Measurements of Femtoscopic Correlations in CMS

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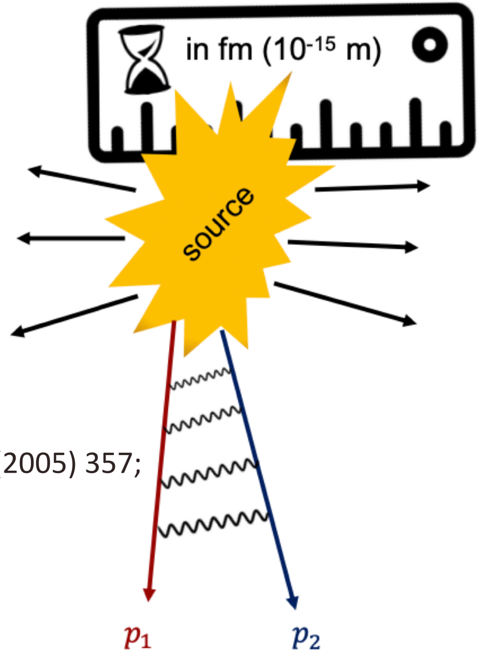
Femtoscopic hadronic correlations



Access

- Space-time dimensions of the particle emitting source
- Hadron-hadron final state interactions

Sensitive to contributions from

- Quantum statistical effects
  - Bose-Einstein or Fermi-Dirac
- Final state interactions (FSI)
  - Strong
  - Coulomb, …

Ann. Rev. of Nucl. and Part. Phys. **55** (2005) 357;
Phys. of Atom. Nucl. **67** (2004) 72,
Sov. J. Nucl. Phys. 35 (1982) 770.

In this talk: correlations of particles produced in PbPb @ 5.02 TeV

- Identified V^0 particles ($K_S^0K_S^0$, $\Lambda K_S^0 \oplus \bar{\Lambda} K_S^0$, $\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$)
- Unidentified charged hadrons ($\pi^+\pi^+ \oplus \pi^-\pi^-$ assumed)
  - Compared to results on pp collisions at 13 TeV (Minimum Bias and High Multiplicity events)

How to access femtoscopic correlations

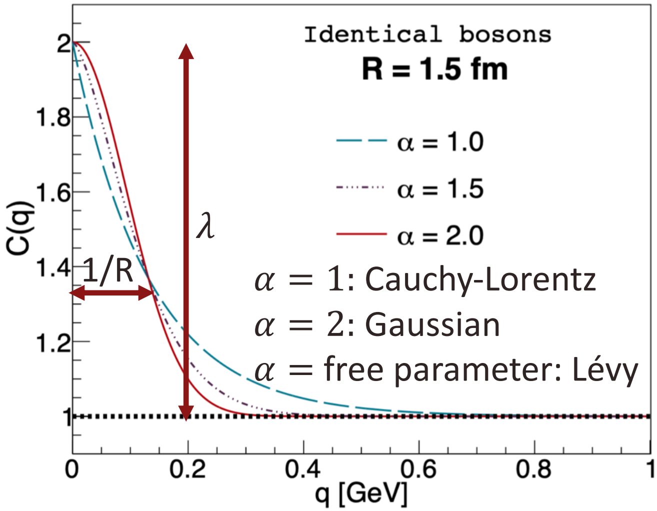
Identical two-particle correlations at low-q

- $q^2 = q_{\text{inv}}^2 = -(p_1 - p_2)^2$

Theoretically

- Fourier transform of the particle source shape
  - $\mathrm{C(q)} \sim 1 \pm \lambda |\mathrm{F}[\tilde{\rho}(q)]|^2 \rightarrow$
  - $C(q) = N\{1 - \lambda + \lambda K_C(q; R, \alpha)[1 + \lambda e^{-|qR|^\alpha}]\}\,\Omega(q)$

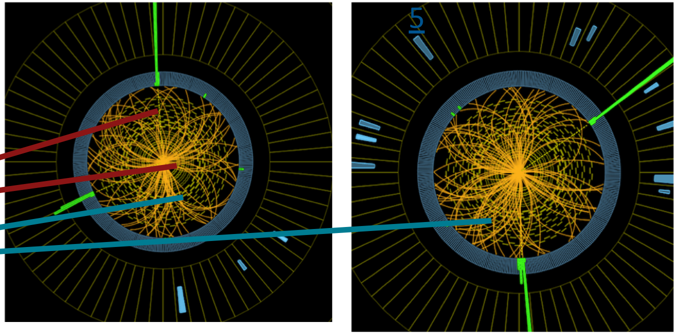
Coulomb correction (Bowler-Sinyukov method) QS fit function non-femtoscopic background



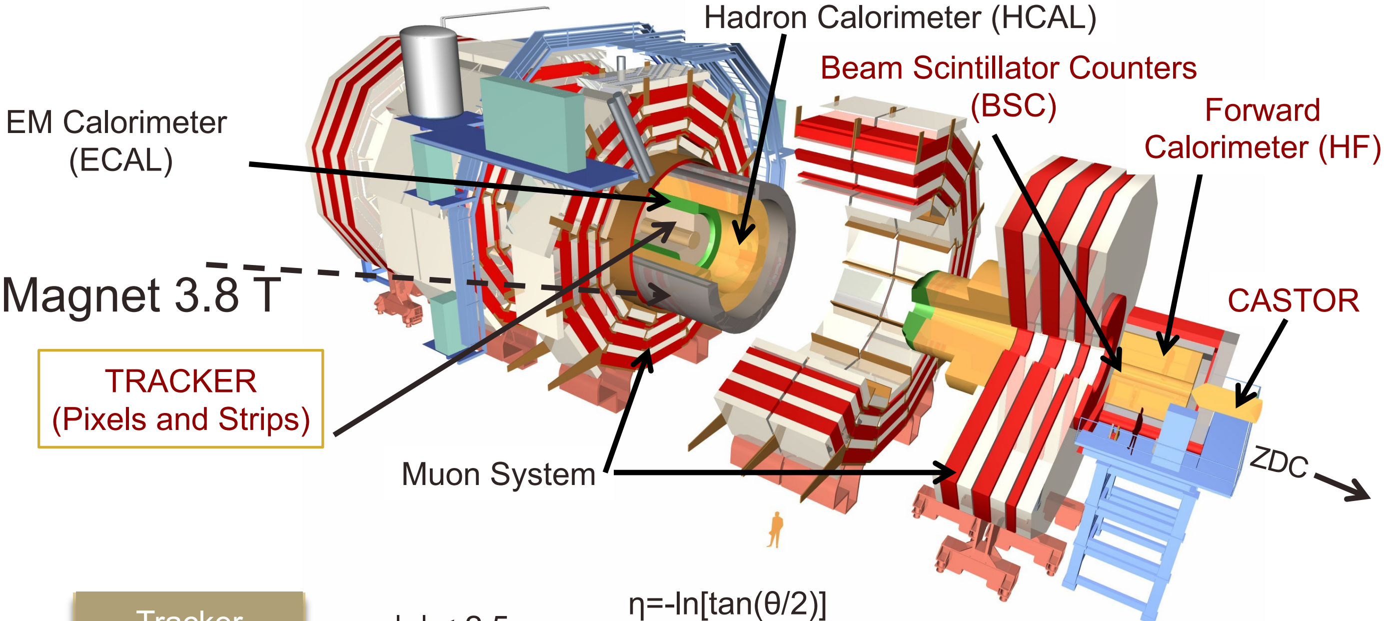
cds.cern.ch/record/273613

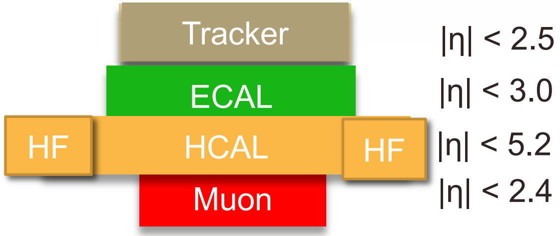
Experimentally

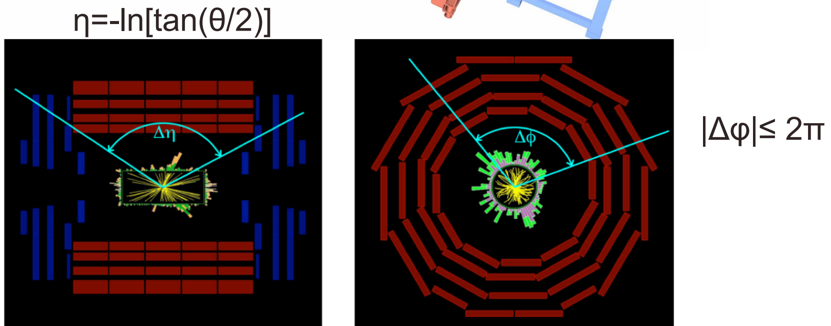
- Single Ratio (SR): $C(q) = \mathrm{N}\,\frac{S(k_1, k_2)}{B(k_1, k_2)}$



