Measurements of Pion and Kaon Form Factors at the EIC

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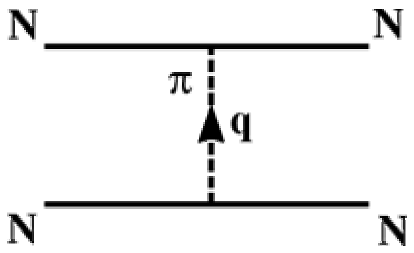
The Pion has Particular Importance

- 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 ρ-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.**

The Pion as a Goldstone Boson

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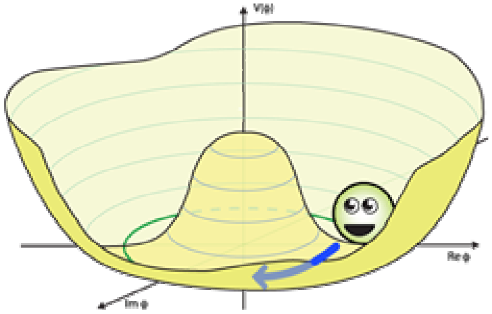
- A remarkable feature of QCD is Dynamical Chiral Symmetry Breaking (DCSB) because it cannot be derived directly from the Lagrangian and is related to nontrivial nature of QCD vacuum.
  - Explicit symmetry breaking, which is put in “by hand” through finite quark masses, is quite different.
- DCSB is 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.

Relevance to Hadron Mass Generation

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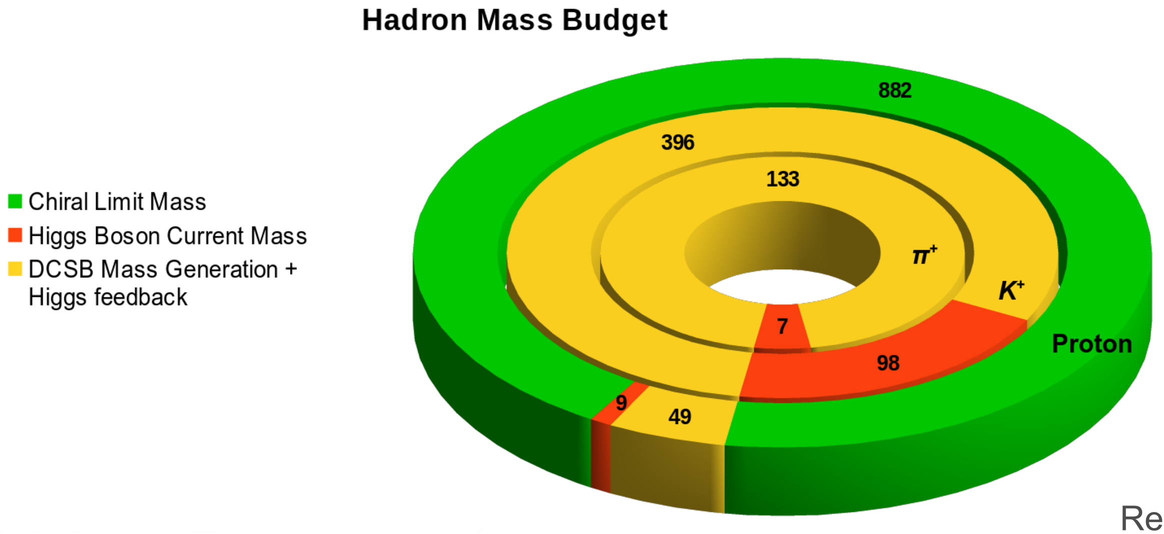


Ref: Craig Roberts (2021)

- 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 π^+ and K^+ form factors over broad Q^2 range is central to this puzzle.**

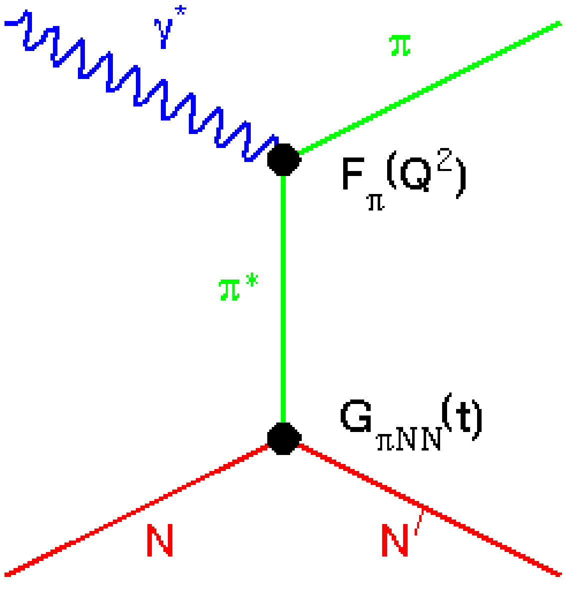
Measurement of F_π via Electroproduction

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

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

- At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
- In Born term model, F_π^2 appears as

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



Drawbacks of this technique:

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

Current and Projected F_π Data

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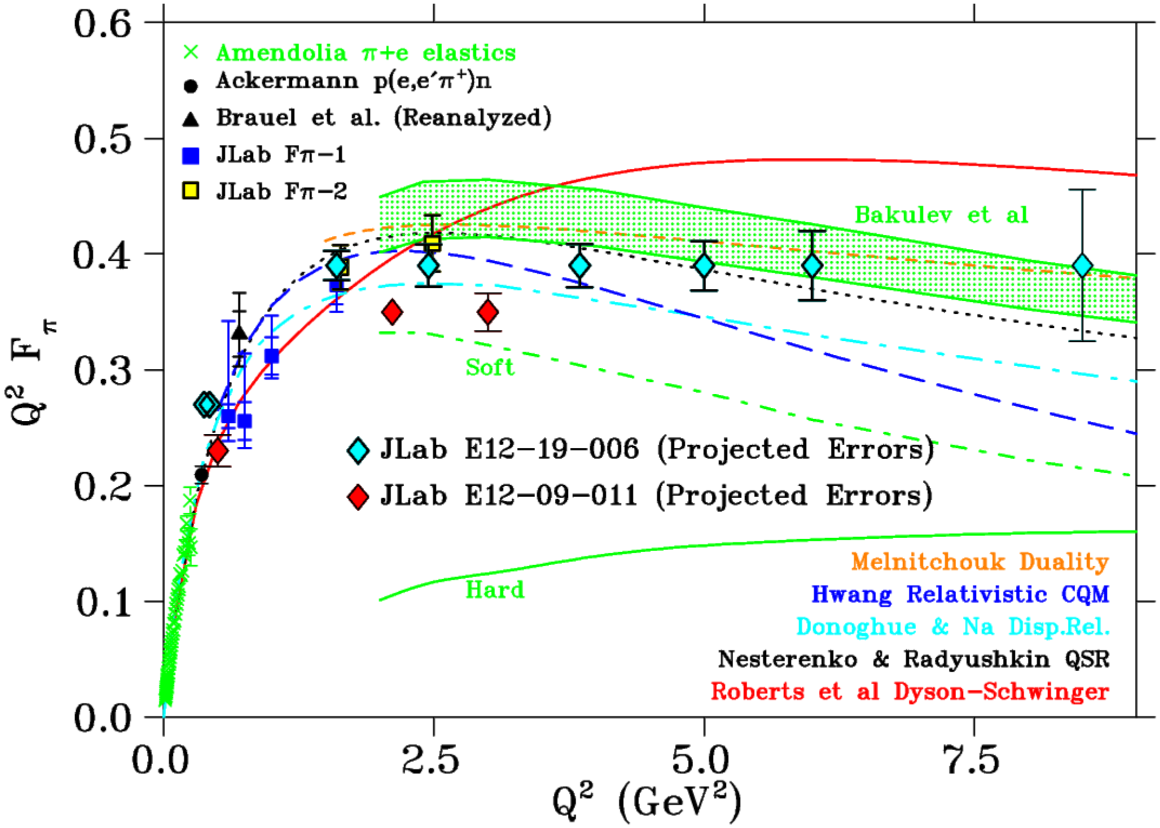
- JLab E12–19–006 will allow measurement of F_π to Q^2=6 with small uncertainties, and to Q^2=8.5 with larger errors (both experimental and theoretical).

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



The ~10% measurement of F_π 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.

Current and Projected F_K Data

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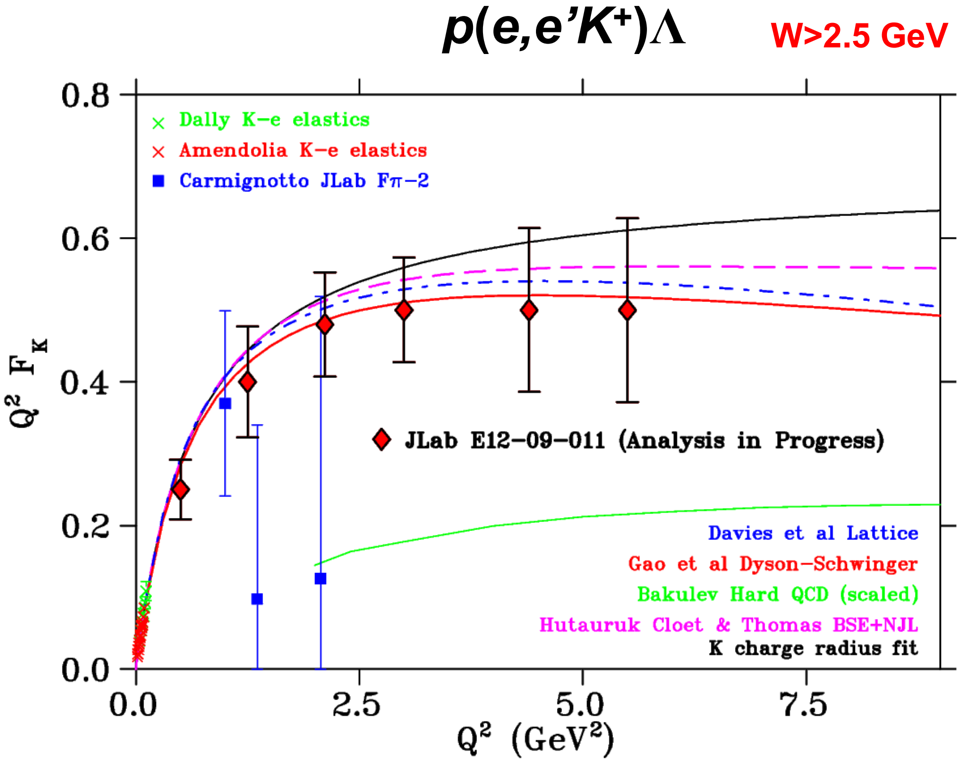
- Similar to π^+ form factor, elastic K^+ scattering from electrons used to measure charged kaon form factor at low Q^2

  [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

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



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

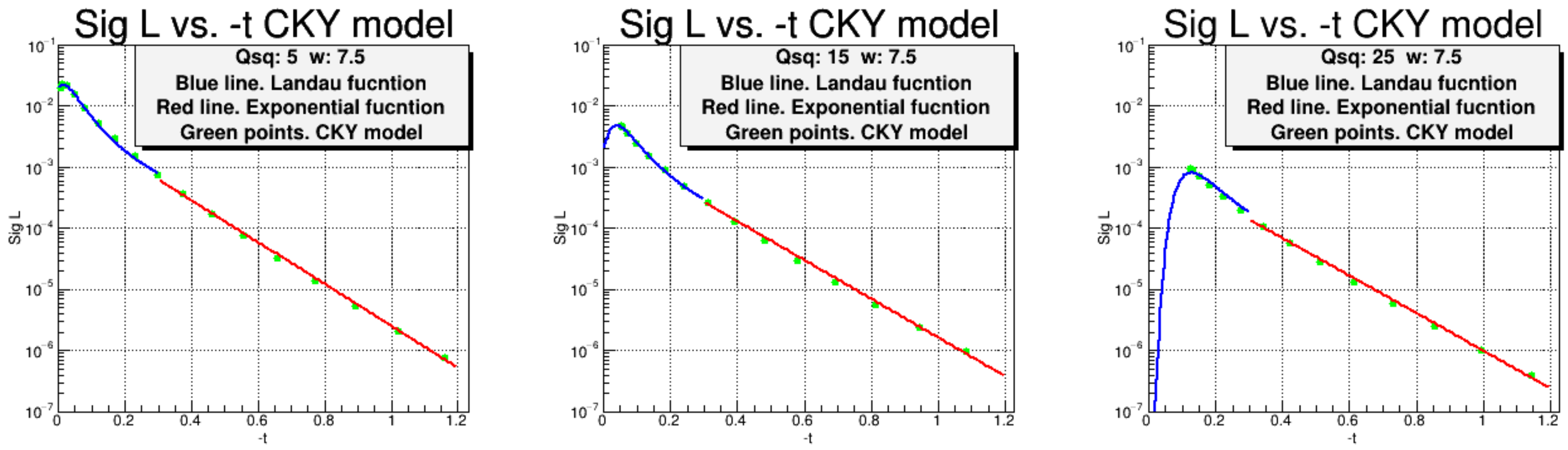
Many of these issues are being explored in JLab E12–09–011

F_π and F_K Studies to Higher Q^2 at EIC

- **Physics Motivation:**
  - JLab measurements have led to a renewed recognition of importance of π^+ and K^+ structure studies 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 Electron–Ion Collider (EIC) may provide this reach
- **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?

DEMP π^+ Event Generator

- We initially looked at the $p(e,e'\pi^+)n$ model by C. Weiss, V. Guzey (2008), which is an extrapolation of a soft model cross section to high Q^2, assuming QCD scaling behavior and $W^2 \gg Q^2$.
  - However, we need to generate many events with $W^2 \sim Q^2$, where this model is unreliable
- Regge-based $p(e,e'\pi^+)n$ model of *T.K. Choi, K.J. Kong, B.G. Yu (CKY) arXiv: 1508.00969* seemed better behaved over a wide kinematic range.
  - Created a MC event generator by parameterizing the CKY σ_L, σ_T for $5<Q^2\ (\mathrm{GeV}^2)<35$ $2.0<W\ (\mathrm{GeV})<10$ $0<-t\ (\mathrm{GeV}^2)<1.2$



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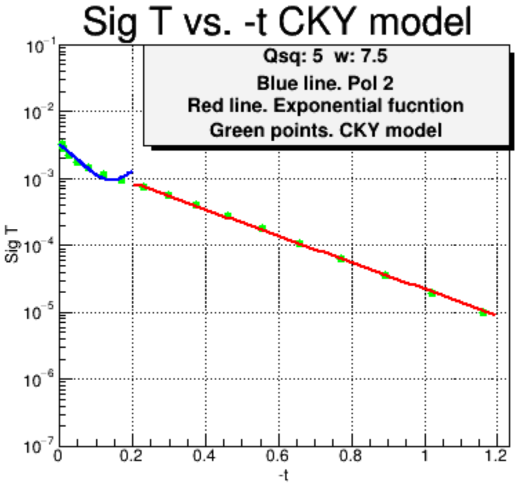

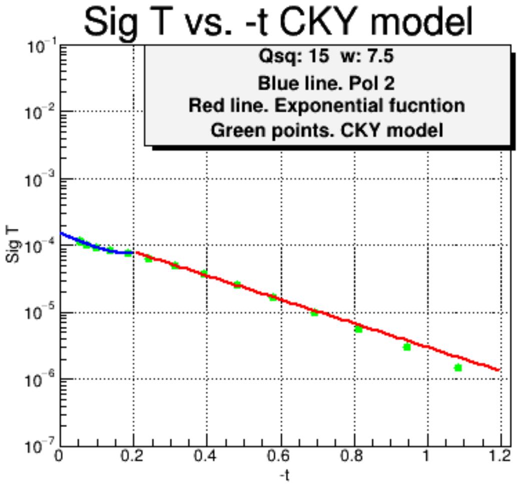

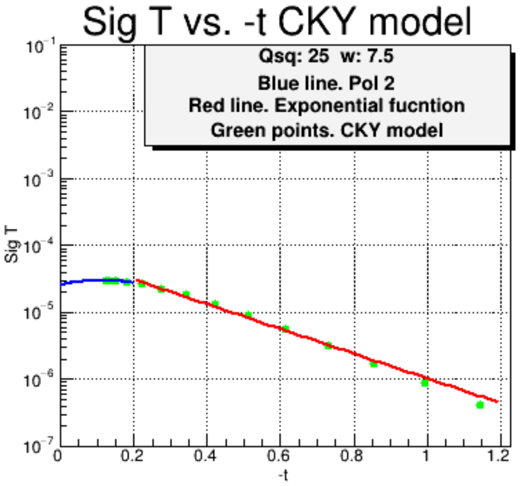

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DEMP n, e', π^+ Acceptance for $-t<0.5$ GeV^2

