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 (Ljubljana Univ.)

Proposal endorsed by the GlueX collaboration.

PAC47 encouraged LOI to be developed into a full proposal[1].

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.

The Gerasimov-Drell-Hearn sum rule

Spin-dependent total photoproduction cross-sections

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

anomalous magnetic moment

spin

Photon energy

Mass

- 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.

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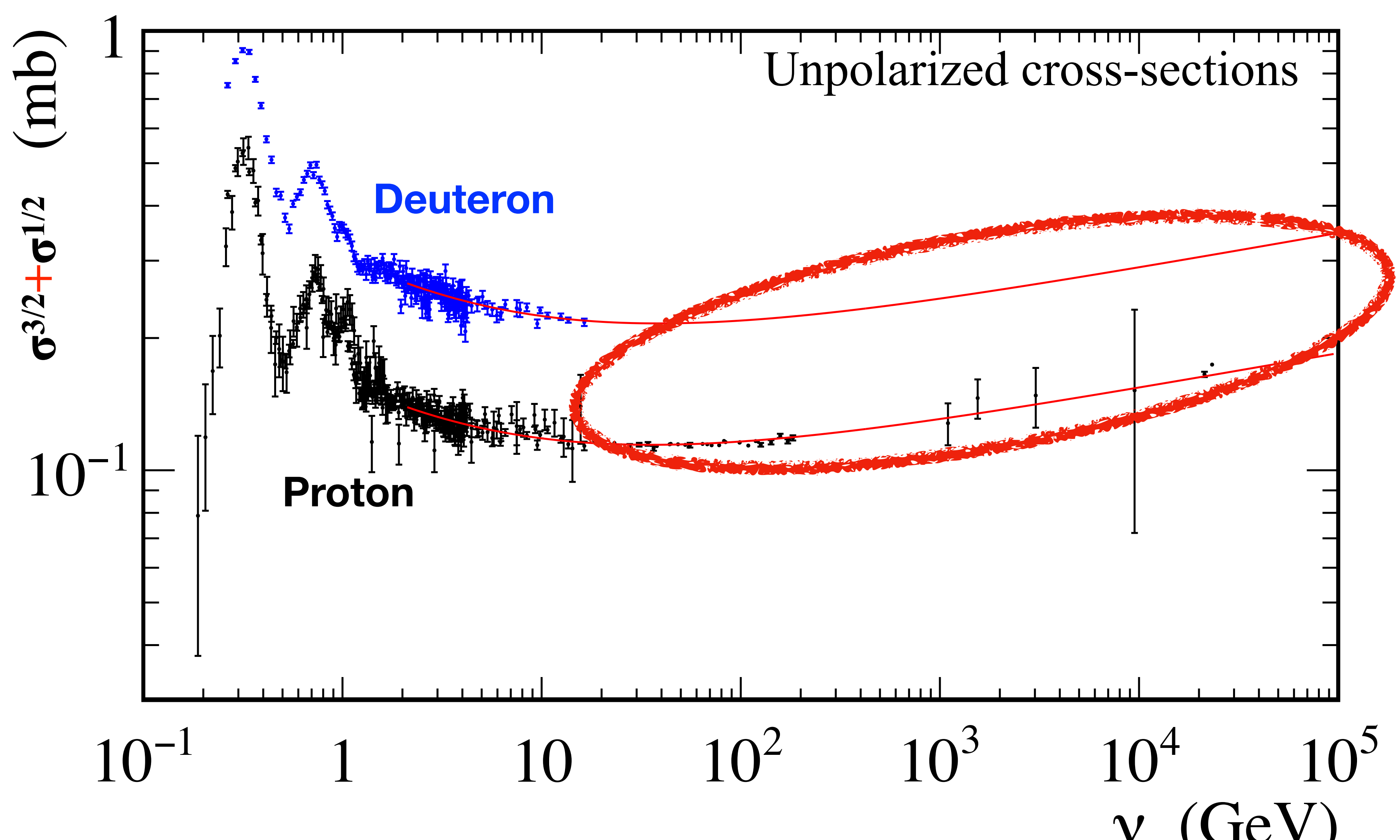

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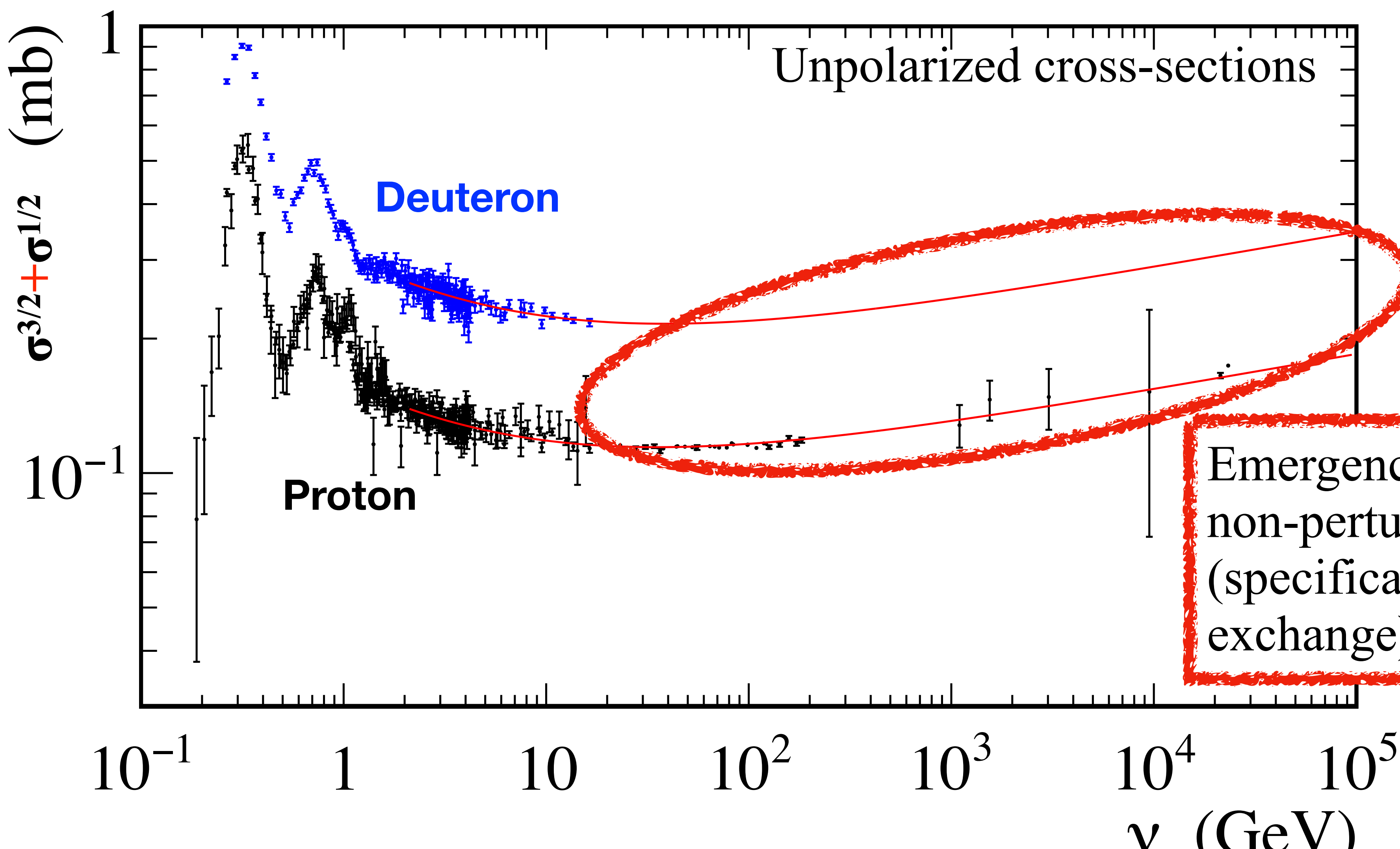

Emergence high-energy non-pertubative reactions (specifically here: pomeron exchange).

