Update on measurement of Bose-Einstein Correlations

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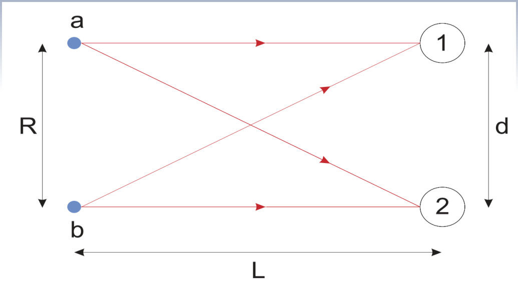
From interferometry to particle Physics



Intensity interferometry was discovered in 1950s by Hanbury-Brown, Twiss (HBT Interferometry) as a method of measuring the angular diameters of radio sources.

It relies on the fact that two photons emitted from the source have to be correlated due to second order interference effect.

$$C(d) = \frac{< I_1 >< I_2 >}{< I_1 I_2 >} \sim k\theta d$$

,where $\theta = R/L$. By changing the d one can measure the diameter of the source.

From interferometry to particle Physics

For two identical particles emited from a source we expect a symmetric wave function:
$\Psi^s_{1,2} = \frac{1}{\sqrt{2}}(\Psi_{11}\Psi_{22} + \Psi_{12}\Psi_{21})$, where Ψ_{ij} is a wave function of a particle emitted at i and observed at j. So the propablity density of observing two bosons with momenta q_1 and q_2 is:
$\left|\Psi^s_{1,2}\right|^2 = 1 + cos(\Delta\overrightarrow{q}\Delta\overrightarrow{r})$, where $\Delta\overrightarrow{q} = q_1 - q_2$, $\Delta\overrightarrow{r} = r_1 - r_2$

From interferometry to particle Physics

Assuming spherical symmetry of the source: $\mathcal{P}(\overrightarrow{q}) = \int \left|\rho(r; \overrightarrow{q})\right|^2 d^3\overrightarrow{r}$,
the probability of observing two particles with two momenta is given by:
$\mathcal{P}(\overrightarrow{q_1}, \overrightarrow{q_2}) = \int \left|\Psi^s_{1,2}\right|^2 \left|\rho(\overrightarrow{r_1})\right| \left|\rho(\overrightarrow{r_2})\right| d^3 r_1 d^3 r_2$,
applying this expression to general 2^{nd} correlation function:

$C_2(q_1, q_2) = \frac{P(q_1, q_2)}{\mathcal{P}(q_1)\mathcal{P}(q_2)} = \frac{P(q_1, q_2)}{P(q_1, q_2)^{ref}}$ one gets:

$$C_2(q_1, q_2) = 1 + \frac{\int cos[\Delta \overrightarrow{q}(\overrightarrow{r_1} - \overrightarrow{r_2}) \left|\rho(\overrightarrow{r_1})\right|^2 \left|\rho(\overrightarrow{r_2})\right|^2}{\mathcal{P}(q_1)\mathcal{P}(q_2)}$$

From interferometry to particle Physics

Performing a Fourier transform:

$$C(Q) = 1 + |\widehat{\rho}(Q)|^2 \qquad ,\text{where } \widehat{\rho}(Q) = \int e^{-irQ} dr$$

Assuming Gaussian spread of the source: $\rho(r) = R_0 e^{-\frac{r^2}{2R^2}}$, we can simplify the correlation function:

$$C(Q) = 1 + e^{-R^2 Q^2}$$

This equation is then corrected for the source incoherence, by introducing an free parameter λ:

$$C(Q) = N(1 + \lambda e^{-R^2 Q^2}) \qquad (1)$$

Eq.(1) is so called Goldhaber parametrization and allows to measure the radius of the source.

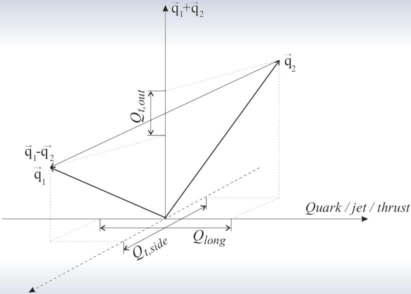
Reference samples

$\mathcal{P}(q_1, q_2)^{ref}$ can be estimated from reference samples:

1. MC without BEC.
   - Absence of Coulomb effects in generator.
   - Data-MC agreement.
2. Unlike-sign charge particles
   - Resonances contribution
   - Derived from data
3. Event-mixing
   - Mixing events.
   - PV mixing.

