Strange and Charged Particle Elliptic Flow in Pb+Au Collisions at 158 GeV

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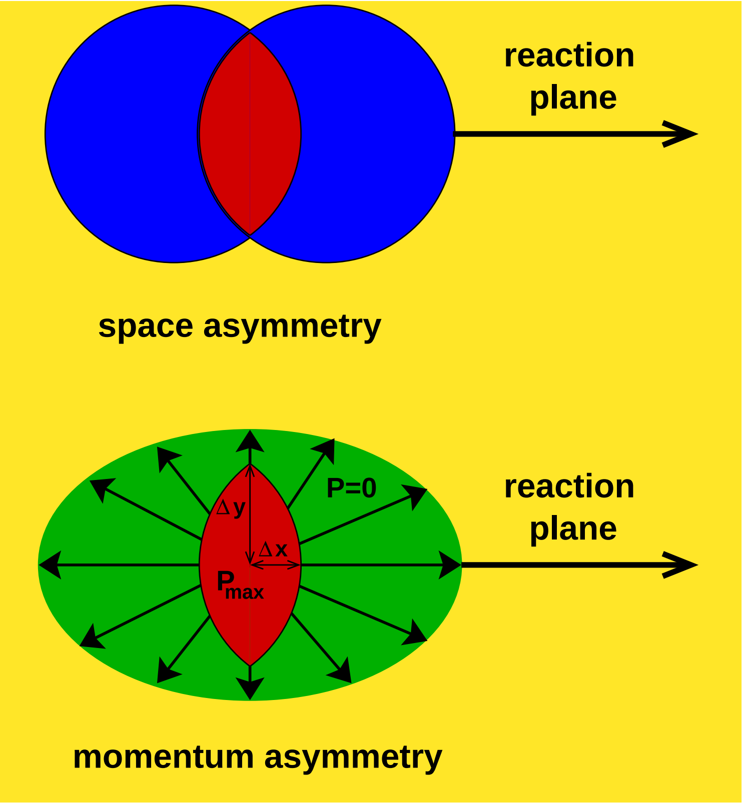
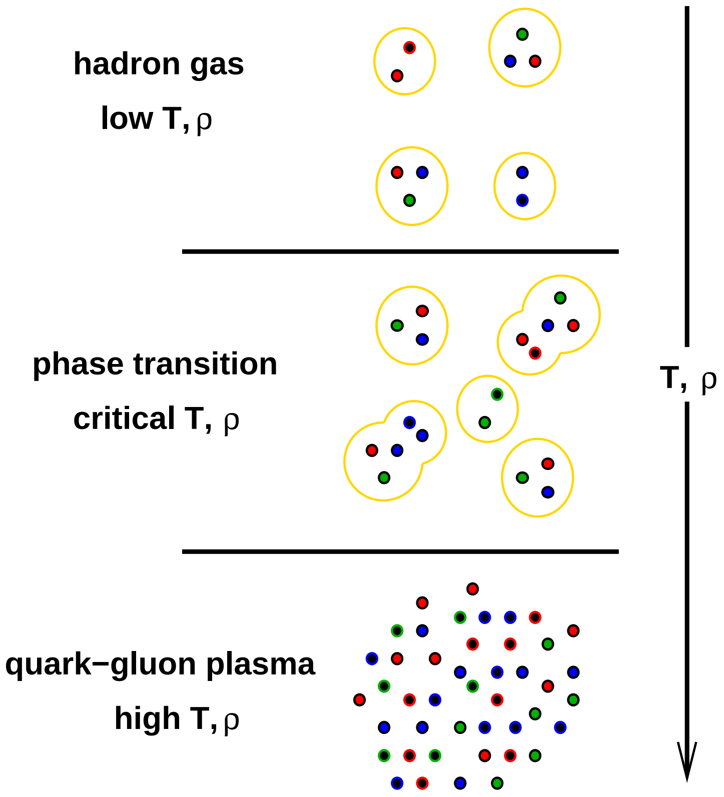
Motivation for studying flow

- $dN/d(\phi - \Psi)$ is not isotropic in non-central collisions. This phenomenon we called flow
- Flow is sensitive to the Equation of State
- Elliptic flow of Λ is important because Λ is a baryon and has one constituent s quark. Comparing scaled flows one concludes about flow of quarks.

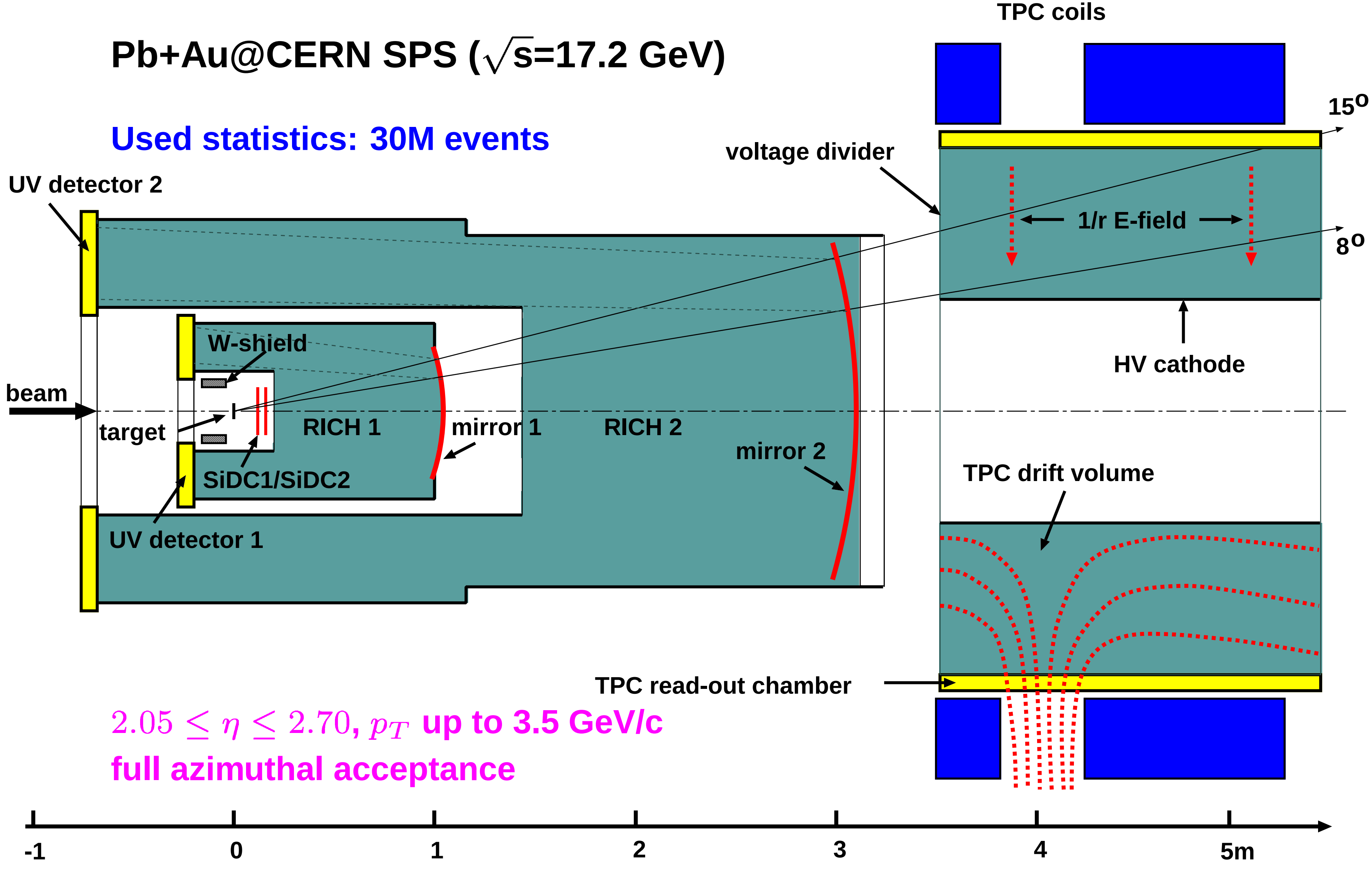




CERES/NA45 experimental setup in year 2000

Pb+Au@CERN SPS ($\sqrt{s}$=17.2 GeV)

Used statistics: 30M events



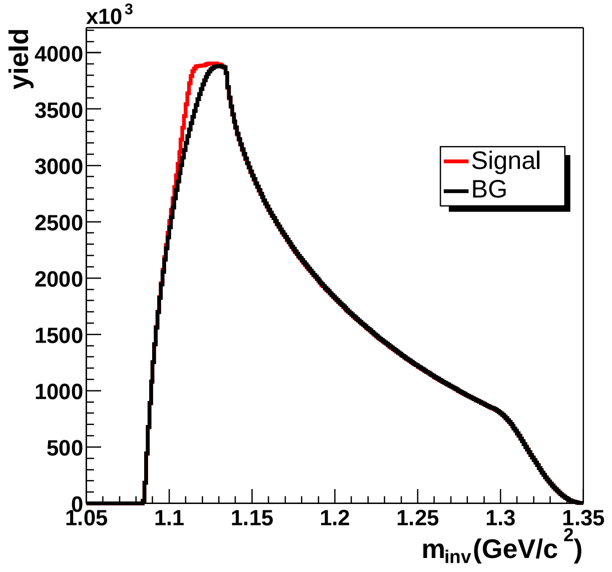
$2.05 \leq \eta \leq 2.70$, p_T **up to 3.5 GeV/c**

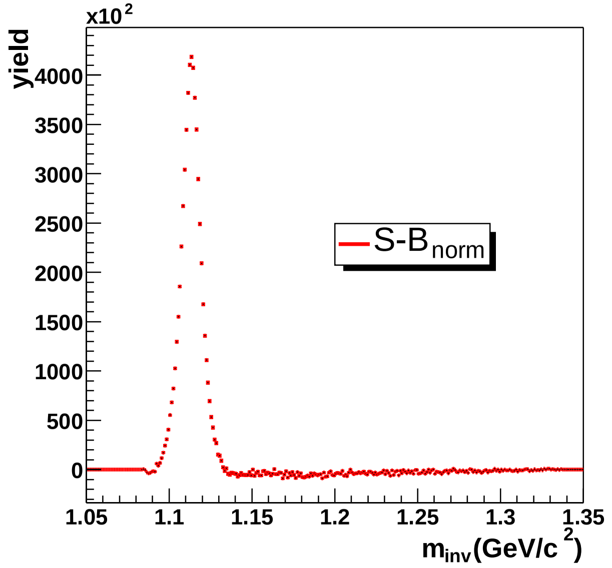
full azimuthal acceptance

Cuts applied to reduce the background; Λ signal

- Reconstructed $\Lambda \rightarrow p + \pi^-$ ($BR = 63.9\%$, $c\tau = 7.89$ cm) using TPC tracks which satisfy:
  - TPC dE/dx cut ($\pm\, 1.5\sigma$ for $\pi^{\pm}$, 1σ for p)
  - Number of hits per track, depending on θ, is between 8 and 12 hits per track
  - $2.05 \leq \eta \leq 2.70$, $\quad p_T \geq 0.05$ GeV/c
  - TPC candidate tracks for Λ daugthers should not match SDD tracks within 3σ due to late decay
  - Armenteros-Podolanski cut: $q_T \leq 0.125$ and $0 \leq \alpha \leq 0.65$
- Pairs of candidates should survive p_T dependent opening angle cuts
- Background is calculated by rotating positive track by a random angle

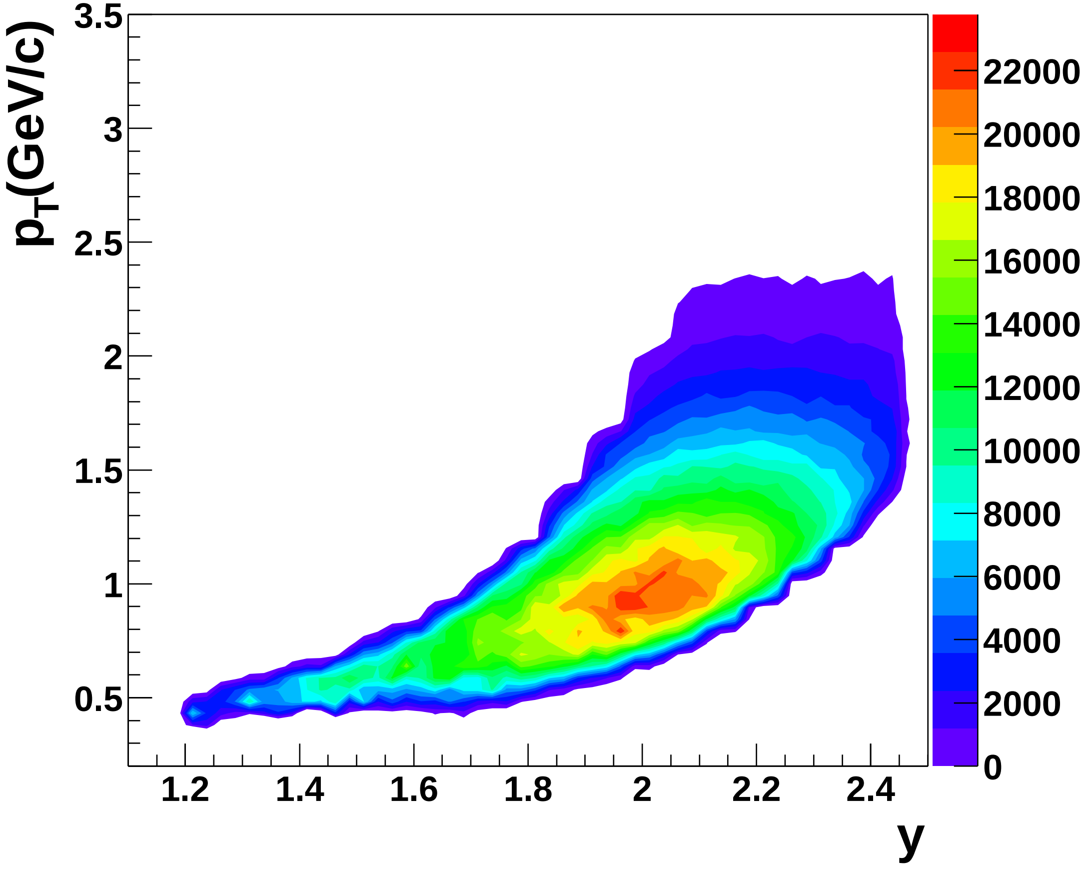
With these cuts optimal values for $\frac{S}{B} \approx 0.04$ and $\frac{S}{\sqrt{B}} \approx 500$ were obtained





