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

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

Spin-dependent total photoproduction cross-sections

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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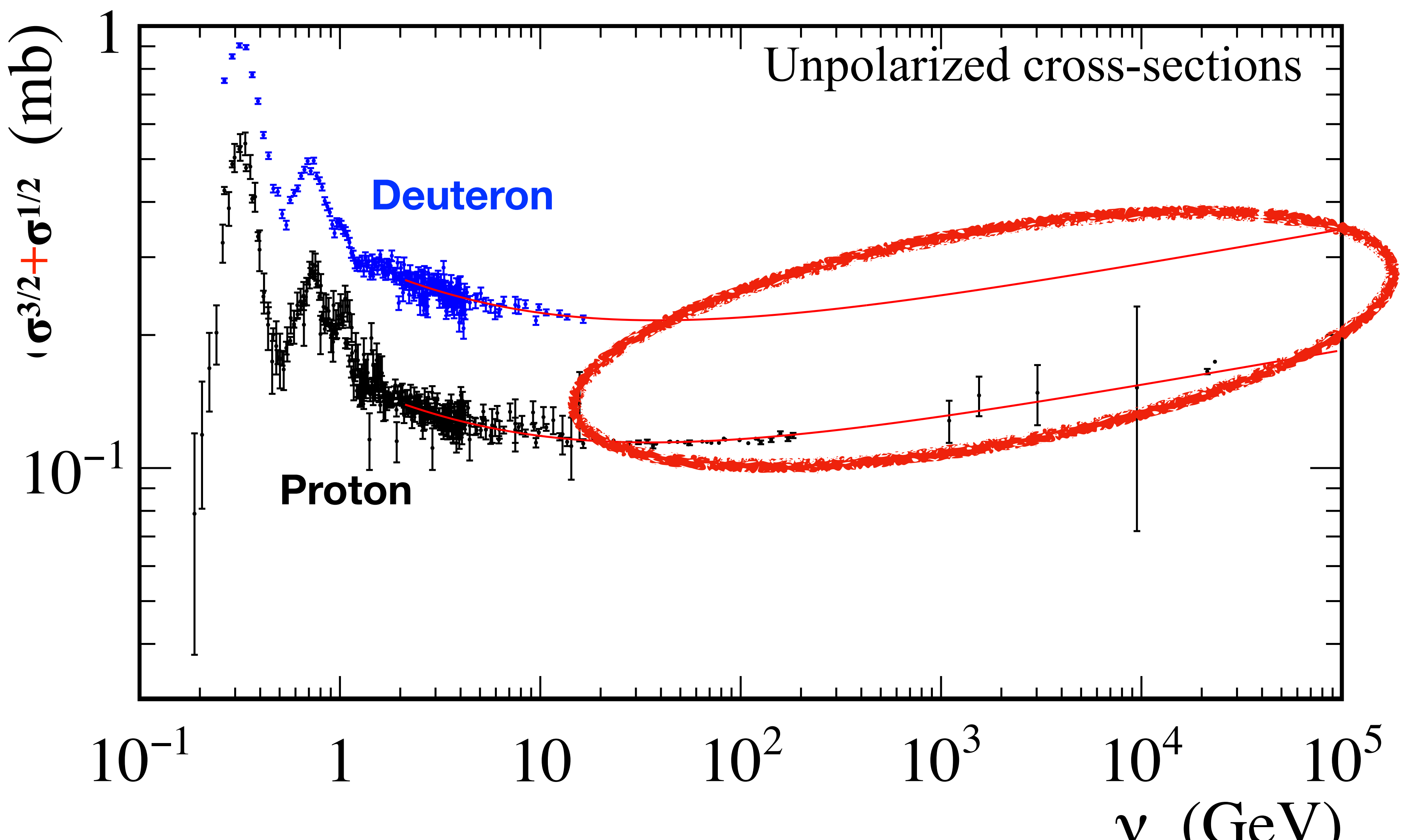

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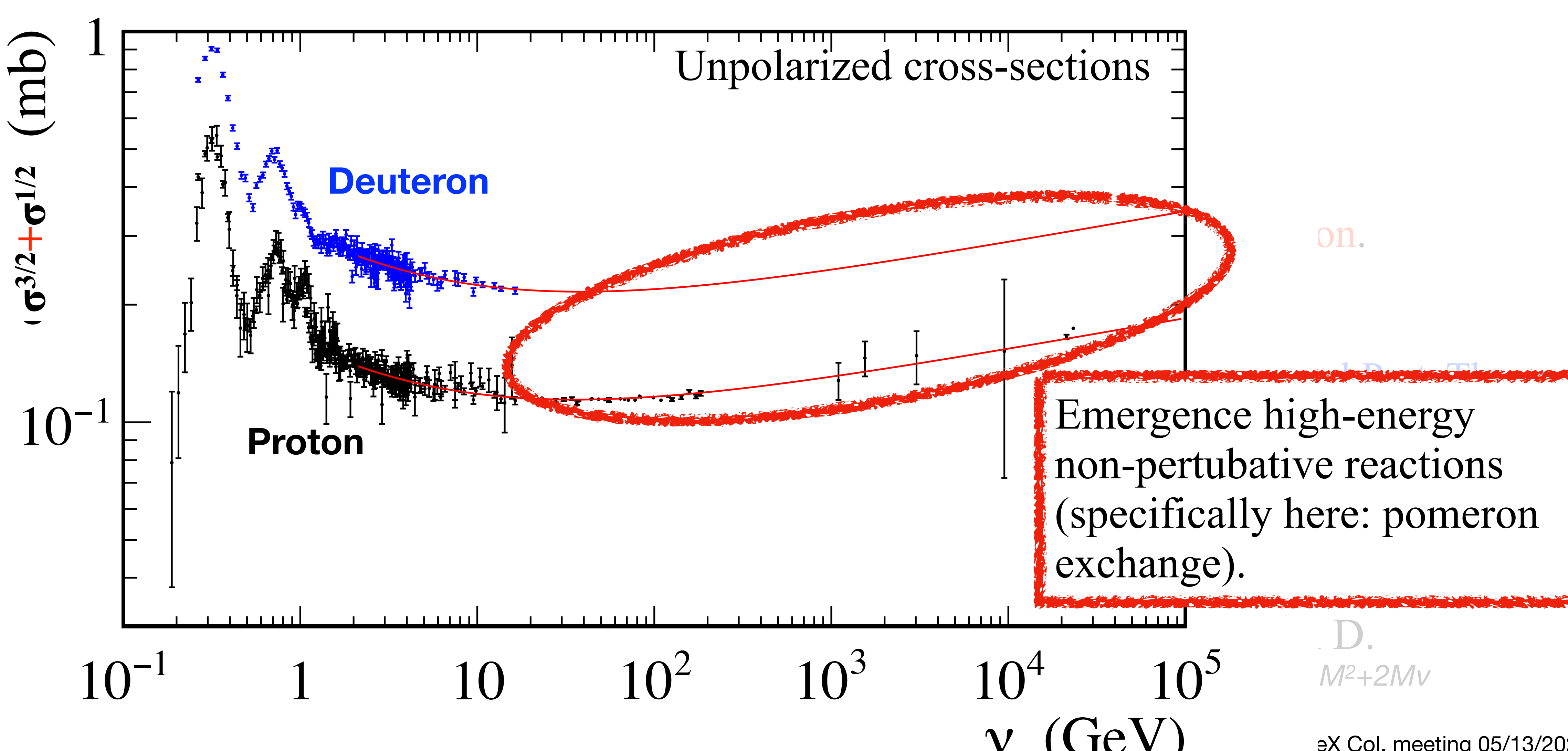

