



Femtoscopic BEC of charged hadrons in pp collisions at 13 TeV in CMS

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Outline of the talk

New: Lengths of homogeneity (R_{inv}) and BEC intensity (λ) in broad multiplicity range (≤ 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 need to be independent on analysis technique
 - Three analysis methods are employed
- ❑ Brief introduction to the three analysis techniques (emphasis in one of them)
- ❑ Brief summary of the systematic uncertainties

Results

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

Outline of analysis methods

Double Ratio (DR),
as in (*), CMS-FSQ-13-002-PAS & (**)

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

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

(**) *CMS*, *arXiv*: 1712.07198

Cluster Subtraction (CS) –
fully data-driven,
as in CMS-HIN-14-013-PAS & (**)

- ❑ Employs Single Ratios only
- ❑ Non-BEC cluster is estimated directly from data (+ –) SR
 - Estimates the amplitude (“height”) of the cluster using ($\pm\pm$) SR in data
- ❑ Fit SR with functional form combining sig+cluster components

Hybrid Cluster Subtraction (HCS) partially data-driven,
as in ATLAS-CONF-2016-027

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

Common to all methods – I (Coulomb and fit)

Final state (Coulomb) interactions

- Analytic formula for Coulomb correction
[HIN-14-014-PAS, arXiv: 1712.07198]

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

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

- In pp collisions → well-approximated by Gamow factors

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

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

One-dimensional fit to Correlation Functions

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

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

- Lévy distribution with $a \rightarrow$ index of stability; particular cases:

◦ exponential fit ($a = 1$)

◦ Gaussian fit ($a = 2$)

◦ $\epsilon \rightarrow$ fit parameter (long-range correlations)

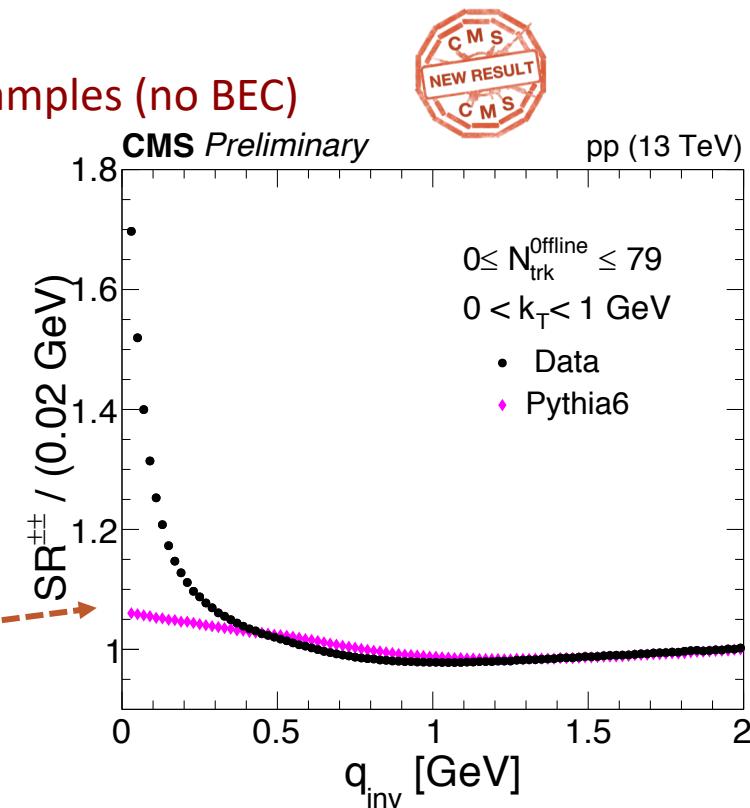
Common to all methods – II (Single Ratios)

Single Ratios (SR)

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

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

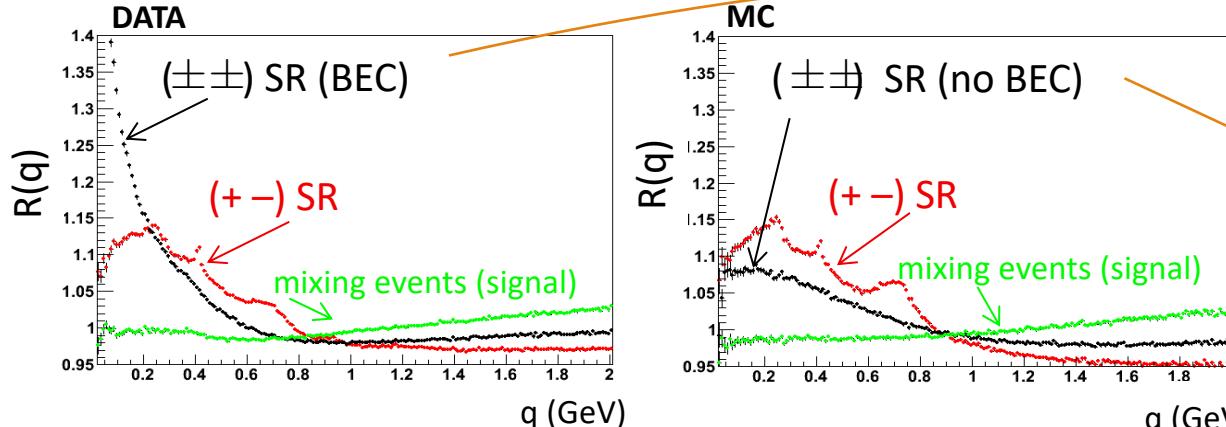


<https://cds.cern.ch/record/2318575> (FSQ-15-009-pas.pdf)

Double Ratios (DR) Method – I

Ref. sample: similar $N_{\text{trk}}^{\text{offline}}$ in same η range (default)

ILLUSTRATION

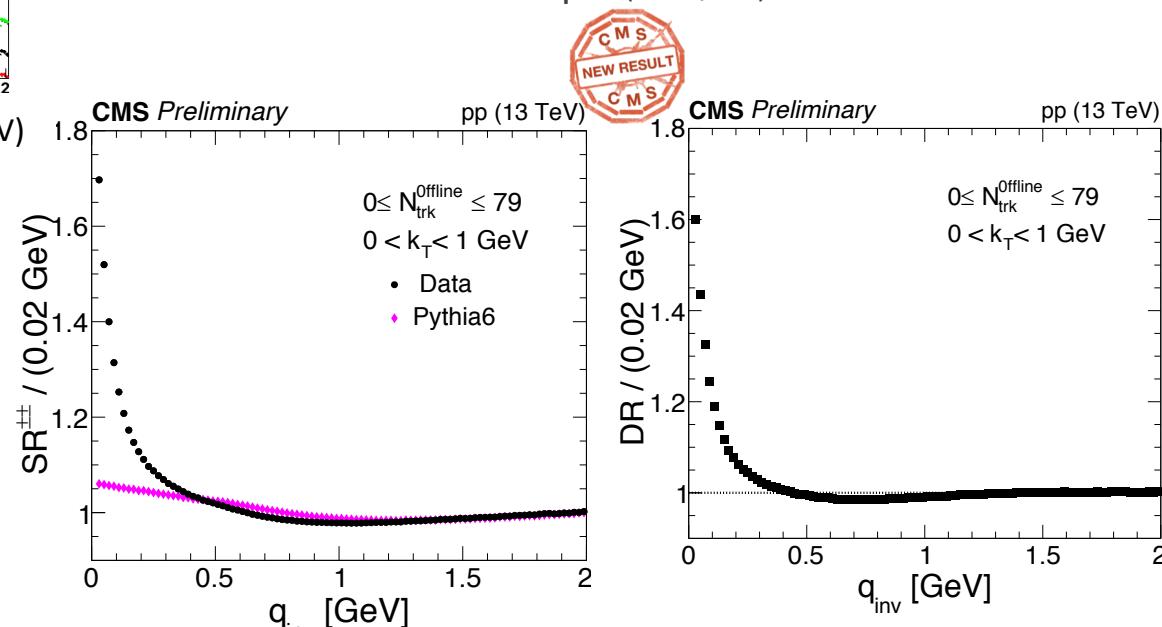


CMS Collab., PRL 105, 032001 (2010)

