Update on the Λ Analysis with Kinematic Fitting at HADES

Jenny Regina

Uppsala University
Department of Physics and Astronomy

PANDA CM
Hyperon and Hypernuclei Session
October 27, 2021

Outline

- **Motivation**
- **Updated analysis procedure**
- **Tests on Data**
- **Outlook**

Why Kinematic refit?
- Λ Polarization in pp reactions

Previous study:

- Polarization of Λ Hyperons In Proton-Proton Reactions At 3.5 GeV Measured With Hades, see **PoS(INPC2016)275**

Number of Λ as a function of cos(ζ)

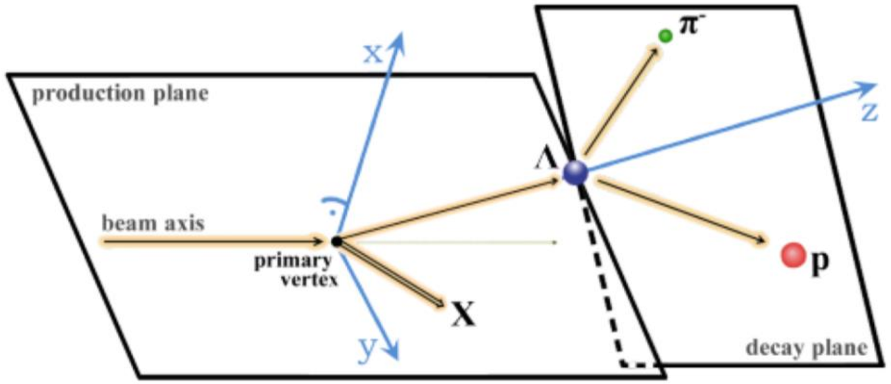
$$\frac{dN}{dcos(\zeta)} = C(1 + \alpha P cos(\zeta))$$

P-polarization
C-constant
α-decay asymmetry parameter of Λ decay

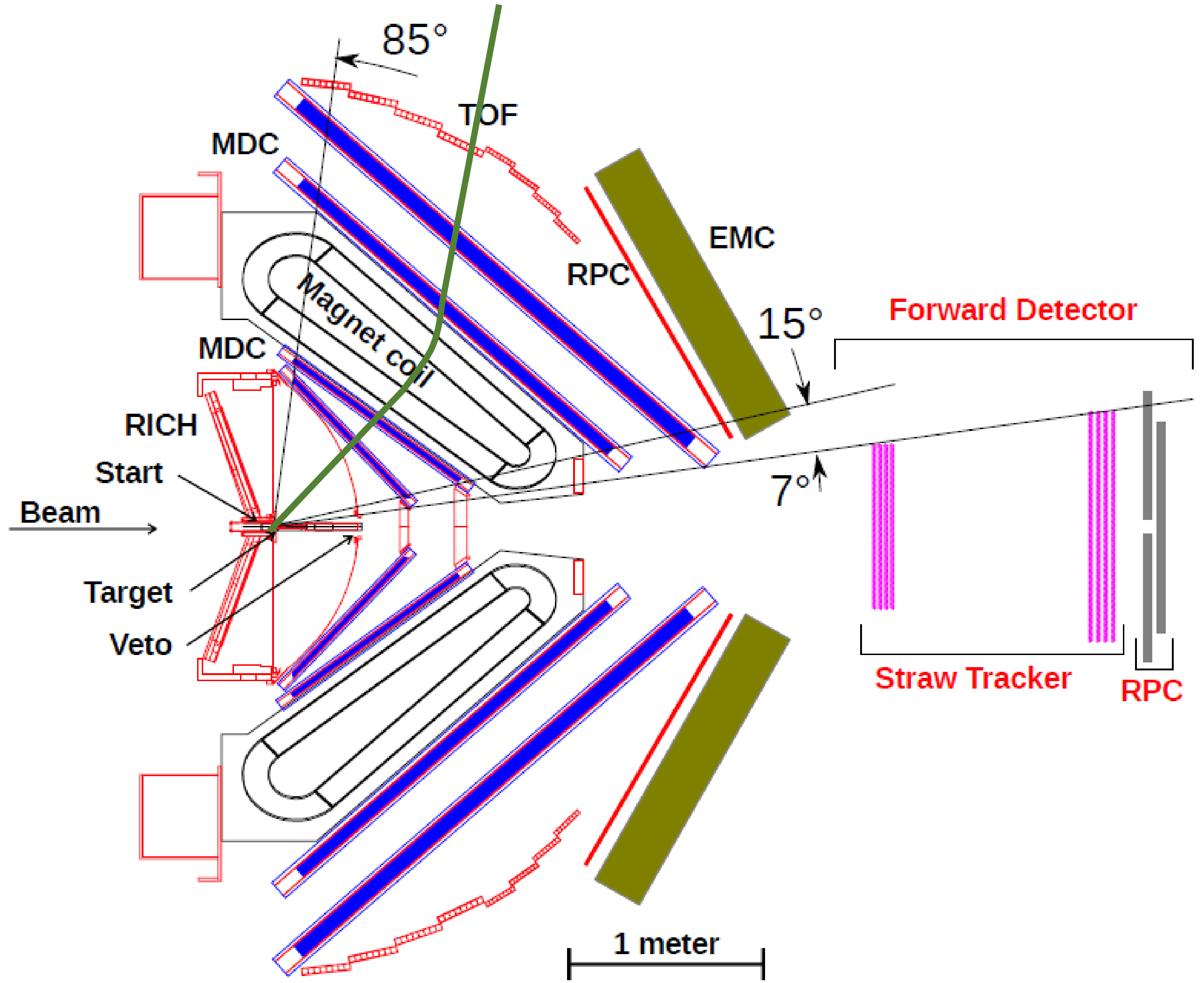
- Difference between generated and reconstructed polarization angle show large uncertainty
  - **Kinematic refit might improve resolutions and hence results**

Coordinate System

$$\vec{n}_x = \frac{\vec{p}_{beam} \times \vec{p}_\Lambda}{|\vec{p}_{beam} \times \vec{p}_\Lambda|}, \quad \vec{n}_y = \vec{n}_x \times \vec{n}_z, \quad \vec{n}_z = \frac{\vec{p}_\Lambda}{|\vec{p}_\Lambda|}$$



HADES Spectrometer



Main HADES Spectrometer

RICH: Electron identification

MDC: Track reconstruction

TOF: Time-of-Flight

RPC: Time-of-Flight

Forward detector

EMC: improved energy information for electrons and leptons

Straw Tracker: Based on PADNA Forward Straw Trackers

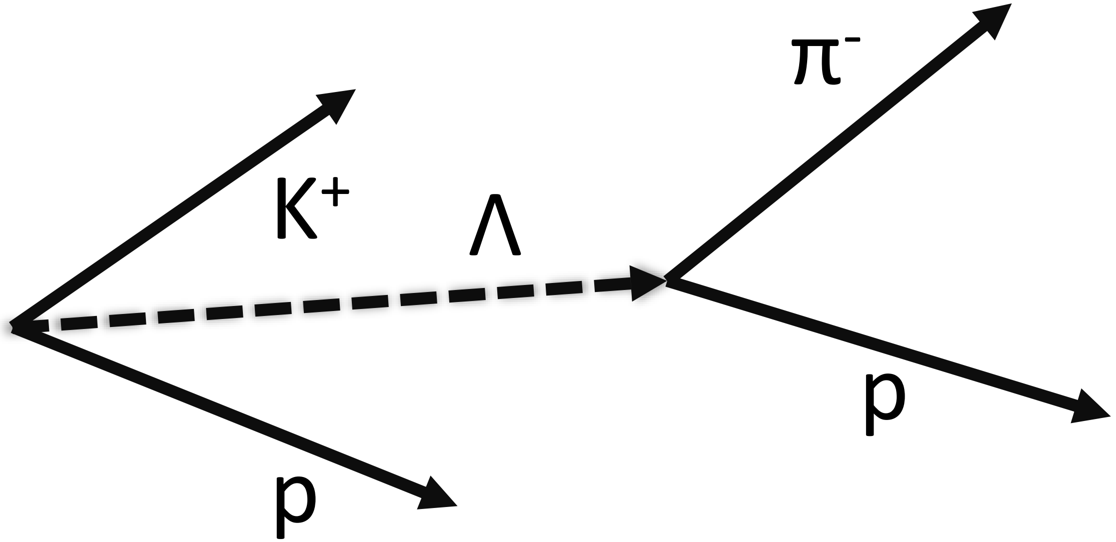
RPC: Time-of-Flight

Tracks

- Tracks represented by straight lines in two regions free from magnetic field
  1) before magnets (Reconstruction in MDC I/II)
  2) after magnets (Reconstruction in MDC III/IV)
- First region extends to ~ 1 m after the nominal interaction point -> **FOCUS ON!**

