

Light hypernuclei production: from intermediate to large collision systems

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IX Reunião Geral - Projeto Especial FAPESP "Física e Instrumentação de Altas Energias com o LHC-CERN"

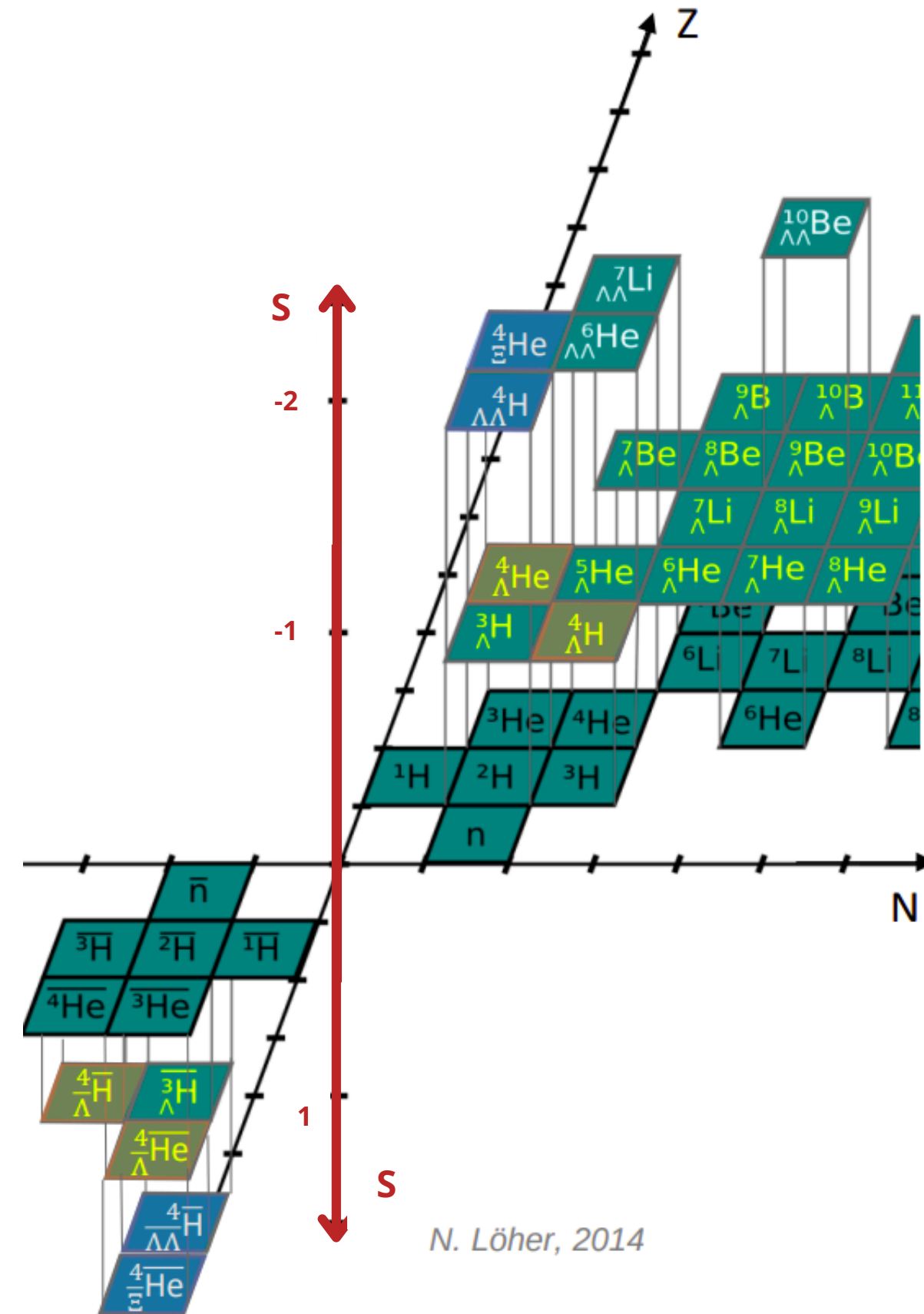
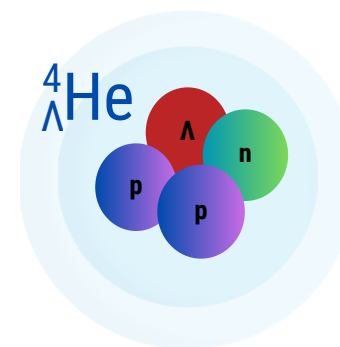
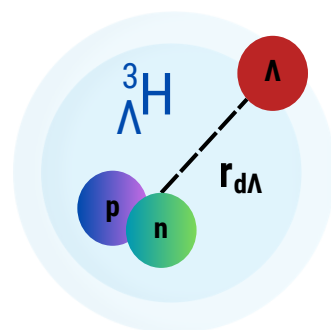


¹CERN

² Universidade de São Paulo

Hypernuclei

- **Hypernuclei:** Bound-state energy of ordinary nucleons and strange baryons (Λ , Σ).
 - Extending the nuclear chart to strangeness dimension.
- Weakly decay after a few centimeters ($c\tau \approx 5-7 \text{ cm}$) into two or more daughter particles.
- Key observables:
 - Decay rate (Γ) = $\frac{1}{\tau} = \Gamma_{\text{MWD}} + \Gamma_{\text{NMWD}}$
 - τ = lifetime
 - Binding energy (B_Λ) : $-B_{\Lambda,\Sigma} = M - (M_{\text{core hypernucleus}} + M_{\Lambda,\Sigma})$
 - M depends of the reconstruction method:
 - Invariant mass reconstruction: $M_{\text{inv}}^2 = (E_1 + E_2)^2 - |\vec{p}_1 + \vec{p}_2|^2$
- Lightest known hypernucleus: ${}^3_\Lambda\text{H}$ (hypertriton).
 - $B_\Lambda \approx 100 \text{ KeV} \rightarrow r_{d\Lambda} \sim 10 \text{ fm}$.^{1,2}
- Heavier hypernuclei at ALICE³: ${}^4_{\Lambda}\overline{\text{He}}$ (anti-hyperhelium-4).
 - A = 4 hypernuclei are more bound and each have an excited state.⁴
 - $B_\Lambda \approx 2 \text{ MeV} \rightarrow r \sim 2 \text{ fm}$.⁵



N. Löhner, 2014

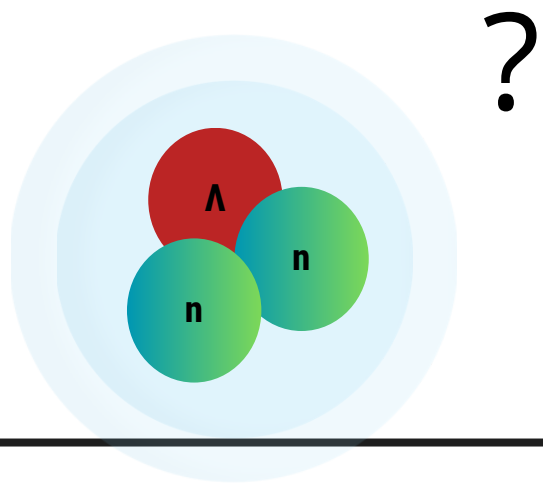
¹ M. Juric et al., Nucl. Phys. B, 52, 1-30, (1973)

² ALICE, Phys. Rev. Lett. 131, 102302 (2023)

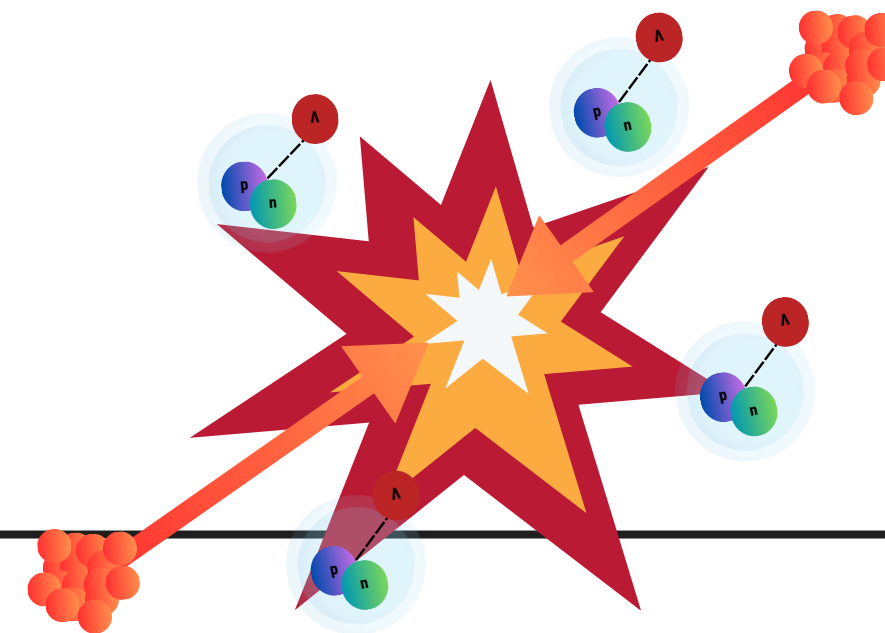
³ ALICE, Phys. Rev. Lett. 134, 162301 (2025)

⁴ M. Schäfer et al., Phys. Rev. Lett. 134, 162301 (2022)

⁵ T. O. Yamamoto et al., Phys. Rev. Lett. 115, 222501 (2015)

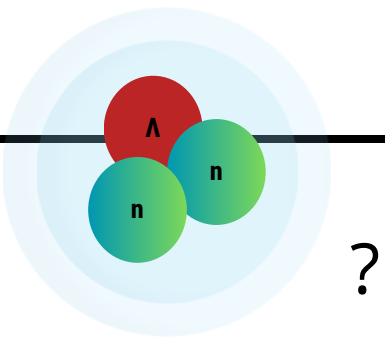


Ongoing analyses:

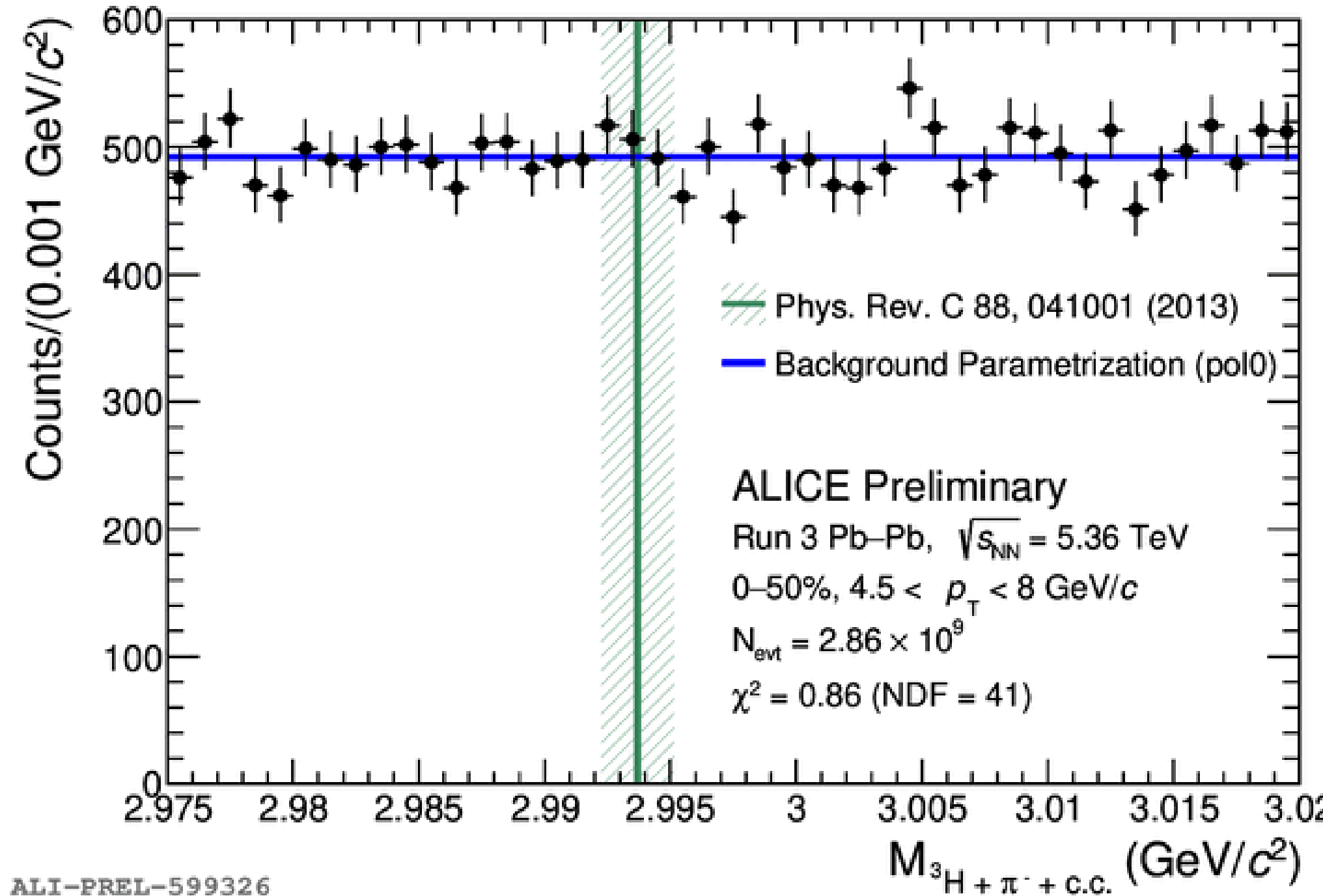


- Searching for the **Λ nn weak-decay signature** in heavy-ion collisions.
 - **Possible existence remains an open question:**
 - First observation claimed in 2013¹, no further experimental evidence has been presented supporting its existence — whereas the state-of-the-art model calculations do not expect it to be bound^{2,3}.
- Investigating **${}^3_{\Lambda}\text{H}$ hypernucleosynthesis** in light-ion collisions.
 - Studied across several collision systems, from low-multiplicity (pp and p-Pb) to high-multiplicity heavy-ion collisions (Pb-Pb), testing hadronization models.
 - **Intermediate system size: Bridge the gap in ${}^3_{\Lambda}\text{H}$ production between small and large systems.**

Previous results on Λ nn reconstruction

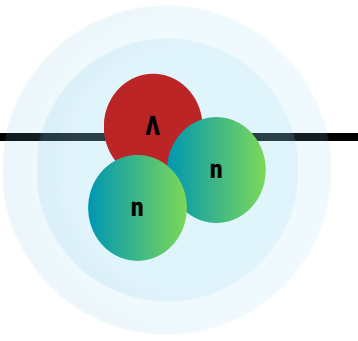


- Pb–Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV collected by ALICE during 2023:
 - 7.0×10^9 events for tracks from the central barrel requiring hadron PID.
- Topological reconstruction of the possible two-body decay channel: Λ nn \rightarrow ${}^3\text{H} + \pi^- + \text{charge conjugate (c.c.)}$.
- Rare probe:
 - Significance scan performed across central and semi-central centrality classes and over 8 p_T bins to find the best centrality and p_T bin to a possible signal:
 - Background estimated via linear interpolation in the sideband region ($\mu \pm 3\sigma$).
 - Signal based on ${}^3\text{H}$ yield in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV¹.
- No statistically significant signal is observed in the region of transverse momentum p_T and centrality with the highest sensitivity to a potential Λ nn signal -corresponding to an expected significance of 4.6σ .



