# Pion Form Factor Projections at the EIC

https://arxiv.org/abs/2403.06000

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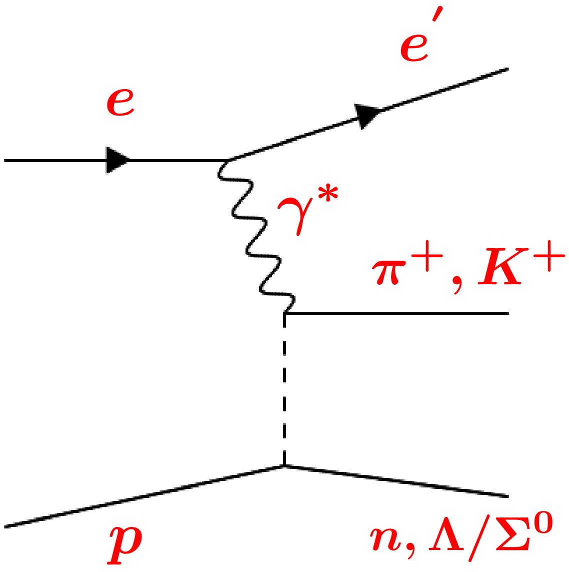
EIC Meson SF WG meeting Meeting

# DEMP reactions

- Form factor measurements through Deep Exclusive Meson Production (DEMP) reactions.
- For $\pi^+$, $K^+$ electroproduction reactions:

$$e + p \rightarrow e^{'} + \pi^+ + n$$
$$\rightarrow e^{'} + K^+ + \Lambda/\Sigma^0$$

- At Jlab, we detect $e^{'}$, $\pi^+$ or $K^+$, and reconstruct $n$ or $\Lambda/\Sigma^0$.
- At EIC (triple coincidence experiment), we need to track all the three final state particles.
  - Missing momentum resolution is insufficient to uniquely reconstruct recoil.
- Need an event generator!




https://arxiv.org/abs/2403.06000

# Kinematic variables

- Basic kinematic invariants can be written as

$$e + p \rightarrow e^{'} + \pi^{+} + n$$
$$\rightarrow e^{'} + K^{+} + \Lambda/\Sigma^{0}$$

  - ep squared CM energy

$$s = (e + p)^{2}$$

  - $\gamma^{*}$p squared CM energy

$$W^{2} = (\gamma^{*} + p)^{2}$$

  - Photon virtuality

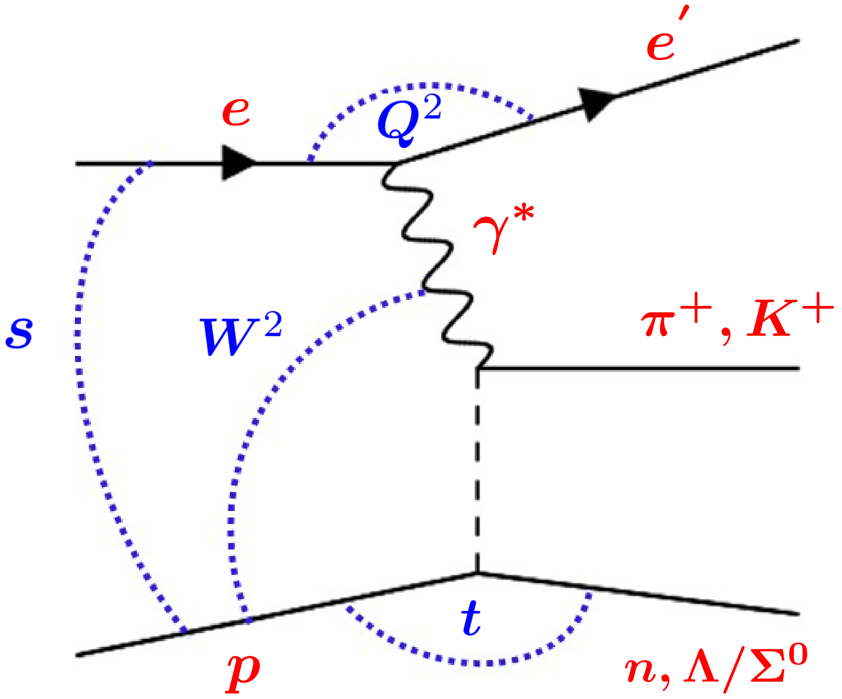
$$Q^{2} = -q^{2} = (e - e^{'})^{2}$$

  - Squared 4-momentum transfer to the nucleon

$$t = (p - Recoil)^{2} = (\gamma^{*} - Ejectile)^{2}$$

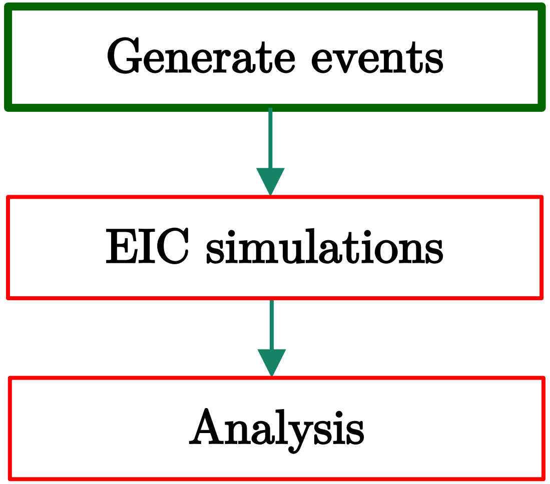
Ejectile : $\pi^{+}$, $K^{+}$

Recoil : n, $\Lambda$, $\Sigma^{0}$



# Feasibility studies at EIC

- Focus on feasibility studies of DEMP reactions through ePIC simulations at EIC.
- The first step will be to generate an event sample.



# Monte Carlo event generator - DEMPgen

- Focuses on two key modules:
  - Colliding beam kinematics mode for the Electron-Ion Collider.
  - Fixed target kinematics mode for the SoLID experiment.
- For the EIC, it currently incorporates three reactions:
  - $p(e,e' \pi^+ n)$ → $\pi^+$ electroproduction
  - $p(e,e' K^+ \Lambda)$
  - $p(e,e' K^+ \Sigma^0)$

  $\left.\begin{array}{l} p(e,e' K^+ \Lambda) \\ p(e,e' K^+ \Sigma^0) \end{array}\right\}$ $K^+$ electroproduction

Ejectile : $\pi^+$, $K^+$

Recoil : $n$, $\Lambda$, $\Sigma^0$

- Consider the head-on collision between the electrons & protons at different beam energies, including, 5(e) × 41(p), 5(e) × 100(p), 10(e) × 100(p), and 18(e) × 275(p).
- It is a weighted event generator.

https://github.com/JeffersonLab/DEMPgen

# Monte Carlo event generator - DEMPgen

- How does the generator work?

Initialization & PSF Check

↓

Random event generation & Kinematics calculation

↓

Event selection cuts

↓

Cross section calculations

↓

Event weighting

↓

Output format

Described based on the latest release, DEMPgen – v1.2.0

# Monte Carlo event generator - DEMPgen

- How does the generator work?

Initialization & PSF Check → Modified

↓

Random event generation & Kinematics calculation

↓

Event selection cuts

↓

Cross section calculations

↓

Event weighting

↓

Output format

# Initialization & PSF check

- Start initialization by reading an input .json file containing several input parameters, such as beam energies, requested events, output file type, electron energies, electron and ejectile angles, etc.

  *Consider 5(e) × 100(p) beam energy combination for $\pi^+$ reaction:*

  User-defined limits:

| e_En_Low | e_En_High | e_Theta_Low | e_Theta_High | Ejectile_Theta_Low | Ejectile_Theta_High |
|---|---|---|---|---|---|
| 2.5 | 12.5 | 60.0 | 175.0 | 0.0 | 50.0 |

- Phase Space Factor (PSF) module constrain the user-defined electron and ejectile energy/angle ranges based on the kinematic variable cuts ($Q^2$ ,W, and -t).

