BOSE-EINSTEIN CORRELATIONS IN PP COLLISIONS AT 13 TEV

MÁTÉ CSANÁD (EÖTVÖS U) FOR THE CMS COLLABORATION

ZIMÁNYI SCHOOL WINTER WORKSHOP 2019
THE CMS DETECTOR

3.8T Solenoid

Forward Hadron Calorimeter (HF)

Hadron Calorimeter (HCAL)

EM Calorimeter (ECAL)

TRACKER (Pixels and Strips)

Muon System

Iron Yoke

CMS detector

\[ \eta = - \ln \left( \tan \left( \frac{\theta}{2} \right) \right) \]

x (LHC center)

y

z

\[ \theta \]

\[ \phi \]
SPACE-TIME STRUCTURE OF A COLLISION

- $5 \cdot 10^{12}$ Kelvin, strongly interacting Quark Gluon Plasma (sQGP) is created
- Expands and cools down, forms a hadron gas in $10^{-22}$ s
- We observe the “frozen” particles: hadrons
- How to access space-time geometry when only momenta are measured?
A SURPRISING DISCOVERY: HBT-CORRELATIONS

• Radio astronomy: Jansky, 1933, weird 24 hour oscillation; stars emit radio frequency waves as well

• R. H. Brown: radio astronomy measurements at Jordell bank

• Strange correlations observed: diameter of a star can be measured

• R. Q. Twiss helps to work out the details
  
HBT IN PARTICLE PHYSICS: FEMTOSCOPY

- Goldhaber, Goldhaber, Lee & Pais: pion pairs in $p+\bar{p}$ collisions, HBT-effect

- Departure from conventional statistics:
  Bose-Einstein statistics

- Understanding: Glauber, Fano, Baym, …
  Phys. Rev. Lett. 10, 84; Rev. Mod. Phys. 78 1267, …

- Birth of femtoscopy: reconstructing femtometer sources
  - Momentum correlation $C(q)$ related to source $S(r)$
    \[ C(q) \approx 1 + \left| \int S(r)e^{iqr}dr \right|^2 \] (under some assumptions)
  - Or the distance distribution $D(r)$:
    \[ C(q) \approx 1 + \int D(r)e^{iqr}dr \]

- Measure $C(q)$: map out source space-time geometry on femtometer scale!
EVENT&TRACK SELECTION, CORRELATIONS

- Event selection to reduce beam background & diffractive events
  - At least 1 reconstructed Primary Vertex: $|V_z| < 15 \text{ cm}$, $|V_r| < 0.15 \text{ cm}$ (vertex distance to beam)
  - At least one tower with $E > 3 \text{ GeV}$ in both HadronForward calorimenter

- Track selection:
  - HighPurity tracks only, $p_T > 0.2 \text{ GeV}$, $|\eta| < 2.4$
  - $|\sigma_{p_T}/p_T| < 0.1$, $|dz/\sigma_{dz}| < 3$, $|d_{xy}/\sigma_{dxy}| < 3$ (d: distance to PrimaryVertex)
  - At least one pixel layer

$N_{\text{track offline}}$ definition: same except $p_T > 0.4 \text{ GeV}$ and no pixelLayer cut

- Pair distribution as a function of $q_{\text{inv}} = \sqrt{-\left(p_1 - p_2\right)^2}$

- In several intervals of $N_{\text{track offline}}$ and $k_T = |p_{1T} + p_{2T}|/2$

- Non-femtoscopic background removed with different methods (see next slides)

- Correlation function fitted with $C(q) = N\left(1 + \lambda e^{-q_{\text{inv}}R_{\text{inv}}}\right)\left(1 + q_{\text{inv}}\epsilon\right)$
PAIR DISTRIBUTION, CORRELATION FUNCTION

• Theoretical definition of Bose-Einstein (femtoscopic) correlation function:

$$C_2(q, K) = \frac{N_2(p_1, p_2)}{N_1(p_1)N_1(p_2)}, \text{where } q = p_1 - p_2 \text{ and } K = \frac{1}{2}(p_1 - p_2)$$

• If assuming Cauchy source, then correlation function: $C_2 = 1 + \lambda e^{-q_{\text{inv}}R_{\text{inv}}}$

• How to realize in experiment? Creating non-femtoscopic background
  • Opposite charge sample (c.f. resonances, Coulomb interaction)
  • Rotation or opposite hemisphere (c.f. residual same-event effects)
  • Event mixing!

