Truth-Level B-Hadron Flight-Distance and Timing Study

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Core goal

Count ground-state B-hadron classes at truth level

Recover decay vertex using daughter-particle vertices

Evaluate whether timing branches give physically usable flight/proper times

Physics target: $B_c^+ \longrightarrow \tau^+ \nu_\tau$

A clean leptonic decay connected to |Vcb|

Channels under study (previous analysis *2305.02998*)

- $B^+/B_c^+ \to \tau^+\nu_\tau$: larger branching fraction;
- $B^+/B_c^+ \to \mu^+\nu_\mu$: helicity suppressed but experimentally clean.

Theory motivation

- CKM extraction independent from exclusive–inclusive tension;
- Potential way to measure B_c hadronisation fraction (no current results);
- Cross check flavour anomalies ($b \to q\ell\nu$), *1611.06676*. A new way to test LFU.

Clean probe of the Standard Model

$$\mathcal{B}(B_q^+ \to \tau^+\nu_\tau)_{\rm SM} = \tau_{B_q^+} \frac{G_F^2 |V_{qb}|^2 f_{B_q}^2 m_{B_q} m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B_q}^2}\right)^2, \quad q = u, c$$

$\to$ Provides theoretically clean determination of $|V_{ub}|$ and $|V_{cb}|$

In the Standard Model, the purely leptonic decay rate is controlled by a small number of inputs:

- Fermi constant GF
- CKM element |Vcb|
- decay constant f_{B_c} from lattice QCD
- Bc mass and lifetime
- τ mass and phase-space factor

Overarching Goal: Extraction of CKM Element Matrix $|V_{cb}|$

If the Bc branching ratio and production rate are known well enough, $\boldsymbol{B_c^+ \longrightarrow \tau^+ \nu_\tau}$ can become an independent handle on |Vcb|.

Overarching Goal: Estimation of Fragmentation/Hadronization fraction f_{B_c}

f($\boldsymbol{b \longrightarrow B_c}$) is the probability for a b quark to produce a Bc hadron in the final state.

What the analysis is doing now

A truth-level, generator-particle analysis built around the EDM4HEP MCParticle / GenParticle content.

Inputs used
Particle collection
Particle#1.index daughter relation
PDG, vertex, endpoint, momentum, mass

→

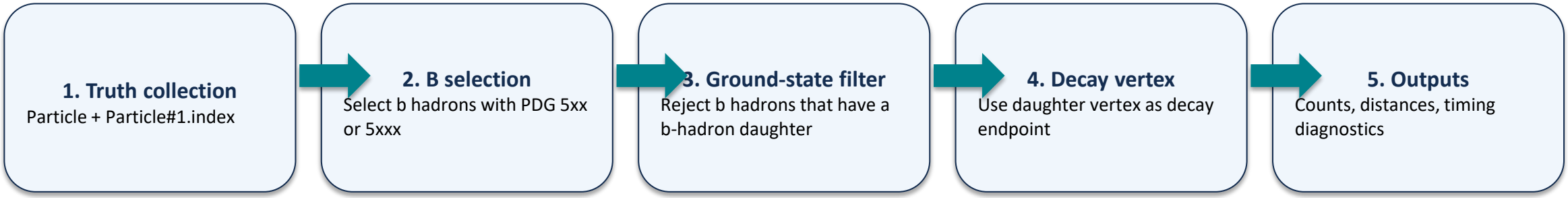
Selection
Keep b hadrons only
Reject b hadrons with b-hadron children
This removes resonance double counting

→

Outputs
Class counts
Flight distance
Lab-frame flight time
Proper decay length and time

Main change: first build a cleaned BHad collection, then calculate all quantities from that cleaned collection.

Updated analysis workflow



Important improvement over the earliest version: the decay endpoint is no longer taken blindly from Particle.endpoint. It is recovered from the daughter particle vertex using the truth daughter relation.

Truth-level branches used

Purpose	Branch / object	Use in current logic
Particle ID	Particle.PDG	B-hadron class and filtering
Production vertex	Particle.vertex.x/y/z	Parent production point
Daughter relation	Particle.daughters_begin/end	Find immediate daughters
Daughter index map	Particle#1.index	Map daughter slots to Particle indices
Stored endpoint check	Particle.endpoint.x/y/z	Cross-check only
Momentum diagnostic	Particle.momentum.x/y/z	Diagnostic only for this sample
Truth time diagnostic	Particle.time	Timing; v5 treats as seconds

The uploaded results show that the momentum branch is not usable for selected ground-state B hadrons in this workflow; the timing calculation should therefore not divide by p.

Old logic vs. latest logic

The difference is not only endpoint vs daughter. It is when the corrected B-hadron collection is constructed.

Earlier endpoint logic
L = |Particle.endpoint − Particle.vertex|

Fast, but depends on stored endpoint being reliable.

Earlier daughter cross-check
L = |daughter.vertex − parent.vertex|

Useful diagnostic but still calculated as an extra branch.

Latest baseline
1. Build BHad
2. Remove b→b resonance parents
3. Replace endpoint with daughter vertex
4. Calculate everything from BHad

Key implementation idea: b.endpoint = Particle[first daughter].vertex; then L = |b.endpoint − b.vertex|.

Counting result from the latest run

Counts are after ground-state filtering, so excited Bc states are not counted separately if they feed a lower Bc.

Class	Count	Fraction
Bd/B0	37,845,248	42.8855%
Bu/B+	37,862,515	42.9051%
Bs	8,421,257	9.5428%
Bc	5,387	0.00610%
Lambda_b	3,228,775	3.6588%
Xi_b	872,176	0.9883%
Omega_b	10,868	0.0123%
Other b baryon	0	0.0000%

Bc diagnostic counts

Bc ground state 541: 5,387
Bc* 543: 0
Bc excited states: 0

Interpretation: after filtering, the selected Bc class is dominated by the weakly decaying ground-state Bc.

B-hadron selection and class definitions

A truth particle is classified as a B hadron when the mass given by the "Particle.PDG“ branch is in the 5xx meson family or 5xxx baryon family.

A candidate is kept only if none of its immediate daughters is another B hadron. This removes excited/resonance states and keeps the ground-state weakly decaying B hadron.

The class code maps the final B hadrons to Bd/B0, Bu/B+, Bs, Bc, Lambda_b, Xi_b, Omega_b, and other b-baryons.

Class	Label	Count	Fraction
Bd_B0	B^{0}_{d}	37,845,248	42.8855%
Bu_Bplus	B^{+}_{u}	37,862,515	42.9051%
Bs_Bs0	B^{0}_{s}	8,421,257	9.5428%
Bc_Bcplus	B^{+}_{c}	5,387	0.0061%
Lb_LambdaB0	#Lambda^{0}_{b}	3,228,775	3.6588%
Xi_b	#Xi_{b}	872,176	0.9883%
Omega_b	#Omega_{b}	10,868	0.0123%
Other_b_baryon	Other b baryons	0	0.0000%

Bc-family check after ground-state filtering

branch	description	count
n_Bc_541	B_c ground state 541	5387
n_BcStar_543	B_c* 543 after ground-state filtering	0
n_BcExc_10541	B_c excited 10541 after ground-state filtering	0
n_BcExc_10543	B_c excited 10543 after ground-state filtering	0
n_BcExc_20543	B_c excited 20543 after ground-state filtering	0

Interpretation: all selected Bc-family candidates are PDG 541 ground-state Bc mesons. No Bc*, 10541, 10543, or 20543 candidates survive the ground-state filtering in the output CSV.

Six plotted quantities: what each name means

The two distance plots are now consistent; the “avgDaughter” version is a diagnostic cross-check.

BHad_flightDistance_mm
3D distance using first-child recovered endpoint
Formula: L = sqrt((ex−vx)^2+(ey−vy)^2+(ez−vz)^2)

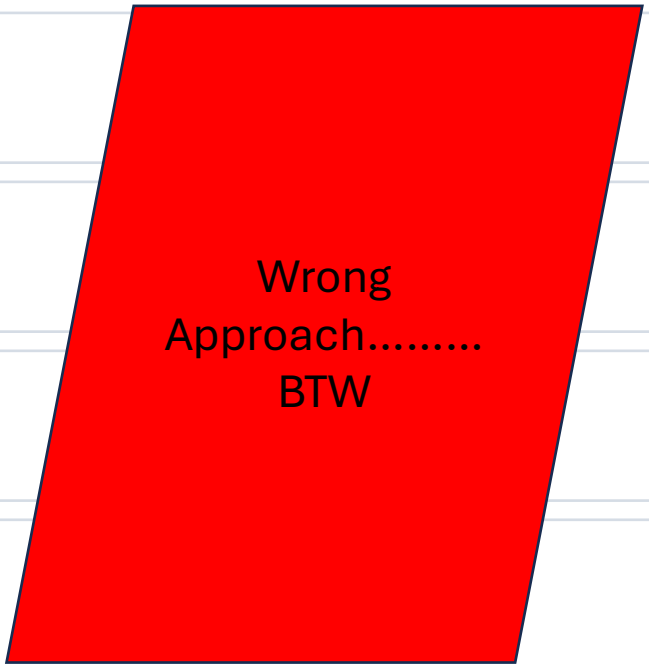
BHad_flightDistance_avgDaughter_mm
3D distance using average daughter vertex as endpoint
Formula: same formula, but endpoint = average daughter vertex

BHad_labFlightTime_ps
Lab-frame flight time
Formula: $t_{lab} = L\,E/(p\,c)$, converted ns → ps

BHad_properDecayLength_ctau_mm
Proper decay length
Formula: $c\tau = L\,m/p$

BHad_properDecayTime_ps
Proper decay time
Formula: $\tau = (L\,m/p)/c$, converted ns → ps

BHad_properDecayTime_avgDaughter_ps
Proper time using average daughter endpoint
Formula: same as above with avg-daughter endpoint



Flight-distance formula and branch logic

Main distance

L_XYZ = sqrt((x_daughter - x_parent)^2 + (y_daughter - y_parent)^2 + (z_daughter - z_parent)^2)

Parent point = Particle[BHad_idx].vertex

Daughter point = Particle[Particle1[daughters_begin]].vertex

Average-daughter diagnostic

x_decay,avg = mean(x_i of immediate daughters)

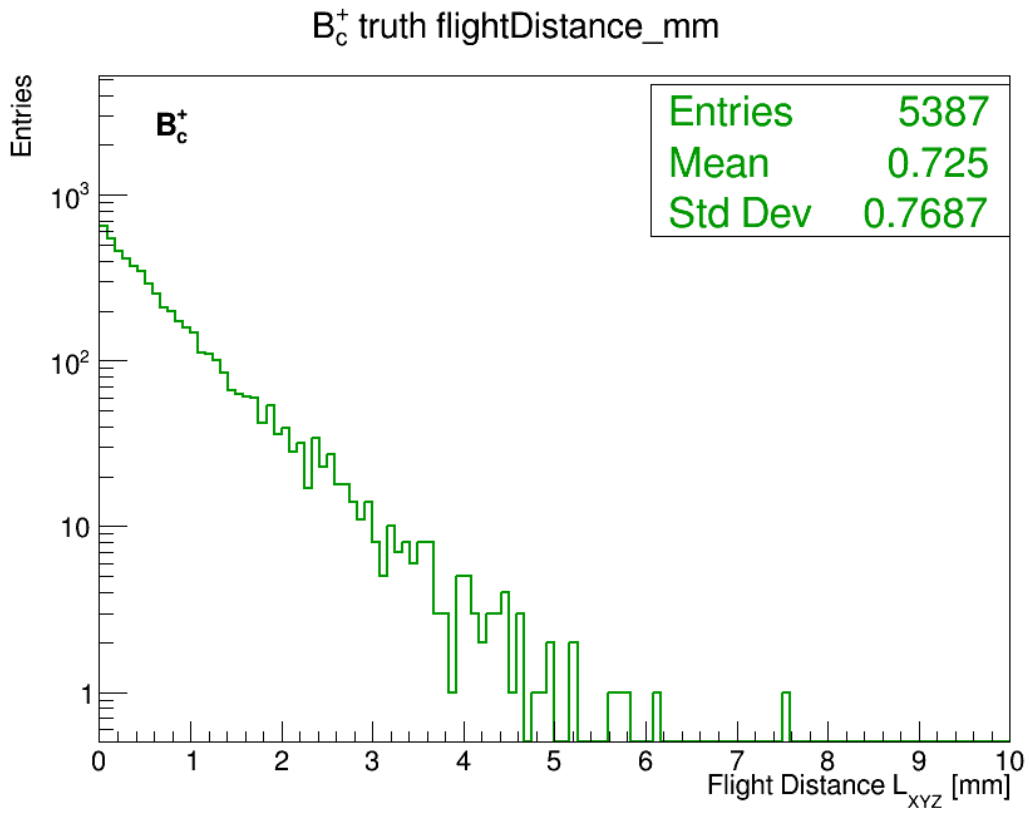
L_avgDaughter = |x_decay,avg - x_parent|

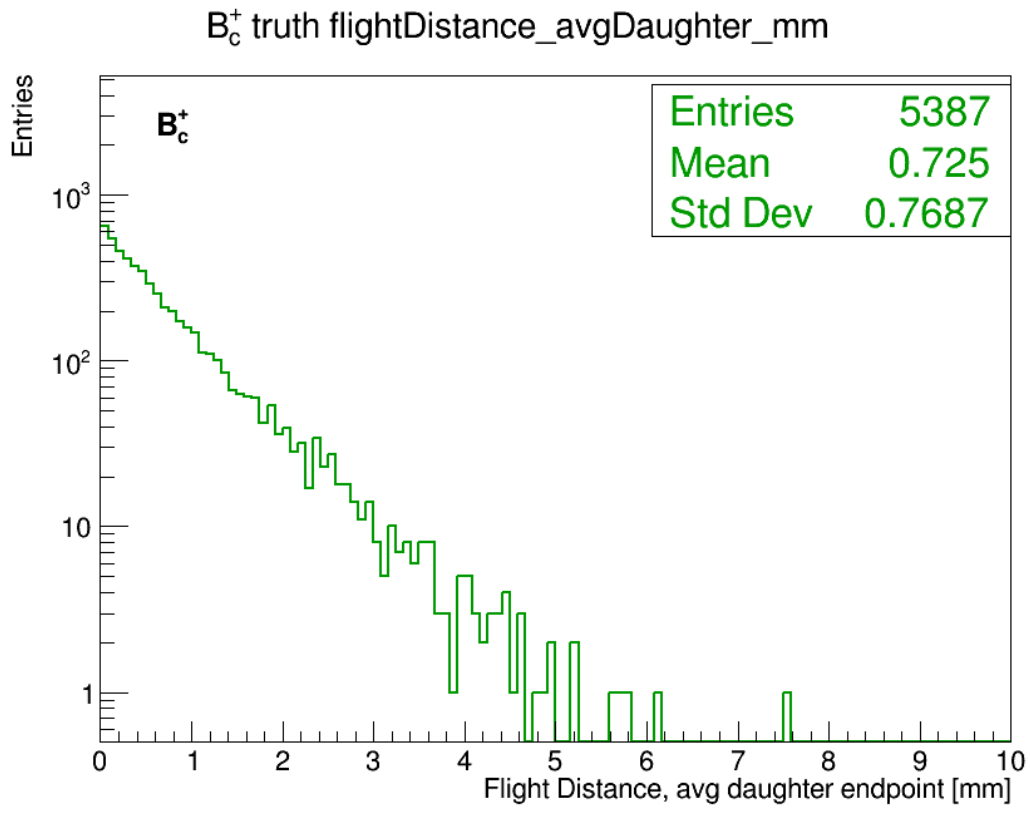
Purpose: cross-check that all immediate daughters point to the same decay vertex

Interpretation: the normal and average-daughter distance plots are visually and numerically identical for each class, which strongly supports the daughter-vertex recovery logic.

