Results on Bose-Einstein correlations of charged hadrons in pp collisions at 13 TeV

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SPRACE & IFT – UNESP

Outline of the talk

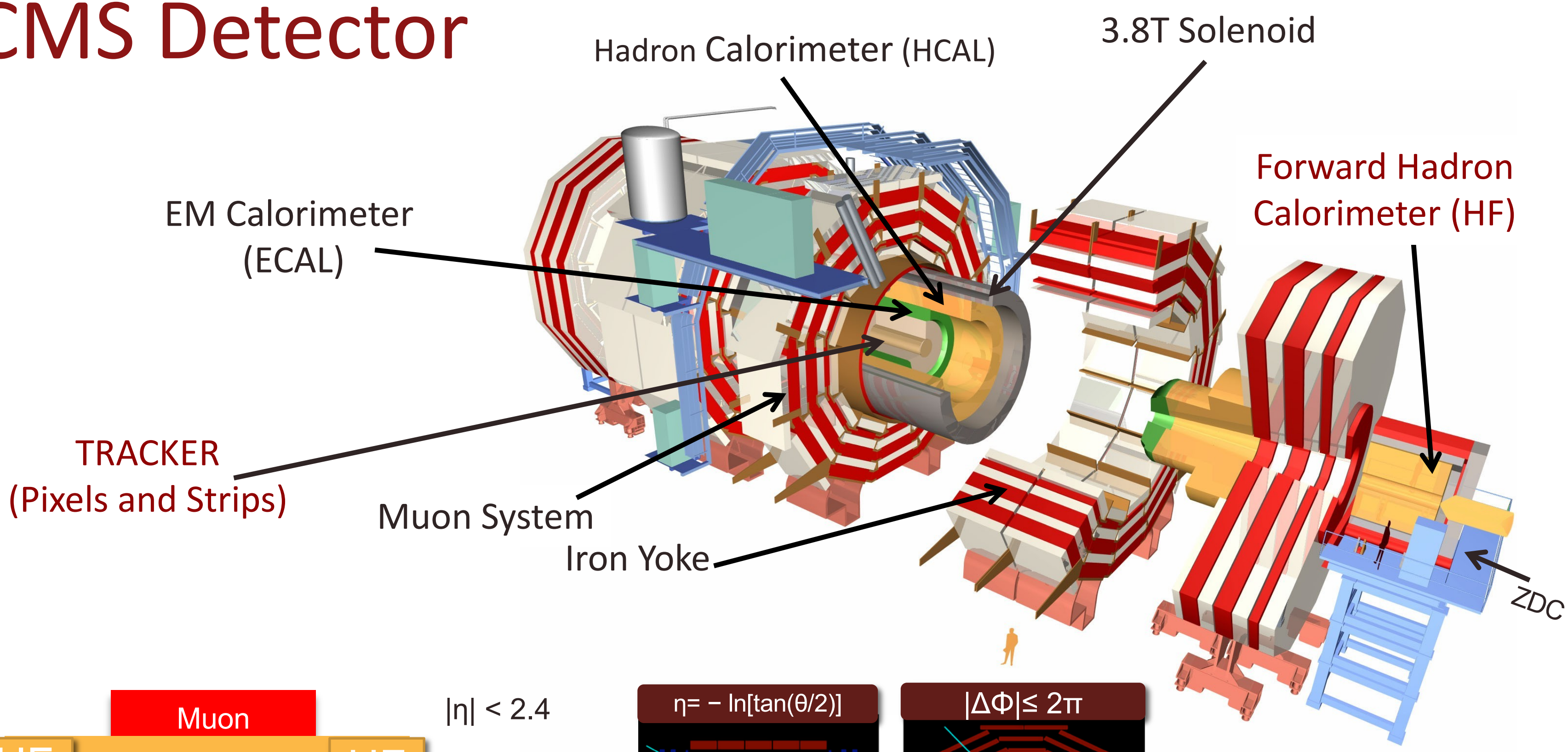
Lengths of homogeneity (R_{inv}) and BEC intensity (λ) parameters in broad multiplicity range ($N_{\text{tracks}} \lesssim 250$)

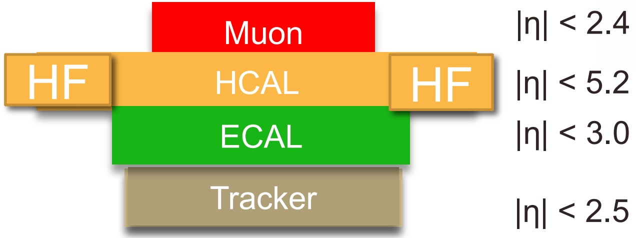
- High multiplicity pp collisions: ridge structure and signs of collectivity (similarities with AA collisions)
  - What femtoscopy could add to this investigation?
- Results and conclusions should be independent on analysis technique
  - Three analysis methods are employed
- Brief introduction to the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

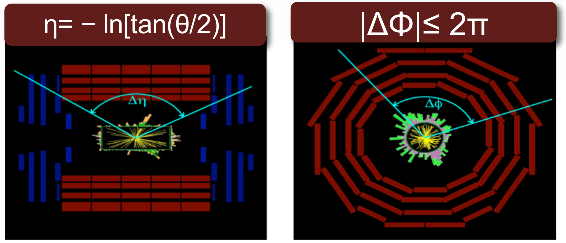
Results

- 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 $\left(\frac{dN_{\text{tracks}}}{d\eta}\right)^{1/3}$