Simulation Details

- 10 000 000 Pluto events
- April 12 Detector setup
- Geant Particle ID (Ideal PID) used to identify p, π^- and K^+
- Choose only reaction particles



Analysis Procedure

Updated since last Analysis Meeting [*]

1. Combine all protons + kaons
   1. **Find the primary vertex**
   2. Combine all protons + pions
   3. **Find the decay vertex**
2. If one primary and one decay vertex found:
   1. **Build the neutral mother candidate** from all possible combinations of vertices
   2. Pass the decay particles + neutral mother candidate to the **kinematic fit**
   3. Select the combination of vertices that correspond to the **kinematic fit** with the highest fit probability
   4. Select only events where both vertices were found with two different protons

Issues:

- Low efficiency for building the entire event, 29% for 1 250 000 events
- Slow, a lot of combinatorics

See backup for details on vertex finding, neutral mother candidate creation and kinematic fitting

[*] https://indico.gsi.de/event/12757/contributions/54285/attachments/36123/48038/LambdaAnalysisAtHADESJenny.pdf

Analysis Procedure

Updated since last Analysis Meeting [*]

1. Combine all protons + kaons
    1. **Find the primary vertex**
2. Combine all protons + pions
    1. **Find the decay vertex**
3. If one primary and one decay vertex found:
    1. **Build the neutral mother candidate** from all possible combinations of vertices
    2. Pass the decay particles + neutral mother candidate to the **kinematic fit**
    3. Select the combination of vertices that correspond to the **kinematic fit** with the highest fit probability
    4. ***Select only events where both vertices were found with two different protons***

New Procedure:

1. Combine all protons + kaons
    1. **Find the primary vertex**
2. Combine all protons + pions
    1. **Find the decay vertex**
3. If one primary and one decay vertex found:
    1. ***Select only events where both vertices were found with two different protons***
    2. **Build the neutral mother candidate** from all possible combinations of vertices
    3. Pass the decay particles + neutral mother candidate to the **kinematic fit**
    4. Select the combination of vertices that correspond to the **kinematic fit** with the highest fit probability

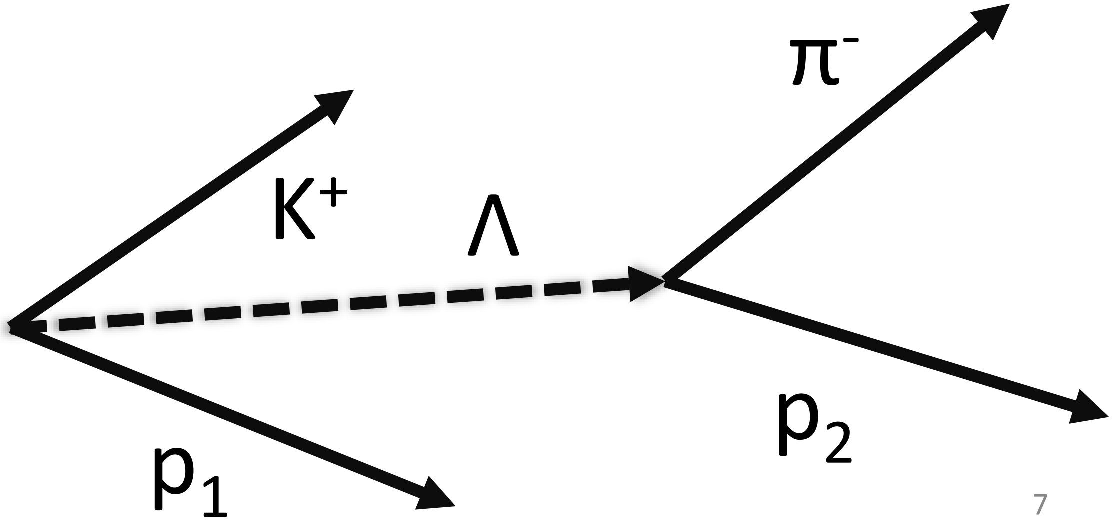
[*] https://indico.gsi.de/event/12757/contributions/54285/attachments/36123/48038/LambdaAnalysisAtHADESJenny.pdf

Efficiencies

Particle in the reaction / combination of particles	Number of reconstructed tracks (% of generated particles)
p_1	3 911 109 (39.1%)
K^+	2 319 958 (23.2%)
p_2	1 915 314 (30.0%)
π^-	2 055 923 (32.2%)
p_1 and K^+ (primary particles)	802 751 (8.0%)
p_2 and π^- (Λ decay products)	777 792 (12.2%)
p_1, K^+ and p_2	101 457 (1.6%)
p_1, K^+ and π^-	127 823 (2.0%)
p_2, π^- and p_1	251 314 (3.9%)
p_2, π^- and K^+	111 173 (1.7%)
p_1, K^+, p_2 and π^- (all particles)	32 155 (0.5%)