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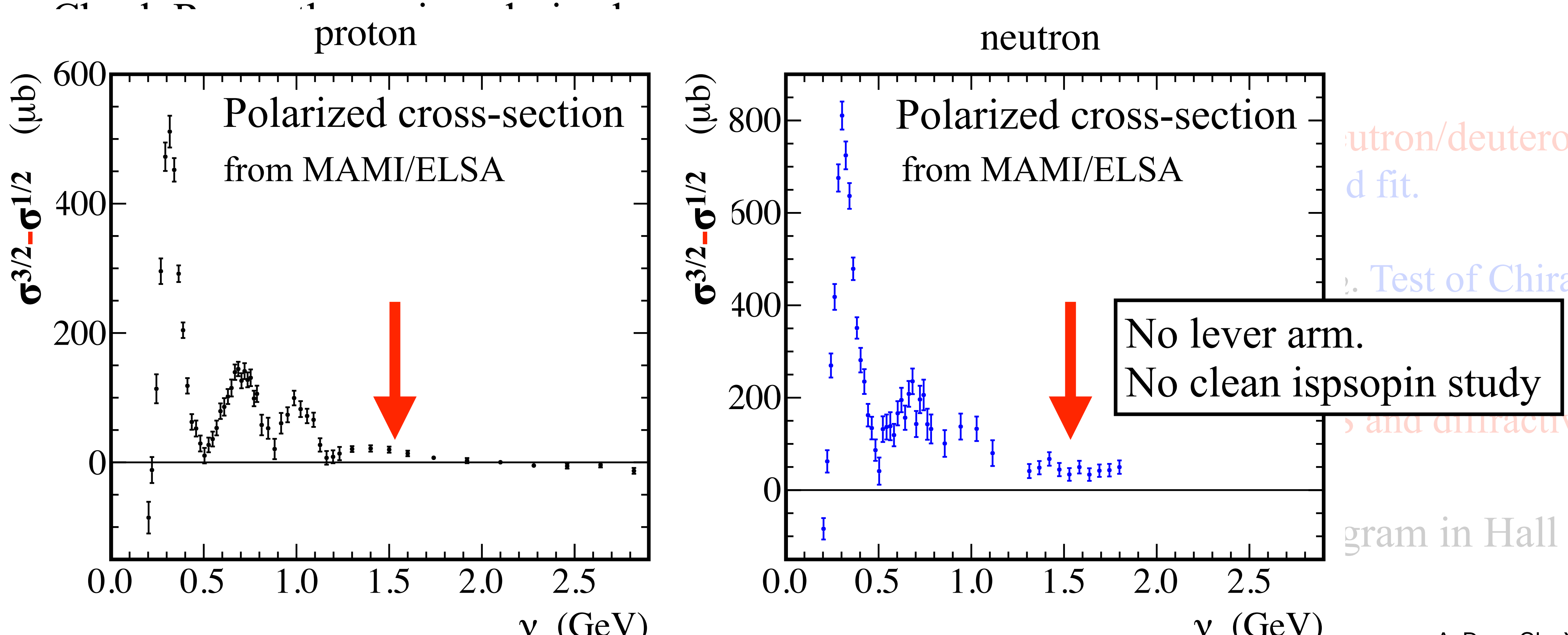

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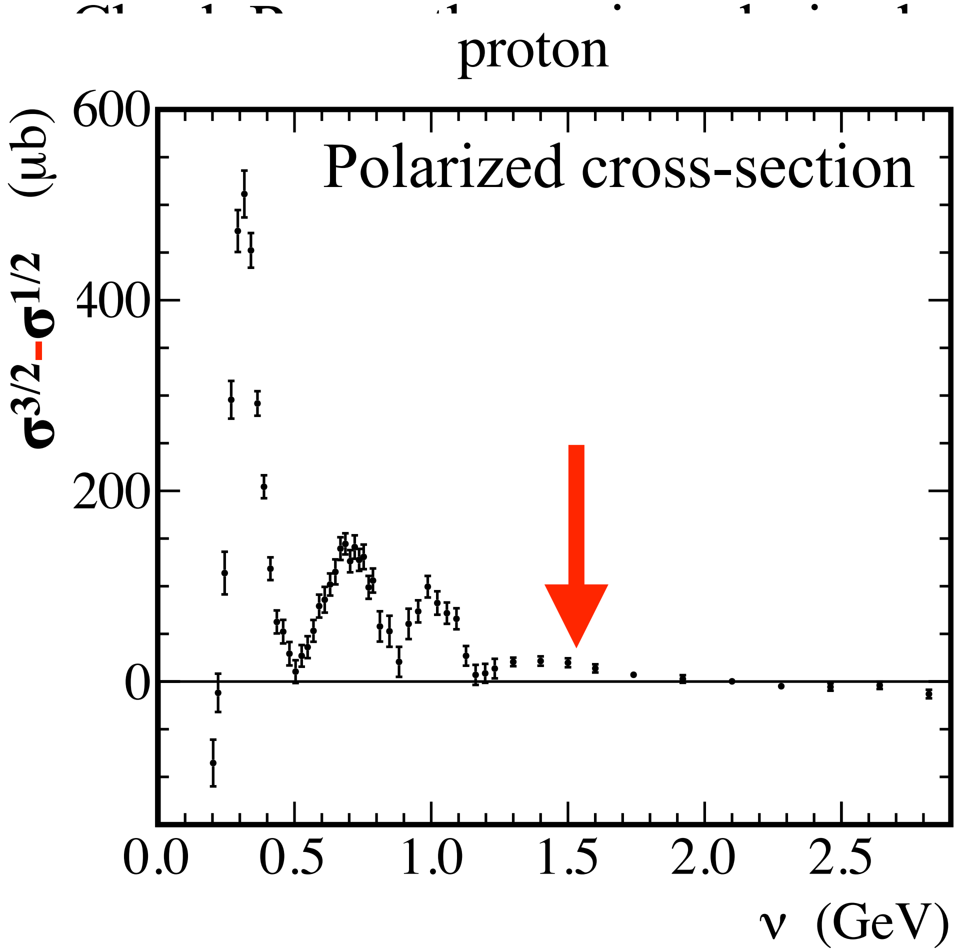

