# Meson Form Factor measurements at the EIC and the importance of B0


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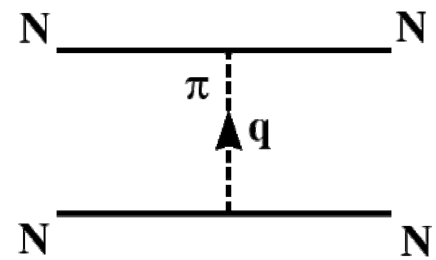
# The Pion has Particular Importance

- The pion is responsible for the long–range part of the nuclear force, acting as the basis for meson exchange forces, and playing a critical role as an elementary field in nuclear structure Hamiltonians.




- As the lightest meson, it must be a valence $q\bar{q}$ bound state, but understanding its structure through QCD has been exceptionally challenging.
  - e.g. Constitutent Quark Models that describe a nucleon with $m_N$=940 MeV as a $qqq$ bound state, are able to describe the $\rho$-meson under similar assumptions, yielding a constituent quark mass of about

$$m_Q \approx \frac{m_N}{3} \approx \frac{m_\rho}{2} \approx 350 \text{ MeV}$$

- The pion mass $m_\pi \approx$140 MeV seems "too light".

- **We exist because nature has supplied two light quarks and these quarks combine to form the pion, which is unnaturally light and hence very easily produced.**

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# The Pion as a Goldstone Boson

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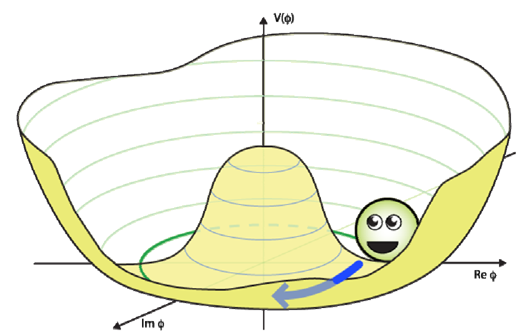
- A remarkable feature of QCD is Dynamical Chiral Symmetry Breaking (DCSB) because it cannot be derived directly from the Lagrangian and is related to nontrivial nature of QCD vacuum.
  - Explicit symmetry breaking, which is put in “by hand” through finite quark masses, is quite different.
- DCSB is now understood to be one of the most important emergent phenomena in the Standard Model, responsible for generation of >98% baryonic mass.




- **Two important consequences of DCSB:**
  1. Valence quarks acquire a dynamical or constituent quark mass through their interactions with the QCD vacuum.
  2. The pion is the spin-0 boson that arises when Chiral Symmetry is broken, similar to how Higgs boson arises from Electroweak Symmetry Breaking.

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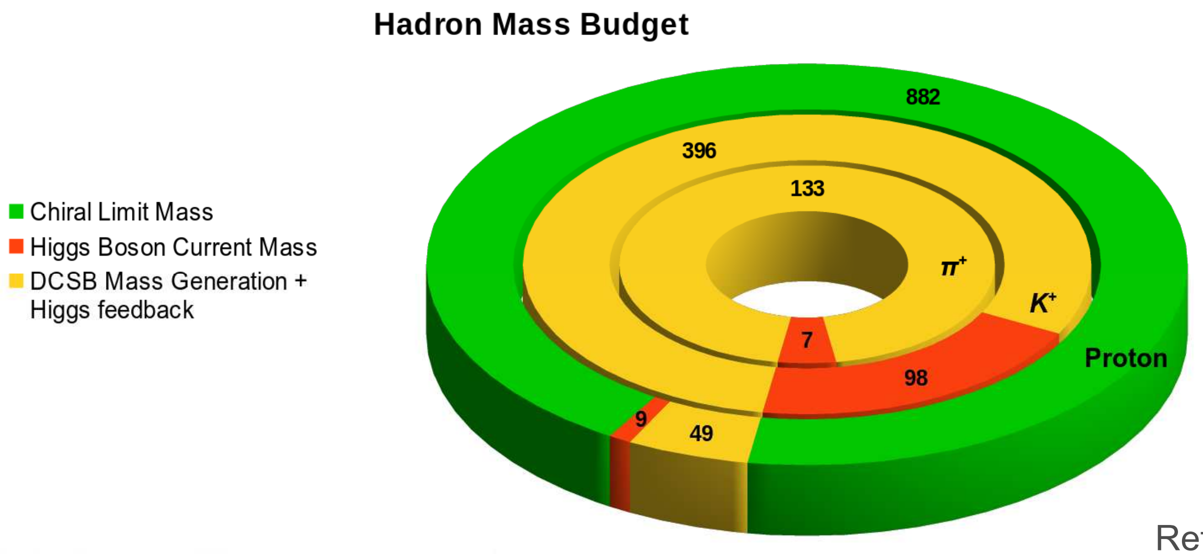
# Relevance to Hadron Mass Generation




Ref: Craig Roberts (2021)

- Proton mass large in absence of quark couplings to Higgs boson (chiral limit). Conversely, *K* and π are massless in chiral limit (i.e. they are Goldstone bosons).
- The mass budgets of these crucially important particles demand interpretation.
- 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*.
- **Understanding $\pi^+$ and $K^+$ form factors over broad $Q^2$ range is central to this puzzle.**

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# Measurement of $F_\pi$ via Electroproduction

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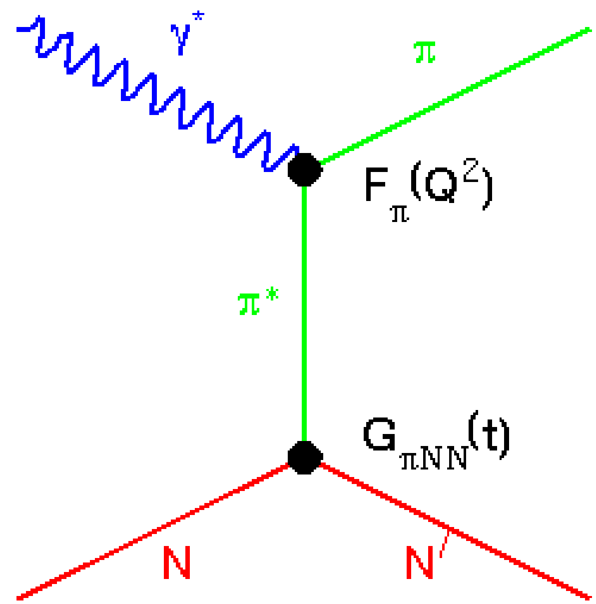
**Above $Q^2$>0.3 GeV$^2$**, $F_\pi$ is measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots$$

- At small $-t$, the pion pole process dominates the longitudinal cross section, $\sigma_L$
- In Born term model, $F_\pi^2$ appears as

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)} g^2_{\pi NN}(t) F_\pi^2(Q^2,t)$$




**Drawbacks of this technique:**

1. Isolating $\sigma_L$ experimentally challenging.
2. The $F_\pi$ values are in principle dependent upon the model used, but this dependence is expected to be reduced at sufficiently small $-t$.

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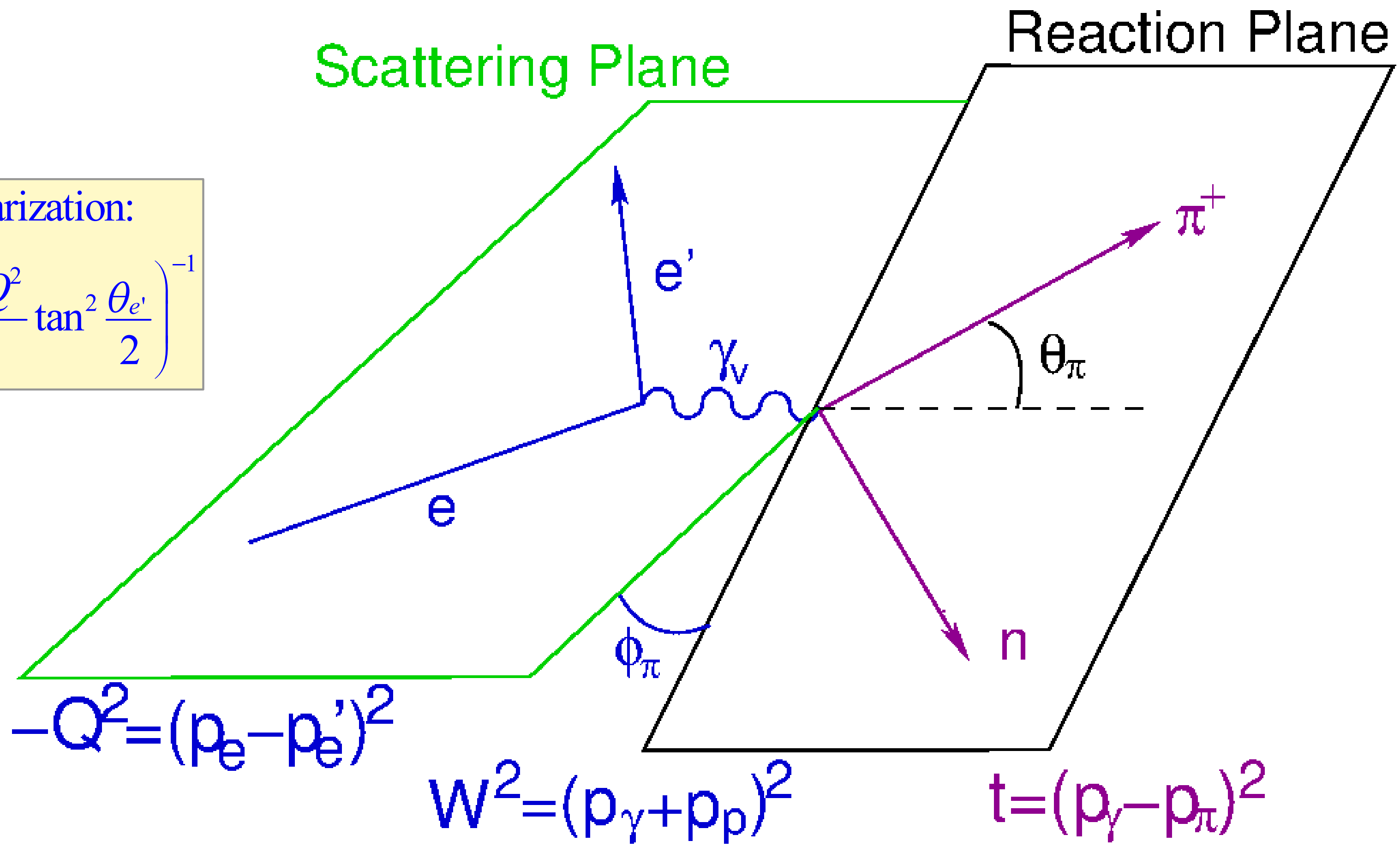
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Virtual-photon polarization:

$$\varepsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$




- **L-T separation required to separate $\sigma_L$ from $\sigma_T$.**
- **Need to take data at smallest available $-t$, so $\sigma_L$ has maximum contribution from the $\pi^+$ pole.**

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# Current and Projected $F_\pi$ Data

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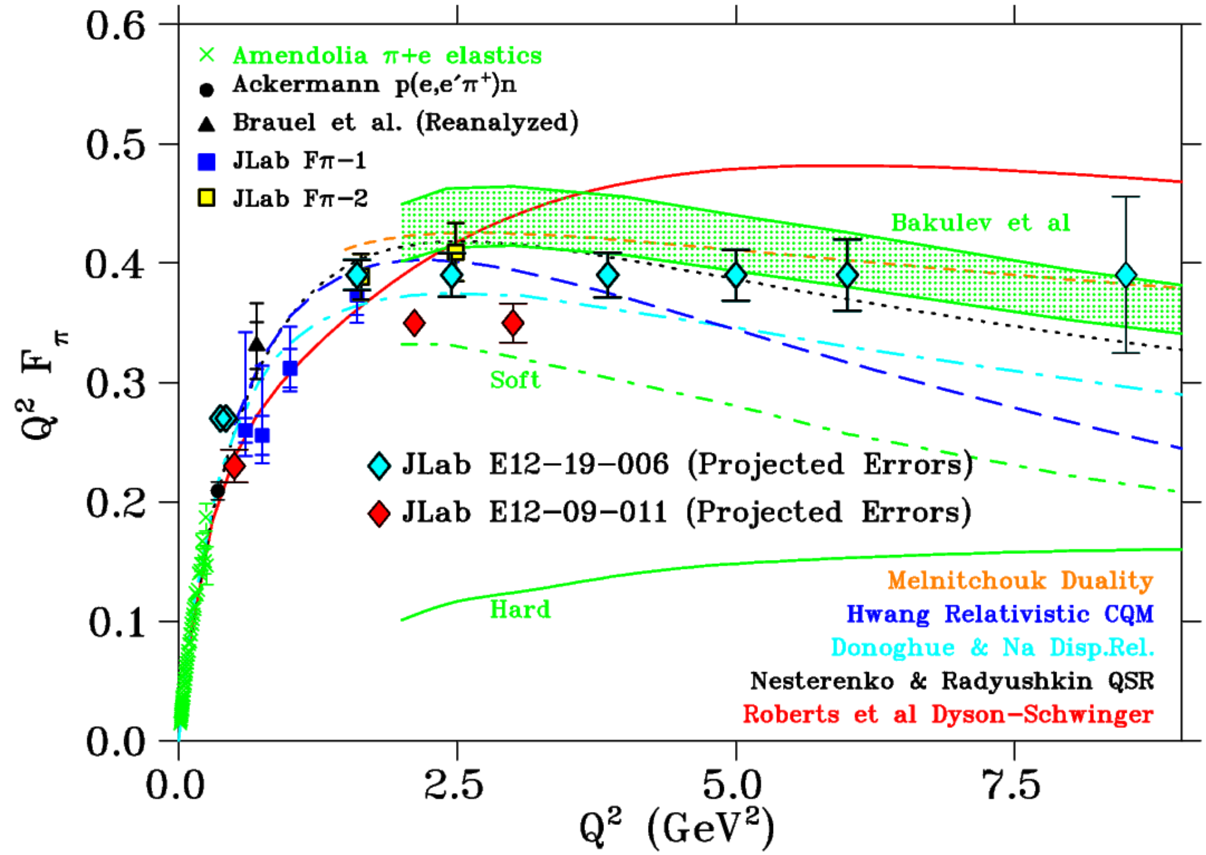
- JLab E12–19–006 will allow measurement of $F_\pi$ to $Q^2$=6 with small uncertainties, and to $Q^2$=8.5 with larger errors (both experimental and theoretical).

- New low $Q^2$ point (data acquired in 2019) will provide comparison of the electroproduction extraction of $F_\pi$ vs. elastic $\pi+e$ data.




