Far Forward Reconstruction Studies for Deep Exclusive Meson Production Reactions at the EIC

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CAP Congress, London, ON
May 28, 2024

Supported by:
NSERC CRSNG
SAPPJ-2023-00041

ePIC Detector at EIC

- One of the lessons learned from HERA is to integrate hermetic detector coverage with the accelerator from the outset, as it is being designed

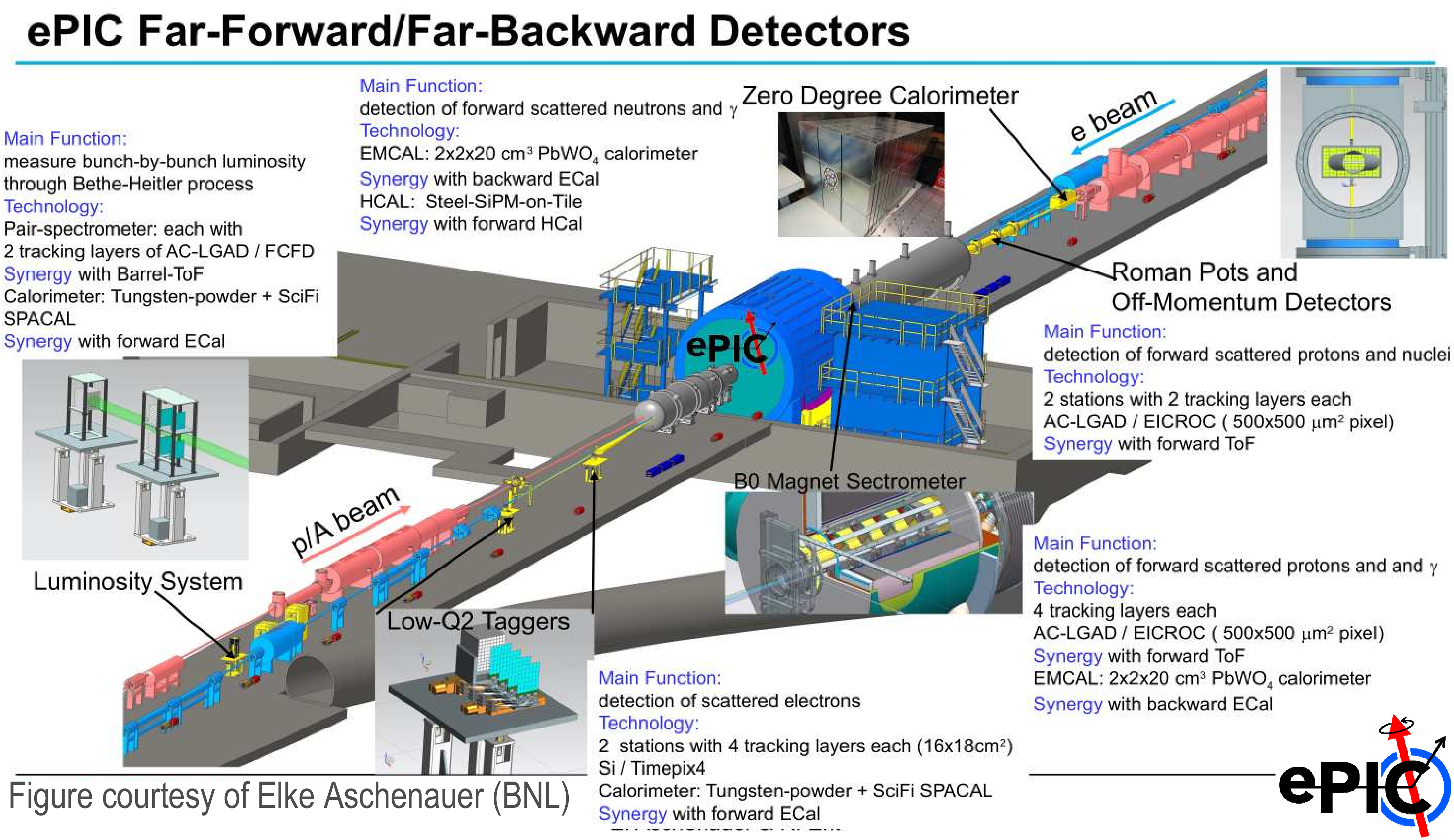

Figure courtesy of Elke Aschenauer (BNL)

Detector Integration → Rich EIC Physics Program

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Far Forward and Far Backward detector arrays allow a Rich Physics Program, needed for EIC's primary physics objectives

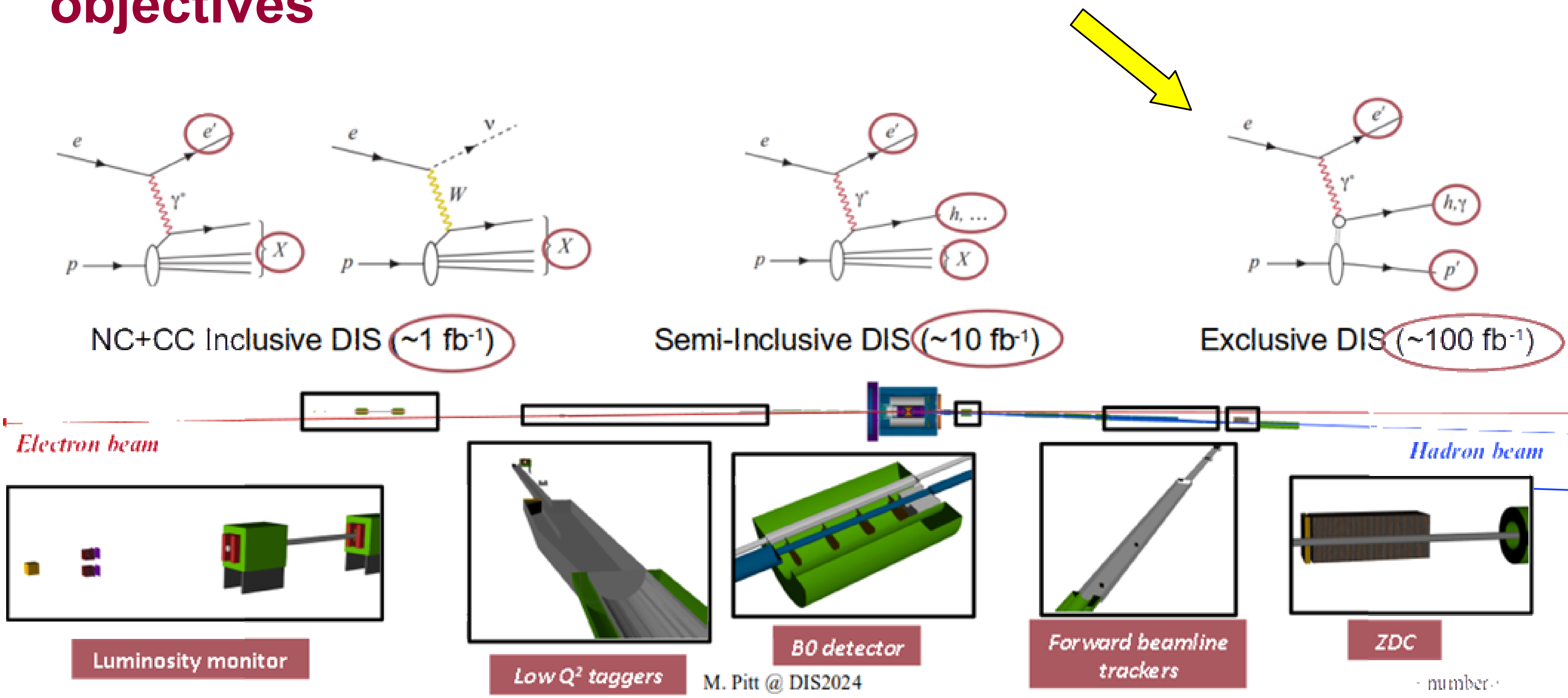

Figure courtesy of Michael Pitt (Kansas)

F_π and F_K Studies to Higher Q^2 at EIC

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- **Physics Motivation:**
  - π^+ and K^+ structure studies are important for understanding QCD's transition from "weak" and "strong" domains, and understanding DCSB's role in generating hadron properties
  - Definite answers to these questions require high Q^2 data well beyond JLab's reach, the EIC may provide these data
- **Experimental Issues:**
  - The DEMP cross section is small, can the exclusive $p(e,e'\pi^+)n$ and $p(e,e'K^+)\Lambda$ channels be cleanly identified?
    - Count rates, Detector Acceptances?
  - Is the detector resolution sufficient to reliably reconstruct (Q^2,W,t)?
  - How to measure the longitudinal cross section $d\sigma_L/dt$ needed for form factor extraction?