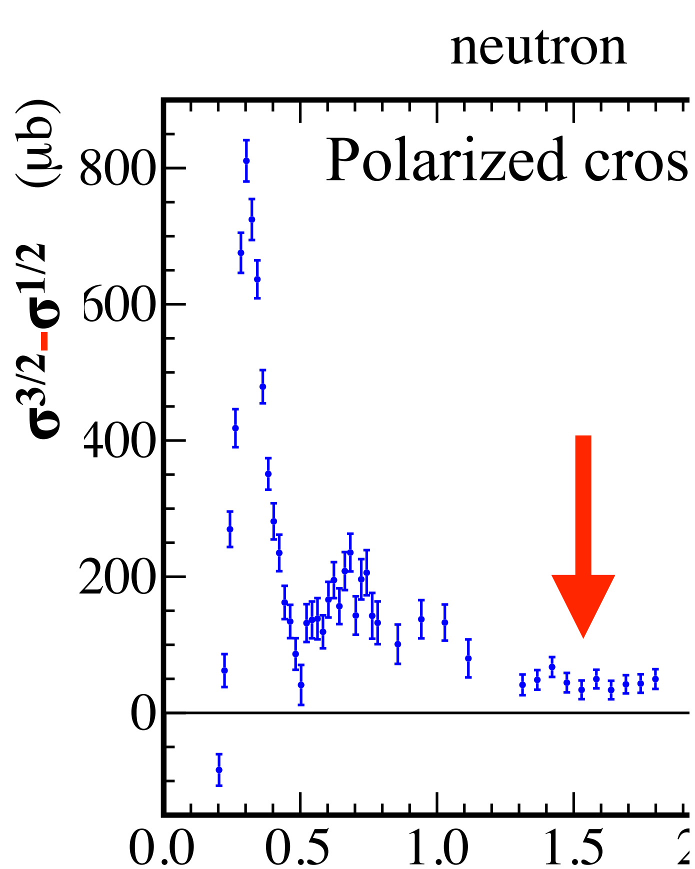

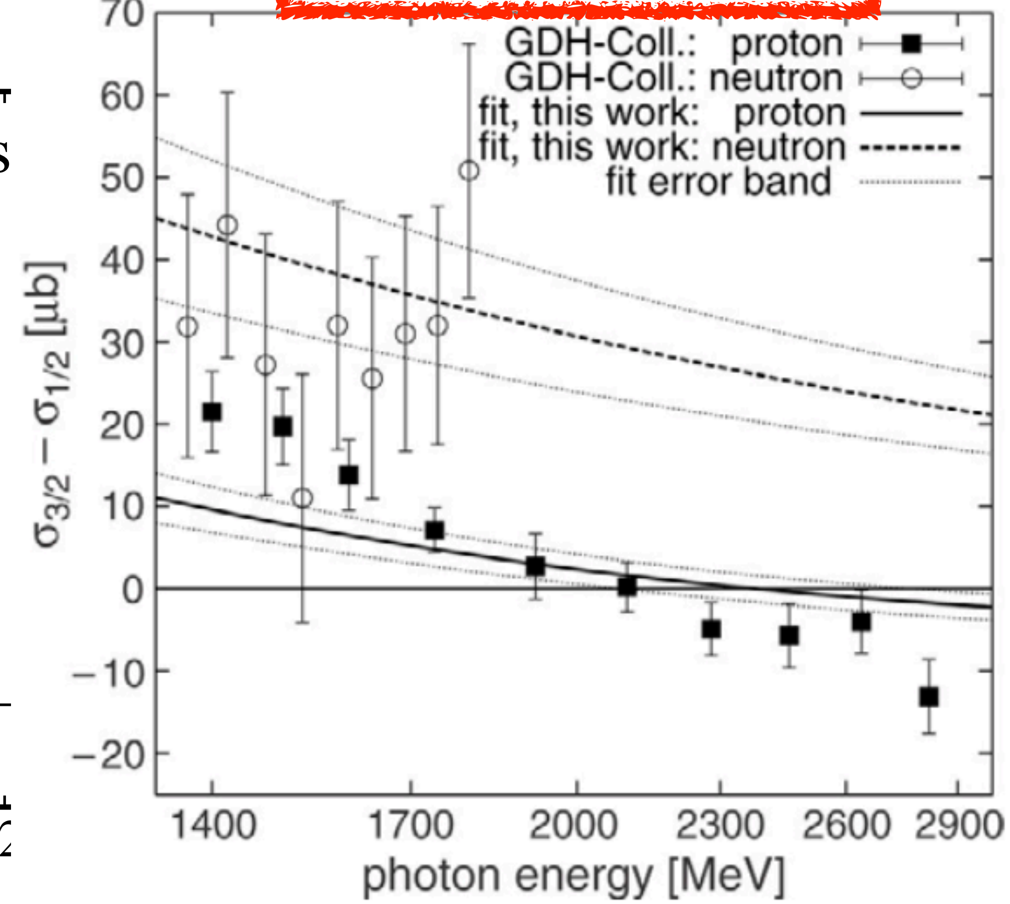

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  - (Assume causality, unitarity and Lorentz and gauge invariances.)
  - Assume vanishing of Compton amplitude $f_2(\nu)$ at large ν to derive the dispersion relation.
  - Assume $\text{Im}(f_2)$ decrease fast enough with ν for integral to converge.
    - $\Rightarrow$ 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 $\nu\rightarrow\infty$.
- 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.
  - Regardless of the sum rule validity, it is an important domain to explore:
    - 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.
    - Q^2=0 baseline for EIC diffractive measurements. Study transition between DIS and diffractive regimes.
    - Constraint on muonic hydrogen hyperfine splitting.
- Simplest doubly polarized experiment: Logical start for doubly polarized program in Hall D.

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.
  ⇒ 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.

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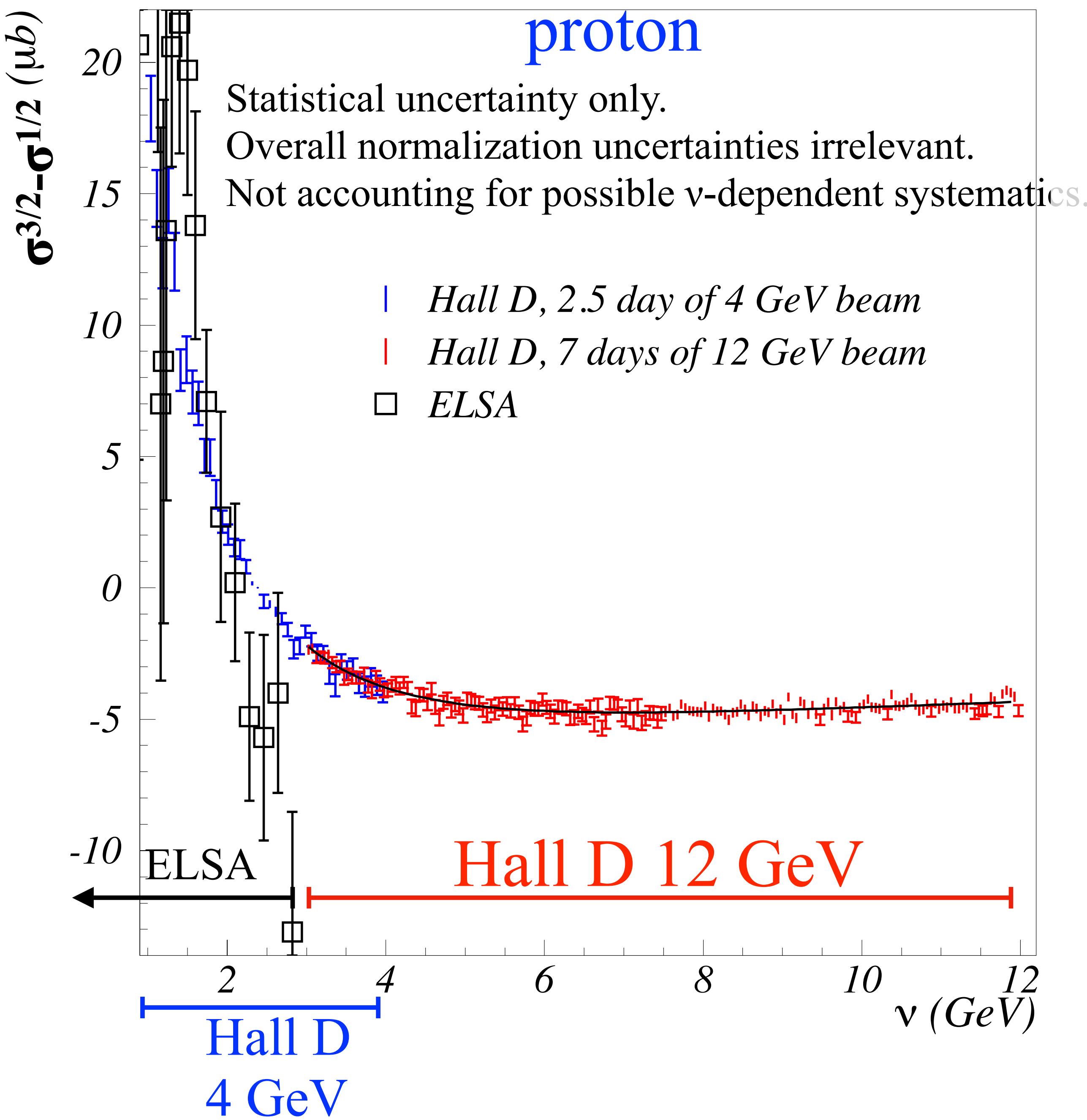

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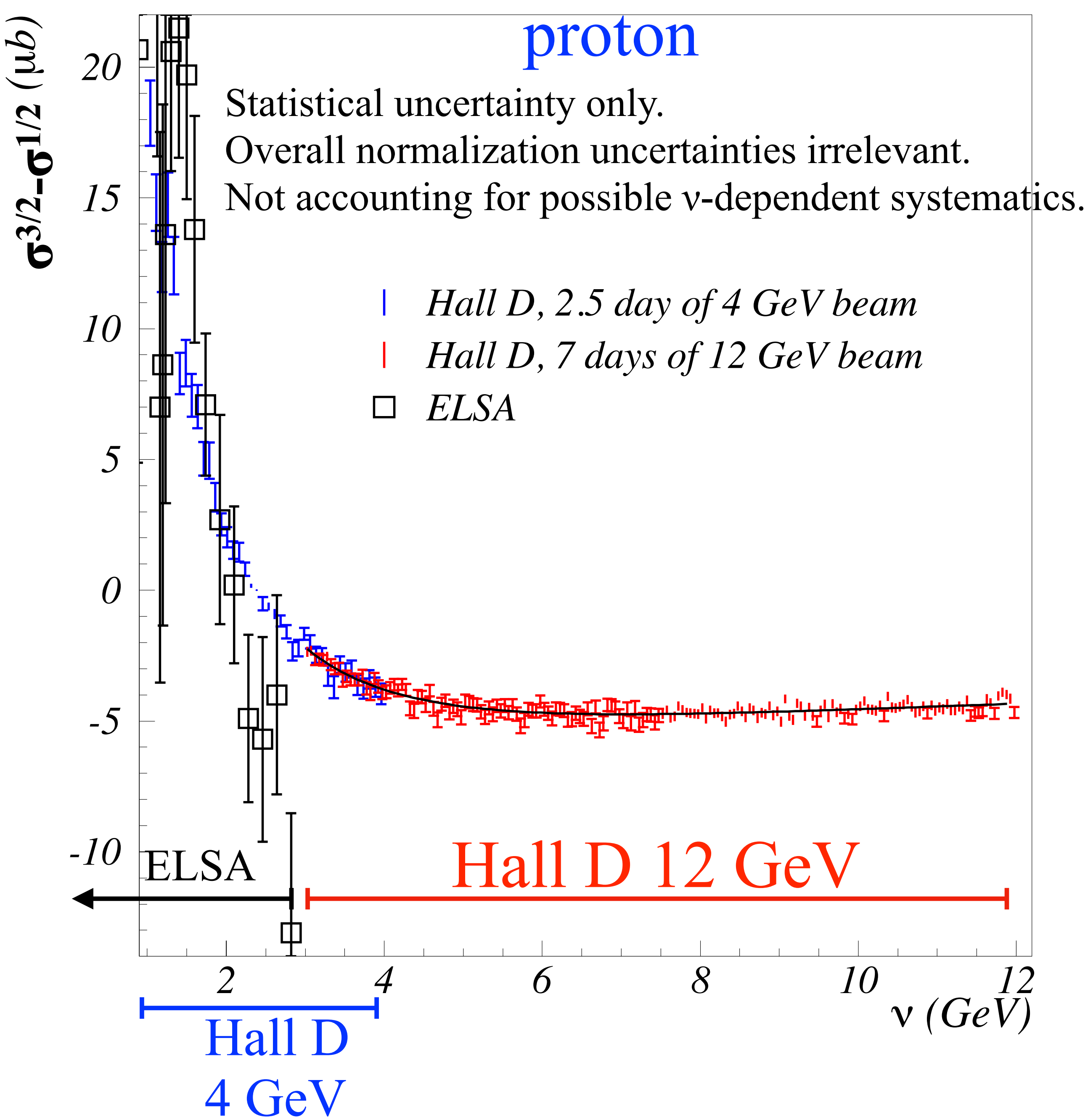