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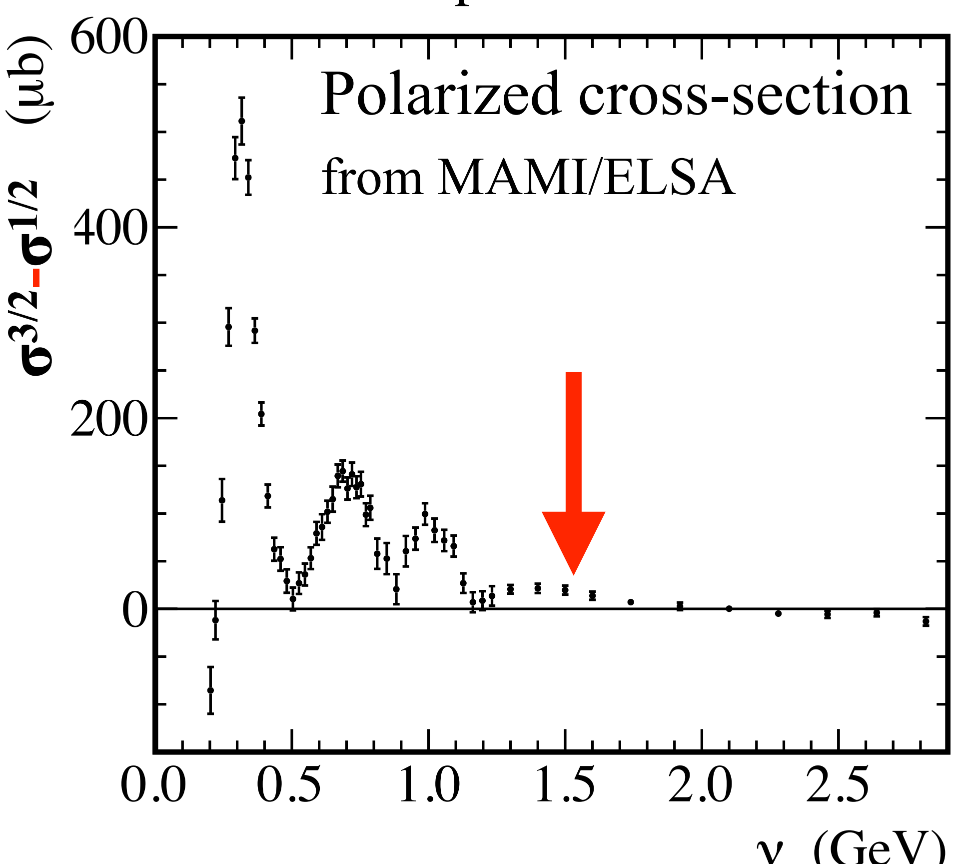
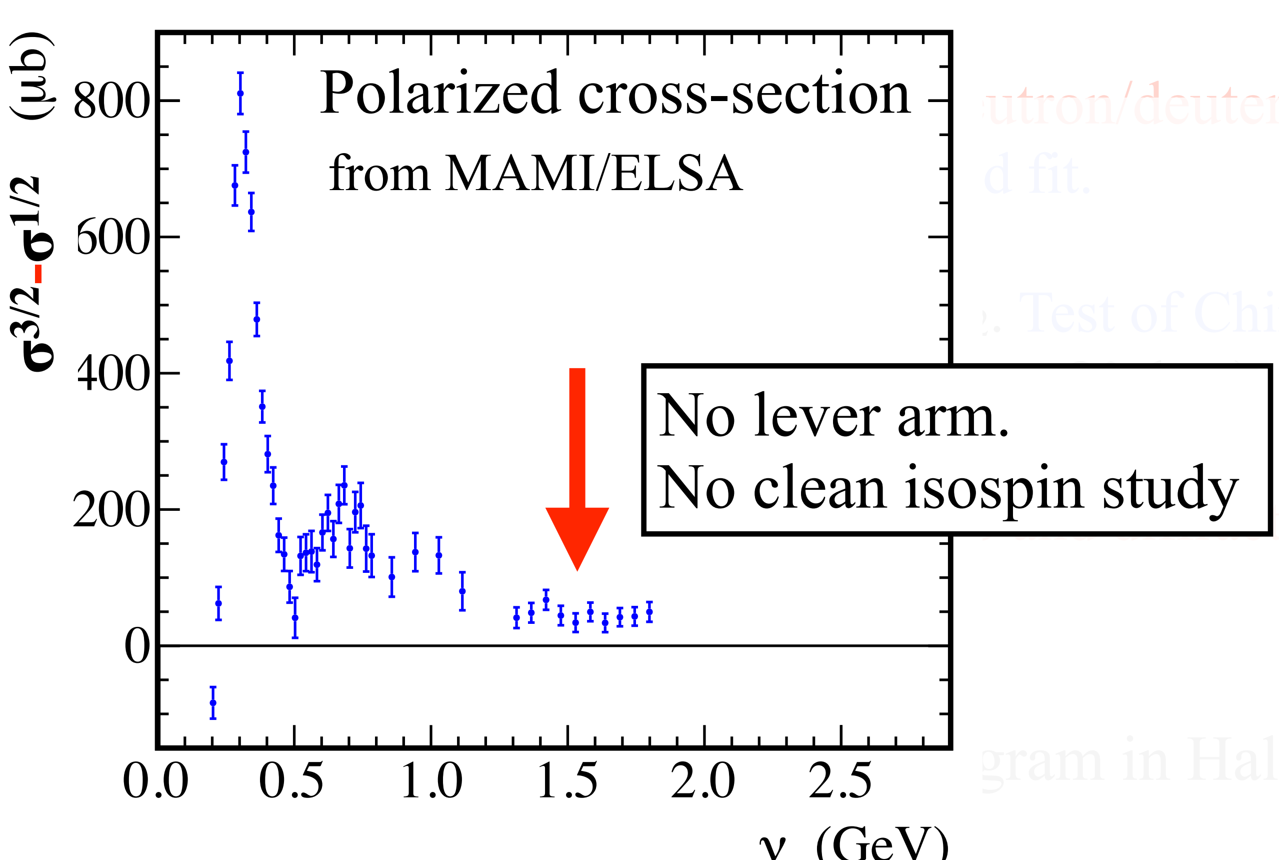


neutron



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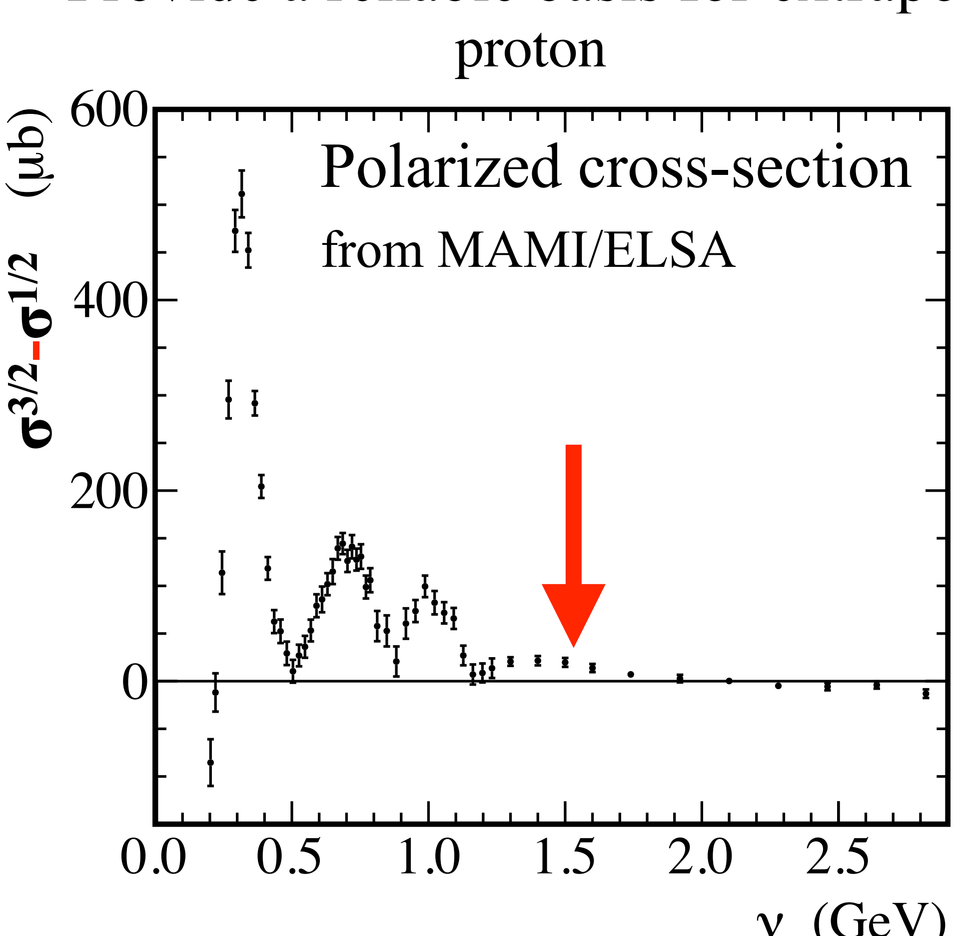
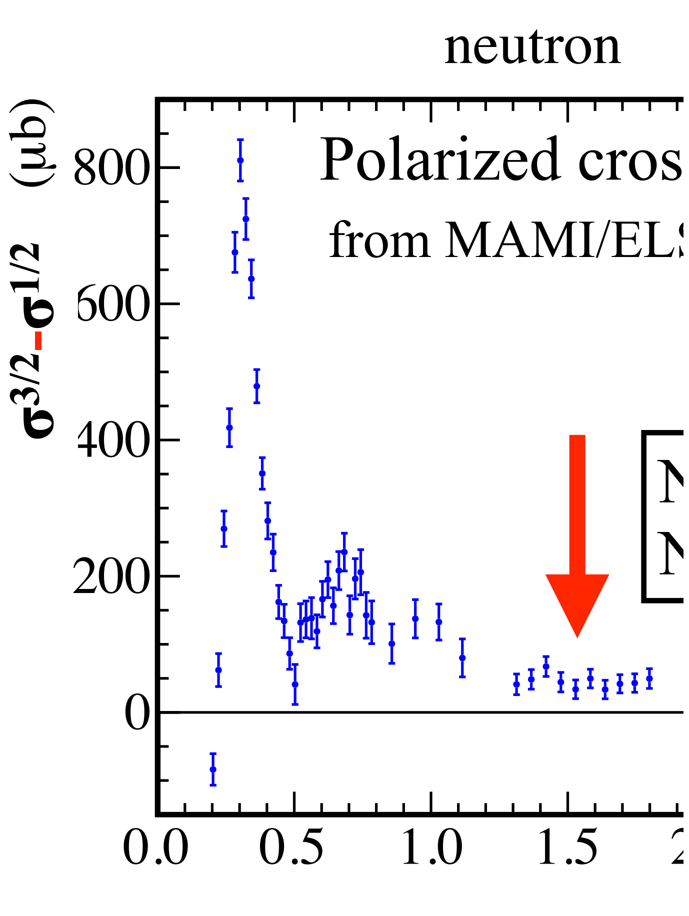
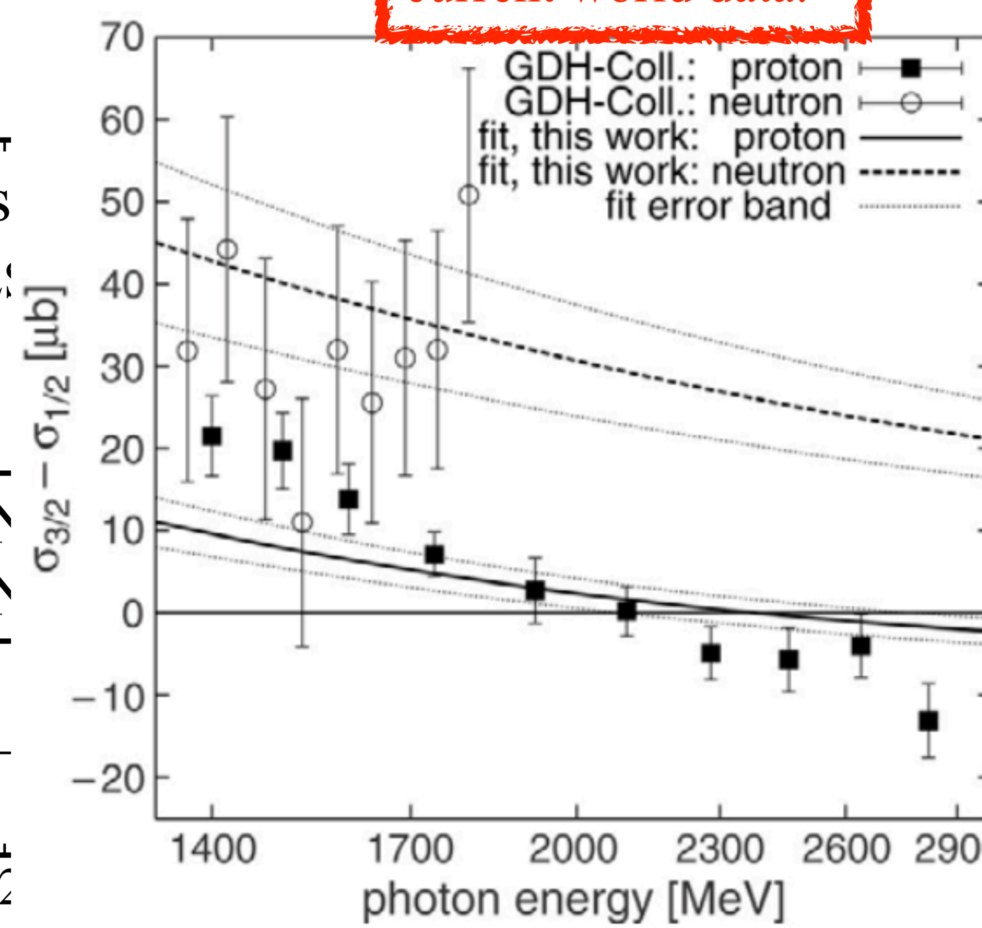
Poor Regge fits for current world data.