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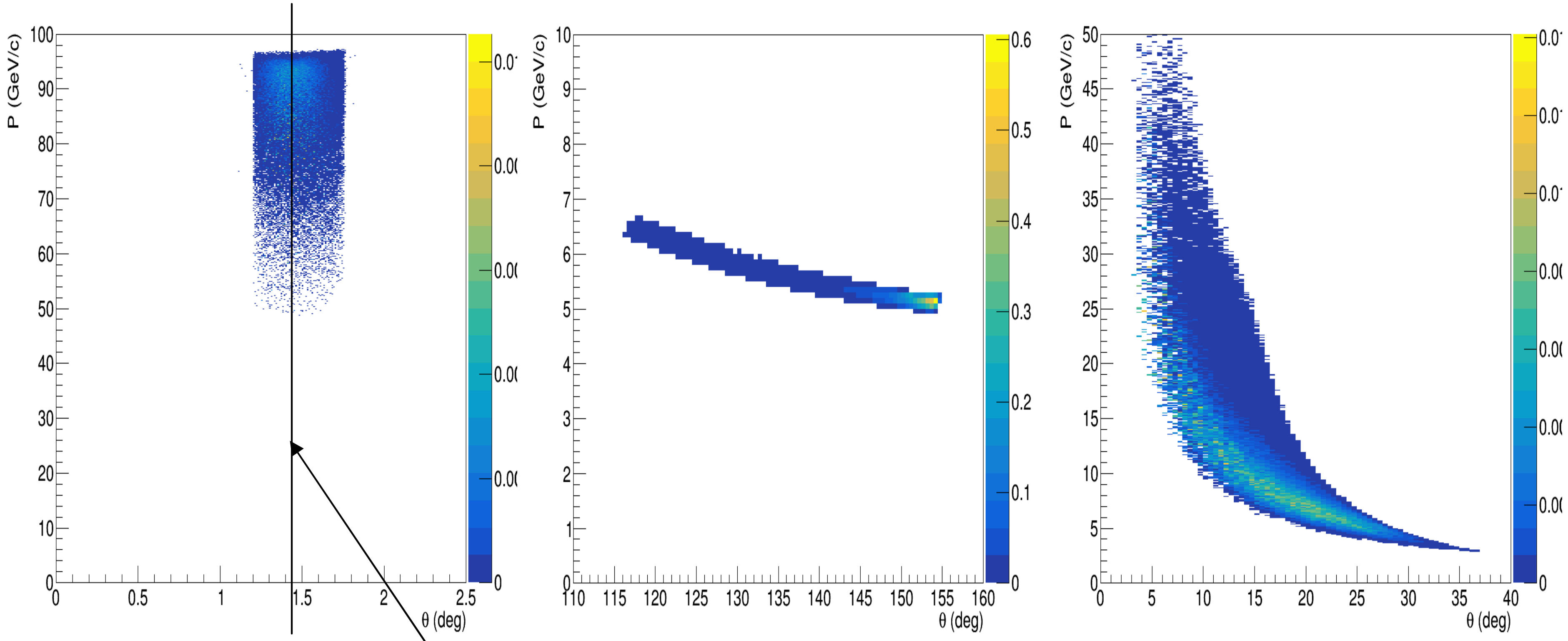
IR6: 5(e^-) x 100(p) GeV Collisions → E_{cm}=44.7 GeV



Offset due to 25 mrad beam crossing angle

Plots by Stephen Kay

Neutrons:
70–98 GeV/c
<0.25° of outgoing proton beam

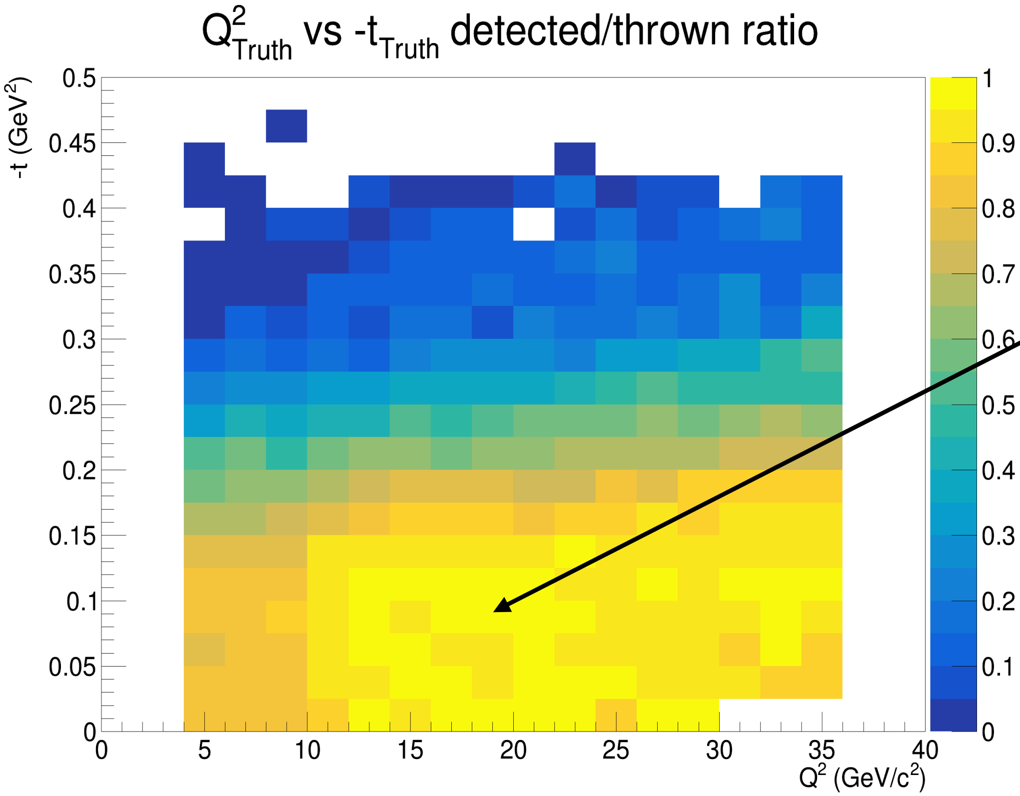
Scattered electrons:
5–7 GeV/c,
25–65° from outgoing e beam

Pions:
3–35 GeV/c,
5–35° from p beam

Assure exclusivity of *p(e,e'π^+n)* reaction by detecting neutron

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

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

Plot by Stephen Kay

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

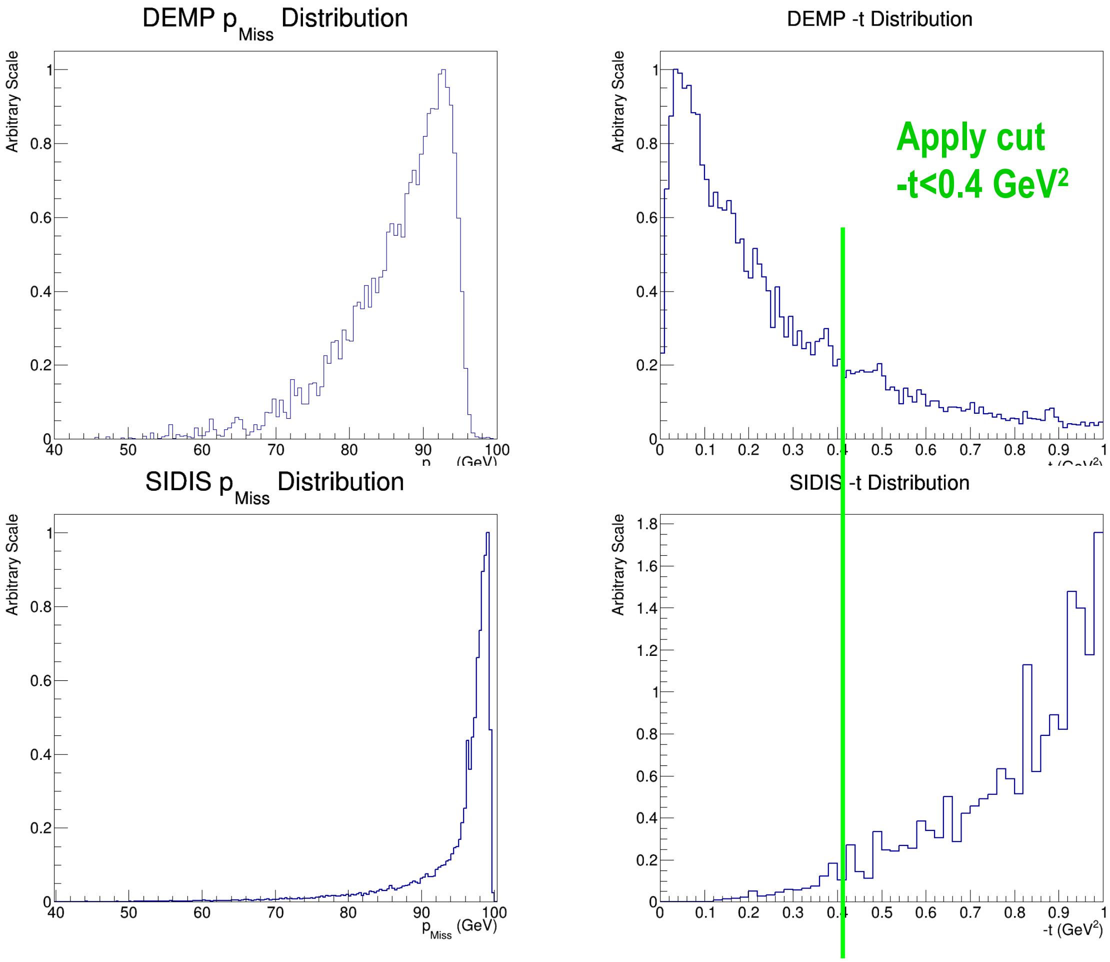
- The SIDIS and DEMP event generators are used to create LUND format files
- Generated events are fed into ECCE Geant4 simulation for both IP6 and IP8 to study acceptance and resolution requirements for different beam energy combinations

Comparison of DEMP and SIDIS kinematics

- SIDIS events are distributed over wider momentum range, and much larger *–t* than foreground DEMP events.

Exclusive
p(e,e'π⁺)n
Foreground

SIDIS
p(e,e'π⁺)X
Background



Plots by
Stephen Kay

DEMP events are e' π^+ n triple coincidence.
SIDIS events are e' π^+ double coincidence, and p_{miss} reconstructed.

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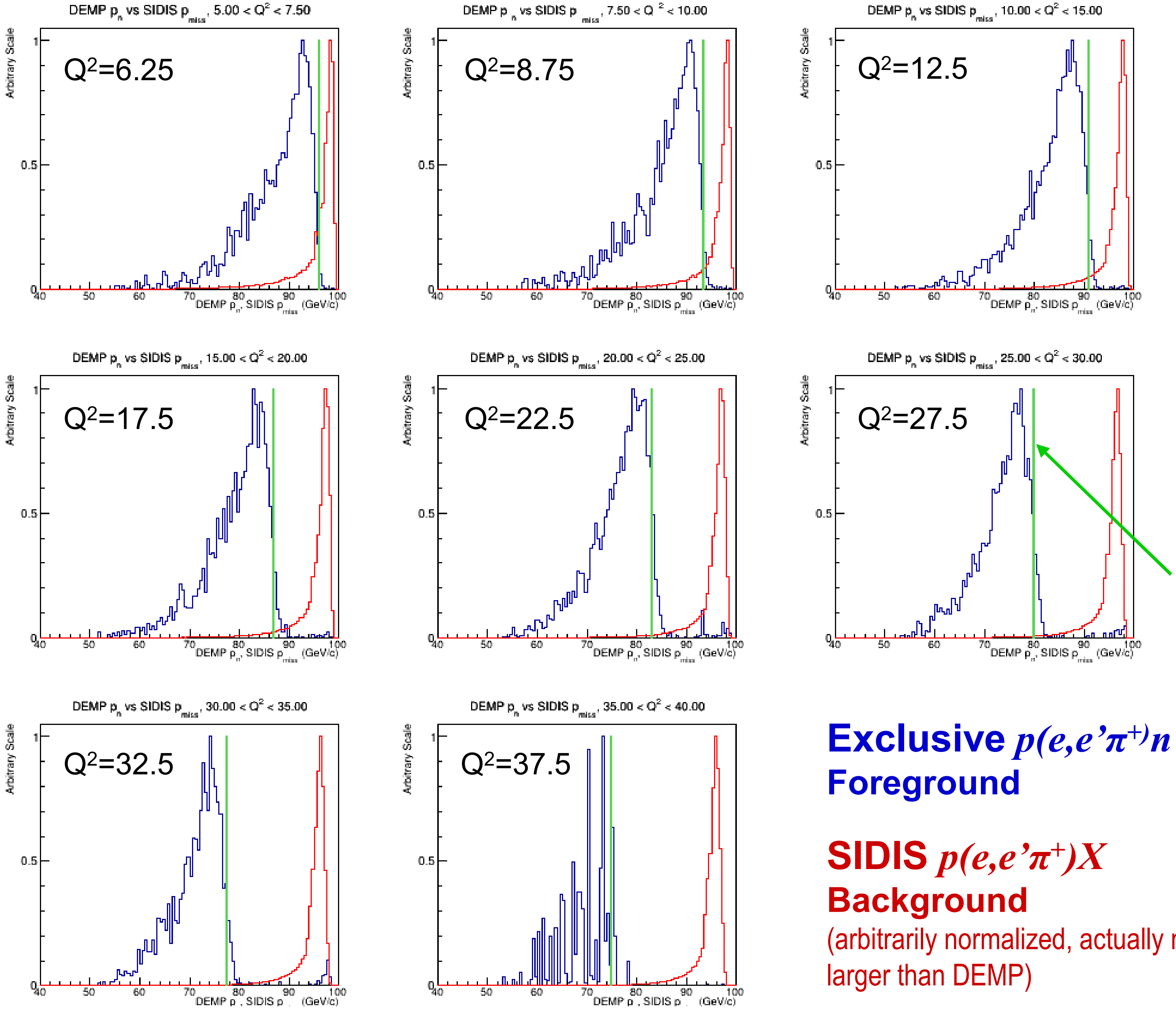
p_{miss} cut vs Q^2–bin (IR6)

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



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Cut value
(varies w/Q^2)

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

SIDIS $p(e,e'\pi^+)X$
Background
(arbitrarily normalized, actually much larger than DEMP)

Another Cut to Remove Background

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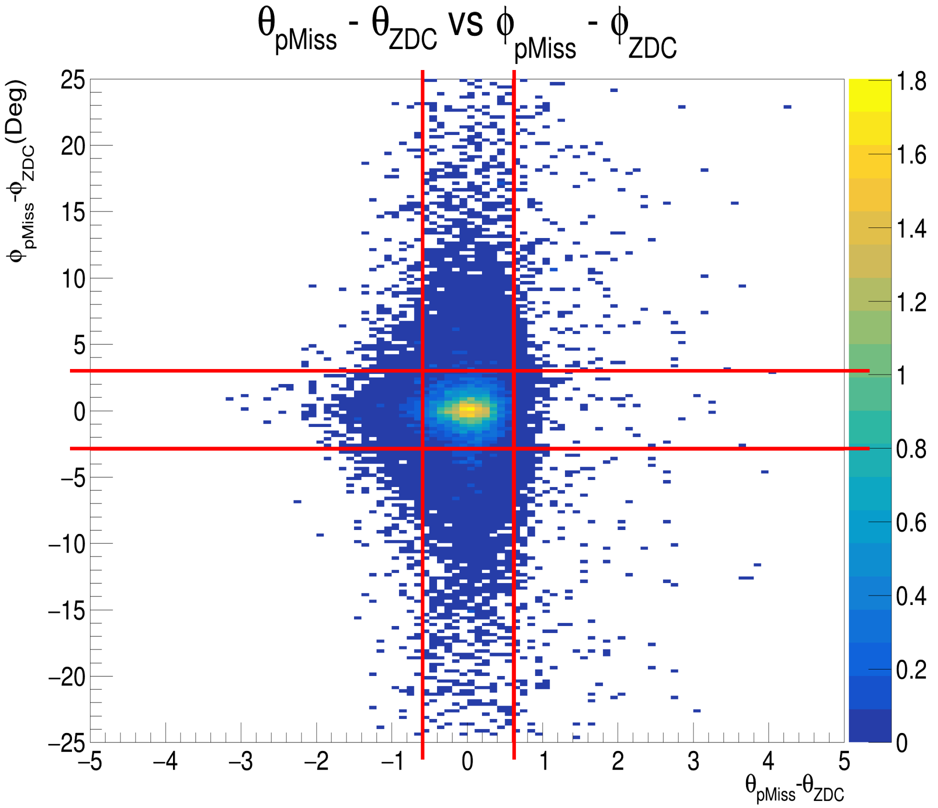
- **Make use of high angular resolution of ZDC to further reduce background events**
  - Compare hit (θ,φ) positions of energetic neutron on ZDC to calculated position from p_{miss}
  - If no other particles are produced (i.e. exclusive reaction) these quantities should be highly correlated
  - Energetic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