The ~10% measurement of $F_\pi$ at $Q^2$=8.5 GeV$^2$ is at higher $-t_{min}$=0.45 GeV$^2$

**The pion form factor is the clearest test case for studies of QCD's transition from non–perturbative to perturbative regions.**

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# $F_\pi$ and $F_K$ Studies to Higher $Q^2$ at EIC

- **Physics Motivation:**
  - $\pi^+$ 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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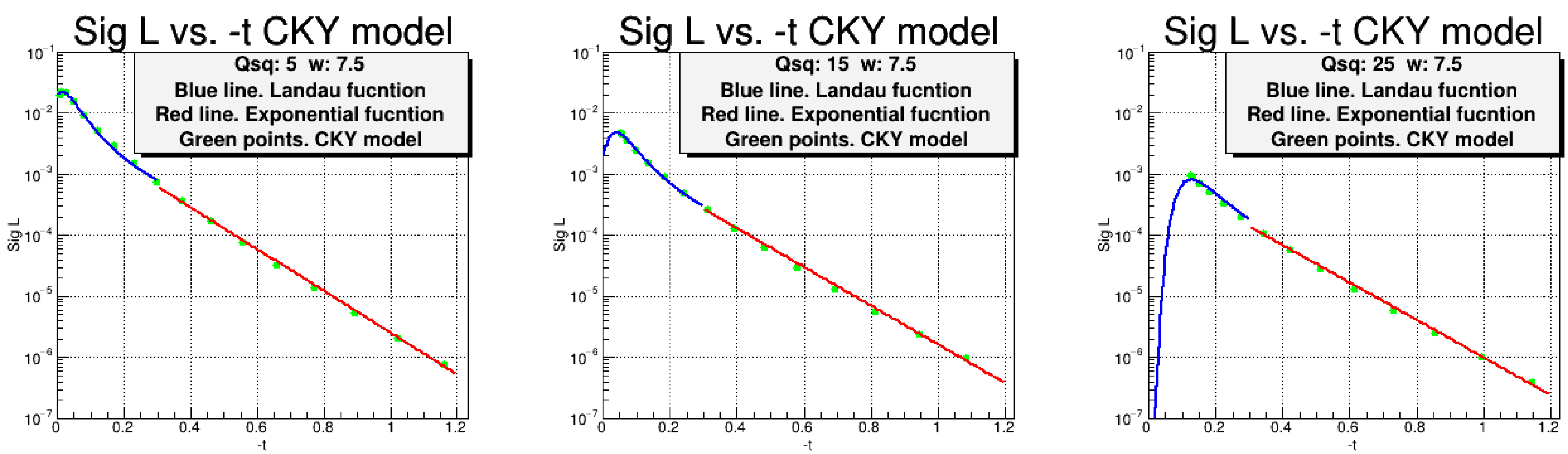
# DEMP $\pi^+/K^+$ Event Generator

- 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 $\sigma_L$, $\sigma_T$ 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]
- DEMPgen paper: Comp.Phys.Commun. 308(2025)109444, arXiv:2403.06000




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

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

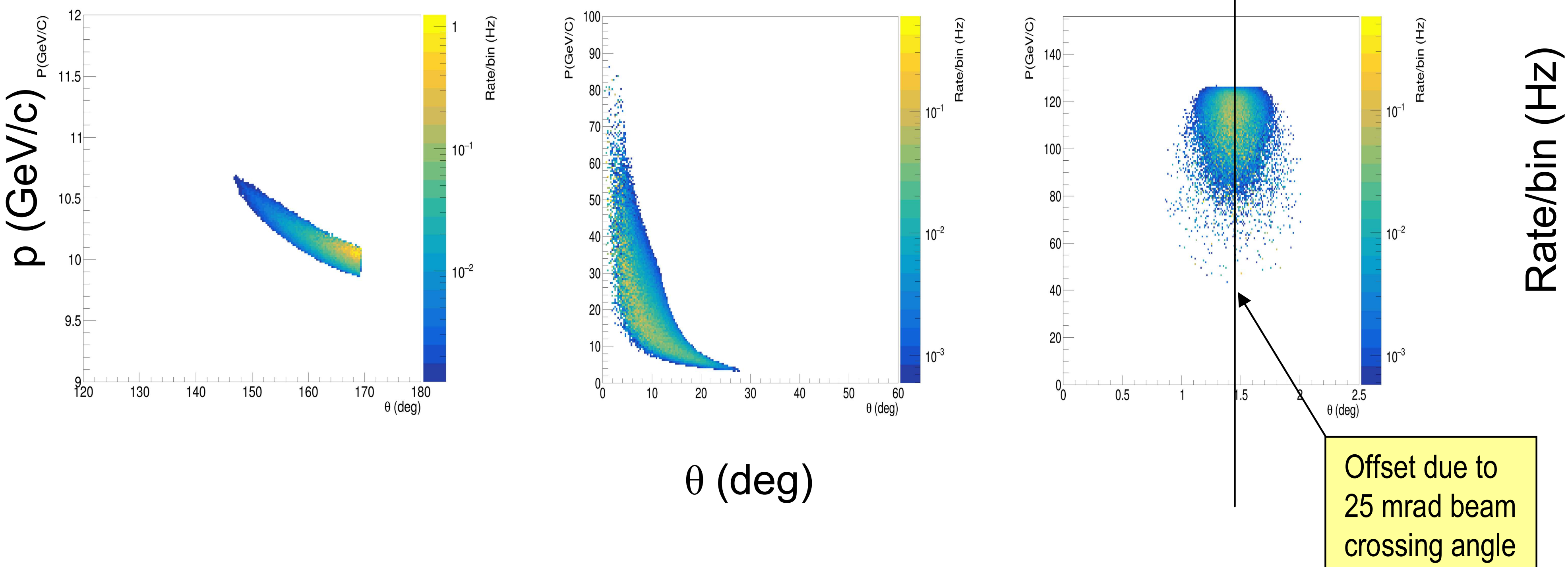
## Assure exclusivity of $p(e,e'\pi^+n)$ reaction by detecting all 3 particles

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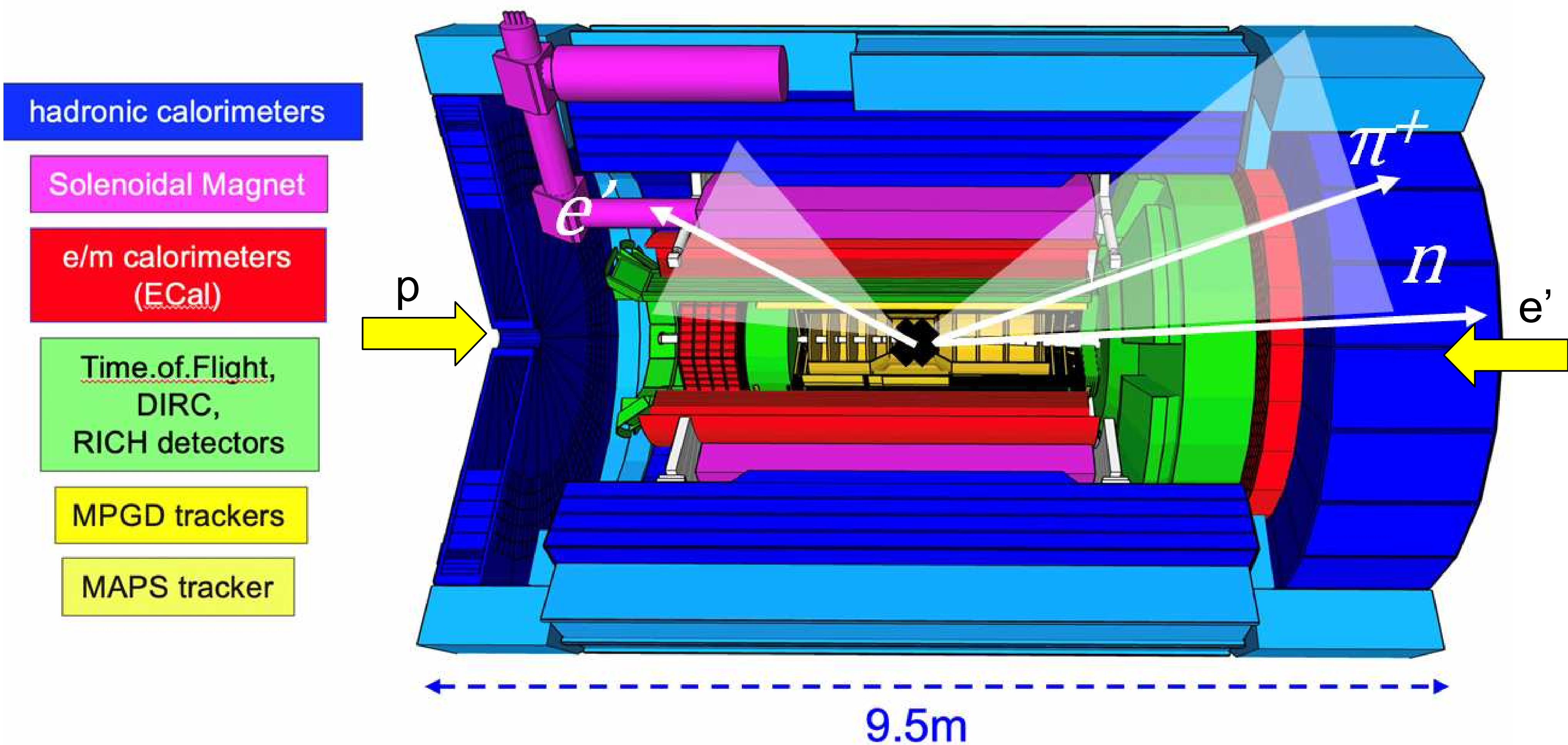
# $p(e,e'\pi^+n)$ Particle Kinematics

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

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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')
    - Recently replaced with something "similar" to Inclusive ElectronFinder
  - 1 positively charged track in +z direction ($\pi^+$)
  - 1 high energy reconstructed neutral cluster in ZDC
    - $E_n$>40 GeV
    - $\theta^*_n$<4 mrad

- The ZDC has excellent position ($\theta$,$\varphi$) resolution, but much poorer energy resolution
- If the detected neutron is from an exclusive event, the ZDC should be near the location predicted from m $\vec{p}_{miss} = \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}$
  - i.e. the location calculated via
  - 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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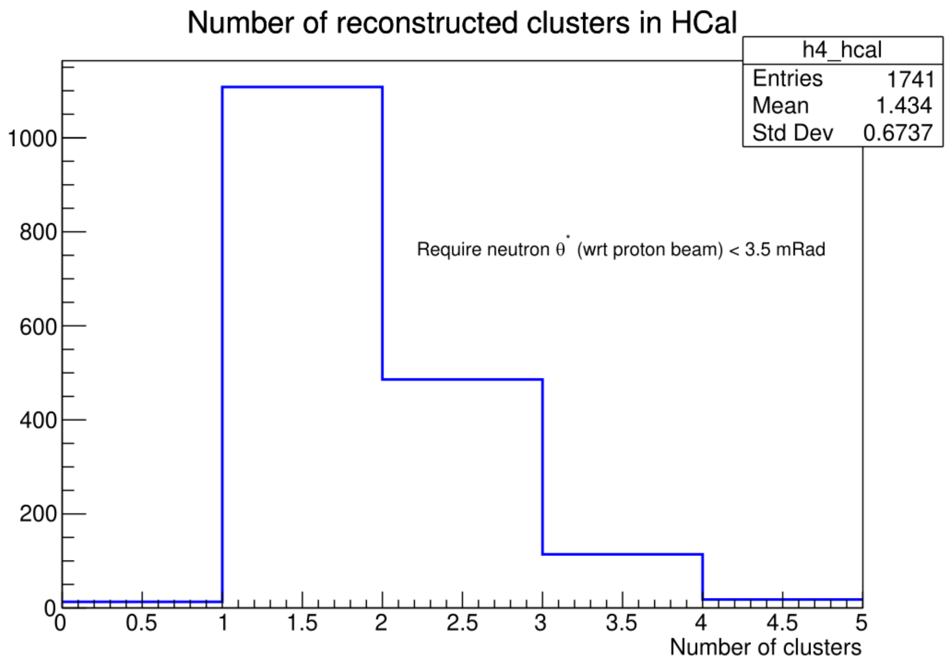
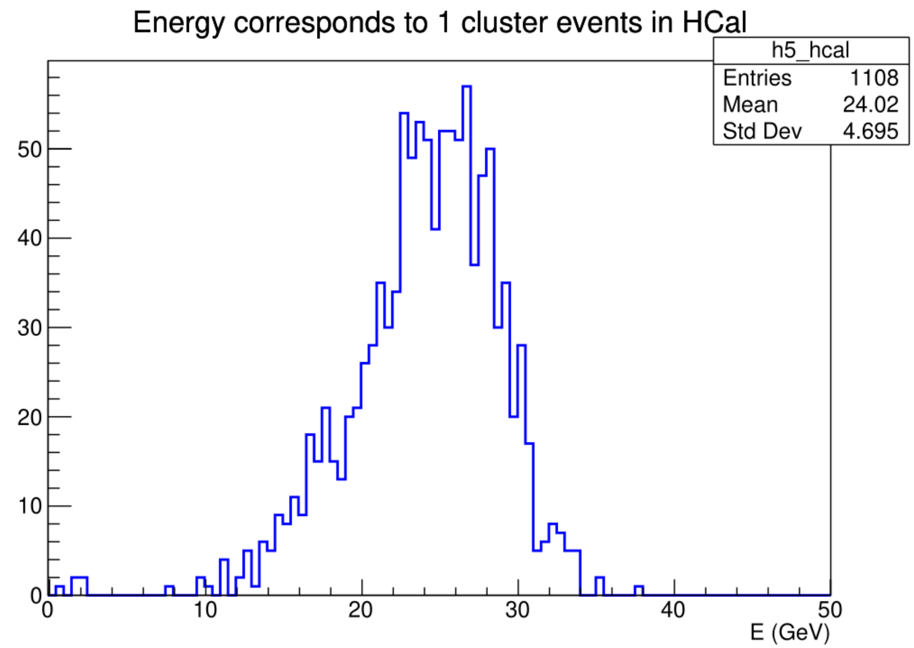
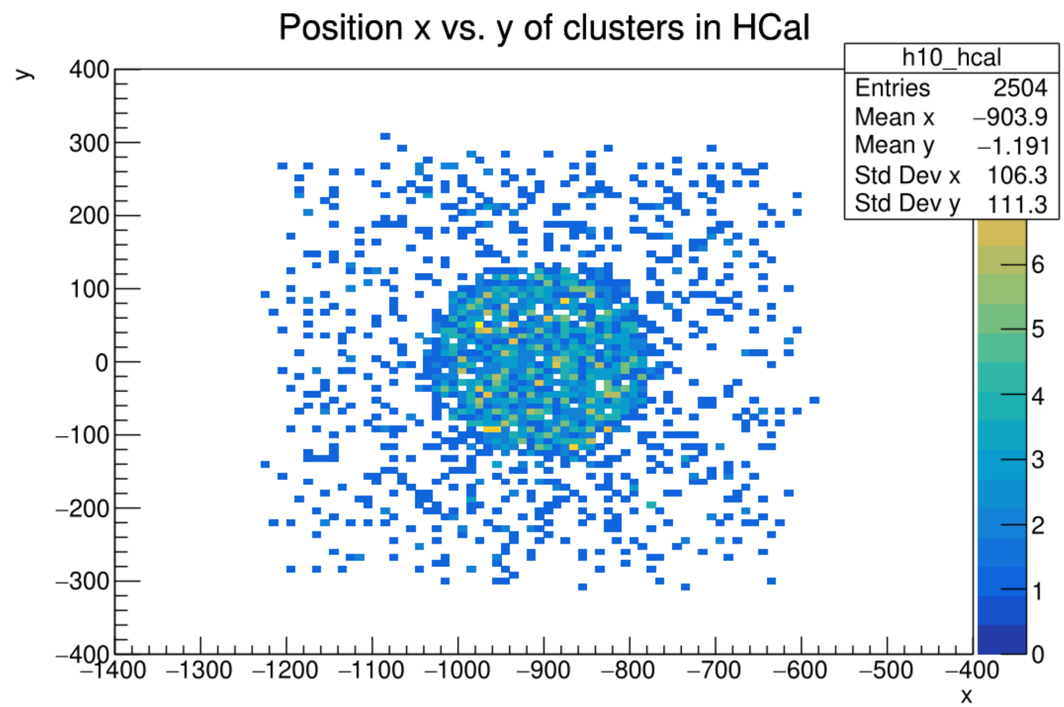
# $p(e,e'\pi^+n)$ Neutron reconstruction in ZDC




- 5x41 e+p collisions
- High proportion of neutron hits have multi–clusters
- (x,y) acceptance of ZDC fully filled
- For 5x41, the B0 is particularly needed to extend the ZDC coverage to higher -t

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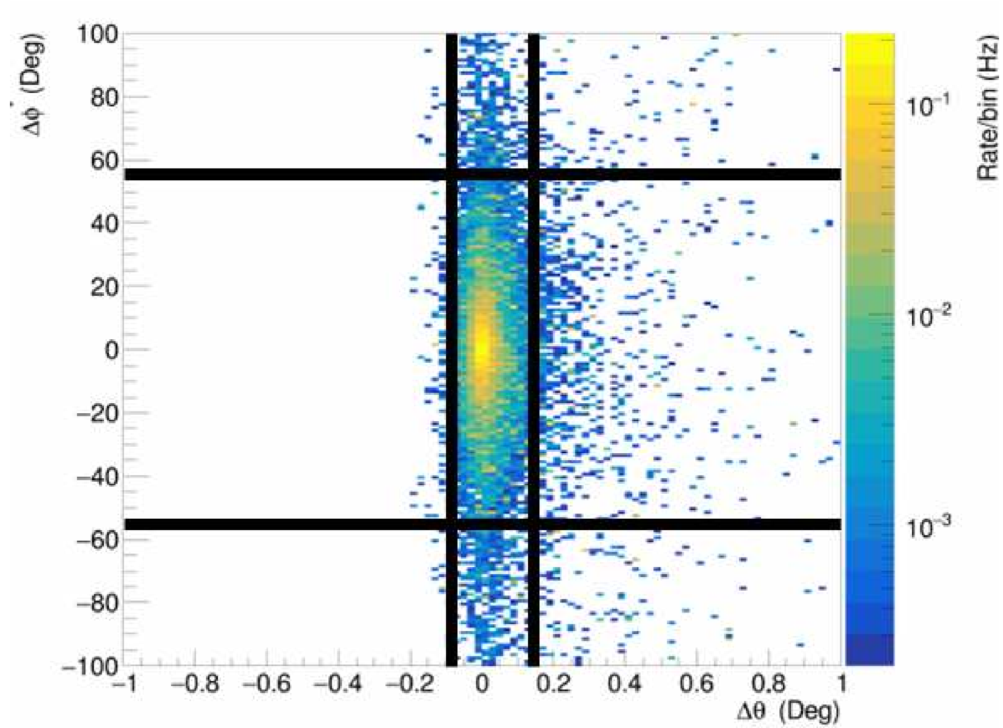
# Example ZDC $p(e,e'\pi^+n)$ Exclusivity Cut

