CBM performance for the measurement of strange hyperons' anisotropic flow in Au+Au collisions at FAIR SIS-100 energies

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FAIRness 2022 workshop, Pieria
May 25, 2022

GSI

CBM

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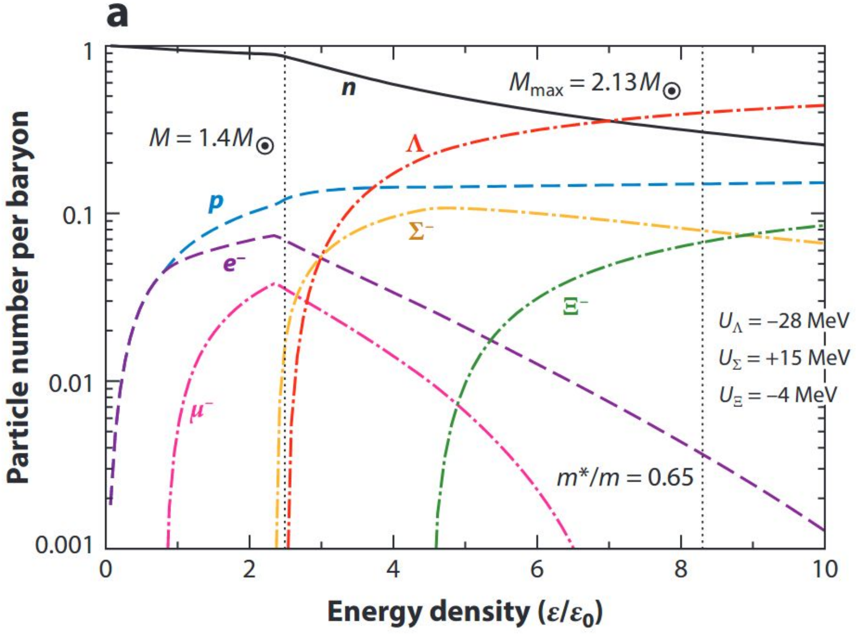
Introduction

Strange particles are important probes of the medium created in HIC:

- Strange hyperons yield depend on nuclear matter density and in the mixed phase state becomes comparable with yield of hadrons made of light quarks

Asymmetry in strange particle emission can shed light on the compressibility / EoS of nuclear matter

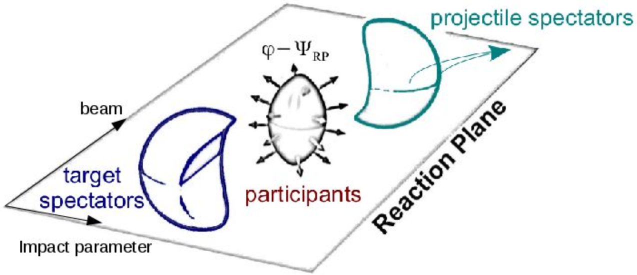
Annu. Rev. Nucl. Part. Sci. 2021.71:377-402



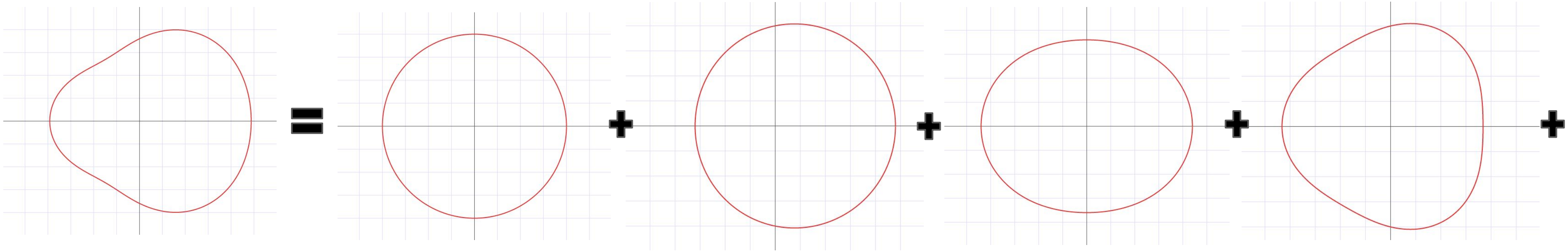
Anisotropic flow:

Spatial anisotropy of the energy density of the medium produced in HIC converts to momentum anisotropy of produced particles due to interaction between them

Anisotropic flow



$$\rho(\varphi, p_T, y) \propto 1 + 2\sum_{n=1}^{\infty} v_n(p_T, y)\cos(n(\varphi - \Psi_{RP}))$$



1 **v_1** **v_2** **v_3**

directed flow **elliptic flow** **triangular flow**

$$v_n = \langle \cos[n(\varphi - \Psi_{RP})]\rangle$$

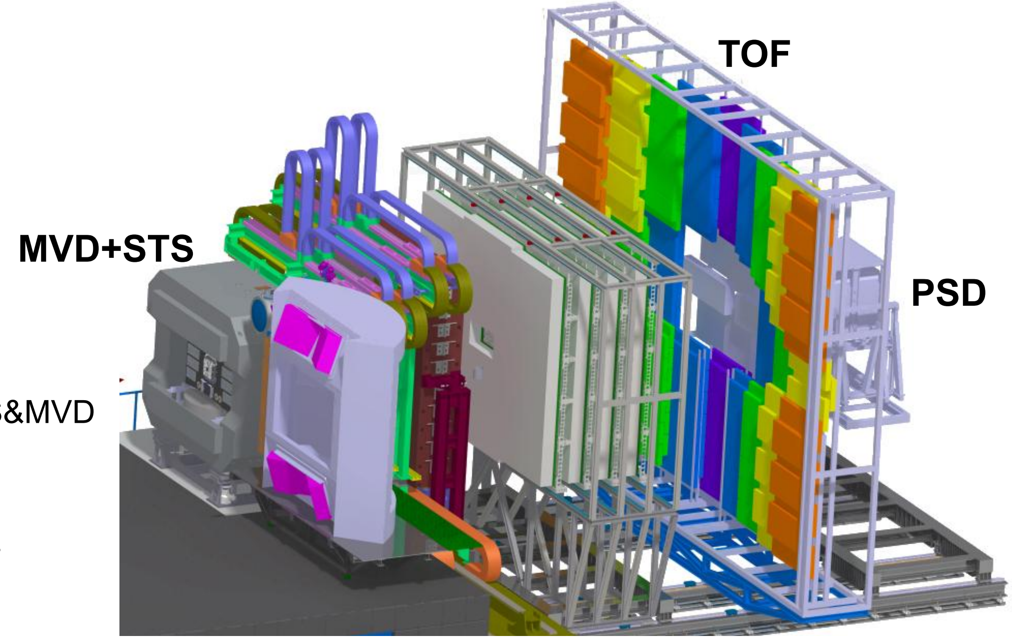
CBM experiment & detector subsystems relevant for hyperon flow measurements

- Fixed target
  - High interaction rate ~10^7 Hz

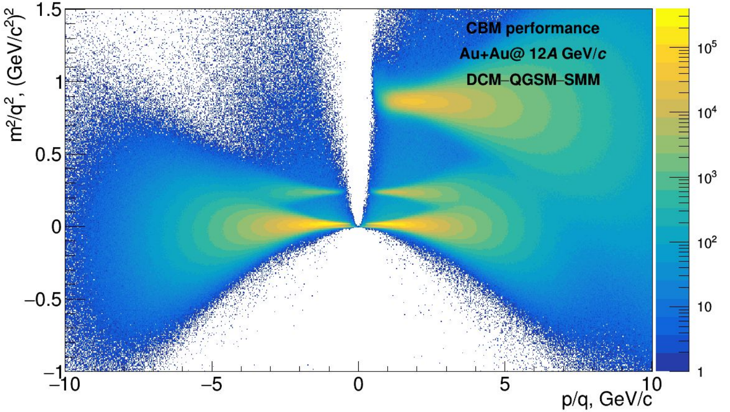
- Tracking system:
  Micro-Vertex Detector (MVD) +
  Silicon Tracking System (STS)

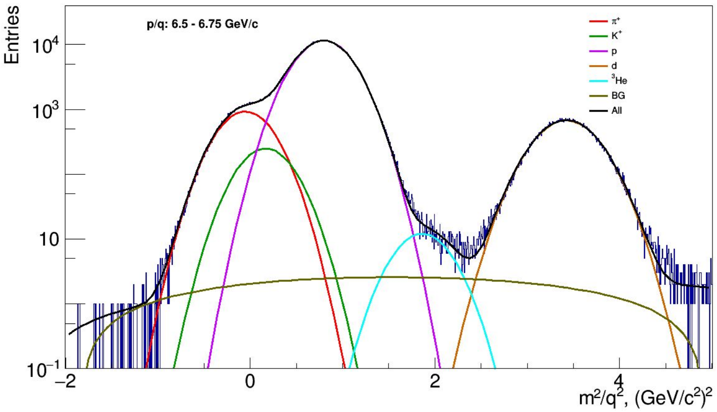
  - acceptance for Λ: $1 < y_{LAB} < 2.5$
  - Track reconstruction: 12 spatial points from STS&MVD
  - magnetic field: 1 Tm
  - momentum resolution: $\Delta p/p \sim 1.5 - 2\%$
  - decay vertex resolution: 50-100 μm along z-axis

- Charged hadrons identification:
  Time of Flight (TOF)
- Reaction plane estimation:
  Projectile Spectator Detector (PSD)

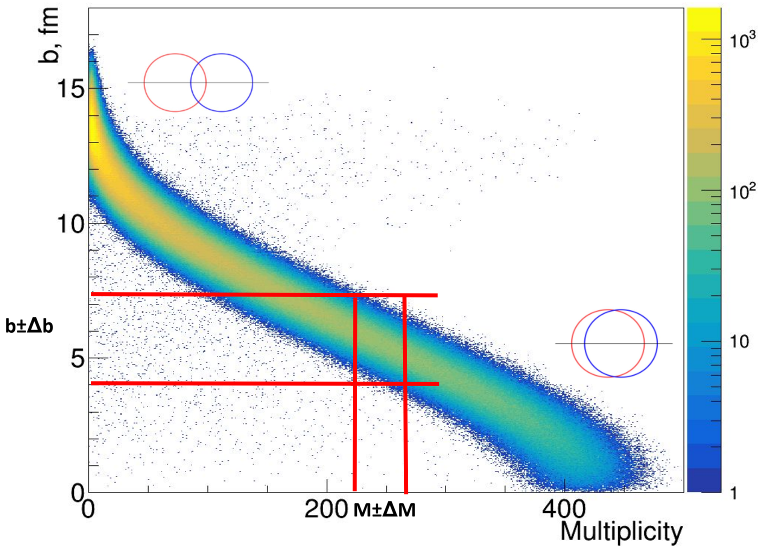


PID and centrality determination





Charged hadrons identification is performed using TOF method.
2D fit of m^2-p distribution is done and Bayesian approach is used.



