Using polarization observables to study medium modifications

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Introduction

Polarization can likely play an interesting role in studying nucleon modification.

Polarization transfer measurements to look for modified nucleon form factors.

Flavor dependence of the EMC effect from parity violating DIS on ^{48}Ca

Direct measurement of the polarized-EMC effect.

1. Spin is not conserved, only angular momentum is.
2. Very few nucleons cary spin so the effect is diluted. But then we can study a single nucleon with potentially known wave-function.
3. Experiments with polarized nuclei are difficult.

GDH Sum Rule

Spin-dependent photoproduction cross-sections

spin

$$\int_{\nu_0}^{\infty} (\sigma^{3/2} - \sigma^{1/2}) \frac{\mathrm{d}\nu}{\nu} = 4\pi^2 \alpha S \frac{\kappa^2}{M^2}$$

anomalous magnetic moment

Photon energy

Mass

Fundamental Quantum Field Theory prediction. Applicable to any type of target.

Links the anomalous magnetic moment κ of a particle to its helicity-dependent photoproduction cross-sections

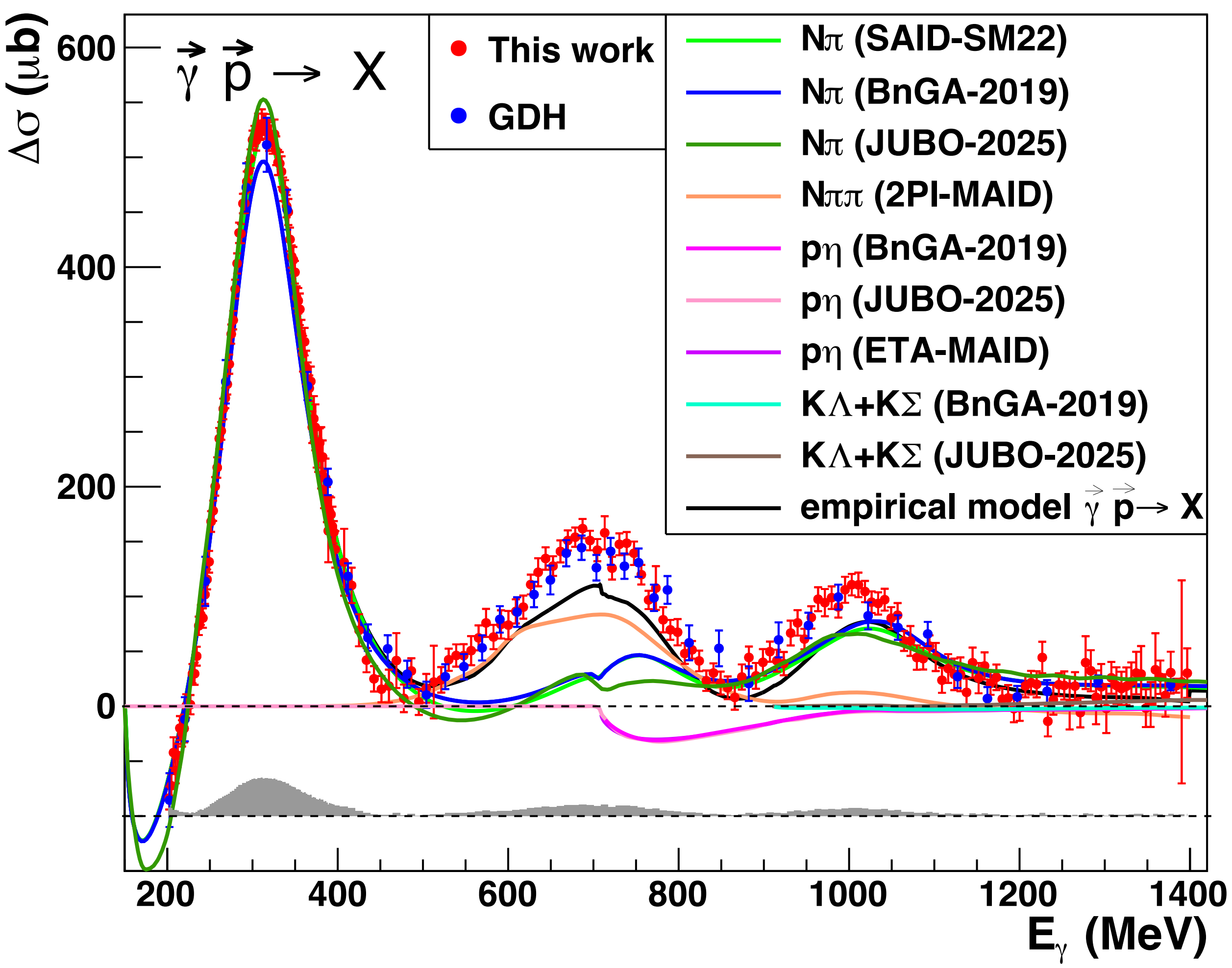
Conditions for the sum rule to be valid:

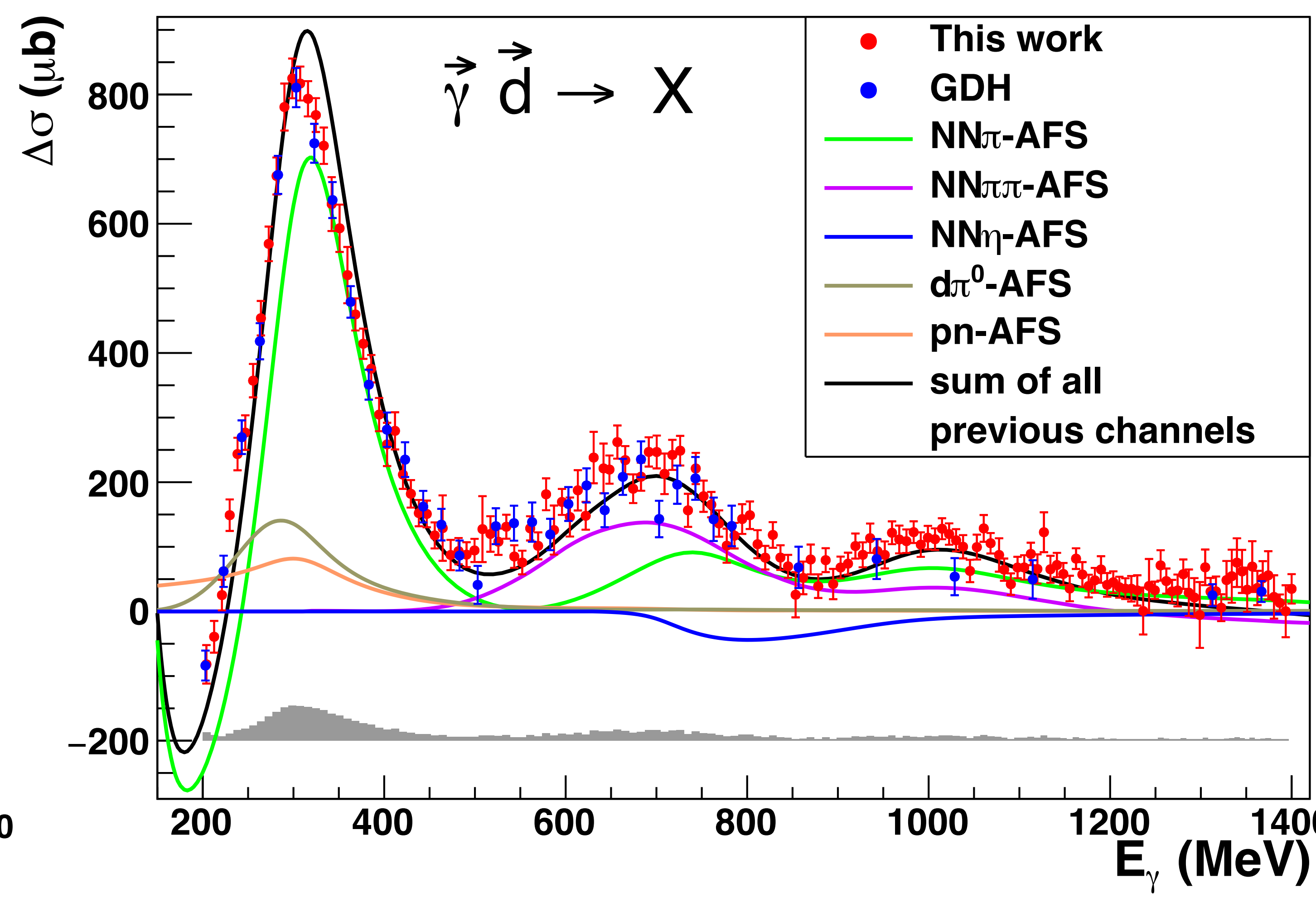
- Spin-dependent forward Compton amplitude f2(v) must vanish at large v (no-subtraction hypothesis).
- Imaginary part of f_2, $(\sigma^{3/2} - \sigma^{1/2})$ must decrease with v faster than ~1/ln(v) (for the integral to converge).

Experimentally verified on the proton to ~10% but not yet for the neutron.

Helicity dependent photoabsorption

Data from MAMI, ELSA and A2 for H and D but almost nothing else.





Threshold ($\nu < 200$ MeV) and very high energy ($\nu > 12$ GeV) regions cannot be measured, need models like MAID/SAID and Regge phenomenology.

https://arxiv.org/abs/2604.14385

REGGE

Real Gamma GDH Experiment

JLab Experiment
E12–20–011

arXiv.2008.11059

Measure the high energy behavior of $\Delta\sigma(\nu)$

Verify **convergence** of integral
  $\Delta\sigma(\nu)$ must decrease faster than $1/\log\nu$

$$\int_{\nu_0}^{\infty} \frac{\Delta\sigma(\nu)}{\nu}\,\mathrm{d}\nu = \frac{4\pi^2 S\alpha\kappa^2}{M^2}$$

Test **validity** of sum rule for
  neutron (first time)
  proton improve by 25% relative

Improve sensitivity to physics that would cause a real (or apparent $\nu \neq \infty$) violation

Failure of sum rule would occur at high energy

Stringent test of Regge theory. Resolve discrepancy in Regge parameter determination

Proton and neutron will allow isospin decomposition

Modification of bound nucleons

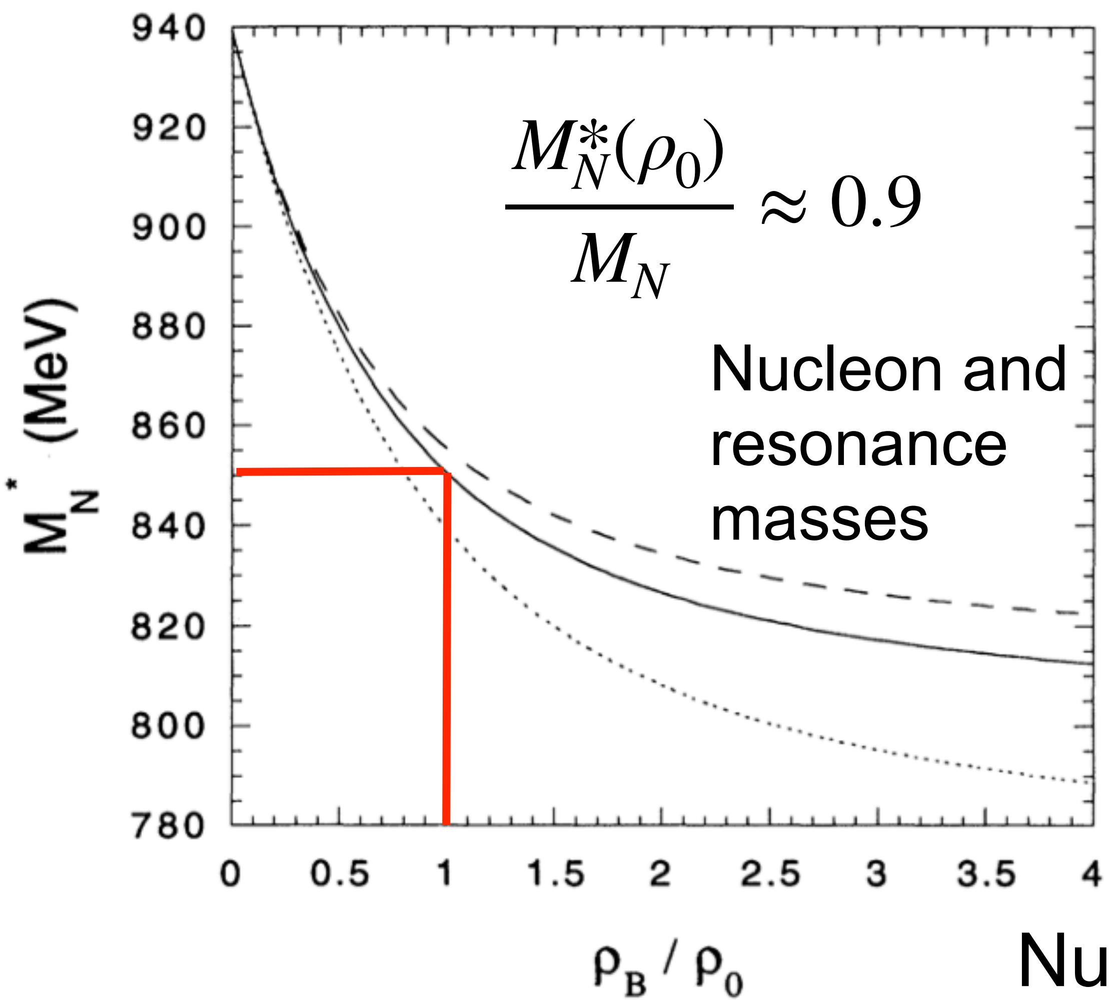
A nucleon in the nuclear medium will be modified
modification of both sides of the GDH sum rule
for the nucleon in the nucleus