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  - Deuteron:
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    - 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, e.g. during 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;
    - Polarized electron beam;
    - Amorphous radiator.
  - Longitudinally polarized target; FROST target.
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- 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;
    - Polarized electron beam;
    - Amorphous radiator.
  - Longitudinally polarized target; FROST target.
  - Large solid-angle detector. 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, e.g. during 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

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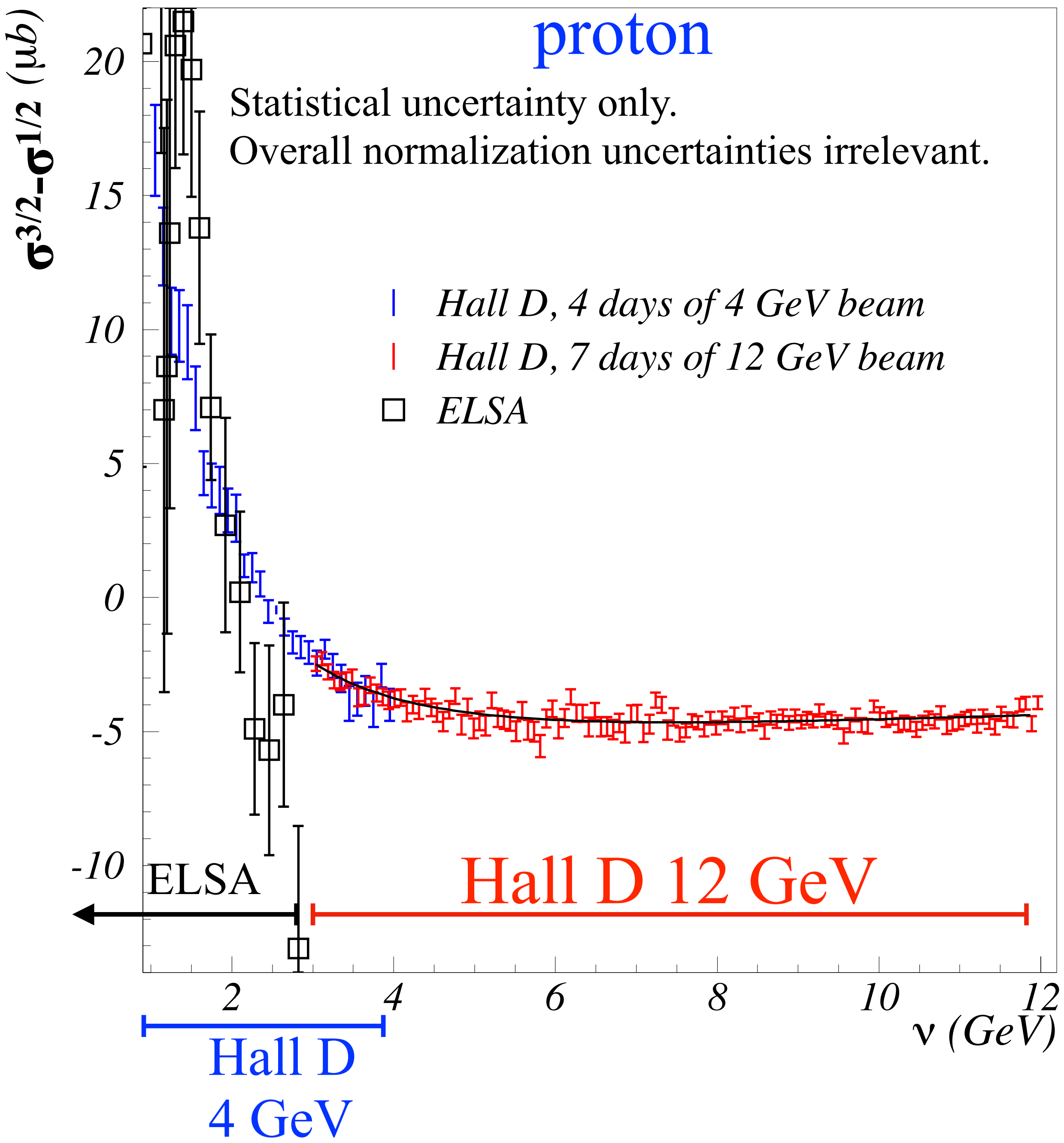
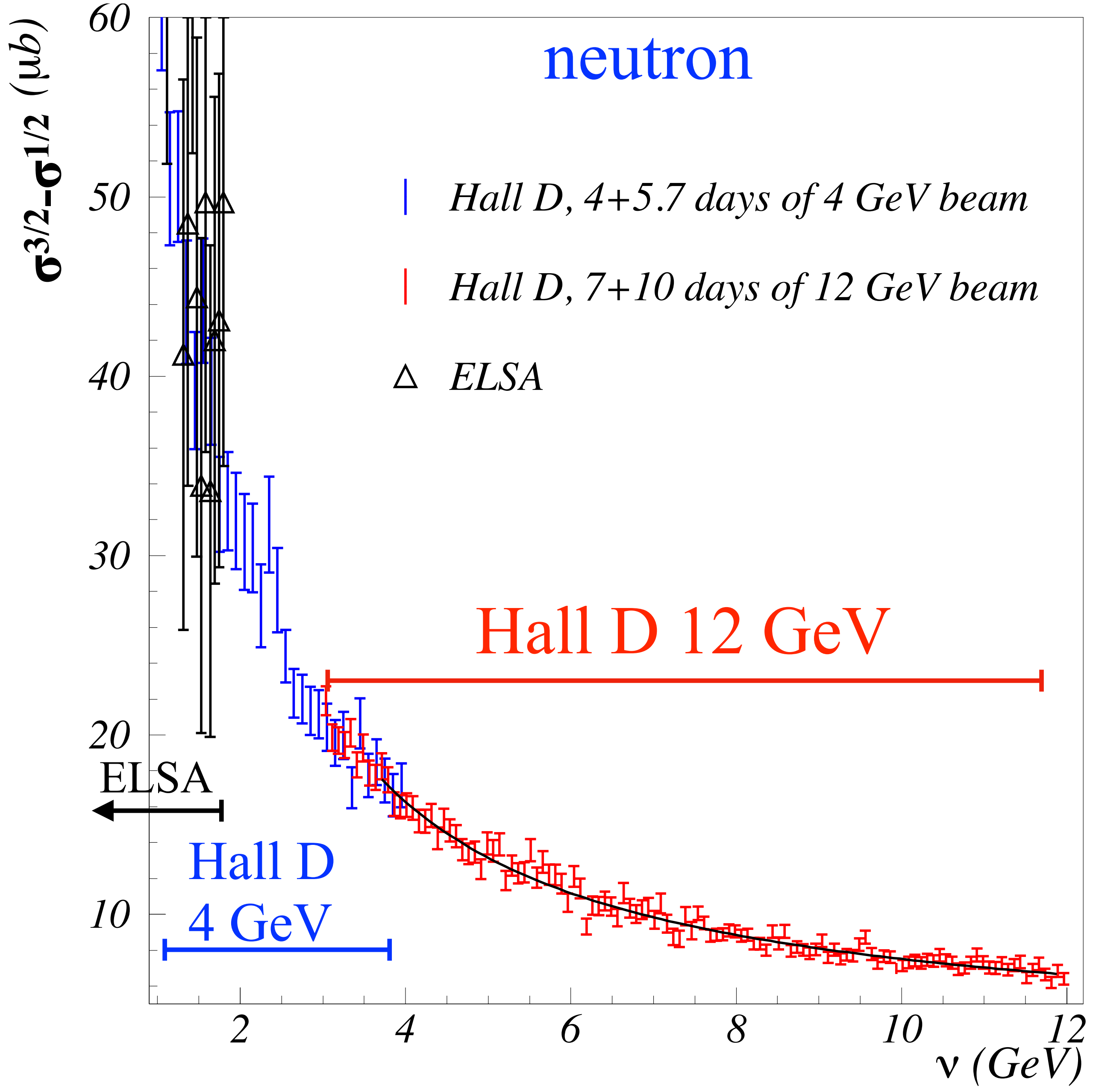
Time request

