π^-/π^+ Exclusive Pion Electroproduction Results from Jefferson Lab

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Jefferson Lab F_π Collaboration

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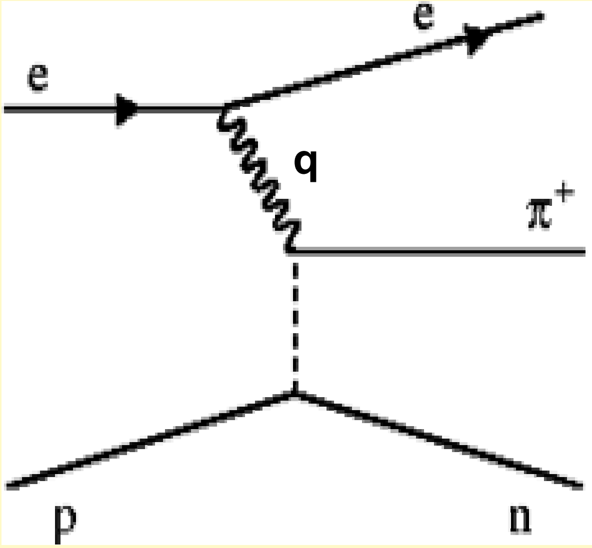
Deep Exclusive Meson Production

- **Single π^+ produced from proton, or π^- from neutron at high momentum transfer.**
- Probes the relevant degrees of freedom within nucleon at different distance scales.
- Use the virtual photon's longitudinal and transverse polarizations to act as a filter on the details of the probing interaction.



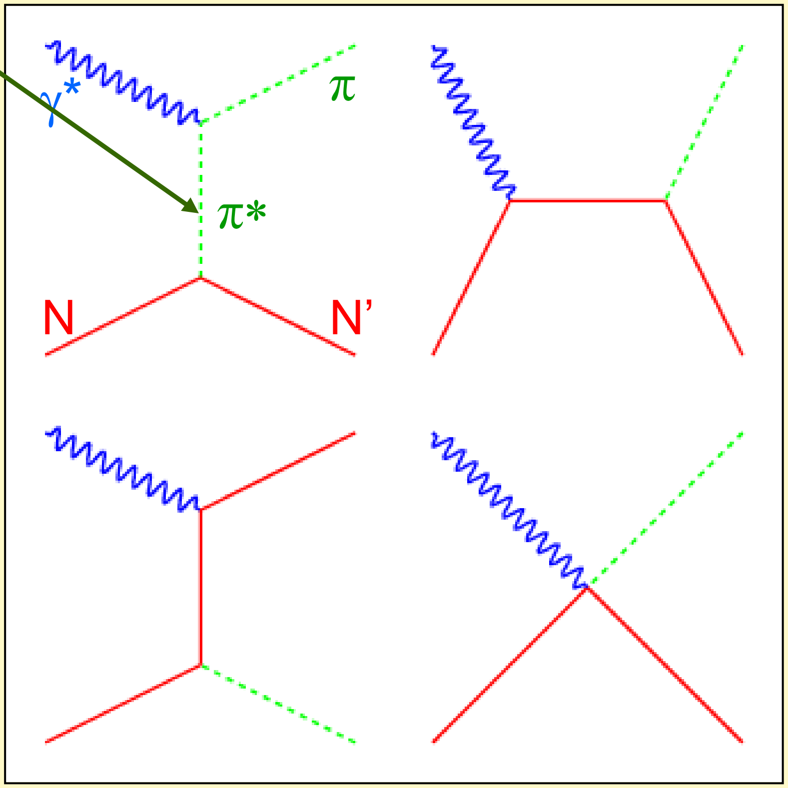
$$R_T = \frac{\gamma_T^* n \to \pi^- p}{\gamma_T^* p \to \pi^+ n} \xrightarrow[high\ -t]{} \frac{2Q_d^2}{2Q_u^2} = \frac{(-1/3)^2}{(+2/3)^2} = \frac{1}{4}$$

A. Nachtmann, Nucl. Phys. **B 115** (1976) 61.

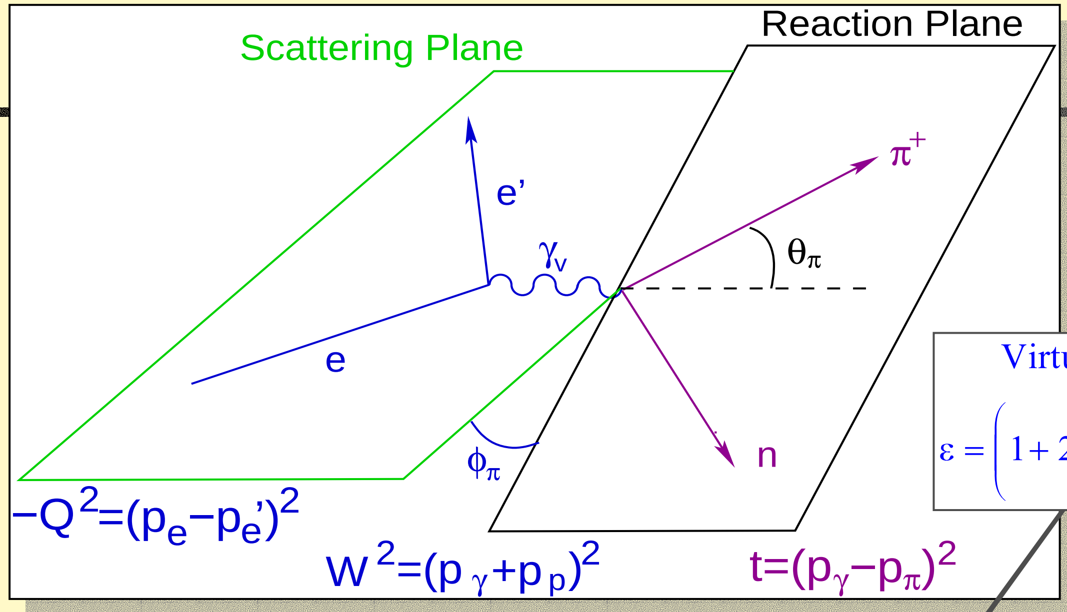
At low –t, Meson-Nucleon Degrees of Freedom

- $\pi^{\pm}$ *t*-channel diagram is purely isovector (G-parity conservation).

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



- A significant deviation of R_L from unity would indicate the presence of Isoscalar backgrounds (such as b_1(1235) contributions to *t*-channel).
- Relevant for the extraction of the pion form factor from $p(e,e'\pi^+)n$ data, which uses a model including some isoscalar background.



