Measurement of the DVCS beam spin asymmetry in the Sullivan process

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Sullivan DVCS: Gateway to pion structure

The meson cloud surrounding the nucleon provides a natural target for studying pion structure.

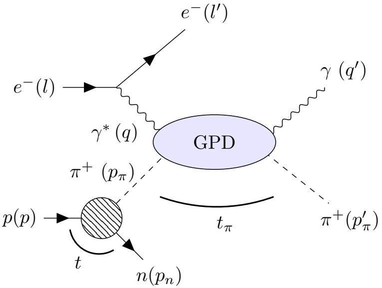

Figure: DVCS off a virtual pion through the Sullivan process.

Use DVCS off the virtual pion to extract observables sensitive to pion GPDs.

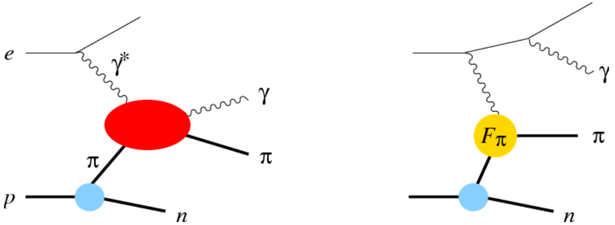

Figure: Feynman diagrams for $ep \to e\gamma\pi^+ n$. Left: Sullivan DVCS. Right: Bethe–Heitler process. [1]

$$\mathrm{d}\sigma \propto \left|\mathcal{M}^{\mathrm{BH}}\right|^2 + \left|\mathcal{M}^{\mathrm{DVCS}}\right|^2 + \mathcal{I}$$

$$\mathcal{I} = \mathcal{I}_{unpol} + \lambda \mathcal{I}_{pol}$$

Beam spin asymmetry

Since the interference term depends on the electron helicity, it enables the extraction of the beam spin asymmetry.

$$\mathcal{A}_{\mathsf{LU}}(\Phi) = \frac{\mathrm{d}\sigma^+(\Phi) - \mathrm{d}\sigma^-(\Phi)}{\mathrm{d}\sigma^+(\Phi) + \mathrm{d}\sigma^-(\Phi)} \propto \mathrm{Im}(\mathcal{H}) \sin(\Phi)$$

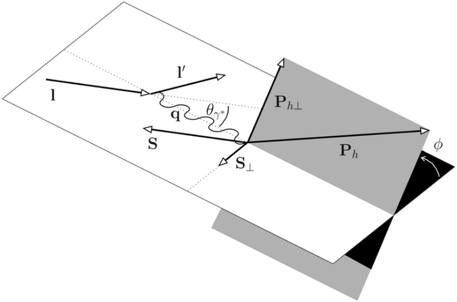

Figure: Definition of the ϕ_{Trento} angle. [2]

$$\mathcal{H}_\pi(\xi, t_\pi, Q^2) = \sum_q e_q^2 \int_{-1}^{1} dx\, C_H^q(x, \xi, Q^2/\mu_F^2) H_\pi^q(x, \xi, t_\pi, \mu_F^2)$$

- $\xi \approx \frac{x_{Bj}^\pi}{2 - x_{Bj}^\pi}$, half the longitudinal momentum transfer ($\xi \in [-1; 1]$).
- $t_\pi = (p_\pi - p'_\pi)^2$, the squared momentum transfer.
- $Q^2 = -q^2$, the virtuality of the exchanged photon.

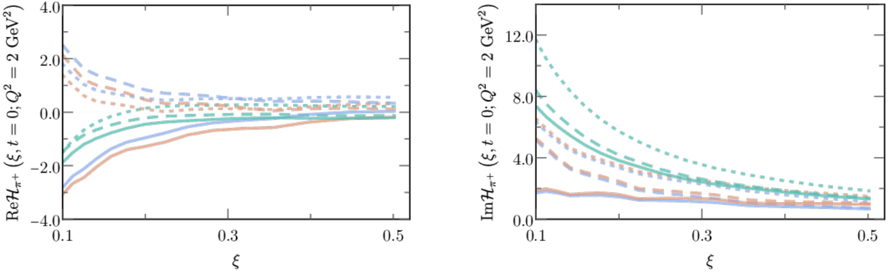

Figure: DVCS Compton form factors predicted by the GPDs models of Chávez et al. [3].

