Probing Light Meson Structure with DEMP

Stephen JD Kay
University of York

ePIC Collaboration Meeting,
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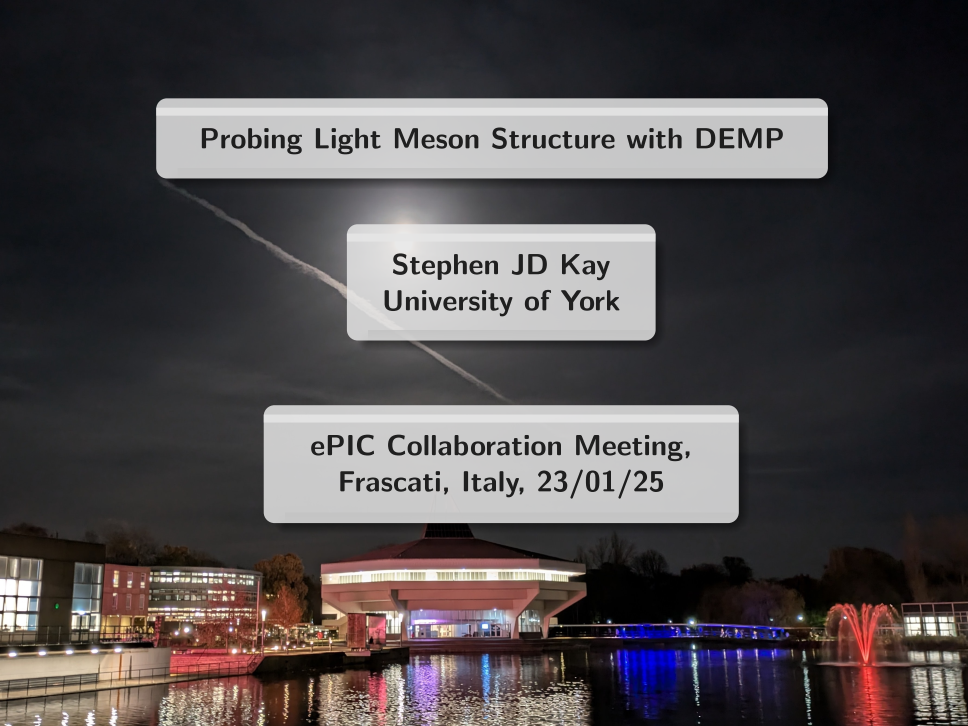

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- ePIC Projections - Latest Results and Improvements

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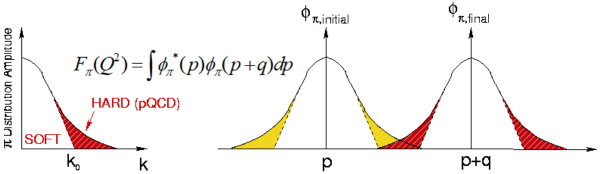

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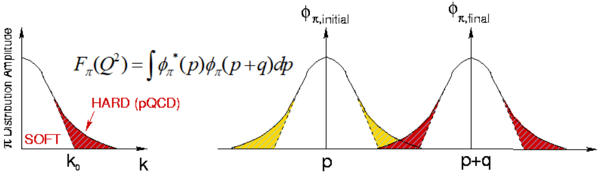

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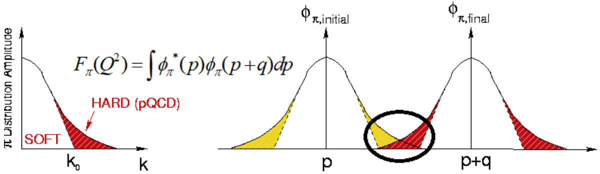

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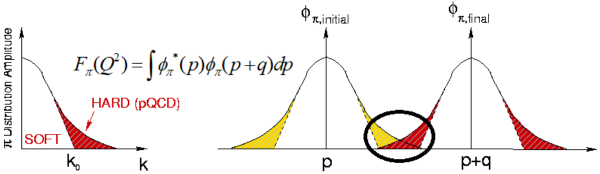

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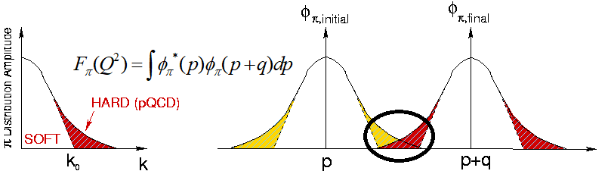