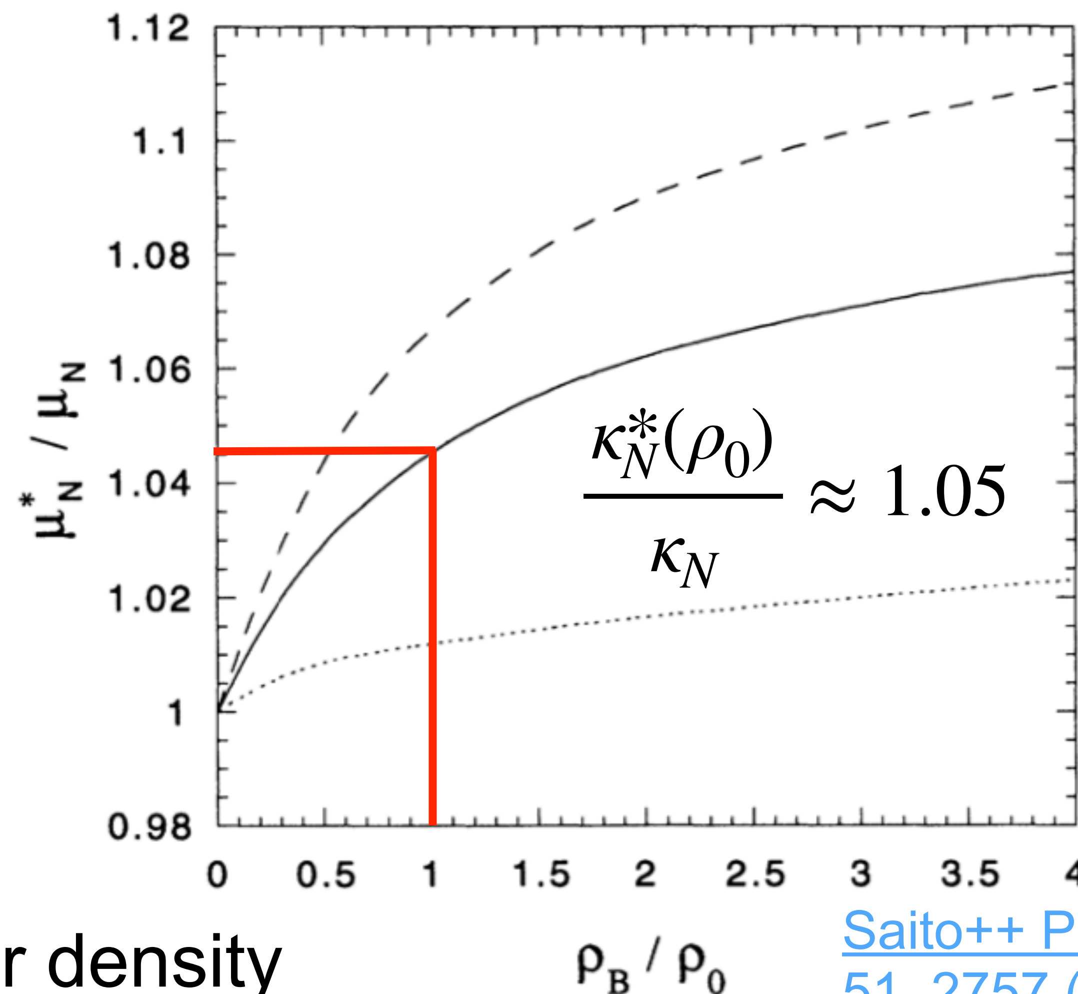
Bass, Acta Phys. Pol. B 52, 42 (2021)
Bass++, arXiv:2212.04795 [nucl-th]

Static Side

$$\left(\frac{\kappa_N^*(\rho_0)}{M_N^*(\rho_0)}\right)^2 \Big/ \left(\frac{\kappa_N}{M_N}\right)^2 \approx 1.3$$

Quark Meson Coupling (QMC) model predicts modification of mass and anomalous magnetic moment.

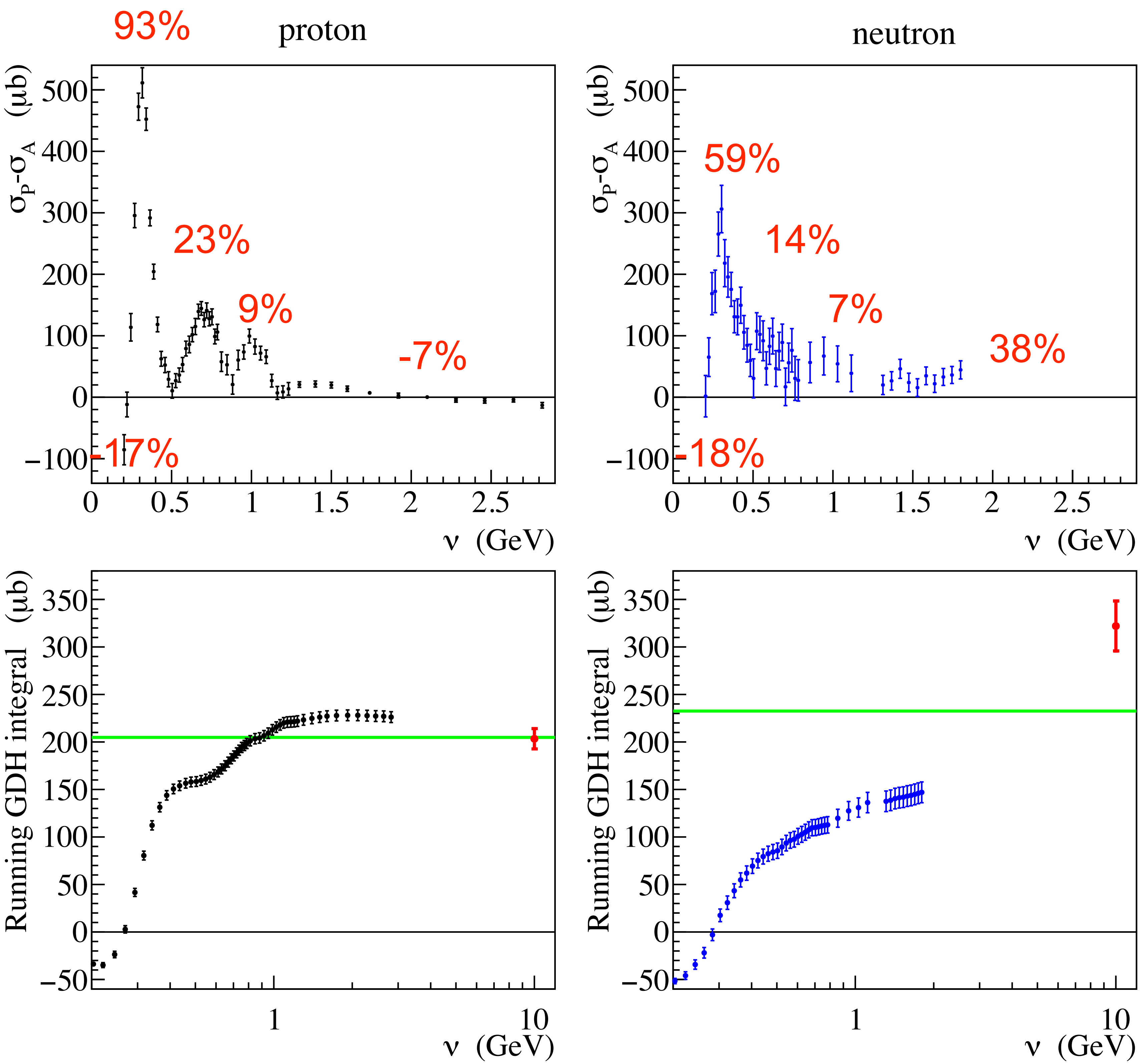




Nuclear density

Saito++ Phys. Rev. C 51, 2757 (1995)

Modification of bound nucleons



Dynamic (integral) Side

$$\int_{\nu_0}^{\infty} \frac{\Delta\sigma(\nu)}{\nu} \mathrm{d}\nu = \frac{4\pi^2 S\alpha\kappa^2}{M^2}$$

In-medium shift of resonance mass, $1/\nu$ dependence (slower than $1/M^2$)

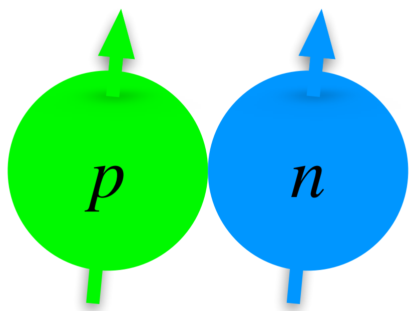
$\Delta(1232)$

$D_{13}(1520)$, $S_{11}(1535)$ expected to be small

3rd resonance and Regge modification

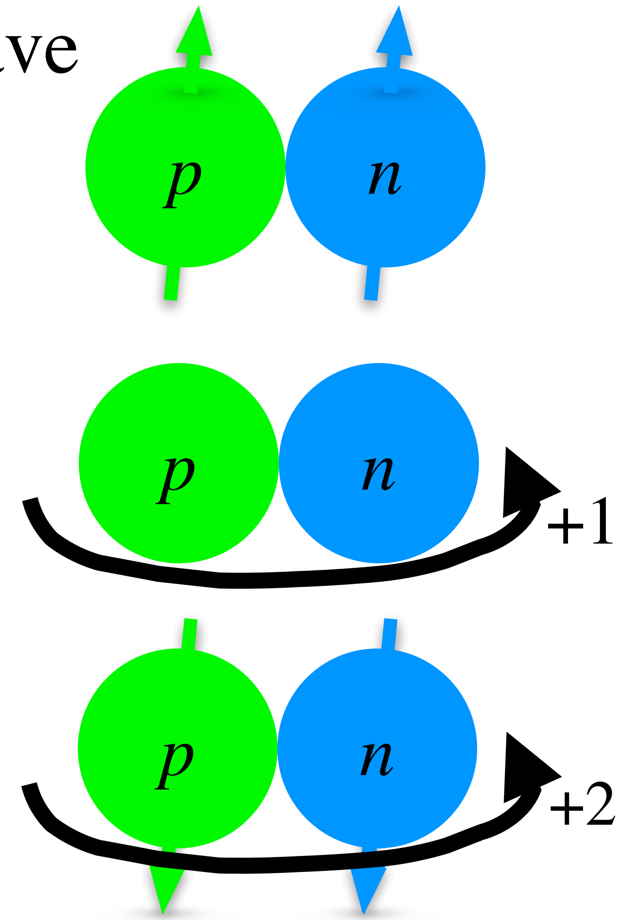
D-wave depolarization

S-wave



$|1\ {+1}\rangle$

D-wave



$\langle 2\ 0; 1\ {+1} | 1\ {+1} \rangle = \sqrt{1/10}$

$\langle 2\ {+1}; 1\ 0 | 1\ {+1} \rangle = -\sqrt{3/10}$

$\langle 2\ {+2}; 1\ {-1} | 1\ {+1} \rangle = \sqrt{3/5}$

- Assume 100% polarized valence nucleon in S-wave with another nucleon
- pair in nucleus are not required to be spin oriented same direction
  - could be a $J_z = 0$ or $J_z = 1$ combination
- SRC interacts through tensor interaction which preserves J_z
- Clebsch-Gordan coefficients for orbital angular momentum $L = 2$
- Valence nucleon polarization changes sign but is only about -10 to -15%.

Thomas IJMP E27 (2018)

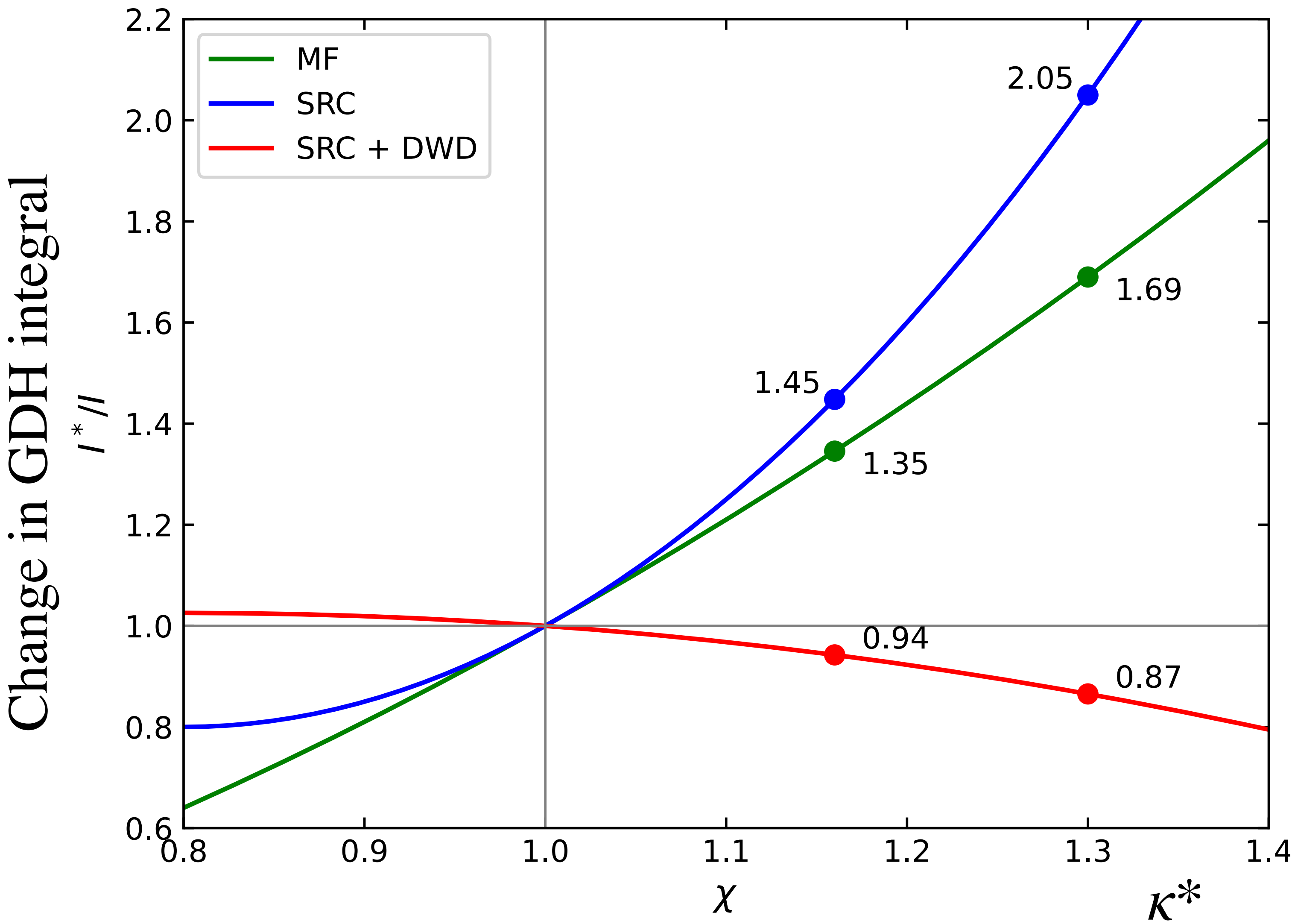
- If SRCs are dominantly $J_z = 1$ then this value changes.
- If SRCs interact in a shell dependent way then this value changes.