Dataset and event selection

- **RGA data:**
  - Fall 2018 Outbending run.
  - Integrated luminosity: $\mathcal{L}_{\text{int}} = 42.589\ \text{fb}^{-1}$ (charge measured with QADB).
- **Event selection:**
  - One scattered electron in the final state (detected in the Forward Detector).
  - One π^+ (detected in the Forward or Central Detector).
  - At least one photon (detected in the Forward Detector or Forward Tagger).
  - One neutron identified via its missing mass.
- **Fiducial cuts:**
  - Fiducial cuts by Stefan Diehl as documented in “Fiducial cuts and PID refinements for RG-A pass 2 (Fa18 and Sp19)” [4].
- **Momentum corrections:**
  - e^- and π^+ in the FD: corrections by Richard Capobianco [5].
  - Photons in the FD: corrections by Juan Sebastian Alvarado [6].
  - Photons in the FT: corrections by Asli Acar [7].

Monte Carlo Simulation

We employ a Monte Carlo simulation based on the DVCS model of Belitsky, Mueller, and Kirchner [8], adapted for the Sullivan process by including the pion flux factor from Amrath et al. [1], and using the GPD model of José Chávez et al. [3].

$$w = \frac{\mathcal{L}_{\text{int}} \cdot d\sigma_{\text{tot}} \cdot d\Phi}{N_{\text{gen}}}$$

- $N_{\text{gen}} = 1.0 \times 10^9$ is the number of generated events.
- $\mathcal{L}_{\text{int}} = 42.589\ \text{fb}^{-1}$ is the integrated luminosity of the data.
- $d\sigma_{\text{tot}}$ is the cross section and $d\Phi$ is the phase space factor.

The same analysis chain is applied to both simulated and experimental data.

Kinematic cuts level 1

- $Q^2 = (l - l')^2 > 1\ \mathrm{GeV}^2$ to select events in the Bjorken kinematic region.
- $W^2 = (p + q)^2 > 4\ \mathrm{GeV}^2$ to guarantee the deeply inelastic regime of the reaction.
- $-t = -(p - p_n)^2 < 0.6\ \mathrm{GeV}^2$ to ensure a weakly off-shell (nearly on-shell) pion whose structure closely resembles that of a real pion.
- $-t_\pi = -(p_\pi - p'_\pi)^2 < 0.6\ \mathrm{GeV}^2$ to select the dominant (leading-twist) contribution.

Exclusivity and kinematic selection cuts

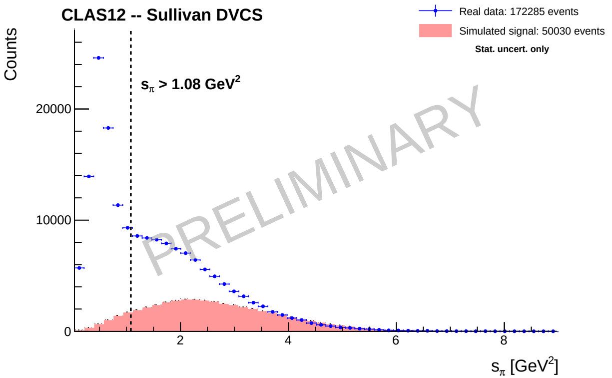

Figure: Distribution of the variable s_π. The black dashed line indicates the cut applied.

We apply the cut $s_\pi = (p_\pi + q)^2 > 1.08 \text{ GeV}^2$ to remove the pion resonance region.