After analysis procedure and selection

Efficiency	Proton selection purity in vertices
24 292 (76%)	99.5%

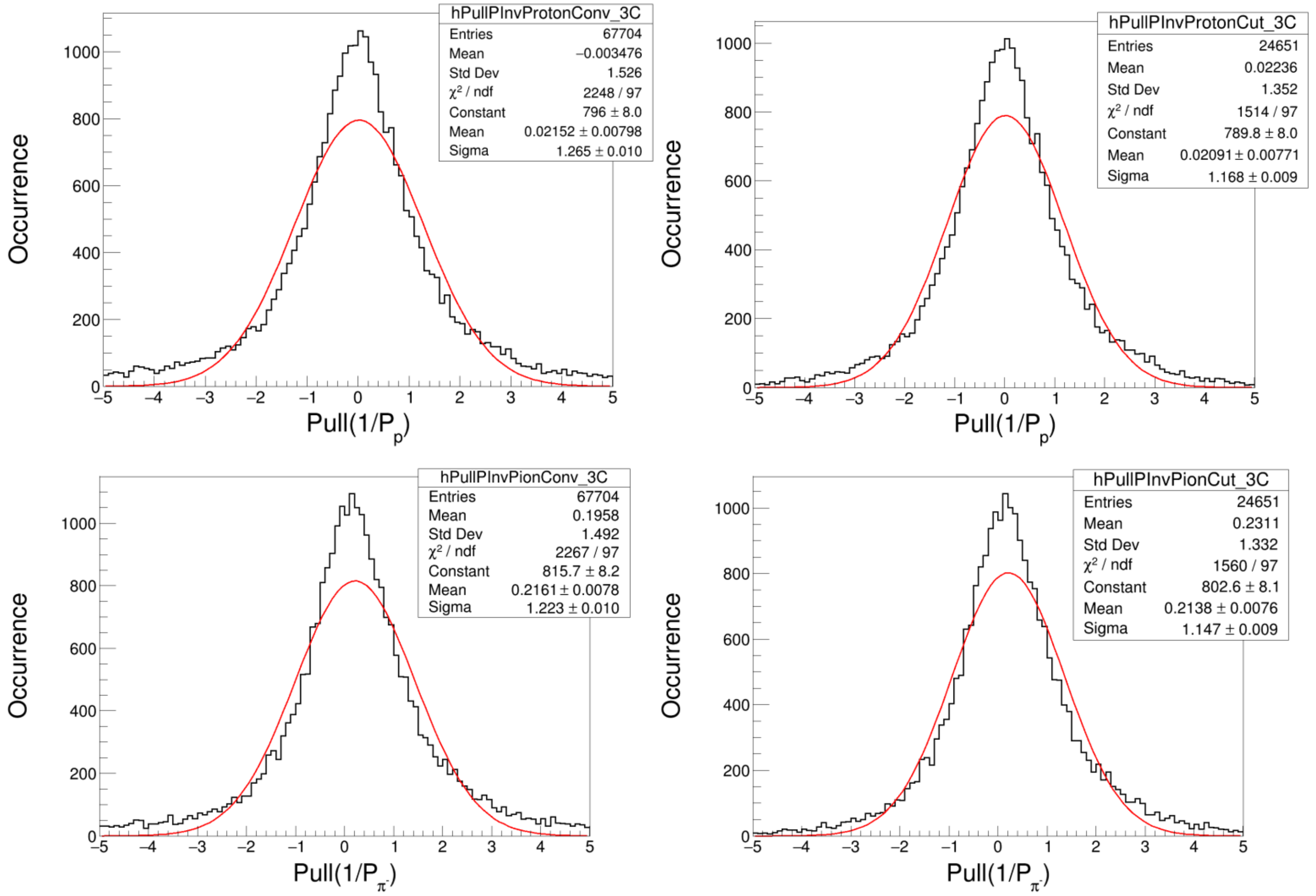


Pulls after the fit

$$z_i = \frac{y_i - \eta_i}{\sqrt{\sigma^2(y_i) - \sigma^2(\eta_i)}}$$

Ideally N(0,1)

- Previously there have been issues with the pull distributions with cutoffs
- Similar for all fitted parameters for proton and pion
- Now the pulls look good
- σ gets closer to 1.0 when applying the probability cut
- Similar for all parameters

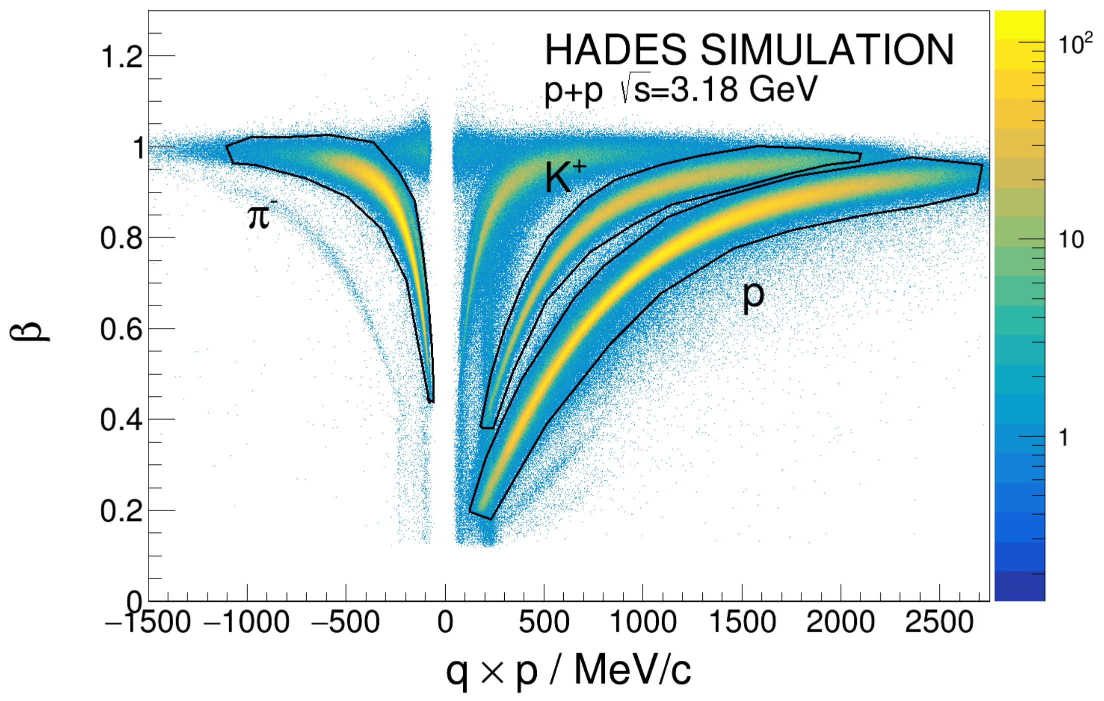


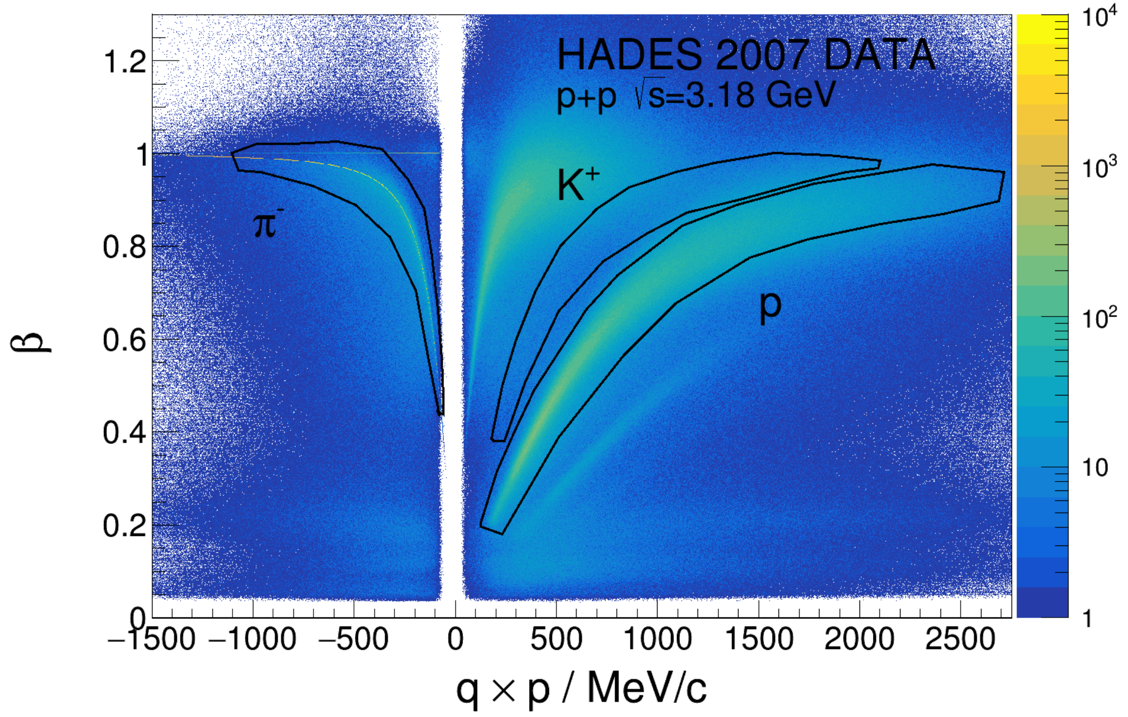
Analysis on Experimental Data

- p + p @ 3.5 GeV Collected in 2007
- Skimmed data set
  - At least 1 negatively charged + 3 positively charged particles
- PID made from MDC information