Characteristics of Λ signal

- Λ signal is fitted with a Gaussian + a constant
- Flow analysis is done separately in each small y and p_T bin where mean and width of Gaussian are constant; results ($dN_\Lambda/d(\phi-\Phi)$) are merged
- Distribution of accepted Λs



Λ flow analysis by reaction plane method

- **Azimuthal distributions of particles with respect to the true reaction plane orientation (Ψ)**

$$E\frac{d^3N}{d^3p} = \frac{d^2N}{p_T dp_T dy}\frac{1}{2\pi}\{1 + 2v_2\cos[2(\phi - \Psi)]\} \tag{1}$$

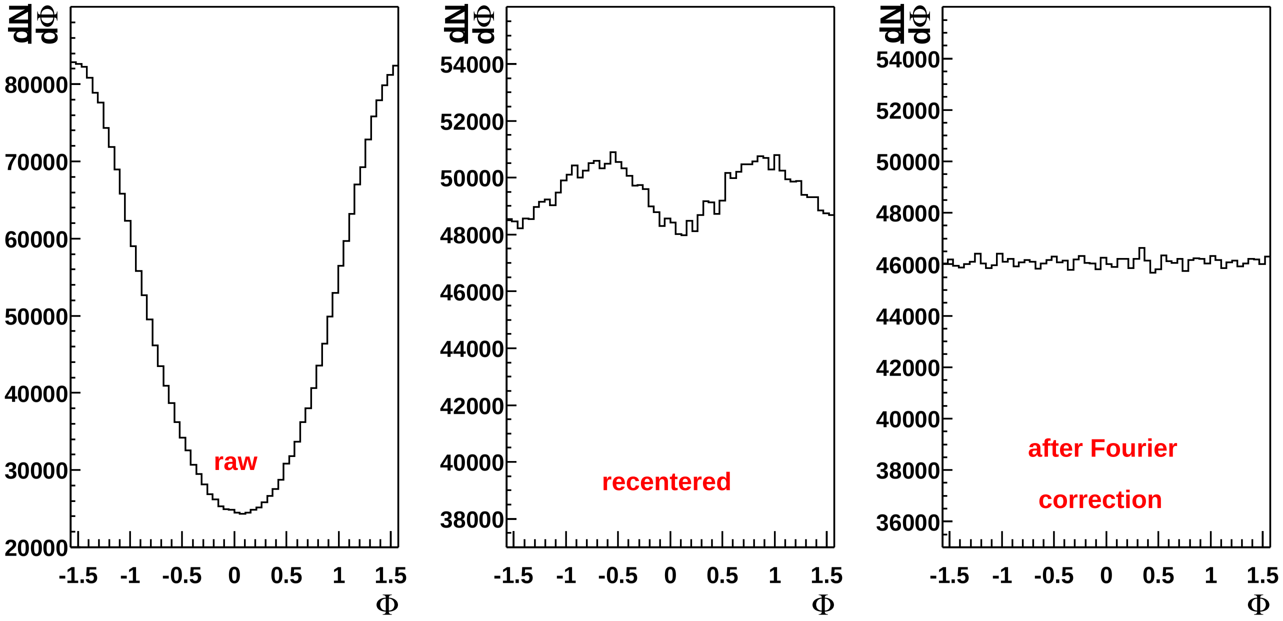
- **Reaction plane orientation (Φ) is measured from the second Fourier harmonic**

$$\Phi = \frac{1}{2}\arctan\left(\frac{Y_2}{X_2}\right) \equiv \frac{1}{2}\arctan\left(\frac{\sum_i \sin(2\phi_i)}{\sum_i \cos(2\phi_i)}\right) \tag{2}$$

- **We avoid autocorrelations using particles which are not candidates for Λ daughters, i.e. we used primary vertex tracks for the reaction plane determination**
- **Flattening of the reaction plane was done by** *recentering* **and** *Fourier Expansion* **of $dN/d\Phi$**
- **Finite resolution of the measured reaction plane. Observed Fourier coefficient v_2' has to be corrected for the resolution:**
  $v_2 = v_2'/\sqrt{2\langle\cos[2(\Phi_a - \Phi_b)]\rangle}$

Flattening of reaction plane

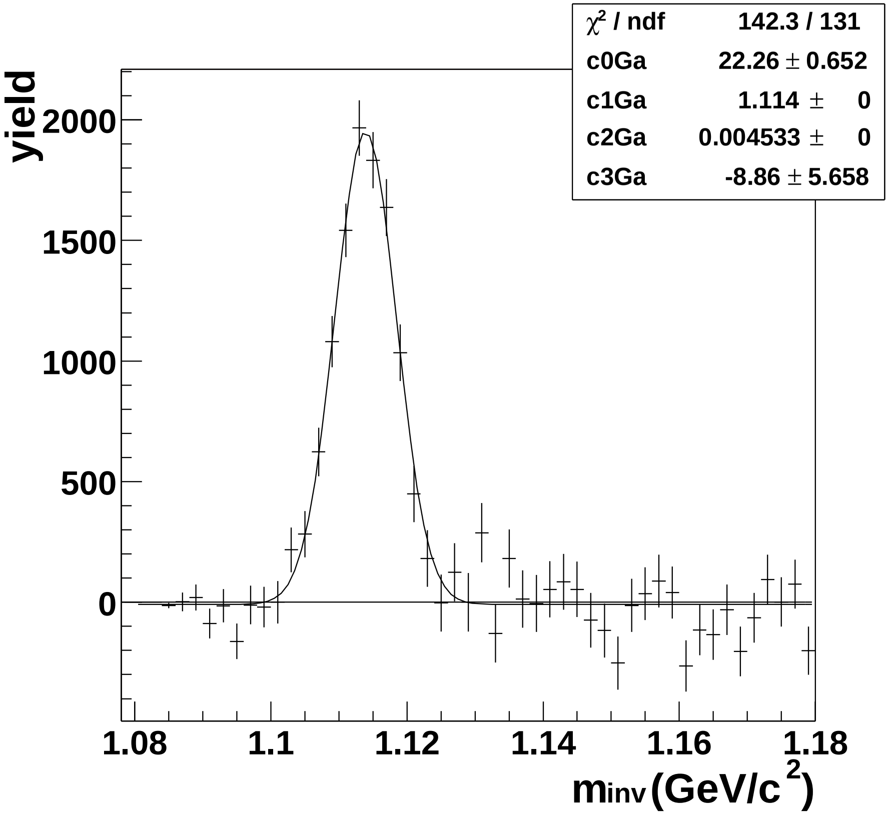
- For an ideal detector $dN/d\Phi$ is flat
- In reality, different detector effects {efficiency in ϕ smaller then 100%, geometrical offset between position of the beam and the center of the detector in the $x-y$ plane} make it nonflat
- Example of flattening of the calculated reaction plane (Φ) in one centrality bin:

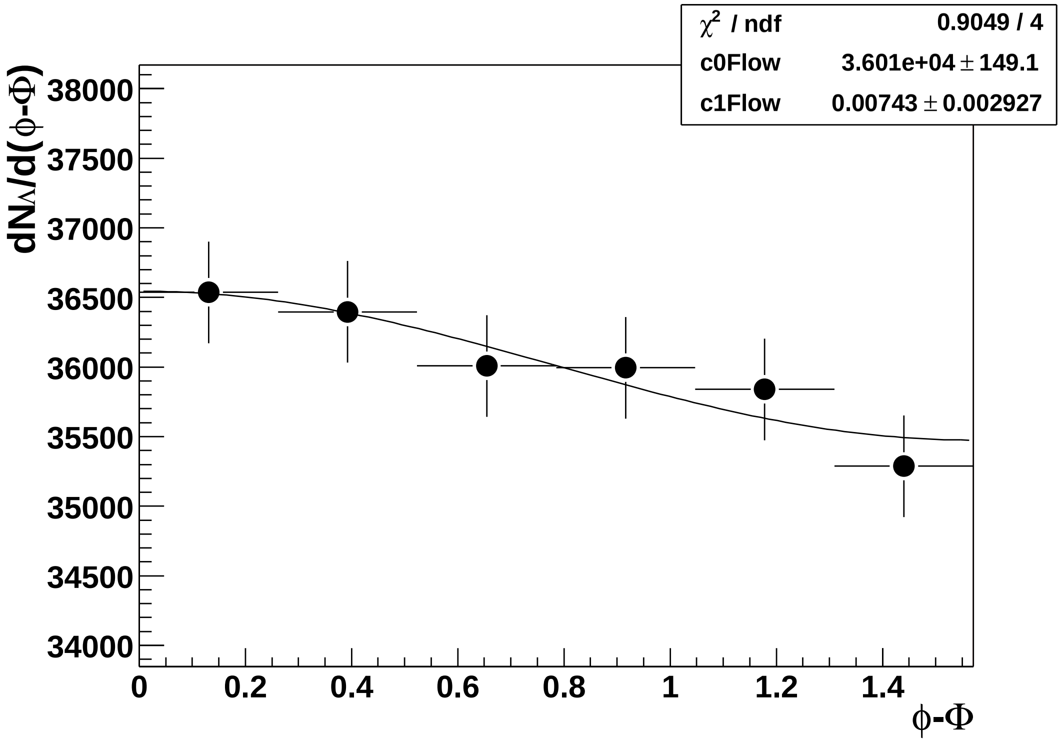


- For consistency, reaction planes from all 4 harmonics were checked

Evaluation of yields vs $(\phi - \Phi)$ angle

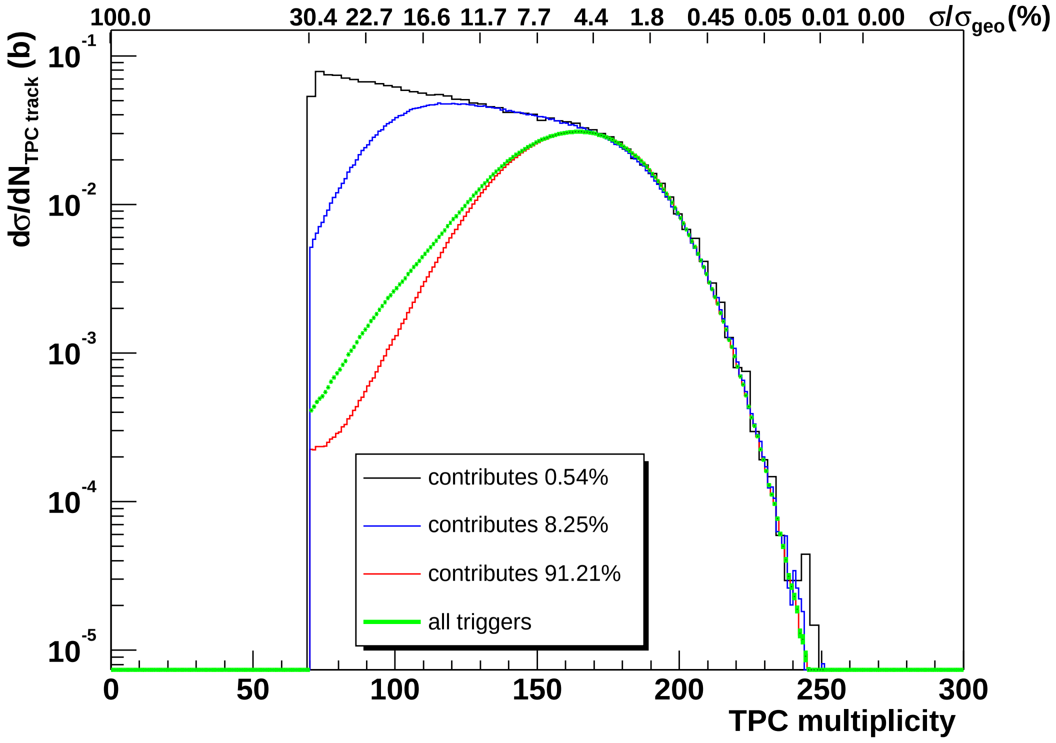
- In each $y - p_T$ bin we reconstructed Λ in 6 $(\phi - \Phi)$ bins
- Uncorrected elliptic flow values v_2' were obtained by fitting $dN_\Lambda/d(\phi - \Phi)$ distributions with $A(1 + 2v_2' \cos[2(\phi - \Phi)])$ flow function