CMS Detector







Outline of analysis methods

Double Ratio (DR), as in (*) & PRC 97 (2018) 064912

- ❑ Ratio of Single Ratios (SR)
  - Data SR divided by MC SR
  - Non-BEC contributions: removed by directly performing the ratio of data to MC
- ❑ Fit double ratio with a function representing the BEC signal alone

Cluster Subtraction (CS) – fully data-driven, as in PRC 97 (2018) 064912

- ❑ Employs Single Ratios only
- ❑ Non-BEC cluster is estimated direcly from data (+ –) SR
  - Estimates the amplitude (``height'') of the cluster using (±±) SR in data
- ❑ Fit SR with functional form combining signal+cluster components

≠

Hybrid Cluster Subtraction (HCS) partially data-driven, as in ATLAS [PRC 96 (2017) 064908]

- ❑ Employs Single Ratios only
- ❑ Uses MC SR to correlate (+ –) and (±±) background
- ❑ Non-BEC effects: estimated from data (+ –) SR
  - Uses MC estimate to convert this contribution into the cluster in the data (±±) SR
- ❑ Fit SR data with combined function for signal + cluster

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

Common to all methods – I (Coulomb and fit)

Final state (Coulomb) interactions

- Analytic form. for Coulomb correction [PRC 97 (2018) 064912]

$$K(q_{\rm inv}) = G_\omega(\zeta)[1+\zeta\, q_{\rm inv}\, R_{\rm inv}/(1.26+q_{\rm inv}\, R_{\rm inv})]$$

$$\zeta = m\alpha_{\rm em}/q_{\rm inv}$$

- In pp collisions → well–approximated by Gamow factors

$$G_\omega^{\rm SS}(\zeta) = \frac{2\pi\zeta}{\exp(2\pi\zeta)-1}$$

$$G_\omega^{\rm OS}(\zeta) = \frac{2\pi\zeta}{1-\exp(-2\pi\zeta)}$$

One-dimensional fit to Correlation Functions

$$C_{BE}(q_{\rm inv}) = C[1+\lambda e^{-(q_{\rm inv}R_{\rm inv})^a}](1+\epsilon\, q_{\rm inv})$$

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

- Lévy distribution with a → index of stability;
  particular cases:
  - exponential fit (a = 1)
  - Gaussian fit (a = 2)
  - ε → fit parameter (long-range correlations)

Common to all methods – II (Single Ratios)

Single Ratios (SR)

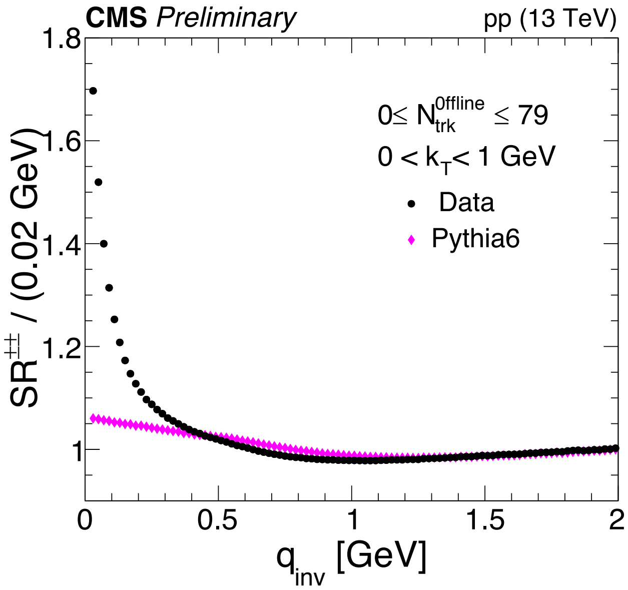
$$R^{\exp}(q = k_1 - k_2) = \frac{\mathcal{S}(k_1,k_2)}{\mathcal{B}(k_1,k_2)} = \left[\frac{dN_{\text{signal}}/dq}{dN_{\text{ref}}/dq}\right]$$

Pairs of same charge tracks from the same event (with BEC)

Different reference samples (no BEC)

Background or Reference Sample pair selection options (one of the main sources of systematic uncertainties):

- Same event – examples:
  - opp. charges (☹ resonances)
  - rotation of 1 track of the pair
- Mixed events (😊) – examples:
  - Tracks with similar multiplicity within same η range (default)
  - Random mixing: Mix 40 events in a given multiplicity range

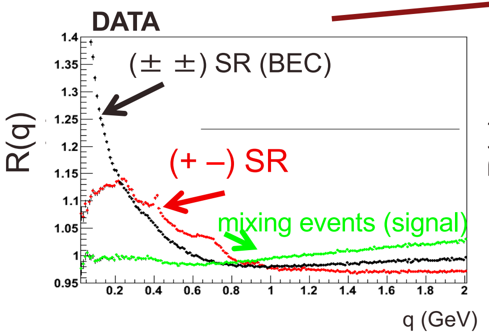


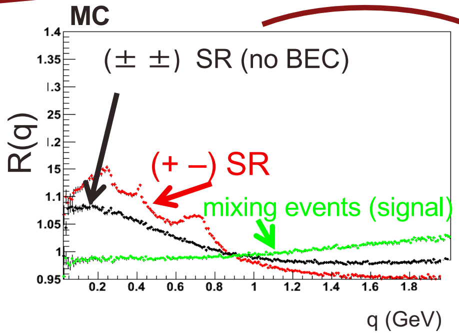
https://cds.cern.ch/record/2318575 (FSQ-15-009-pas.pdf)