PID Selection

Cuts placed for simulation and overlaid for experimental data

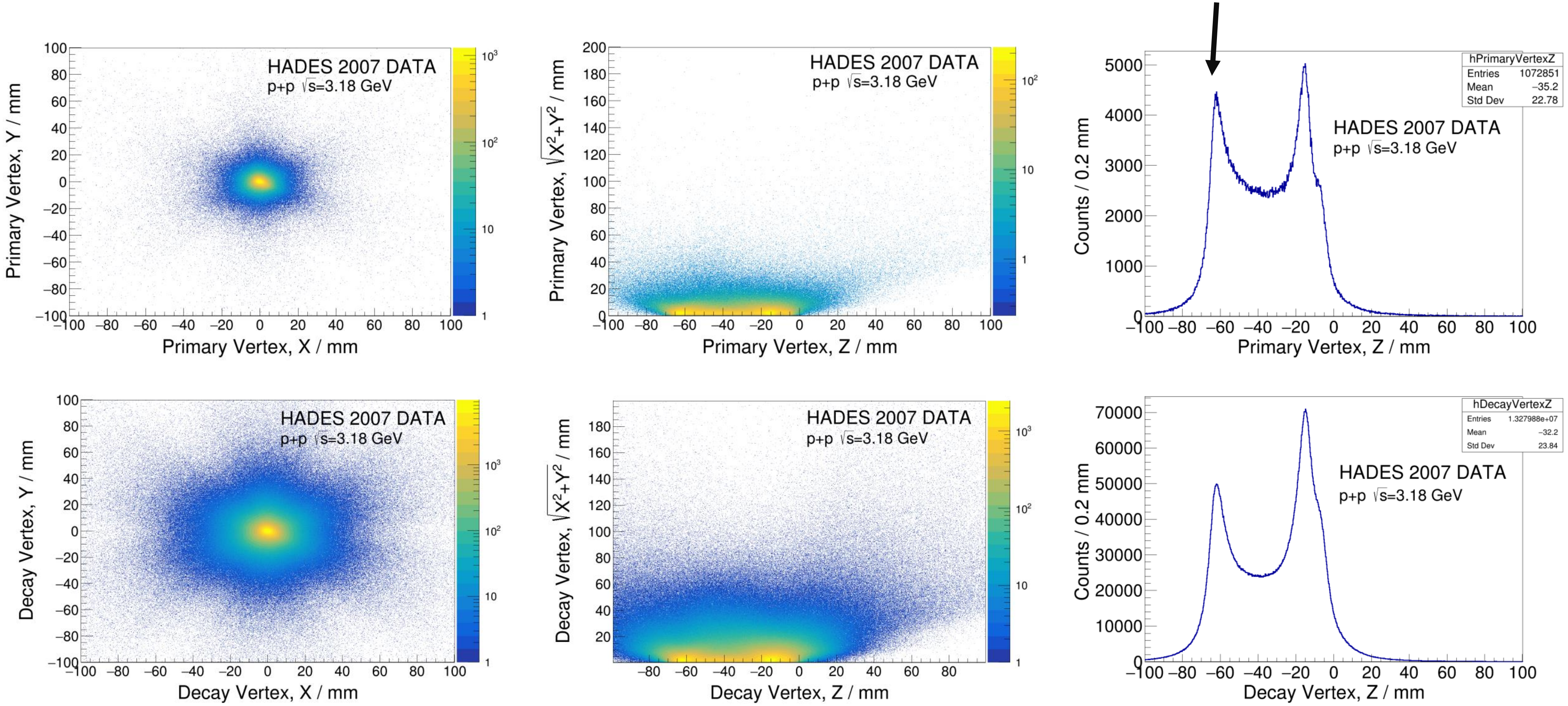




- Might expand cut regions to allow more particles in analysis
- Use everything to the left as negatively charged particles