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DEMP π^+/K^+ Event Generator

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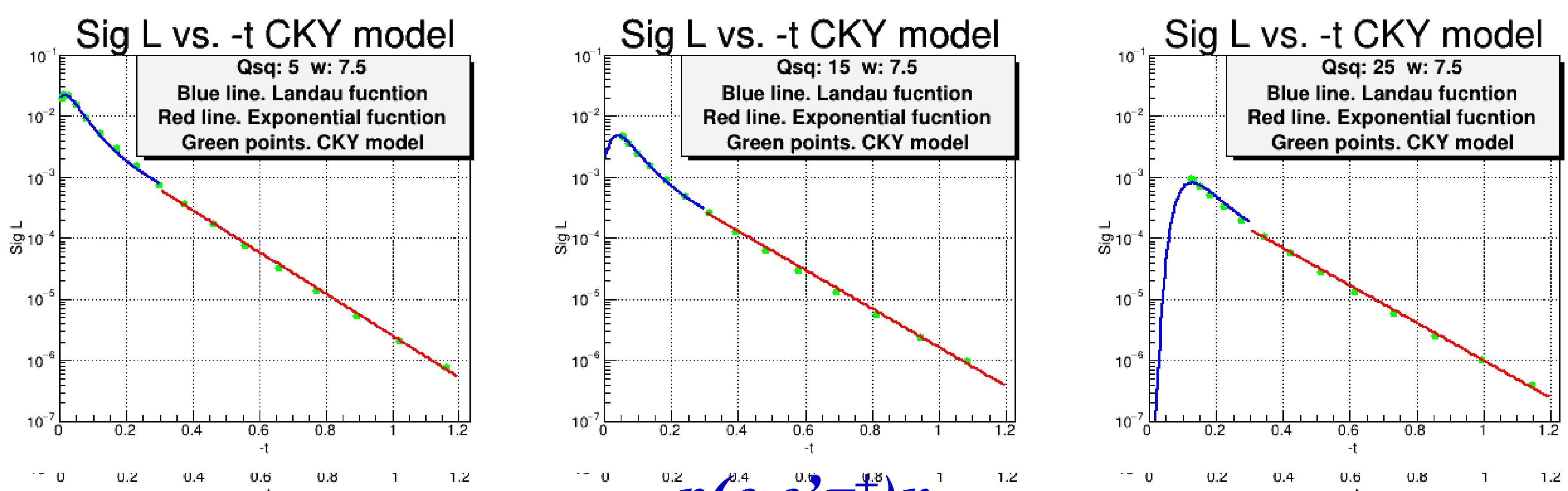
- Regge-based $p(e,e'\pi^+)n$ model of *T.K. Choi, K.J. Kong, B.G. Yu (CKY*) [J.Kor.Phys.Soc. 67(2015)1089]
  - Created a MC event generator by parameterizing CKY σ_L, σ_T for $5<Q^2$ (GeV^2)<35 $2.0<W$ (GeV)<10 $0<-t$ (GeV^2)<1.2
- Extended to $p(e,e'K^+)\Lambda[\Sigma^0]$ by parameterizing Regge-based model of M. Guidal, J.M. Laget, M. Vanderhaeghen (VGL) [PRC 61 (2000) 025204]
- New paper describing our generator arXiv:2403.06000



$p(e,e'\pi^+)n$

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DEMP Particle Kinematics

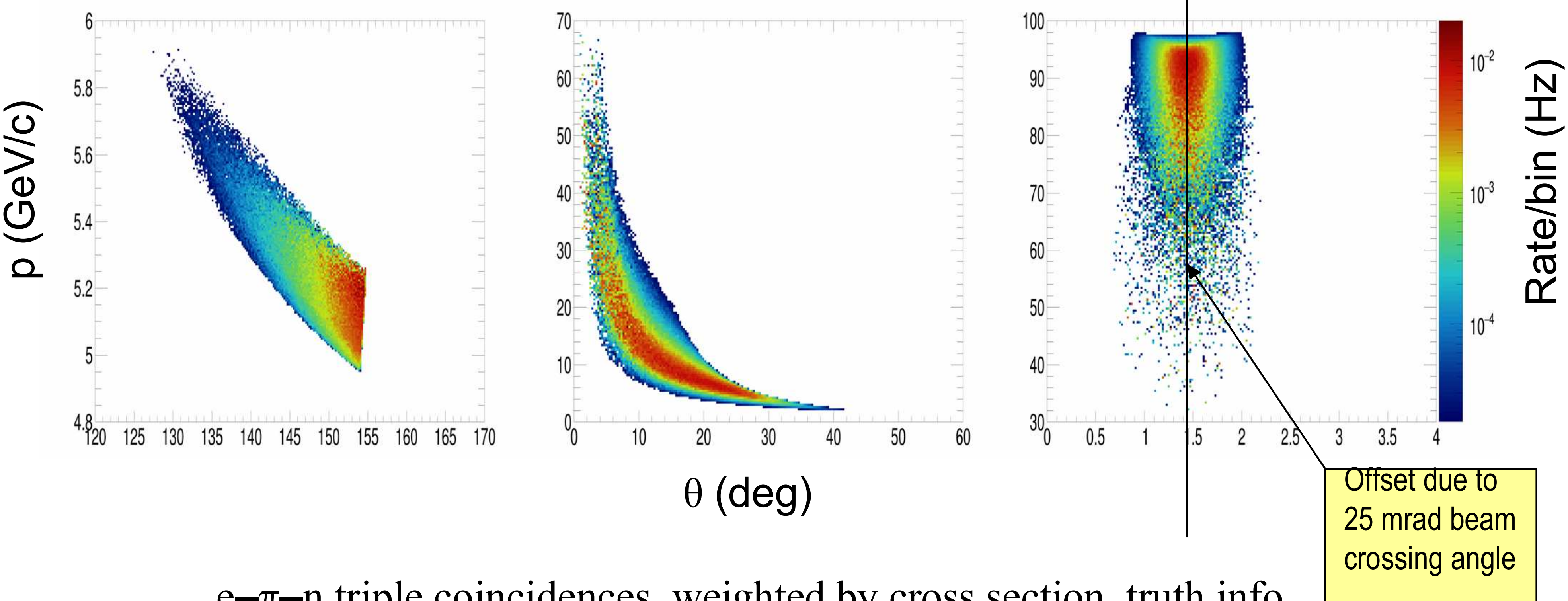
Assure exclusivity of *p(e,e'π⁺n)* reaction by detecting all 3 particles

IR6: 5(e^-) x 100(p) GeV Collisions → E_{cm}=44.7 GeV

Scattered electrons:
5–6 GeV/c,
25–50° from
outgoing e beam

Pions:
3–40 GeV/c,
3–40° from p beam

Neutrons:
65–98 GeV/c
<0.7° of outgoing
proton beam



e–π–n triple coincidences, weighted by cross section, truth info

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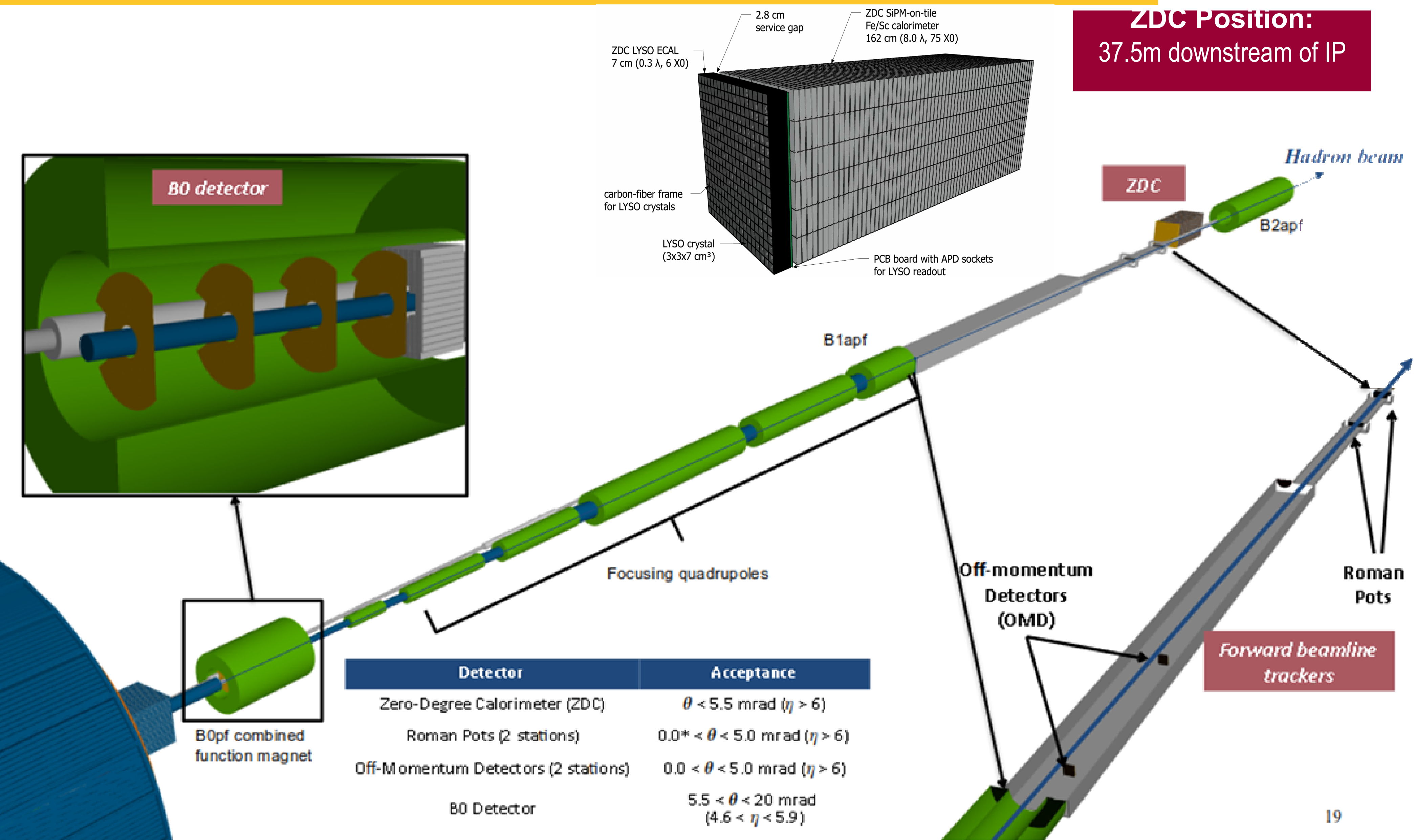
EIC Far Forward Detectors