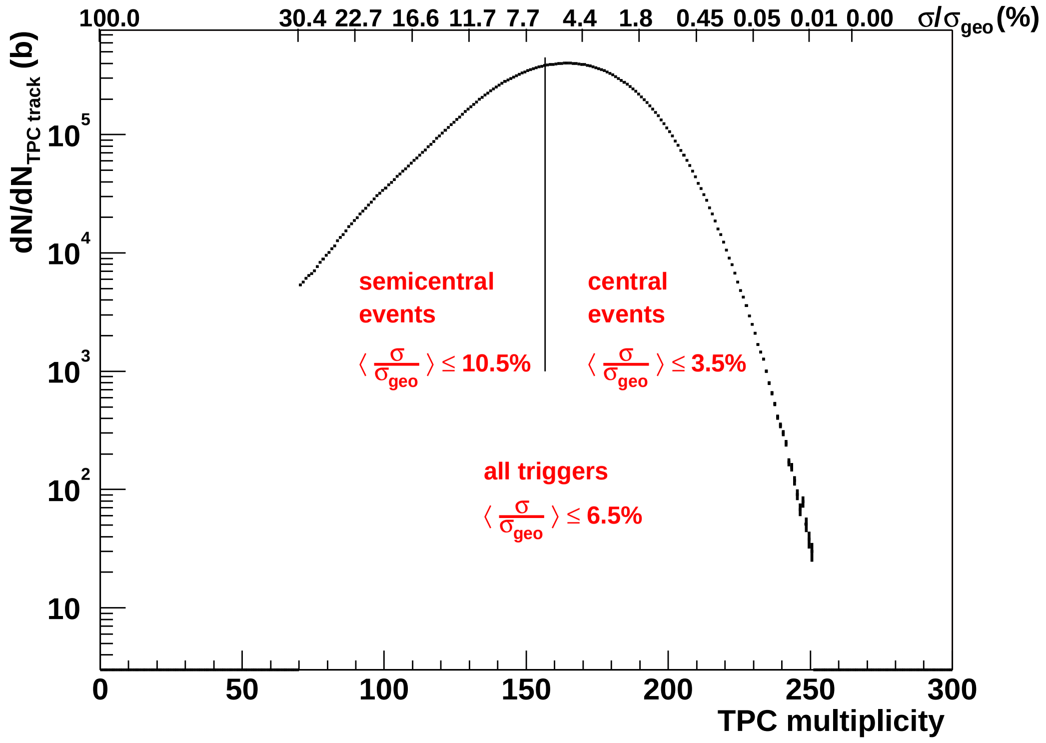




Centrality determination

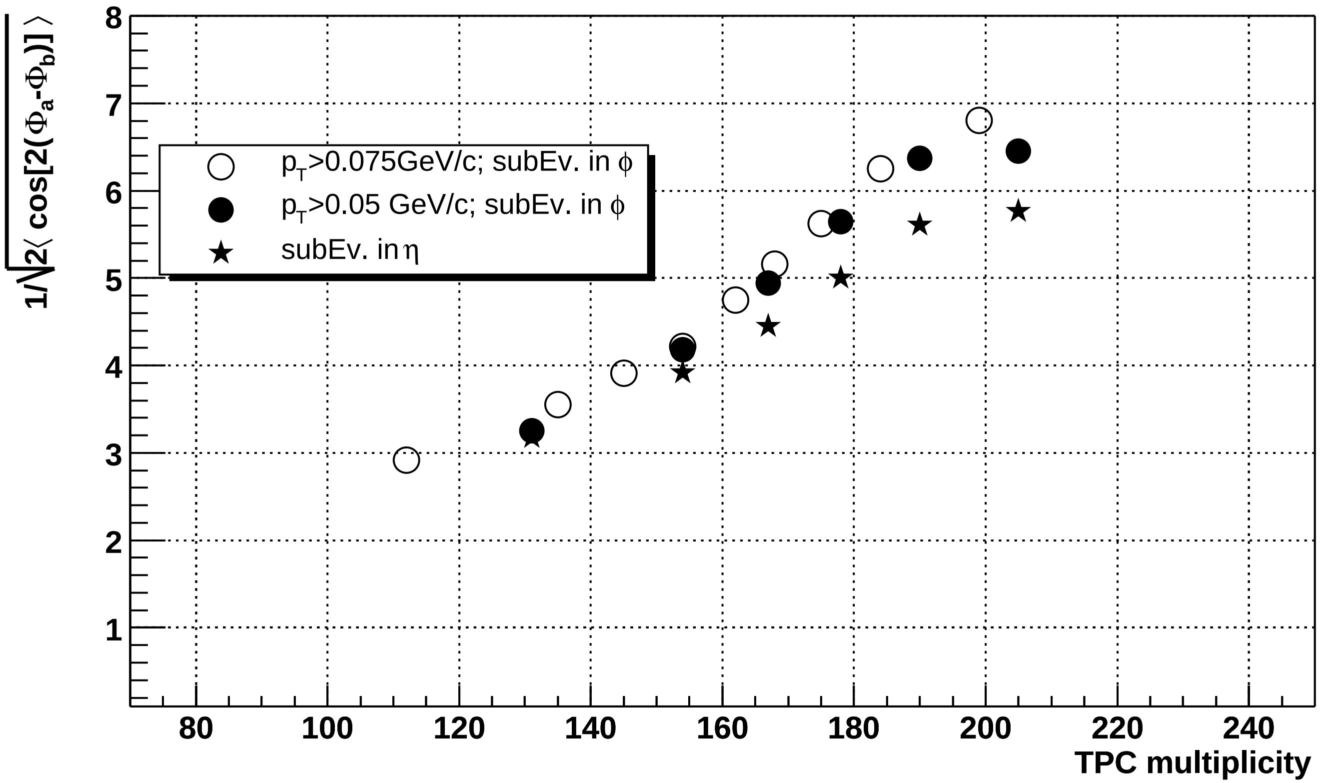
- **3 triggers contribute with 0.54%, 8.25% and 91.21%**
- **Flow analysis is done in 2 centrality bins with weighted mean centrality of 3.5% and 10.5%**





Correction factors for finite reaction plane resolution

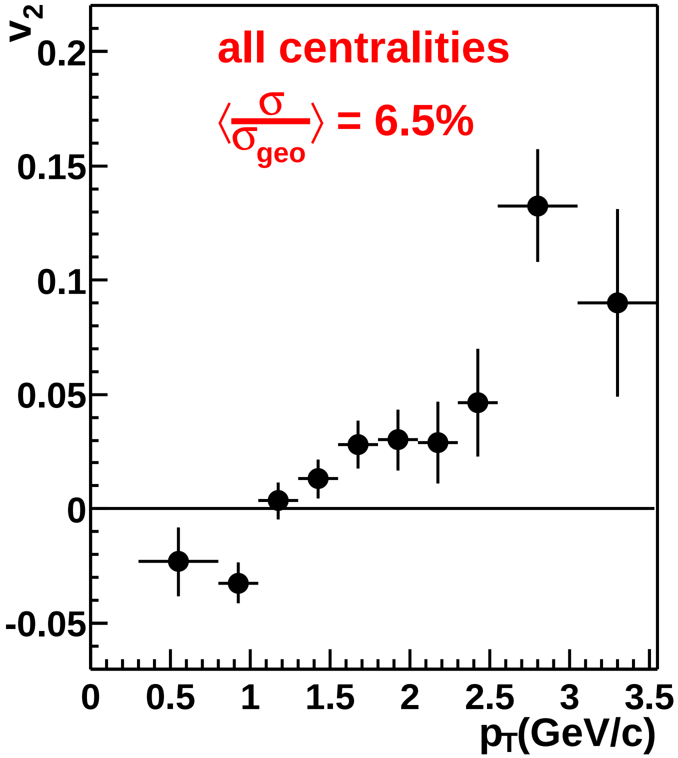
- Correction factors vs TPC multiplicity
- A systematic error due to uncertainty in the determination of the reaction plane was estimated to $\Delta v = 0.11\%$ from the difference between the resolutions obtained from correlations of 2 subevents in ϕ and η

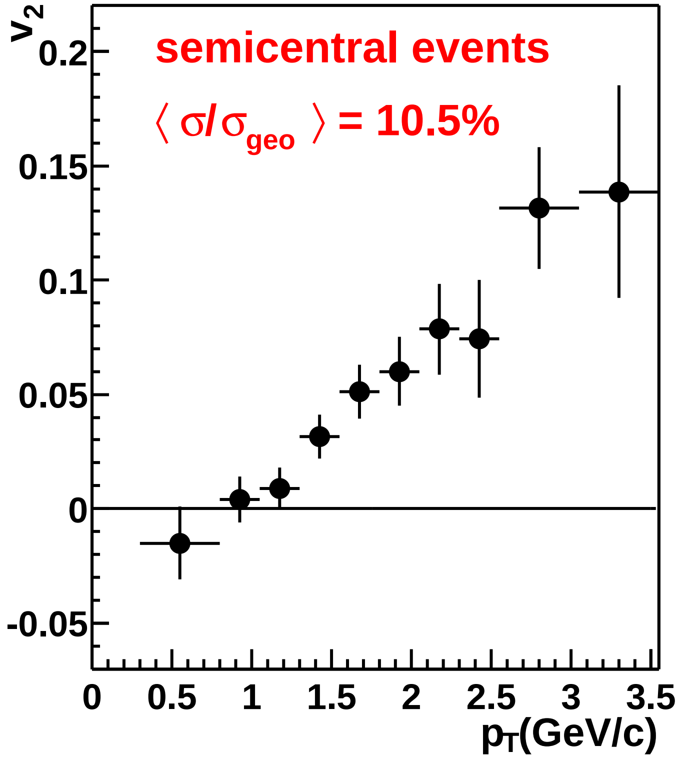


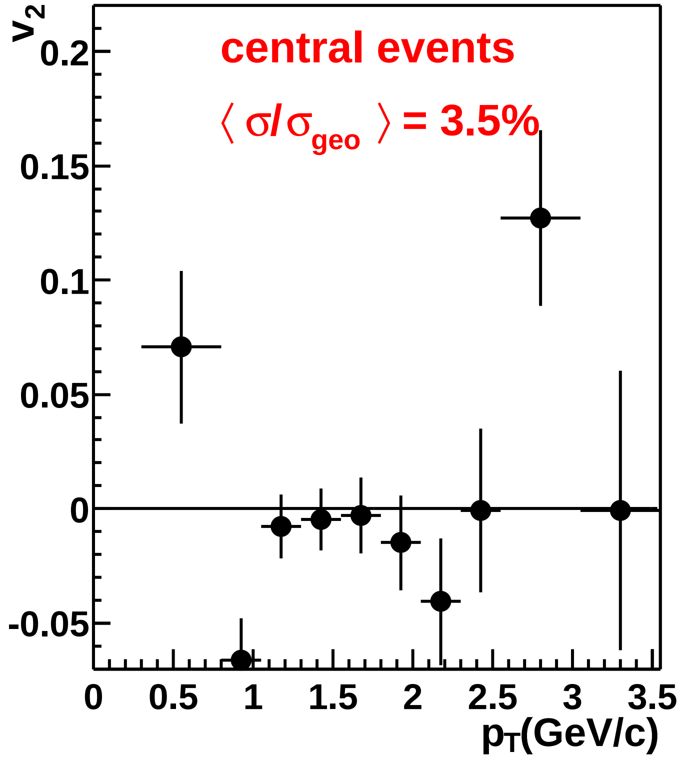
- As expected, they are growing with TPC multiplicity due to decreasing flow

Λ elliptic flow vs p_T for different centralities

- v_2 grows with p_T in noncentral collisions
- A clear difference in the flow intensity between central and semicentral events
- Estimated absolute systematic error Δv is $^{+0.1\%}_{-0.7\%}$ for $p_T < 1.6$ GeV/c and -2% for $p_T > 1.6$ GeV/c

