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

Garth Huber, Love Preet
University of Regina
Stephen Kay
University of York

CAP Congress, Saskatoon, SK
June 9, 2025

Supported by:
NSERC CRSNG
SAPPJ-2025-00040
SAPIN-2021-00026
Center for Frontiers in Nuclear Science

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

Garth Huber, huberg@uregina.ca

QCD is responsible for most mass

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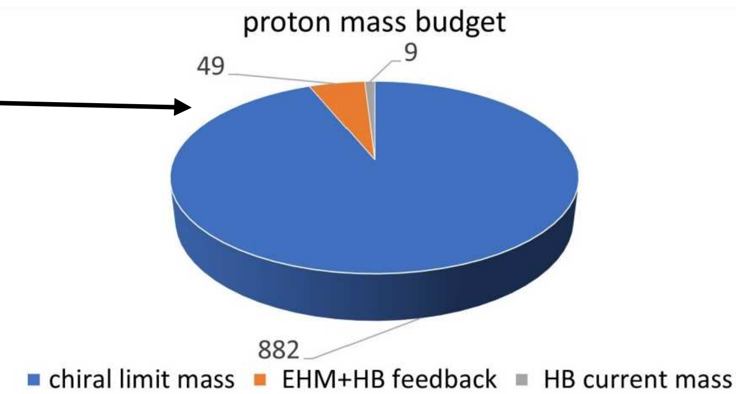
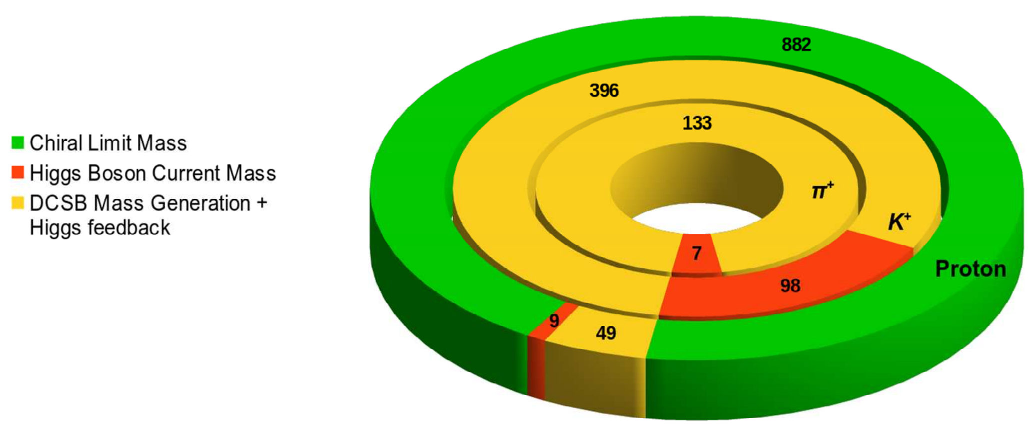
- **In appearance, QCD is simple, but it is also unique**
  - It is a fundamental theory with the capacity to sustain massless elementary degrees-of-freedom, *i.e. quarks and gluons*
  - Yet, quarks and gluons are predicted to acquire mass dynamically
  - The mass of nucleons and almost all hadrons likewise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

