Performance for Λ hyperon anisotropic flow measurements in CBM at FAIR

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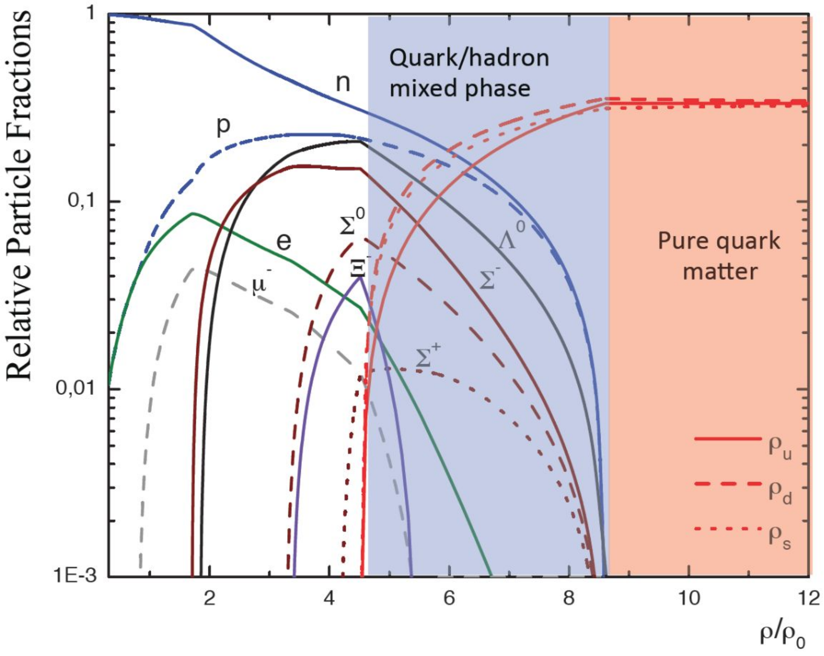
Introduction

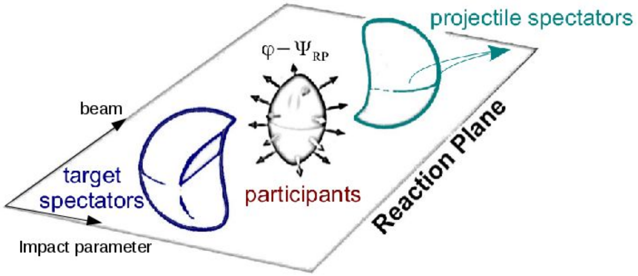
Strange particles are important probes of the medium created in HIC:

- 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 of nuclear matter

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





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:

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

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

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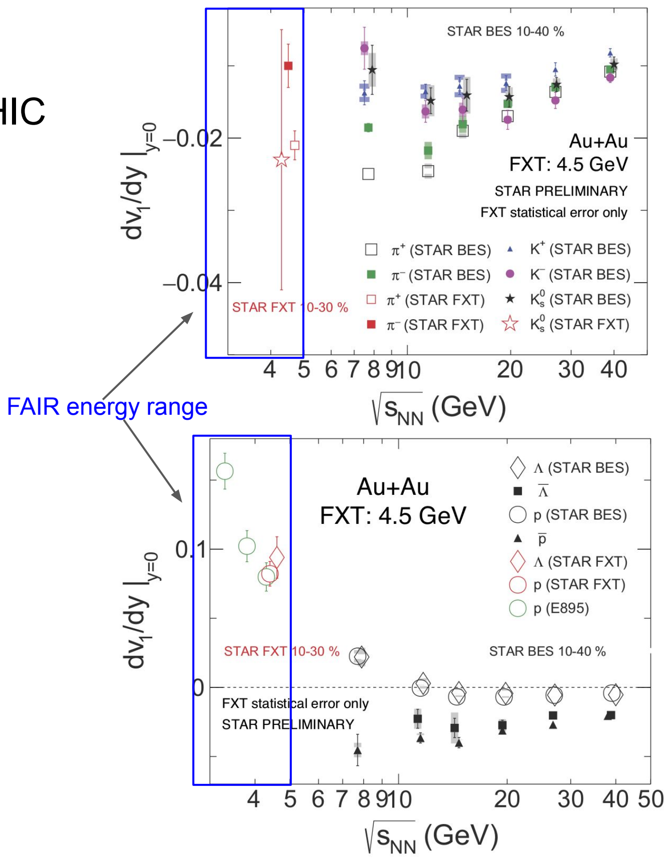


Event plane method

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

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

$$\mathbf{Q}_n = \sum_{i=1}^{M_Q} w_i \mathbf{u}_{n,i}$$

in case of w=1

$$\mathbf{Q}_n = \sum_{i=1}^{M_Q} \mathbf{u}_{n,i}$$

Estimation of the reaction plane angle

$$\Psi_{EP}^n = \frac{1}{n} atan2(Q_x^n, Q_y^n)$$

One needs to use the resolution correction factor R_n,
which quantify how well the estimation of the event plane is correlated with ψ_{RP}.

$$R_n = \langle \cos n(\Psi_{RP} - \Psi_{EP}^n)\rangle$$

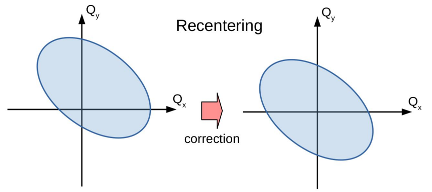
$$\mathbf{q}_n(p_T, y) = \sum_{i=1}^{M_u} w_i \mathbf{u}_{n,i} / \sum_{j=1}^{M_u} w_j$$

The observable for v_n becomes:

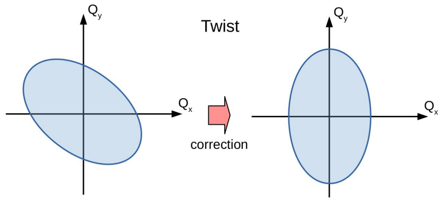
$$v_n = \frac{1}{R_n} \langle \mathbf{q}_n \frac{\mathbf{Q}_n}{|\mathbf{Q}_n|}\rangle$$

Corrections for azimuthal non-uniformity

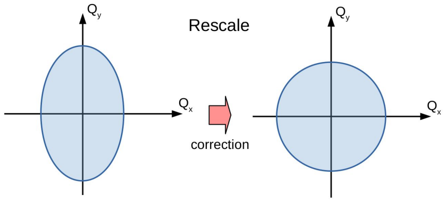
Non-uniformity of experimental setup in φ
(fiducial volume, magnetic field, additional material etc.)
biases results for flow observables



Subtracting from the q-vector components their average values



Rotating the q-vector distribution



Rescaling q-vector distribution in (x,y) directions

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: V. Klochkov and I. Selyuzhenkov, https://git.cbm.gsi.de/pwg-c2f/analysis/flow

Closure test of the efficiency implementation in QnTools

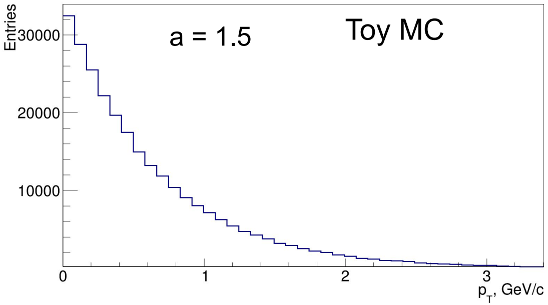
MC toy model setup

- Simulated input (sim):
  - $\frac{dN}{dp_T} \sim e^{-ap_T}$
  - $\frac{dN}{dy} \sim e^{-\frac{(y-y_{beam})^2}{\sigma_y}}$
  - $v_1(p_T, y) = v_1(p_T) = \langle \cos(\varphi - \Psi_{RP}) \rangle = 0.1 p_T$
  - ~ 30 M test particles
- Model reconstruction efficiency
  - $\varepsilon(p_T, y) = \varepsilon(p_T) = k\ p_T + b \quad (k > 0)$
- Correlations with q-vector weight:

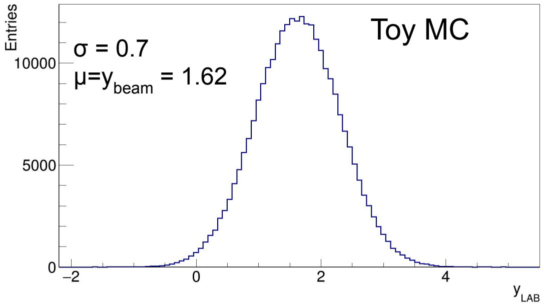
$$w_i(p_T, y) = \frac{1}{\varepsilon(p_{Ti}, y_i)}$$

