Separated π^- / π^+ Ratios from the Pion Form Factor Experiments

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AS ONE WHO SERVES

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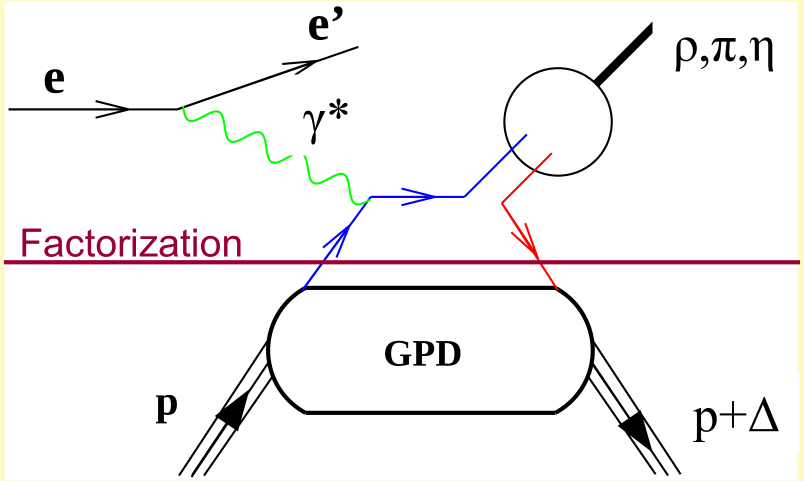
GPDs in Deep Exclusive Meson Production

Four GPDs at leading twist:

→ Unpolarized: $H(x, \xi, t)$, $E(x, \xi, t)$

→ Polarized: $\tilde{H}(x, \xi, t)$, $\tilde{E}(x, \xi, t)$



Second set of four GPDs at twist-3: $\tilde{H}_T$, H_T, $\tilde{E}_T$, E_T

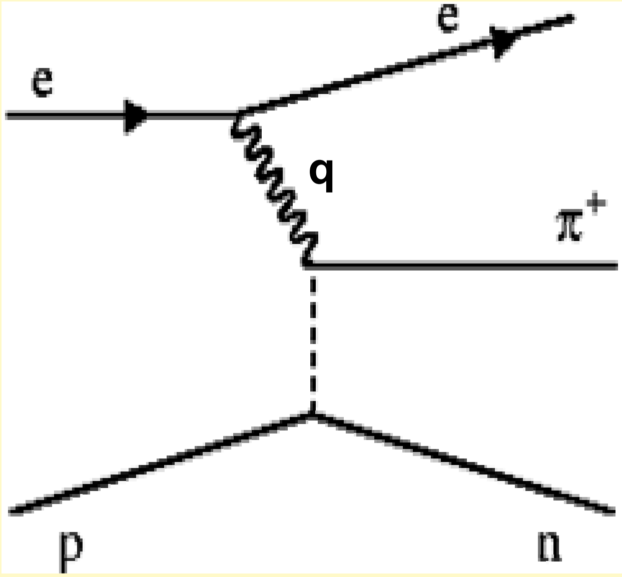
In the forward limit, H_T reduces to the transversity distribution $h_1(x)$.

→ Dominant twist-3 contribution from H_T contributes to $M_{0-,++}$ amplitude

→ Manifested in the transverse cross section or interference terms: σ_T, σ_{TT}, σ_{LT}, and various single spin asymmetries.

Deep Exclusive $\pi^{\pm}$ Production

- **Single π^+ produced from proton, or π^- from neutron at high momentum transfer.**
- **Can form ratios of separated cross-sections for which non-perturbative corrections may partially cancel, yielding insight into soft-hard factorization at modest Q^2.**



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

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

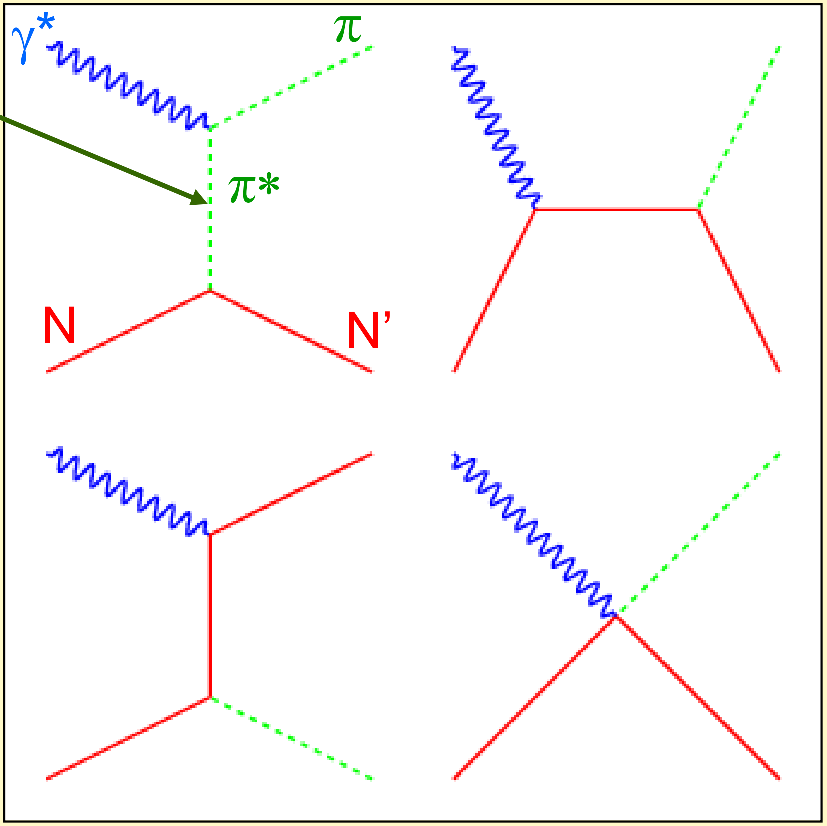
- **Pseudoscalar meson production has been identified as especially sensitive to chiral-odd transverse GPDs.**
  → R_T is not complicated by the π–pole term.

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 extraction of pion form factor from p(e,e'π^+)n data, which uses model including some isoscalar background.

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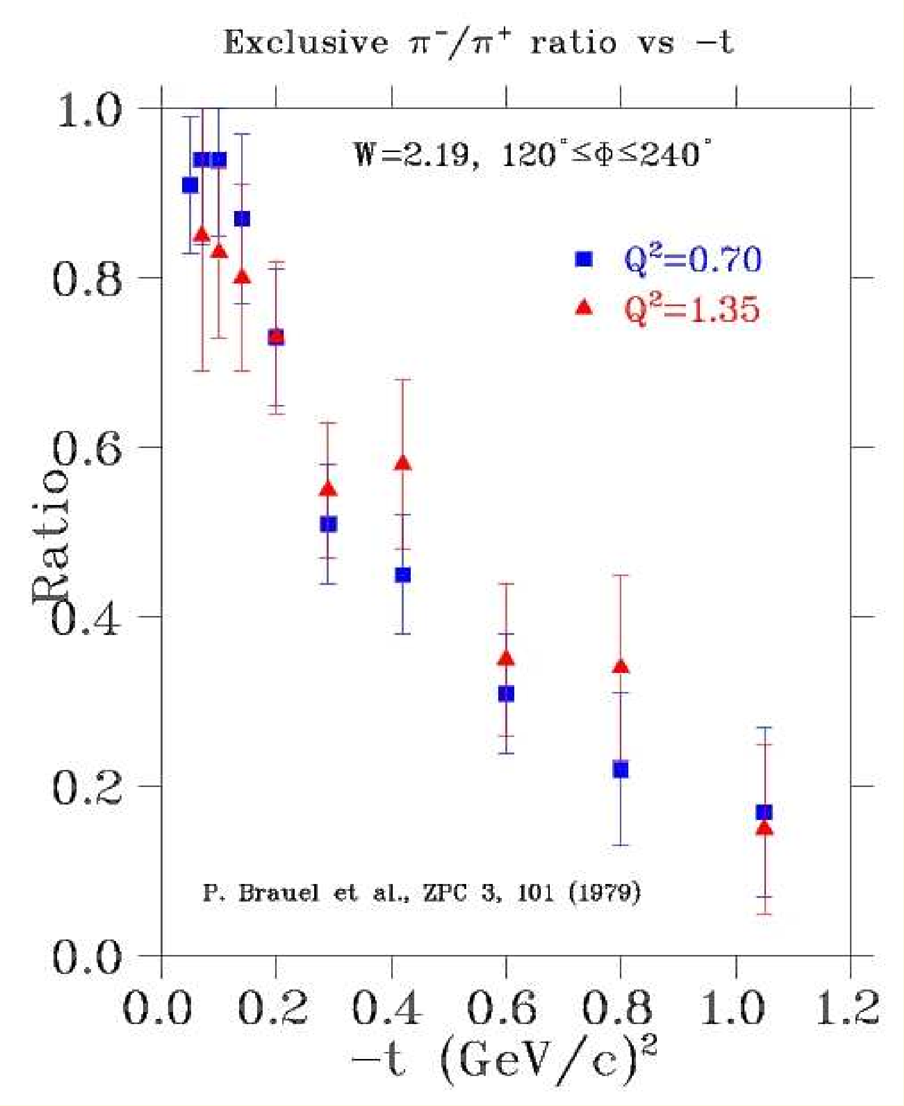
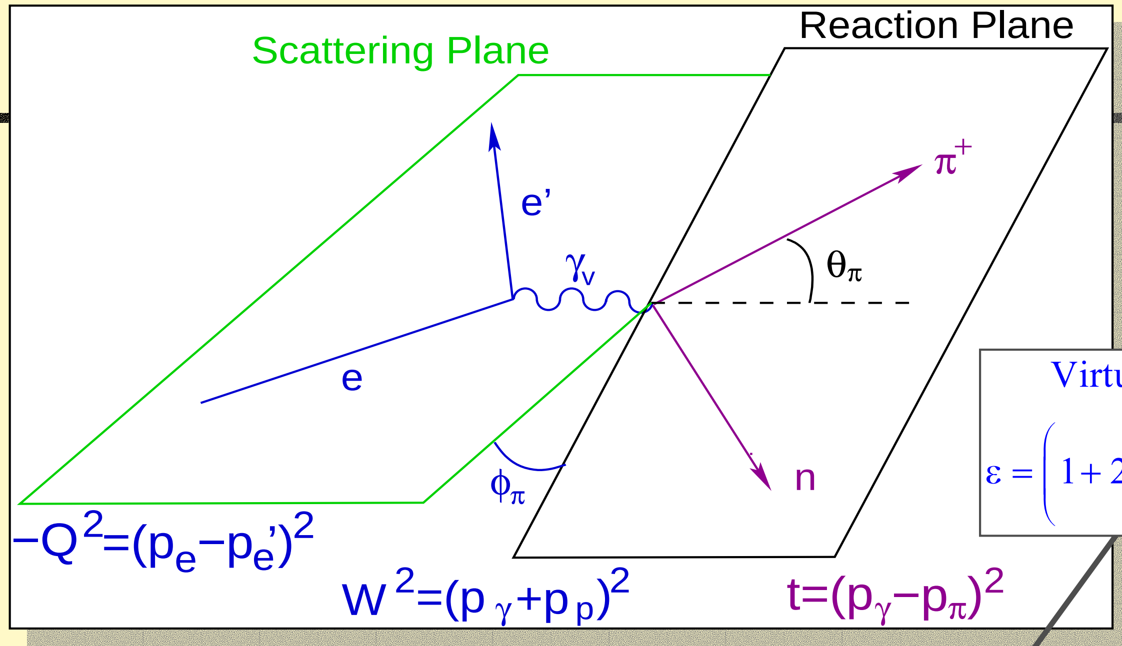
Only Prior ^{2}H(e,e'$\pi^\pm$)NN Data



