Light Meson Structure in Jefferson Lab Hall C - Recent Measurements and Prospects

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University of York

Exotic Hadron Spectroscopy Workshop
04/07/24

Outline

Cover Image - Brookhaven National Lab, https://www.flickr.com/photos/brookhavenlab/

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- Light Meson Structure - Future Prospects

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  - Observed properties of nucleons and nuclei (mass, spin) emerge from this complex interplay
  - Properties of hadrons are emergent phenomena

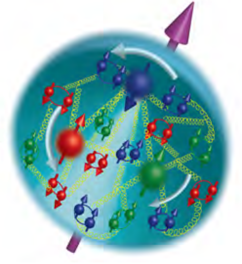

Image - A. Deshpande, Stony Brook University

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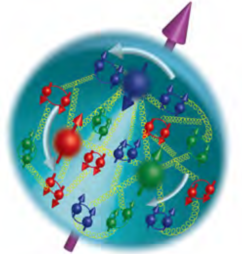

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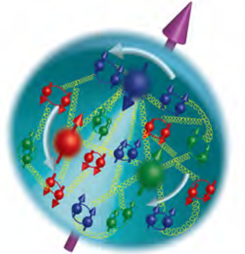

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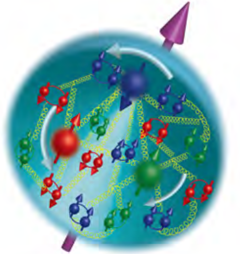

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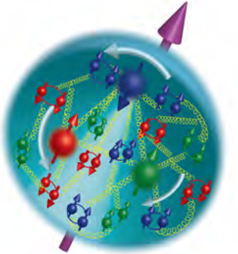

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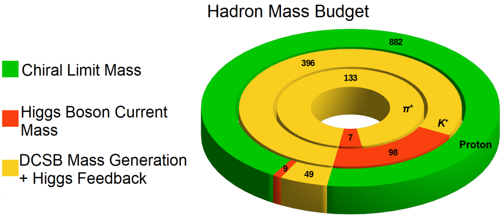
- **A major puzzle of the standard model to try and resolve!**

Hadron Mass Budgets



Revealing the structure of light pseudoscalar mesons at the electron–ion collider

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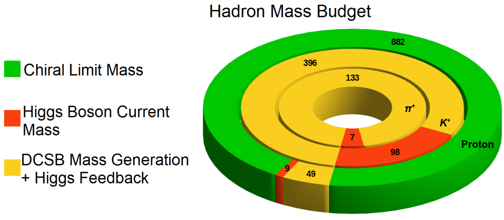

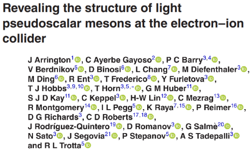

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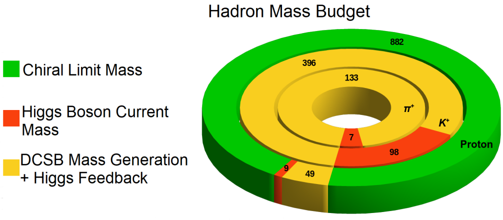

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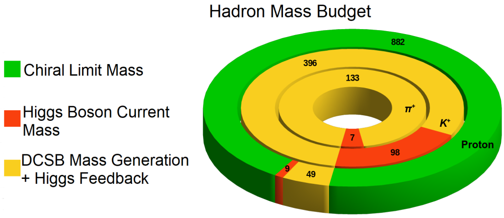

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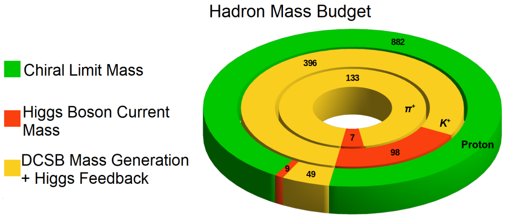

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- **The simple $q\bar{q}$ valence structure of mesons makes them an excellent testing ground**
- What can we examine to look at their structure?

Meson Form Factors

- Charged pion ($\pi^{\pm}$) and kaon ($K^{\pm}$) form factors (F_{π}, F_{K}) are key QCD observables
  - Describe momentum space distributions of partons within hadrons

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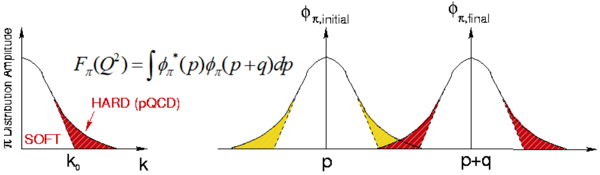

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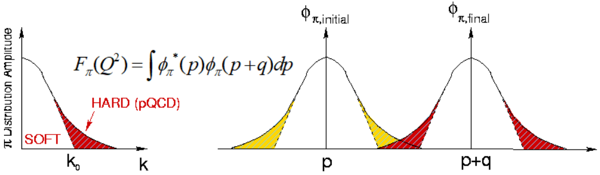

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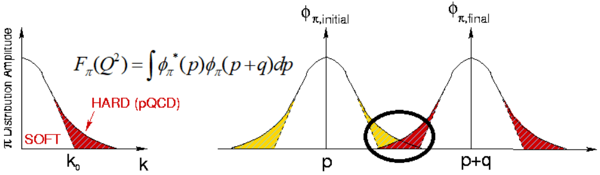

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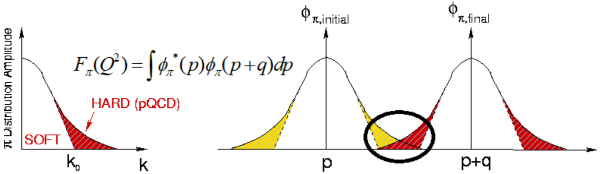

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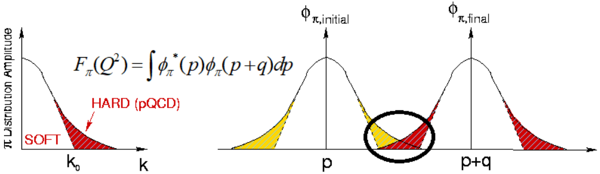

