ATLAS B_c measurements overview

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Introduction

$\mathrm{B_c}$ studies in ATLAS: history

- 2012: Observation of B_c^+ meson with 7 TeV data in $B_c^+ \to J/\psi\pi^+$ mode
  - ATLAS-CONF-2012-028
- 2014: First observation of an excited state of B_c^+ consistent with predictions for $B_c^+(2S)$
  - Phys. Rev. Lett. 113 (2014) 212004, arXiv:1407.1032
- 2015: Study of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays
  - Eur. Phys. J. C 76 (2016) 4, arXiv:1507.07099
- To be continued...

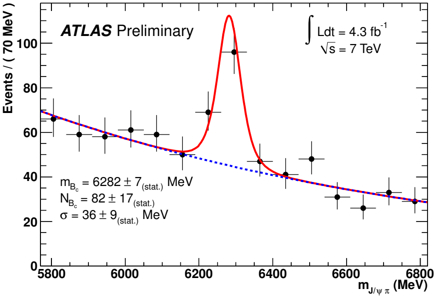
$B_c^+ \to J/\psi\pi^+$ observation

ATLAS-CONF-2012-028

- Full *7 TeV dataset* used
- Muon pairs fitted to a common vertex to form a *J/ψ candidate*
  - $\chi^2/\text{n.d.f.}(J/\psi) < 15$
  - $m(J/\psi)$ within ± 180 MeV around the nominal mass
- Combined with another track, fitted to a *B_c^+ candidate vertex*
  - $\chi^2/\text{n.d.f.}(B_c^+) < 2$
  - $p_\mathrm{T}(\mu_1, \mu_2) > 4, 6$ GeV
  - $p_\mathrm{T}(\pi^+) > 4$ GeV
  - $p_\mathrm{T}(B_c^+) > 15$ GeV
  - transverse impact parameter significance of pion track

$$\frac{d^0_{xy}}{\sigma(d^0_{xy})} > 5$$

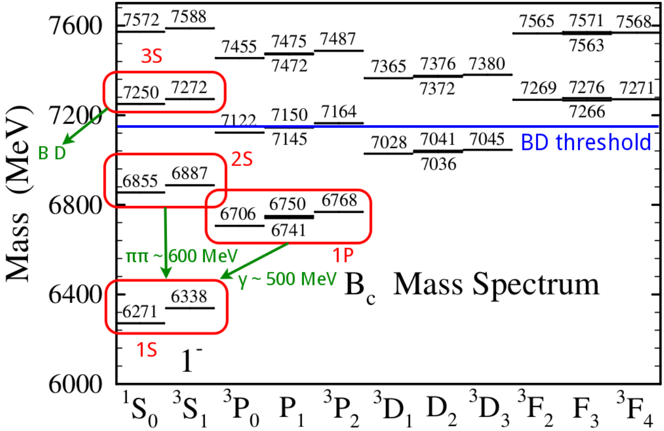
more useful than cutting the decay length (low B_c^+ lifetime)



- Significance of the observed signal exceeds *5 standard deviations*
- No cross-section measurement performed yet – to be done soon

Search for B_c^+ excited states

- No excited states of B_c^+ reported previously
- The spectrum and properties of B_c^+ family are predicted by non-relativistic potential models, perturbative QCD and lattice calculations
- Measurements of the ground and excited states $\rightarrow$ test of these predictions

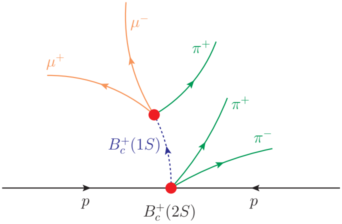


Phys. Rev. D 70 (2004) 054017

Overview of $B_c^+(2S)$ search

Phys. Rev. Lett. 113 (2014) 212004

- The analysis uses *7 TeV and 8 TeV pp collisions data*
  - 4.9 fb^{-1}and 19.2 fb^{-1}, respectively
- Selection optimized using $S/\sqrt{S+B}$ criterion on Monte Carlo
  - Various exclusive backgrounds and inclusive $b\bar{b} \to J/\psi X$ samples used
  - Optimization performed separately for 7 TeV and 8 TeV data



