Axial Form Factor from Weak Capture of Polarized Positrons

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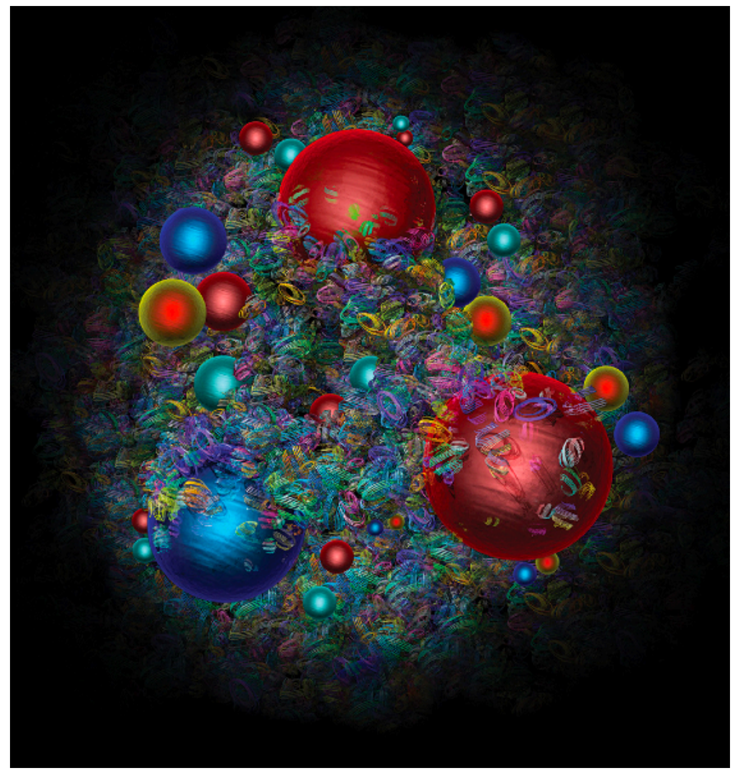
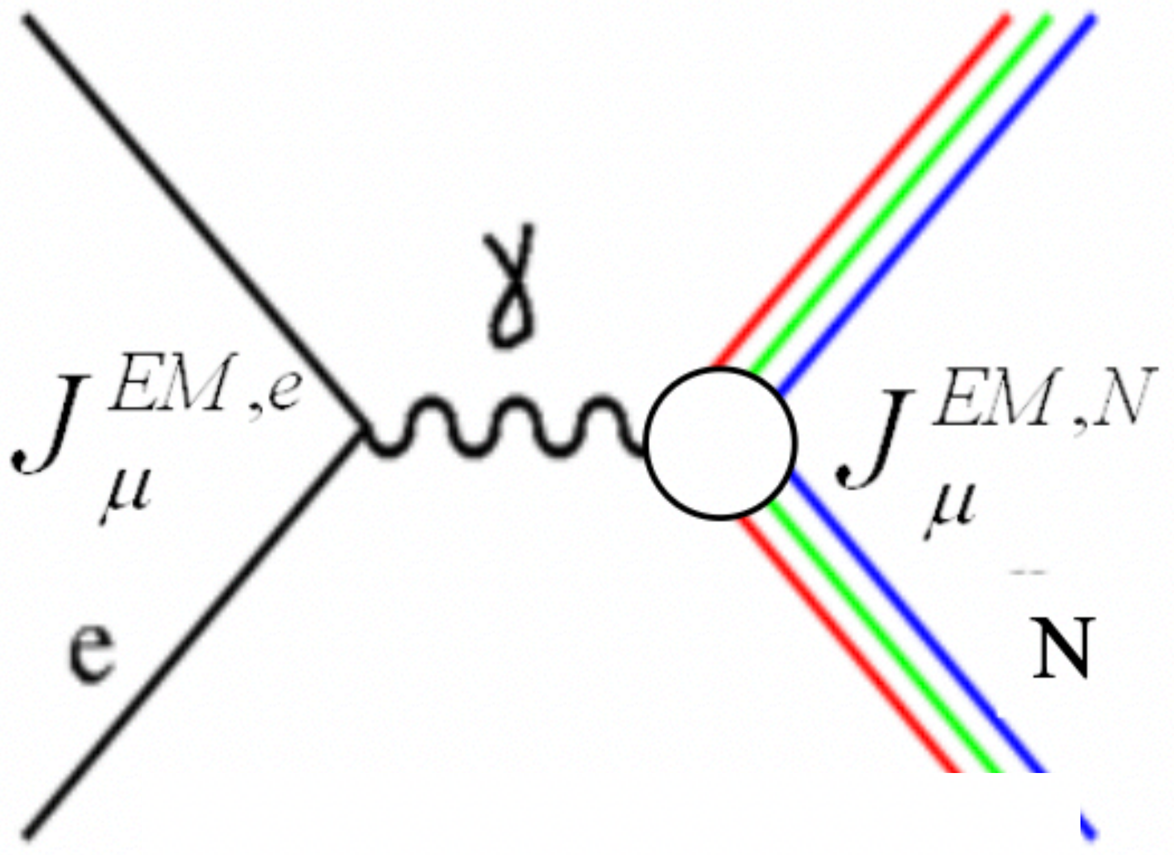
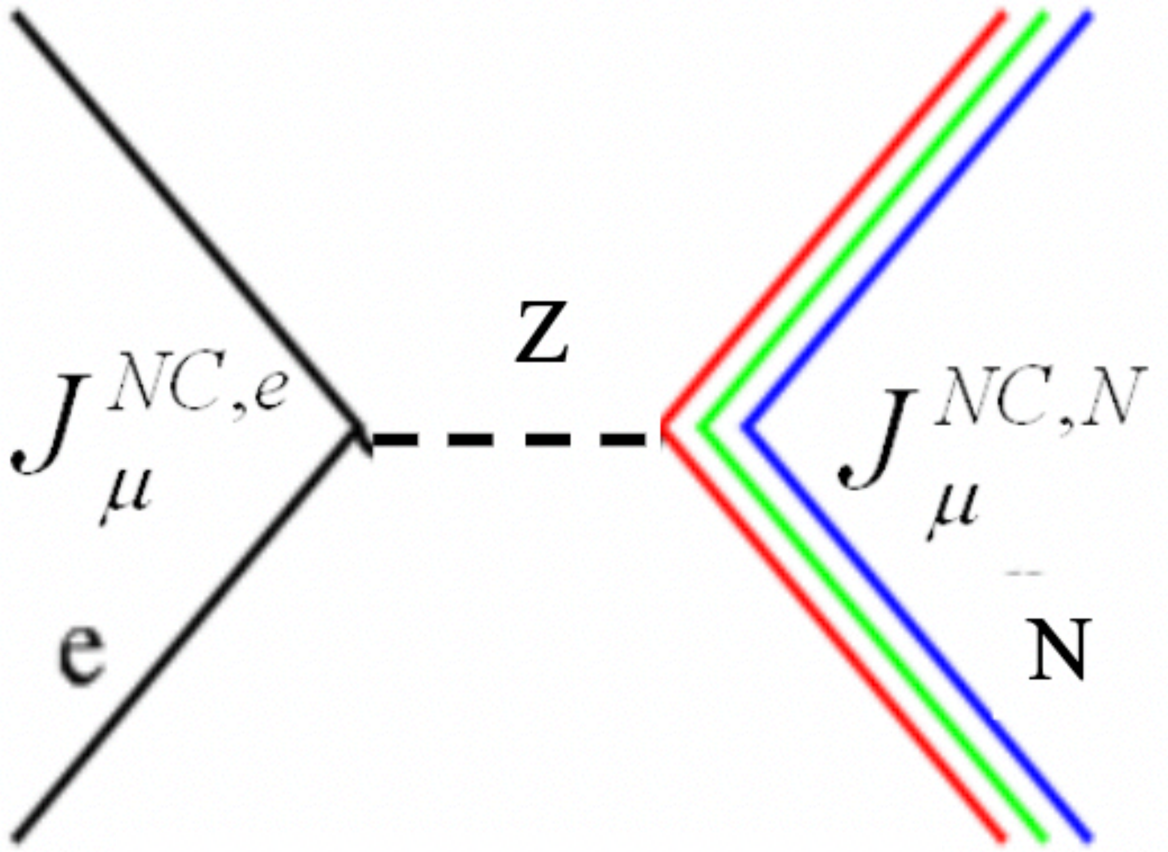
Measuring the electroweak current of a nucleon is one of the key tools for understanding nucleons in terms of the underlying quark & gluons.





$$\langle N | J_\mu^{EM,N} | N \rangle =$$

vector current (EM structure)



$$\langle N | J_\mu^{NC,N} | N \rangle =$$

vector & axial vector currents (Weak structure)

Characterized by EM form factors (G_E, G_M); charge and magnetization distributions in the nucleon

Characterized by Weak form factors (G_E^Z, G_M^Z, G_A, G_P); weak vector charge and magnetization distributions in the nucleon & axial charge distribution

Axial electroweak charge is unique to the weak force

The vector electroweak form factors have been extensively studied using electron scattering

constrained by charge conservation

$$\langle r_p^2 \rangle = -6 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0}$$

