b-hadron production @ ATLAS & CMS

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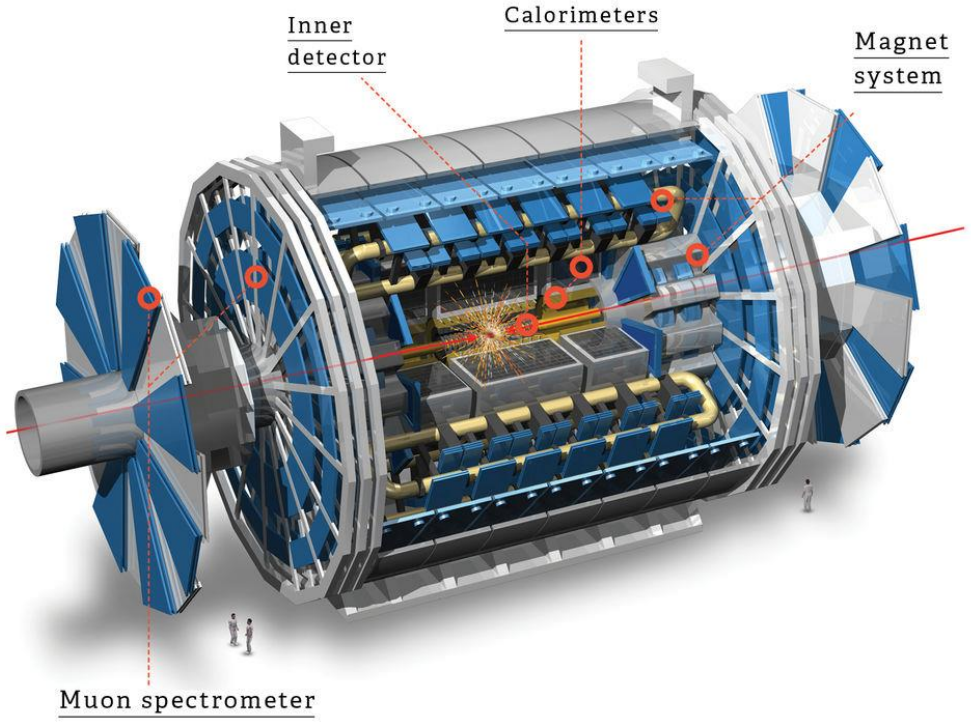
Some taste on b hadron production at ATLAS and CMS

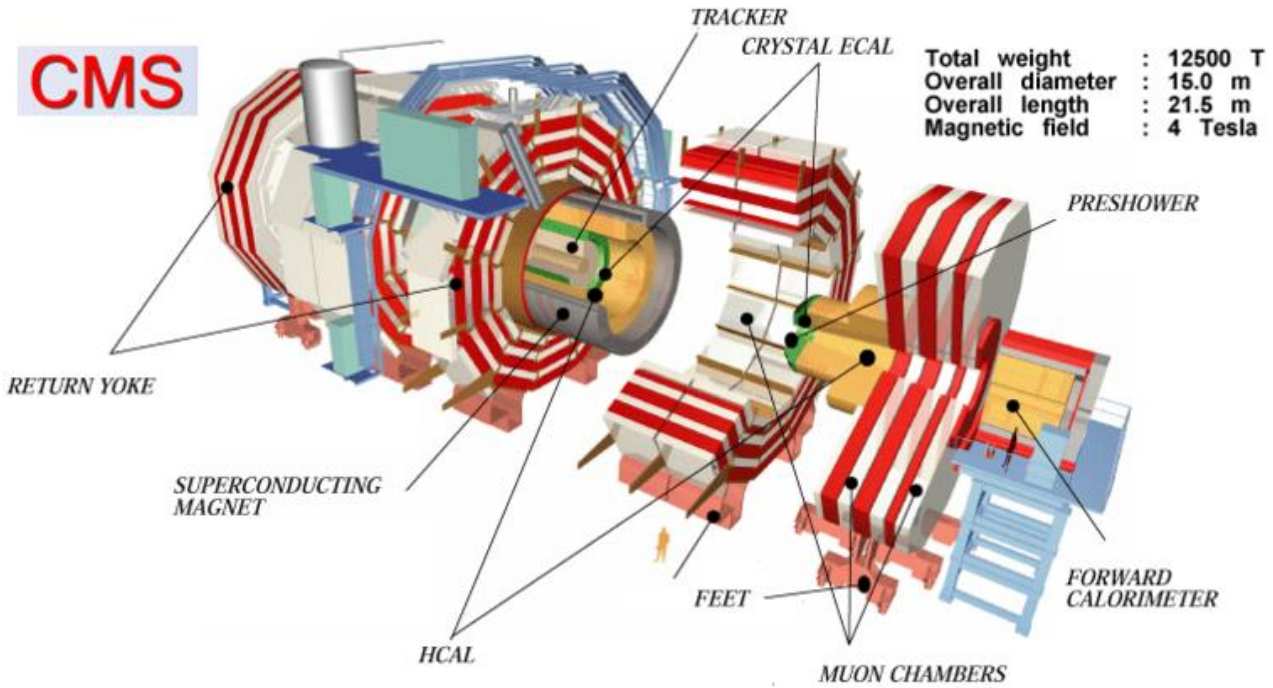
- Quarkonium cross sections at 13 TeV (CMS) and non-prompt fraction (CMS & ATLAS)
- b quark fragmentation (ATLAS)
- B+ cross section and mass measurement (CMS & ATLAS)
- Observation of $B^+ \to \psi(2S)\phi K^+$ (CMS)
- Study of $B_c^+ \to J/\psi\, D_s^{(*)+}$ (ATLAS)
- Observation and branching fraction of $\Lambda_b^0 \to \psi(2S)\Lambda^0$ (ATLAS)
- Helicity study of $\Lambda_b^0 \to J/\phi\, \Lambda$ decays (ATLAS & CMS)
- Search for $X^+(5558) \to B_s\pi^+$ (CMS)
- CP violation phase in $B_s \to J/\psi\, \phi$ (ATLAS & CMS)
- $B^0_s \to J/\psi\ f_0(980)$ (CMS)
- $\Delta\Gamma_d/\Gamma_d$ of the $B^0 - \bar{B}^0$ system (ATLAS)

All heavy flavor results from ATLAS and CMS can be found at:

