Final Analysis of π^-/π^+ data from Pion Form Factor Experiments

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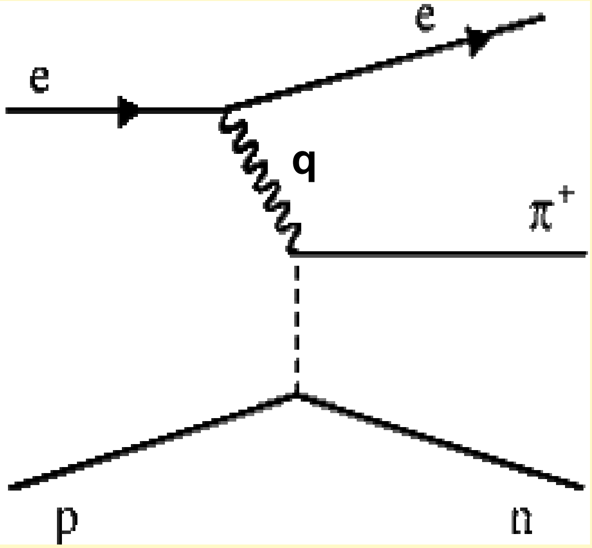
Deep Exclusive Meson Production

- **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.



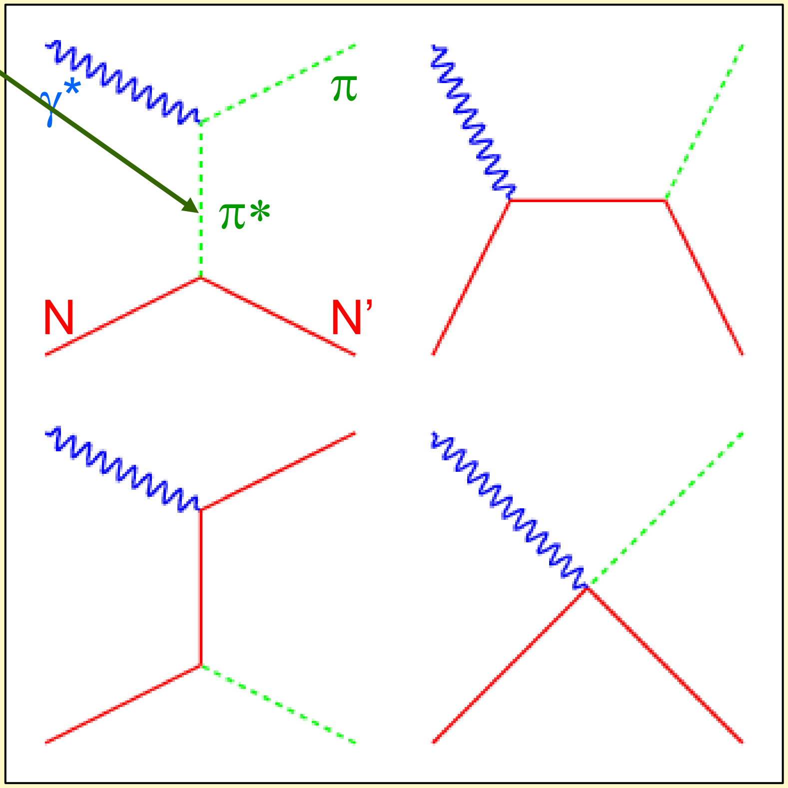
$$R_T = \frac{\gamma_T^* n \to \pi^- p}{\gamma_T^* p \to \pi^+ n} \xrightarrow[high\ -t]{} \frac{2Q_d^2}{2Q_u^2} = \frac{(-1/3)^2}{(+2/3)^2} = \frac{1}{4}$$

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

At low –t, Meson-Nucleon Degrees of Freedom

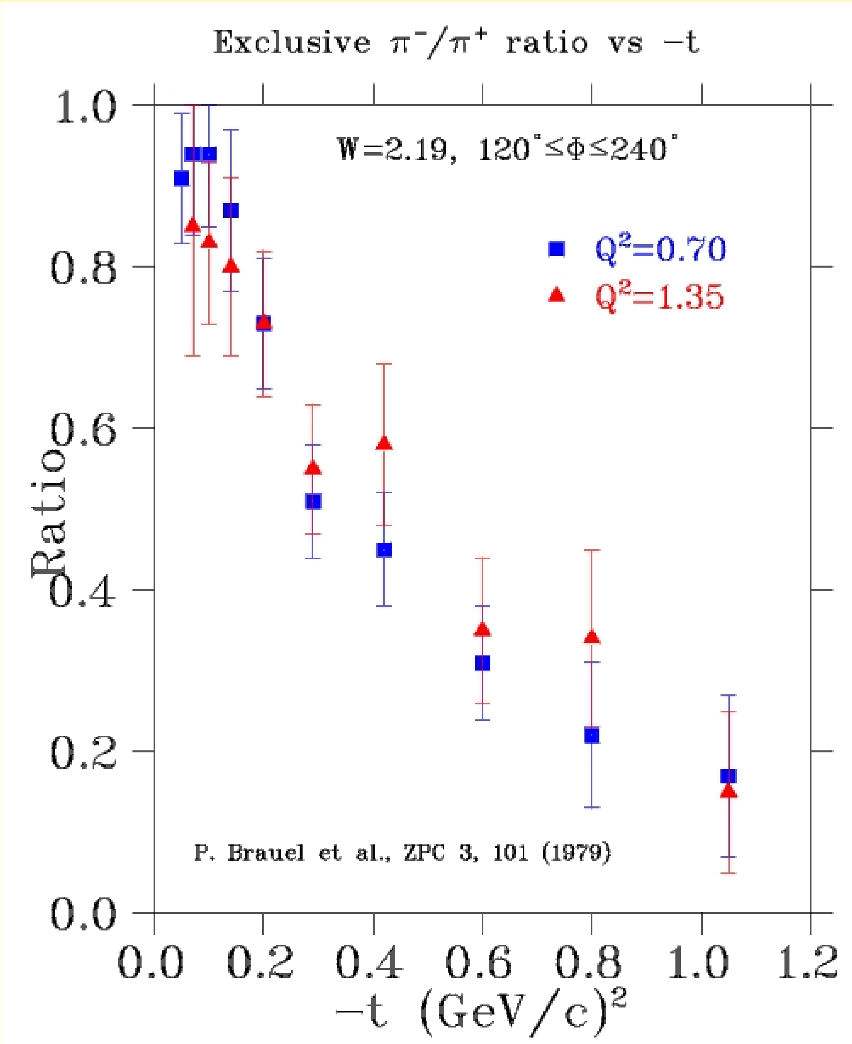
- π^+ *t*-channel diagram is purely isovector (G-parity conservation).