CMS Detector







Strange Hadrons Correlations

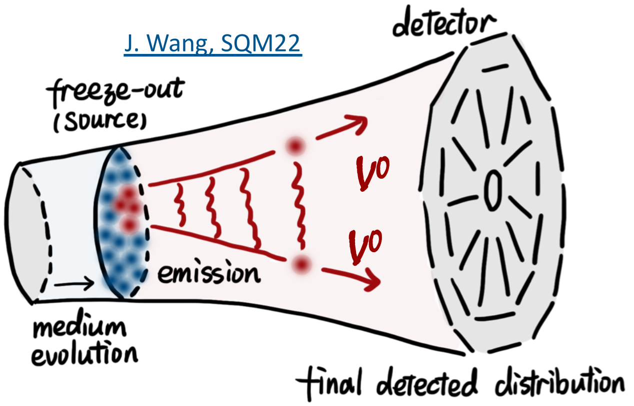
$K^0_S K^0_S$, $\Lambda K^0_S \oplus \bar{\Lambda} K^0_S$, $\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$

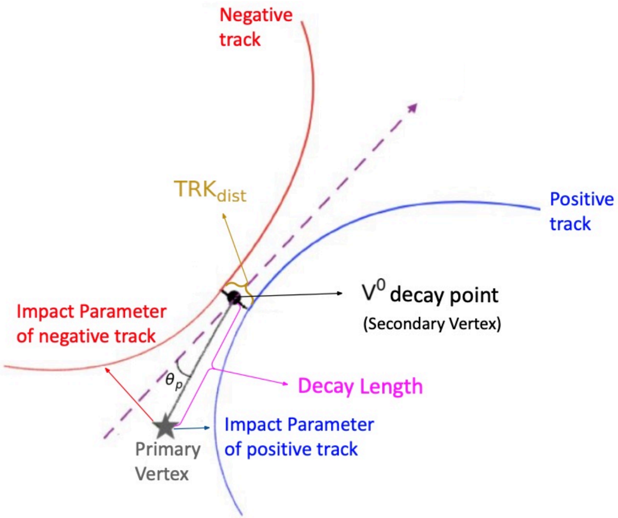
Strange Hadrons Correlations

V^0's: K^0_s, Λ and $\overline{\Lambda}$ correlations:

- ❑ Neutral particles (no Coulomb)
- ❑ Both QS and strong FSI accessible
  - Emitting source size
  - Mesons and baryons interactions
  - Strong interaction parameters
    - Scattering length and effective range
  - Identified via decay into charged hadrons
    - $\Lambda \to p + \pi^- [(63.9 \pm 0.5)\%]$
    - $K^0_S \to \pi^+\pi^- [(69.20 \pm 0.05)\%]$

J. Wang, SQM22





K^0_s and $\Lambda + \bar{\Lambda}$ in PbPb collisions

Particles selected using Boosted Decision Trees method

- $K^0_s \to \pi^+ + \pi^-$, $\Lambda \to p + \pi^-$

Signal: triple Gaussian

Background: 4th order polynomial

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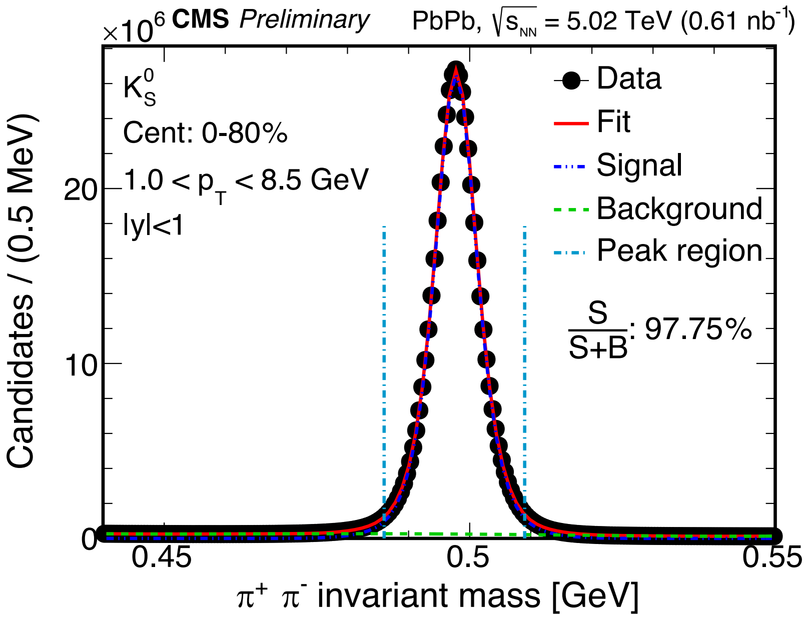
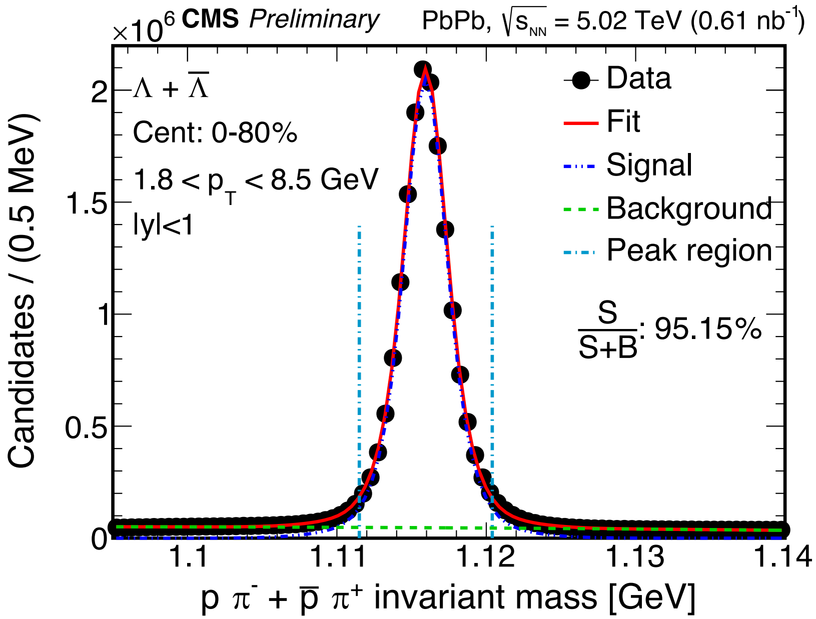




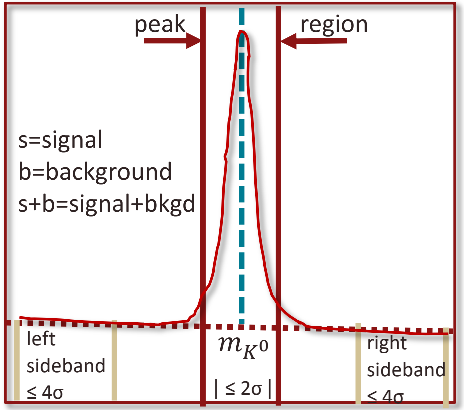
Pair purity in the sample

Purity correction (applied to S and B)

$$D^{meas}(q_{\mathrm{inv}}) = f_{ss}D(q_{\mathrm{inv}}^{ss}) + f_{bb}D(q_{\mathrm{inv}}^{bb}) + f_{Sb}D(q_{\mathrm{inv}}^{Sb})$$

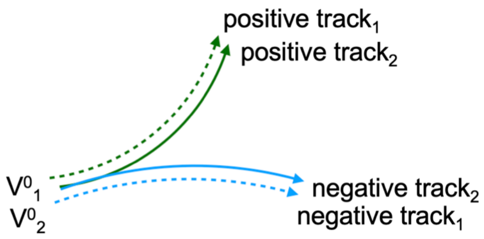
$$D(q_{\mathrm{inv}}^{ss}) = [Dmeas(q_{\mathrm{inv}}) - f_{bb}D(q_{\mathrm{inv}}^{bb}) - f_{Sb}D(q_{\mathrm{inv}}^{Sb})]/f_{ss}$$

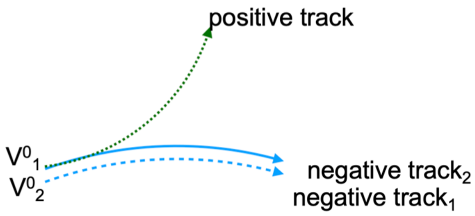
$$f_{ss} = \frac{\binom{s}{2}}{\binom{s+b}{2}},\ f_{bb} = \frac{\binom{b}{2}}{\binom{s+b}{2}} \text{ and } f_{Sb} = 1 - f_{ss} - f_{bb}$$



Duplicate track removal

- Two V^0's share same daughter in the reconstruction (affect signal region)
  - If daughters have same $\chi^2/_{\mathrm{dof}}$ → remove one V^0 randomly





V^0 femtoscopic correlation function

More generally, for considering FSI:

Particle emitting source

$$C(q) = \int S(r)|\Psi_{12}(q,r)|^2 \, d^3r$$

Two-particle wave function

$q = q_{\rm inv} = |q^\mu|, q^\mu = (p_1 - p_2)^\mu - \frac{(p_1-p_2)^\mu . P}{P} P^\mu$ (Ann. Rev. of Nucl. and Part. Phys. **55** (2005) 357)