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

The detectors



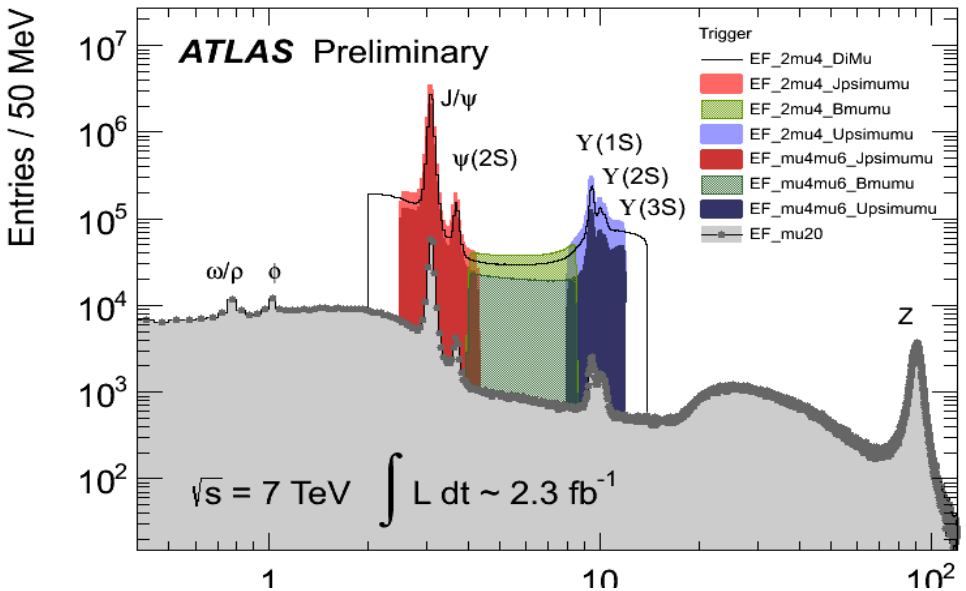


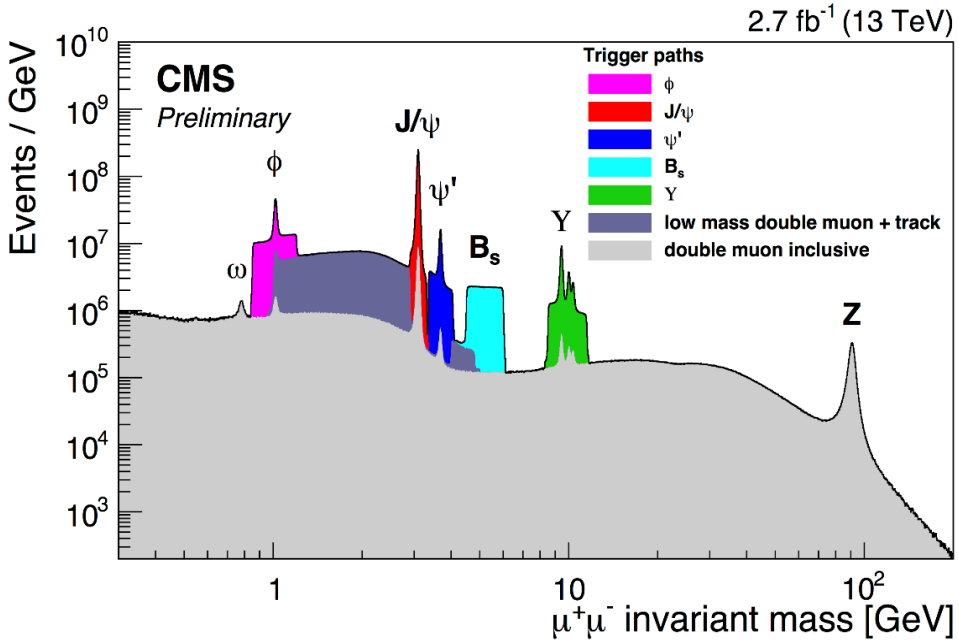
b physics triggers

ATLAS & CMS use dimuon triggers for b and charm physics. In general :

- Quarkonia: $J/\psi \rightarrow \mu\mu, \Upsilon \rightarrow \mu\mu$
- Exclusive decays: $B \rightarrow J/\psi(\mu\mu) + X$
- Rare decays: $B \rightarrow \mu\mu + X$

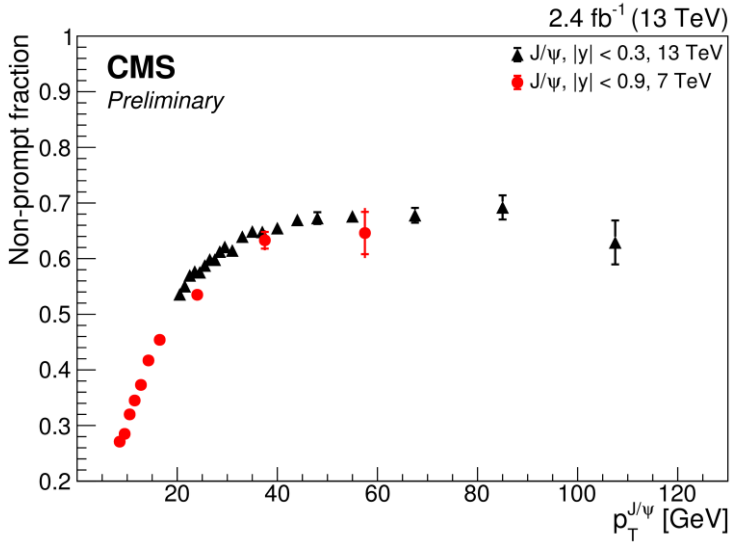
Minimum differences between ATLAS and CMS.

