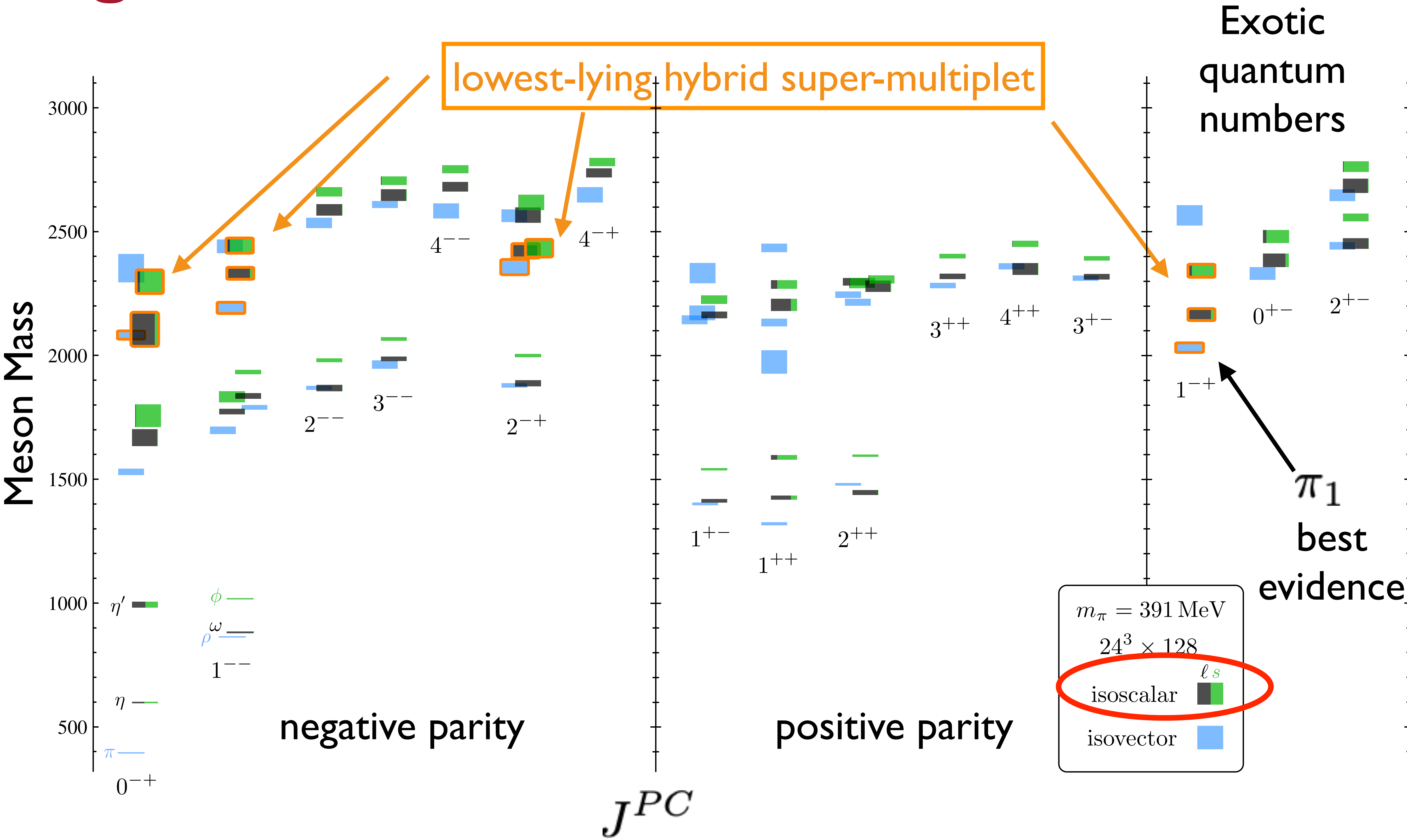
The Polarized Target Program at GlueX

Mark Dalton
for the GlueX Collaboration

Outline

1. Introduction to Hall D and GlueX
2. The GDH sum Rule
3. The approved experiment REGGE
4. Potential extensions to the polarized target program
   1. Spectroscopy
   2. Medium modifications in nuclei
   3. Tensor interaction in nuclei

Light Quark Mesons from Lattice

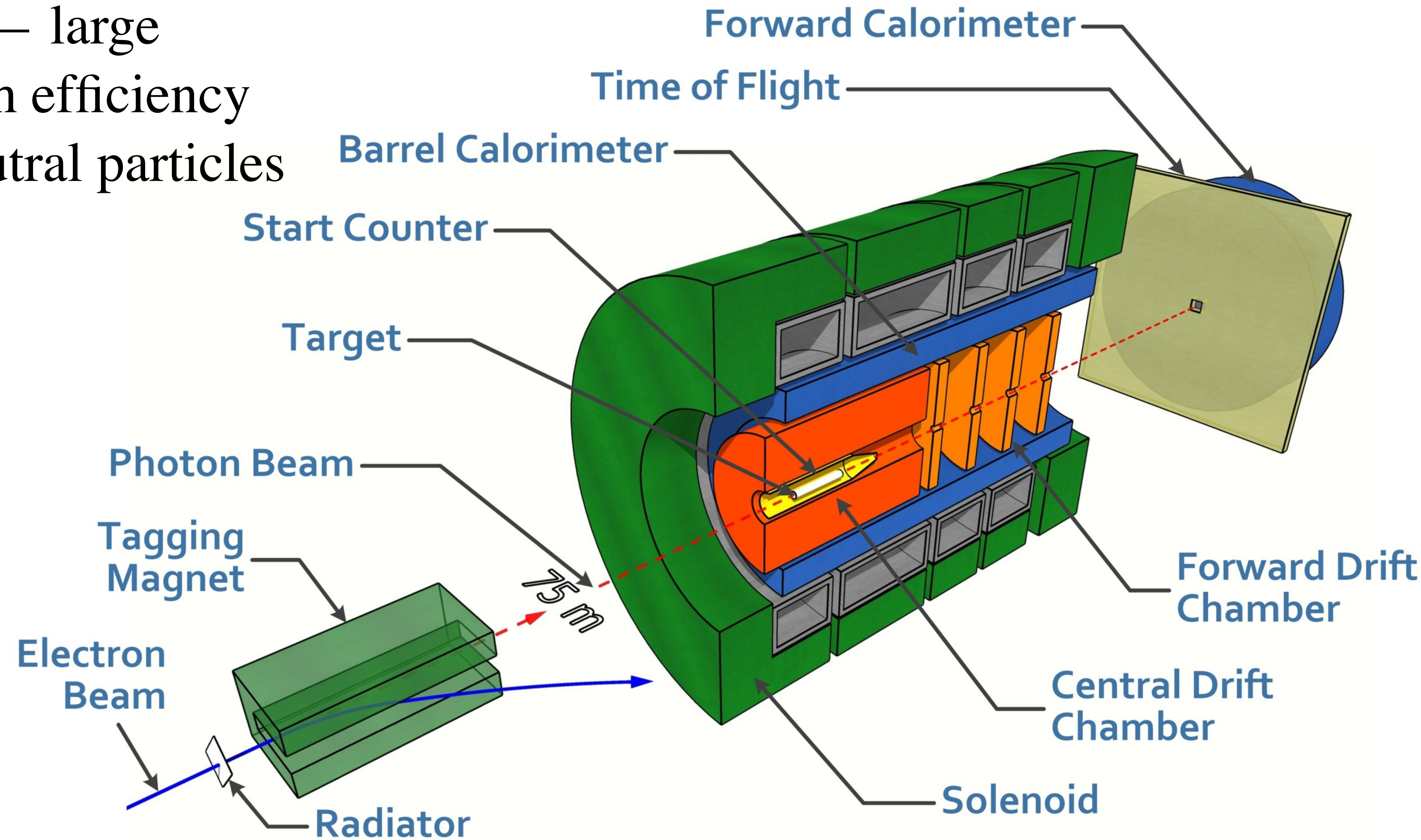


Pattern consistent with 1^{+-} constituent gluon Hadron Sepctrum Dudek et al. PRD 88 (2013) 094505

Experiment and Detector

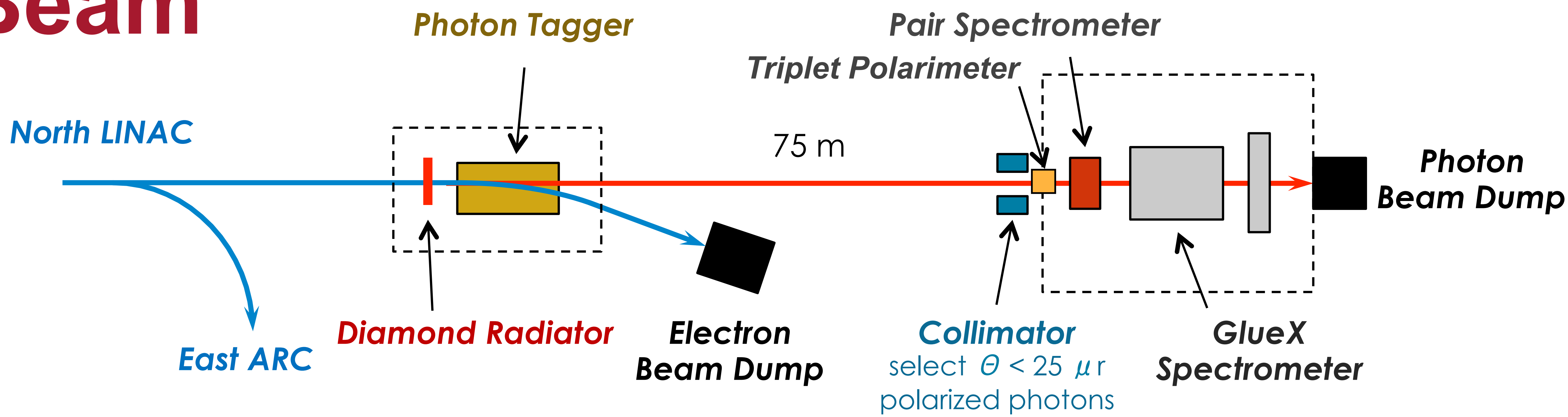
Hall D at Jefferson Lab

Linearly polarized photon beam
Proton target
Hermetic detector — large acceptance and high efficiency for charged and neutral particles



Nucl. Instrum. & Meth. A987, 164807 (2021)

Beam



~12 GeV electrons from CEBAF

Coherent bremsstrahlung on thin diamond wafer

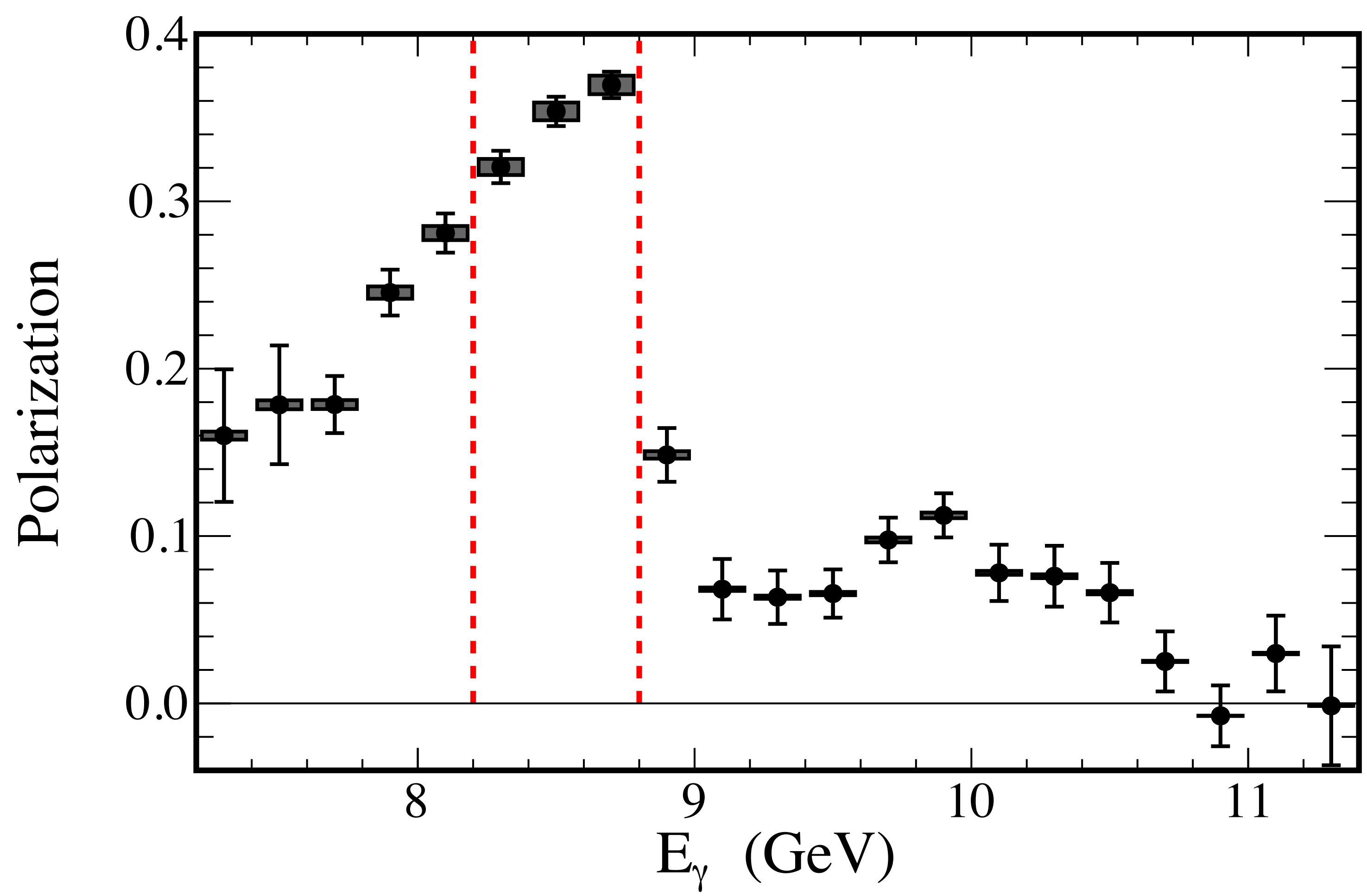
Linearly polarized in coherent peak ~35%

Tagged photon energy

GlueX phase 1 tagged luminosity

8.2 - 8.8 GeV 125 pb^{-1}

6.0 - 11.6 GeV 440 pb^{-1}



Recent Publications

J/ψ production γp → J/ψp (J/ψ → e+e−)

[PRL 123 072001 (2019)](#)

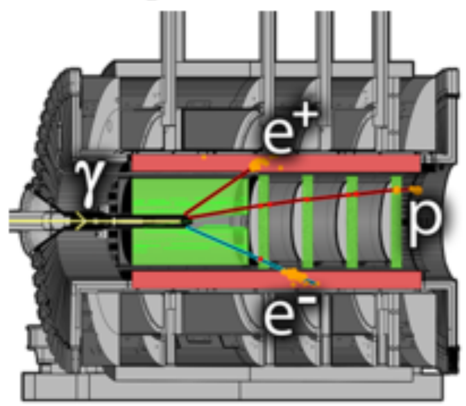
25% of data, 167 citations

Editors' Suggestion

First Measurement of Near-Threshold J/ψ Exclusive Pho Proton

A. Ali *et al.* (GlueX Collaboration)

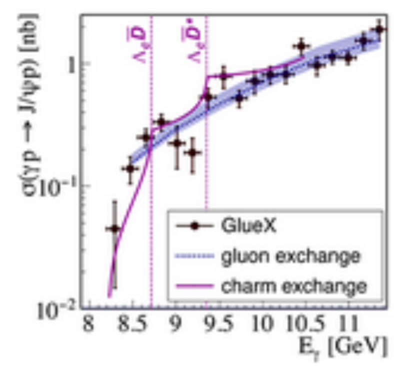
Phys. Rev. Lett. **123**, 072001 (2019) – Published 13 August 2019



New results from the GlueX collaboration probe the gluonic structure of the proton.