CMS Collab., JHEP05(2011)29

CMS Collab., [arXiv:1712.07198](https://arxiv.org/abs/1712.07198), to appear in PRC

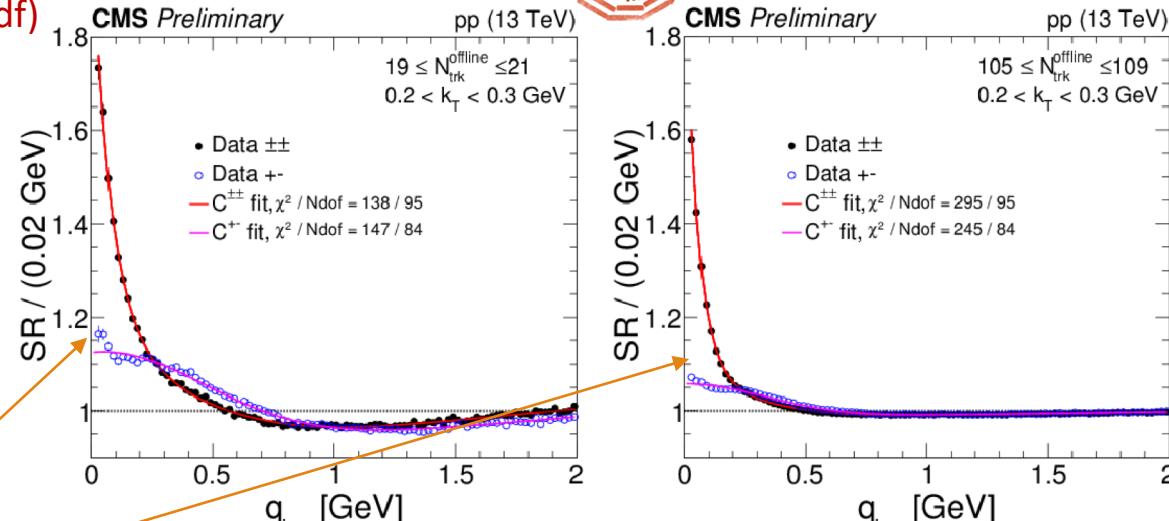
- Data ($\pm\pm$) SR shows BEC
- Data (+-) SR: resonances + cluster (not in mixing)
- MC (+-) SR: reproduces resonances + cluster
- Shows (non-BEC) correlation in ($\pm\pm$) MC
- To eliminate such spurious correlations:
double ratio technique (DATA/MC)



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

Custer Subtraction (CS) method - I

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



Remove non-BEC contributions (CSM, arXiv: 1712.07198)

- ❑ Fully data-driven technique
- ❑ Effect of resonances: decreases with increasing $N_{\text{trk}}^{\text{offline}}$
- ❑ Modulation of non-BEC effect from π^{+-} SR in data

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

- ❑ b and σ_b can be parametrized as

◦ $b \rightarrow$ cluster amplitude:

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

◦ $\sigma_b \rightarrow$ cluster width:

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

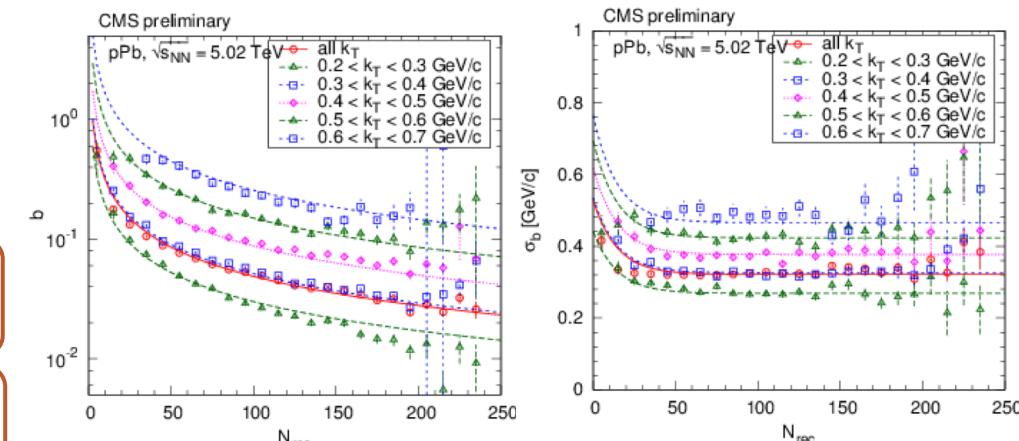


Illustration from CMSPAS-HIN-14-002

Fully Data-Driven (FDD) Method - II

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

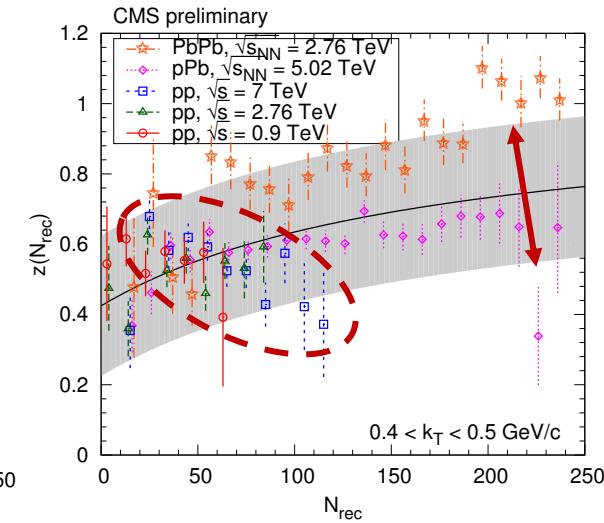
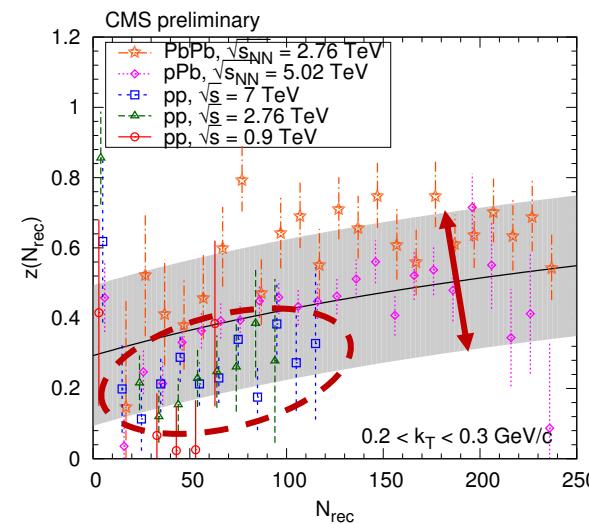
- ❑ The cluster contribution: also present in $h^{\pm\pm}$ pairs, with similar shape but a smaller amplitude (see MC, slide#5)
- ❑ Use the form of the contribution obtained from h^{+-} pairs: b and σ_b fixed
- ❑ Assume the width is the same and determine the ($\pm\pm$) cluster relative amplitude $z(N_{\text{trk}}^{\text{offline}})$