- Compare framework output with the known input

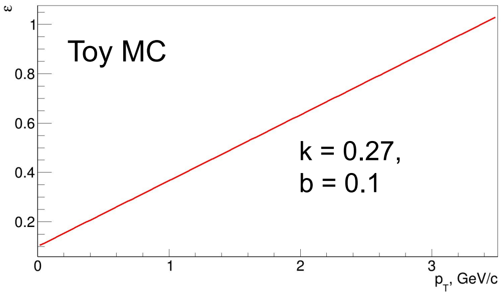
dN/dp_T



dN/dy

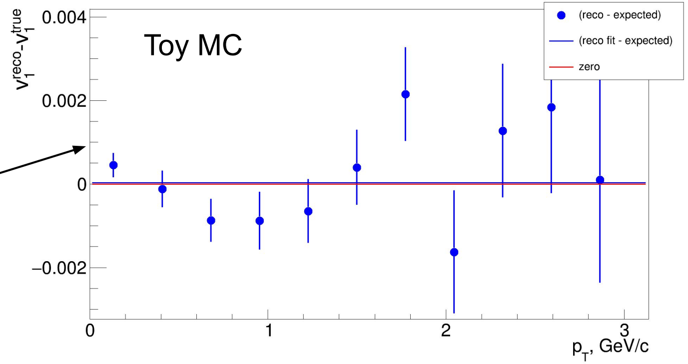


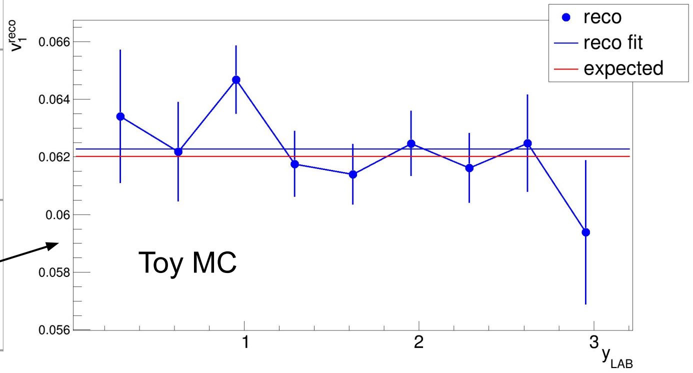
$\varepsilon\ (p_T)$



MC closure test outcome

Conditions	Quantity	Parameter	Expected*)	Calculated with QnTools
100% reconstruction	$v_1(p_T)$	Slope	0.1	0.1000±0.0003
		Intercept	0	$(-3.9 \pm 2.6) \cdot 10^{-4}$
	$\langle v_1 \rangle_y = \frac{\int v_1 dp_T}{\int dp_T}$	Integral	$6.20 \cdot 10^{-2}$	$(6.19 \pm 0.02) \cdot 10^{-2}$
Non-uniform reconstruction efficiency, no weights applied	$\langle v_1 \rangle_y = \frac{\int v_1 dp_T}{\int dp_T}$	Integral	$9.53 \cdot 10^{-2}$	$(9.54 \pm 0.04) \cdot 10^{-2}$
Non-uniform reconstruction efficiency, weights applied			$6.20 \cdot 10^{-2}$	$(6.23 \pm 0.05) \cdot 10^{-2}$





*) Set as an input or calculated analytically

Conclusion: With QnTools input flow values are reproduced within statistical precision of the simulated sample

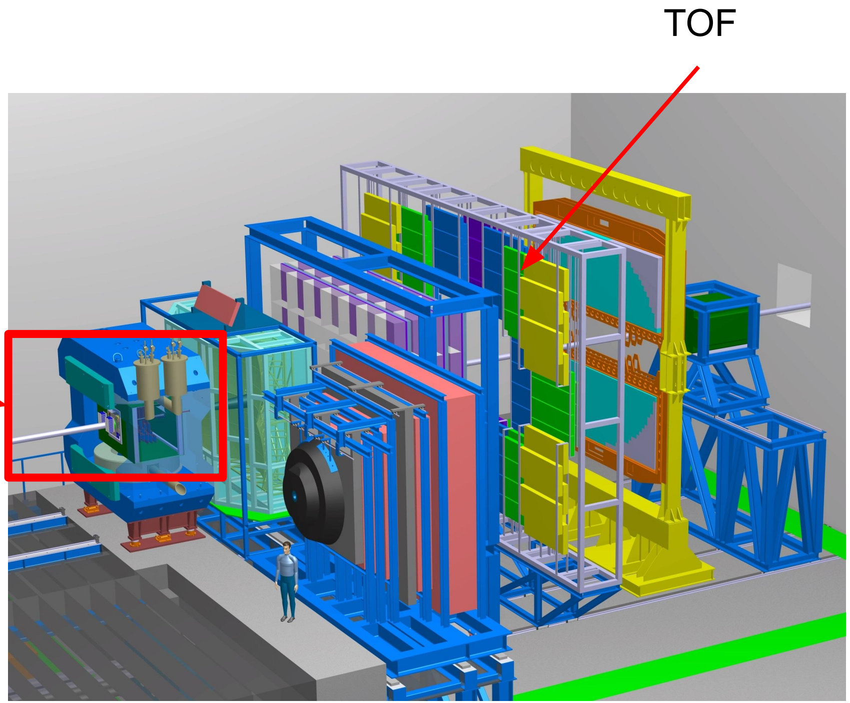
CBM experiment & detector subsystems relevant for hyperon reconstruction

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

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

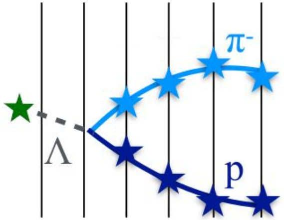
  - acceptance for Λ: $1 < y_{LAB} < 2.5$
  - Track reconstruction: 12 spatial points from STS&MVD
  - magnetic field: 1 Tm
  - momentum resolution: Δp/p~1.5-2%
  - decay vertex resolution: 50-100 μm along z-axis

- Charged hadrons identification:
  Time of Flight (TOF)



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, V. Klochkov, I. Selyuzhenkov,
https://git.cbm.gsi.de/pwg-c2f/analysis/pf_simple

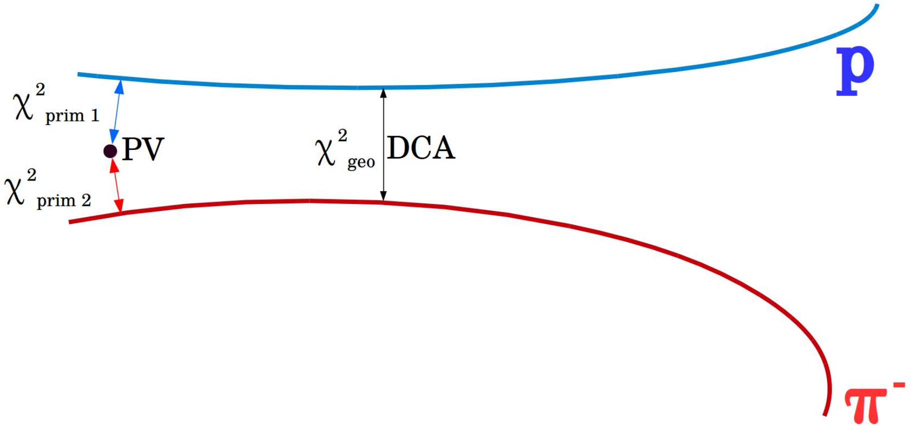
parameter name	**#**	**source**
Track parameters (X, Y, Z, T_x, T_y, Q/P)	6	from CBM L1 tracking
Track charge	1	
Covariance matrix of track parameters	21	
Particle type hypotheses (PDG code)	1	TOF, MC PID, no PID
Magnetic field (MF): $B = (B_x, B_y, B_z)$ parameterized with parabolic function: $B_i = (a_i+b_i(r_i-r_{0,i})+c_i[r_i-r_{0,i}]^2)$	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		

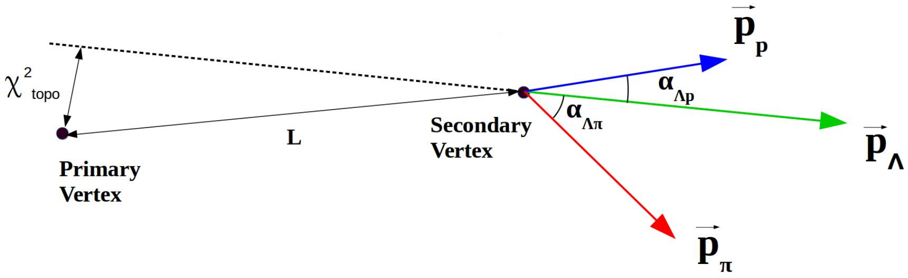
V0-decay reconstruction algorithm

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

V0 selection cuts:

- χ^2_{prim} - χ^2 of extrapolation of the daughter track to the primary vertex
- **DCA** - distance of closest approach between proton and pion tracks
- χ^2_{geo} - χ^2 of extrapolation of daughter tracks to their point of closest approach
- $\alpha_{\Lambda p}$ - angle between proton and lambda momenta
- **L/ΔL** - distance between primary and secondary vertex divided by its error
- χ^2_{topo} - χ^2 of extrapolation of the V_0-candidate trajectory to the primary vertex





Λ hyperon flow analysis configuration

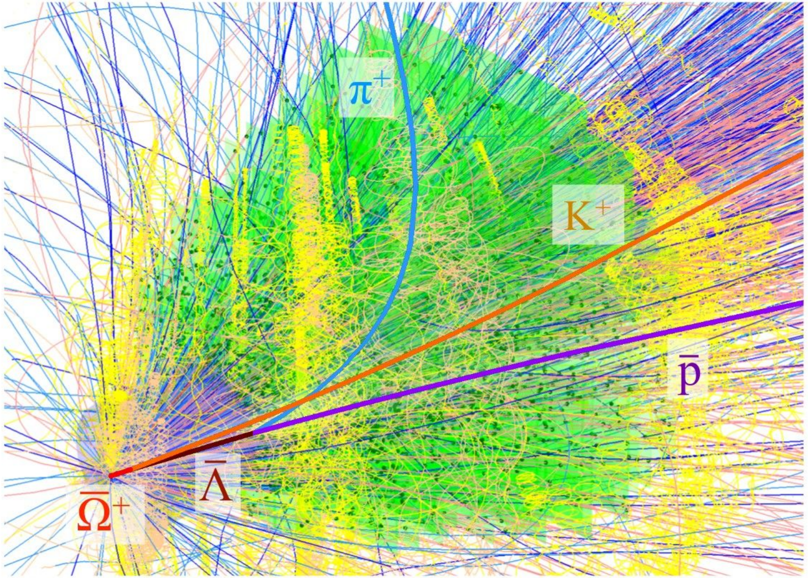
Simulation setup:

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

Λ-candidates selection cuts:

- $\chi^{2\ pos}_{\ prim}$ = 26
- $\chi^{2\ neg}_{\ prim}$ = 110
- $\cos\alpha_{\Lambda p}$ = 0.99825
- L/ΔL = 4
- DCA = 0.15 cm
- $\chi^2_{\ geo}$ = 11
- $\chi^2_{\ topo}$ = 29
- PID selection:
  GEANT PDG code of daughters

CBM event display



Λ hyperon categories:

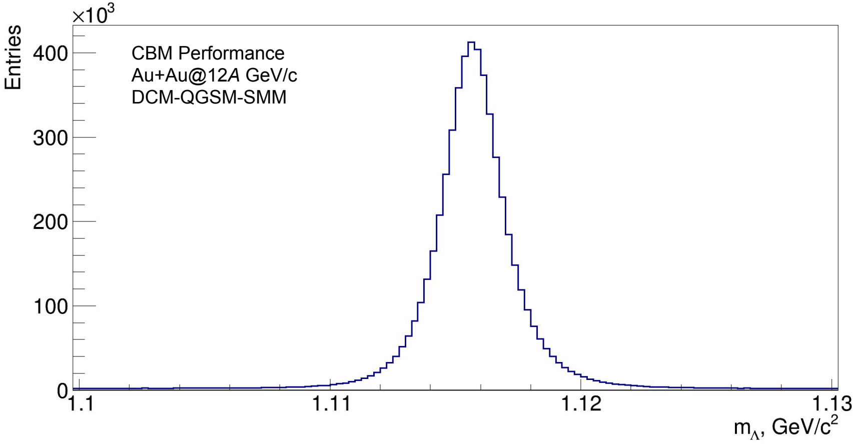
MC-true Λ: Λ's from HI event generator

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

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

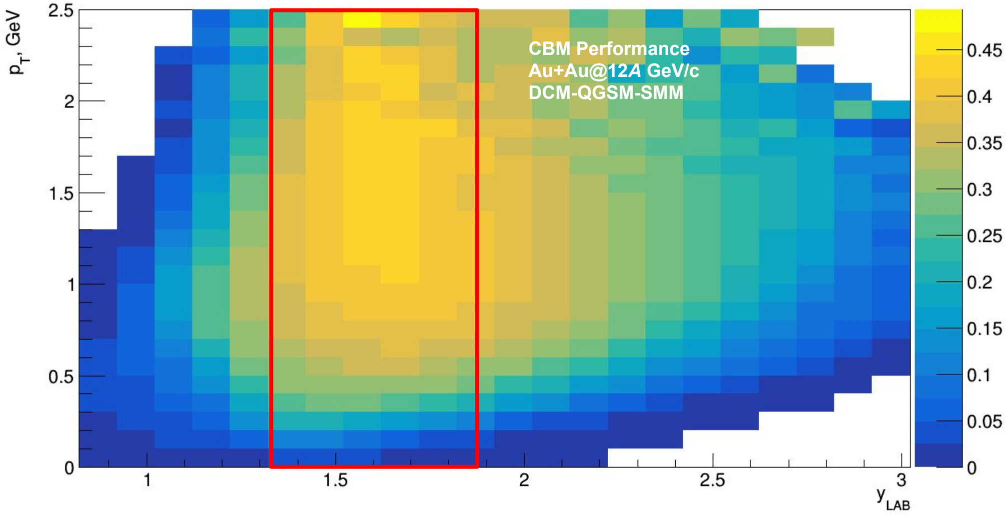
PFSimple performance for Λ reconstruction

Inv. mass distribution of Λ-candidates



High signal to background ratio: S/B ≈30

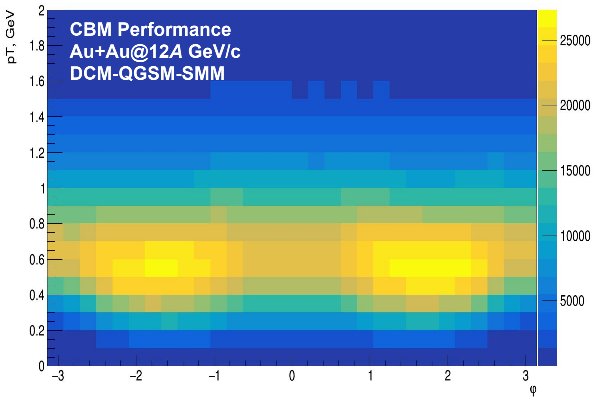
Reconstruction efficiency (p_T, y)



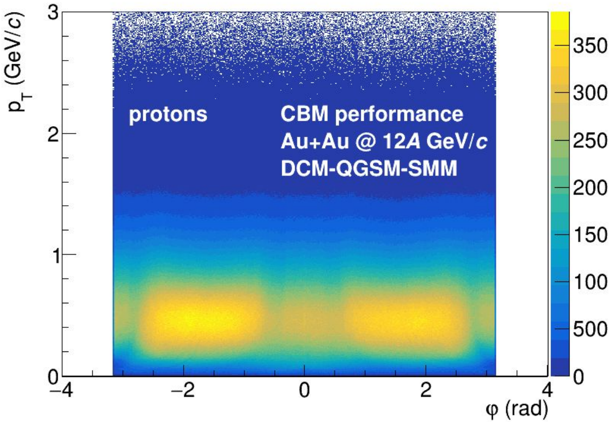
Good reconstruction efficiency in the midrapidity region

Azimuthal non-uniformity of Λ reconstruction

reconstructed Λ



primary protons (see O. Golosov)

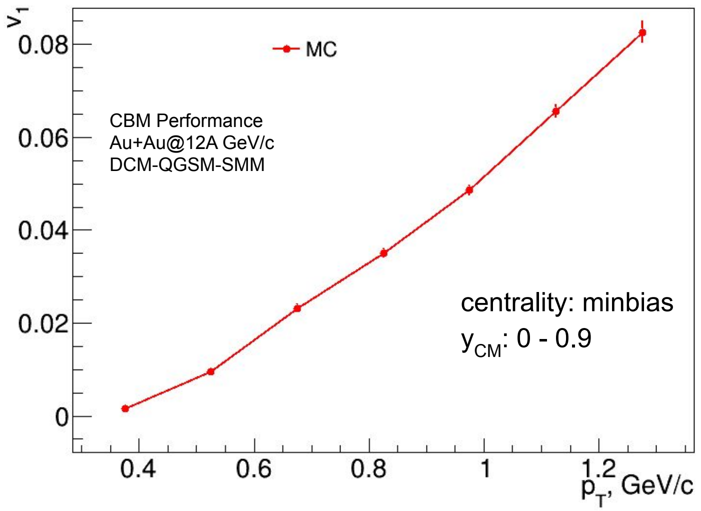


Λ azimuthal non-uniformity is driven by proton's daughter non-uniformity ($m_{pion} << m_p \sim m_\Lambda$)