# Initialization & PSF check

Allowed phase space limits:

| e_En_Low | e_En_High | e_Theta_Low | e_Theta_High | Ejectile_Theta_Low | Ejectile_Theta_High |
|---|---|---|---|---|---|
| 2.5 | 12.5 | 60.0 | 175.0 | 0.0 | 50.0 |
| 4.9 | 6.62 | 116.925 | 158.785 | 1.5 | 50.0 |

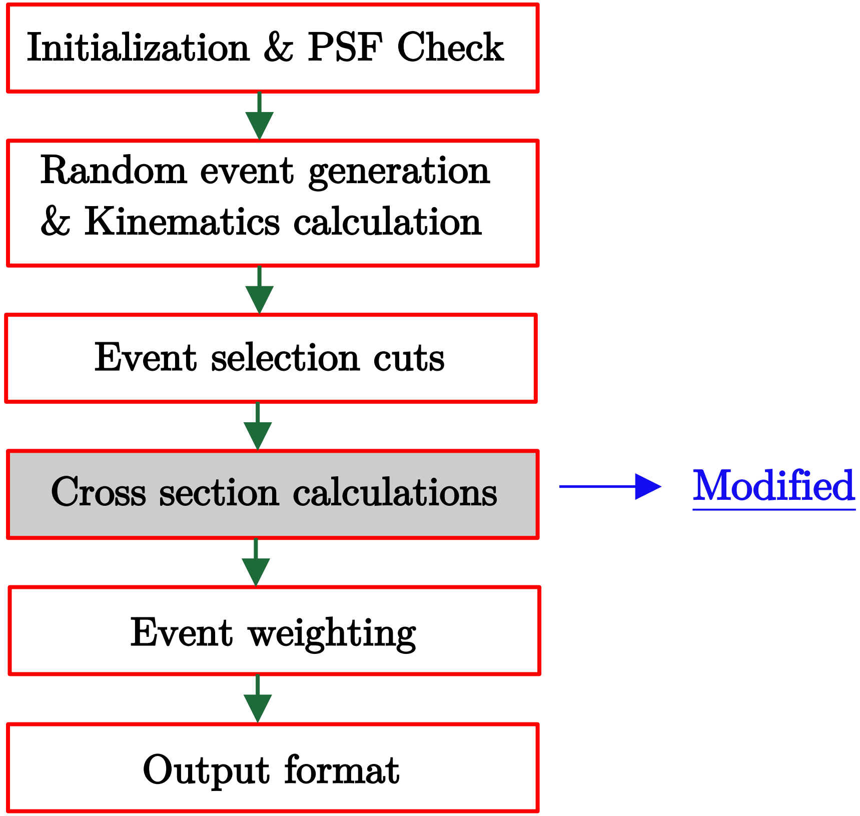
- Calculate the PSF, which is the fraction of the total kinematically accessible phase space that is covered by the event generator, using constrained ranges.
  - Critical for calculating event weights.

$$PSF = (E_{e'Max} - E_{e'Min}) d\Omega_{e'}(\theta, \phi)\, d\Omega_{Ejectile}(\theta, \phi)$$

- Time-efficient, with more recorded events per file, and without wasting CPU resources.

# Monte Carlo event generator - DEMPgen

- How does the generator work?



# Cross section calculations

- Exclusive reaction cross-section in the collider frame is:

$$\frac{d^5\sigma}{dE_{e'}^{Col}\, d\Omega_{e'}^{Col}\, d\Omega_{Ej}^{Col}} = (\Gamma_\nu^{Col}) \left(\frac{d\Omega_{Ej}^{CM}}{d\Omega_{Ej}^{Col}}\right) \left(\frac{d^2\sigma}{d\Omega_{Ej}^{CM}}\right) \longrightarrow \text{Modified}$$

Virtual photon flux factor

Jacobian for the conversion from CM to Col frame

$$\frac{d^2\sigma}{d\Omega_{Ej}^{CM}} = \mathbf{J}\left(\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt}\right)$$

Jacobian

Parametrized theoretical models

https://arxiv.org/abs/2403.06000

# Parametrization of theoretical models for $\pi^+$ & $K^+$ modules

- For the $p(e,e' \pi^+ n)$ module, the generator uses the Regge-based $p(e,e' \pi^+ n)$ model from T. K. Choi, K. J. Kong, and B. G. Yu (CKY) - arXiv 1508.00969
  - MC event generator created by parametrizing CKY $\sigma_L$, $\sigma_T$ for $3<Q^2<35$, $2<W<10.2$, $0<-t<1.3$.
    - Parametrize in step sizes of 0.2 GeV in W and 1 $GeV^2$ in $Q^2$.
  - Parametrize $\sigma_L$ , $\sigma_T$ with landau, exponential, and polynomial.
- Two channels for the kaon module.
- For both $p(e,e' K^+\Lambda/\Sigma^0)$ modules, the generator uses the Regge-based $p(e,e' K^+\Lambda/\Sigma^0)$ model from M. Vanderhaeghen, M. Guidal, and J. -M. Laget (VGL).
  - MC event generator created by parametrizing VGL $\sigma_L$, $\sigma_T$ for $1<Q^2<35$, $2<W<10$, $0<-t<2$.
    - Parametrize in step sizes of 1 GeV in W and 1 $GeV^2$ in $Q^2$.
  - Parametrize $\sigma_L$ , $\sigma_T$ with exponential and polynomial.

T. K. Choi, K. J. Kong, and B. G. Yu, Journal of the Korean Physical Society 67, 1089 (2015),
VGL Model - M. Guidal, J. -M. Laget, M. Vanderhaeghen, Physical Review C 61 (2000) 025204.

# Monte Carlo event generator - DEMPgen

- How does the generator work?

Initialization & PSF Check

↓

Random event generation & Kinematics calculation

↓

Event selection cuts

↓

Cross section calculations

↓

Event weighting

↓

Output format → Modified

# Output format

- Produce output in one of these three options: LUND, Pythia6, or HEPMC3, with an optional ROOT output format.
- Generate a txt file, regardless of the choice, that contains additional information about events, including requested, generated, and those failed due to various cuts, etc.

Colliding beams

Event weight

```
E 1 1 5
U GEV MM
A 0 weight 5.123173147468634e-07
P 1 0 11 6.123233963758798e-16 0.000000000000000e+00 -4.999999973888007e+00 5.000000000000000e+00 5.109989488070365e-04 4
P 2 0 2212 -0.000000000000000e+00 -0.000000000000000e+00 4.100000000000000e+01 4.101073462535657e+01 9.382720881600054e-01 4
V -1 0 [1,2]
P 3 -1 11 -4.765207341187158e+00 -3.732537034594943e-01 -2.925841675750566e+00 5.604201022833585e+00 5.109989383783055e-04 1
P 4 -1 211 3.968428136943284e+00 -1.531575588721116e-01 4.701276523050274e+00 6.155758271509020e+00 1.395701800000037e-01 1
P 5 -1 2112 7.967792042438746e-01 5.264112623316060e-01 3.422456517881229e+01 3.425077533101398e+01 9.395654205001728e-01 1
```

| particle_line | part_id | parent_vertex_id | pdg_id | px | py | pz | energy | particle_mass | status |
|---|---|---|---|---|---|---|---|---|---|

Example of HEPMC3 format

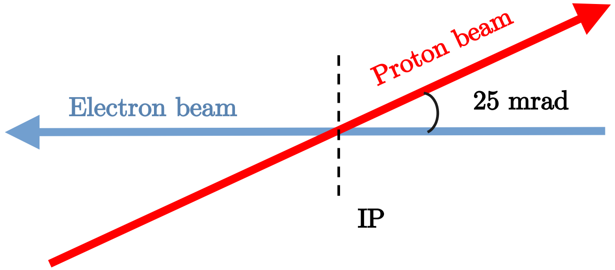
Scattered particles

# Simulation studies using ePIC simulations

- Incoming beams collide at a crossing angle of 25 mrad.

Generate events → Monte Carlo Afterburner → ePIC simulations → Analysis

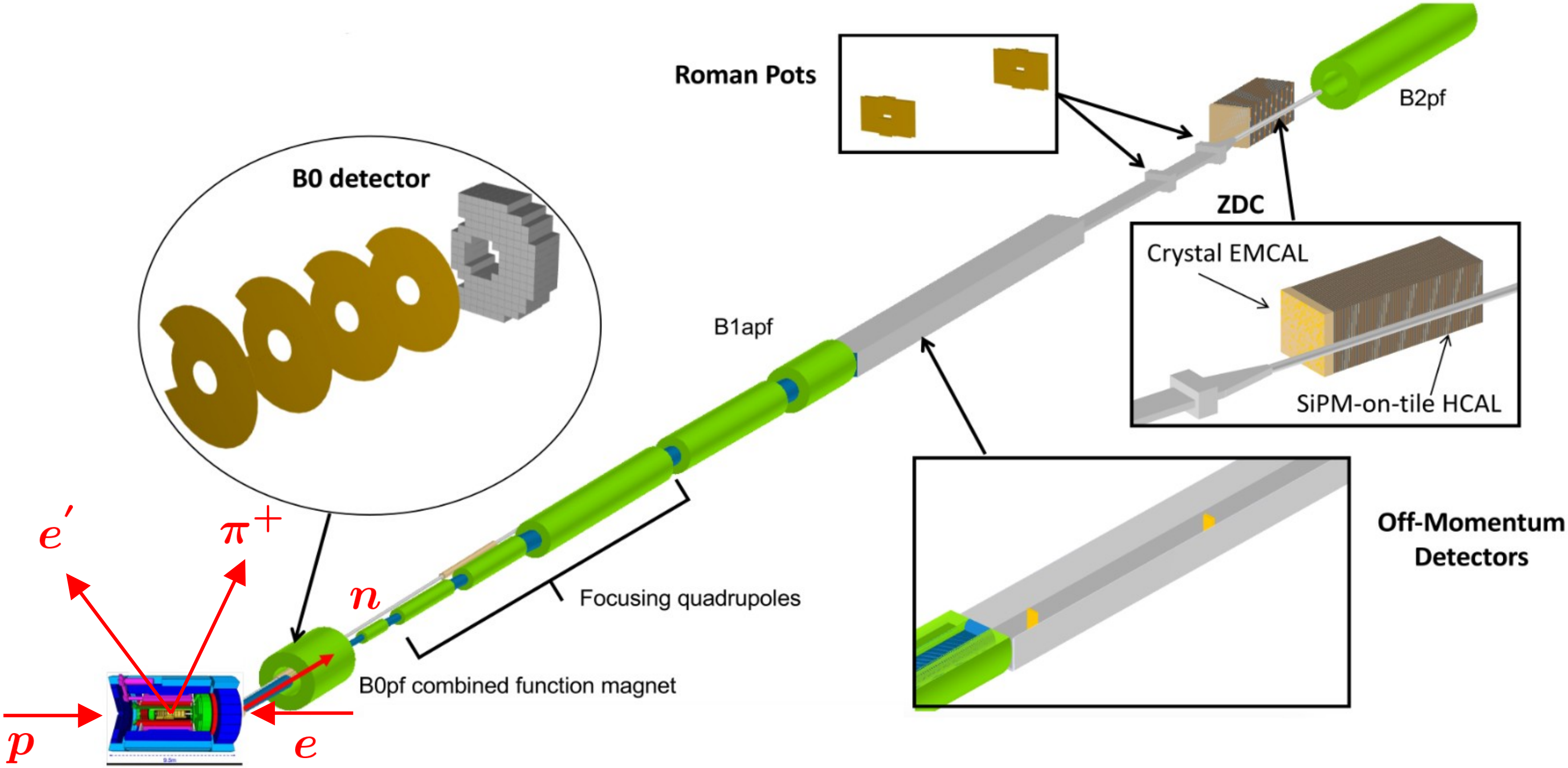
  - Monte Carlo afterburner includes crossing angle, beam energy spread, angular beam divergence, bunch length, etc.