GDH Sum Rule

MF: average over everything.

SRC: 20% of nucleons are modified and 80% are not.

DWD: Modified nucleons contribute with $P_D = -0.1$ and unmodified with $P_S = +1$



$$I^*_{\mathrm{SRC}} = \left(\frac{(\chi - 0.8)^2}{0.2} + 0.8 \right) I$$

$$I^*_{\mathrm{MF}} = \chi^2 I$$

$$I^*_{\mathrm{DWD}} = \frac{1}{0.78} \left(-0.5\ (\chi - 0.8)^2 + 0.8 \right) I$$

Average modification of κ/M for nucleon $\quad \chi = \dfrac{\kappa^*}{M^*}$

https://arxiv.org/abs/2512.20449

Going Further

Schwinger Sum Rule

proton only

$$I_{\mathrm{LT}}(Q^2) \equiv \int_{\nu_0}^{\infty} f_\gamma \frac{\sigma_{\mathrm{LT}}(\nu, Q^2)}{Q\nu}\,\mathrm{d}\nu \xrightarrow[Q^2\to 0]{} \frac{\pi^2\alpha\kappa e_t}{M^2}$$

very low Q^2 electron scattering

$$\kappa^* = \frac{I^*_{\mathrm{GDH}}}{2I^*_{\mathrm{LT}}} \qquad M^* = \pi\sqrt{\frac{\alpha}{2}}\frac{\sqrt{I^*_{\mathrm{GDH}}}}{I^*_{\mathrm{LT}}}$$

can get κ^* and M^* independently

Magnetic Form Factor G^*_M

polarization transfer to a bound proton $(\vec{e}, e'\vec{p})$

$$\kappa^* = \mu^* - e_t$$

$Q^2 = 0$ limit of G^*_M

$$\chi = \sqrt{\frac{\kappa^* I^*_{\mathrm{LT}}}{\pi^2\alpha e_t}}$$

can get I^*_{GDH} and $\chi = \dfrac{\kappa^*}{M^*}$ independently

Determination of M^*

various independent ways to get M^* as a verification

Candidate Nuclei

Choice will depend on target feasibility and FOM

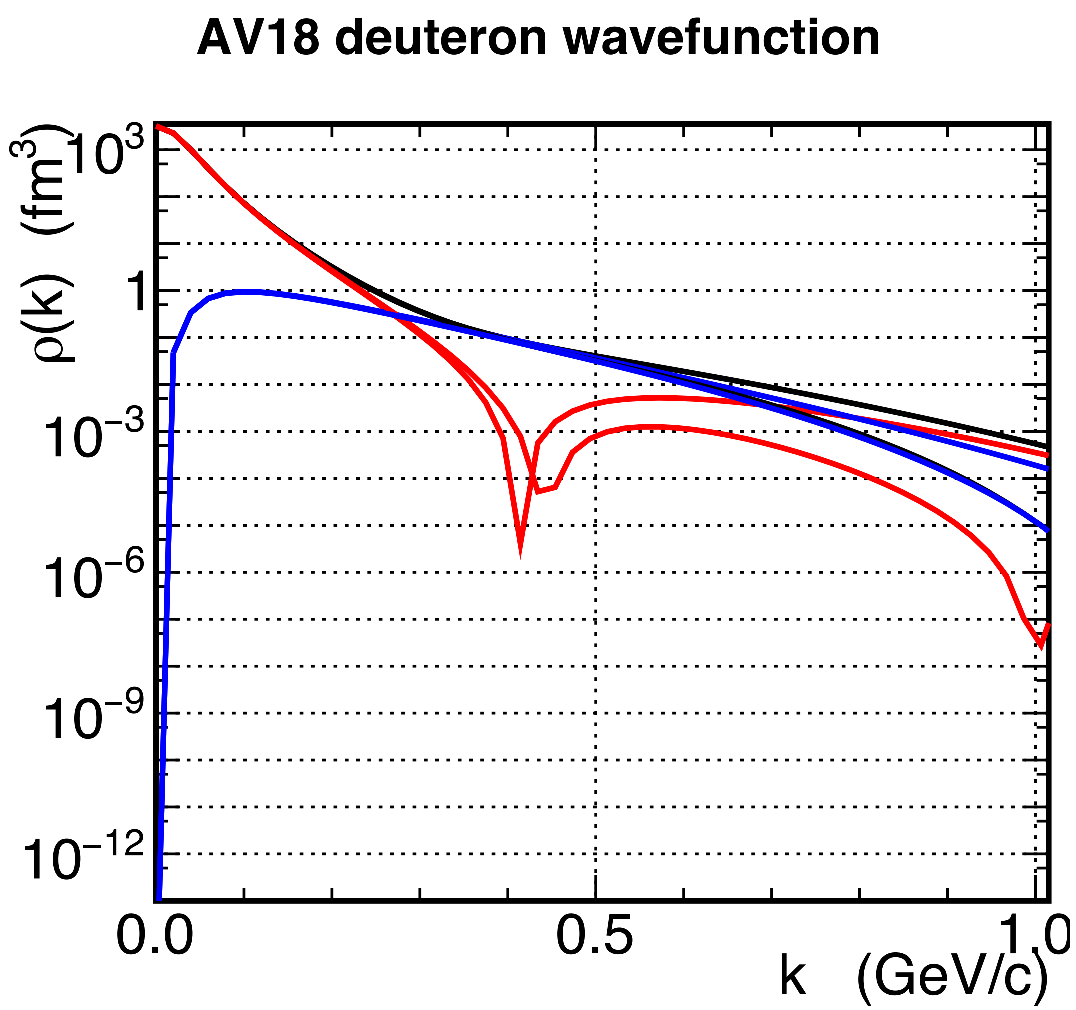
The strongest candidate is ^{7}Li:

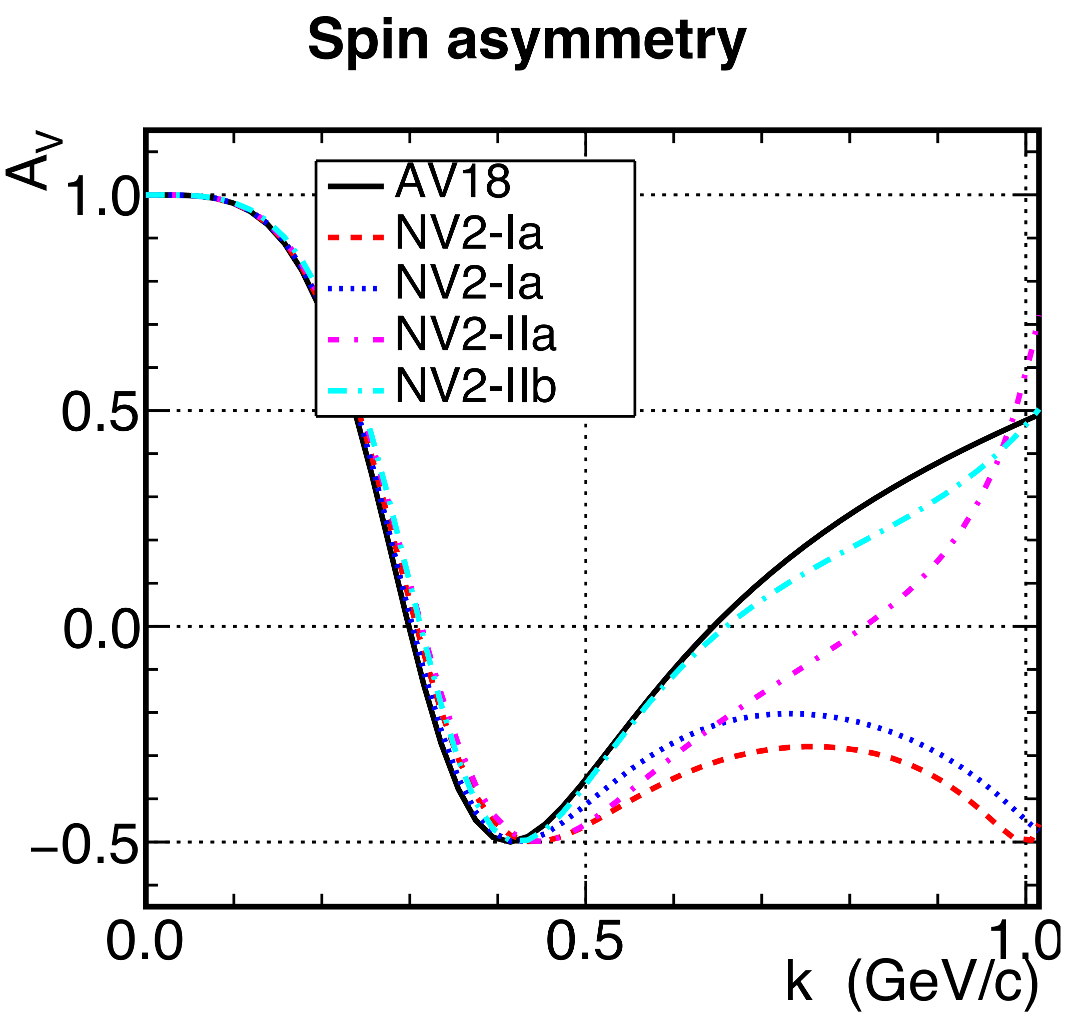
- Also the subject of unpolarized (E12–10–008) and polarized (E12–14–001: $Q^2 > 1\ \mathrm{GeV}^2$) EMC experiments at JLab
- A GDH measurement will provide the $Q^2 \to 0$ limit

	J^π	P	species	molecule	dilution F	FOM P^2F ($\times 10^{-3}$)
^{1}H	$1/2^+$	90%	$\vec{p}$	C_4H_9OH	$10/74 = 0.135$	110
^{2}H	1^+	80%	$\vec{n},\ \vec{p}$	C_4D_9OD	$10/84 = 0.119$	76
^{7}Li	$3/2^-$	80%	$\vec{p}$	$^7Li^2H$	$1/9 = 0.111$	71
^{13}C	$1/2^-$	60%	$\vec{n}$	C_4D_9OD	$4/78 = 0.051$	4.6
^{17}O	$5/2^+$	80%	$\vec{n}$	$C_4D_9{}^{17}OD$	$1/75 = 0.013$	8.5
		80%	$\vec{n}$	$H_2{}^{17}O$	$1/19 = 0.053$	34
^{19}F	$1/2^+$	90%	$\vec{p}$	$^6Li^{19}F$	$1/25 = 0.040$	32
		80%	$\vec{p}$	$C_3H_2{}^{19}F_6O$	$6/168 = 0.036$	23

Spin Nuclear Wave Function

- Polarization observables canconstrain on wavefunction models.
- The spin part of the nuclear wavefunction may be important for measurements of medium modifications using polarization.
- Very few measurements have been made that are directly sensitive to the spin part of the nuclear wavefunction, mostly ^{2}H and ^{3}He.
- Simplest thing to do is polarization dependent quasi-elastic knockout.
- Need to consider FSIs.