Exclusivity and kinematic selection cuts

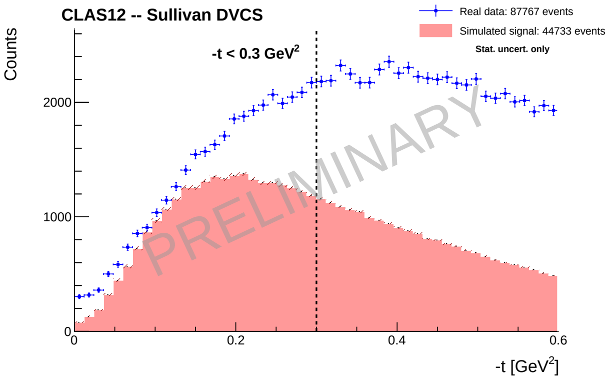

Figure: Distribution of the variable $-t$. The black dashed line indicates the cut applied.

We apply the cut $-t < 0.3\ \mathrm{GeV}^2$ to ensure a nearly on-shell pion whose structure closely resembles that of a real pion and to remove background.

Missing mass of the neutron

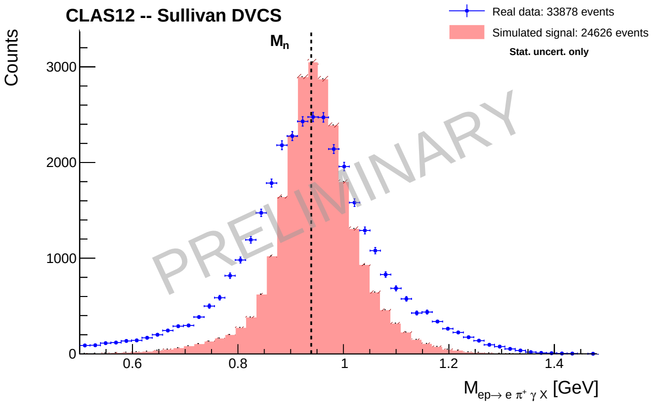

Figure: Distribution of the missing mass $M_{ep\to e\gamma\pi^+X}$.

We will apply resolution corrections to the Monte Carlo simulation in order to bring it into closer agreement with the observed data.

Azimuthal angle Trento ϕ

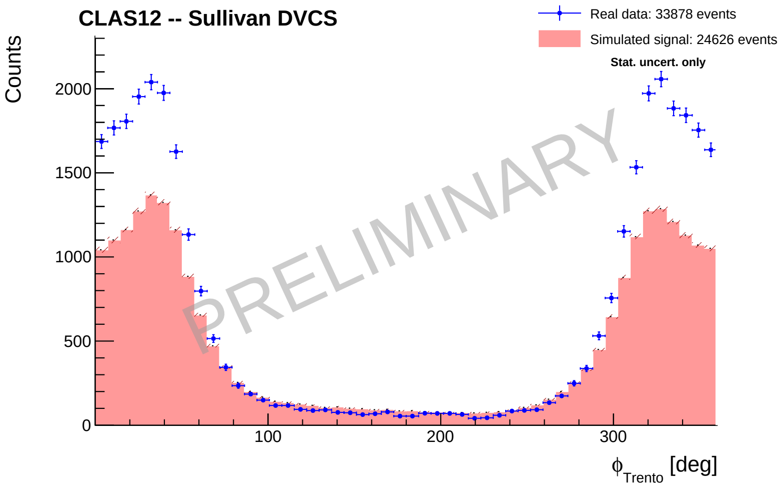

Figure: Distribution of the azimuthal angle ϕ.

Binned extraction of $A_{LU}^{\sin\phi}$ — Preliminary results

$$\mathcal{A}_{\mathrm{LU}}(\phi) = \frac{1}{P_B} \cdot \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$

- $N^+(\phi)$ and $N^-(\phi)$ are the number of events for positive and negative electron helicities, respectively.
- P_B is the effective beam polarization, which is about 86% for the Fall 2018 Outbending run.

