CBM performance for the Λ hyperons' directed flow measurements in Au+Au collisions at 12A GeV/c

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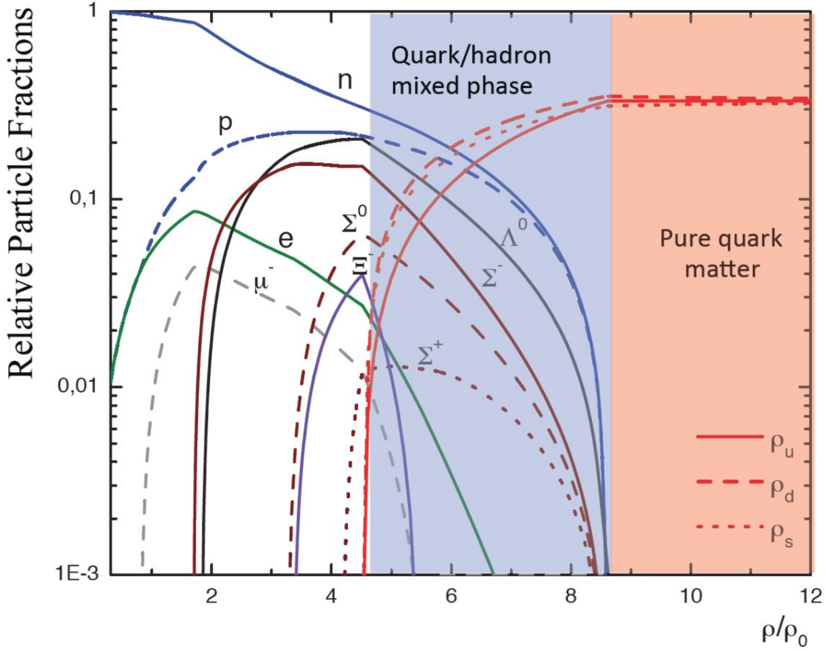
Introduction

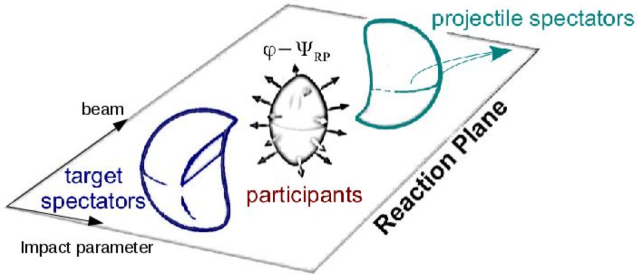
Strange particles are important probes of the medium created in HIC:

- 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

M. Orsaria et.al. PRC89 015806 (2014)





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

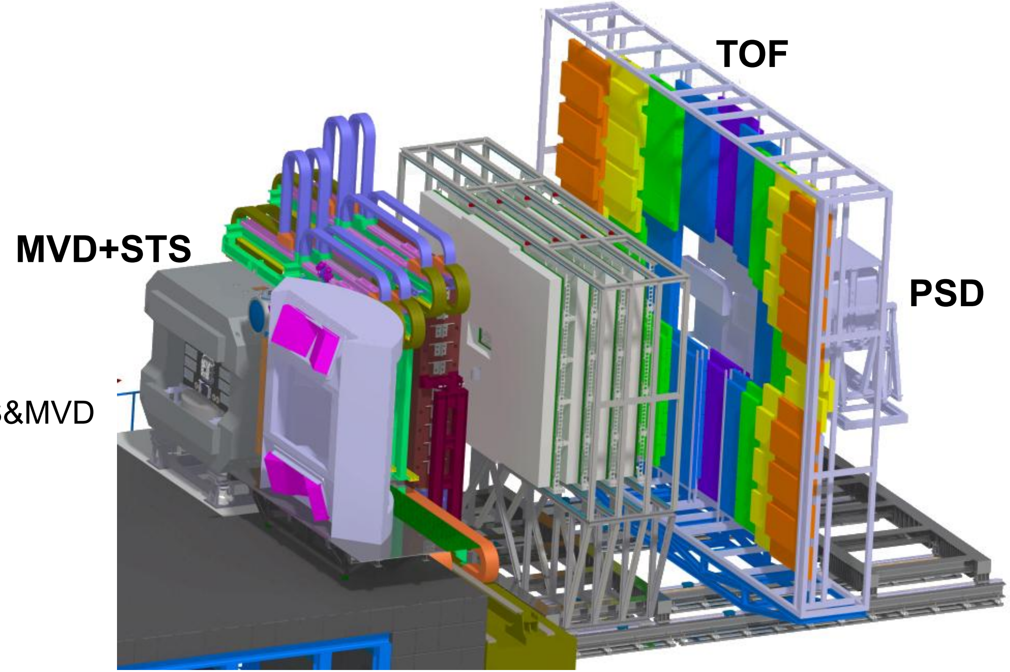
CBM experiment & detector subsystems relevant for hyperon flow measurements

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

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

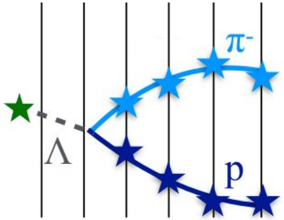
  - acceptance for Λ: $1 < y_{LAB} < 2.5$
  - Track reconstruction: 12 spatial points from STS&MVD
  - magnetic field: 1 Tm
  - momentum resolution: Δp/p ~ 1.5 - 2%
  - decay vertex resolution: 50-100 μm along z-axis

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



Short-lived particles decay reconstruction

Two implementations based on KFParticle mathematics:



KFPFinder (online optimized)
- fast and vectorized
- all-in-one package
- more than 150 decay channels
- V0 decay topology, missing mass method

M. Zyzak et. al. *https://git.cbm.gsi.de/CbmSoft/KFParticle*

PFSimple (physics analysis driven)
- user controlled reconstruction process, all intermediate variables written to the output

O. Lubynets et al.
https://git.cbm.gsi.de/pwg-c2f/analysis/pf_simple

parameter name	**#**	**source**
Track parameters (X, Y, Z, T_x, T_y, Q/P)	6	from CBM L1 tracking
Track charge	1	
Covariance matrix of track parameters	21	
Particle type hypotheses (PDG code)	1	TOF, MC PID, no PID
Magnetic field (MF): $B = (B_x, B_y, B_z)$ parameterized with parabolic function: $B_i = (a_i+b_i(r_i-r_{0,i})+c_i[r_i-r_{0,i}]^2)$	9	using CBM L1 functionality
Reference position for MF calculation: $r_0 = (0,0,z_0)$	1	position of the 1st hit
Primary vertex coordinates	3	from CBM tracking
In total: 42 parameters		

