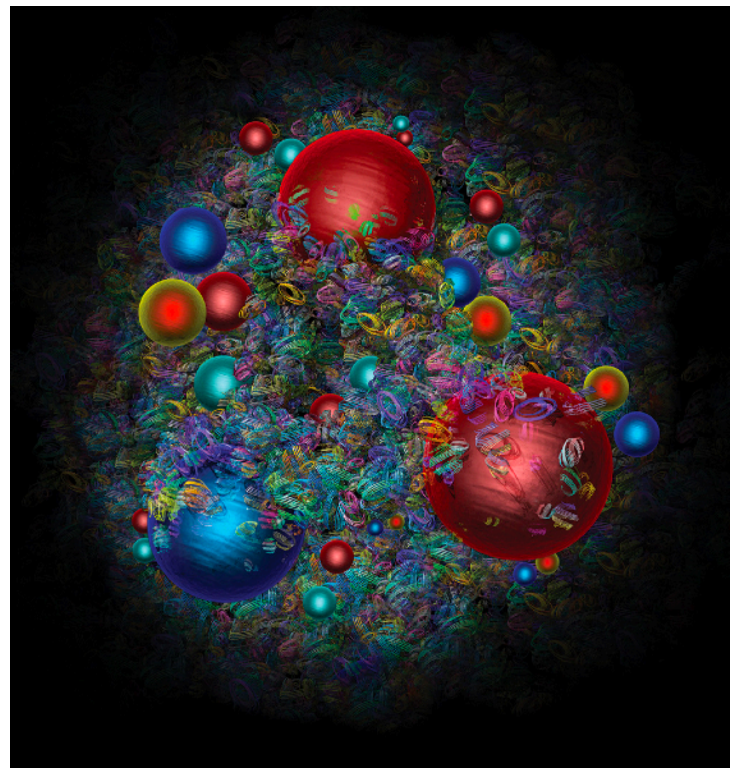
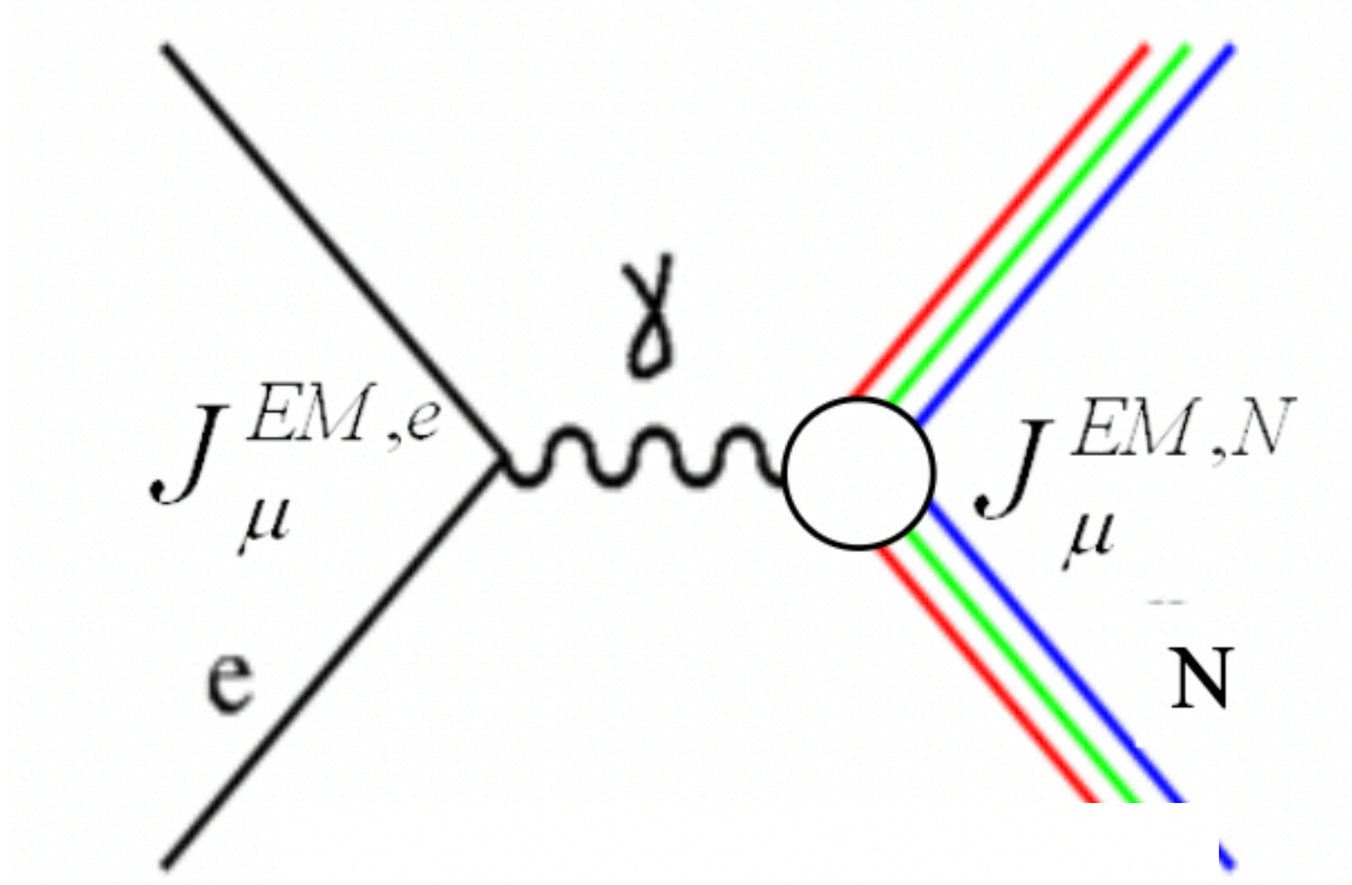
Axial Form Factor from Weak Capture of Polarized Positrons

Dipangkar Dutta
Mississippi State University

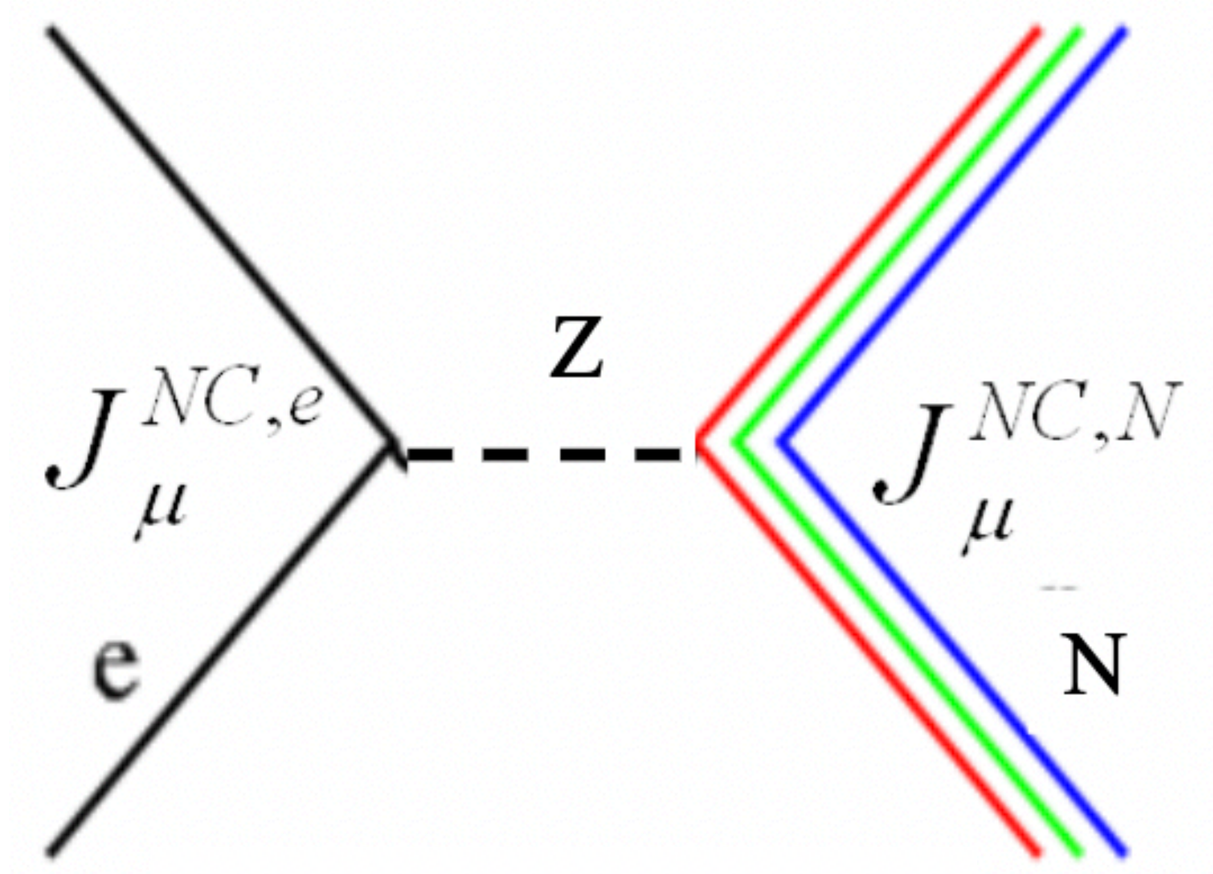
Measuring the electroweak current of a nucleon is one of the key tools for understanding nucleons in terms of the underlying quark & gluons.





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

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 (related to spatial distribution of the spin angular momentum).

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 radii of distribution

PVES has been used to measure weak vector form factors

vector current insensitive to details of QCD

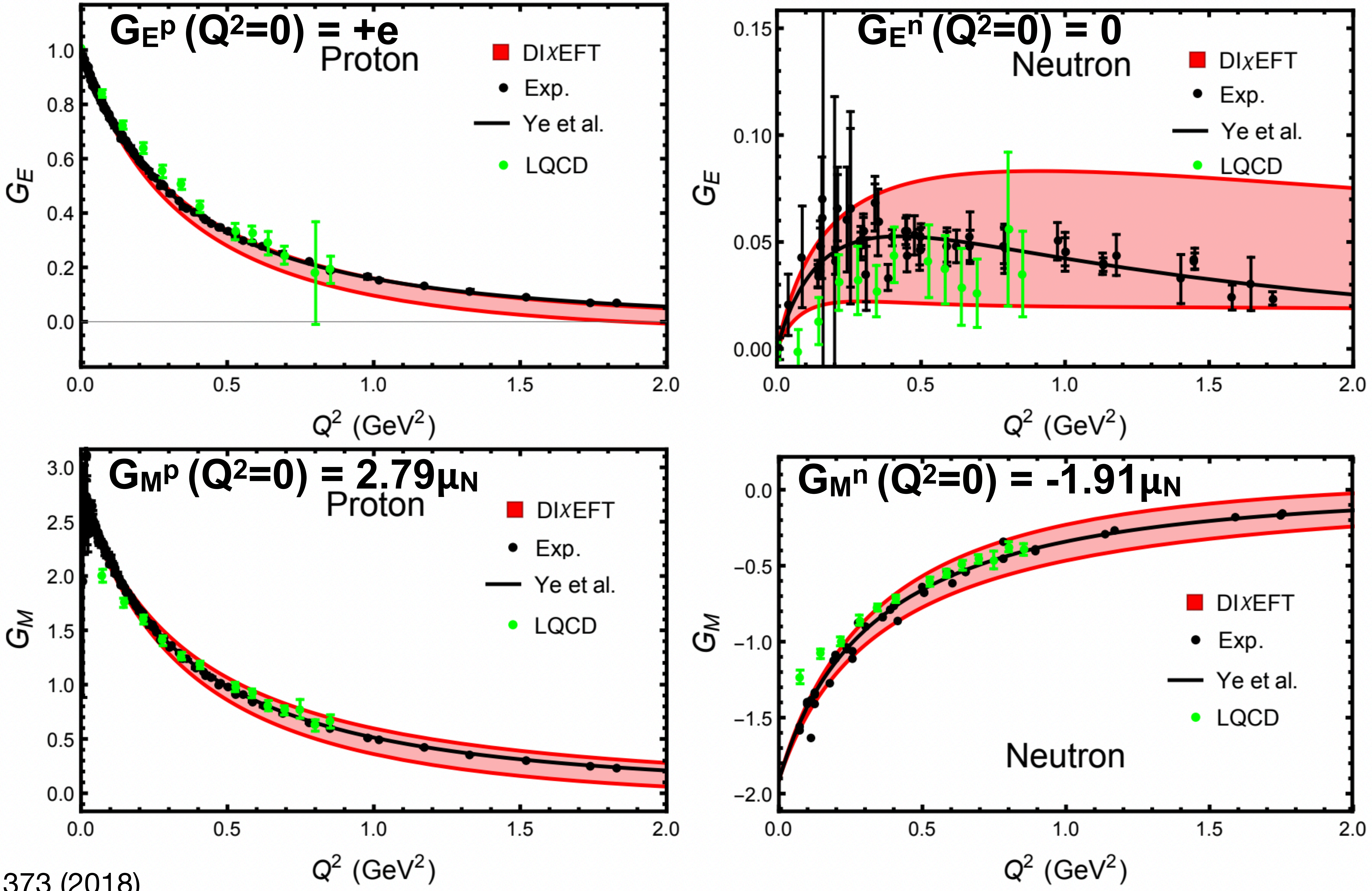


Fig. from Alarcon & Weiss, PLB 784, 373 (2018)

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**

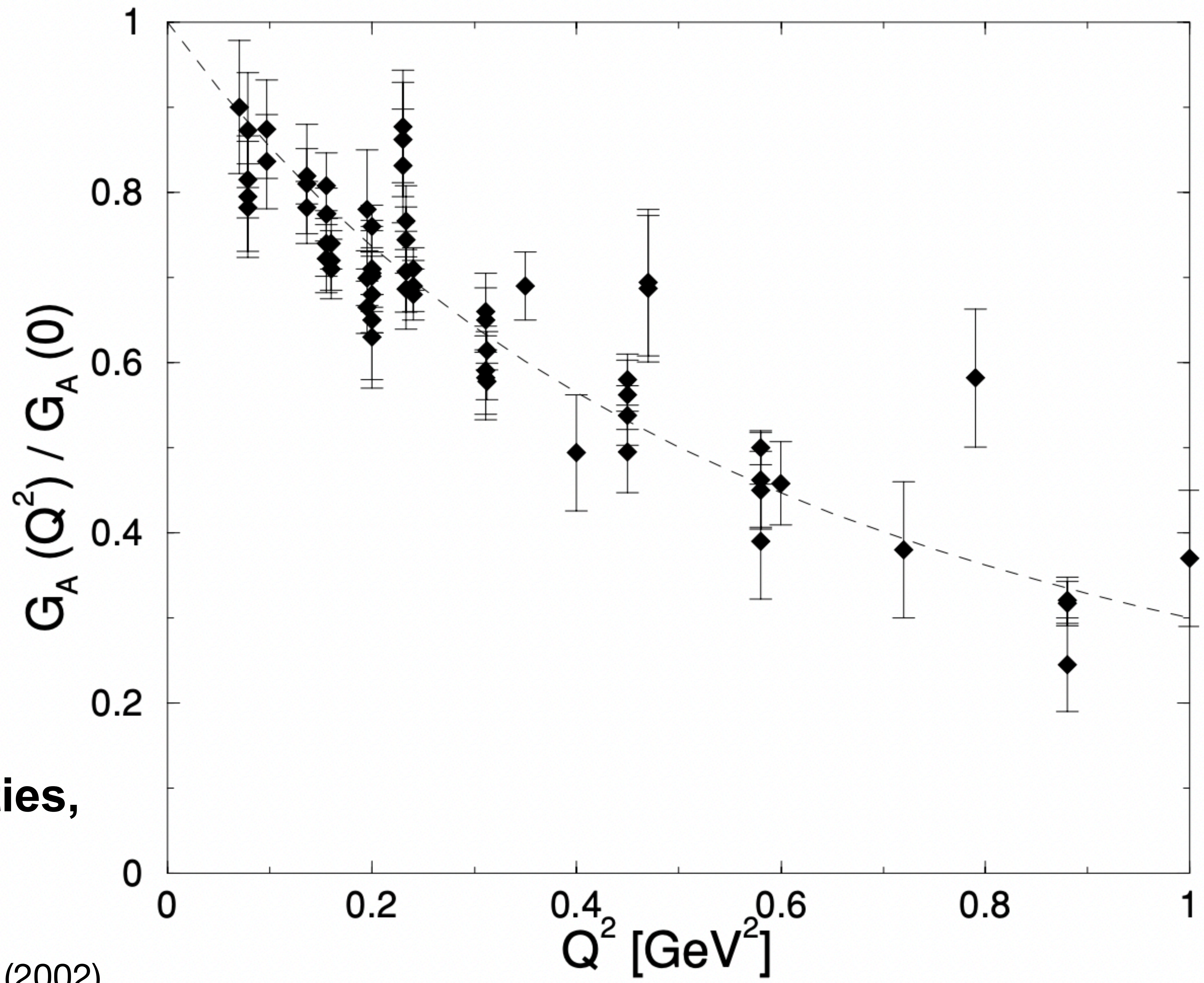


Fig. from Bernard, Elouadrhiri & Missner, J. Phys. G 28, R1 (2002)

The axial charge (g_A) and rms axial radius ($< r_A >^2$) are fundamental weak interaction parameters.

