

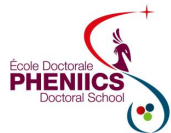
Probing the pion structure with CLAS12

First measurement of the DVCS beam spin asymmetry in the Sullivan process

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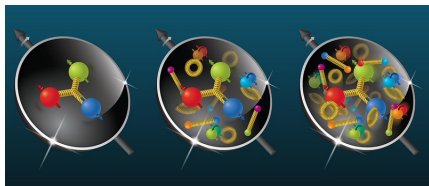


Hadrons: a world of unsolved mysteries

Hadrons are **bound states of quarks and gluons**, governed by Quantum Chromodynamics (QCD).

Yet their internal structure hides **three unsolved mysteries**:

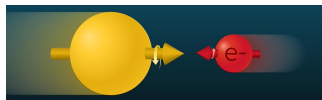
1. **Confinement:** quarks are never observed free.
2. **Mass:** hadrons mass cannot be explained by the sum of their quark masses.
3. **Spin & structure:** how do quarks and gluons build up the proton spin ?



The mass of a proton (938 MeV) is **100×** the sum of its quark masses.
Where does it come from?

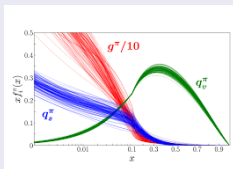
Accessing hadron structure: from PDFs and FFs to GPDs

To probe hadron structure, we need **lepton-hadron** or **hadron-hadron** scattering at high energy, realized in **particle accelerators and colliders**.



PDFs — longitudinal

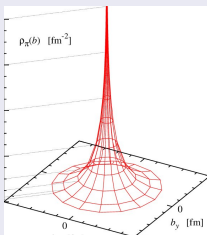
$q(x)$: momentum fraction distribution of quarks.



1D portrait

Form Factors — transverse

$F(t)$: transverse spatial distribution of charge.



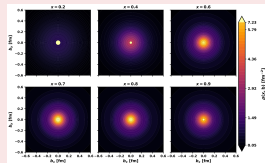
2D portrait

GPDs — full picture

$H(x, \xi, t)$ encodes **both**:

$$H(x, 0, 0) \rightarrow q(x) \\ \int dx H = F(t)$$

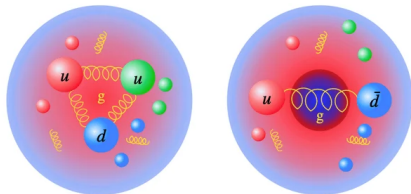
3D tomography of the hadron.



The Pion: lightest hadron, deepest mysteries

What is the pion?

- **Lightest hadron:** $q\bar{q}$ bound state, yet $m_\pi \approx 140 \text{ MeV} \ll \Lambda_{\text{QCD}}$.
- **Pseudo-Goldstone boson** of spontaneous chiral symmetry breaking.
- Carrier of the **nuclear force** at long range \rightarrow central role in hadronic physics.



Why is the pion special to probe?

- **Spin-0** \Rightarrow only **2 GPDs** at leading twist versus 8 for the nucleon.
- Ideal benchmark to test non-perturbative QCD calculations.

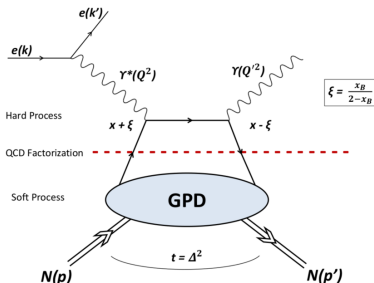
What do we already know?

- **Form factor** $F_\pi(Q^2)$: measured at JLab and DESY.
- **PDFs** $q_\pi(x)$: extracted from Drell-Yan.
- **3D structure**: essentially unknown.

Accessing pion GPDs: DVCS and the Sullivan process

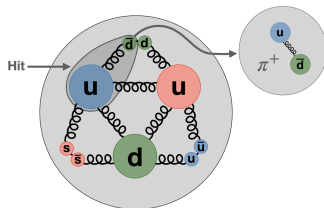
Deeply Virtual Compton Scattering

- Hard exclusive: $e\pi^+ \rightarrow e\gamma\pi^+$.
- Large $Q^2 \Rightarrow$ collinear factorisation:
 $\mathcal{A} = C_{\text{hard}} \otimes H_\pi(x, \xi, t)$.