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



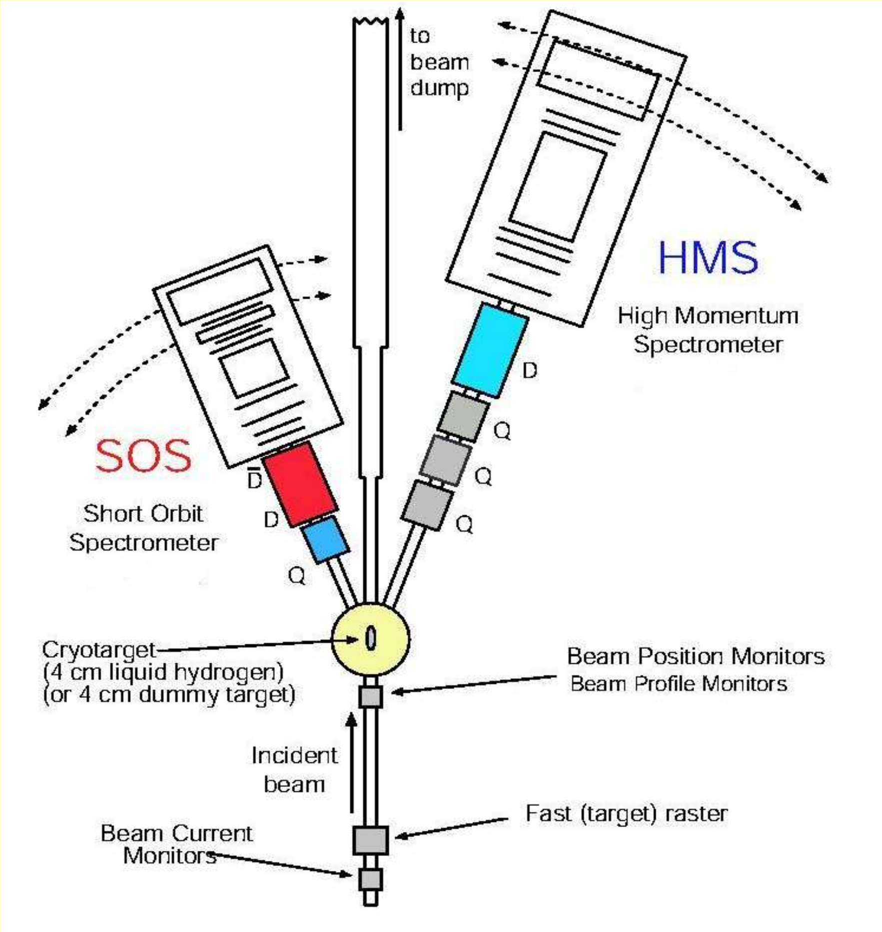
Virtual-photon polarization:

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

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

1. At small $-t$, σ_L has maximum contribution from the π pole.
2. Need to investigate t dependence at relatively fixed Q^2, W, but 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



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.

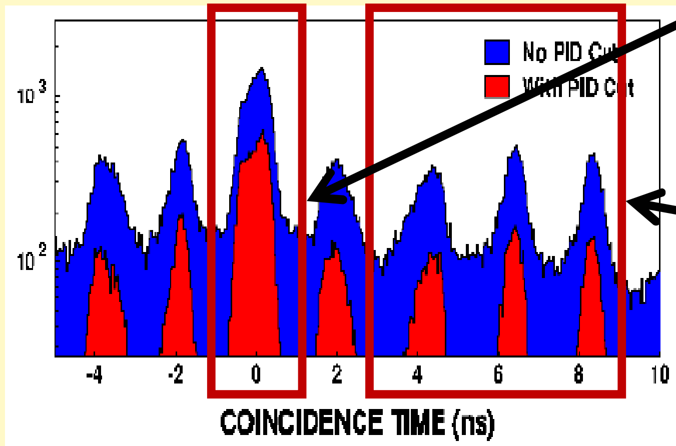
Exp	Q^2 $(GeV/c)^2$	W (GeV)	$\|t_{min}\|$ $(Gev/c)^2$	E_e (GeV)
Fπ-1	0.6-1.6	1.95	0.03-0.150	2.445-4.045
Fπ-2	2.45	2.22	0.189	4.210-5.246

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

Pions detected in HMS – Cerenkov & Coincidence time for PID

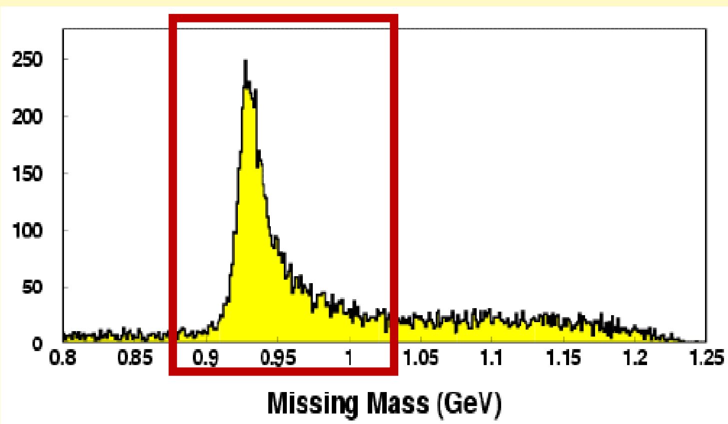
Electrons detected in SOS –Cerenkov & Lead Glass Calorimeter

