

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**:

$$\int_{v_{\text{thr}}}^{\infty} (\sigma^{3/2} - \sigma^{1/2}) \frac{dv}{v} = \frac{4\alpha S \pi^2 \kappa^2}{M^2}$$

Spin-dependent total photoproduction cross-sections

anomalous magnetic moment

spin

Photon energy

Mass

Validity of sum rule mainly **determined by large v behavior of $\sigma^{3/2} - \sigma^{1/2}$**
 \Rightarrow for nucleon target, **tests QCD/nucleon properties.**

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

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

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

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Photon energy
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Hall D: tagger+large solid angle detector+high flux \Rightarrow **uniquely suited** to perform a large- ν GDH measurement.

Motivations

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- Proton: $\nu > 3$ GeV not measured yet.
- Neutron: $\nu > 1.8$ GeV not measured yet.
- 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 7 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.
 - Constraint on hydrogen hyperfine splitting.

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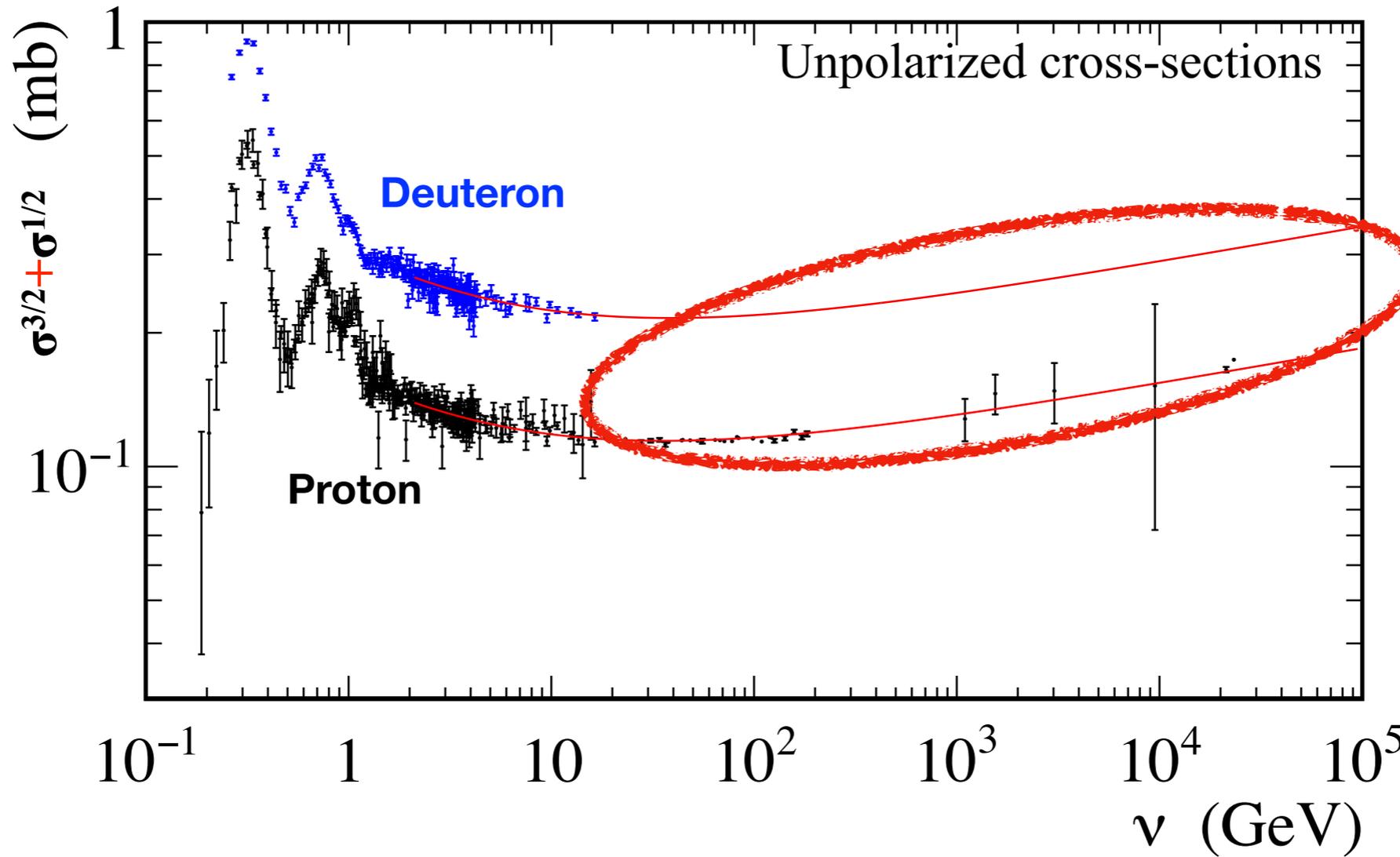
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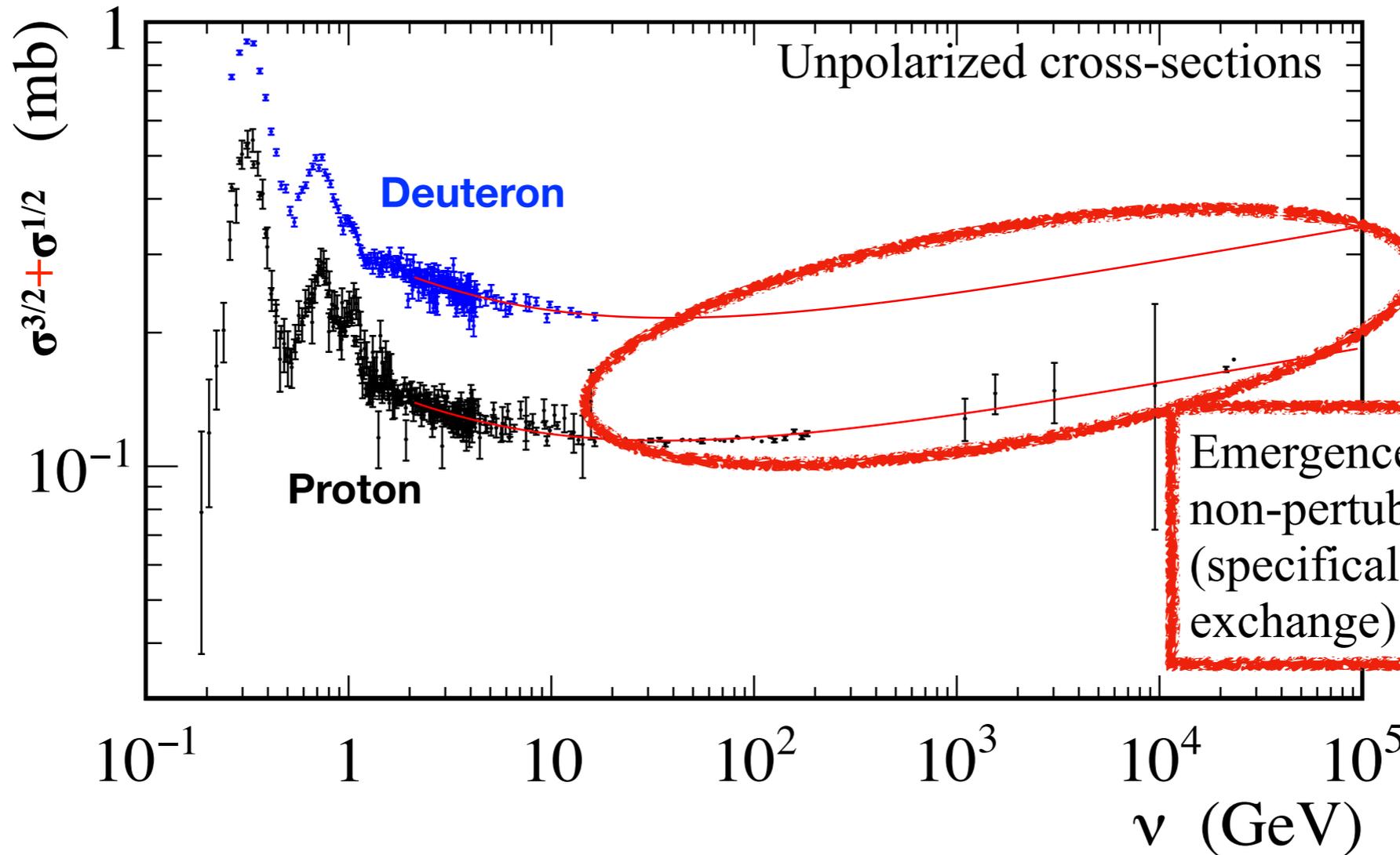
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Emergence of high-energy non-perturbative reactions (specifically here: pomeron exchange).

