Reconstruction of the $pp \to pK^+\Lambda$ Channel using Feb22 gen4 data

Ruhr-Universität Bochum – Fair Forschung NRW

Hades Analysis Meeting VIII
June 24, 2026

Óscar Marcos Pérez Cytron

Advisor:
James Ritman

RUHR
UNIVERSITÄT
BOCHUM

Previous Work

- Master's: Nuclear Physics, Universidad Complutense de Madrid

- Master's Thesis: WASA-FRS Collaboration (CSIC-IEM)
Hypertriton Primary Vertex Reconstruction with Deep Learning Models

- GSI Summer Student 2025:
Developing prototype of unsupervised ML model for HADES QA
→ work presented at XLIX HADES Collaboration Meeting (Sept. 2025)

- February 2026: start of PhD in J. Ritman's group at GSI

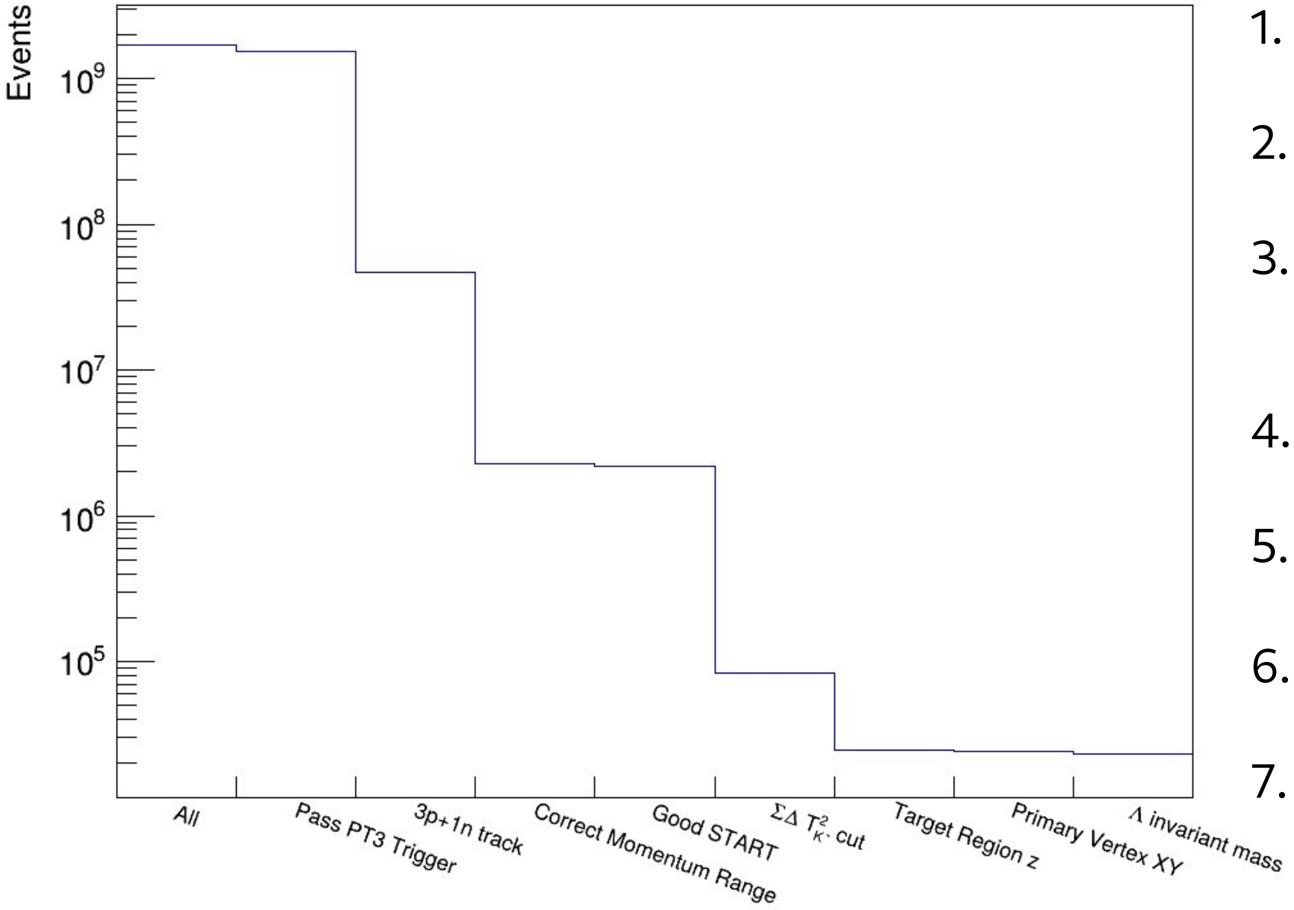
Motivation

- **Measure recoil Λ polarization**
  PWA model constraint

- **Extract differential cross sections and angular distributions**
  sensitive to intermediate nucleon resonances $N^*(1440) - N^*(1710)$

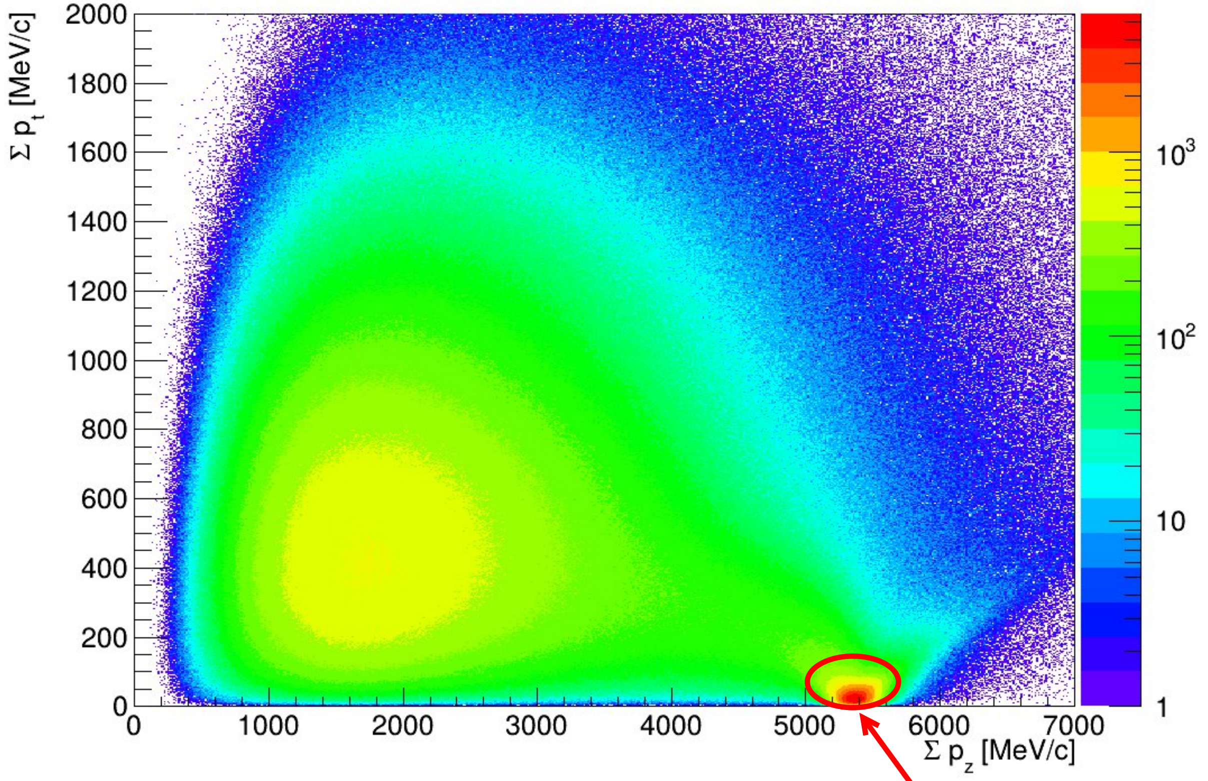
- **Demonstrate performance**
  for an upcoming dedicated pion-beam campaign

Analysis Procedure: Event Reduction



1. PT3 trigger
2. Require at least 3 positive and 1 negative track in HADES
3. Constrain to four tracks conserving initial beam 4-momentum
4. Remove events with poorly determined START time
5. Require ToF information to point better to K^+ than π^+
6. Primary vertex / target region cuts
7. Invariant mass region selection

Analysis Procedure: Momentum Selection



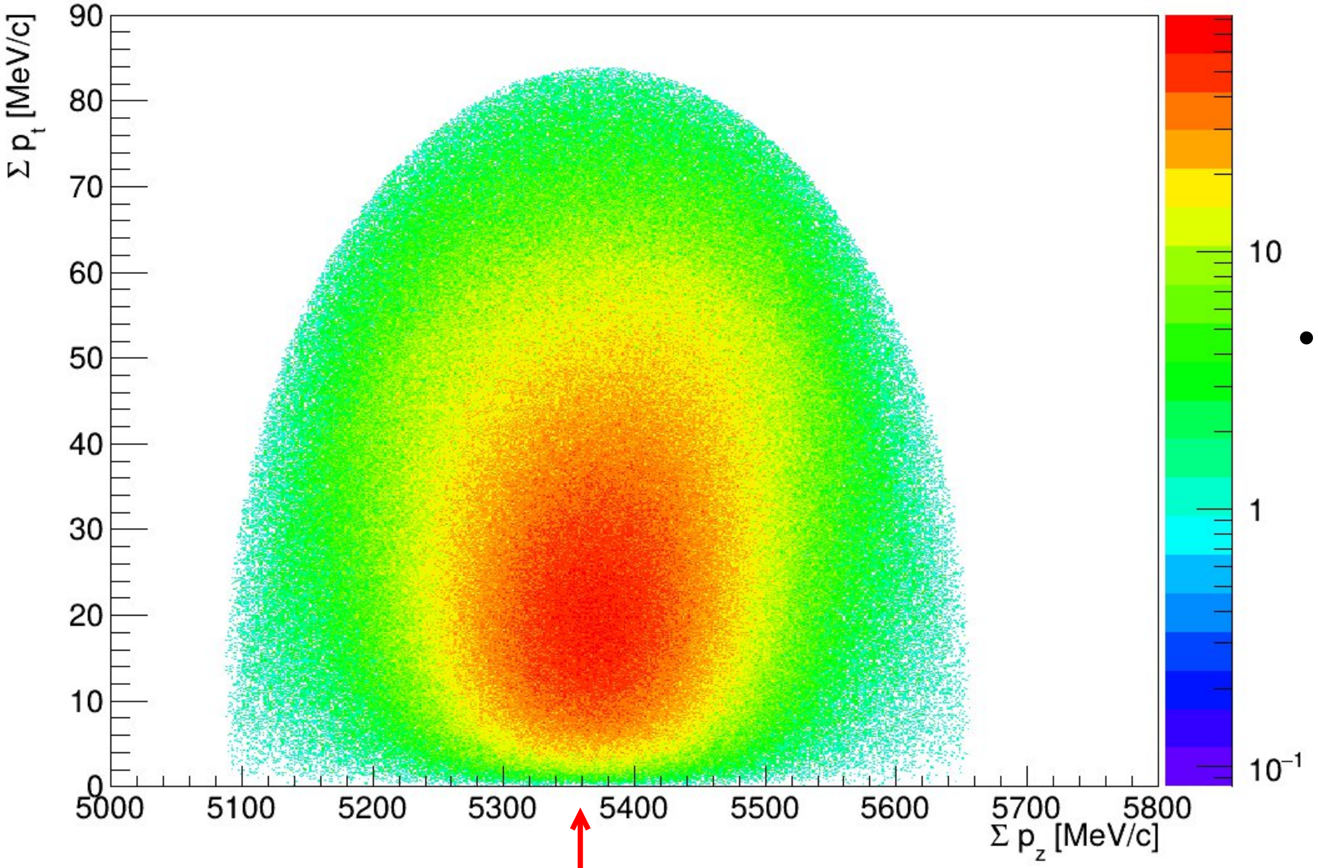
Events conserving initial beam 4-momentum

Events with correct momentum range are constrained via:

- Calculating average p_x, p_y, p_z and their respective σ_{p_x}, σ_{p_y}, σ_{p_z}
- Performing a χ^2-like cut on Δ^2:

$$\Delta^2 = \left(\frac{\Sigma p_z - \langle p_z \rangle}{\sigma_{p_z}}\right)^2 + \left(\frac{\Sigma p_x - \langle p_x \rangle}{\sigma_{p_x}}\right)^2 + \left(\frac{\Sigma p_y - \langle p_y \rangle}{\sigma_{p_y}}\right)^2$$

Analysis Procedure: Momentum Selection



Centered at 5.37 GeV
Theoretical from pp-elastics: 5.39 GeV

- Cut on Δ^2 → select events with $\Delta^2 < 10$

$$\Delta^2 = \left(\frac{\Sigma p_z - \langle p_z \rangle}{\sigma_{p_z}}\right)^2 + \left(\frac{\Sigma p_x - \langle p_x \rangle}{\sigma_{p_x}}\right)^2 + \left(\frac{\Sigma p_y - \langle p_y \rangle}{\sigma_{p_y}}\right)^2$$