- DEMPgen has the capability to generate events directly with the correct crossing angles.
  - Turned it off to maintain compatibility with EIC simulations framework.

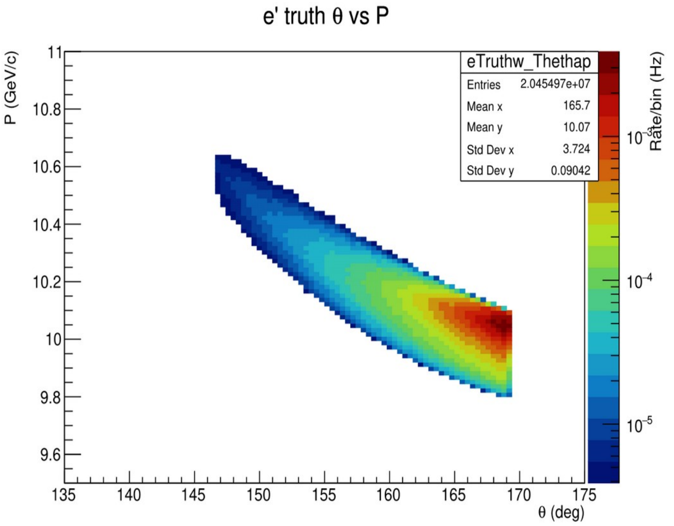
https://github.com/eic/afterburner

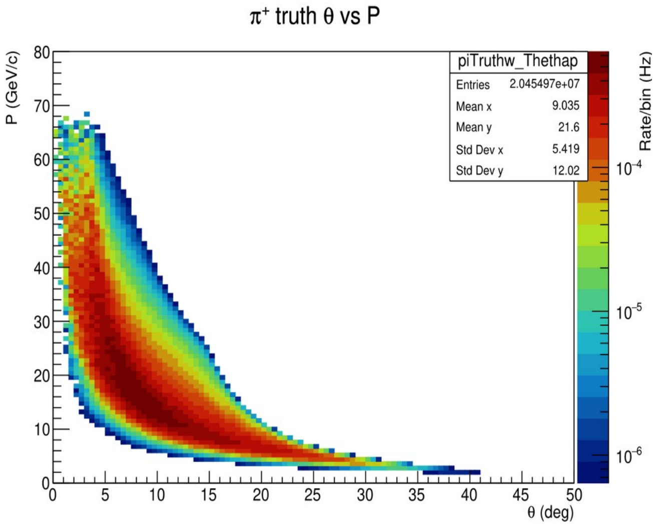
# ePIC detectors (central & far-forward)

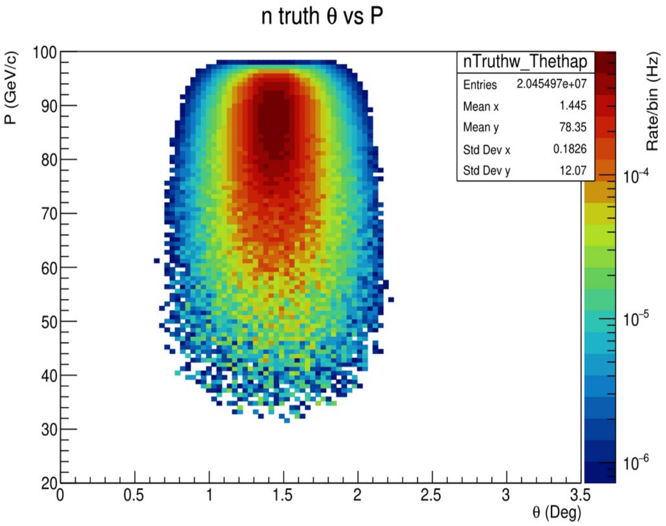


# Spatial topology of weighted truth variables at ePIC detector

- Used simulated files for 10(e) on 100(p) GeV collisions from the recent campaign - 24.09.0.
- e', $\pi^+$ hits the central detector, n hits far-forward detectors (mainly ZDC).



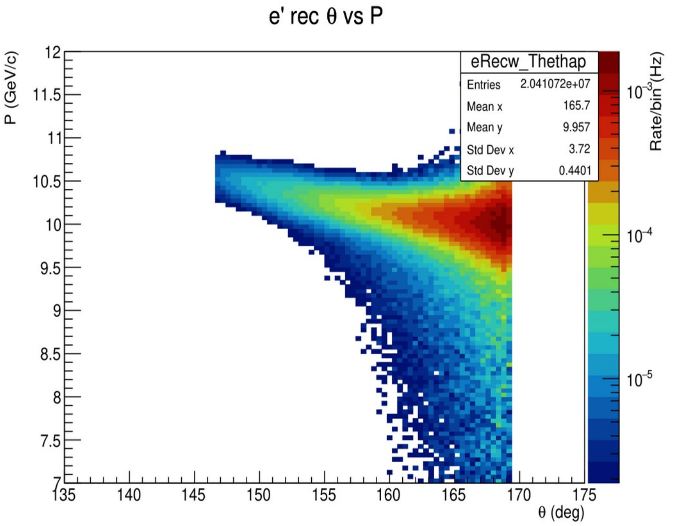



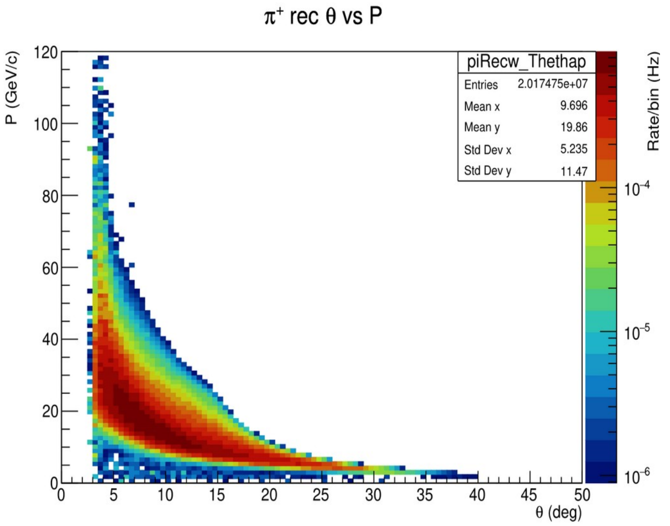



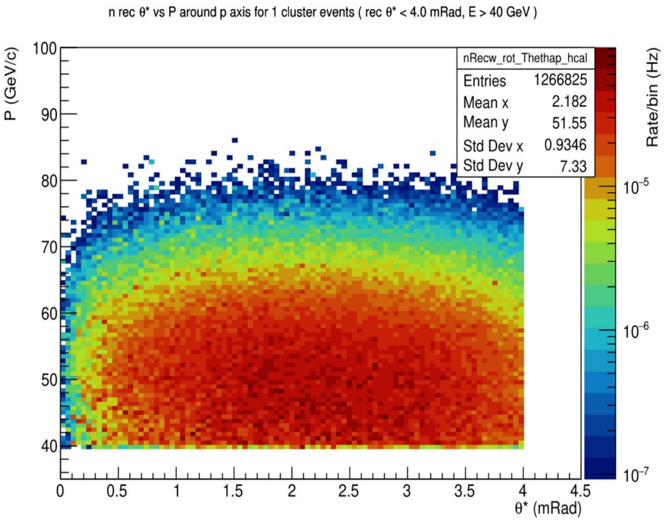
# Spatial topology of weighted rec variables at ePIC detector

- Used simulated files for 10(e) on 100(p) GeV collisions from the recent campaign - 24.09.0.
- e', $\pi^+$ hits the central detector, n hits far-forward detectors (mainly ZDC).