[PRC 108 025201 (2023)](#)

full GlueX-I data, 8 citations



EDITORS' SUGGESTION

Measurement of the J/ψ photoproduction cross section over the full near-threshold kinematic region

New results from the GlueX experiment provide improved cross sections for the photoproduction from the proton of J/ψ mesons via the $\gamma + p \to J/\psi + p$ reaction. Such mesons have charm/anti-charm heavy-quark content. Measurements of this reaction near the kinematic threshold can help constrain aspects of the density distribution of gluons in the proton and how they contribute to the proton mass, under the assumption that J/ψ production proceeds primarily through the exchange of gluons with the proton. However, these new measurements suggest contributions in addition to gluon exchange, pointing to the need for further theoretical work and more precise experimental measurements.

S. Adhikari *et al.* (GLUEX Collaboration)

Phys. Rev. C **108**, 025201 (2023)

- Measurement of Spin-Density Matrix Elements in ρ(770) Production with a Linearly Polarized Photon Beam at Eγ=8.2−8.8GeV
- Measurement of Spin Density Matrix Elements in Λ(1520) Photoproduction at 8.2 GeV to 8.8 GeV
- Search for photoproduction of axion-like particles at GlueX
- Measurement of beam asymmetry for π-Δ++ photoproduction on the proton at Eγ=8.5 GeV
- Measurement of the Beam Asymmetry in γ p -> K+Σ0 at Eγ = 8.5 GeV

GDH Sum Rule

Spin-dependent photoproduction cross-sections

spin

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

anomalous magnetic moment

Photon energy

Mass

Fundamental prediction of Quantum Field Theory. 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:

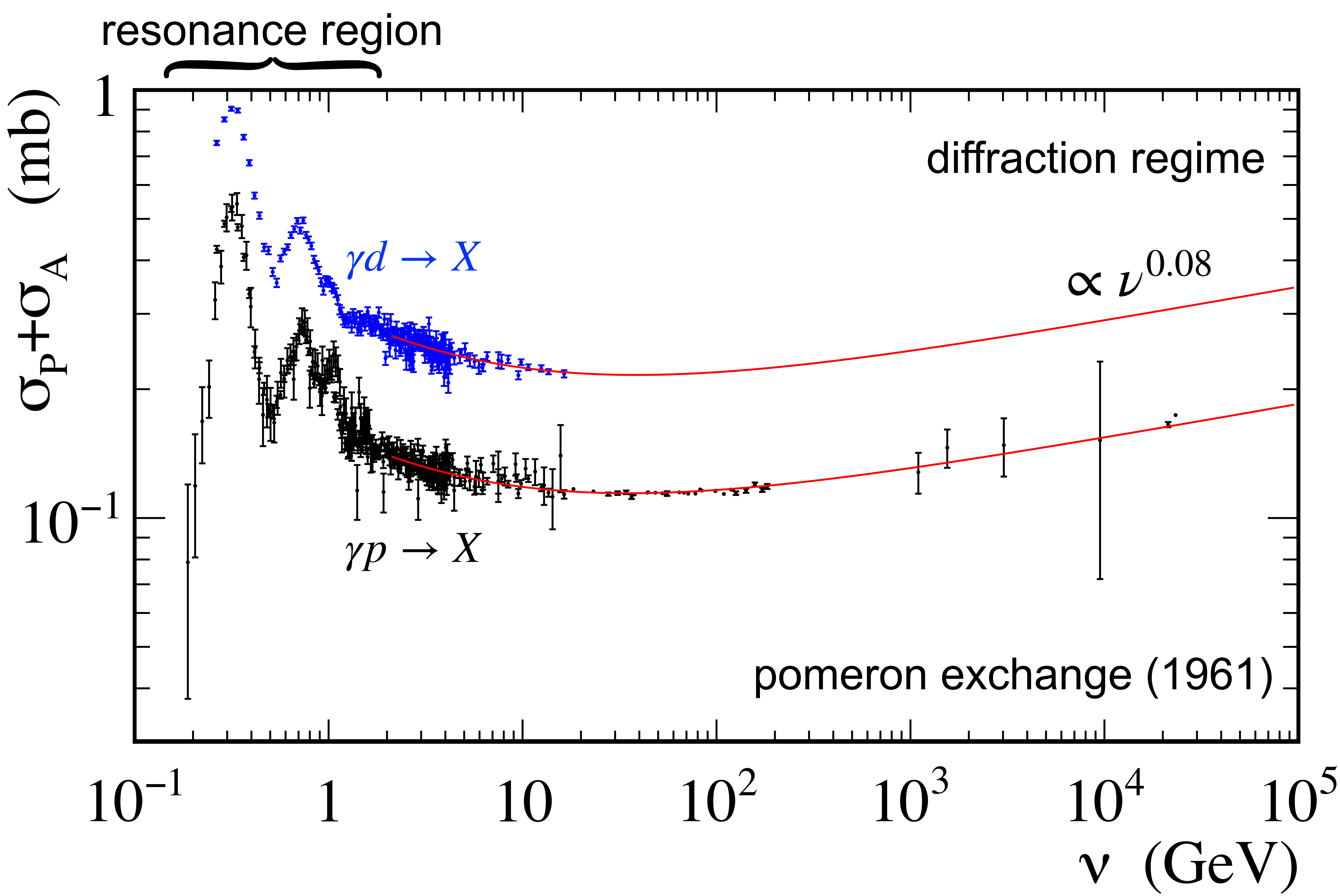
Spin-dependent forward Compton amplitude $f_2(\nu)$ must vanish at large ν (no-subtraction hypothesis).

Imaginary part of f_2, $(\sigma^{3/2} - \sigma^{1/2})$ must decrease with ν faster than $\sim 1/\ln(\nu)$ (for the integral to converge).

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

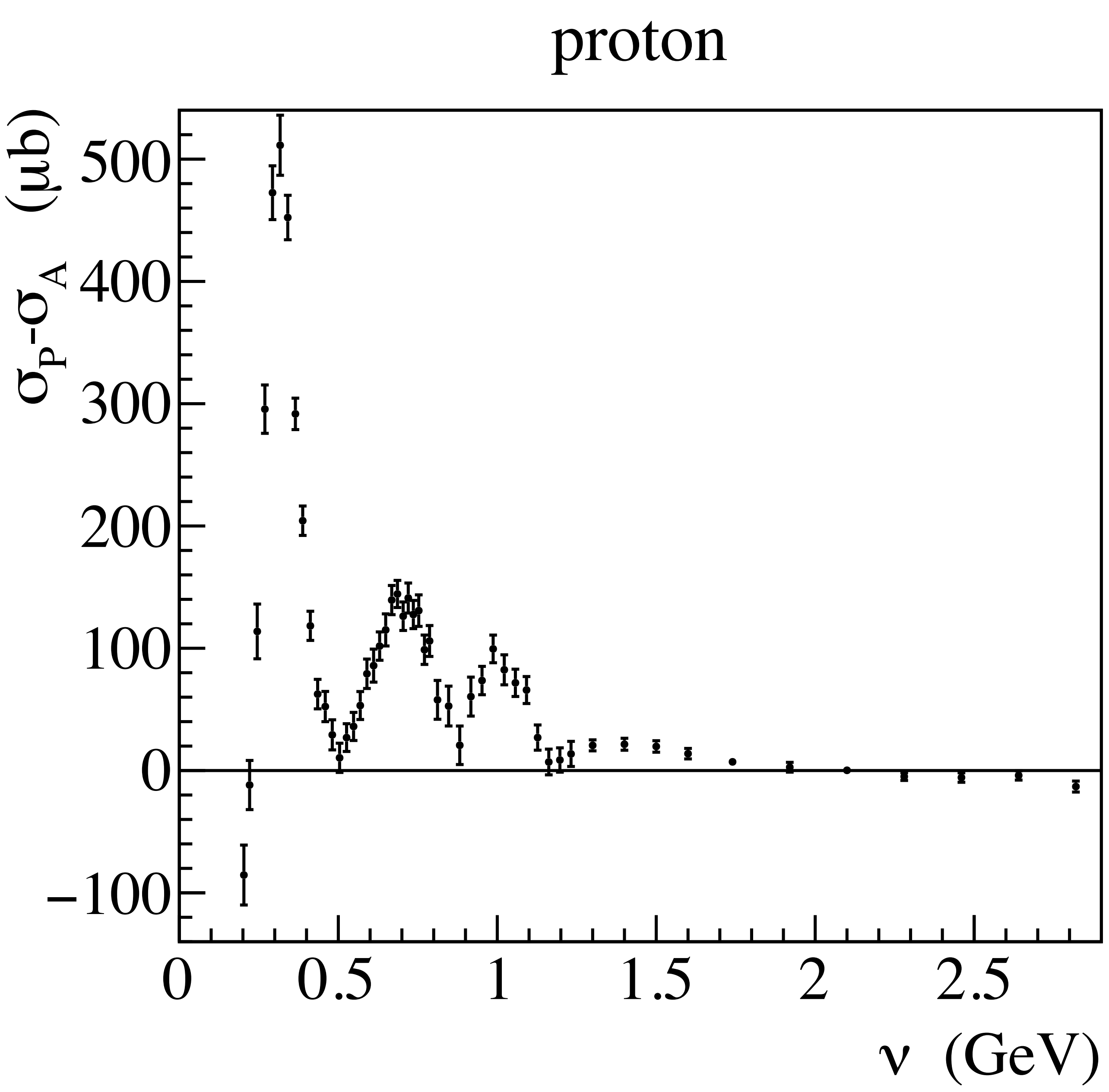
Photoproduction

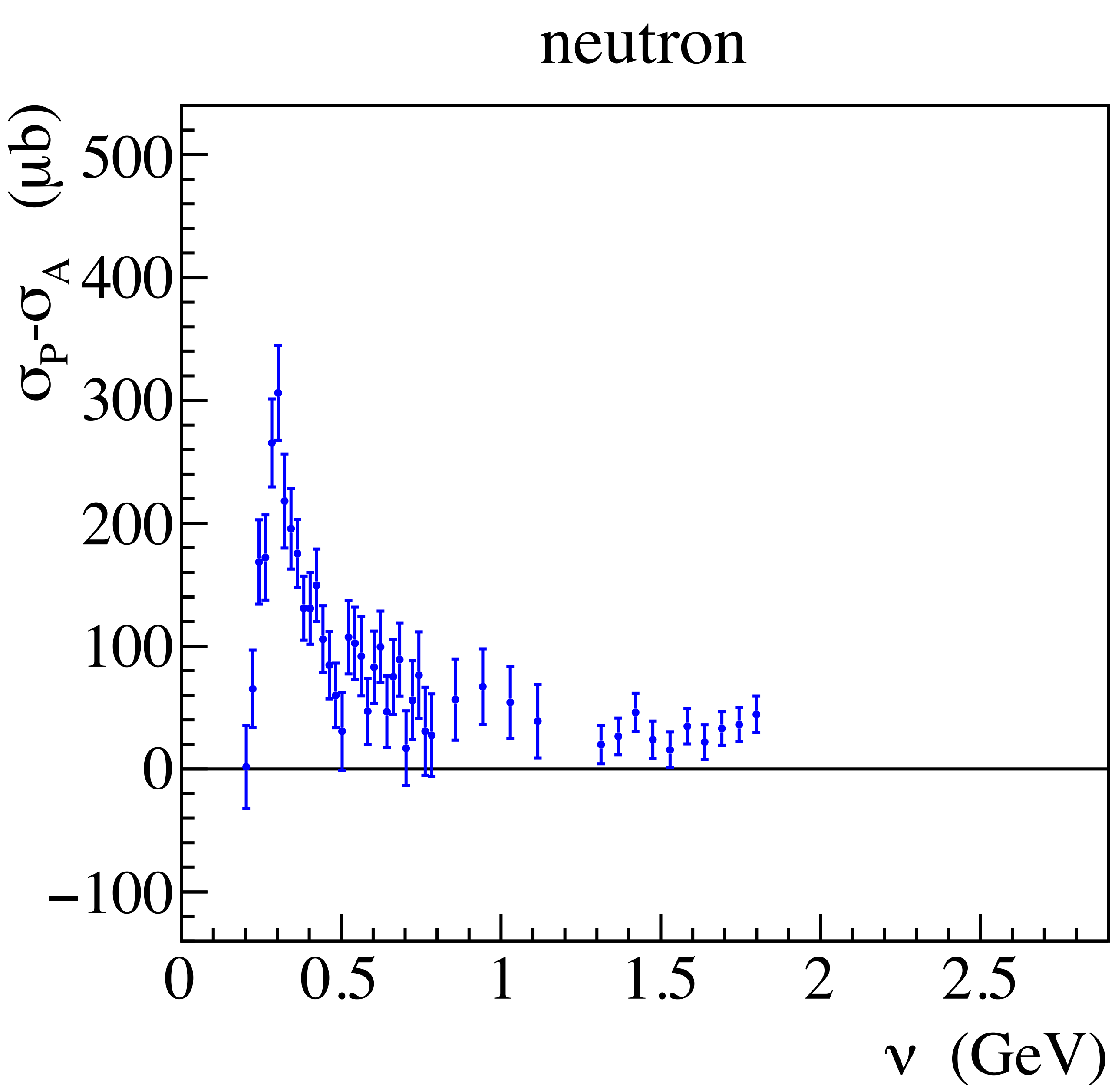
Unpolarized version of GDH integral $\int (\sigma^{3/2} + \sigma^{1/2}) d\nu$ does not converge.



