Probing the pion structure with RGA

Beam-spin asymmetry of the $e\gamma\pi^+ n$ final state in the Sullivan DVCS region

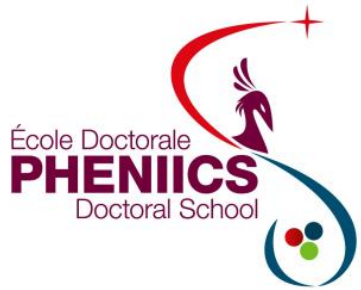
Elouan Ferrand

CEA Saclay

November 18, 2026

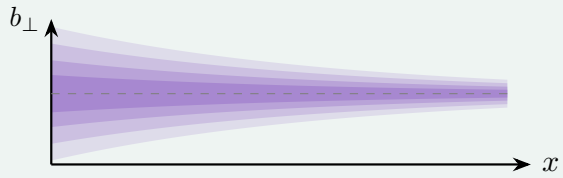






Why the pion, and why its GPDs?

Tomography: $q(x, \vec{b}_\perp)$



3D view of the pion

Why the pion?

- Lightest hadron
- Goldstone boson of chiral symmetry breaking
- Spin 0: only **two GPDs** at leading twist
- **3D structure unexplored**

Generalized Parton Distributions

$H_\pi(x, \xi, t)$

generalized and correlated by

Known, experimentally constrained

Pion PDF

(forward limit, $\xi = 0$, $t = 0$)

$H_\pi(x, 0, 0) = q_\pi(x)$

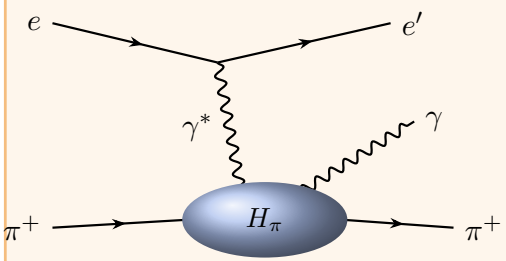
Pion form factor

(integrated over x)

$F_\pi(t) = \int_{-1}^{1} dx\, H_\pi(x, \xi, t)$

DVCS on the pion

(golden channel to access GPDs)



accessed through

properties of the pion

Energy-momentum tensor and mechanical properties

$\int_{-1}^{1} dx\, x\, H_\pi(x, \xi, t) = A_\pi(t) + \xi^2 D_\pi(t) \longrightarrow$ gravitational form factors

mass distribution, pressure and shear forces inside the pion

But: no pion target!

DVCS on a virtual pion: the Sullivan process

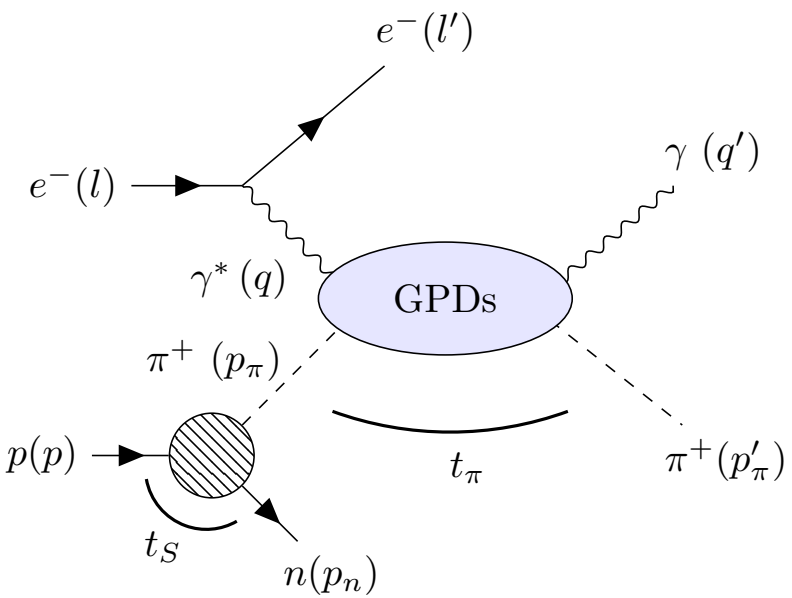
Sullivan process

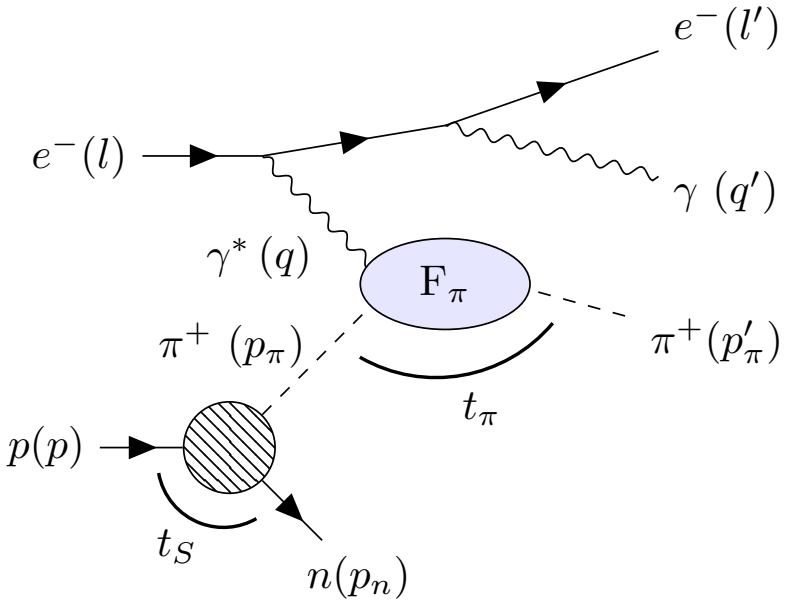
- The proton fluctuates into $\pi^+ n \to$ virtual π^+ acts as a target.
- Quasi-real pion at small virtuality $-t_S = -(p - p_n)^2$.
- Used for the pion form factor at JLab [1].

Observable: beam-spin asymmetry (BSA)

$d\sigma = |T_{\rm BH}|^2 + |T_{\rm DVCS}|^2 + \mathcal{I}_{\rm unpol} + \lambda_e \mathcal{I}_{\rm pol}$ [2]

$A_{LU}(\phi) = \frac{1}{P_B} \frac{N^+ - N^-}{N^+ + N^-} \simeq A_{LU}^{\sin\phi} \sin\phi \Rightarrow$ access to $\mathrm{Im}\,\mathcal{H}_\pi$ at $x = \pm\xi$.





Sullivan DVCS and Bethe–Heitler.

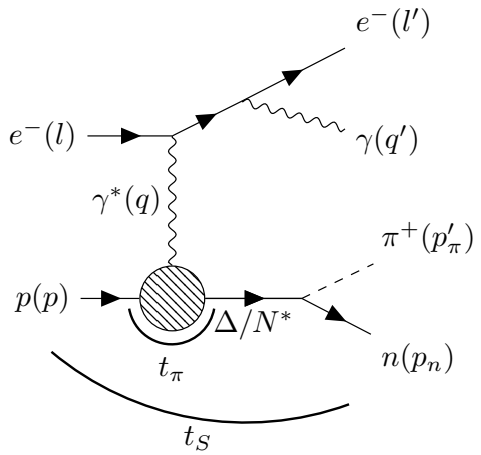
The same final state from baryon resonances

- $e\gamma\pi^+ n$ is also produced by $ep \to e\gamma\,\Delta^+/N^\star \to e\gamma\,\pi^+ n$, through BH *and* DVCS.
- **Irreducible** at JLab energies: the same final state, in the same kinematics.
- This background has a **non-zero BSA** and interferes with the Sullivan process.

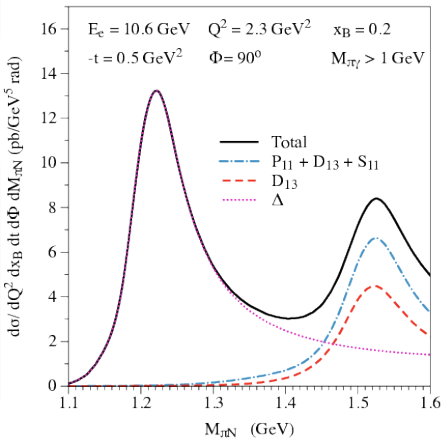
Consequence

We measure the BSA of a **mixture**: its interpretation requires a model of the **full** $e\gamma\pi^+ n$ final state.

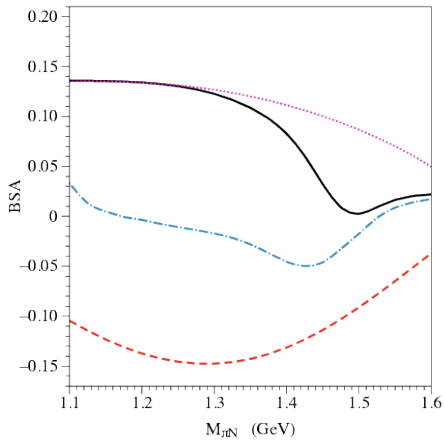
Bethe–Heitler off the $\Delta/N^\star$.



Cross section



BSA



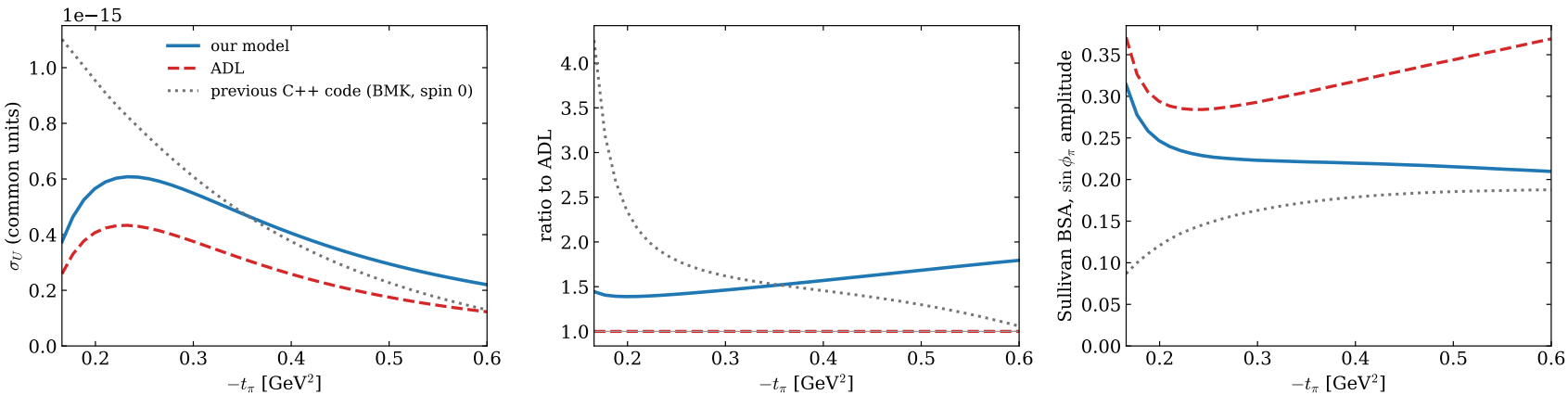
Semenov-Tian-Shansky & Vanderhaeghen [3]

The Sullivan process: a new model

	Previous generator	**ADL** [2]	**This work**
$e\pi \to e\gamma\pi$	BMK, spin-0 target, $M = 0$	leading power in $1/Q$	**full amplitudes**, exact kinematics
Pion virtuality t_S	only in $t_\pi^{\min}$, inside K: BH finite at $t_\pi^{\min}$	exact $t_\pi^{\min}(t_S)$: BH $\propto (t_\pi^{\min} - t_\pi) \to 0$	
Coherent with Δ	no	no	**yes**

$t_S = (p - n)^2$: pion virtuality; $t_\pi = (q - q')^2$: transfer to the pion; $t_\pi^{\min}(t_S)$: its kinematic limit. Same pion flux, F_π and leading-twist NLO CFF (Chávez *et al.* [4]) in the three.

Sullivan process: $Q^2 = 1.8$ GeV^2, $x_B = 0.15$, $M_{\pi N} = 1.3$ GeV, decay angles and ϕ integrated, $s_\pi > 1.08$ GeV^2, $-t_S < 0.3$ GeV^2

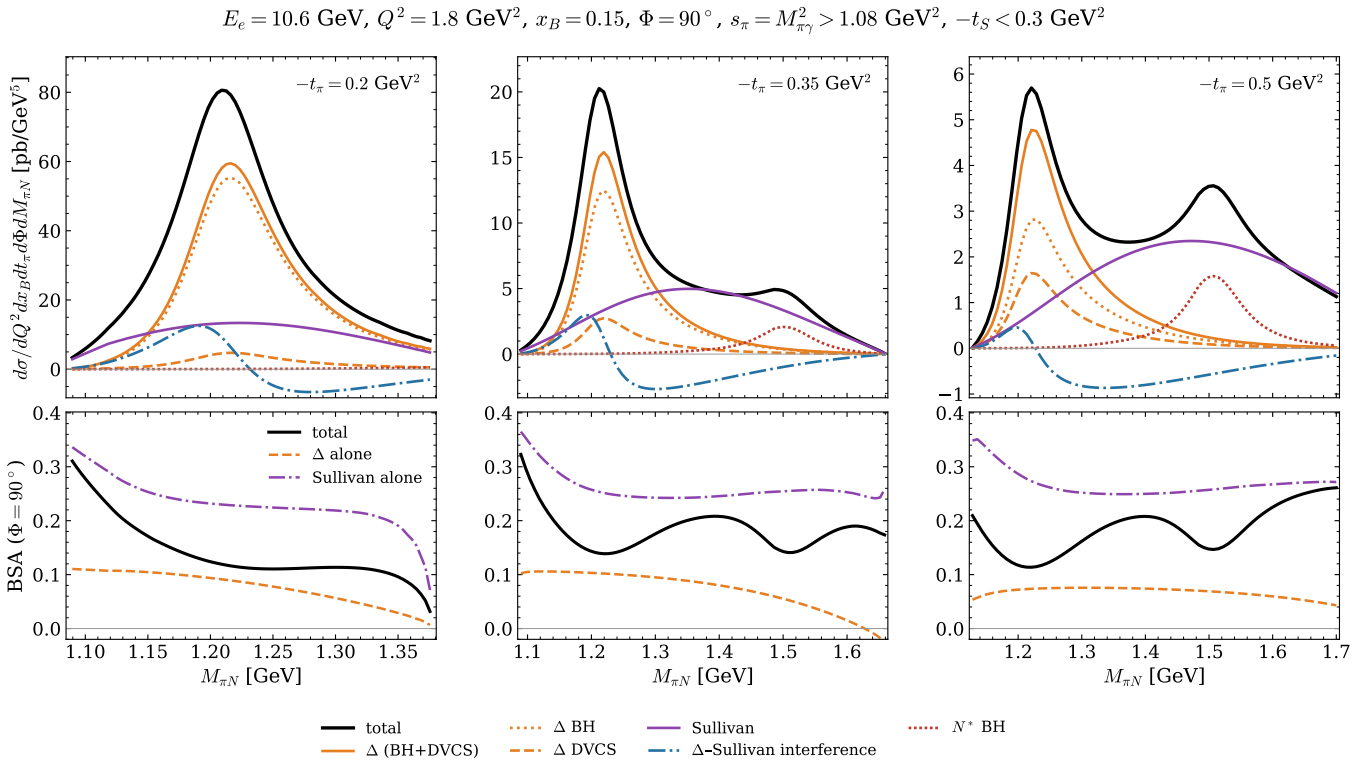


Cross section, ratio to ADL and BSA vs $-t_\pi$, at $Q^2 = 1.8$ GeV^2, $x_B = 0.15$, $M_{\pi N} = 1.30$ GeV.

Ours vs ADL: power corrections (t_π/Q^2, t_S/Q^2), sizeable at CLAS12 Q^2; the two coincide at large Q^2 (checked up to 16 GeV^2).
Previous generator: $M = 0$ drops the M^2/t_π terms of BMK that carry the threshold suppression $(1 - t_\pi^{\min}/t_\pi) \Rightarrow$ BH overestimated near $t_\pi^{\min}$, at any Q^2.

