Measurement of the high-energy contribution to the Gerasimov-Drell-Hearn sum

A. Deur

05/13/2020

Work done with M-M. Dalton (JLab) J. Stevens (W&M) and S. Širca (Ljubljana Univ.)

Information at https://halldweb.jlab.org/wiki/index.php/GDH_in_Hall-D

The Gerasimov-Drell-Hearn sum rule

Spin-dependent total photoproduction cross-sections

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

anomalous magnetic moment

Photon energy Mass spin

- Fundamental Quantum Field Theory prediction. Applicable to any type of target.
  - Different targets test different properties of Nature:
    - Electron target: QED test, electron compositeness…
    - Nucleon target: QCD, nucleon structure…
- Conditions for the sum rule to be valid:
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  - 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).
- GDH on nucleons: Integral gets most contribution for $\nu<2$ GeV, but if the sum rule fails, it would happen at high energy.
  - Proton: $\nu>3$ GeV not measured yet.
  - Neutron: $\nu>1.8$ GeV not measured yet.
- Nucleon polarized cross-section unknown at large ν. Expected to be described by Regge theory.
- Relatively simple experiment and analysis.
- With its tagger, large solid angle detector and high flux, Hall D is the natural place to perform a GDH experiment.

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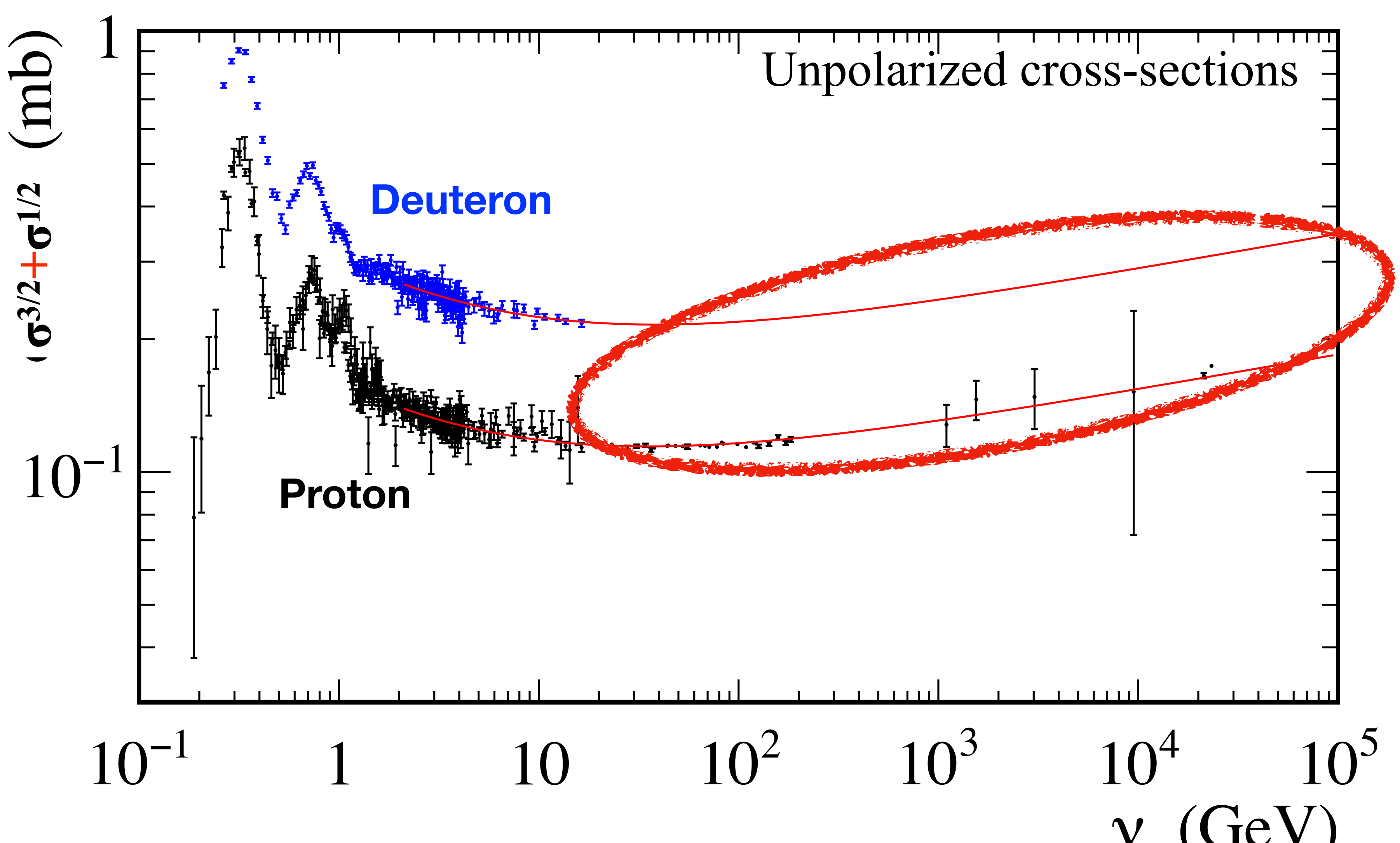

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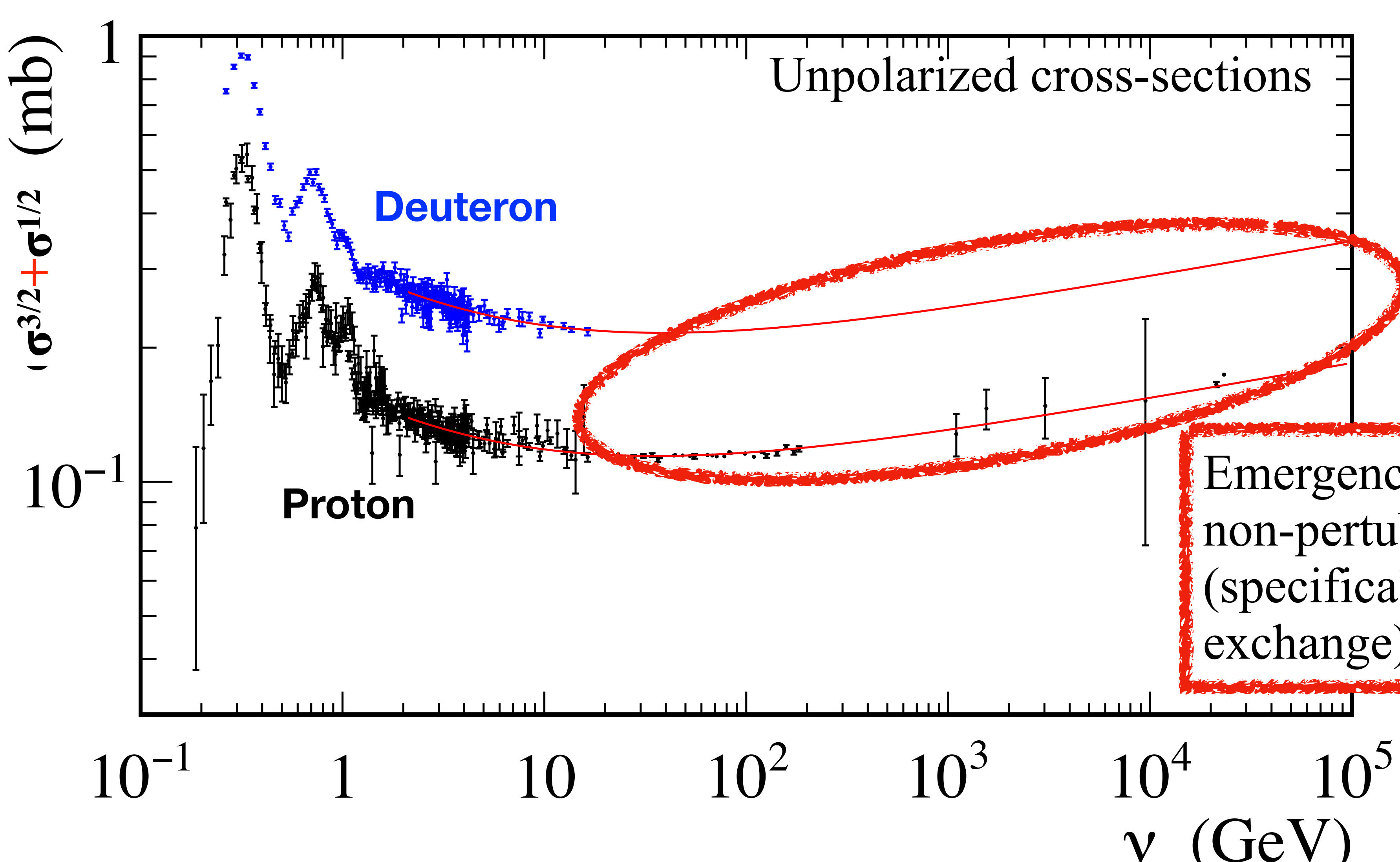

Emergence high-energy non-pertubative reactions (specifically here: pomeron exchange).