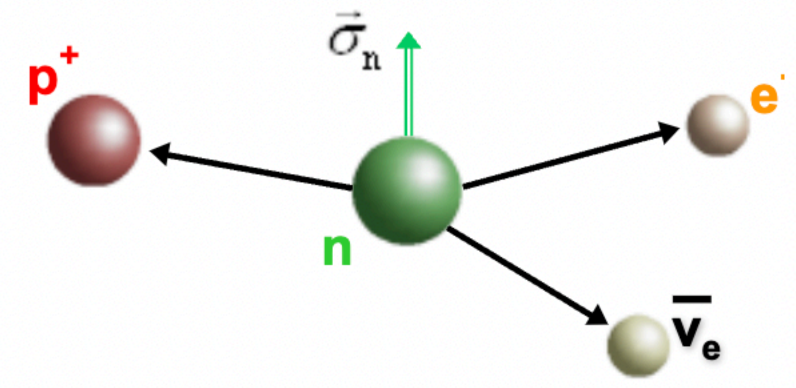
$$G_A^{u-d}(Q^2=0) \to g_A$$

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

Necessary for neutrino oscillation experiments for solar and reactor neutrino fluxes

Critical input for primordial nucleosynthesis and CMB anisotropies

$\lambda = g_A/g_V$ 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 $\lambda = \left|\frac{g_A}{g_V}\right| e^{i\phi}$

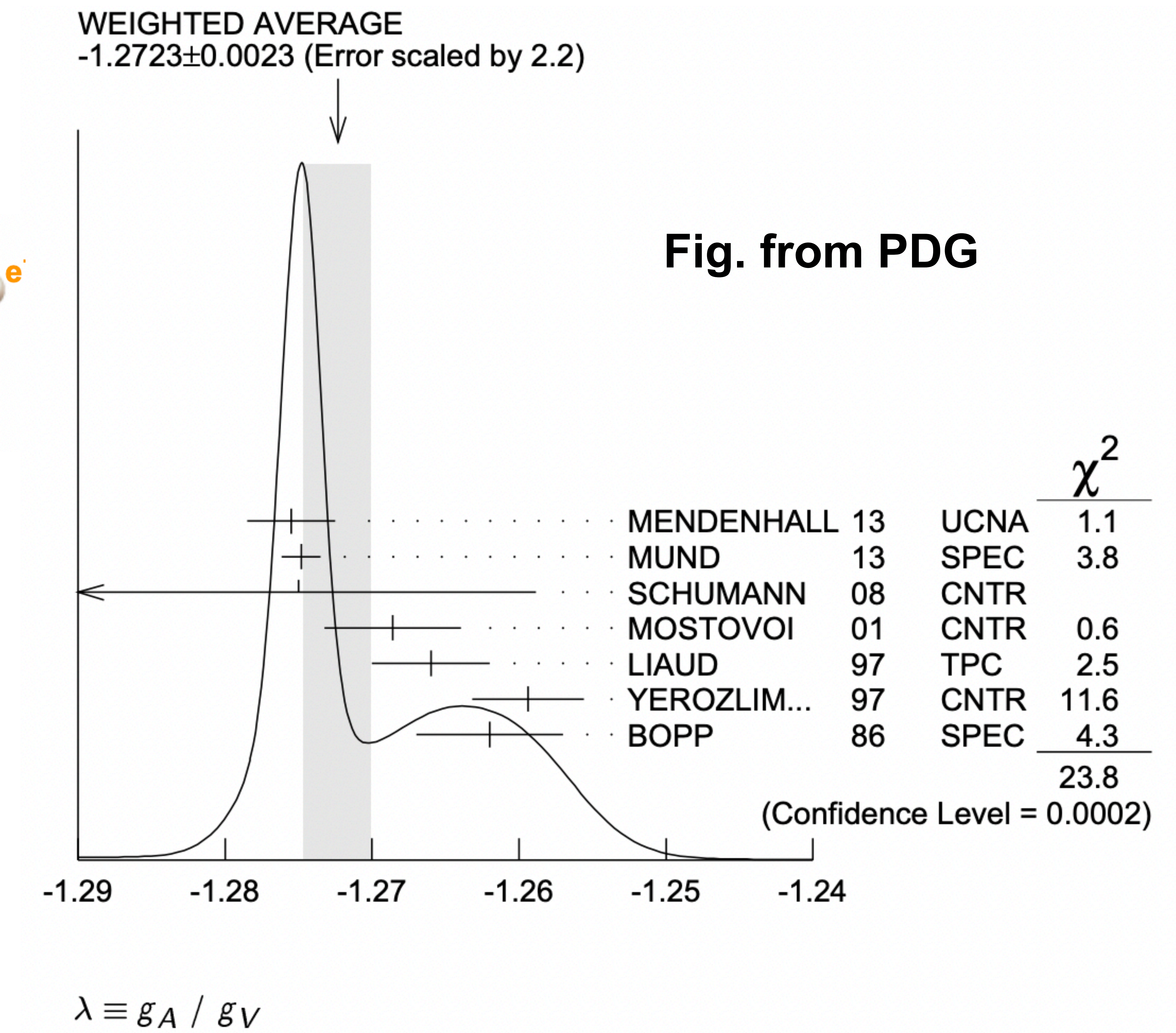
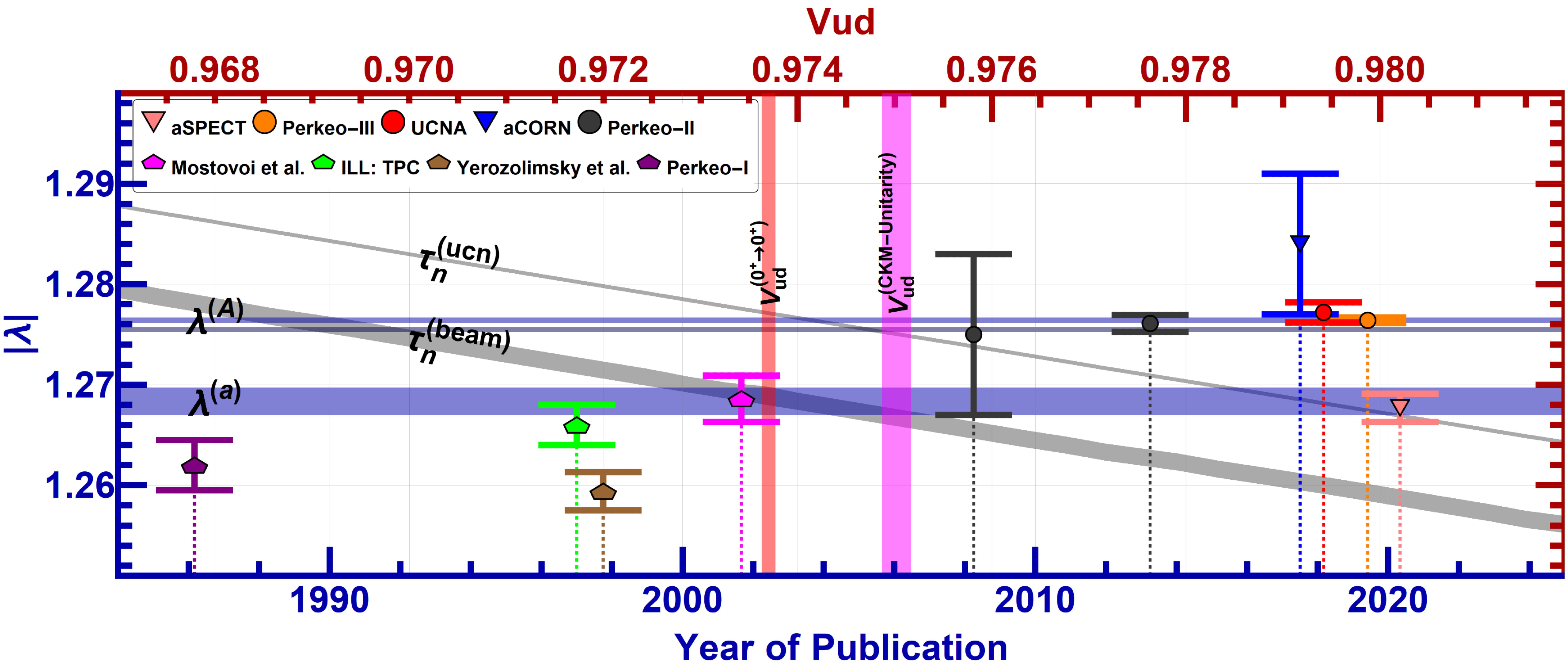


Fig. from PDG

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

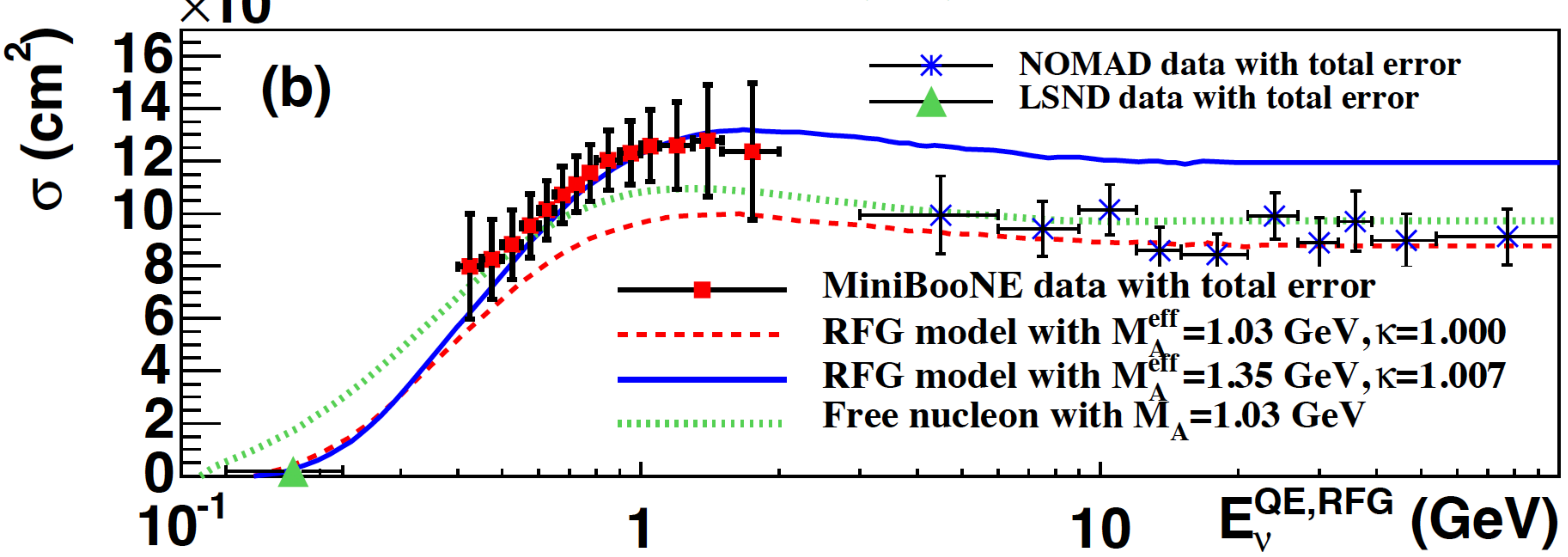
Vud from $0^+ \rightarrow 0^+$ super allowed decays vs from CKM unitarity differ by 4.4σ



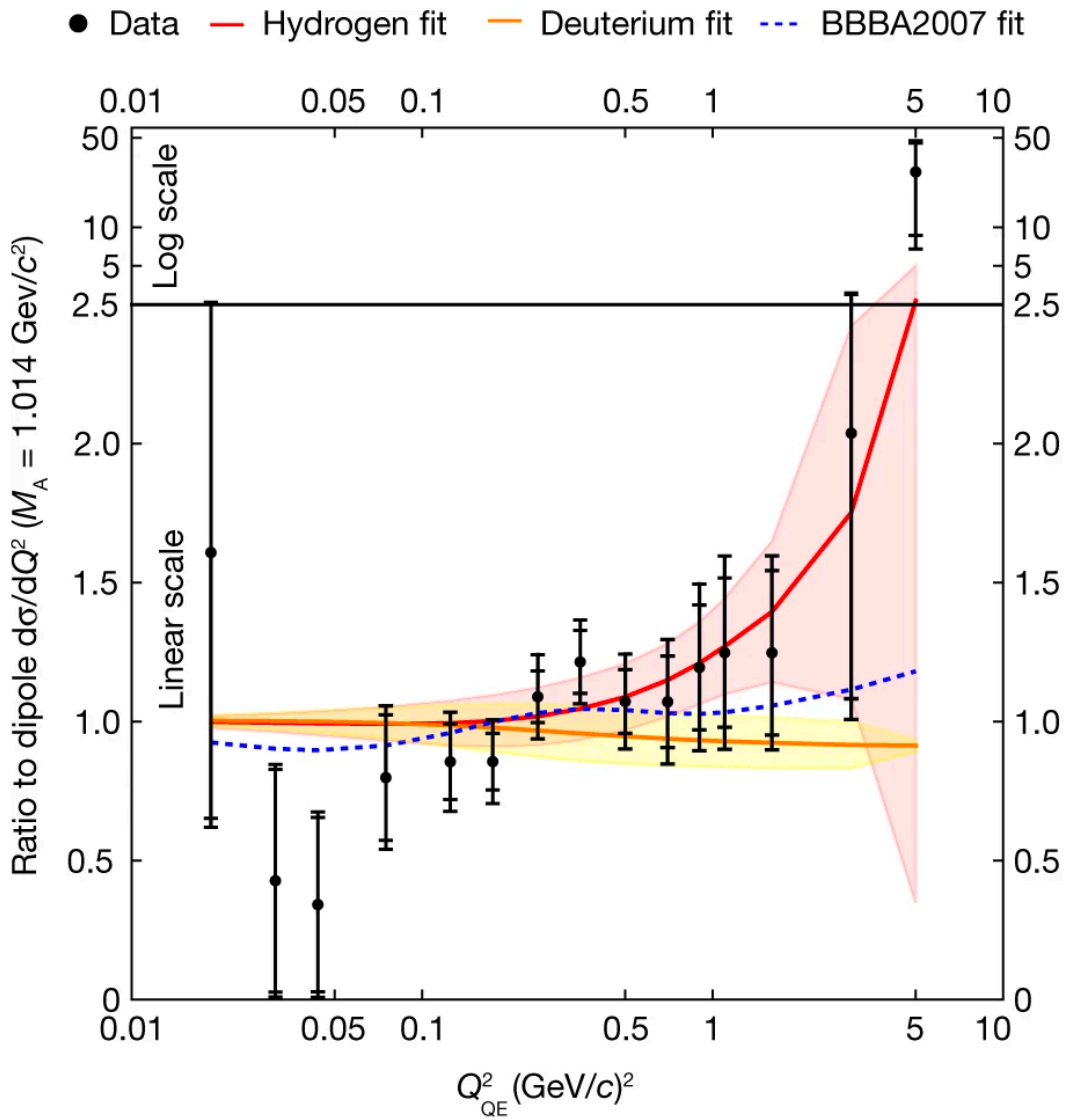
Different neutrino scattering experiments indicate possible large discrepancies in the axial radius ($< r_A >^2$)

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



Recent results from the Minerva experiment have large uncertainties and differ from previous measurements.