V0-decay reconstruction algorithm

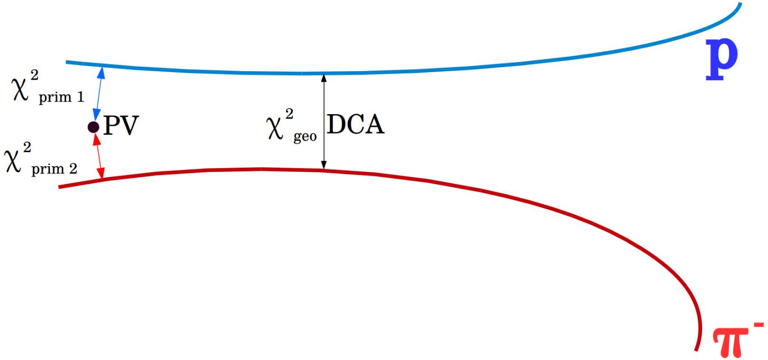
Each negative track is combined with each positive (PID hypothesis can be applied)

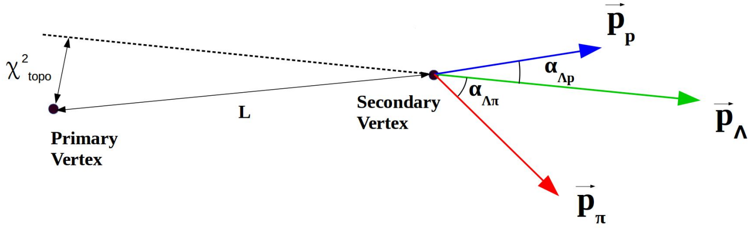
$$\chi^2 = (C^{-1}\Delta\mathbf{r})\Delta\mathbf{r} = C^{-1}_{ij}\Delta r_i \Delta r_j$$

where $\Delta\mathbf{r}$ is a distance between track and PV (between tracks) and C is a covariance matrix of the track

V0 selection cuts:

- χ^2_{prim} - squared distance $\Delta\mathbf{r}$ between the daughter track and the primary vertex divided by its error C
- **DCA** - distance of closest approach between proton and pion tracks
- χ^2_{geo} - squared distance $\Delta\mathbf{r}$ between daughters tracks divided by its error C
- $\alpha_{\Lambda p}$ - angle between proton and lambda momenta
- **L/ΔL** - distance between primary and secondary vertex divided by its error
- χ^2_{topo} - squared distance $\Delta\mathbf{r}$ between V0-candidate trajectory and the primary vertex divided by its error C





Software package: PFSimple by O.Lubynets et al.
based on KFParticle by M.Zyzak et al.

Λ hyperon flow analysis configuration

Simulation setup:

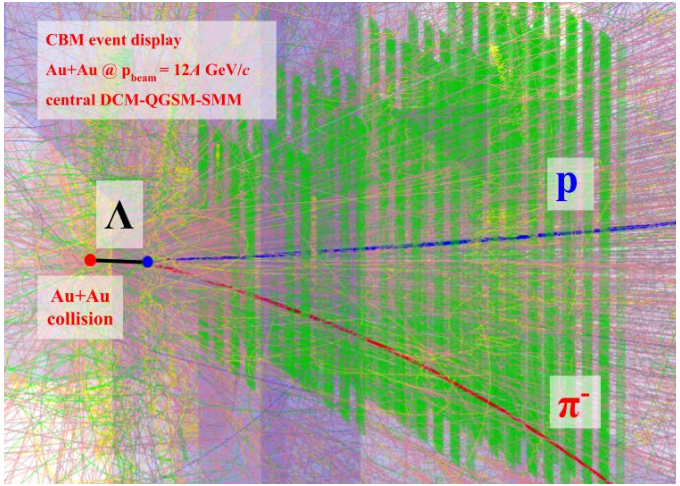
- 5M events
- Au+Au
- 12*A* GeV/*c*
- HI Event generator: DCM-QGSM-SMM
- GEANT4 transport

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:

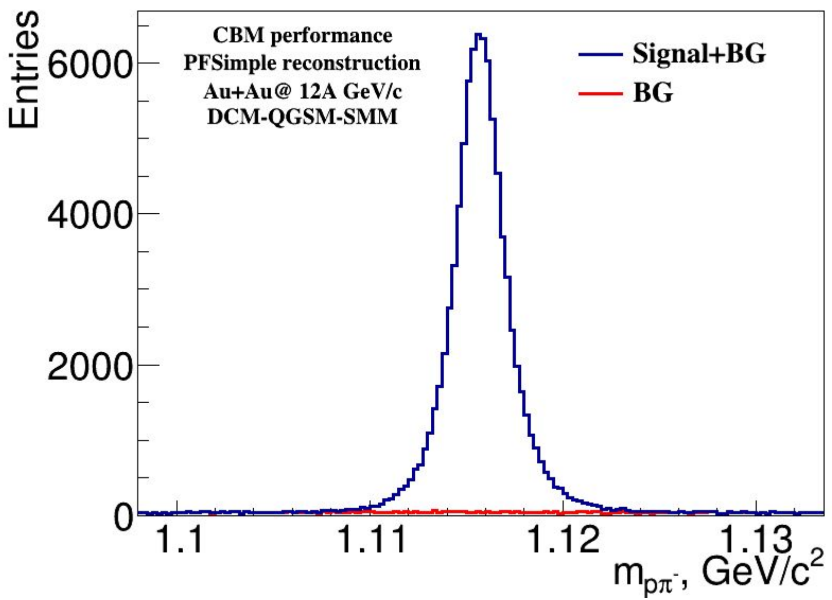
MC-true Λ: Λ's from HI event generator

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

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

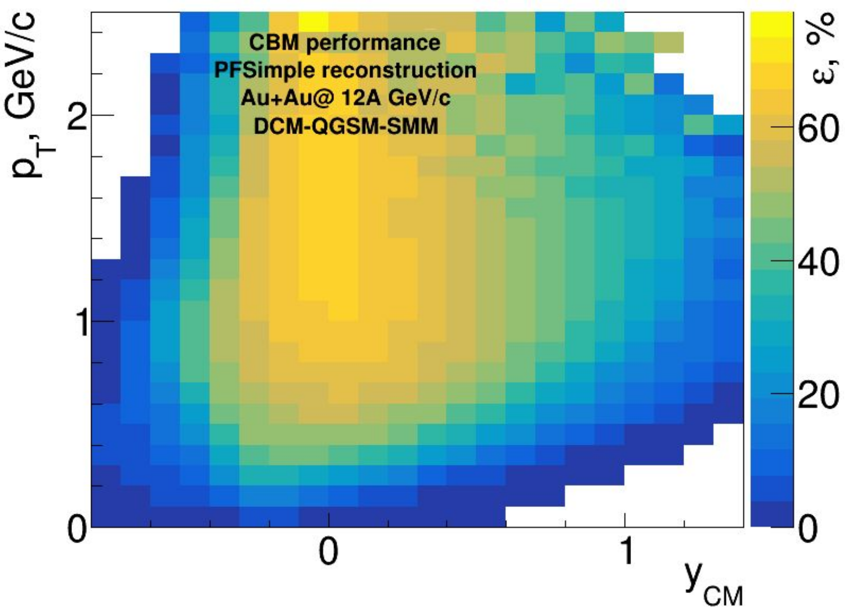
PFSimple performance for Λ reconstruction