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

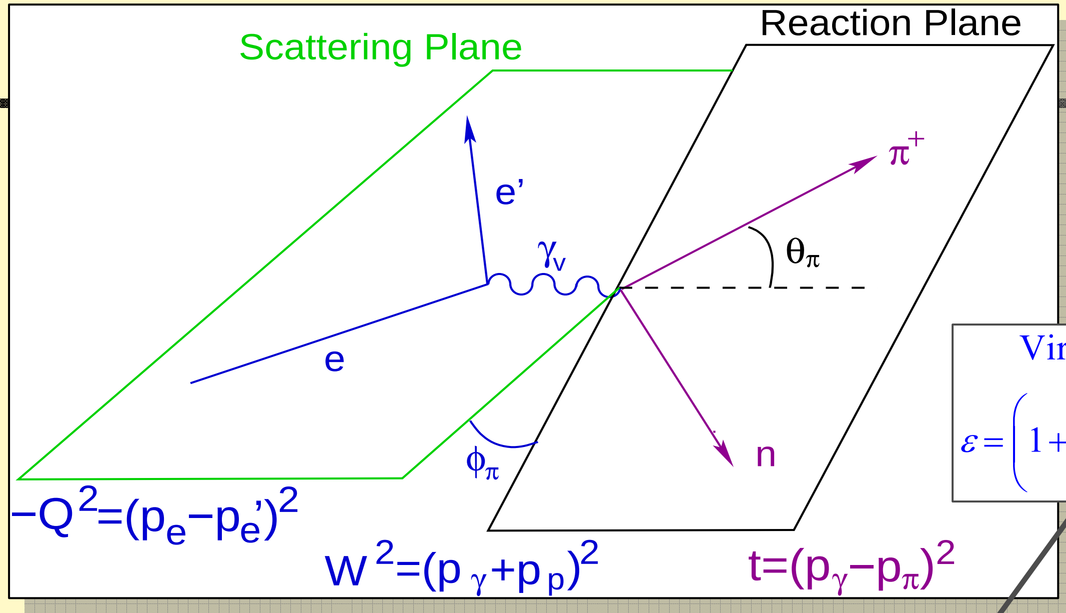


- A significant deviation of R_L from unity would indicate the presence of isoscalar backgrounds (such as b_1(1235) contributions to *t*-channel).
- Relevant for the extraction of the pion form factor from $p(e,e'\pi^+)n$ data, which uses a model including some isoscalar background.

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



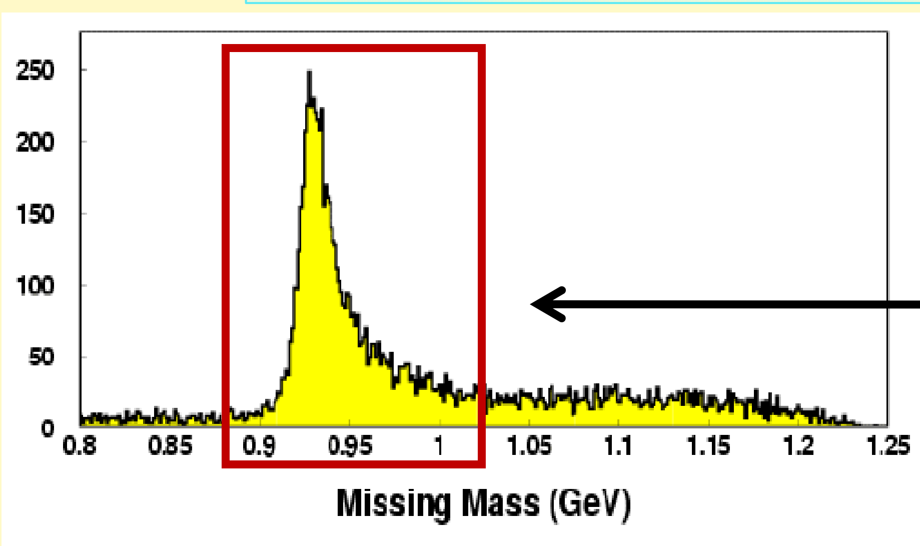
- Only prior exclusive ^{2}H(e,e'$\pi^\pm$)NN data was obtained at DESY in the 1970's.
  - Unseparated cross sections only, due incomplete φ coverage.
  - Q^2=0.70, 1.35 GeV^2.
- π^-/π^+ ratio intriguingly approaches Nachtmann's quark counting ratio $\rightarrow 1/4$ at high $-t$.
- Ratio approaches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



Virtual-photon polarization:

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

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



Exclusivity assured via 0.875<MM<1.03 GeV cut

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

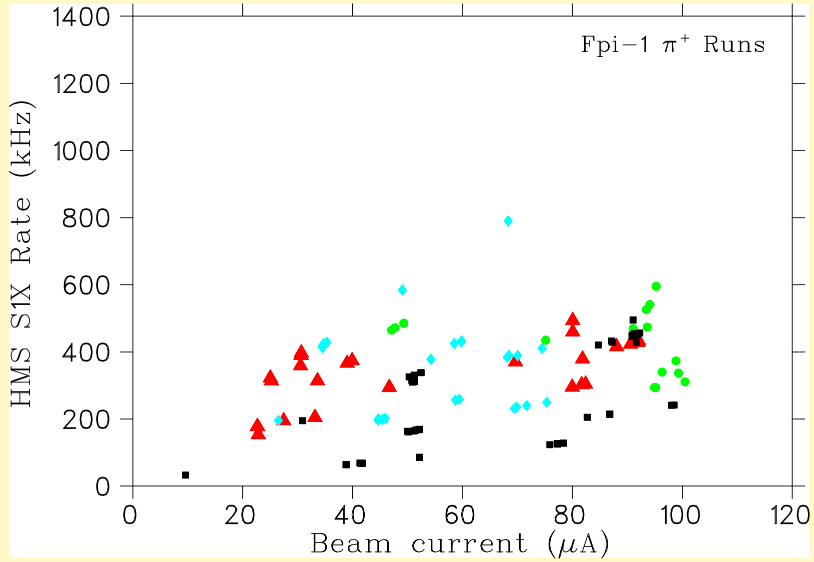
^{2}H data Kinematic coverage

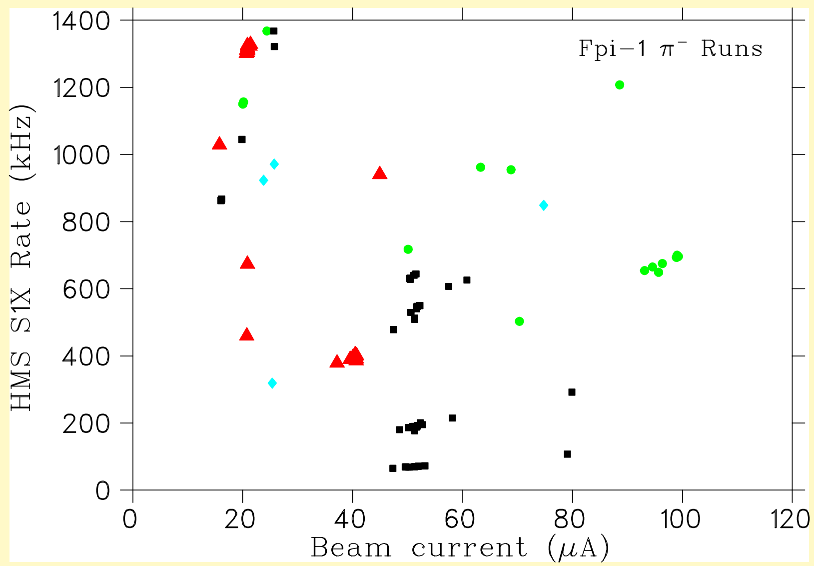
	$^2H(e,e'\pi^+)nn$	$^2H(e,e'\pi^-)pp$
Q^2=0.6 GeV^2, W=1.95 GeV (F_π-1)		
ε=0.37, E_e=2.445 GeV	3 HMS settings: $\theta_{\pi q}$=+0.5,+2.0,+4.0°.	2 HMS settings: Missing +2.0°.
ε=0.74, E_e=3.548 GeV	4 HMS settings: $\theta_{\pi q}$=-2.7, +0.0,+2.0,+4.0°.	1 HMS setting: **Only +0.0°**.
Q^2=0.75 GeV^2, 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°.