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



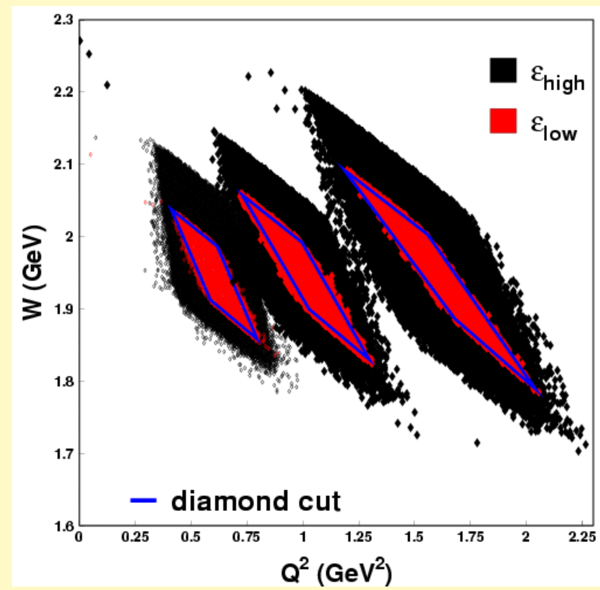
Electron-pion coincidences

Random coincidences



Exclusivity assured via 0.875<MM<1.03 GeV cut

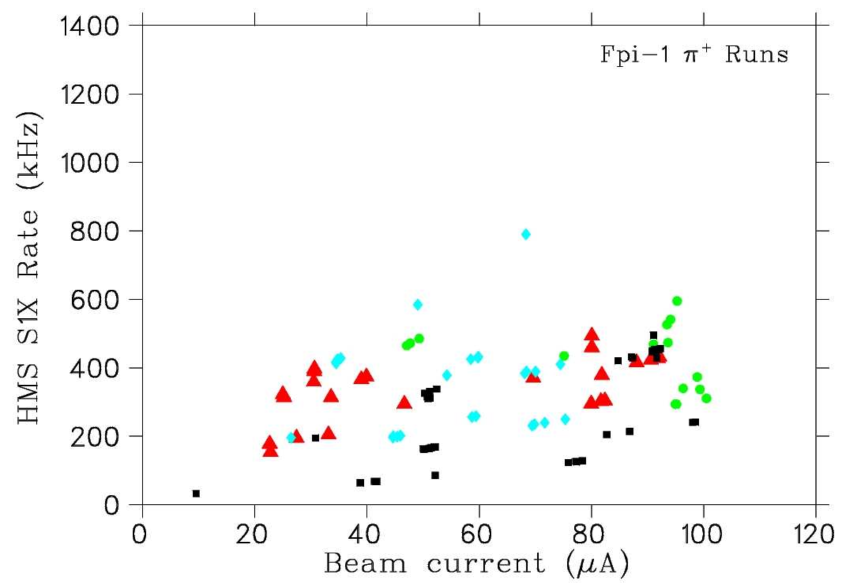
After PID & MM cuts, almost no random coincidences remain.

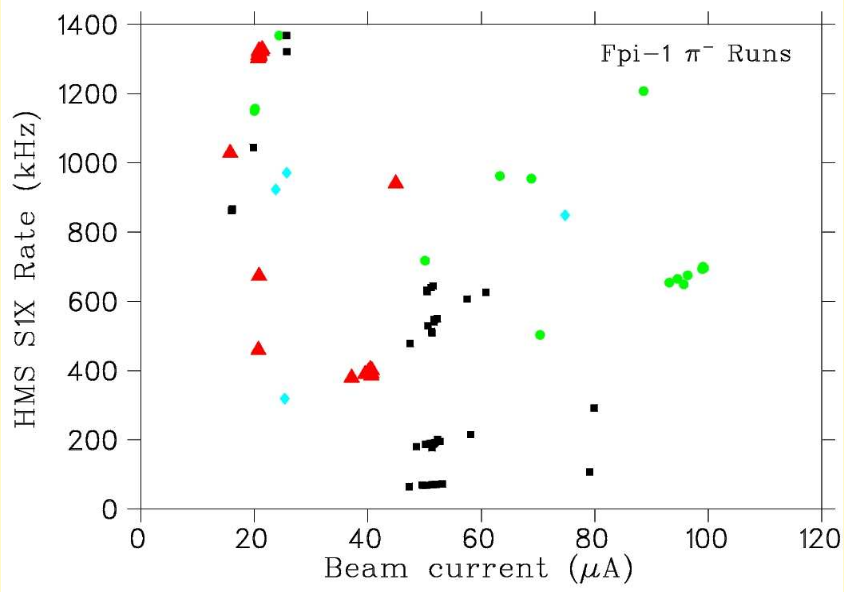


Diamond cuts define common (*W,Q*$^{2)}$ coverage at both ε.

Corrections to π^-, π^+ Data

- **Negative polarity of HMS field for $^2H(e,e'\pi^-)pp$ means these runs have high electron rates not shared by $^2H(e,e'\pi^+)nn$ runs.**
- **Understanding rate dependent corrections very important with respect to separated 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 Čerenkov (13%/MHz e^-).
  - High current ^2H target boiling correction (4.7%/100μA) for old `beer can' target cell and square beam raster.



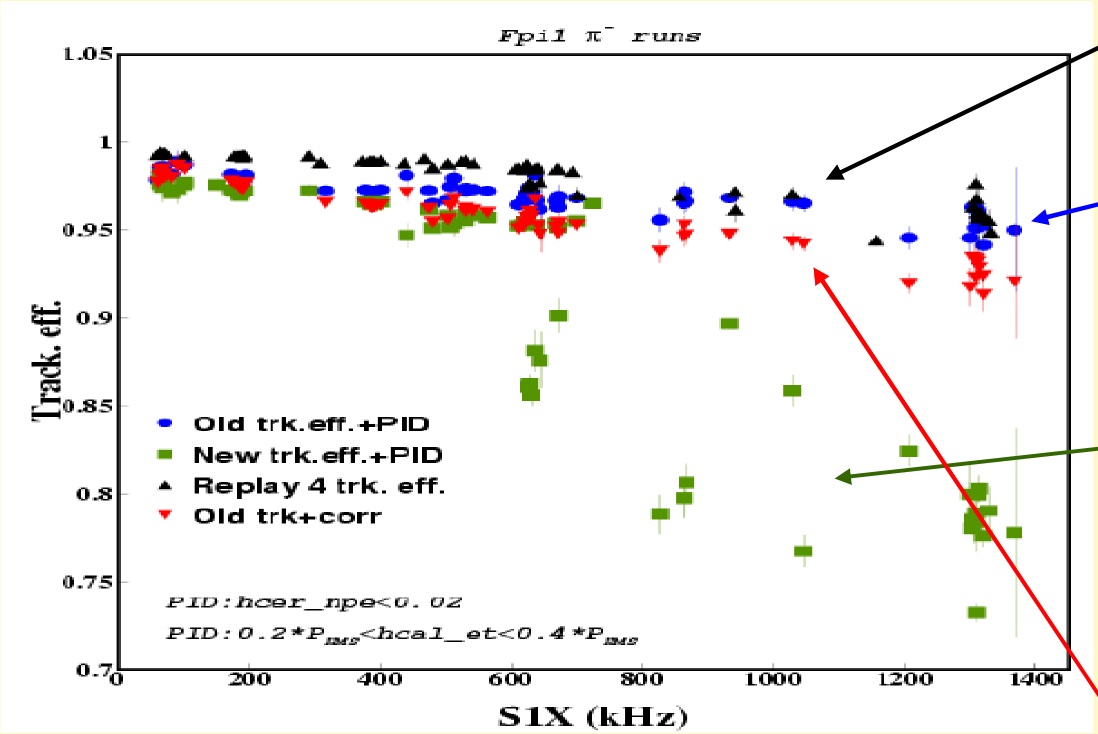


Q^2=0.60, 0.75, 1.0, 1.6 GeV^2

HMS Tracking Efficiencies for High Rate Data

F_π-1 ran in 1997. F_π-2 ran in 2003. Many changes in between.

- To bring F_π-1 data to same level of reconstruction quality as F_π-2 data, a lot of effort went into modifying the Hall C Analysis Engine to accept the older format data.
- Makes use of redesigned tracking algorithm that does a significantly better job in selecting the best track for multi-track events.



1998 Engine overestimates tracking efficiencies, since 2-track events have lower efficiency than 1-track events.

2003 Engine tracking efficiencies are lower, but still overestimated.

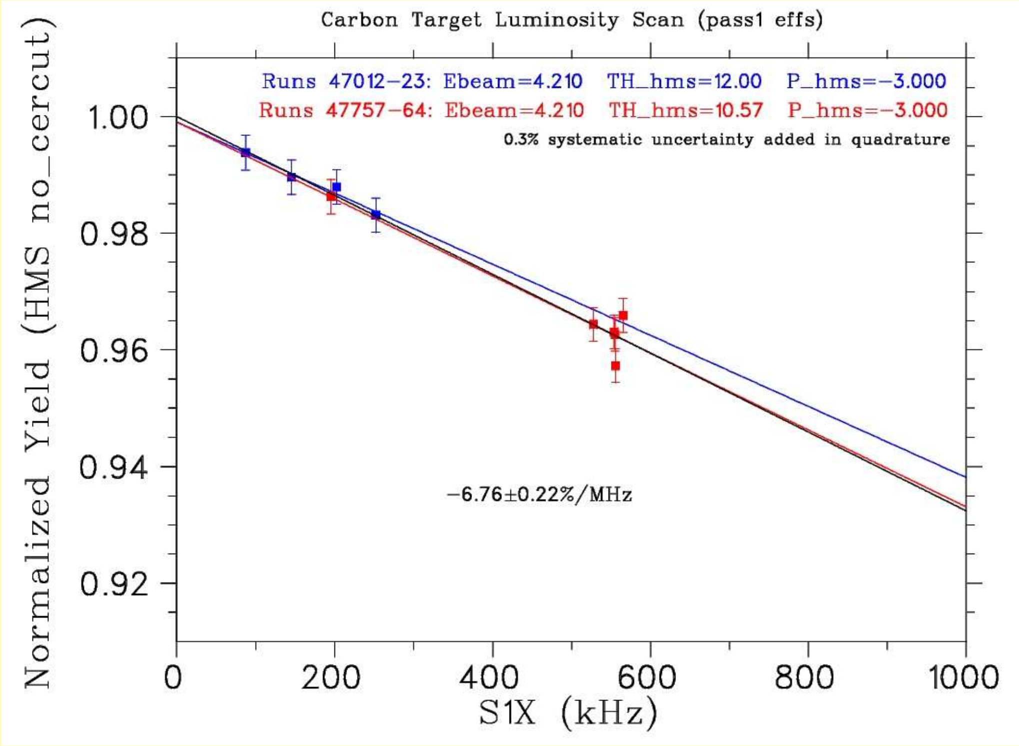
For the F_π-2 $p(e,e'\pi^+)n$ analysis (low rates), it was found that better results were found if the cut to exclude multiple good PMT ADC signals within the fiducial region of the hodoscope plane was removed.
→ **This removal fails at high rates.**

2003 Engine tracking efficiencies with correction factor applied.

Carbon Luminosity Scans

- To better understand HMS tracking efficiencies, the normalized yields from carbon target were studied vs. rate and vs. current.
  - Carbon target should not "boil", so normalized yields should be flat vs. current if all efficiencies are calculated correctly.
- Unfortunately, no ^{12}C luminosity scans were taken at different beam currents in the F_π-1 experiment.

