Elliptic Flow of Λ hyperons in Pb+Pb collisions at 158A GeV

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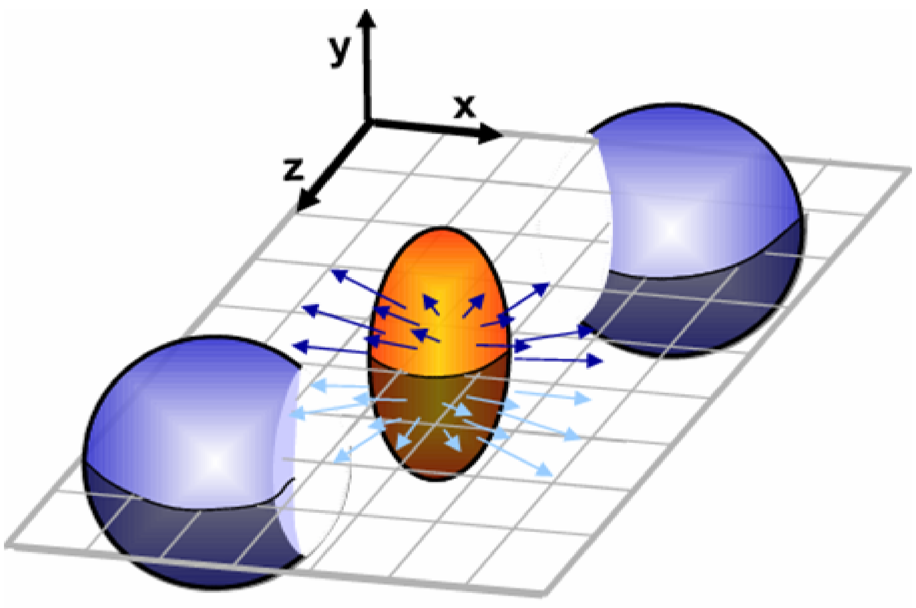
Outline

- Introduction
- NA49 experiment
- The method of flow analysis
- Selection of Λ candidates
- Event plane determination
- Preliminary results on Λ elliptic flow
  - rapidity dependence
  - p_T dependence
    - comparison with CERES data
    - comparison with STAR results
    - comparison with models
- Summary and outlook

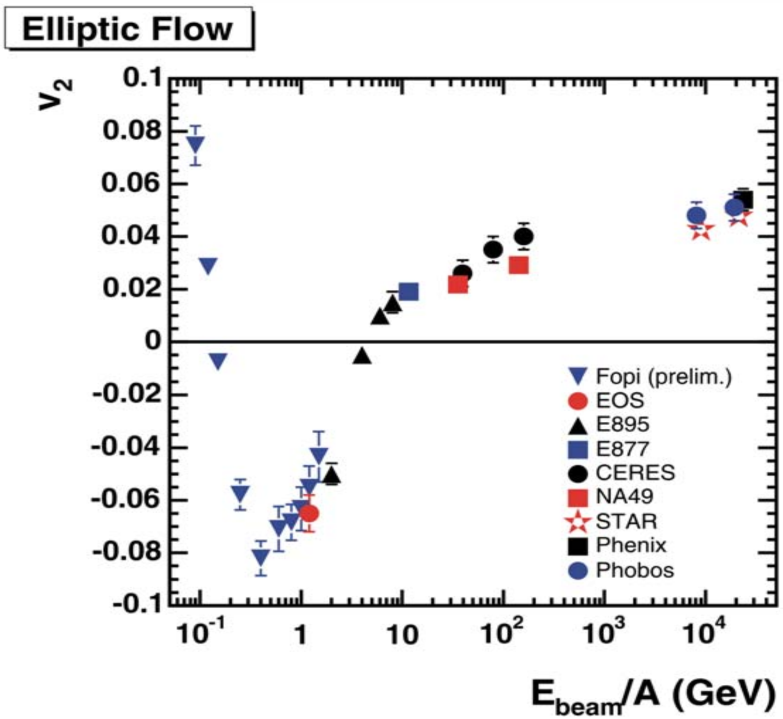


Collective effects propagate the initial spatial anisotropy into momentum space. A characteristic observable is the elliptic flow quantified by $v_2 = \langle\cos(2(\varphi-\Phi_r))\rangle$.

Elliptic flow

- an effect of the pressure gradients in the interaction region
- sensitive to EOS and the degree of thermalization
- v_2 of heavy and strange particles → insight into very early stages of the collision

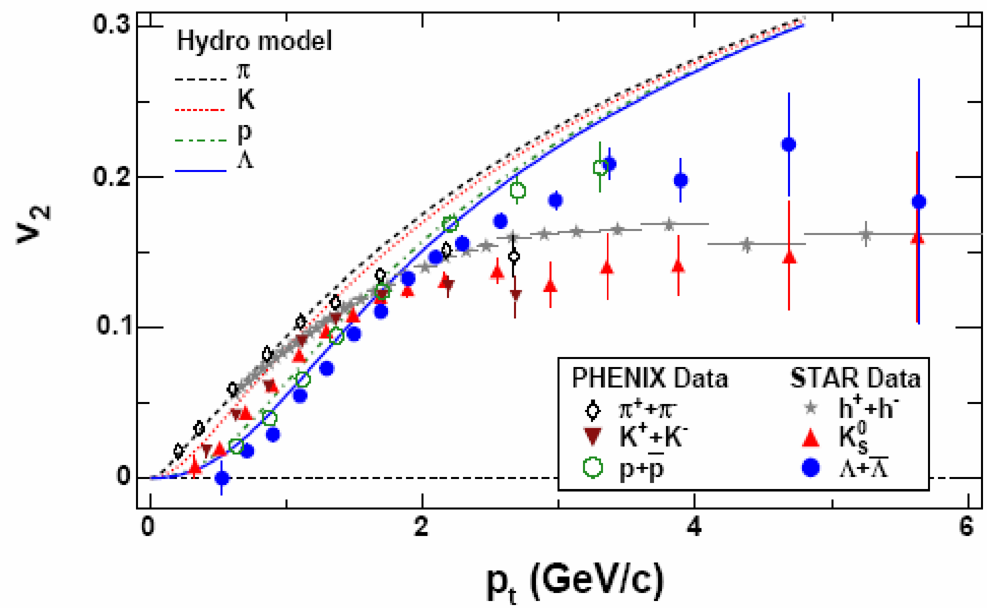
Introduction



Mid-rapidity data, p_T integrated

- smooth increase with collision energy towards RHIC data and hydrodynamic model predictions

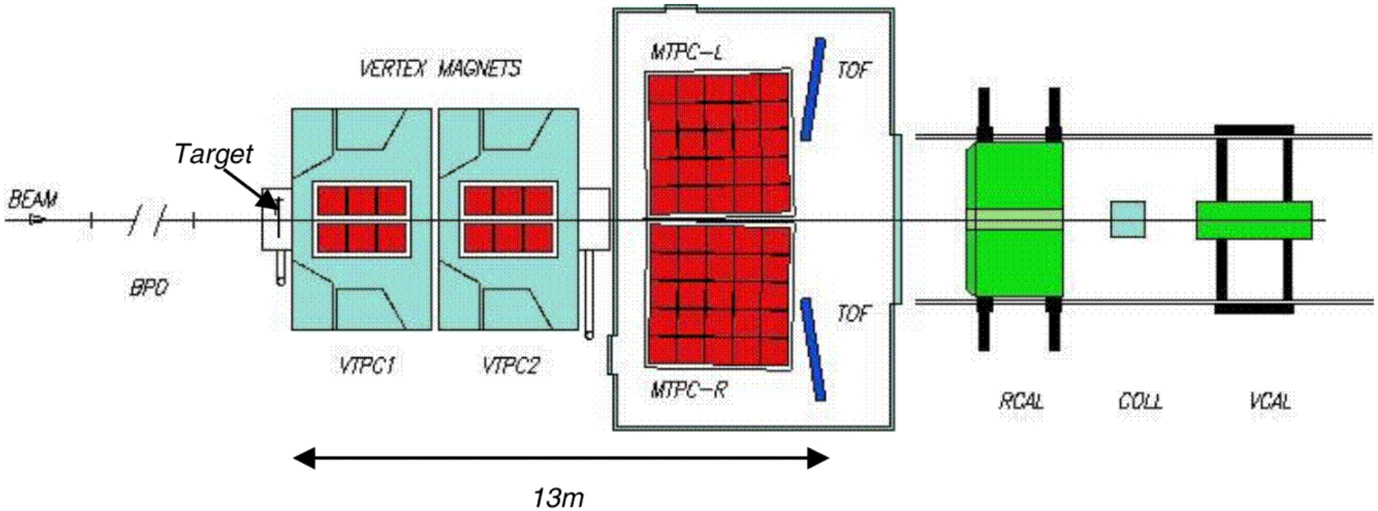
Au+Au, 200 GeV, minimum-bias 0-80 % σ_{TOT}



J.Adams et al., nucl-ex/0409033

- hadron mass ordering of v_2 below $p_T \approx 1.5$ GeV/c
- agreement of hydrodynamic predictions with data for p_T < 2-3 GeV/c
- saturation above 2-3 GeV/c

NA49 Experiment



- Two Vertex TPC (VTPC-1,VTPC-2) inside magnetic field
- Two Main TPC (MTPC-L, MTPC-R) outside magnetic field
- Veto Calorimeter (VCAL) detects projectile spectators

