Results of femtoscopic correlations at CMS

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Introduction and motivation

- Femtoscopy: particle correlations at low-\(q\)
  \[ q^2 = q_{\text{inv}}^2 = -(p_1 - p_2)^2 \]

- Powerful tool to probe space-time dimensions of the particle emitting source

- Sensitive to
  - quantum statistics
  - final-state interactions
  - backgrounds

- In this talk, charged hadron (\(h^\pm\)) correlations
  - pp collisions at 13 TeV: measurements of multiplicity and pair transverse momentum dependence
  - PbPb collisions at 5.02 TeV: study of correlation function shape
Femtoscopic correlation function

Theoretically

\[ C(q) = \frac{P_2(p_1, p_2)}{P_1(p_1)P_1(p_2)} \]

\[ C(q) \sim 1 \pm \lambda |F[\tilde{\rho}(q)]|^2 \]

\[ C(q) = N(1 \pm \lambda e^{-|qR|^\alpha}) \]

Experimentally

- single ratio (SR)

\[ C(q) = \frac{A(q)}{B(q)} \]

One-dimensional fit to correlation function for charged hadrons (Lévy-type)

\[ C(q) = N\{1 - \lambda + \lambda K_C(q; R, \alpha)[1 + \lambda e^{-|qR|^\alpha}]\}\Omega(q) \]

- Coulomb correction
- Quantum Statistics
- Background (bkg)
Fitting the correlation function

\[ C(q) = N \{ 1 - \lambda + \lambda K_C(q; R, \alpha) \left[ 1 + \lambda e^{-|q_R|^\alpha} \right] \} \Omega(q) \]

One-dimensional fit to correlation function for charged hadrons (Lévy-type)
**Background estimate**

- **Double Ratios**
  - Ratio of SR
  - \( DR = \frac{SR_{\text{DATA}}}{SR_{\text{MC}}} \)
  - Strong MC dependence

- **Cluster Subtraction**
  - Fully data-driven
  - Bkg estimated from fit of \((+ -)\) SR
  - Translate \((+ -)\) to \((\pm \pm)\) SR estimating an amplitude factor

- **Hybrid Cluster Subtraction**
  - Fit SR from MC for both \((+ -)\) and \((\pm \pm)\) bkg
  - Find a conversion function (parameters)
  - Fit \((+ -)\) in data and use the conversion to \((\pm \pm)\) SR

- **CMS PAS HIN-21-011** → New method!
  - Similar to double ratios
    
  \[
  DR(q) = \frac{SR(q)}{BG(q)}
  \]

  \( BG(q) = N(1 + \alpha_1 e^{-(qR_1)^2})(1 - \alpha_2 e^{-(qR_2)^2}) \)
Experimental results
pp collisions at 13 TeV
Similar behavior for all the methods

- in agreement for $R_{\text{inv}}$ (or $R$)
  - $R_{\text{inv}}$ increases with $N_{\text{tracks}}$
- $\lambda$ shows small dependence with $N_{\text{tracks}}$
  - except the first bin
- deviations in $\lambda$ using CS method
  - less constrained by the fit
- $R_{\text{inv}}$ and $\lambda$ decrease with $k_T$
  - source expansion in pp collisions?
Comparison with CMS and ATLAS results at 7 TeV

ATLAS: EPJC 75 (2015) 466

CMS at 13 TeV: JHEP 03 (2020) 014

Good agreement with previous measurements!
Comparison with Color Glass Condensate (CGC) predictions

- CGC calculation for pp at 7 TeV
  - without system evolution
    - L. McLerran et al.
      - *NPA* 916 (2013) 210
    - A. Bzdak et al.
      - *PRC* 87 (2013) 064906

- Similar shape, but large difference in magnitude
  - hydrodynamic evolution?
  - cold nuclear matter effects?
  - need more phenomenological studies!

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Comparison with Color Glass Condensate (CGC) prediction

\[
R_{\text{inv}} [\text{fm}] = \left( \frac{\langle dN_{\text{tracks}} / d\eta \rangle}{1/3} \right)^{1/3}
\]

- CMS
- pp (13 TeV)

- HCS method, \( x \equiv (dN_{\text{tracks}} / d\eta)^{1/3} \)
  - Syst.: HCS
  - Intramethod variation
  - Linear fit + constant
  - \( R_{pp}(x) \) CGC, pp @ 7 TeV

- CMS
- *JHEP* 03 (2020) 014

- CMS
- *PRC* 87 (2013) 064906
- *NPA* 916 (2013) 210
$1/R_{inv}^2$ vs $m_T = \sqrt{m_{T}^2 + k_{T}^2}$

- From hydrodynamics ([NPA 946 (2016) 227])
  - intercept: reflects the source geometrical size (at freeze-out)
  - slope: reflects the flow component
    - larger slope (larger flow) $\rightarrow$ lower multiplicities (similar to peripheral AA collisions)
    - smaller slope (lower flow) $\rightarrow$ higher multiplicities (similar to more central AA collisions)
  - similar behavior for multiplicity > 40

For more details see Sandra Padula [poster](April 6th at Section 1 – T07_1)
PbPb collisions at 5.02 TeV
Dependence of Lévy stability index $\alpha$ in $m_T$ and multiplicity

First measurement of $\alpha$ at LHC energies
Does not strongly depend on $m_T$
Between 1.6 and 2.0 from semi-peripheral to central collisions
Centrality dependence not modeled so far $\rightarrow$ challenge for phenomenology
Shape is important in femtoscopic measurements!