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- **F_{π} and F_K of special interest in hadron structure studies**
  - π - Lightest QCD quark system, simple
  - K - Another simple system, contains strange quark

Measurement of F_π at High Q^2

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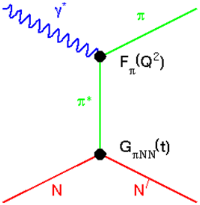

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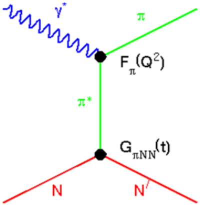

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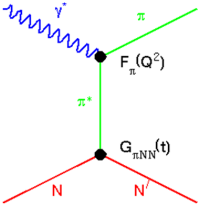

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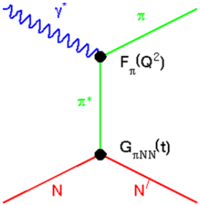

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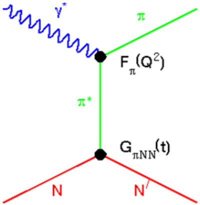

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- Measure **D**eep **E**xclusive **M**eson **P**roduction (**DEMP**)

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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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A. Bylinkin. et. al., NIMA 1052 (2023) 168238 https://doi.org/10.1016/j.nima.2023.168238, DEMPgen https://github.com/JeffersonLab/DEMPgen/releases/tag/v1.2.2

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- Event generator recently modified to generate kaon events
  - Next extension of studies $\rightarrow$ Can we measure F_K too?

More details in recent DEMPgen paper

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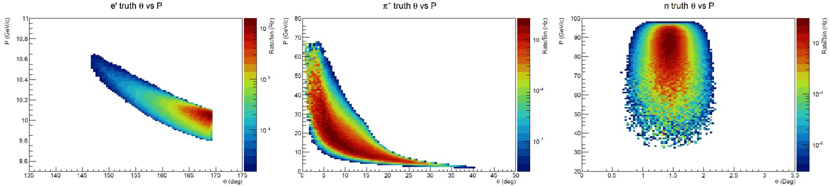

Plot from L. Preet, University of Regina
Note, in η the ranges are $-1.15 < \eta_{e'} < -2.45$, $0 < \eta_{\pi^+} < 0.9$ and $4 < \eta_n < 5.1$.

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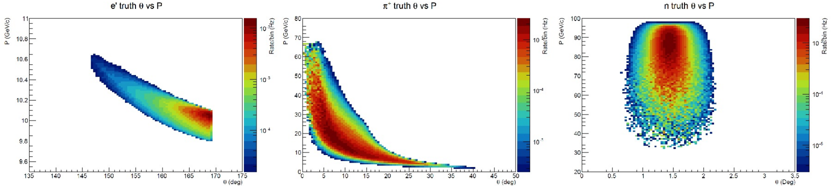
- Note that the Z scale is a rate in *Hz*



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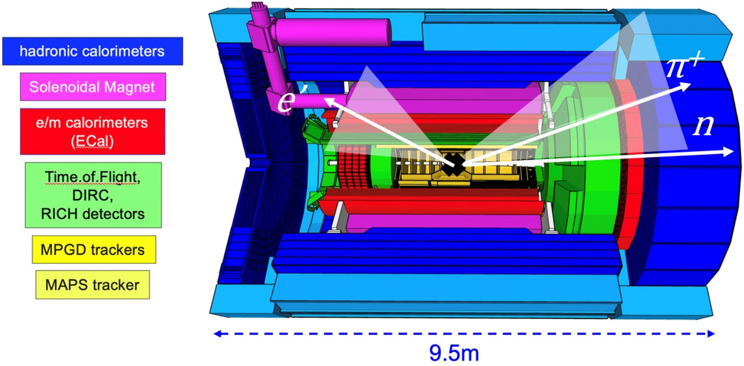

