Azimuthal sensitive HBT in Pb+Pb $\sqrt{s_{NN}} = 2.76TeV$ collisions at LHC-ALICE experiment

A School for young Asian scientists

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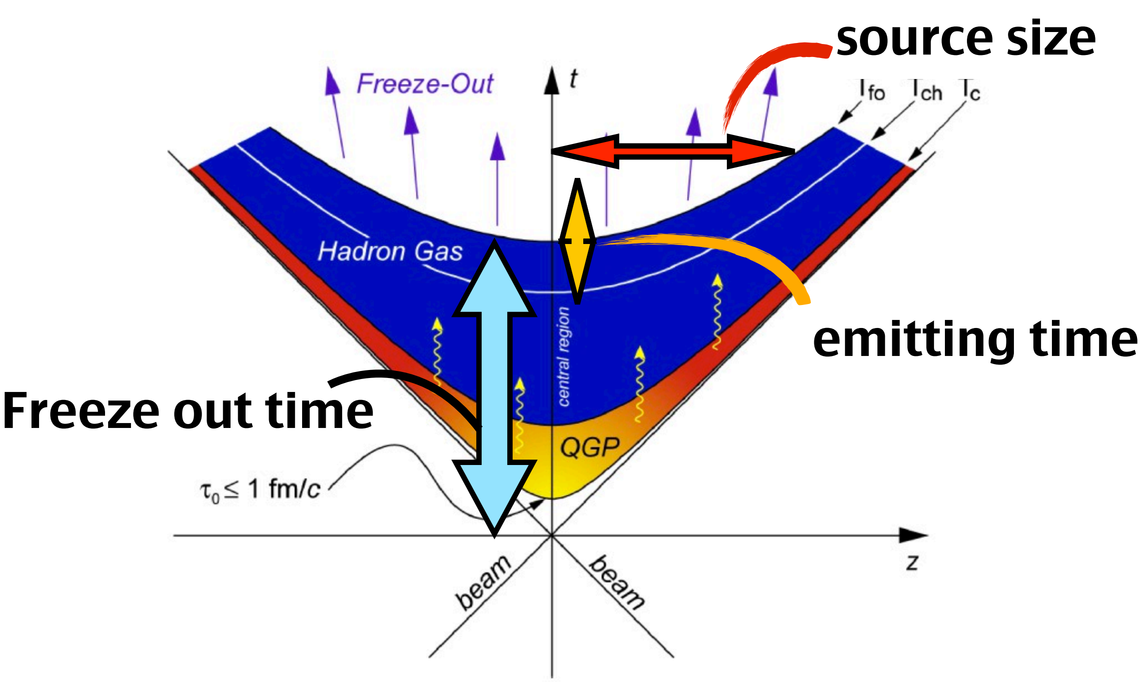
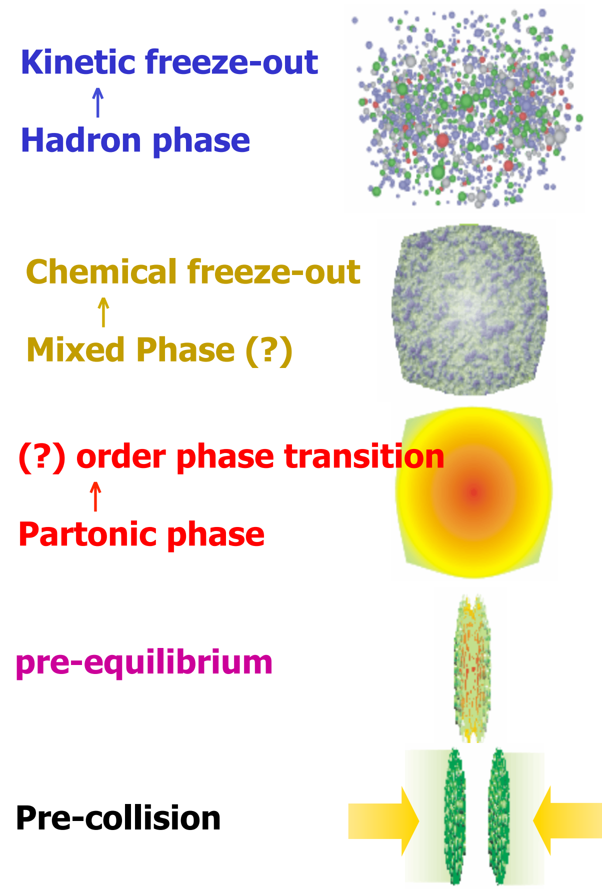
Space - Time Evolution

- To quantify the properties of QGP, a precise understanding of spatial and temporal evolution is required
- HBT correlation is a unique tool to measure the source size at the kinetic freeze-out





HBT interferometry

- Measure the source size with correlation of two identical particles

Robert Hanbury Brown & Richard Q.Twiss

- A test of new stellar interferometer on Sirius(1950s)

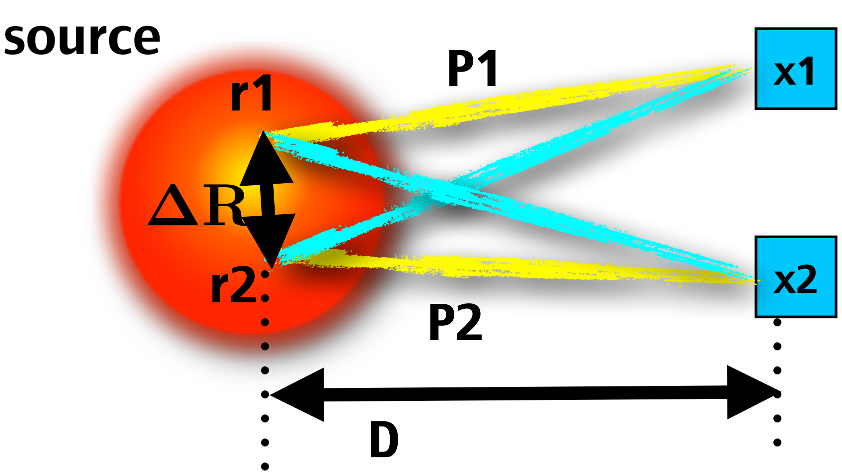
G. Goldhaber, S. Goldhaber, Lee, Paris

- Influence of Bose-Einstein Statistics on the Anti-proton proton annihilation process (1960s)