  → Conclusions from the F_π-2 study will have to be applied.



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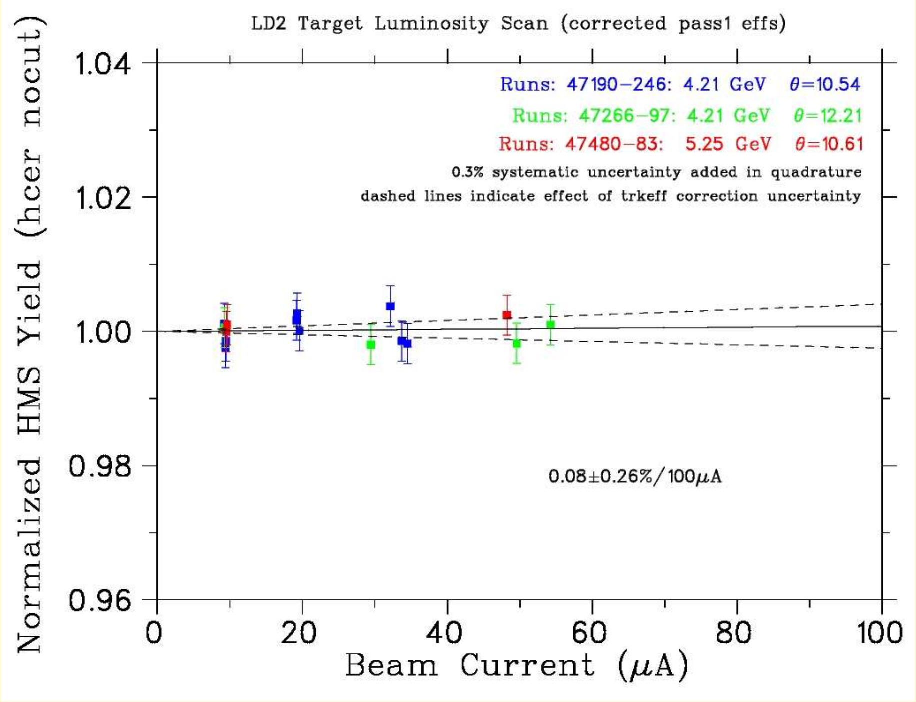
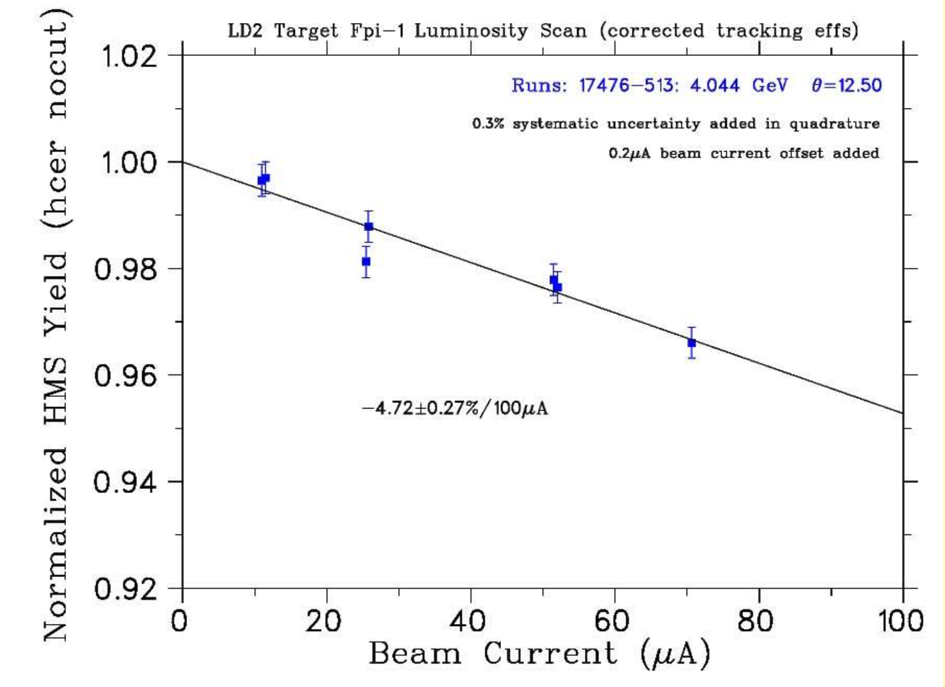
^{2}H Cryotarget Boiling Corrections

- **After the tracking efficiencies are finalized, the cryotarget boiling corrections can be determined.**



F_π-2: "tuna can" target cell and uniform circular rastering.

- Consistent with no ^{1}H cell correction in T. Horn F_π-2 analysis.



F_π-1: "beer can" target cell and non-uniform square rastering.

- Consistent with 6±1% ^{1}H cell correction in J. Volmer F_π-1 analysis.

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HMS Čerenkov Blocking Correction (π^-)

- **In both F_π-1,2, the HMS gas Čerenkov was used as a veto in the trigger for $^2H(e,e'\pi^-)$ runs**

  → needed to avoid high DAQ deadtime due to large e^- rates in HMS.

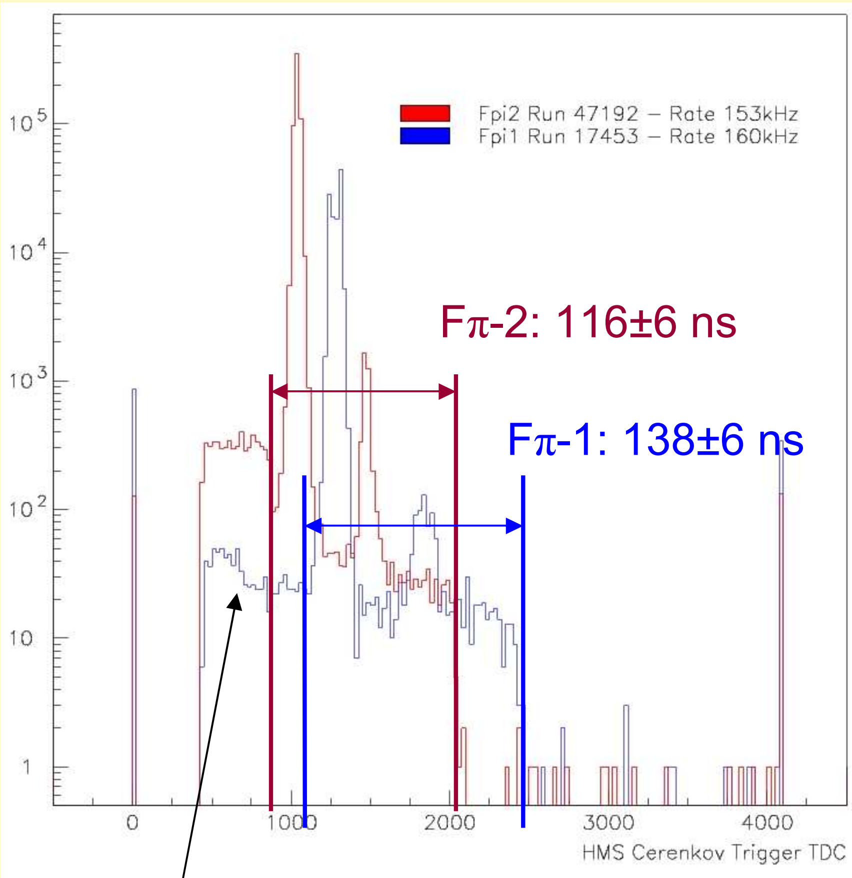
- **Čerenkov Blocking:**

  π^- are lost when e^- pass through the gas Čerenkov within ~100ns after π^- has traversed the detector.

  → results in mis-identification of π^- as e^-

- Actual veto thresholds vary according to PMT gain variations at high rates.
  - slightly more restrictive software thresholds are applied in the analysis:
  - F_π-1: accept < 1.5 hcer_npe
  - F_π-2: accept < 2 hcer_npe

HMS Čerenkov Blocking Correction (π^-)



- Region due to early e- passing through detector before e- associated with trigger.
- Already addressed in coincidence time blocking correction.