Modified from `https://wiki.bnl.gov/EPIC/images/5/5e/Epic072023.png`

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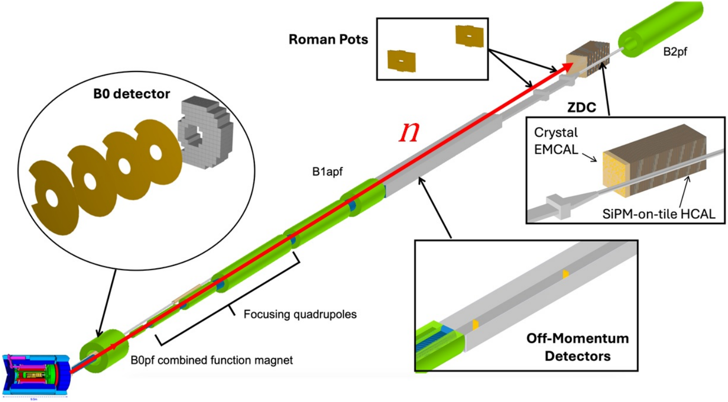

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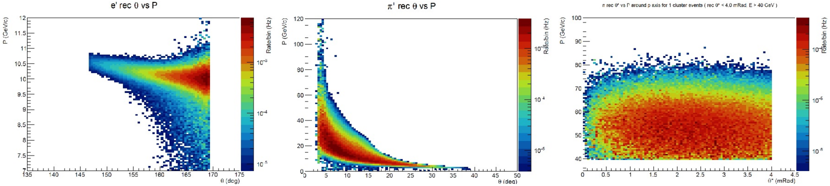

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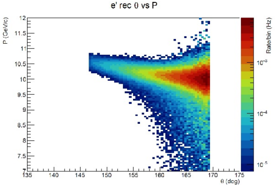
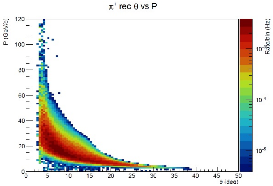
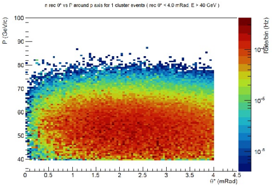
- ZDC performance and $-t$ reconstruction critical







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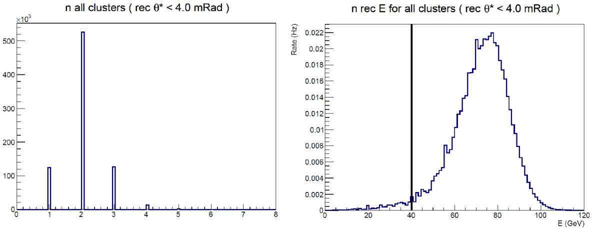

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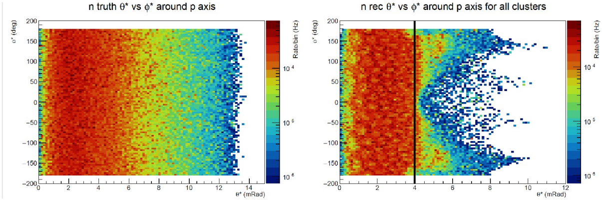

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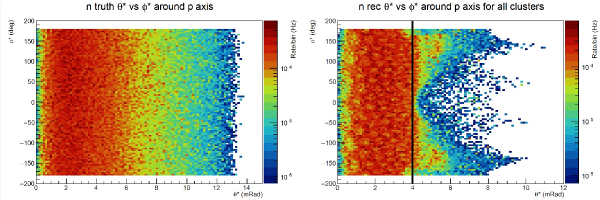
- Select region of uniform acceptance ($\theta^* < 4\ mRad$) to analyse



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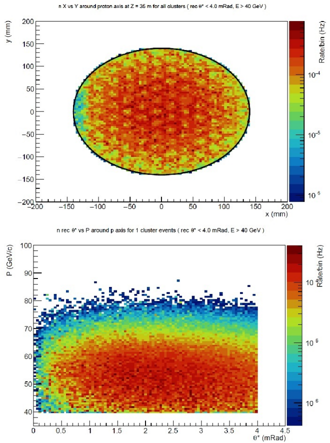

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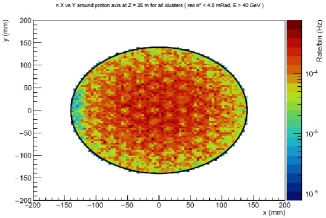

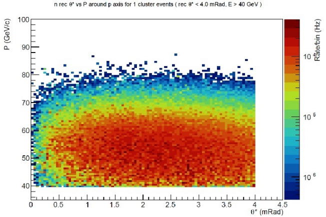

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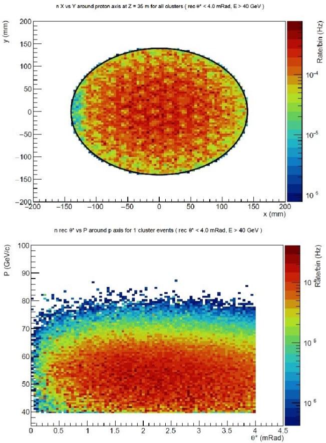
- Not straightforward!



