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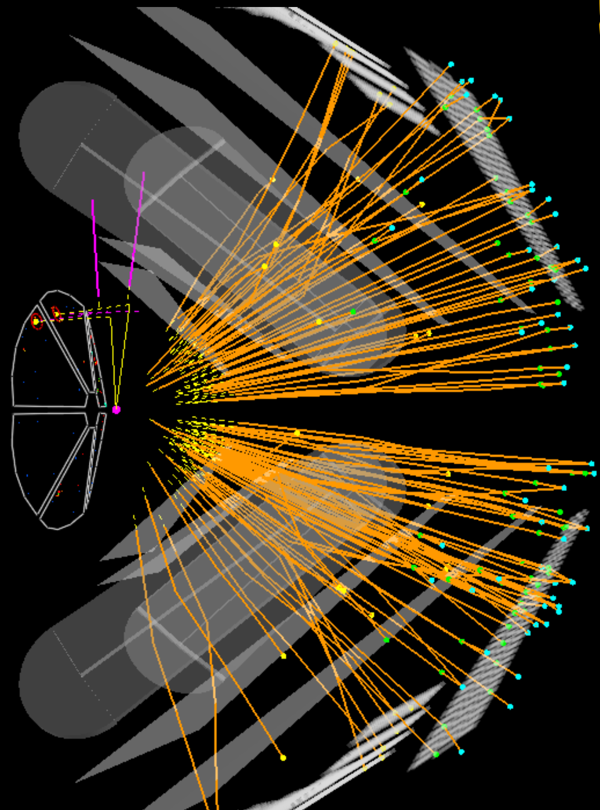
Λ Polarization in Au+Au collisions at $\sqrt{s_{NN}} = 2.4\ GeV$ Measured With HADES



Frederic Kornas
for the HADES collaboration

11.06.2019

Strange Quark Matter 2019

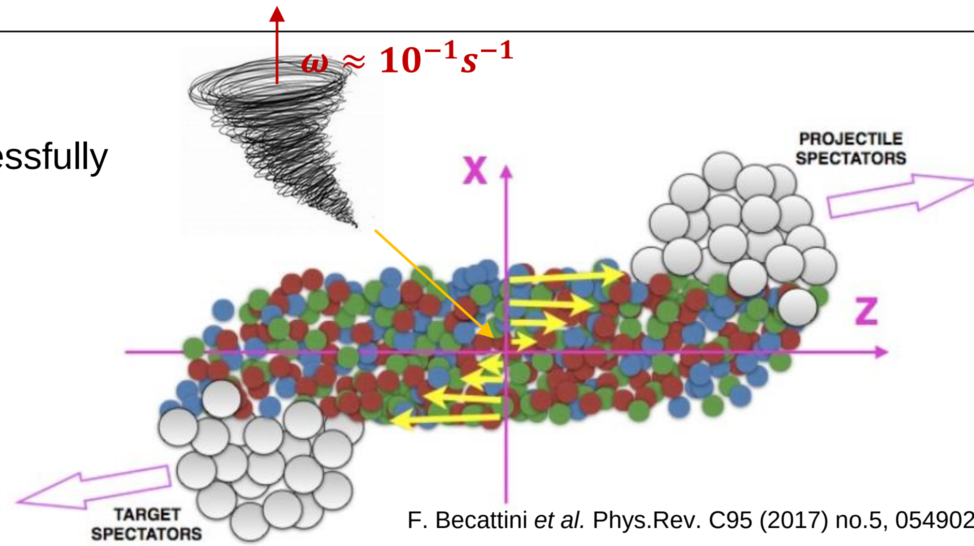
Polarization measurement

Global Polarization Measurement:

- System created in high-energy HICs successfully described by relativistic hydrodynamics.
- In peripheral collisions: $|L| \sim 10^5 \hbar$
- What is the effect on fluid/transport?

Vorticity: $\vec{\omega} = \frac{1}{2} \vec{\nabla} \times \vec{v}$

- Vorticity could be very high $\omega \approx 10^{21} s^{-1}$



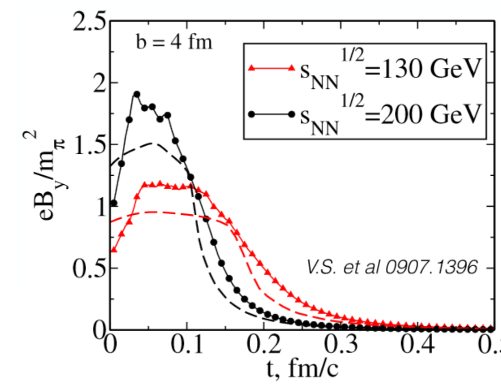
F. Becattini *et al.* Phys.Rev. C95 (2017) no.5, 054902

How to measure the vorticity?

- **Large orbital momentum ⇒ Polarization of the particle spins**

⟶Two contributions:

1. Spin-orbit coupling (same for q and $\bar{q}$)
2. Electromagnetic coupling (opposite for for q and $\bar{q}$)



Magnetic field effect on photon production, V.Skokov, Western Michigan University,2014

Polarization measurement

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STAR Collaboration (Abelev *et al.*) Phys.Rev. C76 (2007) 024915, Erratum: Phys.Rev. C95 (2017) no.3, 039906

How to measure the particle spin?

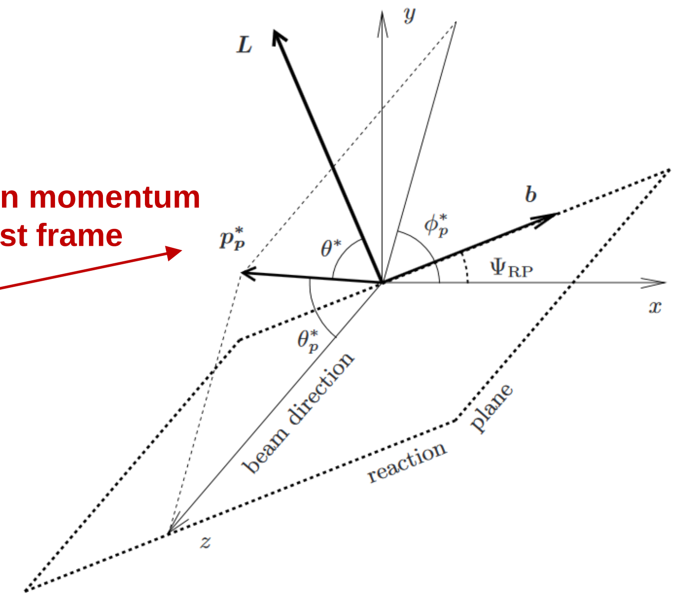
- Spin measurement for most of the hadrons very difficult

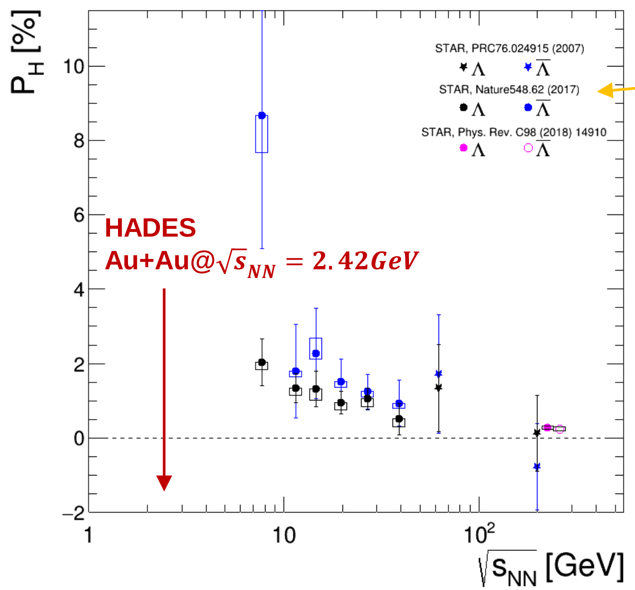
  $\longrightarrow$ Concentrate on **self-analyzing weak decays**
- Good candidate:

$$\Lambda \rightarrow p + \pi^-$$

- ***Proton is predominantly emitted in spin direction!***
- ***Spin measurement $\longrightarrow$ Momentum measurement***

Proton momentum in the Λ rest frame





All Au+Au

Polarization can be measured:

$$P_\Lambda = \frac{8}{\pi\alpha_\Lambda}\frac{\langle sin(\Psi_{EP} - \phi_p^*)\rangle}{R_{EP}}$$