$P = p_1 + p_2$ (for identical particles: $q_{\rm inv} \rightarrow \sqrt{-(p_1 - p_2)^2}$)

Fit to the experimental correlation function (neutral particles)

$$C(q_{\rm inv}) = N\{1 + \lambda[C_{QS}(q_{\rm inv}) + C_{\rm SI}(q_{\rm inv})]\}\Omega(q_{\rm inv})$$

$C_{\rm SI}(q_{\rm inv})$ → Lednicky-Lyuboshitz model (Sov.J.Nucl.Phys. **35** (1982) 770)

- ❑ $\Lambda K^0_S \oplus \bar{\Lambda} K^0_S$ and $\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$ → effective range expansion
- ❑ $K^0_S K^0_S$: strong FSI parameters fixed (Phys. Rev. C **74**, 054902)

$C_{QS}(q_{\rm inv}) = Ae^{-q^2_{\rm inv} R^2}$

- ❑ A = 1 (identical bosons), A=-½ (identical fermions) or A= 0 (non-identical particles)

$\Omega(q_{\rm inv}) = N(1 + \alpha_1 e^{-(q_{\rm inv}R_1)^2})(1 - \alpha_2 e^{-(q_{\rm inv}R_2)^2})$ → non-femto. Bkgd. (CMS PAS HIN-21-011)

- ❑ All the parameters are free during the fit

Correlation function in PbPb

$K_s^0 K_s^0$: QS (Bose-Einstein)+strong FSI ($|K_S^0 K_S^0\rangle = \frac{1}{2}[|K^0 K^0\rangle + |\bar{K}^0 \bar{K}^0\rangle + |K^0 \bar{K}^0\rangle + |\bar{K}^0 K^0\rangle]$)

$\Lambda K_s^0 \oplus \bar{\Lambda} K_s^0$: strong FSI

$\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$: QS (Fermi-Dirac) + strong FSI

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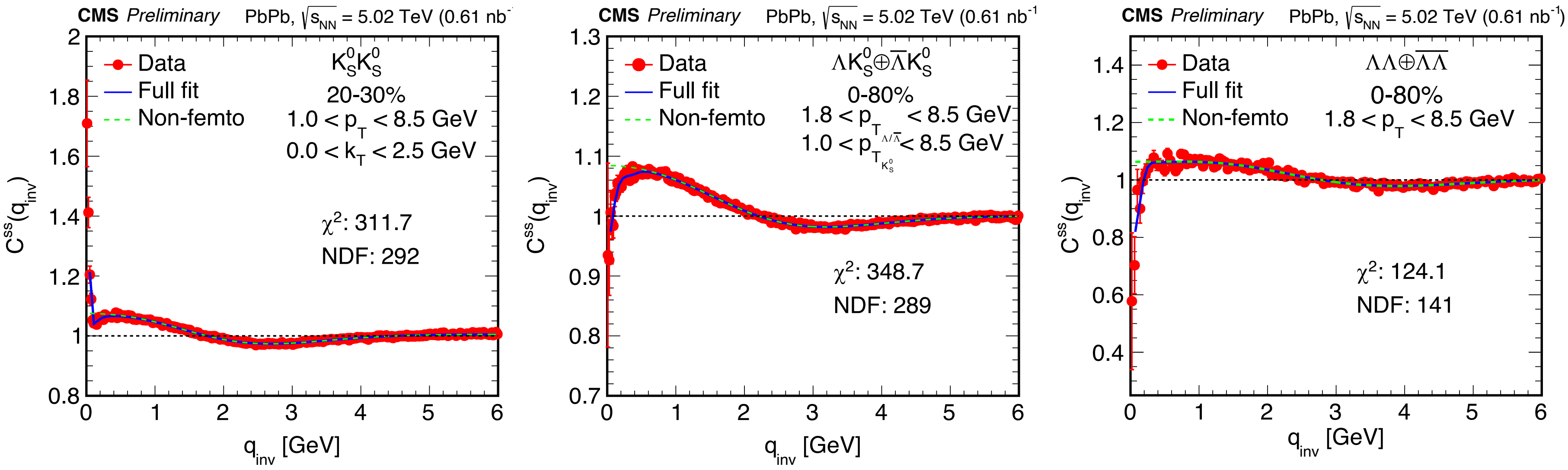
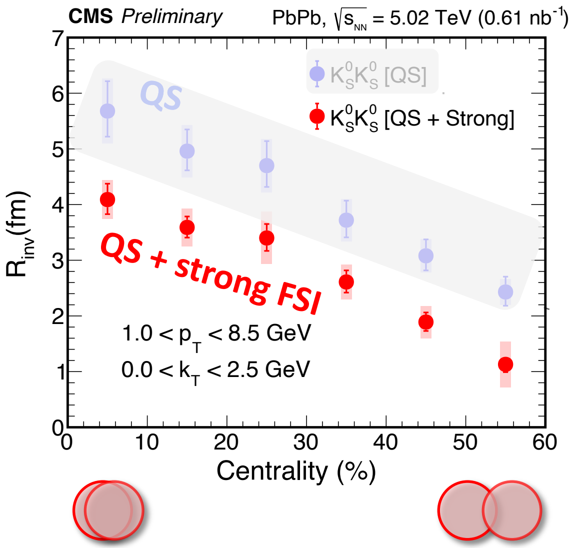
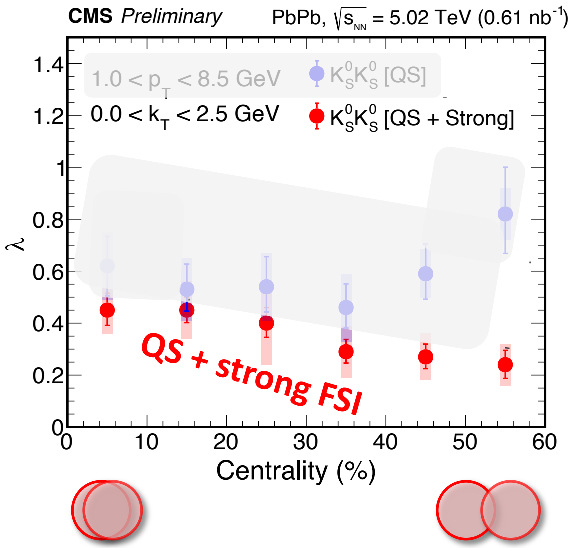


$K^0_S K^0_S$: R and λ as a function of centrality

R and λ as a function of centrality

- Inclusion of FSI term in the fit introduce an overall change in R and λ
- Shows presence of strong FSI





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Strong scattering parameters

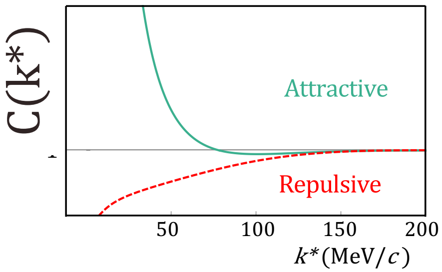
$$f(q) \approx \left[\frac{1}{f_0} + \frac{1}{8} d_0 q^2 - i\frac{q}{2}\right]^{-1}$$

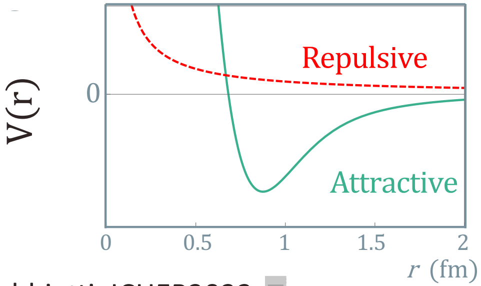
Real scattering length ($\Re f_0$)
Effective range (d_0)

- $\Lambda K^0_s \oplus \bar{\Lambda} K^0_s$: $\Re f_0 < 0$ → depletion below unity (anticorrelation, repulsive correlation function)
  ⇒ attractive strong interaction (potential)

- $\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$: $\Re f_0 > 0$ → correlation above unity, (positive correlation, attractive correl. function)
  ⇒ repulsive strong interaction (potential)

Femtoscopy "convention" (vs. potential)