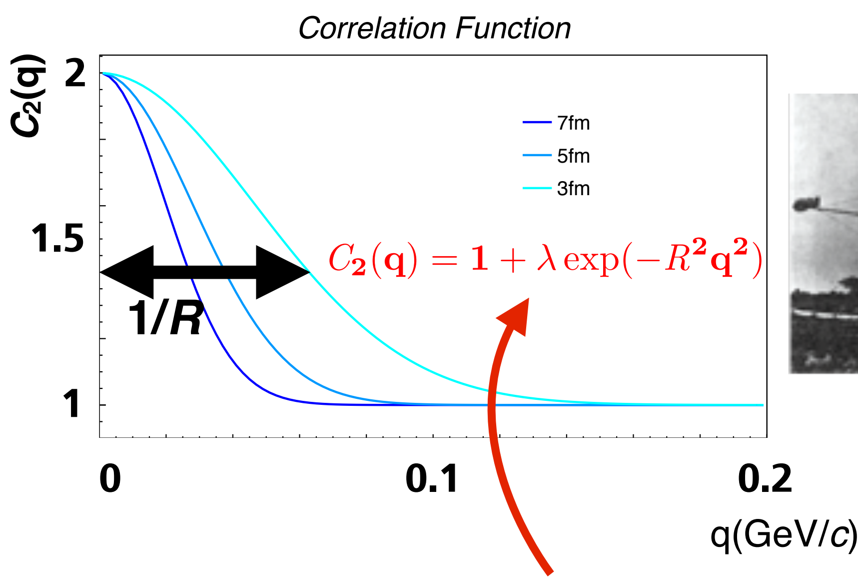
$$\Psi_2(p1,p2) = \frac{1}{\sqrt{2}}\left(e^{ip_1(x_1-r_1)}e^{ip_2(x_2-r_2)} \pm e^{ip_1(x_1-r_2)}e^{ip_2(x_2-r_1)}\right)$$

Robert Hanbury Brown
(1916–2002)

Gerson. Goldhaber
(1924–2010)



$$C_2(p_1,p_2) \equiv \frac{P\ (p_1,p_2)}{P(p_1)P(p_2)}$$



Gaussian distribution particle emitting source

3D HBT analysis

■ For more detailed spatial information, correlation function is expanded to 3-dimension

LCMS (Longitudinally Co-Moving System) $p_{z1} + p_{z2} = 0$ $k_T = \frac{p_{T1} + p_{T2}}{2}$

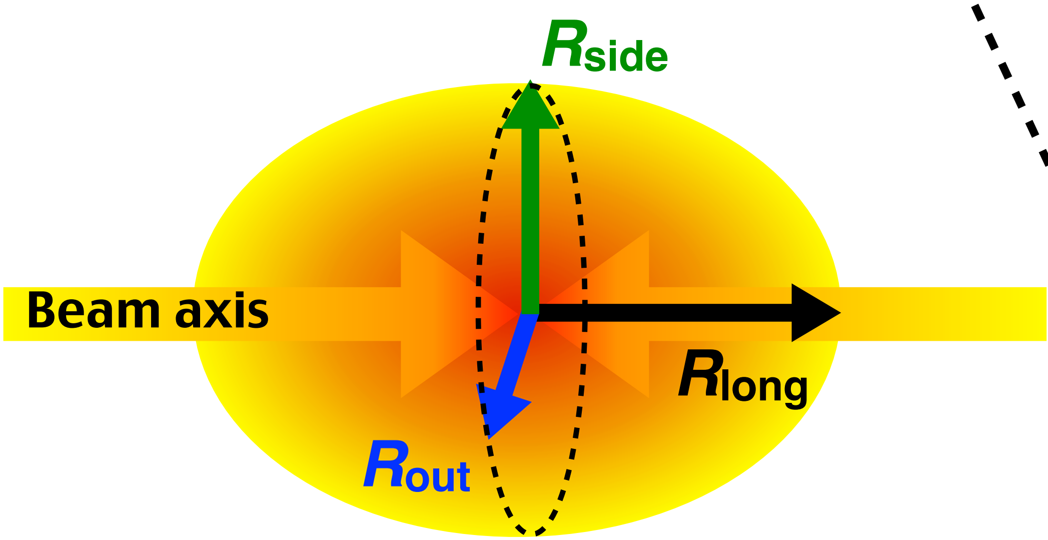
$$C_2(\mathbf{q_{out}}, \mathbf{q_{side}}, \mathbf{q_{long}}) = 1 + \lambda(-R^2_{out}\mathbf{q}^2_{out} - R^2_{side}\mathbf{q}^2_{side} - R^2_{long}\mathbf{q}^2_{long})$$

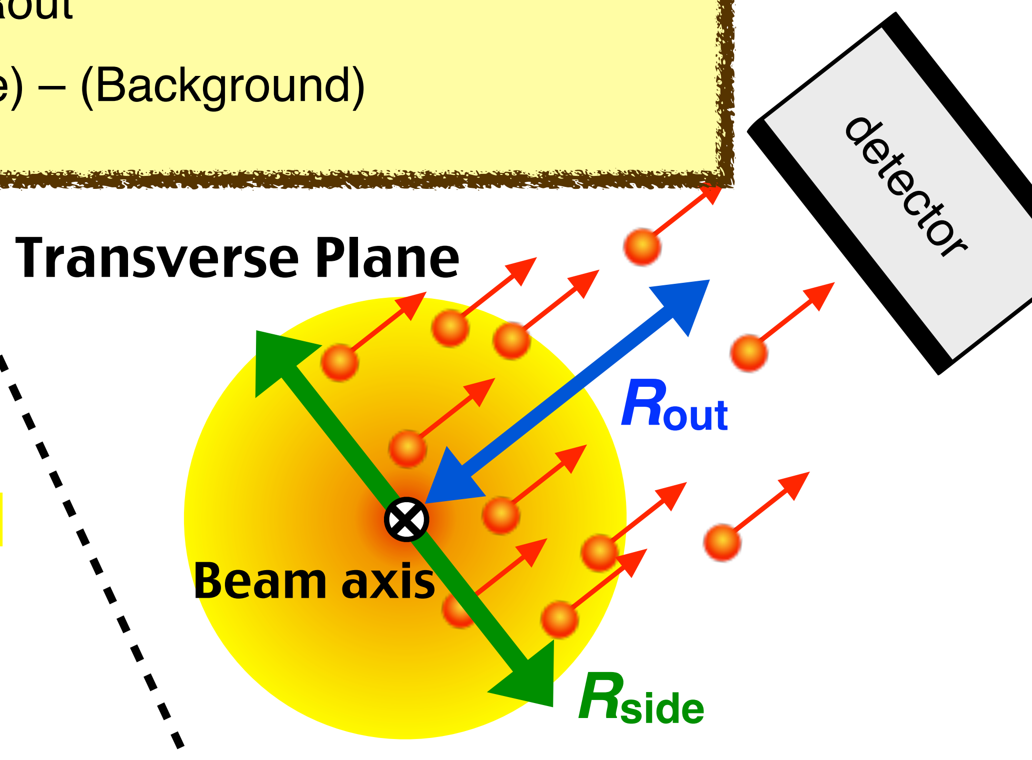
R_{long} : source size along the longitudinal direction (beam direction)

R_{out} : source along the pair transverse momentum + emission duration

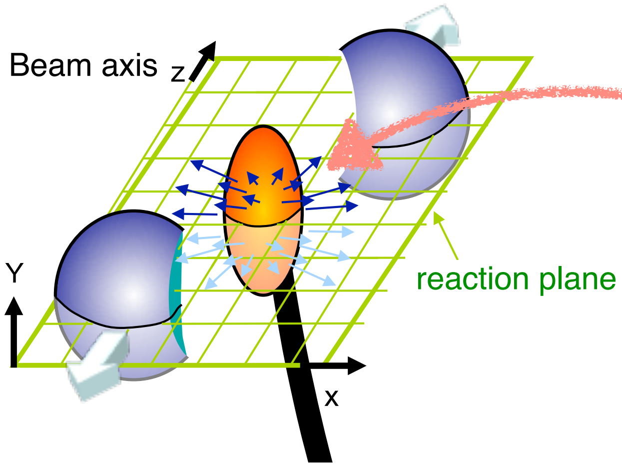
R_{side} : source size along the perpendicular to Rout

