PR12-20-011: Measurement of the high-energy contribution to the Gerasimov-Drell-Hearn sum

A. Deur, for the GlueX collaboration
08/11/2020

Spokespersons: M-M. Dalton (JLab), A.D. (JLab), J. Stevens (W&M) and S. Širca (U Ljubljana)

Proposal internally reviewed and endorsed by the GlueX collaboration.

PAC 47 encouraged LOI to be developed into a full proposal.[1]

Theory Report for PAC 48 concludes that "This an important measurement with impact on nuclear and particle physics"

TAC for PAC 48 reports that while the experiment requires new equipment "no real showstopper has been identified"

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 Gerasimov-Drell-Hearn sum rule

Fundamental prediction linking spin-dependent photoproduction cross-sections to target anomalous magnetic moment:

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

Validity of sum rule mainly determined by large ν behavior of $\sigma^{3/2}$-$\sigma^{1/2}$

⇒ for nucleon target, tests QCD/nucleon properties.

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Spin-dependent total photoproduction cross-sections ($\sigma^{3/2}$, $\sigma^{1/2}$); Photon energy (ν); Mass (M); spin (S); anomalous magnetic moment (κ)

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Knowledge of large ν behavior is critical, yet existing data restricted to low energies:

- Proton: $\nu>3$ GeV not measured yet.
- Neutron: $\nu>1.8$ GeV not measured yet.

Polarized nucleon's behavior unknown at large ν. Expected to be described by Regge theory, but unverified, and photo- and electro-production data in conflict with Regge expectation.

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Hall D: tagger+large solid angle detector+high flux ⇒ uniquely suited to perform a large-ν GDH measurement.

Motivations

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- Unpolarized version of GDH integral $\int(\sigma^{3/2}+\sigma^{1/2})d\nu$ does not converge.
- Large-ν uncertainty dominates proton GDH test. No test possible on neutron yet: ν too low.

- Need to go beyond the resonance bumps to perform reliable Regge-based fit to:
  - Check Regge theory for the first time in the polarized case,
  - Provide a reliable basis for extrapolation to $\nu\rightarrow\infty$.

- Hall D's 3-12 GeV range: 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:
    - Constrains spin-dependent Compton *amplitude* f_2. Test of Chiral Perturbation Theory.
    - No non-zero deuteron signal seen yet at large ν or in the diffractive domain.
    - Discrepancy between Regge expectation and DIS data.
    - Q^2=0 baseline for EIC diffractive measurements. Study transition between DIS and diffractive regimes.
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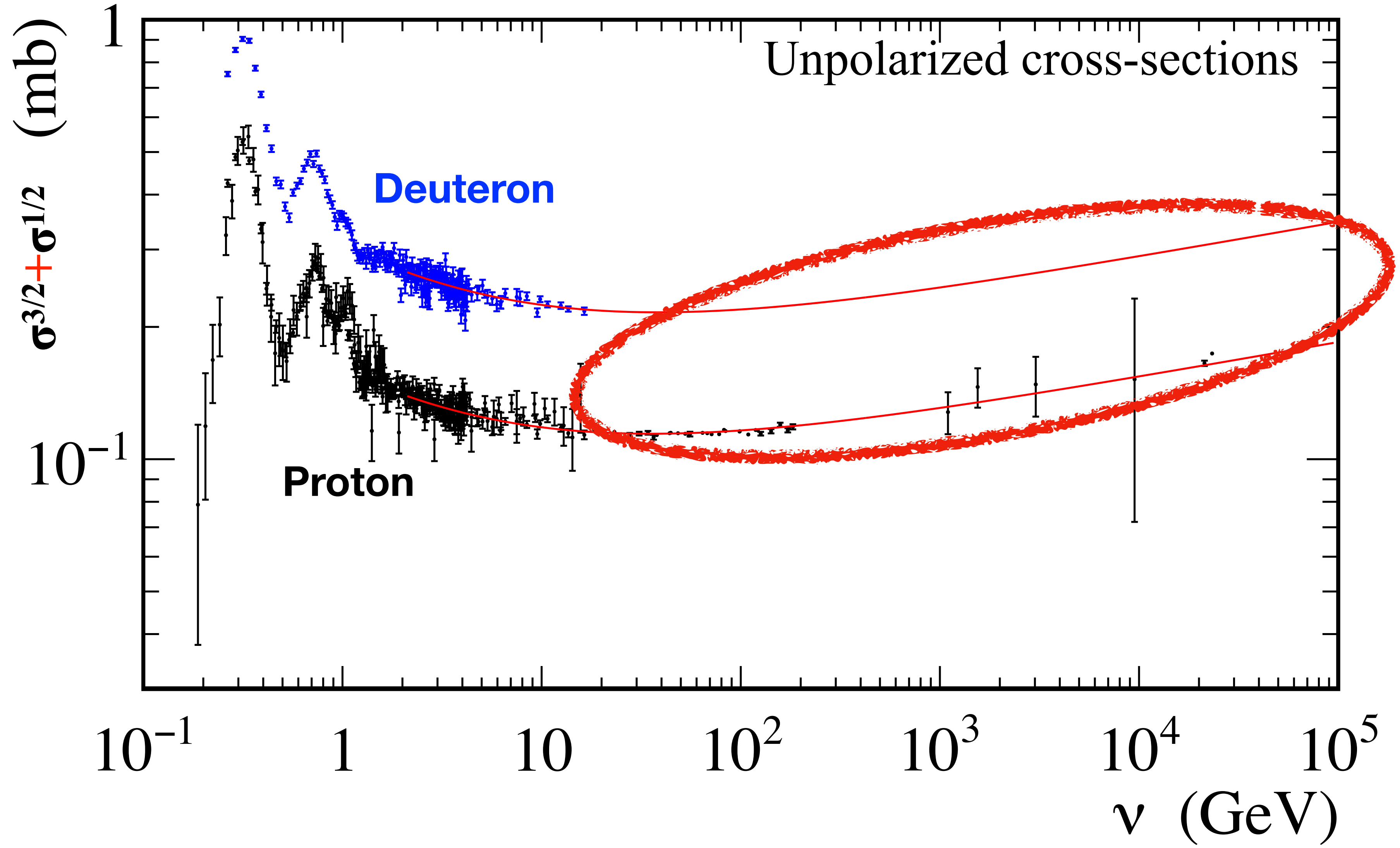

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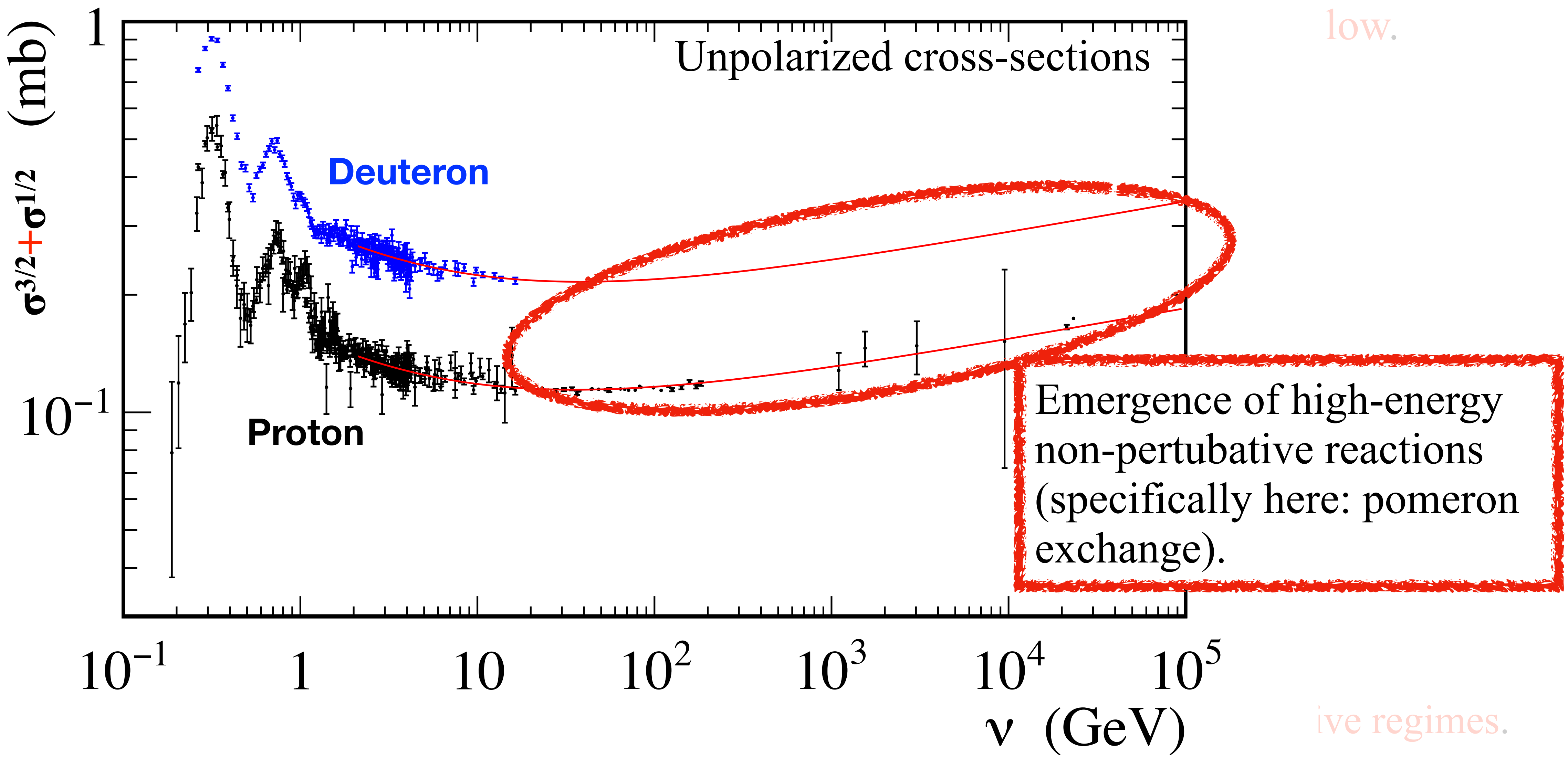

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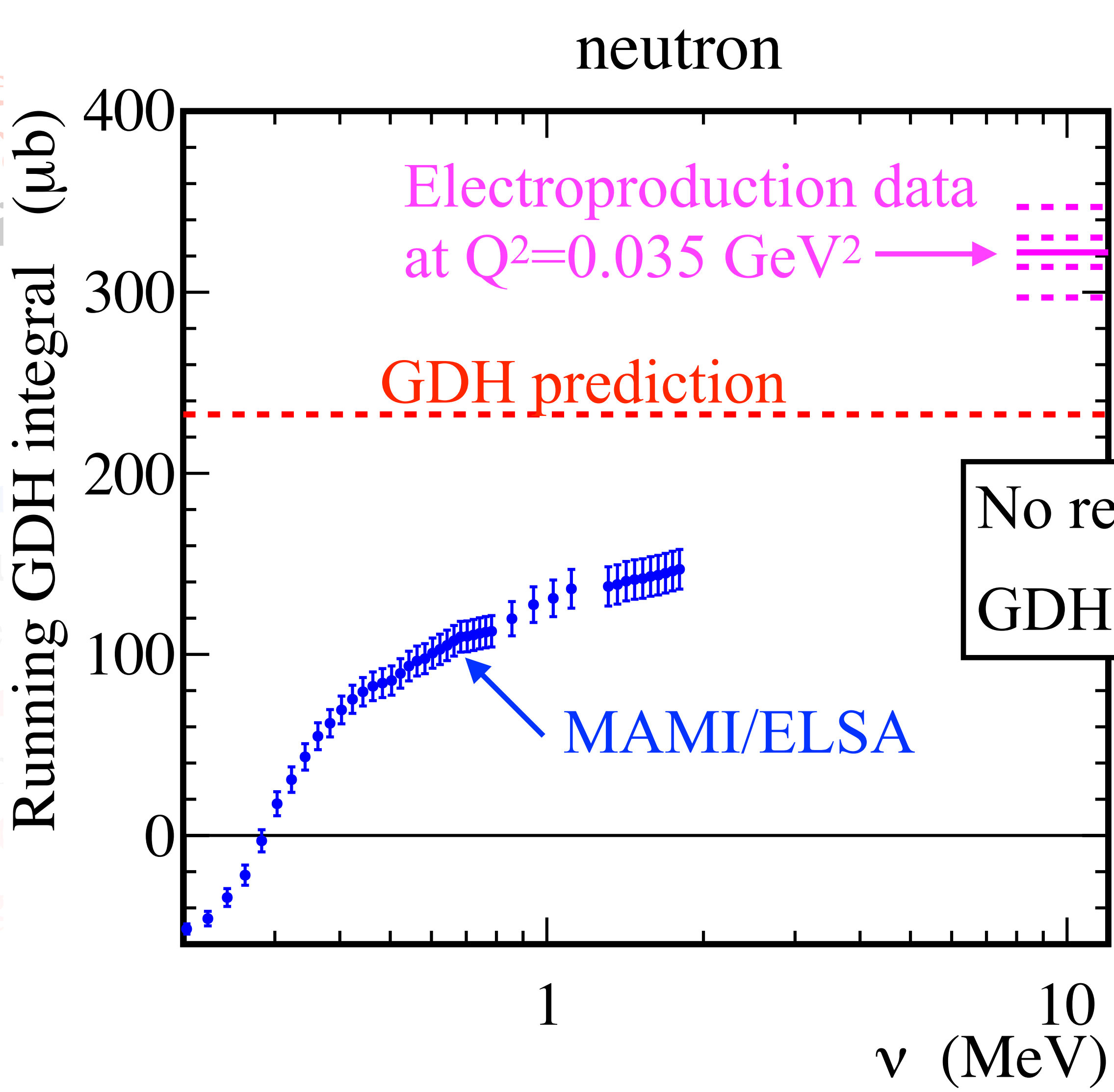

No reliable check available yet for GDH on the neutron.