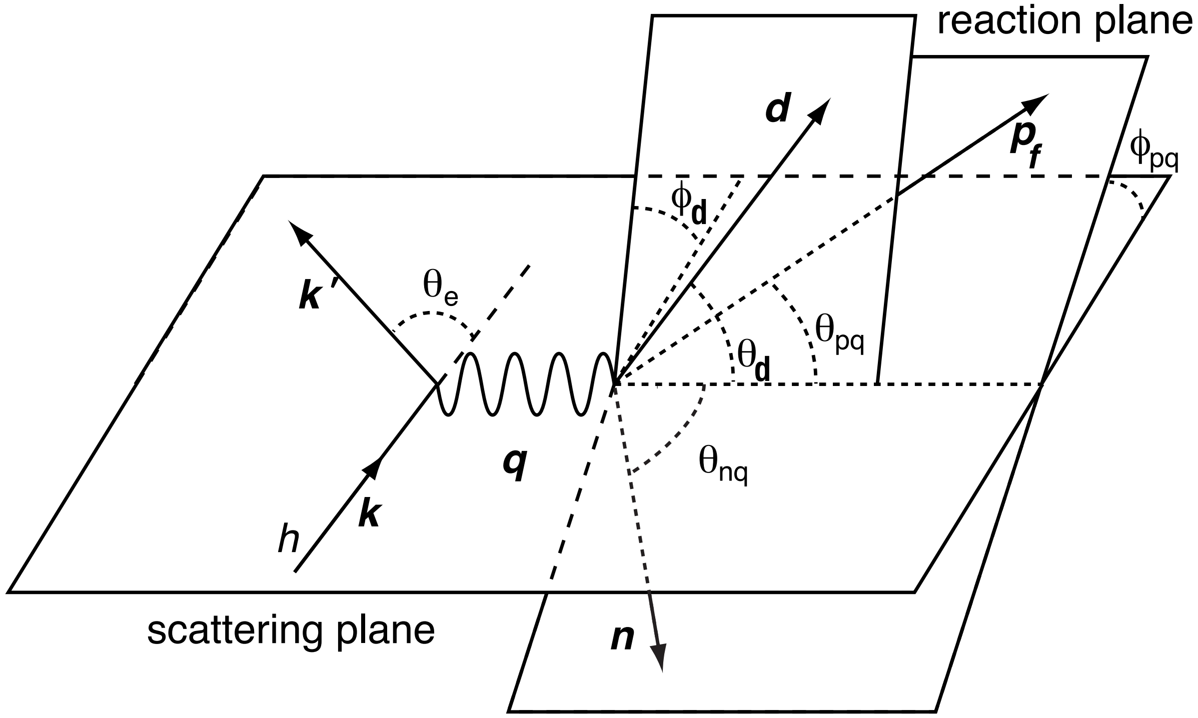


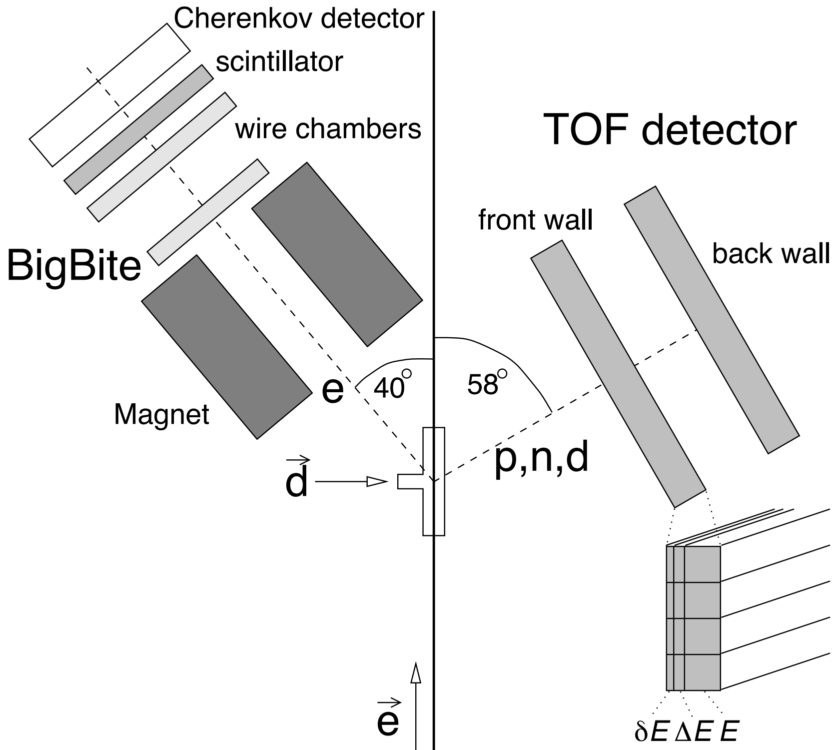


Deuteron Spin Structure

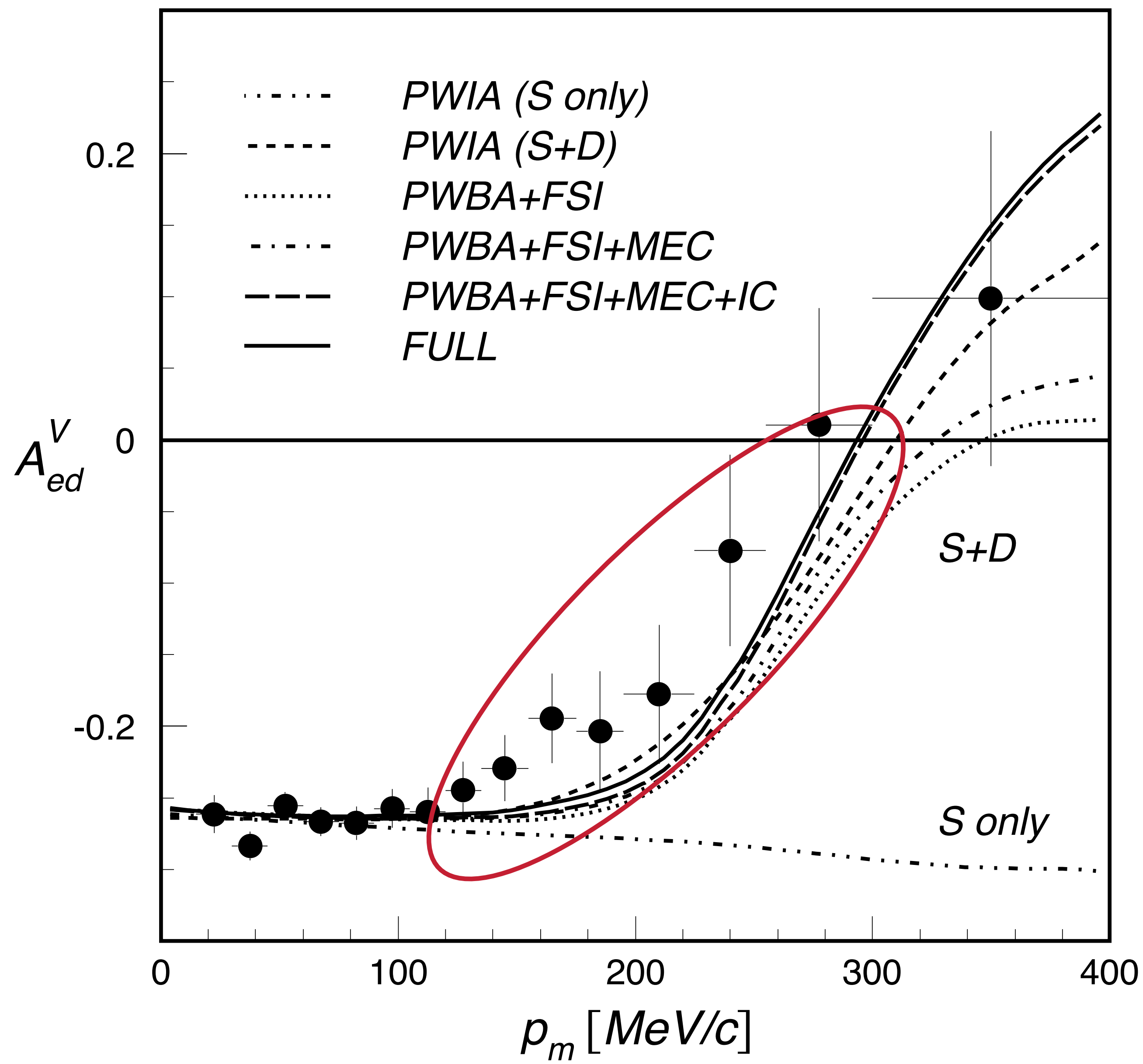
$$\sigma = \sigma_0(1 + P_1^d A_d^V + P_2^d A_d^T + h(A_e + P_1^d A_{\rm ed}^V + P_2^d A_{\rm ed}^T))$$

Arenhövel PhysRevC.46.455





Passchier PhysRevLett.88.102302

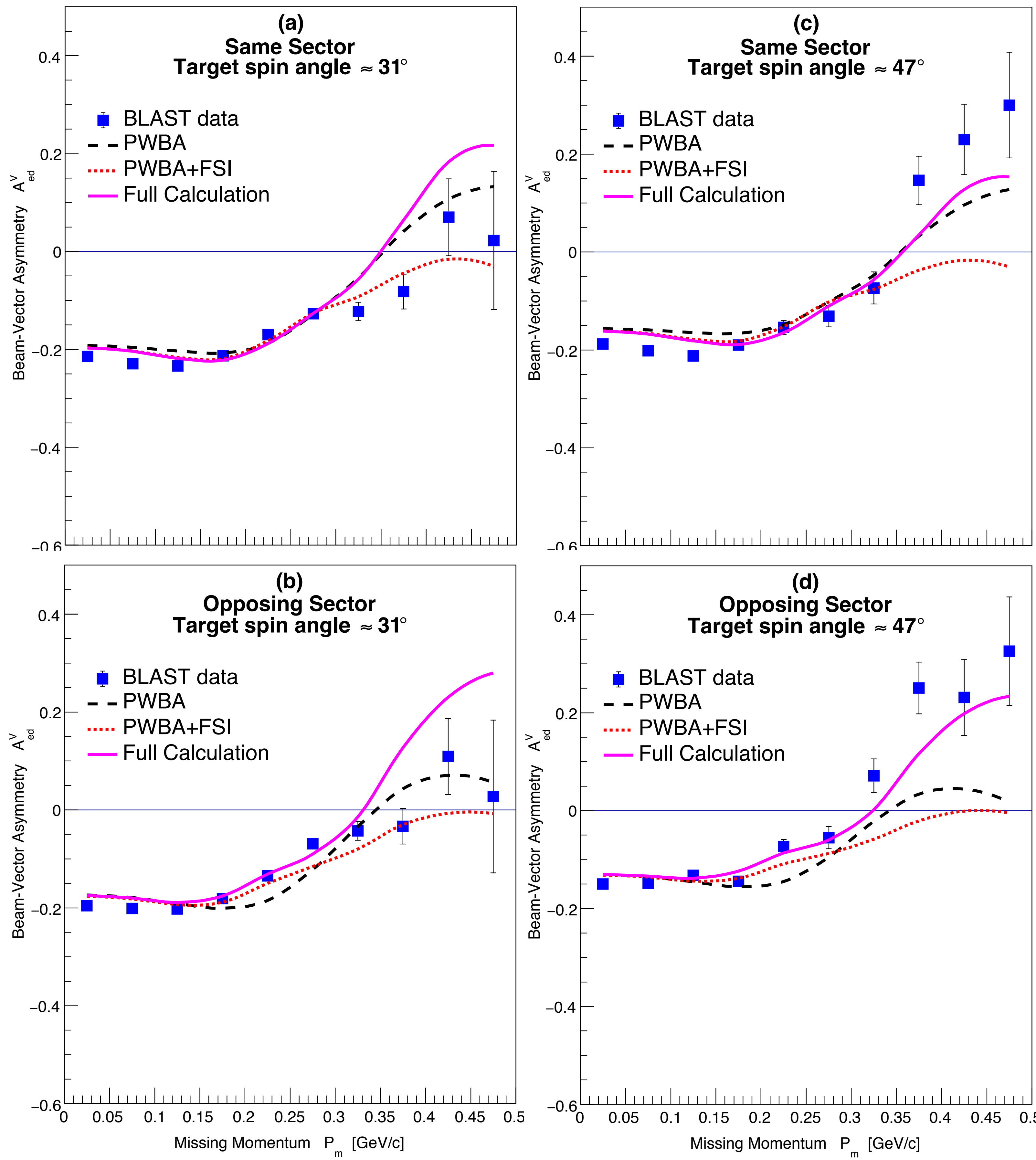


A_{ed}^{V} A_{ed}^{V}

Quasielastic $(\vec{e}, e'p)$ Electron Scattering from Deuterium

Vector double-spin asymmetry

Blast measurements reached to higher P_m and tended to agree with calculations better.



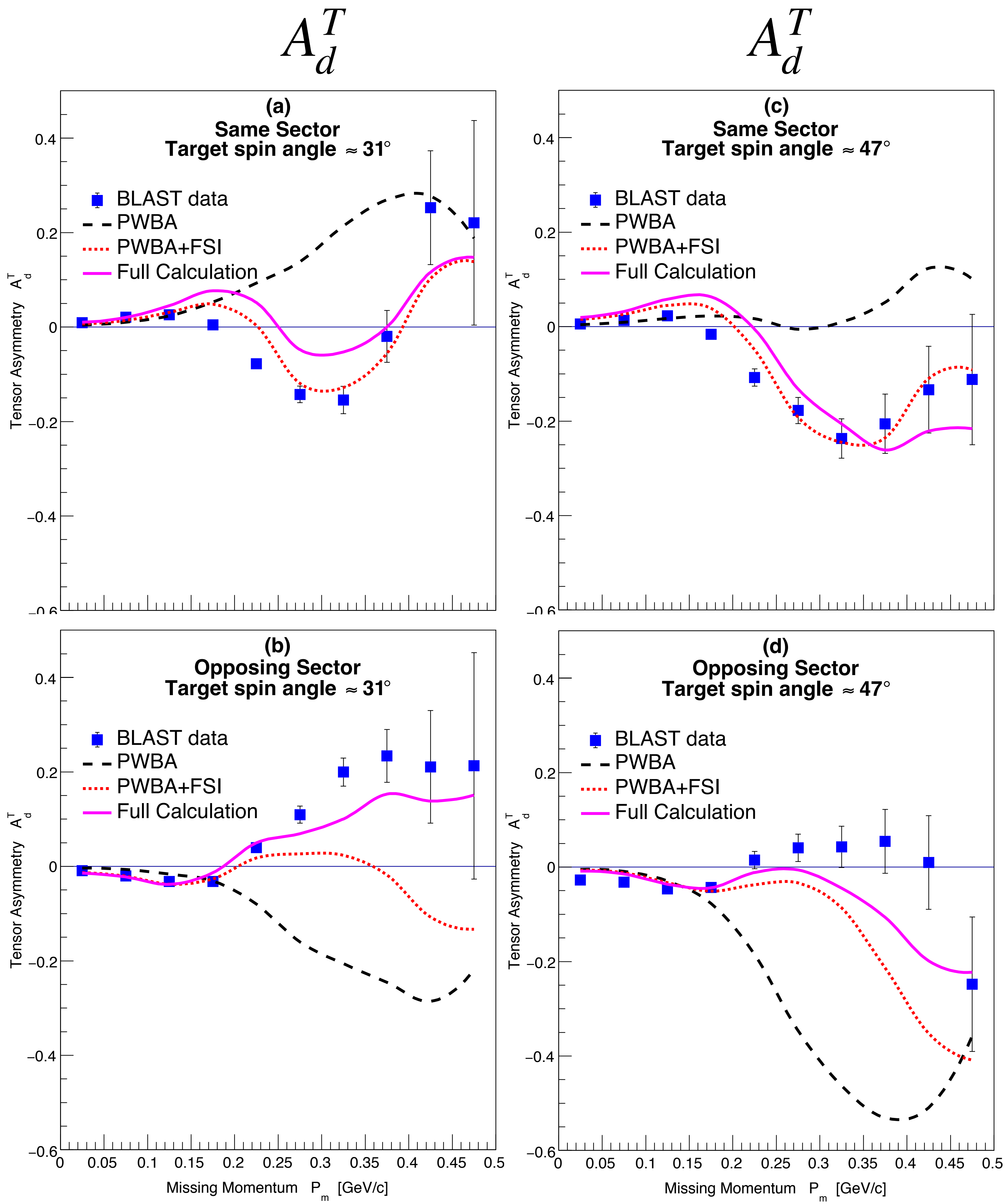
De Grush PhysRevLett.119.182501 2017

Quasielastic $(\vec{e}, e'p)$ Electron Scattering from Deuterium

Tensor target asymmetry.

Tensor asymmetries significantly affected by FSI
Full calculations disagree with data
- meson-exchange currents (MECs),
- isobar configurations (ICs),
- relativistic corrections (RCs).