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 $\rightarrow$ 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 $\rightarrow$ 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

Expectations

Simulated data:





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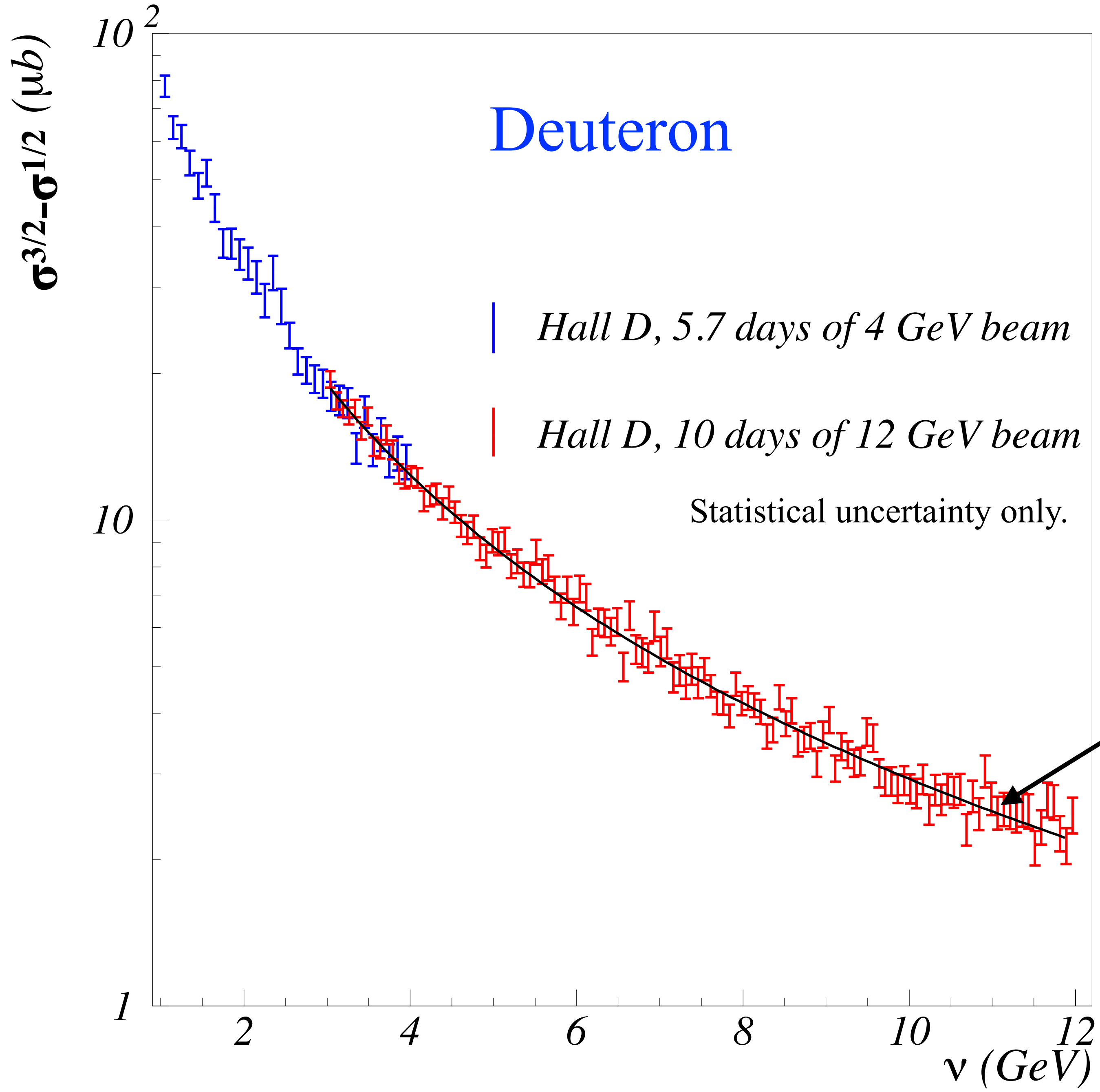


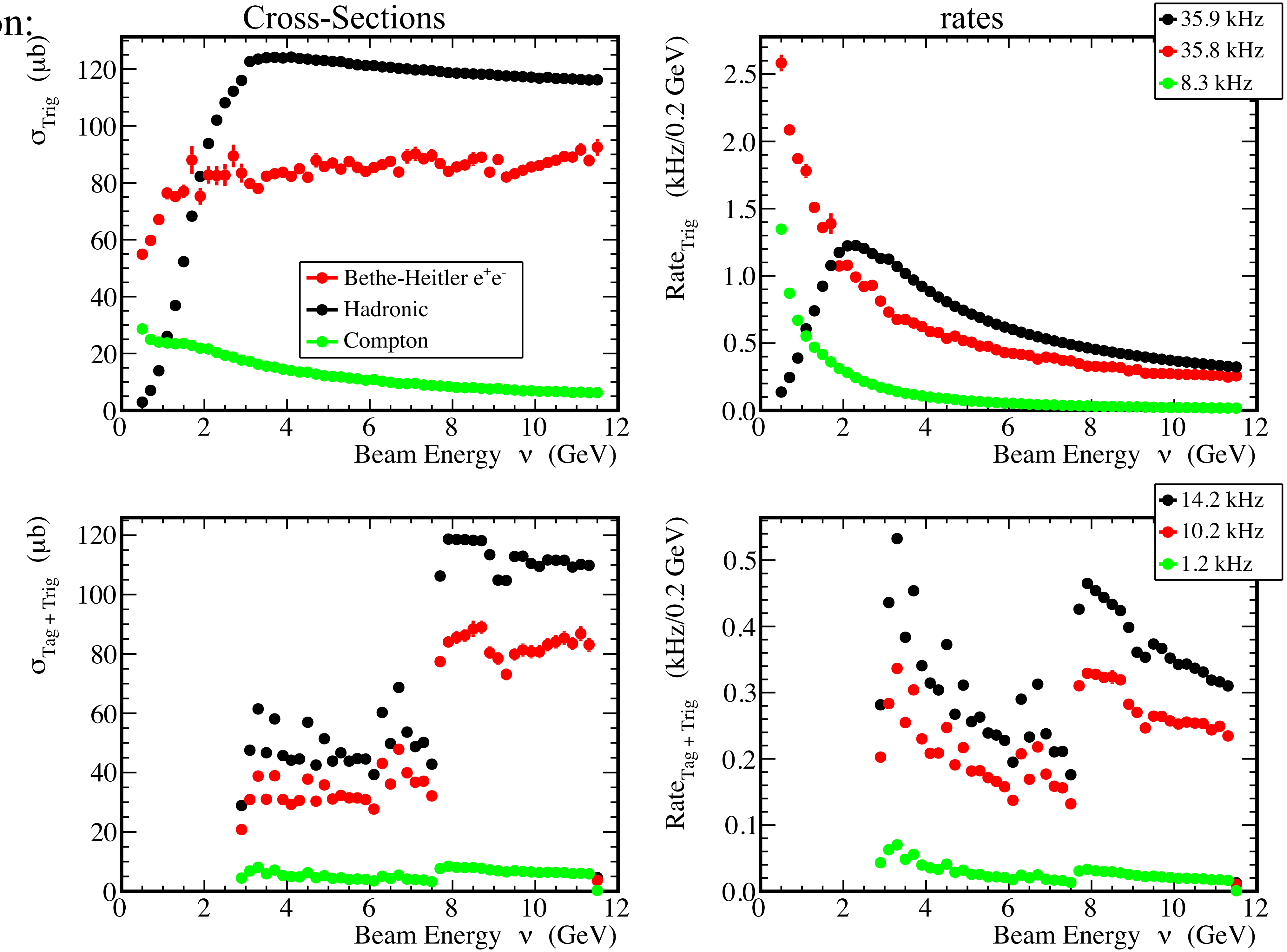
Should measure well the first non-zero deuteron signal in diffractive domain:

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

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

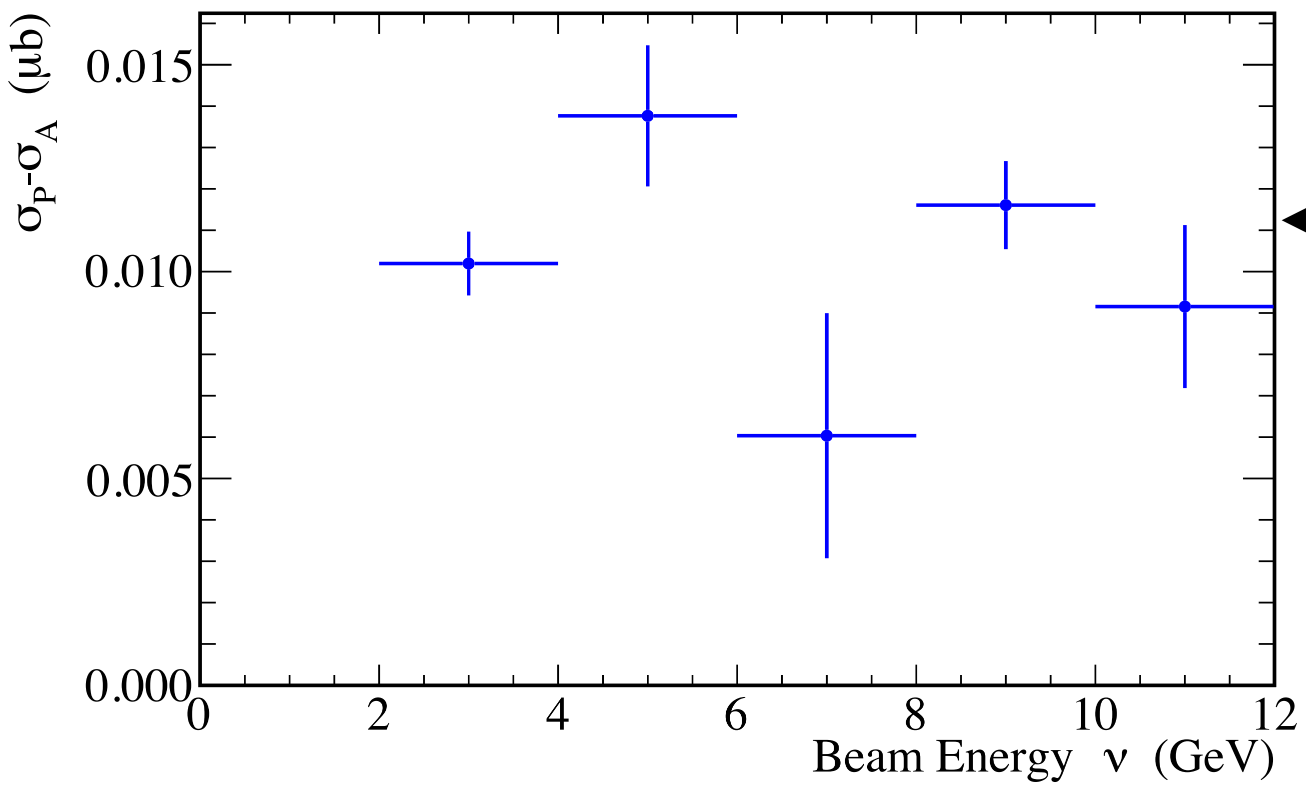
Confirmed by Kapton data (empty target run, with Kapton thickness scaled to 10cm yields ~50 kHz)

Rates and backgrounds

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

Bethe-Heitler Cross-Sections difference

HD GEANT simulation:



Compare 0.01 μb (BH) 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: 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.
  - 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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This wil

- First m
- Obtaining c

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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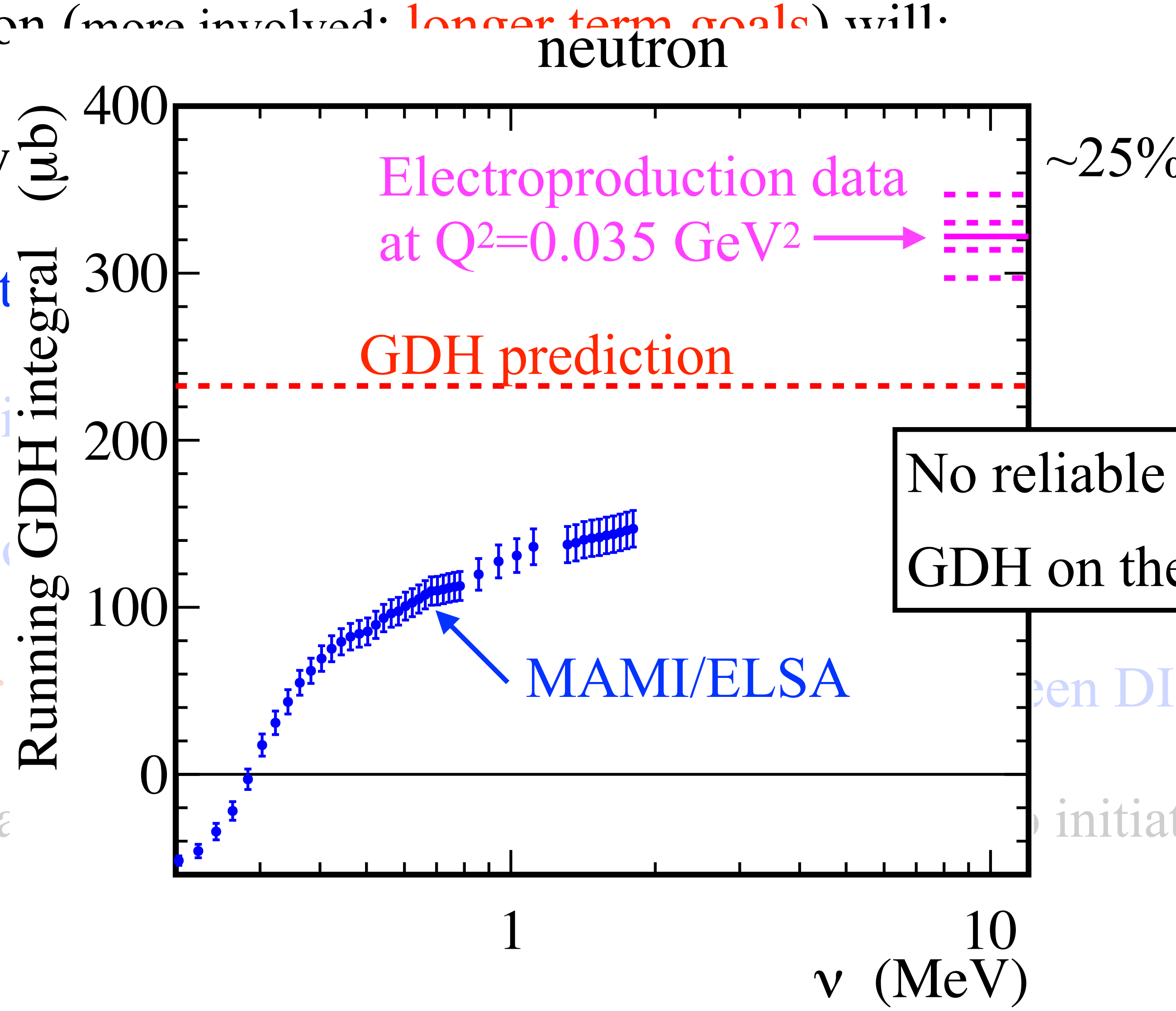

No reliable check available yet for GDH on the neutron.

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

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.
- 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 $\sigma^{3/2}$-$\sigma^{1/2}$ 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.

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

Back-up slides

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 ($Q^2 < 0.02$ 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+2.5° $\Rightarrow Q^2 = 1$ GeV^2.
- Even if all pro/con were balancing, Hall B is more subscribed than Hall D: sensible to do a Hall D experiment.

