Heavy Ion Physics and the Quark-Gluon-Plasma

Hanbury Brown-Twiss Intensity interferometry

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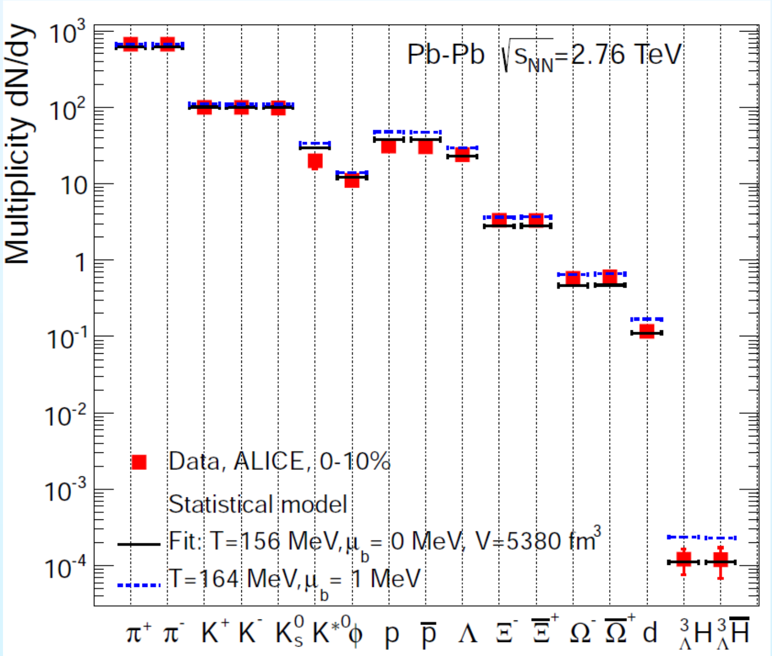
Energy Density and Chemical Equilibrium

SPS ($\sqrt{s_{NN}}$ = 17.3 GeV): $\varepsilon_0 \approx 3$ GeV/fm^3

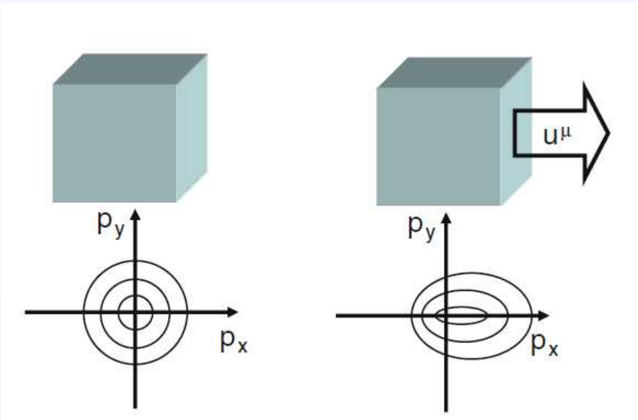
RHIC ($\sqrt{s_{NN}}$ = 200 GeV): $\varepsilon_0 = 5.4$ GeV/fm^3

LHC ($\sqrt{s_{NN}}$ = 2.76 TeV): $\varepsilon_0 = 14$ GeV/fm^3

- **Energy density above 1 GeV/fm^3 (lattice QCD prediction)**
- **Chemical equilibrium (freeze-out T extracted from particle ratios/yields close to lattice QCD simulation)**
- **What about kinetic equilibrium?**

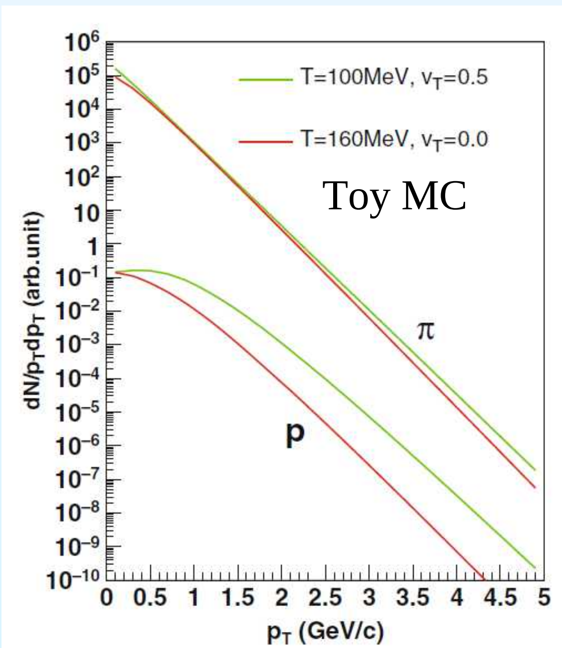


Kinetic Equilibrium



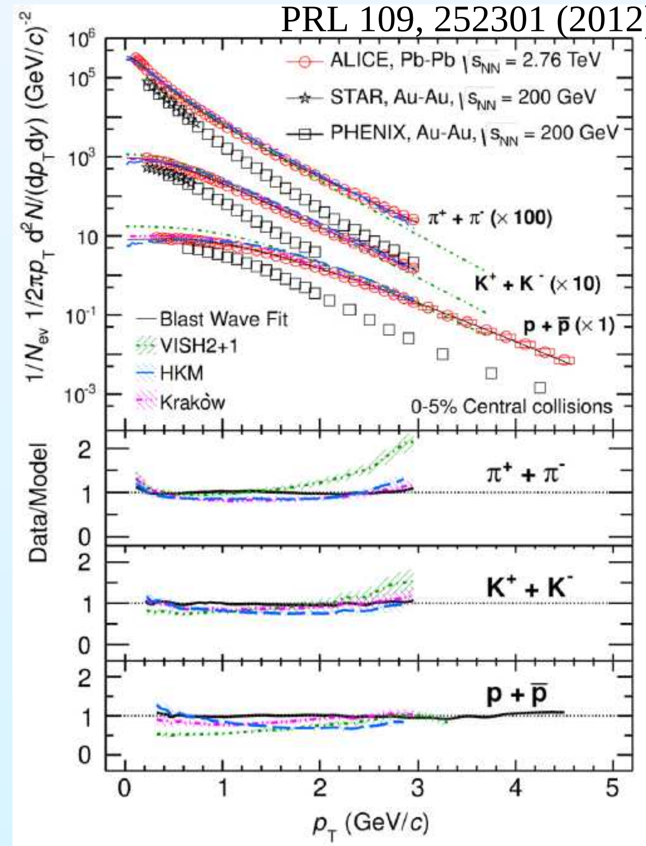
- Matter surrounded by vacuum
- Kinetic equilibrium → collective flow
  → system expands radially (isotropic)
- Matter moving → Lorentz boost
  → visible in p_T spectra