[ 1 cluster events with E>40 GeV, $\theta^*$<4.0 mRad ]



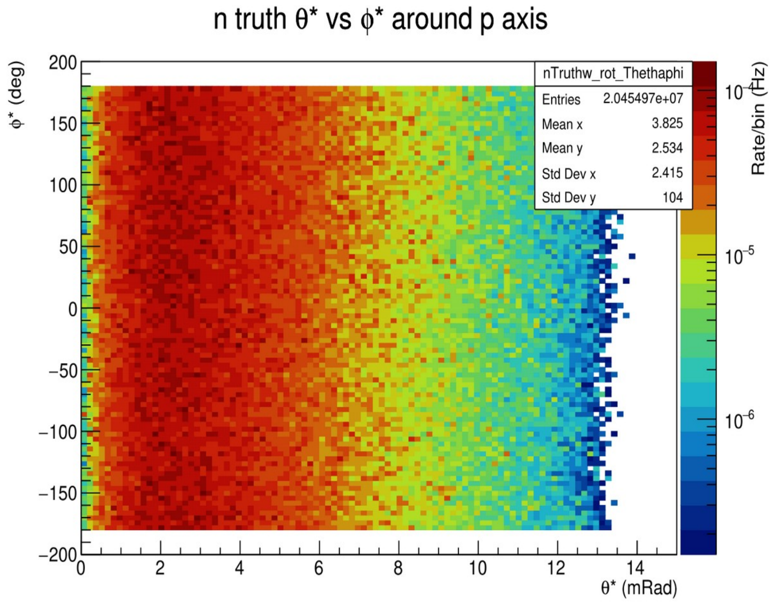

[ Using HcalFarForwardZDCClusters ]

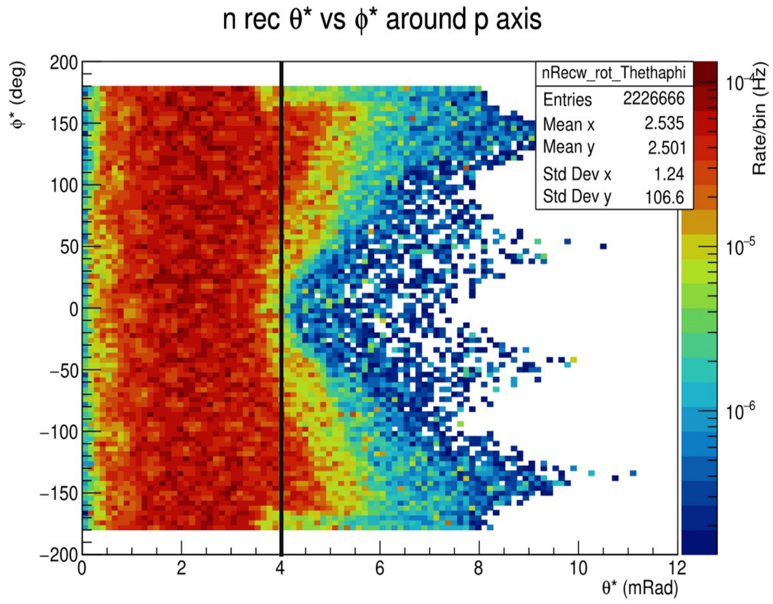
rec stands for reconstructed information

$\theta^*$ is the rotation by 25 mRad around proton axis

# Neutrons truth vs rec distribution

- Reconstructed neutrons using newly merged branch ReconstructedFarForwardZDCNeutrons.

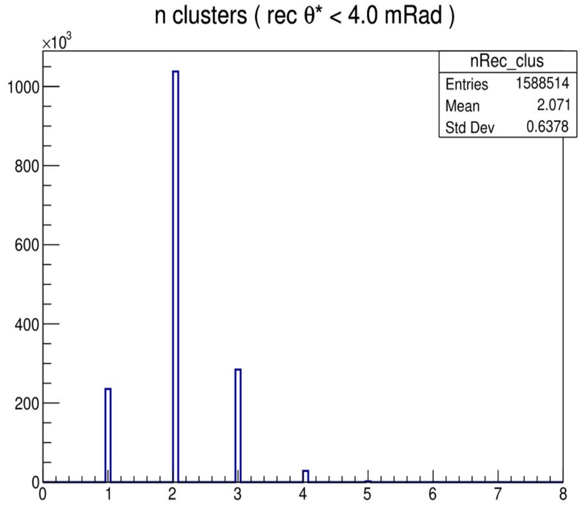


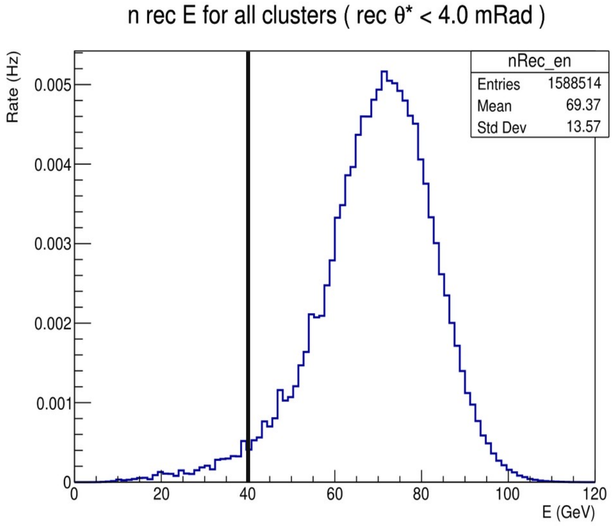

$\theta^*$ , $\phi^*$ is the rotation by 25 mRad around proton axis

# Spatial topology of weighted rec neutrons at ePIC detector

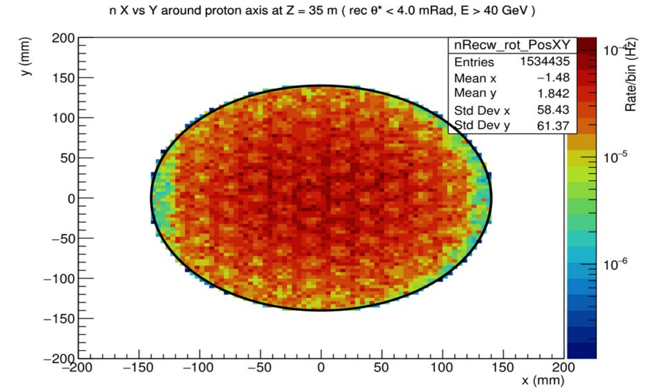
- Reconstructed neutrons using newly merged branch ReconstructedFarForwardZDCNeutrons.
  - Reconstructed neutrons include all the clusters.

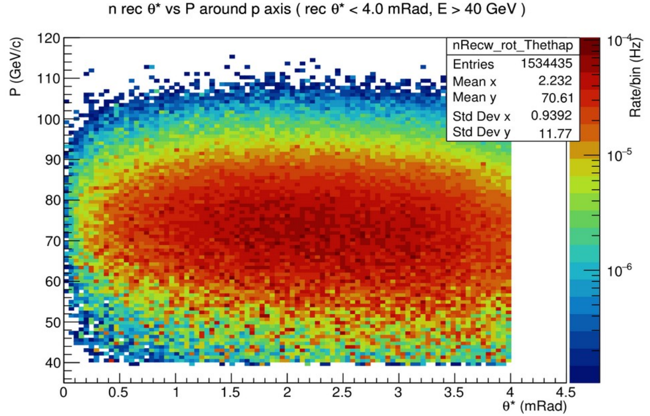



[ Most neutrons have 2+ clusters ]




[ Apply > 40 GeV cluster cut ]



# Accessing form factor through $\pi^+$ electroproduction

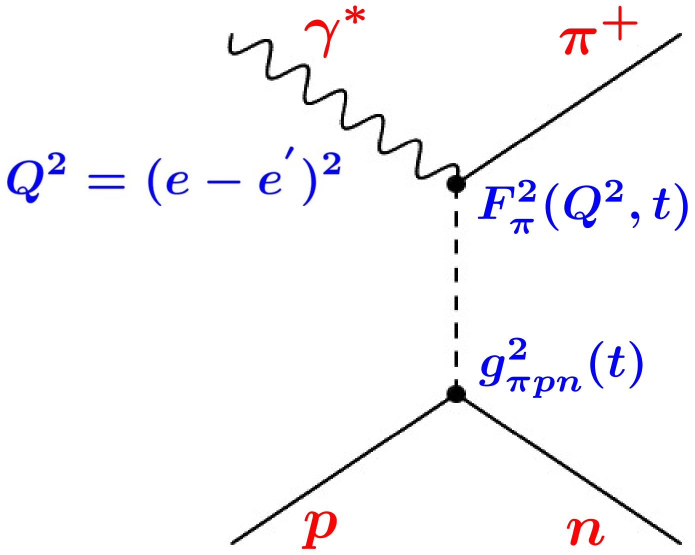
- Measure $e'\pi^+n$ triple coincidence events.