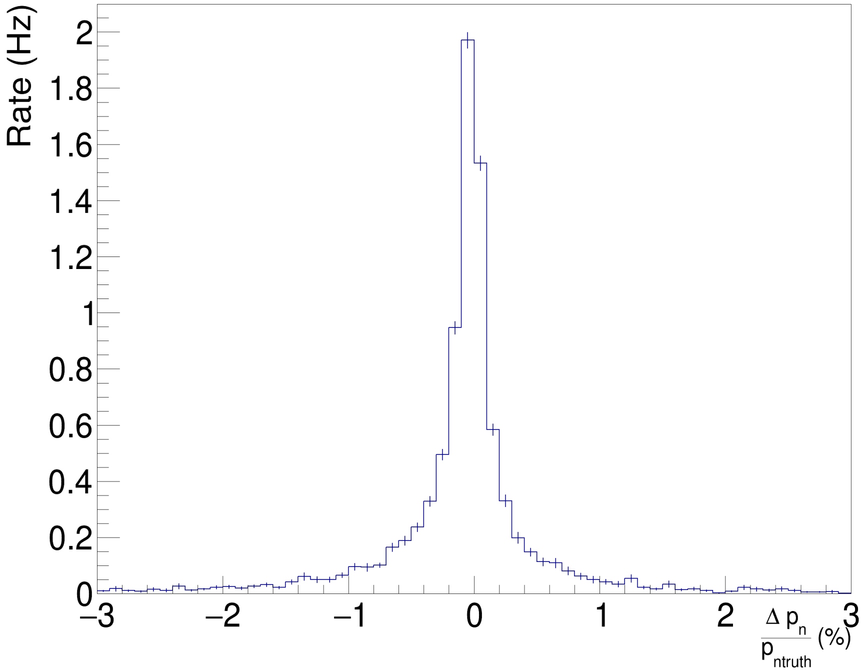
Differences between hit and calculated neutron positions on ZDC for DEMP events (IR6)

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

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

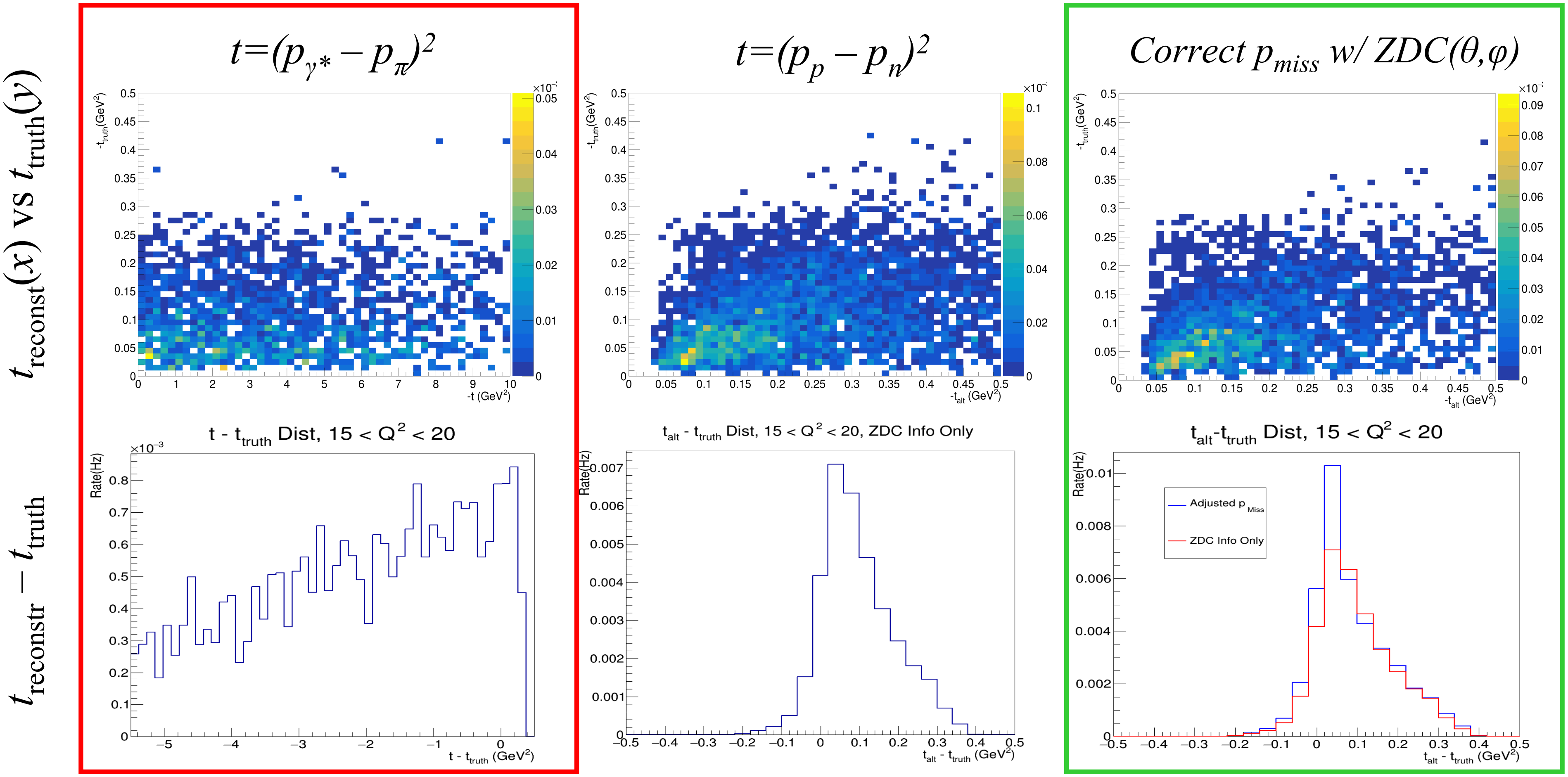


Plot by Stephen Kay

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

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*



Unusable *t* reconstruction

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

Best *t* reconstruction

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

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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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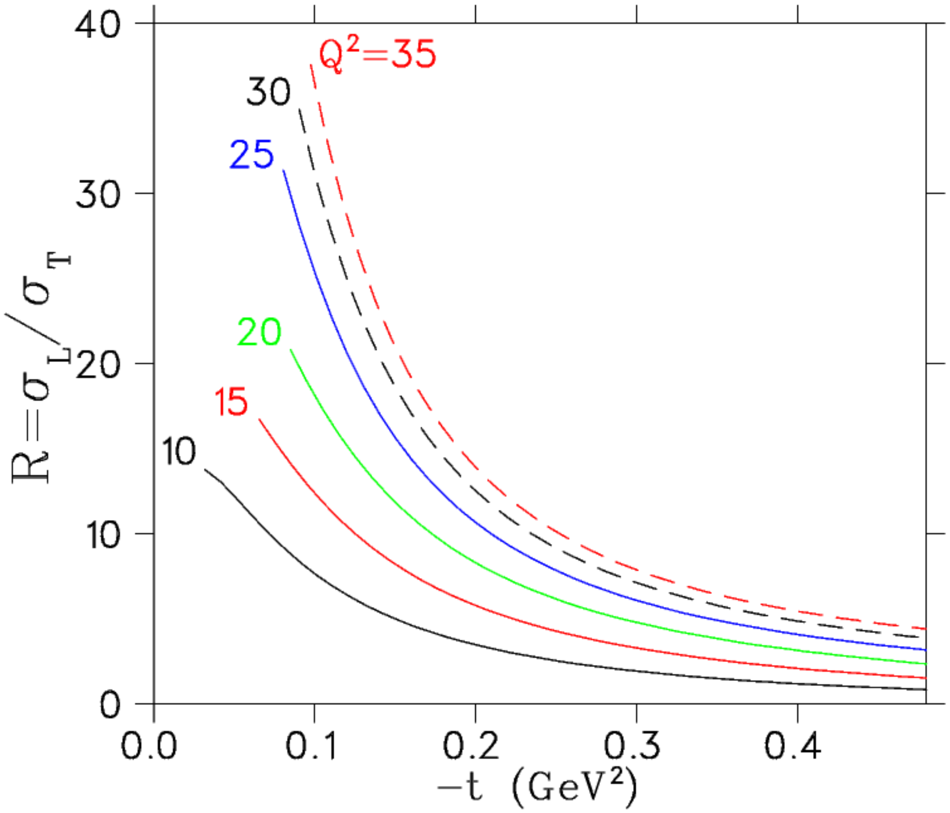
Isolate $d\sigma_L/dt$ using a Model

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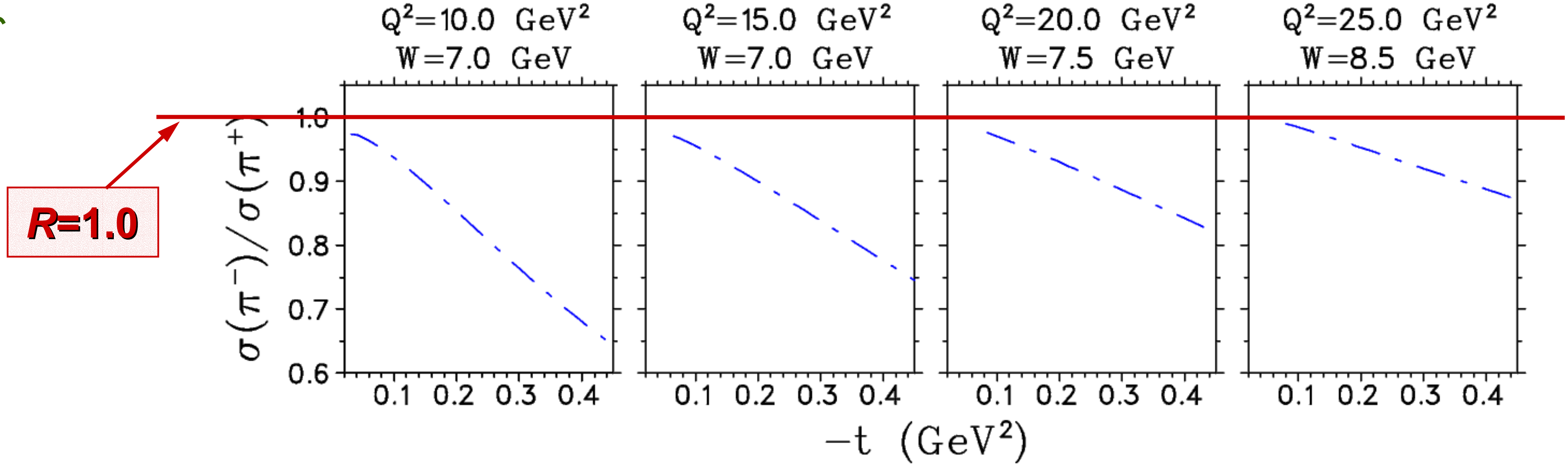
Using π^-/π^+ ratios to confirm $\sigma_L \gg \sigma_T$

- Exclusive $^2H(e,e'\pi^+n)n$ and $^2H(e,e'\pi^-p)p$ in same kinematics as $p(e,e'\pi^+n)$
- π *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 π^-/π^+ ratio will be diluted if σ_T is not small, or if there are significant non-pole contributions to σ_L.**
- **Compare measured π^-/π^+ ratio to model expectations.**



***R*=1.0**

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

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

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EIC Kinematic Reach (IR6)

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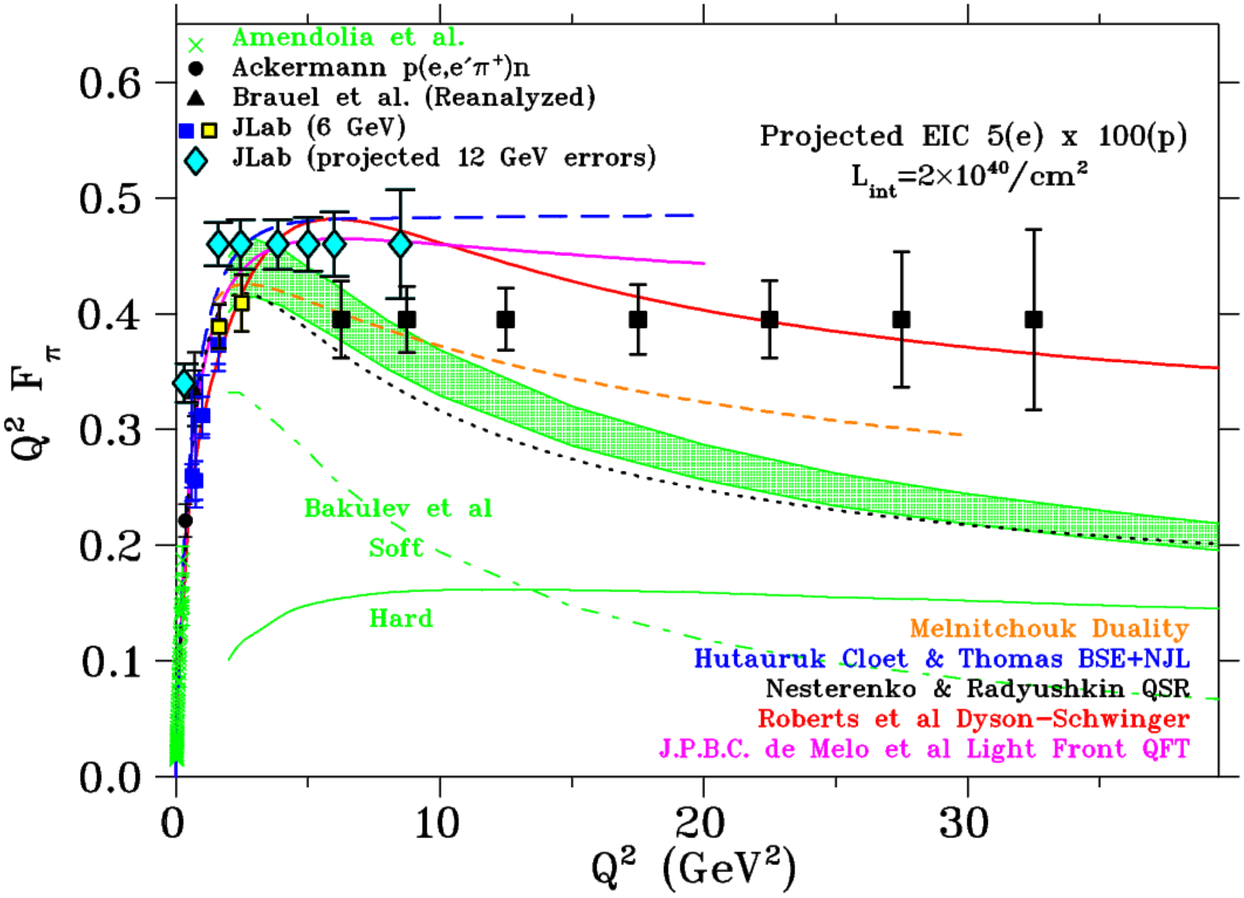


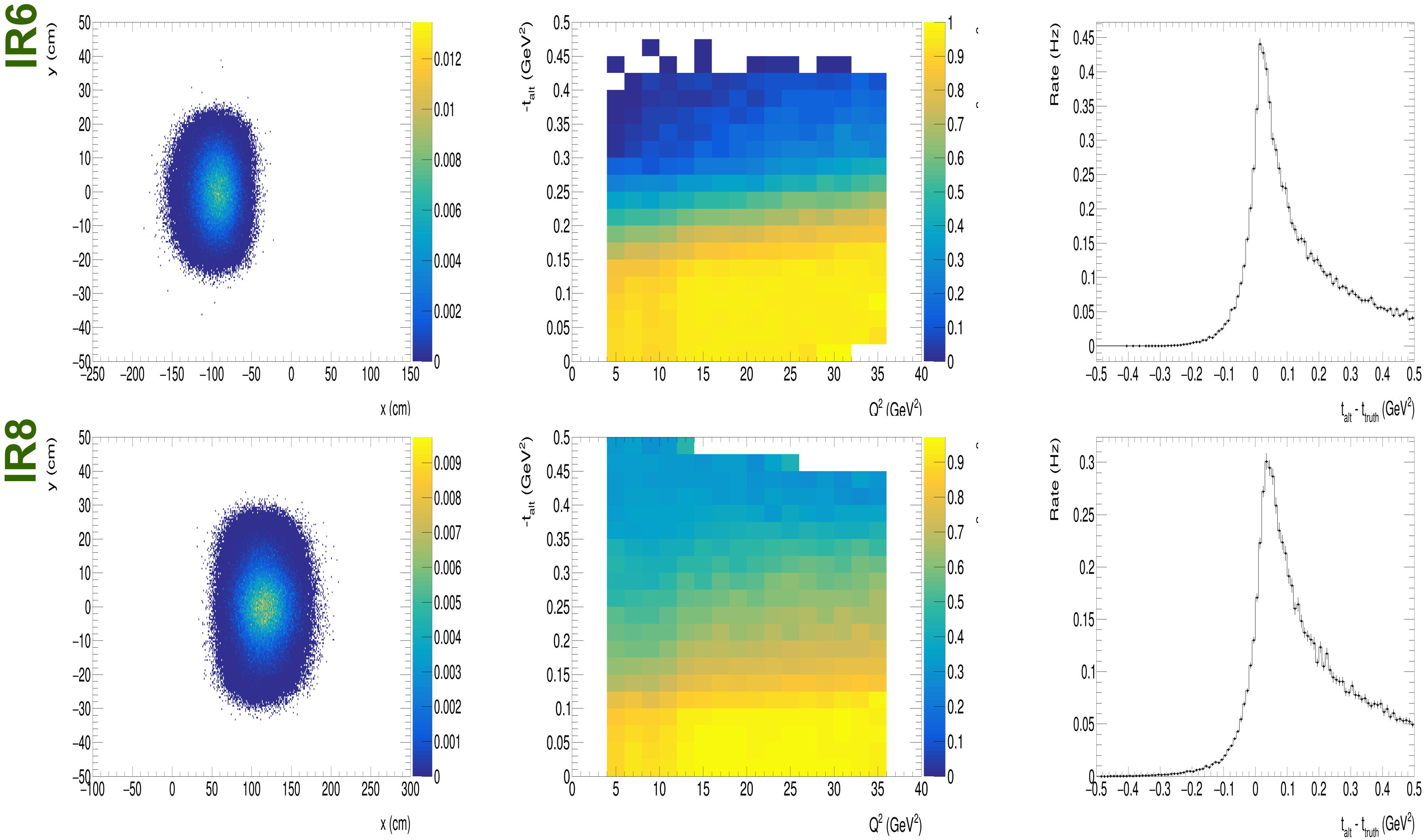
Assumptions:

- 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.