LCMS

- Longitudinal Centre-of-Mass System(LCMS) is defined as a system where sum of 3-momenta $\overrightarrow{q_1} + \overrightarrow{q_2}$ is perpendicular to a reference axis(jet, thrust, z).
- Q^2 can be written: $Q^2 = 1 + \lambda e^{-Q^2_{t,out}R^2_{t,out} - Q^2_{t,side}R^2_{t,side} - Q^2_{t,long}R^2_{t,long}} = 1 + \lambda e^{-Q^2_{t,\perp}R^2_{t,\perp} - Q^2_{t,\parallel}R^2_{t,\parallel}}$
- One can perform 1,2 or 3 dim analysis.



LEP and CMS results

LEP ***(pions):*** *1-dimensional analyses*

Hadron-hadron	Reference sample				Experiment
	Unlike		MC or event-mixed		
	R [fm]	λ	R [fm]	λ	
$\pi^{\pm}\pi^{\pm}$ (BEC)	0.82 ± 0.04	0.48 ± 0.03	0.52 ± 0.02	0.30 ± 0.01	ALEPH
	0.83 ± 0.03	0.31 ± 0.02	0.47 ± 0.03	0.24 ± 0.02	DELPHI
	–	–	0.46 ± 0.02	0.29 ± 0.03	L3
	0.96 ± 0.02	0.67 ± 0.03	0.79 ± 0.02	0.58 ± 0.01	OPAL
$\pi^0\pi^0$ (BEC)	–	–	0.31 ± 0.10	0.16 ± 0.09	L3
	–	–	0.59 ± 0.11	0.55 ± 0.15	OPAL

LEP ***(pions):*** *2- and 3- dimensional analyses*

$R_{t,out}$ [fm]	$R_{t,side}$ [fm]	$R_{\perp}$ [fm]	$R_{\parallel}$ [fm]	Experiment
–	–	0.47 ± 0.01	0.77 ± 0.01	ALEPH
–	–	0.79 ± 0.01	0.87 ± 0.02	ALEPH
–	–	$0.53 \pm 0.02 \pm 0.07$	$0.85 \pm 0.02 \pm 0.07$	DELPHI
$0.53 \pm 0.02^{+0.05}_{-0.06}$	$0.59 \pm 0.01^{+0.03}_{-0.13}$	–	$0.74 \pm 0.02^{+0.04}_{-0.03}$	L3
$0.65 \pm 0.01^{+0.02}_{-0.12}$	$0.81 \pm 0.01^{+0.02}_{-0.03}$	–	$0.99 \pm 0.01^{+0.03}_{-0.02}$	OPAL

LEP and CMS results

LEP: *1-dimensional analyses*

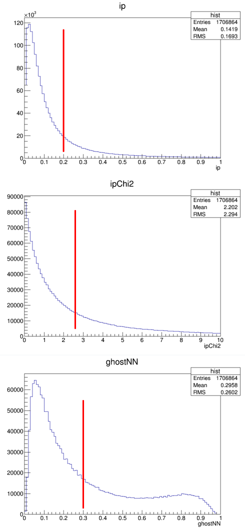
Hadron-hadron	R [fm]	λ	Experiment
$K^\pm K^\pm$ (BEC)	$0.48 \pm 0.04 \pm 0.07$	$0.82 \pm 0.11 \pm 0.25$	DELPHI [47]
	$0.56 \pm 0.08 \, ^{+0.07}_{-0.06}$	$0.82 \pm 0.22 \, ^{+0.17}_{-0.12}$	OPAL [48]
$K^0_S K^0_S$ (BEC)	$0.65 \pm 0.07 \pm 0.15$	$0.96 \pm 0.21 \pm 0.40$	ALEPH (MC ref.) [49]
	$0.57 \pm 0.04 \pm 0.14$	$0.63 \pm 0.06 \pm 0.14$	ALEPH (mix ref.) [50]
	$0.55 \pm 0.08 \pm 0.12$	$0.61 \pm 0.16 \pm 0.16$	DELPHI [47]
	$0.76 \pm 0.10 \pm 0.11$	$1.14 \pm 0.23 \pm 0.32$	OPAL [51]
$\bar{p}\bar{p}$ (FDC)	$0.11 \pm 0.01 \pm 0.01$	$0.49 \pm 0.04 \pm 0.08$	ALEPH [50]
	$0.142 \pm 0.035 \pm 0.047$	$0.76 \pm 0.16 \pm 0.29$	OPAL [52]
$\Lambda\Lambda$ (FDC)	$0.11 \pm 0.02 \pm 0.01$	–	ALEPH [53]
$\Lambda\Lambda$ (FDC)	$0.17 \pm 0.13 \pm 0.04$	–	ALEPH [53]
(spin analyses)	$0.11 \, ^{+0.05}_{-0.03} \pm 0.01$	–	DELPHI [54]
	$0.19 \, ^{+0.37}_{-0.07} \pm 0.02$	–	OPAL [55]