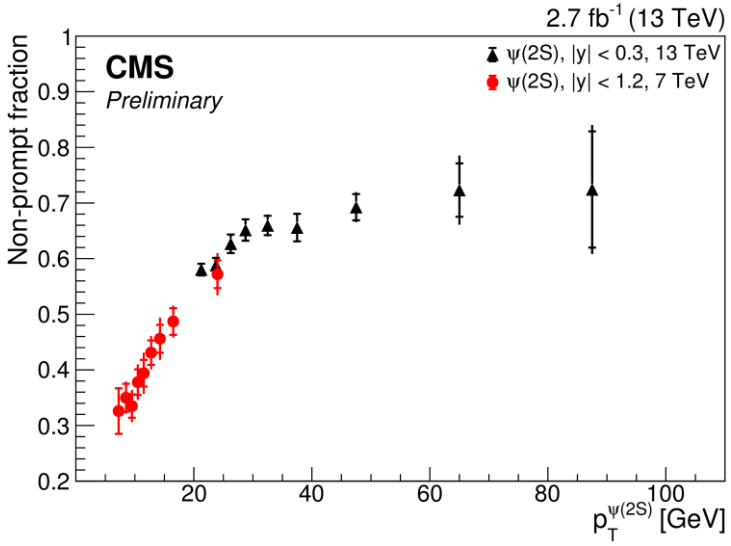


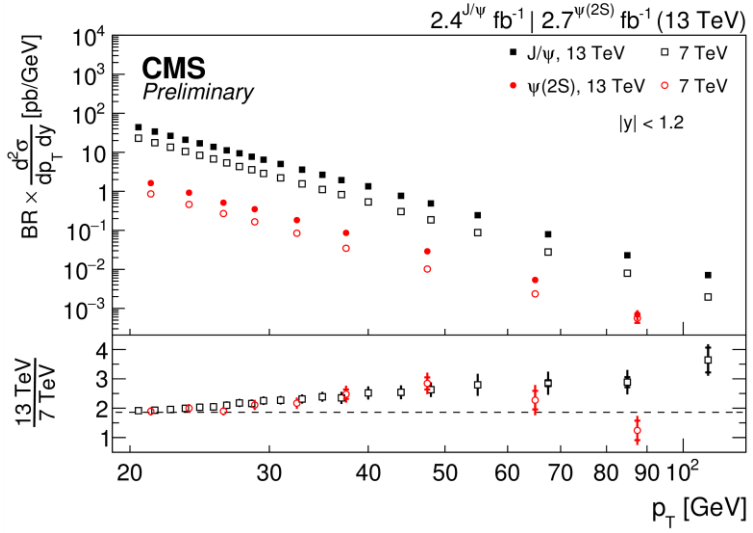


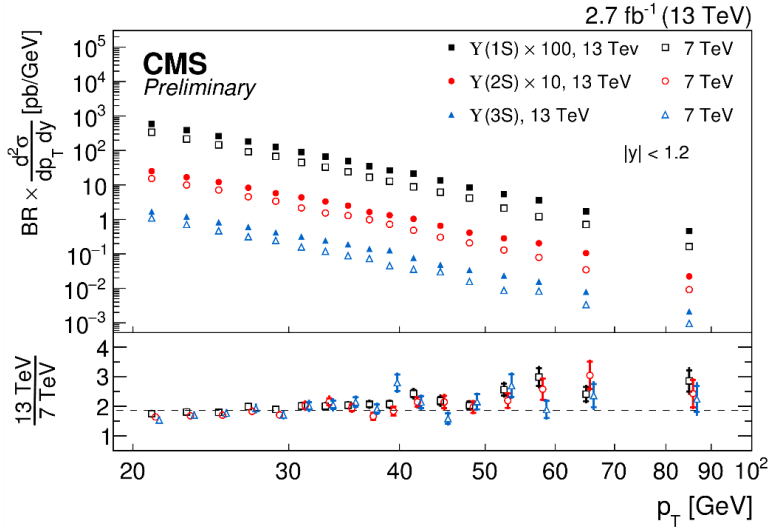
Quarkonium cross section and non-prompt fraction

- Many of the results of b hadron production are based on $J/\psi \rightarrow \mu^+\mu^-$
- Non-prompt production mostly associated with b-hadrons.