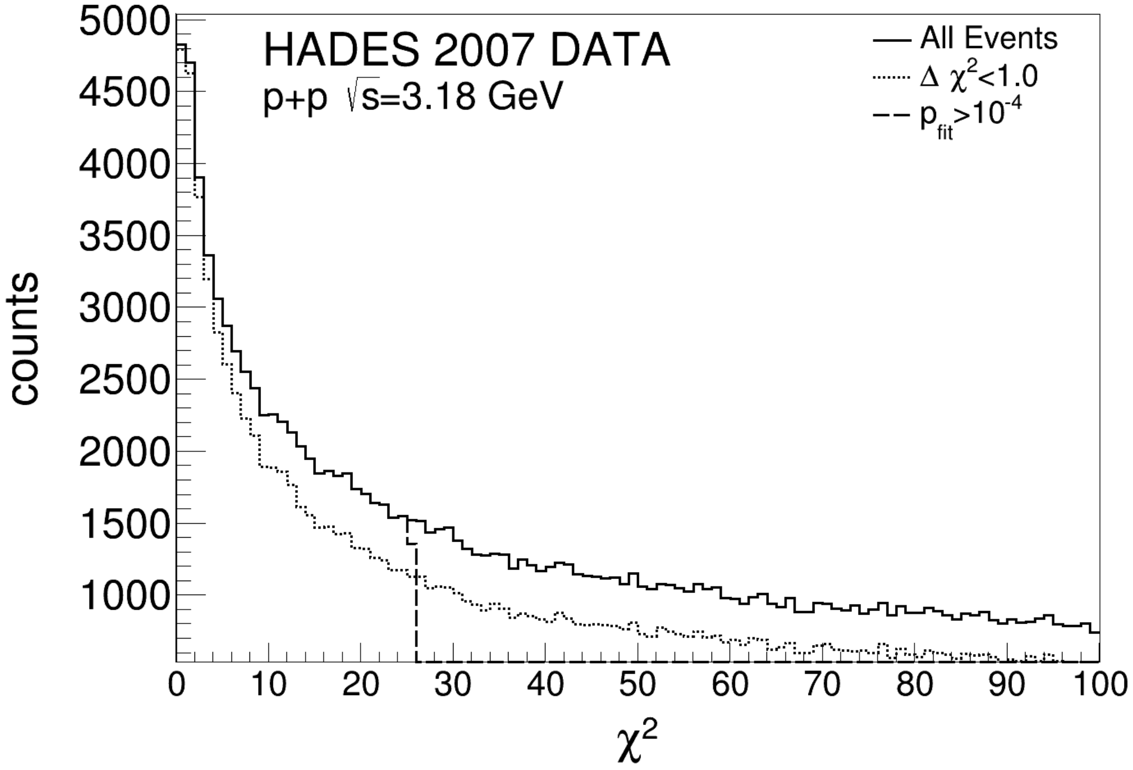
Reconstructed Vertices

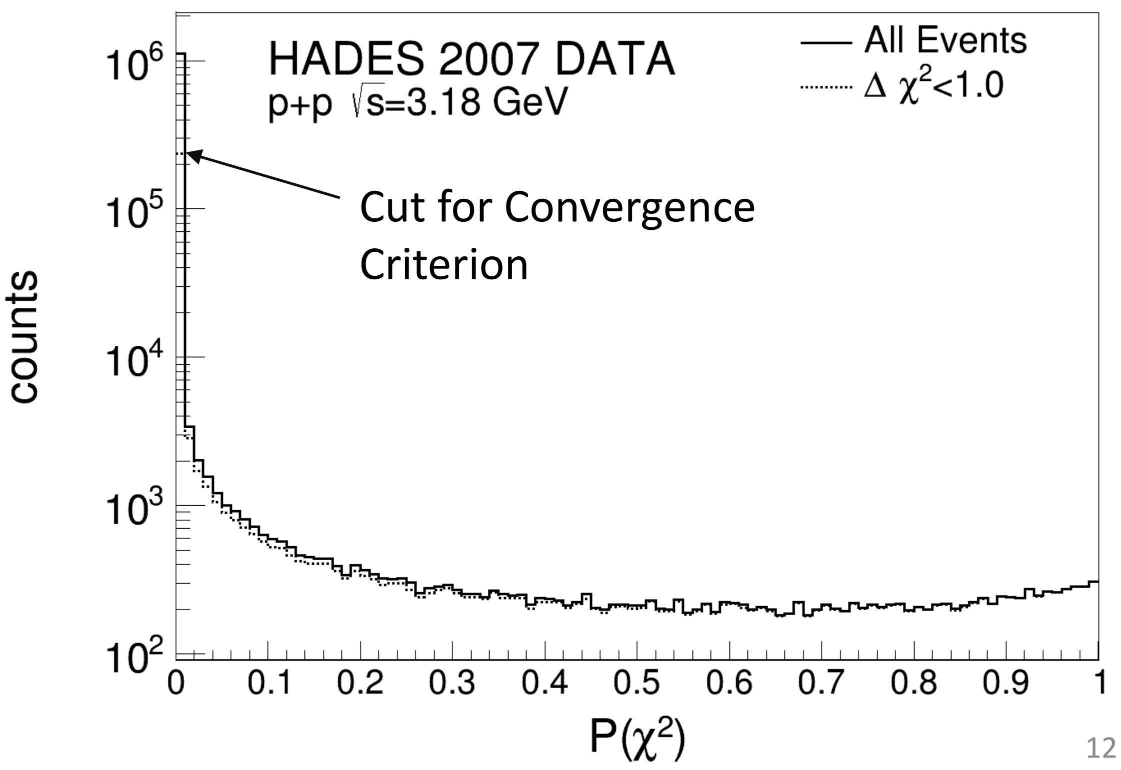
Peaks from kapton windows



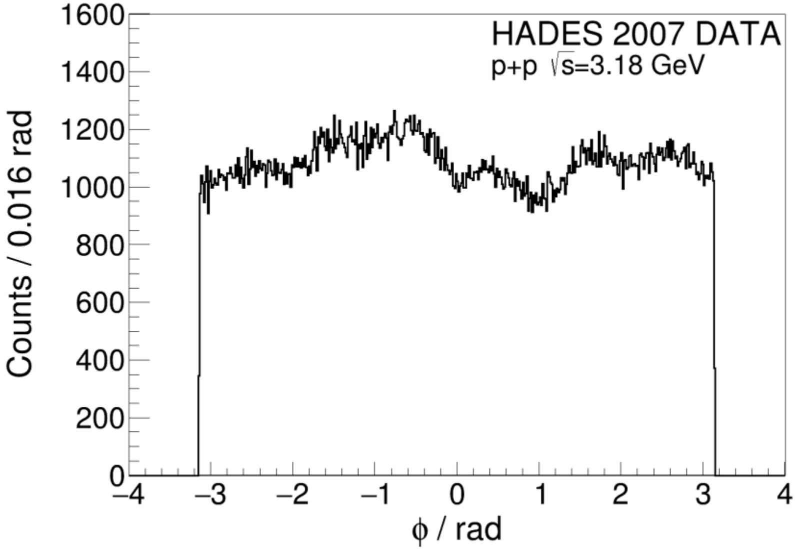
χ^2 and $P(\chi^2)$

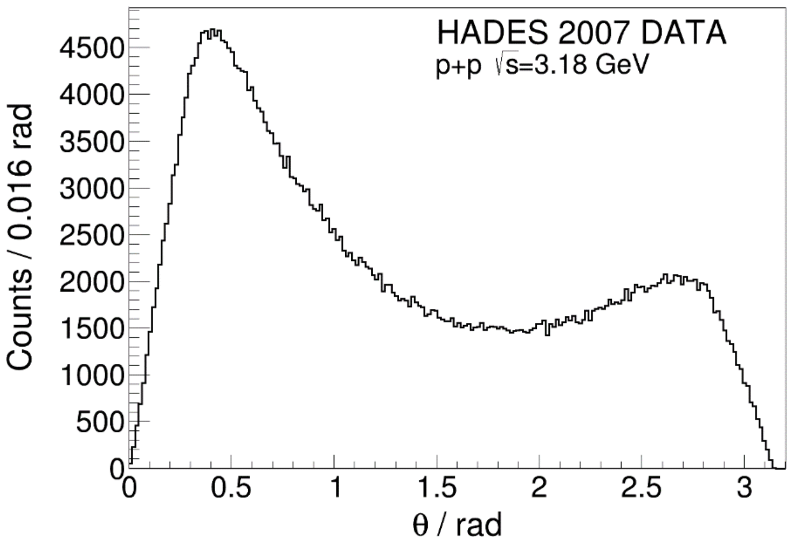
- Allow up to 10 iterations
- Convergence criterion mainly cuts away events with large χ^2 and low probability





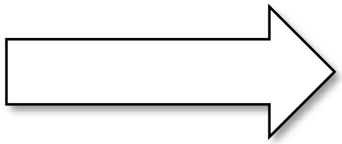
Reconstructed Λ Parameters after Fit



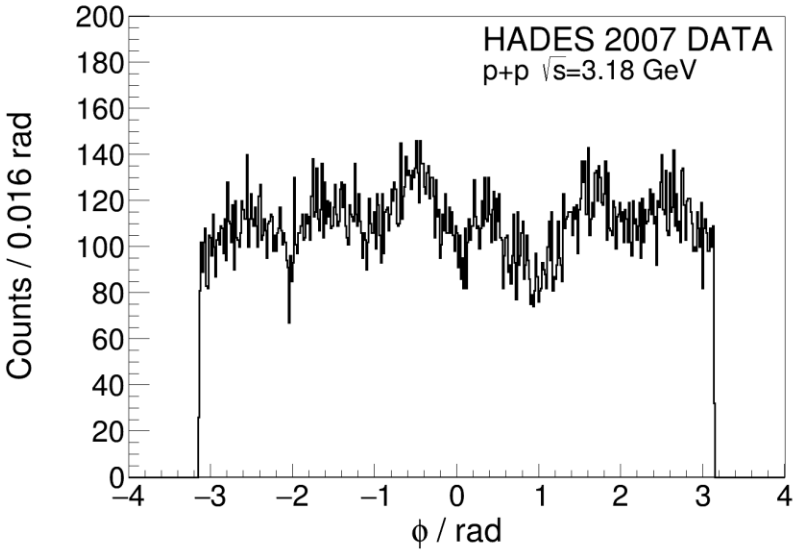


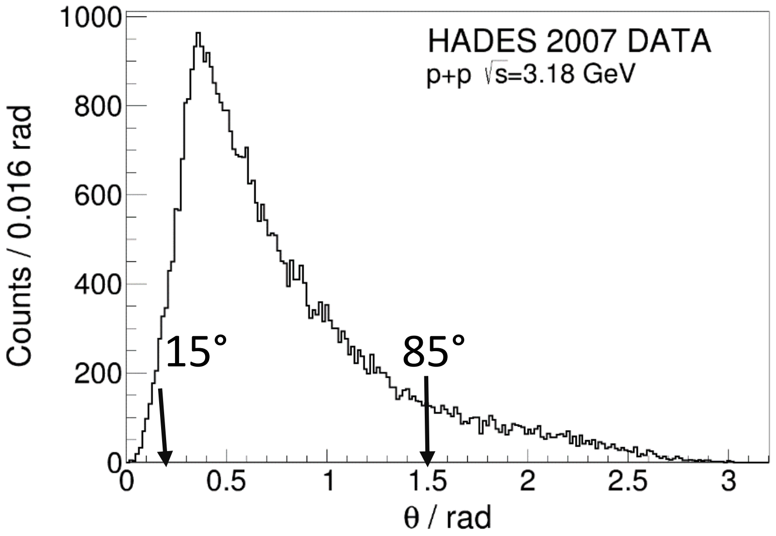
Convergence criterion applied for all histograms