Bc distance result: first daughter vs averaged daughters

For Bc, the two distance methods agree exactly in the shown output.

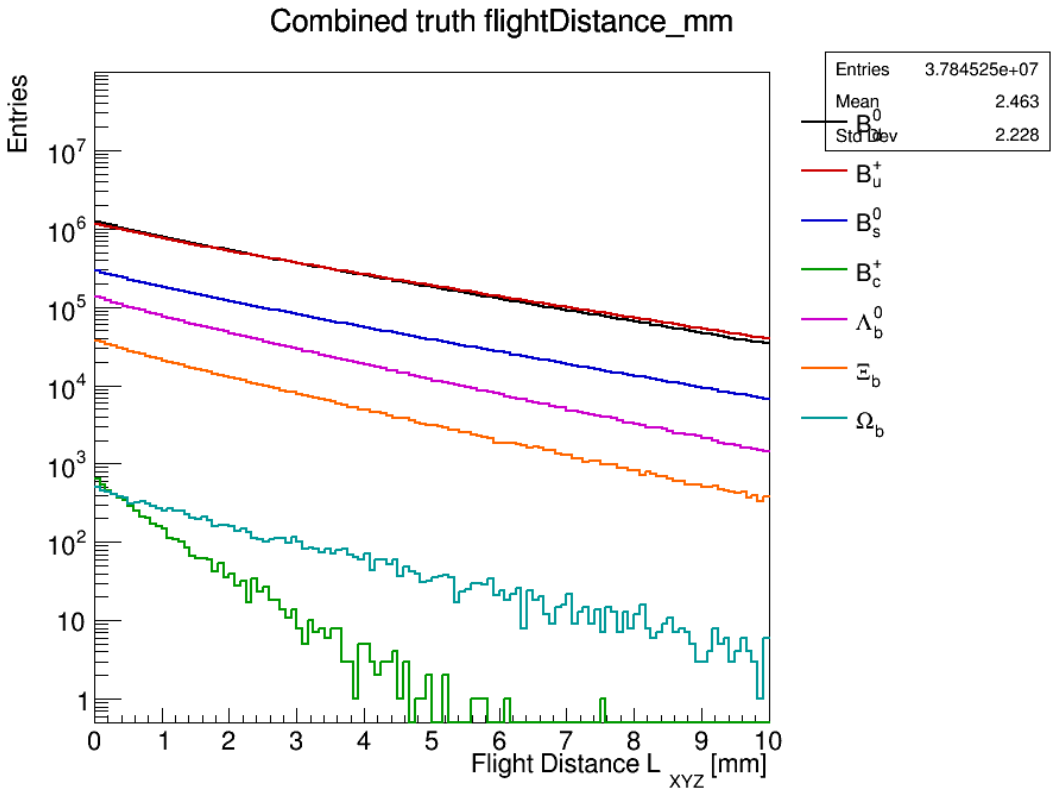


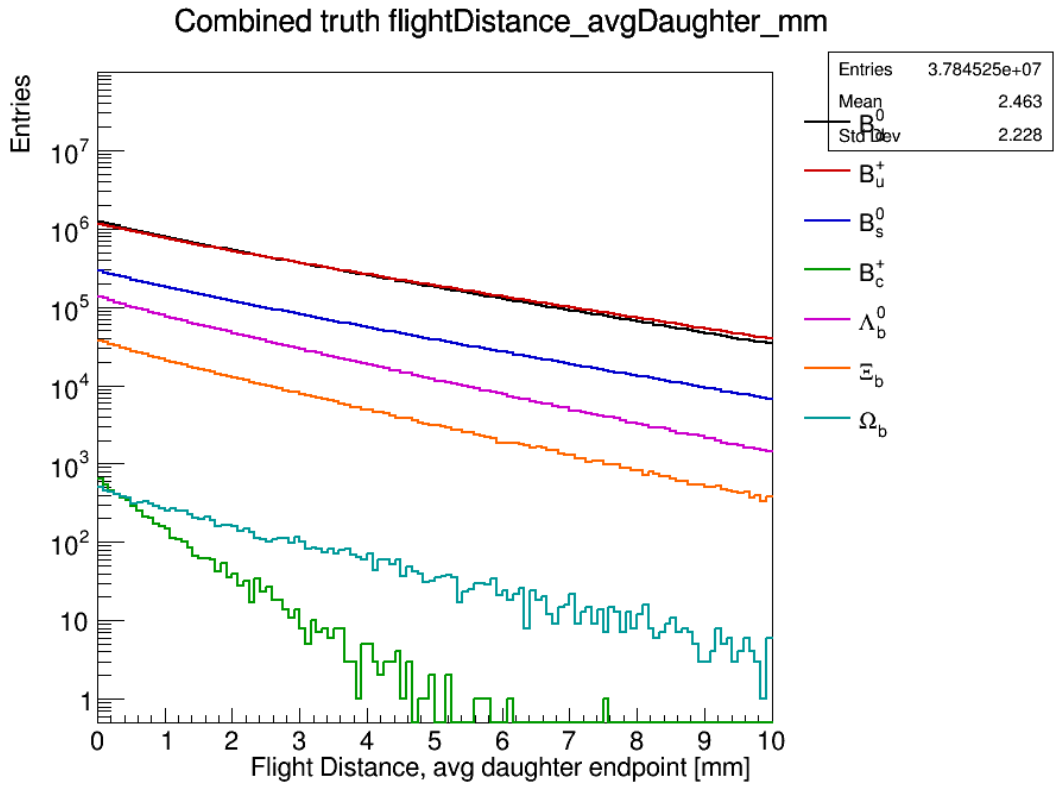


Observation: both plots have Entries = 5387, Mean = 0.725 mm, Std Dev = 0.7687 mm. This is a strong check that first-child and average-daughter endpoints coincide for these Bc decays.

Combined distance result

The combined plot confirms the hierarchy of production rates and the rare Bc component.





The Bc line is low because the selected Bc fraction is about 6.1×10^{-5} of selected ground-state b hadrons. This is consistent with Bc being rare compared with Bd/Bu/Bs.

Flight-distance summary by class

Class	Entries	Mean L_XYZ [mm]	Comment
Bd/B0	37,845,248	2.463	dominant
Bu/B+	37,862,515	2.574	dominant
Bs	8,421,257	2.378	lower rate
Bc	5,387	0.725	rare + shorter
Lambda_b	3,228,775	2.033	baryon
Xi_b	872,176	1.988	baryon
Omega_b	10,868	1.928	rare baryon
Other b baryons	0	—	none selected

Physics interpretation: the rare Bc sample has a noticeably shorter flight-distance scale than Bd, Bu, Bs, and b-baryons, consistent with its shorter lifetime expectation.

Timing formula: corrected v5 logic and validation

v5 correction

Δt_s = Particle[daughter].time - Particle[parent].time

$t_{lab,ps} = \Delta t_s \times 10^{12}$

$\beta = L_{mm} / (299792458000 \times \Delta t_s)$

$\gamma = 1 / \sqrt{1 - \beta^2}$

$\tau_{ps} = \Delta t_s \times 10^{12} / \gamma$

$c\tau_{mm} = 0.299792458 \times \tau_{ps}$

The v4 lab-time histograms are populated, but the scale is off by a factor of 10^9.

The proper-time and cτ histograms are empty because beta = L/(c t_lab) becomes much larger than 1 when t_lab is treated as ns instead of seconds.

After the v5 correction, expected lab-time means move from ~10^-8 ps to the physically plausible ~few–10 ps scale.

v5 correction

$t_{lab,ps} = (t_{daughter} - t_{parent}) \times 10^{12}$

This assumes Particle.time is in seconds.

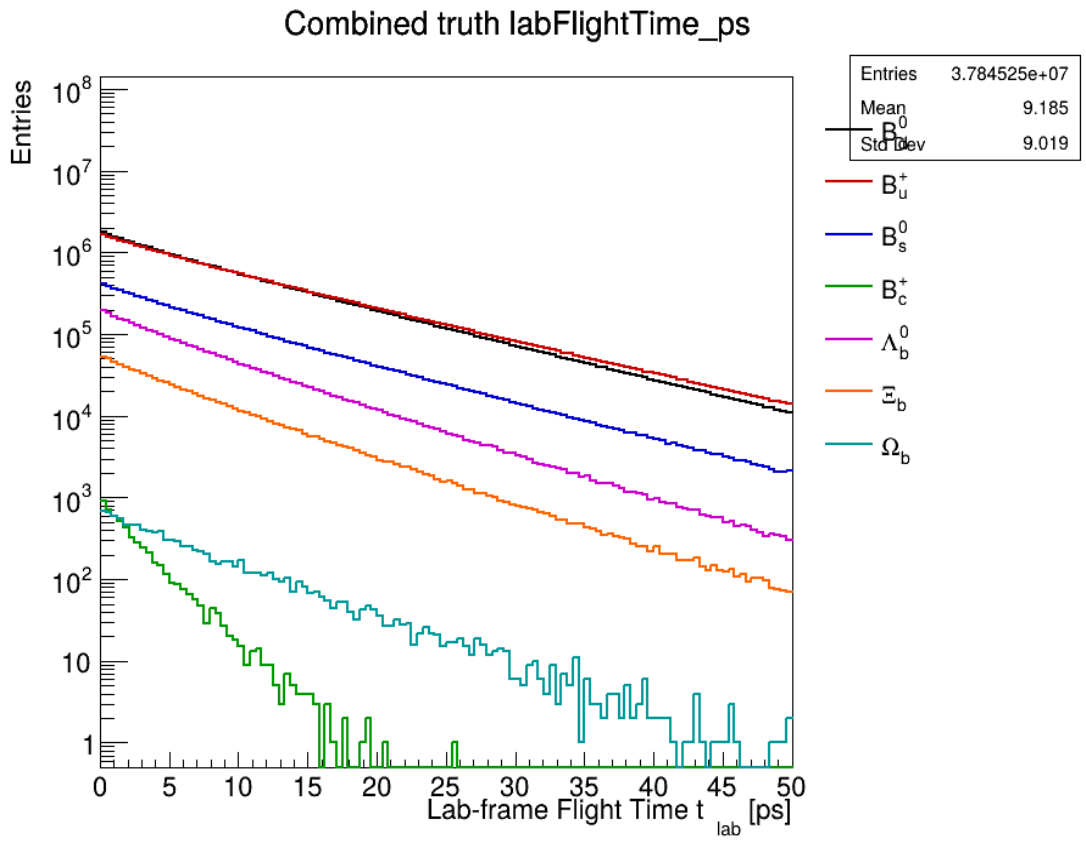
Then beta = $L/(c \times \Delta t_{seconds})$.

Validation

Using the corrected unit convention, the mean β values are ~0.980 for Bd/Bu/Bs, ~0.979 for Λb/Ξb, ~0.977 for Ωb, and ~0.974 for Bc. These are physically sensible for relativistic B hadrons in this sample.

After the rerun, the lab-time histograms are in the few–10 ps range and the proper-time/cτ histograms are populated, so the timing branch is now usable.

Result Interpretation: corrected labFlightTime_ps is now physically scaled



The corrected labFlightTime_ps distributions are now populated on a physically sensible scale.

Mean lab-frame times range from 2.465 ps for Bc to about 9.7 ps for Bu, with Bd and Bs around 9 ps and the b baryons around 6.8–7.3 ps.

These values are consistent with the mm-scale flight-distance plots and with the β sanity check from the terminal study.

The plot therefore supports the interpretation that Particle.time must be treated as seconds before converting to ps.

Conclusion: the v5 correction fixes the timing scale. labFlightTime_ps is now usable as a physics quantity, not just as debugging evidence.

Corrected properDecayTime and cτ are now populated

Key observation

properDecayTime_ps and properDecayLength_ctau_mm are no longer empty after the v5 rerun.

Mean proper times are: Bc 0.453 ps, Bd 1.409 ps, Bs 1.363 ps, Bu 1.480 ps, Λb 1.184 ps, Ξb 1.170 ps, and Ωb 1.167 ps.