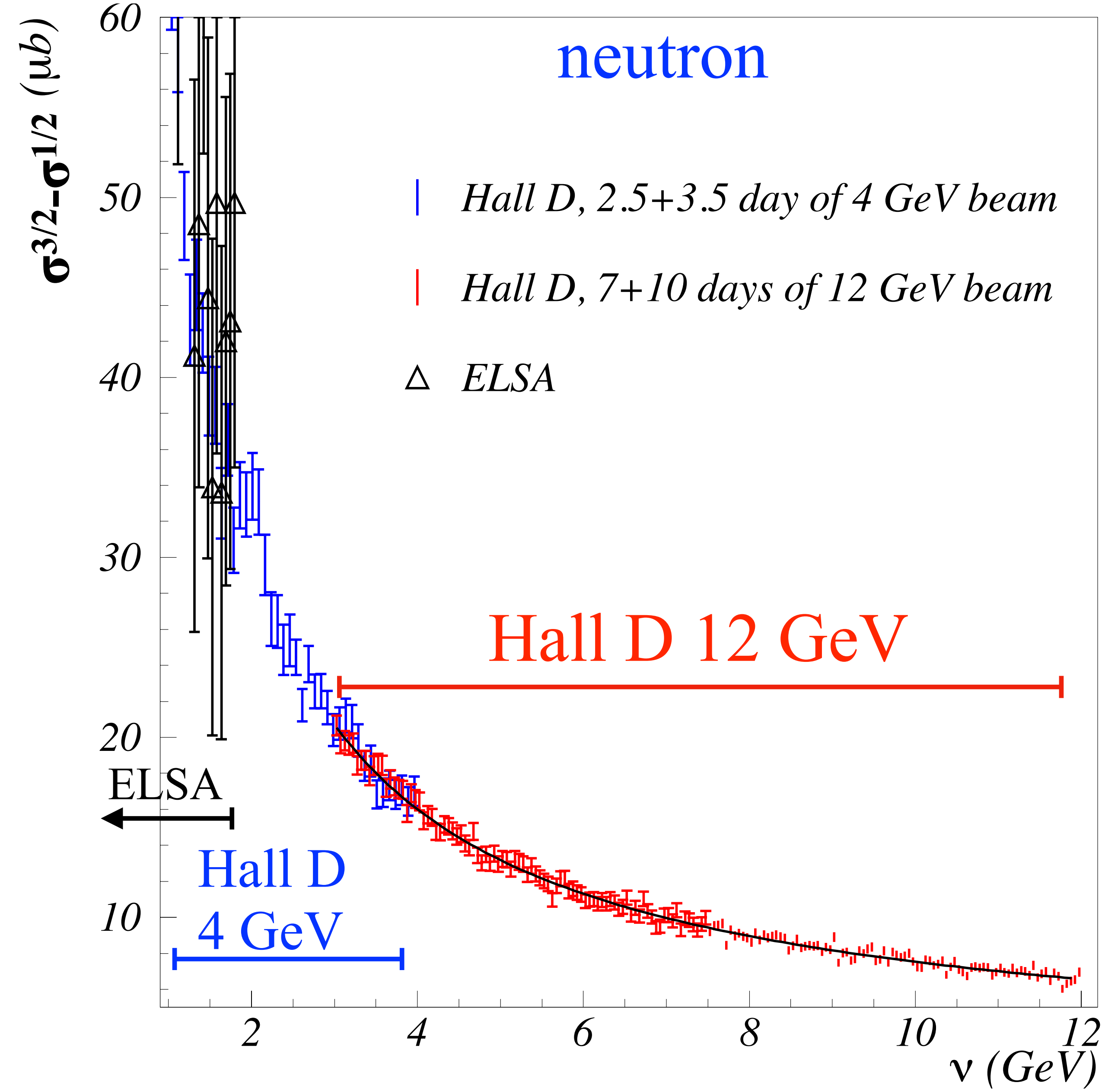

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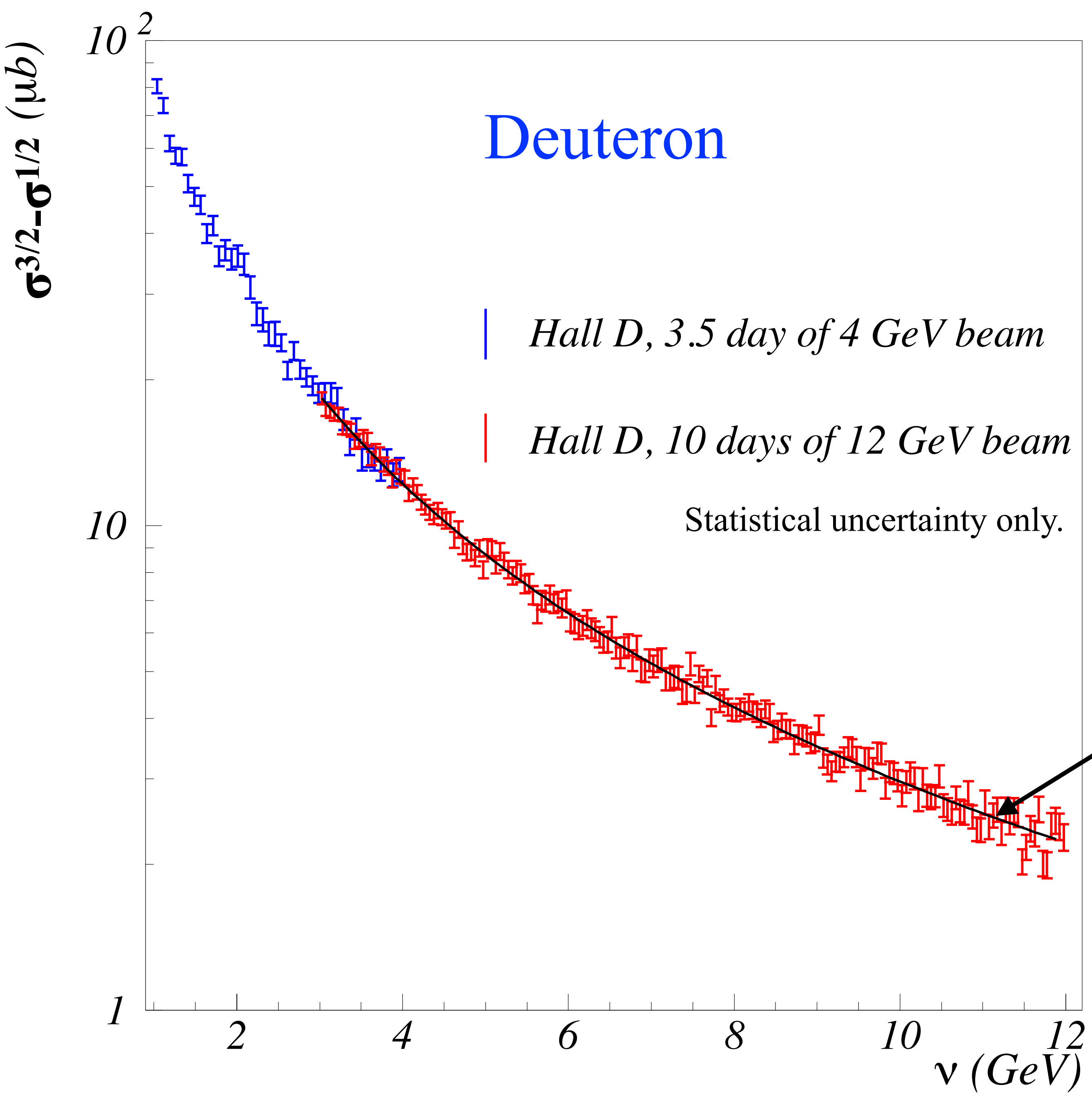

Should measure well the first non-zero deuteron signal in diffractive domain:

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: $\Delta\alpha_{a1} = \pm0.005$ & $\Delta\alpha_{f1} = \pm0.019$. Compare to $\Delta\alpha_{a1} = \pm0.23$ & $\Delta\alpha_{f1} = \pm0.22$ from ELSA. This will enable a reliable assessment of the contribution up to $\nu\rightarrow\infty$.

    - 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.

    - Improve calculation of atomic hyperfine splitting by determining spin structure function $g_1(Q^2=0)$.

    - $Q^2=0$ baseline for g_1 for EIC. $\Longrightarrow$ study of the transition between DIS and diffractive regimes.