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

Illustration from CMS PAS-HIN-14-013

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

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



Hybrid Cluster Subtraction (HCS) Method – I

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

- ❑ Goal: remove the non-Bose-Einstein contributions

Procedure

- ❑ Simulation: used to estimate Background ("Bkg"), i.e., non-femtoscopic correlations, mainly due to jet fragmentation or Cluster (i.e., mini-jets, etc.) contribution, present in SR in the data
 - Obtain conversion functions: relate $[Bkg (+-)] \longleftrightarrow [Bkg (\pm\pm)]$ using SR from MC
 - Use transfer function: convert fit parameters from $[Bkg (+-)]$ into $Bkg (\pm\pm)$ in SR from data
- ❑ Final fit function in data ($\pm\pm$) 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 $(\pm \pm)$ SR

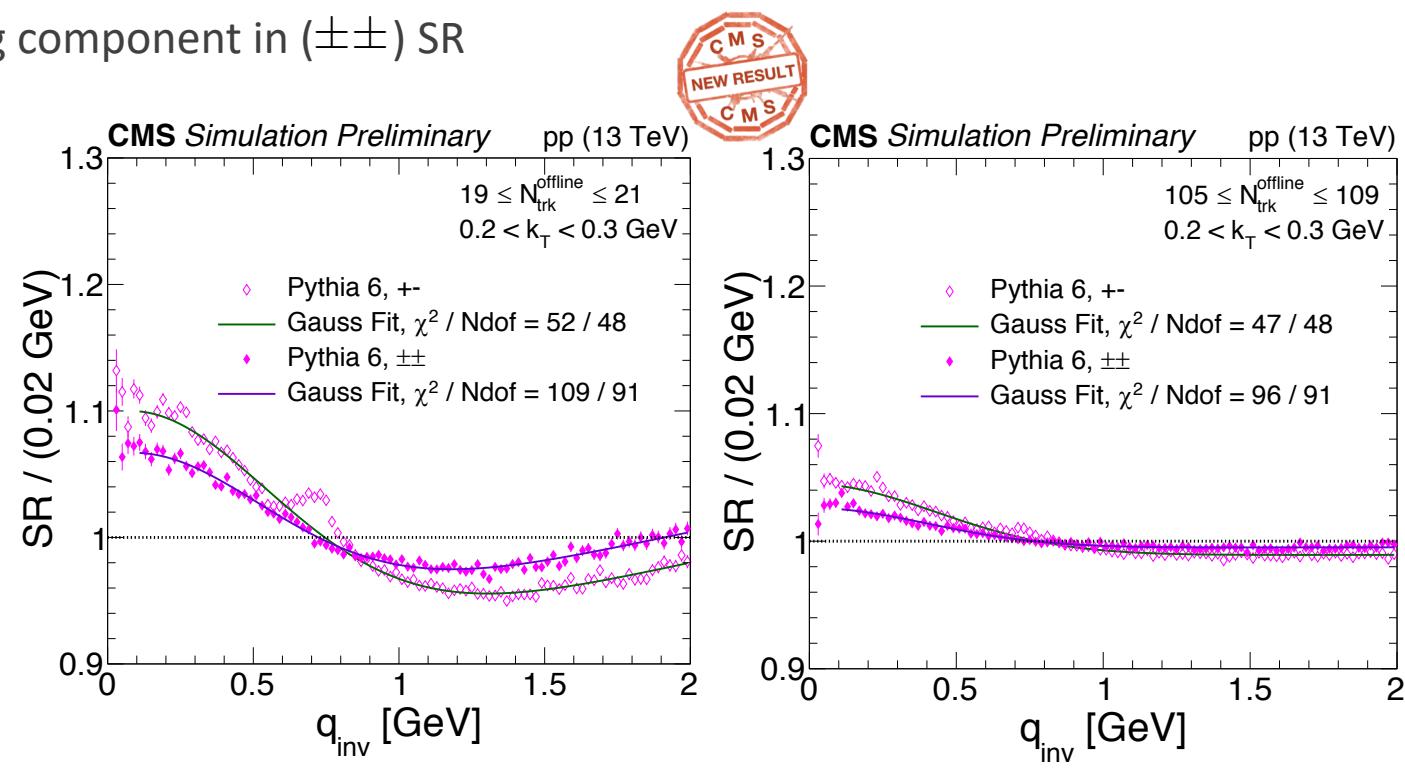
Fit Functions

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

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

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

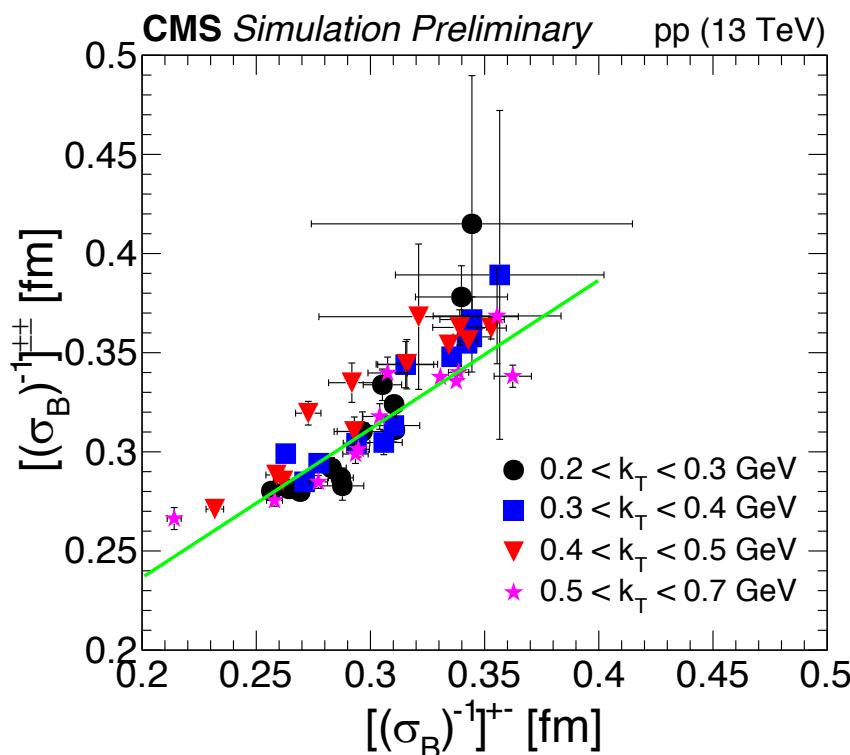
$$B^{\pm\pm} = \mu(k_T) [B^{+-}]^{\nu(k_T)}$$