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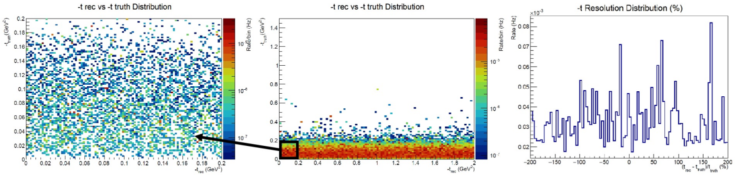

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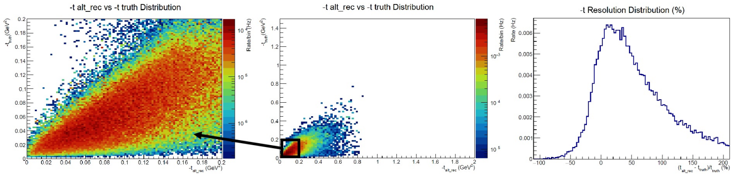
- So, maybe a different approach?
- Use the proton beam and detected neutron



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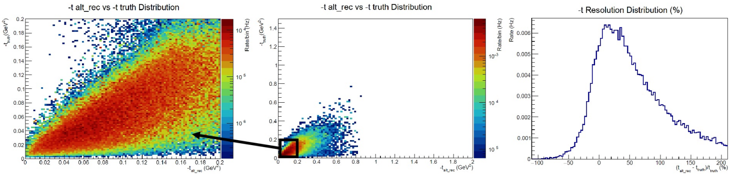
- Not great, not terrible. Try again



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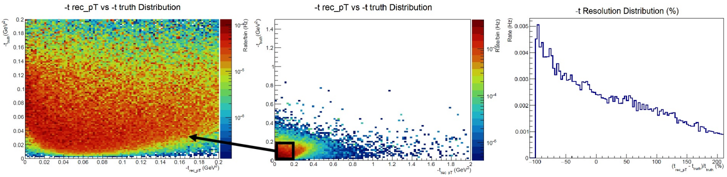

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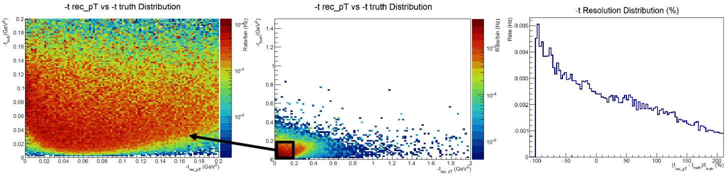
- Use P_T approach
- Even worse! Back to the proton and neutron



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- Exploit what we know, ZDC hit angles, P_{Miss} from π^+, e' and 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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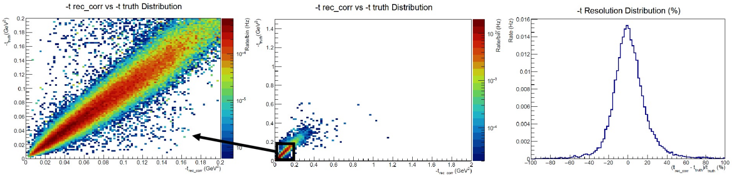
$$-t_{truth} = \left(\vec{\gamma^*} - \vec{\pi^+}\right)^2 \quad -t_{rec} = (\vec{p} - \vec{nCorr})^2$$

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



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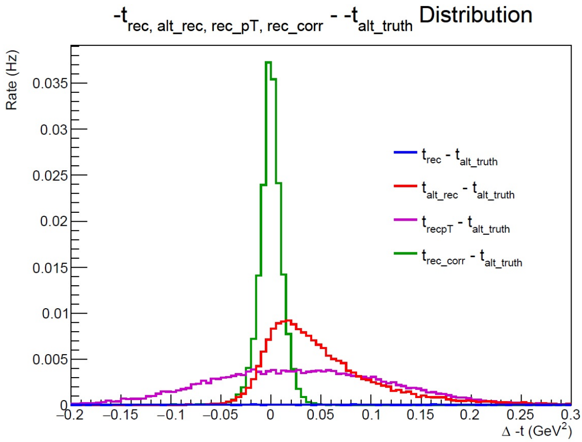
$P_{miss} = |\vec{p_e} + \vec{p_p} - \vec{p_{e'}} - \vec{p_{\pi^+}}|$, see previous paper for more details