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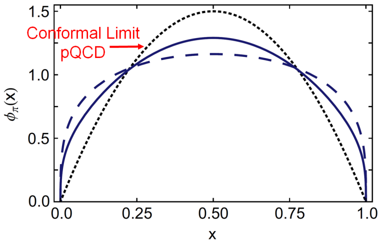
- **F_{π} and F_K of special interest in hadron structure studies**
  - π - Lightest QCD quark system, simple
  - K - Another simple system, contains strange quark

Connecting Pion Structure and Mass Generation

- Calculating the pion PDA, ϕ_π, without incorporating DCSB produces a broad, concave shape



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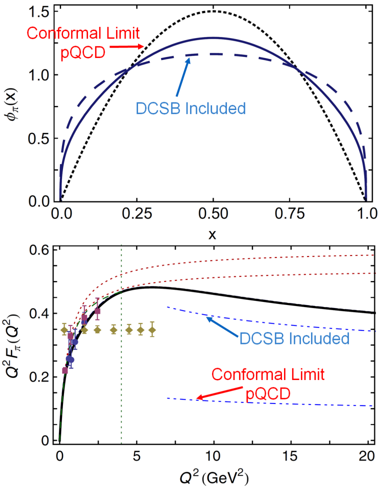

L. Chang, et al., PRL110(2013) 132001, PRL111(2013), 141802

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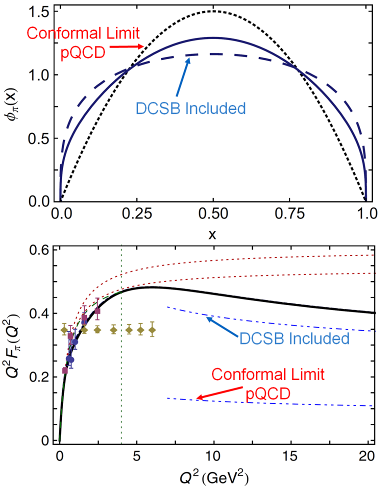
- Pion structure and hadron mass generation are interlinked



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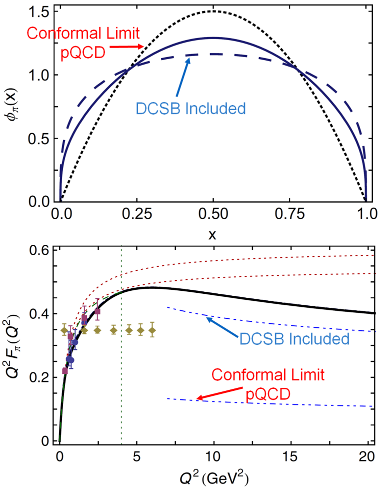
- Similar effect seen with kaon, PDA asymmetric due to heavier s quark



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Form Factors and N^* Resonances, Interconnections

- Can gain insight on dressed quark mass function from structure measurements

Form Factors and N* Resonances, Interconnections

- Feed into N* electroexcitation measurements/predictions

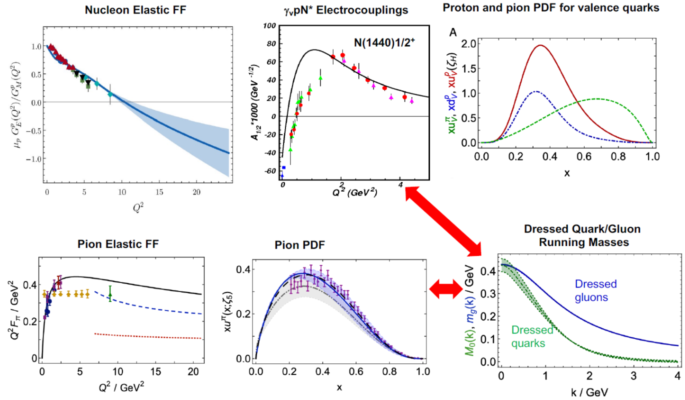
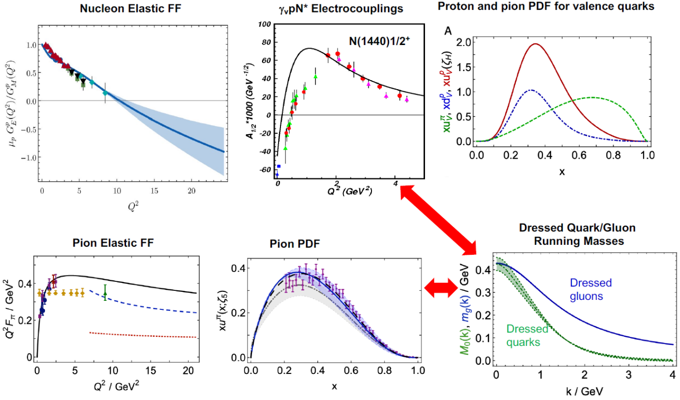


Image - V. I Mokeev, *New Opportunities for Insight into the Emergence of Hadron Mass from Studies of Nucleon Resonance Electroexcitation*, APS DNP Fall 2022, `https://meetings.aps.org/Meeting/DNP22/Session/2WC.1`

Form Factors and N* Resonances, Interconnections

- Describing all with the same dressed quark mass function → Critical validation of insights into emergent mass generation



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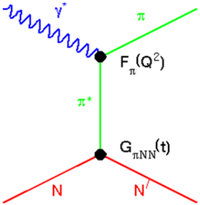

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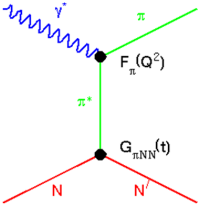

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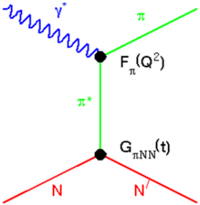

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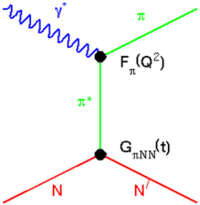