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 final π^-/π^+ ratios.**

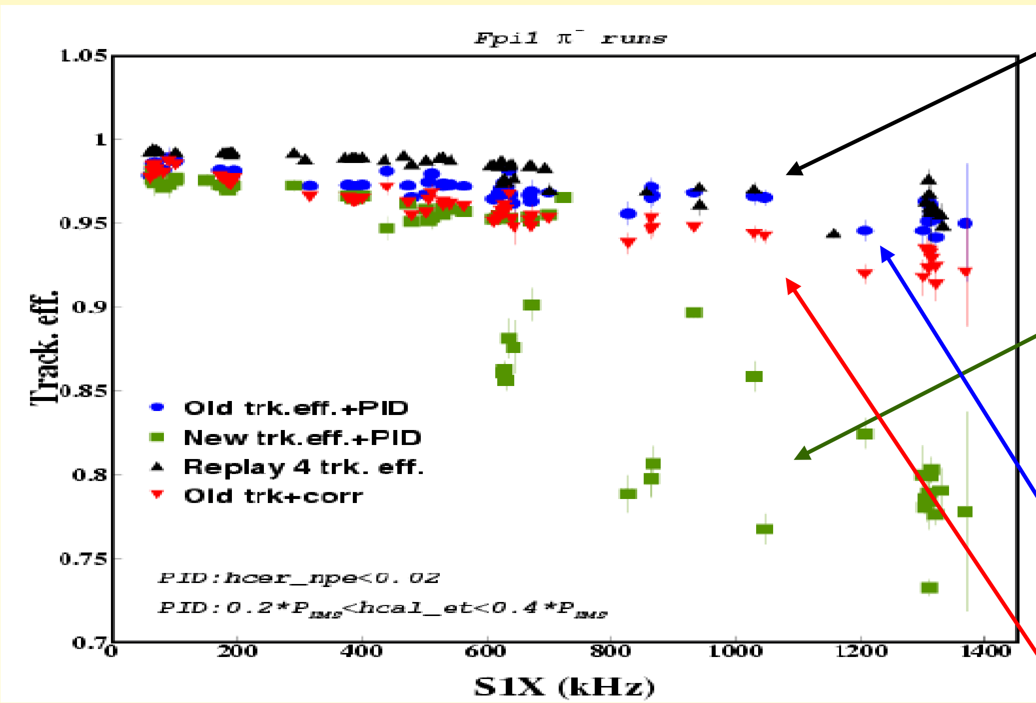




Q^2=0.60, 0.75, 1.0, 1.6 GeV^2

Tracking Efficiencies for High Rate Data

- F_π-1 data taken in 1997 and originally analyzed with "old" (1998) engine.
- To bring the F_π-1 data to the same level of reconstruction quality as the F_π-2 data taken in 2003, Cornel Butuceanu put a lot of effort into modifying the "new" 2003 engine to accept the older format data.
  - Makes use of redesigned (V. Tvaskis) tracking algorithm that does a significantly better job in selecting the best track for multi-track events.



Original analysis with 1998 engine overestimates tracking efficiencies, since 2-track events have lower efficiency than 1-track events.

For the F_π-2 p(e,e'π^+)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.**

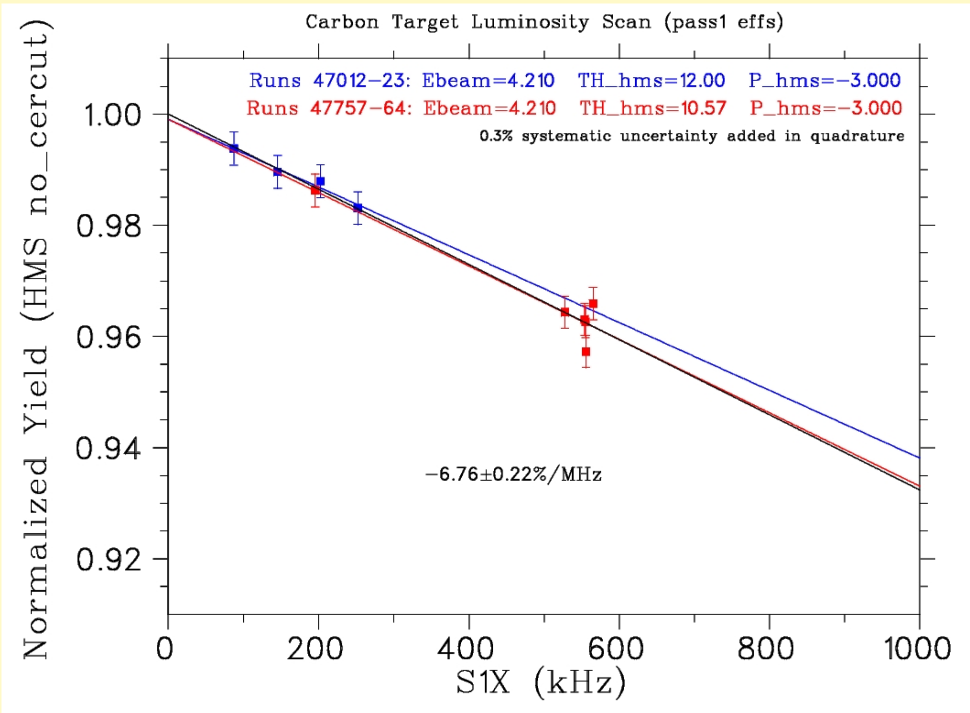
2003 engine tracking efficiencies with PID cuts and multi-good PMT ADC restriction.

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.

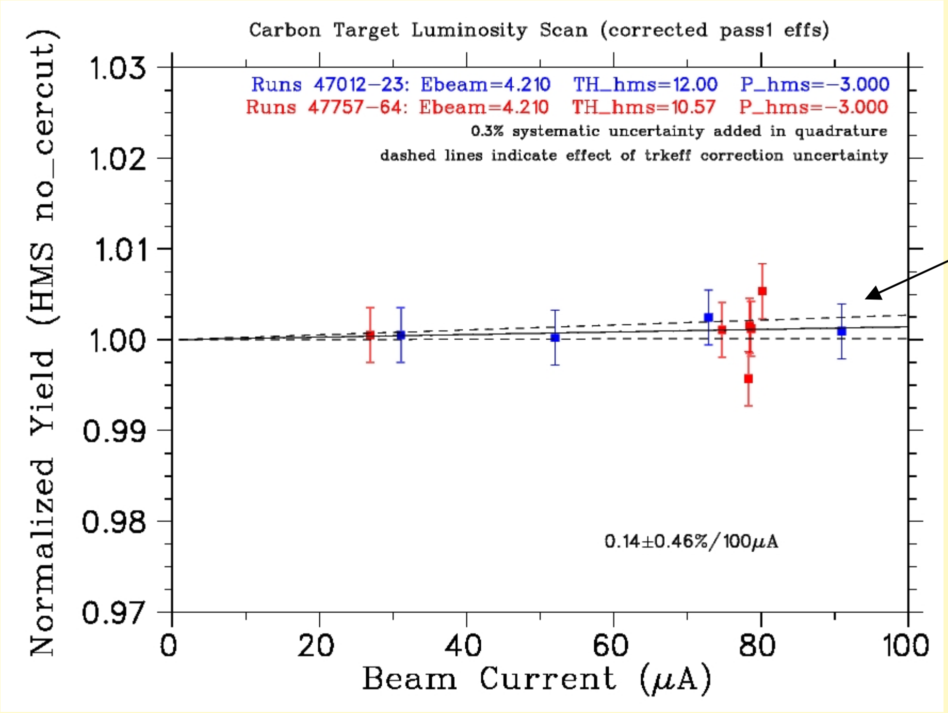
  → Conclusions from the F_π-2 study will have to be applied.