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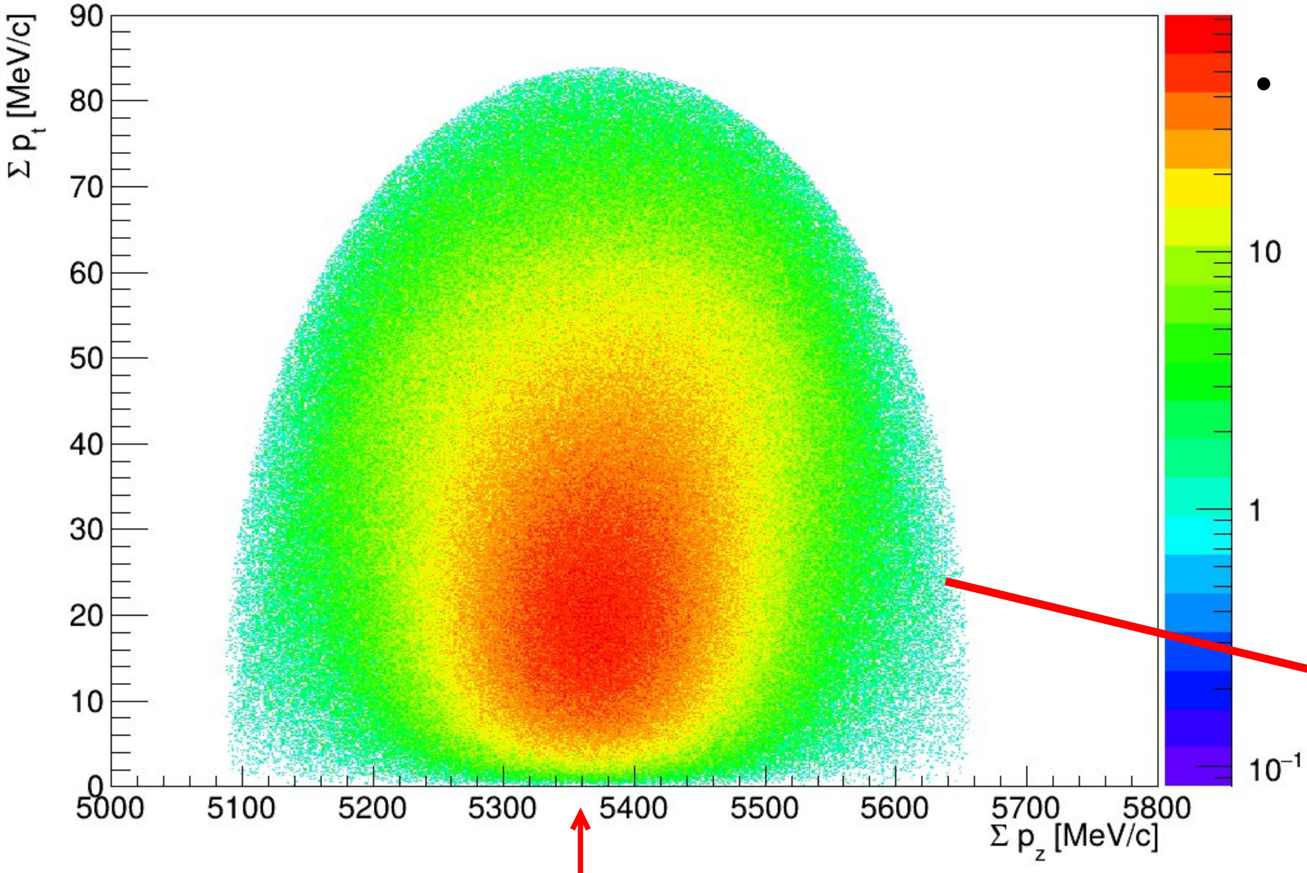

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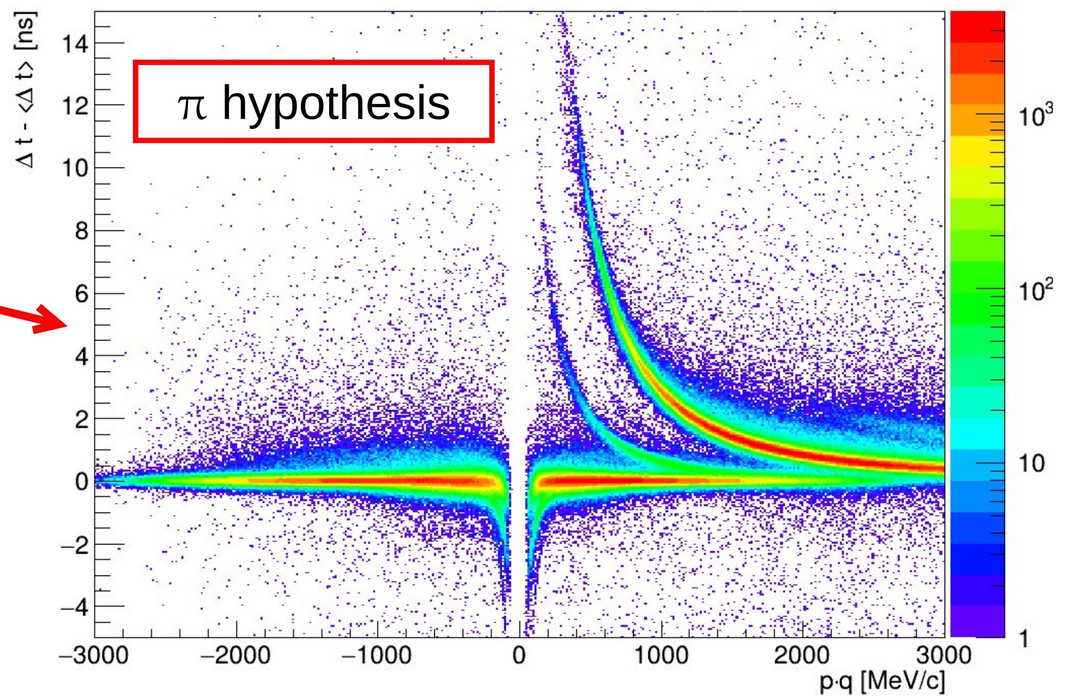

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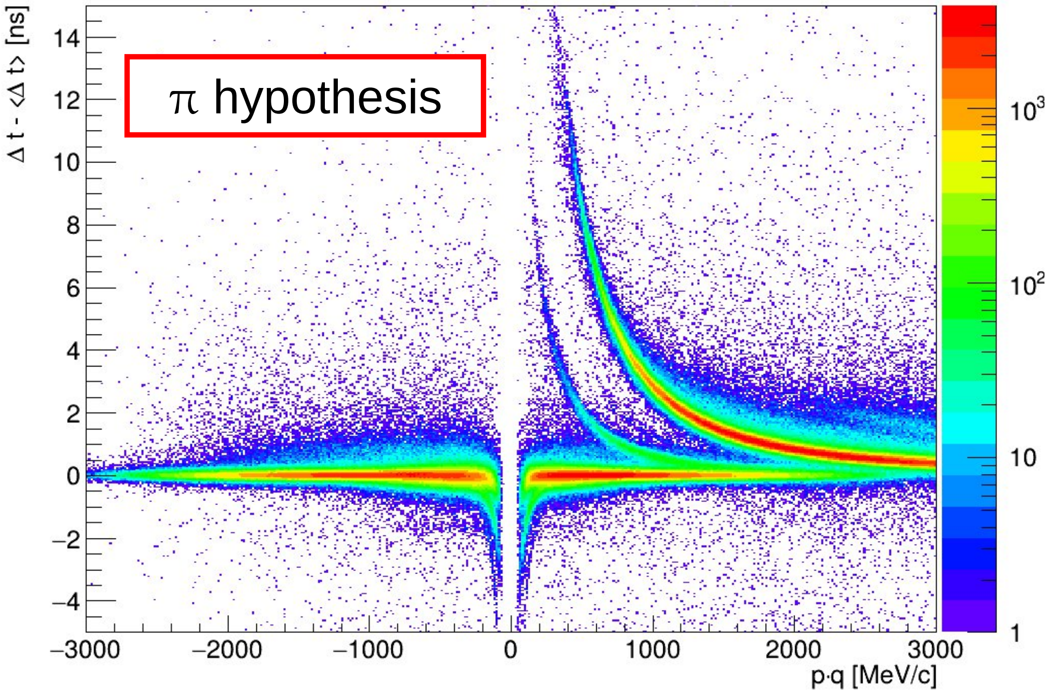
Analysis Procedure: ΔToF-based PID



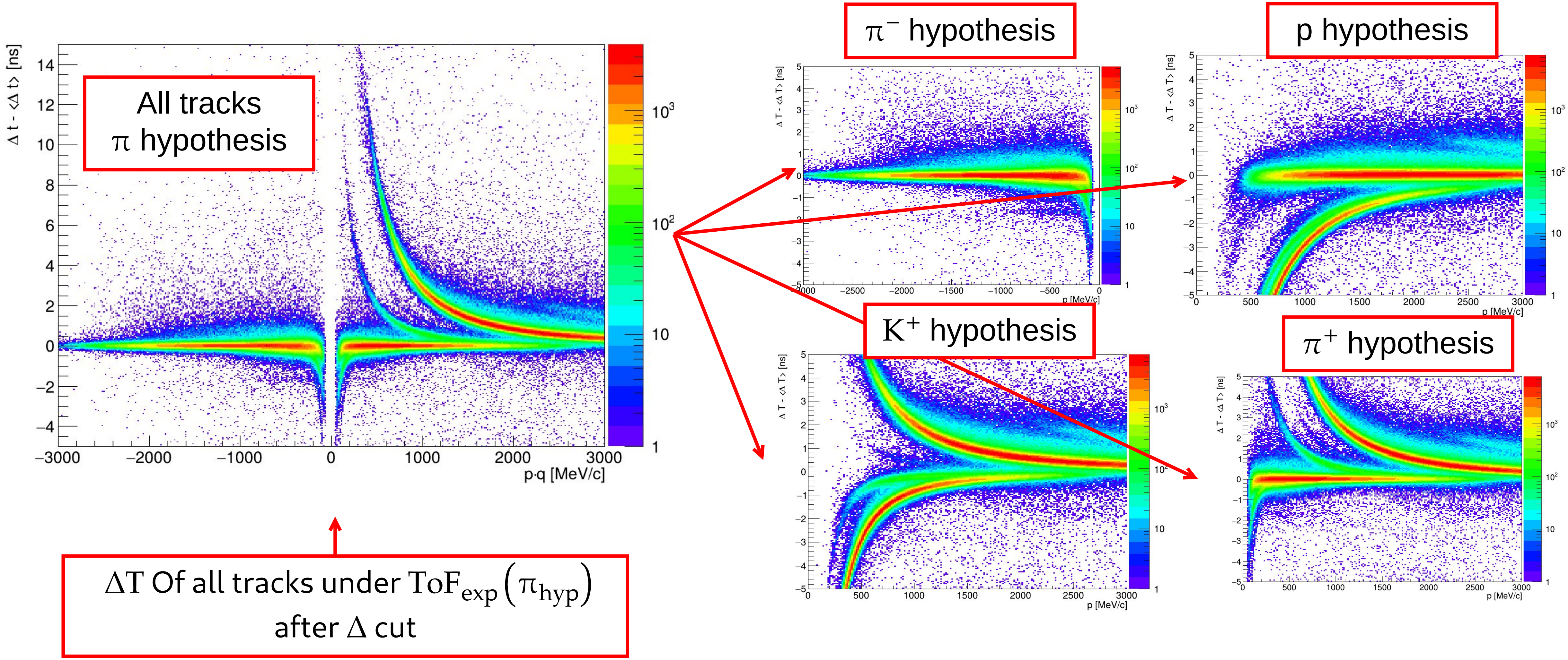
ΔT Of all tracks under $\mathrm{ToF_{exp}}(\pi_{hyp})$ after Δ cut

- Calculate ΔT for all track hypothesis pairings:

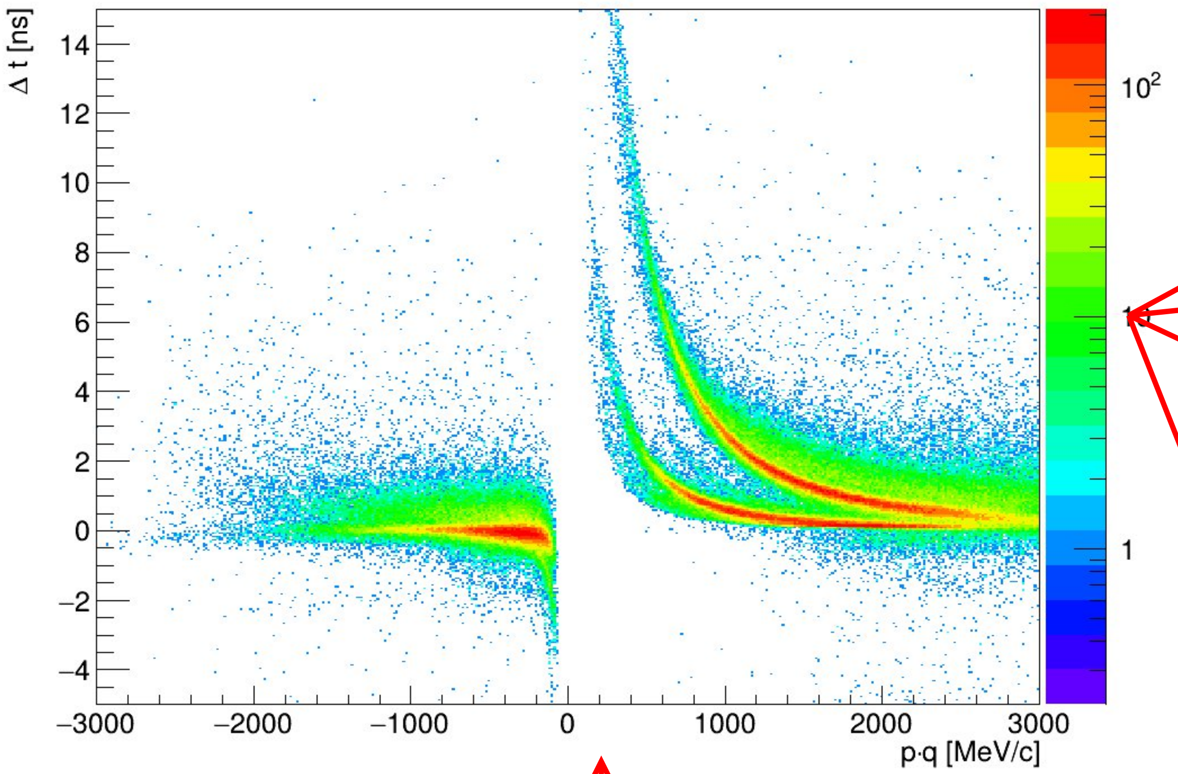
$$\Delta T = \mathrm{ToF_{meas}} - \mathrm{ToF_{exp}}(\mathrm{hyp}) = \mathrm{ToF_{meas}} - \frac{L}{c}\frac{\sqrt{p^2 + m_{hyp}^2}}{p}$$

- Take the track hypothesis with the lowest $\Sigma \Delta T^2$ of all tracks assuming positive tracks are p, p, K^+
- Accept events where K^+ particle hypothesis is most likely

Analysis Procedure: ΔToF-based PID

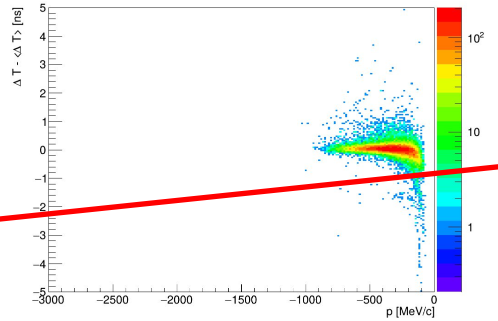


Analysis Procedure: ΔToF-based PID

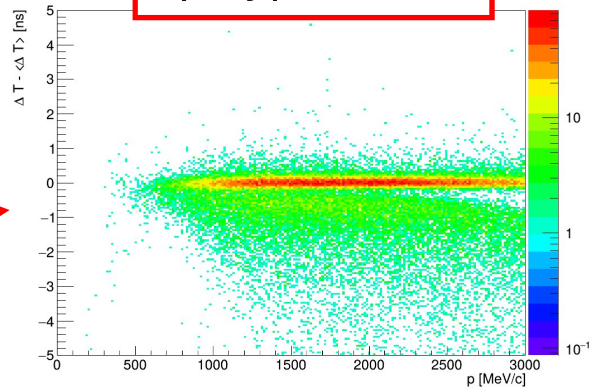


ΔT Of all tracks under $\mathrm{ToF}_{exp}\left(\pi_{hyp}\right)$ after cut on $\Sigma\Delta T^2_{K^+} < \Sigma\Delta T^2_{\pi^+}$

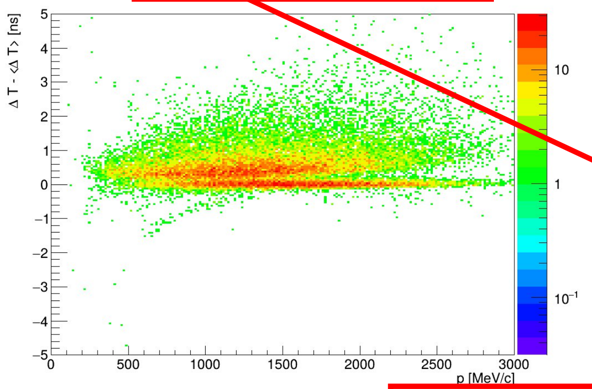
π^- hypothesis



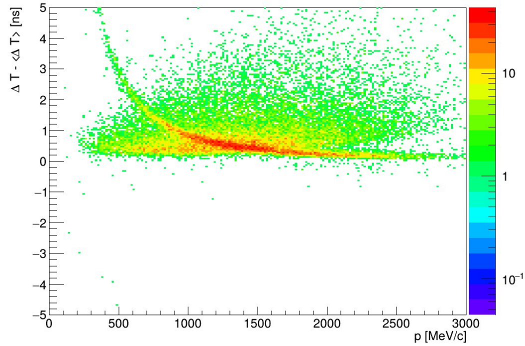
p hypothesis



K^+ hypothesis

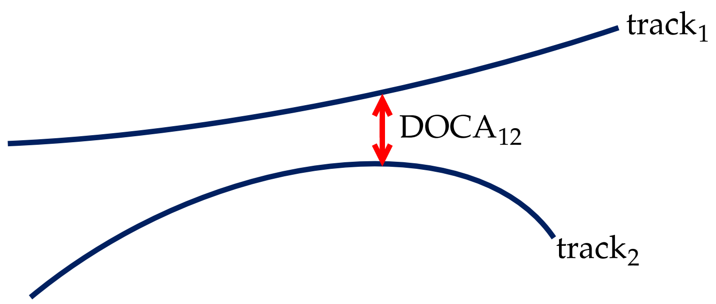


π^+ hypothesis



Both proton candidates, K^+, and π^- candidate tracks identified

Analysis Procedure: Primary vs Secondary Proton



- Calculate the distance of closest approach (DOCA) of the two primary proton-K^+ and secondary proton-π^- hypotheses
- Calculate $\Sigma DOCA^2 = DOCA(pK^+)^2 + DOCA(p\pi^-)^2$
- The hypothesis with lowest $\Sigma DOCA^2$ assigns primary and secondary proton

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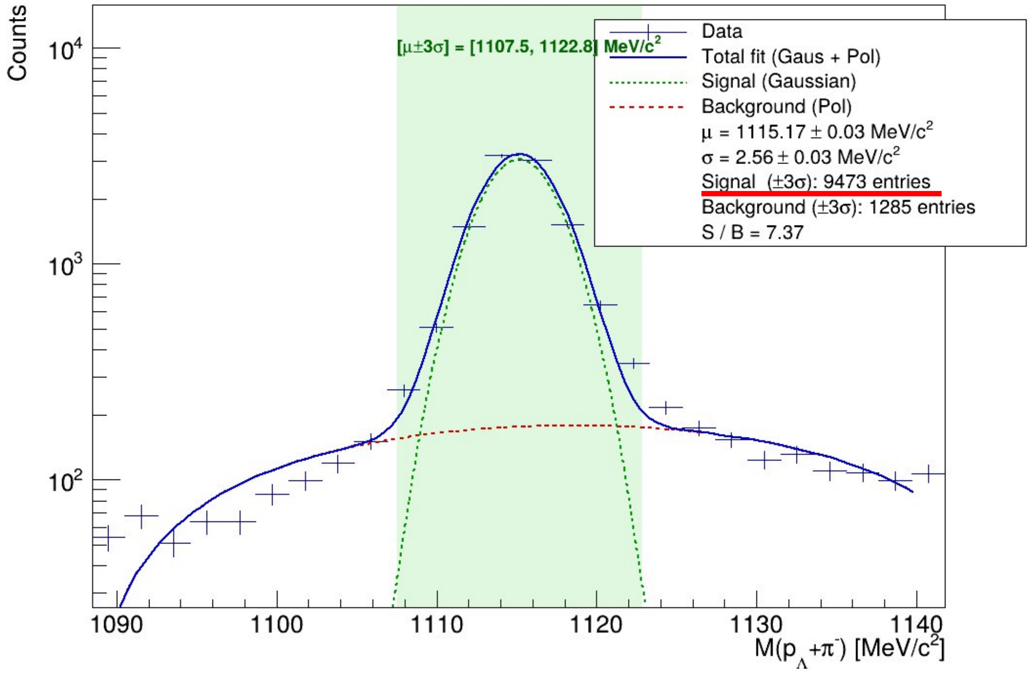

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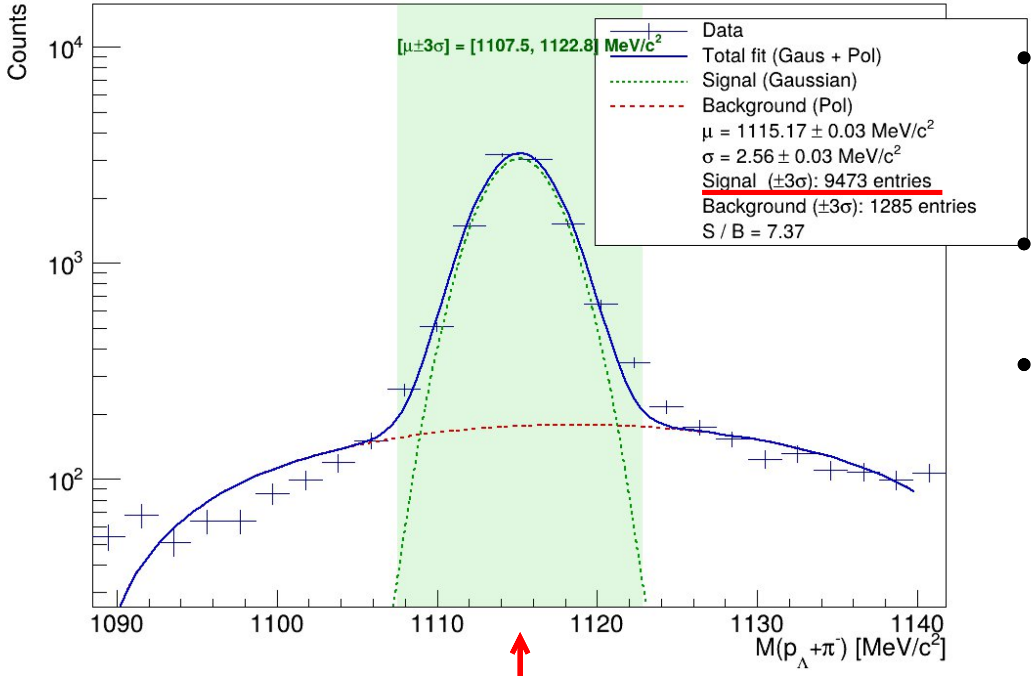

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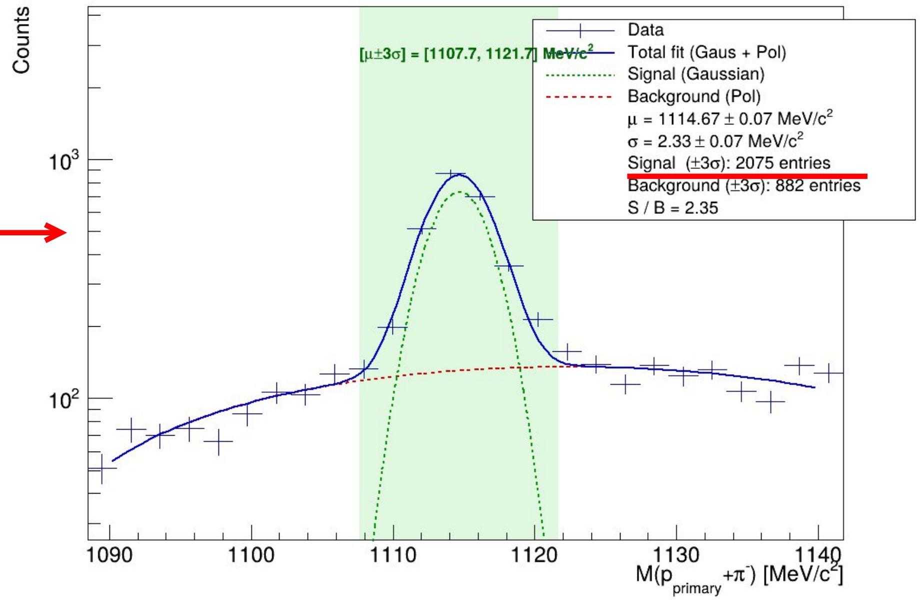
~18% of Λ are lost due to incorrect DOCA hypothesis

