Bose-Einstein correlations in pp and pPb collisions at LHCb

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Outline

- motivation for BEC studies
- LHCb experiment
- analysis method
- results for pp
- overview for pPb
- summary

Motivation

HBT interferometry in particle physics

- correlations in four-momenta (q_1, q_2) of indistinguishable particles emitted from the same source:

$$Q = \sqrt{-(q_1 - q_2)^2}$$

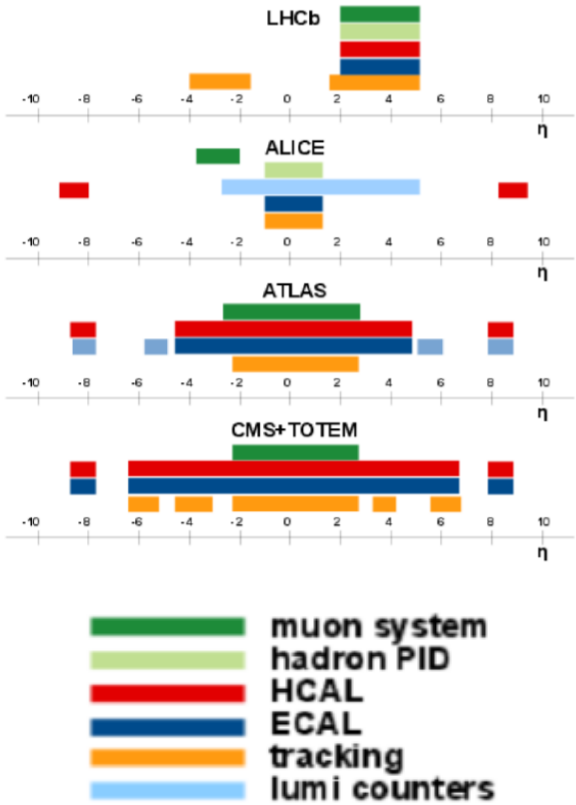
- due to symmetrization (Bose-Einstein correlations – BEC) or antisymmetrization (Fermi-Dirac correlations – FDC) of the total wave function
- useful **tool to probe** the spatial and temporal **structure of the hadron emission volume**
- many results on BEC from SPS, LEP, RHIC, LHC

LHCb and BEC analyses

JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022

- LHCb detector:
  - **single-arm spectrometer** designed mainly to study CP violation in B physics
  - fully instrumented in $2 < \eta < 5$ -> can serve as a **general purpose detector**
  - **unique acceptance** among LHC experiments -> complementary results

- BEC analyses at LHCb:
  - identified same-sign charged pions (2-body)
  - Levy parametrization with $\alpha=1$ (1D)
  - in proton-proton collisions @ 7 TeV
    [published: **JHEP 12 (2017) 025**]
  - in proton-lead collisions @ 5 TeV (ongoing)