Slope of form factor at Q^2 =0 give RMS radiii of distribution

PVES has been used to measure weak vector form factors

vector current insensitive to details of QCD

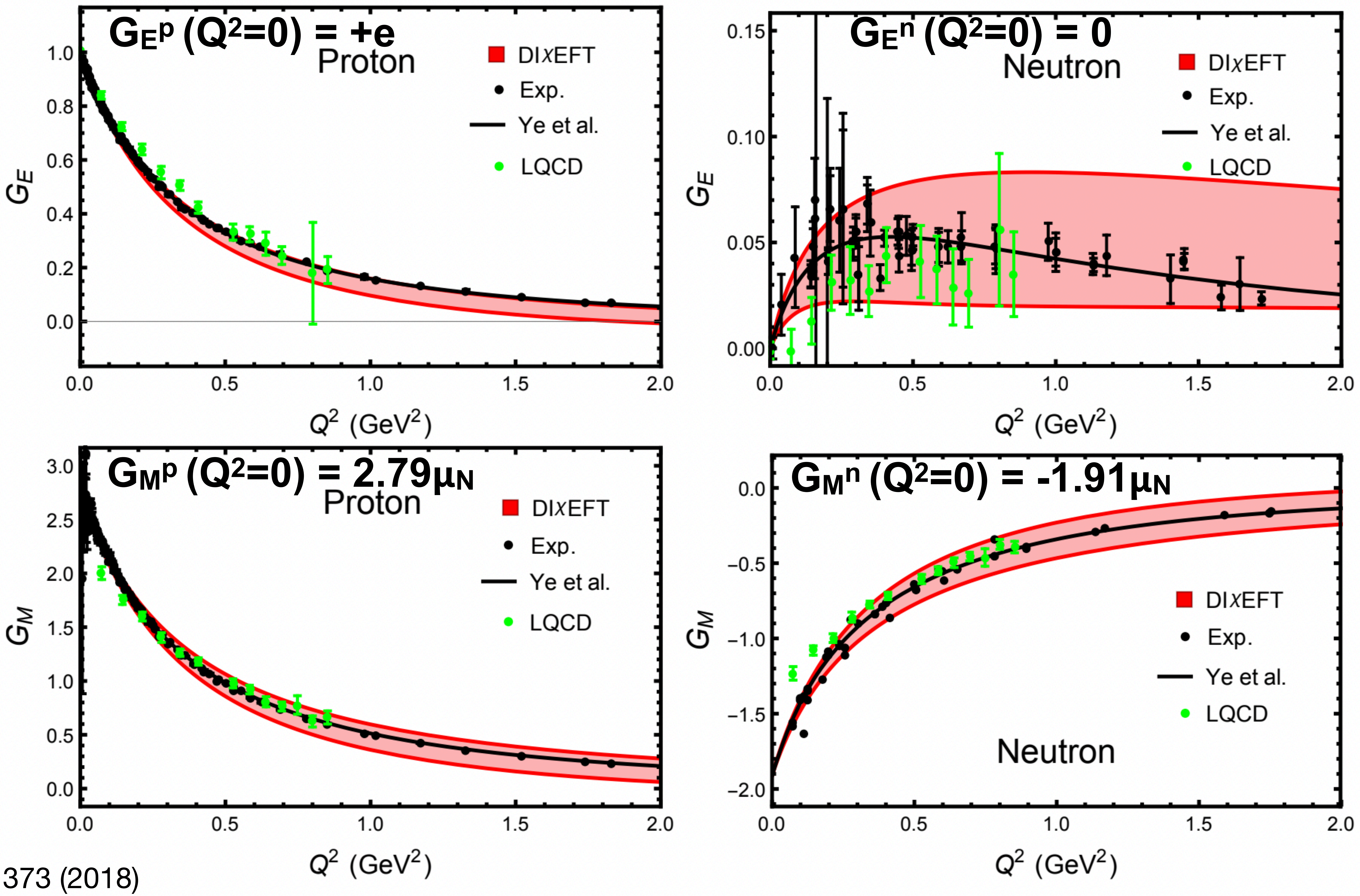


Fig. from Alarcon & Weiss, PLB 784, 373 (2018)

The axial current is more sensitive to QCD details but not as well known

Axial current characterized by the axial and induced pseudo scalar form factors [G_A,(Q^2), G_P(Q^2)];

Not directly accessible in e-scattering

Measured in μ capture, quasi-elastic *ν* scattering and low energy π production.

Measured only at low Q^2, large uncertainties, very little info above Q^2 > 1 GeV^2

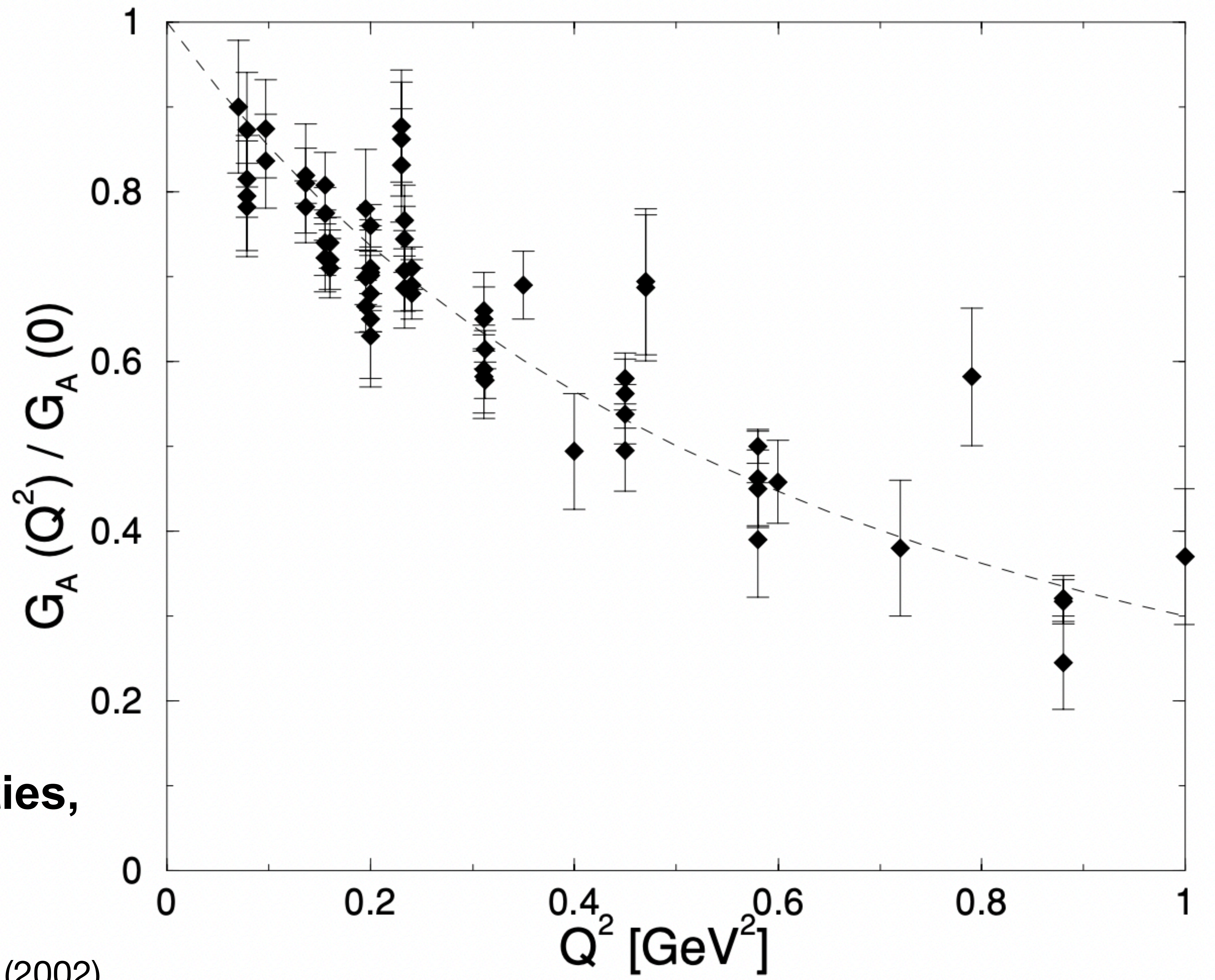


Fig. from Bernard, Elouadrhiri & Missner, J. Phys. G 28, R1 (2002)

The axial charge (g_A) and rms axial radius ($\langle r_A \rangle^2$) are fundamental weak interaction parameters.