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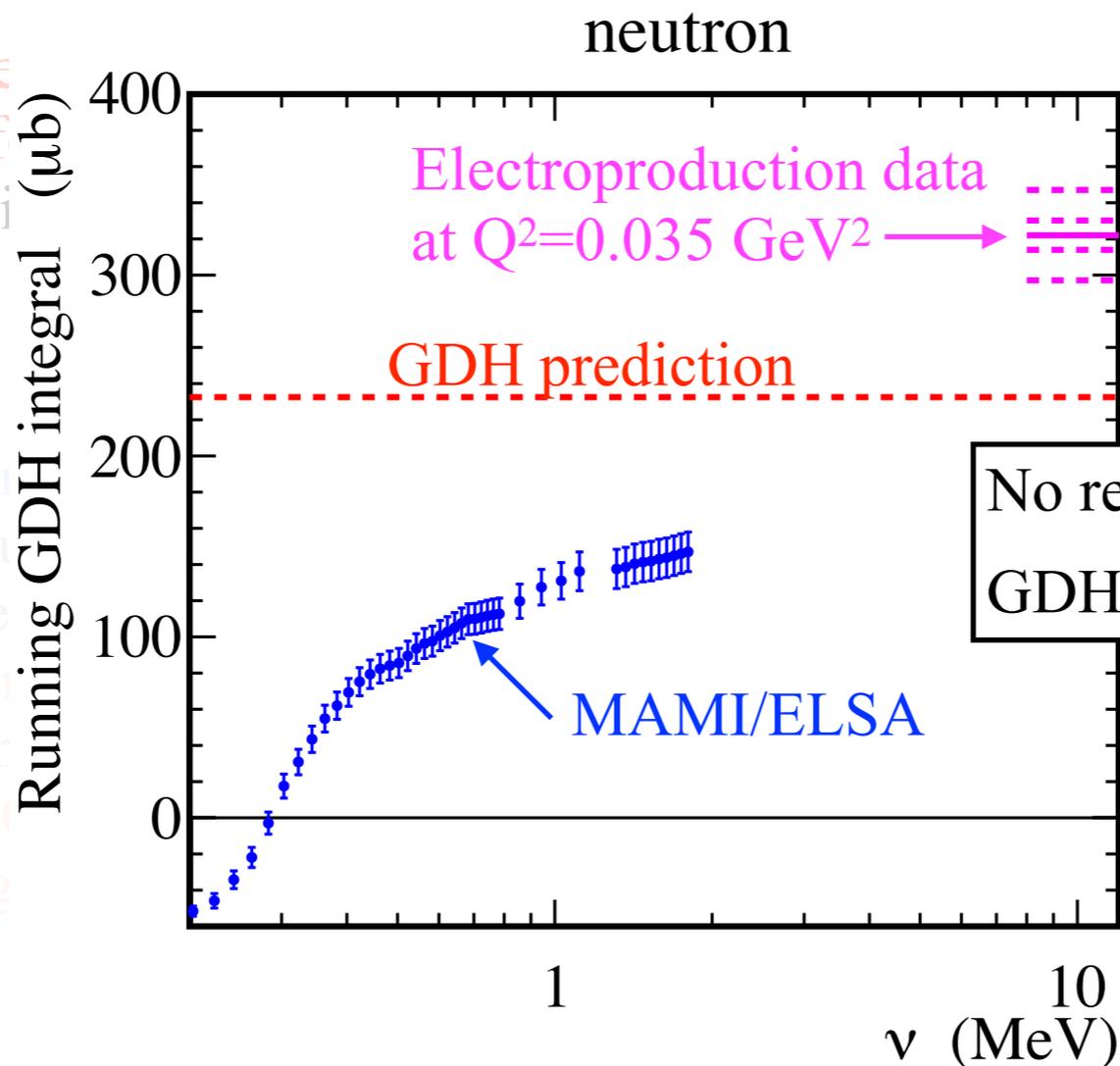
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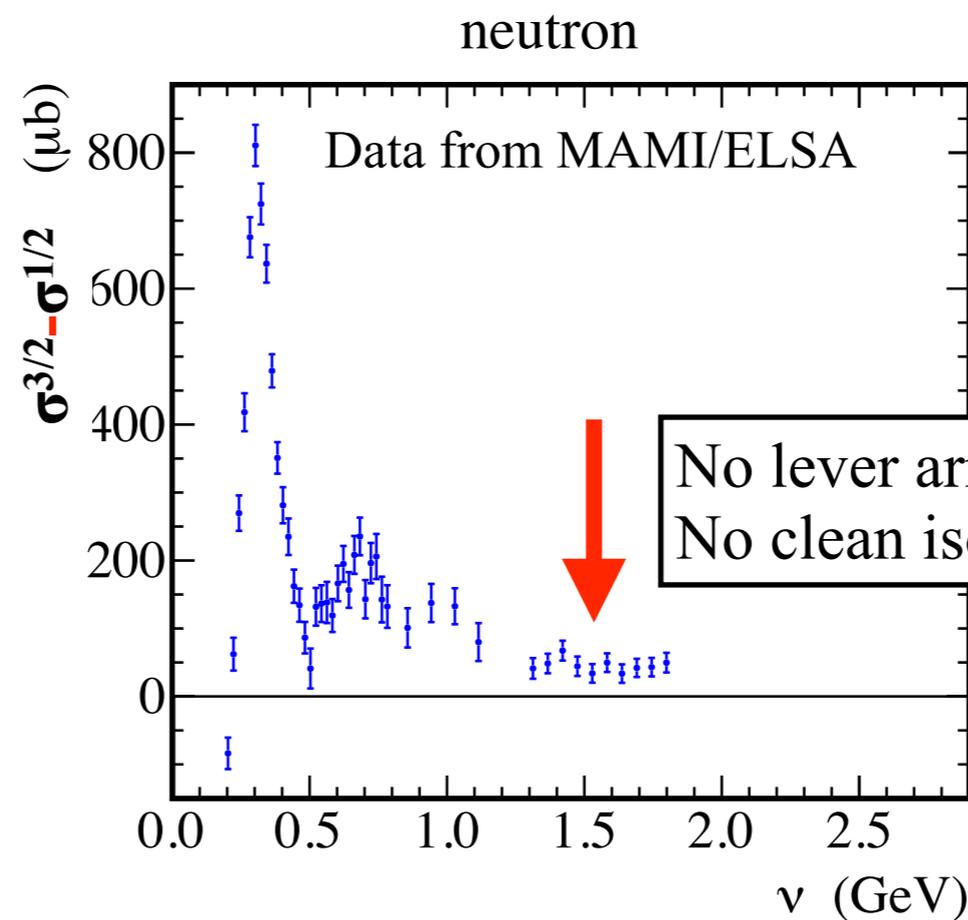
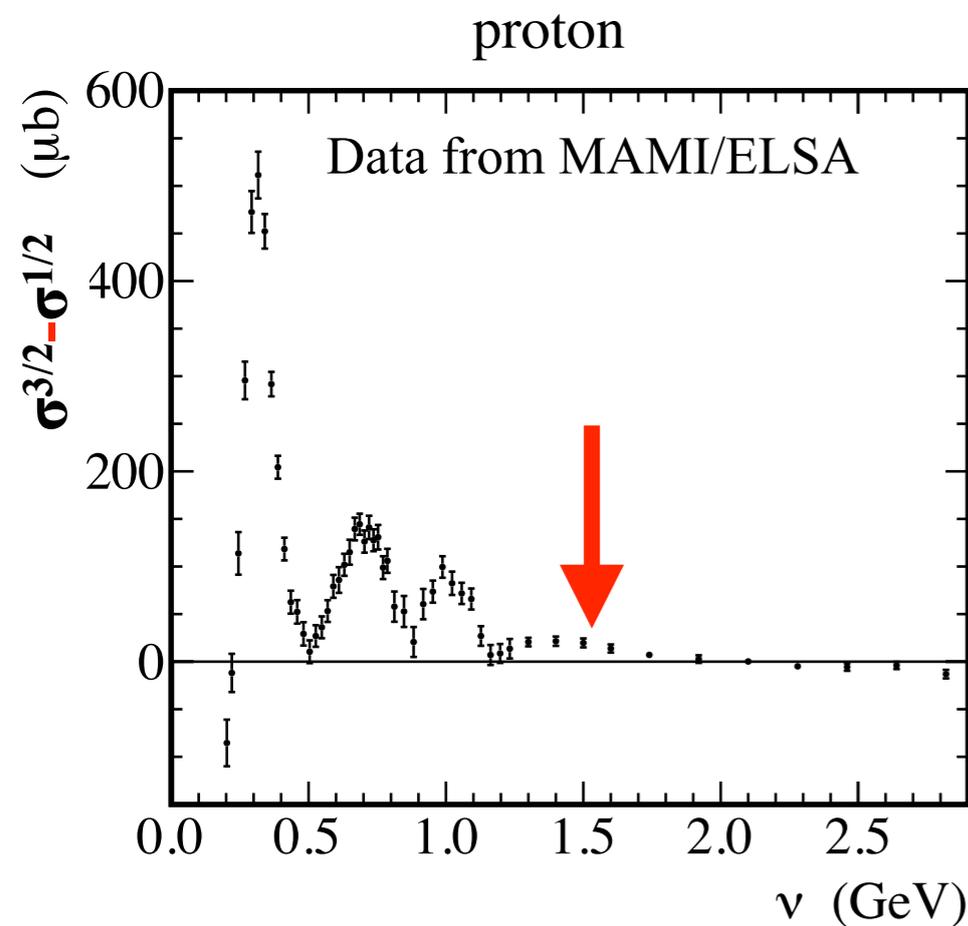
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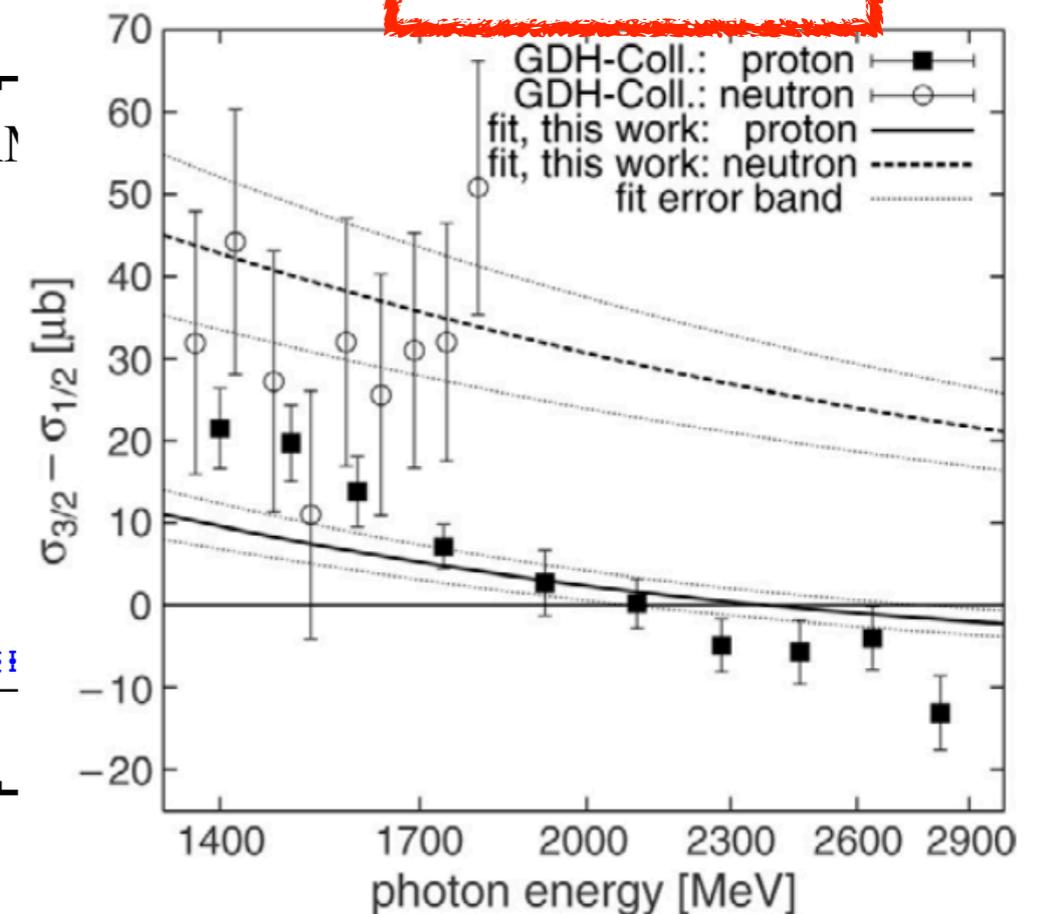
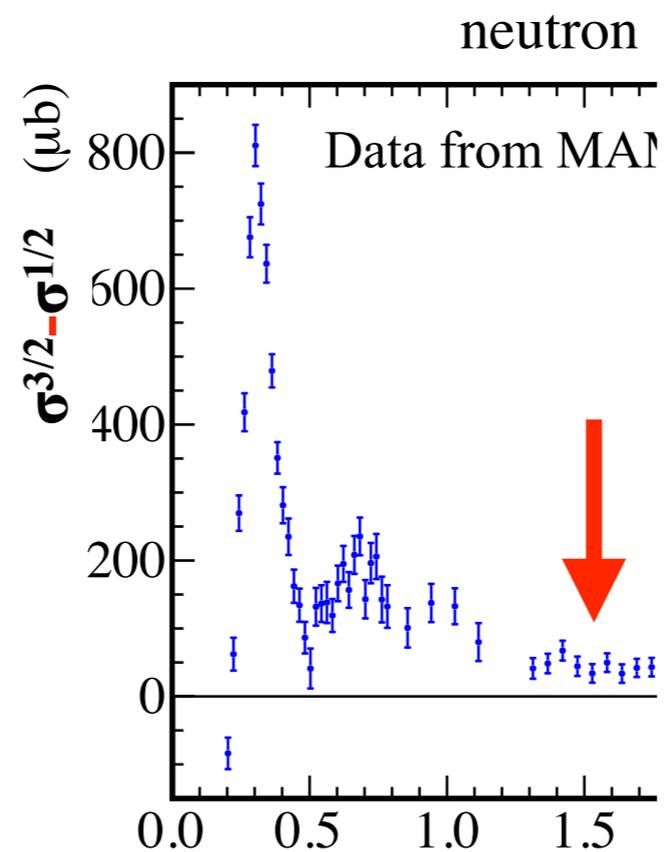
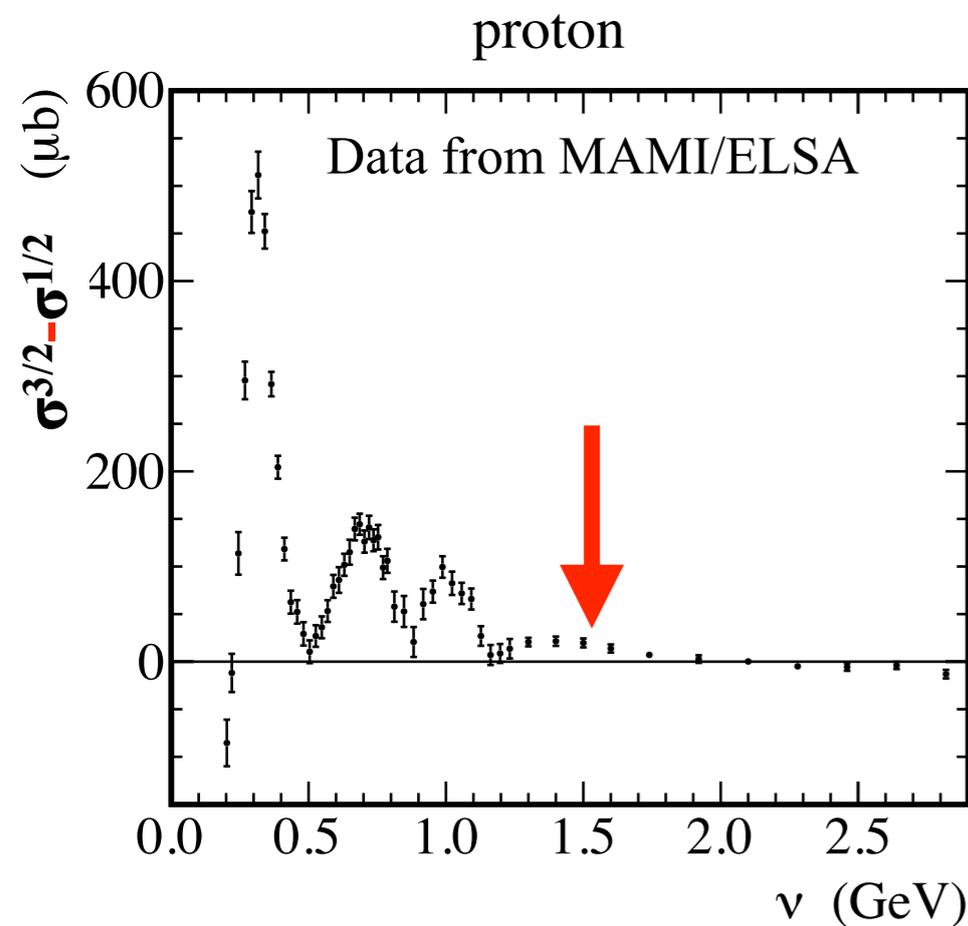
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Poor Regge fits for current world data.