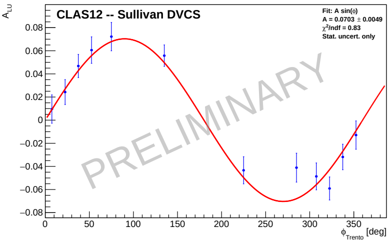

Figure: Beam-spin asymmetry extracted from the simulation and fitted with $A\sin(\phi)$.

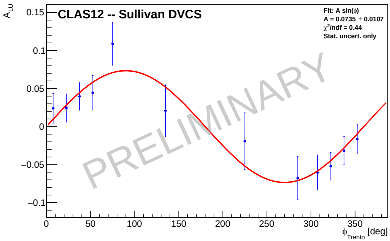

Figure: Beam-spin asymmetry extracted from the data and fitted with $A\sin(\phi)$.

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

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:

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

Sample	$\langle Q^2 \rangle$ [GeV^2]	$\langle x_\pi^{\text{Bj}} \rangle$	$\langle -t_\pi \rangle$ [GeV^2]	A_{LU}^{bin}	A_{LU}^{unbinned}
Data	1.411	0.380	0.327	0.0735 ± 0.0107	0.0728 ± 0.0107
MC	1.396	0.358	0.270	0.0703 ± 0.0049	0.0722 ± 0.0118

Invariant mass of the $\pi^+ n$ system

Our signal falls within the π^+-neutron invariant-mass range characteristic of nucleon resonances.

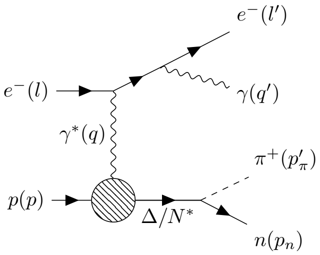

Figure: Bethe–Heitler process with nucleon resonance production.

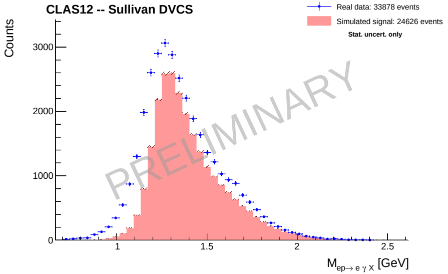

Figure: Distribution of the invariant mass $M_{\pi^+ n}$.

We can estimate that the nucleon-resonance background contribution is likely of the same order as the discrepancy between the data and the simulated signal, i.e. about 30% of our data.

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

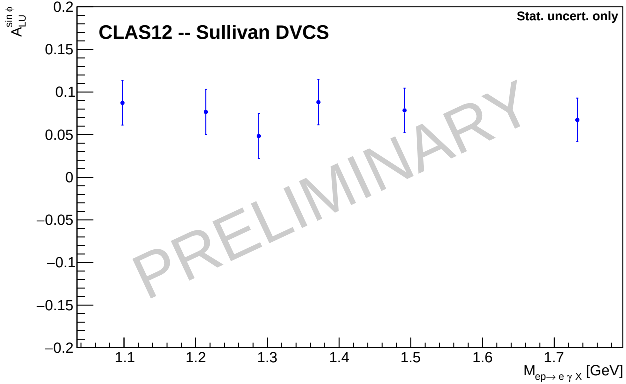

Figure: Evolution of the amplitude $A_{LU}^{\sin\phi}$ as a function of the invariant mass $M_{\pi^+ n}$.

Outlook

- Remove π^0 contamination: $ep \to en\pi^+\pi^0 \to en\pi^+(\gamma\gamma)$. A large fraction of the π^0 contamination is expected to lie at low s_π. Consequently, a significant portion is already eliminated by applying the cut $s_\pi > 1.08\ \mathrm{GeV}^2$.
- Develop a method to estimate the background from nucleon resonances: $ep \to e\gamma N^* \to e\gamma n\pi^+$.
- Include the remaining dataset (Spring 2018) in the analysis.

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[3] 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.