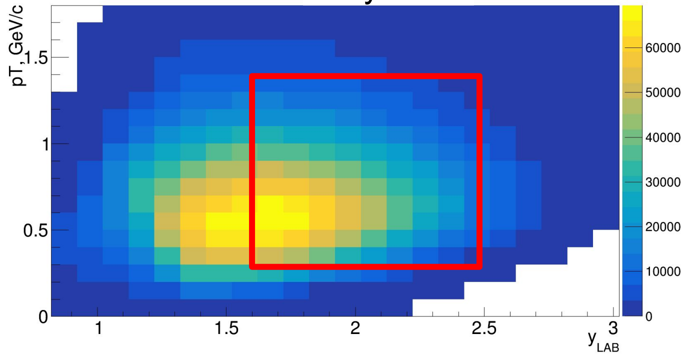
Require differential corrections for non-uniform azimuthal acceptance: Use QnTools for analysis

Systematics in Λ hyperon v_1 analysis

Input v_{1x}



raw yield of Λ



- Separate x/y correlations for detector effects study:

$$v_{1x} = \langle q_{1x} \cos \Psi_{RP} \rangle$$

$$v_{1y} = \langle q_{1y} \sin \Psi_{RP} \rangle$$

- Correct effect of (p_T,y)-dependent efficiency via q-vector weights:

$$\mathbf{q}_n = \sum_{i=1}^{M} w_i \mathbf{u}_{n,i} / \sum_{j=1}^{M} w_j$$

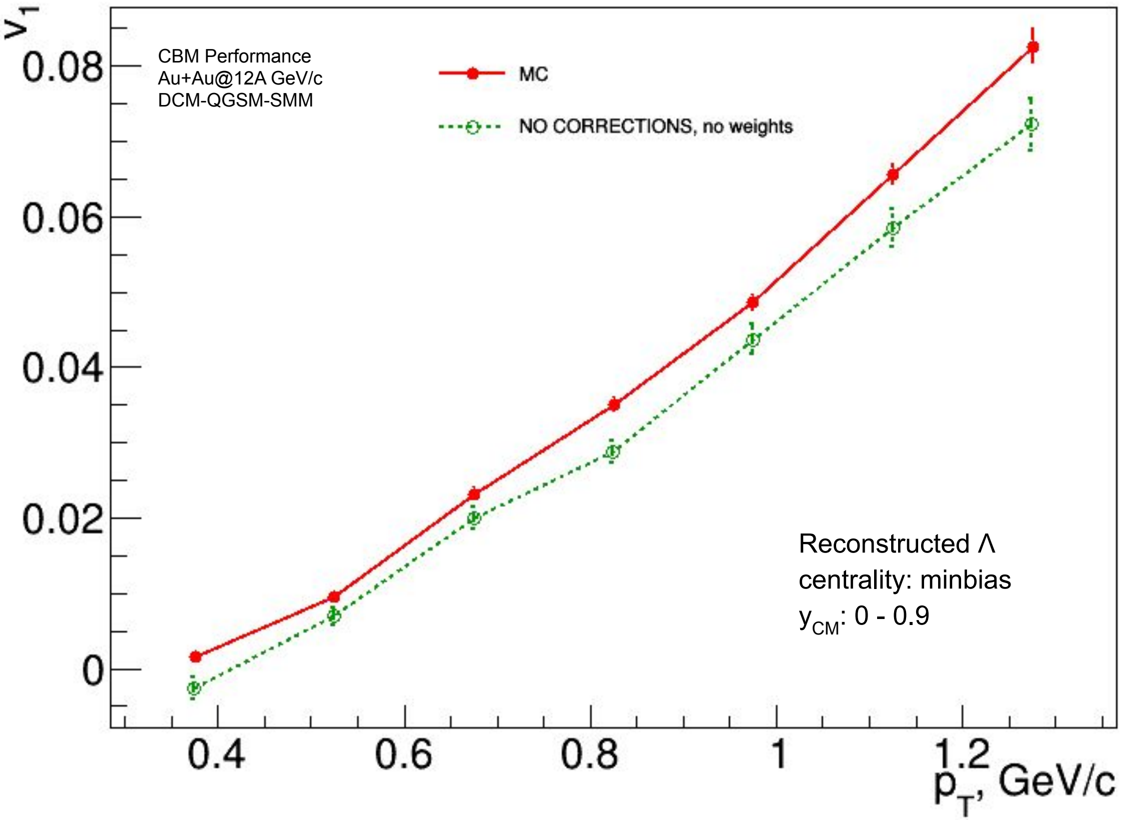
- Different correction steps applied with QnTools

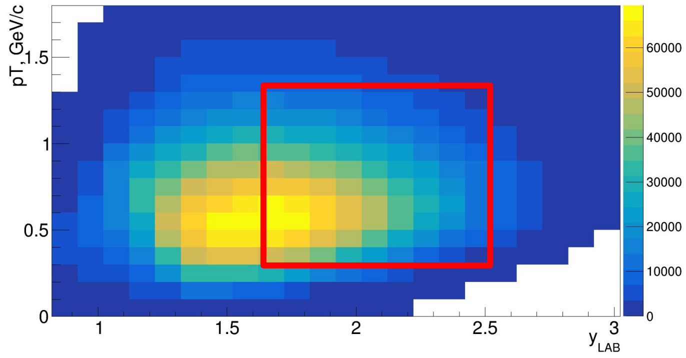
Red box indicates acceptance region used for analysis

All following results are calculated relative to ψ_{RP}

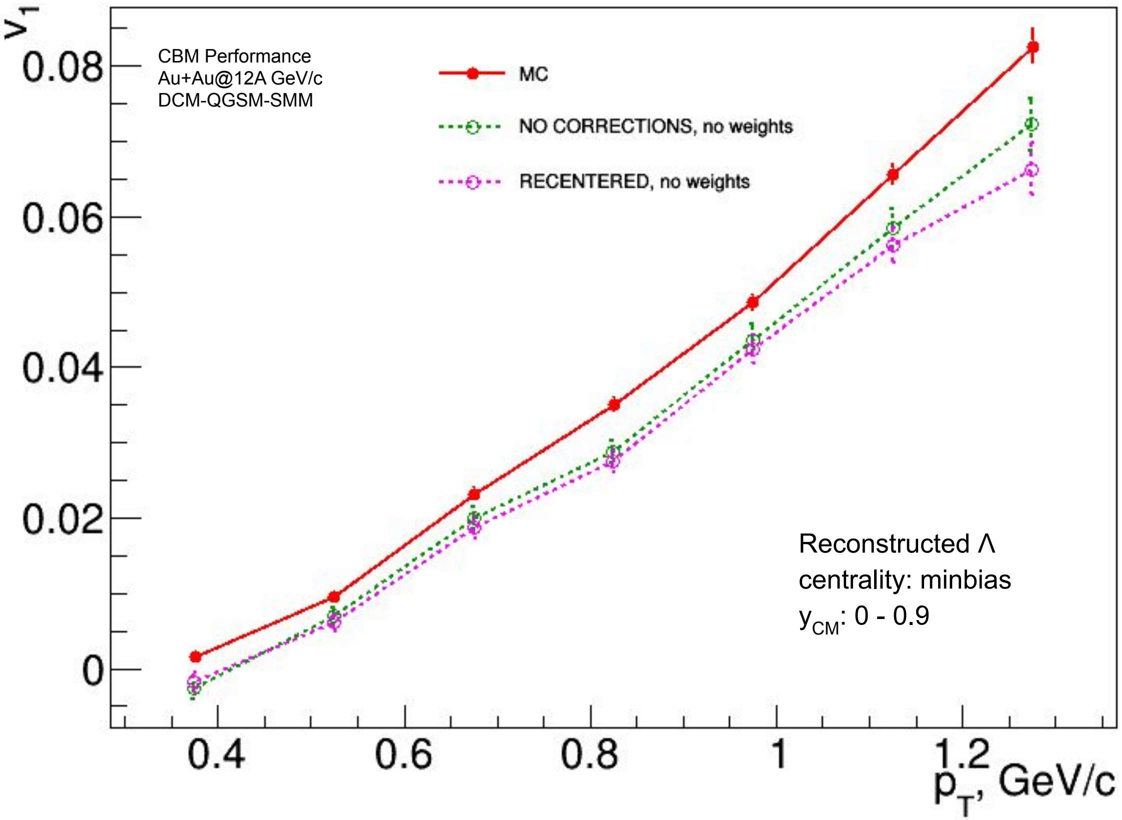
PSD plane resolution study:
see talk by O. Golosov (27/08)

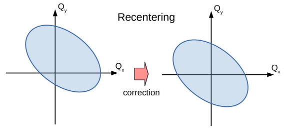
p_T-dependence of $v_{1,x}$: no corrections

