Light Meson Structure from Early EIC Physics

Stephen JD Kay
University of York

ePIC Early Science Workshop
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Stephen JD Kay, Garth Huber,
Love Preet

Form Factors from DEMP at the EIC

- Form factors $\rightarrow$ Momentum space distributions of partons
  - Insights into emergent hadronic mass (EHM)
- Measurements $p(e, e'\pi^{+}n)$ and $p(e, e'K^{+}\Lambda/\Sigma)$ at the EIC can potentially extend the Q^2 reach of F_{π}/F_{K}

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A. Bylinkin. et. al., NIMA 1052 (2023) 168238 https://doi.org/10.1016/j.nima.2023.168238

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- F_{π} measurement feasibility previously demonstrated
- Improvements with ePIC demonstrated previously
  - No 10x130 early science config previously
- F_K studies still to be done
  - Promising signs on Λ reconstruction in ZDC though

See https://doi.org/10.48550/arXiv.2412.12346

Simulation Overview

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  - Assume $\int \mathcal{L} = 5\ fb^{-1}$ in projections

Used $\mathcal{L} \approx 0.2629 \times 10^{33} cm^{-2} s^{-1}$, based upon assumptions on per fill $\int \mathcal{L}$ in Elke's slides

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- Ran $p(e, e'\pi^+ n)$ and $p(e, e'K^+\Lambda)$, split into three Q^2 ranges
  - $3 < Q^2 < 10$, $10 < Q^2 < 20$ and $20 < Q^2 < 35$
  - Roughly $\sim$300k generated per Q^2 range

Technically, actually a cut on the range of $\theta_{e'}$ values, directly feeds into Q^2

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- For π, processed with high acceptance (lower divergence) beam profile
  - Only pion high acceptance analysed so far
- Submit as a request to simulation campaign (300k events total), but also ran independently
  - Used 10x130 epic-craterlake detector config
  - Plots shown are from own simulation

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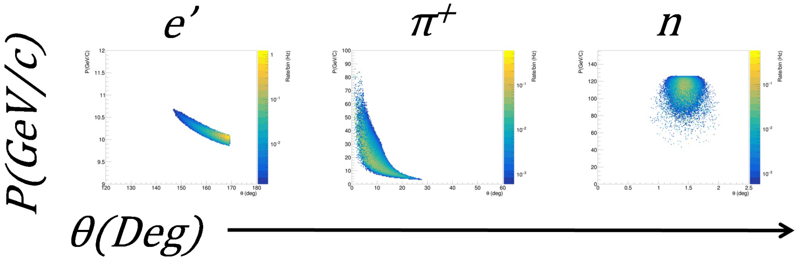
  - ZDC in particular critical for low $-t$ neutrons



Beam effects *not* removed here.
Note, in η the ranges are $-1.15 < \eta_{e'} < -2.45$, $0 < \eta_{\pi^+} < 0.9$ and $4 < \eta_n < 5.1$.

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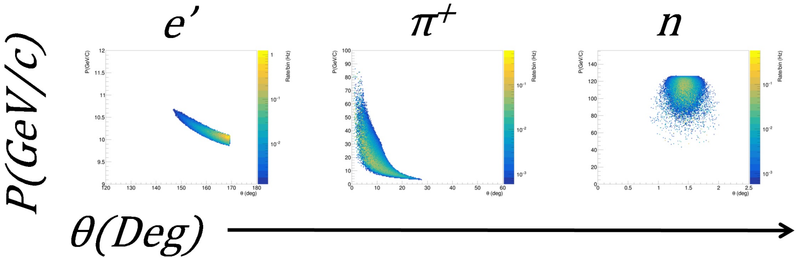
- Note that the Z scale is a rate in Hz



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  - A high energy reconstructed neutron in the ZDC
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θ^* is after a rotation of 25 mRad around the proton axis to remove the crossing angle

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- Cut on difference between ZDC hit and p_{Miss} track angles
  - $-0.09^\circ < \Delta\theta^* < 0.14^\circ$
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$\vec{P}_{Miss} = (\vec{e} + \vec{p}) - (\vec{e'}_{Rec} + \vec{\pi}_{Rec})$ - More on this in a moment

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- Also cut on $-t_{eXBABE} < 1.4$ and $W_{rec} > 0$
  - Using the TRECO convention for -t reconstruction methods

DEMP Analysis Overview - $\Delta\theta^*$ and $\Delta\phi^*$ Cuts

- P_{Miss} vector should correspond with hit location on the ZDC
- For a non-exclusive event, P_{Miss} vector should not correspond to a ZDC hit
  - Effectively an additional "exclusivity" constraint

$\Delta\theta^* = \theta^*_{PMiss} - \theta_{*\,ZDC}$ and $\Delta\phi^* = \phi^*_{PMiss} - \phi^*_{ZDC}$

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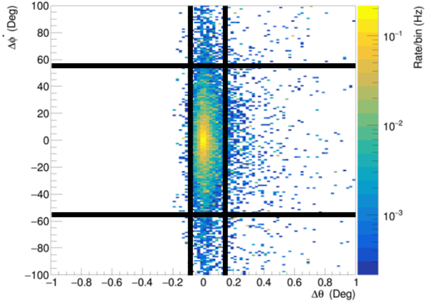

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- $\Delta\theta^* = \theta^*_{pMiss} - \theta^*_{ZDC}$
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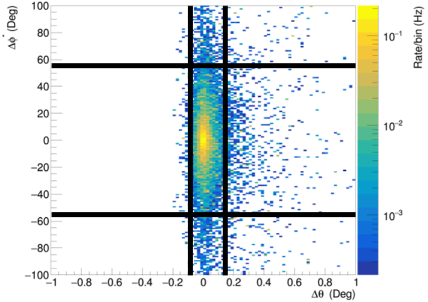
- Simulation is **exclusive only**, inclusive events spread over broader range



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- $\vec{n}_{Corr}$ uses $\vec{P}_{Miss}$, actual ZDC hit info and the exclusive nature of the reaction to "correct" the reconstructed neutron track