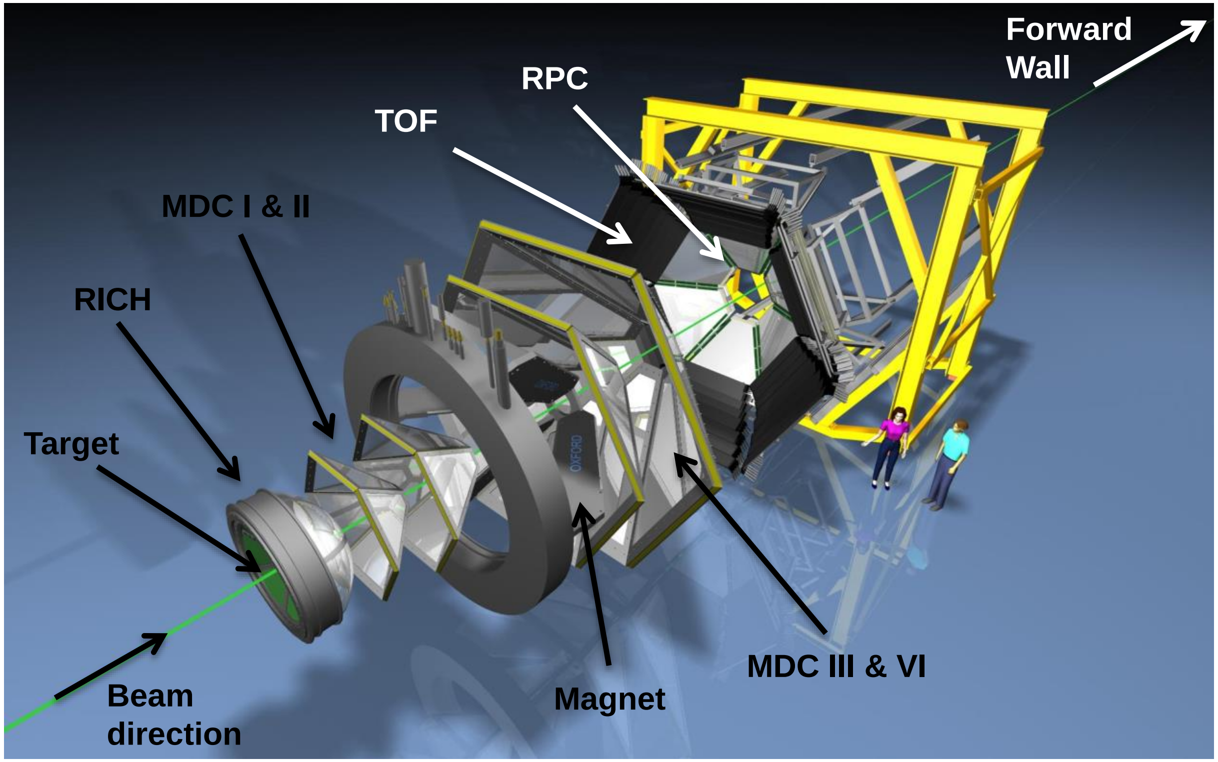
- Decay parameter $\alpha_\Lambda = 0.642 \pm 0.013$
- Orientation with respect to the event plane Ψ_{EP}
- Azimuthal angle of the proton in the Λ frame ϕ_p^*

High Acceptance DiElectron Spectrometer

Fixed-target experiment

Fast detector: $8kHz$ trigger rate for Au+Au

High acceptance: full azimuthal coverage, $18 - 85°$ polar angle



High Acceptance DiElectron Spectrometer

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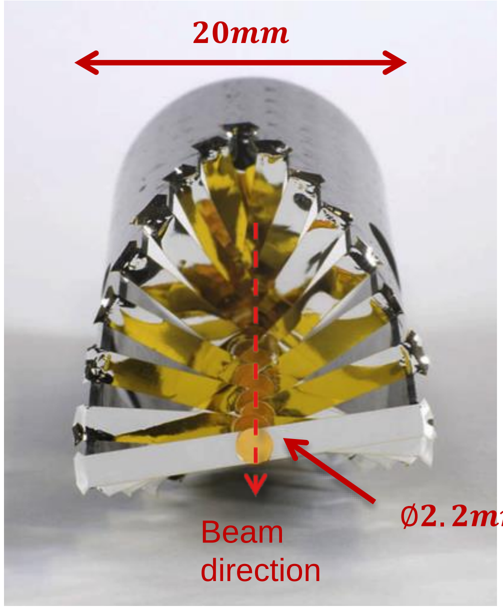


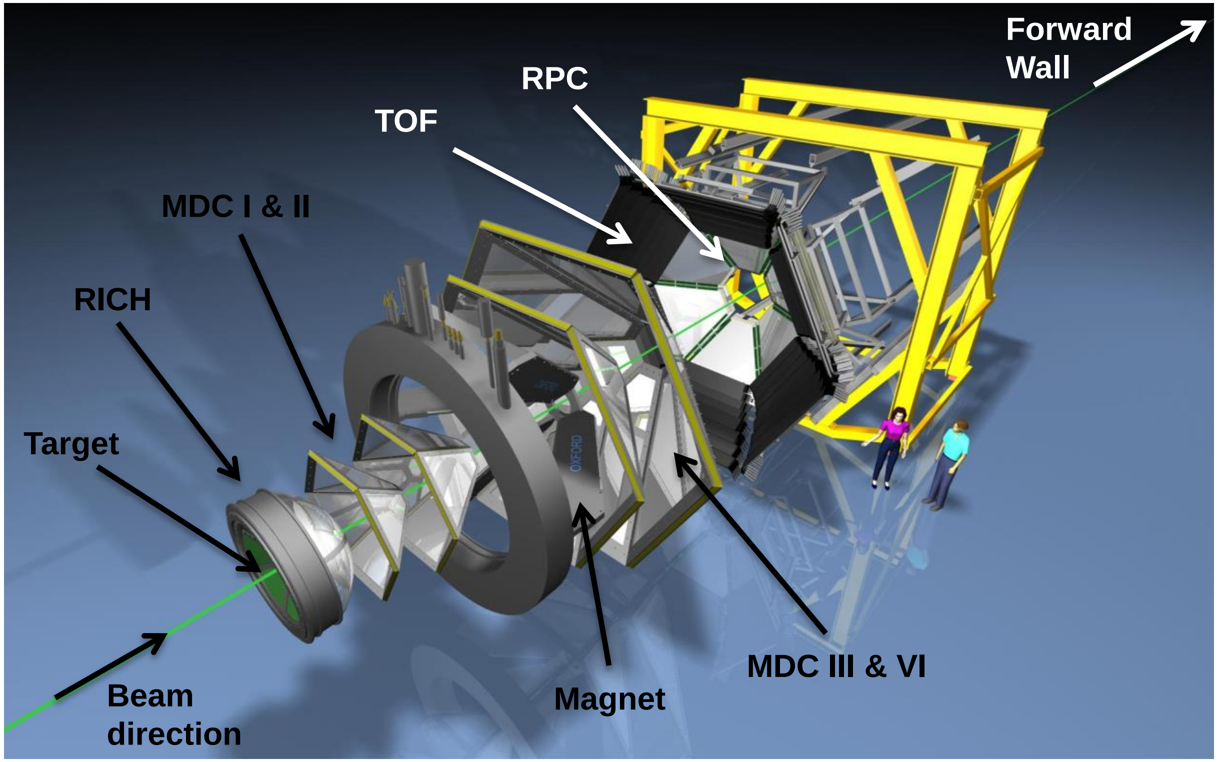
Au+Au run at $\sqrt{s_{NN}} = 2.4GeV$

- Overall: $\mathbf{2.4 \cdot 10^9}$ events analyzed

Fixed-target experiment

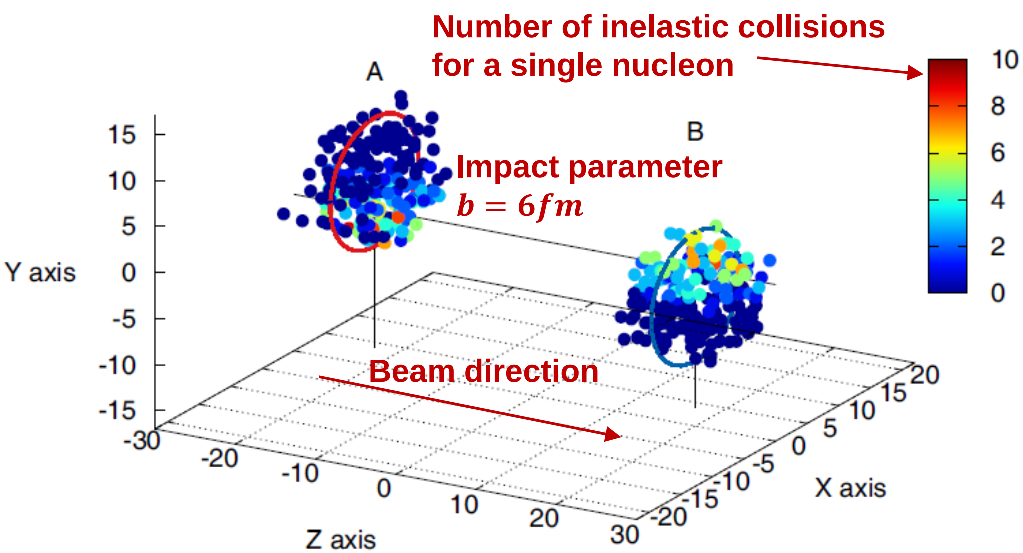
Fast detector: $8kHz$ trigger rate for Au+Au

High acceptance: full azimuthal coverage, $18 - 85°$ polar angle

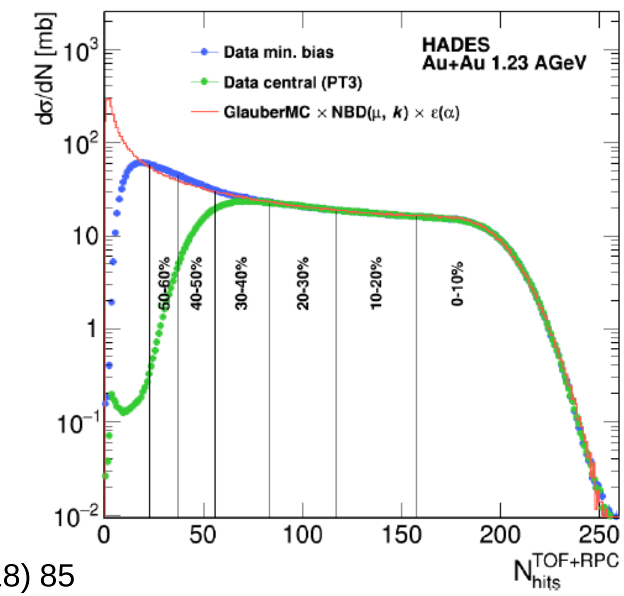


Centrality Estimation

Offline centrality selection based on hit or track multiplicity



- Task: relate observable quantities to the centrality of the collision
- Assumption: $\langle N_{participant} \rangle \sim \langle N_{produced} \rangle$