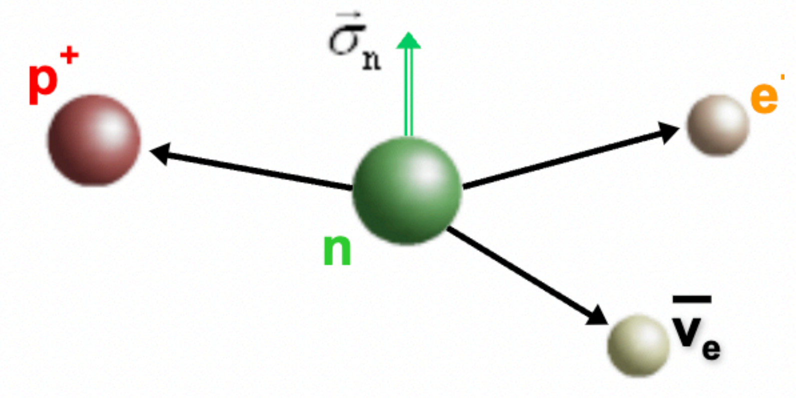
$$G_A^{u-d}(Q^2=0) \rightarrow g_A$$

$$\langle r_A^2 \rangle = -\frac{6}{g_A}\frac{dG_A}{dQ^2}\Big|_{Q^2=0}$$

Necessary for neutrino oscillation experiments for solar and reactor neutrino fluxes

$\lambda = g_A/g_V$ is usually obtained from measurement of neutron beta decay correlation parameters *A* and *a*

But recently 5σ differences between various measurements have arisen



$$dW \propto G_F^2 V_{ud}^2 \left(1+3|\lambda|^2\right) \cdot \left\{1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right) \cdot \vec{\sigma}_n\right\}$$

Neutrino-Electron Correlation

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}$$

Beta-Asymmetry

$$A = -2\frac{|\lambda|^2 + |\lambda|\cos\phi}{1+3|\lambda|^2}$$

Neutron lifetime

$$\tau_n^{-1} \propto G_F^2 V_{ud}^2 \left(1+3|\lambda|^2\right)$$

Weak coupling constant ratio $\lambda = \left|\frac{g_A}{g_V}\right| e^{i\phi}$

Critical input for primordial nucleosynthesis and CMB anisotropies

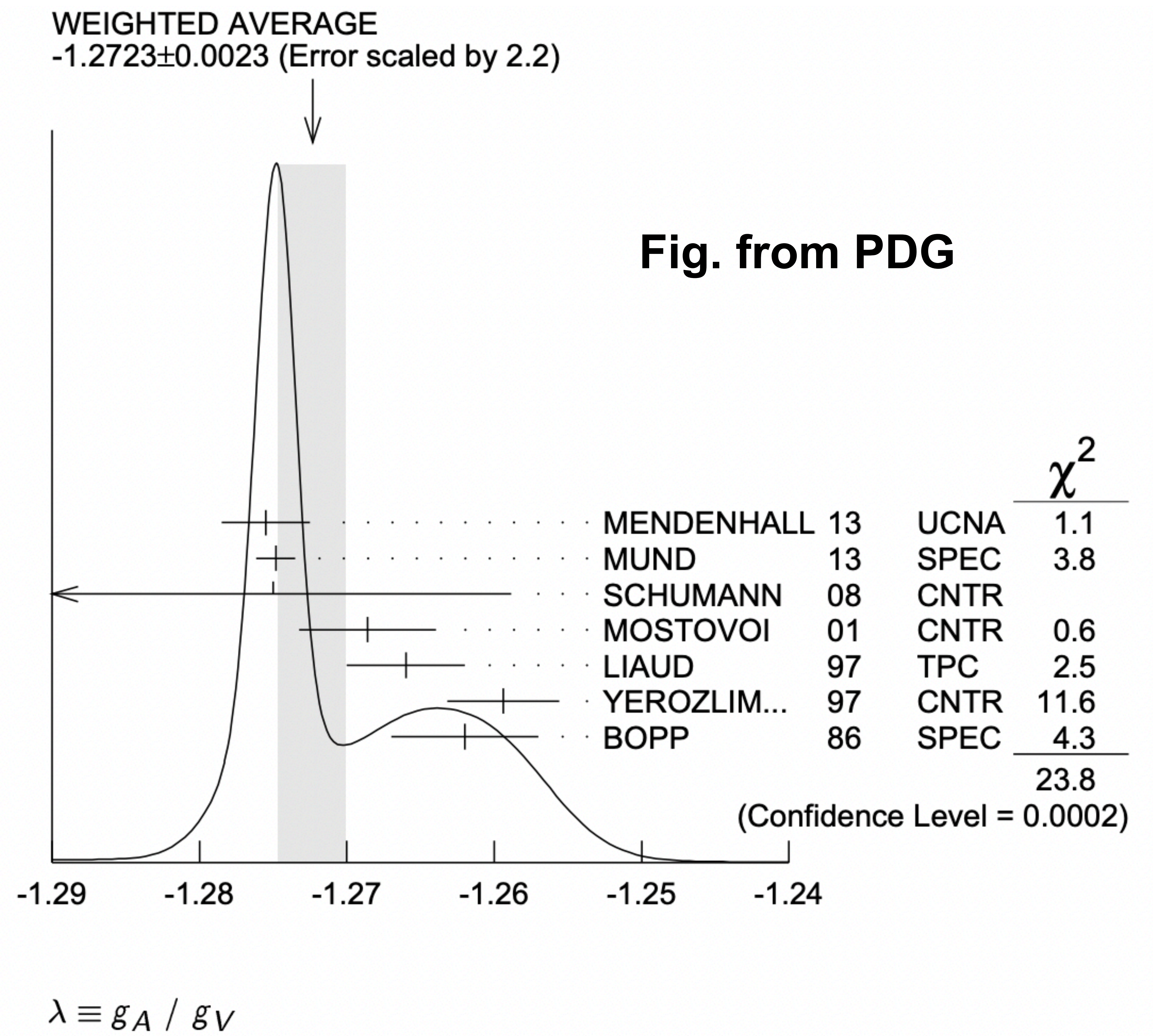
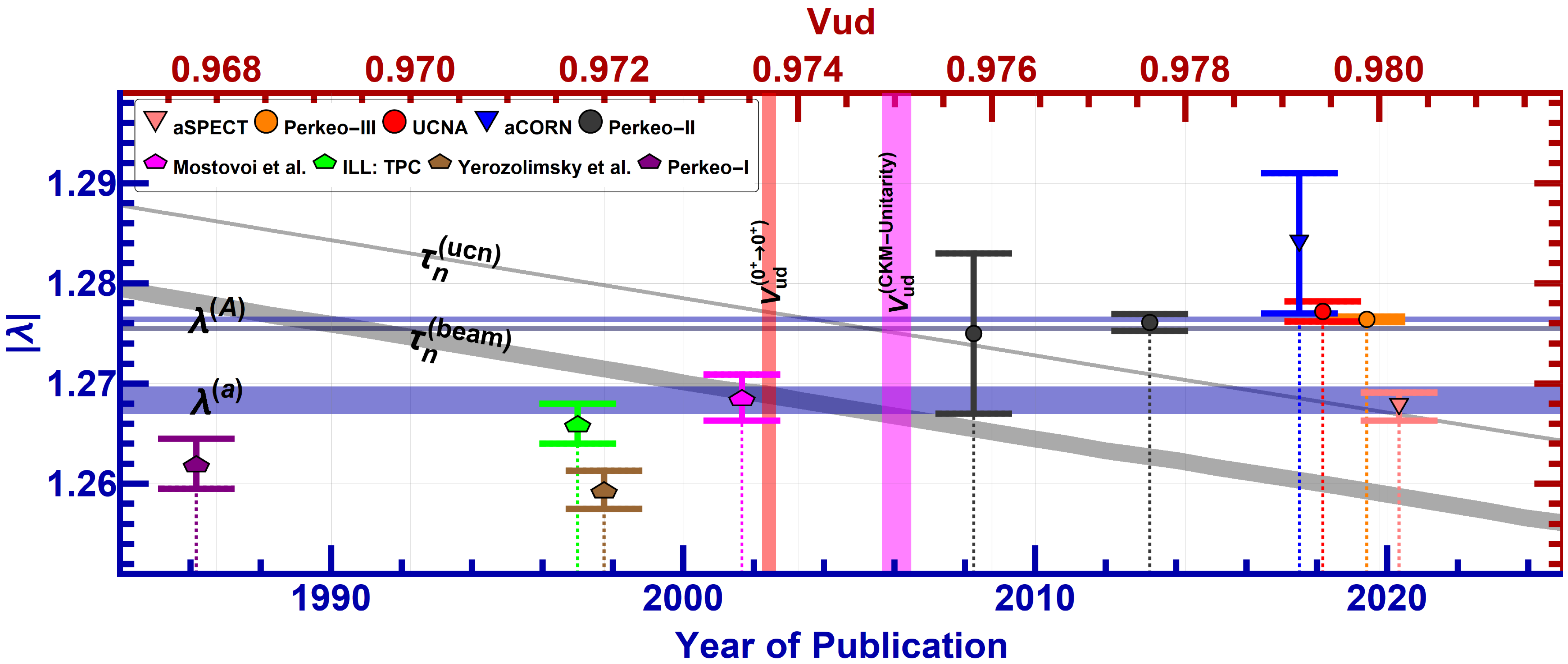


Fig. from PDG

There are related puzzles arising from the >4σ differences in neutron lifetime (τ_n) and the CKM parameter V_{ud}