I.e. it is a neutron, so set the mass to the neutron mass. $\vec{P}_{Miss} = (\vec{e} + \vec{p}) - (\vec{e\prime}_{Rec} + \vec{\pi}_{Rec})$

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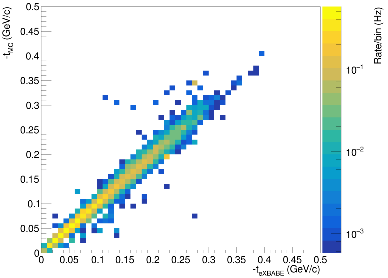

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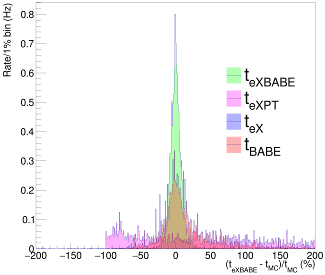
- $-t_{eXBABE}$ correlates well with truth
- Far better than methods using uncorrected neutron track (t_{BABE}) and methods utilising electron information (t_{eX}) and electron P_T (t_{eXPT}) info



$\sigma(eXBABE) = 13.36$, $\sigma(eXPT) = 83.67$, $\sigma(eX) = 111.87$, $\sigma(BABE) = 43.01$. **All $e'\pi^+n$ triple coincidence events**

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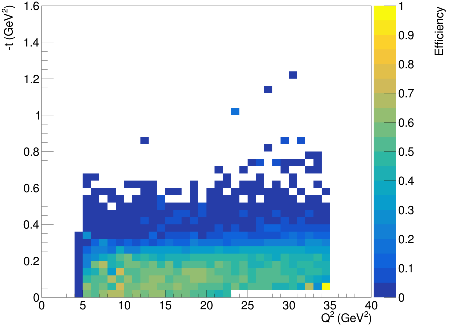

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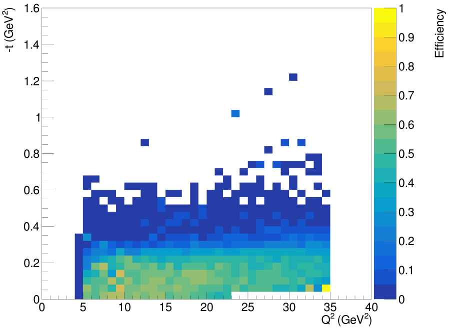
- Without B0, rapid tail off beyond $-t$ of 0.4



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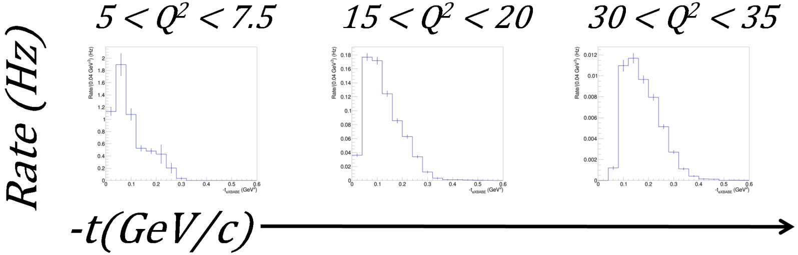

DEMP Analysis Results - $Q^2, -t$ Binning

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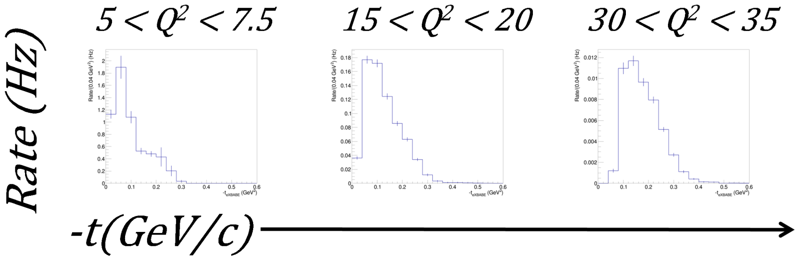

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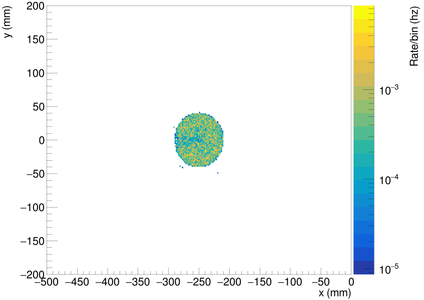

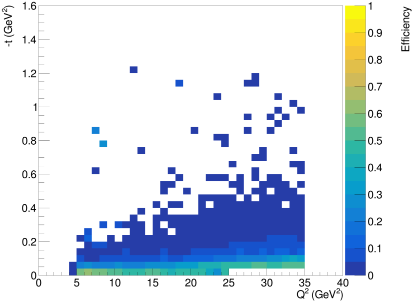

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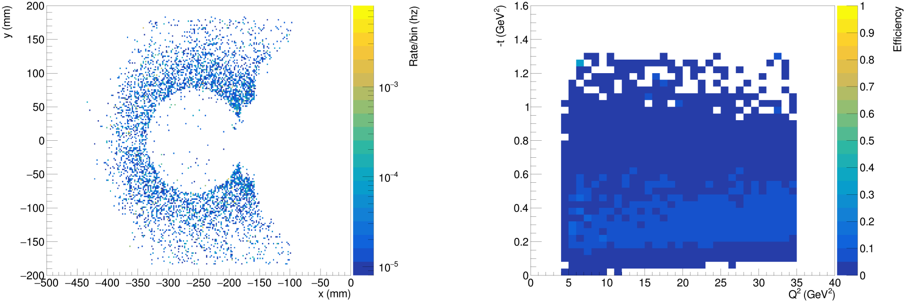