Helicity dependent photoabsorption

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



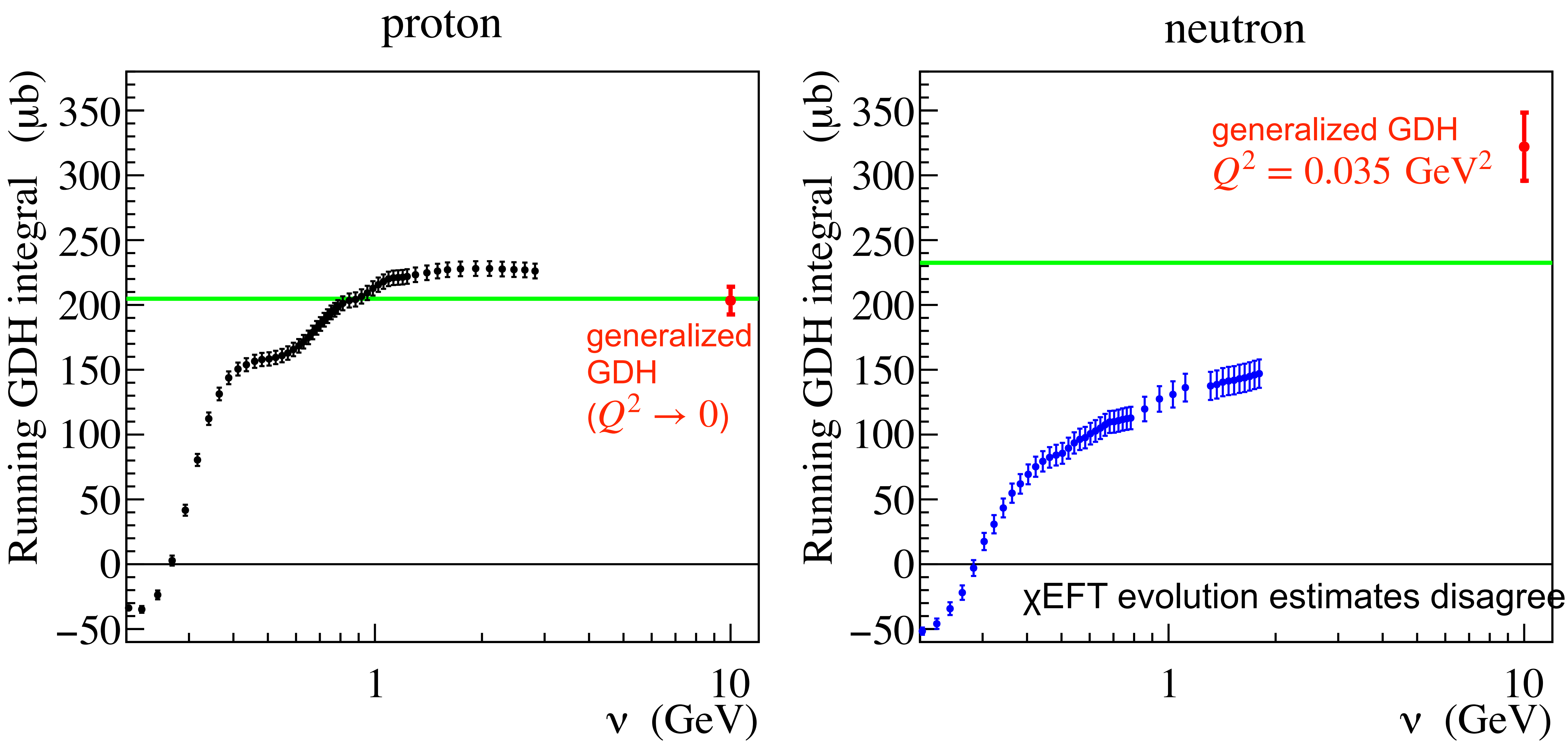


Threshold and high energy regions cannot be measured,
need models like MAID/SAID and Regge phenomenology.

GDH Integral

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

Sep 25, 2023, 4:30 PM
Junior D3



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

Unmeasured part estimated using Regge model. Significant uncertainty.

Has not converged yet

Regge Phenominology

Regge theory at high ν: $\Delta\sigma(\nu) \propto (\nu + M/2)^{\alpha_0 - 1}$

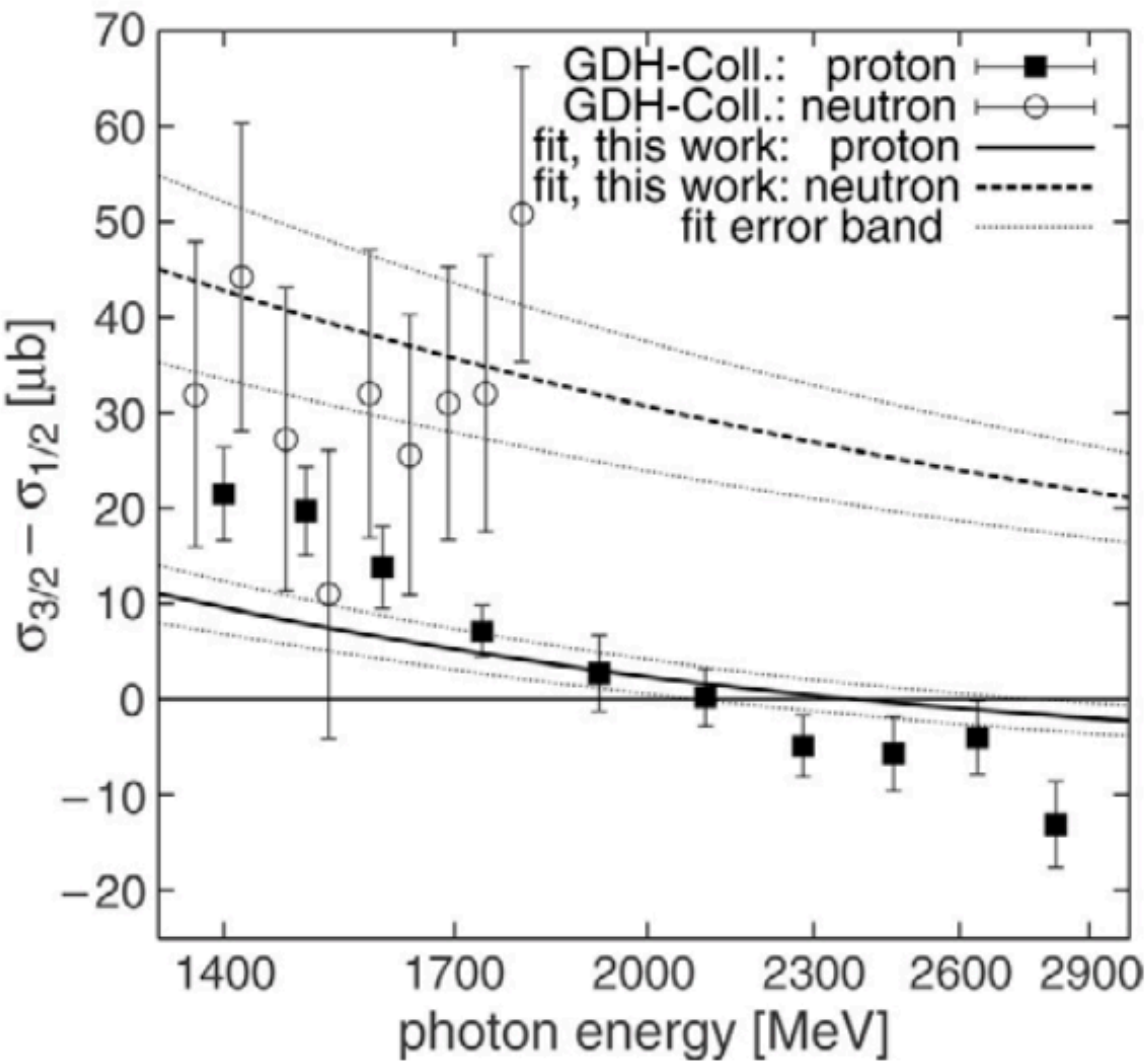
α_0 is Regge intercept

Isovector part: $\Delta\sigma^{p-n} \equiv \Delta\sigma^p - \Delta\sigma^n$
determined by $a_1(1260)$
Isoscaler part: $\Delta\sigma^{p+n} \equiv \Delta\sigma^p + \Delta\sigma^n$
determined by $f_1(1285)$

$$\sigma_P - \sigma_A = \underbrace{I}_{\text{isospin}} \cdot \underbrace{c_1 s^{\alpha_{a_1} - 1}}_{\text{isovector}} + \underbrace{c_2 s^{\alpha_{f_1} - 1}}_{\text{isoscaler}}$$

Value of c_2 unknown and assumed zero in some analyses since existing polarization measurements on deuteron in diffractive regime consistent with 0.

Regge Phenominology



Helbing++ Prog. Part. Nucl. Phys. 57, 405 (2006)

Fits on proton only give a Regge contribution of $-20\ \mu\mathrm{b}$ to $-35\ \mu\mathrm{b}$

combined fits give $-14\ \mu\mathrm{b}$ but don't agree well with the data.

The current uncertainty from this is

$$I_p = 212 \pm \underset{\text{stat}}{5} \pm \underset{\text{syst}}{12} \pm \underset{\text{large-}\nu\text{ projection}}{10}\ \mu\mathrm{b}$$

$$I_p = \frac{4\pi^2\alpha\kappa^2}{M^2} = 204.8\ \mu\mathrm{b}$$

Violation of the Sum Rule

Any failure of the sum rule will happen at high energy:

- Unknown high energy phenomena
  - eg quark substructure (quark anomalous magnetic moment)
- J=1 pole of the nucleon Compton amplitude
- Chiral anomaly (anomalous non-conservation of a chiral current)
- other, more exotic possibilities heave been proposed

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

Experiment Details

1 Circularly polarized tagged photon beam

Generated by electrons from CEBAF with $P_e \approx 80\%$ on amorphous radiator Increasing P_e at large ν compensates the decrease in bremsstrahlung flux

2 Longitudinally polarized target:

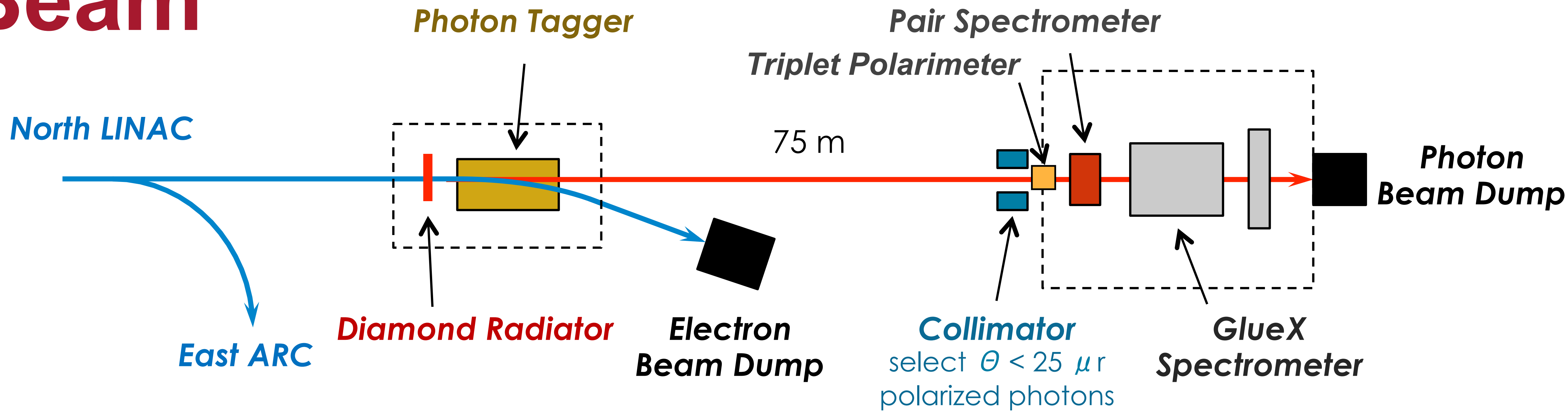
Dynamical nuclear polarization on butanol (C4H9OH), p and d polarizations up to 90 %
Desired sustainable flux: $\approx 10^8$/s or more
Dilution (and other unpolarized backgrounds) cancel:
$(N^+ + N^0) - (N^- + N^0) = N^+ - N^-$

3 Large solid angle detector

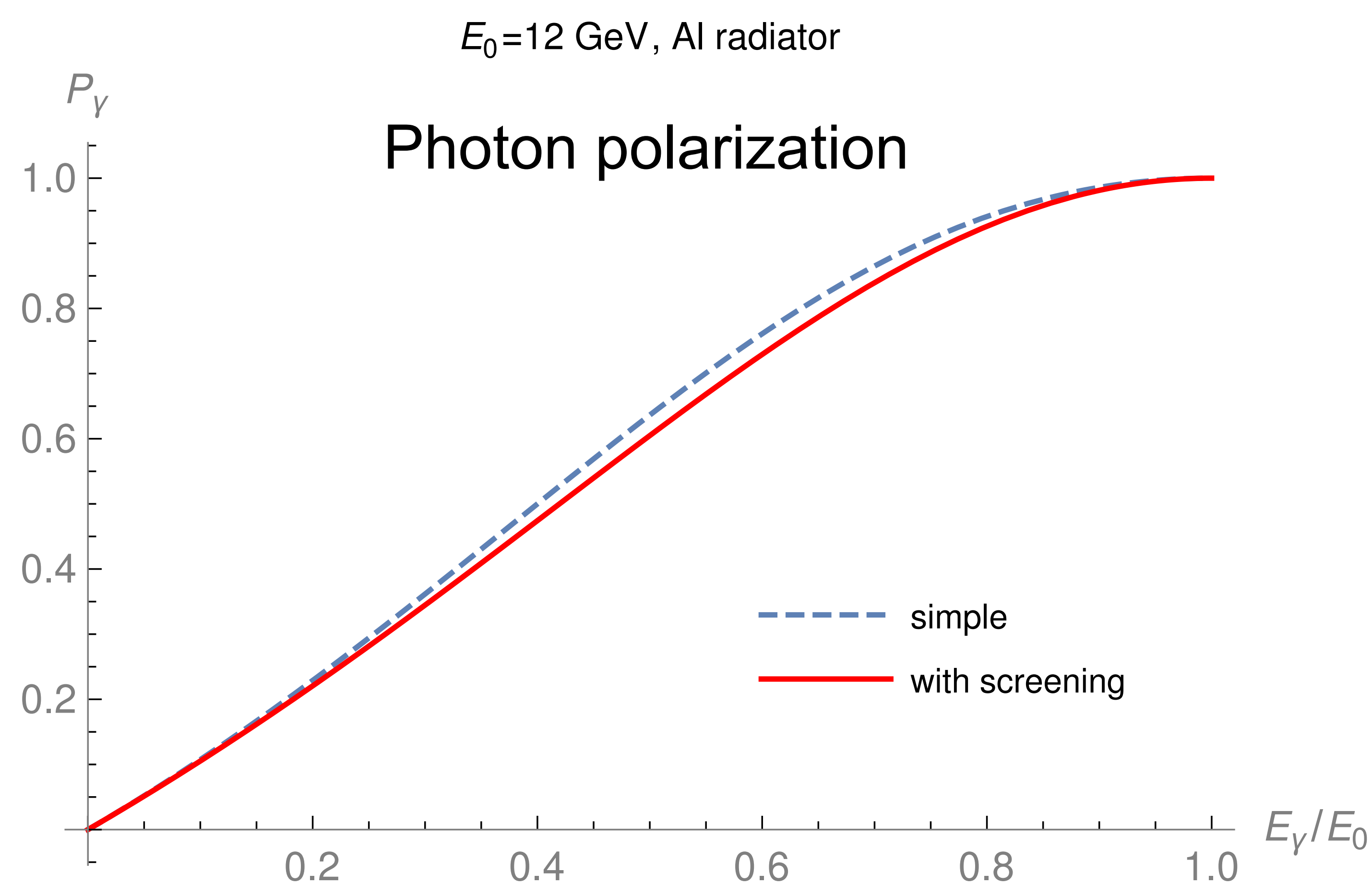
FCal, BCal: 0.4 deg to 145 deg polar coverage, 2π azimuthal coverage
Unpolarized XS ≈ 120 μb gives DAQ rate ≈ 33 kHz on H-butanol, ≈ 40 kHz on D-butanol + target window + EM backgrounds

Note: solely to establish the fall-off of $\Delta\sigma(\nu)/\nu$ the ν-independent normalization factors (beam flux, target density, solid angle, target and beam polarization, detection efficiencies) are irrelevant

Beam



Requires longitudinally polarized electrons.
Electron polarization transferred to photon depending on energy.