- **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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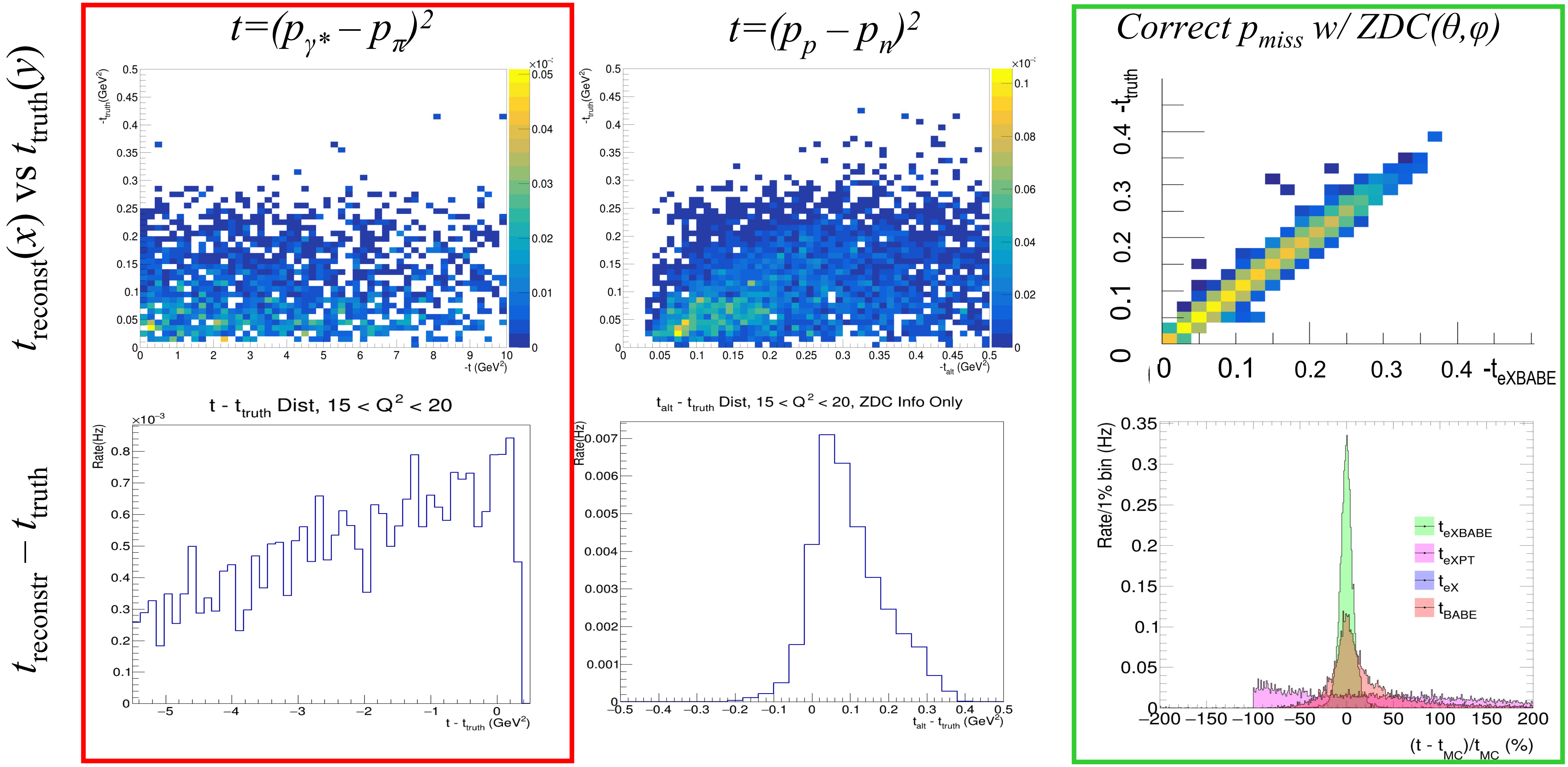
# Reconstructing Mandelstam *t*

- 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*




Unusable *t* reconstruction

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

Best *t* reconstruction

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

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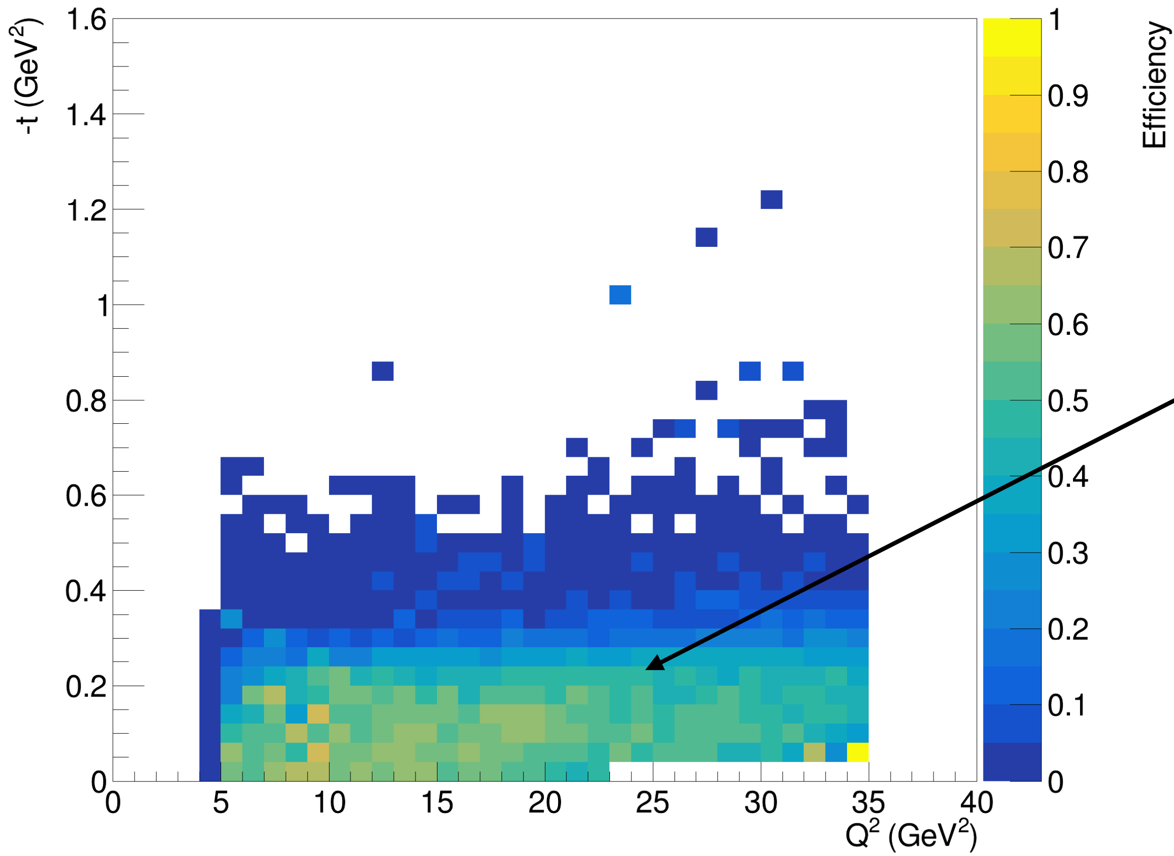
# $p(e,e'\pi^+n)$ Detection Efficiency per ($Q^2$,$t$) bin




Detection efficiency best in crucial low –*t* region

**Require EXACTLY two tracks:**

- One positively charged track in +z direction ($\pi^+$)
- 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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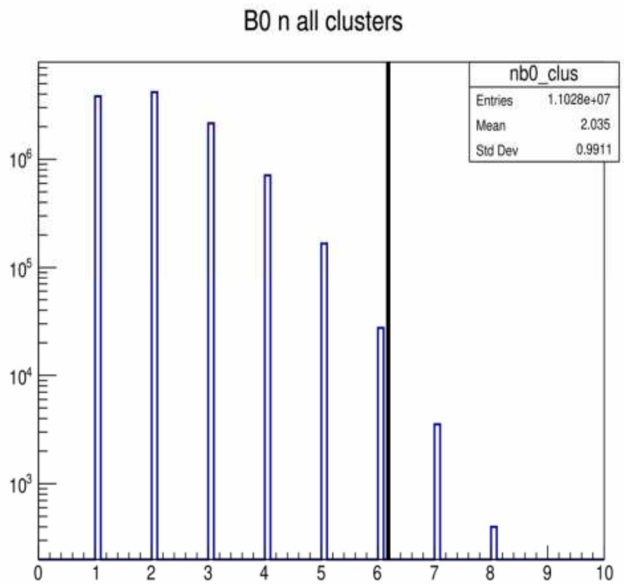
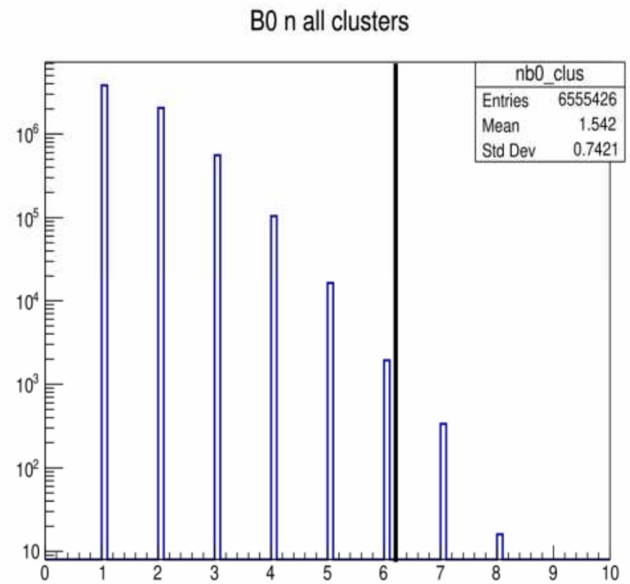
# $p(e,e'\pi^+n)$ B0 event selection

- Reconstruct neutrons from either ZDC or B0 EMCAL
- B0 neutrons correspond to high –t, while ZDC neutrons give access to low -t

Considered and combined first six cluster events by weighted mean of energies.

[Used B0ECalClusters Branch]

| 5on41 | 10on100 |
|---|---|
|  |  |
| [ ≥ 2 cluster events ] | [ ≥ 2 cluster events ] |
| Threshold cluster energy > 100 MeV | Threshold cluster energy > 250 MeV |

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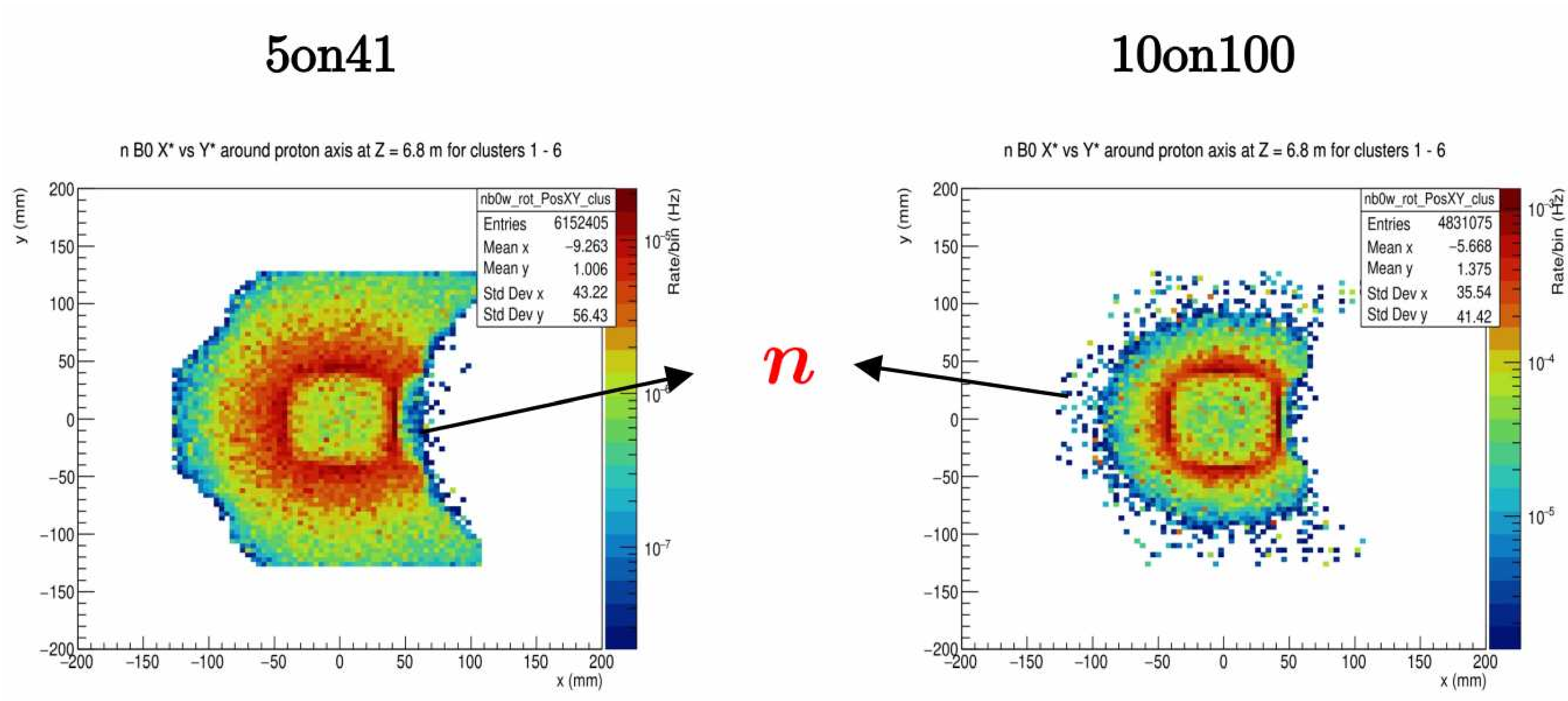
# p(e,e'$\pi^+$n) B0 neutron hit positions