A coherent model of the $e\gamma\pi^+ n$ final state

$$\frac{d\sigma^h}{d\Omega} \propto \left| T^{\mathrm{BH+DVCS}}_{\mathrm{Sull}} + T^{\mathrm{BH+DVCS}}_{\Delta} \right|^2 + \sum_{N^\star} \left| T^{\mathrm{BH}}_{N^\star} \right|^2 = U + h\, P_B\, D$$

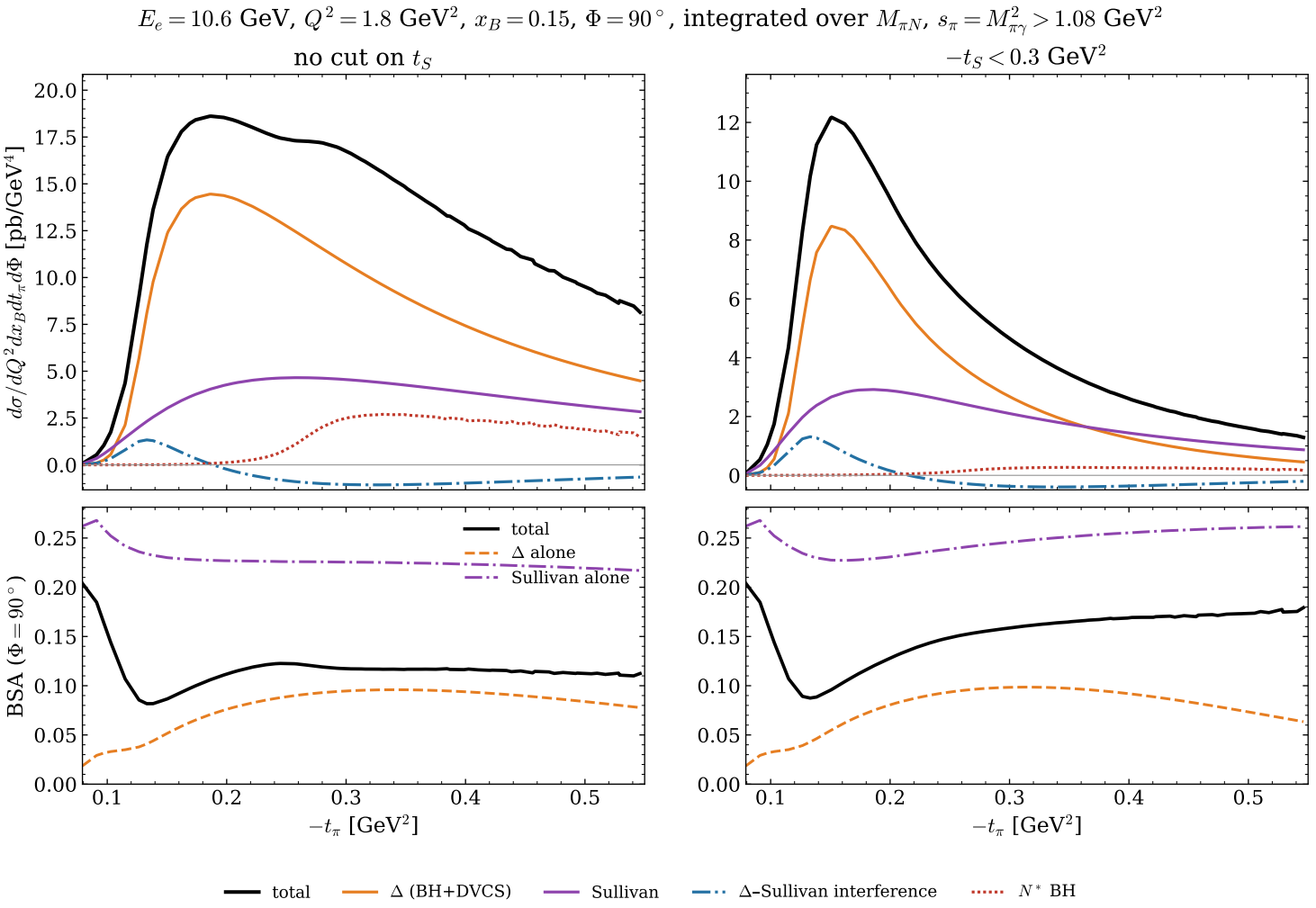


Cross section and BSA of each contribution vs $M_{\pi N}$, $-t_S < 0.3$ GeV^2.

With $N^\star(1440)$, $N^\star(1520)$ and $N^\star(1535)$ only.

- Δ: BH + DVCS, all transition CFFs [3].
- $N^\star$: BH only, $A_{N^\star} = 0 \pm 0.1$ (DVCS predictions not reliable).

Δ contribution is larger than Sullivan at generator level



Generated level

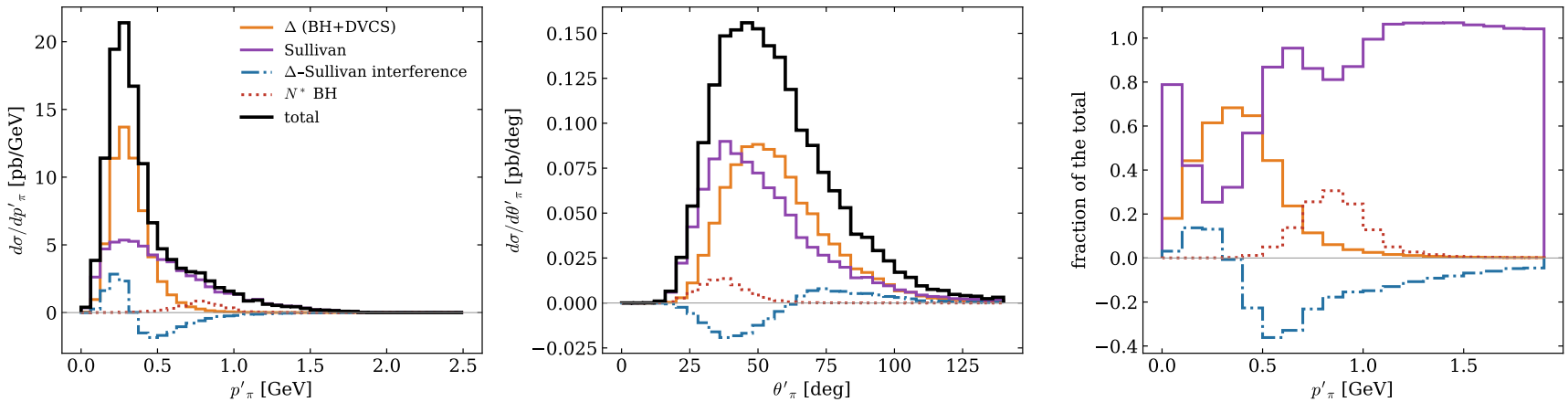
σ_Δ is **2–3 times** σ_{Sull} . . . but after detection: Sullivan 17 555, Δ 9 974 events.

So why more Sullivan than Δ after detection ?

The pion makes the difference

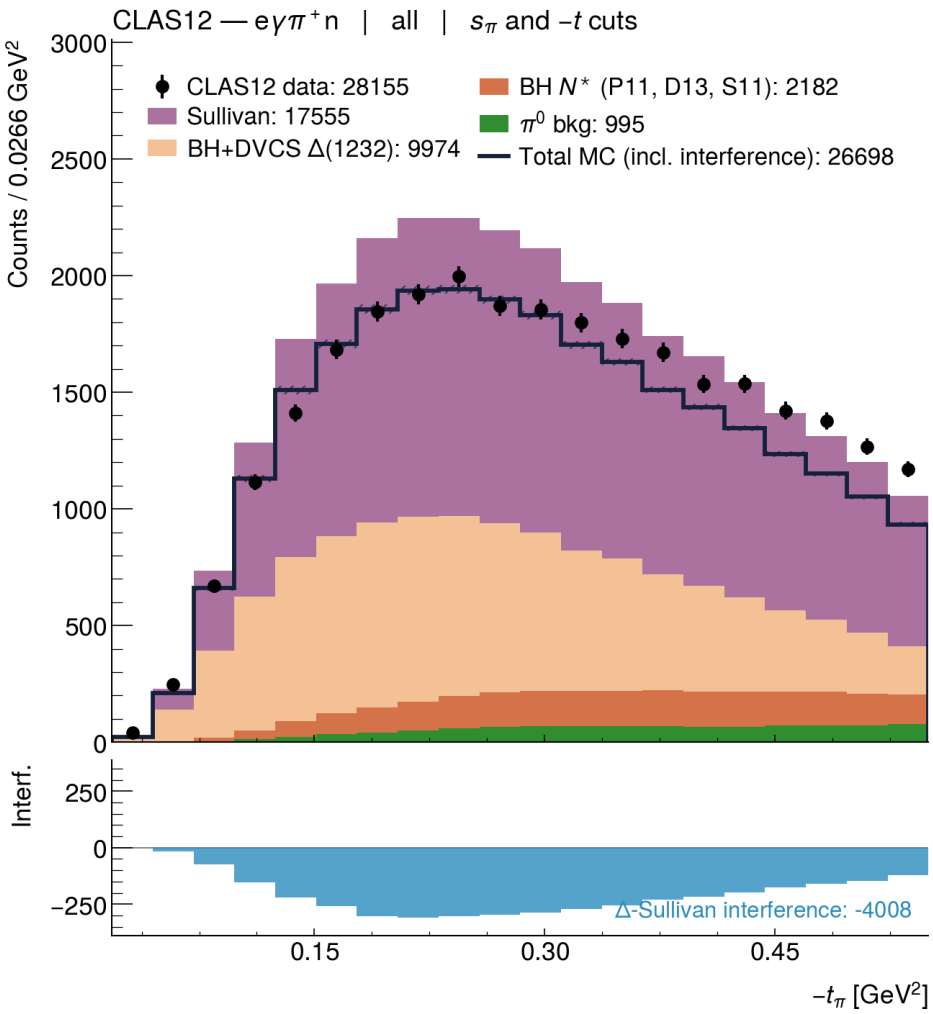
- $\Delta \to \pi^+ n$: **slow** pion, $p_\pi \lesssim 0.5$ GeV.
- Sullivan: harder pion spectrum.
- Low p: CD threshold (0.2 GeV), low efficiency ($\mathrm{SC} \simeq 0.3$–0.6).
- $\Rightarrow \varepsilon_{\mathrm{Sull}}/\varepsilon_{\Delta} \simeq 1.5$.

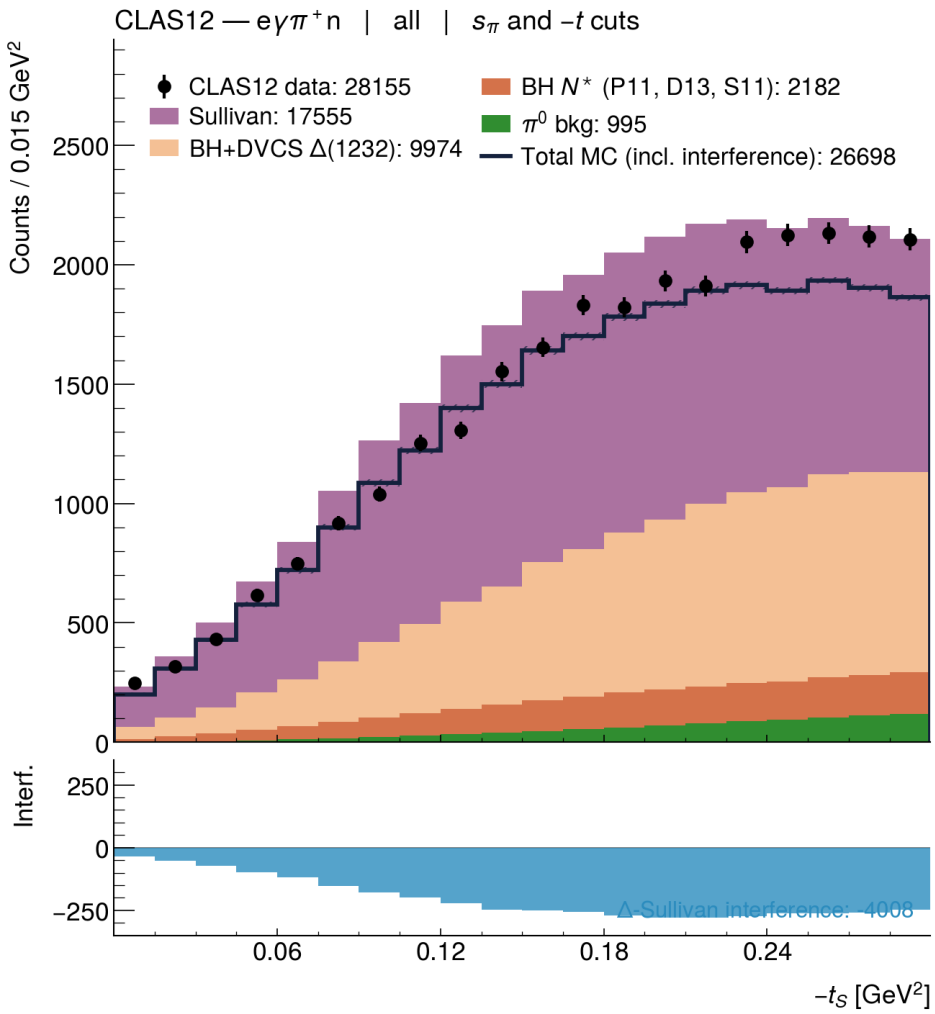
Model without detector, analysis phase space ($Q^2 > 1.0$, $W^2 > 4.0$, $s_\pi > 1.08$, $-t_\pi < 0.55$, $P_e > 2.0$, $P_\gamma > 3.0$, $2.5^\circ < \theta_\gamma < 20^\circ$), $-t_S < 0.3$ GeV^2



Model in the analysis phase space, no detector: π^+ momentum (left), polar angle (middle), fraction of each process vs momentum (right).

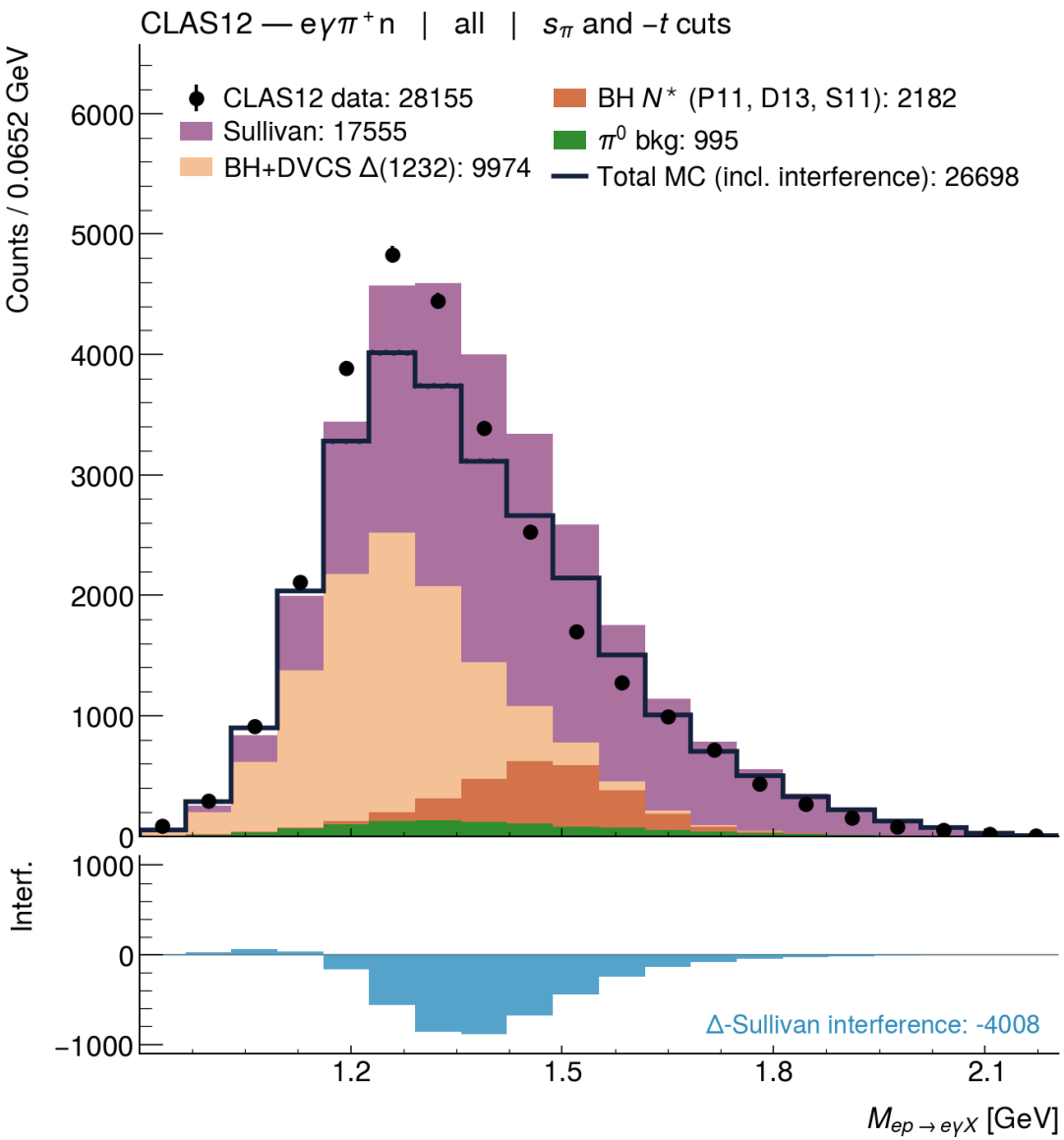
Both t distributions are well described by the new model





Good description of shapes and yields (total within 5%); small differences at large $-t_S$ and $-t_\pi$: missing $N^\star$ DVCS, $N^\star$–Sullivan interference, s/u channels.