λ : chaoticity = (in coherence) – (resonance) – (Background)



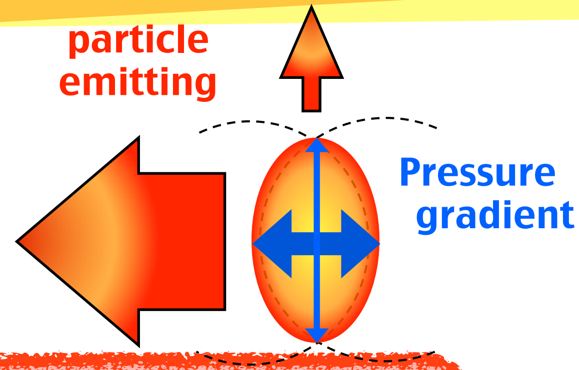


Azimuthal anisotropy



- In non-central collision, initial overlap region is almond shape

  ★Spatial eccentricity



- Local thermal equilibrium is established

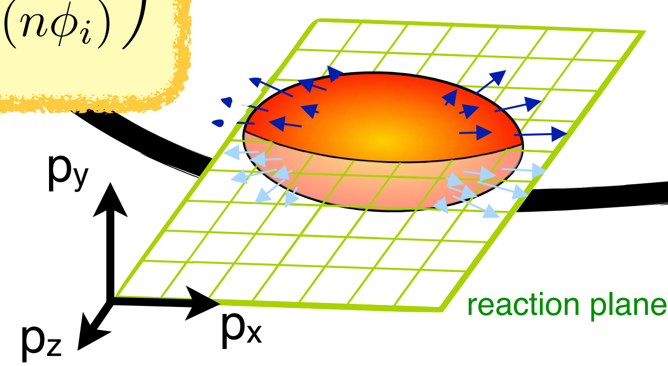
  → mean free path of particles is much shorter than the system size

  ★ Pressure gradient is steeper at shot axis than long one

Event plane

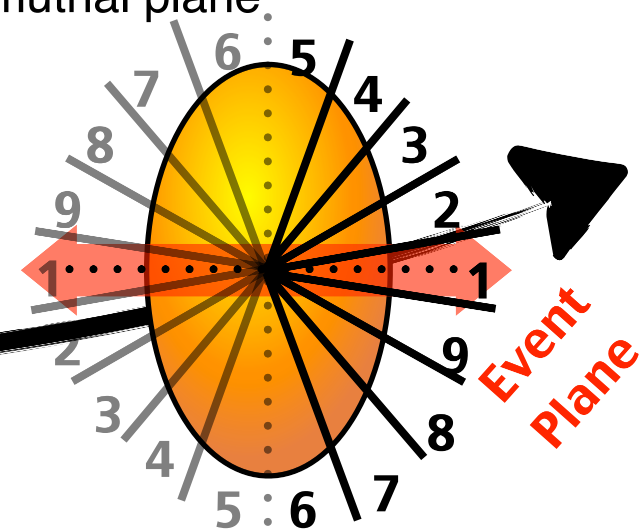
– Measuring emitting particle anisotropy, we can measure the 2_{nd} event plane

$$\Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{\sum w_i \sin(n\phi_i)}{\sum w_i \cos(n\phi_i)}\right)$$



Azimuthally sensitive HBT

– Dividing pair angle w.r.t. Ψ_2 in azimuthal plane -> measure the freeze-out source size in detailed at azimuthal plane



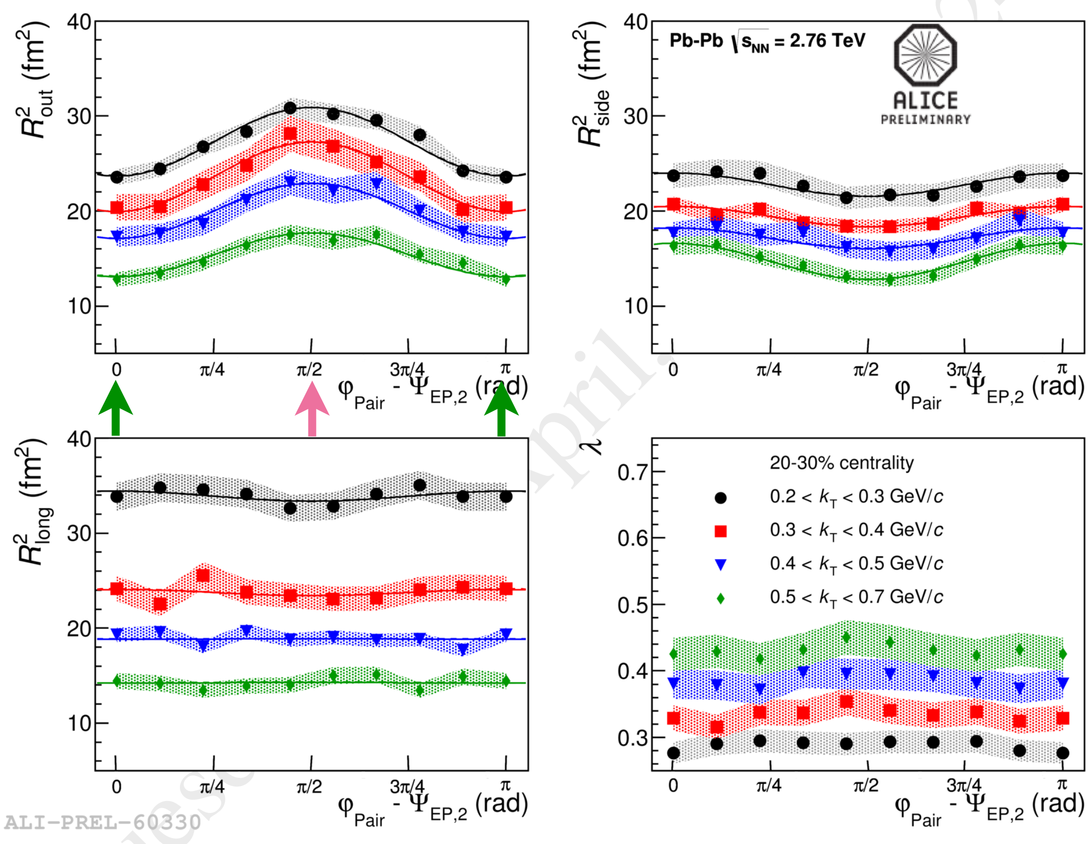
HBT with respect to 2nd oder event plane

