Femtoscopy in Small Colliding Systems at CMS

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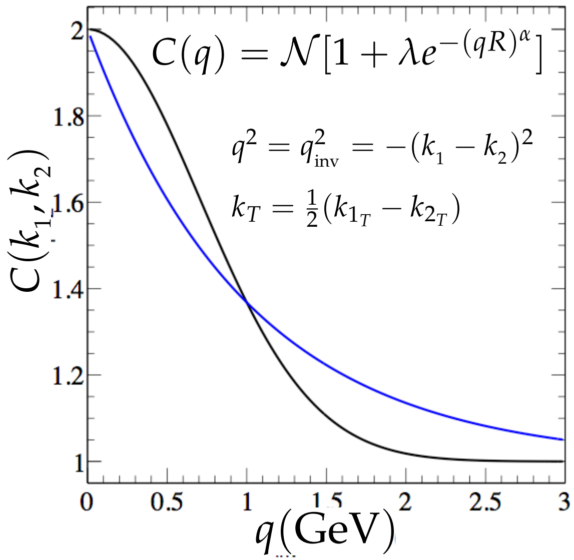
Femtoscopic (Bose-Einstein) correlations in pp at 13 TeV

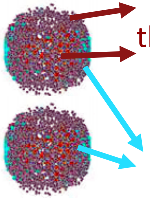
Identical boson correlations can be used to determine the apparent size of the emission source

- by measuring a correlation function vs. q_{inv} in 1-D:

$$C(q=k_1-k_2) = \frac{P_2(k_1,k_2)}{P_1(k_1)P_1(k_2)} \longleftrightarrow 1+\lambda|\mathcal{F}[\tilde{\rho}(q)]|^2$$



- Single Ratios (SR)



$$\frac{\mathcal{S}(k_1,k_2)}{\mathcal{B}(k_1,k_2)} = C(q=k_1-k_2)$$

- $\mathcal{S}(k_1,k_2)$ contains BEC; $\mathcal{B}(k_1,k_2)$ no BEC but everything else → "background removal"
- Fitting the correlation function:

$$C(q_{inv}) = \mathcal{N}(1+\lambda\, e^{-q_{inv}R_{inv}})[1+\epsilon q_{inv}]$$

- When fitting the non-femtoscopic background: $C(q_{inv}) = \Omega(q_{inv}) \times C_{BEC}(q_{inv})$

Analysis methods

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Double Ratio (DR)(*)

[PRC 97 (2018) 064912]

- ❑ Ratio of Single Ratios (SR)
  - $(SR)^{DATA}/(SR)^{MC}$
  - DR Ratio removes non-BEC contributions

(*) PRL **105** (2010) 03200 & JHEP **05** (2011) 029

Cluster Subtraction (CS) – fully data-driven

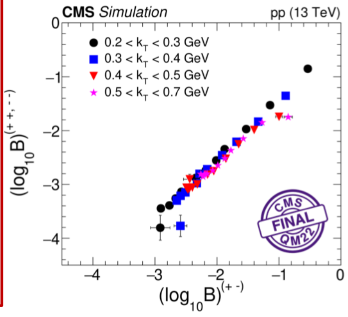
[PRC 97 (2018) 064912]

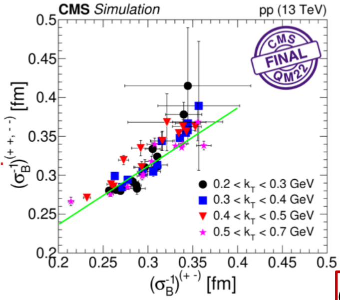
- ❑ Single Ratios only
- ❑ Non-BEC cluster: estimated direcly from data (+ –) SR
  - Cluster amplitude (``height'') estimated by data (±±) SR

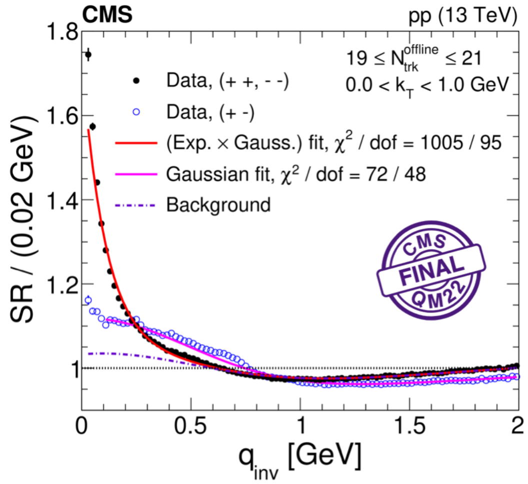
Hybrid Cluster Subtraction (HCS) partially data-driven