Final HMS Tracking Efficiency Correction

$$htr\_corrected = htr\_old \times (1 - S1Xrate(kHz) * 6.76236 \times 10^{-5})$$

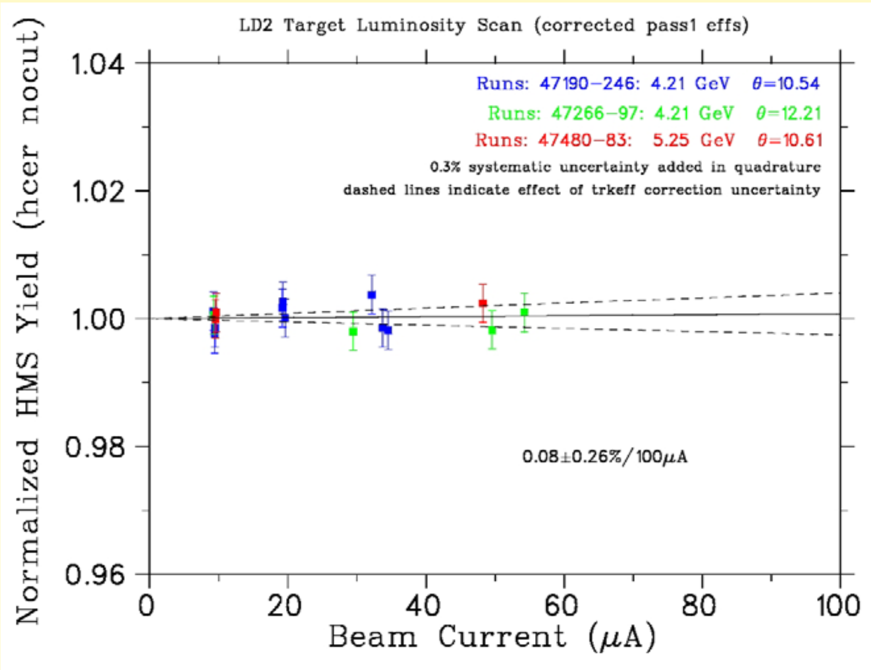
- Correction is applied to both F_π-1 and F_π-2 tracking efficiencies.
- Particularly important for F_π-1 $^2H(e,e'\pi^-)$ data, with HMS rate up to 1.4 MHz.

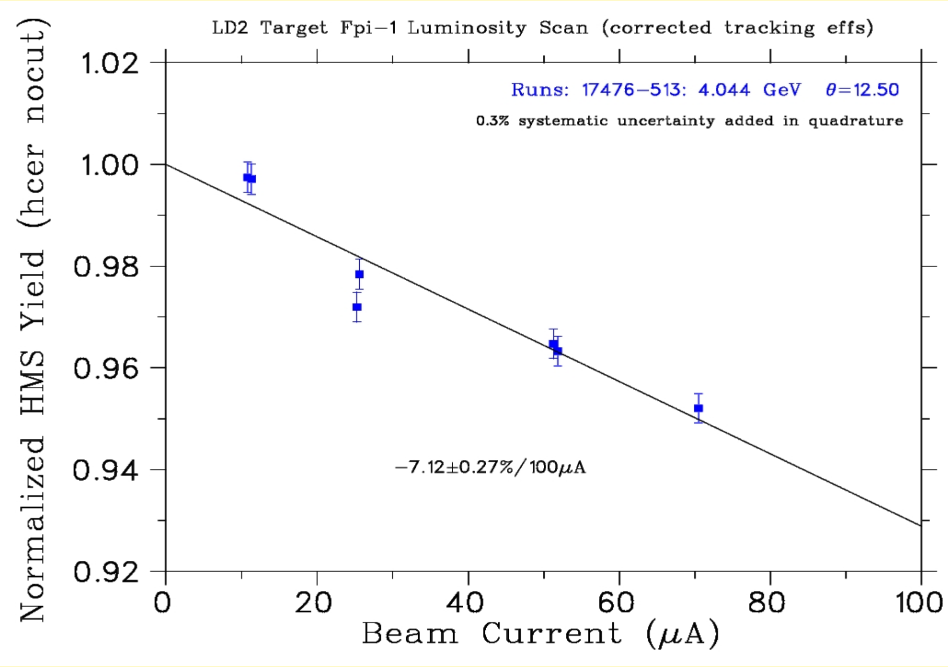


After application of correction, carbon normalized yields show NO residual current dependence.

Final ^{2}H Cryotarget Boiling Correction

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





F_π-2: “tuna can” target cell.
- Consistent with no ^{1}H cell correction in T. Horn F_π-2 analysis.

F_π-1: “soda can” target cell.
- Consistent with 6±1% ^{1}H cell correction in J. Volmer F_π-1 analysis.

- F_π-1 boiling correction found in 2009 analysis significantly larger, 13.5%/100μA.

HMS Cerenkov Blocking Correction (π^-)

- **In both F_π-1,2, the HMS gas Cerenkov 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.

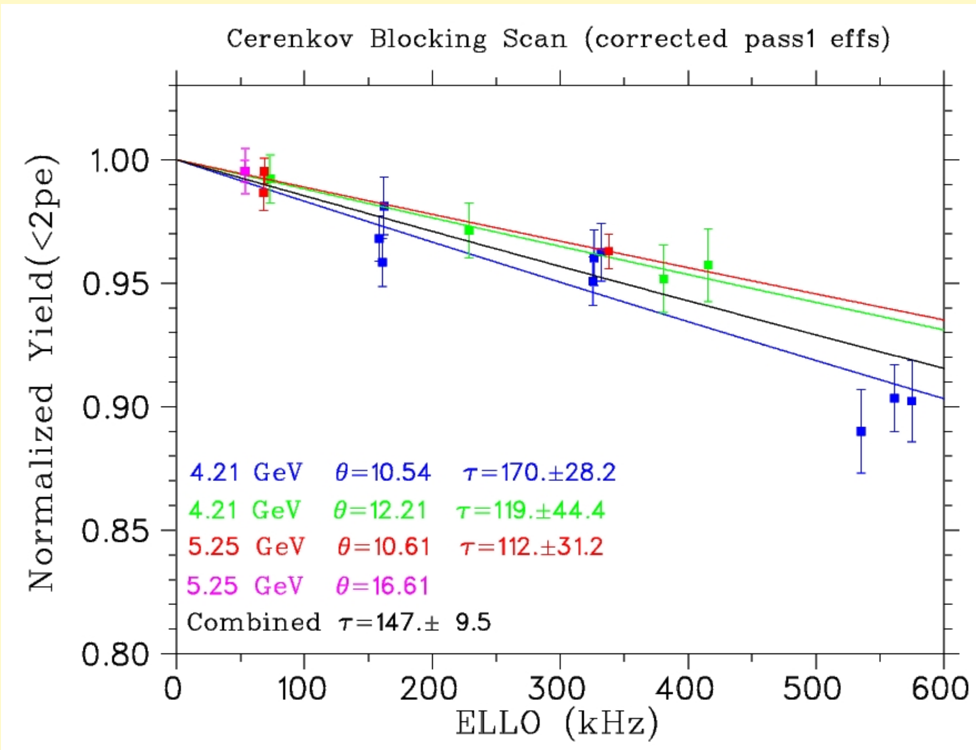
- **Cerenkov Blocking:**

  Need to correct for loss of π^- due to e^- passing through the gas Cerenkov within ~100ns after π^- has traversed the detector, resulting in a 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

F_π-2 HMS Singles Yield Study

- **^{2}H(e,e'π^-) runs were taken without HMS Cerenkov trigger veto at different currents for several kinematic settings.**
  - Apply "veto" via hcer_npe<2.0 cut.
- Expect a loss of yield at higher rate due to Cerenkov blocking.