- At small -t, the pion pole process dominates $\sigma_L$.

$$e + p \rightarrow e' + \pi^+ + n$$

- In the Born model, $F_\pi^2$ appear as [In practice one uses a more sophisticated model]

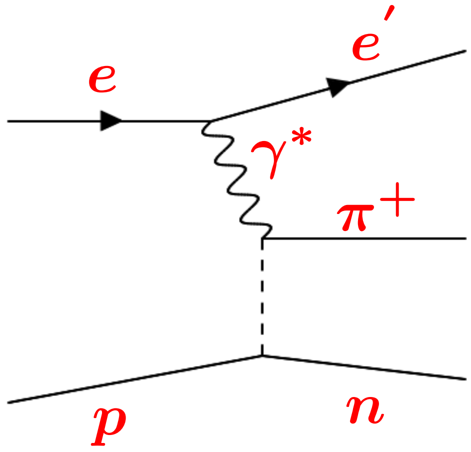
$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)^2} g_{\pi pn}^2(t) F_\pi^2(Q^2, t)$$




- $Q^2$, -t reconstruction resolution is crucial for extracting $F_\pi^2$ from the measured cross section.

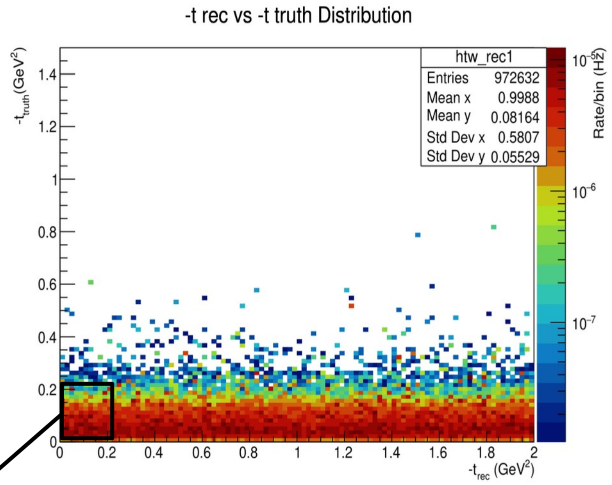
- Different approaches tried to reconstruct -t.

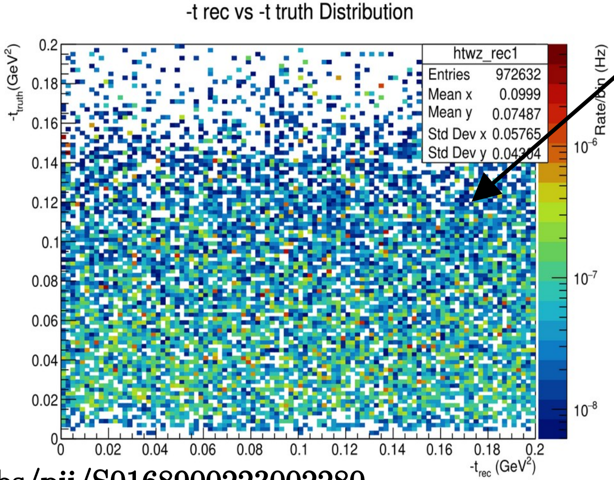
# -t reconstruction using lepton-meson vertex (Method - 1)

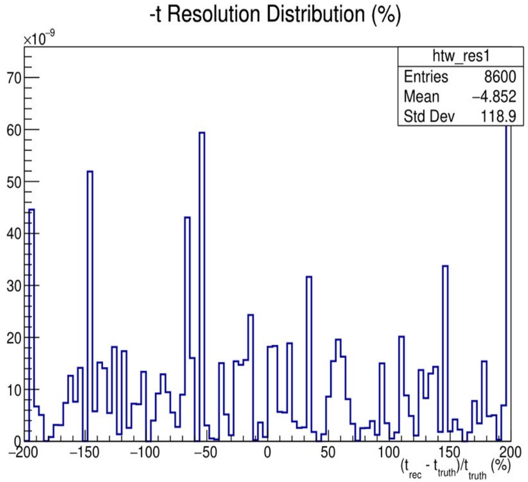



$$-t_{truth} = -(\gamma^* - \pi^+)^2$$

$$-t_{rec} = -(\gamma^* - \pi^+)^2$$

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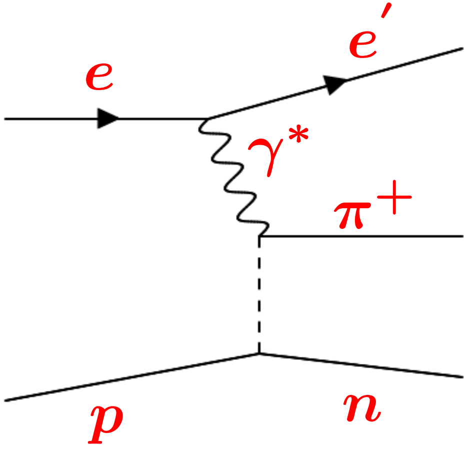
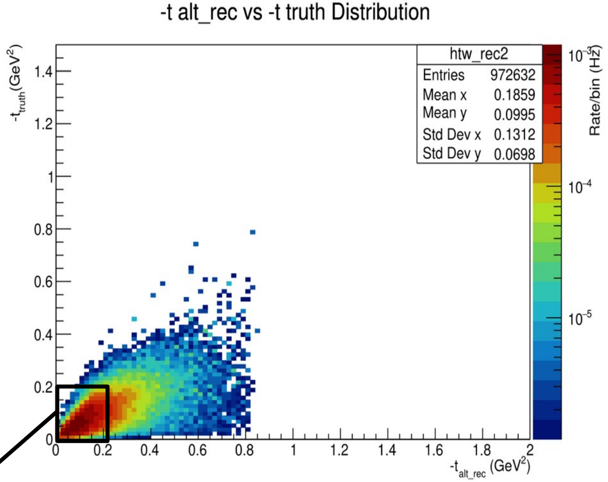
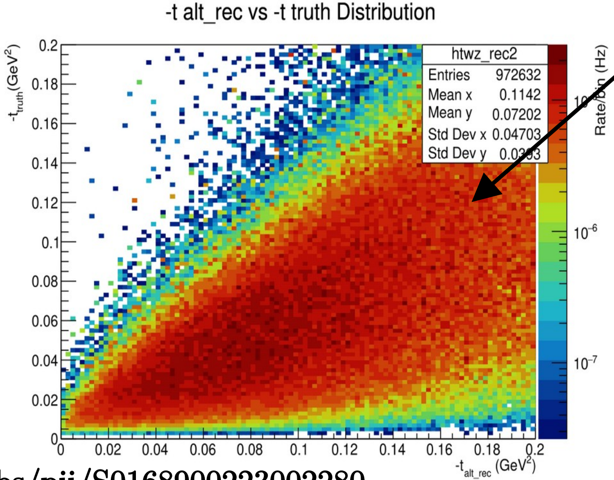
# -t reconstruction using proton-baryon vertex (Method - 2)