- Čerenkov Blocking Correction is obtained from Trigger TDC information, since that is independent of tracking efficiency and cryotarget corrections.
- Result is consistent with τ from other studies (not shown here) within statistical errors.

$$\delta_{CCblock} = e^{-ELLOrate \cdot \tau}$$

F_{π^-}2 τ = 115±6 ns
F_{π^-}1 τ = 138±6 ns

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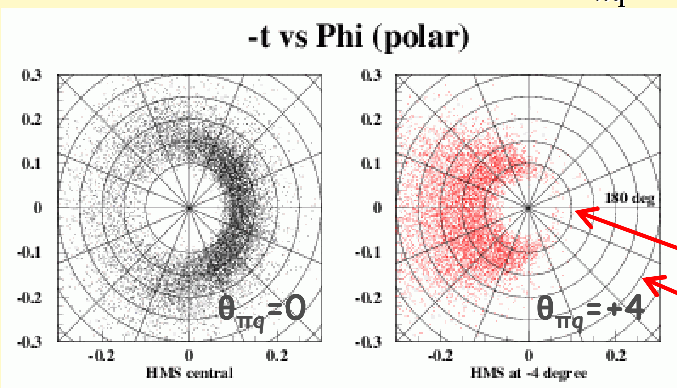
Extract Response Functions through Iterative Procedure

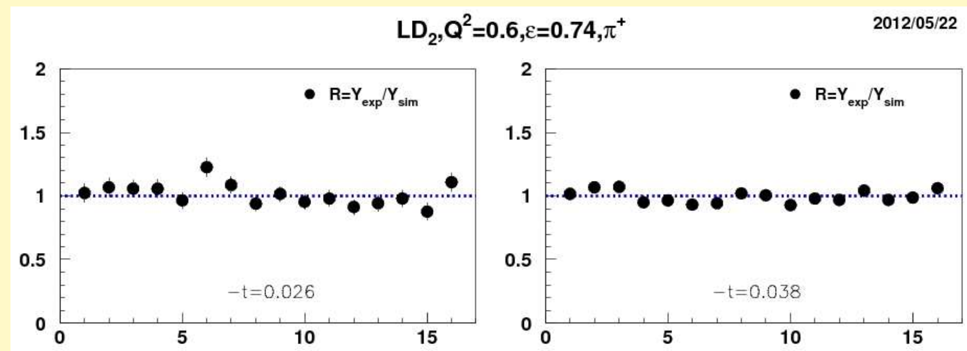
Improve φ coverage by taking data at multiple π (HMS) angles, $-4^o<\theta_{\pi q}<4^o$.

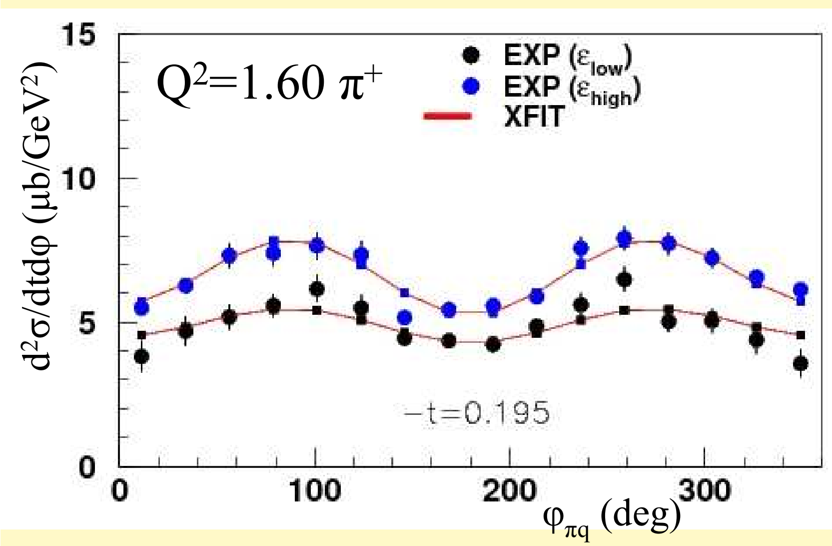


For each π HMS setting, form ratio:

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

Combine ratios for π settings together, propagating errors accordingly.





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

$$\left(\frac{d^2\sigma}{dt d\phi}\right)_{EXP} = \left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\left(\frac{d^2\sigma}{dt d\phi}\right)_{SIMC}$$

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

Systematic Uncertainties (F_π-1)

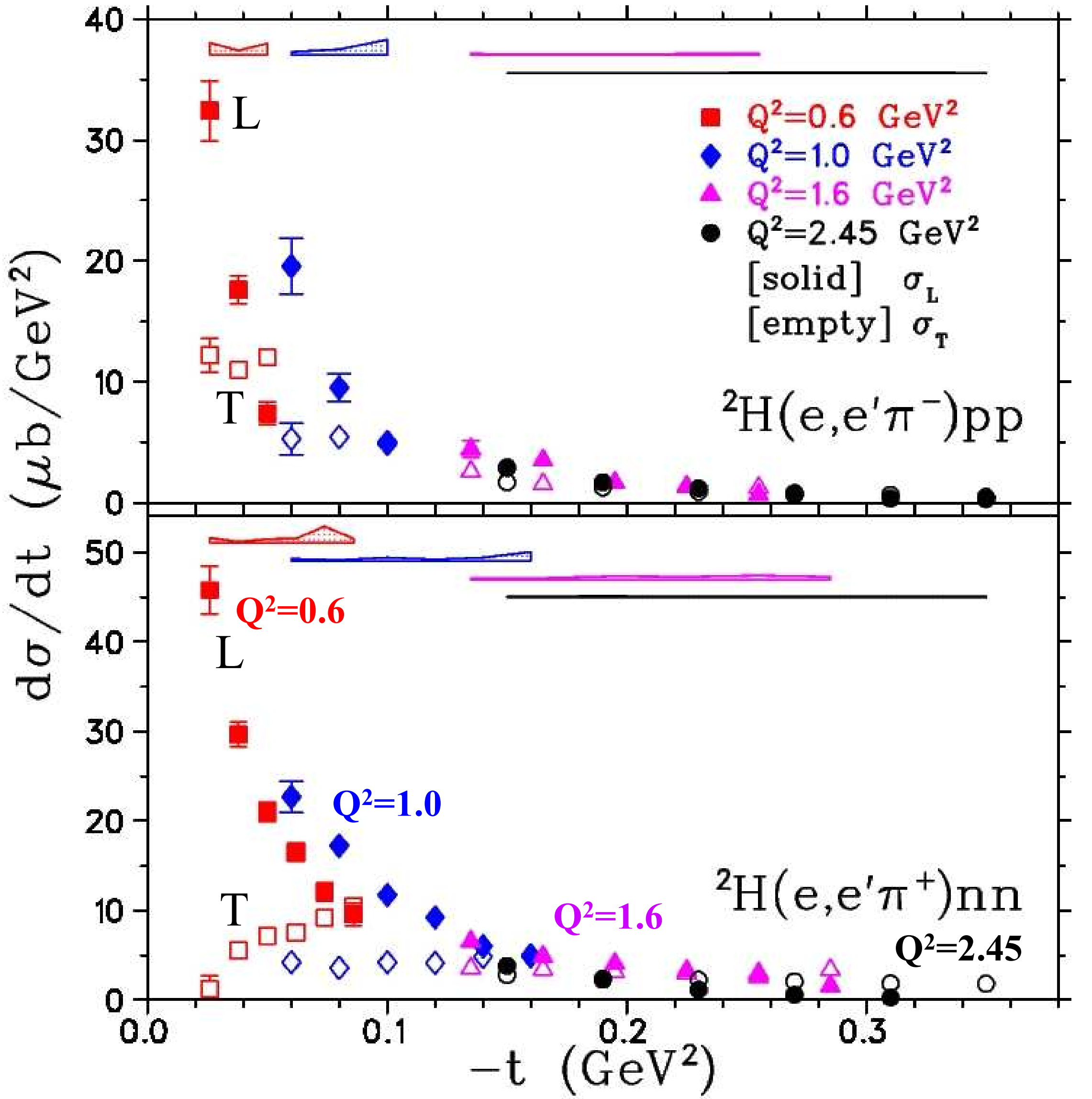
- Over-constrained *p(e,e'p)* reaction and elastic *e*+^{12}C reactions used to calibrate spectrometer acceptances, momenta, offsets, etc.
- Spectrometers well-understood after careful comparison with MC simulations.
  - Beam energy and spectrometer momenta determined to <0.1%.
  - Spectrometer angles 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%**		