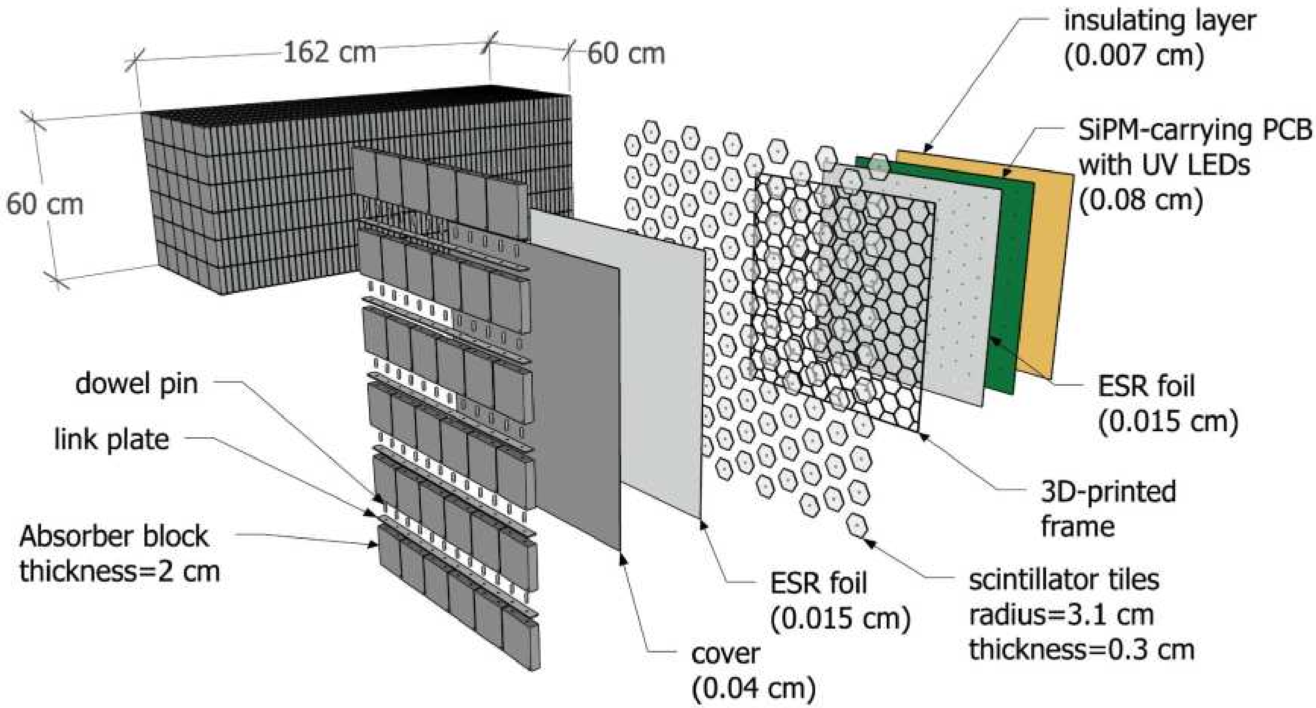
ZDC Position:
37.5m downstream of IP



Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5$ mrad ($\eta > 6$)
Roman Pots (2 stations)	$0.0^* < \theta < 5.0$ mrad ($\eta > 6$)
Off-Momentum Detectors (2 stations)	$0.0 < \theta < 5.0$ mrad ($\eta > 6$)
B0 Detector	$5.5 < \theta < 20$ mrad ($4.6 < \eta < 5.9$)

- Vital to isolate exclusive $p(e,e'\pi^+n)$ process from competing inclusive reactions
- EIC measurement <u>impossible</u> unless recoil high momentum neutron is efficiently detected

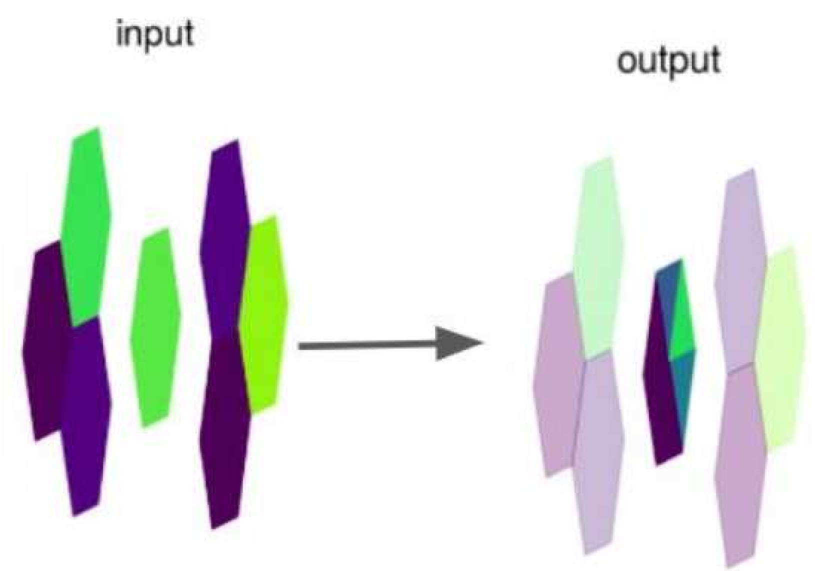
Neutron Reconstruction in ZDC



Figures courtesy of Miguel Arratia (UC Riverside)

- Proposed SiPM–on–Tile design of ZDC divides HCAL into hexagonal cells
- HEXSPIT algorithm defines cells with overlap, assigns weights according to overlap, uses this to reconstruct energy based on subcell energy

HEXPLIT Algorithm



S. Paul, M. Arratia arXiv:2308.06939

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p(e,e’π⁺n) Neutron reconstruction in ZDC

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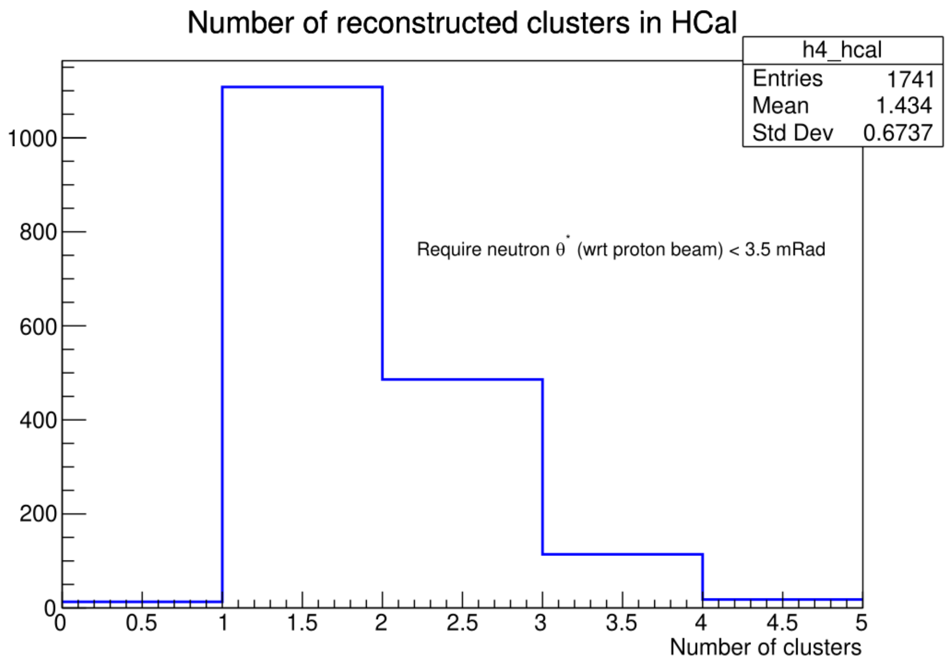
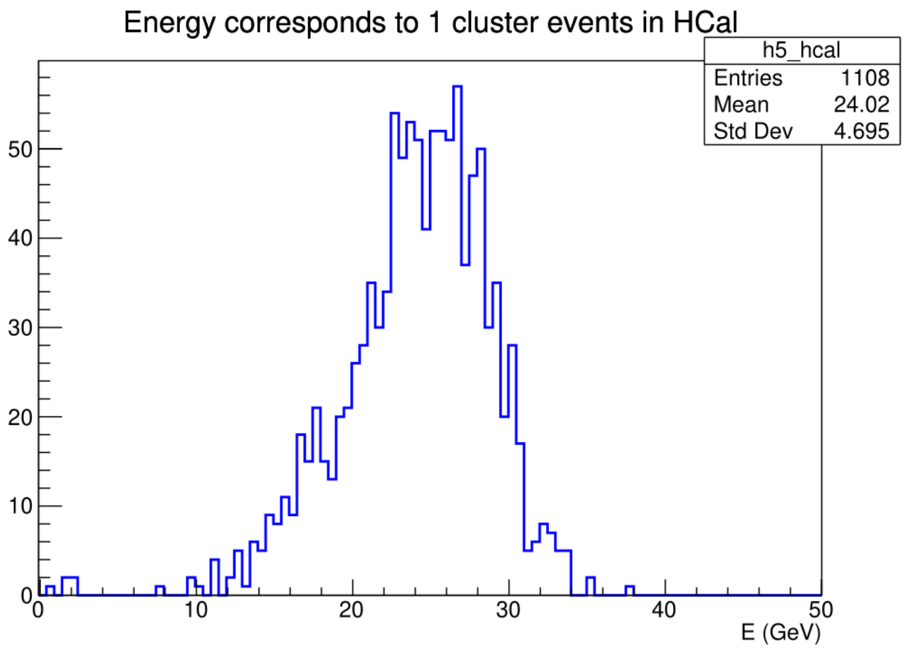
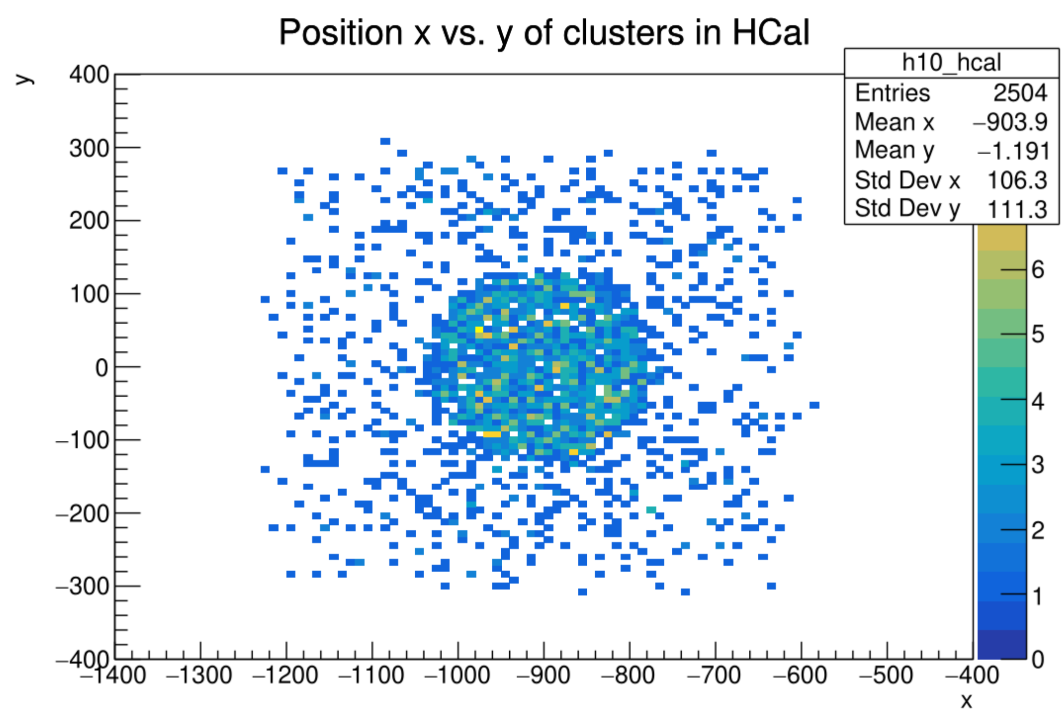