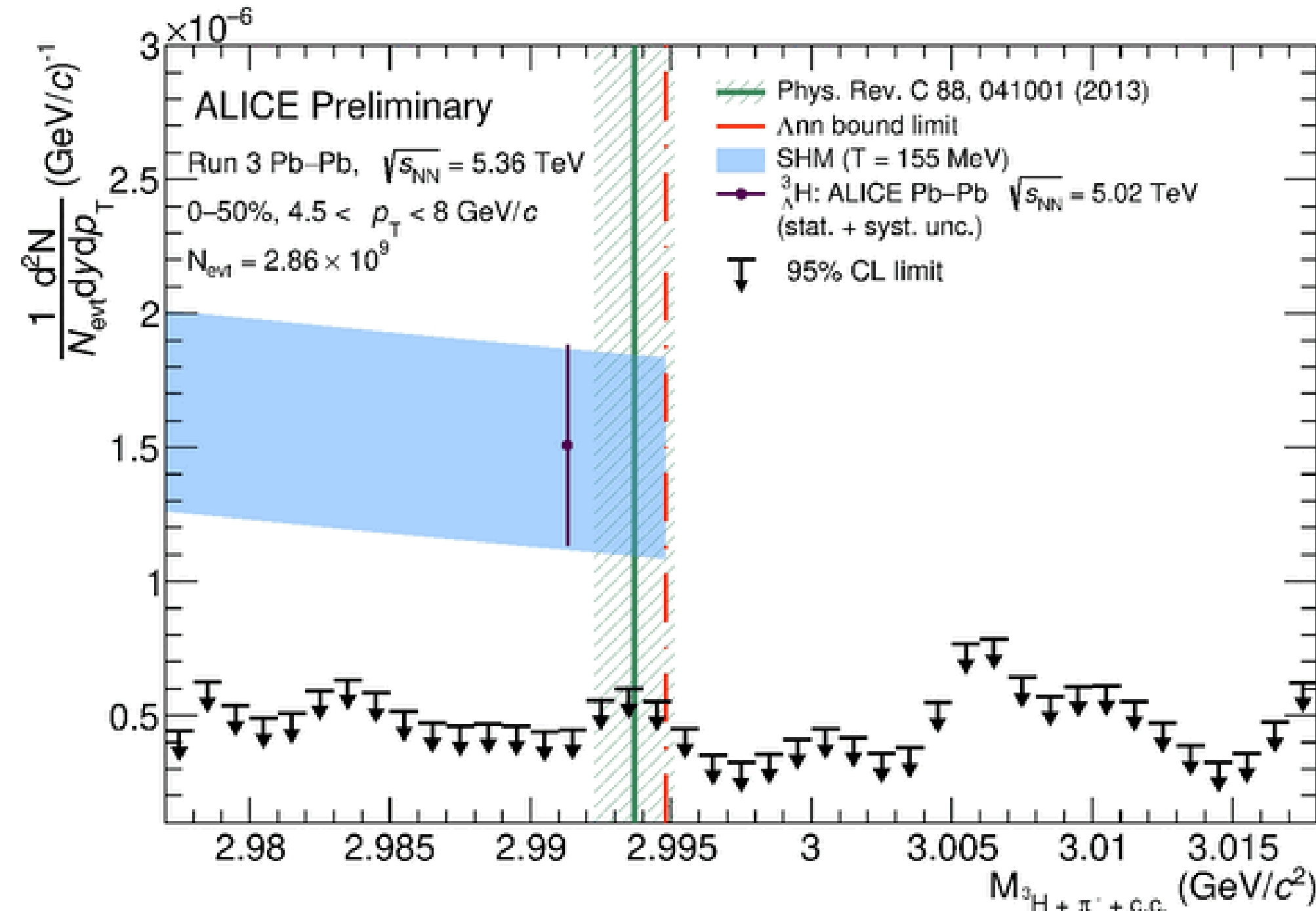
¹ ALICE Collaboration, Phys. Lett. B 858 138943 (2024).

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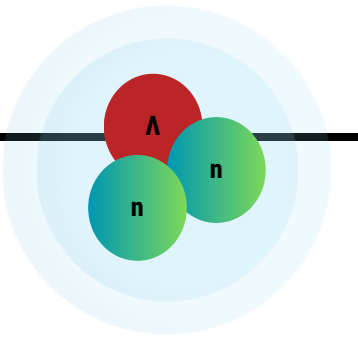
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- No statistically significant signal is observed in the region of transverse momentum p_T and centrality with the highest sensitivity to a potential Λ nn signal -corresponding to an expected significance of 4.6σ .
- Upper limit of the expected Λ nn yield:
 - In the most conservative scenario, the Λ nn yield does not agree with the SHM predictions below the bound state threshold.



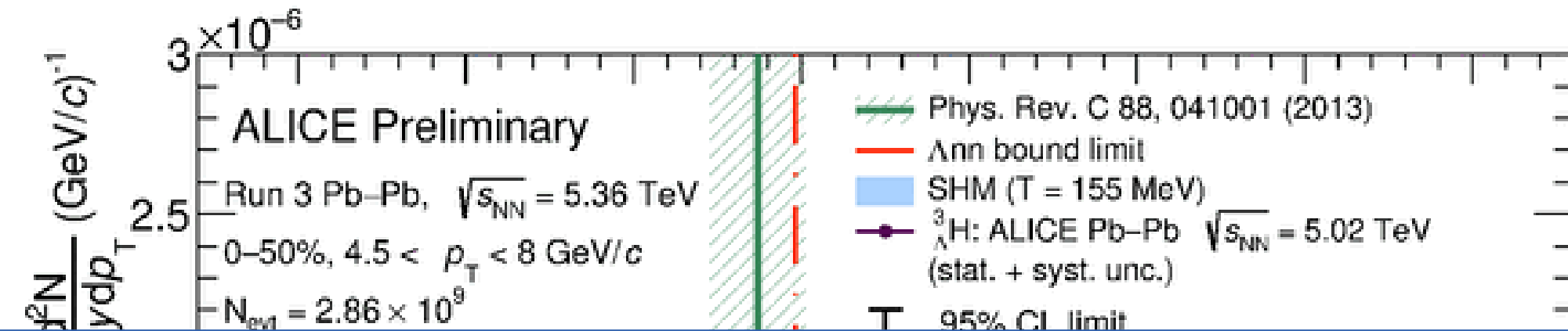
ALI-PREL-599321

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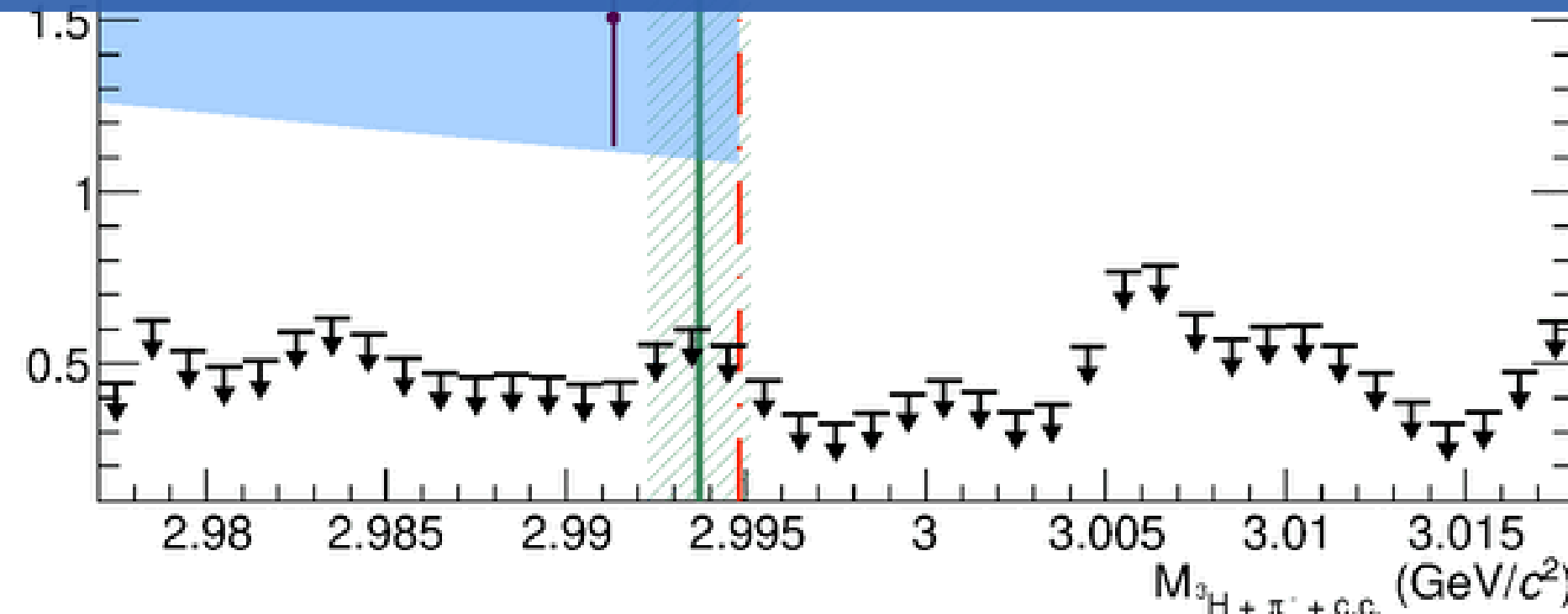


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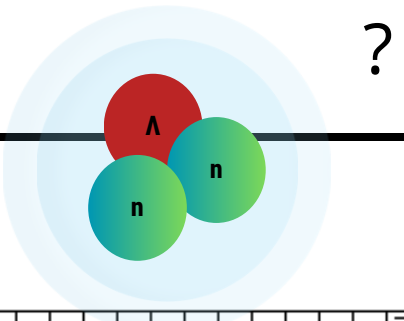
In the absence of a signal, how can we still constrain its existence and formation at freeze-out boundaries?

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ALI-PREL-599321

cτ studies

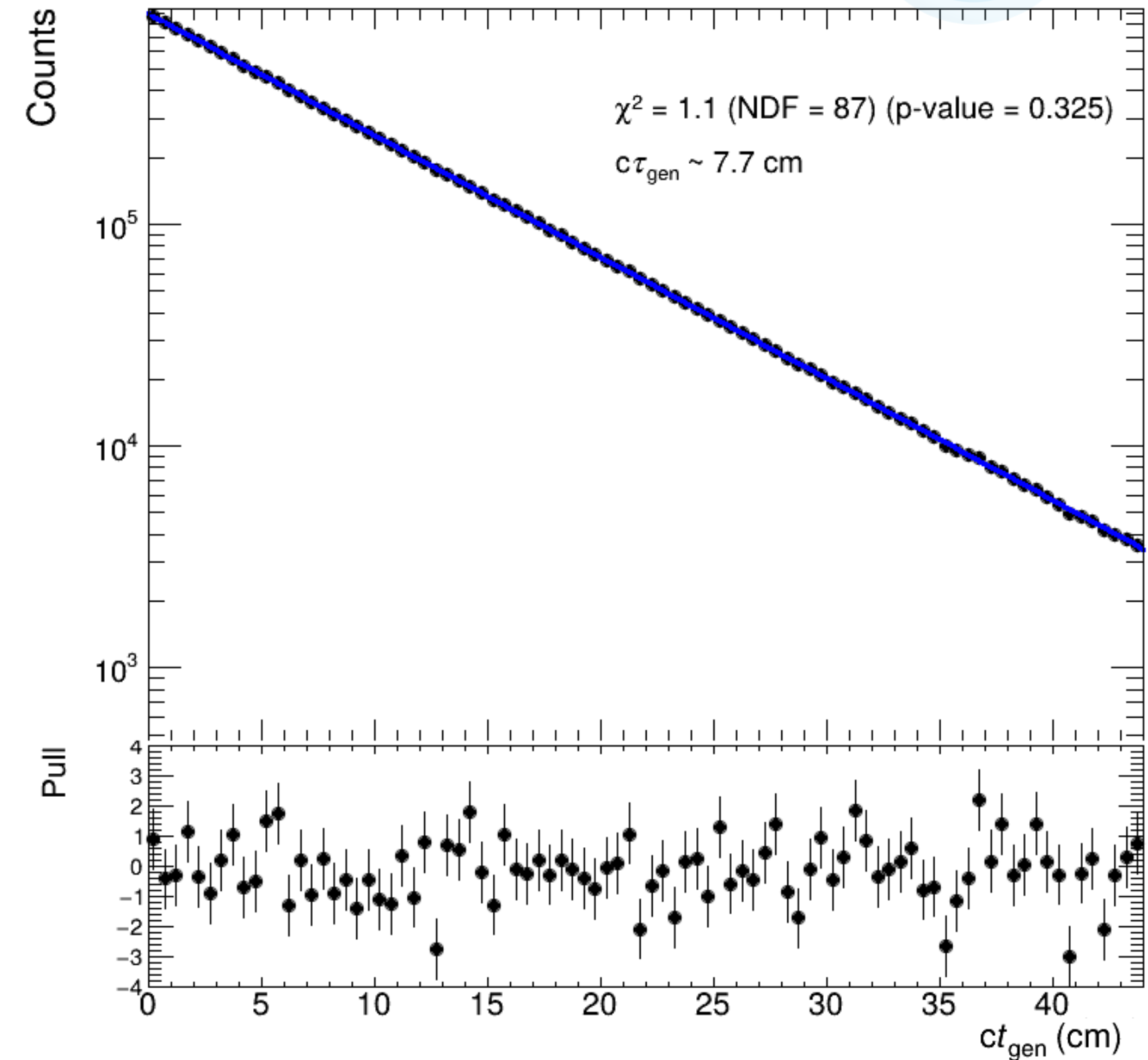


- **Goal:** Obtain the upper limit yield assuming different cτ hypotheses.

- **Step 1:**

- Reweighting the ct_{gen} distributions assuming different $c\tau$ values:

- $c\tau < c\tau_{mean}$: Acceptance-rejection sampling.
 - $P(c\tau) = \exp(ct(1/c\tau_{mean} - 1/c\tau))$
- $c\tau > c\tau_{mean}$: Apply a weight factor ($w(c\tau)$) derived from the ratio between the probability density functions of the original and target distributions, normalized by the number of events in $c\tau = 45$ cm.
 - $w(c\tau) = (c\tau_{mean}/c\tau) \exp(-ct(1/c\tau - 1/c\tau_{mean}))$