The Sullivan process [1]

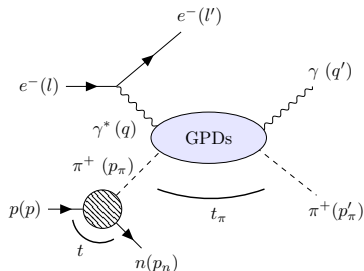
- No free π^+ target \rightarrow use $p \rightarrow \pi^+ + n$ fluctuation.
- Small $|t|$: virtual π^+ is quasi-real.
- Validated for F_π at JLab [2].



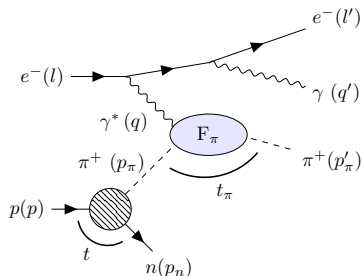
Virtual meson cloud as an effective pion target.

Sullivan DVCS: cross section

Sullivan DVCS



Sullivan Bethe-Heitler



Sullivan cross section: $d\sigma = |T_{\text{BH}}|^2 + |T_{\text{DVCS}}|^2 + \mathcal{I}_{\text{unpol}} + \lambda_e \mathcal{I}_{\text{pol}}$ [3]

The beam spin asymmetry (BSA): $A_{LU}(\phi) = \frac{1}{P_b} \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$

\Rightarrow Direct access to the pion GPDs.

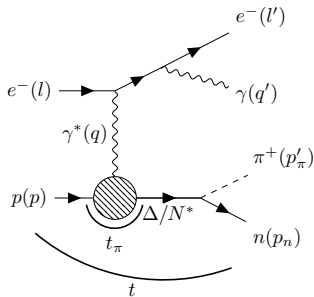
A non-trivial background: baryon resonance transitions

Resonance contribution

- The final state $e\gamma n\pi^+$ can also arise from:

$$ep \rightarrow e\gamma \Delta/N^* \rightarrow e\gamma n\pi^+$$

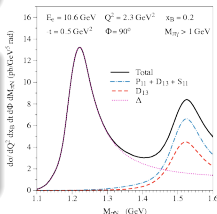
- Both DVCS and BH topologies contribute.
- Irreducible** at JLab energies: cannot be removed by kinematics alone.



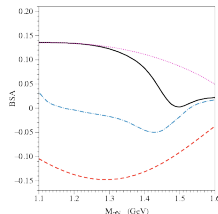
Impact on the analysis

- Contaminates the Sullivan signal.
- Must be **estimated and subtracted** to extract pion GPDs reliably.

Cross section

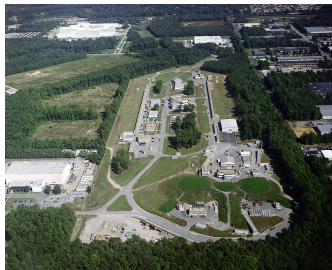


BSA

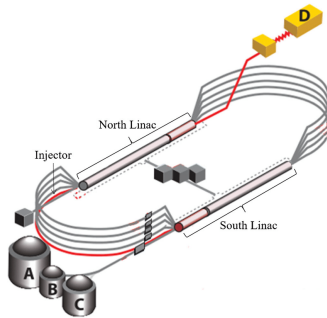


Semenov-Tian-Shansky & Vanderhaeghen [4]

Jefferson Lab & the CEBAF accelerator



Aerial view of Jefferson Lab, Newport News, Virginia, USA



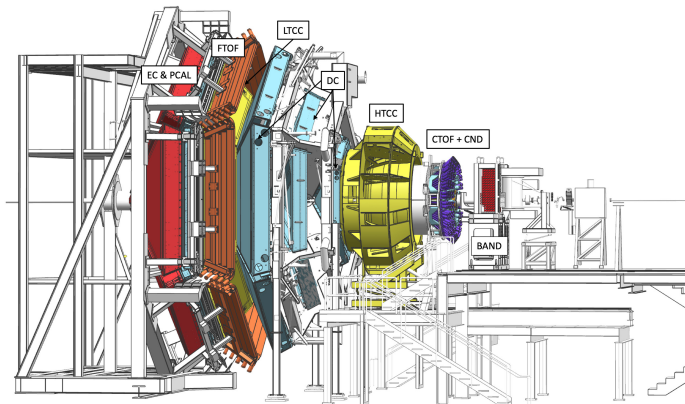
CEBAF: two superconducting linacs connected by recirculating arcs

- **CEBAF** (Continuous Electron Beam Accelerator Facility).
- Delivers a **continuous-wave**, highly **polarized** electron beam at up to **12 GeV**.
- Beam simultaneously distributed to **Halls A, B, C and D**: fixed-target experiments.