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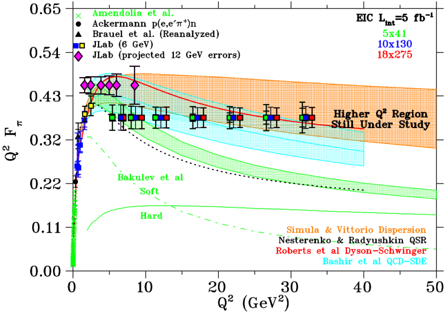

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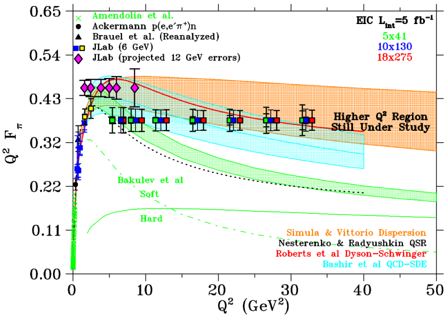

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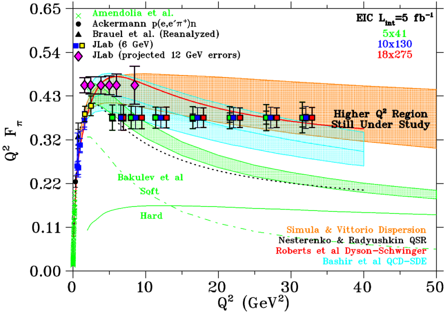

- Even from low $\int \mathcal{L}$ in early science programme, looks promising!
- How high in Q^2 will be possible?

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- $K^+\Lambda$ channel is on the agenda for later in the year

Summary

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  - More broadly, all early running settings look viable with $\int \mathcal{L} = 5\ fb^{-1}$
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  - Λ reconstruction in ZDC looks very promising
  - Expect rapid results when it is available
- New student will need some onboarding time

Thanks for listening, any questions?

stephen.kay@york.ac.uk

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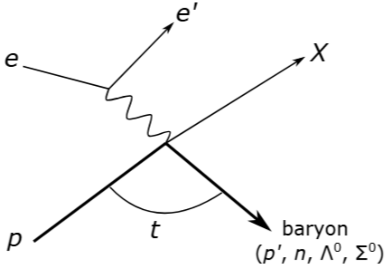
Backup Zone

The TRECO Convention

- The t-Reconstruction (tRECO)$\rightarrow$ standardized nomenclature for methods used to reconstruct the Mandelstam variable t

Class name	Observables used
BABE	$p^{\mu}_{\mathrm{BA}}, p^{\mu}_{\mathrm{BE}}$
eX	$p^{\mu}_{\gamma^*}, p^{\mu}_{\mathrm{X}}$
eXBA	$p^{\mu}_{\gamma^*}, p^{\mu}_{\mathrm{X}}, p^{\mu}_{\mathrm{BA}}$
eXBE	$p^{\mu}_{\gamma^*}, p^{\mu}_{\mathrm{X}}, p^{\mu}_{\mathrm{BE}}$
eBABE	$p^{\mu}_{\gamma^*}, p^{\mu}_{\mathrm{BA}}, p^{\mu}_{\mathrm{BE}}$
XBABE	$p^{\mu}_{\mathrm{X}}, p^{\mu}_{\mathrm{BA}}, p^{\mu}_{\mathrm{BE}}$
eXBABE	$p^{\mu}_{\gamma^*}, p^{\mu}_{\mathrm{X}}, p^{\mu}_{\mathrm{BA}}, p^{\mu}_{\mathrm{BE}}$

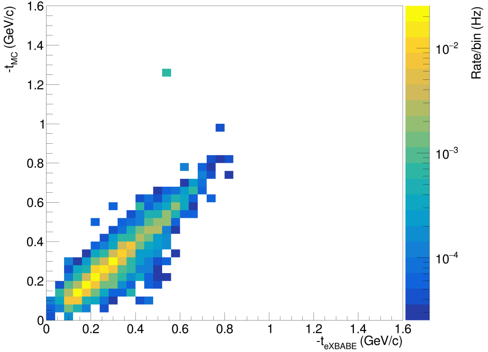


- Subscripts in $-t$ refer to 4-momenta utilised in calculation as shown in table above
  - BA $\rightarrow$ **Ba**ryon, BE $\rightarrow$ Proton **Be**am

DEMP Analysis Overview - $-t$ Reconstruction

- 5x41 events in the B0 still have good $-t$ reconstruction

- Strong correlation with $-t_{MC}$
- Lower resolution that ZDC neutrons though



EIC Early Running - Plans

- Early science programme for ePIC is a current priority
- Proposed schedule has been presented and is evolving

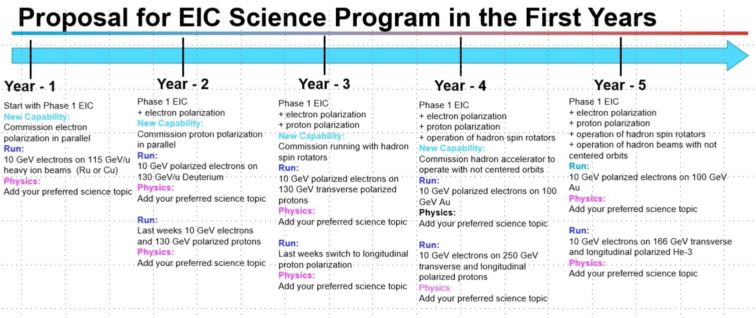


Image - Modified from Elke's slides at ePIC User Group Meeting, Frascati 2025

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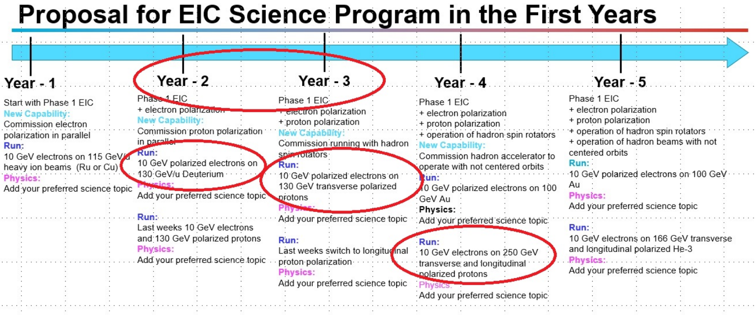
  - Opportunities early on for light meson form factors



