The Proton in the Nuclear Medium: JLab Experimental Constraints on the Modeling of $^4He(e,e'p)^3H$ Reaction

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Overview

- E93-049 and E03-104 in Hall A: search for medium modifications of the proton structure in ^{4}He(e,e'p)^{3}H
  - $\left(\frac{P'_x}{P'_z}\right)_{^4He} \Big/ \left(\frac{P'_x}{P'_z}\right)_H$ Mike Paolone (Ph.D. in Dec. 2008): M. Paolone, S. Malace, S. Strauch *et al.*, submitted to Phys. Rev. Lett.
  - P_y focus of this talk

- H(e,e'p) vs A(e,e'p)B reactions

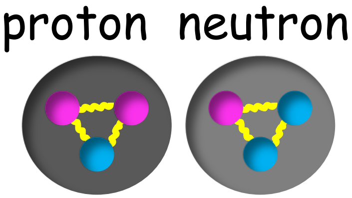
- A(e,e'p)B reactions: nuclear medium effects

- E93-049: data and interpretation

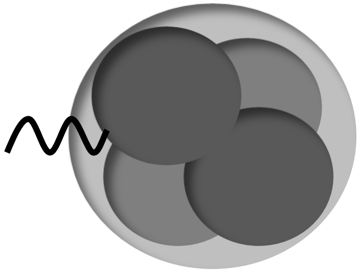
- E03-104: a precise extraction of polarization transfer and induced polarization in ^{4}He(e,e'p)^{3}H

- Do theory calculations describe the most recent, precise data?

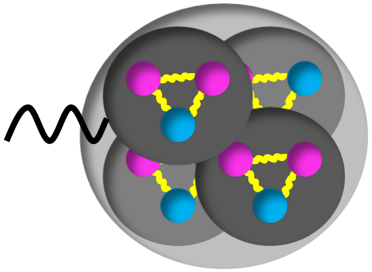
Nucleons in the Nuclear Medium



- ➢ Quarks and gluons are the building blocks of nucleons



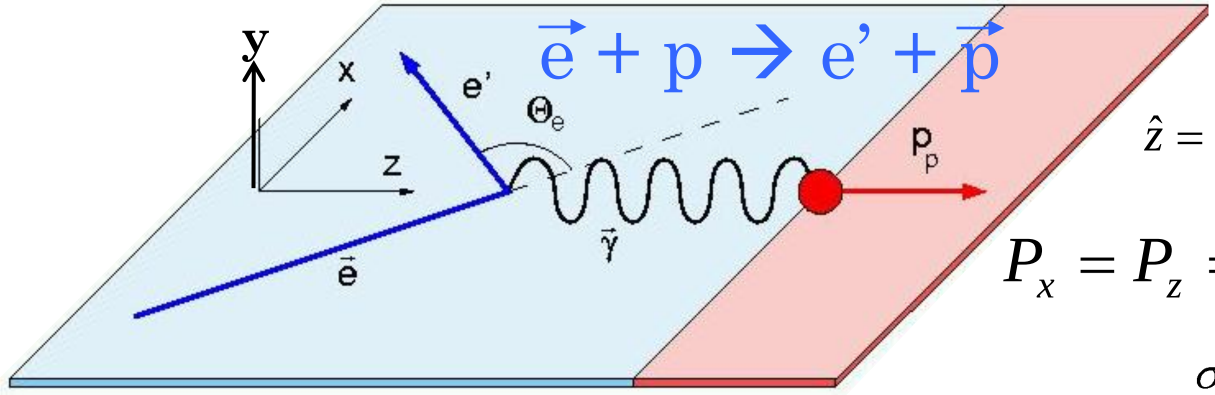
- ➢ Conventional Nuclear Physics: free nucleons and mesons as degrees of freedom; the internal structure of hadrons ignored



- ➢ Are the subnucleonic degrees of freedom relevant for description of nuclei?
  - Nucleon structure function: modified in the nuclear medium (EMC effect)
  - Nucleon form factor: modified in the nuclear medium?
    - Coulomb Sum rule
    - y scaling
    - Polarization transfer ratio

Reaction: H(e,e'p)

- Longitudinally polarized electron elastic scattering off a **free proton:** one-photon-exchange approximation (OPE)



$$\vec{e} + p \rightarrow e' + \vec{p}$$

$$\hat{z} = \frac{\vec{q}}{|\vec{q}\,|}, \quad \hat{y} = \frac{\vec{k} \times \vec{k}'}{|\vec{k} \times \vec{k}'|}, \quad \hat{x} = \hat{y} \times \hat{z}$$

$$P_x = P_z = P_y' = 0 \quad P_y = 0 \text{ (OPE)}$$

$$\frac{d\sigma}{dE_{e'}\, d\Omega_{e'}\, d\Omega_p} = \frac{\sigma_0}{2}[1 + h \cdot (A + P_x' \cdot \hat{S}_x + P_z' \cdot \hat{S}_z)]$$

→

σ_o = unpolarized cross section

h = beam helicity

A = analyzing power

P (P') = induced polarization

(polarization transfer)

$$P_x' = -2\sqrt{\tau(1+\tau)}\frac{\frac{G_{Ep}}{G_{Mp}}}{(\frac{G_{Ep}}{G_{Mp}})^2 + \frac{\tau}{\epsilon}} \tan\frac{\theta_e}{2}$$

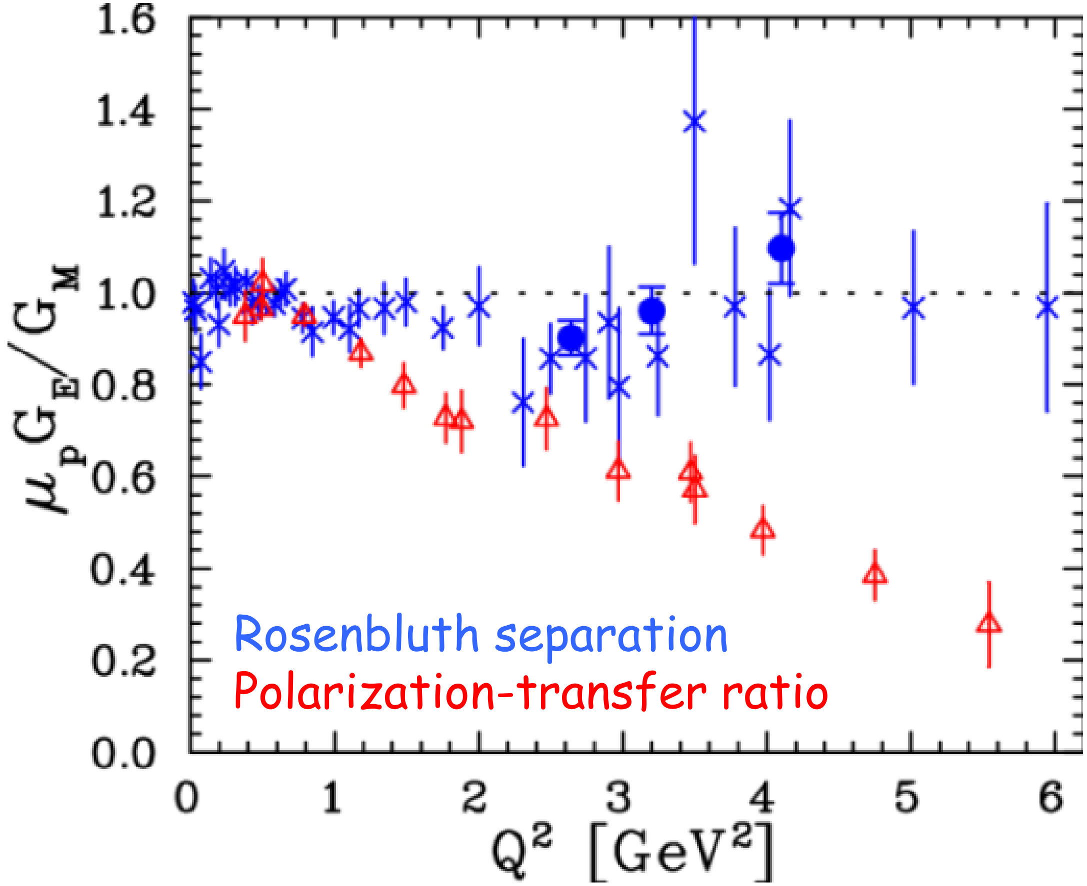
$$P_z' = \frac{1}{m}(E_i + E_f)\sqrt{\tau(1+\tau)}\frac{1}{(\frac{G_{Ep}}{G_{Mp}})^2 + \frac{\tau}{\epsilon}} \tan^2\frac{\theta_e}{2}$$

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_x'}{P_z'}\frac{(E_i + E_f)}{2m}\tan\frac{\theta_e}{2}$$

Polarization Transfer Ratio: H(e,e'p)

- Very precise technique: systematics cancel in the ratio

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P'_x}{P'_z}\frac{(E_i+E_f)}{2m}\tan\frac{\theta_e}{2}$$

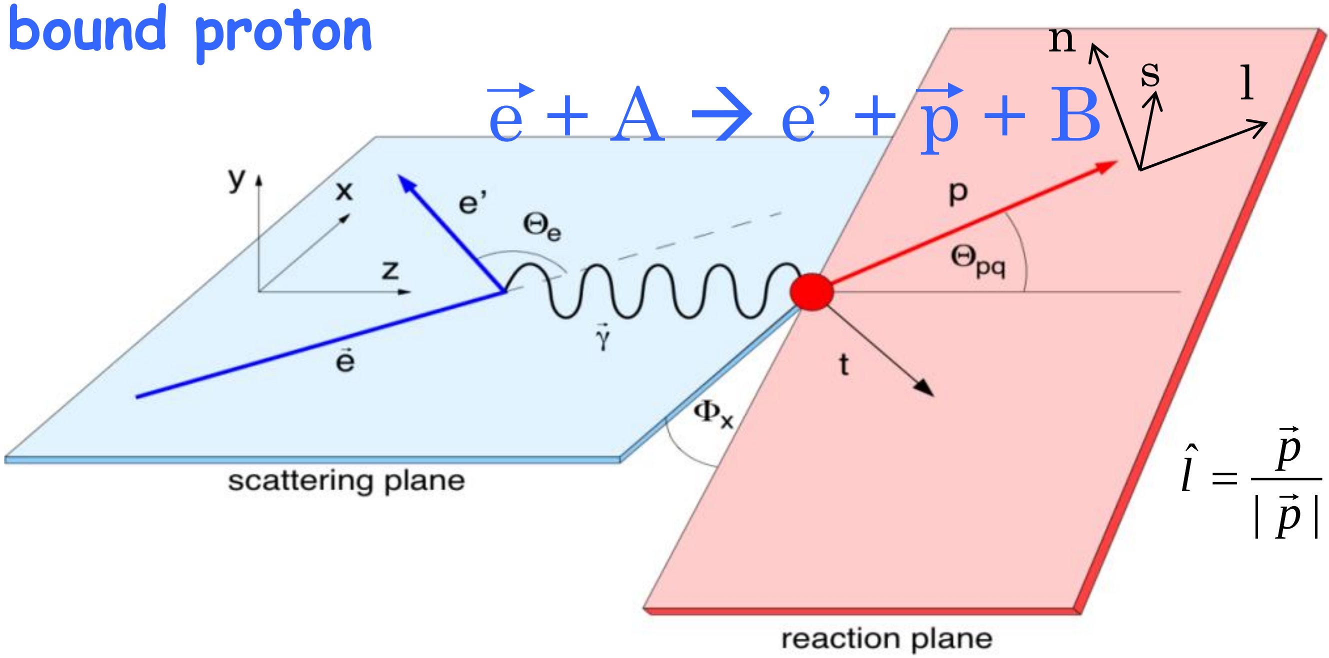


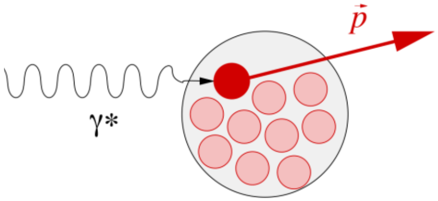
for illustration only (not up-to-date)

Reaction: A(e,e'p)B

- Longitudinally polarized electron quasielastic scattering off a **bound proton**

$\vec{e} + A \rightarrow e' + \vec{p} + B$





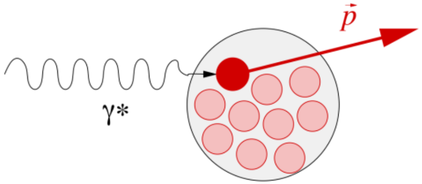
$$\hat{l} = \frac{\vec{p}}{|\vec{p}|}, \quad \hat{n} = \frac{\vec{q}\times\vec{p}}{|\vec{q}\times\vec{p}|}, \quad \hat{s} = \hat{n}\times\hat{l}$$

$$\frac{d\sigma}{dE_{e'}d\Omega_{e'}d\Omega_p} = \frac{\sigma_0}{2}[1 + P_l\cdot\hat{S}_l + P_n\cdot\hat{S}_n + P_s\cdot\hat{S}_s + h\cdot(A + P_l'\cdot\hat{S}_l + P_n'\cdot\hat{S}_n + P_s'\cdot\hat{S}_s)]$$

- From reaction to scattering plane:

$$\begin{pmatrix} P_x(P_x') \\ P_y(P_y') \\ P_z(P_z') \end{pmatrix} = \begin{pmatrix} \sin\theta_{pq}\cos\phi_x & -\sin\phi_x & \cos\theta_{pq}\cos\phi_x \\ \sin\theta_{pq}\sin\phi_x & \cos\phi_x & \cos\theta_{pq}\sin\phi_x \\ \cos\theta_{pq} & 0 & -\sin\theta_{pq} \end{pmatrix} \begin{pmatrix} P_l(P_l') \\ P_n(P_n') \\ P_s(P_s') \end{pmatrix}$$

Reaction: A(e,e'p)B



- ➢ No simple relationship between polarization-transfer ratio and form-factor ratio

- ➢ Cross sections, polarizations: expressed in terms of 18 nuclear response functions (R^L, R^T, ...) constructed by taking the appropriate components of the hadronic tensor $W^{\mu\nu} \propto J_N^{\mu *}(q) J_N^{\nu}(q)$

$$\frac{1}{2}(R^L + R_n^L \hat{S}_n) = W^{00} \qquad \frac{1}{2}(R^T + R_n^T \hat{S}_n) = W^{11} + W^{22} \;\ldots$$

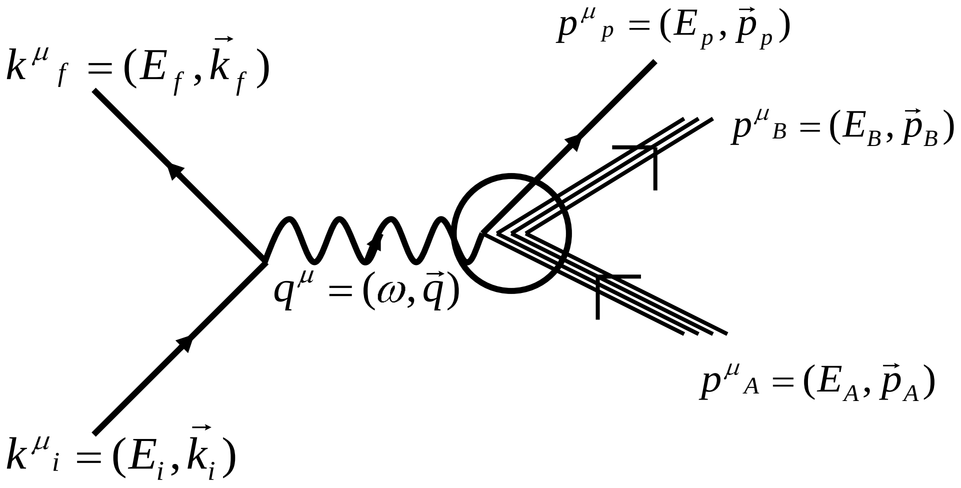
$$\begin{aligned}\frac{d\sigma}{dE_{e'} d\Omega_{e'} d\Omega_p} \propto\; & V_L (R^L + R_n^L \hat{S}_n) + V_T (R^T + R_n^T \hat{S}_n) + \\ & V_{LT}[(R^{TL} + R_n^{TL} \hat{S}_n)\cos\phi_x + (R_l^{TL} \hat{S}_l + R_s^{TL} \hat{S}_s)\sin\phi_x] + \\ & V_{TT}[(R^{TT} + R_n^{TT} \hat{S}_n)\cos 2\phi_x + (R_l^{TT} \hat{S}_l + R_s^{TT} \hat{S}_s)\sin 2\phi_x] + \\ & h\{V_{TL'}[(R_l^{TL'} \hat{S}_l + R_s^{TL'} \hat{S}_s)\cos\phi_x + (R^{TL'} + R_n^{TL'} \hat{S}_n)\sin\phi_x] + \\ & \quad V_{T'}[R_l^{T'} \hat{S}_l + R_s^{T'} \hat{S}_s]\}\end{aligned}$$

- ➢ Calculation of nuclear current ⇔ make choices regarding the inclusion/treatment of various reaction mechanisms

Proton in the Nuclear Medium: A(e,e'p)B

- Example: **A(e,e'p)B** in Born + Impulse Approximation

J. Udias *et al.*, Phys. Rev. *C* 48, 2731 (1993)



$$\frac{d\sigma}{dE_f\, dE_p\, d\Omega_f\, d\Omega_p} \propto |M_{if}|^2$$

$$M_{if} = \int dx \int dy \int \frac{dq}{(2\pi)^2} \underset{\text{electron current}}{\boxed{j_\mu{}^e(x)}} e^{-iq(x-y)} \frac{(-1)}{q_\mu{}^2} \underset{\text{nuclear current}}{\boxed{J_N{}^\mu(y)}}$$

- Nuclear effects have to be taken into account when calculating the currents for e-p_{bound} as opposed to e-p_{free} scattering

A(e,e'p)B: Nuclear Medium Effects

Photon-nucleon vertex current: $J_N{}^{\mu}(r) = \overline{\psi}_F{}^{N}(r)\widehat{J}_N{}^{\mu}\psi_B{}^{N}(r)$