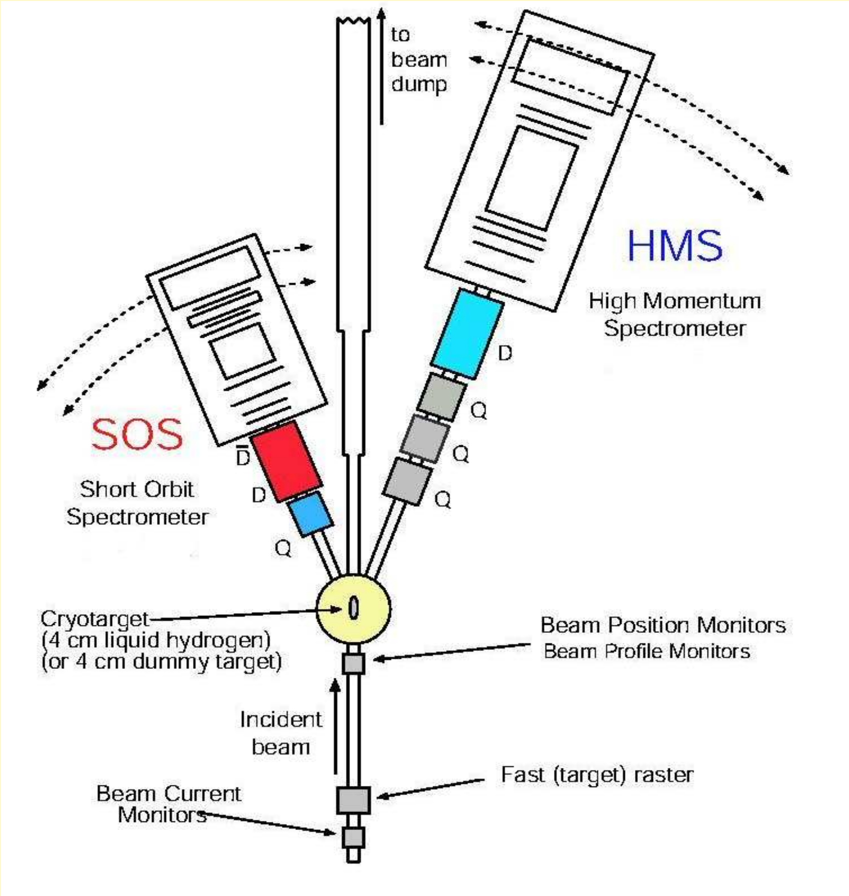
Virtual-photon polarization:

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

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

1. At small $-t$, σ_L has maximum contribution from the π pole.
   - $t=(p_{target}-p_{recoil})^2$ used in this analysis.
   - not necessarily equivalent to $t=(p_\gamma-p_\pi)^2$ due to Fermi momentum and radiation.
2. Only three of Q^2, W, t, θ_π are independent.
   - Vary θ_π to measure t dependence.
   - Since non-parallel data needed, LT and TT must also be determined.

Jefferson Lab Hall C Experimental Setup



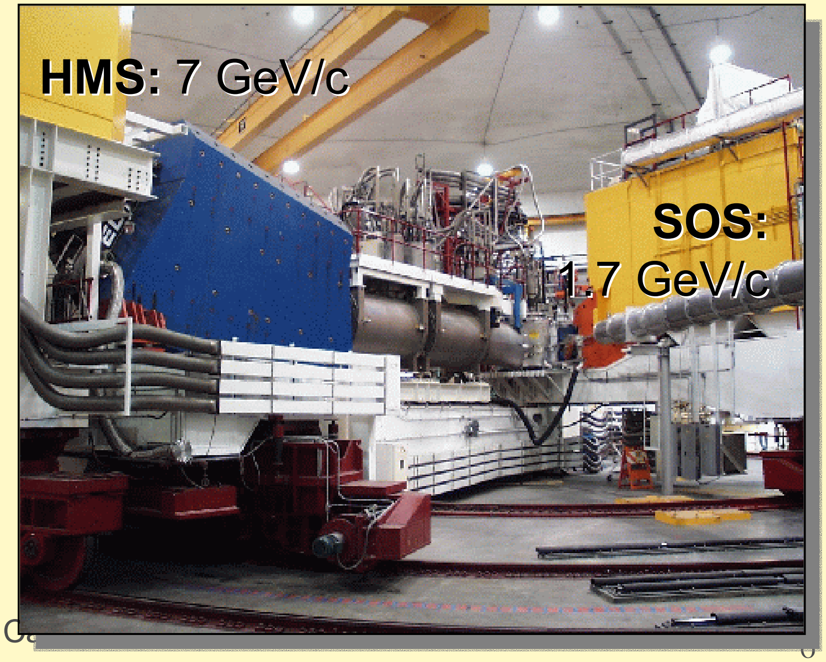
Exp	Q^2 $(GeV/c)^2$	W (GeV)	$\lvert t_{min} \rvert$ $(Gev/c)^2$	E_e (GeV)
Fπ-1	0.6-1.6	1.95	0.03-0.150	2.445-4.045
Fπ-2	2.45	2.22	0.189	4.210-5.246

Hall C spectrometers:

- Coincidence measurement.
- SOS detects e^-.
- HMS detects π^+ and π^-.

Targets:

- Liquid 4-cm H/D cells.
- Al target for empty cell measurement.
- ^{12}C solid targets for optics calibration.