Garth Huber, huberg@uregina.ca

Emergence of Hadron Mass – Contrasts



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

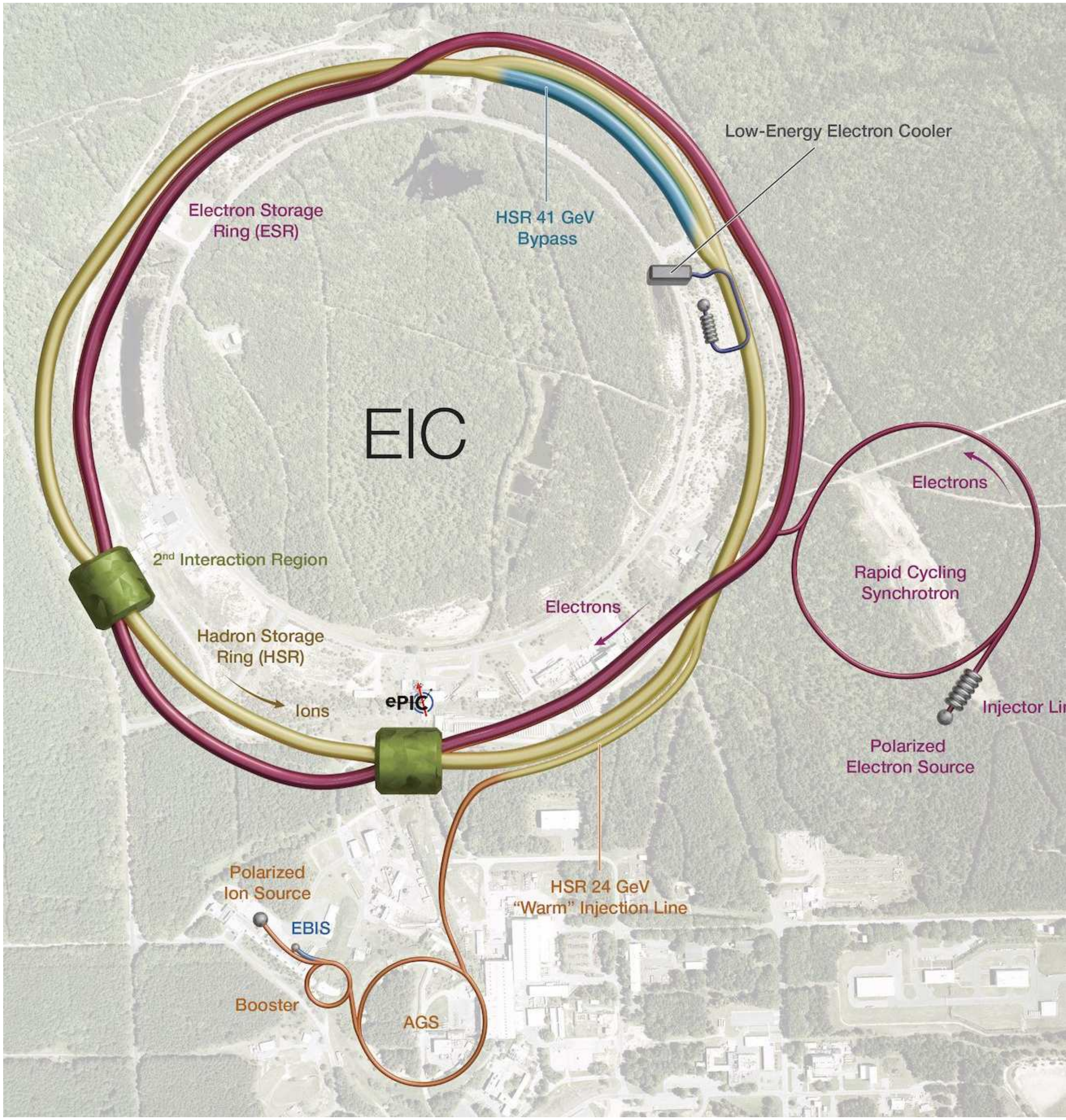
Compare proton, K⁺, π⁺ mass budgets

- 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***

Garth Huber, huberg@uregina.ca

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