Comparison: IR6 vs IR8 (All Events)

e’ π^+ 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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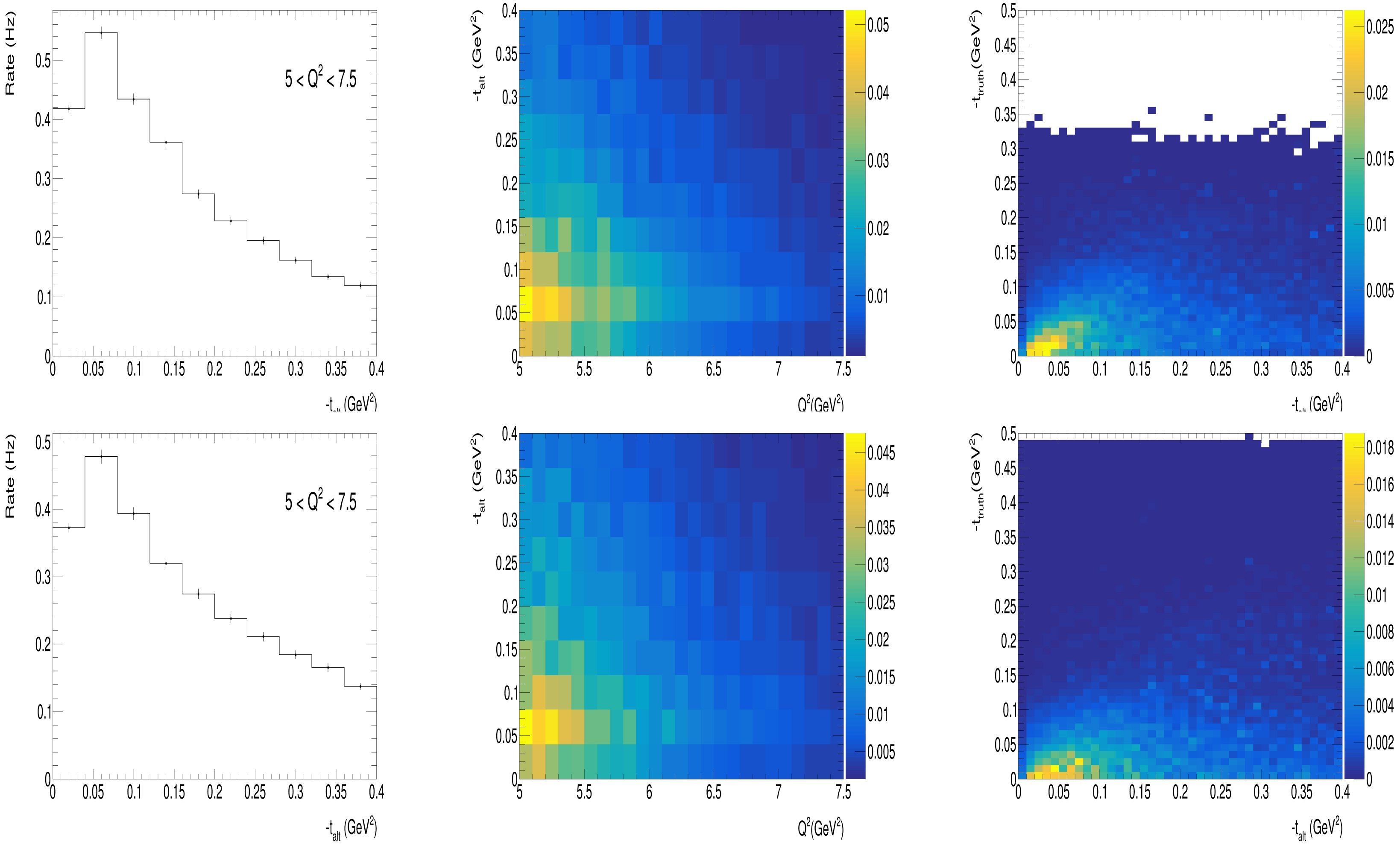
Comparison: IR6 vs IR8 ($5<Q^2<7.5$)

e’ π^+ 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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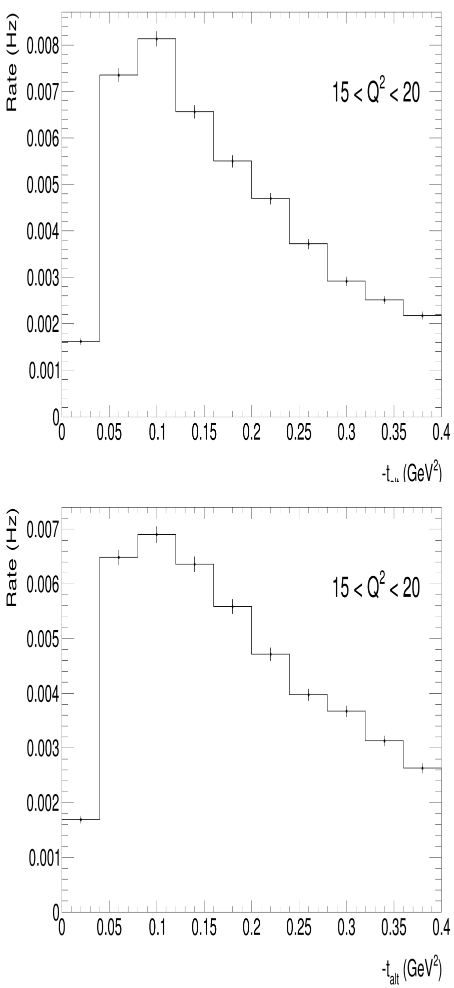
Comparison: IR6 vs IR8 ($15<Q^2<20$)

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

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

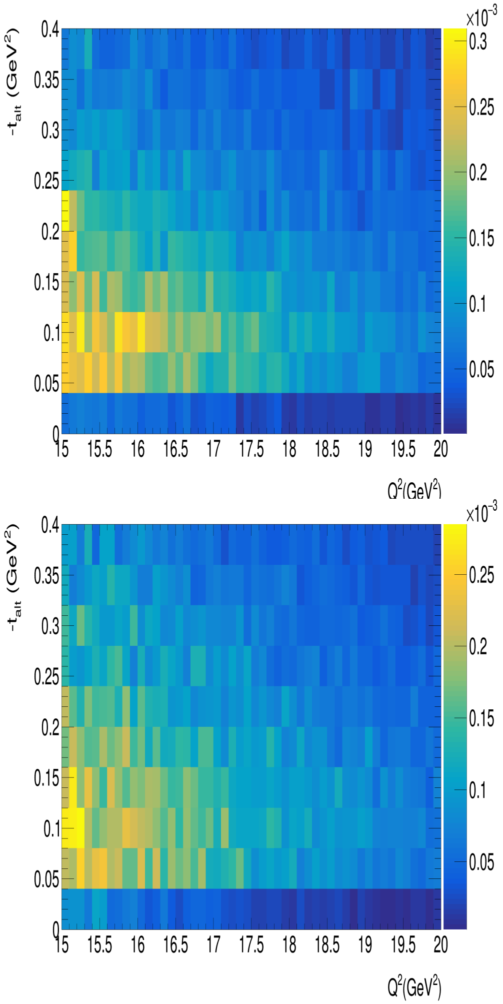
IR6

IR8

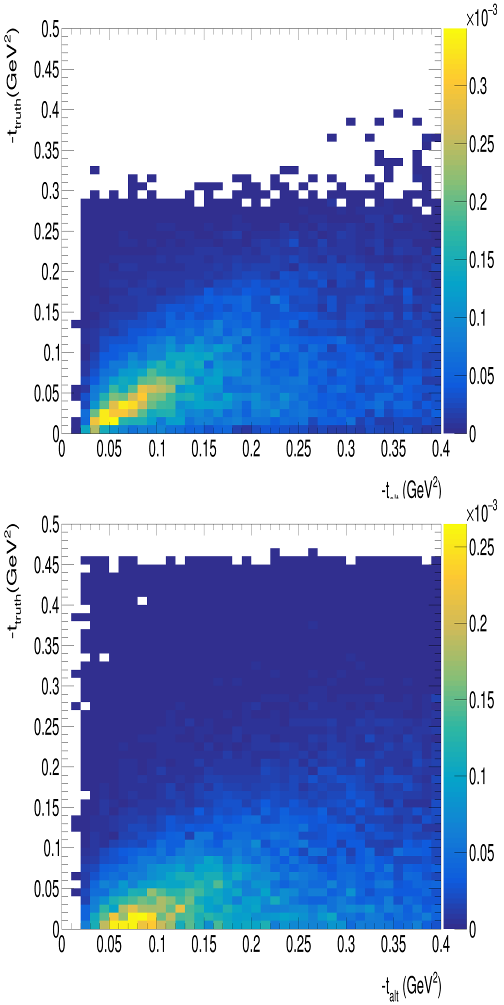


Rate (Hz) per t–bin

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

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

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

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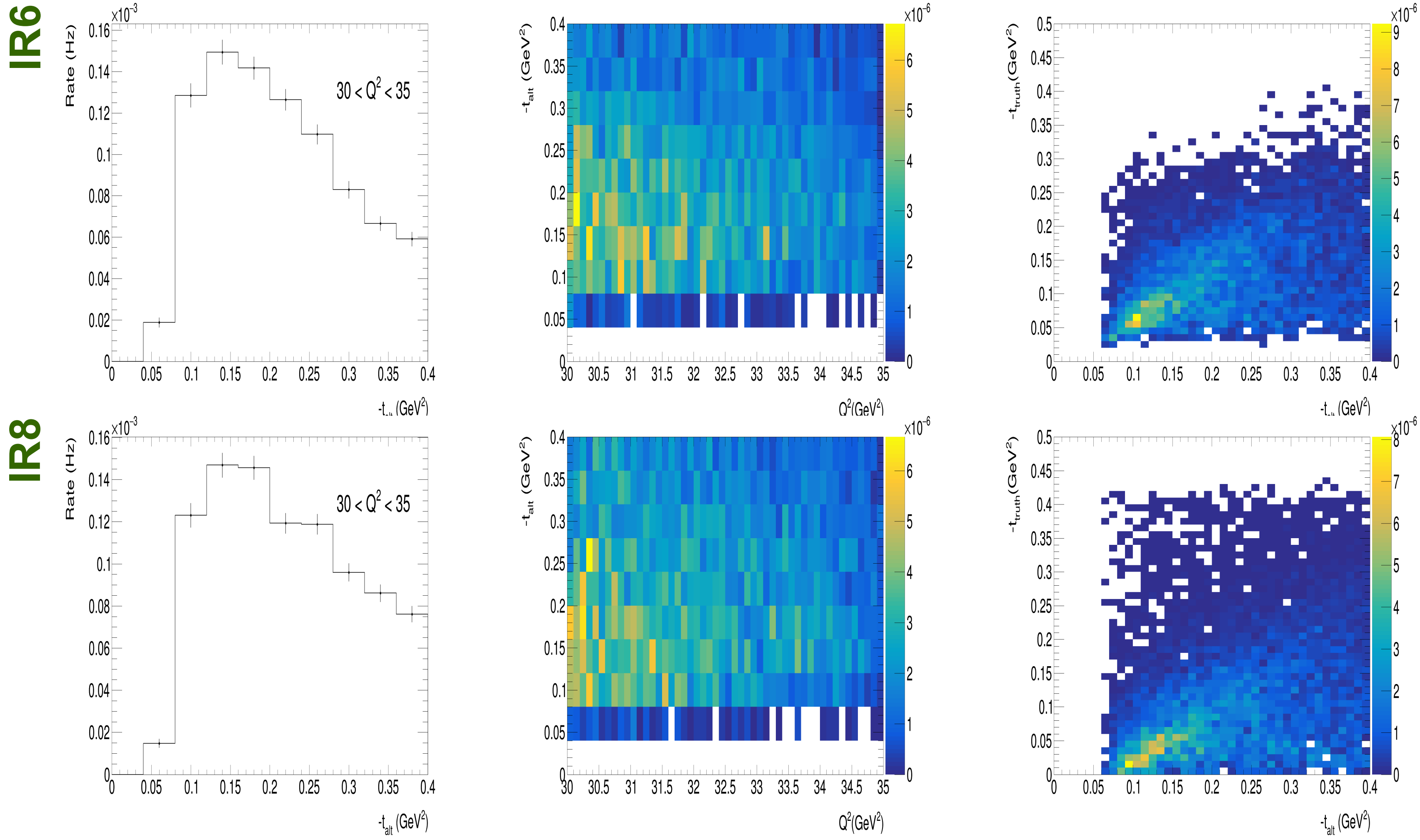

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Rate (Hz) per t–bin
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Rate (Hz) per (Q^2,t)–bin

t_{true} vs t_{alt}
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Can we measure F_K at the EIC?

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- Kaon pole further from kinematically allowed region
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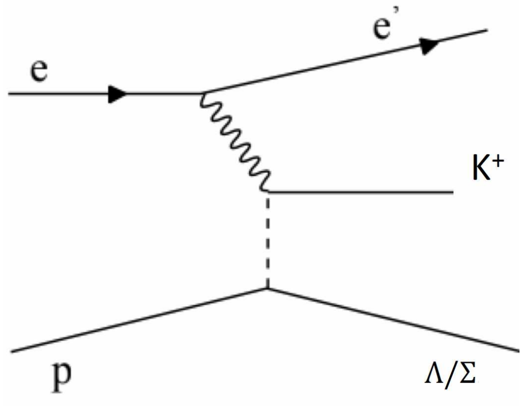

- Propose to use *p(e,e'K⁺Λ/Σ)* reactions for pole dominance test

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

- **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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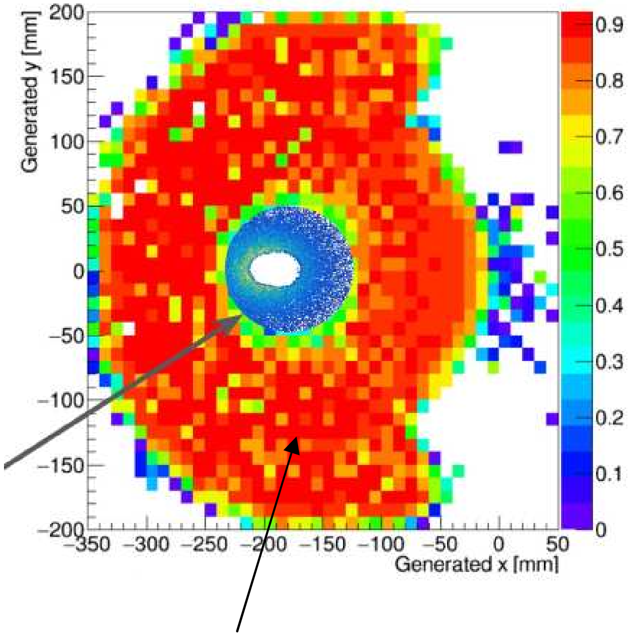
Implications for Det–2 Far Forward

- **Far forward large acceptance will be even more important for *K*$^+$ form factor than for π^+ form factor**
- Identification of forward hyperon will be essential for clean separation of exclusive *K*$^+$ channel from larger π^+ 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, as suggested in ECCE proposal
  - 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!

p(*e*,*e'K*$^+$)Λ Generator Updates

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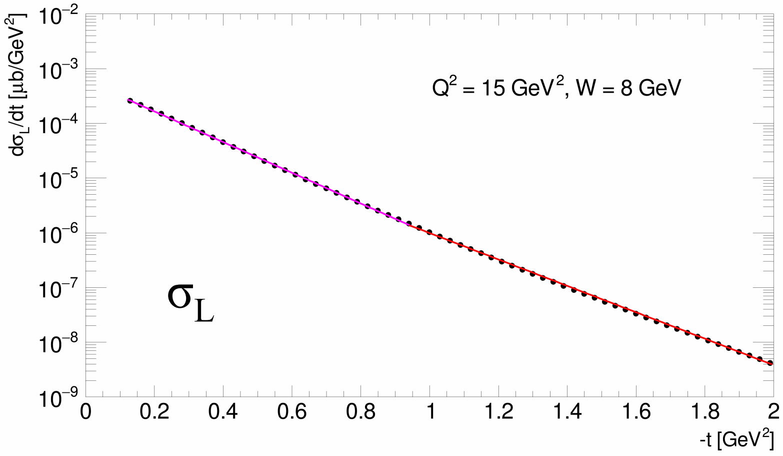
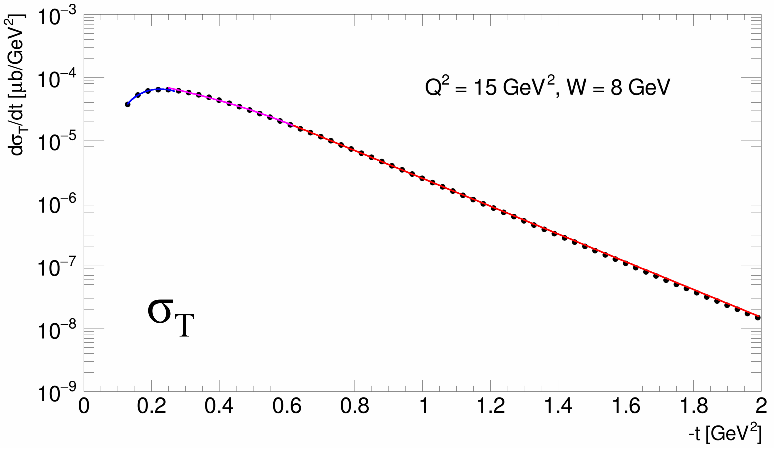
- UofR student Love Preet is working on adding K^+ physics module to our DEMP event generator
  - Parameterize Regge–based model in similar way to π^+
  - $K^+\Lambda$ (soon also $K^+\Sigma$) modules are based on Vanderhaeghen Guidal Laget model [PRC 61 (2000) 025204]
  - σ_L,σ_T parameterizations for: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