Assuming a dipole form $[1/(1+ Q^2/M_A^2)^2]$ for $G_A(Q^2)$;

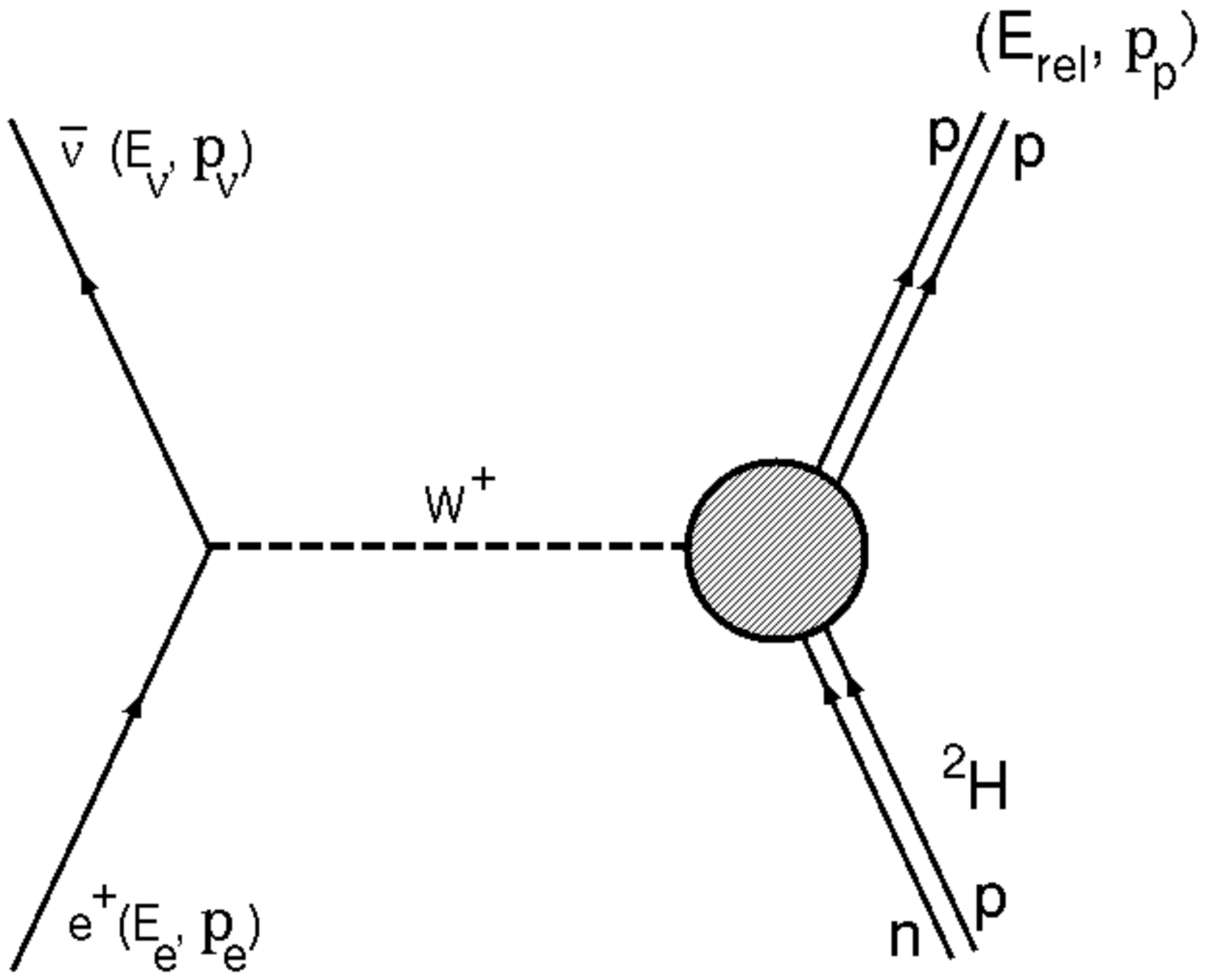
$$\langle r_A^2 \rangle = 12/M_A$$

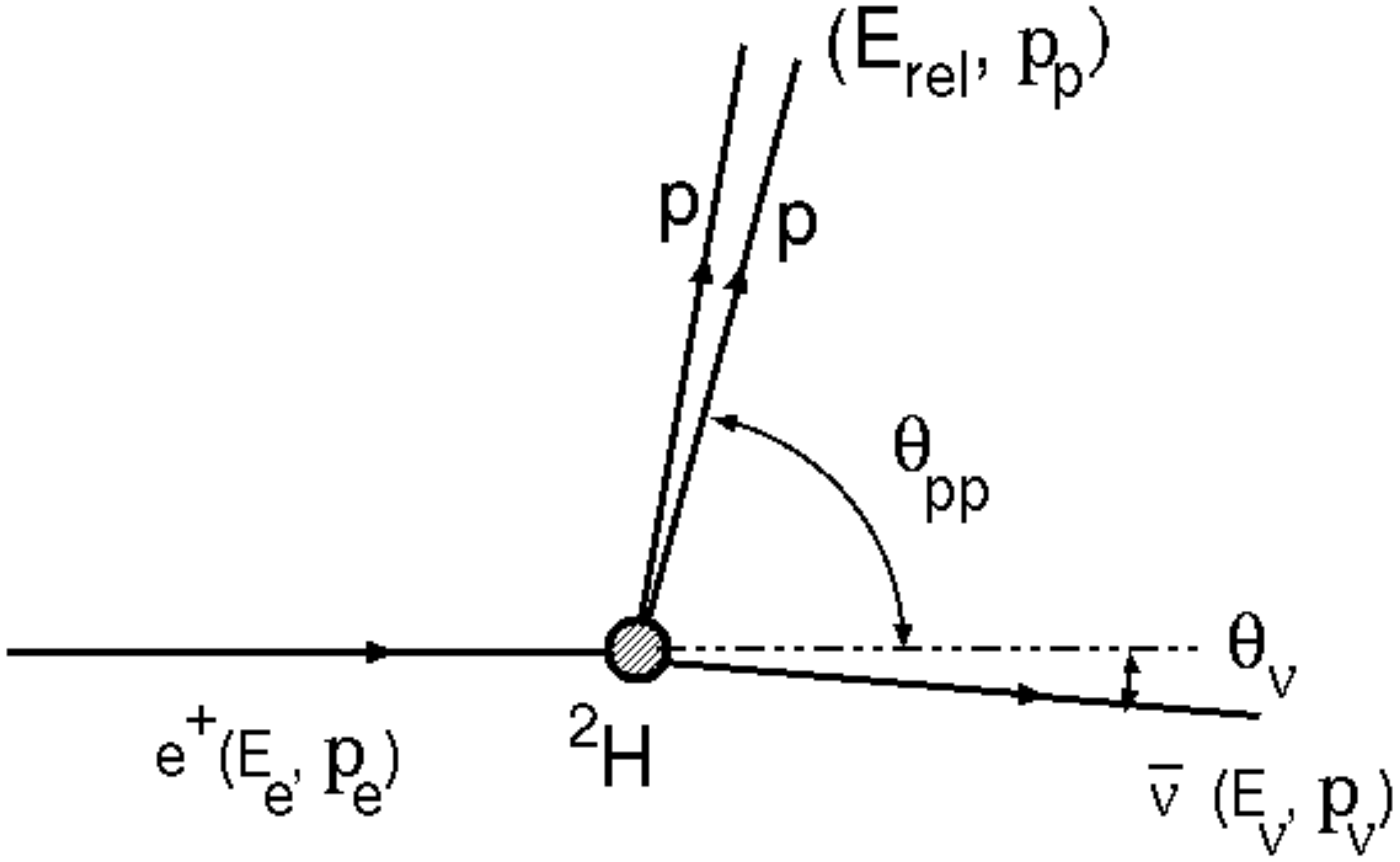
Current knowledge of the weak axial current is ripe for a new experimental technique with completely different systematics

T. Cai et al., Nature 614, 48–53 (2023)

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

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



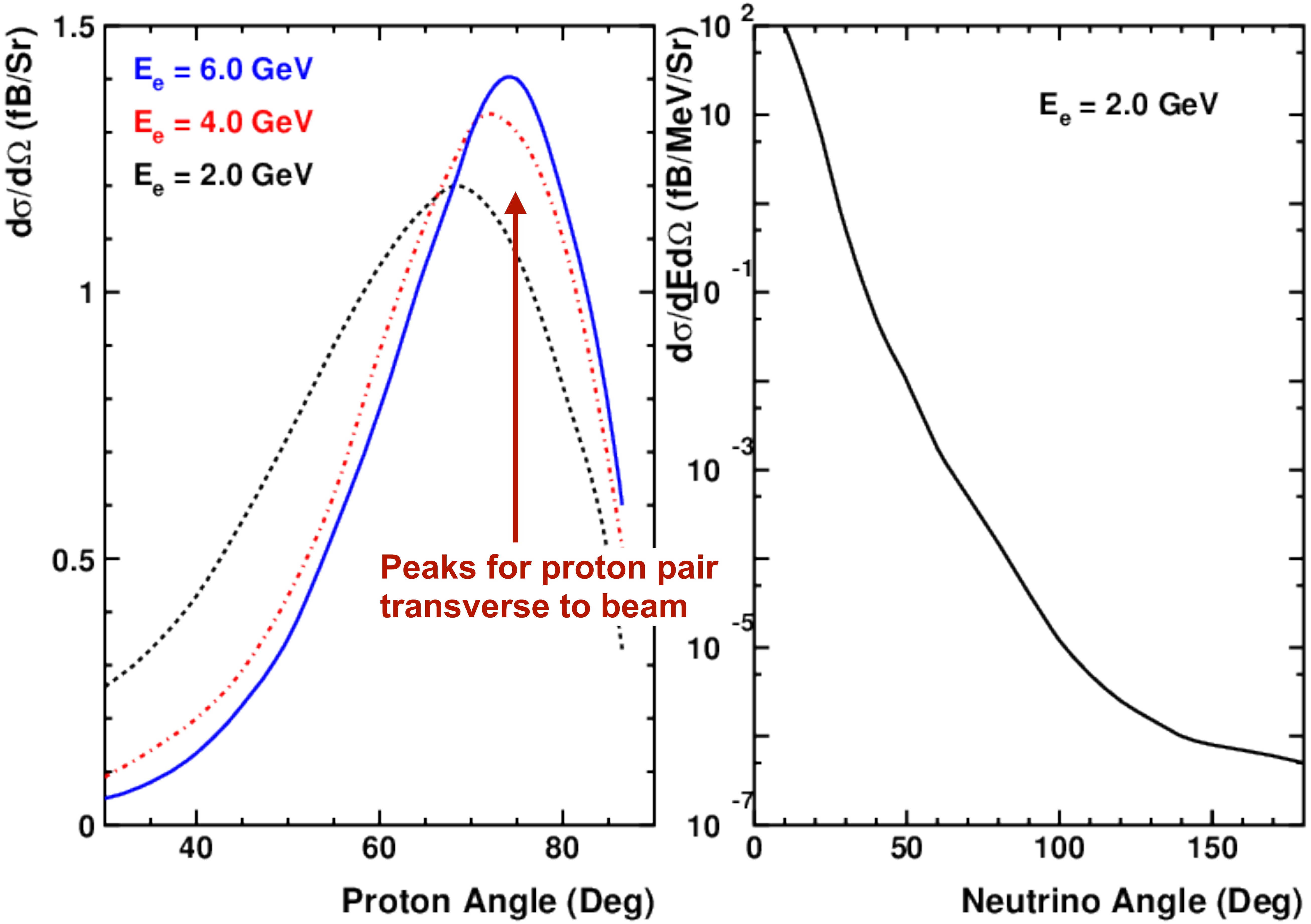


Cross section for right-handed positrons is strictly zero

Cross section increases with beam energy/Q^2

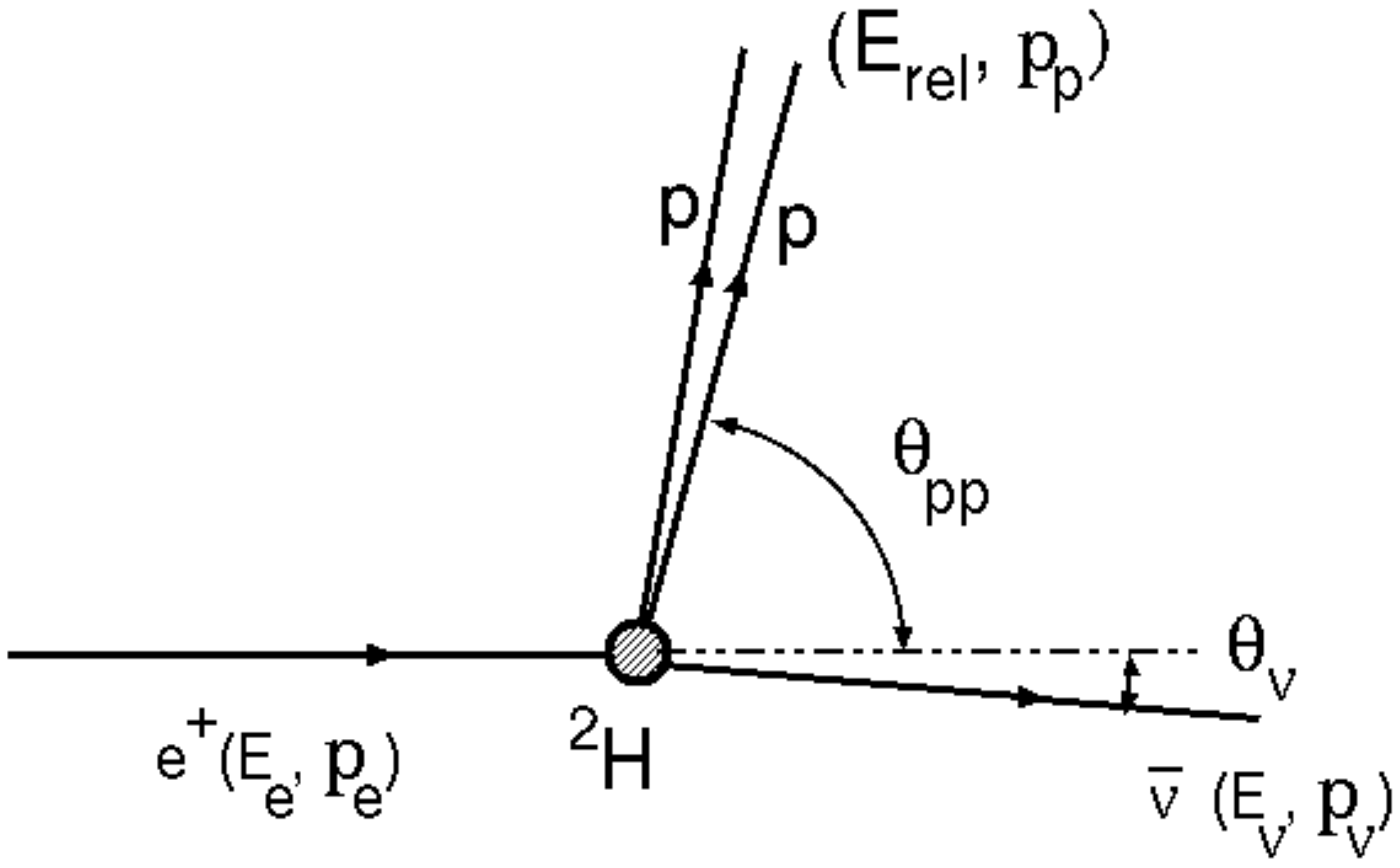
The cross section for 2-6 GeV positrons was calculated as part of early design possibilities for CEBAF