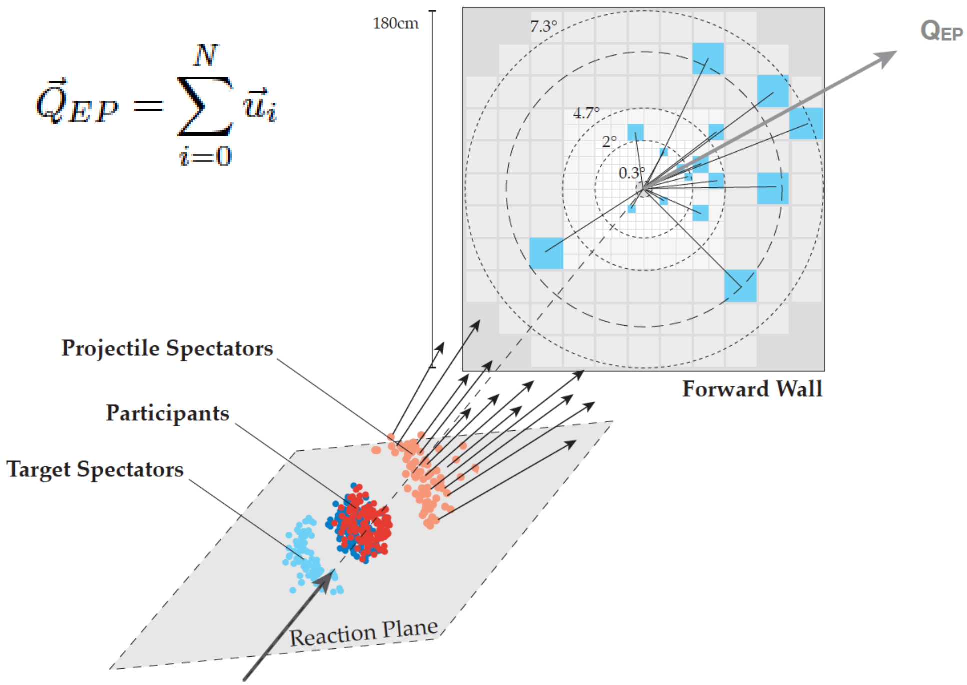


- Centrality determination using Glauber
- Distributions agree with transport model calculations (*processed by GEANT*)

For more Details see:
Eur. Phys. J. A54 (2018) 85

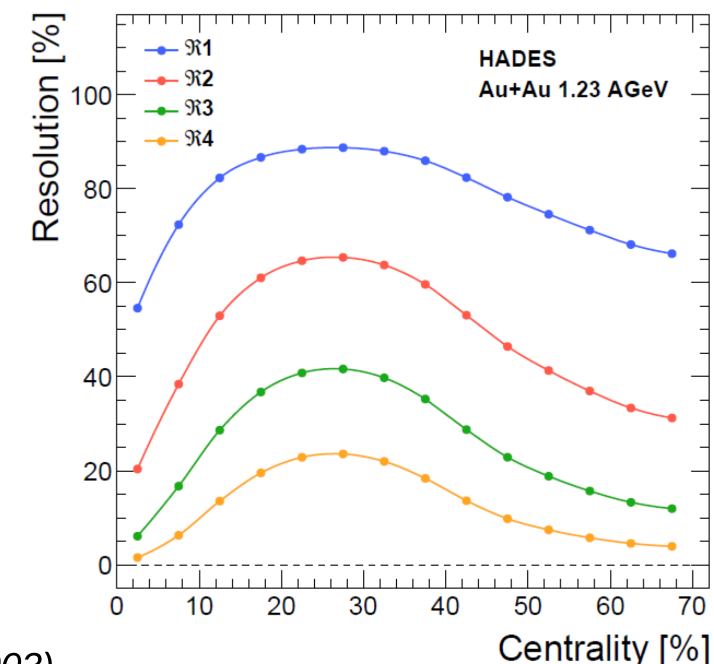
Event Plane Reconstruction

$$\vec{Q}_{EP} = \sum_{i=0}^{N} \vec{u}_i$$



Event Plane Reconstruction:

- Based on hits of charged projectile spectators in the Forward Wall



Event Plane Resolution:

- Determination of Full Resolution from Sub-Event Resolution *(distribution randomly divided into 2 sub-samples)*
- *Based on method by J.-Y. Ollitrault (arXiv:nucl-ex/9711003)*

Analysis procedure

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$$P_\Lambda(\textit{centrality}) = \frac{8}{\pi\alpha_\Lambda}\frac{\langle \sin(\Psi_{EP} - \phi_p^*)\rangle}{R_{EP}}$$

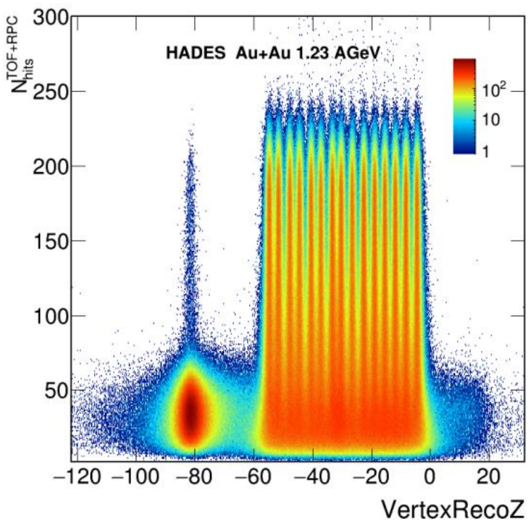
ϕ_p^*: Azimuthal angle of the proton in the Λ rest frame

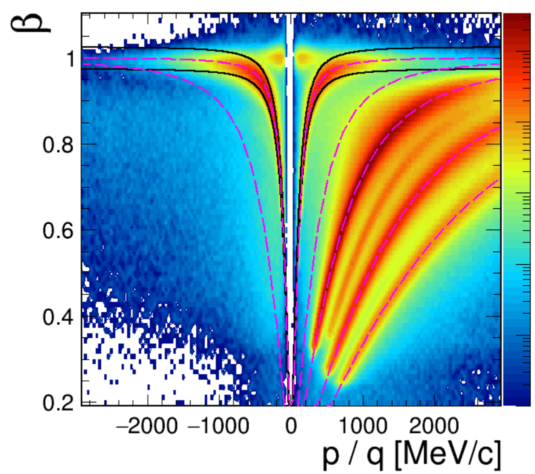
⇒ Particle identification

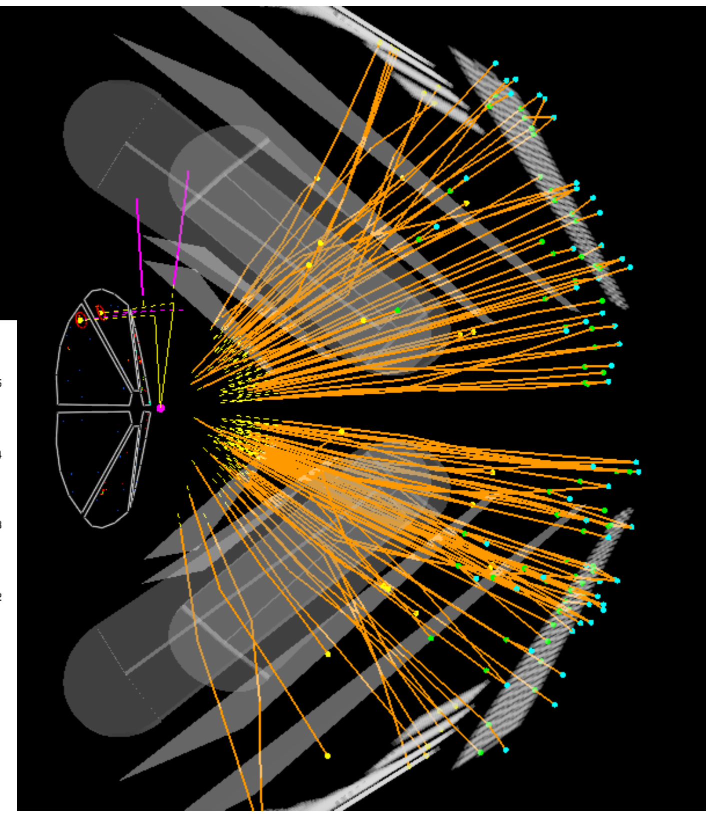
$$\beta = \frac{p}{m}\frac{1}{\sqrt{\left(\frac{p}{m}\right)^2 + 1}}$$

Observables:

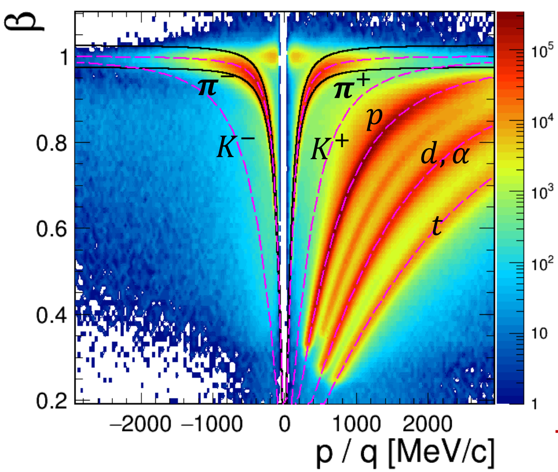
- Velocity
- Momentum
- Energy Loss
- RICH information