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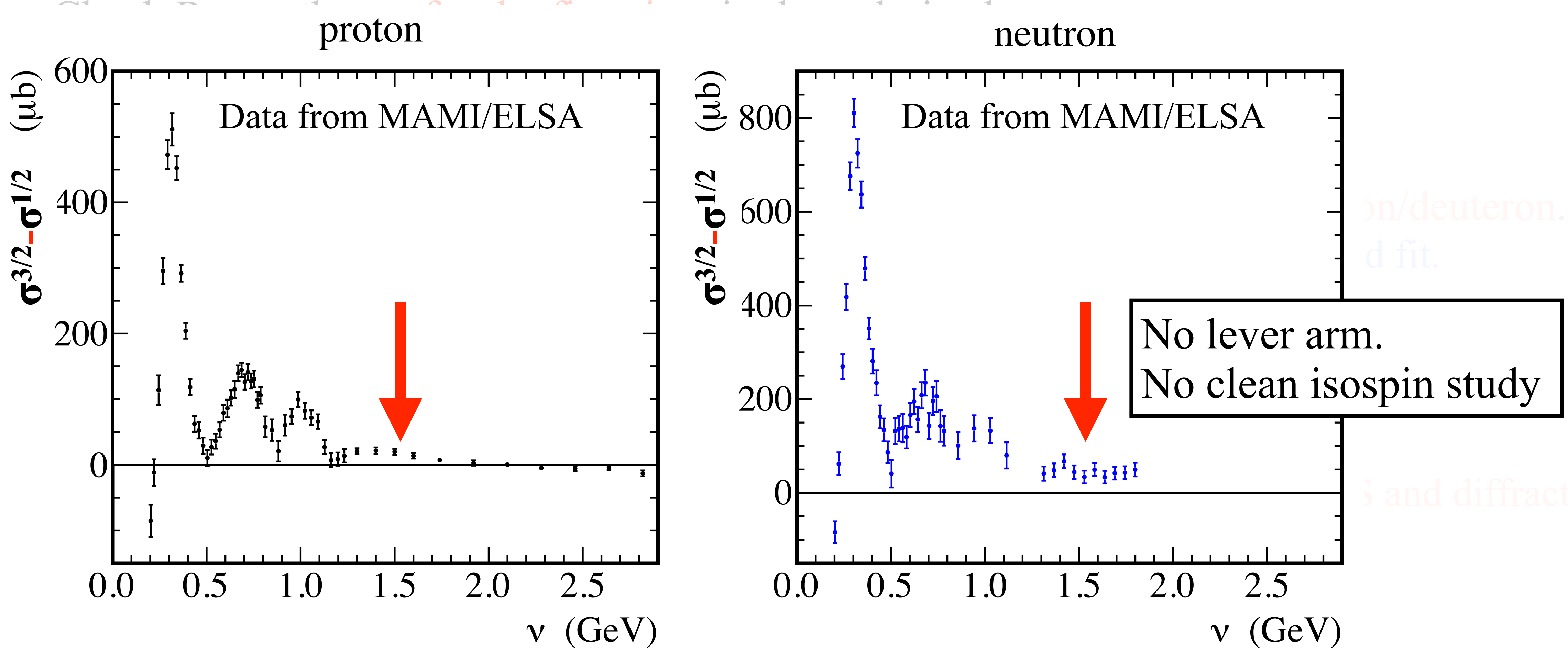

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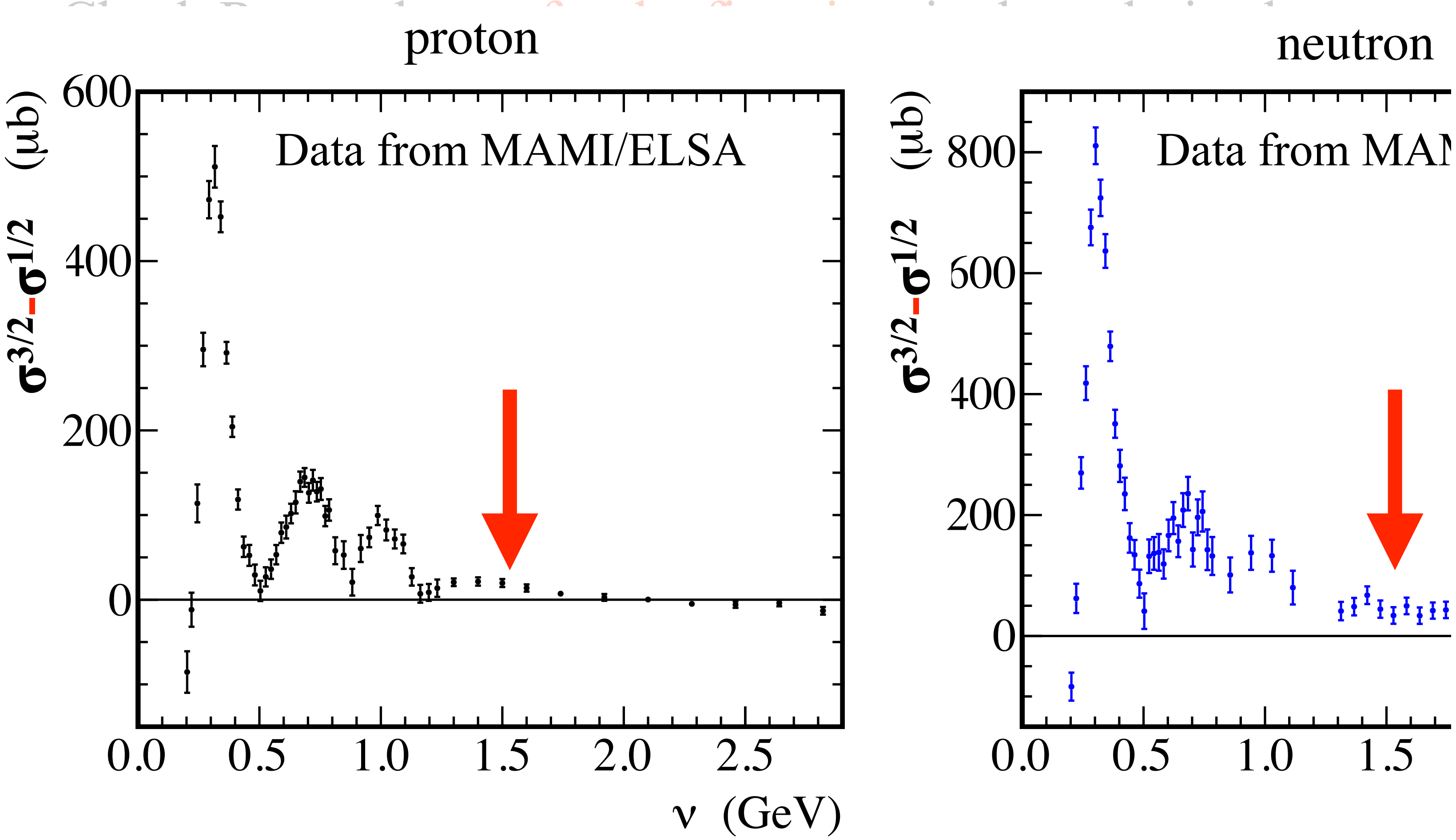
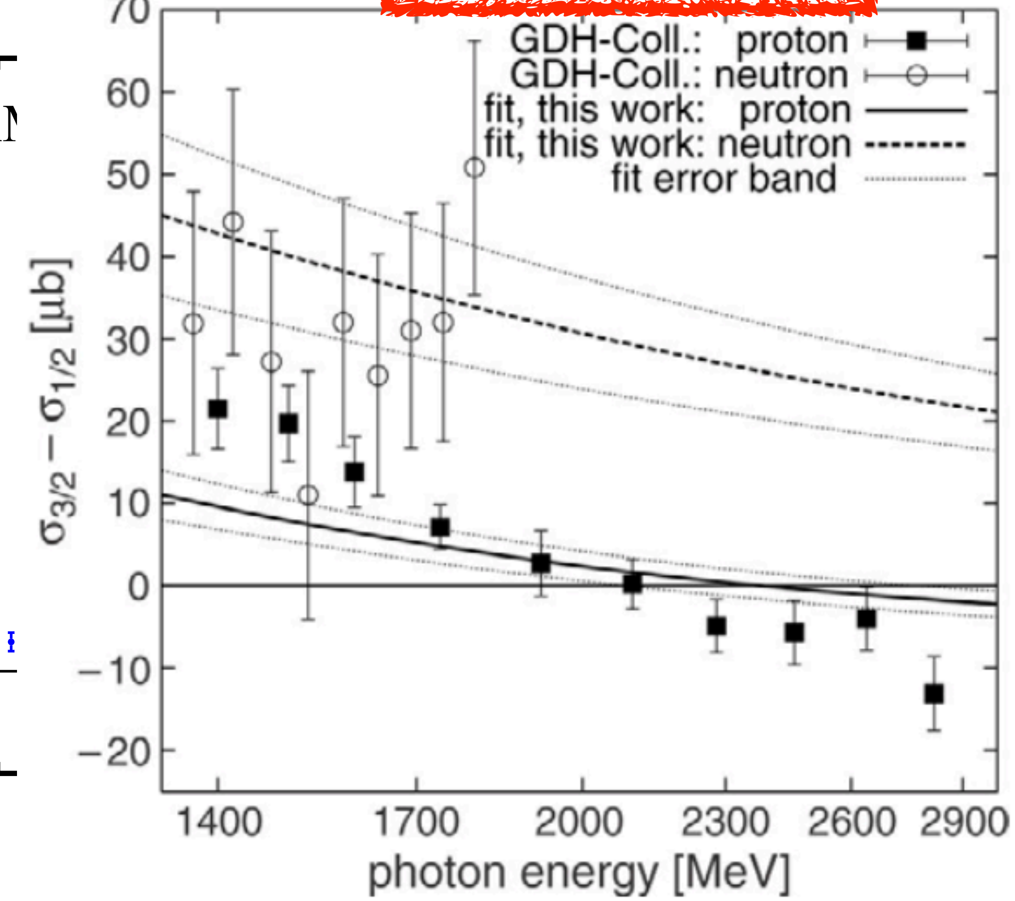
Poor Regge fits for current world data.





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Experimental Setup

- Need both proton and neutron (deuteron) targets:
  - Isospin separation. Regge theory: isoscalar and isovector contributions to ($\sigma^{3/2}$-$\sigma^{1/2}$) come from different meson families (f_1 and a_1, respectively).
  - Deuteron:
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    - No neutron data above 1.8 GeV.

- Energy coverage:
  - $3<\nu<12$ GeV Standard CEBAF at 12 GeV.
  - $1<\nu<4$ GeV Requires CEBAF to run at 4 GeV, e.g. during low energy summer run.