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Electron kinematics

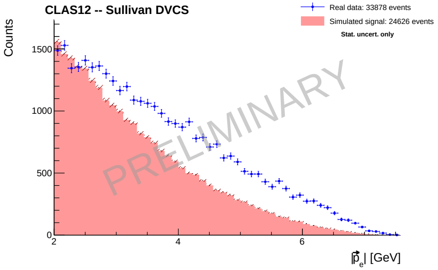


Figure: Momentum distribution.

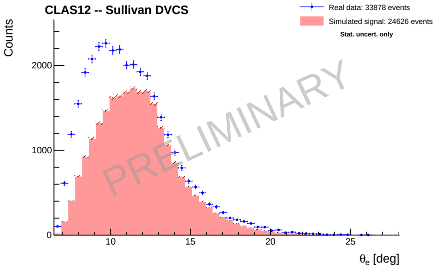


Figure: Polar angle distribution.

All electrons are detected in the FD.

Photon kinematics

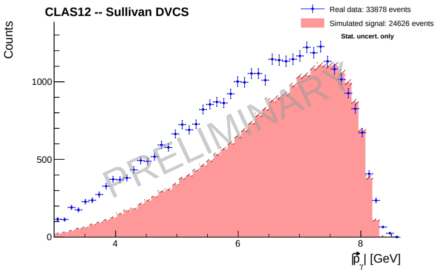


Figure: Momentum distribution.

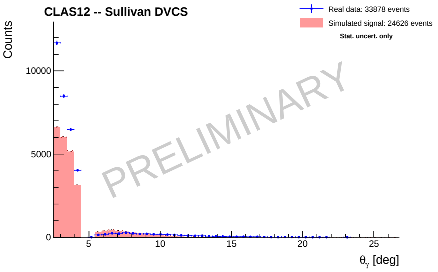


Figure: Polar angle distribution.

Table: Detector regions for the photon

Sample	FT	FD
Data	30 678	3 200
MC	21 024	3 602

Pion kinematics

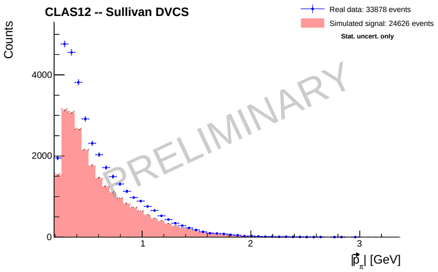


Figure: Momentum distribution.

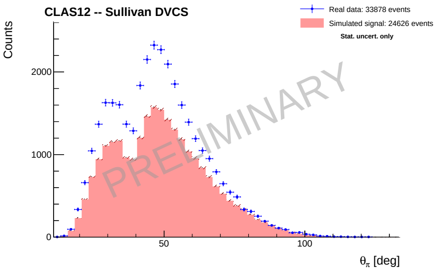
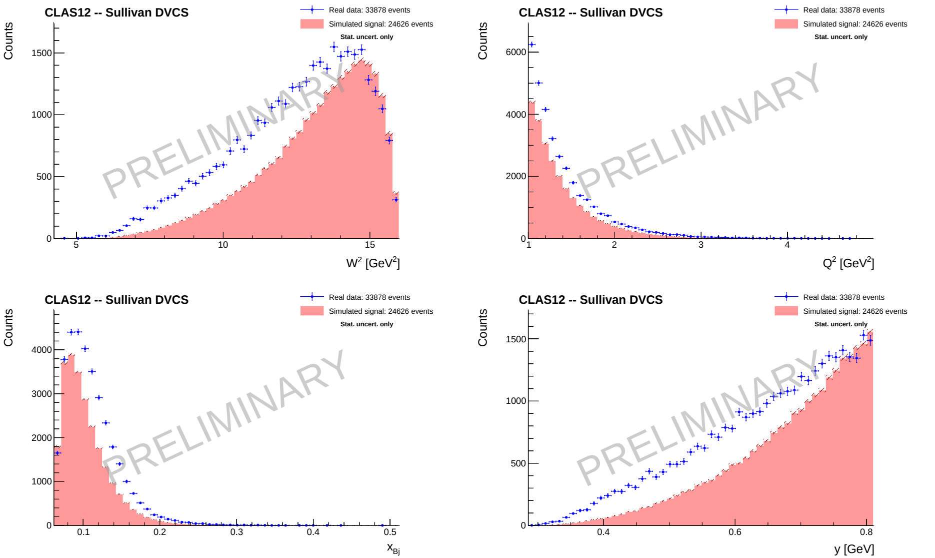