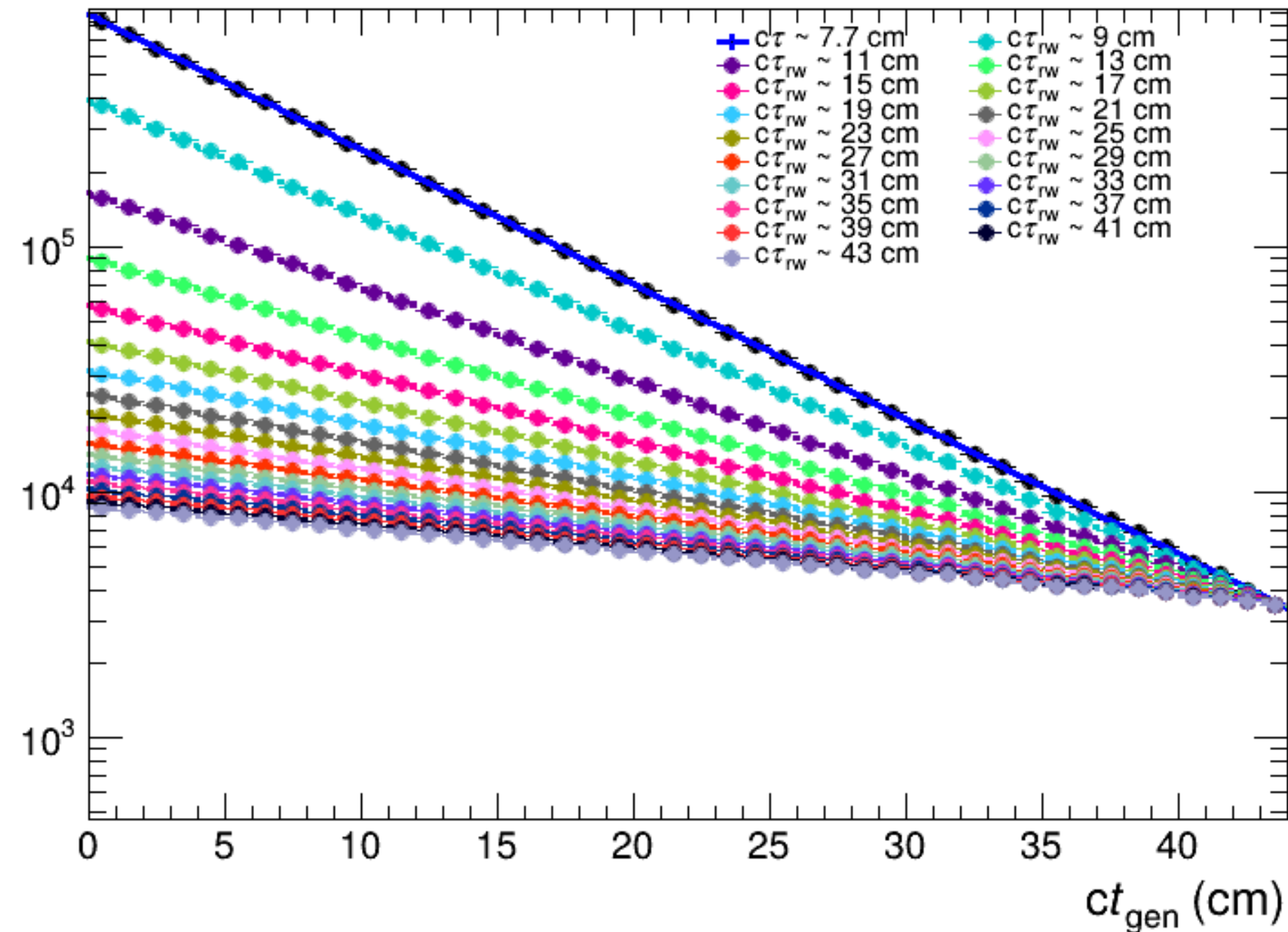
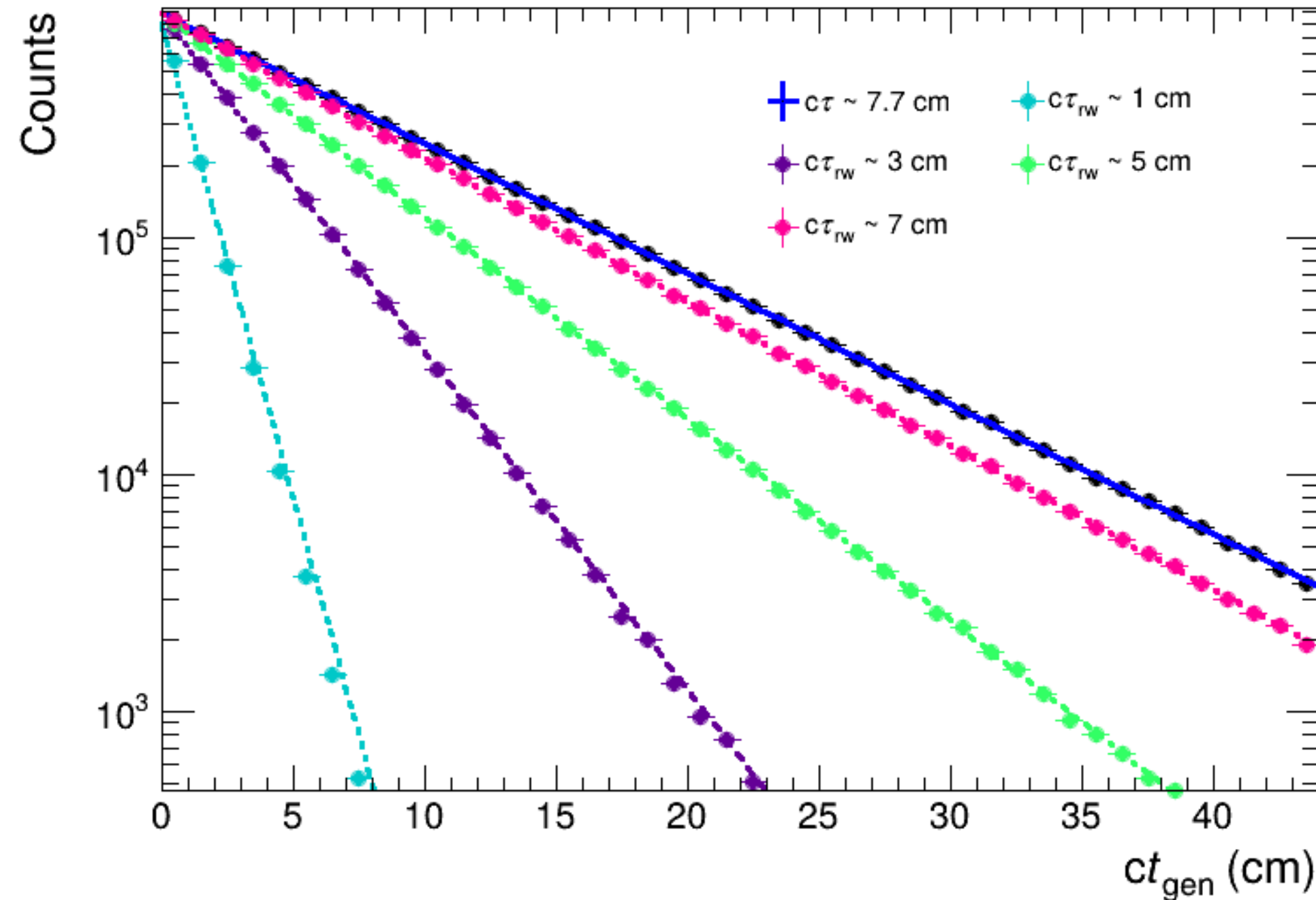
$c\tau_{\text{gen}}$ distribution under different $c\tau$ hypothesis

1) $c\tau < c\tau_{\text{mean}}$:

- Rejection sampling:
 - $P(c\tau) = \exp(ct(1/c\tau_{\text{mean}} - 1/c\tau))$

2) $c\tau > c\tau_{\text{mean}}$:

- Weight factor ($w(c\tau)$) derived from the ratio between the target and original PDFs:
 - $w(c\tau) = (c\tau_{\text{mean}}/c\tau) \exp(-ct(1/c\tau - 1/c\tau_{\text{mean}}))$



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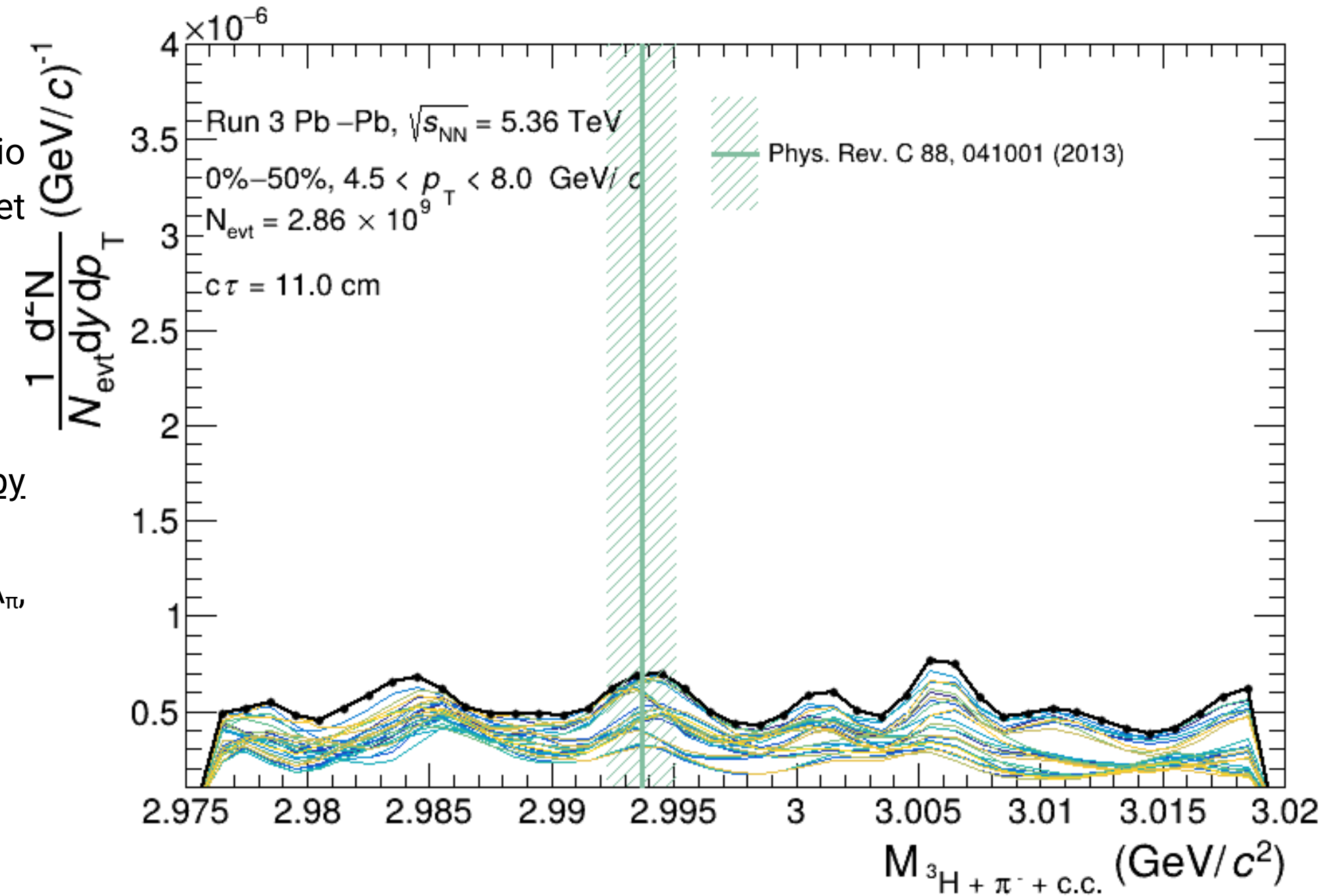
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- Step 2:

- Compute the UL yield as a function of $M_{3H+\pi+c.c.}$ for each dataset created by

$c\tau_{RW}$:

- UL computed for topological selection variations (DCA_{V0} , DCA_{π} , $\cos\theta_{PA}$) applied in p_T analysis.



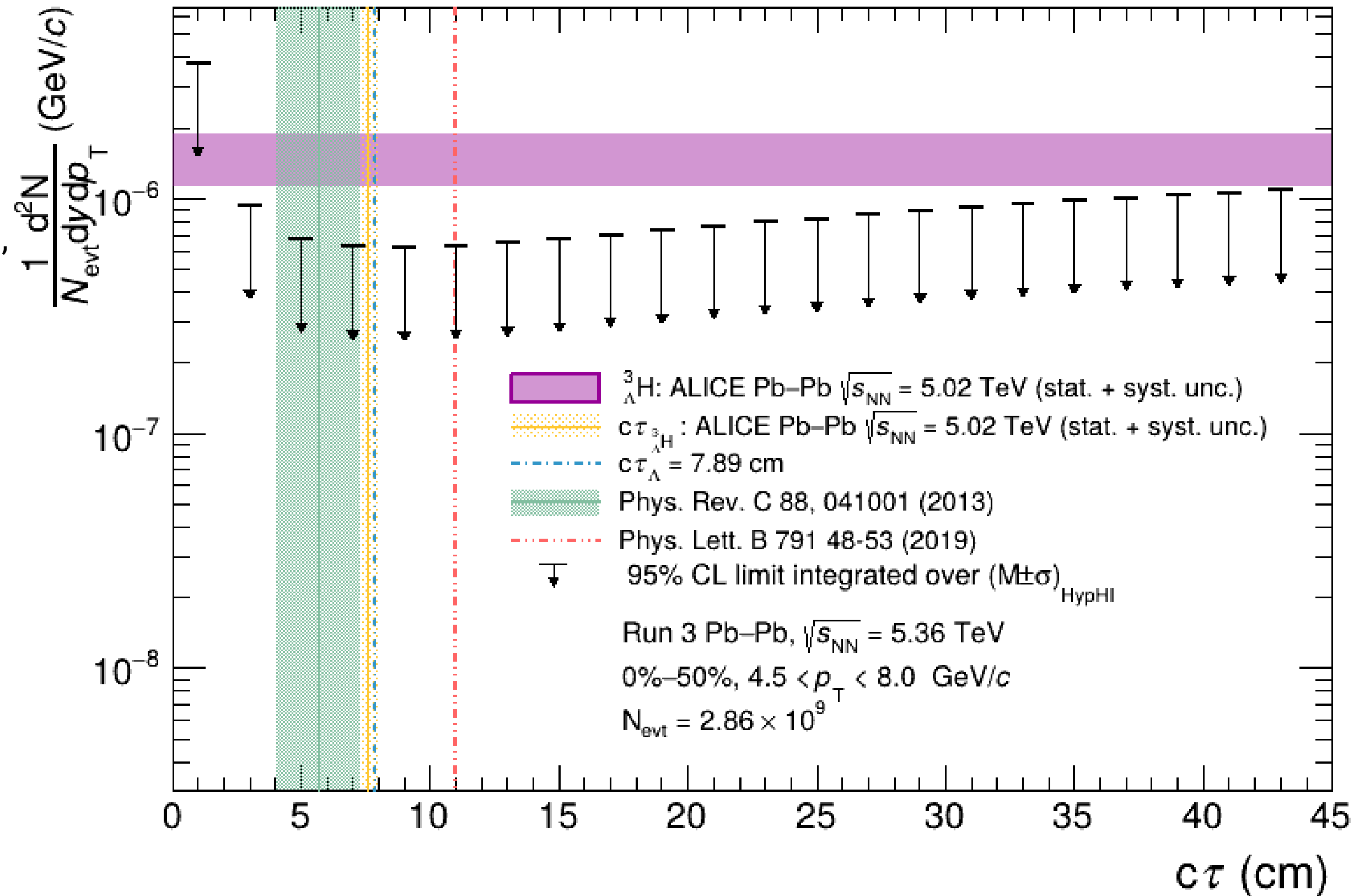
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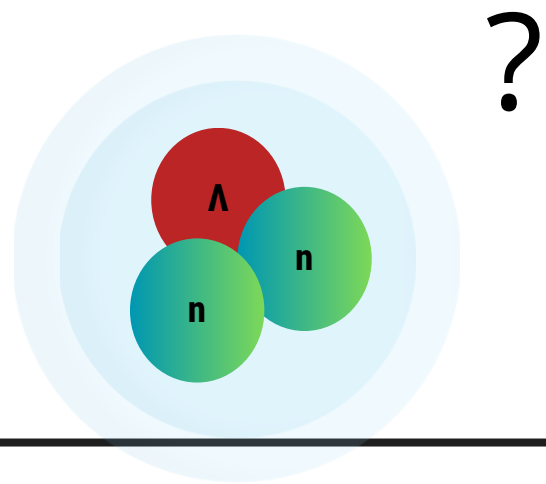
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 - UL computed for topological selection variations (DCA_{V0} , DCA_{π} , $\cos\theta_{PA}$) applied in p_T analysis.
- **Step 3:**
 - Integrate the UL yield over the mass region where the signal peak were claimed:
 - Average UL yield over $(M \pm \sigma)_{HypHI}$.
 - σ = quadratic sum of syst. and stat. uncertainties.
 - $c\tau \sim 7.7 \text{ cm} \rightarrow \text{UL yield} = 6.17 \times 10^{-7}$

cτ (cm)	UL yield over $2.9937 \pm 0.0014 \text{ GeV}/c^2$
1	3.75×10^{-6}
3	9.28×10^{-7}
5	6.67×10^{-7}
7	6.23×10^{-7}
9	6.16×10^{-7}
11	6.26×10^{-7}
13	6.45×10^{-7}
15	6.70×10^{-7}
17	6.99×10^{-7}
19	7.30×10^{-7}
21	7.62×10^{-7}
23	7.95×10^{-7}
25	8.16×10^{-7}
27	8.56×10^{-7}
29	8.91×10^{-7}
31	9.21×10^{-7}
33	9.51×10^{-7}
35	9.80×10^{-7}
37	1.01×10^{-6}
39	1.03×10^{-6}
41	1.06×10^{-6}
43	1.08×10^{-6}