What the sample is made of ?



- Low $M_{\pi N}$: **Δ-dominated**.
- High $M_{\pi N}$: **Sullivan-dominated** (up to $\sim 90\%$).
- Overall: $\sim$2/3 Sullivan, $\sim$1/3 Δ.
- **Interference**: up to -26% of the yield (lower panel), **not negligible**.
- N^*: only few % above 1.4 GeV.
- π^0: a few %.

Extraction of $A_{LU}^{\sin\phi}$

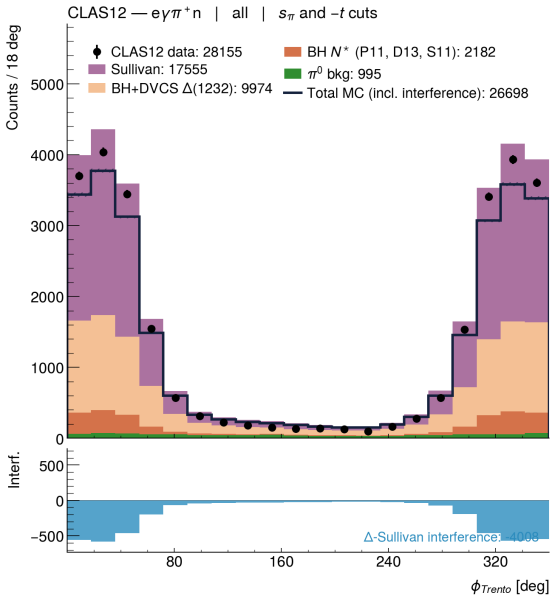
Unbinned maximum likelihood

$$f(h_i, \phi_i; A) = 1 + h_i \, P_B \, A \, \sin\phi_i, \qquad \ln \mathcal{L}(A) = \sum_i \ln f(h_i, \phi_i; A)$$

- Uses every event, **without binning in** ϕ: no sparsely populated ϕ bins.
- Uncertainty from the curvature of $\ln \mathcal{L}$ (Fisher information).
- $P_B = 0.89 \pm 0.025$: effective polarization.

Why it matters here

The ϕ distribution is strongly peaked at $\phi \approx 0$ (BH), and the statistics per kinematic bin is limited: a binned fit in ϕ would suffer from empty and poorly populated bins.



Interpretation: forward folding

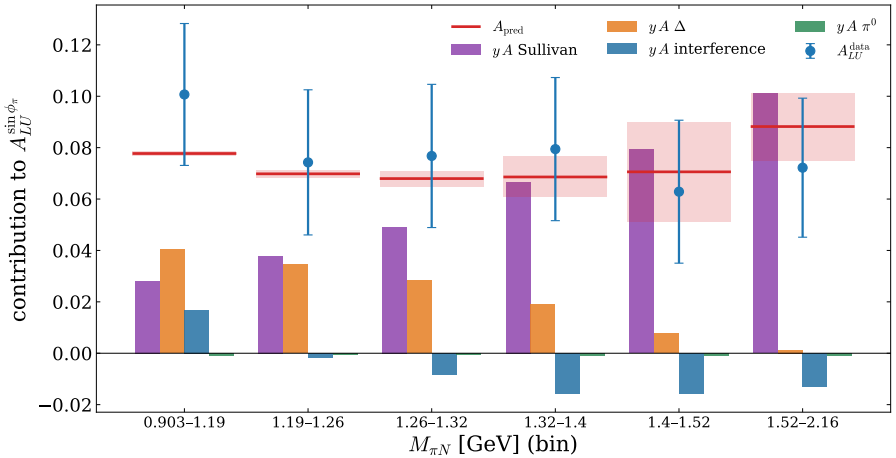
- The full model goes through the **whole simulation**: acceptance, reconstruction, cuts, binning.
- Asymmetry extracted as:

$$A_{\mathrm{MC}} = \frac{\sum D \sin\phi}{\sum U \sin^2\phi}$$

(equivalent to the likelihood fit).

- $+\pi^0$ with its measured fraction and asymmetry.

Reference comparison, all detector effects included... but needs the CLAS12 simulation.

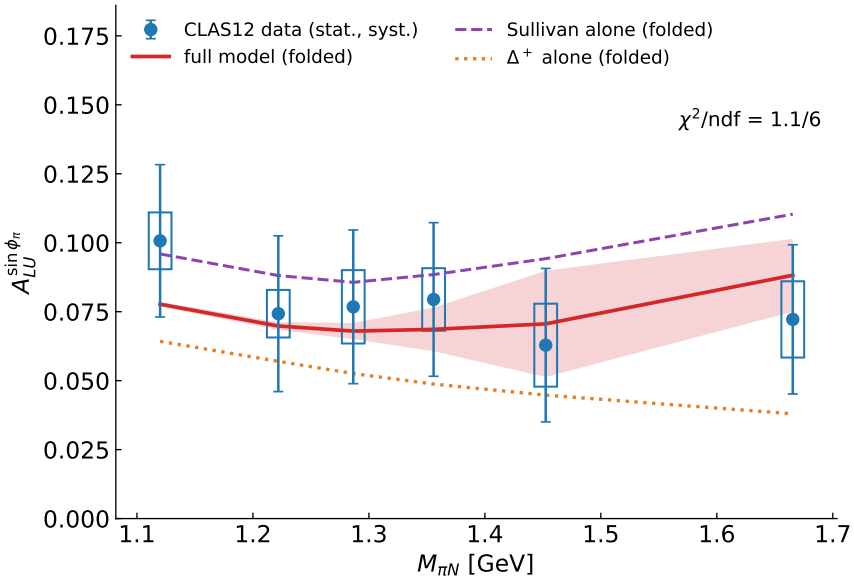


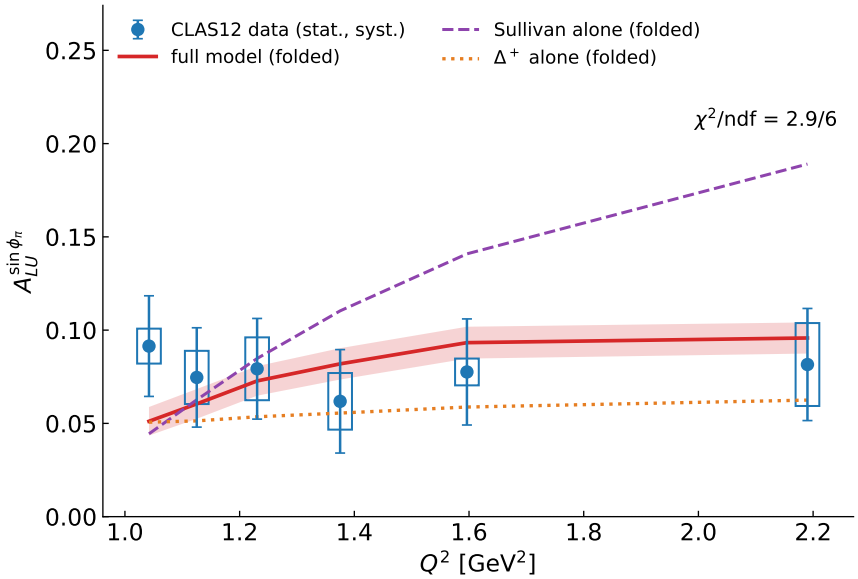
Decomposition: Δ dominant at low $M_{\pi N}$, Sullivan above; negative interference.

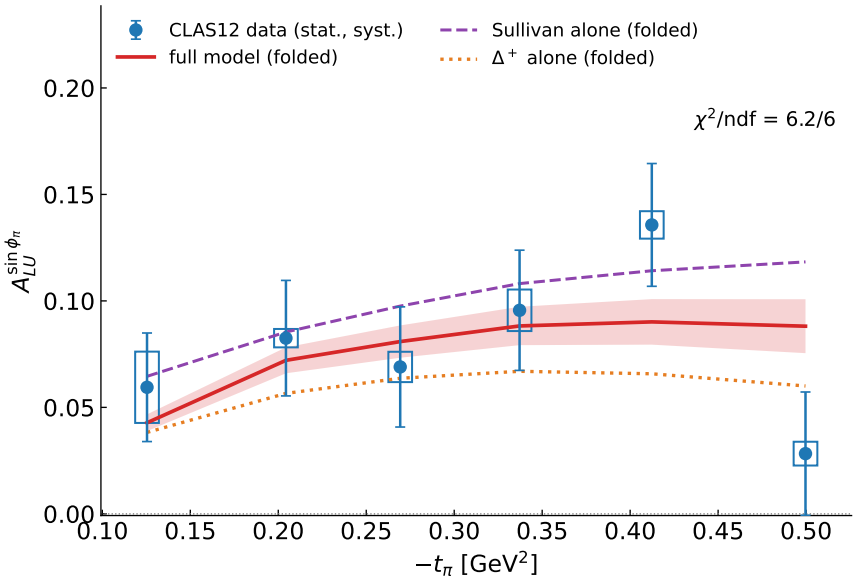
Quick test for any model

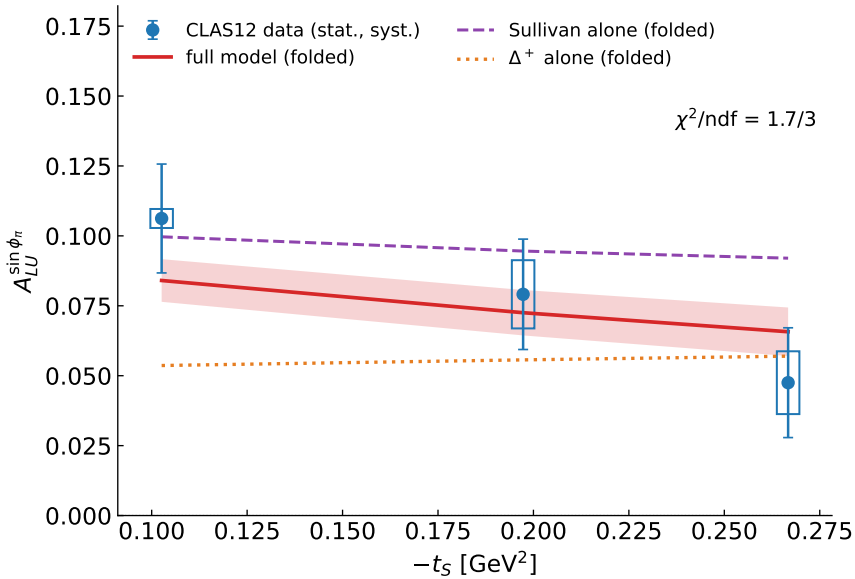
Average the model over each bin at **generated level**, no detector: reproduces well the folding (backup). Needs only the bins and the kinematic cuts.

Data versus the folded model









Summary and outlook

Summary

- **First measurement** of the BSA of $e\gamma\pi^+ n$ in the Sullivan DVCS region, versus $M_{\pi N}$, Q^2, $-t_\pi$ and $-t_S$.
- A coherent model (Sullivan, Δ BH+DVCS, their interference, $N^\star$) describes the data well.
- Interpreting the BSA in terms of pion GPDs requires a **joint treatment of the baryon resonances and the Sullivan process**: more theory work is needed to describe all the contributions to this final state and their impact on the BSA.

Outlook

- **EIC**: the $N \to \Delta$ transition is isovector, gluons are isoscalar $\Rightarrow$ Δ suppressed at small x but not all the $N^\star$ contributions.
- **Event generator** with these models, for CLAS12 and the EIC.
- Analysis note: first review round answered.

Bibliography I

[1] Henk Blok et al. "Charged pion form factor between Q^2=0.60 and 2.45 GeV^2. I. Measurements of the cross section for the ^{1}H$(e, e'\pi^+)n$ reaction". In: *Physical Review. C, Nuclear Physics* 78 (Oct. 2008). ISSN: ISSN PRVCAN. DOI: 10.1103/PhysRevC.78.045202. URL: https://www.osti.gov/biblio/956094.

[2] D. Amrath, M. Diehl, and J.-P. Lansberg. "Deeply virtual Compton scattering on a virtual pion target". In: *Eur.Phys.J.* C58 (2008), pp. 179–192. DOI: 10.1140/epjc/s10052-008-0769-1. arXiv: 0807.4474 [hep-ph].

[3] Kirill M. Semenov-Tian-Shansky and Marc Vanderhaeghen. "Deeply-virtual Compton process $e^- N \to e^- \gamma \pi N$ to study nucleon to resonance transitions". In: (2023). arXiv: 2303.00119 [hep-ph]. URL: https://arxiv.org/abs/2303.00119.

Bibliography II

[4] José Manuel Morgado Chavez et al. "Pion GPDs: A path toward phenomenology". In: *arXiv:2110.06052* (Oct. 2021). arXiv: 2110.06052 [hep-ph].

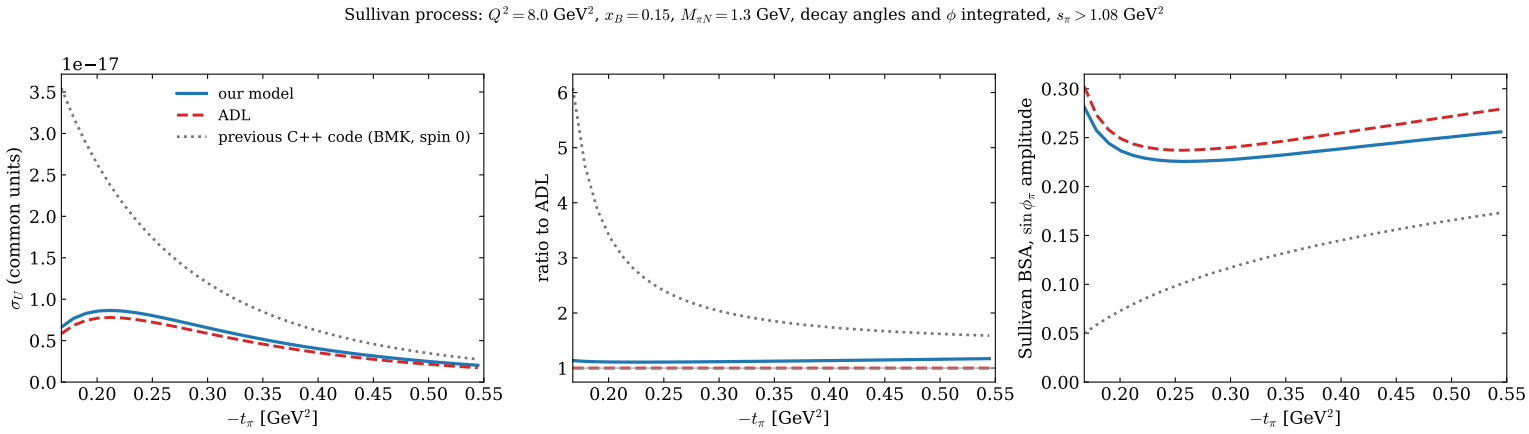
[5] M. Defurne et al. "E00-110 experiment at Jefferson Lab Hall A: Deeply virtual Compton scattering off the proton at 6 GeV". In: *Phys. Rev.* C92.5 (2015), p. 055202. DOI: 10.1103/PhysRevC.92.055202. arXiv: 1504.05453 [nucl-ex].

Backup: π^0 background estimation

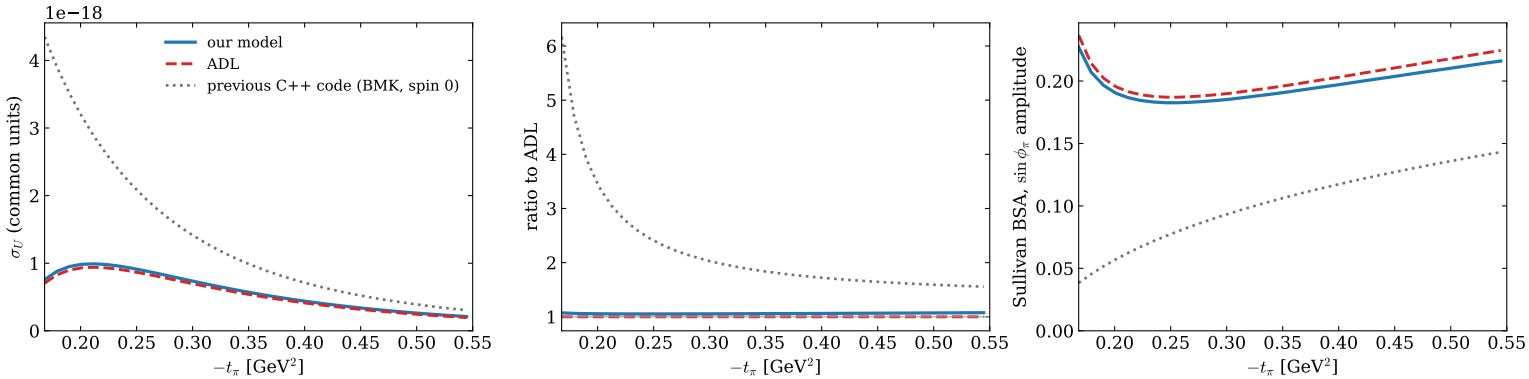
Method [5]

- Reconstructed π^0 in data ($ep \to e\pi^0\pi^+ n$) decayed $N = 1000$ times and passed through GEMC.
- Weight $w_i = 1/N^i_{\pi^0}$ for each fake DVCS event.
- 2–8% of the sample, asymmetry -0.018 ± 0.005: changes the prediction by ~ 0.001.