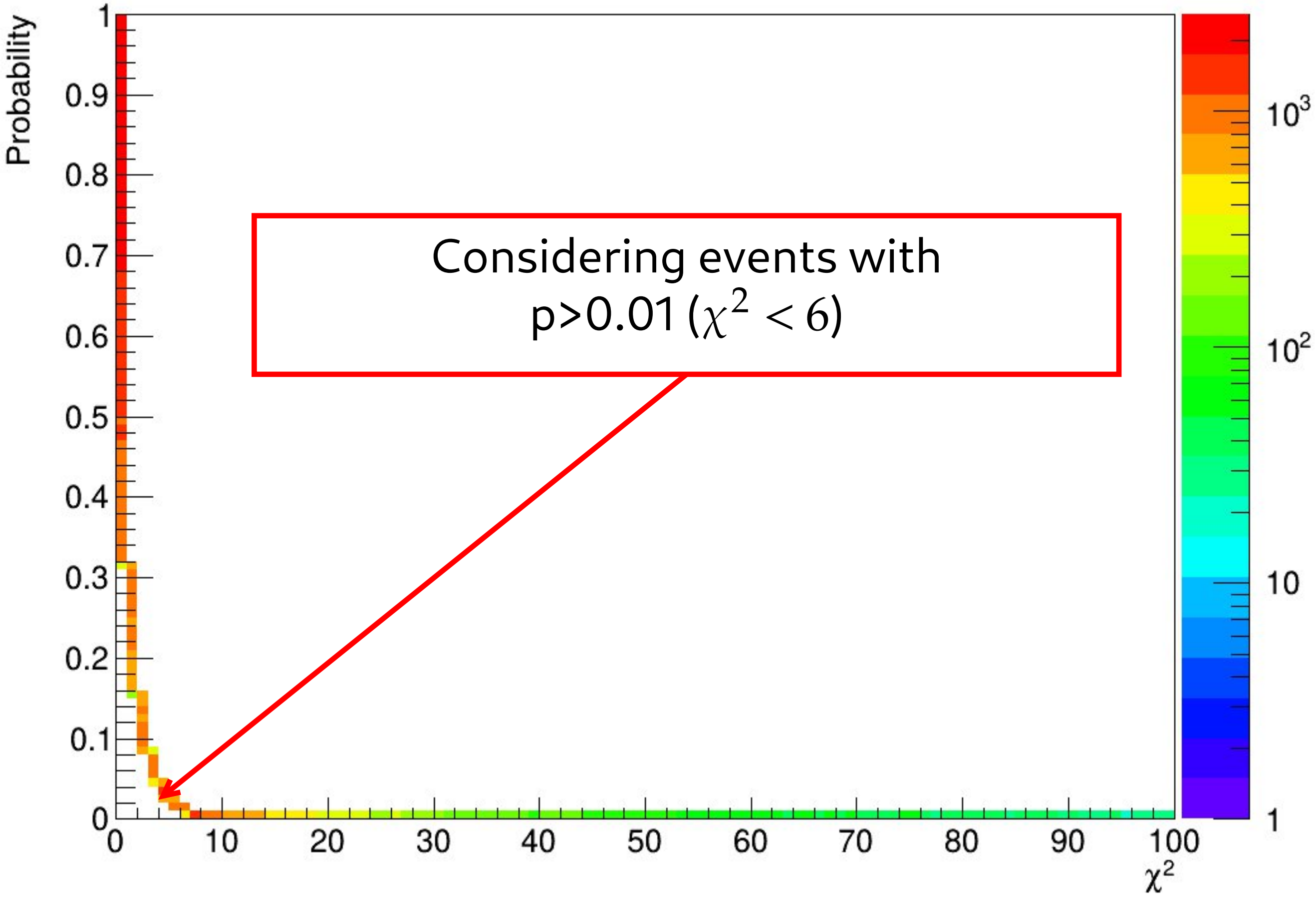
Vertex fitter needed for finer-tuned hyperon track reconstruction

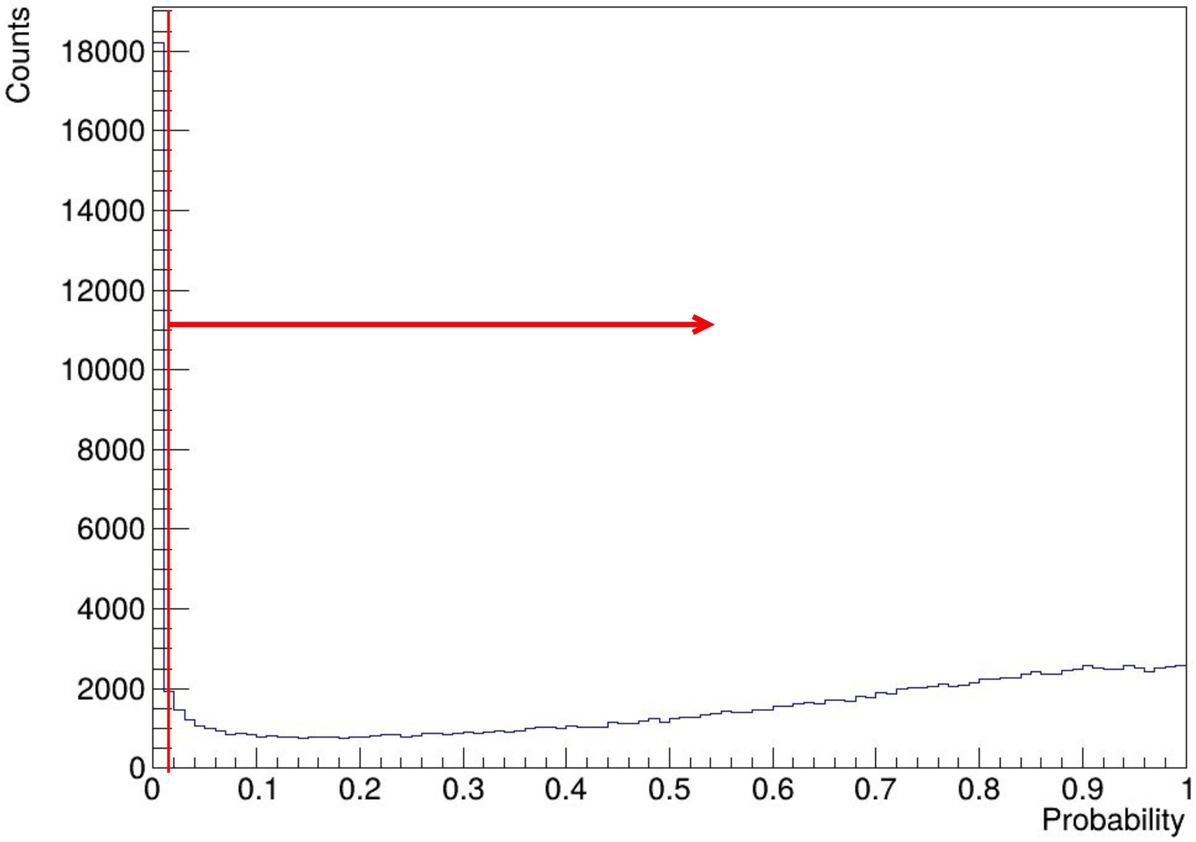


Analysis Procedure: Primary vs Secondary Proton

- Better vertex finding method required $\rightarrow$ Vertex fitter
- Vertex fitter uses covariance matrix $\{1/\rho, \theta, \varphi, R, Z\}$
- Calculate $p\pi^-$ track distances with covariance matrix error and invariant mass in Λ region
- Covariance matrix parameters from PLUTO simulation residuals (only diagonal contributions) $\{1/\rho, \theta, \varphi, R, Z\}$
- Window on $p\pi^-$ invariant mass of 20 MeV
- The hypothesis with lowest χ^2 chosen as secondary proton

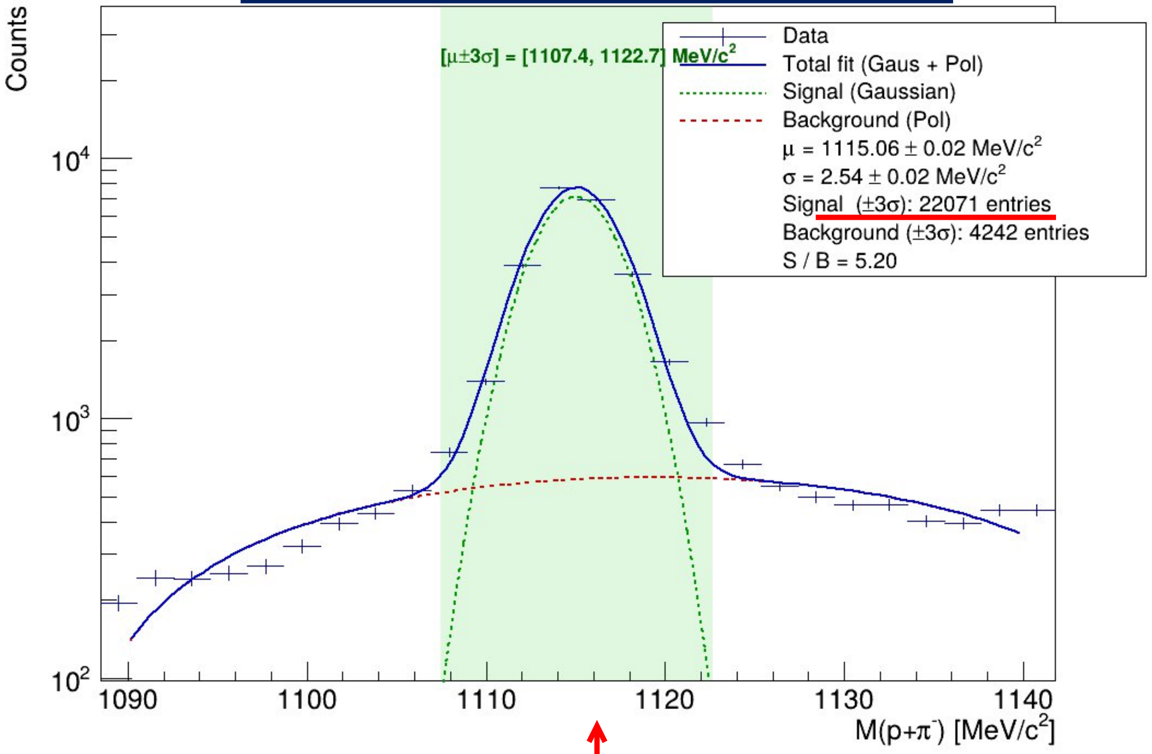
Analysis Procedure: Primary vs Secondary Proton