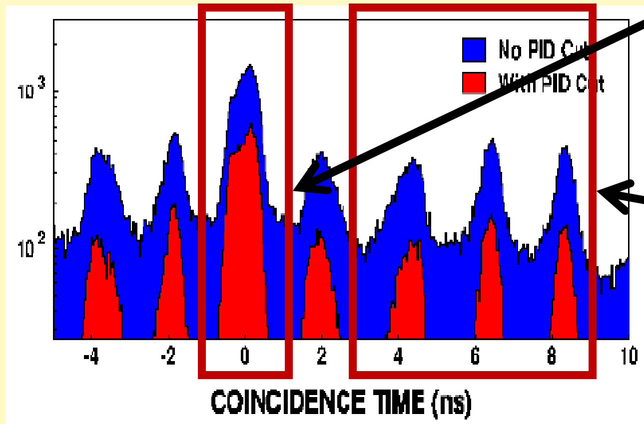


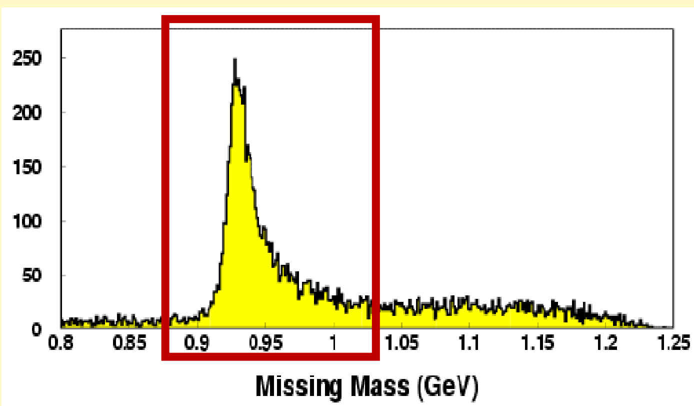
$^2H(e,e'\pi^{\pm})NN$ Event selection

Pions detected in HMS – Cerenkov & Coincidence time for PID

Electrons detected in SOS –Cerenkov & Lead Glass Calorimeter

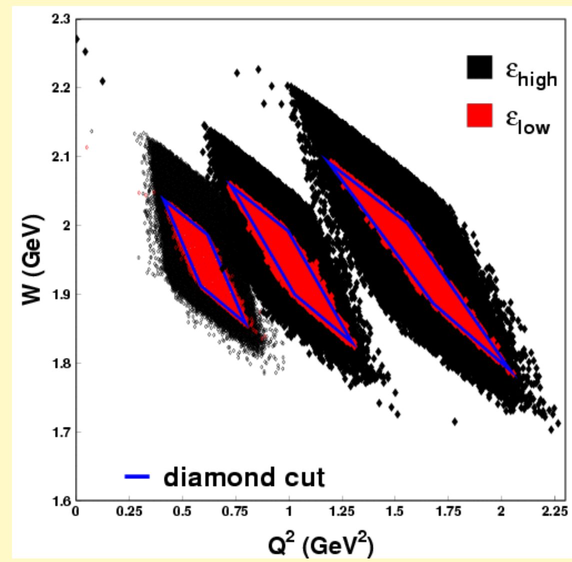
Coincidence time resolution ~200-230 ps. Cut value ±1 ns.





Exclusivity assured via 0.875<MM<1.03 GeV cut

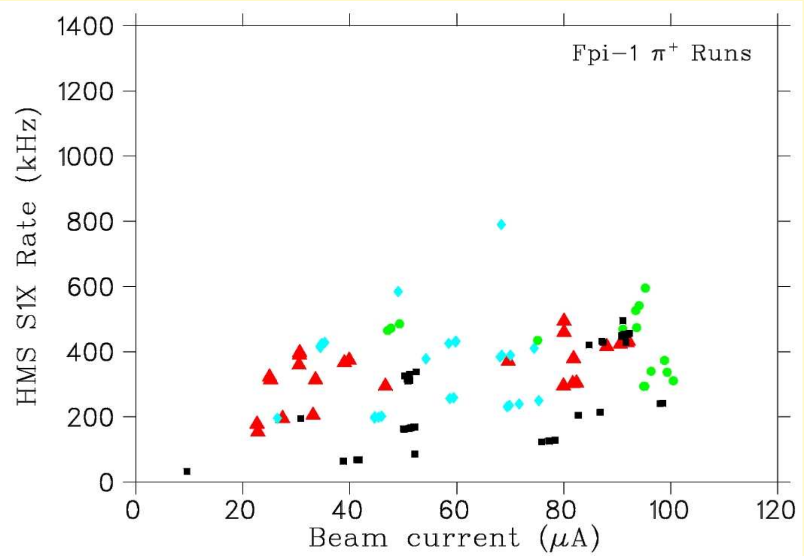
After PID & MM cuts, almost no random coincidences remain.

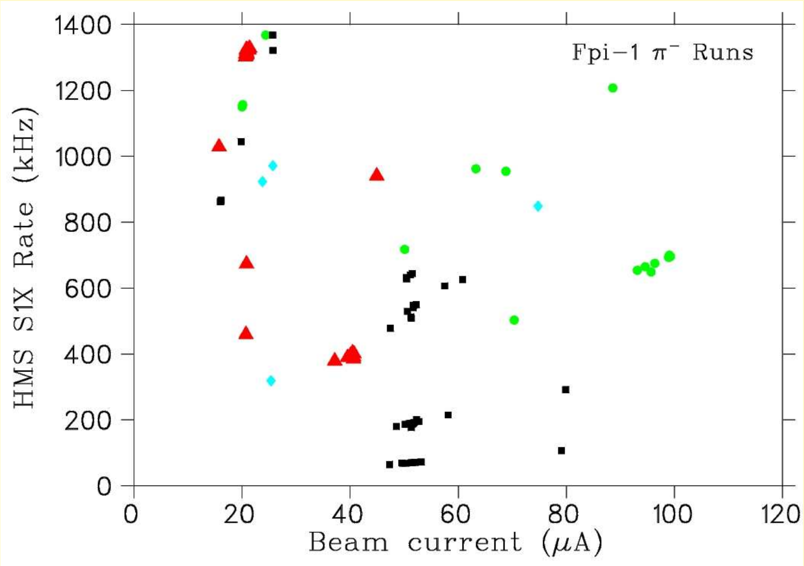


Diamond cuts define common (W,Q^2) coverage at both ε.

Corrections to π^-, π^+ Data

- **Negative polarity of HMS field for ^{2}H(e,e'π^-)pp means these runs have high electron rates not shared by ^{2}H(e,e'π^+)nn runs.**
- **Understanding rate dependent corrections very important with respect to final π^-/π^+ ratios.**
  - Improved high rate HMS tracking algorithm.
  - More accurate high rate tracking efficiencies (91-98%).
  - HMS π^- misidentification correction due to e^- pileup in Cerenkov (13%/MHz e^-).
  - High current ^{2}H target boiling correction (4.7%/100μA).

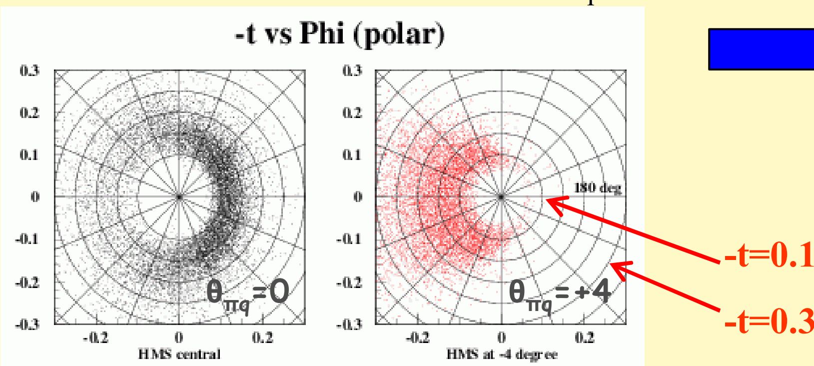




Q^2=0.60, 0.75, 1.0, 1.6 GeV^2

Extract response functions through iterative procedure

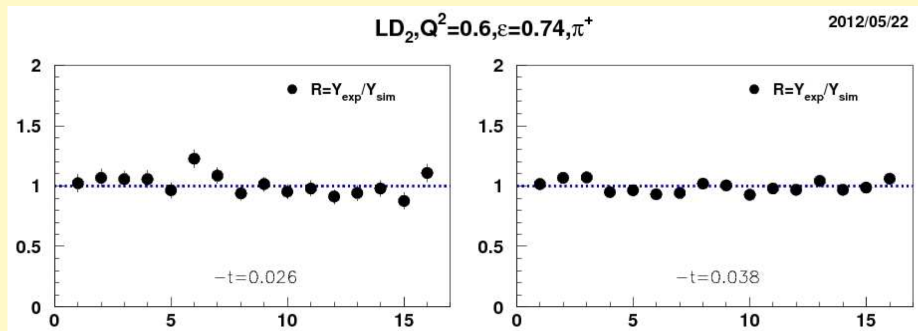
Improve φ coverage by taking data at multiple π (HMS) angles, $-4^o < \theta_{\pi q} < 4^o$.