ALICE Collab.,
PRL 109, 252301 (2012)



- p_T spectra
  - Thermal + boost picture
  - Mass dependence
  - Blast wave parametrization
    → kinetic freeze-out T
    → collective expansion velocity β_T

$T_{kin} \approx 100$ MeV
Typical values $\beta_T \approx 0.65$
compare Bjorken (1D) $\beta_T = 0$



Hanbury Brown-Twiss Interferometry

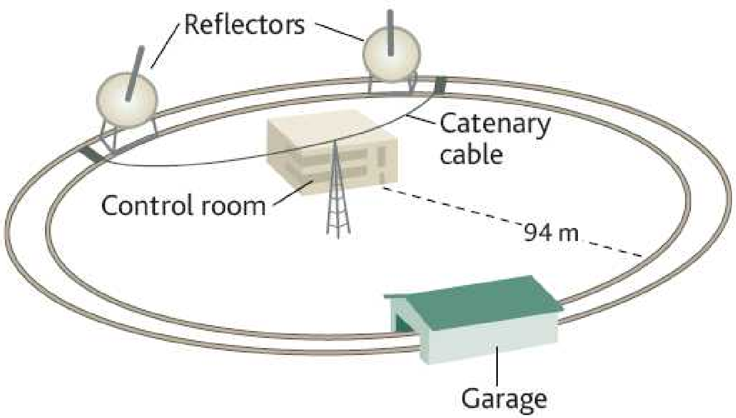
- **What is the size of the particle emitting fireball?**
- **What are its dynamic properties?**
  ⇒ Evidence for transverse expansion
- **What is the lifetime of the fireball?**
  ⇒ Freeze-out time
  ⇒ Emission duration

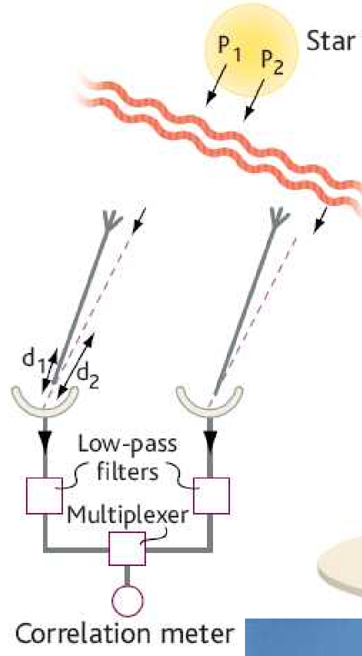
Volume Measurement via Interferometry

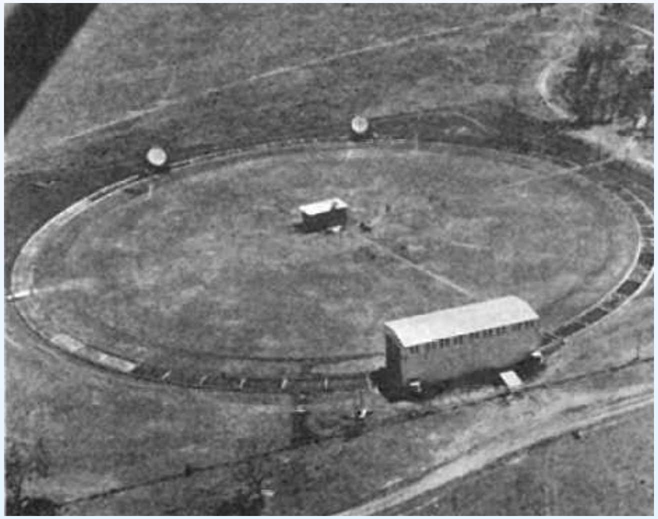
- **Historical**
  - Astronomy
    - Measurement of stellar radii with photon (space-time) correlations
    - Hanbury Brown and Twiss (HBT): Nature 178, 1076 (1956)
  - Particle physics
    - Resonance (ρ^0) measurement via $\pi\pi$ (momentum) correlation,
    - Goldhaber: PRL 3, 181 (1959)
  - Heavy-ion community
    - Determine the space-time dimensions of the particle emission source