Target

A new polarized target for Hall D
Dynamic Nuclear Polarization (Continuously polarize target in place) on butanol (C_4H_9OH), *p* and *d* polarizations up to 90 %

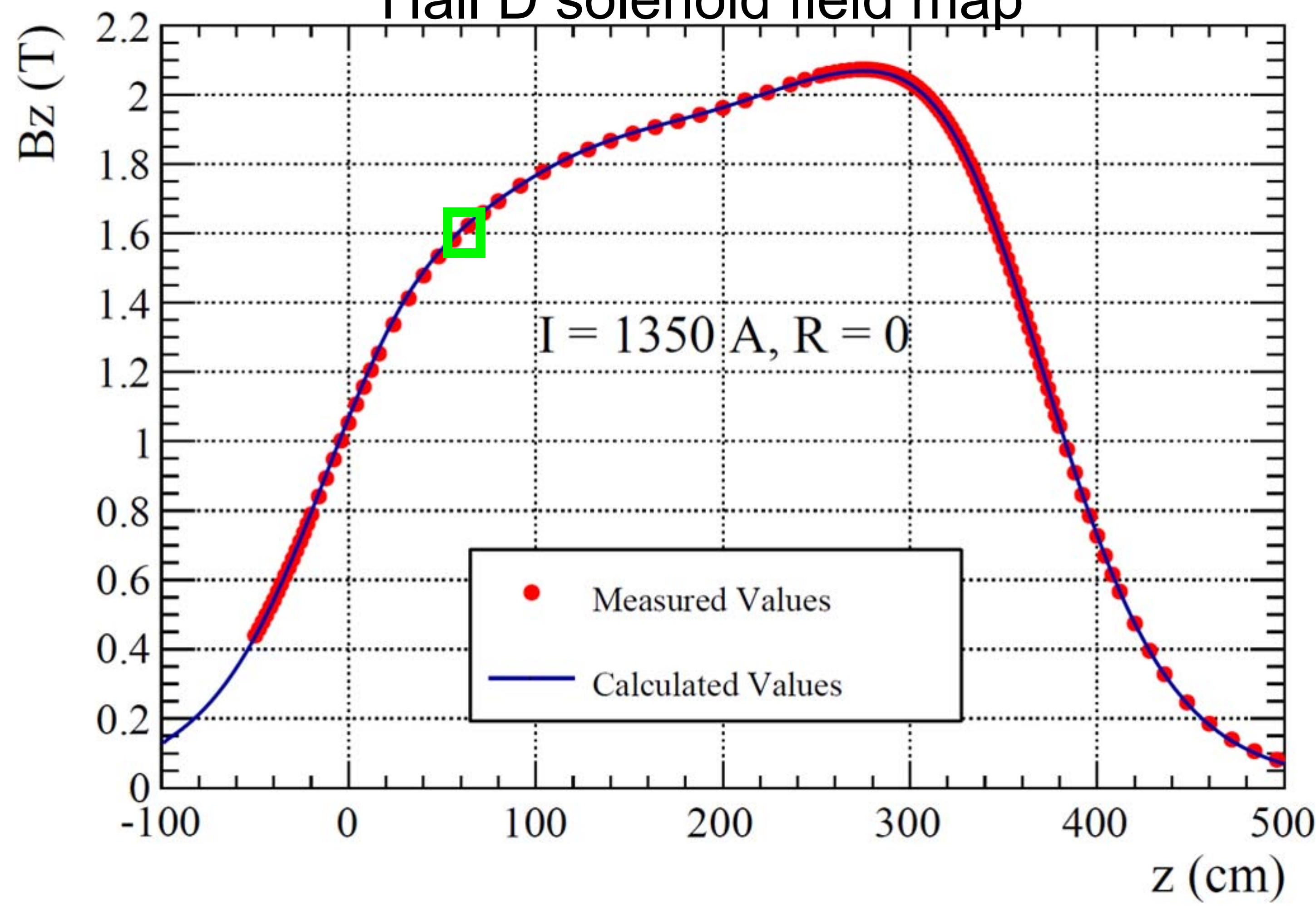
- Requires high (2.5 T) and very uniform (300 ppm) magnetic field
- Requires very low temperatures (300 mK)
- Requires paramagnetic impurities at about 10^{-4} level
- At 300 mK and 2.5 T, unpaired electrons are polarized >99.9%

Microwaves induce spin-flip transitions transferring polarization to the nuclear spins.

Currently region has field ~1.60 to ~1.65 T.

Superconducting coils installed in target will raise field to 2.5 T and make it more homogenous.

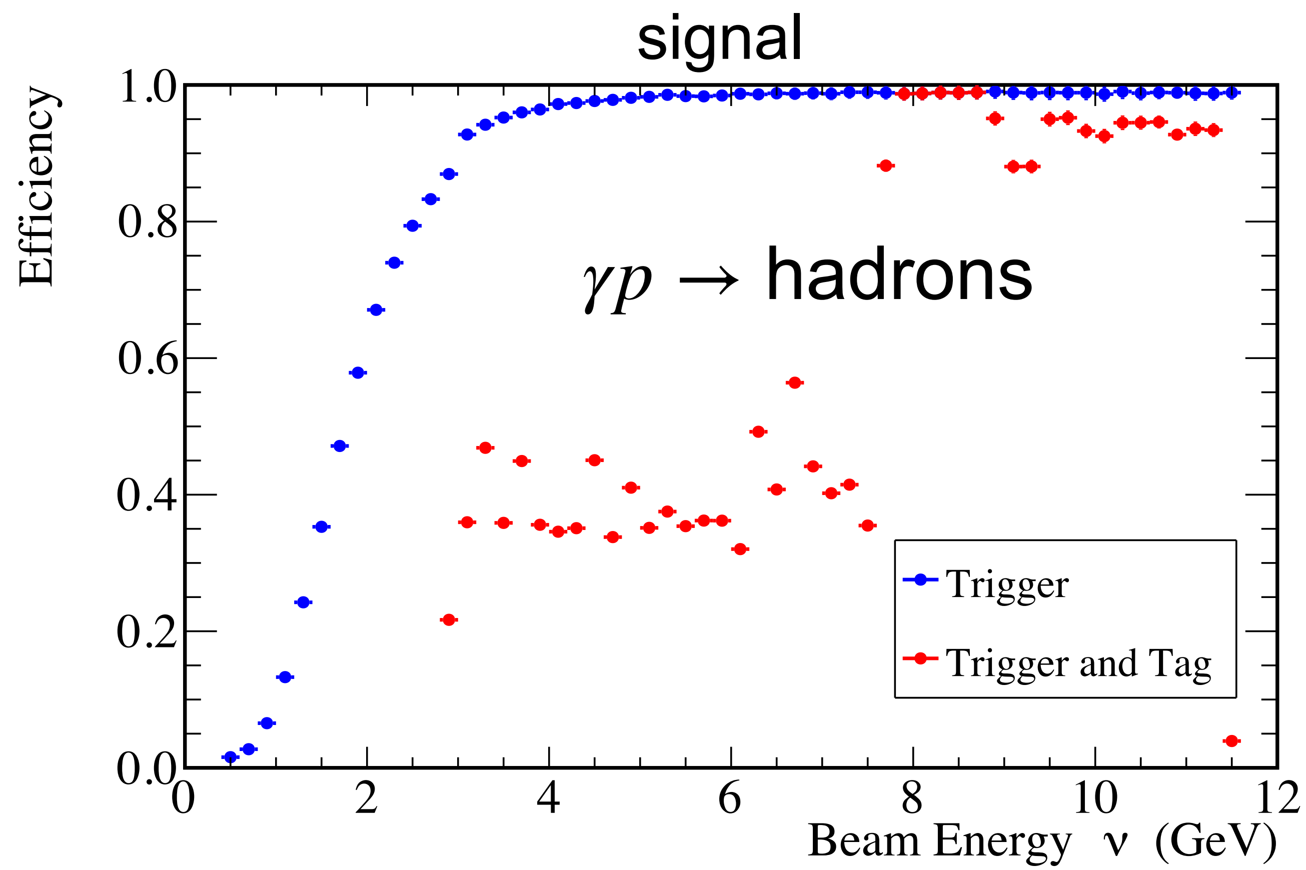
Hall D solenoid field map

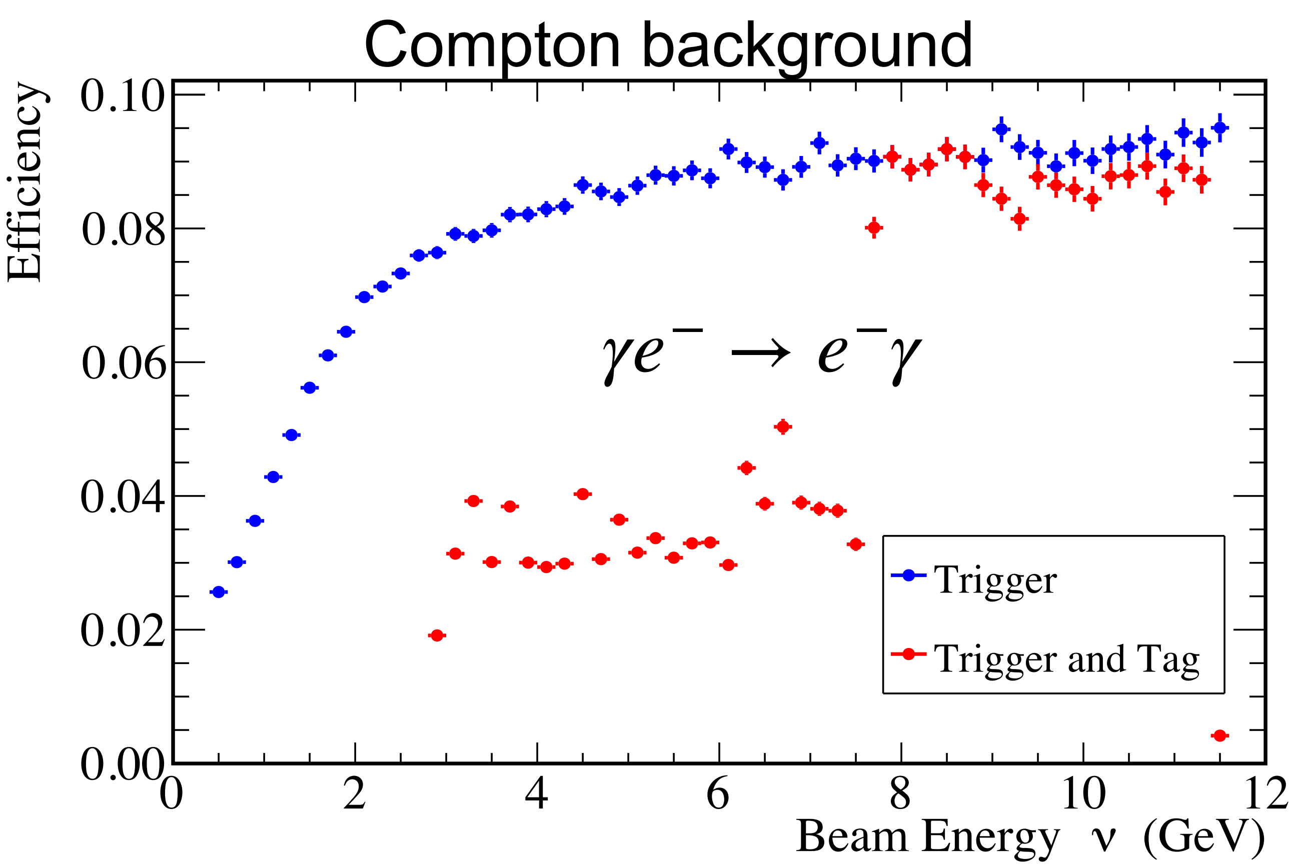


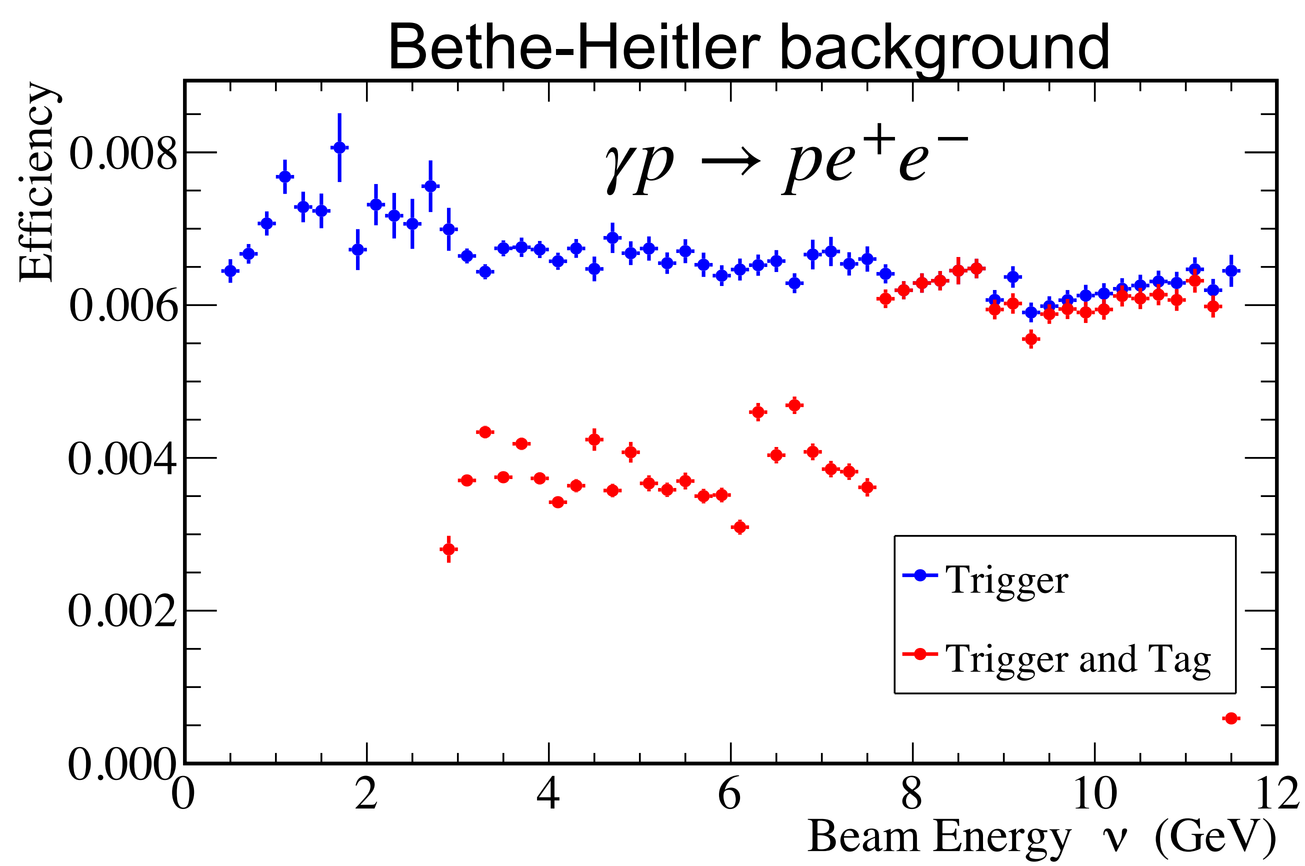
Signal and Background

Using a trigger which requires a high energy deposited in the calorimeters
$E_{\mathrm{BCAL}} + 2E_{\mathrm{FCAL}} > 1\ \mathrm{GeV}$