- B0 X vs Y positions for combined 1-6 clusters

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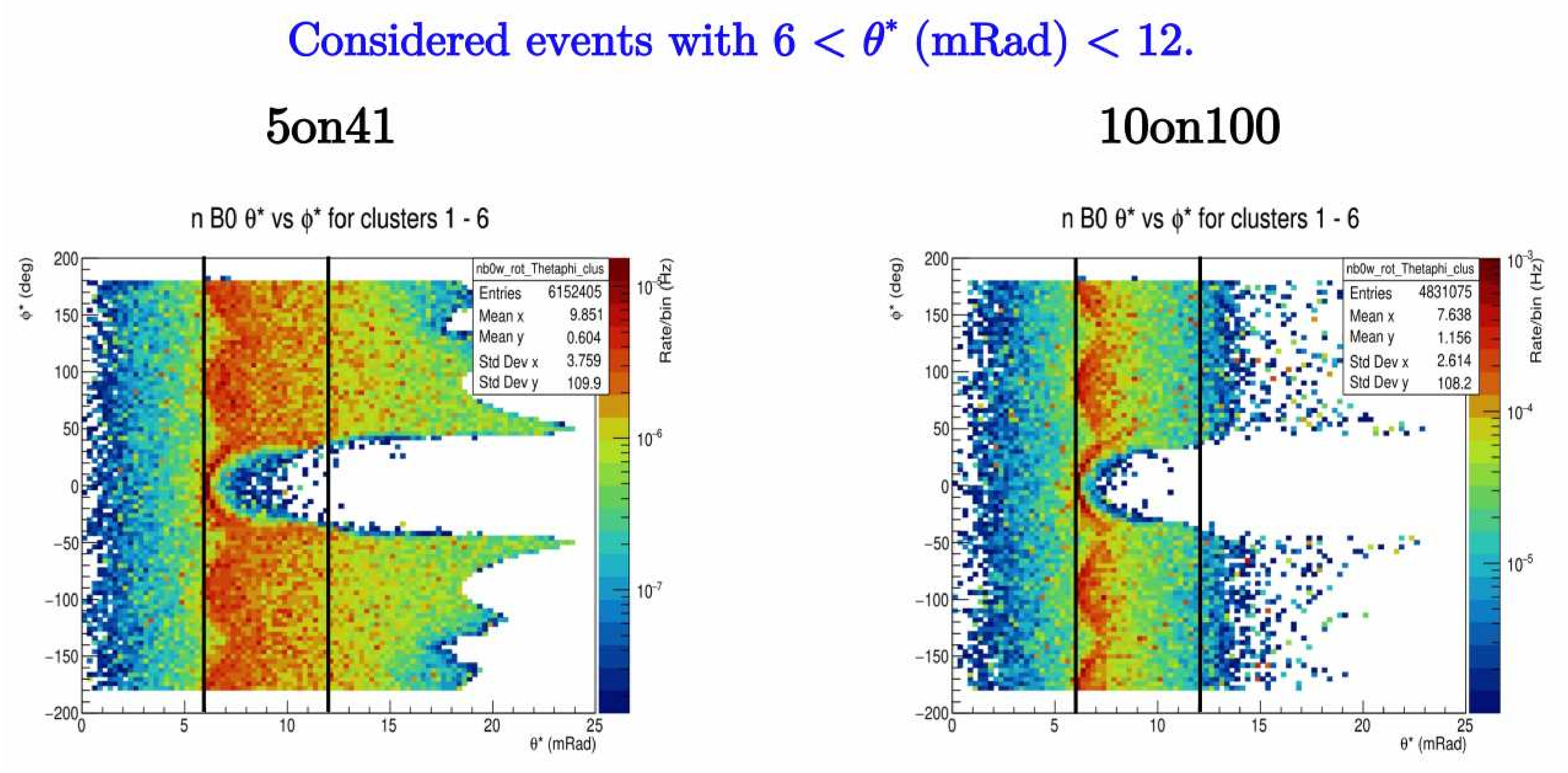
# p(e,e'$\pi^+$n) B0 neutron θ* vs φ*




- θ* is rotated by 25 mrad about the proton axis
- The 6<θ*<12 mrad cut is to give a more uniform azimuthal acceptance
- All events with 1-6 clusters in B0 are combined

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# p(e,e'π⁺n) B0 exclusivity cut

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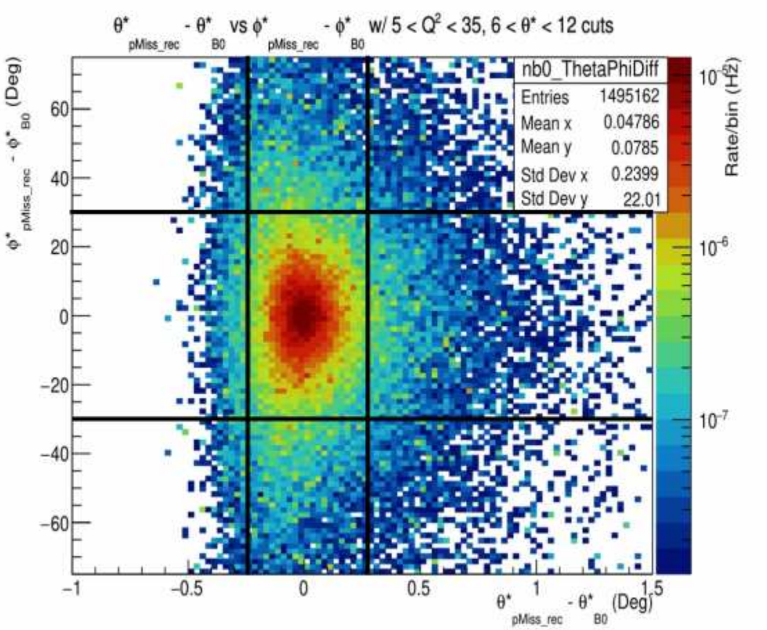
- We analyze the events with neutron in B0 analogous to the neutron in ZDC events
  - Compare hit (θ,φ) positions of energetic neutron on B0 to calculated position from $p_{miss}$
- The Δθ* Δφ* cut limits are larger than for ZDC, but still provide a powerful suppression of non-exclusive backgrounds

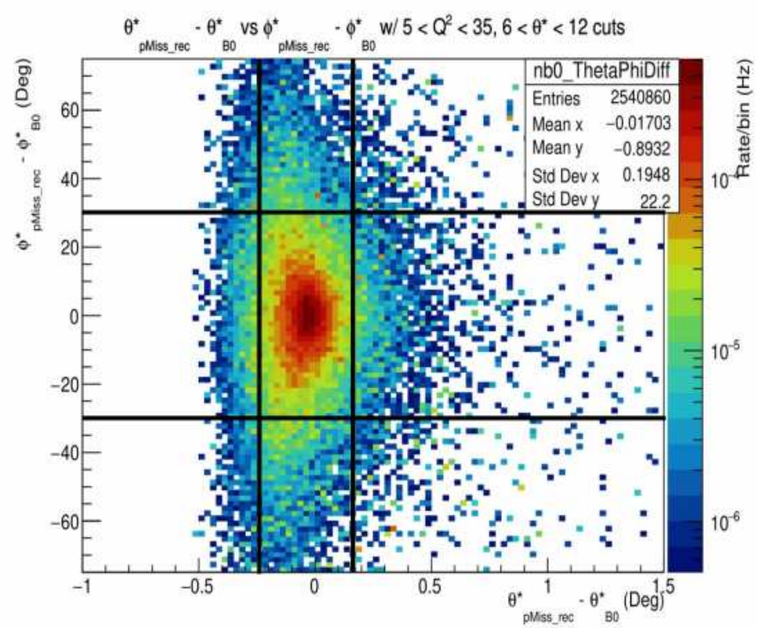
$$\Delta\theta^* = (\theta^*_{\mathrm{pMiss\_rec}} - \theta^*_{\mathrm{B0}}),\ \Delta\phi^* = (\phi^*_{\mathrm{pMiss\_rec}} - \phi^*_{\mathrm{B0}})$$

**5on41**




$[-0.24 < \Delta\theta^* < 0.27,\ -30 < \Delta\phi^* < 30]$

**10on100**




$[-0.26 < \Delta\theta^* < 0.17,\ -30 < \Delta\phi^* < 30]$

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# p(e,e’$\pi^+$n) B0 triple coincidences

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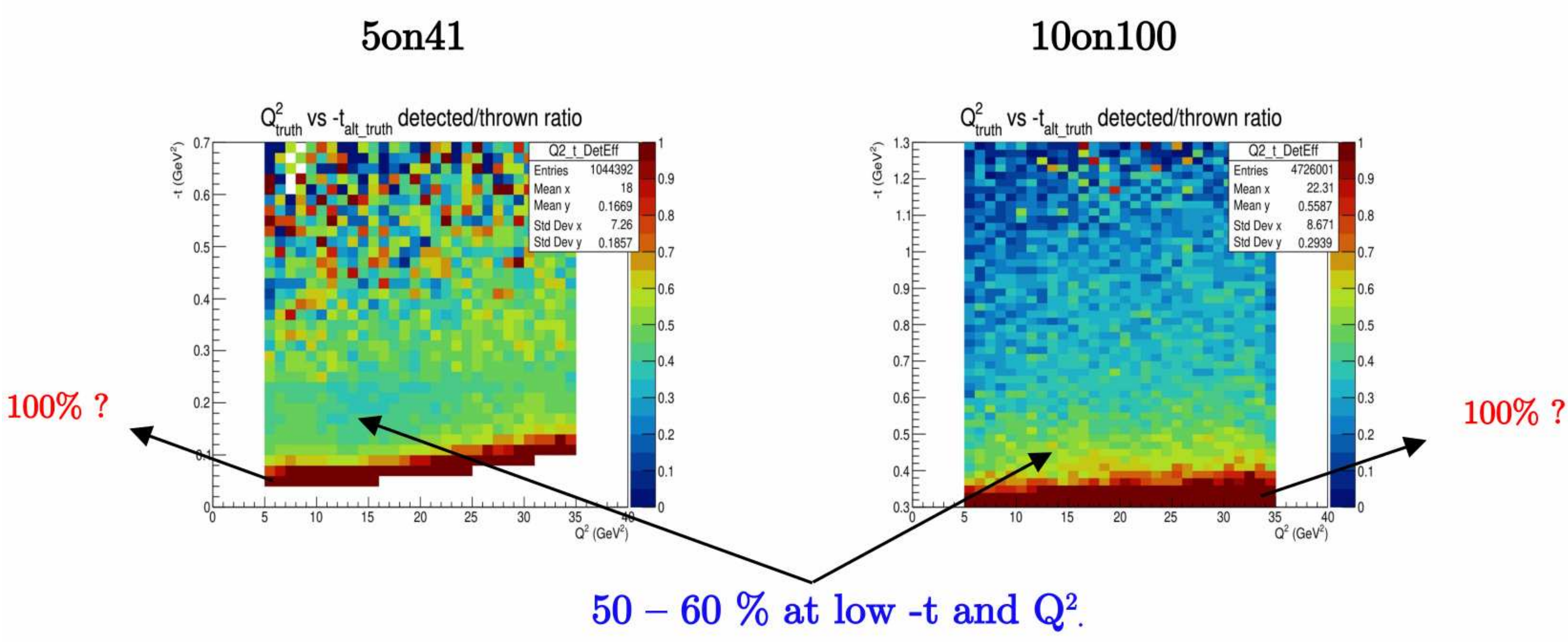


- Triple coincidence detection efficiency per ($Q^2$,t) bin w/ all cuts
- We believe the 100% efficiency region corresponds to photons or neutrons generated from interactions with the beam pipe. We have not had the opportunity yet to confirm this with further analysis.

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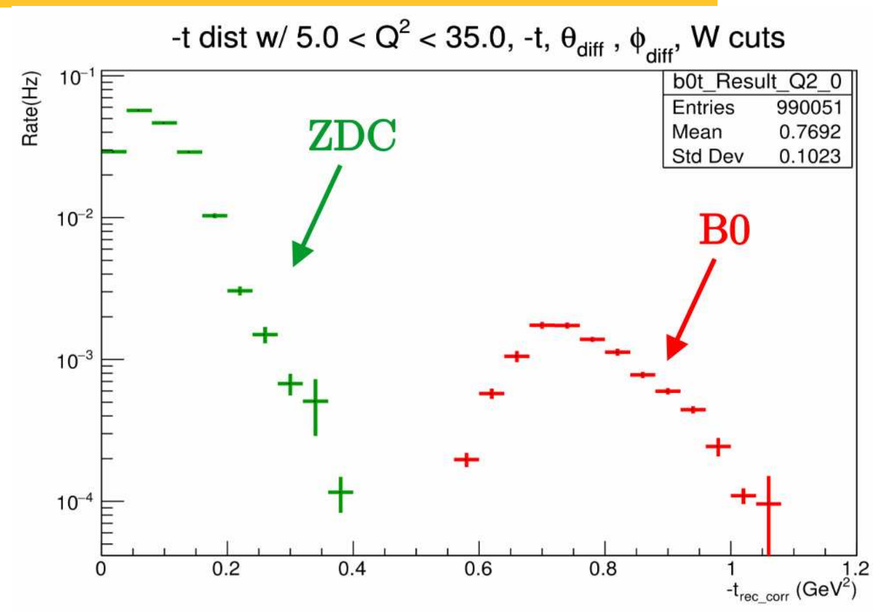
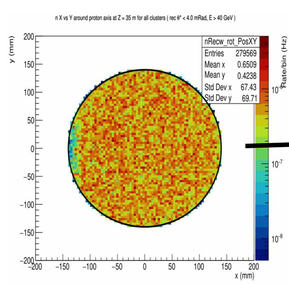
# p(e,e'π⁺n) combining ZDC and B0

- The B0 EMCAL allows the t-coverage to be greatly expanded compared to ZDC alone
- This is particularly important for 5x41, where neutrons scatter over a wider angular range than at higher CM energy.
  - At 5x41, the ZDC t-coverage is too small to permit a reliable pion form factor measurement by itself.

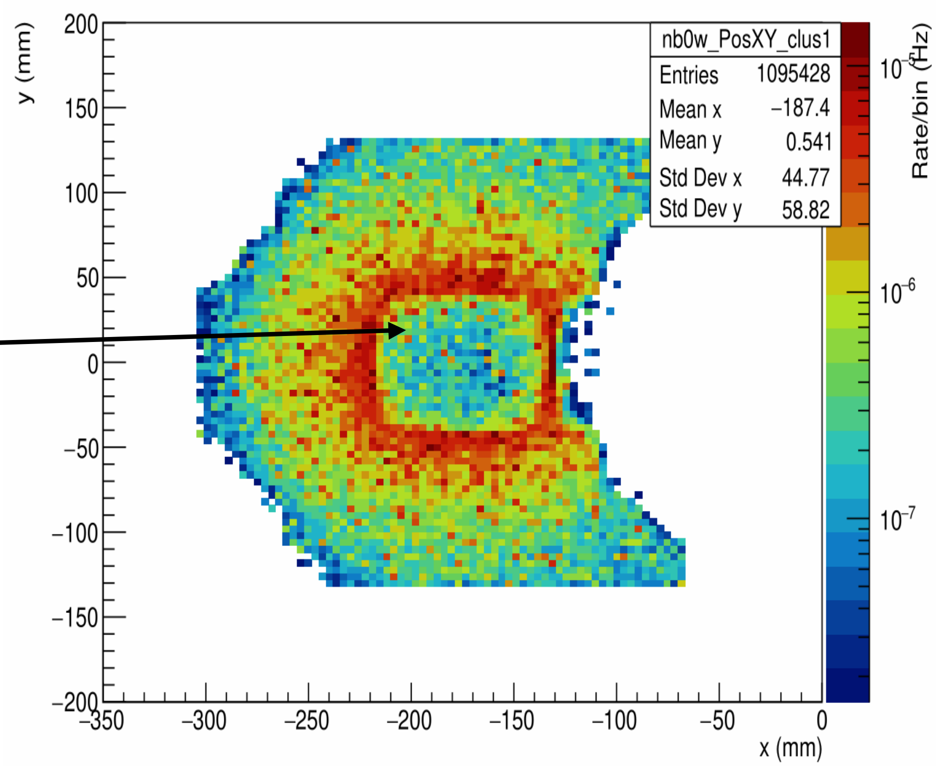



10x100

5x41



neutrons in ZDC




neutrons in B0 EMCAL

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# Separating $\sigma_L$ from $\sigma_T$ in e–p Collider

$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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

- Systematic uncertainties in $\sigma_L$ 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), below the EIC design range