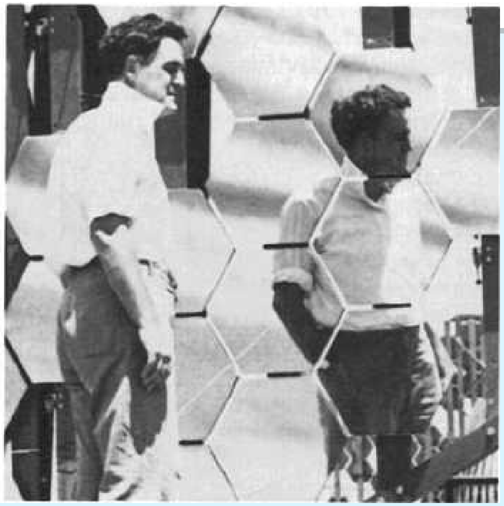
Narrabri Interferometer, Australia

Robert Hanbury Brown
+ Richard Q. Twiss









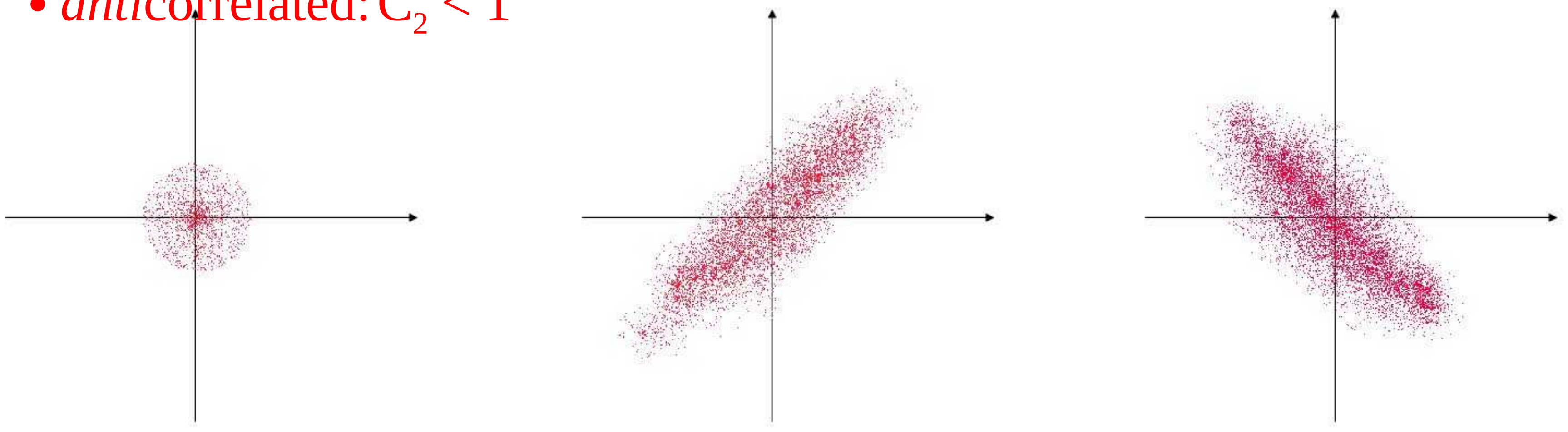
$$C = \frac{\langle I_1(t) I_2(t) \rangle}{\langle I_1(t) \rangle \langle I_2(t) \rangle}$$

Stellar Interferometry (I)

If ΔI_1, ΔI_2 are

- *un*correlated: $C_2 = 1$ (coherent source: $\langle I_1 I_2 \rangle = \langle I_1 \rangle \langle I_2 \rangle$)
- correlated: $C_2 > 1$
- *anti*correlated: $C_2 < 1$

$$C = \frac{\langle I_1(t) I_2(t) \rangle}{\langle I_1(t) \rangle \langle I_2(t) \rangle}$$

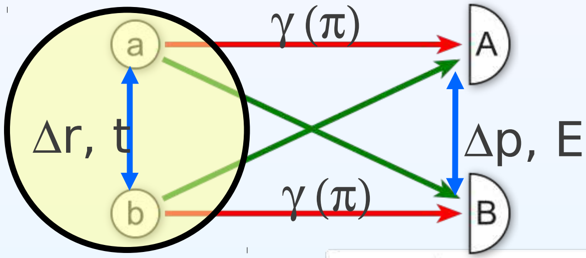


$\langle \Delta x \cdot \Delta y \rangle_a = 0$ uncorrelated

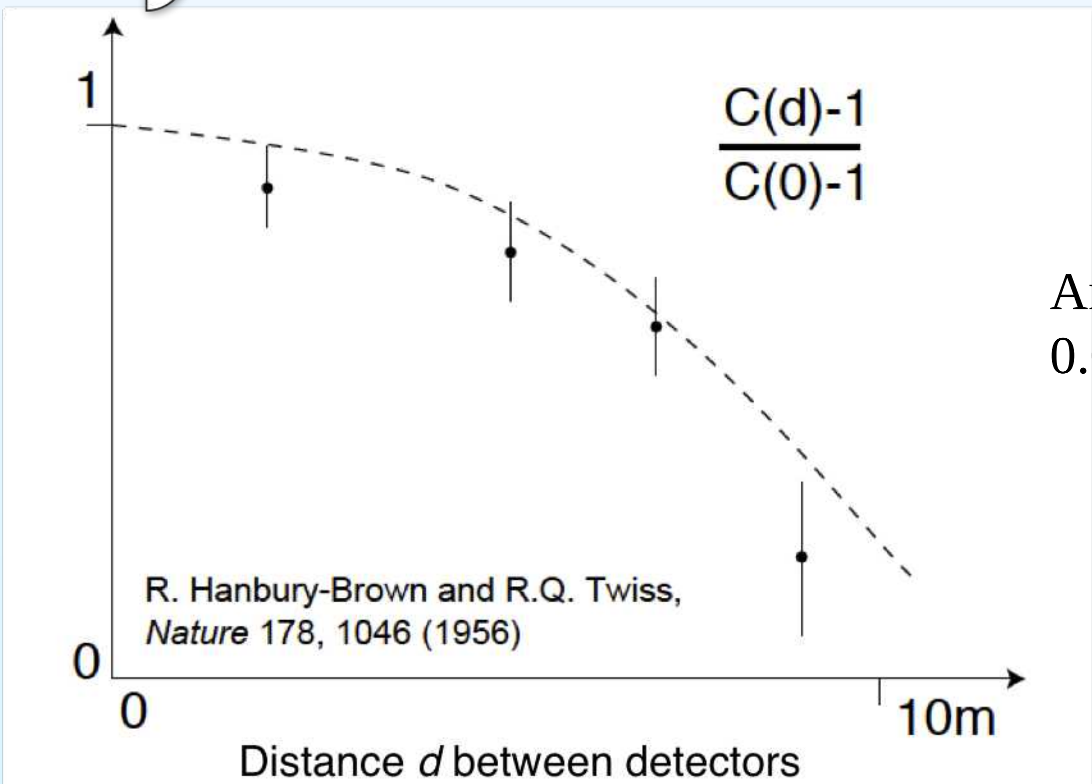
$\langle \Delta x \cdot \Delta y \rangle_a > 0$ correlated

$\langle \Delta x \cdot \Delta y \rangle < 0$ anti - correlated

Stellar Interferometry (II)



2-Photon correlation function: $C = \frac{\langle I_1(t) I_2(t) \rangle}{\langle I_1(t) \rangle \langle I_2(t) \rangle}$



Angular diameter: 0.0068”

⇒ Enhancement due to Bose-Einstein statistics of photons

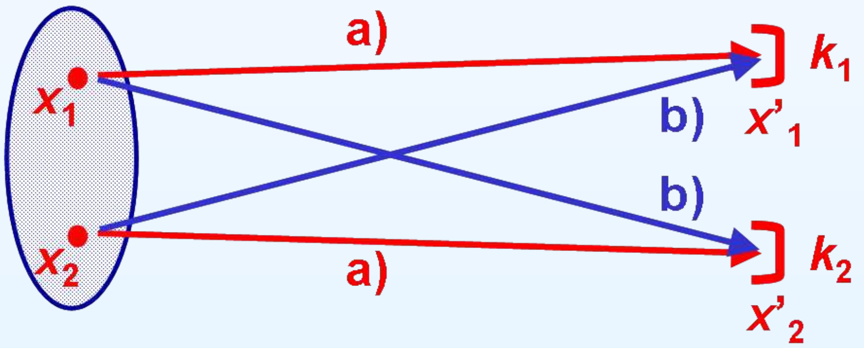
Correlations of identical bosons due to quantum interference – Basic Ideas (I)