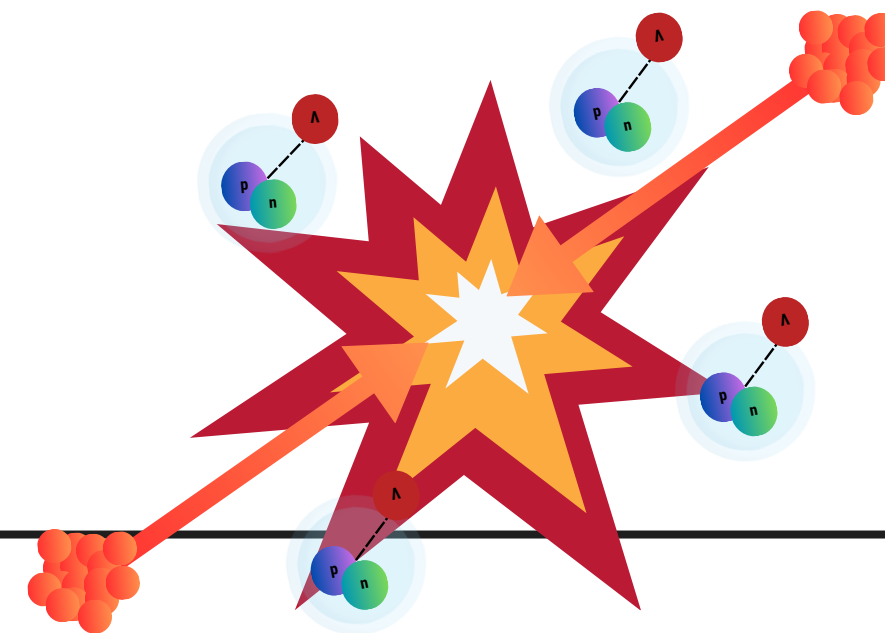
$c\tau$ dependence of Λ_{nn} production

- Very short lifetime ($c\tau \approx 1$ cm):
 - Average yield is high, above ${}^3\Lambda$ production, indicating a possible very fast decay.
- For $c\tau \sim c\tau_\Lambda$:
 - **Clear suppression is observed!**
- Long lifetime ($c\tau > c\tau_\Lambda$):
 - An increasing slope of Λ_{nn} production, after Λ free decays.





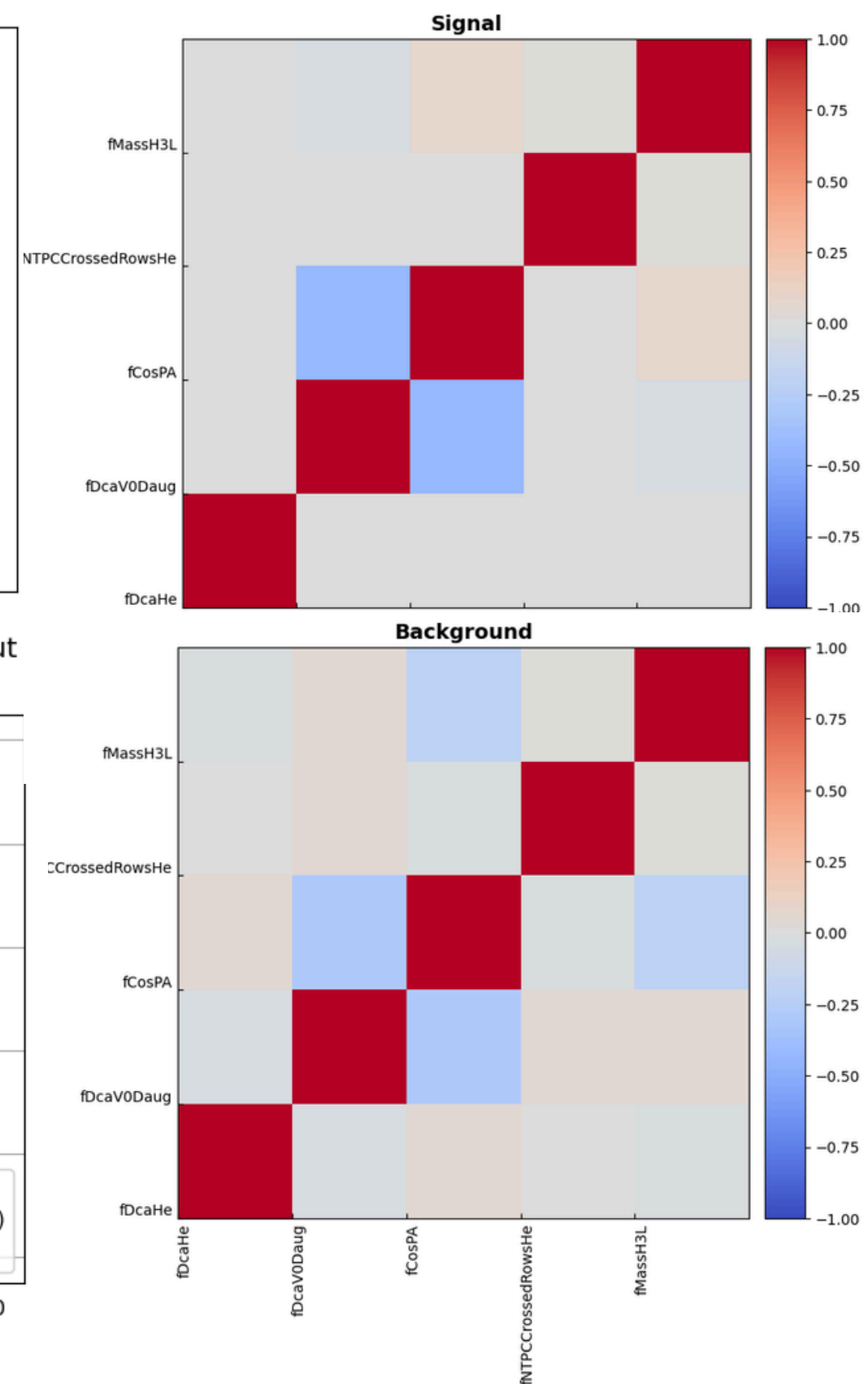
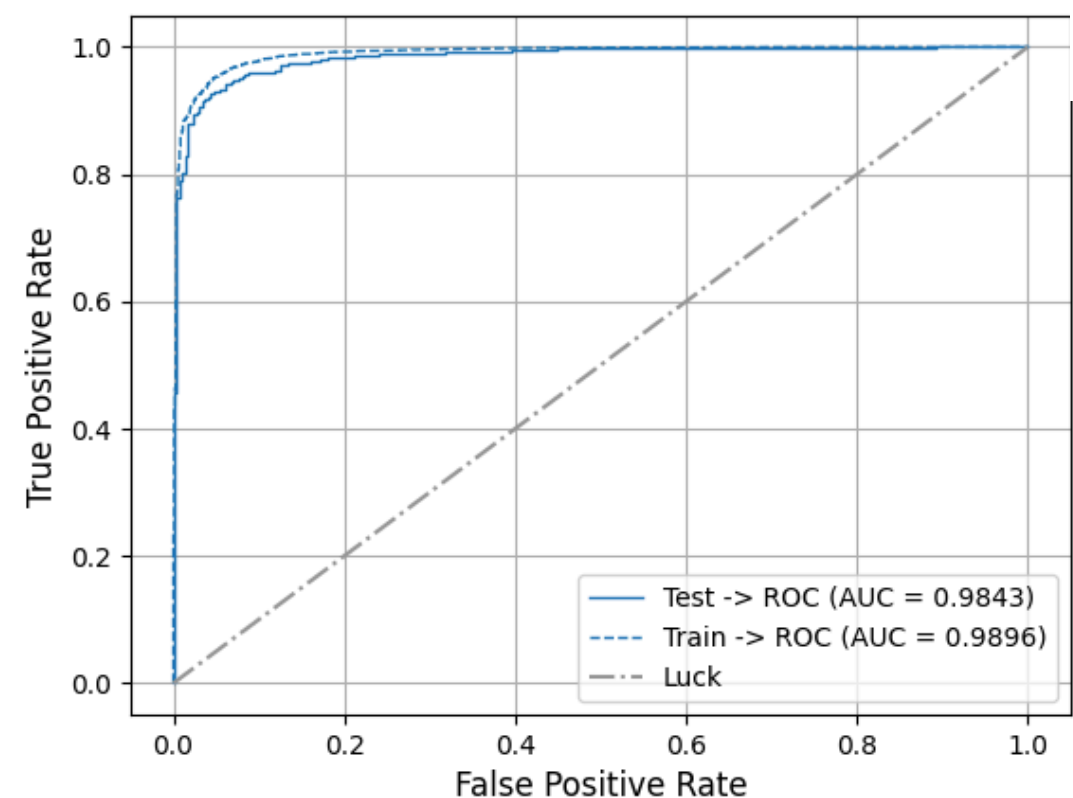
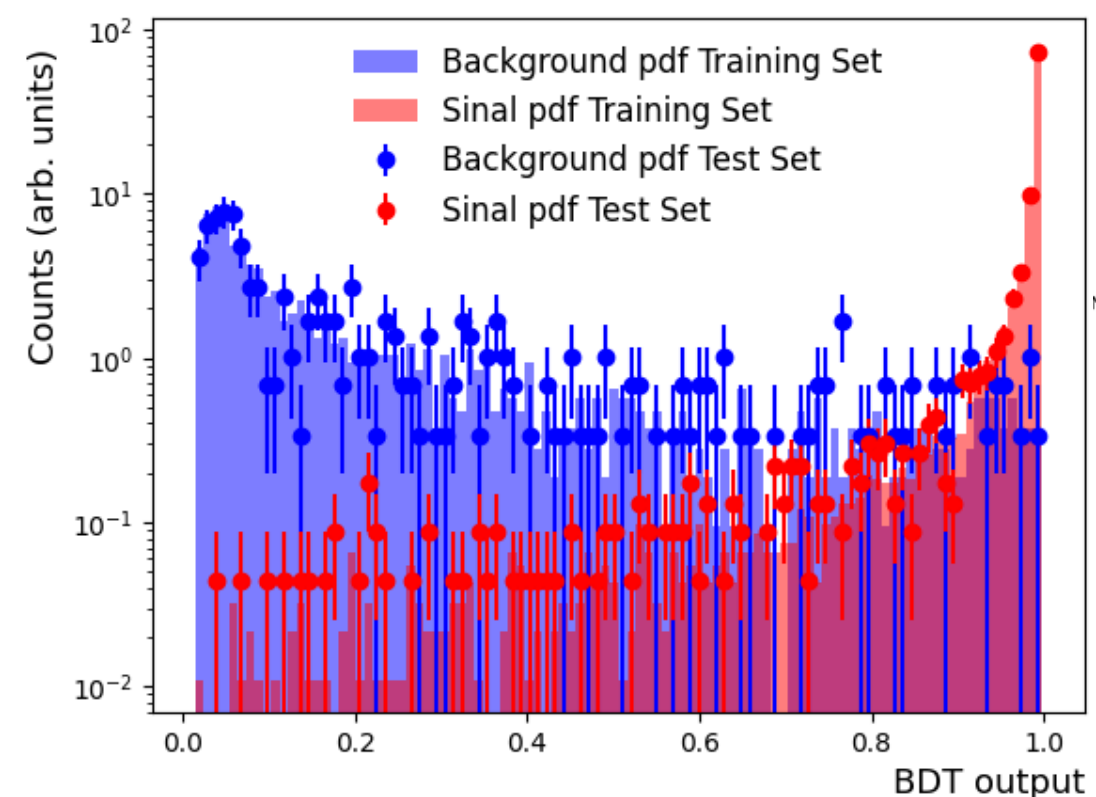
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BDT application for signal extraction

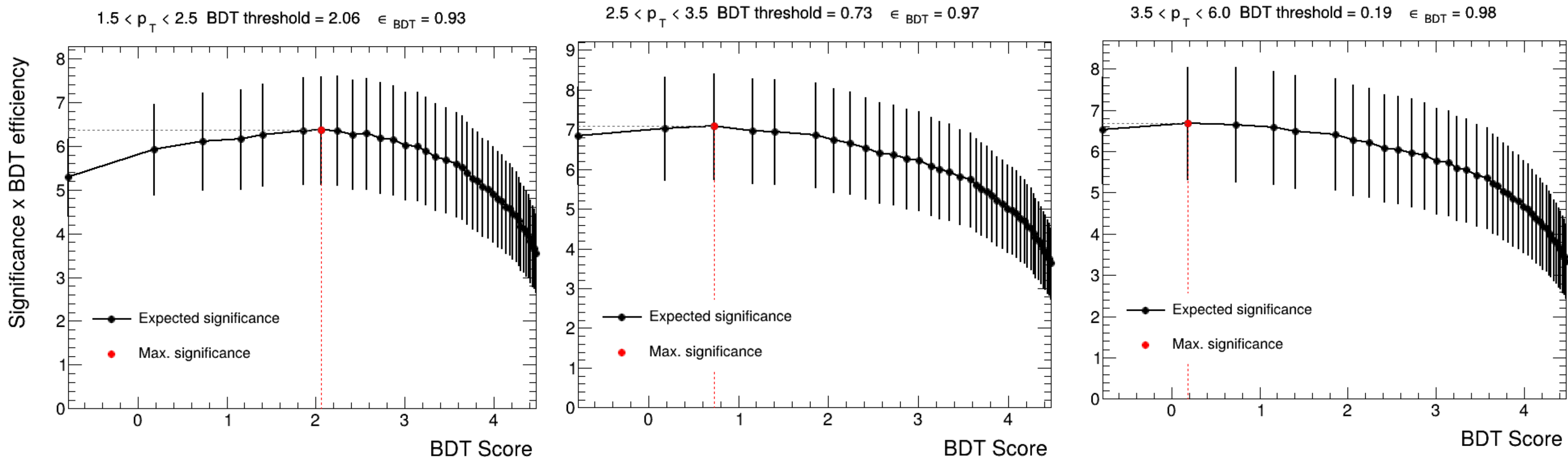
- OO collisions at $\sqrt{s_{NN}} = 5.36$ TeV collected by ALICE during 2025:
 - 2.4×10^9 events for tracks from the central barrel requiring hadron PID.
 - Topological reconstruction of the mesonic two-body decay channel: ${}^3_{\Lambda}H \rightarrow {}^3He + \pi^- + \text{charge conjugate (c.c.)}$
- Global model: p_T -integrated training and testing locally in each p_T -bin.
 - p_T bins [1.5, 2.5, 3.5, 6] and centrality class 0-90%: analysis performed for matter + anti-matter together.
 - Features training: DCA_{V0} , DCA_{3He} , $\cos\theta_{PA}$ and $nTPCCLUSCrossedRows3He$.