- 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

- Experimental configuration and trigger: same as GlueX.

- Signal: Count every trigger and its associated tagged photon. Standard accidentals subtraction.

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Analysis Strategy

- First objective: test the convergence of the GDH integral:

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

  ⇒ Normalization factors not important

  For example, if $\sigma^{3/2}-\sigma^{1/2} = a\nu^b$, we obtain b without need to extract an accurate a.

  - Suppress normalization factor uncertainties.

  - Unpolarized backgrounds (e.g. target dilution) cancel.

- Second objective: test the validity of the GDH sum rule:

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

  ⇒ Normalization required. Unpolarized backgrounds still cancel exactly.

Beam polarization	3%
Target polarization	3%
Detector, trigger and DAQ efficiencies	2-3%
Photon flux	<1%
Total uncertainty	**5%**

(Alternate analysis method using relative asymmetry and known unpolarized cross-section yield similar accuracy: 5.3%)

Time request

Time (day)	Target	Goal/Remarks
10	Deuteron	Main production at 12 GeV
0.3	Deuteron	Spin dance done during above task
1	Deuteron	Target spin-flip/repol./NMR calib. No beam, done at middle of production
0.5	^{4}He	For background subtraction. Includes target change overhead
1	Deteuron → proton switch	No beam. NMR calib.
7	Proton	Main production at 12 GeV
1	Proton	Target spin-flip/repol./NMR calib. No beam, done at middle of production
0.5	Pair. Spec. converter	Absolute flux calib.
12 GeV: 21.3		total time at 12 GeV
5.7	Deuteron	Production 4 GeV
0.3	Deuteron	Spin dance done during above task
0.3	^{4}He	For background subtraction. Includes target change overhead
1	Deuteron → proton switch.	No beam. NMR calib.
4	Proton	Production at 4 GeV
0.5	Pair. Spec. converter	Absolute flux calib.
4 GeV: 11.8		total time at 4 GeV
Total: 33.1		total experiment time

Electron beam energy: 12 GeV

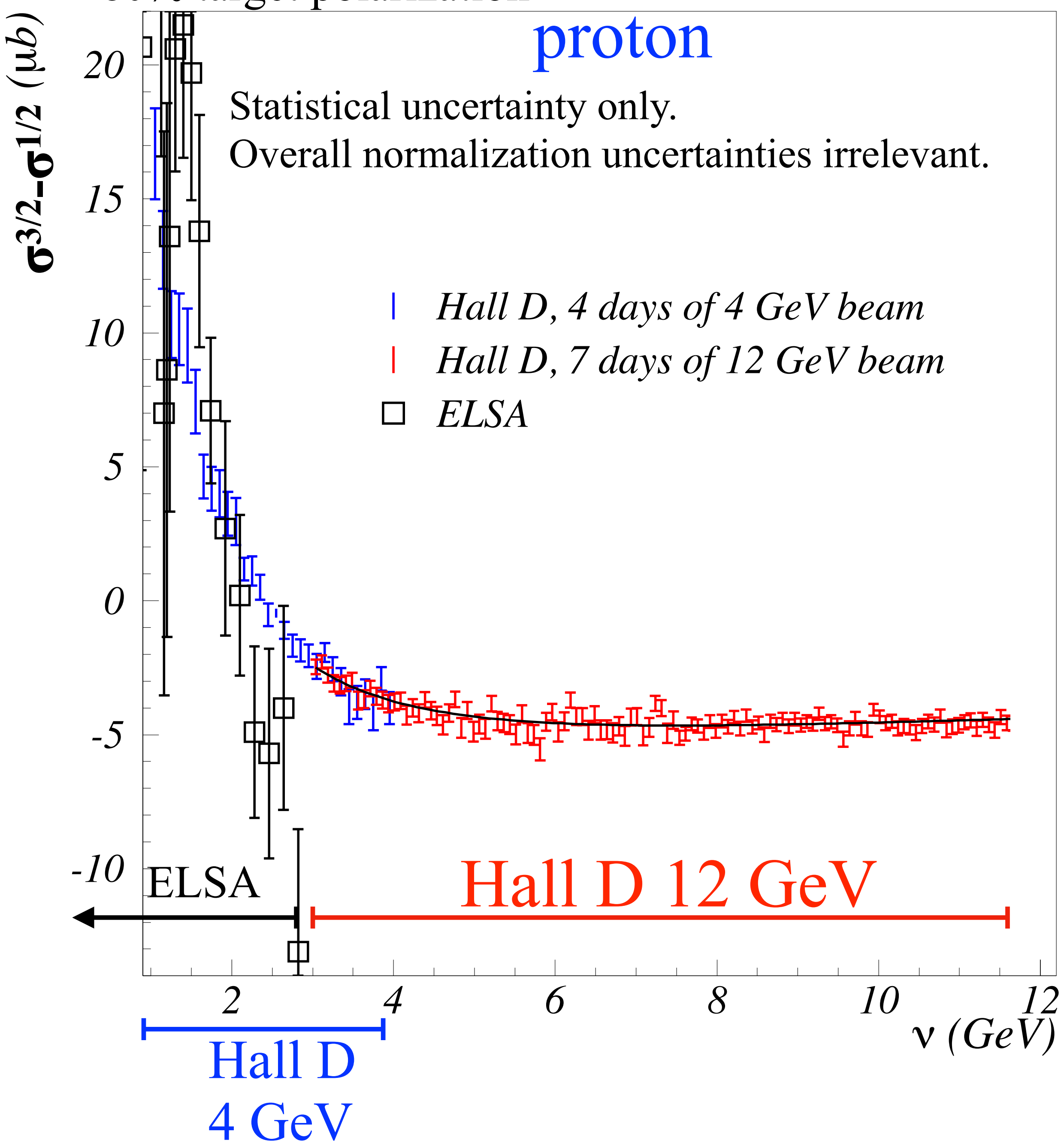
Electron beam energy: 4 or 5 GeV

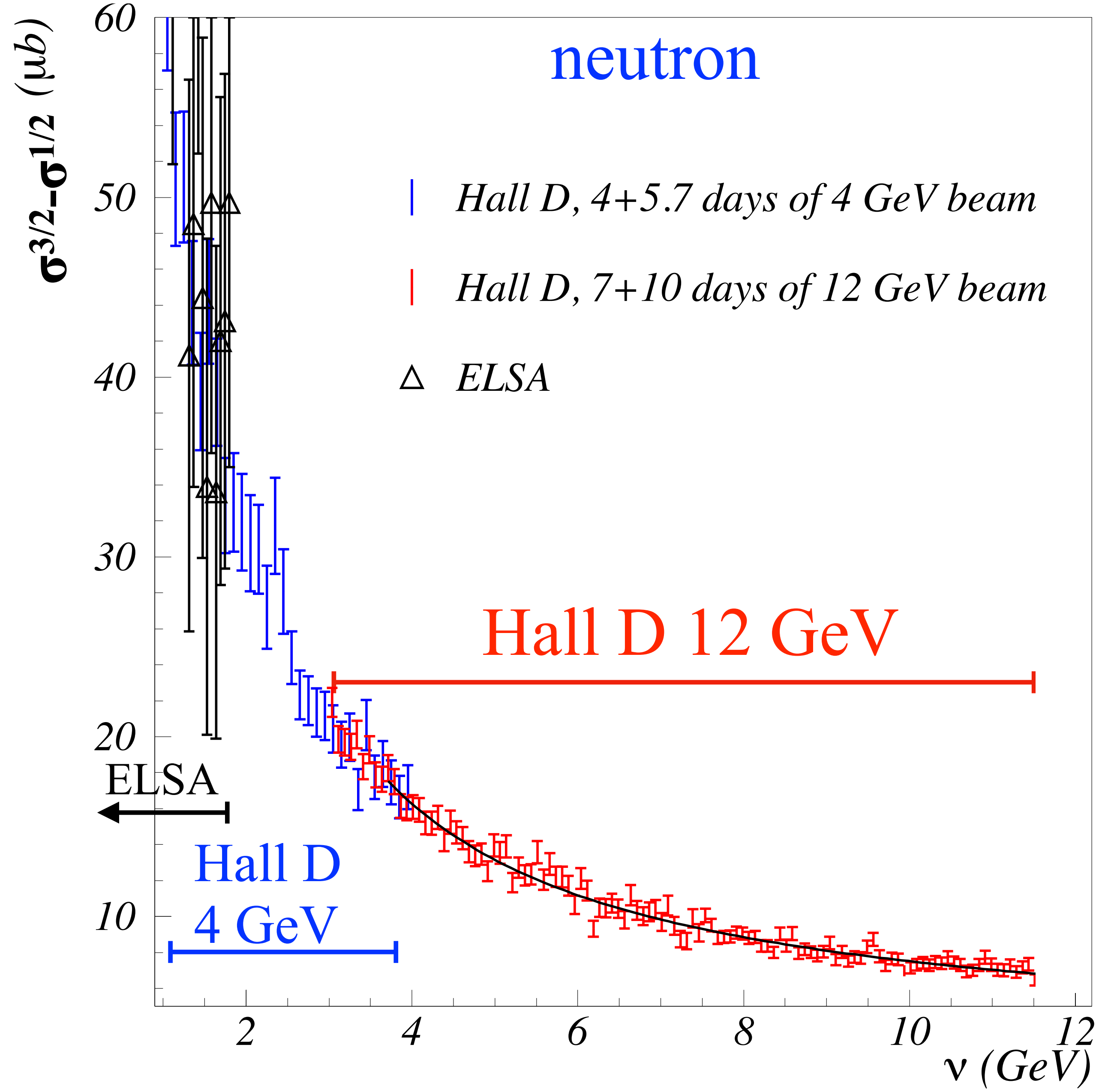
Expectations

Simulated data

Assume:

- 35kHz hadronic rate,
- 80% electron beam polarization
- 80% target polarization





- Statistical accuracy greatly improve compared to previous experiments.
- Much extended energy reach.
- low energy data: overlap with word data. Bridge gap for neutron data.

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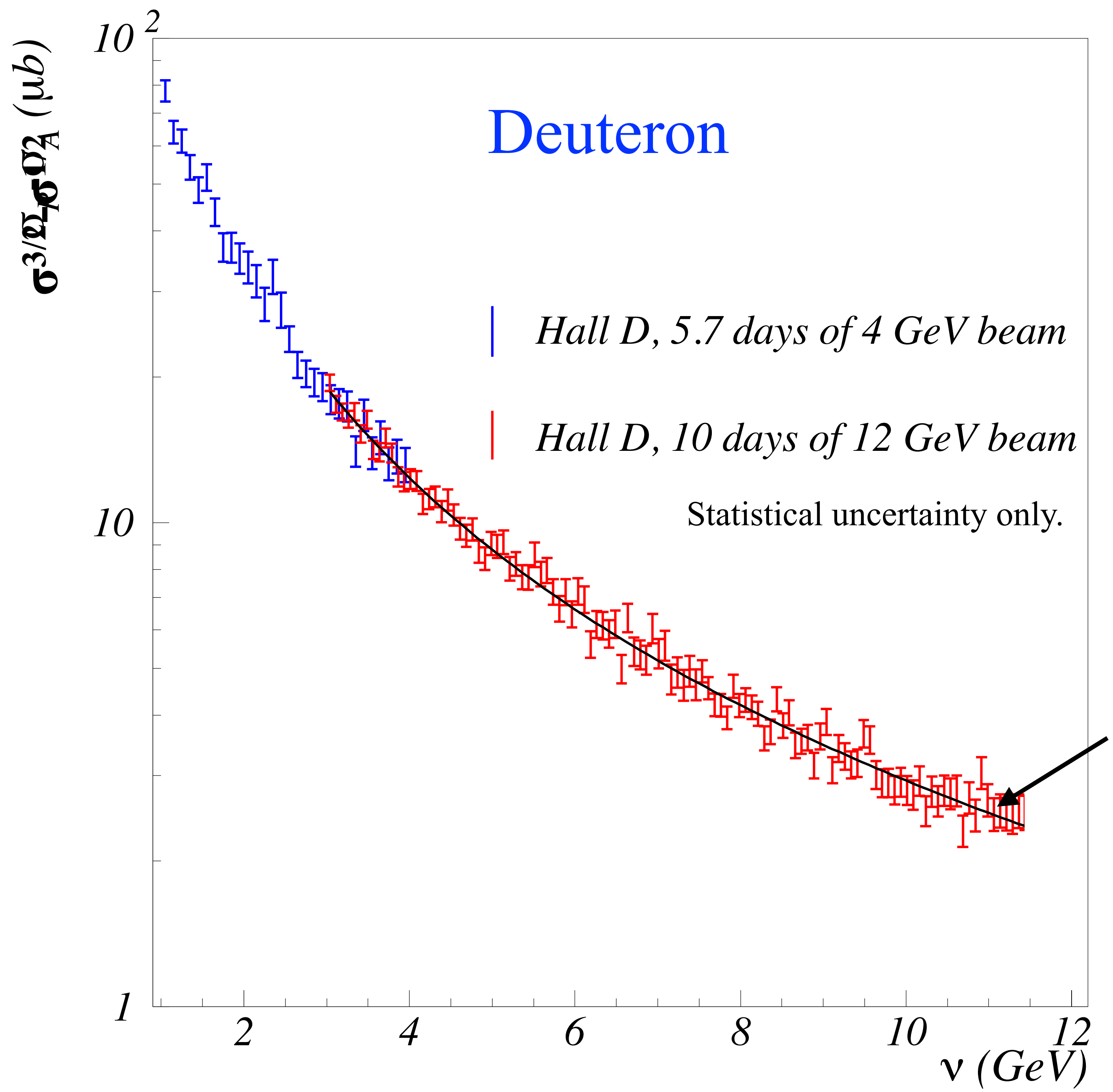
Assume:

- 35kHz hadronic rate,
- 80% electron beam polarization
- 80% target polarization



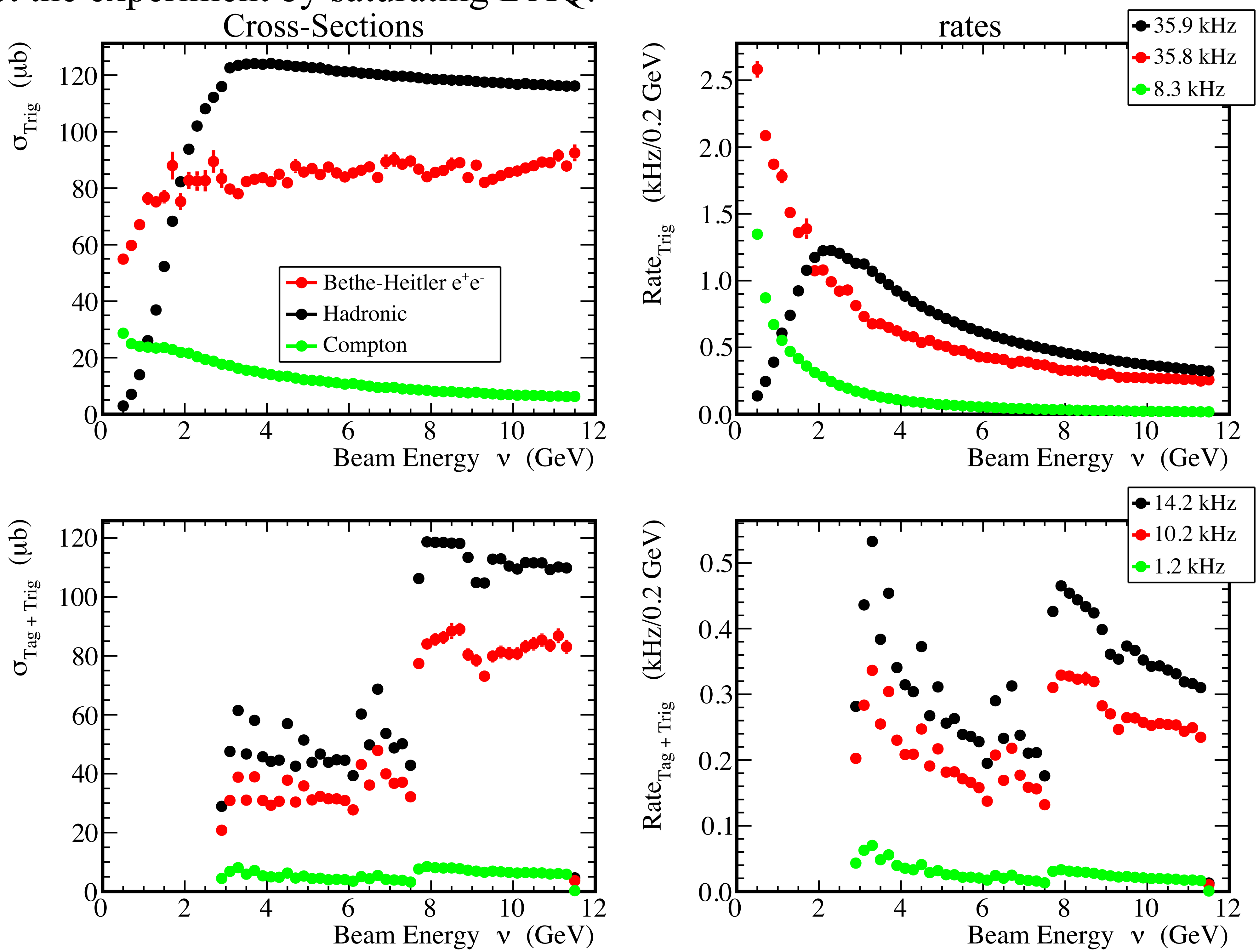
Fit: $\sigma^{3/2}$-$\sigma^{1/2}$ = (450 ± 34)s$^{-0.691 \pm 0.029}$

Should measure well the first non-zero deuteron signal at large ν.

Rates and backgrounds

Unpolarized backgrounds: cancel in yield or cross-section difference.
However, may still affect the experiment by saturating DAQ.

HD GEANT simulation:



Total rate; 80 kHz (Hall D present DAQ capacity)

Useful hadronic rate: 35 kHz

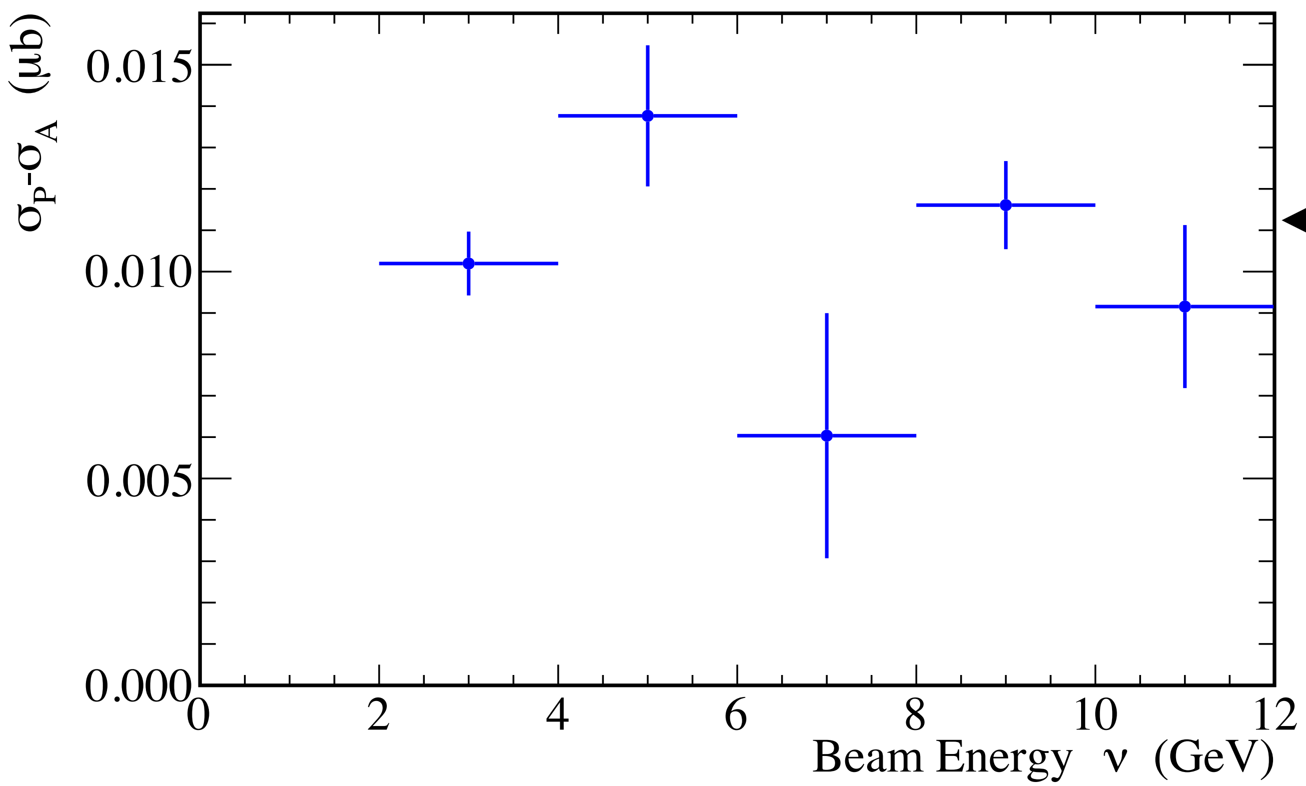
Confirmed with GlueX data (Kapton data from empty target run. Kapton thickness scaled to 10 cm yields ~50 kHz)

Rates and backgrounds

Polarized backgrounds: contribute, but very small (~0.2% contamination).

Bethe-Heitler Cross-Section difference

HD GEANT simulation:



Compare ~0.01 μb (B-H) with ~5 μb (hadronic)

No polarized Compton contribution (FROST electrons unpolarized).

Impact

- Measuring high ν-behavior will test the convergence of GDH sum (fast and robust analysis: early goal)
  - First measurement well outside resonance region: <u>**first**</u> clean test of Regge theory for **polarized case**.
  - If Regge theory works: $\Delta\alpha_{a1} = \pm 0.007$ & $\Delta\alpha_{f1} = \pm 0.029$. 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 at large ν.
- 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.
- 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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  - First measurement well outside resonance region: <u>**first**</u> clean test of Regge theory for **polarized case**.
  - If Regge theory works: $\Delta\alpha_{a1} = \pm 0.007$ & $\Delta\alpha_{f1} = \pm 0.029$. Compare to $\Delta\alpha_{a1} = \pm 0.23$ & $\Delta\alpha_{f1} = \pm 0.22$ from ELSA.

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 $\alpha_{a1} \cong +0.45$.

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

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 integrand $(\sigma^{3/2}-\sigma^{1/2})/\nu$
- Hall D + FROST target (H and D) + polarized electron beam on a amorphous radiator.
- Hall D is uniquely suited for such measurement.
- 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.
- 21-days 12 GeV measurement provides α_{f1} and α_{a1} at 2% level (present uncertainties: 50%)
- 12-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 Regge theory prediction.
- Provide first non-zero data on $\sigma^{3/2}-\sigma^{1/2}$ at high-ν 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 Chiral Perturbation Theory.
  - 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.

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

Back-up slides

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

Photon energy

Mass

spin

anomalous magnetic moment

- 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:
  - 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).
- 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 uniquely suited to perform a GDH experiment.