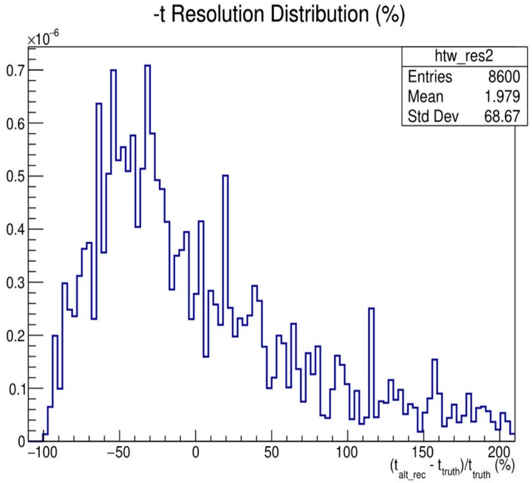



$$-t_{truth} = -(\gamma^* - \pi^+)^2$$

$$-t_{alt\_rec} = -(p - n)^2$$

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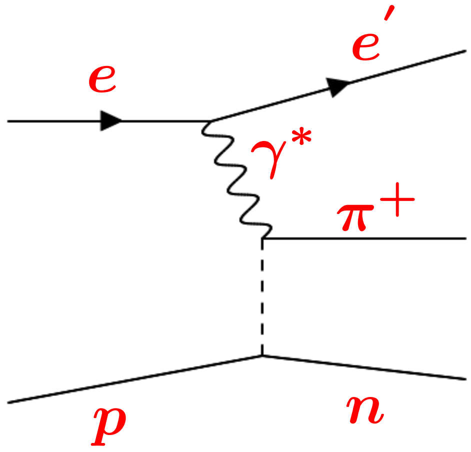
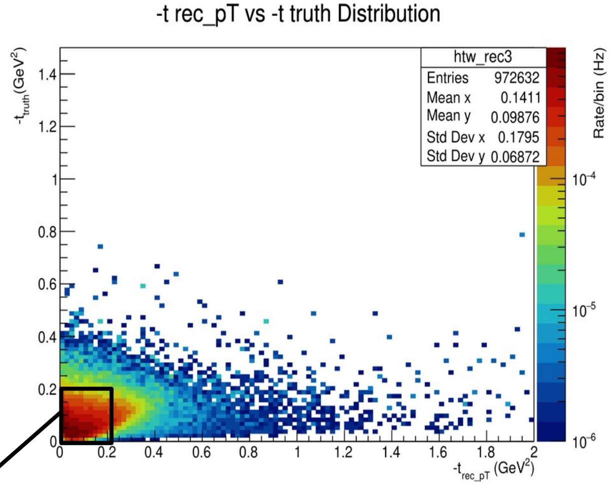
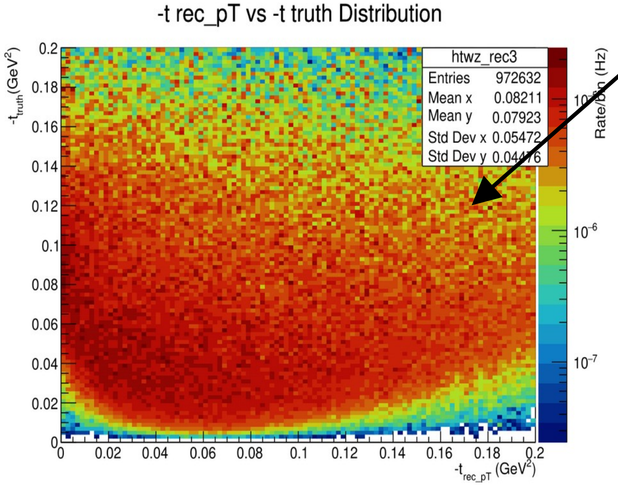
# -t reconstruction using pT of e' and $\pi^+$ (Method - 3)

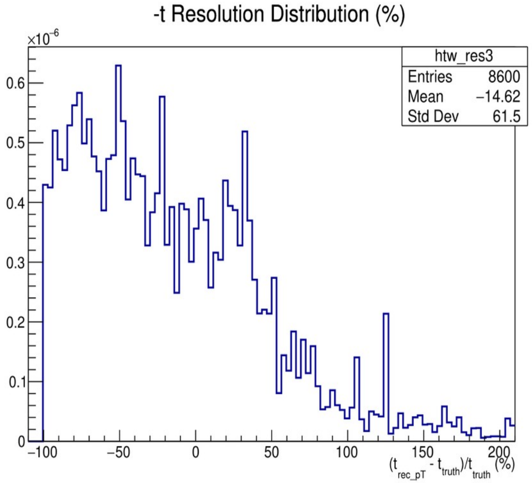



$$-t_{truth} = -(\gamma^* - \pi^+)^2$$

$$-t_{rec\_pT} \approx -(p_{T,\pi^+} + p_{T,e'})^2$$



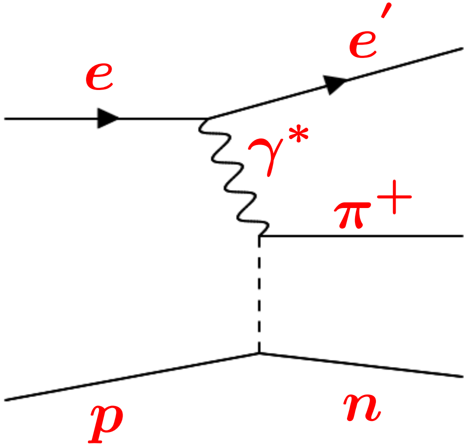




Valid for small -t and small Q$^2$ !

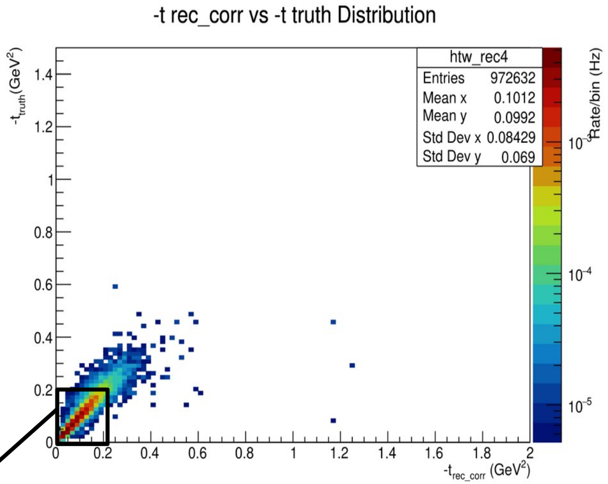
https://arxiv.org/pdf/2005.14706.pdf

# -t reconstruction using corrected n track (Method - 4)




$$-t_{truth} = -(\gamma^* - \pi^+)^2$$

$$-t_{rec\_corr} = -(p - n_{corr})^2$$

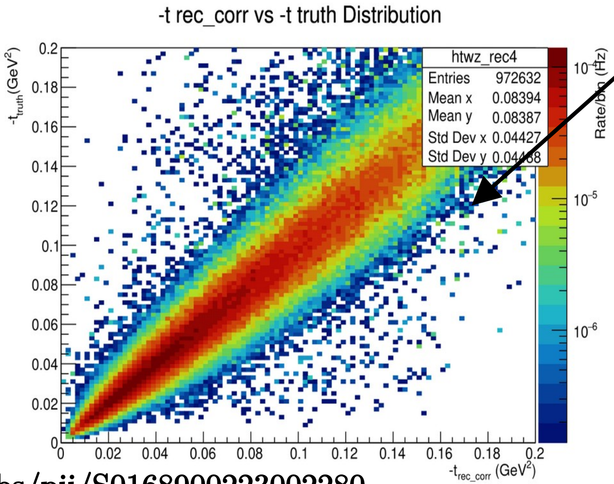


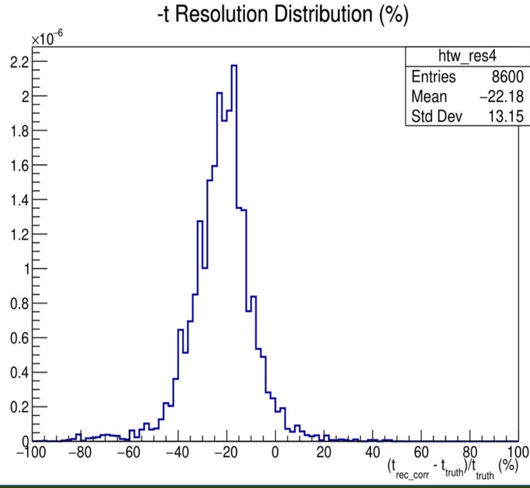

## Reconstructed n_corr:

Using missing momentum information,

$$p_{miss} = |\vec{p_e} + \vec{p_p} - \vec{p_{e'}} - \vec{p_{\pi^+}}|$$

And replaced $\theta_{Miss}$, $\phi_{Miss}$ with $\theta_{ZDC}$, $\phi_{ZDC}$, and fixed the neutron mass.