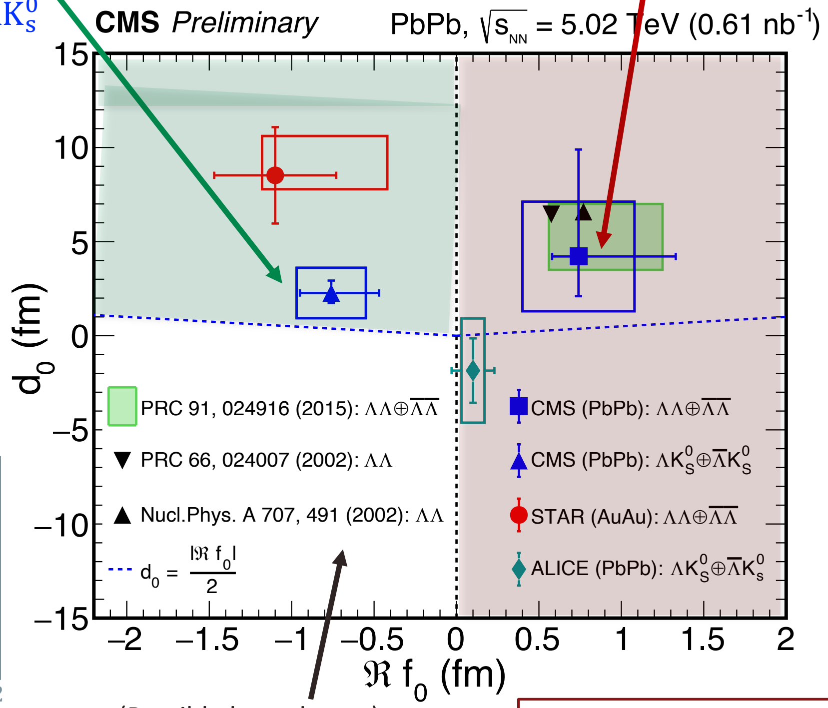
L. Fabbietti, ICHEP2022

(Attractive) Correlation function above unity
⇒ repulsive strong interaction

(Repulsive) Anticorrelation
⇒ attractive strong interaction

$\Lambda K^0_s \oplus \bar{\Lambda} K^0_s$

$\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$



(Possible bound state)

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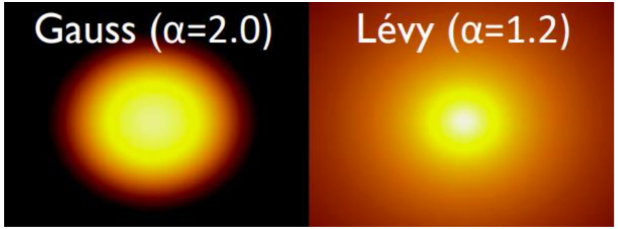
Charged Hadrons Correlations

$\pi^+\pi^+ \oplus \pi^-\pi^- (\sim 80\% - 90\% \rightarrow \pi\text{'}s)$

Charged hadrons femtoscopic correlations

Femtoscopic correlation function

$$C(q) = 1 + \lambda\, e^{-|qR|^{\alpha}}$$



Balázs Kórodi, WPCF 2022

Lévy α-stable distribution

(Csorgo, Hegyi, W. A. Zajc, *Eur.Phys.J.C* 36 (2004) 67 [nucl-th/0310042])

- In PbPb collisions at 5.02 TeV (2.65 billion events)
  - Most common: Gaussian source: $\alpha = 2$
  - CMS: stretched exponential ↔ Cauchy-Lorentz source: $\alpha = 1$ (pp collisions also)
  - At RHIC energies → $1 < \alpha < 2$ (fit parameter)
  - At LHC energies?
    - $C(q)$ → in different centralities and K_T ranges → measured quantities:
      - α → shape (via fitting)
      - Lévy scale parameter R → scale
      - Correlation strength λ → core-halo, partial coherence?
      - $q \equiv |\boldsymbol{q}_{\mathrm{LCMS}}|$, $\boldsymbol{q} = \boldsymbol{p}_1 - \boldsymbol{p}_2$

- In pp collisions at 13 TeV (~0.35 nb^{-1} MB and 459 nb^{-1} High Multiplicity (HM) events)
  - $\alpha = 1$ (fixed)
  - $q = q_{\mathrm{inv}} = \sqrt{-(p_1 - p_2)^2}$

Experimental analyses techniques

Double Ratios (DR)

- ratio of SR
  - $DR = \frac{SR_{Data}}{SR_{MC}}$
- strong MC dependence

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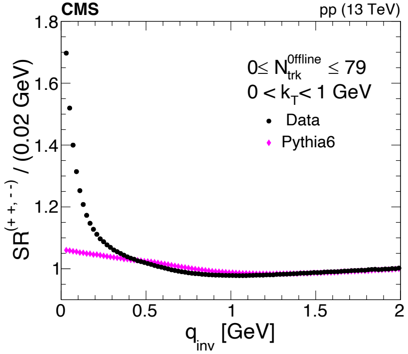

Hybrid Cluster Subtraction (HCS)

- fit SR from MC for both $(+-)$ and $(\pm\pm)$ bkg
  - find a conversion or transfer function (parameters)
- fit $(+-)$ in data and use conversion to $(\pm\pm)$ SR

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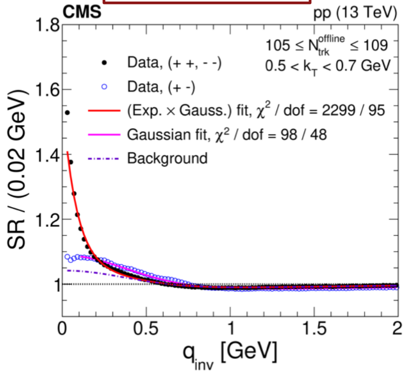

Cluster Subtraction (CS)

- fully data-driven
- bkg estimated from fit of $(+-)$ SR
- translate $(+-)$ to $(\pm\pm)$ SR estimating an amplitude factor

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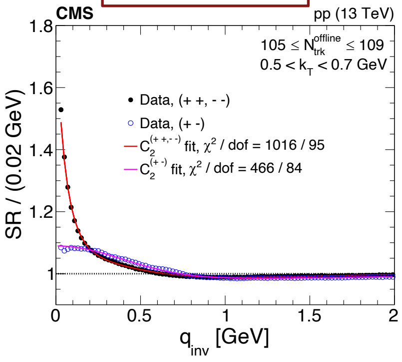

PbPb @5.02 TeV → Double Ratio (alternative)

- Remove remaining non-femtoscopic correlations (resonances, minijets, long-range)

$$DR(q) = \frac{SR(q)}{\Omega(q)}$$

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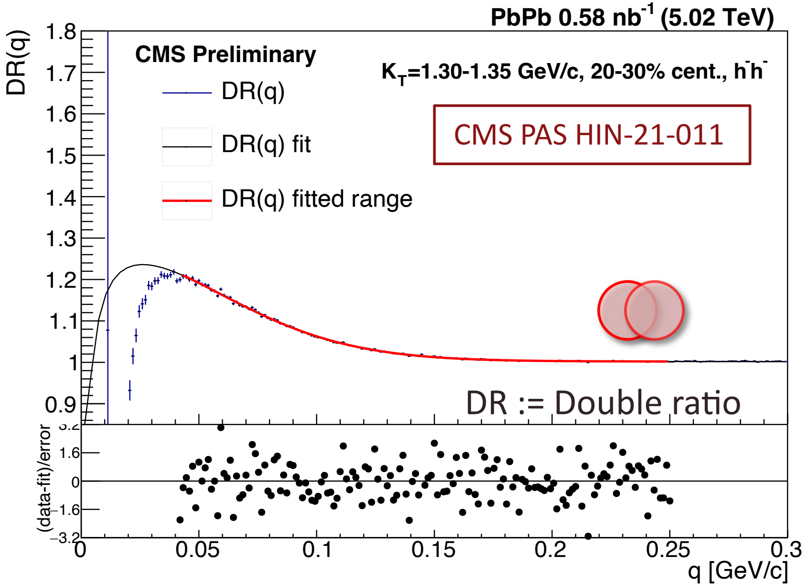
With

$$\Omega(q) = N(1 + \alpha_1 e^{-(qR_1)^2})(1 - \alpha_2 e^{-(qR_2)^2})$$

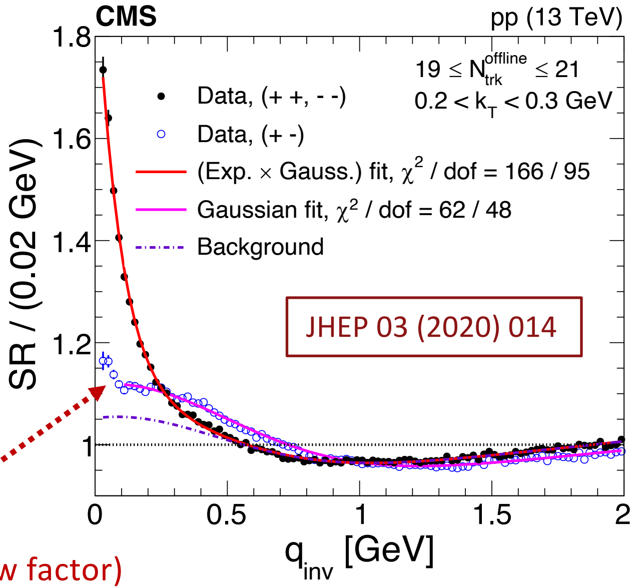
fitted to data

Correlation function in PbPb and pp collisions

Lévy fit in PbPb collisions @5TeV



Exponential fit in pp collisions @13TeV



(Gamow factor)

(long range correlations)

$$C(q) = N\{1 - \lambda + \lambda K_C(q; R, \alpha)[1 + \lambda e^{-|qR|^\alpha}]\}\Omega(q)(1 + \varepsilon q) \rightarrow k_T = \frac{1}{2}|\vec{p}_{T,1} + \vec{p}_{T,2}|$$

In PbPb: Lévy parameter (α)

- Particle emitting source: shape → deviation from Gaussian
- Almost constant as function of m_T
- Depends (decreases) on centrality