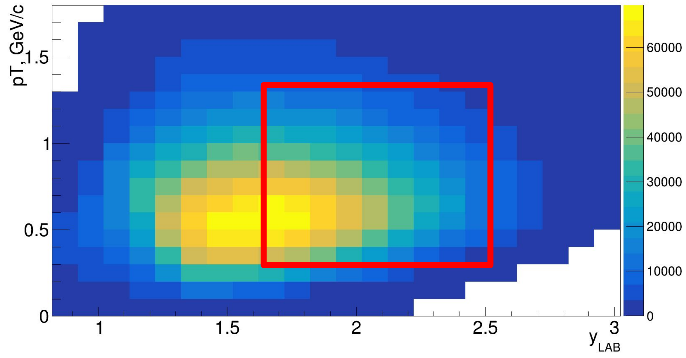




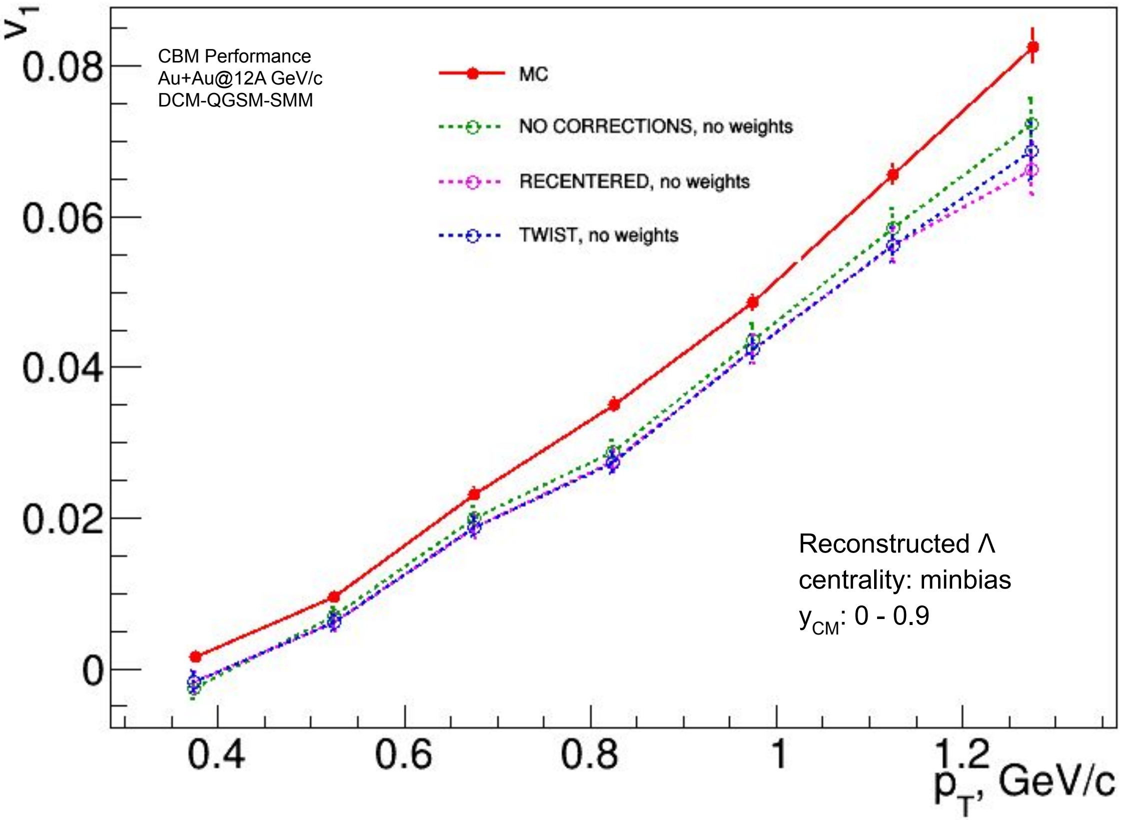
p_T-dependence of $v_{1,x}$: recentering

