Strange Particle Production and Elliptic Flow from CERES

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Definition of elliptic flow and physics motivation

- Interactions occur frequently enough → system equilibrates
- Hydrodynamics: $\partial_\mu T^{\mu\nu} = 0$ and $\partial_\mu j_\mu^{\nu} = 0$, with $T^{\mu\nu} = (\epsilon + p)u_\mu u_\nu = pg^{\mu\nu}$ and $j_\mu^{\nu} = n_i u_\mu$. Equation Of State (EOS): $p = p(\epsilon, n_1, \ldots, n_N)$

- The initial compression → pressure ($p$) → collective flow
- Non-central collisions → $\nabla p_x > \nabla p_y$ → anisotropic flow
- Fourier decomposition:
  
  $$dN/d\phi = N_0 \{1 + \sum_{n=0}^{+\infty} 2v_n \cos(n\phi)\}$$

- Quadrupole component $v_2 = \langle \cos(2\phi) \rangle$ is called elliptic flow

- Comparing $v_2$ of protons, $\Lambda$, $K^0_S$ and $\pi^\pm$ we could test mass ordering effect
- Testing the flow measurements of different particle species against different scaling scenarios may yield information about the origin of flow
CERES/NA45 experimental setup in year 2000

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

Used statistics: 30M events

$2.05 \leq \eta \leq 2.70$, $p_T$ up to 4 GeV/c

full azimuthal acceptance
Centrality determination

- 3 triggers contribute with 0.54% (minimum bias), 8.25% (semicentral) and 91.21% (central) of all events.

- Due to the small statistics, flow analysis of strange particles is done in 2 centrality bins with weighted mean centrality $\langle \sigma / \sigma_{geo} \rangle$ of 3.5% and 10.5%. In the case of pions 6 centrality bins are used.
Reaction plane determination

- The orientation of the reaction plane is not known \textit{a priori} and it is measured from the emitted particles using the second Fourier harmonic $v_2$

$$\Phi = \frac{1}{2} \arctan \left( \frac{\sum_i p_{T,i} \sin(2\phi_i)}{\sum_i p_{T,i} \cos(2\phi_i)} \right)$$

- No detector is perfect. If one wants to measure anisotropies on the level of few $\%$, the reaction plane distribution $dN/d\Phi$ has to be completely flat

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Distribution of TPC tracks

Distribution of reaction plane angles
Correction factors in the elliptic flow analysis

- Due to the finite resolution of the measured reaction plane, observed Fourier coefficient $v'_2$ has to be corrected for the resolution:

$$v_2 = v'_2 / \sqrt{2 \langle \cos[2(\Phi_a - \Phi_b)] \rangle}$$

- Correction factor grows with centrality expressed via TPC multiplicity

- Due to the double multiplicity, correction factors in the 2 subevent method are $\approx \sqrt{2}$ times smaller than in the case of the slice method and roughly equal with those from $\Lambda$ and $K^0_S$ analysis
Dependence of $v_2(\pi^{\pm})$ on $p_T$

- Bose-Einstein quantum correlations produce short range azimuthal correlations which show up as apparent azimuthal anisotropy (HBT effect)
- The peculiar behavior of the pion elliptic flow at low-$p_T$ is produced by HBT effect. It disappears once HBT is properly subtracted
- $v_2$ grows with $p_T$ and saturates at $p_T \geq 2$ GeV/c with the magnitude of $\approx 4\%$
Centrality dependence of $v_2(\pi^\pm)$

- $\pi^\pm$ elliptic flow decreases with centrality
- The HBT effect, becomes more pronounced going from semicentral to central collisions

![Graph showing $v_2(\pi^\pm)$ vs. centrality with and without HBT correction](image)

- 0.0<$p_T$<4.2 GeV/c
- 2.05<$\eta$<2.75

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\( \Lambda \) signal: cuts applied to reduce the background

- Reconstructed \( \Lambda \rightarrow p + \pi^- \) \((BR = 63.9\%, cT = 7.89 \text{ cm})\) using TPC tracks which satisfy:
  - TPC dE/dx cut \((\pm 1.5\sigma \text{ for } \pi^\pm, +1\sigma \text{ for } p)\)
  - Number of hits per track, depending on \( \theta \), is between 8 and 18
  - \( 2.05 \leq \eta \leq 2.70, \quad p_T \geq 0.05 \text{ GeV/c} \)
  - TPC candidate tracks for \( \Lambda \) daughters should not match SDD tracks within \( 3\sigma \) due to late decay
  - Armenteros-Podolanski cut:
    \[ q_T \leq 0.125 \text{ and } 0 \leq \alpha \leq 0.65 \] to suppress \( K^0 \)
  - Pairs of candidates should survive \( p_T \)-dependent opening angle cuts
  - Combinatorial background is calculated by rotating positive track by a random angle around the beam axis