^{2}H data Kinematic coverage

	$^2H(e,e'\pi^+)nn$	$^2H(e,e'\pi^-)pp$
Q^2=0.6 GeV^2, W=1.95 GeV (F_π-1)		
ε=0.37, E_e=2.445 GeV	3 HMS settings: $\theta_{\pi q}$=+0.5,+2.0,+4.0°.	2 HMS settings: Missing +2.0°.
ε=0.74, E_e=3.548 GeV	4 HMS settings: $\theta_{\pi q}$=-2.7, +0.0,+2.0,+4.0°.	1 HMS setting: **Only +0.0°**.
Q^2=0.75 GeV^2, W=1.95 GeV (F_π-1)		
ε=0.43, E_e=2.673 GeV	2 HMS settings: $\theta_{\pi q}$=+0.0,+4.0°.	2 HMS settings: $\theta_{\pi q}$=+0.0,+4.0°.
ε=0.70, E_e=3.548 GeV	3 HMS settings: $\theta_{\pi q}$=-4.0, +0.0,+4.0°.	**NO HMS settings.**
Q^2=1.0 GeV^2, W=1.95 GeV (F_π-1)		
ε=0.33, E_e=2.673 GeV	2 HMS settings: $\theta_{\pi q}$=+0.0,+4.0°.	2 HMS settings: $\theta_{\pi q}$=+0.0,+4.0°.
ε=0.65, E_e=3.548 GeV	3 HMS settings: $\theta_{\pi q}$=-4.0, +0.0,+4.0°.	1 HMS setting: **Only +0.0°**.
Q^2=1.6 GeV^2, W=1.95 GeV (F_π-1)		
ε=0.27, E_e=3.005 GeV	2 HMS settings: $\theta_{\pi q}$=+0.0,+4.0°.	2 HMS settings: $\theta_{\pi q}$=+0.0,+4.0°.
ε=0.63, E_e=4.045 GeV	3 HMS settings: $\theta_{\pi q}$=-4.0, +0.0,+4.0°.	3 HMS settings: $\theta_{\pi q}$=-4.0, +0.0,+4.0°.
Q^2=2.45 GeV^2, W=2.20 GeV (F_π-2)		
ε=0.27, E_e=4.210 GeV	2 HMS settings: $\theta_{\pi q}$=+1.35,+3.0°.	2 HMS settings: $\theta_{\pi q}$=+1.35,+3.0°.
ε=0.55, E_e=5.248 GeV	3 HMS settings: $\theta_{\pi q}$=-3.0, +0.0,+3.0°.	3 HMS settings: $\theta_{\pi q}$=-3.0, +0.0,+3.0°.

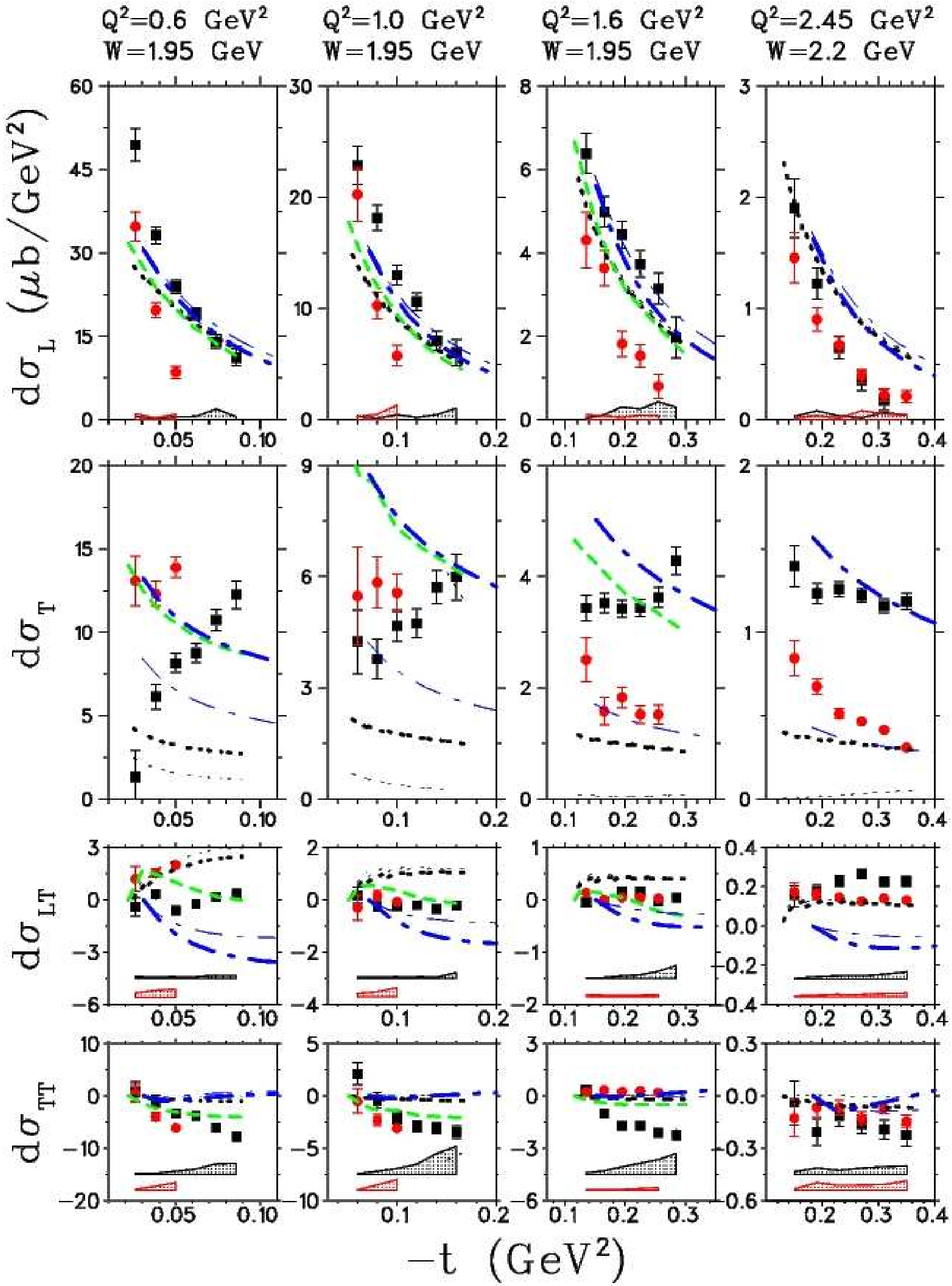
$^2H(e,e'\pi^\pm)NN$ Separated dσ/dt



- 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.**
- **Both follow nearly universal curves vs –t, with weak Q^2-dependence.**

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



Model $d\sigma_x/dt$

VGL Regge Model:

- Free parameters: Λ_π^2, Λ_ρ^2 (from ^{1}H data).
  [PRC **57**(1998)1454]

KM Regge+DIS Model:

- σ_L from ^{1}H data, DIS process dominates σ_T.
  [PRC **81**(2010)045202]

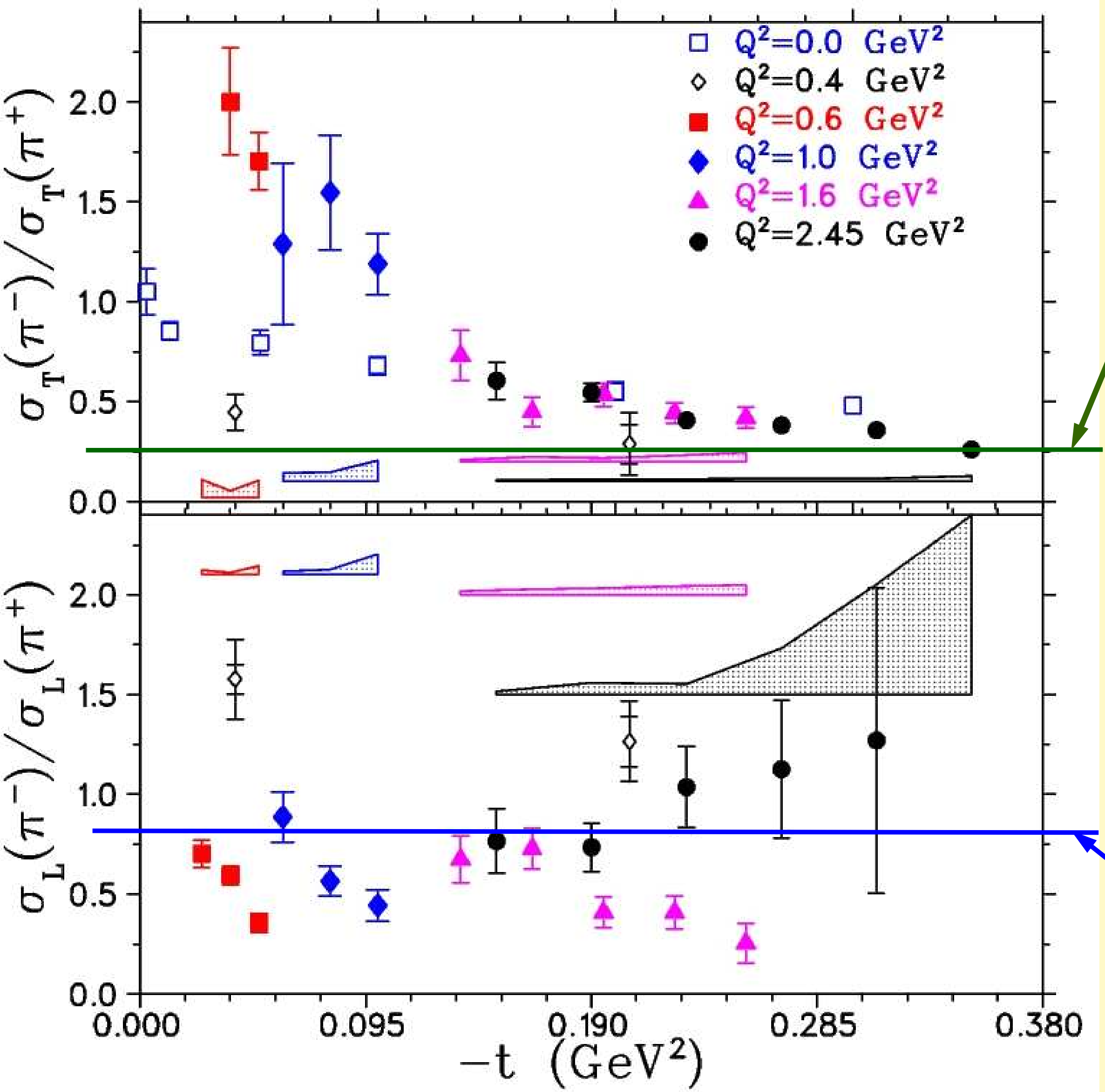
VR Regge+DIS Model:

- Similar to KM but with improved DIS parameters
  [PRC **89**(2014)025203]

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

Canada.