For more details see Balázs Kórodi poster (April 6th at Section 1 – T07_1)
Centrality and $m_T$ dependence

- Similar behavior as observed in pp collisions
  - $\lambda$ decreases with $m_T(k_T)$
  - small centrality dependence
  - $R_{inv}$ (or $R$) increases with centrality and decreases with $m_T$
Centrality and $m_T$ dependence

- Similar behavior as observed in pp collisions
  - $\lambda$ decreases with $m_T(k_T)$
  - small centrality dependence
  - $R_{\text{inv}}$ (or $R$) increases with centrality and decreases with $m_T$
  - $1/R_{\text{inv}}^2$ vs $m_T$: shows linear scaling
  - $1/R_{\text{inv}}^2 = A m_T + B$
  - hydrodynamic prediction
    - working also for Lévy sources
Summary and outlook

- In general, the results show
  - $R_{\text{inv}}$ with $N_{\text{trk}}$/centrality and $\lambda$ with $k_T$
  - $\lambda$ with $N_{\text{trk}}$ and $k_T$ ($m_T$)

- First measurement using MB and HM pp collisions at 13 TeV
  - different background methods studied
  - consistent with previous measurements at 7 TeV
  - qualitative comparison CGC and hydro models

- First measurement of $\alpha$ dependency (centrality and $m_T$) at LHC energies
  - non-Gaussian behavior observed
    - centrality dependent
  - $R_{\text{inv}}$ results show hydro scaling for Lévy sources

-Measurement of correlations with $V^0$'s coming soon
Thank You

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Backup
CMS detector

CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm): ~16m² ~66M channels
- Microstrips (80x180 μm): ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000 A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
- Silicon strips: ~16m² ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres: ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator: ~7,000 channels
Quantum statistics effect

\[ \alpha = 2 \]

\[ C(q) = 1 + \beta e^{-|qR|^\alpha} \]

\[ \beta = 1 \text{ for identical bosons, } -\frac{1}{2} \text{ for identical fermions and } 0 \text{ for non-identical} \]
Coulomb final-state interactions

\[ C(q) = N\{1 - \lambda + \lambda K_C(q; R, \alpha)[1 + \lambda e^{-|qR|^\alpha}]\}\Omega(q) \]

For Gaussian (hypergeometric) and Gamov: see [PRC 80 (2009) 034907]
For Cauchy-Lorentz (alpha = 1), see: [PRC 97 (2018) 064912]
For Lévy-type source (alpha dependency): see [PPN 51 (2020) 238]
Different background subtraction methods
Double ratios

- Ratio of single ratios

\[
DR(q_{\text{inv}}) \equiv C_{2,\text{BE}}(q_{\text{inv}}) = \frac{SR(q_{\text{inv}})}{SR(q_{\text{inv}})_{\text{MC}}} = \frac{\left[ \left( \frac{N_{\text{ref}}}{N_{\text{sig}}} \right) \left( \frac{dN_{\text{sig}}/dq_{\text{inv}}}{dN_{\text{ref}}/dq_{\text{inv}}} \right) \right]}{\left[ \left( \frac{N_{\text{ref}}}{N_{\text{sig}}} \right)_{\text{MC}} \left( \frac{dN_{\text{MC}}/dq_{\text{inv}}}{dN_{\text{MC, ref}}/dq_{\text{inv}}} \right) \right]}
\]

- need MC simulations without femtoscopic signal
  - ideally should remove all background
  - strong MC dependence
Fully data-driven technique

- effect of resonances: decreases with increasing multiplicity
- modulation of bkg effect from \( h^\pm \) SR in data

\[
C_2^{(+)}(q_{\text{inv}}) = c \left[ 1 + \frac{b}{\sigma_b \sqrt{2\pi}} \exp \left( -\frac{q_{\text{inv}}^2}{2\sigma_b^2} \right) \right] \left(1 + \epsilon q_{\text{inv}} \right)
\]

