

# Charged particle correlations with ATLAS



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on behalf of the ATLAS Collaboration



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# Overview

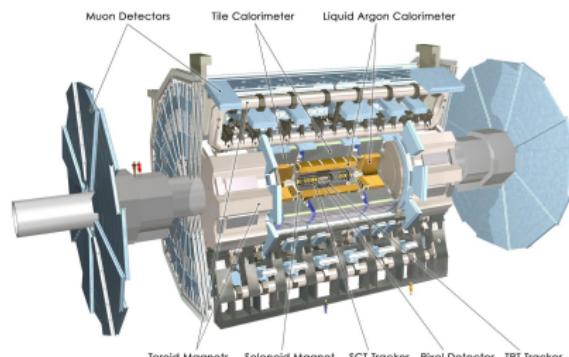
Two-particle **Bose-Einstein correlations** in  $pp$  collisions at  $\sqrt{s} = 13$  TeV measured with the ATLAS Detector at the LHC  
accepted by EPJC, arXiv:2202.02218

data collected in special low-luminosity config. with minimum-bias trigger (integrated luminosity of  $151\mu b^{-1}$ ) and high-multiplicity track trigger ( $8.4nb^{-1}$ )

## Motivation:

source of information about early stages of hadron formation  
probe of space-time geometry of the hadronization region  
better understanding of quark confinement effects

- Plane wave model approach of the origin of BEC
- Recent results of the ATLAS collaboration
- Comparison to CMS results

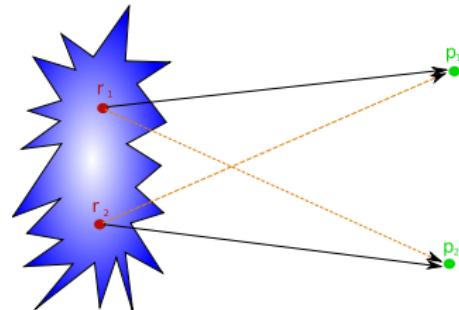


# Bose-Einstein correlations

symmetrical two-particle (boson) wave function:

$$\psi_{p_1, p_2}(r_1, r_2) = \frac{1}{\sqrt{2}} [e^{i(p_1 r_1 + p_2 r_2)} + e^{i(p_1 r_2 + p_2 r_1)}]$$

spherically symmetrical source emission probability distribution described by a single width parameter  $R$  – hadronization source radius



two-particle correlation function:

$$C_2(p_1, p_2) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} = \dots = C_0[1 + \lambda e^{-RQ}](1 + \varepsilon Q) \text{ -- Cauchy-Lorentz fit}$$
$$= C_0[1 + \lambda e^{-R^2 Q^2}](1 + \varepsilon Q) \text{ -- Gaussian fit}$$

$$C_2(p_1, p_2) = \frac{\rho(p_1, p_2)}{\rho_0(p_1, p_2)} = \frac{\rho(++, --)}{\rho(+-)}$$

$\lambda$  - incoherence factor

$\rho$  – two particle density function  
– like-sign charge pairs  $\rho(++, --)$

$C_0, \varepsilon$  - experimental parameters

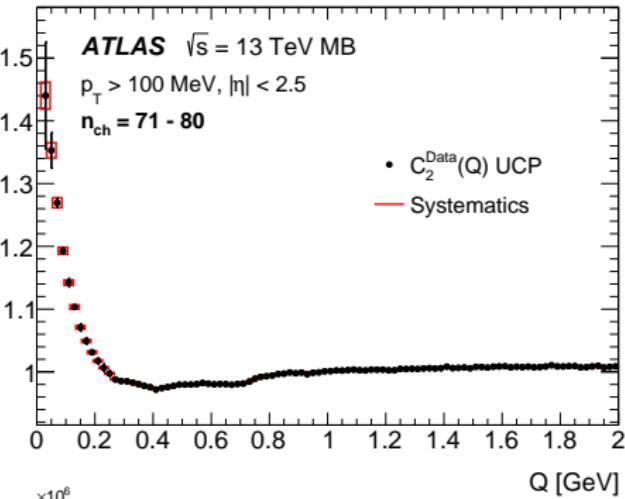
$\rho_0$  – reference function without BEC  
– unlike-sign charge pairs  $\rho(+, -)$

function parametrized in terms of  
Lorentz-invariant four-momentum  
difference  $Q = \sqrt{-(p_1 - p_2)^2}$