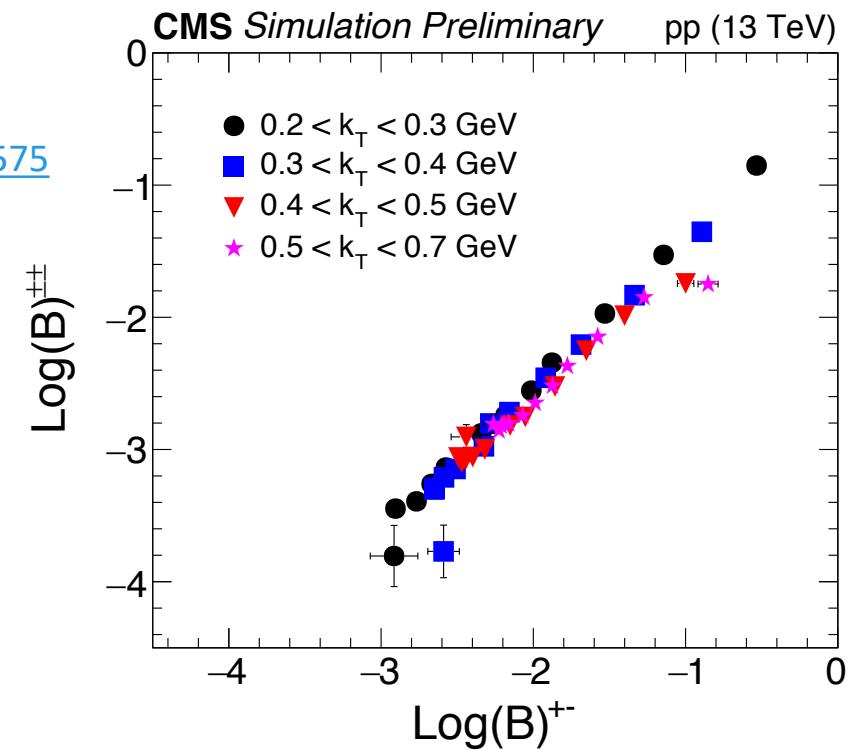
<https://cds.cern.ch/record/2318575> (FSQ-15-009-pas.pdf)

Hybrid Cluster Subtraction (HCS) Method – III

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



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



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

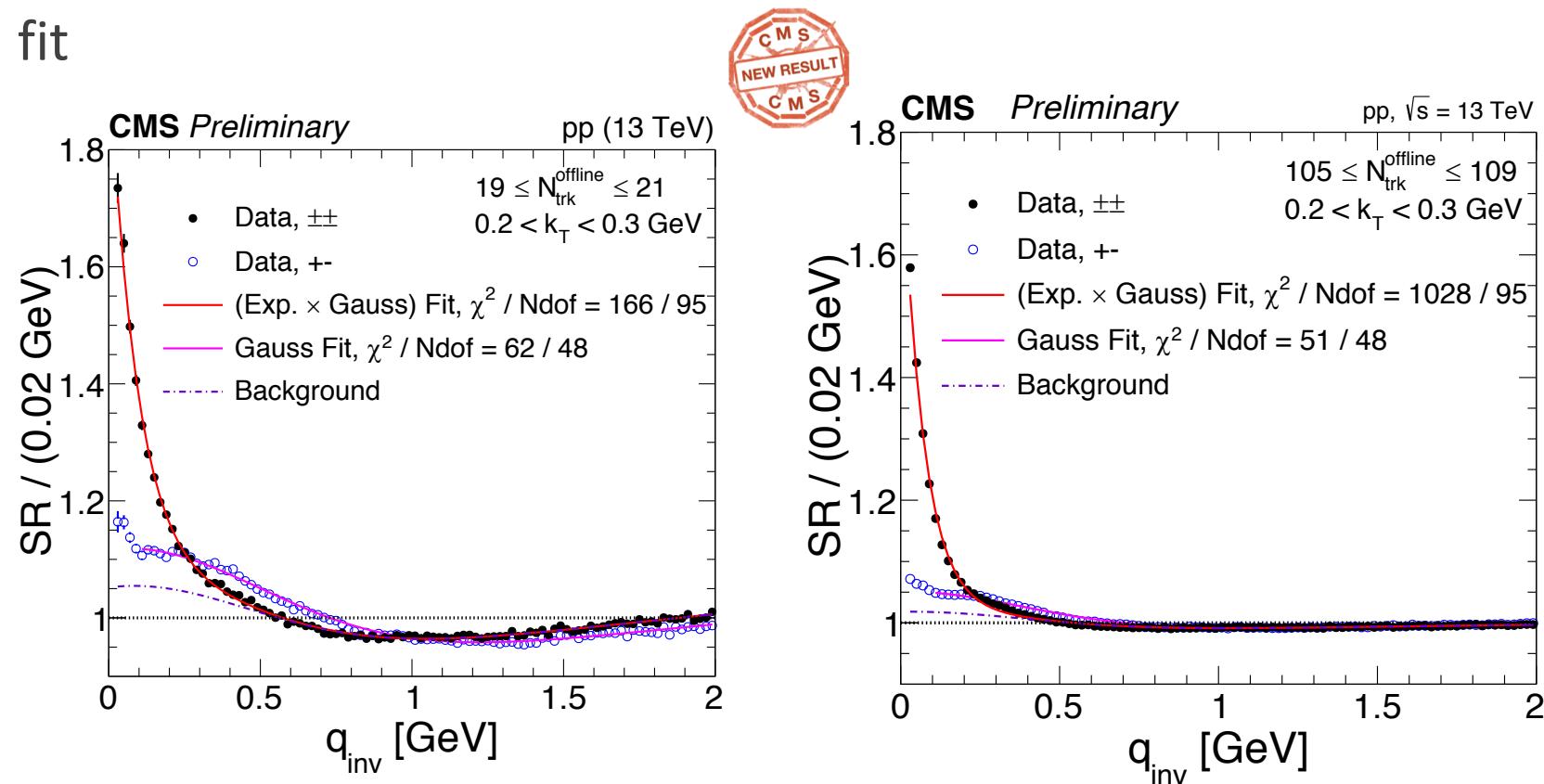
$$\rho = 0.82 \pm 0.04 \text{ (stat.)}; \beta = 0.077 \pm 0.013 \text{ (stat.)}$$

Hybrid Cluster Subtraction (HCS) Method – IV

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

After getting relations for ``Bkg'' fit parameters in Monte Carlo

- ❑ Bkg in data is estimated in (+ -) SR
- ❑ Assume relation of (+ -) SR and ($\pm\pm$) in data is the same as in MC
- ❑ Use conversion function to estimate ``Bkg'' in ($\pm\pm$) SR in data