• Femtoscopic correlation function: signal / background (Single Ratio, SR)

$$C_2(q, K) = \frac{A(q, K)}{B(q, K)}, \text{where } A(q, K): \text{same event pairs, } B(q, K): \text{mixed event pairs}$$

• Background pair distribution $B(q, K)$ removes some non-femtoscopic effects
  • Single particle momentum distribution, tracking, efficiency, acceptance, …
  • How to remove these?
**SINGLE RATIOS AND NON-FEMTOSCOPOIC BKG**

- Single Ratio $C_2(q, K)$ still contains non-femtososcopic effects
  - Final-state effects (Coulomb, strong interaction): handled by corrections
  - Pair reconstruction: handled by cuts in $q$-space
  - Residual correlations due to minijets, clusters, mom. conservation: long range background
  - High-multiplicity collisions: dominant contribution is femtoscopy (scales with multiplicity^2)

- In pp, cluster contribution important, estimation via $(+, -)$ pairs or MC

![Graphs showing data and MC comparisons with fits and significance values.](image-url)
ANALYSIS METHODS: DOUBLE RATIO

• How to remove residual non-femtoscopic background?
  • Due to minijets, momentum conservation, pair acceptance, ...

• Double Ratio (DR) method
  PRC 97 (2018) 064912 [CMS]
  PRL 105 (2010), JHEP 05 (2011) [CMS]

• Single Ratio (SR) from event mixing
  • Both in Data and MonteCarlo

• Data over MonteCarlo: removes non-femtoscopic effects

• Fit Double Ratio with femtoscopic fit function

• Significant dependence on MonteCarlo choice

(arXiv:1910.08815)
ANALYSIS METHOD: CLUSTER SUBTRACTION

- Remove MonteCarlo dependence: estimate non-femtoscopic effects based on data

- **Cluster Subtraction (CS) method**
  PRC 97 (2018) 064912 [CMS]

- Non-femtoscopic clusters: shape estimated via $(+, -)$ pairs

- Cluster strength directly estimated in $(\pm, \pm)$ data

- Fit SR with functional form combining signal+cluster component: exponential (BEC) $\times$ Gauss (non-BEC)

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Mate Csanad, Zimányi 2019

arXiv:1910.08815
ANALYSIS METHOD: HYBRID CLUSTER SUBSTR.

- A further possibility: estimate non-BEC clusters via MonteCarlo

- **Hybrid Cluster Subtraction (HCS) method**
  PRC 96 (2017) 064908 [ATLAS]

- Non-BEC clusters fitted in data and MC, for both $(\pm, \pm)$ and $(+, -)$

- Determine $(\pm, \pm)$ to $(+, -)$ relation in MonteCarlo (Pythia 6 – Z2*)

- Use this to convert $(\pm, \pm)$ to $(+, -)$ in data

- Fit SR with functional form combining BEC+cluster components

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*arXiv:1910.08815*
SHAPE ANALYSIS: ANTICORRELATION/DIP

- Small region of anticorrelation (aka „dip”) at intermediate q
  - Fitted with slope times exponential: statistically not acceptable description
  - Fitted with form based on $\tau$-model [Csörgő, Zimányi NPA 517 (1990) 588]
- Dip depth ($\Delta$) analyzed as a function of multiplicity & transverse momentum
  - Maybe related to DoubleRatio method itself, maybe intrinsic property?
RESULTS: METHOD DEPENDENCE

- Recall three methods:
  - Double Ratio
  - Cluster Substraction
  - Hybrid Cluster Substr.

- Fit parameters:
  - HBT radius $R_{\text{inv}}$
  - Correlation strength $\lambda$

- As a function of:
  - Multiplicity $\langle N_{\text{tracks}} \rangle$
  - Transverse mom $\langle k_T \rangle$

- Methods yield compatible results
RESULTS: MULTIPLICITY DEPENDENCE

- Results compatible with 7 TeV (ATLAS also), much higher multiplicities avail.