Backup: ADL and our model at large Q^2



$Q^2 = 8$ GeV^2

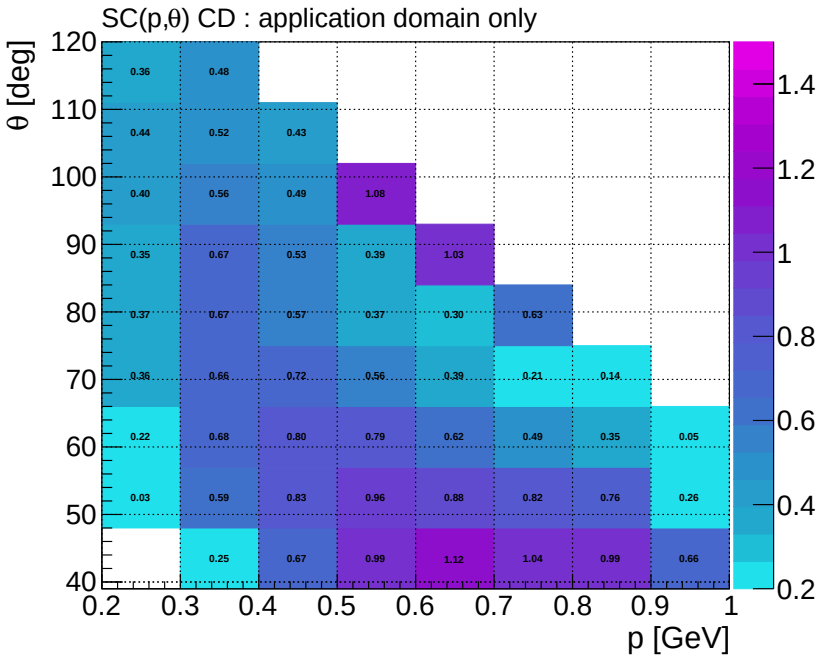


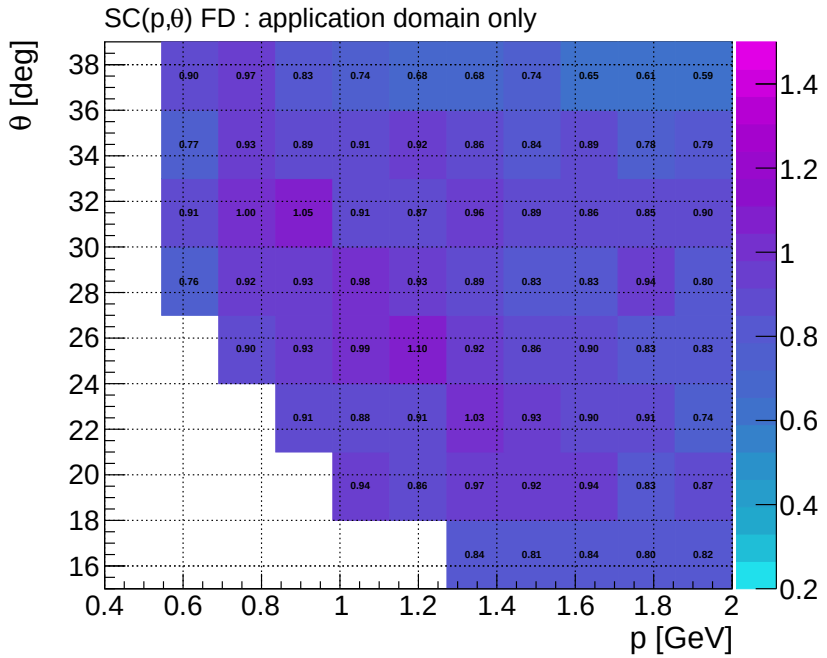
$Q^2 = 16$ GeV^2

Same $x_B = 0.15$, $M_{\pi N} = 1.30$ GeV; beam energy scaled with Q^2 to keep y fixed; no cut on t_S.

Backup: π^+ efficiency — tag and probe with ρ^0

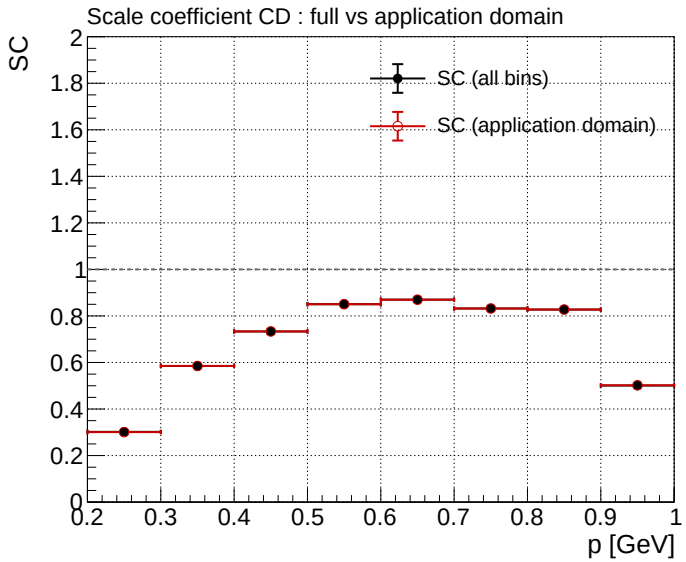
$ep \to ep\rho^0 \to ep\pi^+\pi^-$: the π^+ is predicted from e, p, π^-; $\varepsilon \times \mathrm{Acc} = N_{\mathrm{found}}/N_{\mathrm{predicted}}$ in data and simulation; $\mathrm{SC}(p,\theta) = \varepsilon_{\mathrm{data}}/\varepsilon_{\mathrm{MC}}$, 2D map in the CD and the FD ($\theta_B = 39°$), applied as a weight to the simulation. The domain of validity is a **fiducial cut** in data and simulation. Injection test: known inefficiency recovered (pulls rms 0.96 CD, 1.11 FD).

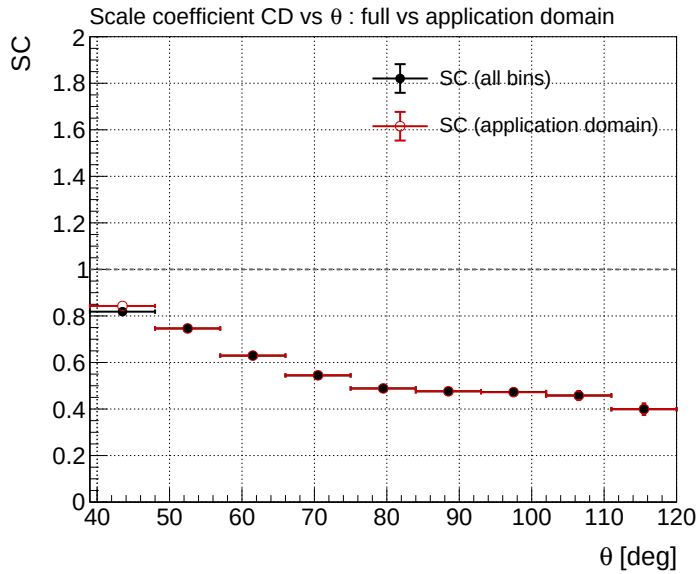


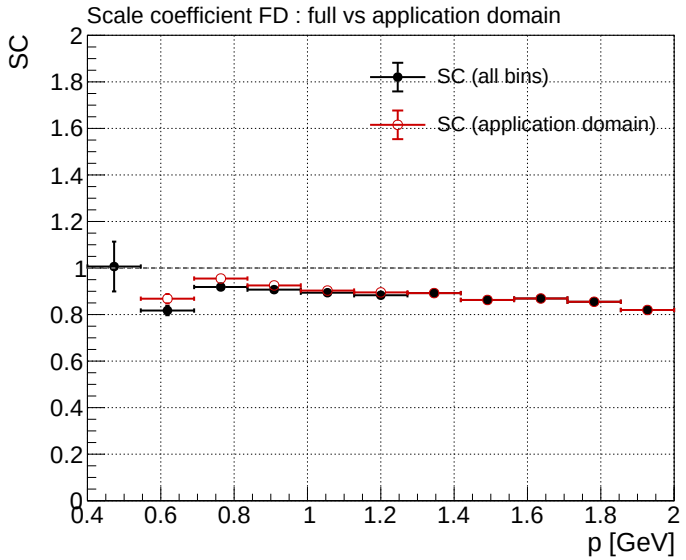


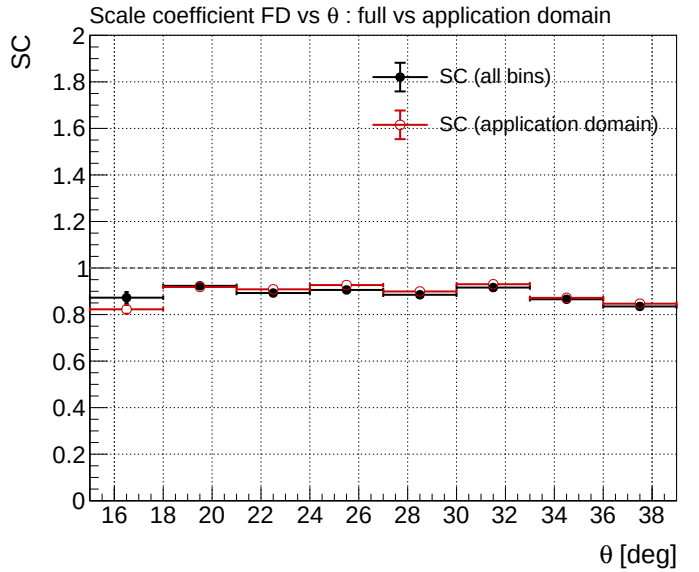
SC in (p,θ) within the domain of validity: CD (left), FD (right).

Backup: π^+ efficiency — scale coefficients







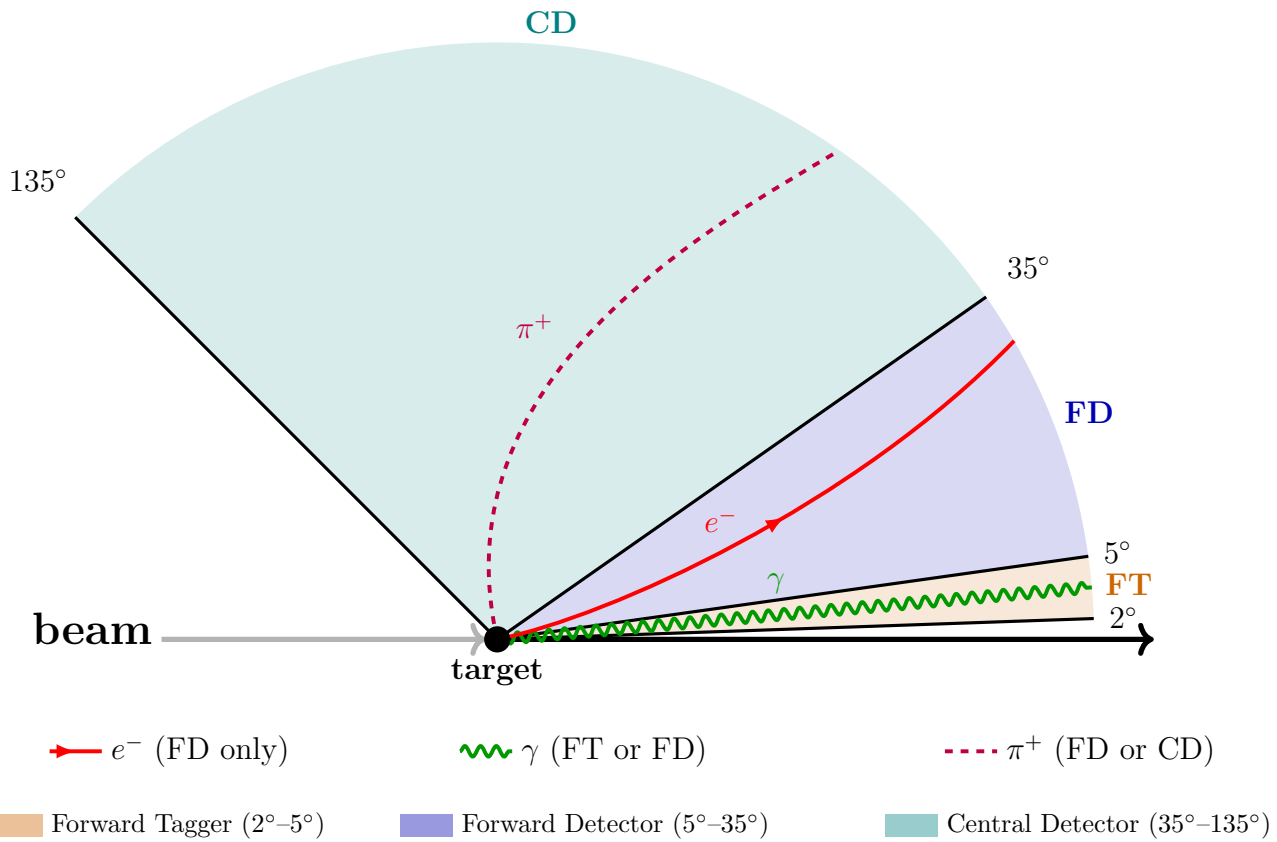


CD (top): SC from 0.3 to 0.87 with p, strong θ dependence (0.82 $\rightarrow$ 0.40) $\Rightarrow$ 2D map. FD (bottom): nearly flat, 0.82–0.92.

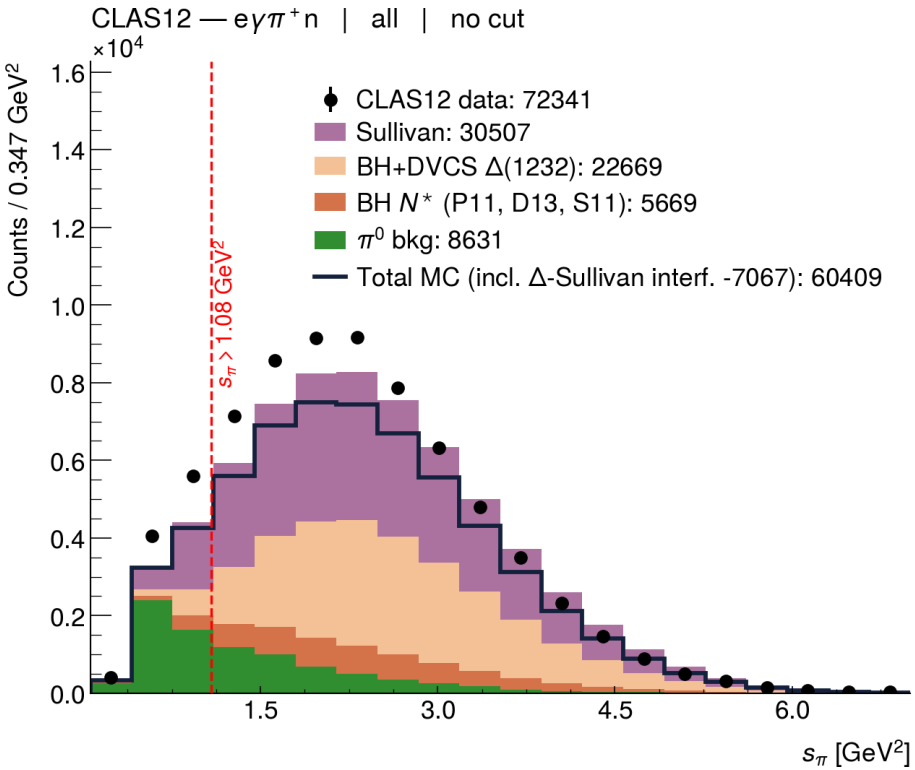
Event topology in CLAS12

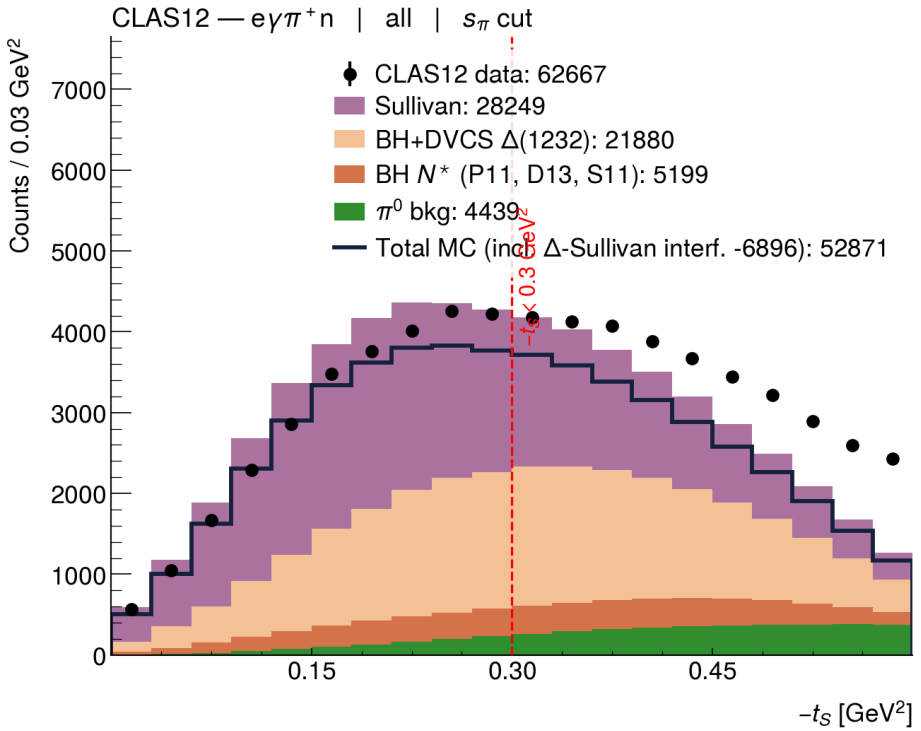
- **Photon**: FT and FD.
- **Pion**: FD and CD.
- **Electron**: FD.