Results with systematics

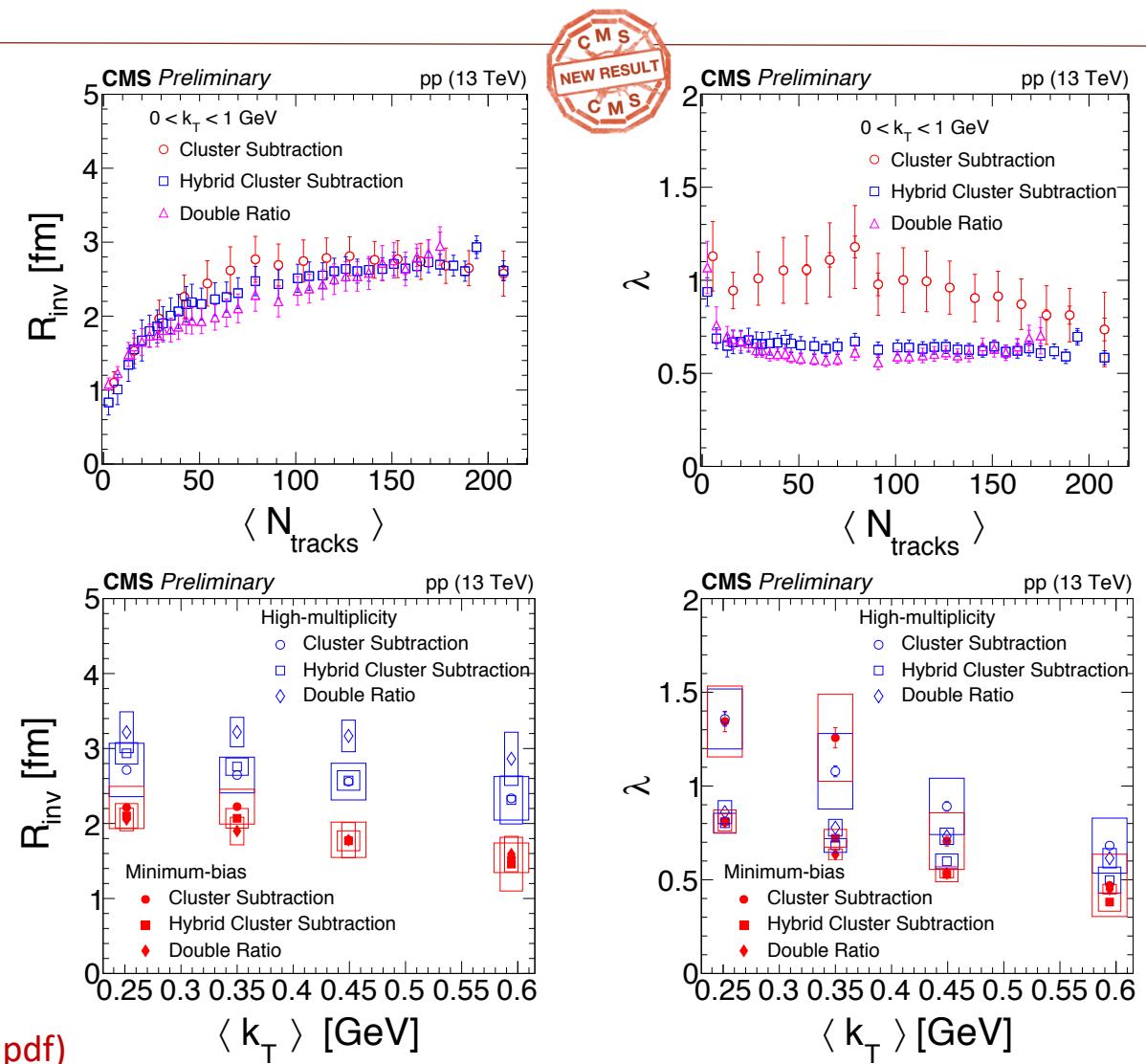
For the three methods

- 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)

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

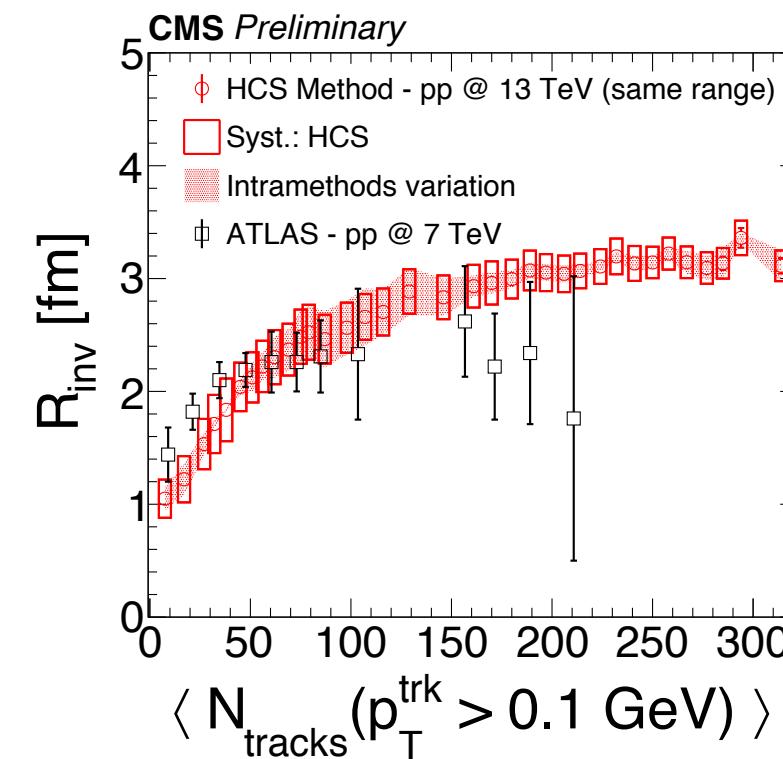
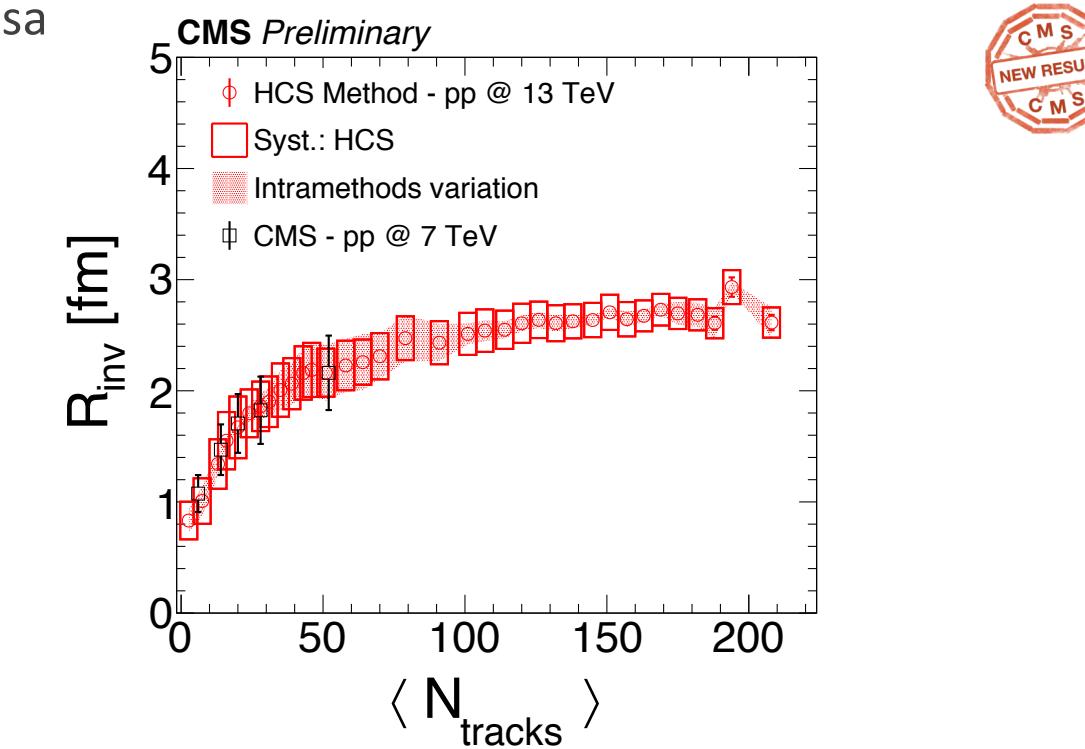


Comparison with CMS and ATLAS @ 7 TeV

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

R_{inv} Results from HCS compared to

- Left: CMS for pp@7 TeV [[arXiv: 1712.07198](https://arxiv.org/abs/1712.07198)] using Double Ratio method (η -mixing reference sample)
- Right: ATLAS for pp@7 TeV [[EPJC 75\(2015\)466](https://doi.org/10.1007/s10635-015-0106-0)] using Double Ratio method (opposite sign reference)



