Early Science Projections for π^+ Form Factor Studies with ePIC at the EIC

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The Big Question

- **Hadrons are nature's smallest composite system, composed of quarks and gluons with scale ~10^{-15}m**
- **Hadron properties arise from unusual features of the QFT (Quantum ChromoDynamics) that governs constituent interactions**
- QCD coupling, α_S, runs dramatically with momentum scale, so that quark-gluon interactions become feeble when two quarks are brought close together within a hadron
- QCD gauge boson, the gluon, self-interacts prolifically, so that quark-gluon interactions become enormously strong when quark separation is increased, leading to "***The Confinement Problem***"
- **Confinement is crucial because it ensures absolute stability of proton**
- **In absence of confinement:**
  - Hydrogen atom would be unstable
  - Nucleosynthesis would be a rare event
  - No stars, Our universe could not exist

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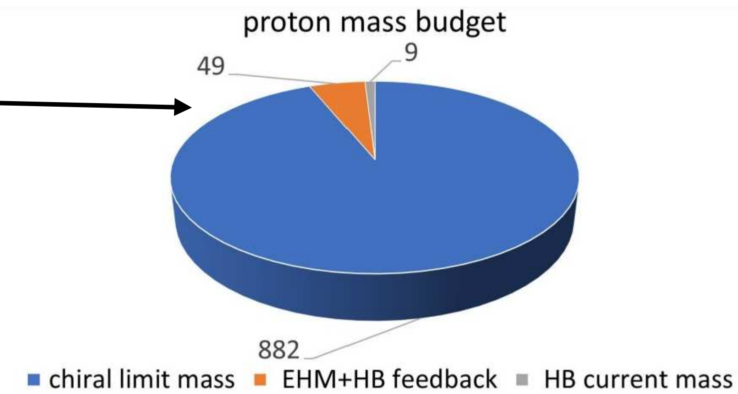
QCD is responsible for most mass

- **In appearance, QCD is simple, but it is also unique**
  - It is a fundamental theory with the capacity to sustain massless elementary degrees-of-freedom, *i.e. quarks and gluons*
  - Yet, quarks and gluons are predicted to acquire mass dynamically
  - The mass of nucleons and almost all hadrons likewise
- **<10% of proton's mass is attributable to Higgs mechanism**



- Clearly, there is another phenomenon in nature extremely effective in producing mass: **EMERGENT HADRON MASS (EHM) of QCD produces 94% of proton's mass**
  - In QFT, mass and length^{-1} are effectively interchangeable
  - *Thus, asking for the origin of >90% of visible mass in the universe is probably equivalent to asking what is the source of the proton's size*
- This is directly linked to the Confinement Scale of QCD
- **How can we better understand these fundamental questions?**

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Emergence of Hadron Mass – Contrasts

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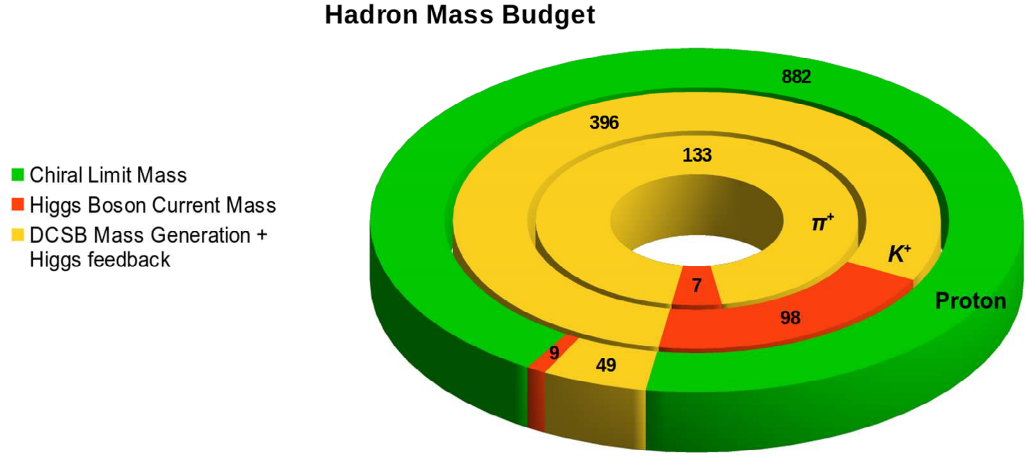

EIC Meson WG: J.Phys.G **48**(2021)075106

Compare proton, K$^+$, π^+ mass budgets

- π and *K* are massless in chiral limit (i.e. they are Nambu-Goldstone bosons of QCD) → No green ring in figure
  - Without the Higgs mechanism, π and *K* would be indistinguishable
- But they are always distinguishable from the proton!
  - Due to Emergent Hadronic Mass (EHM), Proton mass large in absence of quark couplings to Higgs boson (chiral limit) → Large green ring
- Equations of QCD stress that any explanation of the proton's mass is incomplete, unless it simultaneously explains the light masses of QCD's Goldstone bosons, the π and *K*
- Very few things are empirically known about the structures of π and *K*
  - **Progress in understanding confinement and the origin of most mass relies on our better understanding the π and *K***

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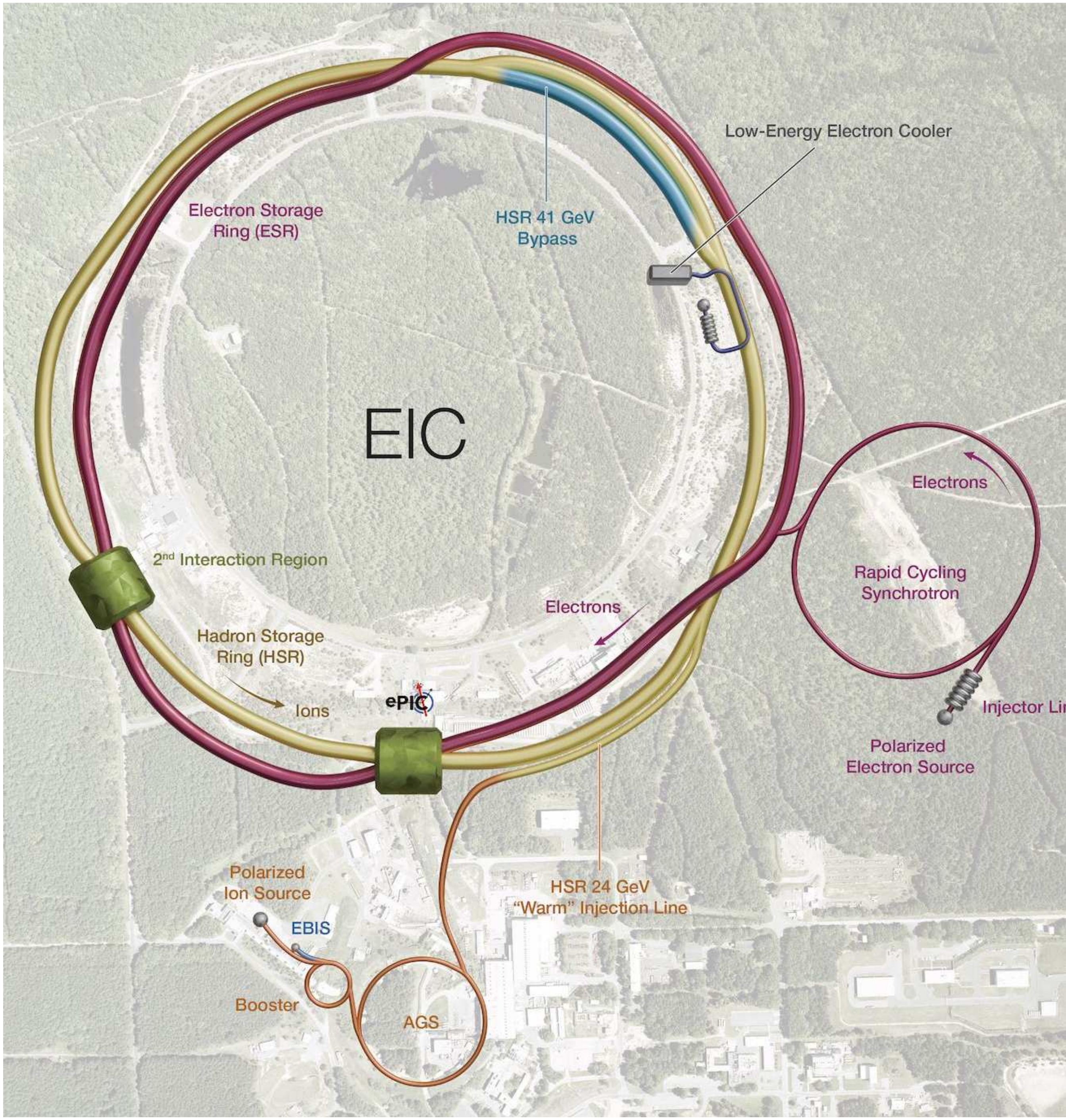
The Electron–Ion Collider (EIC)

- International facility with estimated cost of ~US$2.5B underway at Brookhaven National Lab (NY)
- **Polarized electrons** 10-20 GeV
- **Polarized light ions** (p, d, ^{3}He) and unpolarized nuclei 50-250 GeV
- **High luminosity** of 10^{33}–10^{34} cm^{-2}s^{-1}
- ~1000x higher luminosity than only previous e-p collider, HERA in 1990's
- The world's first polarized-polarized beam collider
- First collisions ~2032