CMS (2010): *1-dimensional analysis, all charged particles, BEC*

Mult. range	p val. (%)	C	λ	r (fm)	δ (10^{-3} GeV^{-1})
2–9	97	0.90±0.01	0.89±0.05±0.20	1.00±0.07±0.05	72±12
10–14	38	0.97±0.01	0.64±0.04±0.09	1.28±0.08±0.09	18± 5
15–19	27	0.96±0.01	0.60±0.04±0.10	1.40±0.10±0.05	28± 5
20–29	24	0.99±0.01	0.59±0.05±0.17	1.98±0.14±0.45	13± 3
30–79	28	1.00±0.01	0.69±0.09±0.17	2.76±0.25±0.44	10± 3

Preselection

1. MiniBias Stripping lines.
2. 2011 data.
3. Stripping 20.
4. Select all particles that come from PV with cuts:
   - $TRKChi2 < 2.6$
   - $IP < 0.2mm$
   - $IPCHI2 < 2.6$
   - $PIDNN(\pi, K) > 0.25$
   - $ghostNN < 0.3$
   - $P > 0.2GeV$
   - $Pt > 0.1GeV$

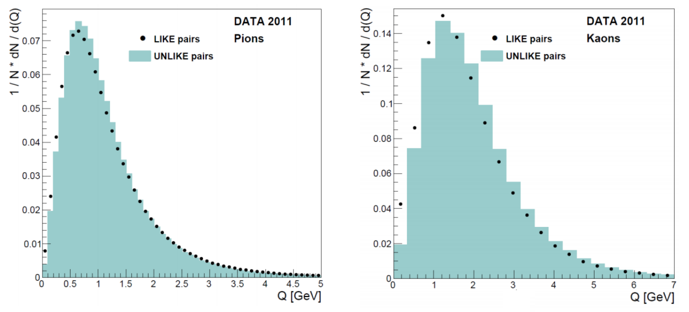


Selection

1. MiniBias Stripping lines.
2. 2011 data.
3. Select all particles that come from PV with cuts:
   - $TRKChi2 < 2.$
   - $IP < 0.1mm$
   - $IPCHI2 < 1.8$
   - $PIDNN(\pi) > 0.8$, $PIDNN(K) > 0.6$
   - $ghostNN < 0.2$
   - $P > 0.2GeV$
   - $Pt > 0.1GeV$

Results in 2011 data

Enhancement at low Q^2 region. We selected $\mathcal{O}(10^8)$ π pairs, and $\mathcal{O}(10^6)$ K pairs.

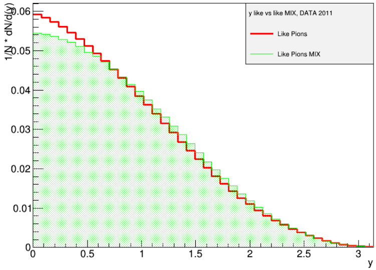


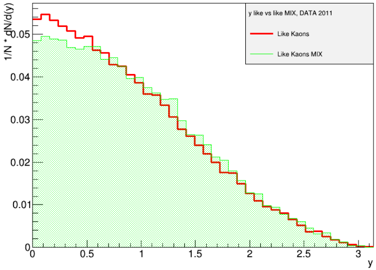
Results in 2011 data

We can rewrite Q in form:

$$Q = \sqrt{-2q_{\perp 1}q_{\perp 2}[cosh(y_1 - y_2) - cos(\phi_1 - \phi_2)]} \quad (2)$$

,where y_i are the pseudo-rapidity, ϕ_i are azimuthal angles. We see BEC



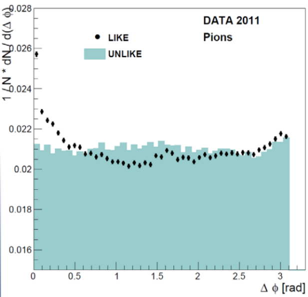


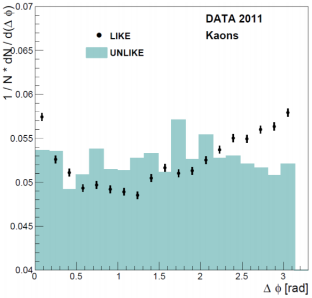
Results in 2011 data

We can rewrite Q in form:

$$Q = \sqrt{-2q_{\perp 1}q_{\perp 2}[cosh(y_1 - y_2) - cos(\phi_1 - \phi_2)]} \tag{3}$$