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Experimental Setup

- Need both **proton** and **neutron** (deuteron) targets:
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 - $3 < \nu < 12$ 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;
 - **Longitudinally polarized target**; FROST target. • Amorphous radiator.
 - **Large solid-angle detector**. Hall D
- Experimental configuration and trigger: same as GlueX.
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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	^4He	For background subtraction. Includes target change overhead
1	Deuteron \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	^4He	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

Electron beam
energy:
12 GeV

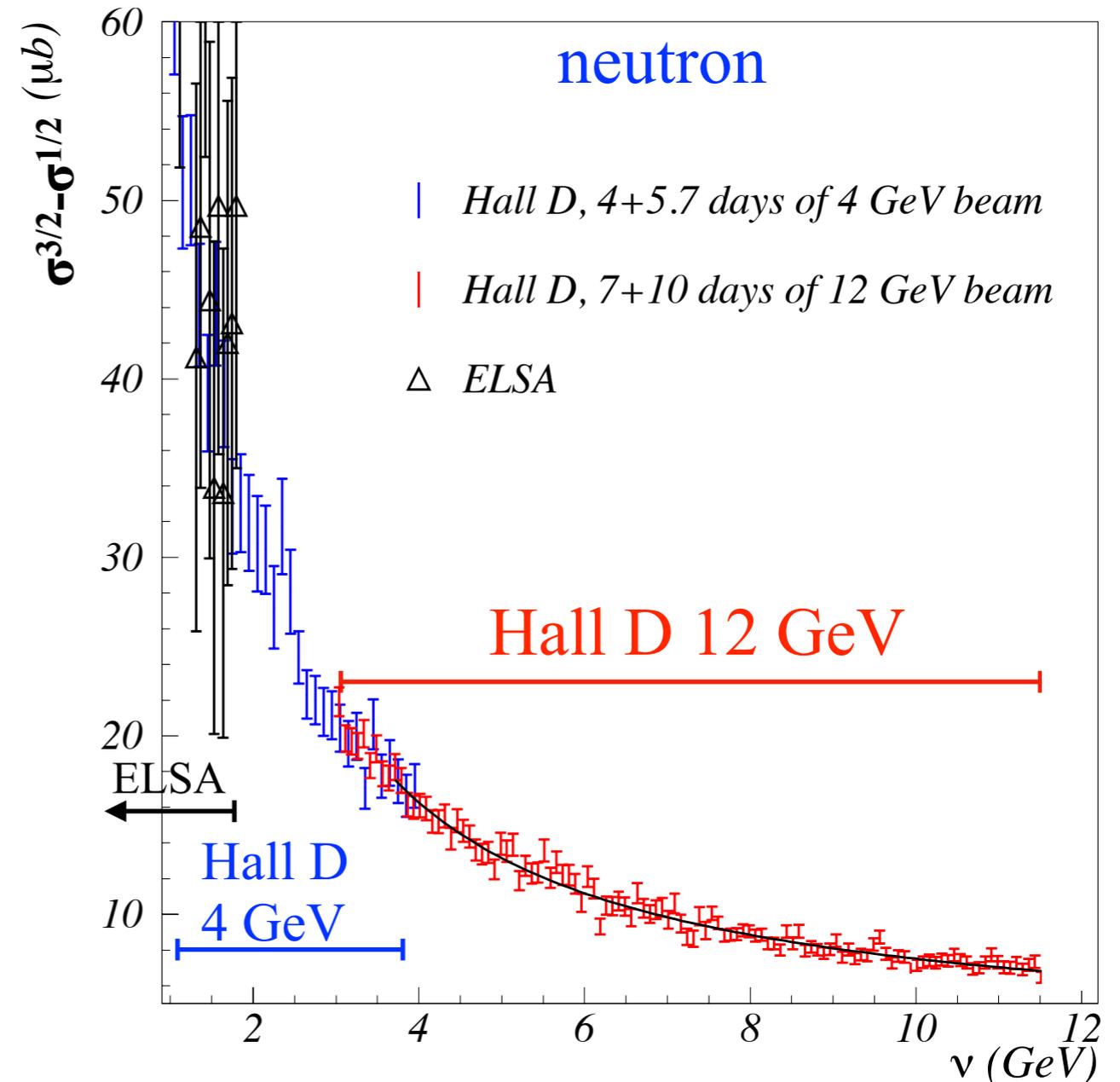
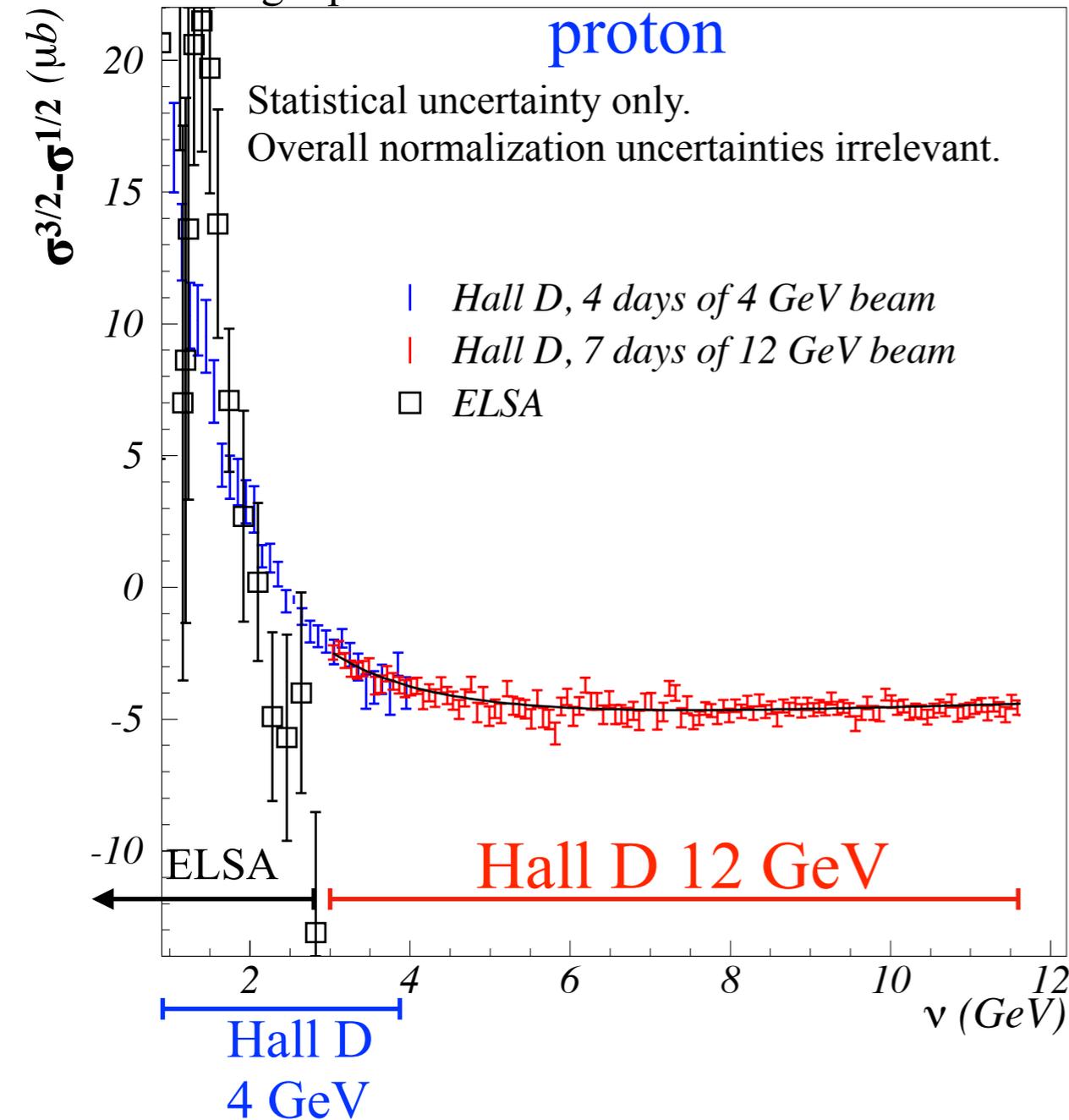
Electron beam
energy:
4 or 5 GeV

Expectations

Simulated data

Assume:

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



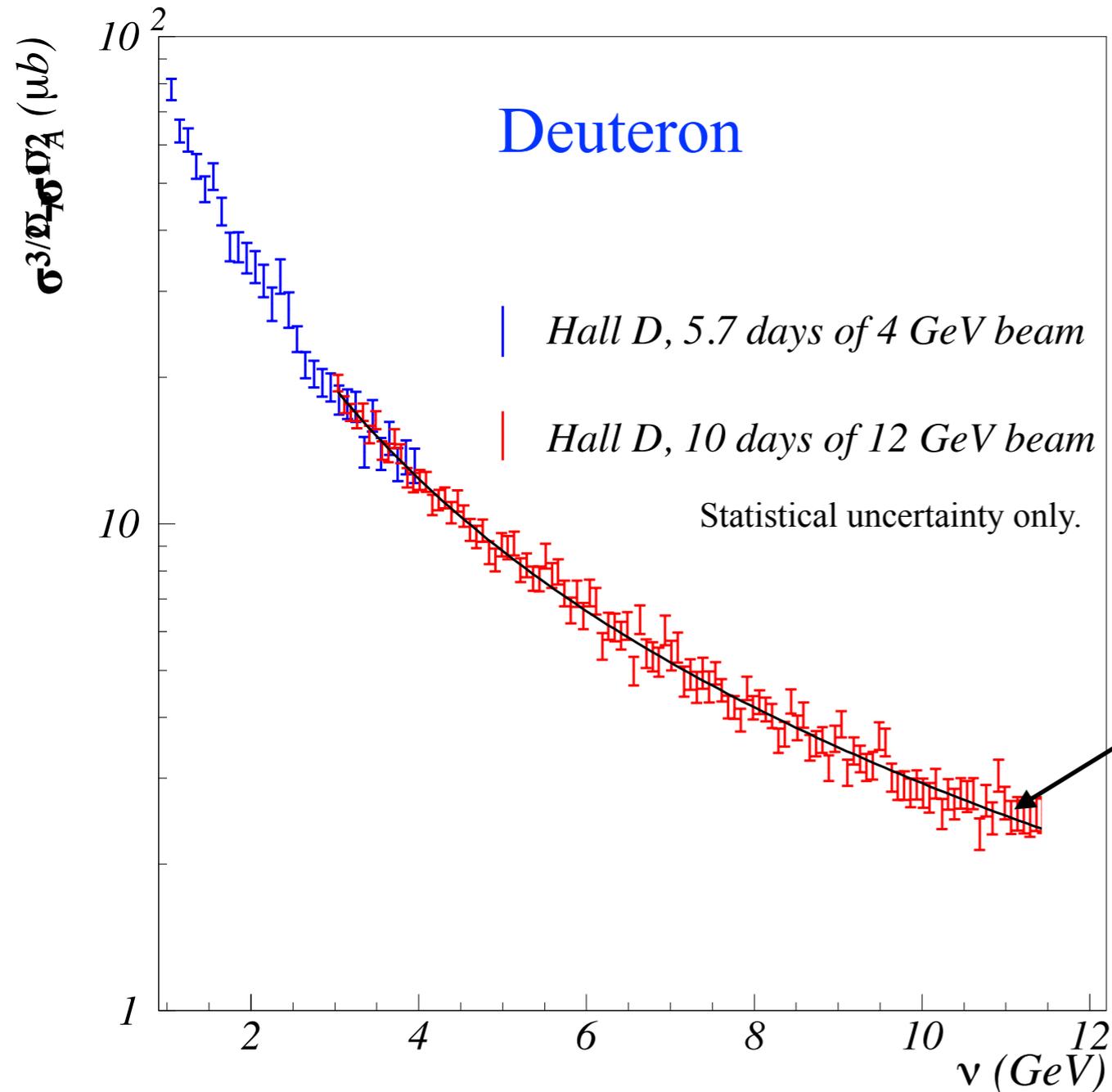
- Statistical accuracy greatly improve compared to previous experiments.
- Much extended energy reach.
- low energy data: overlap with word data. Bridge gap for neutron data.