$\Delta p/p^2 = 7\ (0.3)\ 10^{-4}\ (\mathrm{GeV}/c)^{-1}$

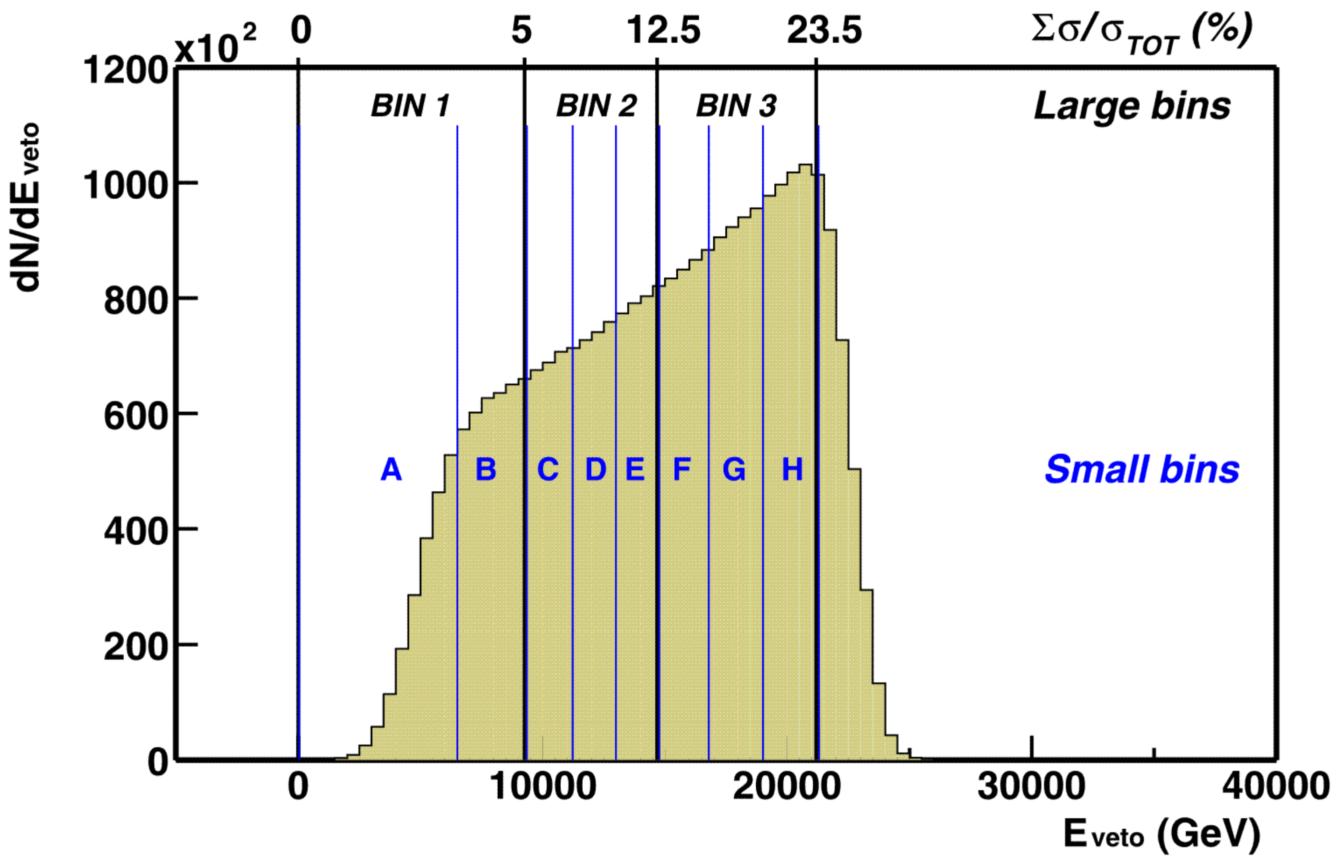
(VTPC-1, VTPC+MTPC)

dE/dx resolution 3-6 %

Identification of π^+, π^-, K^+, K^-, p, $\bar{p}$, K^0_s, Λ, Ξ, Ω, φ

Centrality Determination

- centrality selection based on the energy deposited in the veto calorimeter



Pb+Pb 158*A* GeV

3M events

semi-central trigger
$\sigma/\sigma_{TOT} < 23.5$ %

Method of elliptic flow analysis

- estimate of the reaction plane by the second harmonic event plane ($\Phi_{2\,EP}$)
- determination of the event plane resolution ($<\cos(2(\Phi_{2EP} - \Phi_{2RP}))>$) by correlation of sub-events
- evaluation of the Fourier coefficient v_2' from Λ azimuthal distribution with respect to the event plane

$$dN/d(\varphi_{lab}-\Phi_{2\,EP}) \sim 1 + 2v_2' \cos[2(\varphi_{lab}-\Phi_{2\,EP})] + 2v_4' \cos[4(\varphi_{lab}-\Phi_{2\,EP})]$$

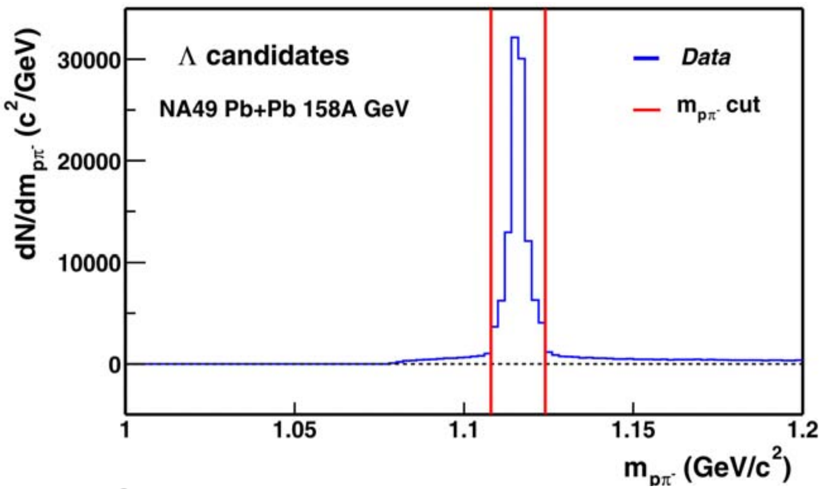
- correction for the event plane resolution

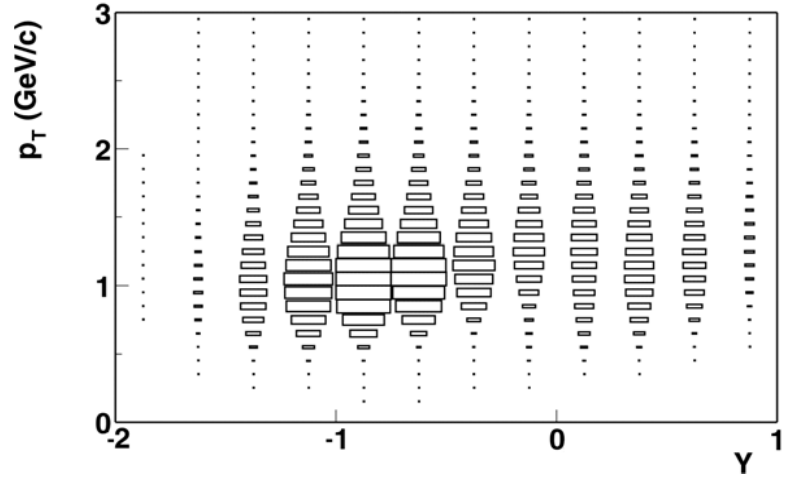
$$v_2 = v_2' / <\cos(2(\Phi_{EP} - \Phi_{RP}))>$$

The method: A.M.Poskanzer and S.A.Voloshin, Phys. Rev. C58 (1998) 1671.

Selection of Λ candidates

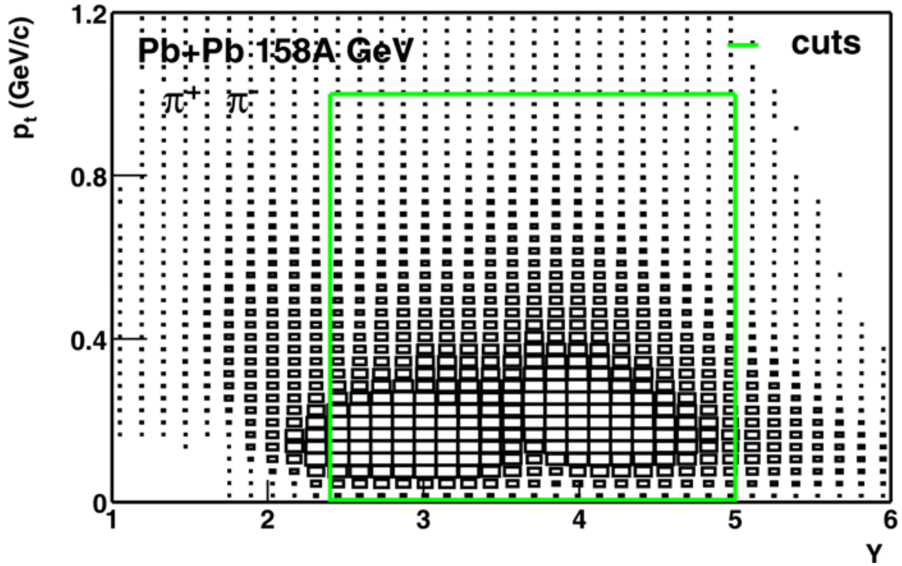
- geometrical cuts and quality criteria for TPC tracks
- reconstruction of Λ decay channel
  $\Lambda \rightarrow p + \pi^-$ (BR = 63.9% , $c\tau$ = 7.89 cm)
  by daughter tracks identification
- background subtraction
- invariant mass cut
  1.108 GeV < $m_{p\pi^-}$ < 1.124 GeV
- accepted Λ hyperons
  $y \approx$ -1.5 – 1.0 $p_T \approx$ 0.4 – 4 GeV/c





Estimate of the event plane

- primary π^-, π^+ , $p_T < 1$ GeV/c , $-0.5 < y < 2.1$



recentering parameters

- extraction of the azimuthal angle of the event plane:

$$X_2 = Q_2 \cos(2\Phi_{2\,EP}) = \sum_i p_{Ti} \, [\cos(2\varphi^i_{lab}) - \langle\cos(2\varphi_{lab})\rangle]$$