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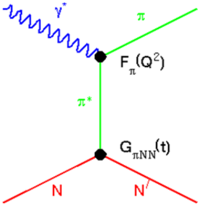

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Isolating σ_L at JLab Hall C

- Physical cross section for the electroproduction process is -

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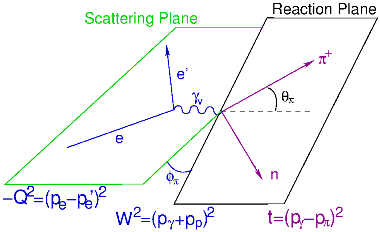

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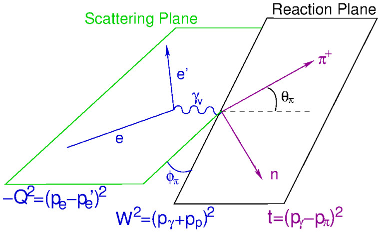
- In JLab Hall C, L-T separation can be used to isolate σ_L from σ_T
- Need data at lowest $-t$ possible, σ_L has maximum pole contribution here



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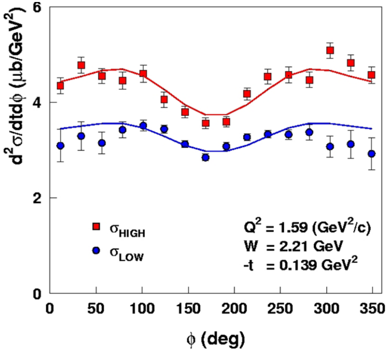

T. Horn, et al., PRL 97(2006) 192001

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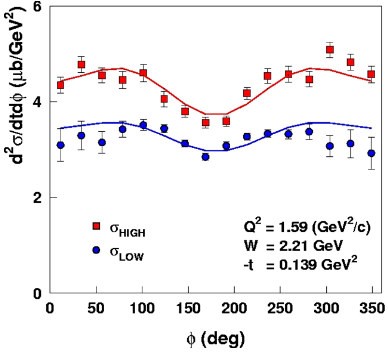
- Careful control of point-to-point systematics crucial, $1/\Delta\epsilon$ error amplification in σ_L
- Spectrometer acceptance, kinematics and efficiencies must all be carefully studied and understood



T. Horn, et al., PRL 97(2006) 192001

Hall C in the 12 GeV era

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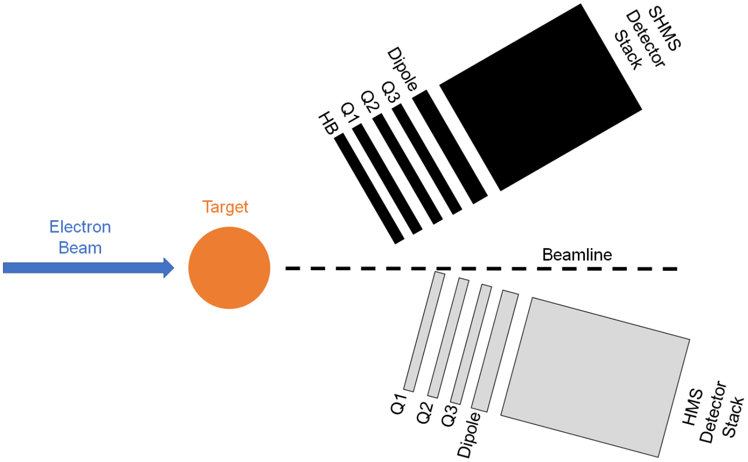

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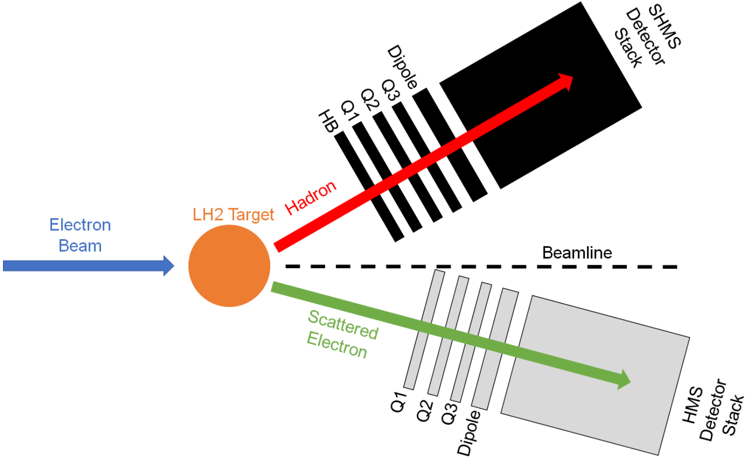

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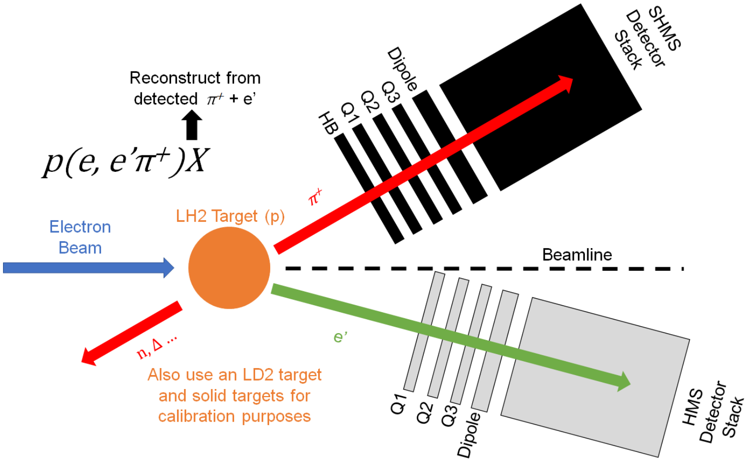