τ_n from bottle vs beam experiments differ by >4σ

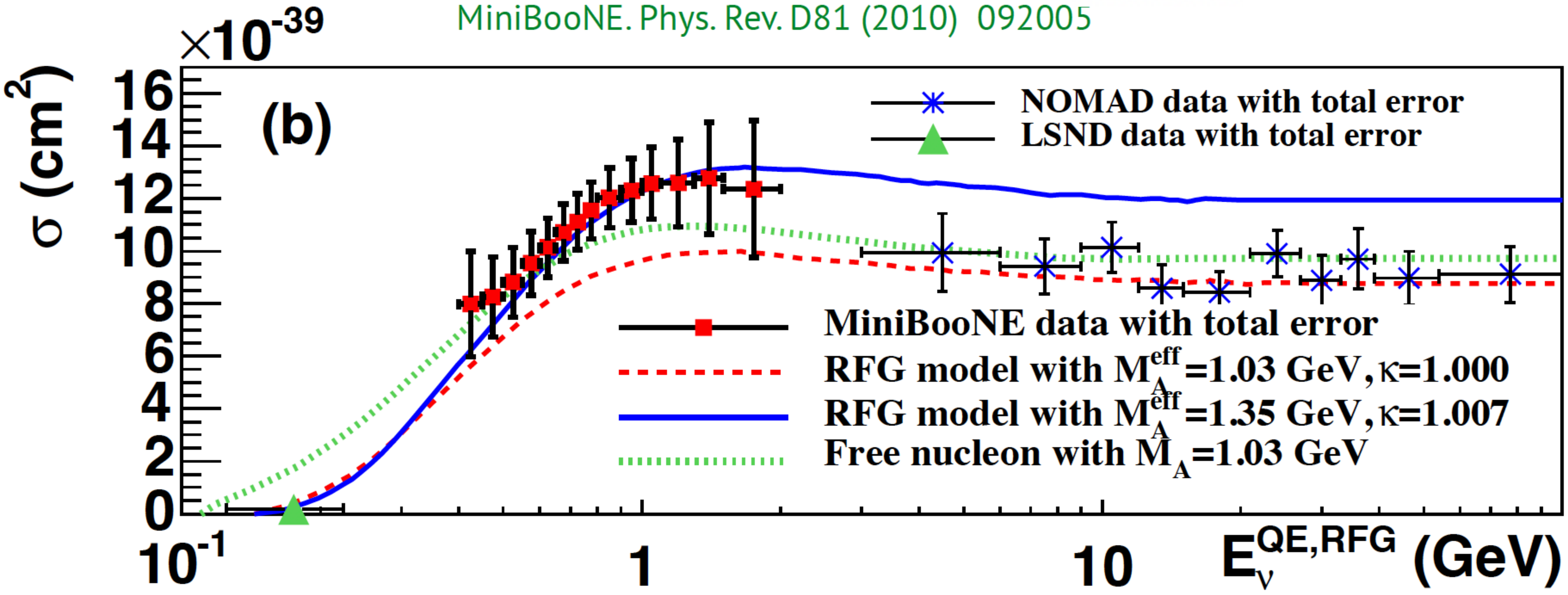
Vud from $0^+ \to 0^+$ super allowed decays vs from CKM unitarity differ by 4.4σ



Different neutrino scattering experiments indicate possible large discrepancies in the axial radius ($< r_A >^2$)

Assuming a dipole form $[1/(1+ Q^2/M_A^2)^2]$ for $G_A(Q^2)$; $\langle r_A^2 \rangle =$ **$12/M_A$**