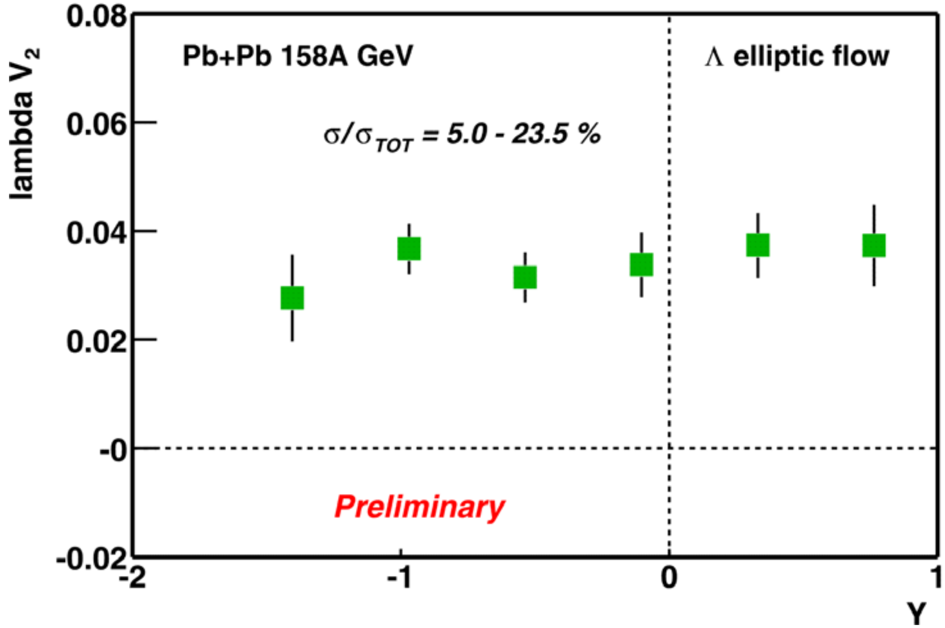
$$Y_2 = Q_2 \sin(2\Phi_{2\,EP}) = \sum_i p_{Ti} \, [\sin(2\varphi^i_{lab}) - \langle\sin(2\varphi_{lab})\rangle]$$

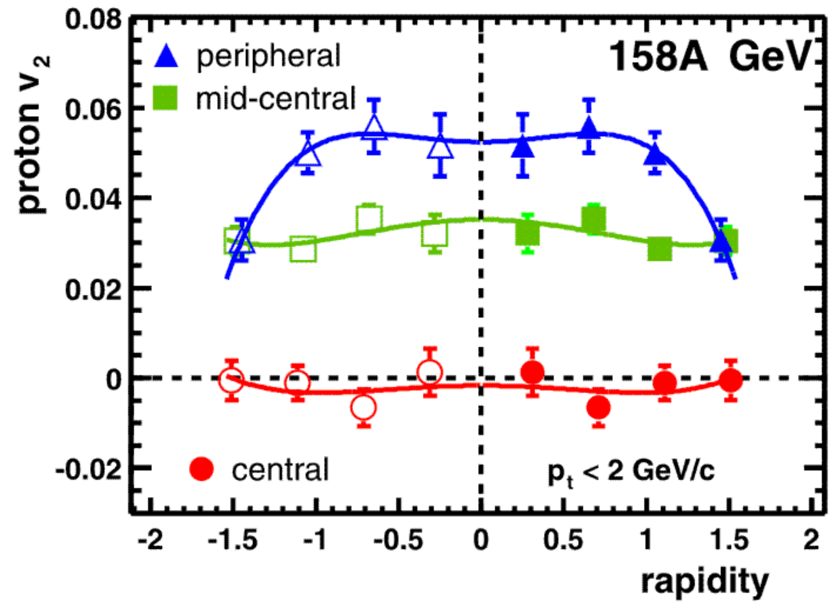
$$\Phi_{2\,EP} = (\tan^{-1} Y_2 / X_2) / 2$$

- acceptance correction by recentering and mixed-events

Details in : C.Alt et al., Phys. Rev. C 68 (2003) 034903

Rapidity dependence



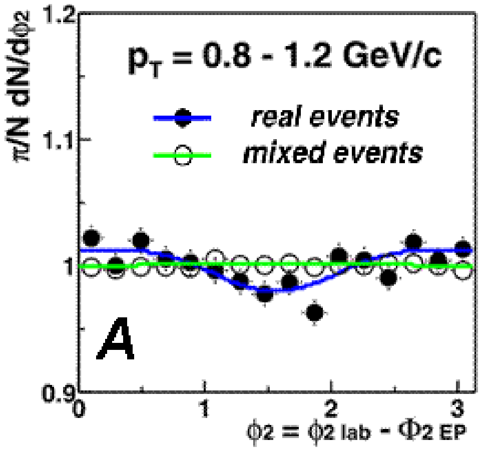


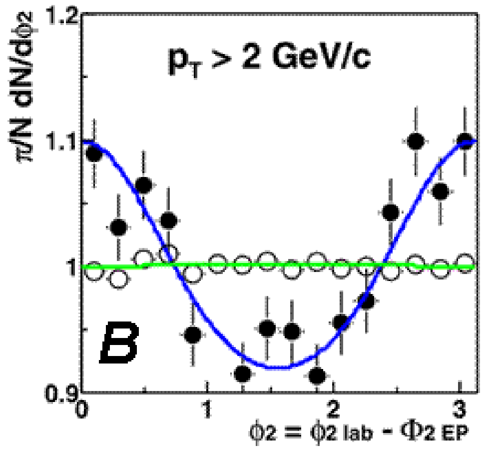
C.Alt et al., Phys. Rev. C 68 (2003) 034903

- no significant dependence of Λ v_2 on rapidity as also seen for the protons
- flat distribution of proton $v_2(y)$ near midrapidity for central and mid-central collisions