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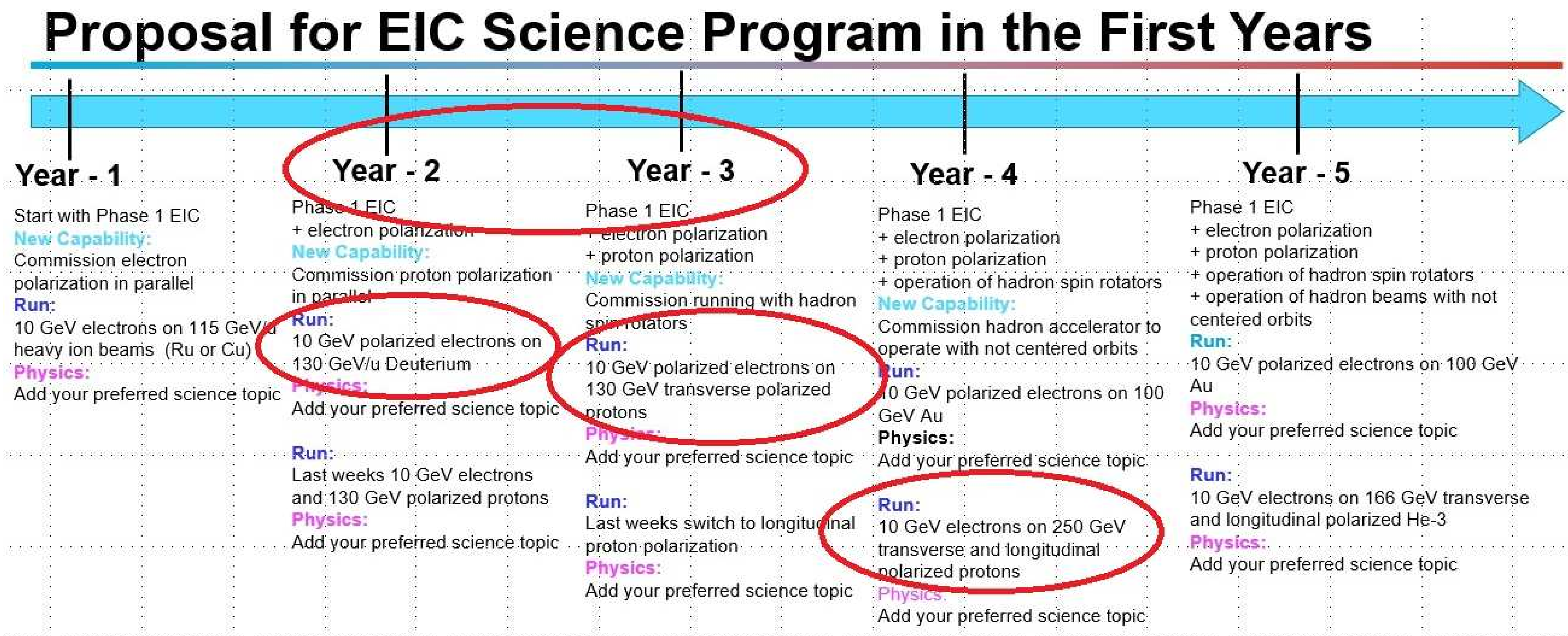
EIC Planned Early Running

- 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}

Garth Huber, huberg@uregina.ca

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

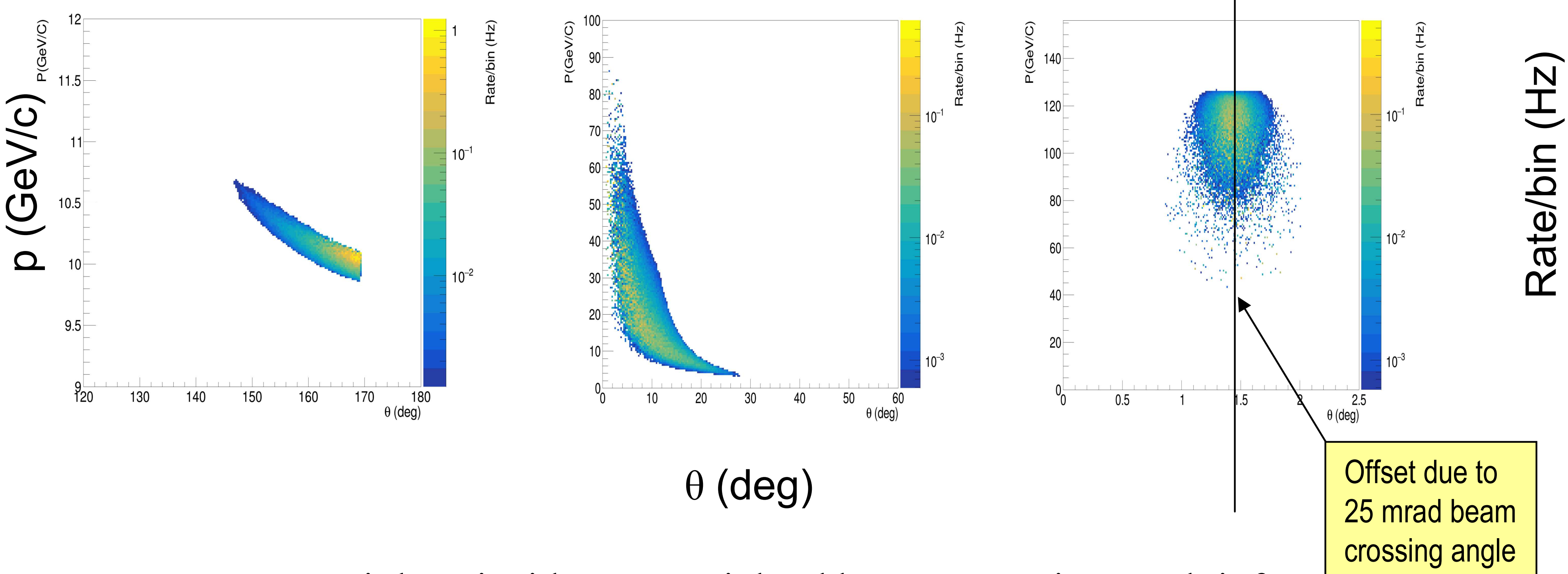
Assure exclusivity of $p(e,e'\pi^+n)$ reaction by detecting all 3 particles