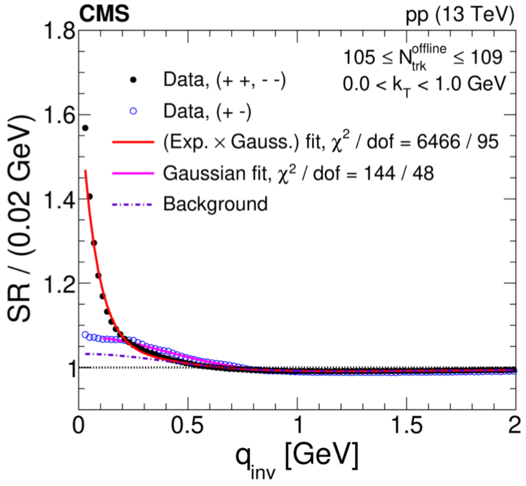
[ATLAS PRC 96 (2017) 064908]

- ❑ Single Ratios only
- ❑ MC SR: correlate (+ –) ⟷ (±±) background
- ❑ Non-BEC effects: estimated from data (+ –) SR
  - MC → conversion function: estimate cluster contribution in data (±±) SR
- ❑ Fit SR data with combined function for signal + cluster



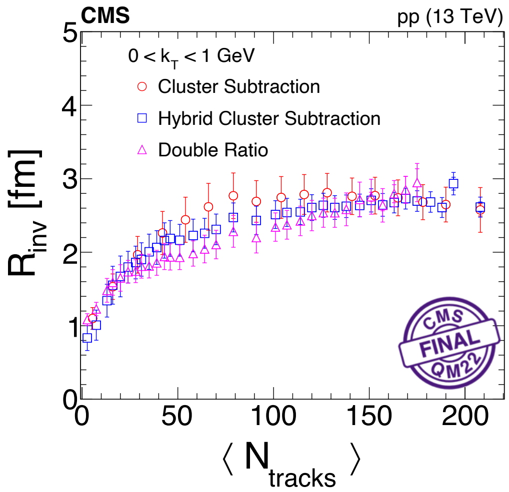


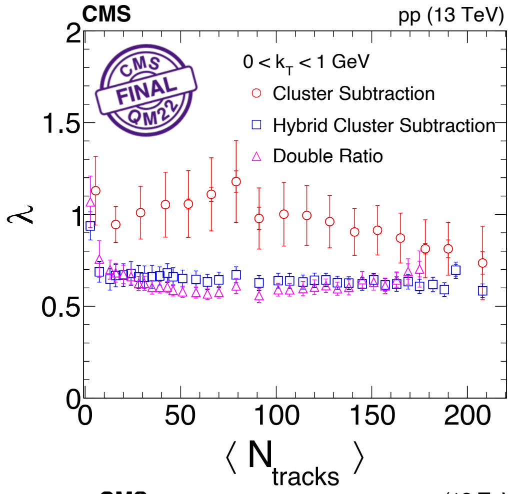




$$\Omega(q_{\mathrm{inv}}) = \mathcal{N}\left(1 + B\exp\left[-\left|\frac{q_{\mathrm{inv}}}{\sigma_B}\right|^{\alpha_B}\right]\right)$$

Results on apparent R_{inv} and intensity λ

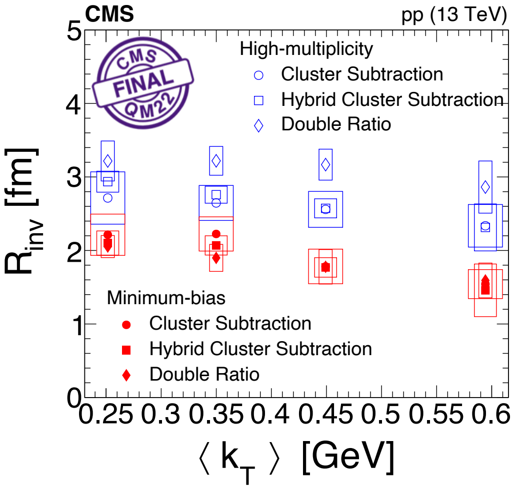




Comparison intramethods

- R_{inv} vs $\langle N_{tracks} \rangle$ ⟶ good agreement
- λ: larger uncertainties in CS
- For further comparisons: HCS

- Decrease with k_T :
  - R_{inv} ↓ for k_T ↑: expanding system
  - More pronounced for Min Bias than for HM events
  - λ decreases similarly for MB and HM events