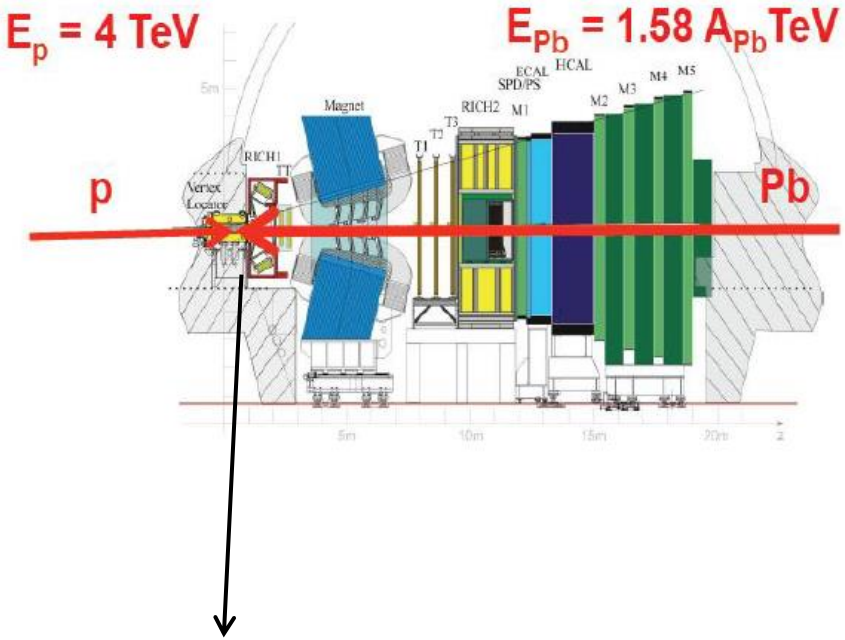


NEW/PLANNED ANALYSES

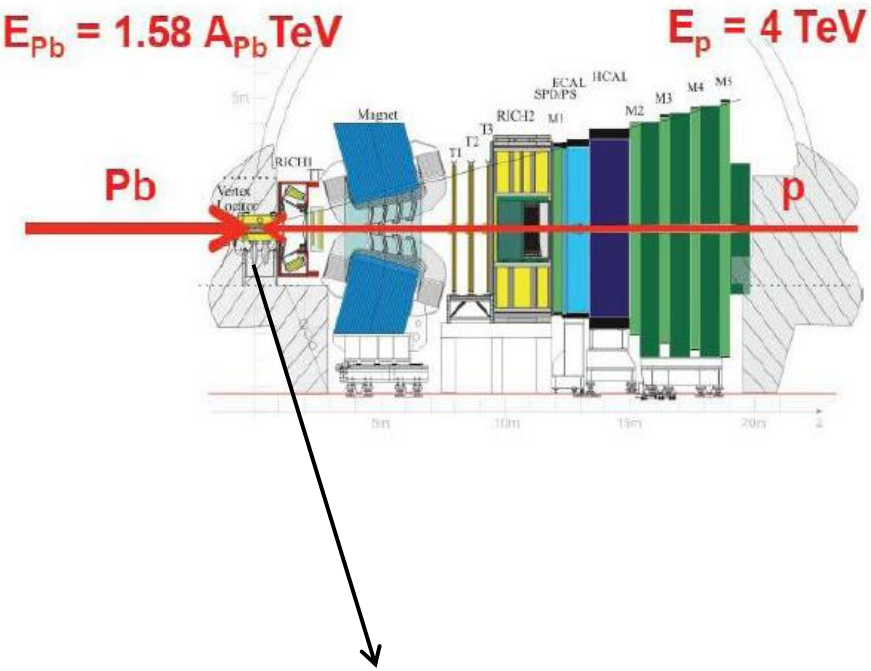
- 3-body correlations in pp @ 7 TeV (ongoing)
- 3D analysis in pp @ 7 TeV
- BEC in PbPb collisions
- BEC study for D mesons

pPb data taking @ LHCb

- two beam modes (pPb/Pbp) with **asymmetric beams**



vertex locator (VELO) used in definition of event activity



higher activity expected when Pb goes `towards` the detector

Event multiplicity bins

- BEC parameters depend on total multiplicity of an event
- **VELO track multiplicity (N_{ch})** is a good probe of that quantity
- PVs are split into multiplicity bins based on N_{ch} distribution (optimized to ensure similar statistics in each bin)
- **unfolding of N_{ch}** allows for comparison between experiments after taking into account different η acceptances (model-dependent)
  - done for pp using PYTHIA 8 in $2 < \eta < 5$
  - planned also for pPb
- in pp: corresponding **activity classes** defined as fractions of N_{ch} distribution (independent of specific experiment features, e.g. efficiency, acceptance)

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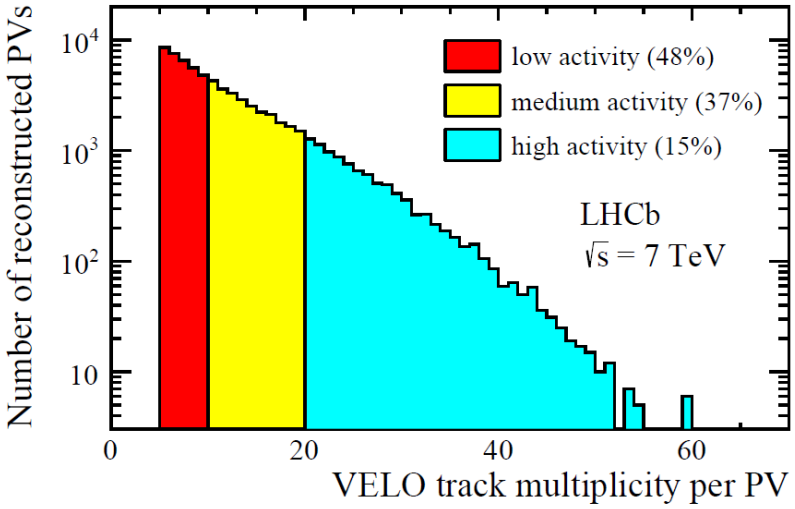