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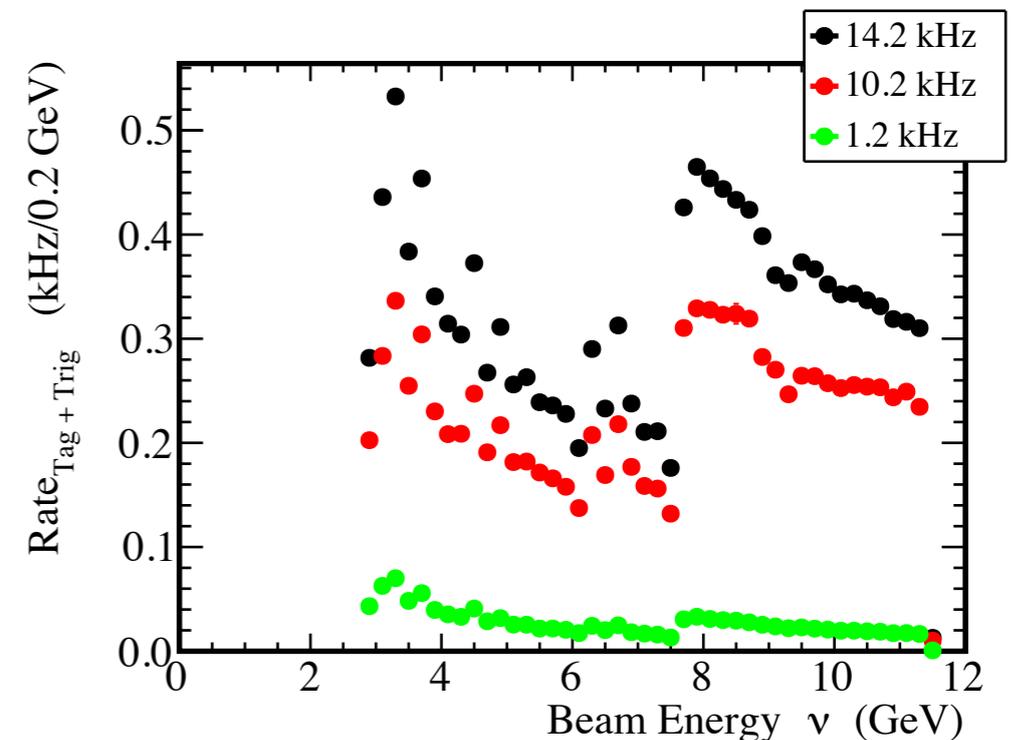
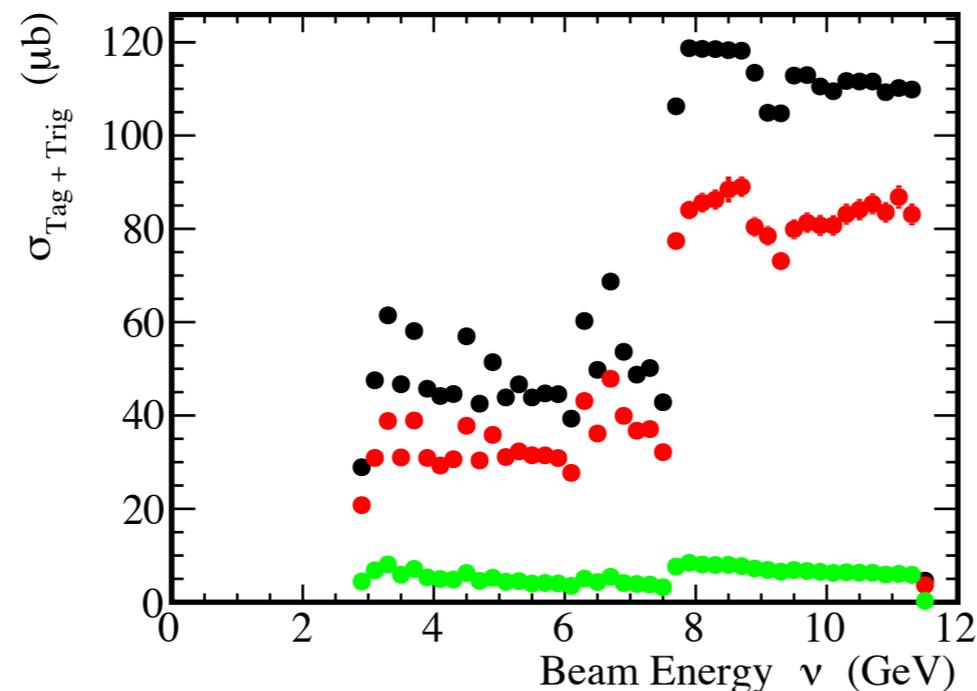
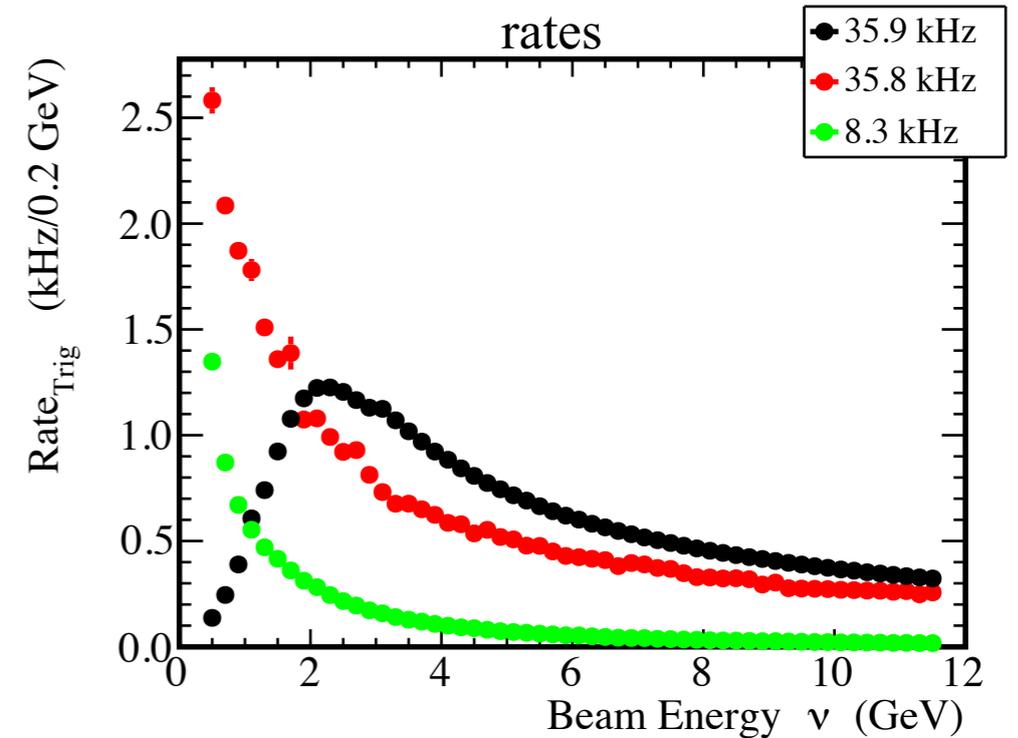
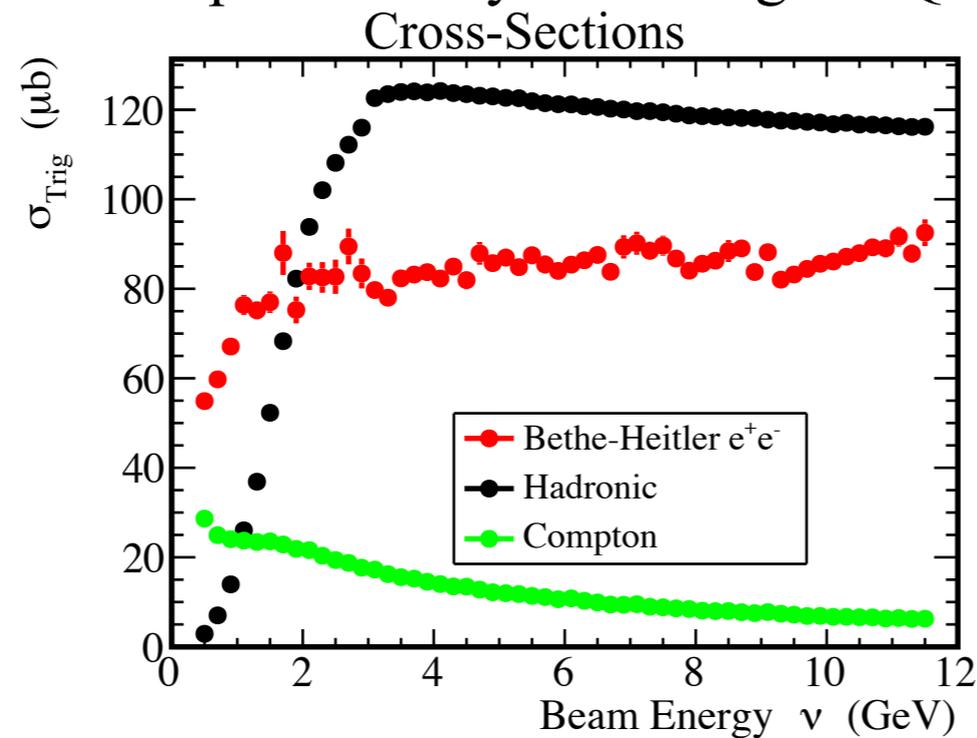
Should measure well the first non-zero deuteron signal at large ν .

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

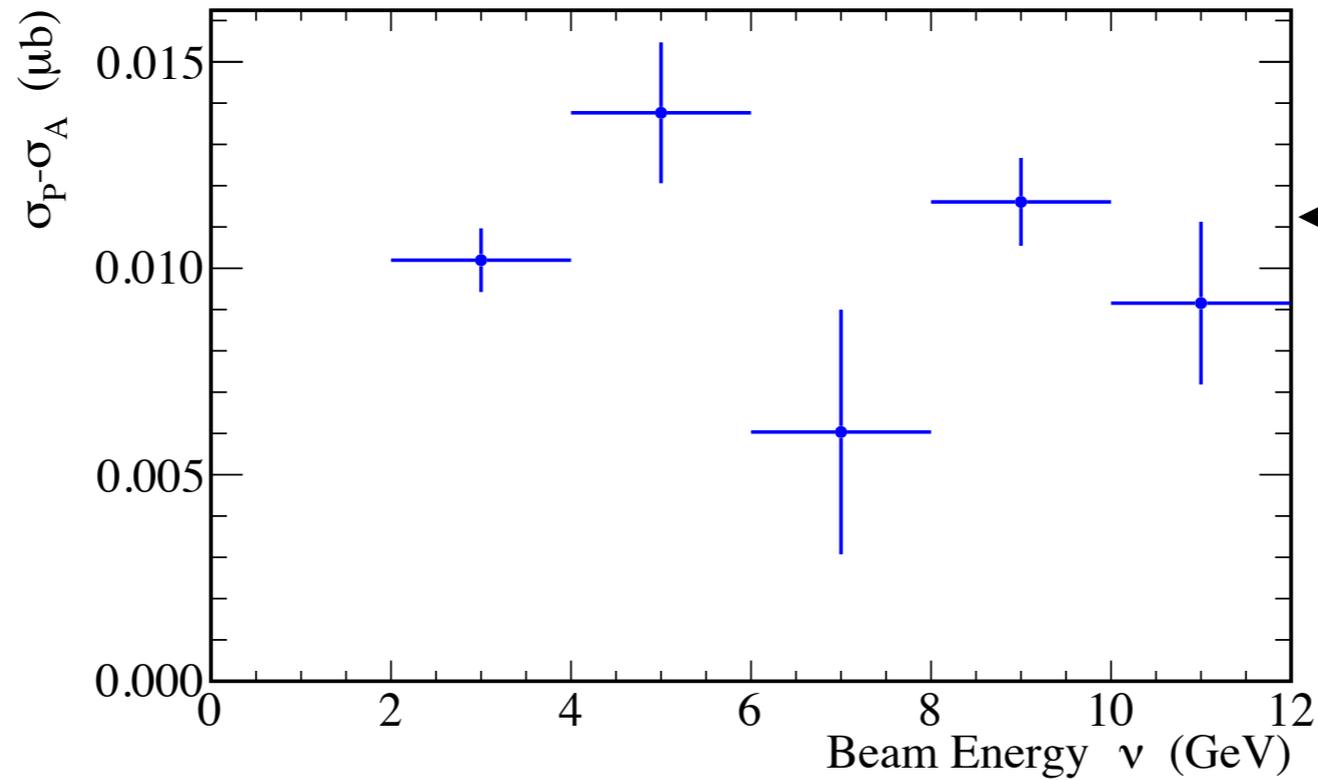
Confirmed with GlueX data (Kapton data from empty target run. Kapton thickness scaled to 10 cm yields ~ 50 kHz)

Rates and backgrounds

Polarized backgrounds: contribute, but very small ($\sim 0.2\%$ contamination).

Bethe-Heitler Cross-Section difference

HD GEANT simulation:



Compare $\sim 0.01 \mu\text{b}$ (B-H)
with $\sim 5 \mu\text{b}$ (hadronic)

No polarized Compton contribution (FROST electrons unpolarized).

Impact

- Measuring high ν -behavior will test the convergence of GDH sum (first step: fast and robust analysis)
 - First measurement well outside resonance region: **first clean test of Regge theory for polarized case.**
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- This will be precise enough to resolve the discrepancy between DIS data and Regge theory.
- First measurement: Regge theory predicts $\alpha_{a1} \cong -0.34$, while
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Thank you

One-slide summary

$$\int_{v_{\text{thr}}}^{\infty} (\sigma^{3/2} - \sigma^{1/2}) \frac{dv}{v} = \frac{2\alpha\pi^2\kappa^2}{M^2}$$

- First measurement of the high- v behavior of GDH integrand $(\sigma^{3/2} - \sigma^{1/2})/v$
- Hall D + FROST target (H and D) + polarized electron beam on a amorphous radiator.
- Hall D is uniquely suited for such measurement.
- High- v is where a failing of the sum rule would be revealed.
- Analysis first step: map yield difference $N^{3/2} - N^{1/2}$ for 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- v for the deuteron.
- Analysis second step (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.
 \implies 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.

$$\int_{v_{\text{thr}}}^{\infty} (\sigma^{3/2} - \sigma^{1/2}) \frac{dv}{v} = \frac{2\alpha\pi^2\kappa^2}{M^2}$$

Back-up slides

The Gerasimov-Drell-Hearn sum rule

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

Spin-dependent total photoproduction cross-sections
Photon energy
anomalous magnetic moment
spin
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.**

Possible mechanisms that could invalidate the GDH sum 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:

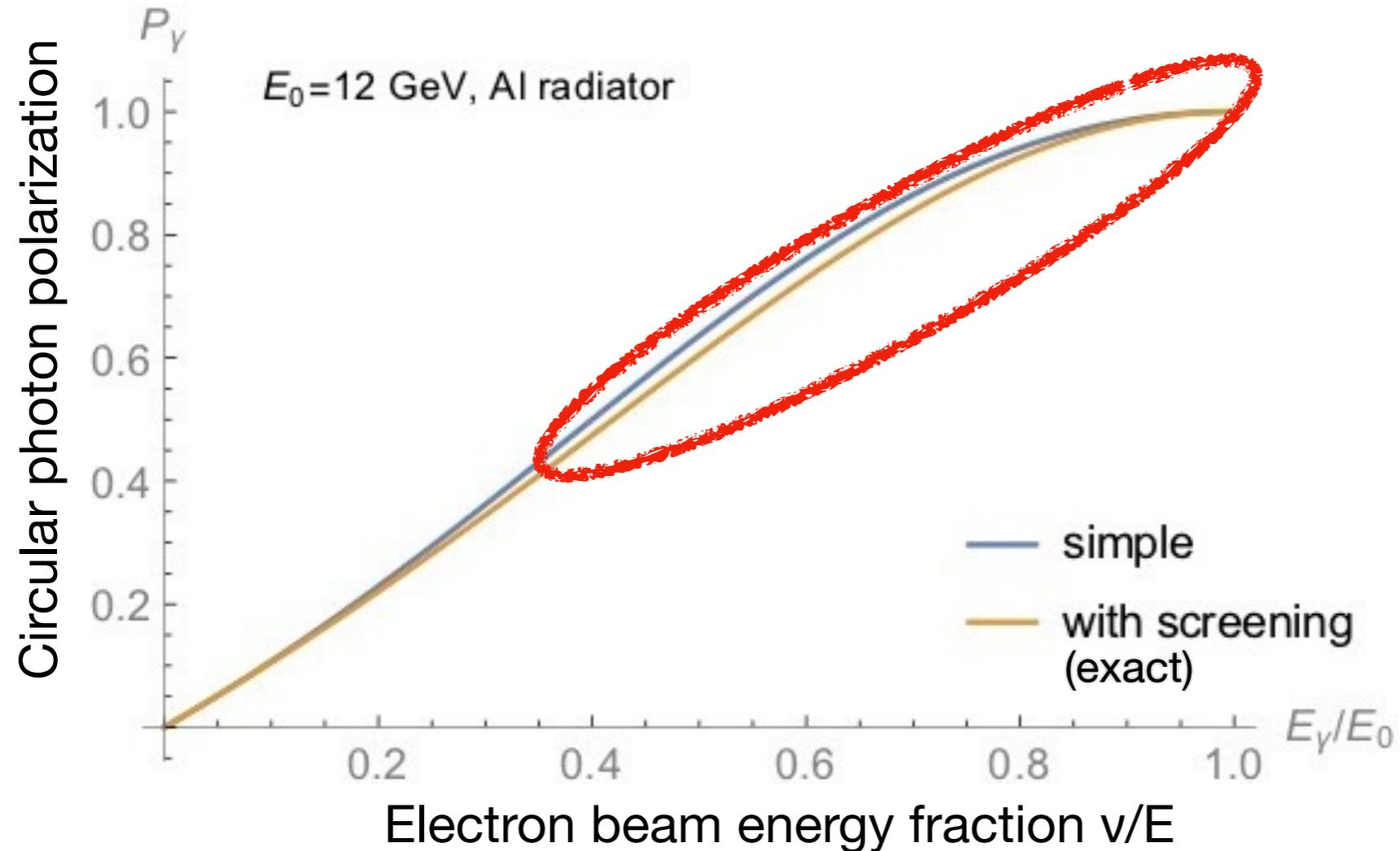
- **Hall D: only Hall with photon tagging** capability,
- A GDH measurement via **electroproduction is not adapted to its study at large ν :**
 - Would need to be done at low enough Q^2 ($< 0.02 \text{ GeV}^2$) to reliably extrapolate to $Q^2 = 0$.
 - At 11 GeV, low enough $Q^2 \Rightarrow$ scattering **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 $2.5^\circ \Rightarrow Q^2 = 1 \text{ GeV}^2$.

CON:

Hall D does not have a polarized target. However, its **cost is moderate ($\sim \$600\text{K}$)** 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

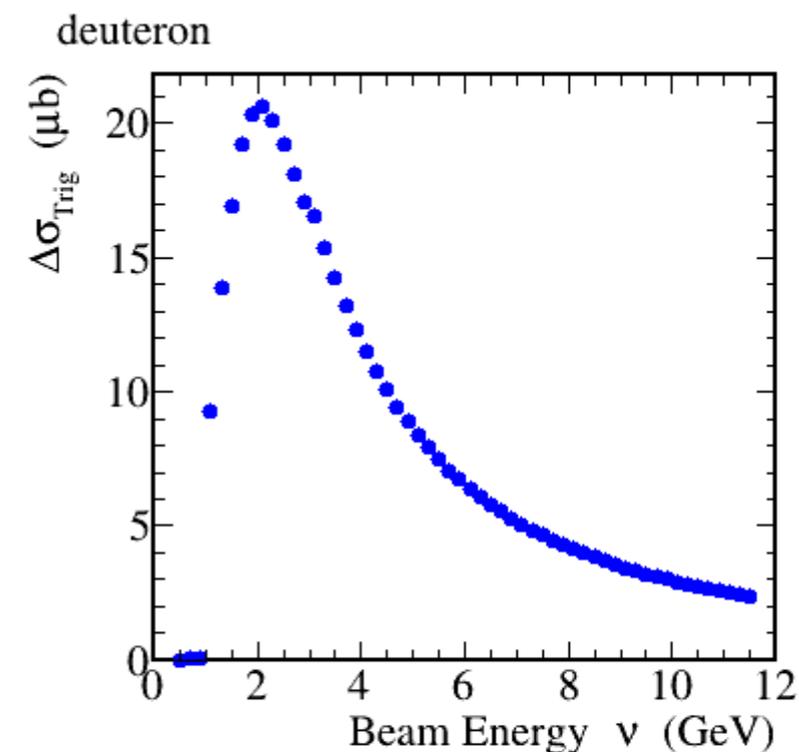
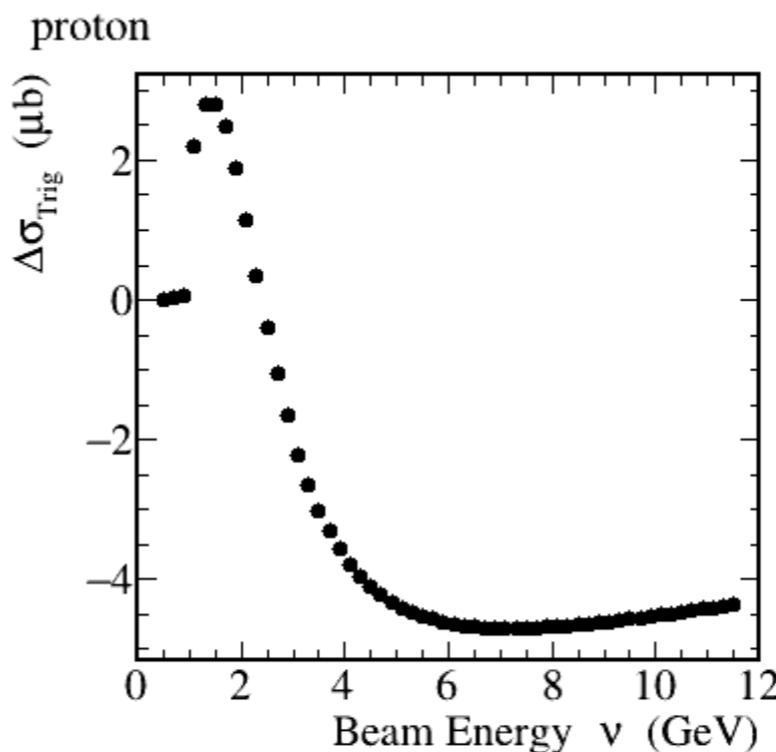
Absolute value measured using injector Mott polarimeter (and potentially Hall A or C polarimeters.)

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.)

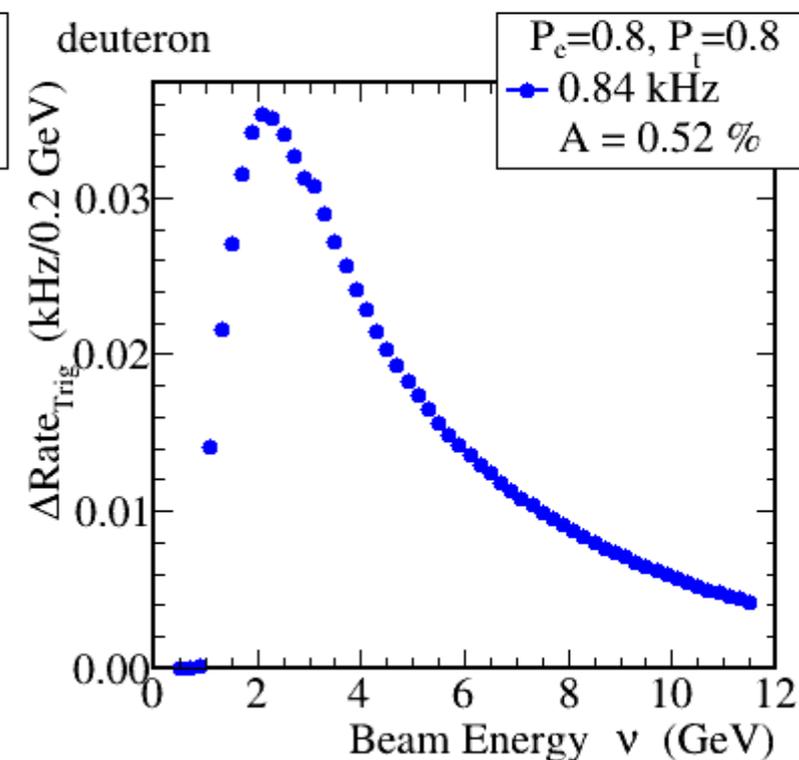
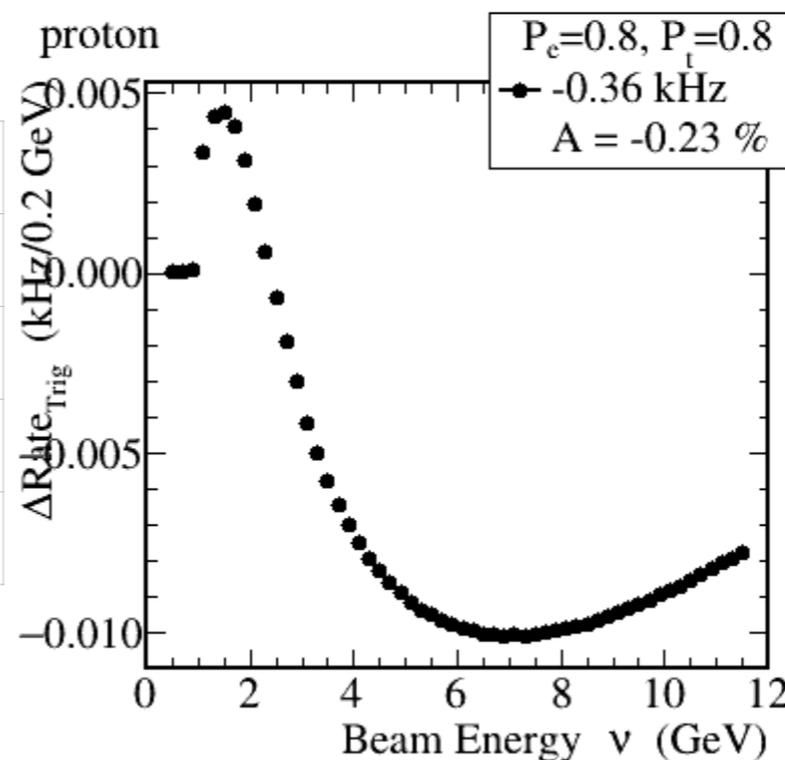
$\frac{\Delta A}{A} = 1.12\%$ in 1 hour at 80 kHz total rate (35 kHz hadronic rate)

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



Polarimetry uncertainties:

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**

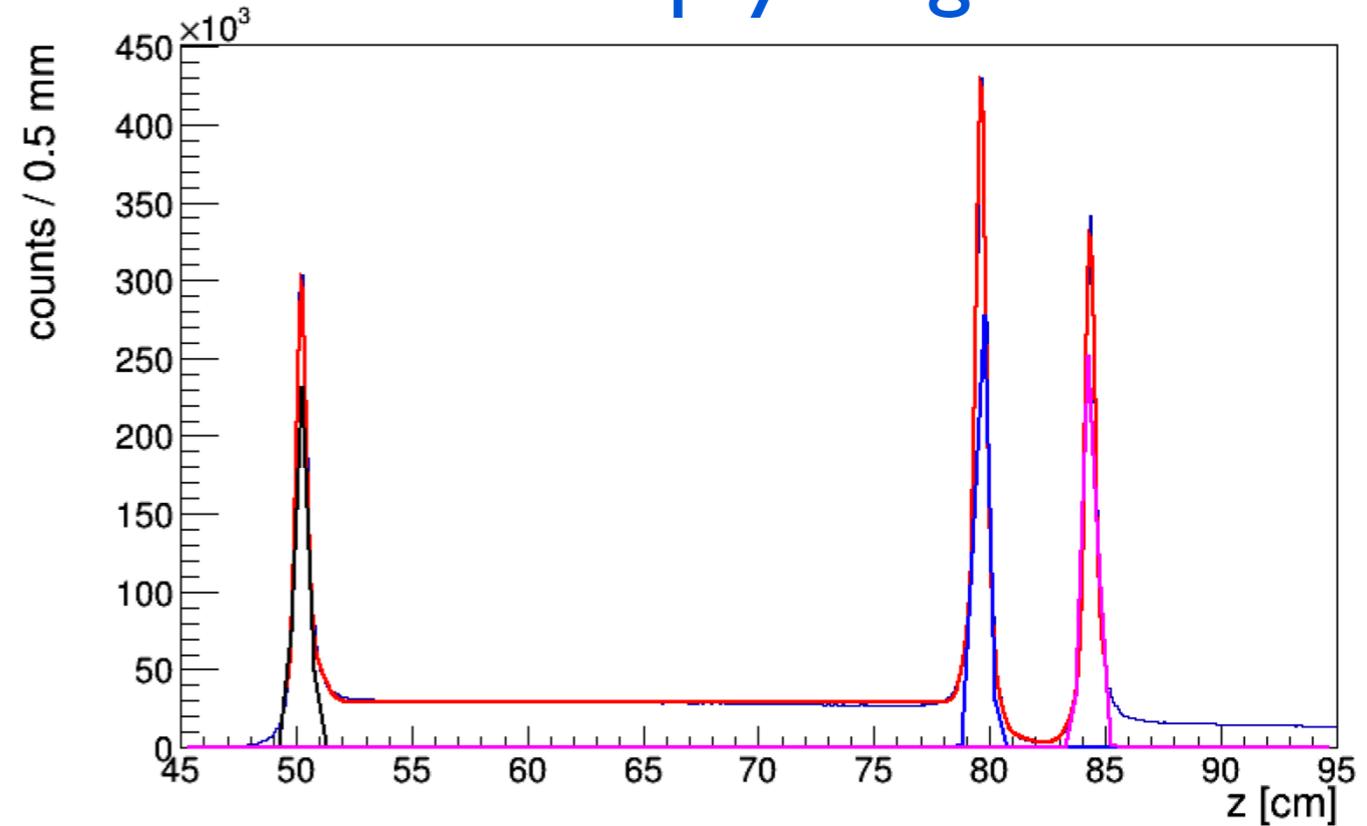
- Target group prefers to build dedicated Hall D FROST target rather than to import Hall B one.
- Two months to install the target. No commissioning needed.
- Cost estimate: ~\$600k

FROST characteristics:

- Dynamical Nuclear Polarization on Butanol (**C₄H₉OH** or **C₄D₉OD**)
- 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 $\sim 10^8$ 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?

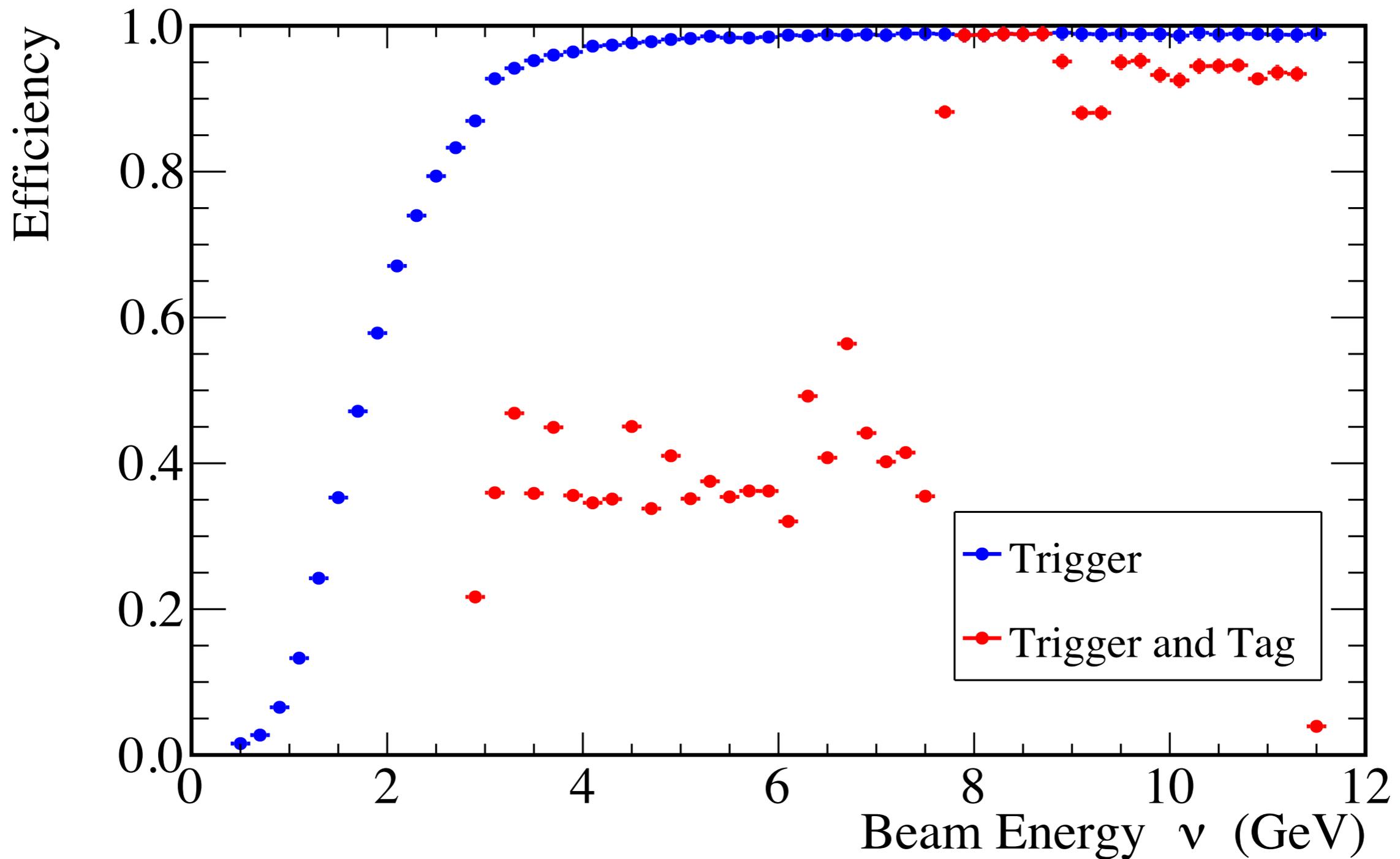


	Position (cm)	Density (g/cm ³)	Length (cm)	Area density (g/cm ²)	2-track yield
LH ₂ gas	50-79.5	0.0015	29.5	0.04425	8.58x10 ⁶
Kapton 1	50	1.42	75x10 ⁻⁴	0.011	1.79x10 ⁶
Kapton 2	79.5	1.42	75x10 ⁻⁴	0.011	2.19x10 ⁶
Aluminum	84.5	2.7	25x10 ⁻⁴	0.007	1.96x10 ⁶

Empty target run rate: 7 kHz.

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

Trigger and tagging efficiencies



Trigger efficiency $\sim 100\% \Rightarrow$ little uncertainty.

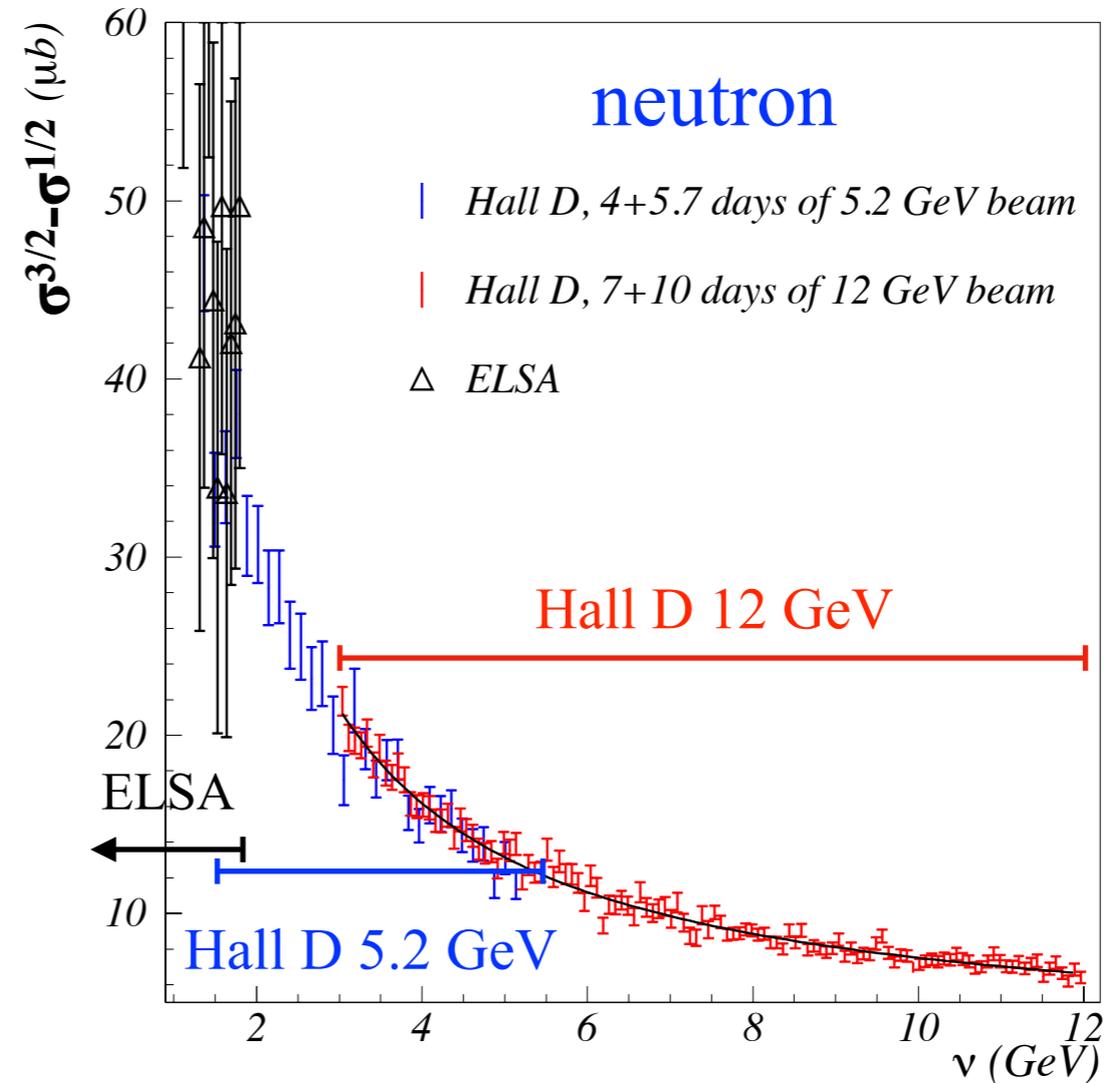
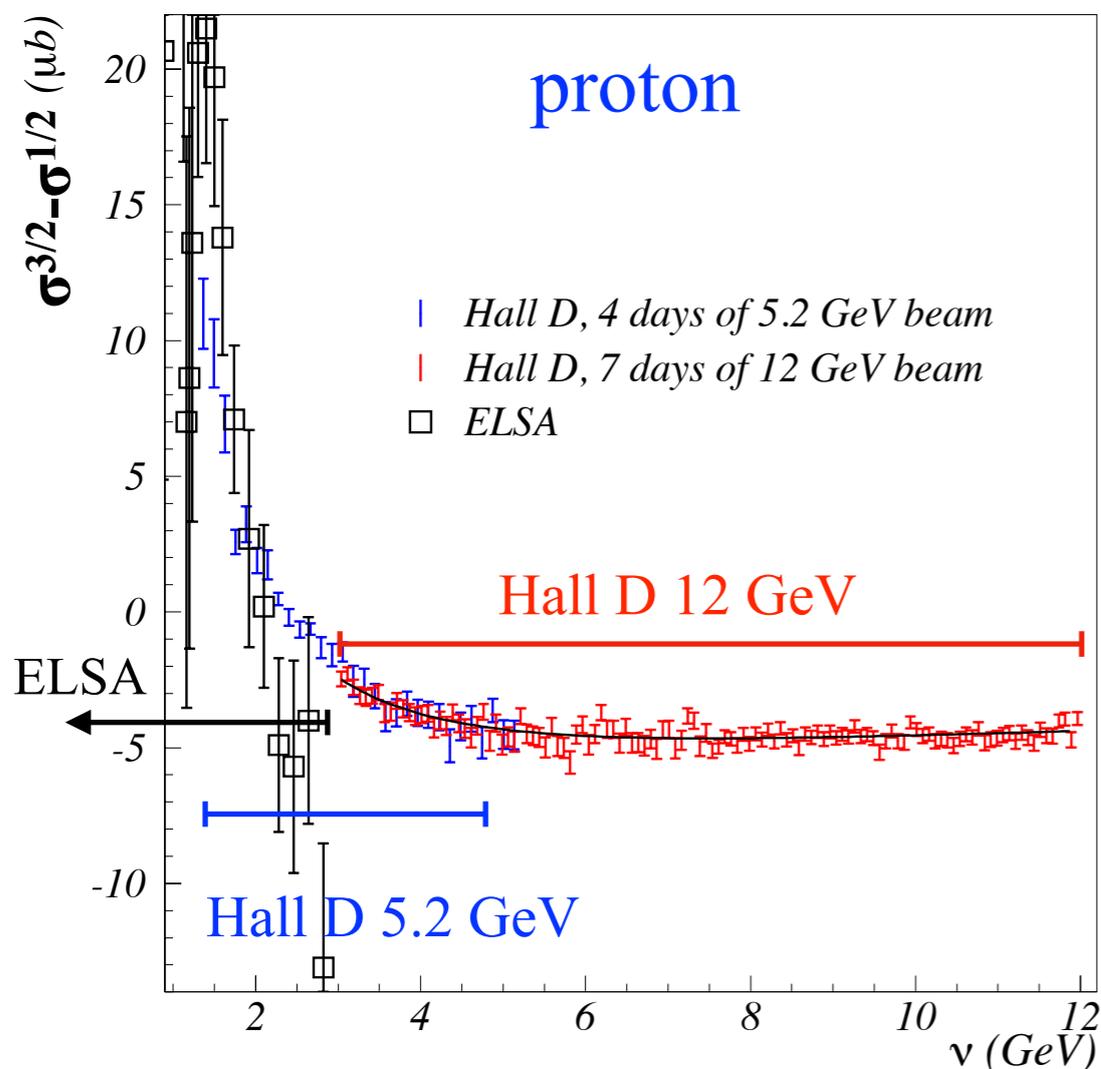
Tagger efficiency measured with $\sim 1\%$ uncertainty.