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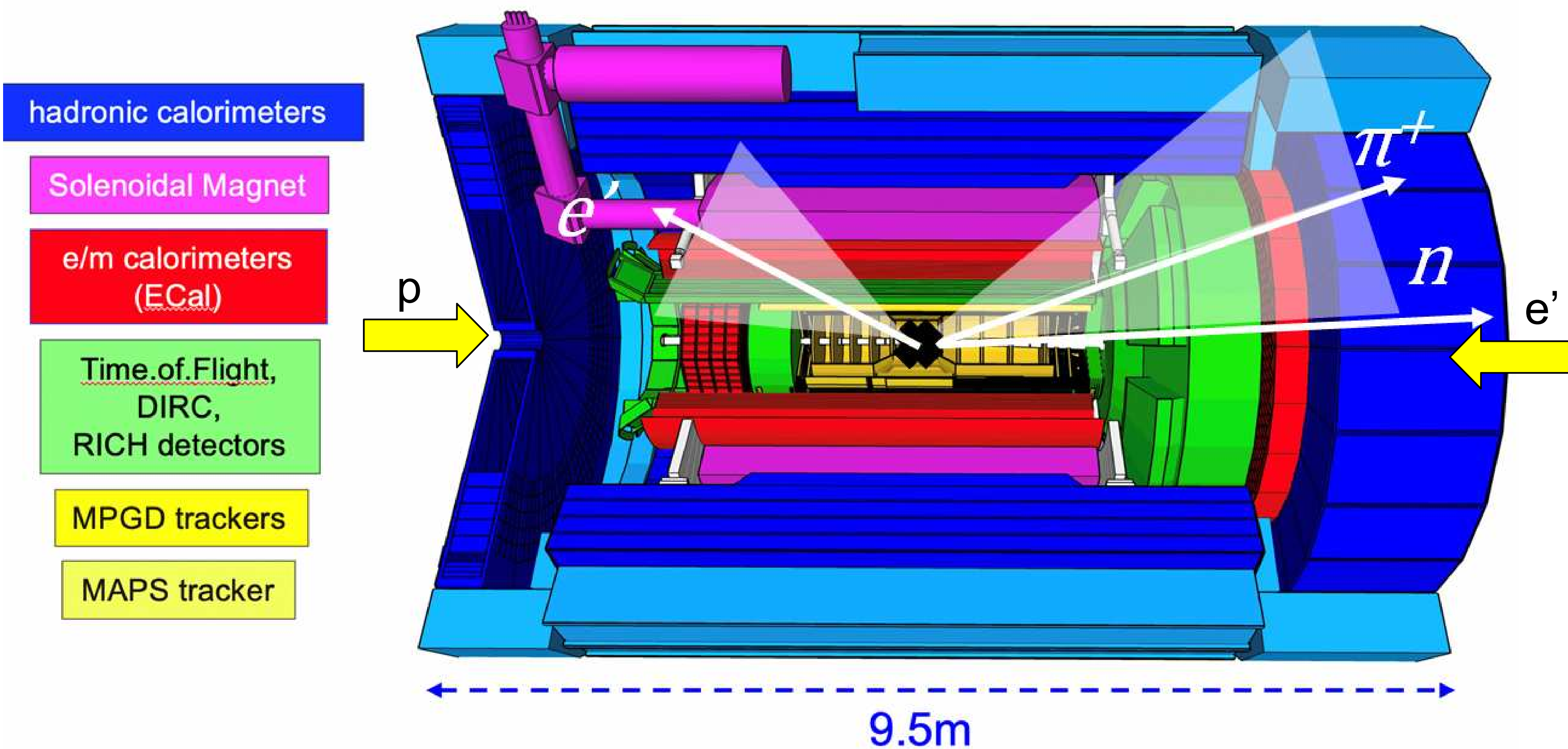
$p(e,e'\pi^+n)$ Particle Kinematics