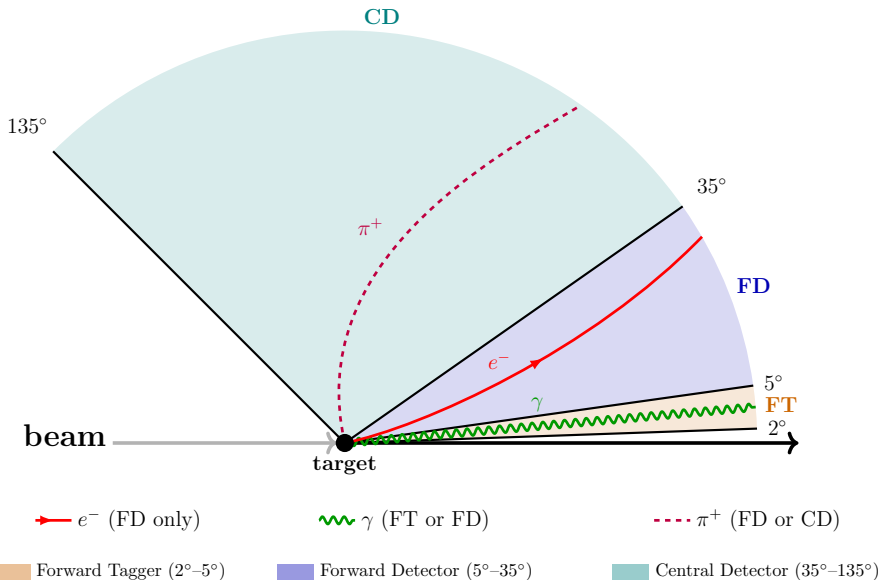
CLAS12: large-acceptance spectrometer in Hall B

CEBAF Large Acceptance Spectrometer (CLAS12)

- **Fixed liquid-hydrogen target** (IH_2).
- **Polarized e^- beam** at 10.6 GeV.
- **Large acceptance:** ideal for exclusive reactions.

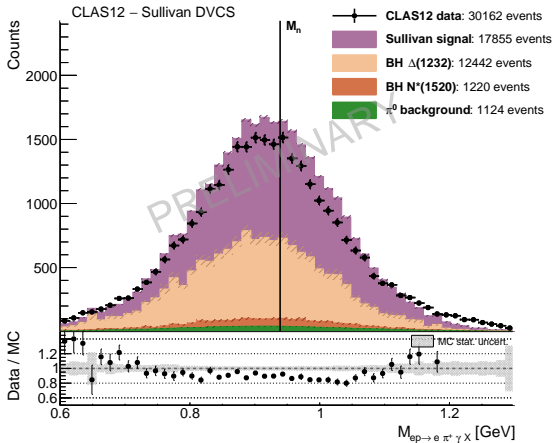


Sullivan DVCS event topology in CLAS12



Exclusivity check: neutron missing mass

$$\text{Neutron missing mass calculated as } M_X = \sqrt{(p + l - l' - q' - p'_\pi)^2}.$$

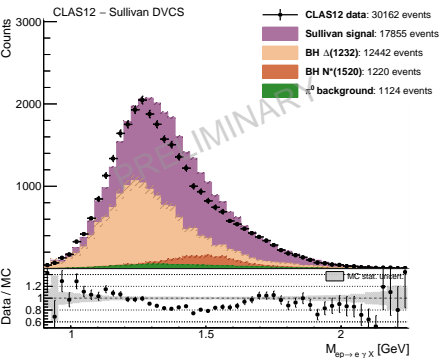


Distribution of the missing mass $M_{ep \rightarrow e \gamma \pi^+ X}$.