BDT cut

BDT threshold score

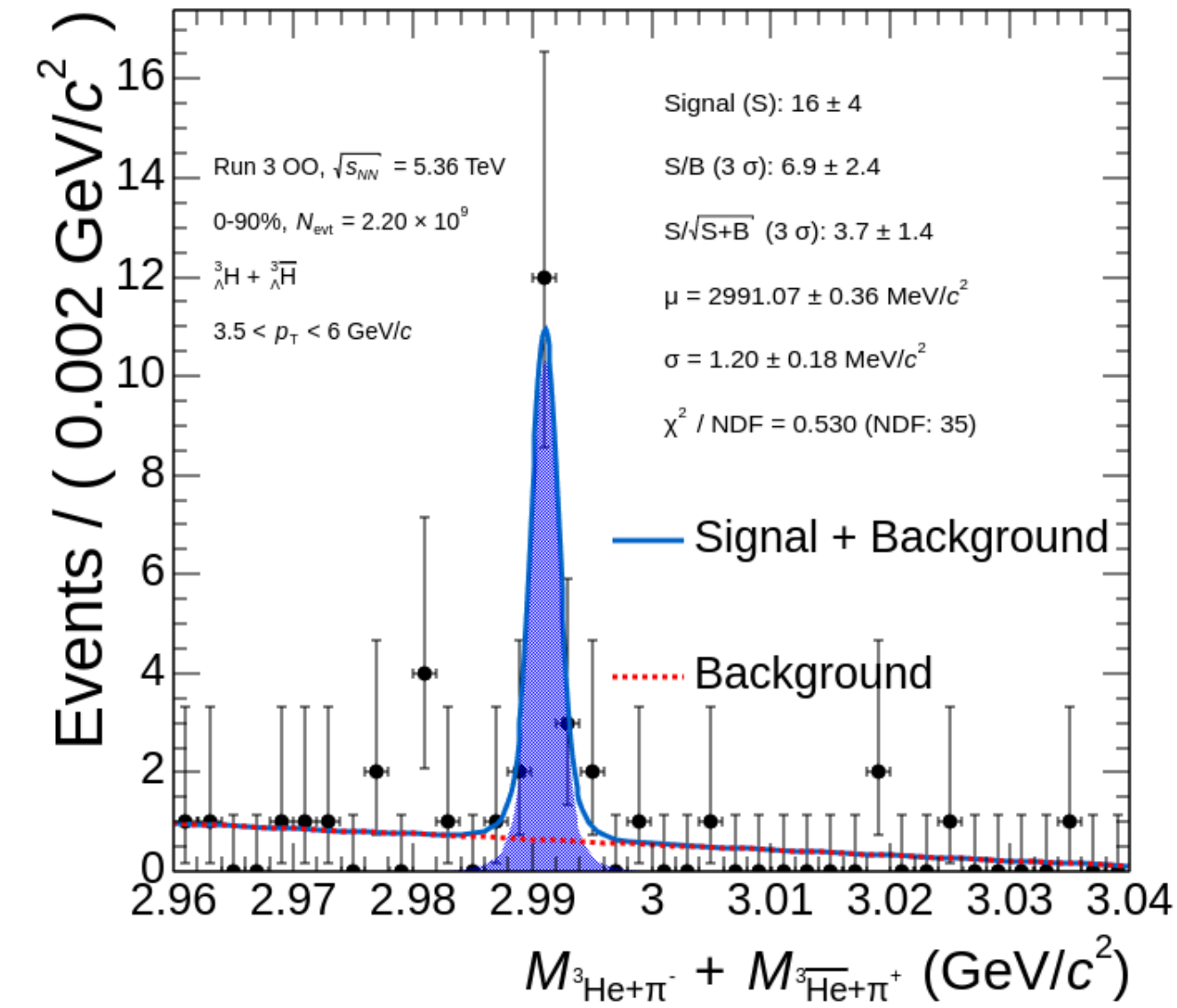
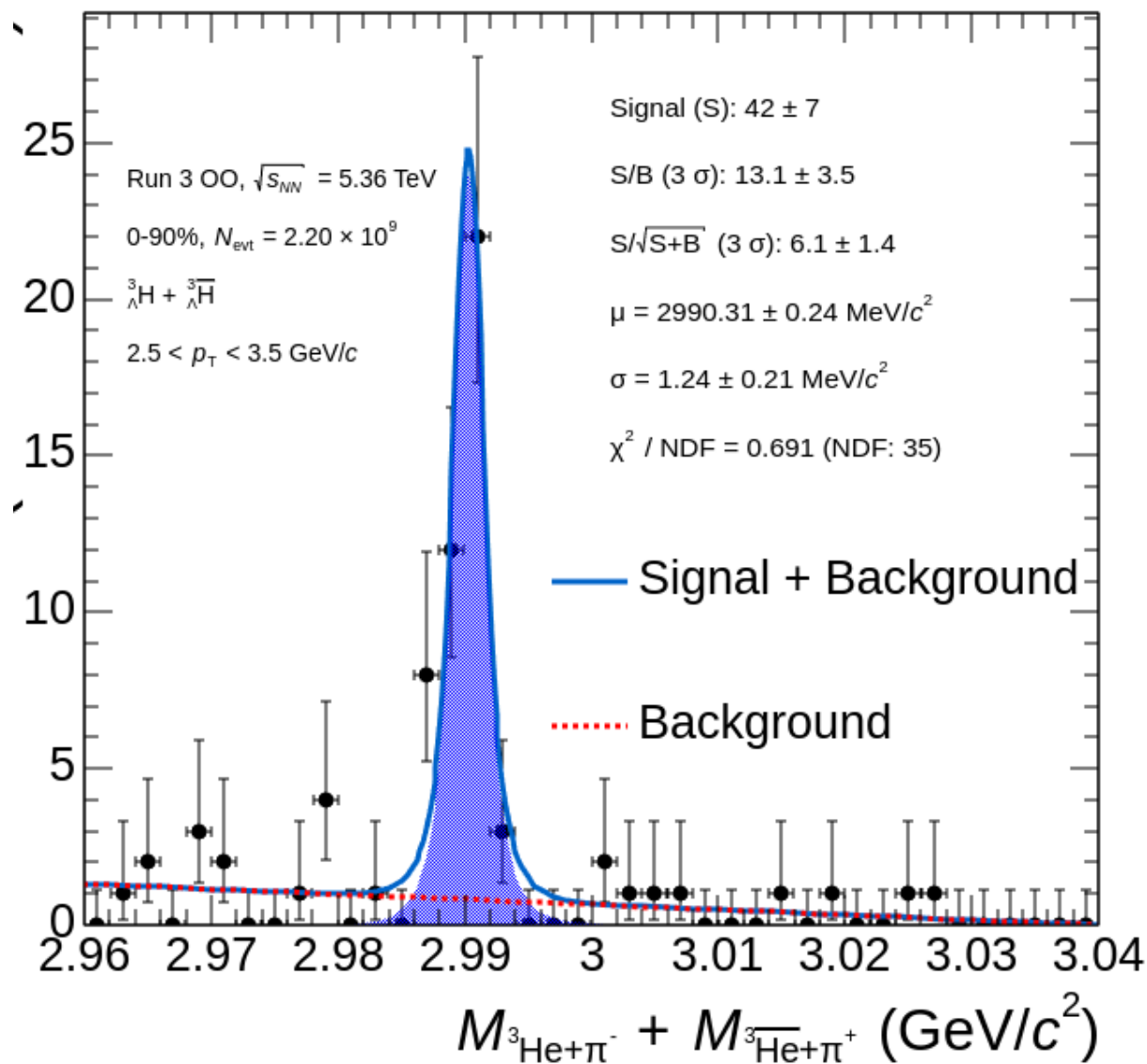
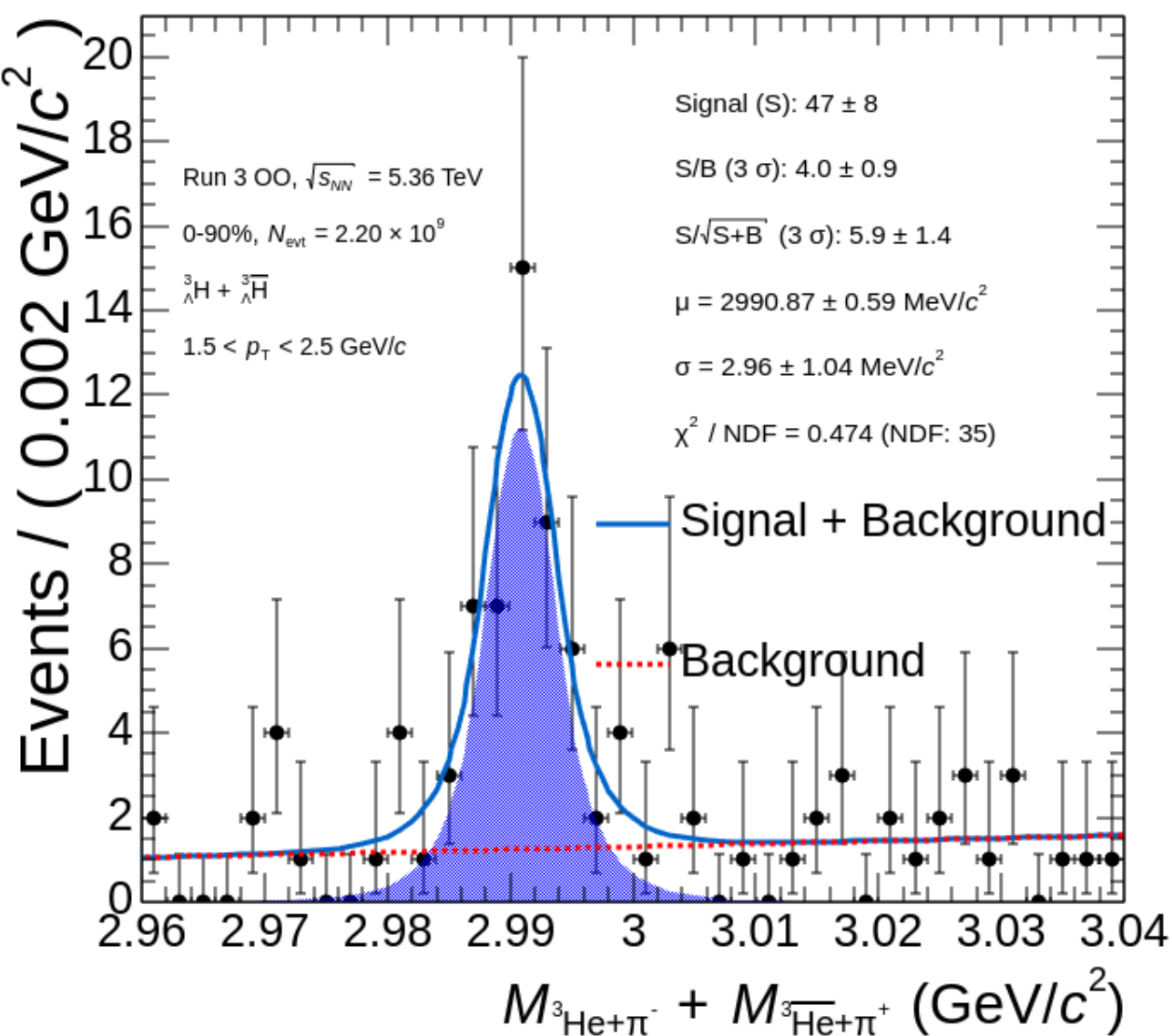
- Determine the BDT threshold that maximizes the expected significance by significance scan.
 - **Backgrounds counts:** Fit the invariant mass in data using a pol1 in the nominal $\pm 5\sigma$ region.
 - **Signal counts:** Expected signal counts for [hypertriton in peripheral heavy-ion collisions \(50-80% centrality class\) in Run 3](#).
 - **BDT_{thr} = arg max[Expected significance × $\epsilon_{\text{BDT}}(\text{thr})$].**



Invariant mass spectrum

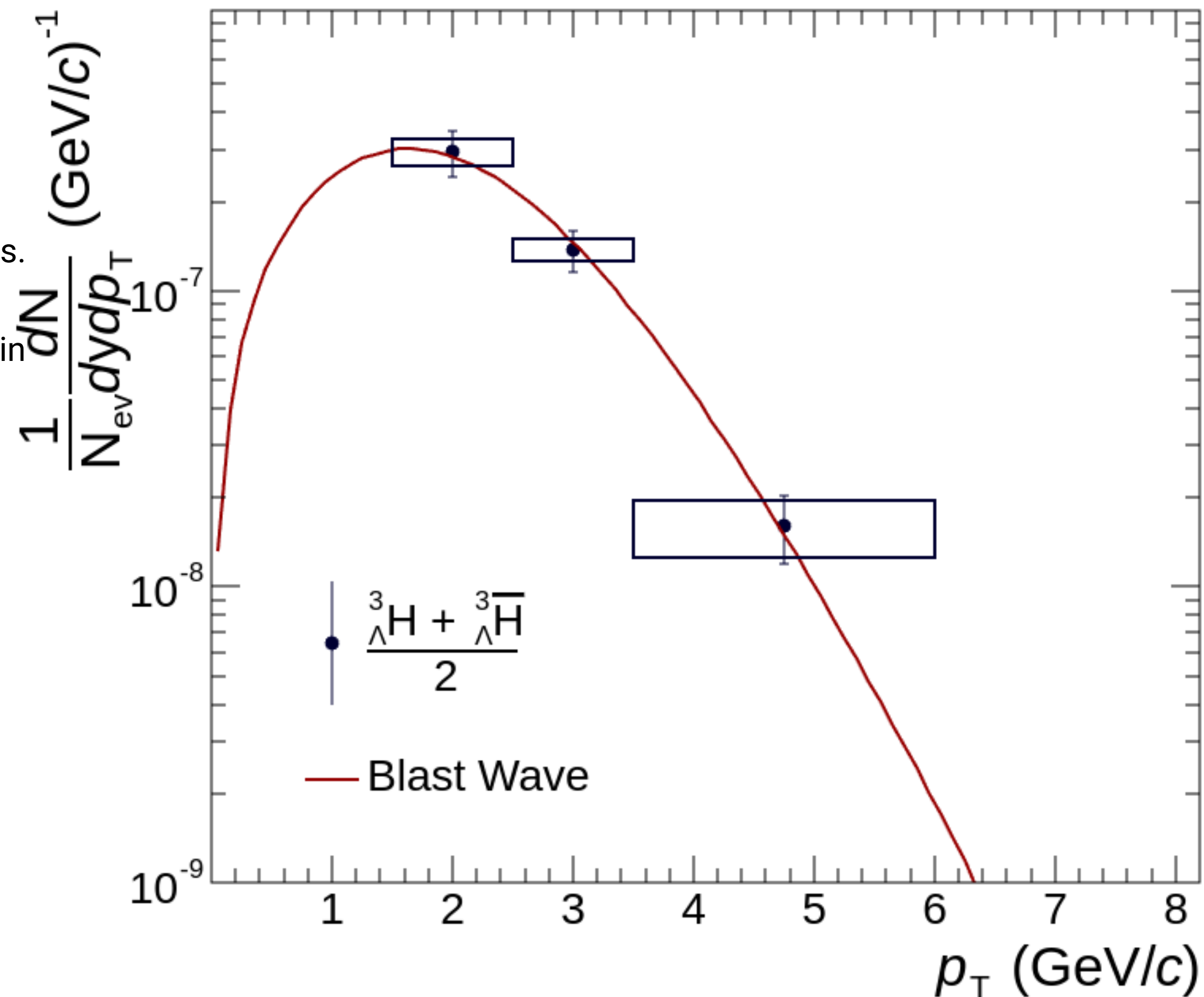
Fit information:

- Model: **Double-sided Crystal Ball** (signal) + **Pol1** (background)
 - Visible peak and considerable suppression of the background.



p_T spectrum

- Corrected p_T spectrum with statistical and systematic uncertainties.
- Blast-Wave fit: ${}^3_\Lambda\text{H}$ mass fixed; β constrained from ${}^3\text{He}$ parameters in peripheral Pb–Pb collisions¹.
- Systematics evaluated via multi-trial method:
 - BDT efficiency varied by $\pm 10\%$, and signal/background fit functions changed (pol2, exponential, Gaussian).
 - Additional contributions: branching ratio (8%) and material absorption ($\sim 2\%$).