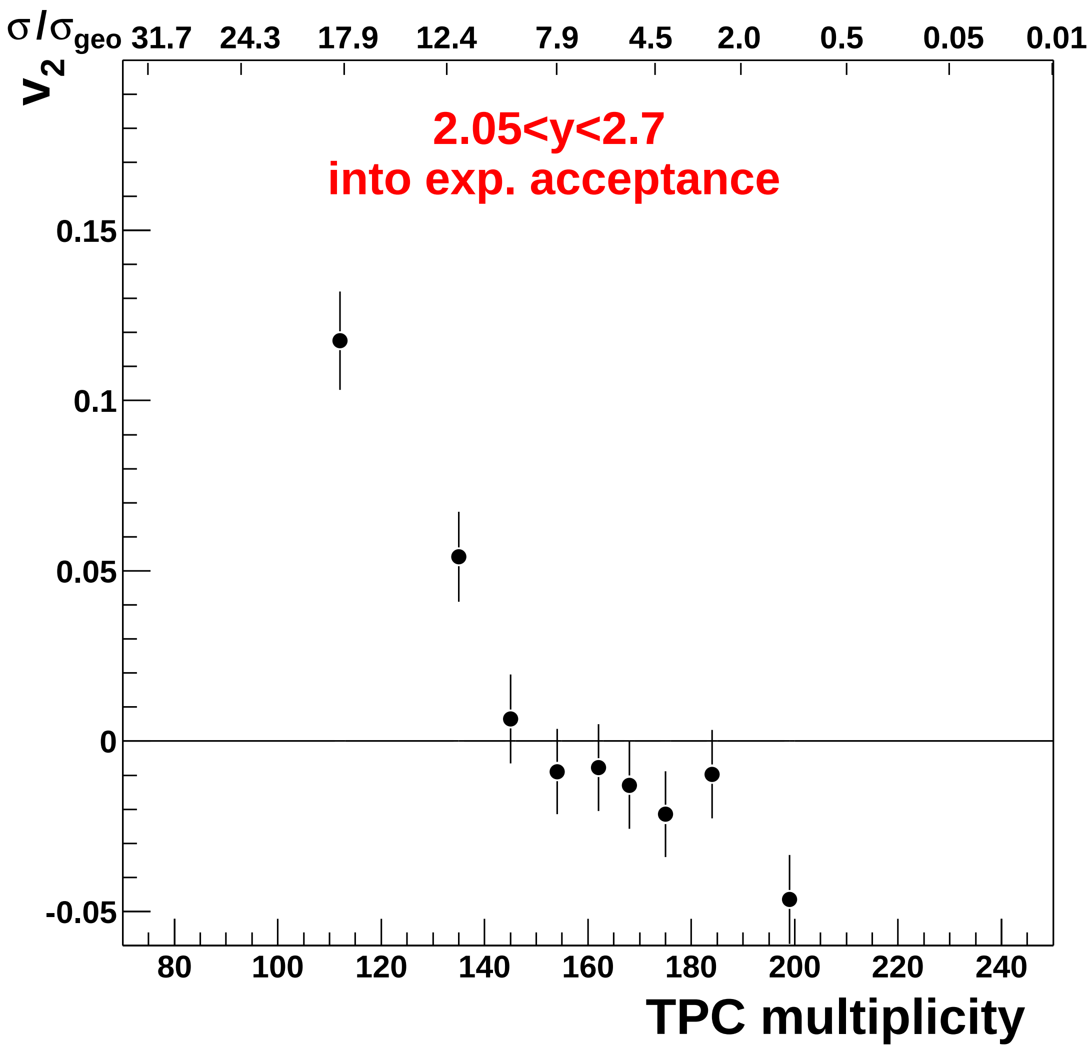






Λ elliptic flow vs centrality

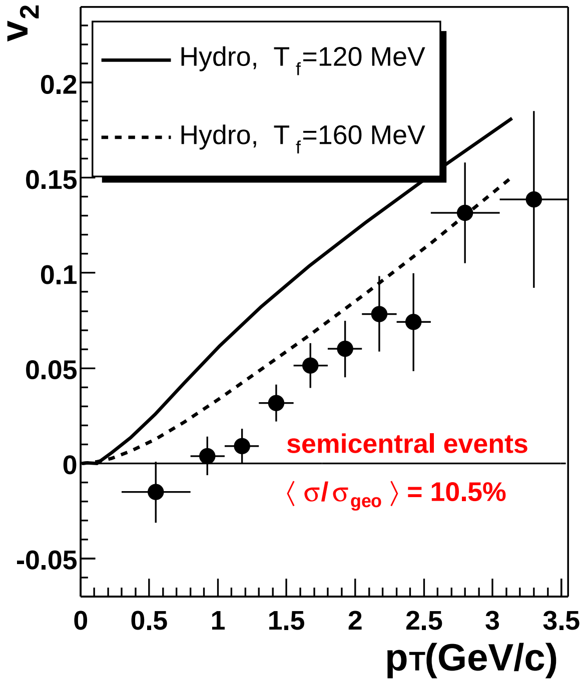
- v_2 **decreasing with increasing centralit2**

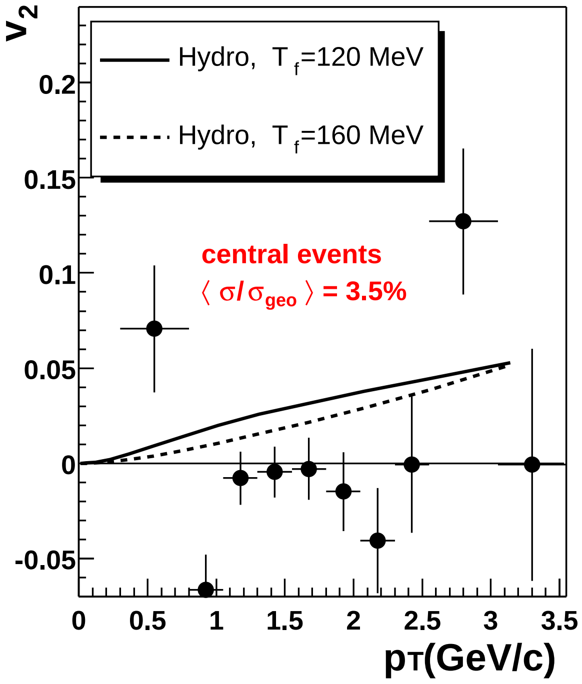


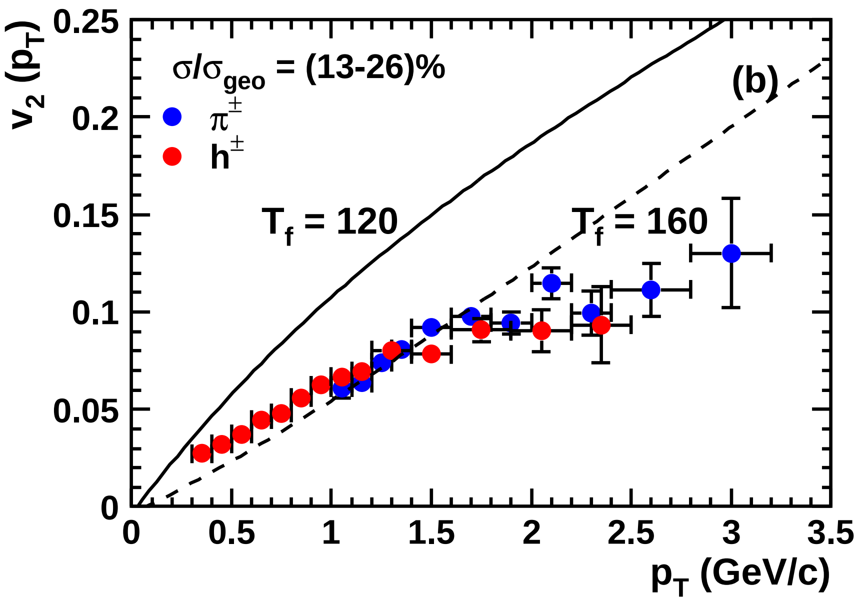
Comparison with hydrodynamical calculations

- **Hydrodynamical calculation with higher freeze-out temperature: $T_f = 160$ MeV is very close to CERES data, while $T_f = 120$ MeV overpredicts data**
- **The same is observed comparing pion flow from CERES to hydrodynamical model**
- **Sensitivity to the EOS**

Hydrodynamical calculation (1-st order phase transition, $T_c = 165$ MeV) by: P. Huovinen



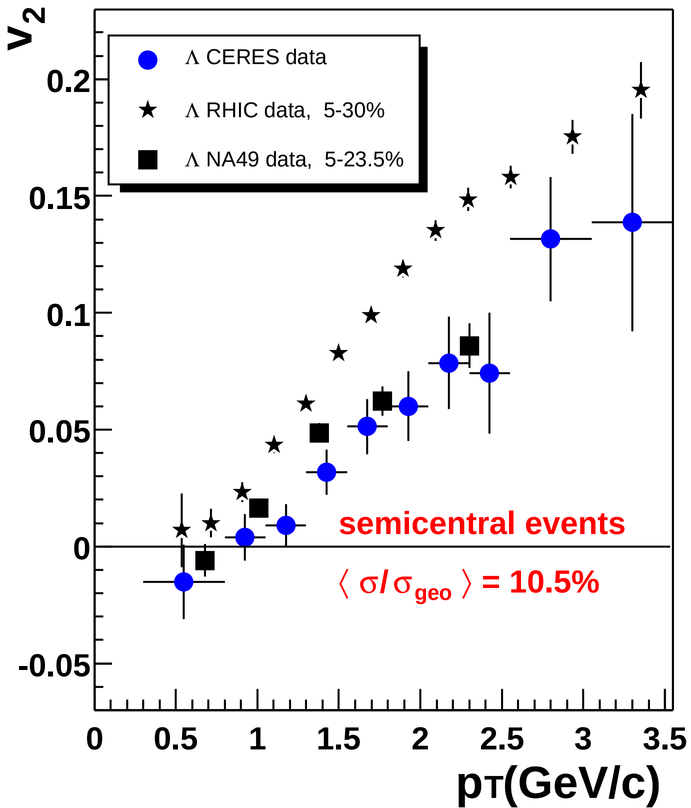


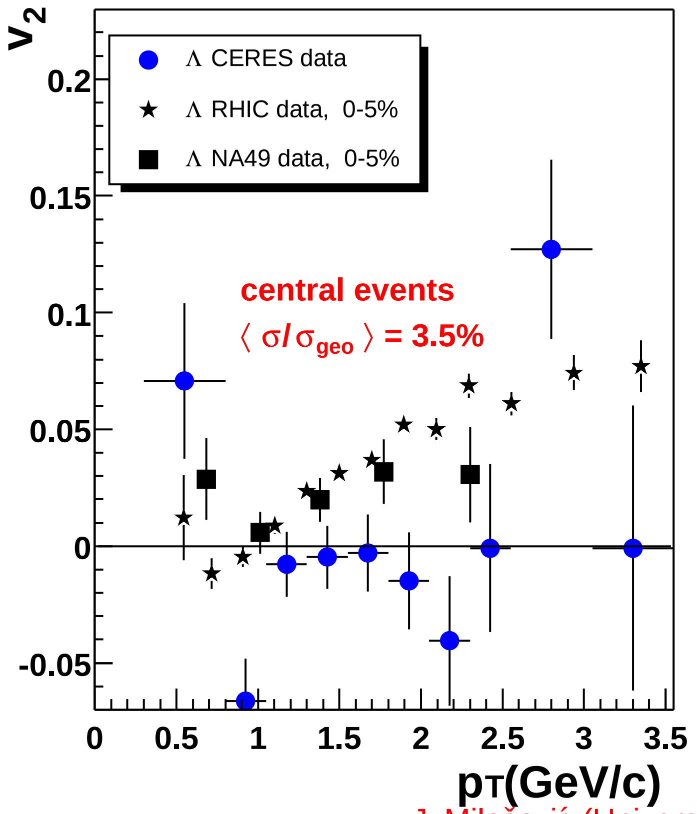


Comparison with RHIC and NA49 results

- **RHIC data shows bigger Λ elliptic flow than CERES data. Partially, it is due to effectively higher centrality used in CERES with respect to the STAR experiment.**
- **Very good agreement for Λ flow intensity between NA49 and CERES data**

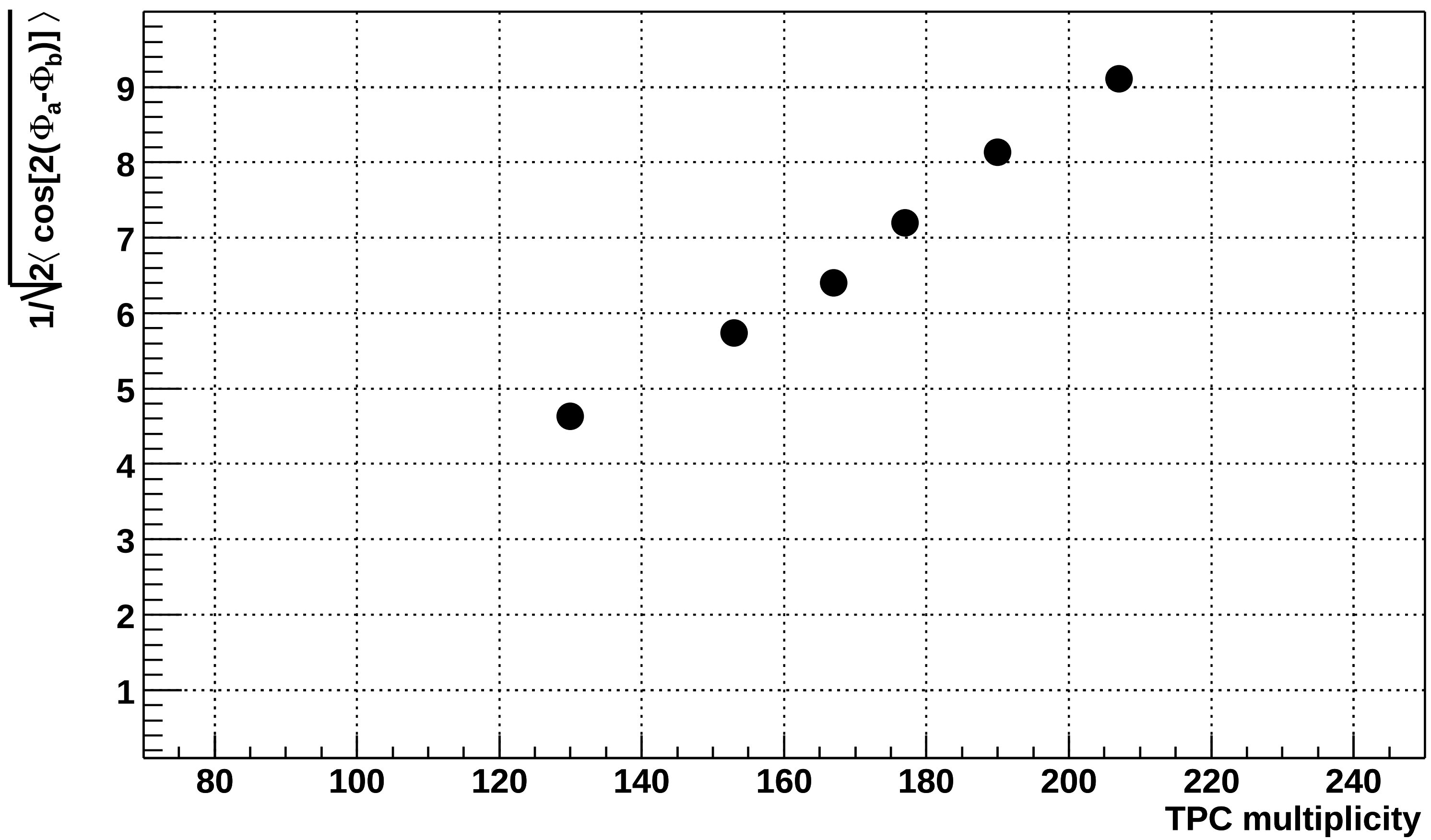
STAR results: Phys. Rev. Lett. ***92****(2004)052302* **(nucl-ex/0306007)**