- 5x41 e+p collisions
- High proportion of neutron hits have multi–clusters
  - No cluster recombining algorithm is implemented yet
- Single cluster events look good
- (x,y) acceptance of ZDC fully filled



$p(e,e'K^+)\Lambda$ Event Reconstruction

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- Significantly more challenging than $p(e,e'\pi^+)n$ reconstruction
- Need to efficiently identify $\Lambda \to n\pi^0 \to n\gamma\gamma$ decay (~33%)
  - Neutral products take straight line paths
  - Cleanly distinguishing n from γ clusters is main challenge
- Dominant $\Lambda \to p\pi^-$ channel (~67%) has its own challenges
  - Avoids issue of distinguishing n from γ clusters
  - Main issue is that p, π^- are deflected in opposite directions by proton ring magnetic elements, and it will not be possible to efficiently detect both of them
- Additional reconstruction issue:
  - Do not know Λ decay vertex when reconstructing $\pi^0 \to \gamma\gamma$ decay
  - SiPM will provide enough information about spatial extent of showers to extract incident angle of γ on EMCAL to enable full 4–vector reconstruction of π^0. Is it sufficiently good?

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Some ZDC Design Choices

- $\Lambda \to n\pi^0 \to n\gamma\gamma$ reconstruction studies will inform ZDC design choices

1. **20cm EMCAL + SiPM–on–Tile:** E resolution is very good, but lose γ angular information needed for Λ reconstruction
2. **~10cm EMCAL + SiPM–on–Tile:** EMCAL can act as a sort of "pre–shower" while still enabling γ angular information
3. **SiPM–on–Tile ONLY:** Allows best γ angular reconstruction, but might lose low–E photon capability, potentially more difficult hadronic/EM shower separation

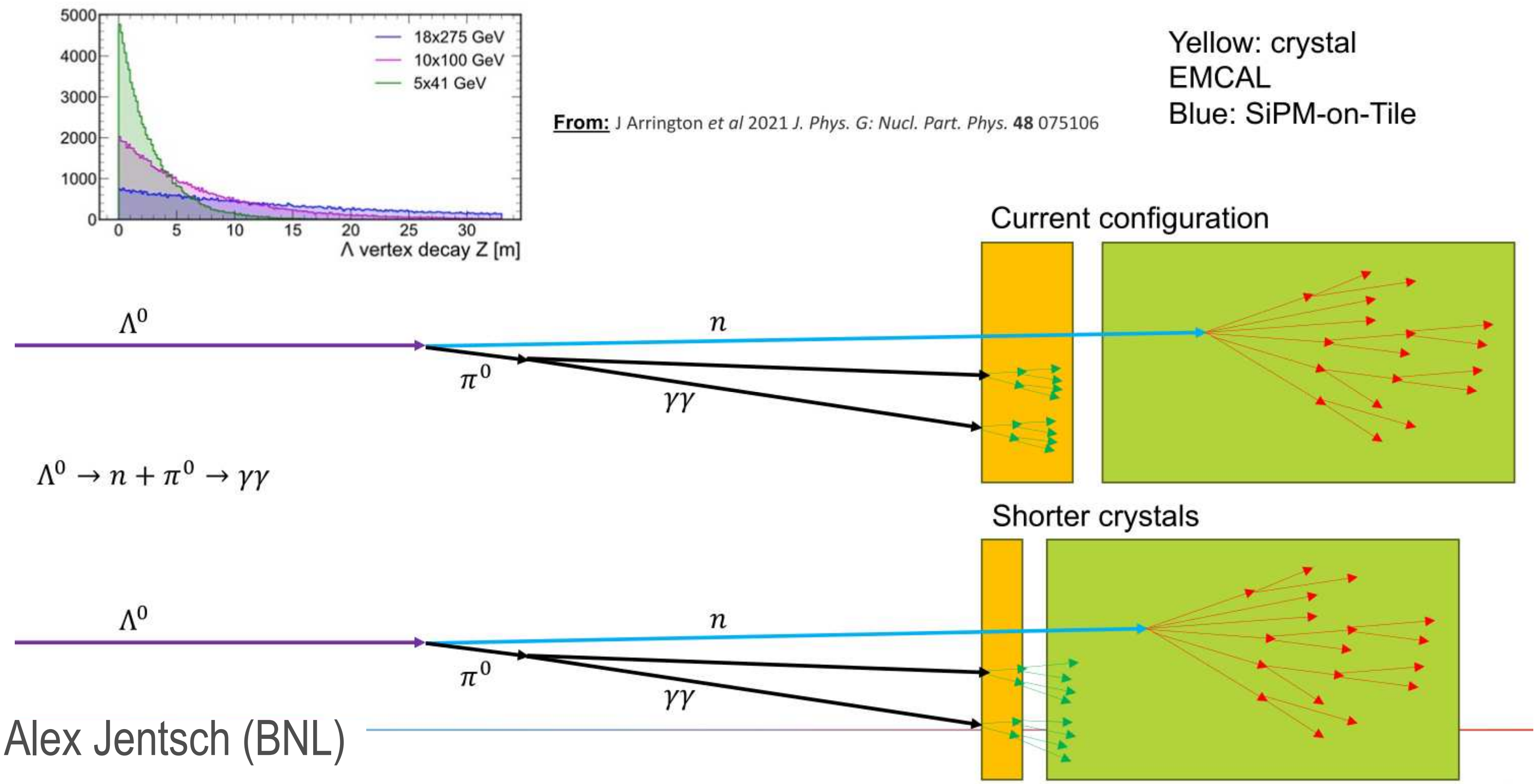

Figure courtesy of Alex Jentsch (BNL)

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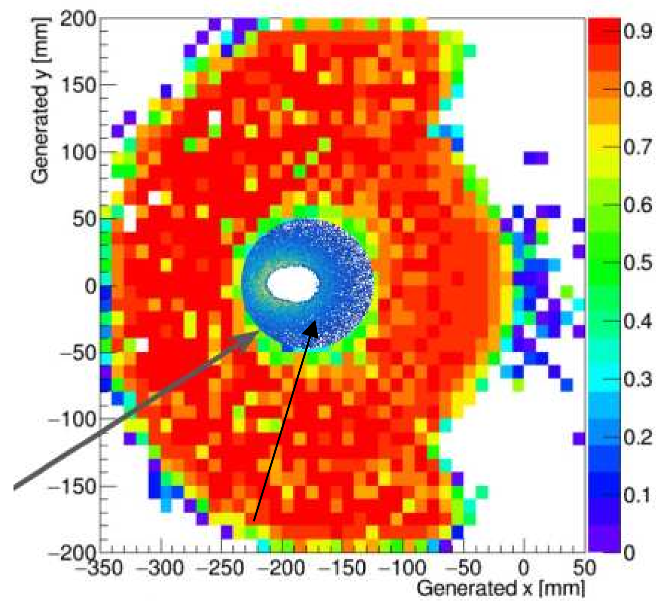
Later Stage $p(e,e'K^+)\Lambda[\Sigma^0]$ Reconstruction

- **Far Forward large acceptance is even more important for K^+ form factor than for π^+ form factor**
- Detection of $e'K^+\Lambda[\Sigma^0]$ triple coincidence over wide range of $-t$ essential for identification of K–pole process, needed for K^+ form factor extraction from data
  - $\Lambda \rightarrow n\pi^0 \rightarrow n2\gamma$ and $\Sigma \rightarrow \Lambda\gamma \rightarrow n3\gamma$ identification over wide $-t$ only possible if ZDC calorimeter acceptance is extended with addition of a B0 calorimeter
  - Not only essential for F_K, but also would improve forward acceptance for u–channel DVCS, and nuclear coherent diffraction studies

ZDC



Possible B0 Calorimeter
• Greatly extends acceptance!