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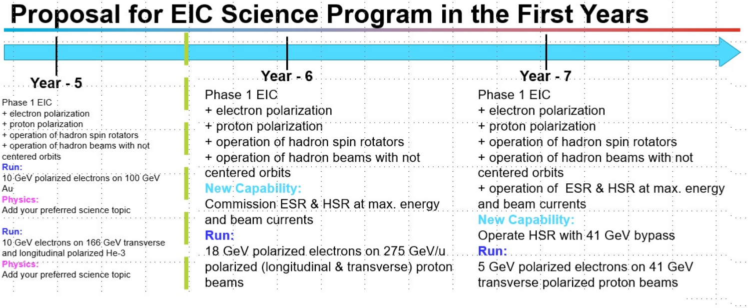
EIC Early Running - Plans

- Early science programme for ePIC is a current priority
- Proposed schedule has been presented and is evolving
  - Opportunities early on for light meson form factors



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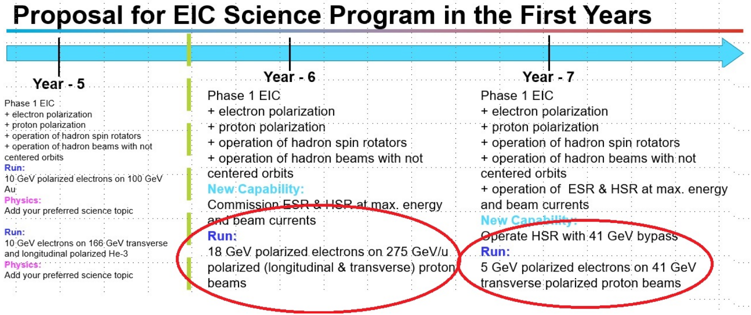

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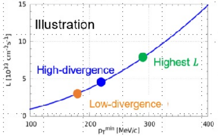
ep Luminosity for Phase-1

High Divergence	Lumi per Fill (5 h)	Lumi per Year	Low Divergence	Lumi per Fill (5 h)	Lumi per Year
5 GeV e x 250 GeV p	9.26 pb^{-1}	6.48 fb^{-1}	5 GeV e x 250 GeV p	6.81 pb^{-1}	4.78 fb^{-1}
10 GeV e x 250 GeV p	13.12 pb^{-1}	9.18 fb^{-1}	10 GeV e x 250 GeV p	8.8 pb^{-1}	6.19 fb^{-1}
5 GeV e x 130 GeV p	6.3 pb^{-1}	4.36 fb-1	5 GeV e x 130 GeV p	5.8 pb^{-1}	4.1 fb^{-1}
10 GeV e x 130 GeV p	7.6 pb^{-1}	5.33 fb^{-1}	10 GeV e x 130 GeV p	7.1 pb^{-1}	4.95 fb^{-1}

Compare to HERA integrated luminosity 1992 – 2007: 0.6 fb^{-1}

Remember:
high divergence: higher lumi, but reduced acceptance for low forward particle p_t^{min}
low divergence: lower lumi, but increased acceptance for low forward particle p_t^{min}
→ important for exclusive processes



- Modest $\int \mathcal{L}$, $\sim 5\ fb^{-1}$, in first few years
- New configurations to check for F_π studies

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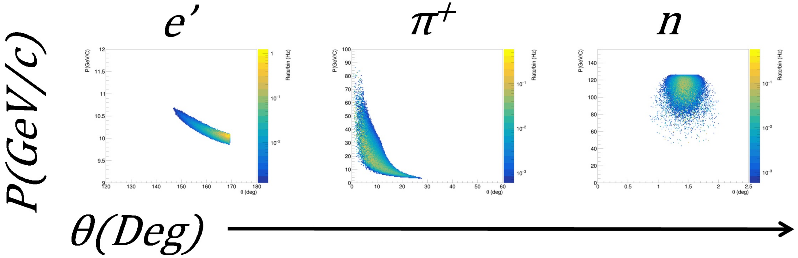
DEMP Kinematics - Reconstructed Distributions

- Processed same 10x130 events through EICrecon



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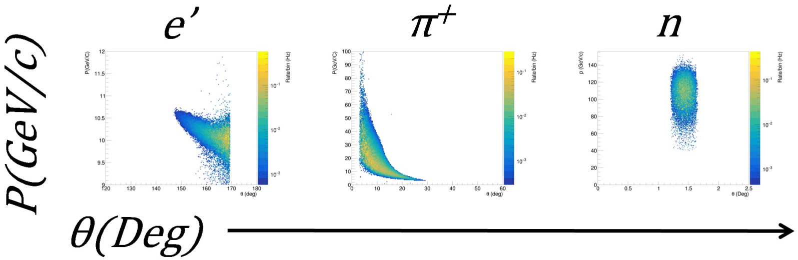

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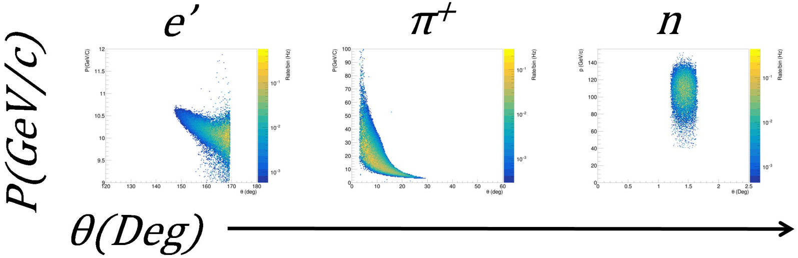
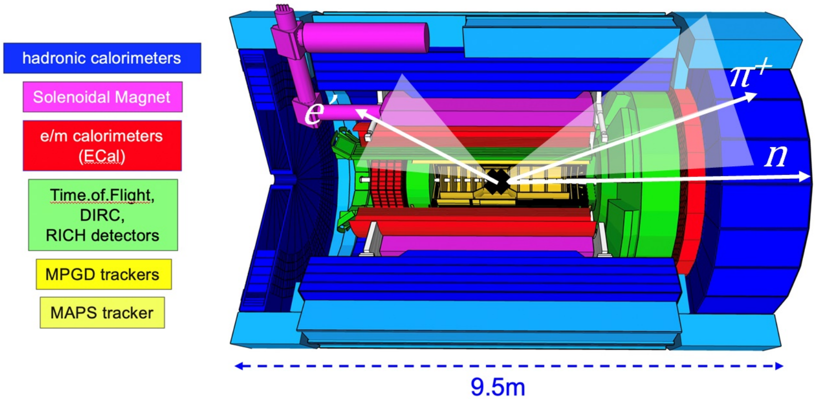
- ZDC performance and $-t$ reconstruction critical