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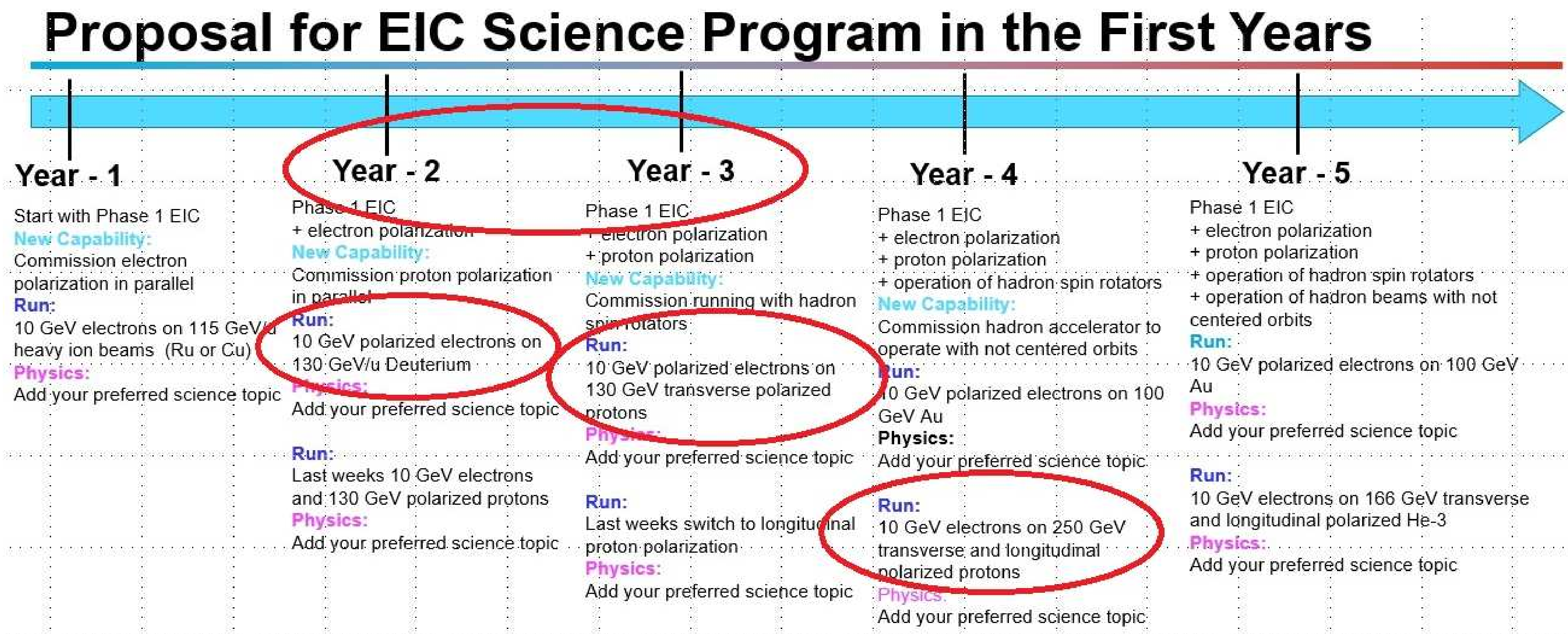
EIC Planned Early Running

- EIC early science program is a current priority and is evolving
- Based on lessons learned from past colliders
- A sequential ramp up of capabilities each year
- Early opportunities for π and *K* form factor studies



Low Divergence	Lumi per Fill (5 h)	Lumi per Year
5 GeV e x 250 GeV p	6.81 pb^{-1}	4.78 fb^{-1}
10 GeV e x 250 GeV p	8.8 pb^{-1}	6.19 fb^{-1}
5 GeV e x 130 GeV p	5.8 pb^{-1}	4.1 fb^{-1}
10 GeV e x 130 GeV p	7.1 pb^{-1}	4.95 fb^{-1}

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

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

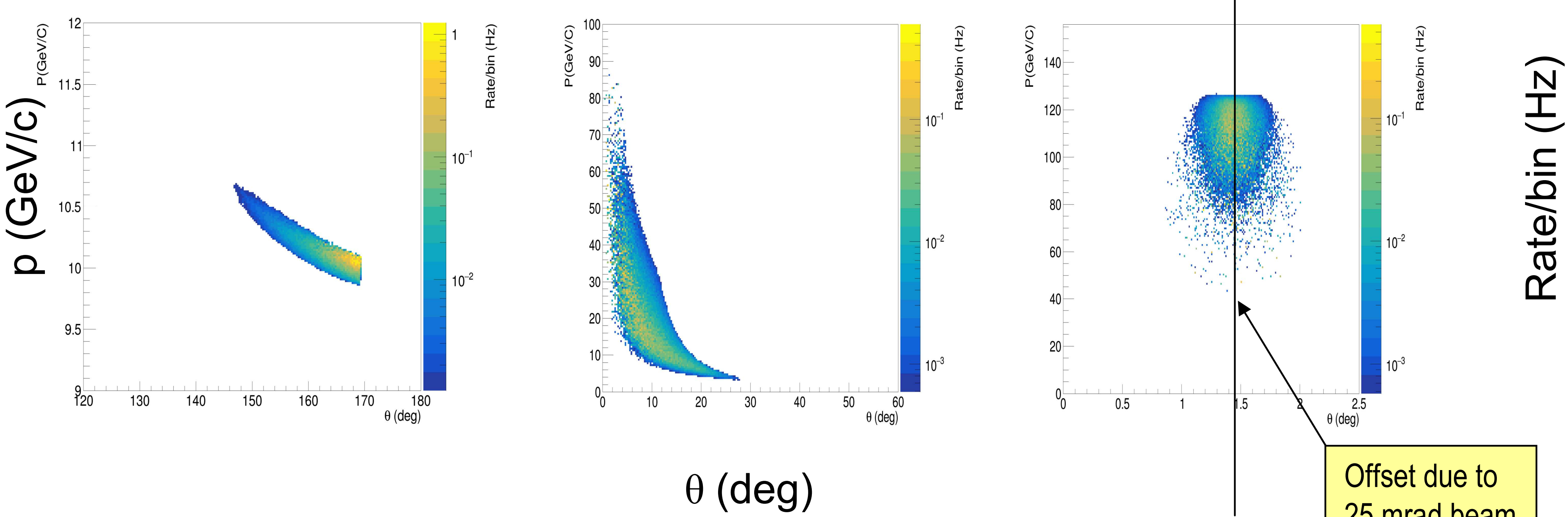
Assure exclusivity of $p(e,e'\pi^+n)$ reaction by detecting all 3 particles

10(e⁻) x 130(p) GeV Collisions

Scattered electrons:
9.8–10.7 GeV/c,
10–35° from
outgoing e beam

Pions:
3–60 GeV/c,
3–28° from p beam

Neutrons:
80–125 GeV/c
<0.6° of outgoing
proton beam



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

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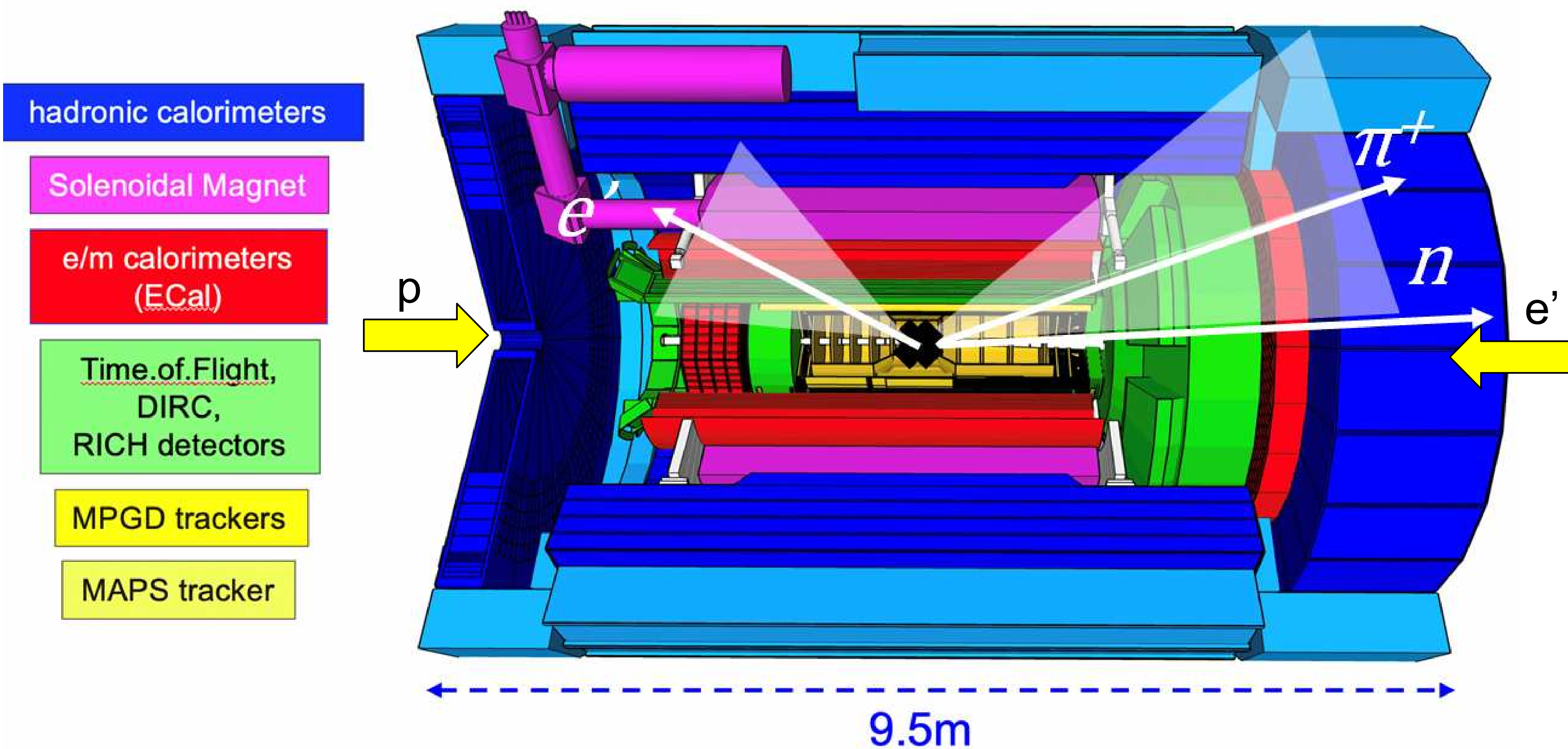
$p(e,e'\pi^+n)$ Particle Kinematics

- e' and π^+ hit the central detector
- The high energy neutron escapes down the ion ring exit