- Off-shell effects (no unambiguous treatment): various prescriptions to impose current conservation T. De Forest, Jr. Nucl. Phys. A392, 232 (1983)

$$\widehat{J}_{cc1}{}^{\mu} = G_M(Q^2)\gamma^{\mu} - \frac{\kappa}{2M}F_2(Q^2)(P_i^{\mu} + P_f{}^{\mu}),$$

$$\widehat{J}_{cc2}{}^{\mu} = F_1(Q^2)\gamma^{\mu} + i\frac{\kappa}{2M}F_2(Q^2)\sigma_{\mu\nu}q_{\nu}$$

$$\widehat{J}_{cc3}{}^{\mu} = F_1(Q^2)\frac{\overline{P}^{\mu}}{2M} + \frac{i}{2M}G_M(Q^2)\sigma_{\mu\nu}q_{\nu}$$

$\widehat{J}_{cc1}, \widehat{J}_{cc2}, \widehat{J}_{cc3}$ equivalent for free nucleon but not guaranteed to produce the same result for bound nucleons

- Vary prescriptions seem to converge with increasing Q^2, especially at low missing momentum

D. Debruyne, J. Ryckebusch, W. Van Nespen and S. Janssen, Phys. Rev. C 62, 024611 (2000)

A(e,e'p)B: Nuclear Medium Effects

Photon-nucleon vertex current: $J_N^{\mu}(r) = \overline{\psi}_F^{\,N}(r)\widehat{J}_N^{\,\mu}\psi_B^{\,N}(r)$

- Many-body currents: IA = "zero order approximation" but realistically we need higher-order corrections to IA

1-body current 2-body current

$$<\psi_f \,|\, \widehat{J}^{\mu} \,|\, \psi_i> = <\chi(1) \,|\, \hat{J}^{\mu}(1b) \,|\, \psi_\beta(1)> + \sum_{\alpha=1}^{A} <\chi(1)\psi_\alpha(2) \,|\, \hat{J}^{\mu}(2b) \,|\, \psi_\beta(1)\psi_\alpha(2) - \psi_\alpha(1)\psi_\beta(2)>$$

A. Meucci *et al.*, Phys. Rev. C 66, 034610 (2002)
R. Schiavilla *et al.*, Phys. Rev. Lett. 94, 072303 (2005)

- Final-State Interactions: the nucleon can interact with its neighbors after being struck by the photon

  - Most calculations account for FSI via **optical potentials (OPT)**

(e,e'p)(p,p) J. Udias *et al.*, Phys. Rev. Lett. 83, 5451 (1999)

(e,e'p)(p,p) + (e,e'n)(n,p) R. Schiavilla *et al.*, Phys. Rev. Lett. 94, 072303 (2005)

  - Some calculations use **Glauber framework** to incorporate FSI

P. Lava, J. Ryckebush, B. Van Overmeire, Phys. Rev. C 71, 014605 (2005)

A(e,e'p)B: Nuclear Medium Effects

Photon-nucleon vertex current: $J_N^{\mu}(r) = \overline{\psi}_F^{\,N}(r)\hat{J}_N^{\mu}\psi_B^{\,N}(r)$

- Form-factors: free or medium modified (density dependent) form-factors in the electromagnetic current operator?

e.g. $\hat{J}_{cc1}^{\mu} = \boxed{G_M}(Q^2)\gamma^{\mu} - \frac{\kappa}{2M}\boxed{F_2}(Q^2)(P_i^{\mu} + P_f^{\mu}) \rightarrow$ free or medium-modified nucleon form-factor ?

For example:

Quark Meson Coupling Model (QMC)

Structure of the nucleon: valence quarks in a bag (Cloudy-bag model)

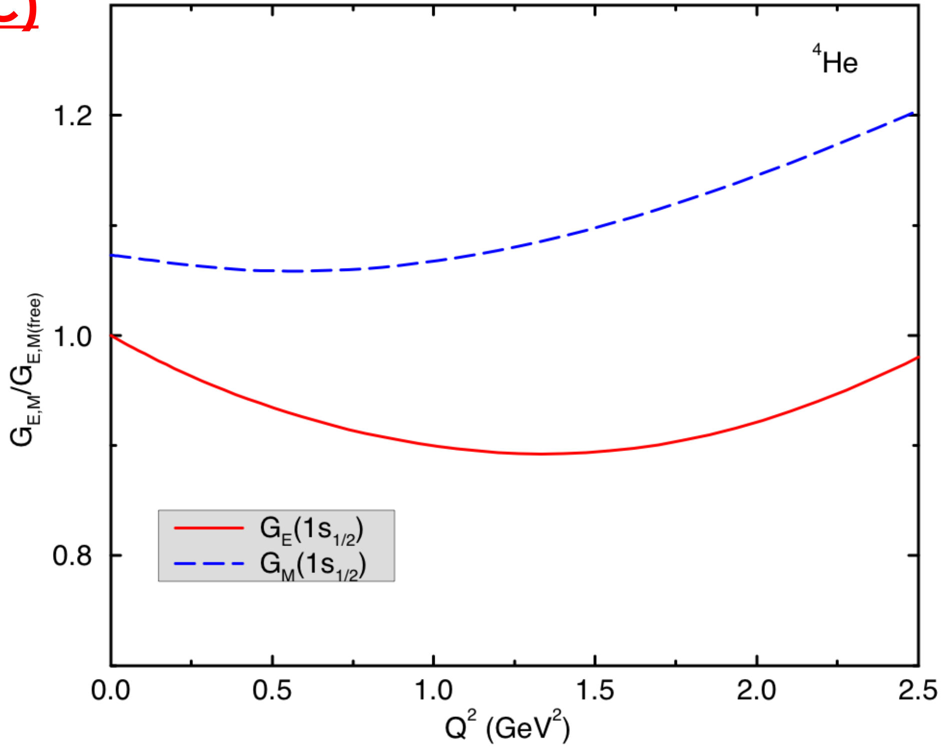
Nuclear system: effective scalar (σ) and vector (ω) meson fields

ω and σ couple directly to confined quarks

$\Downarrow$

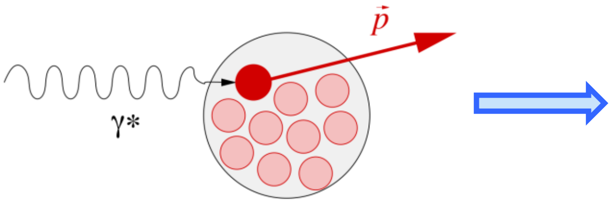
Modification of internal structure of bound nucleon

D.H. Lu *et al.*, Phys. Rev. C 60, 068201 (1999)



Polarization Transfer Technique: A(e,e'p)B

- No simple relationship between polarization-transfer ratio and form-factor ratio



$$\frac{G_{Ep}}{G_{Mp}} \xcancel{=} -\frac{P'_x}{P'_z}\frac{(E_i+E_f)}{2m}\tan\frac{\theta_e}{2}$$

But we can take advantage of this very precise experimental technique…

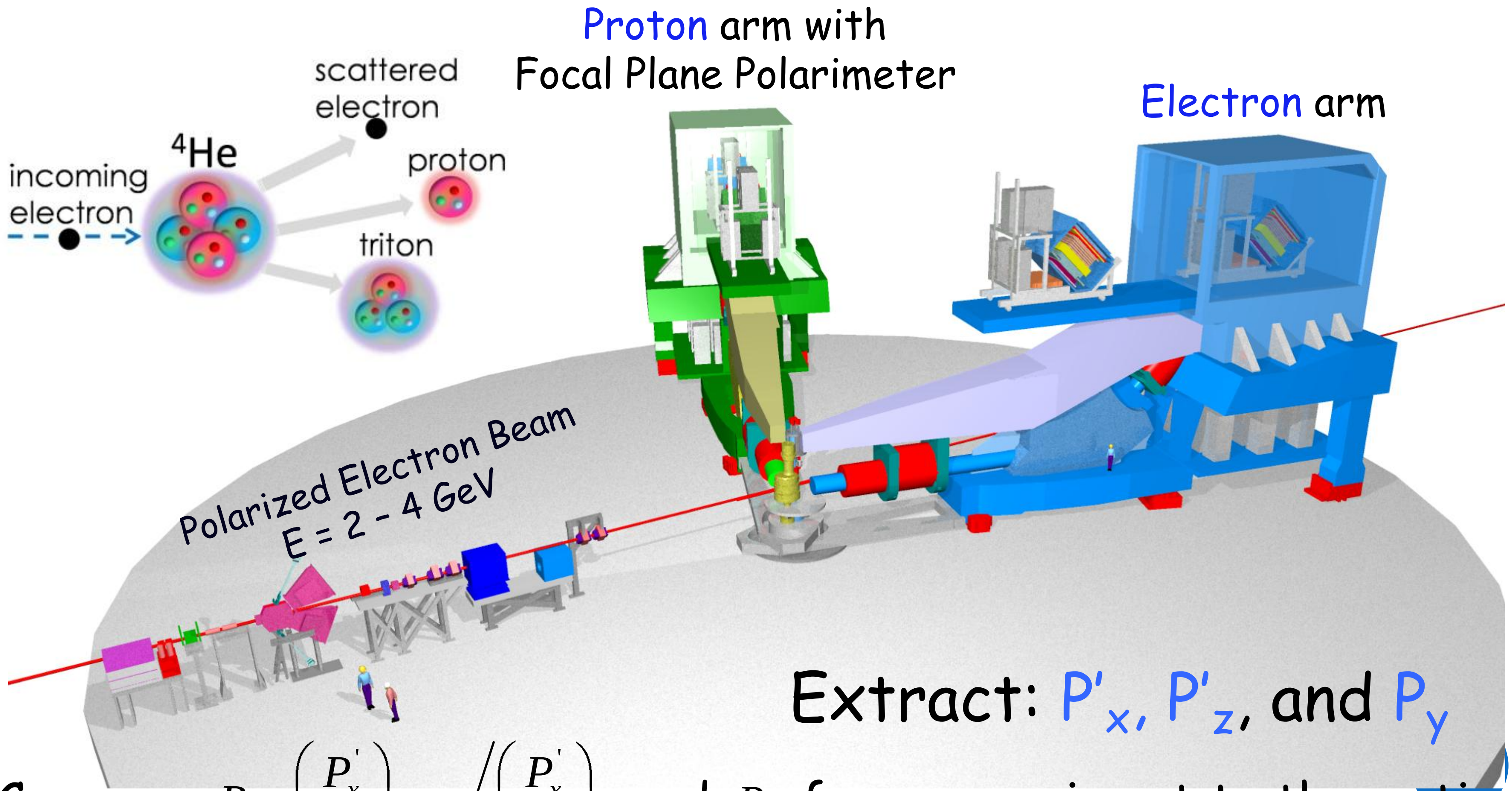
- Compare e-p$_{bound}$ to e-p$_{free}$ by measuring:
  - Polarization transfer double ratio: $R = \left(\frac{P_x^{'}}{P_z^{'}}\right)_A \Big/ \left(\frac{P_x^{'}}{P_z^{'}}\right)_H$
  - Other polarization observables sensitive to medium effects: P_y

Put to test the modeling of nuclear medium effects
in state-of-the-art nuclear physics calculations

E93-049 in Hall A at JLab

4He(e,e′p)3H in quasi-elastic kinematics $Q^2 = 0.5 - 2.6$ GeV^2

H(e,e′p) in elastic kinematics…



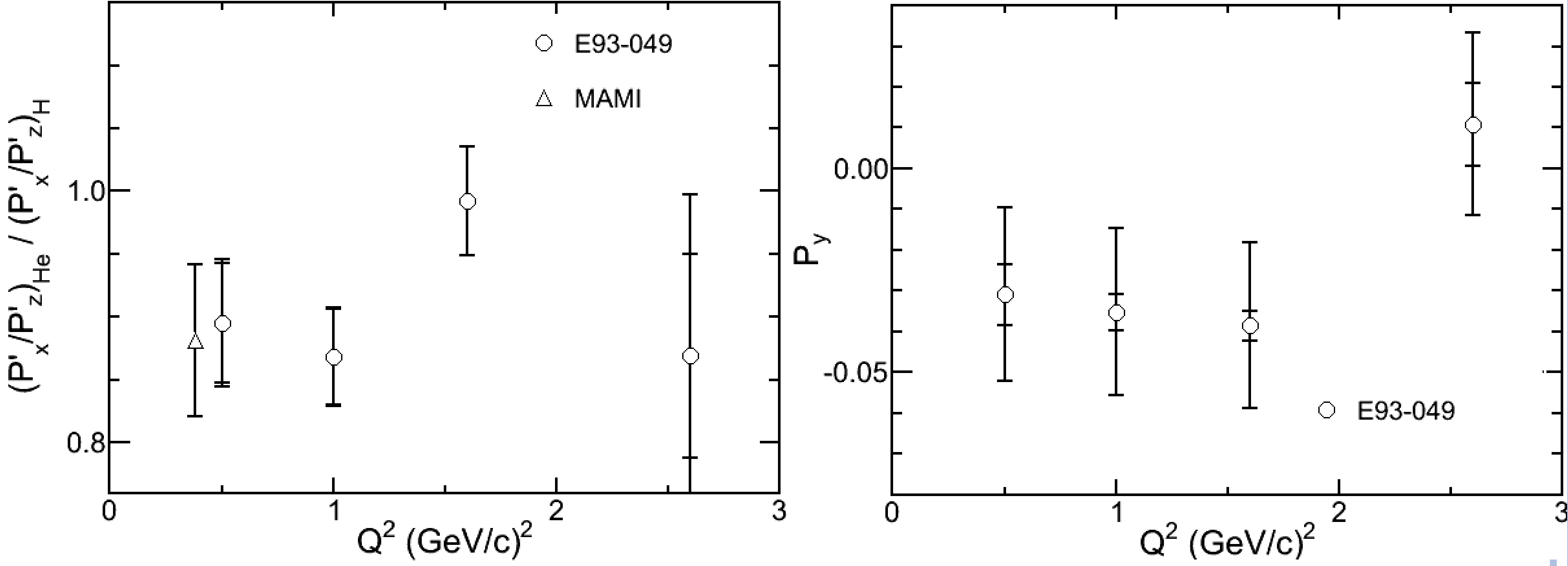
Extract: P'_x, P'_z, and P_y

Compare $R = \left(\frac{P'_x}{P'_z}\right)_{^4He} \Big/ \left(\frac{P'_x}{P'_z}\right)_H$ and P_y from experiment to theoretical calculations

E93-049 Results

Polarization transfer

- ^{4}He differs significantly from ^{1}H: 10% reduction from 1 of $\left(\frac{P_x^{'}}{P_z^{'}}\right)_{^4He} \Big/ \left(\frac{P_x^{'}}{P_z^{'}}\right)_H$



Induced polarization

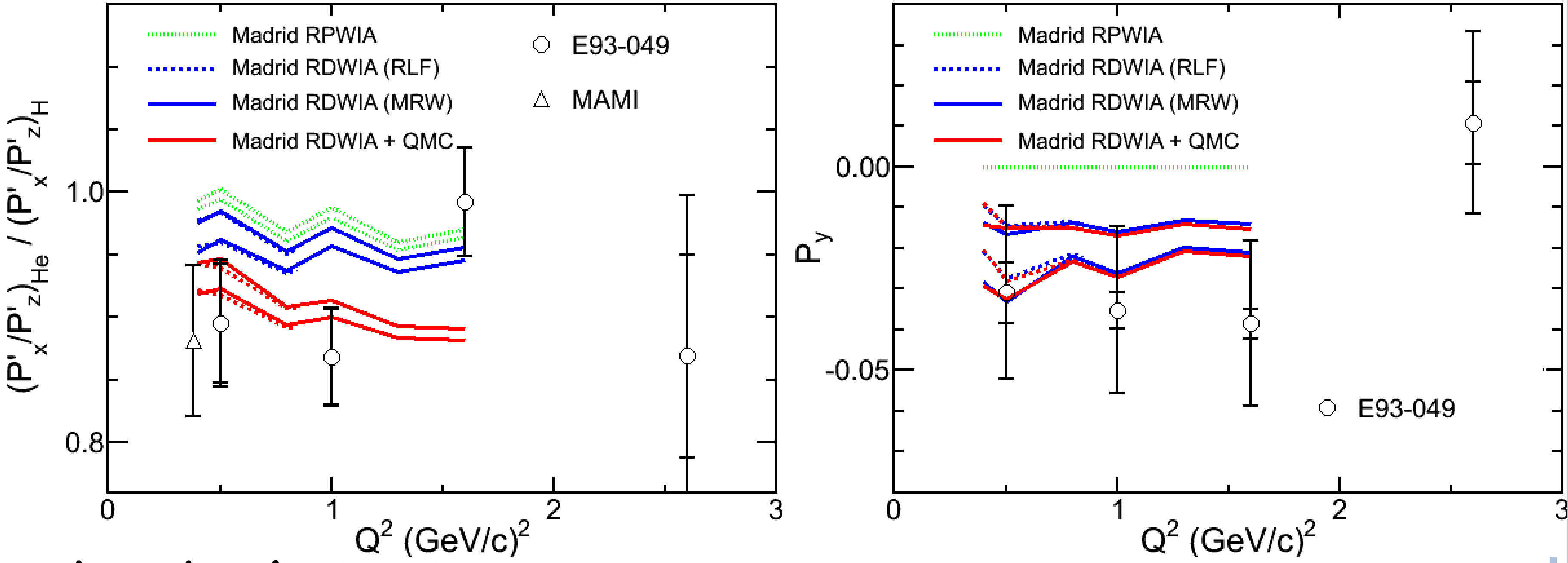
- P_y in ^{4}He(e,e'p)^{3}H is small: ~ -0.035 for Q^2 -> (0.5 - 1.6) GeV^2 (rather large systematic uncertainties)

S. Strauch *et al.*, Phys. Rev. Lett. 91, 052301 (2003)

E93-049: Interpretation (Madrid)

Polarization transfer

- RDWIA calculation from Madrid fails to describe $\left(\frac{P'_x}{P'_z}\right)_{^4He} \Big/ \left(\frac{P'_x}{P'_z}\right)_H$ from data
- RDWIA + QMC (density-dependent form factors) in agreement with data