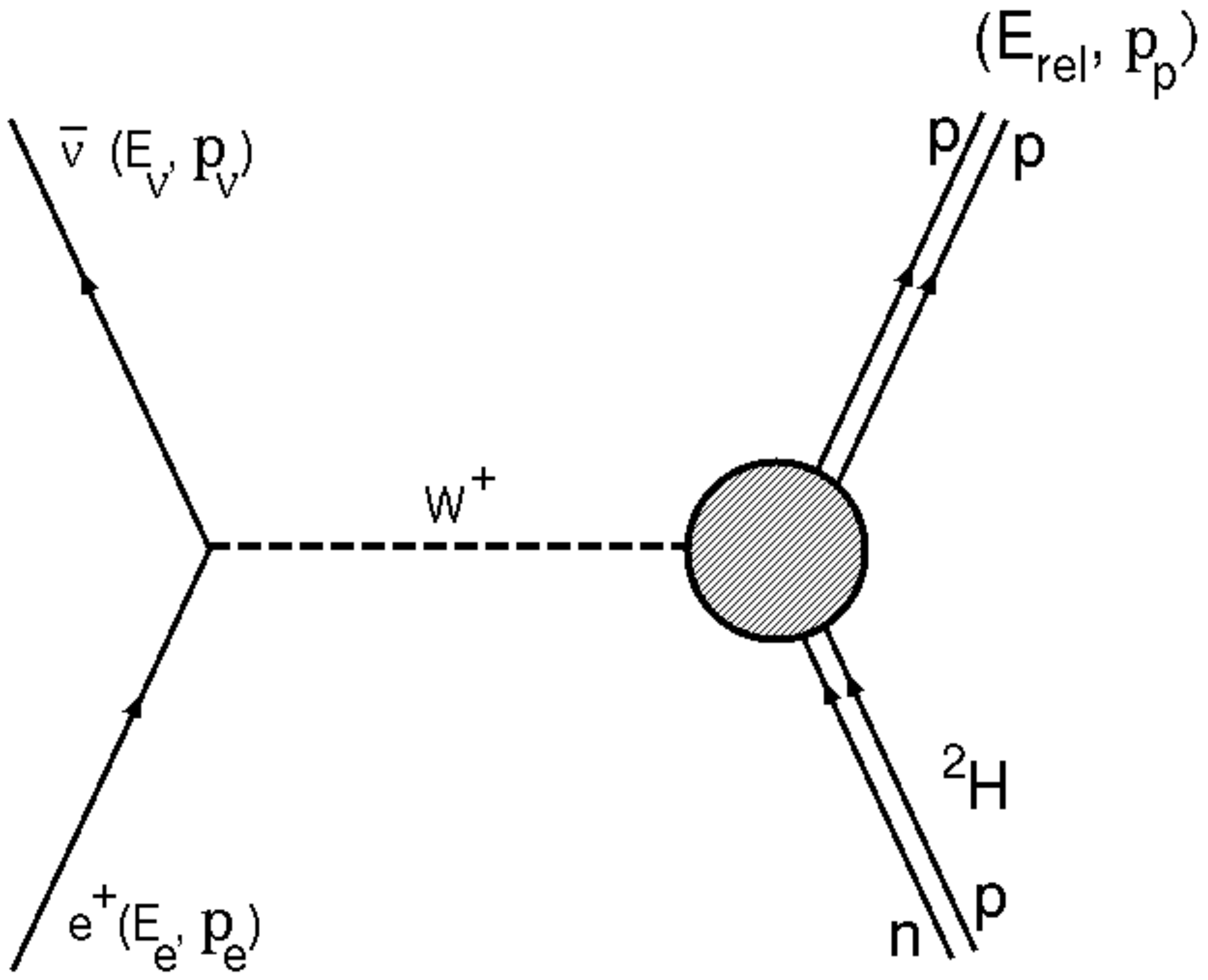
MiniBooNE. Phys. Rev. D81 (2010) 092005

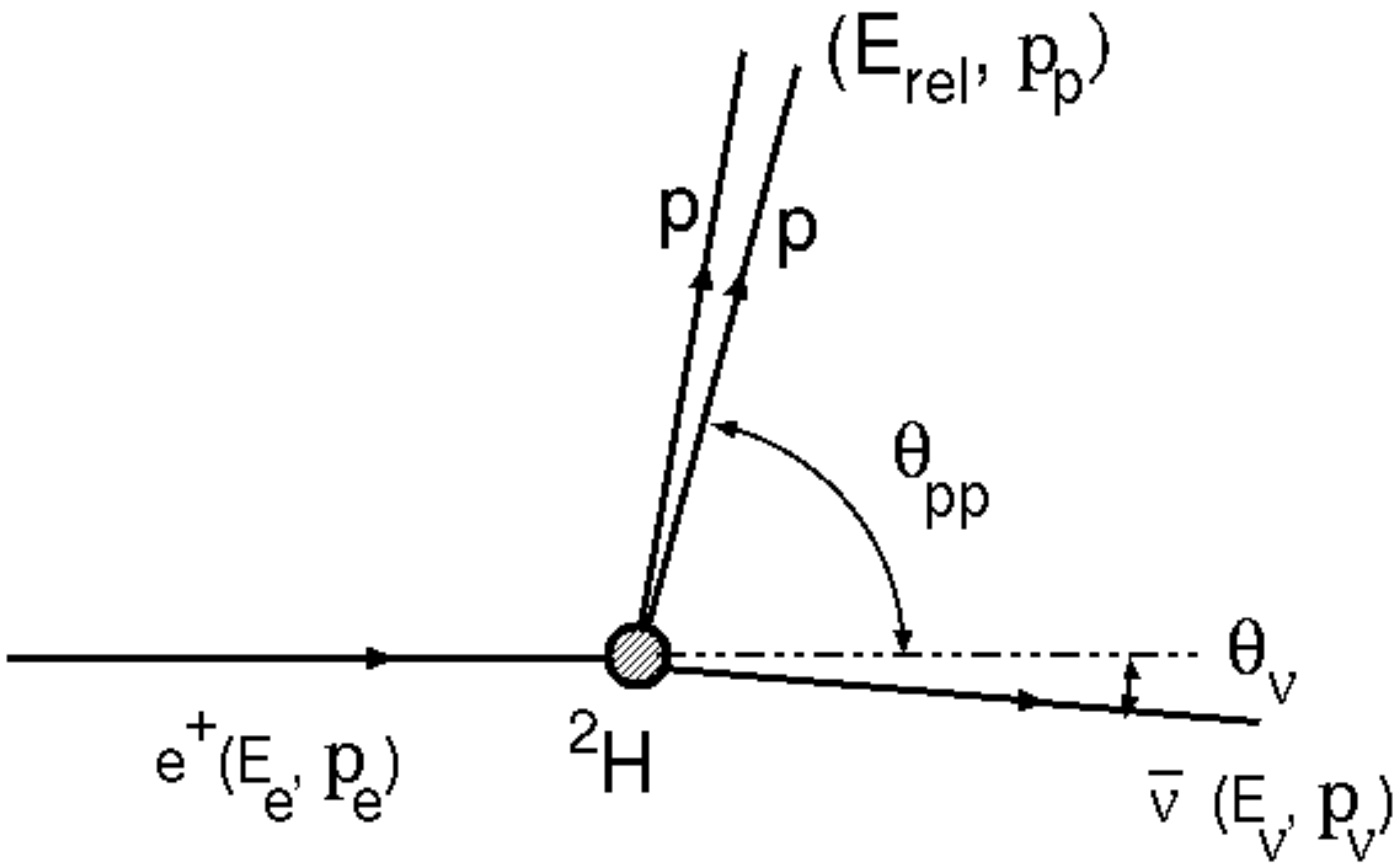


Current knowledge of the weak axial current is ripe for a new experimental technique with completely different systematics

The capture of polarized positrons in deuterium is just such a new technique

This is an inverse beta decay process ($\bar{e}^+ + {}^2H \rightarrow p + p + \nu_e$)



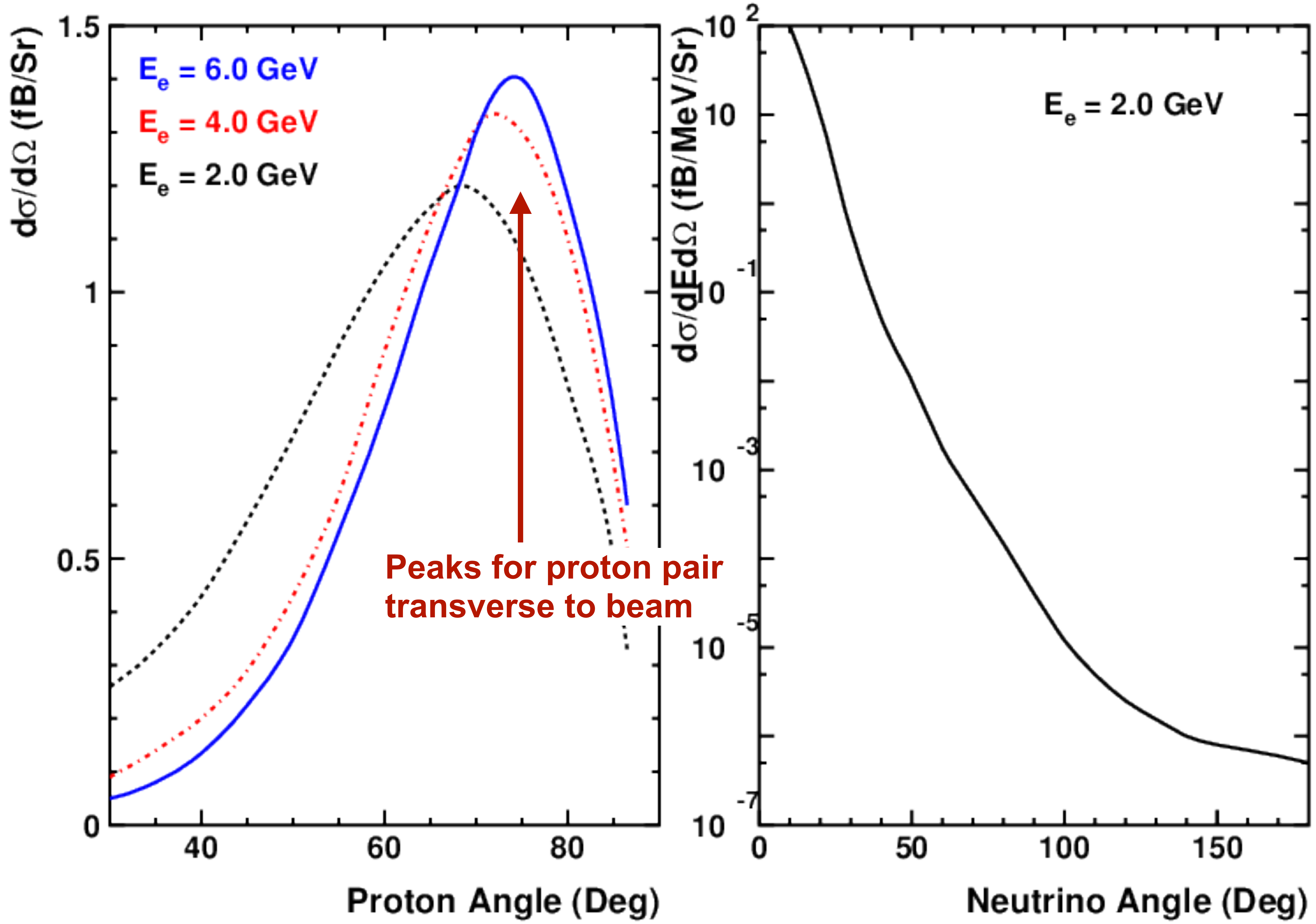


Cross section for right-handed positrons is strictly zero

Cross section increases with Q^2

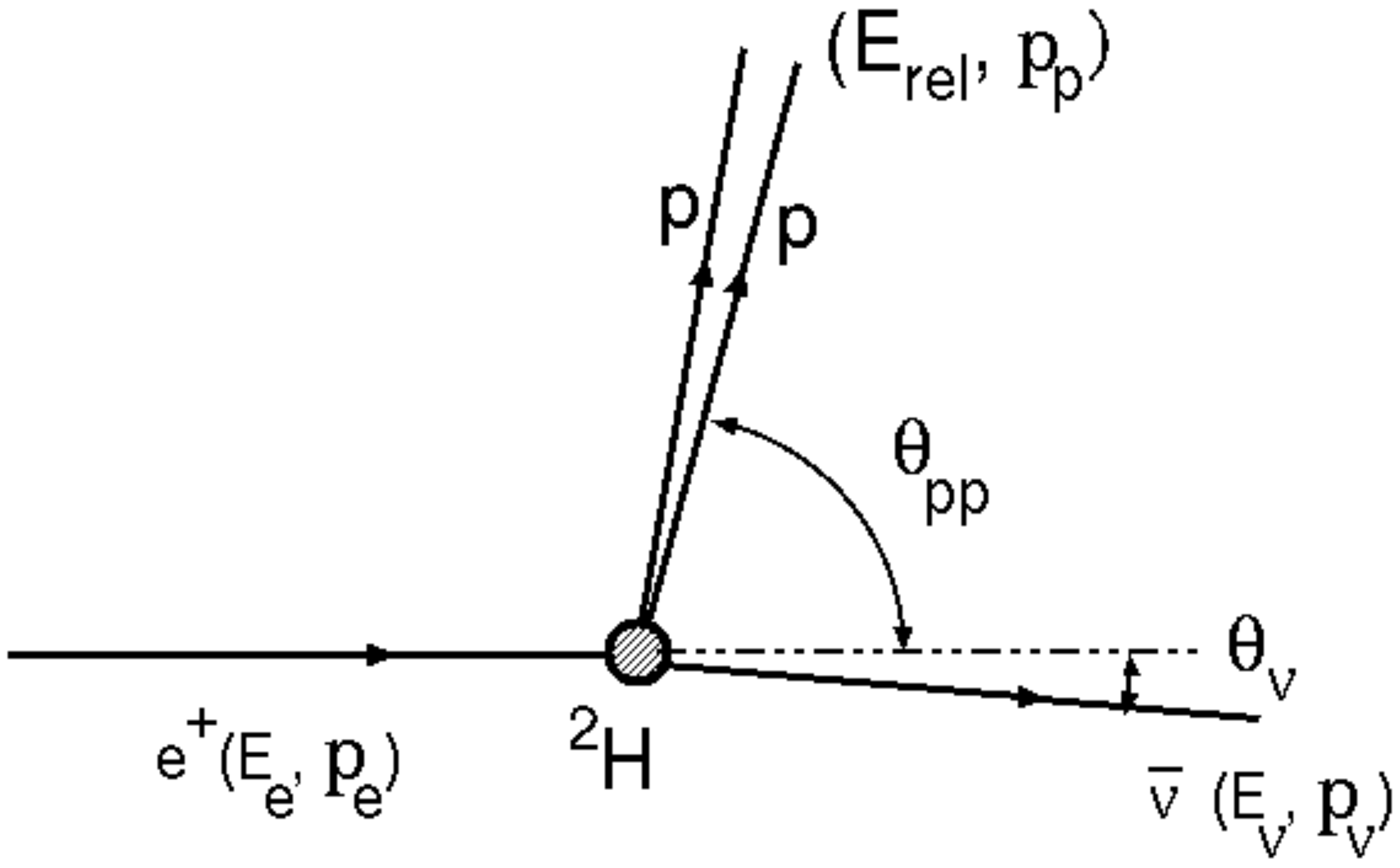
The cross section for 2-6 GeV positrons was calculated as part of early design possibilities for CEBAF