From σ_L to $F_\pi(Q^2)$ with JLab Data

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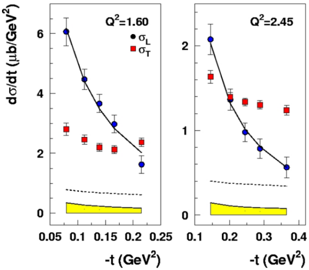

Error bars indicate statistical and random (pt-pt) systematic uncertainties in quadrature. Yellow band indicates the correlated (scale) and partly correlated (t-corr) systematic uncertainties.
$\Lambda_\pi^2 = 0.513, 0.491\ GeV^2$, $\Lambda_\rho^2 = 1.7\ GeV^2$

T. Horn, et al., PRL 97(2006) 192001

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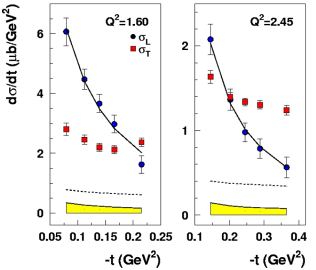

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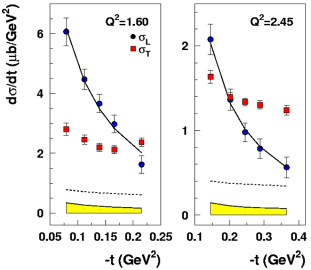

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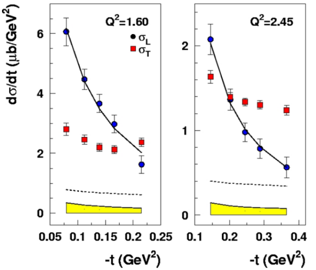
- Free parameters - $\Lambda_\pi, \Lambda_\rho$ - Trajectory cutoff parameters
- At small $-t$, σ_L only sensitive to F_π

$$F_\pi = \frac{1}{1 + Q^2/\Lambda_\pi^2}$$



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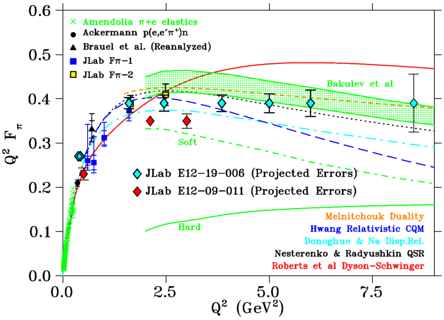

- High precision F_π to $Q^2 = 6\ GeV^2$
- Lower precision F_π point at $Q^2 = 8.5\ GeV^2$

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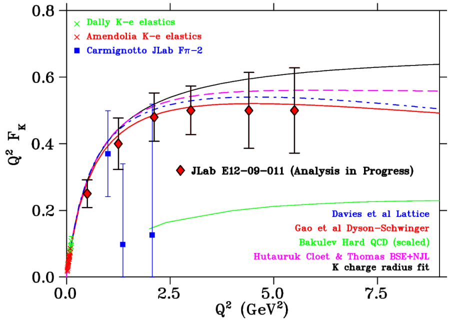

- First measurement of F_K well above resonance region
- Potentially measure up to $Q^2 = 5.5\ GeV^2$

Form Factors from DEMP at the EIC

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A. Bylinkin. et. al., NIMA 1052 (2023) 168238 https://doi.org/10.1016/j.nima.2023.168238

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- Event generator recently modified to generate kaon events
  - Next extension of studies → Can we measure F_K too?

A. Bylinkin. et. al., NIMA 1052 (2023) 168238 https://doi.org/10.1016/j.nima.2023.168238, DEMPgen https://github.com/JeffersonLab/DEMPgen/releases/tag/v1.1.0

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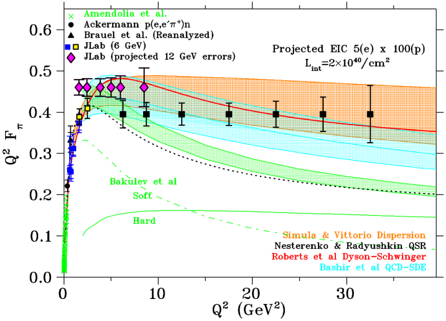
  - $R = 0.013 - 014$ at lowest $-t$ from VR model



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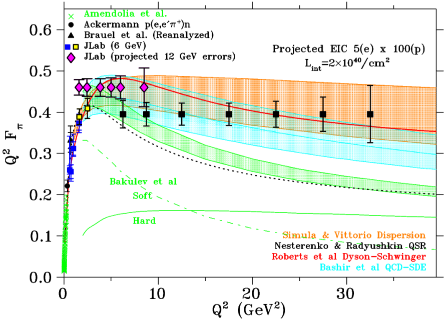

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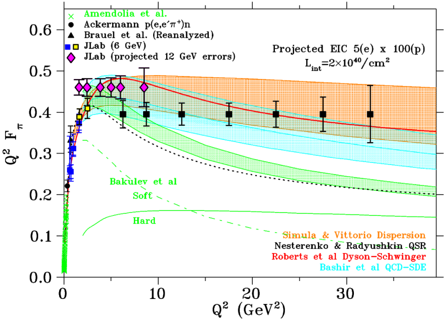

- Results look promising, need to test π^- too
- ePIC looks comparable or better so far

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- Projections for F_π at EIC look very promising
  - Updated projections using ePIC imminent
  - F_K at the EIC now under investigation

Thanks for listening, any questions?