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 E_{beam}

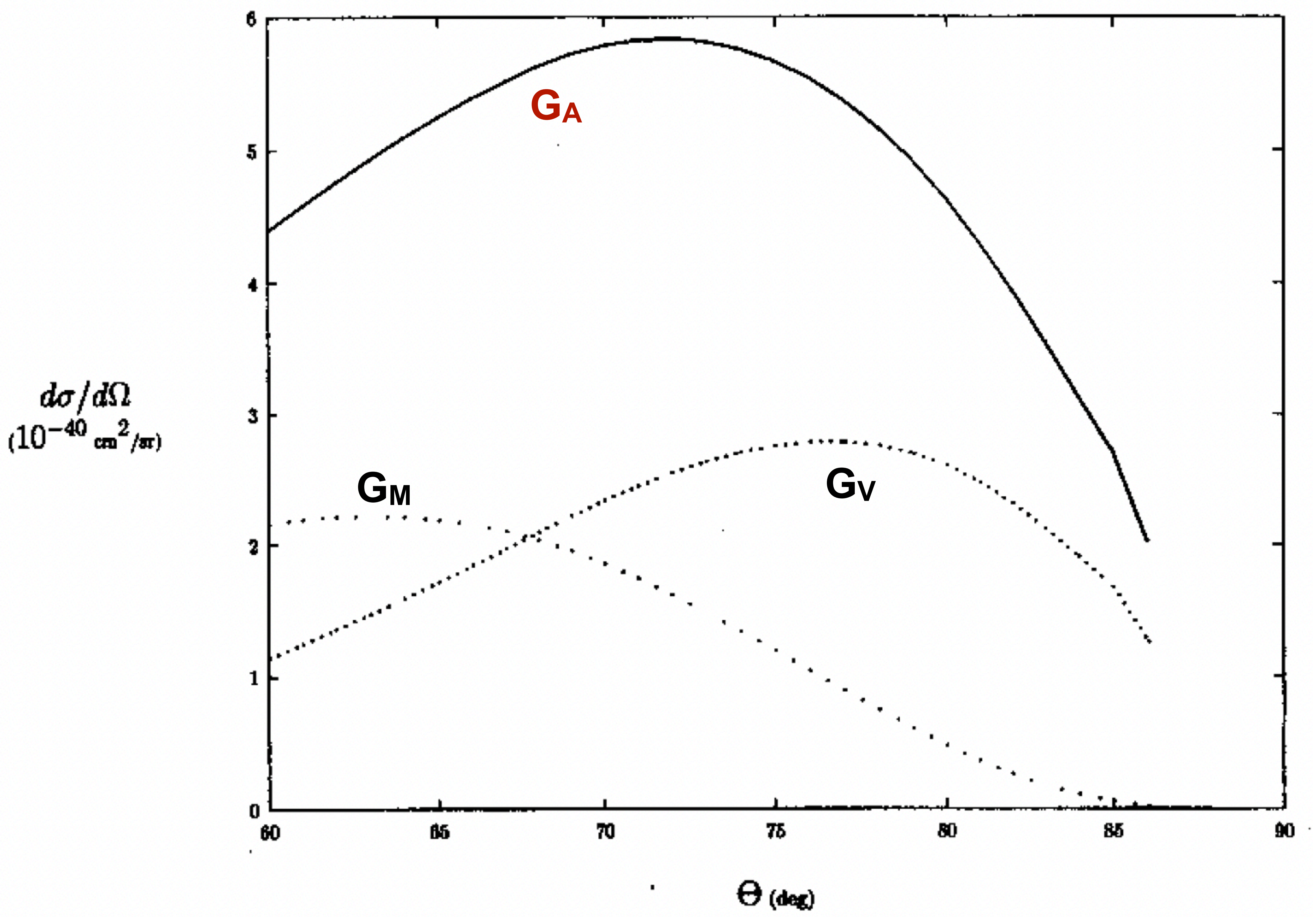


W.-Y. P. Hwang, Phys. Rev. C33, 1370 (1986)
Mintz et al., Int. J Mod. Phy. E6, 111 (1996)

Cross section for right-handed positrons is strictly zero

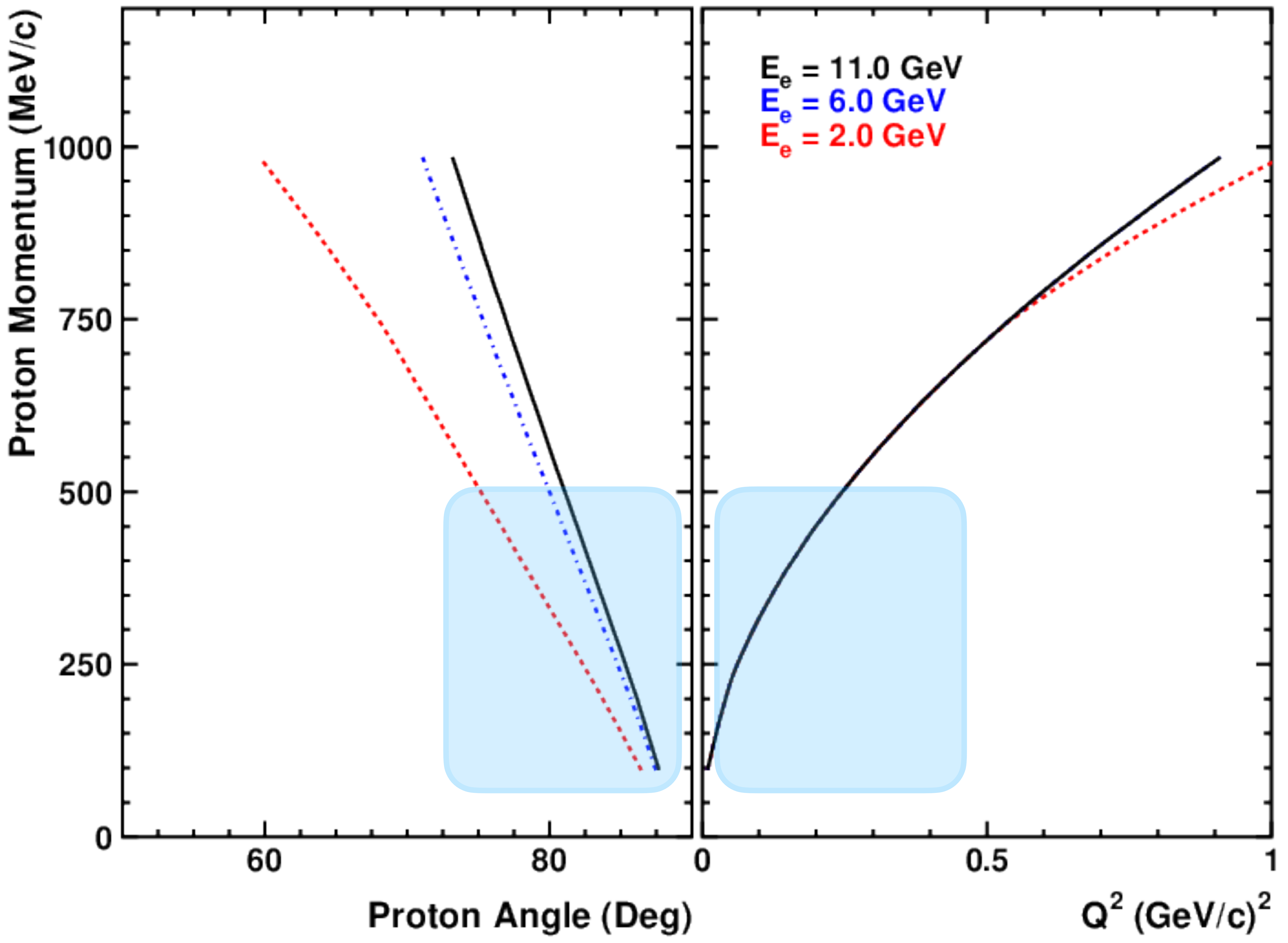
The cross section is dominated by the Axial form factor

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



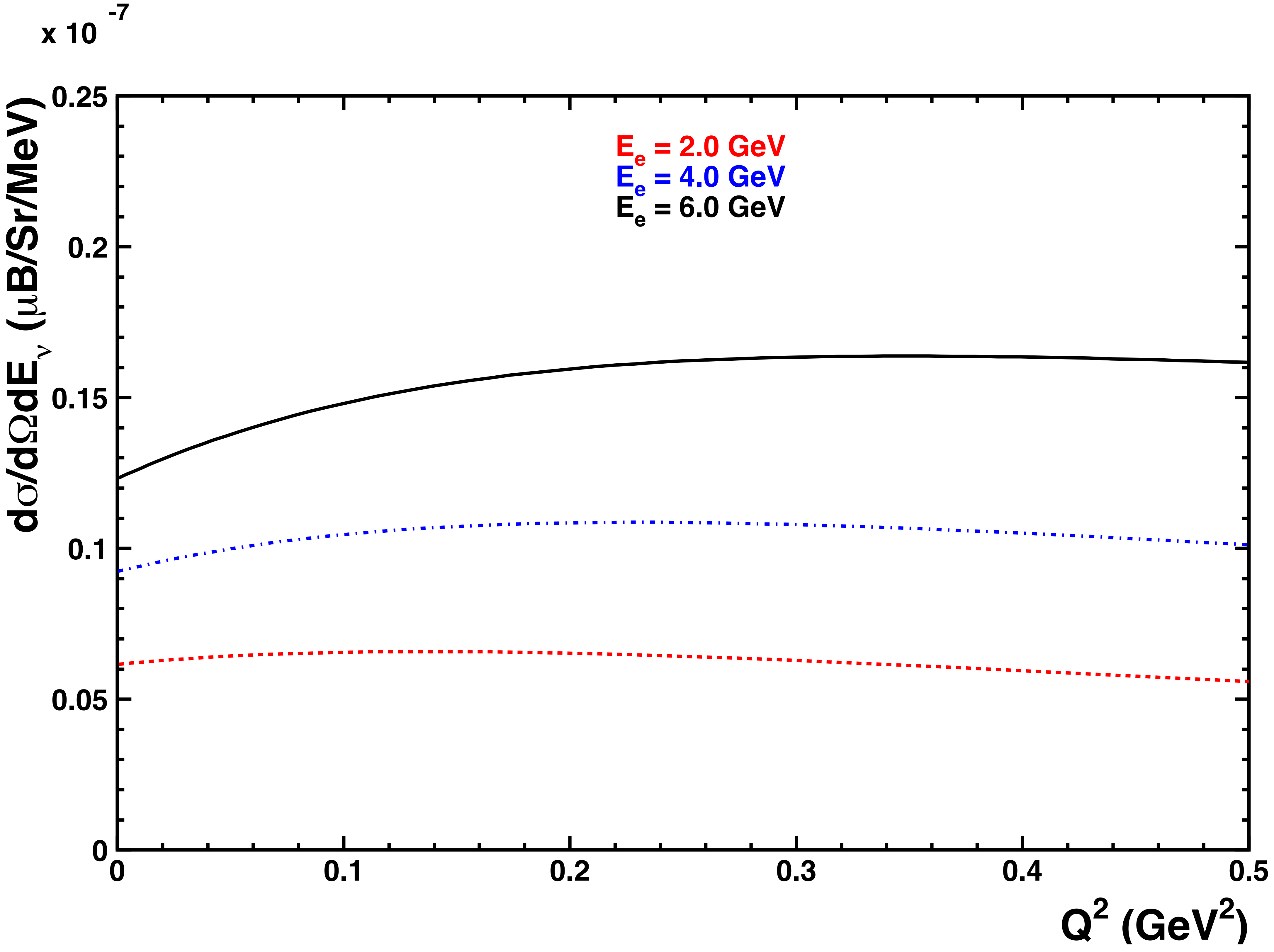
G_V, G_M well known from electron scattering

0.1 - 0.5 GeV/c proton pairs @ 70 - 90 deg :
Q^2 = 0.01 - 0.5 GeV^2

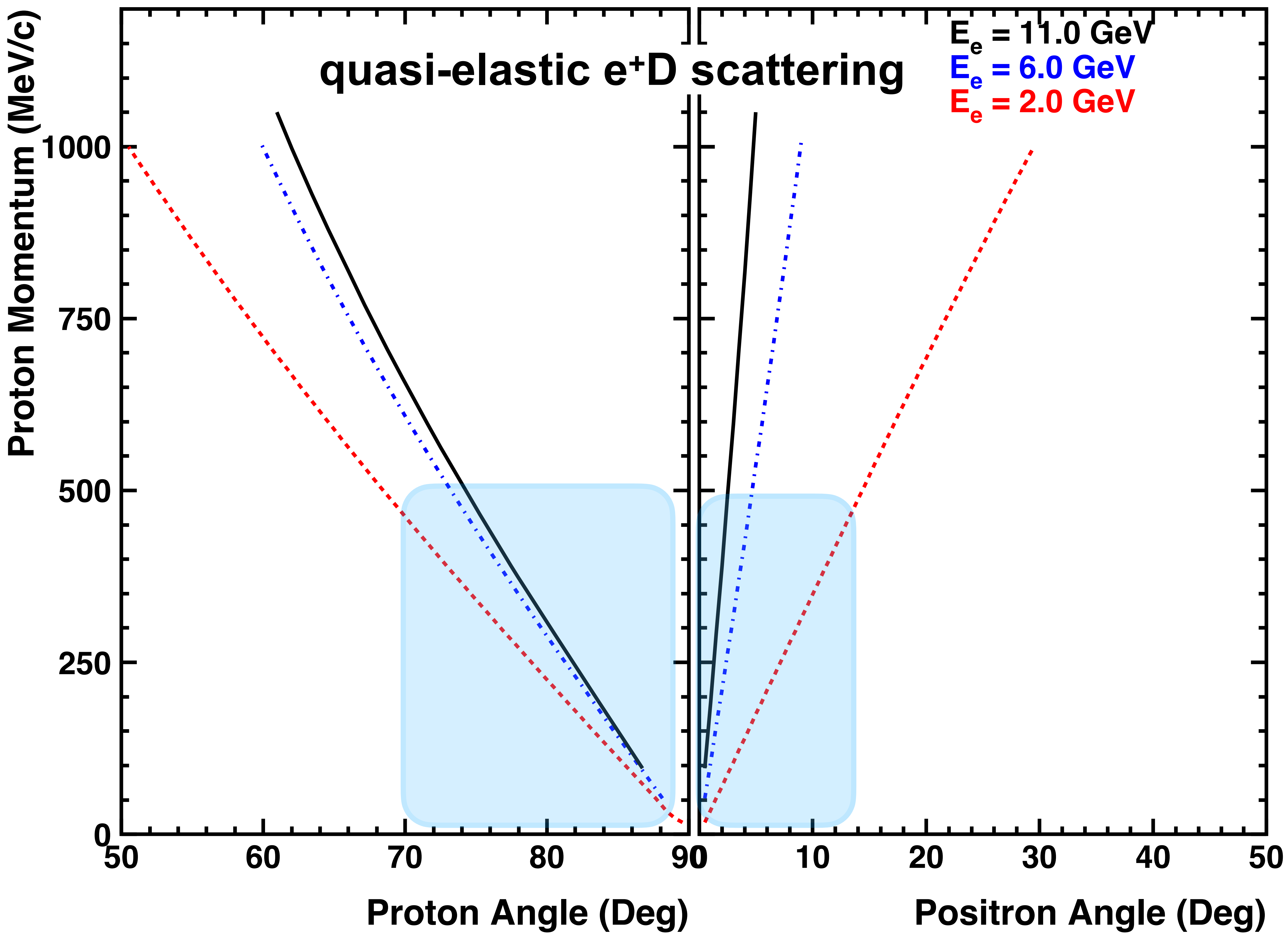


Although cross section increases with beam energy, 2 - 6 GeV is ideal for background suppression.