Integrated yield

Measured yield:

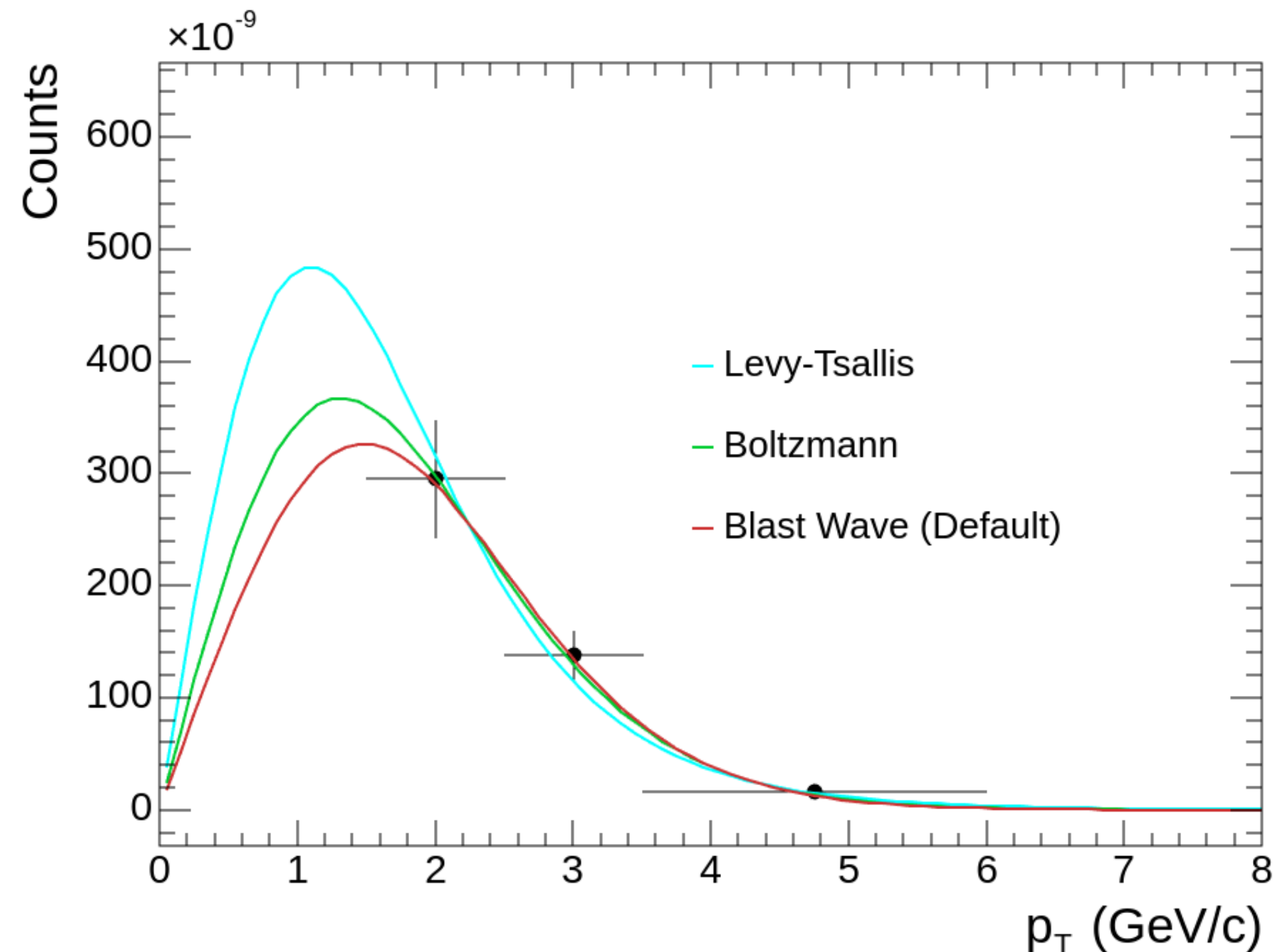
- From the data points in the measured p_T region.

Extrapolated yield:

- p_T -integrated yield obtained using a Blast-Wave fit to the measured data.

Systematics

- Signal Selection & Extraction:
 - Evaluated using uncorrelated combinations of BDT cuts and fit functions (Levy-Tsallis and Boltzmann).
 - RMS of these distributions taken as the systematic uncertainty.
 - Relat. unc. = 6.43%
- Extrapolation Fit at low p_T :
 - Standard deviation of the BW fit.
 - Relat. unc. = 15.79%
- **Fit Function Choice:**
 - RMS of extrapolations with different functions (Levy-Tsallis and Boltzmann)
 - Relat. unc. = 13.97%
- BR and absorption:
 - Relat. unc. = 8% and 2%, respectively



$$\frac{dN}{dy} = 7.39 \times 10^{-7} \pm 0.59 \times 10^{-7} (stat) \pm 1.69 \times 10^{-7} (syst)$$

Testing (hyper)-nucleosynthesis models: ${}^3_{\Lambda}\text{H} / \Lambda$

Average $\Lambda + \bar{\Lambda}$ yields:

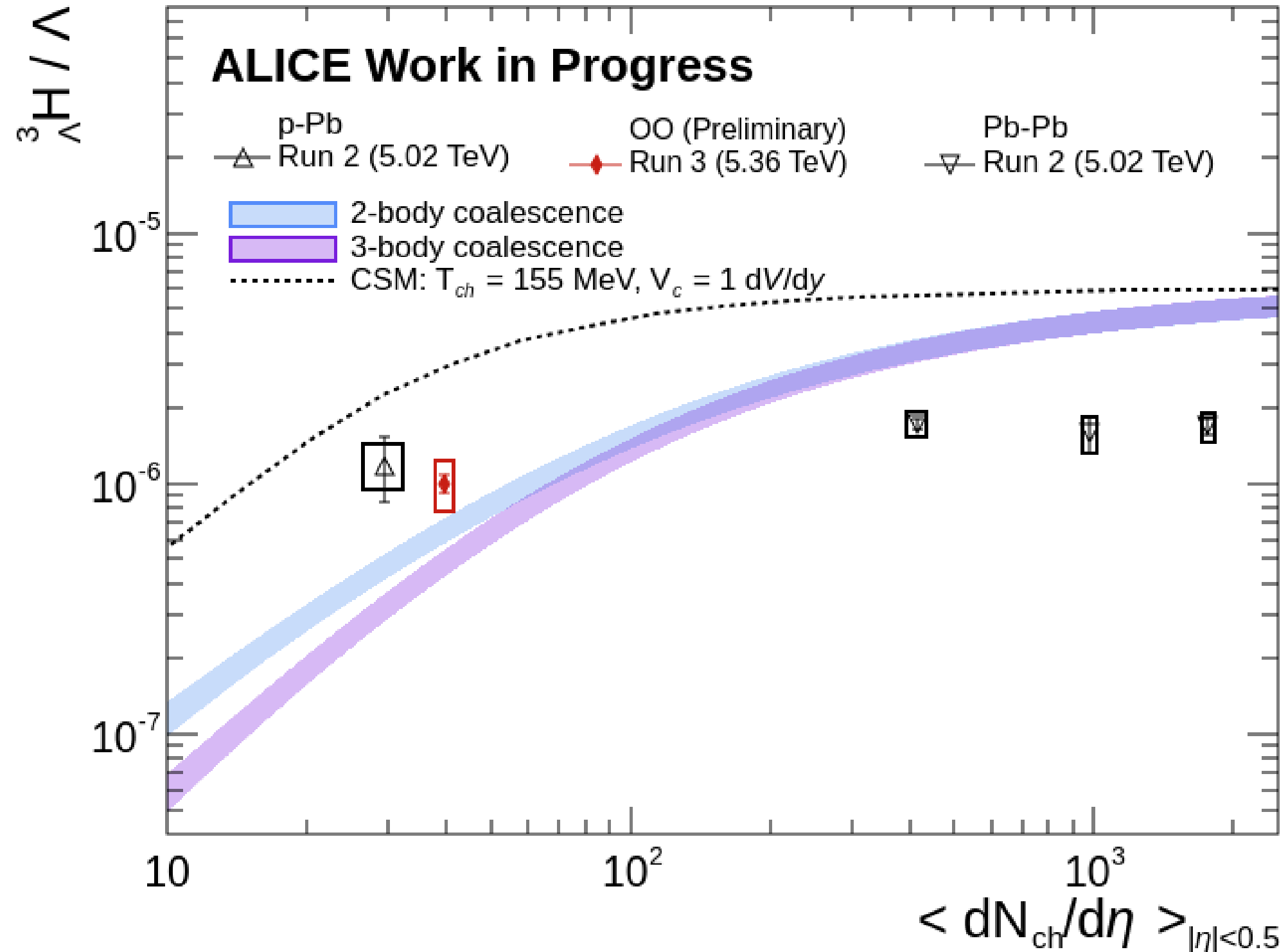
- Compute from the cascades analysis in OO collisions¹

${}^3_{\Lambda}\text{H} / \Lambda$:

- Ratio between the average yield of ${}^3_{\Lambda}\text{H}$ and Λ with statistical and systematic uncertainties computed by error propagation.

Comparison with the theoretical predictions:

- Canonical Statistical Model: $V_c = dV/dy$ ²
- Coalescence³:
 - 2-body: $\sqrt{\langle r^2_{d\Lambda} \rangle} = 10$ fm
 - 3-body: $\sqrt{\langle r^2_{pn\Lambda} \rangle} = 4.9$ fm



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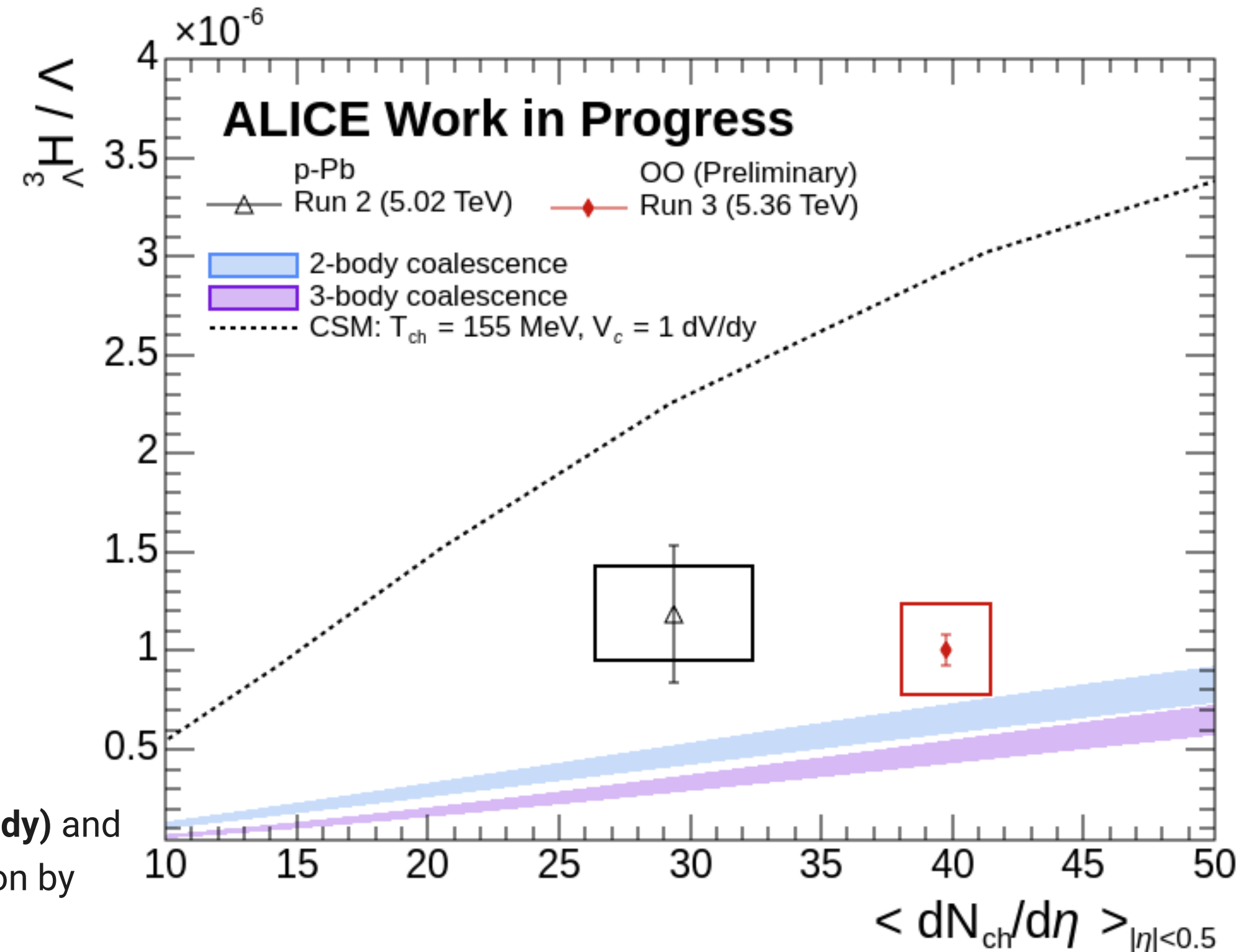
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${}^3_{\Lambda}\text{H} / \Lambda$: measurement in OO collisions:

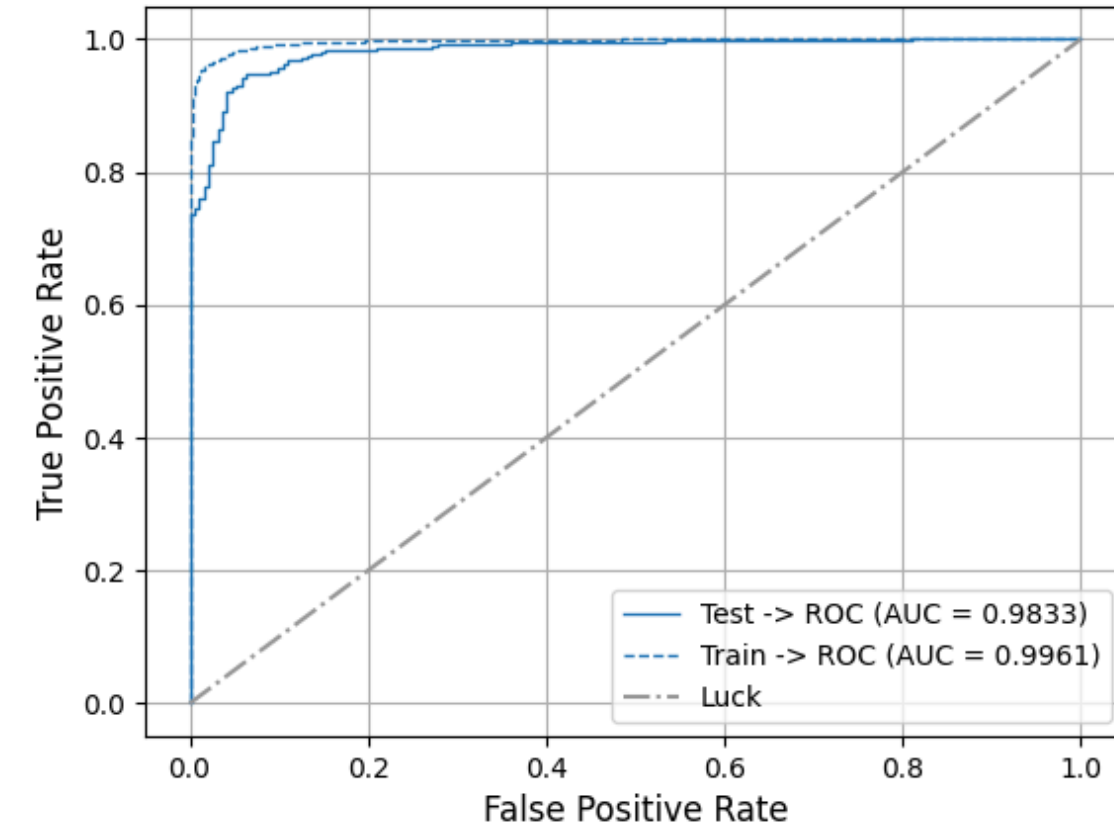
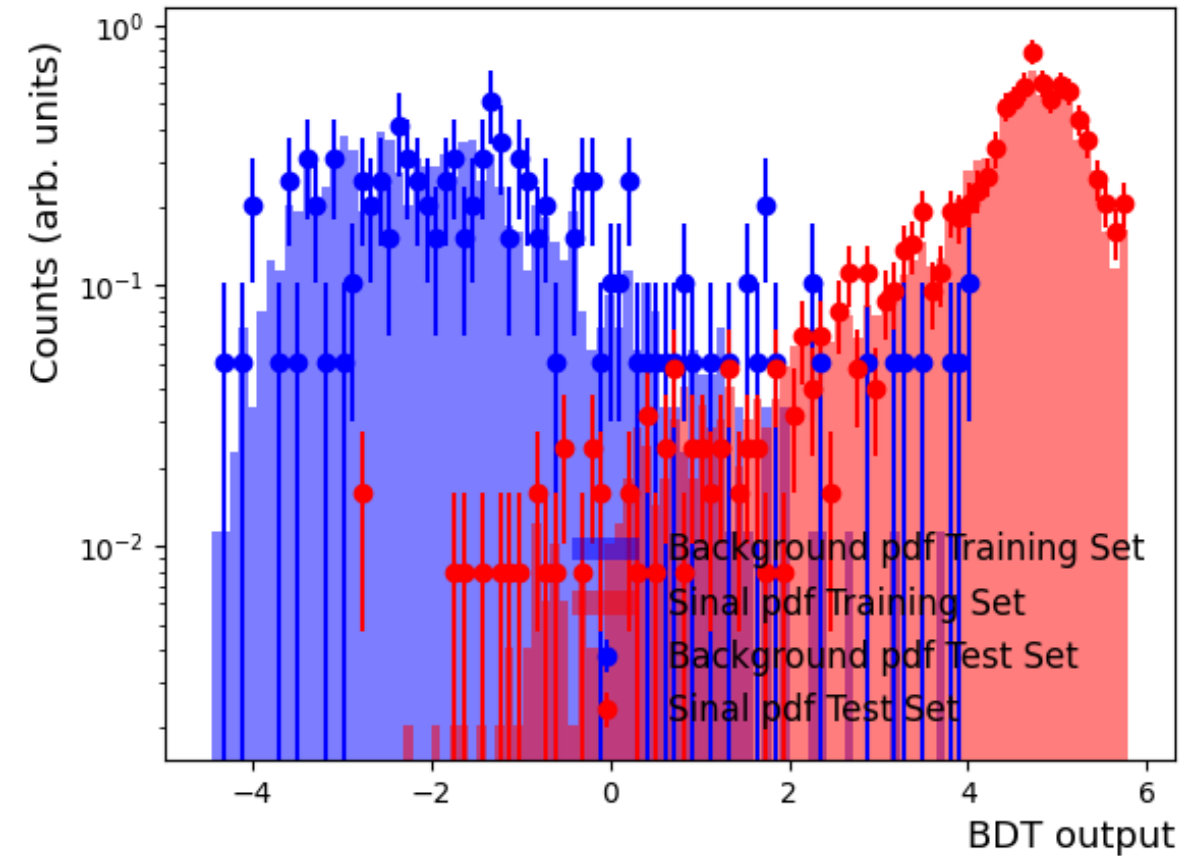
- Lies above the coalescence predictions by about **1.44 σ (2-body)** and **2.13 σ (3-body)**, and deviates from the **canonical SM** prediction by **7.86 σ** .