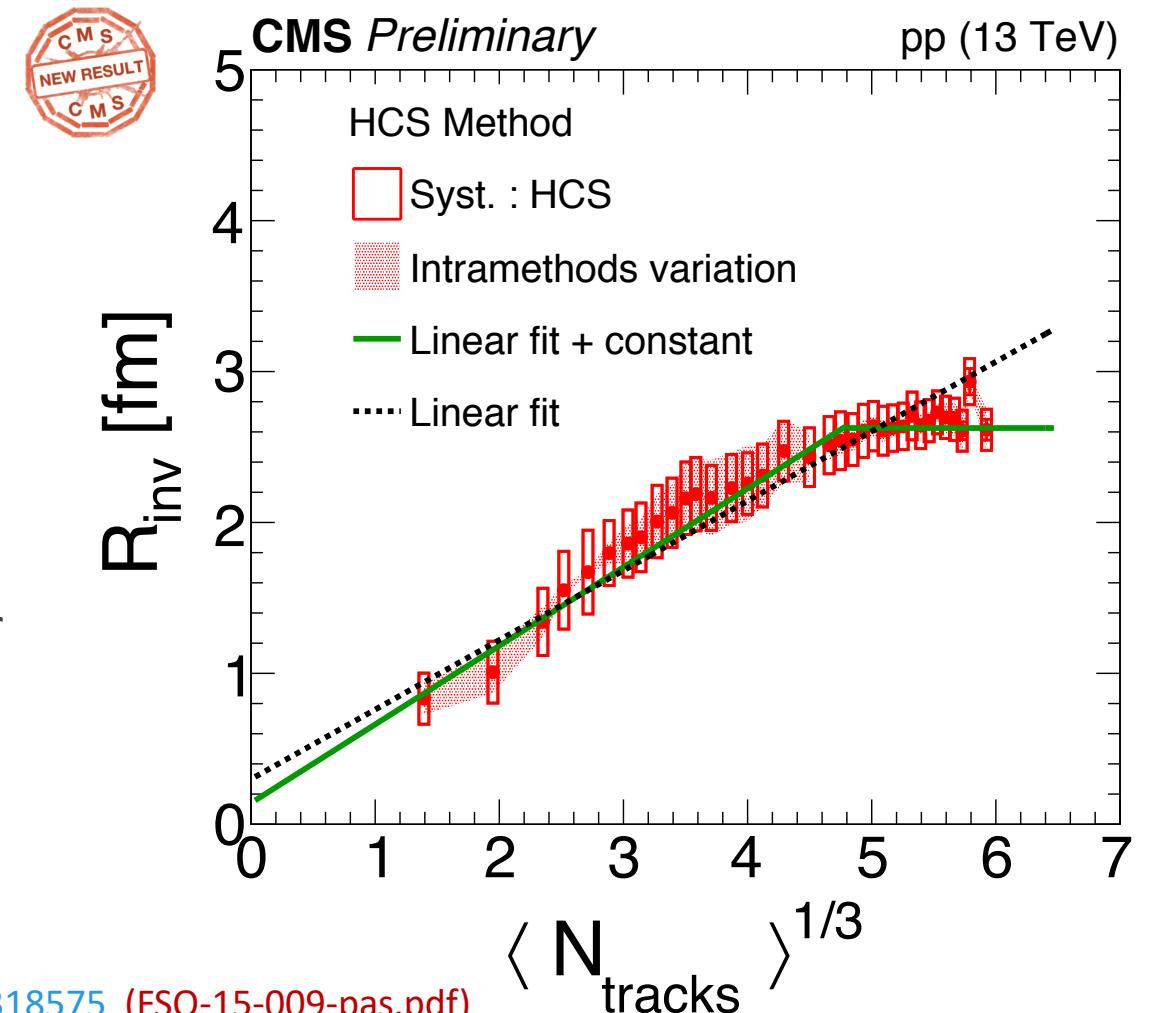
R_{inv} vs. $N_{\text{tracks}}^{1/3}$

All the fits using only statistical uncertainties

- ❑ Linear fit
 - $\chi^2/N_{\text{dof}} = 50$
- ❑ Linear + Constant
 - $\chi^2/N_{\text{dof}} = 40$

Including systematic uncertainties

- ❑ Not trivial to estimate point-to-point correlations
- ❑ Fit quality using fully correlated systematics is similar as using only statistical uncertainties
- ❑ Considering systematics fully uncorrelated
 - Linear fit : $\chi^2/N_{\text{dof}} = 0.4$
 - Linear + constant fit : $\chi^2/N_{\text{dof}} = 0.15$



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

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*]

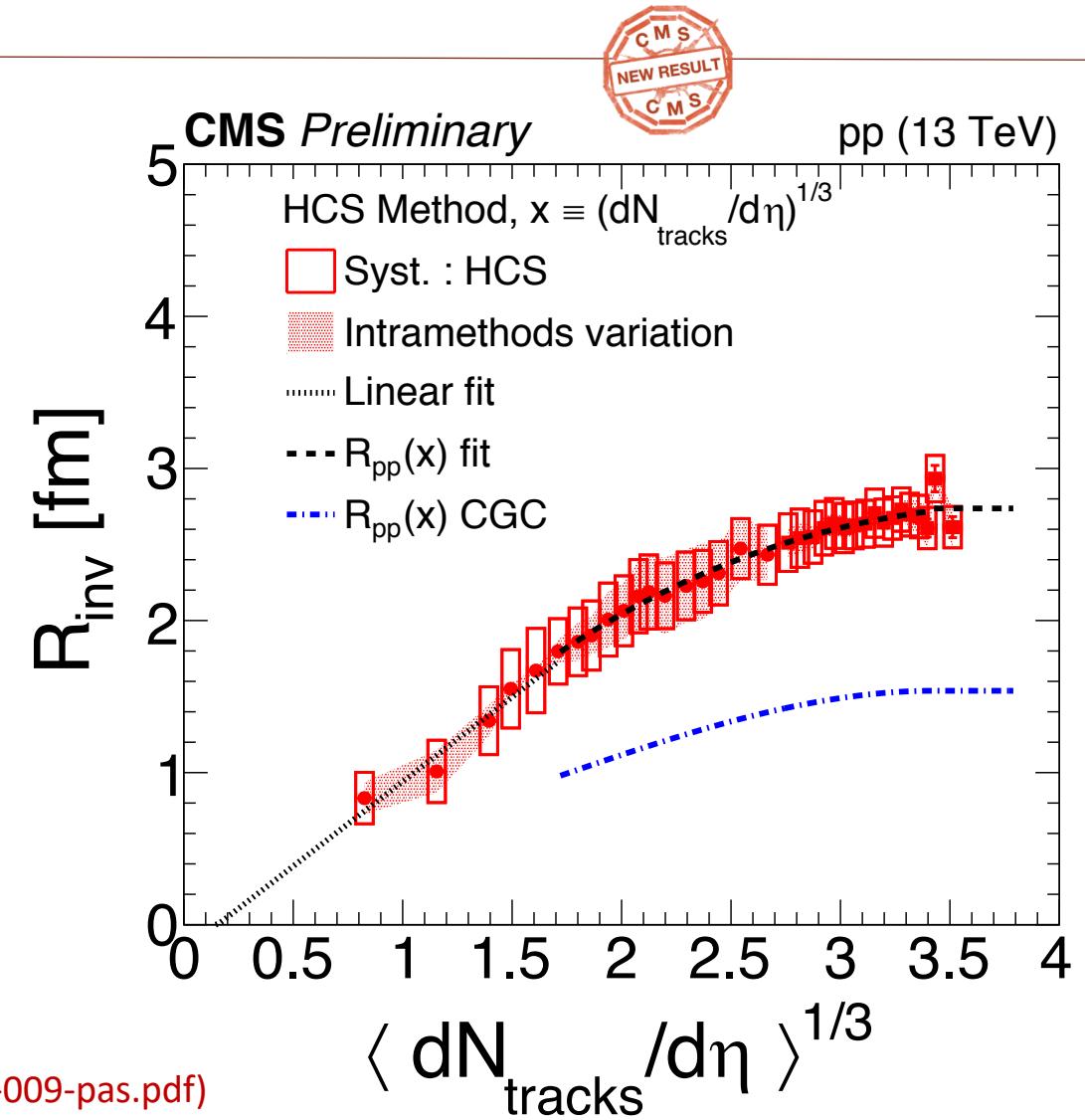
- Calculation for pp @ 7 TeV (does not include evolution of the system)
- Similar shape, but very big difference in magnitude