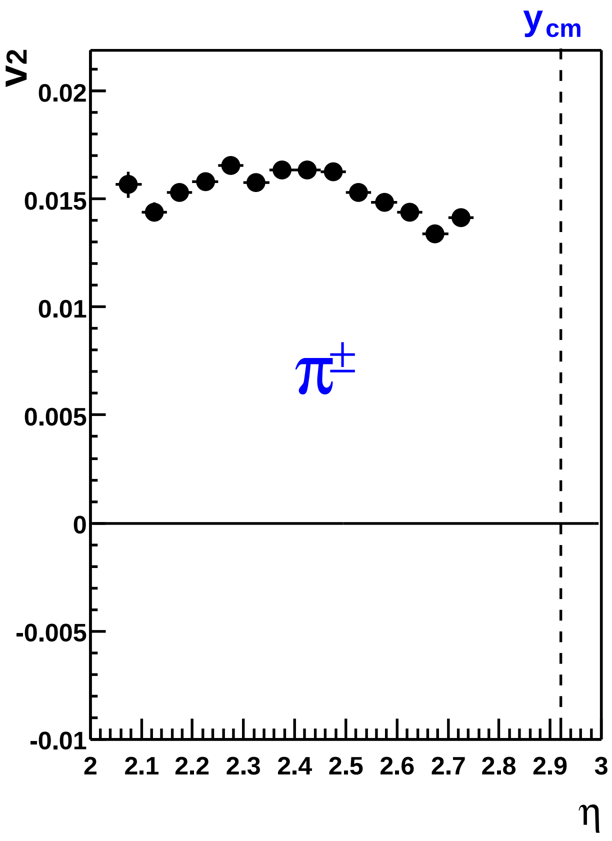
Corrections factors in the case of $\pi^{\pm}$ analysis

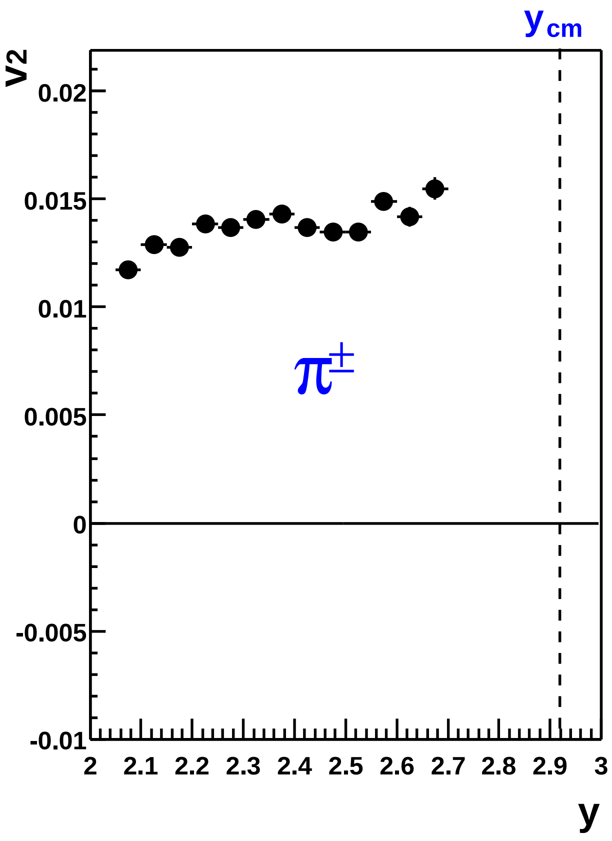
- **Correction factors vs centrality**
- **Correction factors are big due to small multiplicity in each of 4 slices**

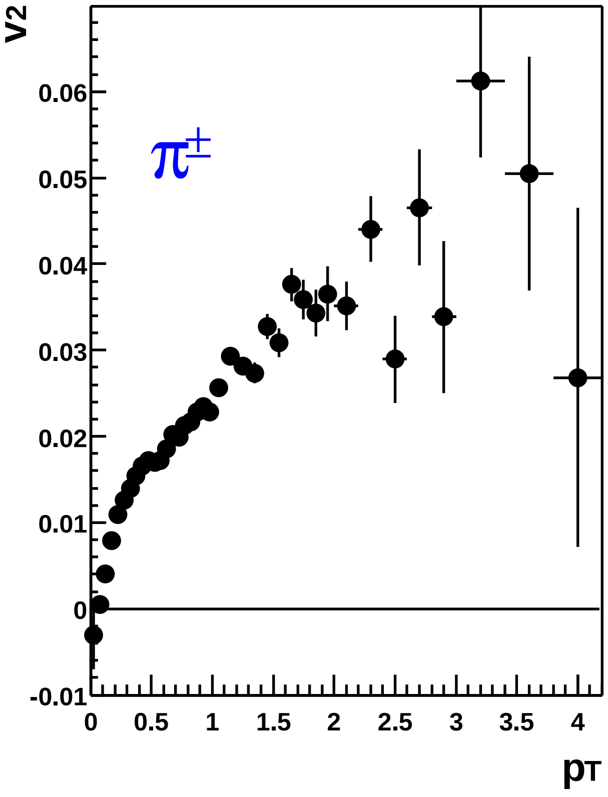


Dependence of $\pi^{\pm}$ elliptic flow on η, y and p_T

- v_2 is rather flat in η and y, and near y_{cm} it has intensity of $\approx$ 1.5%
- v_2 grows with p_T and approaches $\approx 4\%$ at high p_T

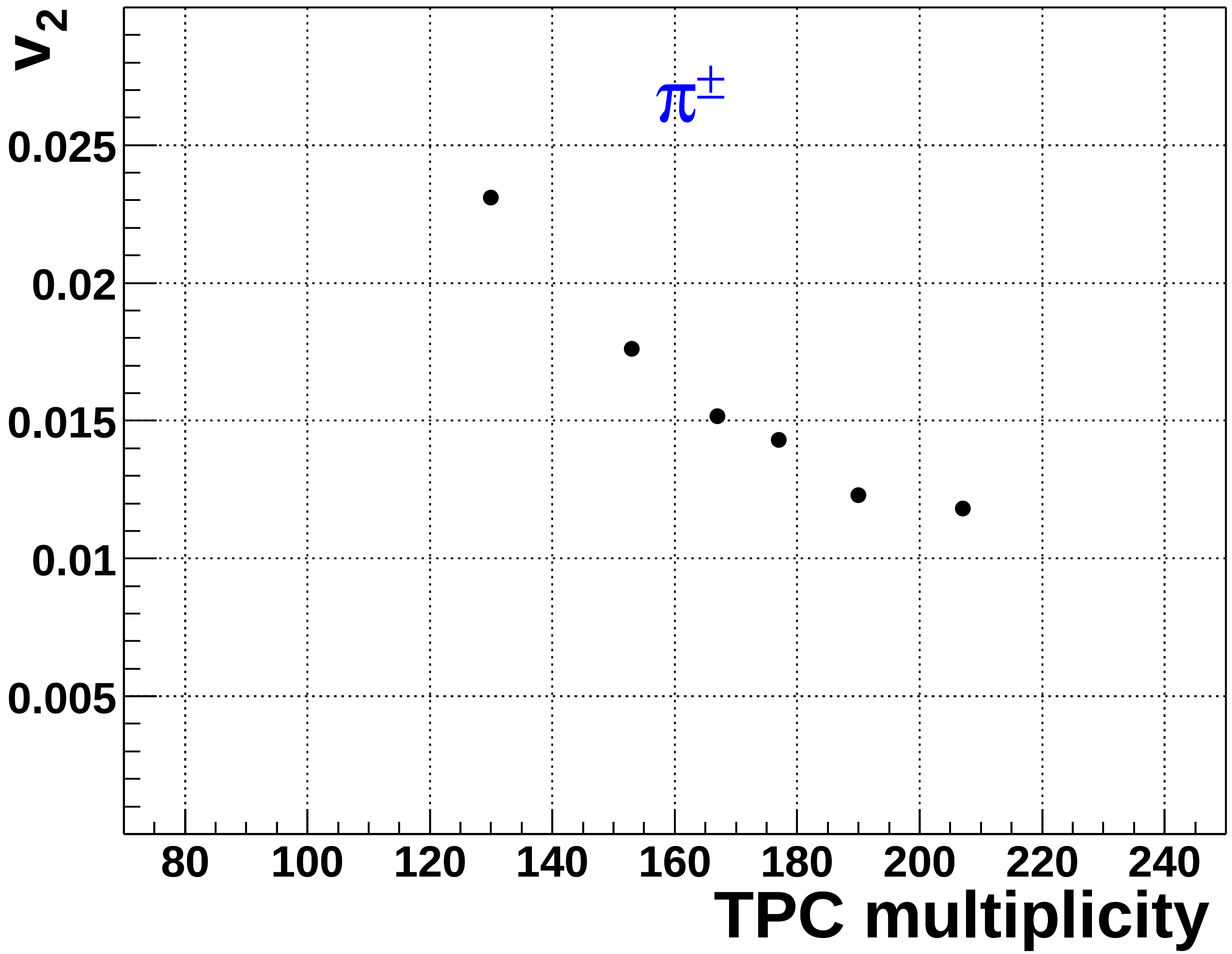






Centrality dependence of π elliptic flow

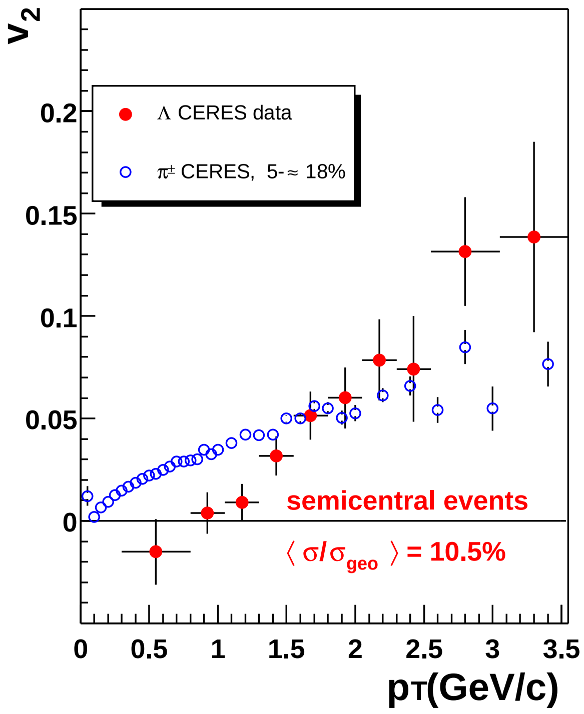
- π elliptic flow decreases with centrality from 2.3% in semicentral to 1.1% in very central collisions

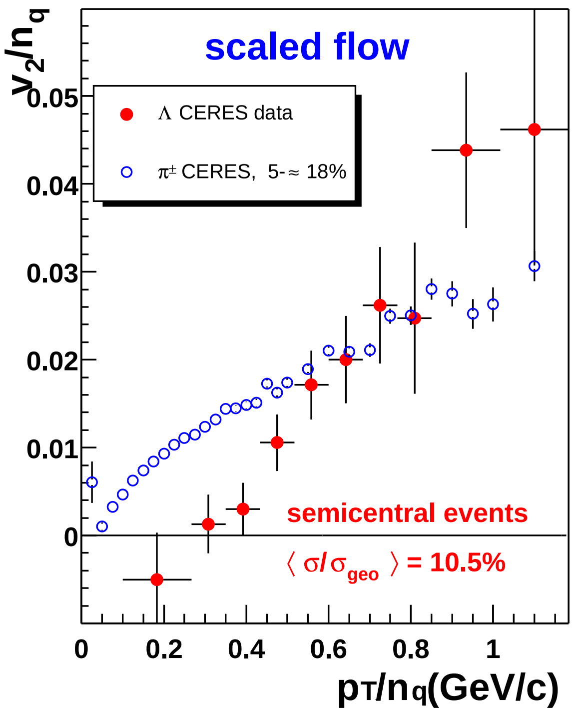


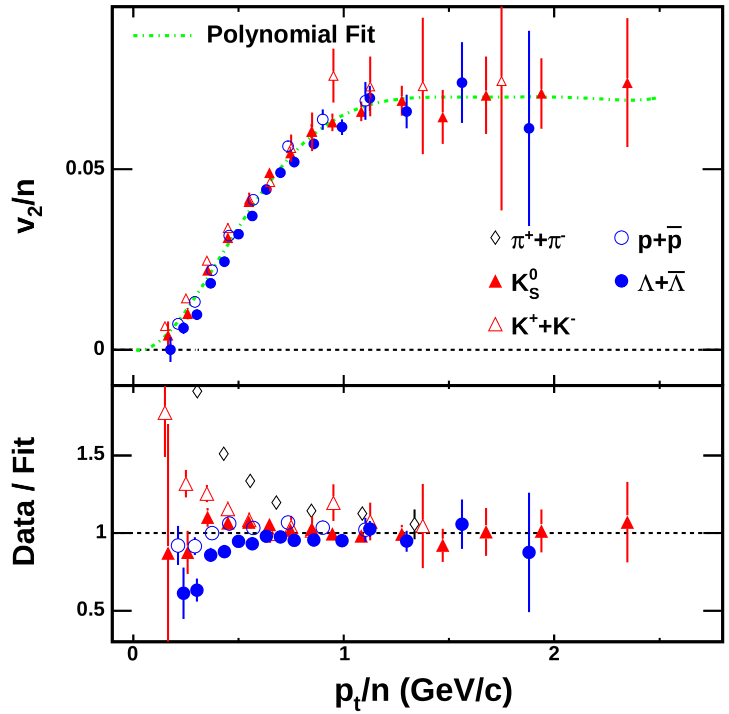
Comparison between Λ and π elliptic flow