Possible mechanisms that could invalidate the GDH rum rule

- GDH: Fundamental QFT prediction.
- 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, e.g. local break-down of EM gauge invariance

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

PRO:

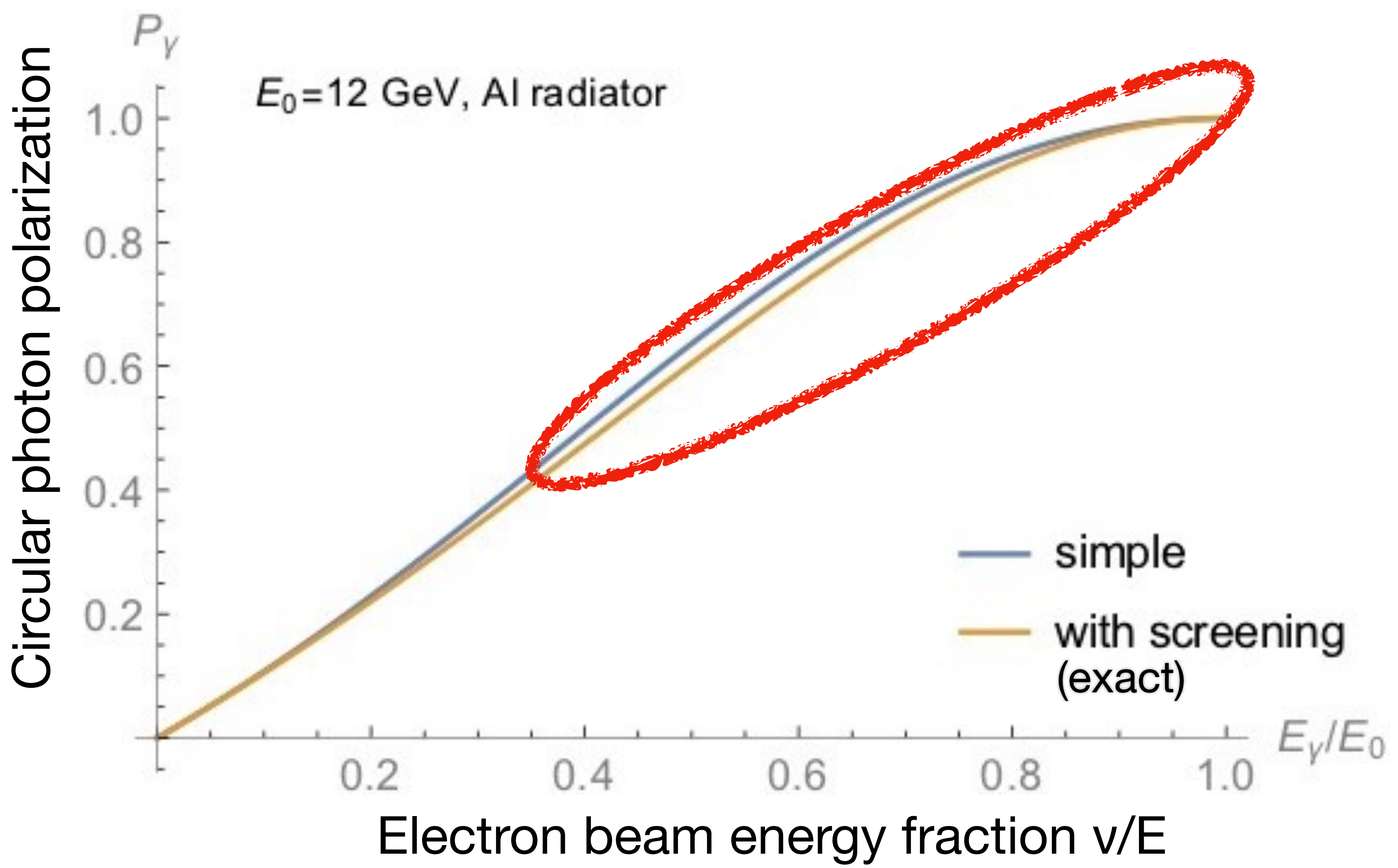
- Hall D: only Hall with photon tagging capability,
- A GDH measurement via electroproduction is not adapted to its study at large ν:
  - Would need to be done at low enough Q^2 (< 0.02 GeV^2) to reliably extrapolate to $Q^2 = 0$.
  - At 11 GeV, low enough $Q^2 \Rightarrow$ scattering angles smaller than 0.8°.
    - No hall has this capability (CLAS12 forward tagger is limited to 2.5°).
    - Elastic radiative tails are prohibitively large. They will furthermore saturate the DAQ.
- g_1 cannot be separated from g_2 in Hall B without a transverse target. Need model input but g_2 behavior at very low Q^2 and large ν is not known.
- The largest ν reachable in Hall B for inclusive data is 8 GeV, compared to 12 GeV in Hall D.
- No possible $Q^2 = 0$ extrapolation: 8 GeV and 2.5° $\Rightarrow Q^2 = 1$ GeV^2.

CON:

Hall D does not have a polarized target. However, its cost is moderate (~$600K) and it opens an opportunity for new physics program.

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);
  - High photon energy resolution (present < 0.5% more than enough).

Electron beam polarimetry

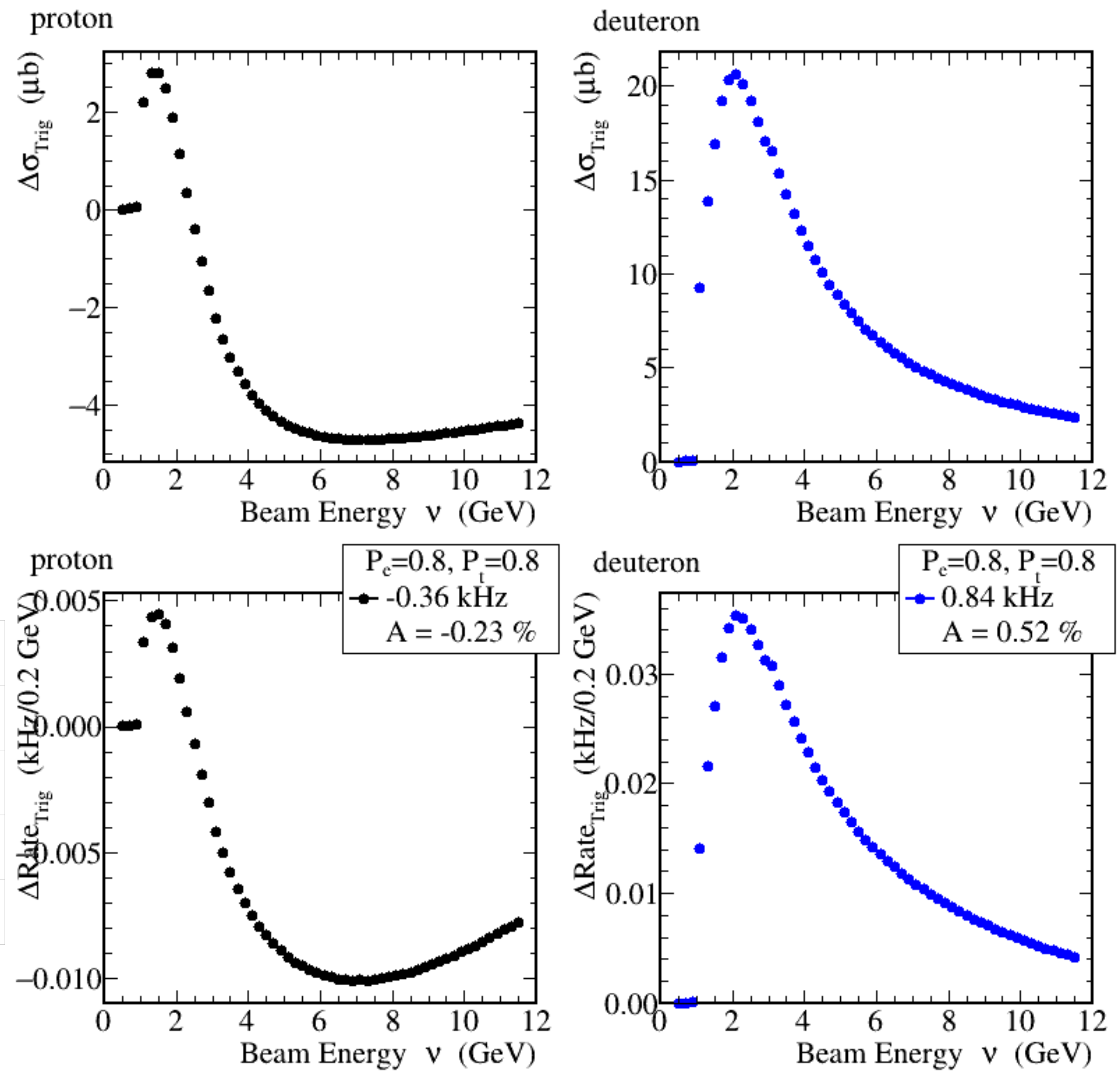
Absolute value measured using injector Mott polarimeter (and potentially Hall A or C polarimeters.)

Initial precession angle directly measured using spin dance with large Hall D trigger asymmetry.

deuterium target: $A = 0.52\,\%$ (assume 80% beam pol. and 80% target pol.))

$\frac{\Delta A}{A} = 1.12\,\%$ in 1 hour at 80 kHz total rate (35 kHz hadronic rate)

Hall D and LINAC beam energy monitored to bound precession variation over time.



<u>Polarimetry uncertainties:</u>

Polarization	1%
Time variation/interpolation	1%
Synchrotron depolarization	1%
Precession angle	2%
TOTAL	**3%**

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. 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

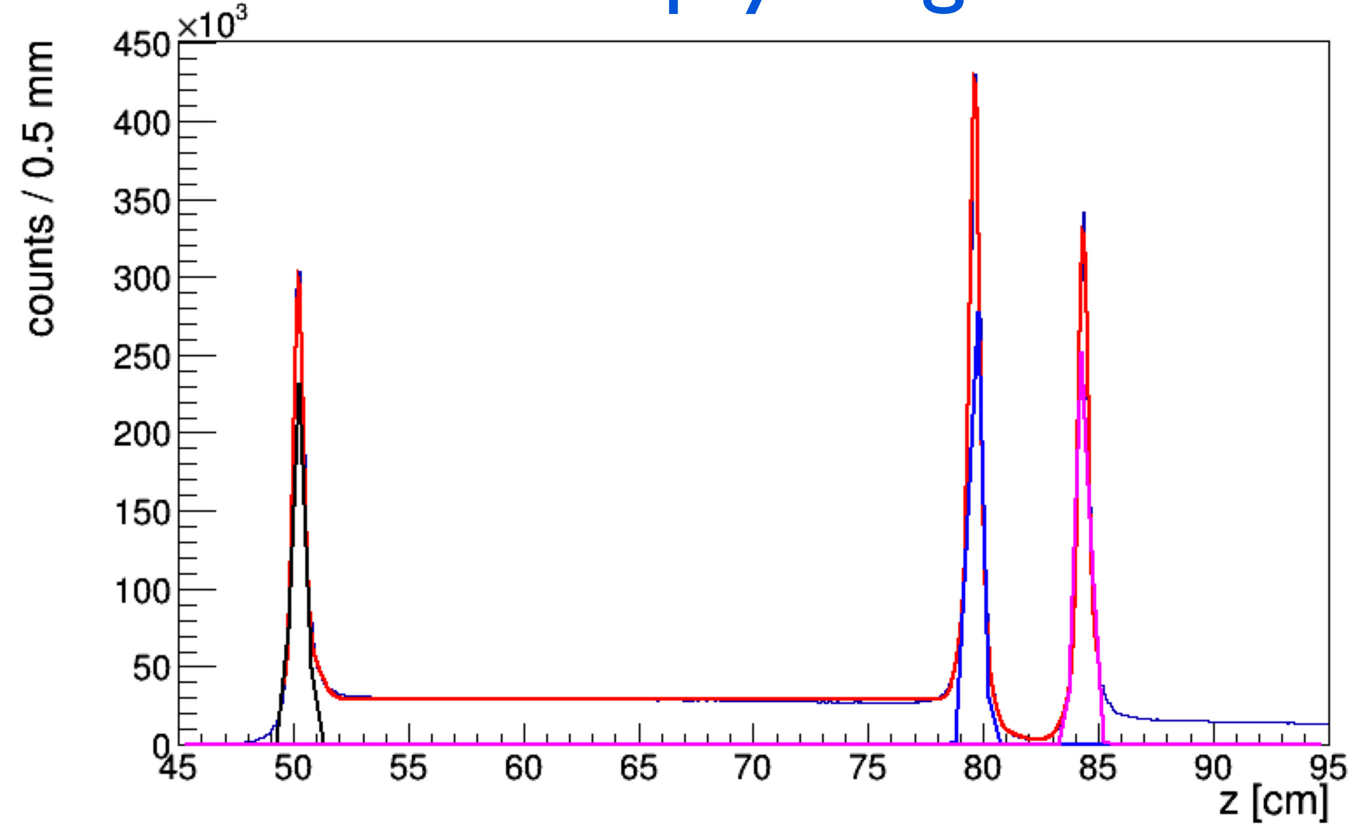
- Target group prefers to build dedicated Hall D FROST target rather than to import Hall B one.
- Two months to install the target. No commissioning needed.
- Cost estimate: ~$600k

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. Not required for GDH.
- 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).