Number of registered charged tracks is used as centrality estimator.
Following conditions on tracks were applied:

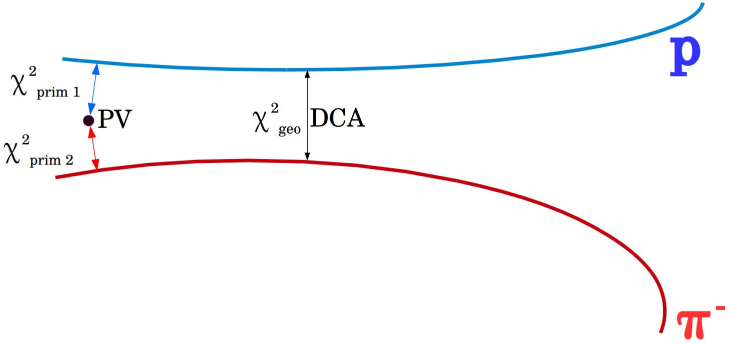
- $\chi^2_{vtx} < 3$
- $n_{hits} > 4$
- $\chi^2/ndf < 3$
- $0.2 < \eta < 6$

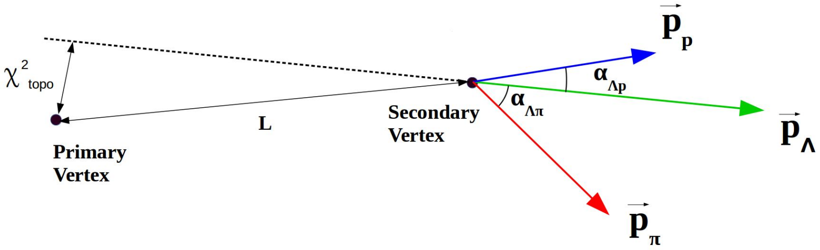
Strange hyperons reconstruction

Each negative track is combined with each positive (PID hypothesis can be applied)

Topological variables:

- χ^2_{prim} between daughter track and primary vertex
- **DCA** - distance of closest approach between daughter tracks
- χ^2_{geo} between daughter tracks
- $\alpha_{\Lambda p}$ - angle between daughter and mother tracks momenta
- **L/ΔL** - distance between primary and secondary vertex divided by its error
- χ^2_{topo} between mother particle trajectory and primary vertex





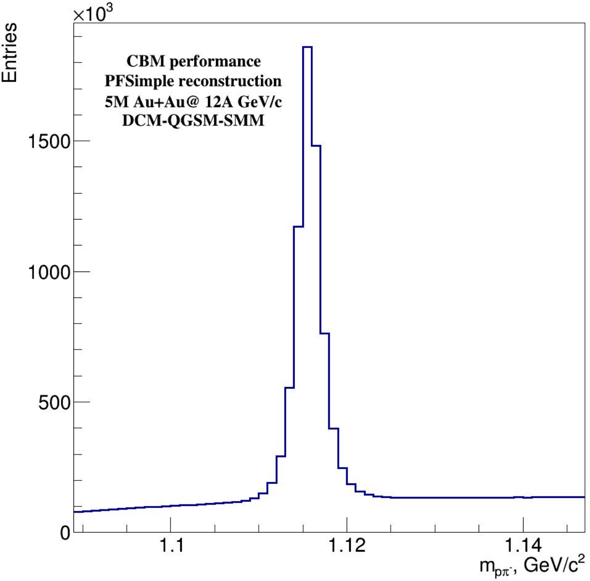
$$\chi^2 = (C^{-1}\Delta\mathbf{r})\Delta\mathbf{r} = C^{-1}_{ij}\Delta r_i \Delta r_j$$

$\Delta \mathbf{r}_i$ is a distance between two objects (track or/and primary vertex)
C_{ij} is a covariance matrix of the combined object

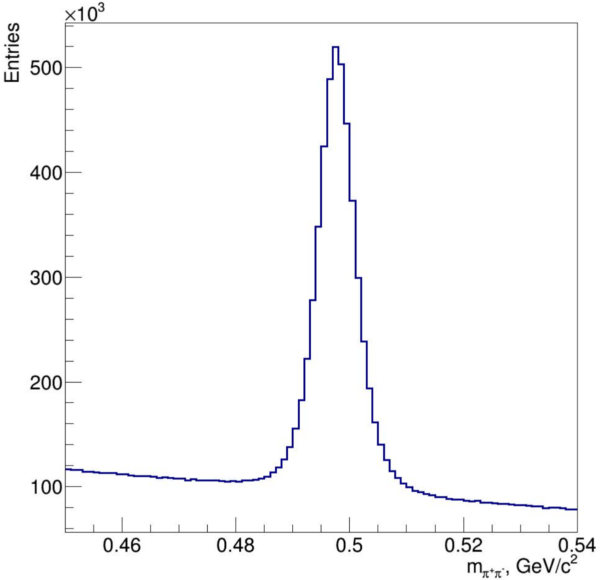
S. Gorbunov, On-line reconstruction algorithms for the CBM and ALICE experiments", 2012
M. Zyzak, Online selection of short-lived particles on many-core computer architectures in the CBM", 2016
M. Zyzak et al. https://github.com/cbmsw/KFParticle
O. Lubynets et al. https://github.com/lubynets/PFSimple

PFSimple performance: invariant mass spectra

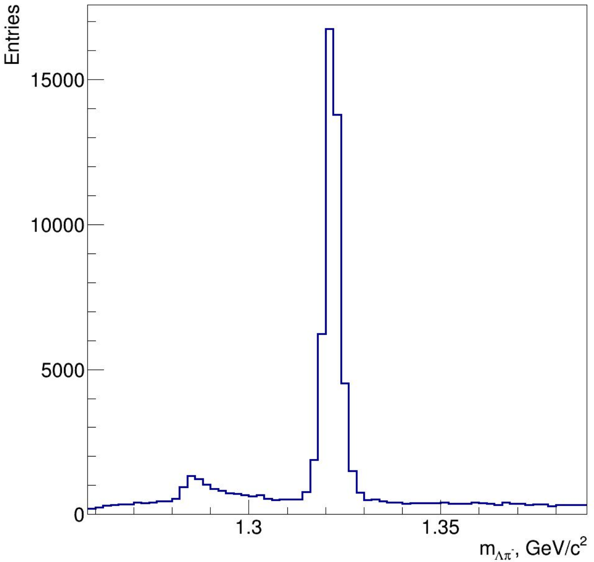
Λ



K^0_S

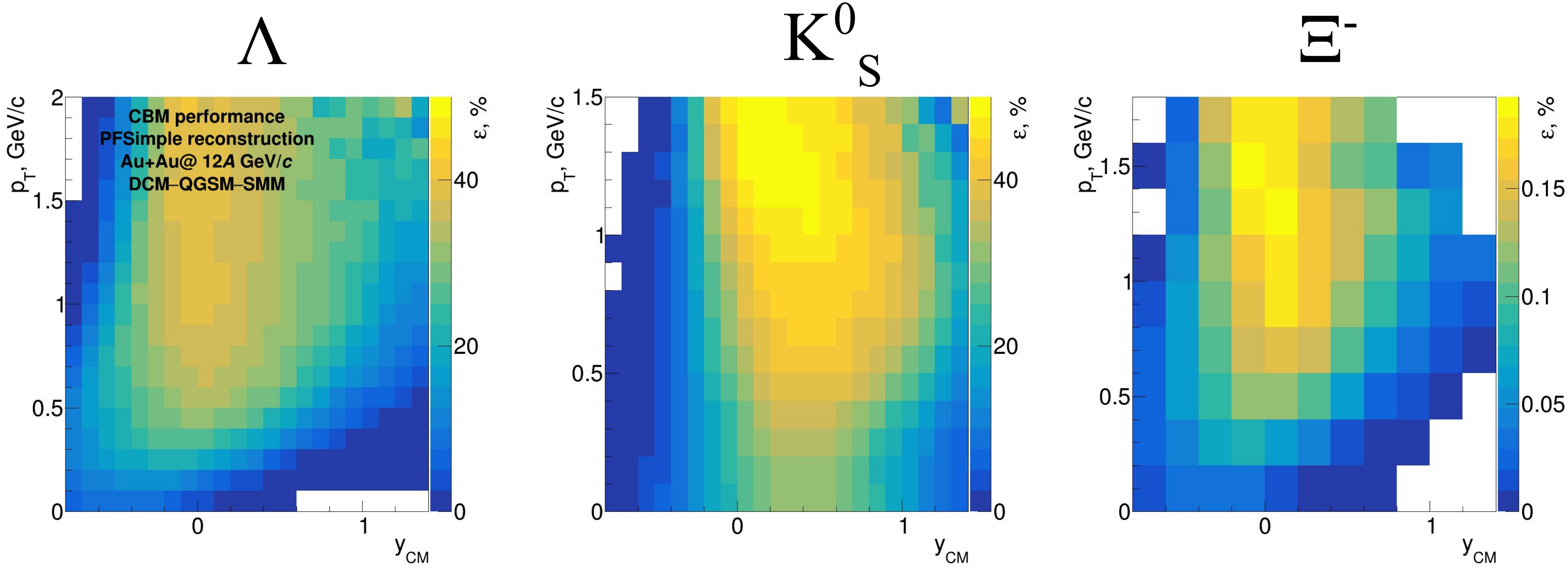


Ξ^-



- Signal to background ratio defined in 3σ region: S/B{Λ} = 5, S/B{K^0_S} = 2, S/B{Ξ^-} = 14,

PFSimple performance: reconstruction efficiency

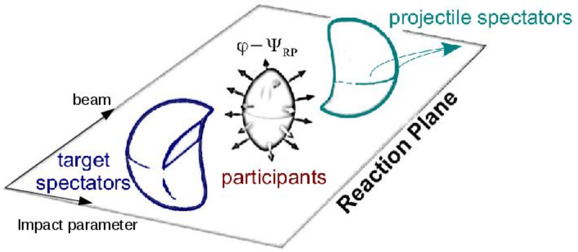


- Reconstruction efficiency in midrapidity up to 50% for Λ and K^0_S and 20% for Ξ^-
- Non-uniformity in reconstruction efficiency can bias flow results and requires correction

Flow vector terminology

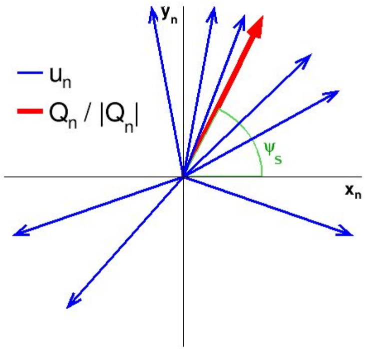
$$\rho(\varphi, p_T, y) \propto 1 + 2\sum_{n=1}^{\infty} v_n(p_T, y)\cos(n(\varphi - \Psi_{RP}))$$

$$v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$



Flow vector for single particle $\mathbf{u}_{n,i} = \{\cos n\varphi_i, \sin n\varphi_i\}$

Flow vector for set of particles $\mathbf{q}_n(p_T, y) = \sum_{i=1}^{M_u} w_i \mathbf{u}_{n,i} / \sum_{j=1}^{M_u} w_j$



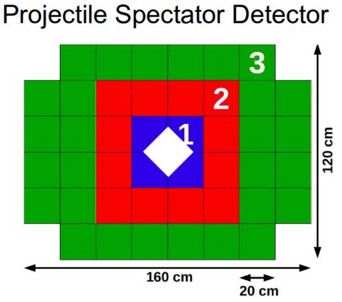
Reaction plane angle Ψ_{RP} is not known. It is estimated using the spectators' energy registered with the PSD.