Mean cτ values are: Bc 0.1358 mm, Bd 0.4329 mm, Bs 0.4177 mm, Bu 0.4565 mm, Λb 0.3598 mm, Ξb 0.3555 mm, and Ωb 0.3548 mm.

The shorter Bc lifetime scale and the similarity among the other weakly decaying ground-state B hadrons are both physically sensible.

This change shows that the earlier empty timing outputs were not a flaw in the decay-vertex logic. They were a pure time-unit problem.

Once Δt is treated in seconds, β becomes physical and the derived τ and cτ distributions are recovered normally.

Important: the timing/lifetime part of the truth analysis is now aligned with the distance/counting part.

Corrected timing summary by class

Class	Entries	Mean t_lab [ps]	Mean τ [ps]	Mean cτ [mm]
Bd/B0	37,845,248	9.185	1.409	0.4329
Bu/B+	37,862,511	9.722	1.480	0.4565
Bs	8,421,255	8.780	1.363	0.4177
Bc	5,387	2.465	0.453	0.1358
Lambda_b	3,228,775	7.250	1.184	0.3598
Xi_b	872,175	7.064	1.170	0.3555
Omega_b	10,868	6.799	1.167	0.3548
Other b baryons	0	—	—	—

Are the current results sufficient?

Analysis component	Status	Reason
Ground-state B-hadron counting	Usable	Stable class counts in CSV
Bc count / Bc-family check	Usable	Only PDG 541 survives the ground-state filter
Flight-distance distributions	Usable	Good entries, sensible shapes, and matching endpoint cross-checks
Average-daughter cross-check	Usable	Agrees with first-daughter distance and proper-time results
Lab-flight-time plots	Usable	Corrected v5 unit treatment gives physically sensible few–10 ps scale
Proper-time and cτ plots	Usable	Both are now populated and internally consistent

Bottom line: yes—the current output is sufficient to present both the corrected distance logic and the corrected truth-level timing/lifetime results. The main caveat is only statistical: Bc and Ωb have much smaller samples than Bd/Bu/Bs.

Summary of Results

Ground-state B-hadron counting is stable and gives the expected hierarchy: B0/B+ dominate, followed by Bs, Λb, Ξb, Ωb, and the rare Bc.

Bc+ remains a rare component of the selected sample: 5,387 candidates, about 0.00610% of selected ground-state b hadrons. The flight-distance distributions are internally consistent: first-daughter endpoint and average-daughter endpoint give the same numerical summaries.

The v5 time-unit correction is successful: lab-frame flight-time means move to the physically reasonable few–10 ps range, while properDecayTime and cτ are now populated for all non-empty classes.

A simple sanity check using $\beta = L/(ct)$ gives mean $\beta \approx 0.974–0.980$ across classes when Particle.time is treated as seconds, strongly supporting the corrected unit choice.

Takeaway: the truth-level distance and timing framework is now consistent enough to present as the current validated result, with only optional cross-checks left for later refinement.

From truth-level validation to |Vcb| extraction

The analysis chain still to be built

Key Message/Takeaway

The truth-level stage is now stable enough to support the next phase, but a final |Vcb| claim requires reconstruction, normalization, efficiency, and systematic studies.

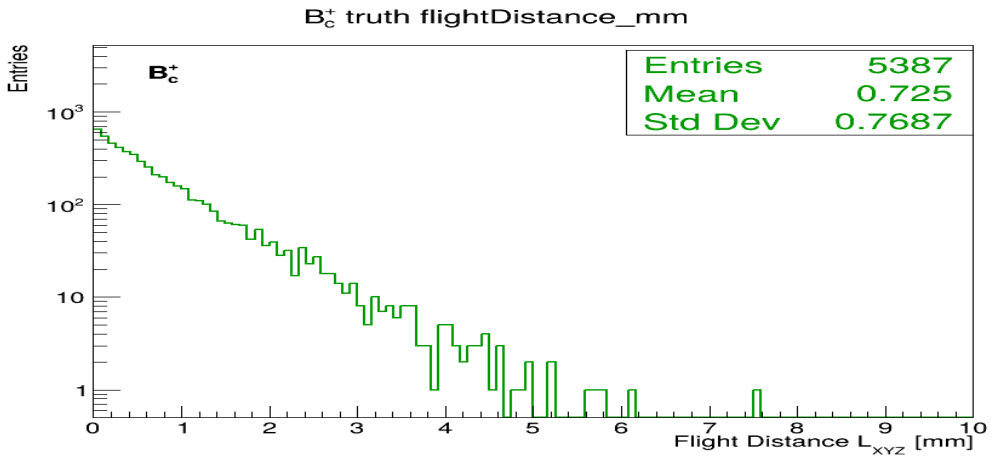
Backup plots: full output stack

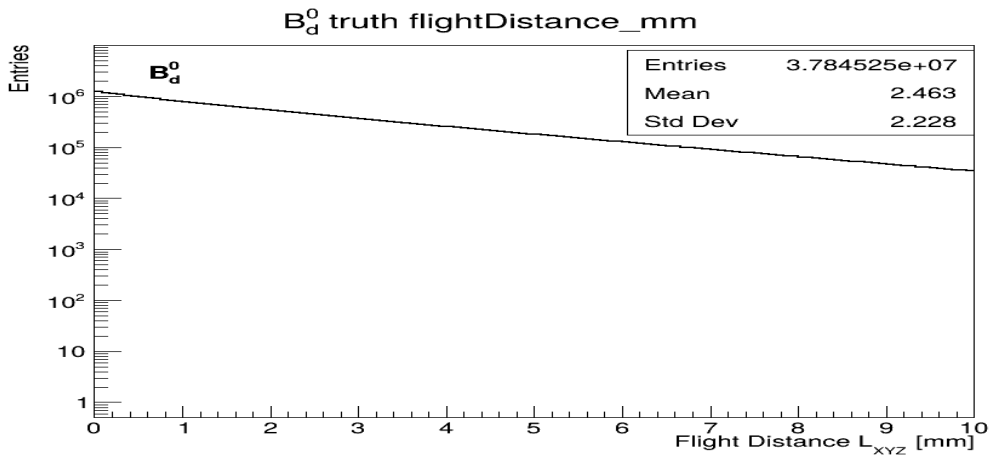
Grouped by plotted quantity and particle class.

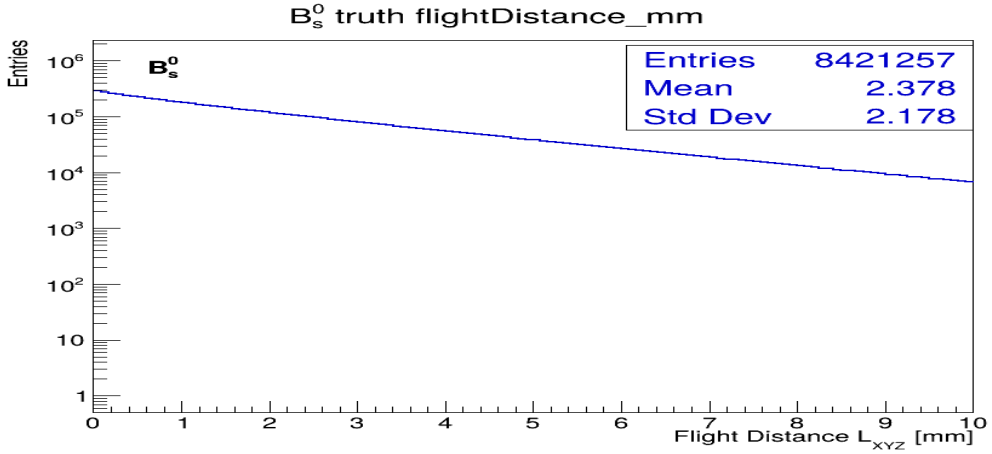
The backup section preserves the uploaded output plots in order: flight distance, average-daughter distance, corrected lab time, corrected proper decay length cτ, corrected proper decay time (average-daughter and first-daughter versions), and combined summary views.

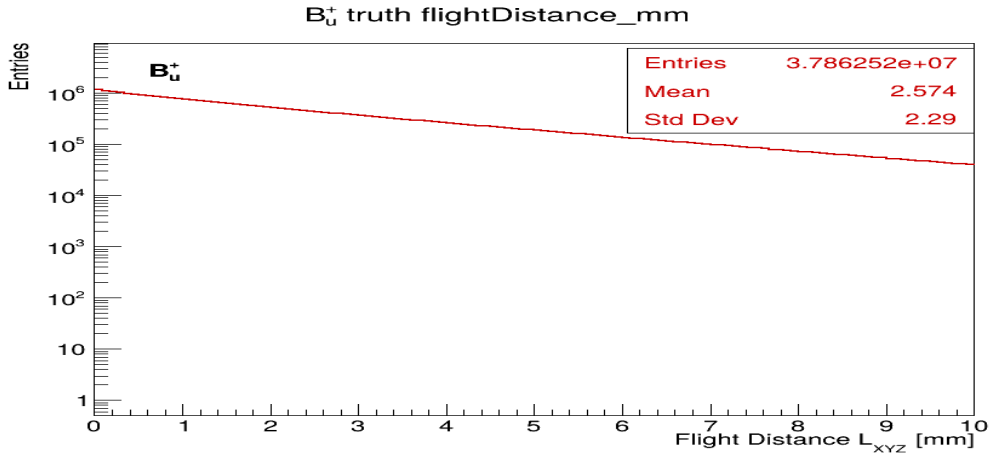
Backup: flightDistance_mm (1/2)

First-daughter recovered endpoint; LXYZ [mm].





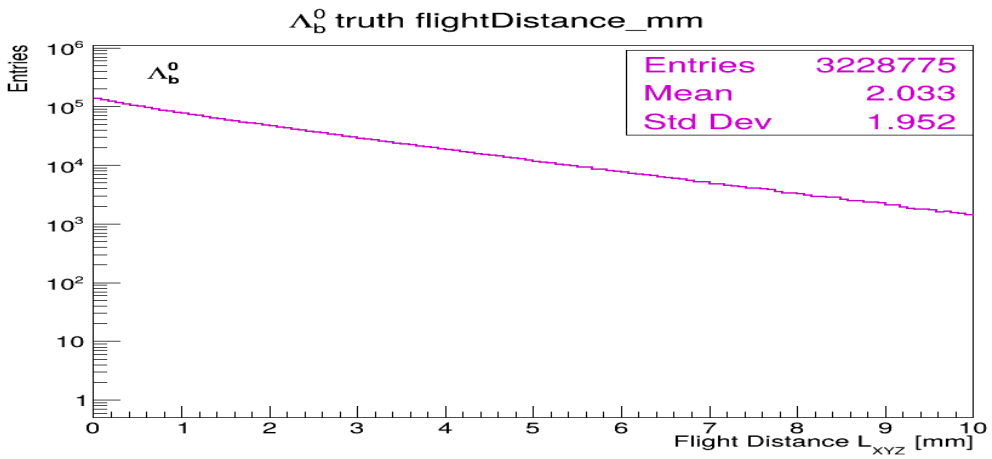


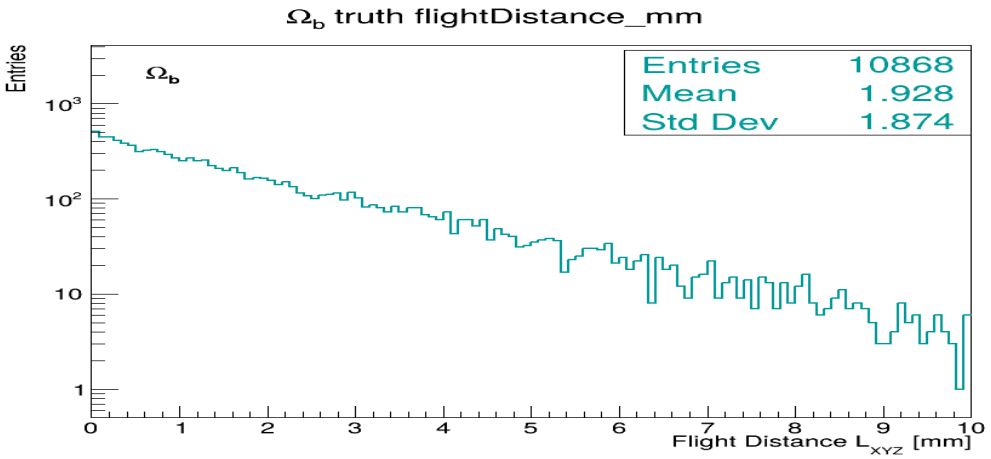


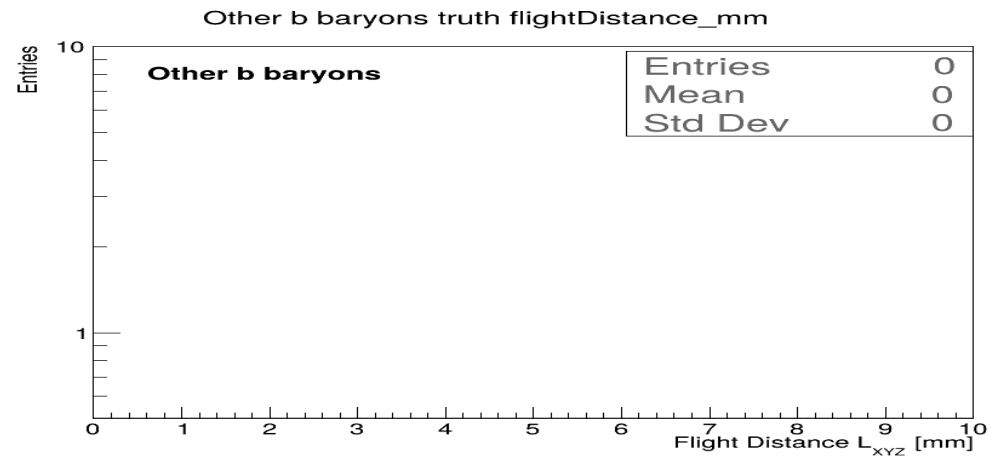
Distance results remain one of the main validated physics outputs.