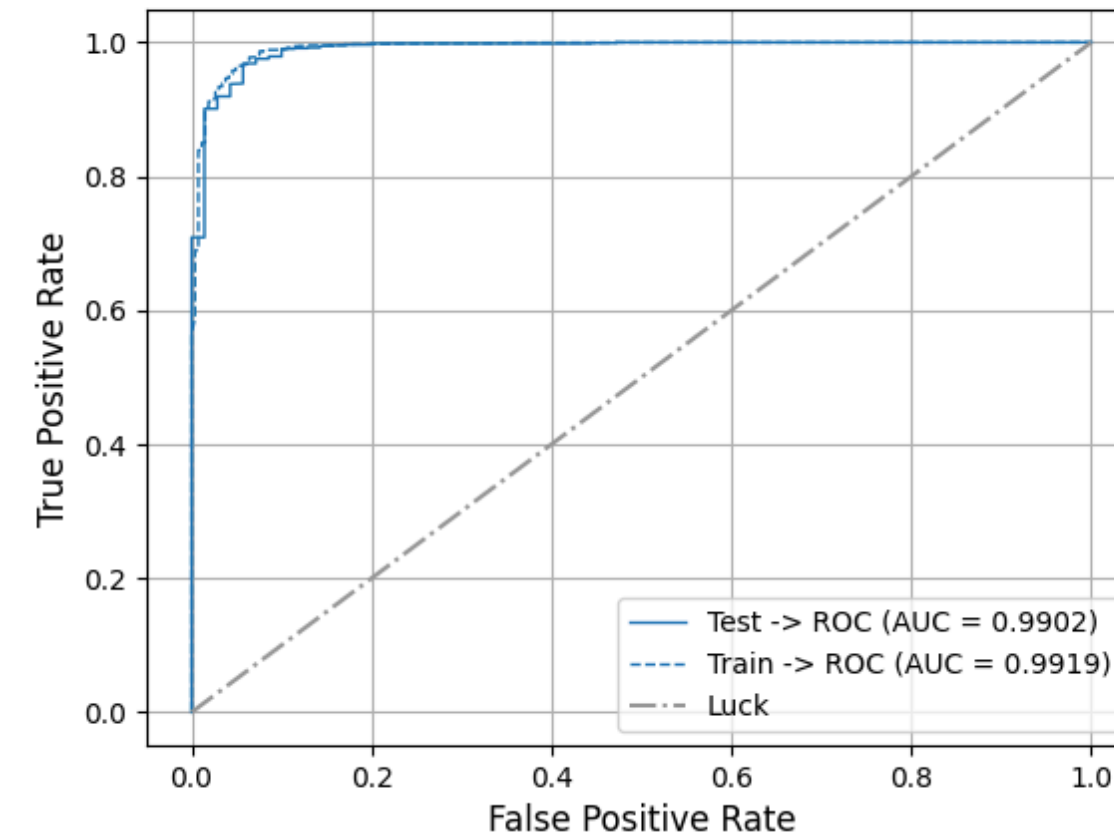
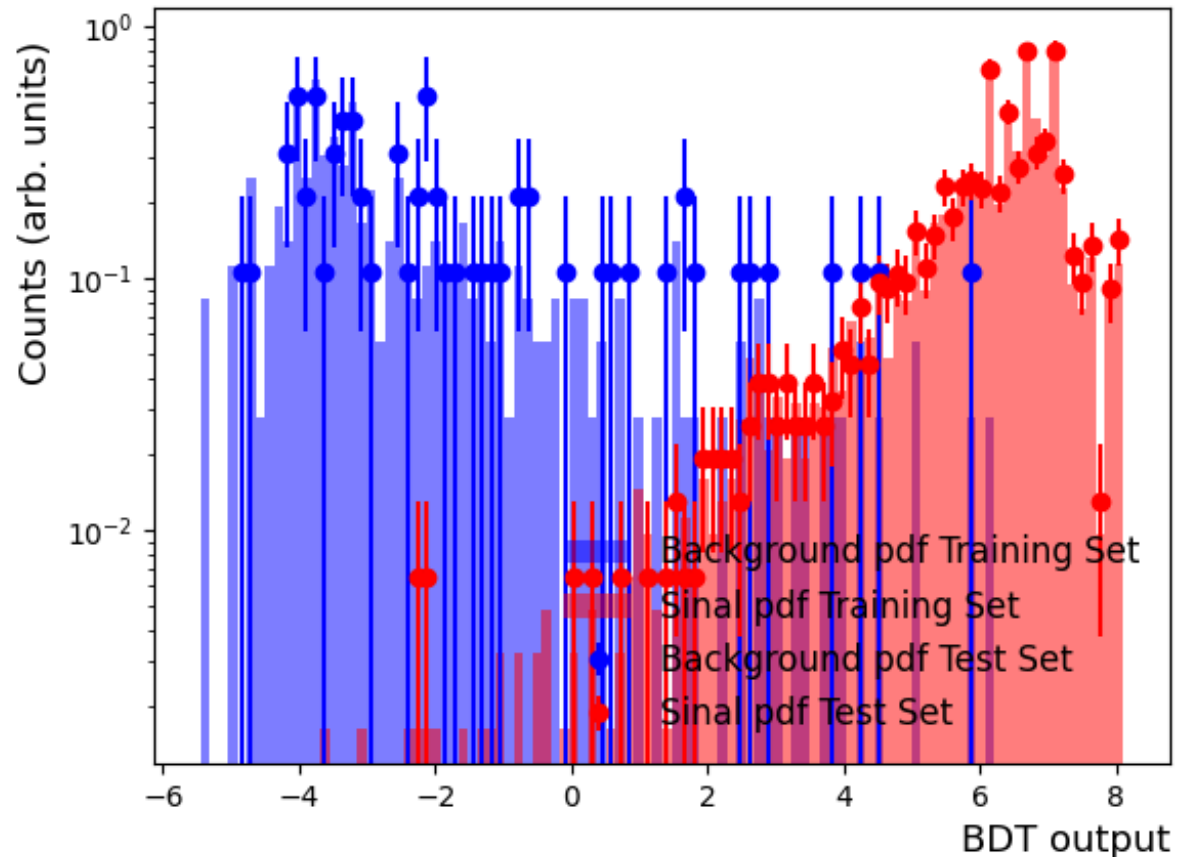
Antimatter-to-matter ratio: BDT for signal extraction