With these cuts optimal values for \( \frac{S}{B} \approx 0.04 \) and \( \frac{S}{\sqrt{B}} \approx 500 \) were obtained
Reconstructed $K_S^0 \rightarrow \pi^+ + \pi^-$ ($BR = 68.95\%$, $c\tau = 2.6739$ cm) using TPC tracks which satisfy:

- TPC dE/dx cut ($\pm 2.0\sigma$ for $\pi^\pm$)
- Number of hits per track, depending on $\theta$, is between 8 and 18
- $2.05 \leq \eta \leq 2.70$, $p_T \geq 0.05$ GeV/c

- Armenteros-Podolanski cut: $q_T \geq 0.12$ to suppress $\Lambda$
- $\chi^2$ probability value for a linear fit applied to 3 points has to be bigger than 0.01
- the radial distance between the back extrapolated $\vec{p}_{K_S^0}$ and the primary vertex has to be smaller than 0.02 cm
- the opening angle $\theta_{\pi^+\pi^-} > 0.05$ rad
- the value of the z-coordinate of the secondary vertex has to be bigger than 1.0 cm

With these cuts optimal values for $\frac{S}{B} \approx 0.92$ and $\frac{S}{\sqrt{B}} \approx 500$ were obtained.

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\( \alpha = (q^+_L - q^-_L)/(q^+_L + q^-_L) \) where \( q^\pm_L \) are the longitudinal momentum components of \( p^\pm \) calculated with respect to the \( \vec{p}_{\Lambda(K^0_S)} = \vec{p}^+_L + \vec{p}^-_L \). The \( q_T \) variable is defined as the momentum component of \( \vec{p}^+_L \) in the transverse plane perpendicular to the \( \vec{p}_{\Lambda(K^0_S)} \).
Evaluation of $\Lambda$ ($K_S^0$) yields vs $\phi$ angle

- In each $y - p_T$ bin we reconstructed $\Lambda$ ($K_S^0$) in 6 $\phi$ bins
- Uncorrected elliptic flow values $v'_2$ were obtained by fitting $dN_{\Lambda(K_S^0)}/d\phi$ distributions with $A(1 + 2v'_2 \cos(2\phi))$ flow function

$\Lambda$:
- $1.61 < y < 1.69$
- $0.68 < p_T < 0.8$ GeV/c
- $15^\circ < \phi < 30^\circ$

$K_S^0$:
- $1.62 < y < 1.69$
- $0.68 < p_T < 0.8$ GeV/c
- $15^\circ < \phi < 30^\circ$

$\Lambda$:
- $p_T \approx 2.7$ GeV/c
- $K_S^0$:
- $p_T \approx 2.1$ GeV/c
Elliptic flow vs centrality

- $v_2$ decreases with centrality measured via TPC multiplicity

- $2.05 < y < 2.7$
- into exp. acceptance

**Graph:**
- $\frac{\sigma}{\sigma_{geo}}$ values: 31.7, 24.3, 17.9, 12.4, 7.9, 4.5, 2.0, 0.5, 0.05, 0.01
- TPC multiplicity values: 80 to 240
\( \Lambda (K_S^0) \) elliptic flow \( v_2 \) vs \( p_T \) in non-central collisions

For both kind of strange particles, \( v_2 \) grows with \( p_T \) in non-central collisions.
Comparison with RHIC and NA49 results

- Very good agreement for $\Lambda$ flow magnitude between NA49 and CERES data, measured at the same beam energy.

- $v_2$ values at the RHIC, after rescaling to the centrality used in the CERES experiment, are 10 – 15% higher due to the higher beam energy at the RHIC as compared to the SPS.

![Graph 1](image1.png)

![Graph 2](image2.png)
Comparison with hydrodynamical calculations

- **Hydrodynamical calculation with higher freeze-out temperature:** $T_f = 160$ MeV is very close to CERES results on both charged pion, and strange particle elliptic flow, while $T_f = 120$ MeV overpredicts data.

*Hydrodynamical calculation (1-st order phase transition, $T_c = 165$ MeV) by: P. Huovinen*
Comparison between $v_2$ of protons, $\Lambda$, $K_S^0$ and $\pi^\pm$

Similarly as in the case of the STAR results, a mass ordering effect was observed: $v_2(\Lambda) < v_2(K_S^0) < v_2(\pi^\pm)$ at small $p_T$, while at high $p_T$ it is opposite.

