# Future Pion Structure Studies with JLab 22 GeV and the EIC

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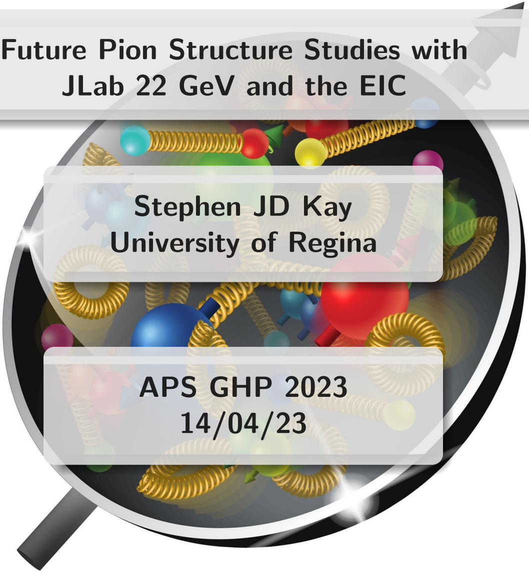
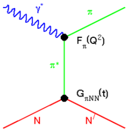
APS GHP 2023
14/04/23



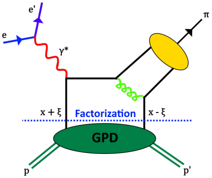
# Pion Structure Studies with Exclusive Measurements

- 1) Determine the pion form factor, $F_\pi$ to high $Q^2$
- $F_\pi$ is a key QCD observable
- Measure $F_\pi$ indirectly using pion cloud of the proton via $p(e,e'\pi^+)n$

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



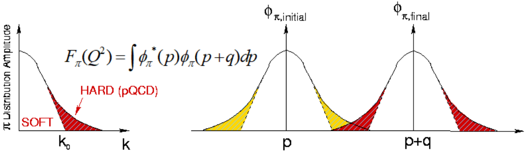

- 2) Study the hard-soft factorisation regime
- Determine region of validity of hard-exclusive reaction mechanism
- Can only extract GPDs where factorisation applies
- Separated $p(e,e'\pi^+)$ $\sigma$ vs $Q^2$ at fixed $x_b$ to investigate reaction mechanism towards 3D imaging




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

# Meson Form Factors

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




- Meson wave function can be split into $\phi_\pi^{\mathrm{soft}}$ $(k < k_0)$ and $\phi_\pi^{\mathrm{hard}}$, the hard tail
  - Can treat $\phi_\pi^{\mathrm{hard}}$ in pQCD, cannot with $\phi_\pi^{\mathrm{soft}}$
  - Form factor is the overlap between the two tails (right figure)
- **$F_\pi$ and $F_K$ of special interest in hadron structure studies**
  - $\pi$ - Lightest QCD quark system, simple
  - $K$ - Another simple system, contains strange quark

# The Pion in pQCD

- At very large $Q^2$, $F_\pi$ can be calculated using pQCD

$$F_\pi(Q^2) = \frac{4}{3}\pi\alpha_s \int_0^1 dxdy \frac{2}{3}\frac{1}{yQ^2}\phi(x)\phi(y)$$

- As $Q^2 \rightarrow \infty$, the pion distribution amplitude, $\phi_\pi$ becomes -

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

- $F_\pi$ can be calculated with pQCD in this limit to be -

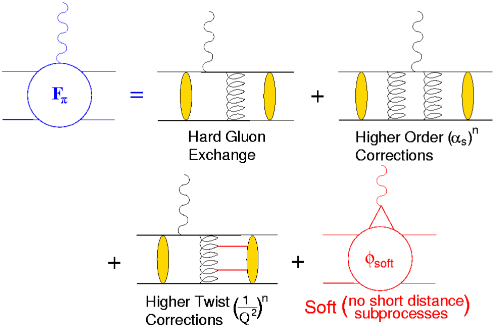
$$Q^2F_\pi \xrightarrow[Q^2\rightarrow\infty]{} 16\pi\alpha_s(Q^2)f_\pi^2$$

- This is a **rigorous** prediction of pQCD
- $Q^2$ **reach of existing data doesn't extend into this region**
  - Need unique, cutting edge experiments to push into this region
  - QCD is *not* found in scaling, found in **scaling violations**

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

# The Pion in pQCD

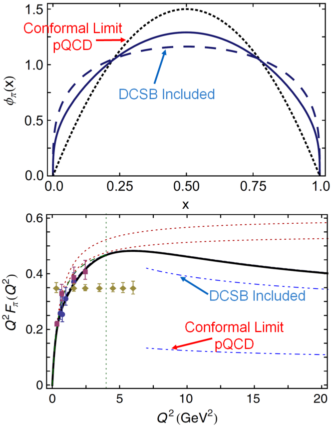
- At experimentally accessible $Q^2$, both the hard and soft components contribute




- Interplay of hard and soft contributions poorly understood
- Experiments can study the transition from soft to hard regime

# Connecting Pion Structure and Mass Generation

- $\phi_\pi$ as shown before has a broad, concave shape
- Previous pQCD derivation (conformal limit) did not include DCSB effects
- Incorporating DCSB changes $\phi_\pi(x)$ and brings $F_\pi$ calculation much closer to the data
    - "Squashes down" PDA
- Pion structure and hadron mass generation are interlinked
- How can we measure $F_\pi$?