Comparison of $-t$ Reconstruction Methods

- Corrected neutron track clearly gives best $-t$ reconstruction
- $\sim \pm 0.02$ in $-t$ for this method



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- Can now use new 4-vector in t calculation

Simulation Results - Neutron Reconstruction

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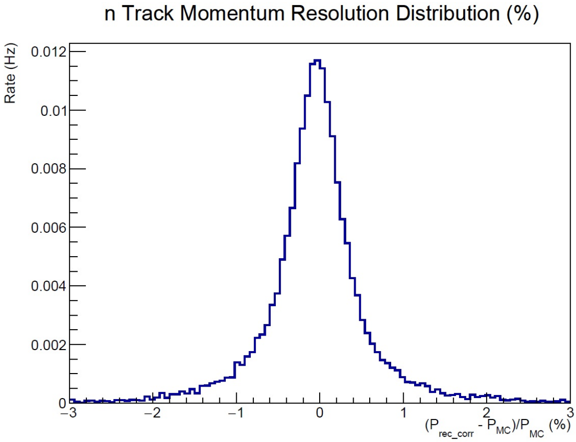
- Few % resolution



DEMP - Event Selection Cuts

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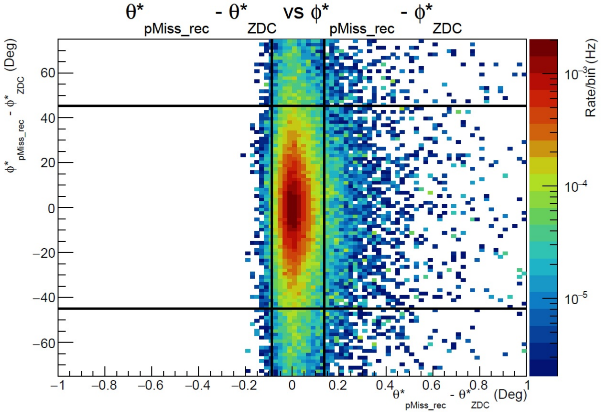

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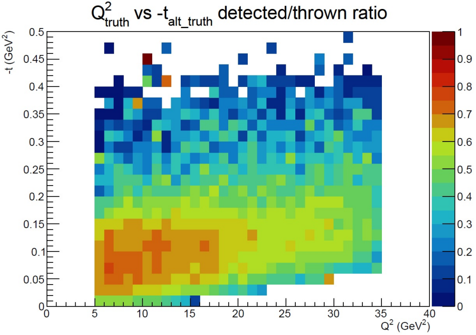
  - Cuts on W, $\Delta\theta$, $\Delta\phi$, Q^2, E_{ZDC} and $-t$
- Detection efficiency is good, comparable to previous results
  - Crucially, efficiency is highest in low $-t$ region



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  - 2.5% point-to-point
  - 12% scale
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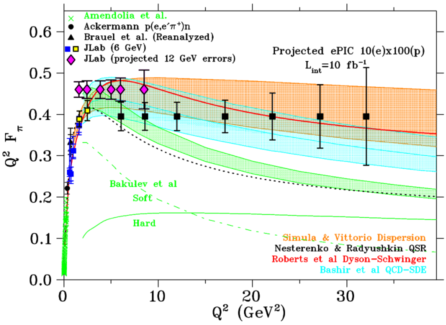

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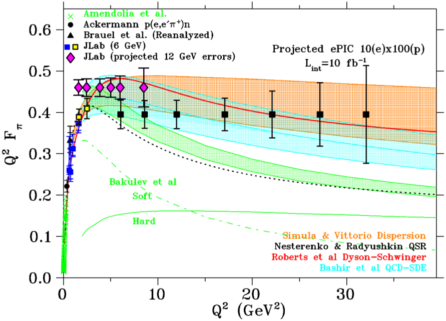

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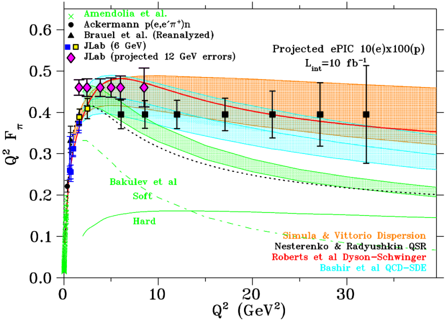

- ePIC might enable higher Q^2 points!
- Early physics programme $\rightarrow$ Need to look at π^-!