- Plot normalized HMS singles yields for each kinematic setting vs. rate.
- For each setting, fit with $Ae^{-b\tau}$ and divide by A.
- τ values sensitive to applied tracking eff. and cryotarget boiling corrections.
- These τ values determined with singles events, and need to be adjusted for effective gate width for coincidence evts.

$$\tau_{yield\_study} = 99 \pm 19 ns$$

- τ value found in 2009 analysis significantly larger, 160ns.

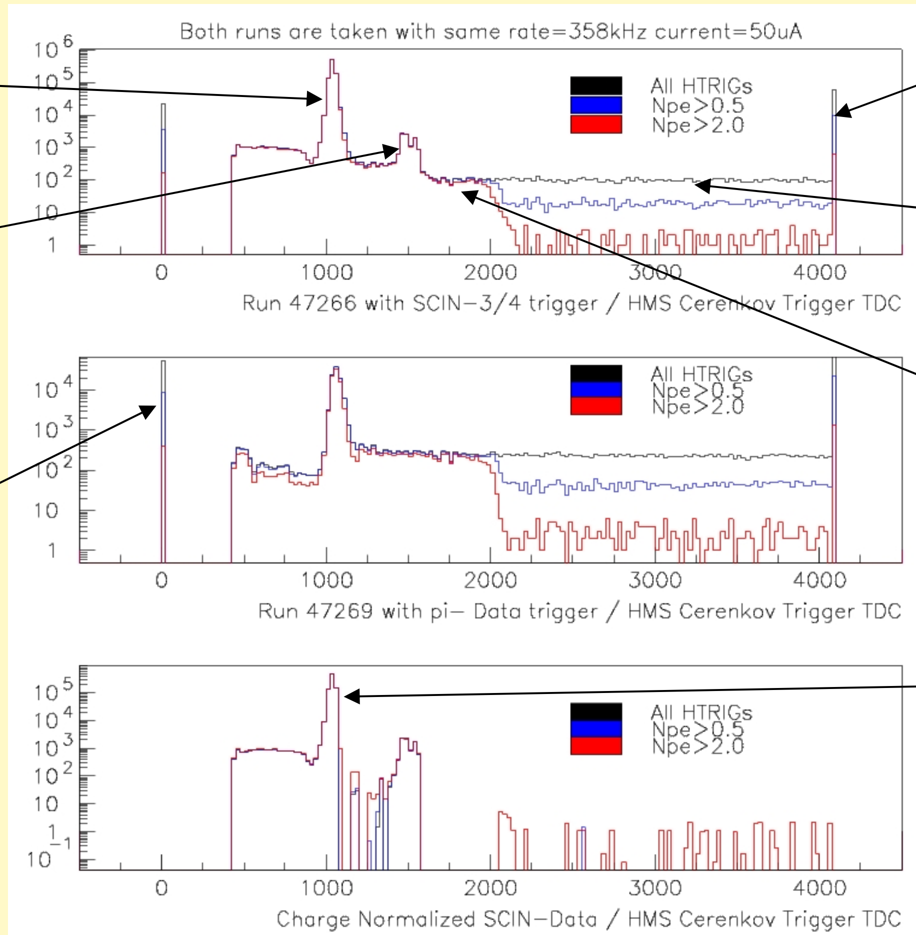
F_π-2 HMS Cerenkov Trigger TDC study

- **Multi-hit TDC of the Cerenkov signal into the HMS trigger was investigated for HMS singles rate up to ~600kHz.**
- **Compare runs without and with HMS Cerenkov veto.**

Main peak:
Signal (primarily e^-) that starts TDC.

2^{nd} peak:
Second e^- arriving within timing window, but after 1st 40ns long discriminator pulse.

Chan 0:
- Mostly π^-, not giving TDC stop.
- Ratio of 0 to 1^{st} peak much greater with veto trigger.



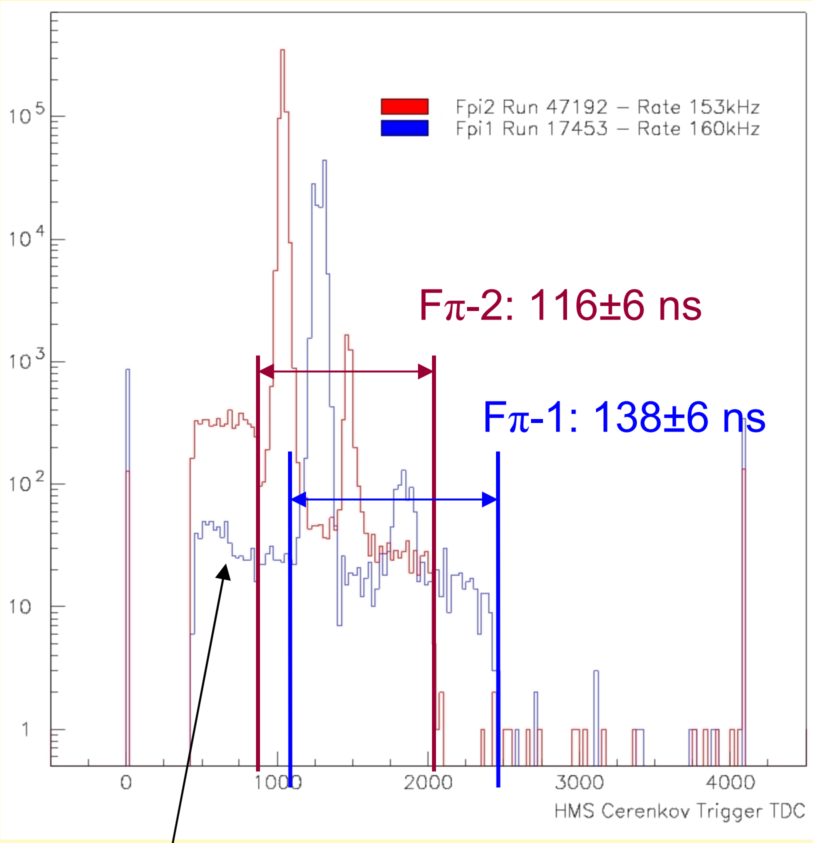
Chan 4096:
Very late TDC stops.

Tail to 410ns:
Noise crossing discriminator threshold.

Pedestal:
Earlier or later e^-.

Cerenkov trigger about 90% efficient at vetoing electrons.

Final HMS Cerenkov Blocking Corrections



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

- Final Cerenkov Blocking Correction is obtained from Trigger TDC information, since that is independent of tracking efficiency and cryotarget corrections.
- Result is consistent with τ from yield study within statistical errors.