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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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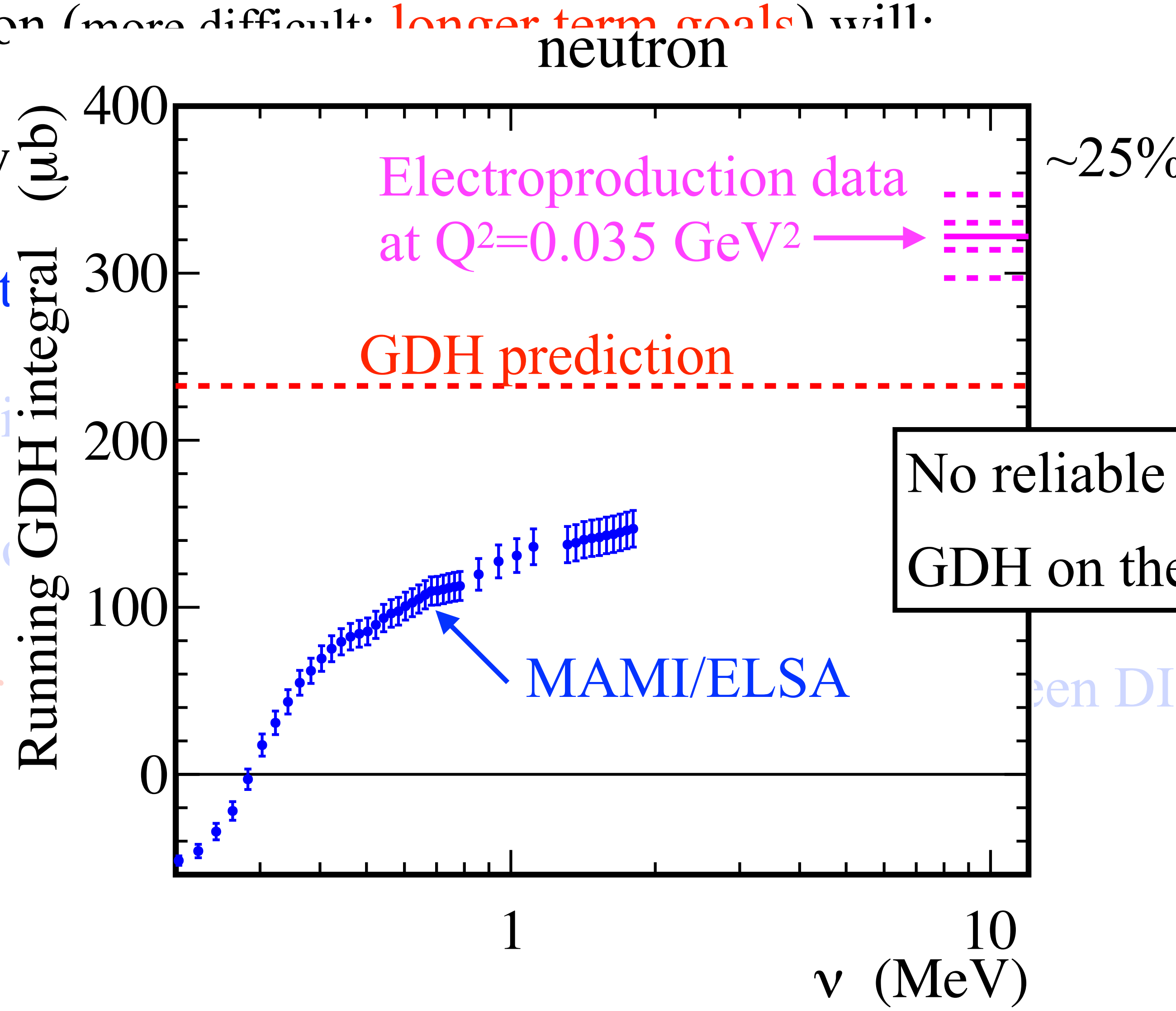

No reliable check available yet for GDH on the neutron.

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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.
  - Point-to-point correlated errors cancel.
  - Unpolarized background cancel.
- 17-days 12 GeV measurement provides α_{f1} and α_{a1} at 2% level (present uncertainties: 50%)
- 7-days at 4 GeV bridge gap between 12 GeV and low energy data. Data overlap: much improved precision + cross-check of experiments.
- Solve discrepancy between DIS data and Regee theory prediction.
- Provide first non zero data on $\sigma^{3/2}-\sigma^{1/2}$ for the deuteron.
- Longer term goals (regardless of the convergence and sum rule validity):
  - Verify proton GDH sum rule within 6% & allows first verification of neutron GDH sum rule.
  - Allow extraction of complex Compton amplitude f_2 and new test of χpT.
  - Improve knowledge of atomic hyperfine splitting.
  - Polarized diffractive scattering phenomenology essentially unknown. $Q^2=0$ baseline for g_1 for EIC.

  $\Longrightarrow$ study of the transition between DIS and diffractive regimes.
- Once Hall D has a polarized target, a rich program opens. Sensible to initiate it with simplest experiment and a robust observable.

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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

Why Hall D is uniquely suited for a large-ν GDH measurement

The experiment is not doable in other halls since they lack the photon tagging capability of Hall D and a GDH measurement via electroproduction is not adapted to a study of its large ν domain. The measurement would have to be done at low enough Q^2 so that a reliable extrapolation to $Q^2 = 0$ can be done. However, at with a 11 GeV beam, this would requires a measurement at scattering angles smaller than 0.8, which no hall can reach and where the elastic radiative tails are prohibitively large.

1) With a 11 GeV beam, and keeping in mind that:
a) the most interesting part for a proposal is for $\nu > 3$ GeV;
b) for the neutron we need to be at $Q^2 < 0.02$ GeV^2 to allow extrapolation to $Q^2 = 0$,
these numbers imply that we need to do the measurement below 0.8 degree. However, the CLAS12 forward tagger is limited to 2.5 degree. Restricting measurement to lower nu does not help (and is not the proposal goal). In fact it requires even smaller angles.

2) The radiative elastic tail will saturate the DAQ and also drown any inclusive signal (what's need for GDH studied with electroproduction). I studied these tails many years ago for a Hall B proposal and for $Q^2 < 0.02$ GeV^2 even the $\Delta 1232$ will not be measurable, let alone higher ν. Those are the worst issues. Others are that:

3) a $Q^2 \rightarrow 0$ extrapolation is not possible right now for the neutron given the state of the theory unless the data are below at least 0.02 GeV^2, with 0.01 GeV^2 being safer. Regardless of whether a consistent theory guidance is available for the extrapolation, this would always introduce a model dependence in the measurement.

4) One cannot separate g_1 from g_2 in Hall B unless one has a transverse target (something difficult to do). Thus we have yet another model input, and it's unclear how to model g2 at very low Q^2 and large ν.

5) The largest we can reach in Hall B for inclusive data would be 8 GeV, compared to 12 GeV in Hall D, at 8 GeV is at $Q^2 = 1$ GeV^2 (again, this quickly decreases at lower Q^2 because of the radiative tails and other forward backgrounds).

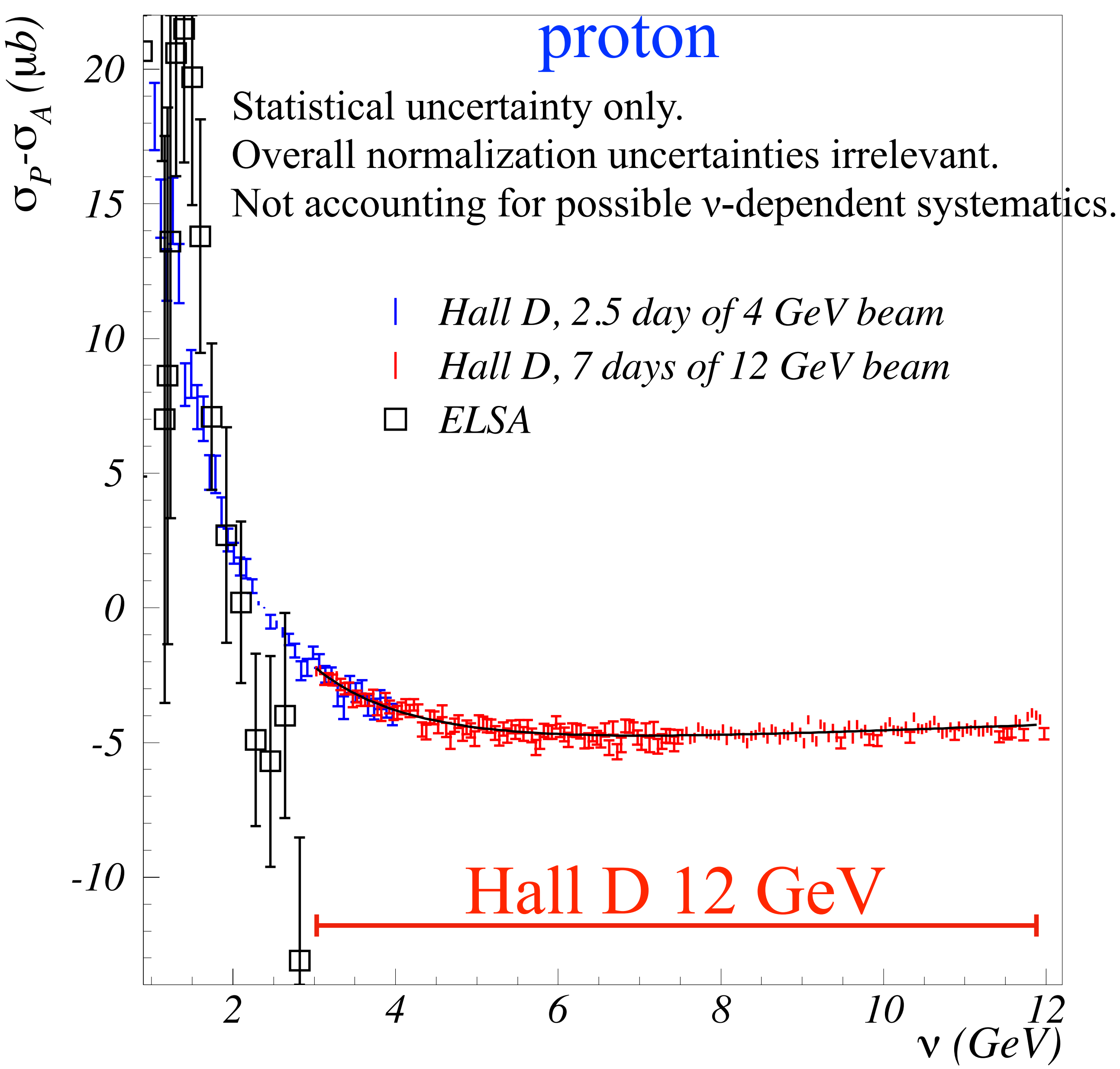
6) Finally, Hall B is more subscribed than Hall D, so even if all other pro/con were balancing, it seems sensible to do the experiment there.