Unpolarized background rates from GlueX empty target data

- Spring 2017 empty target data
- Fit yield of 2-track vertices and extract contributions from windows
- Ratio of yields between gas and windows matches areal density?

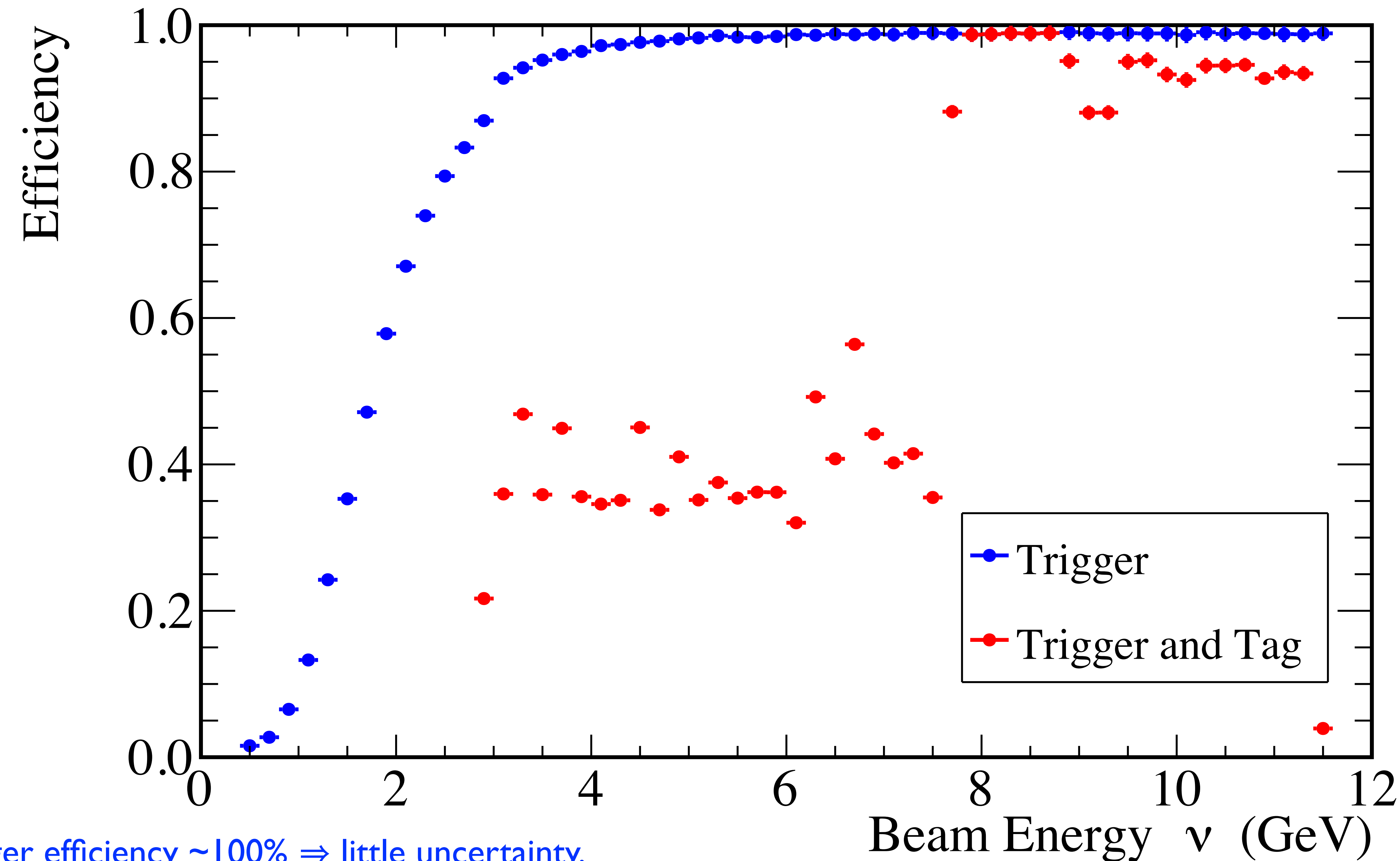


	Position (cm)	Density (g/cm³)	Length (cm)	Area density (g/cm²)	2-track yield
LH_2 gas	50-79.5	0.0015	29.5	0.04425	8.58×10^{6}
Kapton 1	50	1.42	75×10^{-4}	0.011	1.79×10^{6}
Kapton 2	79.5	1.42	75×10^{-4}	0.011	2.19×10^{6}
Aluminum	84.5	2.7	25×10^{-4}	0.007	1.96×10^{6}

Empty target run rate:7 kHz.

Scaled rate for PR12-20-011 from empty target run ~50 kHz

Trigger and tagging efficiencies



Trigger efficiency ~100% ⇒ little uncertainty.

Tagger efficiency measured with ~1% uncertainty.

Trigger will be optimized to improve low photon energy trigger efficiency.

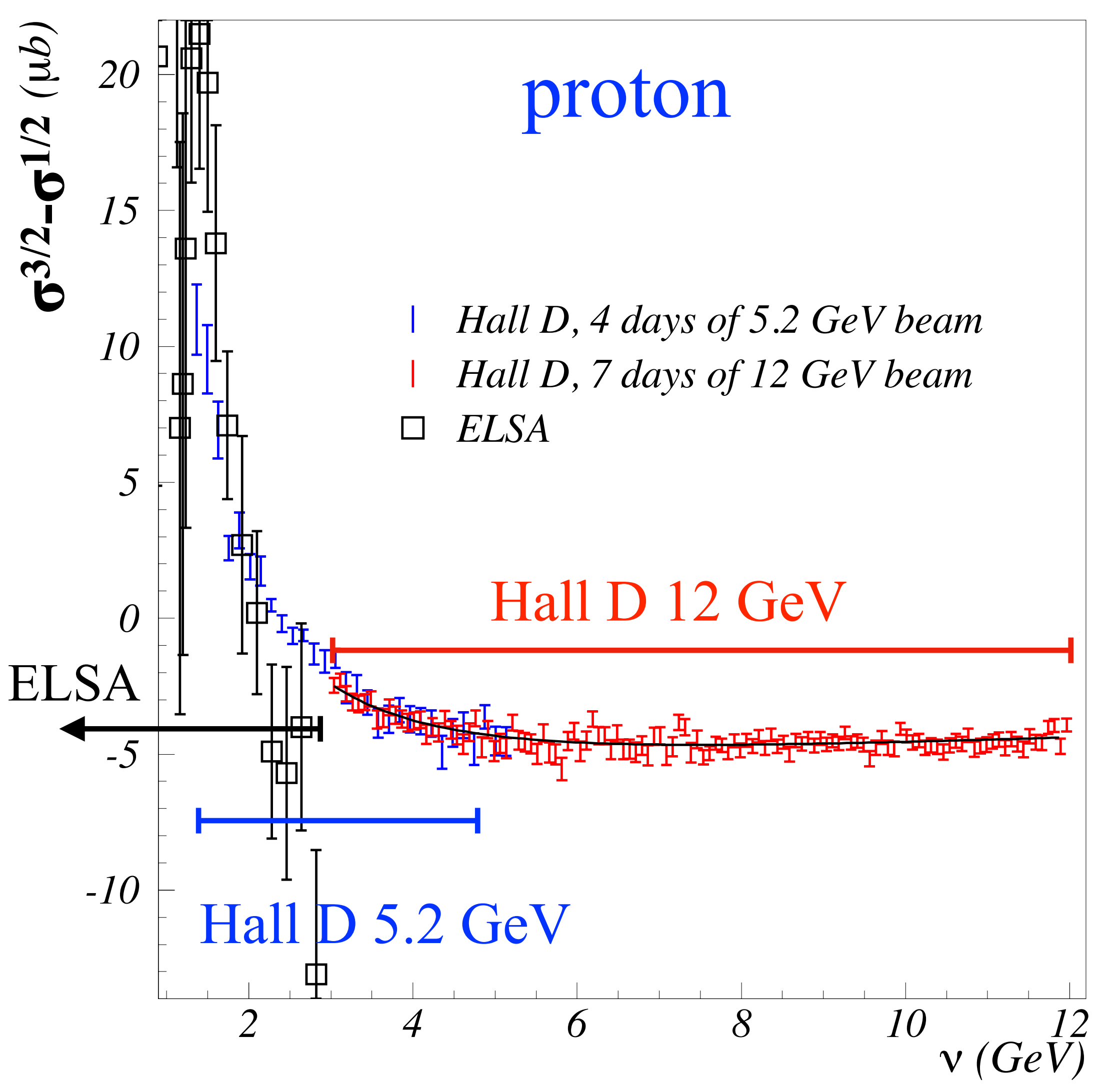
Prescaled minimum bias trigger will help determine trigger efficiency .

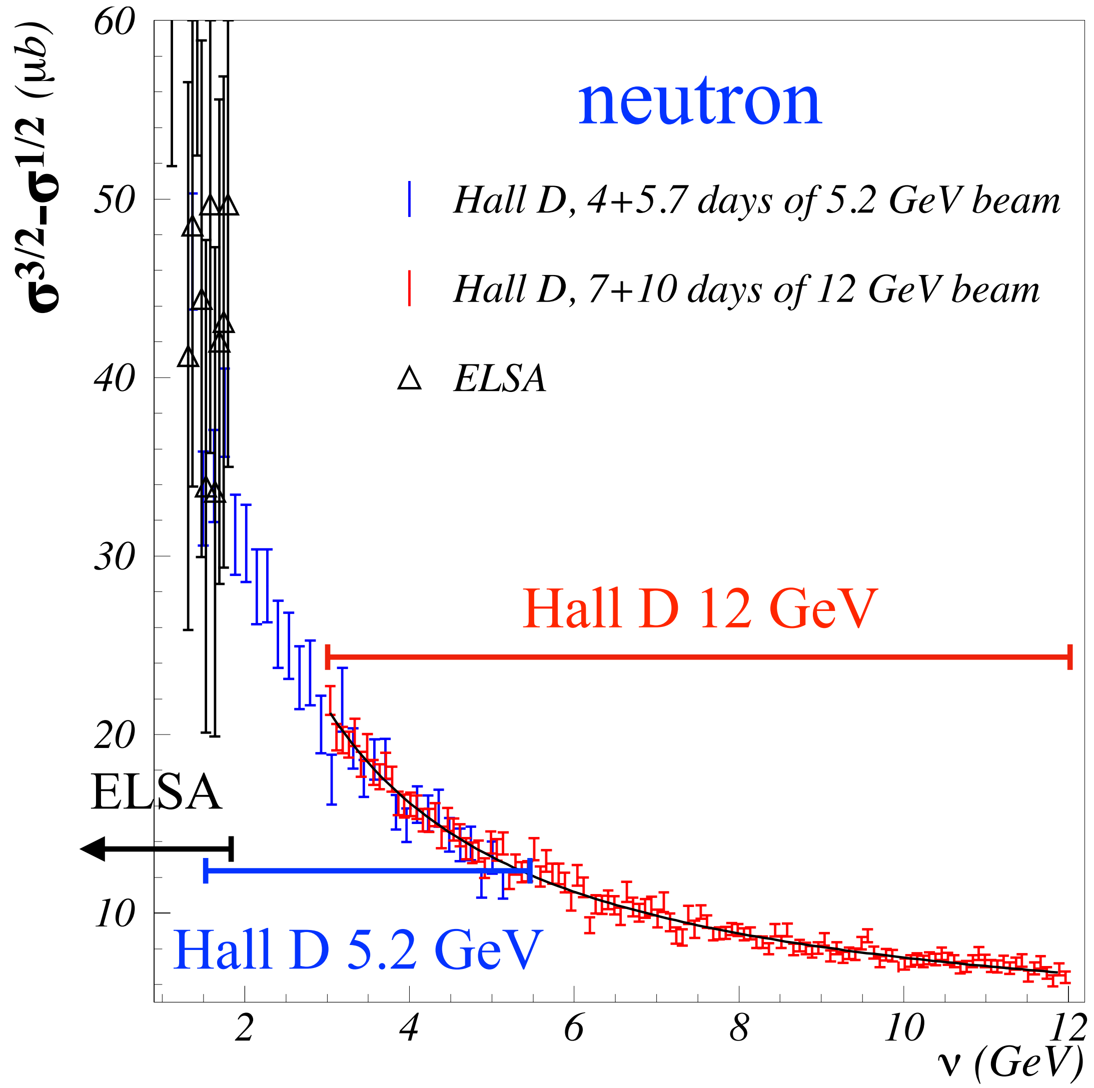
Lower energy run will overlap with low tagger energy data from 12 GeV run.