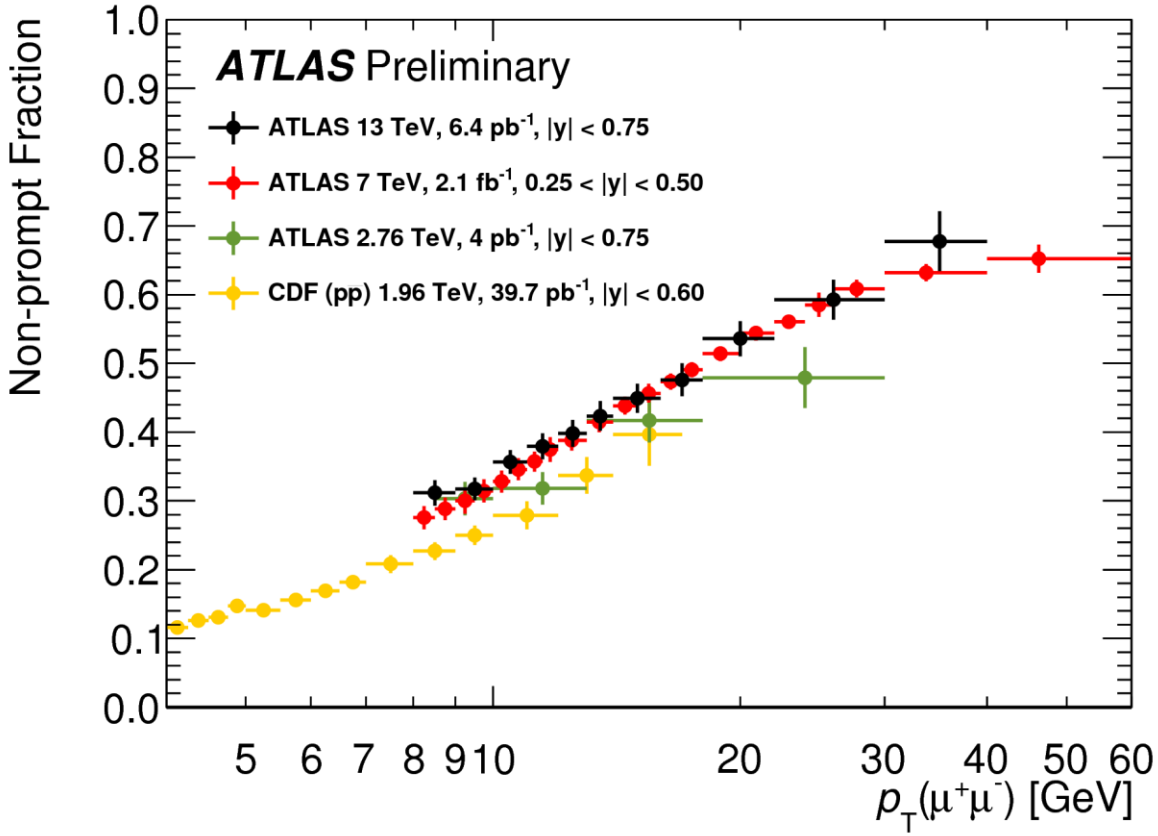


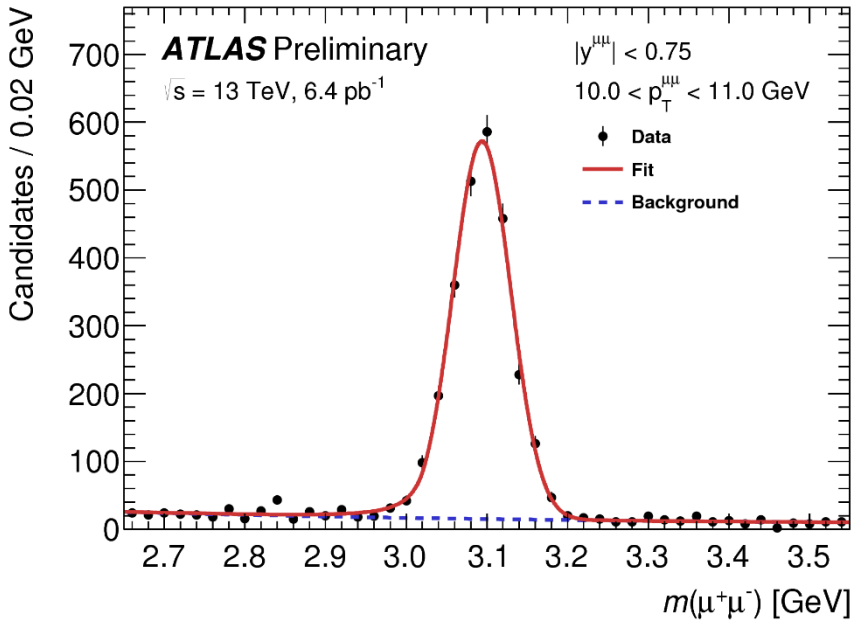


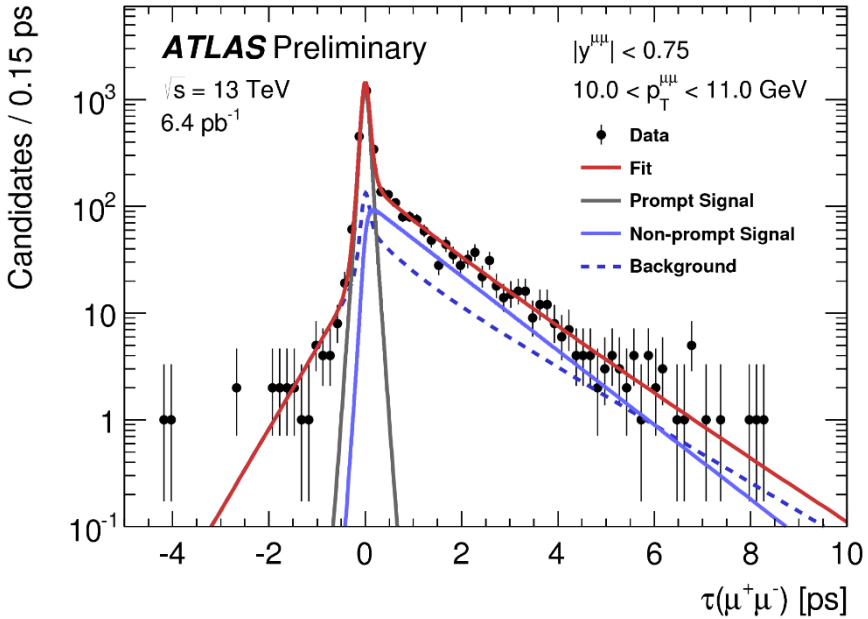




Non-prompt fraction







New results at 13 TeV very consistent with previous results at 7 TeV.

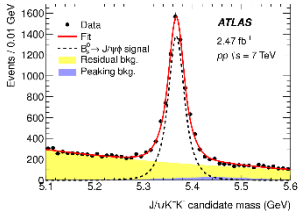
b quark fragmentation fraction f_s / f_d

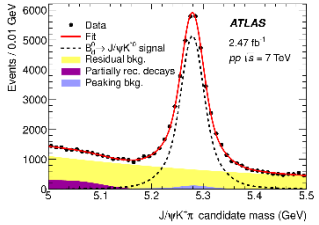
Of interest in the study of rare decays $B_{(s)} \to \mu^+\mu^-$

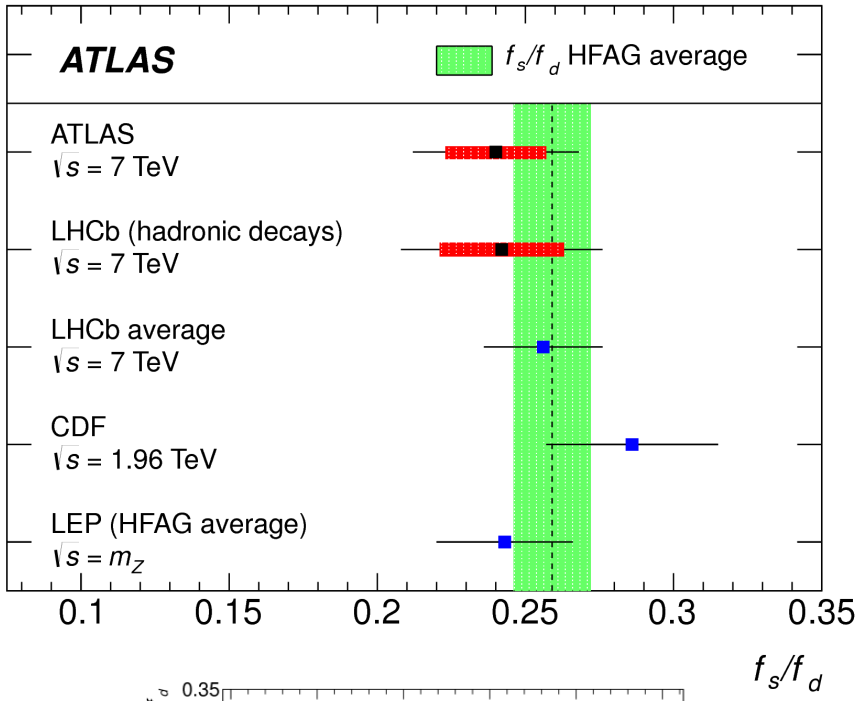
By using the decays

- $B_s^0 \to J/\psi\ \phi$
- $B_d^0 \to J/\psi\ K^{*0}$

we can measure:



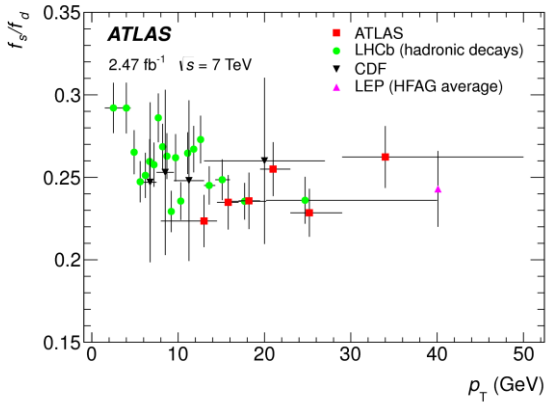




$$\frac{f_s Br(B_s^0 \to J/\psi\ \phi)}{f_d Br(B_d^0 \to J/\psi\ K^{*0})} = 0.199\ \pm 0.004\ (stat.) \pm 0.008\ (syst.)$$

This can be translated into*:

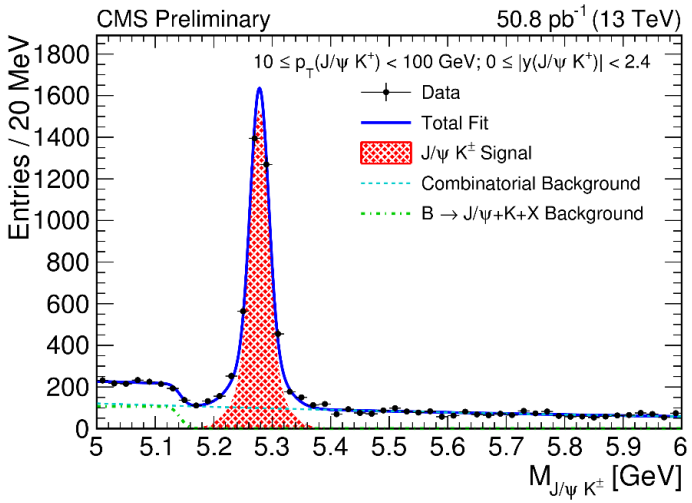
$$\frac{f_s}{f_d} = 0.240\ \pm 0.004\ (stat.) \pm 0.010\ (syst.) \pm 0.017\ (th)$$