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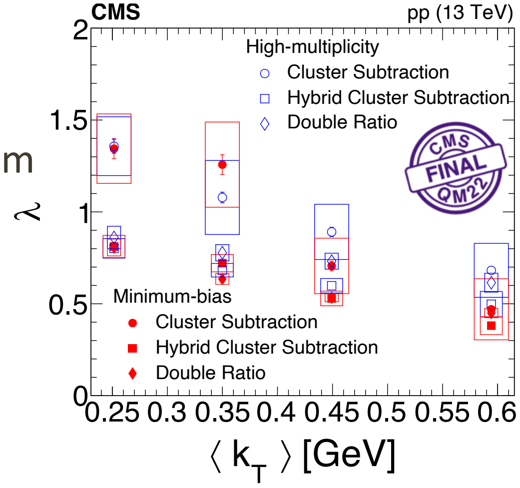
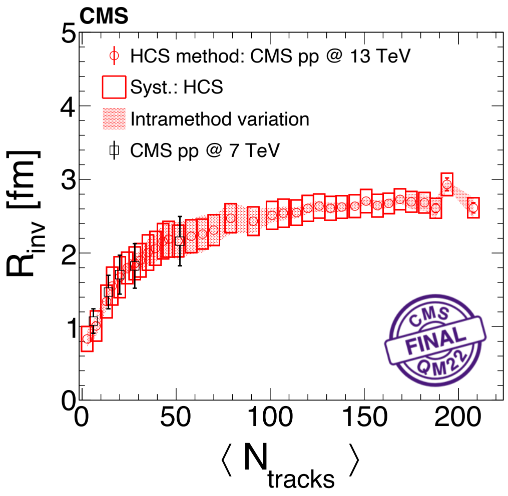


Comparison with other experimental data



- **(Left)** R_{inv} vs $<N_{tracks}>$: no dependence on incident energy

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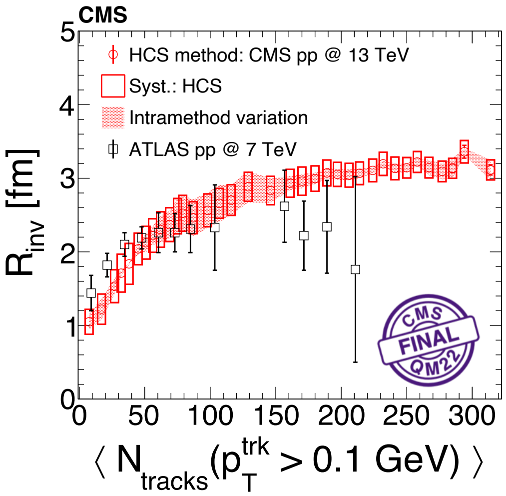
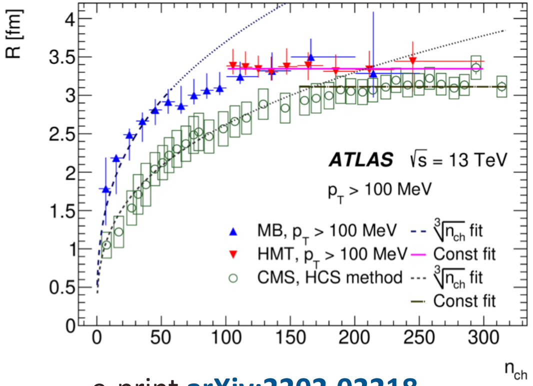
- **(Right)** Similar trend as for ATLAS results on pp at 7 TeV

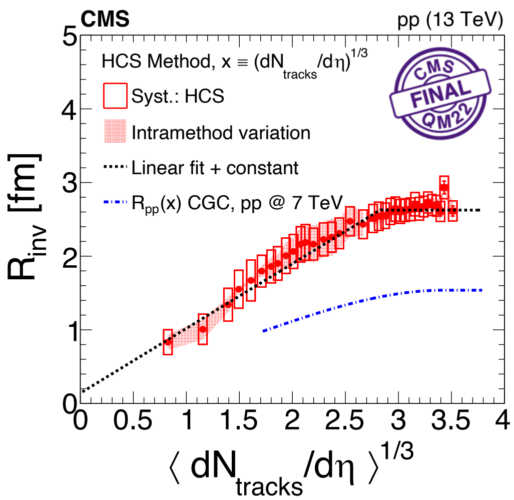


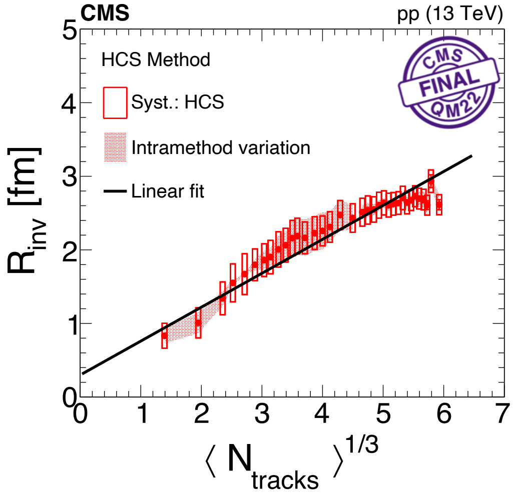
- **(Right)** New comparison by ATLAS with CMS results R_{inv} vs n_{ch} from pp collisions at 13 TeV:
  - Similar trends, seeming to saturate for large n_{ch}
  - ATLAS new R_{inv} : larger than for CMS at low n_{ch}