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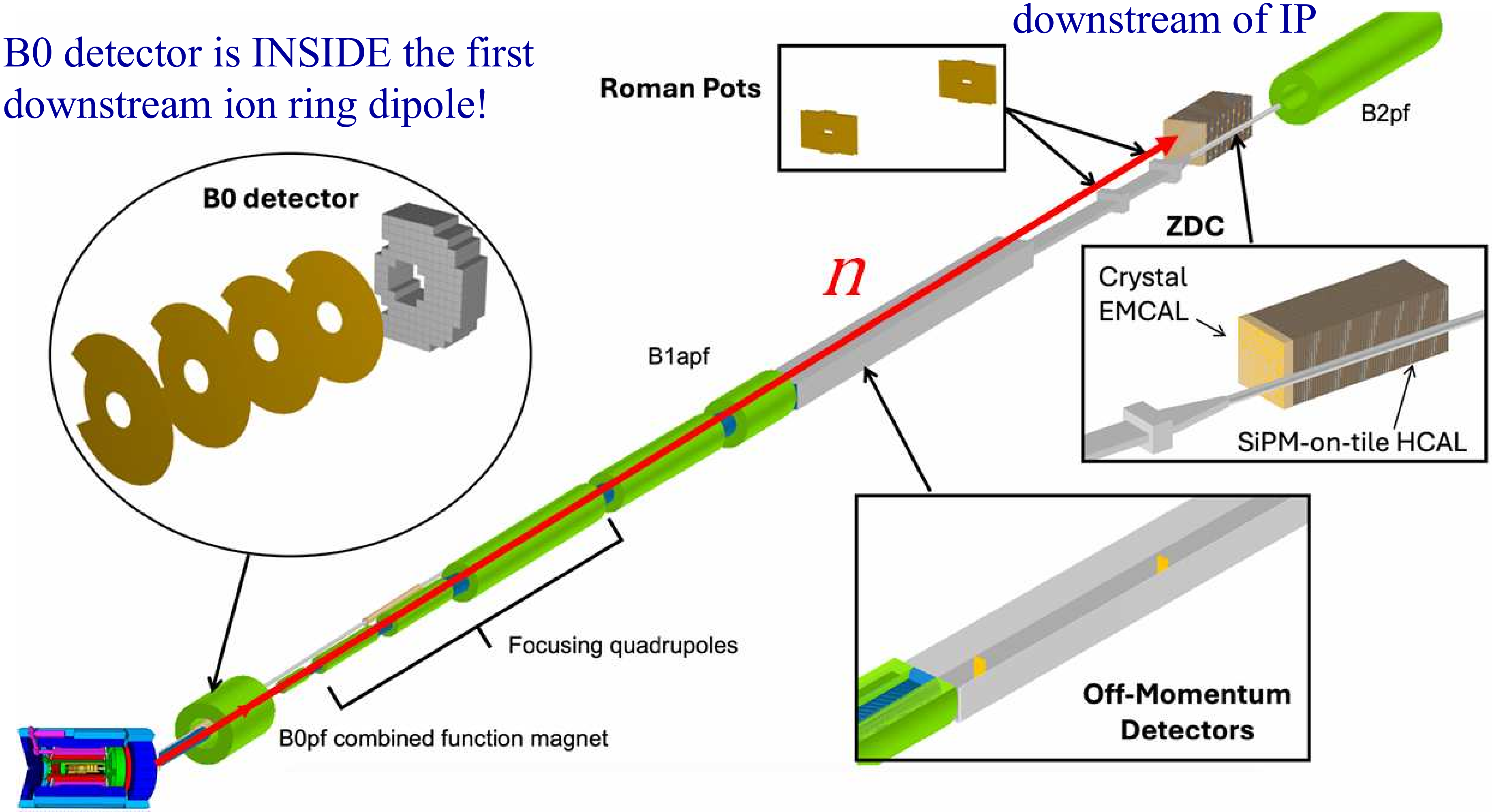
$p(e,e'\pi^+n)$ Particle Kinematics

- One of the lessons learned from HERA is to integrate hermetic detector coverage with the accelerator from the outset, as it is being designed
- Neutrons are very forward focused, hit ZDC or B0 detectors

Zero Degree Calorimeter (ZDC) detects 0º neutrals 35m downstream of IP

B0 detector is INSIDE the first downstream ion ring dipole!



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

- Need to cleanly identify $e'\pi^+n$ triple coincidence events in midst of large inclusive $e'\pi^+$ coincidence background
- To begin, require that simultaneously we have:
  - 1 negatively charged track in –z direction (e')
  - 1 positively charged track in +z direction (π^+)
  - 1 high energy reconstructed neutral cluster in ZDC
    - E_n>40 GeV
    - θ^*_n<4 mrad
- The ZDC has excellent position (θ,φ) resolution, but much poorer energy resolution
- If the detected neutron is from an exclusive event, the ZDC should be near the location predicted from momentum conservation
  - i.e. the location calculated via $\vec{p}_{miss} = \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}$
  - This condition only true if there are NO other emitted particles, i.e. the event is from an EXCLUSIVE $p(e,e'\pi^+n)$ reaction

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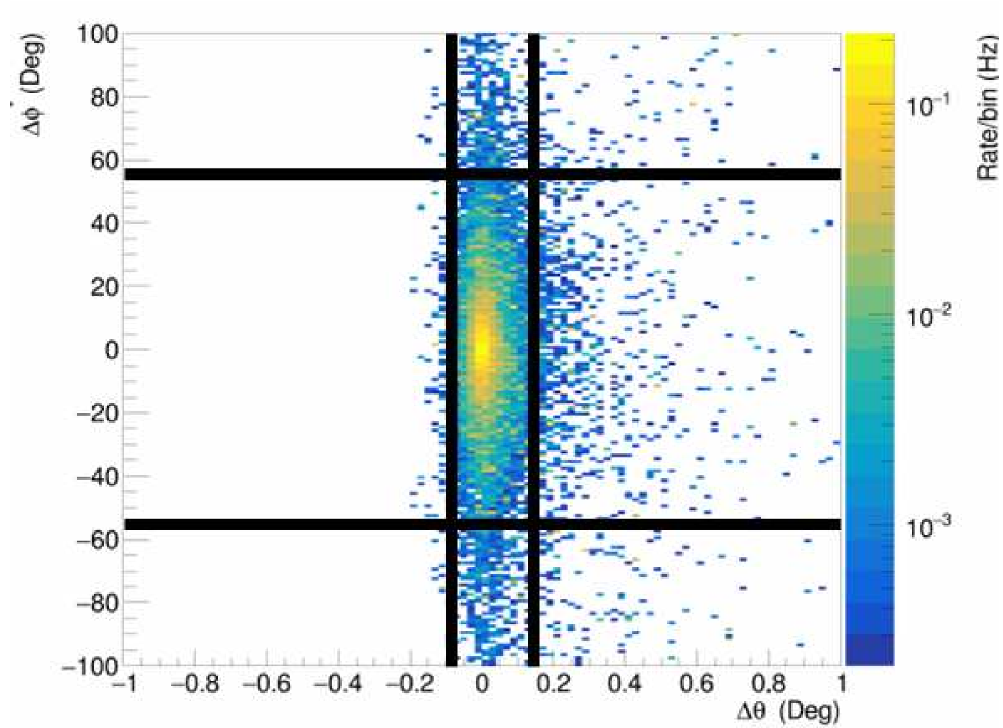
Example $p(e,e'\pi^+n)$ Exclusivity Cut

- **Make use of high angular resolution of ZDC to reduce non-exclusive 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 $p(e,e'\pi^+n)$ events

Cuts applied: $-0.09^o<\Delta\theta<0.14^o$ $-55^o<\Delta\varphi<55^o$ in addition to triple coincidence cuts

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$p(e,e'\pi^+n)$ Detection Efficiency per (Q^2,t) bin

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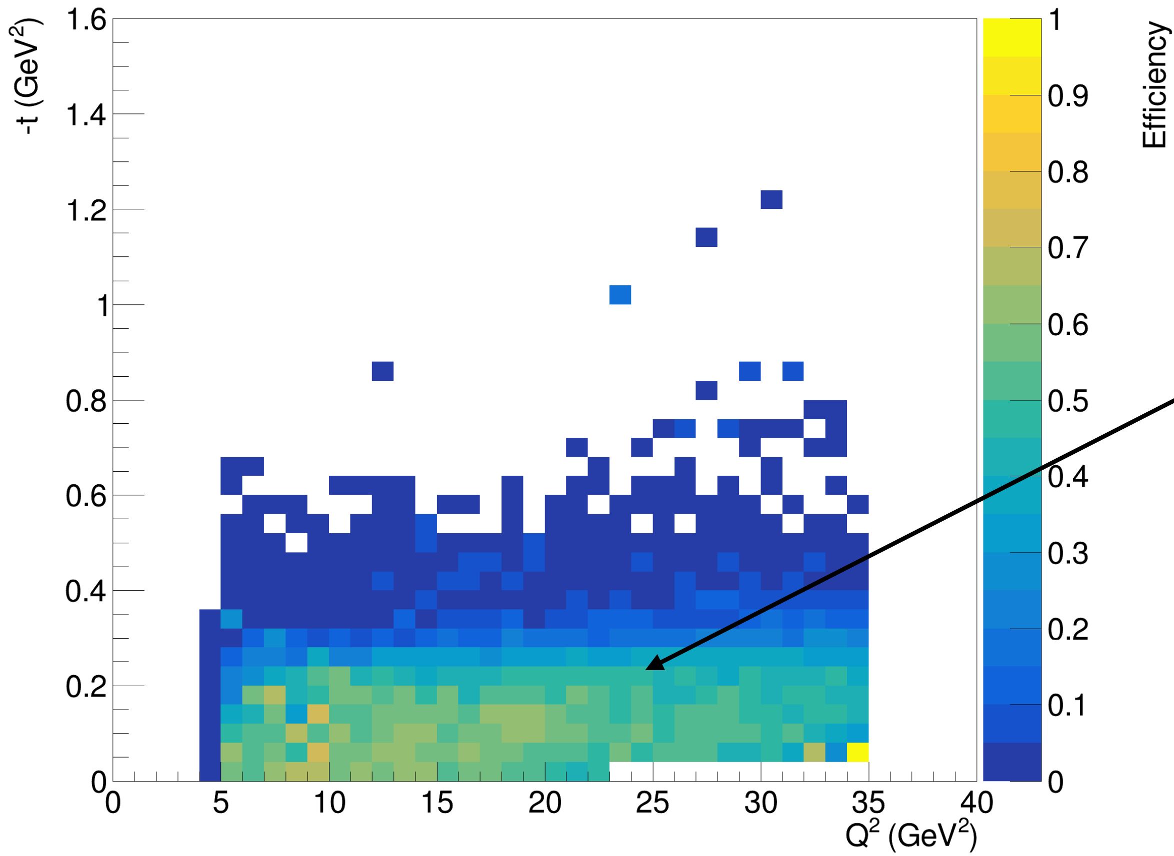

Detection efficiency best in crucial low –*t* region

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 10x130 events, require the hit has Energy Deposit > 40 GeV