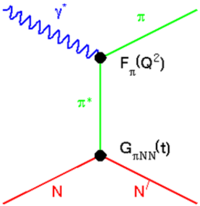



L. Chang, et al., PRL110(2013) 132001, PRL111(2013), 141802

# Measurement of $F_\pi$ at High $Q^2$

- To access $F_\pi$ at high $Q^2$, must measure $F_\pi$ indirectly
  - Use the "pion cloud" of the proton via $p(e, e'\pi^+)n$
- At small $-t$, the pion pole process dominates $\sigma_L$
- In the Born term model, $F_\pi^2$ appears as -

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




- We do not use the Born term model
- Drawbacks of this technique -
  - Isolating $\sigma_L$ experimentally challenging
  - Theoretical uncertainty in $F_\pi$ extraction
    - Model dependent (smaller dependency at low -t)
- Can isolate $\sigma_L$ with an L-T separation measurement

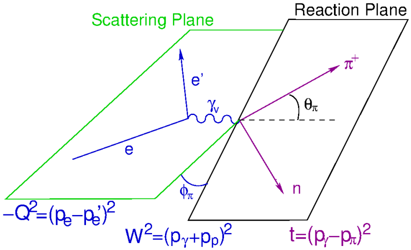
# LT Separation

- L-T Separation can be utilised to separate $\sigma_L$ from $\sigma_T$

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

$$\epsilon = \left(1+2\frac{(E_e-E_{e'})^2+Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1} \quad \text{Virtual photon polarisation}$$

- Need to take data at smallest available $-t$
  - Maximise $\pi^+$ pole contribution to $\sigma_L$
- Need to measure $t$-dependence of $\sigma_L$ at fixed $Q^2$, $W$




- Measure cross section at two (or more) values of $\epsilon$, **errors in $\sigma_L$ amplified by a factor** $1/\Delta\epsilon \rightarrow$ Problematic for a collider!

# Isolating $\sigma_L$ from $\sigma_T$ 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 $\sigma_L$ 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** $\sigma_L$ at the EIC
- Measure **D**eep **E**xclusive **M**eson **P**roduction (**DEMP**) reactions instead, isolate $\sigma_L$ using a model

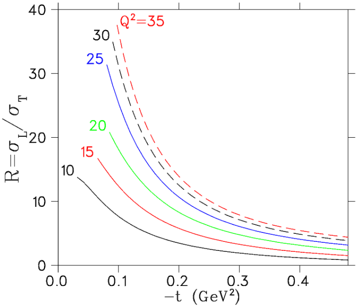
# DEMP Studies at the EIC

- Measurements of the $p(e, e'\pi^+ n)$ reaction at the EIC can potentially extend the $Q^2$ reach of $F_\pi$
- A challenging measurement however
  - Need good identification of $p(e, e'\pi^+ n)$ triple coincidences
  - Conventional L-T separation not possible $\rightarrow$ would need lower than feasible proton energies to access low $\epsilon$
  - Need to use a model to isolate $d\sigma_L/dt$ from $d\sigma_{uns}/dt$
- Utilise new EIC software framework to assess the feasibility of the study with updated design parameters
  - Feed in events generated from a DEMP event generator - DEMPGen
  - Results presented used the ECCE simulation
- DEMPGen being modified to generate kaon events

DEMPGen - `https://github.com/JeffersonLab/DEMPGen`

# $\sigma_L$ 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 $\sigma_L$ by using a model to isolate dominant $d\sigma_L/dt$ from measured $d\sigma_{UNS}/dt$
- Critical to confirm the validity of the model used!

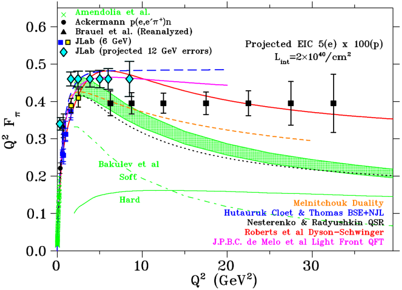



Predictions are assuming $\epsilon > 0.9995$ with the kinematic ranges seen earlier

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

# EIC $F_\pi$ Prospects - ECCE Simulation Results

- ECCE appeared to be capable of measuring $F_\pi$ to $Q^2 \sim 32.5\ GeV^2$
- **Error bars represent real projected error bars**
- Overlap with JLab data at the low end of $Q^2$ range
- Data here can address mass generation questions
  - One of the key science questions for the EIC!

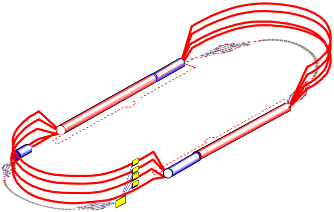



- More details in upcoming ECCE NIM paper
- Will re-evaluate with ePIC

- Remember, EIC data **<u>not</u> LT separated!**
- JLab will remain only source of LT separated data, what could a 22 GeV JLab give us?

# JLab Energy Upgrades - A 22 GeV JLab?

- Could upgrade energy of JLab accelerator again
- Replace some arcs with a Fixed Field Alternating Gradient (**FFA**) arcs, new injector
- Could push energy to the $20 - 24\ GeV$ range
- See talk by P. Rossi from 12/04/23 (10:00) for more
- Fixed target experiments still useful, facility has unique capabilities
  - Many possibilities to extend existing Hall C pion structure measurements with a higher energy machine

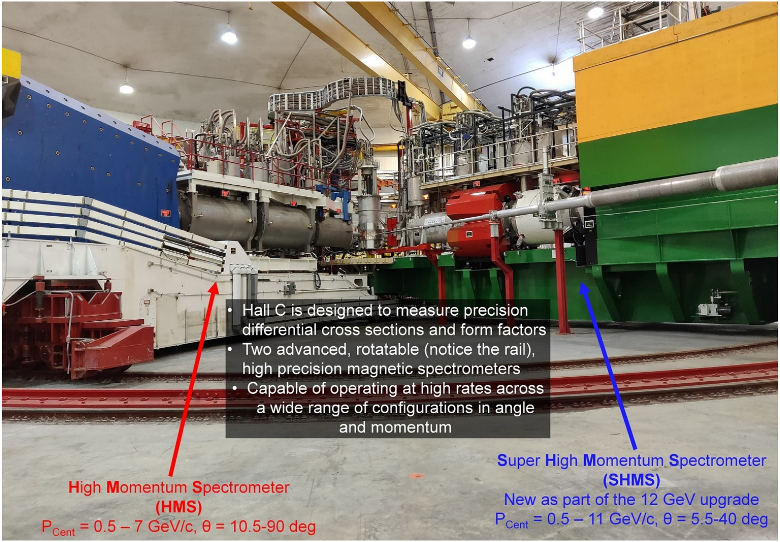


New injector not shown.