,where y_i are the pseudo-rapidity, ϕ_i are azimuthal angles. We see BEC





Generalization of two body correlations

Assuming no correlations in space the Wigner function can be expressed[1]

$$W(p_1, p_2, p_3, x_1, x_2, x_3) = \Omega_0(p_1, p_2, p_3) w(p_1, x_1) w(p_2, x_2) w(p_3, x_3) \quad (4)$$

This leads to correlation function:

$$C_3(p1, p2, p3) = |\widehat{w}(P_{12}, \Delta_{12})|^2 + |\widehat{w}(P_{23}, \Delta_{23})|^2 + |\widehat{w}(P_{31}, \Delta_{31})|^2 + 2\mathcal{R}[\widehat{w}(P_{12}, \Delta_{12})\widehat{w}(P_{23}, \Delta_{23})\widehat{w}(P_{31}, \Delta_{31})] \quad (5)$$

,where $\Delta_{ij} = p_i - p_j$, and $\widehat{w}(P_{ij}, \Delta_{ij}) = \int dx_i dx_j W(P_{ij}, x) e^{ix\Delta_{ij}}$

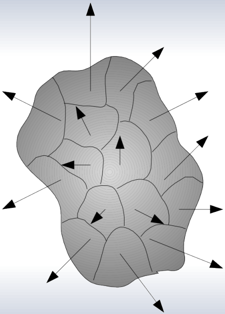
[1] Based on Prof. Bialas's talk at cern in July on soft QCD

Probing Cluster Model

Let us consider simple ansatz:

$$W(p_1, p_2, x_1, x_2) = \Omega_0(p_1, p_2)[V(x_1)V(x_2) + \alpha V_2(x_1, x_2)] \quad (6)$$

,where $V(x) = \int \phi(x - X)V_c(X)dX$,
$V_2 = \int V_c(X)\phi(x_1 - X)\phi(x_2 - X)dX$



Probing Cluster Model

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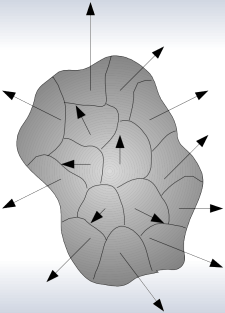
$$W(p_1, p_2, x_1, x_2) = \Omega_0(p_1, p_2)[V(x_1)V(x_2) + \alpha V_2(x_1, x_2)] \quad (6)$$



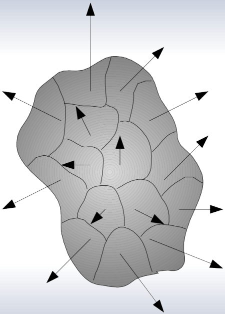
,where $V(x) = \int \phi(x - X)V_c(X)dX$,
$V_2 = \int V_c(X)\phi(x_1 - X)\phi(x_2 - X)dX$
$V_c(X)$ is the distribution of clusters in space.
$\phi(x - X)$ is the shape of the cluster.
$V(x_1)V(x_2)$ emission from two clusters.
$V_2(x_1, x_2)$ emission from single cluster.

Probing Cluster Model

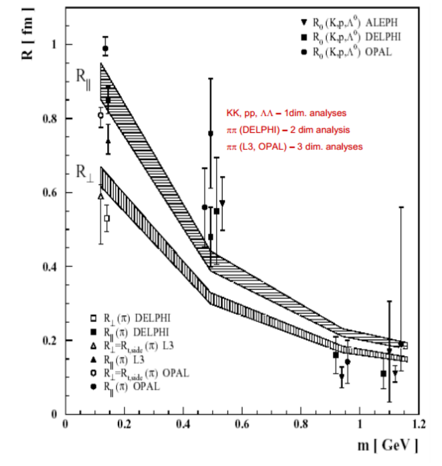
The correlation function for this ansatz takes form:

$$C(p_1, p_2) = |\widehat{V_c}(\Delta_{12})\widehat{\phi}(\Delta_{12})|^2 + \alpha|\widehat{\phi}(\Delta_{12})|^2 \quad (7)$$

where $\widehat{\phi}(\Delta_{12}) = \int dx \phi(x) e^{ix\Delta_{12}}$



Dependence R on hadron mass



1. Bialas, Zalewski, Phys.Rev. D62 (2000) 114007
2. LHCb can access much higher masses than LEP.
3. Measurement of BEC in charm sector.

Conclusions

- Theoretical support from Krakow theorists: prof. Bialas, prof. Zalewski.
- BEC clearly visible in data.
- Analysis systematically dominated.
- Enough events to perform first measurement of 3 body correlations.
- BEC measurements in charm sector.