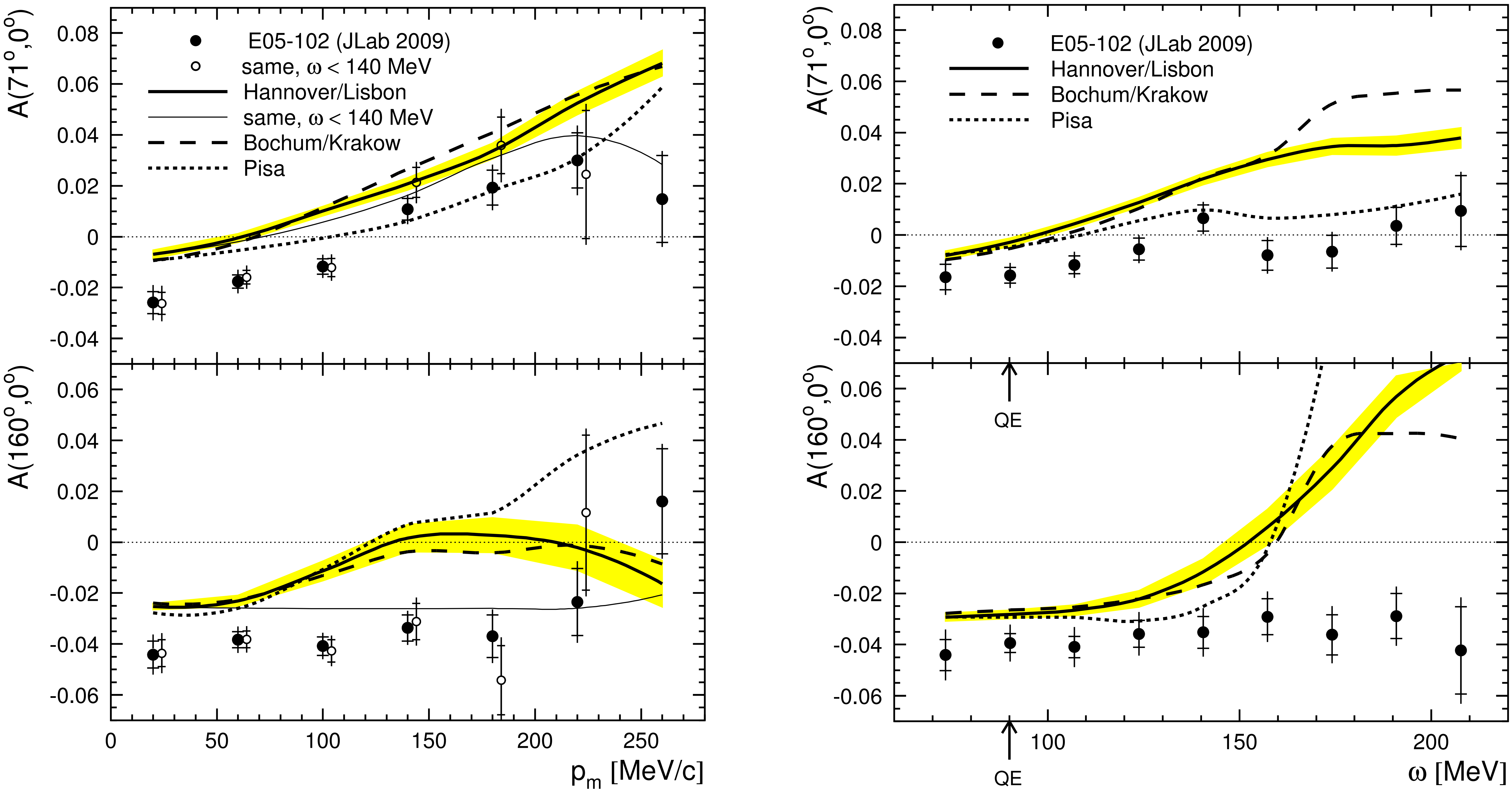
insensitive to the choice of different realistic potentials



Helium-3 Spin Structure

$^3\overrightarrow{\mathrm{He}}(\vec{e}, e'd)$ study a polarized deuteron in the nucleus

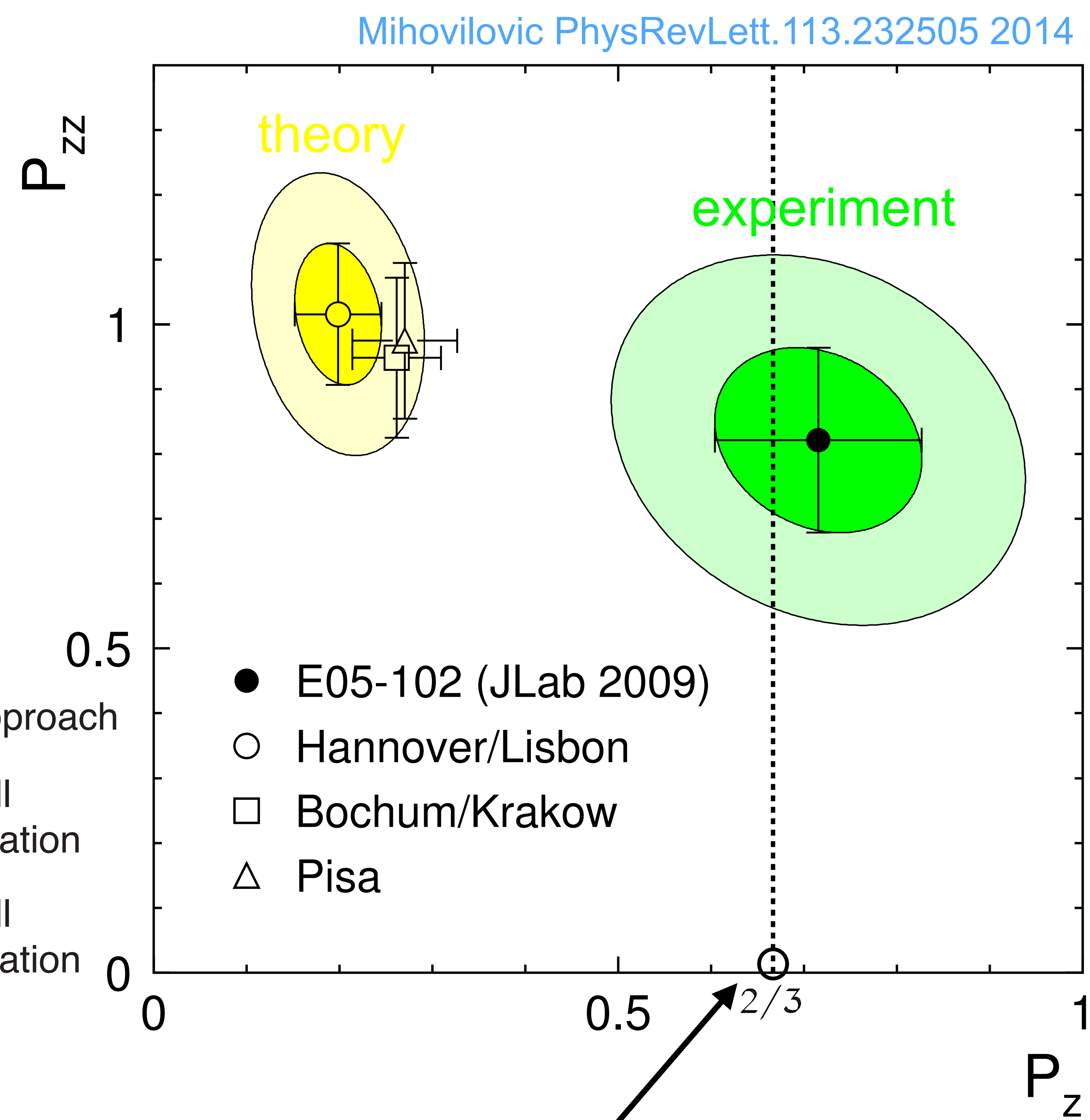
Mihovilovic++ PhysRevLett.113.232505



Helium-3 Spin Structure

Asymmetry as $p_m \to 0$ gives access to polarizations.

Theoretical calculations of the vector polarization of the deuteron in $^{3}\mathrm{He}$ appear underestimated.



diagrammatic approach

independent full Faddeev calculation

independent full Faddeev calculation

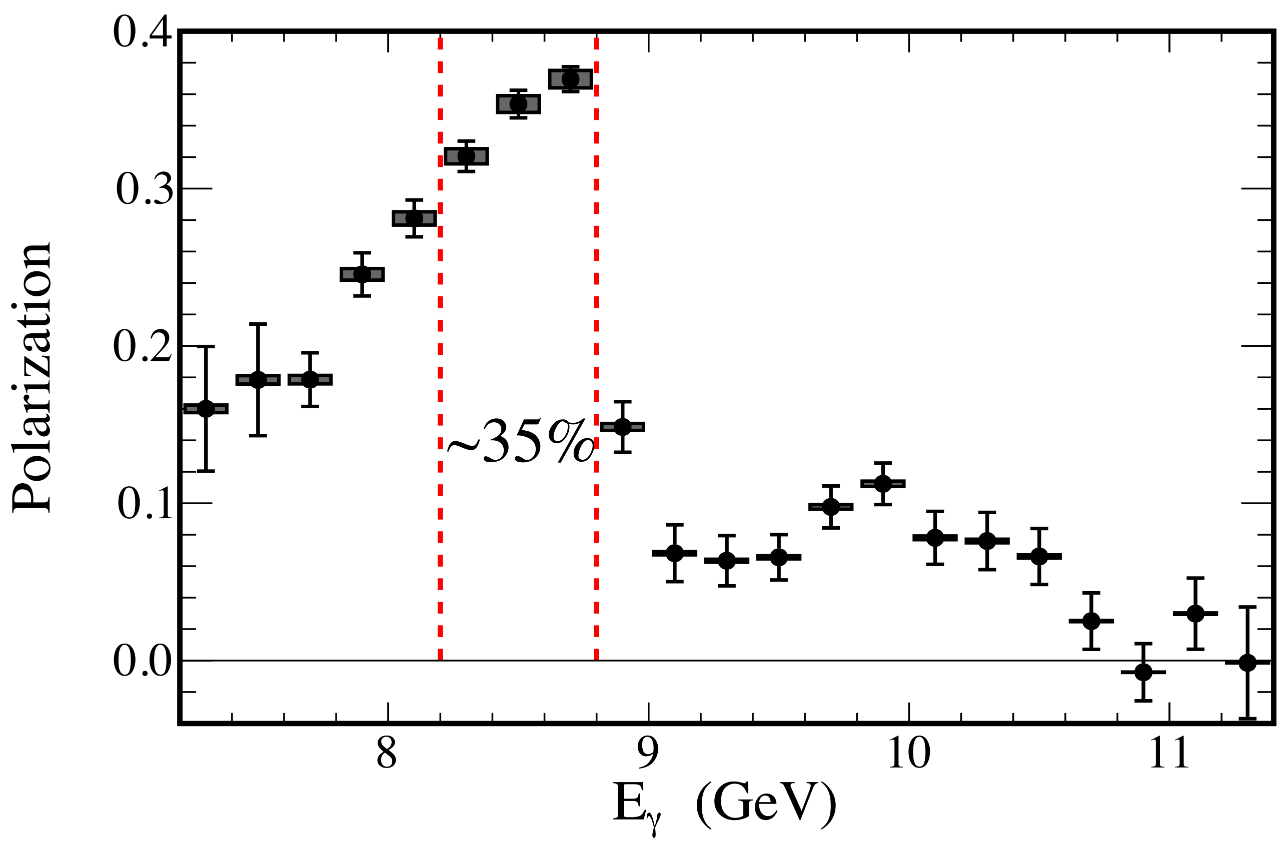
Simple $p + D$ Clebsch-Gordan expectation

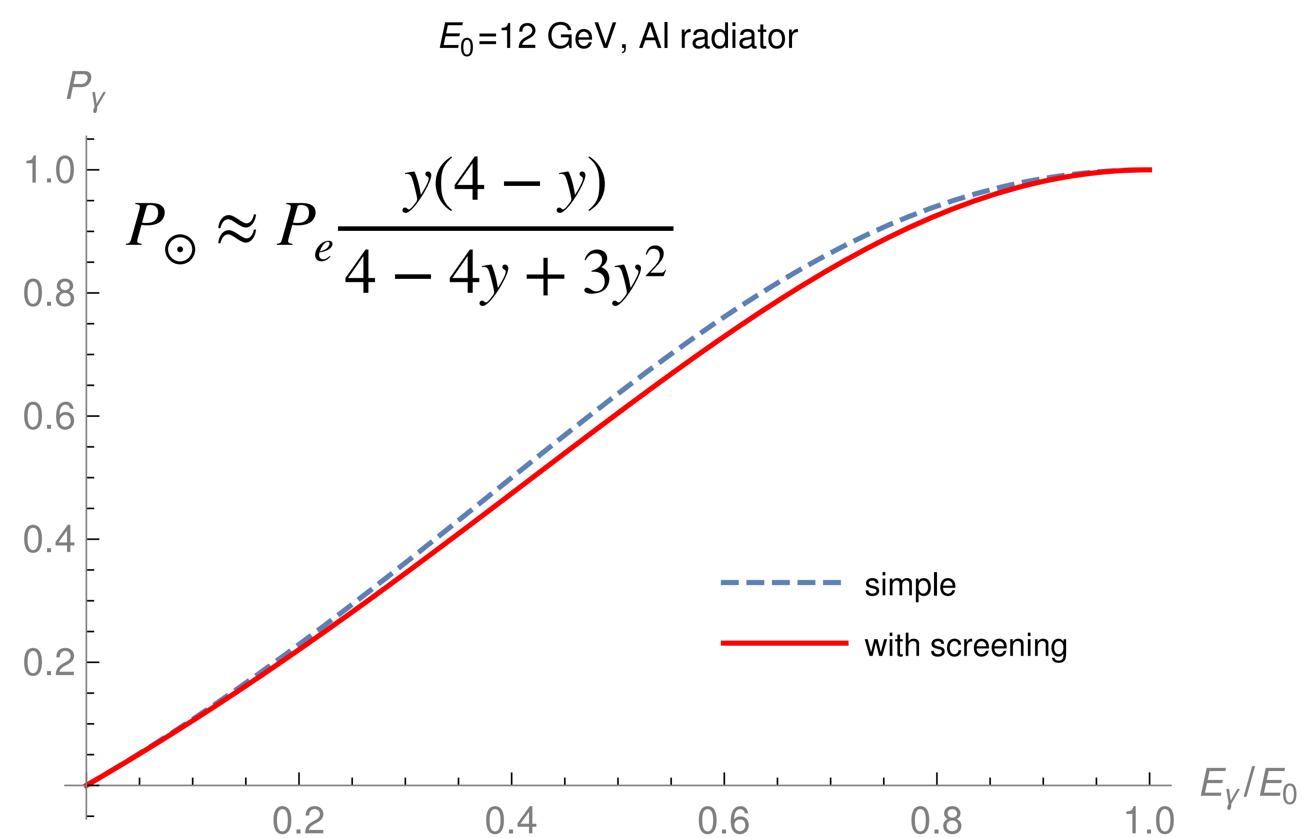
Exclusive Asymmetries

Real photon beam is sensitive to the polarization state of nucleons through beam-target asymmetries G and E.