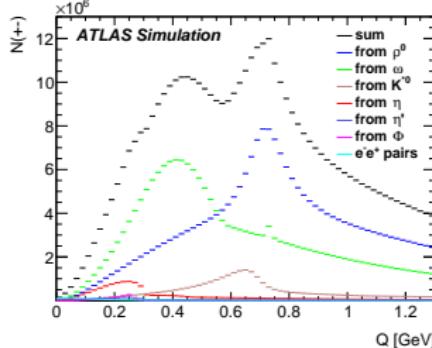
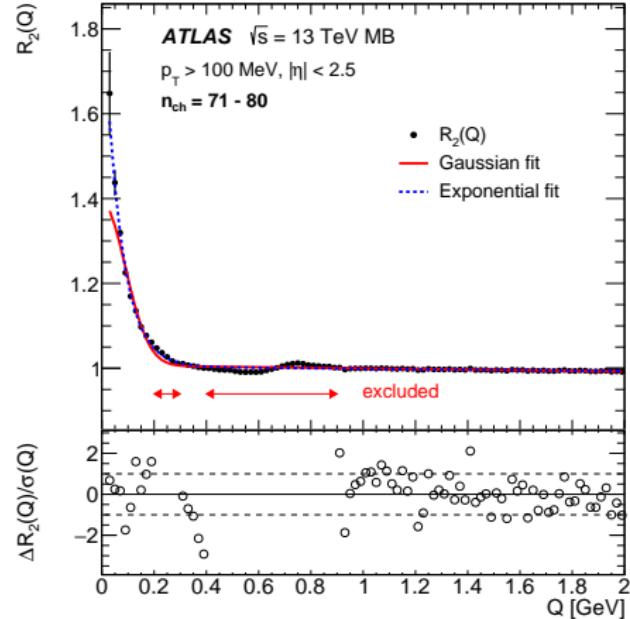
# $C_2(Q)$ and $R_2(Q)$ functions

BEC results in enhancement of same-sign particle pairs at low  $Q$

$C_2(Q)$



$R_2(Q)$

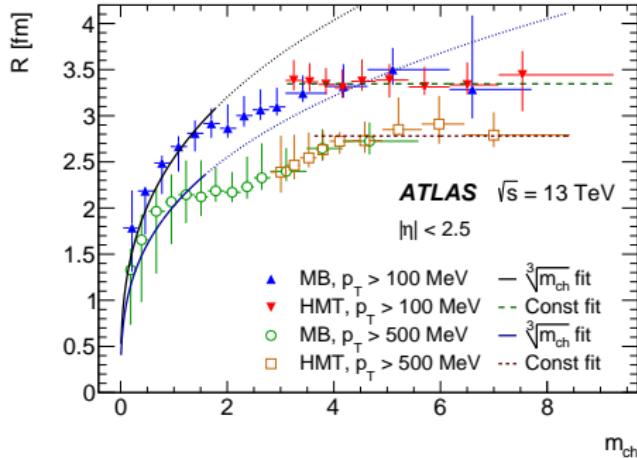
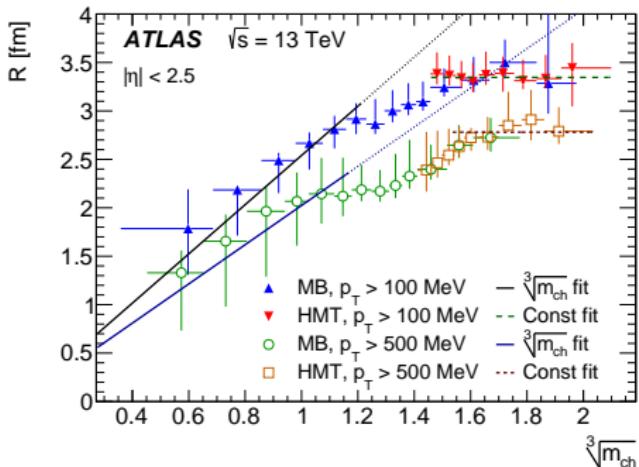