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 $p(e,e'\pi^+n)$ 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 σ_L from $d\sigma_{UNS}/dt$ → Used also for $Q^2=10$ GeV^2 Cornell expt (1978)
  - Best to use exclusive π^-/π^+ ratio in e+d collisions to validate model
  - **Studies look very encouraging for data to $Q^2\approx30$ GeV^2, IR6 IR8 very similar**
- 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

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

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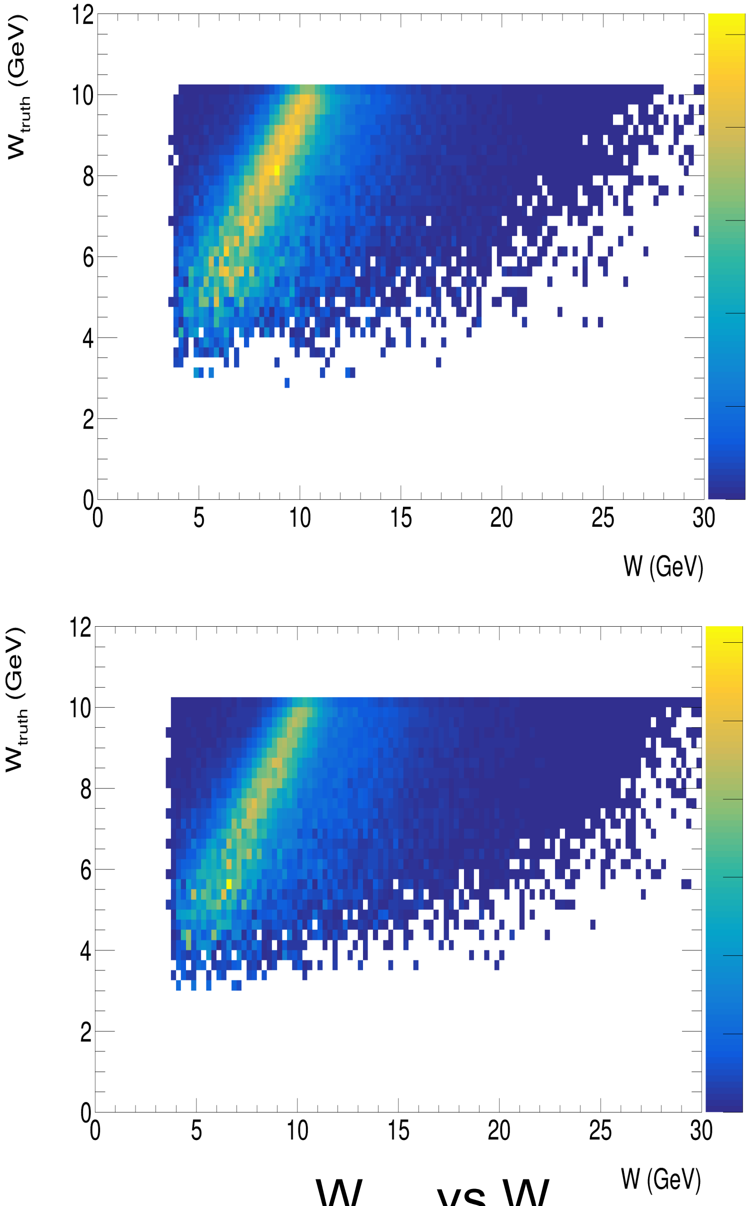
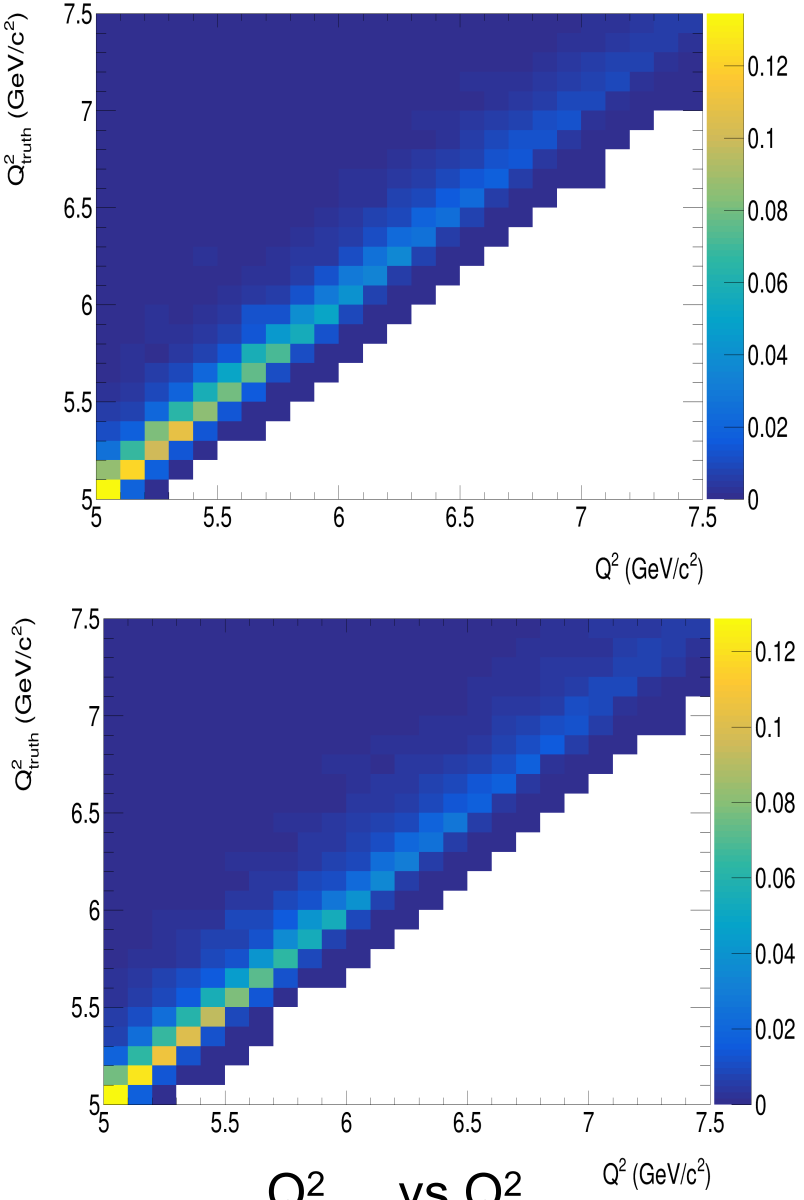
IR6

IR8



W_{true} vs W
- tighter correlation for IR6



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

Plots by Stephen Kay

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

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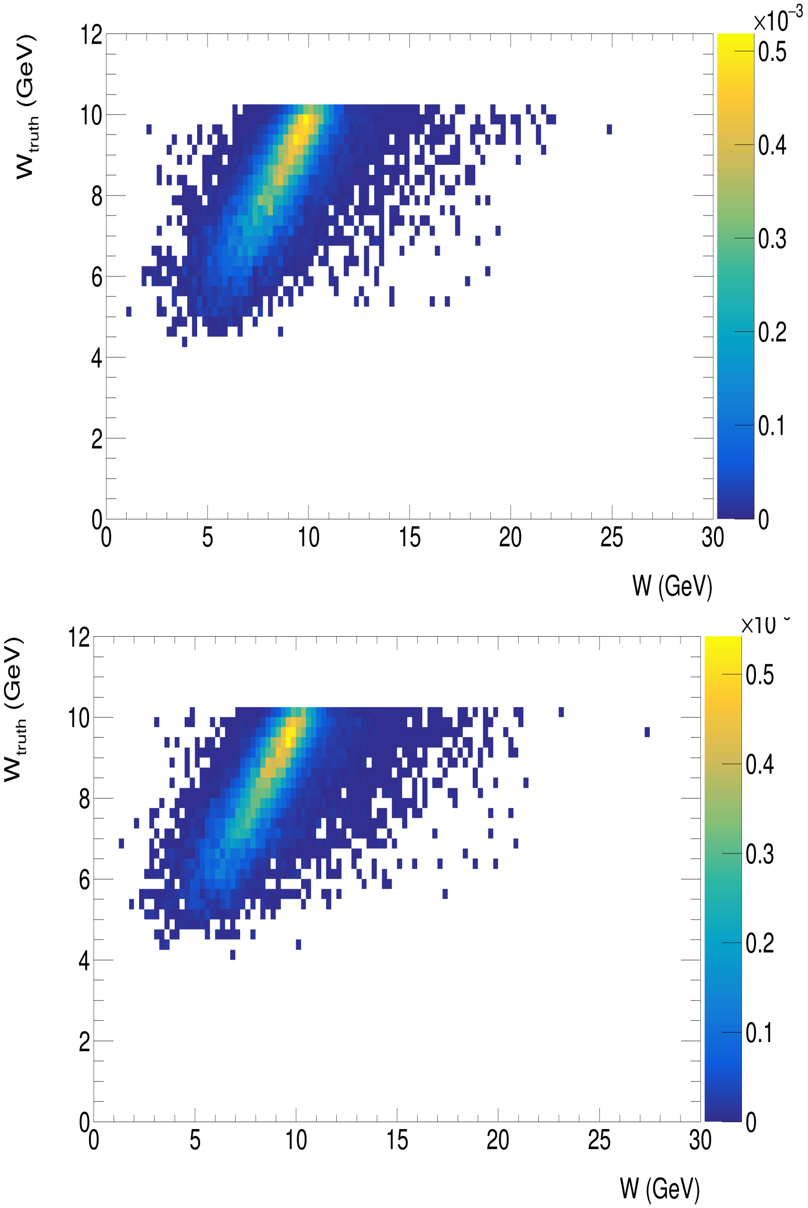
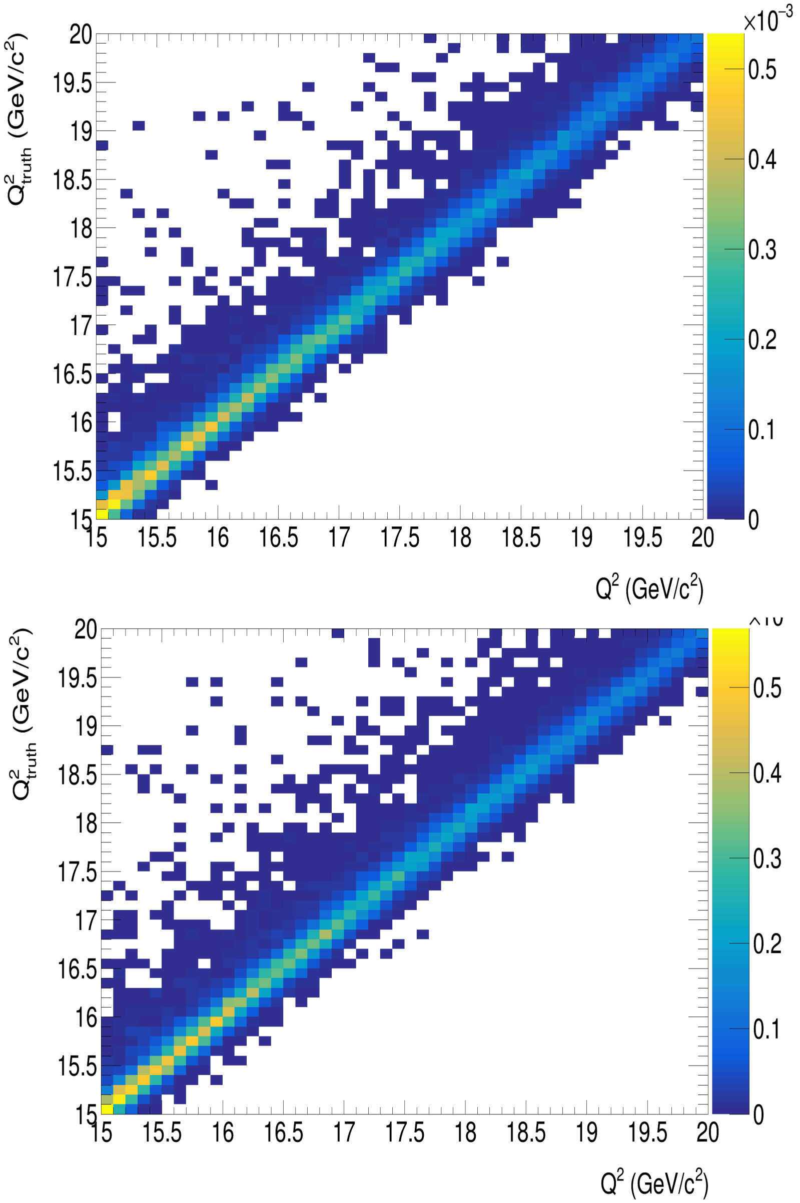
IR6

IR8



W_{true} vs W

- resolutions very similar



Q^2_{true} vs Q^2

- resolutions very similar

Plots by Stephen Kay

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

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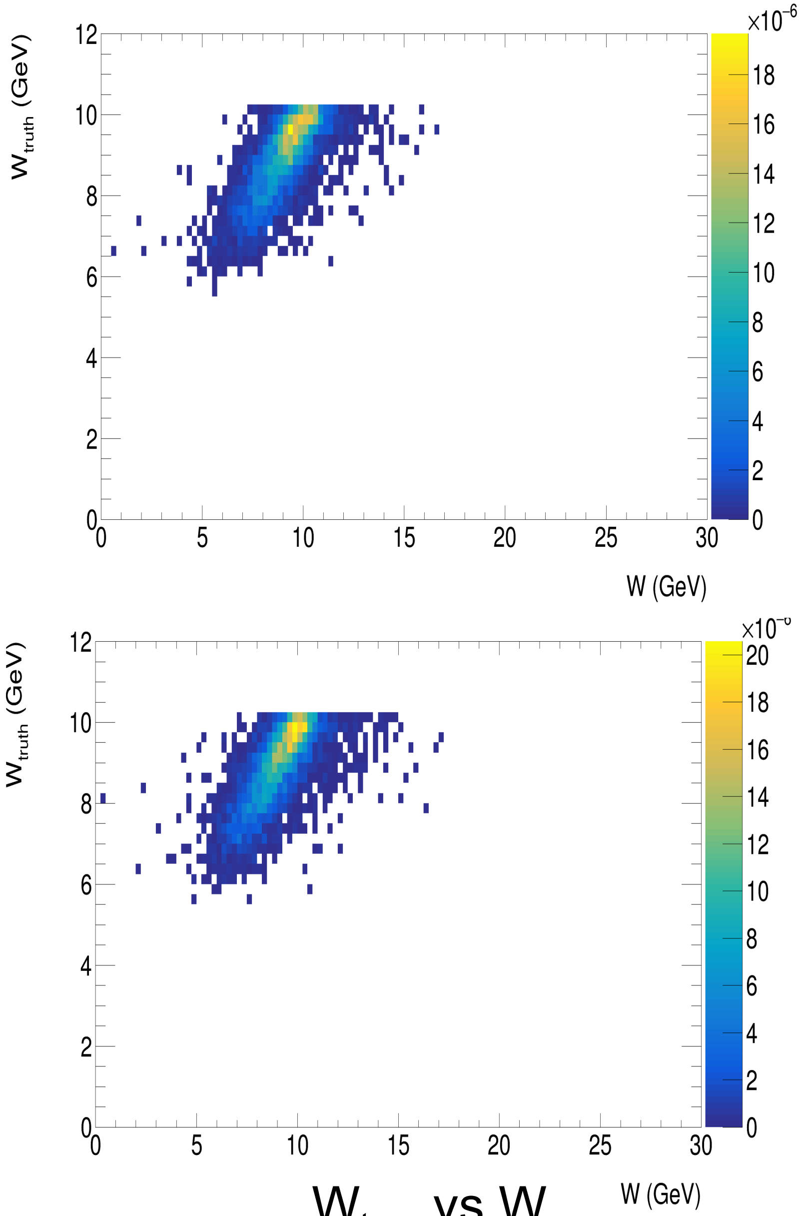
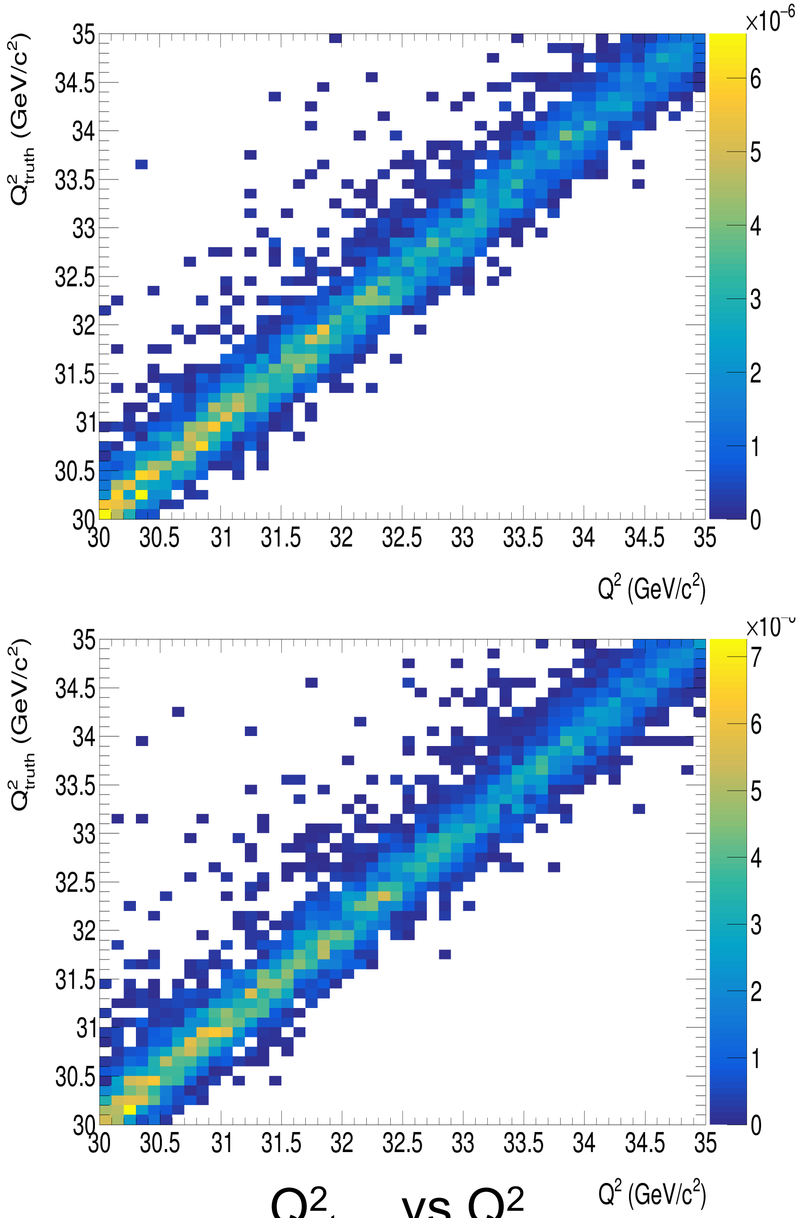
IR6