- *J/ψ candidates* reconstructed by fitting a muon pair to a common vertex
- Combining a J/ψ candidate with another track $\to$ *$B_c^+(1S)$ candidate*
  - Di-muon mass is constrained to the J/ψ world average in 3-prong vertex fit
- *$B_c^+(2S)$ candidates* formed from $B_c^+(1S)$ and two tracks from primary vertex with $\pi^\pm$ masses assigned
  - Cascade fit with $B_c^+(1S)$ combined momentum *constrained to point to $B_c^+(2S)$ vertex*

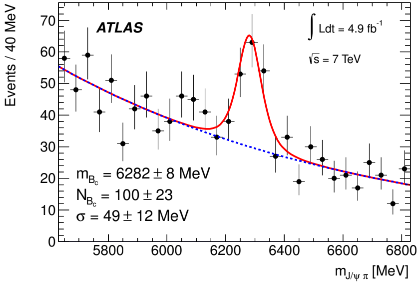
$B_c^+(1S)$ selection and fit

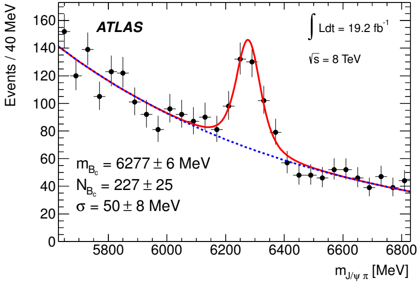
$\mathbf{B_c^+}(\mathbf{1S})$ selection for 2011 (2012) data

- $p_T(\mu_1, \mu_2) > 4, 6$ GeV
- $\chi^2/\text{n.d.f.}(J/\psi) < 15$
- $m(J/\psi)$ within $\pm 3\sigma$ of the nominal (σ depending on the rapidity range)
- $\chi^2/\text{n.d.f.}(B_c^+) < 2.0\ (1.5)$
- $p_T(B_c^+) > 15$ GeV (18 GeV)
- $\frac{d^0_{xy}}{\sigma(d^0_{xy})}(\pi^+) > 5\ (4.5)$

Extended unbinned fit of the mass distribution

- *Signal*: Gaussian with per-candidate errors
- *Background*: exponential





$B_c^+(2S)$ selection and fit

Selection of $\mathbf{B_c^+(2S) \to B_c^+(1S)\pi^+\pi^-}$ candidates

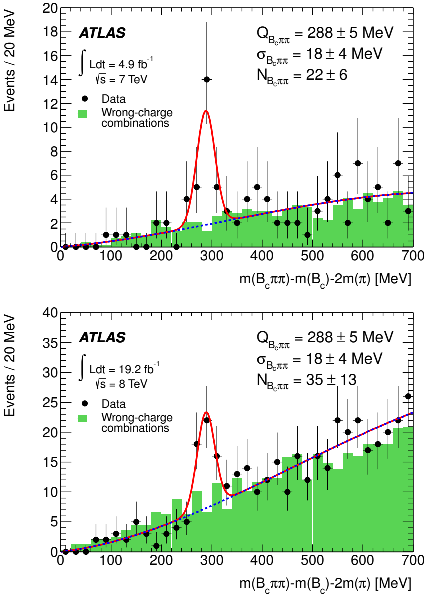
- $B_c^+(1S)$ candidates within $\pm 3\sigma$ of the fitted mass
- $p_T(\pi^+, \pi^-) > 400$ MeV
- for several candidates in event, the one with the best cascade fit χ^2 is kept

Extended unbinned fit of Q-value distribution

$$Q_{B_c^+\pi\pi} = m(B_c^+\pi^+\pi^-) - m(B_c^+) - 2m(\pi^+)$$

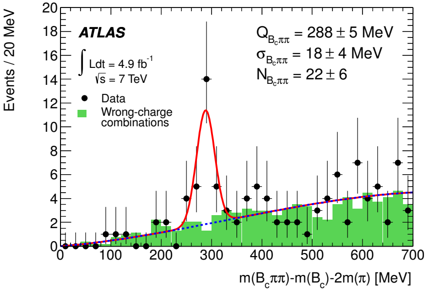
- *Signal*: Gaussian
- *Background*: 3rd order polynomial