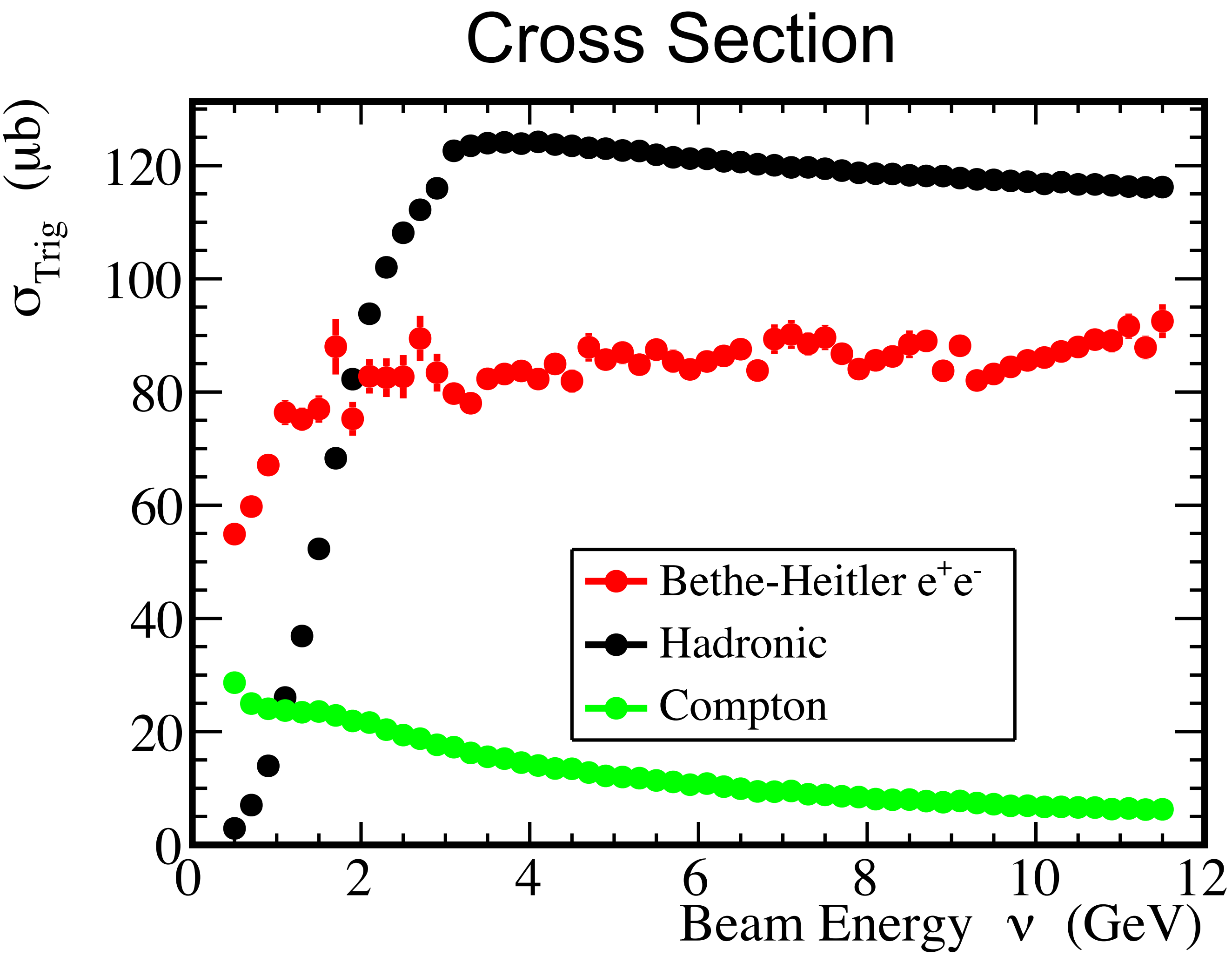
but cuts out very small angles, first 3 blocks of FCAL $\theta \gtrsim 2^\circ$

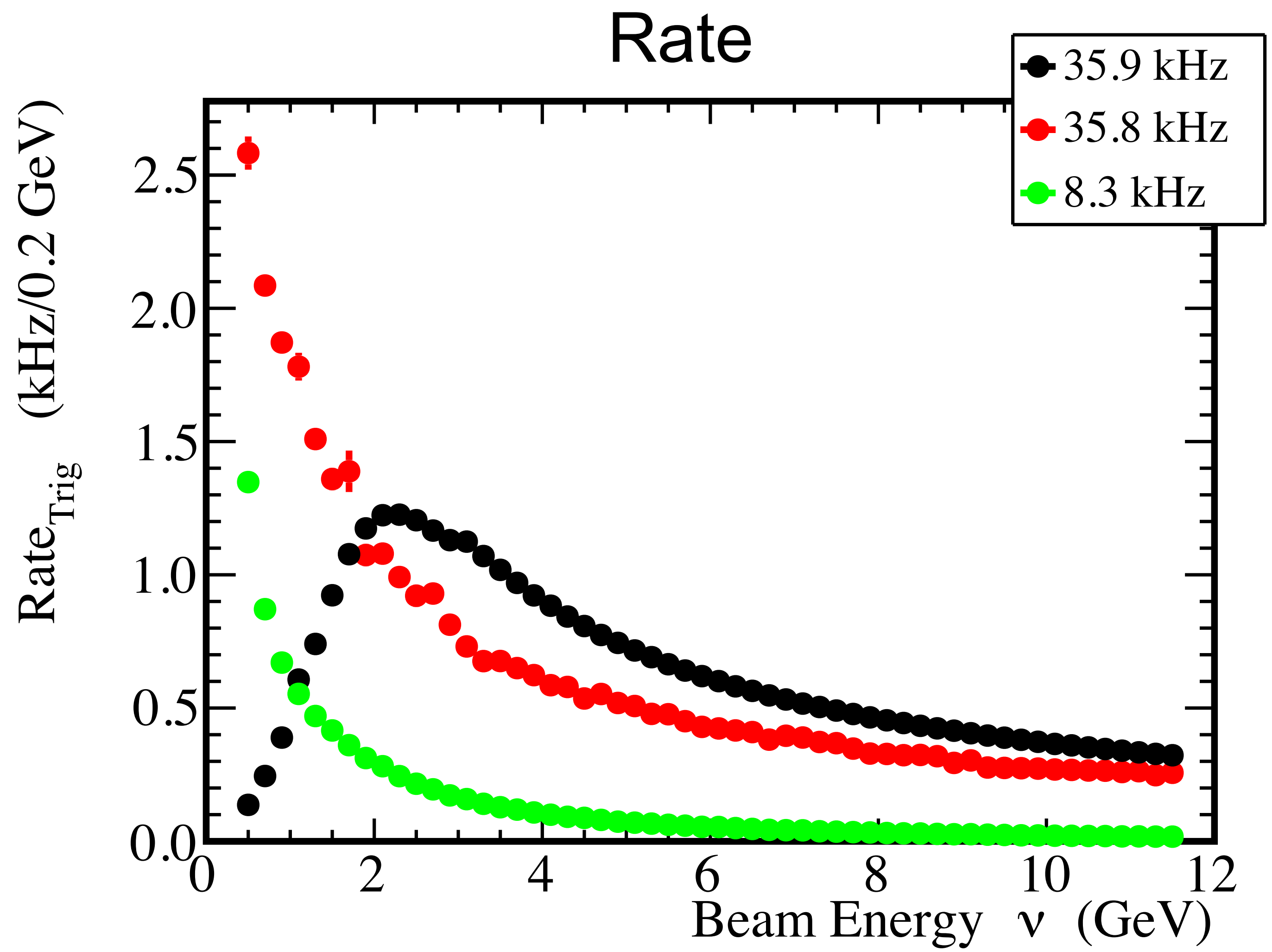






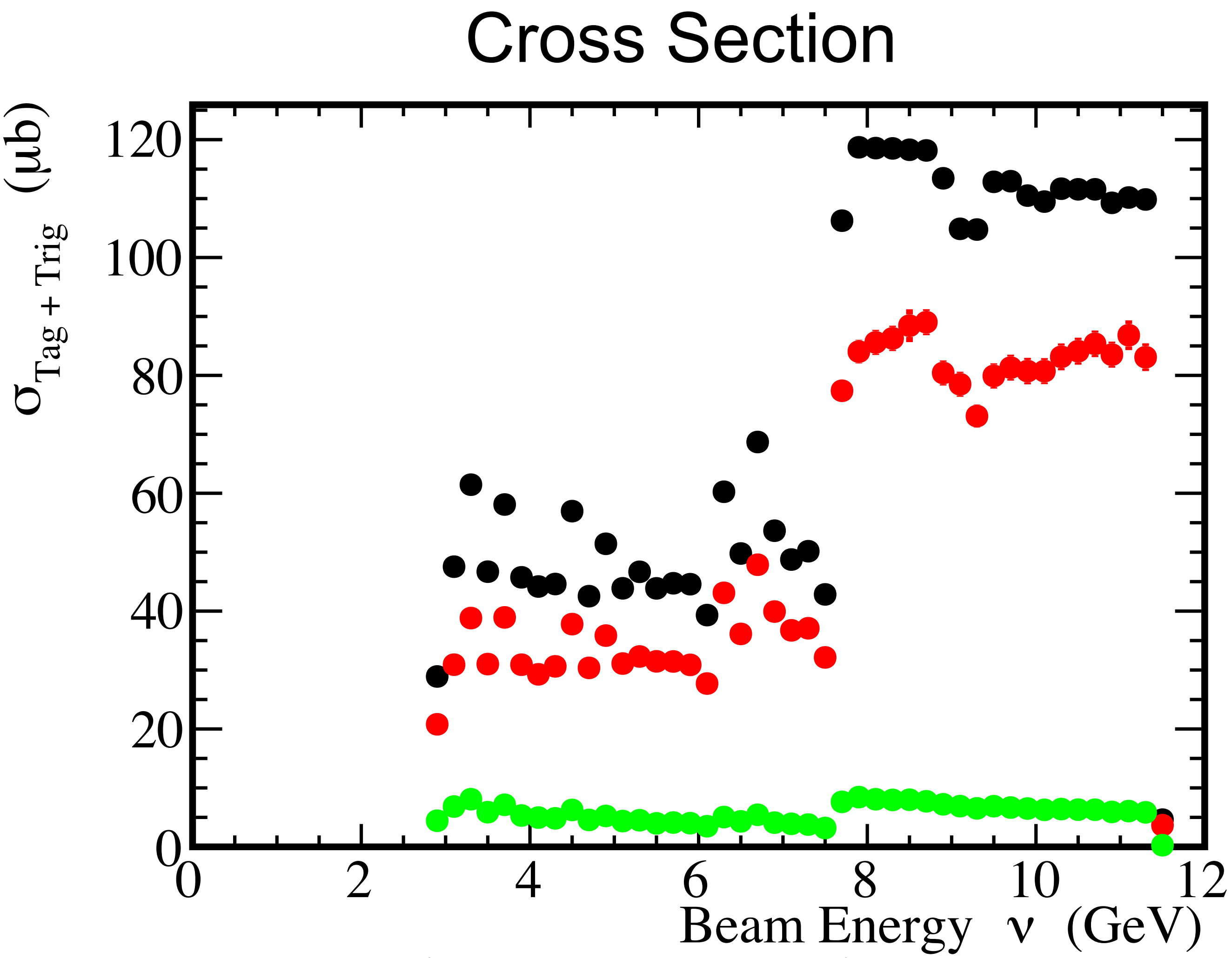
Signal and Background

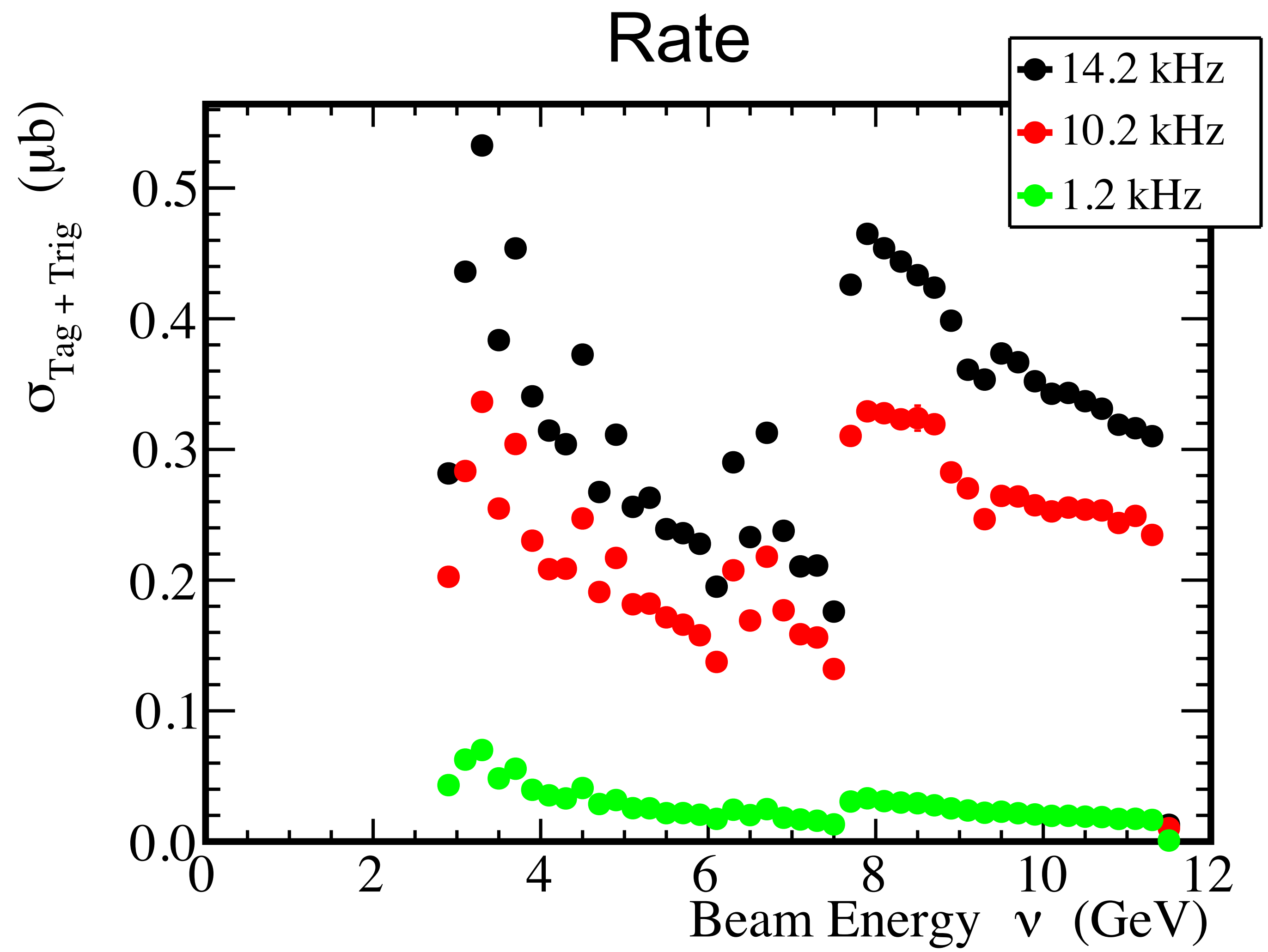




Data Acquisition has limit of ~80 kHz.
Backgrounds eat up a half of this rate.
Bethe Heitler has cross section of 12-15 mb.