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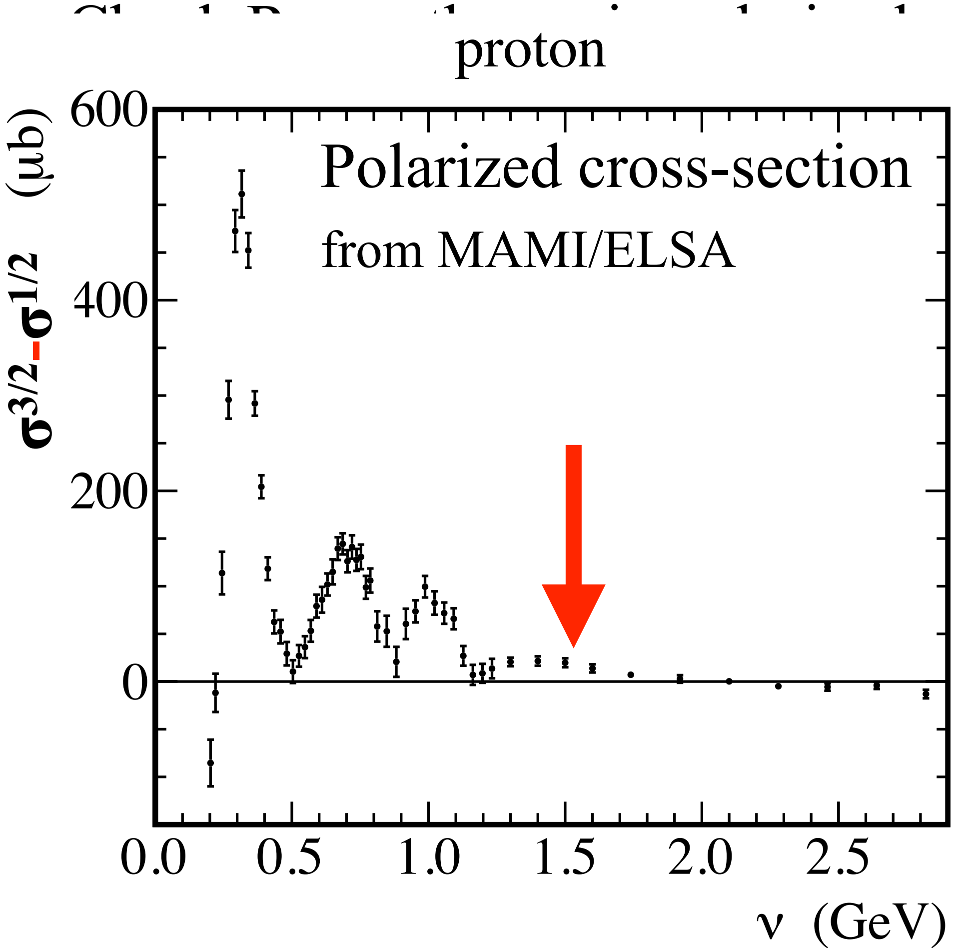
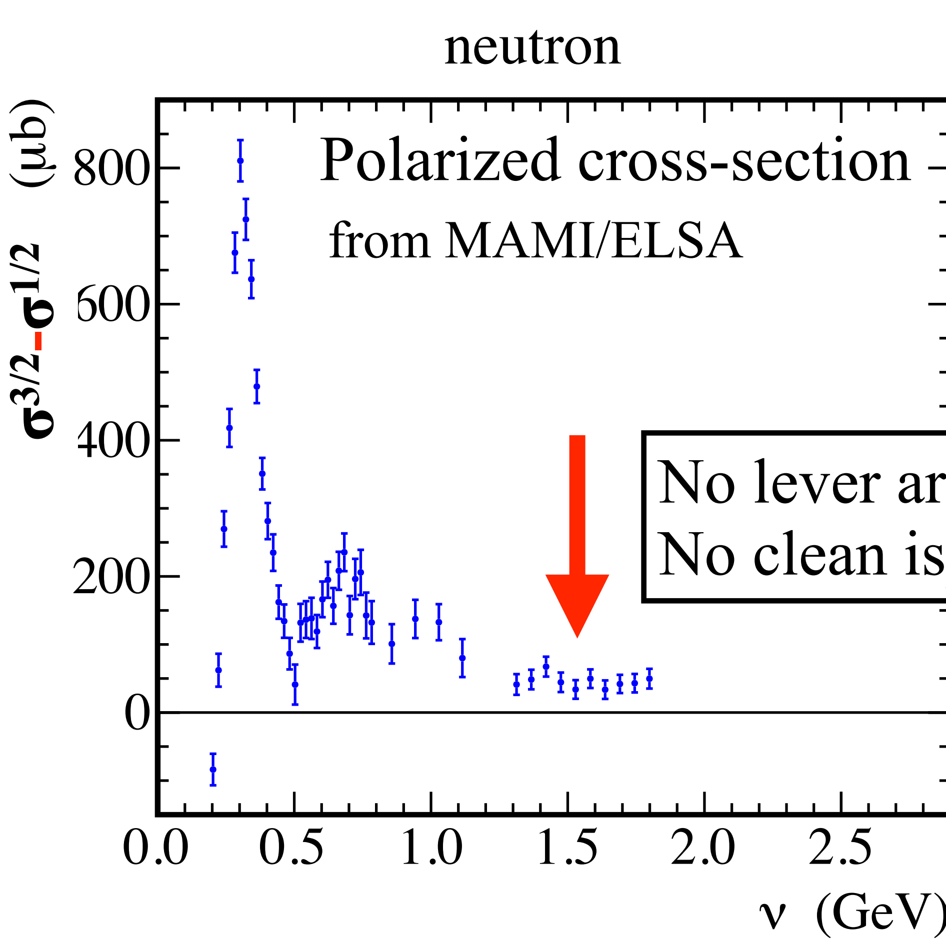


neutron



No lever arm.
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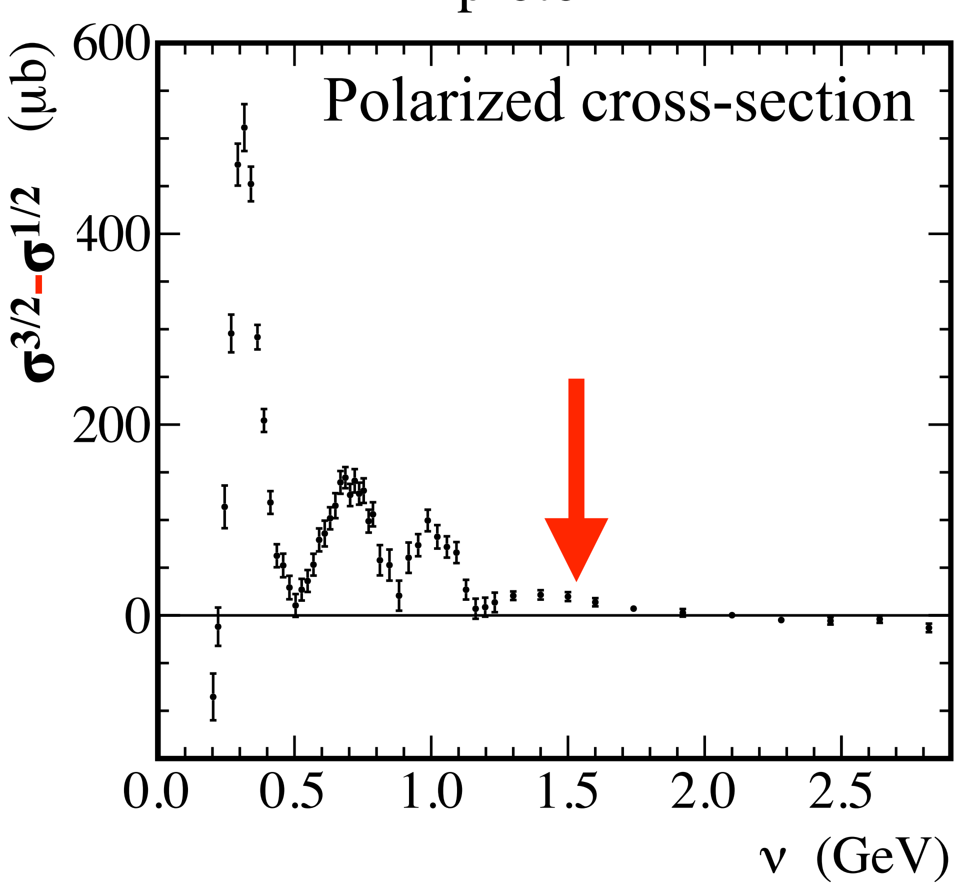

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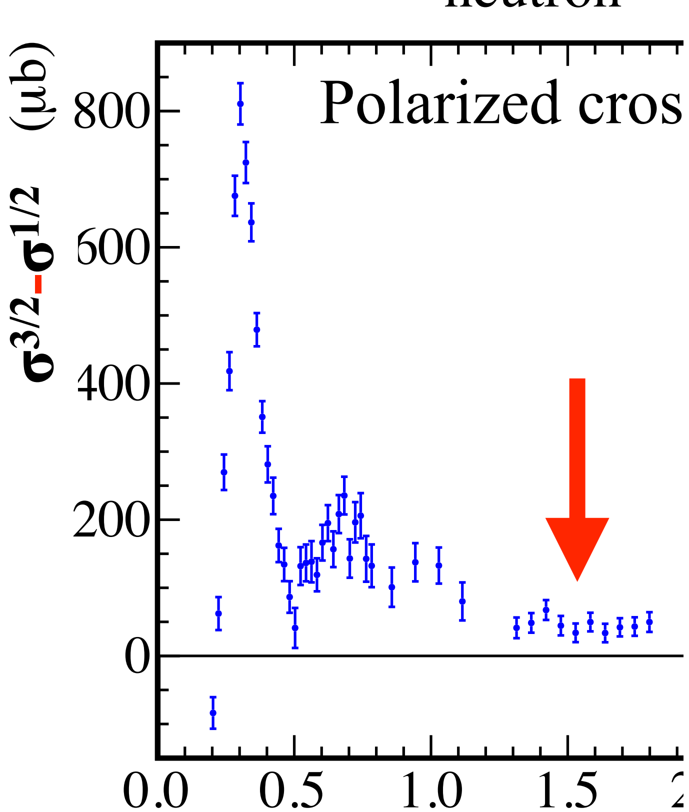