- $R_{\text{inv}}$ increasing with multiplicity: geometrical understanding of HBT radius
  - $N_{\text{tracks}}^{1/3}$: final state size; $R_{\text{inv}}$: length of homogeneity; two related in hydro (especially $R_{\text{long}}$)

- CGC predicts specific dependence, qualitatively confirmed
  
  Campanini et al., PLB 703 (2011) 237; McLerran et al., NPA 916 (2013) 210; A. Bzdak, et al. PRC 87 (2013) 064906

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![Graphs showing $R_{\text{inv}}$ vs. $\langle N_{\text{tracks}} \rangle$ and $\langle N_{\text{tracks}} \rangle^{1/3}$](image.png)
RESULTS: TRANSVERSE MOMENTUM DEPENDENCE

- Universally observed $R^{-2} \sim a + b \cdot m_T$ dependence, based on Hubble flow
  - Transverse flow, also temperature gradient
- Simple estimate of Hubble-coefficient (if $T_{\text{freeze-out}} = 150$ MeV assumed)
  - $H_{\text{HighMultiplicity}} = 0.17 \pm 0.04 \, c/\text{fm}$, $H_{\text{MinimumBias}} = 0.298 \pm 0.004 \, c/\text{fm}$
  - Similar to results in heavy ion collisions (also multiplicity dependence of slope)
SUMMARY

- BEC measured in pp collisions at 13 TeV
  - First investigation with both Minimum Bias and High Multiplicity
- Three different techniques employed:
  - Double Ratios with MC (as in earlier CMS BEC)
  - Fully data-driven Cluster Subtraction (as in earlier CMS BEC)
  - Hybrid Cluster Subtraction (as in ATLAS BEC)
- 1-D BEC (exponential fit): $R_{\text{inv}}$ (and $\lambda$)
  - As a function of multiplicity and momentum
  - Slope change, saturation with $N_{\text{tracks}} \rightarrow$ compatible with data
  - Continuous growth with $(N_{\text{tracks}})^{1/3} \rightarrow$ compatible with data
  - $m_T$ scaling works: Hubble-flow stronger in MB than in HM
- Complete results:
  - CMS-PAS-FSQ-15-009
  - arXiv:1910.08815
THANK YOU FOR YOUR ATTENTION

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BACKUP
RESULTS AT CMS

- Analysis performed at 0.9-13 TeV, Pb+Pb, p+Pb, p+p
- Using $\alpha = 1$ fixed
- 3D analysis for 0.9-7 TeV
  - Analysis: Wigner (F. Siklér)
  - Detailed geometry exploration
  - Elongated source: p+p and p+Pb
- High multiplicity 13 TeV p+p: similar results as ion-ion
  - Geometric multiplicity scaling
  - Hydro type of mT scaling?
  - Analysis: USP+ELTE
**INTERACTIONS: THE COULOMB-EFFECT**

- Plane-wave result, based on \( \left| \Psi_2^{(0)}(r) \right|^2 = 1 + e^{iqr} \):
  
  \[
  C_2(q, K) \equiv \int D(r, K) \left| \Psi_2^{(0)}(r) \right|^2 dr = 1 + \int D(r, K)e^{iqr} dr
  \]

- If there is interaction:
  \( \Psi_2^{(0)}(r) \to \Psi_2^{(\text{int})}(r_1, r_2) \)

- For Coulomb:
  \[
  \left| \Psi_2^{(C)}(r) \right|^2 = \frac{2\pi\zeta}{e^{2\pi\zeta} - 1} \cdot \text{(complicated hypergeometric expression)}
  \]

- Direct fit with this, or the usual iterative Coulomb-correction:
  \[
  C_{\text{Bose–Einstein}}(q)K(q), \text{ where } K(q) = \frac{\int D(r,K)\left| \Psi_2^{(C)}(r) \right|^2 dr}{\int D(r,K)\left| \Psi_2^{(0)}(r) \right|^2 dr}
  \]

- In this analysis: assuming point-like (Dirac-delta) source
  \[
  K(q) = \frac{2\pi\zeta}{(\exp(2\pi\zeta) - 1)}, \quad \zeta = m\alpha_{\text{QED}}/q
  \]
THE HBT CORRELATION

• Observation of Hanbury Brown & Twiss: at small detector distances, large correlation between the two detectors

• Joint intensity „too frequent”: \( I(A, B) > I(A)I(B) = 1 + \text{correlation} \)

• What is the reason for it? Interference?