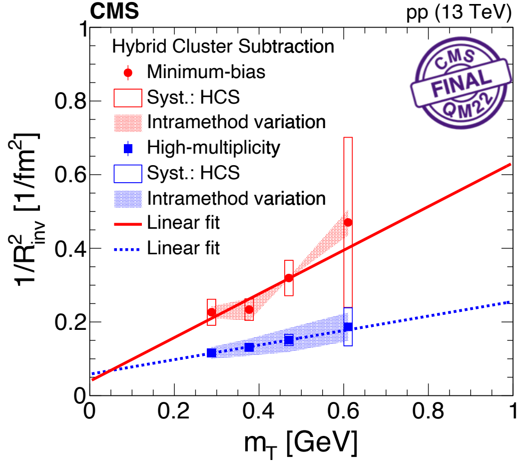


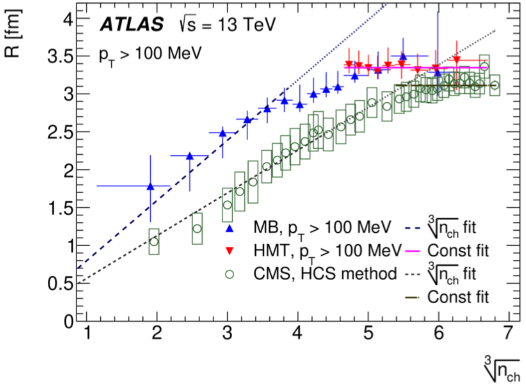
e-print arXiv:2202.02218

Comparison with other experimental data & models









R_{inv} vs. $N_{tracks}^{1/3}$

- CMS data compared with CGC expectation (top left)
- CMS data compared hydrodynamics linear expectation (top middle)
- CMS and ATLAS comparison with hydrodynamics linear rise

$^1/_{R^2_{inv}}$ vs $m_T = \sqrt{m_\pi^2 + k_T^2}$ (hydro)

- Intercept ⟷ emitting source geometrical size (freeze-out)
- Slope: reflects the flow component:
  - Larger slope (larger flow) ⟷ lower <N_{tracks}> (~peripheral AA collisions)
  - smaller slope ⟷ higher <N_{tracks}> (~central AA)

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Femtoscopy in Small Colliding Systems at CMS

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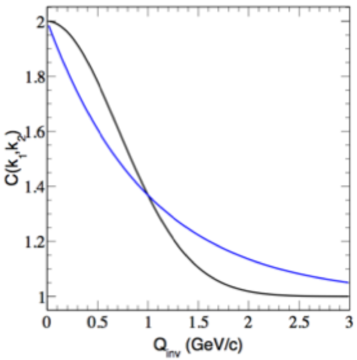
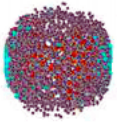
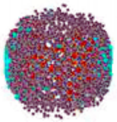
OVERVIEW:

Femtoscopic correlations of charged hadrons are measured over a broad multiplicity range using data from the LHC Run II collected by the CMS experiment. Results are shown for correlations of charged hadrons produced in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV. Such results are compared to data from CMS and ATLAS collaborations at lower energies, as well as to recent ones from ATLAS in pp collisions at 13 TeV. The Additional comparisons are made with theoretical expectations from the Color Glass Condensate (CGC) and from hydrodynamical models. In particular, the hydrodynamical prediction of scaling of the inverse square radius with the pair transverse mass is investigated, showing interesting similarities with observations in large colliding systems.

$$C(q=k_1-k_2) = \frac{P_2(k_1,k_2)}{P_1(k_1)P_1(k_2)} \quad 1+\lambda\left|\mathcal{F}[\tilde{\rho}(q)]\right|^2$$







$$\frac{\mathcal{S}(k_1,k_2)}{\mathcal{B}(k_1,k_2)} = C(q=k_1-k_2)$$

$$C_{BEC}(q_{\text{inv}}) = \mathcal{N}[1+\lambda e^{-q_{\text{inv}}R_{\text{inv}}}][1+\epsilon q_{\text{inv}}]$$