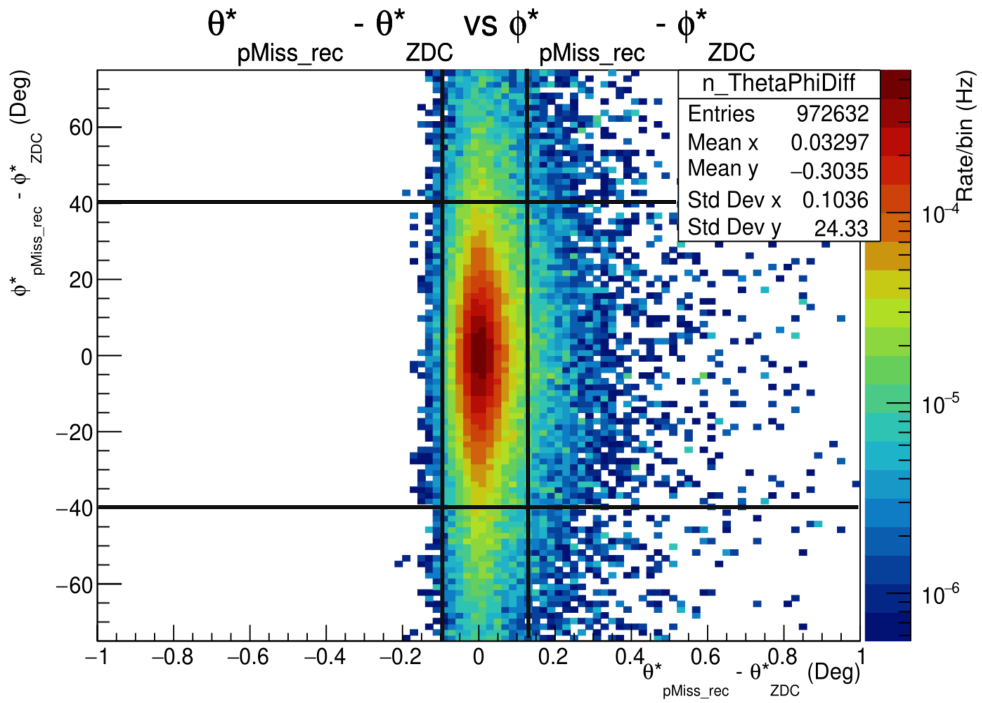


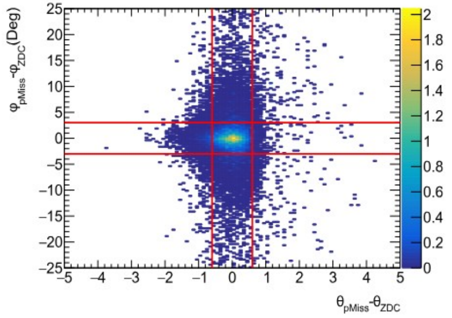




https://www.sciencedirect.com/science/article/abs/pii/S0168900223002280

# Diff. b/w rec & detected simulated angles for the neutrons

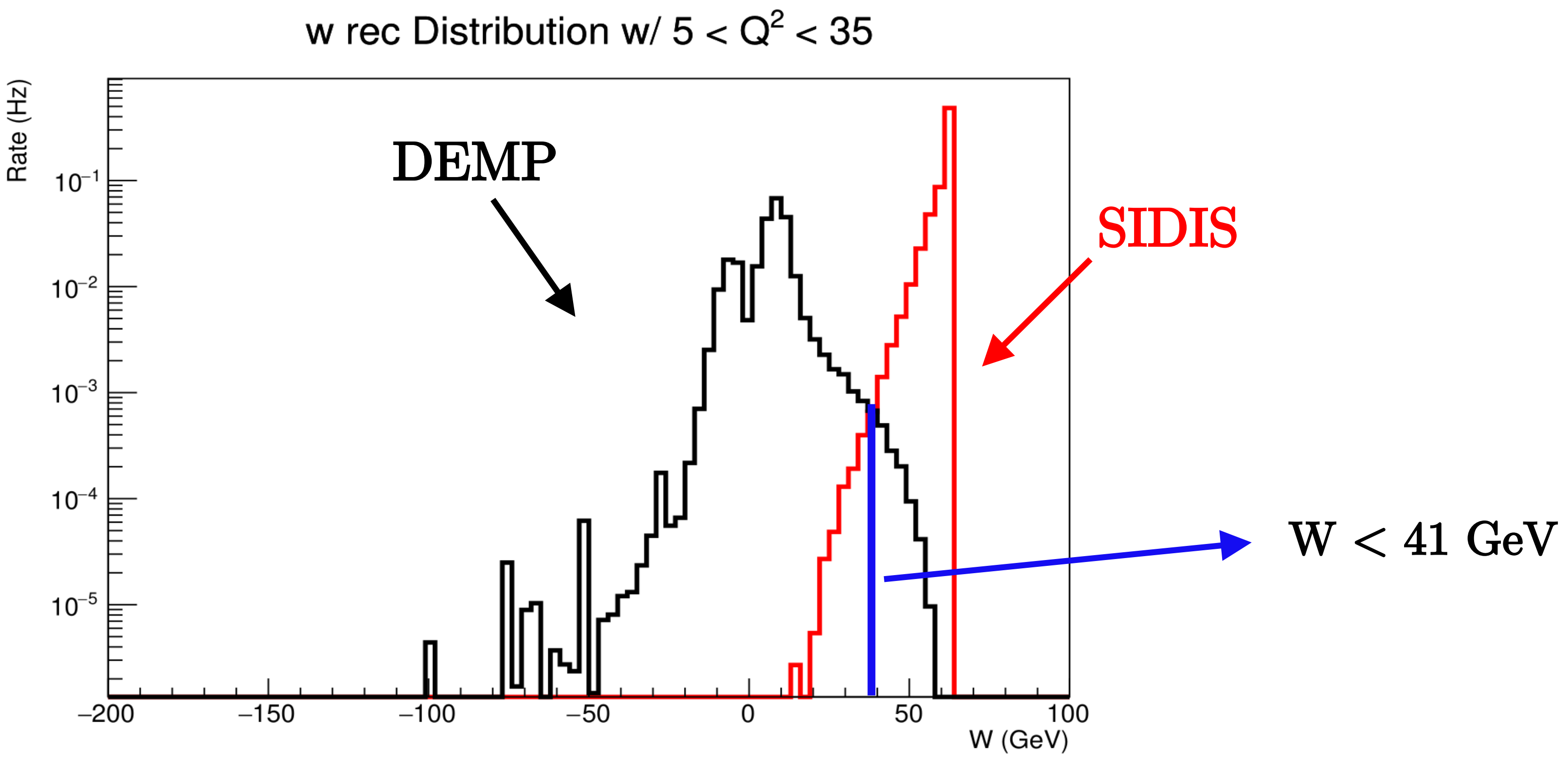
- Considered $-0.09 < \Delta\theta < 0.13$ & $-40 < \Delta\phi < 40$ events.



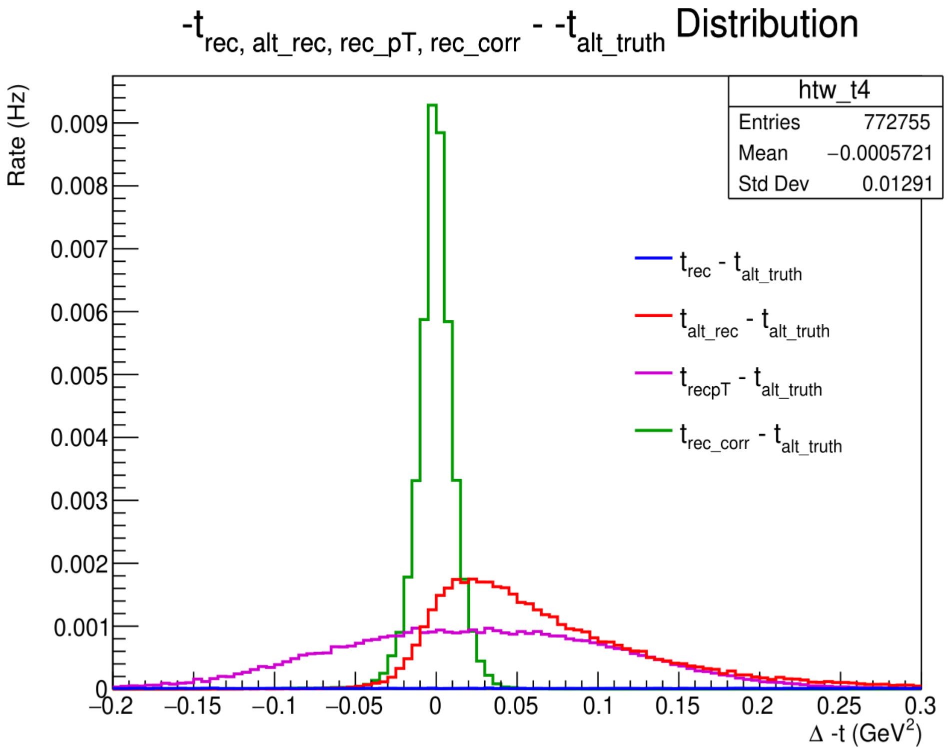

[Using ECCE simulations for 5(e) on 100(p)]

# Removed SIDIS background with W cut



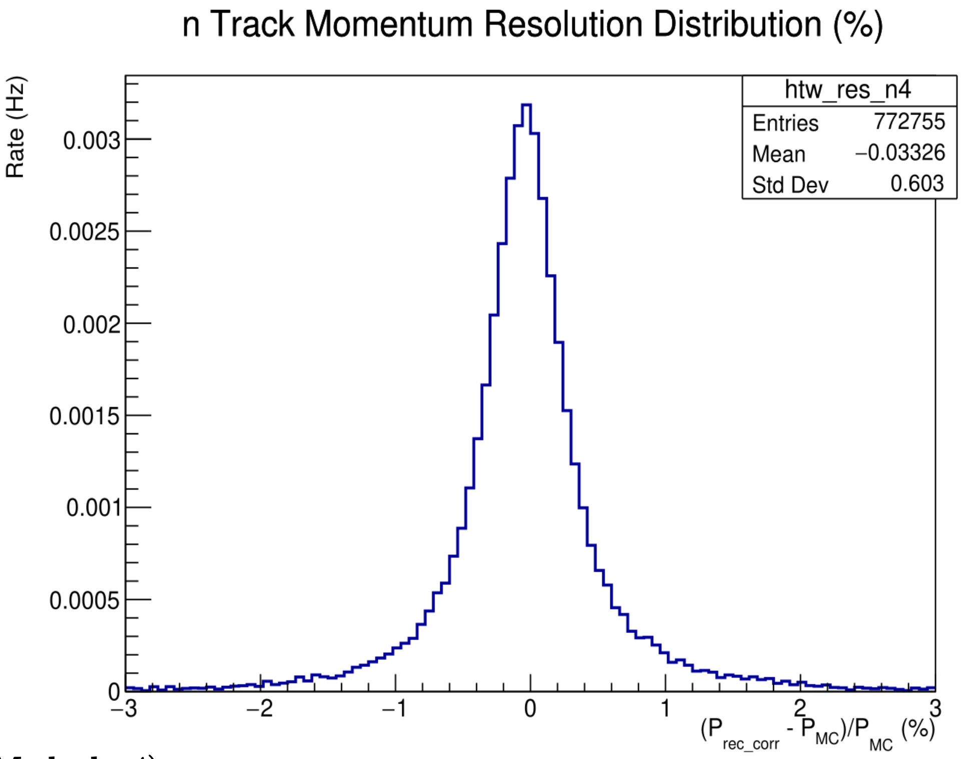
# Comparison of $\Delta$ -t from various methods

