Polarization Observables with a Photon Probe

Spin physics in Nuclear Reactions and Nuclei
SPIN 2023

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Outline

Introduction to Polarized Target Program in Hall D

GDH sum rule on a nuclear target

Exclusive SRC Measurements with Polarization Observables

GDH Sum Rule

Spin-dependent photoproduction cross-sections

spin

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

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.

REGGE Real Gamma GDH Experiment

JLab Experiment E12–20–011

arXiv.2008.11059

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

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

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

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

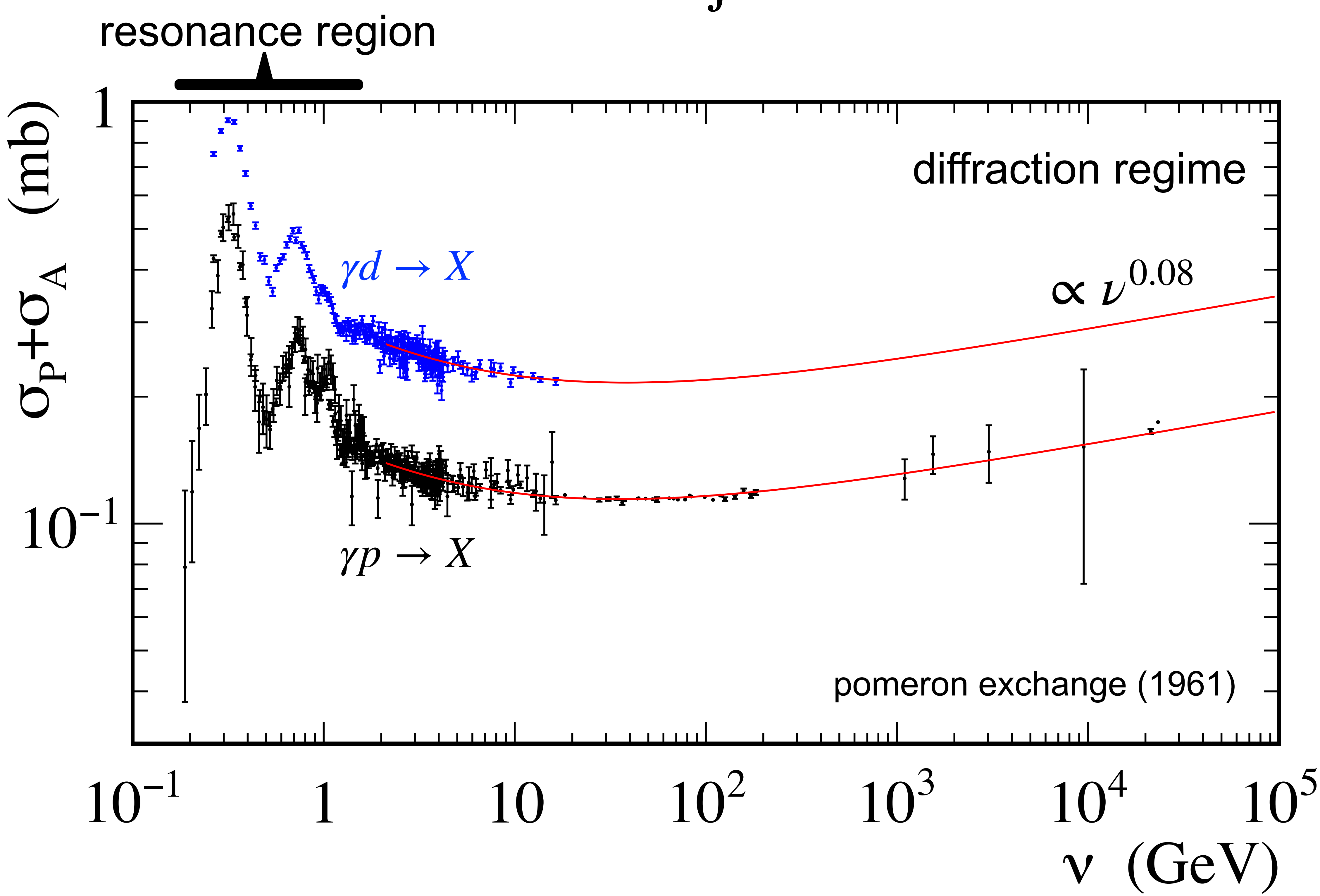
Failure of sum rule would occur at high energy

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

Proton and neutron will allow isospin decomposition

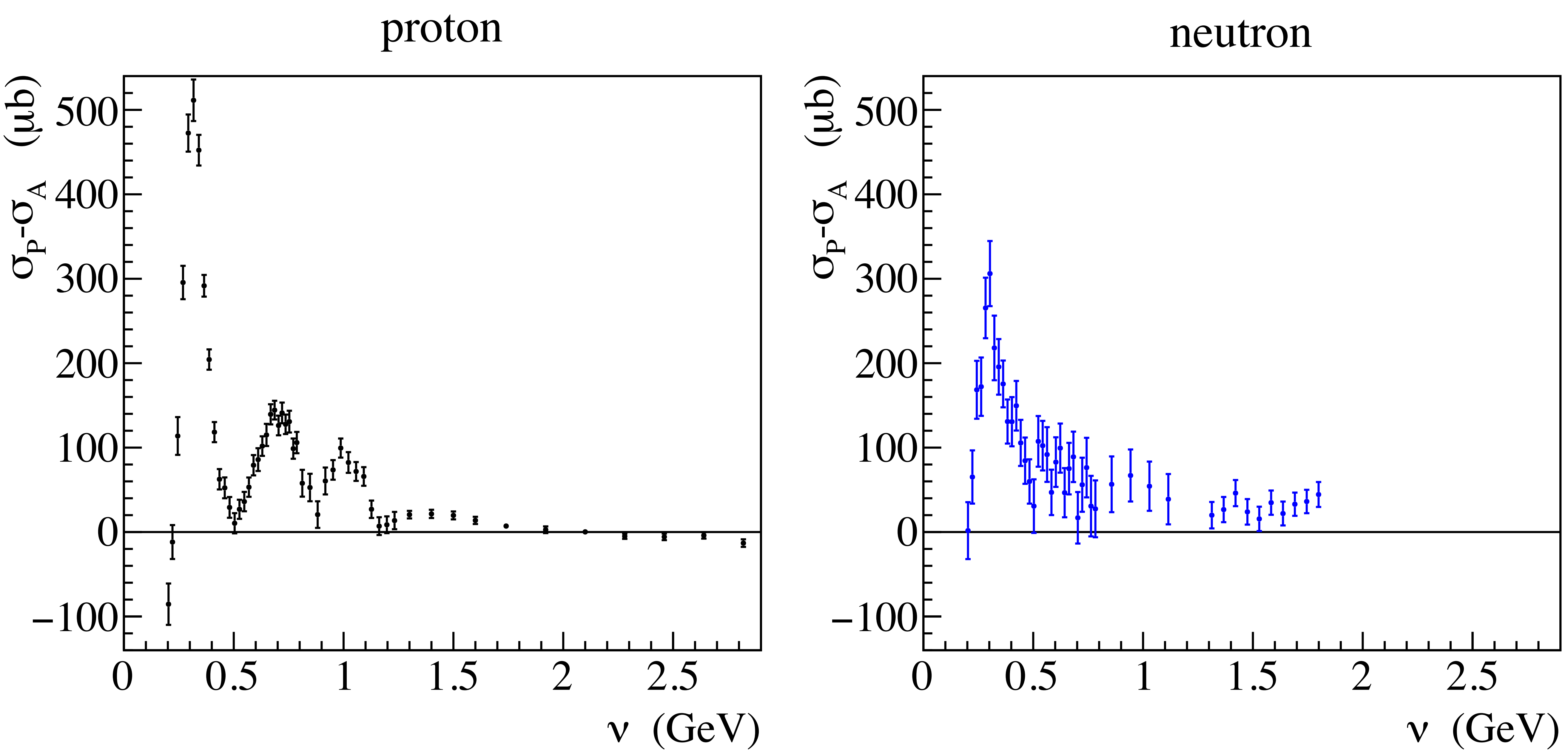
Photoproduction

Unpolarized version of GDH integral $\int (\sigma^{3/2} + \sigma^{1/2}) d\nu$ does not converge.



Helicity dependent photoabsorption

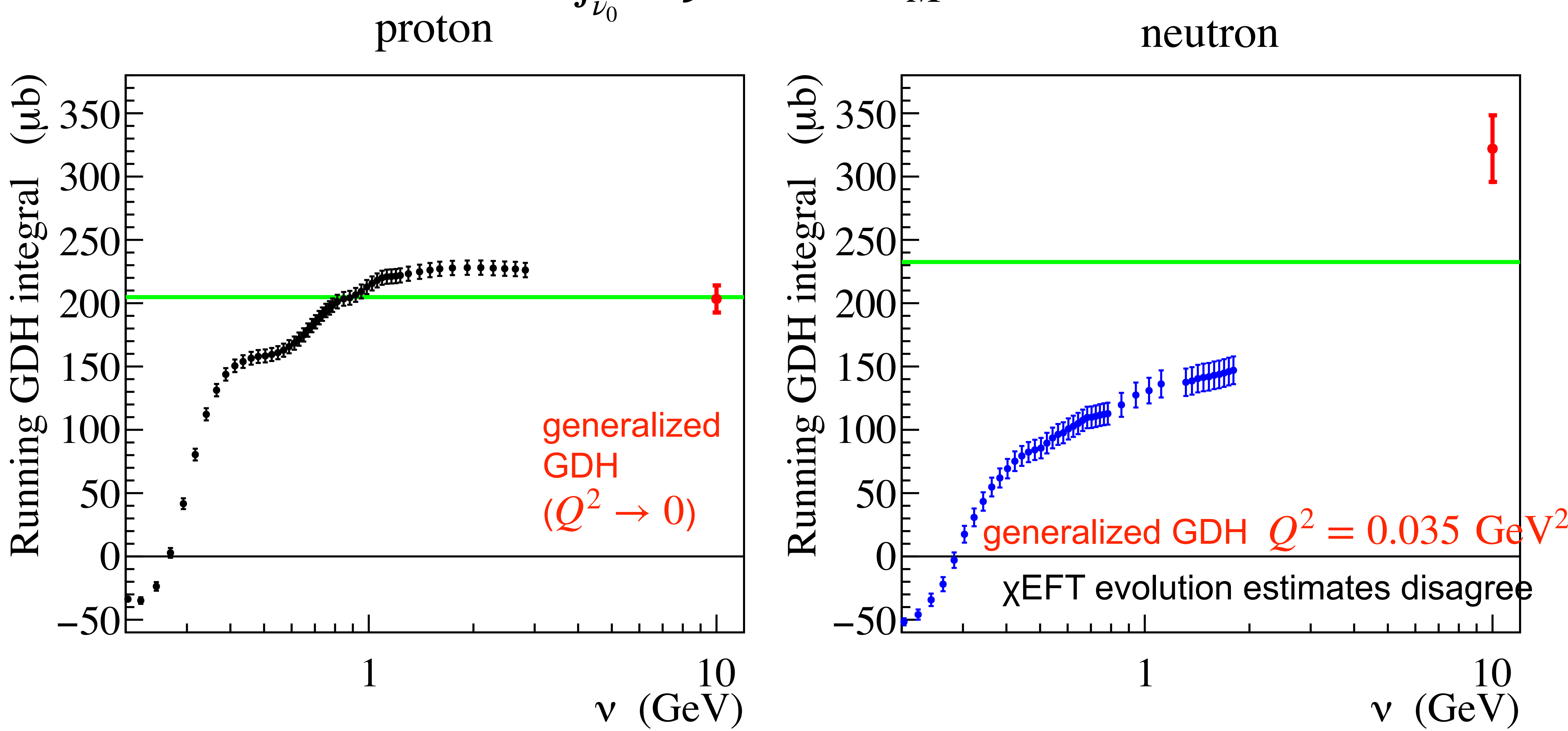
Existing data from MAMI and ELSA. Partial contributions from LEGS and CLAS.



Threshold and high energy regions cannot be measured,
need models like MAID/SAID and Regge phonomenology.

GDH Integral

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



Unmeasured part estimated using Regge model. Dominates uncertainty.

Has not converged yet

Contributions below 0.2 GeV: $\approx -28\ \mu$b (proton), $\approx -41\ \mu$b (neutron)

From Nucleons to Nuclei

Inclusive Measurements

Modification of bound nucleons

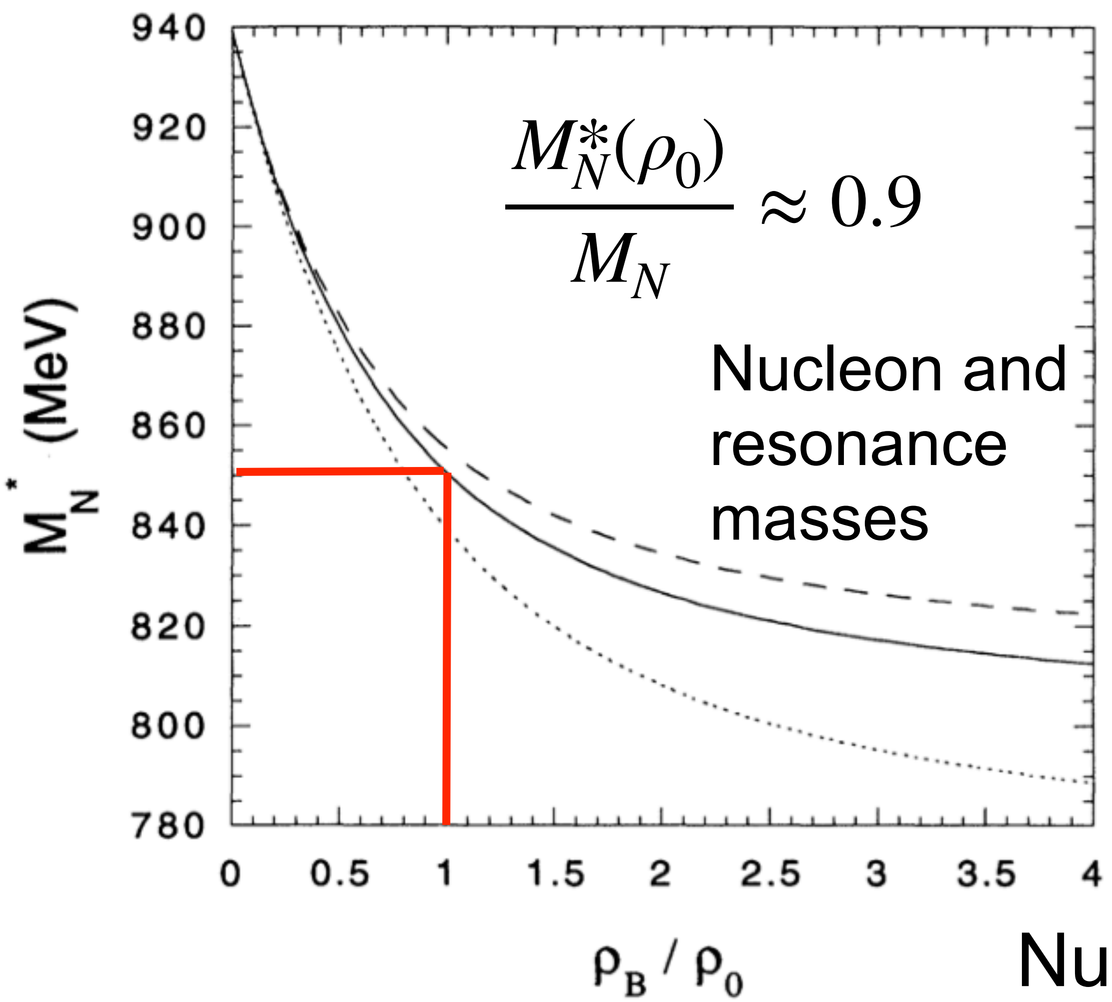
A nucleon in the nuclear medium will be modified
modification of both sides of the GDH sum rule for the nucleon in the nucleus