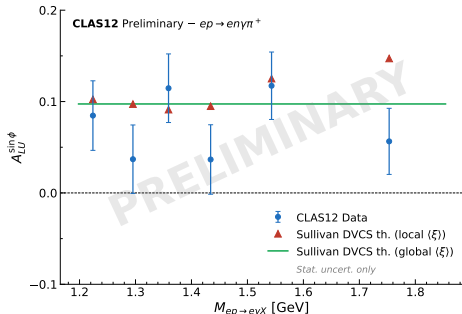
- **Purple:** MC events from the Sullivan signal.
- **Brown:** MC events from the BH on $\Delta^+(1232)$.
- **Orange:** MC events from the BH on $N^*(1520)$.
- **Green:** π^0 background.

Baryon resonance background

- Signal lies in the $\pi^+ n$ invariant-mass region characteristic of baryon resonances.



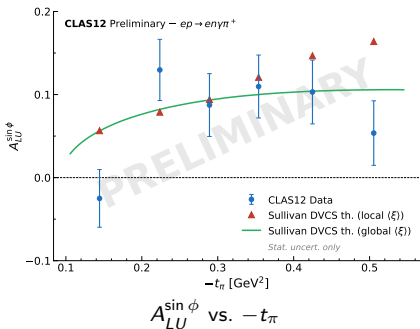
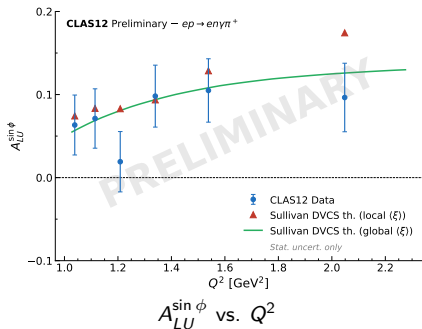
Distribution of the invariant mass of the pion-neutron system $M_{\pi^+ n}$.



Evolution of the amplitude $A_{LU}^{\sin \phi}$ as a function of the invariant mass $M_{\pi^+ n}$.

- The contribution from the baryon resonances is significant and must be properly estimated to extract the pion GPDs.

Preliminary results for $A_{LU}^{\sin\phi}$



- The total amplitude can be expressed as a weighted sum of the individual contributions:

$$A_{LU, \text{Total}}^{\sin\phi} = \sum_i w_i A_{LU, i}^{\sin\phi} \implies A_{LU, \text{Sulli}}^{\sin\phi} = \frac{1}{w_{\text{Sulli}}} \left(A_{LU, \text{Total}}^{\sin\phi, \text{data}} - \sum_{i \neq \text{Sulli}} w_i A_{LU, i}^{\sin\phi} \right)$$

where i runs over the different contributions and w_i are the corresponding yield fractions.



Predictions of $A_{LU}^{\sin\phi}$ for each resonance contribution are required to isolate the pion GPD signal.

Summary and Outlook

Summary

- **First measurement** of $A_{LU}^{\sin\phi}$ for $ep \rightarrow e\gamma\pi^+$ in Sullivan region at CLAS12.
- Comparison of results with Sullivan DVCS predictions [5] as a function of Q^2 , and $-t_\pi$.
- Baryon resonance contributions (for the Δ) are non-negligible and must be **disentangled** before extracting pion GPDs.

Next steps

- Obtain $A_{LU}^{\sin\phi}$ predictions for each resonant channel.
- Evaluate systematic uncertainties.
- \Rightarrow Extract **pion GPDs** via the yield decomposition: $A_{LU}^{\text{tot}} = \sum_i w_i A_{LU,i}^{\sin\phi}$

Long-term outlook: the EIC

- The future **Electron-Ion Collider (EIC)** will reach kinematics well **beyond the resonance region**, providing a clean Sullivan window with negligible resonance contamination.
- This will enable a model-independent extraction of the **pion GPDs** [6].