Analysis Procedure: Primary vs Secondary Proton

$p\pi^-$ Invariant mass before vertex fit



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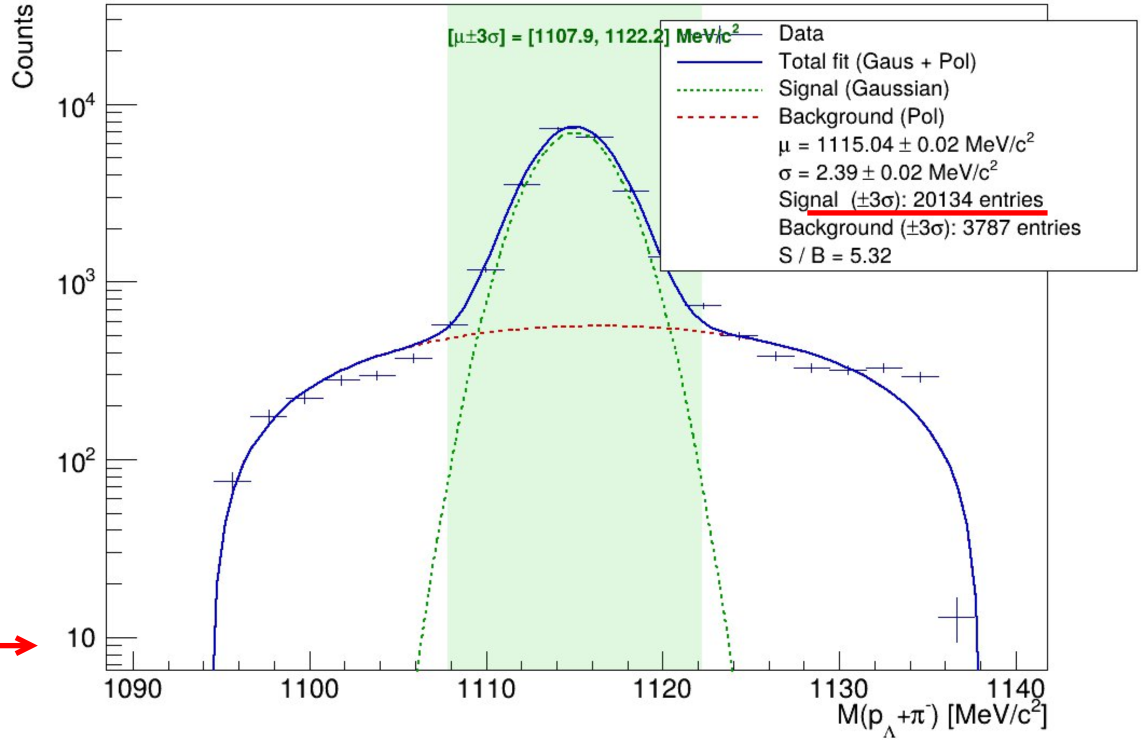
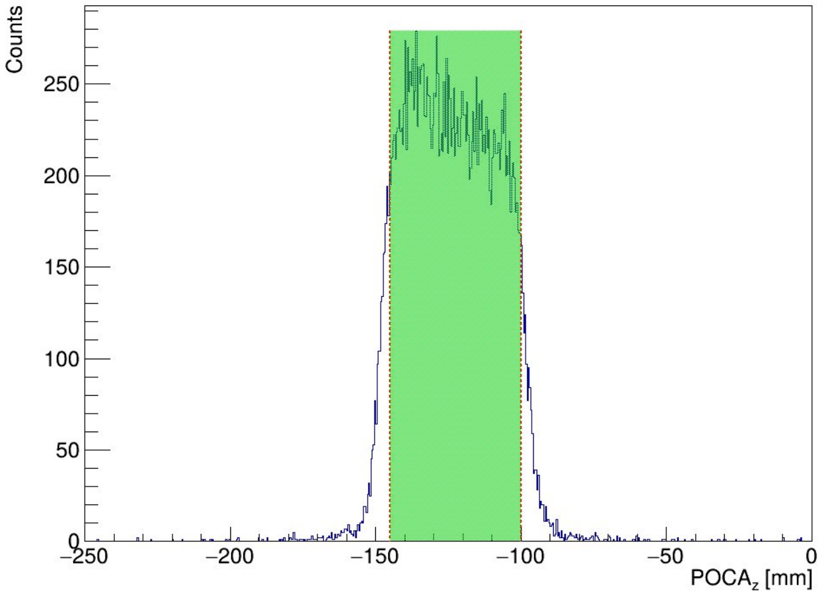
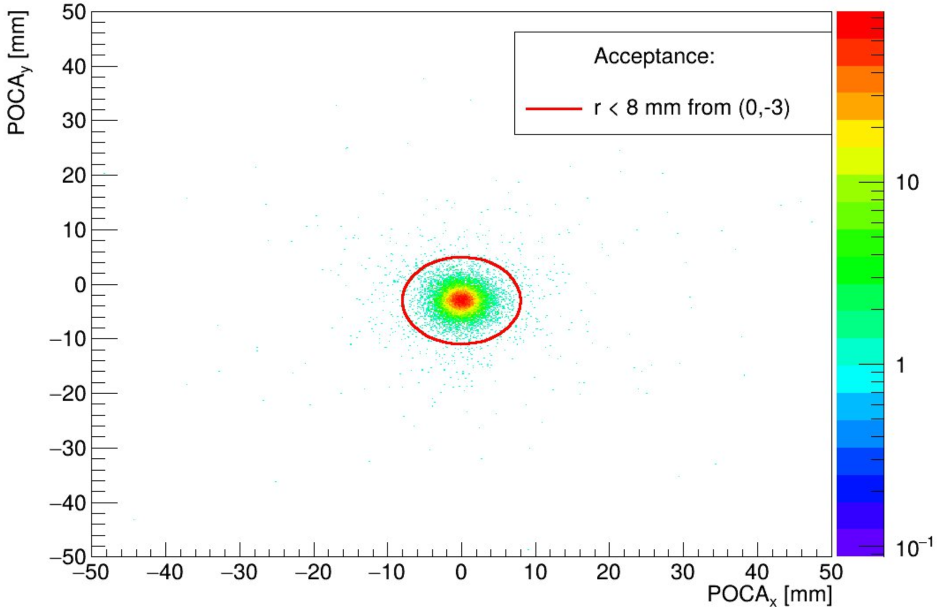


~8% of Λ are lost due to incorrect secondary proton hypothesis

Analysis Procedure: Target Region Selection

- Knowing the primary proton and kaon, we select tracks within the target region of the point of closest approach (POCA)
- Select events with $\mathrm{POCA}\left(\mathrm{p_{primary}K^+}\right)_z \in$ (-145, -100) mm
- Select events with $\mathrm{POCA}\left(\mathrm{p_{primary}K^+}\right)_r < 8$ mm





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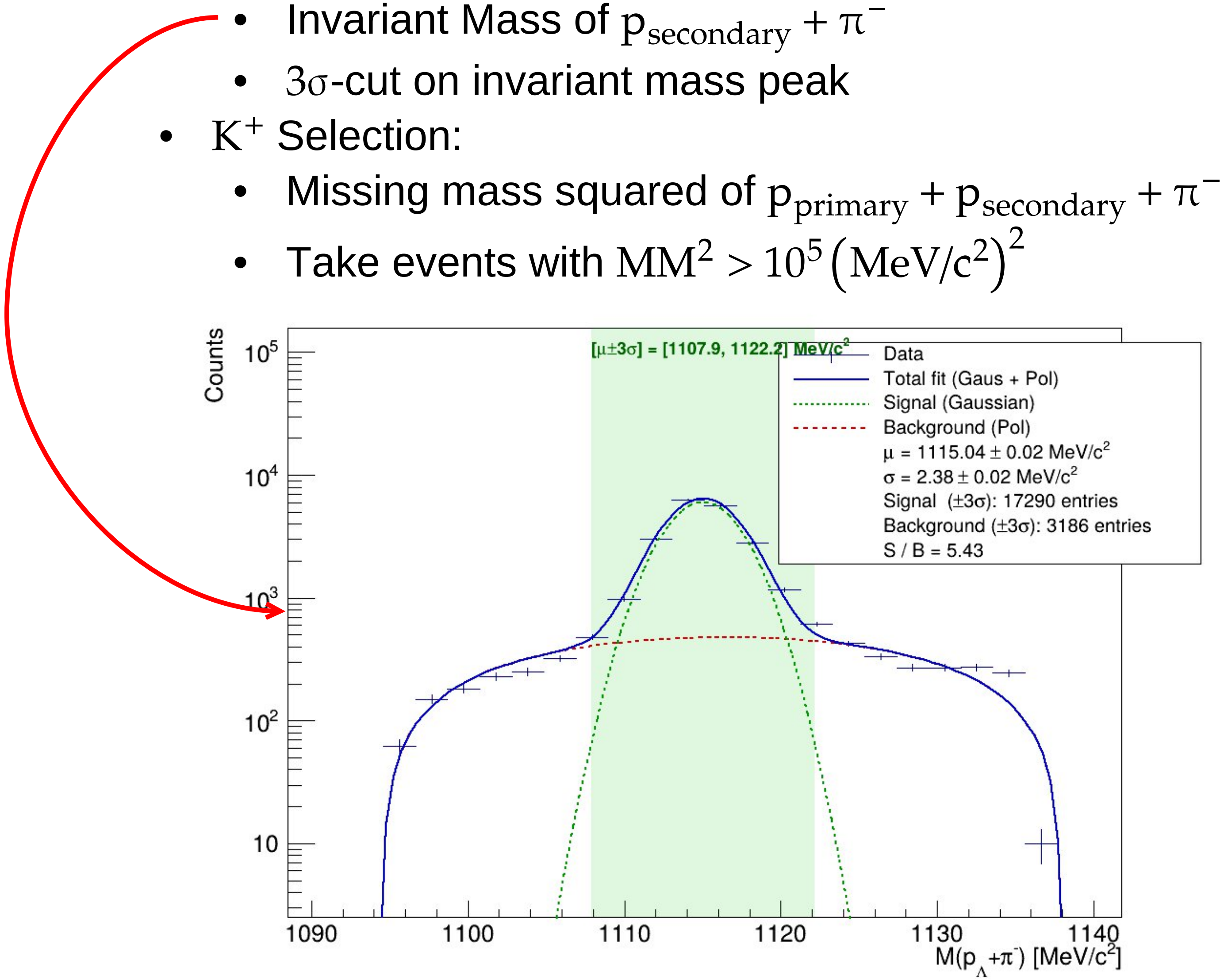
Analysis Procedure: Λ and K^+ selection

- Λ Selection:
  - Invariant Mass of $p_{secondary} + \pi^-$
  - 3σ-cut on invariant mass peak
- K^+ Selection:
  - Missing mass squared of $p_{primary} + p_{secondary} + \pi^-$
  - Take events with $MM^2 > 10^5 \left(MeV/c^2\right)^2$



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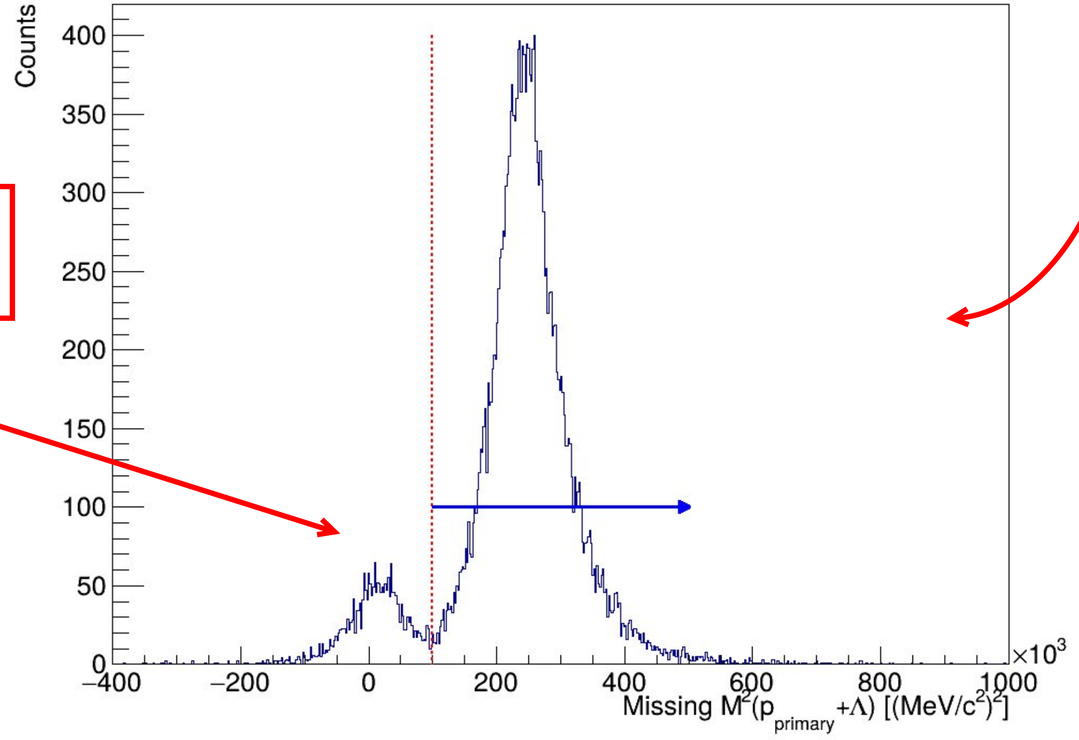

primary background channel:
$pp \rightarrow pp\pi^+\pi^-$

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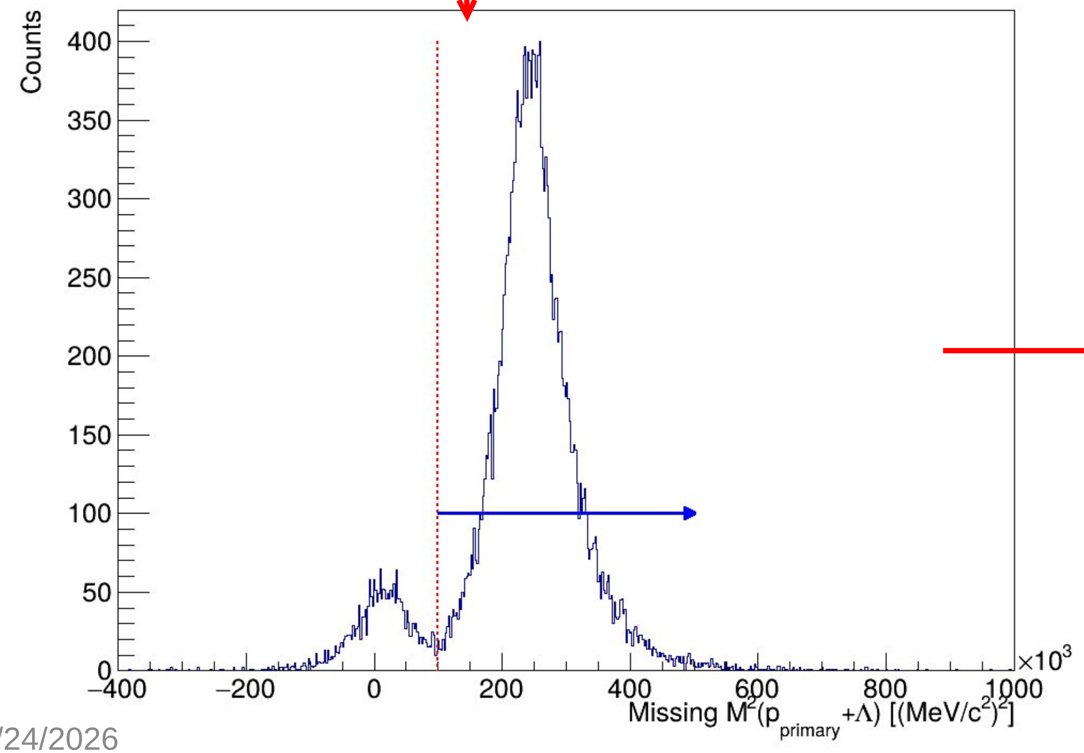