With thanks to all of my colleagues in the Pion/KaonLT collaboration, ePIC Collaboration and the Meson Structure Working Group.

stephen.kay@york.ac.uk

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Backup Zone

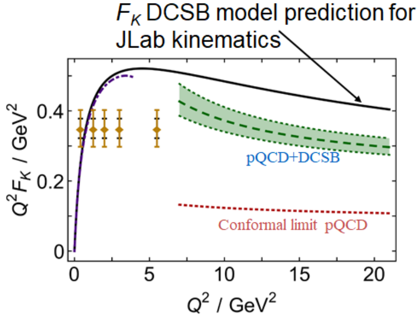
EIC Studies - Next Steps

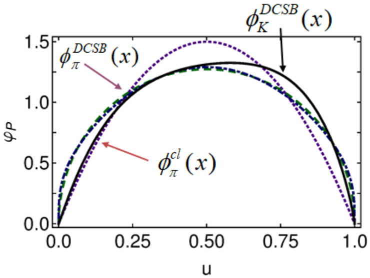
- Need to process full F_π analysis again with ePIC
- Analysis roadblocks cleared $\rightarrow$ **New projections imminent!**
  - Event weight accessible
  - ZDC HCal now implemented
    - B. Schmookler and group at UCRiverside working on ZDC HCal design/construction
- DEMP is a key benchmarking channel for FF detectors
  - Well defined, but progressively more complicated reconstruction
    - $ep \rightarrow e'\pi^+ n$
    - $ep \rightarrow e'K^+\Lambda^0(\Lambda^0 \rightarrow n\pi^0$ OR $\Lambda^0 \rightarrow \pi^- p)$
    - $ep \rightarrow e'K^+\Sigma^0(\Sigma^0 \rightarrow \gamma\Lambda^0)$
- Need last two for F_K at the EIC
- Very challenging to detect
  - Directly influence design choices for ZDC/FF

https://arratialab.ucr.edu/eic

What About the Kaon?

- K^+ PDA, ϕ_K, is also broad and concave, but asymmetric
- Heavier *s* quark carries more bound state momentum than the *u* quark

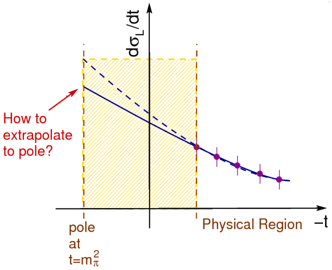




C. Shi, et al., PRD 92 (2015) 014035, F. Guo, et al., PRD 96(2017) 034024 (Full calculation)

Chew-Low Method to determine F_π

- $p(e, e'\pi^+)n$ data obtained away from $t = m_\pi^2$ pole
- "Chew Low" extrapolation method - must know analytical dependence of $d\sigma_L/dt$ in unphysical region
- Extrapolation method last used in 1972 by Devenish and Lyth
- Very large systematic uncertainties
- Failed to produce a reliable result
- Different polynomial fits equally likely in physical region
  - Form factor values divergent when extrapolated
- **We do not use the Chew-Low method**



Extracting F_π at JLab

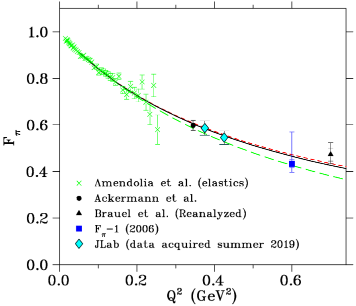
- Only reliable approach for extracting F_π from σ_L is to use a model that incorporates the π^+ production mechanism and the spectator nucleon
- JLab F_π experiments so far use the VGL Regge model
  - Reliably describes σ_L across a wide kinematic domaon
- Ideally, want a better understanding of the model dependence of the result
- There has been considerable recent interest
  - T.K. Choi, K.J. Kong, B.G. Yu, arXiv 1508.00969
  - T. Vrancx, J. Ryckebusch, PRC 89(2014)025203
  - M.M. Kaskulov, U. Mosel, PRC 81(2010)045202
  - S.V. Goloskokov, P.Kroll, EPJC 65(2010)137
- **We aim to publish our experimentally measured cross section data so that updated values of F_π can be extracted as the models improve**

VGL - Vanderhaeghen-Guidal-Laget Model - Vanderhaeghen, Guidal, Laget, PRC 57(1998) 1454

F_π Validation - Electroproduction Cross Check

- Low Q^2 data is an important test
  - Does electroproduction really measure the on-shell form factor?

- Test with $p(e, e'\pi^+)n$ measurements at same kinematics as $e\pi^+$ elastics
- New data points at $Q^2 = 0.375$ and 0.425 $GeVc^{-2}$, DESY (Ackermann) point at 0.35 $GeVc^{-2}$
- -t closer to pole than DESY data, 0.008 GeV^2 vs 0.013 GeV^2



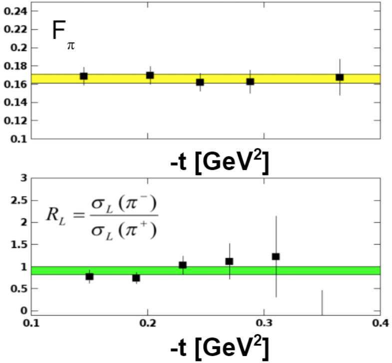
Amendolia, et al., NPB 277(1986) p168, P. Brauel, et al., ZPhysC (1979), p101, H. Ackerman, et al., NPB137 (1978), p294

Two F_π Validation Methods

- Test #1 - Measure F_π at fixed Q^2/W, but vary $-t$
  - F_π values should not depend on -t
- Test #2 - π^+ t-channel diagram is purely isovector
- Use a deuterium target to measure $\sigma_L\,[n(e,e'\pi^-)p]$
- Examine the ratio -

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

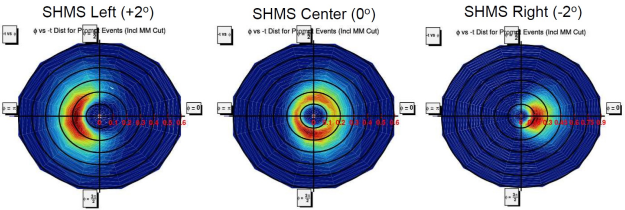
- Will test at $Q^2 = 1.6, 3.85, 6.0\ GeV^2$



T. Horn, C.D. Roberts, J. Phys. G43 (2016) no.7, 073001
G. Huber et al, PRL112 (2014)182501
R. J. Perry et al., arXiV:1811.09356 (2019)