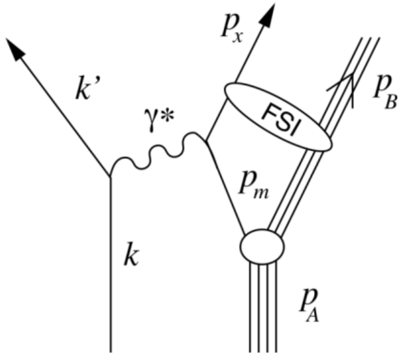
Induced polarization

- Data reasonably well described by RDWIA (within the large systematic uncertainties of data)
- P_y insensitive to inclusion of density-dependent form factors but sensitive to the cc and FSI used

The Madrid Calculation

Relativistic Distorted Wave Impulse Approximation (RDWIA)

J.M. Udias *et al.*, Phys. Rev. Lett. 83, 5451 (1999)

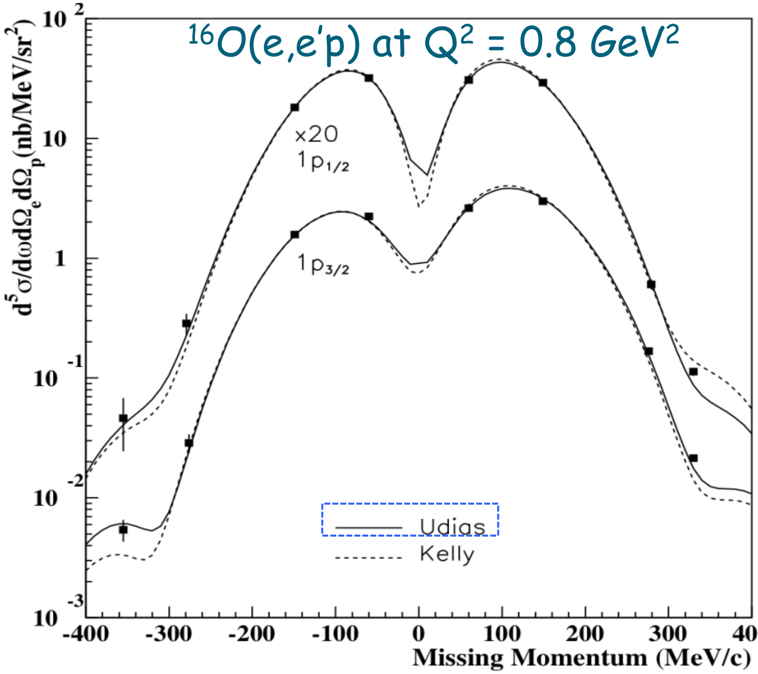


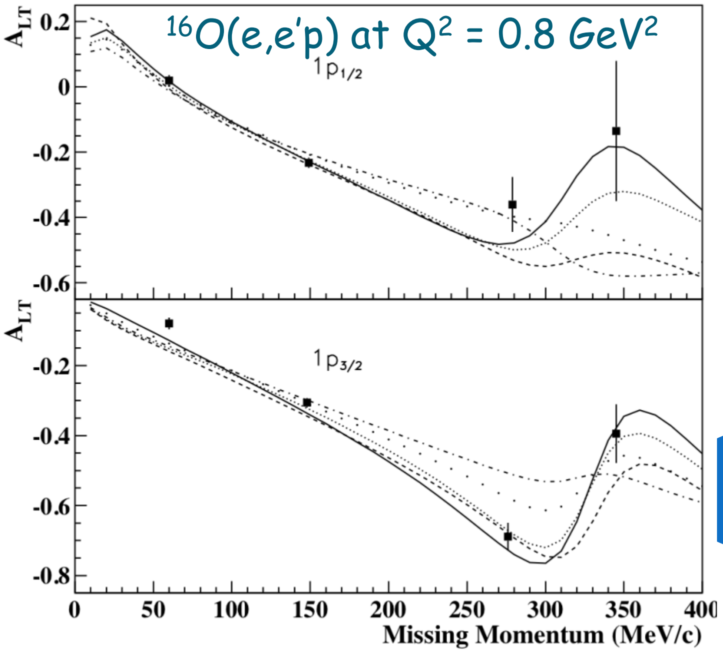
$$J^{\mu}_{N}(\omega,\vec{q}) = \int d\vec{p}\,\bar{\psi}_F(\vec{p}+\vec{q})\hat{J}^{\mu}_{N}(\omega,\vec{q})\psi_B(\vec{p})$$

$\psi_B(\vec{p})$ relativistic wave function for initial bound proton

$\hat{J}^{\mu}_{N}(\omega,\vec{q})$ relativistic one-body proton current operator

$\psi_F(p' + \vec{q})$ relativistic wave function for final outgoing proton: solution of Dirac eq. with global optical potentials (central + spin dependent)





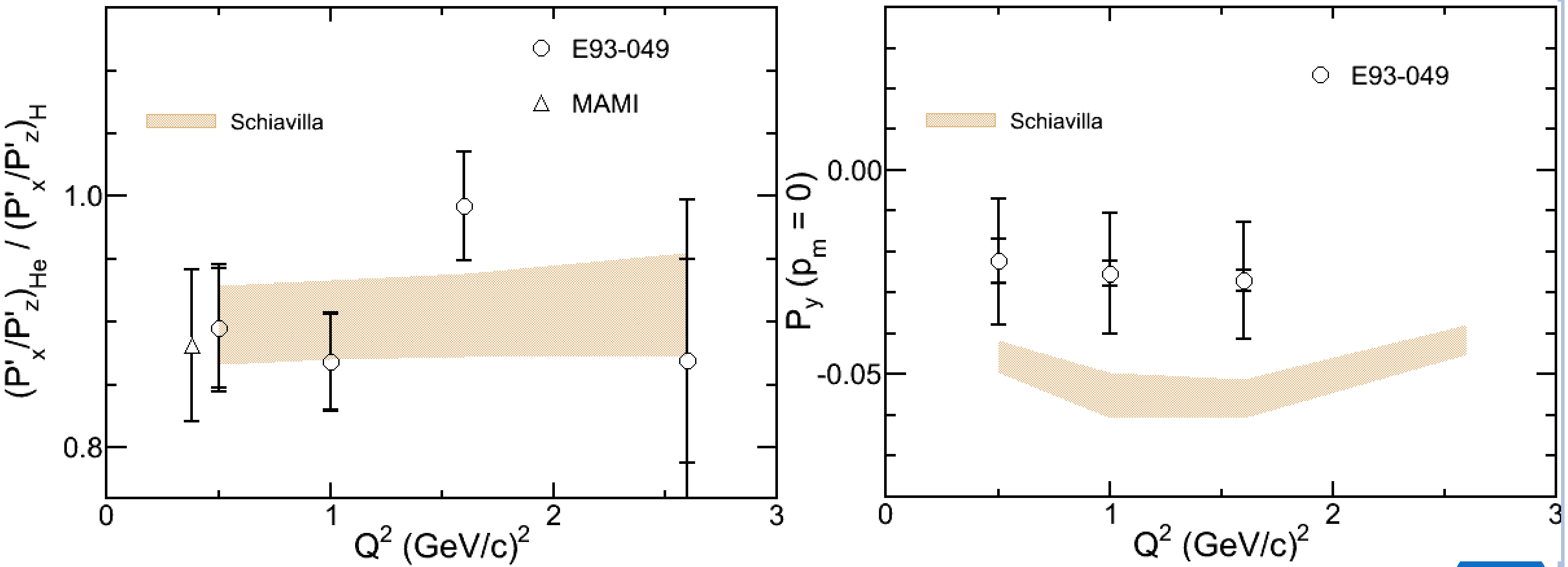
E93-049: Different Interpretation

(R. Schiavilla *et al.*)

Polarization transfer

- $\left(\frac{P'_x}{P'_z}\right)_{^4He} \Big/ \left(\frac{P'_x}{P'_z}\right)_H$ from data described by a calculation from Schiavilla *et al.*

(free nucleon form factors but different modeling of FSI and wave function + 2-body current)



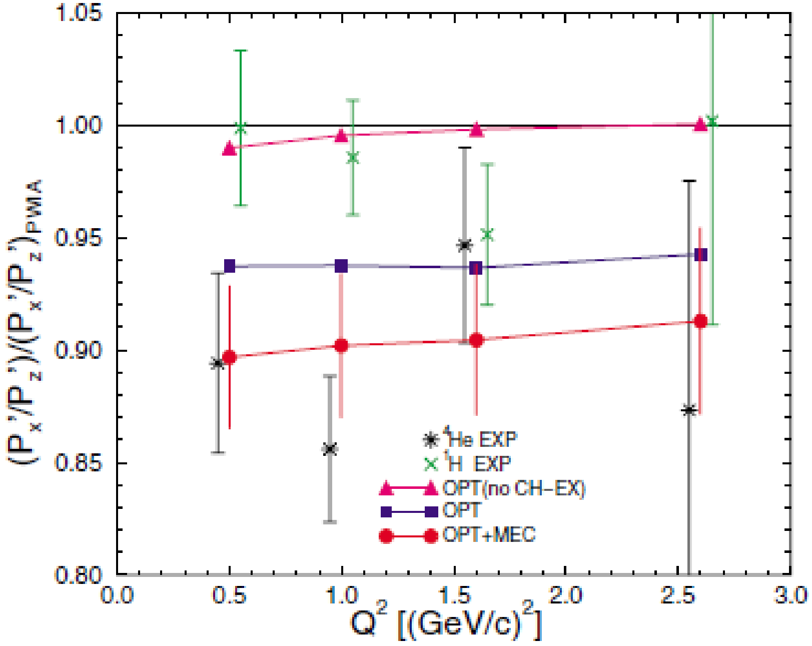
Induced polarization

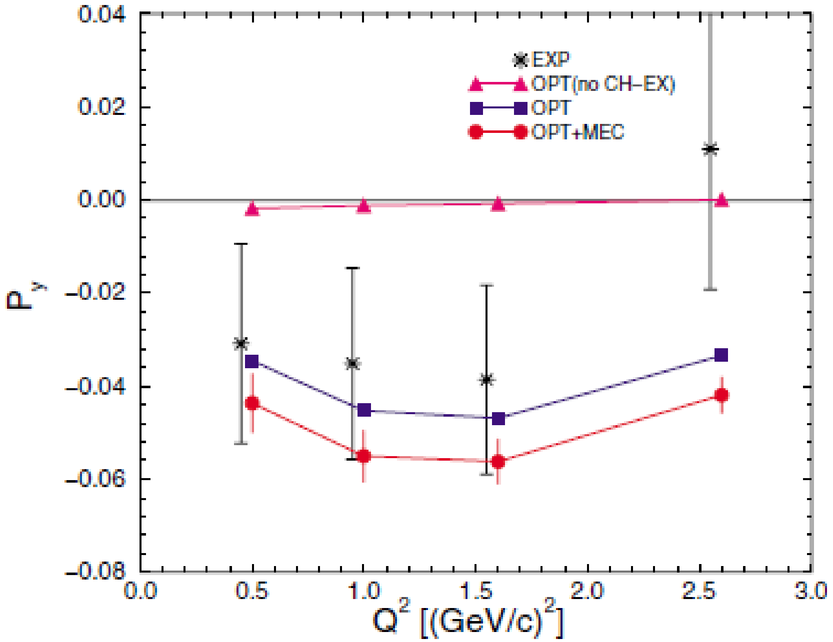
- P_y : calculation slightly overestimates the data (absolute value)

Calculation from R. Schiavilla

- Variational wave functions for the bound three- and four-nucleon systems
- 2-body current: nonrelativistic MEC
- FSI: optical potentials with an additional charge-exchange term, largely unconstrained
- Free proton form factors

R. Schiavilla *et al.*, Phys. Rev. Lett. 94, 072303 (2005)





- FSI, no CH-EX: reduction by ~ 0.5 %
- FSI + CH-EX: reduction by ~ 5.5 %
- MEC: reduction by ~ 4%

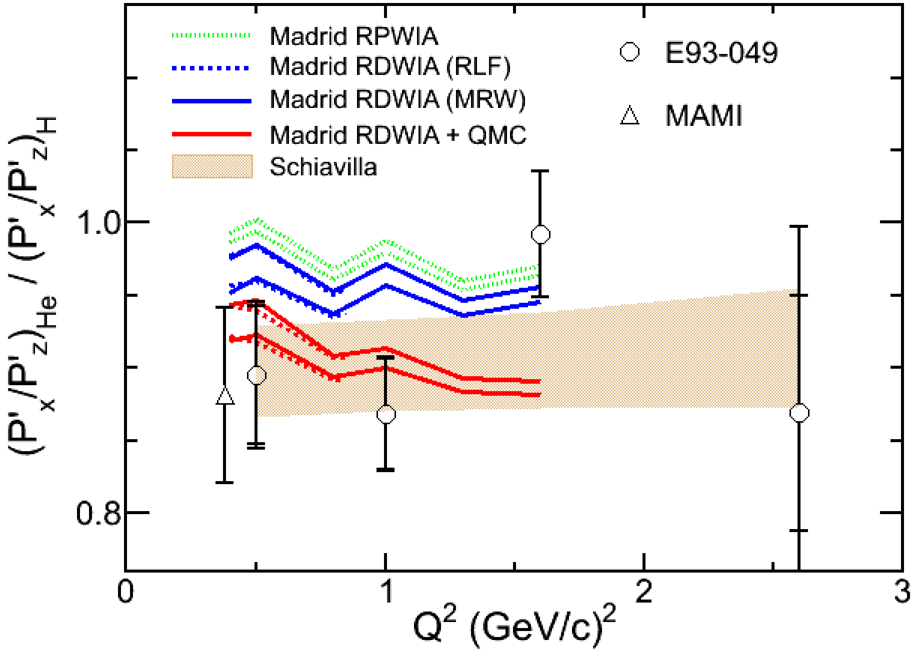
- FSI, no CH-EX: ~ 0
- FSI + CH-EX: ~ -0.045
- MEC: ~ -0.055

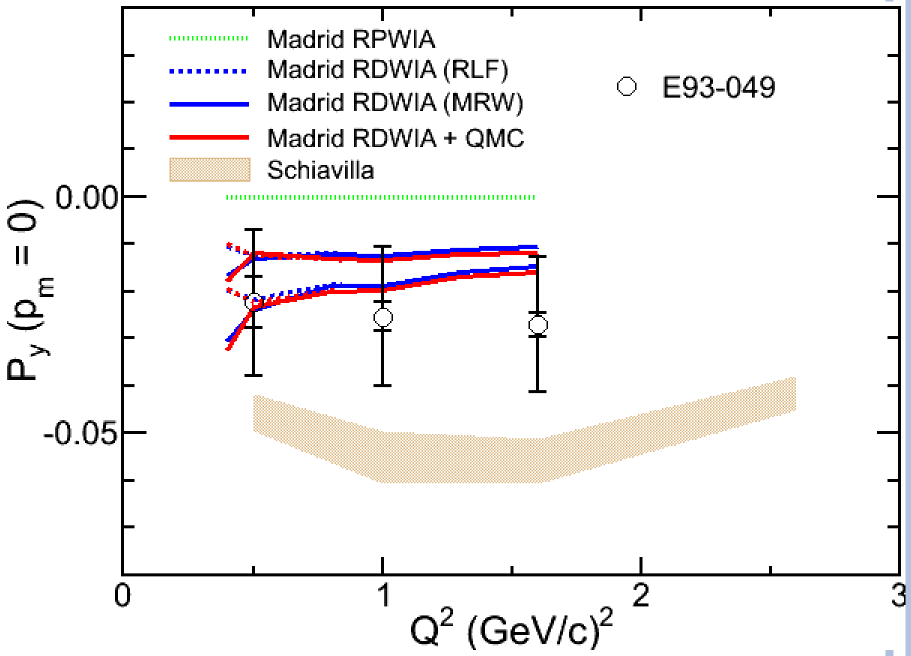
Recap

Polarization transfer

- Data consistent with: RDWIA + QMC (medium-modified form-factors)

or FSI with charge-exchange + MEC + free form-factors





Induced polarization

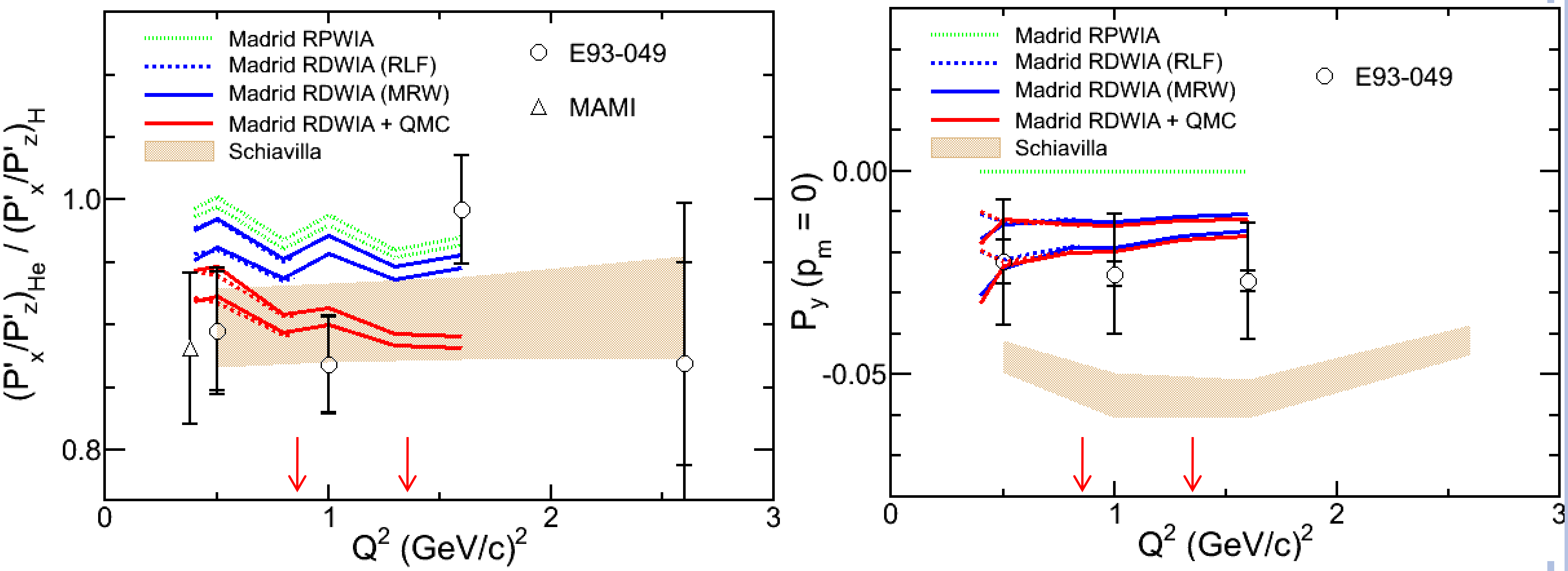
- The two calculations differ in their description of P_y
- Systematic uncertainties on data too large to make a definite claim
- P_y becomes the key in the interpretation of the polarization-transfer ratio