$$C(q_{\text{inv}}) = \Omega(q_{\text{inv}}) \times C_{BEC}(q_{\text{inv}})$$

$$\mathcal{B}(k_1, k_2)$$

$$C(q) = \mathcal{N}[1 + \lambda e^{-(qR)^{\alpha}}]$$

$$q^2 = q^2_{\text{inv}} = -(k_1 - k_2)^2$$

$$k_T = \frac{1}{2}(k_{1_T} - k_{2_T})$$

$$C(k_1, k_2)$$

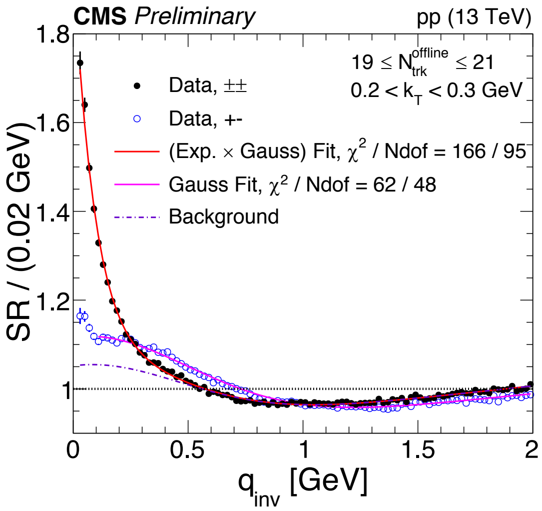
$$q(\text{GeV})$$

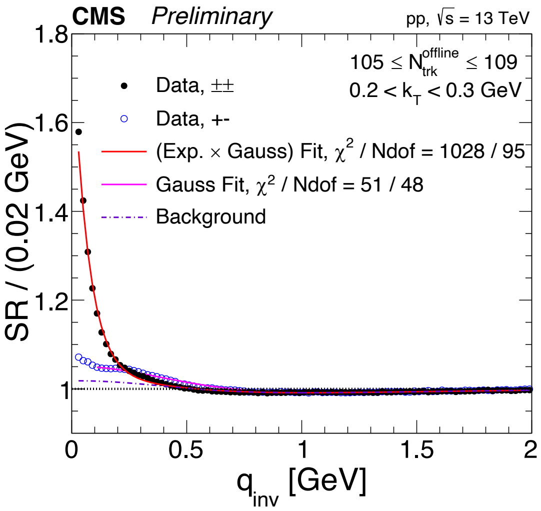
$$\mathcal{S}(k_1, k_2)$$

Hybrid Cluster Subtraction (HCS) Method – IV

After getting relations for ``Bkg'' fit parameters in 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: $C(q_{\mathrm{inv}}) = \Omega(q_{\mathrm{inv}}) \times C_{\mathrm{BEC}}(q_{\mathrm{inv}})$





https://cds.cern.ch/record/2318575 (CMS-PAS-FSQ-15-009)

Outline of the talk

Lengths of homogeneity (R_{inv}) and BEC intensity (λ) parameters in broad multiplicity range ($N_{\text{tracks}} \lesssim 250$)

- ❑ High multiplicity pp collisions: ridge structure and signs of collectivity (similarities with AA collisions)
  - What femtoscopy could add to this investigation?
- ❑ Results and conclusions should be independent on analysis technique
  - Three analysis methods are employed
- ❑ Brief introduction to the three analysis techniques (emphasis in one of them)

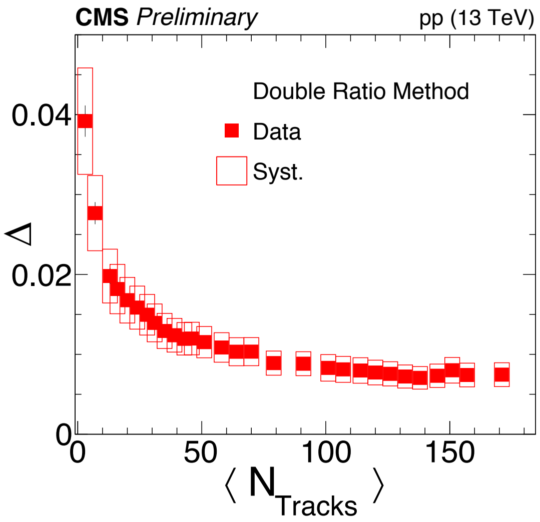
Results

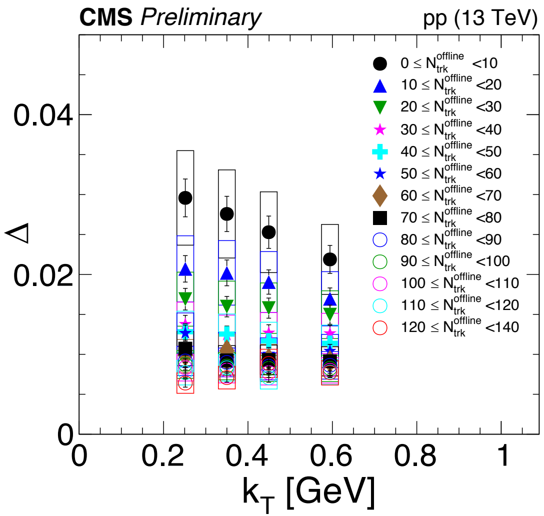
- ❑ Comparisons of the three methods
  - R_{inv} and λ fit parameters vs. N_{tracks} and vs. (N_{tracks}, k_T)
- ❑ Comparison with results from pp collisions at 7 TeV
- ❑ Comparison with model expectations
  - Study R_{inv} vs. $\left(N_{\text{tracks}}\right)^{1/3}$ and $\left(\frac{dN_{\text{tracks}}}{d\eta}\right)^{1/3}$

Results: discussion about anticorrelation (II)