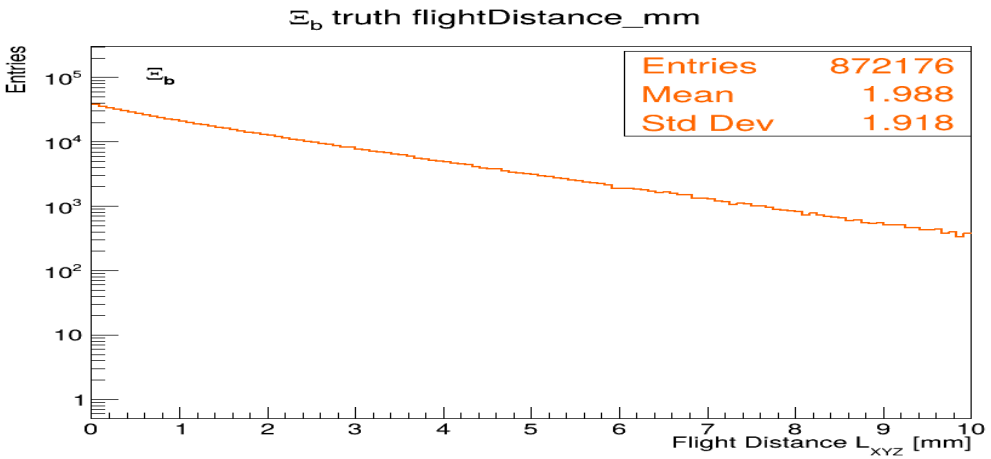
Backup: flightDistance_mm (2/2)

First-daughter recovered endpoint; LXYZ [mm].





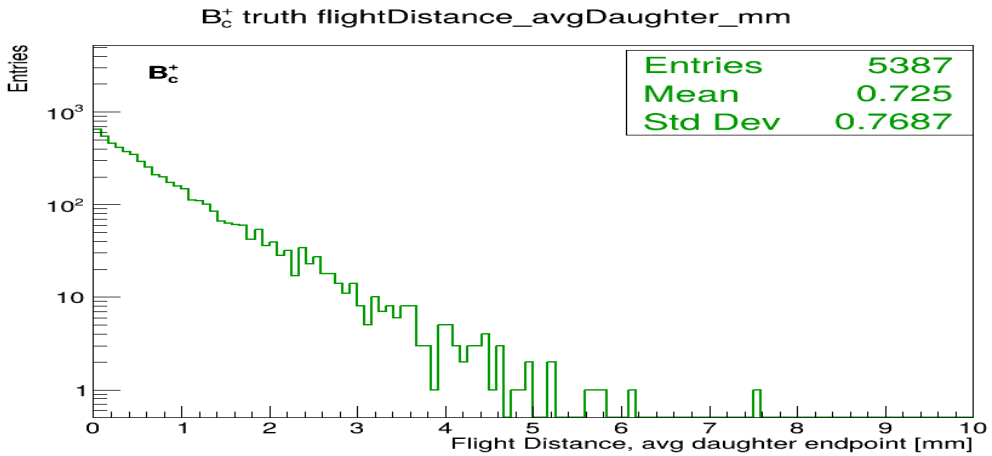


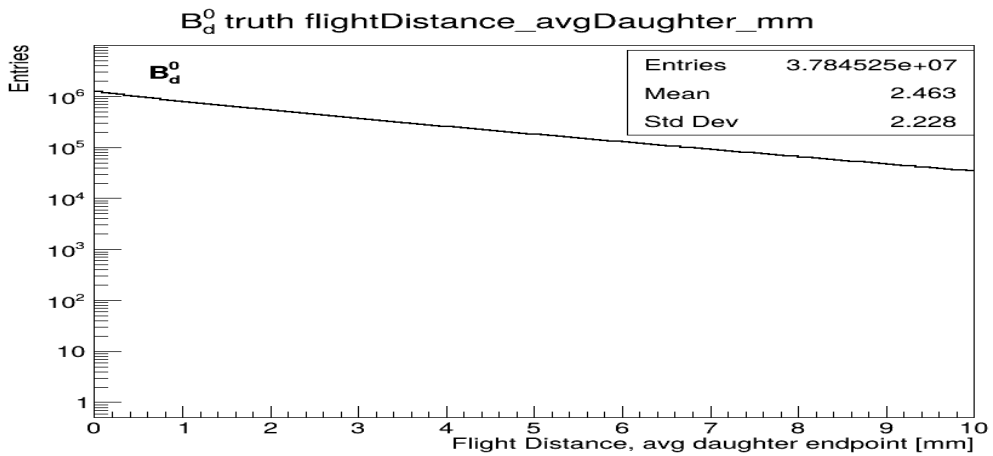


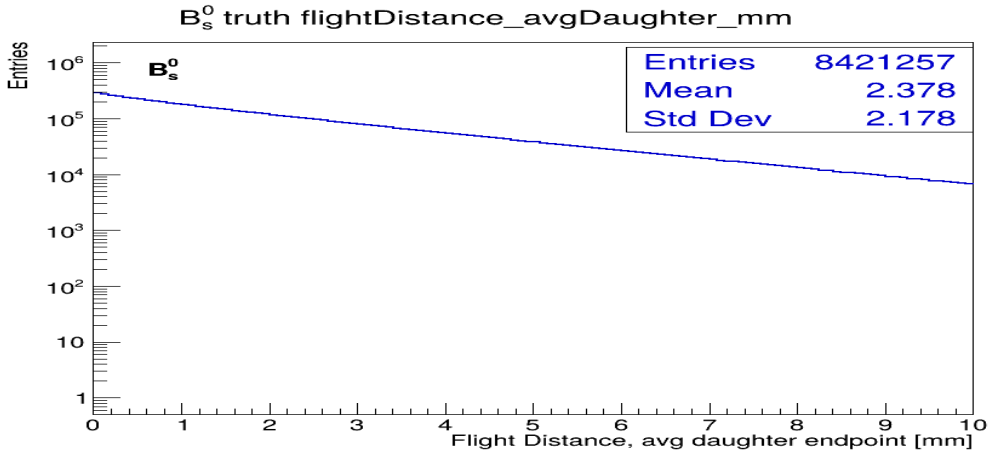
Distance results remain one of the main validated physics outputs.

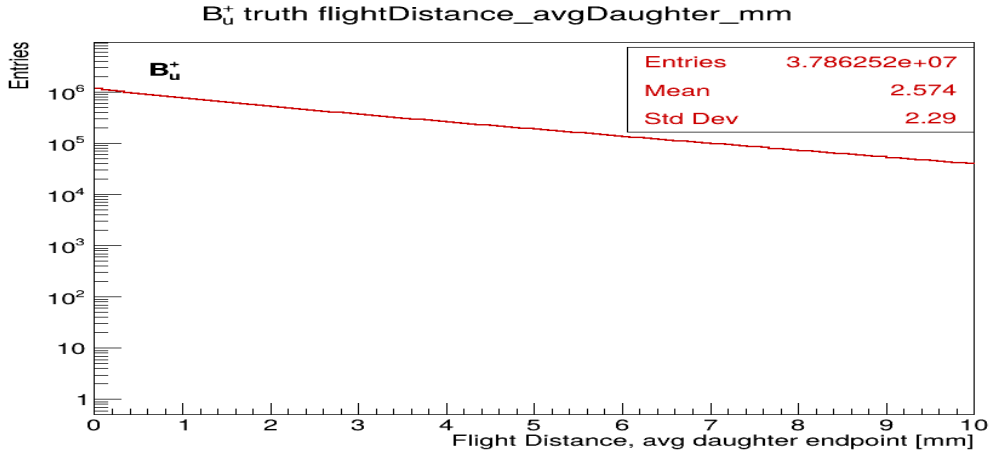
Backup: flightDistance_avgDaughter_mm (1/2)

Average immediate-daughter endpoint; diagnostic cross-check.





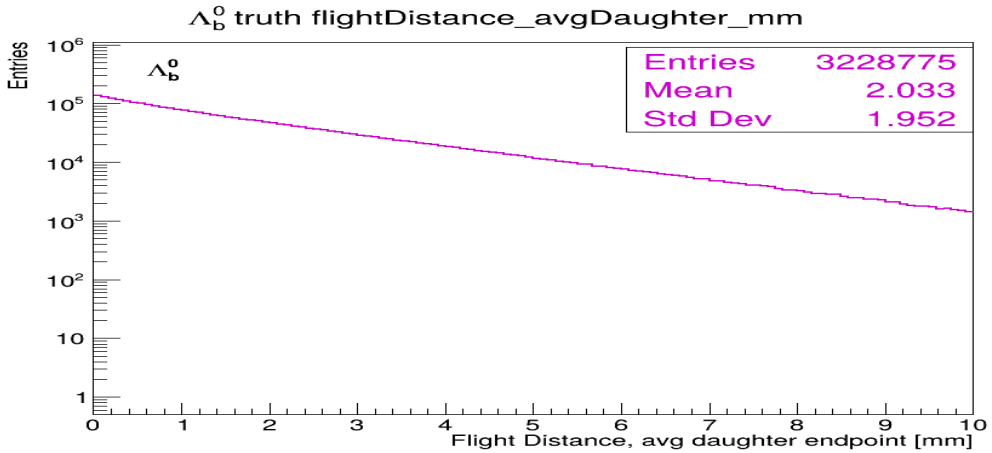


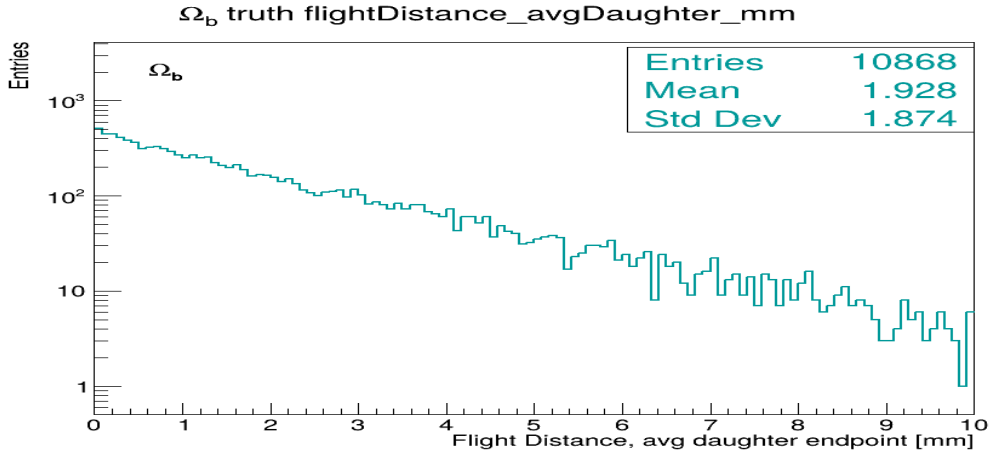


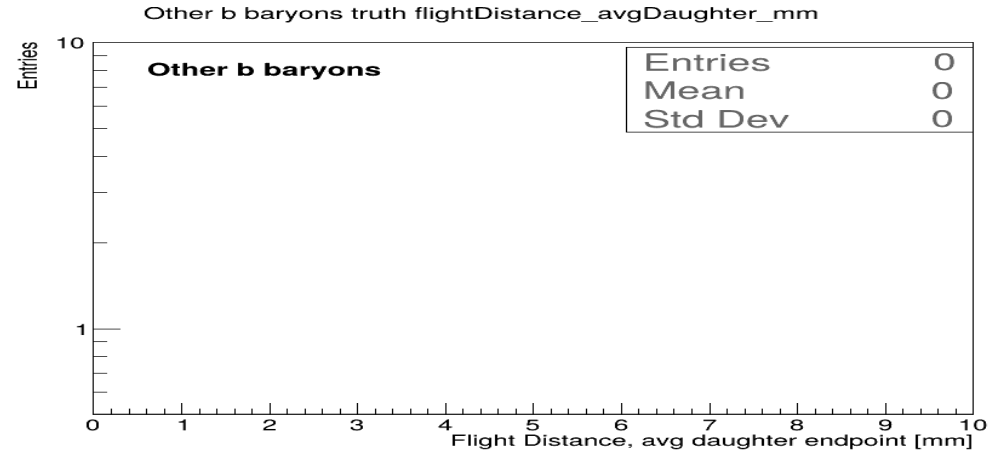
Average-daughter results match first-daughter results.

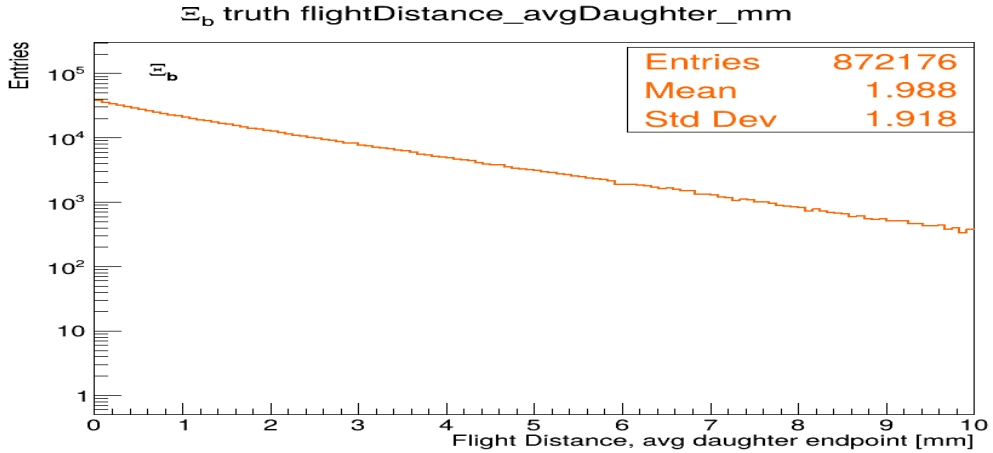
Backup: flightDistance_avgDaughter_mm (2/2)

Average immediate-daughter endpoint; diagnostic cross-check.