For each π HMS setting, form ratio:

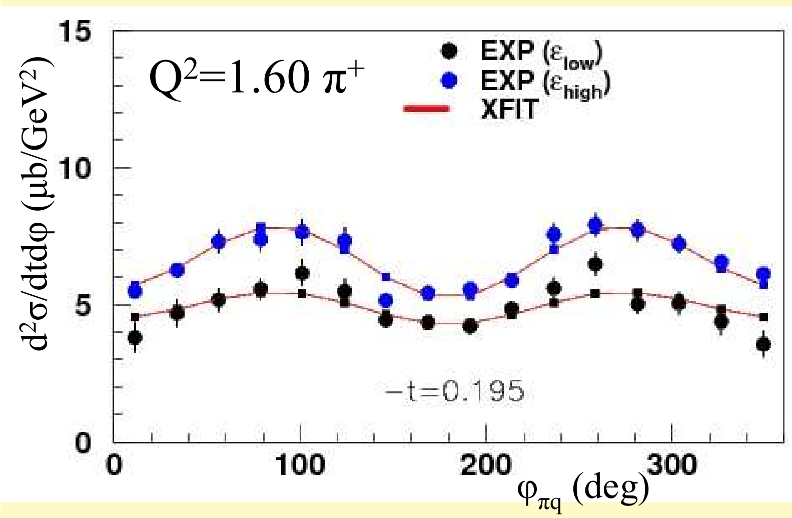
$$R = \frac{Y_{EXP}}{Y_{SIMC}}$$

Combine ratios for π settings together, propagating errors accordingly.



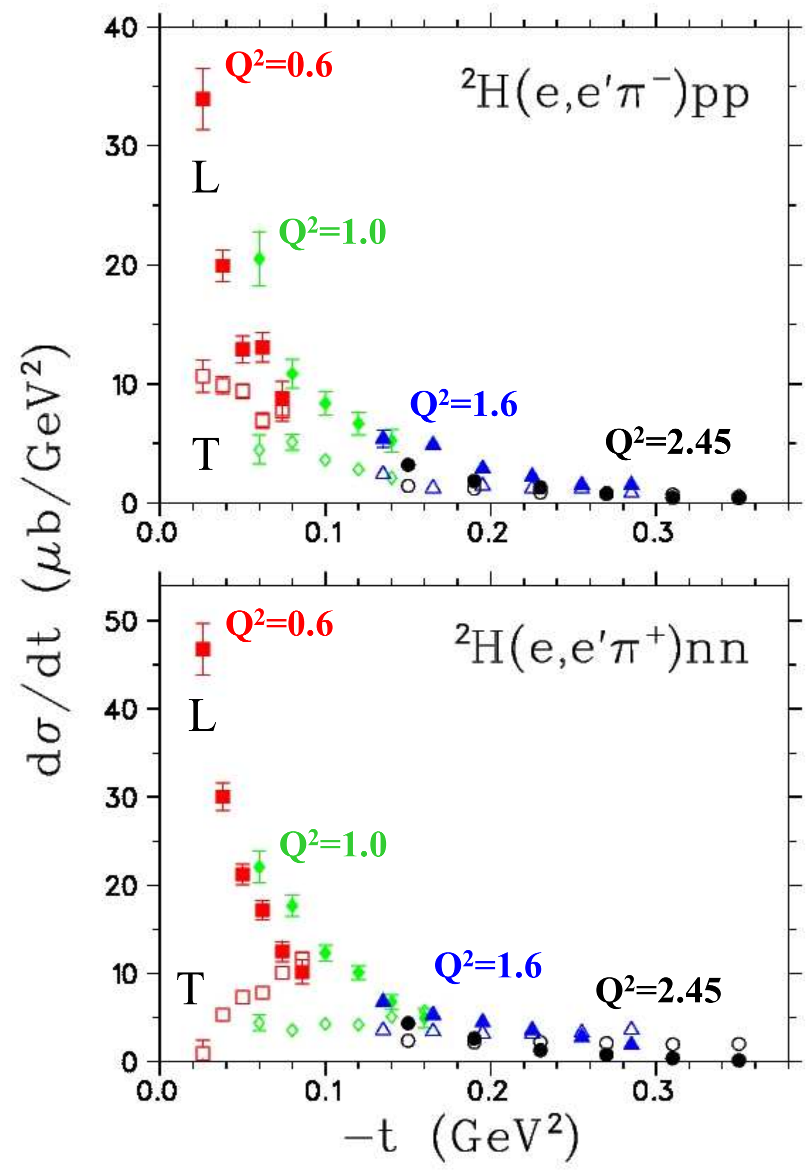
$$\left.\frac{d^2\sigma}{dtd\varphi}\right|_{EXP} = \left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\left.\frac{d^2\sigma}{dtd\varphi}\right|_{SIMC}$$