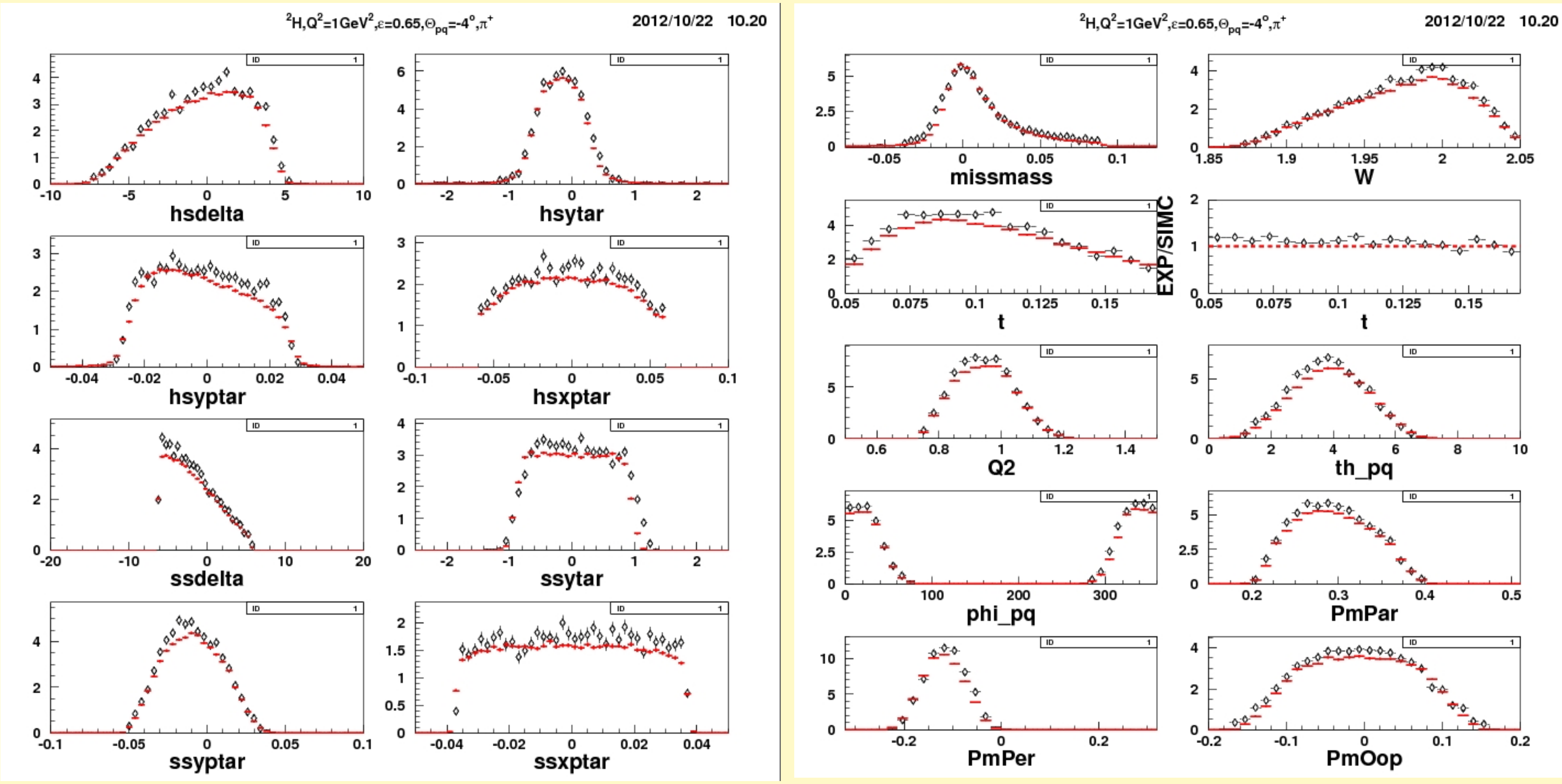
$$\boxed{\delta_{CCblock} = e^{-ELLOrate \cdot \tau}}$$

F_π-2: τ = 115±6 ns
F_π-1: τ = 138±6 ns

Changes to ^{2}H(e,e'π)NN MC Model Reconstruction

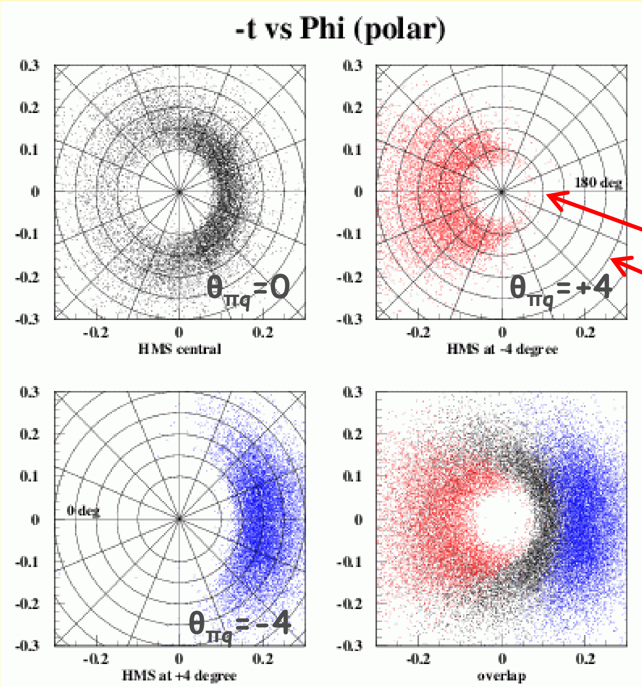
- **Our earlier ^{2}H analyses used as input to SIMC the quasi-free model developed by D. Gaskell for NucPi experiment.**
  - π is produced from interacting N with Fermi momentum k_F.
  - CM frame is virtual γ and moving N, $\varphi_{CM} \neq \varphi_{LAB}$.
- **Model has virtue that the used cross section is presumably closest to that used in the ^{1}H analysis.**
  - But there is no direct relation between the separated response functions in the SIMC model and the experimentally determined ones, since θ_{CM}, φ_{CM} depend on the assumed Fermi momentum.
  - Fitting of response functions gets complicated.
- **For these reasons, we decided to use in the SIMC physics reconstruction the same simple quasi-free model used in the experimental data reconstruction.**
  - CM frame is virtual γ and stationary N, $\varphi_{CM} = \varphi_{LAB}$, as in ^{1}H analysis.
  - SIMC simulation and data reconstruction are now consistent.
- **Extracted response functions are now effective ones, not trivially comparable to those from ^{1}H.**

Good Agreement for Optics and Kinematic Variables



Data
SIMC

Extract response functions through iterative procedure



-t=0.1

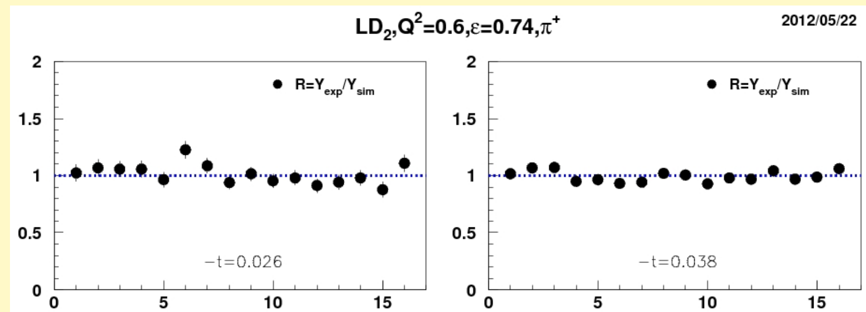
-t=0.3

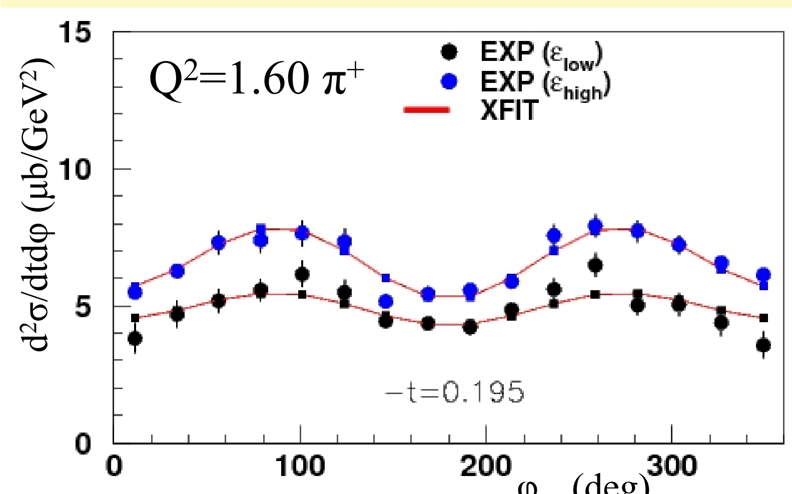
Improve φ coverage by taking data at multiple π (HMS) angles, $-4^o<\theta_{\pi q}<4^o$.