- Values raging from 1.6 to 2.0 (semi-peripheral to central collisions)
  - $\langle \alpha \rangle$ increases with $\langle N_{part} \rangle$
  - Systematically larger for h^+h^+

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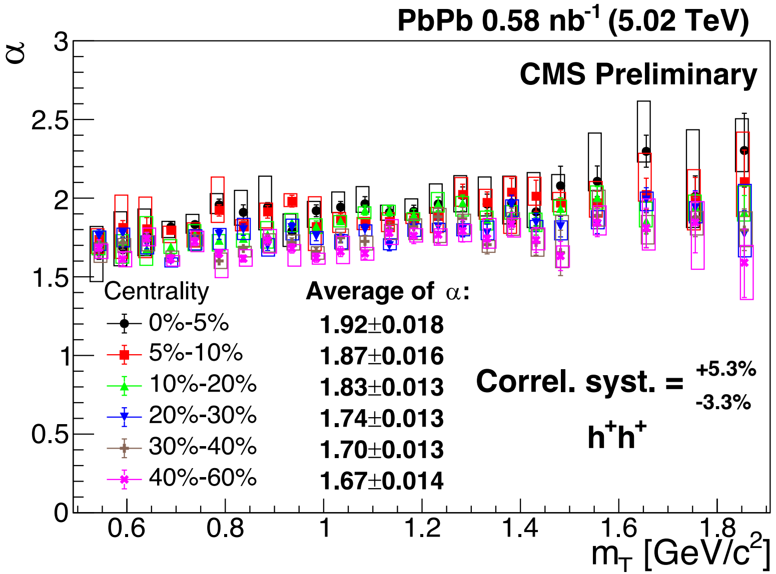

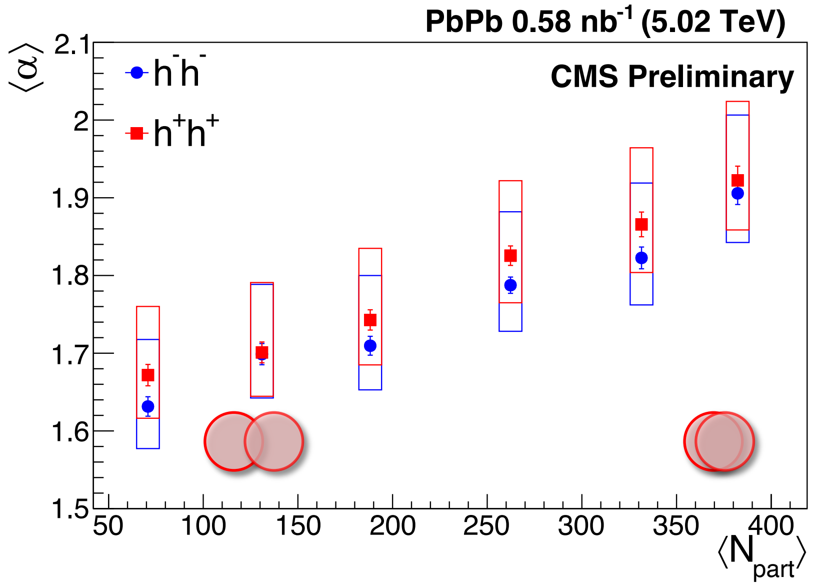

m_T scaling – PbPb collisions

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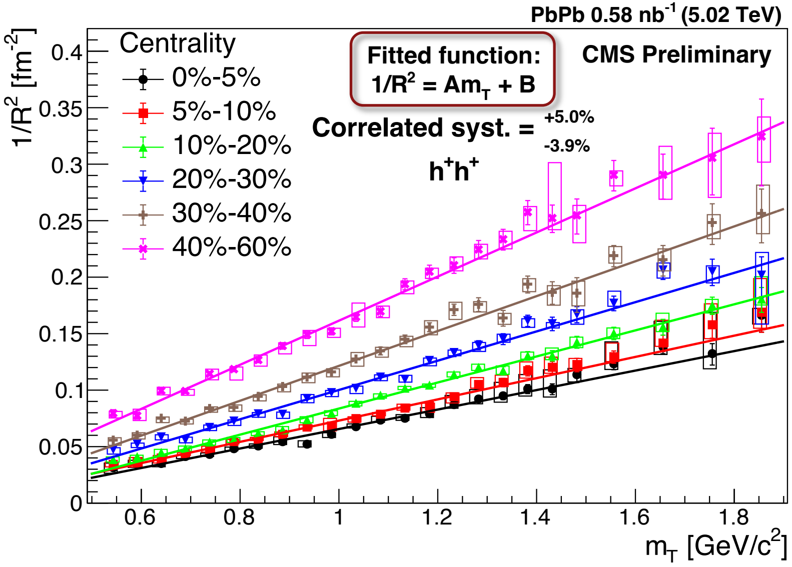
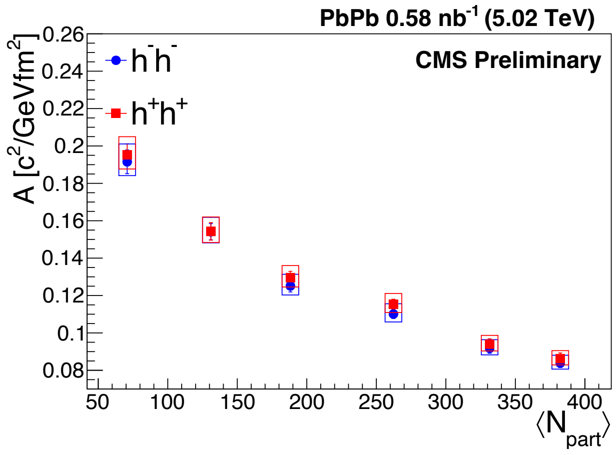
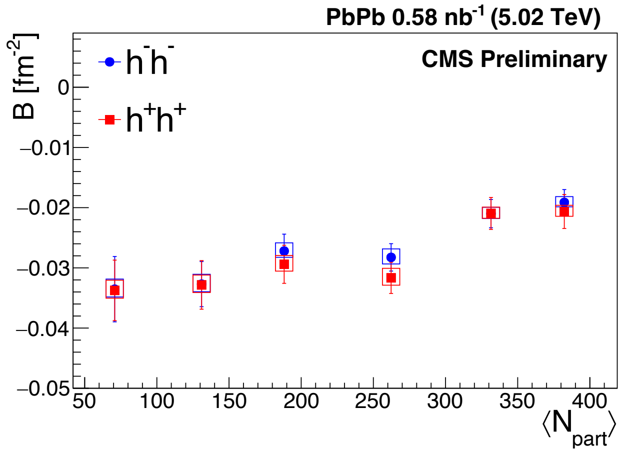
Charged particles



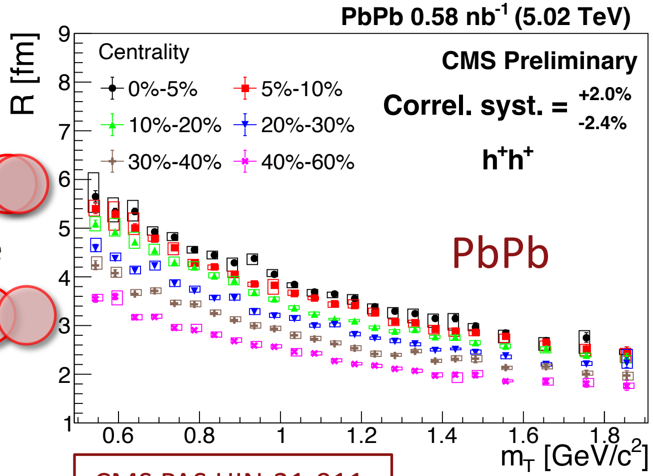




Length of homogeneity (R or R_{inv})

As function of m_T or k_T

- ❑ $m_T = \sqrt{m_\pi^2 + k_T^2}$
- ❑ Indication of an expanding source
- ❑ Smaller sizes in
  - ▪ more peripheral PbPb
  - ▪ lower multiplicities pp



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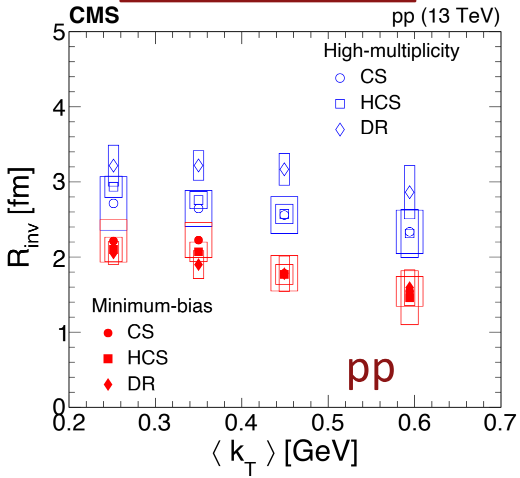

As function of number of participants (N_{part}) and charged particle multiplicity (N_{track})

- ❑ Radius proportional to $N_{part}^{1/3}$ in PbPb
- ❑ Hint of saturation as function of $N_{tracks}^{1/3}$ for pp (but also $\propto N_{part}^{1/3}$)