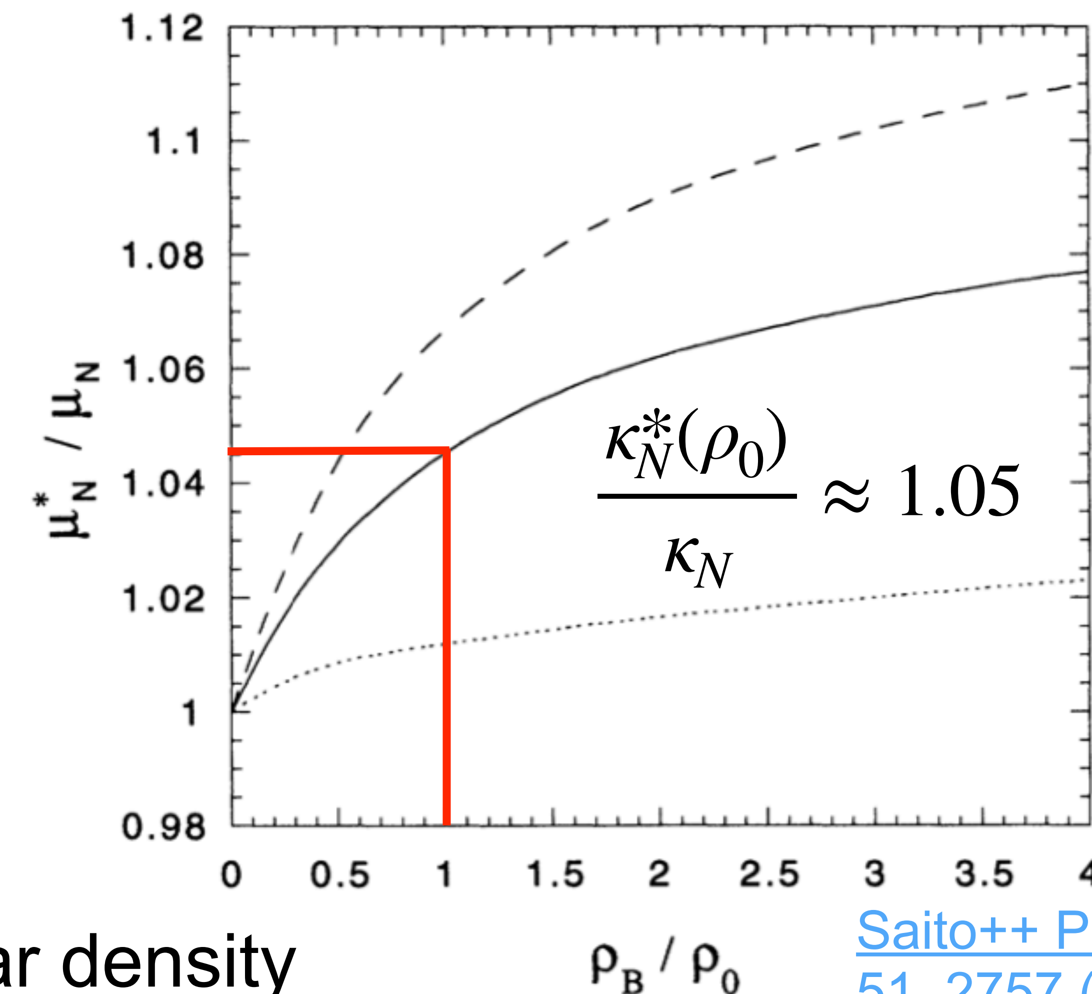
Bass, Acta Phys. Pol. B 52, 42 (2021)
Bass++, arXiv:2212.04795 [nucl-th]

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)

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

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

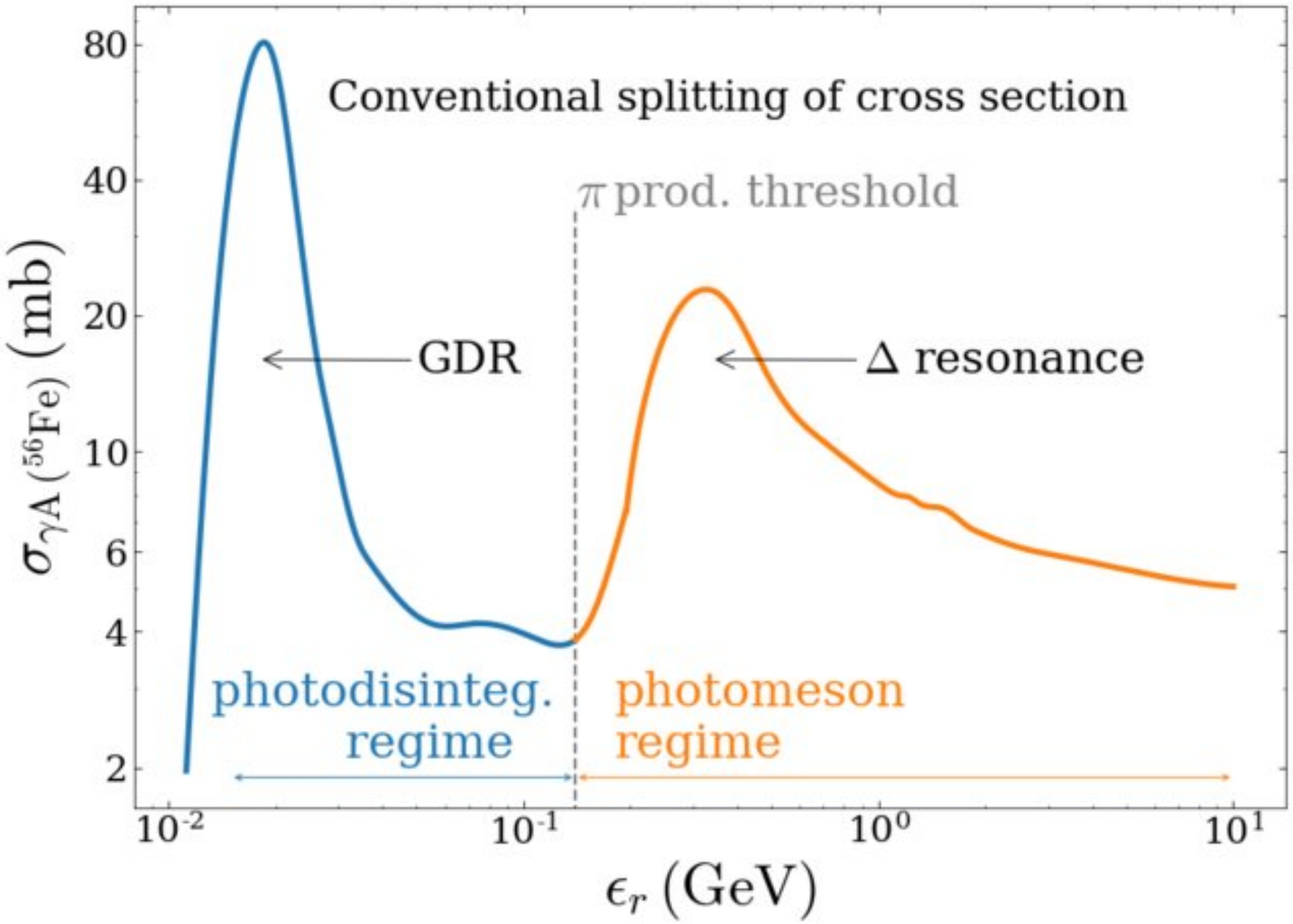
This allows us to calculate κ for all stable nuclei with spin and compute the static part of the GDH sum rule.

Nuclear spectrum

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

photo excitation of nucleus
properties of nucleus

photoproduction of hadrons
properties of nucleon



negative

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

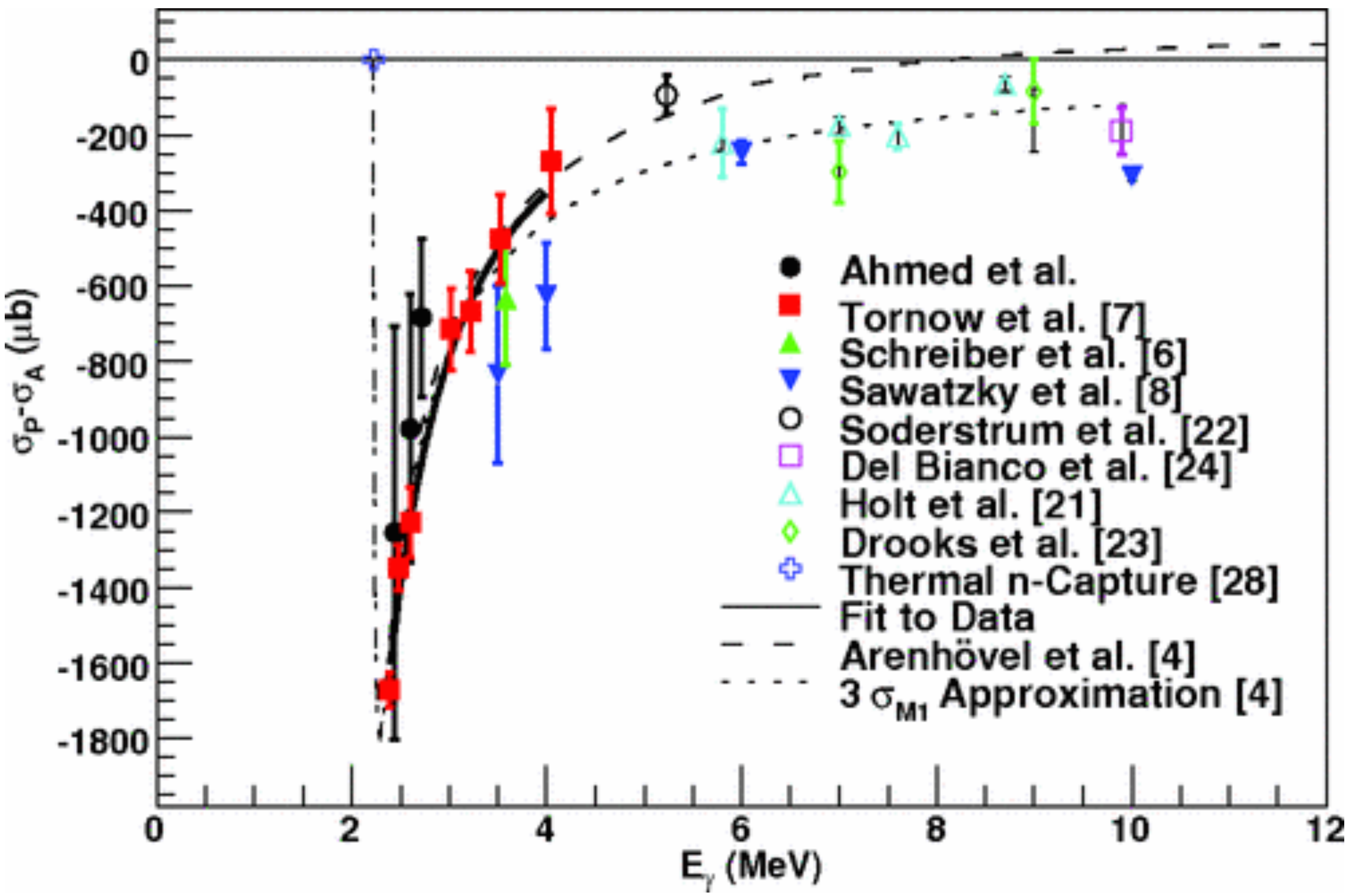
example for ^{7}Li

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

Morejon++ JCAP 11, 007 (2019)

Deuteron

Large negative GDH integrand at low energy.