For each π HMS setting, form ratio:

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

Combine ratios for π settings together, propagating errors accordingly.



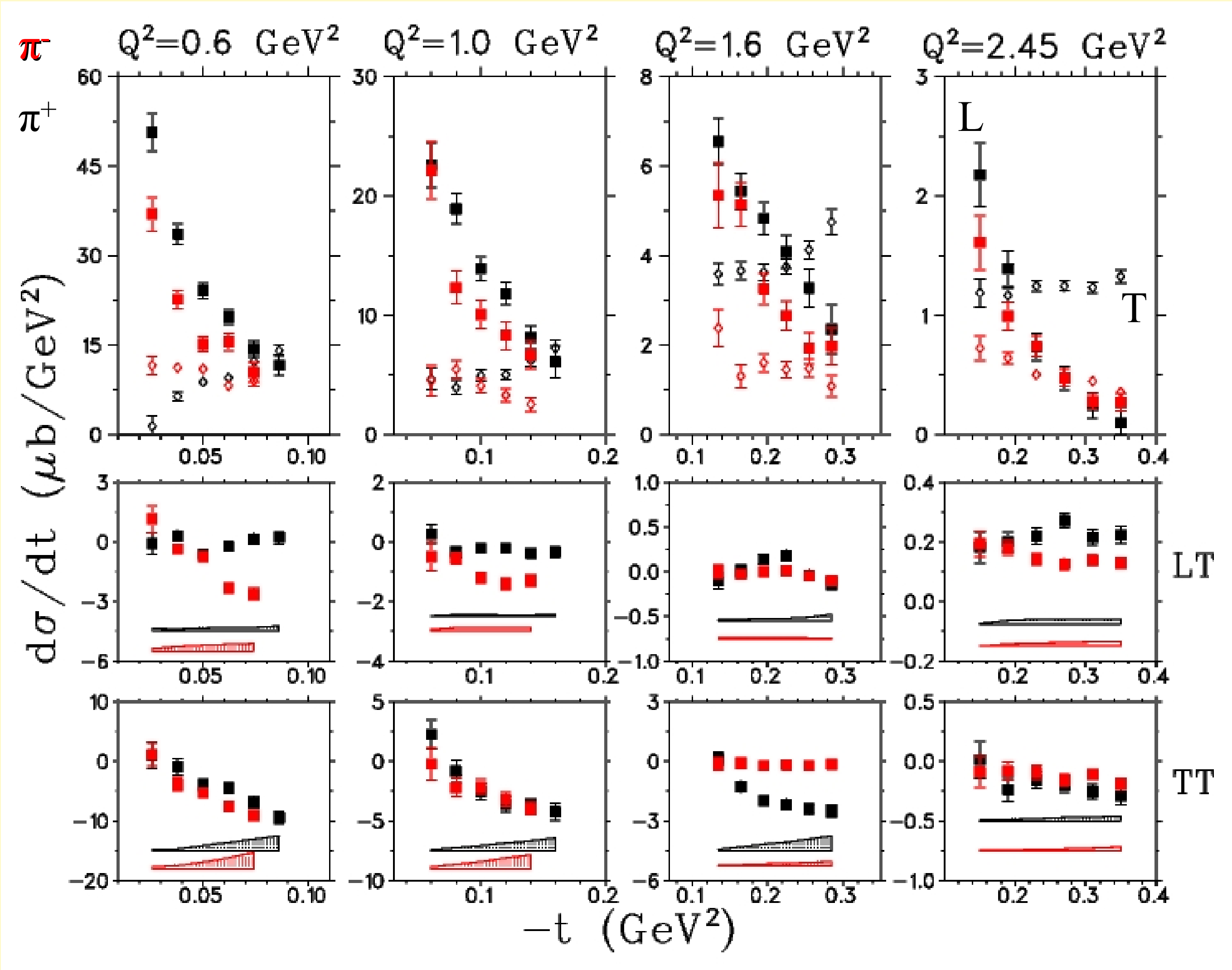


Extract via simultaneous fit of L,T,LT,TT

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

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

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



- 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.

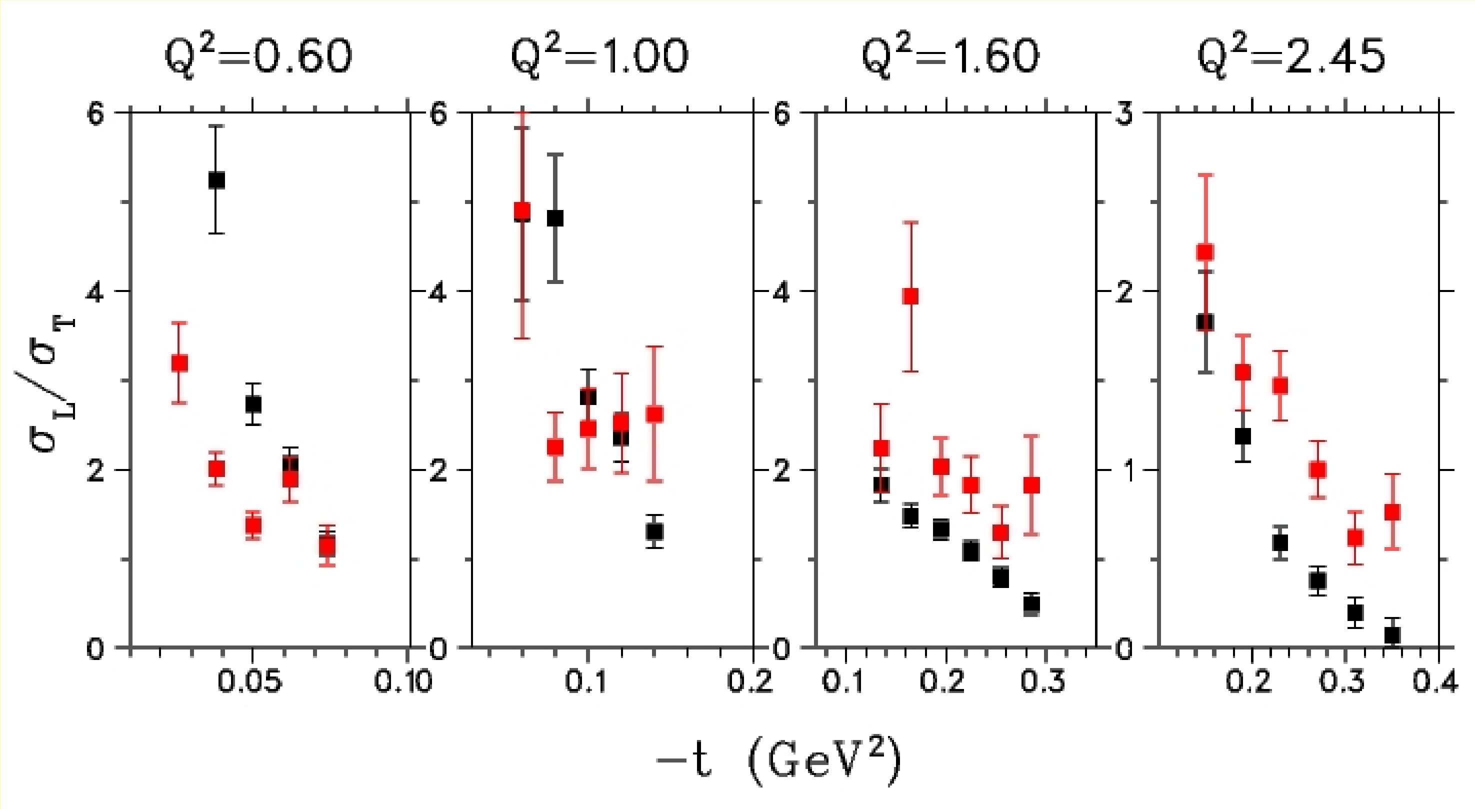
Dr. Garth Huber, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.