- **Stochastic emission from extended source**
- **Consider 2 identical bosons (photons, pions, …)**
- **Cannot distinguish paths because of identical particles**
- **Phase space volume**

$$\Delta x \Delta p \leq \hbar$$

→ a chaotic system of identical non-interacting particles exhibits quantum fluctuations following Bose-Einstein (or Fermi-Dirac) statistics

- **Integration over all source points yields total intensity in each detector**
  - Direct relation to source dimensions
- **Correlation largest for chaotic source, vanishes for coherent emission**



Correlation Function:

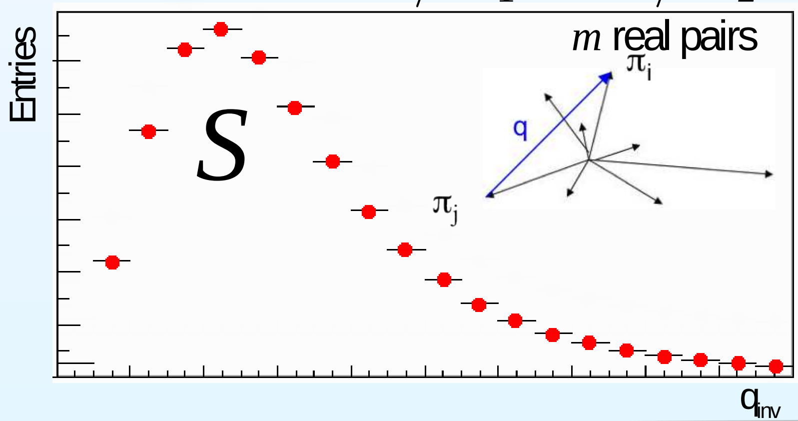
$$C_2(k_1, k_2) = \frac{P(k_1, k_2)}{P(k_1)P(k_2)}$$

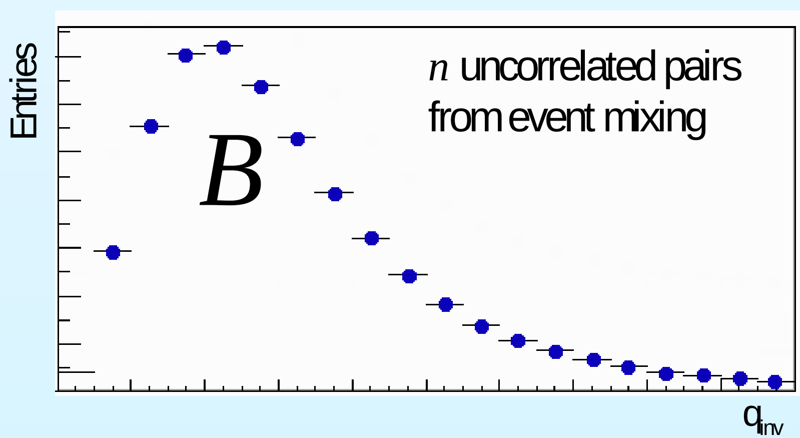
How to Measure Two-Particle Correlations

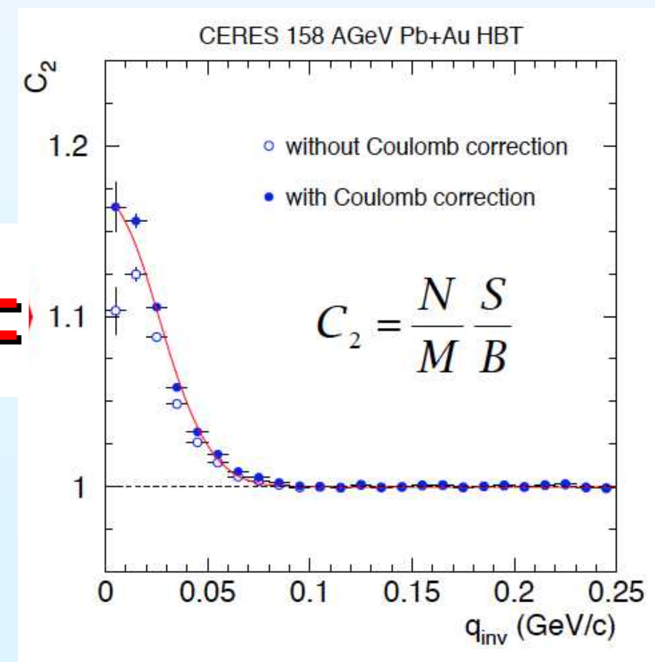
- Measure amplitude for detecting e.g. two pions with (four) momenta k_1 and k_2
- Compare to product of single amplitudes (mixed events)

$$C_2(\vec{k}_1 - \vec{k}_2) = \frac{d^6N/d\vec{k}_1 d\vec{k}_2}{d^3N/d\vec{k}_1 \cdot d^3N/d\vec{k}_2}$$

Relative momentum $q = k_1 - k_2$







Correlations of identical bosons due to quantum interference – Basic Ideas (II)

- The correlation strength is directly related to the Fourier transform of the (effective) source distribution ρ(r)

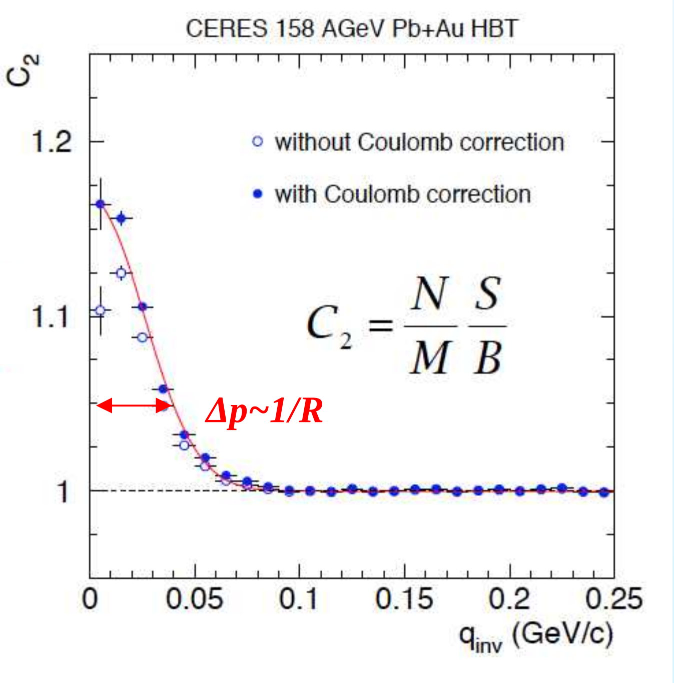
$$C_2(q;k_1,k_2) = 1 + \lambda|\widetilde{\rho}(q;k_1,k_2)|^2$$