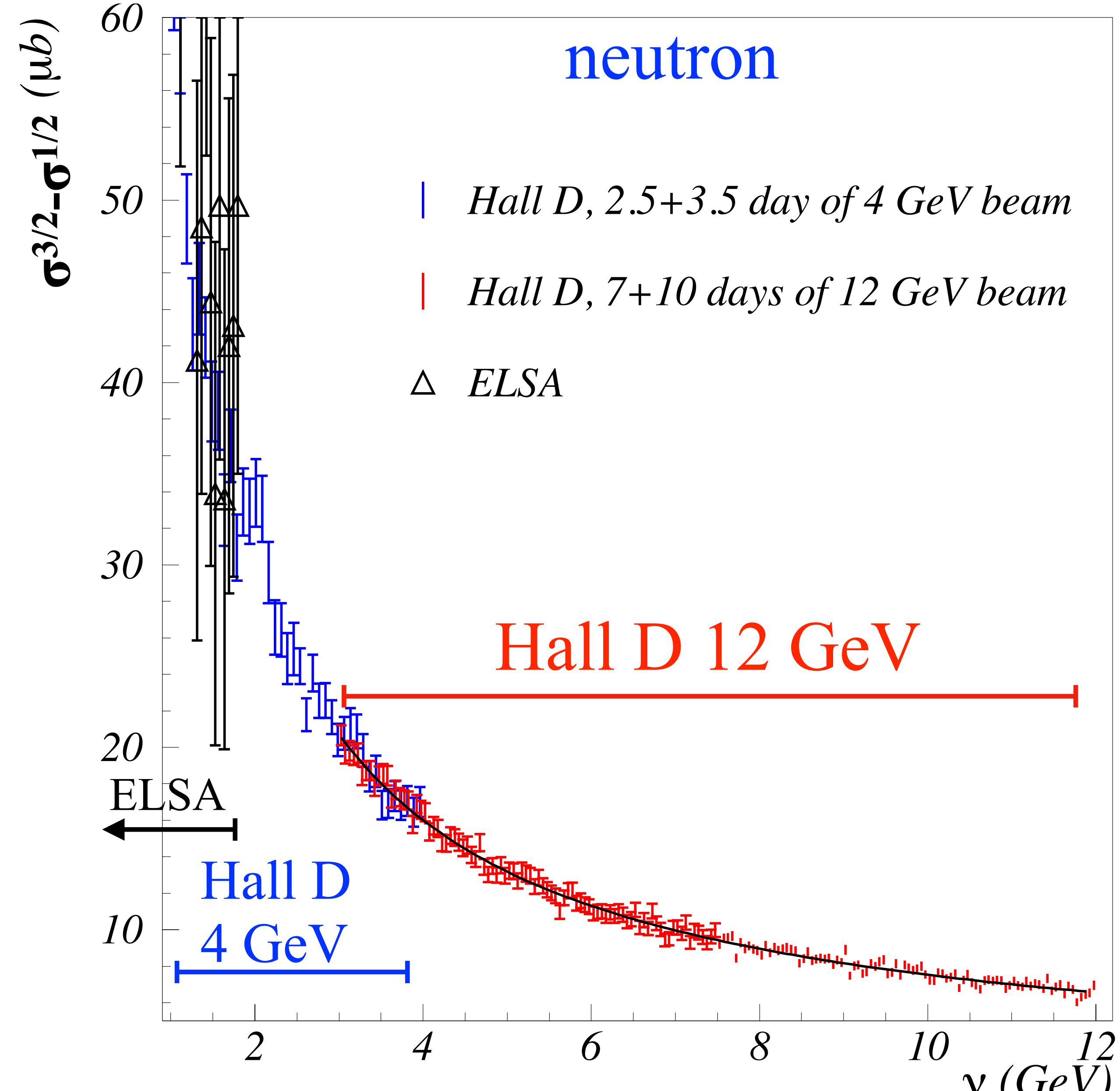
Hall D does not have the above issues and I think installing a polarized target is an opportunity for new physics rather than a handicap.

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

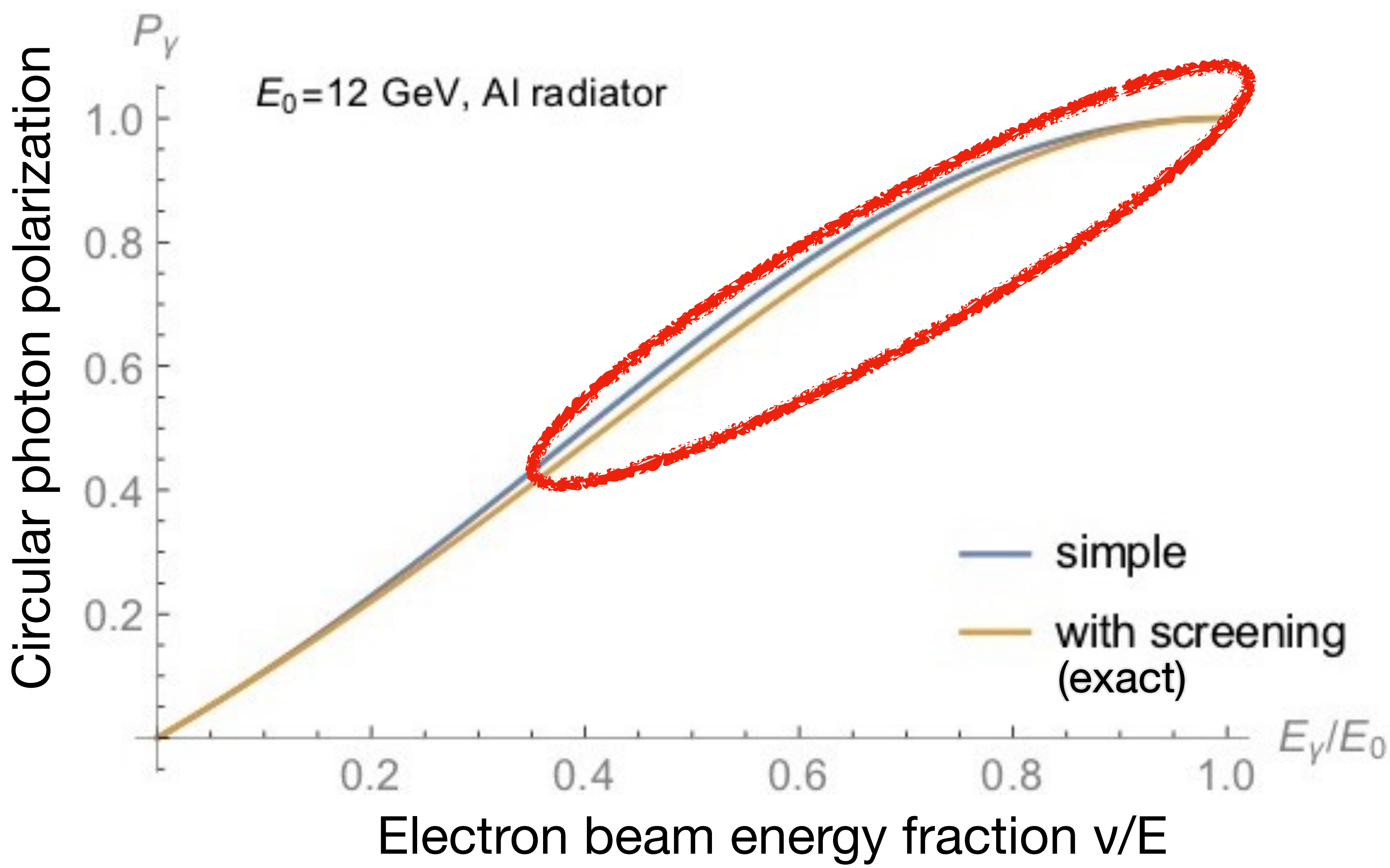




Isospin analysis $\Rightarrow$ $\boxed{\Delta\alpha_{a1}=\pm0.006 \ \& \ \Delta\alpha_{f1}=\pm0.016}$