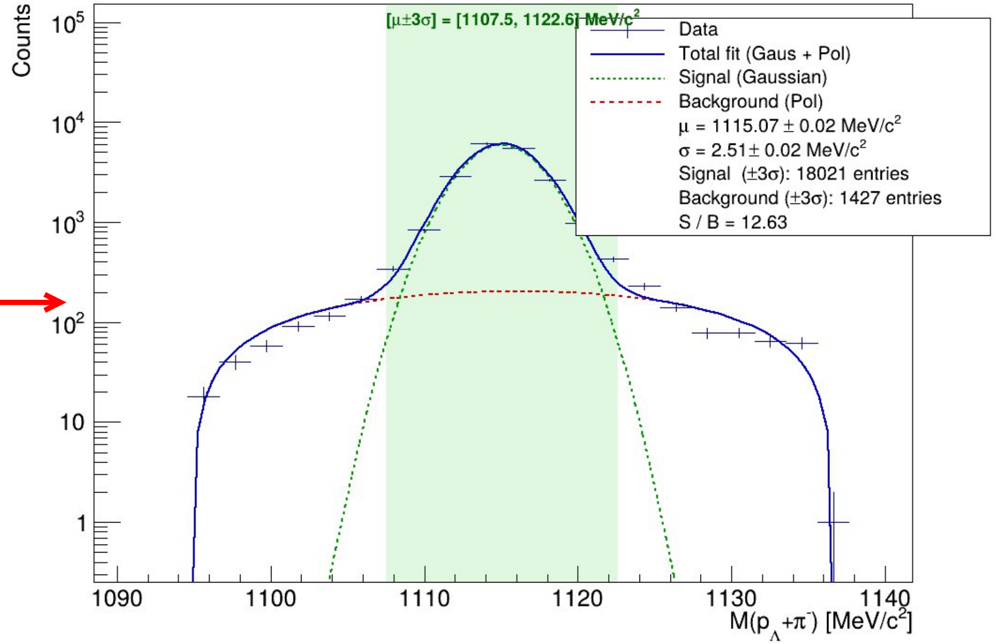

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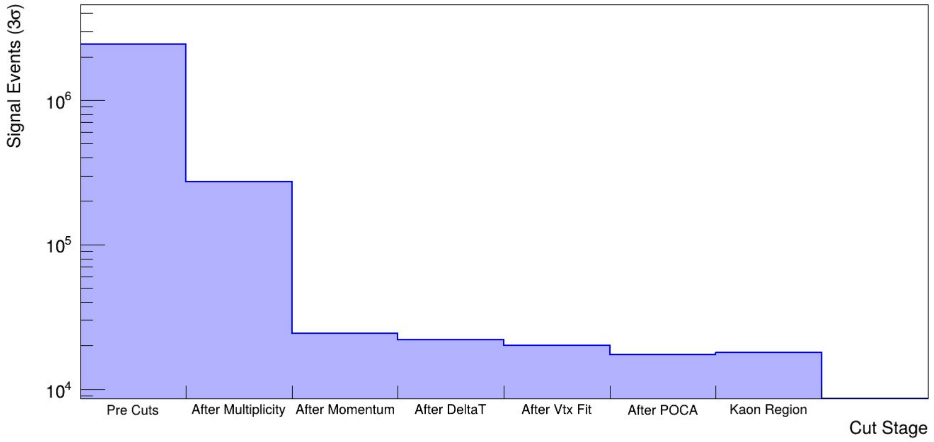
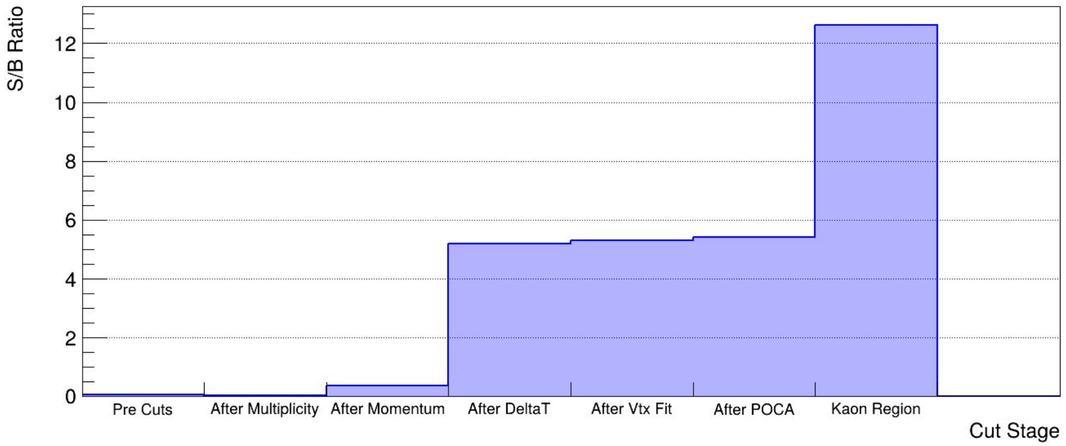
Results Evaluation: Λ yield and S/B ratio

- Λ Signal for tracks

- Selecting events only in HADES removes a large amount of good signal
  Can be improved by:
  - Including forward detector information
  - Allowing missing particle

- Primary/Secondary proton assignment loses ~15% of hyperons:
  Need for a higher resolution on vertex reconstruction



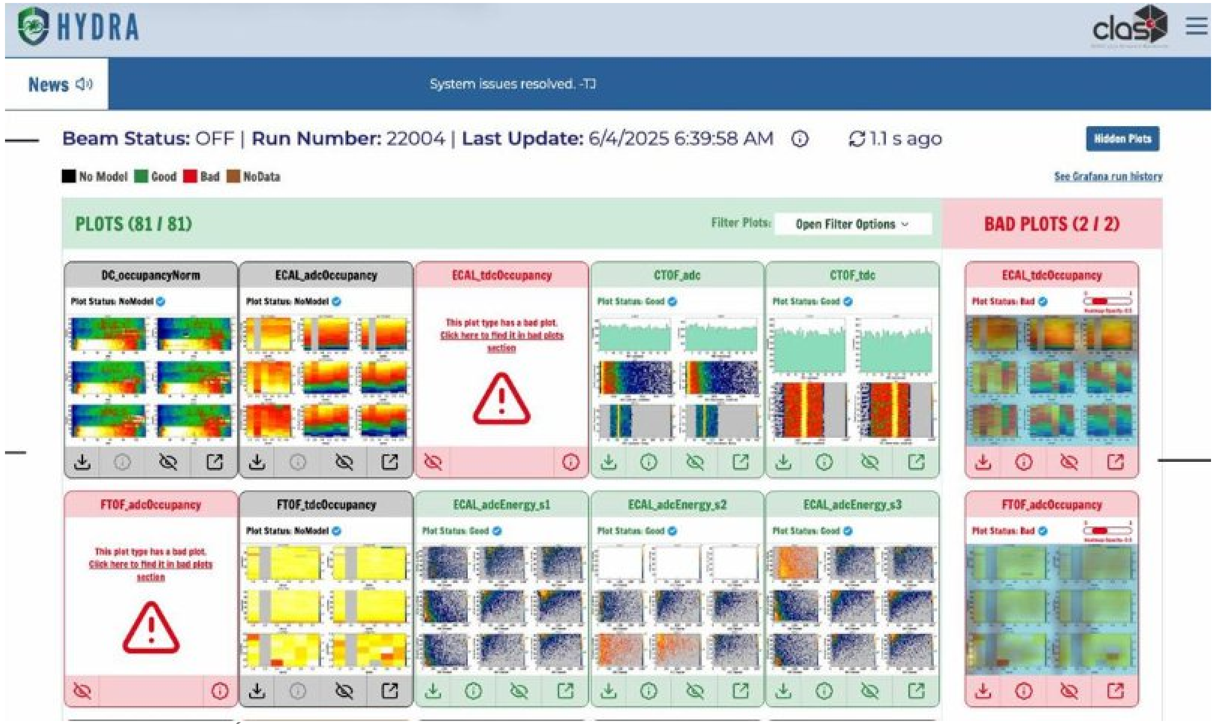


Next Steps:

- Kinematic fit (in progress)
- Including forward detector information
- Use simple machine learning model (MLP) to optimize selection cuts using simulations (Simon Spies PhD)

An Aside: JLab-HYDRA QA System

- JLab-HYDRA is a real-time machine learning QA system developed at JLab
- Implementation for future CBM experiments carried out by Sachin Gupta (FFN)
- Testing on hades-qa machines on previous HADES data pulled from webQA upcoming
- More news in time



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Backup: START Detector Corrections and Flags

Average ΔT of all 4 tracks
assuming $pp \rightarrow pp\pi^+\pi^-$ reaction
$(\Delta T_{\pi^-} + \Delta T_{\pi^+} + \Delta T_{p_1} + \Delta T_{p_2})/4$

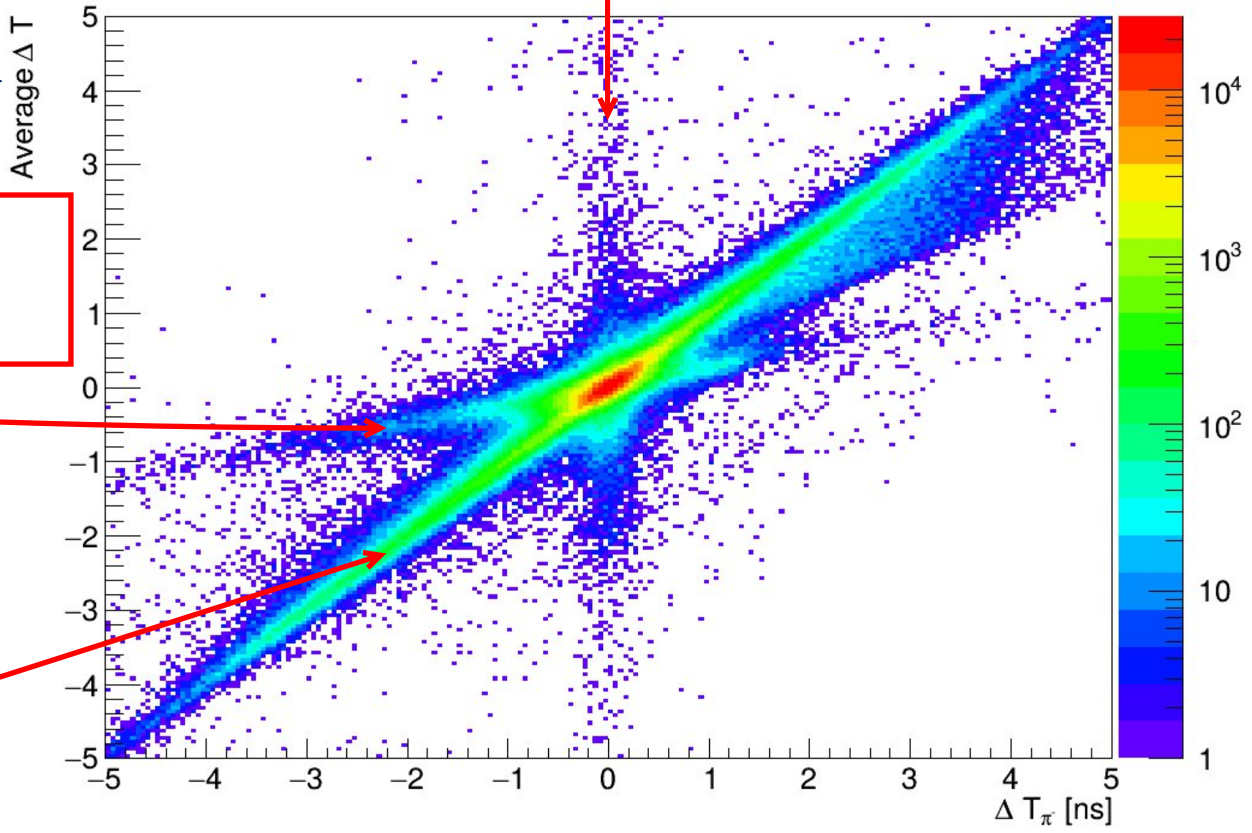
Vertical ΔT band
positive track wrong PID
π^+ candidate is e^+, μ^+, or K^+
p candidate is d or K^+

Low angle shifted ΔT diagonal
negative track wrong PID
π^- candidate is e^-, μ^-, or K^-