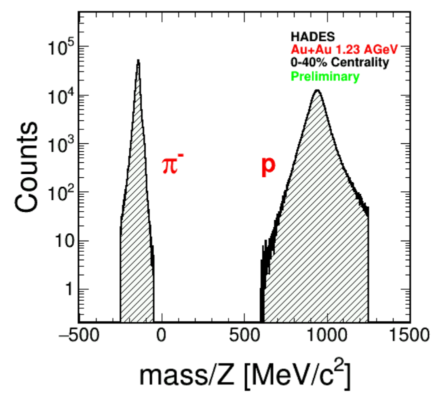


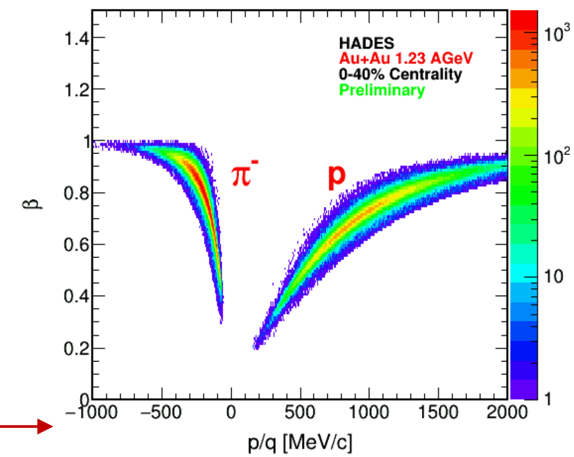


Particle Identification



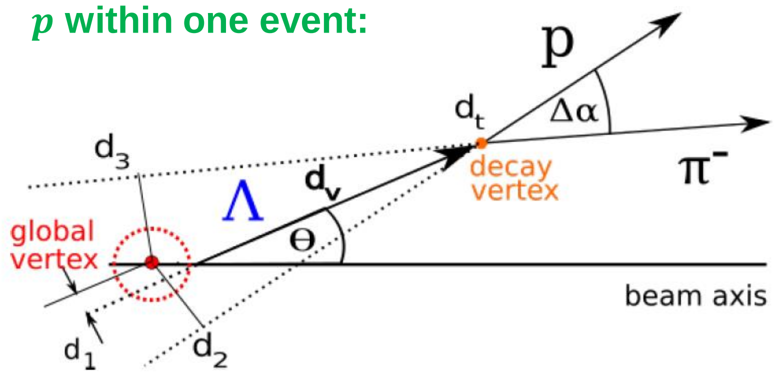
Loose Mass Cut





Create all possible combinations of π^- and p within one event:

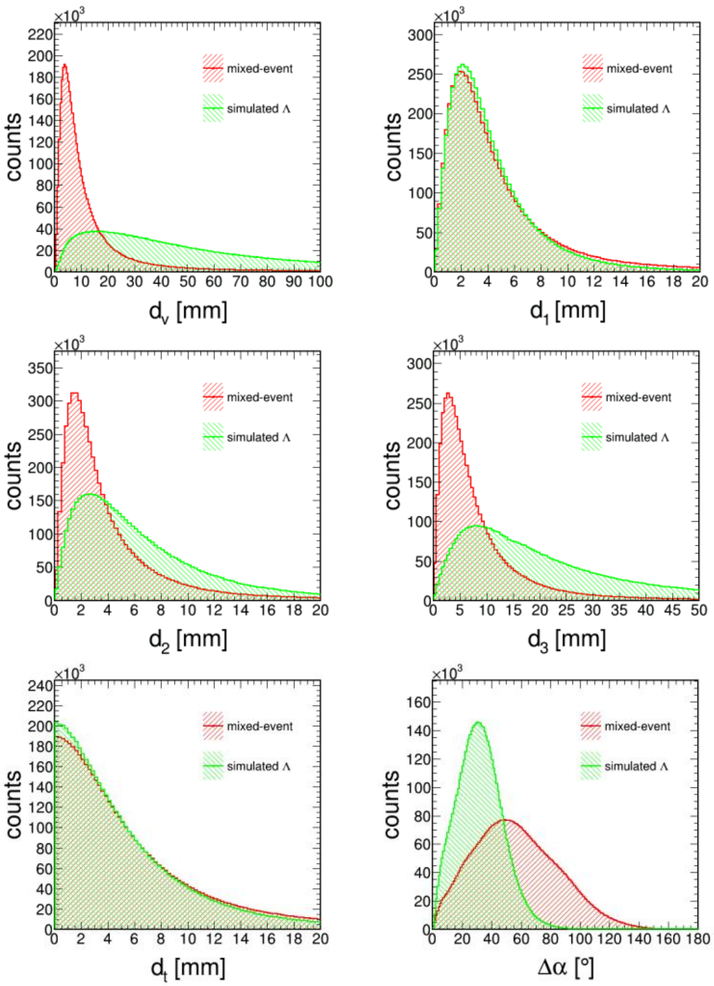
Decay channel:
$\Lambda \rightarrow p + \pi^-$



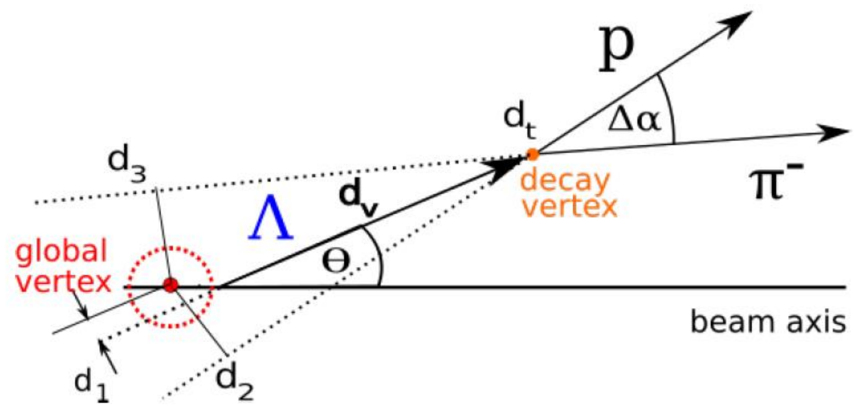
Decay topology

- d_1: Λ has to come from the primary vertex
- d_2, d_3: p and π^- are most likely not pointing to the global vertex
- d_t: common crossing point for p and π^- track
- d_v: Λ distance before it decays ($c\tau \sim 8cm$)
- $\Delta\alpha$: Opening angle, added to account for efficiency loss of closed pairs

Decay Topology



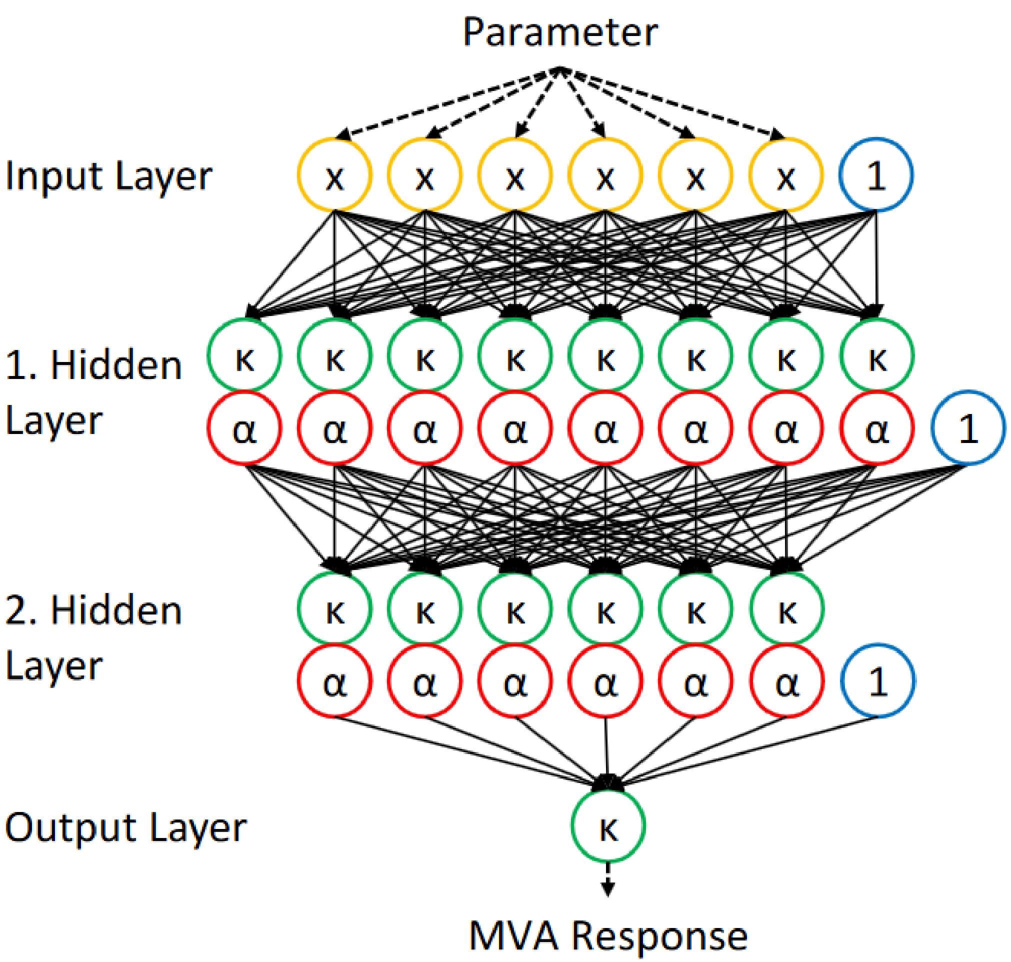
- **Simulations: Thermal Λs embedded into real data (1Λ per event)**
- **Mixed-event method on real data to describe the background**



- **Enough statistics very crucial for the polarization analysis (Hard-cut analysis removes a lot of the signal)**
- **Employ neural network in order to gain more statistics!**

Neural Network Analysis

Toolkit for Multivariate Data Analysis (TMVA) included in ROOT (https://root.cern.ch/tmva)



Input

Signal:
Thermal Λs embedded into real data

Background:
Mixed-Event –
π^- from one event and p from another event

Input Parameters

Topological parameters: d_v, d_1, d_2, d_3, d_t

In addition: m_π, m_p, p_Λ ⟵ significant increase of the efficiency

Training

Convergence of the weights for maximal descrimination between signal and background!