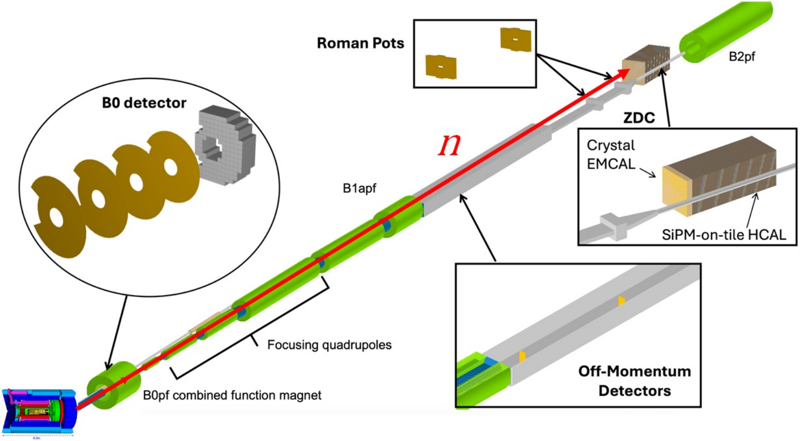
DEMP Kinematics - Visualising with ePIC

- e' and π^+ hit the central detector



DEMP Kinematics - Visualising with ePIC

- e' and π^+ hit the central detector
- n very forward focused, ZDC or B0



Meson Form Factors

- Charged pion ($\pi^{\pm}$) and kaon ($K^{\pm}$) form factors (F_{π}, F_{K}) are key QCD observables
  - Momentum space distributions of partons within hadrons

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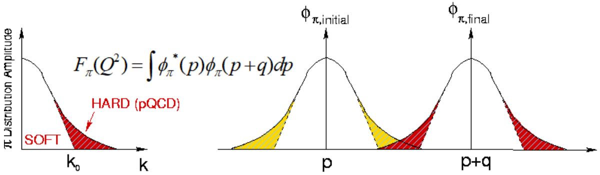

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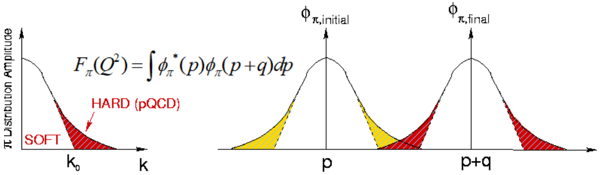

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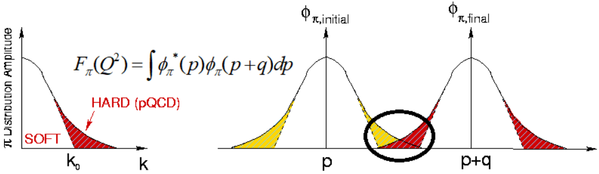

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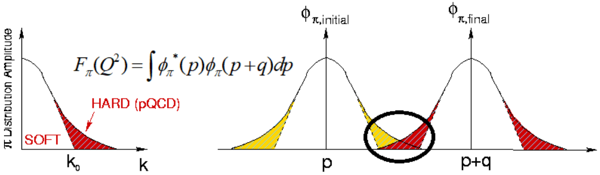

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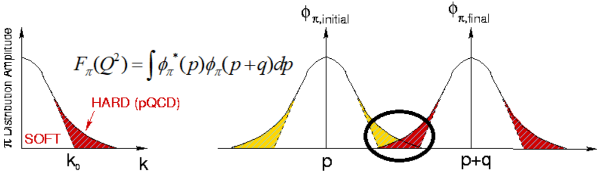

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- **F_π and F_K of special interest in hadron structure studies**
  - π - Lightest QCD quark system, simple
  - K - Another simple system, contains strange quark

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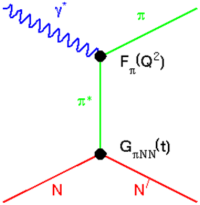

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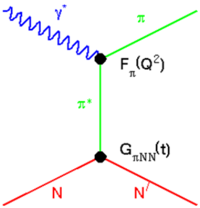

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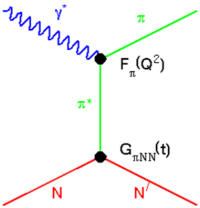

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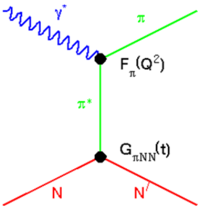

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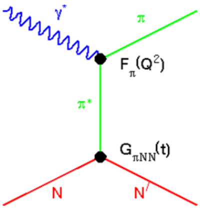

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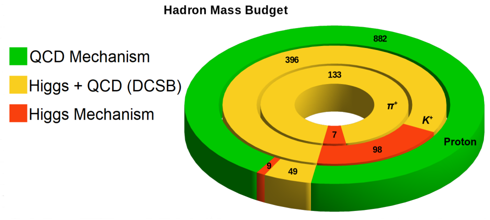
- Measure **D**eep **E**xclusive **M**eson **P**roduction (**DEMP**)

Hadron Mass Budgets



Revealing the structure of light pseudoscalar mesons at the electron–ion collider