$n_{ch}$  - unfolded number of charged particles with  $pT > 100$  MeV

to remove undesired correlations:

$$R_2 = \frac{C_2^{\text{data}}}{C_2^{\text{MC}}} = \frac{\frac{\rho^{\text{data}}(++,--)}{\rho^{\text{data}}(+-)}}{\frac{\rho^{\text{MC}}(++,--)}{\rho^{\text{MC}}(+-)}}$$

# Multiplicity dependence of the fit parameters

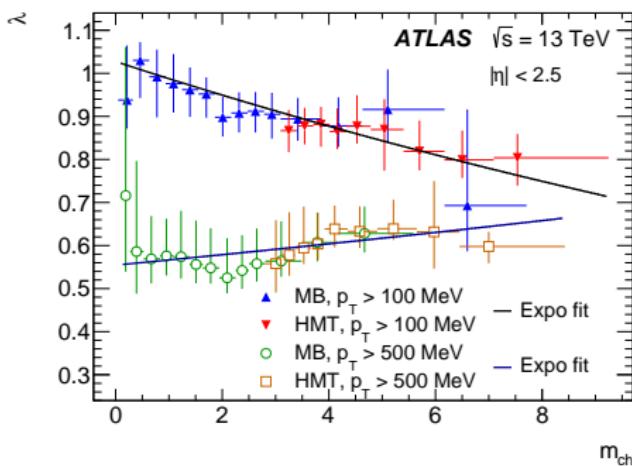
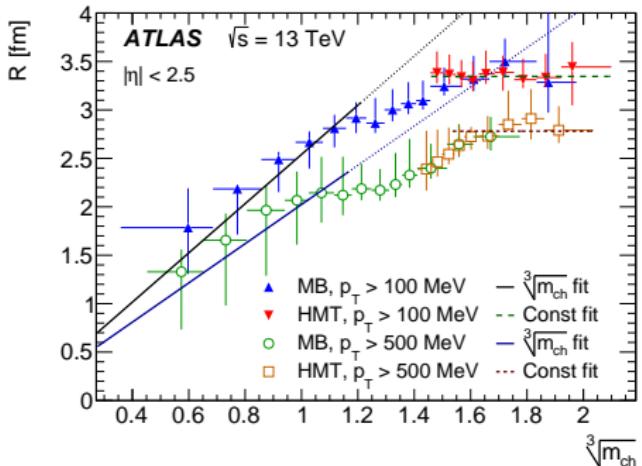


fit results of Cauchy-Lorentz parametrization:  $R_2(Q) = C_0[1 + \lambda e^{-RQ}](1 + \varepsilon Q)$

scaled charged-particle multiplicity:  $m_{\text{ch}} \equiv n_{\text{ch}} / \left\langle n_{\text{ch}}^{|\eta| < 2.5} \right\rangle \cong n_{\text{ch}} / 32.5 \quad (p_T > 100 \text{ MeV})$   
 $\cong n_{\text{ch}} / 16.2 \quad (p_T > 500 \text{ MeV})$

- $R$  increases with multiplicity, similarly for both  $p_T$  thresholds  
 linear increase of  $R$  with  $\sqrt[3]{m_{\text{ch}}}$  up to  $m_{\text{ch}} = 1.2$   
 $\rightarrow$  hadronization volume proportional to the number of produced particles
- saturation of  $R$  for high multiplicity at:  $3.35^{+0.20}_{-0.09} \text{ [fm]} \quad (p_T > 100 \text{ MeV})$   
 $2.78^{+0.23}_{-0.09} \text{ [fm]} \quad (p_T > 500 \text{ MeV})$