IR8



W_{true} vs W

- tighter correlation for IR8



Q^2_{true} vs Q^2

- resolutions very similar

Plots by Stephen Kay

Charged Pion Form Factor

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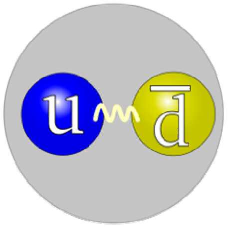
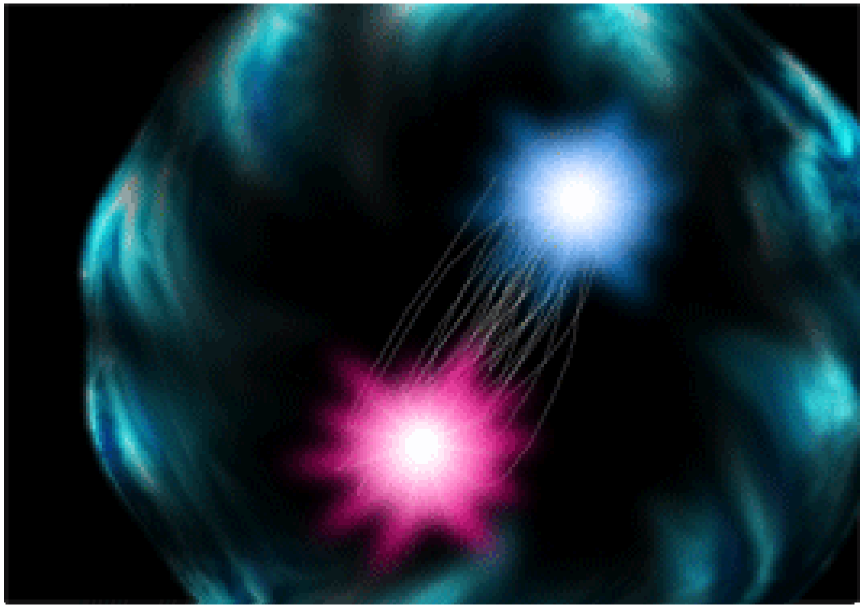
- **The pion is attractive as a QCD laboratory:**
- Simple, 2 quark system



- Electromagnetic form factor can be calculated exactly at very large momentum transfer (small distances).
- For moderate Q^2, it remains a theoretical challenge.
  - “the positronium atom of QCD”



Pion’s structure is determined by two valence quarks, and the quark-gluon sea.

Downside for experimentalists:

- No “free” pion targets.
- Measurements at large momentum transfer difficult.

Measurement of π^+ Form Factor – Low Q^2

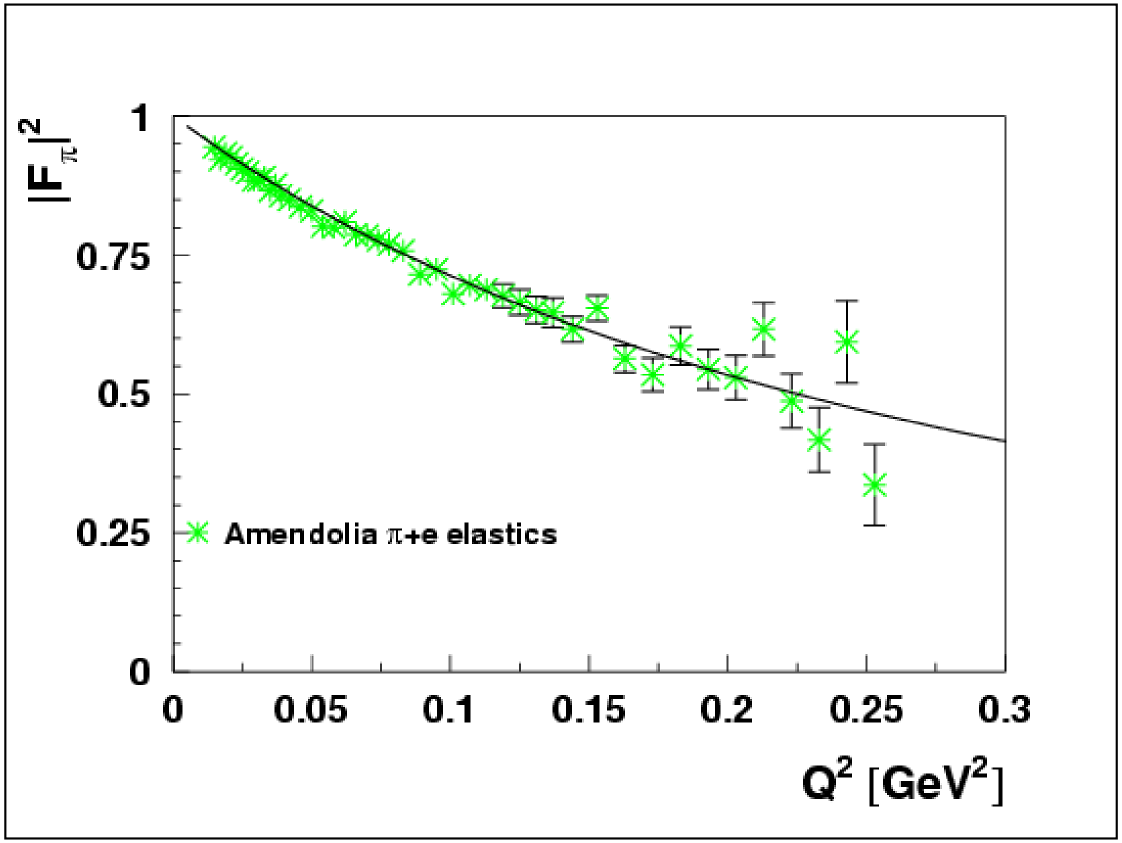
At low Q^2, F_π can be measured model–independently via high energy elastic π^- scattering from atomic electrons in Hydrogen

- 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



Measurement of K^+ Form Factor

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

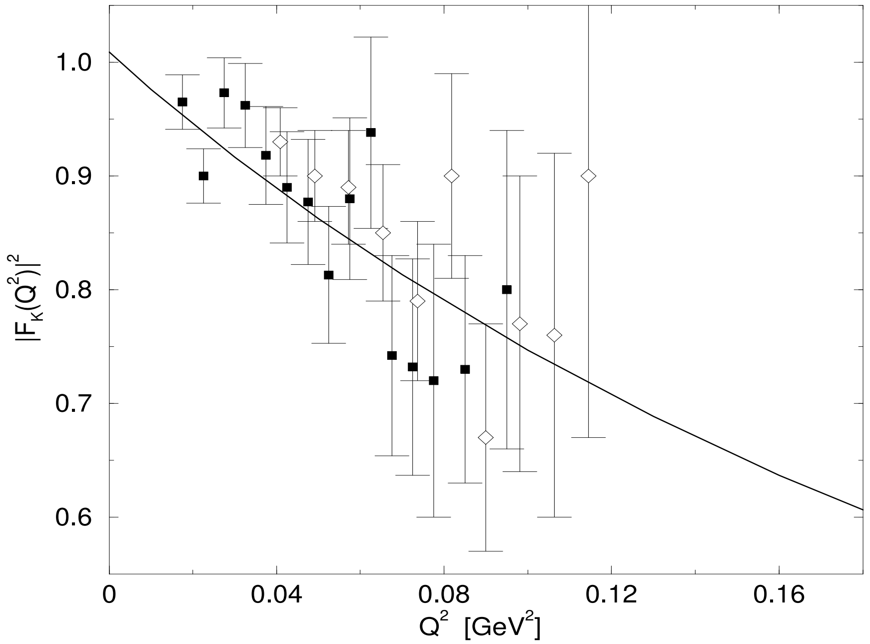
  [Amendolia, et al., PL **B178** (1986) 435]

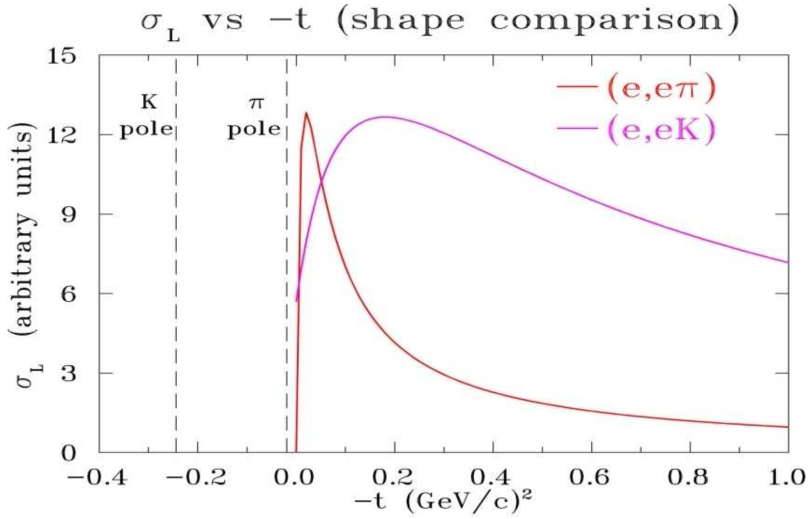
- Can "kaon cloud" of the proton be used in the same way as the pion to extract kaon form factor via ***p(e,e'K⁺)***Λ ?

- Kaon pole further from kinematically allowed region

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

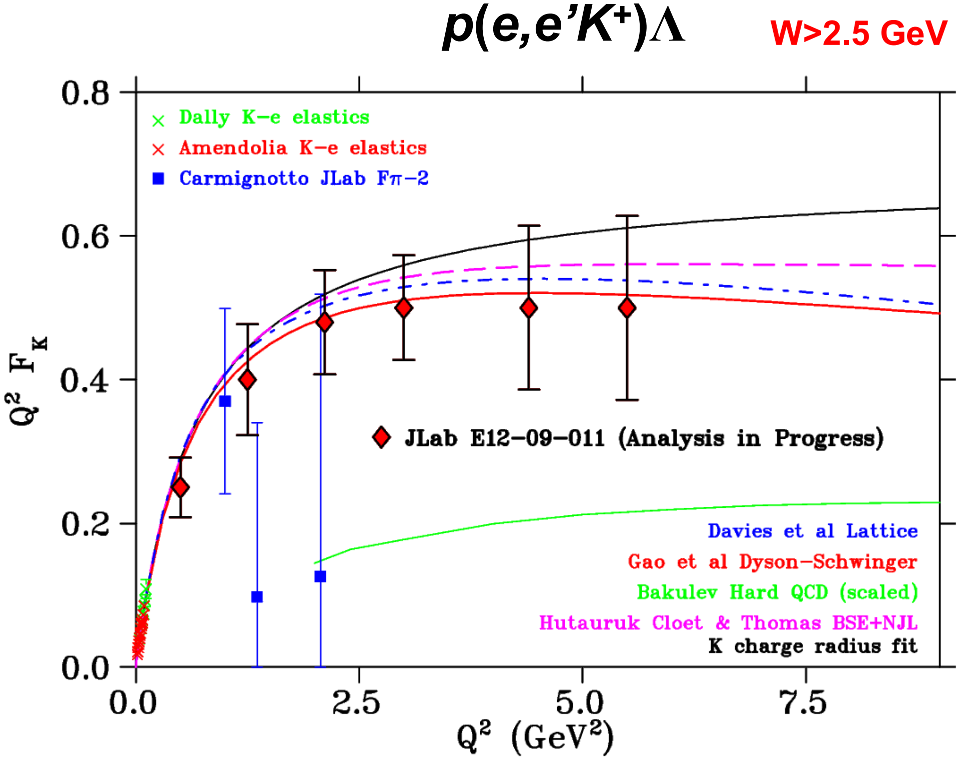
- Many of these issues are being explored in JLab E12–09–011





Current and Projected F_K Data

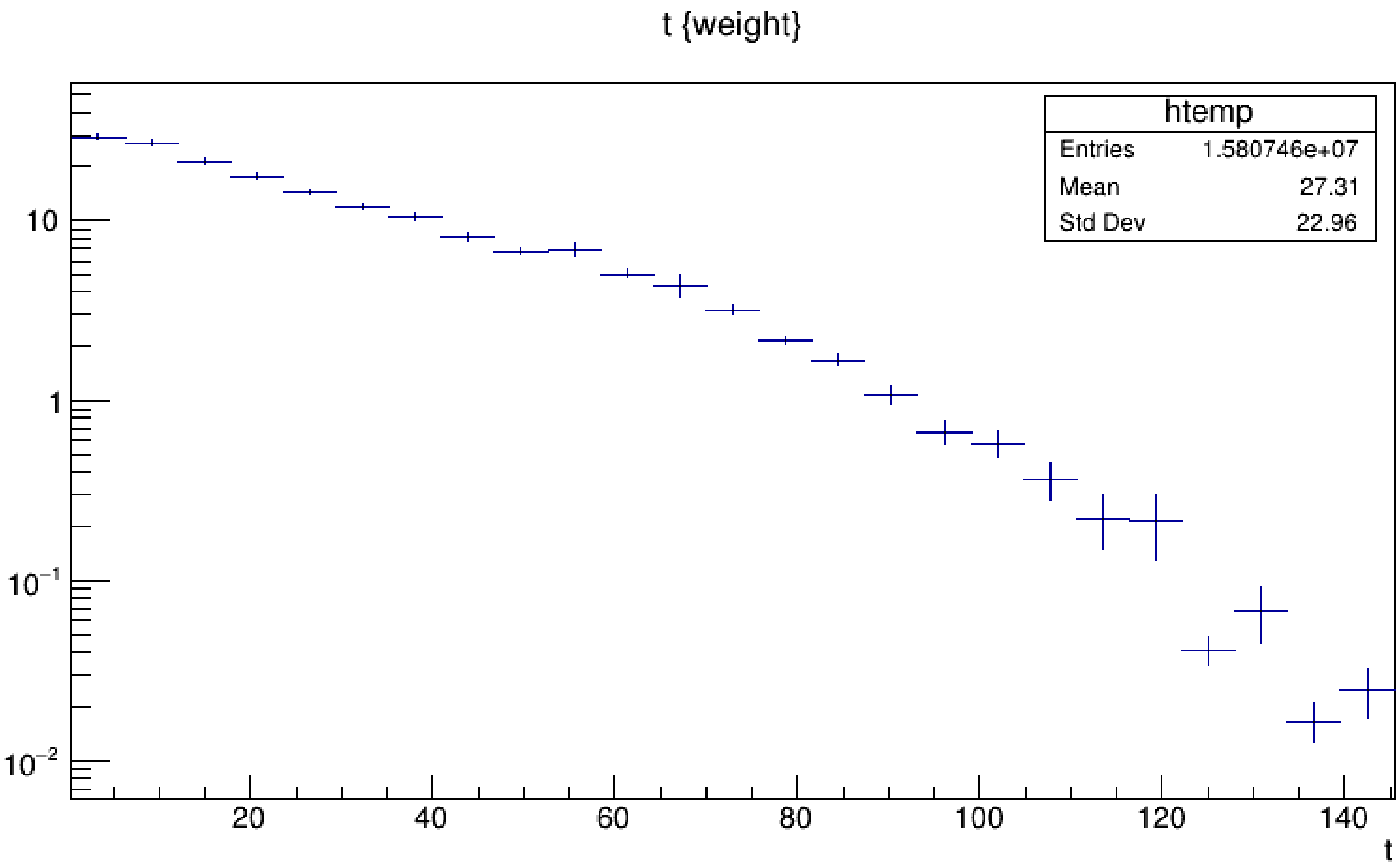
- JLab E12–09–11 will be first measurement of F_K well above the resonance region.
- Measure form factor to Q^2=3 GeV^2 with good overlap with elastic scattering data.
  - Limited by –t<0.2 GeV^2 requirement to minimize non–pole contributions.
- Data will provide an important second $q\overline{q}$ system for theoretical models, this time involving a strange quark.