Signal and Background



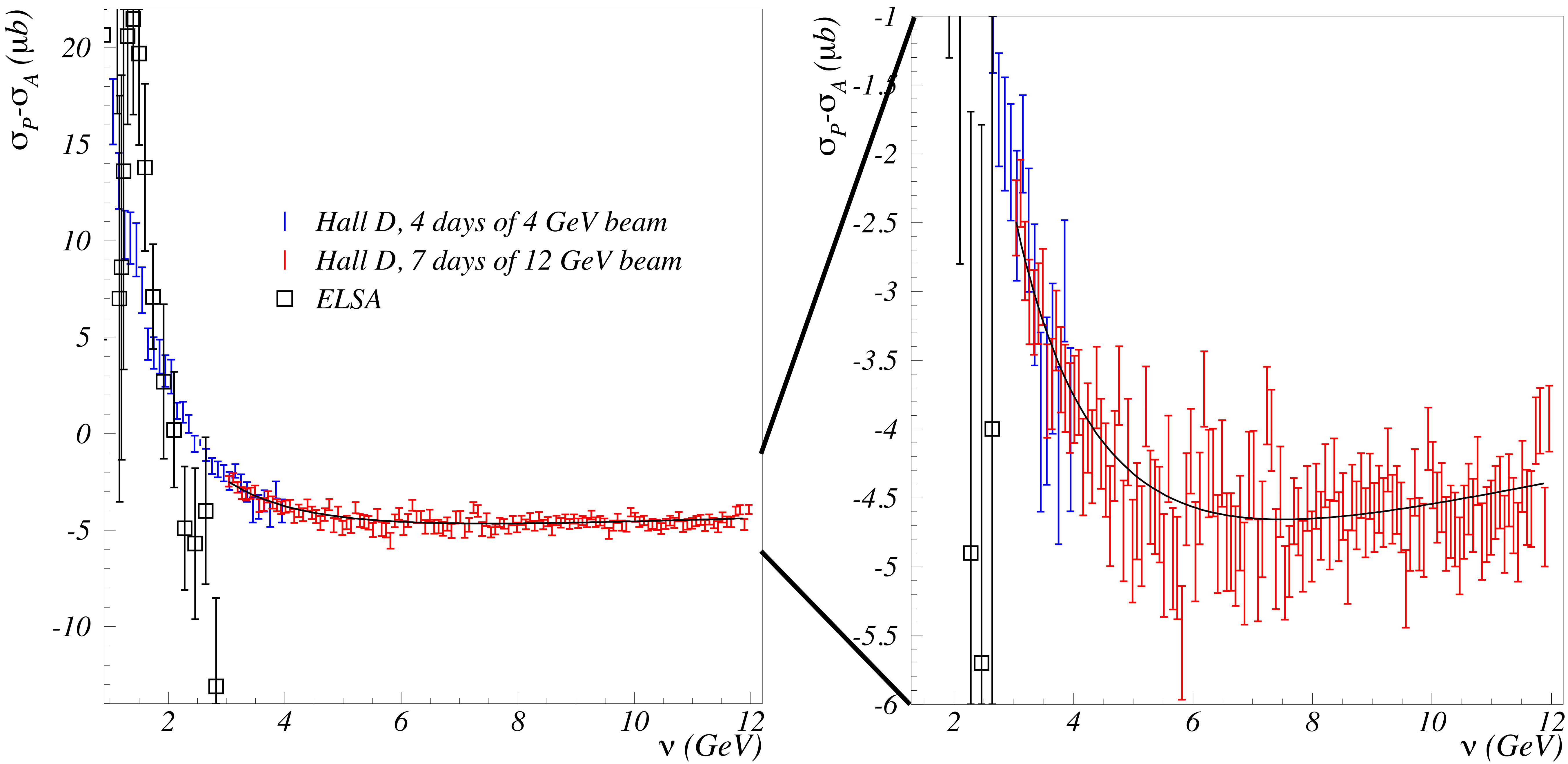


45% coverage

Tagging photons reduces the efficiency.
Depends on geometrical acceptance of tagger.

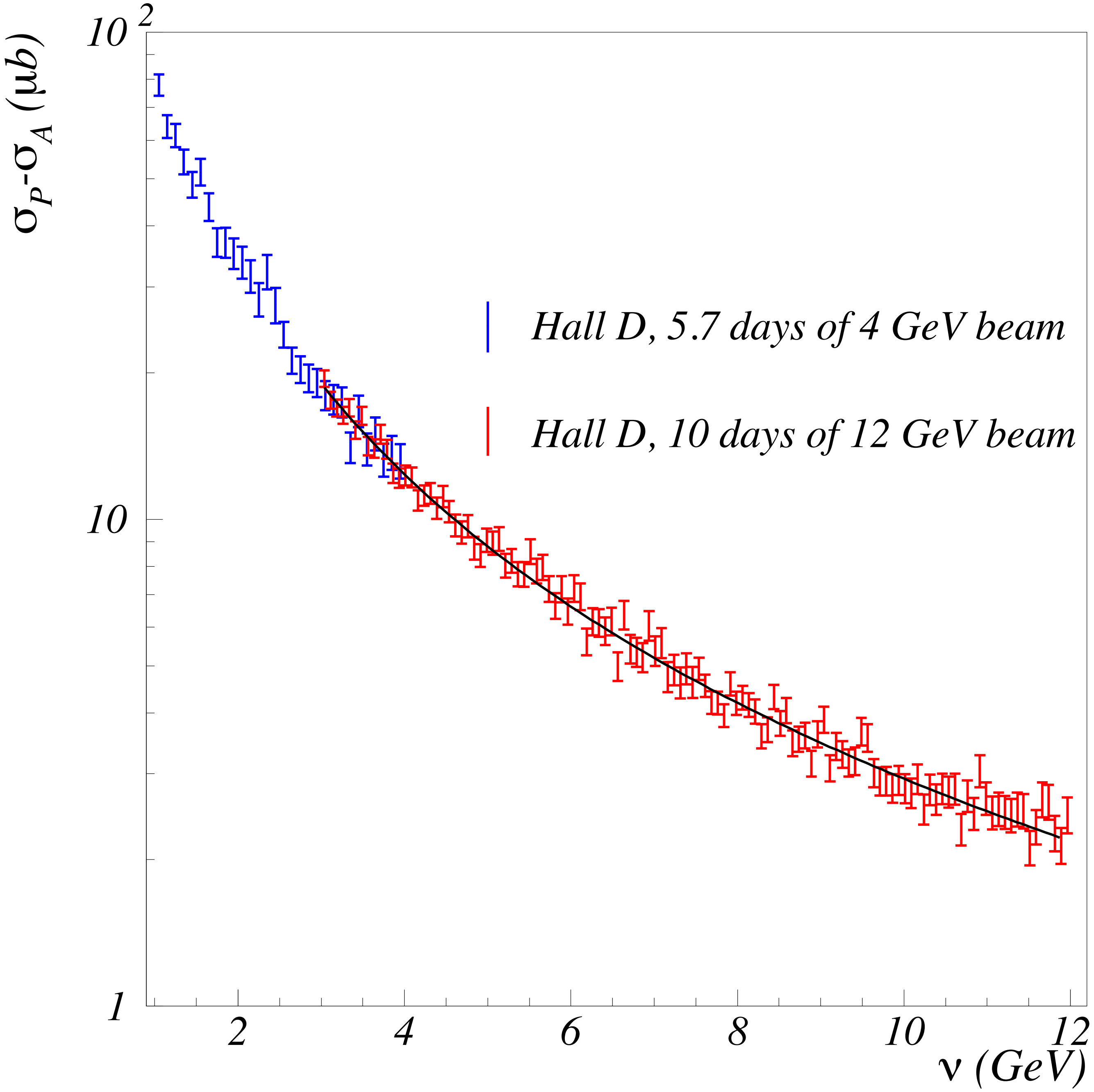
Projected Results (Proton)

Projection using $\alpha_{a_1} = 0.412,\ \alpha_{f_1} = -0.629$

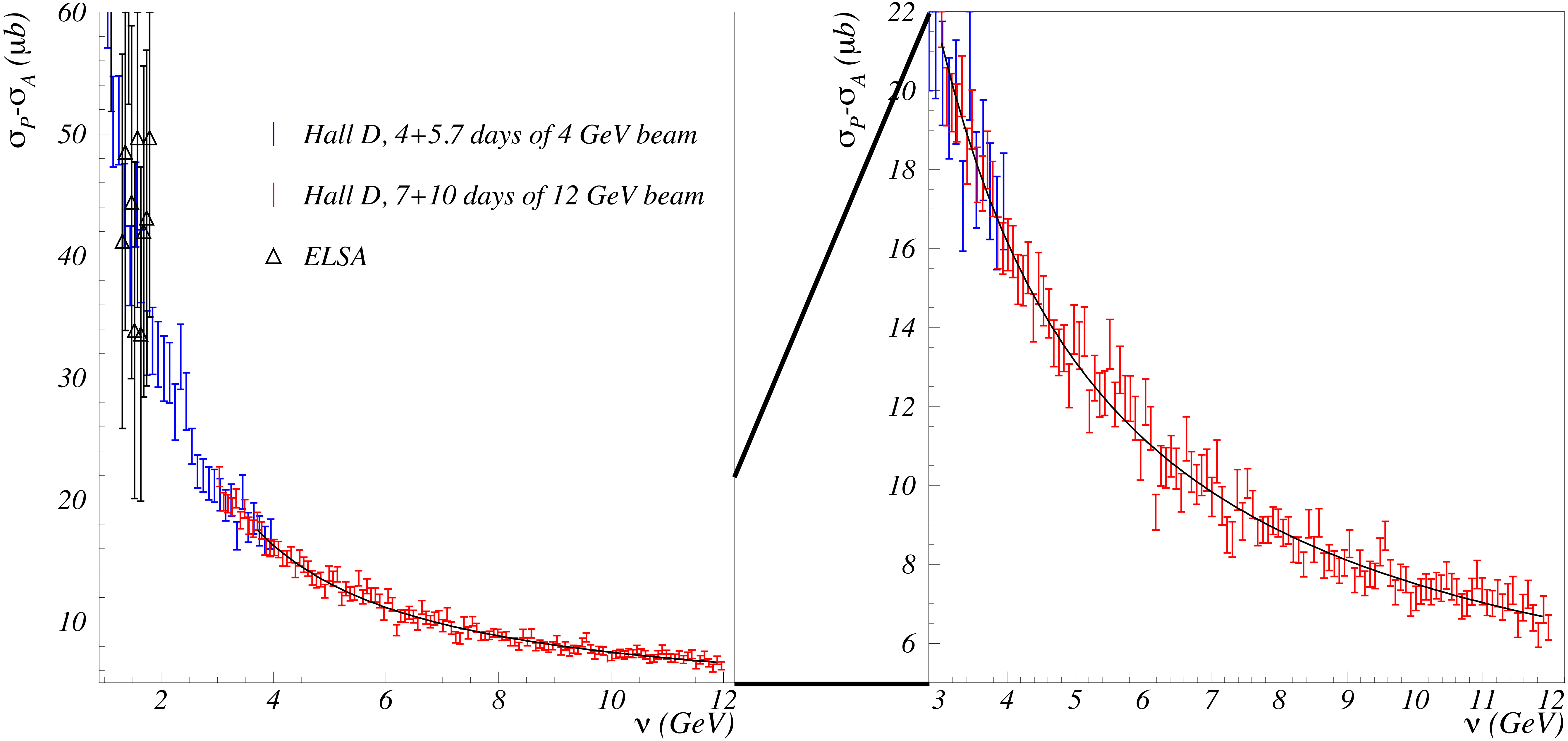


Shape measurement to ~1%, absolute cross sections to ~5%

Projected Results (Deuteron)



Projected Results (Neutron)



Based on the subtraction $\Delta\sigma_n = \Delta\sigma_d/(1 - 1.5\omega_d) - \Delta\sigma_p$
with $\omega_d = 5.6\,\%$ the probability to be in a D-state