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

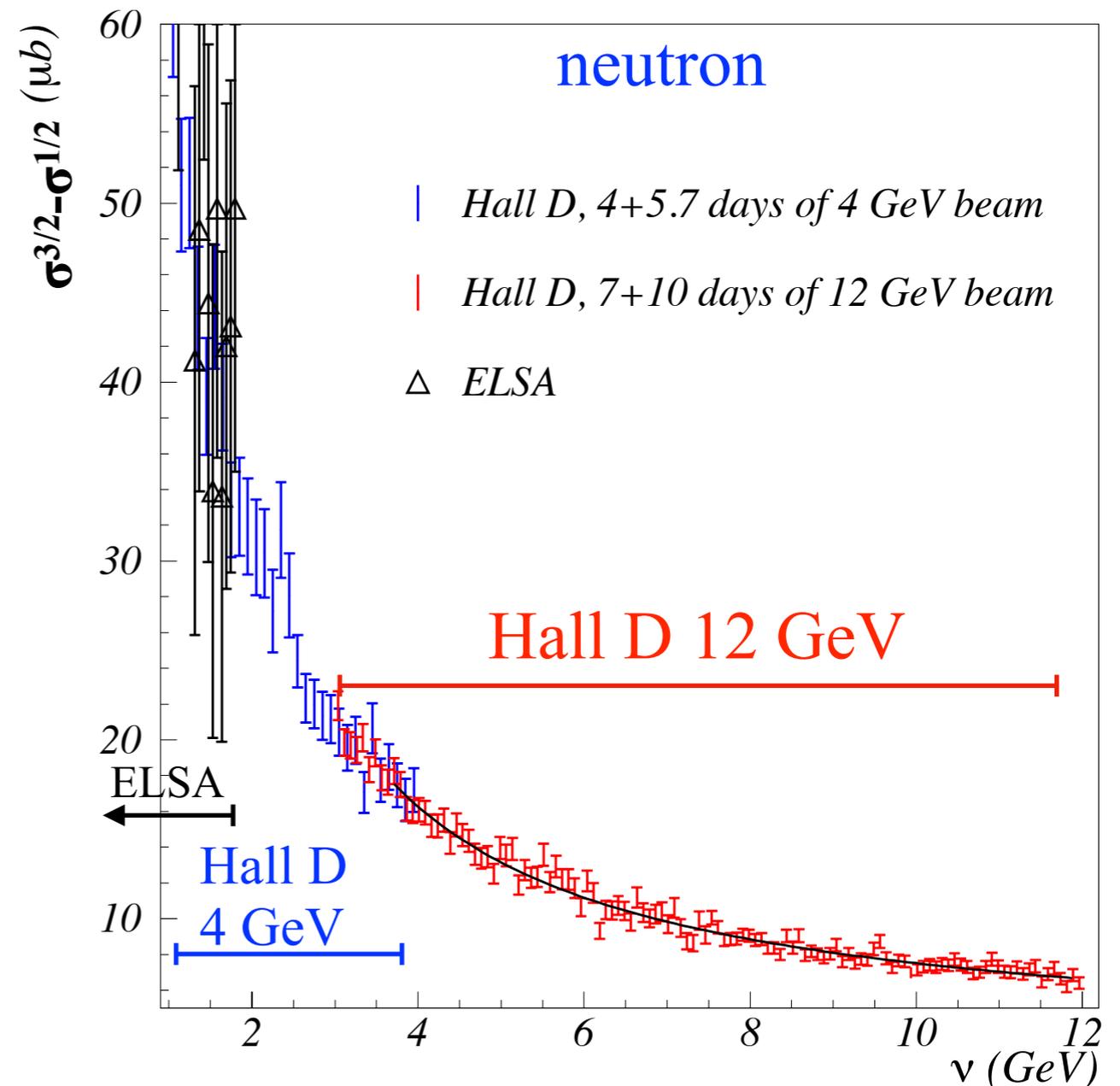
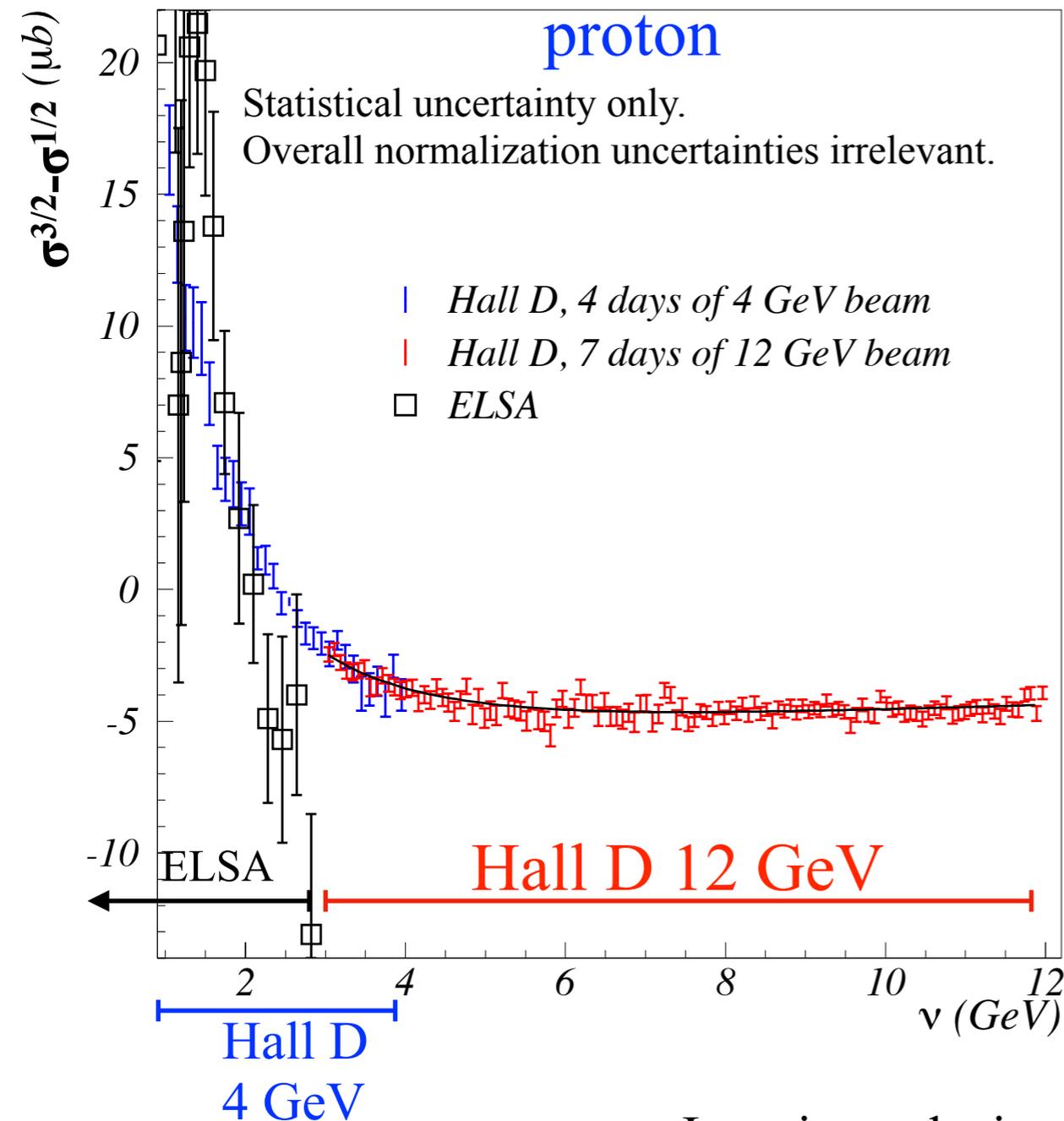
- Allows to **overlap/bridge gap** between ELSA and Hall D data.
- 12 days. Nominal energy: **4 GeV**.
- Consulted with accelerator experts (J. Benesh, T. Satogata). **Feasible**, with two solutions:
 - 1: **Run at lower linac energy**:
 - Advantage: **simplest solution**.
 - Issues:
 - Invasive to other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

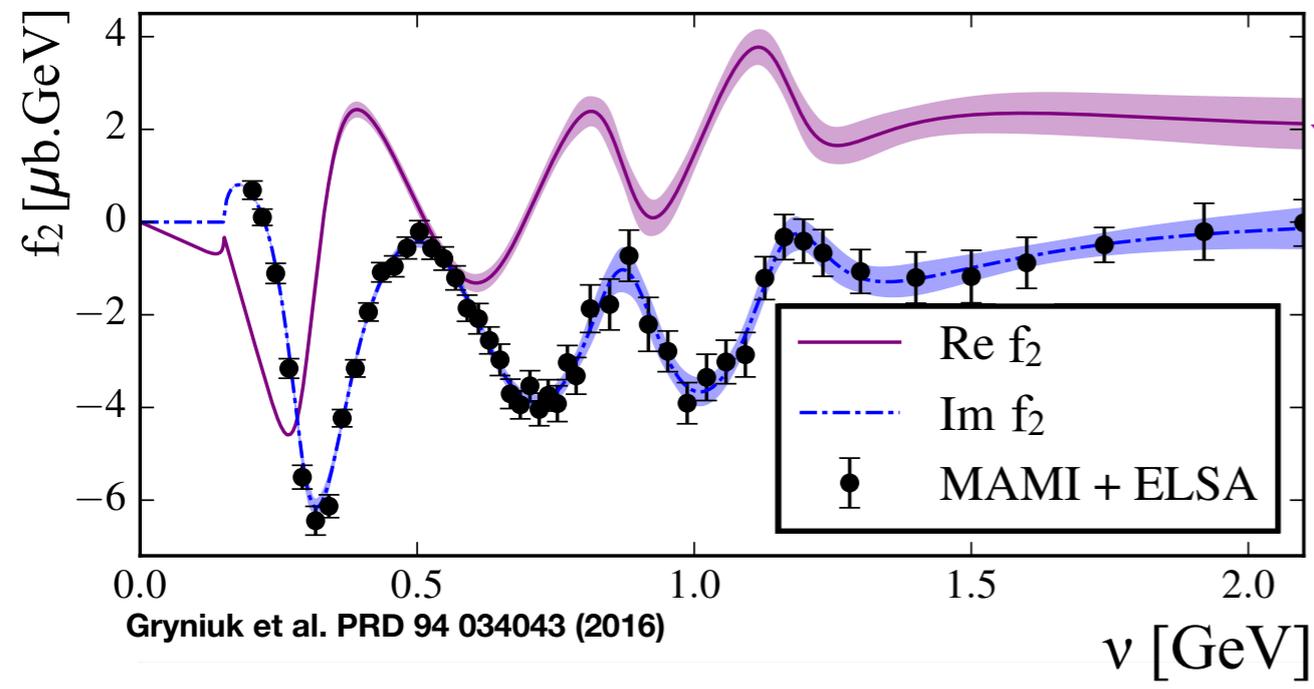
- **1 week of running on proton:** Minimum reasonable time, given overhead \Rightarrow **10 days on deuteron.**
- Valuable to also take data at lower energy: **1 week (p+n) at 4 GeV.**
- For simulating expected data, use Regge theory: $\sigma^{3/2}-\sigma^{1/2} = c_2 s^{\alpha_{f_1}-1} \pm c_1 s^{\alpha_{a_1}-1}$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