This is an inverse beta decay process ($\bar{e}^+ + {}^2H \rightarrow p + p + \nu_e$)



Assumptions: $M_\nu = 0$; $E_{rel}(pp) < 10$ MeV; neglect m_{e+}

Cross section increases with Q^2

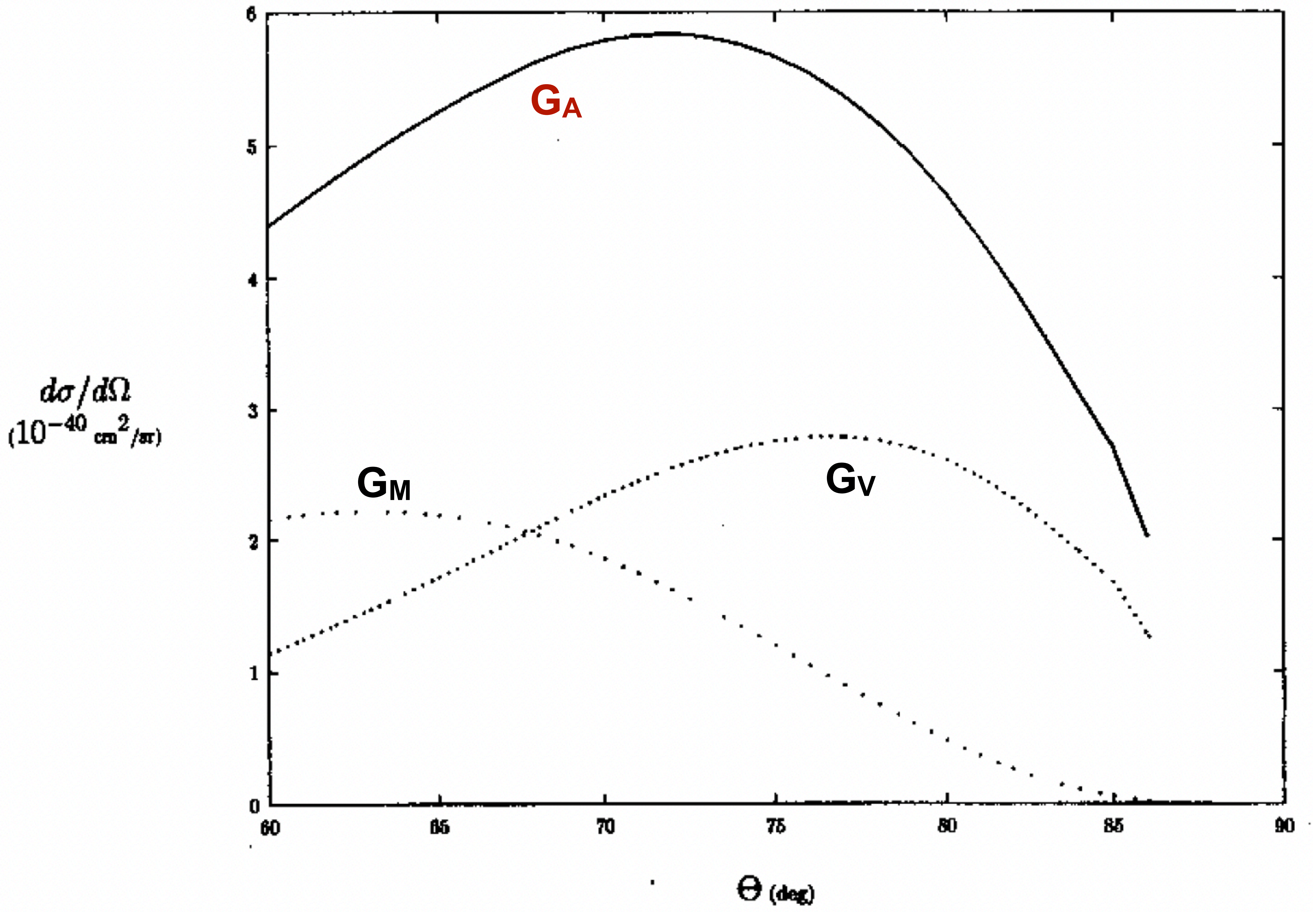


W.-Y. P. Hwang, Phys. Rev. C33, 1370 (1986)
Mintz et al., Int. J Mod. Phy. E6, 111 (1996)

Cross section for right-handed positrons is strictly zero

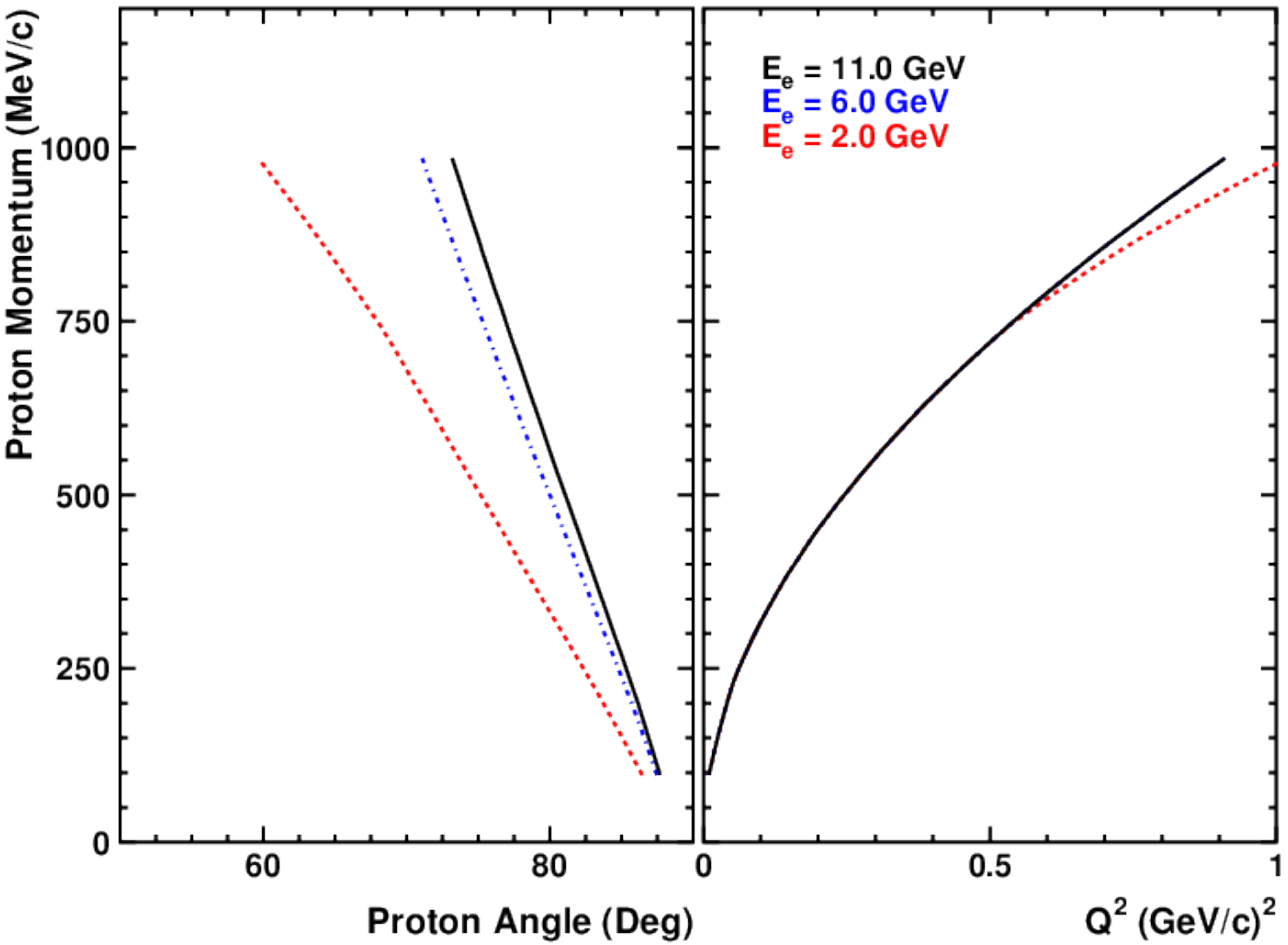
The cross section is dominated by the Axial form factor

W.-Y. P. Hwang, Phys. Rev. C33, 1370 (1986)
Mintz et al., Int. J Mod. Phy. E6, 111 (1996)



