THE PHYSICS OF NONCENTRAL COLLISIONS AT HIGH ENERGIES (EVENT-BY-EVENT ANALYSES)

CERN, MAY 17-22, 1999

1) ANISOTROPIES IN NON-CENTRAL COLLISIONS
   \( \phi \) = ANGLE BETWEEN \( \vec{p}_t \) AND REACTION PLANE

2) ELLIPTIC FLOW: \( V_2 \)

3) HBT RADI: \( R_{0.15,0.5} (\phi) \)

4) J/\psi SUPPRESSION: \( \psi (\phi) \)
   MATTIELLO, Nucl.-Th/9812...

5) EVENT-BY-EVENT FLUCTUATIONS
   BAYM, Nucl.-Th/9905022

6) AMPLITUDES AND PHASE TRANSITIONS

H. Heiselberg
THE PHYSICS OF NONCENTRAL COLLISIONS AT HIGH ENERGIES (EVENT-BY-EVENT ANALYSES) CERN, MAY 17-22, 1999

1) ANISOTROPIES IN NONCENTRAL COLLISIONS
   \( \phi \equiv \text{angle between } p_t \text{ and reaction plane} \)

2) ELLIPTIC FLOW: \( V_2 \)
   LEVY, PRC 59 (1999) 2716

3) HBT RADIi: \( R_{0.5,0.5}(\phi) \)
   PRl, 82 (1999) 2052

4) J/\Psi SUPPRESSION: \( \psi(\phi) \)
   MATTIELLO, NUCL-TH/9812...

5) EVENT-BY-EVENT FLUCTUATIONS
   BAYM, NUCL-TH/9905022

6) AMPLITUDES AND PHASE TRANSITIONS
\[ \langle p_t \rangle \]

Tapp

\[ \text{d}N/\text{dy} \]

or: \[ \sqrt{s}, g \]

or: \[ E_T \leftrightarrow b \]

CENTRALITY

STUDY CENTRALITY DEPENDENCE OF OBSERVABLES

EVENT-BY-EVENT ANALYSES w. REACTION PLANE DETERMINATION → MANY NEW OBSERVABLES
**Geometry of Semi-Central Collisions**

**Reaction Plane (X, Z)**

- **Z = Beam Axis**
- **Impact Parameter:** b

**Transverse Plane (X, Y)**

- **Semicentral Pb+Pb Collision**
  - b = R = 7 fm

**Deformation:**
\[ \delta = \frac{R_y^2 - R_z^2}{R_y^2 + R_z^2} \approx \frac{b}{2R} \]  
(Initially)

**Azimuthal Angle:** φ  
Between Reaction Plane and P⊥
**FLOW:**

\[
\frac{dN}{dy dp_x dp_\phi} = \frac{1}{2\pi} \frac{dN}{dy dp_\ell} \left( 1 + 2v_1 \cos \phi + 2v_2 \cos 2\phi + \ldots \right)
\]

**TRANSVERSE FLOW:**

\[
\frac{dN}{dy dp_\ell} \sim e^{-m_\ell/T_{app}}, \quad T_{app} = T_0 + m <U^2>
\]

**DIRECTED FLOW:** \( V_1 \)

**ELLIPTIC FLOW:** \( V_2 \)

**NON-RELATIVISTIC ENERGIES -> SHADOWING \( \Rightarrow V_2 < 0 \)**

**ULTRA- \(-u-\) \(-\rightarrow\) MORE COMPRESSION \( \Rightarrow V_2 > 0 \) IN X-DIRECTION**

**HYDRO. CALC.:** OLLITRAODT, TEAMER, SHURYAK, SOLLFRANK, NMUOVINE,...

**CASCADE:** SORGE, SNELLING, SOFF et al.,...
ELLiptic Flow
Energy dependence from SIS to SPS energies of the elliptic flow (second Fourier coefficient).
ELLIPITIC FLOW FROM RESCATTERINGS:

\[
\left( \frac{d}{dt} + \vec{v}_p \cdot \vec{\nabla} \right) n_i = \sum \frac{d\vec{v}_i}{dt} \left[ n_b n_i (1 \pm n_i) (1 \pm \vec{v}_i \cdot \vec{v}_j - n_1 n_2 (1 \pm n_3) (1 \pm \vec{v}_4) \right]
\]