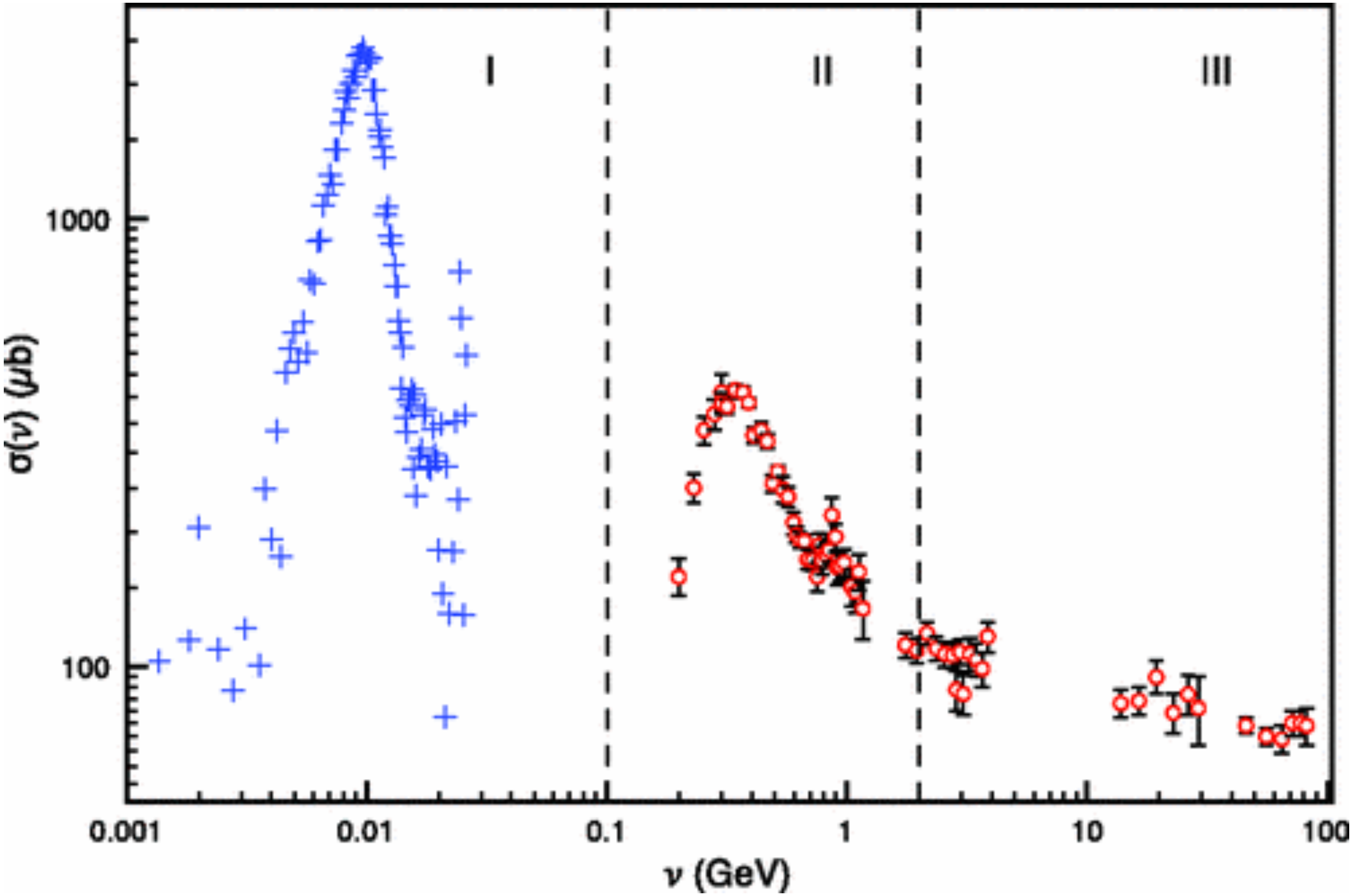


Deuteron GDH indirect

Ahmed++, PRC 77, 044005 (2008)

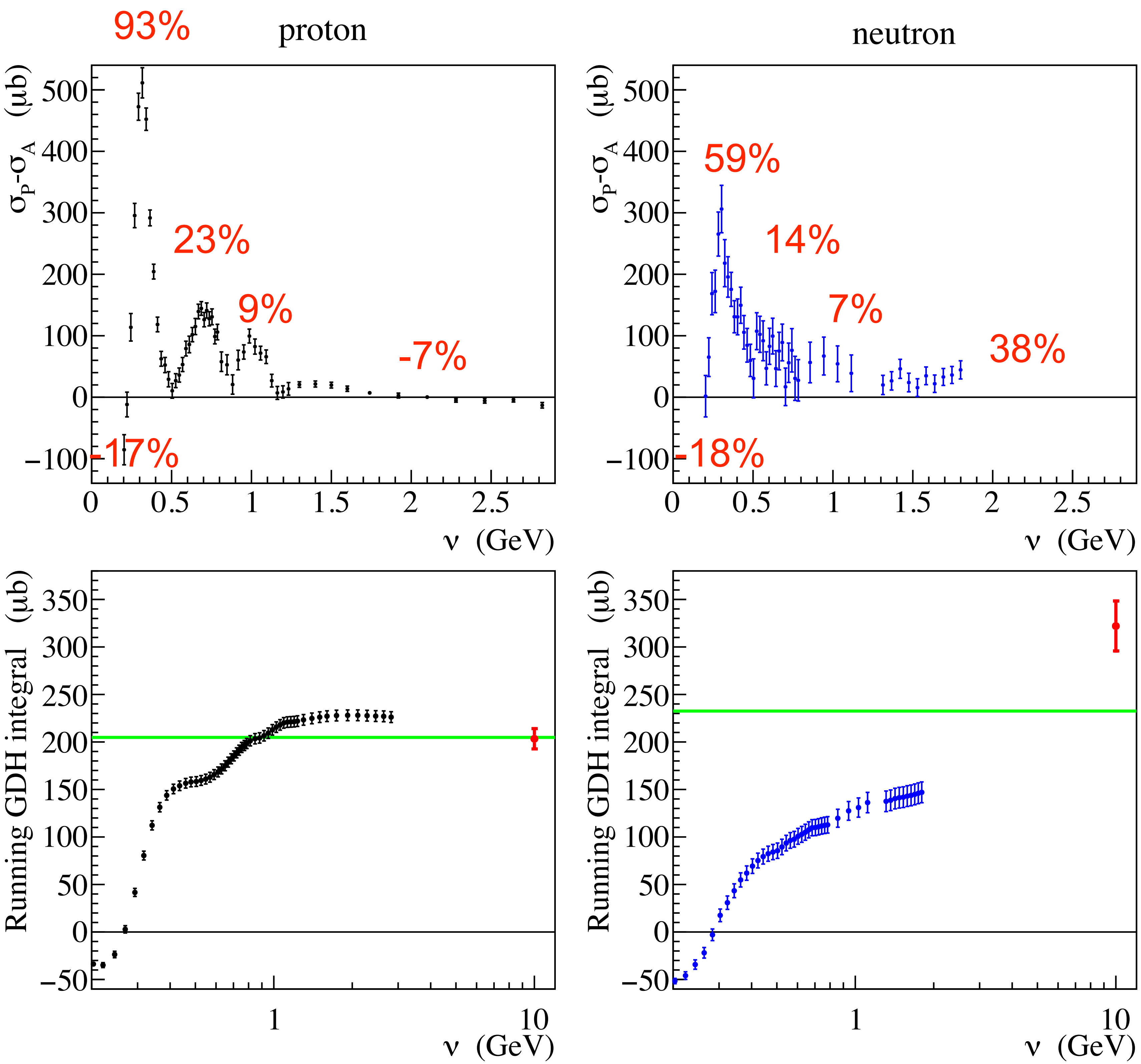
Nuclear spectrum

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



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

Modification of bound nucleons



Dynamic (integral) Side

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

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

Δ(1232)

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

3rd resonance and Regge modification

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	μ	κ	M	I_{GDH}
^{1}H	$1/2^+$	2.793	1.793	0.9383	204.8
^{2}H	1^+	0.857	−0.1426	1.875	0.6484
^{3}He	$1/2^+$	−2.128	−8.383	2.808	499.9
^{7}Li	$3/2^-$	3.256	4.598	6.532	83.39
^{13}C	$1/2^-$	0.702	3.131	12.11	3.753
^{17}O	$5/2^+$	−1.894	−14.44	15.83	233.4
^{19}F	$1/2^+$	2.628	40.94	17.69	300.5

Target FOM

	J^π	P	species	molecule	dilution F	FOM P^2F ($\times10^{-3}$)	days 12 GeV	days 4 GeV
^{1}H	$1/2^+$	90%	$\vec{p}$	C_4H_9OH	$10/74 = 0.135$	110	7	4
^{2}H	1^+	80%	$\vec{n},\ \vec{p}$	C_4D_9OD	$10/84 = 0.119$	76	10	6
^{7}Li	$3/2^-$	80%	$\vec{p}$	$^7Li^2H$	$1/9 = 0.111$	71	11	6
^{13}C	$1/2^-$	60%	$\vec{n}$	C_4D_9OD	$4/78 = 0.051$	4.6	42	24
^{17}O	$5/2^+$	80%	$\vec{n}$	$C_4D_9{}^{17}OD$	$1/75 = 0.013$	8.5	90	51
		80%	$\vec{n}$	$H_2{}^{17}O$	$1/19 = 0.053$	34	23	13
^{19}F	$1/2^+$	90%	$\vec{p}$	$^6Li^{19}F$	$1/25 = 0.040$	32	24	14
		80%	$\vec{p}$	$C_3H_2{}^{19}F_6O$	$6/168 = 0.036$	23	34	19

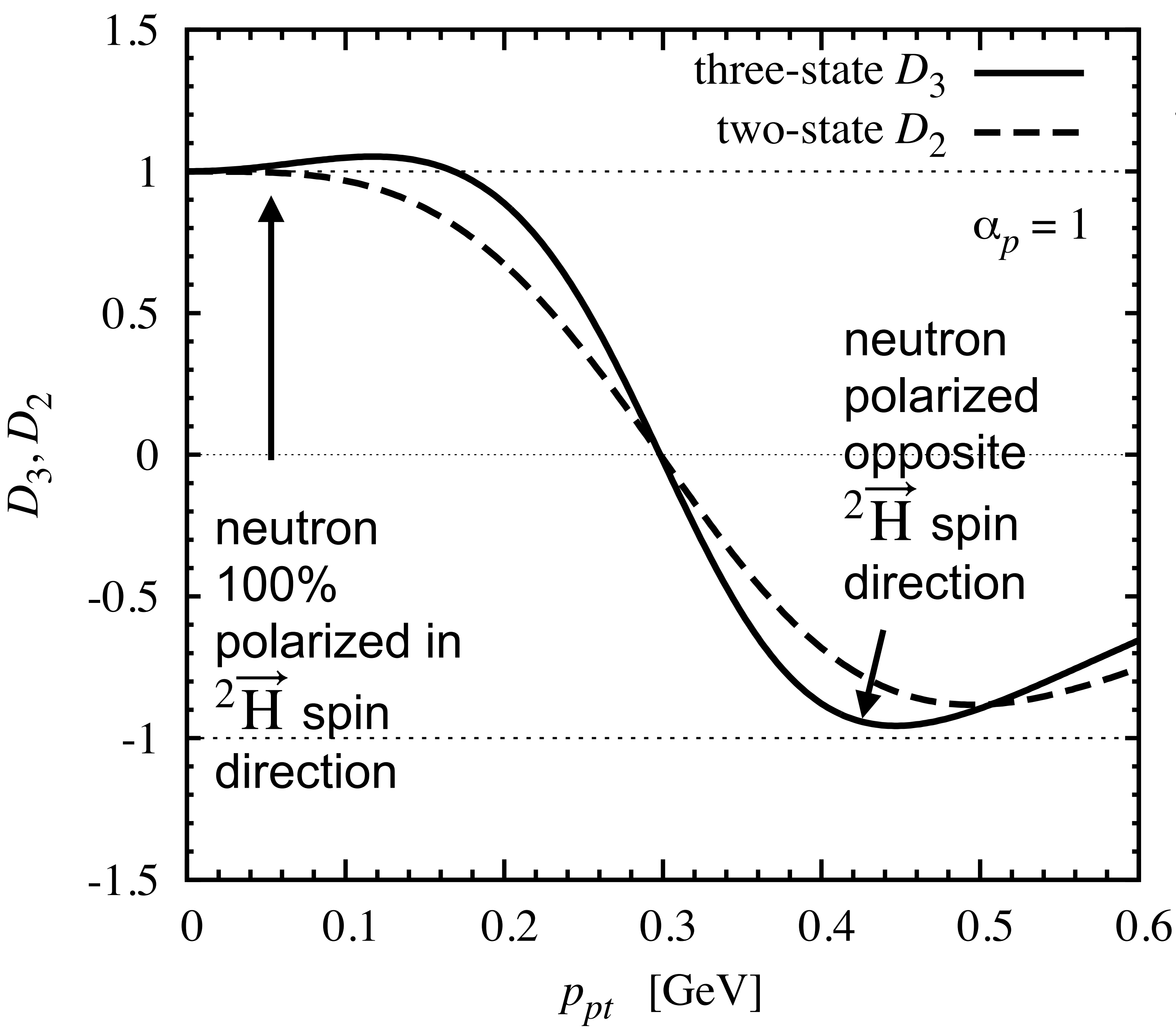
Continuous polarization using dynamic nuclear polarization (DNP)
Temperature 200-300 mK.
Internal superconducting coils, increase field to 2.5 T, improve homogeneity.