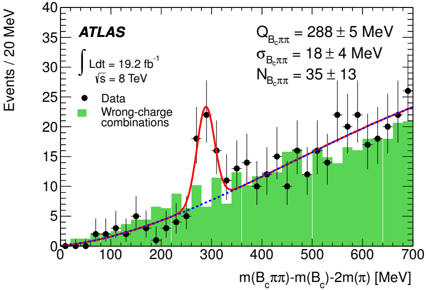
Wrong charge combination (same-sign π) used for background control



$B_c^+(2S)$ observation

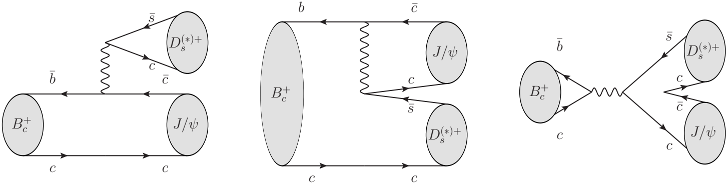
- Significance of the observed signal calculated with toy studies accounting for a *"look elsewhere effect"*
  - 3.7σ in 7 TeV data
  - 4.5σ in 8 TeV data
  - Combined significance is 5.2σ
  - (local significance is 5.4σ)
- Dominant source of systematic of the Q-value is the *fitting procedure*
- A new state observed at $Q = 288.3 \pm 3.5\ (\text{stat.}) \pm 4.1\ (\text{syst.})$ MeV (error-weighted mean of 7 and 8 TeV values)
- Corresponds to a mass $6842 \pm 4\ (\text{stat.}) \pm 5\ (\text{syst.})$ MeV, that is consistent with the predicted mass of $B_c^+(2S)$





$B_c^+ \to J/\psi D_s^{(*)+}$: motivation

- Decays with charmonia and $D_s^{(*)+}$ represent $\bar{b} \to \bar{c}c\bar{s}$ transition in B_c^+ sector
  - Can go through annihilation diagram (suppressed for lighter B mesons)

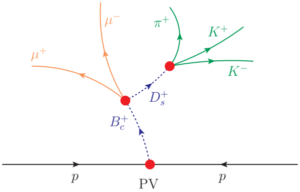


- Various model predictions available: *branching ratios*, *polarization*
  - Test for fragmentation hypothesis (similar decays of B^0, B^+)
- Earlier observed only in LHCb (PRD 87 (2013) 112012)

Eur. Phys. J. C 76 (2016) 4

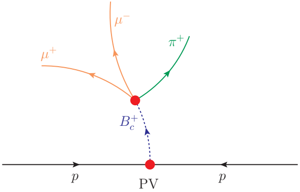
Signal channels: $B_c^+ \to J/\psi D_s^{(*)+}$

- Intermediate resonances via $J/\psi \to \mu^+\mu^-$ and $D_s^+ \to \phi(K^+K^-)\pi^+$
- Two distinct vertices of B_c^+ and D_s^+ decays
- J/ψ and D_s^+ masses *are fixed to PDG* in cascade fit
- $D_s^{*+} \to D_s^+\gamma/\pi^0$, neutral particle escapes detection



Reference channel: $B_c^+ \to J/\psi\pi^+$

- B_c^+ decay forms a secondary vertex; J/ψ mass *is fixed to PDG* in vertex fit
- Large statistics $\to$ used as a reference for $\mathcal{B}$ measurement
- Measures ratios are
  $\mathcal{R}_{D_s^+/\pi^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$,
  $\mathcal{R}_{D_s^{*+}/\pi^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^{*+})/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$,
  $\mathcal{R}_{D_s^{*+}/D_s^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^{*+})/\mathcal{B}(B_c^+ \to J/\psi D_s^+)$



Polarization in $B_c^+ \to J/\psi D_s^{*+}$ decay

- Pseudoscalar B_c^+ decays into two vectors $\to$ *3 helicity amplitudes* A_{00}, A_{++}, A_{--}
- Longitudinal A_{00} and transverse $A_{\pm\pm}$ components have different kinematics:
  $J/\psi D_s^+$ mass shape and J/ψ helicity angle
- Are distinguished by fit of these variables $\to$ measure $\Gamma_{\pm\pm}/\Gamma$