45 degree ΔT diagonal
All tracks equally shifted ΔT

Globally shifted START time

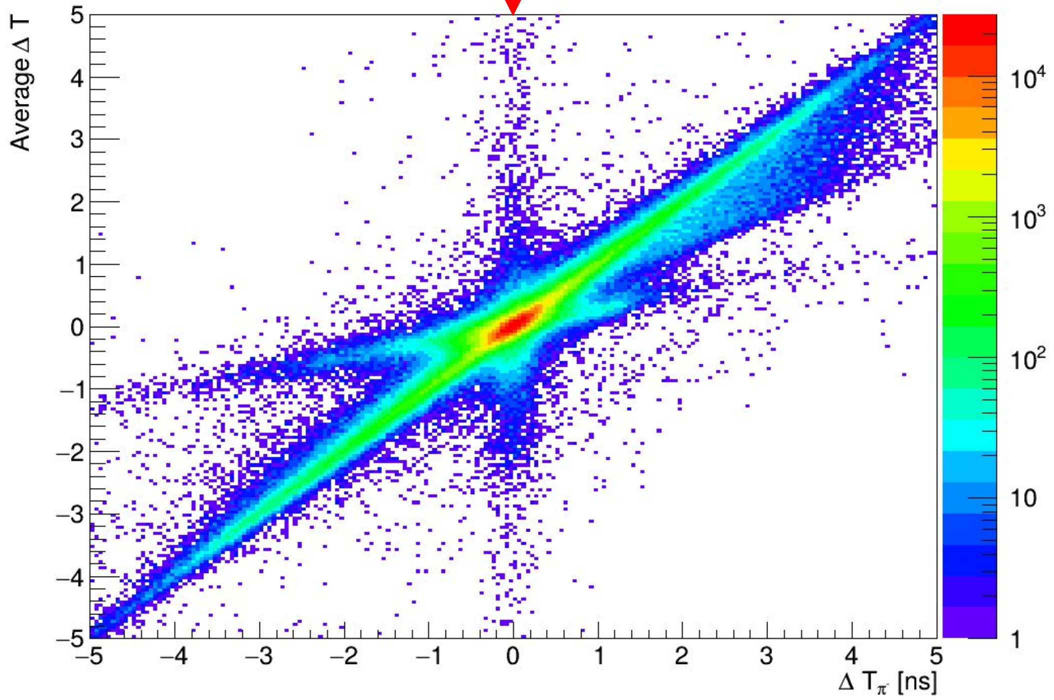
Can be corrected by removing average
ΔT of all four tracks to each ΔT measurement



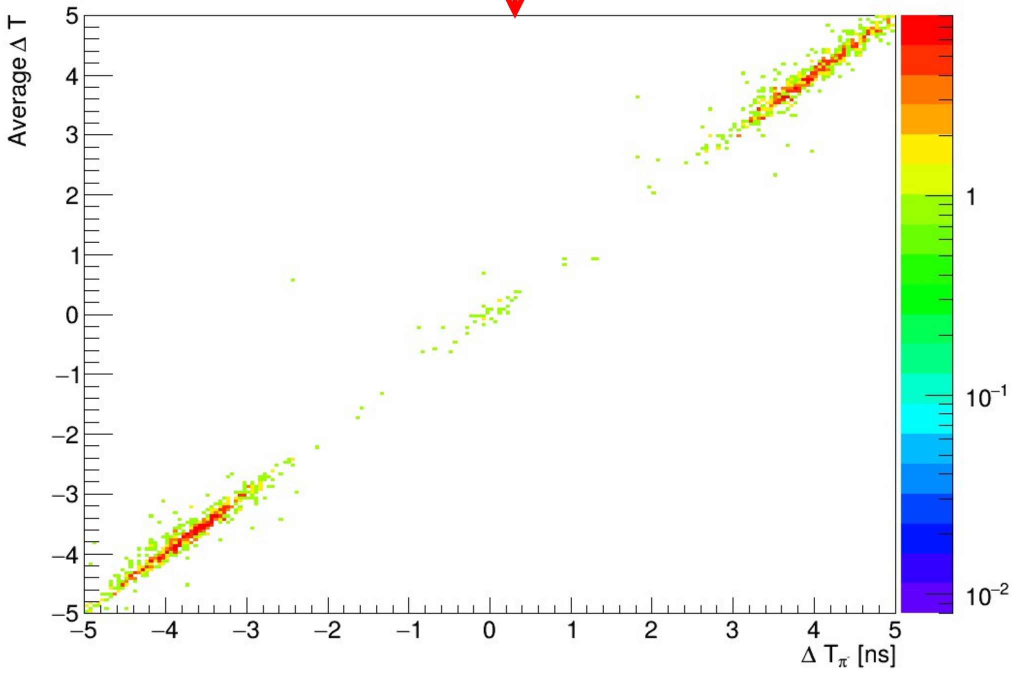
ΔT of π^- candidates

Backup: START Detector Corrections and Flags

Iteration 3
iTOF START information
used to improve resolution



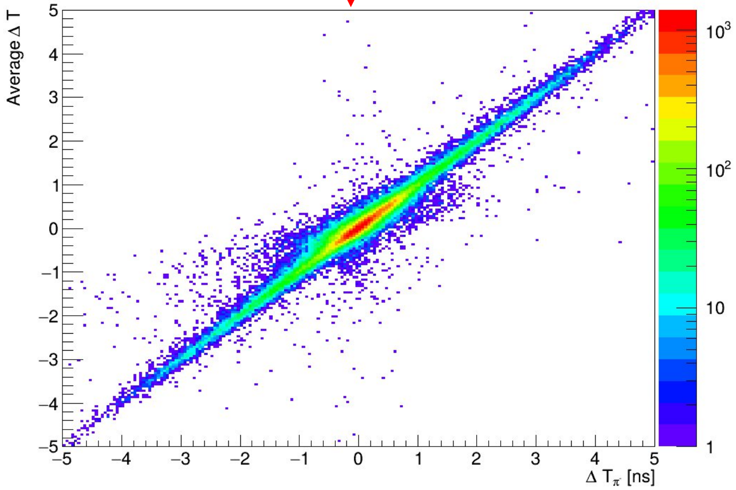
Iteration 2
Poor START time
iTOF not considered



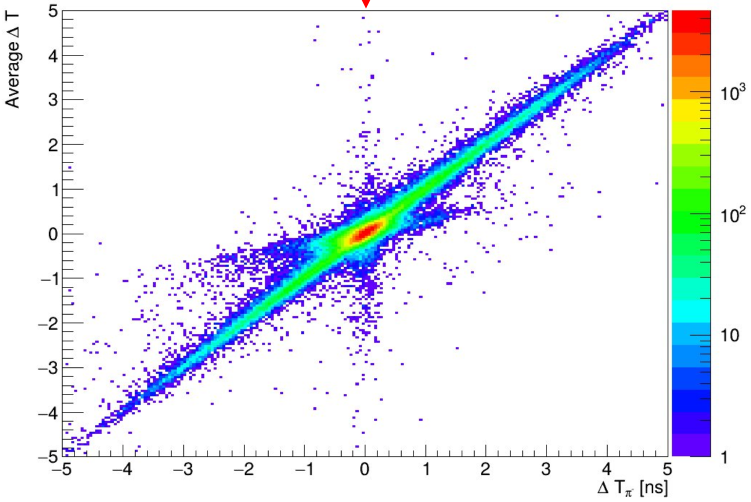
“Good START” cut
removes Iteration 2 events

Backup: START Detector Corrections and Flags

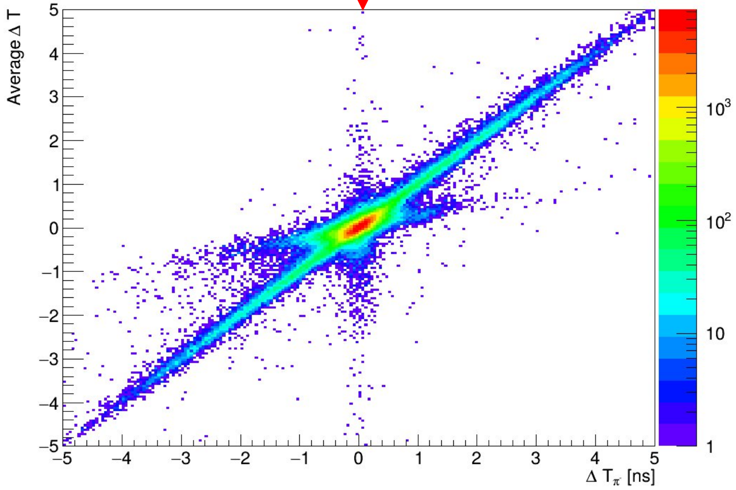
CorrFlag 0
hits from LGAD module 0



CorrFlag 1
hits from LGAD module 1



CorrFlag 2
hits from both LGAD
module 0 and 1 at once

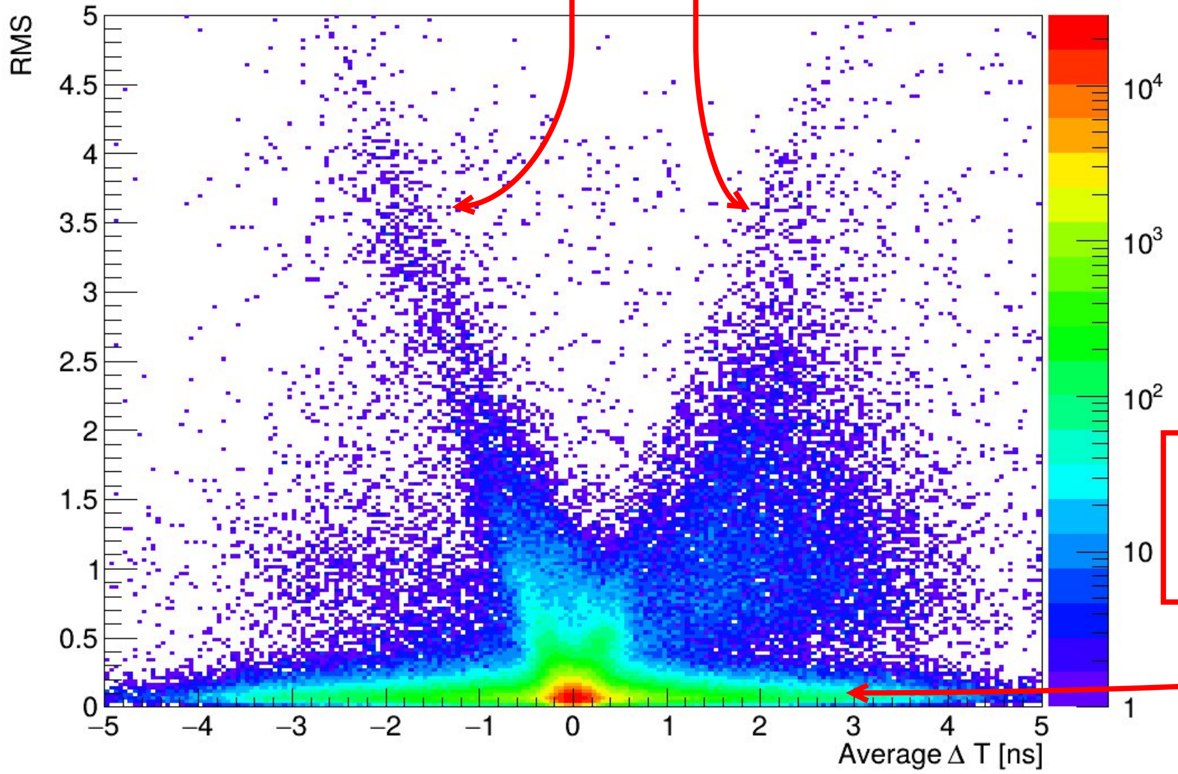


"Good Event" if LGAD included in START

$$\text{CorrFlag} \geq 0$$

Backup: RMS all tracks

Lines at shifted RMS$\propto\sqrt{3}$
one track from other event with
different START **(pileup)**



$$RMS = \sqrt{\Sigma_{i=0}^{3}(\Delta T_i - <\Delta T>)^2/4}$$

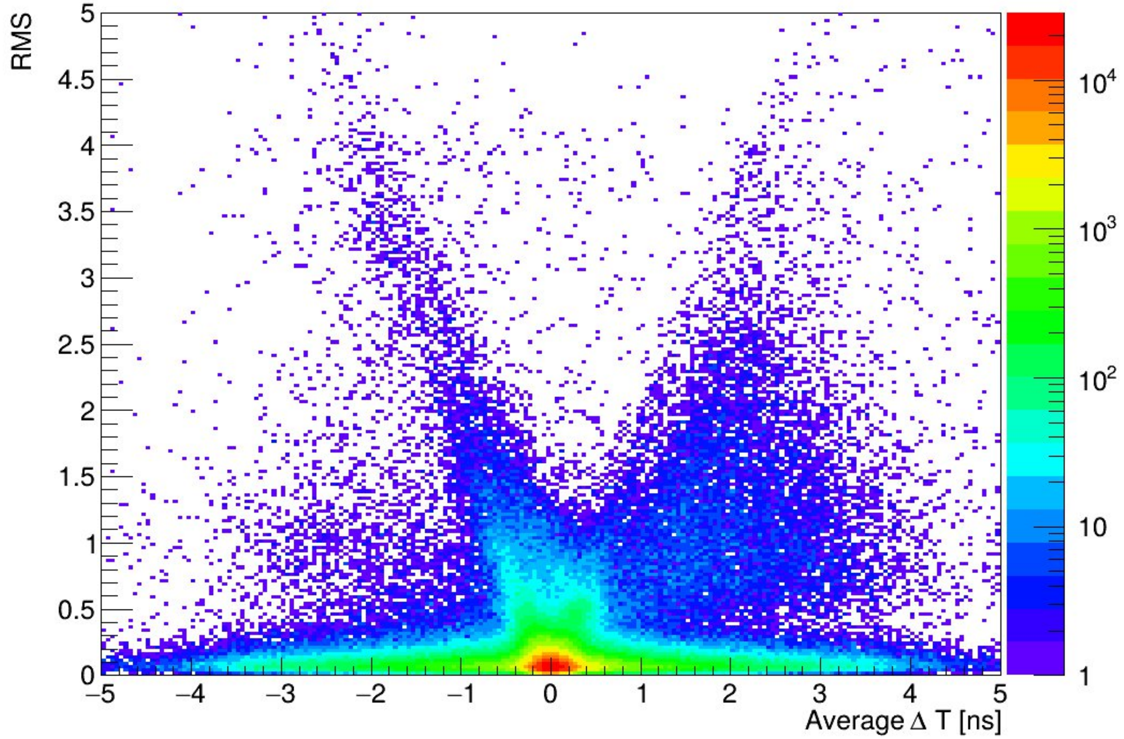
$$<\Delta T> = \Sigma_{i=0}^{3}\Delta T_i/4$$