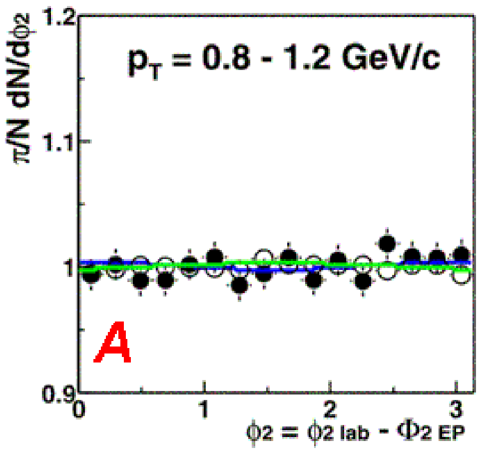
Differential flow – $v_2(b,p_T)$

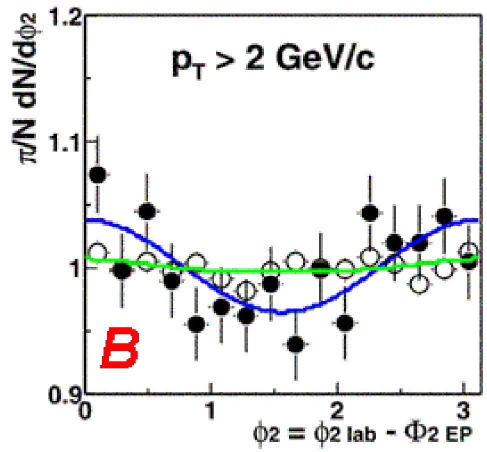
σ/σ_{TOT} = 12.5 - 23.5 %

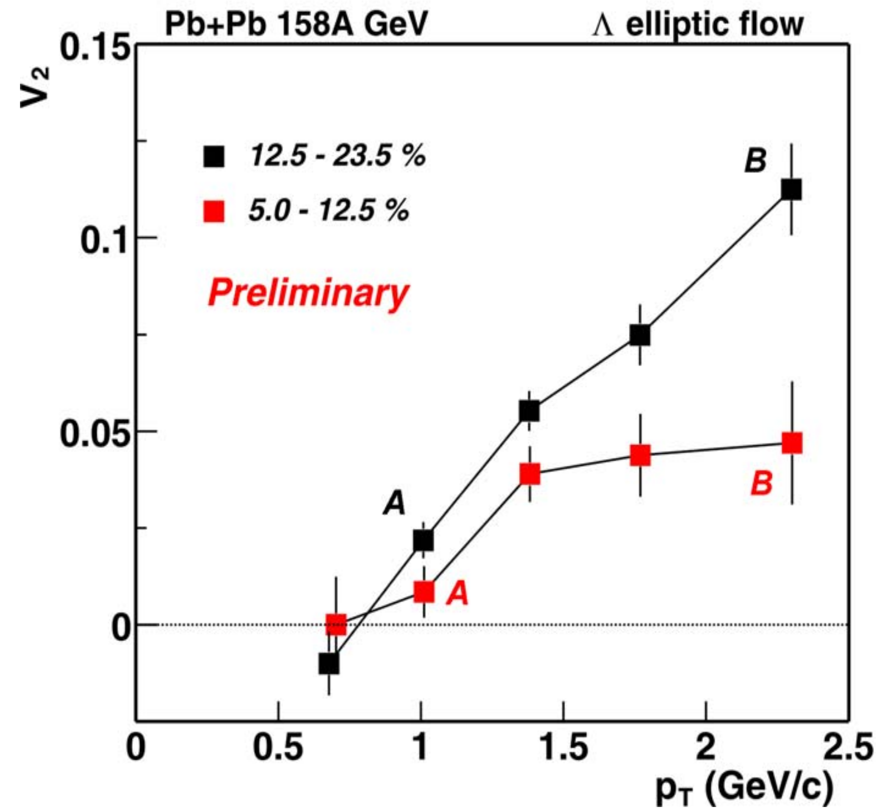




σ/σ_{TOT} = 5 - 12.5 %

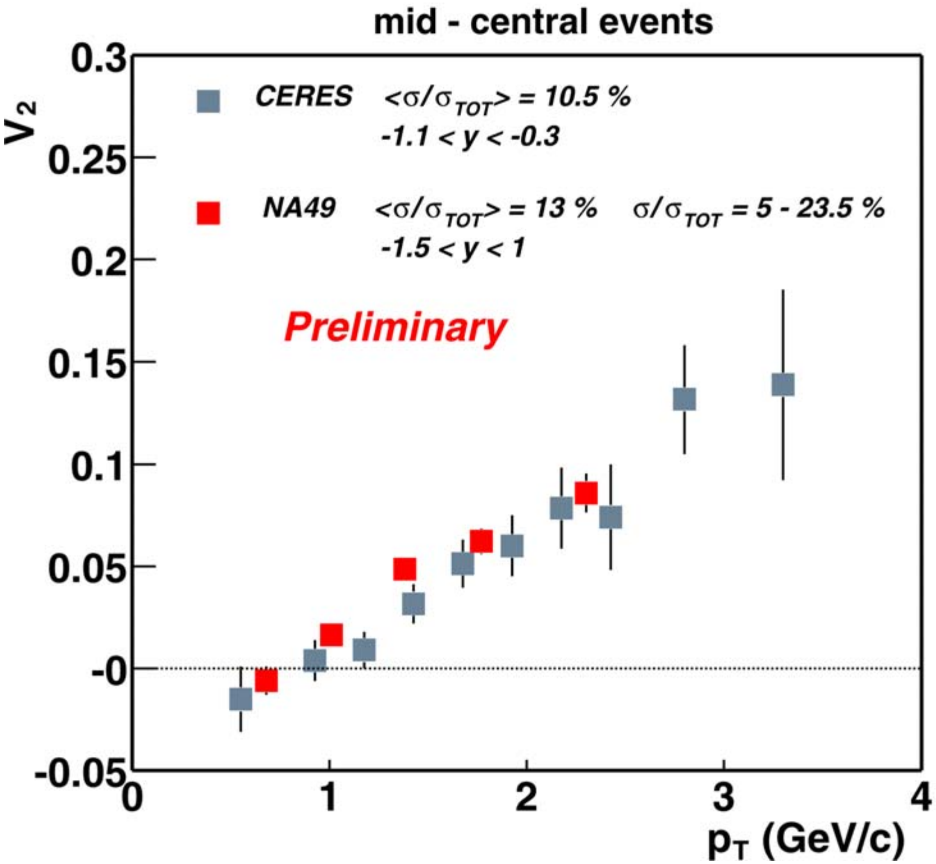


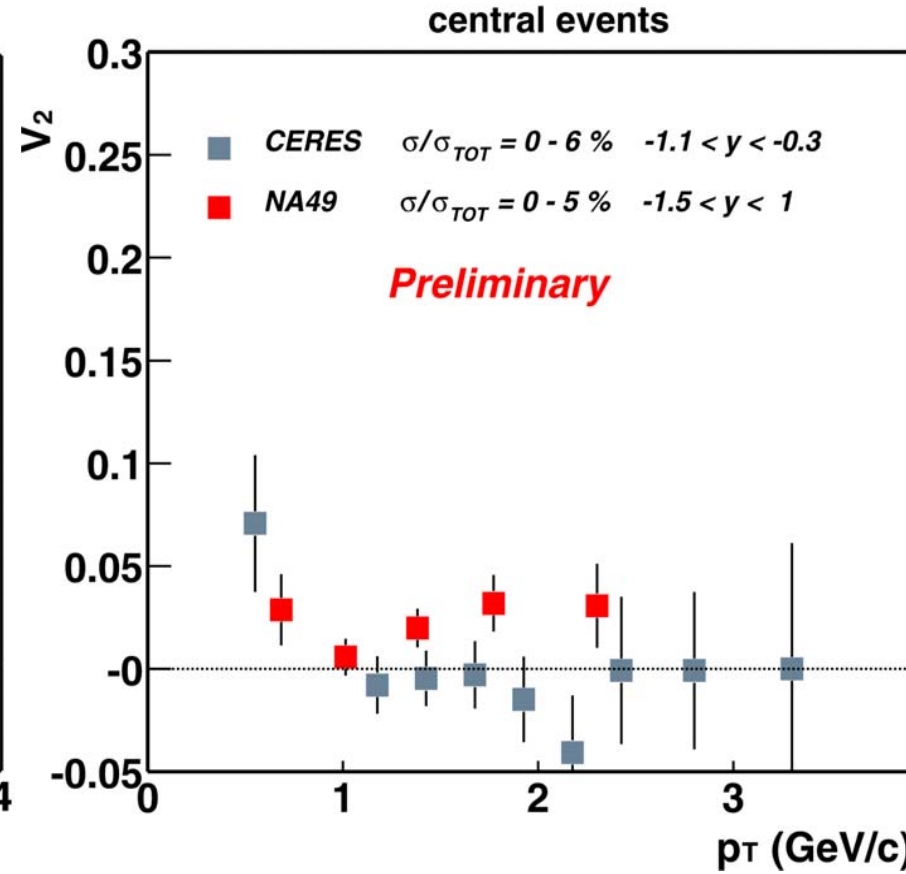




- significant increase of Λ v_2 with p_T
- stronger increase in more peripheral collisions

Λ Elliptic Flow at SPS

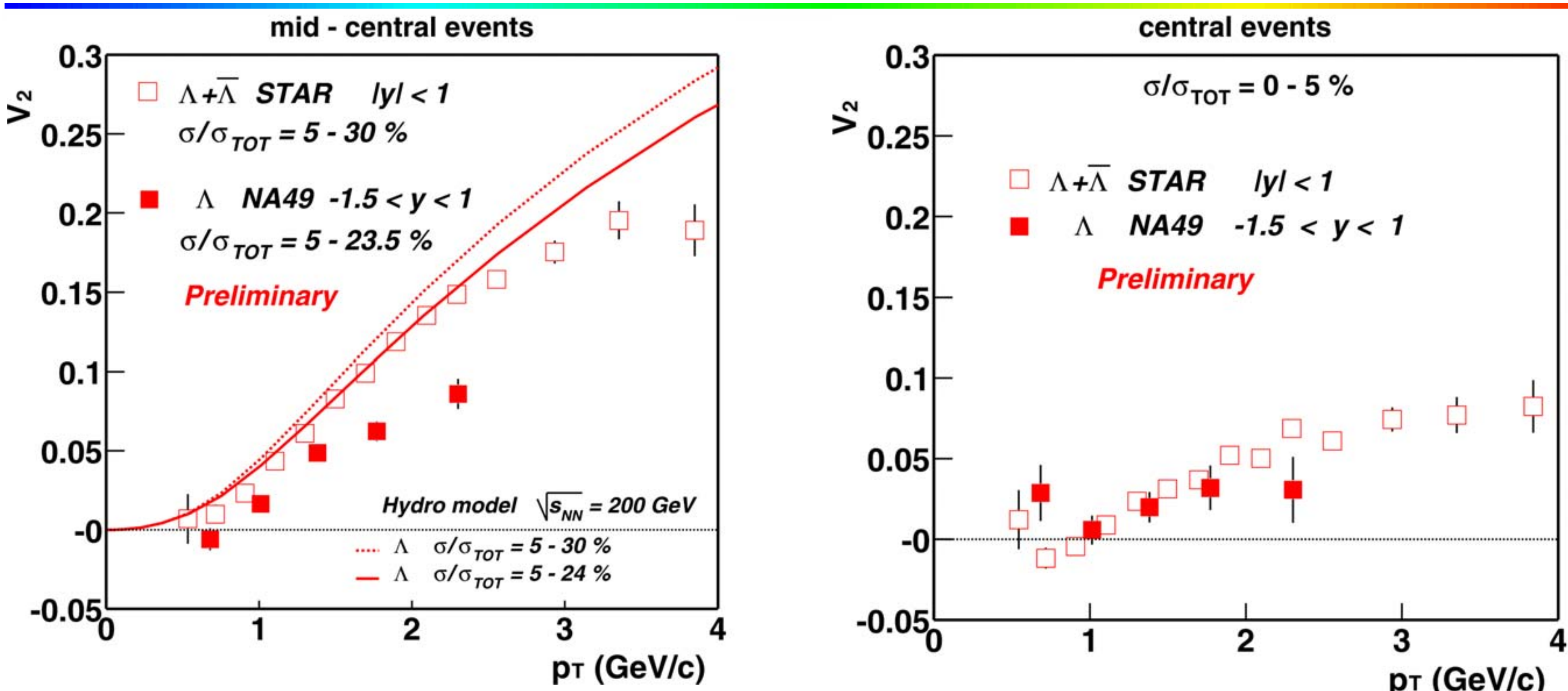




Agreement between NA49 and CERES $v_2(p_T)$ of Λ hyperons

Ceres data: J.Milosevic next talk

Λ Elliptic Flow SPS - RHIC

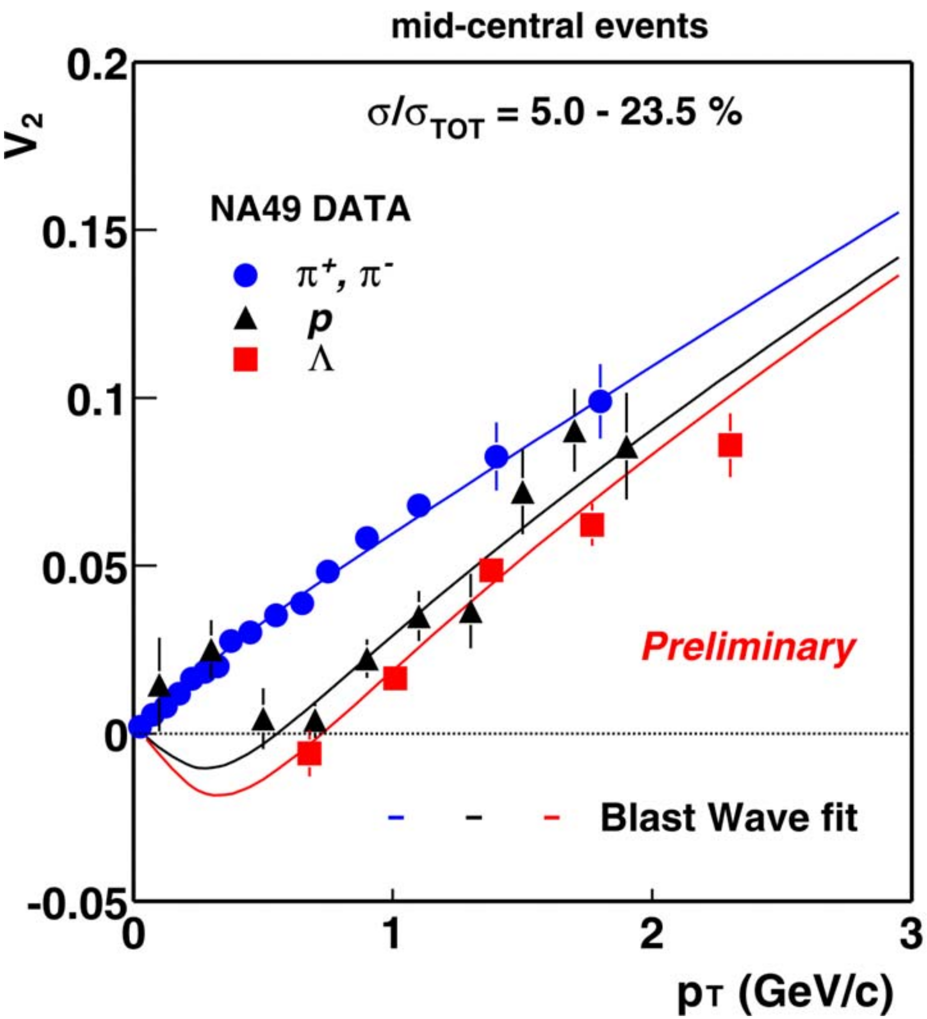


- linear rise of $v_2(p_T)$ up to 2 GeV/c
- weaker increase at SPS than at RHIC
  → partly due to different centrality
- similar $v_2(p_T)$ at SPS and RHIC below $p_T \approx 2$ GeV/c