Signal event selection

Dataset

- 2011 and 2012 pp data: 4.9 fb^{-1}@ 7 TeV + 20.6 fb^{-1}@ 8 TeV

Triggers

- Use 5–11 trigger chains depending on data period
- Search of *single-*, *di-* and *tri-muon* signatures with $J/\psi \to \mu^+\mu^-$ candidate

Offline selection of candidates

- Aims mostly at combinatorial background suppression
- Synchronous between the signal and reference channels if possible
- Selection cuts:
  - Kinematical properties (tracks and D_s^+ candidate p_{T})
  - Cascade fit quality ($\chi^2/\mathrm{n.d.f.}$)
  - Secondary and tertiary vertex displacement ($L_{xy}(B_c^+)$ and $L_{xy}(D_s^+)$)
  - Intermediate resonance mass windows (J/ψ, D_s^+, ϕ)
  - Suppression of $B_s^0 \to J/\psi\phi$ reflection (exclude $5.34 < m(J/\psi\phi) < 5.40$ GeV region)
  - Angular properties

$J/\psi D_s^+$ candidate fit

- 2D extended unbinned ML fit of $m(J/\psi D_s^+)$ and $|\cos\theta'(\mu^+)|$ distributions
  - Helicity angle $\theta'(\mu^+)$ is the angle between μ^+ and D_s^+ momenta in the J/ψ rest frame

Mass part

- *$B_c^+ \to J/\psi D_s^+$ signal:* modified Gaussian function

$$\mathrm{Gauss}^{\mathrm{mod}} \sim \exp\left[-\frac{x^{1+\frac{1}{1+x/2}}}{2}\right],$$

$$x = |M_0 - m(J/\psi D_s^+)|/\sigma,$$

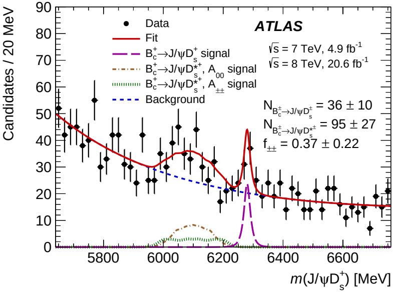
  width σ fixed to the MC value
- *$B_c^+ \to J/\psi D_s^{*+}$ A_{00} and $A_{\pm\pm}$ signals:* templates from MC
- *Background:* 2-parametric exponential

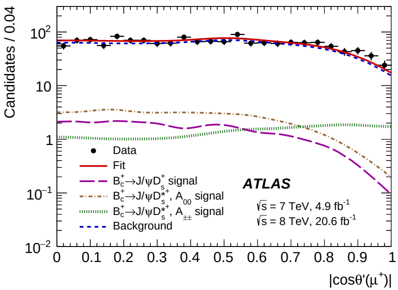
$$\exp\left[a \cdot m(J/\psi D_s^+) + b \cdot m(J/\psi D_s^+)^2\right]$$

Angular part

- *Singals:* MC templates to account for detector effects
  - Analytically:
  - $B_c^+ \to J/\psi D_s^+$: $\cos\theta' \sim \sin^2\theta'$
  - $B_c^+ \to J/\psi D_s^{*+}$ A_{00}: $\cos\theta' \sim \sin^2\theta'$
  - $B_c^+ \to J/\psi D_s^{*+}$ $A_{\pm\pm}$: $\cos\theta' \sim 1 + \cos^2\theta'$
- *Background:* templates from $m(J/\psi D_s^+)$ sidebands
  - Left: $m(J/\psi D_s^+) < 5900$ MeV
  - Right: $m(J/\psi D_s^+) > 6360$ MeV
  - In between: linear interpolation of the two templates

$B_c^+ \to J/\psi D_s^{(*)+}$ signal (1)