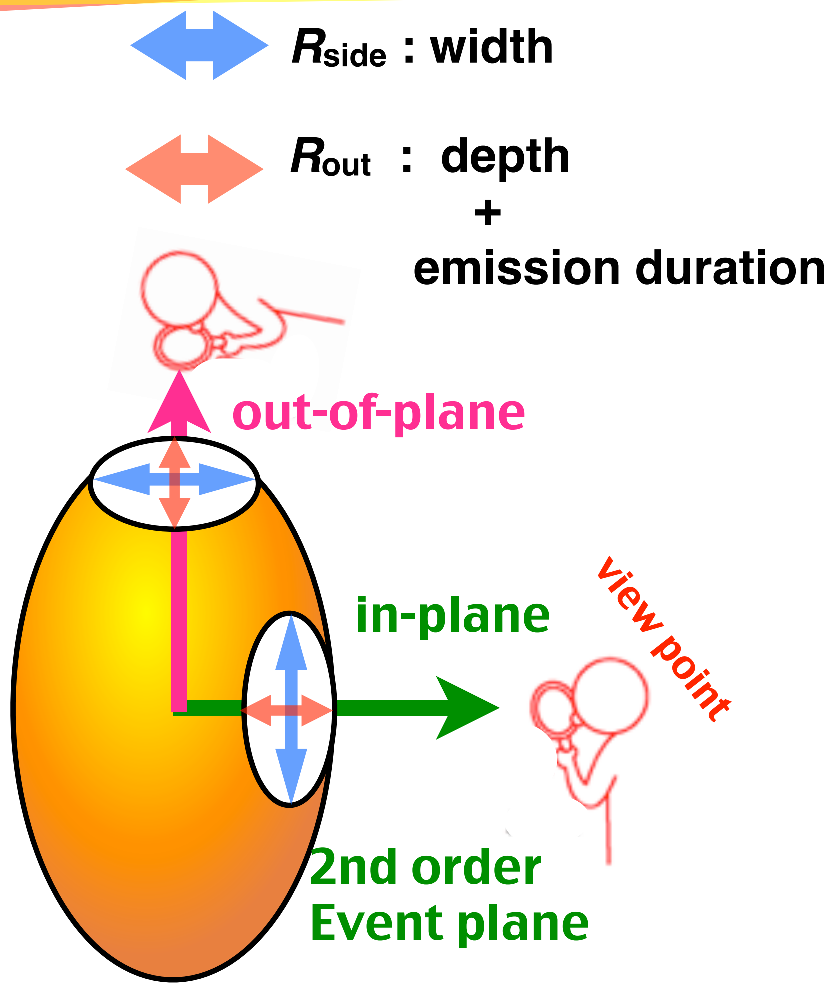
- φ_{pair} - $\Psi_{EP,\,2}$ is the angle between pair and $\Psi_{EP,\,2}$
- R_{out}, R_{side} oscillate

$$R^2_{\mu,0}(\varphi - \Psi_2) = R^2_{\mu,0} + 2R^2_{\mu,2}\cos(2(\varphi - \Psi_2))$$

$$(\ \mu = \mathrm{side, out, long}\ )$$

$$R^2_{\mathrm{os},0}(\varphi - \Psi_2) = R^2_{\mathrm{os},0} + 2R^2_{\mathrm{os},2}\cos(2(\varphi - \Psi_2))$$





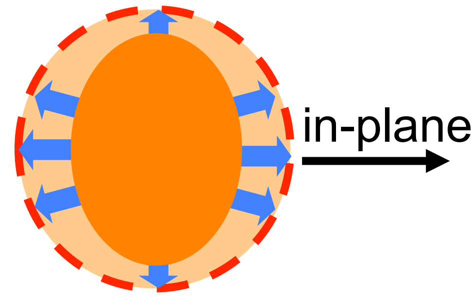
Azimuthal plane

- in-plane : small R_{out} , large R_{side}
- out-plane : large R_{out}, small R_{side}

→ Initial ellipticity still remains at freeze out despite there is strong elliptic flow !

Final eccentricity at LHC

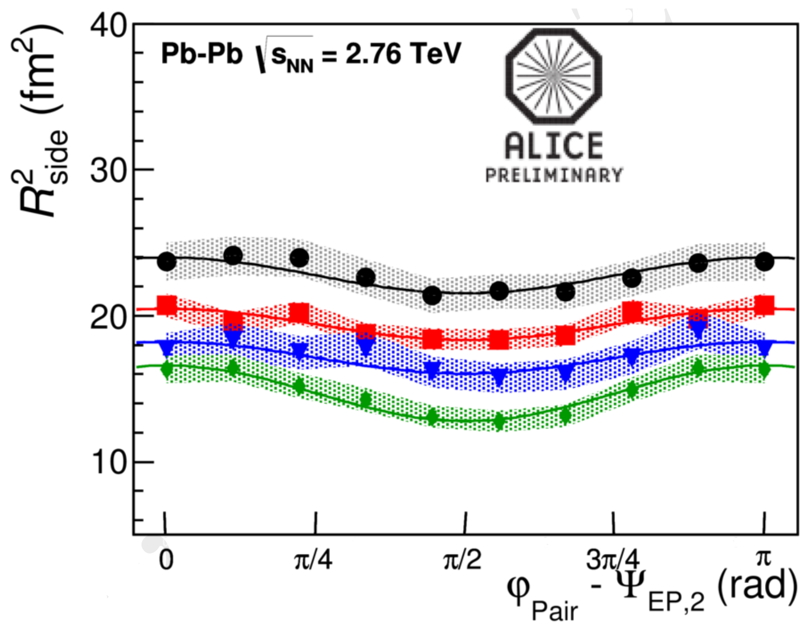
- **Final eccentricity is determined by initial eccentricity, pressure gradient and expand time etc.**