PionLT - $t - \phi$ Coverage

- Measure σ_{LT}, σ_{TT} $\rightarrow$ measure either side of q-vector
  - Typically $\pm 2°$ or $\pm 3°$
- $t - \phi$ coverage from $Q^2 = 3.85\ GeV^2$, $W = 3.07\ GeV$, high ϵ



- Control systematics $\rightarrow$ understand spectrometer acceptance
  - Use $p(e, e'p)$ and inelastic $e +^{12} C$ reactions
    - Calibrate acceptance, momenta, kinematic offsets...
- Point-to-point systematic uncertainties must be well controlled $\rightarrow$ $1/\Delta\epsilon$ error amplification in σ_L

Image Credit - N. Heinrich, University of Regina

SHMS Detector Stack

- SHMS detects hadrons
- HMS detects electrons
- Wide angular and momentum range for each
- SHMS Aero and HGC used for PID
    - Aerogel $\rightarrow K/p$ separation
        - Four different n used
    - HGC $\rightarrow K/\pi$ separation
- PionLT included an NGC too $\rightarrow e/\pi$ separation

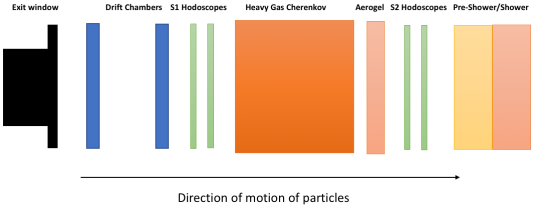
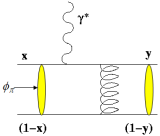


Image Credit - A. Usman, University of Regina

Rigorous Predictions for the Pion from pQCD

- At very large four-momentum transfer squared, Q^2, F_π can be calculated using pQCD



- As $Q^2 \to \infty$, the pion distribution amplitude, ϕ_π becomes -

$$\phi_\pi(x) \to \frac{3f_\pi}{\sqrt{n_c}}x(1-x)$$ $f_\pi = 93\ MeV$, $\pi^+ \to \mu^+\nu$ decay constant

- F_π can be calculated with pQCD in this limit to be -

$$Q^2 F_\pi \xrightarrow[Q^2\to\infty]{} 16\pi\alpha_s(Q^2)f_\pi^2$$

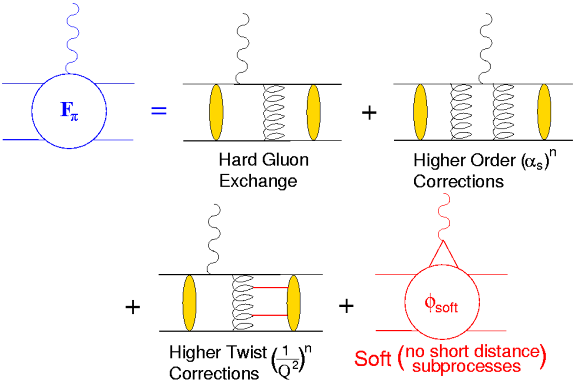
- This is a **rigorous** prediction of pQCD
- Q^2 **reach of existing data doesn't extend into transition region**
  - Need unique, cutting edge experiments to push into this region

Eqns - G.P. Lepage, S.J. Brodsky, PLB 87, p359, 1979

The Pion in pQCD

- At very large Q^2, F_π can be calculated using pQCD via -

$$F_\pi(Q^2) = \frac{4_F \alpha_s(Q^2)}{Q^2} \left| \sum_{n=0}^{\infty} a_n \left(\log\left(\frac{Q^2}{\Lambda^2}\right)\right)^{-\gamma_n} \right|^2 \left[1 + O\left(\alpha_s(Q^2), \frac{m}{Q}\right)\right]$$



Isolating σ_L from σ_T in an e-p Collider

- For a collider -

$$\epsilon = \frac{2(1-y)}{1+(1-y)^2} \quad \text{with} \quad y = \frac{Q^2}{x(s_{tot} - M_N^2)}$$

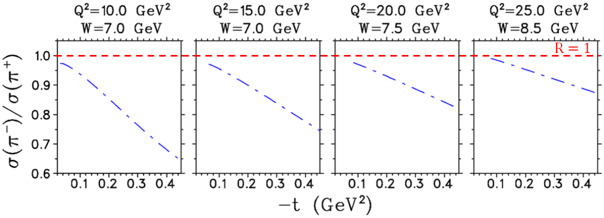
  - y is the fractional energy loss
- Systematic uncertainties in σ_L magnified by $1/\Delta\epsilon$
  - Ideally, $\Delta\epsilon > 0.2$
- To access $\epsilon < 0.8$ with a collider, need $y > 0.5$
  - Only accessible at small s_{tot}
  - Requires low proton energies ($\sim 10\ GeV$), luminosity too low
- **Conventional L-T separation not practical, need another way to determine σ_L**

Model Validation via π^-/π^+ ratios

- Measure 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 $\rightarrow$ G-Parity conserved

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

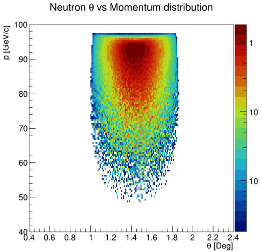
- R will be diluted if σ_T *not* small *or* if there are significant non-pole contributions to σ_L
- Compare R to model expectations

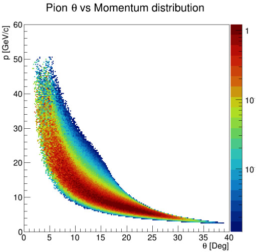


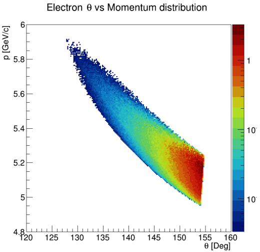
T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

DEMP Kinematics for $-t < 0.5\ GeV^2$

- $5(e^-)$ on $100(p)$ *GeV* collisions, 25 *mrad* crossing angle
- Events weighted by cross section
- No smearing
- Old YR plots, just to demonstrate event kinematics