Required output

Signal: $D_{ideal}=1$ ⟷ **Background:** $D_{ideal}=0$

Actual Output: $0 < D_{real} < 1$

Neural Network Analysis

Toolkit for Multivariate Data Analysis (TMVA) included in ROOT (https://root.cern.ch/tmva)

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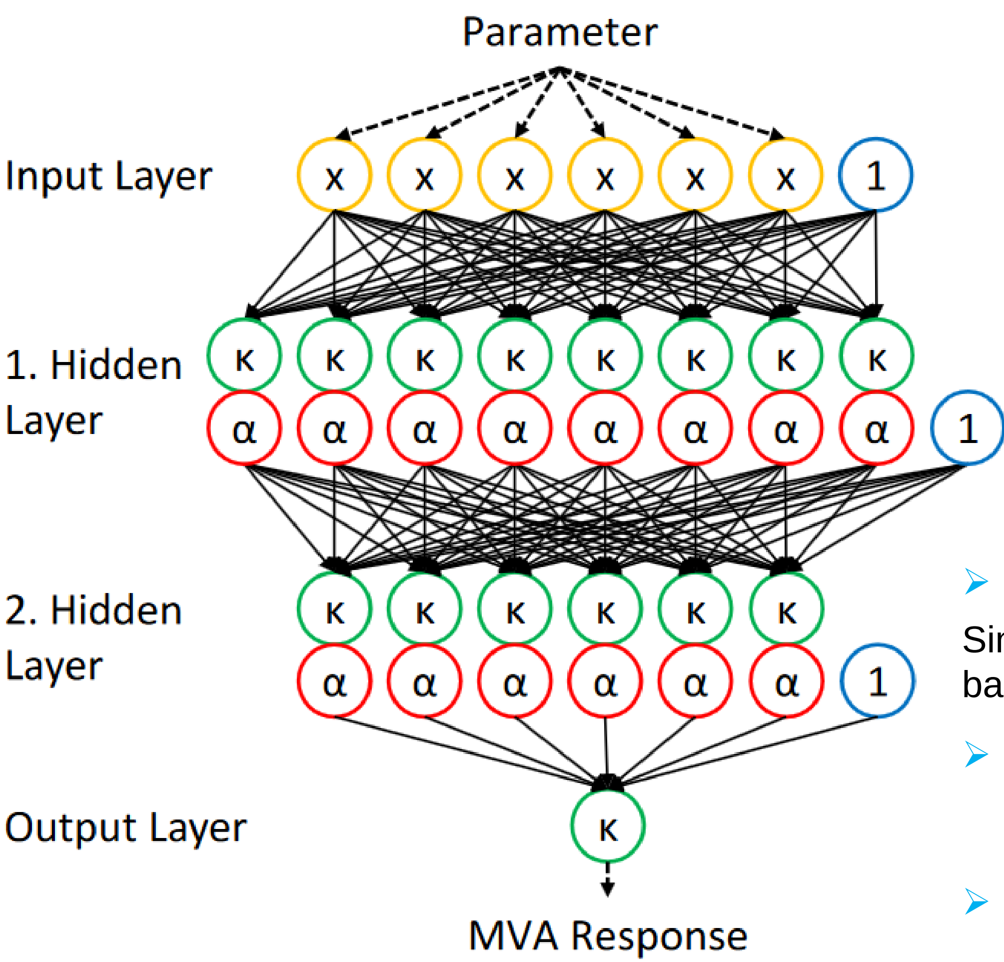
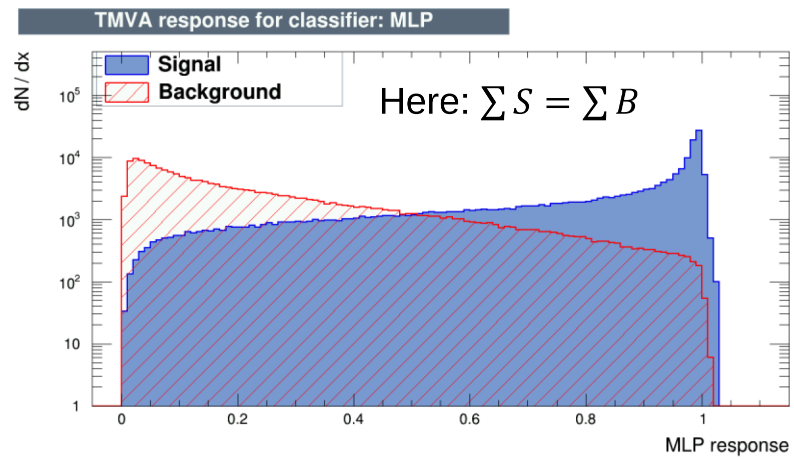


MVA Response



- **Clear discrimination of signal and background**:

Simulated Λs peak at D=1 while mixed-event background peaks at D=0 as expected

- In real data (same event) the signal fraction is much lower:

$$\sum S \ll \sum B$$

- Vary D to find the ideal cut value (i.e. with maximum significance) $\boldsymbol{D_{min} = 0.9}$

Invariant mass distribution

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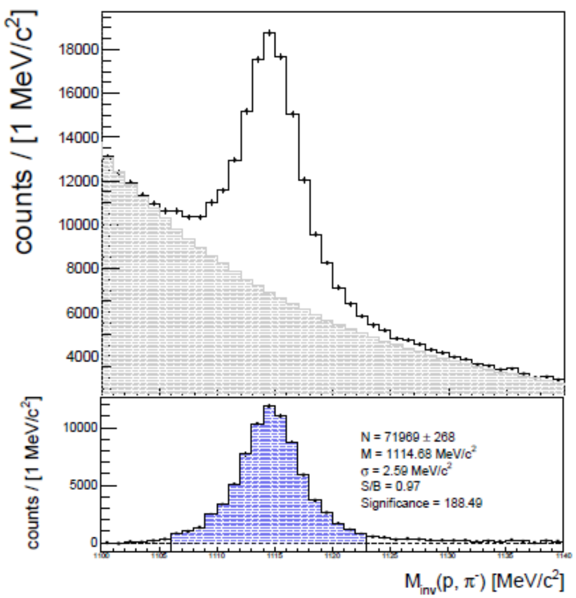
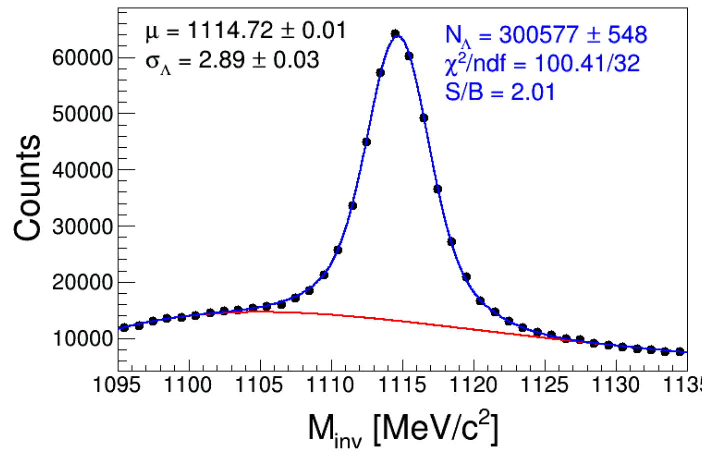
„Hard cut“ analysis:



This analysis

0-40% centrality



Topology Parameter	Cut Style	Hard Cut	Pre-Cut
$d_1\ [mm]$	$<$	5	12
$d_2\ [mm]$	$>$	8	5
$d_3\ [mm]$	$>$	24	15
$d_v\ [mm]$	$>$	65	50
$d_t\ [mm]$	$<$	6	10
$\Delta\alpha\ [°]$	$>$	15	15

$$N_\Lambda^{old} = 0.7 \cdot 10^5 \qquad \rightarrow \qquad N_\Lambda^{new} = 3.0 \cdot 10^5$$

$$SIG = 188.49 \qquad\qquad SIG = 448.02$$

- MVA strongly supresses the background
- Even with lower topological cuts, the significance is much higher
- Increase of the identified Λs by $\sim 300\%$ compared to hard-cut analysis

Polarization analysis for 10-40% centrality:

$$N_\Lambda^{10-40\%} = 1,9 \cdot 10^5$$

Λ Polarization: two approaches

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	(1) Event plane method	(2) Invariant mass fit method
General procedure	➢ Get $\mathrm{dN}/\mathrm{d}M_{inv}$ in a certain $\Delta\phi_p^*$-bin ➢ Get net amount of Λs in that bin ➢ Plot distribution of $N_\Lambda(\Delta\phi_p^*)$ ➢ Fit this distribution to get $\langle \sin(\Delta\phi_p^*) \rangle$ ➢ Calculate P_Λ	➢ Plot the distribution of $\langle sin(\Delta\phi_p^*) \rangle_{tot}$ as a function of M_{inv} ➢ Get S/B-ratio in each bin: $f(M_{inv})$ ➢ Make assumption for $\langle sin(\Delta\phi_p^*) \rangle_{BG}$ ➢ Fit the distribution to get $\langle sin(\Delta\phi_p^*) \rangle_{SG}$ ➢ Calculate P_Λ
Correction for R_{EP}	➢ Final result is corrected by $1/R_{EP}$ while $R_{EP}^{10-40\%}$ is used	➢ $1/R_{EP}^{10\%}$ in 10% centrality bins is weighted event-by-event when filling $\langle sin(\Delta\phi_p^*) \rangle_{tot}$
Advantage/ Drawback	➢ **D:** second decomposition in $\Delta\phi_p^*$-bins ➢ **A:** no background assumption	➢ **A:** direct extraction of $\langle sin(\Delta\phi_p^*) \rangle_{SG}$ ➢ **D:** background assumption needed

(1) Event plane method

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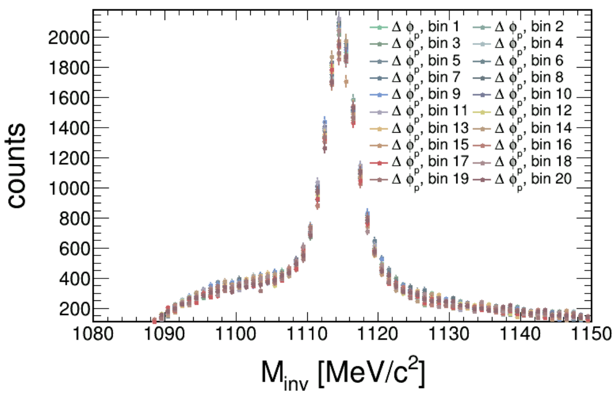