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



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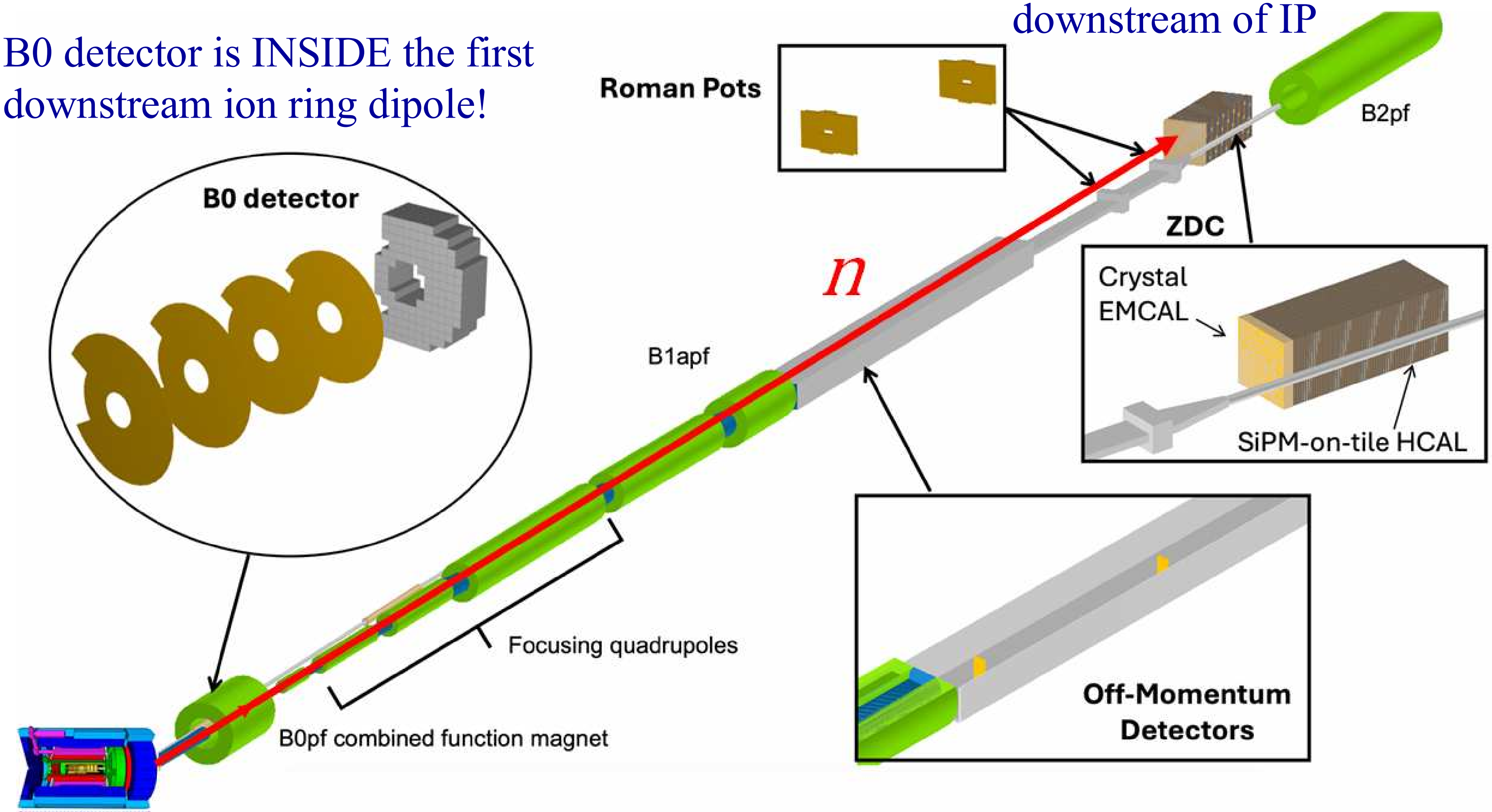
$p(e,e'\pi^+n)$ Particle Kinematics