• „Interference between different photons never occurs” P.A. M. Dirac, Quantum Mechanics

• Why does the correlation reduce with distance?

\[ \text{Correlation strength} \approx 1/R \]
HBT IN HEAVY ION AND PARTICLE PHYSICS

- Goldhaber, Goldhaber, Lee & Pais: pion pairs in p+\( \bar{p} \) collisions
  

- Departure from conventional statistics: Bose-Einstein statistics
  
  • \( N \) pion final states: symmetrized wave functions needed

- Understanding: Glauber, Fano, Baym, …
  
  Phys. Rev. Lett. 10, 84; Rev. Mod. Phys. 78 1267, …

- Wavefunction:

  1-particle: \( \Psi_a (r), \Psi_b (r) \) plane/spherical wave

  2-particle: \( \Psi_{A,B} = \Psi (R_A, R_B) = \frac{1}{\sqrt{2}} (\Psi_a (R_A) \Psi_b (R_B) + \Psi_a (R_B) \Psi_b (R_A)) \)

- Two-particle probability: \( \left< |\Psi_{A,B}|^2 \right> \sim 1 + \cos \frac{kRd}{L} = 1 + \cos R\Delta k \)

- Correlation function: \( C_{AB} - 1 = \left< |\Psi_{A,B}|^2 \right> - 1 = \cos R\Delta k \)
HBT EFFECT FOR EXTENDED SOURCES

• What happens for an $S(r)$ source distribution?

• Similarly to the previous description:

\[
\Psi(r) = e^{ikr}, \Psi_2(r_1, r_2) = \frac{1}{\sqrt{2}} \left( e^{ik_1 r_1} e^{ik_2 r_2} + e^{ik_1 r_2} e^{ik_2 r_1} \right)
\]

\[
N_1(k) = \int S(r, k)|\Psi(r)|^2 d^4r
\]

\[
N_2(k_1, k_2) = \int S(r_1, k_1)S(r_2, k_2)|\Psi_2(r_1, r_2)|^2 d^4r_1 d^4r_2
\]

\[
C_2(k_1, k_2) = \frac{N_2(k_1, k_2)}{N_1(k_1)N_1(k_2)} \approx 1 + \left| \frac{\tilde{S}(q, K)}{\tilde{S}(0, K)} \right|^2
\]

where $q = k_1 - k_2, K = (k_1 + k_2)/2$

• Simply $C(q) = 1 + \left| \tilde{S}(q) \right|^2$, where $\tilde{S}(q) = \int S(r)e^{iqr}$

• Invertable (sort of), $S(r)$ can be reconstructed from $C(q)$

• Approximations: no interaction, no multiparticle correlation, thermal emission …
SOURCE OR PAIR DISTRIBUTION?

- Under some circumstances (thermal emission, no interactions, ...):

\[
C_2(q, K) = \int S\left(r_1, K + \frac{q}{2}\right) S\left(r_2, K - \frac{q}{2}\right) |\Psi_2(r_1, r_2)|^2 dr_1 dr_2 \
\approx 1 + \left| \int S(r, K) e^{iqr} dr \right|^2
\]

- Let us introduce the spatial pair distribution:

\[
D(r, K) = \int S\left(\rho + \frac{r}{2}, K\right) S\left(\rho - \frac{r}{2}, K\right) d\rho
\]

- Then the Bose-Einstein correlation function becomes:

\[
C_2(q, K) \approx \int D(r, K) |\Psi_2(r)|^2 dr = 1 + \int D(r, K) e^{iqr} dr
\]

- Bose-Einstein correlations measure spatial pair distributions!