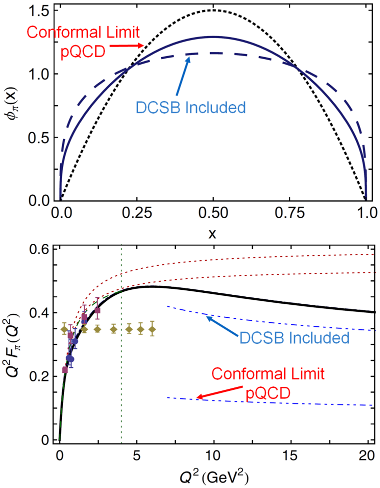
J Arrington[1], C Ayerbe Gayoso[2], P C Barry[3,4], V Berdnikov[5], D Binosi[6], L Chang[7], M Diefenthaler[3], M Ding[6], R Ent[3], T Frederico[8], Y Furletova[3], T J Hobbs[3,9,10], T Horn[3,5,*], G M Huber[11], S J D Kay[11], C Keppel[3], H-W Lin[12], C Mezrag[13], R Montgomery[14], I L Pegg[5], K Raya[7,15], P Reimer[16], D G Richards[3], C D Roberts[17,18], J Rodríguez-Quintero[19], D Romanov[3], G Salmè[20], N Sato[3], J Segovia[21], P Stepanov[5], A S Tadepalli[3] and R L Trotta[5]

- Only the portion in red is directly from the Higgs current
- Multiple mechanisms at play to give hadrons their mass
  - Mass generation mechanisms intricately connected to structure
- **The simple $q\bar{q}$ valence structure of mesons makes them an excellent testing ground**
- What can we examine to look at their structure?

Image - G. Huber, modified figure from paper listed.

Connecting Pion Structure and Mass Generation

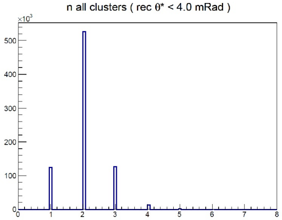
- Calculating the pion PDA, ϕ_π, without incorporating DCSB produces a broad, concave shape
- Incorporating DCSB changes $\phi_\pi(x)$ and brings F_π calculation much closer to the data
    - "Squashes down" PDA
- Pion structure and hadron mass generation are interlinked

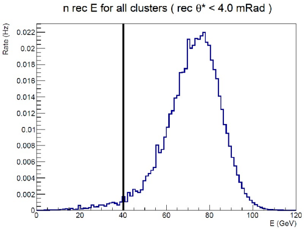


L. Chang, et al., PRL110(2013) 132001, PRL111(2013), 141802

ZDC Neutron Reconstruction

- ePIC ZDC design updated significantly recently
- Most events in ZDC have more than 1 cluster, select large energy deposition events

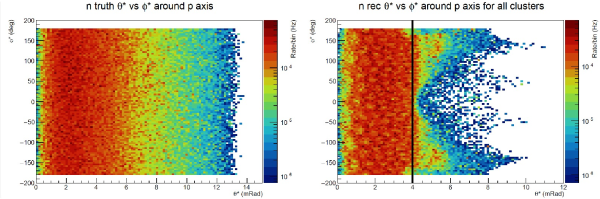




Plot from L. Preet, University of Regina

ZDC Neutron Reconstruction

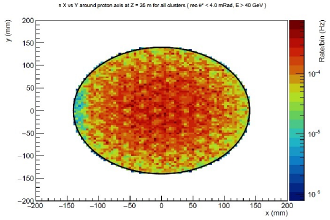
- ePIC ZDC design updated significantly recently
- Most events in ZDC have more than 1 cluster, select large energy deposition events
- New “ReconstructedFarForwardZDCNeutrons” branch
  - Reconstructed events combine clusters already
- Select region of uniform acceptance ($\theta^* < 4\ mRad$) to analyse

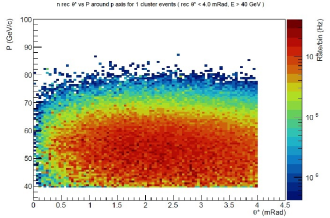


Plot from L. Preet, University of Regina
θ^* and * are after a rotation of 25 mRad around the proton axis to remove the crossing angle.

ZDC Neutron Reconstruction - Does it make sense?

- Selected reconstructed neutrons should actually hit the ZDC
  - Quick to check!
- Events all fall on face of ZDC
- Hexagonal pattern seen, consequence of ZDC reconstruction algorithm
- Next step, reconstruct $-t$ and apply further cuts
- Not straightforward!

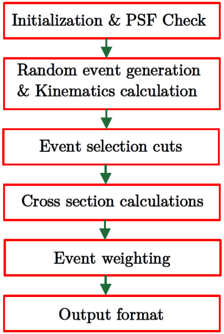




Plots from L. Preet, University of Regina

DEMPgen

- DEMPgen - **D**eep **E**xclusive **M**eson **P**roduction event generator
- Fixed target (JLab) and colliding beams (EIC) modes
- Feed in an input .json file
  - Specify conditions
  - Beam energies, number of events etc
- Several reactions available
  - $p(e, e'\pi^+ n)$
  - $p(e, e' K^+ \Lambda)$
  - ...
- Further details in recent paper

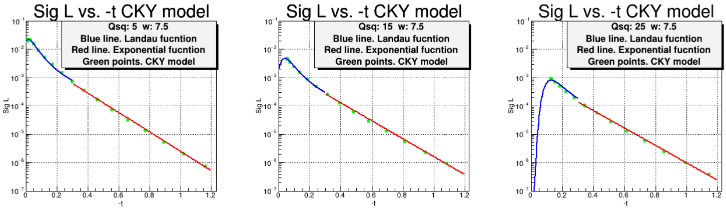


https://doi.org/10.1016/j.cpc.2024.109444

DEMPgen - Parametrisation

- DEMPgen uses parameterised Regge-based models
  - For $p(e, e'\pi^+n)$, use CKY model