Extract via simultaneous fit of L,T,LT,TT



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

$^2H(e,e'\pi^{\pm})NN$ Separated dσ/dt



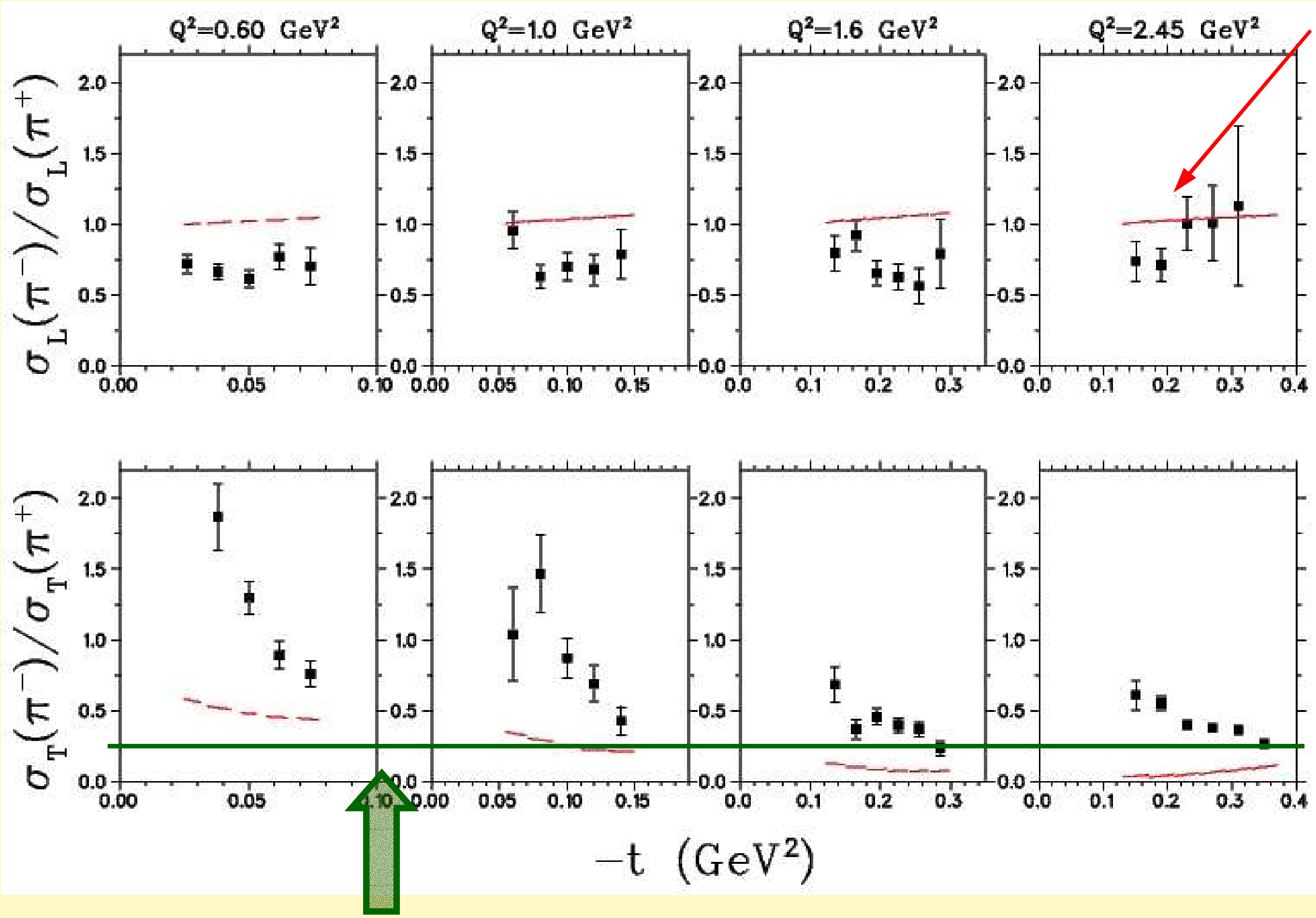
- Data points have slightly different $\overline{W}, \overline{Q}^2$
- All data scaled to W=2.0 GeV assuming $1/(W^2\text{-}M^2)$ dependence, M=free nucleon mass.
- No scaling applied in Q^2.

- **Longitudinal cross-section shows steep rise due to π pole at small –t.**
- **Transverse cross-section much flatter, generally smaller for π^-.**
- **Both follow nearly universal curves vs –t, with only a weak Q^2-dependence.**

Error bars indicate statistical and pt-pt systematic uncertainties in quadrature.

Dr. Garth Huber, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.

π^-/π^+ Separated Response Function Ratios



VGL Regge Model:

- π electroproduction in terms of exchange of π and ρ Regge trajectories.
  [PRC **57**(1998)1454]
- Model parameters fixed from pion photoproduction.
- Free parameters: Λ_π^2 and Λ_ρ^2 (from ^{1}H data).

R_L=0.8 consistent with $|A_S/A_V|$<6%.

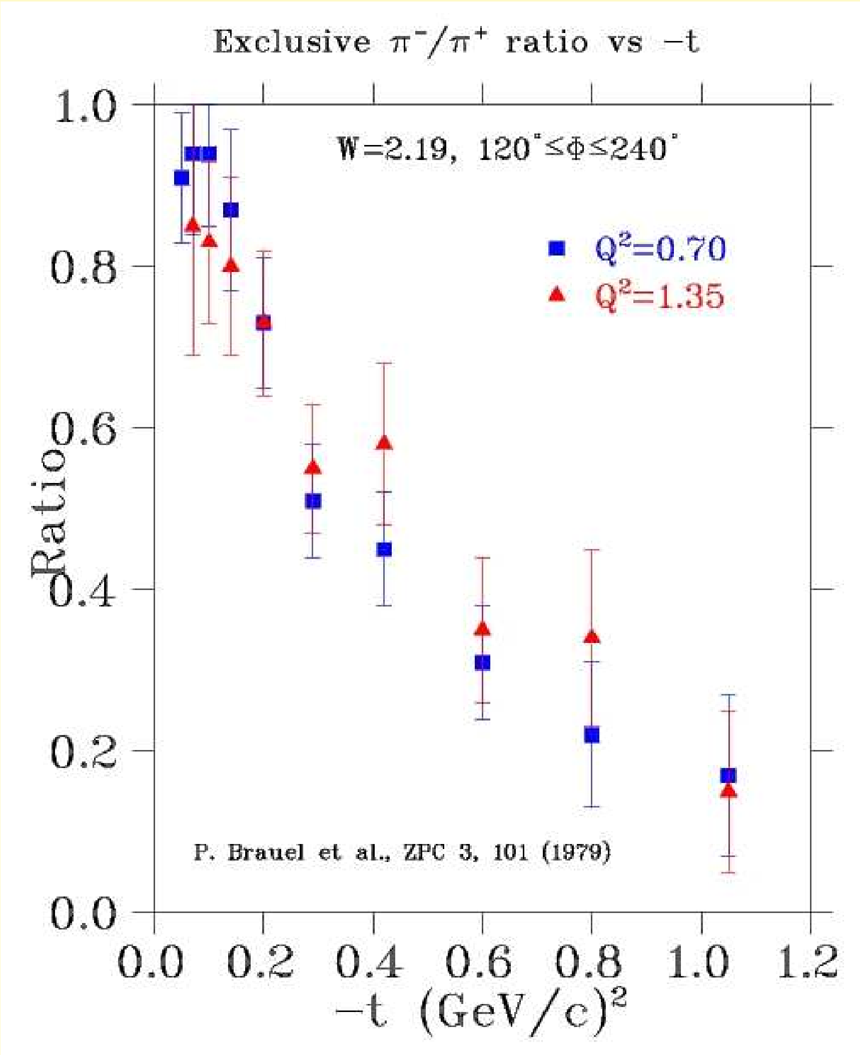
- Transverse Ratios tend to ¼ as –t increases:
  → Is this an indication of Nachtmann's quark charge scaling?
- -t=0.3 GeV² seems too low for this to apply. Might indicate the partial cancellation of soft QCD corrections in the formation of the ratio.