- At small p_T, $v_2(\pi) > v_2(\Lambda)$, while it is opposite in case of high p_T
- Comparison of v_2 scaled to the number of constituent quarks between Λ and π shows the same behaviour as it is observed at RHIC

STAR results: Phys. Rev. Lett. **92***(2004)052302* **(nucl-ex/0306007)**

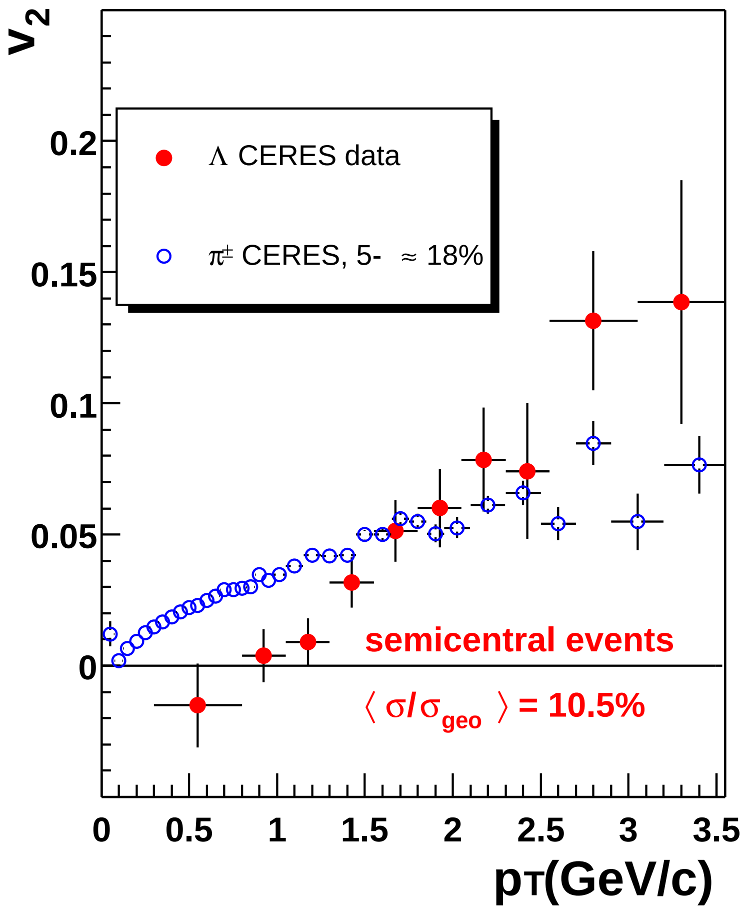


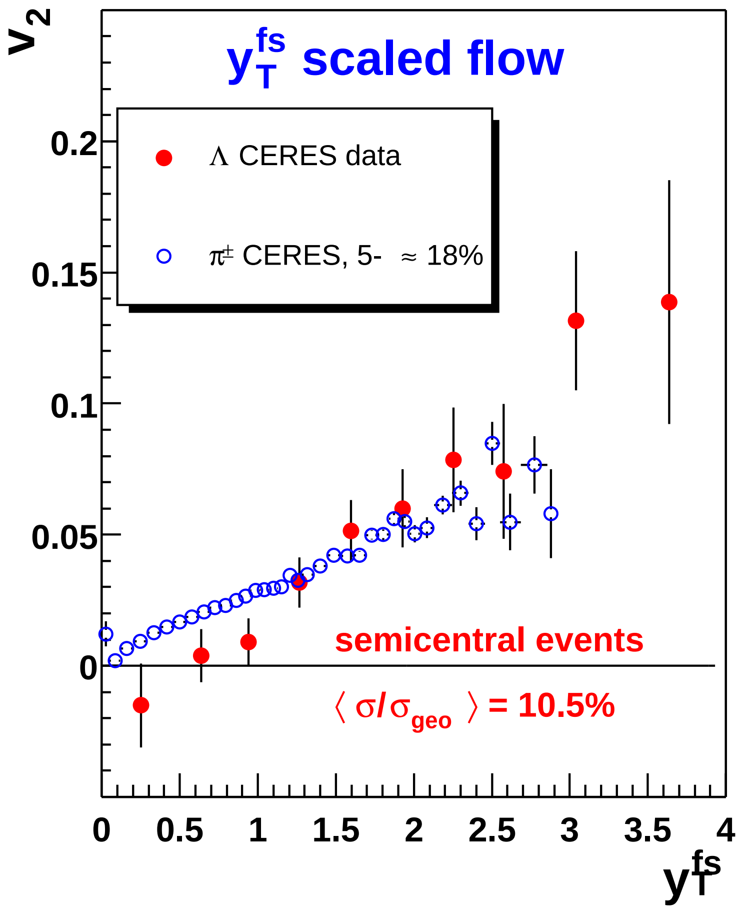




y_T^{fs} scaling

- y_T^{fs} scaling of v_2 of Λ and π shows the same behaviour as it is in the case of scaling to the number of constituent quarks ($y_T^{fs} = k_m y_T^2 m$)





Conclusions

- **Λ elliptic flow**
  - **v_2 increases with p_T**
  - **v_2 decreases with centrality**
  - **CERES data are compared with RHIC and NA49 data**
  - **Hydro-calculation with higher freeze-out temperature: $T_f = 160$ MeV is very close to CERES data, while $T_f = 120$ MeV overpredicts data**
  - **The same is observed comparing pion flow from CERES to hydrodynamical model**
- **π elliptic flow**
  - **v_2 approaches $\approx$ 1.5% near y_{cm}**
  - **v_2 grows with p_T and approaches $\approx$ 4% at high p_T**
  - **π elliptic flow decreases with centrality**
  - **Comparison of v_2 scaled to the number of constituent quarks between Λ and π shows the same behaviour as it is observed at RHIC**
  - **There is no evidence for y_T^{fs} scaling between Λ and $\pi^{\pm}$ elliptic flow**

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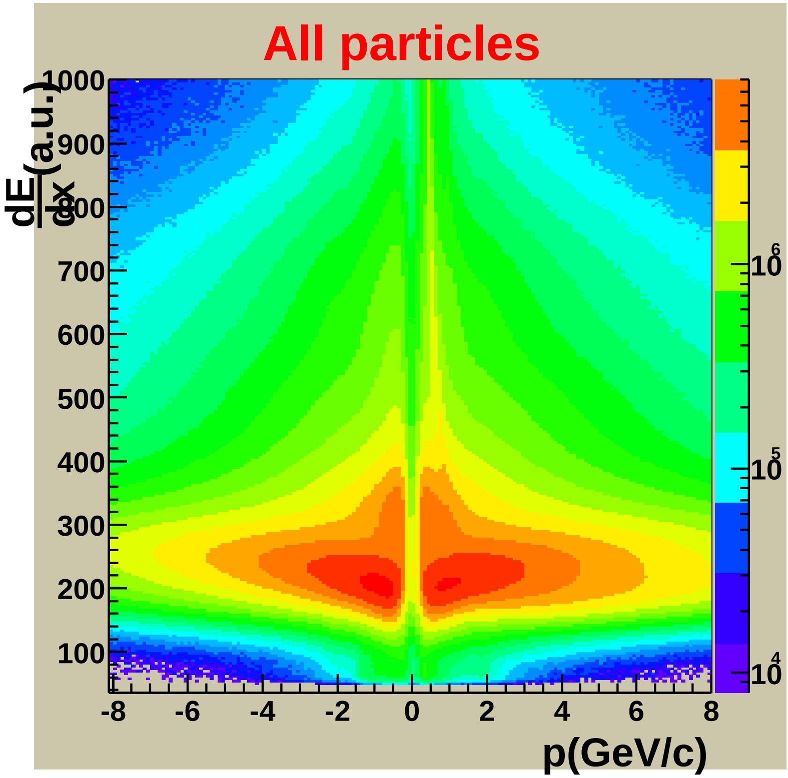
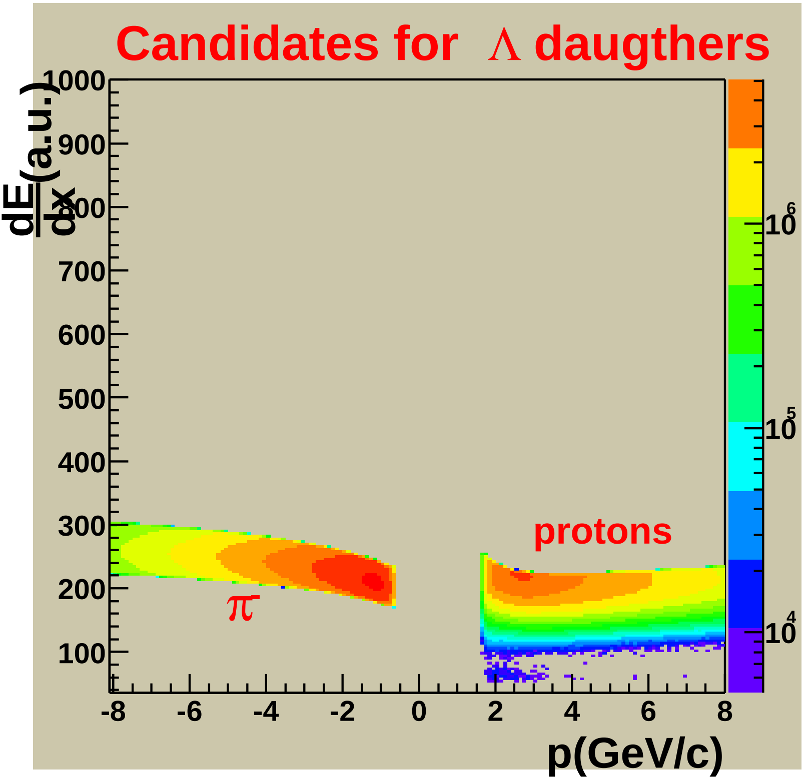
for hydrodynamics calculations

Suppression of the background via TPC dE/dx

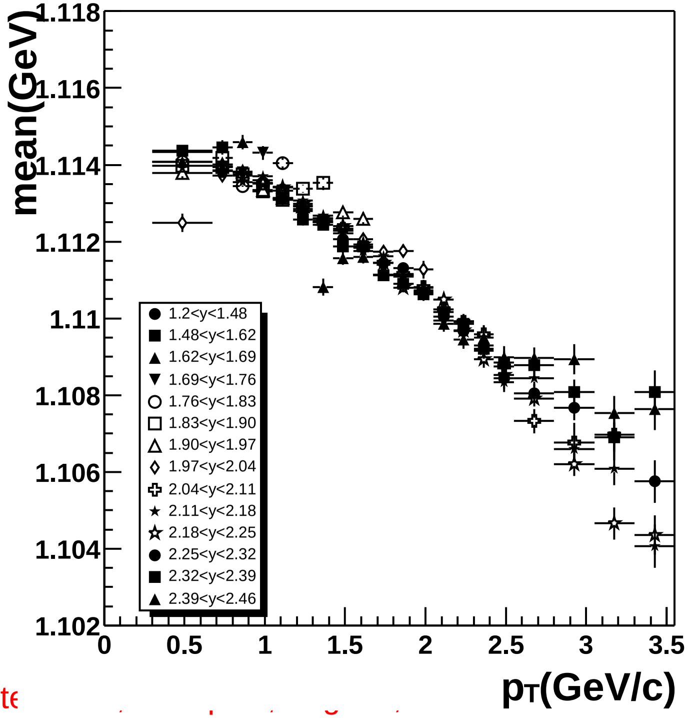
- Protons: positive particles with $dE/dx \leq 1.1\ dE/dx(p, |\vec{p}|)$ ($\hat{=} + 1\sigma$) using Bethe-Bloch equation
- π^-: negative particles with $0.85\ dE/dx(\pi^-, |\vec{p}|) \leq dE/dx \leq 1.15\ dE/dx(\pi^-, |\vec{p}|)$ ($\hat{=} \pm 1.5\sigma$)