E03-104 in Hall A at JLab

4He(e,e'p)3H in quasi-elastic kinematics Q^2 = 0.8 and 1.3 GeV^2

H(e,e'p) in elastic kinematics…

Small missing momenta (< 120 MeV)

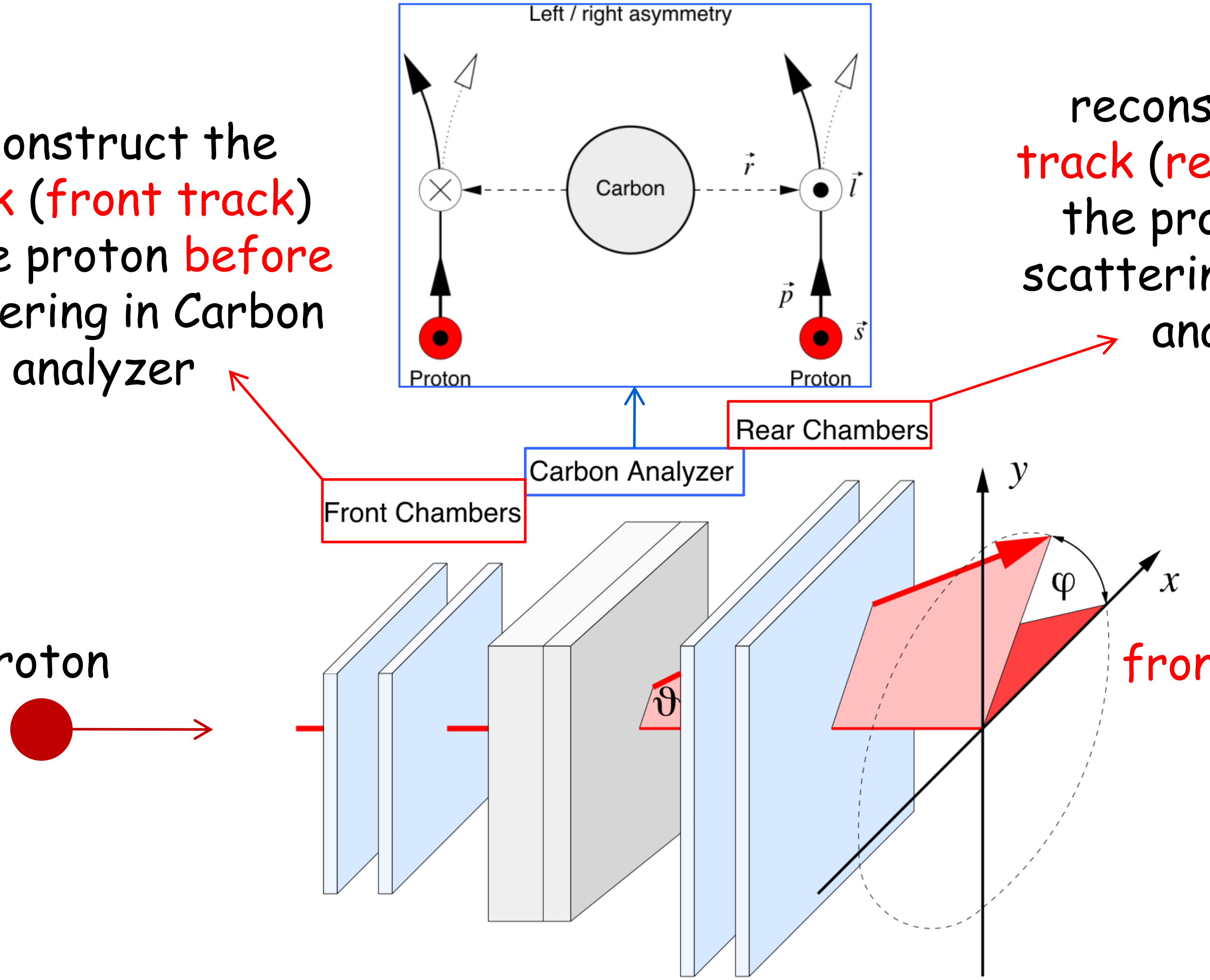


- ➢ Extract with greater accuracy $(P'_x/P'_z)_{He}/(P'_x/P'_z)_H$ and P_y
- ➢ Set tight constraints on the modeling of nuclear medium effects

Polarization Measurements

reconstruct the
track (front track)
of the proton before
scattering in Carbon
analyzer

reconstruct the
track (rear track) of
the proton after
scattering in Carbon
analyzer



front and rear tracks

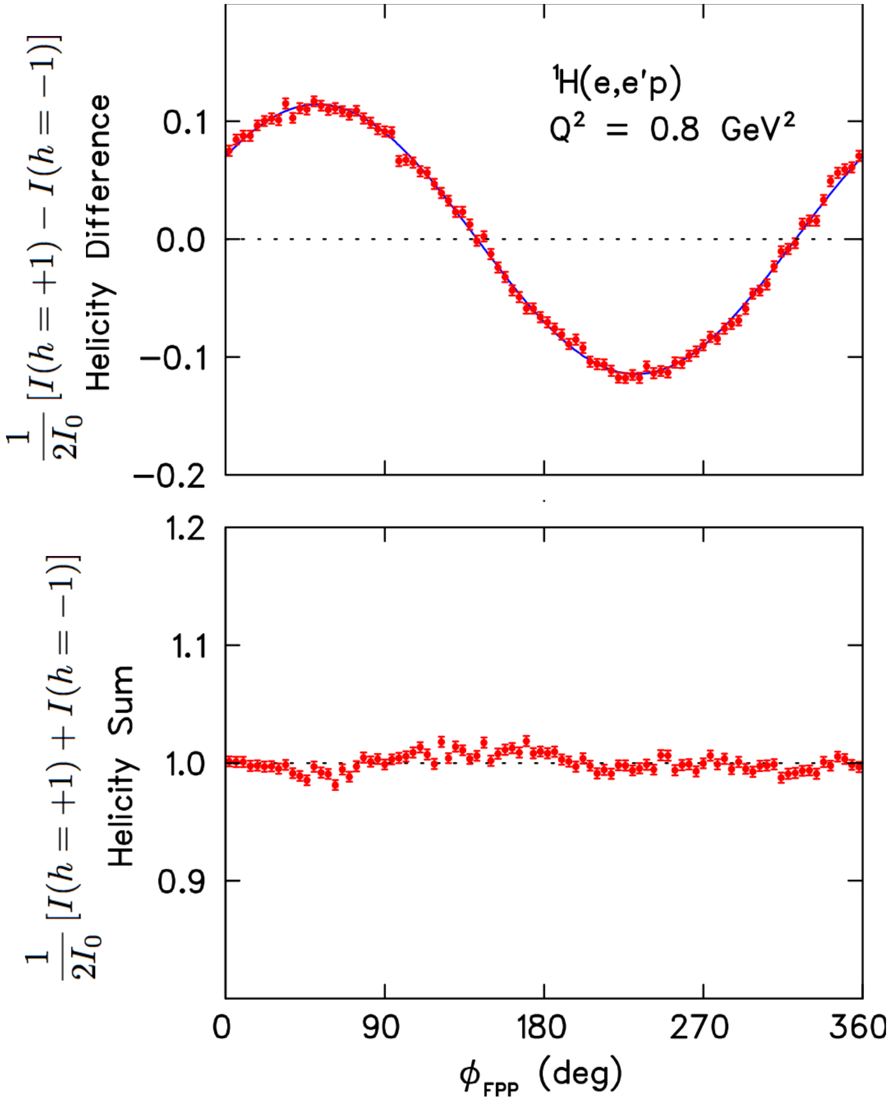
⇩

φ *and* θ

- Observed angular distribution:

$$\begin{aligned} I(\vartheta,\varphi) &= I_0(\vartheta)\,(1+\epsilon_y\cos\varphi+\epsilon_x\sin\varphi) \\ &= I_0(\vartheta)\,[1+A_C(P_y\cos\varphi-P_x\sin\varphi)] \end{aligned}$$

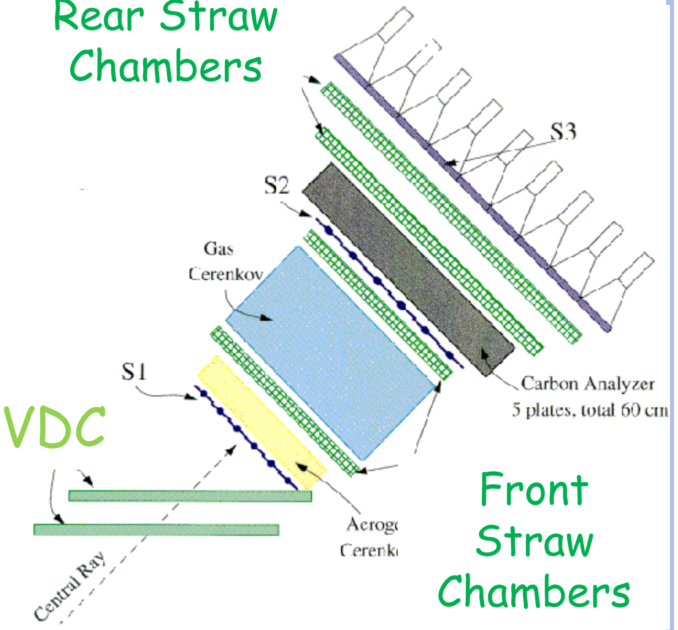
Observed Angular Distribution for H(e,e’p)



- ➢ Very good control of systematic uncertainties for polarization transfer
- ➢ Extract G_E/G_M and the analyzing power A_c
- ➢ Instrumental asymmetries complicate the extraction of the induced polarization
- ➢ P_y in H(e,e’p) (zero in OPE) can be roughly used as a check for instrumental asymmetries (similar coverage for H as for ^{4}He)

Chambers Info

- ➢ VDC (wire chambers): proton track before entering the FPP
- ➢ Front & Rear FPP chambers (straw chambers): proton track before and after scattering in the Carbon analyzer => the angular distribution