Summary

- **Separated σ_L, σ_T, σ_{LT}, σ_{TT} cross sections for the $^2H(e,e'\pi^{\pm})NN$ reactions were extracted using the Rosenbluth L/T separation technique.**
  - Fπ-1: W=1.95 GeV: Q^2=0.6, 1.0, 1.6 GeV^2.
  - Fπ-2: W=2.2 GeV: Q^2=2.45 GeV^2.

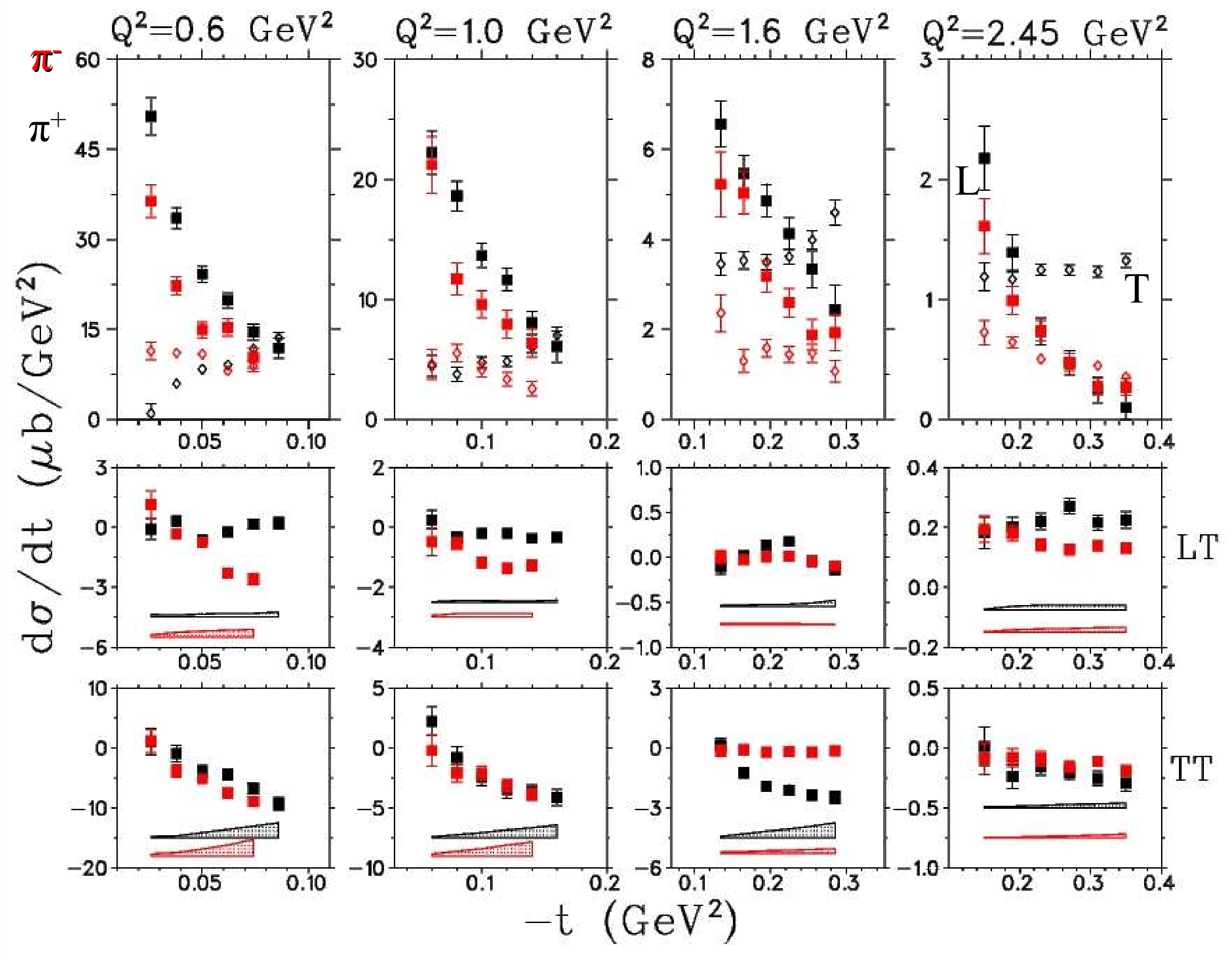
- **π^-/π^+ ratios for σ_L, σ_T extracted as a function of -t.**
  - $R_L \approx 0.8$, trending towards unity at low –t.
    - Indicates the dominance of isovector processes at low –t in the longitudinal response function.
  - The evolution of R_T with –t shows rapid fall off consistent with earlier theoretical predictions, expected to approach ¼, the square of the ratio of the quark charges involved.
    - Further theoretical work needed re. alternate explanations.

Only Prior $^2H(e,e'\pi^\pm)NN$ Data



- Only prior exclusive $^2H(e,e'\pi^\pm)NN$ data was obtained at DESY in the 1970's.
  - Unseparated cross sections only, due incomplete φ coverage.
  - Q^2=0.70, 1.35 GeV^2.
- π^-/π^+ ratio intriguingly approaches Nachtmann's quark counting ratio $\rightarrow 1/4$ at high $-t$.
- Ratio approaches π pole dominance $\rightarrow 1$ at low $-t$.
- Need separated $^2H(e,e'\pi^\pm)NN$ data over a wide kinematic range to better interpret ratios!

$^2H(e,e'\pi^{\pm})NN$ Separated $d\sigma/dt$



- Longitudinal cross-section shows steep rise due to π pole at small $-t$.
- Transverse cross-section much flatter, generally smaller for π^-.
- Negative TT.
- LT nearly zero.