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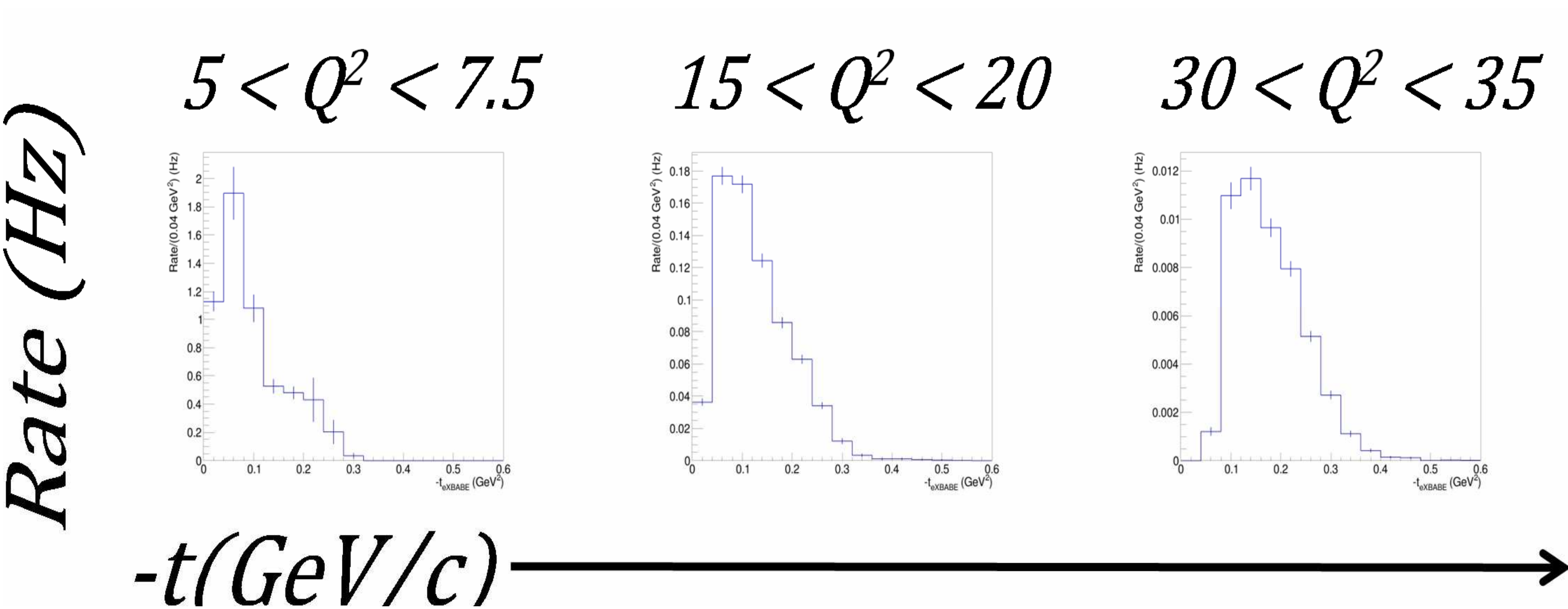
Predicted $p(e,e'\pi^+n)$ rates per Q^2-t bin

- Rates after applying cuts, binned in Q^2 and t for 10x130 beam combo with L=4.48 x 10^{33} $cm^{-2}s^{-1}$
- Q^2 bins: 2.5 GeV^2 wide for $Q^2 \leq 10$ GeV^2, 5 GeV^2 wide for $Q^2 > 10$ GeV^2
- From rate/bin, calculate #events for $\int L$ =5 fb^{-1}, project to F_π uncertainties



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F_π EIC Early Running Projections

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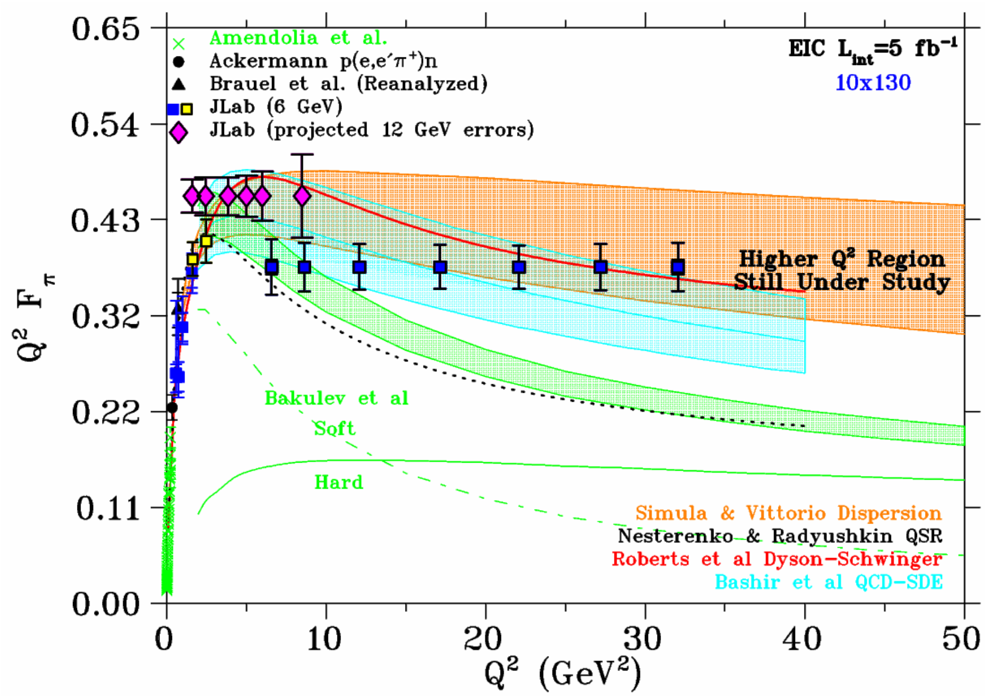

- 10(e^-) x 130(p)
- $\int L$=5 fb^{-1}
- Based on full ePIC detector reconstruction including cuts for clean identification of exclusive $p(e,e'\pi^+n)$ events
- ***y*-axis location of projected data is ARBITRARY, what is meaningful are the error bars, which represent real projected errors, including:**
  - Syst. Unc: 2.5% pt–pt and 12% scale.
  - $R=\sigma_L/\sigma_T$=0.013–0.14 at lowest $-t$, and $\delta R=R$ syst. unc. in model subtraction to isolate σ_L
  - π pole dominance at small $-t$ confirmed in e+d π^-/π^+ ratios

- **Higher Q^2 data on π^+, K^+ form factors vital to several key problems:**
  - Pion and kaon properties are intimately connected with dynamical chiral symmetry breaking (DCSB), which is the origin of >90% of the mass of the visible universe and is deeply linked to our understanding of confinement
- **Next steps include:**
  - Extension of $p(e,e'\pi^+n)$ event generator to higher Q^2
  - Simulation of e+d 10x130 collisions to be available in Year 2 of EIC running
  - Refinements to event simulation/reconstruction, such as π^+ PID in Forward DIRC, and Far Forward event reconstruction algorithms

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F_π and F_K Studies to Higher Q^2 at EIC

- **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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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

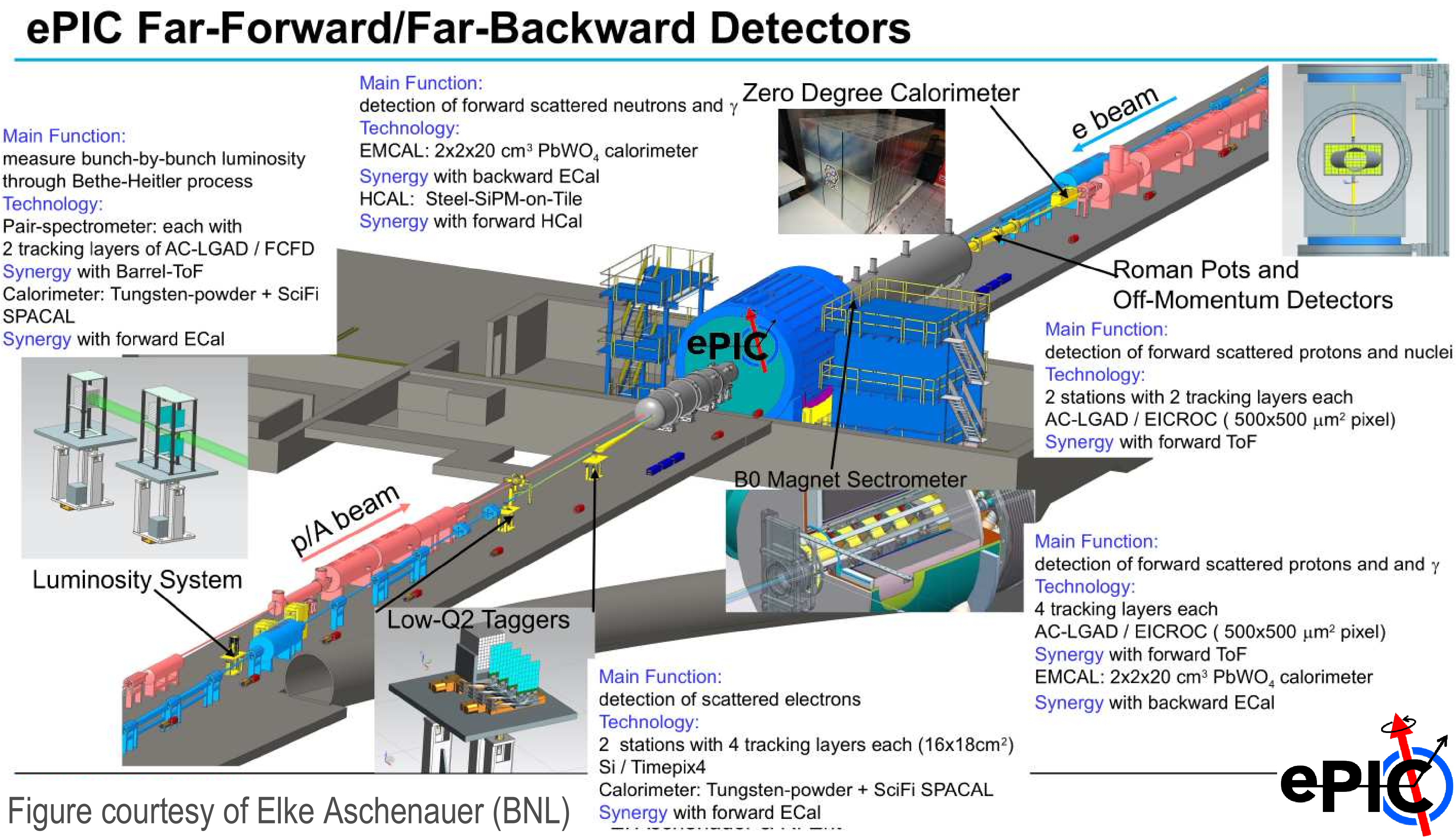

Figure courtesy of Elke Aschenauer (BNL)