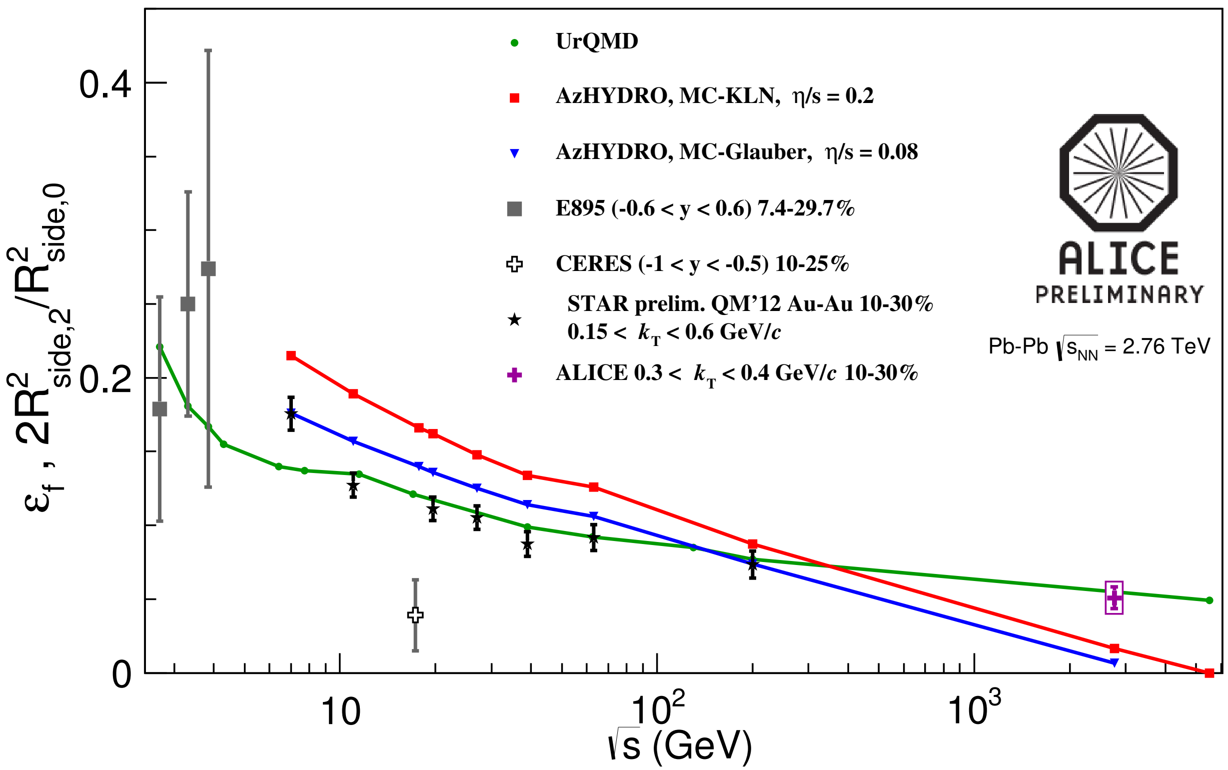


$\varepsilon_{\text{final}}$

$$R^2_{\text{side},0}(\varphi-\Psi_2) = R^2_{\text{side},0} + 2R^2_{\text{side},2}\cos(2(\varphi-\Psi_2))$$

$$\varepsilon_{\text{f}} = 2\frac{R^2_{side,2}}{R^2_{side,0}}$$

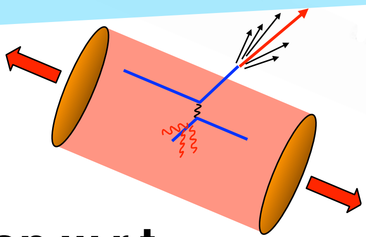




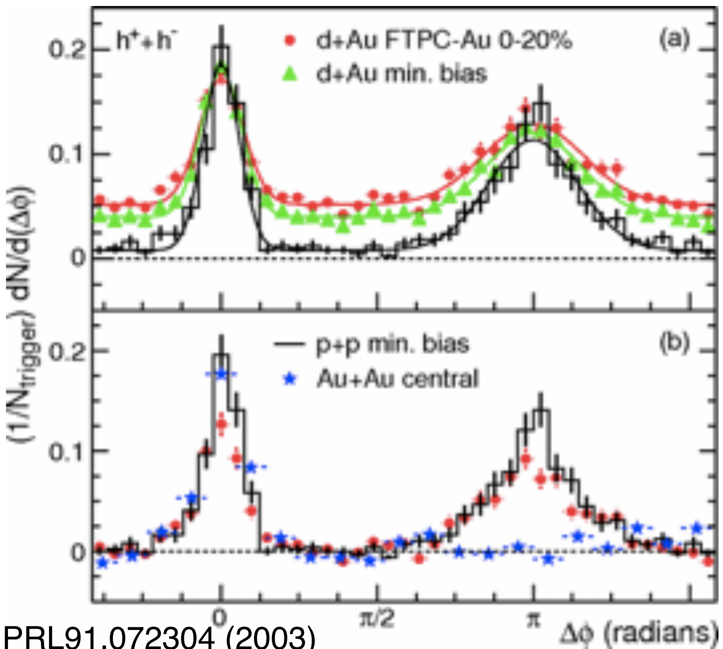
★ **ALICE data has lowest ε_f**

- **longer Freeze out time?**
- **effect of elliptic flow**

What is already known about Jet



- **Jet quenching**
  - **Azimuthal correlation w.r.t. high p_T leading particle (trigger)**



PRL91.072304 (2003)

p_T^{trig} =4-6 GeV/c, p_T^{assoc} > 2 GeV/c

pp : clean di-jet

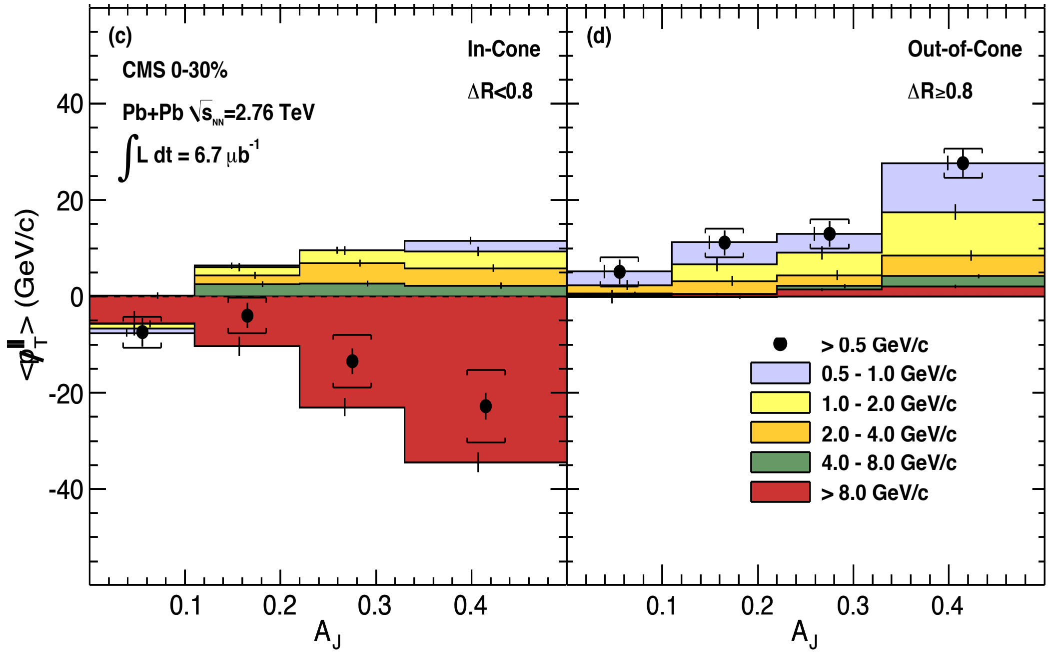
dAu : similar to pp

Au+Au : similar on the same side
back-to-back disappeared

Direct evidence of Jet quenching

- **Quenched Jet energy goes where?**

Phys.Rev.C 84, 024906(2011)

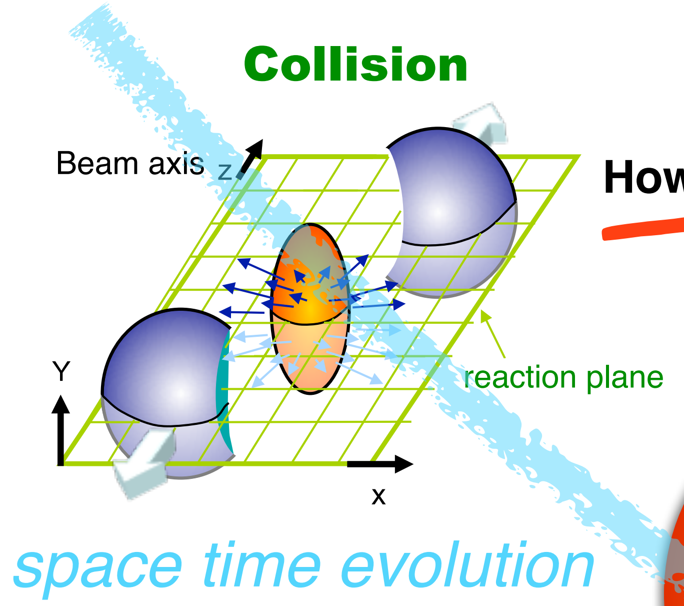


$$< p_T^{||} >= \sum_i -p_T^i \cos(\phi_i - \phi_{leading-jet})$$

$$A_j = \frac{p_T^{lead} - p_T^{sub-lead}}{p_T^{lead} + p_T^{sub-lead}}$$

★ **Missing energy of Jet is redistributed as low p_T hadrons toward large angle**