- λ : chaoticity parameter; $0 < \lambda < 1$
  $\lambda = 0$ for coherent source, $q = k_1 - k_2$

  Two-pion correlation function probes phase space configuration of the source at the time of pion emission.

- Often used parameterization:
  Gaussian emission

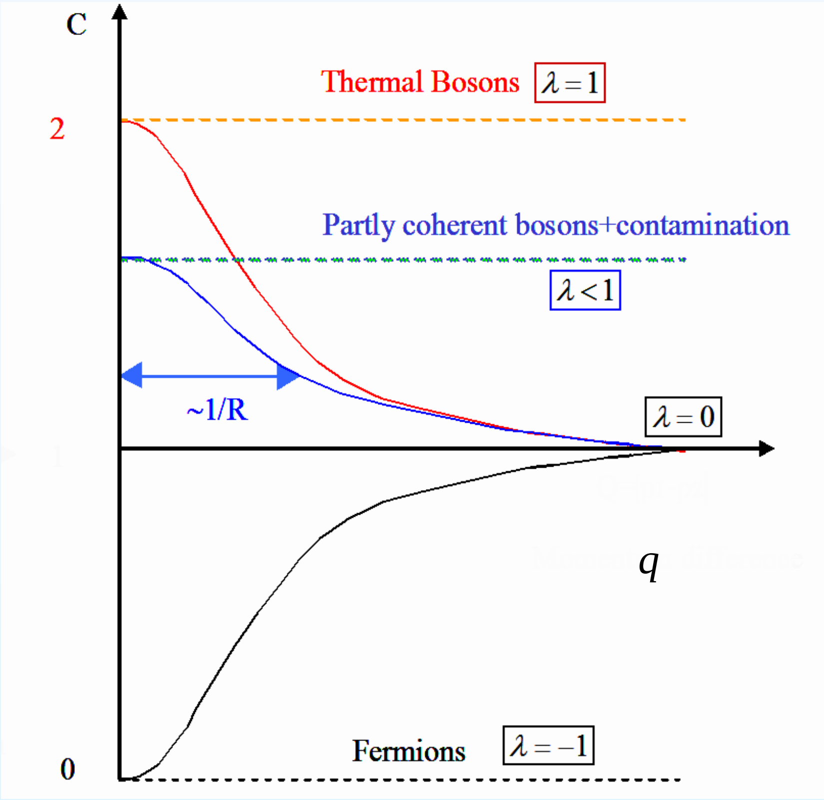
$$\rho(r) = A \cdot \exp\left(-\frac{r^2}{2R^2}\right) \quad => \quad C_2(q) = 1 + \exp\left(-q^2R^2\right)$$



in heavy ion collisions typical dimensions 1-10 fm,
→ leads to interference at momentum differences of 20-200 MeV/c

General 2-Particle Correlations

- Identical bosons:
  ⇒ enhancement for small q
- Identical fermions:
  ⇒ depletion for small q
- λ : chaoticity parameter
  0 < λ < 1
- Width of correlation function is inversely proportional to the size of the particle emitting source

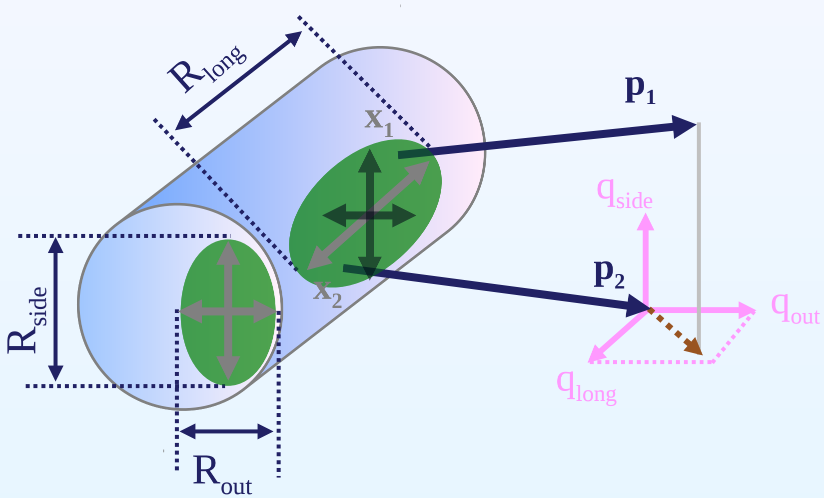


⇒ Measurement of fireball size in heavy ion reactions

Information on source dynamics

⇒ Transverse expansion
⇒ Lifetime
⇒ Emission duration

Correlations of identical bosons due to quantum interference – Basic Ideas (II)



P. Soerensen

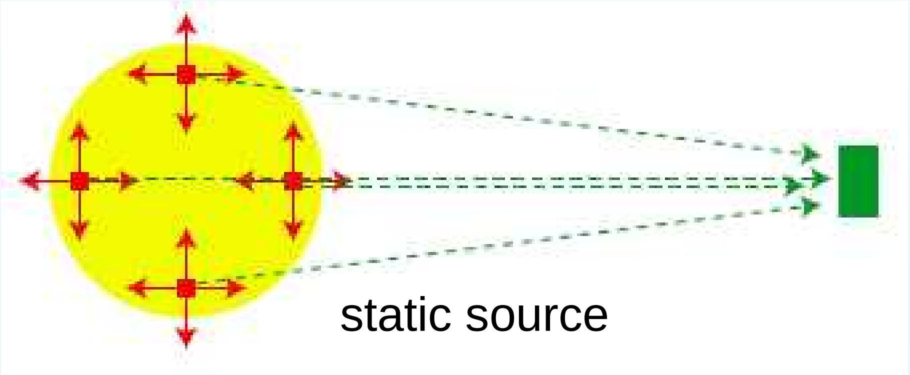
Cross-term between q_{out},q_{long} (0 for mid-rapidity and symmetric system)