Apply probability cut



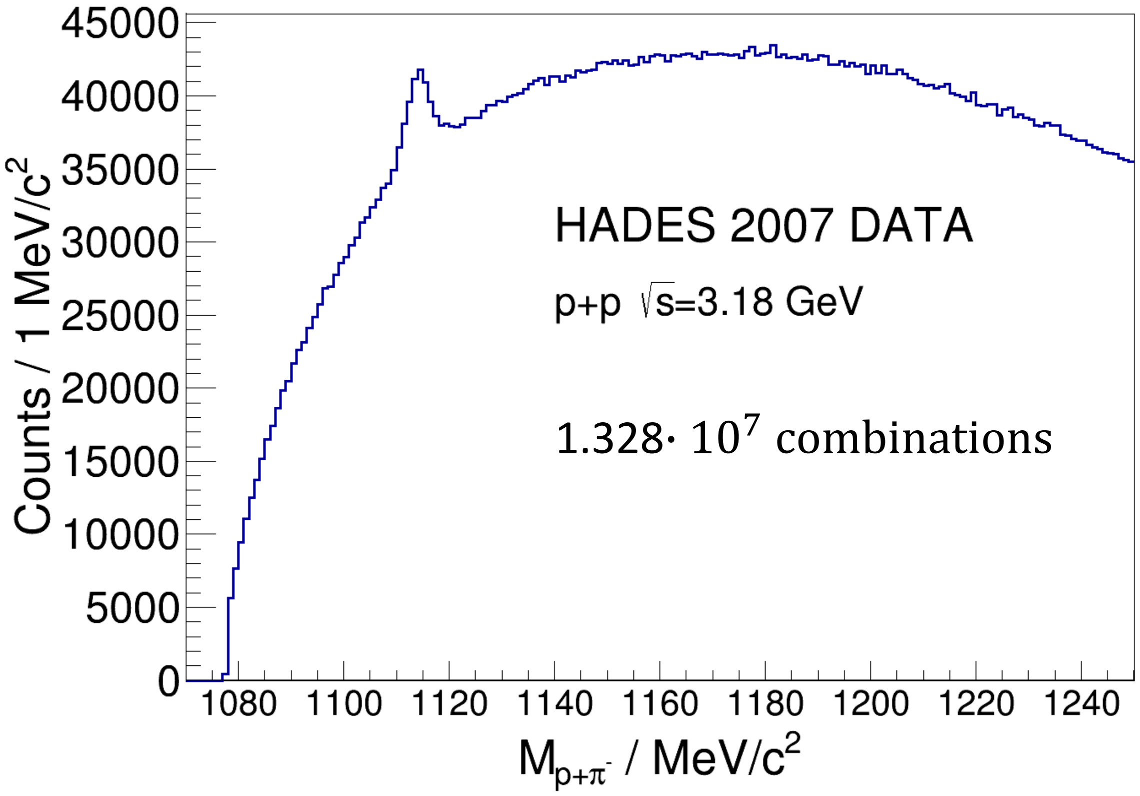
Applying probability cut mainly keeps events with θ in HADES acceptance