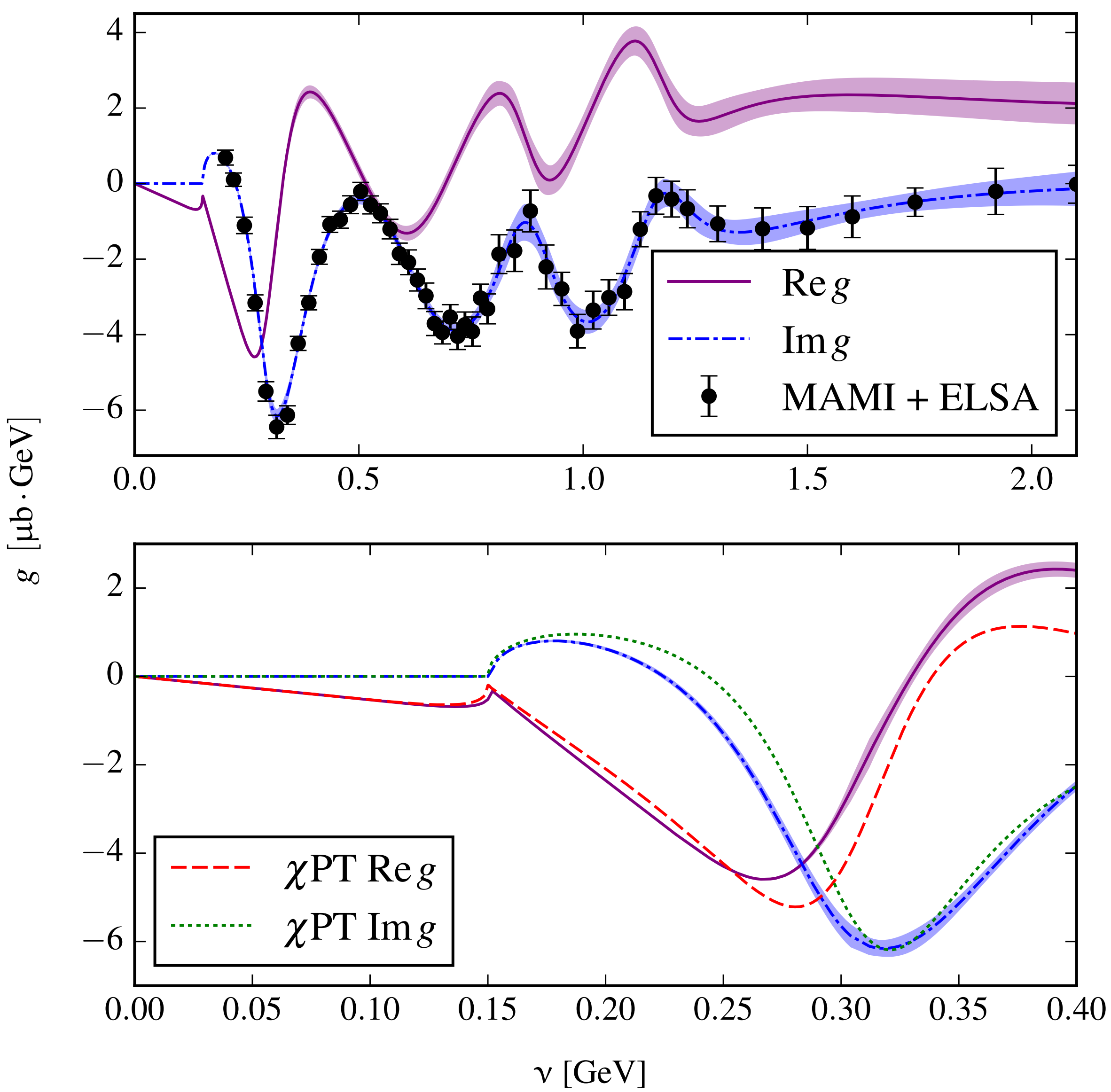
Interpretation of REGGE data

Spin-dependent Compton Amplitude

$$\Im\left(f_2(\varepsilon)\right) = \frac{\varepsilon}{8\pi}\Delta\sigma$$

Directly measure imaginary part of the amplitude

Access real part by dispersion relation $$\Re\left(f_2(\varepsilon)\right) = \frac{2\nu}{\pi}P\int_0^{+\infty}\frac{\Im\left(f_2(\varepsilon)\right)}{\varepsilon^2-\nu^2}d\varepsilon$$



Gryniuk++ Phys. Rev. D 94 (2016)

Extend existing data by factor of 6 in energy

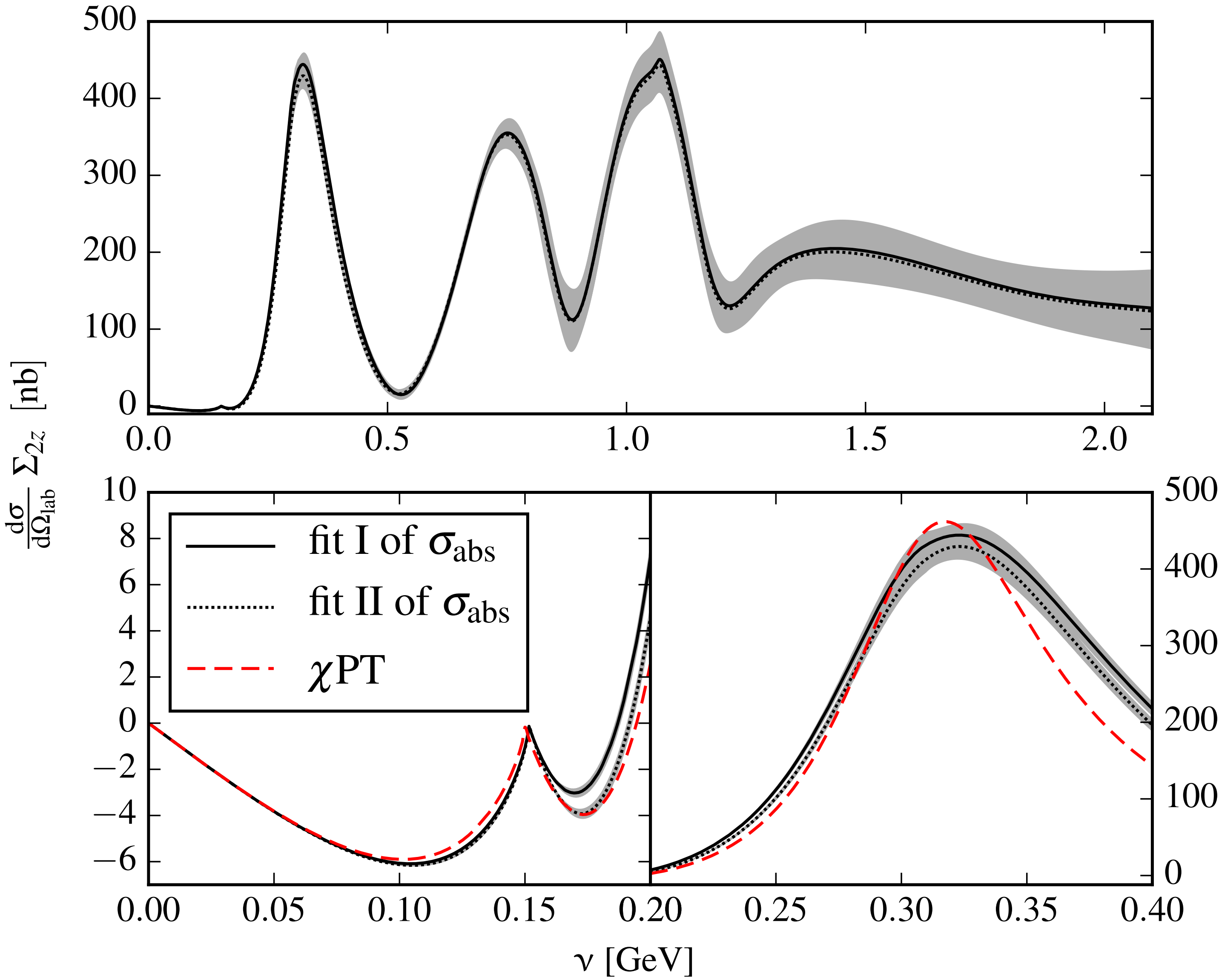
Study Compton scattering without doing a dedicated Compton scattering experiment

Noticeable difference between data and NNLO χEFT calculation at ~0.25 GeV.

Spin-dependent Compton Amplitude

Since unpolarized amplitude f_1 is well measured

Can determine cross section and beam-target asymmetry in forward limit.



$$\left.\frac{d\sigma}{d\Omega}\right|_{\theta=0} = |f_1|^2 + |f_2|^2$$

$$\left.\Sigma_{2z}\right|_{\theta=0} = \frac{2\mathfrak{R}(f_1 f_2^*)}{|f_1|^2 + |f_2|^2}$$

Expand analysis to neutron and deuteron

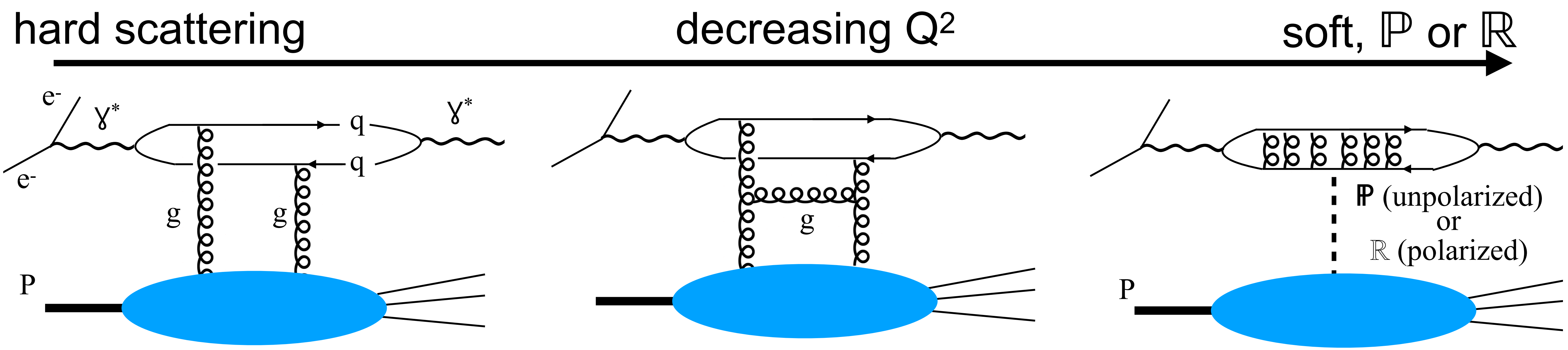
Describing spin observables from JLab low-Q^2 has been a challenge for χEFT. Data in a different regime is valuable.

Gryniuk++ Phys. Rev. D 94 (2016)

Deur++, Rep. Prog. Phys. 82, 076201 (2019)

Transition to diffractive regime

Explore transition between polarized DIS and diffraction regimes



Diquark picture of low-x ep scattering. Coherence length $\propto x^{-1}M^{-1}$

Pomeron $\mathbb{P}$: unpolarized diffractive scattering

Reggeon $\mathbb{R}$: doubly polarized diffractive scattering (will be measured at EIC)

Will provide $Q^2 = 0$ baseline for these transition studies.

Exotic Spectroscopy

Speculative potential new application

The $\pi_1 \to \eta\pi$ so we are interested in $\gamma p \to \eta\pi^-\Delta^{++}$ in GlueX.

There are 8 transitions between N and Δ. If we can eliminate some of them that would help the amplitude analysis.

$$\left(-\frac{1}{2}, +\frac{1}{2}\right) \to \left(-\frac{3}{2}, -\frac{1}{2}, +\frac{1}{2}, +\frac{3}{2}\right)$$

We can study the reaction $\gamma p \to \pi^-\Delta^{++}$ to study the Δ^{++} Spin Density Matrix Elements in a simple final state with more statistics, even study $\gamma p \to \eta\pi^-\Delta^{++}$ directly.

What will be common or transferable from one reaction to others?

How precisely would we need to know these double asymmetries to be useful in the understanding the $\gamma p \to \eta\pi^-\Delta^{++}$ reaction?

Modification of bound nucleons

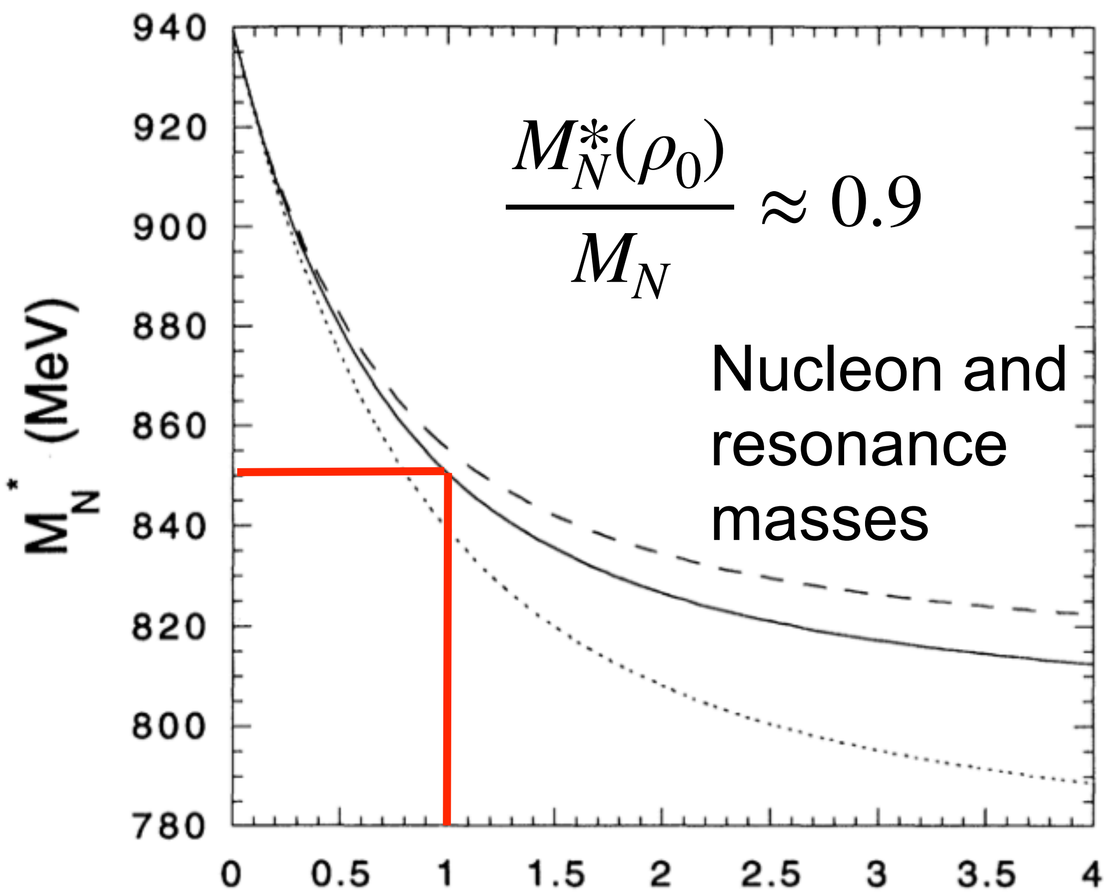
A nucleon in the nuclear medium will be modified
modification of both sides of the GDH sum rule
for the nucleon in the nucleus

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

Static Side

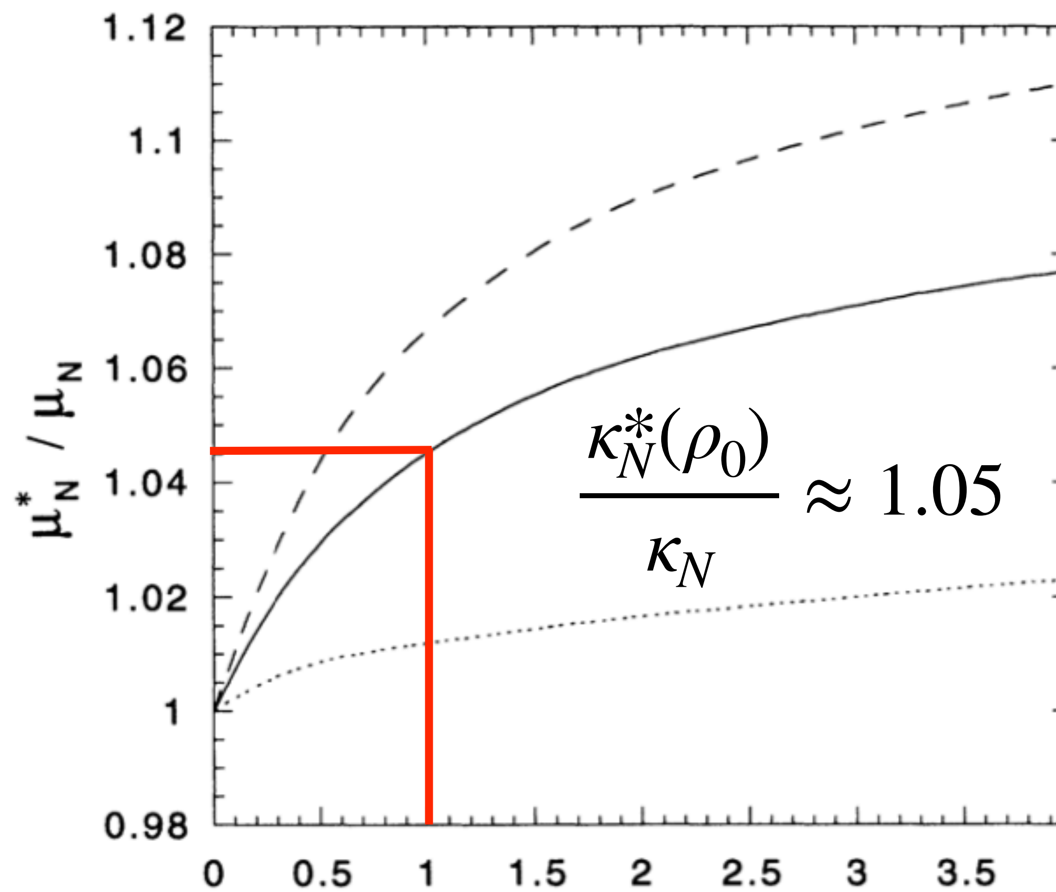
Quark Meson Coupling (QMC) model predicts modification of mass and anomalous magnetic moment.