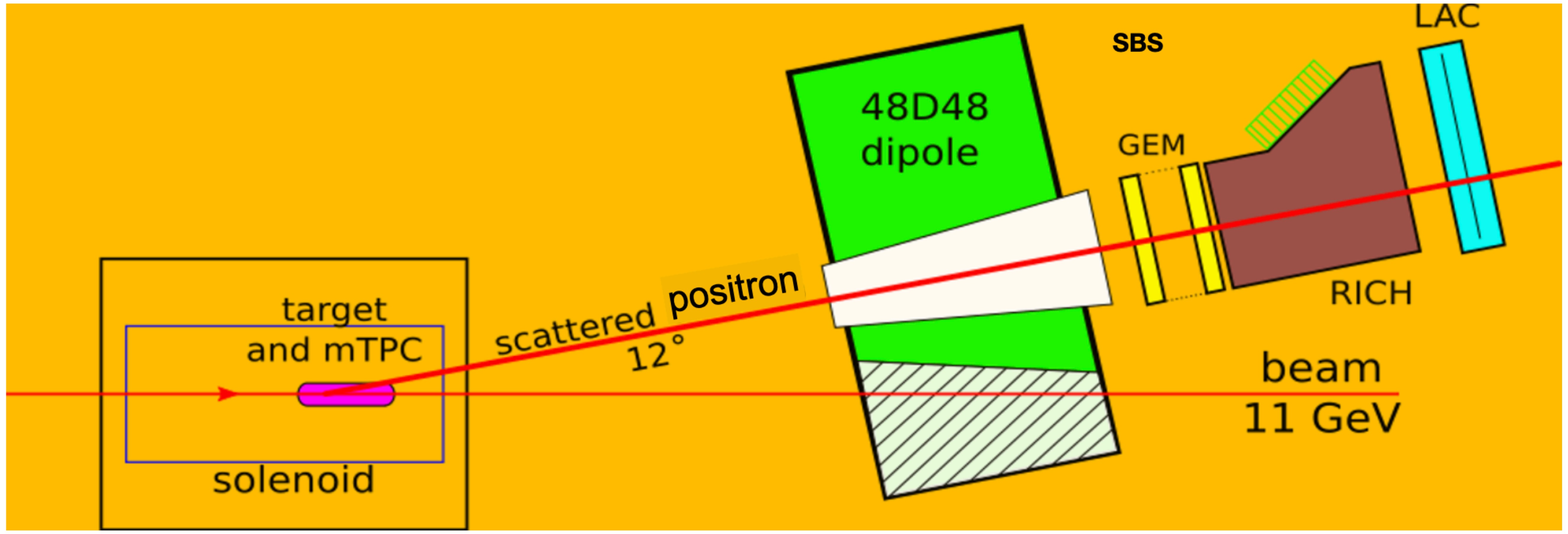
Cross section about flat with Q^2

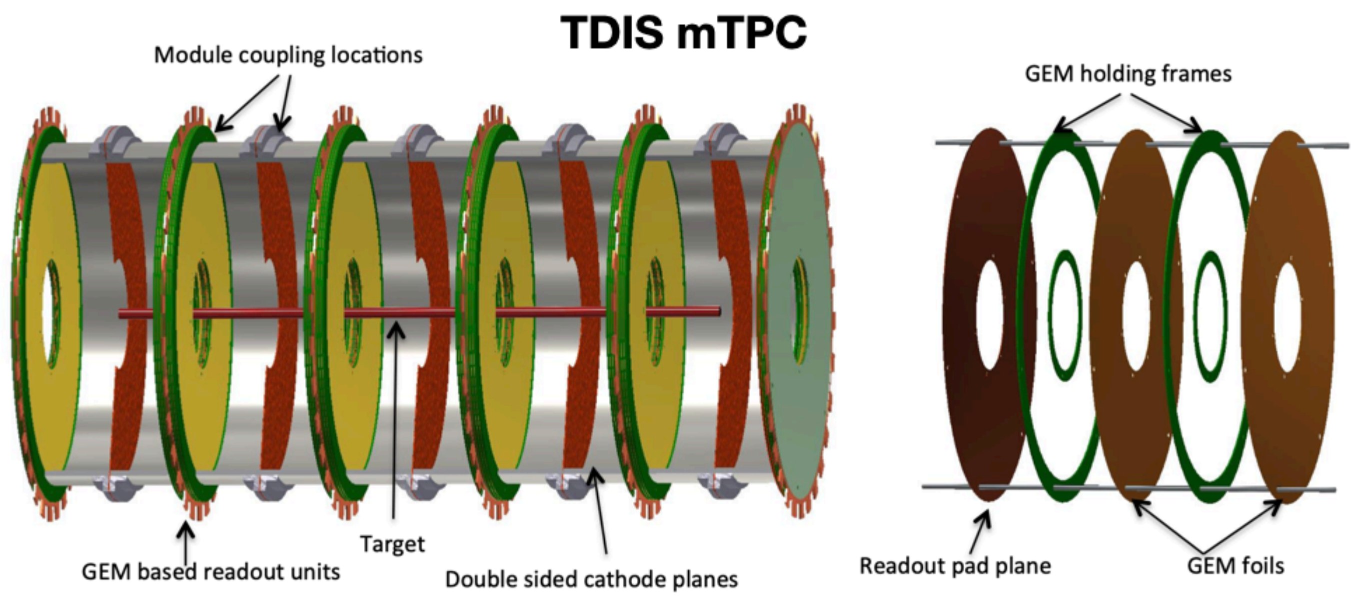


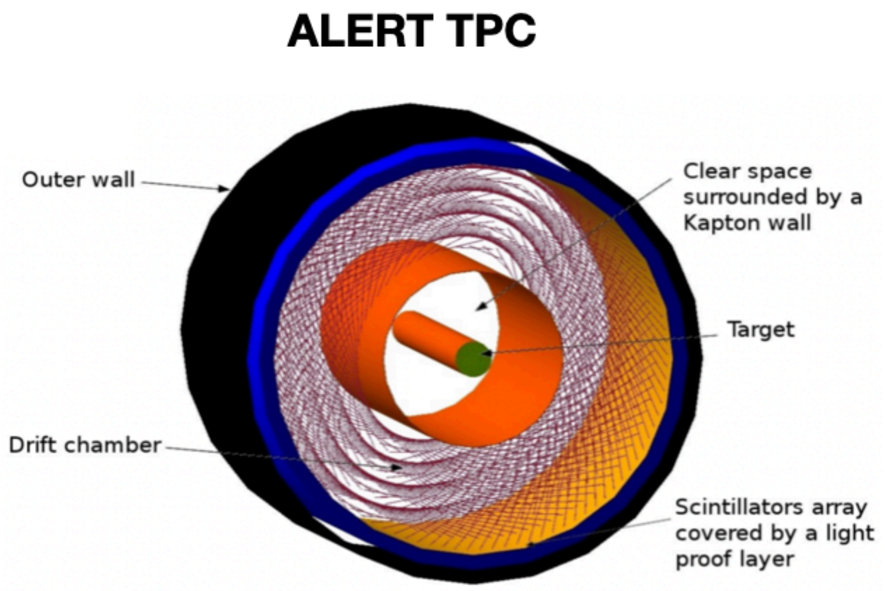
At higher beam energies the scattered positron from the main background process is < 5 deg. Need to detect positrons to veto the quasi-elastic e^+D scattering.

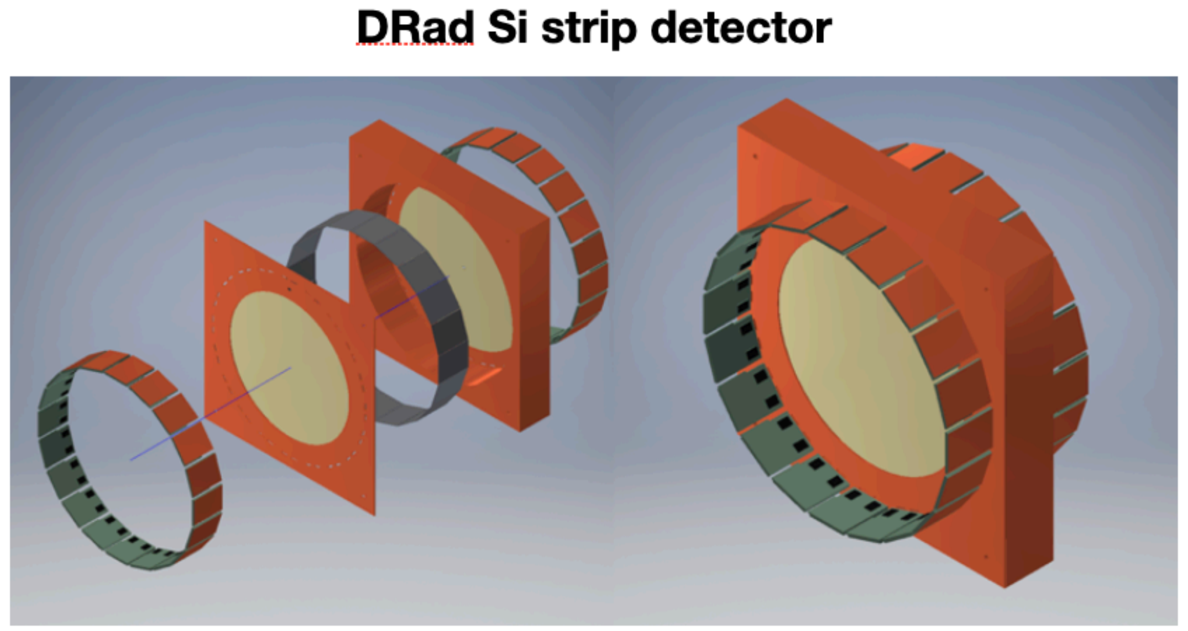


Experiment would need a recoil detector for the proton pair operated in anti-coincidence with scattered positrons









0.1 - 0.5 GeV/c proton pairs @ 70 - 90 deg : Q^2 = 0.01 - 0.5 GeV^2

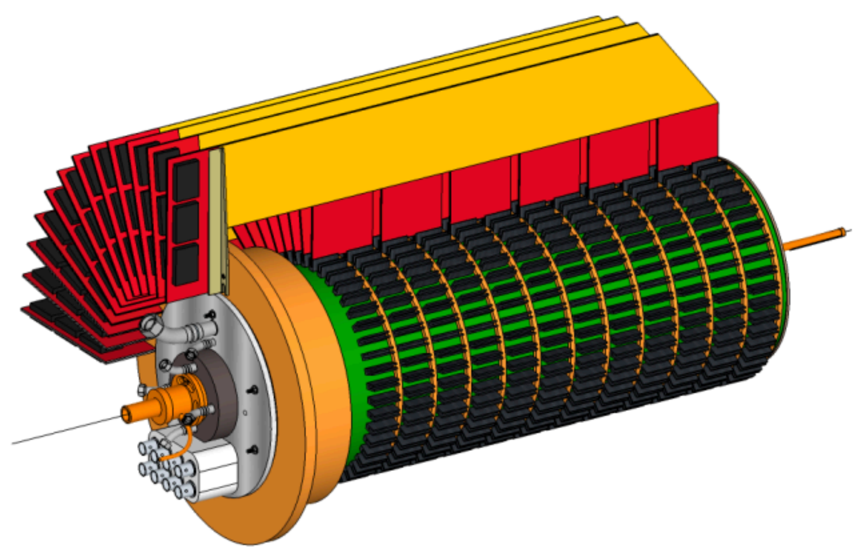
The quasi-elastic scattered positrons have to be detected in time and vertex anti-coincidence with the proton pair.

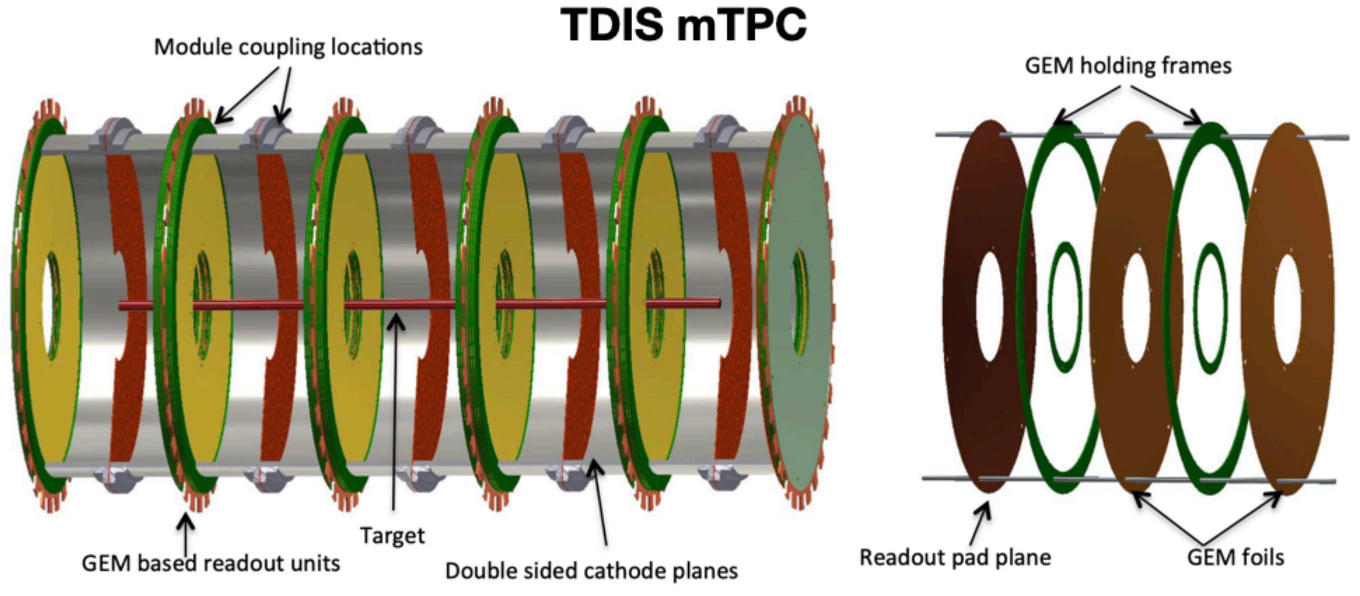
Needs a recoil detector and a small angle positron spectrometer/detector

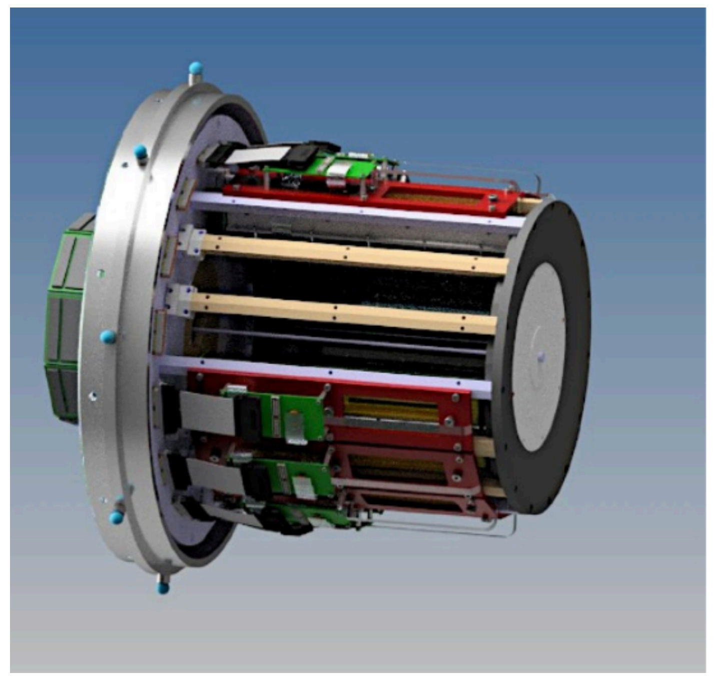
Solenoid around the target will control the load from Bhabha scattering.