Double Ratios (DR) Method

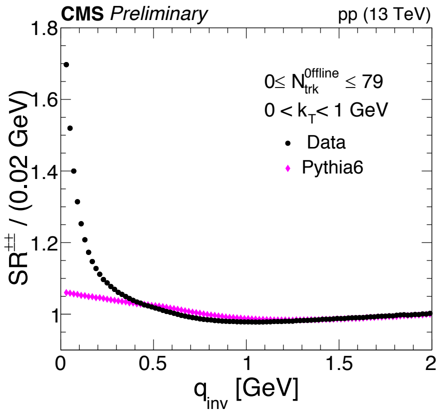
Ref. sample: similar $N_{trk}^{offline}$ in same η range

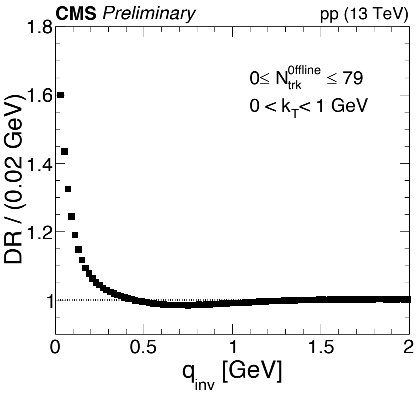
- Data (± ±) SR shows BEC
- Data (+ –) SR: resonances & cluster (not in mixing)
- MC (+ –) SR: reproduces resonances + cluster
- Shows (non-BEC) correlation in (± ±) MC
- To eliminate such spurios correlations
  - double ratio technique (DATA/MC)





CMS Collab., PRL 105, 032001 (2010)
CMS Collab., JHEP05(2011)29
CMS Collab., PRC 97 (2018) 064912





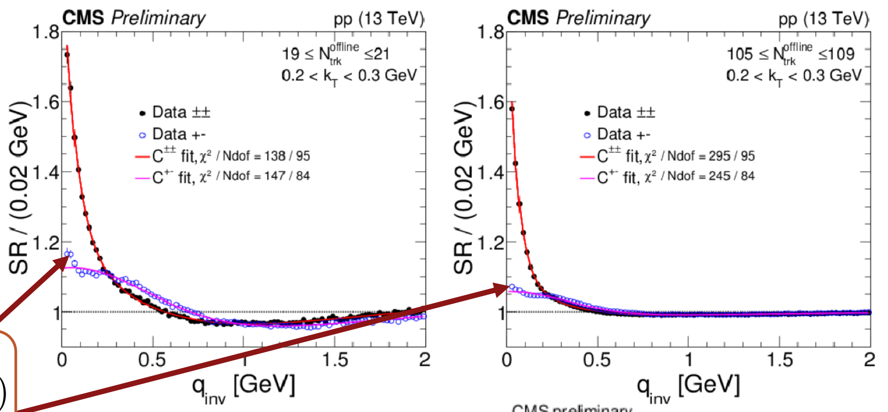
Double Ratios (DR)→remove non-BEC and reduce bias

$$C_{BE}(q) = \frac{R(q)}{R_{MC}(q)} = \frac{\left[\frac{dN_{signal}/dq}{dN_{ref}/dq}\right]}{\underbrace{\left[\frac{dN_{signal}/dq}{dN_{ref}/dq}\right]}_{\text{(No BEC in MC)}}}$$

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

Cluster Subtraction (CS) method – I

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



Remove non-BEC contributions [PRC 97 (2018) 064912]

- Fully data-driven technique
- Effect of resonances: decreases with increasing $N_{\mathrm{trk}}^{\mathrm{offline}}$
- Modulation of non-BEC effect from h$^{\pm}$ SR in data

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

- *b* and σ_b can be parametrized as
  - b → cluster amplitude:

$$b(N_{\mathrm{trk}}^{\mathrm{offline}}, k_T) = \frac{b_0}{N_{\mathrm{trk}}^{\mathrm{offline}}}\exp\left[-\left(\frac{k_T}{k_0}\right)\right]$$

  - σ_b → cluster width:

$$\sigma_b(N_{\mathrm{trk}}^{\mathrm{offline}}, k_T) = \left[\sigma_0 + \sigma_1 \exp\left(-\frac{N_{\mathrm{trk}}^{\mathrm{offline}}}{N_0}\right)\right]k^{n_T}$$

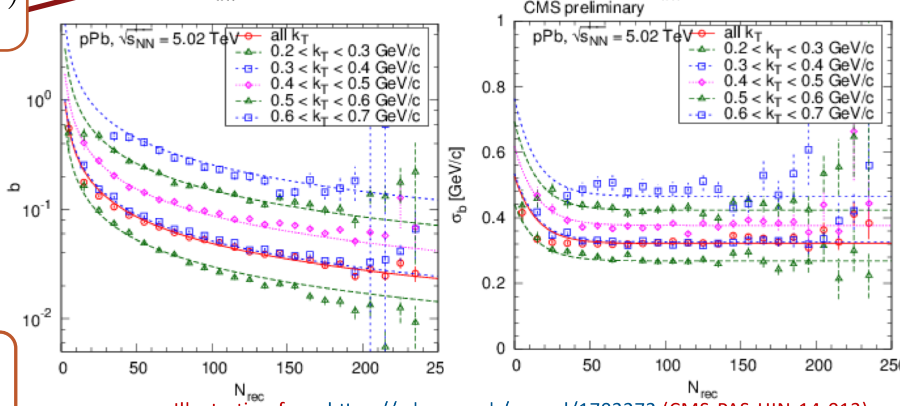


Illustration from https://cds.cern.ch/record/1703272 (CMS-PAS-HIN-14-013)

Cluster Subtraction (CS) method – II

Modulation of non-BEC effect in $h^{\pm}$ correlations:

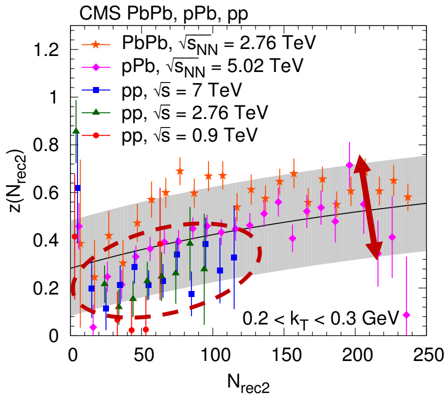
- The cluster contribution: also present in $h^{\pm}$ pairs, with similar shape but a smaller amplitude (see slide # 7)
- Use the form of the contribution obtained from $h^{\pm}$ pairs: b and σ_b fixed
- Assume the width is the same and determine the $(\pm\pm)$ cluster relative amplitude $z(N_{\rm trk}^{\rm offline})$

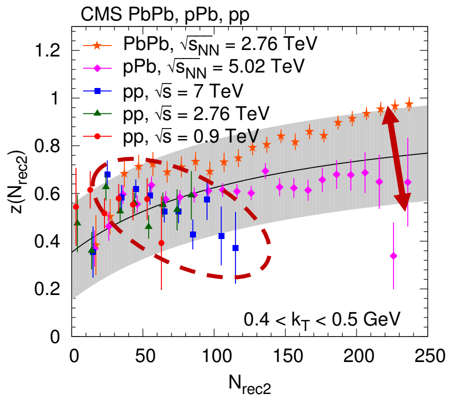
$$C^{\pm\pm}(q_{\rm inv}) = c\left[1 + z\left(N_{\rm trk}^{\rm offline}\right)\frac{b}{\sigma_b\sqrt{2\pi}}\exp\left(-\frac{q_{\rm inv}^2}{2\sigma_b^2}\right)\right]C_{BE}(q_{\rm inv})$$

$$z(N_{\rm trk}^{\rm offline}) = \left(\frac{aN_{\rm trk}^{\rm offline}+b}{1+N_{\rm trk}^{\rm offline}+b}\right)$$

$$C_{BE}(q_{\rm inv}) = [1+\lambda\exp(-q_{\rm inv}R_{\rm inv})]$$

Illustration from
PRC 97 (2018) 064912





Hybrid Cluster Subtraction (HCS) Method – I

Technique used by ATLAS [PRC 96 (2017) 064908] in BEC analysis with pPb events

- Goal: remove the non-Bose-Einstein contributions

Procedure

- Simulation → goal: estimate the Background (*Bkg*), non-BEC, present in data SR
  - Obtain *conversion functions*: relate [*Bkg* (+ –)] ↔ [*Bkg* (±±)] using SR from MC
  - Use *conversion functions*: convert fit parameters from [*Bkg* (+ –)] into Bkg (±±) in SR from data

- Final fit function in data (±±) SR: combination of *Signal* + *Bkg* forms
  - *Bkg* fixed with the parameters obtained in the previous step
  - **Notation: Background parameters denoted as *B* and σ_B (as defined in the next slide)**
  - Resulting *Signal*: described by free parameters (λ and R_{inv}) fitted with exponential function

Hybrid Cluster Subtraction (HCS) Method – II

Fitting Same-Sign and Opp-Sign **SR in MC**

- ❑ In Monte Carlo: no Bose-Einstein effects → Bkg can be modeled by fit parameters
- ❑ In data: BE effect **not** present in [(+ –)] component – Bkg only
  - Use the relations from MC to estimate the Bkg component in (±±) SR

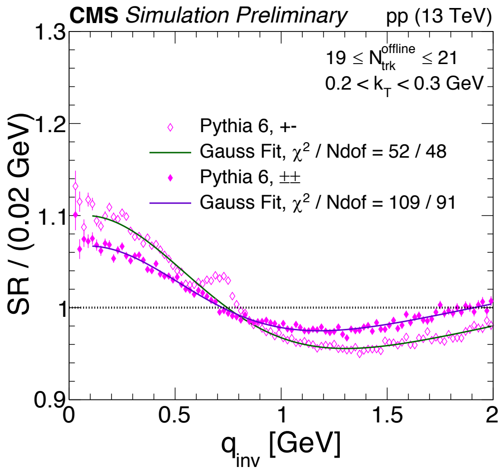
Fit Functions

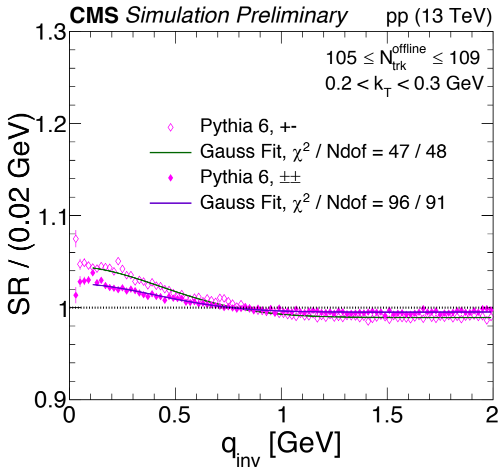
$$\Omega(q_{\rm inv}) = \mathcal{N}\left(1 + B\exp\left[-\left|\frac{q_{\rm inv}}{\sigma_B}\right|^{\alpha_B}\right]\right)$$