**A conventional L–T separation is impractical, need some other way to identify $\sigma_L$.**

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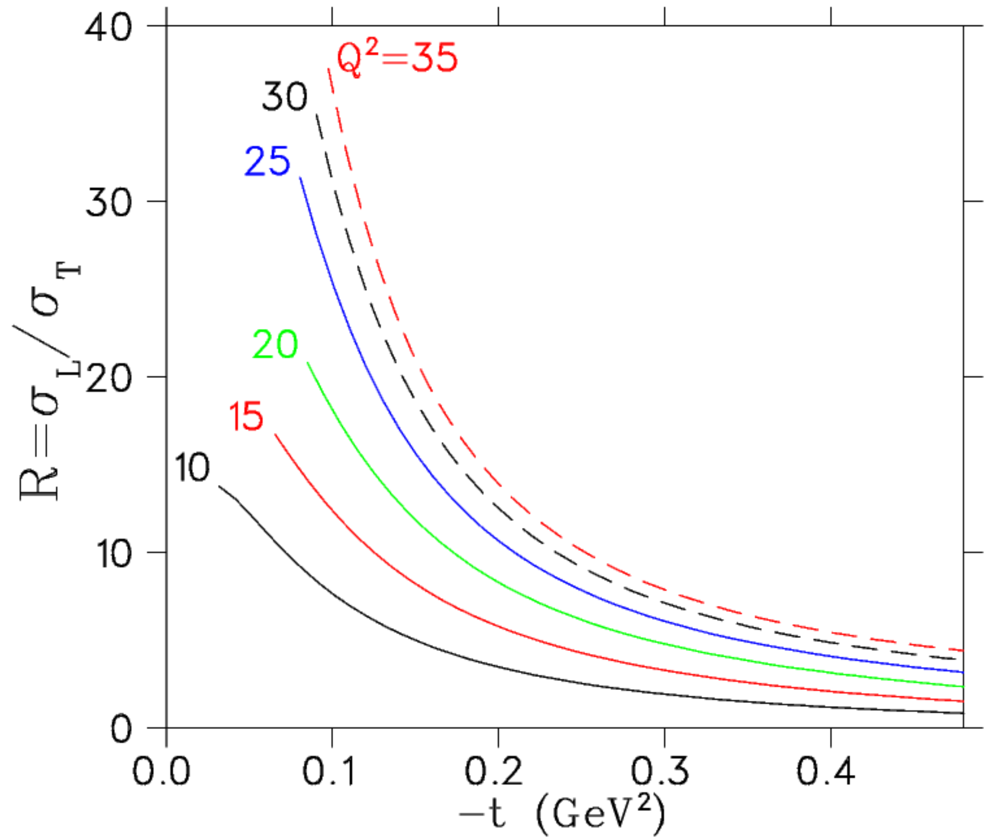
# Isolate $d\sigma_L/dt$ using a Model

- 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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# $F_\pi$ EIC Early Running Projections

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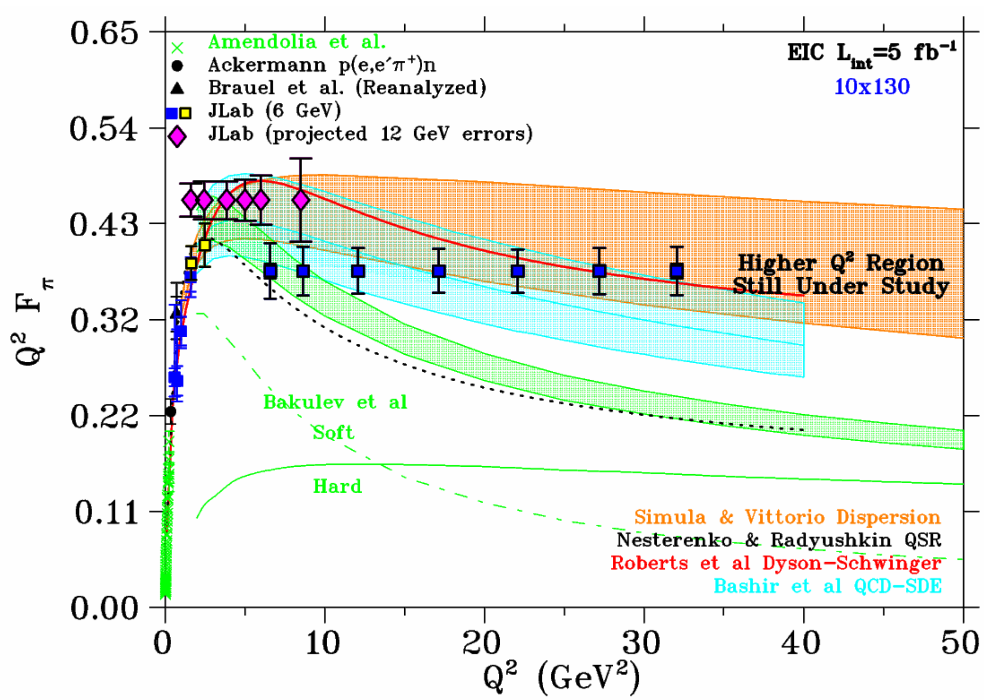


- 10($e^-$) x 130($p$)
- $\int L$=5 fb$^{-1}$
- Based on full ePIC detector reconstruction including cuts for clean identification of exclusive $p(e,e'\pi^+n)$ events
- ***y*-axis location of projected data is ARBITRARY, what is meaningful are the error bars, which represent real projected errors, including:**
  - 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 $\sigma_L$
  - $\pi$ pole dominance at small $-t$ confirmed in e+d $\pi^-/\pi^+$ ratios

# Can we measure $F_K$ at the EIC?

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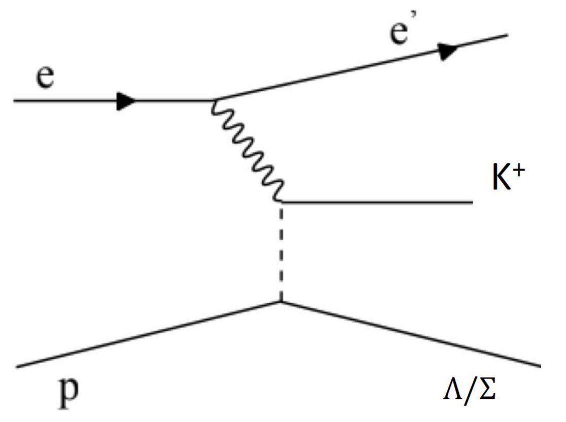
- **Can the "kaon cloud" of proton be used in same way as the pion to extract kaon form factor via *p(e,e'K⁺)*Λ ?**
- Kaon pole further from kinematically allowed region
- Many of these issues are being explored in JLab E12–09–011




- 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**
- **$\Sigma^0$ identified from $\Sigma^0\rightarrow\Lambda\gamma\rightarrow\Lambda\pi^0\rightarrow n3\gamma$ decay**

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# $p(e,e'K^+)\Lambda$ 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 $\gamma$ clusters is main challenge
- Dominant $\Lambda \rightarrow p\pi^-$ channel (~67%) has its own challenges
  - Avoids issue of distinguishing n from $\gamma$ clusters
  - Main issue is that $p$, $\pi^-$ 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 $\gamma$ on EMCAL to enable full 4–vector reconstruction of $\pi^0$. Is it sufficiently good?

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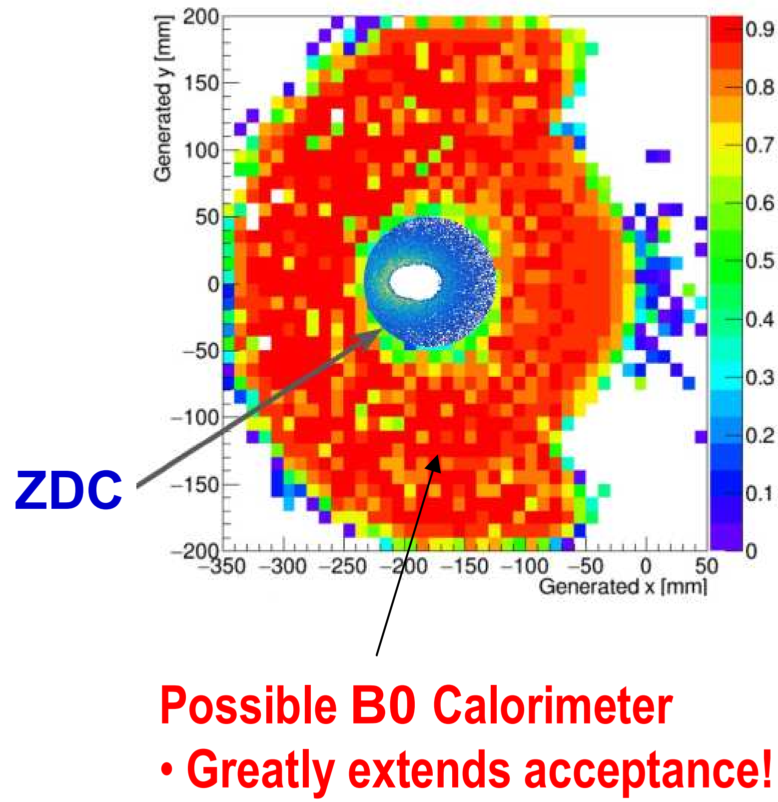
# Implications for Det–2 Far Forward

- **Far forward large acceptance will be even more important for $K^+$ form factor than for $\pi^+$ form factor**
- Identification of forward hyperon will be essential for clean separation of exclusive $K^+$ channel from larger $\pi^+$ channel
  - $\Lambda \rightarrow n\pi^0 \rightarrow n2\gamma$ and $\Sigma \rightarrow \Lambda\gamma \rightarrow n3\gamma$ identification likely 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

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# Summary

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- Higher $Q^2$ data on $\pi^+$ 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 $F_\pi$ at EIC has various challenges
  - Need efficient identification of $p(e,e'\pi^+n)$ triple coincidences
  - Need good resolution $t$ reconstruction to avoid excessive bin migration
  - Conventional L–T separation not possible as can't access $\varepsilon<0.8$
  - As $\sigma_L \gg \sigma_T$ expected, most likely possibility is to use model to extract $\sigma_L$ from $d\sigma_{UNS}/dt$ → Used also for $Q^2$=10 GeV$^2$ Cornell expt (1978)
  - Best to use exclusive $\pi^-/\pi^+$ ratio in e+d collisions to validate model
  - **Studies look very encouraging for data to $Q^2 \approx 30$ GeV$^2$**
- Measurement of $F_K$ is probably only possible at IR8
  - Our studies are in early stage, but it is already obvious that a larger far forward calorimeter acceptance is essential
  - B0 calorimeter would give 2nd Detector unique capabilities

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# Comparison: IR6 vs IR8 ($5<Q^2<7.5$)

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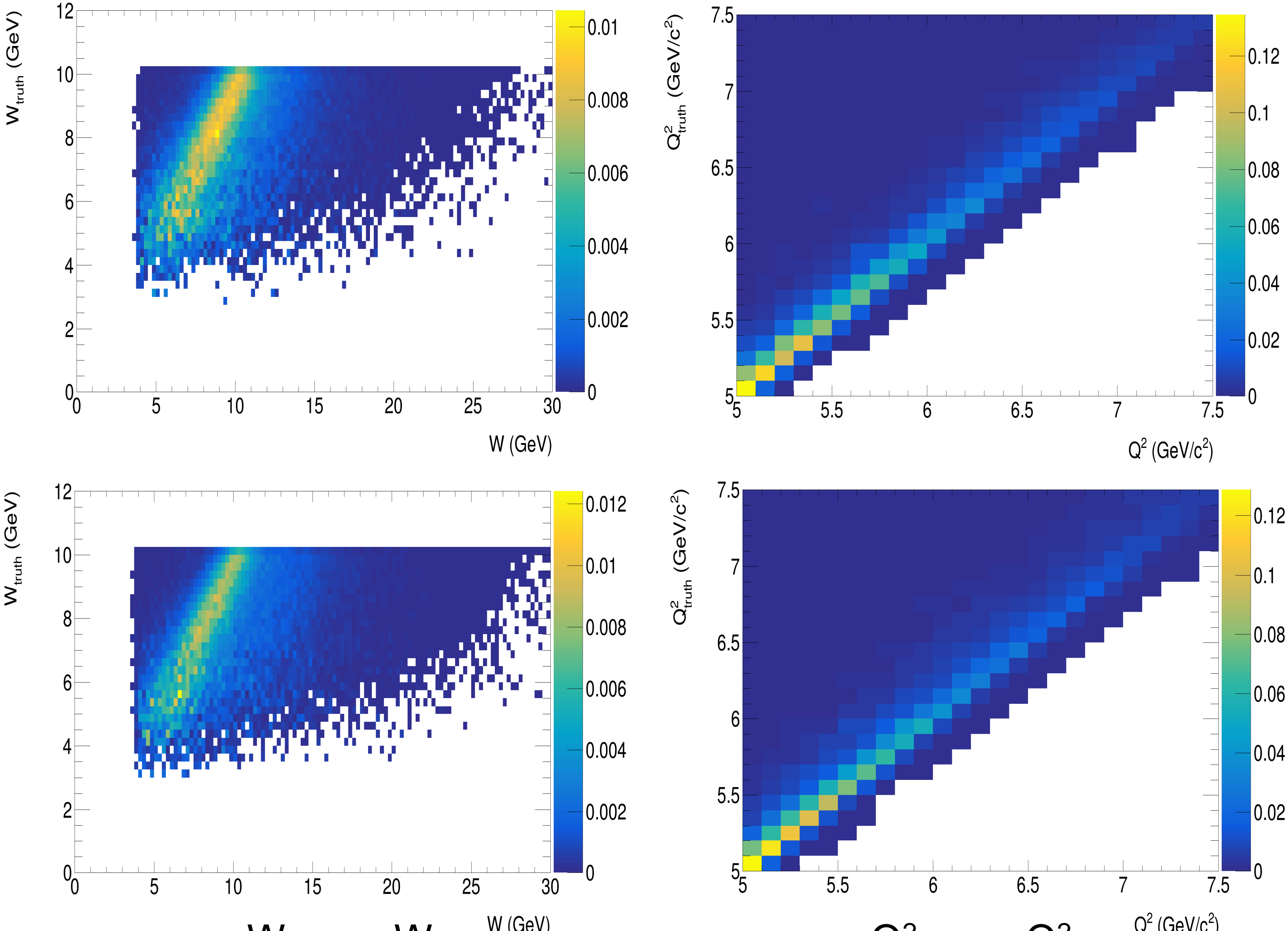
IR6

IR8




**$W_{true}$ vs W**
- tighter correlation for IR6

**$Q^2_{true}$ vs $Q^2$**
- resolutions very similar

Plots by Stephen Kay

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# Comparison: IR6 vs IR8 ($15<Q^2<20$)