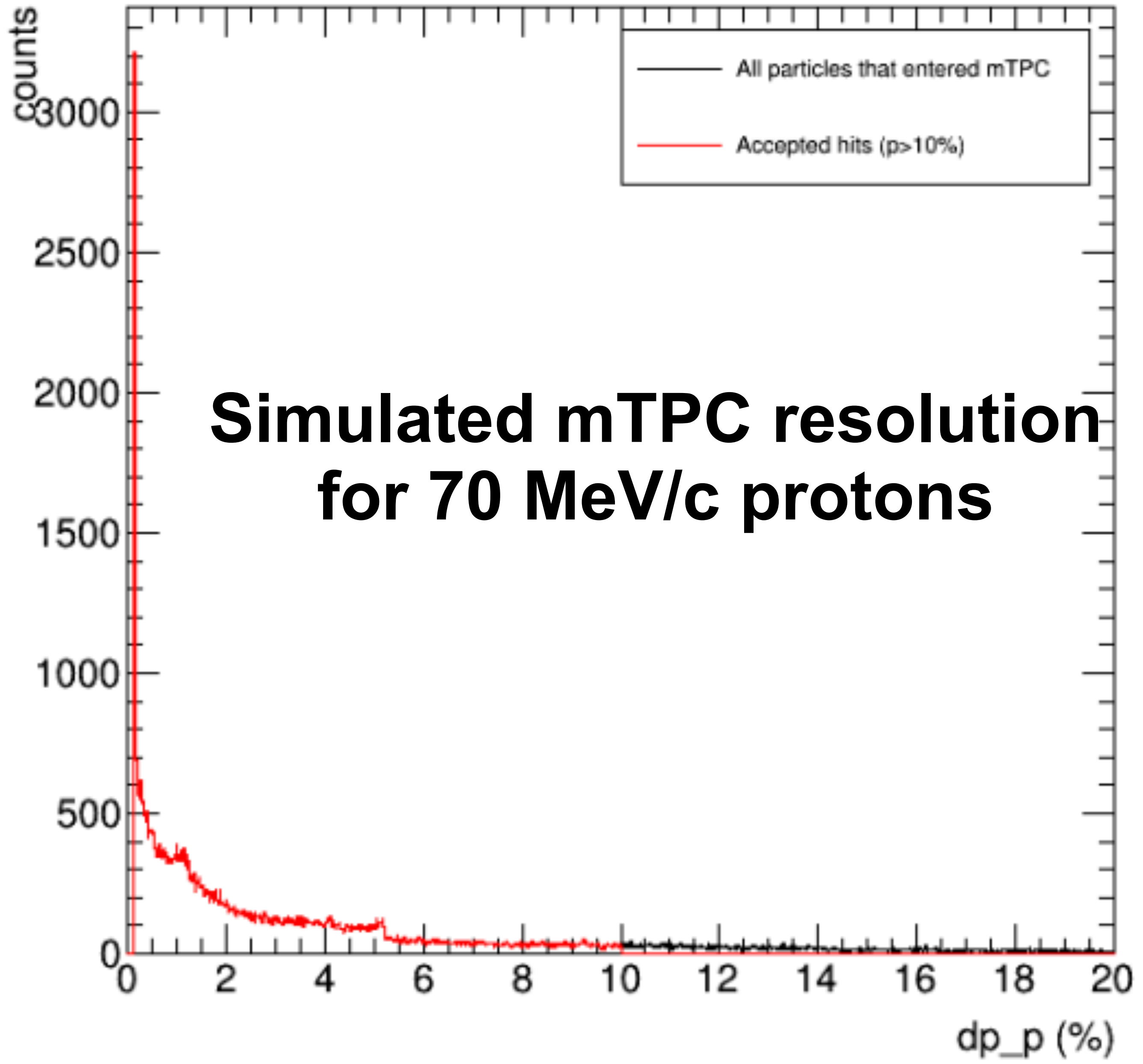
Positron polarization will also be used to distinguish between capture process and background processes. (capture only allowed for left handed positrons)

Several recoil detector already built or currently under development fit the bill



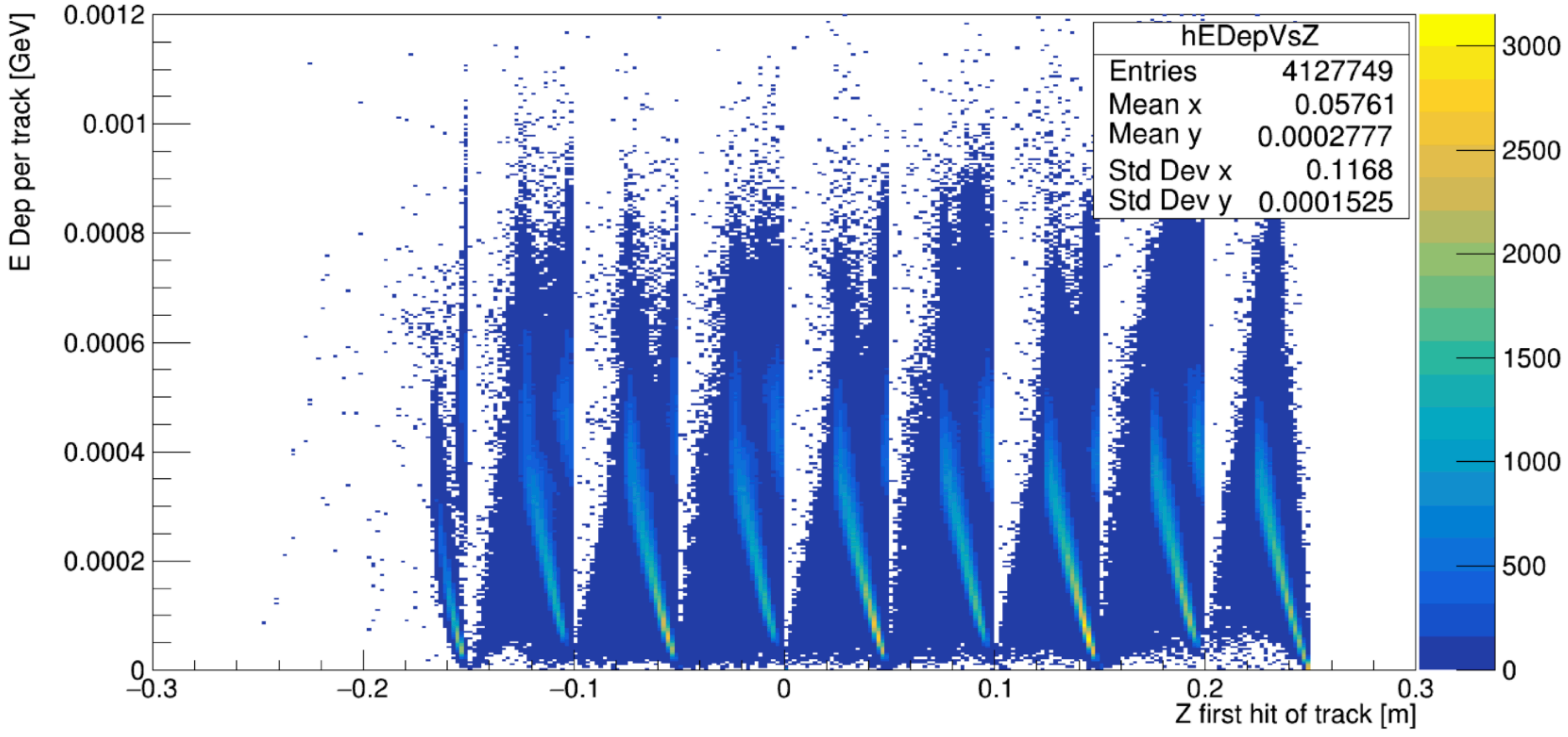






Detector property	RTPC	mTPC	ALERT
Length	40 cm	40 cm	35 cm
Momentum range	70 - 250 MeV/c	70 - 500 MeV/c	70 - 250 MeV/c
azimuthal coverage	360 deg	360 deg	340 deg
Momentum resolution	10% (100 MeV/c p)	0.5% (70 MeV/c p) 5% (400 MeV/c p)	10% (100 MeV/c p)
z resolution	3 mm	1 mm	3 mm

Simulated 70 MeV/c protons in mTPC



$\Delta Q^2 / Q^2 \propto 2\Delta p/p \sim 1\% - 10\%$

Quasi-elastic knockout of protons in accidental coincidence is the largest background to the capture process.

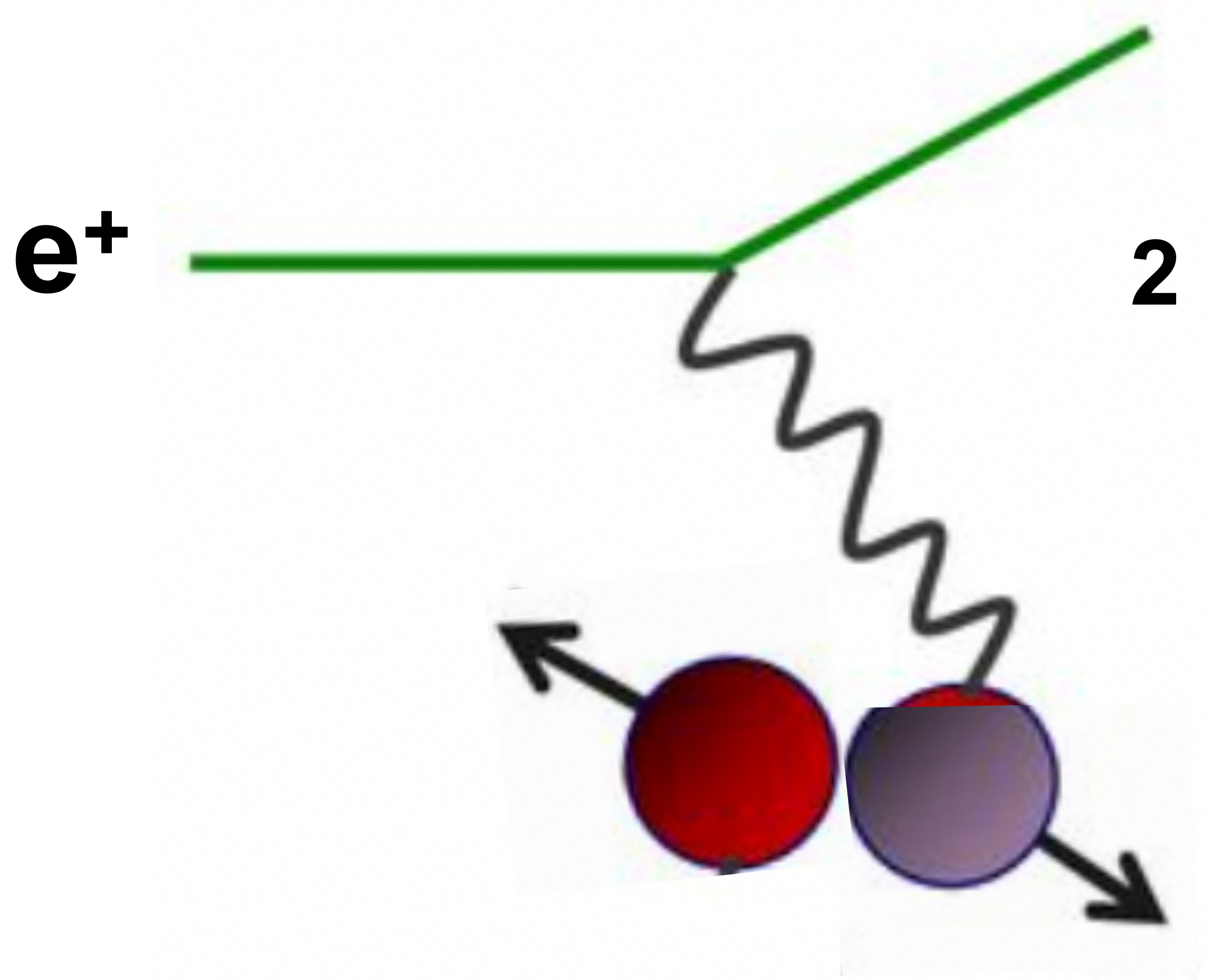
Beam & Target: 4 GeV polarized positrons (60% polarization), 200 nA current on 40 cm, 6 atm. ^{2}H target = a luminosity of $8\text{x}10^{34}$ cm^{-2}/s

proton pair detection: 2π azimuthal coverage, 10 deg polar angle bin, 100 MeV/c proton momentum bin ⇒ 30 MeV ν energy bin

capture cross section
~ 1.0 $\text{x}10^{-9}$ μB/sr/MeV

positron capture (signal) count rates of ~3 $\text{x}10^{-2}$ /s

QE scattering cross section is ~1.0 μB/sr (10^9 larger)