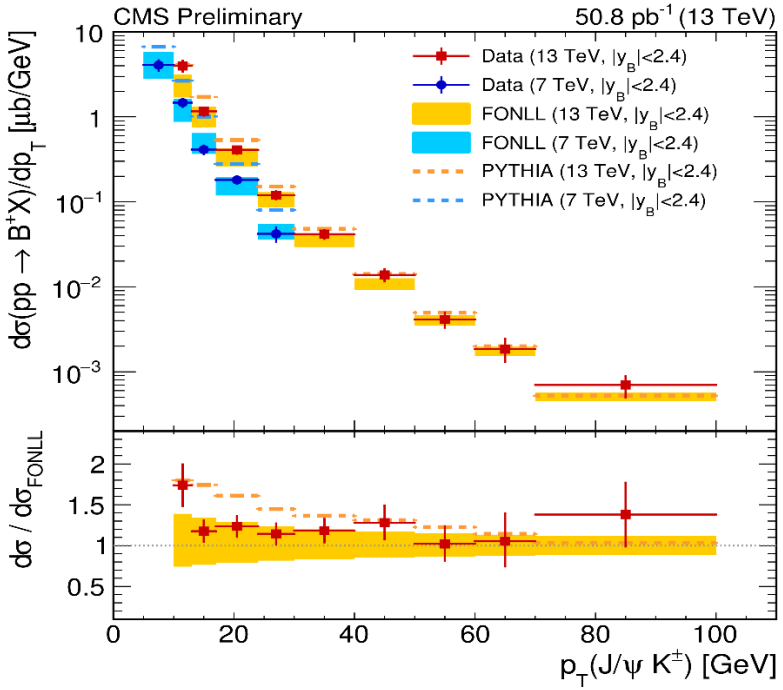


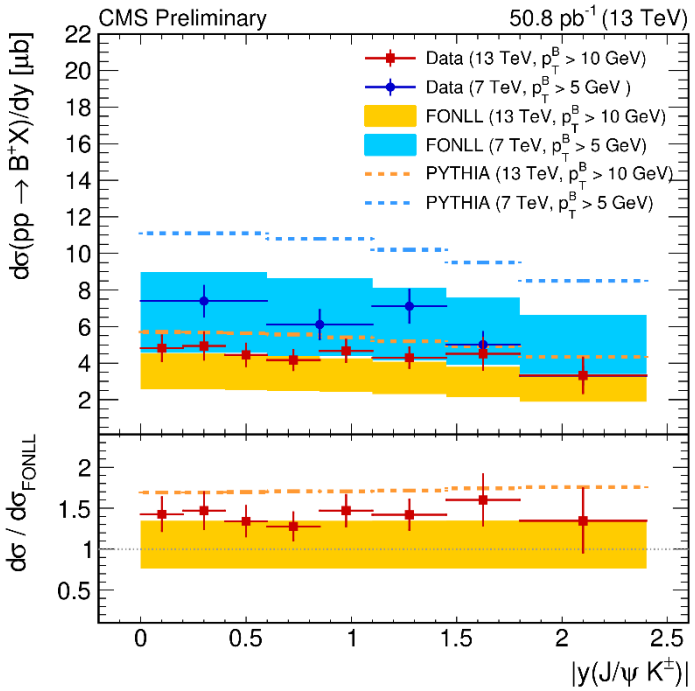
*Phys. Rev. D 89 (2014) 094010

B^+ production @ 13 TeV

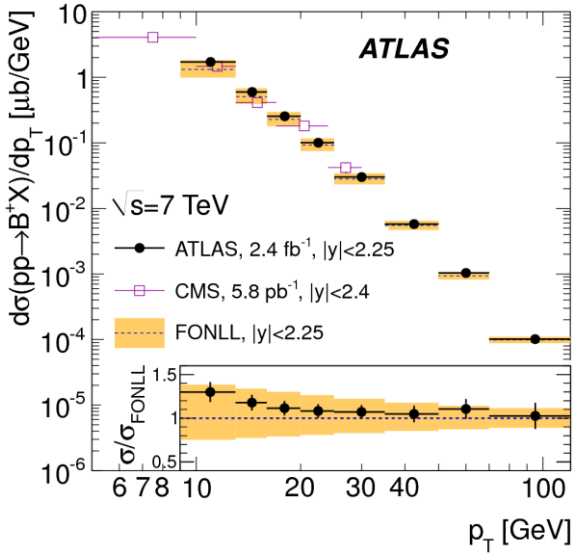
- Signal reconstructed in $B^+ \to J/\psi\, K^+$ decays
- Signal yield measured using unbinned maximum likelihood fits to the mass distribution of B^+ in several bins of momentum and rapidity.







