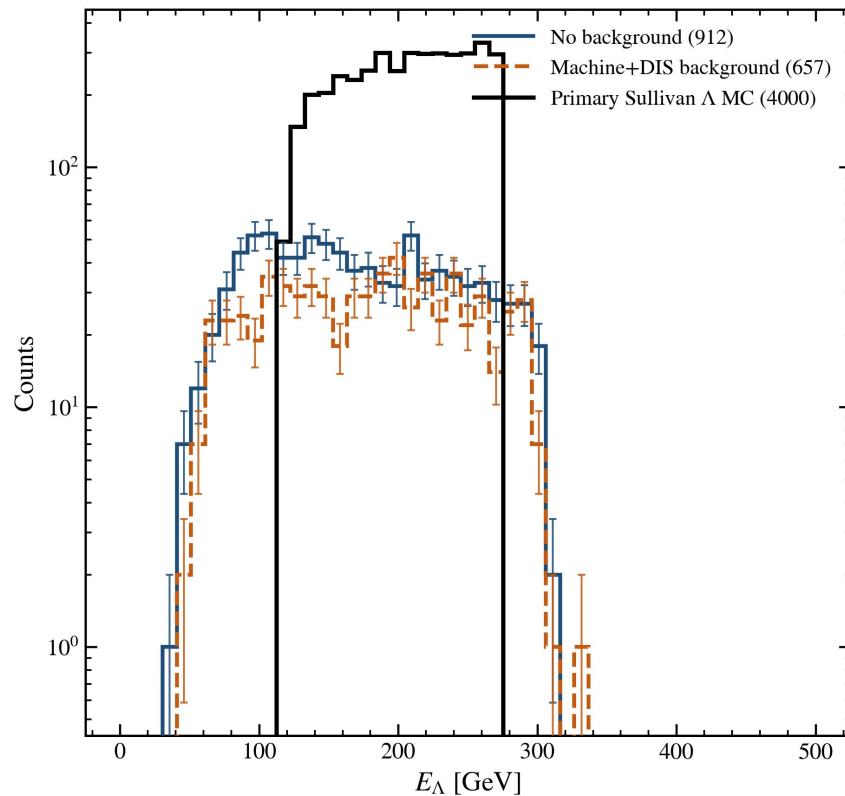
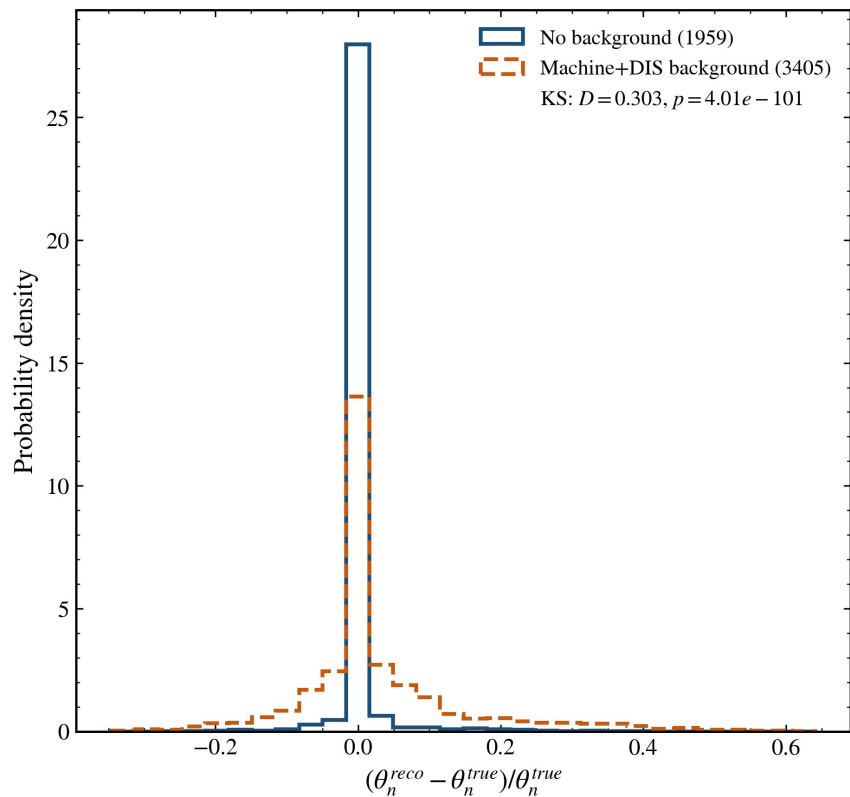
Reweighting the replicas (w_i) to reflect a global fit approach

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

New effective number of replicas

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

Background contamination examples



Loss budget analysis example (original clustering in ZDC)

=== 18x275 : Lambda efficiency budget ===

stage	count	eff [%]
Generated Lambda	10000.0	100.000
Lambda decayed before ZDC (79.5%)	7950.0	79.500
Lambda -> n pi0 (35.8%)	2846.1	28.461