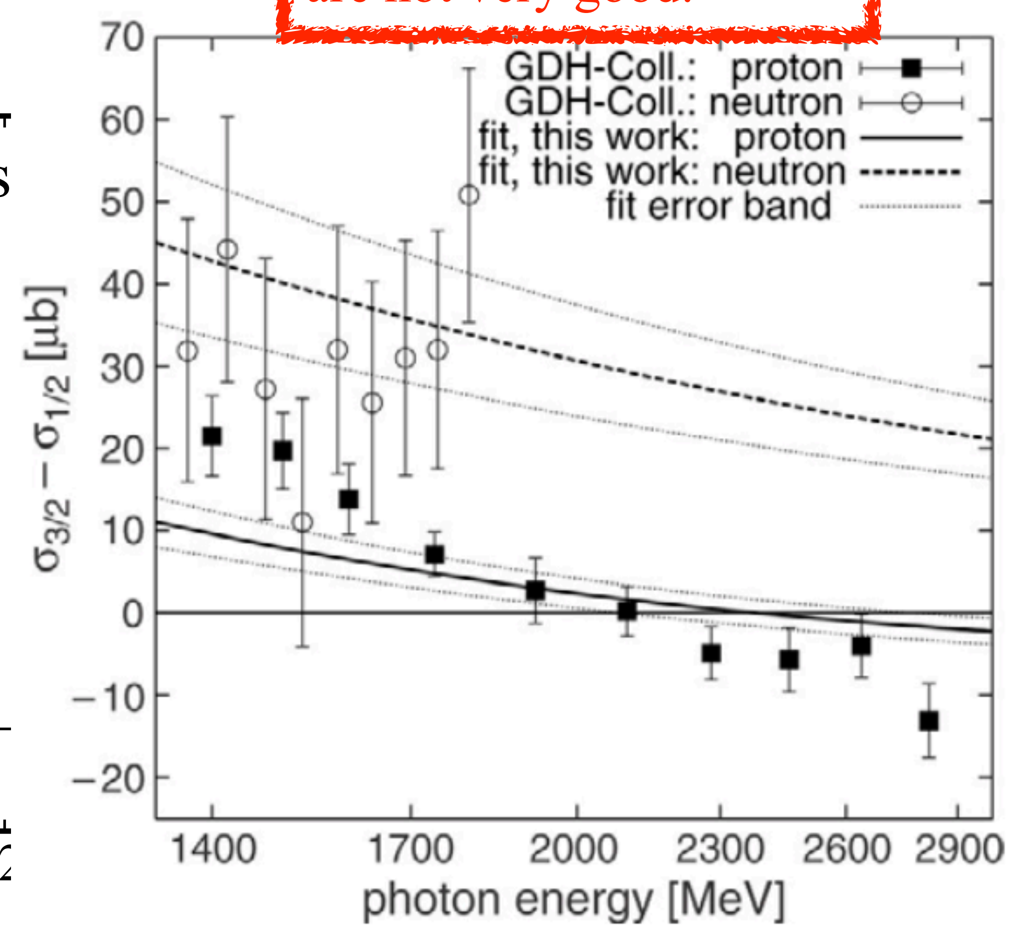

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    - Dispersion relation analysis provides access to spin-dep Compton *amplitude* f_2. Test of Chiral Pert. Theory.
    - No non-zero signal seen yet in the existing deuteron diffractive data (large ν, low Q^2 data).
    - Discrepancy between DIS data and diffractive regime and Regge expectation.
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    - Constraint on muonic hydrogen hyperfine splitting.
- Simplest doubly polarized experiment: Logical start for doubly polarized program in Hall D.

Motivations

- GDH: Fundamental QFT prediction.
  - (Assume causality, unitarity and Lorentz and gauge invariances.)
  - Assume vanishing of Compton amplitude $f_2(\nu)$ at large ν to derive the dispersion relation.
  - Assume $\mathrm{Im}(f_2)$ decrease fast enough with ν for integral to converge.
    - $\Rightarrow$ for GDH on hadron: QCD determines convergence of integral and sum rule validity.
  - Possible violation mechanisms:
    - A J=1 pole of the nucleon Compton amplitude;
    - Chiral anomaly;
    - Quark substructure (non-zero quark anomalous moment);
    - Other, more exotic possibilities, have been proposed.
  - Unpolarized version of GDH integral $\int(\sigma^{3/2}+\sigma^{1/2})d\nu$ does not converge.
- High-ν part not measured yet. Possible violation mechanisms are at high-ν, not at low-ν.
- Need to be past the resonance bumps to perform reliable Regge-based fit to:
  - Check Regge theory in polarized case,
  - Provide a reliable basis for extrapolation to $\nu\to\infty$.
- Hall D's 3-12 GeV coverage: extend coverage by factor 4 for proton and 6 for neutron/deuteron.
  - Sensitive domain for sum rule violation; smooth cross-section allows Regge-based fit.
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Experimental strategy and setup

- Need to measure both proton and neutron (deuteron) for
  - isospin separation. Regge theory: isoscalar and isovector contributions to ($\sigma^{3/2}$-$\sigma^{1/2}$) come from different meson families ($f_1(1285)$ and $a_1(1260)$ respectively).
  - Deuteron:
    - no non-zero ($\sigma^{3/2}$-$\sigma^{1/2}$) seen yet for D in diffractive regime (both photo- and electro-absorption).
    - No neutron data above 1.8 GeV.

- Energy coverage:
  - $3<\nu<12$ GeV Standard running (CEBAF at 12 GeV).
  - $1<\nu<4$ GeV Requires CEBAF to run at 4 GeV. Either invasive to other halls, or low energy summer run.

- First: get yield difference $\Delta y(\nu) = N^{3/2} - N^{1/2}$. Sufficient to study GDH convergence.

  $\Rightarrow$ ν-independent normalization factors of secondary importance

  For ex. if $\sigma^{3/2}$-$\sigma^{1/2} = a\nu^b$, we get b, without need to extract an accurate a.
  - Suppress normalization factor uncertainties.
  - Unpolarized backgrounds (e.g. target dilution) cancel.

- Then: Extract absolute cross-section $\sigma^{3/2}$-$\sigma^{1/2}$: Study GDH SR validity for both nucleons + other goals

- 3 main ingredients needed:
  - Circularly polarized tagged photon beam;
  - Longitudinally polarized target;
  - Large solid-angle detector.

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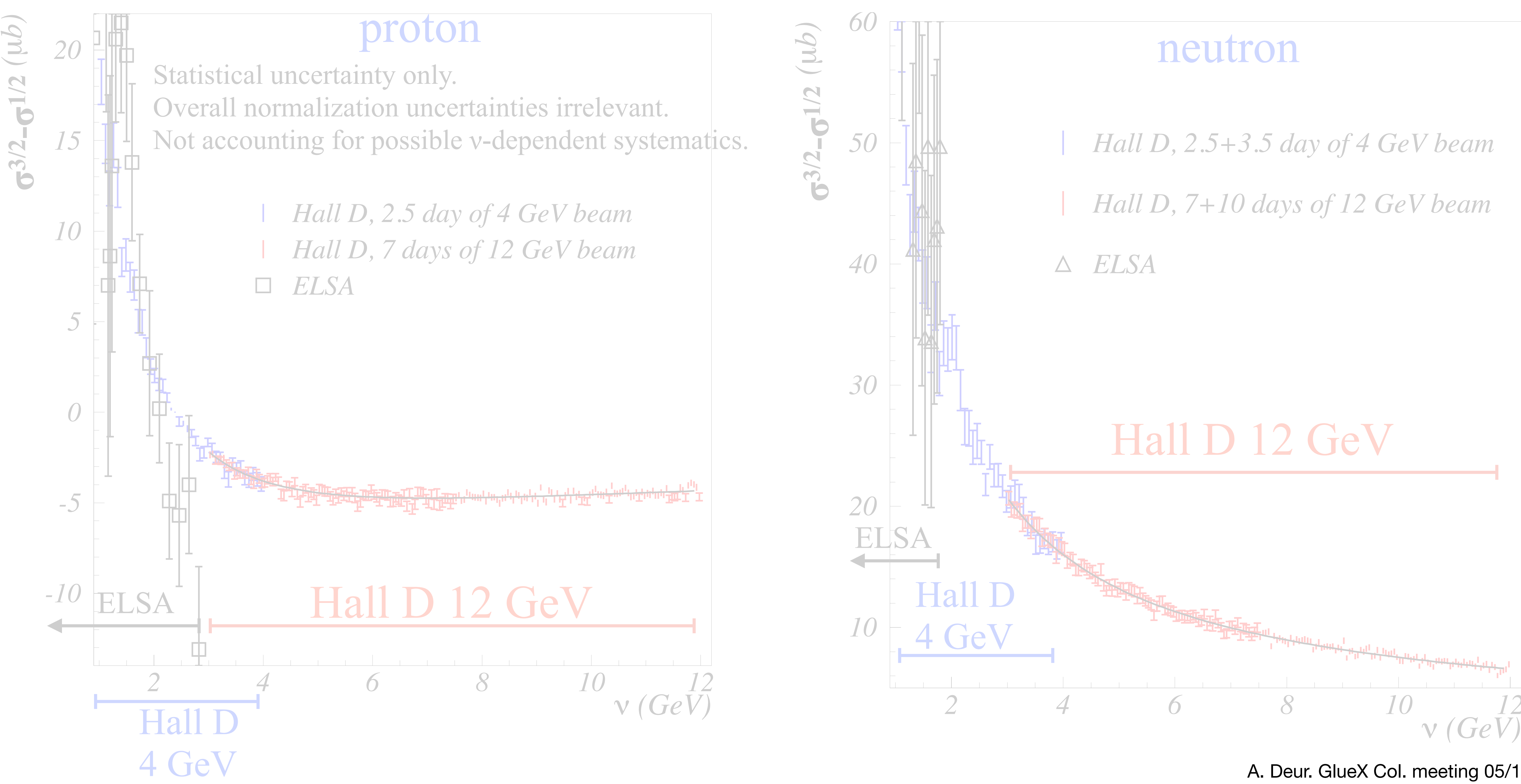
- 3 main ingredients needed:
  - Circularly polarized tagged photon beam;
    - Polarized electron beam;
    - Amorphous radiator.
  - Longitudinally polarized target; FROST target.
  - Large solid-angle detector. Hall D

Expectations

- 1 week of running on proton: Minimum time, given two months investment to install the target.
  $\Rightarrow$ 10 days on deuteron so that neutron uncertainty is similar to proton's one.
- Valuable to also take data at lower energy: assume additional 1 week (p+n) at 4 GeV.
- With overheads (TAC runs, target operations…): 27 days.

Simulated data:



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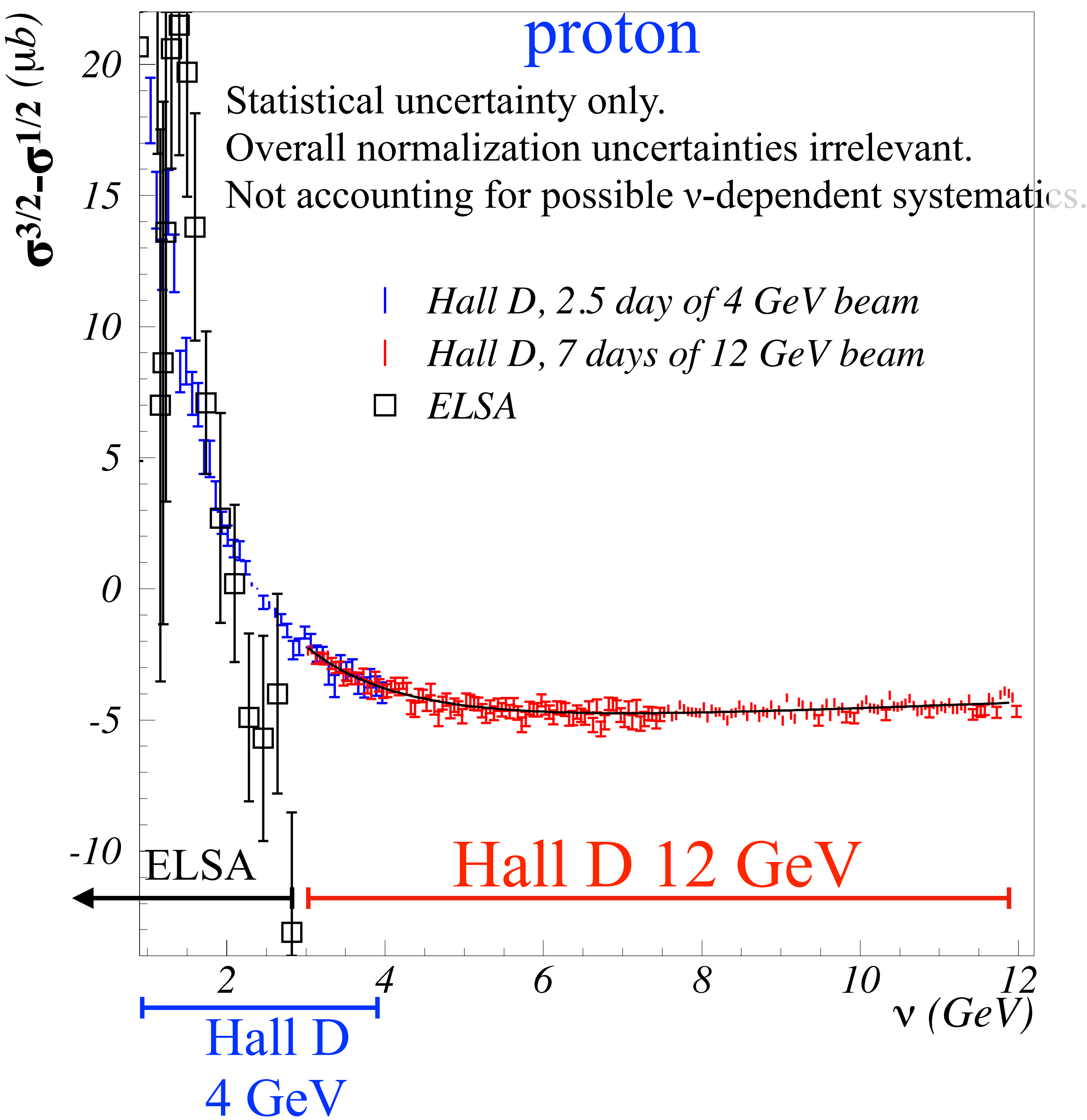

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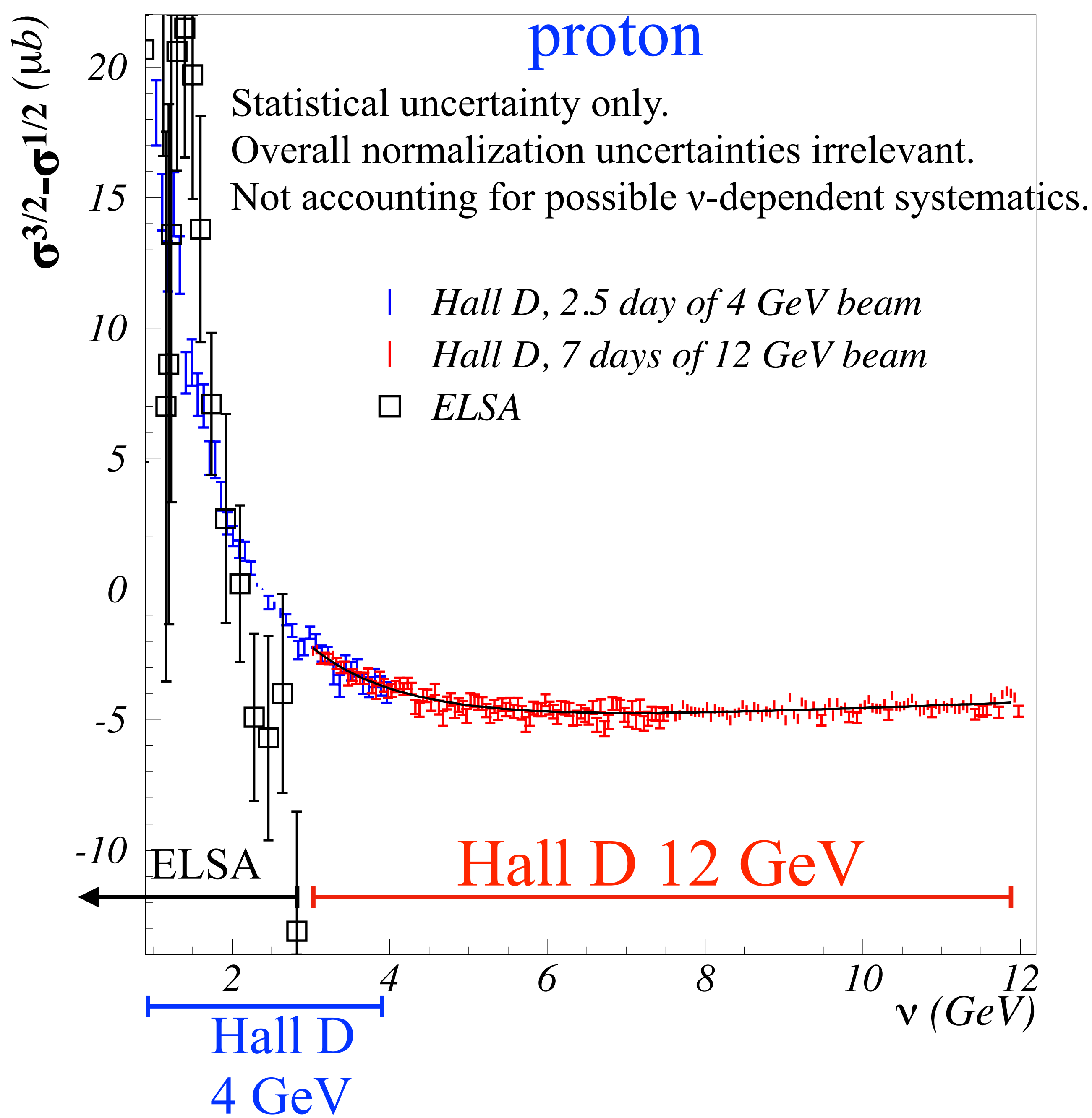