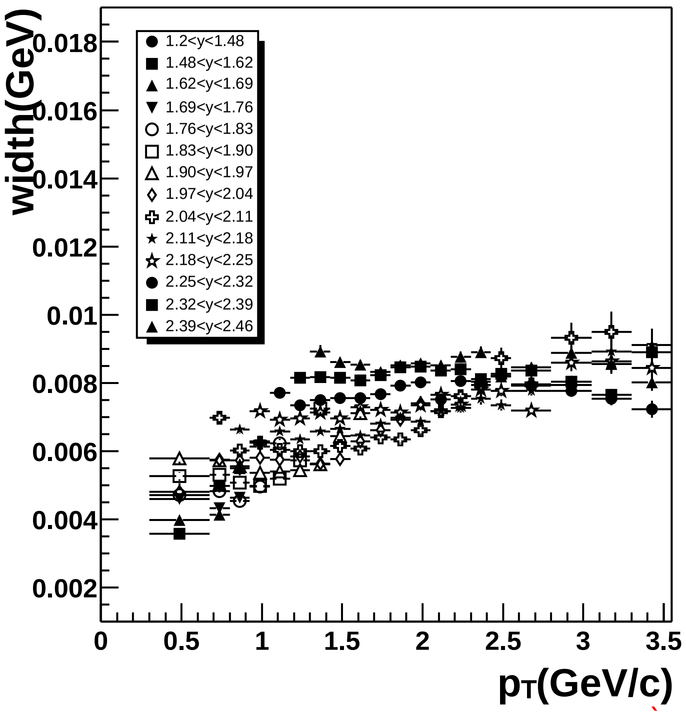

All particles


Candidates for Λ daugthers

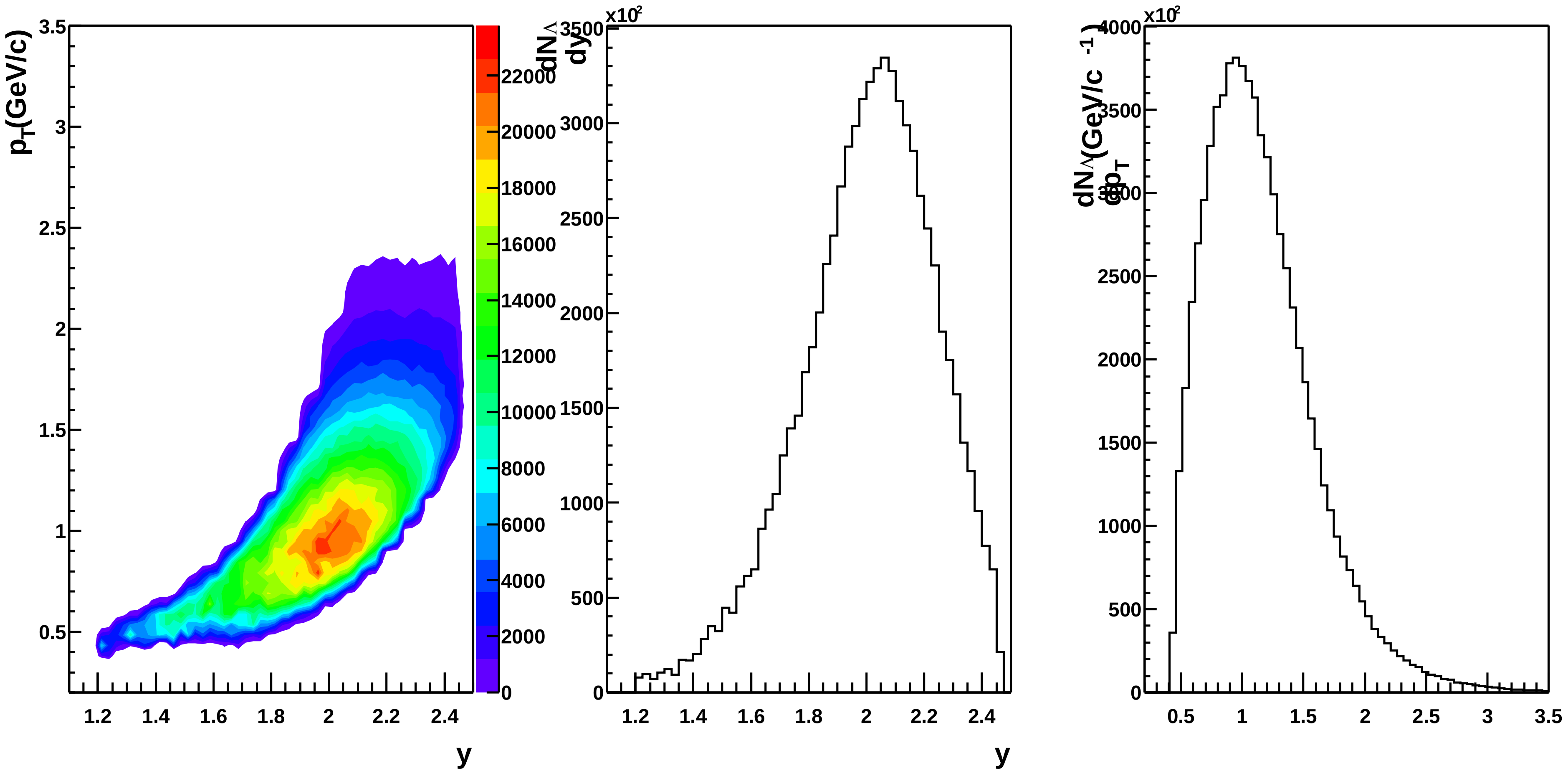
Characteristics of Λ signal

- Λ signal is fitted with **a Gaussian + a constant**
- Mean values and width of the Gaussian depend on y and p_T because the displaced secondary decay vertex is not used for recalculation of the angles
- Secondary vertex depends on p_T
- Flow analysis is done separately in each small y and p_T bin where mean and width of Gaussian are constant; results ($dN_\Lambda/d(\phi-\Phi)$) are merged



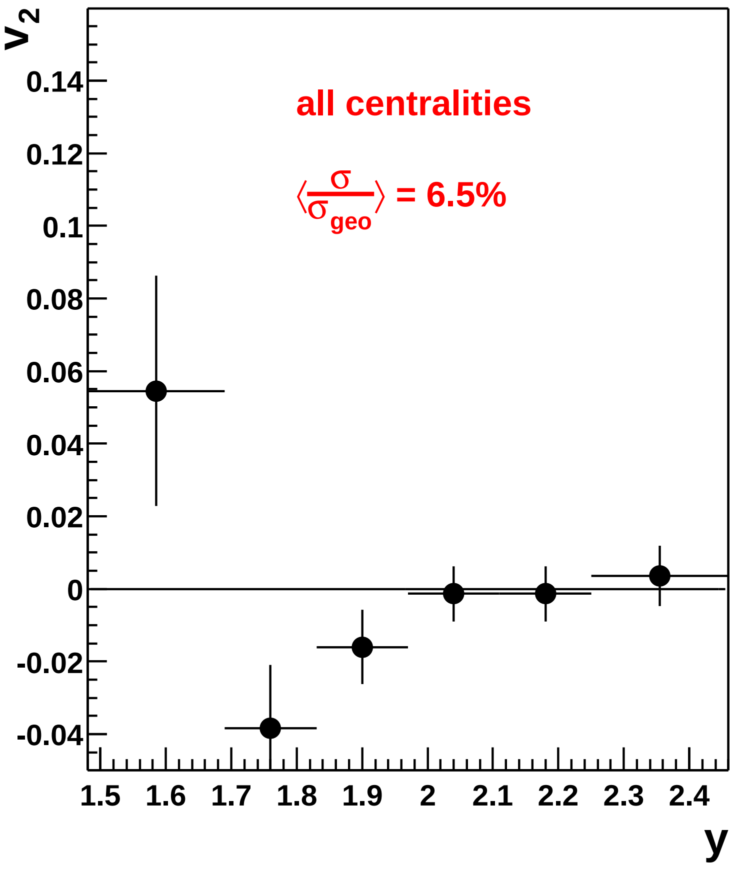


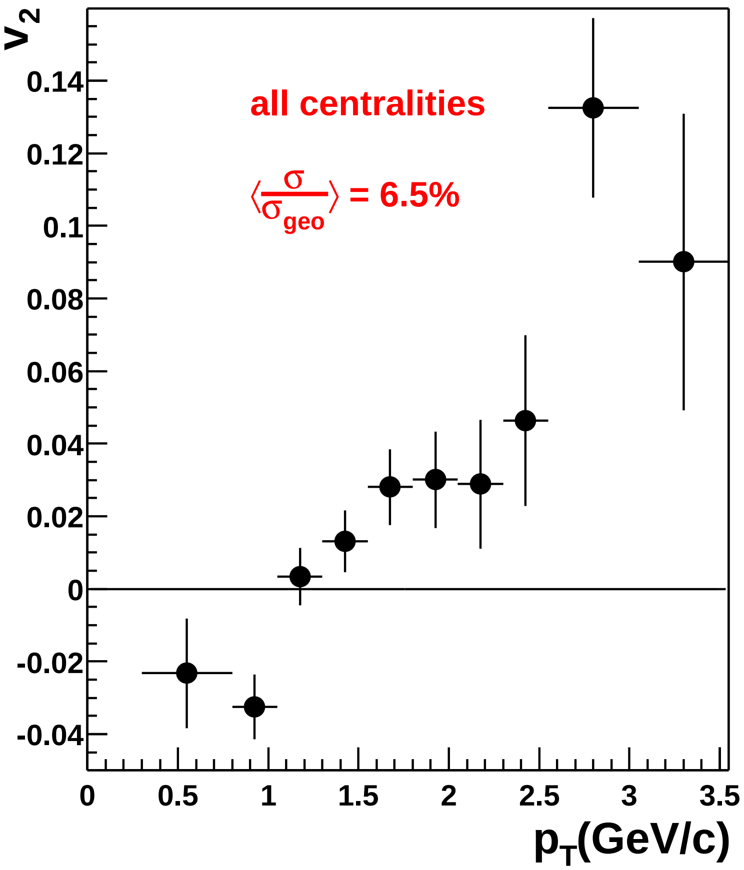
Distributions of accepted Λs



Dependence of Λ elliptic flow on y and p_T

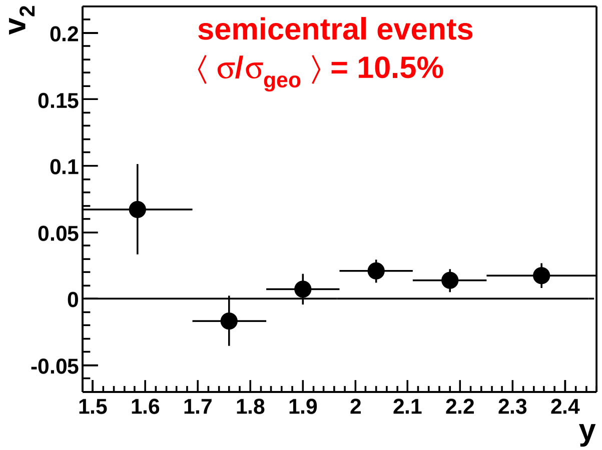
- Elliptic flow values were corrected for the reaction plane resolution
- v_2 slowly grows with y due to Λ acceptance in p_T
- v_2 increases with p_T and approaches $\approx$ 6% at 3 GeV/c

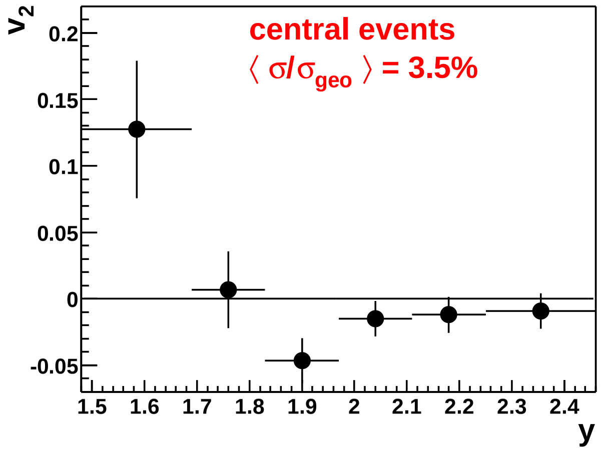


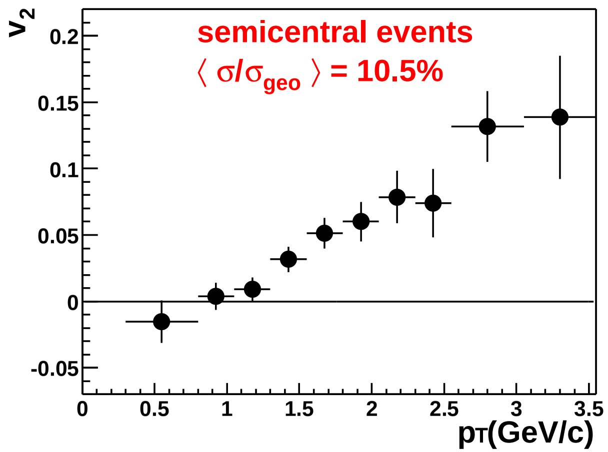


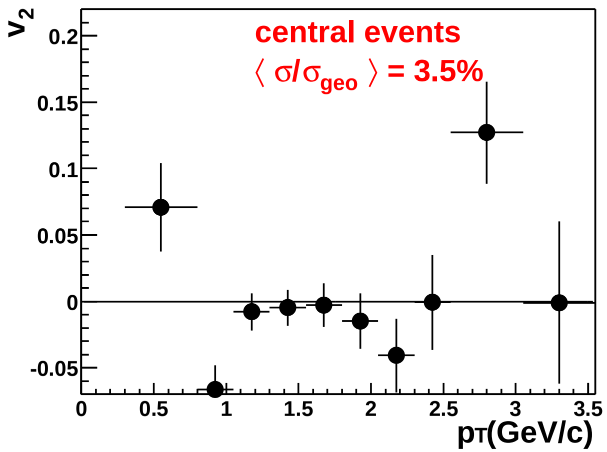
Λ elliptic flow for central and semicentral collisions

- **v_2 slowly grows with y due to Λ acceptance in p_T**
- **A clear difference in the flow intensity between central and semicentral events**