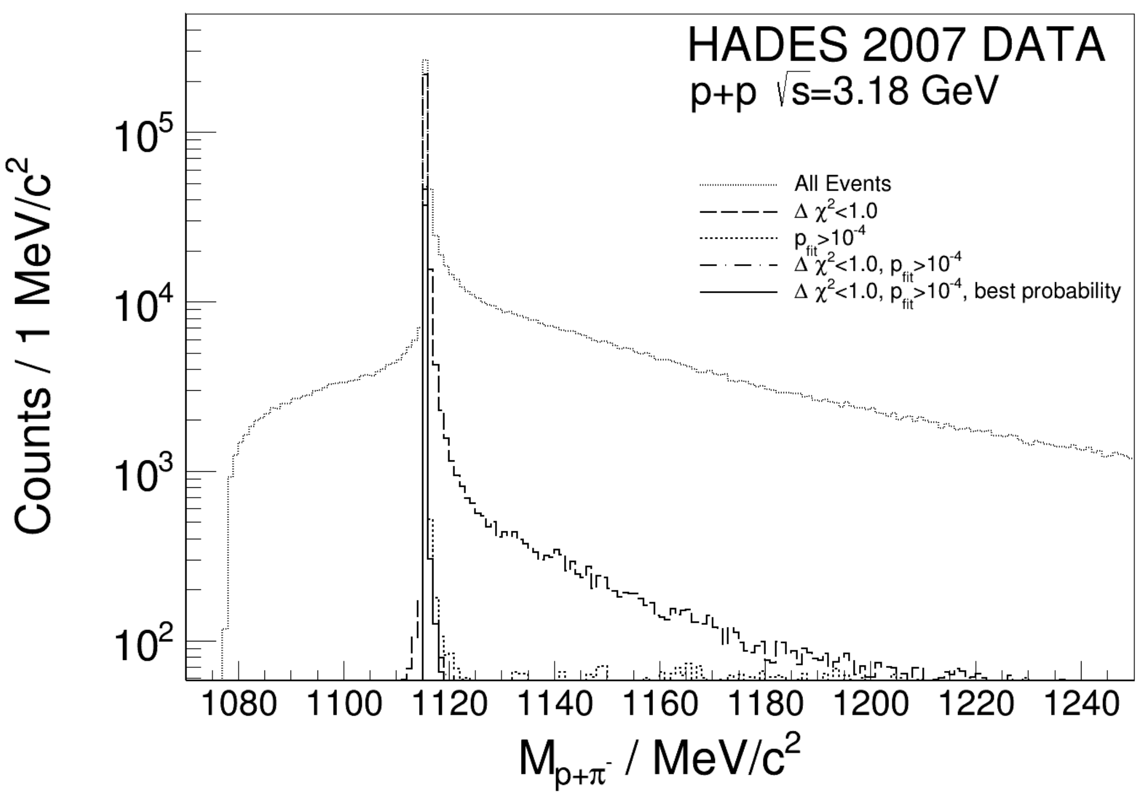


Mass histograms

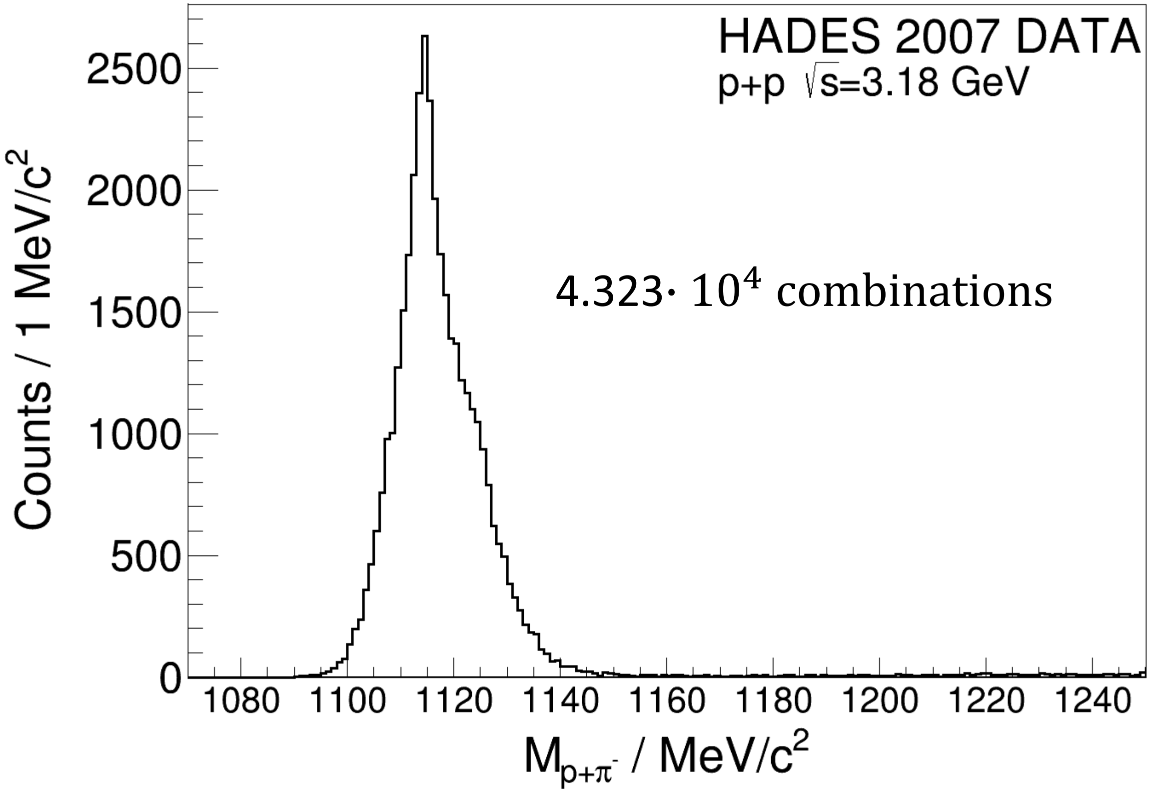
Mass histogram for all combinations



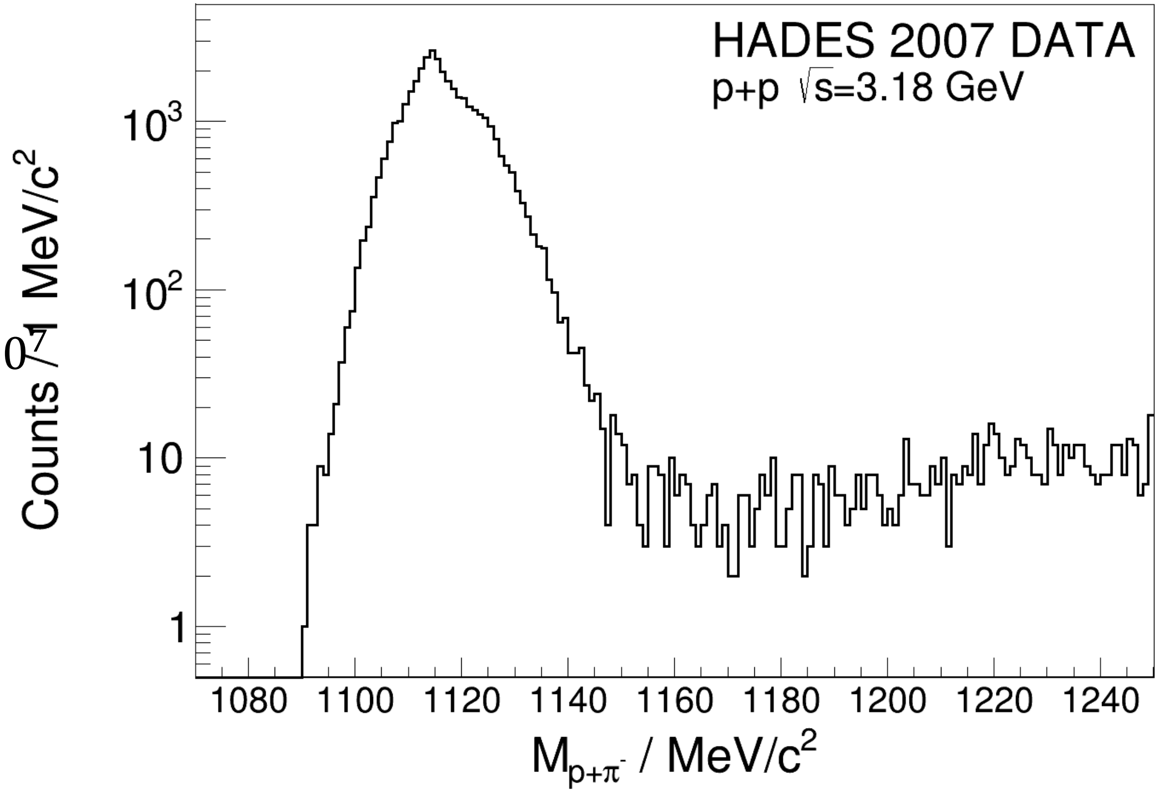
Mass histograms after fit with different conditions



Final Mass



$\cdot 10^7$



Mass mainly chosen around nominal Λ mass
(Should add cut to remove contribution from kapton windows)

Summary

- An analysis method based on kinematic fitting has been developed for neutral hyperons or relatively long-lived particles
- Yields high efficiencies after final selection
- Excellent combinatorial background suppression –chooses correct proton in correct vertex
- The fitting works for the old experimental data

Outlook

- Add background to simulation
    - Do in older HYDRA version with similar detector setup and target geometry as that for the data taking
- Calculate signal over background ratios
- In data: apply cut to remove contribution from kapton windows
- Can expand analysis procedure to work inclusively at the calculation of the primary vertex

Summary

- An analysis method based on kinematic fitting has been developed for neutral hyperons or relatively long-lived particles
- Yields high efficiencies after final selection
- Excellent combinatorial background suppression –chooses correct proton in correct vertex
- The fitting works for the old experimental data

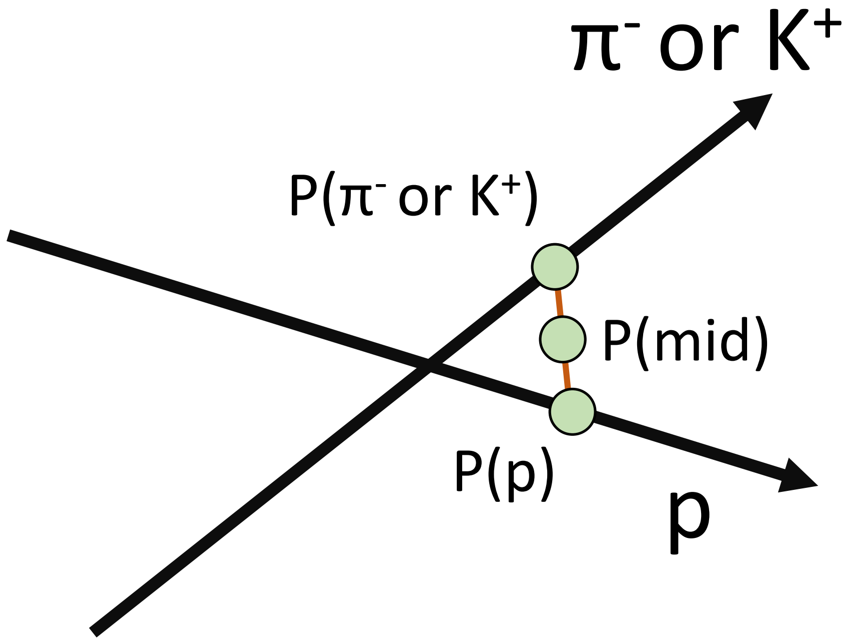
Thank you for your attention!
Questions?

Vertex Estimation

- Done for both primary vertex and decay vertex
- Calculate P(mid) = 1/2 (P(π^- or K^+) - P(p))
- Take P(mid) as estimated vertex

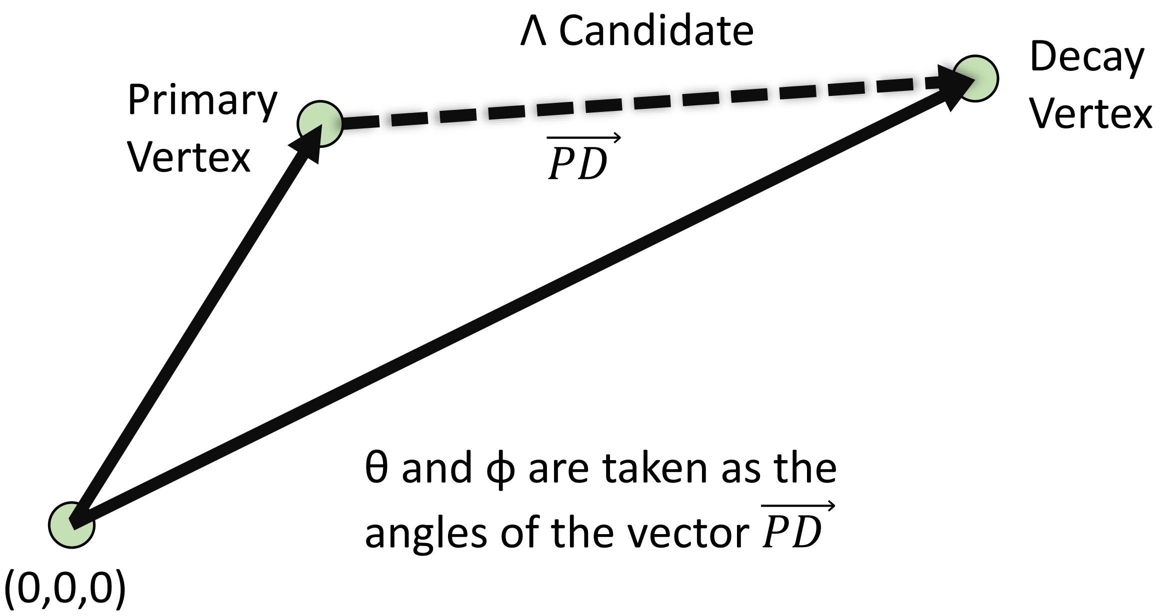
Class from HYDRA (HADES Framework): HGeomVertexFit.C