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 $\sim 10^8$ 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

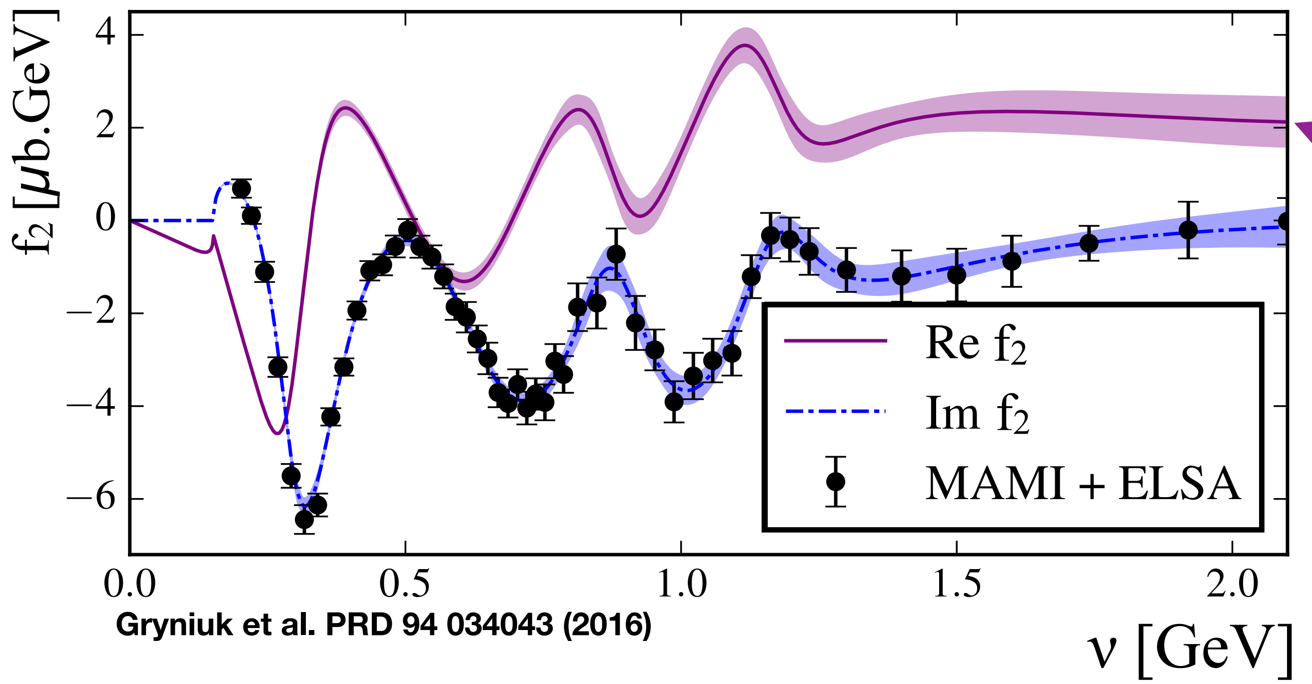
•Measure total photoproduction yield.

•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

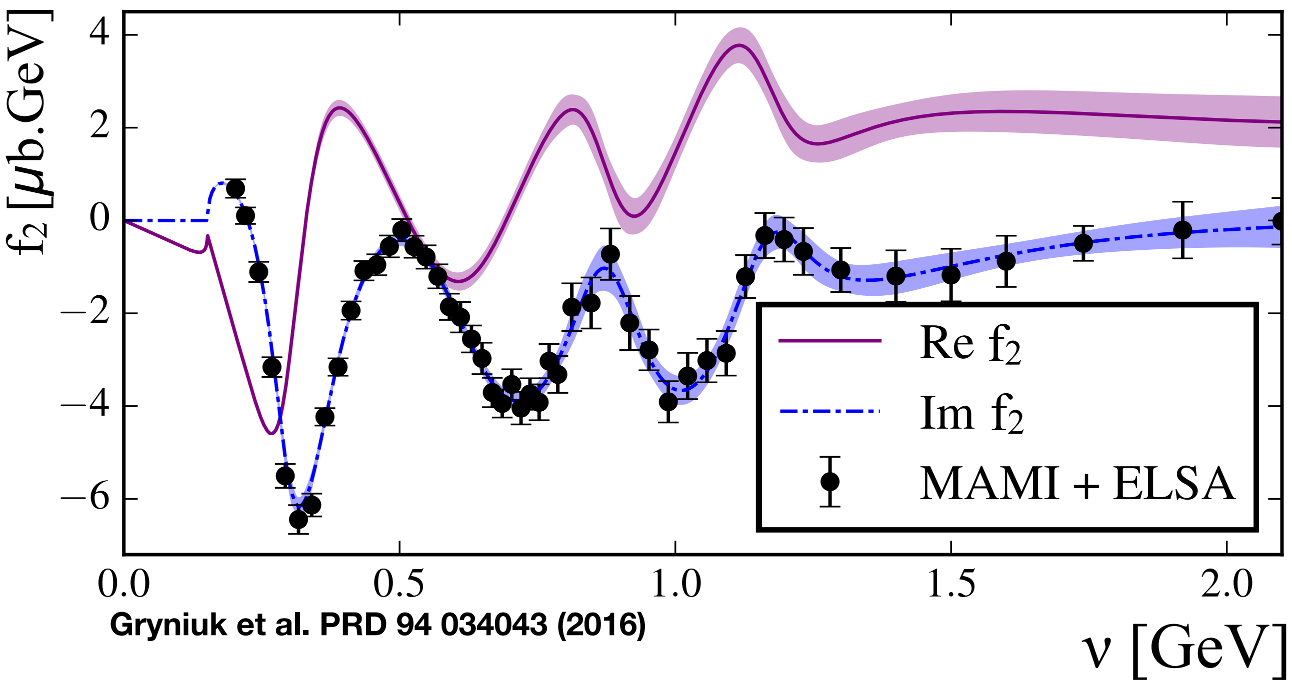
Extraction of the real and imaginary parts of Compton amplitude f_2



Gryniuk et al. PRD 94 034043 (2016)

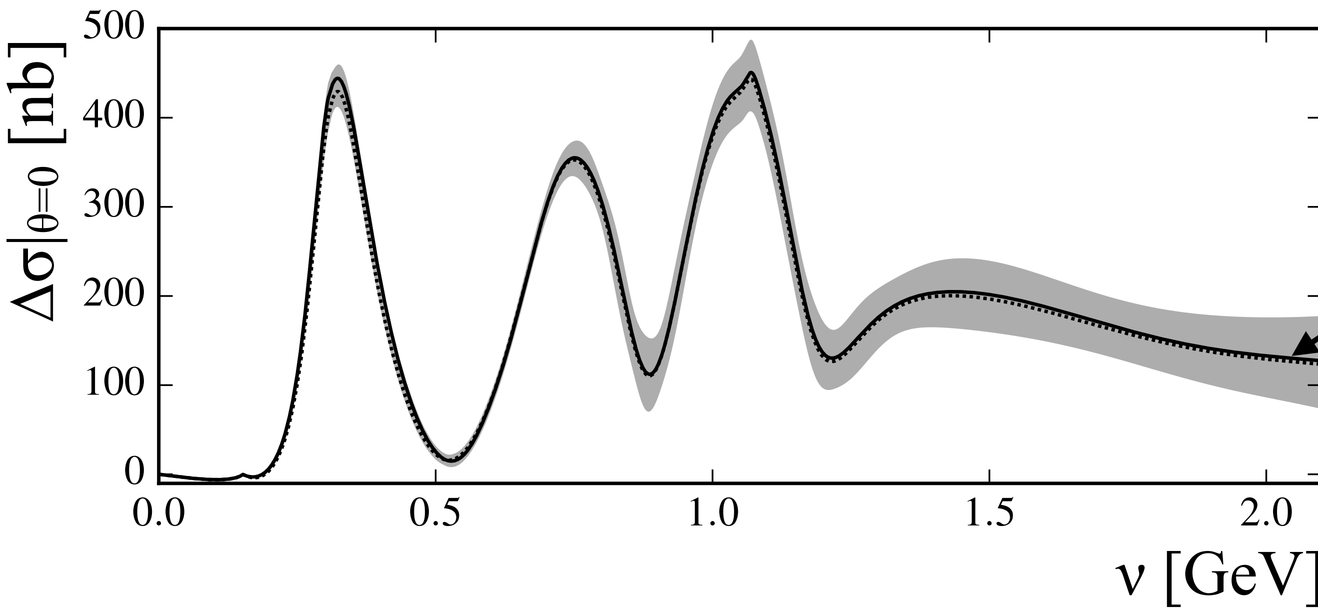
Dispersive analysis from Im(f_2) data. Large ν data will constrain both Re(f_2) and Im(f_2) error bands.