Above 1.7 : fit with same function obtained from CGC prediction

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

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

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



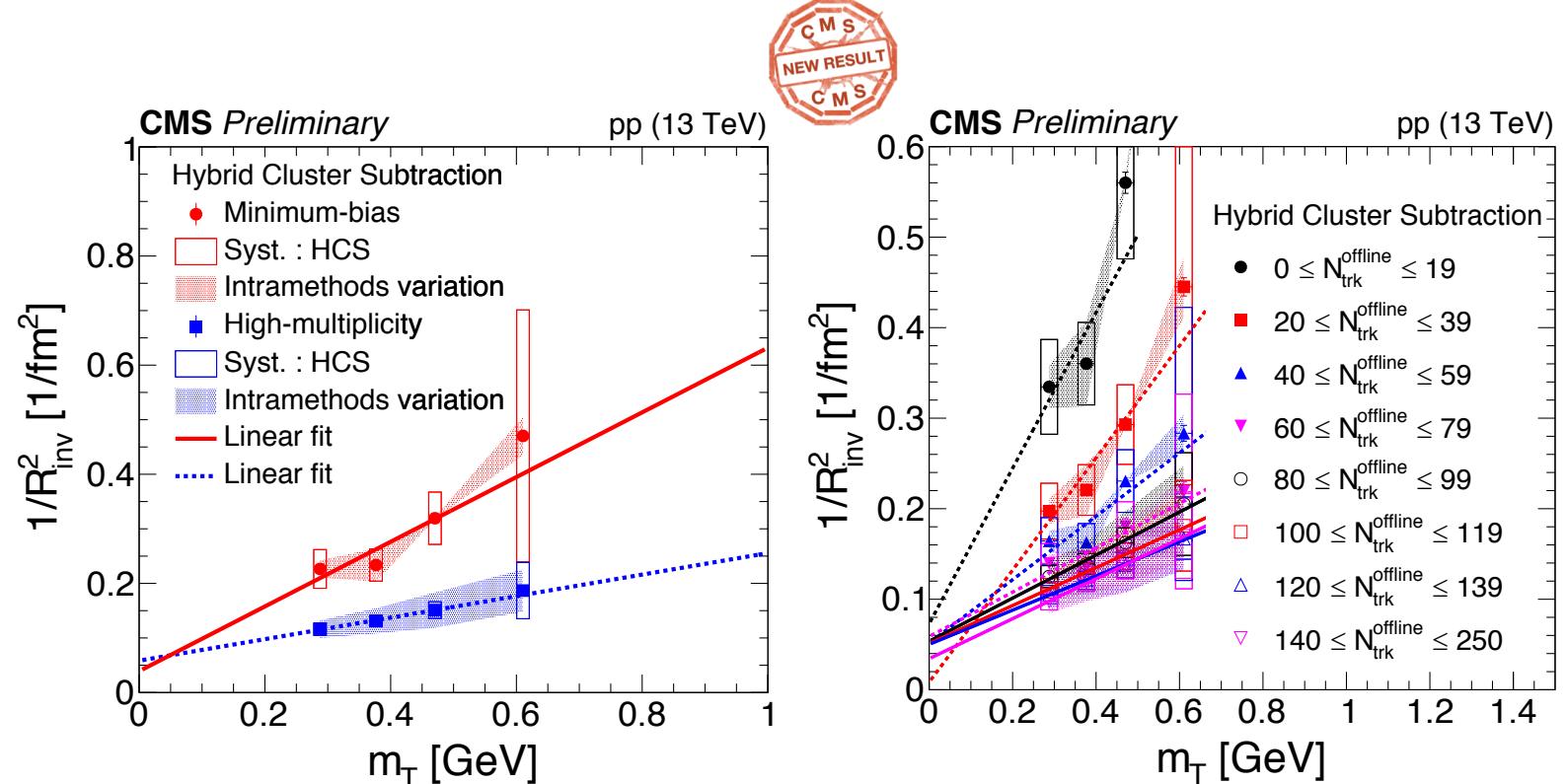
m_T dependence

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

- ❑ In hydrodynamic models
- [Sinyukov et al., NPA 946 (2016) 227]
- Intercept connected with the geometrical size of the source freeze-out)
- Slope connected to 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)