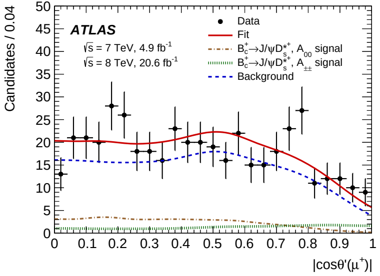




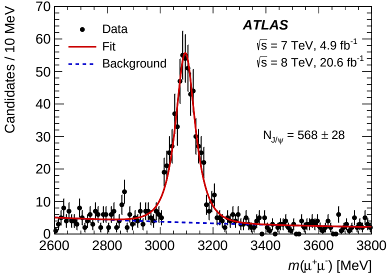
- Signal yields agree with 1D mass fit
- Fit correctness checked with toy MC studies
  - 2D fit is much more sensitive to $f_{\pm\pm}$ than 1D
- Statistical significance of the two signals: 4.9σ

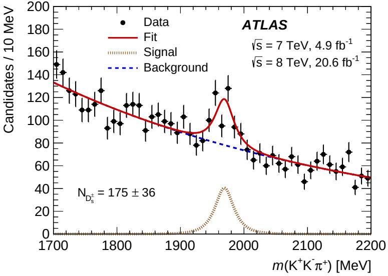
Parameter	Value
$m_{B_c^+ \to J/\psi D_s^+}$ [MeV]	6279.9 ± 3.5
$N_{B_c^+ \to J/\psi D_s^+}$	36 ± 10
$N_{B_c^+ \to J/\psi D_s^{*+}}$	95 ± 27
$f_{\pm\pm}$	0.37 ± 0.22

$B_c^+ \to J/\psi D_s^{(*)+}$ signal (2)

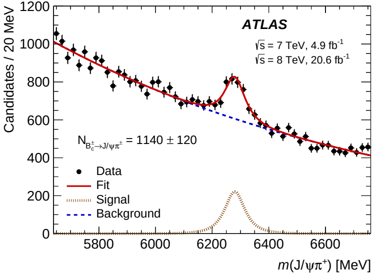


- ← angular fit projection to the $B_c^+ \to J/\psi D_s^{*+}$ signal region, $5950 < m(J/\psi D_s^+) < 6250$ MeV
- ↙↓ $J/\psi \to \mu^+\mu^-$ and $D_s^+ \to \phi(K^+K^-)\pi^+$ signals corresponding to the selected $B_c^+ \to J/\psi D_s^+$ candidates
  - The same selection, but the cascade fit *w/o fixing the intermediate resonance masses*





Reference channel $B_c^+ \to J/\psi\pi^+$



$B_c^+ \to J/\psi\pi^+$ fit

1D extended unbinned ML fit

- *Background:* exponential
- *Signal:* modified Gaussian

Parameter	Value
$m_{B_c^+\to J/\psi\pi^+}$ [MeV]	6279.9 ± 3.9
$\sigma_{B_c^+\to J/\psi\pi^+}$ [MeV]	33.9 ± 4.2
$N_{B_c^+\to J/\psi\pi^+}$	1140 ± 120

$$\mathcal{R}_{D_s^{(*)+}/\pi^+} \equiv \frac{\mathcal{B}_{B_c^+\to J/\psi D_s^{(*)+}}}{\mathcal{B}_{B_c^+\to J/\psi\pi^+}} = \frac{1}{\mathcal{B}_{D_s^+\to\phi(K^+K^-)\pi^+}} \times \frac{N_{B_c^+\to J/\psi D_s^{(*)+}}}{N_{B_c^+\to J/\psi\pi^+}} \times \frac{\mathcal{A}_{B_c^+\to J/\psi\pi^+}}{\mathcal{A}_{B_c^+\to J/\psi D_s^{(*)+}}}$$

$$\mathcal{R}_{D_s^{*+}/D_s^+} \equiv \frac{\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+\to J/\psi D_s^+}} = \frac{N_{B_c^+\to J/\psi D_s^{*+}}}{N_{B_c^+\to J/\psi D_s^+}} \times \frac{\mathcal{A}_{B_c^+\to J/\psi D_s^+}}{\mathcal{A}_{B_c^+\to J/\psi D_s^{*+}}}$$

$$\Gamma_{\pm\pm}/\Gamma = f_{\pm\pm} \times \frac{\mathcal{A}_{B_c^+\to J/\psi D_s^{*+}}}{\mathcal{A}_{B_c^+\to J/\psi D_s^{*+},\mathcal{A}_{\pm\pm}}}$$