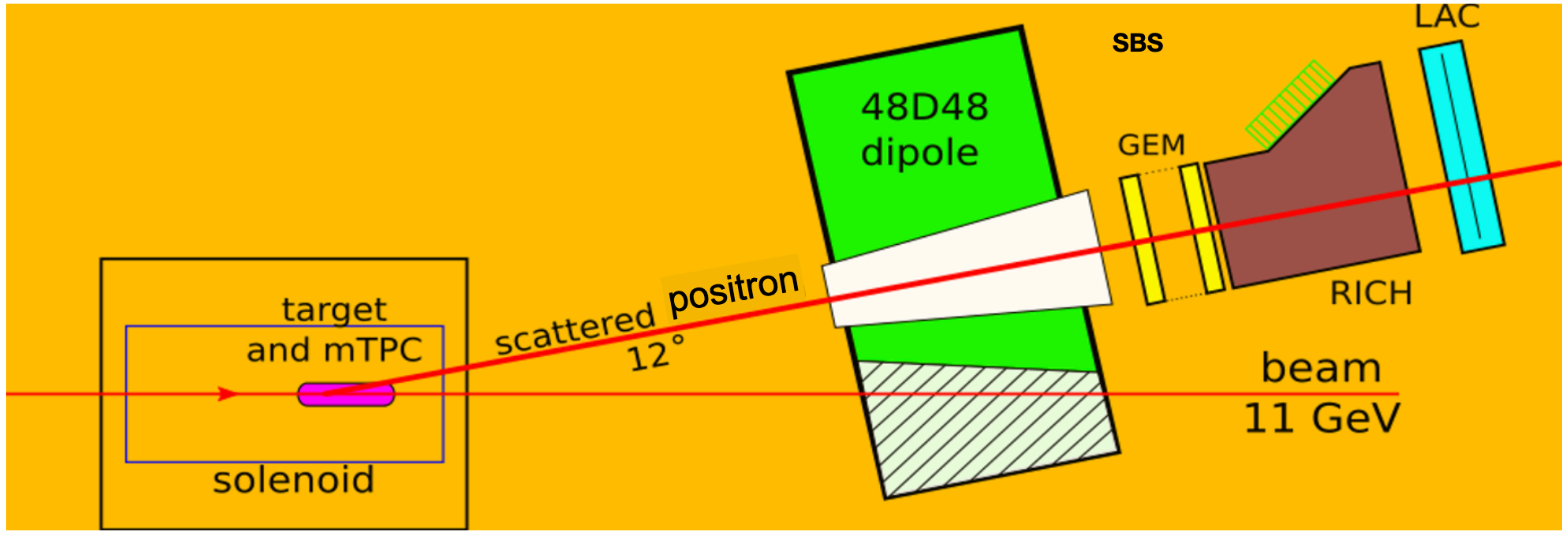
G_V, G_M well known from electron scattering

Cross section increases with Q^2

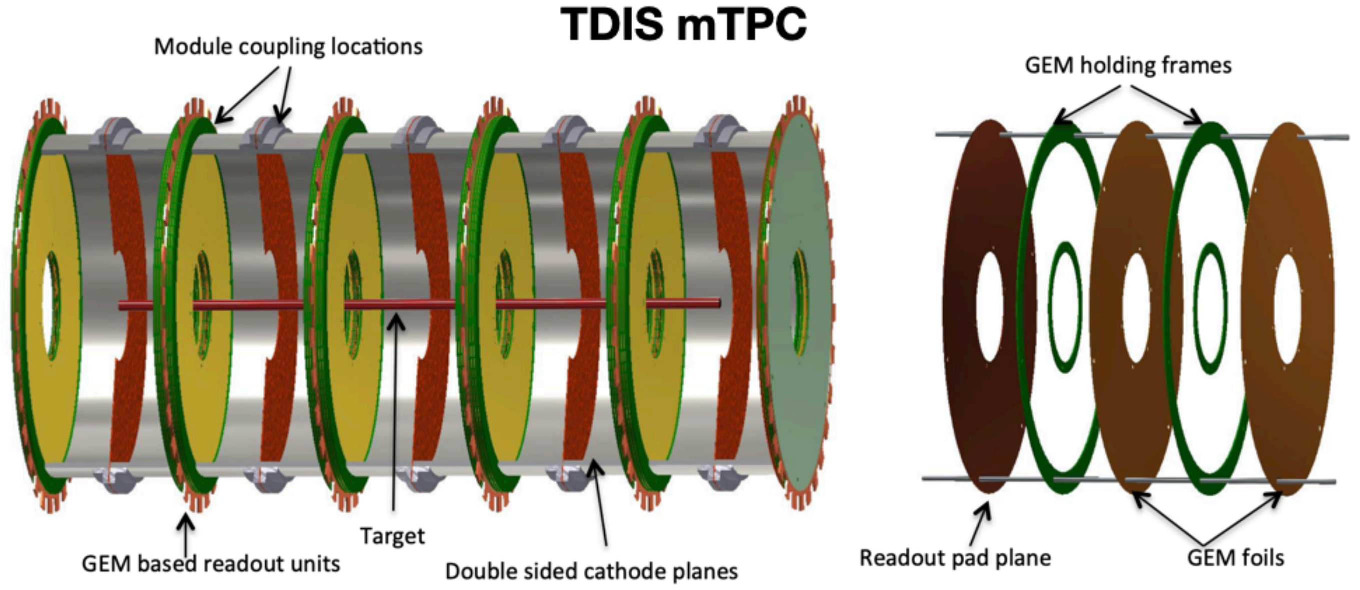


0.1 - 1 GeV proton pairs @ 60 - 90 deg : Q^2 = 0.01 - 1 GeV^2

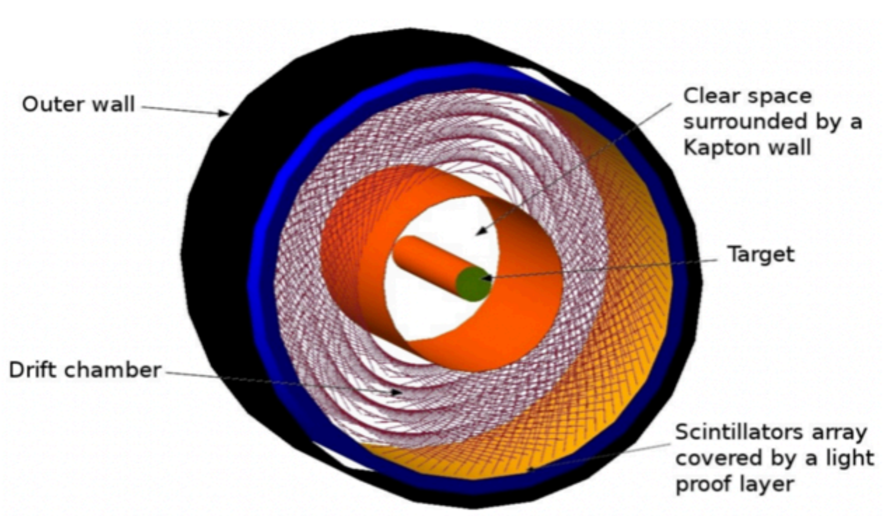
Experiment would need a recoil detector for the proton pair operated in anti-coincidence with scattered positrons