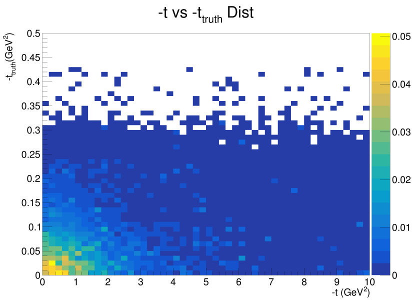




- Neutrons within 0.2° of outgoing proton beam, offset is due to the crossing angle ($25\ mrad \approx 1.4^\circ$)

Simulation Results - t Reconstruction

- Reconstruction of $-t$ from detected e' and π^+ tracks proved highly unreliable
  - $-t = -(p_e - p_{e'} - p_\pi)^2$
- Calculation of $-t$ from reconstructed neutron track matched "truth" value closely
  - $-t_{alt} = -(p_p - p_n)^2$
- Only possible due to the excellent position accuracy provided by a good ZDC



- Plot from ECCE analysis
- Note that the x-axis $-t$ scale here runs to 10 GeV^2!

More details in NIMA 1052 (2023), 168238 `https://doi.org/10.1016/j.nima.2023.168238`

Simulation Results - t Reconstruction

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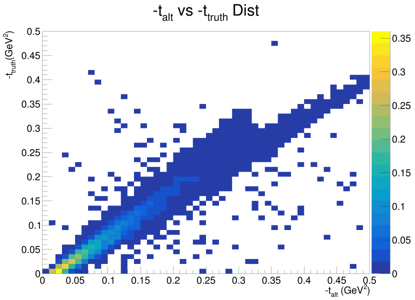
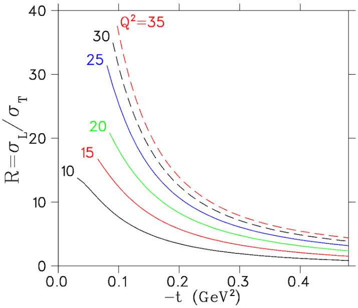


- Plot from ECCE analysis
- x-axis $-t$ scale an order of magnitude smaller now!

More details in NIMA 1052 (2023), 168238 https://doi.org/10.1016/j.nima.2023.168238

σ_L Isolation with a Model at the EIC

- QCD scaling predicts $\sigma_L \propto Q^{-6}$ and $\sigma_T \propto Q^{-8}$
- At the high Q^2 and W accessible at the EIC, phenomenological models predict $\sigma_L \gg \sigma_T$ at small $-t$
- Can attempt to extract σ_L by using a model to isolate dominant $d\sigma_L/dt$ from measured $d\sigma_{UNS}/dt$
- Examine π^+/π^- ratios as a test of the model

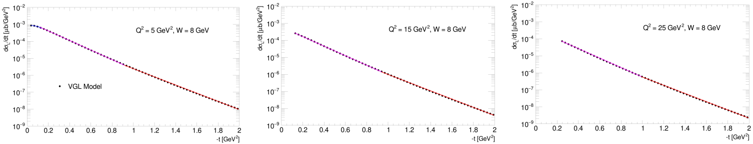


Predictions are assuming $\epsilon > 0.9995$ with the kinematic ranges seen earlier

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

F_K at the EIC - Generator Updates

- URegina MSc student Love Preet added new Kaon DEMP event generator module to DEMPgen
  - Starting with $p(e, e'K^+\Lambda)$
- Parametrise a Regge-based model
- For $p(e, e'K^+\Lambda)$ module, use the Vanderhagen, Guidal, Laget (VGL) model
- Parametrise σ_L, σ_T for $1 < Q^2 < 35$, $2 < W < 10$, $-t < 2.0$
  - Parametrise with a polynomial, exponential and exponential



VGL Model - M. Guidal, J.-M. Laget, M. Vanderhaeghen, PRC 61 (3000) 025204

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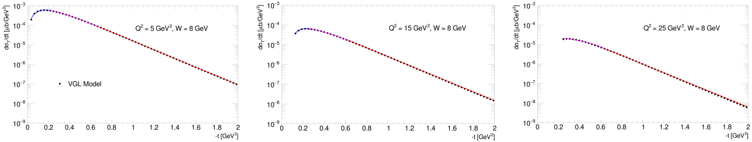

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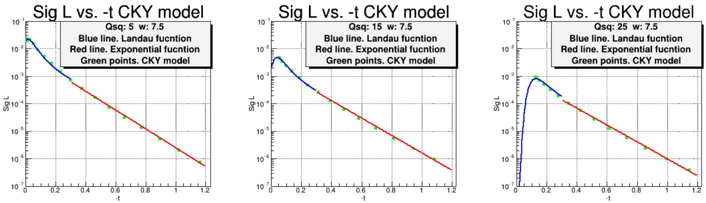
DEMP Event Generator - Pions

- Want to examine exclusive reactions
  - $p(e, e'\pi^+ n)$ exclusive reaction is reaction of interest
    $\rightarrow p(e, e'\pi^+)X$ SIDIS events are background
- Generator uses Regge-based $p(e, e'\pi^+)n$ model from
  T.K. Choi, K.J. Kong and B.G. Yu (CKY) - arXiv 1508.00969
  - MC event generator created by parametrising CKY σ_L, σ_T for
    $5 < Q^2 < 35$, $2 < W < 10$, $0 < -t < 1.2$



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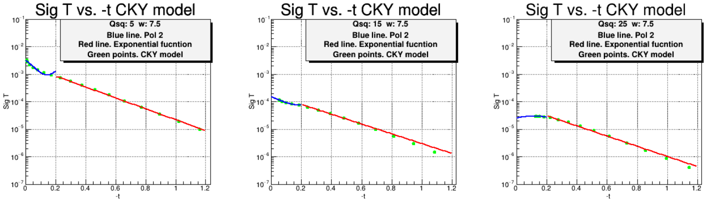
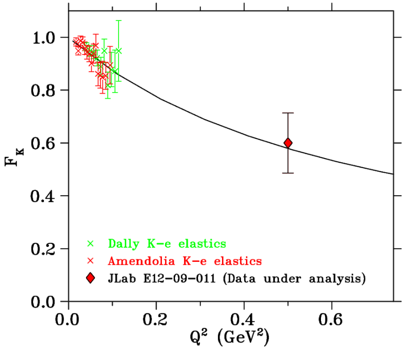