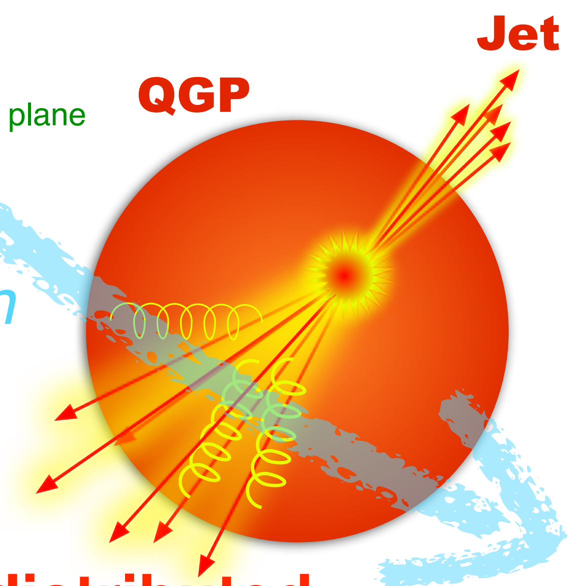
Azimuthal sensitive HBT w.r.t. Jet axis

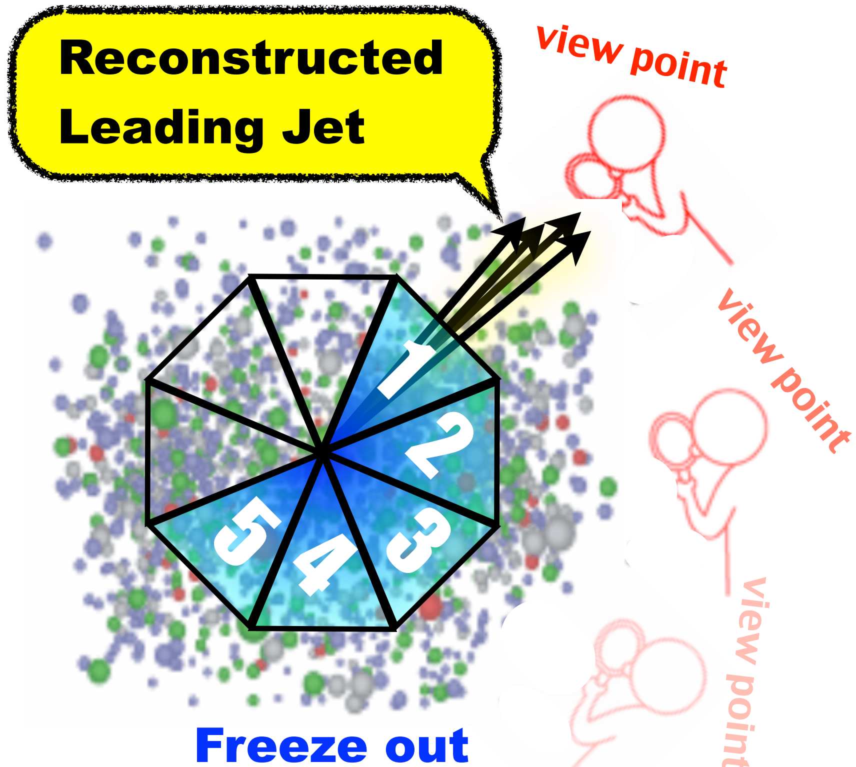


How is the effect to source size??

Jet reconstruction Parameters

- input track : ITS + TPC
- algorithm : anti k_T
- R size ($=\sqrt{\Delta\eta^2 + \Delta\phi^2}$) : 0.3
- p_T cut of single particle : 0.15 (GeV/c)
- Leading Jet p_T threshold : 20 (GeV/c)





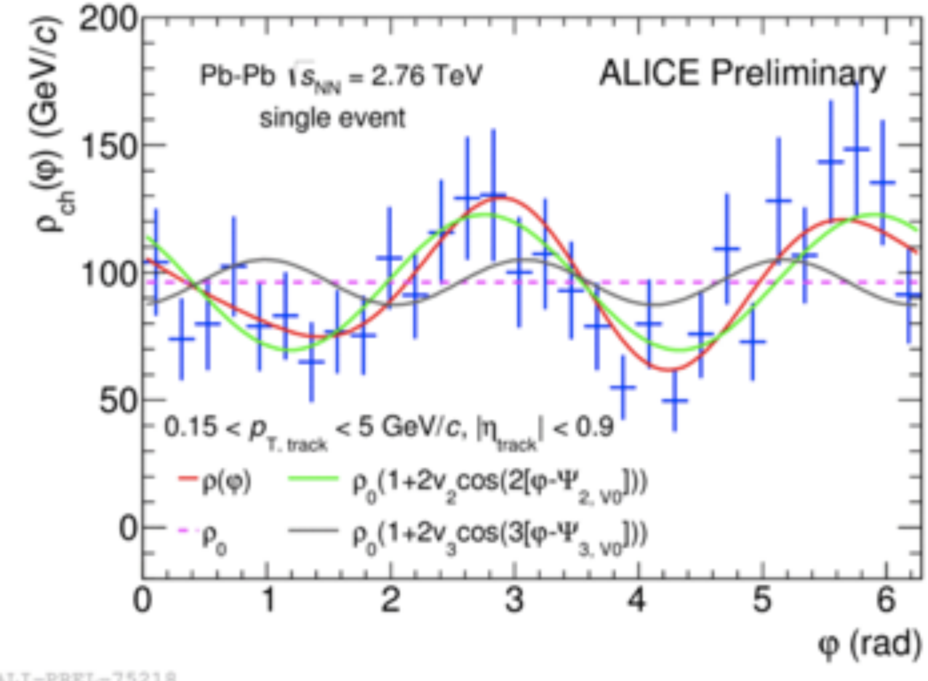
★**Jet energy is re-distributed into low p_T particles**

★ **If Jet modification affect the geometry of source, HBT radii oscillate w.r.t. Jet axis**

Jet v_2

- Background flow of underlying event
  - Event plane : VZERO
    (2.8 < η < 5.1, -3.7 < η < -1.7)
  - Background : E by E fourier fitting

$$\rho(\varphi) = \rho_0 \times \left(1 + \{v_2^{obs}\cos(2[\varphi - \Psi_{2,EP}]) + v_3^{obs}\cos(3[\varphi - \Psi_{3,EP}])\}\right)$$