π^-/π^+ Separated Response Function Ratios

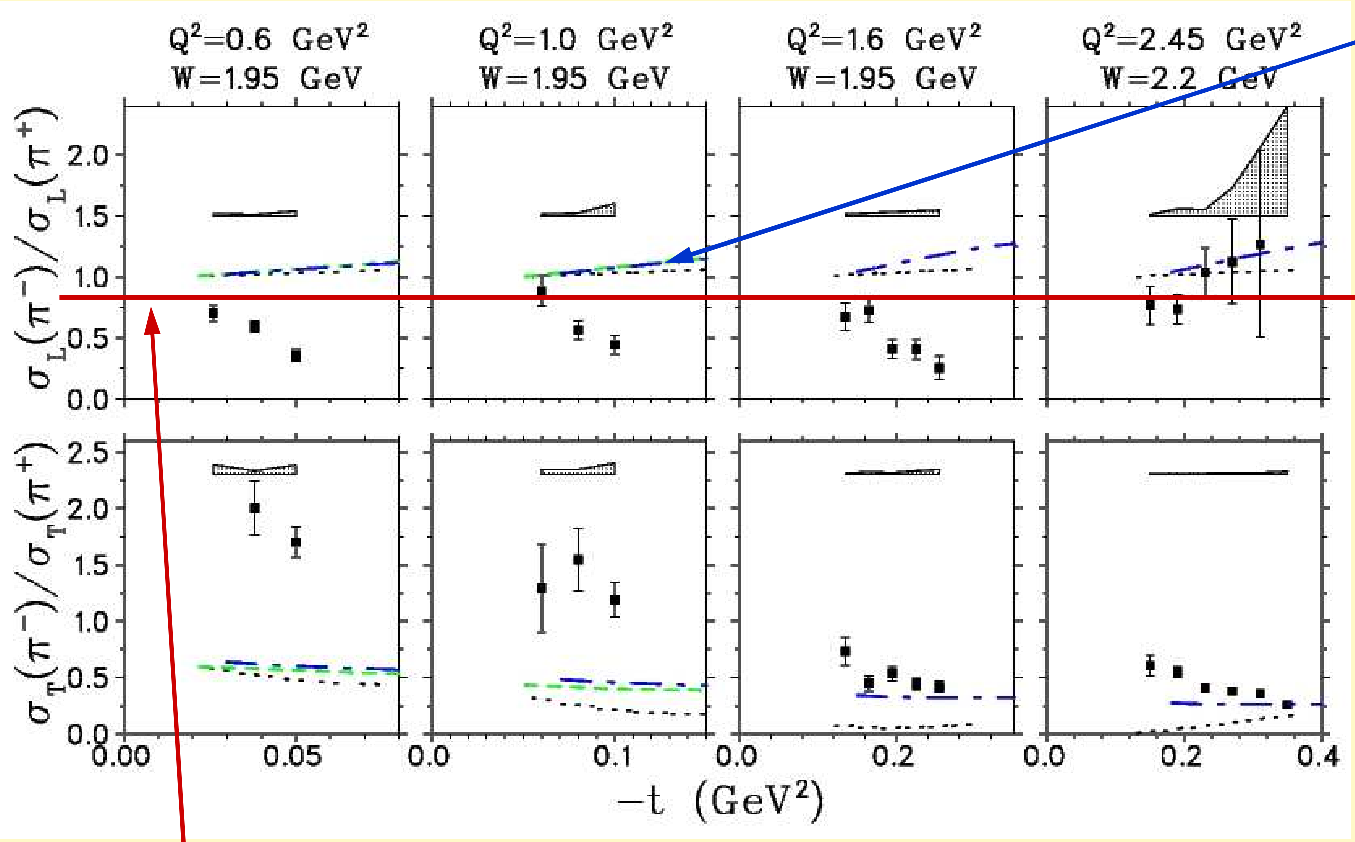


- **Transverse Ratios tend to ¼ as –t increases:**
  → Is this an indication of Nachtmann's quark charge scaling?
- **-t=0.3 GeV² seems too low for this to apply. Might indicate the partial cancellation of soft QCD corrections in the formation of the ratio.**

R_L≈0.8 near $-t_{min}$ at each Q^2.
Predicted in large N_c limit calculation.
Frankfurt, et al.
PRL **84**(2000)2589.

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

Relevance to Pion Form Factor Extraction



Vrancx-Ryckebusch Model:

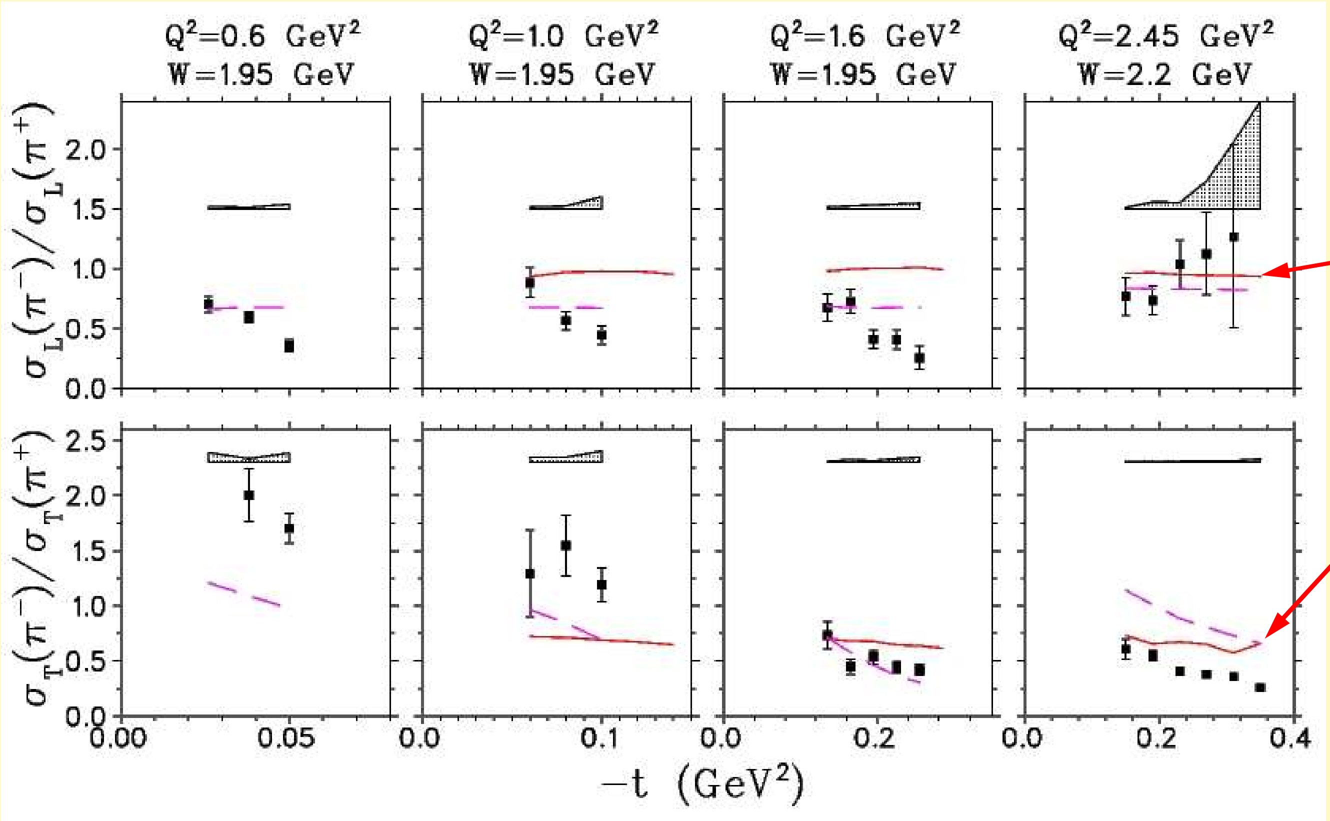
- VGL Regge Model underpredicts σ_T by large factor.
- VR extend VGL with hard DIS process of virtual photons off nucleons.

[PRC **89**(2014)025203]

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

- Qualitatively in agreement with our Fπ-1 analysis:
  - We found evidence for small additional contribution to σ_L at W=1.95 GeV not taken into account by the VGL model.
- We found little evidence for this contribution in Fπ-2 analysis at W=2.2 GeV.