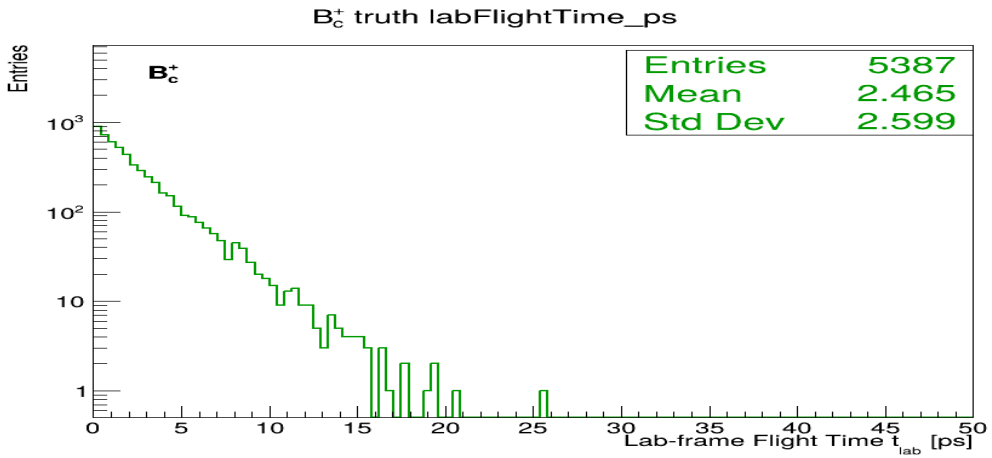


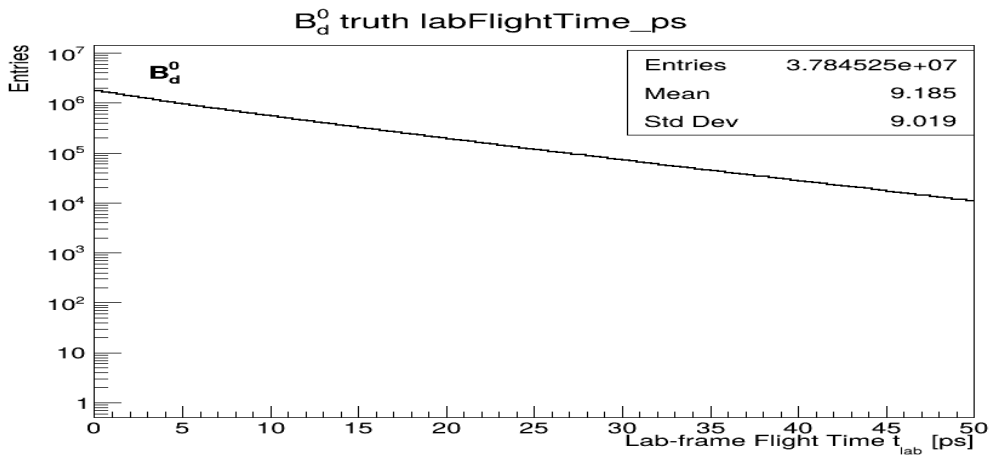


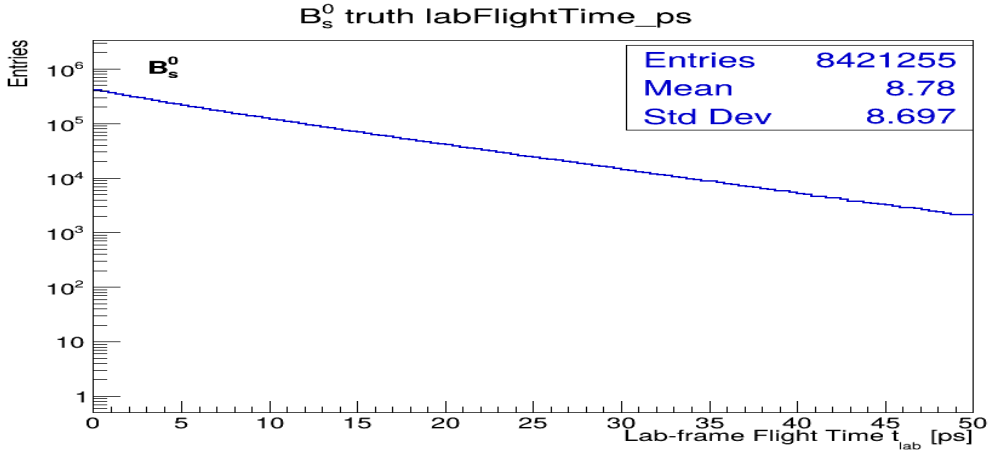
Average-daughter results match first-daughter results.

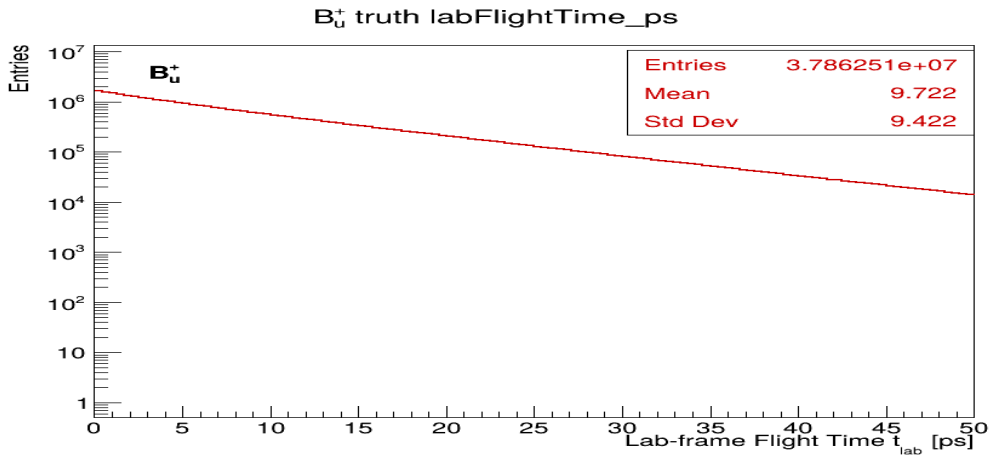
Backup: labFlightTime_ps (1/2)

Corrected v5 lab-frame timing output.





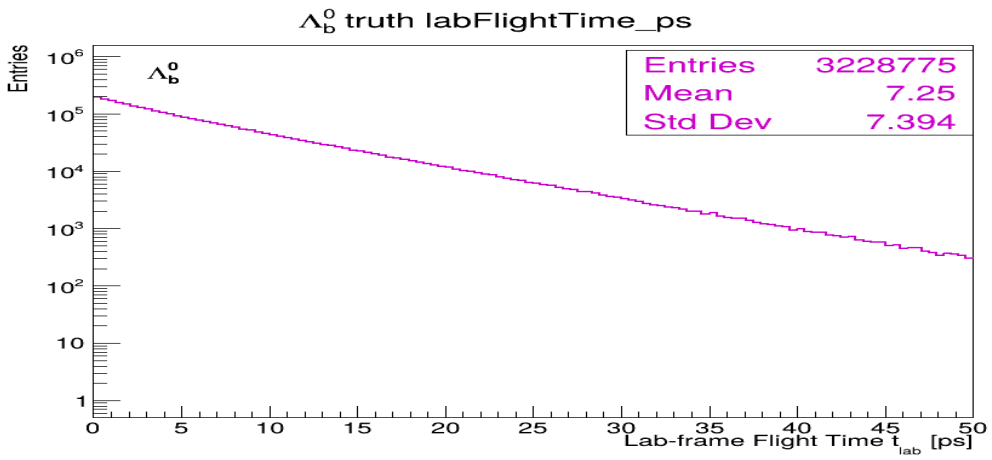


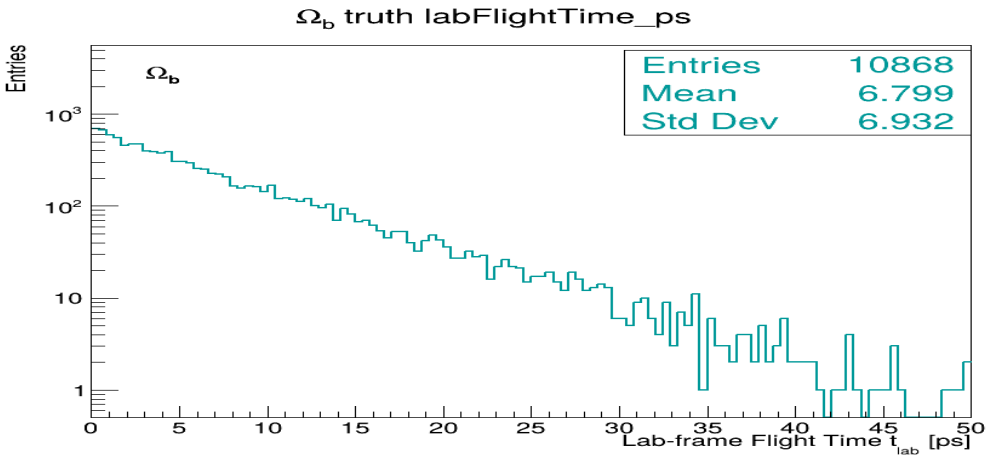


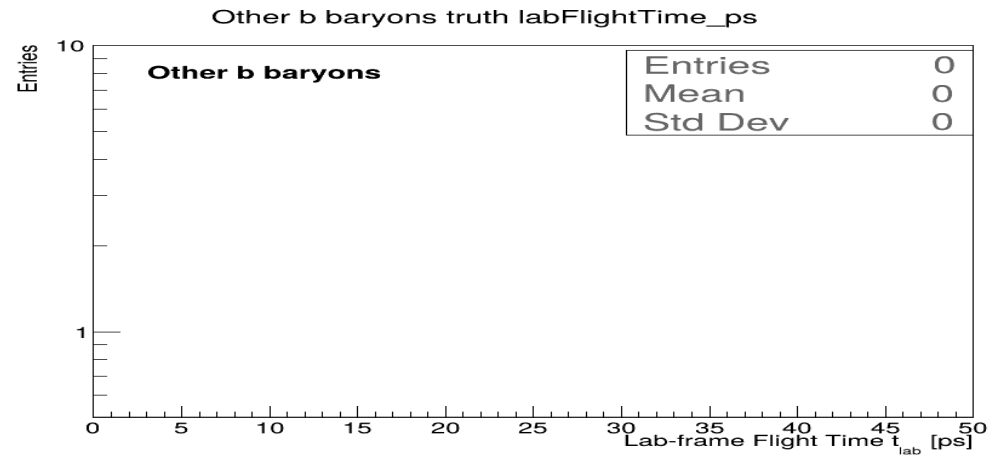
Corrected v5 timing output; physically scaled and populated.

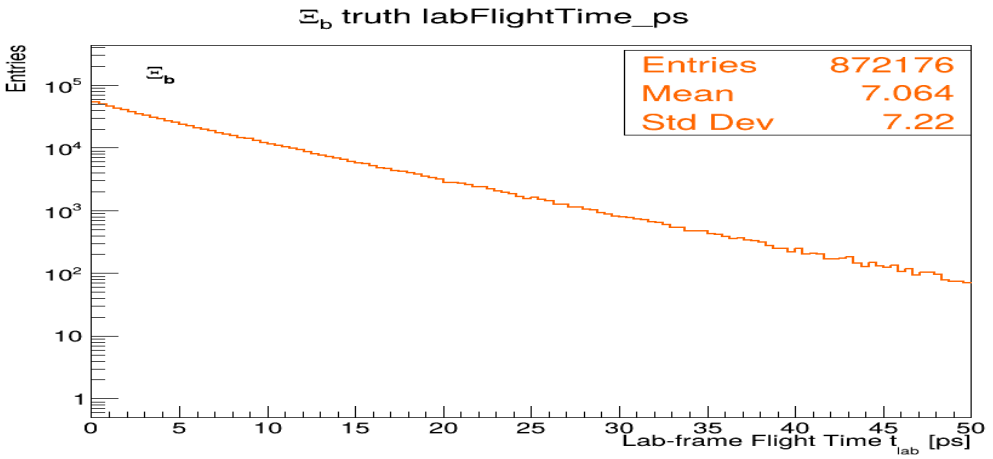
Backup: labFlightTime_ps (2/2)

Corrected v5 lab-frame timing output.