# Multiplicity dependence of the fit parameters

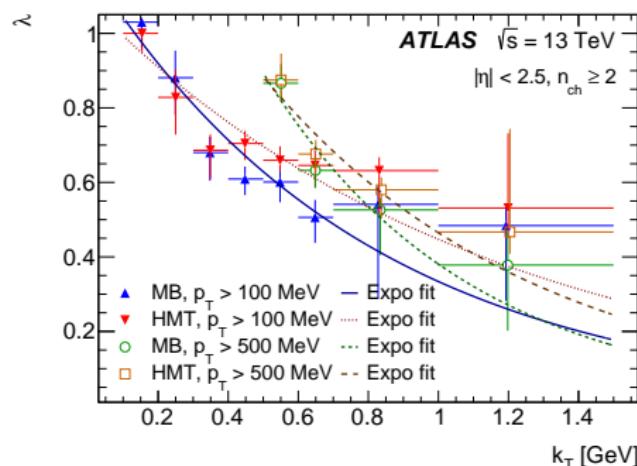
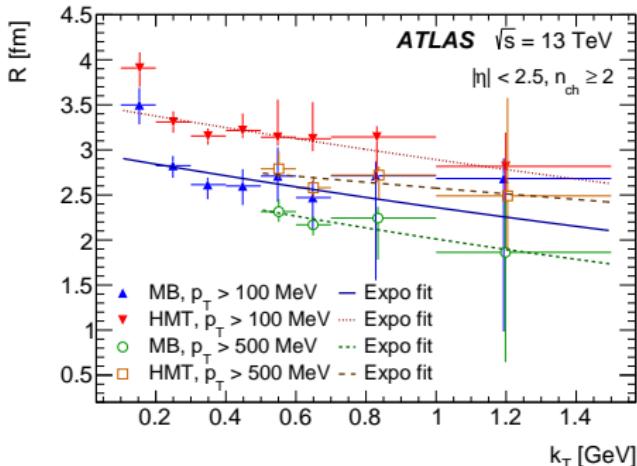


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 $\cong n_{\text{ch}} / 16.2 \text{ } (p_T > 500 \text{ MeV})$

- $\lambda$  at  $p_T > 100 \text{ MeV}$  decreases with multiplicity
- $\lambda$  at  $p_T > 500 \text{ MeV}$  only a weak dependence on multiplicity, constant within measurement uncertainties
- different behaviour for 2  $p_T$  cuts explained in 3 slides

# Pair transverse momentum dependence



fit results of Cauchy-Lorentz parametrization:  $R_2(Q) = C_0[1 + \lambda e^{-RQ}](1 + \varepsilon Q)$

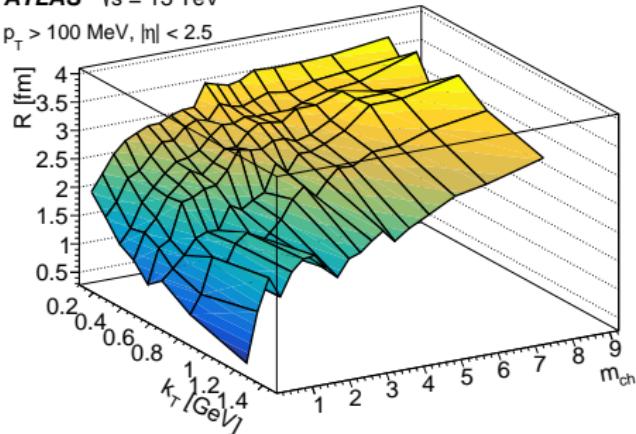
pair transverse momentum  $k_T = \frac{|\mathbf{p}_{T,1} + \mathbf{p}_{T,2}|}{2}$

- $R$  and  $\lambda$  decrease with  $k_T$
- dependences well described by exponential decrease