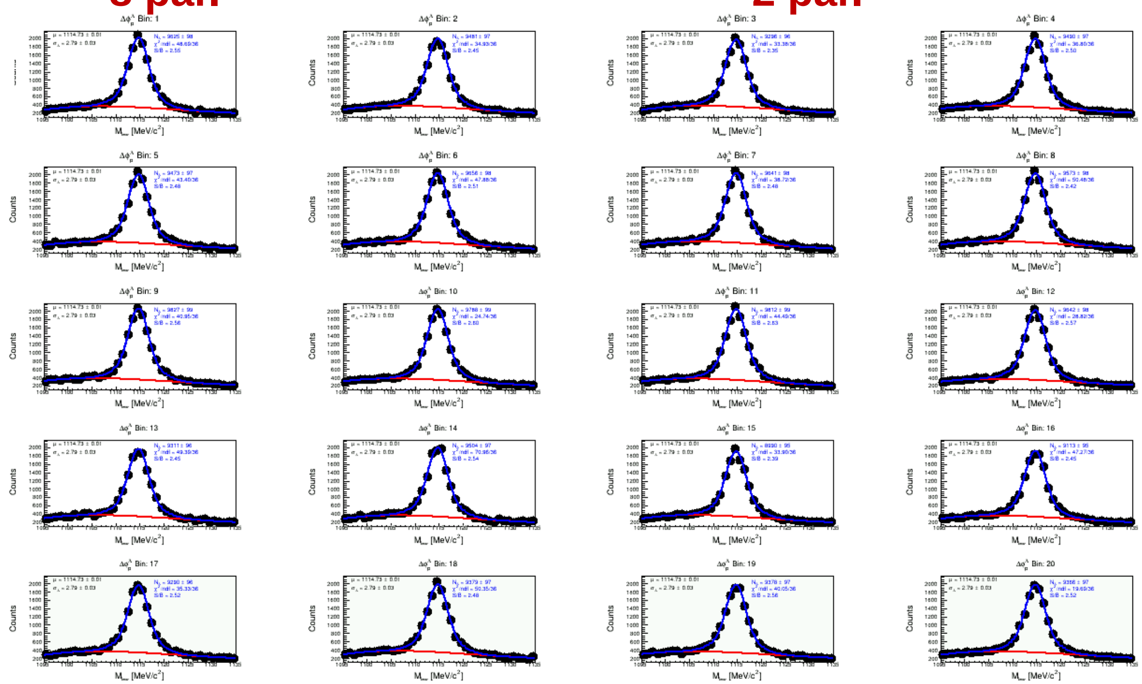
Description of the distribution: *Landau + 2 Gaussian*

$$f_{global}(M_{inv}) = \frac{C}{2\pi i}\int_{c-i\infty}^{c+i\infty} e^{s\cdot\log(s)+M_{inv}s}ds + G_1^{\mu,\sigma_1,A_1}(M_{inv}) + G_2^{\mu,\sigma_2,A_2}(M_{inv})$$

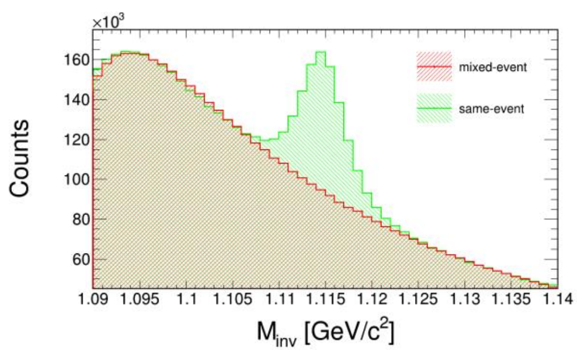
- Fix: $\mu, \sigma_1, \sigma_2, A_1/A_2$ for the Λ peak and L_1, L_2 for BG

Global fit → **Differential fit**

8 par. **2 par.**



- Also very good description by the mixed-event method

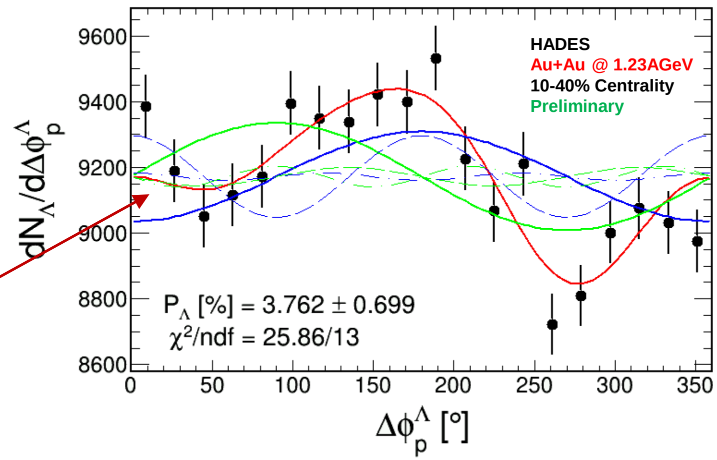


HADES

(1) Event plane method

Fit the distribution of the polarization angle $\Delta\phi_p^* = \Psi_{EP} - \phi_p^*$

- Get distribution of M_{inv} in a certain $\Delta\phi_p^*$-bin
- Get net amount of Λs in that bin
- Plot distribution of $N_\Lambda(\Delta\phi_p^*)$
- Fit this distribution to get $\langle \sin(\Delta\phi_p^*) \rangle$
- Calculate P_Λ



Green: Sin-Terms
Blue: Cos-Terms

$$\frac{dN}{d\Delta\phi_p^\Lambda} = N_0\left[1 + 2b_1 \sin(\Delta\phi_p^*) + 2c_1 \cos(\Delta\phi_p^*) + 2b_2 \sin(2\Delta\phi_p^*) + 2c_2 \cos(2\Delta\phi_p^*) + \cdots\right]$$

$$P_\Lambda = \frac{8}{\pi\alpha_\Lambda}\frac{b_1}{R_1}$$

First order event plane resolution

Parameter	Value/10^{-3}	Error/10^{-3}
N_0	9172	21
b_1	8.91	1.65
c_1	-7.45	1.66

$\Rightarrow \boldsymbol{P_\Lambda\ [\%] = 3.762 \pm 0.699\ (stat.)}$

- c_1: comparable magnitude to b_1

(2) Invariant mass fit method

Fit the distribution of $\langle sin(\Delta\phi_p^*)\rangle$

- Plot the distribution of $\langle sin(\Delta\phi_p^*)\rangle_{tot}$ as a function of M_{inv}
- Get S and B in each bin: $f(M_{inv}) = S/(S+B)$
- Make assumption for $\langle sin(\Delta\phi_p^*)\rangle_{BG}$
- Fit the distribution to get $\langle sin(\Delta\phi_p^*)\rangle_{SG}$
- Calculate P_Λ

$$\langle \sin(\Delta\phi_p^*)\rangle_{tot} = f(M_{inv})\langle \sin(\Delta\phi_p^*)\rangle_{SG} + (1 - f(M_{inv}))\langle \sin(\Delta\phi_p^*)\rangle_{BG}$$

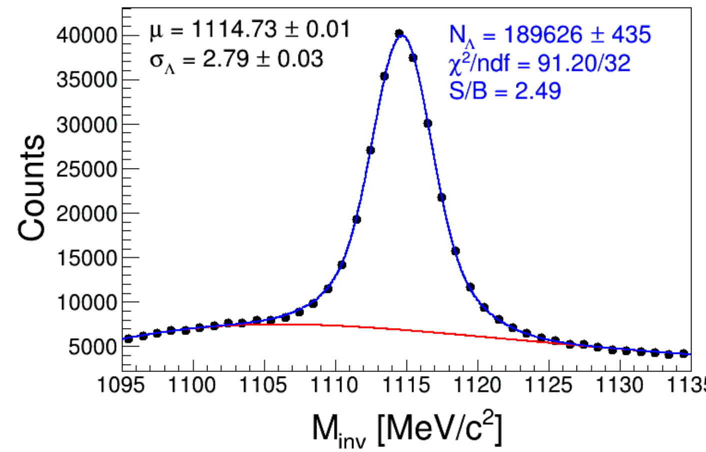
$$P_\Lambda = \frac{8}{\pi\alpha_\Lambda}\langle \sin(\Delta\phi_p^*)\rangle_{SG}$$

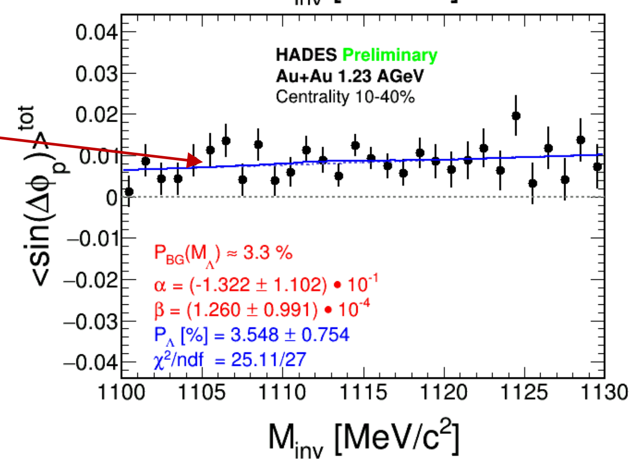
$$\langle \sin(\Delta\phi_p^*)\rangle_{BG} = \alpha + \beta \cdot M_{inv}$$

$$\Rightarrow \boldsymbol{P_\Lambda[\%] = 3.548 \pm 0.754(stat.)}$$

- **Background shows non-zero correlations with magnitude similar to the Λ signal!**