Inv. mass distribution of Λ-candidates



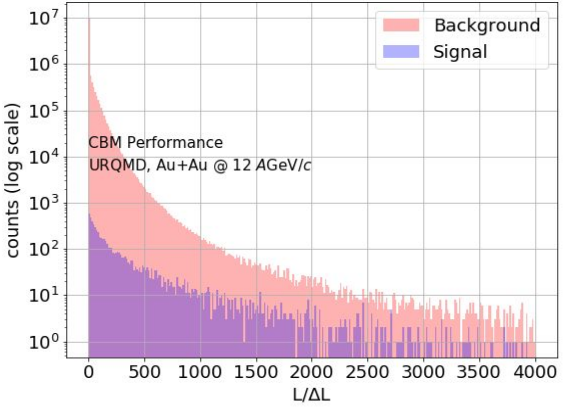
High signal to background ratio: S/B ≈30

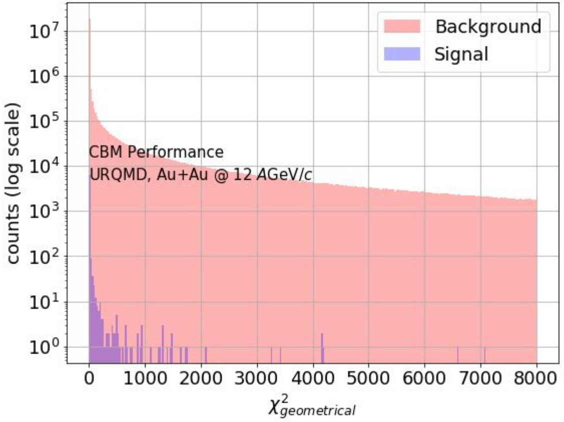
Reconstruction efficiency (p_T, y) and (φ, p_T)



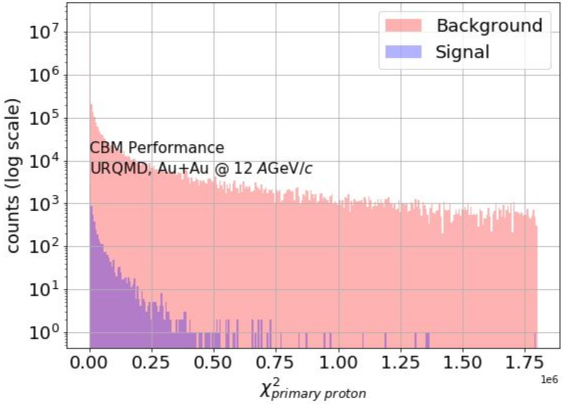
Non-uniformity in reconstruction efficiency can bias results. Need to be corrected.

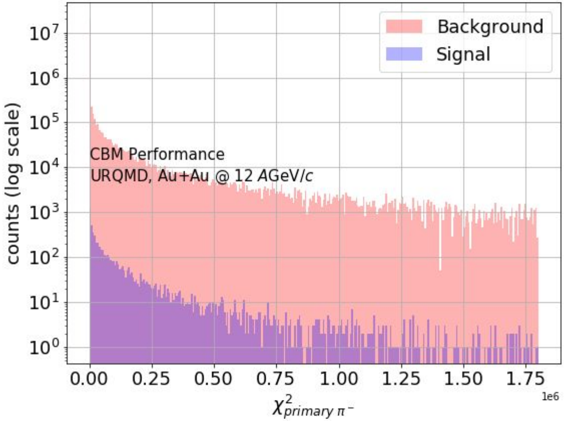
ML application for signal-background separation

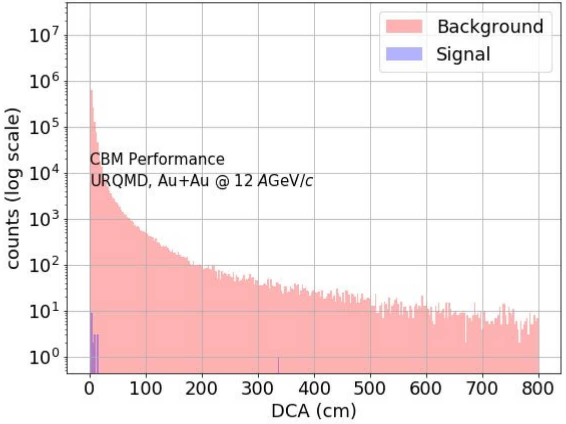




Distribution of MC signal (pure signal) and background plotted for the variables used in this study