- Final state: $e' n \gamma \pi^+$.
- Detected: e', γ, π^+.
- Neutron: missing mass.



The two cuts that select the Sullivan region



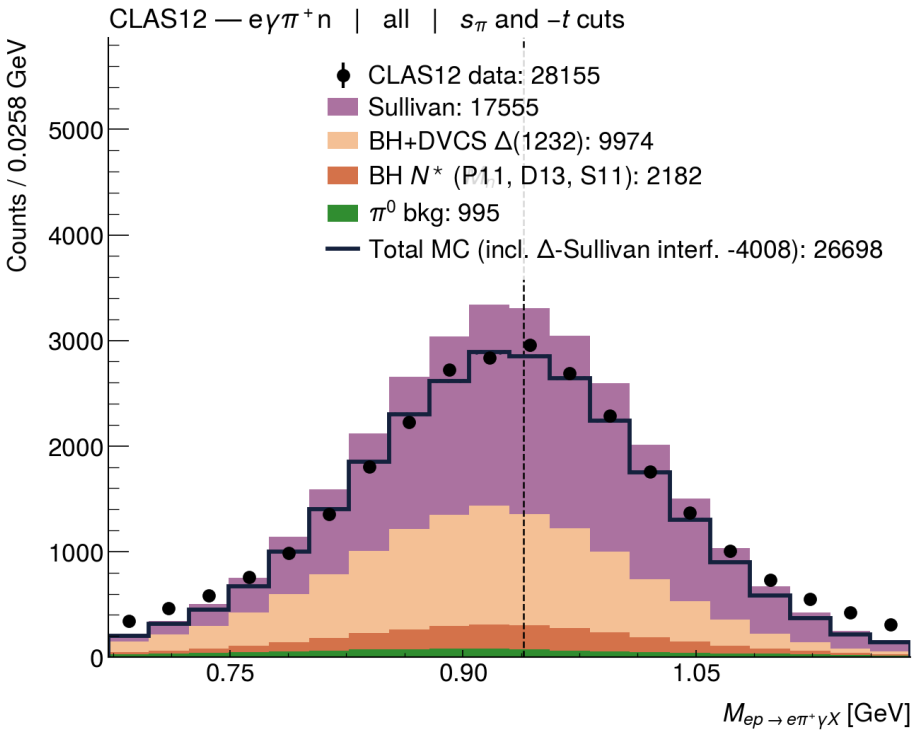


$s_\pi = (p_\pi + q)^2 > 1.08$ GeV^2: removes the region of the ρ^+.

$-t_S < 0.3$ GeV^2: close to the pion pole, where the Sullivan process is enhanced and the virtual pion is quasi-real.

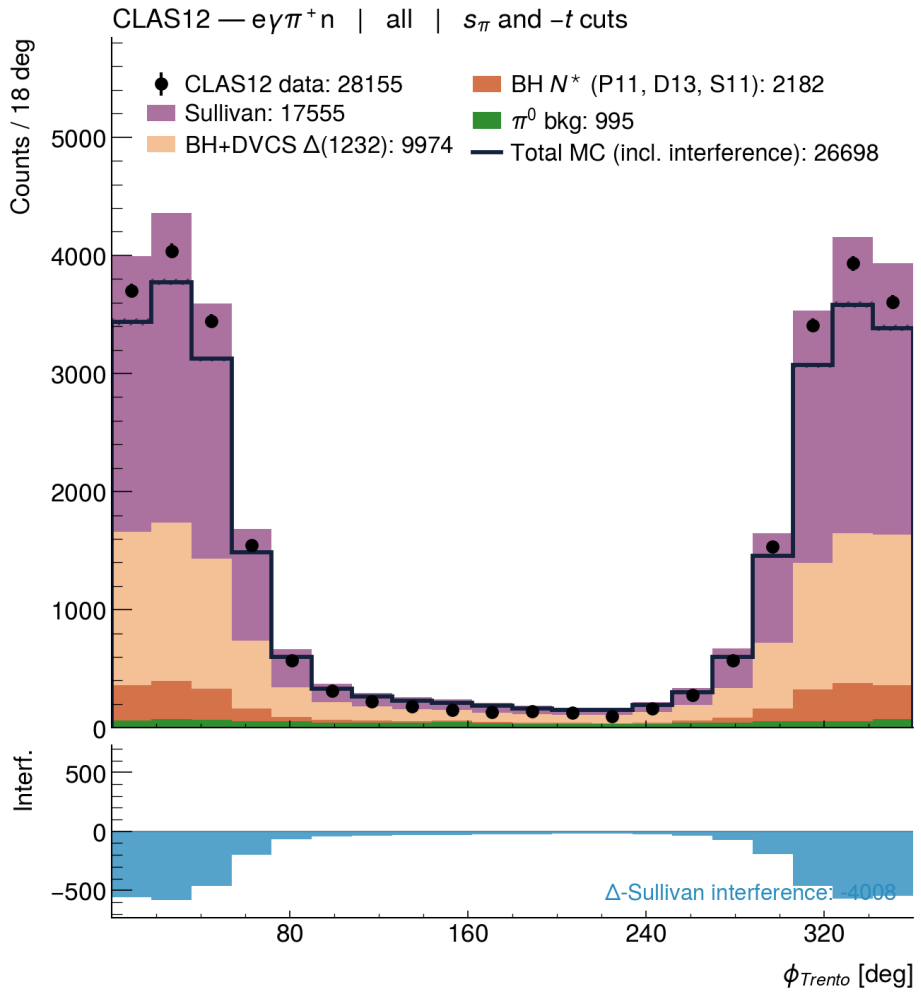
Also: $Q^2 > 1$ GeV^2, $W^2 > 4$ GeV^2, $-t_\pi < 0.55$ GeV^2, exclusivity on the missing neutron mass.

Exclusivity and the ϕ distribution



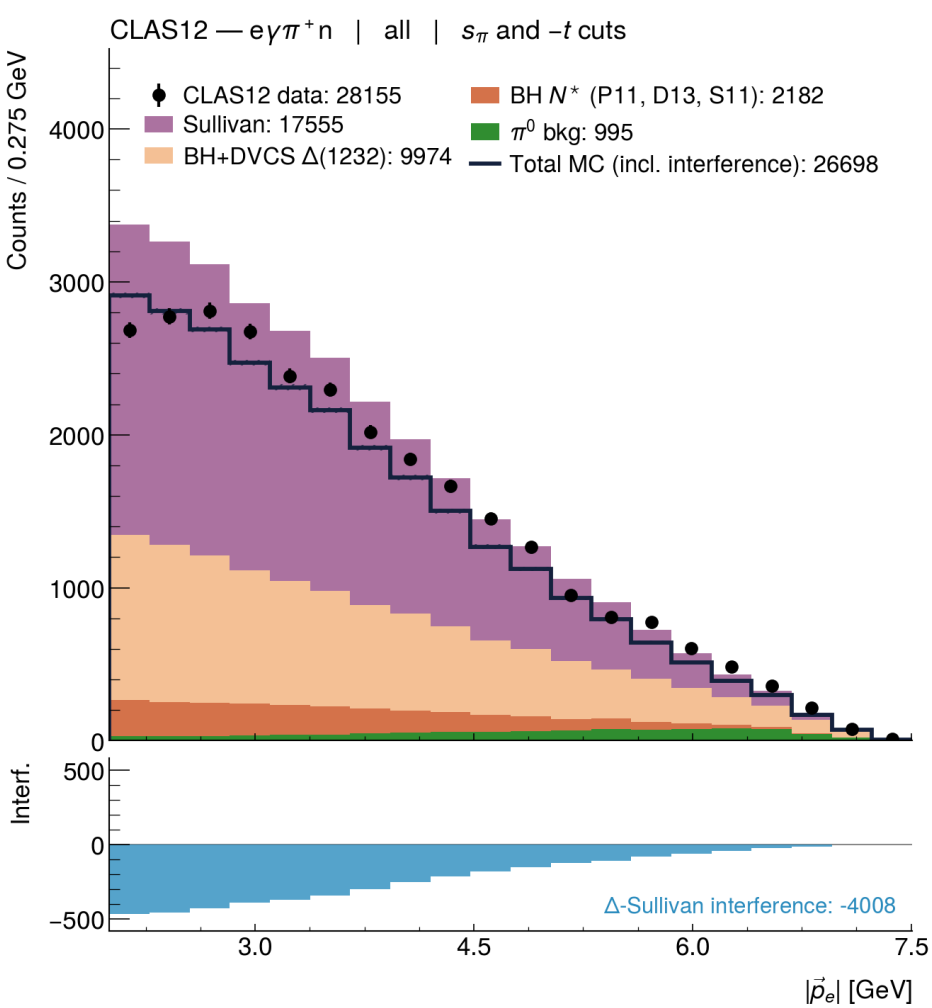
Missing neutron mass: clear peak at m_n.

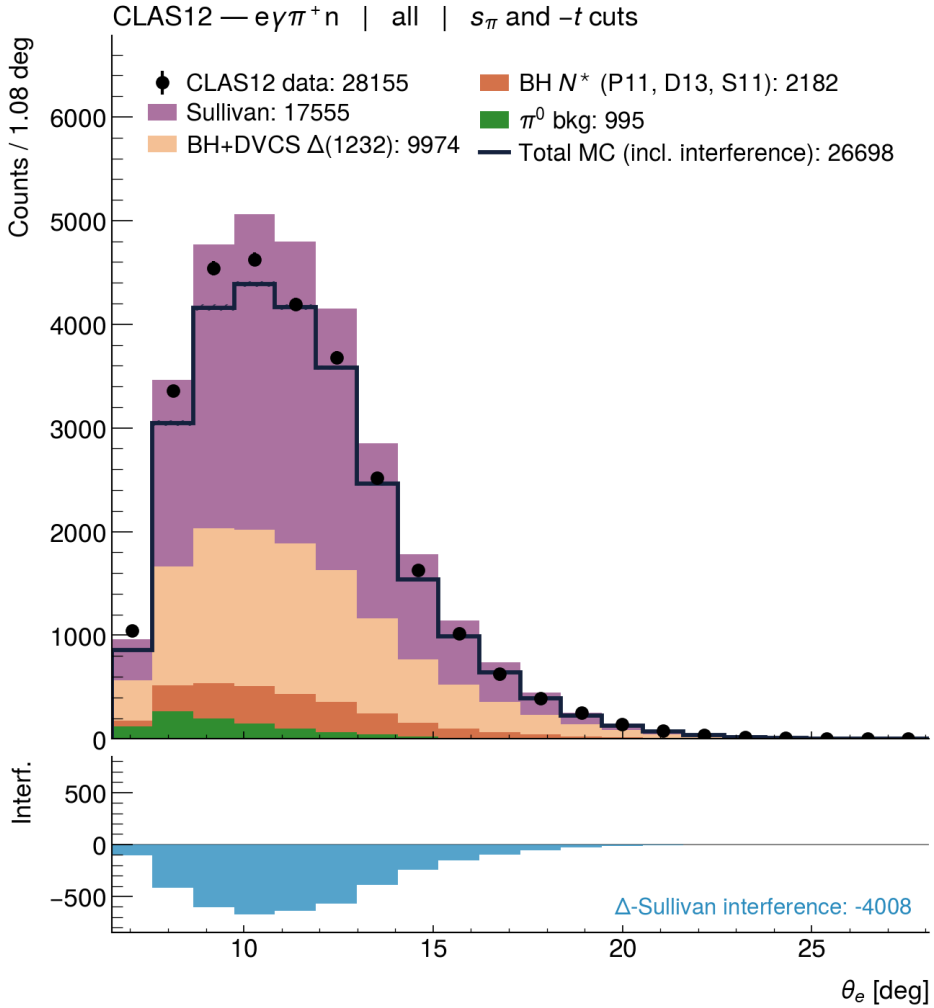
The sum of the contributions describes the data well (dark blue line).



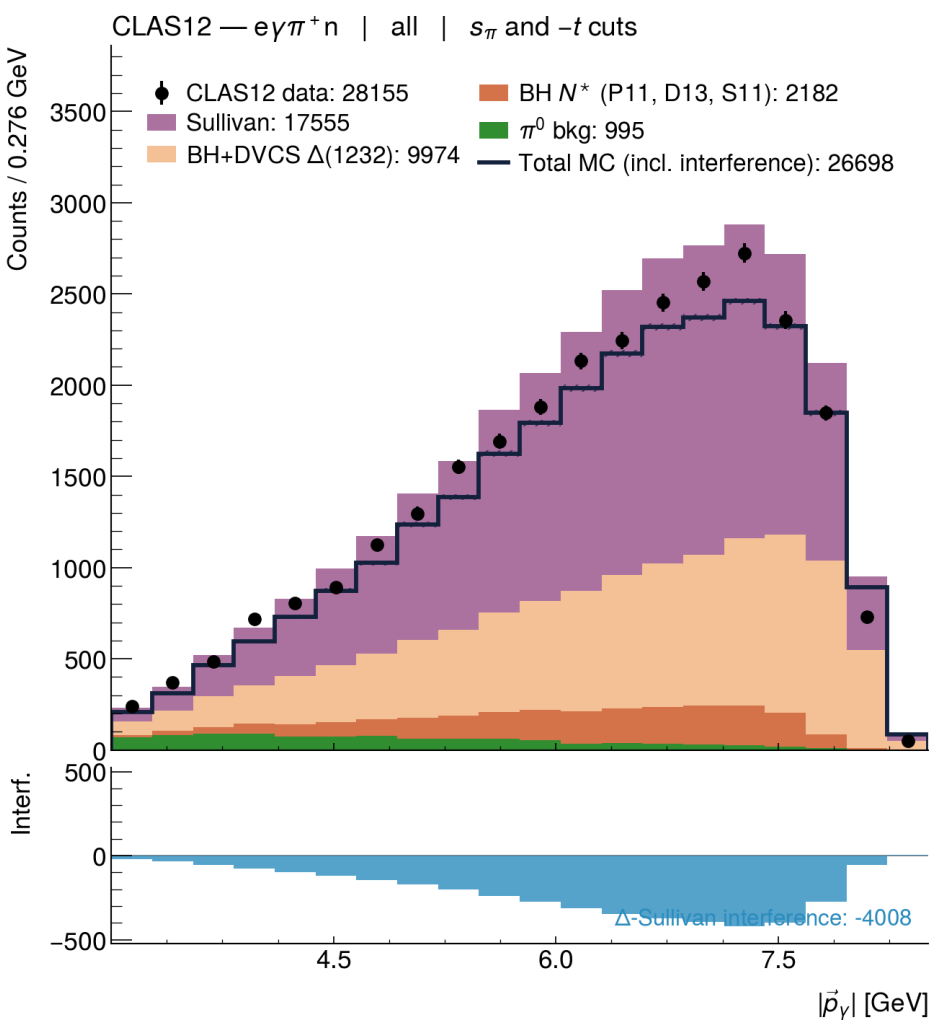
ϕ_π (Trento): BH-driven, peaked at $\phi \approx 0$.