Testing of the two scaling scenarios in CERES data

- For three analyzed kind of particles, the NCQ scaling works approximately for $p_T / n_q \geq 0.5$ GeV/c and fails for lower $p_T / n_q$ for low $\Lambda$ and pions.

- The transverse rapidity scaling is fulfilled reasonably well over the whole $y_T$ range, where $y_T^{fs} = k_m y_T^2 m$ with $y_T = \sinh^{-1}(p_T / m)$.

![NCQ scaling](image1)

![$y_T^{fs}$ scaling](image2)

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Two $K^0_S$ analyses from the CERES data

- Two independent $K^0_S$ analyses from the CERES data were done based on
  - reconstruction of $K^0_S$ without PID and secondary vertex reconstruction (S. Radomski)
  - reconstruction of $K^0_S$ without PID but with secondary vertex reconstruction (W. Ludolphs)

![Graph 1](image1)

- Counts ($a.u.$) vs. invariant mass (GeV/c$^2$)

  - $2 < y < 2.6$
  - $p_T < 1.8$ GeV/c

![Graph 2](image2)

- Counts vs. $m_{\pi\pi}$ [GeV/c$^2$]

  - $0.2 < p_T < 0.4$ GeV/c
  - $2.2 < y < 2.4$
Rapidity and $p_T$ spectrum of $K^0_S$

S. Radomski, Doctoral Thesis 2006, preliminary

CERES Preliminary - PbAu 7%

\[
\frac{dN}{dy}_{\text{ycm}=0} = 21.2 \pm 0.9_{\text{stat}} ^{+1.7}_{-1.7}_{\text{syst}}
\]

\[
\sigma = 1.31 \pm 0.20
\]

CERES preliminary

\[
Y = 2.15 - 2.30
\]

\[
\frac{dN}{dY} = 19.0 \pm 0.4
\]

\[
\frac{dN}{dY_{\text{fit}}} = 19.0 \pm 0.4
\]

\[
T = 218 \pm 3 \text{ MeV}
\]
dN/dy of $K_S^0$ compared to other experiments

- Within CERES acceptance the results agree with NA57 data
- Disagreement on the fits
- A rather good agreement between NA49 analysis of charged kaons and CERES $K_S^0$ results in shape and yield. Difference in the yield is only 5%
- NA49 analysis of $K_S^0$ shows a similar shape as one from CERES. There is a relatively good agreement in the yield


A good agreement between a fit on the NA49 data and CERES results

Data are fitted via

$$\frac{d^2 N}{p_T dp_T dy} = \frac{dN/dy}{T(T+m)} \exp\left( -\frac{\sqrt{m^2 + p_T^2} - m}{T}\right), \quad m = m_{K_S^0}$$

Two independent CERES analyses agree rather well

CERES results: W. Ludolphs, Doctoral Thesis 2006, published
Within CERES acceptance all four measurements are compatible
A good agreement between extracted temperatures from NA49 and CERES data
**$\phi$ meson reconstruction**

- $\phi$ meson simultaneously reconstructed in $e^+ e^-$ and $K^+ K^-$ channel


$$2.0 < y_\phi < 2.4 \quad p_T^\phi > 0.75 \text{ GeV/c}$$

### Pb-Au 158 AGeV

- $p_t > 200$ MeV/c
- $\Theta_{ee} > 35$ mrad
- $2.1 < \eta < 2.65$

#### $\phi \rightarrow e^+ e^-$

- Solid line: hadron decay cocktail
- Dashed line: in medium spread $p$ width + the dilepton yield from the QGP phase
$m_t$ and $p_T$ spectra of $\phi$ meson

- $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ agree within errors. Enhancement by a factor larger than 1.6 at the 95% C.L. can be excluded.

- CERES results in both decay channels are consistent with the results from the NA49 experiment, and disagree with the NA50 result.

Conclusions

- The elliptic flow is measured for $\pi^\pm$, $K^0_S$, protons and $\Lambda$ in CERES at \( \sqrt{s_{NN}} = 17.2 \) GeV
- Good agreement with NA49. RHIC data only 15-20% above present SPS 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
- Mass ordering effect is observed: $v_2(\Lambda) < v_2(K^0_S) < v_2(\pi^\pm)$ at small $p_T$, while at high $p_T$ it is opposite
- $v_2$ scales with number of constituent quarks for high $p_T$ ($p_T/n_q \geq 0.5$ GeV/c)
- The transverse rapidity scaling is fulfilled reasonably well over the whole $y_T^{fs}$ range
- $dN/dy$ and $p_T$ spectrum of $K^0_S$ are measured in CERES. Good agreement between two CERES analyses and NA49. Na57 data agrees only within CERES acceptance
- $\phi$ meson simultaneously reconstructed in $e^+e^-$ and $K^+K^-$ channel
- $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ agree within errors. Enhancement by a factor larger then 1.6 at the 95% C.L. can be excluded. Results agree with NA49, but disagree with NA50 data
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Thanks to P. Huovinen
for hydrodynamics calculations
Flattening of reaction plane