DEMP π^+/K^+ Event Generator

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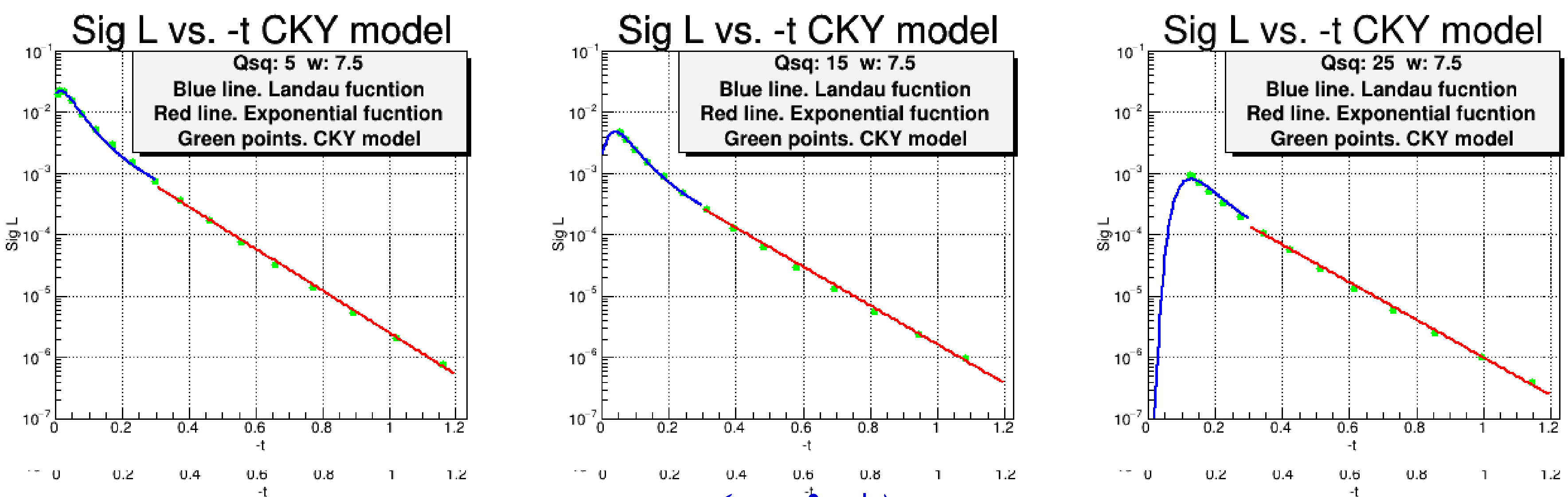
- Regge-based $p(e,e'\pi^+)n$ model of *T.K. Choi, K.J. Kong, B.G. Yu (CKY)* [J.Kor.Phys.Soc. 67(2015)1089]
  - Created a MC event generator by parameterizing CKY σ_L, σ_T for $5<Q^2$ (GeV^2)<35 $2.0<W$ (GeV)<10 $0<-t$ (GeV^2)<1.2
- Extended to $p(e,e'K^+)\Lambda[\Sigma^0]$ by parameterizing Regge-based 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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$p(e,e'K^+)\Lambda$ Generator Updates

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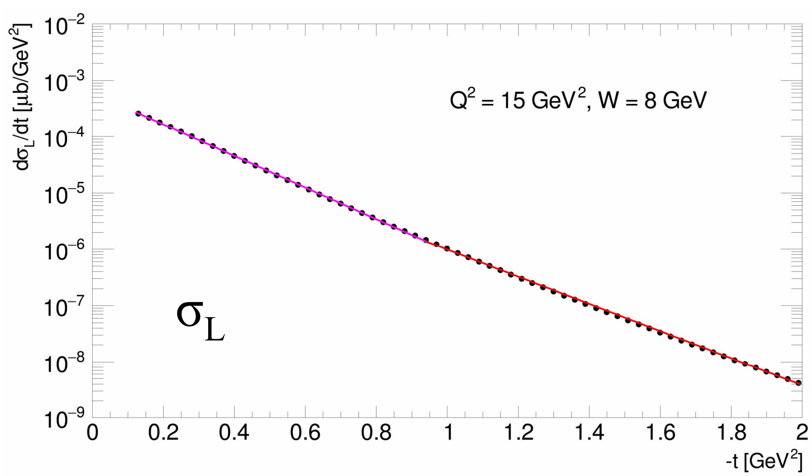
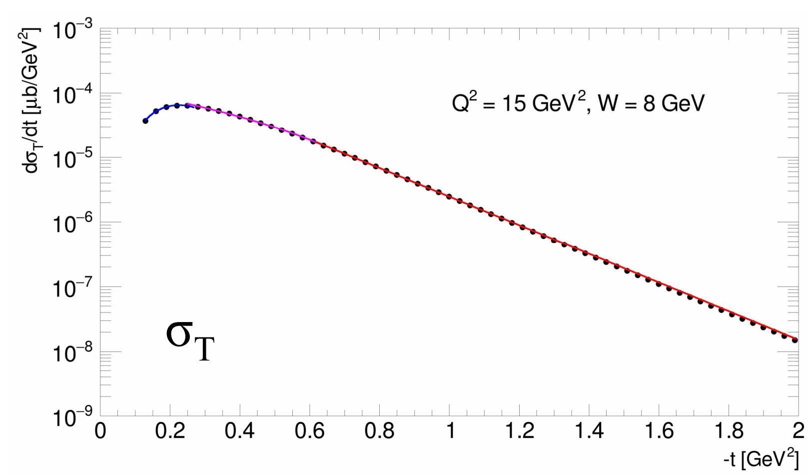
- UofR student Love Preet added K^+ physics module to our DEMP event generator
  - Parameterize Regge–based model in similar way to π^+
  - $K^+\Lambda$ (soon also $K^+\Sigma$) modules are based on Vanderhaeghen Guidal Laget model [PRC 61 (2000) 025204]
  - σ_L,σ_T parameterizations for: $1<Q^2<35$ $2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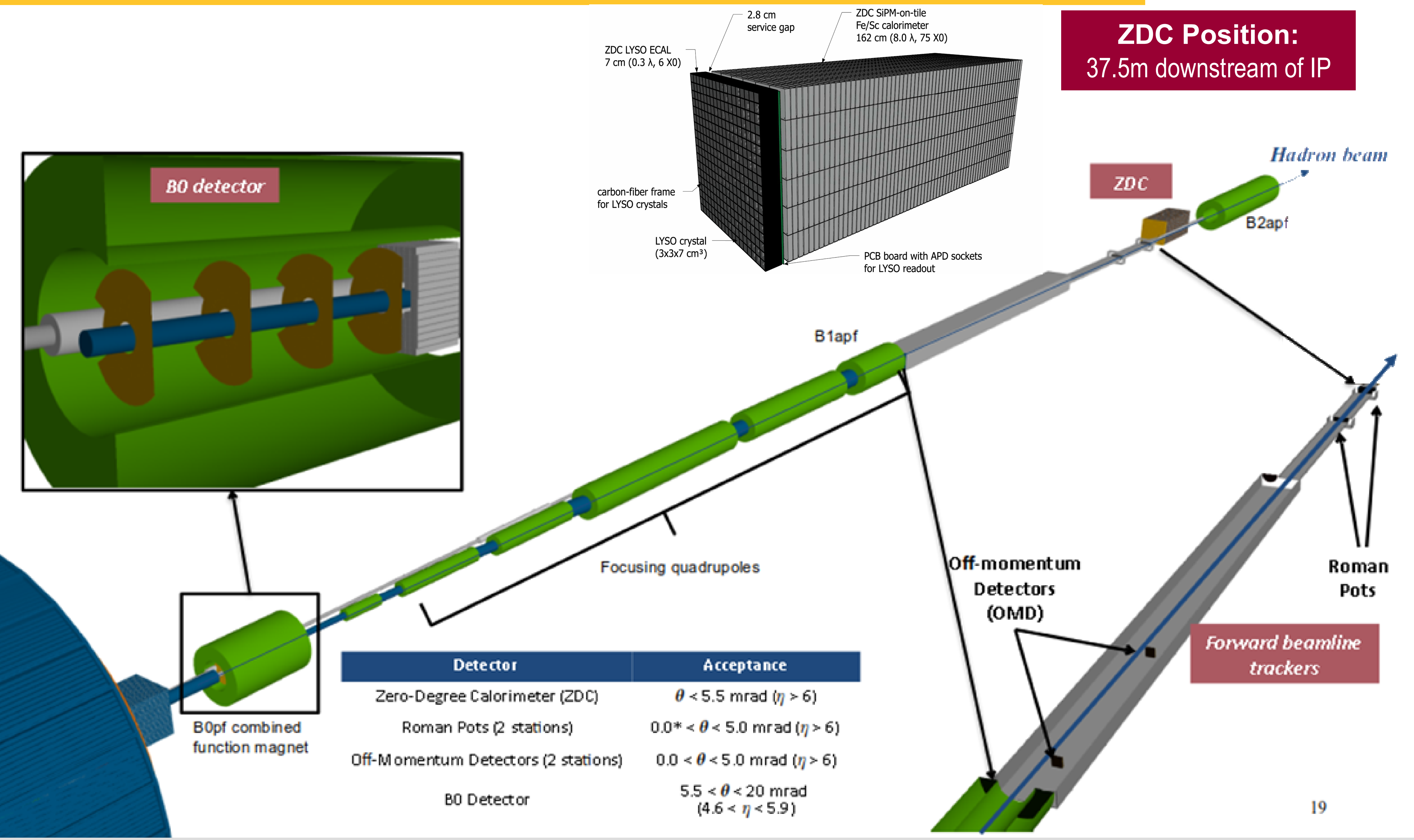
EIC Far Forward Detectors