Model: P.Huovinen nucl-th/0505036 and private communication (T_c=165 MeV, T_f=130 MeV, EoS=Q)

STAR data: J.Adams et al., Phys. Rev. Lett. 92 (2004) 052302

Λ Elliptic flow - different species

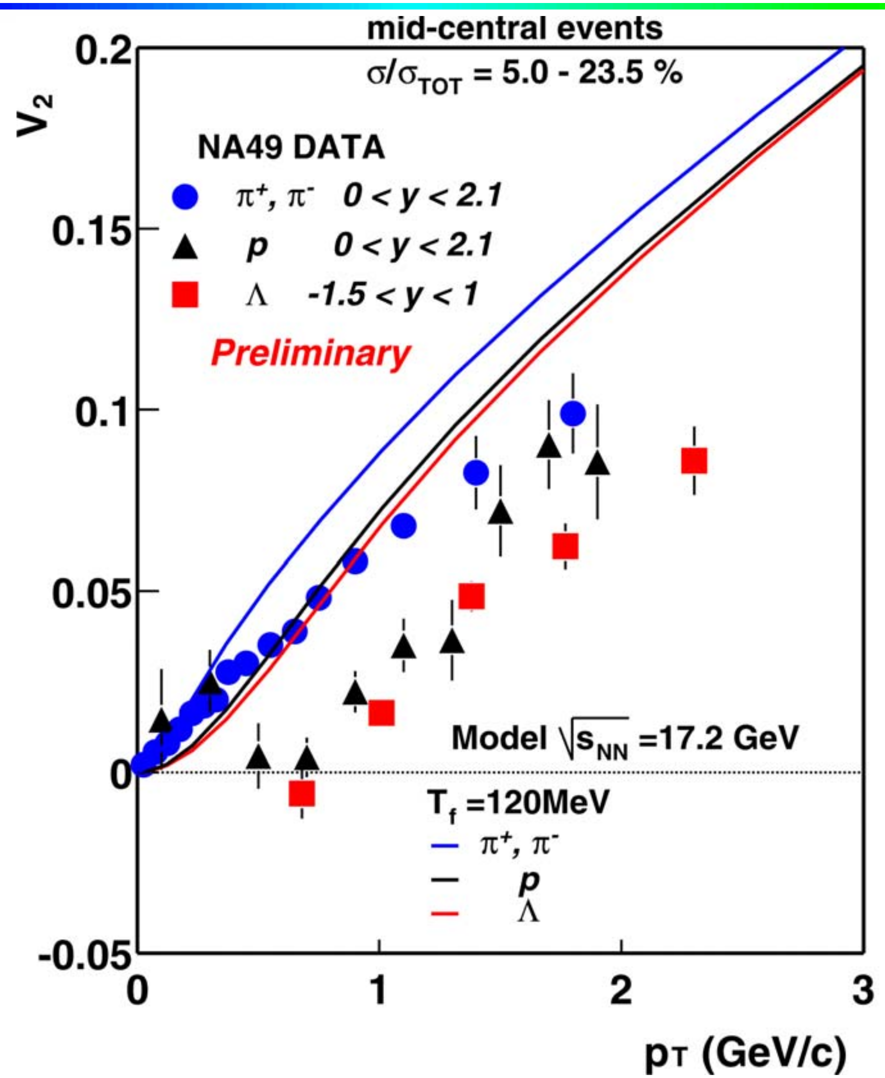


- linear increase of v_2 with p_T for all species in mid-central events
- mass hierarchy $v_2(\pi) > v_2(p) > v_2(\Lambda)$ at $p_T < 2$ GeV/c)
- similar magnitude of v_2 for all particle species at $p_T \sim 2$ GeV/c
- blast wave fit (T=92 MeV, $<\rho_0>=0.8$) reproduces data quite well
  → parameters similar like for p_T spectra and HBT sizes fits

Model:
P.Huovinen et al., Phys. Lett. B 503 (2001) 58
C.Adler et al., Phys. Rev. Lett. 87 (2001) 182301
F.Retiere, A.M.Lisa, Phys. Rev. C 70 (2004) 044907

Data on pions and protons on basis of:
C.Alt et al. , Phys. Rev. C 68 (2003) 034903

Comparison with models



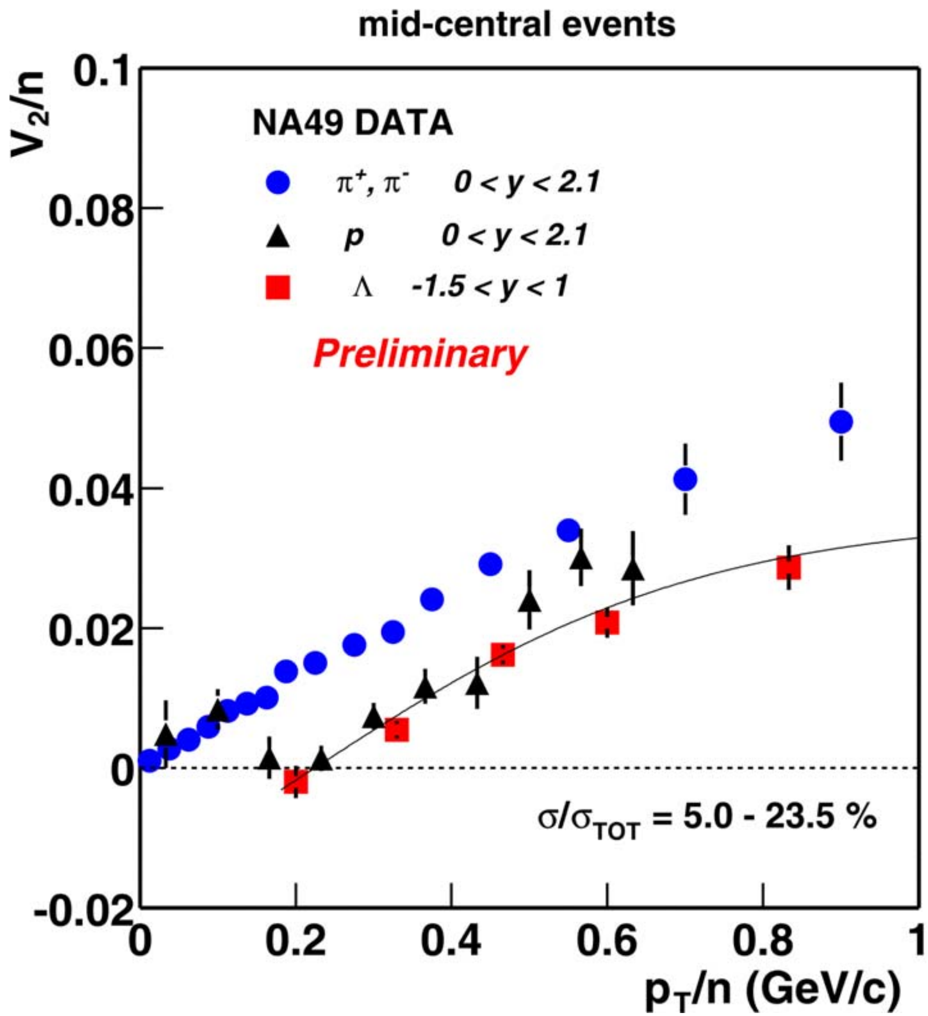
Hydrodynamic model

- hydrodynamic calculations with T_f =120 MeV reproduce p_T spectra but overpredict $v_2(p_T)$ SPS data

Hydrodynamic calculations by P.Huovinen: 1-st order phase transition, T_c=165 MeV

Data on pions and protons on basis of: C.Alt et al. , Phys. Rev. C 68 (2003) 034903

Comparison with models



Coalescence model

- v_2 of protons and Λ hyperons agree with naive quark coalescence model

V.Greco, C.M.Ko Phys. Rev. C 70 (2004) 024901

- pions show a larger elliptic flow below p_T = 2 GeV/c
  → possible explanation by resonance decays and quark momentum distribution in hadrons

Data on pions and protons on basis of:
C.Alt et al. , Phys. Rev. C 68 (2003) 034903

Conclusions on Λ elliptic flow

- weak dependence of v_2 on rapidity
- v_2 increases with decreasing centrality
- v_2 grows linear with transverse momentum up to $p_T \approx 2.5$ GeV/c
- p_T dependence in agreement with CERES data
- weaker p_T dependence at SPS than at RHIC energy
- Blast Wave model reproduces $v_2(p_T)$ and p_T spectra simultaneously with similar set of parameters
- hydrodynamic models have problems with consistent description of $v_2(p_T)$