10-40% centrality





Λ Polarization: Results

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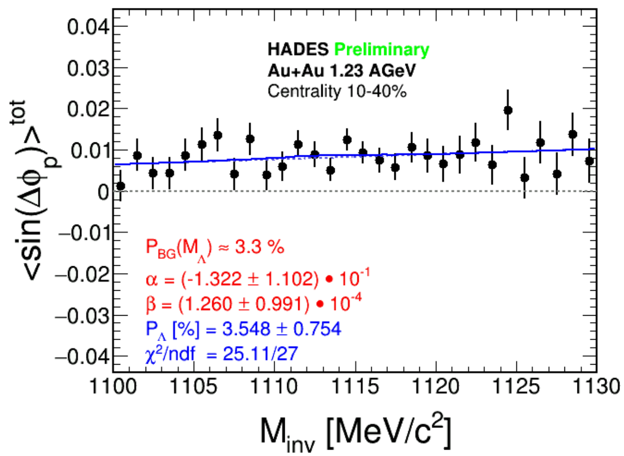
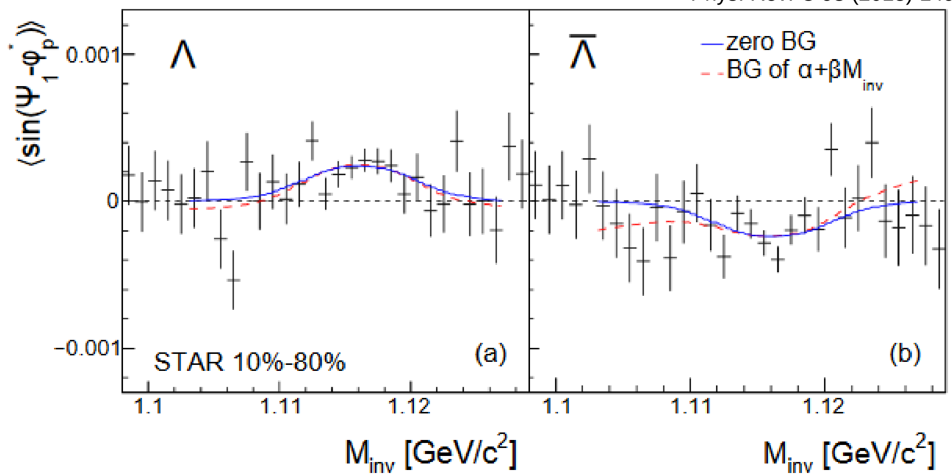
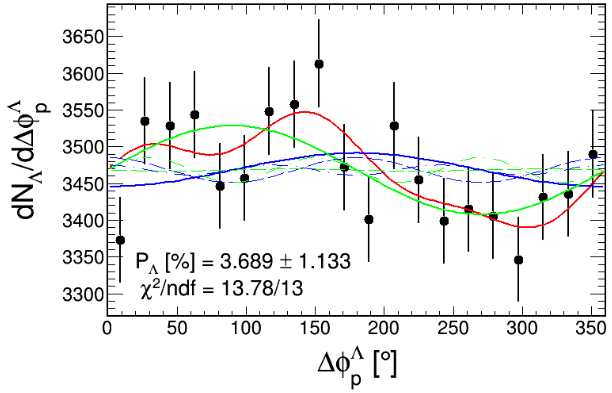


Comparison to STAR @ $\sqrt{s_{NN}} = 200GeV$:

Phys. Rev. C **98** (2018) 14910



Event Plane Method for background under the Λ peak:



- Both methods are consistent:

$$P_\Lambda^{EPM}[\%] = 3.762 \pm 0.699\ (stat.)$$
$$P_\Lambda^{IMM}[\%] = 3.548 \pm 0.754(stat.)$$

- But background correlations of the same order:

$$P_{BG}^{EPM}[\%] = 3.689 \pm 1.133(stat.)$$

- Effect not seen in the uncorrelated background (mixed-event, ϕ rotation) ⇒ correlated effect!

Summary and Outlook

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Summary:

- Neural network to improve Λ identification :

→ factor ~4 more Λs in comparison to previous analysis

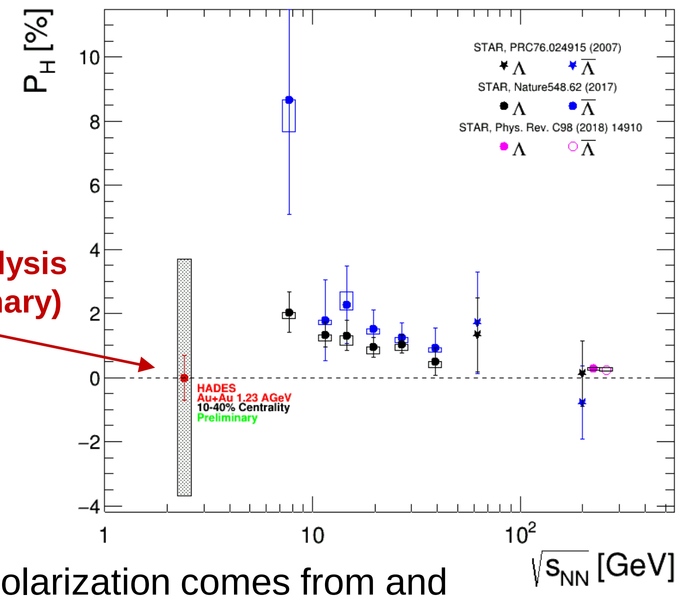
- Polarization measurement:

→ 2 different methods applied: both in consistence

- Dominant source of systematics:

→ Non-zero background correlations in the P_{Λ} signal extraction, which has similar magnitude

Results:
This analysis
(Preliminary)



Outlook:

- Estimate systematic errors: check where the background polarization comes from and apply corrections

- **How does the finite detector acceptance influences the polarization measurement?**

→ Use Pluto (Monte-Carlo simulation framework for HIC collisions and hadronic physics) to generate Λs**:**

1. Unpolarized: Guide them trough the HADES detector (GEANT) and apply analysis procedure (result $P_{\Lambda} = 0$, but without flow)
2. Different degree of polarization: Do the same procedure → What do we measure as P_{Λ}?

Ongoing!

Back Up
Neural network analysis

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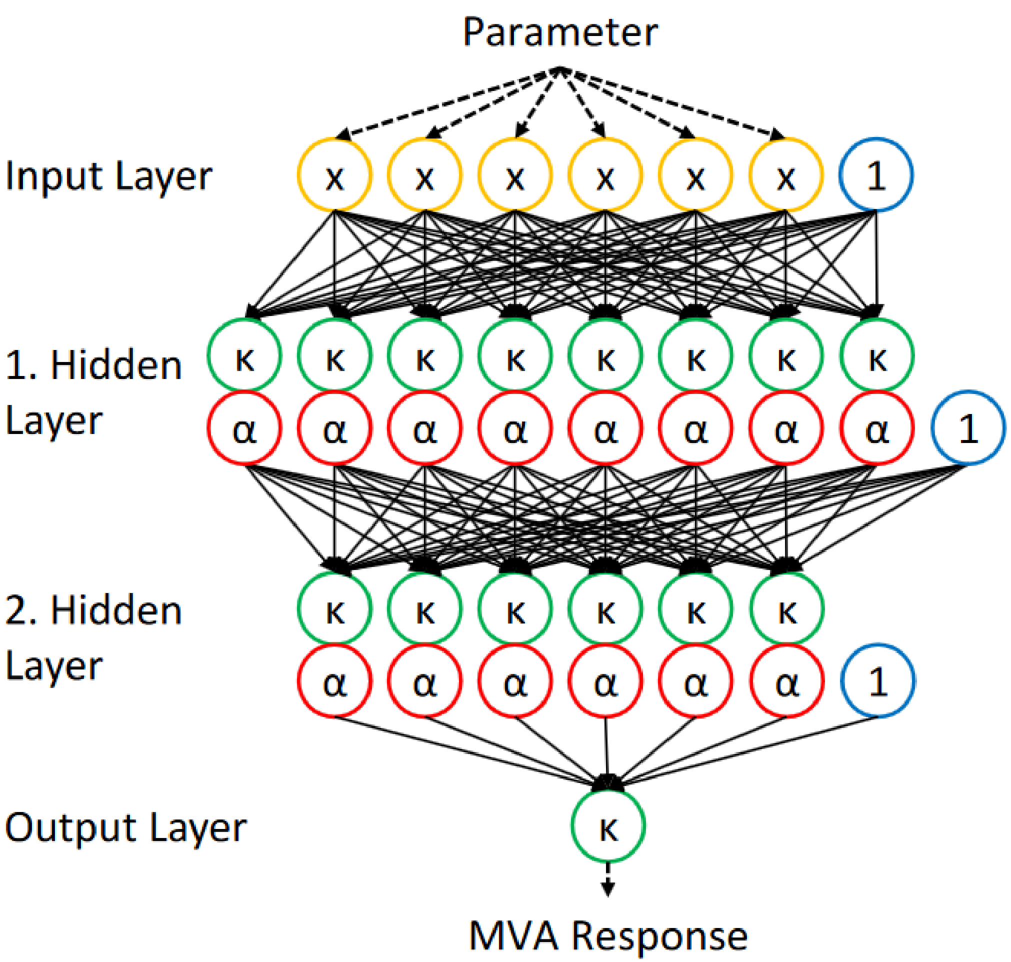


Input

Signal:
Thermal Λs embedded into real data

Background:
Mixed-Event –
π^- from one event and
p from another event

Input Parameters

Topological parameters: d_v, d_1, d_2, d_3, d_t
In addition: m_π, m_p, p_Λ ⟵ significant increase of the efficiency

Synapse

Connections between the neurons, adjusted with a weight w_{ij}^l

Hidden Layers

1. Synapse Function:

$$\kappa: \left(x_{ij}^{l-1} \middle| w_{ij}^{l-1}\right) \mapsto w_{0j}^{l-1} + \sum_{i=1}^{n} w_{ij}^{l-1} x_i^{l-1}$$