SRC Measurements with Photon Probe

Exclusive Measurements

Deuteron Spin Structure

Required for using the deuteron as a polarized neutron target.



$$\mathcal{D}_2(\alpha_P, |p_{pT}|) \equiv \frac{\Delta\mathcal{S}_S(\alpha_P, |p_{pT}|)}{[\mathcal{S}_U + \mathcal{S}_T](\alpha_P, |p_{pT}|)}$$

$$\mathcal{D}_3(\alpha_P, |p_{pT}|) \equiv \frac{\Delta\mathcal{S}_S(\alpha_P, |p_{pT}|)}{\mathcal{S}_U(\alpha_P, |p_{pT}|)}$$

$\mathcal{S}_U$, $\Delta\mathcal{S}_S$, $\mathcal{S}_T$ are three distinct LF helicity projections of the spectral function

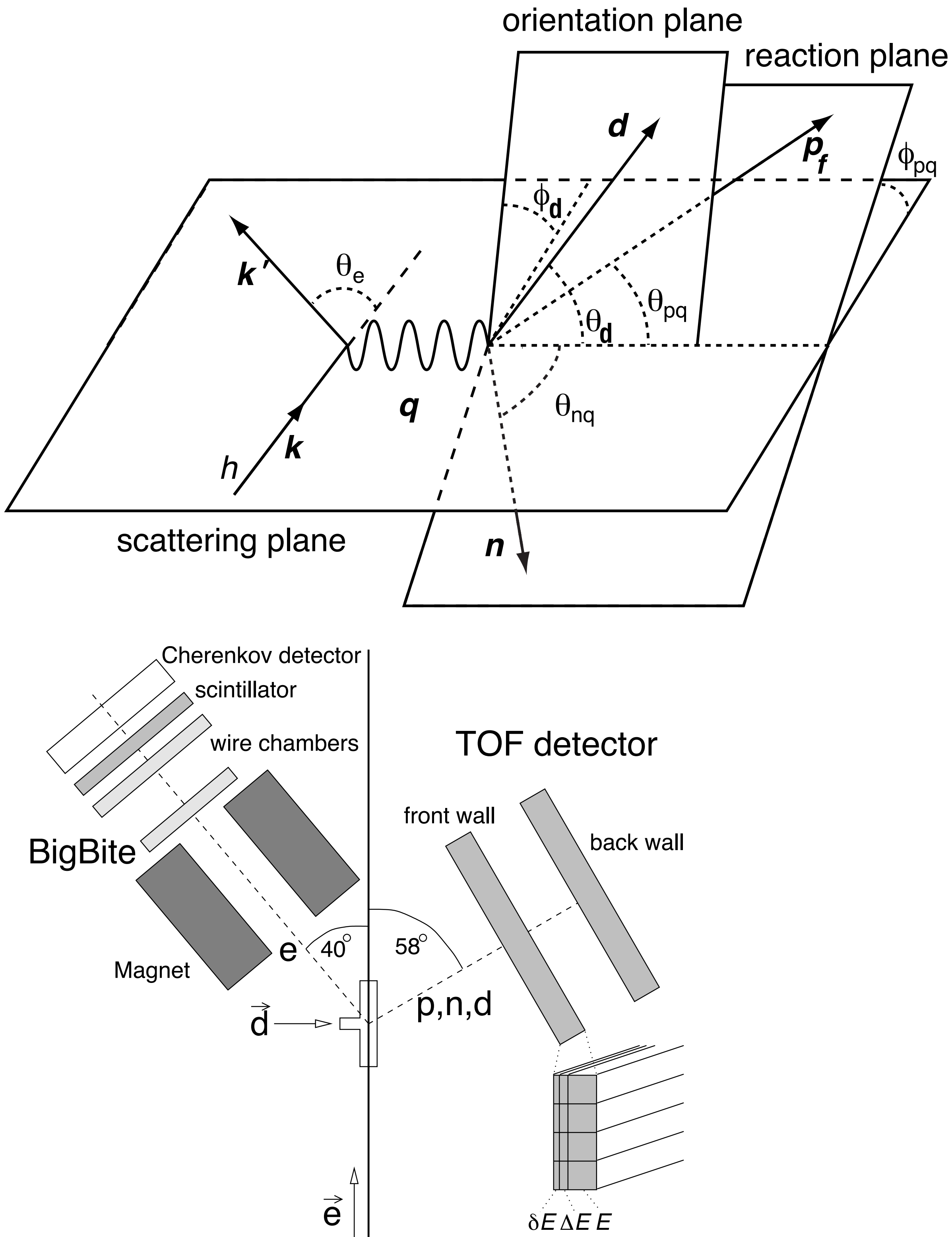
describing an unpolarized, vector-polarized, and tensor-polarized ensemble quantized along the z-axis,

W. Cosyn, C. Weiss / PLB 799 (2019) 135035

Deuteron Spin Structure

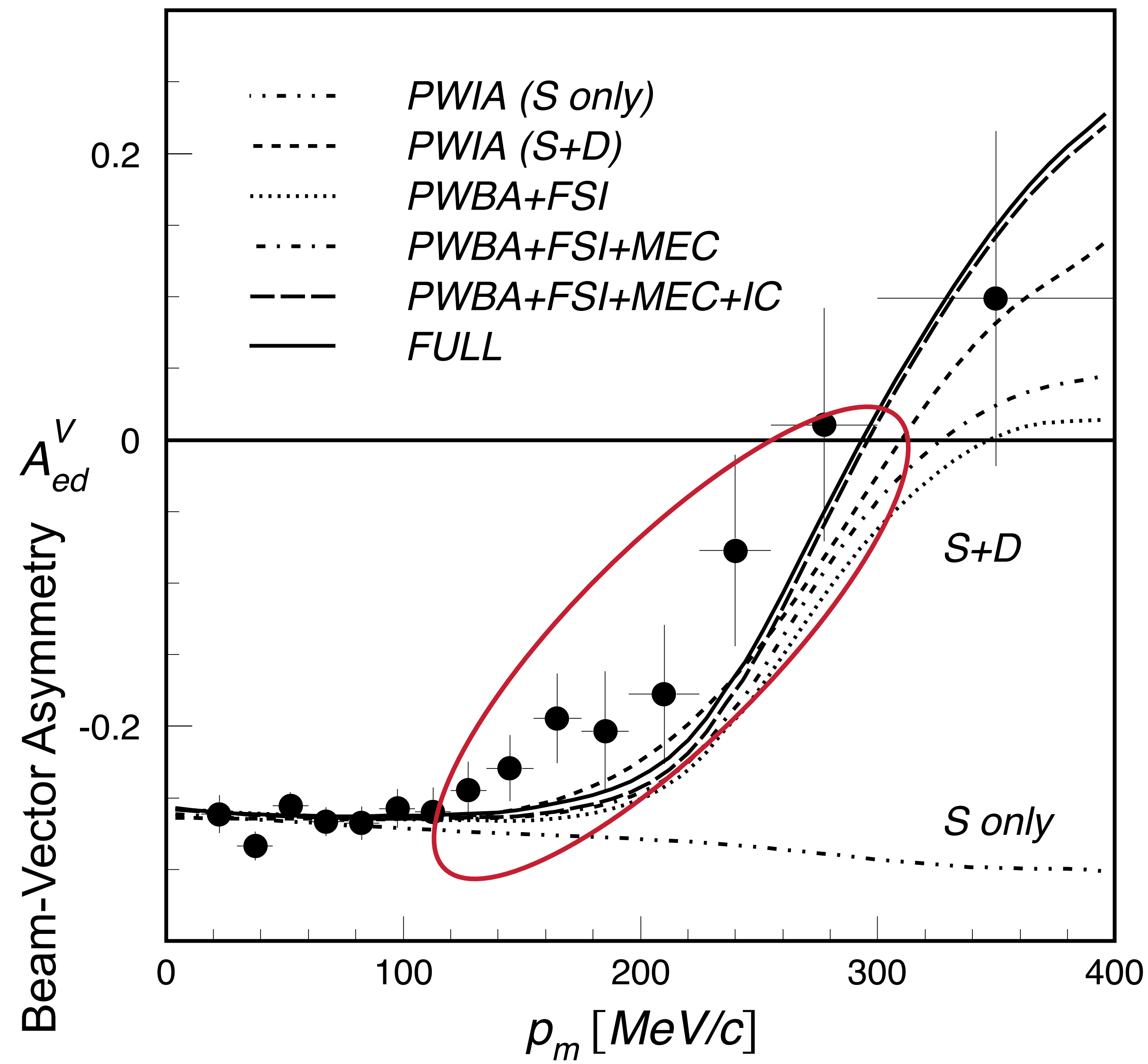
$$\sigma = \sigma_0(1 + P_1^d A_d^V + P_2^d A_d^T + h(A_e + P_1^d A_{ed}^V + P_2^d A_{ed}^T))$$

Arenhövel PhysRevC.46.455



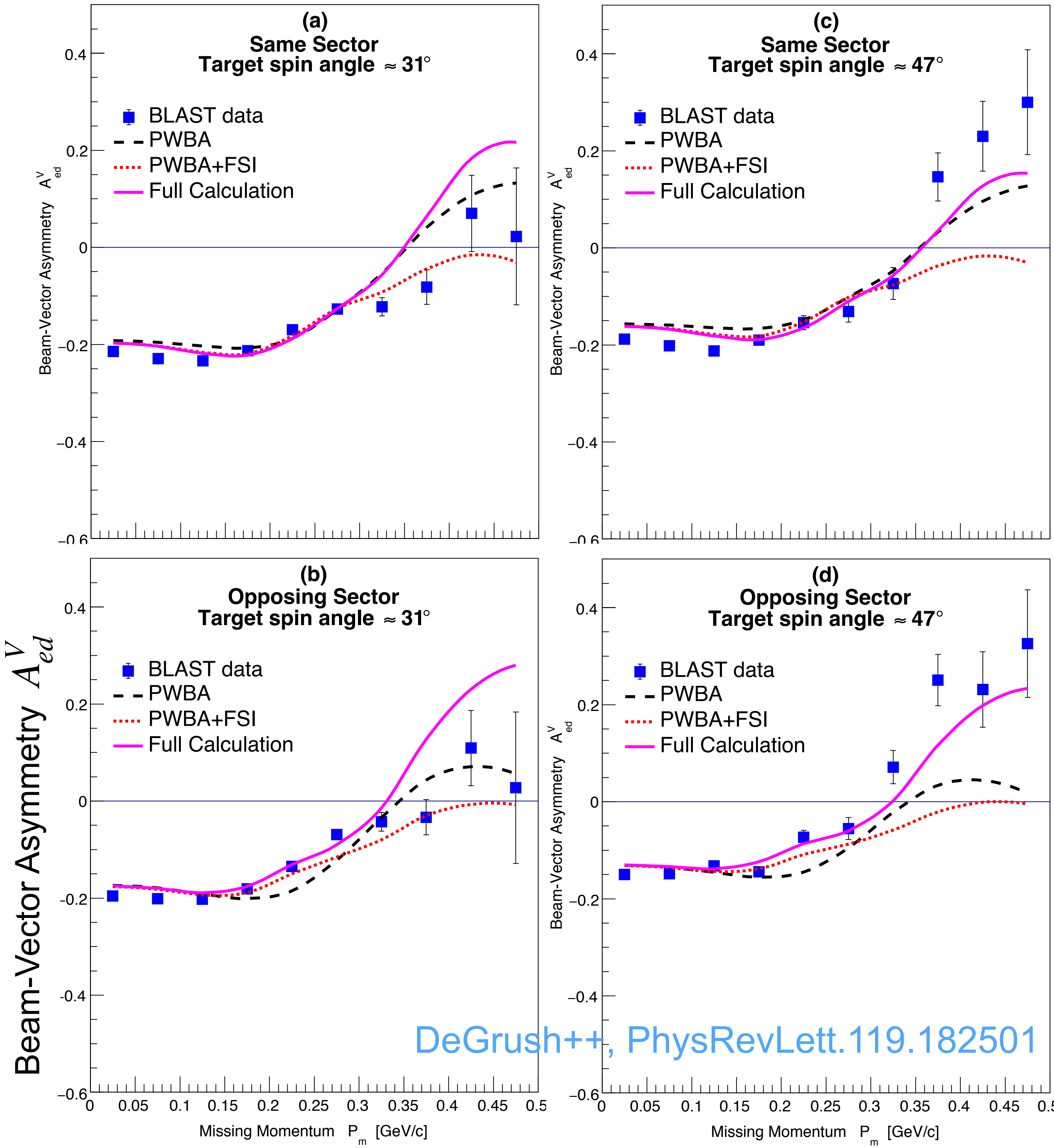
$^2\overrightarrow{H}(\vec{e}, e'p)n$ at Nikhef