Low energy run

- Allows to overlap/bridge gap between ELSA and Hall D data.
- 12 days. Nominal energy: 4 GeV.
- Consulted with accelerator experts (J. Benesh, T. Satogata). Feasible, with two solutions:
  1: Run at lower linac energy:
  - Advantage: simplest solution.
  - Issues: •Invasive to other halls high energy runs ⇒ Scheduled during a low energy summer run?
    - Operate somewhat below CEBAF dipoles mapping ⇒ Beam set-up will take longer.

  2: Run at less than 5.5 passes:
  - Issue: Never done before. Require R&D and tests.
  - Advantages: •Non-invasive.
    - Expand Hall D capabilities.
- If the above is too difficult, 5.2 GeV possible. Same as Summer 2019: known configuration. Only a scheduling matter.

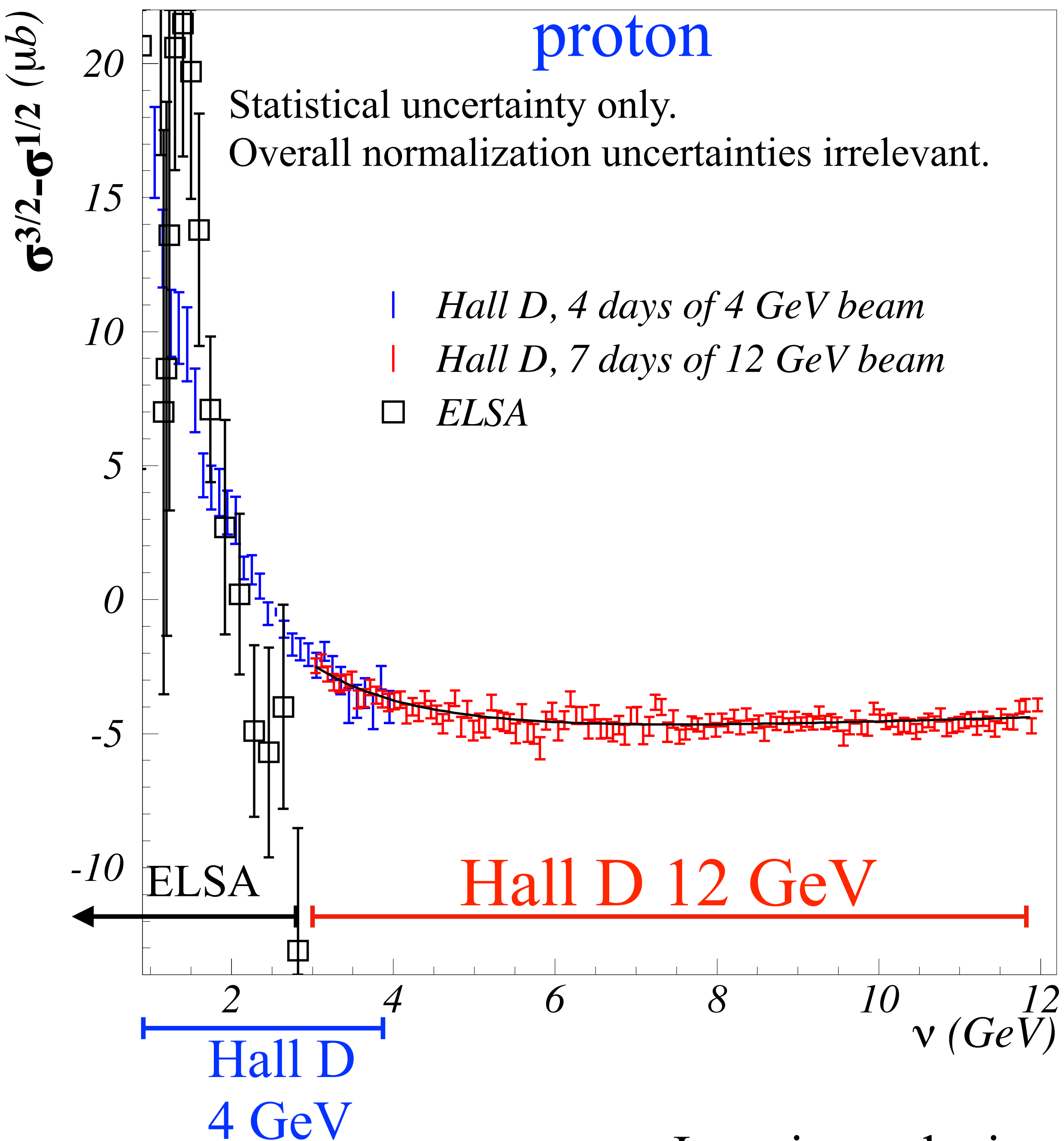


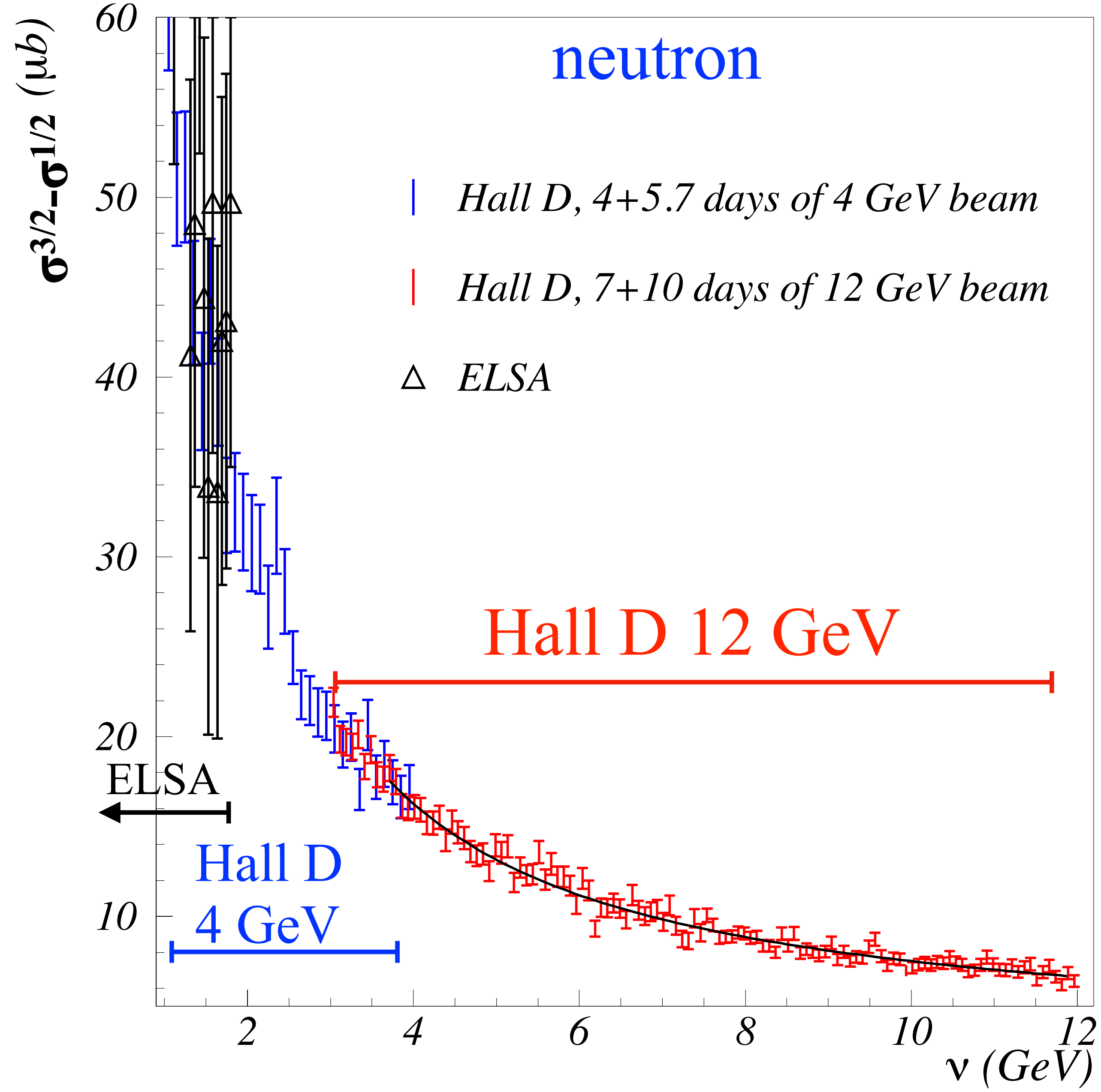


Expectations

- 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)

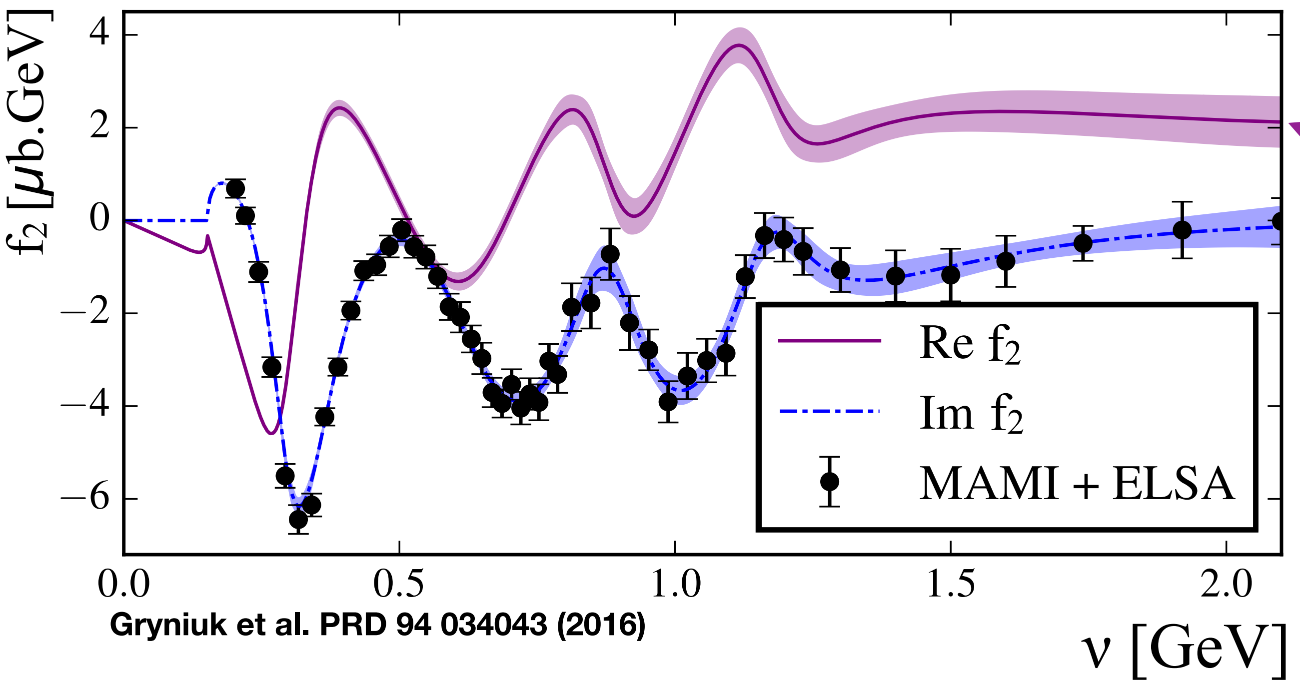
  $s=2M\nu+M^2$, α_{f1}, α_{a1}: Regge intercepts of $f_1(1285)$ and $a_1(1260)$ trajectories, and $c_{2,1}$: parameters.
- 7×10^7 s^{-1} collimated flux ($3<\nu<12$ GeV), Pb=80%, Pt=80%.
- 10 cm target on usual butanol density