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



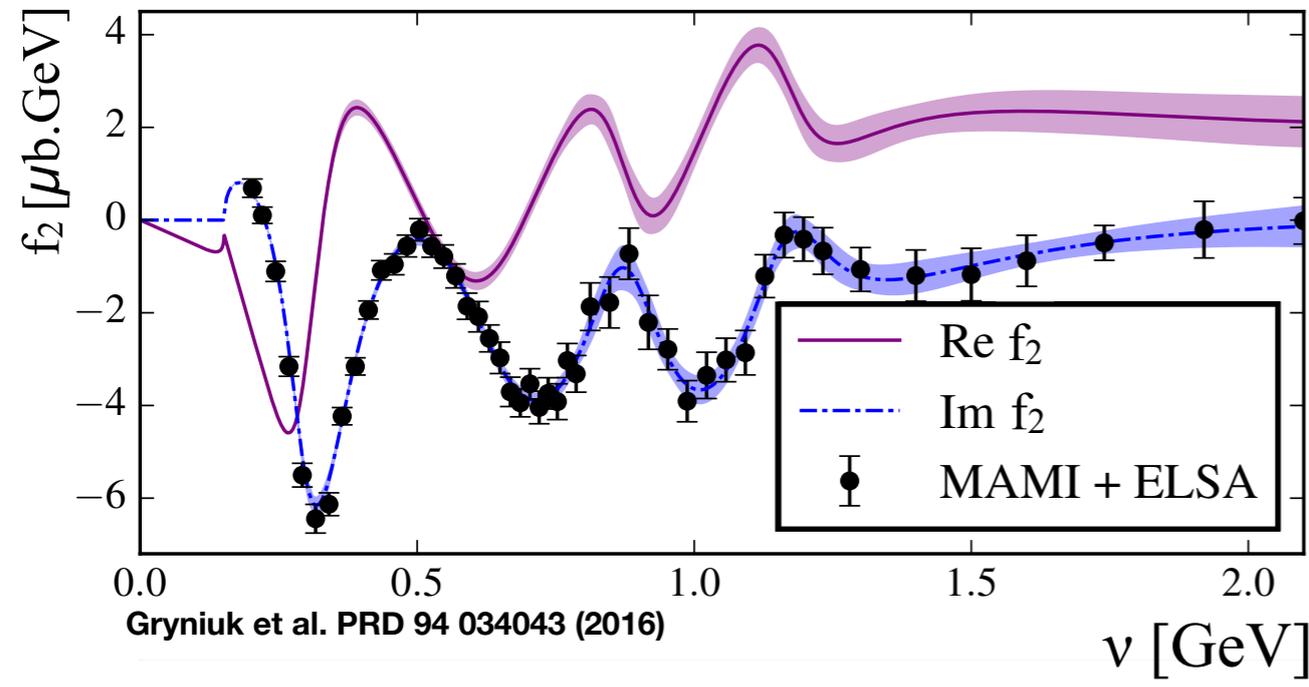
Isospin analysis \Rightarrow $\Delta\alpha_{a_1} = \pm 0.007$ & $\Delta\alpha_{f_1} = \pm 0.029$

Extraction of the real and imaginary parts of Compton amplitude f_2

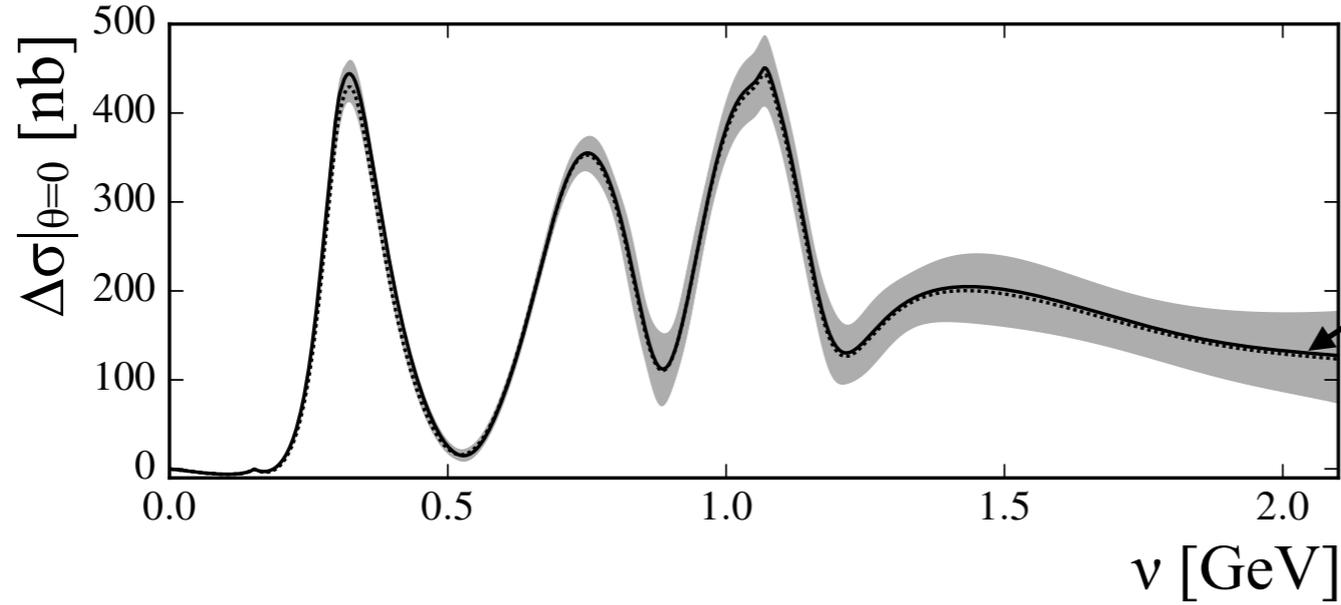


Dispersive analysis from $\text{Im}(f_2)$ data. Large ν data will constrain both $\text{Re}(f_2)$ and $\text{Im}(f_2)$ error bands.

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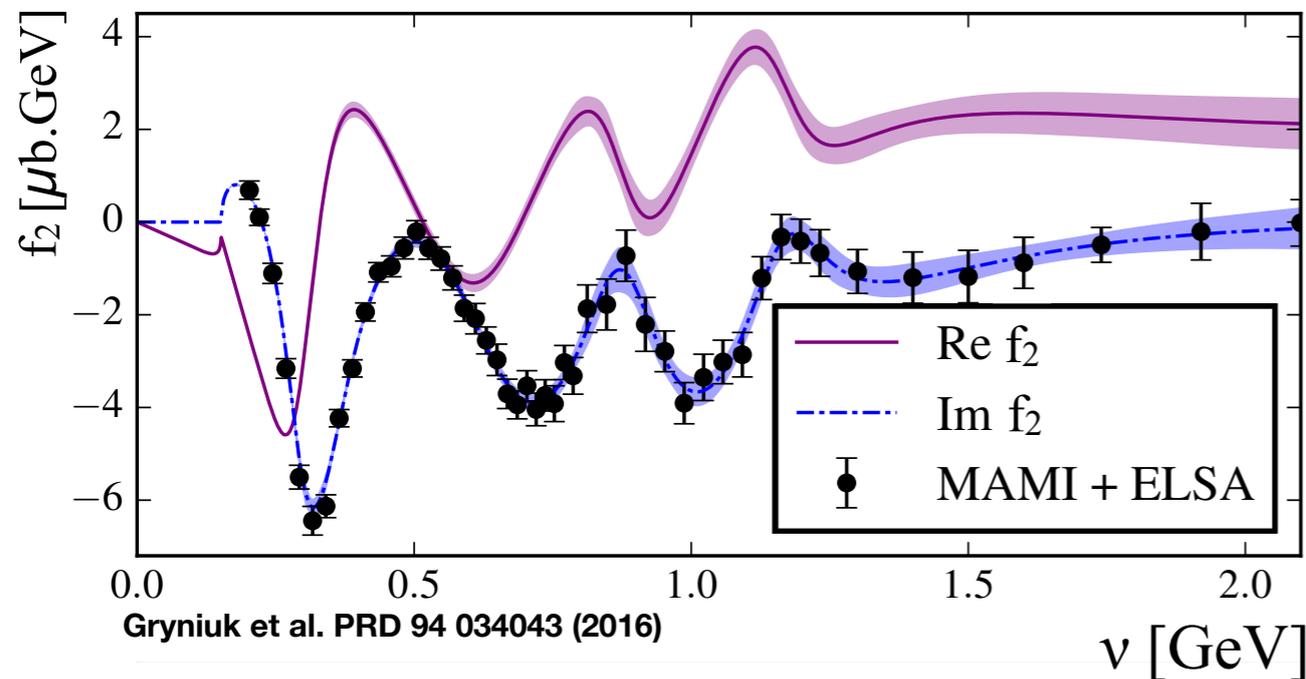


From $\text{Re}(f_2)$ and $\text{Im}(f_2)$ and the well measured unpolarized f_1 , one gets $\sigma^{3/2} - \sigma^{1/2} \stackrel{\text{def}}{=} \Delta\sigma$ in the forward limit.

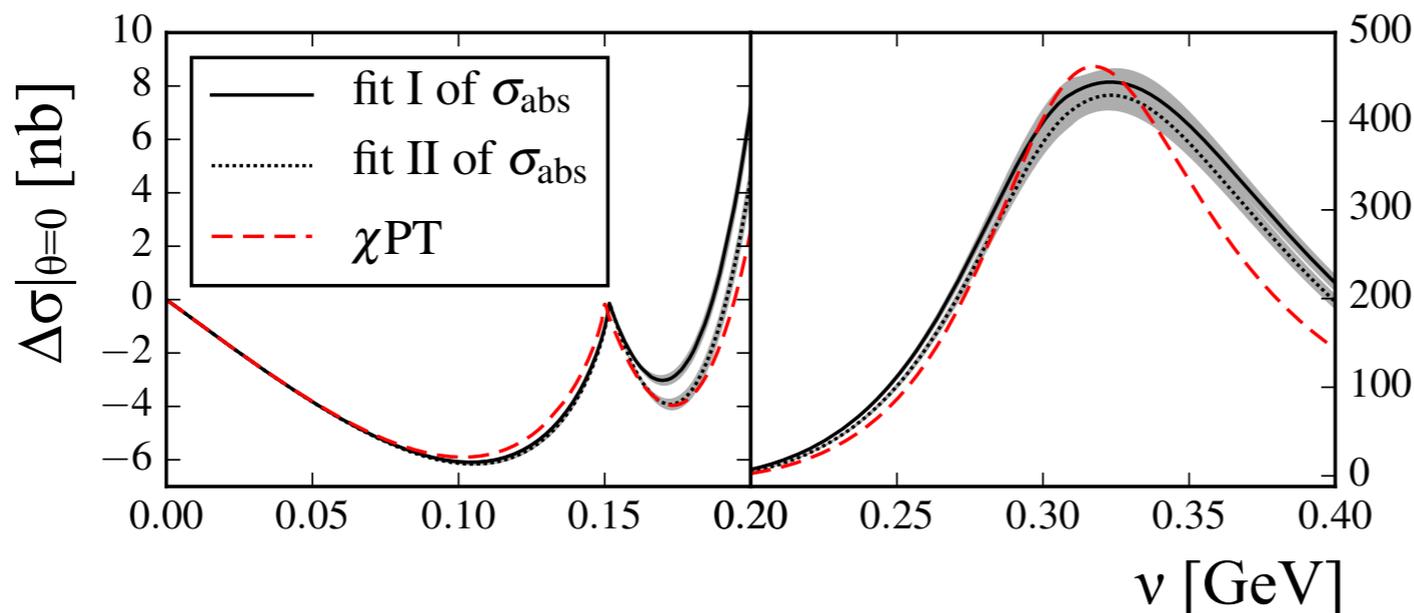
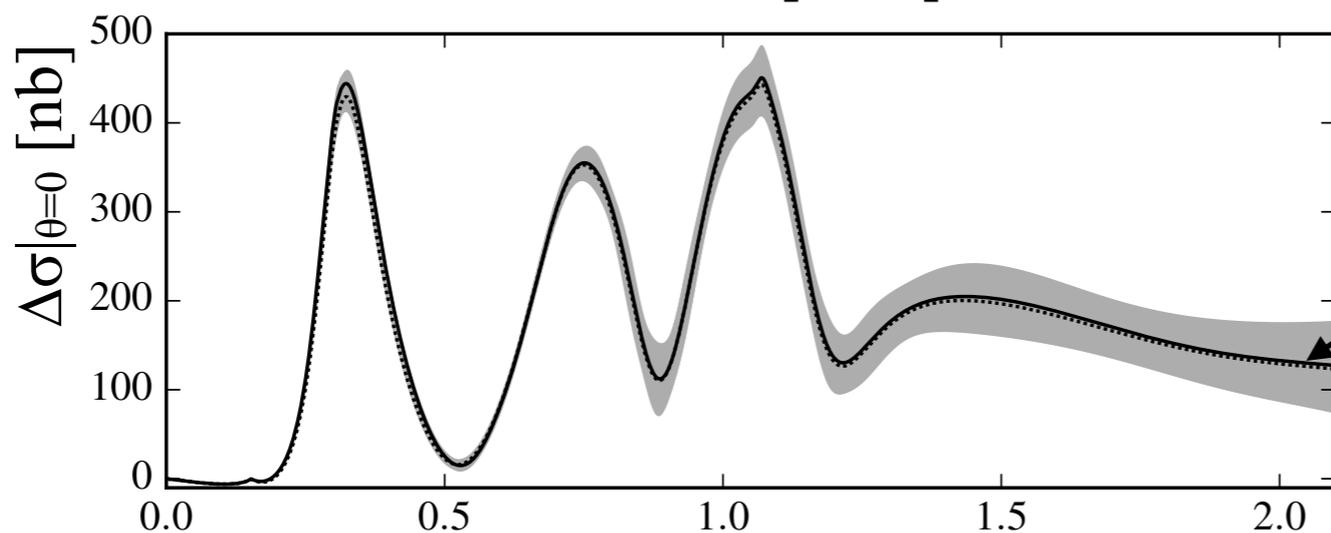


Large v data will constrain increasing error band.

Extraction of the real and imaginary parts of Compton amplitude f_2



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



Chiral Perturbation Theory (χpT) calculation available.

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

\Rightarrow Test of χpT at $Q^2=0$.

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