$$\overrightarrow{P}_{\gamma} = (-P_T \cos 2\Phi, -P_T \sin 2\Phi, P_{\odot}) \qquad \overrightarrow{P} = (0,0,P_z)$$

$$I(\Phi) = \frac{\mathrm{d}\sigma}{\mathrm{d}t}\left[1 + P_T\Sigma\cos 2\Phi + P_T P_z G \sin 2\Phi - P_{\odot} P_z E\right]$$

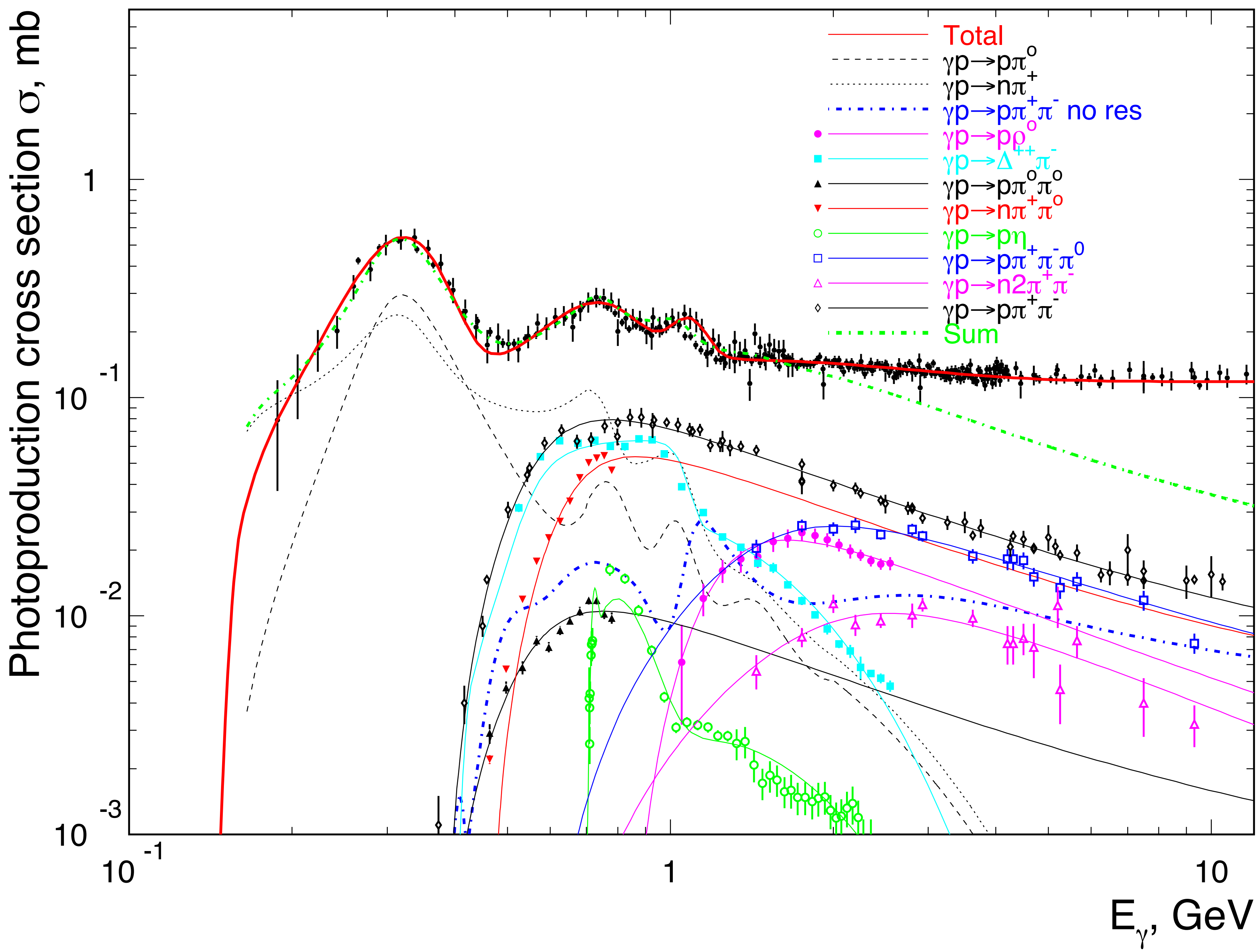




Working with Vincent Matthieu from JPAC to predict asymmetries for vector and pseudo-scaler meson production.

Final States

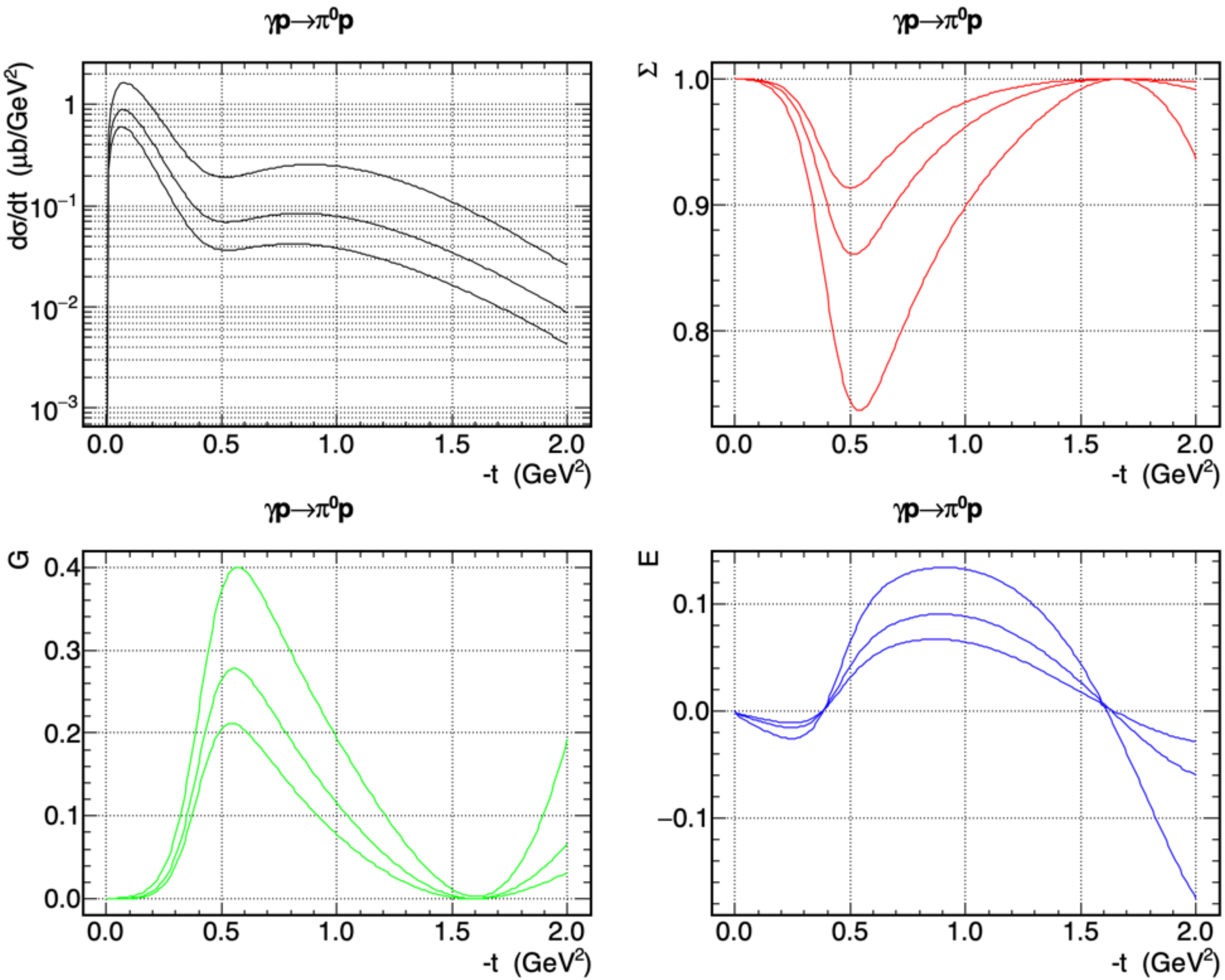
There are many final states where one can perform this procedure. They should all agree on the conclusions. Regge models predict the asymmetries.



Vector meson production has highest cross section.

initial	final
nn	$np\ \rho^-$
nn	$np\ \pi^-$
np	$pp\ \rho^-$
np	$np\ \omega$
np	$pp\ \pi^-$
pp	$pp\ \rho^0$
pp	$pp\ \omega$
pp	$pp\ \pi^0$

Example: $\gamma p \to p\pi^0$



Regge calculations predict many final state.