Datasets

pp

- pp data 2011@7 TeV
  (40M minimum bias events)
- MC – PYTHIA 8
  (20M minimum bias events)
- 3 bins in N_{ch}

bin #	VELO N_{ch}	activity class	unfolded N_{ch}
1	5-10	low	8-18
2	11-20	medium	19-35
3	21-60	high	36-96

*** k_T – average transverse momentum of particles in a pion pair**

pPb

- pPb/Pbp data 2013@ 5 TeV
  (70M minimum bias events for each beam configuration)
- MC – EPOS
  (12M for each beam configuration)
- 6 bins in N_{ch}
- 3 bins in N_{ch} + 3 bins in k_T^* (preliminary)

bin #	VELO N_{ch}	
	p-Pb	Pb-p
1	5 - 25	5 - 30
2	26 - 33	31 - 45
3	34 – 40	46 – 55
4	41 – 47	56 – 65
5	48 – 54	66 – 80
6	55 – 80	81 - 140

Correlation function

- **correlation function** (experimentally):

$$C_2(Q) = \frac{N(Q)^{SAME}}{N(Q)^{REF}}$$

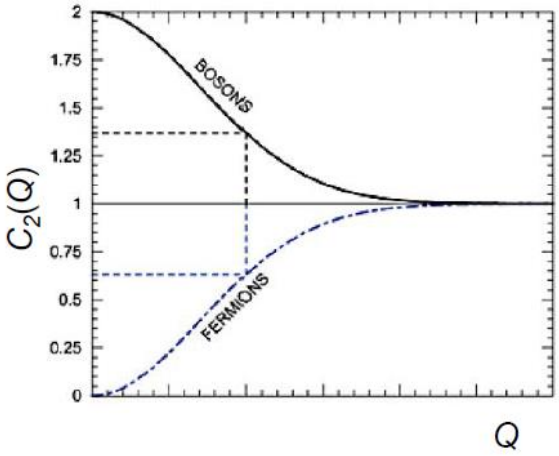
distribution for pairs of same-sign pions from same PV [BEC effect present]

distribution for reference sample [no BEC effect]

- **event-mixed reference sample** is used:
  - pairs of pions from different events from PVs with same VELO N_{ch}
  - other correlations also removed -> construct **double ratio** (next slide)
- in this analysis - **Levy parametrization** (with **α=1**) + long-range correlations:

$$C_2(Q) = N\left(1 \pm \lambda e^{-|RQ|^{\alpha}}\right) * (1 + \delta Q)$$

R – radius of a spherical static source
λ – chaoticity parameter
(0 – coherent source, 1 – chaotic emission)
N – normalization factor
δ – long-range correlations
α – index of stability



Double ratio

- **double ratio** $r_d(Q)$ – an improved correlation function:

$$r_d(Q) = \frac{C_2(Q)^{DATA}}{C_2(Q)^{MC}}$$

BEC effect **not** **simulated** in MC

- MC correlation function contains **similar pattern of distortions** as correlation function for data, therefore constructing double ratio:
  - reduces possible imperfections of the reference sample
  - eliminates second order effects to large extent
  - corrects for long-range correlations (if properly simulated)

Coulomb correction

- **Coulomb effect** is not simulated in MC
- in pp analysis: corrected by applying **Gamov penetration factor** $G_2(Q)$ to the Q distribution for signal pairs in data:

$$G_2(Q) = \frac{2\pi\zeta}{e^{2\pi\zeta}-1}, \text{ where } \zeta = \pm\frac{\alpha m}{Q}$$

- in pPb analysis: **Bowler-Sinyukov formalism** planned to be used to account for the Coulomb effect

BEC in pp - results (I)