CON:

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

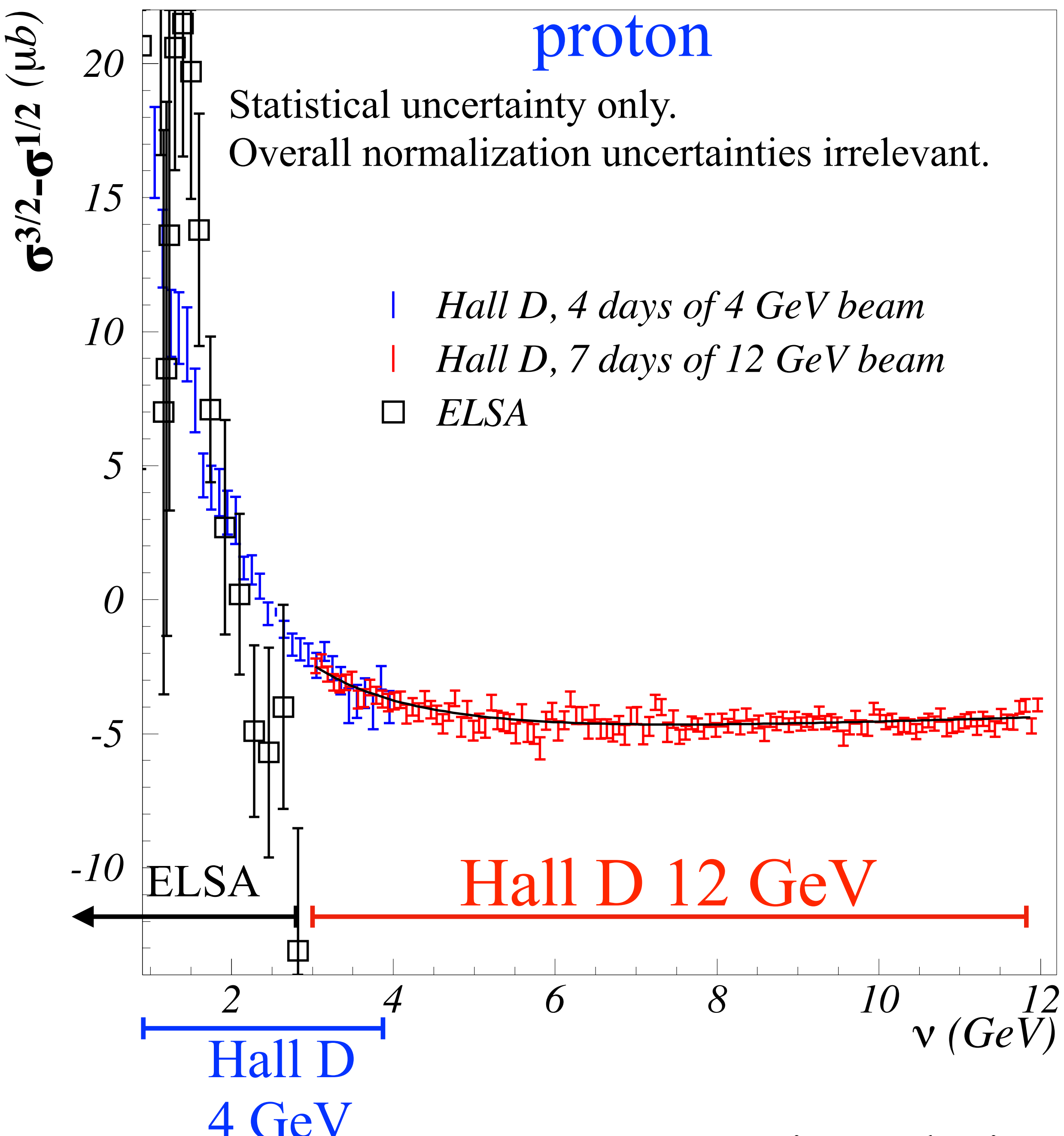
Possible mechanisms that could invalidate the GDH rum rule

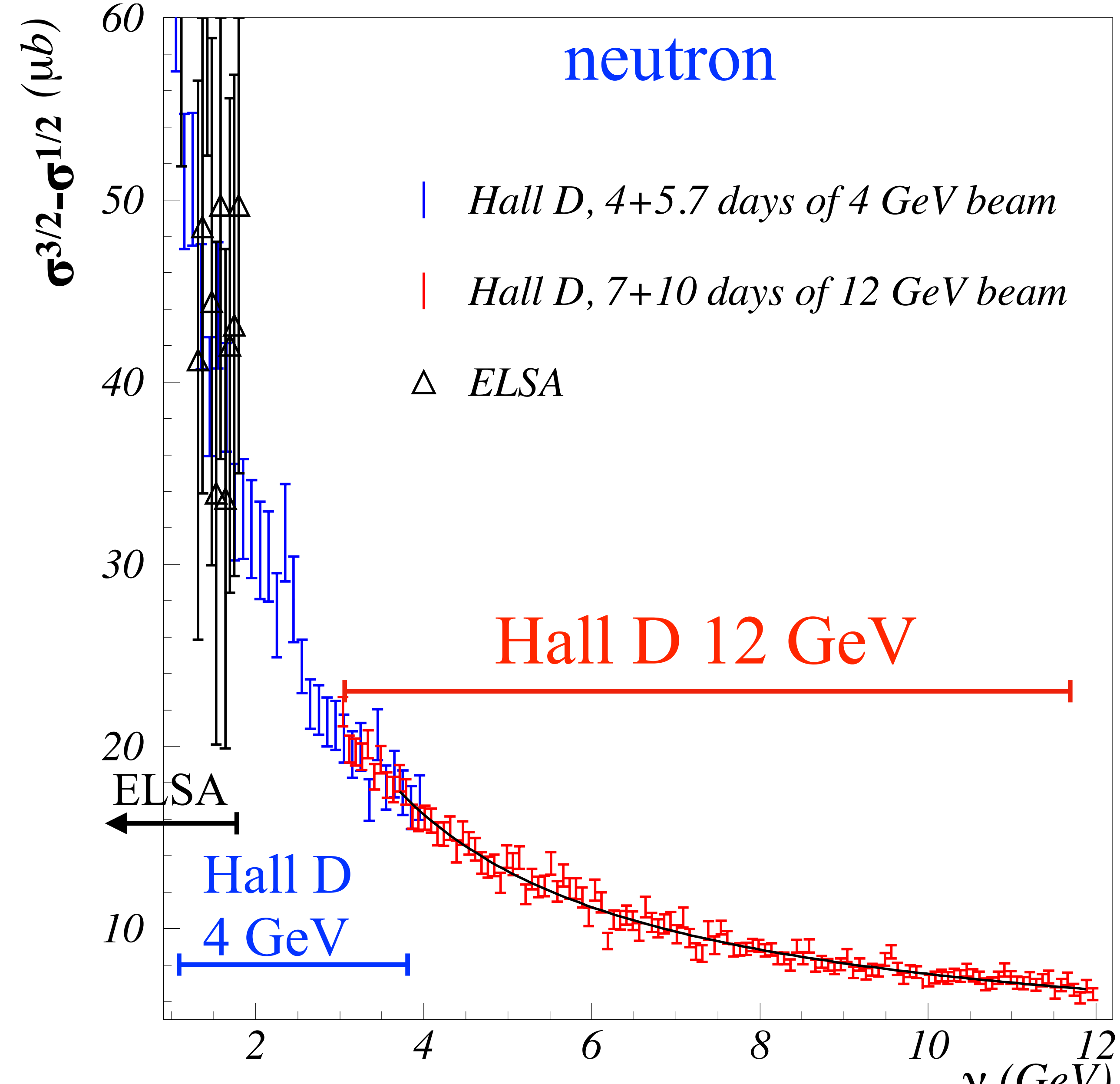
- GDH: Fundamental QFT prediction.
- for GDH on hadron: QCD determines convergence of integral and sum rule validity.
  - Possible violation mechanisms:
    - A J=1 pole of the nucleon Compton amplitude;
    - Chiral anomaly;
    - Quark substructure (non-zero quark anomalous moment);
    - Other, more exotic possibilities, have been proposed, e.g. local break-down of EM gauge invariance

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: $\sigma^{3/2}\text{-}\sigma^{1/2} = c_2 s^{\alpha_{f_1}-1} \pm c_1 s^{\alpha_{a_1}-1}$ (+ 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