Selecting Good Simulated Events

- Pass through a full Geant4 simulation (ECCE)
  - More realistic estimates of detector acceptance/performance than earlier studies
- Identify $e'\pi^+n$ triple coincidences in the simulation output
- For a good triple coincidence event, require -
  - **Exactly** two tracks
    - One positively charged track going in the $+z$ direction (π^+)
    - One negatively charged track going in the $-z$ direction (e')
  - At least one hit in the zero degree calorimeter (ZDC)
    - For 5 (e', GeV) on 100 (p, GeV) events, require that the hit has an energy deposit over 40 GeV
- Both conditions must be satisfied
- Determine kinematic quantities for remaining events

F_K Validation

- Need to simultaneously study Λ^0 and Σ^0 channels
- Can conduct a pole dominance test through the ratio -
$$\frac{\sigma_L\left[p(e,e'K^+)\Sigma^0\right]}{\sigma_L\left[p(e,e'K^+)\Lambda^0\right]}$$
- Should be similar to ratio of $g^2_{pK\Lambda}/g^2_{pK\Sigma}$ if t-channel exchange dominates



Simulation Results - Neutron Reconstruction

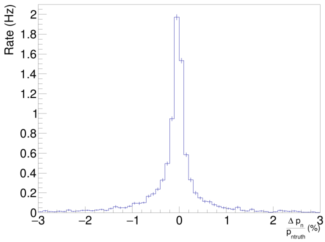
- High energy ZDC hit requirement used as a veto
  - ZDC neutron ERes is relatively poor though

$$\frac{35\%}{\sqrt{E}} \oplus 2\%$$

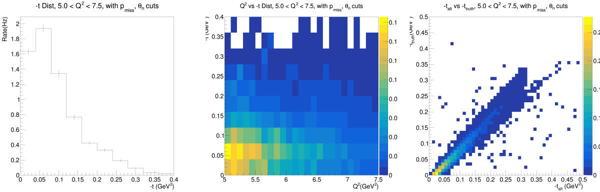
- However, position resolution is excellent, $\sim 1.5\ mm$
- Combine ZDC position info with missing momentum track to reconstruct the neutron track

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

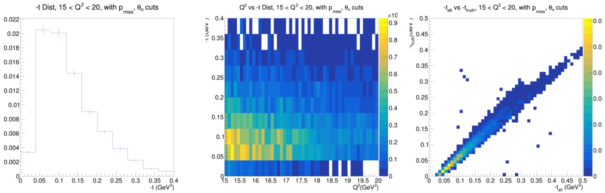
- Use ZDC angles, θ_{ZDC} and ϕ_{ZDC} rather than the missing momentum angles, θ_{pMiss} and ϕ_{pMiss}
- Adjust E_{Miss} to reproduce m_n
- After adjustments, reconstructed neutron track matches "truth" momentum closely



Simulation Results - Q^2 $5 - 7.5$ GeV^2



- Predicted $e'\pi^+n$ triple coincidence rate, binned in Q^2 and $-t$
  - 5 (e', GeV) on 100 (p, GeV) events
  - $\mathcal{L} = 10^{34} cm^{-2} s^{-1}$ assumed
  - $-t$ bins are 0.04 GeV^2 wide
  - Cut on θ_n $(\theta_n = 1.45 \pm 0.5^\circ)$ and $\vec{p}_{miss} = \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}$ (varies by Q^2 bin) to simulate removal of SIDIS background
    - New cut on difference between p_{miss} and detected ZDC angles implemented too, $|\Delta\theta| < 0.6^\circ$, $|\Delta\phi| < 3.0^\circ$
- $-t_{min}$ migrates with Q^2 as expected



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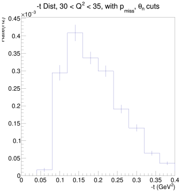
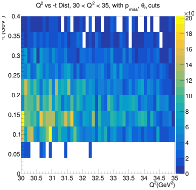
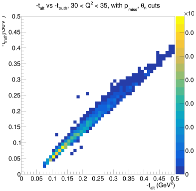
Simulation Results - Q^2 $30 - 35$ GeV^2







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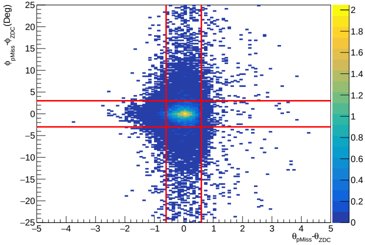
    - New cut on difference between p_{miss} and detected ZDC angles implemented too, $|\Delta\theta| < 0.6^\circ$, $|\Delta\phi| < 3.0^\circ$
- $-t_{min}$ migrates with Q^2 as expected

$\Delta\theta$ and $\Delta\phi$ Cuts

- Make use of high angular resolution of ZDC
- Compare hit θ/ϕ positions of neutron on ZDC to calculated θ/ϕ from p_{miss}
- If no other particles produced, quantities should be correlated
  - True for DEMP events
- Energetic neutrons from inclusive background processes will be less correlated
  - Additional lower energy particles produced



- $\theta_{pMiss} - \theta_{ZDC}$ and $\phi_{pMiss} - \phi_{ZDC}$ cut upon, in addition to other cuts
- $|\theta_{pMiss} - \theta_{ZDC}| < 0.6^{\circ}$, $|\phi_{pMiss} - \phi_{ZDC}| < 3.0^{\circ}$

DEMPGen Improvements

- In addition to adding the $p(e, e'K^+\Lambda)$ module, improvements to the generator implemented
- New method to interpolate parametrisation
- Interpolation matches generator output very closely
  - Even at points far from the initial parametrisation
- Will incorporate improvements in pion model too in the near future