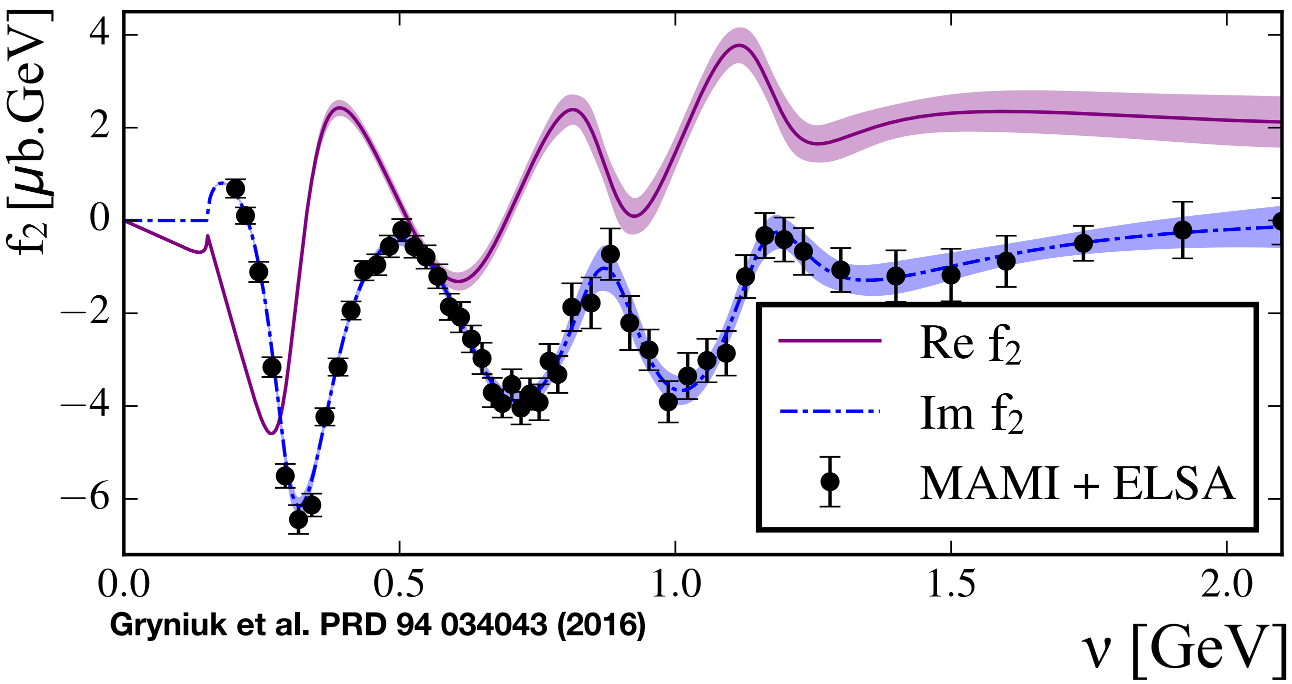
Isospin analysis $\Rightarrow$ $\Delta\alpha_{a1}=\pm0.007$ & $\Delta\alpha_{f1}=\pm0.029$

Extraction of the real and imaginary parts of Compton amplitude f_2



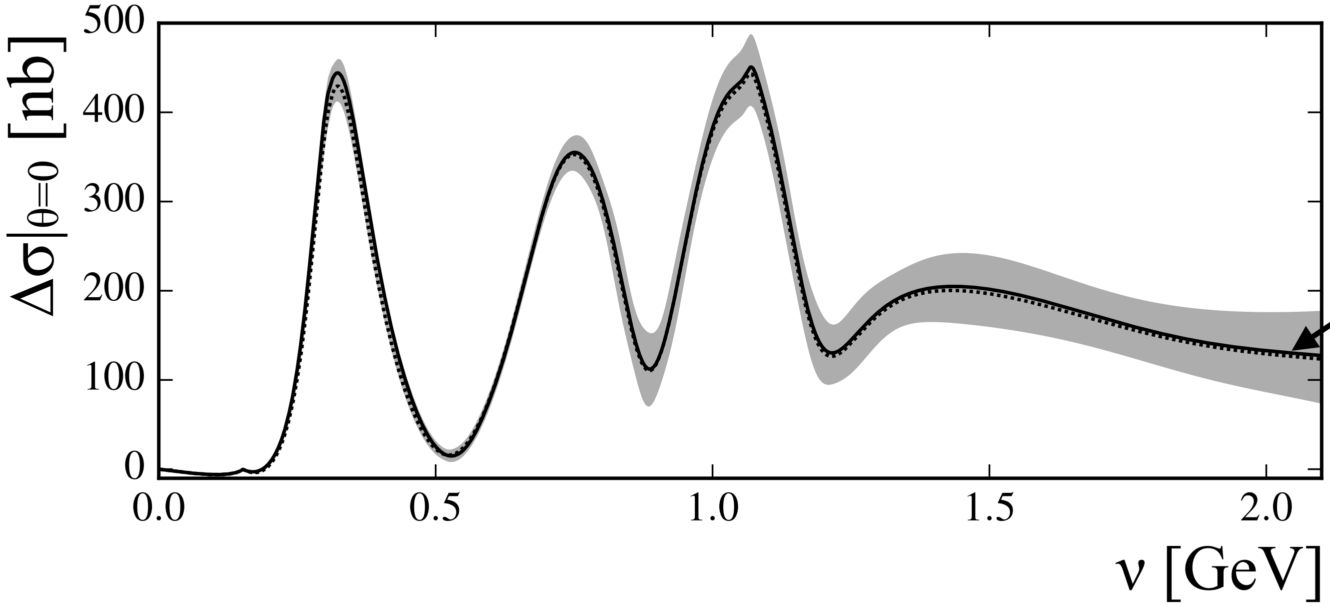
Dispersive analysis from $\mathrm{Im}(f_2)$ data. Large ν data will constrain both $\mathrm{Re}(f_2)$ and $\mathrm{Im}(f_2)$ error bands.

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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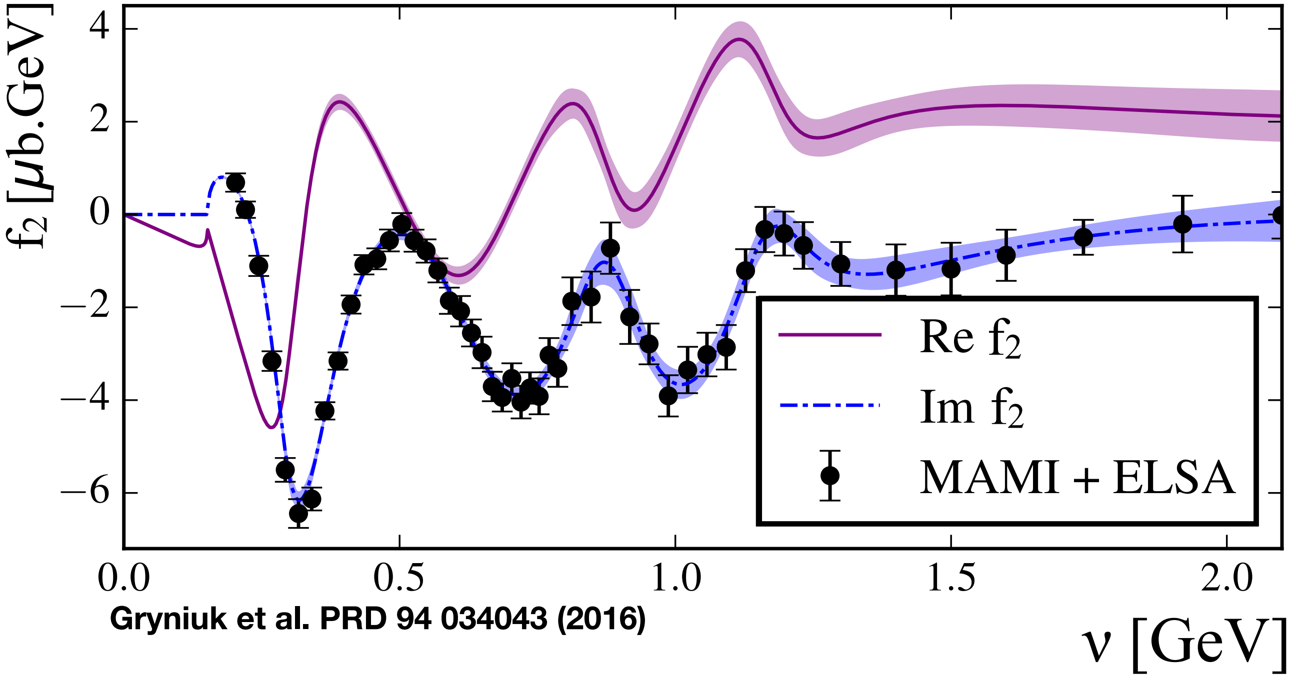

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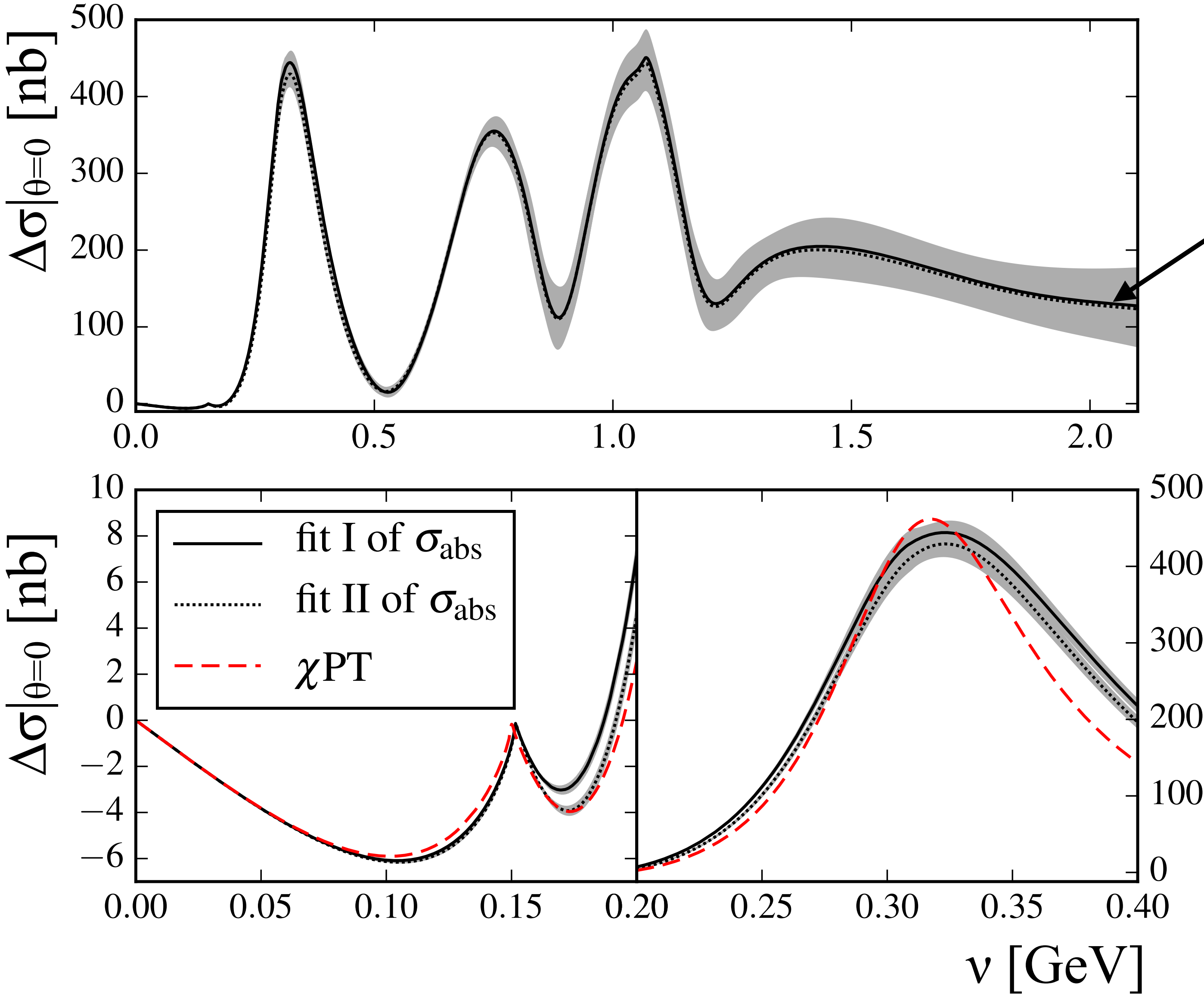

Large ν data will constrain increasing error band.

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)