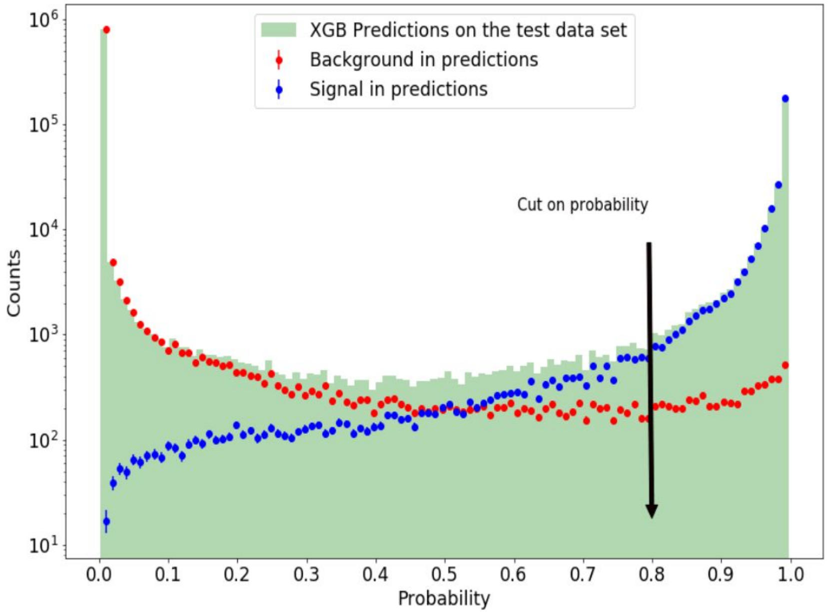


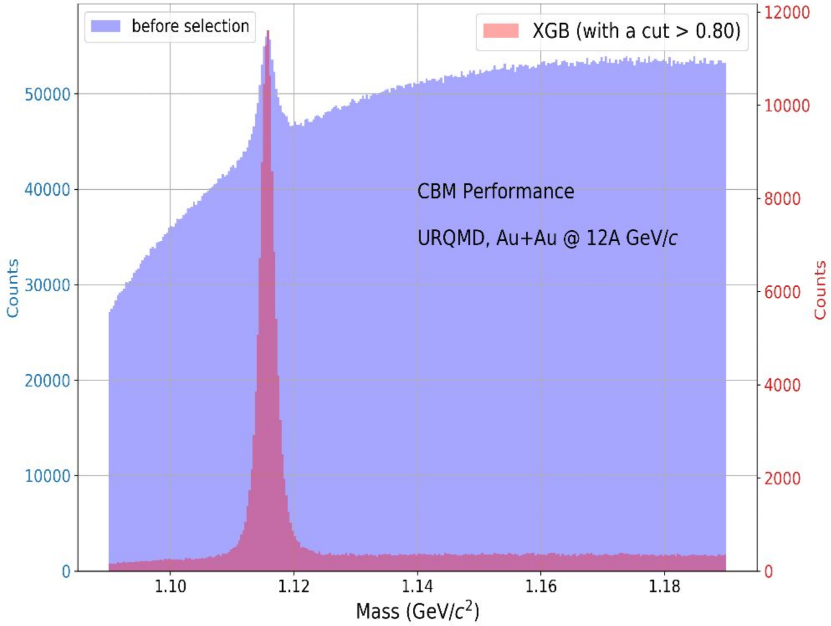




Selection criteria are optimized multi-dimensionally, non-linearly and in an automatized way with Machine Learning algorithms

ML application: performance



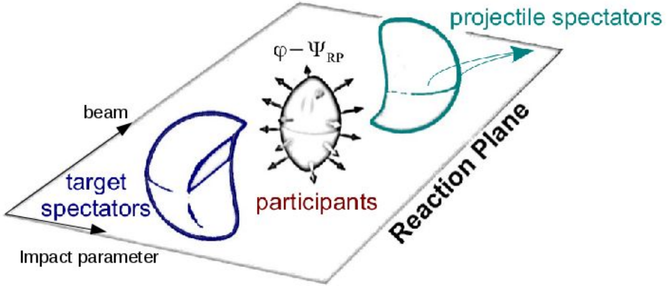


- XGB trained and tested model applied to DCM and URQMD 100k events
- Preserve smooth background shape after XGB selection

arXiv:2109.02435 by S. Khan et al.

Flow vector terminology

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



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

Reaction plane angle Ψ_{RP} is not known. Its estimation and corresponding resolution correction extraction using the spectators' energy registered with the PSD is is a topic of separate work [O. Golosov, 20 Sep, Section 4], and in current work the Ψ_{RP} from the event generator was used.

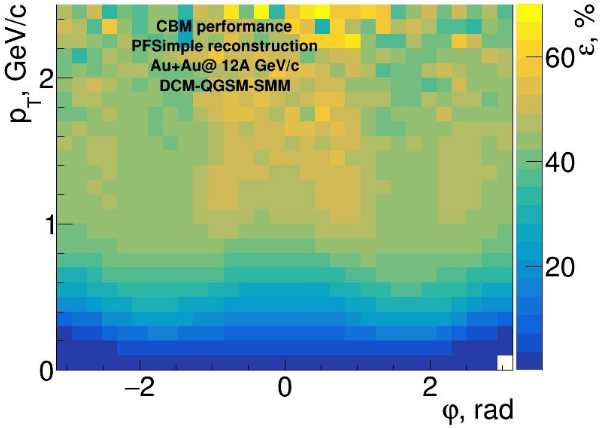
Two independent estimates from projections in the x and y direction of the laboratory frame are used:

$$v_{1x} = 2\langle\cos\varphi_\Lambda \cos\Psi_{RP}\rangle$$

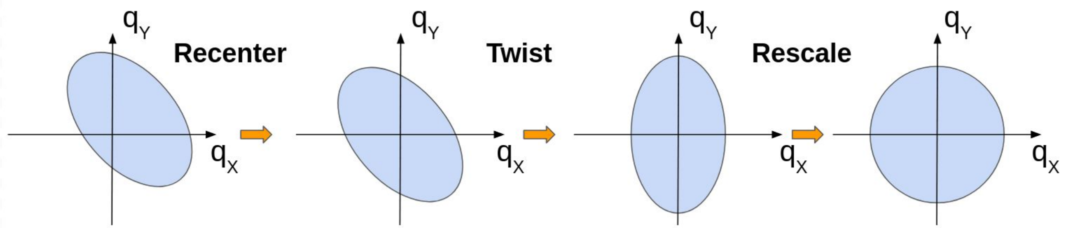
$$v_{1y} = 2\langle\sin\varphi_\Lambda \sin\Psi_{RP}\rangle$$