- \( b \) and \( \sigma_b \) can be parametrized as
  - \( b \rightarrow \) bkg amplitude:
    \[
b(N_{\text{trk}}^{\text{ offline}}, k_T) = \frac{b_0}{(N_{\text{trk}}^{\text{ offline}})^{n_b}} \exp \left( \frac{k_T}{k_0} \right)
\]
  - \( \sigma_b \rightarrow \) cluster width:
    \[
    \sigma_b(N_{\text{trk}}^{\text{ offline}}, k_T) = \left[ \sigma_0 + \sigma_1 \exp \left( -\frac{N_{\text{trk}}^{\text{ offline}}}{N_0} \right) \right] k_T^{n_T}
    \]

https://cds.cern.ch/record/2318575

JHEP 03 (2020) 014
Cluster Subtraction (CS) method – II

- Modulation of background effect in charged hadron correlations:
  - also present in \( h^\pm \) pairs, with similar shape but a smaller amplitude
  - use the form of the contribution obtained from \( h^\pm \) pairs: \( b \) and \( \sigma_b \) fixed
  - assume the width is the same and determine the (\( \pm \pm \)) bkg amplitude \( z(N_{\text{trk}}) \)

\[
C_2^{(++,---)}(q_{\text{inv}}) = c \left[ 1 + z(N_{\text{trk}}^\text{offline}, k_T) \frac{b}{\sigma_b \sqrt{2\pi}} \exp \left( -\frac{q_{\text{inv}}^2}{2\sigma_b^2} \right) \right] C_{BE}(q_{\text{inv}})
\]

\[
z(N_{\text{trk}}) = \left( \frac{aN_{\text{trk}}^\text{offline} + b}{1 + N_{\text{trk}}^\text{offline} + b} \right)
\]

\[
C_{BE}(q_{\text{inv}}) = [1 + \lambda \exp(-q_{\text{inv}} R_{\text{inv}})]
\]
Hybrid Cluster Subtraction (HCS) Method – I

- Technique first used by ATLAS ([PRC 96 (2017) 064908]) in pPb collisions at 5.02 TeV
- Fitting ($\pm\pm$) and (+ –) SR in MC
  - in Monte Carlo: no femtoscopic effects $\rightarrow$ bkg can be modeled by fitting parameters
  - in data: Bose-Einstein correlations not present in (+ –) component – Bkg only
    - use the relations from MC to estimate the bkg component in ($\pm\pm$) SR

- Fit Functions
  \[
  \Omega(q_{inv}) = N \left( 1 + B \exp \left[ - \left| \frac{q_{inv}}{\sigma_B} \right|^{\alpha_B} \right] \right)
  \]
  - Parameters relation ($\alpha_B = 2$)
  \[
  \left[ (\sigma_B)^{-1} \right]^{\pm\pm} = \rho \left[ (\sigma_B)^{-1} \right]^{+-} + \beta \\
  B^{\pm\pm} = \mu(k_T) \left[ B^{+-} \right]^{\nu(k_T)}
  \]
Hybrid Cluster Subtraction (HCS) Method – II

Relation $\left[ (\sigma_B)^{-1} \right]^{\pm\pm} \text{ vs. } \left[ (\sigma_B)^{-1} \right]^{+-}$

$$\rho = 0.82 \pm 0.04 \text{ (stat.); } \beta = 0.077 \pm 0.013 \text{ (stat.)}$$

Relation $(B)^{\pm\pm} \text{ vs. } (B)^{+-}$

$$B^{(++,--)} = \mu(k_T) [B^{+-}]^{\nu(k_T)}$$
After getting relations from Monte Carlo

- bkg in data is estimated in (+ −) SR
- assume relation of (+ −) SR and (±±) in data is the same as in MC
- use conversion function to estimate bkg in (±±) SR in data
- fit with:

\[ C(q_{\text{inv}}) = \Omega(q_{\text{inv}}) \times C_{\text{BEC}}(q_{\text{inv}}) \]
Previous measurements
Charged hadrons
First femtoscopic measurement at LHC – pp collisions

- Performed in pp at 0.9 and 2.36 TeV
- Double ratio technique applied
- Coulomb corrected using Gamov
- Exponential fit shows a better agreement with data
  - Observed in higher energies
  - $R_{\text{Gauss}} \approx \sqrt{\pi} R_{\text{Expo}}$

PRL 105 (2010) 032001
Comparison with CMS and ATLAS results at 7 and 13 TeV

Good agreement with previous results!

Differences observed when compared with ATLAS results at 13 TeV
Identified particles
Particle identification

CMS pPb, $\sqrt{s_{NN}} = 5.02$ TeV

$\ln(\varepsilon/[\text{MeV/cm}])$

$p$ [GeV]

$> 99.5\%$ purity

PRC 97 (2018) 064912
Charged pions and kaons in pp, pPb and PbPb

Assuming a Cauchy source function (α = 1)
Cluster subtraction method used for background determination
Coulomb correction for α = 1 applied

PRC 97 (2018) 064912