σ_L and σ_T across broad kinematic range applicable to EIC
  - $5 < Q^2 < 35$, $2 < W < 10$, $0 < -t < 1.2$
  - Ranges currently being revisited
  - Upgrades from kaon parameterisation being incorporated



Authors of model are - T.K. **C**hoi, K.J. **K**ong and B.G. **Y**u - **CKY**

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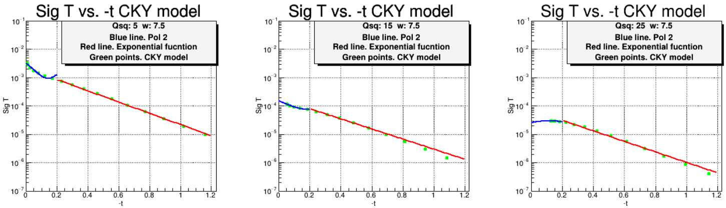

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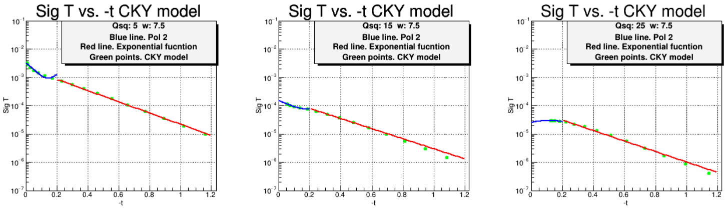


- Kaon reactions $\rightarrow$ Use VGL model

Authors of model are - M.**V**anderhaeghen, M. **G**uidal and J.-M.**L**aget - **VGL**

Isolating σ_L from σ_T in an e-p Collider

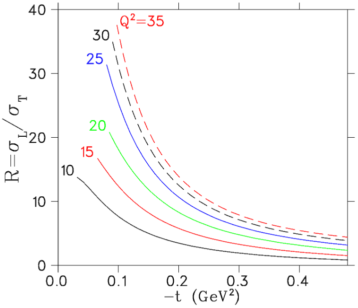
- For a collider -

$$\epsilon = \frac{2(1-y)}{1+(1-y)^2} \quad \text{with} \quad y = \frac{Q^2}{x(s_{tot} - M_N^2)}$$

  - y is the fractional energy loss
- Systematic uncertainties in σ_L magnified by $1/\Delta\epsilon$
  - Ideally, $\Delta\epsilon > 0.2$
- To access $\epsilon < 0.8$ with a collider, need $y > 0.5$
  - Only accessible at small s_{tot}
  - Requires low proton energies (~ 10 GeV)
- **Conventional L-T separation not practical, need another way to determine σ_L**

σ_L Isolation with a Model at the EIC

- QCD scaling predicts $\sigma_L \propto Q^{-6}$ and $\sigma_T \propto Q^{-8}$
- At the high Q^2 and W accessible at the EIC, phenomenological models predict $\sigma_L \gg \sigma_T$ at small $-t$
- Can attempt to extract σ_L by using a model to isolate dominant $d\sigma_L/dt$ from measured $d\sigma_{UNS}/dt$
- Examine π^+/π^- ratios as a test of the model

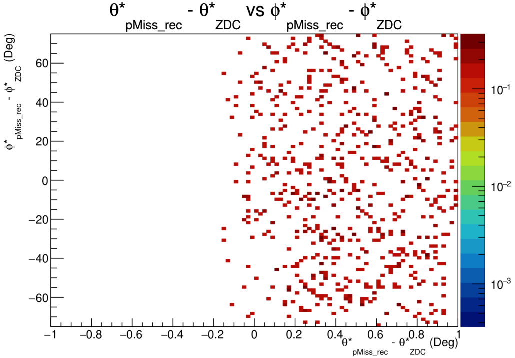


Predictions are assuming $\epsilon > 0.9995$ with the kinematic ranges seen earlier

T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

Background Events

- Main source of background is SIDIS, $p(e, e'\pi^+)X$, events
- Compare SIDIS events for same beam energy
- Very few fall in comparable $\Delta\theta$ and $\Delta\phi$ range



Plot from L. Preet, University of Regina

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- Need data at lowest possible $-t$ for form factor extraction
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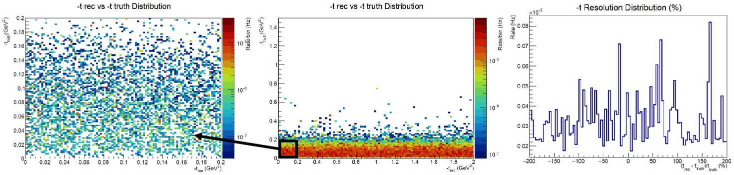

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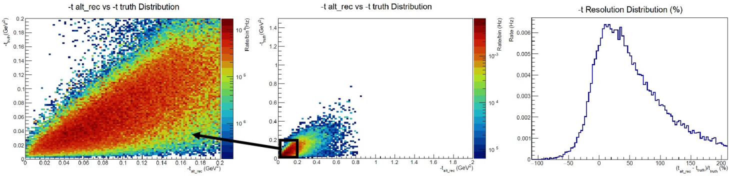
$$-t_{truth} = \left(\vec{\gamma^{*}} - \vec{\pi^{+}}\right)^{2} \quad -t_{rec} = (\vec{p} - \vec{n})^{2}$$

- So, maybe a different approach?
- Use the proton beam and detected neutron



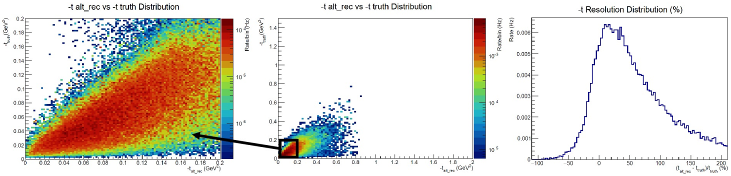
Plots from L. Preet, University of Regina