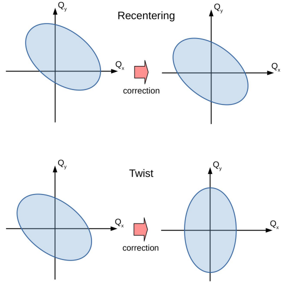


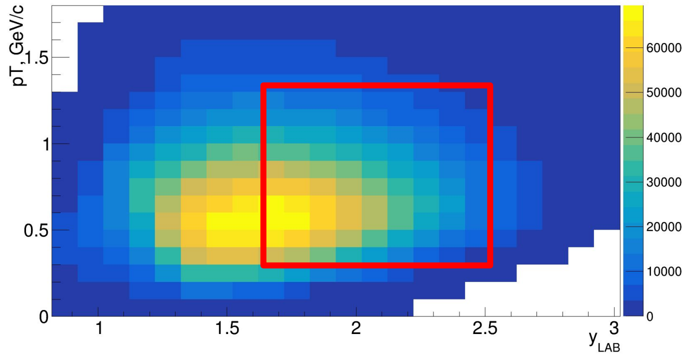




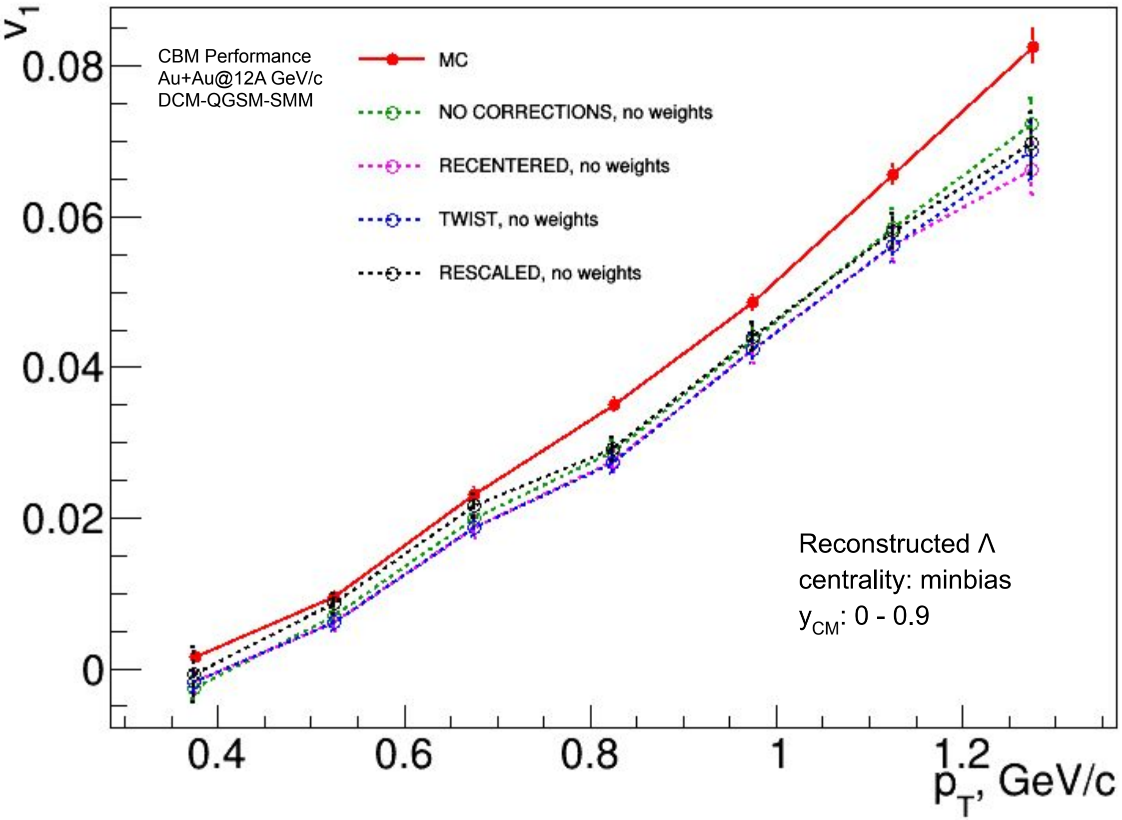
p_T-dependence of $v_{1,x}$: twist

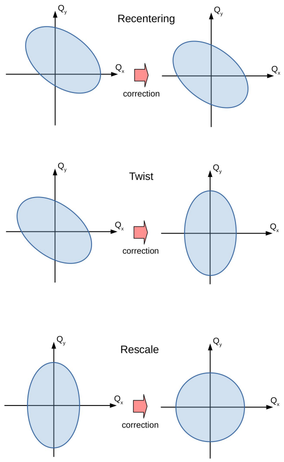


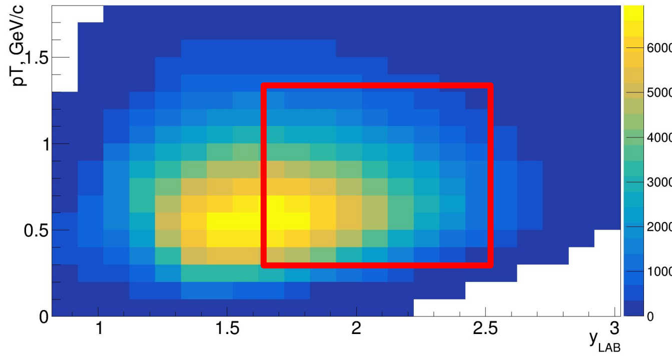




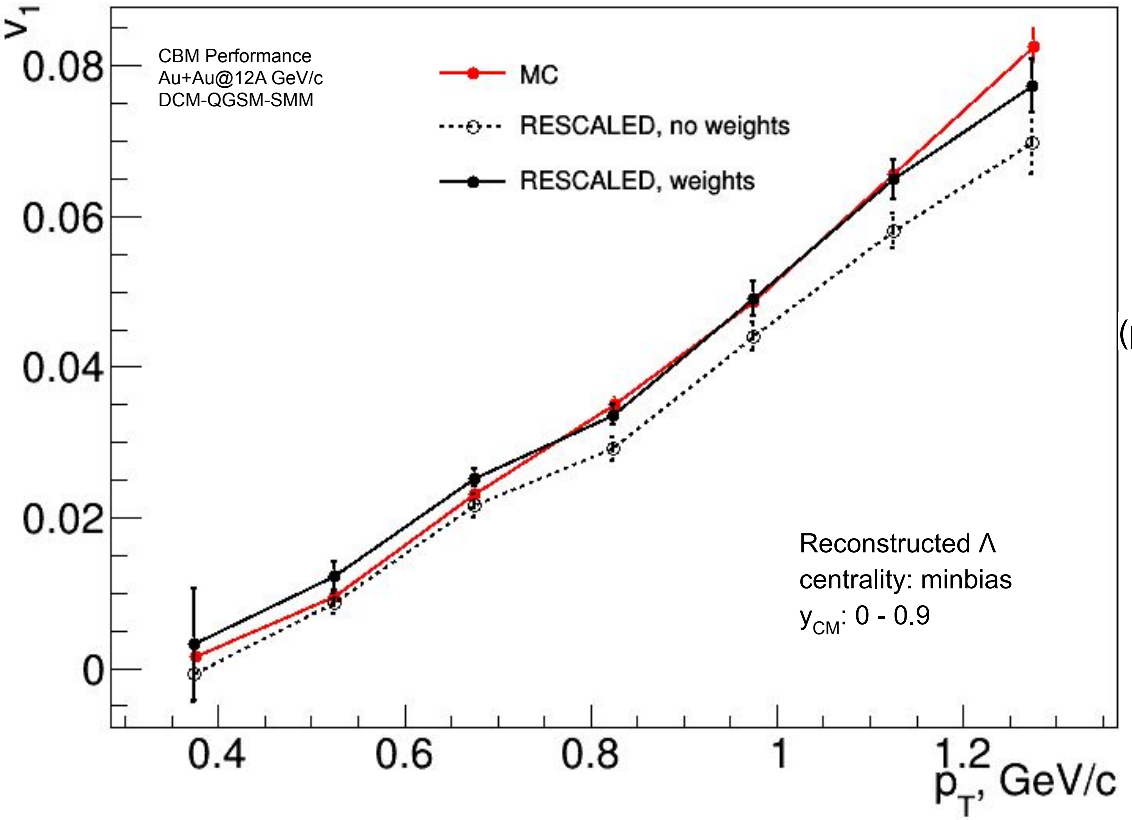
p_T-dependence of $v_{1,x}$: rescale



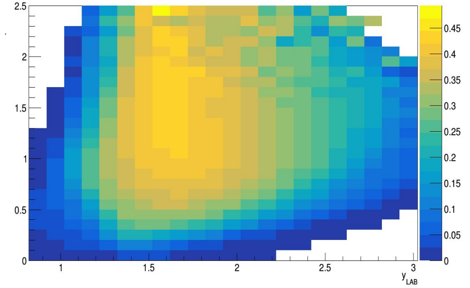




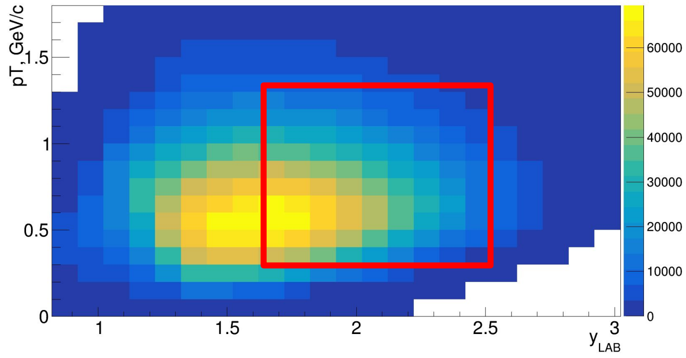
p_T-dependence of $v_{1,x}$: effect of efficiency weights



(p_T,y) efficiency of Λ

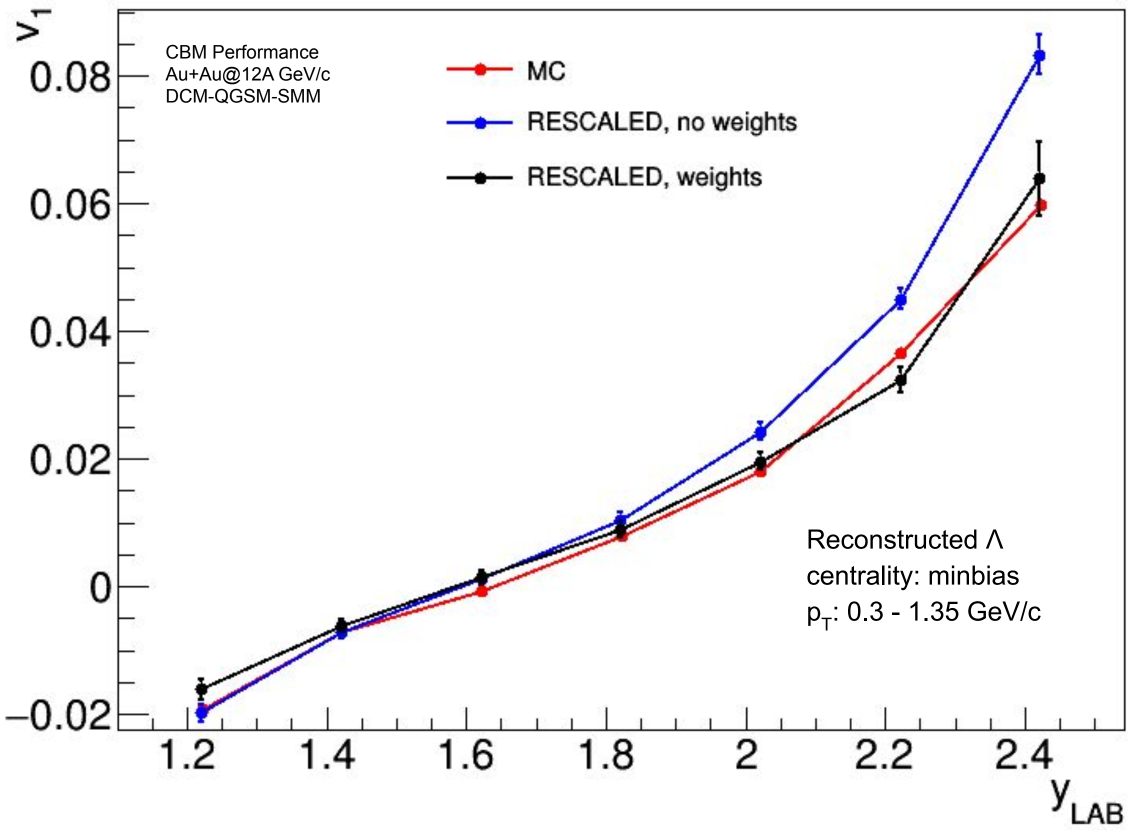


(p_T,y) efficiency weights: $$w_i(p_T, y) = \frac{1}{\varepsilon(p_{Ti}, y_i)}$$

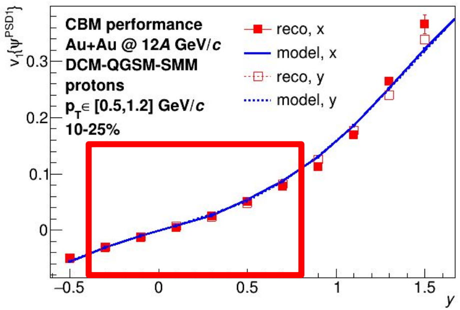


After performing all correction steps and applying efficiency weights the result reproduces MC input