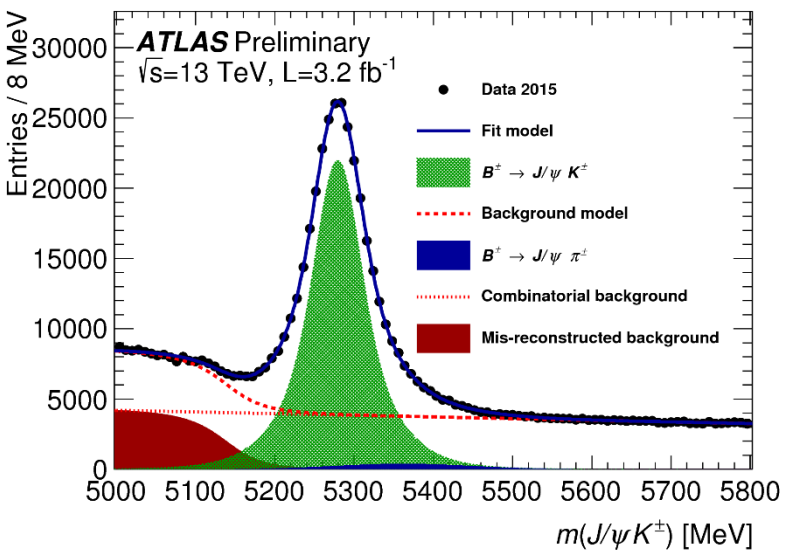
Results in agreement with predictions

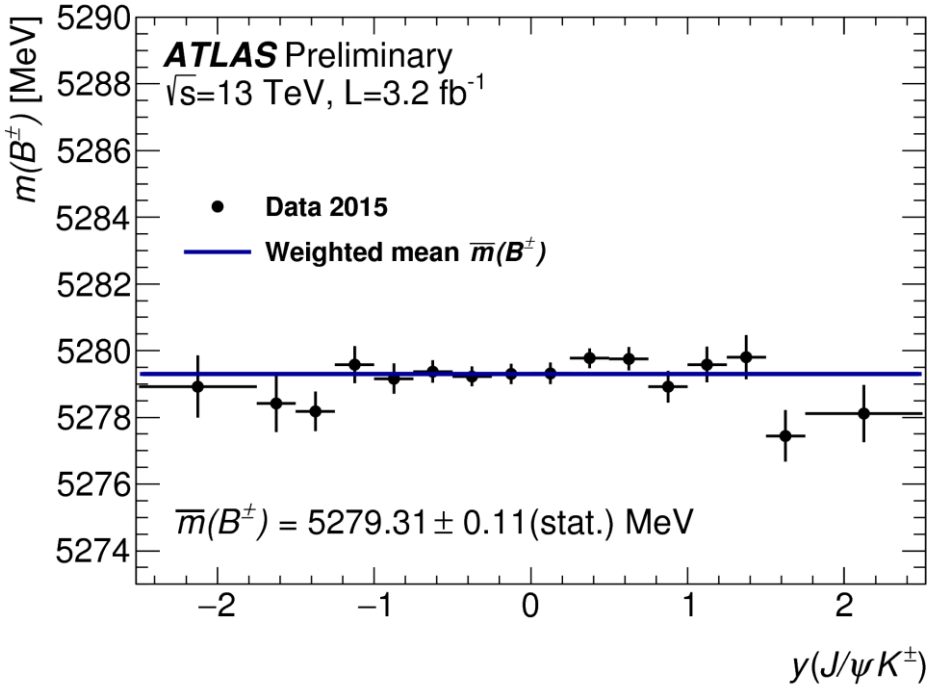


Very good agreement between ATLAS and CMS @ 7 TeV

B^+ production @ 13 TeV

- ATLAS used 2015 dataset to reconstruct the mass of the B^+ in several rapidity interval using $B^+ \rightarrow J/\psi\, K^+$ decays.
- Excellent test for momentum calibration of the Inner Detector Tracking.





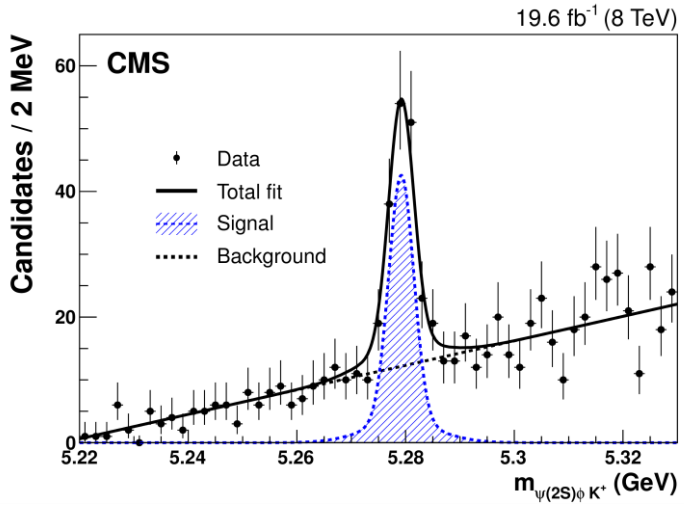
$$m(B^+) = 5279.31 \pm 0.11\ (stat)$$

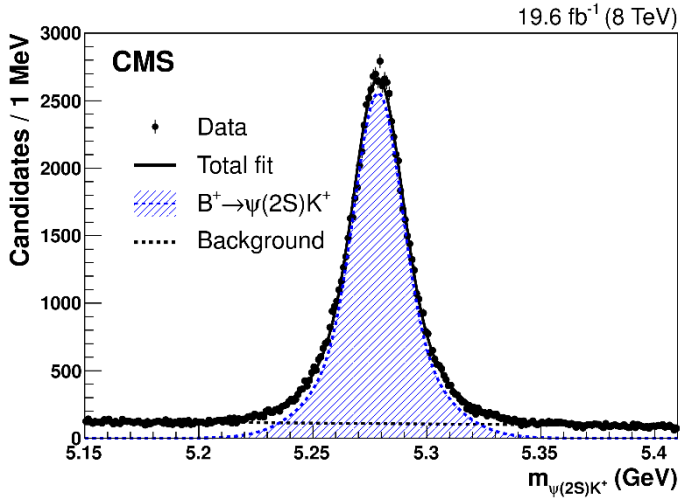
Source	Systematic Error [MeV]
y-Dependence	0.11
Signal Mass Model	0.09
Background Mass Model	0.17
Mass Fit Window	0.14
Background:	
Fraction	0.02
Line Shape	0.04
MC Reweighting	0.04
Total	0.25

Observation of $B^+ \to \psi(2S)\phi K^+$

- Several experiments have reported the observation of structures in the $J/\psi\ \phi$ mass spectrum of $B^+ \to J/\psi\ \phi\ K^+$decays.
- Natural extension is to study the mass of $\psi(2S)\phi$ in $B^+ \to \psi(2S)\ \phi\ K^+$ decays.
- The branching ratio measure from:

$$Br(B^+ \to \psi(2S)\ \phi\ K^+) = \frac{N_{B^+\to\psi(2S)\ \phi\ K^+}\ Br(B^+ \to \psi(2S)\ K^+)}{N_{B^+\to\psi(2S)\ K^+}\varepsilon_{rel} Br(\phi \to K^+K^-)}$$



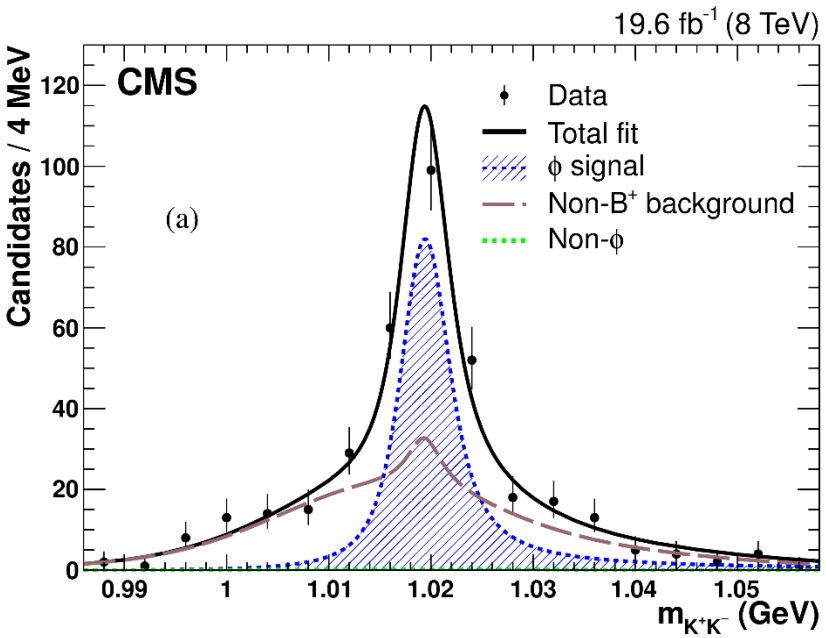


Observation of $B^+ \to \psi(2S)\phi K^+$

$$\mathrm{Br}(B^+ \to \psi(2S)\,\phi\,K^+) = \left(4.0 \pm 0.4\,(stat) \pm 0.6\,(syst) \pm 0.2\,(B)\right) \times 10^{-6}$$