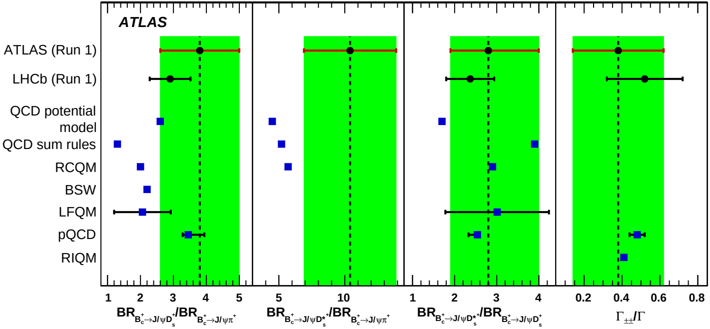
Systematics

- Systematics dominated by uncertainties of the signal fits, both $B_c^+ \to J/\psi D_s^{(*)+}$ and $B_c^+ \to J/\psi \pi^+$ modes
  - Ratios $\mathcal{R}$ mostly affected by signal and background mass shape variations
  - $\Gamma_{\pm\pm}/\Gamma$ uncertainty dominated by background angular modelling

Source	Uncertainty [%]			
	$R_{D_s^+/\pi^+}$	$R_{D_s^{*+}/\pi^+}$	$R_{D_s^{*+}/D_s^+}$	$\Gamma_{\pm\pm}/\Gamma$
Simulated $p_{\mathrm{T}}(B_c^+)$ spectrum	0.4	0.9	0.5	0.4
Simulated $\lvert\eta(B_c^+)\rvert$ spectrum	1.9	2.4	0.6	0.2
Tracking efficiency	0.5	0.5	< 0.1	< 0.1
B_c^+ lifetime	1.2	1.3	< 0.1	< 0.1
D_s^+ lifetime	0.3	0.3	< 0.1	< 0.1
$B_c^+ \to J/\psi D_s^{(*)+}$ signal extraction	4.4	10.5	10.7	17.4
$B_c^+ \to J/\psi \pi^+$ signal extraction	8.5	8.5	–	–
D_s^{*+} branching fractions	< 0.1	< 0.1	< 0.1	1.1
MC sample sizes	2.3	2.4	2.7	2.2
Total	10.3	14.2	11.0	17.6
$\mathcal{B}_{D_s^+ \to \phi(K^+K^-)\pi^+}$	5.9	5.9	–	–

Results

- $\mathcal{R}_{D_s^+/\pi^+} = \frac{\mathcal{B}_{B_c^+ \to J/\psi D_s^+}}{\mathcal{B}_{B_c^+ \to J/\psi \pi^+}} = 3.8 \pm 1.1\ (\text{stat.}) \pm 0.4\ (\text{syst.}) \pm 0.2\ (\text{BF})$
- $\mathcal{R}_{D_s^{*+}/\pi^+} = \frac{\mathcal{B}_{B_c^+ \to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+ \to J/\psi \pi^+}} = 10.4 \pm 3.1\ (\text{stat.}) \pm 1.5\ (\text{syst.}) \pm 0.6\ (\text{BF})$
- $\mathcal{R}_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}_{B_c^+ \to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+ \to J/\psi D_s^+}} = 2.8^{+1.2}_{-0.8}\ (\text{stat.}) \pm 0.3\ (\text{syst.})$
- $\Gamma_{\pm\pm}/\Gamma = 0.38 \pm 0.23\ (\text{stat.}) \pm 0.07\ (\text{syst.})$



Conclusion

Main ATLAS B_c highlights:

- First and so far the only observation of an excited state of B_c
  - Non-observation by LHCb and lack of CMS results motivates further study
- Measurement of $B_c^+ \to J/\psi D_s^{(*)+}$ decays properties
  - We were not the first, but rather competitive
  - Good performance of ATLAS with such complicated decay topologies motivates a number of other related studies

Further ATLAS B_c results to come soon, stay in tune!