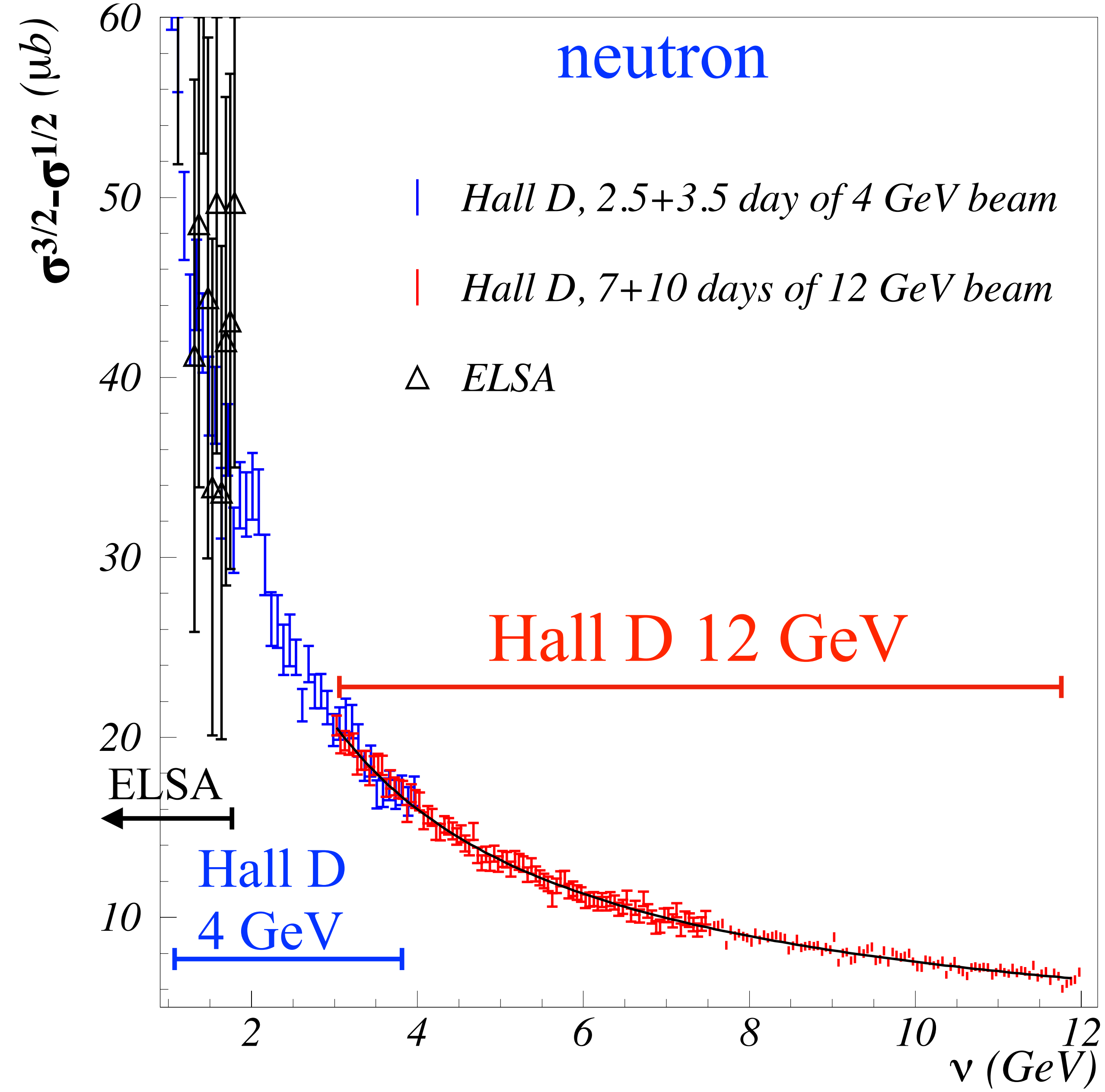

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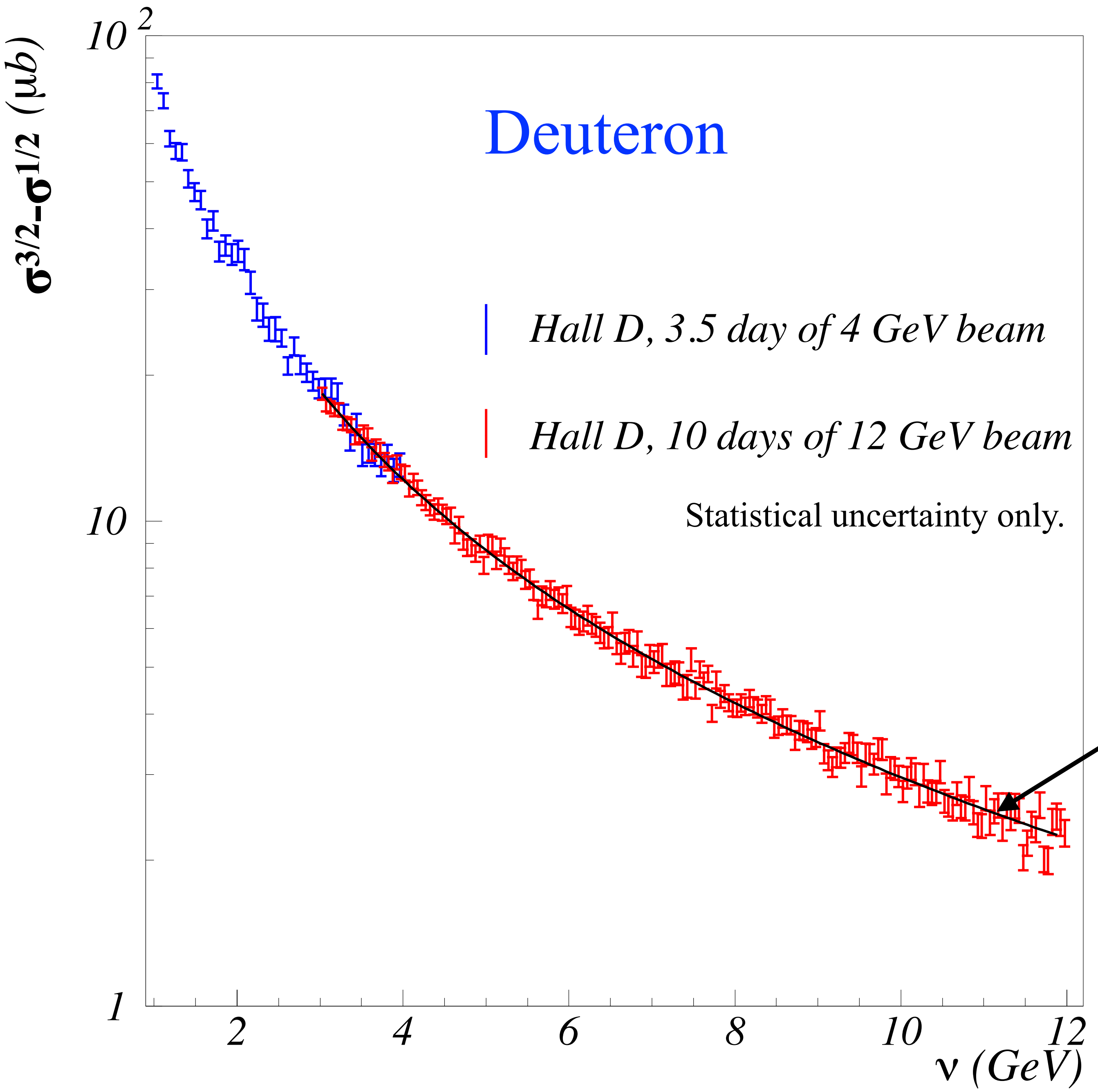

Should measure well the first non-zero deuteron signal in diffractive domain:

Fit: $\sigma^{3/2}-\sigma^{1/2} = (415 \pm 20)s^{-1.660 \pm 0.019}$

Impact

- Measuring high ν-behavior will test the convergence of GDH sum (fast and robust analysis: early goal)
  - First measurement well outside resonance region: first clean test of Regge theory for polarized case.
  - If Regge theory works: $\Delta\alpha_{a1} = \pm 0.005$ & $\Delta\alpha_{f1} = \pm 0.019$. Compare to $\Delta\alpha_{a1} = \pm 0.23$ & $\Delta\alpha_{f1} = \pm 0.22$ from ELSA. This will enable a reliable assessment of the contribution up to $\nu \to \infty$.
  - First measurement of non-zero polarized signal for deuteron in diffractive region.
- Obtaining cross-section (more difficult: longer term goals) will:
  - Improve accuracy of proton GDH Sum Rule determination by ~25%
  - Allow for the first neutron GDH Sum Rule determination
  - Allow the determination of Compton amplitude f_2.
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This wil

Precise enough to resolve the discrepancy between DIS data and Regge theory.

Regge theory predicts $\alpha_{a1} \cong -0.34$, while

Several DIS fits yield $\alpha_{a1} \cong +0.45$.

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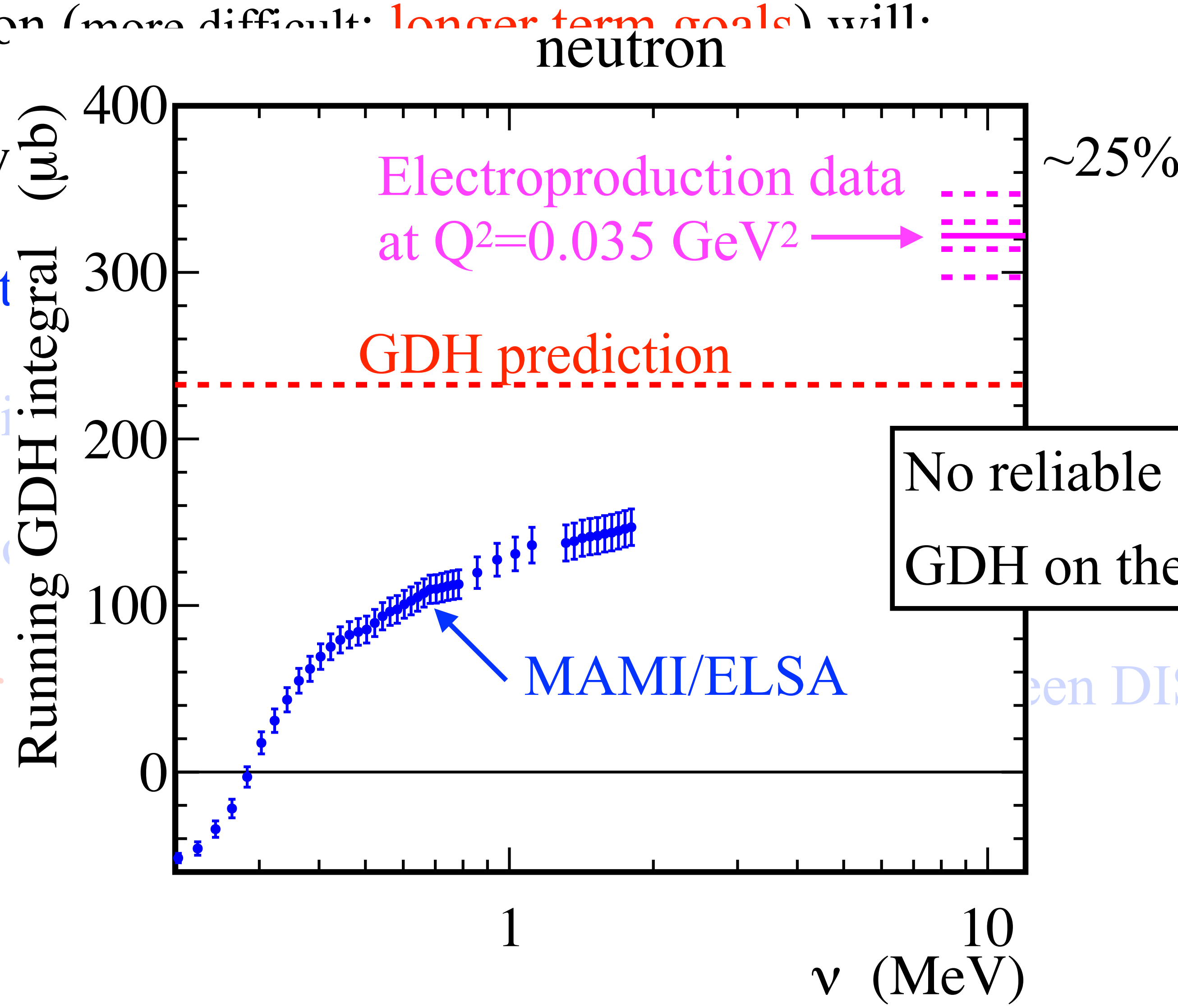

No reliable check available yet for GDH on the neutron.

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Status

- Letter of Intent submitted to PAC 47, which encouraged development into a full proposal[1].

- GlueX board, following the review committee recommendation (G. Huber, F. Nerling), approved the proposal for review by the collaboration. https://halldweb.jlab.org/wiki/images/9/9e/GDH_review_final.pdf

- Ongoing work on proposal:
    - Implementing comments from GlueX review committee/finalizing writing proposal.
        - Will commit by Friday the updated version of the proposal to DocDB.

    - GEANT simulation, including polarized Bethe-Heitler and Compton event generators for background studies.

1 The PAC recognizes the science case for this LOI and recommends preparation of a full proposal with focus on the extraction of the actual value of the GDH integral at high energies. The PAC would be pleased to see the development of ideas towards a full program with a circularly polarized photon beam and a polarized target in Hall~D.

$$\boxed{\int_{\nu_{thr}}^{\infty}(\sigma^{3/2}-\sigma^{1/2})\,\frac{d\nu}{\nu}=\frac{2\alpha\pi^2\kappa^2}{M^2}}$$

Thank you

One-slide summary

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

- First measurement of the high-ν behavior of GDH integrant $(\sigma^{3/2}-\sigma^{1/2})/\nu$
- Hall D + FROST target (H and D) + polarized electron beam on a amorphous radiator.
- High-ν is where a failing of the sum rule would be revealed.
- Early goal: map yield difference $N^{3/2}-N^{1/2}$ for the proton and neutron. This will elucidate the convergence of GDH integrals.
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Back-up slides

Expectations

- 1 week of running on proton: Minimum time, given two months investment to install the target.
  $\Rightarrow$ 10 days on deuteron so that neutron uncertainty is similar to proton's one.
- Valuable to also take data at lower energy: assume additional 1 week (p+n) at 4 GeV.
- With overheads (TAC runs, target operrations…): 27 days.