Anticorrelation depth

- Integrated in k_T
  - Decreases with $<N_{tracks}>$, tend to ≈ const. above 100
- and differential in k_T
  - Decrease with k_T for lower $<N_{tracks}>$ ranges
  - For $<N_{tracks}> > 30$ → ≈ const. with increasing k_T





Dip's depth at the highest multiplicities: tends to a constant (not zero) value →

- Possible consequence of the DR method
- or an intrinsic characteristic of the collision system
  - keep memory of its initially small size, even at the highest track multiplicities produced in pp collisions

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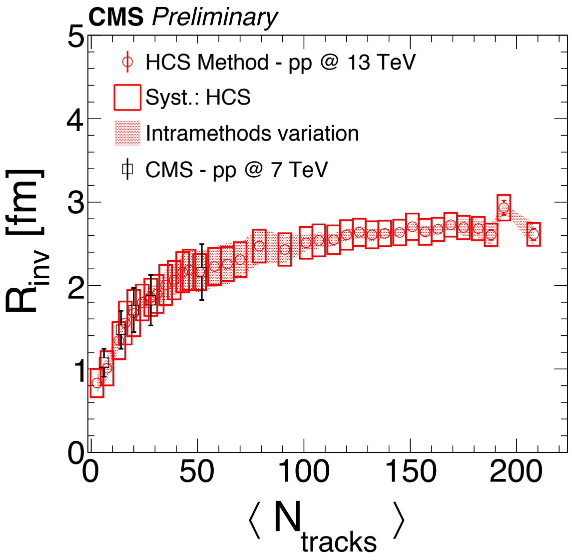
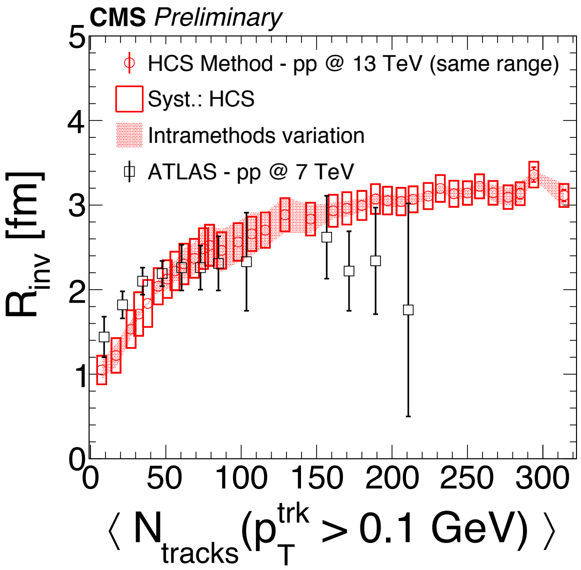
Comparison with CMS and ATLAS @7 TeV

R_{inv} Results from HCS compared to

- CMS for pp@7 TeV [PRC 97 (2018) 064912] using Double Ratio method (η-mixing reference sample)
- ATLAS for pp@7 TeV [EPJC **75** (2015) 466] using Double Ratio method (opposite sign reference sample)





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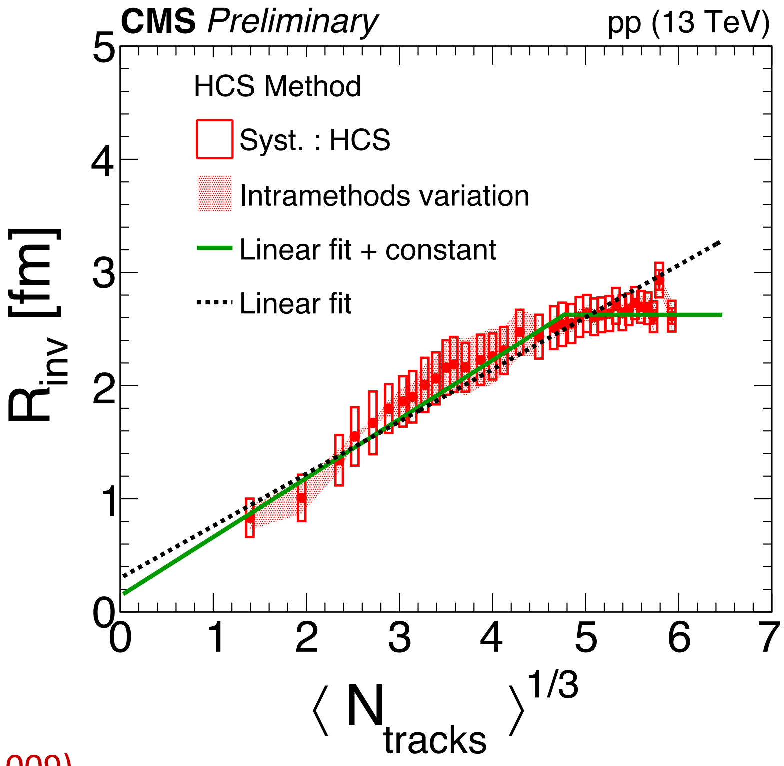
R_{inv} vs. $N_{\mathrm{tracks}}^{1/3}$