The NA49 Collaboration

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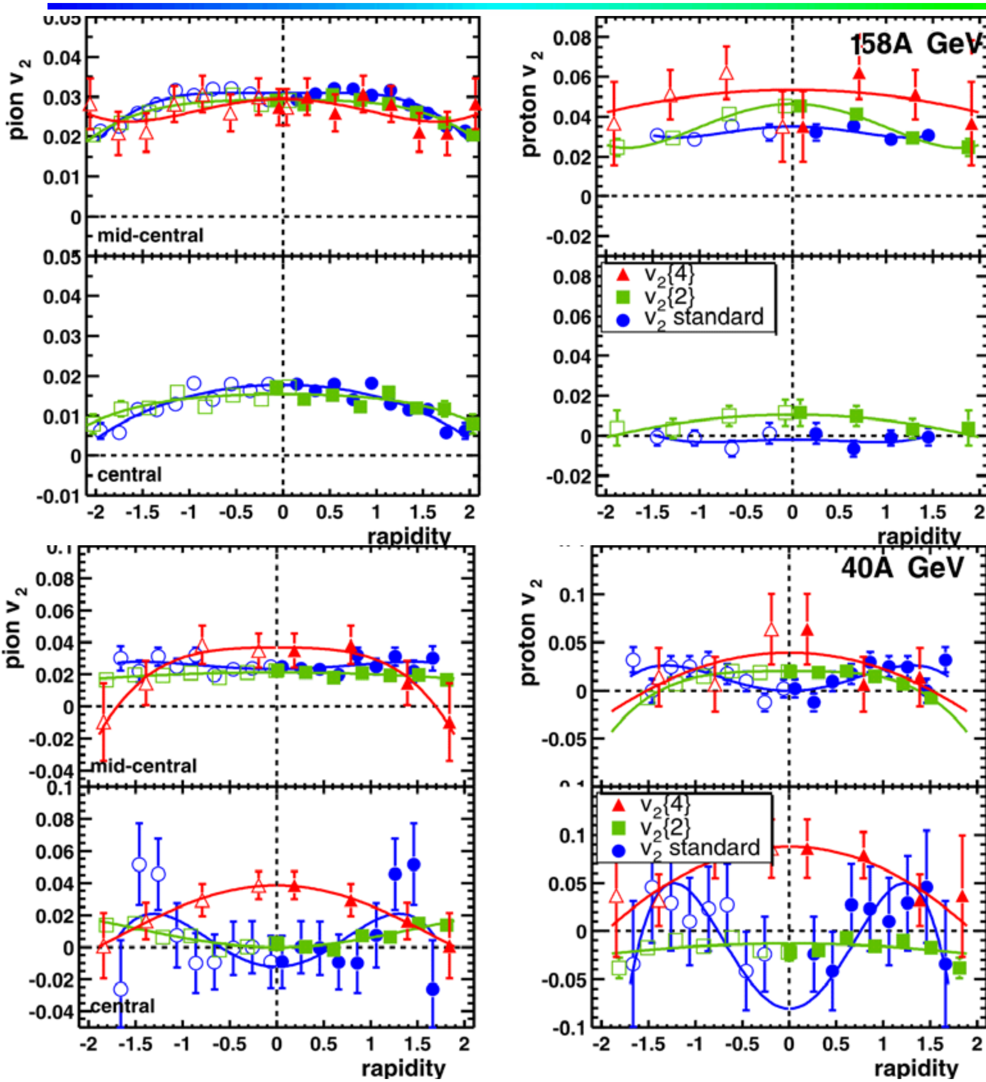
Institute for Experimental Physics, University of Warsaw, Warsaw, Poland.
Rudjer Boskovic Institute, Zagreb, Croatia.

Backup slides

Introduction

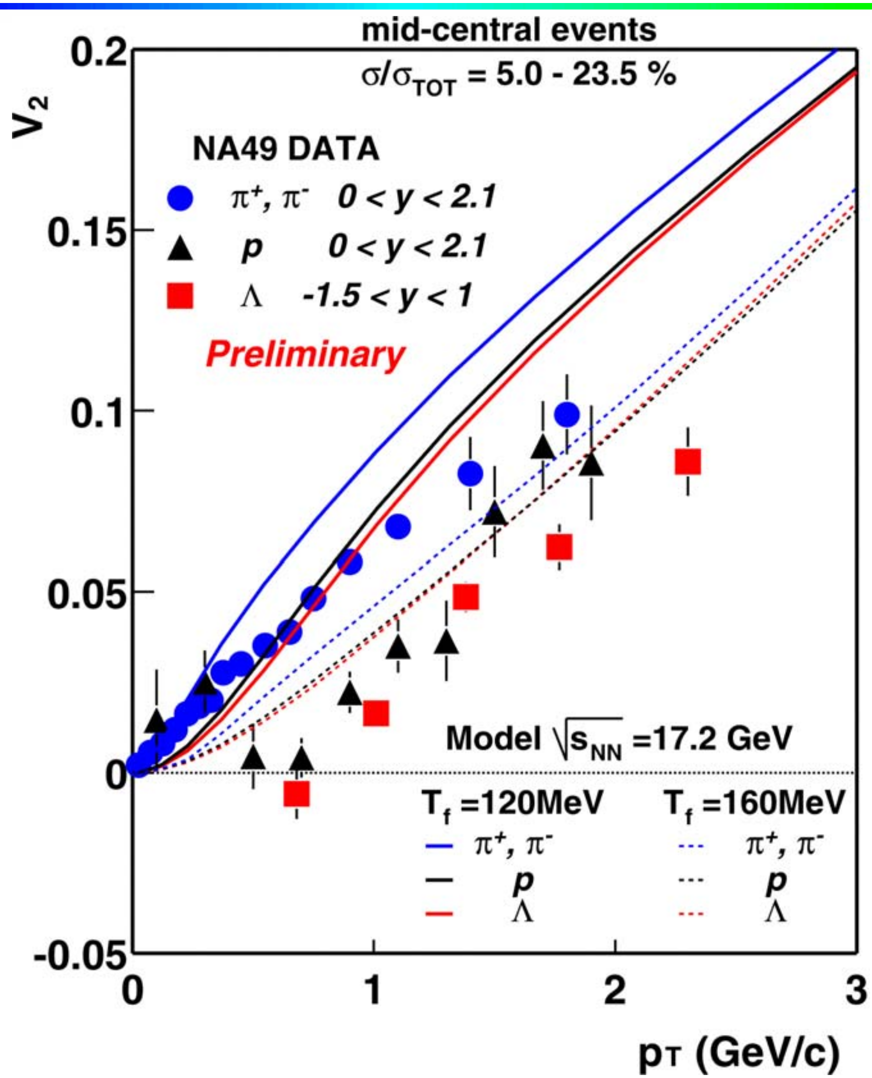


- 158 AGeV - usual bell shape with maximum at midrapidity

- 40 AGeV- the dip at midrapidity for standard and $v_2\{2\}$ cumulant but not for the four-particle $v_2\{4\}$ cumulant free from 2-particle nonflow effects
  - π mesons ρ decays
  - protons ????

The situation is unclear !!!

Comparison with models



Hydrodynamic model

- hydrodynamic calculations with T_f =120 MeV reproduce p_T spectra but overpredict $v_2(p_T)$ SPS data
- predicitions with high temperature T_f =160 MeV closer to Λ v_2 (p_T) data but can't reproduce p_T spectra

Hydrodynamic calculations by P.Huovinen: 1-st order phase transition, T_c=165 MeV

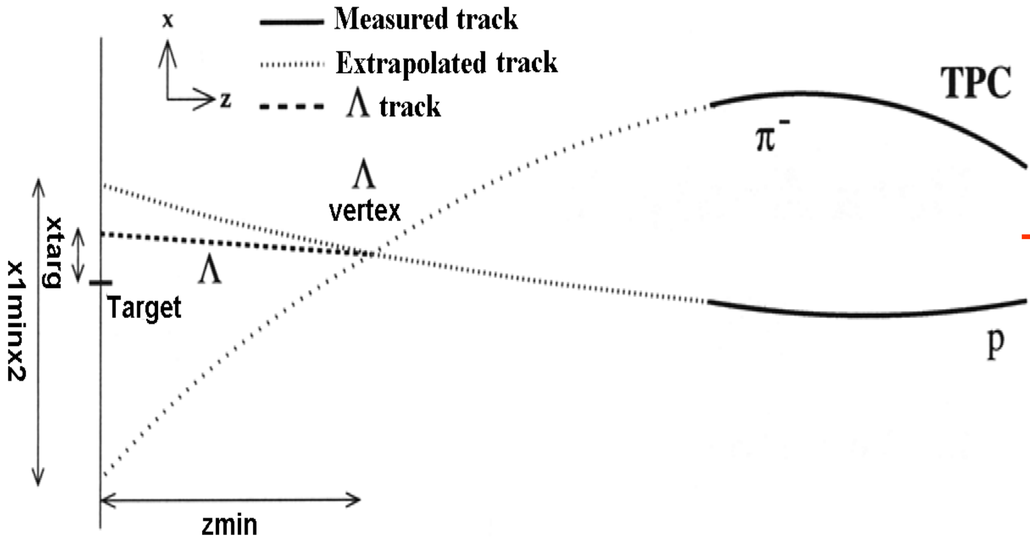
Data on pions and protons on basis of: C.Alt et al. , Phys. Rev. C 68 (2003) 034903

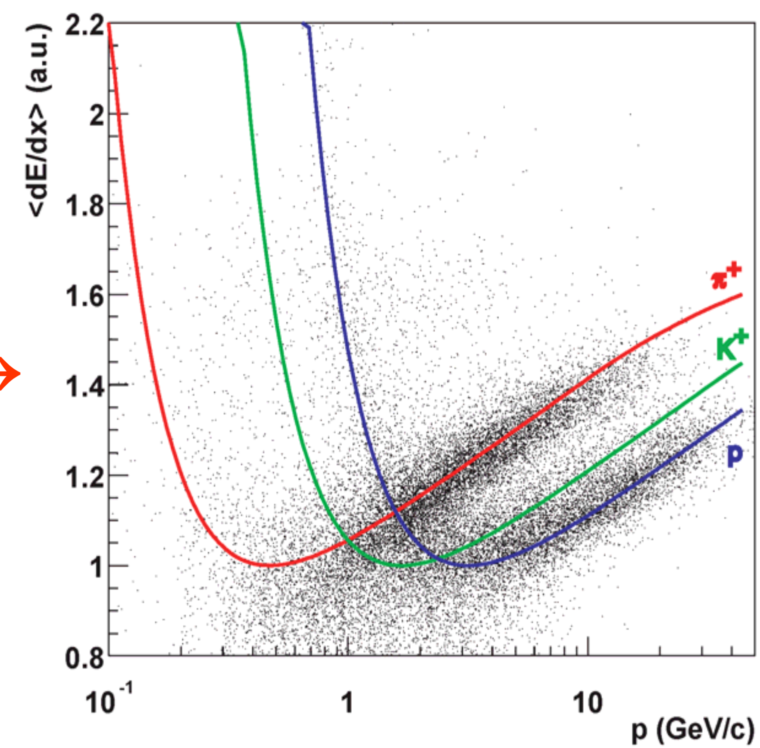
Selection of Λ candidates

- Geometrical cuts applied on V0 candidates:
  - position of the secondary vertex: zmin = -555 cm
  - x, y position of the neutral particle in the target plane: $V0_x$ = xtarg < 0.75 cm, $V0_y$ = ytarg < 0.375 cm
  - separation between daughter tracks in x direction x1minx2 > 2.5 cm
  - both daughter tracks with at least 20 points in VTPC1 or VTPC2