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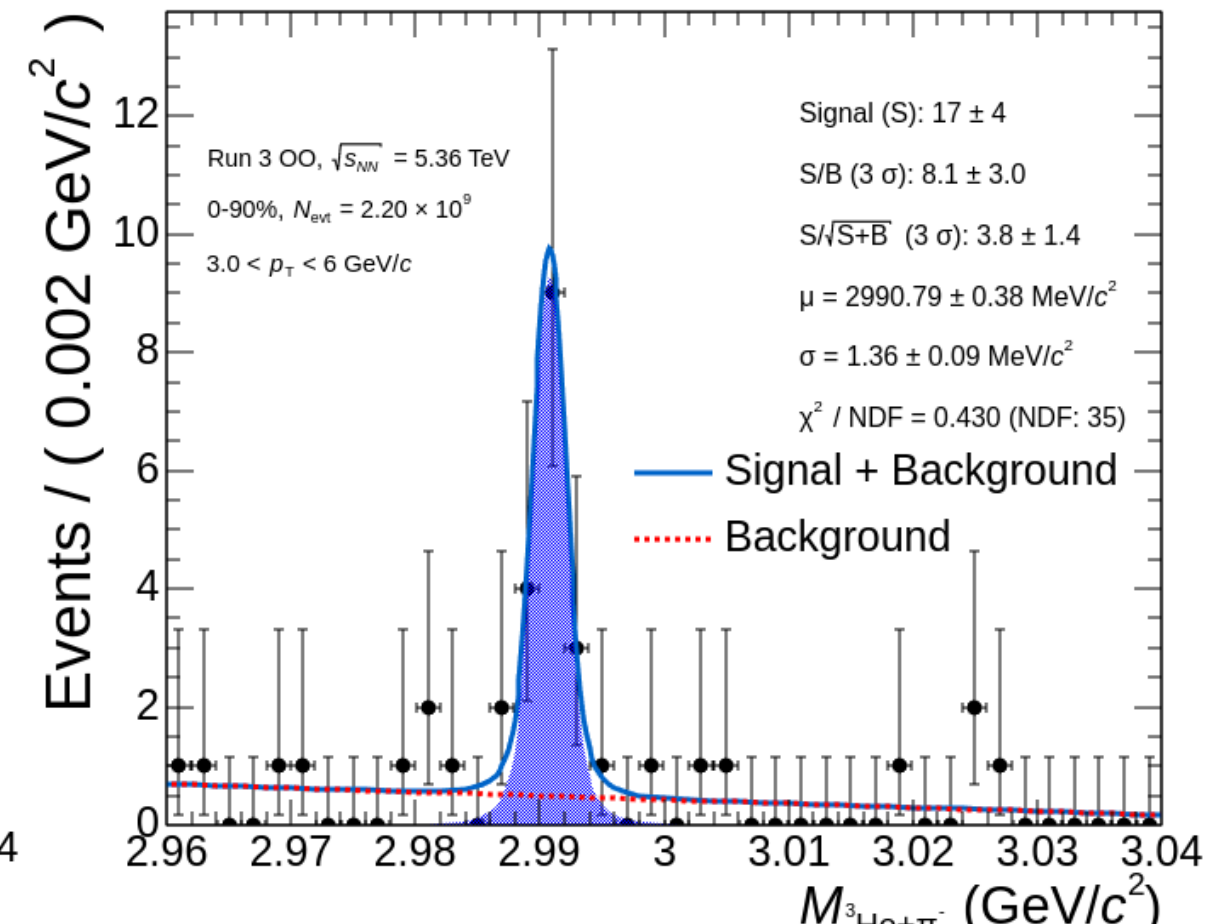
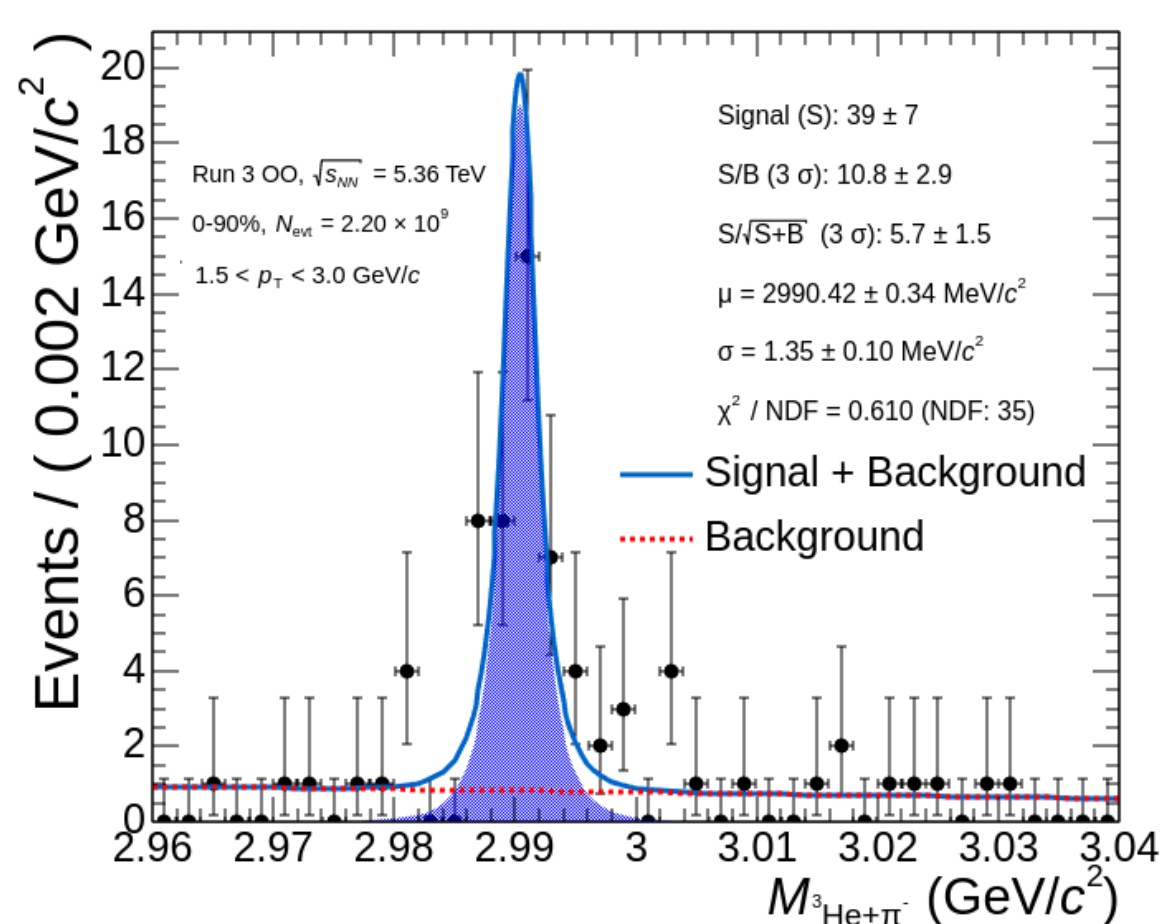
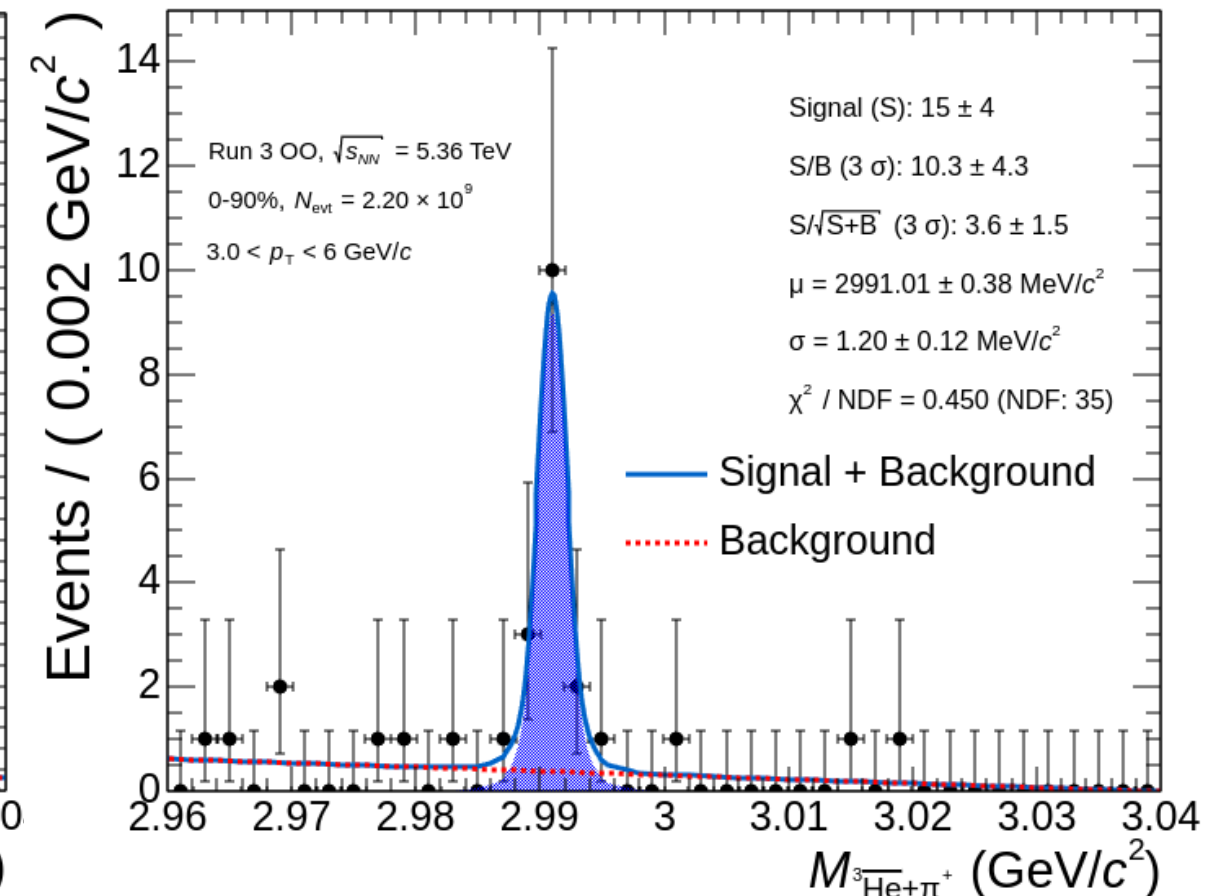
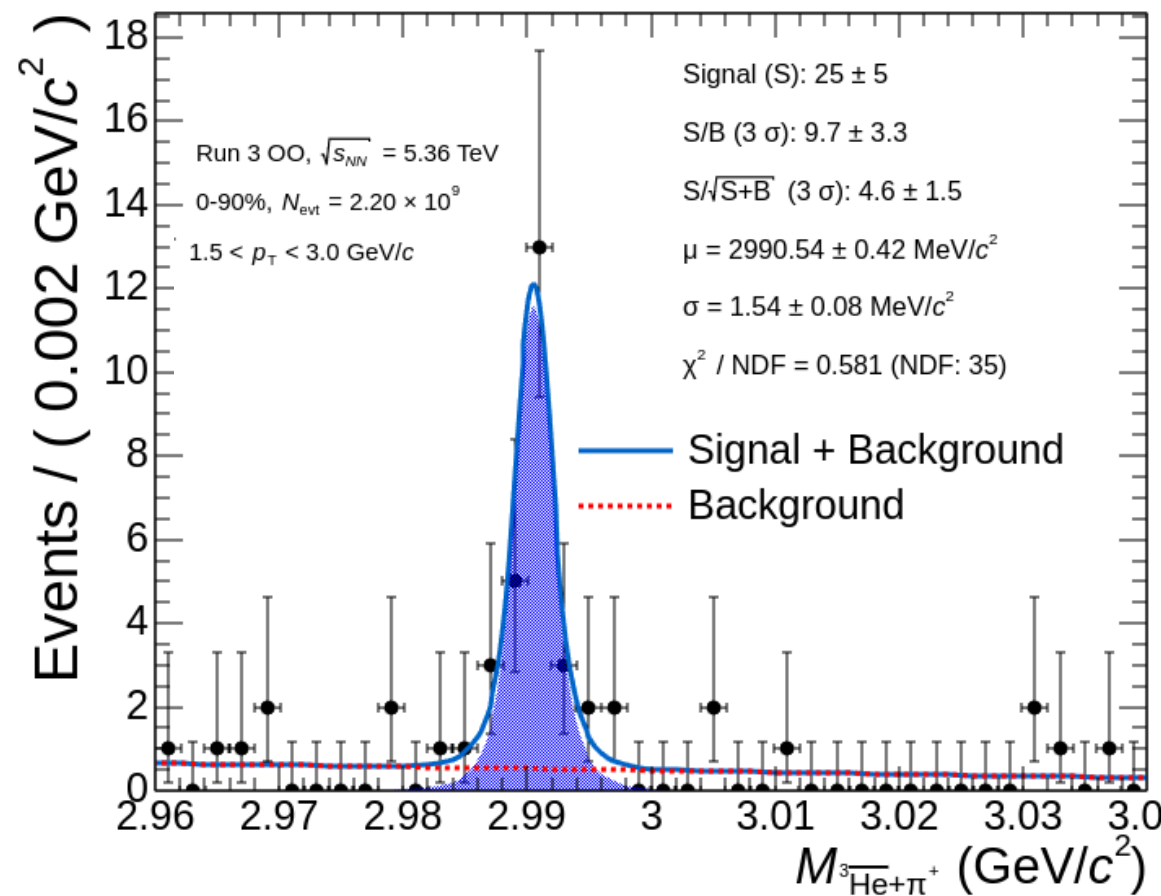
${}^3\Lambda$ candidates



${}^3\bar{\Lambda}$ candidates



Invariant mass spectra

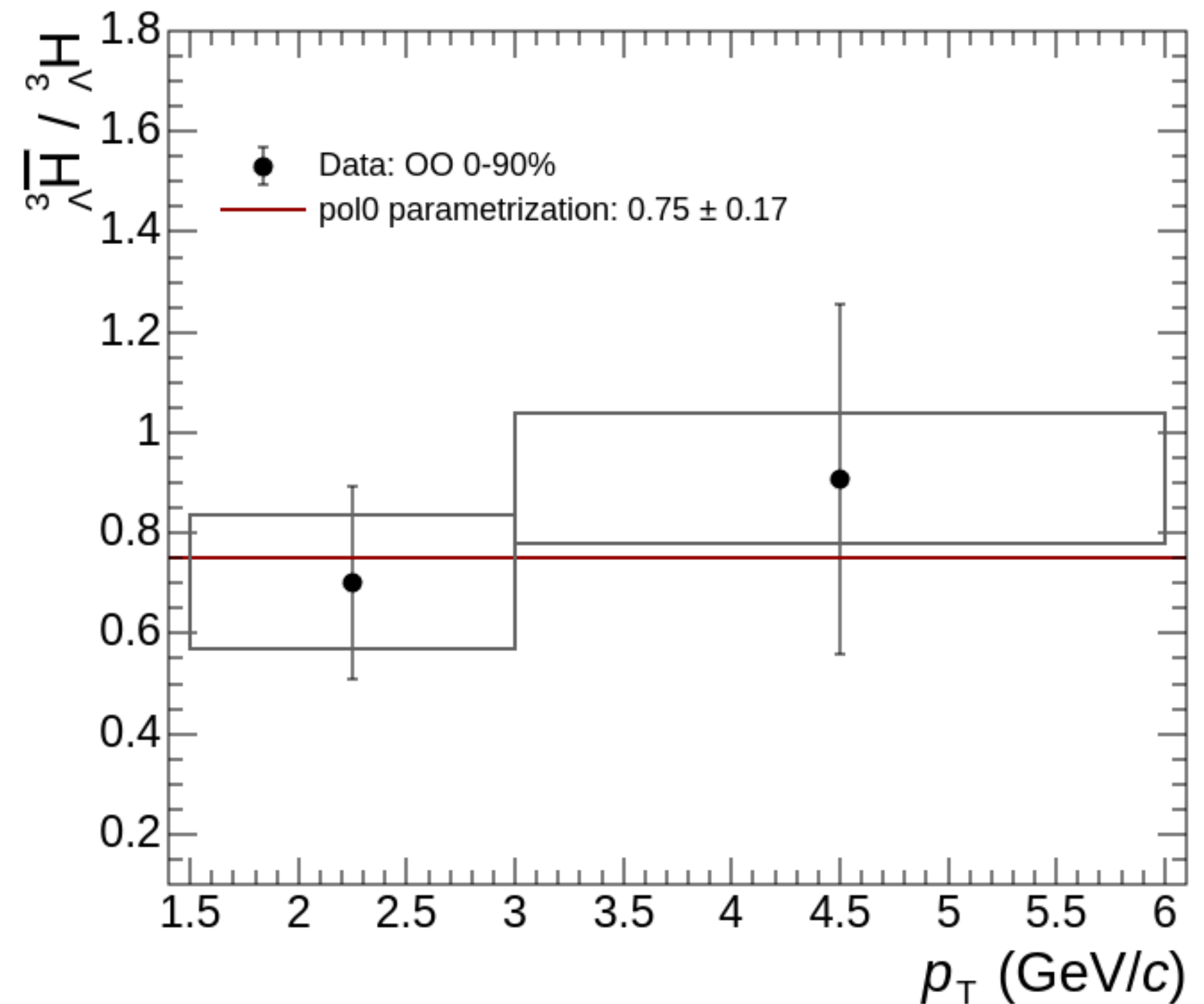
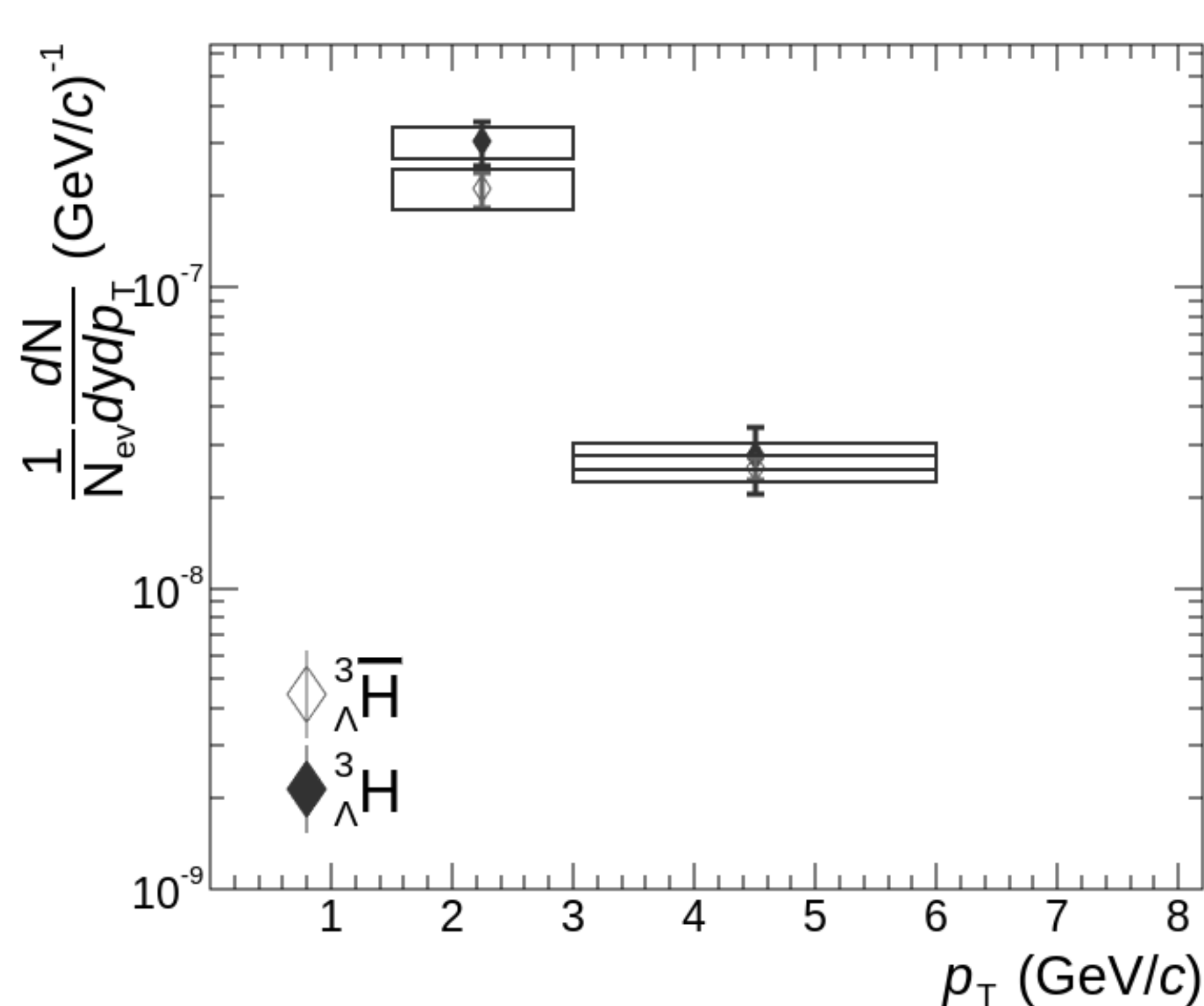


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- **Double-sided Crystal Ball** (signal) + **Pol1** (background)
 - Visible peak and considerable suppression of the background.

p_T spectrum and ${}^3\bar{\Lambda}$ -to- ${}^3\Lambda$ balance

- Corrected p_T spectrum with statistical and systematic uncertainties.
- Matter-to-antimatter ratio consistent with unity within uncertainties.



Outlook

Summary:

- **Ann weak-decay signature in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV:**

- No statistically significant signal is observed. The first estimate of the yield is set as an upper limit (UL). The region below the mass threshold does not match with the thermal model expectations.
- The observed trend of the average UL yield as a function of $c\tau$ hypothesis (high production at very short lifetimes, suppression at intermediate lifetimes, and gradual increase at longer lifetimes) indicates that there is no stable bound state.

- **${}^3\Lambda\text{H}$ production in OO collisions at $\sqrt{s_{NN}} = 5.36$ TeV:**

- Candidates were selected using a Boosted Decision Tree (BDT) approach, improving signal and background discrimination.
- The transverse-momentum spectrum is well described by a Blast-Wave function, indicating collective expansion consistent with hydrodynamic behavior of the created system.
- The ${}^3\Lambda\text{H}/\Lambda$ ratio favors coalescence model predictions (1.44σ for 2-body and 2.13σ for 3-body implementations) and shows a strong deviation from the canonical statistical model (7.86σ).
- The antimatter-to-matter ratio is consistent with unity, indicating a balance between matter and antimatter production.

Obrigada!