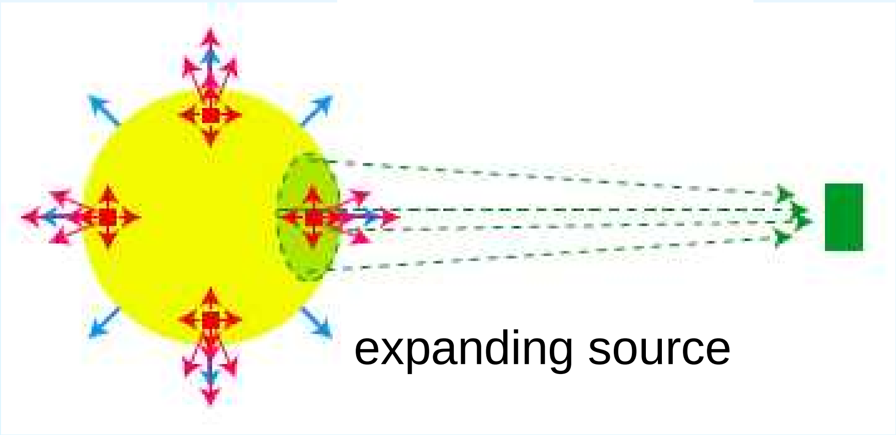
$$C_2(q;k_1,k_2) = 1 + \lambda \cdot e^{-R_x^2 q_x^2 - R_y^2 q_y^2 - R_z^2 q_z^2 - \sigma_t^2 q_t^2}$$

dimensions (length of homogeneity) in the source centre of mass system different decompositions (R_x,R_y,R_z) (R_{in},R_{out},R_{long}) R_{inv}

Important Effects

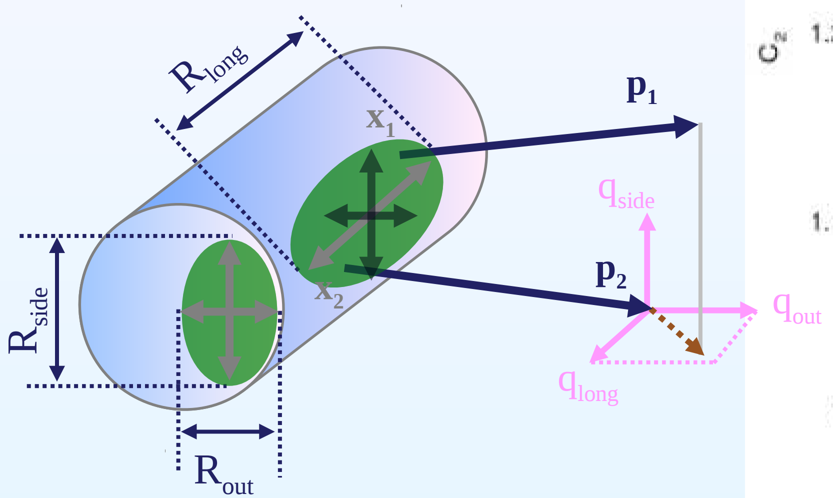
- **Particle interactions**
  - Coulomb
  - Strong interaction
- **Resonances**
  - Source appears enlarged (cf. Goldhaber)
- **Coherence**
- **Expansion**
  - Source only partially seen
  - Lots of information on hydrodynamic evolution





Powerful measurement sensitive to many details of the expansion

Expanding Medium



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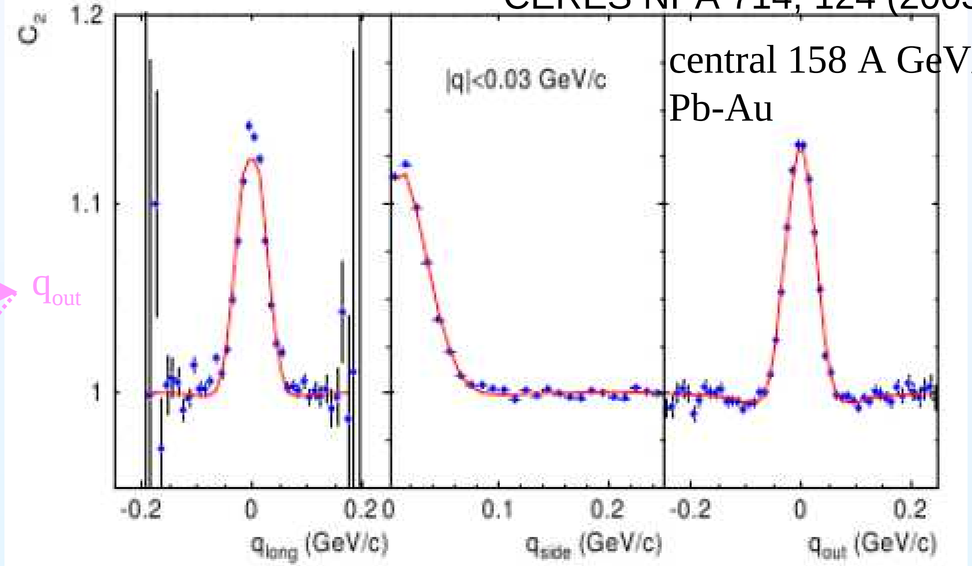
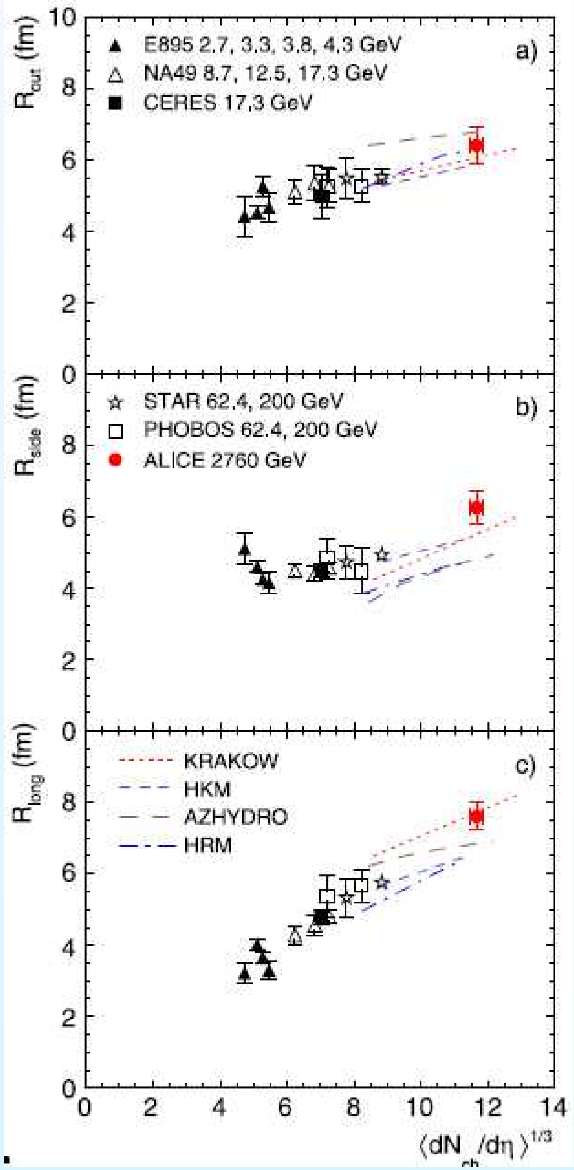
CERES NPA 714, 124 (2003)