- 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 0° neutrals 35m downstream of IP

B0 detector is INSIDE the first downstream ion ring dipole!



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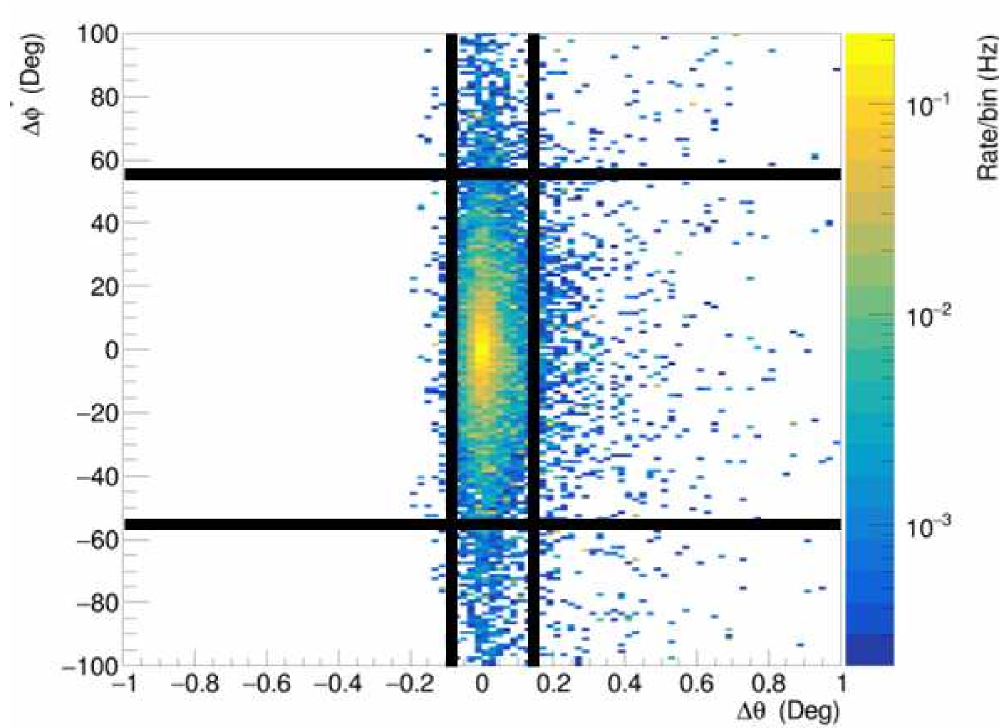
Selecting Exclusive $p(e,e'\pi^+n)$ Events