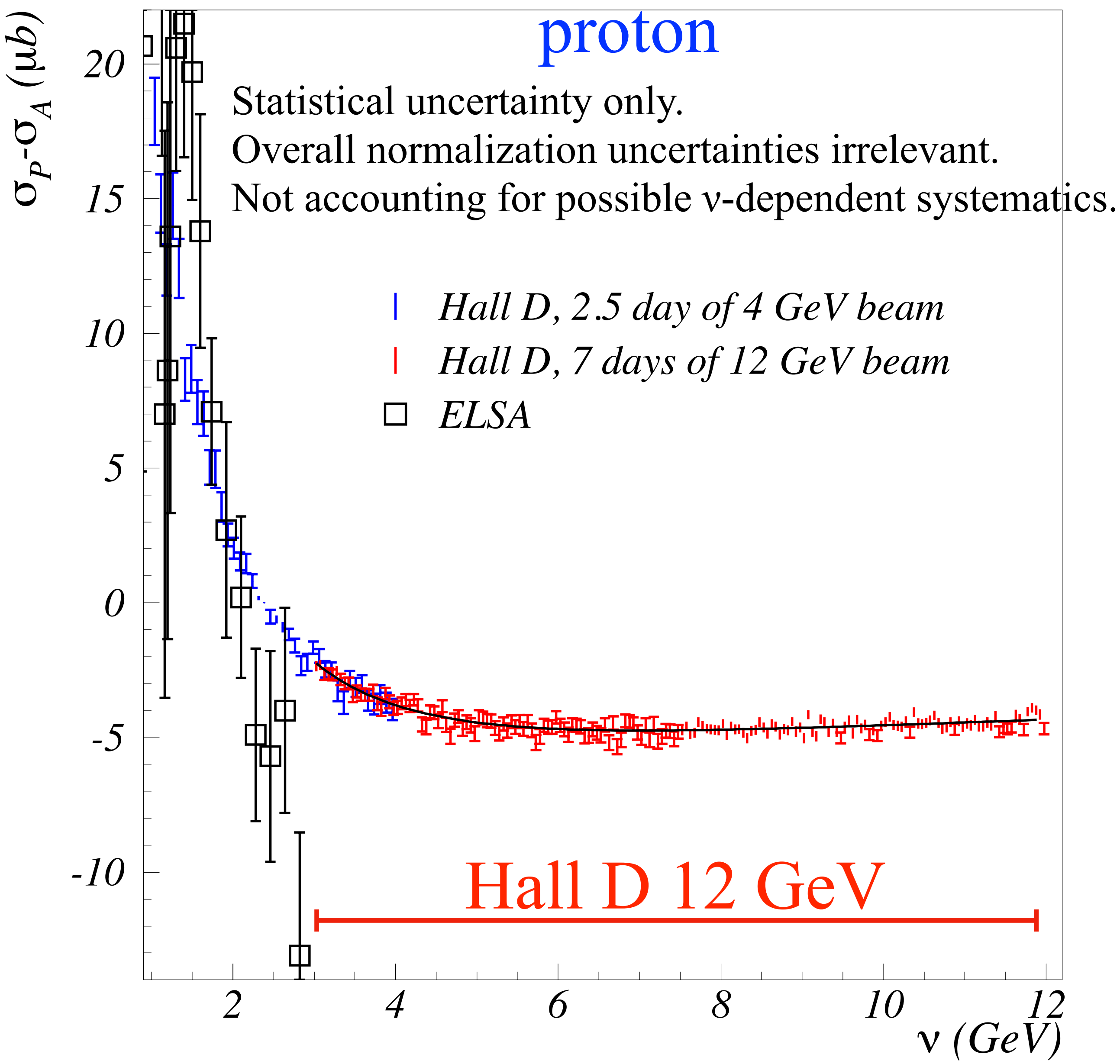
Time (day)	Target	Goal/Remarks
10	Deteuron	Main production at 12 GeV
0.3	Deuteron	Spin dance done during above task
0.5	deuteron	Target spin-flip/repol. No beam, done at middle of production
0.5	Deteuron $\rightarrow$ proton switch	No beam
7	Proton	Main production at 12 GeV
0.5	proton	Target spin-flip/repol. No beam, done at middle of production
0.5	Pair. Spec. converter	Absolute flux calib.
3.5	Deuteron	Production 4 GeV
0.3	Deuteron	Spin dance done during above task
0.5	Deteuron $\rightarrow$ proton switch	No beam
2.5	Proton	Production at 4 GeV
0.5	Pair. Spec. converter	Absolute flux calib.
Total: 26.6		

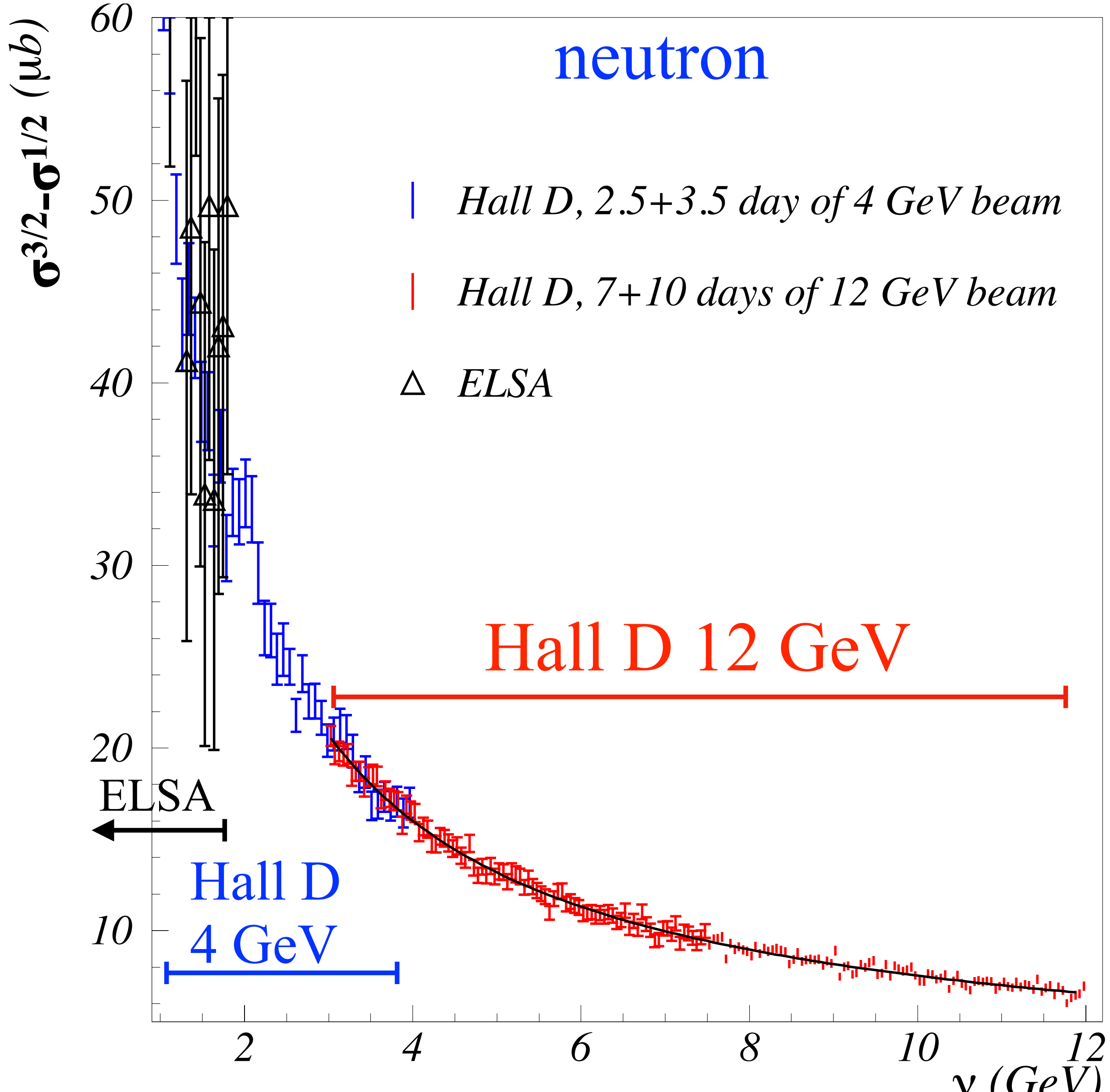
Expectations

- 1 week of running on proton: Minimum reasonable time, given overhead $\Rightarrow$ 10 days on deuteron.
- Valuable to also take data at lower energy: 1 week (p+n) at 4 GeV.
- For simulating expected data, use Regge theory: $\sigma^{3/2}-\sigma^{1/2} = c_2 s^{\alpha_{f_1}-1} \pm c_1 s^{\alpha_{a_1}-1}$ (+: proton, −: neutron)

$s=2M\nu+M^2$, α_{f1}, α_{a1}: Regge intercepts of $f_1(1285)$ and $a_1(1260)$ trajectories, and $c_{2,1}$: parameters.

- 2.5×10^7 s^{-1} tagged flux ($3<\nu<12$ GeV), Pb=80%, Pt=80%, $\Delta\Omega=0.75\times\pi$, 80% detector efficiency.
- 5cm target on usual butanol density