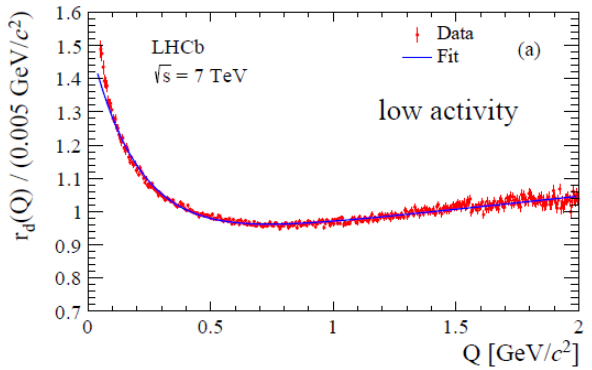
- fits to double ratio with Levy parametrization with α=1:

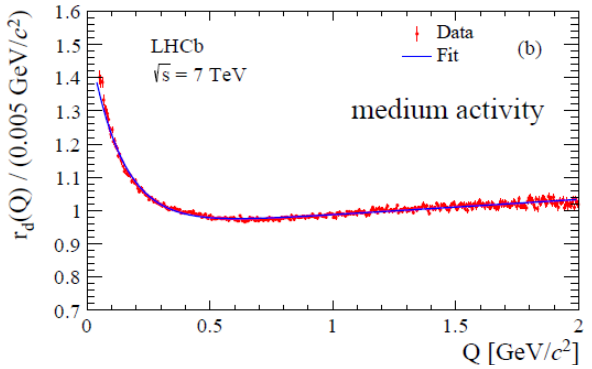
$$C_2(Q) = N(1 \pm \lambda e^{-RQ}) * (1 + \delta Q)$$

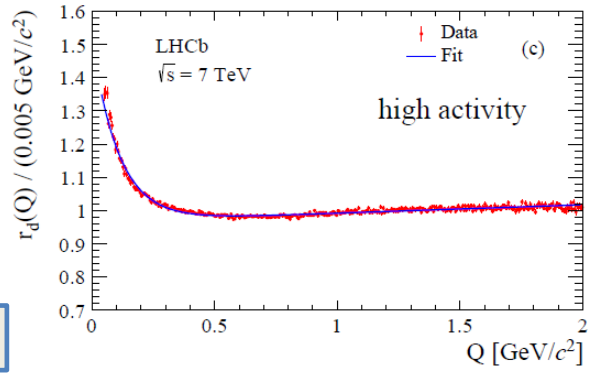
- clear **enhancement due to BEC** effect observed in Q->0

Activity class	R [fm]	λ
low	1.01 ± 0.01 ± 0.10	0.72 ± 0.01 ± 05
medium	1.48 ± 0.02 ± 0.17	0.63 ± 0.01 ± 0.05
high	1.80 ± 0.03 ± 0.16	0.57 ± 0.01 ± 0.03

Systematic uncertainty (~10%) dominated by generator tunings and pile-up effects.







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BEC in pp - results (II)

Results show a trend compatible with previous observations at LEP and other LHC experiments:

- **source size increases with activity**
- **λ decreases with growing activity**