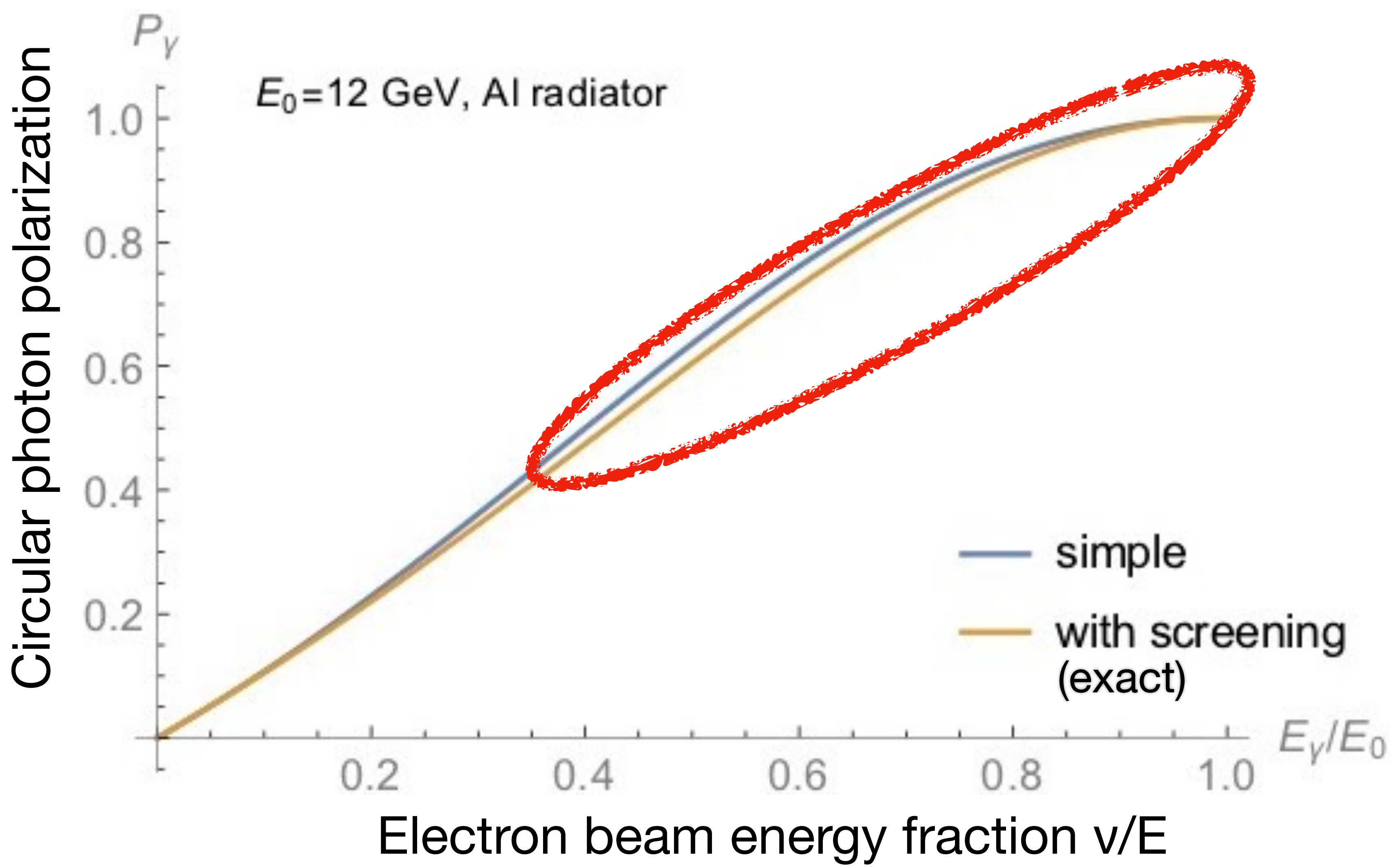




Isospin analysis $\Rightarrow$ $\boxed{\Delta\alpha_{a1}=\pm0.007 \ \&\ \Delta\alpha_{f1}=\pm0.029}$

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: $(N^{3/2}+N^0) - (N^{1/2}+N^0) = N^{3/2} - N^{1/2}$

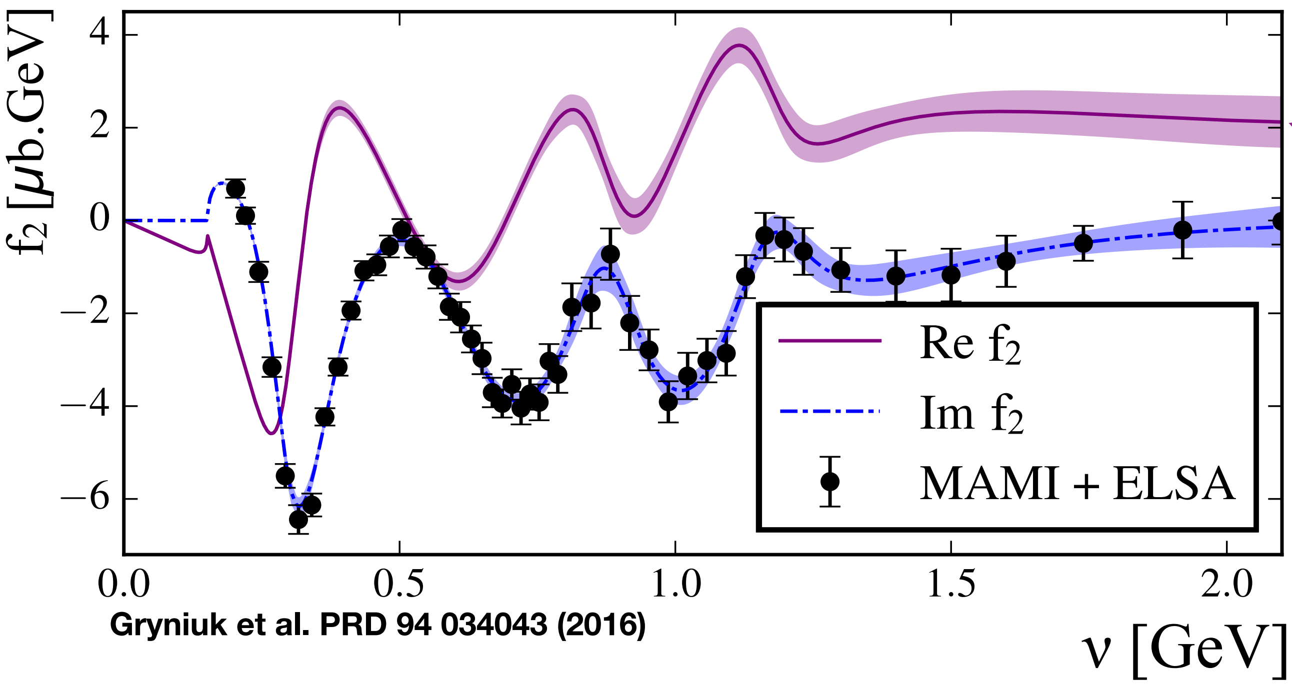
  $\Rightarrow$ use FROST

- 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.
- 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. 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.

Extraction of the real and imaginary parts of Compton amplitude f_2



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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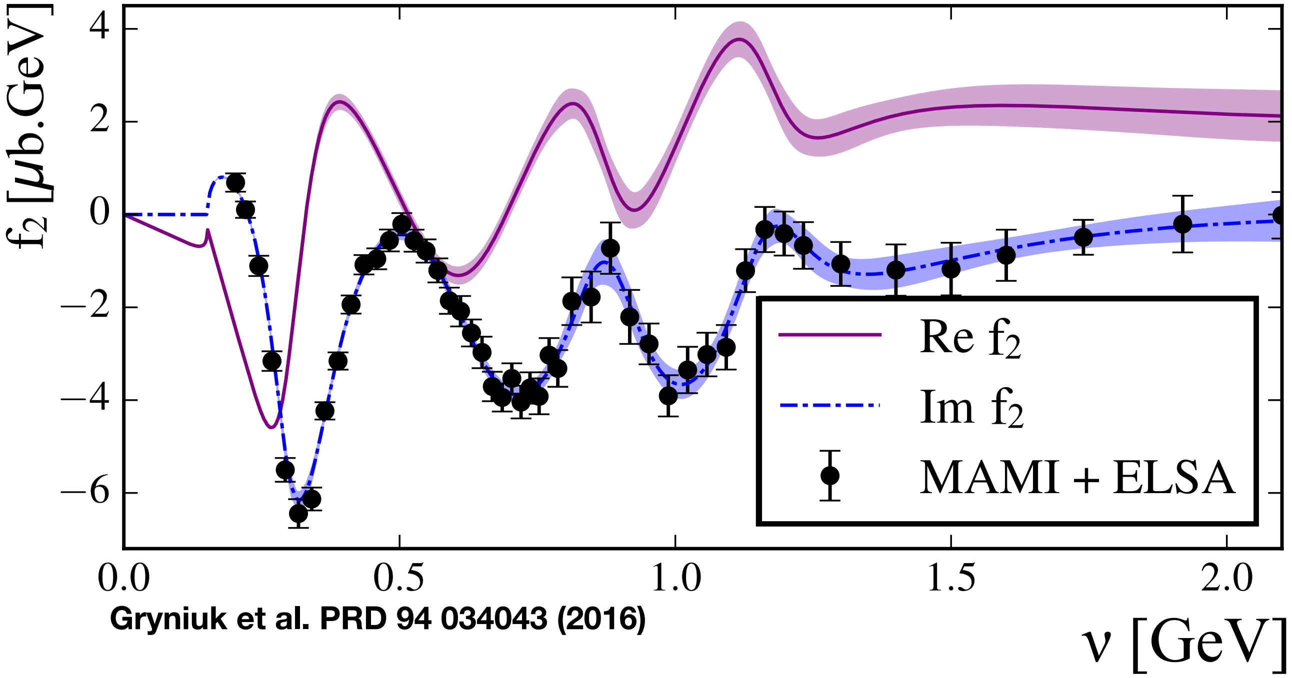
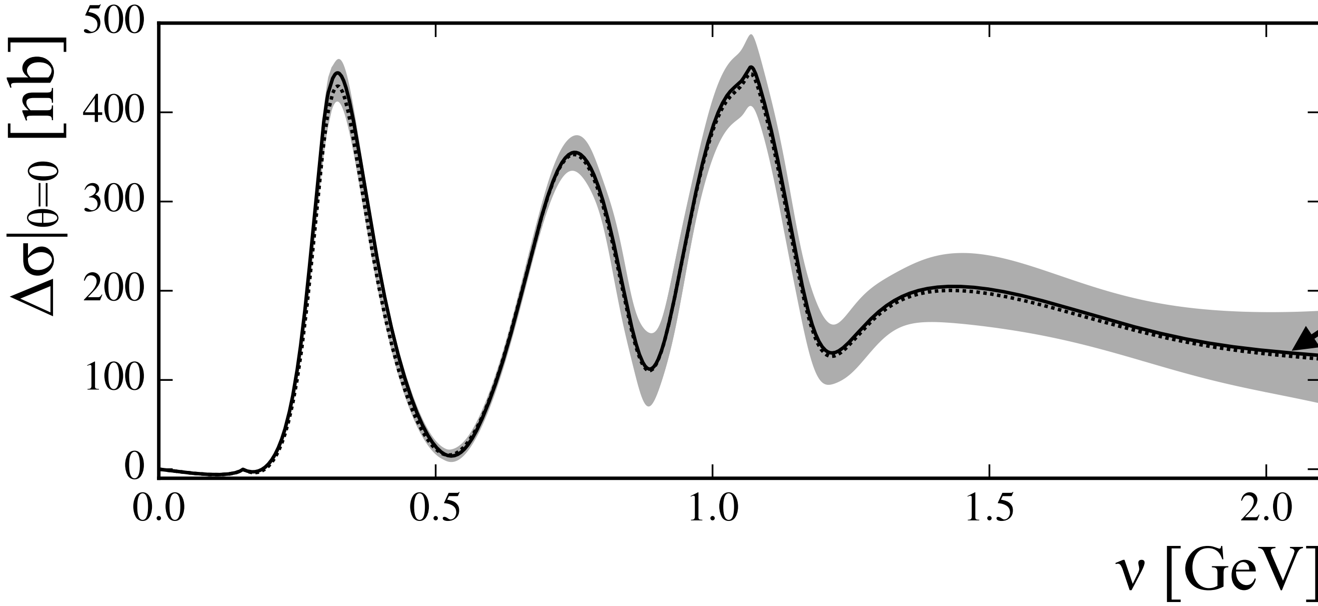