Selection of Λ candidates

$\Lambda \to p + \pi^-$ (BR = 63.9% , cτ = 7.89 cm)



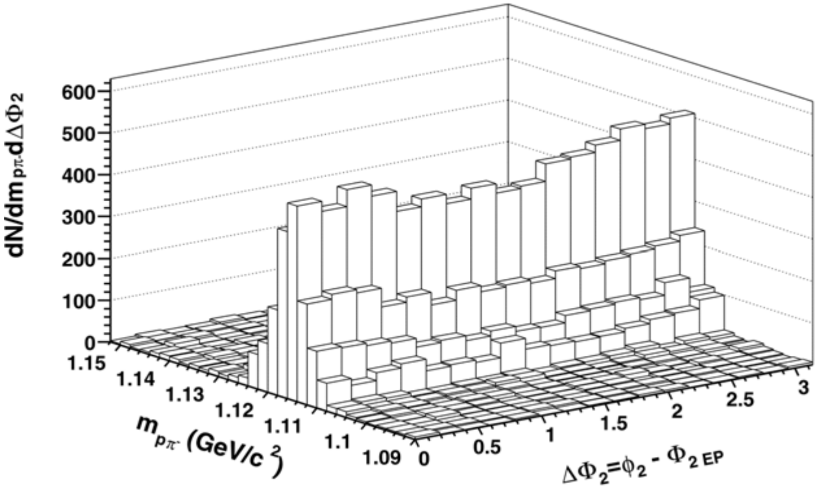


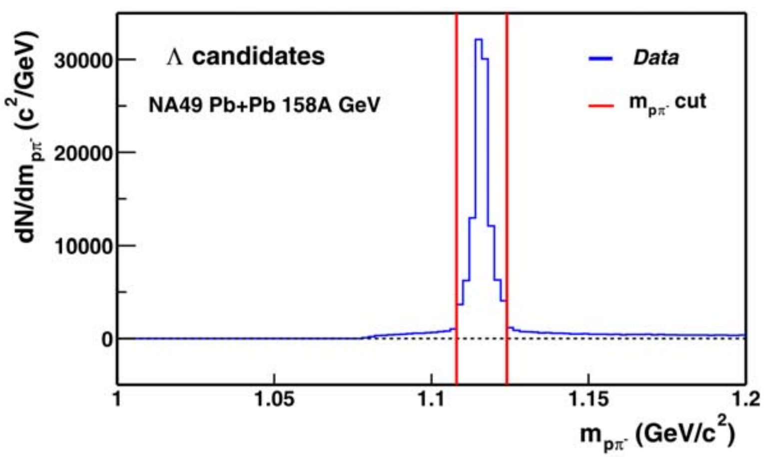
Selection of Λ candidates by geometrical cuts

Reconstruction of Λ decay channel by daughter tracks identification

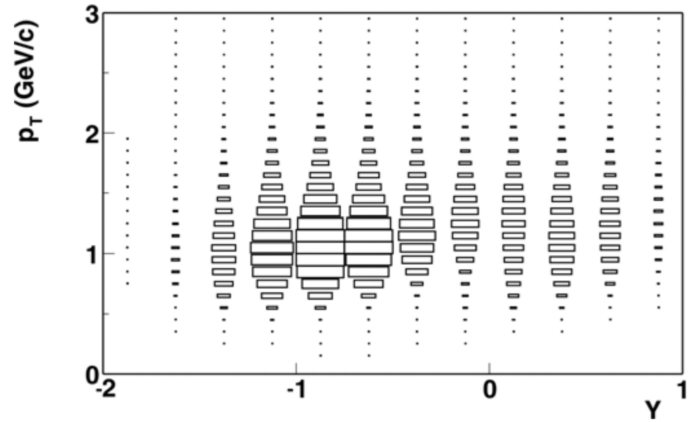
Selection of Λ candidates

1.108 GeV < $m_{p\pi^-}$ < 1.124 GeV

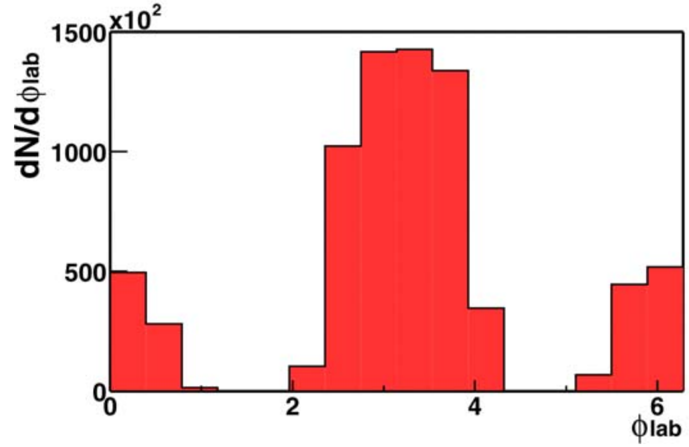




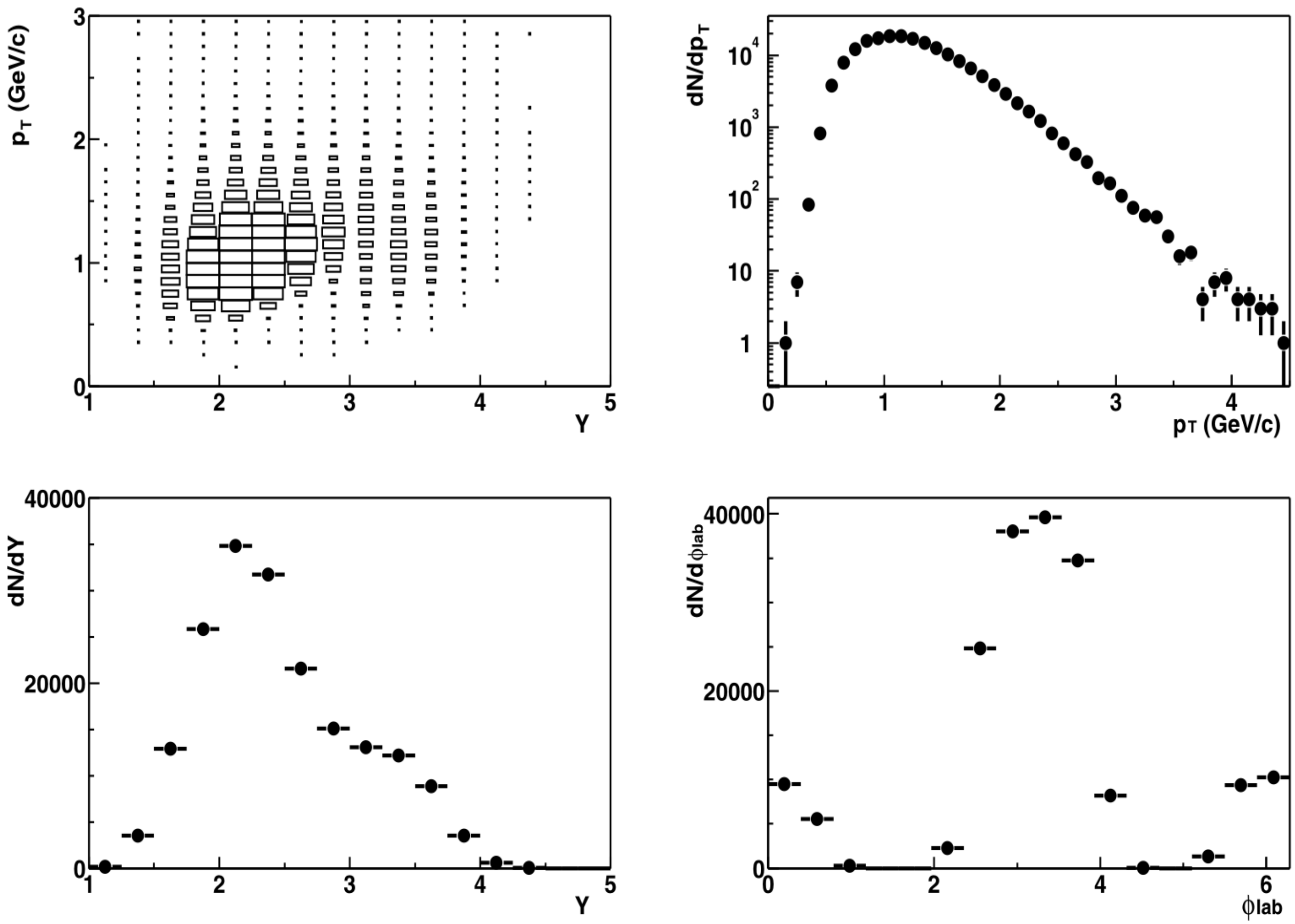
y ≈ -1.5 - 1.0, p_T ≈ 0.4 – 4 GeV/c



Azimuthal distribution



Accepted Λ hyperons



$y = 1.3 - 4.0$

$p_T = 0.4 - 4$ GeV/c

$\langle y \rangle \approx 2.5$

$\langle p_T \rangle \approx 1.25$ GeV/c

Large anisotropy in the azimuthal distribution

Estimate of the event plane

- primary π^-, π^+ identified by dE/dx with $p_T < 1$ GeV/c ; $2.4 < y < 5$
- non-target interactions removed by cuts on:
  – deviation from vertex nominal position in space, 0.5 cm in all directions
- quality criteria for reconstructed tracks
- reduction of tracks from weak decays and other secondary vertices by cut on track distance from reconstructed event vertex in the target plane:
  – ± 3 cm in bending direction
  – ± 0.5 cm in non-bending direction
- avoiding autocorrelations by removing tracks with first, last point in TPCs same as for Λ candidate daughter track