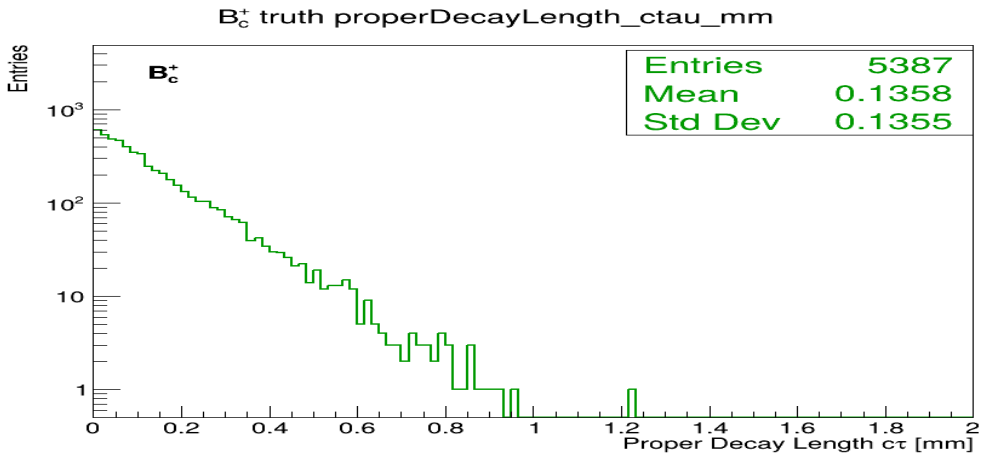


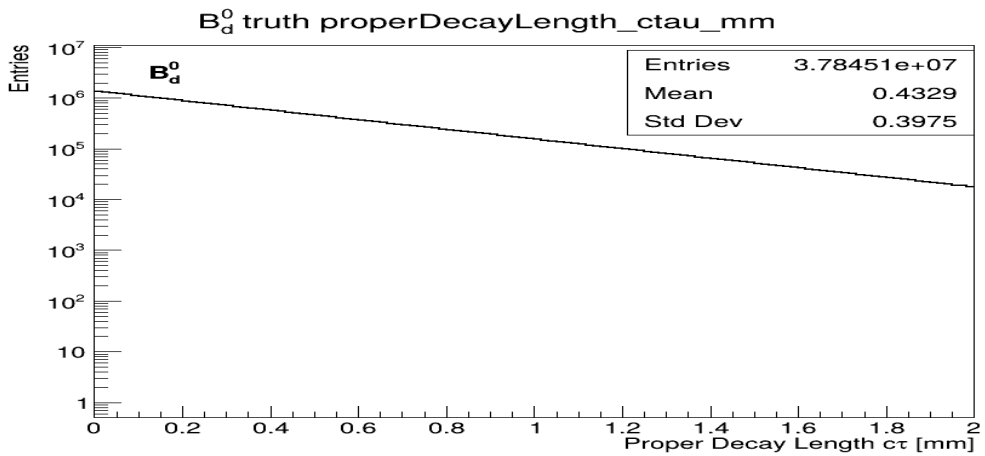


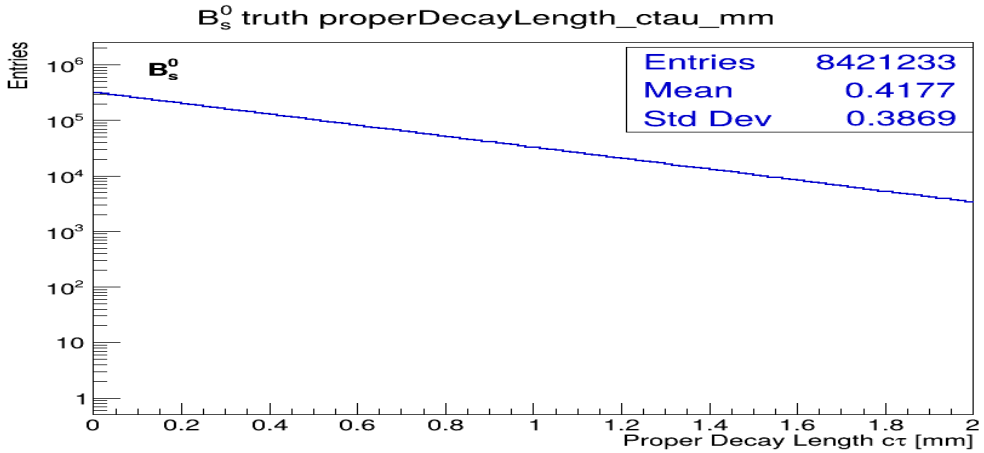
Corrected v5 timing output; physically scaled and populated.

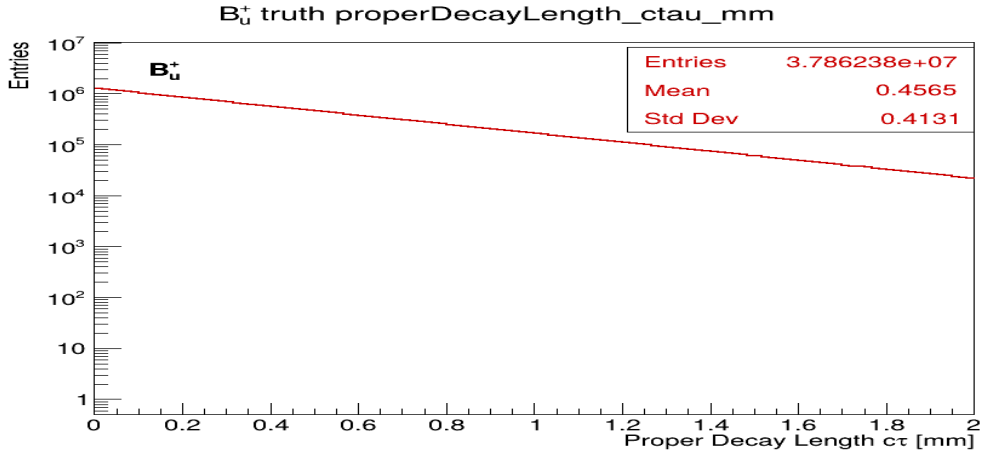
Backup: properDecayLength_ctau_mm (1/2)

Corrected v5 proper decay length cτ.





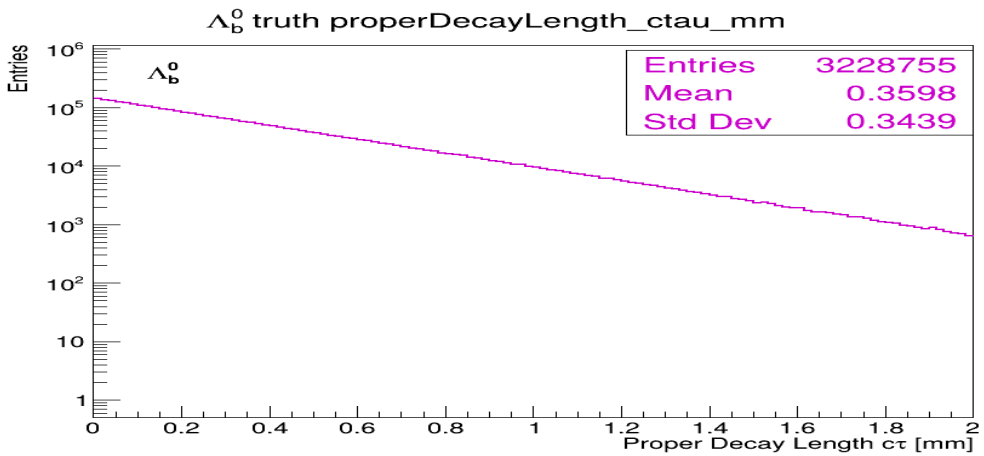


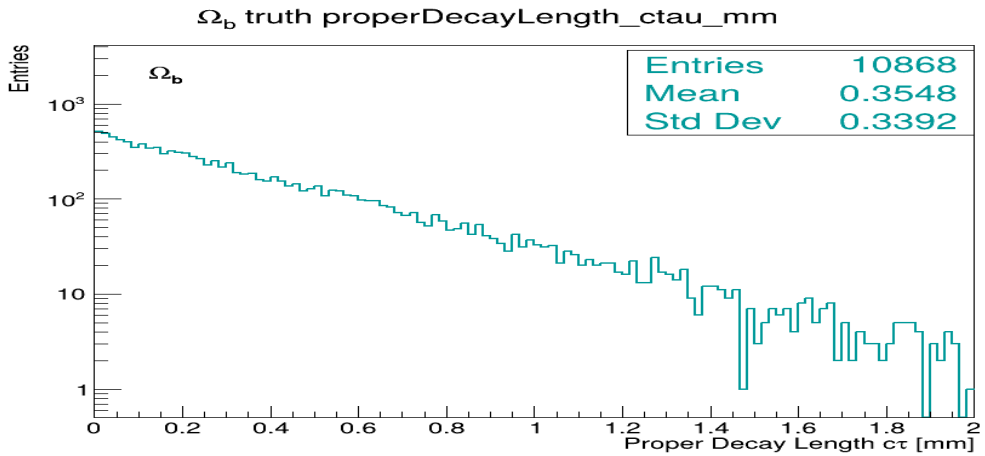


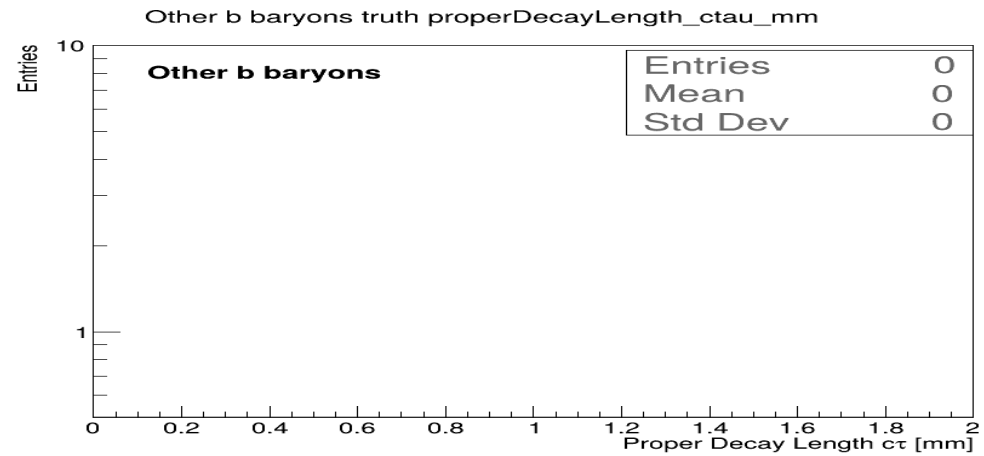
Corrected v5 output; proper decay length cτ is now populated and physically sensible.

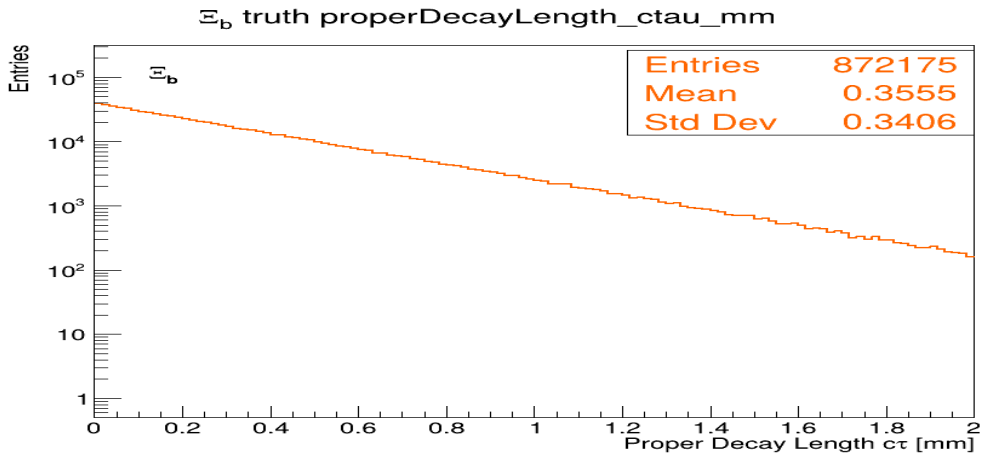
Backup: properDecayLength_ctau_mm (2/2)

Corrected v5 proper decay length cτ.





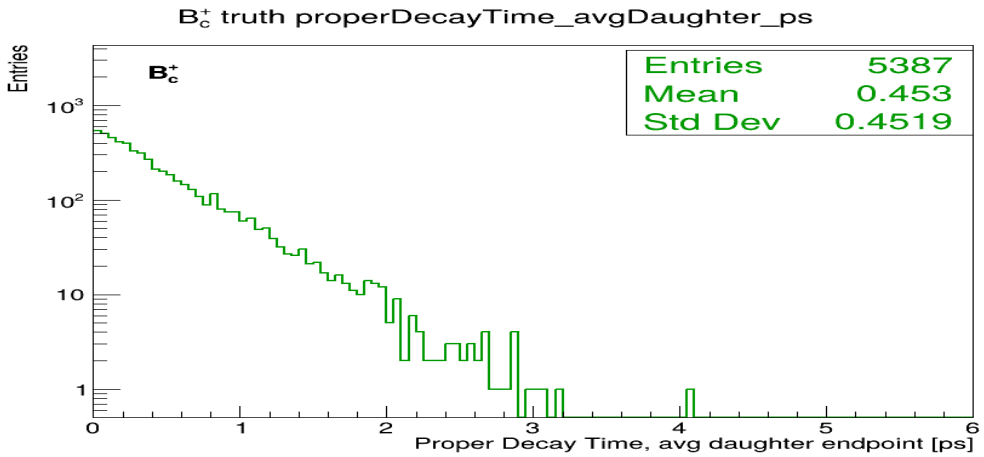


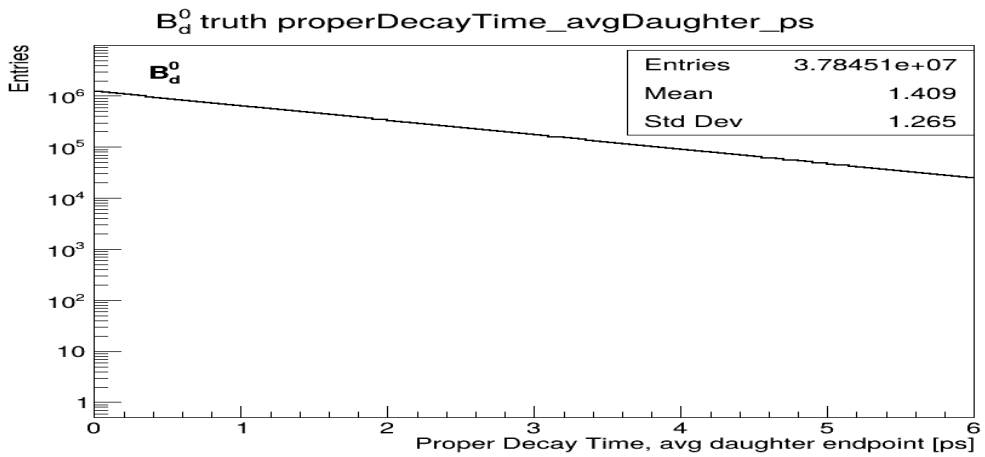


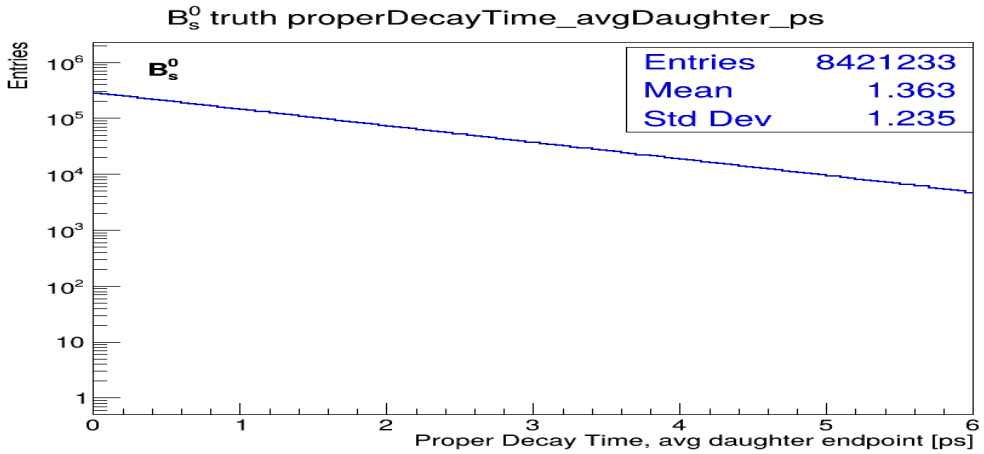
Corrected v5 output; proper decay length cτ is now populated and physically sensible.