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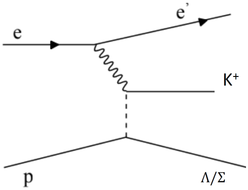

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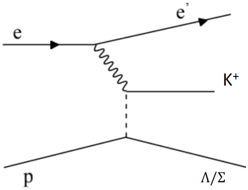

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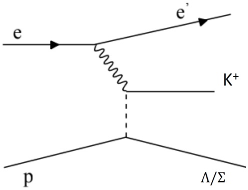

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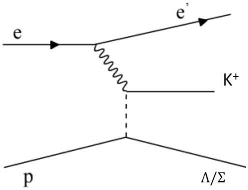

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- Challenging final states to detect

ZDC Lambda and Sigma Reconstruction

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

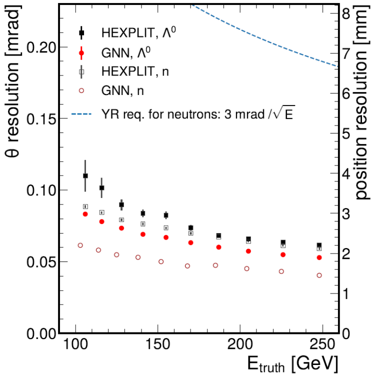

Figure from - https://arxiv.org/abs/2412.12346

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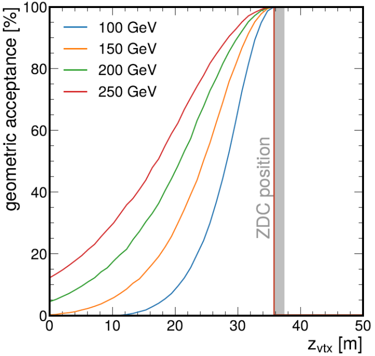

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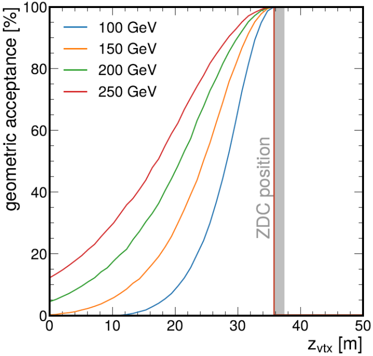
- Depends strongly upon decay z_{vtx}
- Smear MC truth and apply acceptance in line with paper
- Potential for rapid F_K projections
- Need updated projections to lower Λ^0 energies for 10x100 or 5x41



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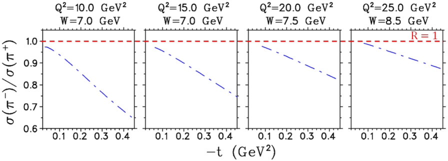

T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

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- $p(e, e'\pi^+ n)$ analysis now well established ePIC analysis
- Benchmark for this channel being finalised

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- Deuteron modifications to DEMPgen and improvements to pion parametrisation to follow soon

Thanks for listening, any questions?

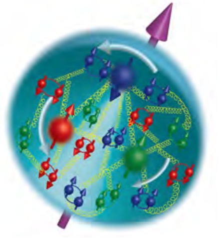
With thanks to Garth Huber and Love Preet at the University of Regina, as well as all of my colleagues in the ePIC Collaboration and the Meson Structure Working Group.

stephen.kay@york.ac.uk

This research was supported by UK Research and Innovation: Science and Technology Facilities council (UKRI:STFC) grant ST/W004852/1 and the Natural Sciences and Engineering Research Council of Canada (NSERC) grant SAPPJ-2023-00041