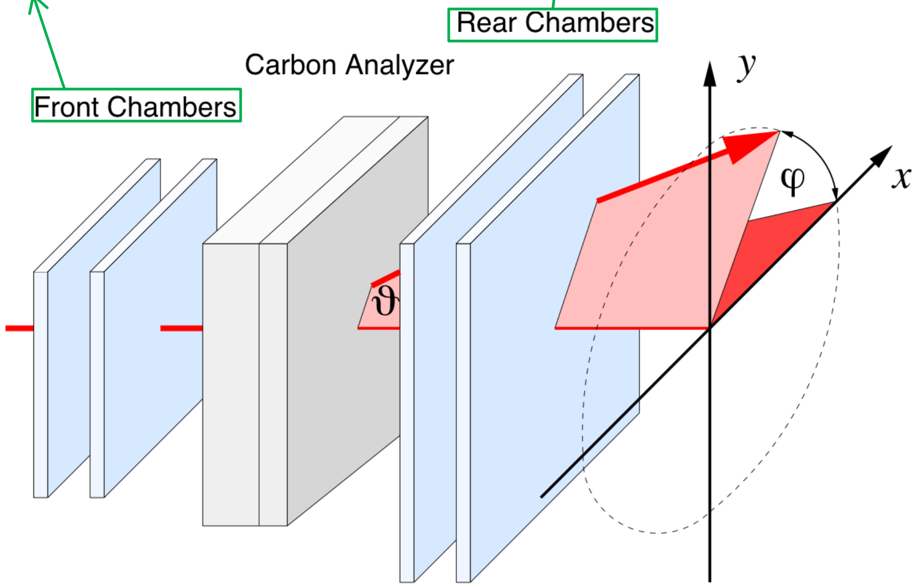
Rear Straw Chambers

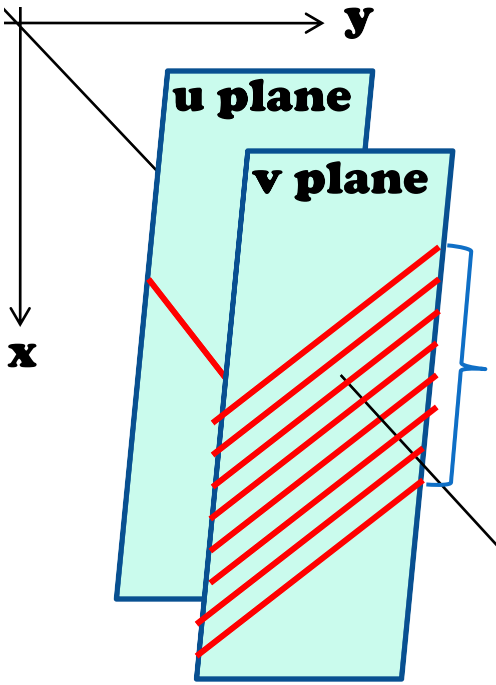
VDC

Front Straw Chambers

3 u and 3 v planes each

Rear 1: 2 u, 2 v
Rear 2: 3 u, 3 v

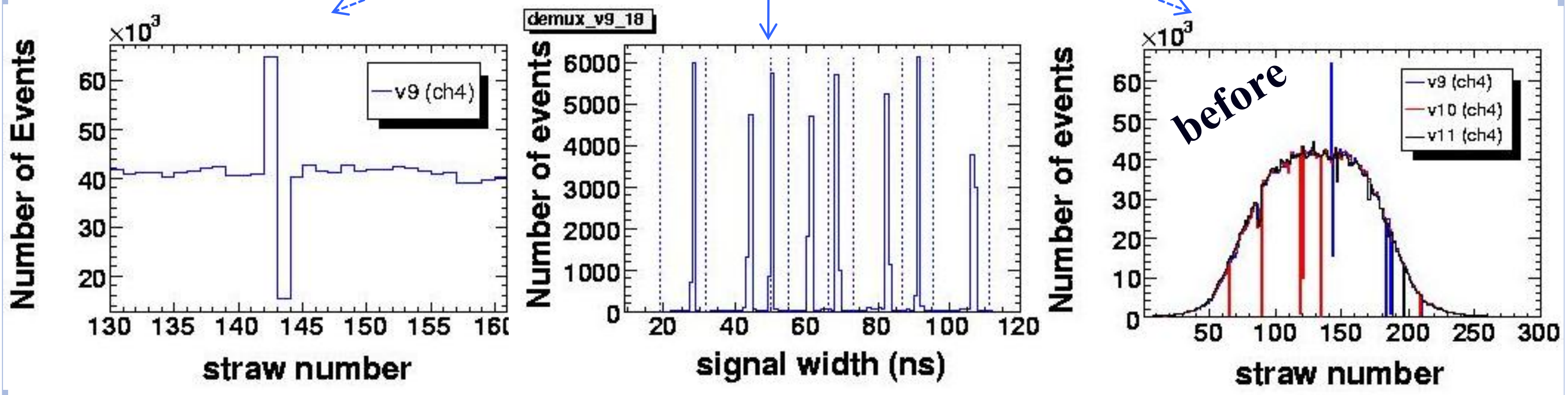




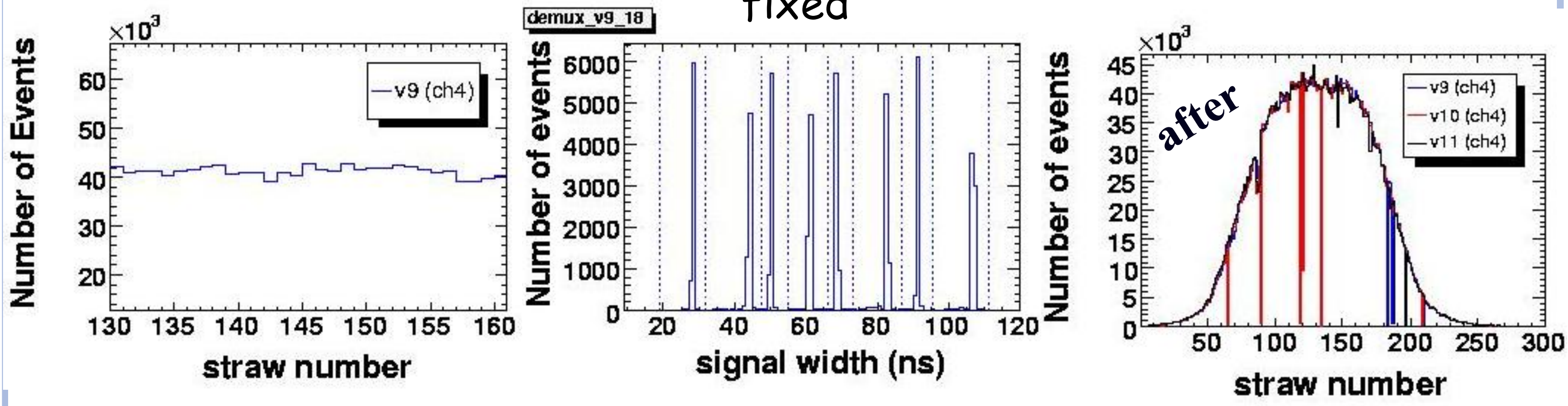
straws multiplexed in groups of 8

FPP Chambers: Demultiplexing Cuts

wrong
demultiplexing
cut

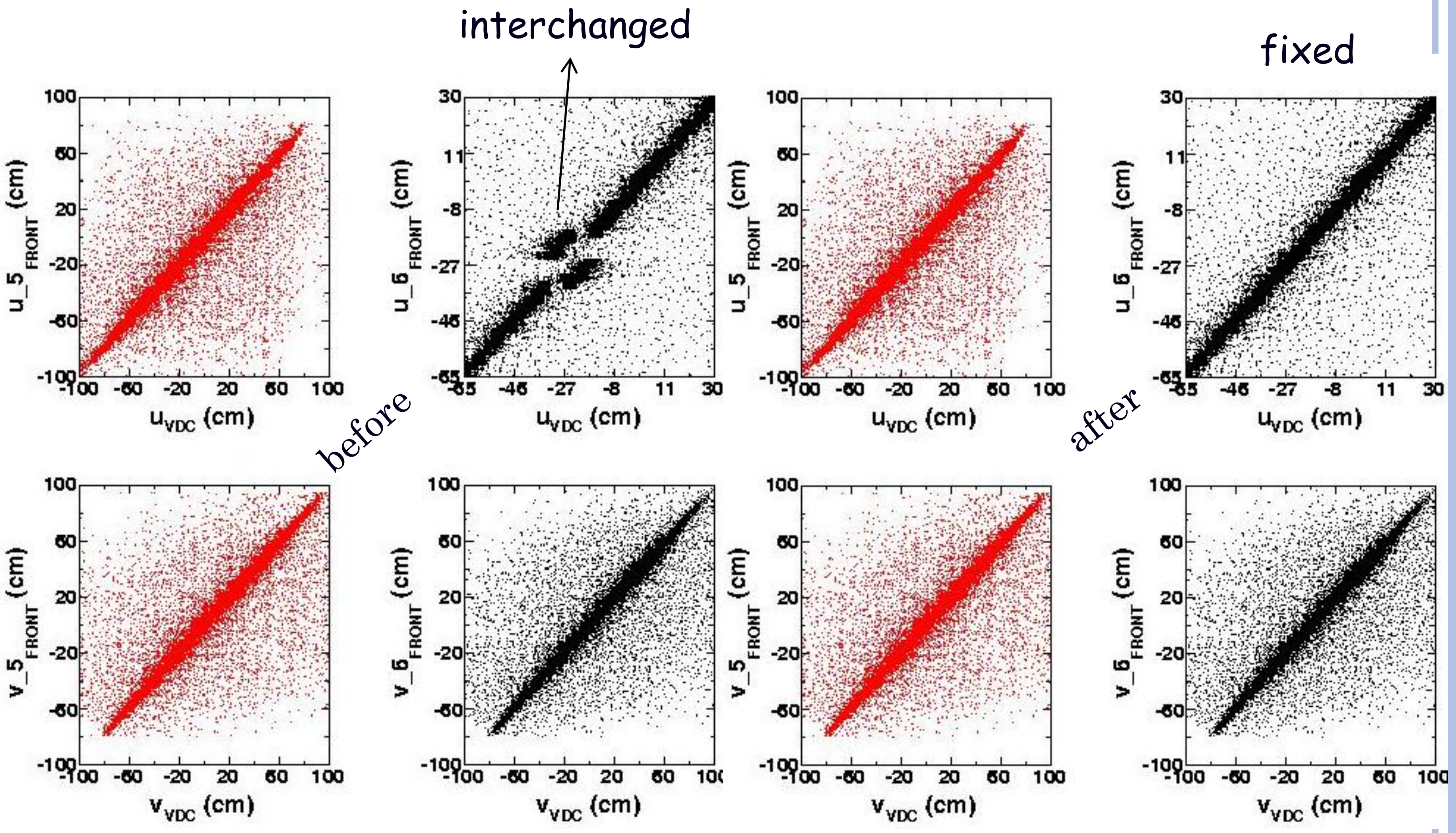


fixed



Wire Groups

- Check for interchanged wire groups: in the last plane u of second Front chamber: wire groups 10 and 11 interchanged



Tracking

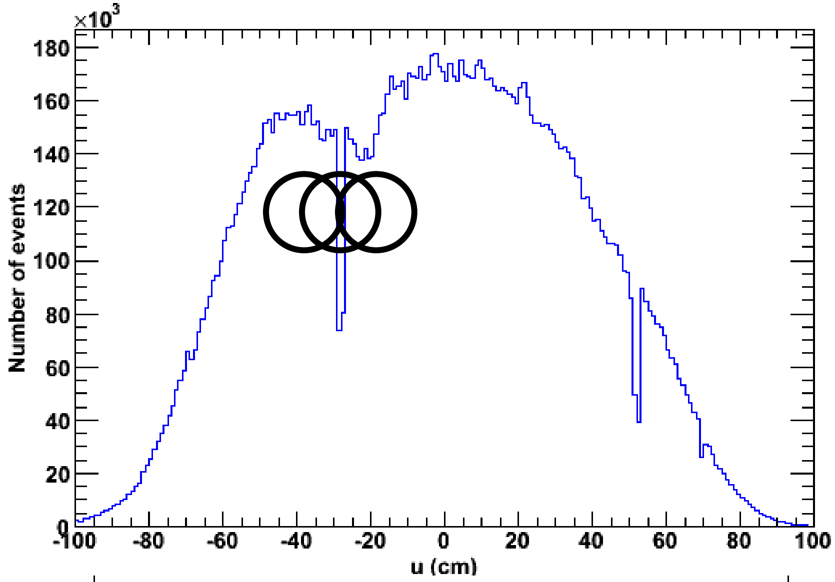
- ➢ Dead wires in FPP chambers: strict requirements of the standard tracking algorithm cannot be met => "holes" in the event distribution

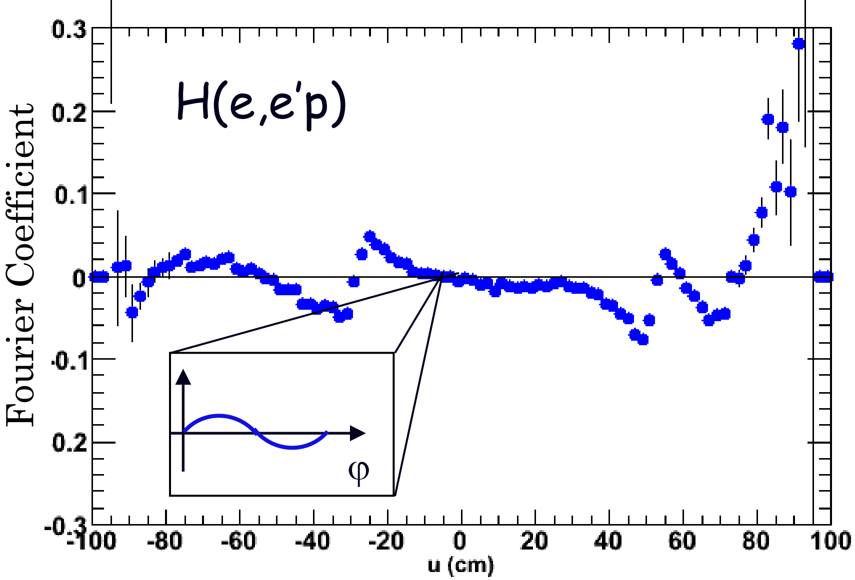
- ➢ Inefficient regions in chambers cause instrumental asymmetries

First order Fourier Coefficients (asymmetries):

$$\varepsilon_y = \frac{\sum \sin\phi}{\sum \sin^2\phi} \qquad \varepsilon_x = \frac{\sum \cos\phi}{\sum \cos^2\phi}$$

- Plan of attack: accept poorer tracking resolution in order to fill the holes => relaxed tracking algorithm



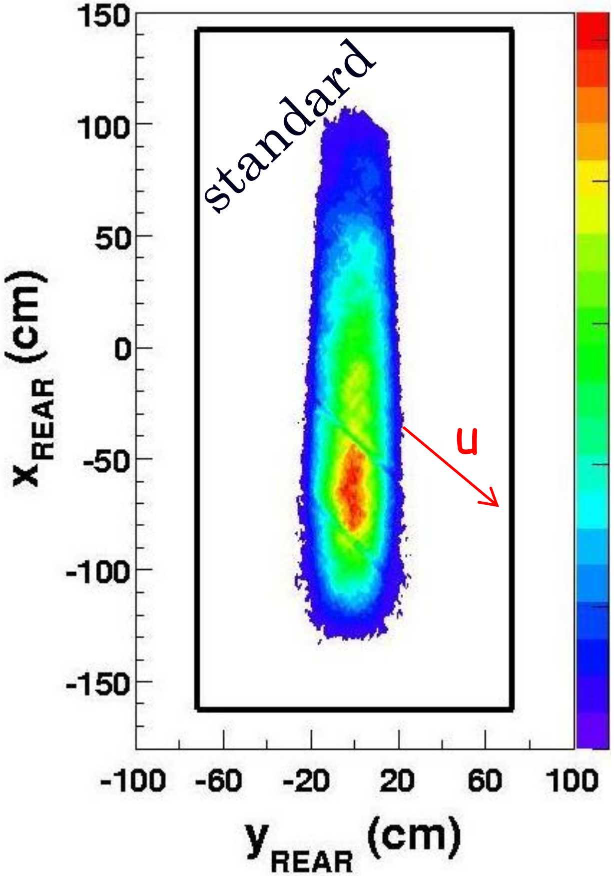


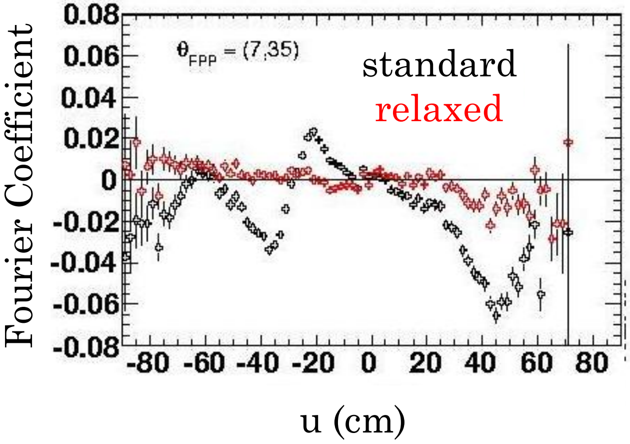
Relaxed Tracking

- **Standard tracking**:

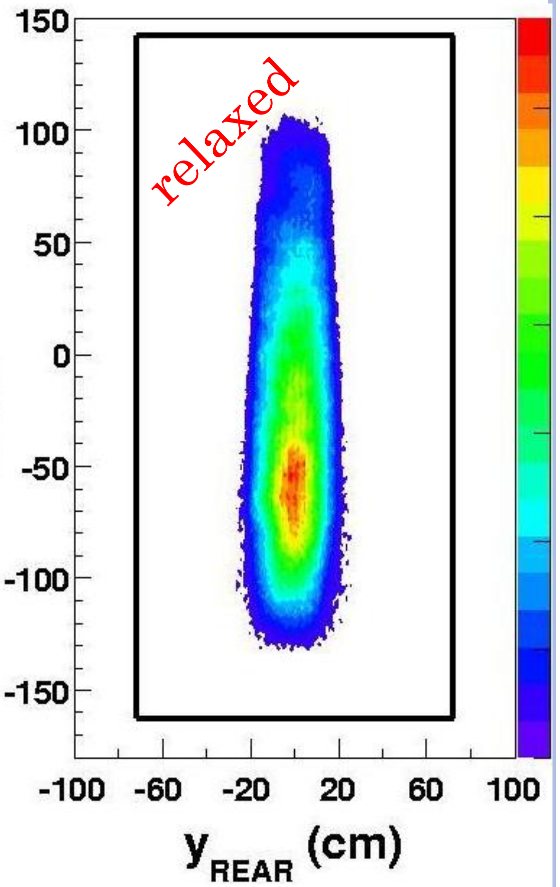
  \- at least 1 hit in each chamber & at least 3 hits in total (left-right ambiguities)

  - Standard tracking algorithm *too restrictive* if planes have dead wires
- Relaxed tracking: at least 1 hit in each of the rear chambers
  - if 1 hit in each chamber => track
  - if 1 hit just in one of the chambers => hit + p-Carbon vertex = track





Relaxed tracking: local false asymmetries gone



Alignment

- Front and Rear chambers: aligned for proper reconstruction of θ and ϕ (angular distribution)

Standard procedure

- Use "straight-through" runs to:

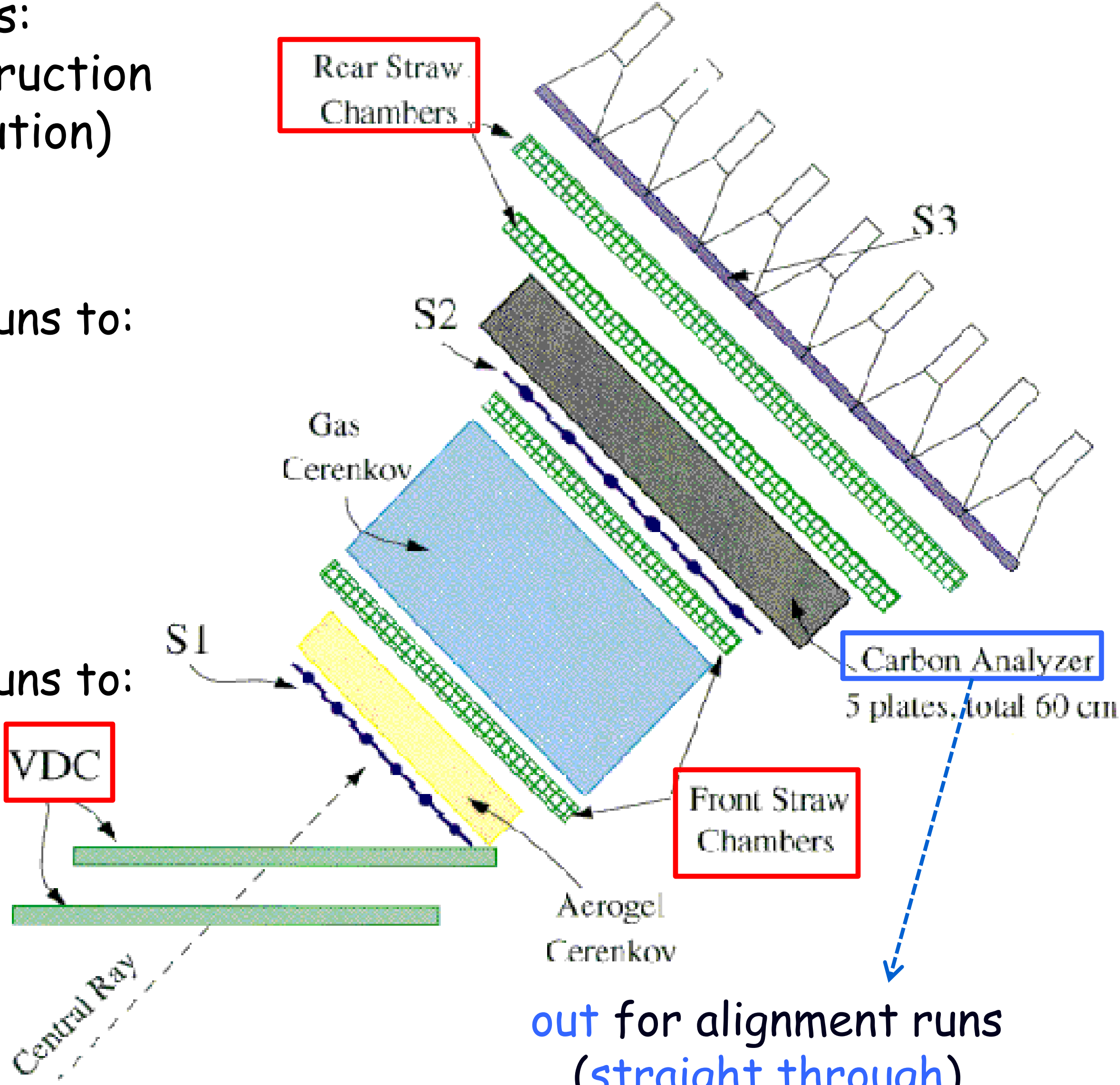
- align VDC-Front tracks
- align Front-Rear tracks

Our procedure

- Use "straight-through" runs to:

- align VDC-Front planes
- align Front-Rear planes

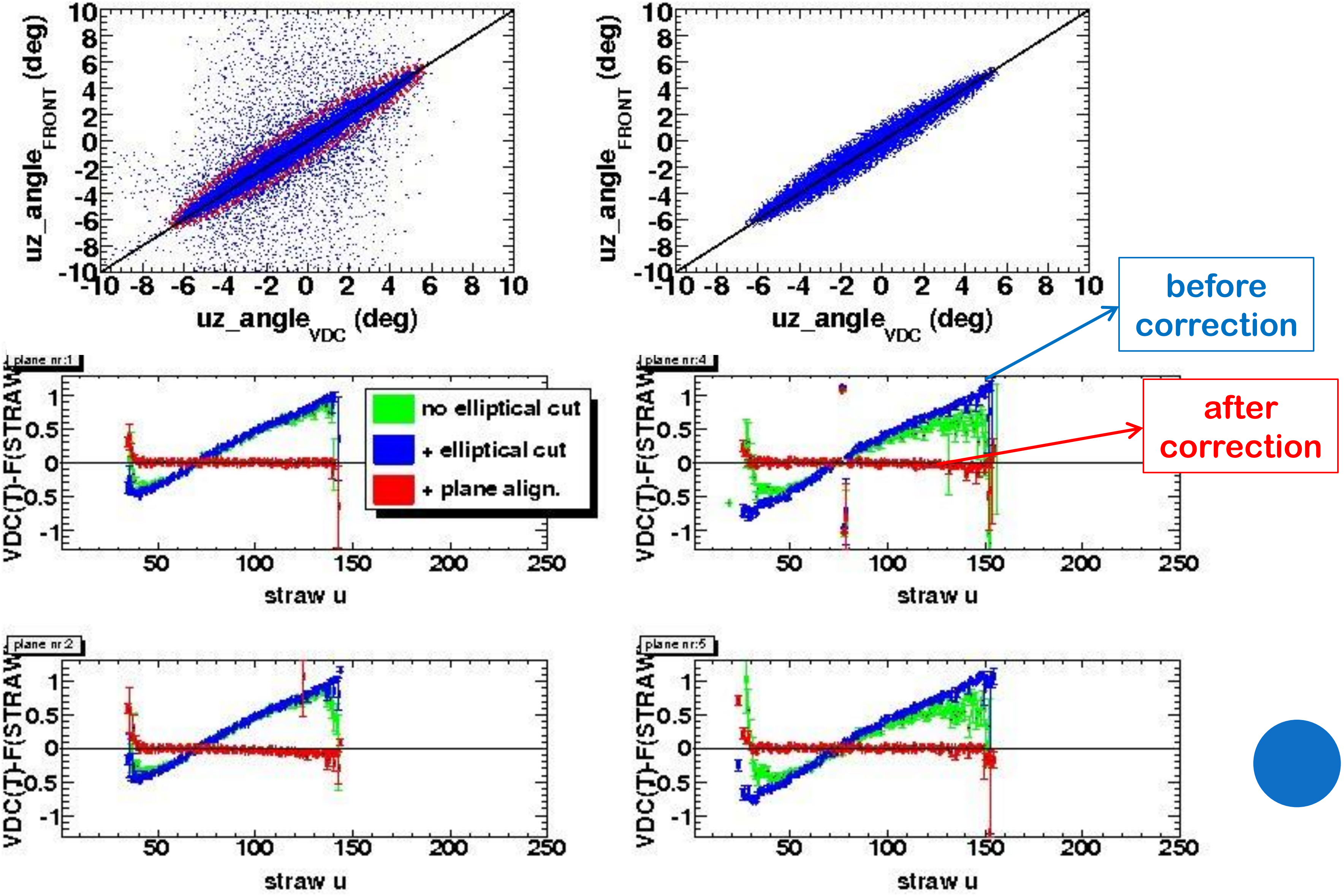
- align tracks if necessary



out for alignment runs (straight through)