Estimate of the event plane

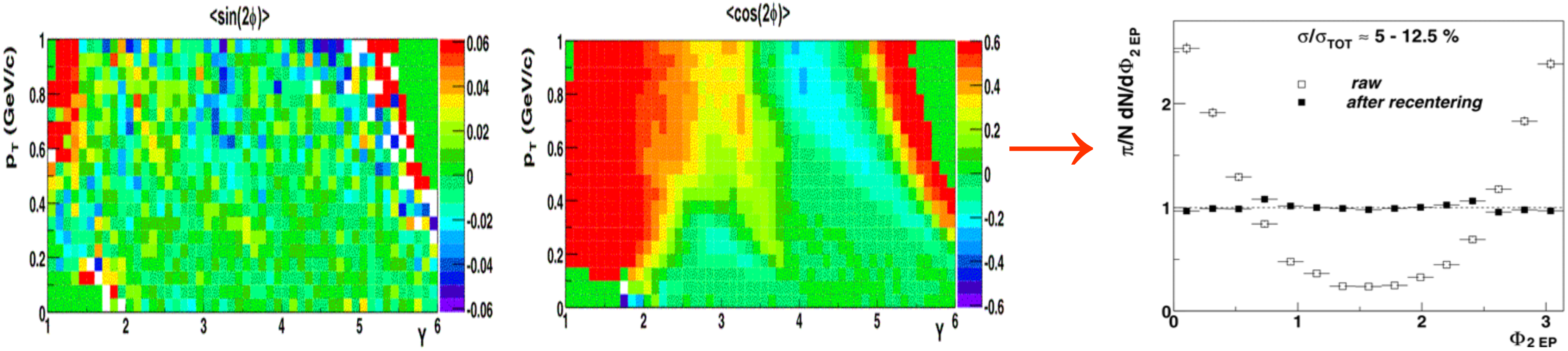
- extraction of the azimuthal angle of the event plane:
  - $X_2 = Q_2 \cos(2\Phi_{2\,EP}) = \sum_i p_{Ti} [\cos(2\varphi^i_{lab}) - \langle\cos(2\varphi_{lab})\rangle]$

    $Y_2 = Q_2 \sin(2\Phi_{2\,EP}) = \sum_i p_{Ti} [\sin(2\varphi^i_{lab}) - \langle\sin(2\varphi_{lab})\rangle]$

    $\Phi_{2\,EP} = (\tan^{-1} Y_2 / X_2) / 2$
- acceptance correction by recentering the distribution
  - $\langle\cos(2\varphi_{lab})\rangle$, $\langle\sin(2\varphi_{lab})\rangle$ averaged over all events, stored in a matrix
    - pt = 0.0-1.0 GeV/c - 20 bins
    - y = 1- 6 - 50 bins
    - centrality - 8 bins
    - elapse time - 10 bins

Corrections

- acceptance correction by recentering the azimuthal distribution of π^+, π^-



- additional acceptance correction by artificial mixed-events

$$dN/d(\varphi_{lab}-\Phi_{2\ EP})=dN_{real}/d(\varphi_{lab}-\Phi_{2\ EP})\ /\ dN_{mix}/d(\varphi_{lab}-\Phi_{2\ EP})$$

- background subtraction from $m_{p\pi}$ distribution of Λ candidates in every azimuthal bin

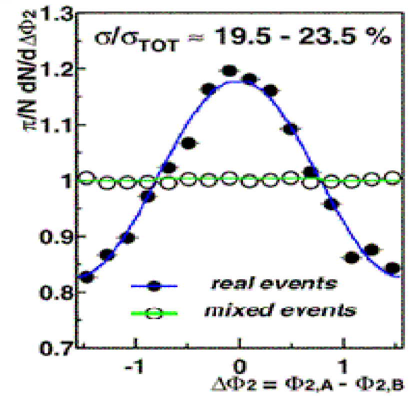
Event Plane Resolution

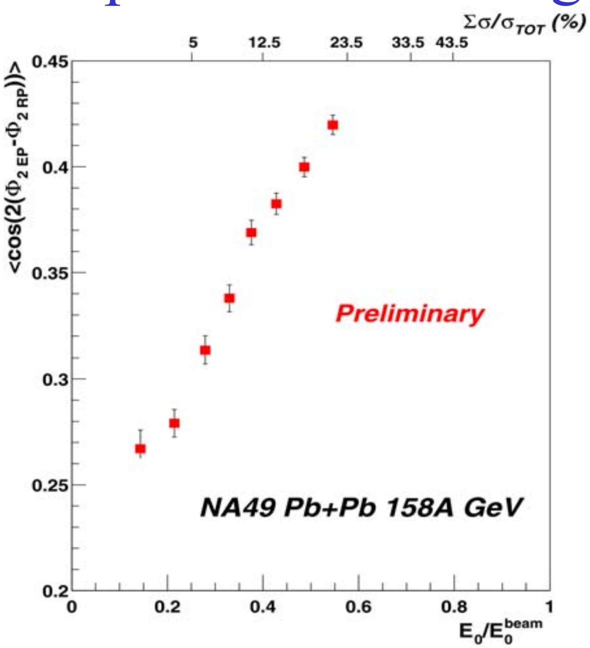
- the sub-event resolution is determined from the fit

$$F(\Delta\Phi_2)=1 + 2 \langle\cos(2\Delta\Phi_2)\rangle \cos(2\Delta\Phi_2), \quad \Delta\Phi_2 = \Phi_{2A} - \Phi_{2B}$$

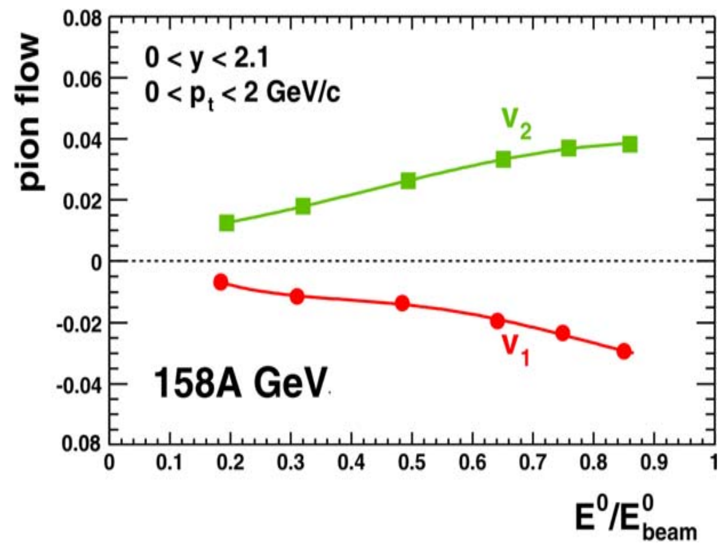
$$\langle\cos(2(\Phi_{2EP} - \Phi_{2RP}))\rangle = [2\langle \cos(2(\Phi_{2A}-\Phi_{2B}))\rangle]^{1/2}$$

- event plane resolution follows the increase of the elliptic flow for charged π mesons





C.Alt et al., PRC68, 034903

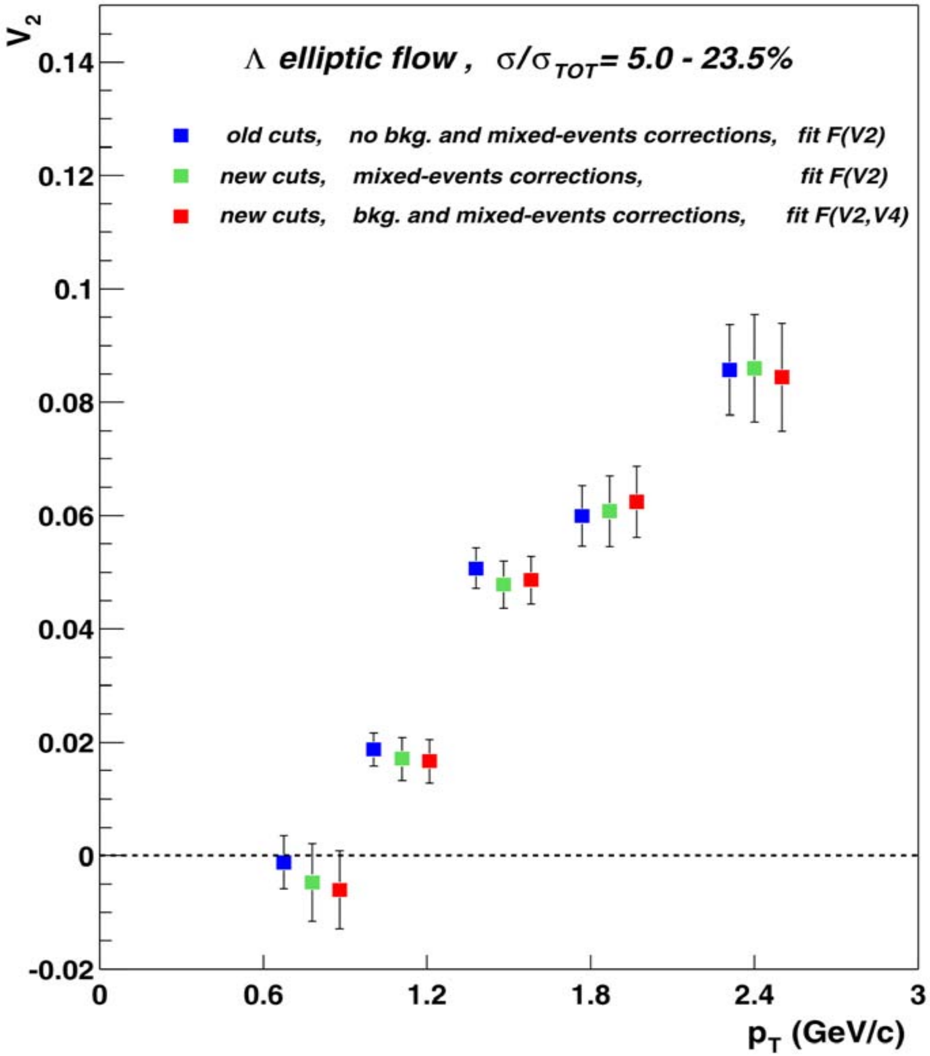


Outlook

- analysis of different particles K^0_s, φ, Ξ at top SPS in progress

- π, p, Λ, K^0_s at 20, 30, 40 GeV

Modifications of the method



- succesive modifications of the method don't change the elliptic flow values significantly
- difference between data sets can be treat as an estimate of the systematic error of the method