2 proton accidental coincidence rate [$3\text{x}10^7$ x $3\text{x}10^7$ x 20 ns x (2.5 σ_z/L) x (2.5 σ_z/L)]

coincidence window — 2 mm — 400 mm

~2800 /s

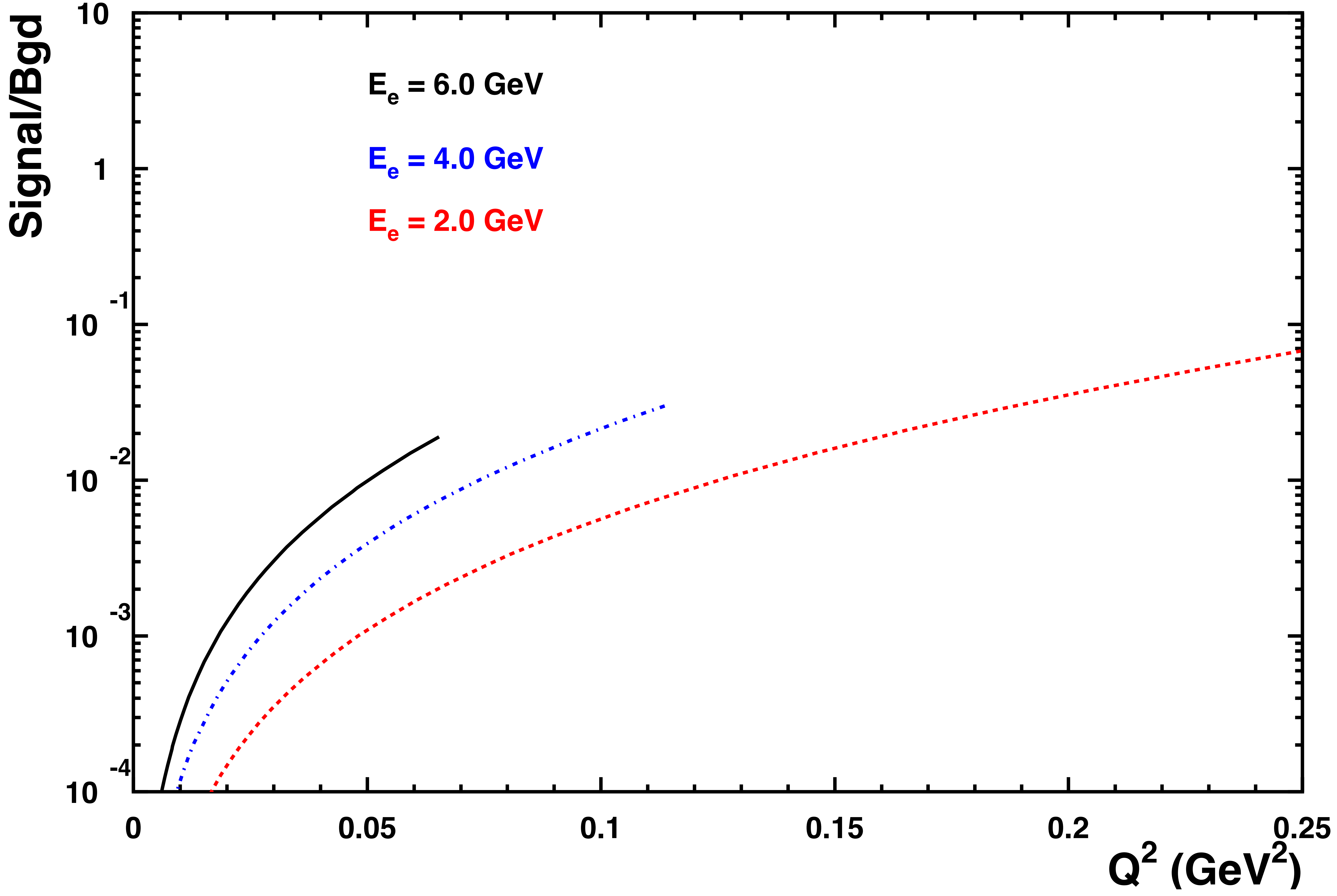
using positrons in vertex and time anti-coincidence with 99.9% efficiency background rates would be ~3 /s

proton knockout
+
accidental 2 proton
coincidence

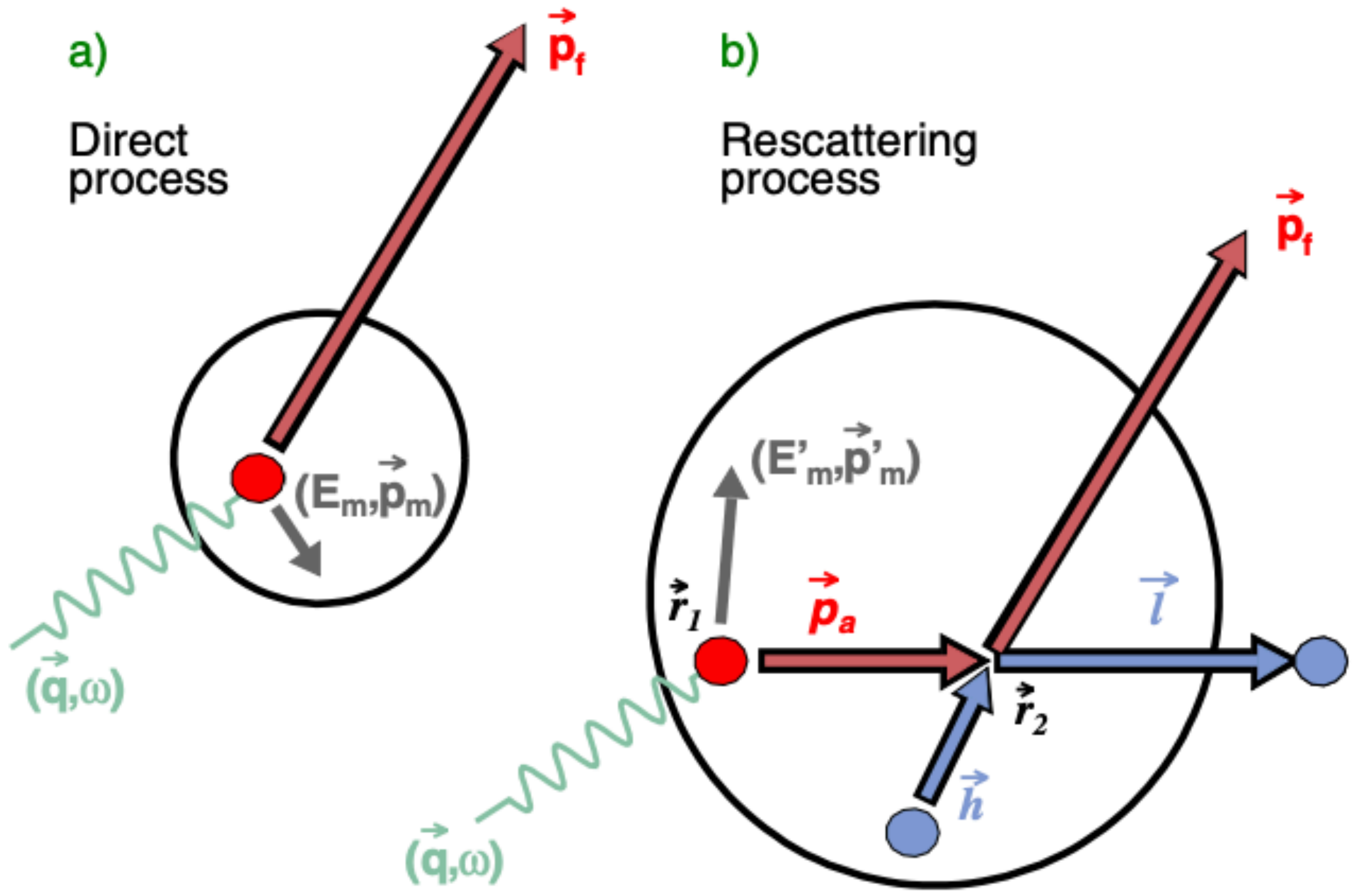
gives S/B ~ 10^{-2}

A few beam energies are needed to cover a range of Q^2

Beam & Target: 4 GeV polarized positrons (60% polarization), 200 nA current on 40 cm, 6 atm. ^2H target = a luminosity of $8x10^{34}$ cm^{-2}/s



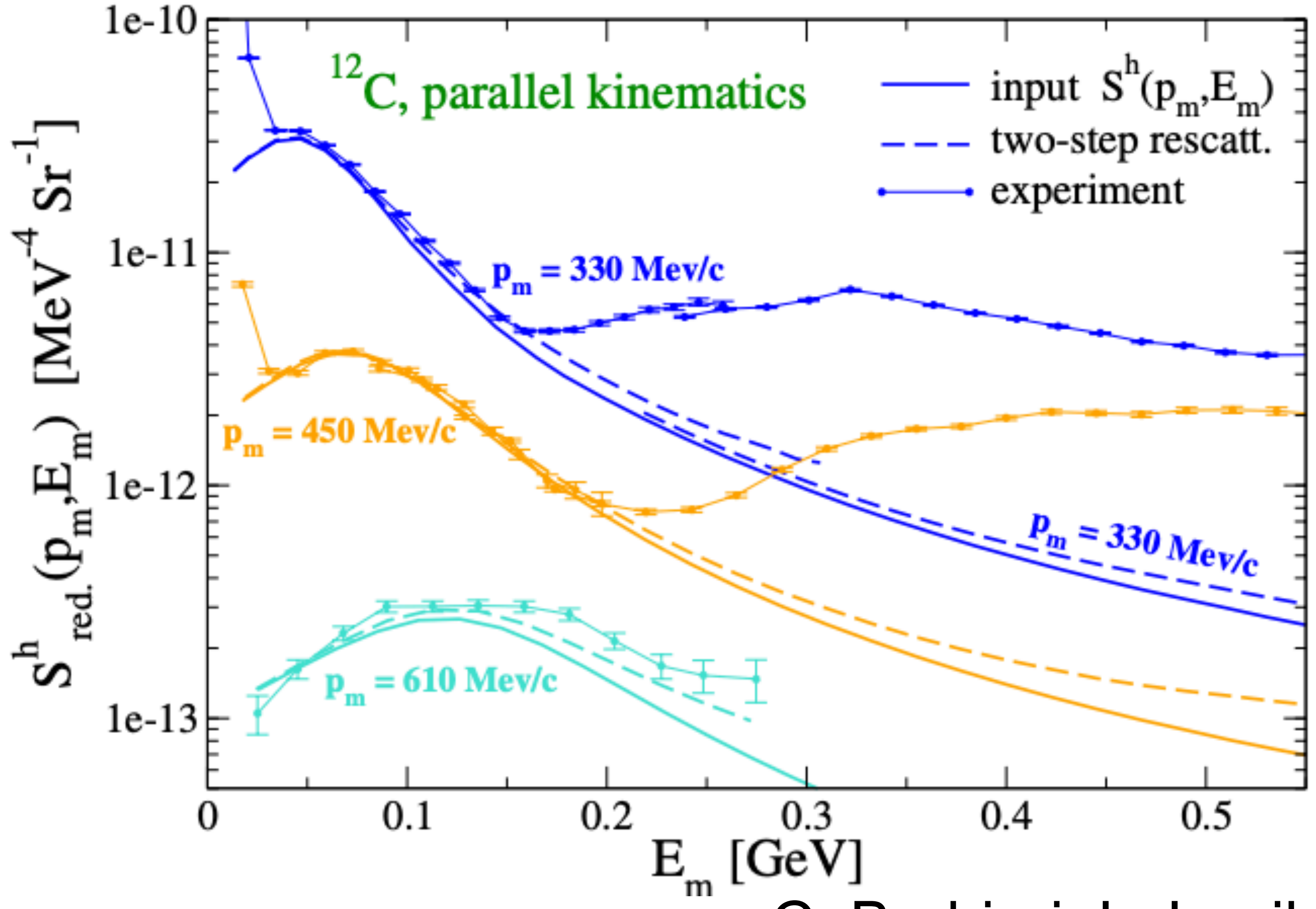
Quasi-elastic knockout of neutron followed by a charge exchange re-scattering, is another background to the capture process.



In parallel kinematics (along the q-vector), rescattering cross sections are at least one order of magnitude lower than the direct process.

2 proton accidental coincidence rate [$3\times10^7 \times 3\times10^6 \times 20$ ns $\times (2.5\,\sigma_z/L) \times (2.5\,\sigma_z/L)$]

< 280 /s — coincidence window: 20 ns; σ_z: 2 mm; L: 400 mm



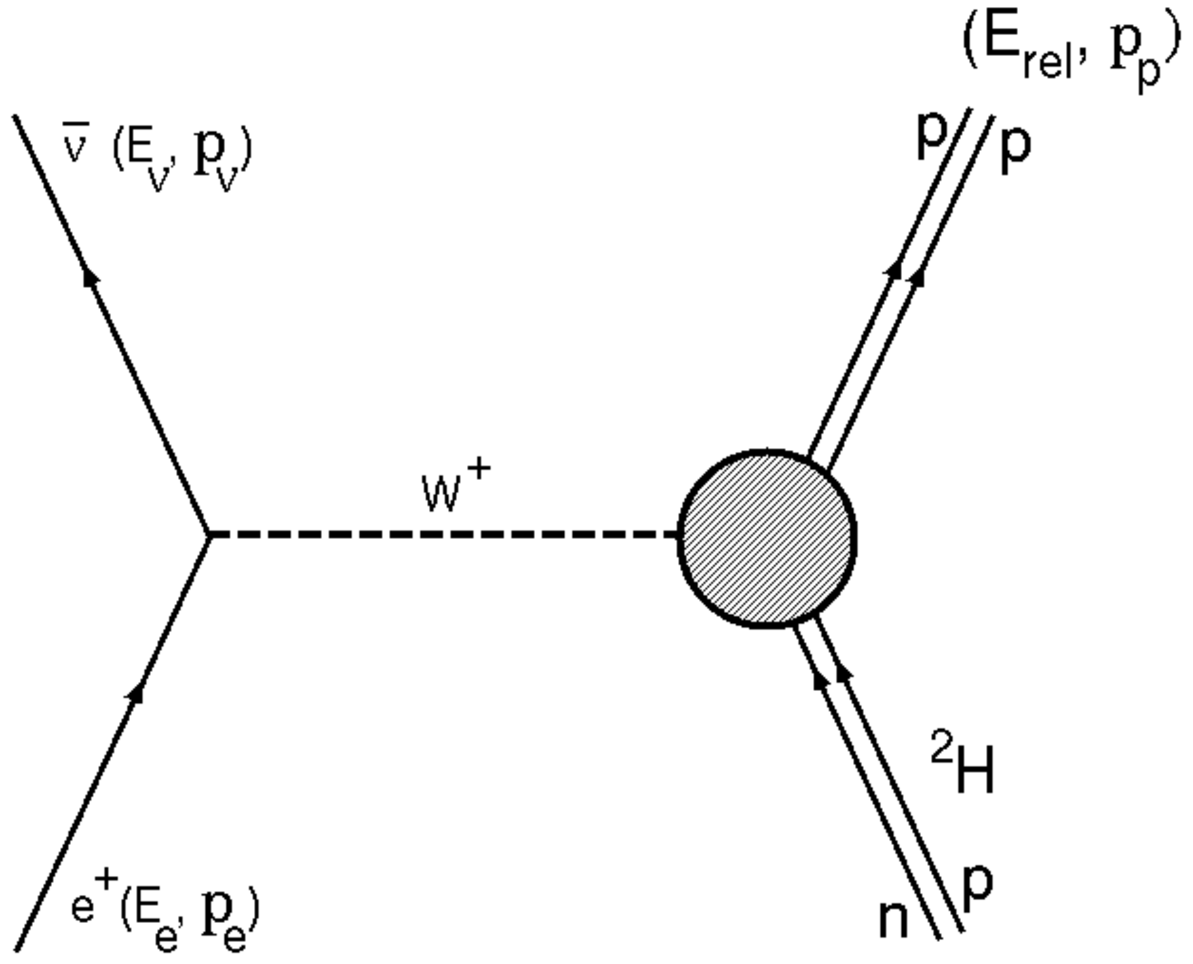
using positrons in vertex and time anti-coincidence with 99.9% efficiency background rates would be < 0.3 /s

gives S/B > 10^{-1}

C. Barbieri, L. Lapikás, D. Rohe, Two step rescattering in (e,e'p) reactions, EPJA 24, 85 (2005).

The capture process occurs only for left-handed positrons, providing another handle for isolating the signal