σ_L/σ_T Ratios for π^+, π^-

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

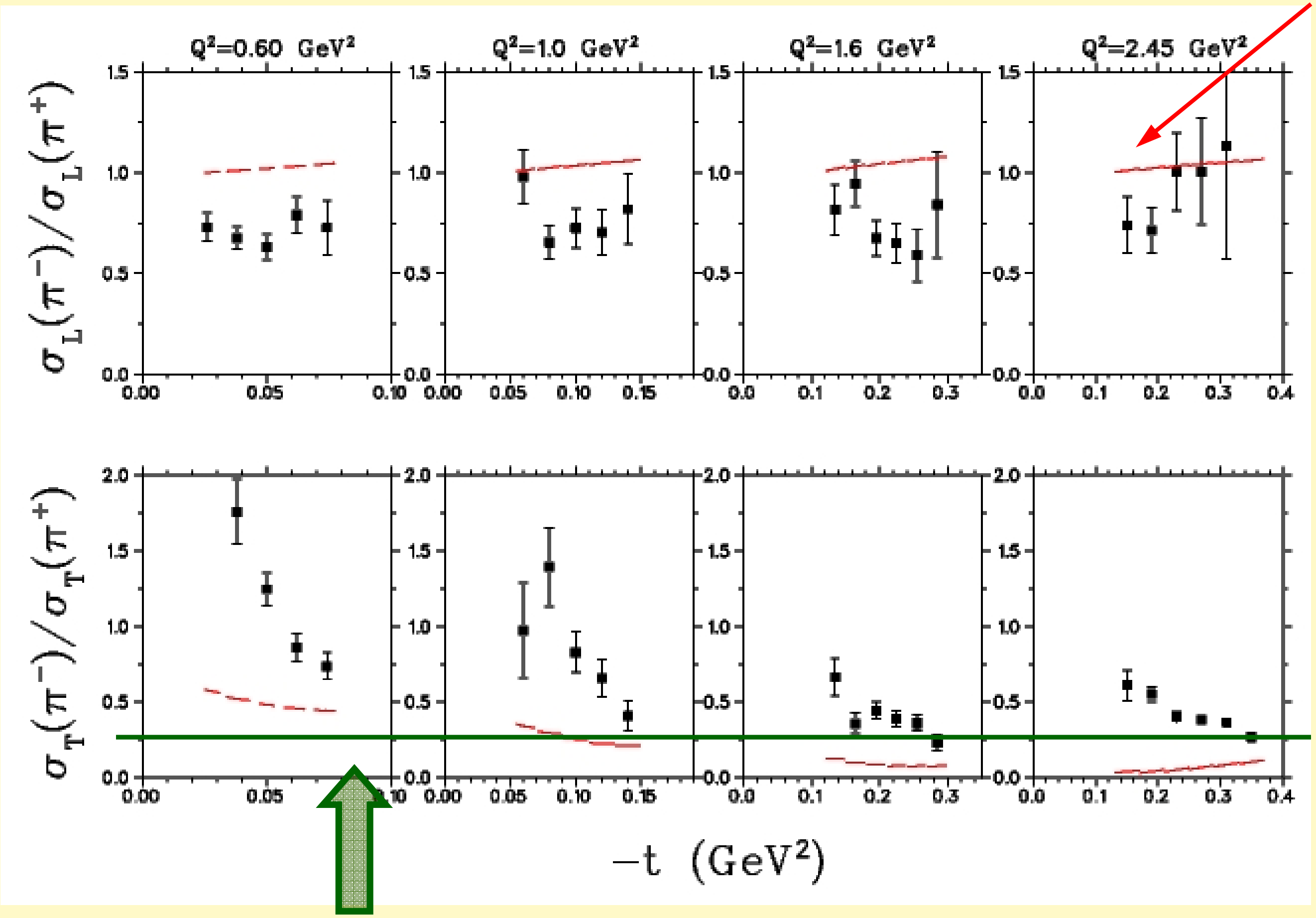
$^2H(e,e'\pi^+)nn$

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



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

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).

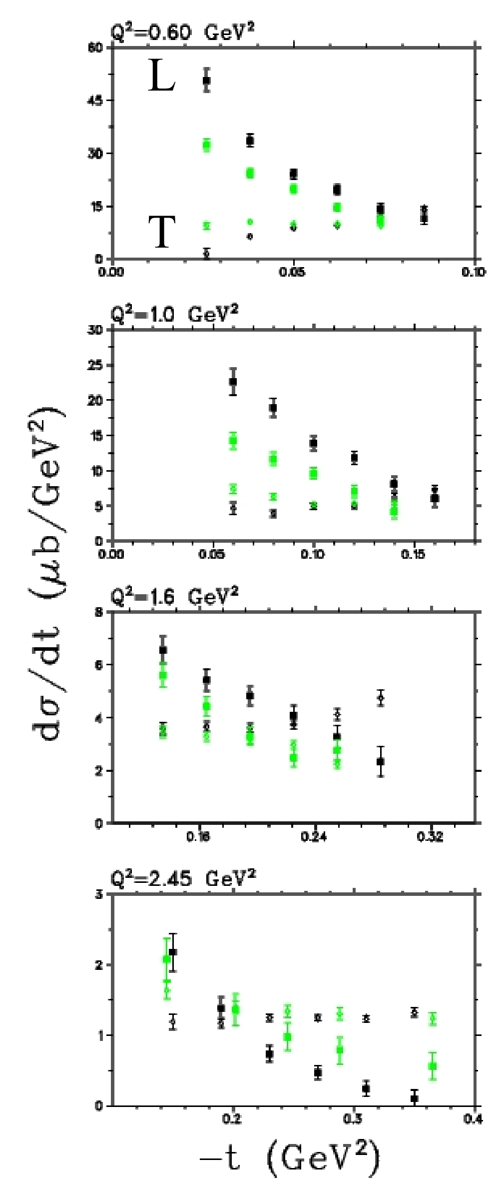
***R$_L$*=0.8 consistent with |*A$_S$*/*A$_V$*|<6%.**

- 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.

Comparison of π^+ from ^{1}H and ^{2}H

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

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



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

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

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

Next Steps

- **Technical Note has been prepared, explaining the $^2H(e,e'\pi^{\pm})$ analysis in detail (60 pages).**
  - Note will be released to the F_π Collaboration in the next 1-2 weeks.
  - Note will form the basis for 1-2 papers on these data.
  - Your opinions will be solicited.
- **Main Results:**
  - $R_L \approx 0.8$, trending towards unity at low –t.
  - Indicates the dominance of isovector processes at low –t in the longitudinal response function.
- Evolution of R_T with –t shows a 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.