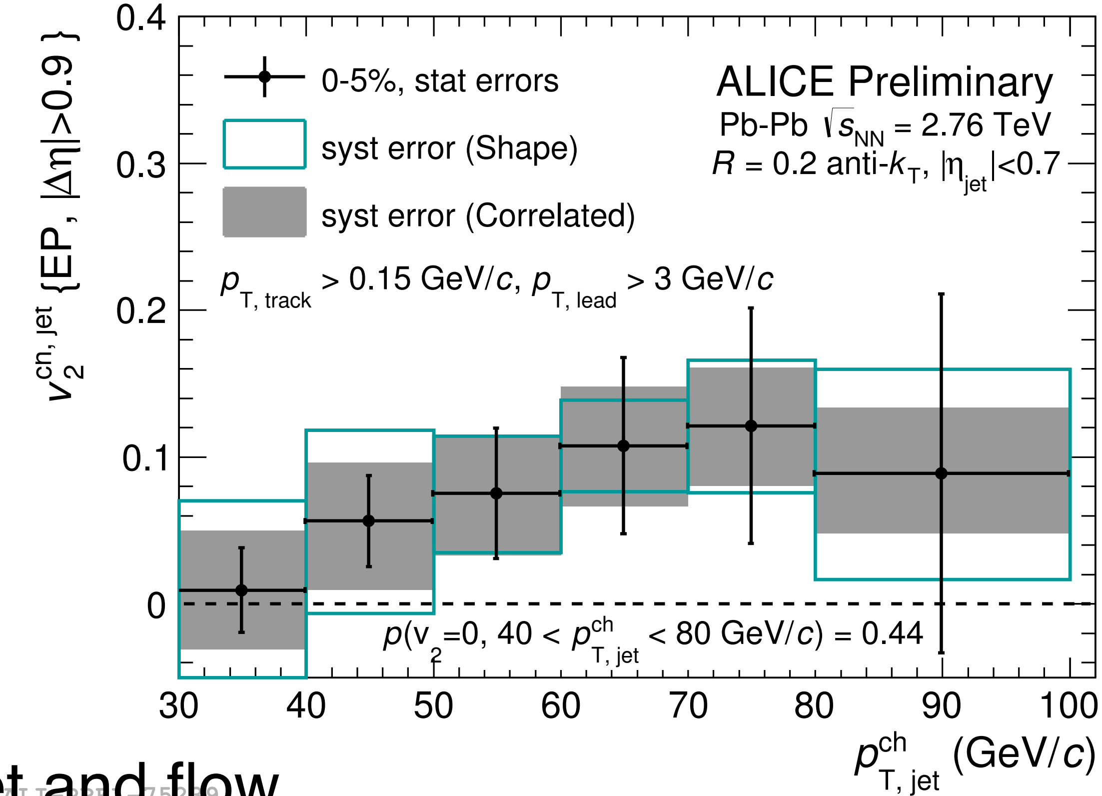


p_{T} **dependence of** $\mathrm{v}_2^{\mathrm{ch,jet}}$

* **Even if v_2 background is estimated, There is non-zero v_2 signal**

★ **path-length dependence**

$$\mathrm{v}_2^{\mathrm{ch,jet}} = < \cos(2(\varphi^{\mathrm{ch,jet}} - \Psi_{2,V0})) >$$



★ Cannot perfectly separate Jet and flow

Outlook to understand Jet-flow correlation

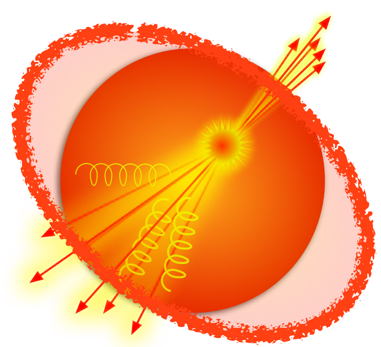
★ Estimate v_2 background to measure the correct Jet p_T

★ cannot perfectly separate Jet and flow

-> It seems Jet modification effect is buried in flow effect
in geometrical space...

★ Subtract Ψ_2 effect

- if there is Jet modification (re-distribution of Jet) to geometrical size
jet and flow effects are superposition



Summary

Azimuthally sensitive HBT with respect to Ψ_2

- R_{out}, R_{side} have azimuthal dependence
- R_{out}, R_{side} oscillate out-of-phase
- Initial ellipticity still remains at freeze out despite there is strong elliptic flow
- Final eccentricity at LHC is lowest because of expansion time and v_2

Azimuthally sensitive HBT with respect to Jet axis

- Azimuthally sensitive HBT w.r.t. Jet axis has similar oscillation to Ψ_2 HBT
- It's necessary to estimate v_2 background
- To see clearly jet modification in geometrical space, we should understand jet - flow correlation and subtract v_2 effect to HBT radii

Back up

HBT measurement in experiment

How to calculate correlation function C_2 in experiment

$$C_2 = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} = \frac{Q_{Real}}{Q_{Mix}}$$

Q_{Real} : pair in same event (HBT effect)
Q_{Mix} : pair in different event (no HBT effect)

C_2 : Correlation function

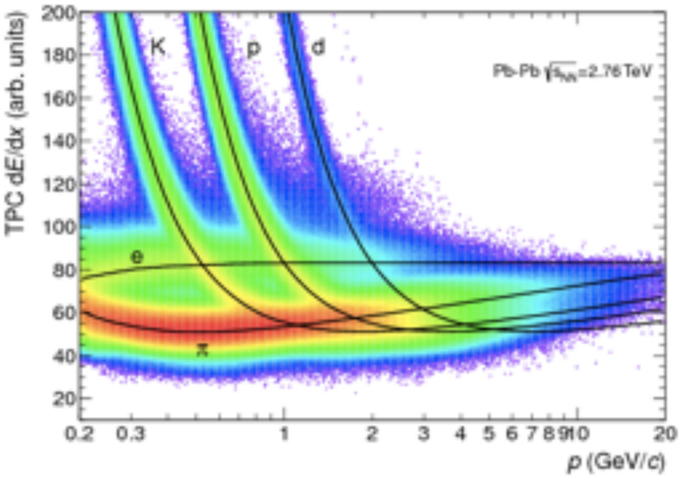
- Event Mixing
  - Selecting Real event and Mix event in similar event (centrality, z-vertex),
    we can exclude correlation from acceptance and efficiency