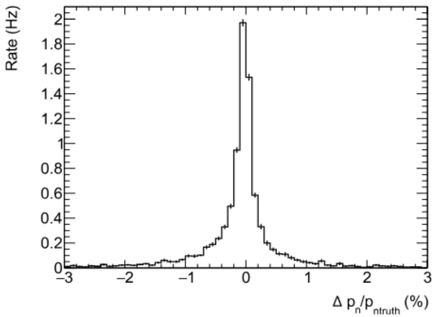
- Cuts: -t, E, $\Delta\theta$, $\Delta\phi$, $Q^2$, and W.



# Neutron track momentum resolution

- Cuts: -t, E, $\Delta\theta$, $\Delta\phi$, $Q^2$, and W.



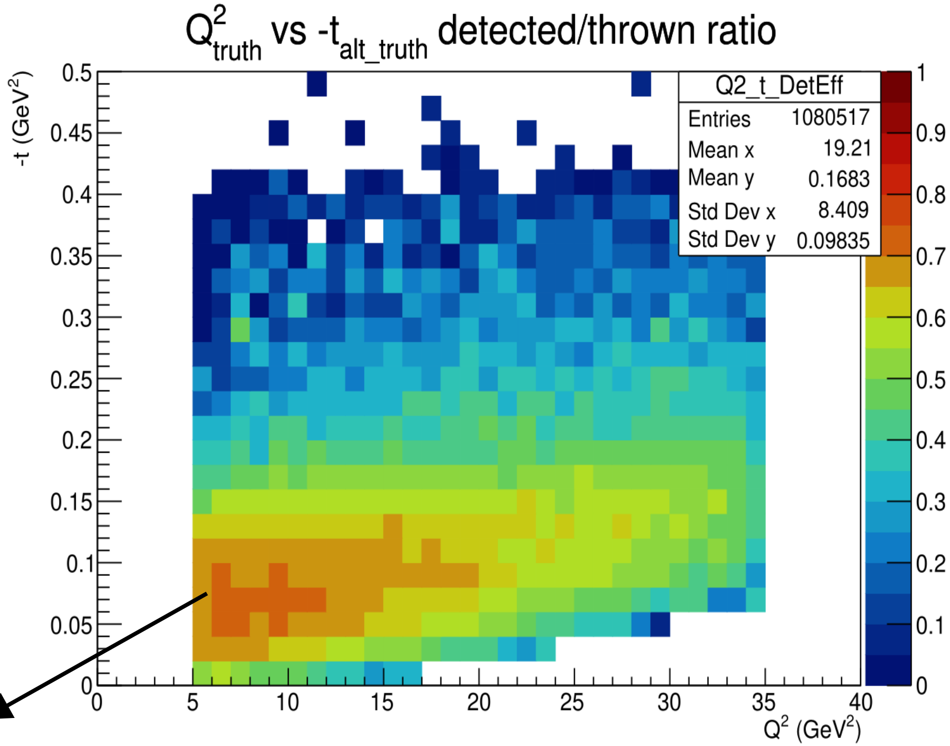



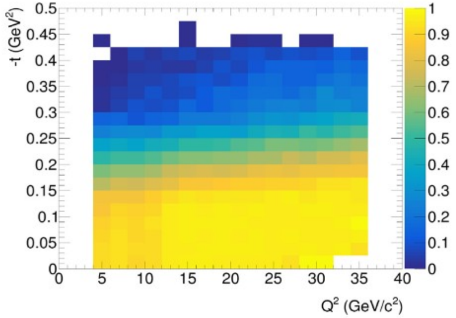

[Using ECCE simulations for 5(e) on 100(p)]

Using corrected neutron track (or Method - 4).

# Detection efficiency per ($Q^2$,t) bin

- Cuts: -t, E, $\Delta\theta$, $\Delta\phi$, $Q^2$, and W.



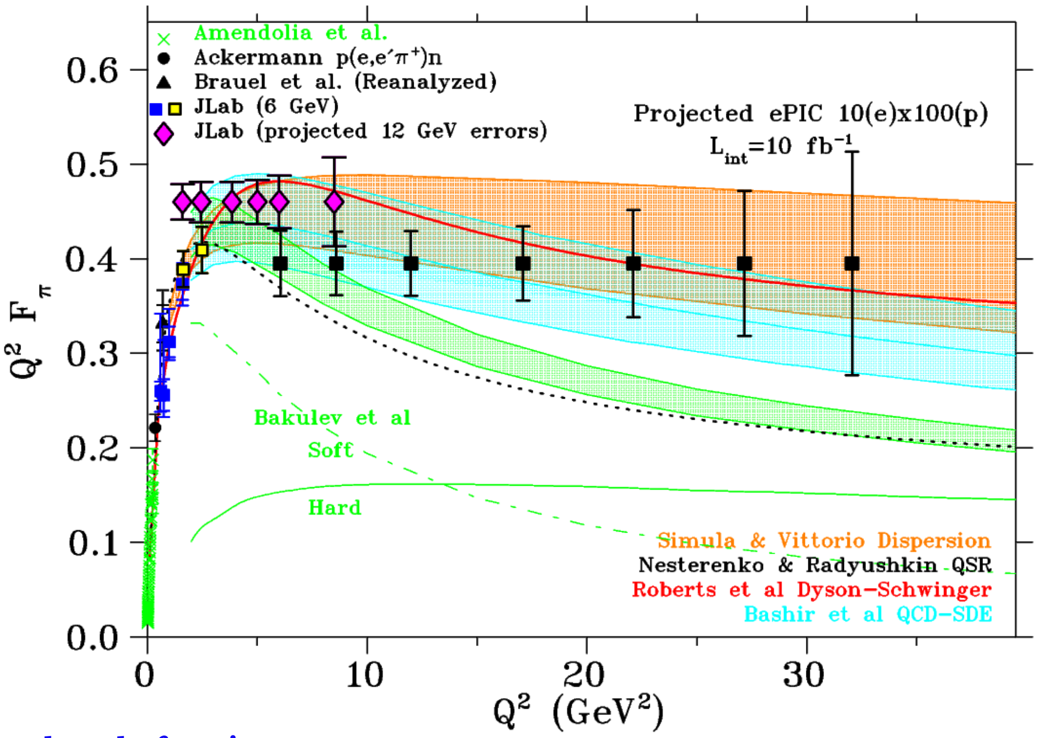



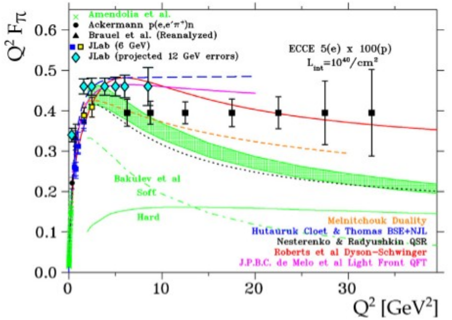

[Using ECCE simulations for 5(e) on 100(p)]

Detection efficiency best in crucial low -t region.

# Form factor projections

- Cuts: -t, E, $\Delta\theta$, $\Delta\phi$, $Q^2$, and W.




[Using ECCE simulations for 5(e) on 100(p)]

Higher $Q^2$ is now more feasible than before !

# Summary

- Results so far look more promising than the previous simulation framework.
- Reconstructed neutrons using B0 – EMCAL information, enable achieving higher values of -t.
- Accessing -t distribution over a wide range by combining information from ZDC – HCAL & B0 – EMCAL.

To-do list:

- Focus on the kaon electro-production reaction.
- Reconstruction of $\Lambda/\Sigma^0$ is considerably more challenging.
- Extend the parametrization ranges for the $\pi^+$ module to higher $Q^2$.
- Improve the parametrization for the $\pi^+$ module in DEMPgen.
- Incorporate the studies with the Deuteron beam in DEMPgen.
- Will update the status in the upcoming meetings.

# Thank you !

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EIC-Canada

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