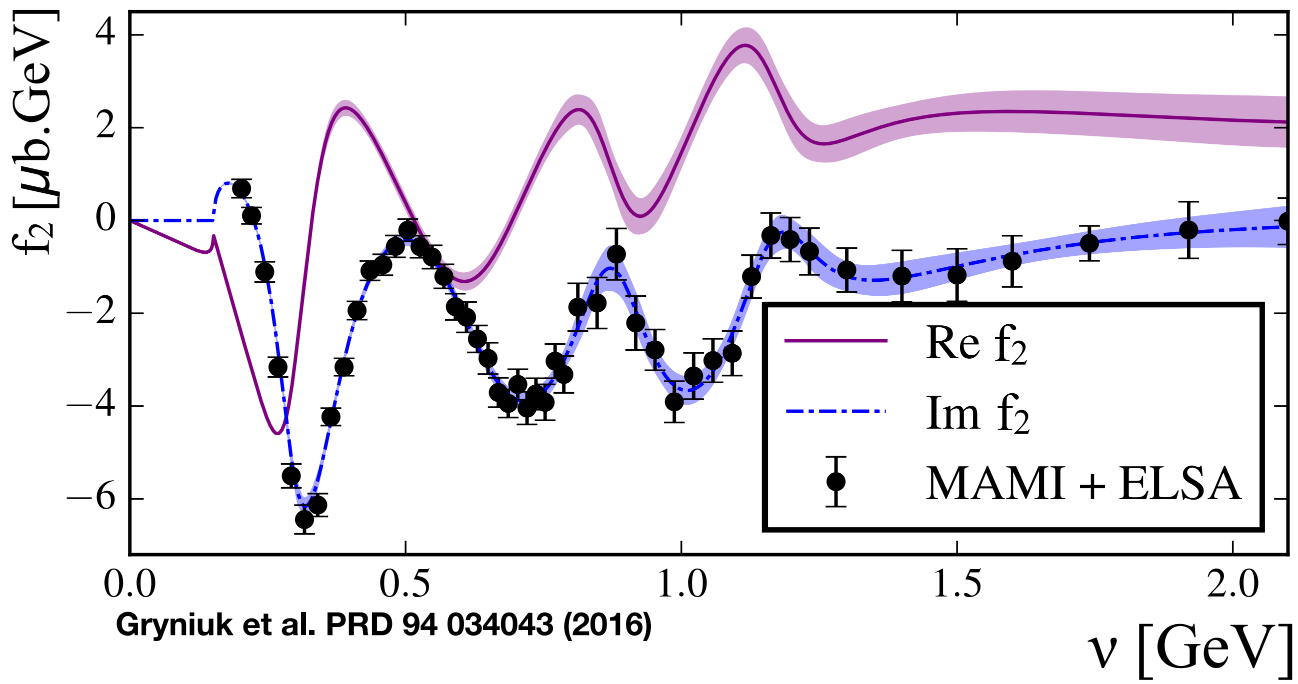
Gryniuk et al. PRD 94 034043 (2016)

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.

Extraction of the real and imaginary parts of Compton amplitude f_2



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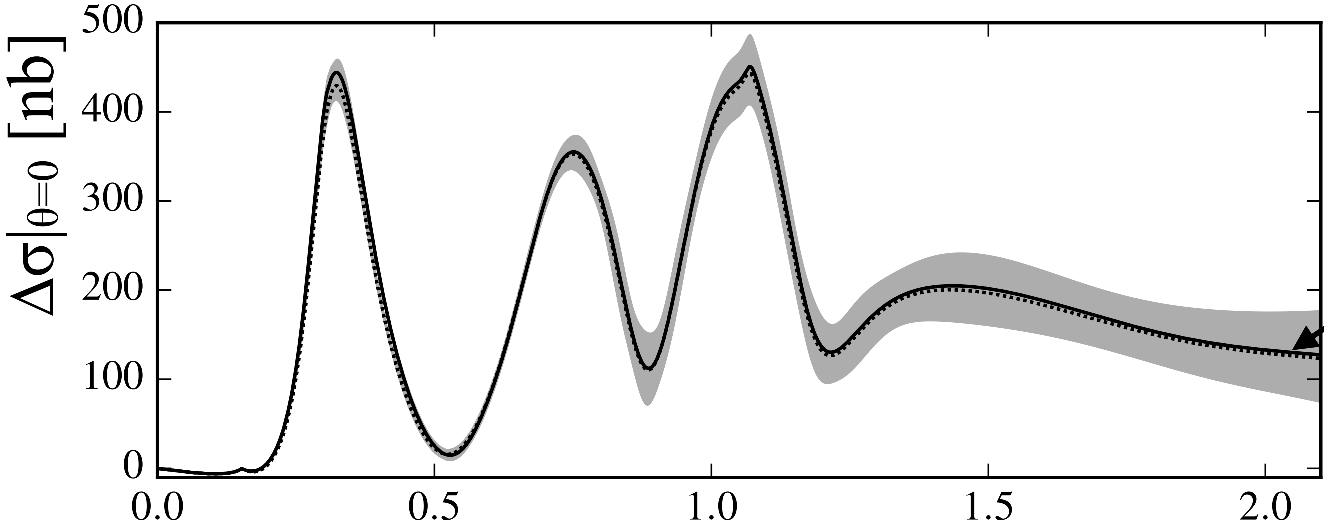
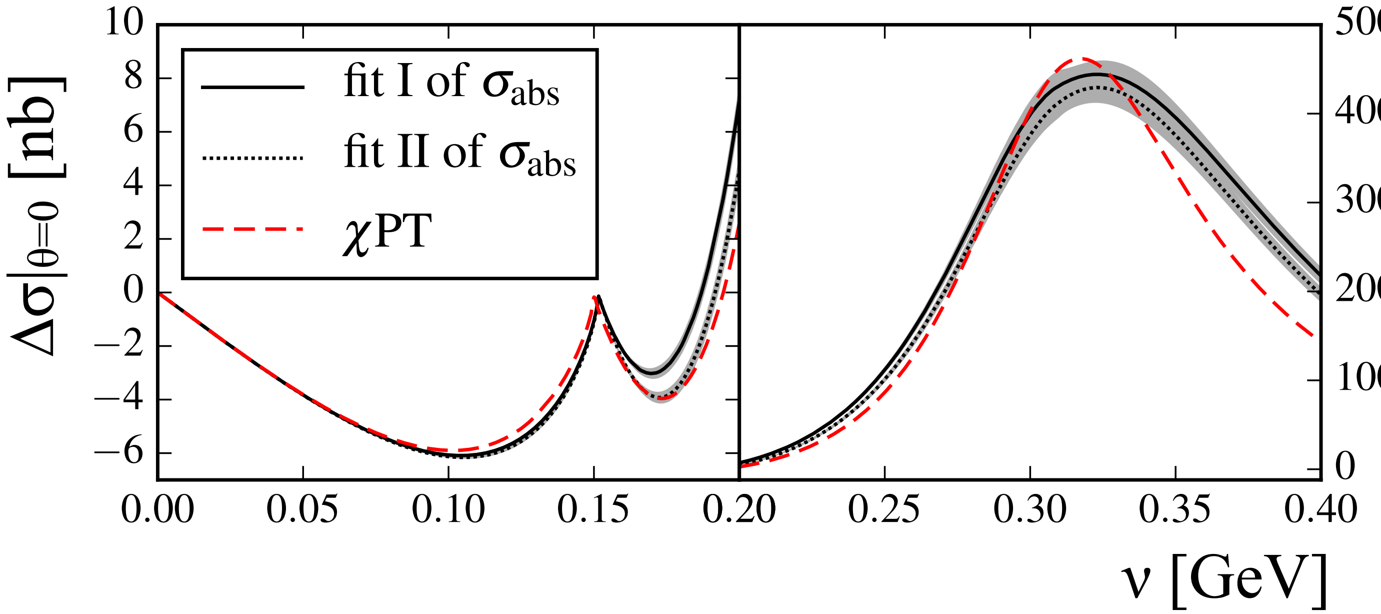
From Re(f_2) and Im(f_2) and the well measured unpolarized f_1, one gets $\sigma^{3/2}$-$\sigma^{1/2} \stackrel{\text{def}}{=} \Delta\sigma$ in the forward limit.



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.

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