$-t$ Reconstruction

- Need data at lowest possible $-t$ for form factor extraction
- Can calculate $-t$ via -

$$-t_{truth} = \left(\vec{\gamma^*} - \vec{\pi^+}\right)^2 \quad -t_{rec} = (\vec{p} - \vec{n})^2$$

- Not great, not terrible. Try again



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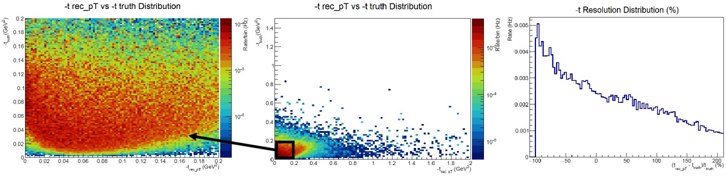

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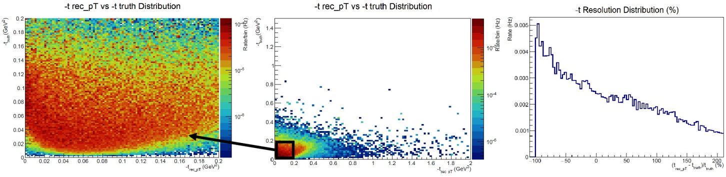
- Use P_T approach
- Even worse! Back to the proton and neutron



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

- Exploit what we know, ZDC hit angles, P_{Miss} from π^+, e' <u>and</u> the mass of the remaining particle

$P_{miss} = |\vec{p_e} + \vec{p_p} - \vec{p_{e'}} - \vec{p_{\pi^+}}|$, see previous paper for more details

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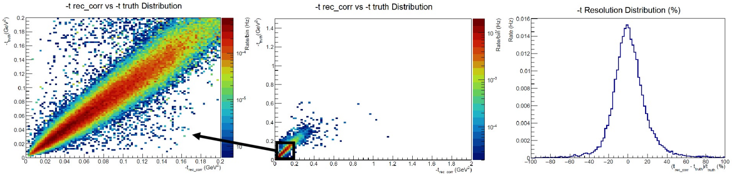
$$-t_{truth} = \left(\vec{\gamma^*} - \vec{\pi^+}\right)^2 \quad -t_{rec} = (\vec{p} - n\vec{Corr})^2$$

- Exploit what we know, ZDC hit angles, P_{Miss} from π^+, e' <u>and</u> the mass of the remaining particle
- Correct neutron 4 vector using this info - n_{corr}



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$P_{miss} = |\vec{p_e} + \vec{p_p} - \vec{p_{e'}} - \vec{p_{\pi^+}}|$, see previous paper for more details

“Hold on, what was that bit about the neutron...”

- Utilise **position info** from ZDC and that reaction is **exclusive**
  - $\vec{P}_{Miss} = (\vec{e} + \vec{p}) - (\vec{e\prime}_{Rec} + \vec{\pi}_{Rec})$
  - $\vec{n}_{Rec} \rightarrow$ Get from ZDC hit info, determine angles
    - θ_{nRec}
    - ϕ_{nRec}
- Make a new vector, $\vec{n}_{Corr}$
  - Use $|\vec{P}_{Miss}|$, θ_{nRec},ϕ_{nRec} and set mass to neutron mass

- This is incorporated in the main analysis loop
- Can now use new 4-vector in t calculation

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  - $P_x \rightarrow |\vec{P}_{Miss}| \times \sin(\theta_{nRec}) \times \cos(\phi_{nRec})$...
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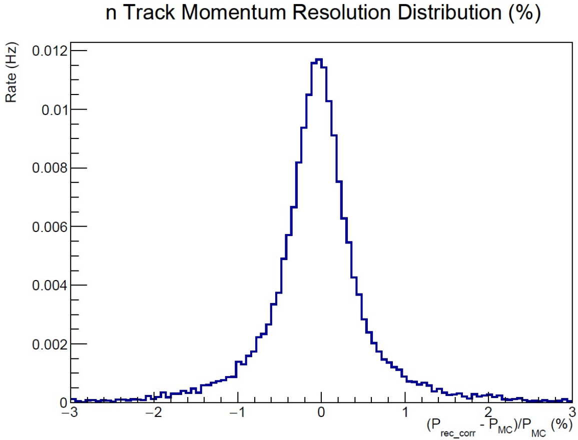
Simulation Results - Neutron Reconstruction

- $\vec{n}_{Corr}$ resolution very good
- Few % resolution



ZDC Lambda and Sigma Reconstruction

- Exciting new study on the arXiv just before Christmas
  - https://doi.org/10.48550/arXiv.2412.12346
  - S.J. Paul et. al.
- Λ^0 and Σ^0 detection in the ZDC looks promising!

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- Position and angular resolution **far exceed YR requirements for neutrons**
- Performance very similar to neutron detection

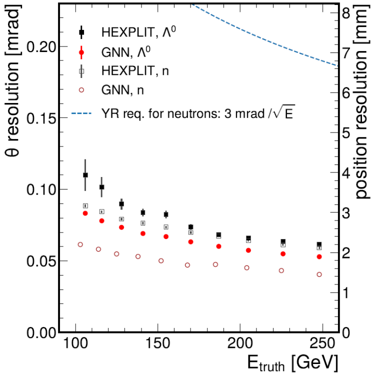

Figure from - https://arxiv.org/abs/2412.12346

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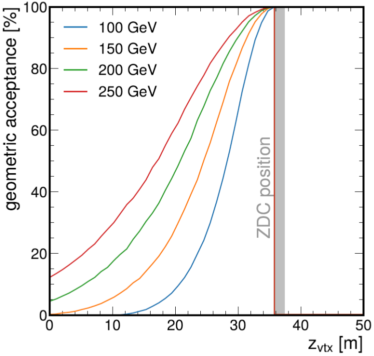

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- Acceptance for neutral decay improves with Λ^0 energy
- Depends strongly upon decay z_{vtx}
- Smear MC truth and apply acceptance in line with paper
- Potential for rapid F_K projections
- Need updated projections to lower Λ^0 energies for 10x100 or 5x41