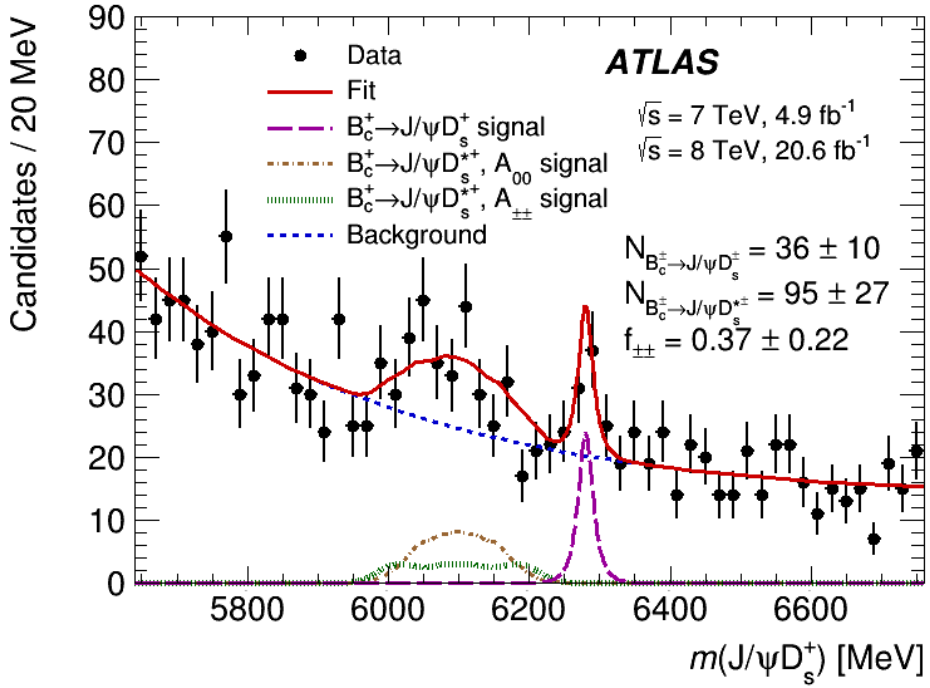
Last uncertainty (B) reflects in the imprecision on $Br(B^+ \to \psi(2S)\,K^+)$

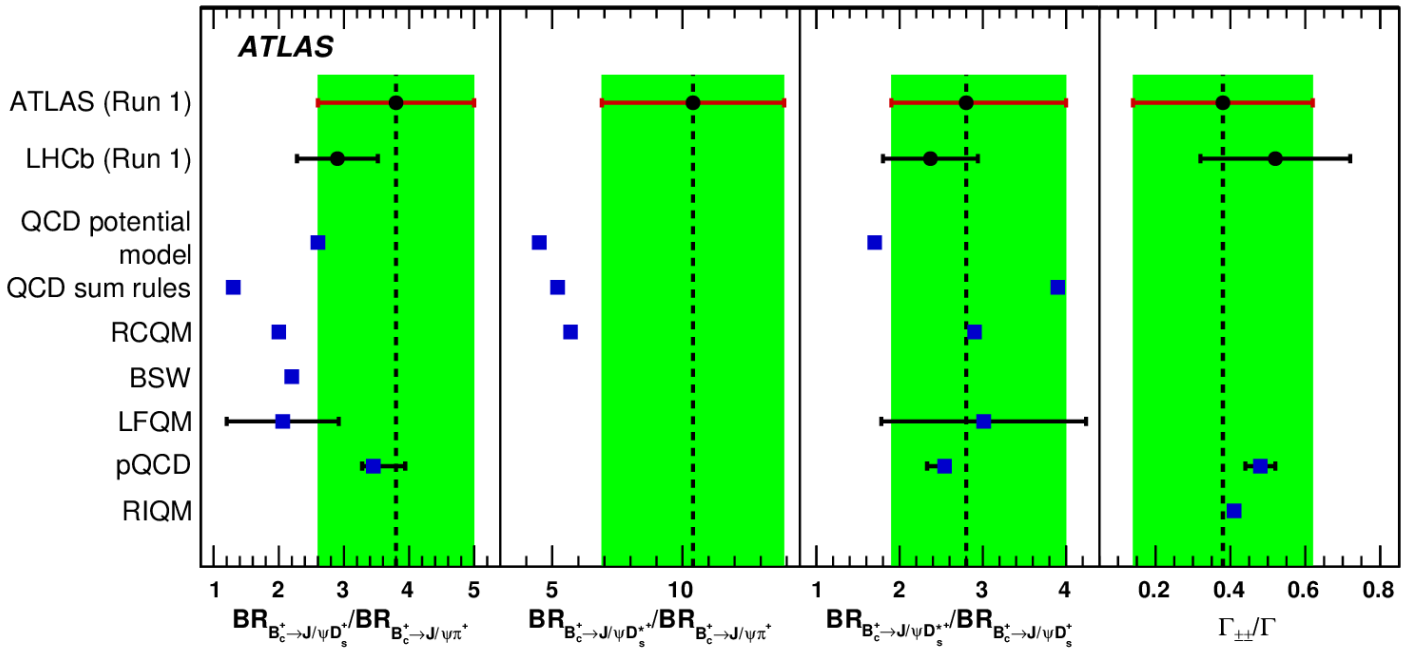
Source	Uncertainty (%)
ϕ purity	5.0
Charged particle track reconstruction efficiency	7.8
Modeling of p_T dependence of B^+ efficiency	5.3
B^+ mass shape for signal mode	8.6
B^+ mass shape for normalization mode	1.0
Mass distribution for the background in the signal	2.9
Background distribution in the normalization channel	2.2
Uncertainty in relative efficiency of signal and normalization	2.3
Angular distributions of K^+K^- systems	1.9
$\mathcal{B}(\phi \to K^+K^-)$ uncertainty	1.0
Total	15



The upper limit on the fraction of $B^+ \to \psi(2S)(not\ \phi)K^+$ decays in the $B^+ \to \psi(2S)K^+K^-K^+$ channel is found to be 0.26 at 95% confidence level.