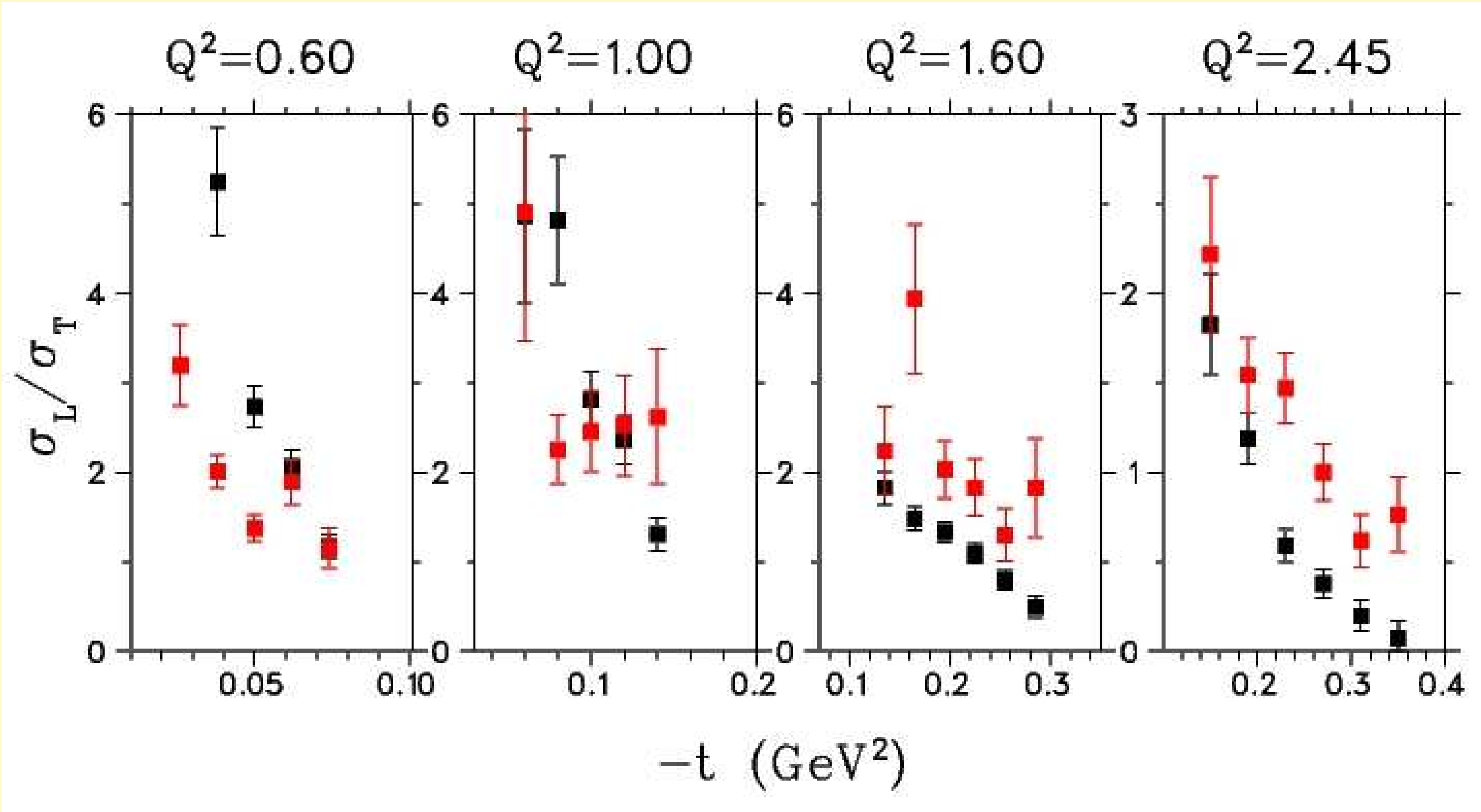
Error bars indicate statistical and pt-pt systematic uncertainties in quadrature.
Bands indicate LT,TT MC model dependence systematic uncertainty.

σ_L/σ_T Ratios for π^+, π^-

- L/T ratio becomes more favorable for π^- production as Q^2 increases.

$^2H(e,e'\pi^+)nn$

$^2H(e,e'\pi^-)pp$



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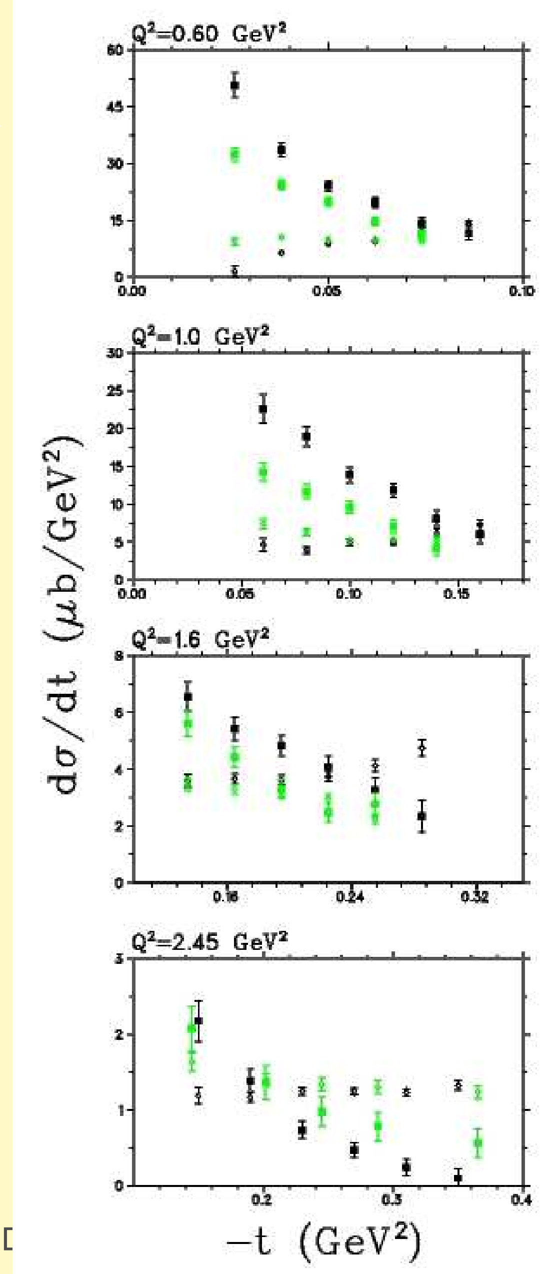
Comparison of π^+ from ^1H and ^2H

$^2H(e,e'\pi^+)nn$

$^1H(e,e'\pi^+)n$



- **Intriguing differences between π^+ production from hydrogen and deuterium.**
- σ_L consistently larger from ^2H than ^1H.
- σ_T t-dependences different as well.

- **Keep in mind that ^2H cross sections are effective ones, not trivially comparable to ^1H.**
- Role of off-shell effects in ^2H?
- Role of Fermi momentum in ^2H?