# Double-differential dependence of fit parameters

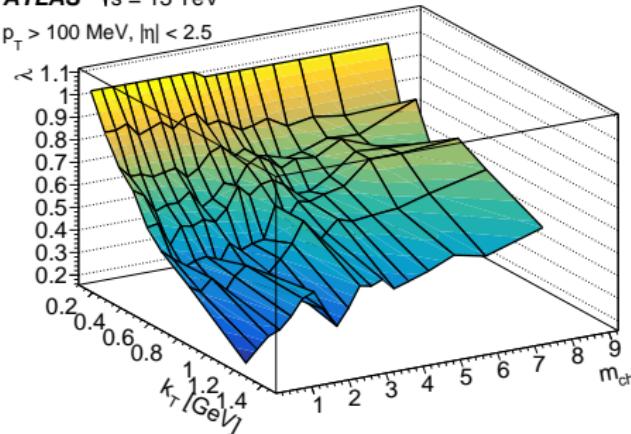
ATLAS  $\sqrt{s} = 13 \text{ TeV}$

$p_T > 100 \text{ MeV}, |\eta| < 2.5$



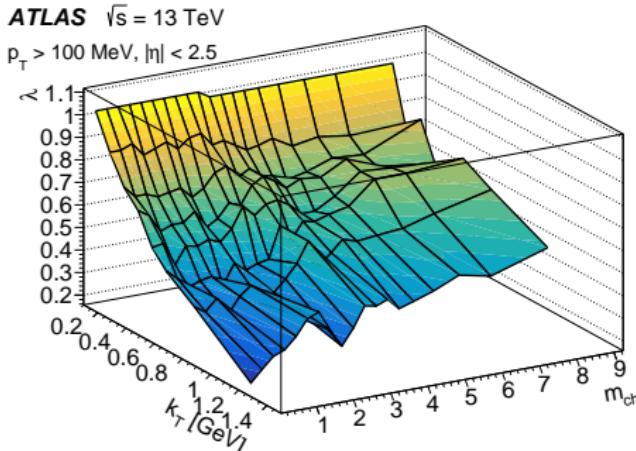
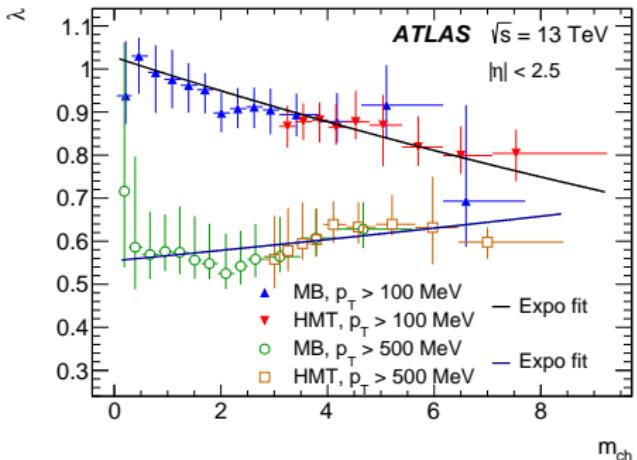
ATLAS  $\sqrt{s} = 13 \text{ TeV}$

$p_T > 100 \text{ MeV}, |\eta| < 2.5$



- $R$  monotonically decreases with  $k_T$  in all  $m_{ch}$  intervals
- $R$  increases with  $m_{ch}$  in all  $k_T$  intervals & flattens off to a plateau
- $\lambda$  monotonically decreases with  $k_T$  in all  $m_{ch}$  intervals
- $\lambda$  vs  $m_{ch}$ : rather flat for  $k_T \lesssim 500 \text{ MeV}$  & slight rise for  $k_T \gtrsim 500 \text{ MeV}$