SOLVE BOLTZMANN EQ.:

\[
\left( \frac{d}{dt} + \vec{v}_p \cdot \vec{\nabla} \right) n_i = \sum \frac{d\vec{v}_i}{dt} \left[ n_b n_i (1 \pm n_i) (1 \pm \vec{v}_i \cdot \vec{v}_j - n_1 n_2 (1 \pm n_3) (1 \pm \vec{v}_4) \right]
\]

FOR PERIPHERAL & SEMICENTRAL COLL: S, R SHALL ~ FREE STREAMING:

\[
n(x, p) \approx \frac{(2\pi)^3}{2m} \delta(y_n) \frac{dN}{dp} \text{ } S_+ (\vec{r} - \vec{v}_+ (z - z_0))
\]

\[
S_+ (k_\perp y) \approx \frac{1}{2\pi R_x R_y} \exp \left[ -\frac{k_\perp^2}{2R_x^2} - \frac{y^2}{2R_y^2} \right]
\]

CALCULATE TO FIRST ORDER IN COLLISIONS:

\[
\sum \frac{dN}{dp} \frac{d\vec{p}}{dp} \cdot \vec{v}_2 \cos 2\theta
\]

ONE FINDS:

\[
\vec{v}_2 \approx \frac{\vec{v}_i \delta}{4} \frac{V_{i+}^2}{\langle V_{i+}^2 \rangle}
\]

\[
\delta_i = \sum \frac{dN}{dy} \frac{\langle V_{i+} \delta_{i+} \rangle}{\delta_0 R_x R_y}
\]

\[
\delta = \frac{R_x^2 - R_y^2}{R_y R_x} = \frac{b}{2R} = \text{DEFORMATION}
\]

\[
\delta \text{ AND } V_2 \text{ VANISH IN CENTRAL COLL. ANYWAY.}
\]
ELLiptic FLOW AT SPS

\[ \langle v_2 \rangle = \frac{\frac{\delta E}{E}}{\frac{V_{1}}{\langle V_{1} \rangle}} \]

\[ \delta = \frac{2}{3} \]

- Protons (NA49 data)
- Pions (NA49 data)
- Protons (coll. less)
- Pions (coll. less)
- Pions and protons (hydro.)

\[ V_{1}[\text{GeV/c}] \]

\[ p_t[\text{GeV/c}] \]
INTERFEROMETRY OF IDENTICAL PARTICLES
(HANABY - BROWN & TWISS EFFECT)

![Diagram of interferometry setup]

Emission function or source:
\[ S(x, p) \]
\[ X_i \sim R_i \quad \text{(source size)} \]

Single particle distribution:
\[ E \frac{d^3N}{d^3p} = \int d^4x \ S(x, p) \]

Two particle correlation function
\[ C(k_1, k_2) = N \frac{d^6N/d^3k_1 d^3k_2}{(d^3N/d^3k_1)(d^3N/d^3k_2)} \]
\[ = 1 + \frac{\left| \int d^4x \ e^{i\mathbf{q} \cdot \mathbf{x}} \ S(x, k) \right|^2}{\left| \int d^4x \ S(x, k) \right|^2} \]

Assuming:
- Incoherent emission
- Plane wave propagation after emission
- Corrected for Coulomb & resonances

\[ k = \frac{p_1 + p_2}{2} \]
\[ q = p_1 - p_2 \]
HBT RADII:

\[ R^2 = \frac{T}{m^2} \frac{T_f^2}{\cosh^2 y} \]

\[ R_s^2 = R^2 \]

\[ R_0^2 = R^2 + \beta_0^2 \delta T^2 \]

Exp.: \( R_0^2 \approx R^2 \) \Rightarrow \beta_0 = \frac{P_t}{m^2} = TR. VELOCITY

\[ \delta T = DURATION \ OF \ EMISSION \]

\[ \delta T \leq 2 \text{ fm/c in c. Pb+Pb} \]

"PION FLASH"

BUT FOR AN "OPAQUE" SOURCE (BLACK BODY):

\[ R_0^2 = g_s R^2 + \beta_0^2 \delta T^2 \]

\( \delta \sim 5 \text{c} \)