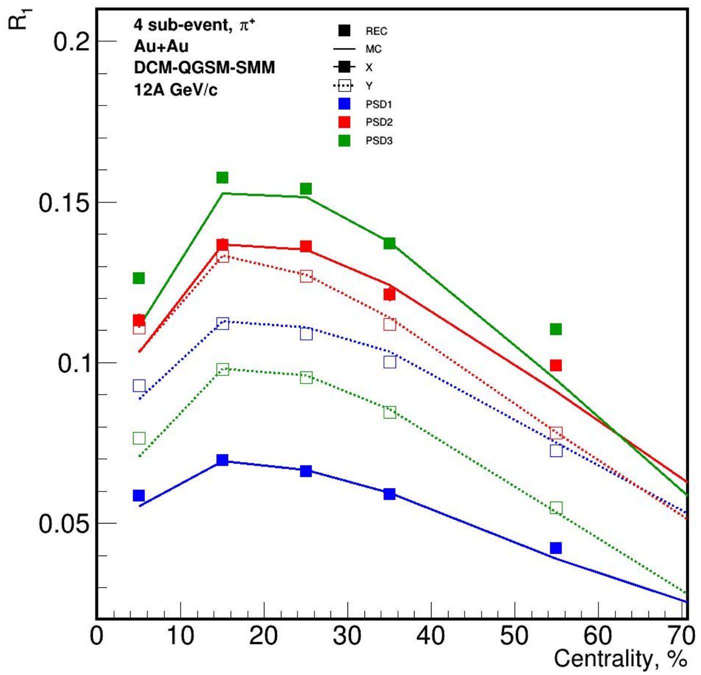
Then the flow coefficient equals: $v_{1,i} = \frac{2\langle u_{1,i} Q_{1,i} \rangle}{R_{1,i}}, i = x, y$

$R_{1,i}$ is a 1st order event plane resolution correction (details in the following slide)

Resolution of the reaction plane determination

Resolution is estimated using subsets of spectators or produced particles separated kinematically (so-called subevents) and therefore assumed to be uncorrelated. (All correlations between subevents are only due to common reaction plane)





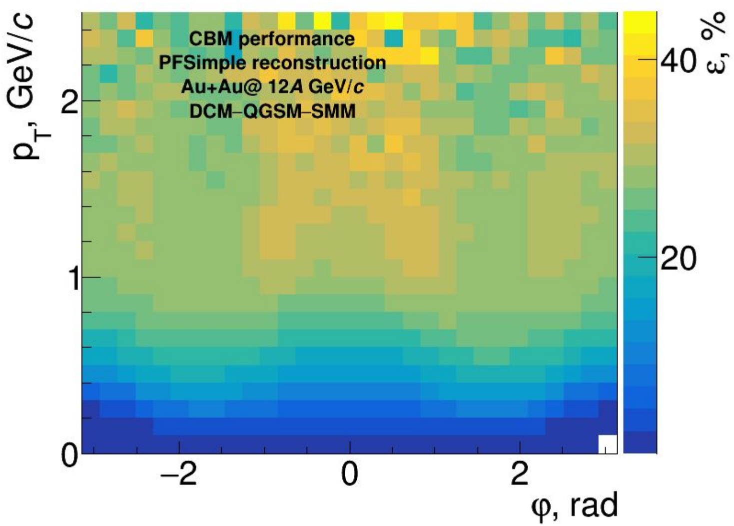
3-subevents method

$$R^A_{1,\alpha}\{B,C\} = \sqrt{2\frac{\langle Q^A_{1,\alpha} Q^B_{1,\alpha}\rangle \langle Q^A_{1,\alpha} Q^C_{1,\alpha}\rangle}{\langle Q^B_{1,\alpha} Q^C_{1,\alpha}\rangle}}$$

4-subevents method

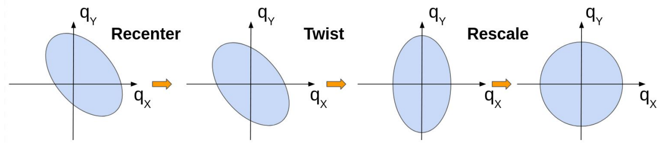
$$R^B_{1,\alpha} = \frac{\langle Q^B_{1,\alpha} Q^D_{1,\alpha}\rangle}{R^D_{1,\alpha}}, \quad R^D_{1,\alpha} = \sqrt{2\frac{\langle Q^A_{1,\alpha} Q^D_{1,\alpha}\rangle \langle Q^C_{1,\alpha} Q^D_{1,\alpha}\rangle}{\langle Q^A_{1,\alpha} Q^C_{1,\alpha}\rangle}}$$

Corrections for detector non-uniformity

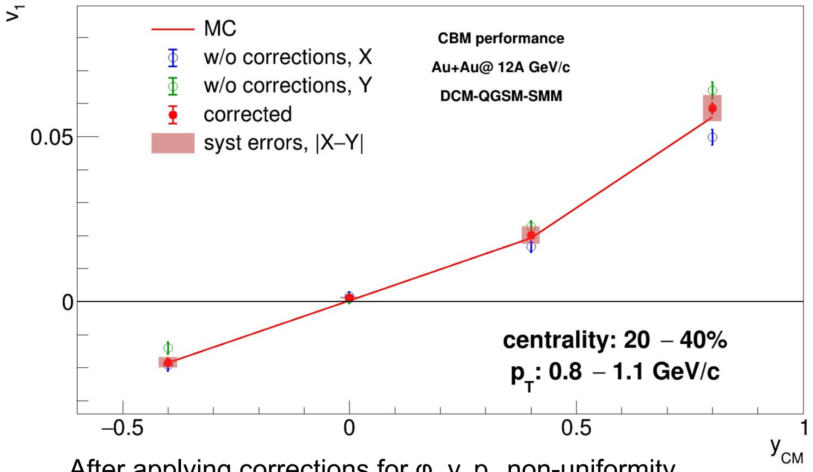


Non-uniformity of the Λ reconstruction in p_T and y is taken into account by weighting the Λ candidates in the v_1 calculation with the inverse value of efficiency for a given p_T and y region.

Correction for azimuthal non-uniformity:



Correction procedure: I. Selyuzhenkov and S. Voloshin, PRC77, 034904 (2008)
Software package: QnTools by L. Kreis and I. Selyuzhenkov, https://github.com/HeavyIonAnalysis/QnTools
Interface for flow analysis: E. Kashirin and I. Selyuzhenkov, https://github.com/HeavyIonAnalysis/QnAnalysis



After applying corrections for φ, y, p_T non-uniformity the Monte Carlo input is reproduced within the statistical precision

v_n vs. invariant mass method

Step 1.

Fit the invariant mass distribution of the decay candidates to extract the signal & background yields:

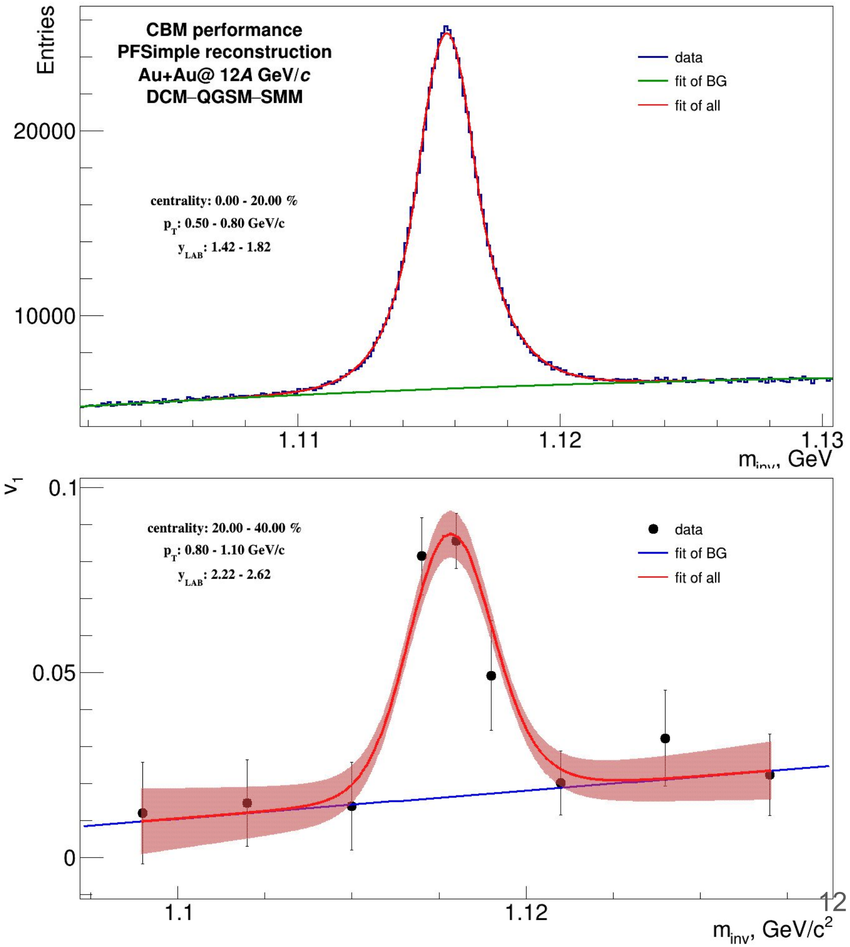
- signal: double-sided crystal ball function
- background: smooth (polynomial) function

Step 2.