- If this goes ahead, will be beyond 2030.

Image - Alex Bogacz, 20-24 GeV FFA CEBAF Energy Upgrade

# Hall C in the 12 GeV era



# JLab22 - Hall C Upgrade Scenarios

- Various ways in which Hall C could be upgraded, a staged approach seems reasonable
- Phase 1 - Higher beam energy, HMS and SHMS unchanged
- Then upgrade/replace one or both of the magnetic spectrometers
  - Max central momentum
  - Opening angle
- Phase 2 - Example scenario, replace the HMS with a new spectrometer
  - **V**ery **H**igh **M**omentum **S**pectrometer - VHMS?
  - Very large upgrade over HMS momentum, upgrade opening angle too, $7\ GeV/c \rightarrow 20 GeV/c$, $\theta_{Open} - 18.00^{\circ} \rightarrow 15.00^{\circ}$

# Phase 1 - Only $E_{Beam}$ Upgraded - $F_\pi$ Prospects

- 7.2 $GeV/c$ HMS and 11.0 $GeV/c$ SHMS kinematically flexible, with no upgrades
- Beam energy and high $Q^2$ reach constrained by sum of HMS and SHMS momenta
- Could do this immediately with JLab 22 GeV though!

| | 10.6 GeV | 18.0 GeV | Improvement in $\delta F_\pi/F_\pi$ |
|---|---|---|---|
| $Q^2$=8.5 | $\Delta\varepsilon$=0.22 | $\Delta\varepsilon$=0.40 | 16.8%→8.0% |
| $Q^2$=10.0 | New high quality $F_\pi$ data | | |
| $Q^2$=11.5 | Larger $F_\pi$ extraction uncertainty due to higher $-t_{min}$ | | |

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

| $E_{beam}$ | $\theta_{HMS}$ (e') | $P_{HMS}$ (e') | $\theta_{q(SHMS)}$ ($\pi^+$) | $P_{SHMS}$ ($\pi^+$) | Time FOM |
|---|---|---|---|---|---|
| $Q^2$=8.5 $W$=3.64 $-t_{min}$=0.24 $\Delta\varepsilon$=0.40 | | | | | |
| 13.0 | 34.30 | 1.88 | 5.29 | 10.99 | 64.7 |
| 18.0 | 15.05 | 6.88 | 8.94 | 10.99 | 2.2 |
| $Q^2$=10.0 $W$=3.44 $-t_{min}$=0.37 $\Delta\varepsilon$=0.40 | | | | | |
| 13.0 | 37.78 | 1.83 | 5.56 | 10.97 | 122.7 |
| 18.0 | 16.39 | 6.83 | 9.57 | 10.97 | 4.5 |
| $Q^2$=11.5 $W$=3.24 $-t_{min}$=0.54 $\Delta\varepsilon$=0.29 | | | | | |
| 14.0 | 31.73 | 2.75 | 7.06 | 10.96 | 82.4 |
| 18.0 | 17.70 | 6.75 | 10.05 | 10.96 | 8.8 |

- Extension of L-T separated data increases $F_\pi$ overlap with EIC

# Phase 2 - 20 $GeV/c$ VHMS - $F_\pi$ Prospects

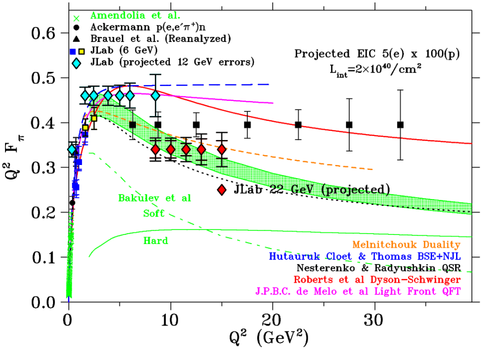
- Replace HMS with **V**ery **H**igh **M**omentum **S**pectrometer, VHMS
  - Assume $\theta_{min} = 5.5°$, $\theta_{open} = 15.0°$
- Use VHMS for $\pi^+$, SHMS for $e'$
- Same $Q^2$ reach as last option, but shorter run times
- $P_{VHMS} = 15.0\ GeV/c$ would be sufficient, **constrained by max beam energy**

**p(e,e'π⁺)n Kinematics**

| $E_{beam}$ | $\theta_{SHMS}$ (e') | $P_{SHMS}$ (e') | $\theta_{q(HMS')}$ ($\pi^+$) | $P_{HMS'}$ ($\pi^+$) | Time FOM |
|---|---|---|---|---|---|
| $Q^2$=8.5 $W$=4.18 $-t_{min}$=0.15 $\Delta\varepsilon$=0.28 | | | | | |
| 17.0 | 21.39 | 3.63 | 5.55 | 13.29 | 20.5 |
| 22.0 | 12.15 | 8.63 | 7.62 | 13.29 | 1.8 |
| $Q^2$=10.0 $W$=4.08 $-t_{min}$=0.21 $\Delta\varepsilon$=0.30 | | | | | |
| 17.0 | 24.49 | 3.27 | 5.52 | 13.62 | 53.3 |
| 22.0 | 13.46 | 8.27 | 7.85 | 13.62 | 4.3 |
| $Q^2$=11.5 $W$=3.95 $-t_{min}$=0.29 $\Delta\varepsilon$=0.31 | | | | | |
| 17.0 | 27.34 | 3.03 | 5.55 | 13.82 | 124.8 |
| 22.0 | 14.66 | 8.03 | 8.12 | 13.82 | 9.3 |
| $Q^2$=13.0 $W$=3.96 $-t_{min}$=0.35 $\Delta\varepsilon$=0.25 | | | | | |
| 18.0 | 27.55 | 3.18 | 5.54 | 14.63 | 209.5 |
| 22.0 | 16.49 | 7.18 | 7.69 | 14.63 | 24.4 |
| $Q^2$=15.0 $W$=3.73 $-t_{min}$=0.52 $\Delta\varepsilon$=0.26 | | | | | |
| 18.0 | 30.24 | 3.06 | 5.73 | 14.66 | 560 |
| 22.0 | 17.88 | 7.06 | 8.07 | 14.66 | 65.7 |