- Fit parameters relation ($\alpha_{B,A}^{\rm inv}$ =2)

$$\left[(\sigma_B)^{-1}\right]^{\pm\pm} = \rho\left[(\sigma_B)^{-1}\right]^{+-} + \beta$$

$$B^{\pm\pm} = \mu(k_T)\,\left[B^{+-}\right]^{\nu(k_T)}$$





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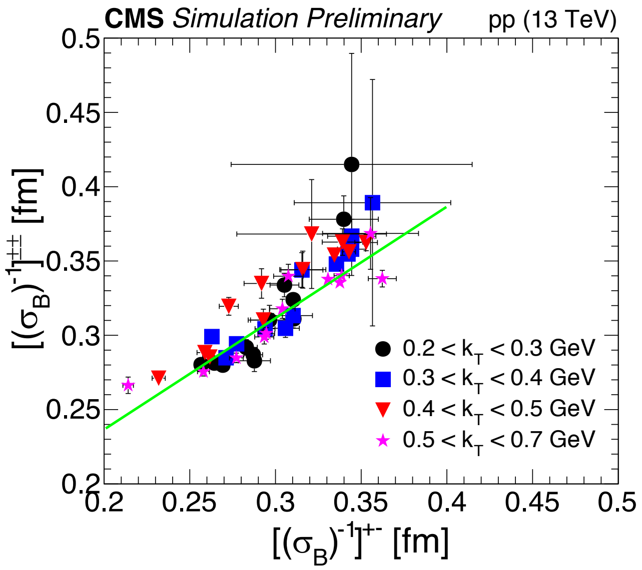
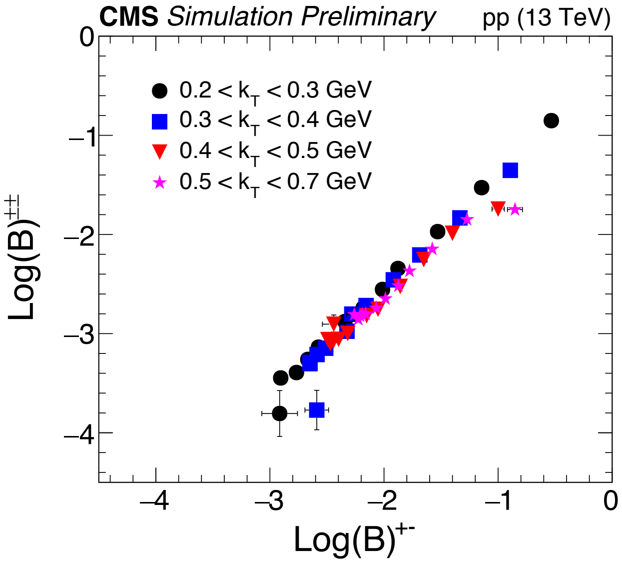
Hybrid Cluster Subtraction (HCS) Method – III

Relation $[(\sigma_B)^{-1}]^{\pm\pm}$ vs. $[(\sigma_B)^{-1}]^{+-}$ (Pythia6 Z2*):



$$[(\sigma_B)^{-1}]^{\pm\pm} = \rho[(\sigma_B)^{-1}]^{+-} + \beta$$

Relation $(B)^{\pm\pm}$ vs. $(B)^{+-}$ (Pythia6 Z2*):



ρ=0.82 $\pm$ 0.04 (stat.); β = 0.077 $\pm$ 0.013 (stat.)

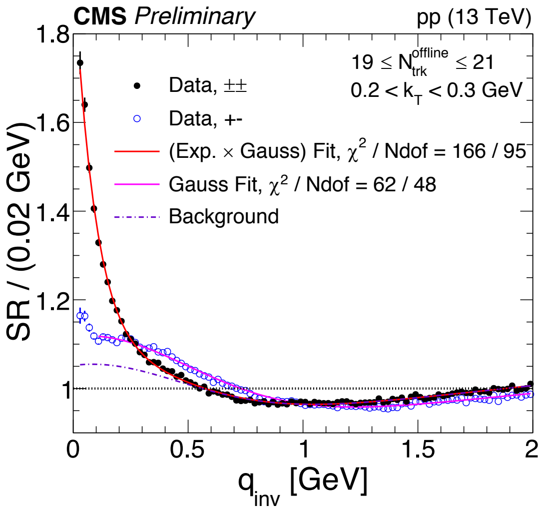
https://cds.cern.ch/record/2318575

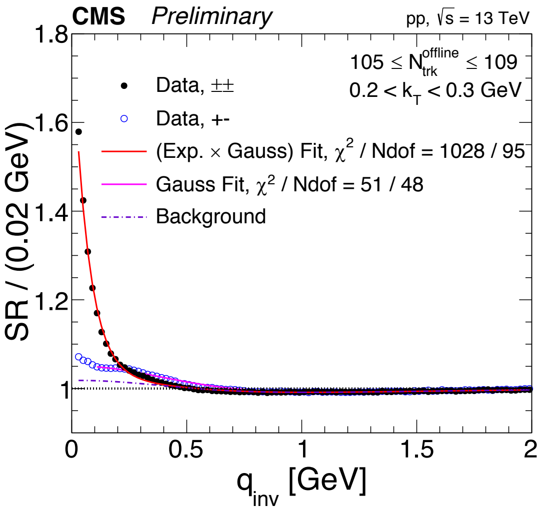
(CMS-PAS-FSQ-15-009)