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

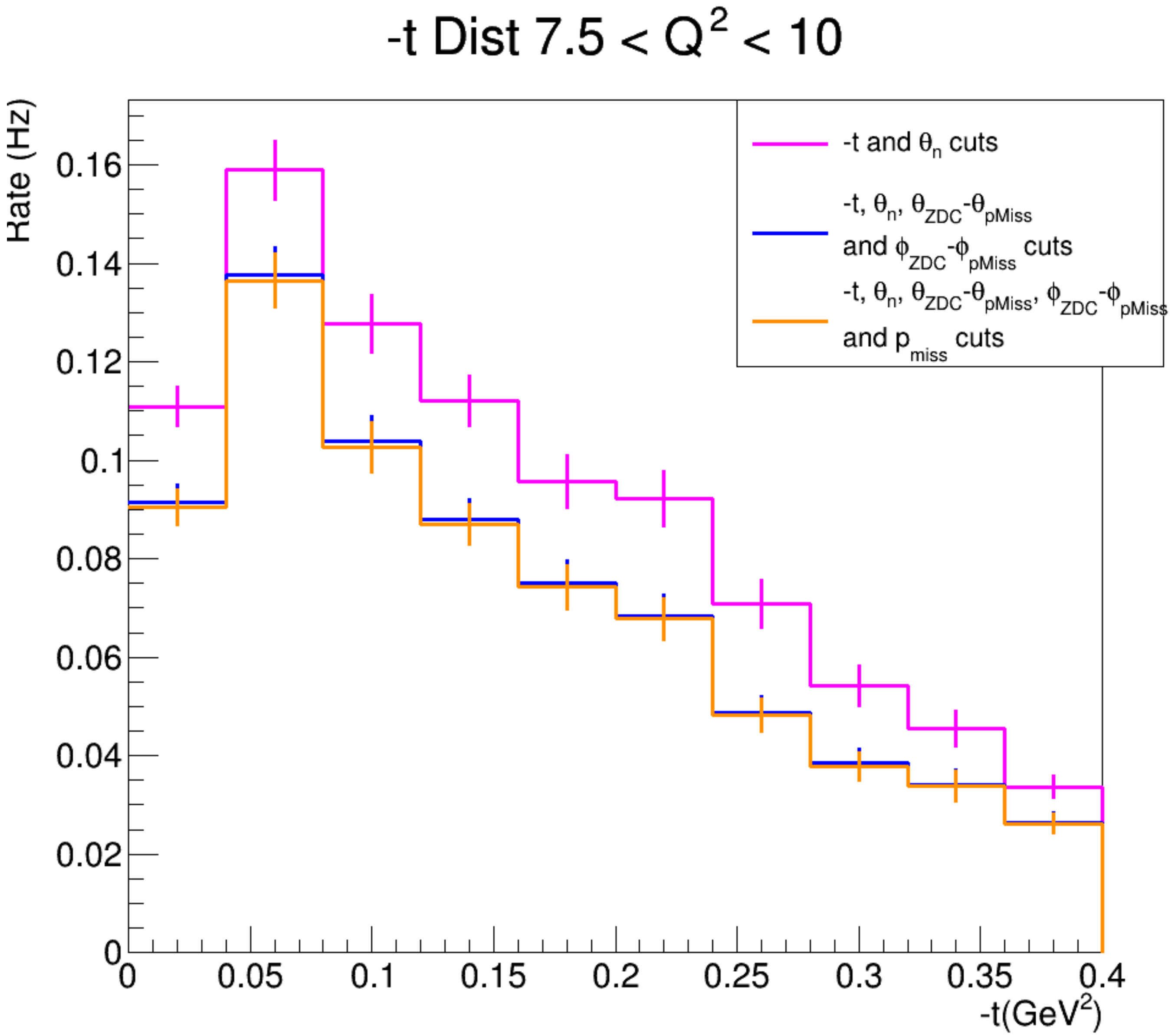
Partially completed as an early SHMS commissioning experiment: LT–separation. (E12–09–011: T. Horn, G. Huber and P. Markowitz, spokespersons)

SIDIS *t*–distribution



DEMP Rates as Cuts Applied – *Q^2*=8.75 GeV^2

Rate (Hz) per –*t* bin



Only –*t*<0.4 GeV^2 and triple coincidence cuts

Add ΔθΔφ ZDC cuts

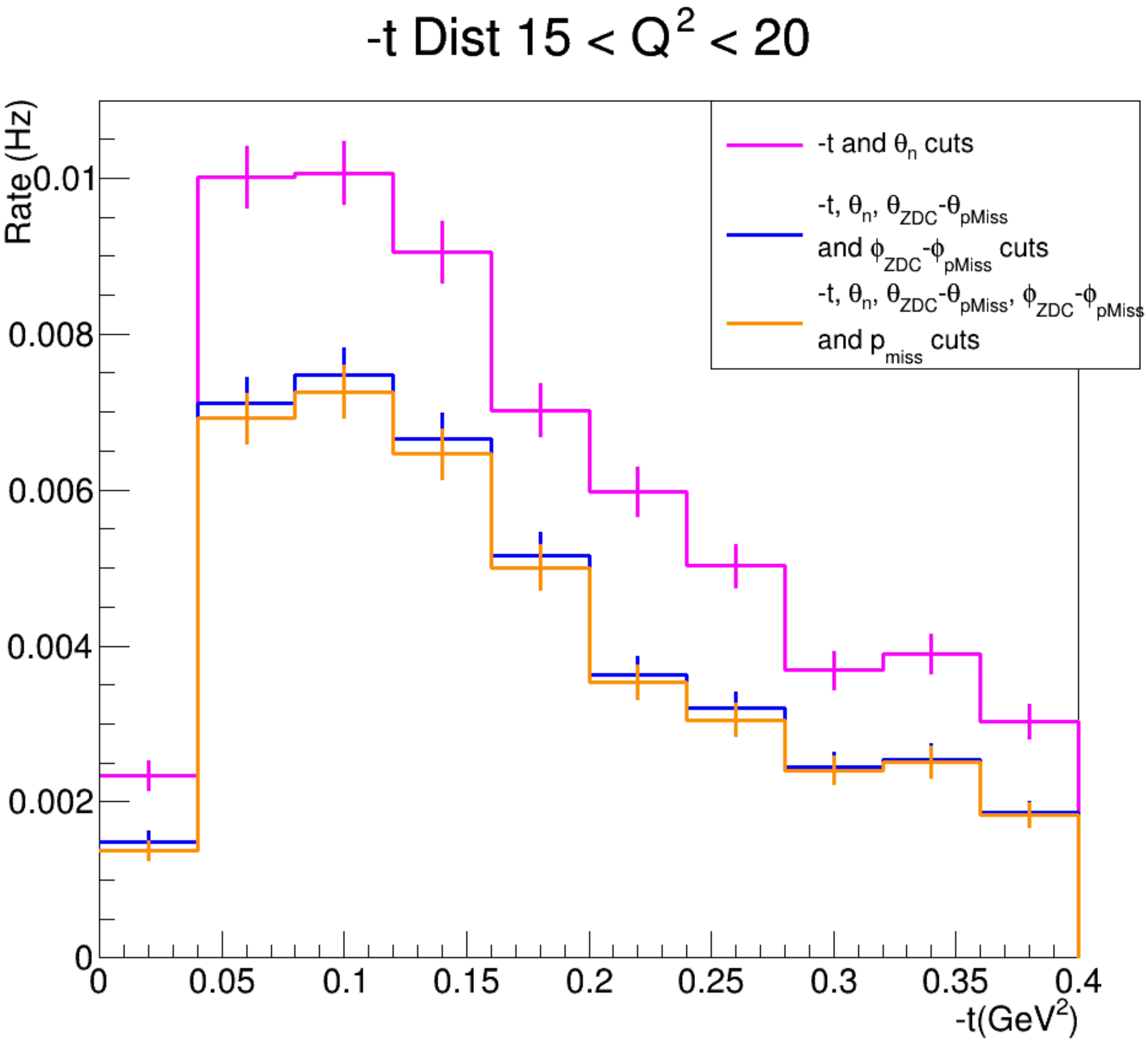
Add p_{miss}<93 GeV cut
(removes only SIDIS background)

Plot by Stephen Kay

Garth Huber, huberg@uregina.ca

DEMP Rates as Cuts Applied – Q^2=17.5 GeV^2

Rate (Hz) per –*t* bin



Only –*t*<0.4 GeV^2 and triple coincidence cuts

Add ΔθΔφ ZDC cuts

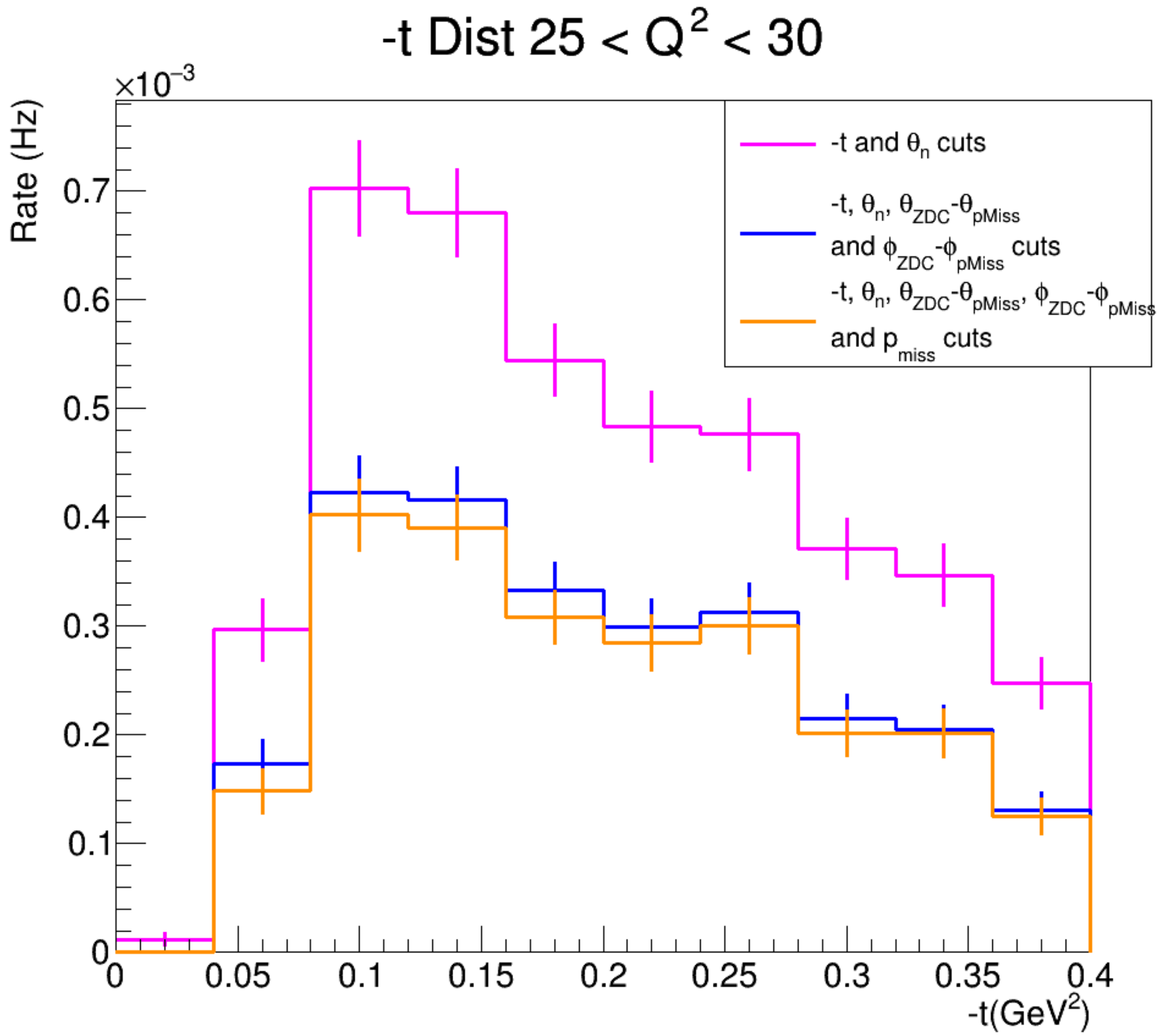
Add p_{miss}<87 GeV cut
(removes only SIDIS background)

Plot by Stephen Kay

Garth Huber, huberg@uregina.ca

DEMP Rates as Cuts Applied – Q^2=27.5 GeV^2

Rate (Hz) per –*t* bin



Only –*t*<0.4 GeV^2 and triple coincidence cuts

Add ΔθΔφ ZDC cuts

Add p_{miss}<80 GeV cut
(removes only SIDIS background)

Plot by Stephen Kay

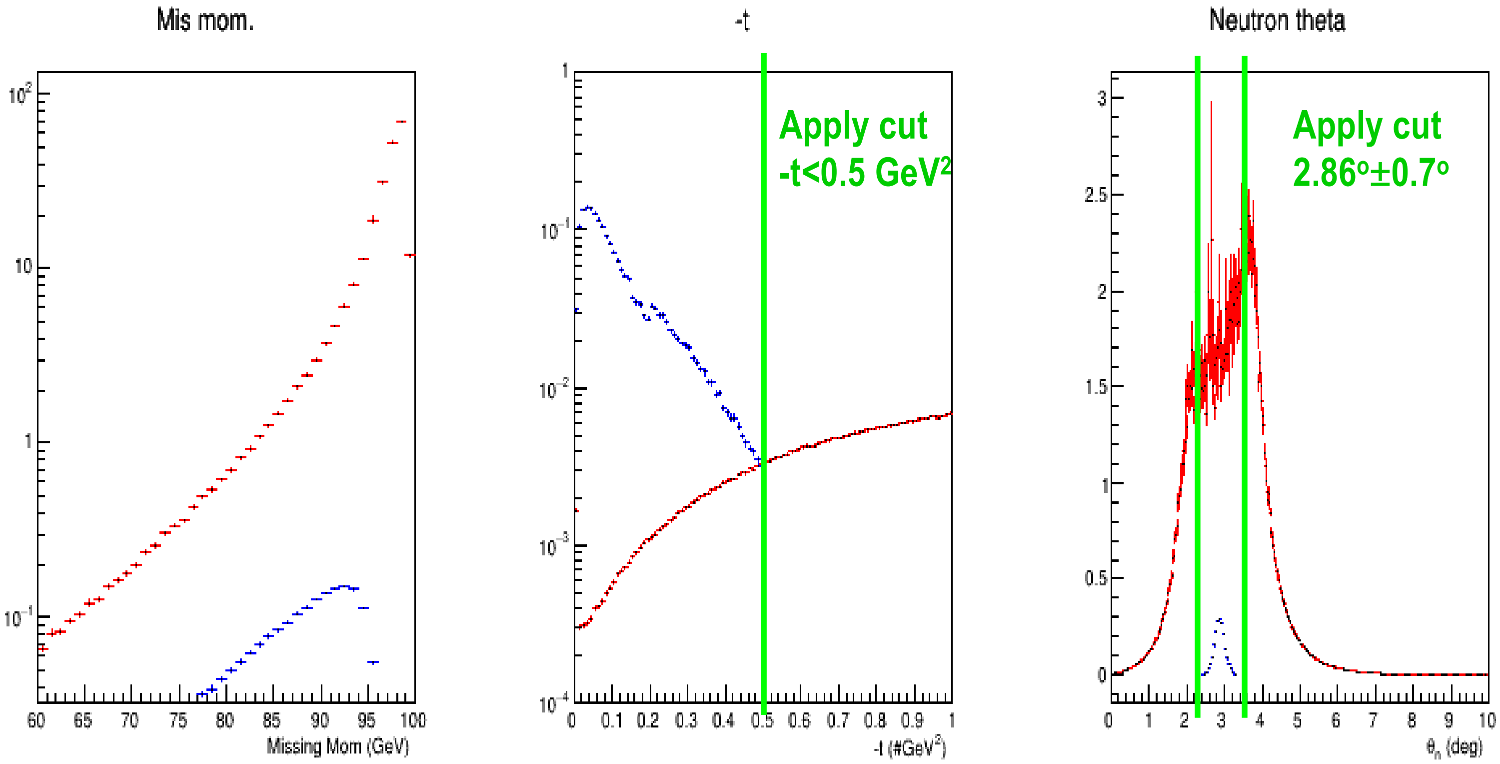
Garth Huber, huberg@uregina.ca

Comparison of DEMP and SIDIS kinematics

DEMP events are e' π^+ n triple coincidence.
SIDIS events are e' π^+ double coincidence, and p_{miss} reconstructed.