- [1] J. D. Sullivan. “One-Pion Exchange and Deep-Inelastic Electron-Nucleon Scattering”. In: *Phys. Rev. D* 5 (7 Apr. 1972), pp. 1732–1737. DOI: [10.1103/PhysRevD.5.1732](https://doi.org/10.1103/PhysRevD.5.1732). URL: <https://link.aps.org/doi/10.1103/PhysRevD.5.1732>.
- [2] G. M. Huber et al. “Charged pion form-factor between $Q^{*2} = 0.60\text{-GeV}^{*2}$ and 2.45-GeV^{*2} . II. Determination of, and results for, the pion form-factor”. In: *Physical Review C* 78.4 (Oct. 2008). ISSN: 1089-490X. DOI: [10.1103/physrevc.78.045203](https://doi.org/10.1103/physrevc.78.045203). URL: <http://dx.doi.org/10.1103/PhysRevC.78.045203>.
- [3] Daniela Amrath, Markus Diehl, and Jean-Philippe Lansberg. “Deeply virtual Compton scattering on a virtual pion target”. In: *Eur. Phys. J. C* 58 (2008), pp. 179–192. DOI: [10.1140/epjc/s10052-008-0769-1](https://doi.org/10.1140/epjc/s10052-008-0769-1). arXiv: 0807.4474 [hep-ph].

- [4] Kirill M. Semenov-Tian-Shansky and Marc Vanderhaeghen. *Deeply-virtual Compton process $e^- N \rightarrow e^- \gamma \pi N$ to study nucleon to resonance transitions*. 2023. arXiv: 2303.00119 [hep-ph]. URL: <https://arxiv.org/abs/2303.00119>.
- [5] José Manuel Morgado Chávez et al. “Pion generalized parton distributions: A path toward phenomenology”. In: *Phys. Rev. D* 105 (9 May 2022), p. 094012. DOI: 10.1103/PhysRevD.105.094012. URL: <https://link.aps.org/doi/10.1103/PhysRevD.105.094012>.
- [6] José Manuel Morgado Chávez et al. “Accessing the Pion 3D Structure at US and China Electron-Ion Colliders”. In: *Phys. Rev. Lett.* 128.20 (2022), p. 202501. DOI: 10.1103/PhysRevLett.128.202501. arXiv: 2110.09462 [hep-ph].

Main cuts applied to the data

Virtuality of the photon Q^2

- $Q^2 > 1 \text{ GeV}^2$ with $Q^2 = -(l - l')^2$ to ensure the hard scattering regime.

Inelasticity W^2

- $W^2 > 4 \text{ GeV}^2$ with $W^2 = (p + l - l')^2$ to guarantee the deeply inelastic regime of the reaction.

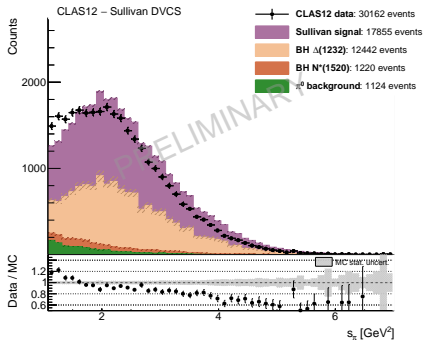
Momentum transfer to the recoil pion t_π

- $-t_\pi < 0.55 \text{ GeV}^2$ with $t_\pi = (p_\pi - p'_\pi)^2 = (p - p_n - p'_\pi)^2$ to select the dominant (leading-twist) contribution.

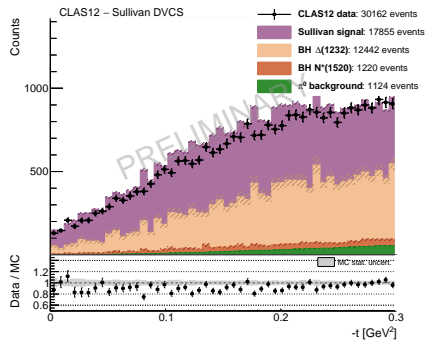
Neutron missing mass $M_{ep \rightarrow e\gamma\pi^+X}$

- $M_{ep \rightarrow e\gamma\pi^+X} \in [0.6, 1.3] \text{ GeV}$, the missing mass of the $ep \rightarrow e\gamma\pi^+X$ system, to select events consistent with a neutron in the final state.

Kinematic distributions after s_π and $-t$ selection cuts

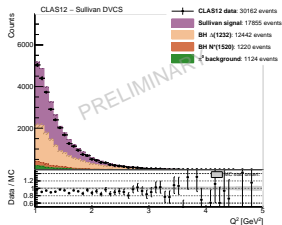


Distribution of s_π .