Comparison with Goloskokov-Kroll GPD model



- $\pi^{\pm}$ electroproduction in a handbag framework.
- Modified perturbative approach with full $F_{\pi}(Q^2)$.
- Substantial contributions from transverse photons as twist-3 effect (H_T) [Eur.Phys.J.A**47**(2011)112]

- Model parameters optimized for small skewness ($\xi<0.1$) and W>4 GeV.
- Application to our kinematics requires substantial extrapolation in W, ξ.
  → Please be cautious in the comparison.
- Although model does reasonable job at predicting ratios, agreement of model with our σ_T is not good.
- Model optimized for JLab kinematics should be sensitive to transverse GPD, $\boldsymbol{H_T}$

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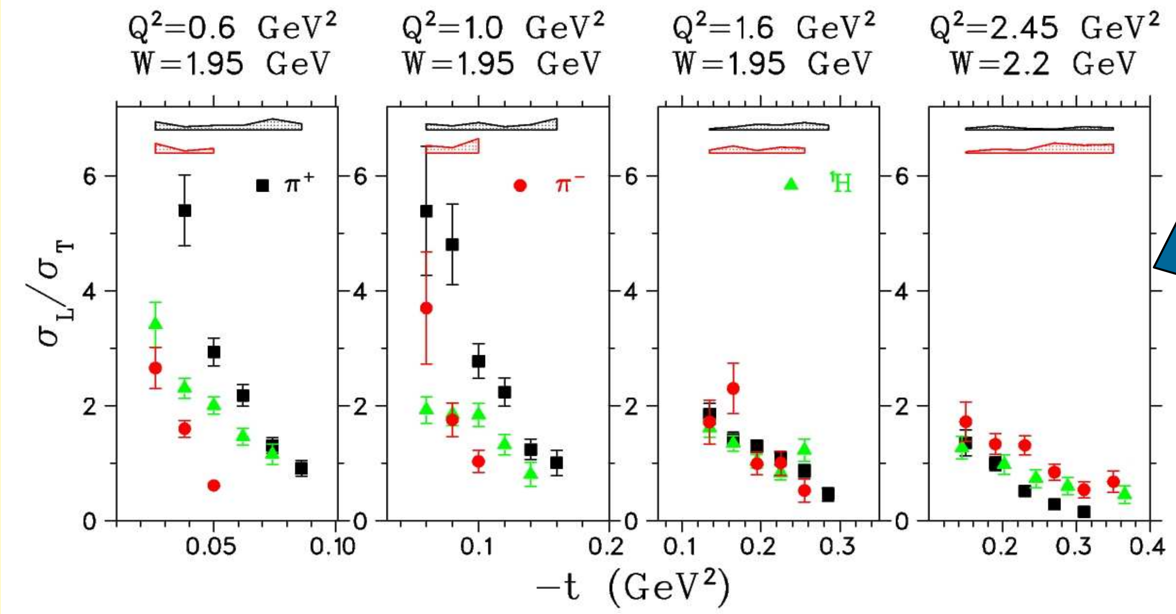
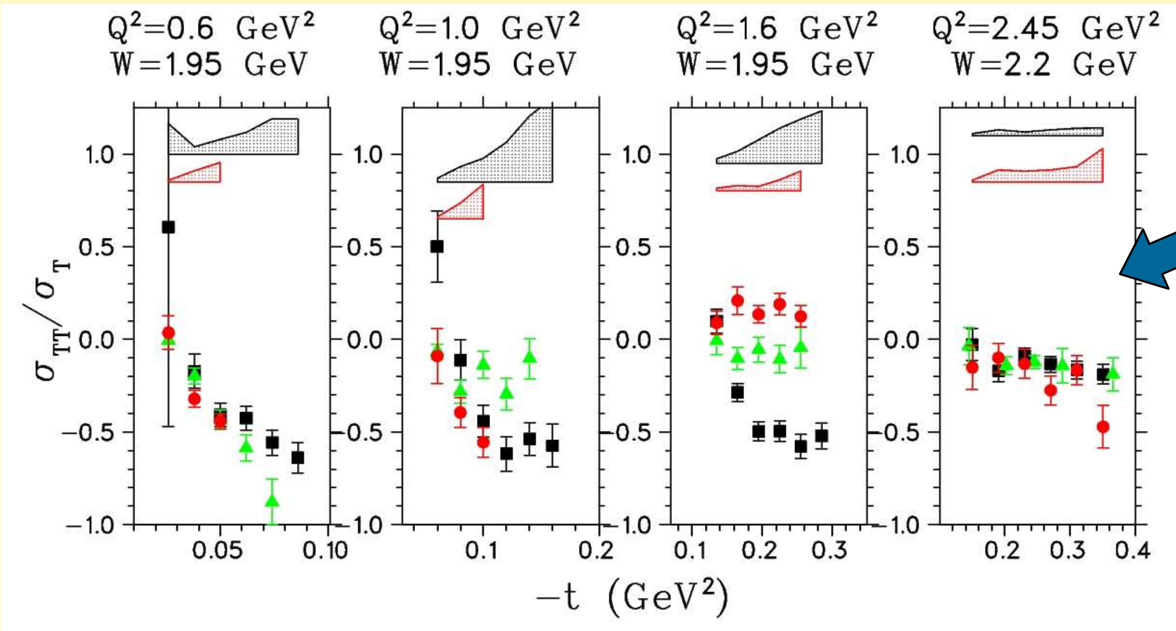
σ_L/σ_T and σ_{TT}/σ_T Ratios for π^+, π^-

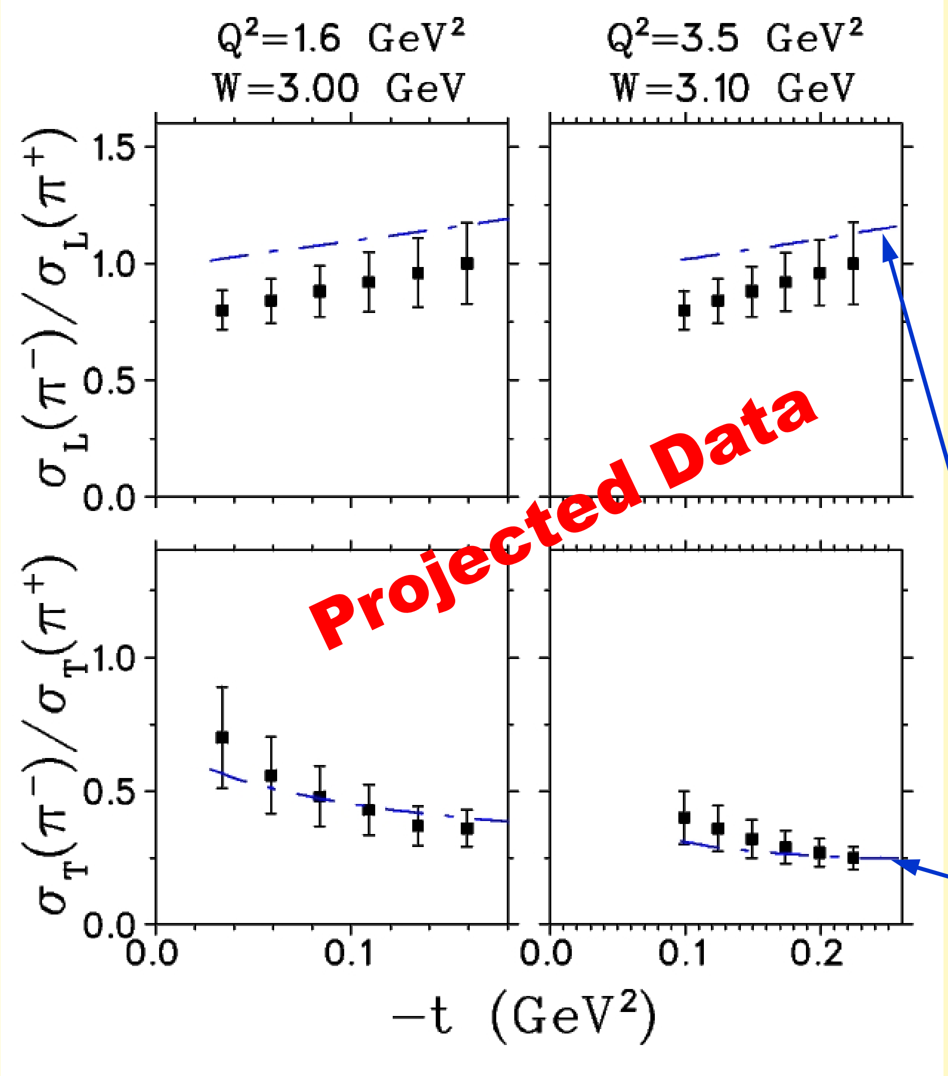




- L/T ratio becomes more favorable for π^- production as Q^2 increases.
- Another prediction of quark-parton mechanism is the suppression of σ_{TT}/σ_T due to *s*-channel helicity conservation.
- Data qualitatively consistent with this, since σ_{TT} decreases more rapidly than σ_T with increasing Q^2.

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

Projected Data from Fπ-12 Experiment



- E12-06-101 approved for 52 days of beam with SHMS+HMS, A rating, selected by PAC41 as "High Impact".
- ^{2}H data to determine R_L π^-/π^+ ratio to constrain modeling of non-pole backgrounds in σ_L, relevant for extraction of pion form factor
  - 44 hrs (π^+), 174 hrs (π^-).
- If R_T is ~1/4 at higher Q^2 and similar x_B, the hypothesis of a quark knockout mechanism will be strengthened.

Predictions of Vrancx-Ryckebusch Regge+DIS Model
[PRC **89**(2014)025203]

Summary

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