# JLab22 $F_\pi$ Data in the EIC Era

- L-T separations not possible at the EIC
- JLab will remain **only** source of quality L-T separated data!
- Phase 2 with upgraded HMS (VHMS)
  - Extends region of high quality $F_\pi$ values to $Q^2 = 13\ GeV^2$
  - Larger error point at $Q^2 = 15\ GeV^2$

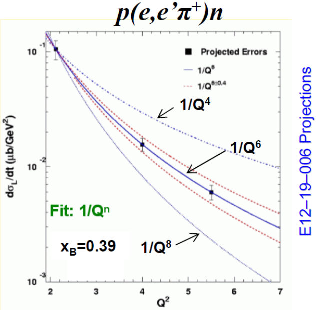



- JLab energy upgrade and Hall C upgrade provides much improved overlap of $F_\pi$ data between JLab and EIC

# JLab22 DEMP $Q^{-n}$ Hard-Soft Factorisation Tests

- One of the most stringent tests of hard-soft factorisation is the $Q^2$ dependence of $\pi$ electroproduction $\sigma$
- JLab 22 GeV opens up the opportunity to expand upon ongoing studies here too
  - $Q^{-n}$ scaling test range nearly doubles with an 18 $GeV$ $e^-$ beam and existing HMS+SHMS (Phase 1 scenario)

| $x$ | $Q^2$ (GeV$^2$) | $W$ (GeV) | $-t_{min}$ (GeV$^2$) |
|---|---|---|---|
| 0.31 | 1.45–3.65 | 2.02–3.07 | 0.12 |
| | 1.45–6.5 | 2.02–3.89 | |
| 0.39 | 2.12–6.0 | 2.05–3.19 | 0.21 |
| | 2.12–8.2 | 2.05–3.67 | |
| 0.55 | 3.85–8.5 | 2.02–2.79 | 0.55 |
| | 3.85–11.5 | 2.02–3.23 | |




See talk from Nathan Heinrich yesterday (13/04/2023, 15:00) for more on scaling studies in Hall C.

## Summary and Outlook

- EIC has the potential to push the $Q^2$ reach of $F_\pi$ measurements into the 30 $GeV^2$ range
- $F_\pi$ work previously featured in the EIC yellow report
- ECCE projections to be published in an upcoming NIM paper
  - arXiv:2208.14575v1
  - Will continue to develop simulations with ePIC
- JLab22 GeV would enable high quality LT separated measurements to high $Q^2$
  - Possible even without upgrades to existing Hall C equipment
  - Strong case for a phased approach to Hall C upgrades
- JLab 22GeV data would be **highly complementary** with EIC measurements of $F_\pi$
  - Significant overlap between JLab 22 GeV and EIC $F_\pi$ data
- JLab likely to remain our only source of high quality L-T separated data over a broad kinematic range for decades

R. Abdul Khalek et al. EIC Yellow Report. 2021. arXiv:2103.05419, Sections 7.2.1 and 8.5.1

# Thanks for listening, any questions?

**Meson Structure Working Group - Stephen JD Kay**, Garth M Huber, Zafar Ahmed, Love Preet, Ali Usman, John Arrington, Carlos Ayerbe Gayoso, Daniele Binosi, Lei Chang, Markus Diefenthaler, Rolf Ent, Tobias Frederico, Yulia Furletova, Timothy Hobbs, Tanja Horn, Thia Keppel, Wenliang Li, Huey-Wen Lin, Rachel Montgomery, Ian L. Pegg, Paul Reimer, David Richards, Craig Roberts, Dmitry Romanov, Jorge Segovia, Arun Tadepalli, Richard Trotta, Rik Yoshida

**EIC-Canada**

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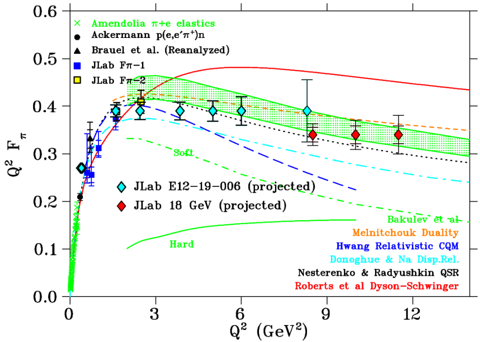
The University of Regina is situated on the territories of the nehiyawak, Anihsināpēk, Dakota, Lakota, and Nakoda, and the homeland of the Métis/Michif Nation. The University of Regina is on Treaty 4 lands with a presence in Treaty 6.

Backup Zone

# Phase 1 (Only $E_{Beam}$ Upgraded) - $F_{\pi}$ Projections

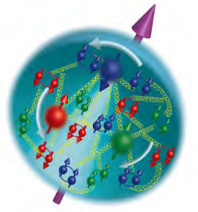
- $Y$-axis values of projected data are arbitrary
- Errors projected based upon $\Delta\epsilon$ and T/L ratio calculated from VR model
- Inner error bar is projected statistical and systematic error
- Outer error bar includes model uncertainty from $F_{\pi}$ extraction

VR - Vrancx Ryckebusch




- $F_{\pi}$ errors based on $F\pi - 2$ and $E12 - 19 - 006$ experience

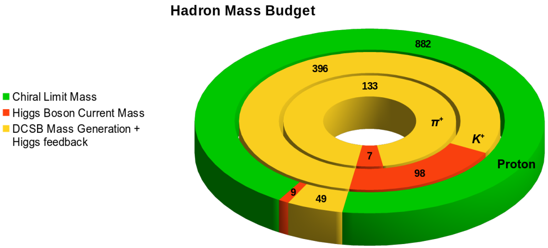
# Understanding Dynamic Matter



- Interactions and structure are not isolated ideas in nuclear matter
  - Observed properties of nucleons and nuclei (mass, spin) emerge from this complex interplay
  - Properties of hadrons are emergent phenomena
- Mechanism known as **D**ynamical **C**hiral **S**ymmetry **B**reaking (**DCSB**) plays a part in generating hadronic mass
- QCD behaves very differently at short and long distances (high and low energy)
  - How do our two distinct regions of QCD behaviour connect?
- **A major puzzle of the standard model to try and resolve!**
- How can we examine hadronic structure?