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Summary

- Higher Q^2 data on π^+ and K^+ form factors are vital to our better understanding of hadronic physics
  - Pion and kaon properties are intimately connected with dynamical chiral symmetry breaking (DCSB), which explains the origin of more than 98% of the mass of visible matter in the universe
- Measurement of F_π at EIC has various challenges
  - Need efficient identification of *p(e,e'π⁺n)* triple coincidences
  - Neutron reconstruction in ZDC is underway, studies promising, but algorithm still needs some improvements (cluster merging)
- Measurement of F_K at EIC even more challenging
  - Λ reconstruction studies are likely to inform ZDC design choices
  - Expectation is that a reduction of ZDC–EMCAL thickness to ~10cm will be beneficial

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Isolating Exclusive $p(e,e'\pi^+)n$ Events

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- **Can we isolate a clean sample of exclusive $p(e,e'\pi^+n)$ events by detecting the neutron, or are other requirements needed in addition?**

- For a source of background $p(e,e'\pi^+)X$ events we used the EIC SIDIS generator written by Tianbo
  - located on JLab farm at /work/eic/evgen/SIDIS_Duke/e5p100
- Since the generator does not output the neutron momentum, we use the missing momentum as a proxy

- The SIDIS and DEMP event generators are used to create LUND format files
- Generated events are fed into ECCE Geant4 simulation for both IP6 and IP8 to study acceptance and resolution requirements for different beam energy combinations

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p_{miss} cut vs Q^2–bin (IR6)

$$p_{miss} = \left| \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+} \right|$$

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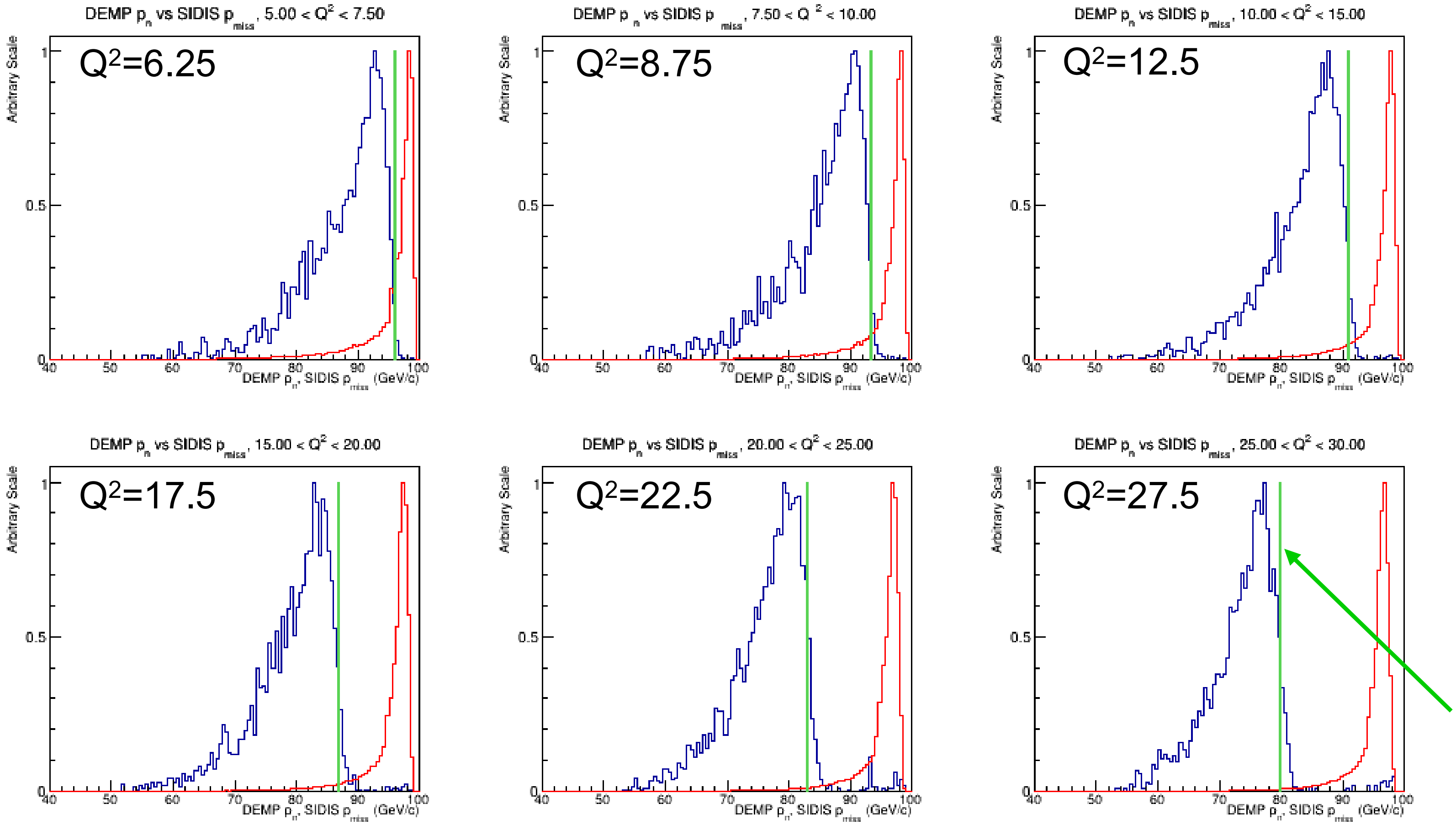
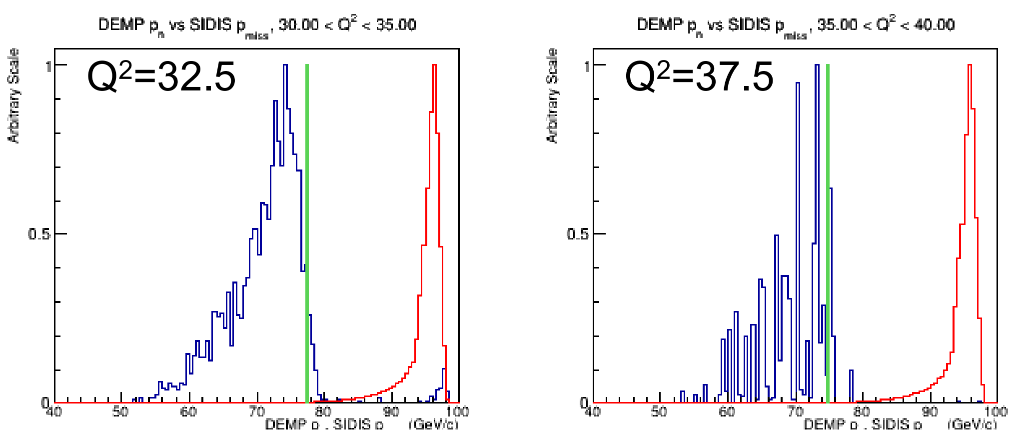


Plots by Stephen Kay



Exclusive *p(e,e'π⁺)n*
Foreground

SIDIS *p(e,e'π⁺)X*
Background
(arbitrarily normalized, actually much larger than DEMP)

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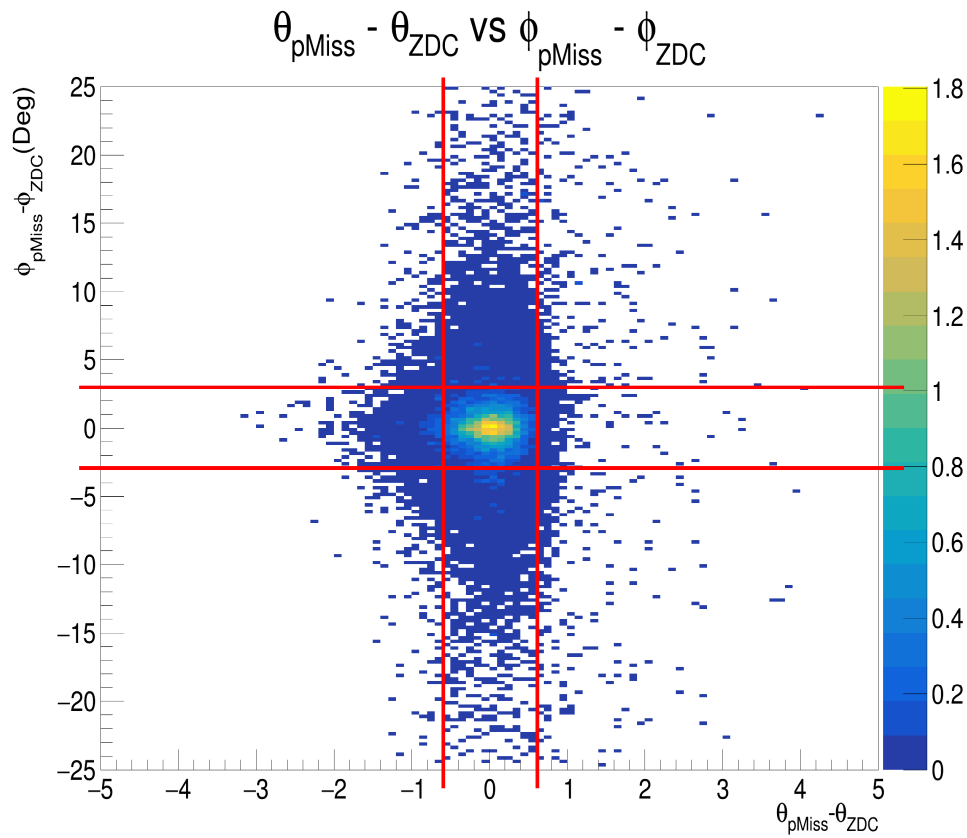
Another Cut to Remove Background