Flow vector $$\mathbf{q_1} = \{\cos\varphi_\Lambda, \sin\varphi_\Lambda\}$$

Corrections for detector non-uniformity



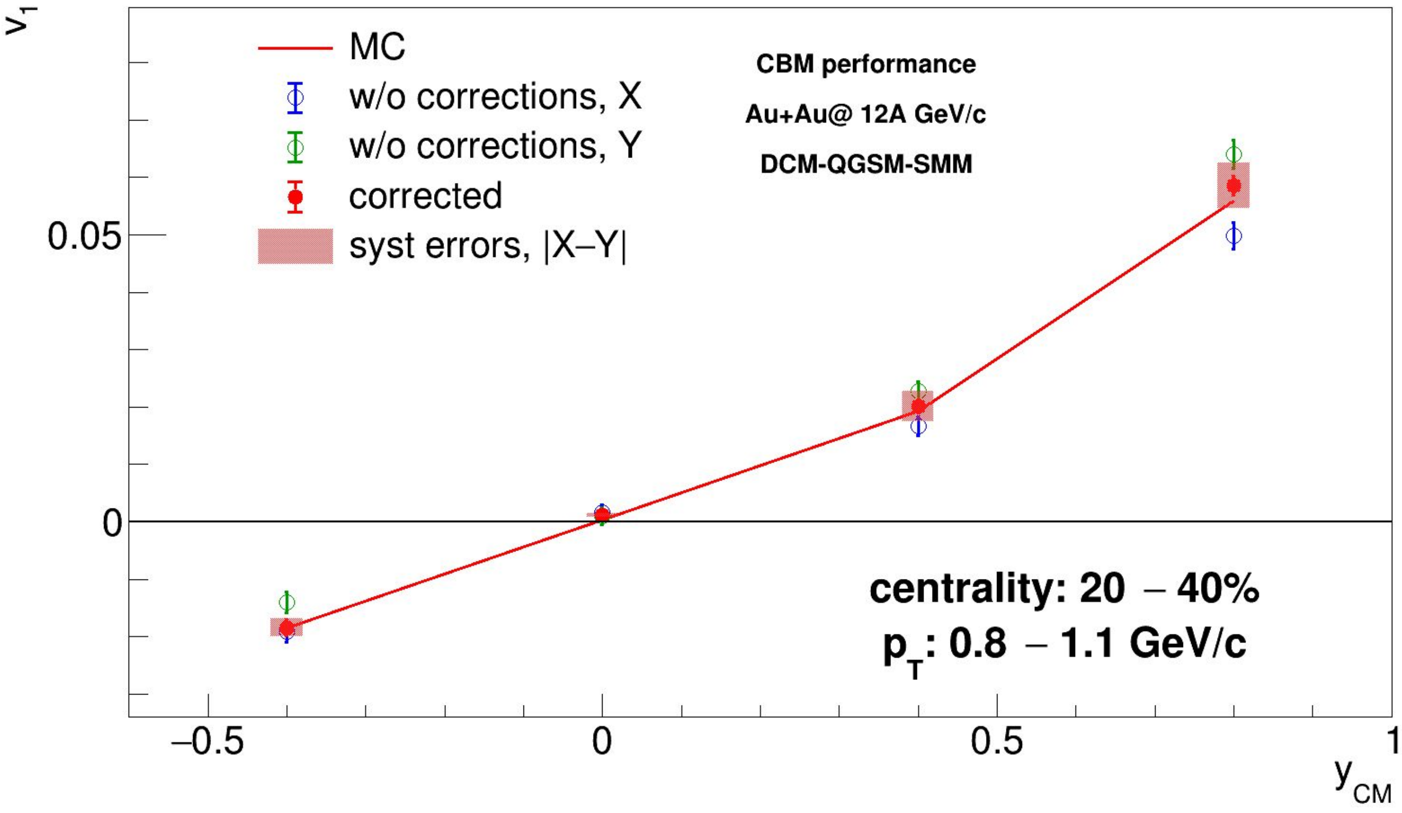
Correction for azimuthal non-uniformity:



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

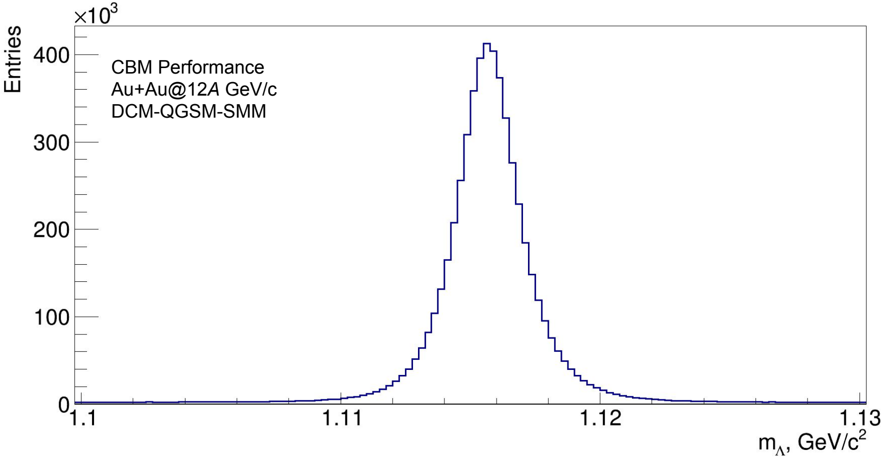
Non-uniformity of the Λ reconstruction in p_T and y is taken into account by weighting the Λ candidates in the v_1 calculation with the inverse value of efficiency for a given p_T and y region.