Paschier++ PhysRevLett.88.102302



${}^2\overrightarrow{H}(\vec{e}, e'p)n$ at Bates

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

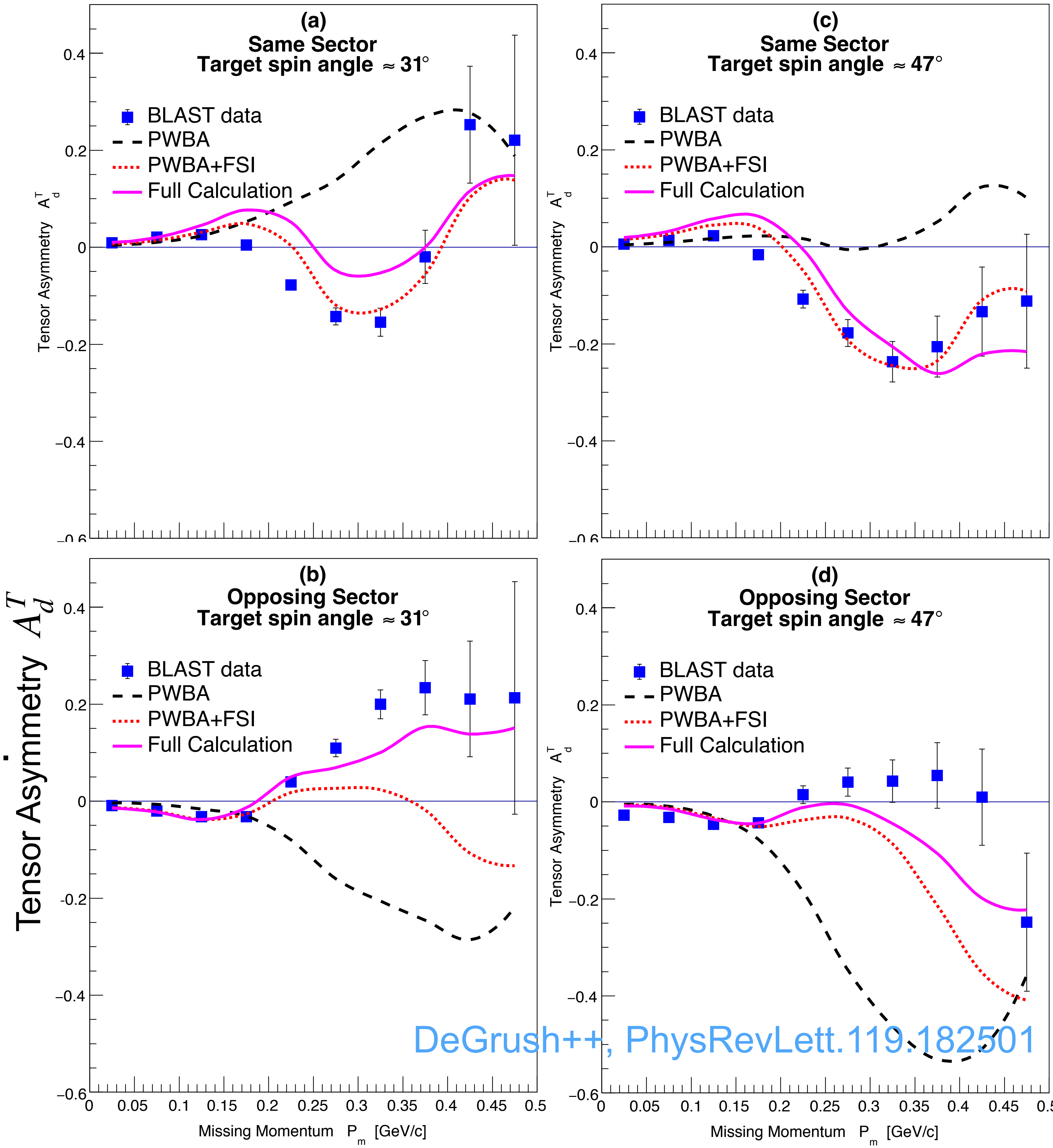


DeGrush++, PhysRevLett.119.182501

$^2\overrightarrow{H}(\vec{e}, e'p)n$ at Bates

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

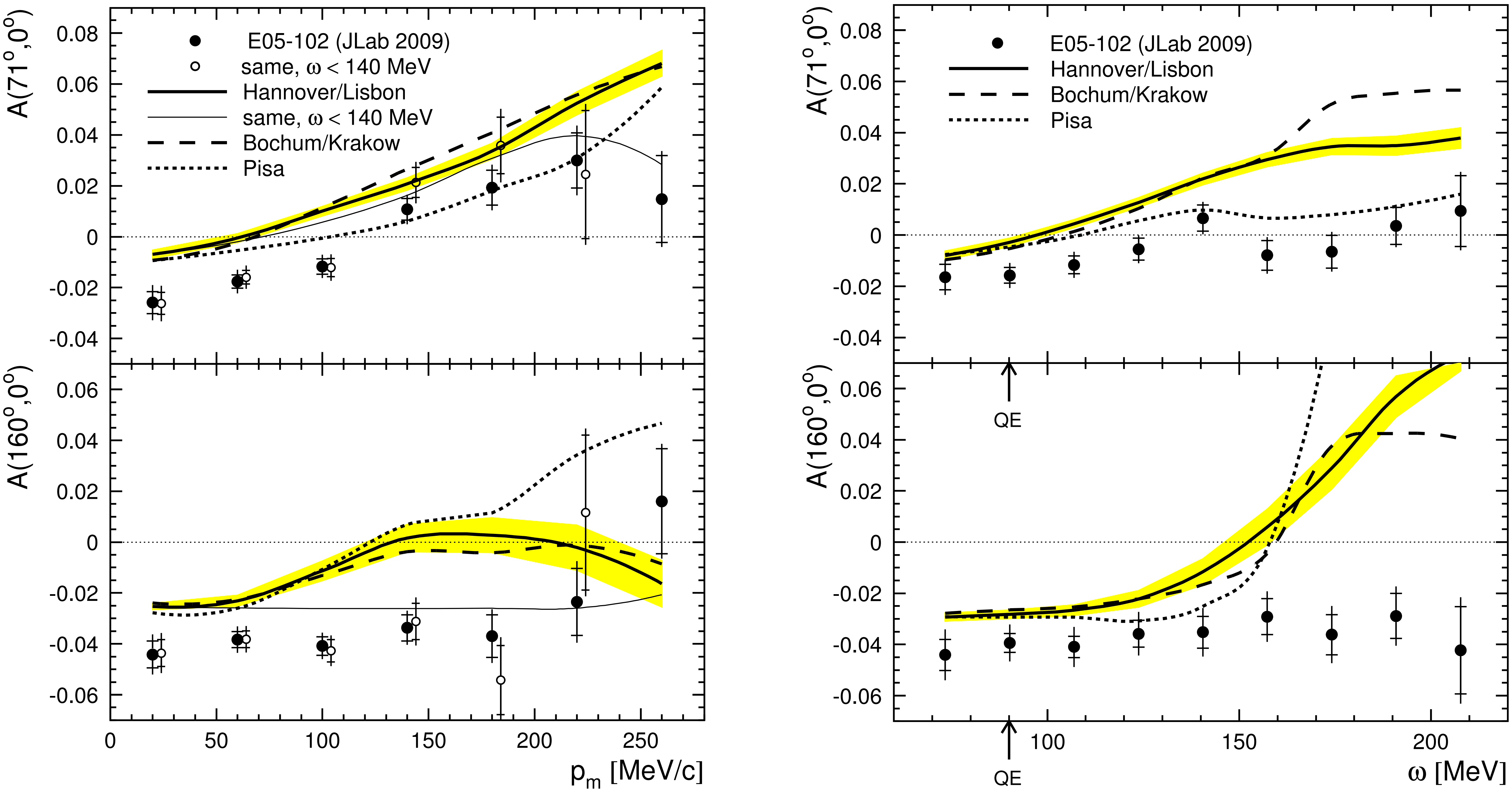


DeGrush++, PhysRevLett.119.182501

Helium-3 Spin Structure

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

Mihovilovic++ PhysRevLett.113.232505



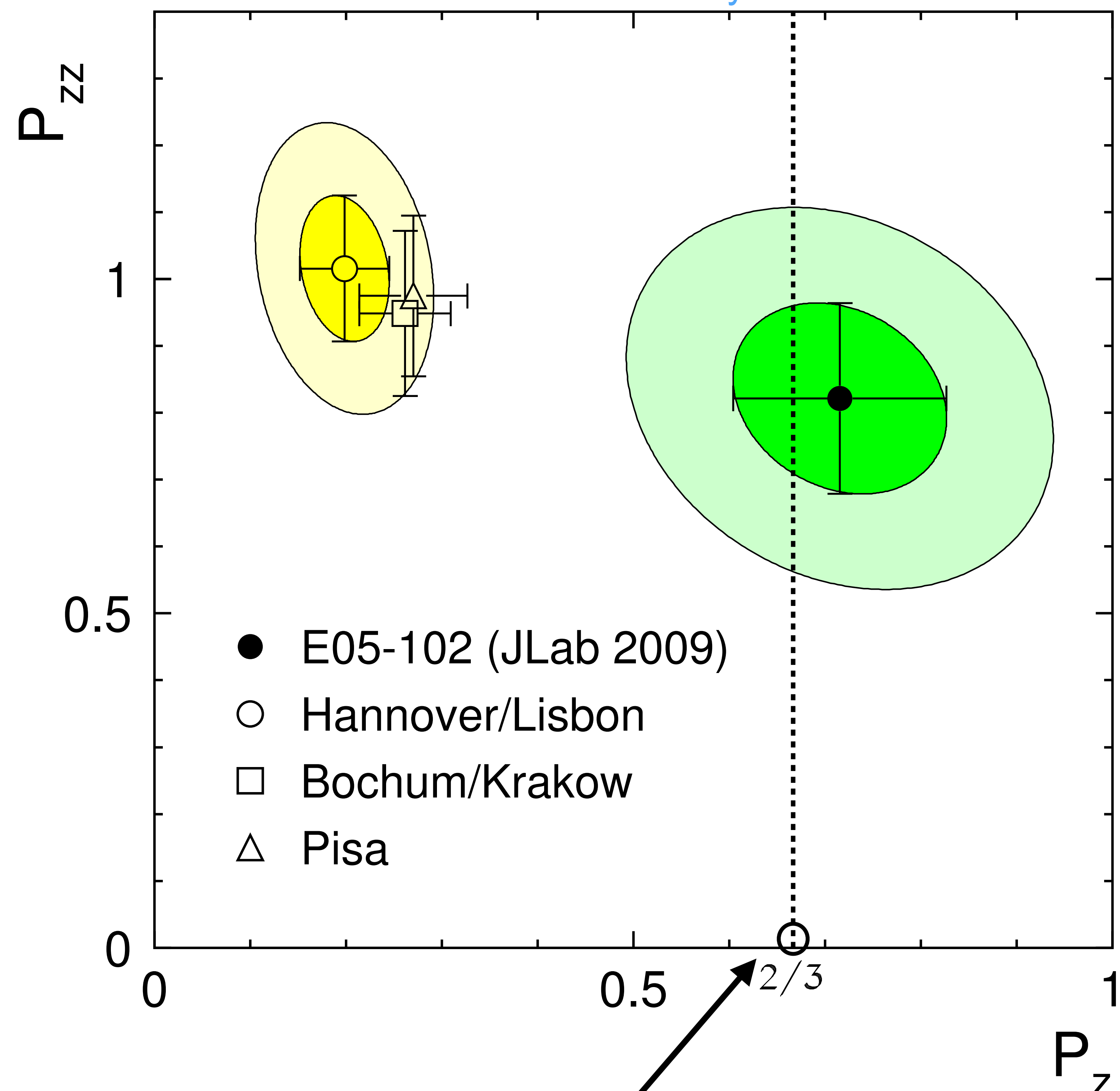
$p_m = |\boldsymbol{q} - \boldsymbol{p}_d|$ is momentum of recoil proton

Helium-3 Spin Structure

Effective polarizations from asymmetries as $p_m \to 0$

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

Mihovilovic++ PhysRevLett.113.232505



Simple Clebsch-Gordan expectation

Short Range Correlated np pairs

Experiment E12-14-001 approved to study polarized EMC effect using DIS on $^7\mathrm{Li}$ in Hall B.

- mean field model predict a significant polarized EMC effect
- SRC pairs might produce no effect if they are depolarized

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%.

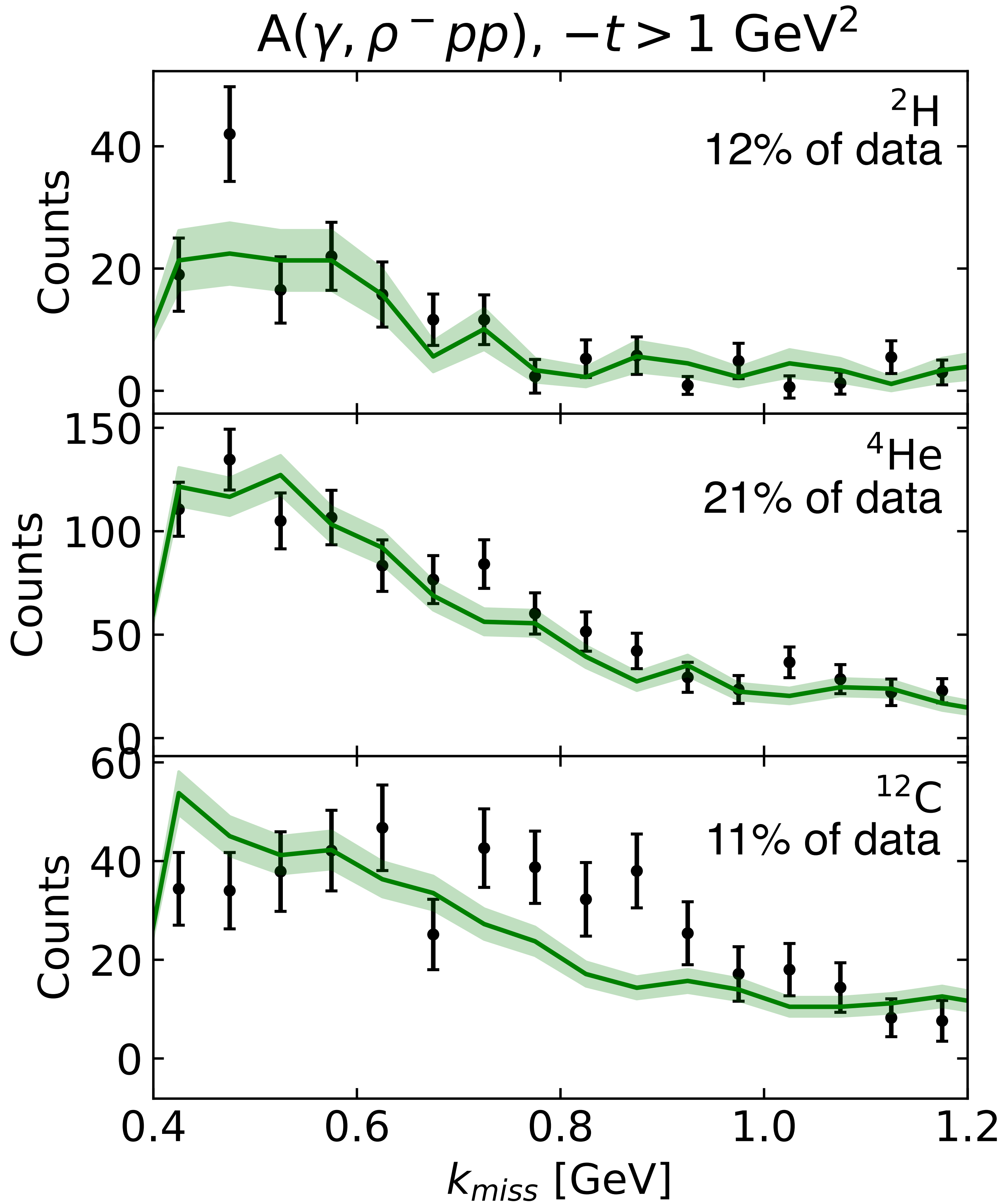
Thomas IJMP E27 (2018)