Fit dependence of flow of all decay candidates:

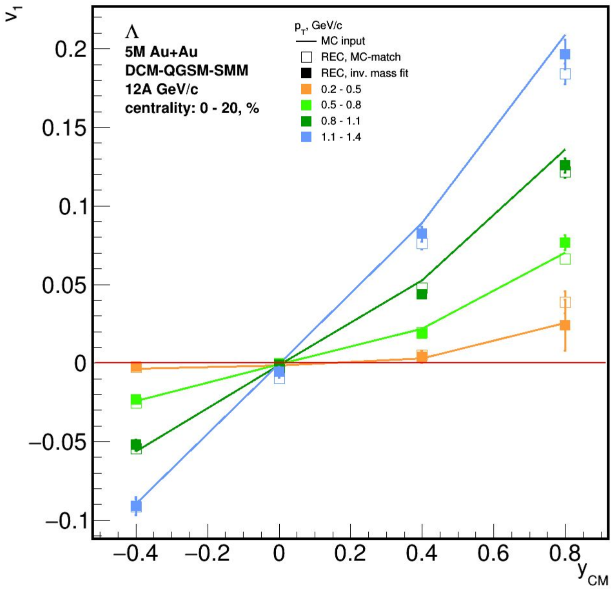
$$v_{EXP}(m_{inv}) = \frac{v_S N_S(m_{inv}) + v_{BG}(m_{inv}) N_{BG}(m_{inv})}{N_S(m_{inv}) + N_{BG}(m_{inv})}$$

- $v_{EXP}(m_{inv})$ of the all decay candidates
- v_S of the true signal (independent on m_{inv})
- $v_{BG}(m_{inv})$ of the background candidates: smooth (polynomial) function

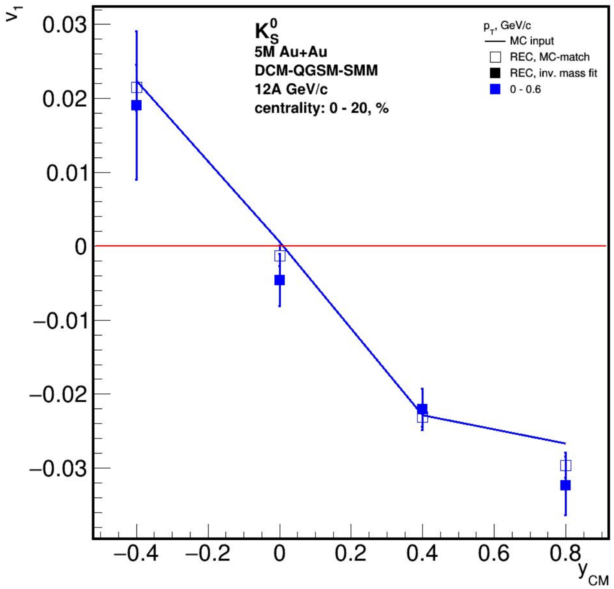


Directed flow (v_1) of strange hadrons

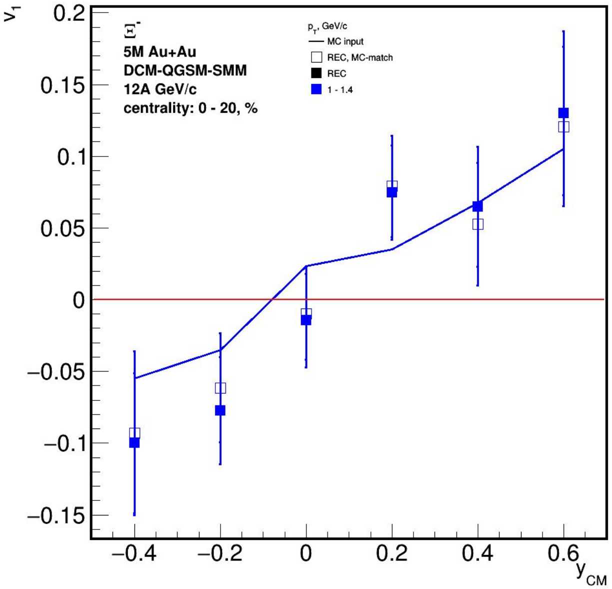
Λ



K_0^S



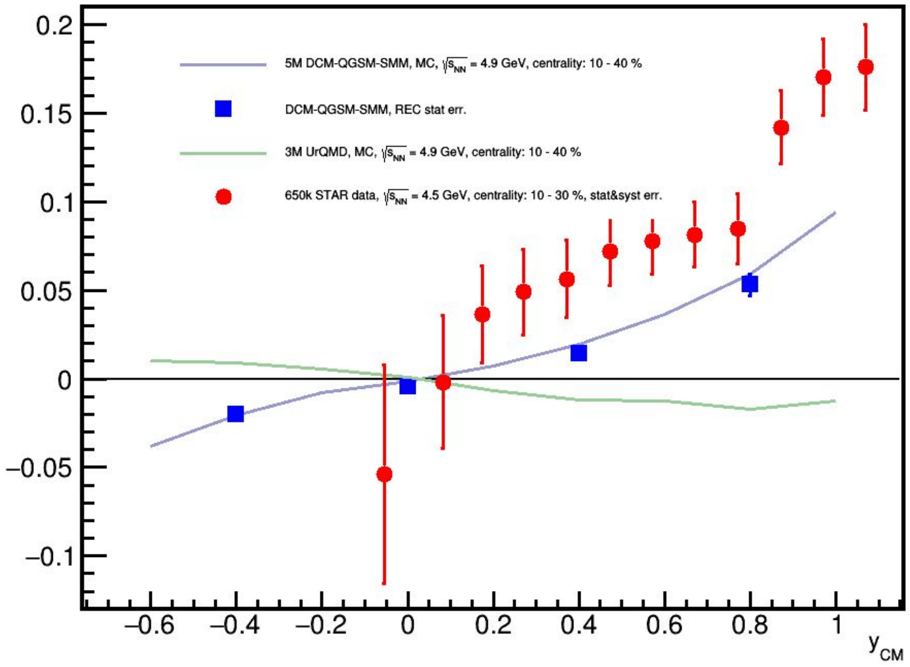
Ξ^-



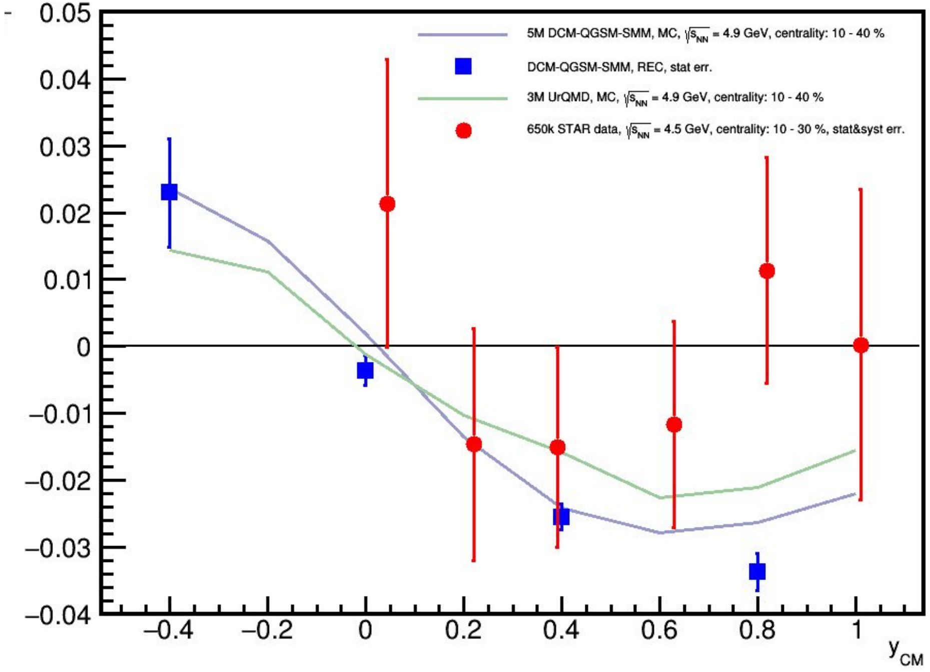
- Signal's extraction using invariant mass fit method gives results consistent with MC-extraction
- Flow coefficient calculated in data-driven mode reproduces MC-input within statistical errors

Directed flow: model and real data comparison

Λ



K_0^S



- Similar magnitude of v_1 {Λ / K_0^S} predicted by DCM-QGSM-SMM and STAR FXT data [https://doi.org/10.48550/arXiv.2007.14005]
- Similar behaviour of v_1 {K_0^S} and opposite slope of dv_1 {Λ}/dy predicted by UrQMD and STAR FXT data
- UrQMD simulation performed in cascade mode (EOS=0), no hard Skyrme EOS
  (note: collision energy and centrality ranges used by STAR are slightly different)

Summary

- Performance of the CBM experiment for the measurements of the directed flow of strange hyperons is presented
- The Monte Carlo input is reproduced within the statistical precision after applying corrections for (φ, y, p_T) non-uniformity
- Invariant mass fit method for signal extraction gives results consistent with MC-based signal extraction
- Multi-differential study of v_1 for (multi-)strange hyperons: Λ, K_0^S, and Ξ^-; models comparison with real data

Outlook

- Multi-differential p_T, y and centrality analysis with higher statistics
- Integration of ML technique for candidate selection in flow analysis (see O. Lavoryk's talk)

Backup

Flow of strangeness at FAIR energies

Anisotropic flow:
Spatial anisotropy of the energy density of the medium produced in HIC converts to momentum anisotropy of the produced particles due to interaction between them