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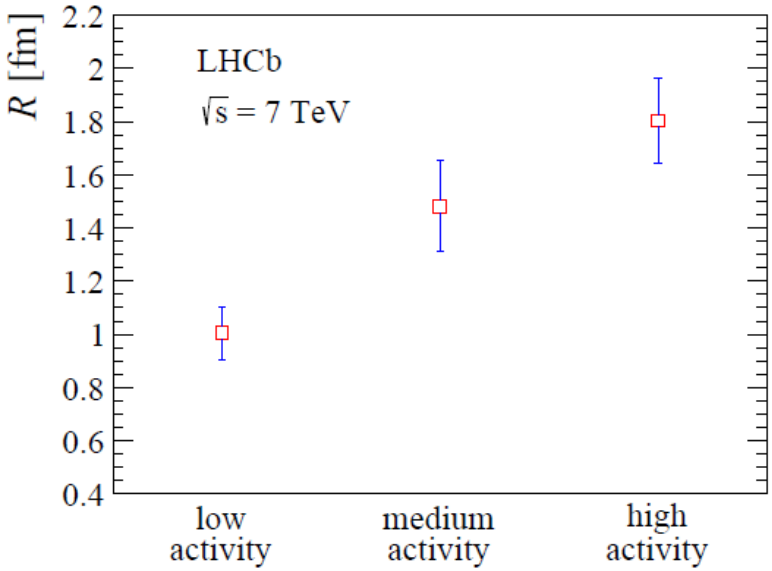
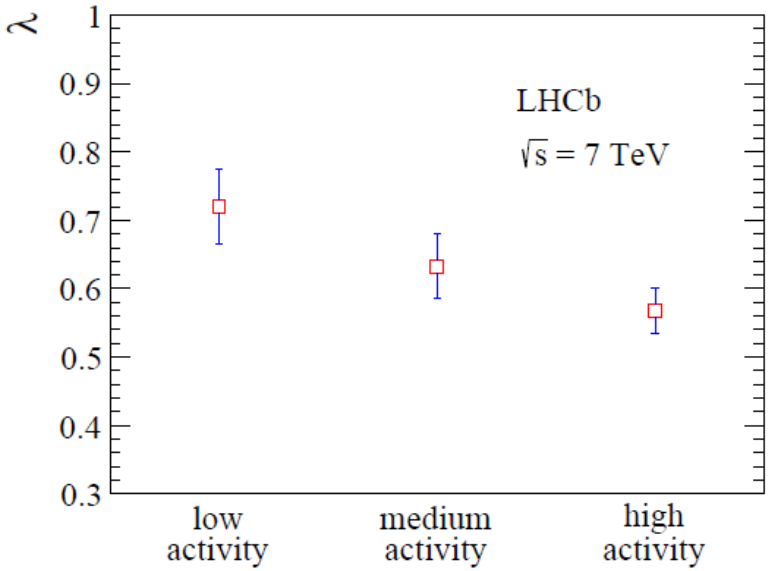




R and λ parameters measured **in the forward region are slightly lower** than results for central rapidity obtained by ATLAS (direct comparison, by **extrapolating LHCb N_{ch} to ATLAS acceptance** using simulation – see backup)

BEC in pPb - overview

- plans
  - analysis in 6 N_{ch} bins and (3 N_{ch} + 3 k_T) bins
  - use **Levy parametrization** with **α=1** (for comparison with previous results)
  - use **τ-model** to study interesting effects in the correlation function (**oscillations**, **anticorrelation dip**)
- status
  - advanced: data samples + selection ready
  - double ratio constructed for N_{ch} bins, k_T bins optimization in progress
  - next step: Coulomb correction + fits

PHYSICAL OUTPUT

- direct comparison between pp/pPb systems at LHCb
- comparison between forward and central rapidity region in pPb
- tests of the **τ-model** in pPb system

Summary

Bose-Einstein correlations studied for same-sign pions in pp @ 7 TeV

- first measurement in the forward region $2 < \eta < 5$
- observed trends compatible with previous results and predictions
- BEC parameters in the forward region slightly lower wrt central rapidities

Ongoing analysis for pPb @ 5 TeV

- analysis planned in both N_{ch} and k_T bins
- the τ-model will be used for fits, to study possible oscillations
- planned comparisons between pp/pPb systems and forward/central rapidity

NEW/PLANNED ANALYSES

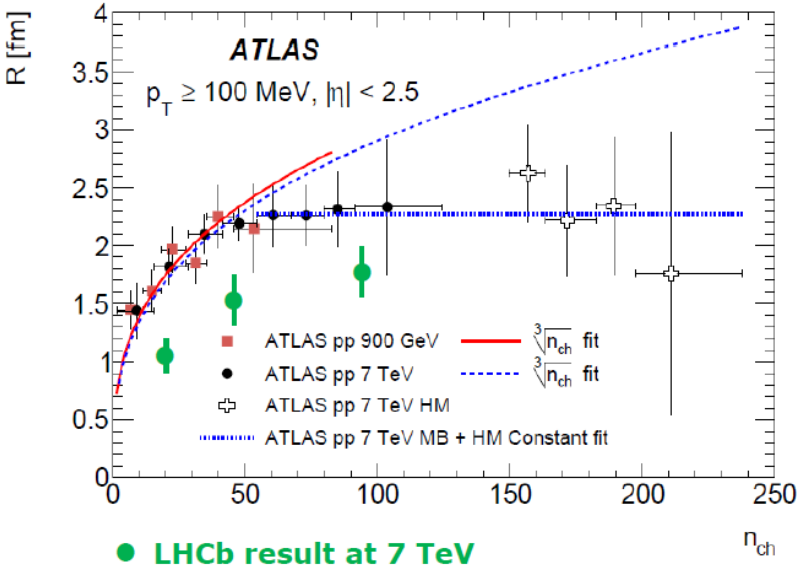
- 3-body correlations in pp @ 7 TeV (ongoing)
- 3D analysis in pp @ 7 TeV
- BEC study for D mesons
- BEC in PbPb collisions