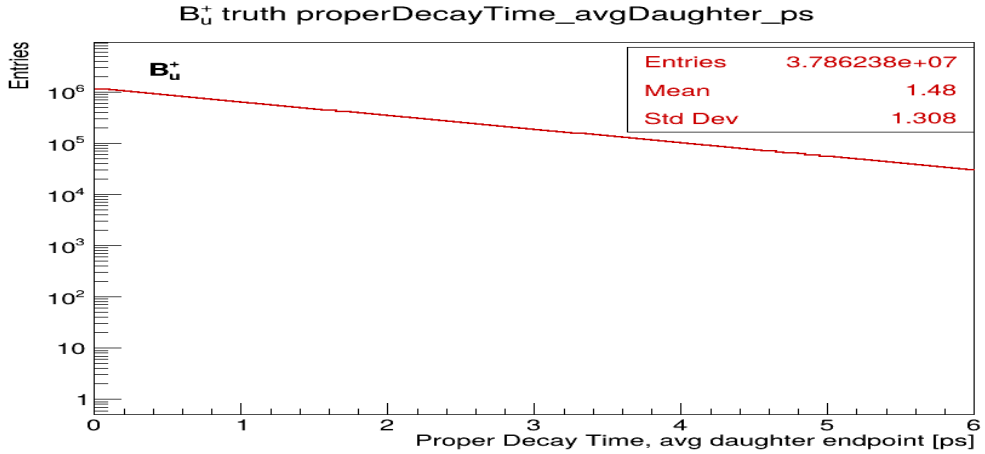
Backup: properDecayTime_avgDaughter_ps (1/2)

Corrected v5 proper decay time using average daughter endpoint.





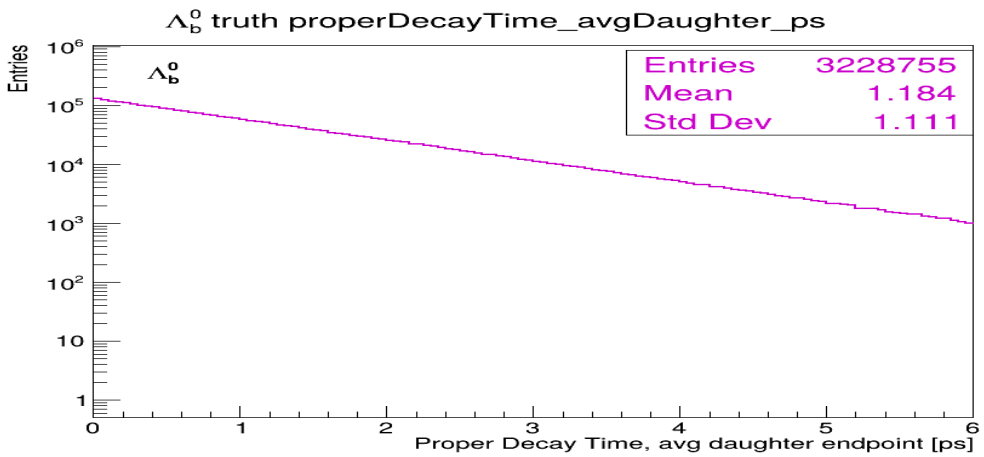


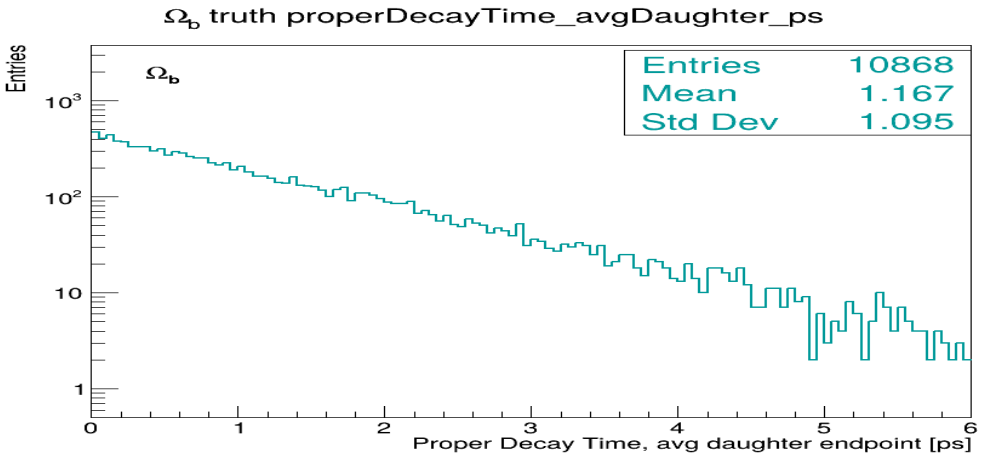


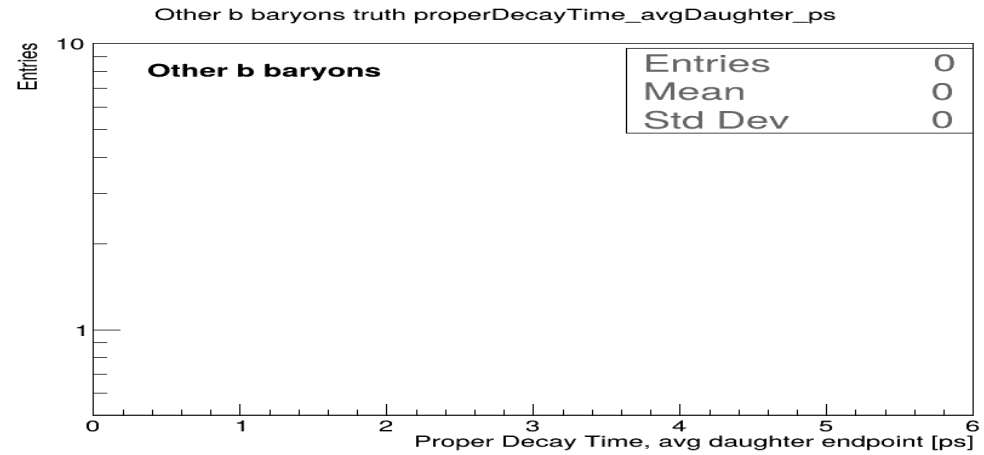
Corrected v5 output; average-daughter proper time agrees with the first-daughter result.

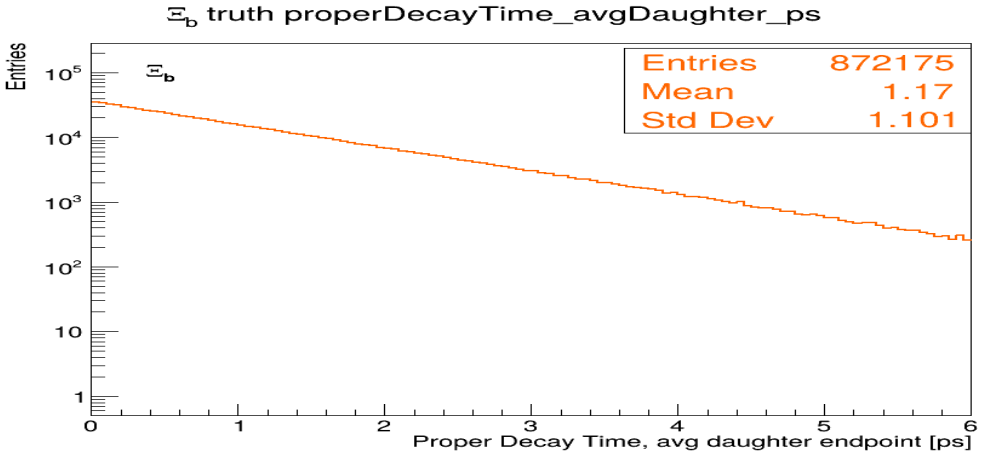
Backup: properDecayTime_avgDaughter_ps (2/2)

Corrected v5 proper decay time using average daughter endpoint.





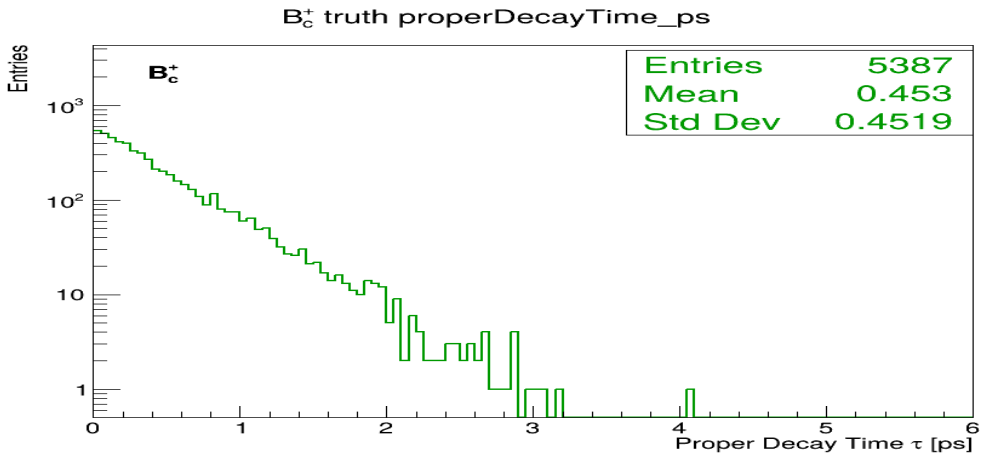


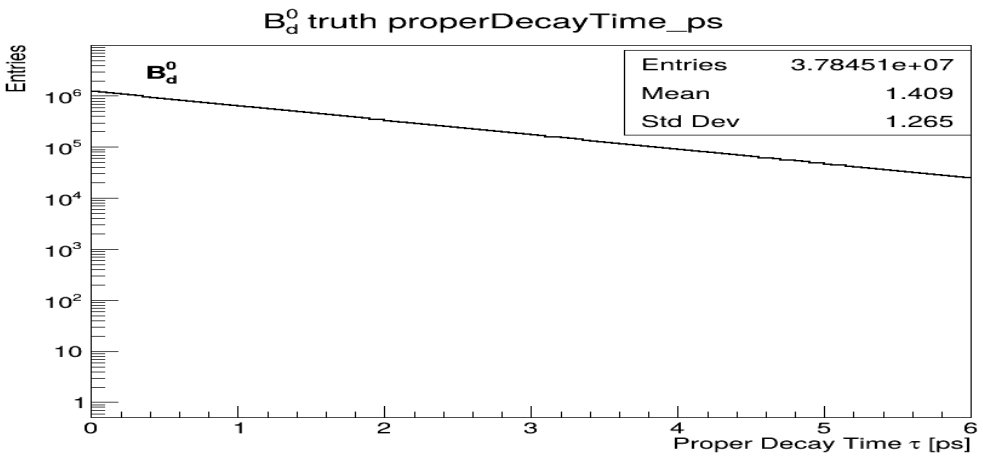


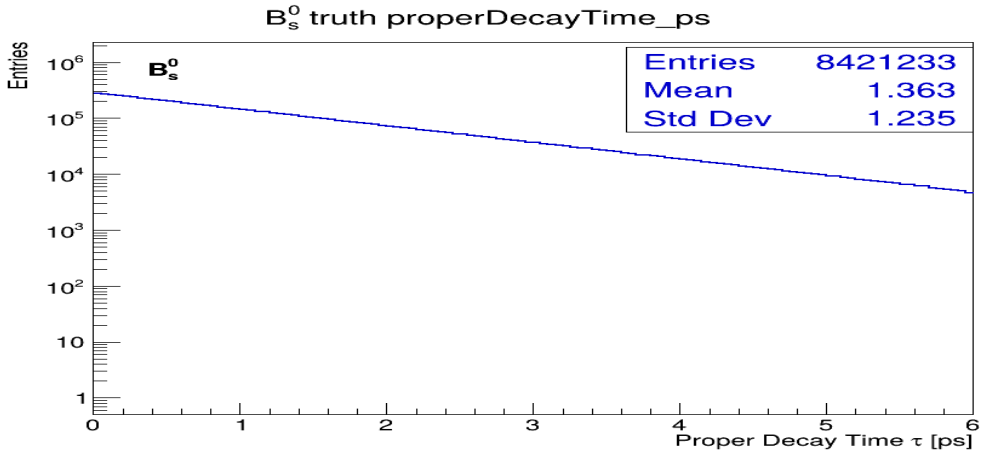
Corrected v5 output; average-daughter proper time agrees with the first-daughter result.