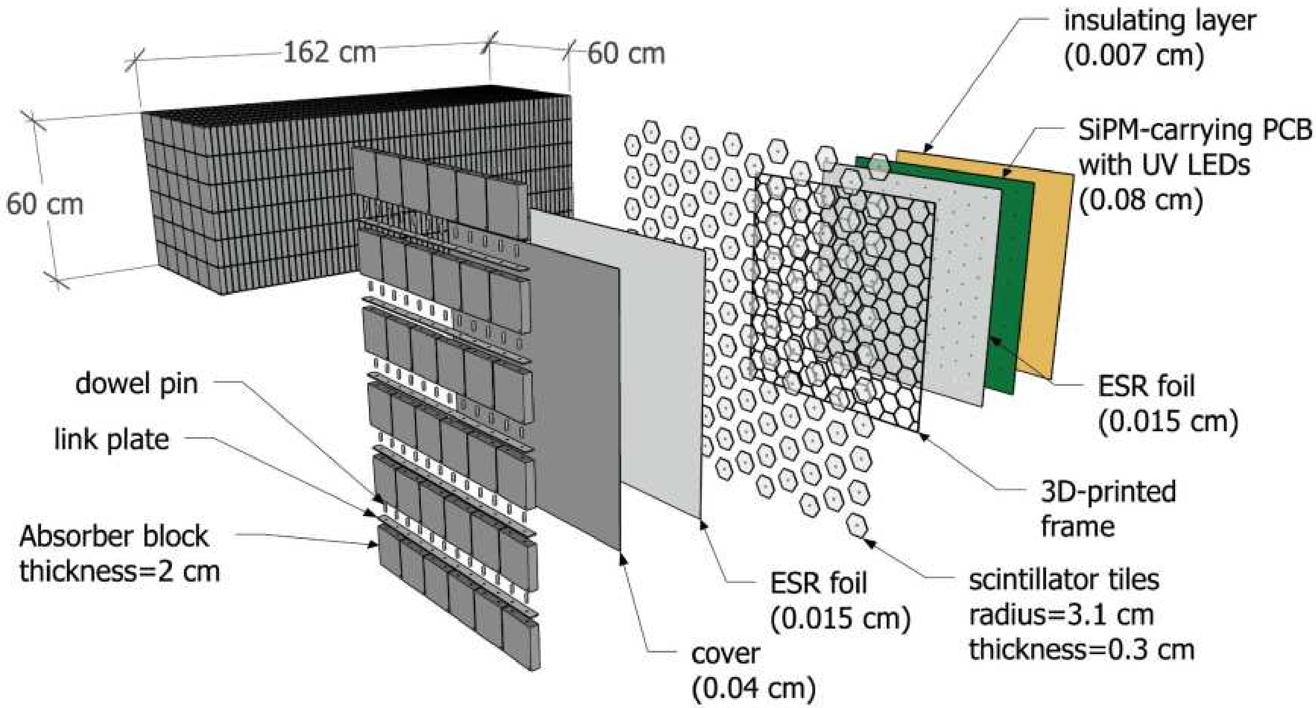
ZDC Position:
37.5m downstream of IP



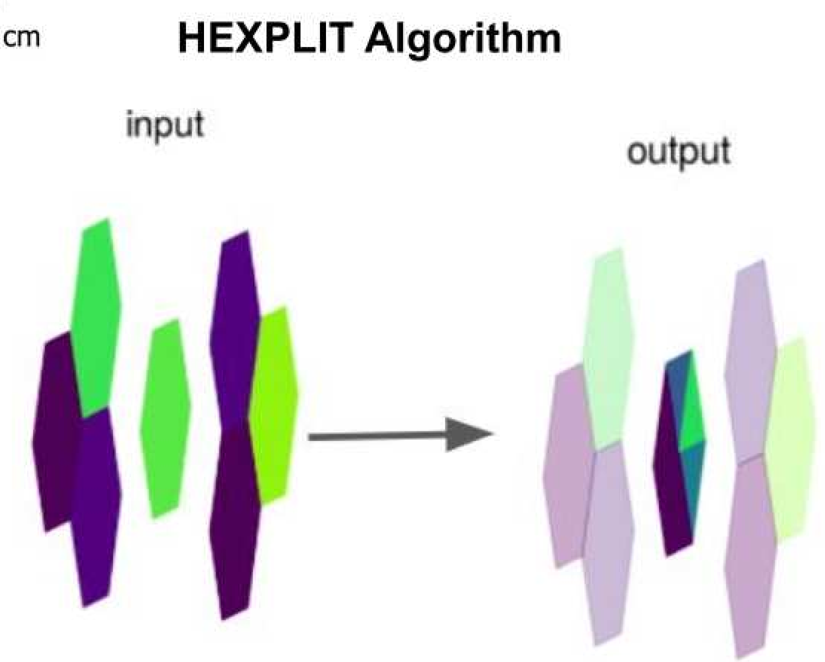
Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5$ mrad ($\eta > 6$)
Roman Pots (2 stations)	$0.0^* < \theta < 5.0$ mrad ($\eta > 6$)
Off-Momentum Detectors (2 stations)	$0.0 < \theta < 5.0$ mrad ($\eta > 6$)
B0 Detector	$5.5 < \theta < 20$ mrad ($4.6 < \eta < 5.9$)

- 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



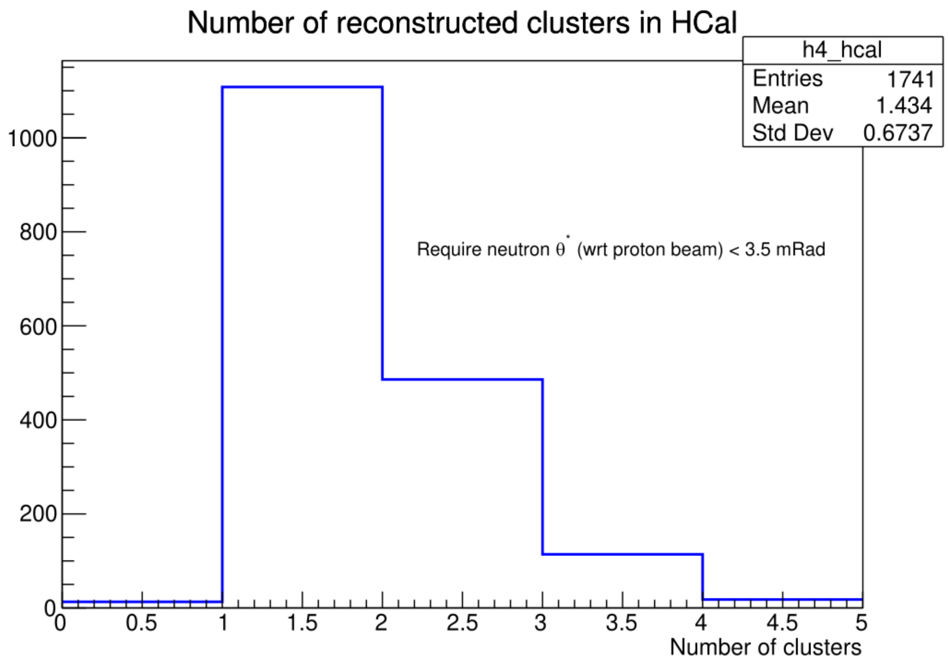
Figures courtesy of Miguel Arratia (UC Riverside)

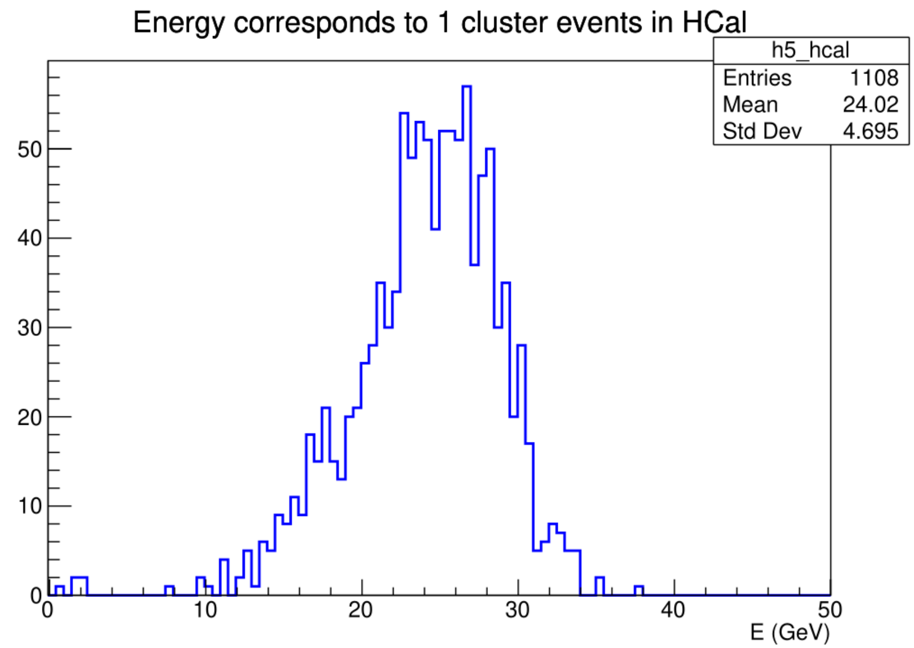


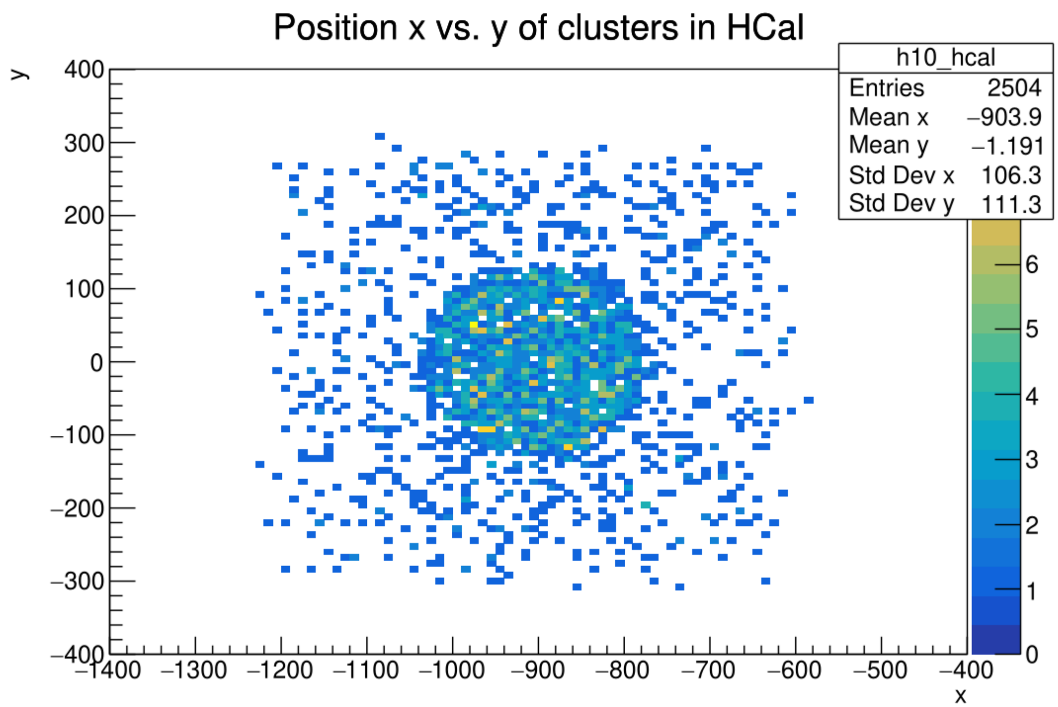
S. Paul, M. Arratia arXiv:2308.06939

- 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

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







- 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

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

- Significantly more challenging than $p(e,e'\pi^+)n$ reconstruction
- Need to efficiently identify $\Lambda \rightarrow n\pi^0 \rightarrow n\gamma\gamma$ decay (~33%)
  - Neutral products take straight line paths
  - Cleanly distinguishing n from γ clusters is main challenge
- Dominant $\Lambda \rightarrow p\pi^-$ 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 $\pi^0 \rightarrow \gamma\gamma$ 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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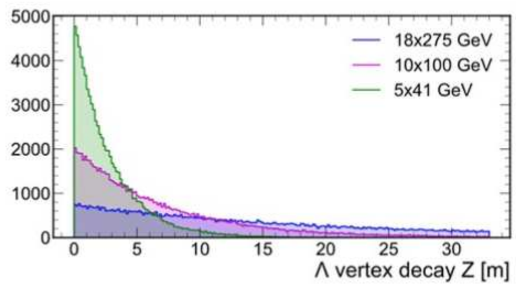
Some ZDC Design Choices