Backup Zone

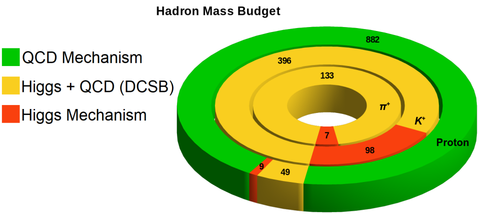
Understanding Dynamic Matter



- Interactions and structure are not isolated ideas in nuclear matter
  - Observed properties of nucleons and nuclei (mass, spin) emerge from this complex interplay
  - Properties of hadrons are emergent phenomena
- Mechanism known as **D**ynamical **C**hiral **S**ymmetry **B**reaking (**DCSB**) plays a part in generating hadronic mass
- QCD behaves very differently at short and long distances (high and low energy)
  - How do our two distinct regions of QCD behaviour connect?
  - How does QCD generate $\sim 99\%$ of the mass of hadrons?
- **A major puzzle of the standard model to try and resolve!**

Image - A. Deshpande, Stony Brook University

Hadron Mass Budgets



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

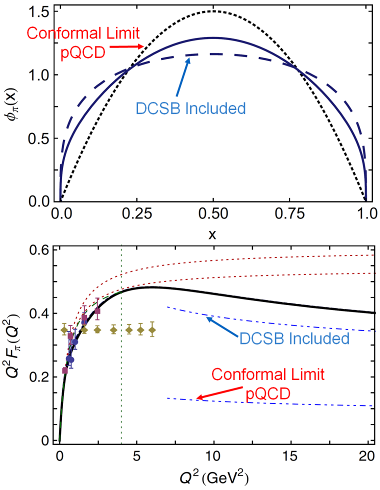
J Arrington[1], C Ayerbe Gayoso[2], P C Barry[3,4], V Berdnikov[5], D Binosi[6], L Chang[7], M Diefenthaler[3], M Ding[6], R Ent[3], T Frederico[8], Y Furletova[3], T J Hobbs[3,9,10], T Horn[3,5,*], G M Huber[11], S J D Kay[11], C Keppel[3], H-W Lin[12], C Mezrag[13], R Montgomery[14], I L Pegg[5], K 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

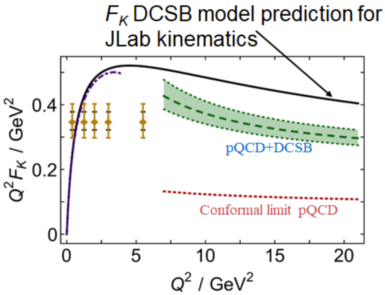
- Calculating the pion PDA, ϕ_π, without incorporating DCSB produces a broad, concave shape
- Incorporating DCSB changes $\phi_\pi(x)$ and brings F_π calculation much closer to the data
  - "Squashes down" PDA
- Pion structure and hadron mass generation are interlinked

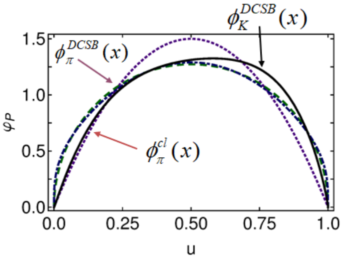


L. Chang, et al., PRL110(2013) 132001, PRL111(2013), 141802

What About the Kaon?

- K^+ PDA, ϕ_K, is also broad and concave, but asymmetric
- Heavier *s* quark carries more bound state momentum than the *u* quark

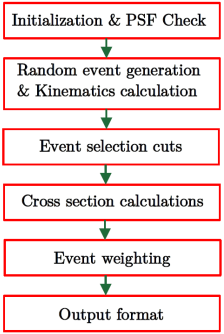




C. Shi, et al., PRD 92 (2015) 014035, F. Guo, et al., PRD 96(2017) 034024 (Full calculation)

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
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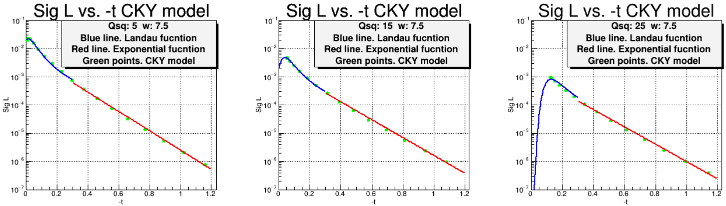