Expansion to Heavier Nuclei

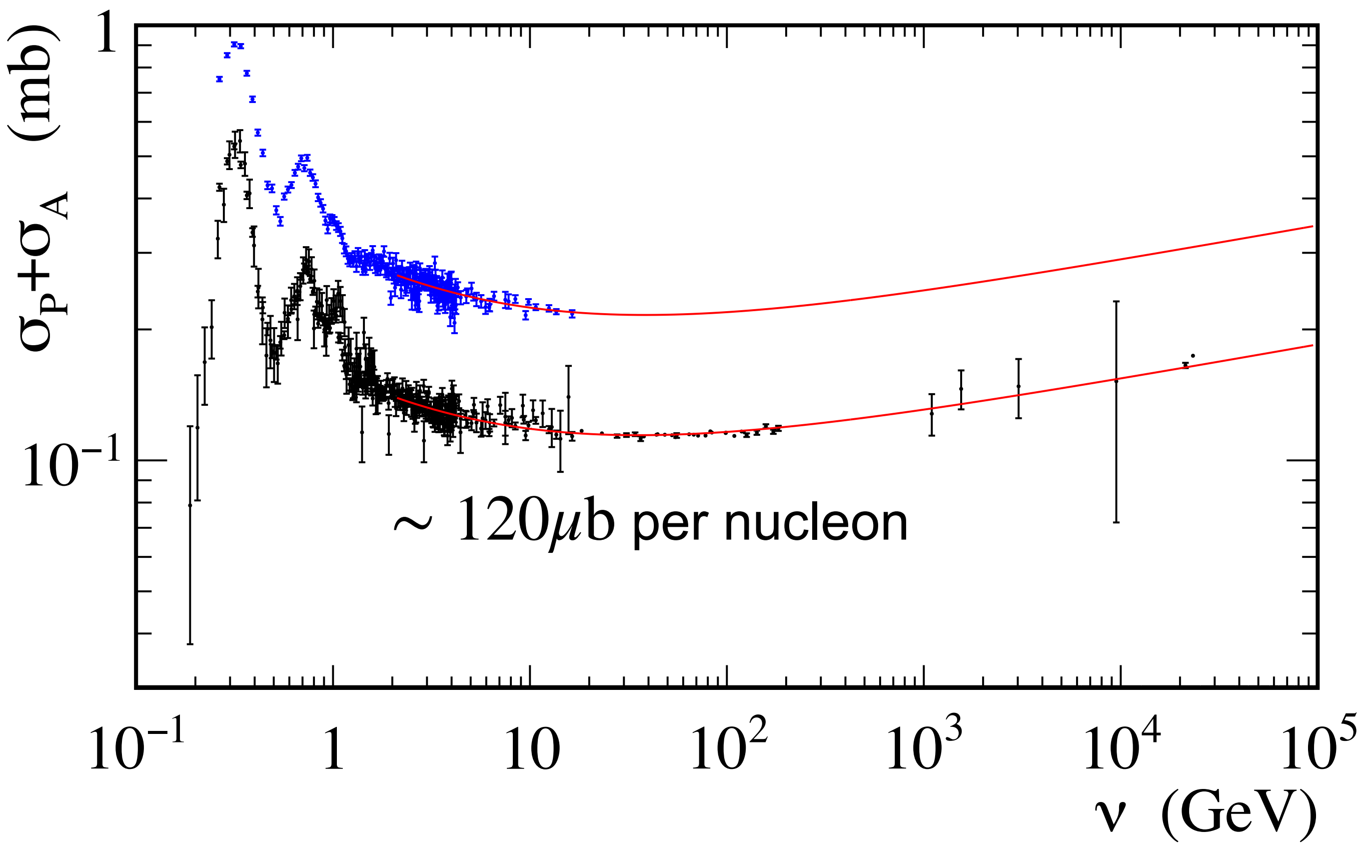
SRC/CT Experiment in Hall D

^{2}H	4 days	350 per day
^{4}He	10 days	520 per day
^{12}C	14 days	340 per day

events above $k_{\text{miss}} > 0.4$ GeV
$-t > 1$ GeV^2, $-u > 1$ GeV^2,
$E_\gamma > 7$ GeV



Inclusive Asymmetries

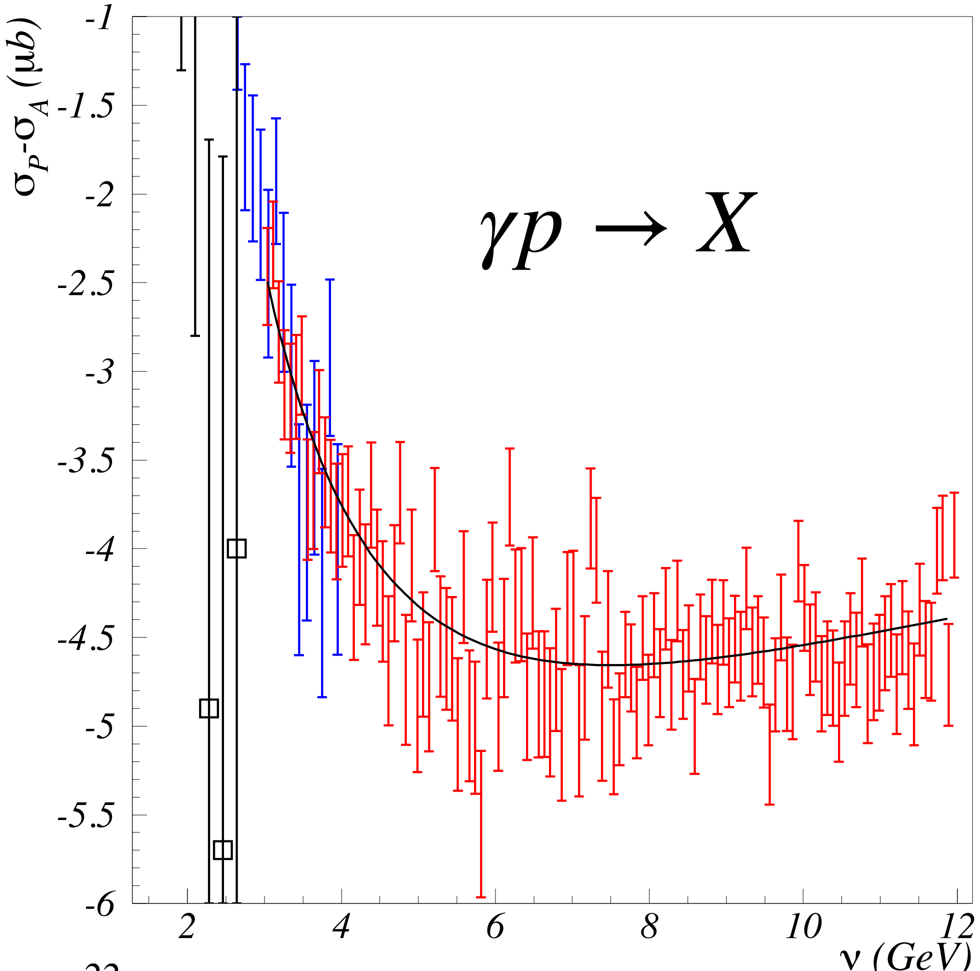


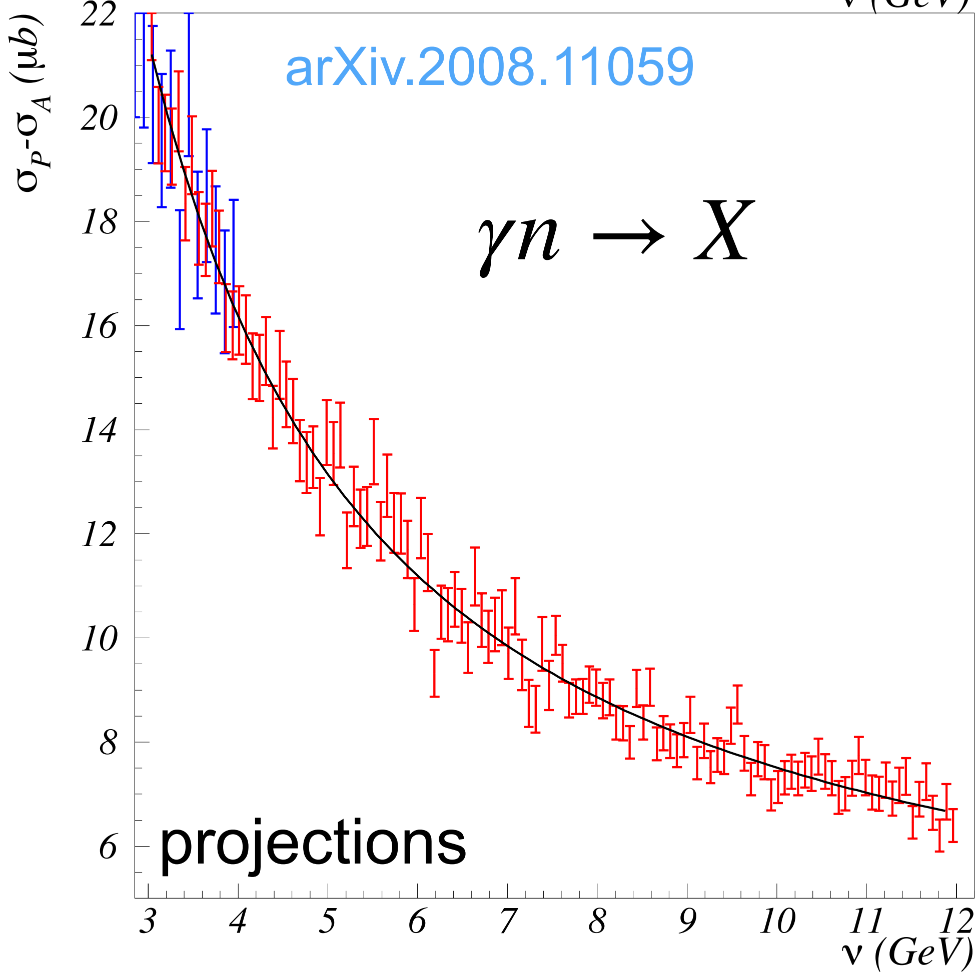
Regge phenomenology predicts inclusive asymmetries:

proton $-4\,\%$

neutron $5\,\%$ to $10\,\%$

Will be measured by REGGE

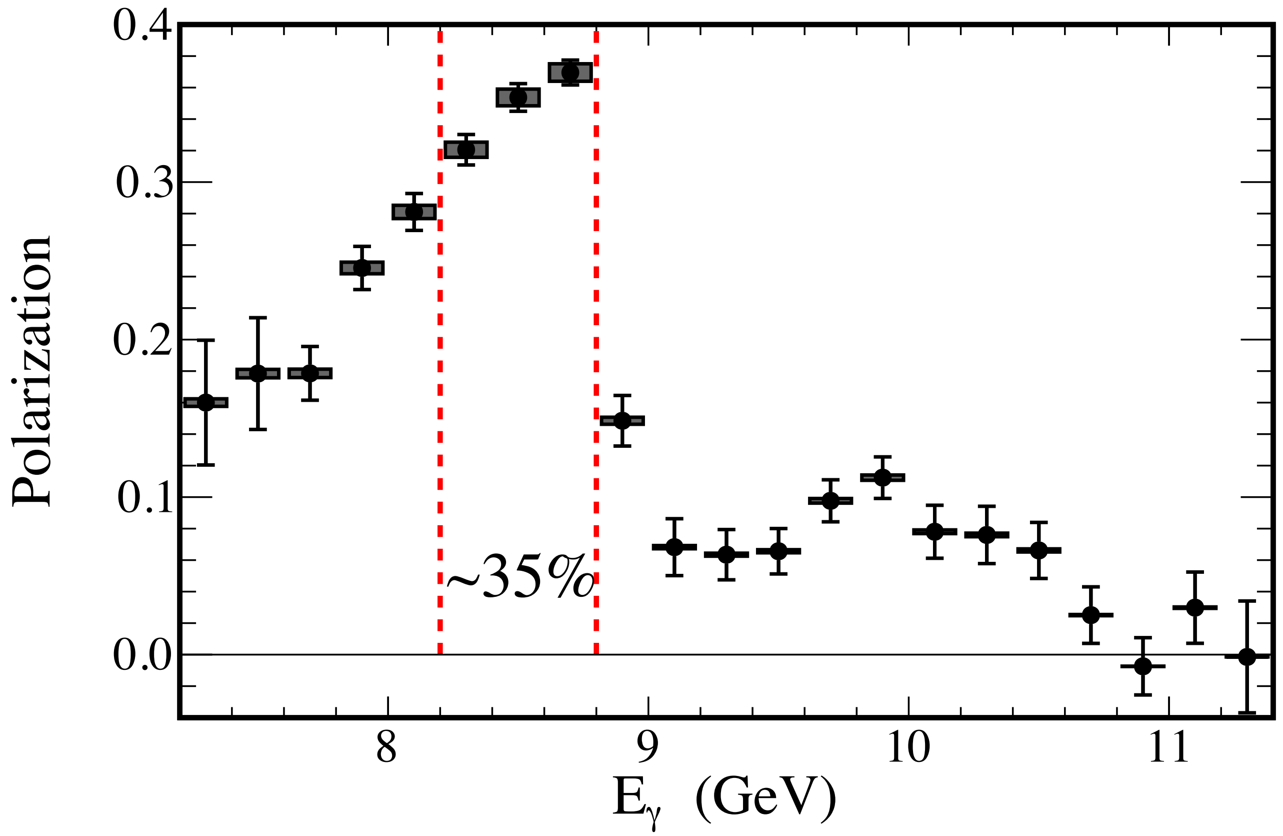


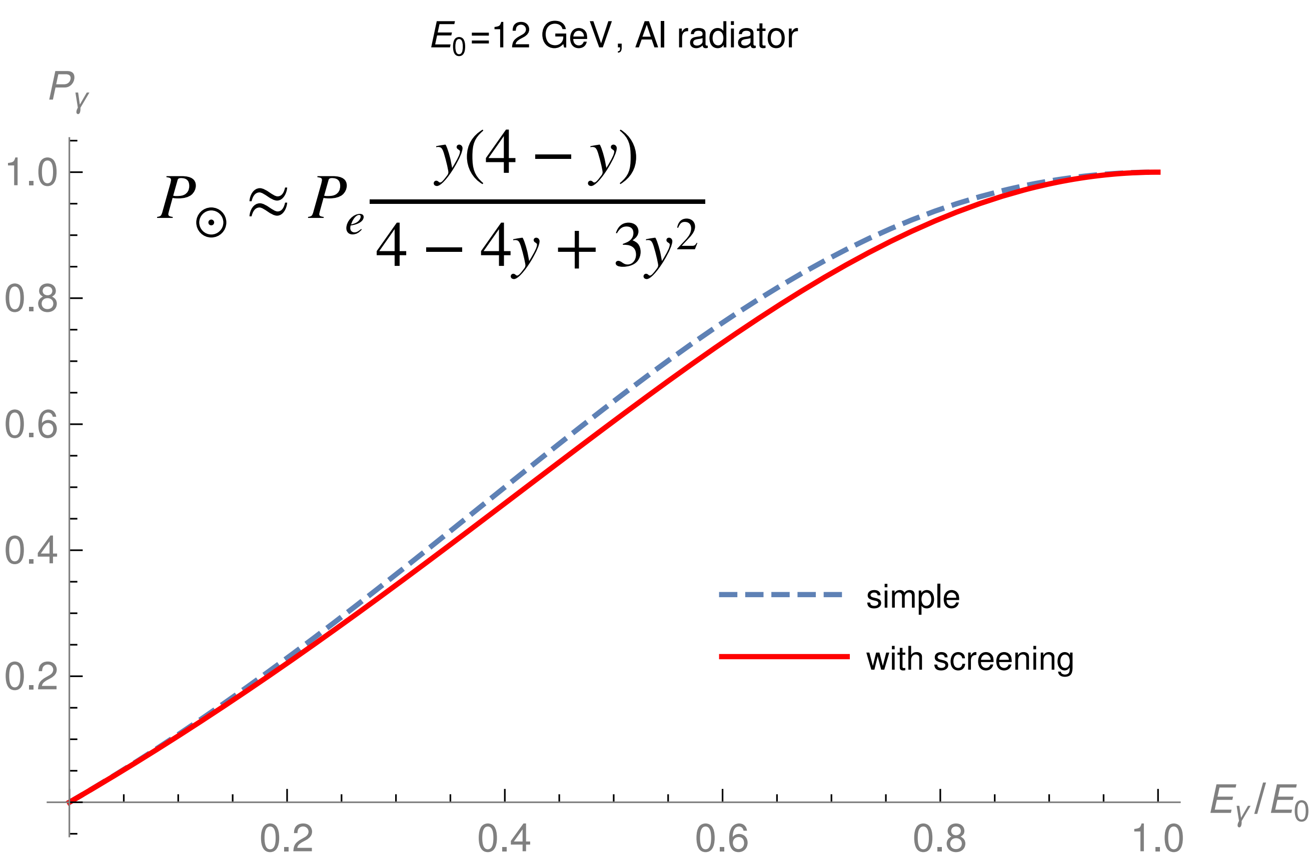


Exclusive Asymmetries

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

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



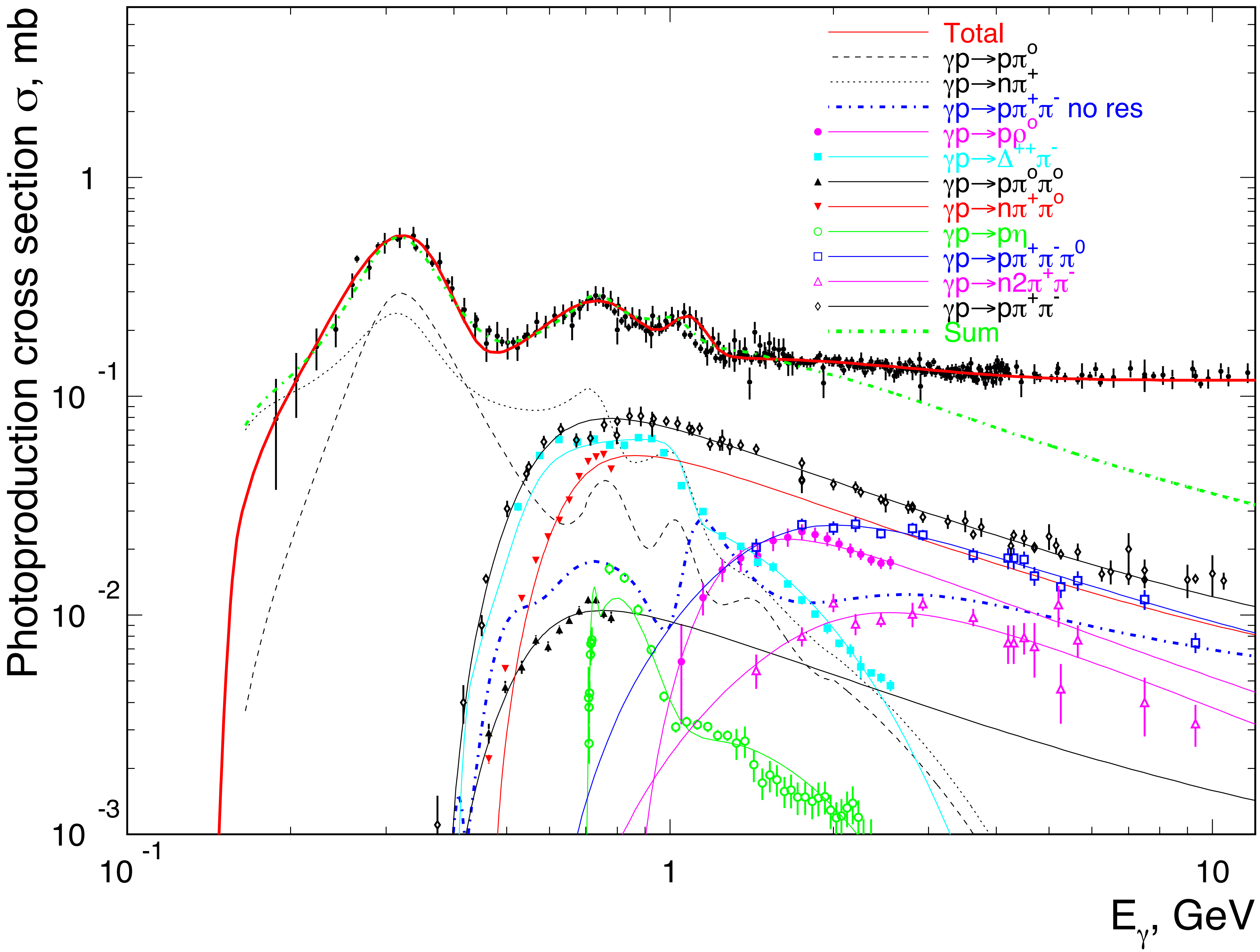


$$P_\odot \approx P_e \frac{y(4-y)}{4-4y+3y^2}$$

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

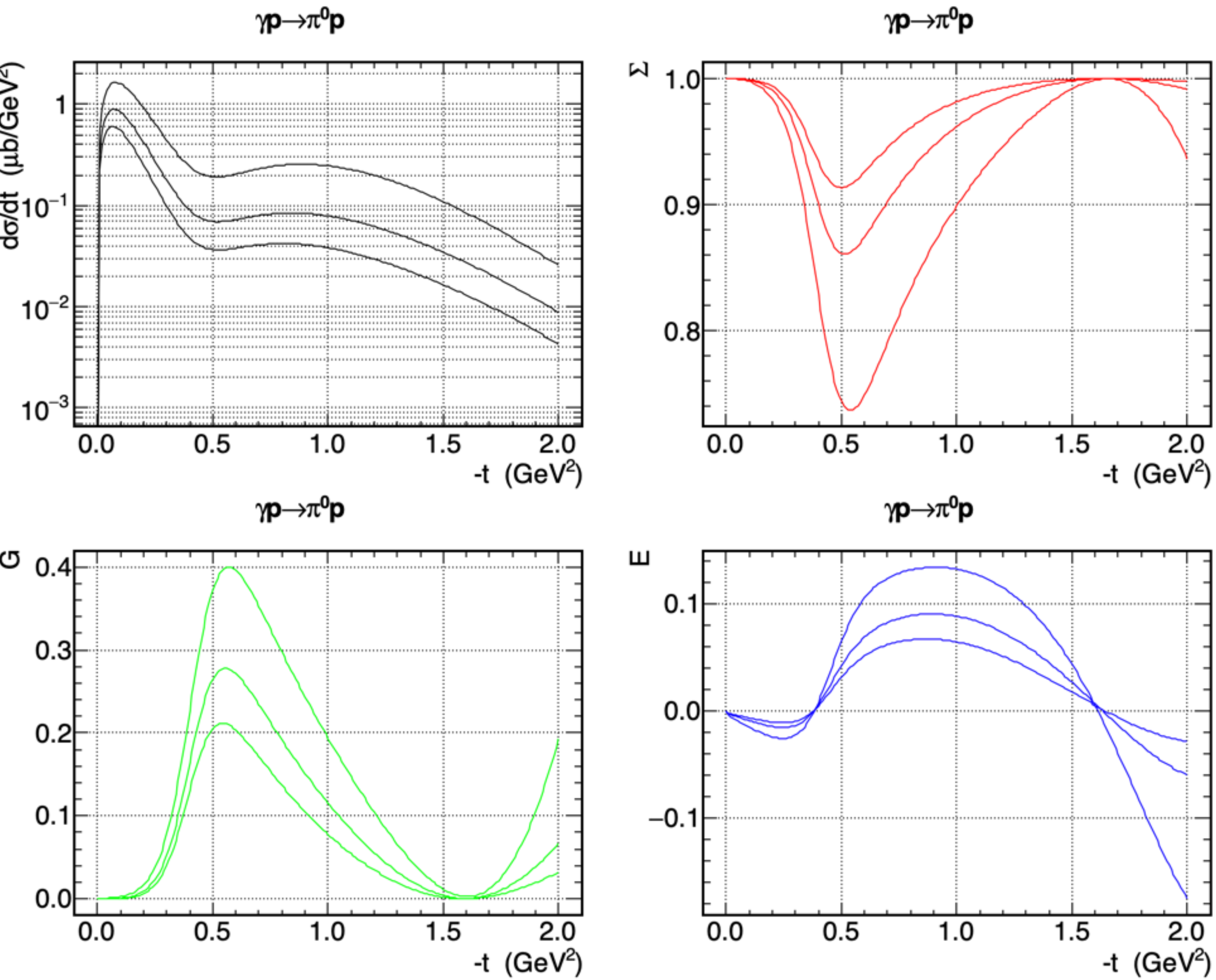
Final States

Vector meson production has highest cross section.



initial	final
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 calculation

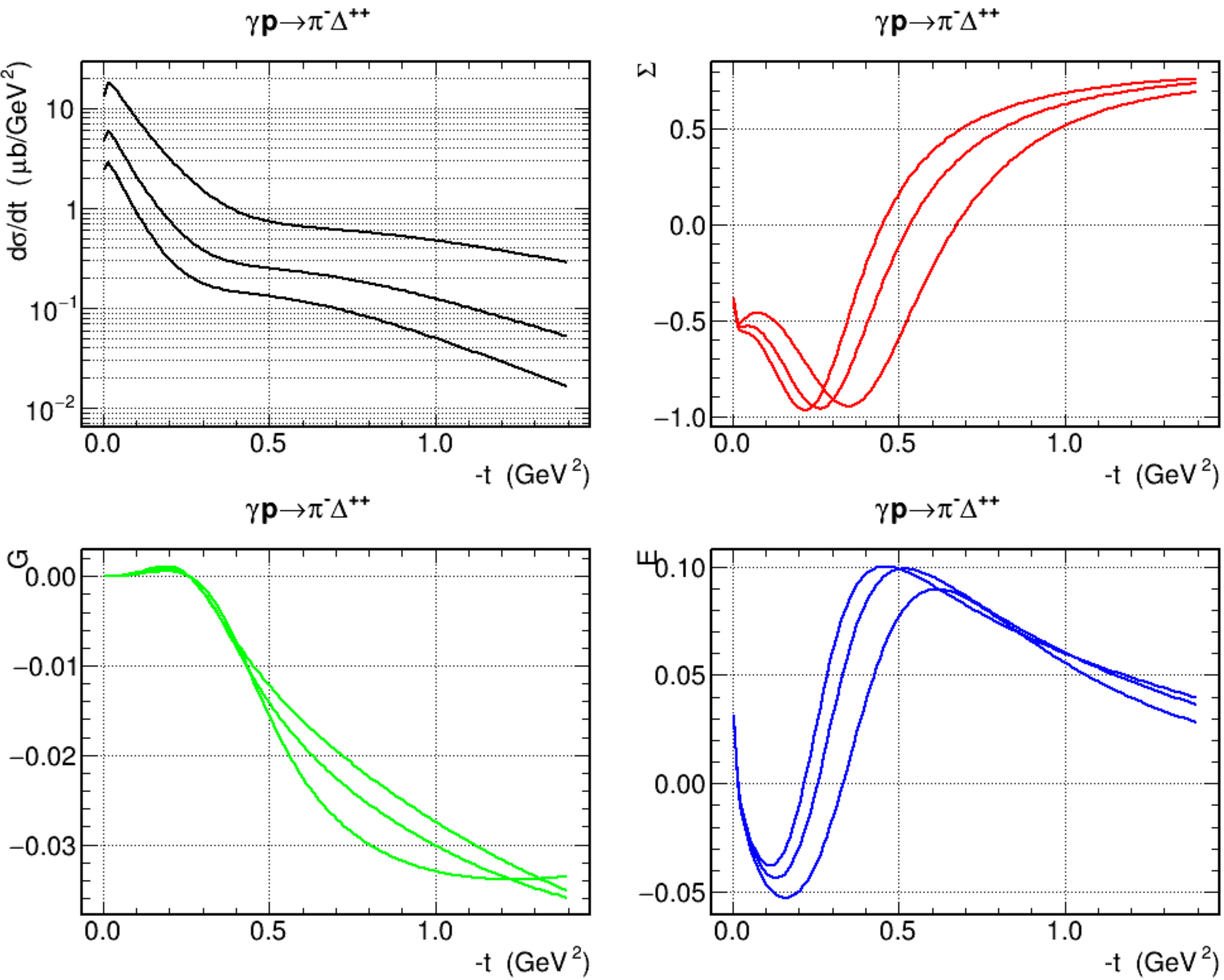
Curves at 4.5, 7.5, 10.5 GeV

Σ asymmetry matches data well

G and E asymmetries completely untested

Mathieu++, PHYSICAL REVIEW D 92, 074013 (2015)