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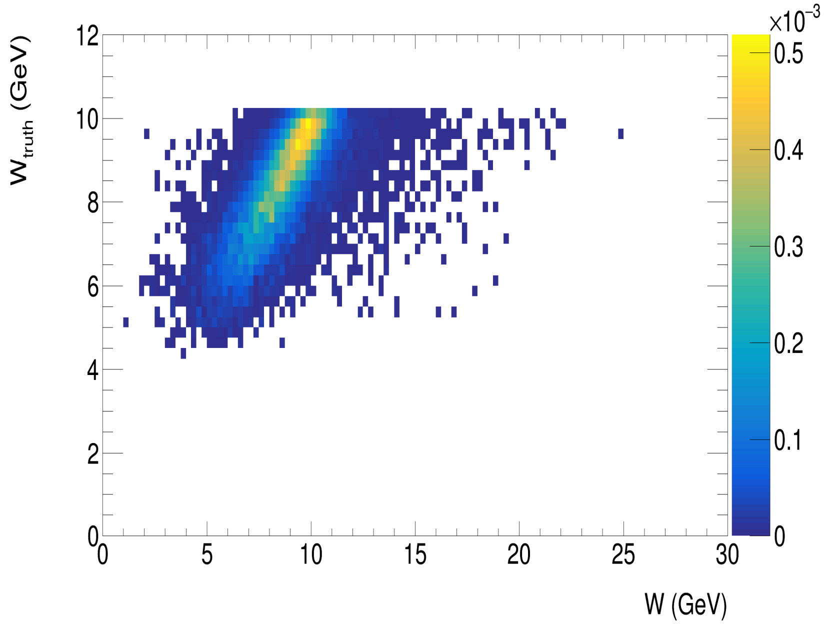
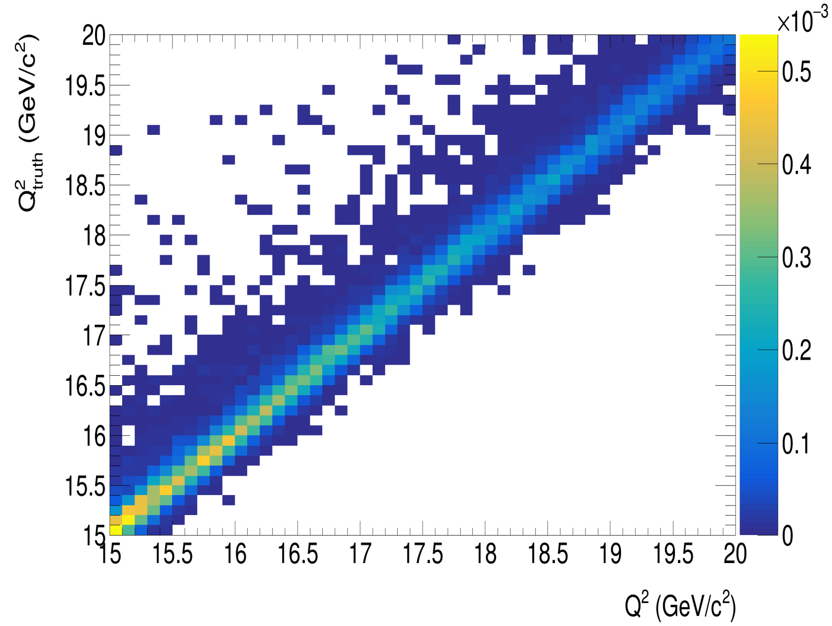
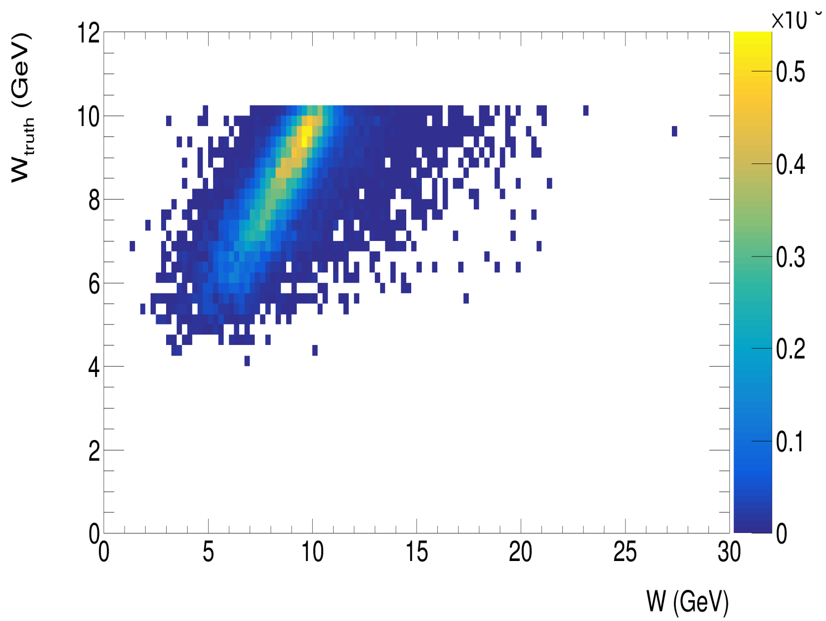
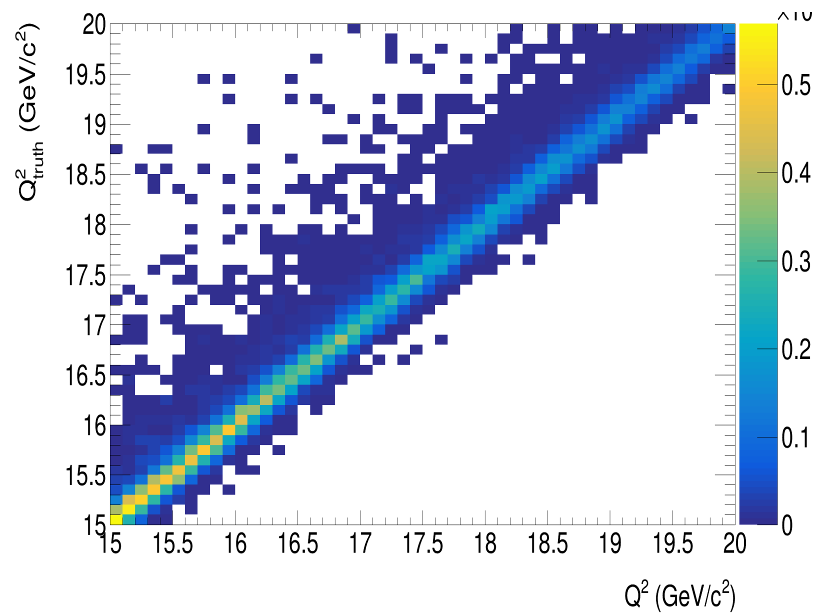
IR6




IR8




Plots by Stephen Kay

$W_{true}$ vs W
- resolutions very similar

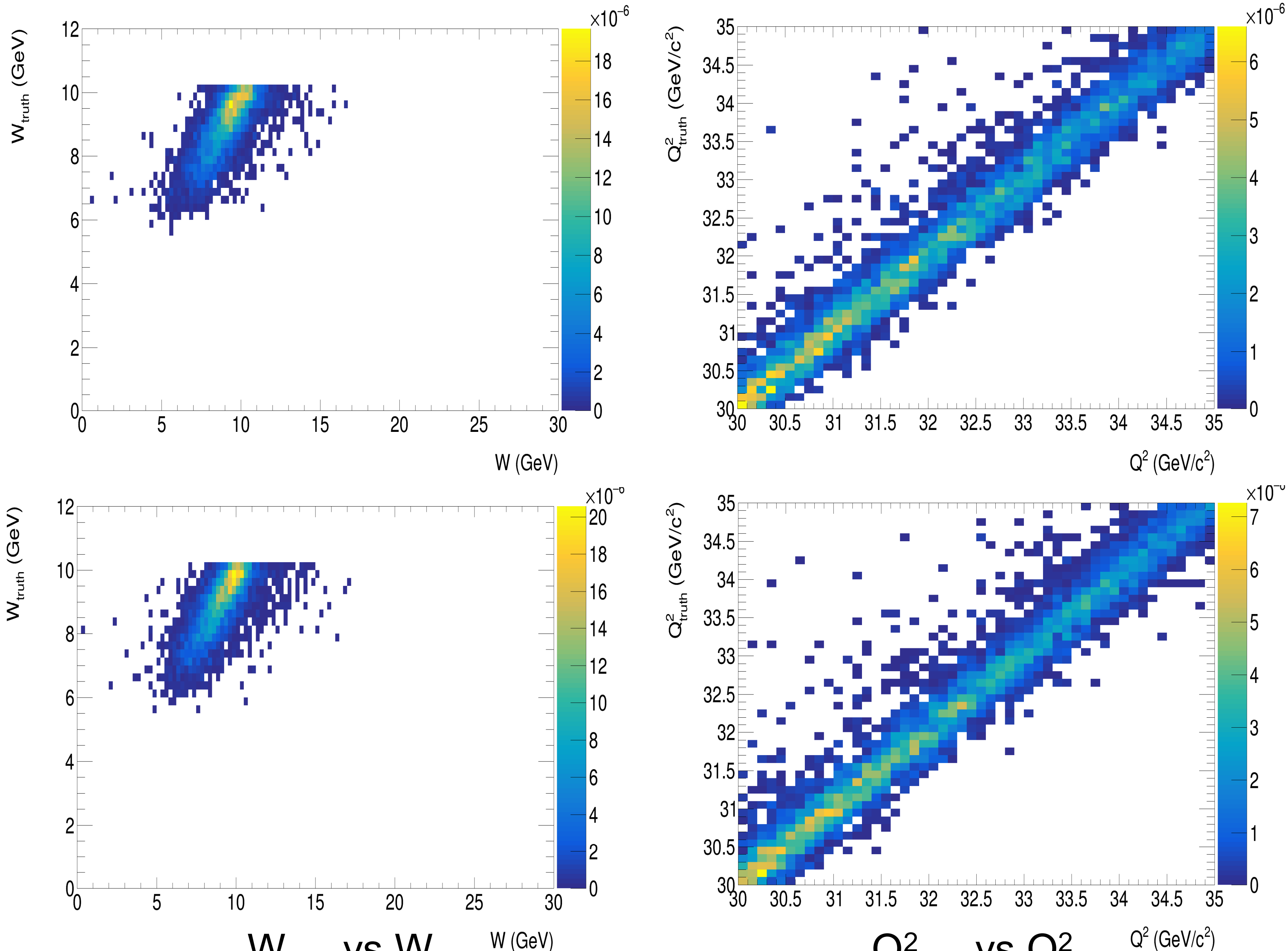
$Q^2_{true}$ vs $Q^2$
- resolutions very similar

# Comparison: IR6 vs IR8 ($30<Q^2<35$)

University of Regina

IR6

IR8




## $W_{true}$ vs W

- tighter correlation for IR8

## $Q^2_{true}$ vs $Q^2$

- resolutions very similar

Plots by Stephen Kay

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# Comparison: IR6 vs IR8 (All Events)

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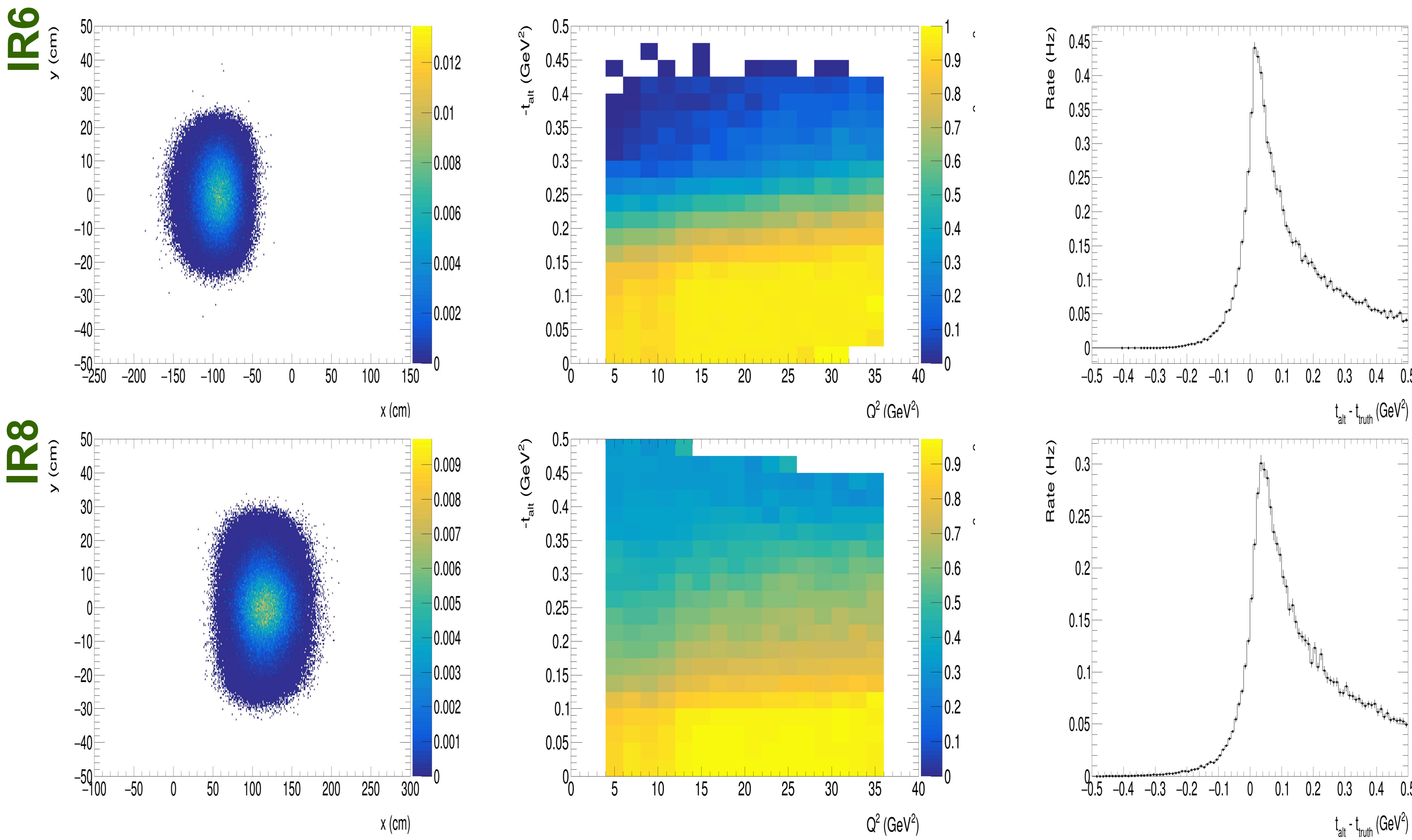
e’ $\pi^+$ n Triple Coincidence Rate for 5x100 @ L=$10^{34}$

Cuts applied: $|\theta_n - \theta_{cent}|$ , $p_{miss}$, $|\Delta\theta|$, $|\Delta\varphi|$, y>0.01




*neutron* hits on ZDC
- Not suprisingly, IR8 has larger acceptance

Detection Efficiency per ($Q^2$,$t$)–bin
- IR8 better at –t=0.35

$t_{true}$–$t_{alt}$
- IR6, IR8 reconstruction resolutions similar

Plots by Stephen Kay

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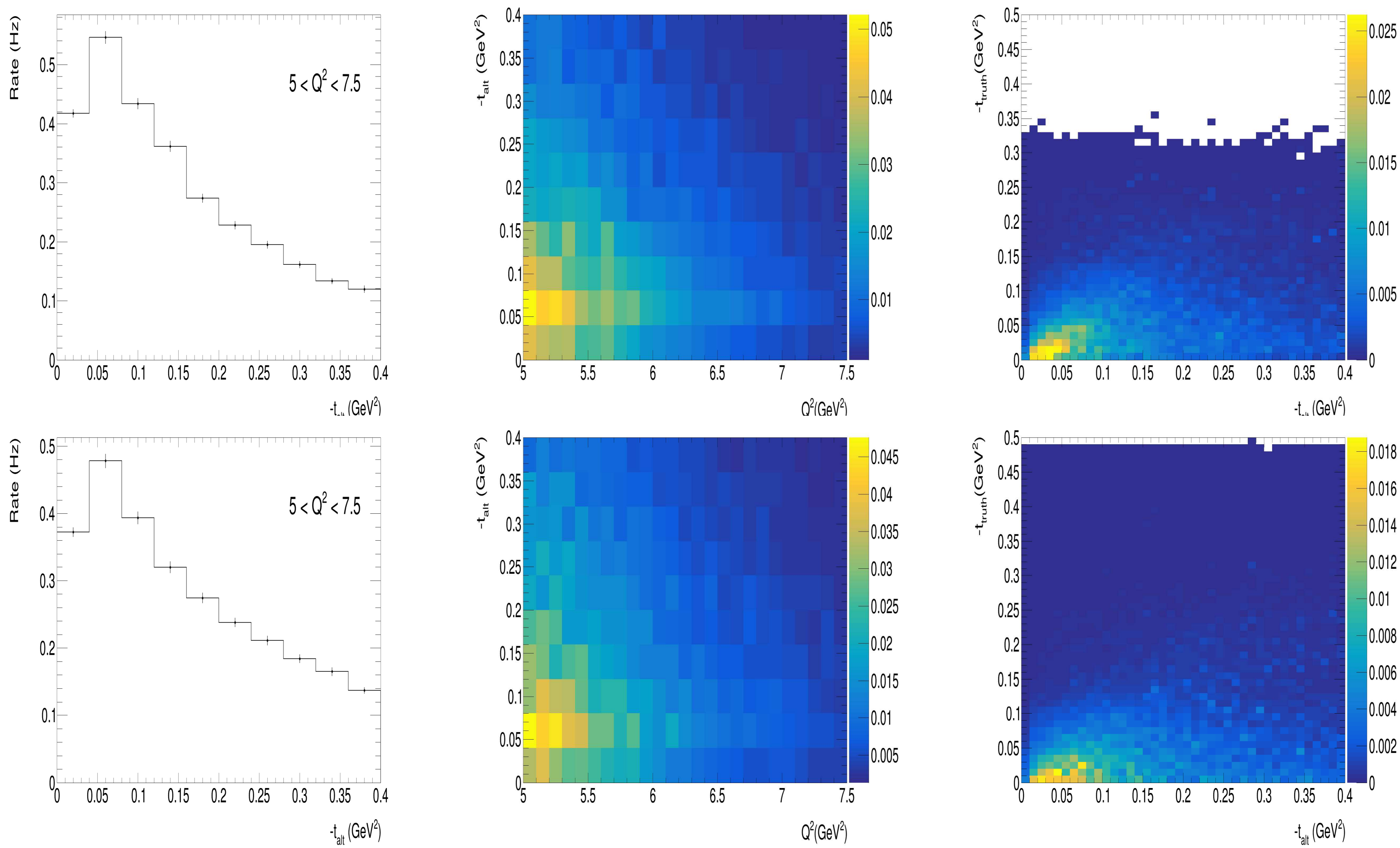
# Comparison: IR6 vs IR8 ($5<Q^2<7.5$)

e' $\pi^+$ n Triple Coincidence Rate for 5x100 @ L=$10^{34}$

Cuts applied: $|\theta_n - \theta_{cent}|$ , $p_{miss}$, $|\Delta\theta|$, $|\Delta\varphi|$, $y>0.01$