Authors of model are - T.K. **C**hoi, K.J. **K**ong and B.G. **Y**u - **CKY**

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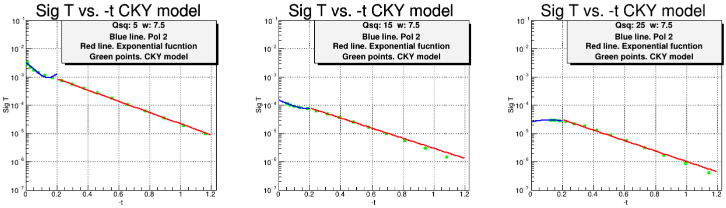
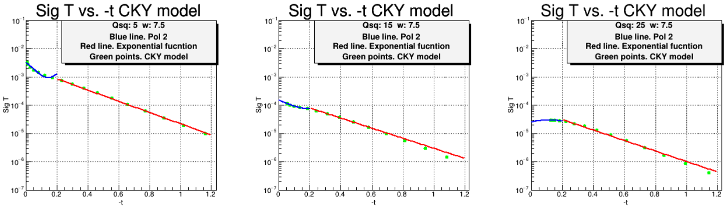


Authors of model are - T.K. **C**hoi, K.J. **K**ong and B.G. **Y**u - **CKY**

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



- Kaon reactions → 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

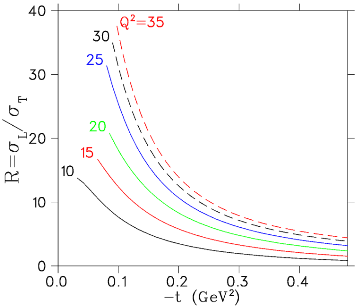
- For a collider -

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

  - 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

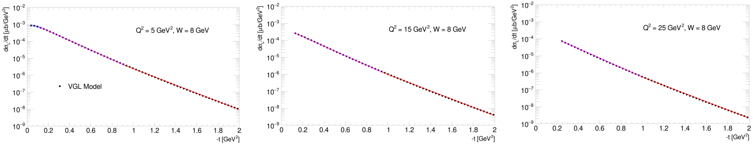


Predictions are assuming $\epsilon > 0.9995$ with the kinematic ranges seen earlier

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

F_K at the EIC - Generator Updates

- URegina researcher Love Preet added new Kaon DEMP event generator module to DEMPgen
  - Starting with $p(e, e'K^+\Lambda)$
- Parametrise a Regge-based model
- For $p(e, e'K^+\Lambda)$ module, use the Vanderhagen, Guidal, Laget (VGL) model
- Parametrise σ_L, σ_T for $1 < Q^2 < 35$, $2 < W < 10$, $-t < 2.0$
  - Parametrise with a polynomial, exponential and exponential



VGL Model - M. Guidal, J.-M. Laget, M. Vanderhaeghen, PRC 61 (3000) 025204

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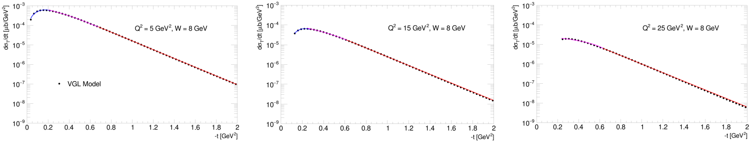
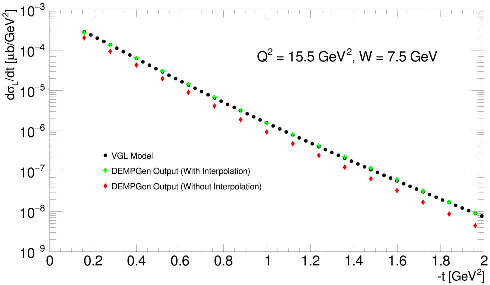


VGL Model - M. Guidal, J.-M. Laget, M. Vanderhaeghen, PRC 61 (3000) 025204

DEMPGen Improvements

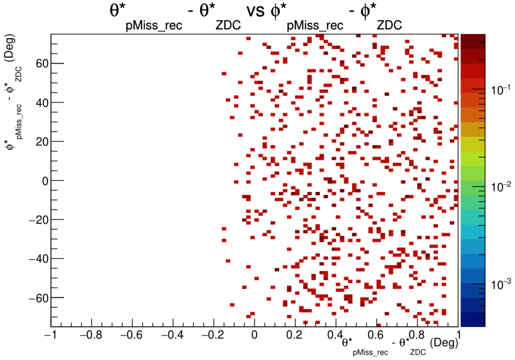
- In addition to adding the $p(e, e'K^+\Lambda)$ module, improvements to the generator implemented
- New method to interpolate parametrisation
- Interpolation matches generator output very closely
  - Even at points far from the initial parametrisation
- Will incorporate improvements in pion model soon



Plot from L. Preet, University of Regina

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