\( g_s \leq 1 \), OPACITY FACTOR

CAN BE DETERMINED FOR CYL. SOURCES
HBT RADII FOR DEFORMED SOURCES

\[ \delta = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2}, \quad R^2 = \frac{R_y^2 + R_x^2}{2} \]

\[ c_2 = 1 + \exp \left[ -R_y^2 q_5^2 - R_0^2 q_0^2 - 2R_0^2 q_0 q_5 \right] \]

**TRANSPARENT SOURCE:**

\[ R_5^2 = R^2 \left[ 1 + \delta \cos 2\phi \right] \]
\[ R_0^2 = R^2 \left[ 1 - \delta \cos 2\phi \right] + \beta_0^2 \delta \tau^2 \]
\[ R_{05}^2 = R^2 \delta \sin 2\phi \]

**OPAQUE SOURCE:**

\[ R_5^2 = g_5 R^2 \left[ 1 + \delta \cos 2\phi \right] \]
\[ R_0^2 = g_0 R^2 \left[ 1 - \delta \cos 2\phi \right] + \beta_0^2 \delta \tau^2 \]
\[ R_{05}^2 = g_5 R^2 \cdot \delta \cdot \sin 2\phi \]

\( g_0, g_5 \) are model-dependent opacity factors; generally: \( g_0/g_5 \leq 1 \), decrease with opacity.

**Note:** 5 observables > 4 parameters

\( g_5 R^2, \delta, \delta \tau, g_0/g_5 \)

- Allows full determination of all physical quant.
- Without reaction plane determination: 2 observable.
Freeze-out parameters deduced from the hadro-chemical analysis of particle production yields at SIS, AGS, and SPS energies. At the higher energies the freeze-out points approach the phase boundary.
$J/\psi$ suppression in semi-central collisions

$\psi = J/\psi, \psi', \chi, \ldots$ - cc states 3.7 mb 0-3% b

$N_\psi = N_\psi^0 \times \exp \left[ -\int_2^{2'} d^2 \phi \int_0^b \epsilon_\psi(b, \phi') \sigma_{\psi NN} \right] \times \exp \left[ -\int_0^b \epsilon_\psi(c, \phi) \sigma_{\psi NN} \right]$

Glauber abs.

Comover abs.

More Comover absorption due to rescatterings in $y$- than $x$- direction, i.e., $\phi$-dependence!!

- Glauber absorption only in $z$-direction, i.e., no $(x,y)$ or $\phi$ dependence!
- Glauber abs. reduced at RHIC & LHC energies due to Lorentz-delay of $J/\psi$ formation time.
COMOVER ABSORPTION:

\[ c = \text{COMOVER} \]

B.E.:
\[ \left( \frac{d}{dt} + \mathbf{v}_f \cdot \nabla \right) n_{\nu} = -\frac{1}{4\pi} \int \frac{d^3 p_c}{(2\pi)^3} \mathbf{v}_q \cdot \mathbf{c} \mathbf{c} \cdot n_{\nu} \cdot n_c \]

ASSUME BJORKEN SCALING: \[ v_2 = \frac{1}{t} \]

ASSUME FREE STREAMING AFTER INITIAL COLLISIONS:

\[ n_i \simeq \frac{(2\pi)^3}{2} \delta (y - \eta) \frac{dN_i}{dy} d^3 p_t \cdot S_t \left( \mathbf{v}_t - \mathbf{v}_t \right) \]

\[ S_t(x,y) = \frac{1}{2\pi r_x r_y} \exp \left[ -\frac{x^2}{2 r_x^2} - \frac{y^2}{2 r_y^2} \right] \]

\[ R_x(b) \leq R_y(b) : \text{r.m.s. radii} \]

DEFINE "TRANSVERSE OPACITY":

\[ \bar{\sigma}_\nu = \frac{\Delta dN_c}{d\mathbf{c}} \frac{\langle \mathbf{v}_q \cdot \mathbf{c} \rangle}{4\pi r_x r_y} \]

\[ \approx 0.3 \quad \text{at SPS - almost independent of b} \]

\[ 0.6 \quad \text{at RHIC} \] \{scales with \( \frac{dN}{dy} \)}

\[ 0.9 \quad \text{at LHC} \]

INTEGRATE B.E. IN SPACE AND TIME FROM

COMOVER FORMATION TIME: \[ t_0 \approx 1 - 2 \text{ fm/c} \]
By solving B.E. approx.:

\[
\frac{N_\psi}{N_\psi^0} \approx \left( \frac{\langle V_\psi \rangle c_0}{2R} \right)^{\tilde{\sigma}_\psi} \left( 1 + \frac{\tilde{\sigma}_\psi \cdot \delta \cdot V_\psi^2}{2 \langle V_\psi^2 \rangle} \cos 2\phi \right)
\]

- *Average abs.*: \( \left( \frac{\langle V_\psi \rangle c_0}{2R} \right)^{\tilde{\sigma}_\psi} \sim E_T^{-\tilde{\sigma}_\psi/2} \) power-law (since \( R^2 \sim E_T \)).