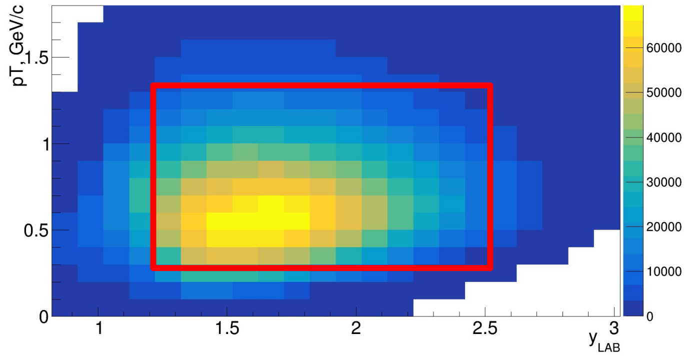
Rapidity dependence of $v_{1,x}$



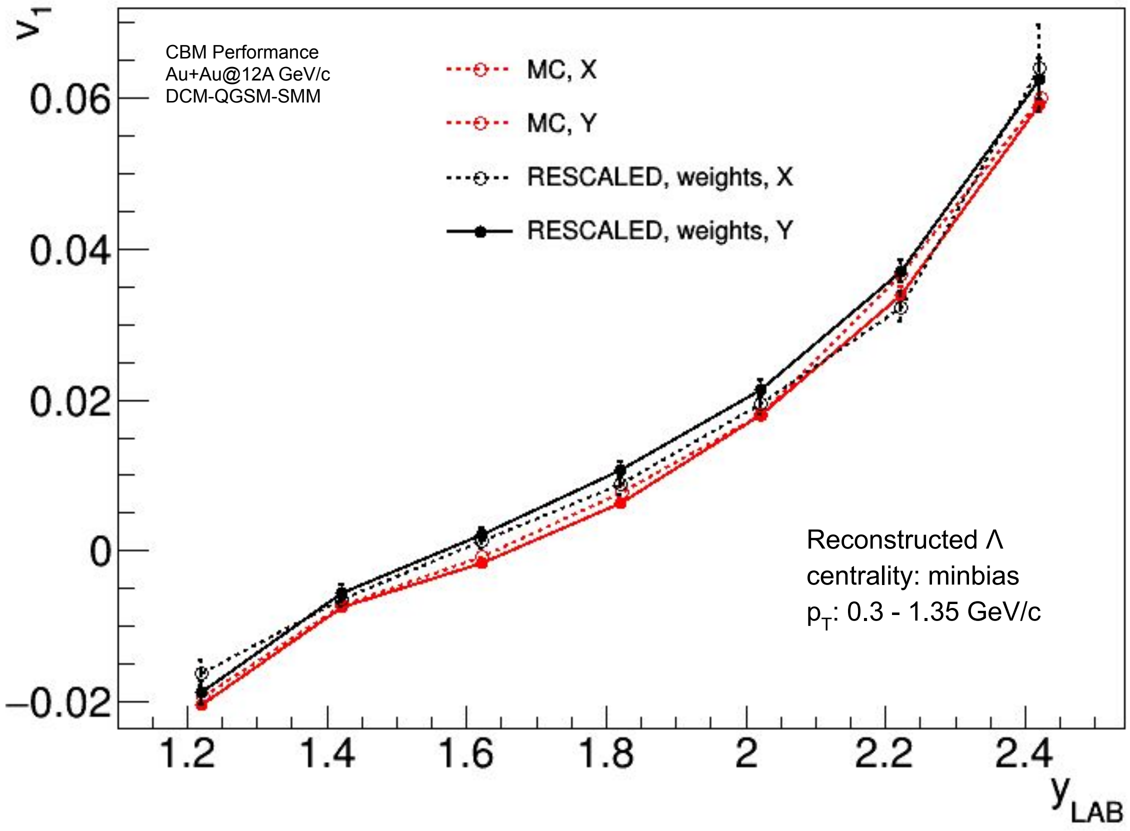
primary proton v_1



O. Golosov, 27/08



v_1 rapidity dependence



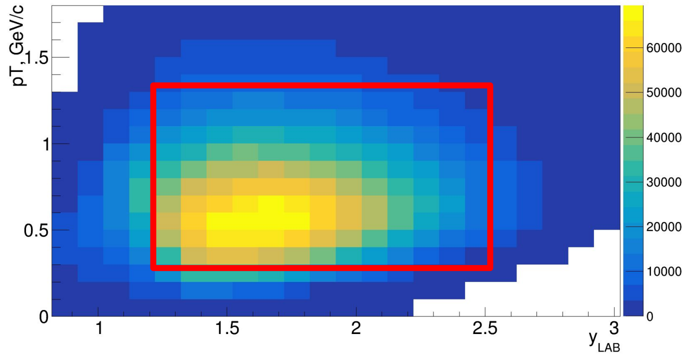
$$v_{1x} = \langle q_{1x} \cos \Psi_{RP} \rangle$$