Plane Alignment

- Select a "clean" sample of events and determine $\Delta u, v(wire)$



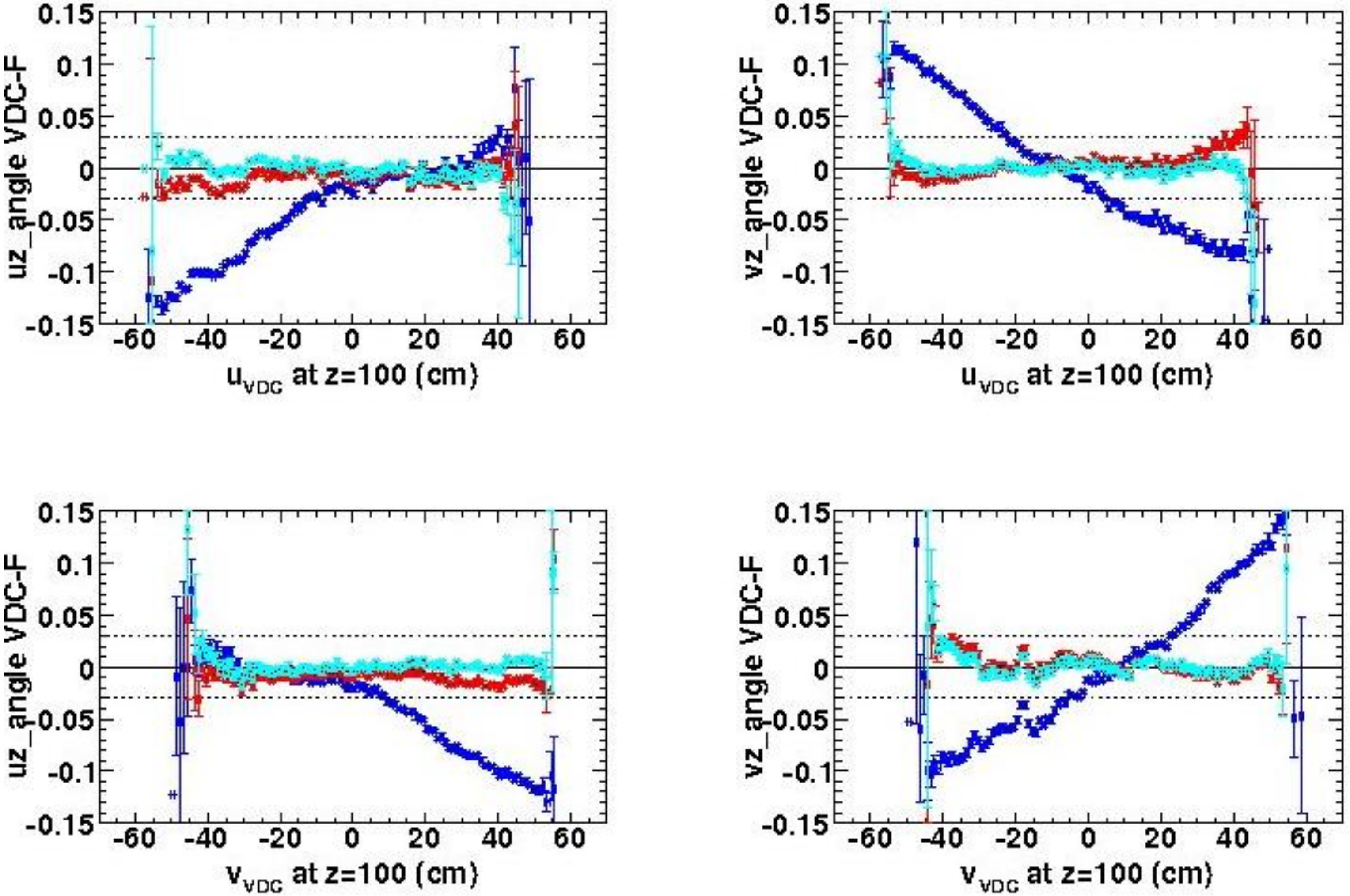
before correction

after correction

Track Alignment

- Align tracks in u and v: VDC-Front

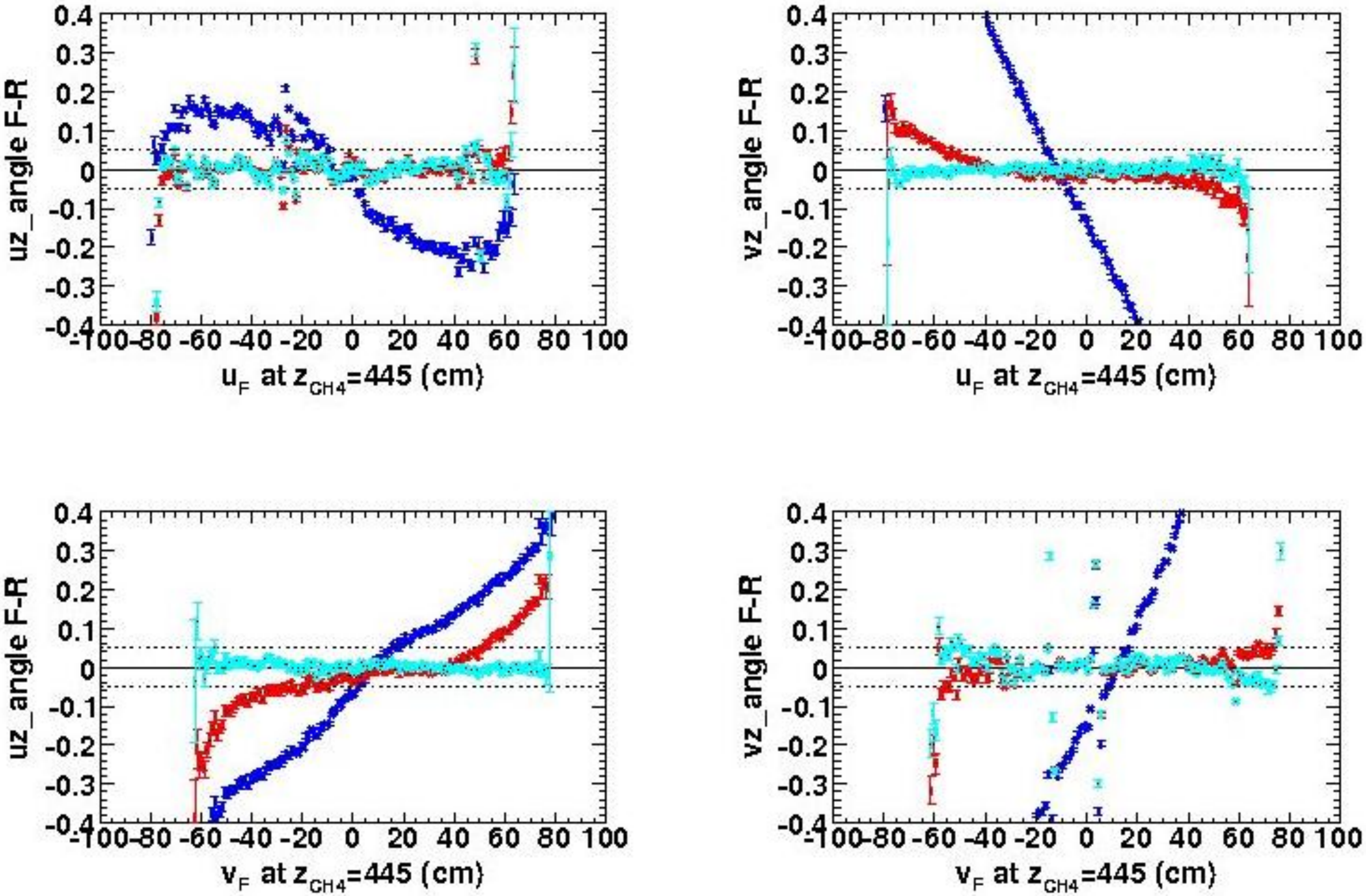
No alignment
Plane alignment
Plane + track alignment



Track Alignment

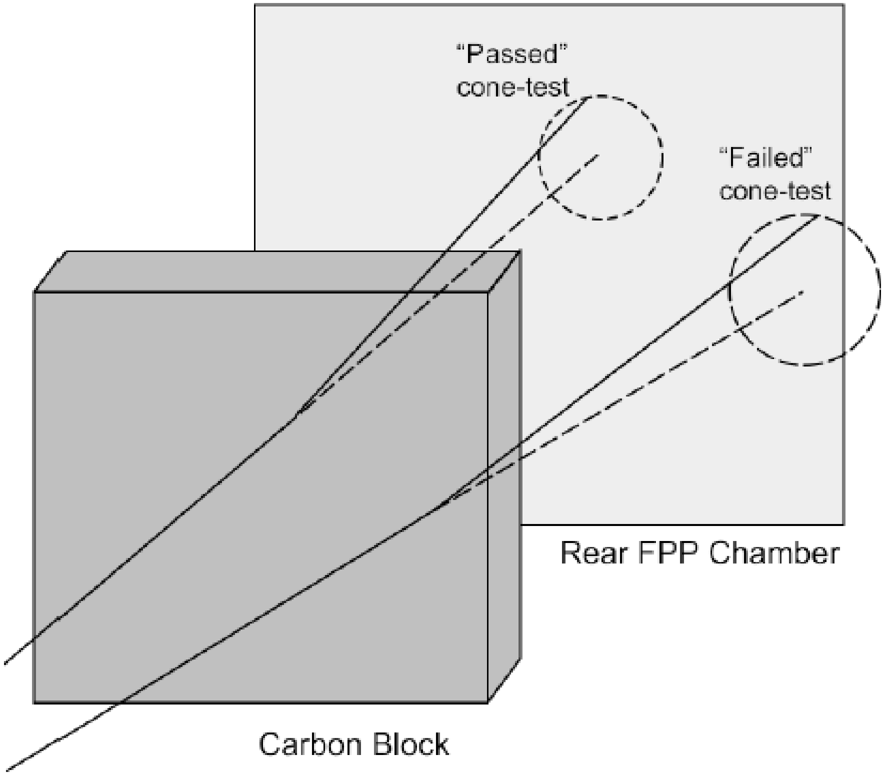
- Align tracks in u and v: Front-Rear

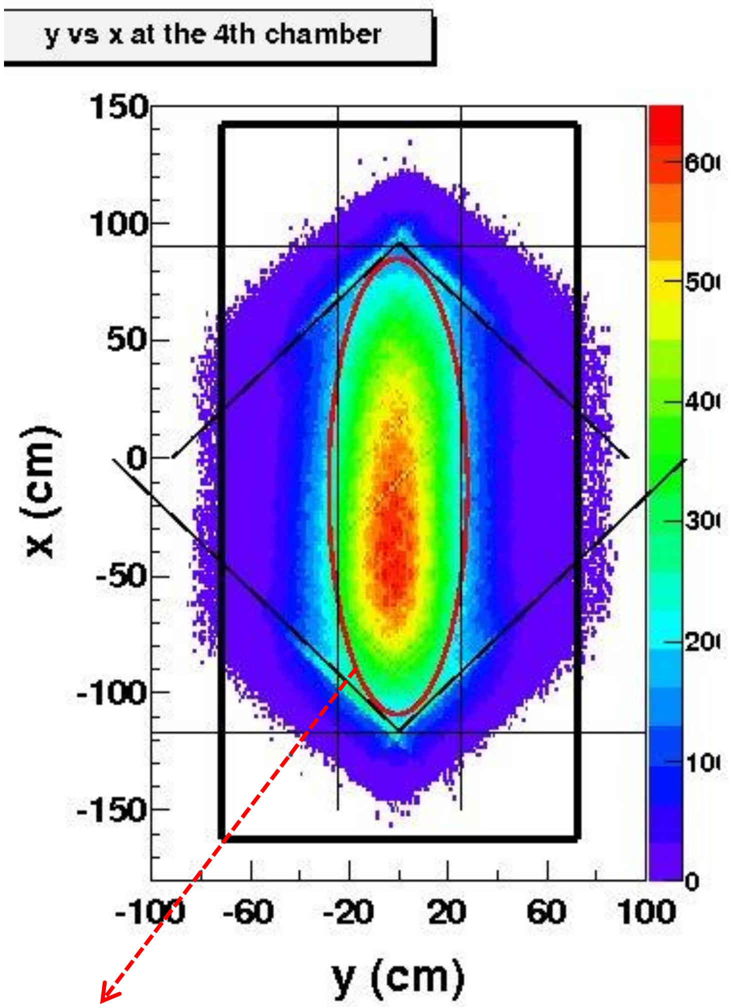
No alignment
Plane alignment
Plane + track alignment