Image - A. Deshpande, Stony Brook University

# More Than Just Protons



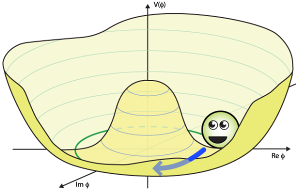

- Multiple mechanisms at play
- DCSB not experimentally demonstrated
- What can we examine to understand hadron structure?
- **The simple $q\bar{q}$ valence structure of mesons makes them an excellent testing ground**

J Arrington et al 2021 J. Phys. G: Nucl. Part. Phys. 48 075106 - `http://dx.doi.org/10.1088/1361-6471/abf5c3`

# The Pion as a Goldstone Boson

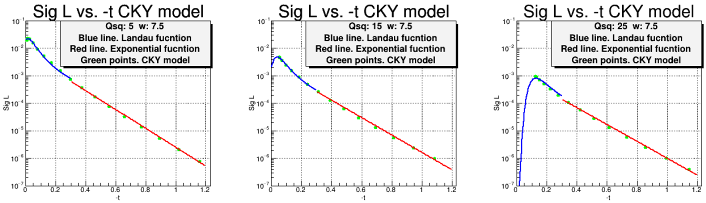
- DCSB cannot be derived directly from the QCD Lagrangian
  - It is related to the nontrivial nature of the QCD vacuum
  - Explicit symmetry breaking, which is put in "by hand" through finite quark masses, is quite different
- DCSB is one of the most important emergent phenomena in the standard model
- **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 Higgs from Electroweak Symmetry Breaking)



# DEMP Event Generator

- 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 $\sigma_L$, $\sigma_T$ for
    $5 < Q^2 < 35$, $2 < W < 10$, $0 < -t < 1.2$



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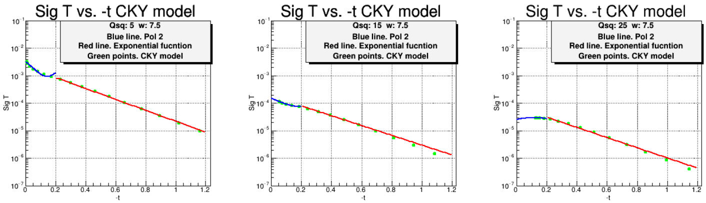
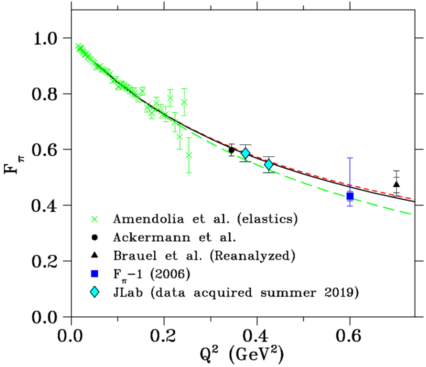


# Measurement of $F_\pi$ - Low $Q^2$

- At low $Q^2$, $F_\pi$ can be measured model independently
  - High energy elastic $\pi^-$ scattering from atomic electrons in $H$
- CERN SPS - 300 $GeV$ pions to measure $F_\pi$ up to $Q^2 = 0.25\ GeV^2$
- Used data to extract pion charge radius - $r_\pi = 0.657 \pm 0.012\ fm$
- Maximum accessible $Q^2$ approximately proportional to pion beam energy
  - $Q^2 = 1\ GeV^2$ requires 1 $TeV$ pion beam (!)




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

# L-T Separation Error Propagation

- Error in $d\sigma_l/dt$ is magnified by $1/\Delta\epsilon$, $\Delta\epsilon = (\epsilon_{Hi} - \epsilon_{Low})$
  - To keep magnification factor $< 5x$, need at least $\Delta\epsilon > 0.2$

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

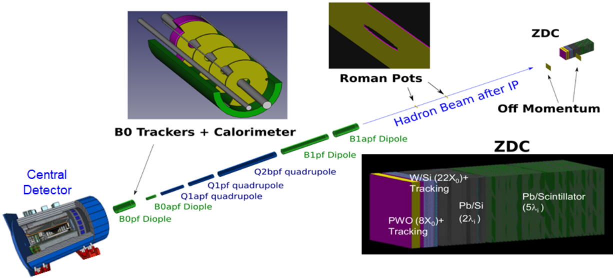
$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{\epsilon_1 - \epsilon_2} \left(\frac{\Delta\sigma}{\sigma}\right) \sqrt{\left(R+\epsilon_1\right)^2 + \left(R+\epsilon_2\right)^2} \quad \text{where} \quad R = \frac{\sigma_T}{\sigma_L},$$

$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{\epsilon_1 - \epsilon_2} \left(\frac{\Delta\sigma}{\sigma}\right) \sqrt{\epsilon_1^2\left(1 + \frac{\epsilon_2}{R}\right)^2 + \epsilon_2^2\left(1 + \frac{\epsilon_1}{R}\right)^2}$$