IR6

IR8




Rate (Hz) per t–bin
- IR6 higher at $-t_{min}$
- IR8 higher at $-t=0.35$

Rate (Hz) per ($Q^2$,$t$)–bin

$t_{true}$ vs $t_{alt}$
- tighter correlation for IR6

Plots by Stephen Kay

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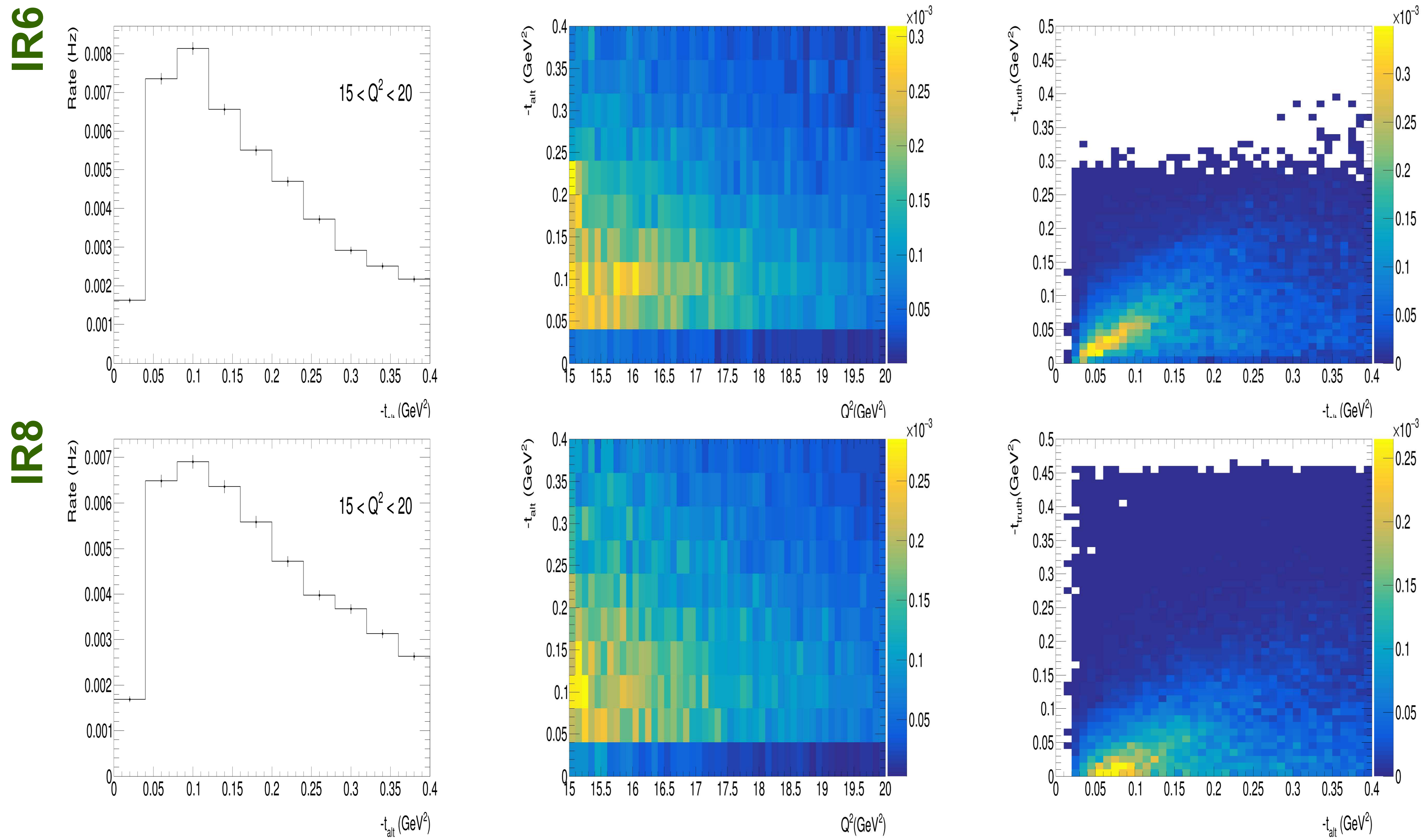
# Comparison: IR6 vs IR8 ($15<Q^2<20$)

e’ $\pi^+$ n Triple Coincidence Rate for 5x100 @ L=$10^{34}$

Cuts applied: $|\theta_n - \theta_{cent}|$ , $p_{miss}$, $|\Delta\theta|$, $|\Delta\varphi|$, y>0.01




Rate (Hz) per t–bin

- IR6 higher at $-t_{min}$
- IR8 higher at –t=0.35

Rate (Hz) per ($Q^2$,$t$)–bin

$t_{true}$ vs $t_{alt}$

- tighter correlation for IR6

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Plots by Stephen Kay

# Comparison: IR6 vs IR8 ($30<Q^2<35$)

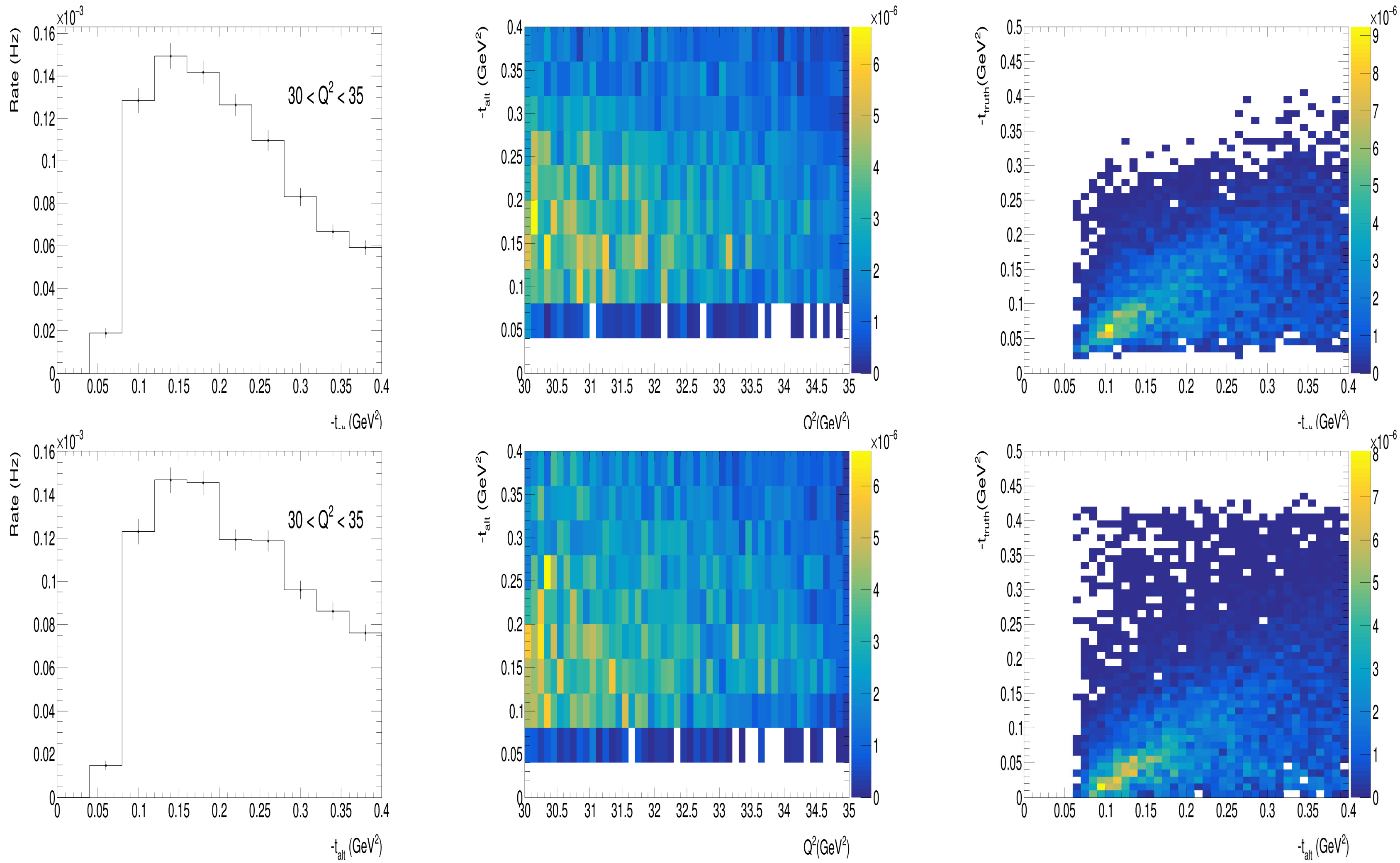
University of Regina

e' $\pi^+$ n Triple Coincidence Rate for 5x100 @ L=$10^{34}$

Cuts applied: $|\theta_n - \theta_{cent}|$ , $p_{miss}$, $|\Delta\theta|$, $|\Delta\varphi|$, y>0.01

IR6

IR8




Rate (Hz) per t–bin

- IR6 higher at $-t_{min}$
- IR8 higher at –t=0.35

Rate (Hz) per ($Q^2$,$t$)–bin

$t_{true}$ vs $t_{alt}$

- tighter correlation for IR6

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Plots by Stephen Kay

# Measurement of $\pi^+$ Form Factor – Low $Q^2$

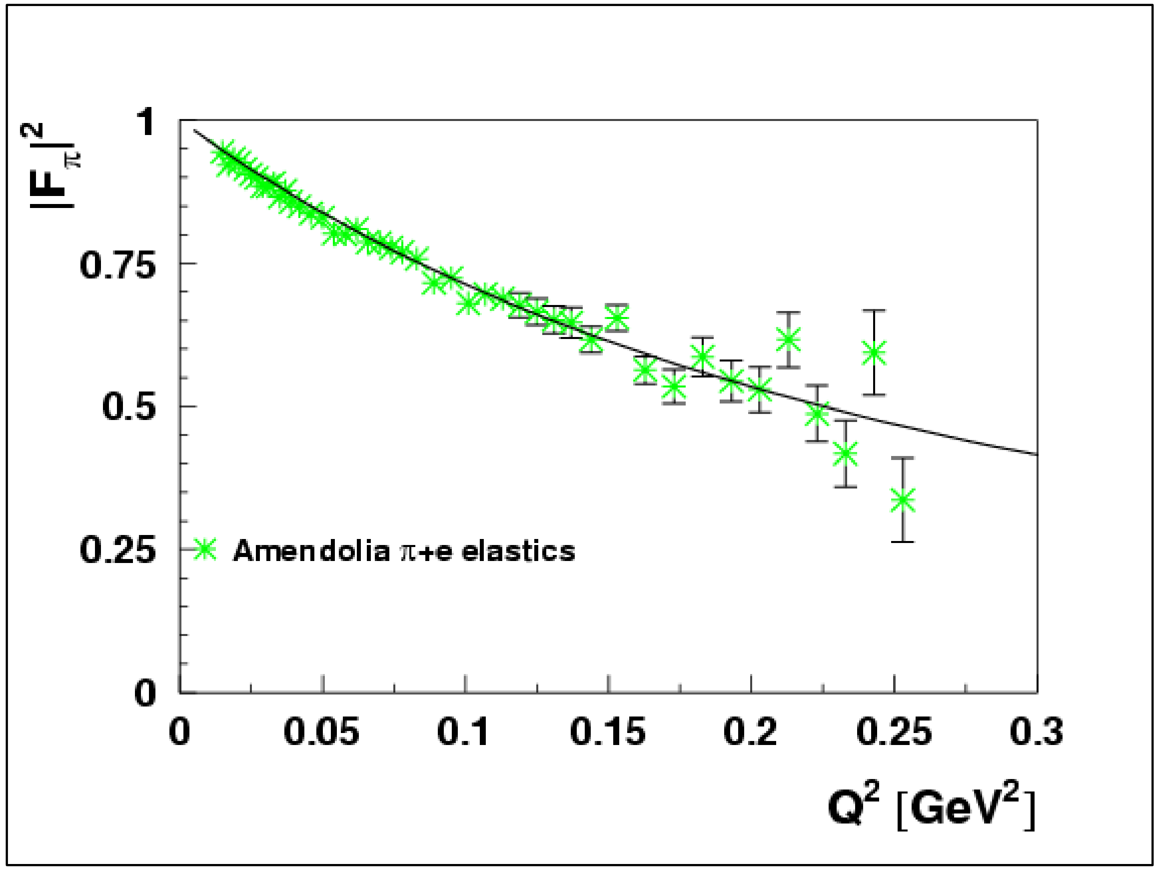
**At low $Q^2$**, $F_\pi$ can be measured model–independently via high energy elastic $\pi^-$ scattering from atomic electrons in Hydrogen

- CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV$^2$ *[Amendolia, et al., NPB **277**(1986)168]*

- Data used to extract pion charge radius
  $r_\pi = 0.657 \pm 0.012$ fm

Maximum accessible $Q^2$ roughly proportional to pion beam energy

*$Q^2$=1 GeV$^2$ requires 1 TeV pion beam*

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# Measurement of $K^+$ Form Factor

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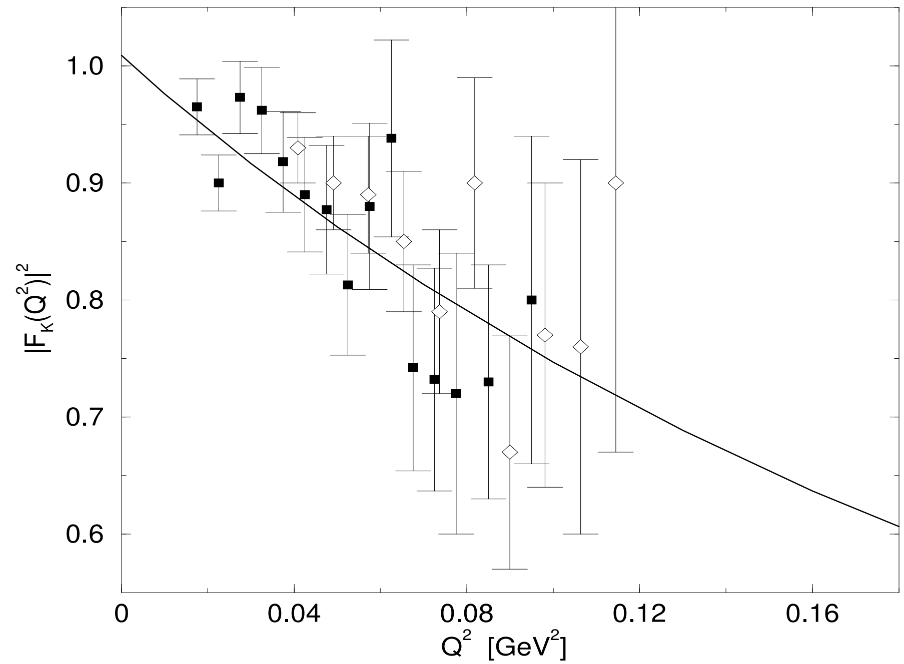
- Similar to $\pi^+$ form factor, elastic $K^+$ scattering from electrons used to measure charged kaon form factor at low $Q^2$

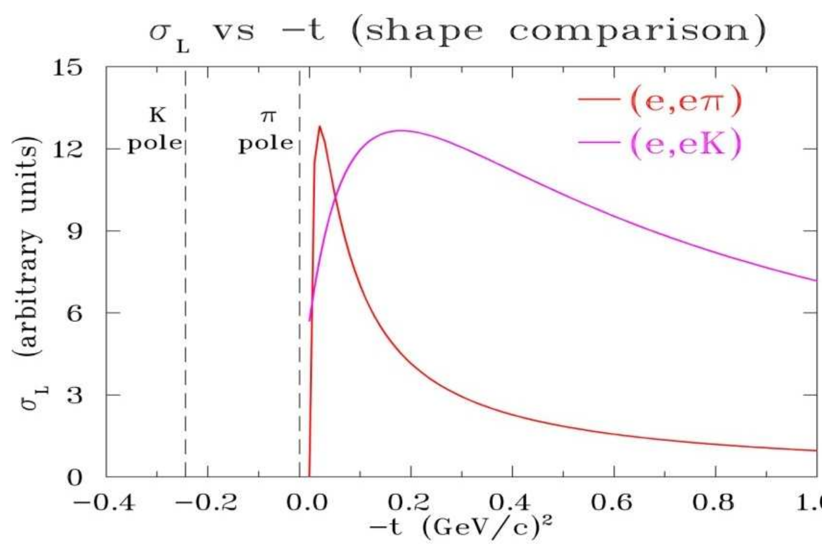
  [Amendolia, et al., PL **B178** (1986) 435]