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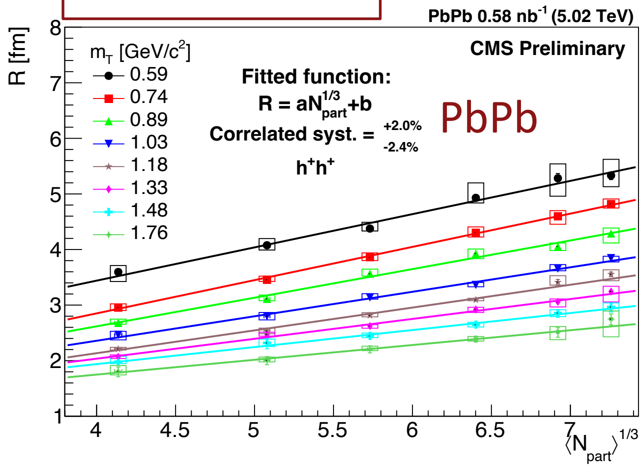
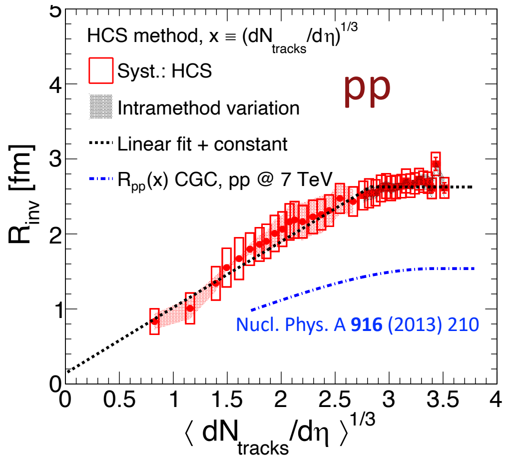




NB: boxes → systematic uncertainties
error bars → stat. uncertainties

$^1/_{R^2}$ as function of m_T

Hydrodynamic prediction: [NPA **946** (2016) 227]

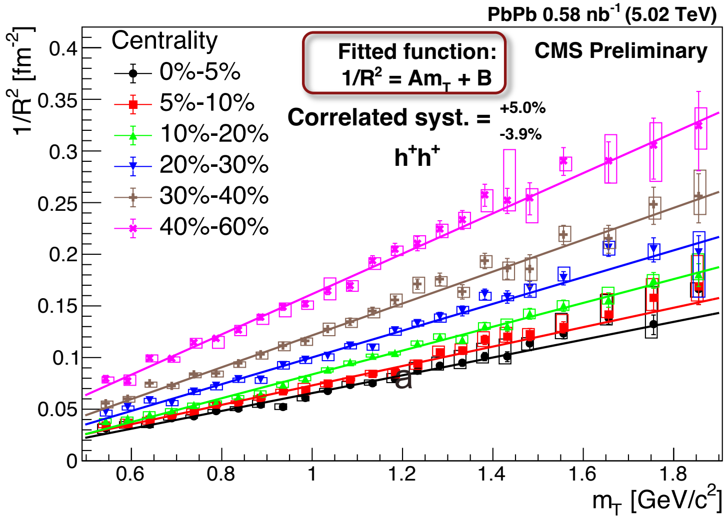
$$^1/_{R^2} = A\, m_T + \mathrm{B}$$

Slope $A = {}^{H^2}/_{T_f}$ ($H \rightarrow$ Hubble constant)

Intercept $B = {}^1/_{R_f^2}$ geom. size (at freeze-out)

PbPb at 5.02 TeV:

- Centrality dependent
- $H \rightarrow$ (0.12 fm^{-1} , 0.18 fm^{-1})



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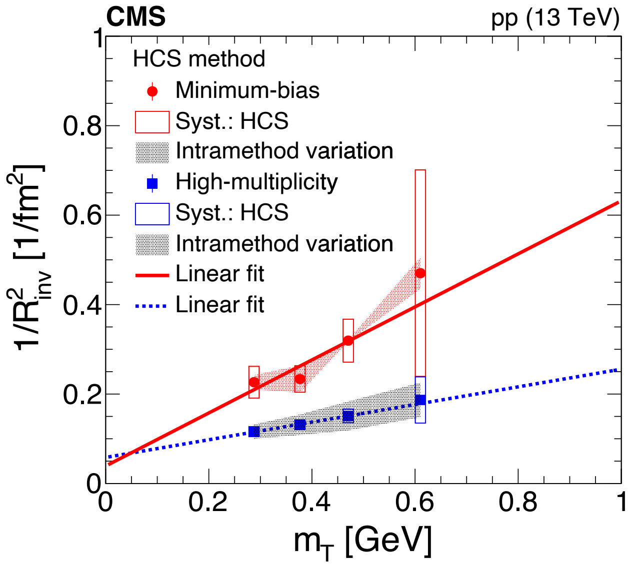
Similar trends between PbPb and pp collisions

pp collisions:

- H_{HM} = 0.17 ± 0.04 (stat) fm^{-1} and
- H_{MB} = 0.298 ± 0.004 (stat) fm^{-1}

Geometric size at freezeout R_G^f

- R_G^{MB} = 5.1 ± 0.4 (stat) fm
- R_G^{HM} = 4.2 ± 1.1 (stat) fm,



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The correlation strength (λ)

Measure λ
- decreases with m_T

No PID
- Pairs of non-identical particles → decrease λ

Rescaling $\lambda \rightarrow \lambda^*$
- By fraction of π's

$$\lambda^* \leq \frac{\lambda}{\left(N_\pi / N_{hadron}\right)^2}$$

Scaled λ^*
- Almost flat with m_T
- Depends on centrality

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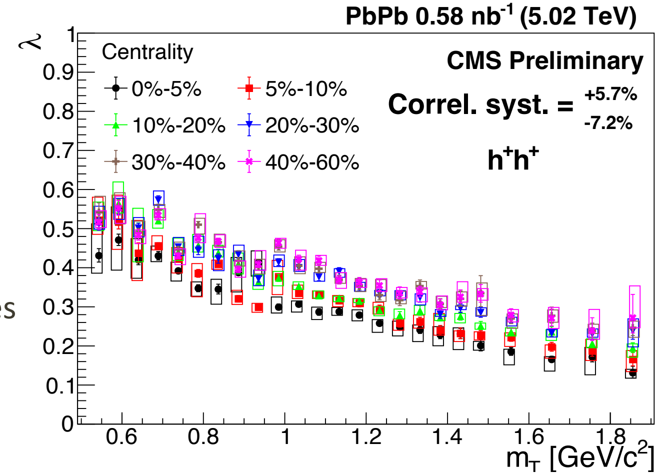

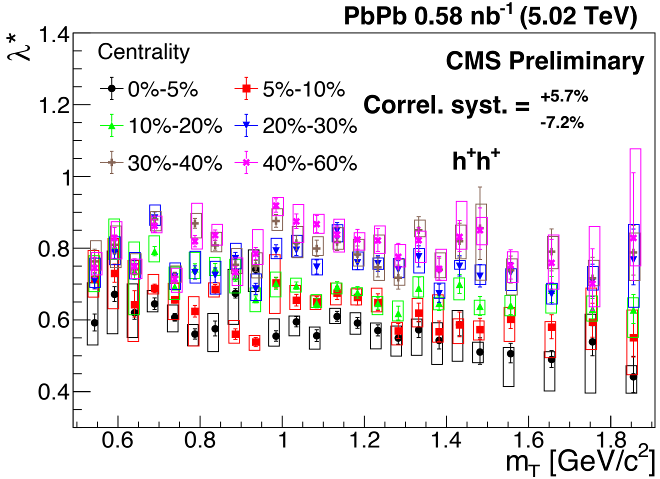

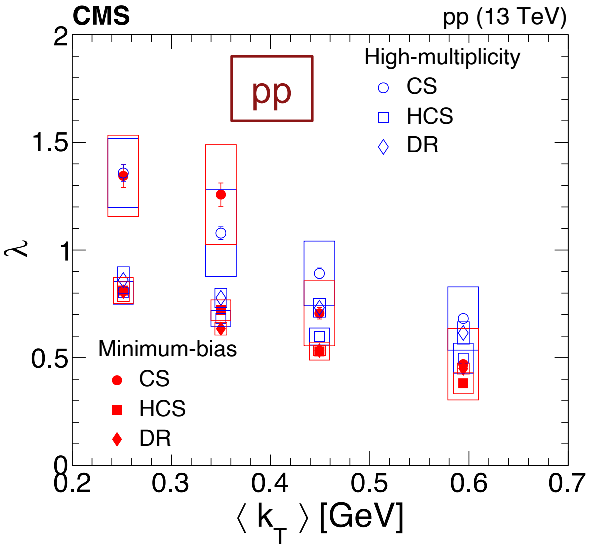

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Summary

For $K_s^0K_s^0$ and charged hadron correlations in PbPb and pp collisions

- ❑ Length of homogeneity (R or R_{inv})
  - Increases with N_{track} or more central collisions
  - Decreases with m_T or k_T