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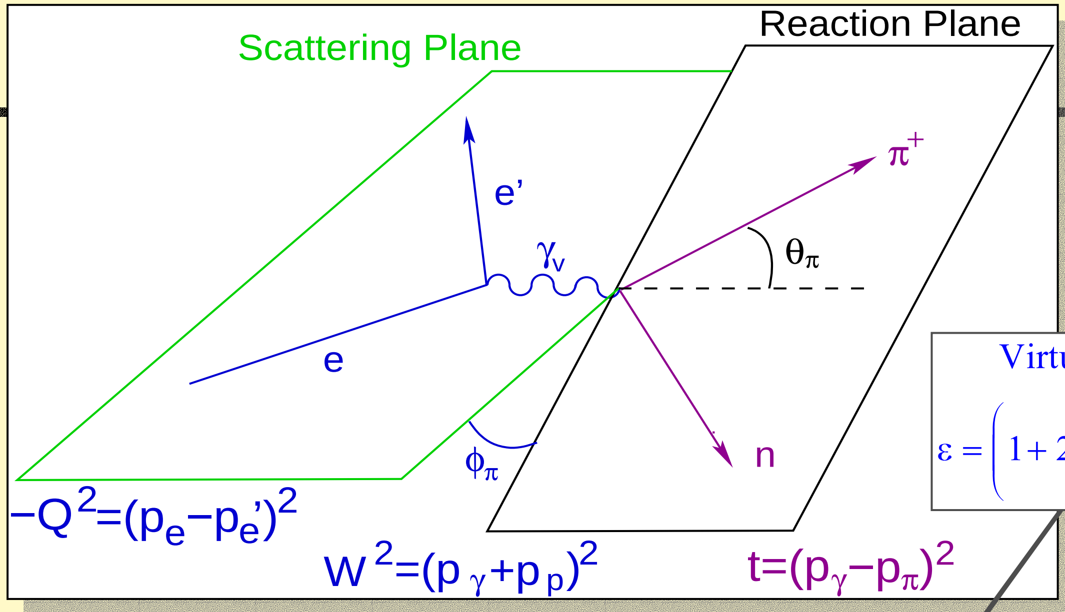

Virtual-photon polarization:

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   - Vary θ_π to measure t dependence.
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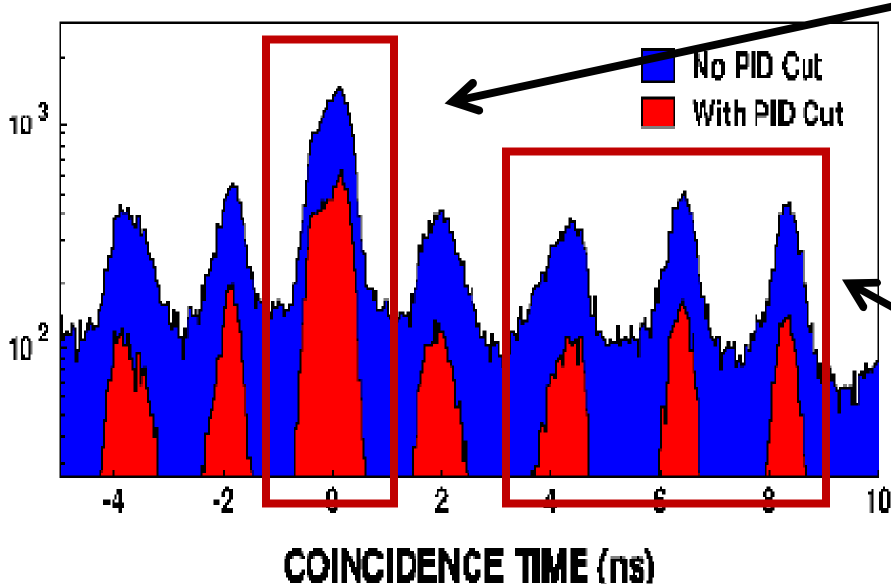
$^2H(e,e'\pi^{\pm})NN$ Event selection

Electron-pion coincidences

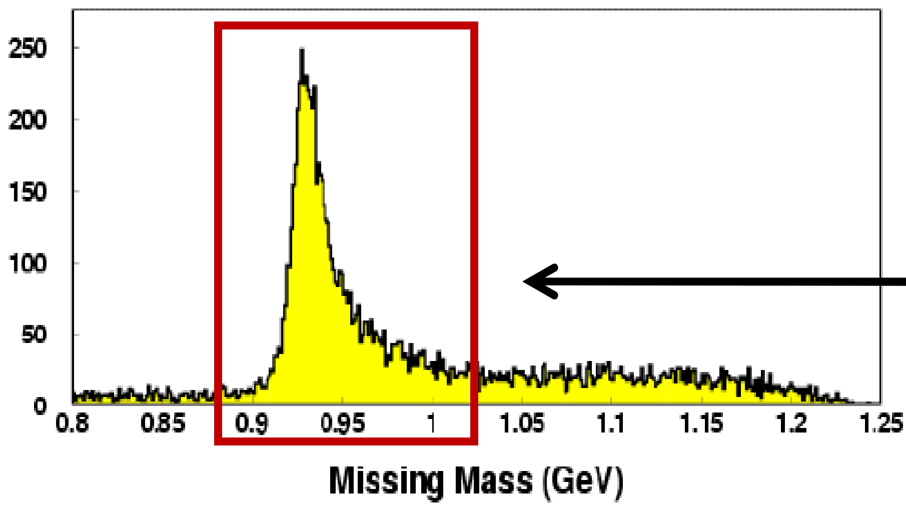


Pions detected in HMS – Cerenkov & Coincidence time for PID

Coincidence time resolution ~200-230 ps.

Cut value ±1 ns.

Random coincidences



Electrons detected in SOS – Cerenkov & Lead Glass Calorimeter

Exclusivity assured via $0.875<MM<1.03$ GeV cut

- **After PID & MM cuts, almost no random coincidences remain.**

Magnetic Spectrometer Calibrations

- Over-constrained *p(e,e'p)* reaction and elastic *e*+^{12}C reactions used to calibrate spectrometer acceptances, momenta, offsets, etc.
- Spectrometers well-understood after careful comparison with MC simulations.
  - Beam energy and spectrometer

    momenta determined to <0.1%.
  - Spectrometer angles to <1 mrad.
- Agreement with published *p*+*e* elastics cross sections <2%.

Source	Pt-Pt	ε uncorr. t corr,	Scale
Beam and Spectrometer Kinematic Offsets	0.2%	0.8-1.1%	
HMS β-cut corrections	0.4%		
Particle ID		0.2%	
Pion Absorption Correction			1.0%
Pion Decay Correction	0.03%		1.0%
HMS Tracking		0.4% (π+) 1.3% (π-)	1.0% (π+) 1.0% (π-)
SOS Tracking		0.2%	0.5%
Integrated Beam Charge	0.3%		0.5%
Target Thickness		0.3%	1.0%
CPU and Trigger Dead time		0.3%	
HMS Cerenkov Veto Correction (π-)	0.7%		2.0%
Missing Mass Cut	0.8%		1.3%
Spectrometer Acceptance	1.0%	0.6%	1.0%
MC Model Dependence (L,T)	0.4%	0.7-3.5%	0.3-2.0%
Radiative Corrections		0.4%	2.0%
TOTAL (π+)	**1.4%**	**1.4-3.6%**	**3.1-3.5%**
TOTAL (π-)	**1.6%**	**2.3-4.4%**	**3.7-4.2%**
Typical Statistical Uncertainty (per t-bin)	**5-10%**		