Cone Test & Cone Test Cuts

➢ Cuts to delimit the region where alignment coefficients are constrained

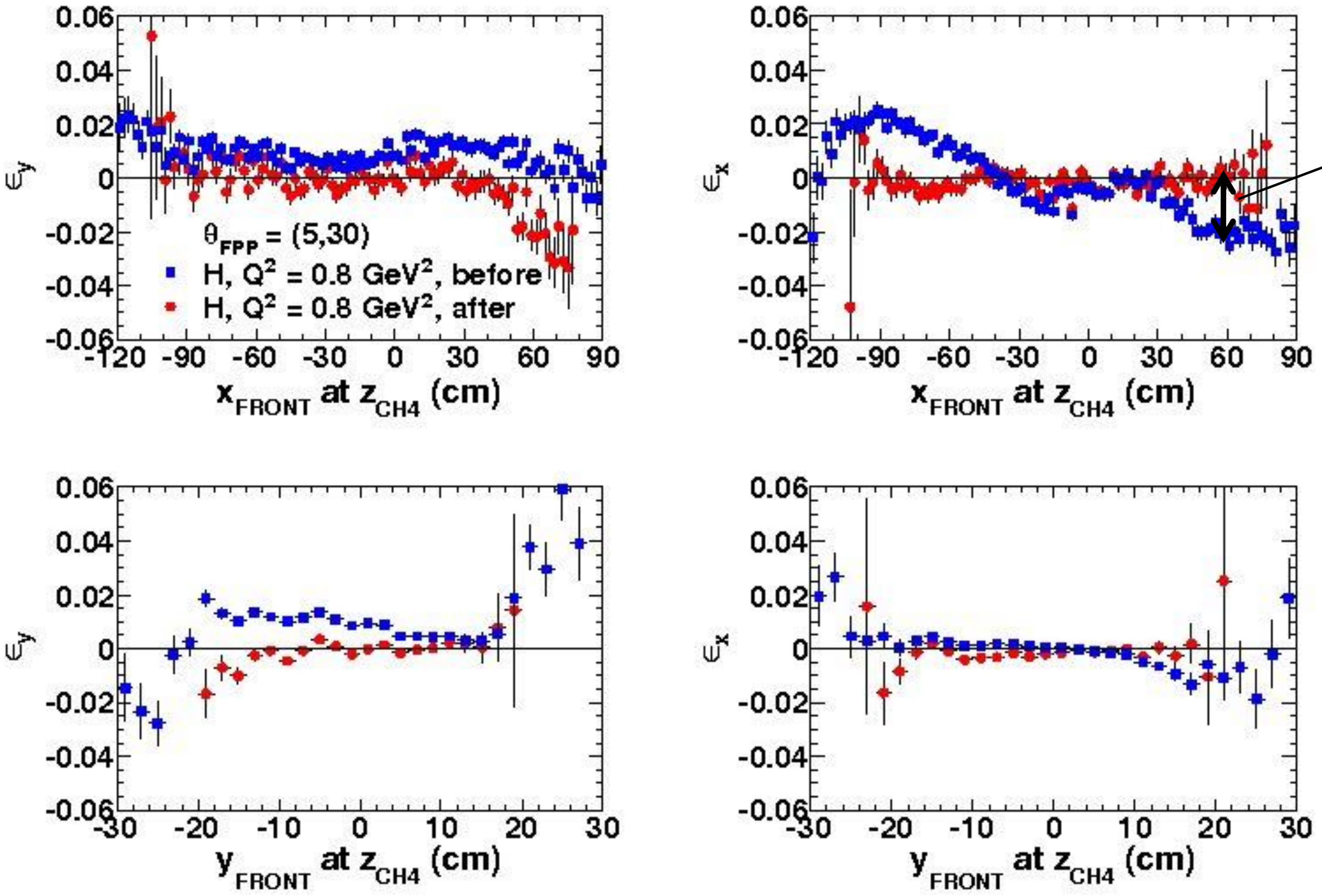




➢ Elliptical cut to select the safe active region to be used

Fourier Coefficients

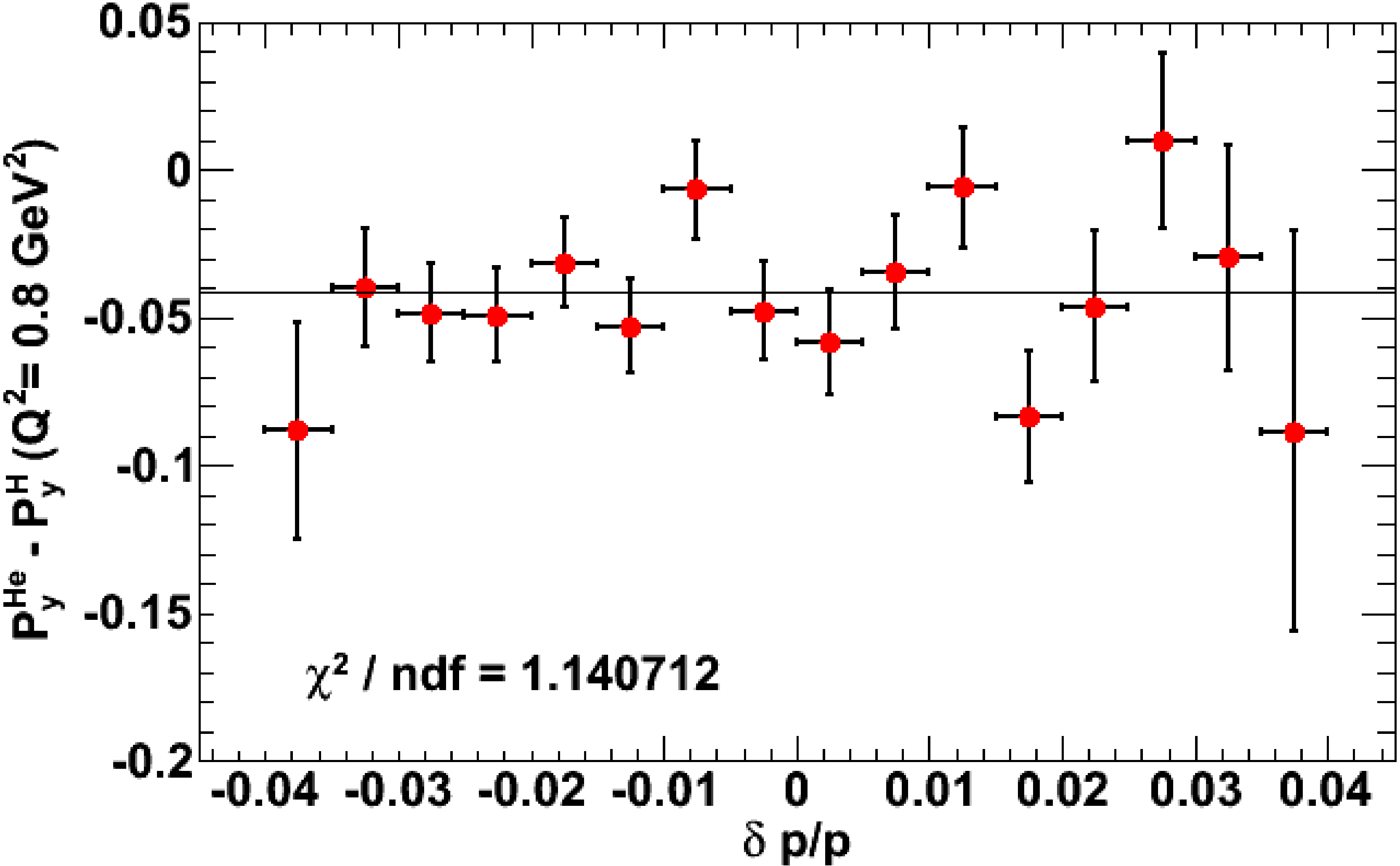
- ➢ After new tracking, alignment and news cone test cuts: reduction of false asymmetries



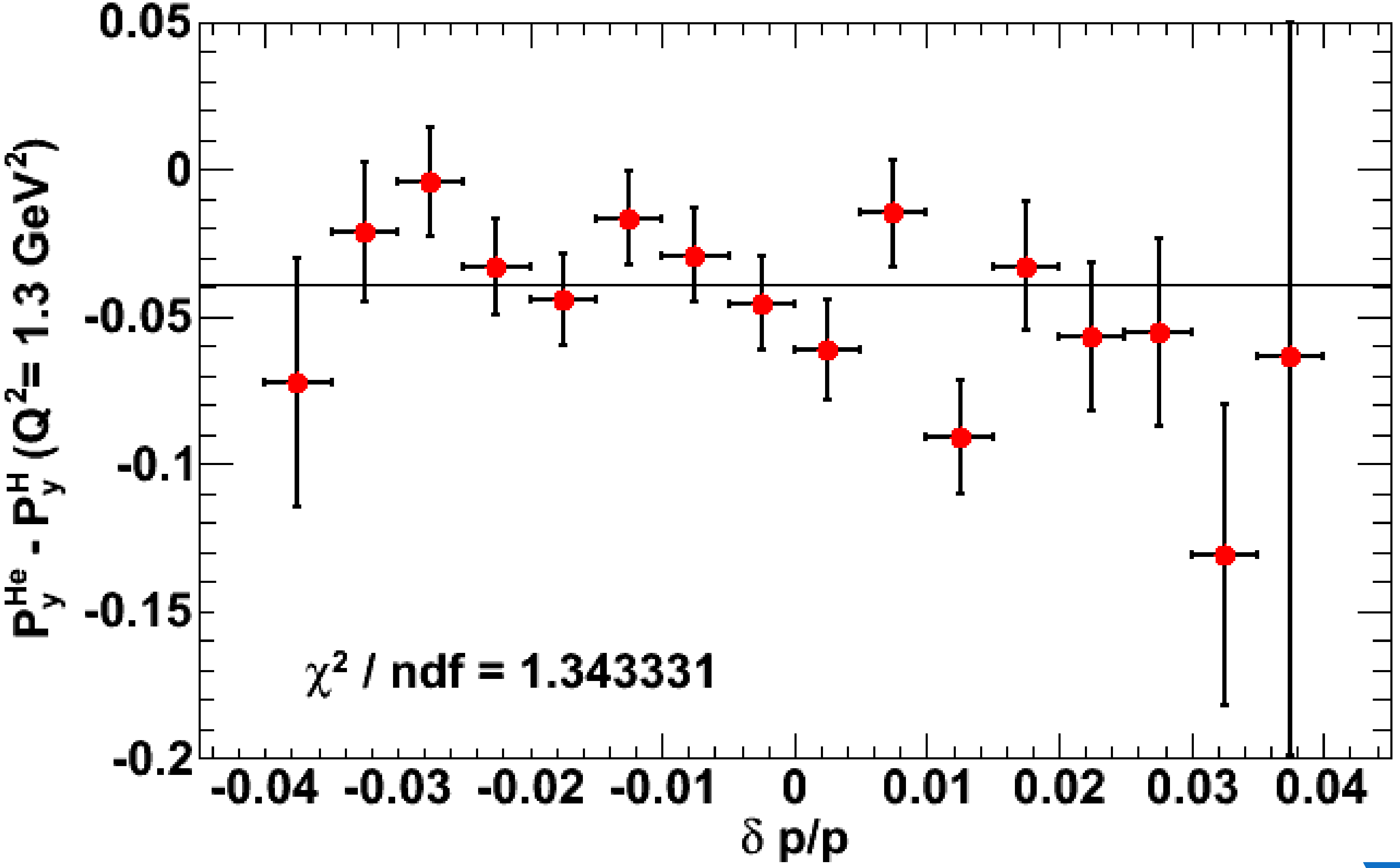
reduction
by factor
of 4

- ➢ Not perfect so we still rely on subtraction of $P_y(H)$ from $P_y(He)$ to cancel some of the remaining false asymmetries