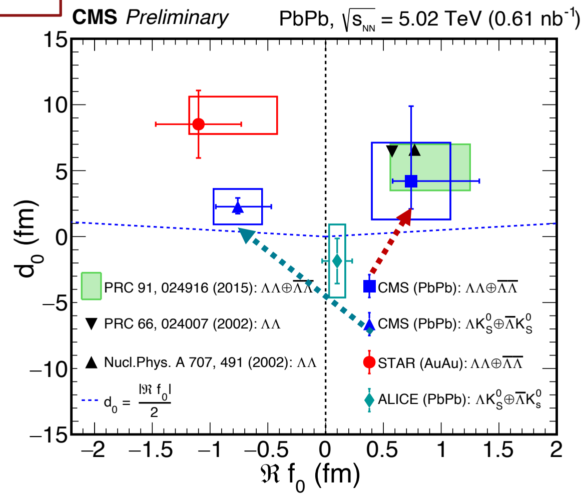
First time Lévy shape is analysed @LHC for PbPb

- ❑ Non-Gaussian behavior: centrality dependent
- ❑ R or R_{inv} shows m_T scaling (hydro) also for Lévy shape

Femtoscopic correlations with other strange hadrons

- ❑ First measurement of $\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$ correlation in PbPb collisions at LHC:
  - $\Lambda\Lambda \oplus \overline{\Lambda\Lambda}$ → repulsive scattering potential ("attractive" correlation function, above unity)
- ❑ $\Lambda K_s^0 \oplus \bar{\Lambda}K_s^0$ correlations
  - attractive scattering potential ("repulsive" correlation function, below unity)

CMS PAS HIN-21-006



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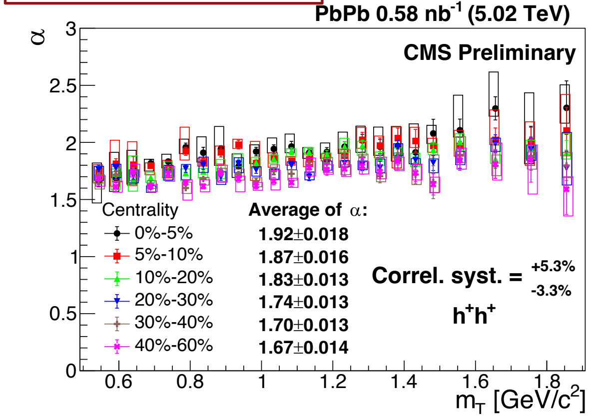


SPRACE

Thank You!

THIS MATERIAL IS BASED UPON WORK SUPPORTED BY THE SÃO PAULO RESEARCH FOUNDATION (FAPESP) GRANTS NO. 2018/01398-1 AND NO. 2013/01907-0. ANY OPINIONS, FINDINGS, AND CONCLUSIONS OR RECOMMENDATIONS EXPRESSED IN THIS MATERIAL ARE THOSE OF THE AUTHOR(S) AND DO NOT NECESSARILY REFLECT THE VIEWS OF FAPESP.

CNPQ GRANT 312369/2019-0

BACKUP

Theoretical fit function: $K^0_s K^0_s$

Fit function

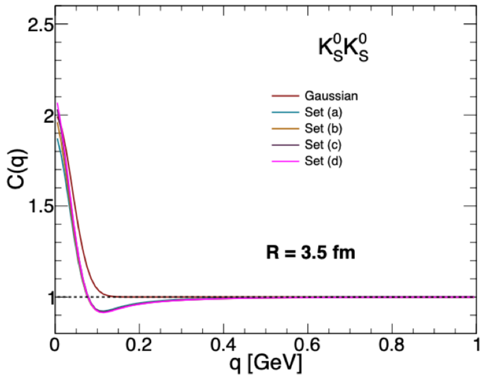
- Fit parameters:
  - R_{inv}, λ, N

$$C(q) = 1 + C_{QS}(q) + C_{SI}(q)$$
$$= 1 + Ae^{-q^2R^2} + \frac{1}{2}\left[\frac{|f(q)|^2}{R^2} + \frac{4\Re f(q)}{\sqrt{\pi}R}F_1(qR) - \frac{2\Im f(q)}{R}F_2(qR)\right]$$

$$F_1(qR) = \int_0^{qR} dx \frac{e^{x^2-(qR)^2}}{qR} \quad \text{and} \quad F_2(qR) = \frac{1-e^{(qR)^2}}{qR} \qquad f(q) = \frac{f_{f_0}(q) + f_{a_0}(q)}{2}$$

$$f_{f_0}(q) = \frac{\gamma_{f_0 \to K^0\overline{K}^0}}{m^2_{f_0} - s - i\gamma_{f_0 \to K^0\overline{K}^0} q/2 - i\gamma_{f_0\to\pi\pi} p_{f_0\to\pi\pi}} \qquad f_{a_0}(q) = \frac{\gamma_{a_0 \to K^0\overline{K}^0}}{m^2_{a_0} - s - i\gamma_{a_0 \to K^0\overline{K}^0} q/2 - i\gamma_{a_0\to\pi\eta} p_{a_0\to\pi\eta}}$$

Reference	m_{f_0}	$\gamma_{f_0\to K^0\overline{K}^0}$	$\gamma_{f_0\to\pi\pi}$	m_{a_0}	$\gamma_{a_0\to K^0\overline{K}^0}$	$\gamma_{a_0\to\pi\eta}$
Martin et. al. (a) [208]	0.978	0.792	0.199	0.974	0.333	0.222
Antonelli et. al. (b) [209]	0.973	2.763	0.528	0.985	0.404	0.371
Achasov et. al. (c) [206]	0.996	1.305	0.268	0.992	0.555	0.440
Achasov et. al. (d) [207]	0.996	1.305	0.268	1.003	0.836	0.458



- Lednicky-Lyuboshitz (LL) model:
  Sov.J.Nucl.Phys. **35** (1982) 770, Phys. Rev. C **74**, 054902 N

Theoretical fit function: $\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$ or $\Lambda K_s^0 \oplus \bar{\Lambda}K_s^0$

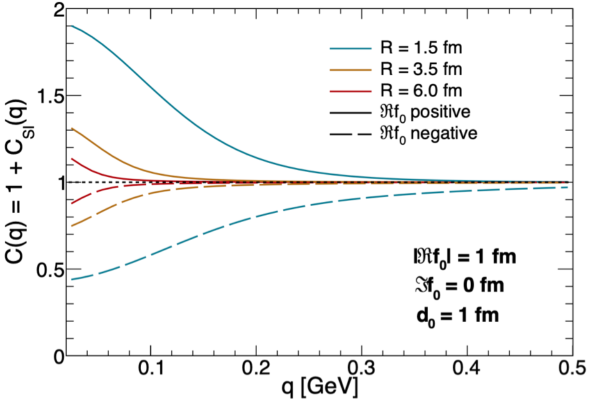
- ❑ Fit function

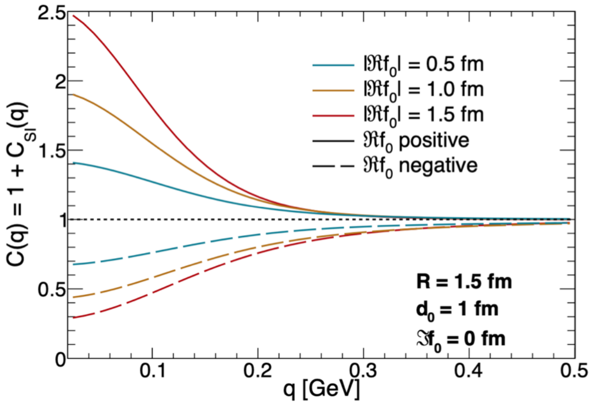
$$C(q) = 1 + C_{QS}(q) + C_{SI}(q) = 1 + Ae^{-q^2R^2} + \sum_S \rho_S \left[\frac{|f^S(q)|^2}{2R^2}\left(1 - \frac{d_0^S}{2\sqrt{\pi}R}\right) + \frac{2\Re f^S(q)}{\sqrt{\pi}R}F_1(qR) - \frac{\Im f^S(q)}{R}F_2(qR)\right]$$

- LL model: Sov.J.Nucl.Phys. **35** (1982) 770

$$f(q) \approx \left[\frac{1}{f_0} + \frac{1}{8}d_0q^2 - i\frac{q}{2}\right]^{-1}$$

- ❑ Effective range expansion
- ❑ ρ_S: weight of spin state





Theoretical fit function: $\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$ or $\Lambda K_s^0 \oplus \bar{\Lambda} K_s^0$