- Can "kaon cloud" of the proton be used in the same way as the pion to extract kaon form factor via ***p(e,e'K⁺)****Λ* ?
- Kaon pole further from kinematically allowed region

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_K^2)} g^2_{K\Lambda N}(t) F_K^2(Q^2,t)$$

- Many of these issues are being explored in JLab E12–09–011



# Current and Projected $F_K$ Data

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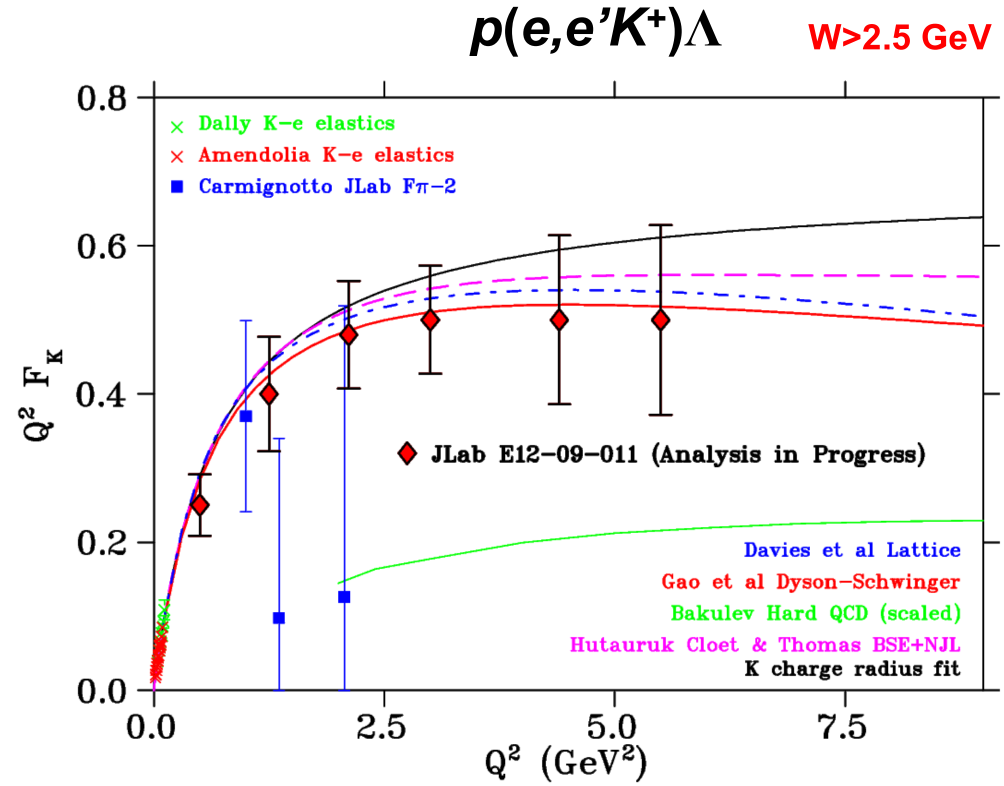
- Similar to $\pi^+$ form factor, elastic $K^+$ scattering from electrons used to measure charged kaon form factor at low $Q^2$

  [Amendolia, et al., PL **B178** (1986) 435]

- **Can "kaon cloud" of the proton be used in the same way as the pion to extract kaon form factor via *p(e,e'K⁺)Λ* ?**

- Kaon pole further from kinematically allowed region

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_K^2)} g_{K\Lambda N}^2(t) F_K^2(Q^2,t)$$




Extraction of $F_K$ from $Q^2$>4 GeV$^2$ data is more uncertain, due to higher $-t_{min}$

**Many of these issues are being explored in JLab E12–09–011**

# L/T–separation error propagation

University of Regina

## Error in $d\sigma_L/dt$ is magnified by $1/\Delta\varepsilon$

→ To keep magnification factor <5x, need $\Delta\varepsilon$>0.2, preferably more!

$$\frac{d^2\sigma}{dt\,d\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi_\pi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi_\pi$$

$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{(R+\varepsilon_1)^2+(R+\varepsilon_2)^2} \qquad \text{where } R=\frac{\sigma_T}{\sigma_L}$$

$$\frac{\Delta\sigma_T}{\sigma_T} = \frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{\varepsilon_1^2\left(1+\frac{\varepsilon_2}{R}\right)^2+\varepsilon_2^2\left(1+\frac{\varepsilon_1}{R}\right)^2}$$

**The relevant quantities for $F_\pi$ extraction are $R$ and $\Delta\varepsilon$**

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)}\, g_{\pi NN}^2(t)\, F_\pi^2(Q^2,t)$$

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# $\sigma_L$ via Beam and Target Polarization

**Although the technique has not been tested for this reaction, it is in principle possible to extract $R=\sigma_L/\sigma_T$ using polarization degrees of freedom**

For parallel kinematics (outgoing meson along $\vec{q}$) in proton rest frame

$$R = \frac{\sigma_L}{\sigma_T} = \frac{1}{\varepsilon_L}\left(\frac{1}{\chi_z} - 1\right)$$

Longitudinal polarization of virtual photon

$$\varepsilon_L = \left(Q^2 / \omega_{cm}^{\ 2}\right)\varepsilon$$

$z$-component of proton "reduced" polarization in exclusive pseudoscalar meson production

$$\chi_z = \frac{1}{2P_e P_p\sqrt{1-\varepsilon^2}} A_z$$

$A_z$ = double-spin asymmetry

Schmieden, Tiator Eur.Phys.J. A **8**(2000)15-17.

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# Polarization Technique Considerations

- **A point in favor of this technique is that $P_p$ (component of proton polarization parallel to $\vec{q}$) should be readily optimizable at EIC.**
- **Need to keep in mind that the $R=\sigma_L/\sigma_T$ polarization relation only strictly applies in parallel kinematics.**
  - The detector geometry enforces very tight constraints, as recoil neutron angle is very sensitive to $\theta_{CM}$.

$$\sigma_L \propto P_e P_p \sqrt{1-\varepsilon^2} A_z$$

- **Figure of merit for this technique vanishes for ε≈1.0.**
- ε≈0.95 gives $\sqrt{1-\varepsilon^2} \approx 0.31$
- Requires $E_{CM}$<20 GeV, e.g. 3x25. Luminosity low.
- **At best, this could be used as a spot-check only in specific kinematics. Generally not feasible.**

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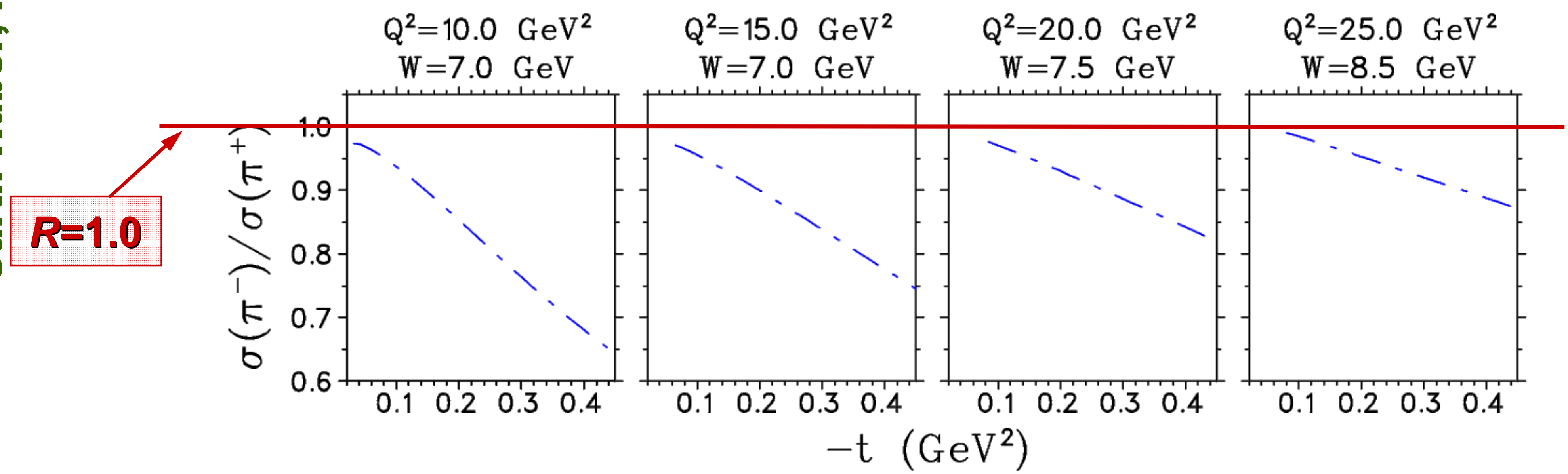
# Using $\pi^-/\pi^+$ ratios to confirm $\sigma_L \gg \sigma_T$

- Exclusive $^2$H(e,e'$\pi^+$n)n and $^2$H(e,e'$\pi^-$p)p in same kinematics as p(e,e'$\pi^+$n)
- $\pi$ *t*–channel diagram is purely isovector (G–parity conservation).

$$R = \frac{\sigma[n(e,e'\pi^- p)]}{\sigma[p(e,e'\pi^+ n)]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

- **The $\pi^-/\pi^+$ ratio will be diluted if $\sigma_T$ is not small, or if there are significant non-pole contributions to $\sigma_L$.**
- **Compare measured $\pi^-/\pi^+$ ratio to model expectations.**




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

**$^2$H(e,e'$\pi^+$n)n $^2$H(e,e'$\pi^-$p)p EIC studies not yet started**

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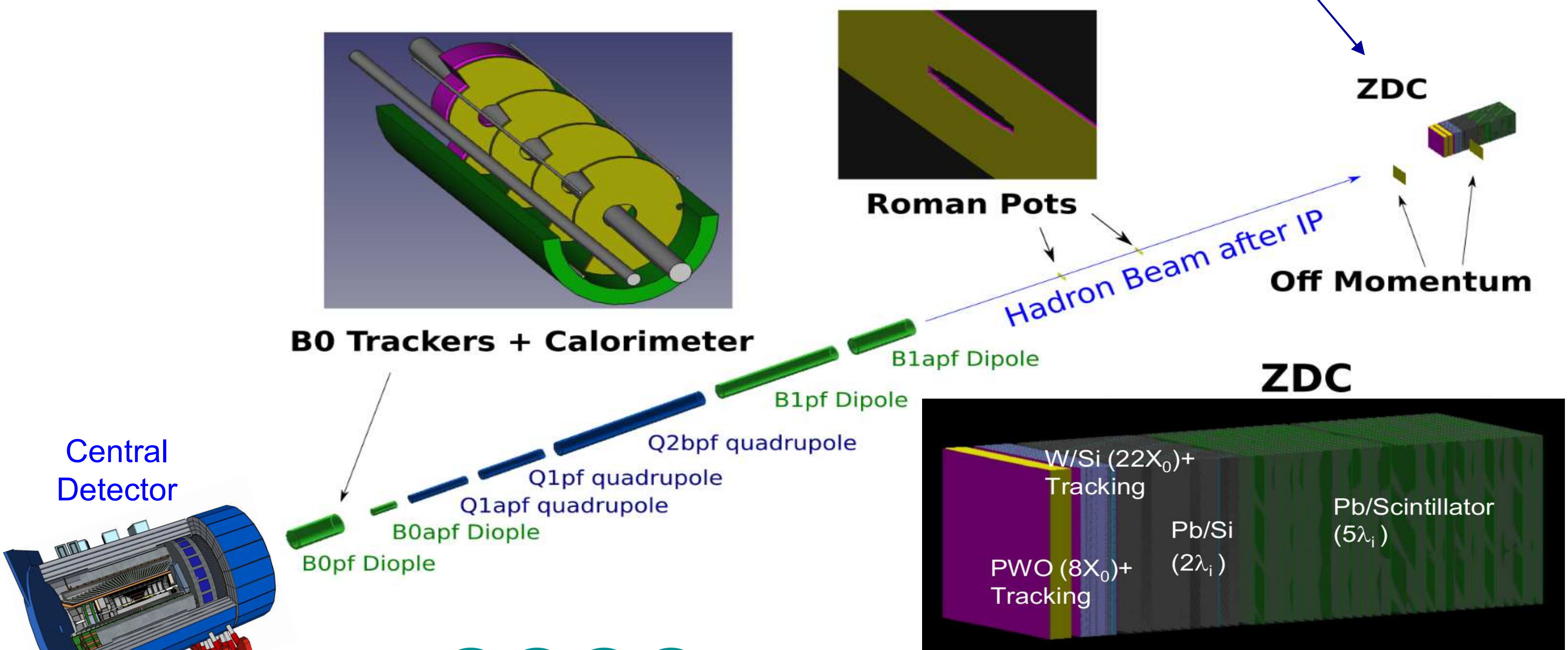
# EIC Far Forward Detectors

- Crucial to cleanly separate exclusive $p(e,e'\pi^+n)$ process from competing inclusive reactions
- EIC measurement <u>impossible</u> unless recoil neutron (very high momentum, <1° from outgoing hadron beam) is efficiently detected
- **High quality Zero Degree Calorimeter (ZDC) essential**




Position: 37.5m downstream of IP

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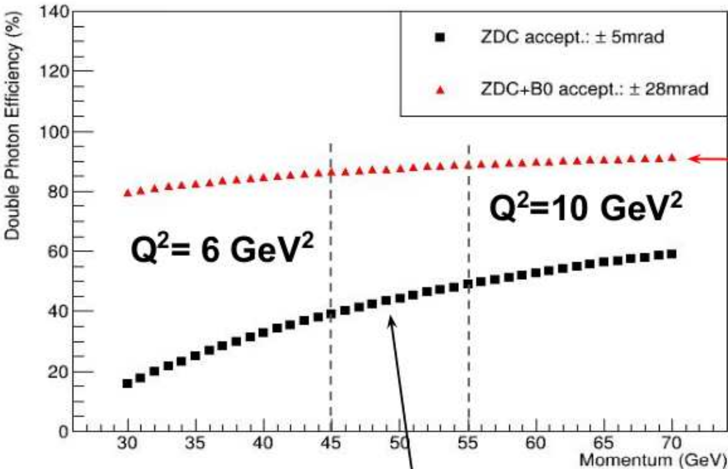
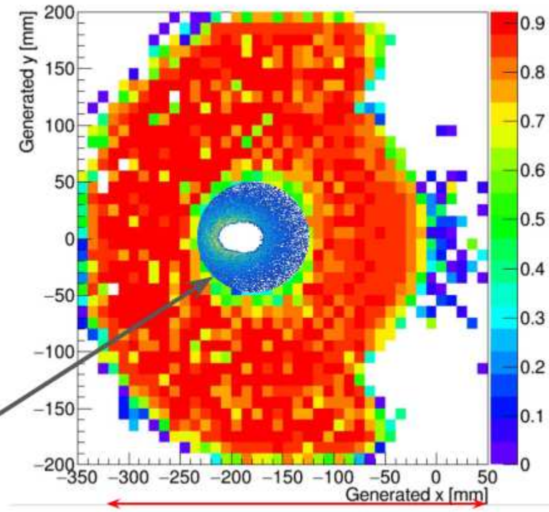
## Two photon detection efficiency

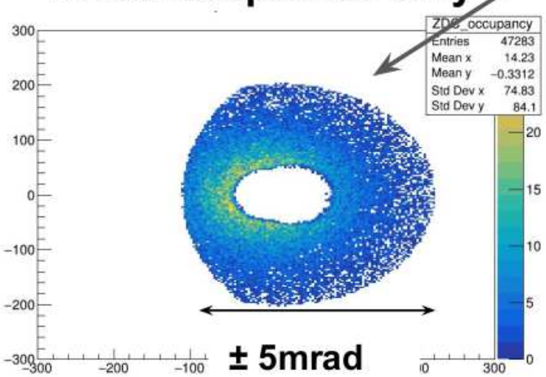



## ZDC + B0 calorimeter




**± 28mrad !**

## ZDC Acceptance only




**B0 Calorimeter**

**B0 Trackers**