Curves at 4.5, 7.5, 10.5 GeV

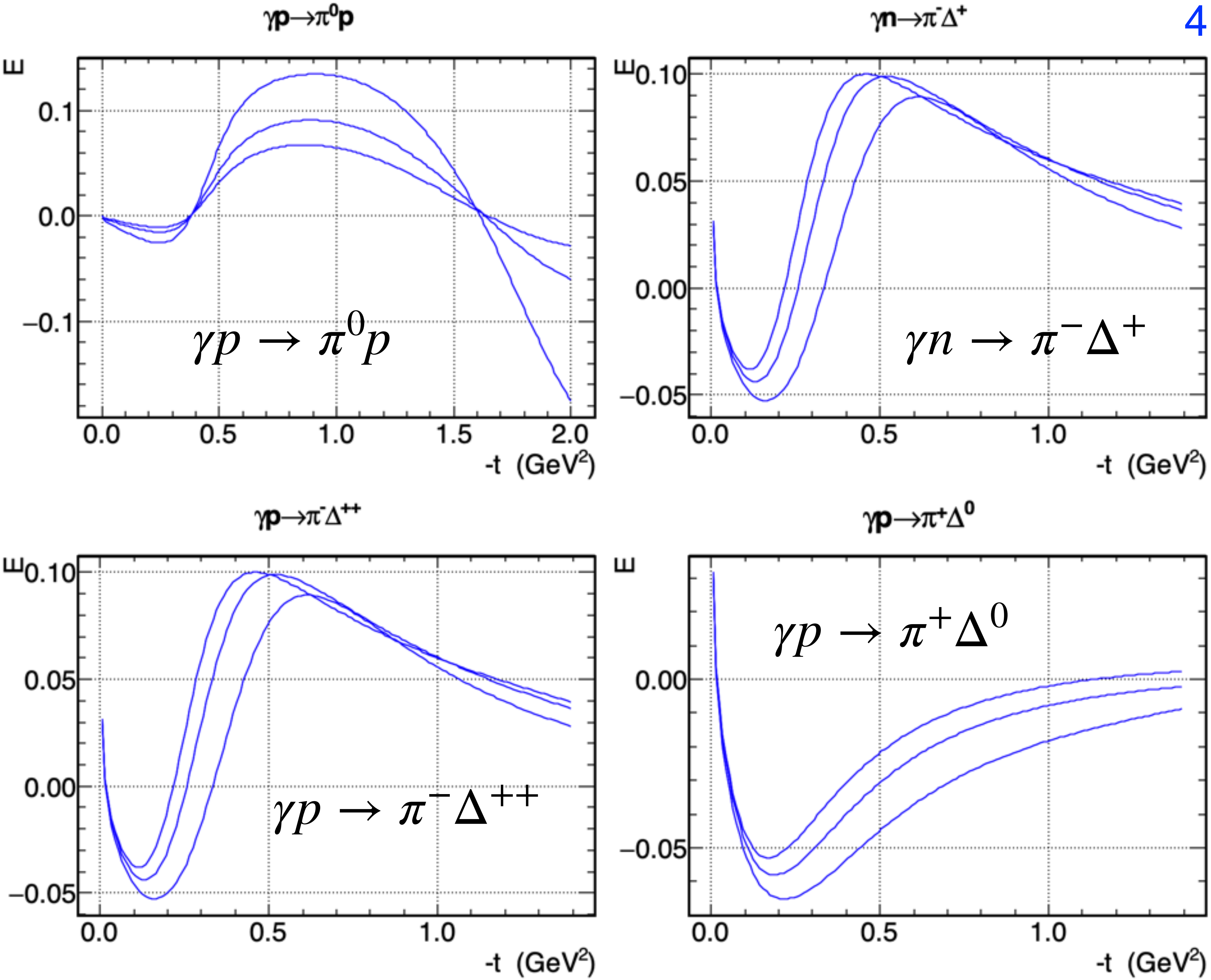
Σ asymmetry matches data well

G and E asymmetries completely unmeasured and untested

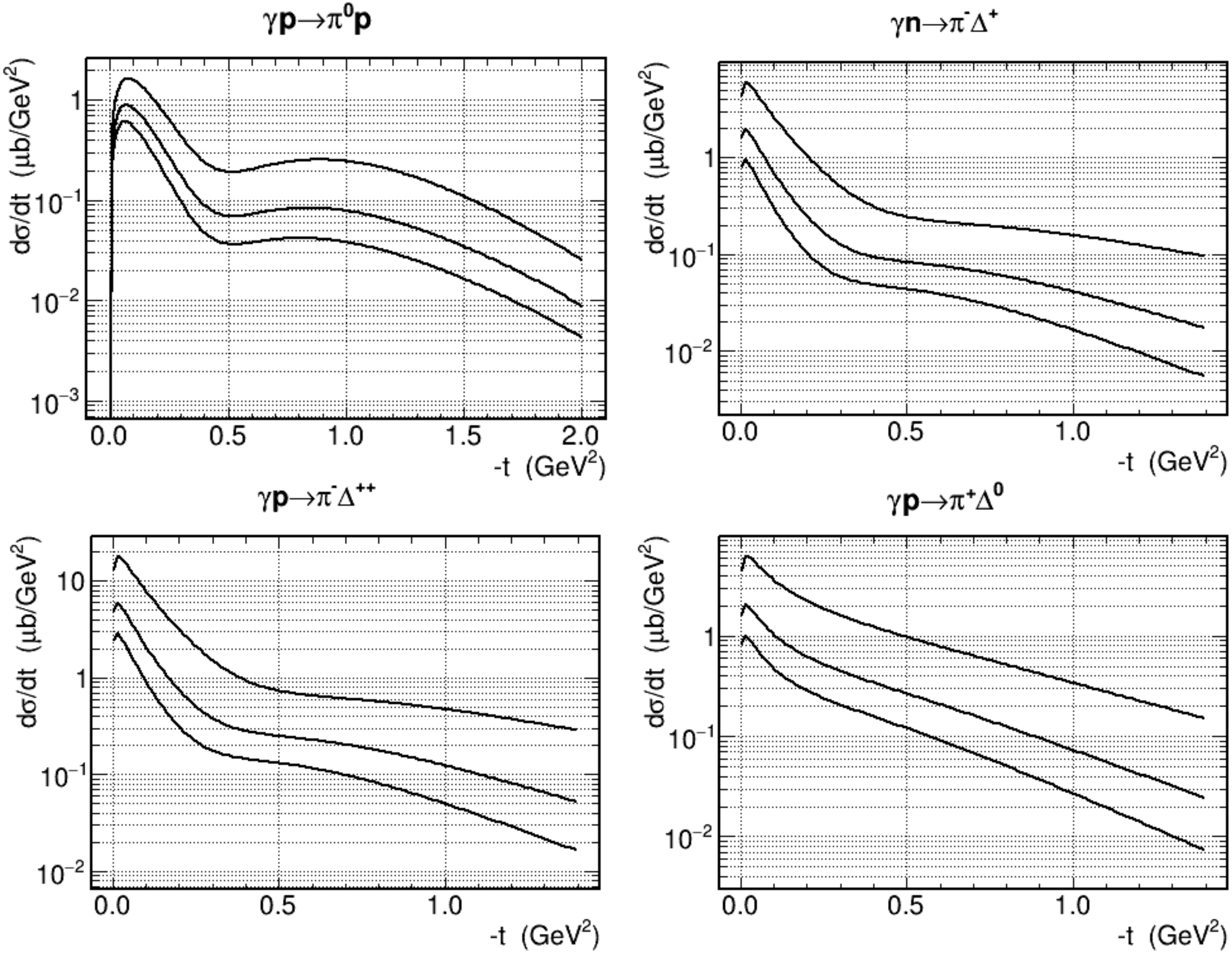
Mathieu++, Phys Rev D 92, 074013 (2015)

Asymmetry E in single π production

4.5, 7.5, 10.5 GeV



Cross Section in single π production



4.5 GeV
7.5 GeV
10.5 GeV

Summary

Hall D has an approved polarized target program to measure the GDH integrand on hydrogen and deuterium.

The GDH integrand on nuclei is sensitive to the uniformity of medium modifications.

Application of the sum rule and Mean Field nuclear theory (QMC) suggest there will be a significant difference from free protons or neutrons in the Regge region.

Polarized targets are significantly easier with a photon beam which allows higher polarizations and potentially unique species.

Measurements of exclusive asymmetries as a function of pair relative momentum are feasible, beyond the Fermi momentum may be challenging statistically.

Backup

The GDH Sum on Nuclei

REGGEON: REGGE on Nuclei

Magnetic moment of a particle with charge Qe, mass M and spin $\vec{S}$:

$$\vec{\mu} = \frac{e}{M}(Q + \kappa)\vec{S}$$

For a nucleus of mass $M \approx AM_p$ and charge Ze

$$\vec{\mu} = \frac{e}{AM_p}(Z + \kappa)\vec{S} \implies \kappa = \frac{A}{2|\vec{S}|}\frac{\mu}{\mu_N} - Z$$

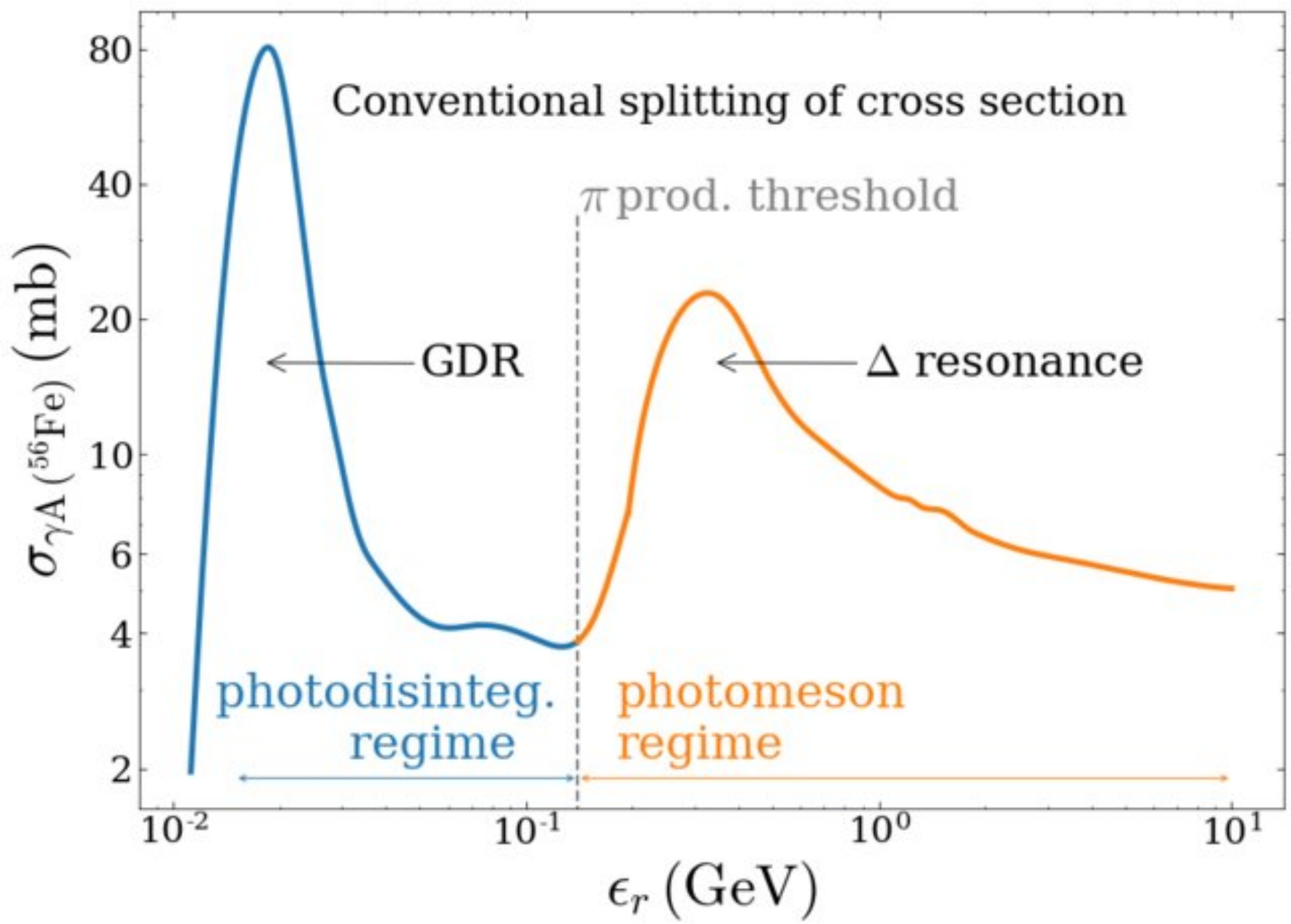
This allows us to calculate κ for all stable nuclei with spin and compute the static part of the GDH sum rule.

Nuclear spectrum

photo excitation of nucleus
properties of nucleus

photoproduction of hadrons
properties of nucleon

No data on $\Delta\sigma$ exists for A>3



negative

$I_{\mathrm{GDH}}^{p*} \approx 270\ \mu\mathrm{b}$

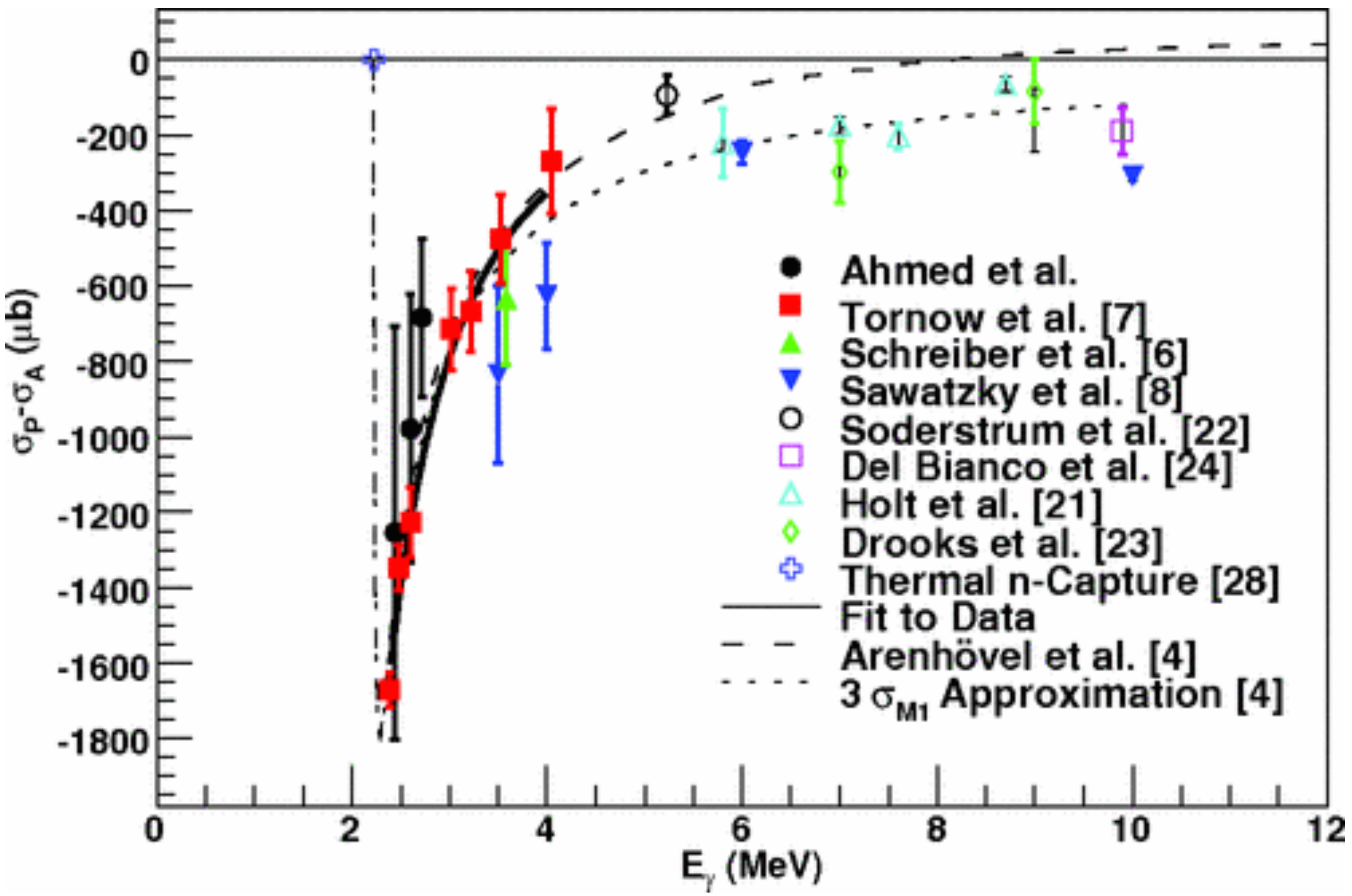
example for ^{7}Li

$I_{\mathrm{GDH}}^{^7\mathrm{Li}} \approx 83\ \mu\mathrm{b}$

Morejon++ JCAP 11, 007 (2019)

Deuteron

Large negative GDH integrand at low energy.