Extraction of the real and imaginary parts of Compton amplitude f_2



Gryniuk et al. PRD 94 034043 (2016)

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.



Large ν data will constrain increasing error band.

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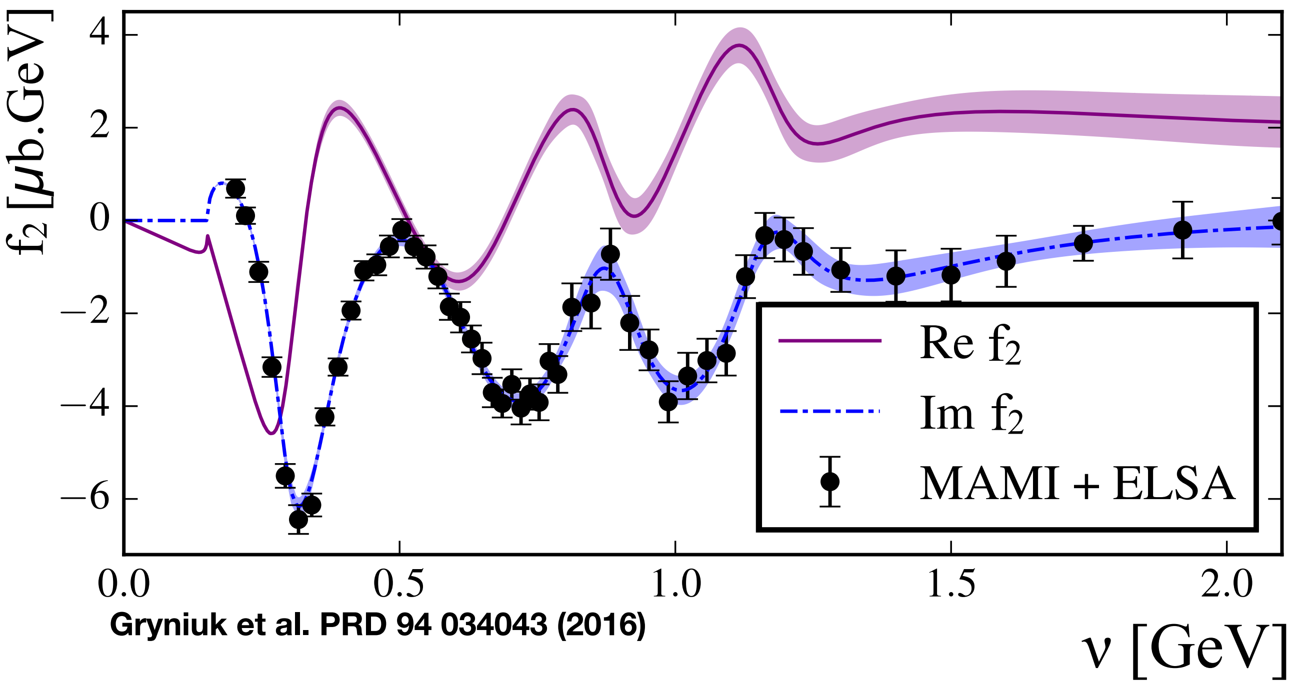

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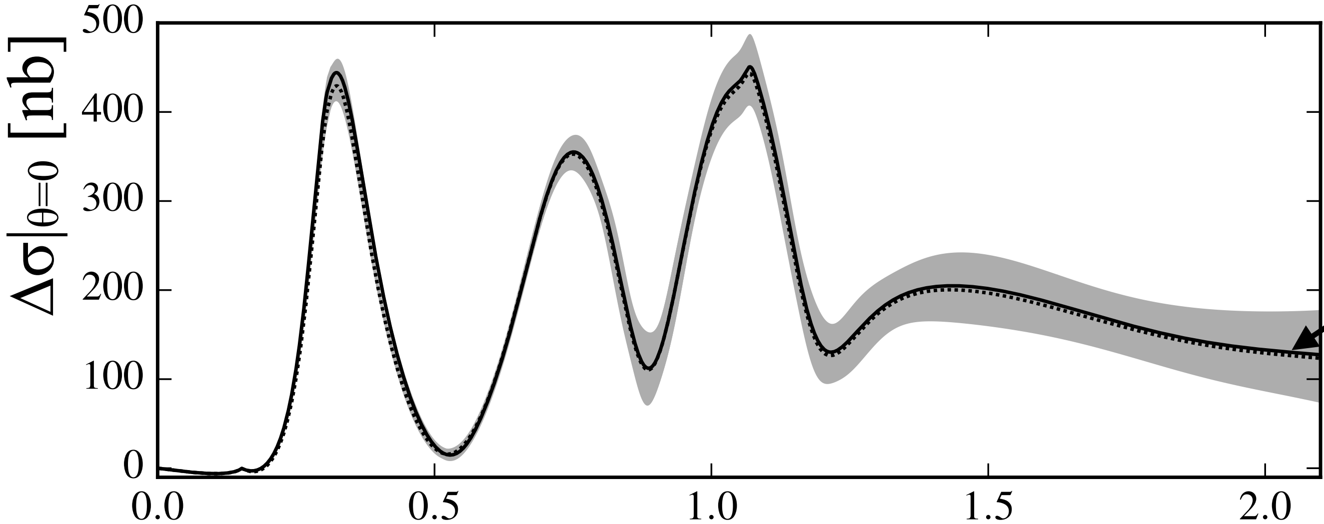

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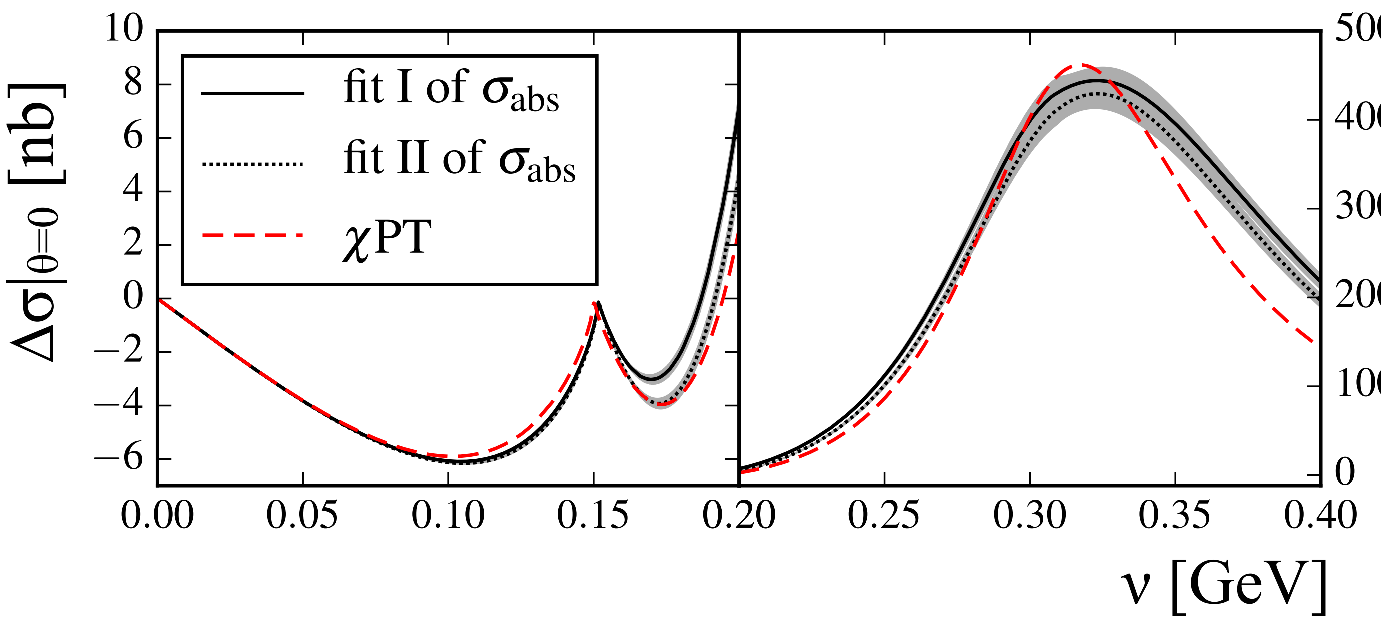

Chiral Perturbation Theory (χpT) calculation available.

$\Delta\sigma|_{\theta=0}$ 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.

Gryniuk et al. PRD 94 034043 (2016)

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.
  - Point-to-point correlated errors cancel.
  - Unpolarized background cancel.
- 17-days 12 GeV measurement provides α_{f1} and α_{a1} at 2% level (present uncertainties: 50%)
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- Solve discrepancy between DIS data and Regee theory prediction.
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  - Polarized diffractive scattering phenomenology essentially unknown. $Q^2=0$ baseline for g_1 for EIC.

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