$$v_{1y} = \langle q_{1y} \sin \Psi_{RP} \rangle$$

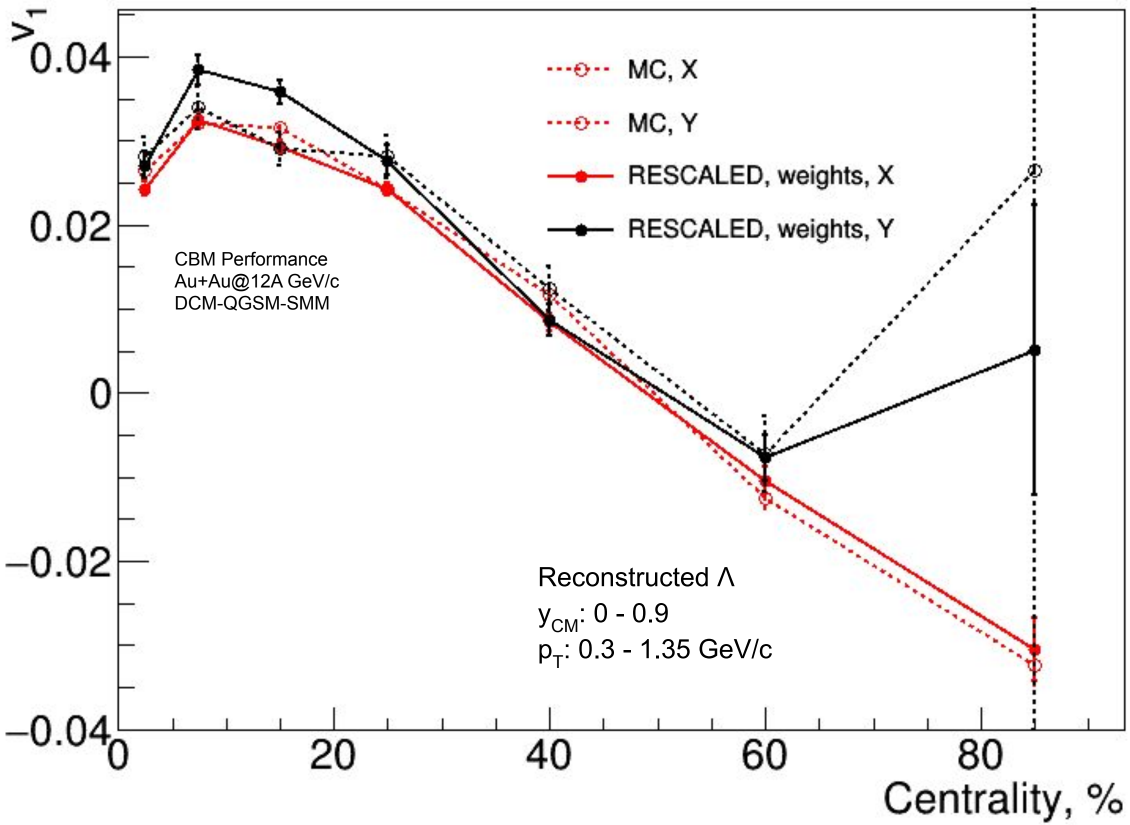
Positive slope of Λ v_1 is reproduced

v_{1x} shows better agreement with input v_1 than v_{1y}

more differential analysis (more statistics) is needed



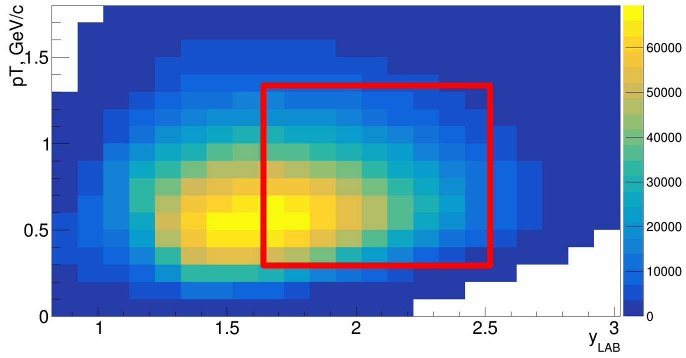
v_1 centrality dependence



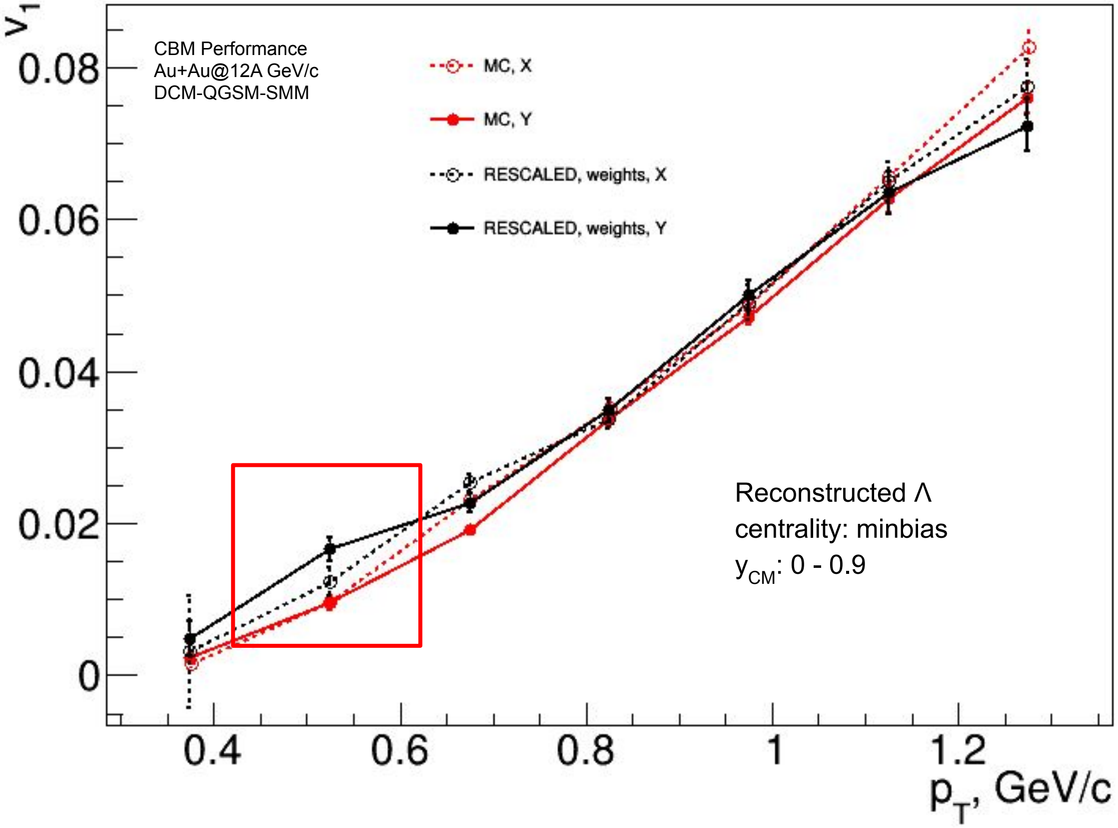
Slope of v_1 (dv_1/dy) changes sign with centrality around 50%

v_{1x} shows better agreement with input v_1 than v_{1y}

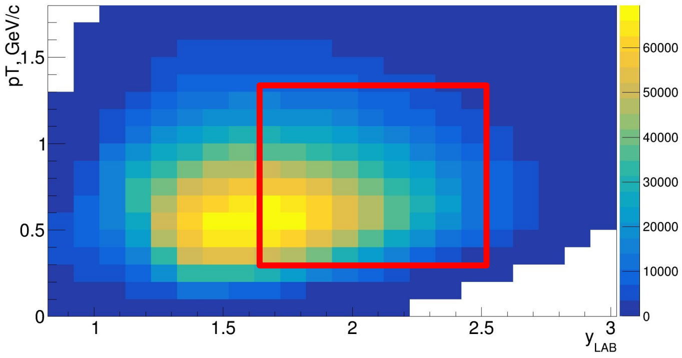
more differential analysis (more statistics) is needed



p_T-dependence of v_1

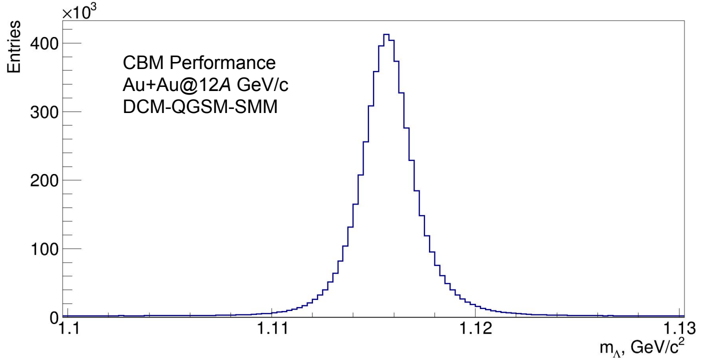


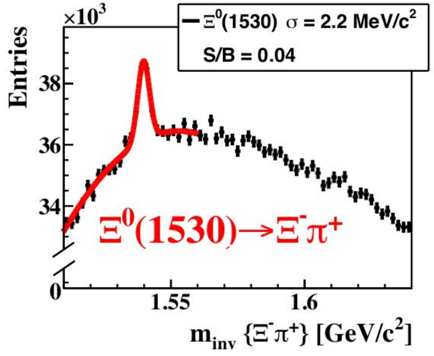
Difference between v_{1x} and v_{1y} localized at small p_T ~ 0.5 GeV/c



Extracting flow with v_n vs inv. mass method

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



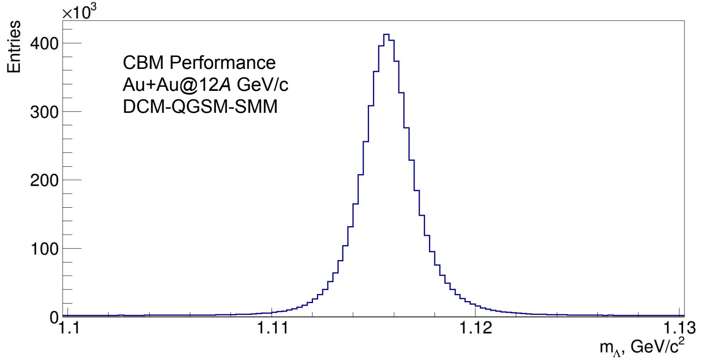


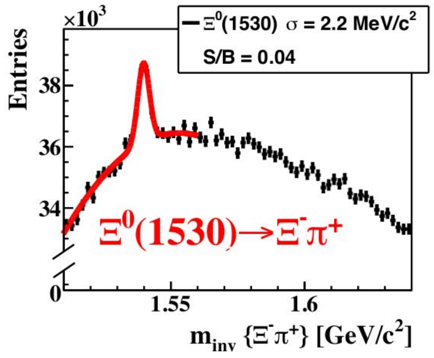
CBM Performance
Au+Au@10*A* GeV/c
UrQMD

M. Zyzak, PhD thesis @ UFra, 2016

Extracting flow with v_n vs inv. mass method

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





CBM Performance
Au+Au@10*A* GeV/c
UrQMD

M. Zyzak, PhD thesis @ UFra, 2016

Measurement technique

Step 1. Measure and parametrize/fit signal & background yields vs. invariant mass m_{inv}

- signal shape: Gaussian
- background shape: smooth function (polynomial)

$$v^{V0}\{m_{inv}\} = \frac{v^{sig} N_{sig}\{m_{inv}\} + v^{bg}\{m_{inv}\} N_{bg}\{m_{inv}\}}{N_{sig}\{m_{inv}\} + N_{bg}\{m_{inv}\}}$$

Step 2. Measure and fit flow of V_0 candidates

- $v^{V0}(m_{inv})$ - measured
- $v^{sig} = inv(m_{inv})$ - sought. Constant fitting parameter
- $v^{bg}(m_{inv})$ - assumed to be a smooth function (polynomial)

Summary

- Investigated performance of the CBM experiment for anisotropic flow of Λ hyperons
  - Differential measurements (p_T, y, centrality)
  - Positive slope of lambda v_1 as a function of rapidity is reproduced
  - Slope of lambda v_1 changes sign at centrality around 50%
- Detector biases and corresponding corrections were studied:
  - (p_T, y) dependence of efficiency (reweighting q-vectors)
  - φ non-uniformity (recentering, twist and rescaling q-vectors)

Outlook

- Perform differential analysis with refined binning in p_T, y and centrality (requires higher statistics)
- Take into account feed down of secondary Λ's (e.g. from cascades)
- Use PSD signals for the spectator plane determination