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



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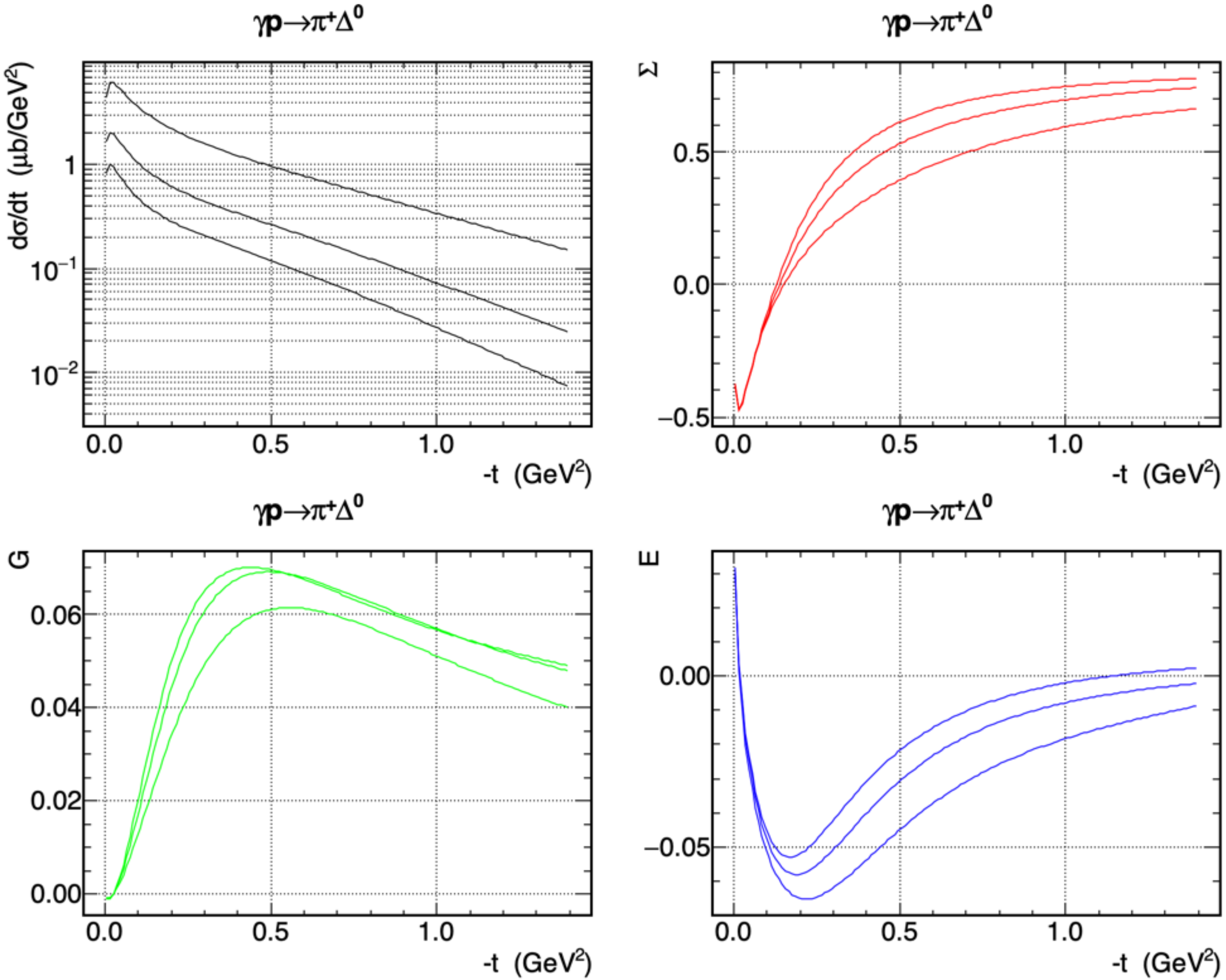
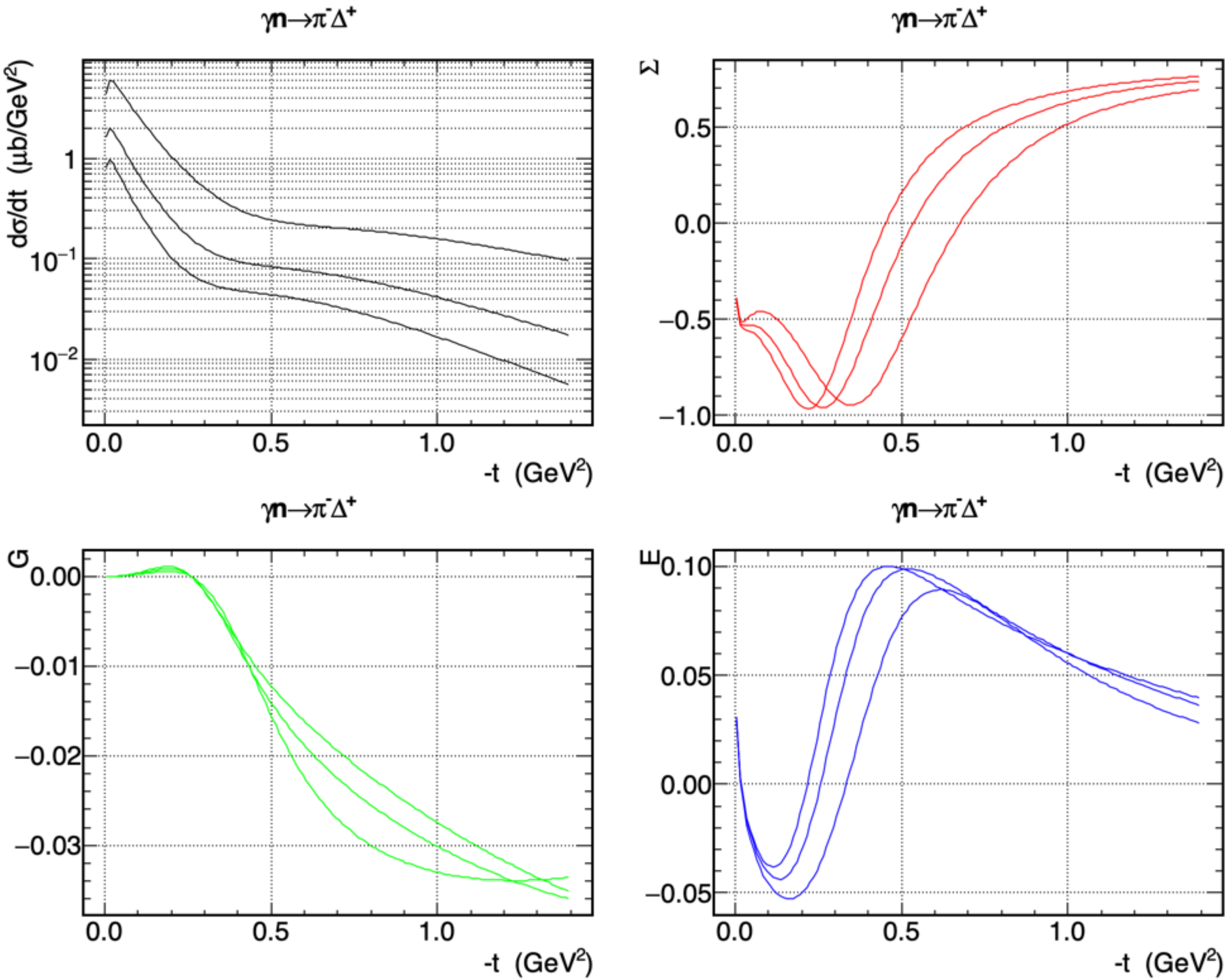
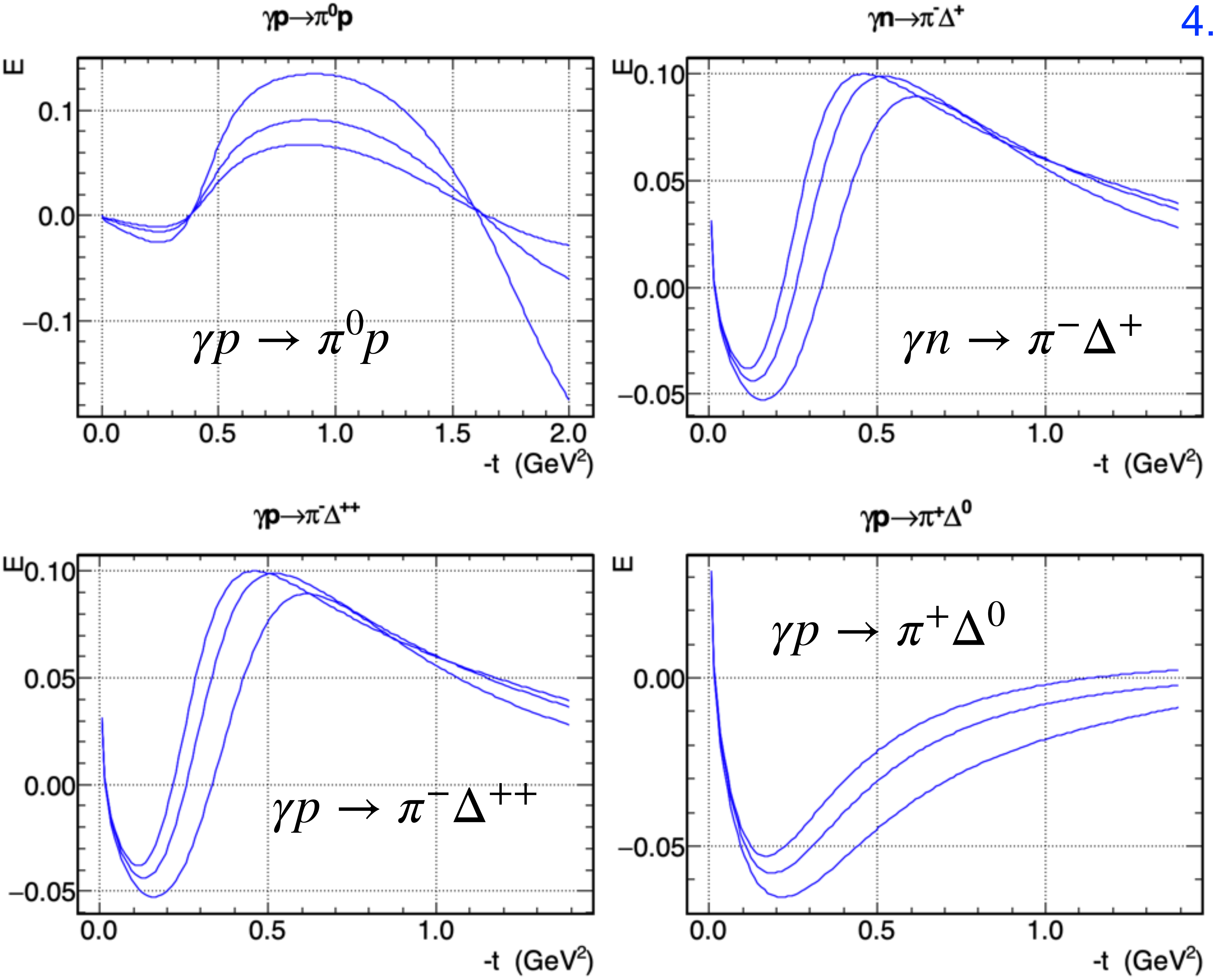


Example: $\gamma n \rightarrow \pi^- \Delta^+$

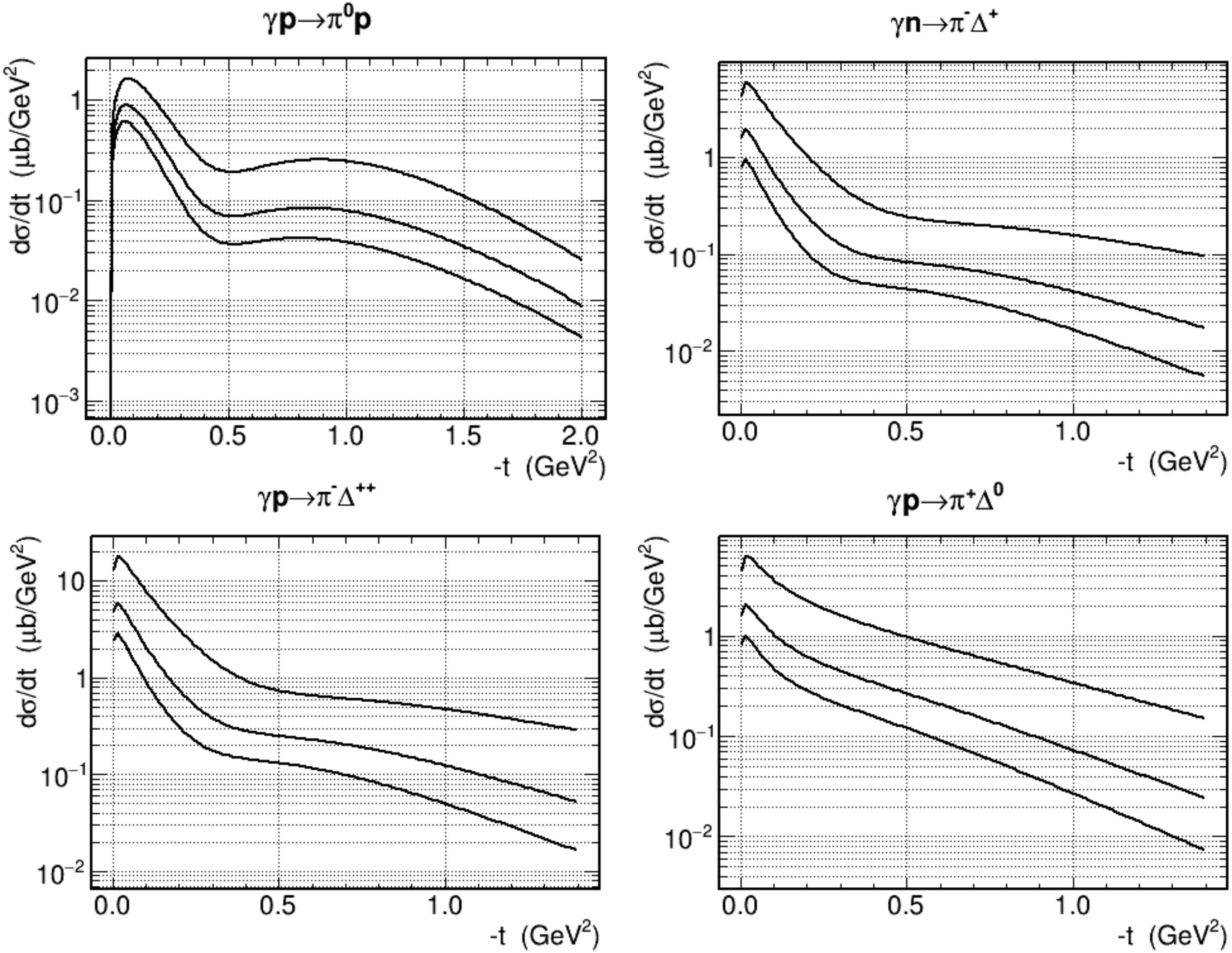


Asymmetry E in single π production

4.5, 7.5, 10.5 GeV



Cross Section in single π production



4.5 GeV
7.5 GeV
10.5 GeV

Prospects

The difficulty is primarily statistical
- Predicted asymmetries are smallish: 1% to 5%
- Cross sections are small for individual channels
- The photon beam polarization drops with energy
- There is a dilution from unpolarized nucleons

Detailed projections including the nuclear spectral function are needed

Tensor Polarization

A photon beam allows a very high deuteron vector polarization to be achieved.

This also means a very high tensor polarization (alignment) +65% to +75%.

What can we learn with a tensor polarized deuteron target and polarized photon beam?

Summary

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

The GDH integrand on nuclei may be sensitive to medium modifications in a novel way.

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.

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

Polarized targets are significantly easier with a photon beam which allows higher polarizations and potentially unique species. A very high tensor polarization is possible for deuterium.