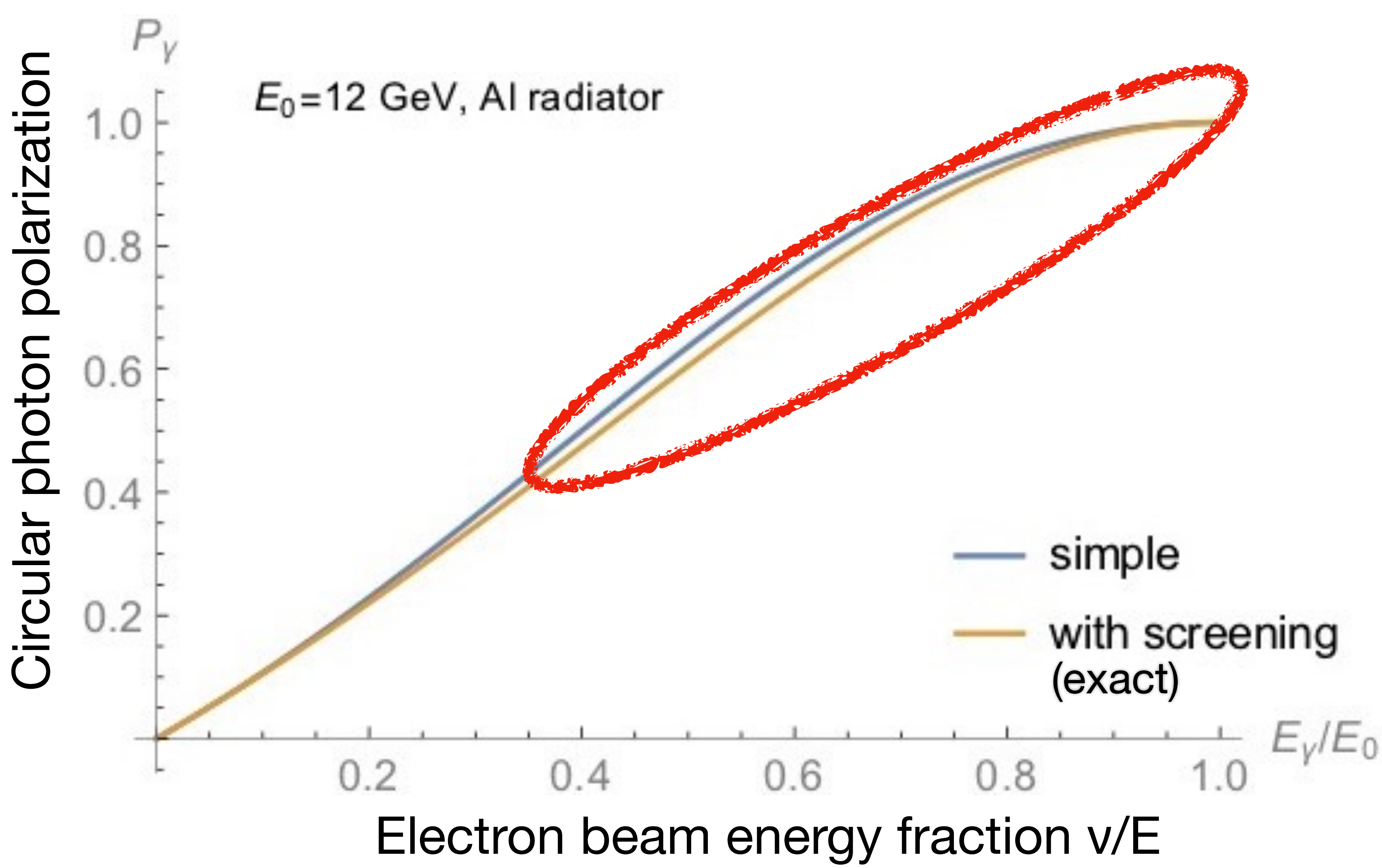




Isospin analysis $\Rightarrow$ $\boxed{\Delta\alpha_{a1}=\pm0.006 \ \& \ \Delta\alpha_{f1}=\pm0.016}$

Circularly polarized beam

- Polarized electron beam;
- Amorphous radiator.



- Needed
  - Electron beam helicity reporting
  - Beam charge asymmetry control

- Not needed
  - polarimetry (can still be done with injector's Mott polarimeter+spin precession).
  - flux knowledge
  - High photon energy resolution (present < 0.5% more than enough).

Polarized target

- Options are polarized HDice or FROST
  - HDice: best figure of merit (low dilution, high sustainable photon flux), but complex to prepare and use.
  - FROST: best polarization, easier to use, but high dilution and lower maximum flux.

- Running one short experiment: not enough to invest in HDice.
- FROST dilution not an issue for GDH thanks to high rate Hall D DAQ: total rate with max flux<DAQ limit. Also, dilution cancels in physics analysis: $(N^{3/2}+N^0) - (N^{1/2}+N^0) = N^{3/2} - N^{1/2}$

  $\Rightarrow$ use FROST

- Target group prefers to build dedicated Hall D FROST target rather than import Hall B one.
- Two months to install the target. No commissioning needed.

FROST characteristics:

- Dynamical Nuclear Polarization on Butanol (C_4H_9OH or C_4D_9OD)
- P and D polarizations: up to 90%. Need to be re-polarized every 5-7 days (5h process).
- Only longitudinal polarization needed. Anti-parallel polarization possible. Useful for GDH but not required.
- Need to install cryogen lines (or dewars) for cooling.
- Sustainable *total* photon flux ~10^8 s^{-1}. Could be up to 10^9 s^{-1} (need additional small magnet on target nose). 10^9 s^{-1} would be useful, especially since DAQ rate is currently not limiting and will improve with years.

Detectors and DAQ

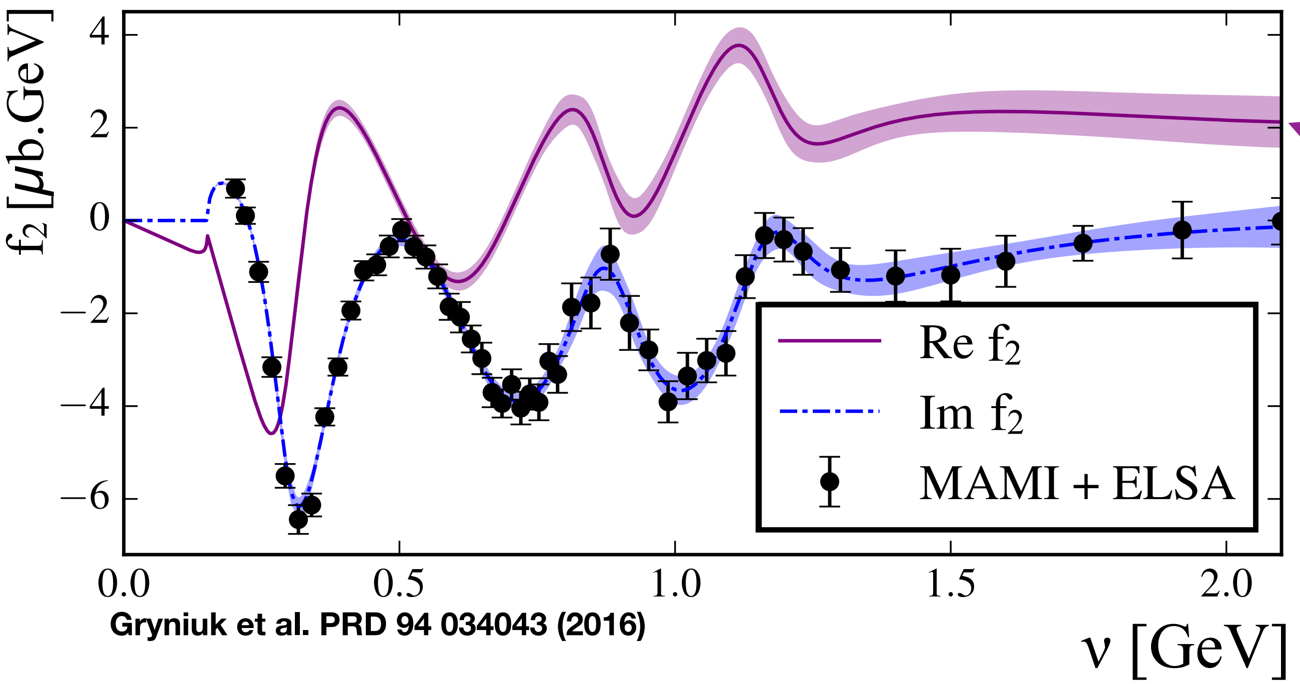
•Measure total photoproduction yield.

•BCal, FCal, Compcal. (CDC/FDC a priori not needed.): 0.2^{o} to 145^{o} polar coverage. (Compare to 1.6^{o} to 174^{o} coverage by ELSA's GDH detector). 2π azimuthal coverage.

•DAQ: total unpol. photoprod. cross-section: ~120 μb. ⇒ 33 kHz on H-butanol and 40 Khz on D-butanol. (Not accounting for target window and electromagnetic background).

•Rate below DAQ limit ⇒ experiment insensitive to unpolarized target material and backgrounds

Extraction of the real and imaginary parts of Compton amplitude f_2



Gryniuk et al. PRD 94 034043 (2016)

Dispersive analysis from Im(f_2) data. Large ν data will constrain both Re(f_2) and Im(f_2) error bands.

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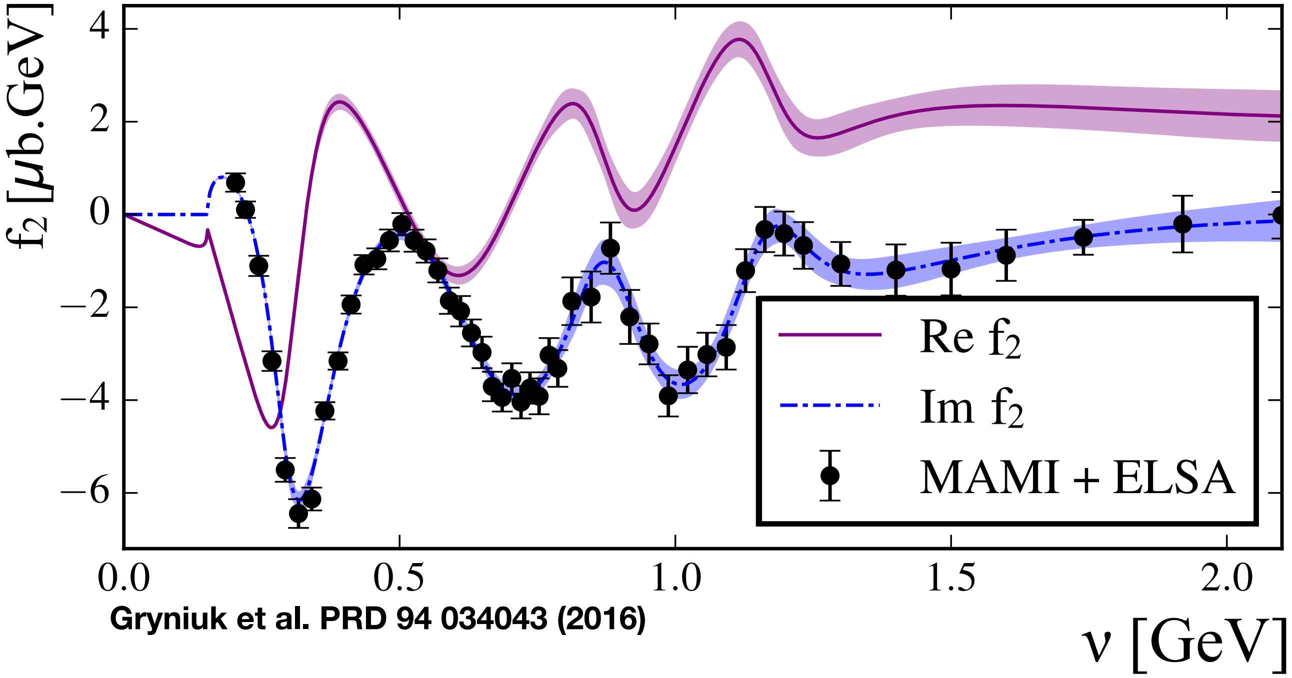