# Double-differential dependence of fit parameters

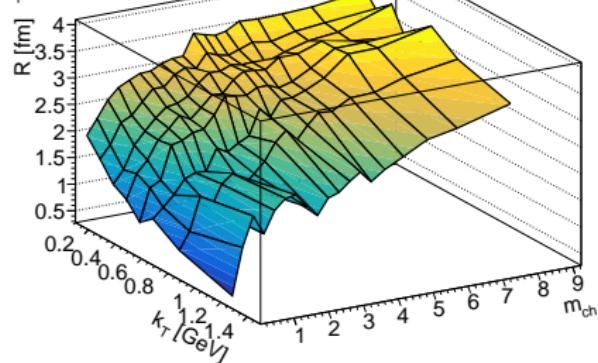


- $R$  monotonically decreases with  $k_T$  in all  $m_{\text{ch}}$  intervals
- $R$  increases with  $m_{\text{ch}}$  in all  $k_T$  intervals & flattens off to a plateau
- $\lambda$  monotonically decreases with  $k_T$  in all  $m_{\text{ch}}$  intervals
- $\lambda$  vs  $m_{\text{ch}}$ : rather flat for  $k_T \lesssim 500 \text{ MeV}$  & slight rise for  $k_T \gtrsim 500 \text{ MeV}$ 
  - slight decrease of  $\lambda$  with  $m_{\text{ch}}$  when integrated over all  $k_T$  because particle  $p_T$  ( $\Rightarrow$  pair  $k_T$ ) increases with  $m_{\text{ch}}$