Shifted START due to
globally shifted START time
for all tracks

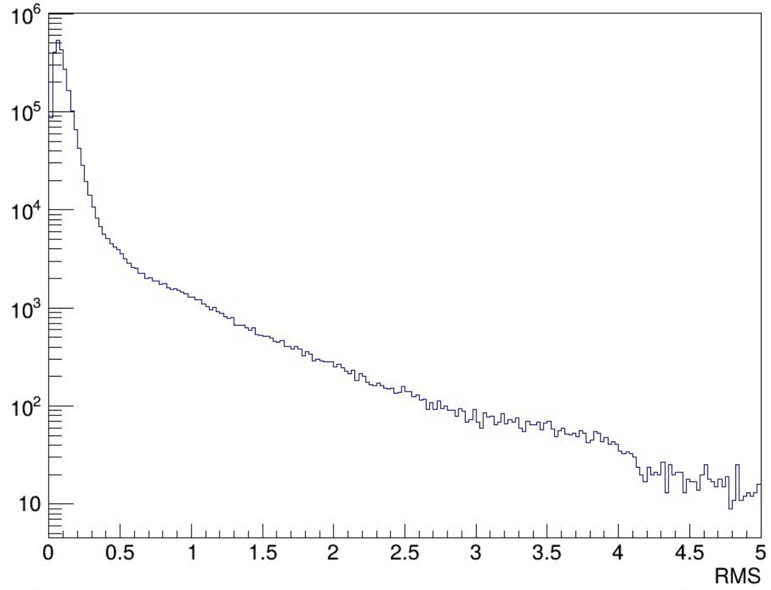
Backup: RMS all tracks

$$RMS = \sqrt{\Sigma_{i=0}^{3}(\Delta T_i - <\Delta T>)^2/4}$$

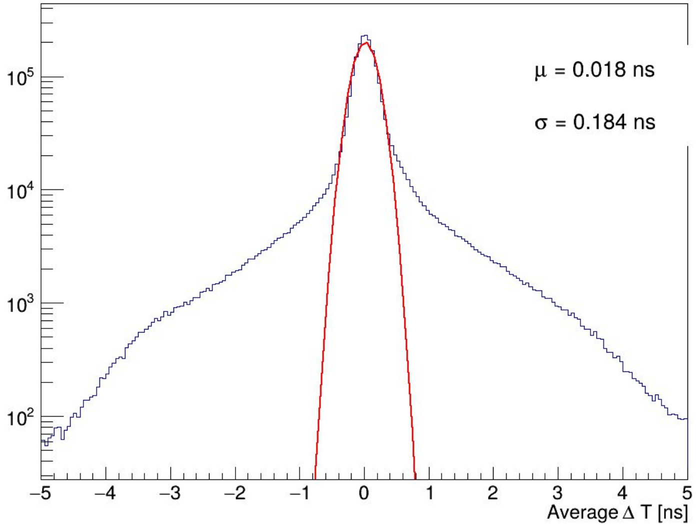
$$<\Delta T> = \Sigma_{i=0}^{3}\Delta T_i/4$$



Y projection



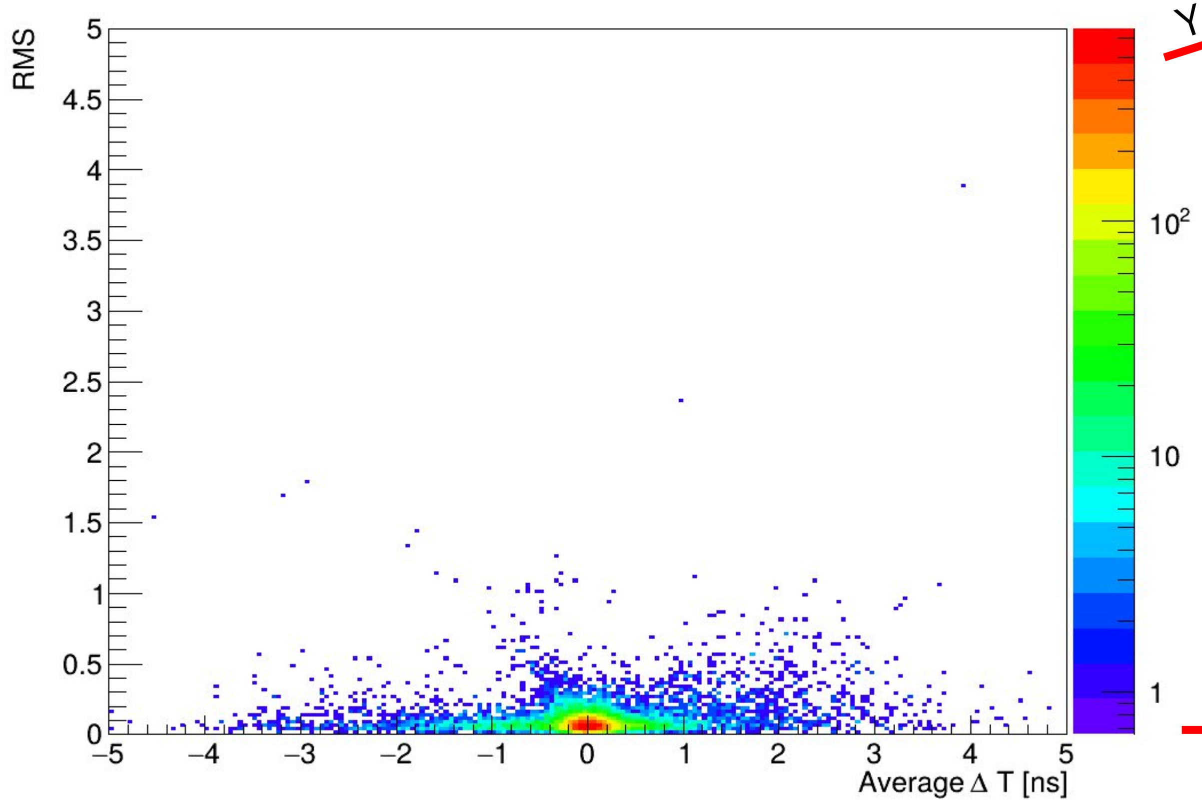
X projection



Backup: RMS $pK^+\Lambda$ candidates

$$RMS = \sqrt{\Sigma_{i=0}^{3} (\Delta T_i - < \Delta T >)^2/4}$$

$$< \Delta T >= \Sigma_{i=0}^{3} \Delta T_i/4$$



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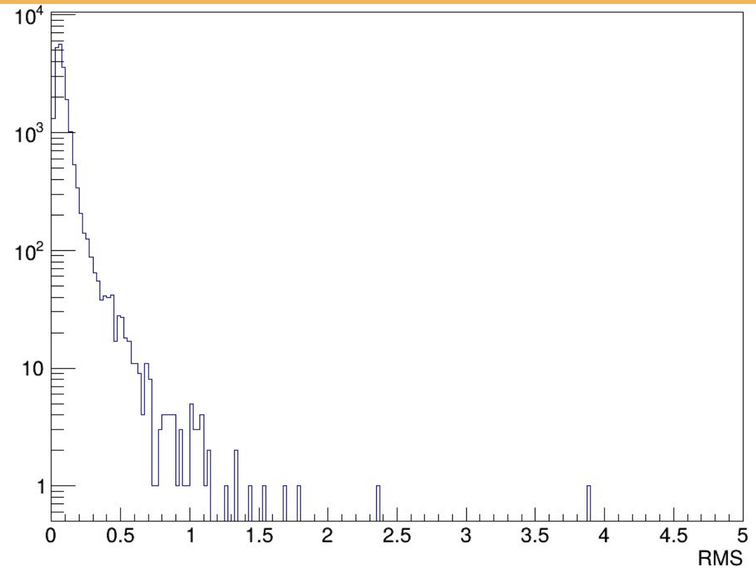

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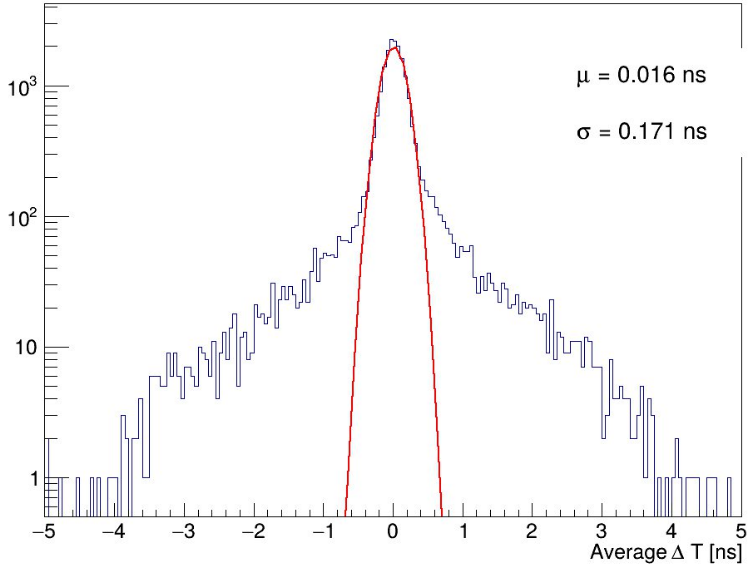
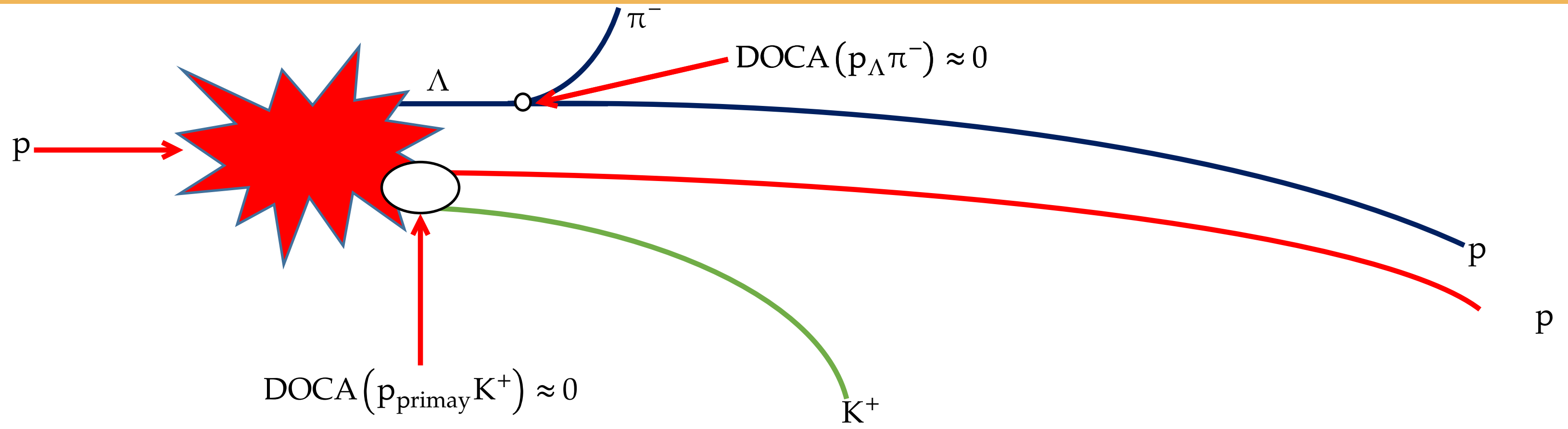


Analysis Procedure: Primary vs Secondary Proton



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