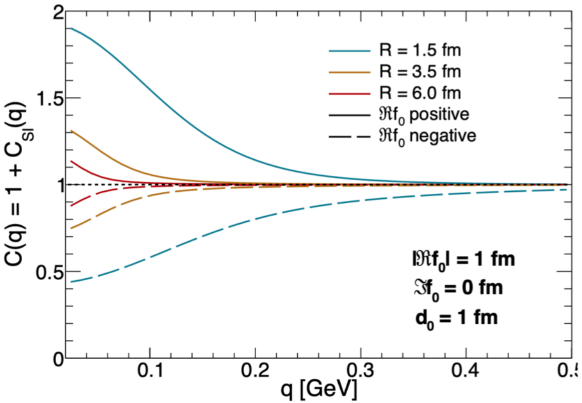
- Fit function

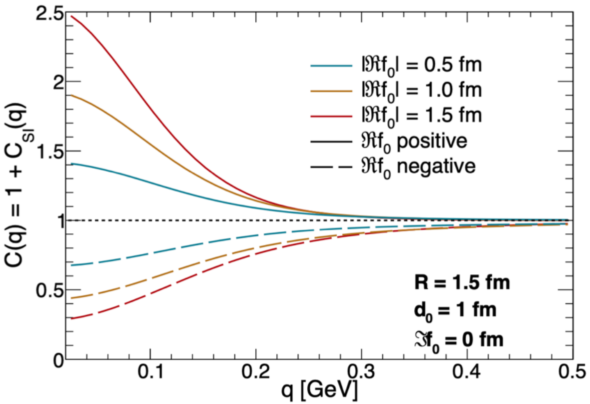
$$C(q) = 1 + C_{QS}(q) + C_{SI}(q) = 1 + Ae^{-q^2R^2} + \sum_S \rho_S \left[\frac{|f^S(q)|^2}{2R^2}\left(1 - \frac{d_0^S}{2\sqrt{\pi}R}\right) + \frac{2\Re f^S(q)}{\sqrt{\pi}R} F_1(qR) - \frac{\Im f^S(q)}{R} F_2(qR) \right]$$

  - ρ_S: weight of spin state
  - LL model: [Sov.J.Nucl.Phys. **35** (1982) 770]

- Effective range expansion

$$f(q) \approx \left[\frac{1}{f_0} + \frac{1}{8} d_0 q^2 - i\frac{q}{2} \right]^{-1}$$





Experimental analyses techniques: PbPb @ 5.02 TeV

$$C(q) = \frac{S(q)}{B(q)}\left(\frac{\int B}{\int S}\right)$$

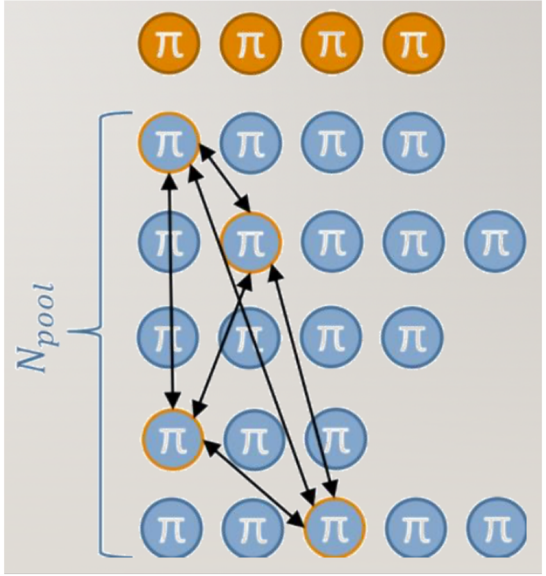
- $S(q)$ → all same charged pairs of a given event
- $B(q)$ → reference sample obtained by mixing events
  - Mix particles from different events

Double Ratio technique → DR (q)

- Remove remaining non-femtoscopic correlations (resonances, minijets, long-range)

$$DR(q) = \frac{C(q)}{\Omega(q)}$$

$$\Omega(q) = N\left(1 + \alpha_1 e^{-(qR_1)^2}\right)\left(1 - \alpha_2 e^{-(qR_2)^2}\right)$$

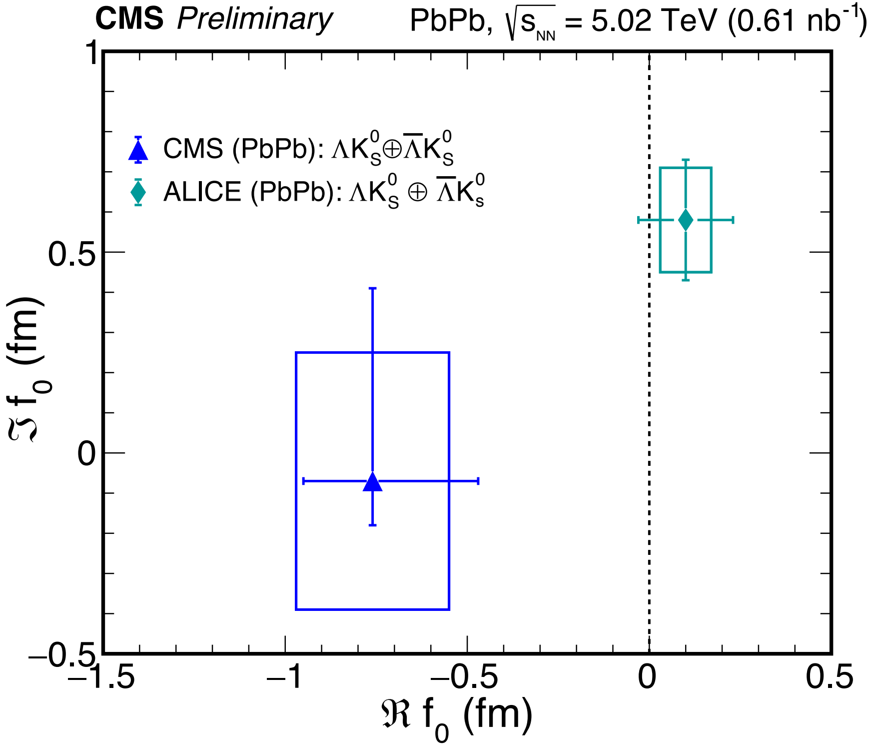


Balázs Kórodi, WPCF 2022

Scattering parameters: $\Lambda K^0_s \oplus \bar{\Lambda} K^0_s$

Effective range expansion

- [Sov.J.Nucl.Phys. 35 (1982) 770, Yad. Fiz. 35 (1981) 1316-1330]
- Real scattering length ($\Re f_0$)
- Imaginary scattering length ($\Im f_0$)
- Effective range (d_0)
- $\Im f_0 > 0$ → usually means annihilation process



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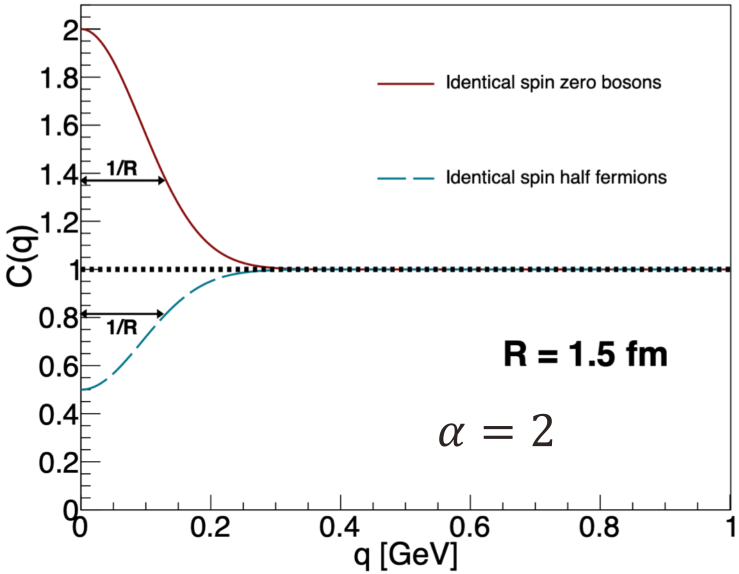
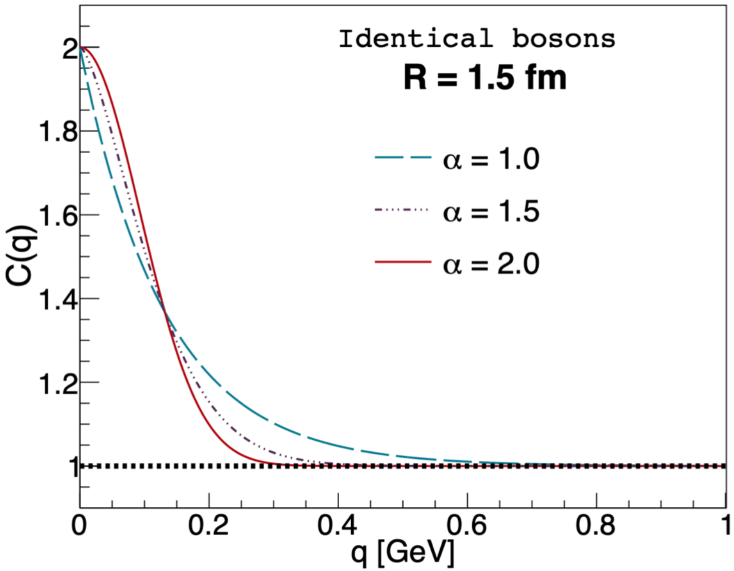
Effects of quantum statistics





$$C_{QS}(q) = 1 + Ae^{-|qR|^{\alpha}}$$

- A = 1 → identical bosons,
- A = -½ for identical fermions
- A = 0 for non-identical articles