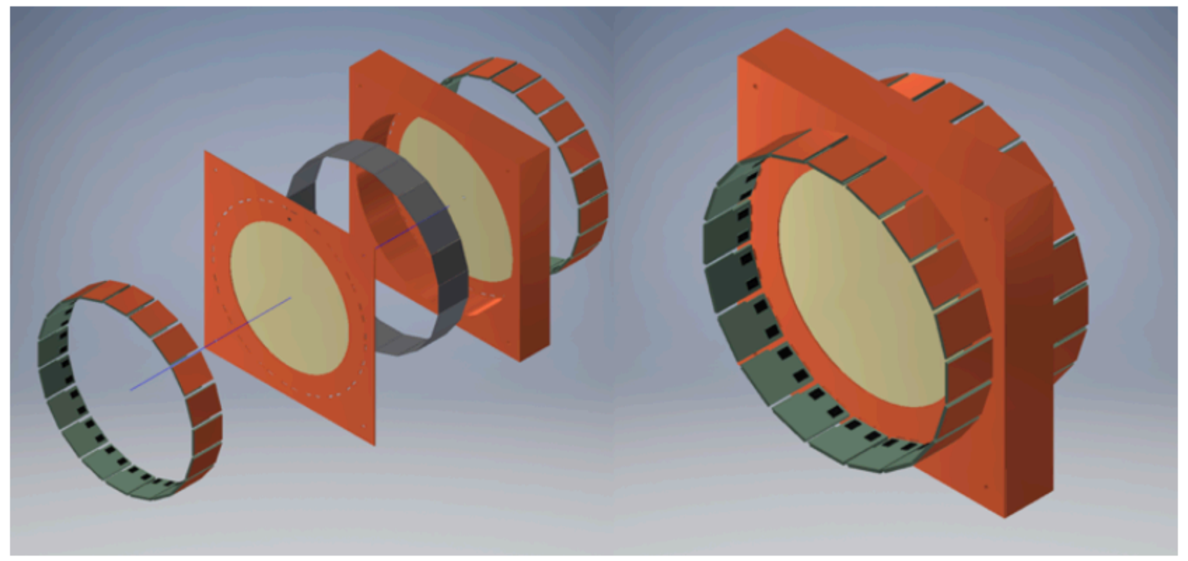
TDIS mTPC



ALERT TPC



DRad Si strip detector



0.1 - 1 GeV proton pairs @ 60 - 90 deg : Q^2 = 0.01 - 1 GeV^2

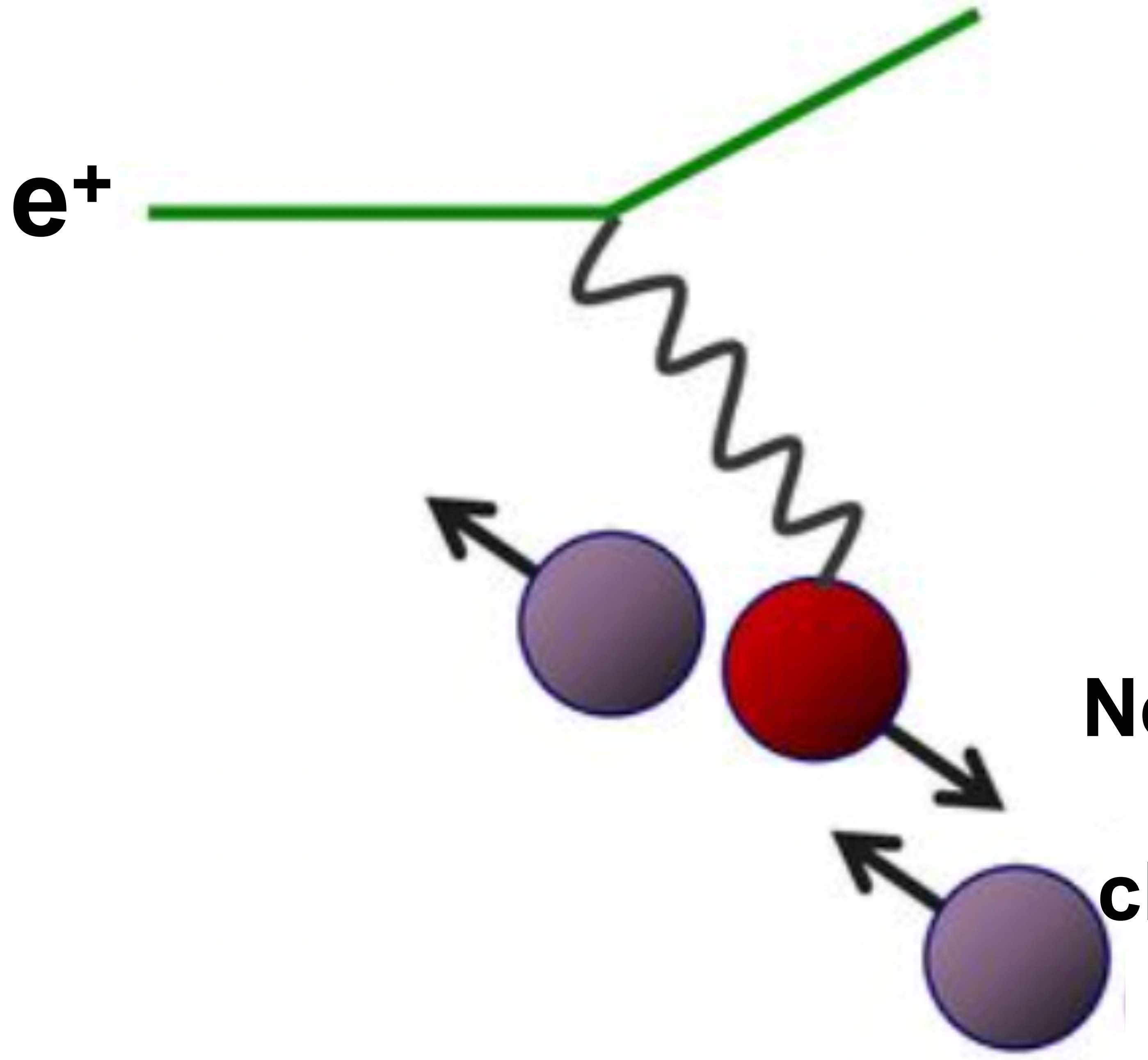
The quasi-elastic scattered positrons have to be detected in time and vertex anti-coincidence with the proton pair.

Needs a recoil detector and a small angle positron spectrometer/detector

Solenoid around the target will control the load from Bhabha scattering.

Positron polarization will also be used to distinguish between capture process and background processes. (capture only allowed for left handed positrons)

Quasi-elastic knockout of neutron followed by a charge exchange re-scattering, is the largest background to the capture process.



Neutron knockout
+
charge exchange
rescattering

Assuming a luminosity of 10^{36} cm^{-2}/s
we get count rates of ~3 x10^{-4} /s

QE scattering is ~10^{11} larger, if 0.01% of the QE event re-scatter to produce proton pairs and 0.01% of these are in vertex and time anti-coincidence, the background rate will be 0.3/s

gives S/B = 10^{-3}

The capture process only occurs for left handed positrons

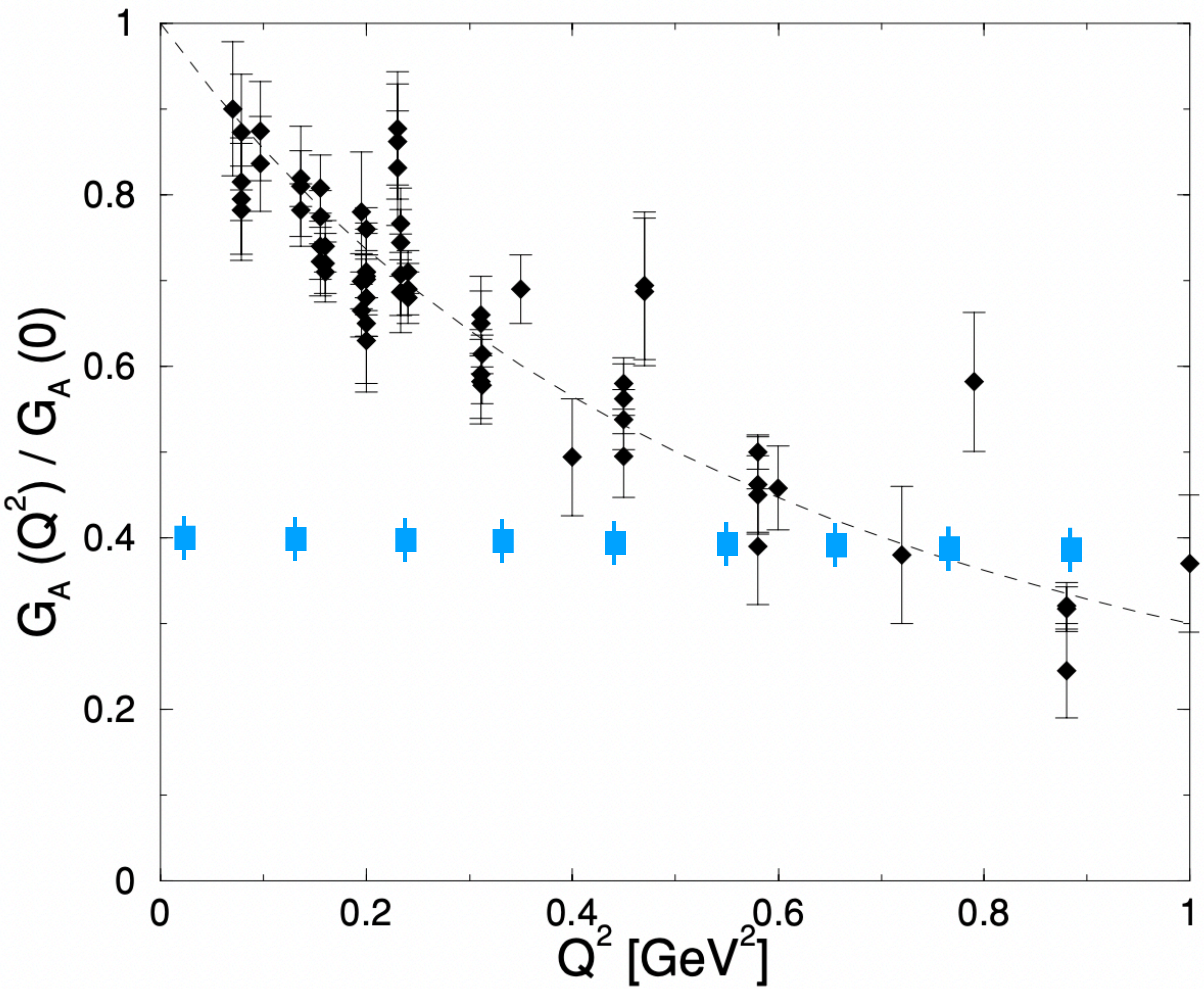
therefore the capture asymmetry = 0.1%

Rates can be obtained from BoNuS12 data

This asymmetry can be measured with an uncertainty of 3% with 30 days of beam time

To perform the measurement at 3 different beam energies we need ~100 days beam time

The axial form factor can be extracted from the measured asymmetry



Extrapolating to $Q^2 = 0$ we can extract g_A

and from the slope we can extract $\langle r_A \rangle^2$

each with a few % stat. uncertainty

Summary

The weak capture of positrons in ^2H with a medium energy polarized positron beam, can provide a new and unique measurement of the Q^2 dependence of $G_A(Q^2)$, the weak axial coupling g_A and the rms axial charge radius $<r_A>^2$.

These measurements would use detection techniques that are already in use or currently being developed for experiments at JLab.

The positron capture based measurement would have a completely different set of systematic uncertainties compared to all known methods and may help resolve several current puzzles.