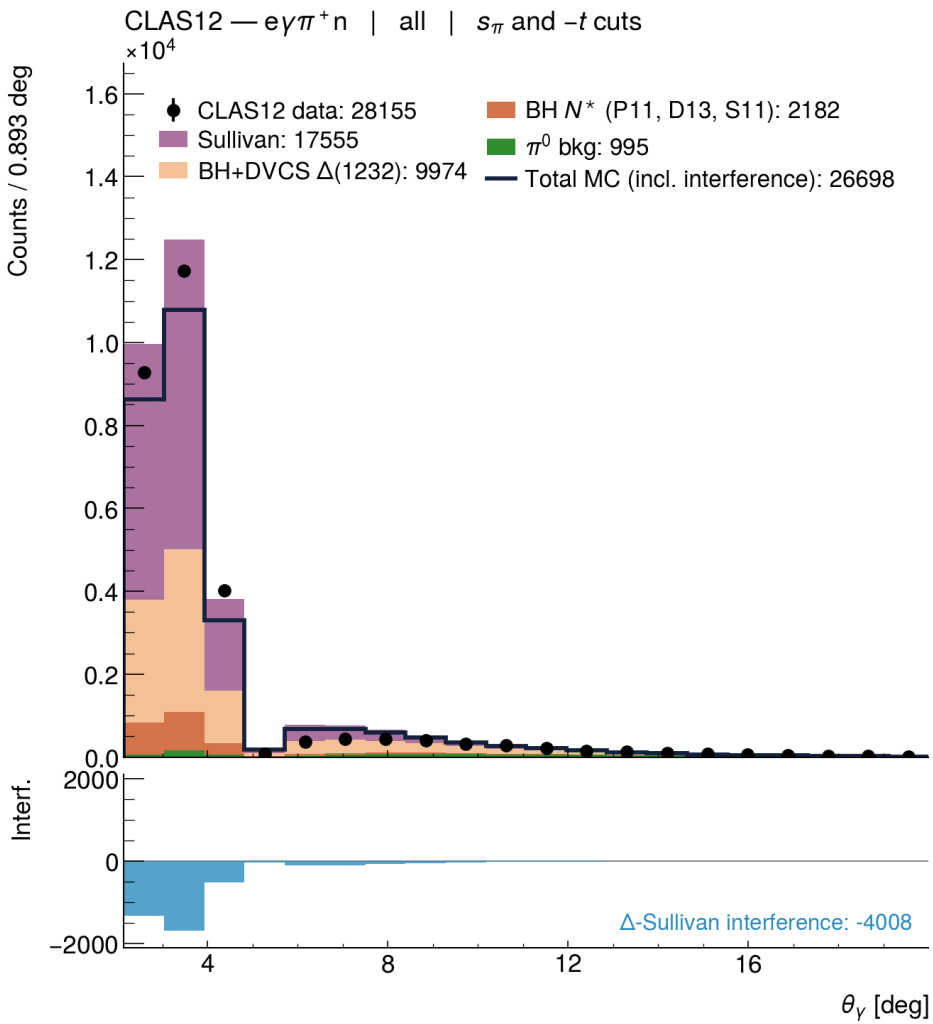
Backup: kinematic distributions



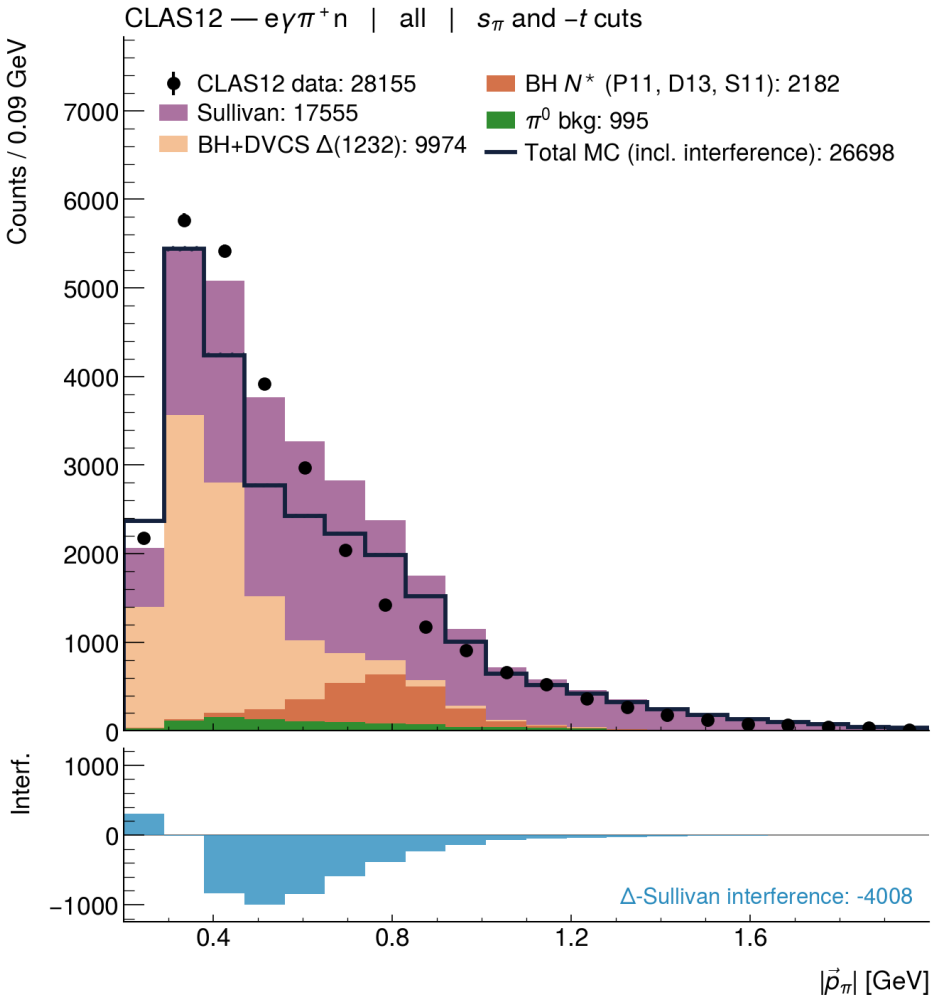


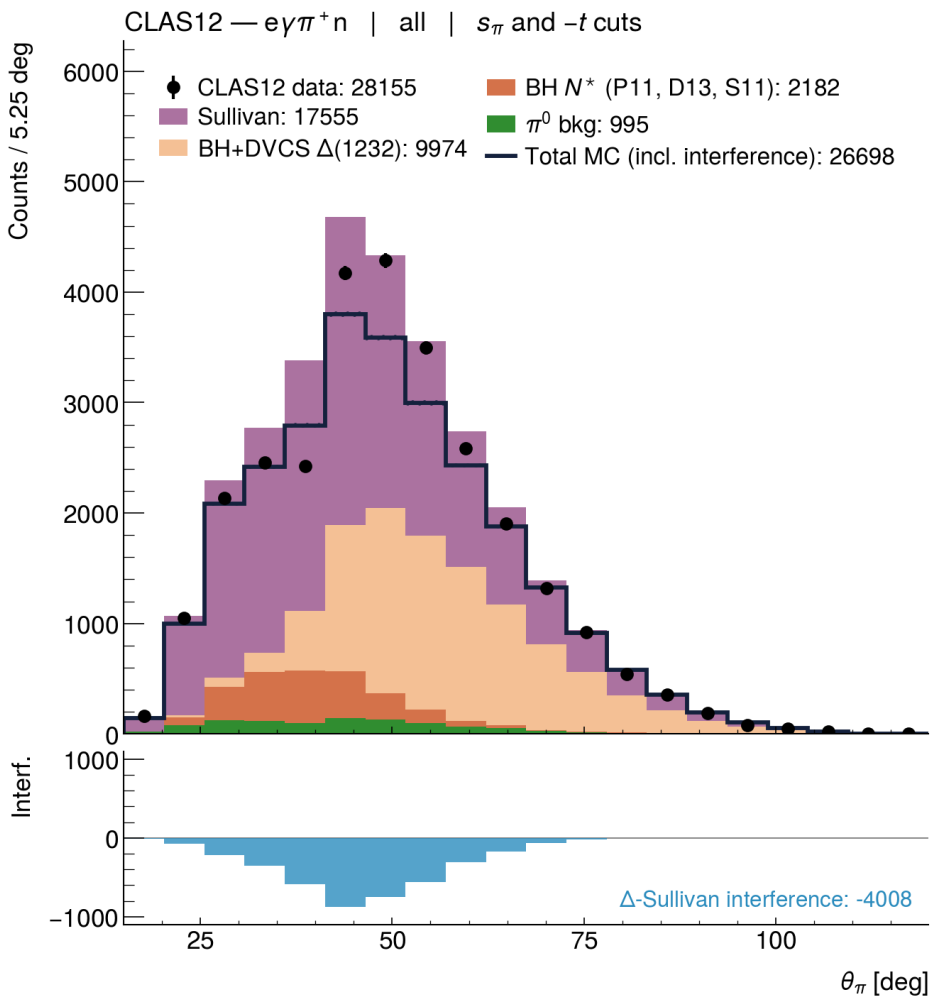
Backup: kinematic distributions



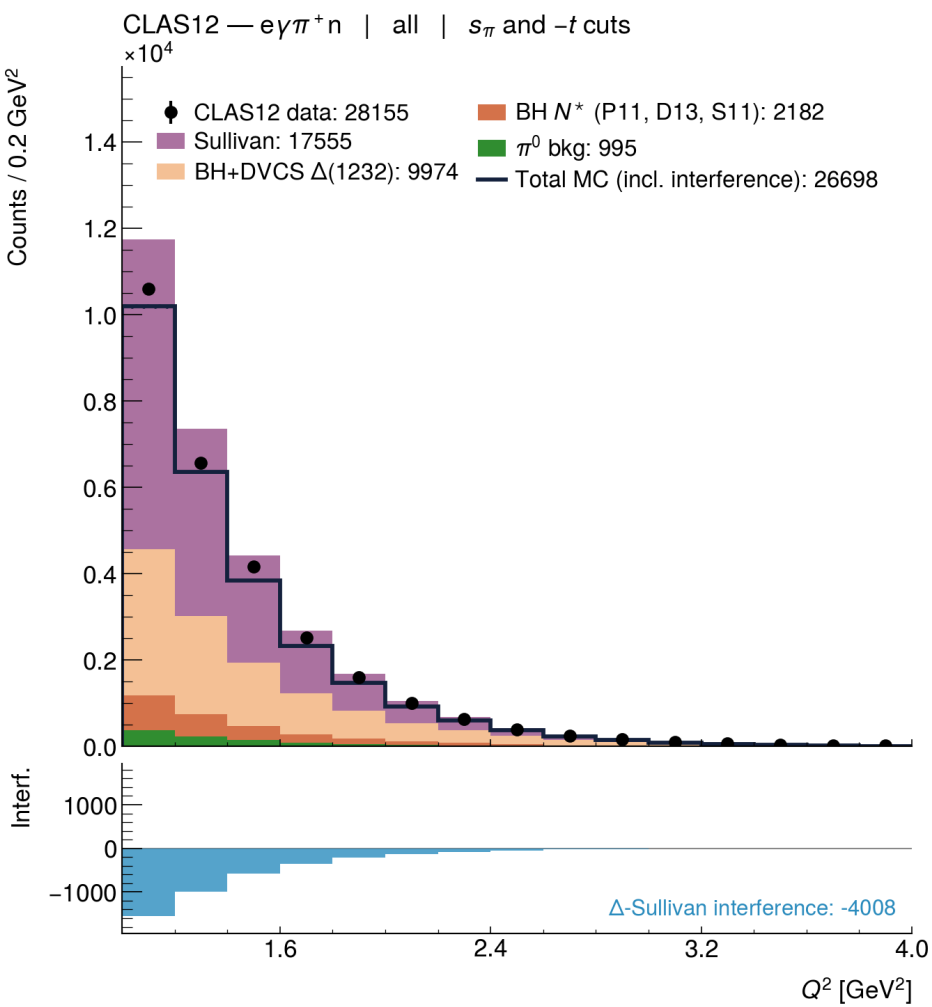


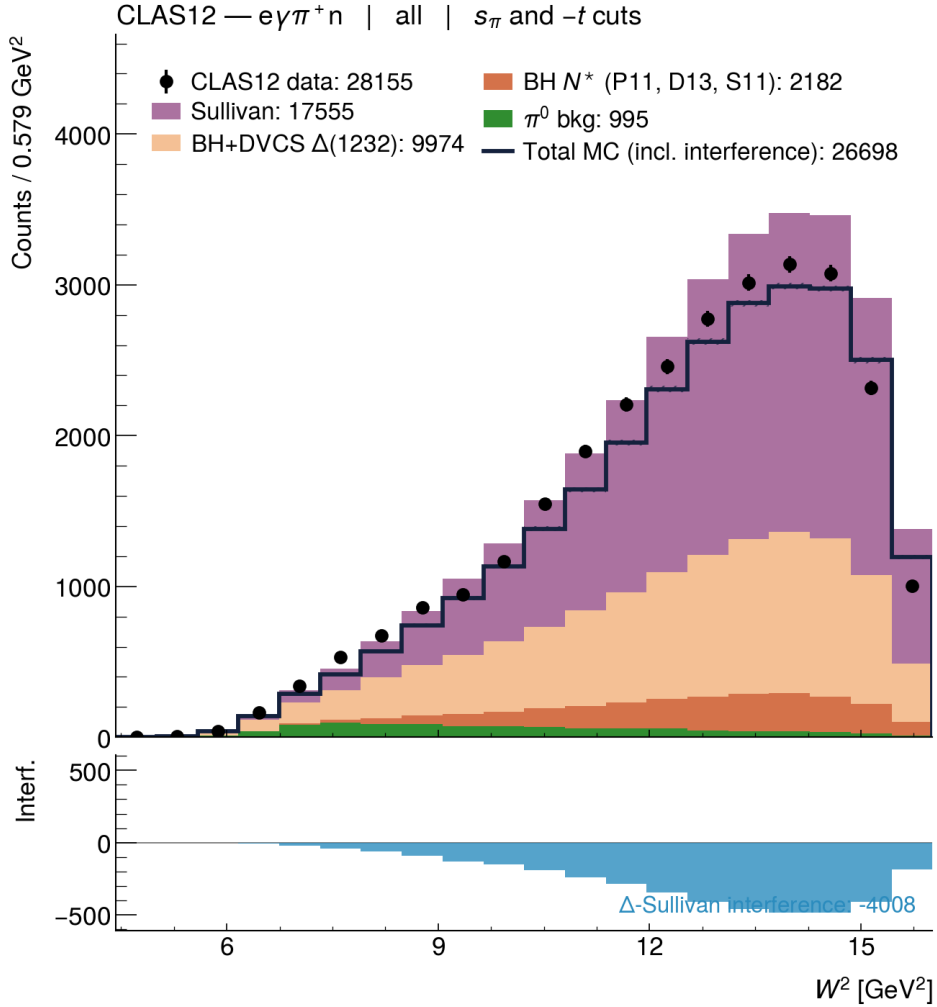
Backup: kinematic distributions



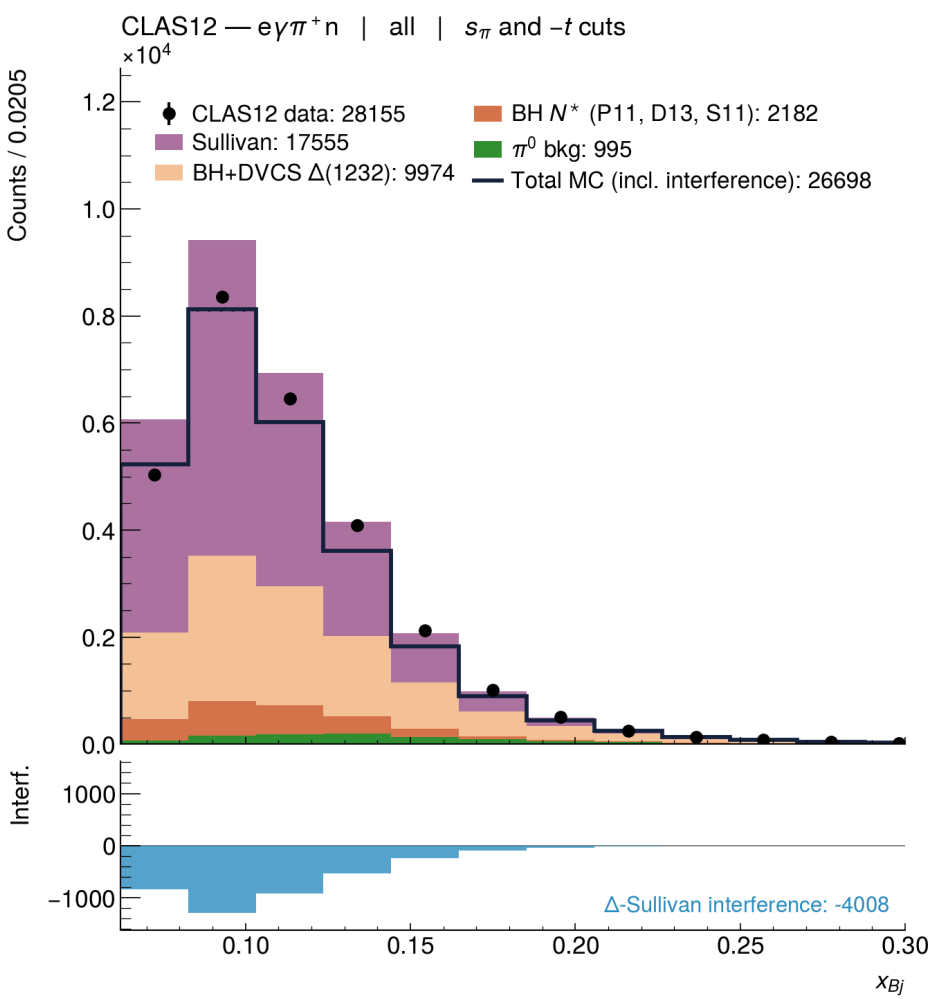


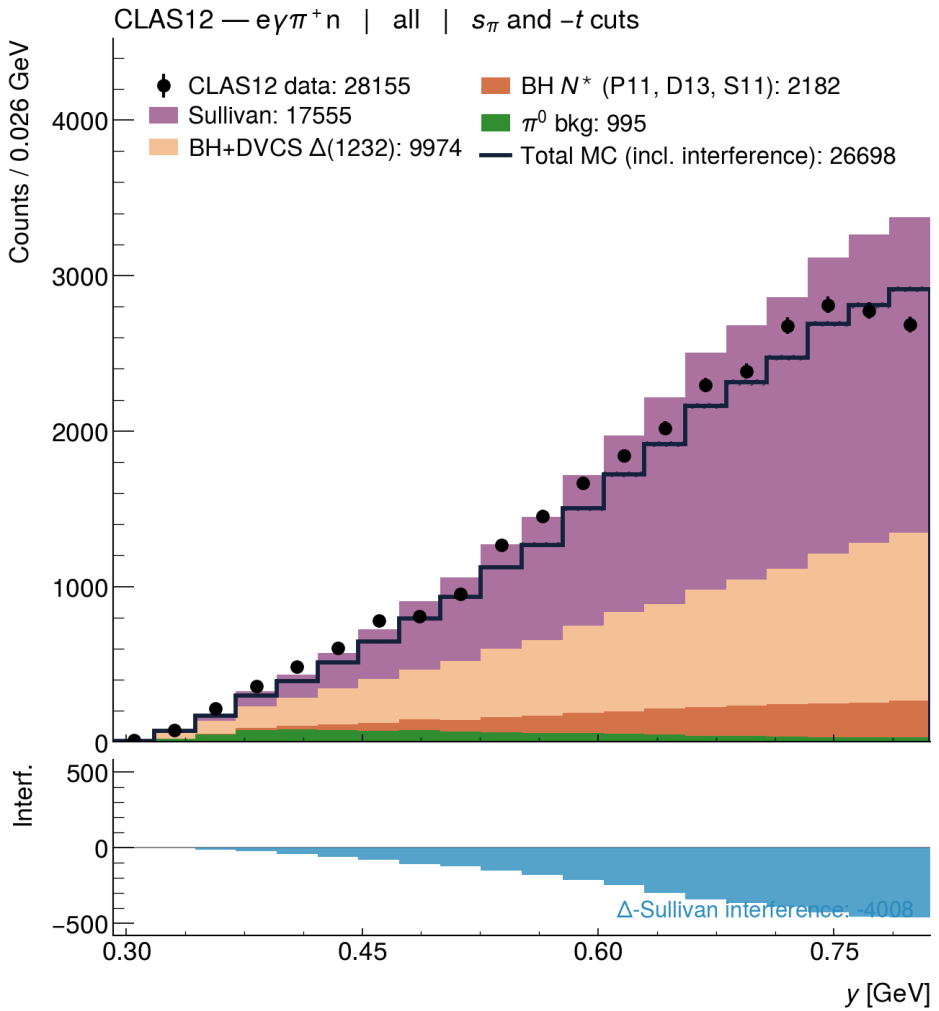
Backup: kinematic distributions



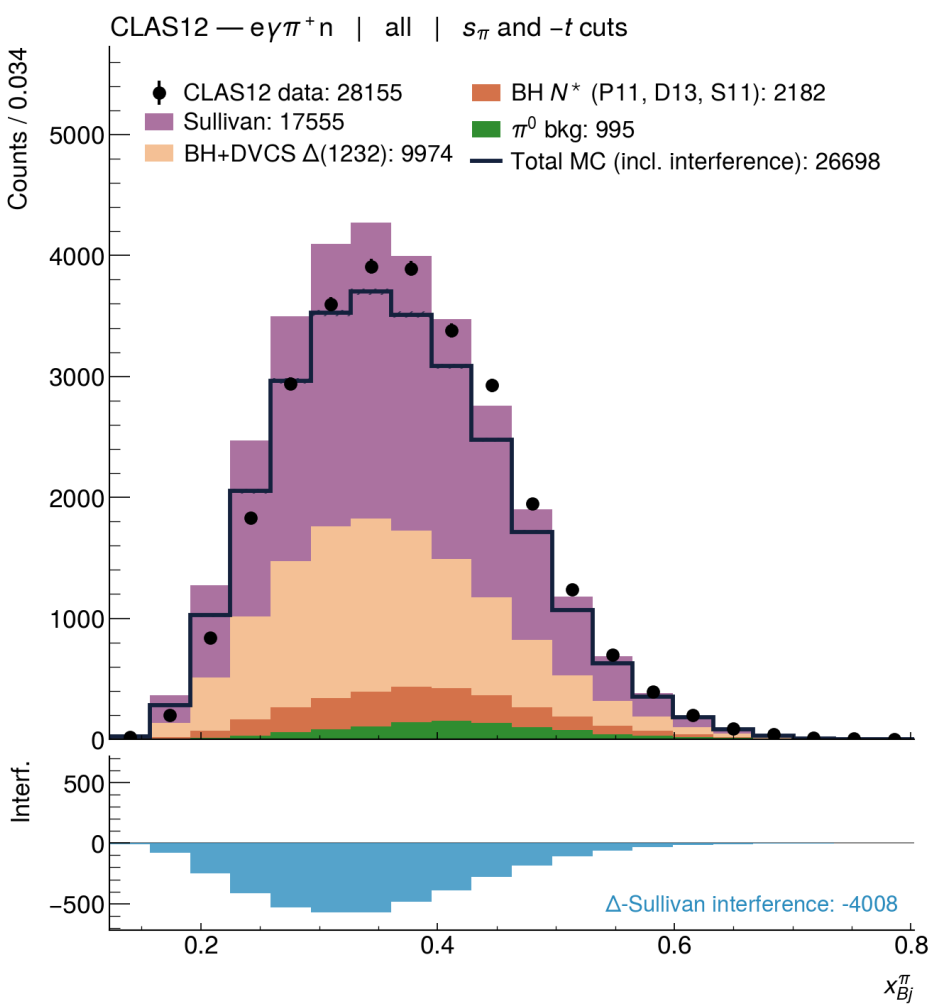


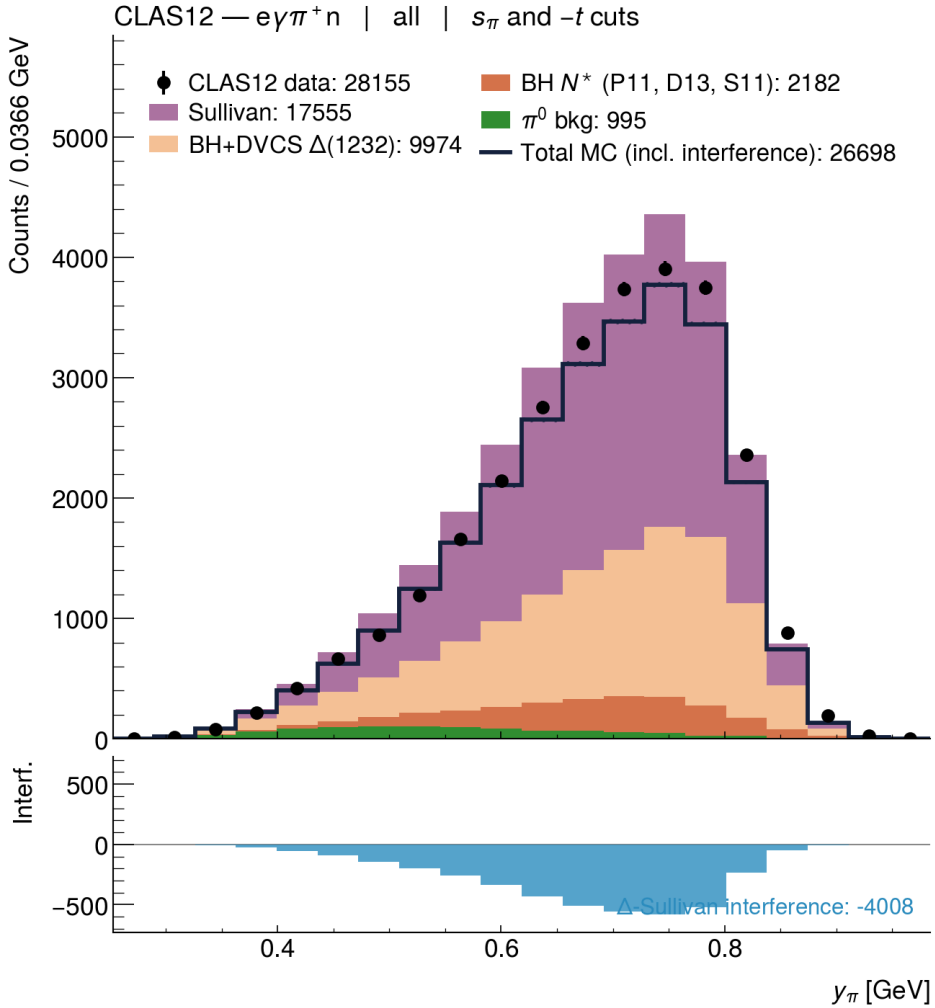
Backup: kinematic distributions



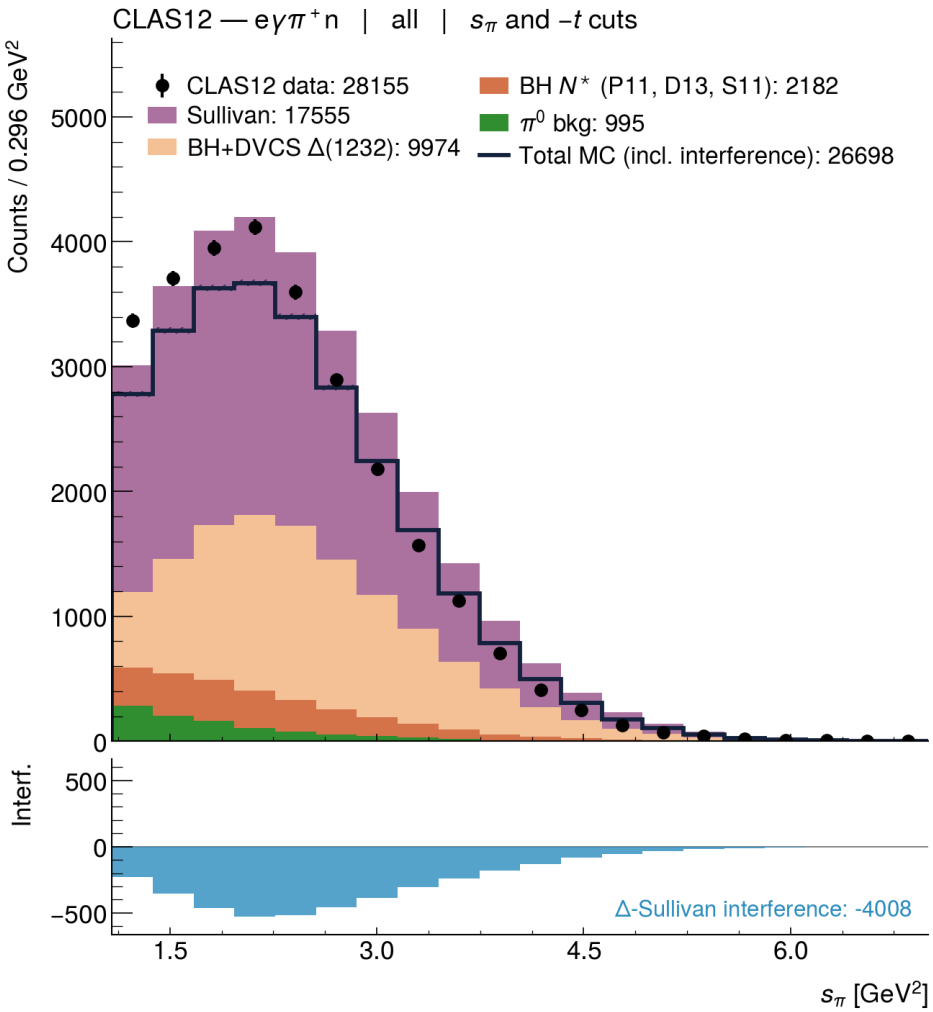


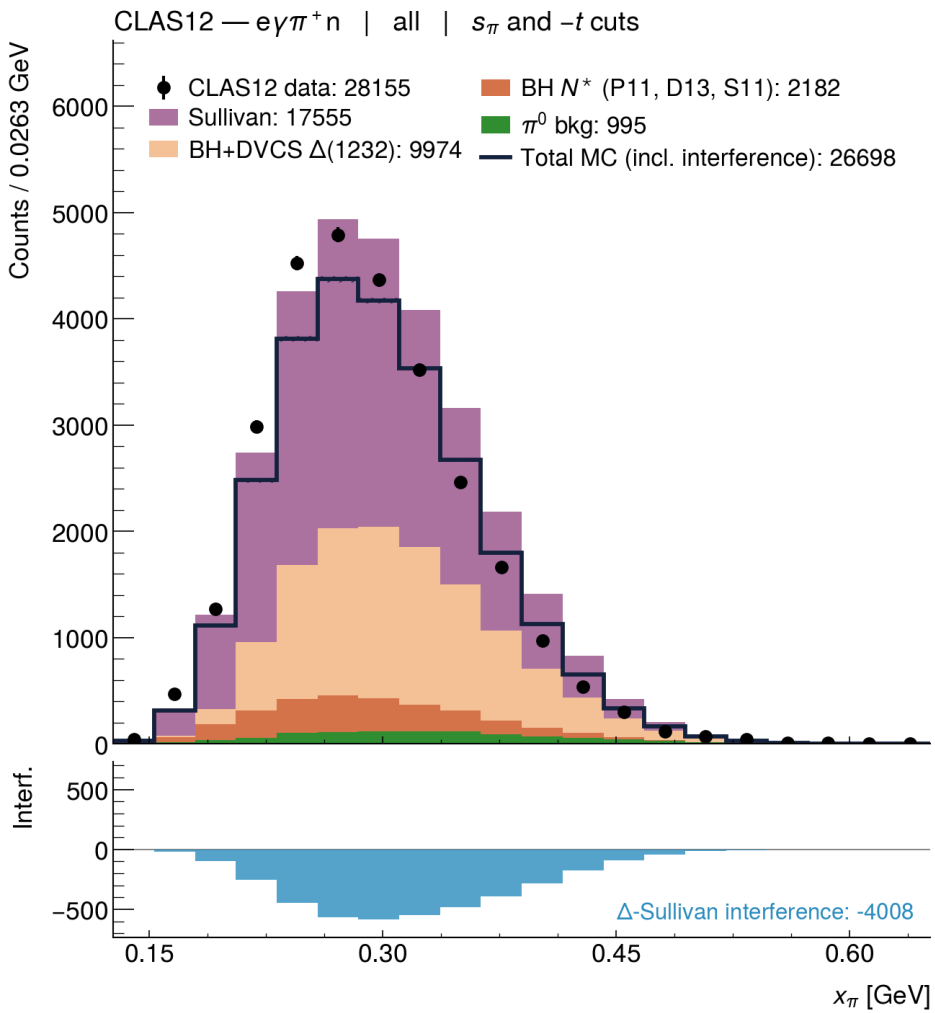
Backup: kinematic distributions





Backup: kinematic distributions





Backup: cross-checks of the extraction

Cross-check	**Tests**	**Result**
Closure test	bias, uncertainties (known asymmetries injected in the full simulation)	pull width 1.00–1.01, bias $< 0.1\,\sigma$
Binned vs unbinned fit	method	differences $0.28\,\sigma$ rms (0.24 expected)
Harmonic content	$\sin\phi$-only model	$\sin 2\phi$: 0.016 ± 0.015; BIC favours $\sin\phi$ in all bins
Parity-forbidden terms	detector, helicity effects	$\cos\phi$ term and offset compatible with 0
Helicity randomization	false asymmetry	pulls: mean $\simeq 0$, rms 0.99 and 0.97
Stability	time, run groups, sectors, ϕ hemispheres	compatible within statistics
Beam-charge asymmetry	helicity luminosity	effect $< 0.005\,\sigma$
Bin migration, resolution	reconstructed vs generated	$0.27\,\sigma$ on average; ϕ dilution $< 10^{-3}$

Over all the tests: 104 p-values (4 below 0.05, $\sim$5 expected) and 622 pulls of rms 1.07 $\Rightarrow$ **consistent with statistical fluctuations**.