- The relevant quantities for $F_\pi$ extraction are $R$ and $\Delta\epsilon$

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

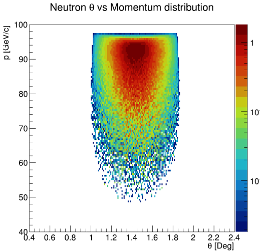
# EIC Detector Overview

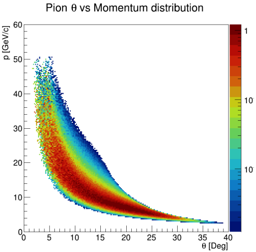


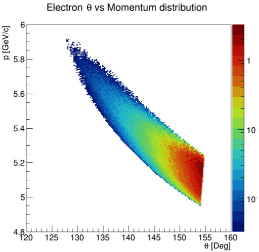

- Feed generator output into detector simulations
- Far forward detectors critical for form factor studies
- Current simulation effort has been focused on the EIC Comprehensive Chromodynamics Experiment (ECCE)
  - `https://www.ecce-eic.org/`

# DEMP Acceptance for $-t < 0.5\ GeV^2$

- $5(e^-)$ on $100(p)$ $GeV$ collisions, 25 $mrad$ crossing angle
- Events weighted by cross section
- No smearing




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

# ECCE Simulations - 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 ($\pi^{+}$)
    - 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

# Simulation Results - Neutron Reconstruction

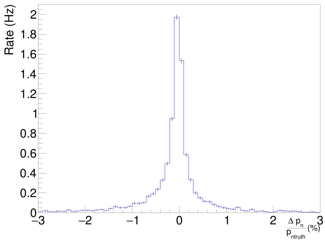
- High energy ZDC hit requirement used as a veto
  - ZDC neutron ERes is relatively poor though

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

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

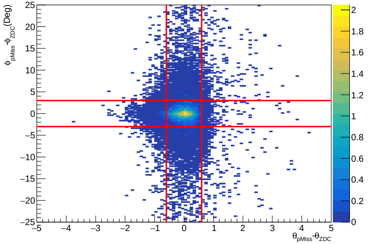
$$p_{miss} = |\vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}|$$

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



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

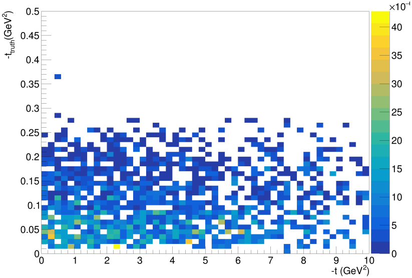
- Make use of high angular resolution of ZDC
- Compare hit $\theta/\phi$ positions of neutron on ZDC to calculated $\theta/\phi$ from $p_{miss}$
- If no other particles produced, quantities should be correlated
  - True for DEMP events
- Energetic neutrons from inclusive background processes will be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




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

# Simulation Results - $t$ Reconstruction

- Reconstruction of $-t$ from detected $e'$ and $\pi^+$ 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




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

# Simulation Results - $t$ Reconstruction

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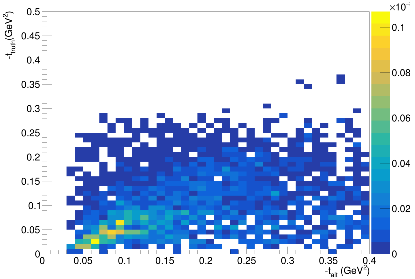
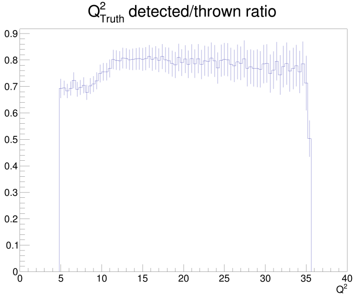



- $x$-axis $-t$ scale an order of magnitude smaller now!

# Simulation Results - Detection Efficiency

- Can examine truth quantities too, quick check of detection efficiency
- $\text{Efficiency} = \frac{\text{Accepted}}{\text{Thrown}}$
- Detection efficiency fairly high, $\sim 80\%$
- Nearly independent of $Q^2$
- Detection efficiency highest for low $-t$
  - Falls off rapidly with increasing $-t$
  - Dictated by size of ZDC



# Simulation Results - Detection Efficiency

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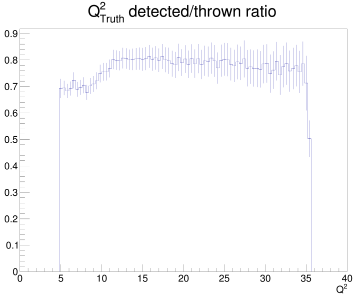
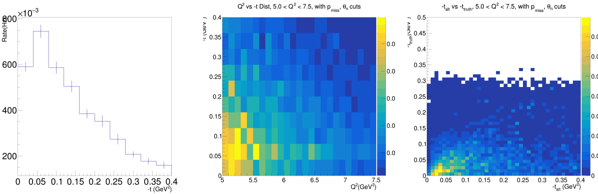
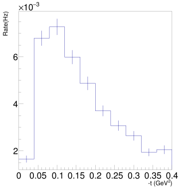


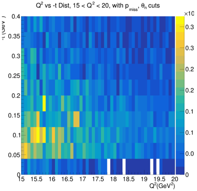
# Simulation Results - $Q^2$ $5 - 7.5$ $GeV^2$

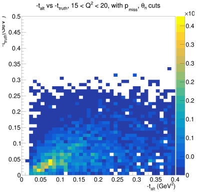



- Predicted $e'\pi^+n$ triple coincidence rate, binned in $Q^2$ and $-t$
  - 5 $(e', GeV)$ on 100 $(p, GeV)$ events
  - $\mathcal{L} = 10^{34}cm^{-2}s^{-1}$ assumed
  - $-t$ bins are 0.04 $GeV^2$ wide
  - Cut on $\theta_n$ $(\theta_n = 1.45 \pm 0.5^\circ)$ and $\vec{p}_{miss} = \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}$ (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