- **The medium expands differently in longitudinal and transverse direction**
  - Cf. Bjorken model
  - Radius parameters are sensitive to expansion
  - R_{long} in longitudinal direction
  - Transverse components

Space-Time Extent of Fireball (I)

- R_{long} **shows largest increase**
- $\langle dN_{ch}/d\eta\rangle^{1/3} \sim \text{Volume}$
- **for reference: R ≃ 1 fm in pp collisions**



ALICE collab., arXiv:1012.4035

Energy dependence of the Freeze-Out Volume

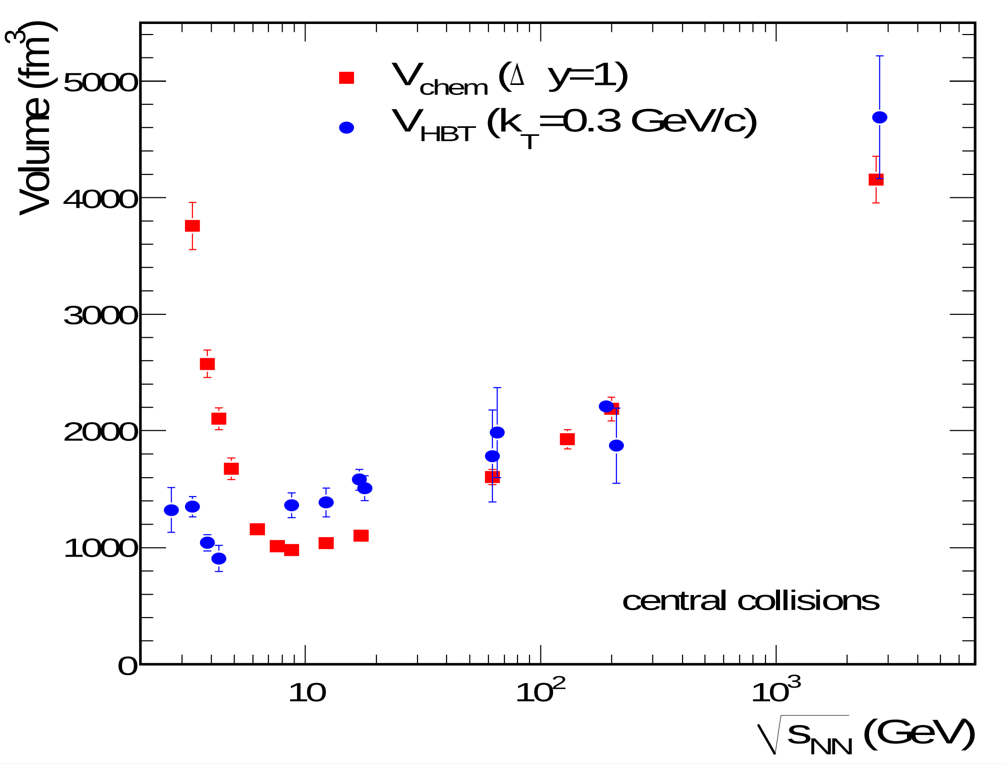
- HBT radii allow to estimate the volume at freeze-out
  - Volume at the last interaction

$$V_{HBT} = (2\pi)^3 R_{side}^2 R_{long}$$

  - Change with beam energy: ≈ 2000 – 5000 fm^3

- From statistical model fits (A. Andronic)

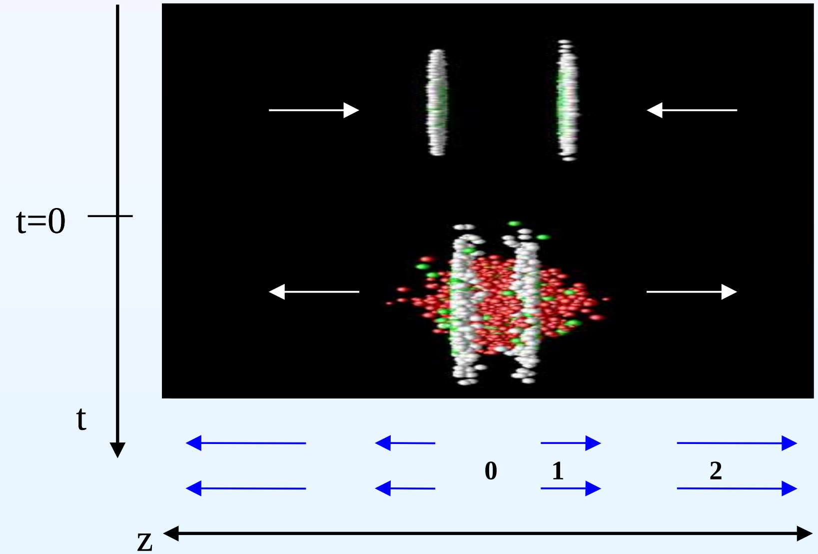
$$V_{chem} = (dN/dy)/n_{ch}^{therm}, \mathrm{n}_{\mathrm{ch}}^{\mathrm{therm}}$$