} Physical loss ~72%

ZDC acceptance, normalized to Lambda -> n pi0

stage	count	frac [%]
1 neutron in ZDC	2434.0	85.524
1 gamma in ZDC	2720.0	95.573
2 gammas in ZDC	73.0	2.565
1 neutron + 2 gammas in ZDC	66.0	2.319

} High acceptance (85-95%)
but strong loss due to
non optimal clustering
($\pi^0 \rightarrow \gamma\gamma$, highly boosted)

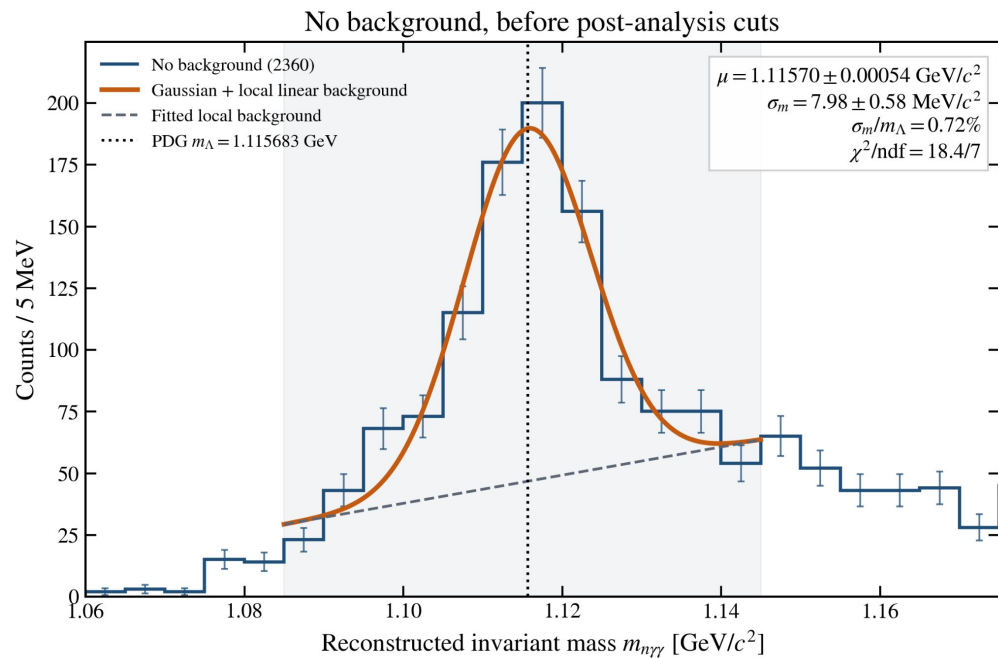
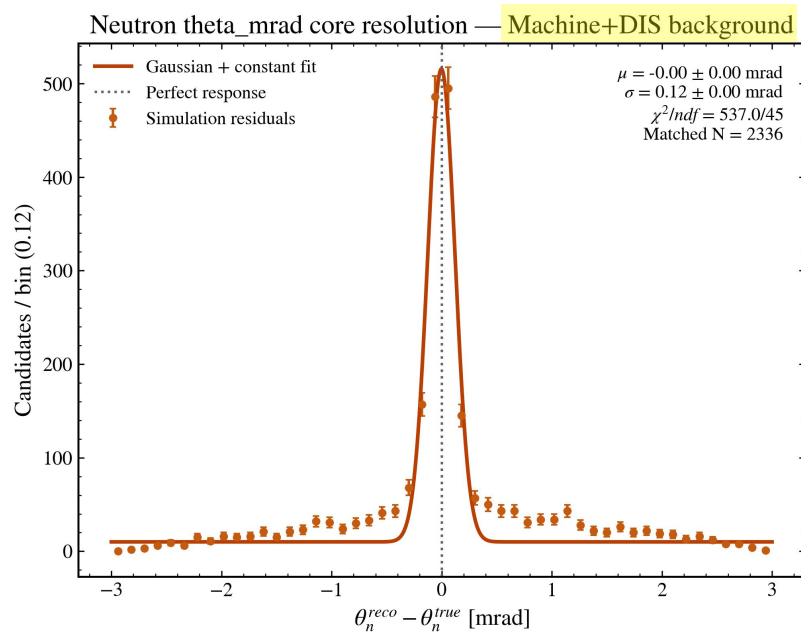
n + 2 gammas in ZDC	66.0	0.660
Final reconstructed Lambda, all detectors	448.0	4.480
Gain from other calo (B0, LFHCAL, Endcap)		+3.814

If not limited by clustering
 $0.85 * 0.95^2 * 0.28 \sim 20\%$

**=> need for optimized
clustering in the ZDC**

Contribution of other calorimeters for
decay products falling out of ZDC

Reconstruction resolutions examples



Q^2 dependence (pion case)