Azimuthal angle distribution of produced particles is decomposed in Fourier series:

$$\rho(\varphi, p_T, y) \propto \frac{d^2 N}{dp_T dy}[1 + 2\sum_{n=1}^{\infty} v_n(p_T, y)\cos(n(\varphi - \Psi_{RP}))]$$

$$v_n = \langle\cos[n(\varphi - \Psi_{RP})]\rangle$$

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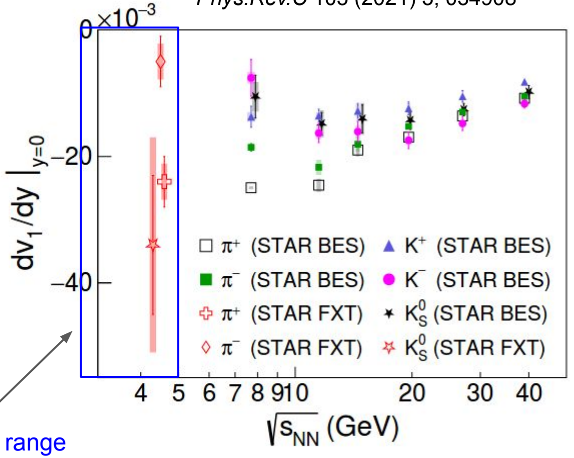
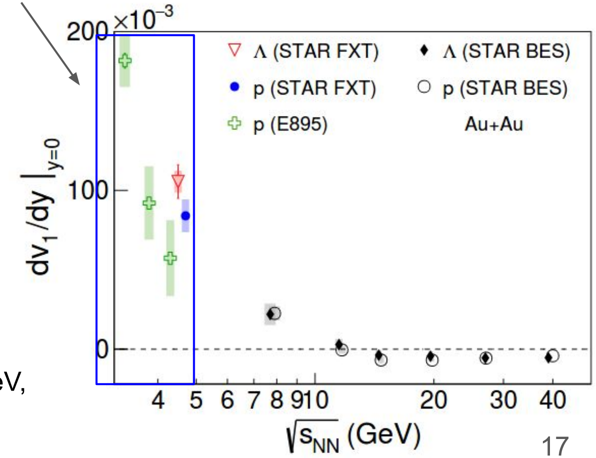


FAIR energy range



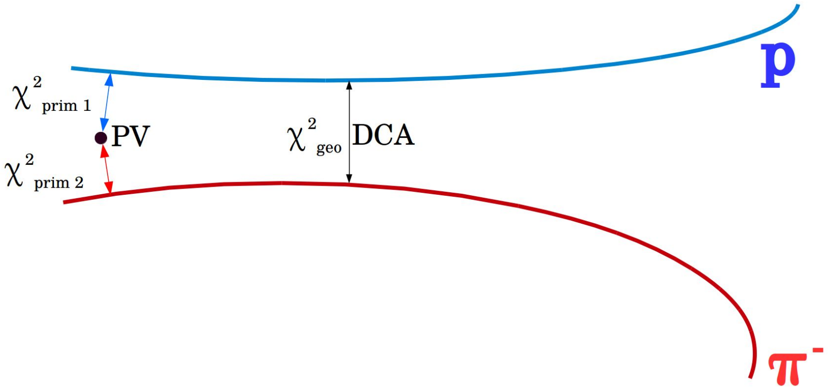
K^0_S , $K^{\pm}$ and Λ anisotropic flow at $\sqrt{s_{NN}}$ = 3 GeV,
(STAR contribution at SQM2021)

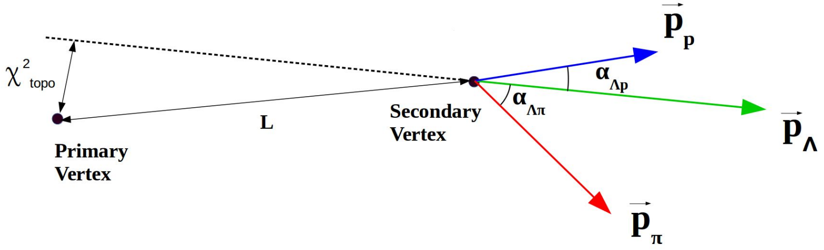
2-daughters decay topology selection algorithm

Each negative track is combined with each positive (PID hypothesis can be applied)

Topological variables:

- χ^2_{prim} between daughter track and primary vertex
- **DCA** - distance of closest approach between daughter tracks
- χ^2_{geo} between daughter tracks
- $\alpha_{\Lambda p}$ - angle between daughter and mother tracks momenta
- **L/ΔL** - distance between primary and secondary vertex divided by its error
- χ^2_{topo} between mother particle trajectory and primary vertex

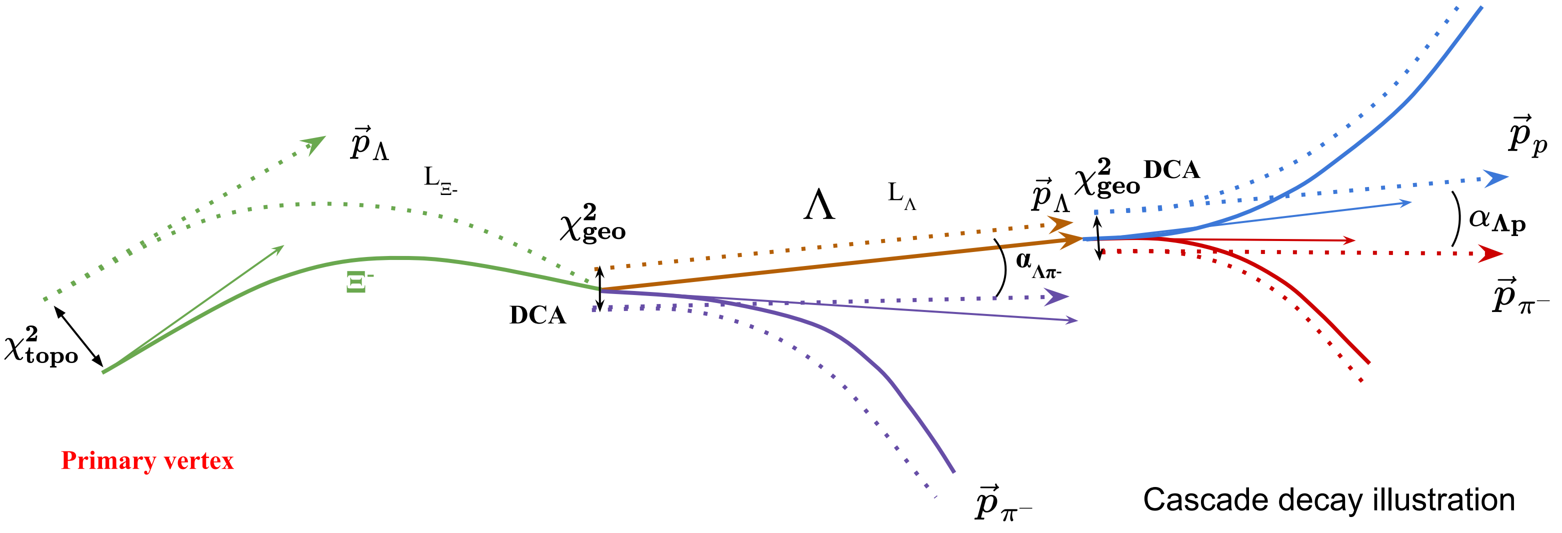




$$\chi^2 = (C^{-1}\Delta\mathbf{r})\Delta\mathbf{r} = C^{-1}_{ij}\Delta r_i \Delta r_j$$

$\Delta \mathbf{r}_i$ is a distance between two objects (track or/and primary vertex)
C_{ij} is a covariance matrix of the combined object

PFSimple extension: cascade decay reconstruction



Cascade decay illustration

$\Xi^- \to \Lambda\pi^-$
$\Lambda \to p\pi^-$

Reconstruction of Ξ^- from the cascade decay:
2 nested loops with some additional actions:

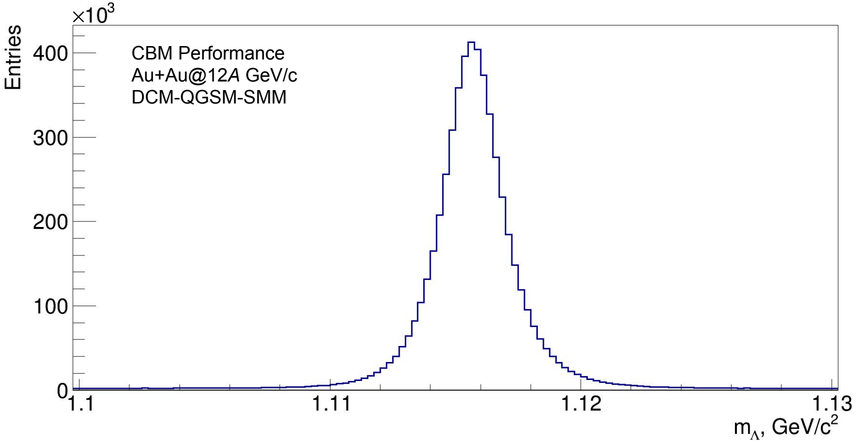
1) Constraint on Λ invariant mass using KFParticle implementation

$$(E_\Lambda, \overrightarrow{p_\Lambda}) \to (E'_\Lambda, \overrightarrow{p_\Lambda}') : E'^2_\Lambda - \overrightarrow{p_\Lambda}'^2 = m^2_{\Lambda PDG}$$

2) Avoid usage of the same daughter particle (π^-) twice

PFSimple performance for Λ reconstruction

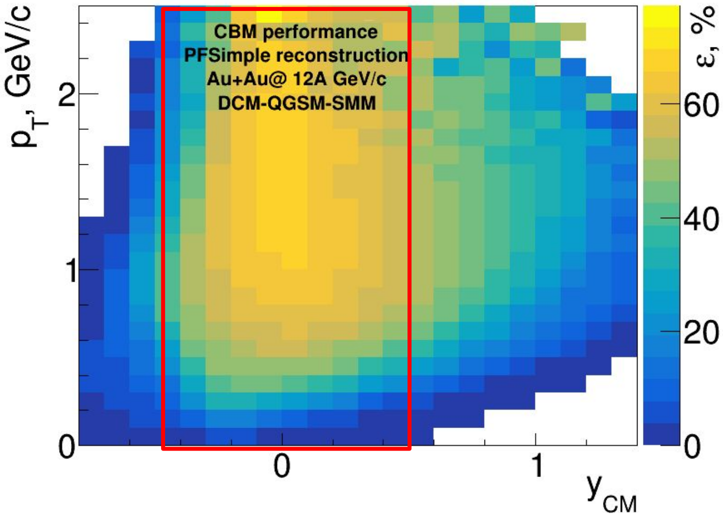
Inv. mass distribution of Λ-candidates



High signal to background ratio: S/B ≈30

Reconstruction efficiency (p_T, y)