Freeze-out volume huge growth at LHC

Lifetime of the Fireball:
Basic Parametrisation (I)

Consider a one- dimensional expansion in z:



H. Appelshaeuser

If the velocity of a source element is coherent in time:

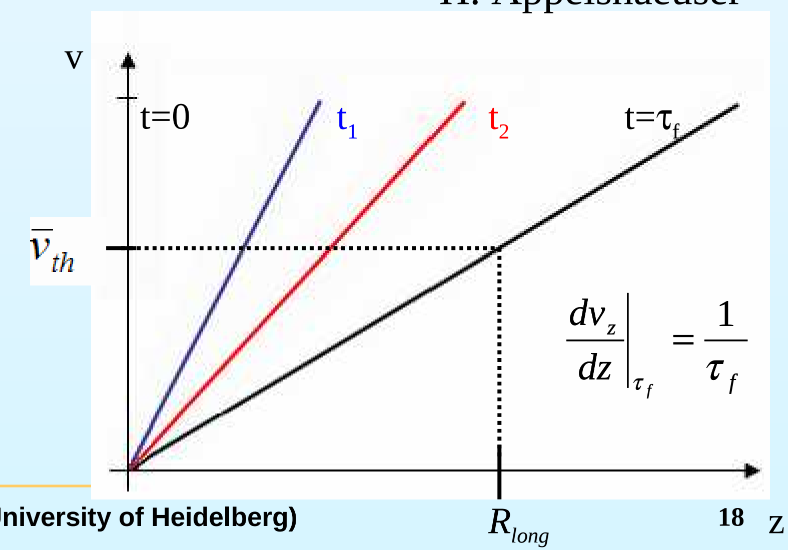
$$v_z = \frac{z(t)}{t}$$

⇨ $\frac{dv_z}{dz(t)} = \frac{1}{t}$ velocity gradient, which decreases with time (analogue to Hubble-Expansion of the universe)

<u>What HBT would measure:</u>

⇨ The HBT- length of homogeneity will correspond to the spatial distance Δz, over which the collective velocity difference $\Delta v_z = \Delta z / \tau_f$ is equal to the average thermal velocity:

$$R_{long} = \Delta z = \tau_f \cdot \Delta v_z = \tau_f \cdot \bar{v}_{th}$$



Lifetime of the Fireball:
Basic Parametrisation (II)

- For thermal velocity in one dimension we get with

$$\frac{1}{2} m_\pi \bar{v}_{th}^{\;2} = \frac{1}{2} k T_f \quad => \quad \bar{v}_{th} = \sqrt{\frac{T_f}{m_\pi}} \qquad \text{k = 1}$$

- If T ≈ m_π we have to do a relativistic calculation:

$$m_{rel} = \sqrt{m_\pi^{\;2} + p^2}$$

- Assuming $p_z << p_T$ with p_T perpendicular to the beam (z-axis) it yields:

$$m_{rel} = \sqrt{m_\pi^2 + p_T^2} = m_T \qquad R_{long} = \tau_f \sqrt{\frac{T}{m_T}} = R_{therm}$$

(Makhlin and Sinyukov, 1988)

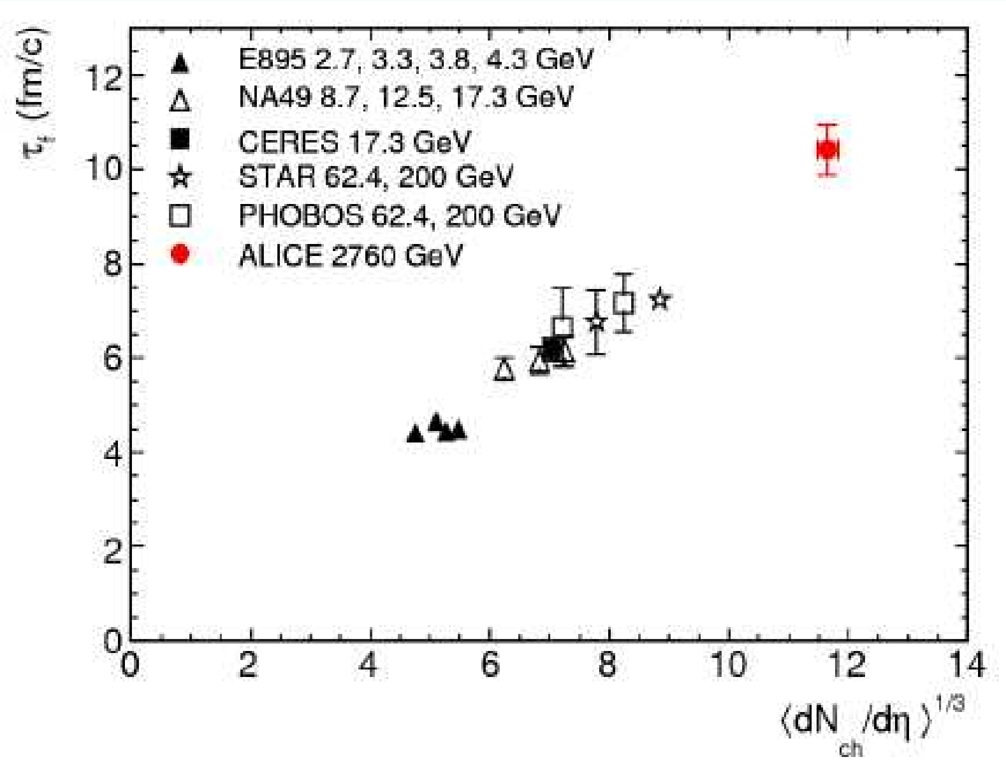
Lifetime of the Fireball

From R_{long}: expansion at LHC > 10 fm/c

- **Duration of the expansion τ can be related to R_{long}**

$$R_{long} = \tau_f \sqrt{\frac{T}{m_T}} = R_{therm}$$

- **T the kinetic freeze-out temperature (spectra fit)**



The size of the homogeneity region is inversely proportional to the velocity gradient of the expanding system. The longitudinal velocity gradient in a high energy nuclear collision decreases with time as 1/τ. R_{long} is proportional to the total duration of the longitudinal expansion, τ_f.

Take-Home Message

- **Hanbury Brown-Twiss correlations of identical particles determine**
  - The size of the emitting source
    - Source size at LHC 10-35% larger than at RHIC
  - The lifetime of the system
    - At LHC ~40% larger than at RHIC