- *Relative amplitude*:
  \[
  \frac{\tilde{\sigma}_\psi \cdot \delta \cdot V_\psi^2}{2 \langle V_\psi^2 \rangle} \sim 5-20% \quad \begin{cases} \tilde{\sigma}_\psi \approx 0.3-0.4 \\ \delta \leq 1 \\ V_\psi \approx 0.3c \\ V_\psi \approx 0.6c \end{cases}
  \]

- Whereas average abs. occur at early times \( \tau \sim 2c \), the amplitude is sensitive to late time absorption: \( \tau \sim 2R/V_\psi \) !!

- Thus average abs. and amplitude are sensitive to different physics/time scales!

- If phase transition occurs at high energy densities at early times, it should lead to anomalous suppression of average abs. — but not amplitude!

- Amplitude is an additional observable. can be exploited to separate Glauber and comover abs.
AVERAGE $J/\psi$ SUPPRESSION

$B_{\mu\mu} \sigma(\psi)/\sigma(D\gamma_{29,45})$

$E_T/E_{T,max}$

- NA50
- NA50 (min. bias)
- 0 (pure Glauber)
- 0.3 (SPS)
- 0.6 (RHIC)
- 0.9 (LHC)

$\tau_\psi = 0$
$6\psi_{N} = 3.6\, mb$
$6\psi_{C} = 2.4\, mb$
$\tau_0 = 1\, fm/c$
VARIATION IN $H^+$ SUPPRESSION

RHIC PREDICTION: $\tilde{\sigma}_F = 0.6$ (6$\psi_c = 2.4$ mb)
### New Physics With and Without Reaction Plane and Event-by-Event Analyses:

<table>
<thead>
<tr>
<th></th>
<th>Without</th>
<th>With</th>
<th>New Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>$u_1, T$</td>
<td>$2 + v_1 v_2$</td>
<td>4 $\overline{v}, p, opacity$</td>
</tr>
<tr>
<td>HBT</td>
<td>$R_{0,s,l}$</td>
<td>$3 + \langle R_{0,s,s} \rangle$</td>
<td>6 $\text{deformations, emission times, opacity}$</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>$\langle \psi \rangle$</td>
<td>$1 + \langle \psi(\phi) \cos 2\phi \rangle$</td>
<td>2 $\text{glauber vs. comover}$</td>
</tr>
<tr>
<td>$\psi, \chi, \text{strange}$</td>
<td></td>
<td>1</td>
<td>2 $\text{late vs. early times}$</td>
</tr>
</tbody>
</table>
NA49 Pb+Pb Event-by-Event Fluctuations

Mixed Events

Single Event K/π Ratio

Events

Events

< 1% in \langle p_T \rangle
< 15% in K/π

Dynamical Event-by-Event Fluctuations:
SUMMARY:

IN FUTURE: MEASURE REACTION PLANE \((x, y)\) EVENT-BY-EVENT - ALSO IN COINCIDENCE WITH HBT RADII, \(T/Y\), ...........

- MORE THAN DOUBLES # OF OBSERVABLES:
  - FLOW: 1 \(\rightarrow\) 3
  - HBT RADII: 2 \(\rightarrow\) 5
  - \(T/Y\): 1 \(\rightarrow\) 2

- THE AMPLITUDES: TELL NEW PHYSICS OF LATER TIMES, WHICH COMPLEMENTS EARLY TIMES

- HBT RADII RESOLVES OPACITY VS. DURATION OF EAIS - SIDEBAR INTERESTING BEHAVIOR FOR PH. TR.

- \(T/Y\): CHECKS THE SUPPRESSION MECHANISM AND ANOMALOUS SUPPRESSION DUE TO PHASE TRANSITION

- CENTRALITY DEPENDENCE: MAY REVEAL PH. TRANSITION