# $p_T > 100 \text{ MeV}$ vs $p_T > 500 \text{ MeV}$

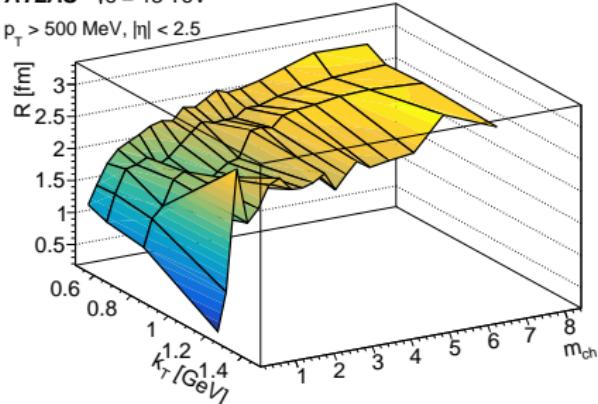
ATLAS  $\sqrt{s} = 13 \text{ TeV}$

$p_T > 100 \text{ MeV}, |\eta| < 2.5$



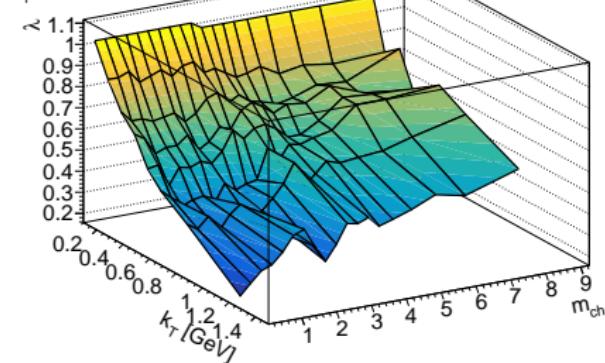
ATLAS  $\sqrt{s} = 13 \text{ TeV}$

$p_T > 500 \text{ MeV}, |\eta| < 2.5$



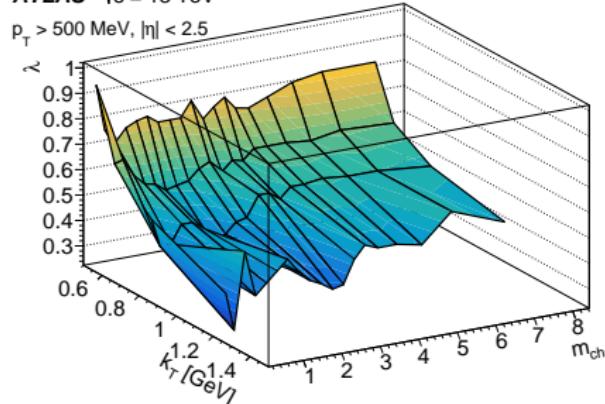
ATLAS  $\sqrt{s} = 13 \text{ TeV}$

$p_T > 100 \text{ MeV}, |\eta| < 2.5$



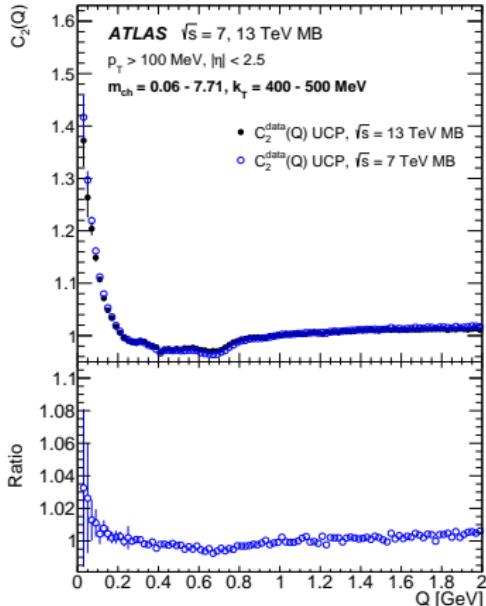
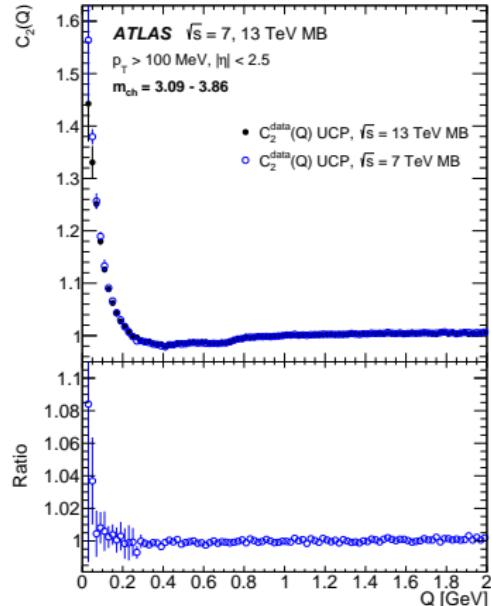
ATLAS  $\sqrt{s} = 13 \text{ TeV}$

$p_T > 500 \text{ MeV}, |\eta| < 2.5$



features similar for both  $p_T$  cuts,  $R$  plateau systematically lower for  $p_T > 500 \text{ MeV}$

# Comparison of $C_2^{\text{data}}(Q)$ functions at 13 and 7 TeV



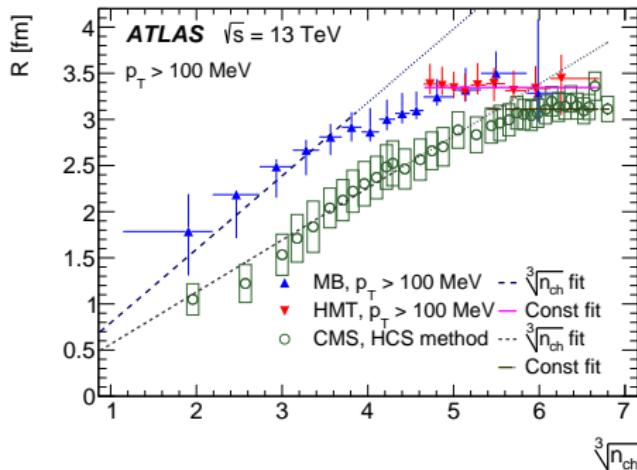
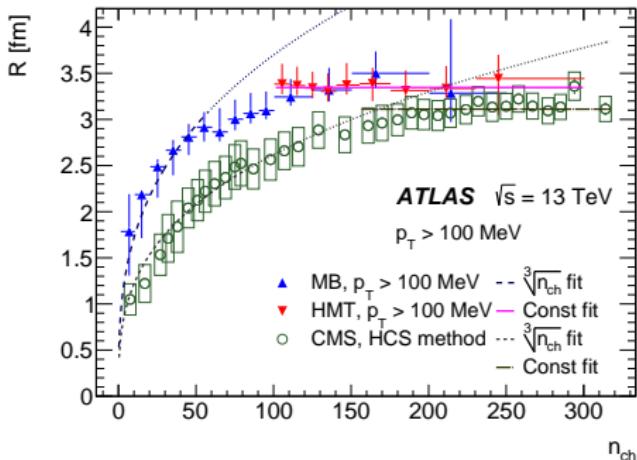
$$m_{\text{ch}}^{13\text{TeV}} \cong n_{\text{ch}}^{13\text{TeV}} / 32.5$$

$$m_{\text{ch}}^{7\text{TeV}} \cong n_{\text{ch}}^{7\text{TeV}} / 29.4$$

$$k_T = \frac{|\mathbf{p}_{T,1} + \mathbf{p}_{T,2}|}{2}$$

- $C_2^{\text{data}}(Q)$  functions at 13 and 7 TeV are in agreement within total uncertainty