- 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

Garth Huber, huberg@uregina.ca

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

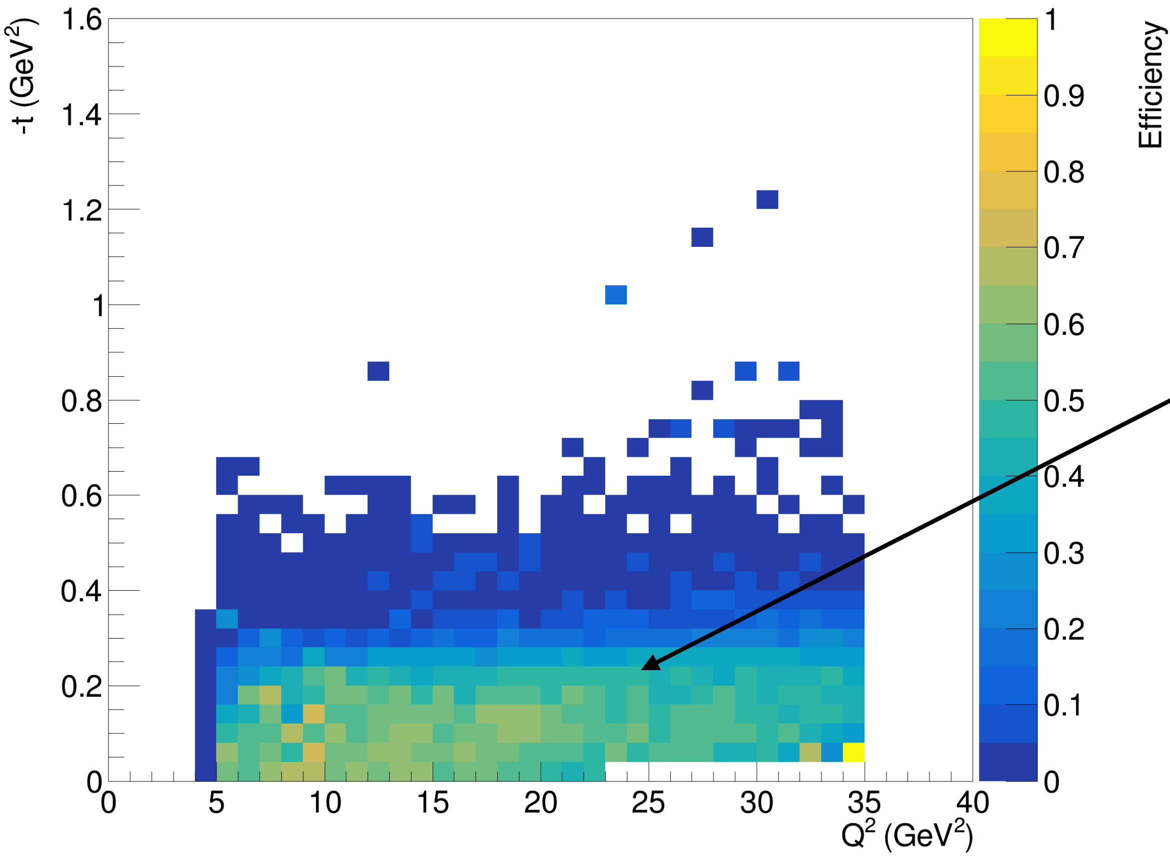


Differences between hit and calculated neutron positions on ZDC for $p(e,e'\pi^+n)$ events

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

Garth Huber, huberg@uregina.ca

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



Detection efficiency best in crucial low $-t$ region

Garth Huber, huberg@uregina.ca

Require EXACTLY two tracks:

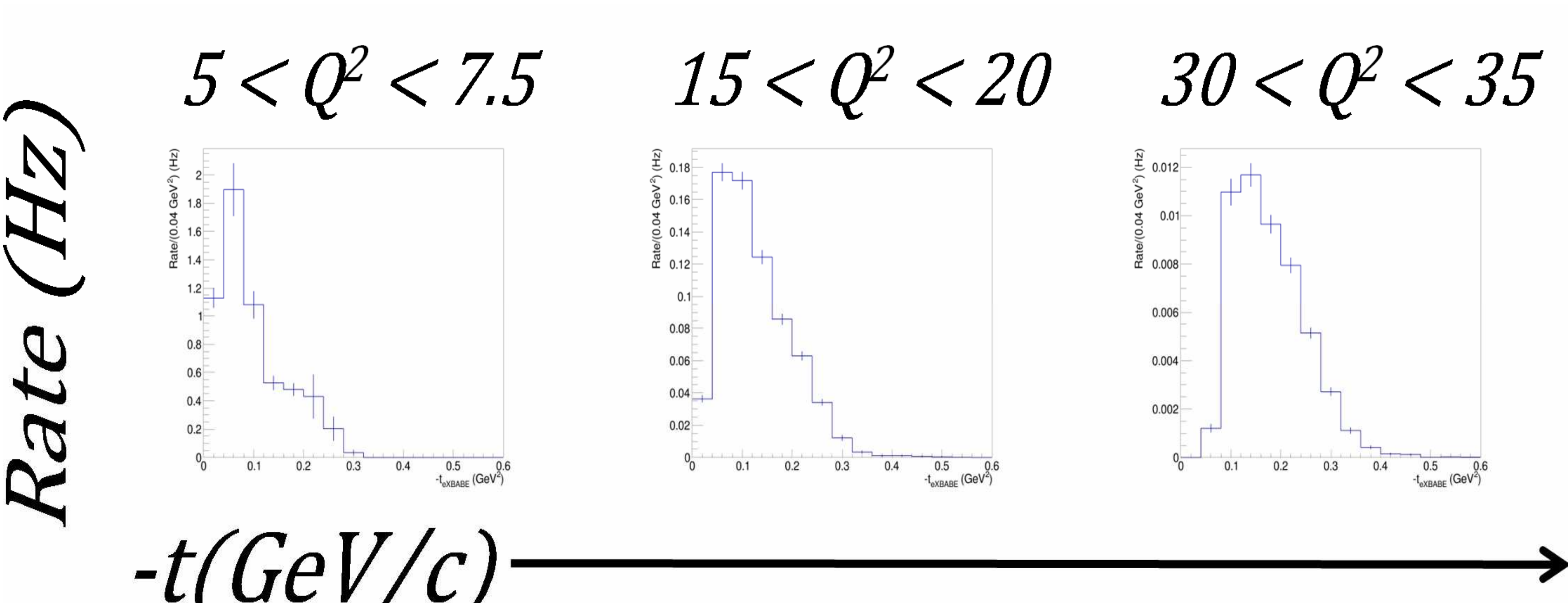
- One positively charged track in +z direction (π^+)
- One negatively charged track in –z direction (e')