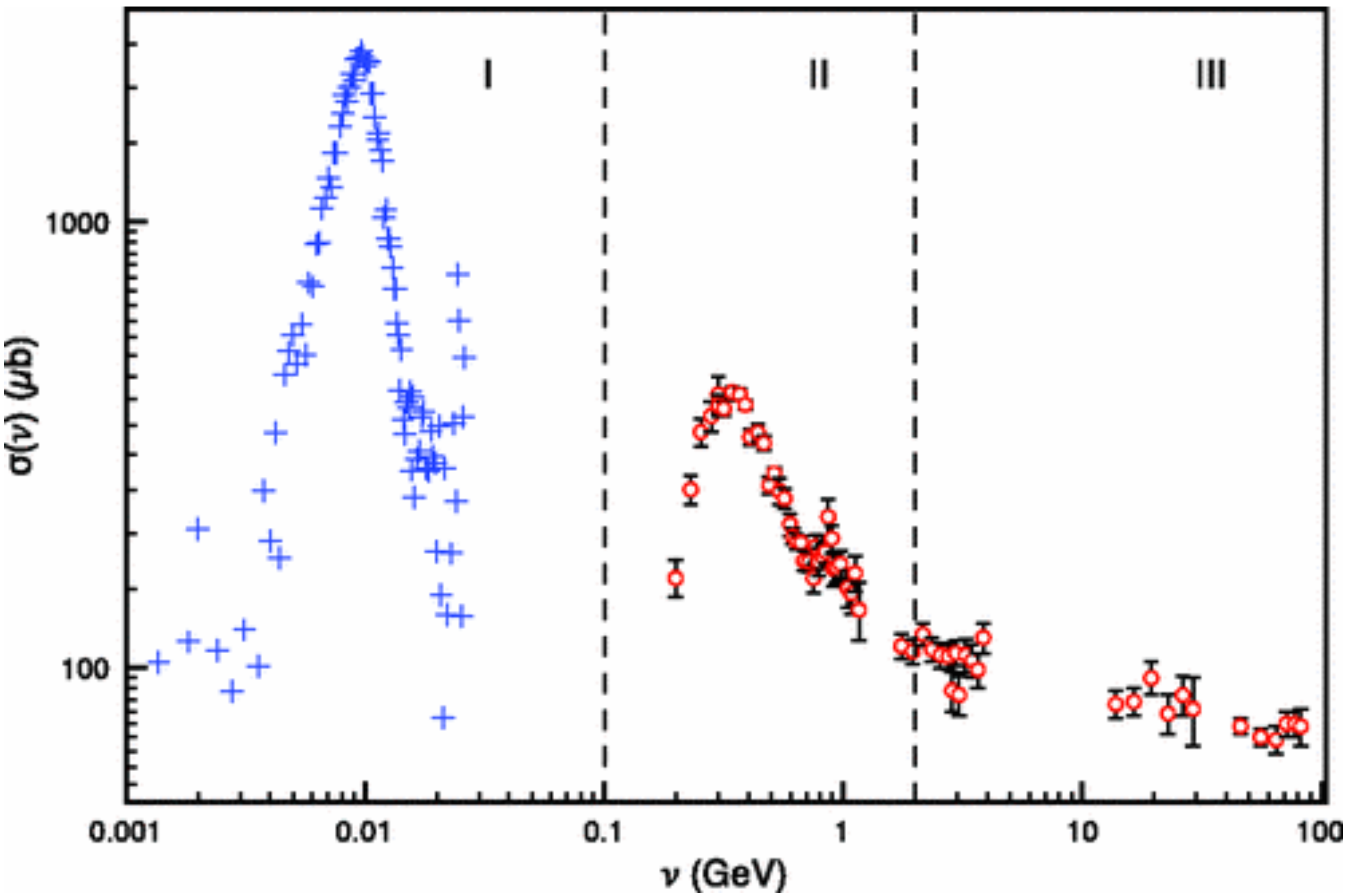


Deuteron GDH indirect

Ahmed++, PRC 77, 044005 (2008)

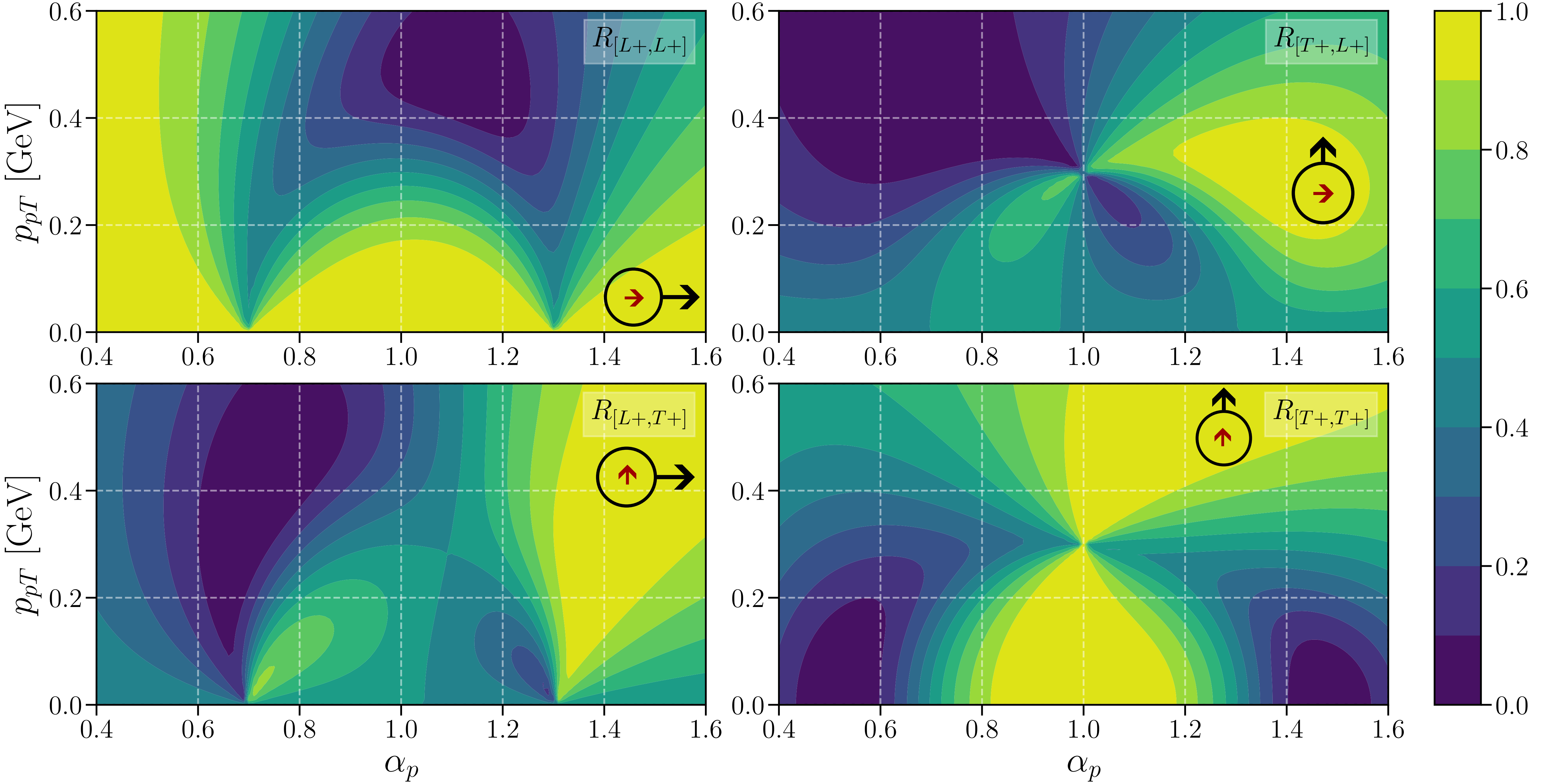
Nuclear spectrum

Photoabsorption cross-section data for a ^{207}Pb target

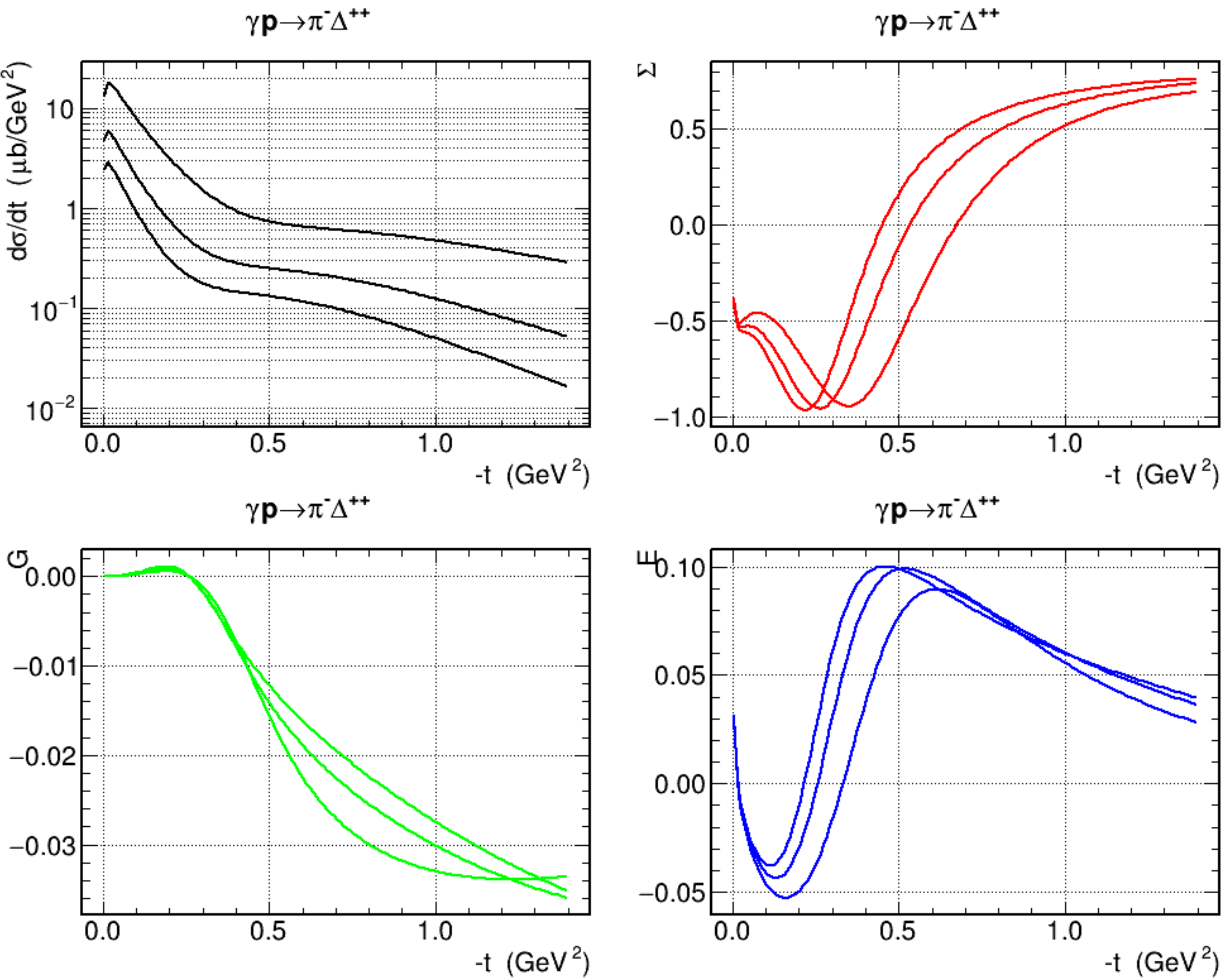


Gorchtein++ Phys. Rev. C 84 (2011)

Probabilistic Distributions for pure states



Example: $\gamma p \to \pi^- \Delta^{++}$



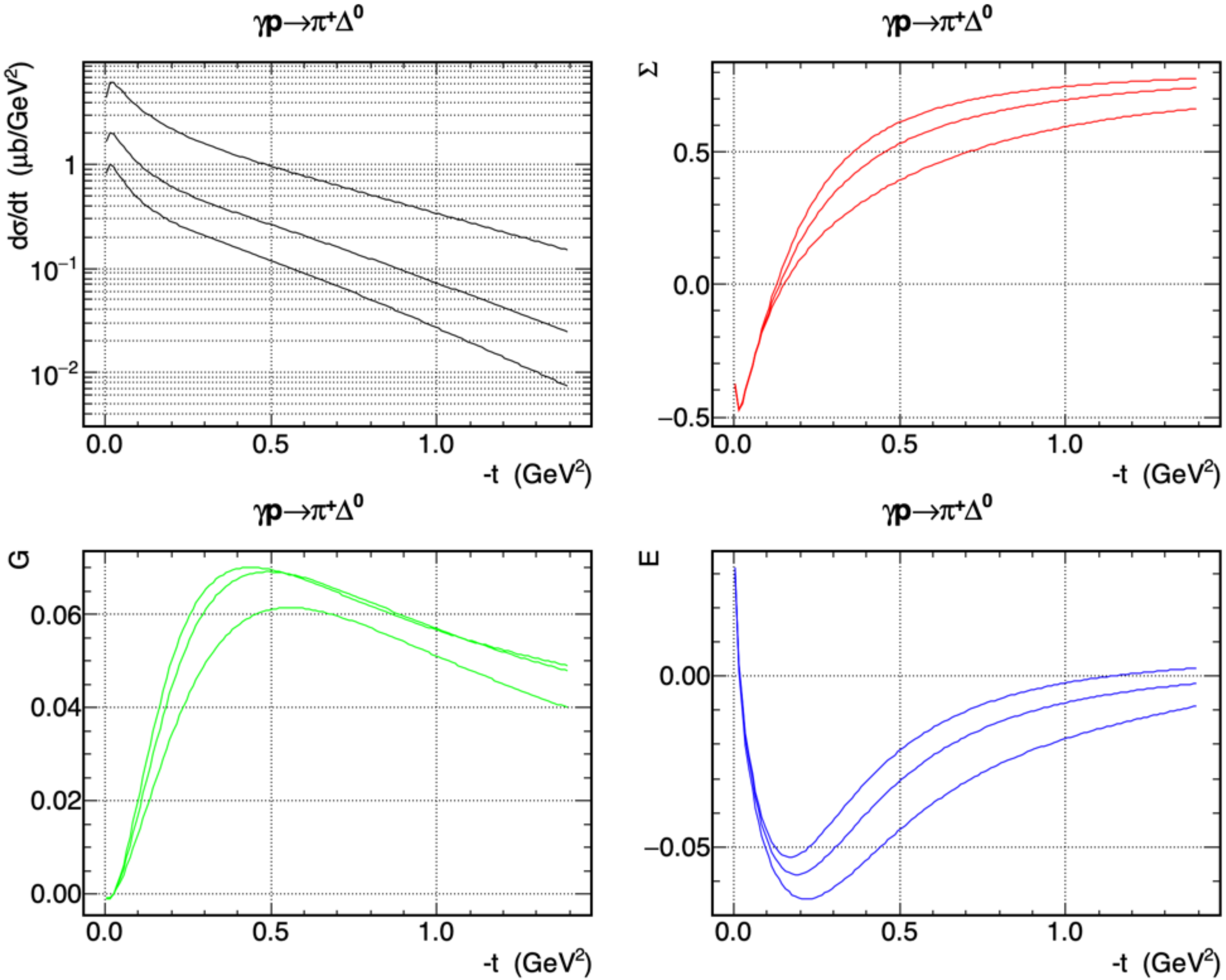
Regge calculation

Curves at 4.5, 7.5, 10.5 GeV

Σ asymmetry matches data well

G and E asymmetries completely untested

Example: $\gamma p \to \pi^+\Delta^0$



Example: $\gamma n \to \pi^- \Delta^+$