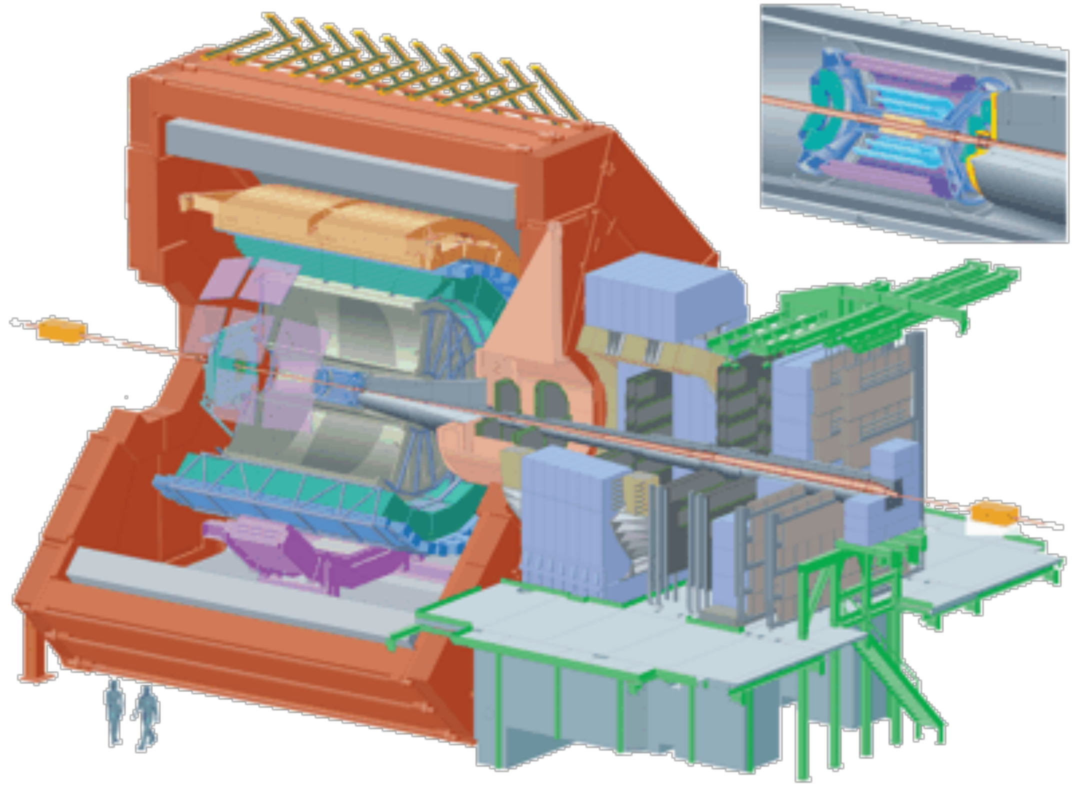
→ C_2 includes HBT effect and any other physics correlations

- Pair cut
- Coulomb interaction

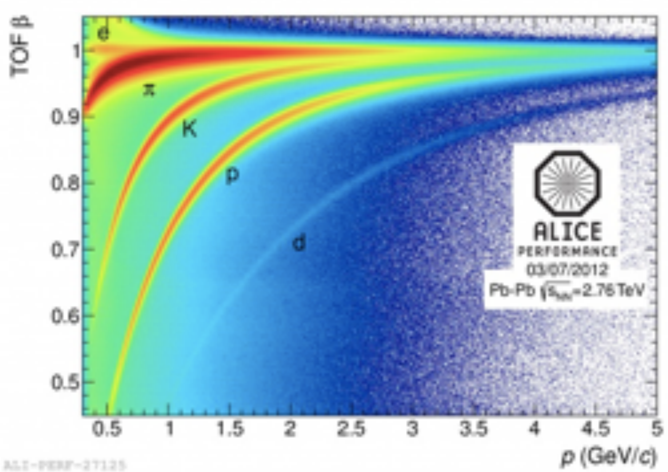
ALICE Detectors & performance

- ITS+TPC (|η| < 0.9)
  - ◊ charged particle tracking
  - ◊ PID dE/dx (p = 0.15 - 0.5 (GeV/*c*))

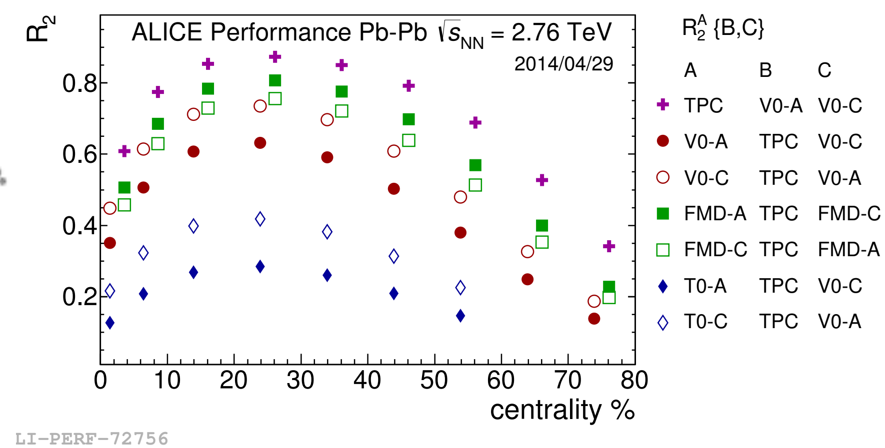




- TOF (|η| < 0.9)
  - $m^2 = p^2\left(\left(\frac{ct}{L}\right)^2 - 1\right)$
  - PID momentum range (p = 0.5 - 3.0 (GeV/*c*))



- VZERO (2.8 < η < 5.1, -3.7 < η < -1.7)
  - centrality determination, Event trigger
  - measure the event plane



Jet reconstruction & background subtraction

Jet reconstruction

- Information from charged track by TPC+ITS

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta R^2}{R^2} \begin{cases} p = 1 & k_T \text{ algorithm} \\ p = 0 & \text{Cambridge/Aachen algorithm} \\ p = -1 & \text{anti-}k_T \text{ algorithm} \end{cases}$$

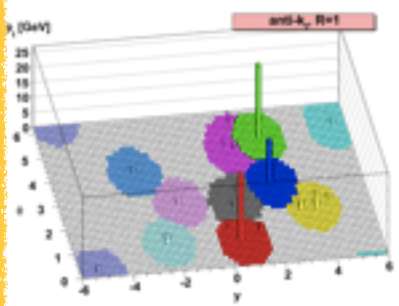
$$d_{iB} = 1/p_{Ti}$$

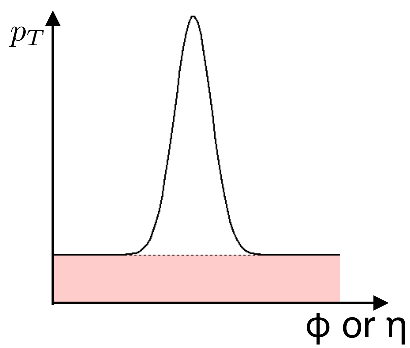
$$k_{ti} = p_{Ti}$$

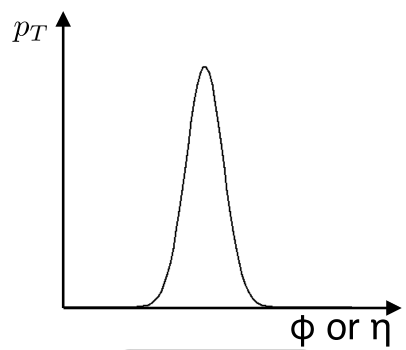
Parameters

- R size ($= \sqrt{\Delta\eta^2 + \Delta\phi^2}$) : 0.3
- p_T cut of single particle : 0.15 (GeV/c)
- Jet p_T threshold : 20 (GeV/c)

$$p_T^{jet} = p_T^{rec} - \rho_{ch} \cdot \text{Area}^{jet}$$







Raw Jet p_T	→	Background calculation	→	Correct Jet p_T
anti-k_T clustering algorithm		Calculate background density ρ		Remove underlying event contribution

Azimuthally sensitive HBT

– Dividing pair angle w.r.t. Leading Jet in azimuthal plane (8 division)
-> measure the freeze-out source size in detailed at azimuthal plane