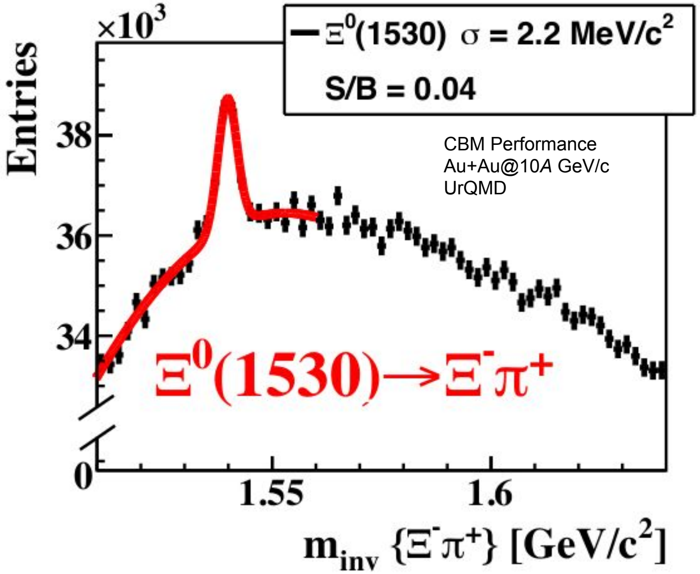
Corrections for detector non-uniformity



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

Signal and background in flow study: motivation

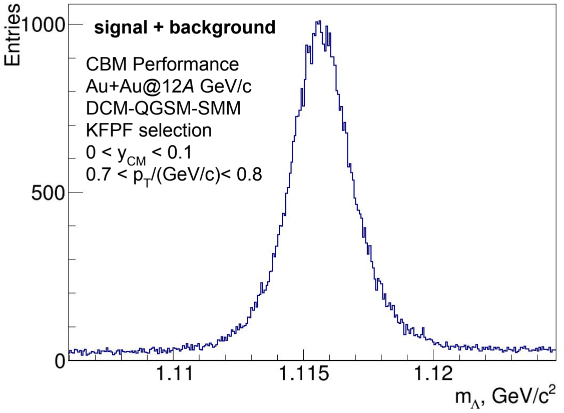


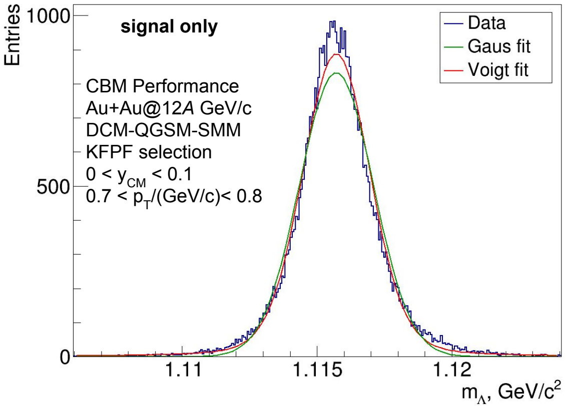


M. Zyzak, PhD thesis @ UFra, 2016

In case of large combinatorial background (e.g. multi-strange hyperons) need a procedure to separate contribution to v_n

v_n vs. invariant mass method





Voigt: $V(x,\sigma,\gamma) = \int_{-\infty}^{\infty} G(x\prime,\sigma)L(x - x\prime,\gamma)dx\prime$

Step 1.

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

- signal: Gaussian or Voigt (or template, or smth else)
- 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

Implemented in QnAnalysisDiscriminator package (work in progress)

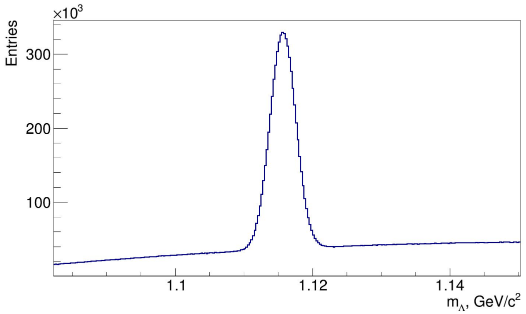
https://github.com/lubynets/QnAnalysis/tree/discriminator/src/QnAnalysisDiscriminator by O. Lubynets et. al.

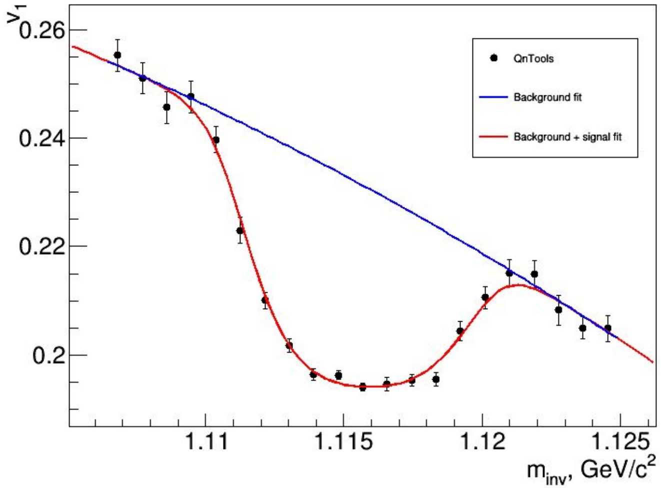
Toy MC illustration of v_n vs. invariant mass method

- Input yield:
  - signal: inv mass distribution: Norm * Gaus(μ, σ)
  - background: 2^{nd} order polynomial

    Norm * $(1 + a_1 (x-\mu) + a_2 (x-\mu)^2)$
- Input flow:
  - $v_{1,s}$ = const
  - 2^{nd} order polynomial