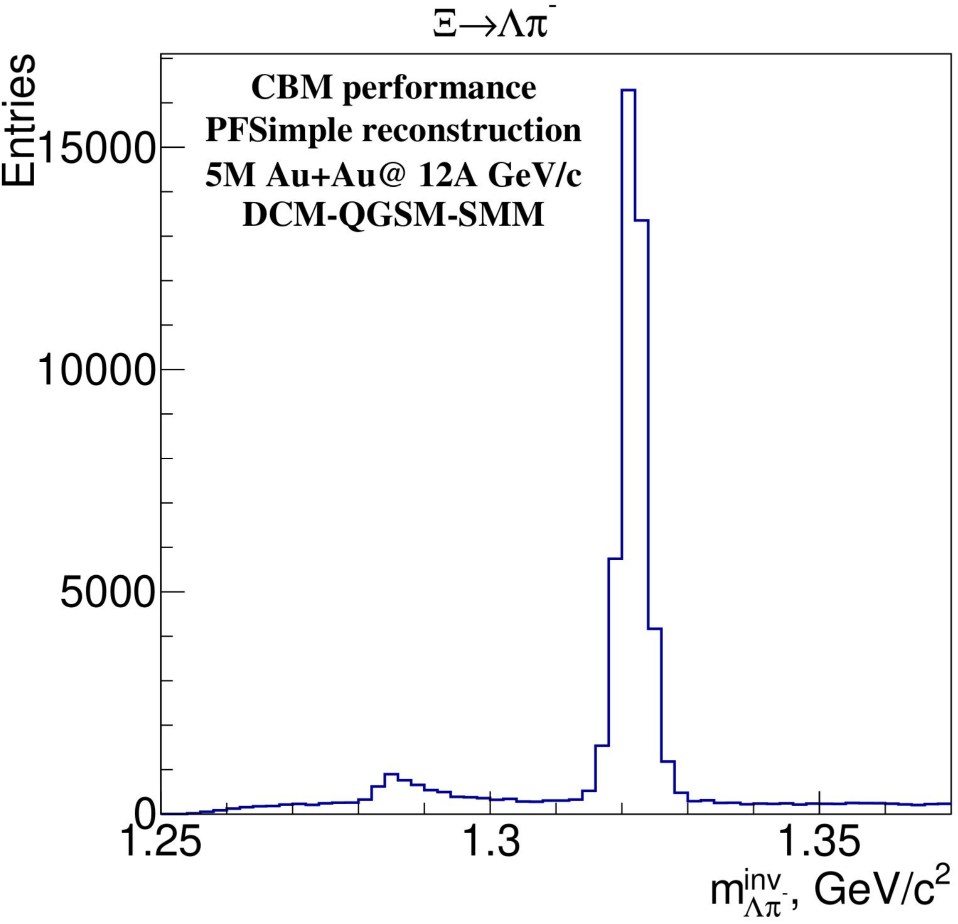
$$\varepsilon = \frac{N_{rec}}{N_{sim} \times BR}$$

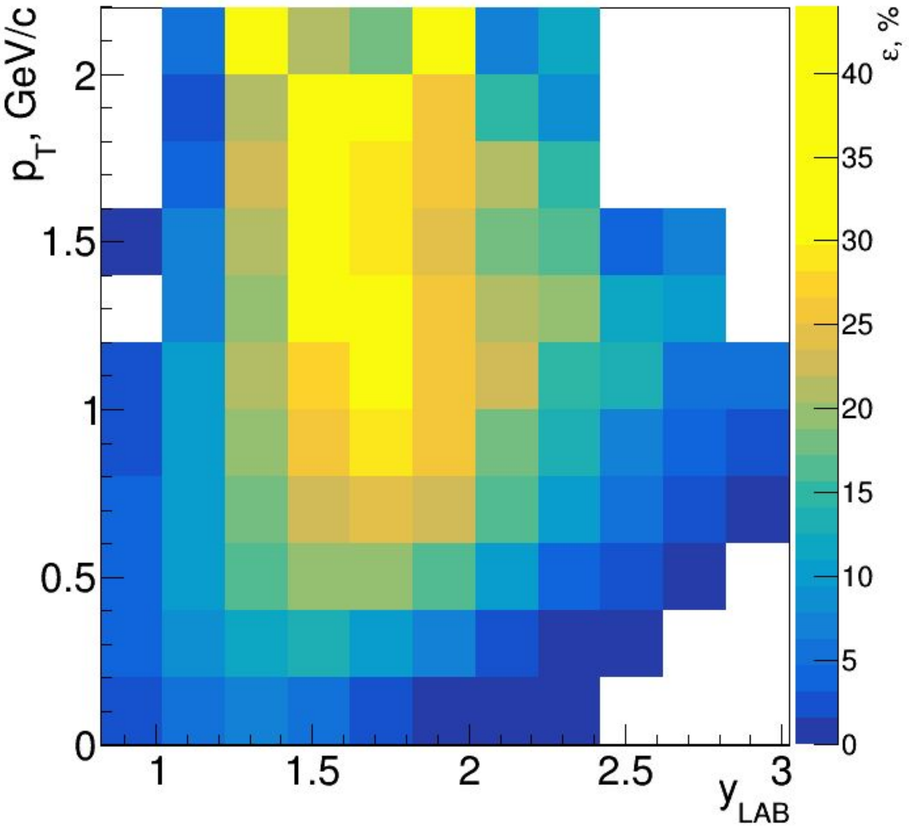


Good reconstruction efficiency in the midrapidity region, consistent with results by M. Zyzak:

ϵ = 65.4% for Au+Au UrQMD @ 10A GeV/c with TOF PID

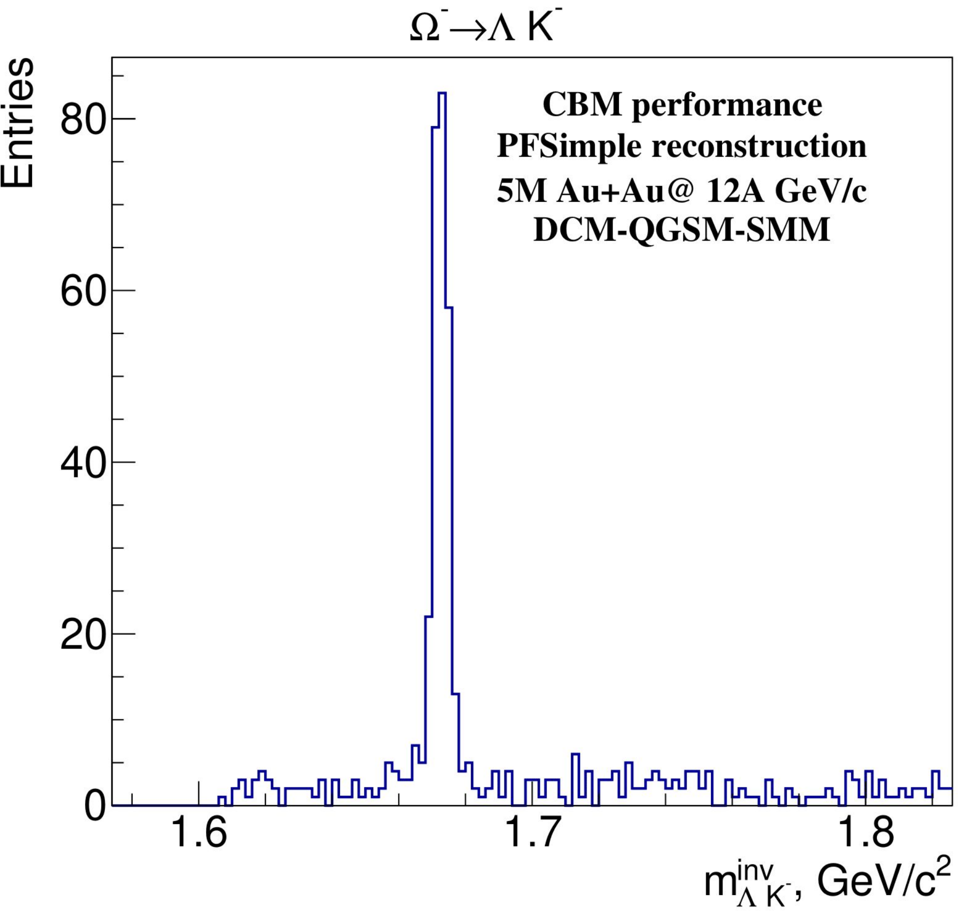
PFSimple performance for Ξ^- reconstruction

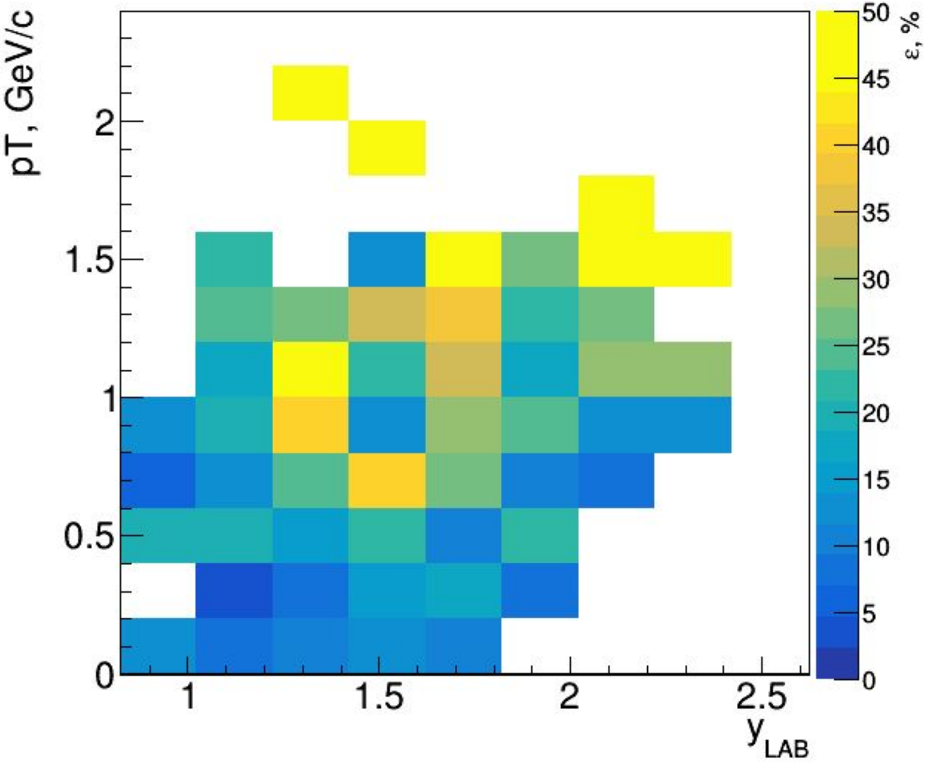




~40k Xi baryons reconstructed

PFSimple performance for Ω^- reconstruction





266 Omega baryons reconstructed;
more statistics is required

Λ hyperon flow analysis configuration

Simulation setup:

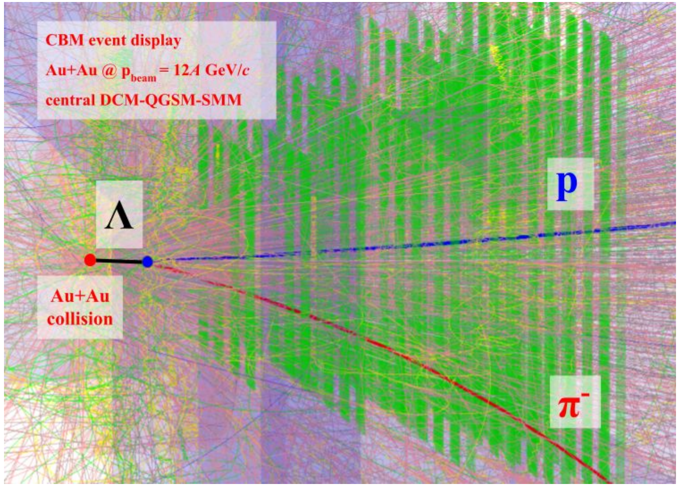
- 5M events
- Au+Au
- 12*A* GeV/*c*
- HI Event generator: DCM-QGSM-SMM
- GEANT4 transport

Centrality determination:

- multiplicity of reco tracks with cuts:
- $\chi^2_{vtx} < 3$
- $n_{hits} > 4$
- $\chi^2/ndf < 3$
- $0.2 < \eta < 6$

Λ-candidates selection cuts	
Cut	PFSimple
$\chi^{2\,pos}_{prim}$	26
$\chi^{2\,neg}_{prim}$	110
DCA	0.15 cm
L/ΔL	4
χ^2_{geo}	11
$\cos\alpha_{\Lambda p}$	0.99825
χ^2_{topo}	29

CBM event display



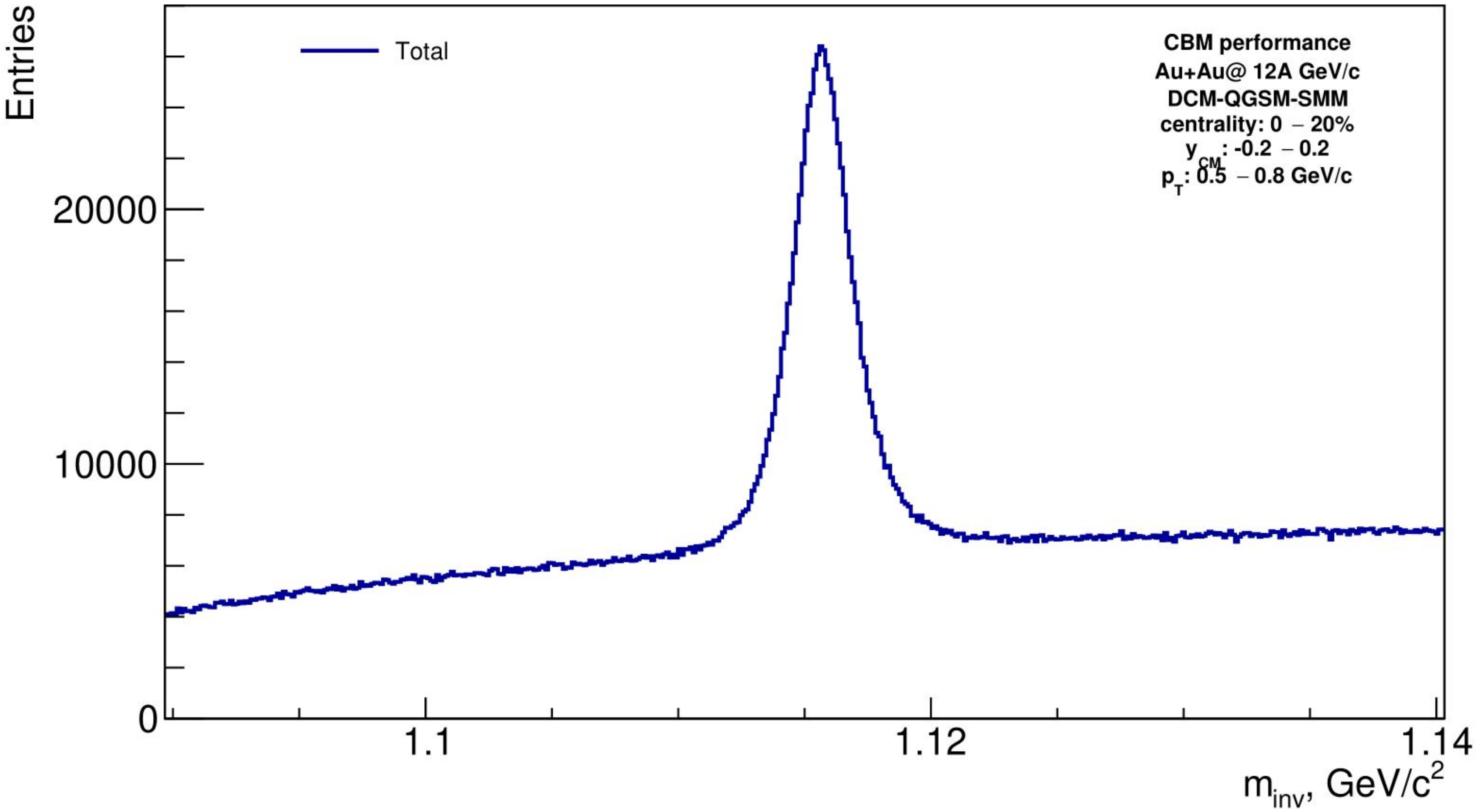
Λ hyperon categories:

MC-true Λ: Λ's from HI event generator

Λ-candidate: pairs of proton + pion passed selection criteria

Reconstructed Λ: Λ-candidates matched with MC-true Λ

Step 1: signal and background shape determination



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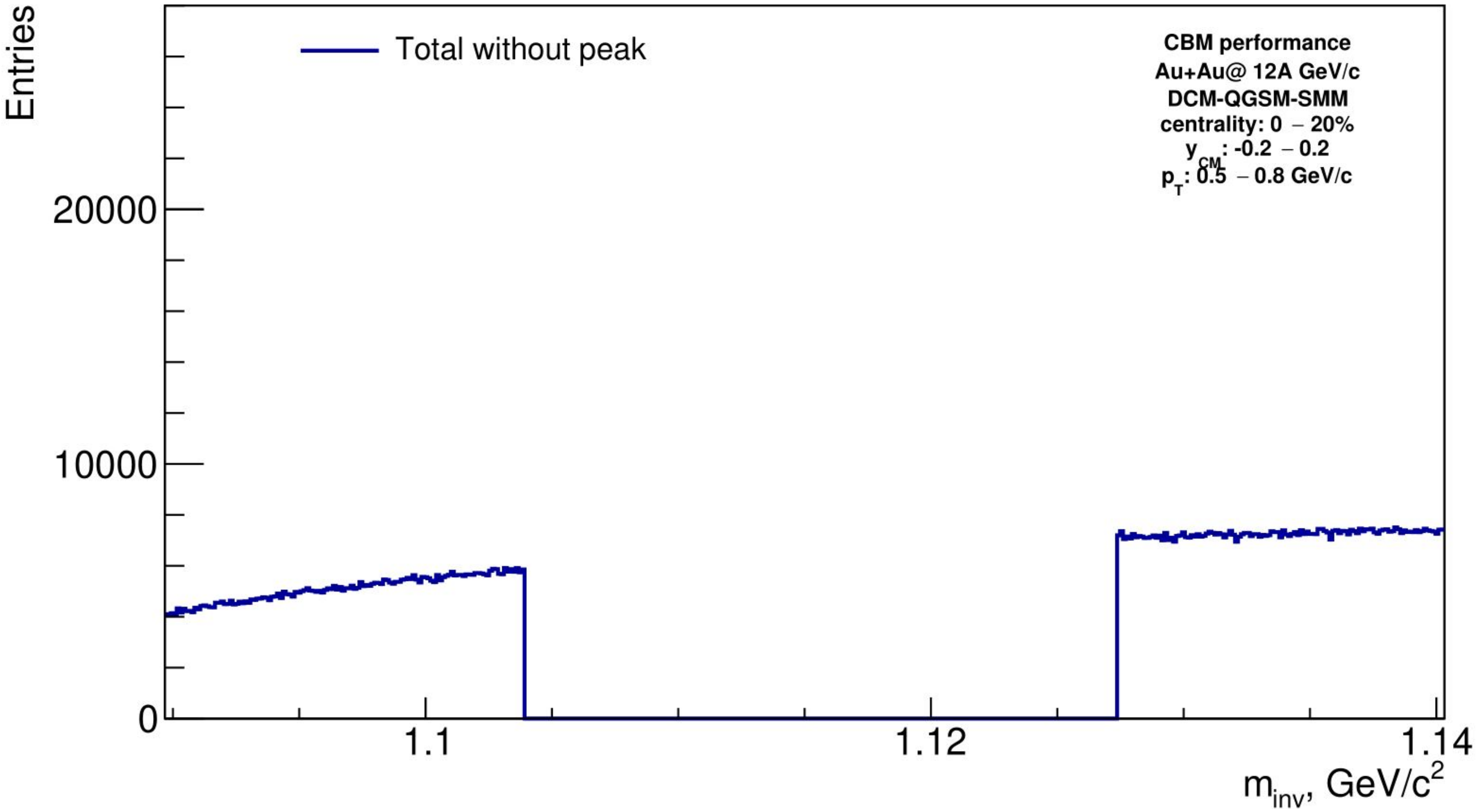