Figure: Polar angle distribution.

Table: Detector regions for the pion.

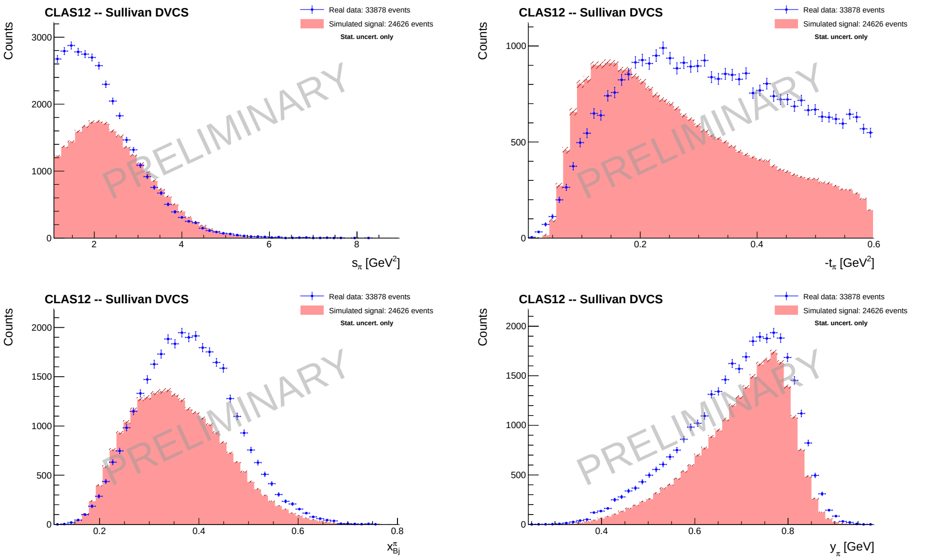
Sample	CD	FD
Data	23 913	9 965
MC	17 434	7 192

DIS kinematic variables



Distribution of kinematic variables W^2, Q^2, x_{Bj}, and y.

DVCS kinematic variables



Distribution of kinematic variables s_π, t_π, x_{Bj}^π, and y_π.

Kinematic variables relative to the emission of the virtual pion

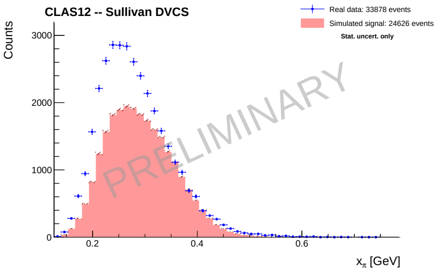


Figure: Distribution of the variable x_π.

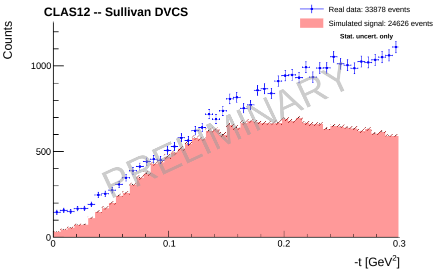


Figure: Distribution of the variable $-t$.

- $x_\pi = \frac{p_\pi \cdot l}{p \cdot l}$
- $-t = -(p - p_n)^2$

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:

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

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

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

Demonstration of the event probability density function

Analytic expression for the asymmetry

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

Normalized by the beam polarization P_B:

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

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

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

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