- **Make use of high angular resolution of ZDC to further reduce background events**
  - Compare hit (θ,φ) positions of energetic neutron on ZDC to calculated position from p_{miss}
  - If no other particles are produced (i.e. exclusive reaction) these quantities should be highly correlated
  - Energetic neutrons from inclusive background processes will be less correlated, since additional lower energy particles are produced



Differences between hit and calculated neutron positions on ZDC for DEMP events (IR6)

Cuts applied: $|\Delta\theta|<0.6^o$ $|\Delta\varphi|<3.0^o$ in addition to triple coincidence cuts

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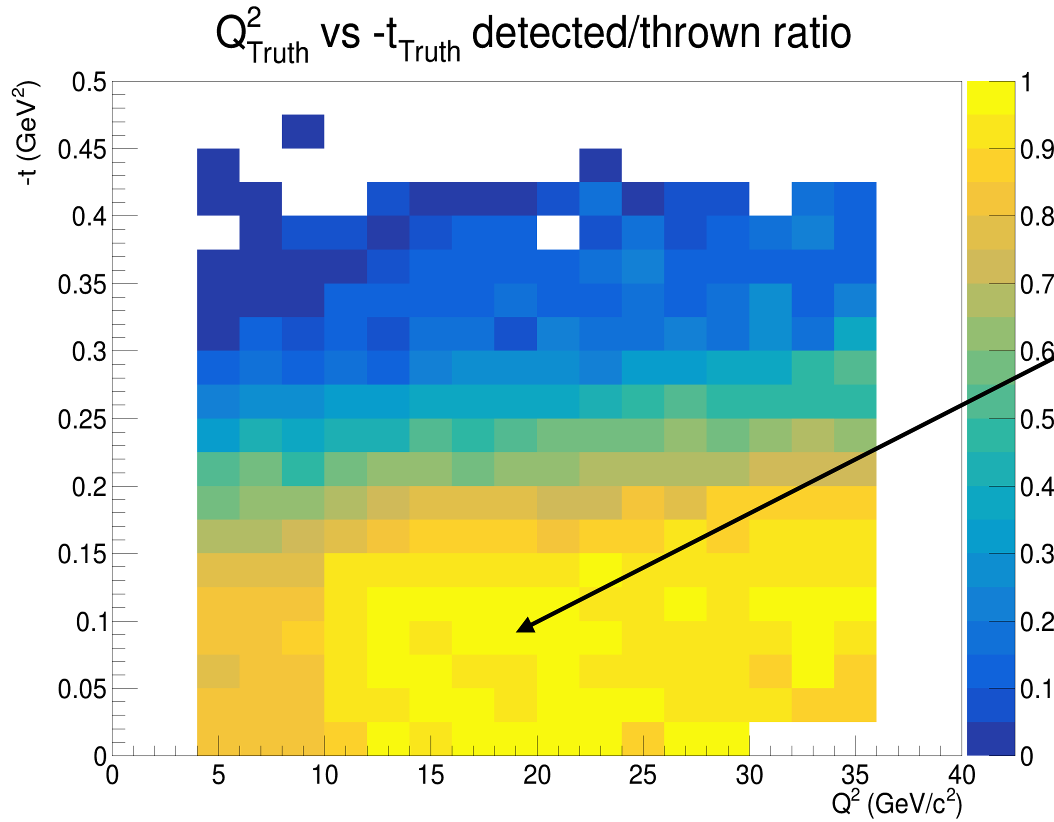
Plot by Stephen Kay

Detection efficiency per (Q^2, t) bin (IR6)



Detection efficiency best in crucial low $-t$ region

Require EXACTLY two tracks:

- One positively charged track in +z direction (π^+)
- One negatively charged track in –z direction (e')

AND at least one hit in Zero Degree Calorimeter (ZDC)

- For 5x100 events, require the hit has Energy Deposit > 40 GeV

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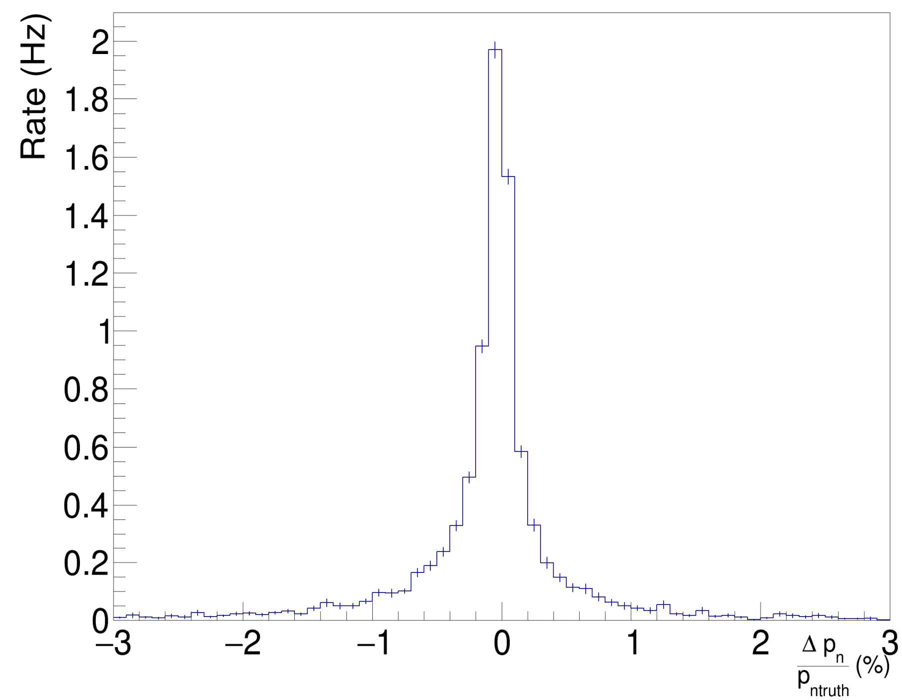
Plot by Stephen Kay

Improving *neutron* reconstruction resolution

- **Exclusive $p(e,e'\pi^+n)$ event selection requires exactly one high energy ZDC hit as a veto**
- Since the neutron hit position from ZDC is known to high accuracy, this information can be used to "correct" the missing momentum track

$$p_{miss} = \left| \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+} \right|$$



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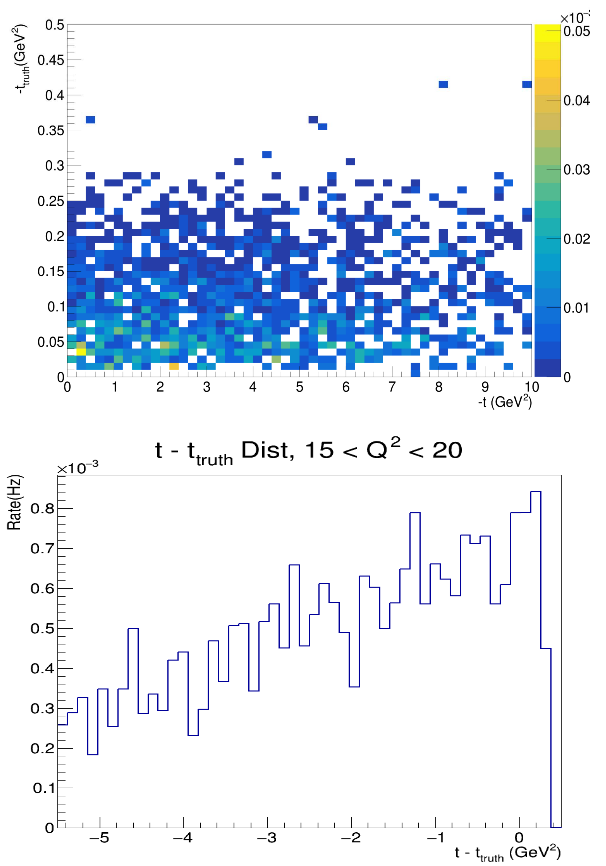
Reconstructing Mandelstam *t* (IR6)

- Extraction of pion form factor from $p(e,e'\pi^+n)$ data requires *t* to be reconstructed accurately, as we need to verify dominance of the *t*–channel process from the dependence of $d\sigma/dt$ *upon t*