Qualitative comparisons: fits with statistical uncertainties only

- Linear fit
- Linear + Constant
- Both return compatible results

Including systematic uncertainties

- Point-to-point correlations → not trivial
- Studies of extreme cases only
  - Fit considering fully correlated systematics → similar results as using only statistical uncertainties
  - Fit considering systematics fully uncorrelated



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R_{inv} vs. $\left(\frac{dN_{\text{tracks}}}{d\eta}\right)^{1/3}$

Comparison with CGC prediction

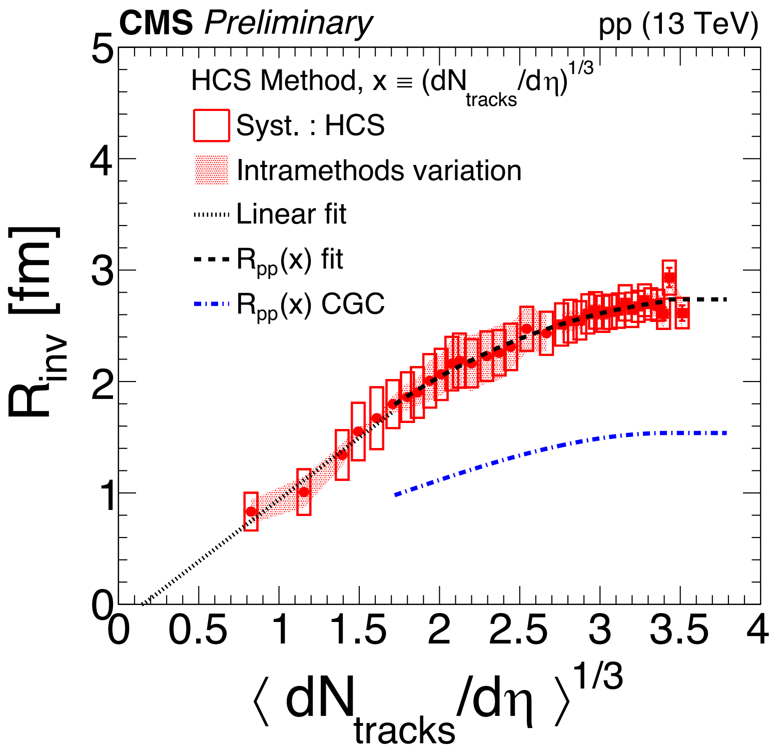
- [*McLerran, Schenke, NPA* **916** (2013) 210;
  P. T. A. Bzdak et al, *PRC* **87** (2013) 064906]

- Calculation for pp @ 7 TeV (does not include the system evolution)
- Similar shape, but very large difference in magnitude

- Above 1.7 : fit with same function obtained from CGC prediction (dashed black curve; stat. uncert. only)

$$R_{pp}(x) = \begin{cases} (1\,\text{fm}) \times [a + b\,x + c\,x^2 + d\,x^3], & \text{for } x < 3.4 \\ e\,(\text{fm}), & \text{for } x \geq 3.4 \end{cases}$$

- $x = \left({}^{\text{dN}_{\text{tracks}}}/{}_{\text{d}\eta}\right)^{1/3}$



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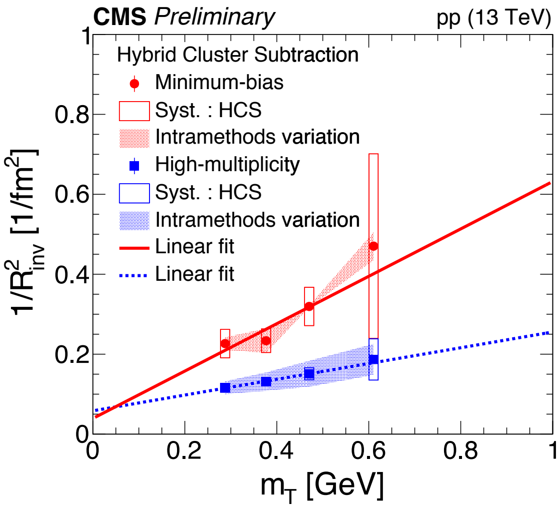
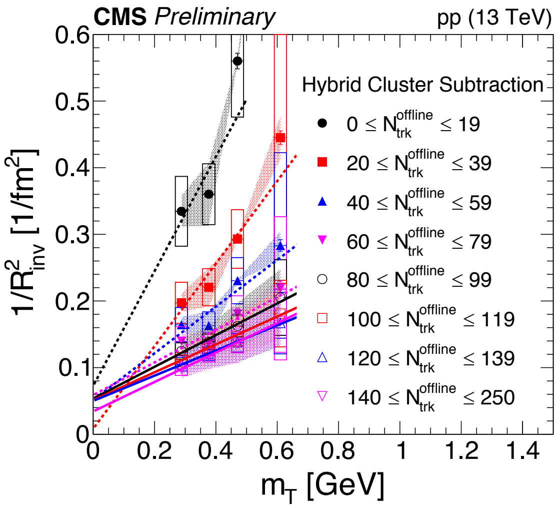
m_T dependence

$$1/R_{inv}^2 \text{ vs } m_T = \sqrt{m_\pi^2 + k_T^2}$$

- In hydrodynamic models [Sinyukov et al., NPA 946 (2016) 227]
  - Intercept: reflects the source geometrical size (at freeze-out)
  - Slope: reflects the flow component …
    - Larger slope (larger flow) for lower multiplicities (similar to peripheral AA collisions)