- Uses a least square fit to find the vertex as the midpoint between a set of tracks
- Used in current analysis with two tracks



Building the Neutral Mother Candidate

1. Calculate the angles and errors



θ and ϕ are taken as the angles of the vector $\overrightarrow{PD}$

Errors in θ and ϕ:
Take the vertex resolutions in each direction (x,y,z) as the errors (slide 11)
Propagate to θ and ϕ (see backup slides)

2. Calculate the initial momentum

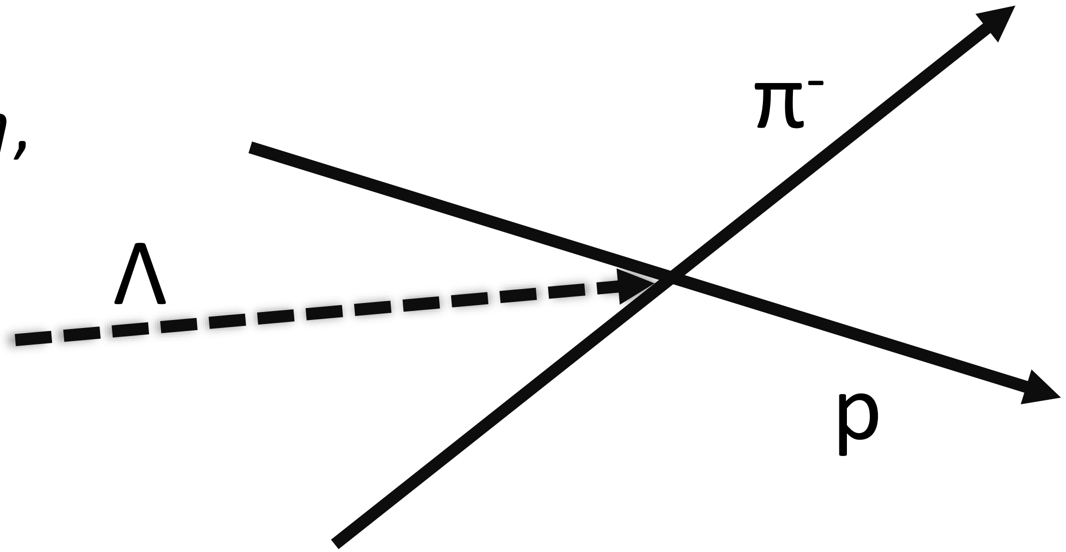
Initial Λ momentum estimate

$$p_\Lambda = \sqrt{E_p^2 + 2E_pE_{\pi^-} + E_{\pi^-}^2 - m_\Lambda^2}$$

$$E = \sqrt{m^2 + p^2}$$ ← For both proton and pion

4 Momentum Conservation In Decay Vertex

Iterative fitting procedure based on Lagrange multipliers (see backup for equations)



Constraint Eqs. f, with measured, η, and unmeasured, ξ , quantities:

$$f_K\ (\eta_1, \eta_2, \dots, \eta_N, \xi_1, \xi_2, \dots, \xi_J) = 0$$

where

$$\vec{\eta} = (P_{\pi^-}, \theta_{\pi^-}, \varphi_{\pi^-}, P_p, \theta_p, \varphi_p, \theta_\Lambda, \varphi_\Lambda)$$

$\vec{\xi} = (P_\Lambda)$ $\quad P_\Lambda$ - need start value for iterations

$\theta_\Lambda = \arccos\left(\frac{z}{r}\right)$

$\varphi_\Lambda = \arctan\left(\frac{y}{x}\right)$

where

$r = \sqrt{(x^2 + y^2 + z^2)}$

x,y,z – coordinates of calculated Λ vector

3C fit constraints:

$$f_1 = -p_\Lambda sin\theta_\Lambda cos\varphi_\Lambda + p_{\pi^-} sin\theta_{\pi^-} cos\varphi_{\pi^-} + p_p sin\theta_p cos\varphi_p = 0 \quad (p_x)$$

$$f_2 = -p_\Lambda sin\theta_\Lambda sin\varphi_\Lambda + p_{\pi^-} sin\theta_{\pi^-} sin\varphi_{\pi^-} + p_p sin\theta_p sin\varphi_p = 0 \quad (p_y)$$

$$f_3 = -p_\Lambda cos\theta_\Lambda + p_{\pi^-} cos\theta_{\pi^-} + p_p cos\theta_p = 0 \quad (p_z)$$

$$f_4 = -\sqrt{p_\Lambda^2 + m_\Lambda^2} + \sqrt{p_{\pi^-}^2 + m_{\pi^-}^2} + \sqrt{p_p^2 + m_p^2} = 0 \quad (E).$$

Vertex Constraint in Fitting Procedure

Iterative fitting procedure based on Lagrange multipliers (see backup for equations)

Track Representation

$$\left(\frac{1}{p}, \theta, \varphi, R, Z\right)$$

p – particle momentum
θ – polar angle
ϕ – azimuthal angle
R- closest **distance** of track to beam line
Z- closest **point** along beamline

Vertex Constraint, 1C fit

$$d = (d_1 \times d_2) \cdot (b_1 - b_2)$$

Equivalent to minimizing the distance between two lines

Direction Vector

$$\begin{cases} d_x = \sin(\theta) \cdot \cos(\varphi) \\ d_y = \sin(\theta) \cdot \sin(\varphi) \\ d_z = \cos(\theta) \end{cases}$$

Base Vector

$$\begin{cases} b_x = R \cdot \cos\left(\varphi + \frac{\pi}{2}\right) \\ b_y = R \cdot \sin\left(\varphi + \frac{\pi}{2}\right) \\ b_z = z \end{cases}$$

Fitting Procedure

Equations

$$f_K(\eta_1, \eta_2, \dots, \eta_N, \xi_1, \xi_2, \dots, \xi_J) = 0$$

$$\chi^2 = (y - \eta)^T V^{-1}(y - \eta) = minimum$$

$$f(\eta, \xi) = 0$$

$$\chi^2 = (y - \eta)^T V^{-1}(y - \eta) + 2\lambda^T f(\eta, \xi) = minimum$$

f- constraint function
η – set of measured quantities
ξ – set of unmeasured quantities
λ – Lagrange multipliers

Finding parameters that minimize the equations

$$\nabla_\eta \chi^2 = -2V^{-1}(y - \eta) + 2\, F_\eta^T \lambda = 0$$

$$\nabla_\xi \chi^2 = 2F_\xi^T \lambda = 0$$

$$\nabla_\lambda \chi^2 = 2\, f(\eta, \xi) = 0$$

$$(F_\eta)_{ki} = \frac{\partial f_k}{\partial \eta_i} \qquad (F_\xi)_{kj} = \frac{\partial f_k}{\partial \xi_j}$$

Fitting Procedure

Solution can be found iteratively

1. $\xi^{\nu+1} = \xi^{\nu} - lr(F_{\xi}^{T} S^{-1} F_{\xi})^{-1} F_{\xi}^{T} S^{-1} \mathrm{r}$

2. $\lambda^{\nu+1} = S^{-1}[\mathrm{r} + F_{\xi}(\xi^{\nu+1} - \xi^{\nu})]$

3. $\eta^{\nu+1} = y - lrVF_{\lambda}^{T}\lambda^{\nu+1}$

4. $V^{\nu+1} = V^{\nu} - lrV^{\nu}[F_{\eta}^{T} S^{-1} F_{\eta} - ((F_{\eta}^{T} S^{-1} F_{\xi})(F_{\xi}^{T} S^{-1} F_{\xi})^{-1}(F_{\eta}^{T} S^{-1} F_{\xi})^{T})]\, V^{\nu}$

where

$r = f^{\nu} + F_{\eta}^{\nu}(y - \eta^{\nu})$ $\qquad S = F_{\eta}^{\nu} V^{-1} (F_{\eta}^{T})^{\nu}$

lr – parameter between 0 and 1

Reconstructed Λ Parameters