- $\Lambda \rightarrow n\pi^0 \rightarrow n\gamma\gamma$ 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



From: J Arrington *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* **48** 075106

Yellow: crystal EMCAL
Blue: SiPM-on-Tile

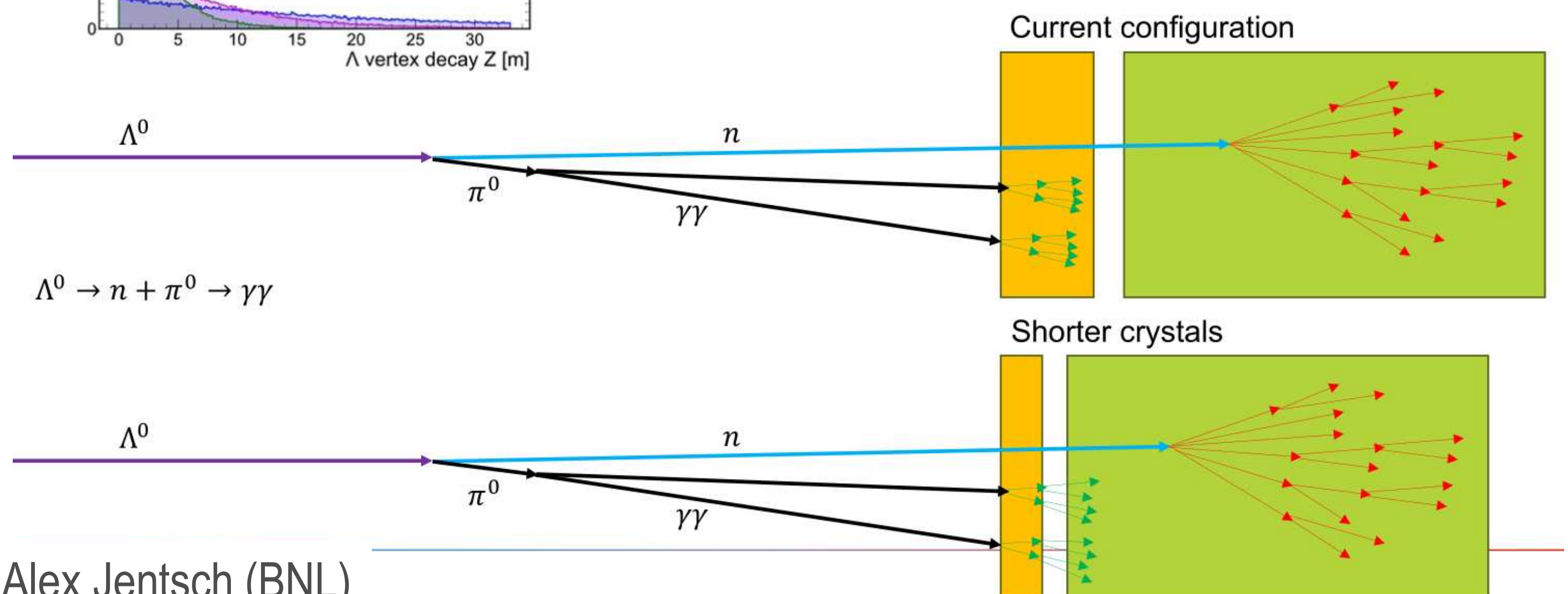


Figure courtesy of Alex Jentsch (BNL)

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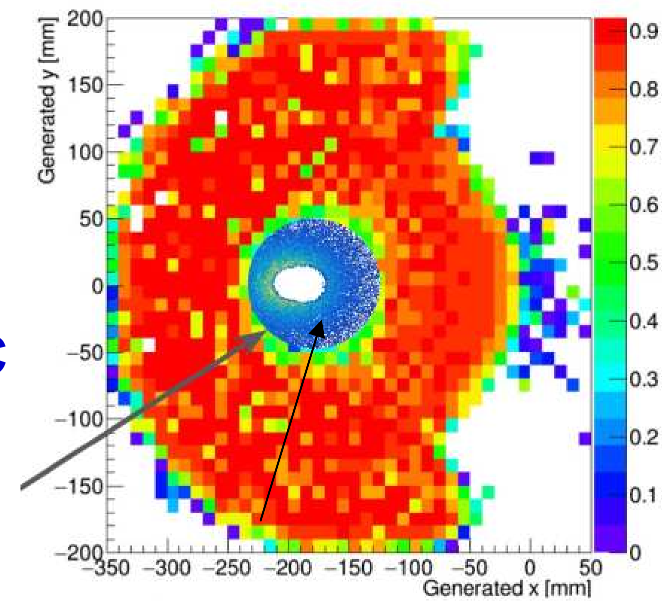
Later Stage $p(e,e'K^+)\Lambda[\Sigma^0]$ Reconstruction

- **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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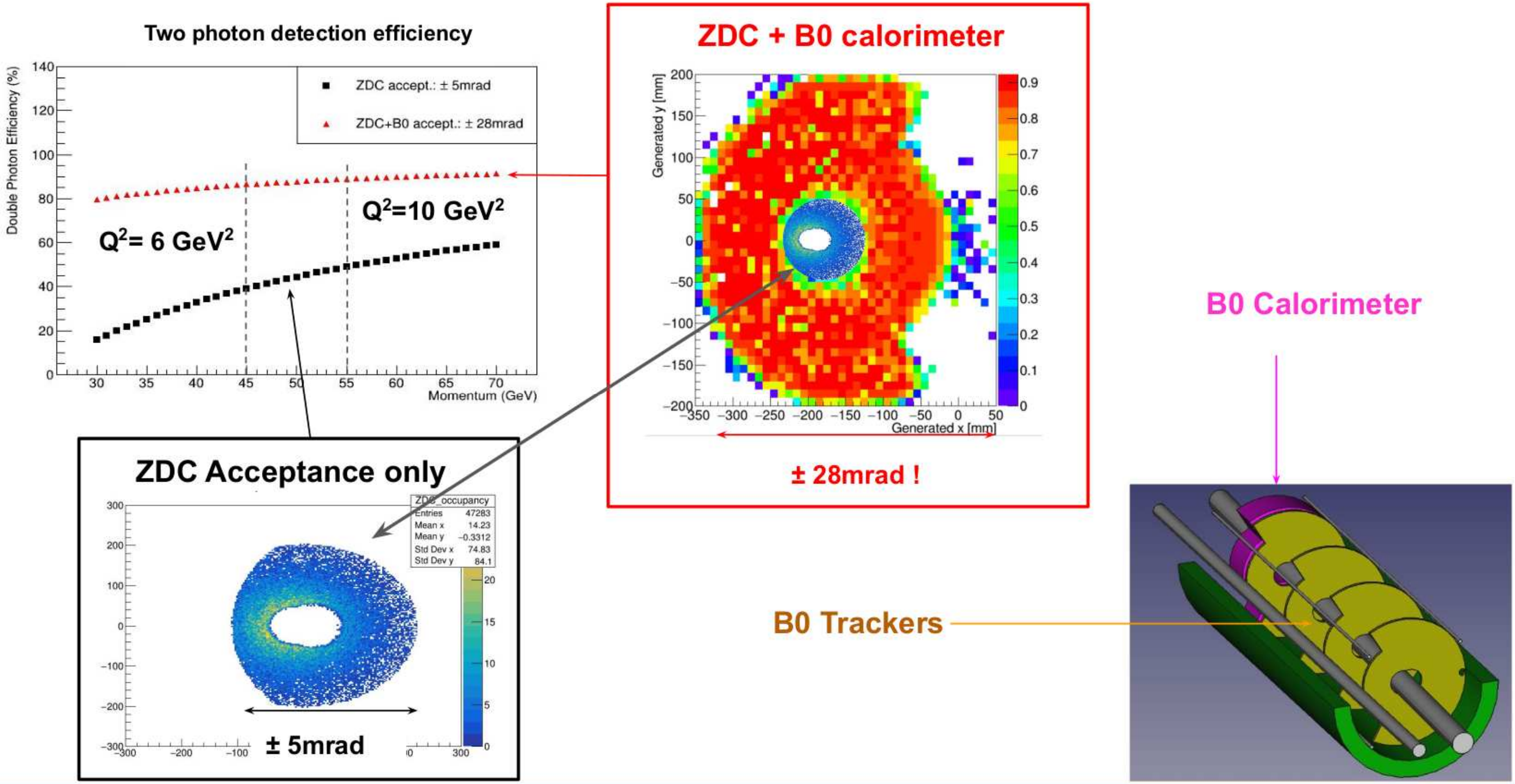
Two photon detection efficiency
Double Photon Efficiency (%)
Momentum (GeV)
ZDC accept.: ± 5mrad
ZDC+B0 accept.: ± 28mrad
Q²= 6 GeV²
Q²=10 GeV²
ZDC + B0 calorimeter
Generated y [mm]
Generated x [mm]
± 28mrad !
ZDC Acceptance only
ZDC_occupancy
Entries 47283
Mean x 14.23
Mean y -0.3312
Std Dev x 74.83
Std Dev y 84.1
± 5mrad
B0 Calorimeter
B0 Trackers