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



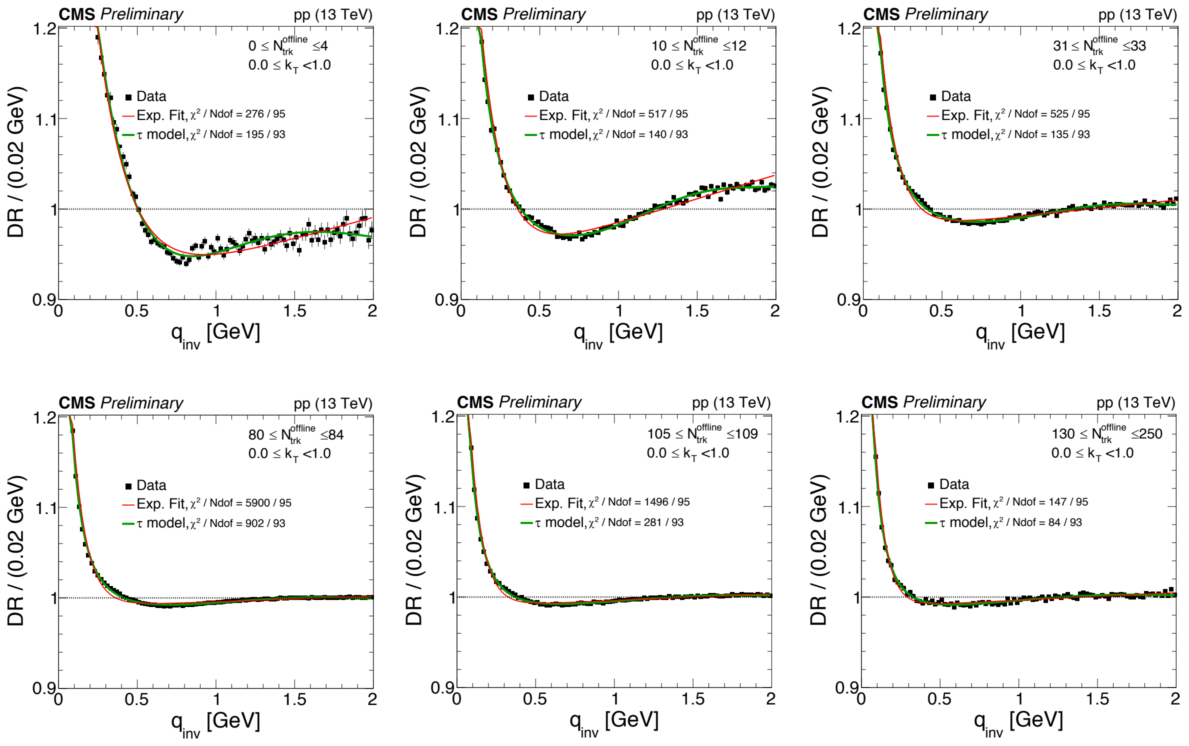


https://cds.cern.ch/record/2318575 (CMS-PAS-FSQ-15-009)

Results: discussion about anticorrelation (I)

Zoomed (along the y-axis) correlation functions from DR method

- Fits with exponential (red) and τ-model [Csörgö, Zimányi NPA **517** (1990) 588] (green)
- τ-model explains better the overall behavior of data
- Dip‘s depth (Δ):
  - distance of the τ-model fit at its minimum and the baseline $C(1+\varepsilon\, q_{inv})$

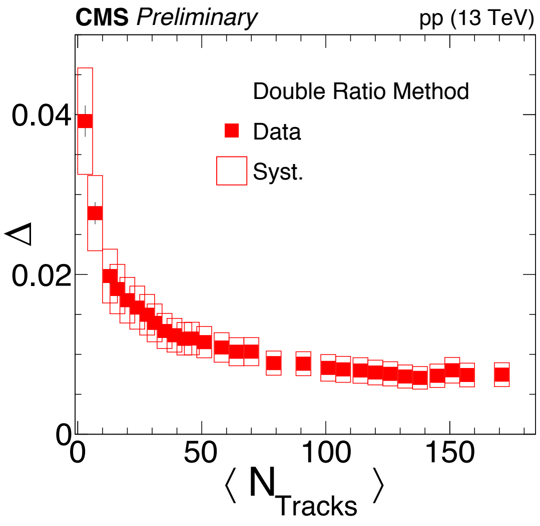


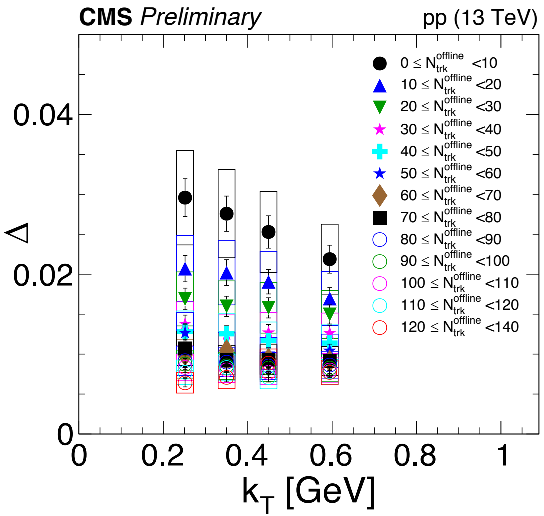
https://cds.cern.ch/record/2318575 (CMS-PAS-FSQ-15-009)