- For an ideal detector $dN/d\Phi$ is flat
- In reality, different detector effects (efficiency in $\phi$ smaller than 100%, geometrical offset between position of the beam and the center of the detector in the $x-y$ plane) make it nonflat
- An example of flattening of the calculated reaction plane ($\Phi$):

![Graph showing flattening of reaction plane](image)
Centrality dependence of $\pi$ elliptic flow

- $\pi$ elliptic flow decreases with centrality from 4.0% in semicentral to 1.2% in very central collisions

![Graph showing elliptic flow $v_2$ vs. centrality (\(\sigma/\sigma_{geo}\)) for $0.0<p_T<4.2$ GeV/c and $2.05<\eta<2.75$. The graph includes data points from 2005 and 2001 analyses.]
$v_2(\pi^\pm)$ vs $p_T$ for different centralities

- Threshold for the saturation moves to smaller $p_T$ going from semicentral to central collisions
- The maximal $v_2$ values goes from 8% in semicentral to 3% in central collisions
Suppression of the background via TPC $dE/dx$

- Protons: positive particles with $dE/dx \leq 1.1 \, dE/dx(p, |\vec{p}|) (\equiv +1\sigma)$ using Bethe-Bloch equation

- $\pi^-$: negative particles with $0.85 \, dE/dx(\pi^-, |\vec{p}|) \leq dE/dx \leq 1.15 \, dE/dx(\pi^-, |\vec{p}|) (\equiv \pm 1.5\sigma)$

![Candidates for $\Lambda$ daughthers](image)
Distributions of accepted $\Lambda$s and $K_S^0$
Characteristics of $\Lambda$ signal

- $\Lambda$ signal is fitted with a Gaussian + a constant
- Mean value 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
$v_2(\Lambda)$ from two different calculations

- I run had a sharp cut on proton $p_T \leq 0.4 \text{ GeV/c}$
- II run had $p_T$ dependent opening angle cut
- Good agreement between two results $\rightarrow$ small systematic error

![Graphs showing $v_2$ vs. $p_T$ for different cuts and events]

- Semicentral events: $\langle \frac{\sigma}{\sigma_{geo}} \rangle = 10.5\%$
- Central events: $\langle \frac{\sigma}{\sigma_{geo}} \rangle = 3.5\%$
$K_S^0$ elliptic flow vs $p_T$ for different centralities

- As in the case of $v_2(\Lambda)$, $v_2(K_S^0)$ grows with $p_T$ in non-central collisions
- A difference in the $K_S^0$ elliptic flow magnitude between events from the two centrality classes

![Graph](image)

**Semicentral events**

$\langle \frac{\sigma}{\sigma_{geo}} \rangle = 10.5\%$

**Central events**

$\langle \sigma/\sigma_{geo} \rangle = 3.5\%$
Characteristics of $K^0_S$ signal

![Graph showing mean and width vs. $p_T$](image)

- Mean (GeV):
  - $2.0 < y < 2.075$: 0.49
  - $2.075 < y < 2.15$: 0.495
  - $2.15 < y < 2.225$: 0.5
  - $2.225 < y < 2.3$: 0.505
  - $2.3 < y < 2.375$: 0.51
  - $2.375 < y < 2.45$: 0.515
  - $2.45 < y < 2.525$: 0.52
  - $2.525 < y < 2.6$: 0.525

- Width (GeV):
  - $2.0 < y < 2.075$: 0.006
  - $2.075 < y < 2.15$: 0.008
  - $2.15 < y < 2.225$: 0.01
  - $2.225 < y < 2.3$: 0.012
  - $2.3 < y < 2.375$: 0.014
  - $2.375 < y < 2.45$: 0.016
  - $2.45 < y < 2.525$: 0.018
  - $2.525 < y < 2.6$: 0.02

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Correction factors grow with TPC multiplicity due to decreasing flow

An absolute systematic error due to uncertainty in the determination of the reaction plane was estimated to $\Delta v_2 = 0.11\%$ from the difference between the resolutions obtained from correlations of 2 subevents in $\phi$ and $\eta$. 

![Graph showing the relationship between TPC multiplicity and $\frac{1}{2}\cos[2(\phi - \Phi)]$.](image-url)