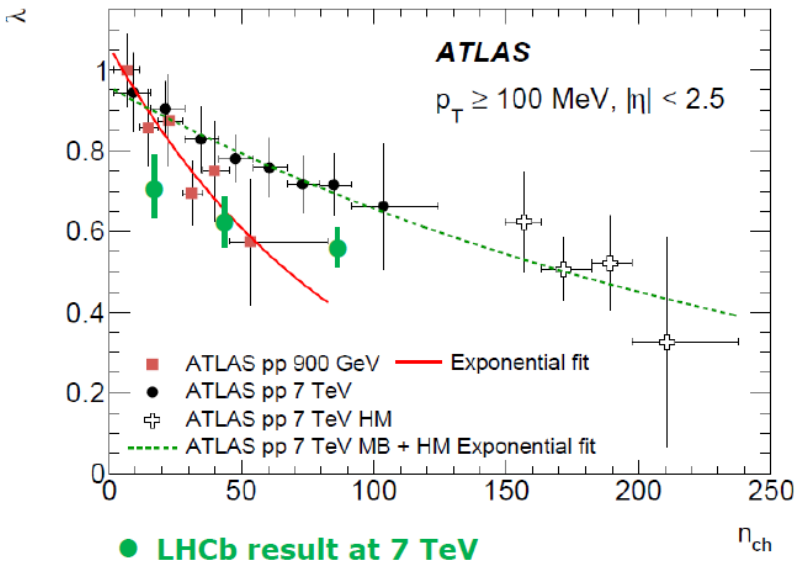
Thank you for your attention

BEC pp – central VS forward

Unfolded N_{ch} of LHCb ($2 < \eta < 5$) at 7 TeV is extrapolated to the ATLAS acceptance($|\eta| < 2.5$, $p_T > 0.1$ GeV/c) using simulation (PYTHIA 8):

- ***R* and λ parameters** measured **in the forward region are slightly lower** than results for central rapidity obtained by ATLAS
- planned to check that also in future analyses at LHCb, e.g. in pPb collisions





ATLAS: Eur. Phys. J. C75 (2015) 466
LHCb: JHEP 12 (2017) 025

Offline selection

Single track:

- false isMuon flag
- if tracks share all VELO hits -> keep one with best χ^2
- $2 < \eta < 5$
- track $\chi^2 < 2.0$
- probNN(ghost) < 0.25
- probNN(kaon,proton) < 0.5
- probNN(pion) > 0.65

Pairs with Q<0.05 GeV are rejected (clones and ghosts removal).

BEC pp- systematics

Source	Low activity		Medium activity		High activity	
	ΔR [%]	$\Delta\lambda$ [%]	ΔR [%]	$\Delta\lambda$ [%]	ΔR [%]	$\Delta\lambda$ [%]
Generator tunings	6.6	4.3	8.9	3.5	6.5	1.5
PV multiplicity	5.9	5.8	6.1	4.5	3.9	4.3
PV reconstruction	1.8	0.1	1.4	1.2	0.1	<0.1
Fake tracks	0.4	1.1	1.7	3.9	1.1	0.8
PID calibration	1.3	0.3	0.8	0.6	2.7	0.9
Requirement on pion PID	2.9	1.8	1.6	0.1	1.3	0.1
Fit range at low-Q	1.2	1.0	1.2	1.5	1.8	2.7
Fit range at high-Q	1.8	0.1	2.1	0.8	2.4	1.4
Total	9.8	7.6	11.4	7.3	8.8	5.6