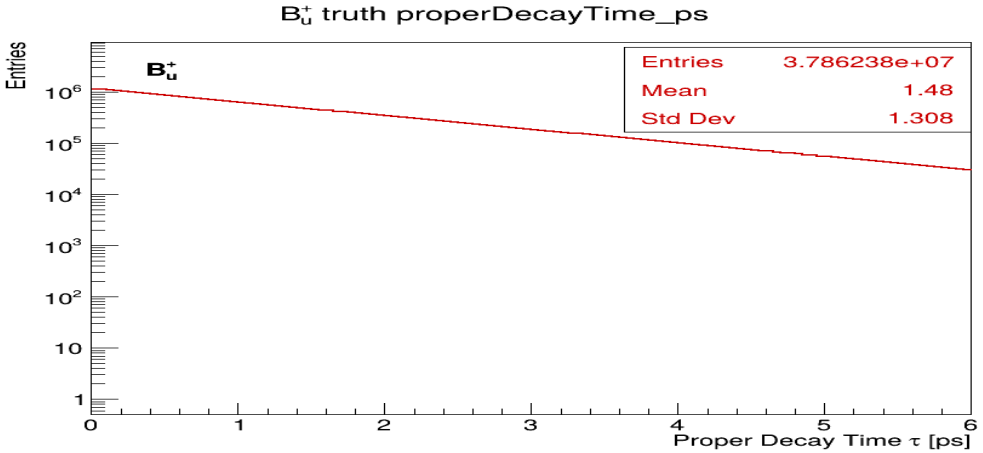
Backup: properDecayTime_ps (1/2)

Corrected v5 proper decay time.





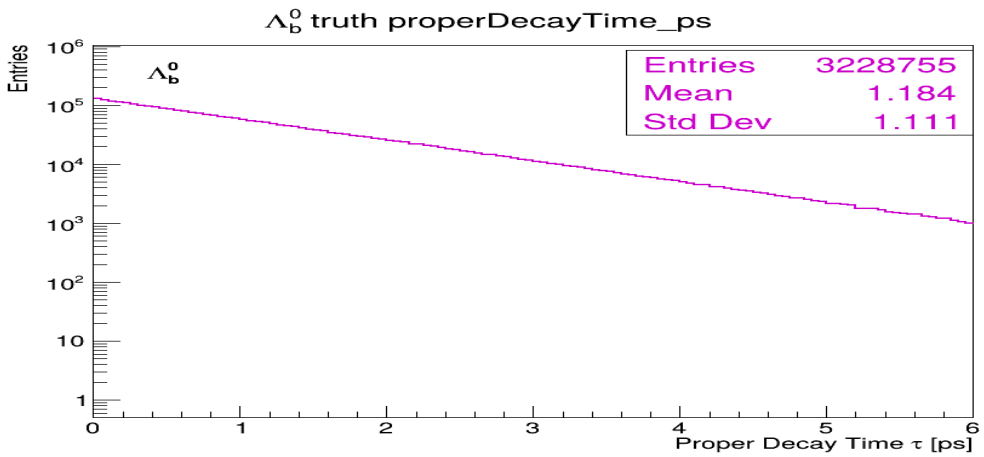


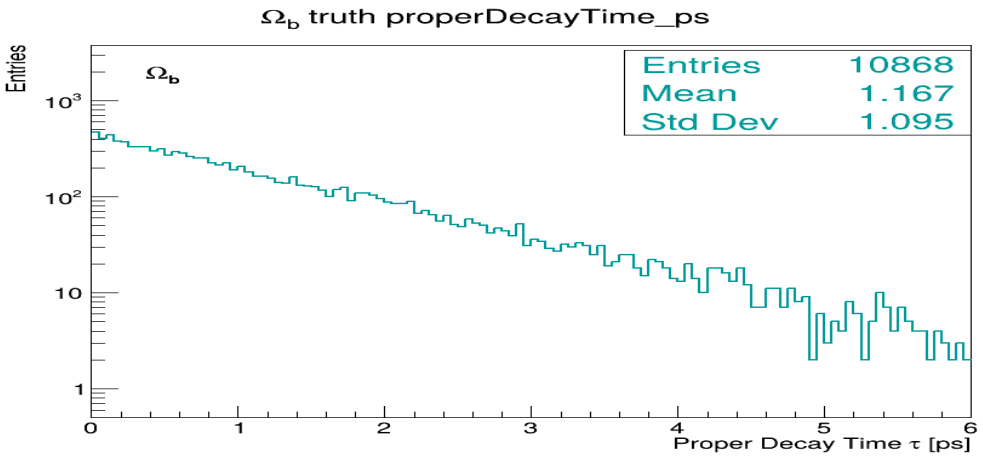


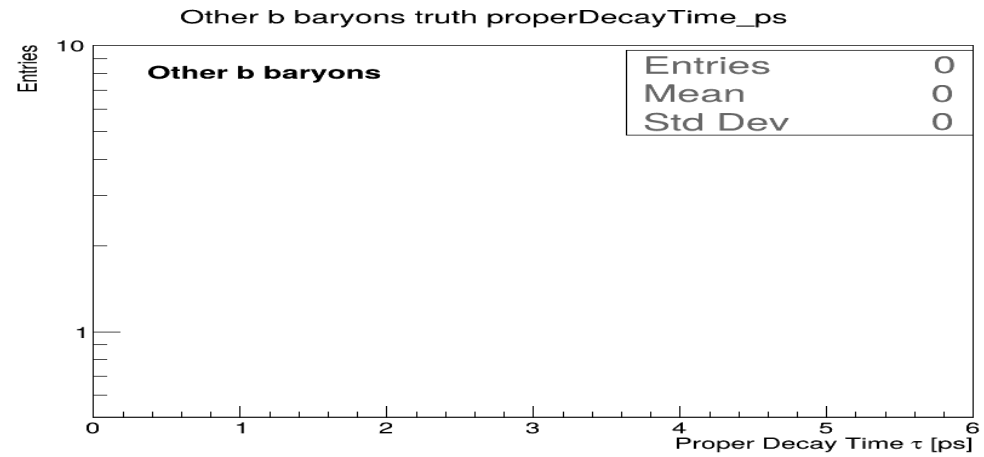
Corrected v5 output; proper decay time is populated for all non-empty classes.

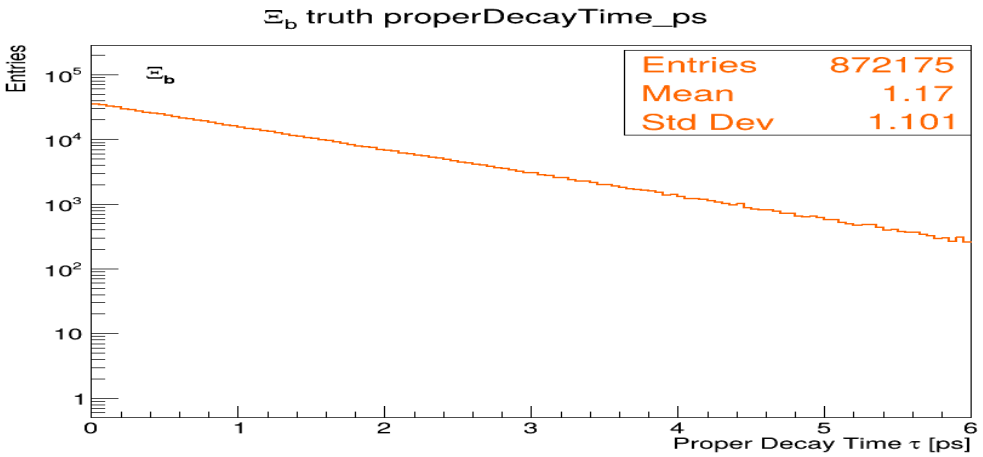
Backup: properDecayTime_ps (2/2)

Corrected v5 proper decay time.



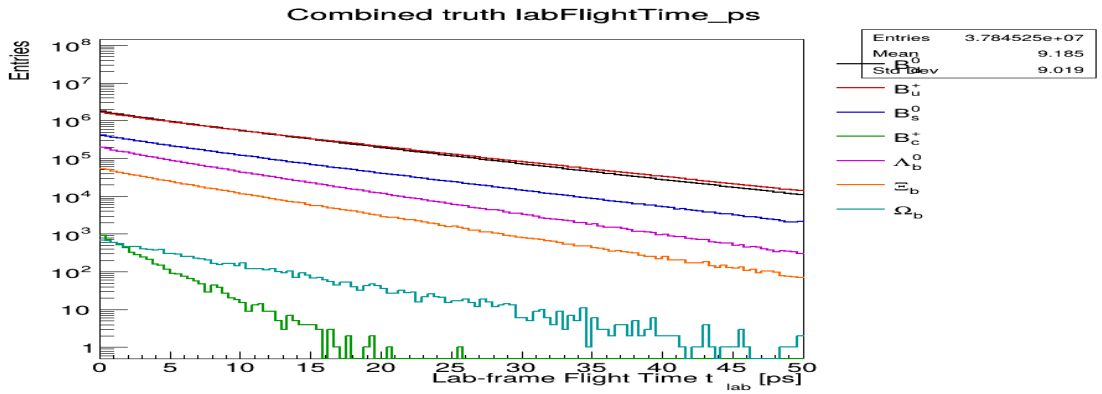


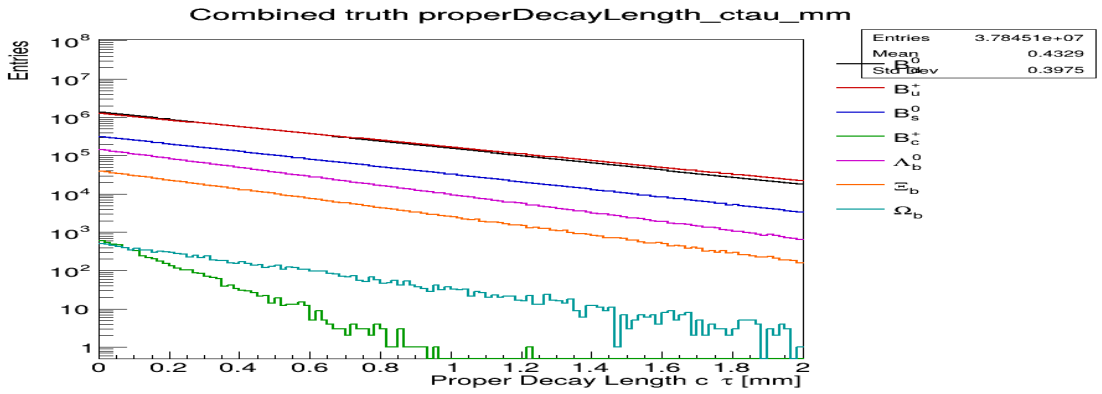


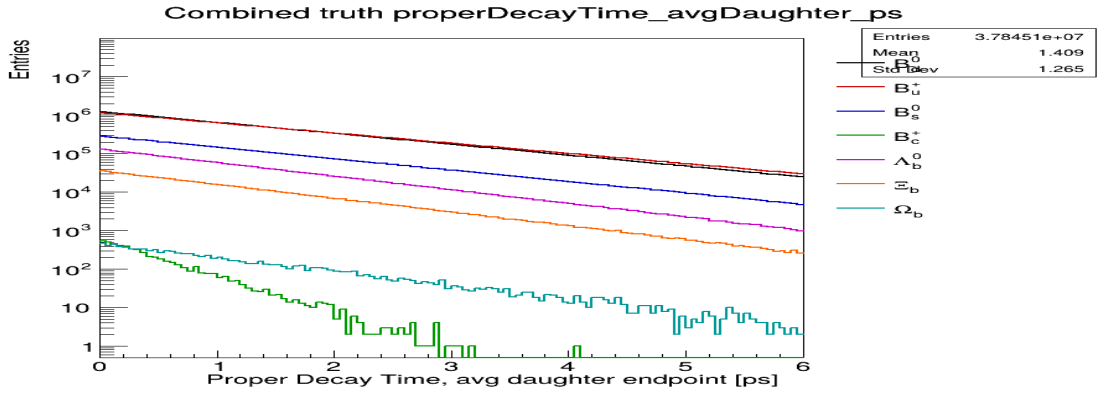


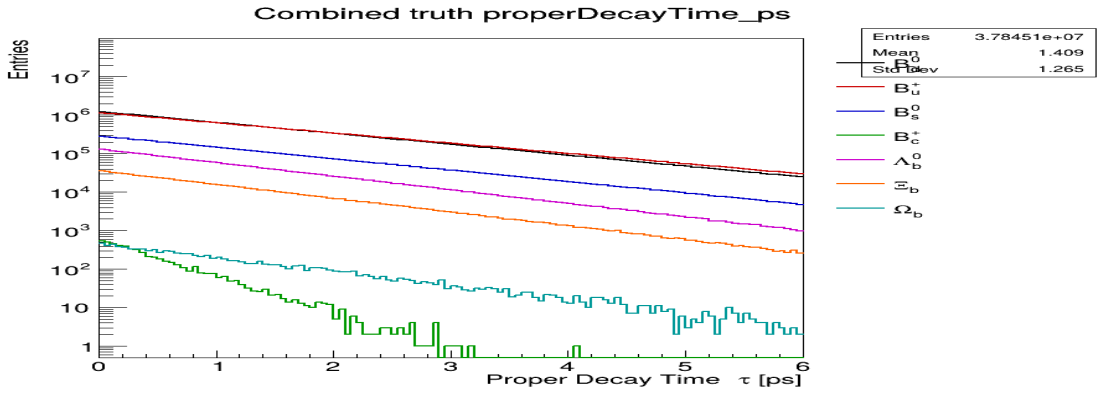
Corrected v5 output; proper decay time is populated for all non-empty classes.

Backup: combined corrected timing output plots









Combined lab-time, cτ, and proper-time plots all show sensible populated distributions after the time-unit correction. The combined distance plots are shown earlier in the main section and distance backup slides.