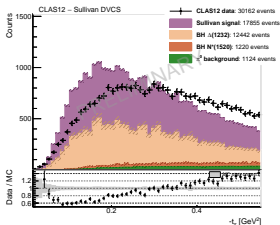


Distribution of $-t$.

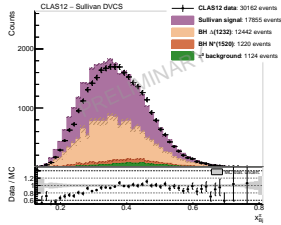
Overview of the reconstructed kinematic variables



Distribution of Q^2 .
 $\langle Q^2 \rangle = 1.43 \text{ GeV}^2$

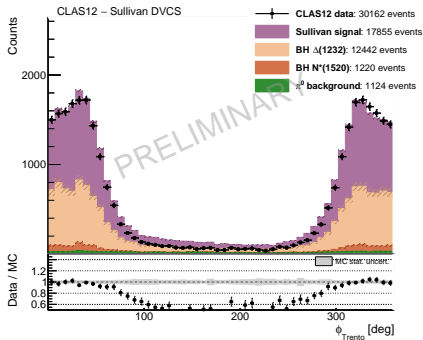


Distribution of $-t_\pi$.
 $\langle -t_\pi \rangle = 0.311 \text{ GeV}^2$

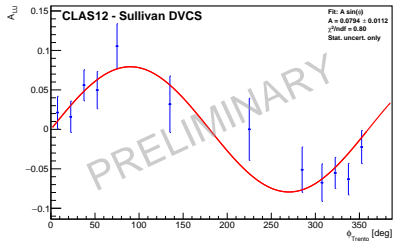


Distribution of $x_{B_J}^\pi$.
 $\langle x_{B_J}^\pi \rangle = 0.373$

Trento azimuthal angle ϕ and BSA as a function of ϕ



Distribution of ϕ_{Trento}



$A_{LU}^{\sin \phi}$ fit with $f(\phi) = A \times \sin \phi$.

Unbinned extraction of $A_{LU}^{\sin \phi}$ — Method

- Due to limited statistics and a non-uniform event distribution in ϕ , a binned extraction of A_{LU} can introduce statistical fluctuations and bin-width-dependent biases.
- To avoid this, an unbinned maximum likelihood fit is performed.

Event probability density function

$$f(h_i, \phi_i; A) = 1 + h_i P_B A \sin \phi_i$$

where $h_i = \pm 1$ is the beam helicity and P_B the effective beam polarization.

Log-likelihood function

$$\ln \mathcal{L}(A) = \sum_{i=1}^N \ln f(h_i, \phi_i; A)$$

The best-fit amplitude A_{fit} minimizes:

$$\chi^2 = -2 \ln \mathcal{L}(A)$$

Demonstration of the event probability density function

Event probability density function

For each event i with helicity $h_i = \pm 1$, the event probability is:

$$f(\phi_i, h_i; A) = 1 + h_i P_B A \sin \phi_i$$

Definition of asymmetry

The beam-spin asymmetry is defined as:

$$\mathcal{A}_{\text{LU}}(\phi) = \frac{\text{Prob}(h = +1|\phi) - \text{Prob}(h = -1|\phi)}{\text{Prob}(h = +1|\phi) + \text{Prob}(h = -1|\phi)}$$

Conditional probabilities from $f(\phi_i, h_i; A)$

$$\text{Prob}(h = \pm 1|\phi) = \frac{1 \pm P_B A \sin \phi}{2}$$

Demonstration of the event probability density function

Analytic expression for the asymmetry

$$\mathcal{A}_{LU}(\phi) = \frac{(1 + P_B A \sin \phi) - (1 - P_B A \sin \phi)}{(1 + P_B A \sin \phi) + (1 - P_B A \sin \phi)} = P_B A \sin \phi$$

Normalized by the beam polarization P_B :

$$\mathcal{A}_{LU}(\phi) = A \sin \phi$$

Uncertainty on $A_{LU}^{\sin \phi}$

The statistical uncertainty is obtained from the curvature of the log-likelihood at its minimum:

$$\sigma_A = \left(\frac{\partial^2(-\ln \mathcal{L})}{\partial A^2} \Big|_{A=A_{\text{fit}}} \right)^{-1/2}$$