      … as compared to
    - higher multiplicities (similar to more central AA collisions)





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Summary of results in pp collisions at 13 TeV

BEC in Minimum Bias and High Multiplicity events in pp collisions at 13 TeV

- First investigation with both MB and HM events → three different techniques employed:
  - Double Ratios involving data and MC (Pythia 6 – Z2* tune) [PRC 97 (2018) 064912]
  - Fully Data-driven as used in CMS [PRC 97 (2018) 064912]
  - Hybrid Data-driven (transfer function from Pythia 6 – Z2* tune) – [ATLAS, PRC 96 (2017) 064908]

- 1-D BEC (exponential fit): R_{inv} (and λ)
  - Scrutinized in detail as a function of multiplicity, searching for:
    - Changes of slope [PLB **703** (2011) 237]
    - Continuous growth with $(N_{tracks})^{1/3}$ → compatible with data
    - Possible saturation of R_{inv} in the high multiplicity range → also compatible with data
  - Detailed investigation as a function of k_T (in MB and HM ranges)
  - m_T – scaling with different slopes in MB and HM: Hubble-type of flow larger in MB than in HM

- Qualitative comparison with models →
  - CGC/IP-GLASMA [NPA 916 (2013) 210; PRC87 (2013) 064906]
  - Hydrodynamic models (with different Initial Conditions and EoS) [Sinyukov et al., NPA 946 (2016) 227]
  - Both classes of models qualitatively describe the experimental results within uncertainties

- Complete results: https://cds.cern.ch/record/2318575 (CMS-PAS-FSQ-15-009)

THANK YOU!!

ADDITIONAL SLIDES

Experimental cuts and definitions adopted

$N_{trk}^{offline}$ definition

- HighPurity
- $p_T > 0.4$ GeV
- $|\eta| < 2.4$
- $|\sigma_{pT}/p_T| < 0.10$
- $|d_z/\sigma_{dz}| < 3$ wrt PV
- $|d_{xy}/\sigma_{dxy}| < 3$ wrt PV

Track selection for BEC analysis

- HighPurity
- $p_T > 0.2$ GeV
- $|\eta| < 2.4$
- $|\sigma_{pT}/p_T| < 0.10$
- $|d_z/\sigma_{dz}| < 3$ wrt PV
- $|d_{xy}/\sigma_{dxy}| < 3$ wrt PV
- pixelLayersWithMeasurement > 1

Other variables

- $N_{trk}^{offline}$ = 0 – 250
- k_T (GeV) < 1 GeV or
  k_T **ε** {0.2-0.3, 0.3-0.4, 0.4-0.5, 0.5-0.7}

$$k_T\ (\text{GeV}) = |p_{T,1} + p_{T,2}|/2$$

- q_{inv} (GeV) = 0.02 – 2.0

$$q^2 = q_{\text{inv}}^2 = -(k_1 - k_2)^2 = M_{\text{inv}}^2 - 4m_{\pi^2}$$

- Fit Function used :

$$C[1 + \lambda\, e^{-(q_{\text{inv}} R_{\text{inv}})}]\ (1 + \epsilon\, q_{\text{inv}})$$

Sources of systematic uncertainties

Main sources of systematic uncertainties

- **Reference samples**
- **Monte Carlo modeling of correlation functions**
- **Cluster amplitude $z(N^{off}_{trk})$ in the Full Data-Driven method**
- Track selections
- Coulomb corrections

Other sources (less significant)

- PU dependence
- Z-vertex position dependence
- HM HLT trigger bias
- Track corrections

Offline Event and Track Selections

Event Selection

- At least 1 Reconstructed Primary Vertex: $|V_z| < 15$cm
- $\rho < 0.15$ cm (transversal distance)
- Reject beam scraping → HighPurity track fraction > 0.25 for with multiplicity > 10
- HF Coincidence Filter

Track selection for BEC analysis

- HighPurity
- $p_T > 0.2$ GeV
- $|\eta| < 2.4$
- $|\sigma_{pT}/p_T| < 0.10$
- $|d_z/\sigma_{dz}| < 3$ wrt PV
- $|d_{xy}/\sigma_{dxy}| < 3$ wrt PV
- pixelLayersWithMeasurement > 1