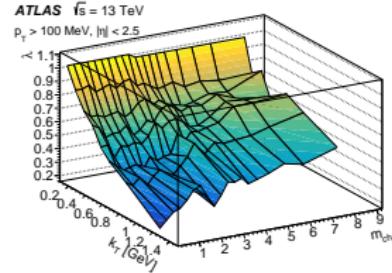
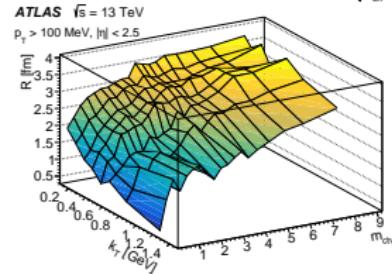
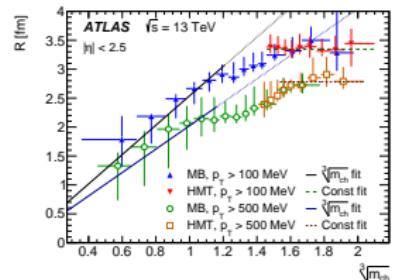
# Comparison with CMS results



- CMS results:  $p_T > 200 \text{ MeV}$ ,  $|\eta| < 2.4$ ,  $k_T < 1 \text{ GeV}$   
hybrid cluster subtraction method  
adjusted to match ATLAS kinematic region ( $p_T > 100 \text{ MeV}$ ,  $|\eta| < 2.5$ )
- qualitatively similar behaviour of  $R$  in both experiments
- differences at low  $n_{\text{ch}}$  probably caused by different kinematic coverage and reference sample constructing approaches → further investigation

# Summary

- Source radius parameter increases linearly with  $\sqrt[3]{m_{ch}}$  up to  $m_{ch} \lesssim 1.7$   
( $n_{ch} \lesssim 56$  for  $p_T > 100$  MeV)  
→ hadronization volume proportional to the number of produced particles
- The BEC radius  $R$  found to be independent of the charged-particle multiplicity for high multiplicity ( $n_{ch} \gtrsim 100$  for  $p_T > 100$  MeV)  
→ confirming previous observation at lower energy  
→ saturation occurs independently of pair  $k_T$ 
  - saturation of  $R$  at:  
 $3.35^{+0.20}_{-0.09}$  [fm] ( $p_T > 100$  MeV)  
 $2.78^{+0.23}_{-0.09}$  [fm] ( $p_T > 500$  MeV)
- double-differential dependences of fit parameters all monotonic
- results compatible with previous measurements by ATLAS → collision energy independence



## Selection criteria

minimum-bias (MB) data selected by MBTS trigger:  
one counter above threshold from either side of the detector

high-multiplicity track (HMT) trigger:

- > 900 SCT space-points,
- > 60 reconstructed good charged tracks with  $p_T > 400$  MeV associated with highest multiplicity vertex

data collected in special configuration with low beam currents & reduced beam focusing, producing low mean number of interactions per bunch-crossing  $\langle \mu \rangle$ :  
0.003 – 0.007 (MB events)  
0.01 – 0.04 (HMT events)

Event selection: primary vertex with  $\geq 2$  associated tracks

Track selection:  $p_T > 100$  MeV,  $|\eta| < 2.5$ ,

- $\geq 1$  Pixel hit, hit in first Pixel layer if expected,
- at least 2 ( $p_T < 300$  MeV), 4 ( $p_T < 400$  MeV) or 6 ( $p_T > 400$  MeV) SCT hits,
- $|d_0| < 1.5$  mm,     $|z_0| \cdot \sin(\theta) < 1.5$  mm