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



ρ_B / ρ_0

Nuclear density



ρ_B / ρ_0

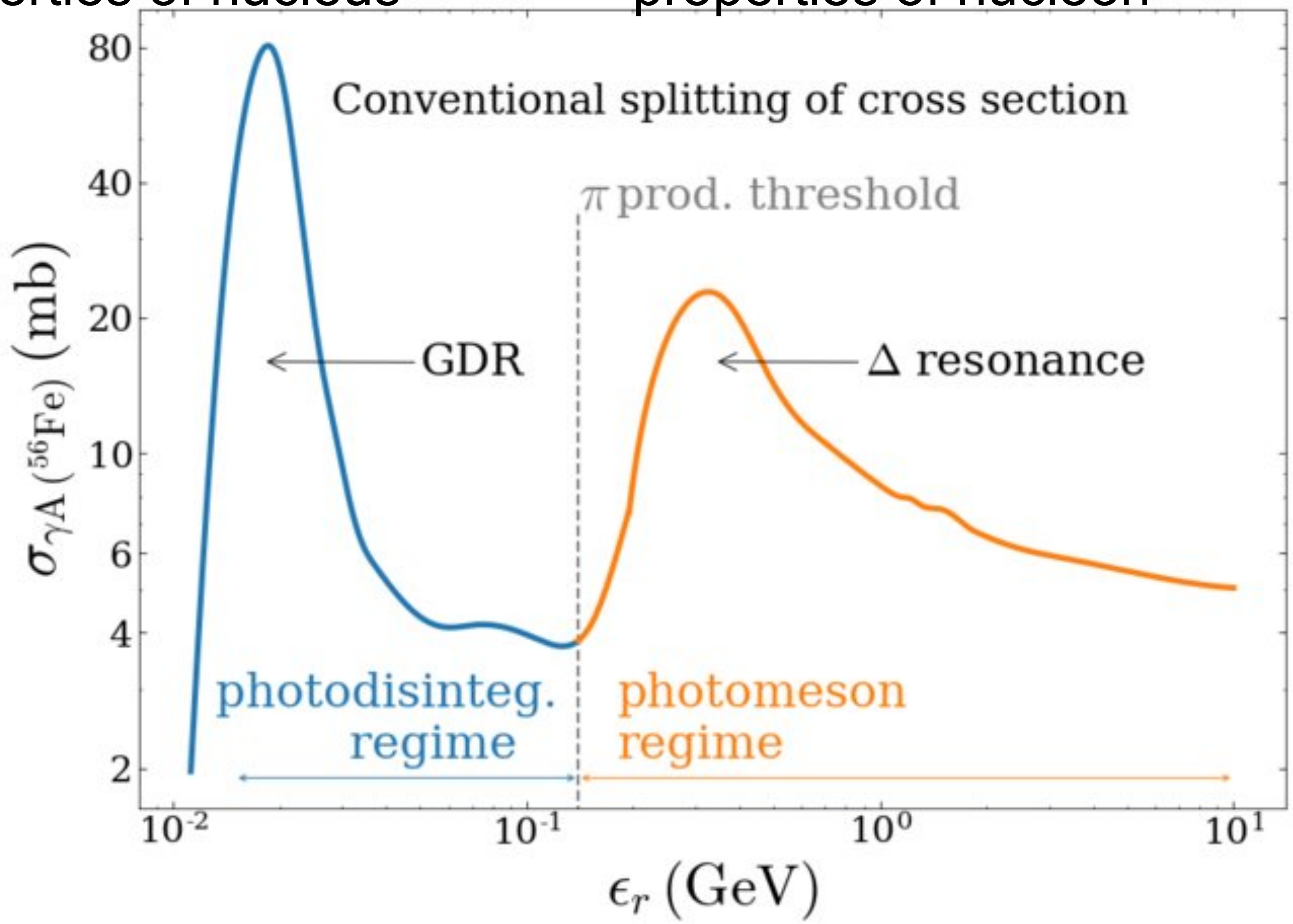
Saito++ Phys. Rev. C 51, 2757 (1995)

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

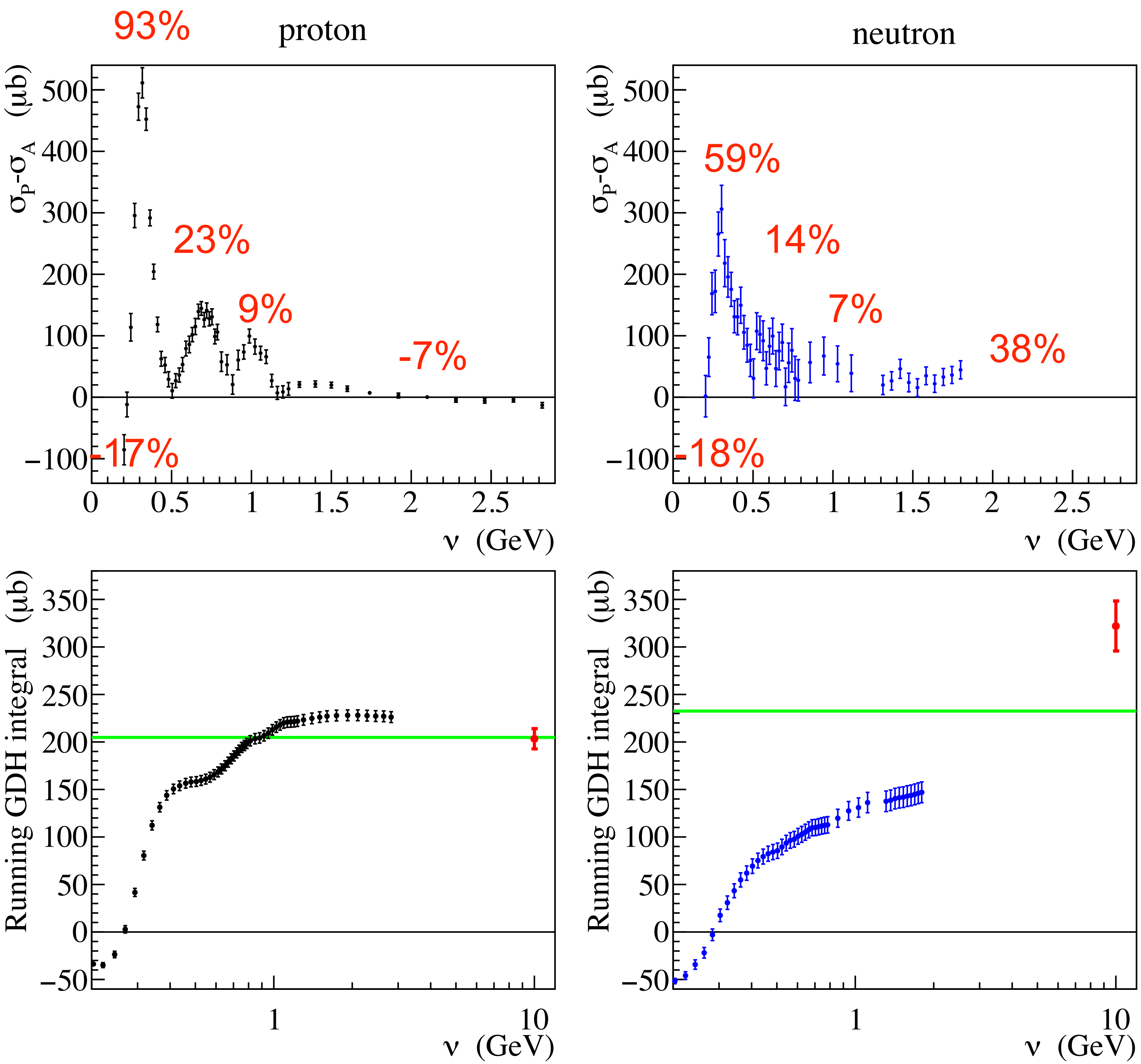
$I_{\mathrm{GDH}}^{p*} \approx 270\ \mu\mathrm{b}$

example for ^{7}Li

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

Morejon++ JCAP 11, 007 (2019)

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 $1/M^2$)

Δ(1232)

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

3rd resonance and Regge
modification

Short Range Correlated np pairs

Thomas IJMP E27 (2018)

Experiment E12-14-001 approved to study polarized EMC effect on ^{7}Li
- mean field model predict a significant 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

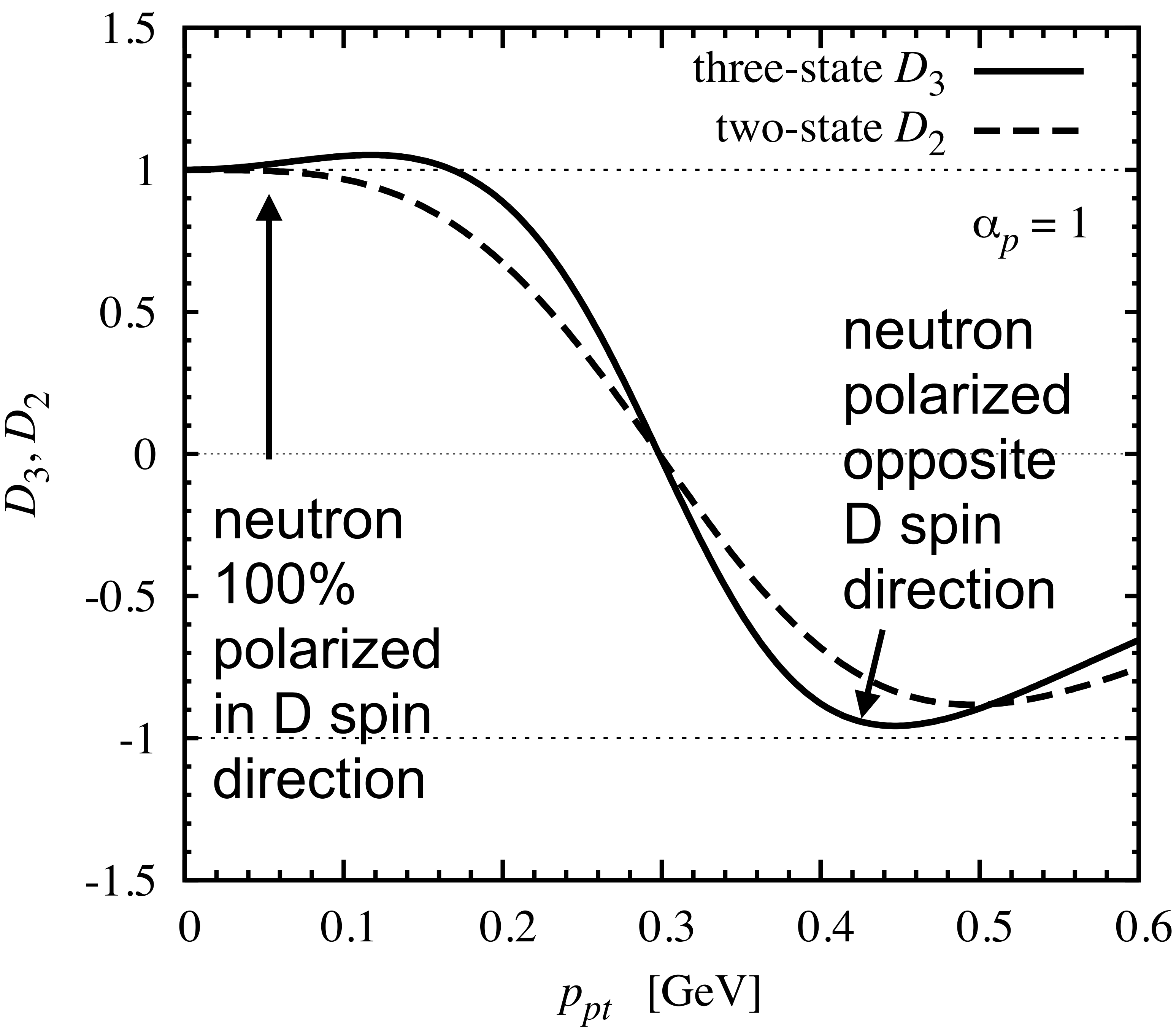
SRC interacts through tensor interaction which preserves J_z

Apply Clebsch-Gordan coefficients for orbital angular momentum $L = 2$

Valence nucleon polarization changes sign but is only about -10 to -15%.

Deuteron Spin Structure

Required for using the deuteron as a polarized neutron target.



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

Has to a certain extent been verified at Nikhef for A_{ed}^{V} in $^2\overrightarrow{H}(\vec{e}, e'p)n$

Passchier++ PhysRevLett.88.102302

and BLAST at Bates for A_{ed}^{V} and A_d^T in $^2\overrightarrow{H}(\vec{e}, e'p)n$

DeGrush++ PhysRevLett.119.182501

Summary

A polarized target in Hall D would allow studying the GDH sum rule on the proton and the neutron.

- Convergence of the integral directly tested
- Sum rule validity for neutron tested for the first time
- Proton uncertainty decreased by 25%
- Test Regge phenomenology in polarized domain - α_{f1} and α_{a1} at 2% level (present uncertainties: 50%)
- Help determine the real and imaginary parts of the spin-dependent Compton amplitude

The experiment is relatively easy extension of the GlueX program which requires a new polarized target.

We are exploring ideas to expand the program into both nuclear physics and spectroscopy.

We welcome new collaborators.