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

- **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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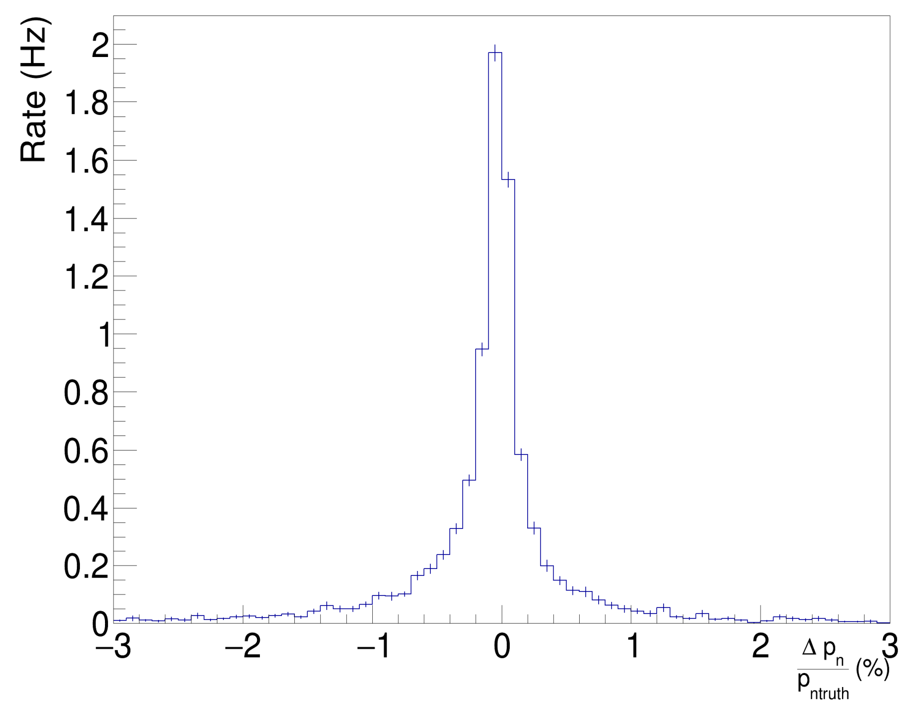
Improving *neutron* reconstruction resolution

- **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 $p_{miss} = \left| \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+} \right|$
- **Use ZDC hit positions θ_{ZDC}, φ_{ZDC} instead of calculated θ_{miss}, φ_{miss} angles**
- E_{miss} also adjusted to reproduce neutron mass
- After these adjustments, the neutron track momentum was reconstructed to <1% of "true" momentum (IR6)



$\Delta p_n = (p_{n\ track} - p_{n\ truth}) / p_{n\ truth}$

Plot by Stephen Kay

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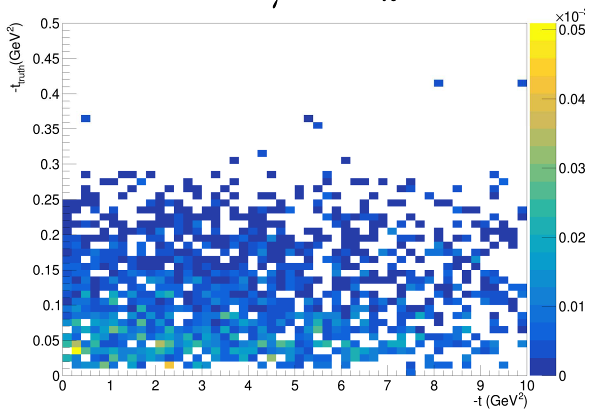
Reconstructing Mandelstam *t* (IR6)

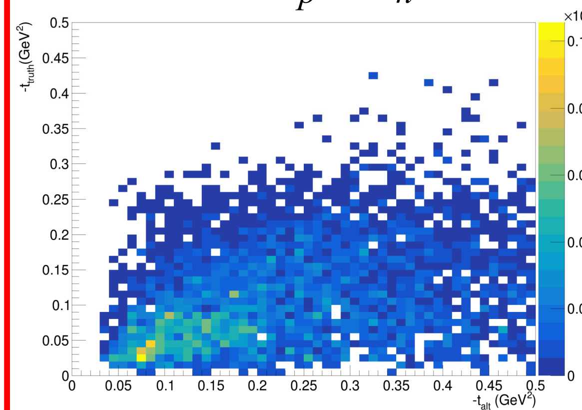
- Extraction of pion form factor from $p(e,e'\pi^+n)$ data requires *t* to be reconstructed accurately, as we need to verify dominance of the *t*–channel process from the dependence of $d\sigma/dt$ upon *t*

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

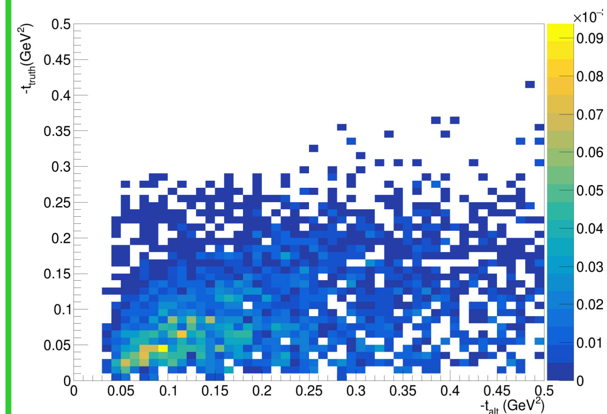
$t=(p_{\gamma*}-p_{\pi})^2$



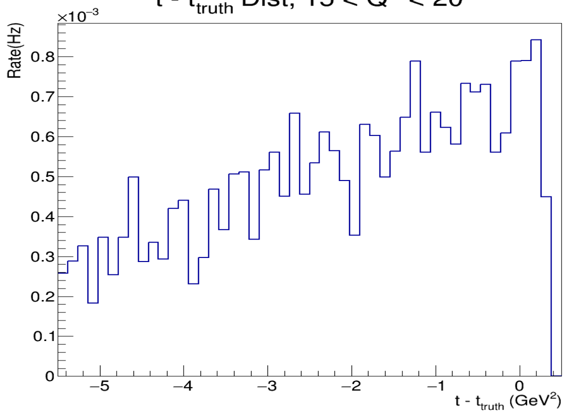
$t=(p_p-p_n)^2$

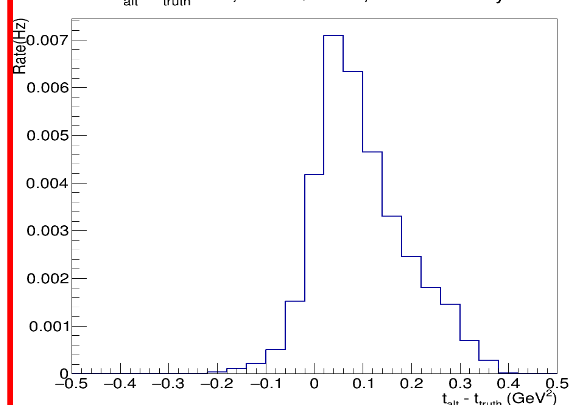


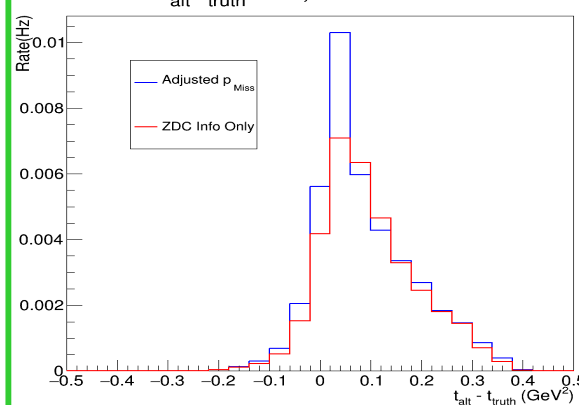
Correct p_{miss} *w/ ZDC(θ,φ)*



$t_{reconstr} - t_{truth}$







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

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

Plots by Stephen Kay

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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 ε<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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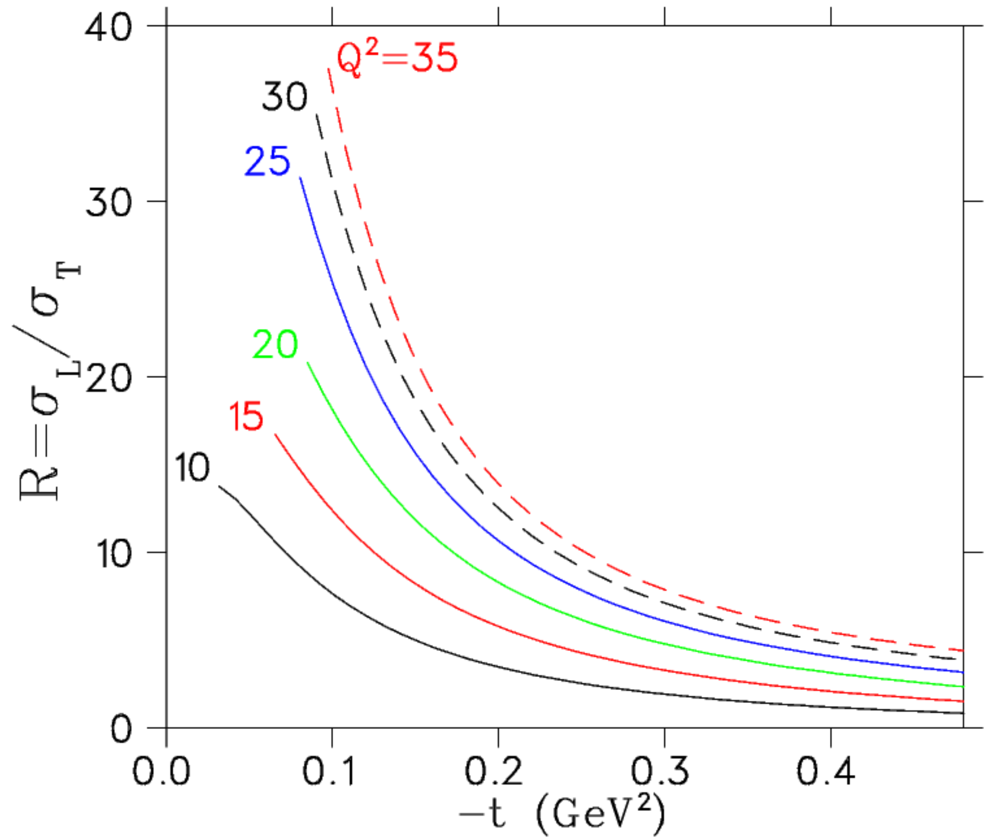
Isolate $d\sigma_L/dt$ using a Model

- 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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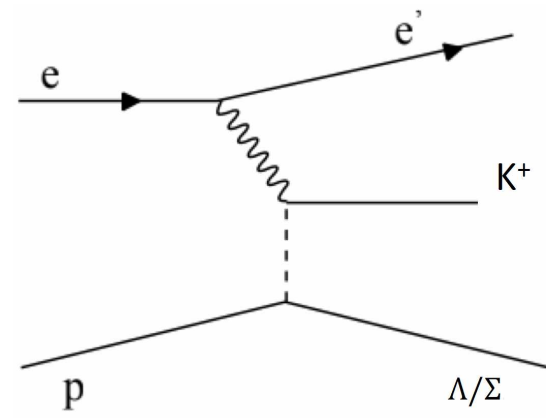
Can we measure F_K at the EIC?

- **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

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

- **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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