$(\vec{e}^{+} + {}^{2}H \rightarrow p + p + \nu_e)$



$N+ = N^{+}_{s} + N^{+}_{bgd}$; $N- = 0 + N^{-}_{bgd}$; $P_b = 0.6$

$$N+ - N- = P_b\,(N_s + 2\langle N_{bgd}\rangle A_{bgd})$$

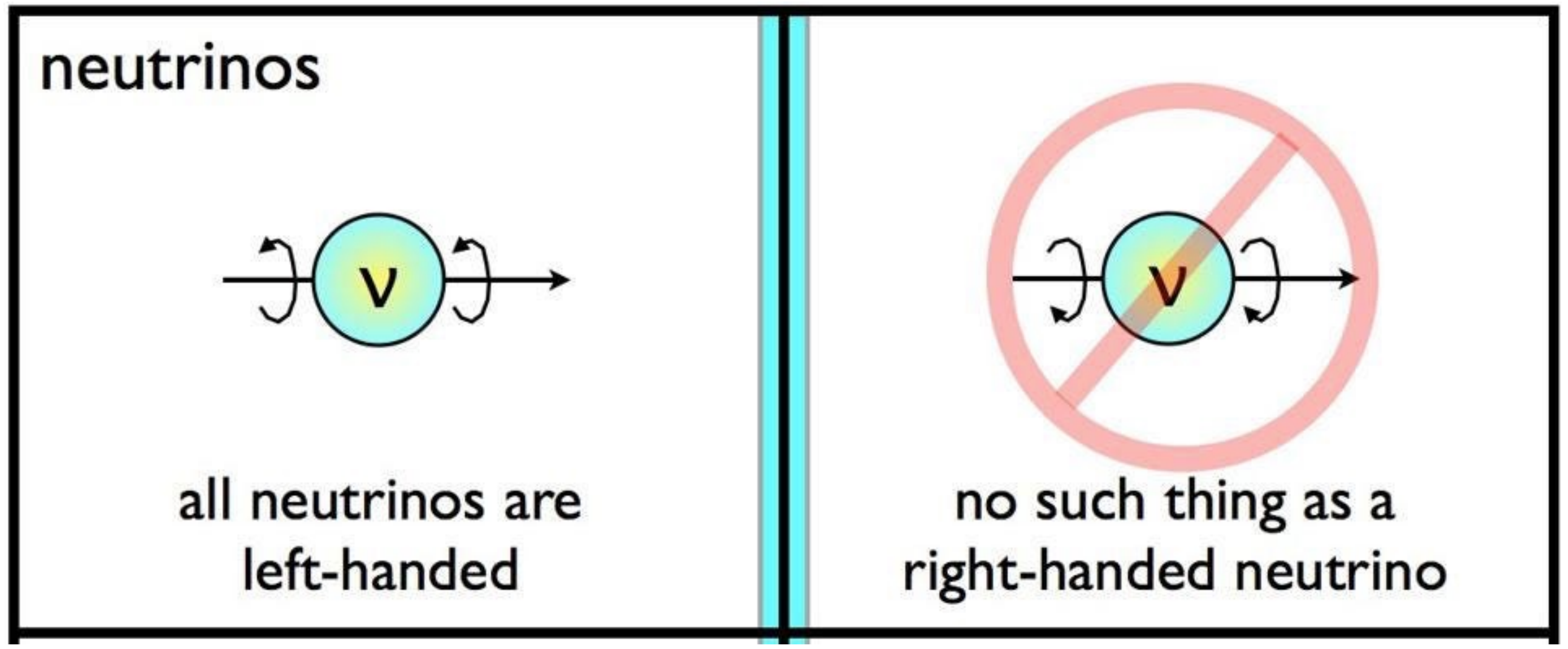
$A_{bgd} = 0 \pm$ stat.

$$A_{meas} = P_b\left(\frac{N_s}{2\langle N_{bgd}\rangle} + A_{bgd}\right)$$

Can be measured with very high statistics (300 ppm/hr) (without positron veto)

$A_{capture}$ ~0.7%

$\Delta A \approx 1/\sqrt{2N_{bgd}}$

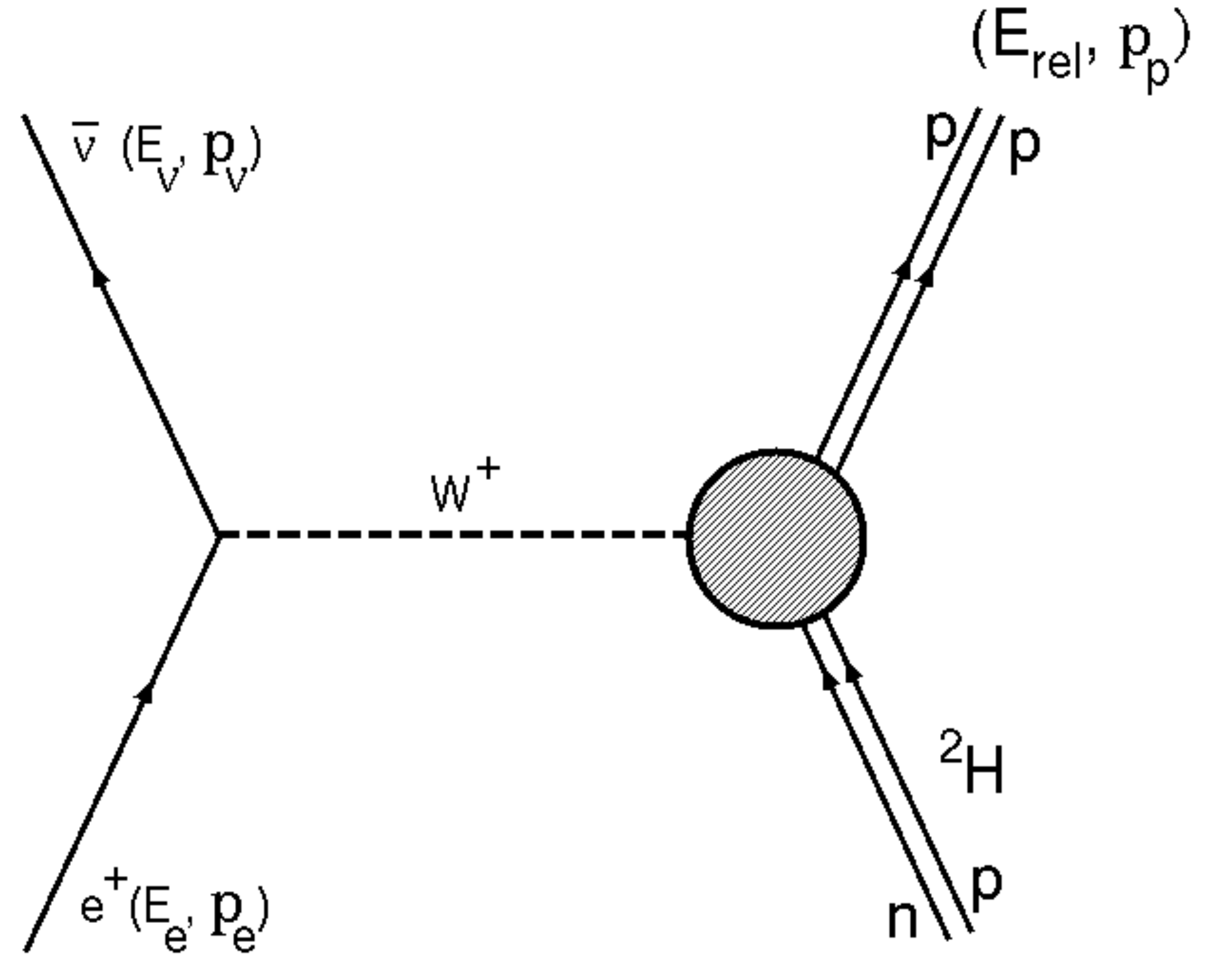


The asymmetry can be measured with 3% stat. uncertainty using 20 days of beam time.

To perform the measurement at 3 different beam energies (2, 4, 6 GeV) we need ~60 days beam time

Highest beam polarization available is desired to control systematic uncertainties

$(\vec{e}^{+} + {}^{2}H \rightarrow p + p + \nu_e)$



$$A_{capture} = \frac{A_{meas}/P_b - f^{*}A_{bgd}}{1 - f}$$

The EM background is large and polarization is a means for suppressing this large background.

Additional beam time for P_b lower than 0.6 is $(1-P_b)/0.4$

S/B ~ 1/current and ΔA ~ 1/current

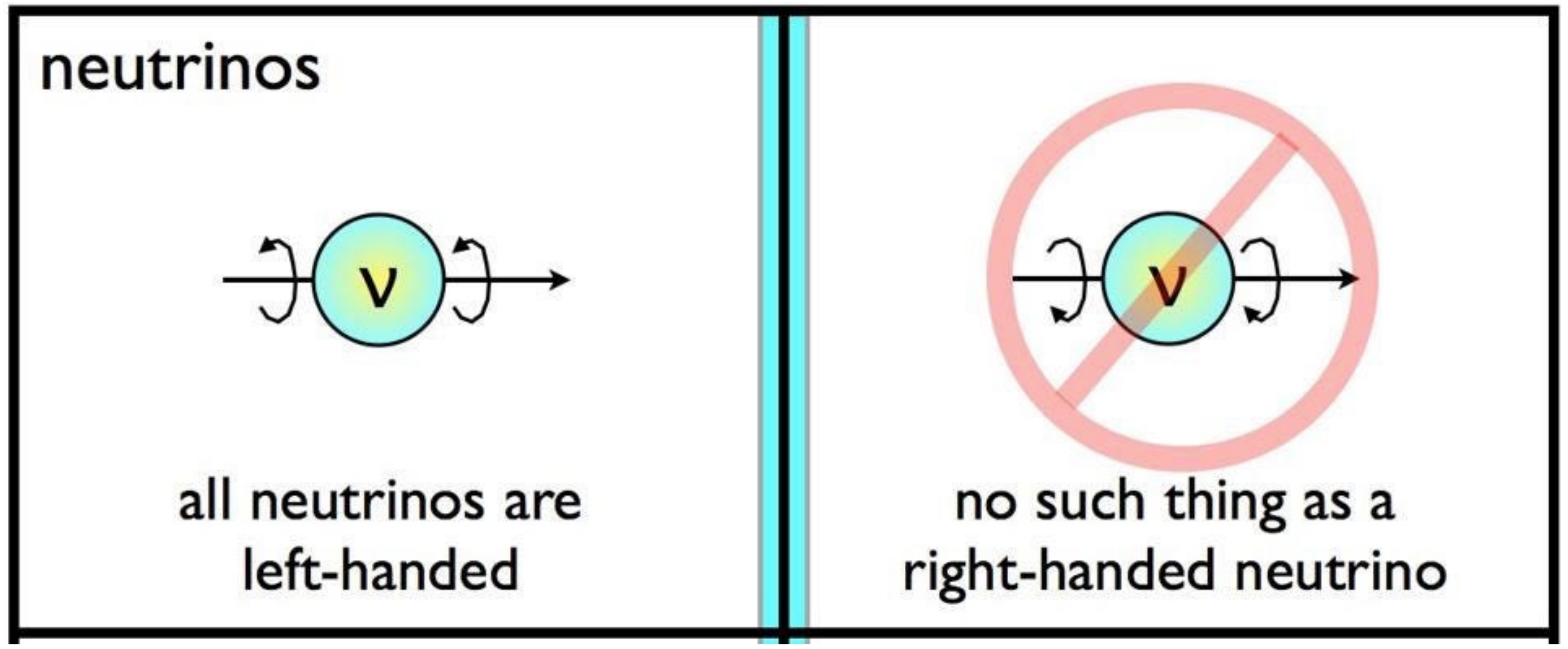
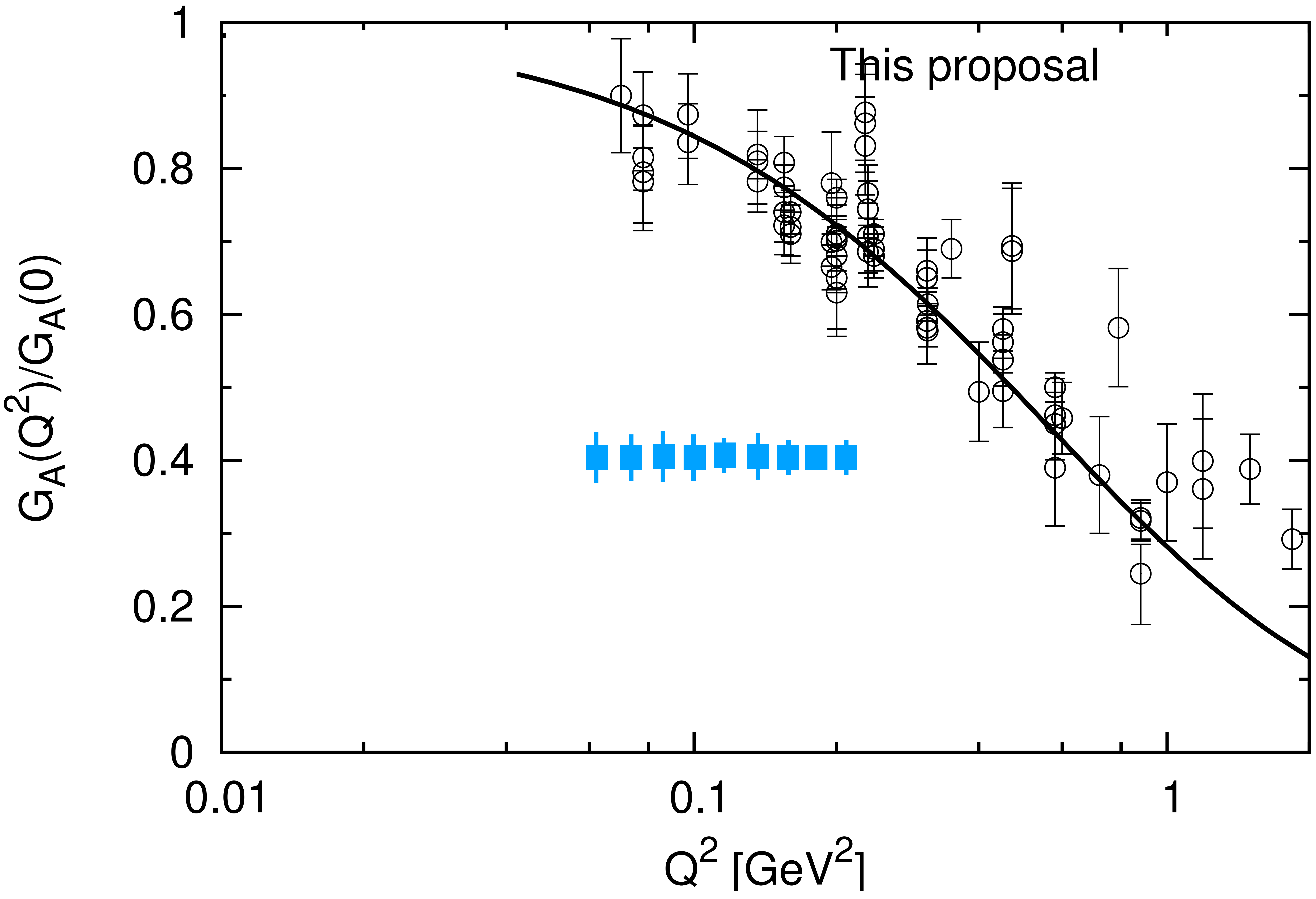


Figure of merit for the asymmetry does not improve with lowering polarization for higher current.

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 <r_A>^{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 $\langle r_A \rangle^2$.

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.