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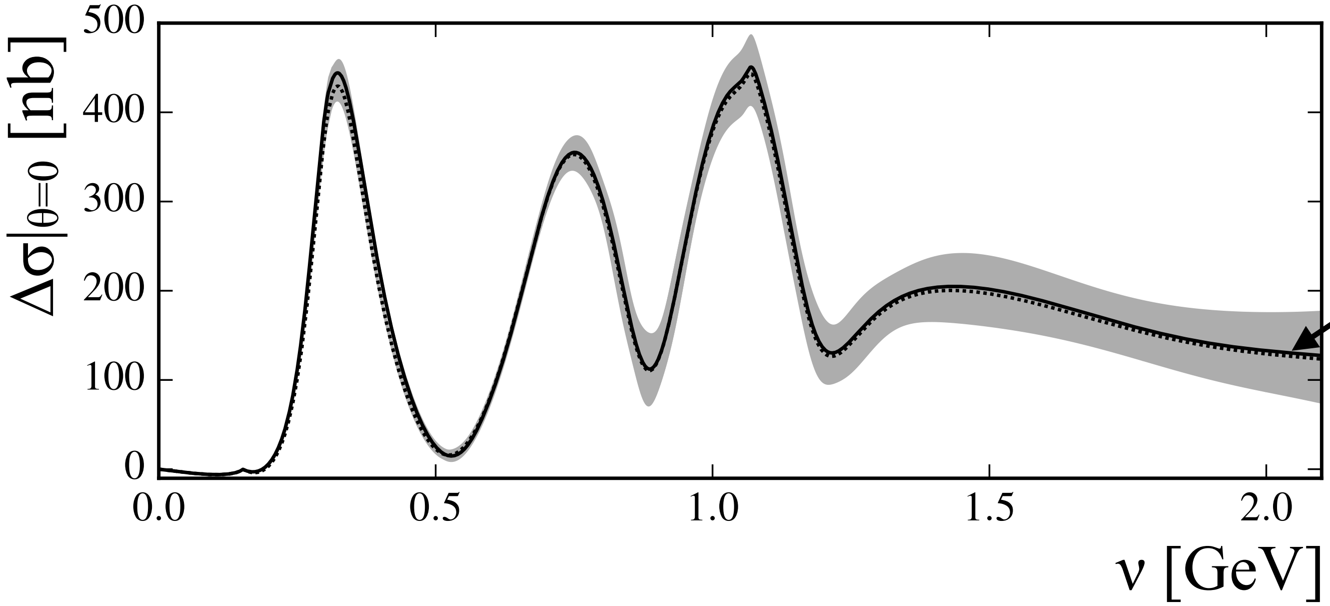
From Re(f_2) and Im(f_2) and the well measured unpolarized f_1, one gets $\sigma^{3/2}-\sigma^{1/2} \stackrel{\text{def}}{=} \Delta\sigma$ in the forward limit.



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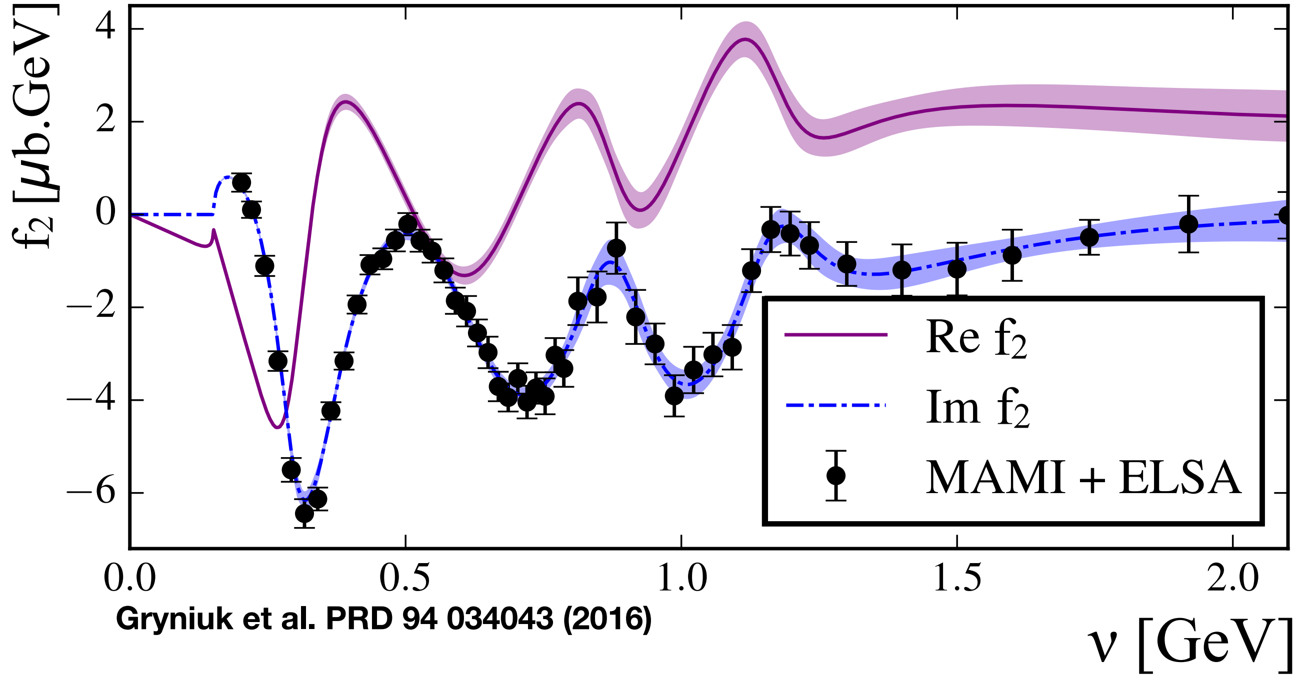

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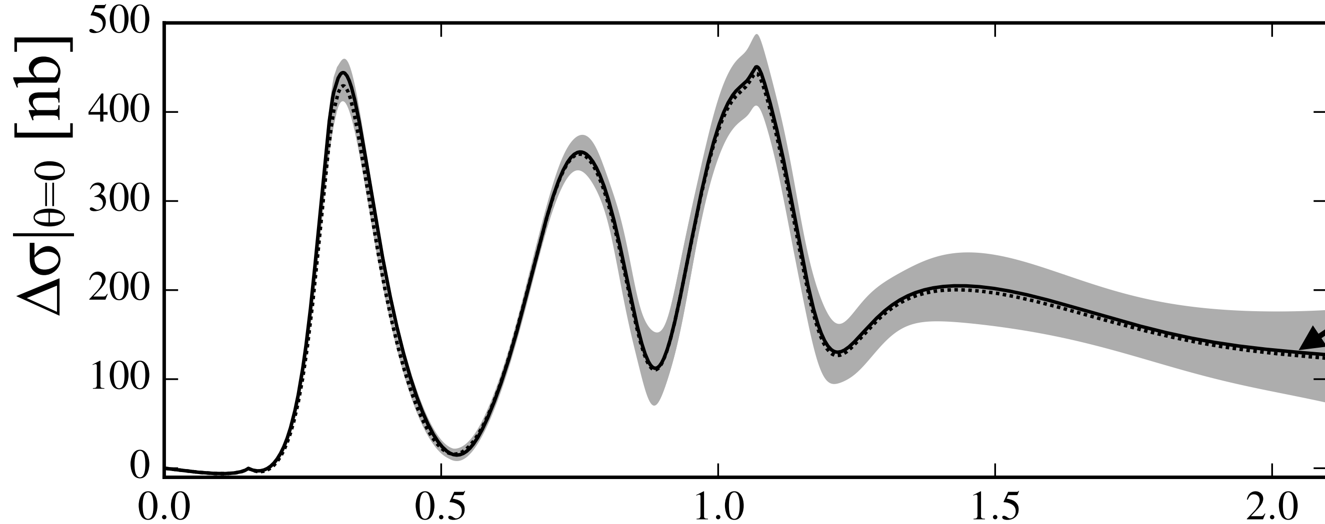

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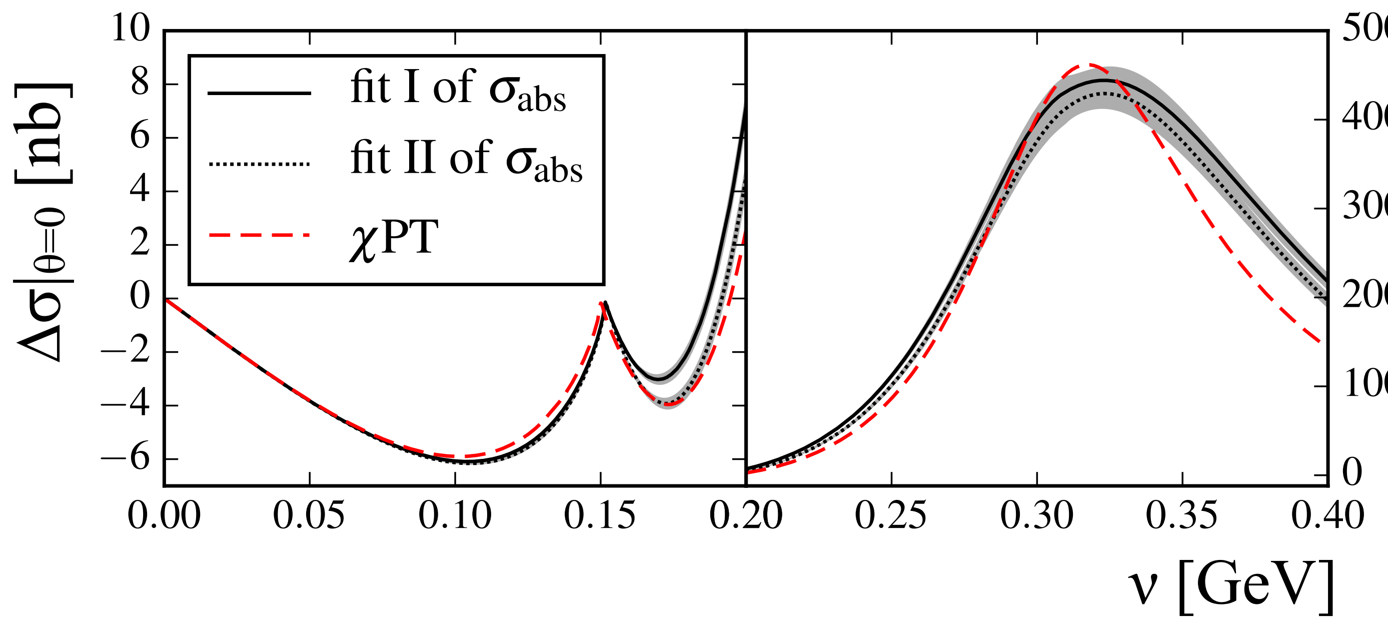

Chiral Perturbation Theory (χpT) calculation available.

$\Delta\sigma|_{\theta=0}$ very sensitive to chiral loops.

$\Longrightarrow$ Test of χpT at Q^2=0.

Complement JLab program GDH at low Q^2 that tested and challenged χpT in the polarized sector.

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