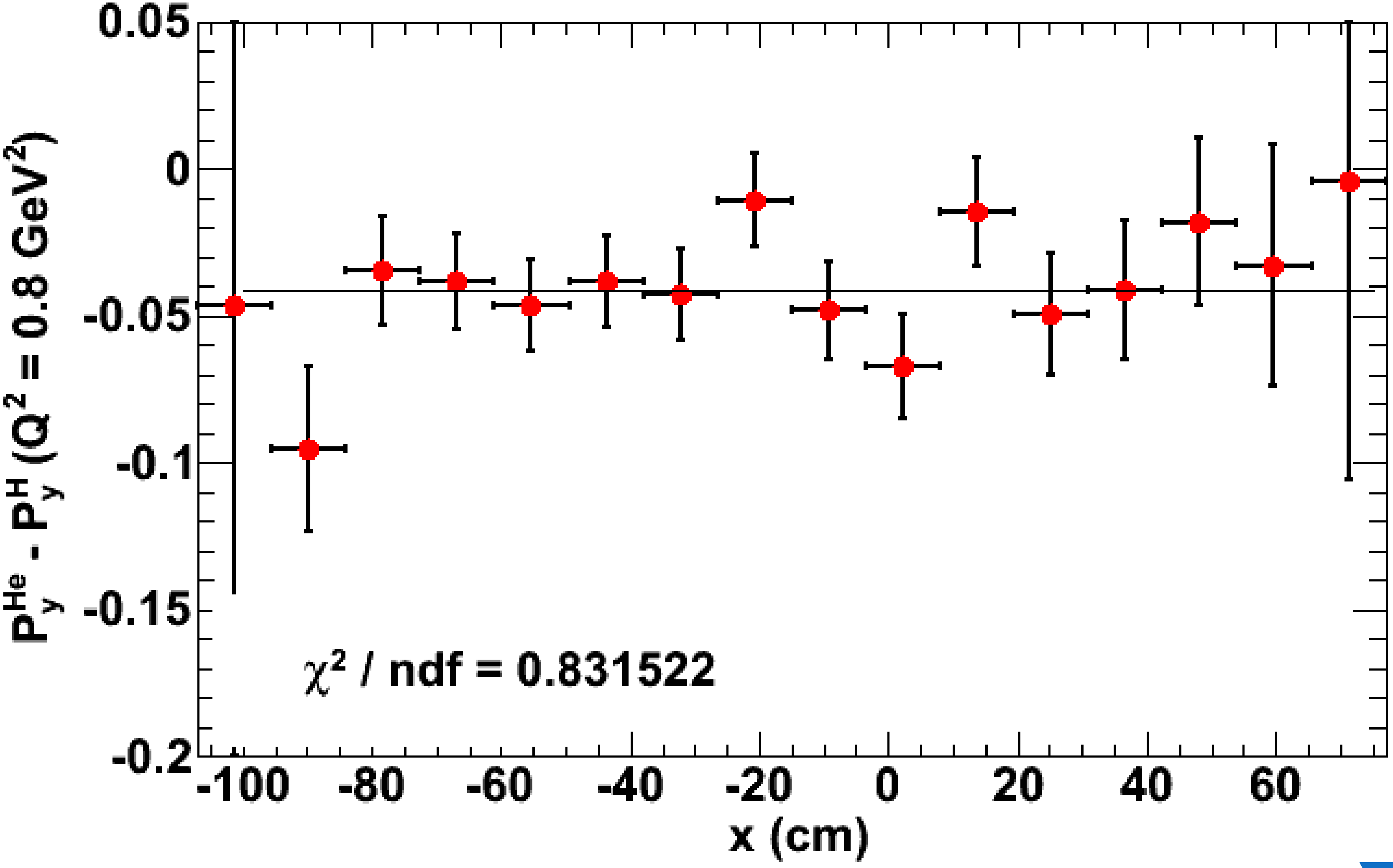
P_y: Systematic Checks



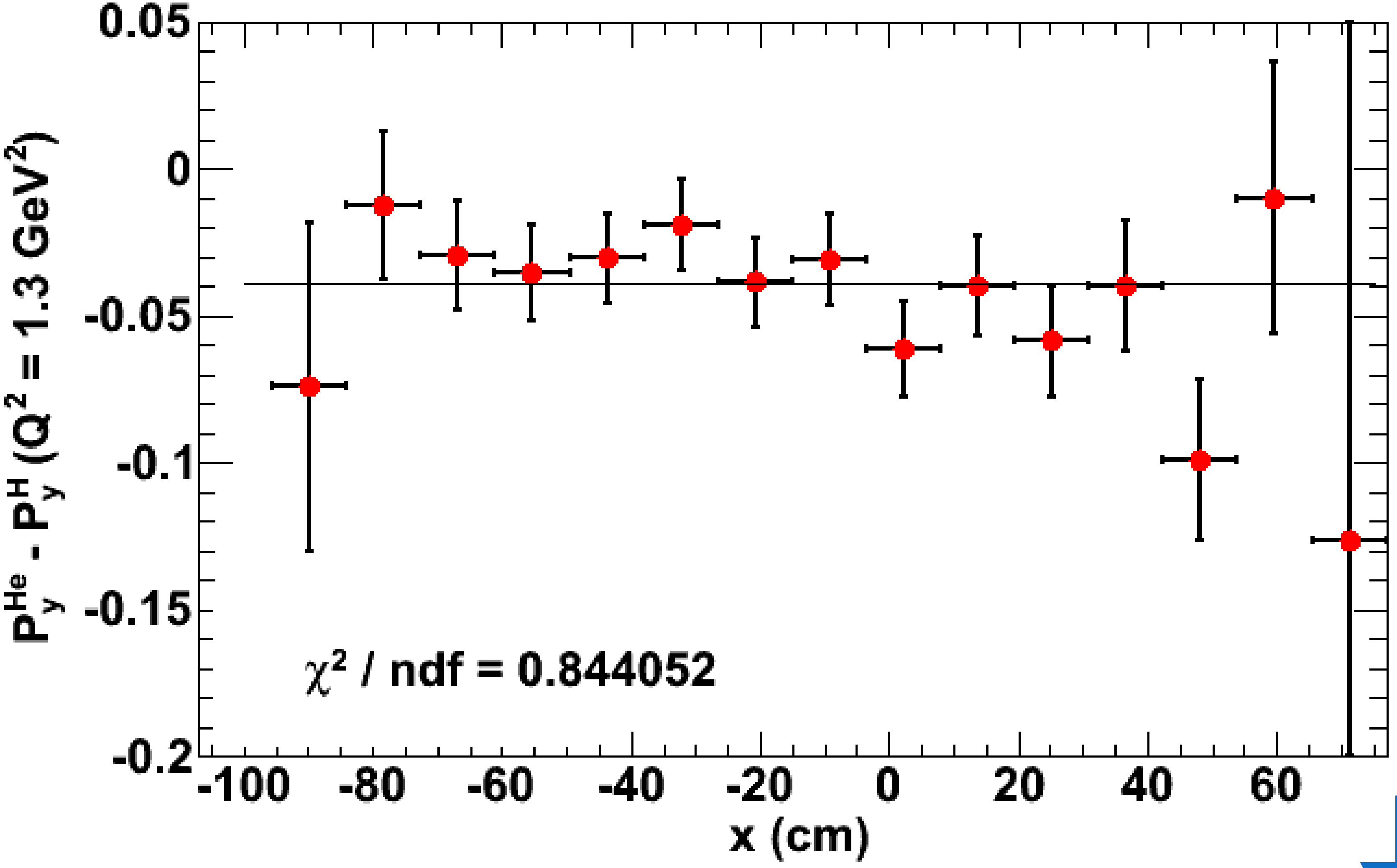
P_y: Systematic Checks



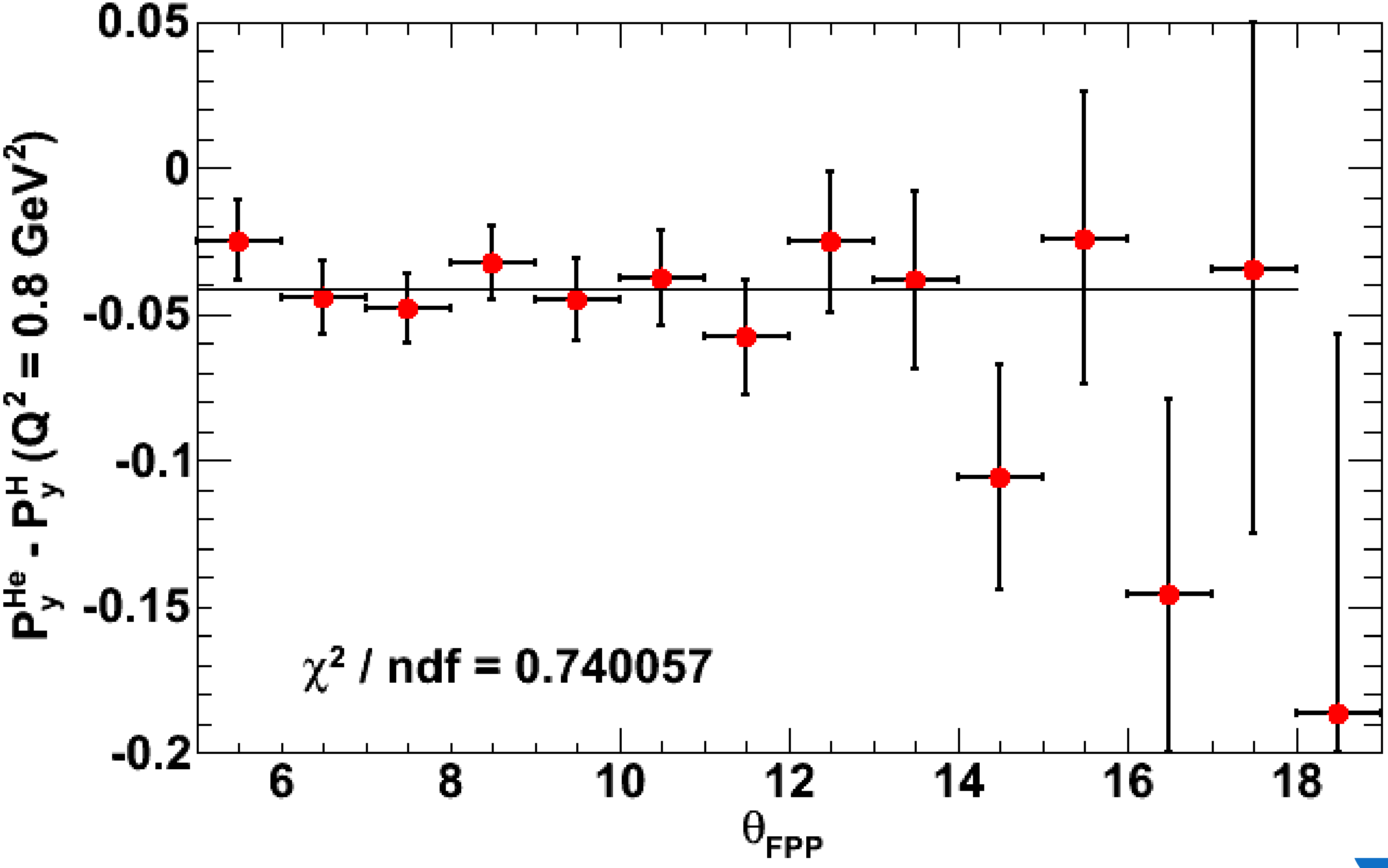
P_y: Systematic Checks



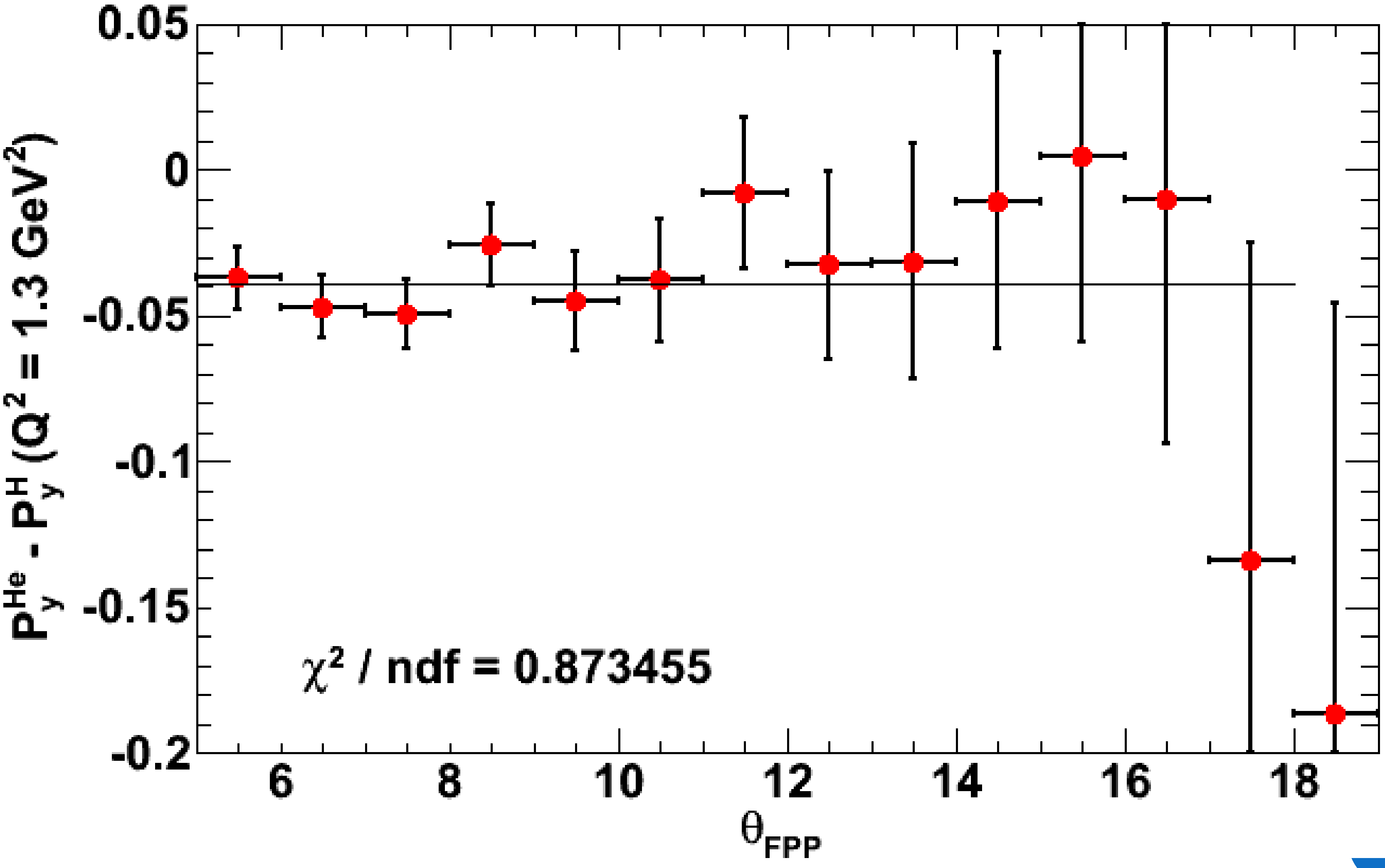
P_y: Systematic Checks



P_y: Systematic Checks

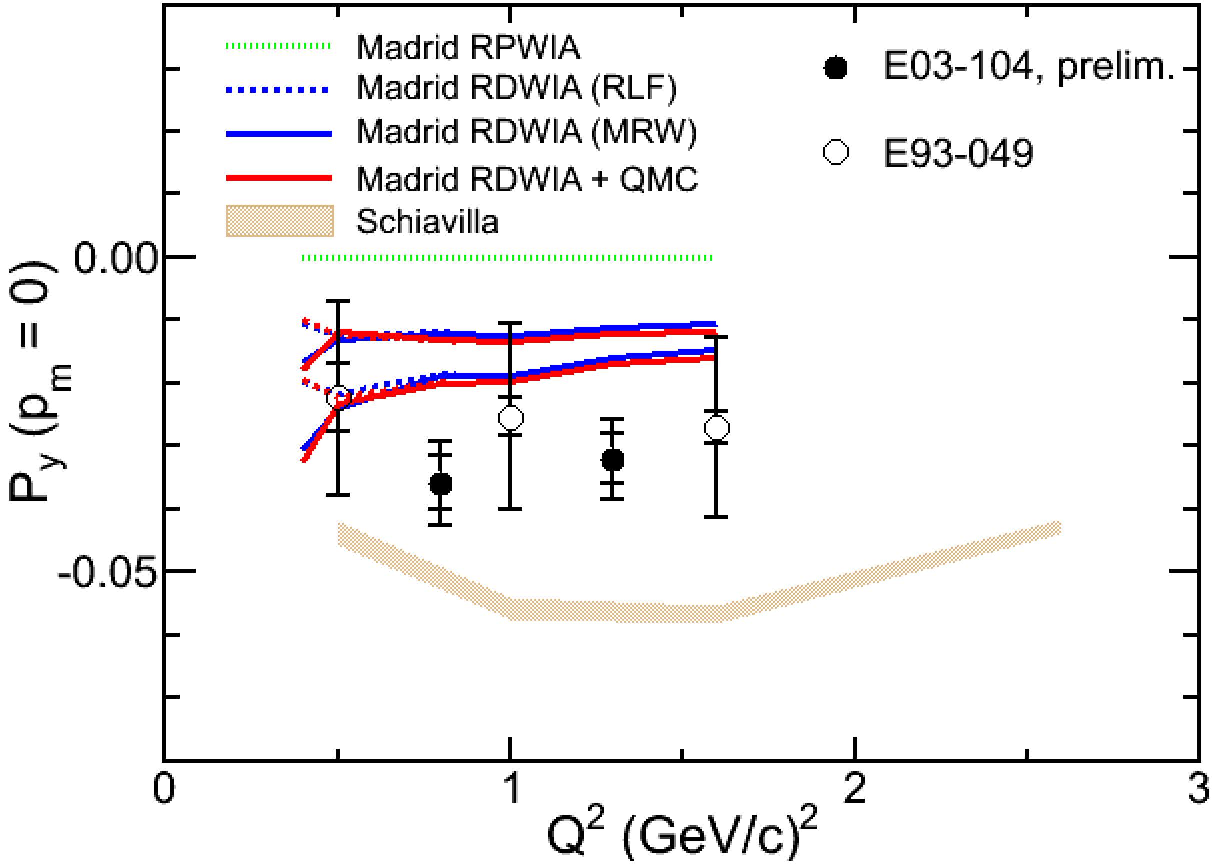


P_y: Systematic Checks



P_y vs Q^2

- Greatly reduced systematic uncertainties for E03-104: preliminary upper limit for systematic 0.006, i.e. ~ 3 times smaller than E93-049



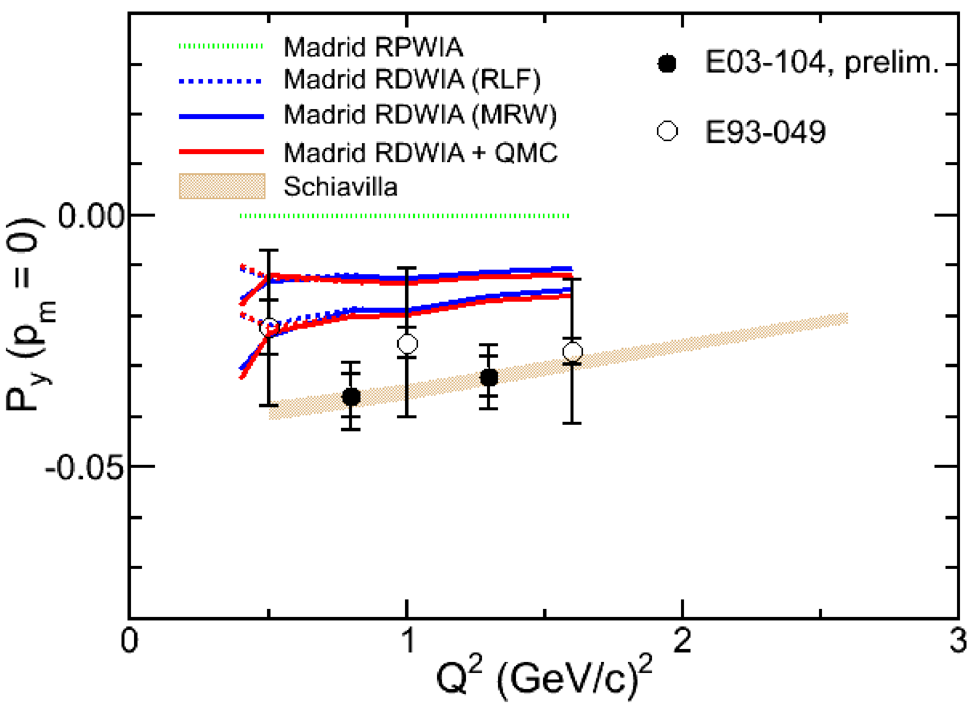
- Not Madrid nor Schiavilla:2005 offer a satisfactory description of latest data

New Calculation from R. Schiavilla (2010)

- Optical potential:

charge-exchange terms

$$v_{opt} = [v^{c} + (4T-3)v^{c\tau}] + [v^{b} + (4T-3)v^{b\tau}] \cdot l \cdot s$$



- Constrain the spin-independent charge-exchange term ($v^{c\tau}$) to the combined set of data from E93-049 and E03-104

⇩

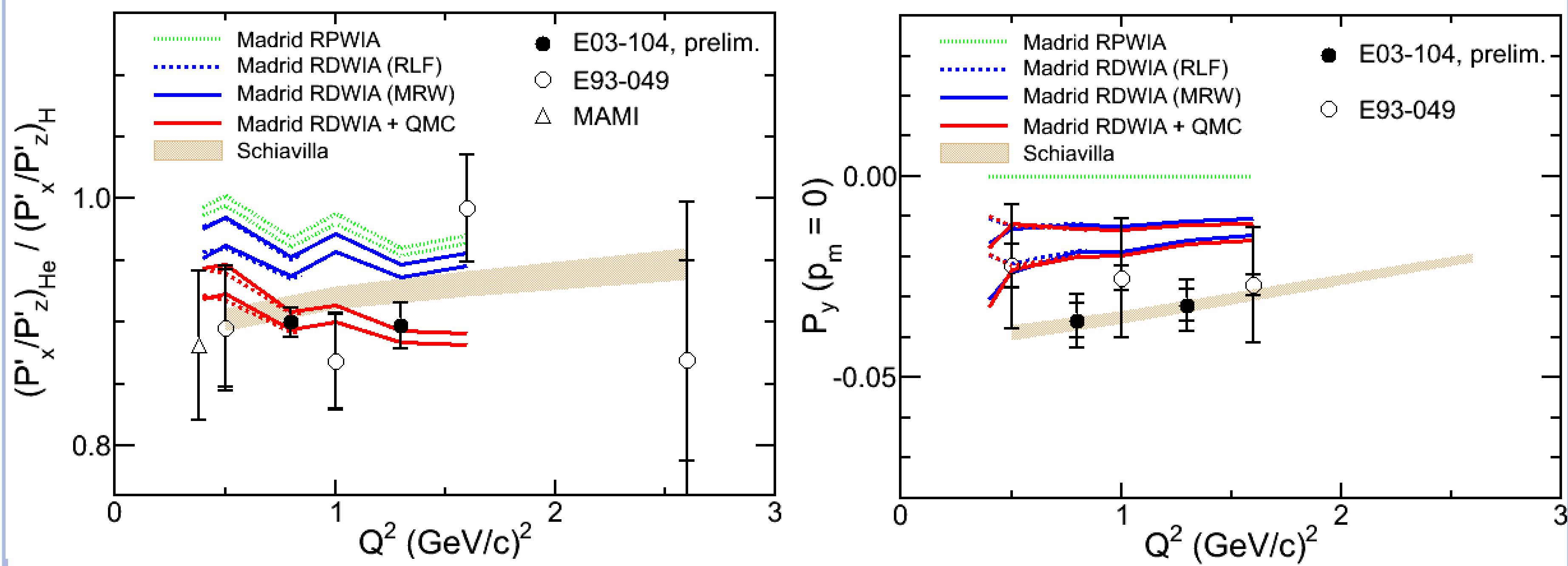
- Reduction in P_y from Schiavilla:2005 to Schiavilla:2010 at higher Q^2

- Does the new calculation describe the polarization transfer?

New Calculation from R. Schiavilla (2010)

Polarization transfer

Induced polarization

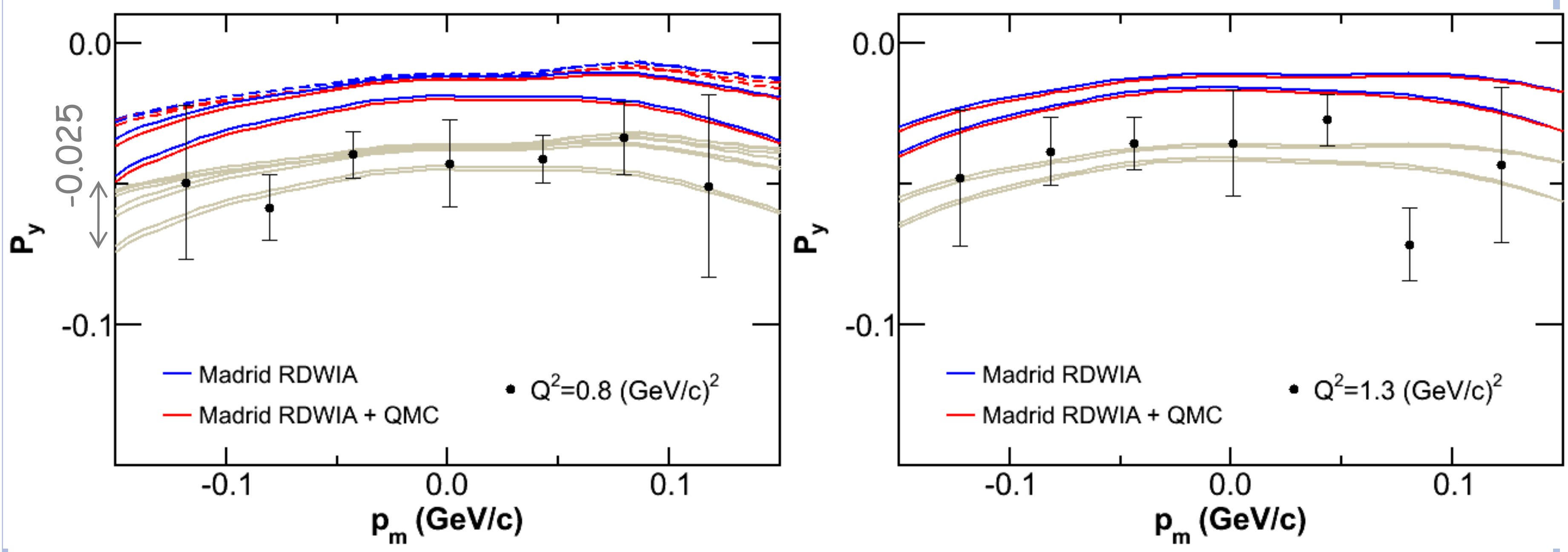


- “It seems possible to obtain a good fit of both the polarization ratio and P_y by reducing the strength of the charge-exchange independent spin-orbit component of the optical potential. This should not change significantly the fits to the p-^{3}H elastic scattering data”

- Charge-exchange dependent spin-orbit term remains unconstrained

P_y vs Missing Momentum p_m

- Madrid describes the “shape” of P_y with p_m but underpredicts the magnitude in absolute value (~ 0.025)



- Coming soon: new calculation from Madrid…

Summary

- The induced polarization P_y is crucial to clarify the role of conventional nuclear medium effects when searching for signatures of medium-modified form factors in ^{4}He(e,e'p)^{3}H

- E03-104 extracted the induced polarization P_y in ^{4}He(e,e'p)^{3}H with great accuracy (~3 times better systematic than previously achieved)

- Our data put to stringent test nuclear physics calculations
  - Presently, the Madrid calculation underestimated E03-104 data on P_y ; new calculation from Madrid expected soon
  - Schiavilla:2005 overestimates E03-104 data; our data offer constraints for Schiavilla:2010 calculation