# Simulation Results - $Q^2$ $15 - 20$ $GeV^2$

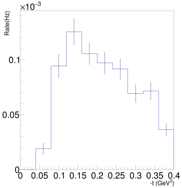


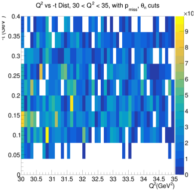



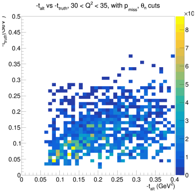




- Predicted $e'\pi^+n$ triple coincidence rate, binned in $Q^2$ and $-t$
  - $5$ $(e', GeV)$ on $100$ $(p, GeV)$ events
  - $\mathcal{L} = 10^{34} cm^{-2} s^{-1}$ assumed
  - $-t$ bins are $0.04$ $GeV^2$ wide
  - Cut on $\theta_n$ $(\theta_n = 1.45 \pm 0.5^\circ)$ and $\vec{p}_{miss} = \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}$ (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

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



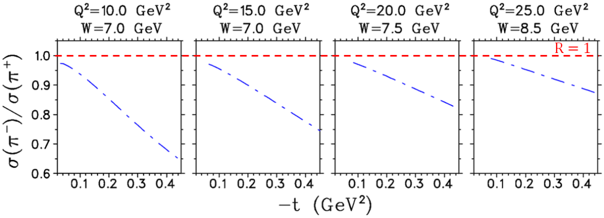

- Predicted $e'\pi^+n$ triple coincidence rate, binned in $Q^2$ and $-t$
  - 5 $(e', GeV)$ on 100 $(p, GeV)$ events
  - $\mathcal{L} = 10^{34} cm^{-2}s^{-1}$ assumed
  - $-t$ bins are 0.04 $GeV^2$ wide
  - Cut on $\theta_n$ ($\theta_n = 1.45 \pm 0.5^\circ$) and $\vec{p}_{miss} = \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}$ (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

# Model Validation via $\pi^-/\pi^+$ ratios

- Measure exclusive $^2H(e,e'\pi^+n)n$ and $^2H(e,e'\pi^-p)p$ in same kinematics as $p(e,e'\pi^+n)$
- $\pi$ $t$-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 $\sigma_T$ *not* small *or* if there are significant non-pole contributions to $\sigma_L$
- Compare $R$ to model expectations

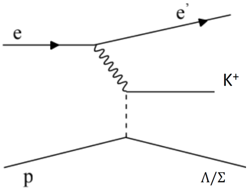



T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

# $F_K$ at the EIC - Challenges and Possibilities

- $F_K$ at the EIC via DEMP will be extremely challenging
- Would need to measure two reactions
  - $p(e, e'K^+\Lambda)$
  - $p(e, e'K^+\Sigma)$
  - Need both for pole dominance tests

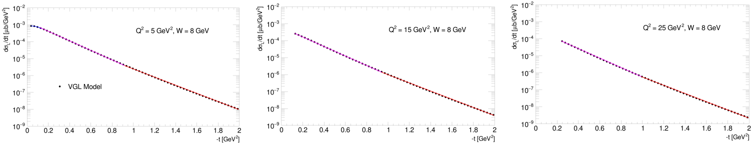
$$R = \frac{\sigma_L\left[p(e, e'K^+\Sigma^0)\right]}{\sigma_L\left[p(e, e'K^+\Lambda^0)\right]} \rightarrow R \approx \frac{g^2_{pK\Sigma}}{g^2_{pK\Lambda}}$$




- Consider just the $\Lambda$ channel for now
  - $\Lambda$ plays a similar role to neutron in $\pi$ studies
  - Very forward focused, **but**, $\Lambda$ will decay
    - $\Lambda \rightarrow n\pi^0$ - $\sim 36$ %
    - $\Lambda \rightarrow p\pi^-$ - $\sim 64$ %
  - Neutral channel potentially best option
    - **Very challenging 3 particle final state**

# $F_K$ at the EIC - Generator Updates

- URegina MSc student Love Preet working on adding Kaon DEMP event generator module to DEMPGen
  - Starting with $p(e, e'K^+\Lambda)$
- Parametrise a Regge-based model in a similar way to the pion
- For $p(e, e'K^+\Lambda)$ module, use the Vanderhagen, Guidal, Laget (VGL) model
- Parametrise $\sigma_L$, $\sigma_T$ 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 (2000) 025204

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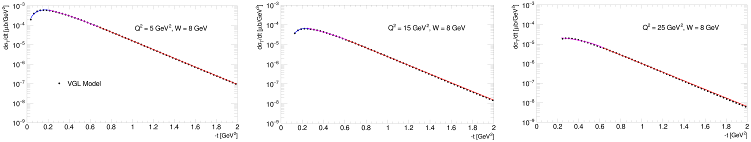
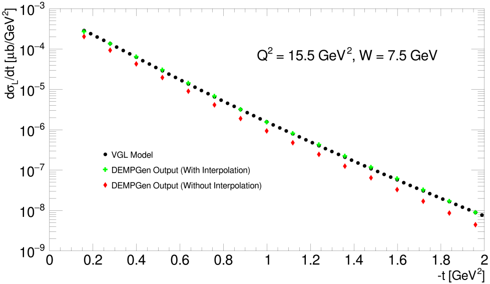



VGL Model - M. Guidal, J.-M. Laget, M. Vanderhaeghen, PRC 61 (2000) 025204

# 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



# Phase 2 Alternative Scenario - 14 $GeV/c$ HMS - $F_\pi$ Prospects

- Replace HMS with higher momentum spectrometer
- Usable beam energy constrained by sum of HMS and SHMS momenta still
- New HMS would not extend $Q^2$ reach beyond the phase 1 scenario
- However, it would result in smaller error bars
  - Larger $\Delta\epsilon$
  - Faster high $\epsilon$ data rates

| $p(e,e'\pi^+)n$ Kinematics | | | | | |
|---|---|---|---|---|---|
| $E_{beam}$ | $\theta_{HMS}$ (e') | $P_{HMS}$ (e') | $\theta_{q(SHMS}$ ($\pi^+$) | $P_{SHMS}$ ($\pi^+$) | Time FOM |
| $Q^2$=8.5 $W$=3.64 $-t_{min}$=0.24 $\Delta\varepsilon$=0.53 | | | | | |
| 13.0 | 34.30 | 1.88 | 5.29 | 10.99 | 64.7 |
| 22.0 | 10.81 | 10.88 | 10.23 | 10.99 | 0.6 |
| $Q^2$=10.0 $W$=3.44 $-t_{min}$=0.37 $\Delta\varepsilon$=0.54 | | | | | |
| 13.0 | 37.78 | 1.83 | 5.56 | 10.97 | 122.7 |
| 22.0 | 11.76 | 10.83 | 10.97 | 10.97 | 1.3 |
| $Q^2$=11.5 $W$=3.24 $-t_{min}$=0.54 $\Delta\varepsilon$=0.29 | | | | | |
| 14.0 | 31.73 | 2.75 | 7.06 | 10.96 | 82.4 |
| 22.0 | 12.66 | 10.75 | 11.56 | 10.96 | 2.5 |