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

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

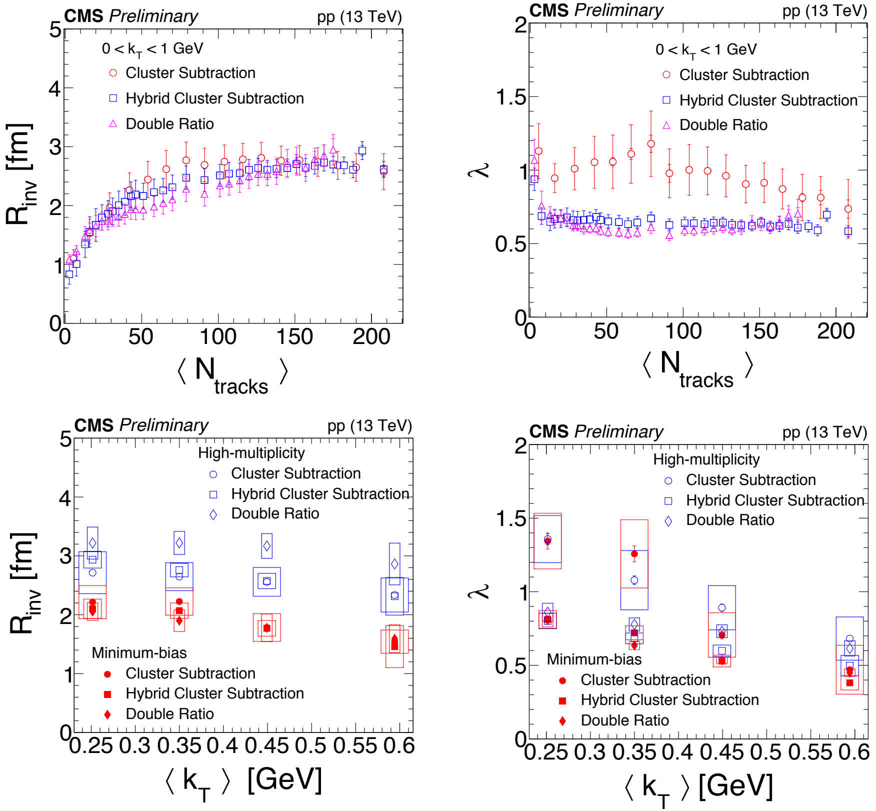
Results for R_{inv} and λ (with systematics)

For the three methods

- ❑ R_{inv} and λ as functions of multiplicity and k_T

Similar trends for all the methods

- ❑ R_{inv} increases with multiplicity and decreases with k_T
- ❑ λ decreases with multiplicity (mainly for lower values) and decreases with k_T
- ❑ Larger deviations in the magnitude of λ for CS technique (larger uncertainties in this method)
- ❑ HCS chosen for comparison (with relative uncert.)

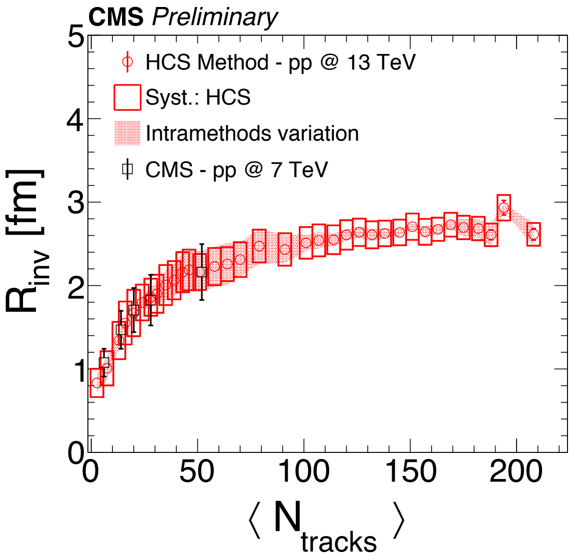


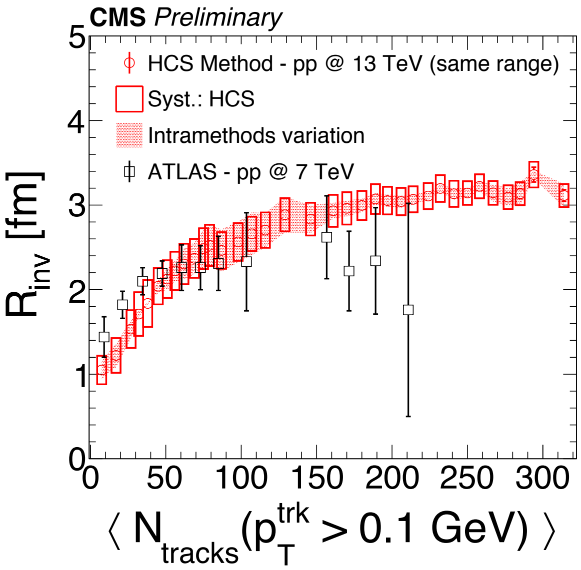
https://cds.cern.ch/record/2318575 (CMS-PAS-FSQ-15-009)