$t_{reconst}(x)$ vs $t_{truth}(y)$

$t_{reconstr} - t_{truth}$

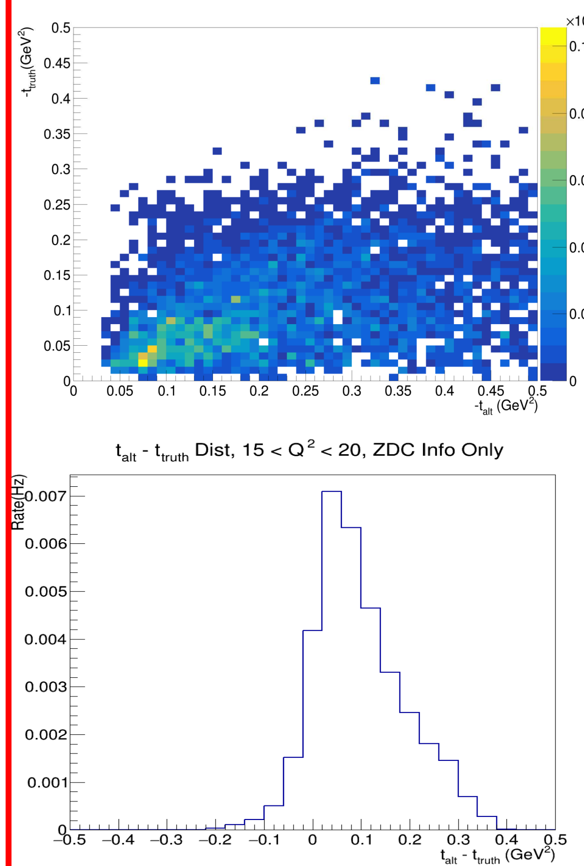
$t=(p_{\gamma *} - p_{\pi})^2$



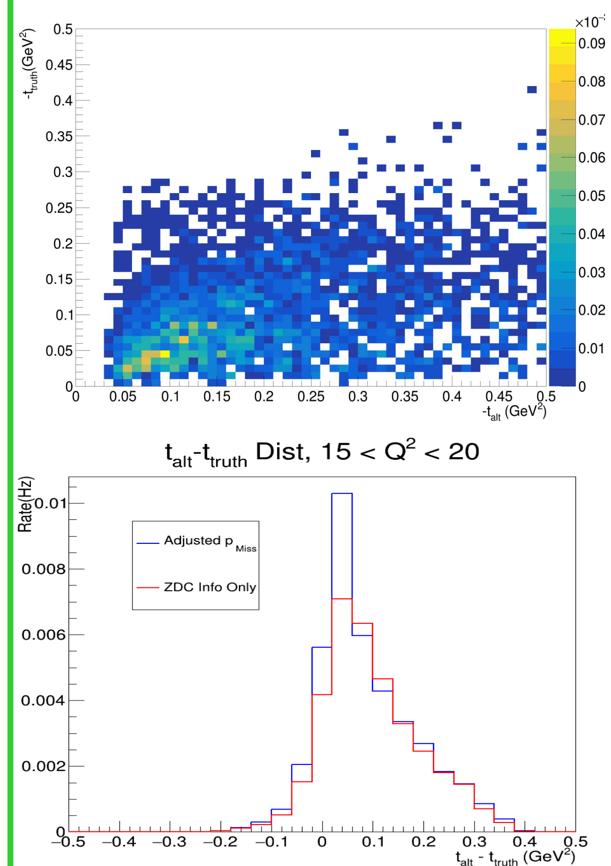
Unusable *t* reconstruction

$\sigma_{t\ reconstr}$ =3.4 GeV^2

$t=(p_p - p_n)^2$



Correct p_{miss} *w/ ZDC*(θ,φ)



Best *t* reconstruction

$\sigma_{t\ reconstr}$ =0.073 GeV^2

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Separating σ_L from σ_T in e–p Collider

$$\varepsilon = \frac{2(1-y)}{1+(1-y)^2} \quad \text{where the fractional energy loss } y = \frac{Q^2}{x(s_{tot} - M_N^{\ 2})}$$

- Systematic uncertainties in σ_L are magnified by $1/\Delta\varepsilon$.
  - Desire $\Delta\varepsilon > 0.2$.
- **To access $\varepsilon < 0.8$, one needs $y > 0.5$.**
  - This can only be accessed with small s_{tot},

    i.e. low proton collider energies (5–15 GeV), where luminosities are too small for a practical measurement.
- **A conventional L–T separation is impractical, need some other way to identify σ_L.**

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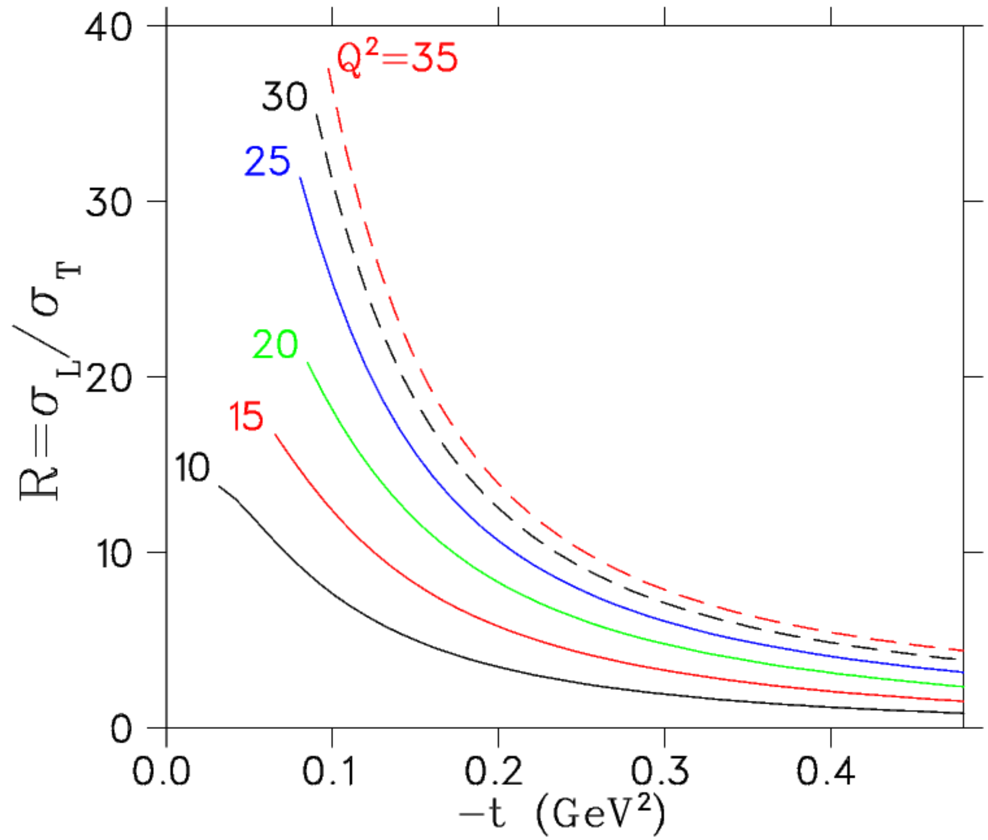
Isolate $d\sigma_L/dt$ using a Model

- In the hard scattering regime, QCD scaling predicts $\sigma_L \propto Q^{-6}$ and $\sigma_T \propto Q^{-8}$.
- At high Q^2, W accessible at EIC, phenomenological models predict $\sigma_L \gg \sigma_T$ at small $-t$.
- The most practical choice might be to use a model to isolate dominant $d\sigma_L/dt$ from measured $d\sigma_{UNS}/dt$.
- **In this case, it is very important to confirm the validity of the model used.**



- T. Vrancx, J. Ryckebusch, PRC **89**(2014)025203.
- Predictions are for ε>0.995 Q^2, W kinematics shown earlier.

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EIC Kinematic Reach (IR6)

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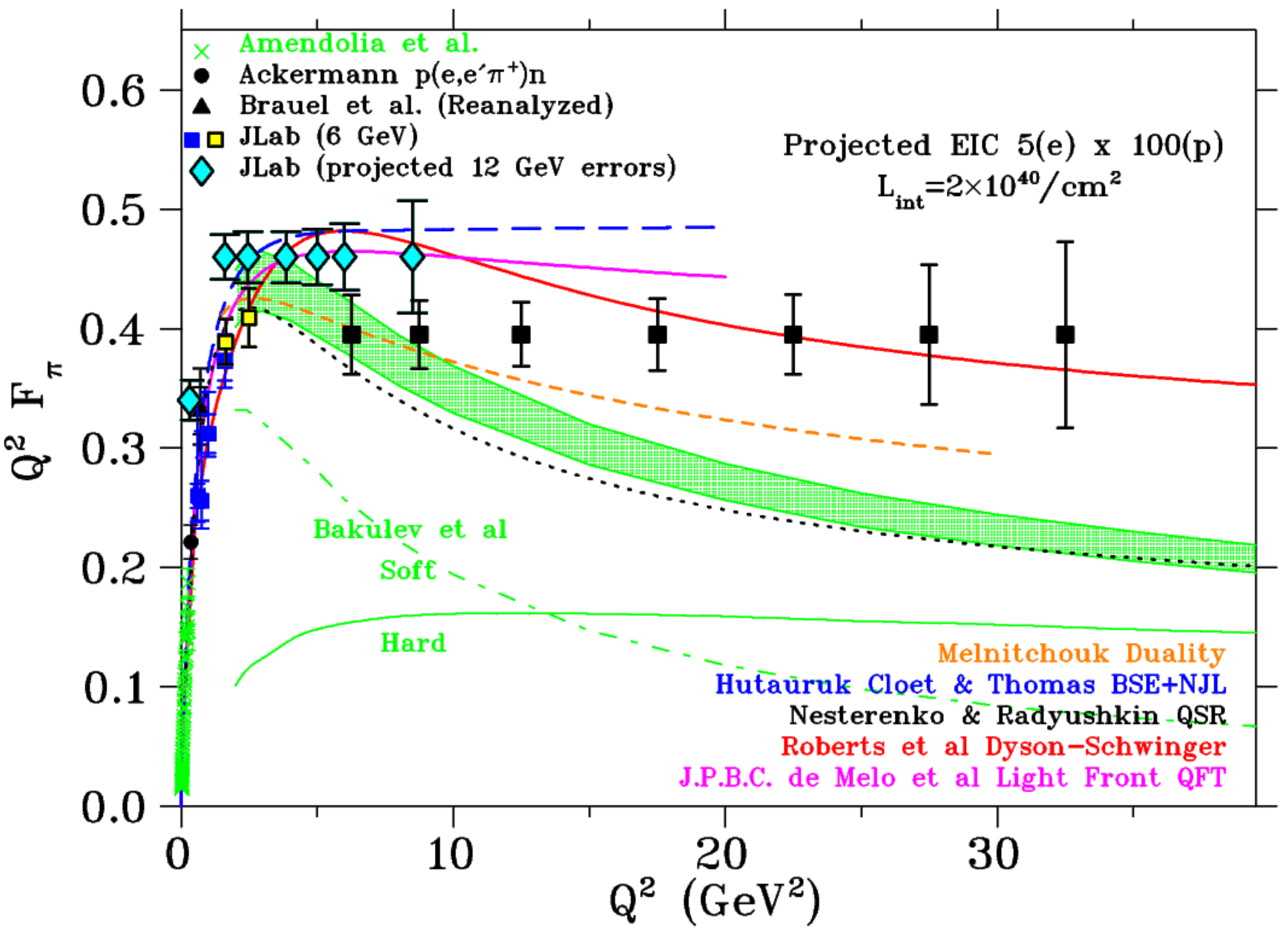