Exclusive
p(e,e'π⁺)n
Foreground

SIDIS
p(e,e'π⁺)X
Background



- As expected, the SIDIS events overwhelm the foreground exclusive events. But they are distributed over a much wider momentum range, and are primarily at larger –*t* than the DEMP events.

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DEMP Kinematic Coverage for 5x100

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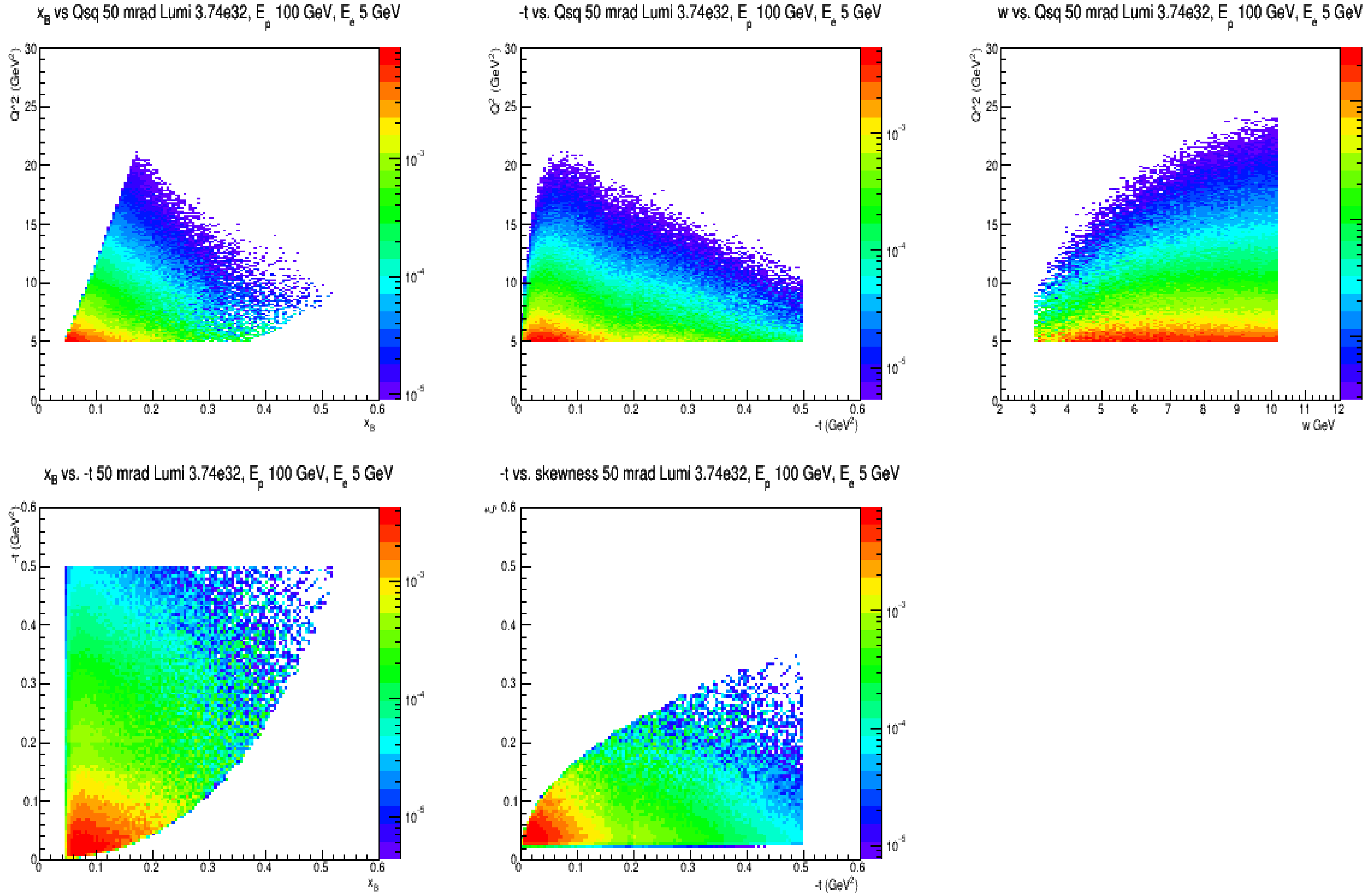


x_B vs Qsq 50 mrad Lumi 3.74e32, E_p 100 GeV, E_e 5 GeV

-t vs. Qsq 50 mrad Lumi 3.74e32, E_p 100 GeV, E_e 5 GeV

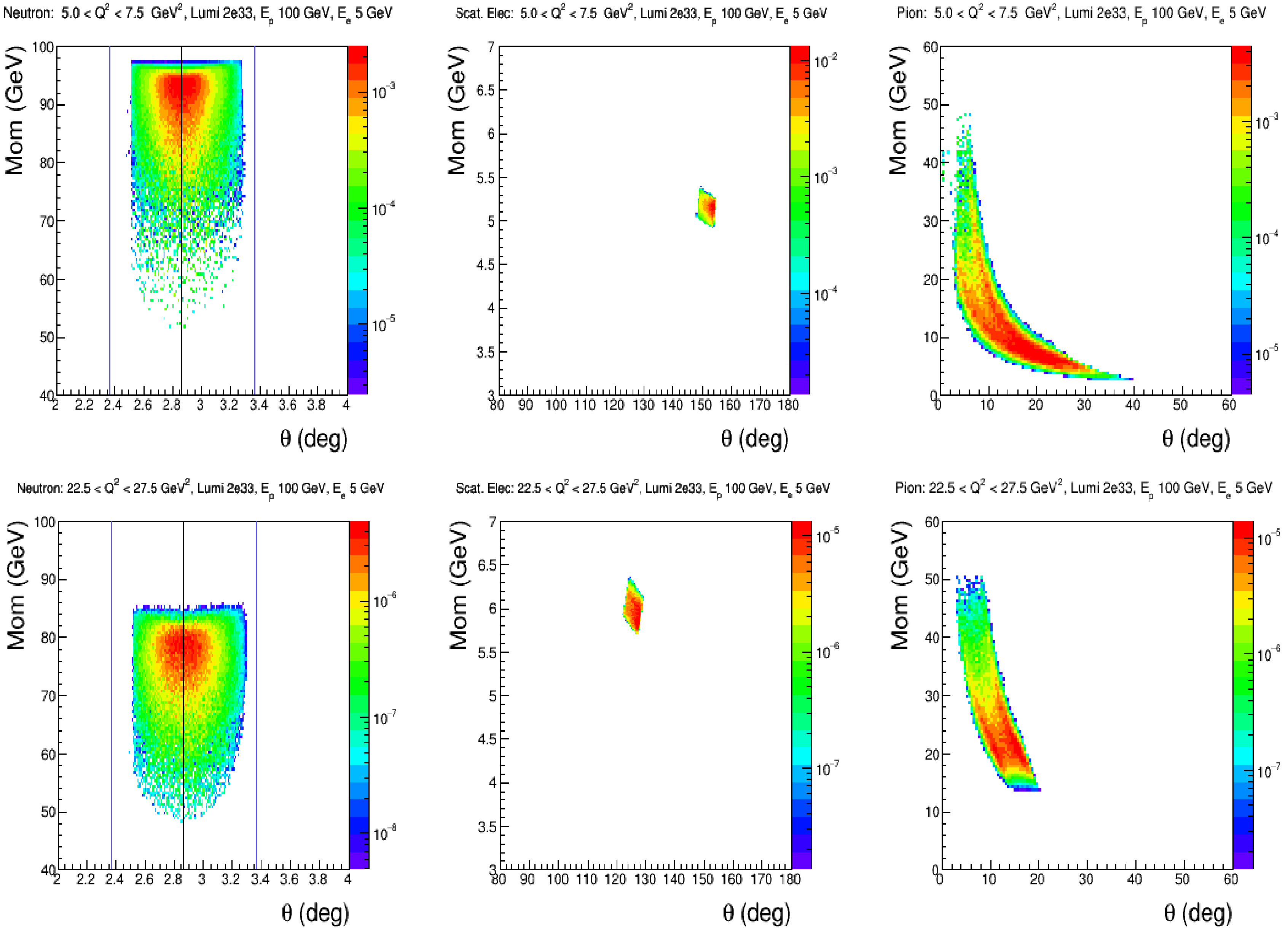
w vs. Qsq 50 mrad Lumi 3.74e32, E_p 100 GeV, E_e 5 GeV

x_B vs. -t 50 mrad Lumi 3.74e32, E_p 100 GeV, E_e 5 GeV

-t vs. skewness 50 mrad Lumi 3.74e32, E_p 100 GeV, E_e 5 GeV

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

Acceptance for Q^2=6 and 25 GeV^2



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

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Identifying exclusive $p(e,e'\pi^+n)$ $d\sigma_L/dt$

- **Even though SIDIS model is likely inaccurate in this high *z* regime, it appears a combination of triple e–π–n coincidence and event selection cuts have some chance to cleanly isolate the exclusive π^+ reaction.**
  - Needs further study, given the difficult experience HERMES had in isolating exclusive events.
- **Next step is to separate $d\sigma_L/dt$ from $d\sigma_T/dt$, needed for extraction of pion form factor from data.**

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

  - **$\varepsilon<0.8$, i.e. $y>0.5$, 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.
- **Conventional L–T separation is impractical, need some other way to identify $d\sigma_L/dt$.**

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σ_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

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

A_z = double-spin asymmetry

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

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 θ_{CM}.

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

- **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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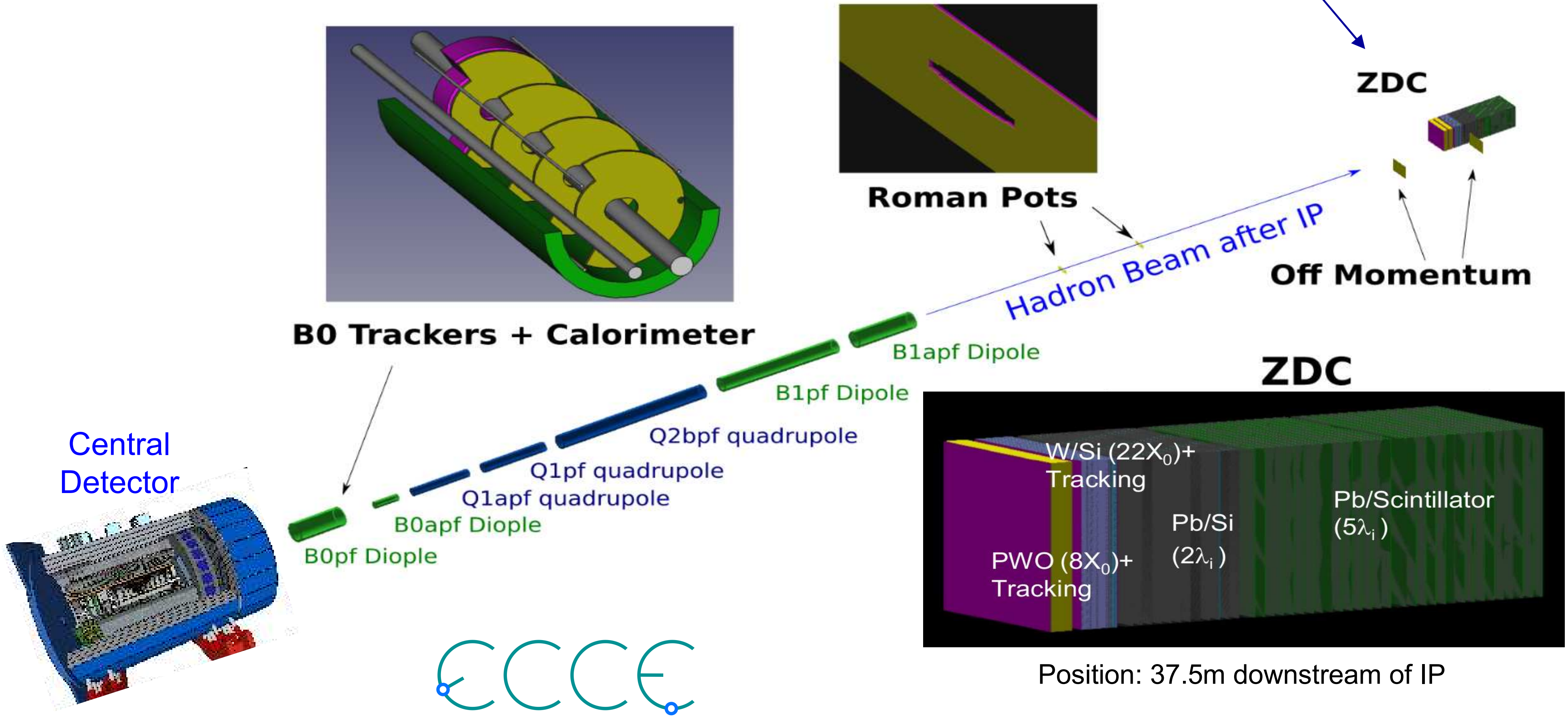
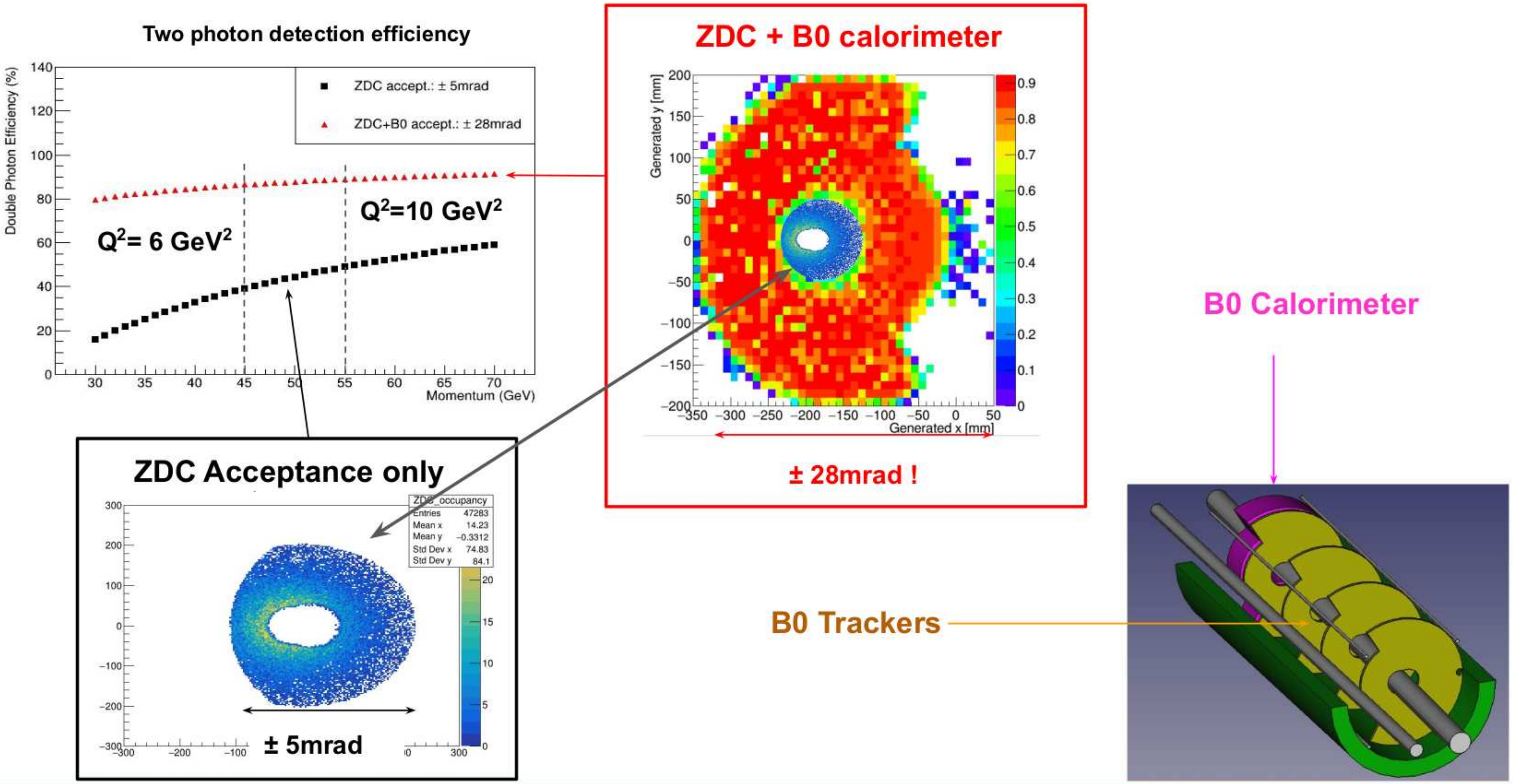
EIC Far Forward Detectors

- 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


Two photon detection efficiency
Double Photon Efficiency (%)
140
120
100
80
60
40
20
0
30
35
40
45
50
55
60
65
70
Momentum (GeV)
ZDC accept.: ± 5mrad
ZDC+B0 accept.: ± 28mrad
Q²= 6 GeV²
Q²=10 GeV²
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
ZDC + B0 calorimeter
Generated y [mm]
Generated x [mm]
± 28mrad !
B0 Calorimeter
B0 Trackers