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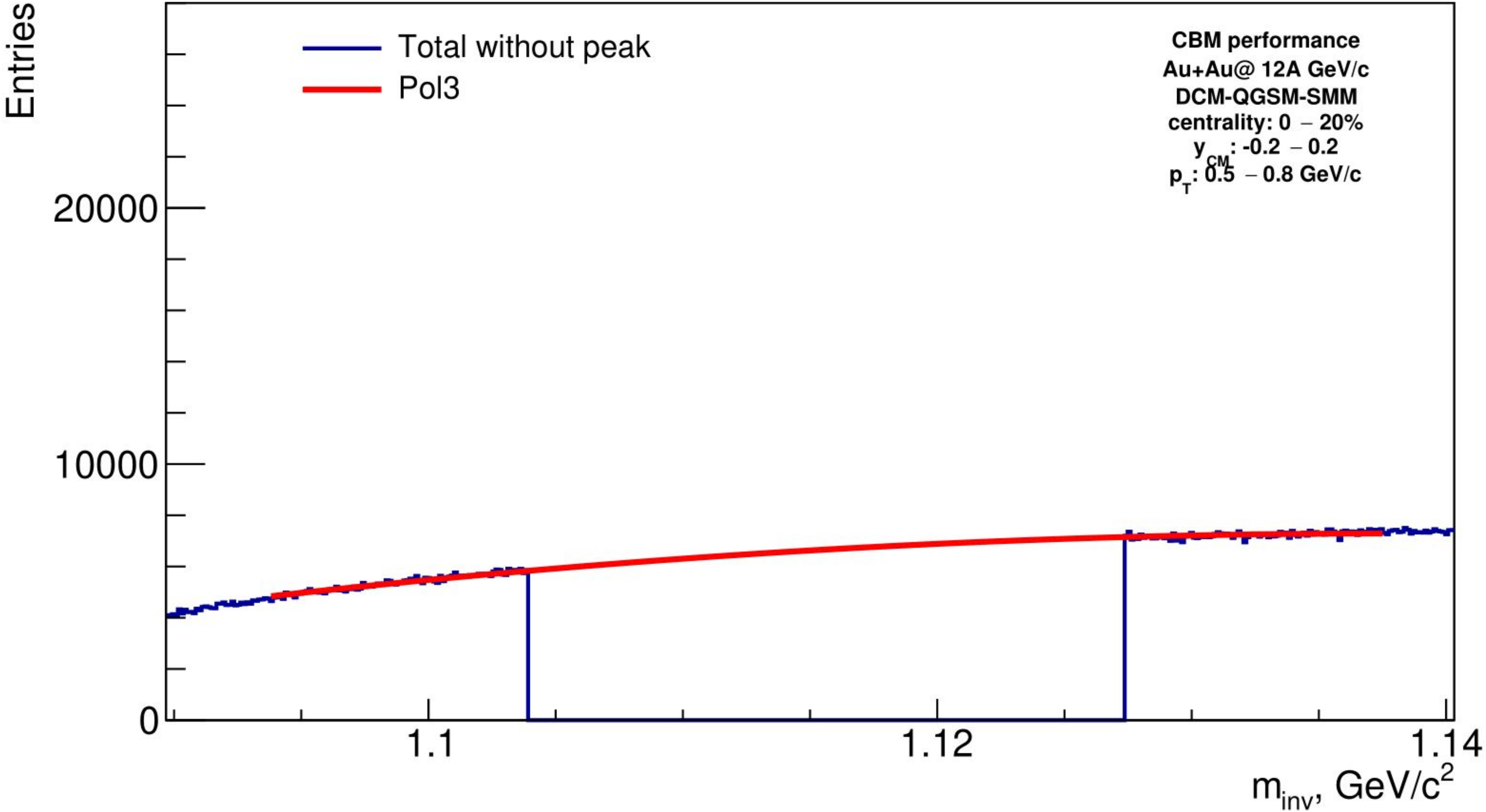

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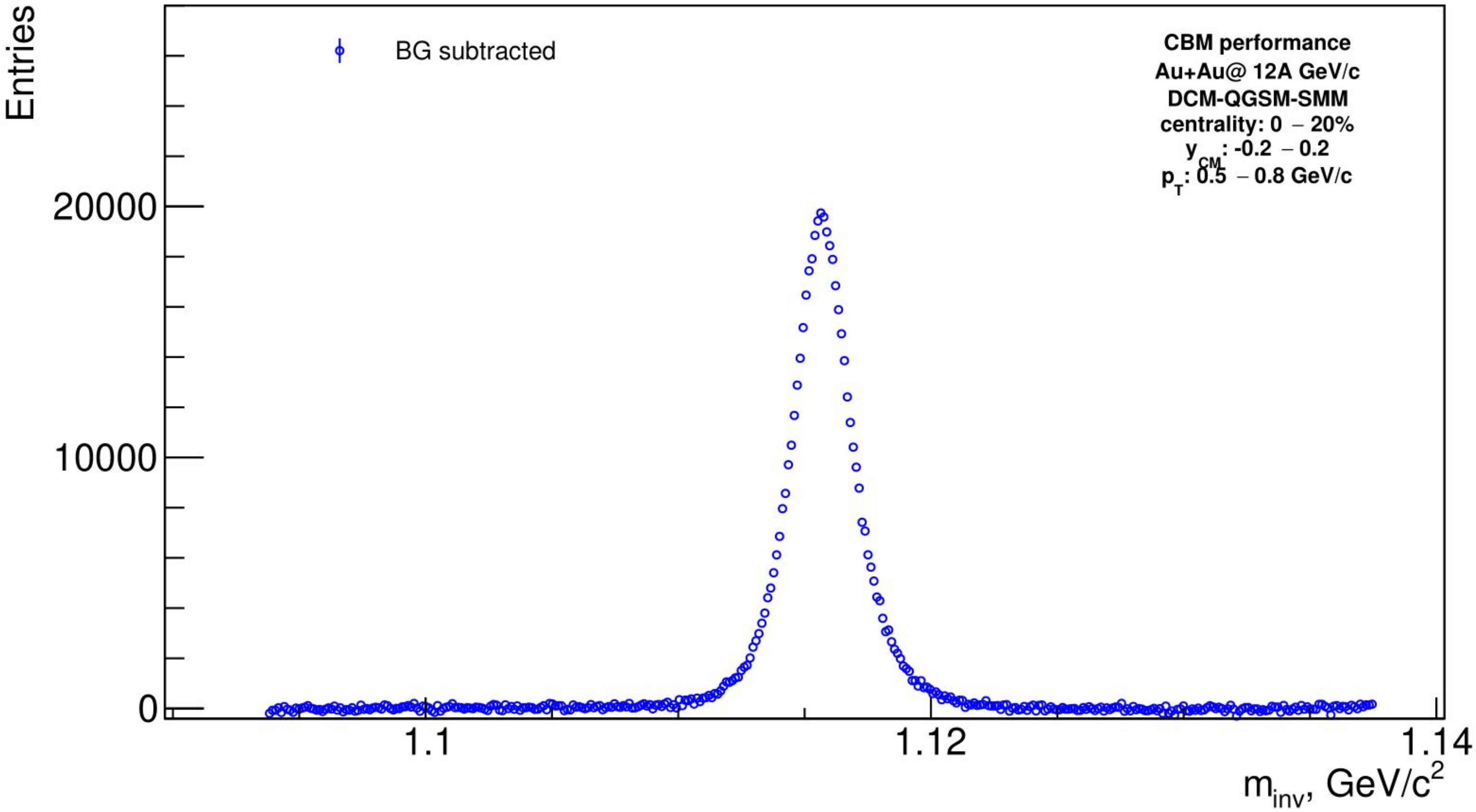

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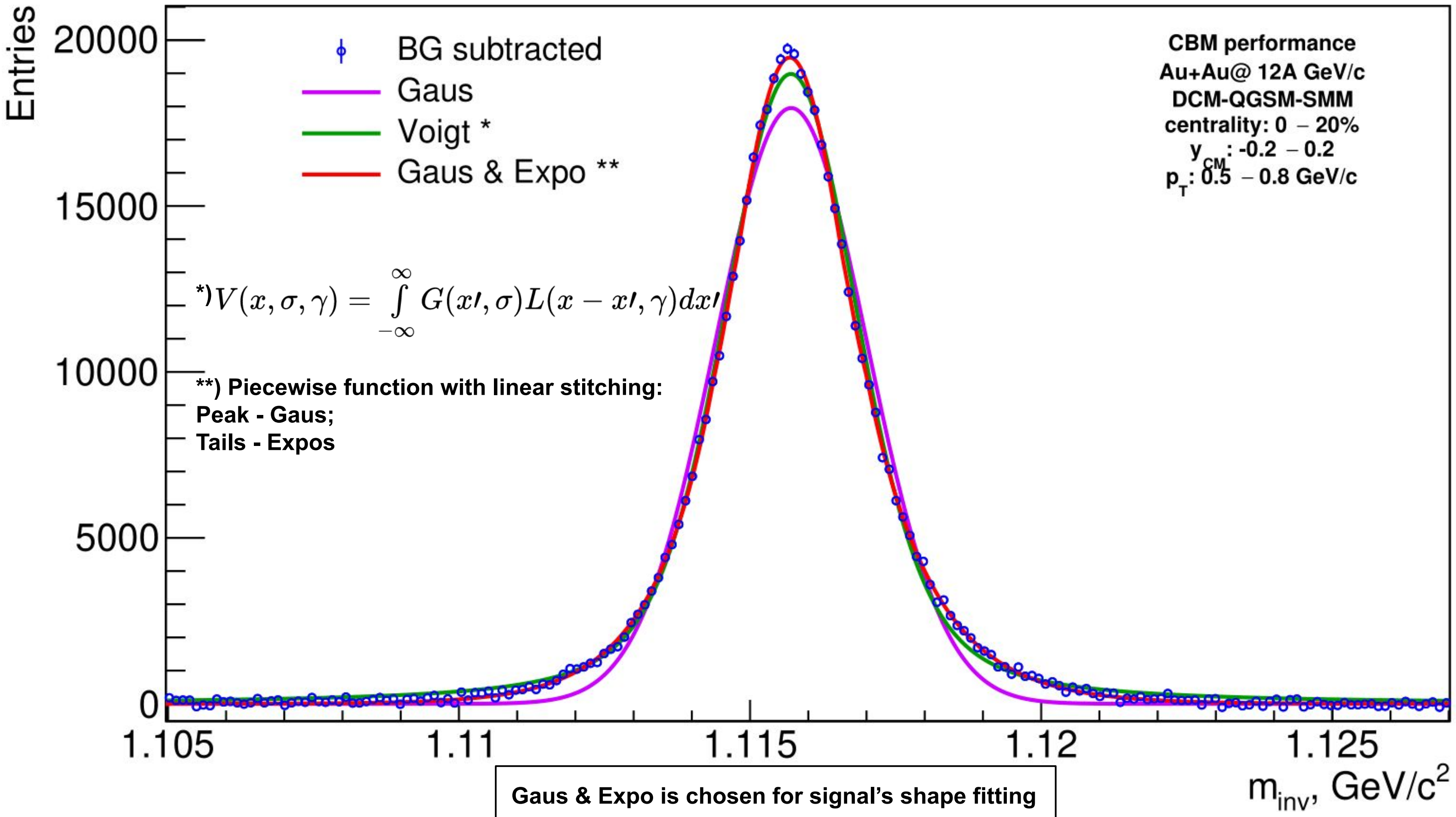

Gaus & Expo is chosen for signal's shape fitting

Step 1: signal and background shape determination