Systematic uncertainties

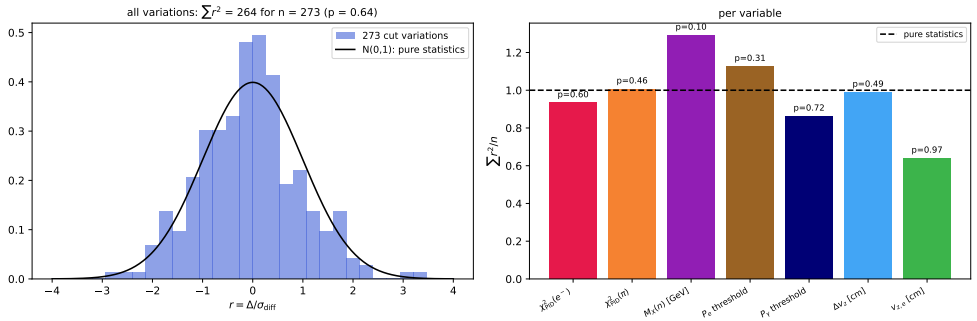
Method

- Cut variations: PID χ^2, vertices, M_n, minimum electron and photon momenta.
- A shift is partly statistical: subtract it,

$$c = \sqrt{\max(\Delta^2 - \sigma_{\text{diff}}^2, 0)}$$

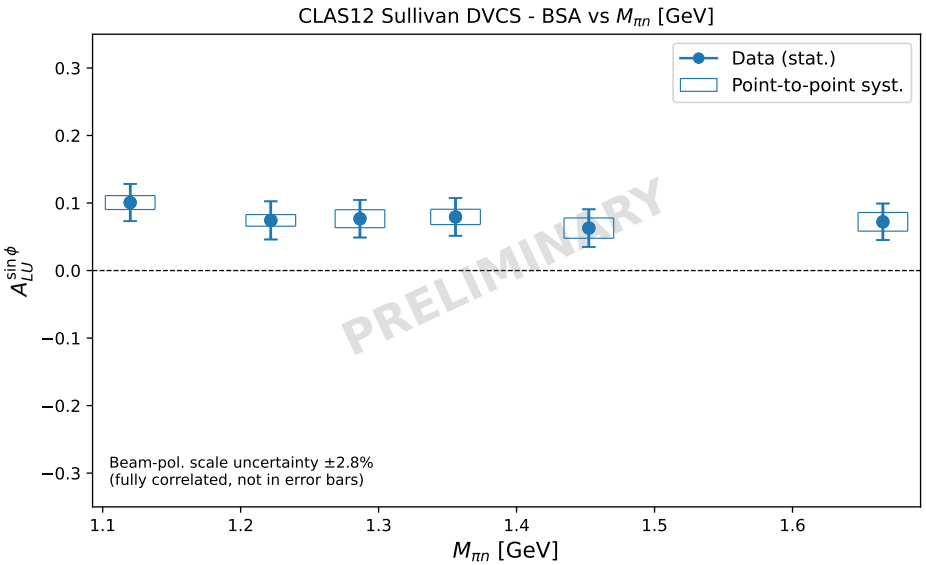
  continuous, no threshold.
- Polarization: separate 2.8% scale uncertainty.

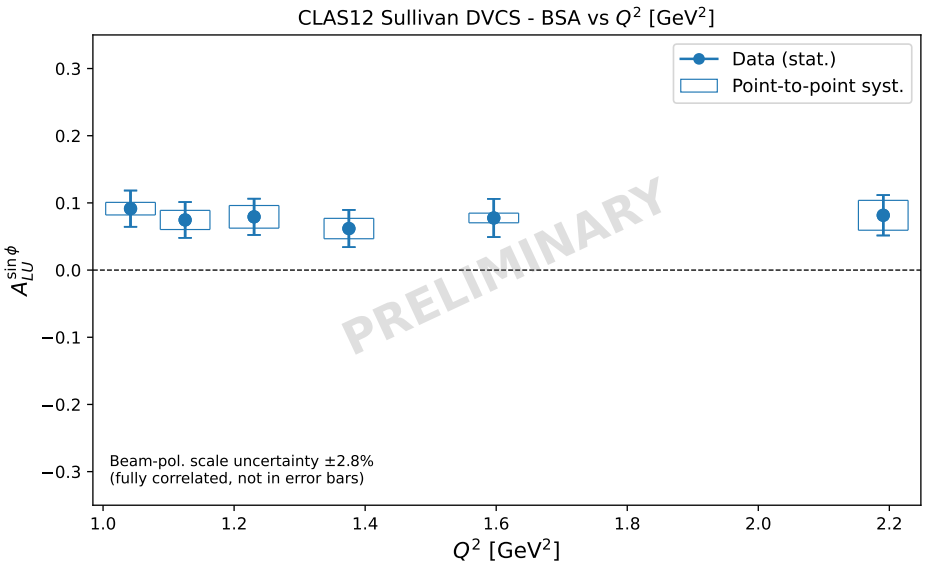
All variations are **compatible with statistics**: the systematic uncertainty ($\sim 40\%$ of the statistical one) is conservative $\rightarrow$ as expected for a BSA, a ratio in which most effects cancel.

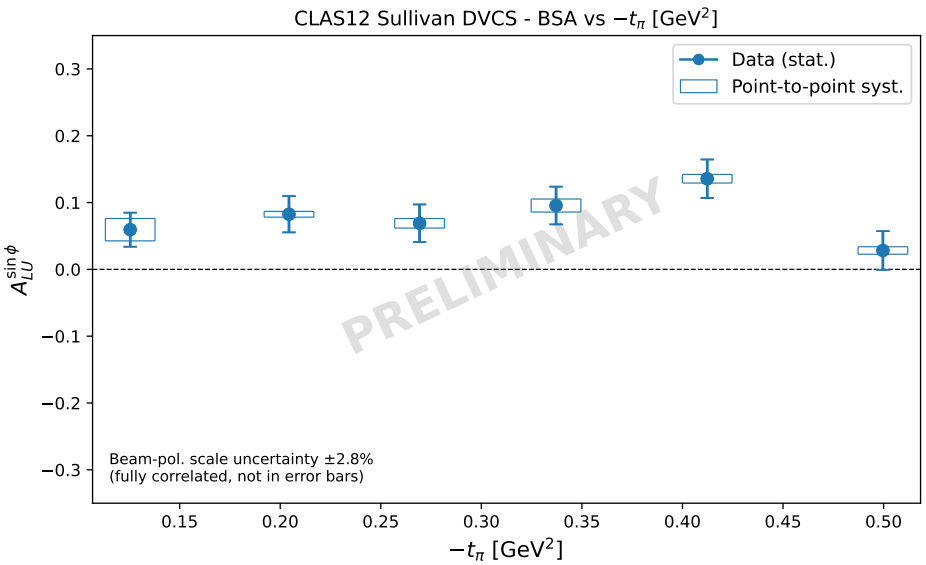


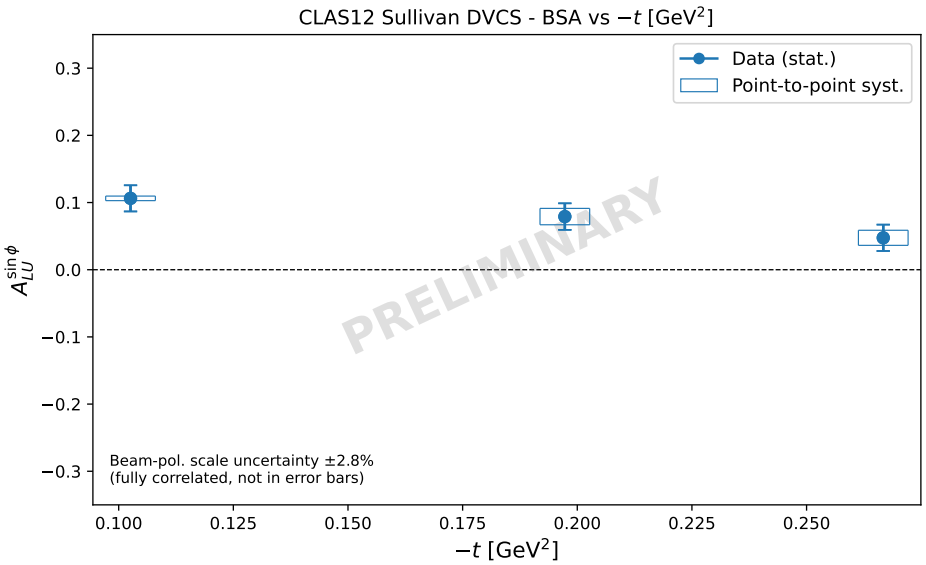
Shifts / their statistical part: unit normal, as for pure statistics.

Measured beam-spin asymmetry









Positive everywhere, integrated $A_{LU}^{\sin\phi} = 0.078 \pm 0.011$; 0.02–0.03 (stat.) and ~ 0.01 (syst.) per

Backup: the model averaged over the bins

Why the previous method failed

Theory at the **mean point** of each bin overestimates the asymmetry ($\chi^2 = 61/21$): the asymmetry varies **non-linearly** within a bin, so its value at the mean point is not its average over the bin.

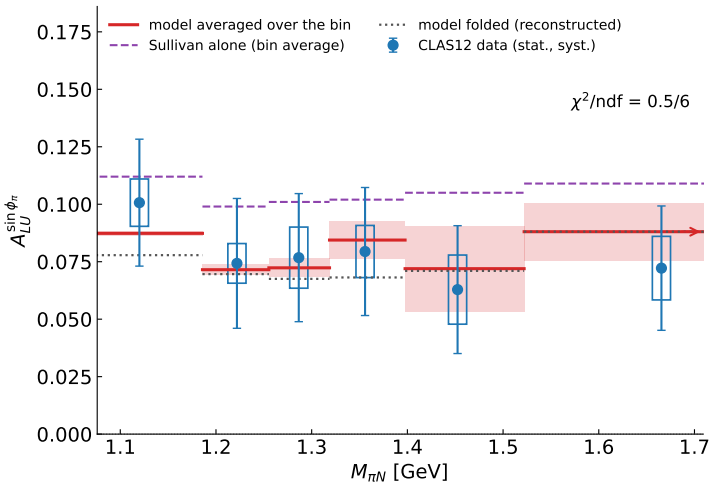
Generator-level bin average

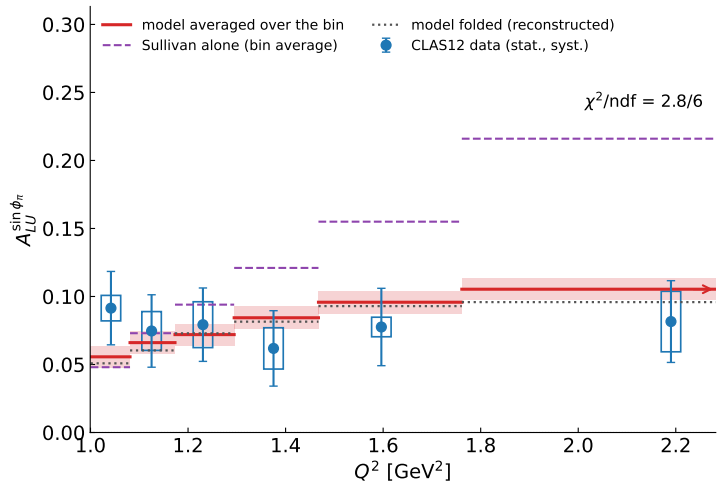
- Average the model over the **phase space** of each bin, at generated level, no detector.
- Reproduces the folding: the acceptance cancels in the ratio at first order.
- **Reproducible by anyone** from the bins and the kinematic cuts.

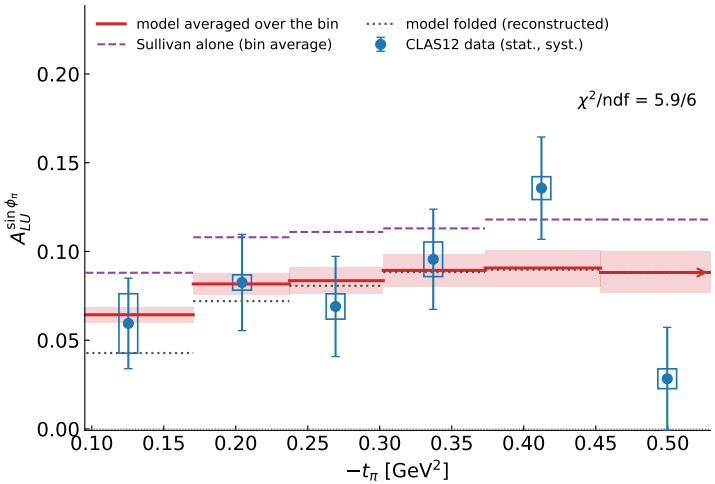
$$A_{\text{bin}} = \frac{\int_{\text{bin}} d\Omega \; D \sin\phi_\pi}{\int_{\text{bin}} d\Omega \; U \sin^2\phi_\pi}, \qquad d\Omega = dQ^2 \, dy \, dx_\pi \, dt_S \, d\phi_n \, dt_\pi \, d\phi_\pi$$

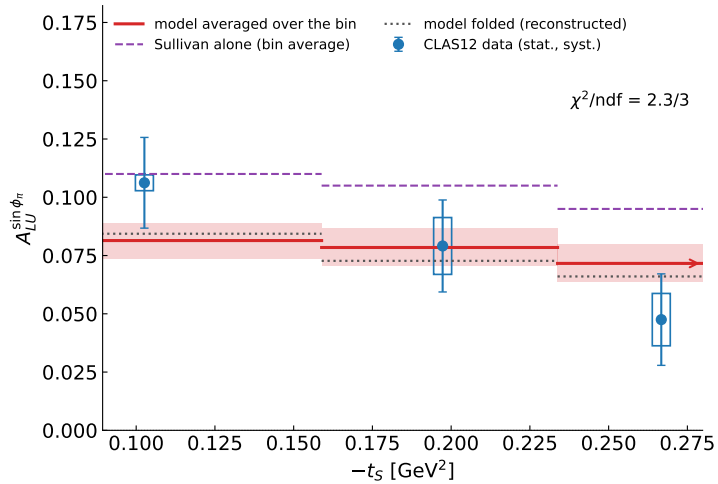
Binning variable within the bin, the others over the full analysis range, kinematic cuts at generated level; full model (Sullivan, Δ^+, interference, N^*), exact kinematics, no detector.

Backup: data versus the model averaged over the bins









Red: bin average; dotted: folded; dashed: Sullivan alone. $\chi^2/21$: folded 12.0, bin average 11.7, mean point (previous method) 60.6.

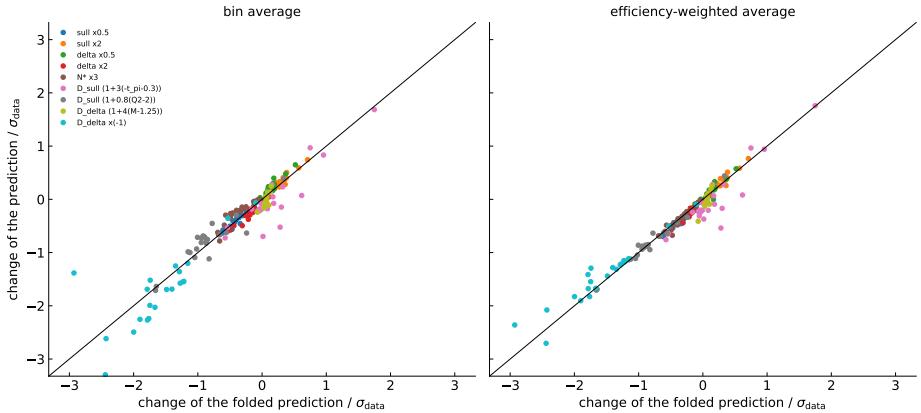
Backup: what the BSA is sensitive to ?

A weighted mean of asymmetries

$A \simeq \sum_c y_c A_c$: a change of composition moves A by $(A_{\mathrm{Sull}} - A_\Delta)\,\Delta y$ only.

Sullivan $\simeq 0.10$, $\Delta \simeq 0.055$: same sign, similar size.

Doubling the Sullivan $\Rightarrow$ $0.084 \rightarrow 0.093$ $(0.3\,\sigma_{\mathrm{data}})$.



Normalization $\times 2$: 0.2–0.4 σ; shape of the asymmetry: up to 1.7 σ. The bin average follows the folding.

Consequences

- The BSA probes the **asymmetries**, i.e. the GPD content, more than the composition.
- Separating Sullivan and Δ: the $M_{\pi N}$ binning, where the composition changes most.
- It is also why the acceptance barely changes the BSA.