(at

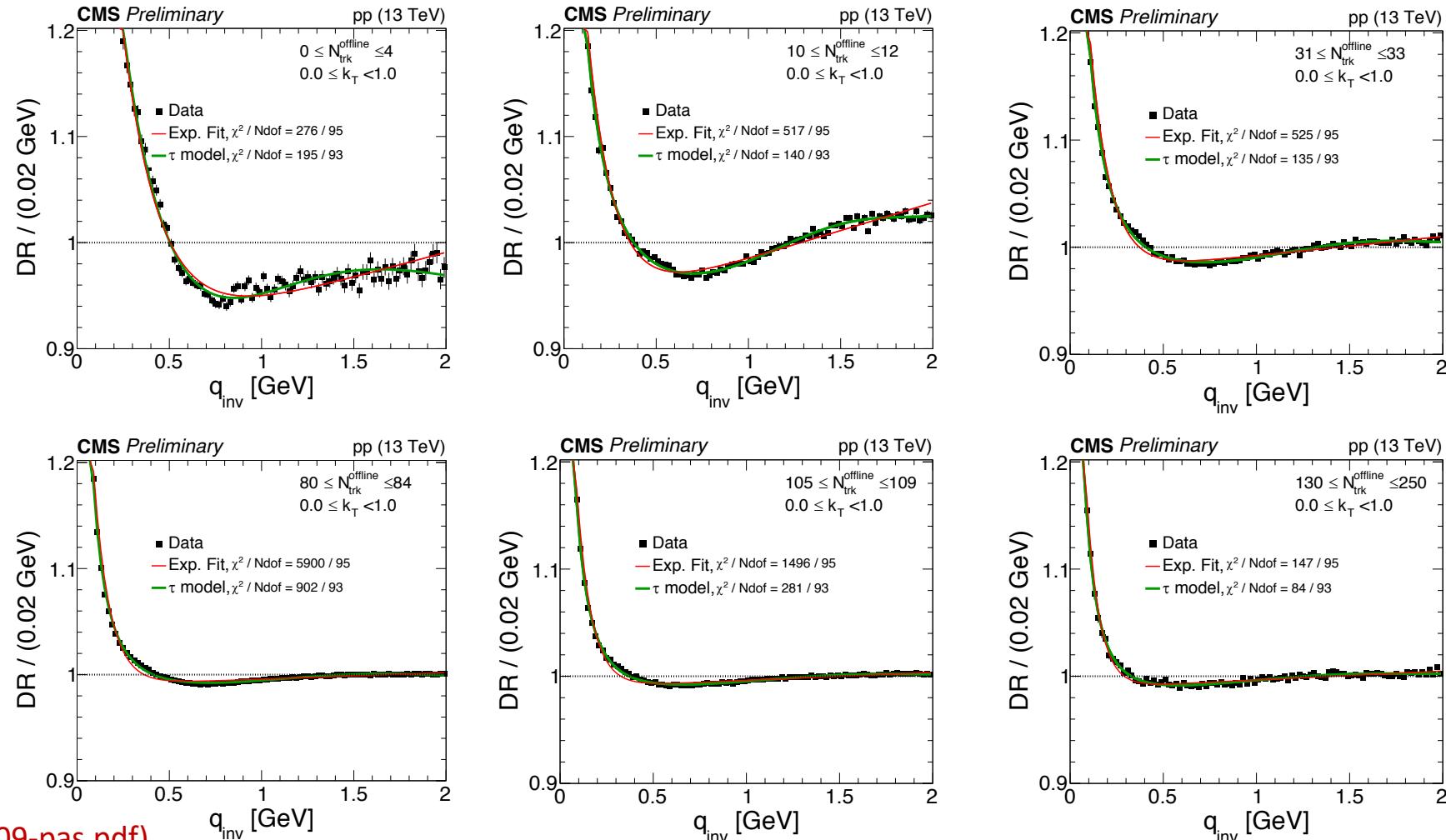


<https://cds.cern.ch/record/2318575> (FSQ-15-009-pas.pdf)

Discussion about an 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

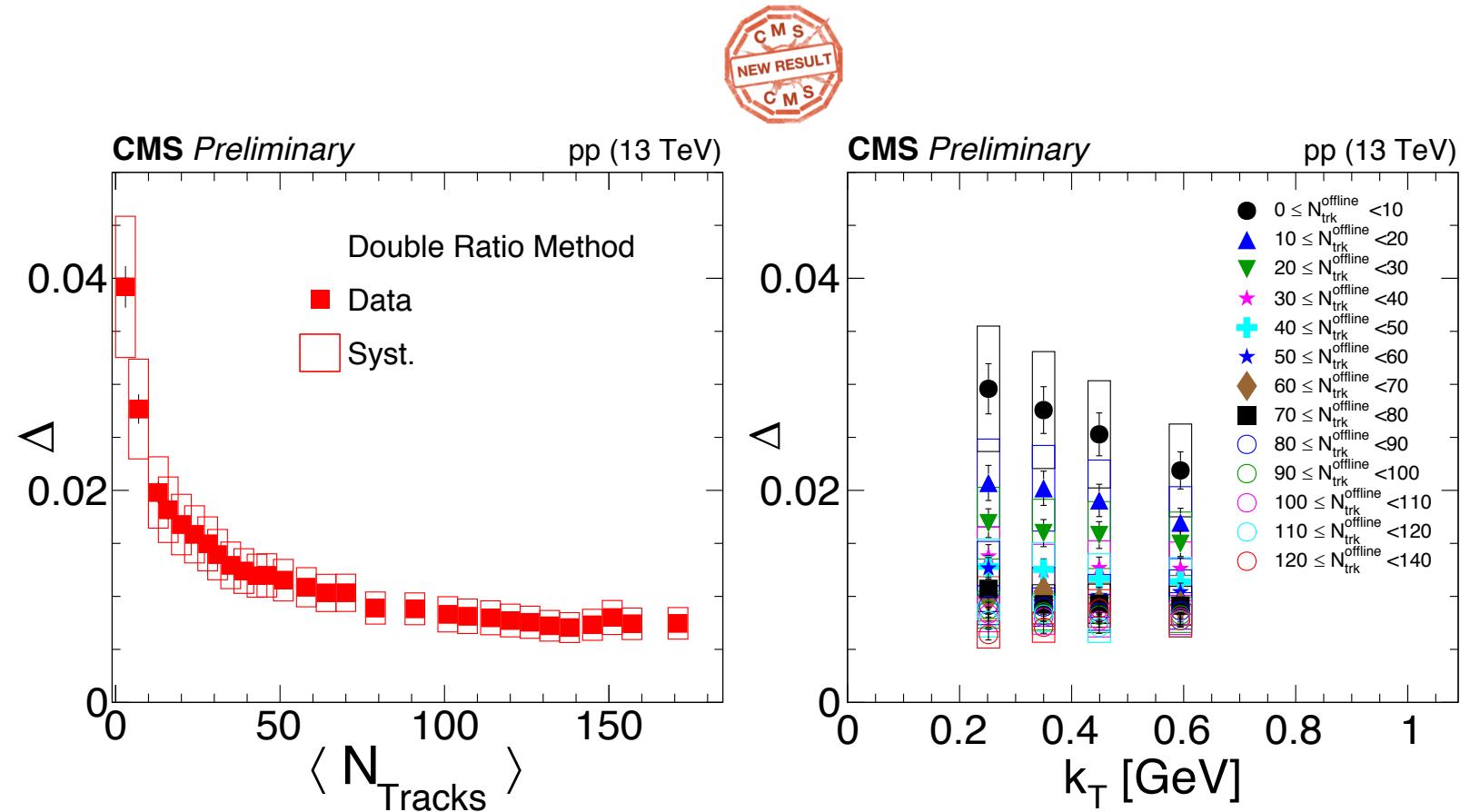


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Discussion about an anticorrelation (II)

Anticorrelation depth

- Integrated in k_T
 - Decreases with $\langle N_{\text{tracks}} \rangle$, and tend to $\sim \text{const.}$ above 100
- and differential in k_T
 - Decrease with k_T for lower $\langle N_{\text{tracks}} \rangle$ ranges
 - For $\langle N_{\text{tracks}} \rangle > 30 \rightarrow \sim \text{const.}$ with increasing k_T



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

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) – (FSQ-13-002-PAS, [arXiv:1712.07198](https://arxiv.org/abs/1712.07198))
 - Fully Data-driven as used in CMS – (HIN-14-013-PAS, [arXiv:1712.07198](https://arxiv.org/abs/1712.07198))
 - Hybrid Data-driven (transfer function from Pythia 6 – Z2* tune) – as proposed in ATLAS-CONF-2016-027
- ❑ 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 $(N_{\text{tracks}})^{1/3}$ 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 , searching for:
 - Possible change in behavior of R_{inv} results while moving from event in the MB to the HM regions, etc.
 - m_T – scaling with different slopes in MB and HM: Hubble-type of flow larger in MB than in HM
- ❑ 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]

<https://cds.cern.ch/record/2318575>; <https://cds.cern.ch/record/2318575/files/FSQ-15-009-pas.pdf>

ADDITIONAL SLIDES

Sources of systematic uncertainties

Main sources of systematic uncertainties

- ❑ Reference samples
- ❑ Monte Carlo modeling of correlation functions
- ❑ Cluster amplitude $z(N_{\text{trk}}^{\text{off}})$ 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

Experimental cuts and definitions adopted

$N_{\text{trk}}^{\text{offline}}$ definition

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

Track selection for BEC analysis

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

Other variables

- ❑ $N_{\text{trk}}^{\text{offline}} = 0 - 250$
- ❑ $k_T (\text{GeV}) < 1 \text{ GeV}$ or
 $k_T \in \{0.2-0.3, 0.3-0.4, 0.4-0.5, 0.5-0.7\}$
- $$k_T (\text{GeV}) = |p_{T,1} + p_{T,2}|/2$$

- ❑ $q_{\text{inv}} (\text{GeV}) = 0.02 - 2.0$

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

- ❑ Fit Function used :

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