- This scenario is probably not worth it, for $F_\pi$ alone

# Phase 2, Alternative Scenario - 15 $GeV/c$ SHMS - $F_\pi$ Prospects

- Replace SHMS with higher momentum spectrometer
- Dramatic increase in $Q^2$
- Error bars for $Q^2 = 8.5 - 11.5\ GeV^2$ decrease substantially
  - Smaller $-t_{min}$
  - Better $R = \sigma_T/\sigma_L$
  - Shorter running times
- $Q^2 = 15.0\ GeV^2$ point "expensive" in terms of running time, but high scientific priority
- Compelling case for a phase 2 upgrade option

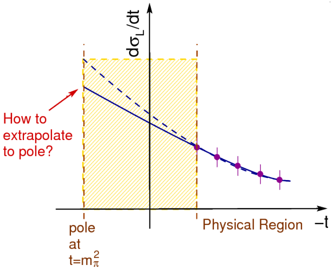
**$p(e,e'\pi^+)n$ Kinematics**

| $E_{beam}$ | $\theta_{HMS}$ (e') | $P_{HMS}$ (e') | $\theta_{q(SHMS)}$ ($\pi^+$) | $P_{SHMS}$ ($\pi^+$) | Time FOM |
|---|---|---|---|---|---|
| $Q^2$=8.5 $W$=4.06 $-t_{min}$=0.17 $\Delta\varepsilon$=0.26 | | | | | |
| 16.0 | 23.68 | 3.15 | 5.52 | 12.75 | 17.7 |
| 20.0 | 14.00 | 7.15 | 7.55 | 12.75 | 1.9 |
| $Q^2$=10.0 $W$=3.96 $-t_{min}$=0.23 $\Delta\varepsilon$=0.28 | | | | | |
| 16.0 | 27.41 | 2.78 | 5.41 | 13.09 | 47.7 |
| 20.0 | 15.60 | 6.78 | 7.72 | 13.09 | 4.5 |
| $Q^2$=11.5 $W$=3.96 $-t_{min}$=0.29 $\Delta\varepsilon$=0.27 | | | | | |
| 17.0 | 27.54 | 2.98 | 5.49 | 13.86 | 76.3 |
| 21.0 | 16.10 | 6.98 | 7.72 | 13.86 | 8.1 |
| $Q^2$=13.0 $W$=3.96 $-t_{min}$=0.35 $\Delta\varepsilon$=0.25 | | | | | |
| 18.0 | 27.55 | 3.18 | 5.54 | 14.63 | 123.6 |
| 22.0 | 16.49 | 7.18 | 7.69 | 14.63 | 14.4 |
| $Q^2$=15.0 $W$=3.78 $-t_{min}$=0.50 $\Delta\varepsilon$=0.27 | | | | | |
| 18.0 | 31.30 | 2.86 | 5.46 | 14.87 | 391 |

## Chew-Low Method to determine $F_\pi$

- $p(e, e'\pi^+)n$ 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 $F_\pi$ at JLab

- Only reliable approach for extracting $F_\pi$ from $\sigma_L$ is to use a model that incorporates the $\pi^+$ production mechanism and the spectator nucleon
- JLab $F_\pi$ experiments so far use the VGL Regge model
  - Reliably describes $\sigma_L$ 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 $F_\pi$ can be extracted as the models improve**

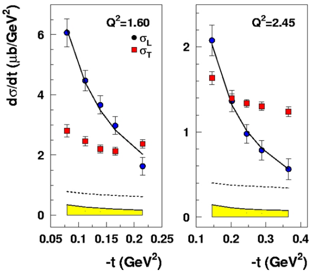
VGL - Vanderhaeghen-Guidal-Laget Model - Vanderhaeghen, Guidal, Laget, PRC 57(1998) 1454

# $F_\pi(Q^2)$ from JLab Data

VGL model incorporates $\pi^+$ production mechanism and spectator neutron effects

- Feynman propagator - $\frac{1}{t-m_\pi^2}$ replaced by $\pi$ and $\rho$ Regge propagators
- Represents the exchange of a series of particles, compared to a single particle
- Free parameters - $\Lambda_\pi, \Lambda_\rho$ - Trajectory cutoff parameters
- At small $-t$, $\sigma_L$ only sensitive to $F_\pi$

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



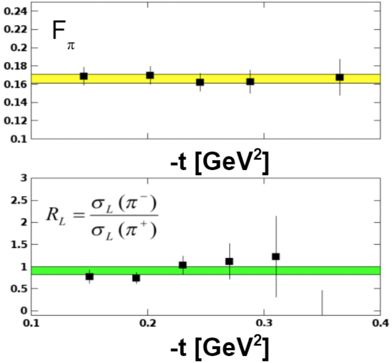

Error bars indicate statistical and random (pt-pt) systematic uncertainties in quadrature. Yellow band indicates the correlated (scale) and partly correlated (t-corr) systematic uncertainties.
$\Lambda_\pi^2 = 0.513, 0.491\ GeV^2$, $\Lambda_\rho^2 = 1.7\ GeV^2$
T. Horn, et al., PRL 97(2006) 192001

# Two $F_\pi$ Validation Methods

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

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

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

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