Assumptions:

- 5(e^-) x 100(p)
- Integrated L=20 fb^{-1}/yr
- Clean identification of exclusive $p(e,e'\pi^+n)$ events
- t reconstruction resolution based on ECCE detector design
- Syst. Unc: 2.5% pt–pt and 12% scale
- $R=\sigma_L/\sigma_T$ =0.013–0.14 at lowest $-t$ from VR model, and $\delta R=R$ syst. unc. in model subtraction to isolate σ_L.
- π pole dominance at small $-t$ confirmed in ^{2}H π^-/π^+ ratios.

Can we measure F_K at the EIC?

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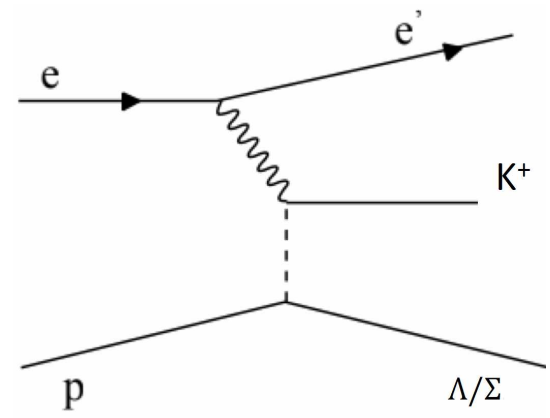
- **Can the "kaon cloud" of proton be used in same way as the pion to extract kaon form factor via *p(e,e'K⁺)*Λ ?**
- Kaon pole further from kinematically allowed region
- Many of these issues are being explored in JLab E12–09–011



- Propose to use $p(e,e'K^+\Lambda/\Sigma)$ reactions for pole dominance test

$$R=\frac{\sigma_L[p(e,e'K\Sigma^0)]}{\sigma_L[p(e,e'K\Lambda)]}\rightarrow R\approx\frac{g^2_{pK\Sigma}}{g^2_{pK\Lambda}}$$

- **Decay modes: $\Lambda\rightarrow n\pi^0$ 36%, $\Lambda\rightarrow p\pi^-$ 64%**
  - **Neutral channel most likely best option**
  - **Avoids deflection of $p\pi^-$ away from detectors by ion ring elements**
- **Σ^0 identified from $\Sigma^0\rightarrow\Lambda\gamma\rightarrow\Lambda\pi^0\rightarrow n3\gamma$ decay**

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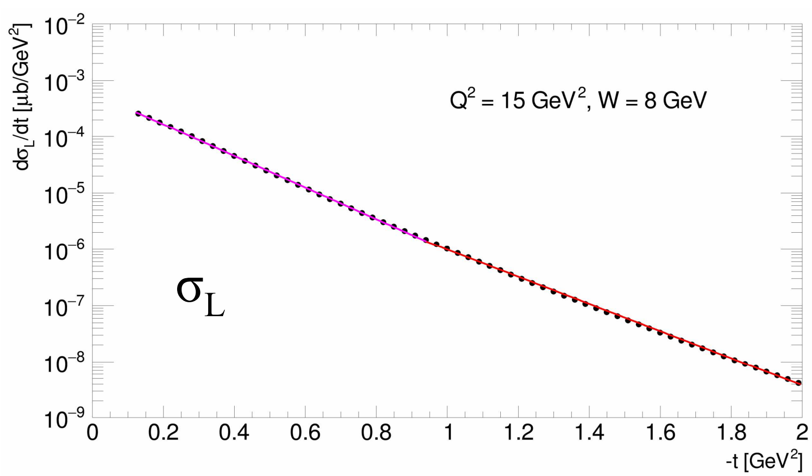
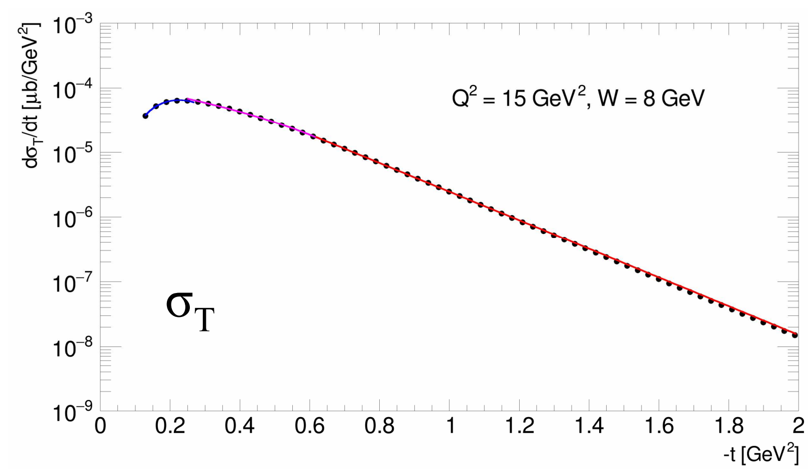
$p(e,e'K^+)\Lambda$ Generator Updates

- UofR student Love Preet is working on adding K^+ physics module to our DEMP event generator
  - Parameterize Regge–based model in similar way to π^+
  - $K^+\Lambda$ (soon also $K^+\Sigma$) modules are based on Vanderhaeghen Guidal Laget model [PRC 61 (2000) 025204]
  - σ_L,σ_T parameterizations for: $1<Q^2<35$ $2<W<10$ $-t<2.0$ GeV^2
    - **Polynomial** **Exponential** **Exponential**





- Study will need $\Lambda\rightarrow n\pi^0$ tracking to be fixed in Geant4 simulation. For ECCE studies, only $\Lambda\rightarrow p\pi^-$ was working

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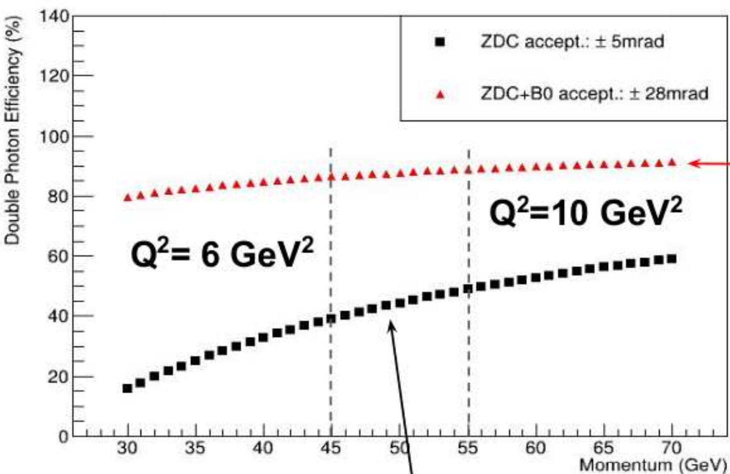
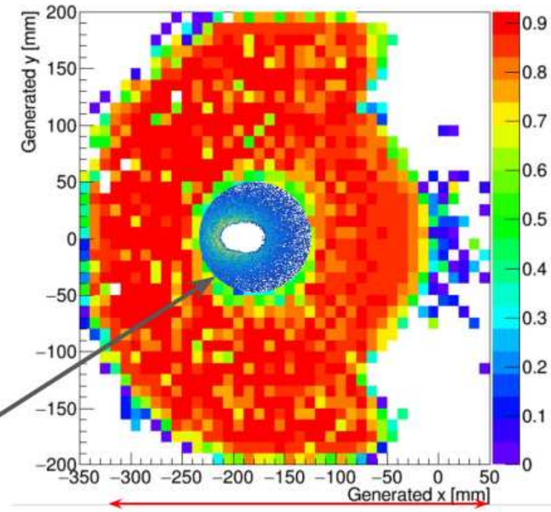
Two photon detection efficiency

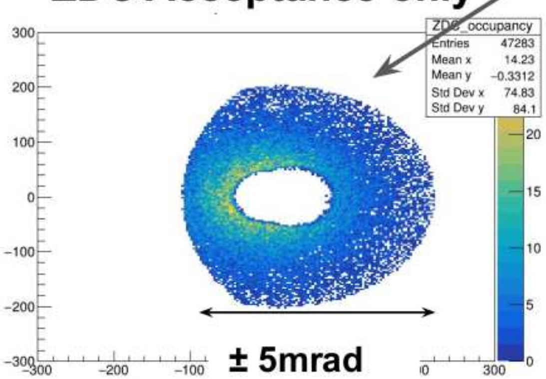


ZDC + B0 calorimeter



± 28mrad !

ZDC Acceptance only



± 5mrad

B0 Calorimeter

B0 Trackers