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

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

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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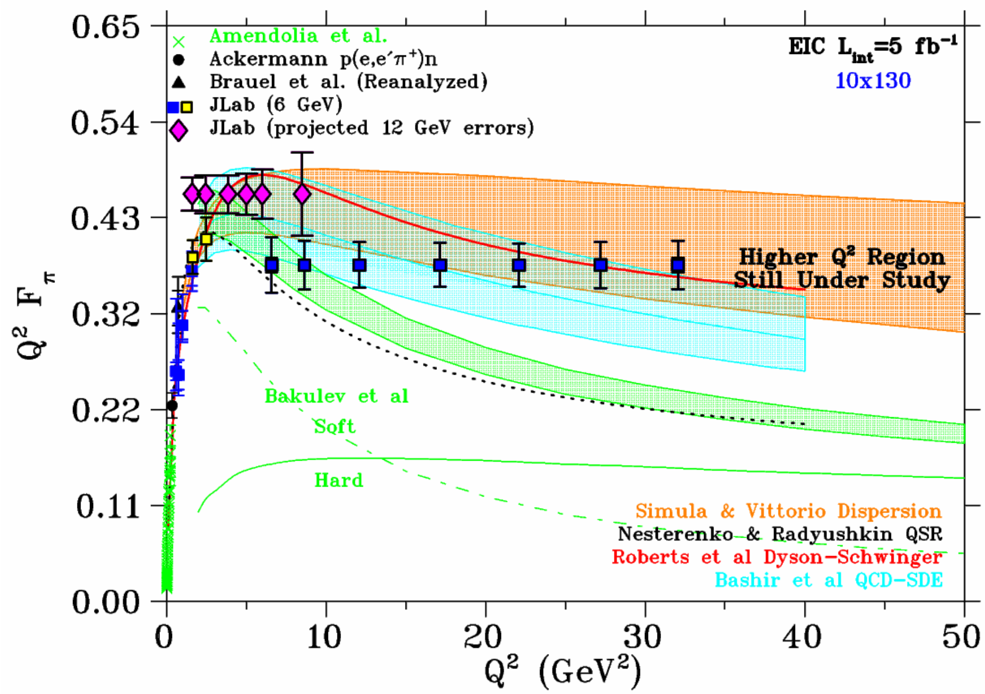

- 10(e^-) x 130(p)
- $\int L$=5 fb^{-1}
- Based on full ePIC detector reconstruction including cuts for clean identification of exclusive $p(e,e'\pi^+n)$ events
- ***y*-axis location of projected data is ARBITRARY, what is meaningful are the error bars, which represent real projected errors, including:**
  - 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

Garth Huber, huberg@uregina.ca