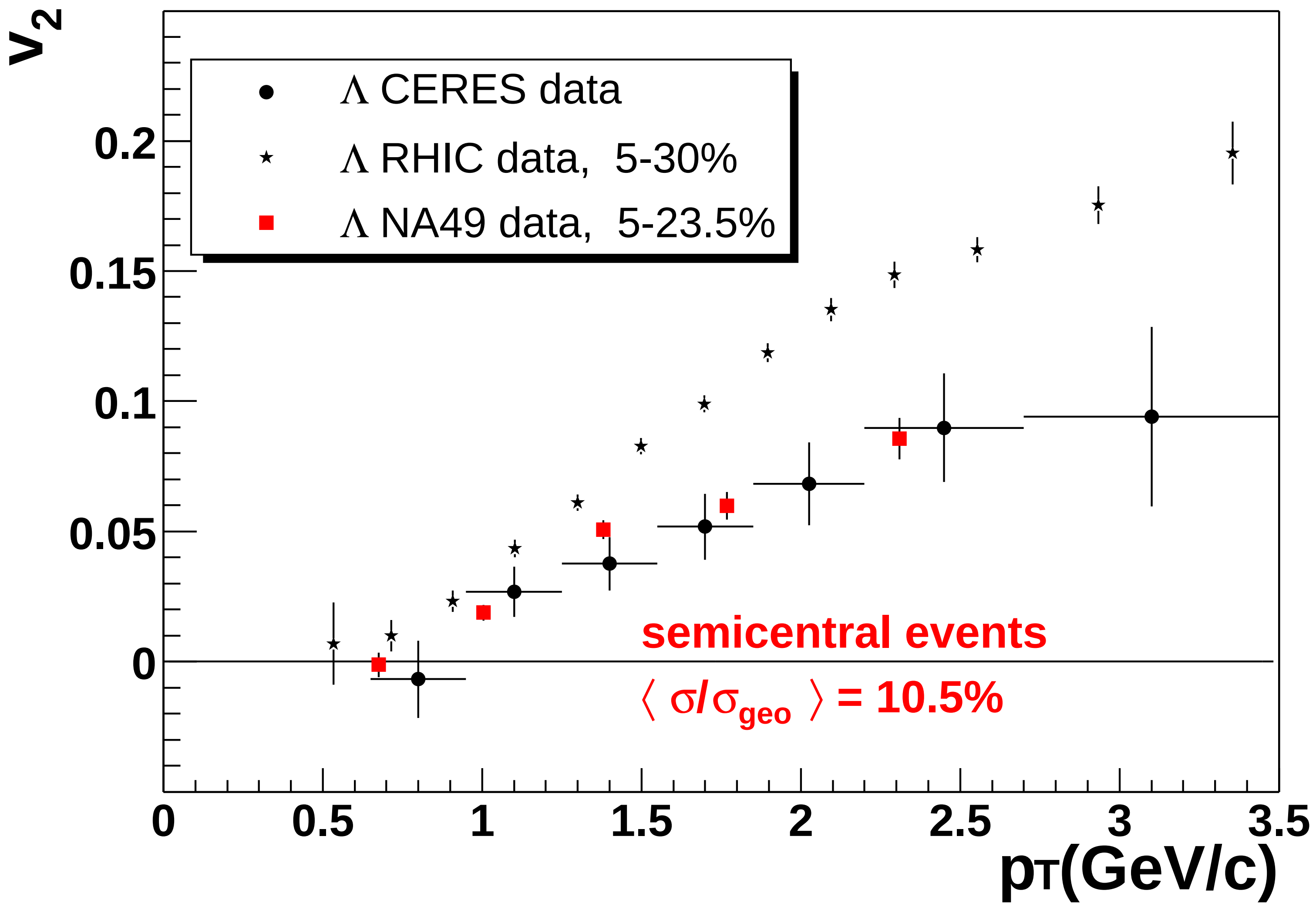






Comparison between NA49 and CERES Λ elliptic flow

- **Very good agreement for Λ flow intensity between NA49 and CERES data**



$\pi^{\pm}$ elliptic flow: method of reaction plane determination

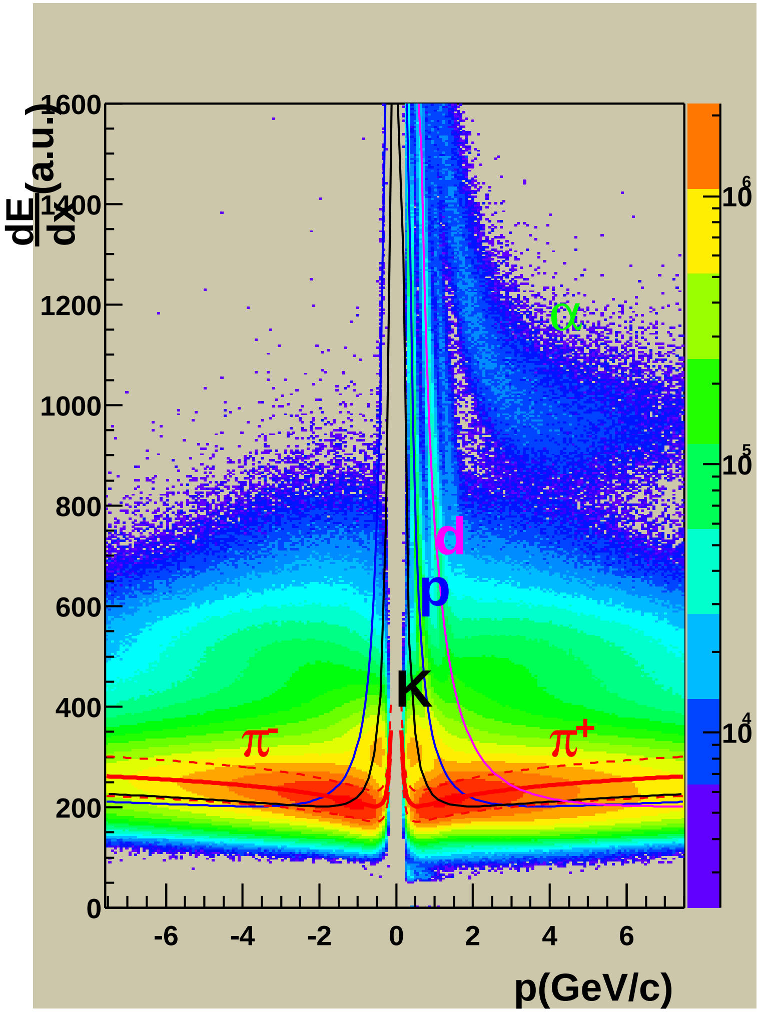
- **Reaction plane orientation (Φ) is measured from the second Fourier harmonic v_2**

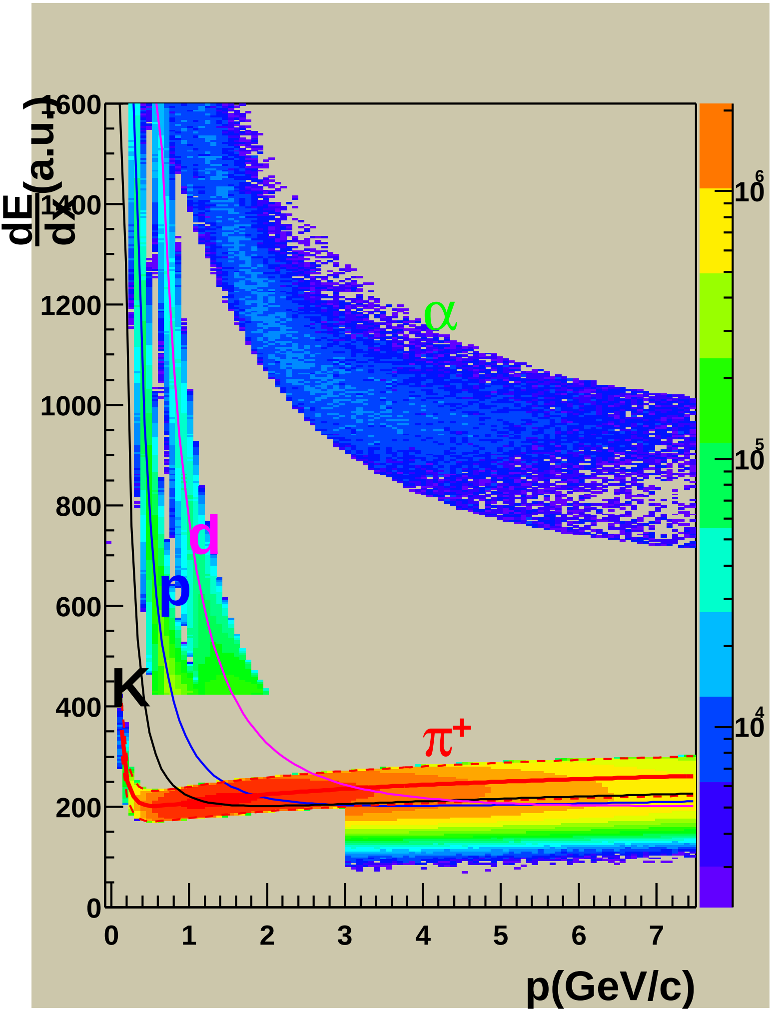
$$\Phi_2 = \frac{1}{2}\arctan\left(\frac{Y_2}{X_2}\right) \equiv \frac{1}{2}\arctan\left(\frac{\sum_i \sin(n\phi_i)}{\sum_i \cos(n\phi_i)}\right) \qquad (3)$$

- **Reaction plane is reconstructed from 2 subevents formed from positive and negative pions**
- **We avoid autocorrelations by correlating given particle to the reaction plane reconstructed from another subevent**
- **Flattening of the reaction plane was done by** *recentering* **and** *Fourier Expansion* **of $dN/d\Phi$**
- **Finite resolution of the measured reaction plane. Observed Fourier coefficient v_2' has to be corrected for the resolution:** $v_2 = v_2'/\sqrt{2\langle\cos[2(\Phi_a - \Phi_b)]\rangle}$
- **18.5 M events is used statistics**

Pions identification via TPC dE/dx

- $\pi^{\pm}$: $0.85\ \frac{dE}{dx}(\pi^{\pm}, |\vec{p}|) \leq \frac{dE}{dx} \leq 1.15\ \frac{dE}{dx}(\pi^{\pm}, |\vec{p}|)$ ($\hat{=} \pm 1.5\sigma$)



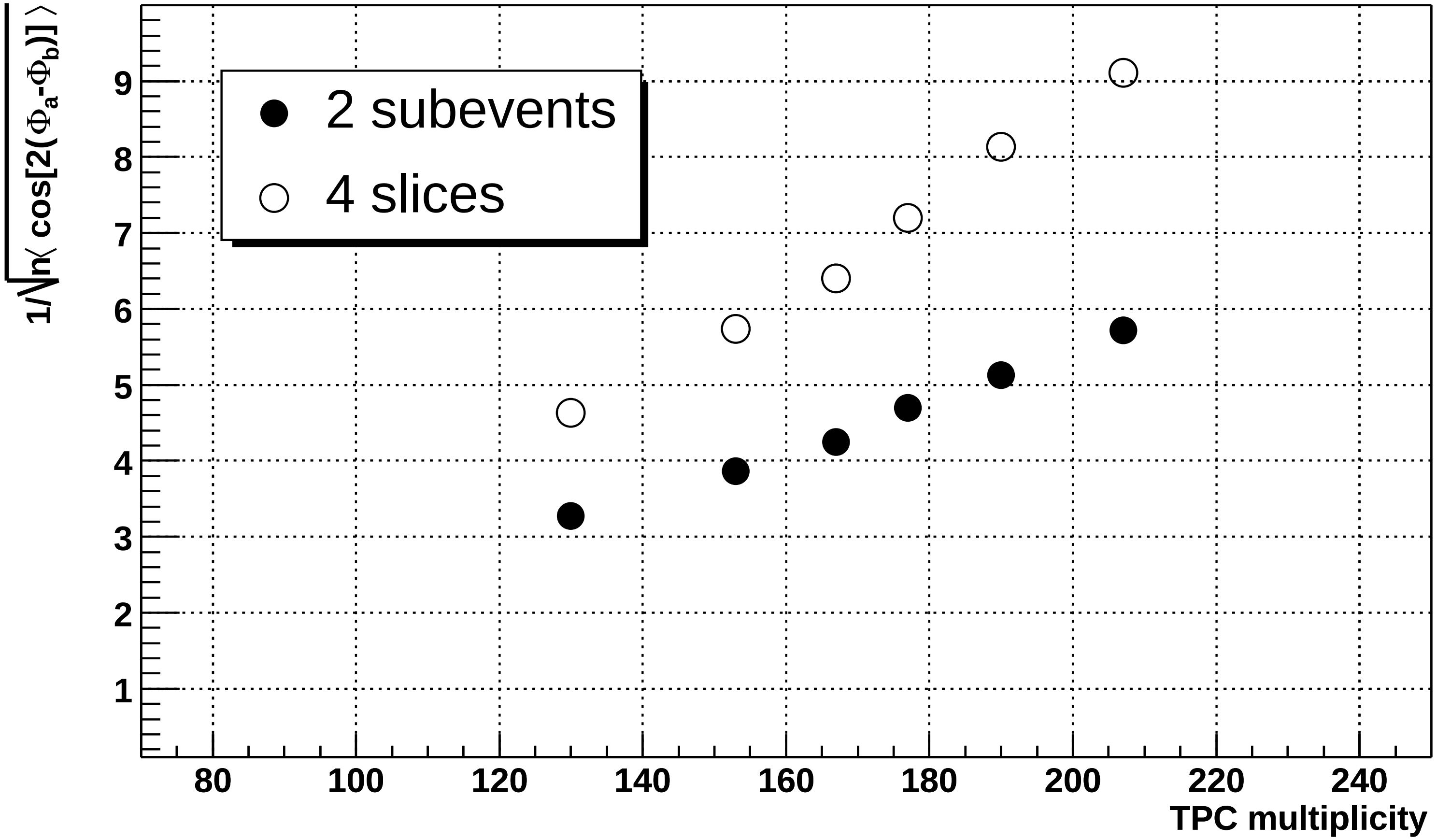


Outlook

- **Λ elliptic flow**
  - **To include small p_T identified protons in order to get one more small p_T point in $v_2(\Lambda)$**
- **π elliptic flow**
  - **More statistics (28M events)**
  - **Systematic error of v_2 using** *slice* **method**
  - **Correction for possible HBT effects**
  - **Directed flow**
- **K_S^0 elliptic flow**
- **Elliptic flow of identified protons and deuterons**
- **Reexamination of the** *cumulants* **and** *Lee-Yang zero* **method on the CERES data**

Corrections factors in the case of $\pi^{\pm}$ analysis

- Correction factors vs centrality



- Due to roughly double multiplicity, correction factors in 2 subevent method are $\approx \sqrt{2}$ times smaller then in case of slice method