    $(b_0 + b_1 (x-\mu) + b_2 (x-\mu)^2)$

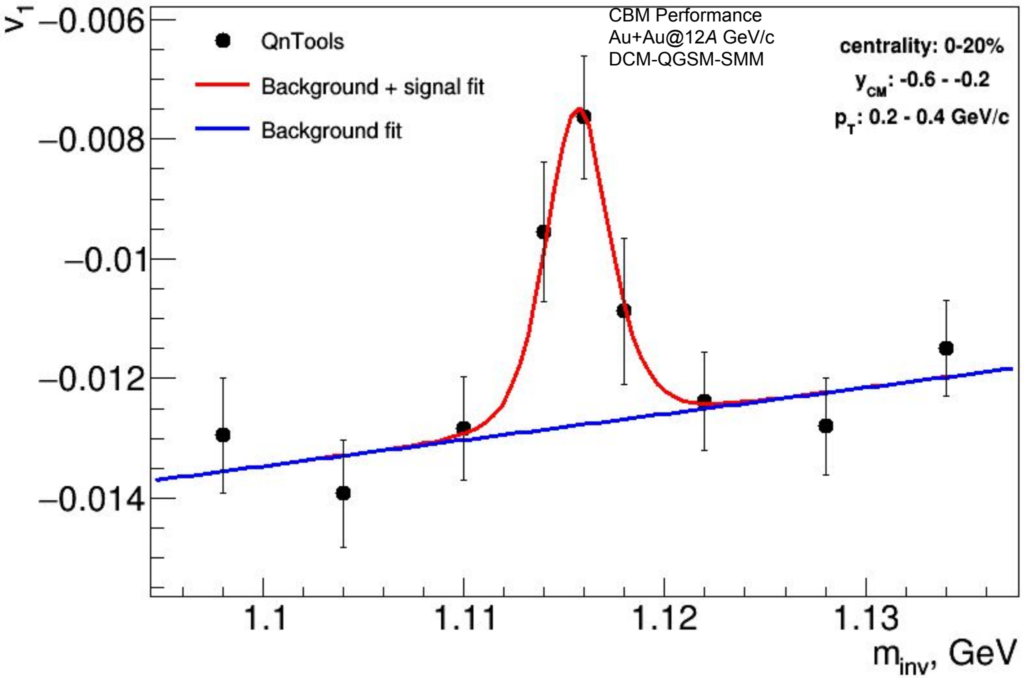


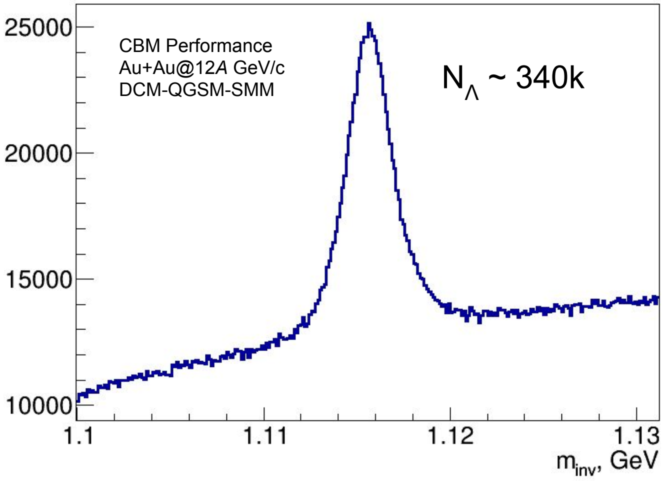


reproduced input within statistical precision of the simulated sample

$v_1(m_{inv})$ fit

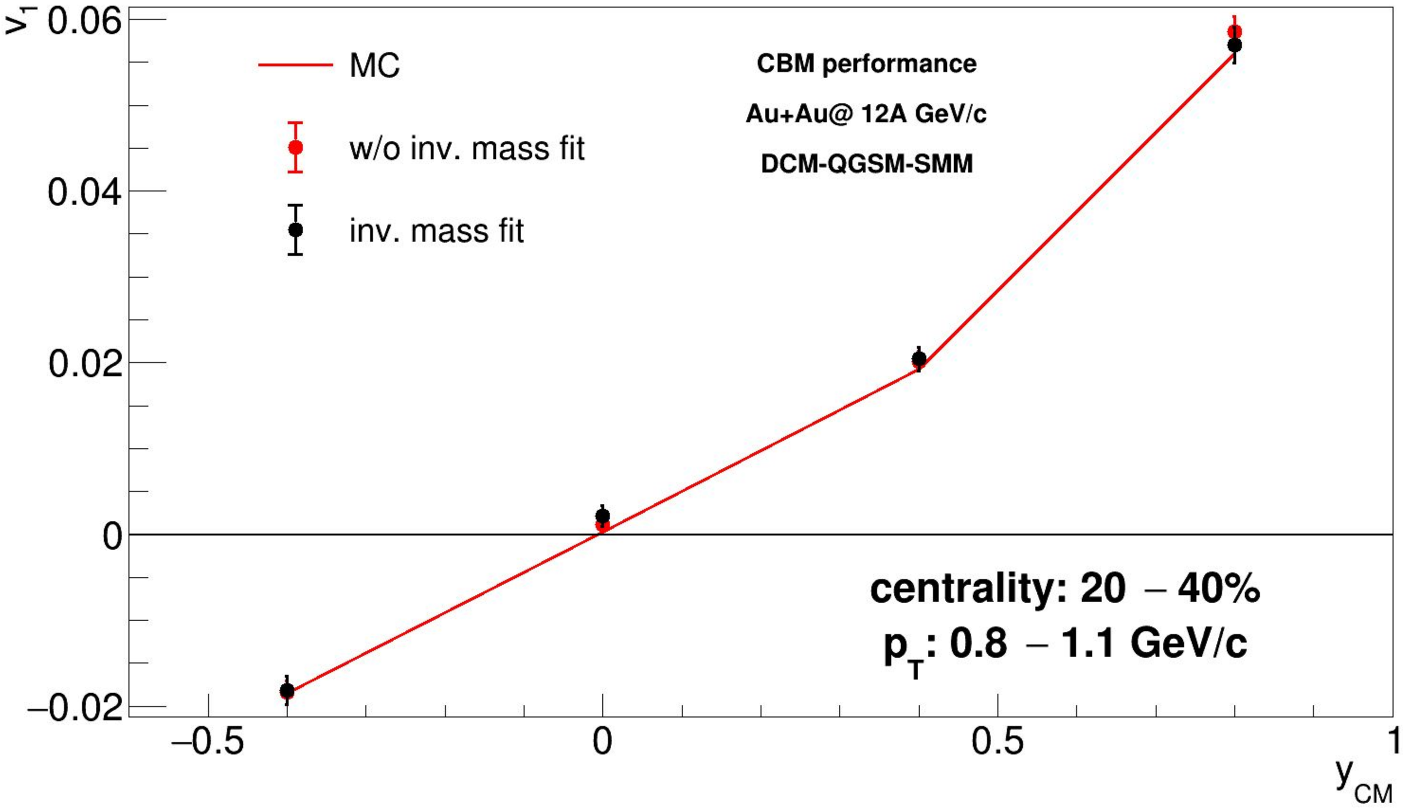
- Cuts relaxed in order to increase amount of background
- Signal & background shape: from MC-true
- Background flow (v_{bckgr}): linear function





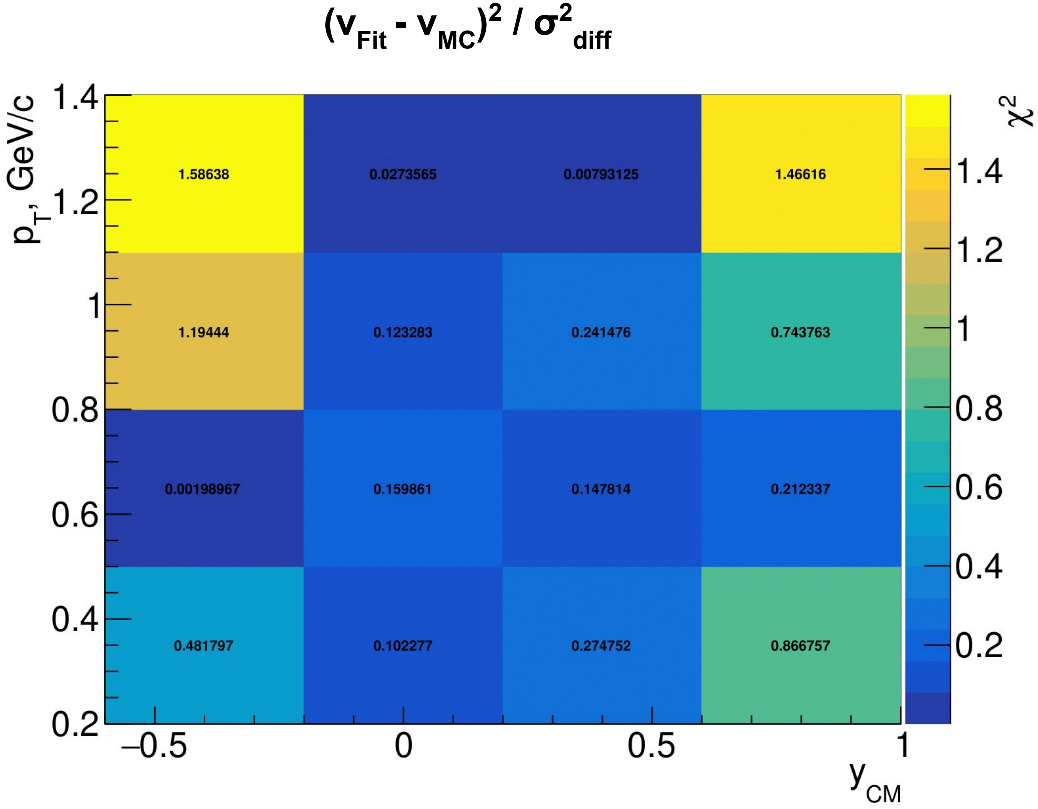
Param	Fit result	Expected (from independent fit of v_{signal} & v_{bckgr})
$v_{1,s}$	-0.0016 ± 0.0020	-0.0019 ± 0.0010
b_0	-0.0128 ± 0.0003	-0.0127 ± 0.0003
b_1	0.044 ± 0.03	0.041 ± 0.03