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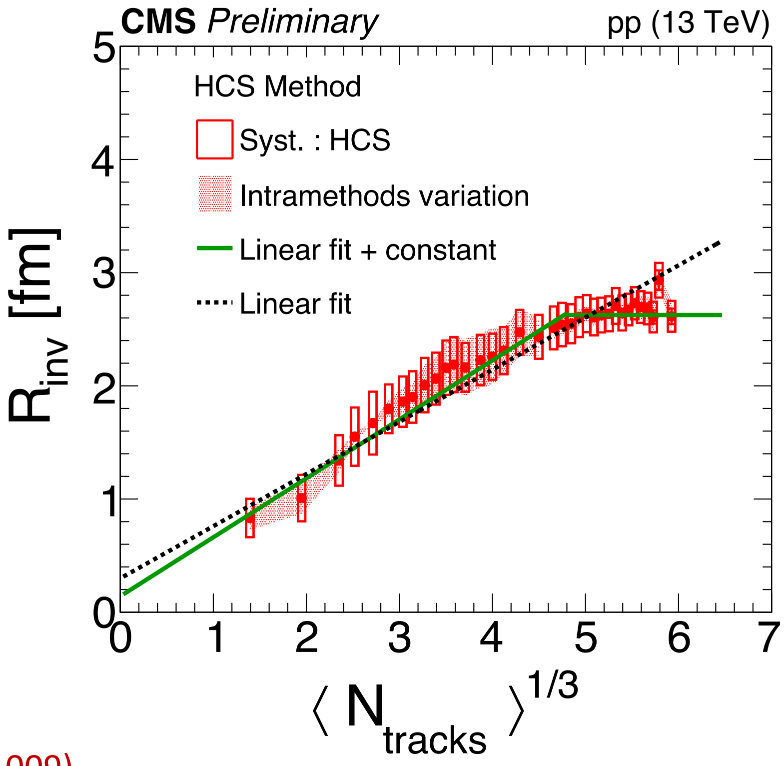
R_{inv} vs. $N_{\mathrm{tracks}}^{1/3}$

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

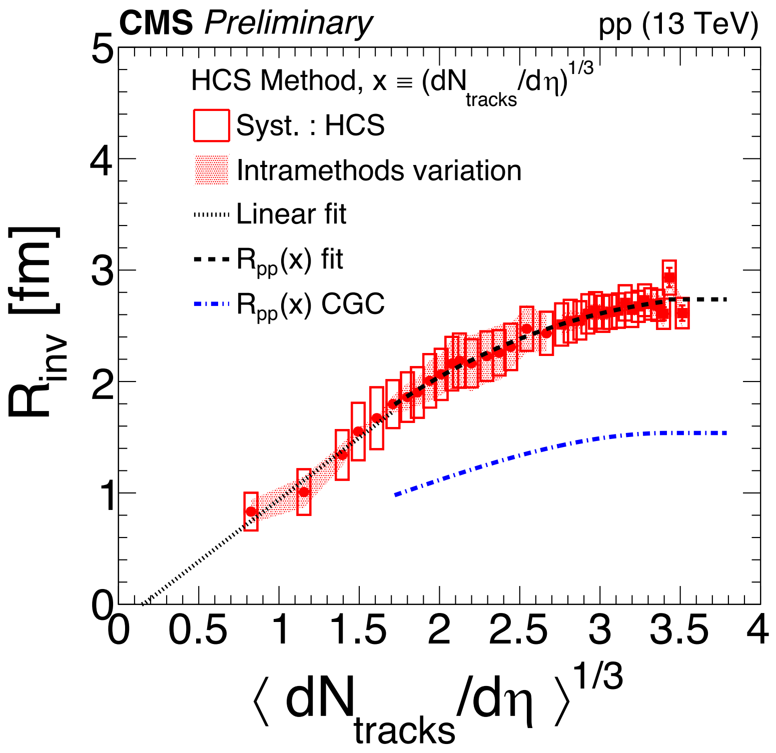
- [*McLerran, Schenke, NPA* **916** (2013) 210; P. T. A. Bzdak et al, *PRC* **87** (2013) 064906]

- 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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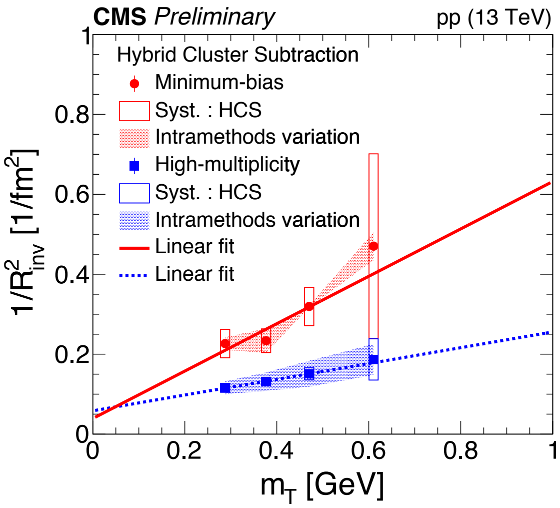
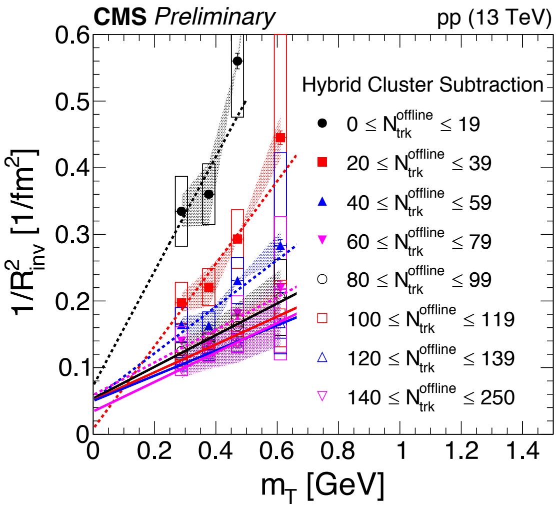
m_T dependence

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

- 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

$N_{\mathrm{trk}}^{\mathrm{offline}}$ 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

- $N_{\mathrm{trk}}^{\mathrm{offline}} = 0 - 250$
- k_T (GeV) < 1 GeV or
  $k_T \in \{0.2\text{-}0.3, 0.3\text{-}0.4, 0.4\text{-}0.5, 0.5\text{-}0.7\}$

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

- q_{inv} (GeV) = 0.02 – 2.0

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

- Fit Function used :

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

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