2. Neuron Activation Function:

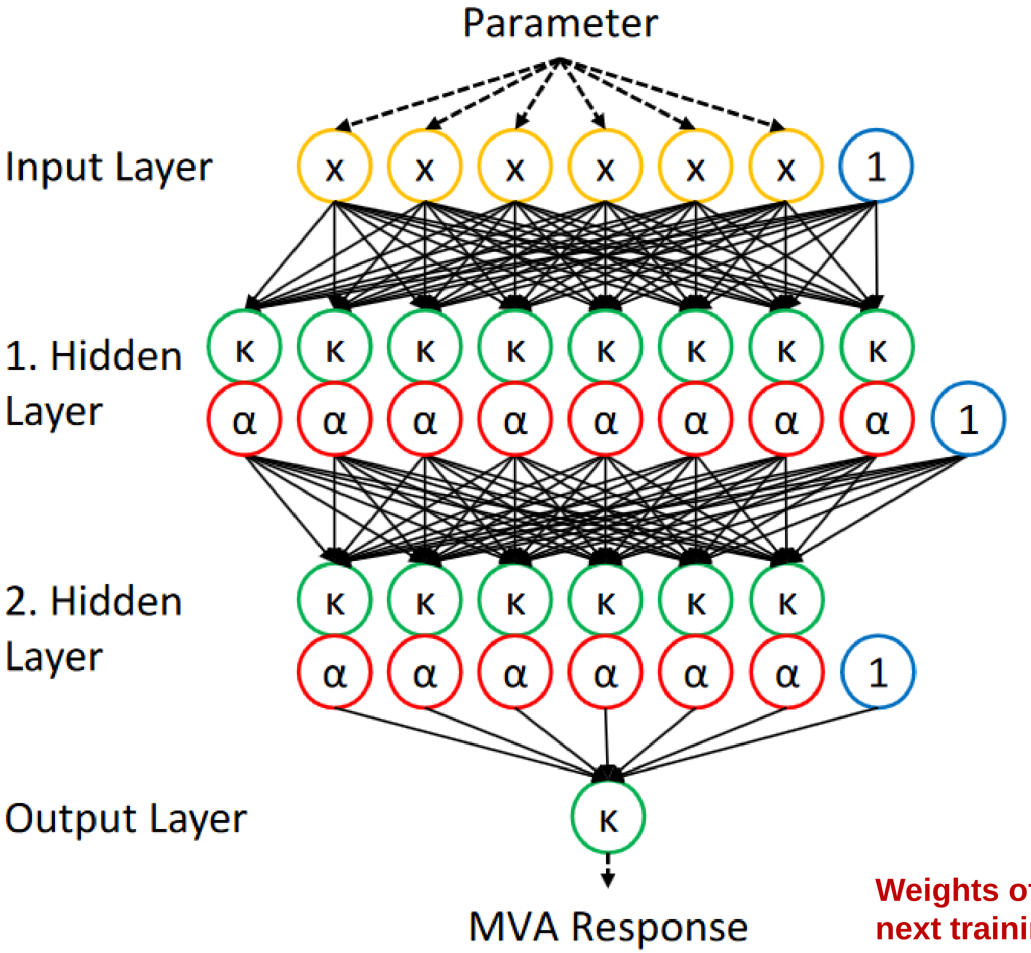
$\alpha: x \mapsto \frac{1}{1+e^{-kx}}$ **(Sigmoid)**

Output Layers

Combines the information into one discriminant D

HADES

Back Up
Neural network analysis



Input

Signal:
Thermal Λs embedded into real data

Background:
Mixed-Event –
π^- from one event and
p from another event

Training

Convergence of the weights for maximal descrimination between signal and background!

Required output

Signal: D_{ideal}=1 ⟷ **Background:** D_{ideal}=0

Actual Output: $0 < D_{real} < 1$

Adjusting the weights: Back-Propagation

Error function: $E(x_1, \dots, x_N) = \sum_{n=1}^{SG+BG} \frac{1}{2} (D_{ideal} - D_{real})^2$

Aim: Minimize the error function!

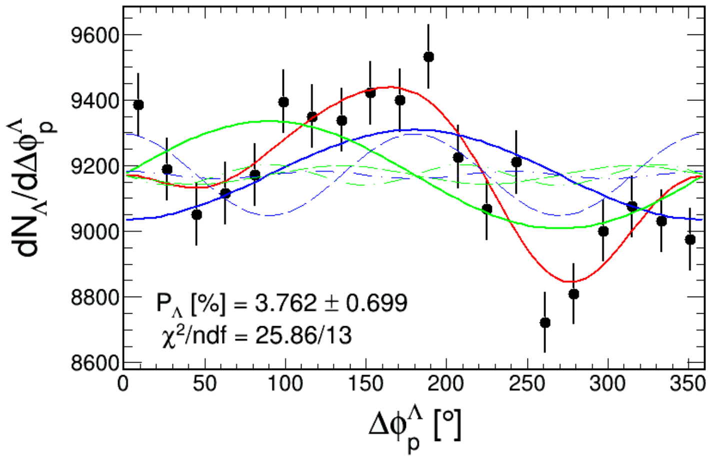
Weights are updated: $w^{k+1} = w^k - \eta \nabla_w E$

- w^{k+1}: Weights of the next training cycle
- w^k: Weights of the current training cycle
- η: Learning rate
- $\nabla_w E$: Max. gradient in w-space

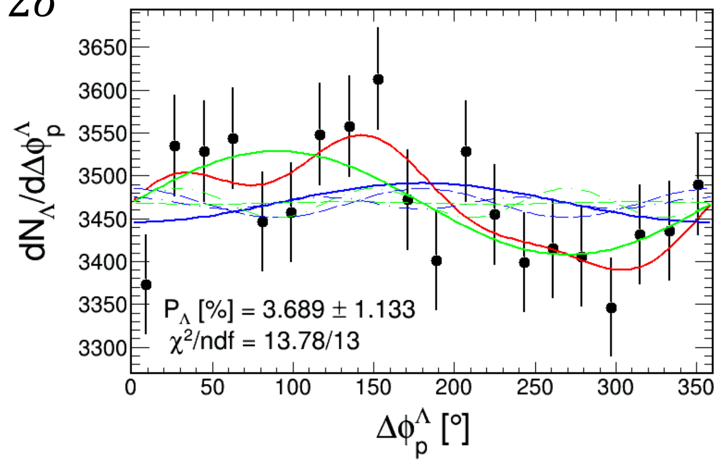
Back Up
Event Plane Method – Fit Parameter

Range: $\mu \pm 2\sigma$

Signal distribution



Background distribution

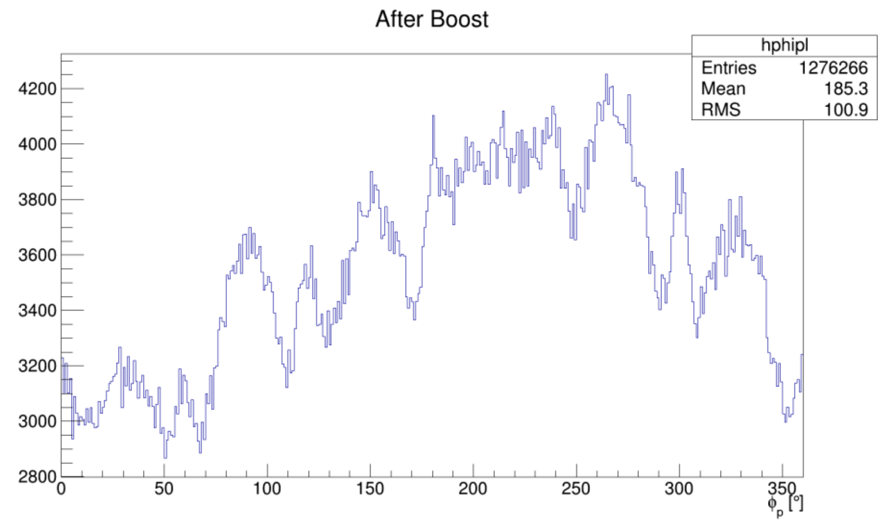


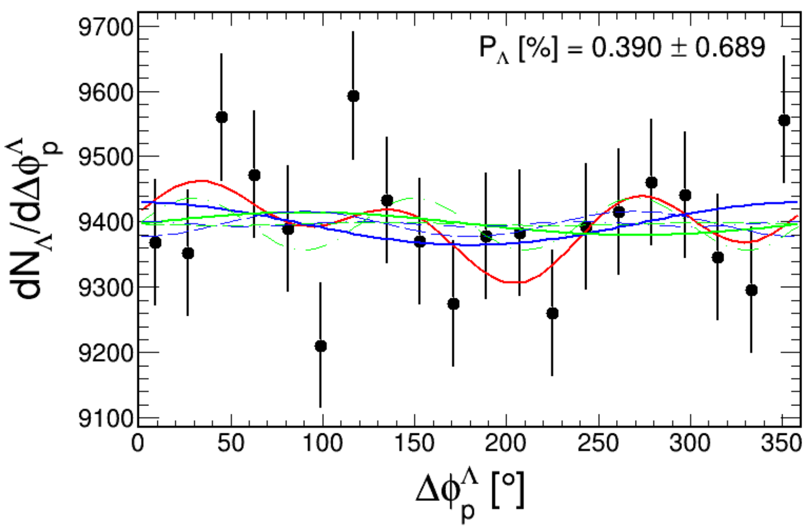
Parameter	Value/10^{-3}	Error/10^{-3}
N_0	9172	21
b_1	8.91	1.65
c_1	-7.45	1.66
b_2	-1.54	1.65
c_2	6.79	1.65
b_3	-1.71	1.65
c_3	0.60	1.65

Parameter	Value/10^{-3}	Error/10^{-3}
N_0	3468	13
b_1	8.74	2.68
c_1	-3.29	2.69
b_2	-0.20	2.69
c_2	2.42	2.68
b_3	2.43	2.69
c_3	0.97	2.68

Back Up
Phi Rotation

- Phi Rotation with probability distribution according to ϕ_p^* (right panel)
- Parameters consistent with 0!
- Background polarization must be a correlated effect





Parameter	Value/10^{-3}	Error/10^{-3}
N_0	9397	22
b_1	0.92	1.63
c_1	1.74	1.63
b_2	-0.12	1.63
c_2	-1.03	1.63
b_3	2.12	1.63
c_3	0.20	1.63