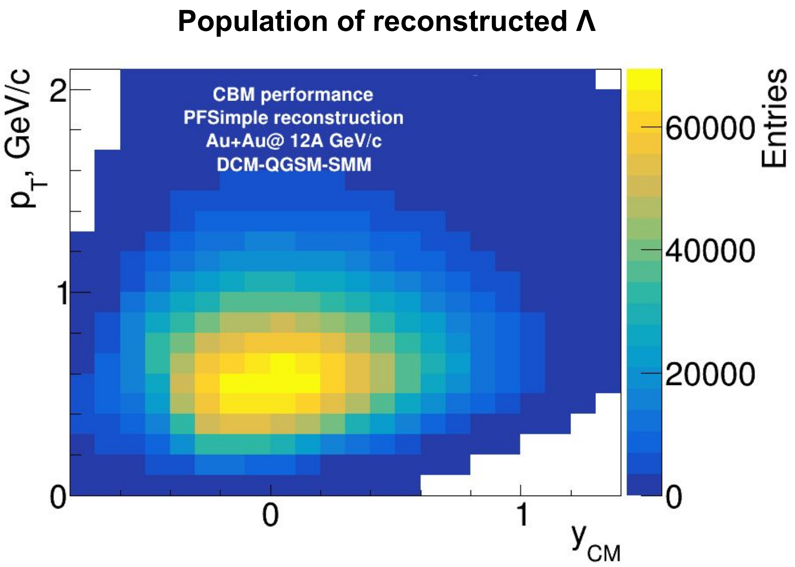
Result of the $v_1(m_{inv})$ fit



v_1 calculated using invariant mass fit method coincides within statistical errors with v_1 calculated using MC-matching for separation signal from background

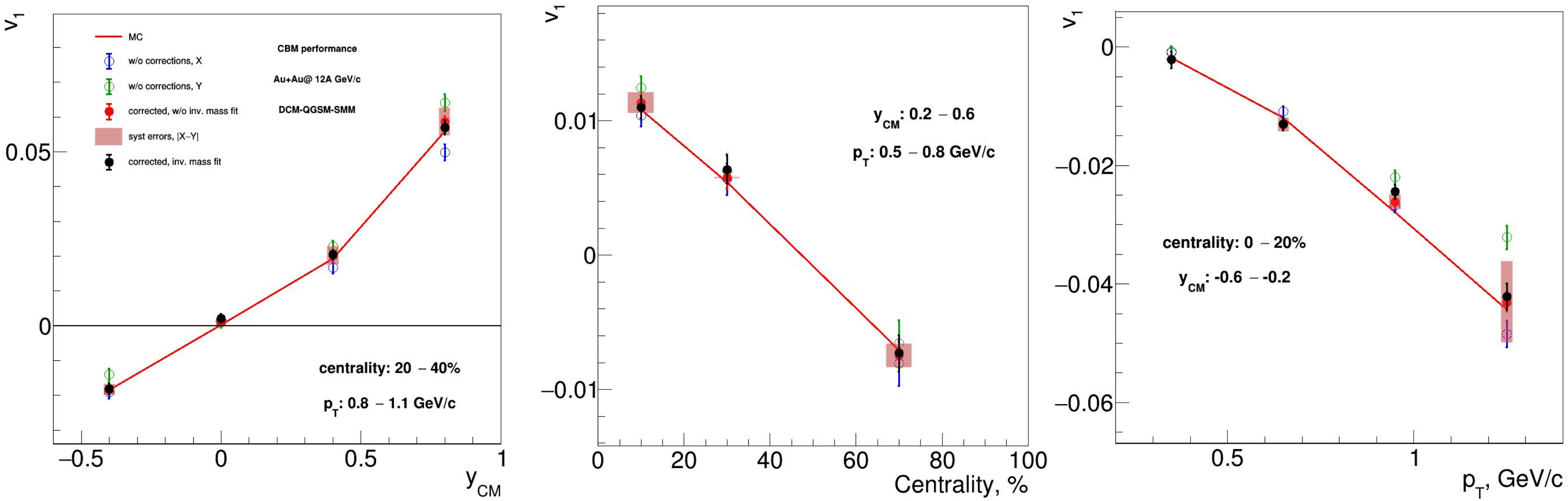
Multi-differential results for $v_1(p_T, y)$: comparison with MC input





In general v_1 calculated using invariant mass fit method coincides within statistical errors with v_1 calculated using MC-matching for separation signal from background. Existing discrepancies correspond to phase space areas with small Λ population.

v_1 (p_T, y, centrality) dependence



- A positive slope of Λ $v_1(y)$ is reproduced, with v_1 being consistent within the statistical precision with the Monte Carlo input values
- The sign change of v_1 with centrality around 50% is reproduced
- A negative slope of Λ $v_1(y)$ is reproduced
- v_1 calculated using invariant mass fit method coincides within statistical errors with v_1 calculated using MC-matching for separation signal from background

Summary

- Performance of the CBM experiment for the measurements of the directed flow of Λ hyperons was investigated
- After applying corrections for φ, y, p_T non-uniformity the Monte Carlo input is reproduced within the statistical precision
- Invariant mass fit method for signal extraction gives results consistent with MC-based signal extraction

Outlook

- Use the data-driven procedure for the reaction plane estimation with the PSD
- Develop further the invariant mass fit method for signal–background separation
- Perform multi-differential p_T, y and centrality analysis
- Include higher harmonics and (multi)strange particles in analysis
- Use ML-based optimization of selection criteria

Acknowledgements

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