Observation of $B_c^+ \to J/\psi\, D_s^{(*)+}$

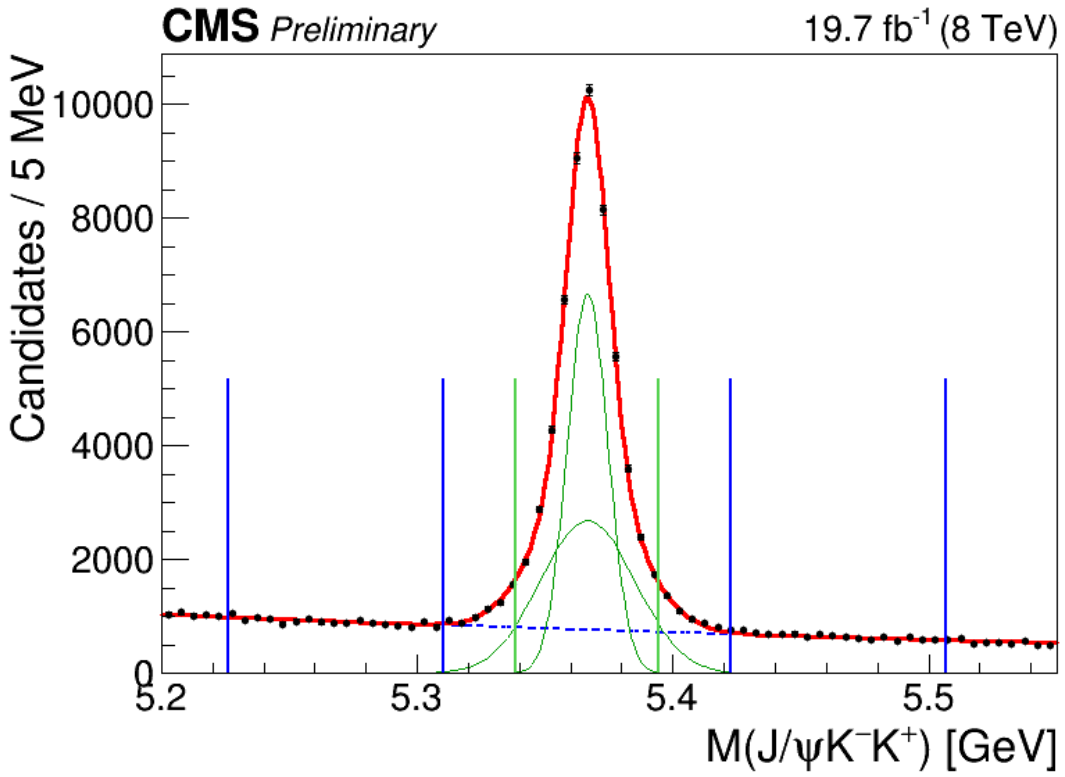




- Studied in both 7 TeV and 8 TeV datasets.
- Ratios measured with respect to $B_c \to J/\psi\, \pi$
- Transverse polarization measure as the fraction $\frac{\Gamma_{\pm\pm}}{\Gamma}$

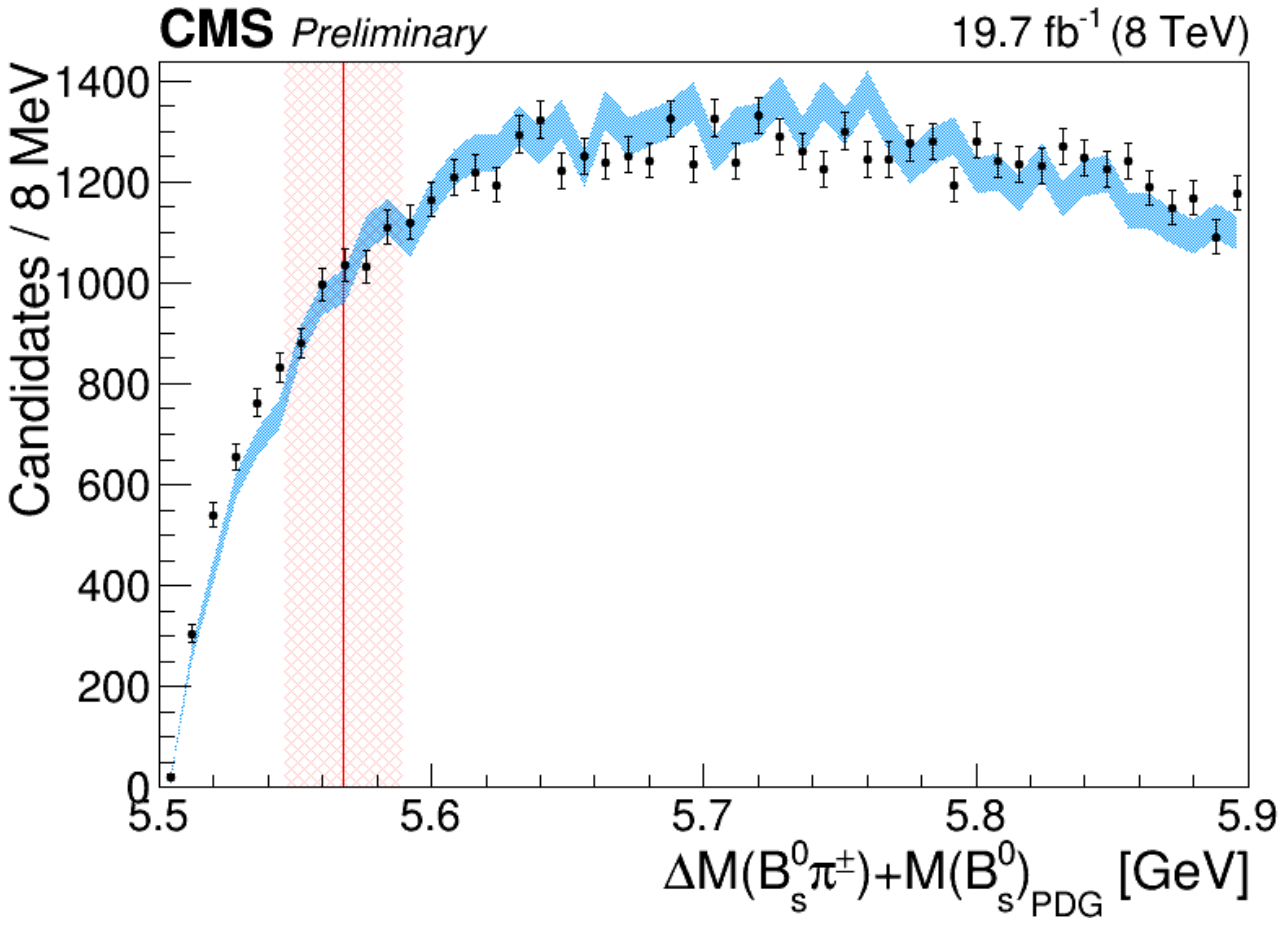
Search for $X^+(5568) \to B_s\pi^+$

- DZero reported the observation of a tetraquark candidate in $X^+(5568) \to B_s\pi^+$
- LHCb reported a non-confirmation result of these candidate.
- CMS has recollected several thousands of $B_s \to J/\psi\ \phi$ decays on what to look for.

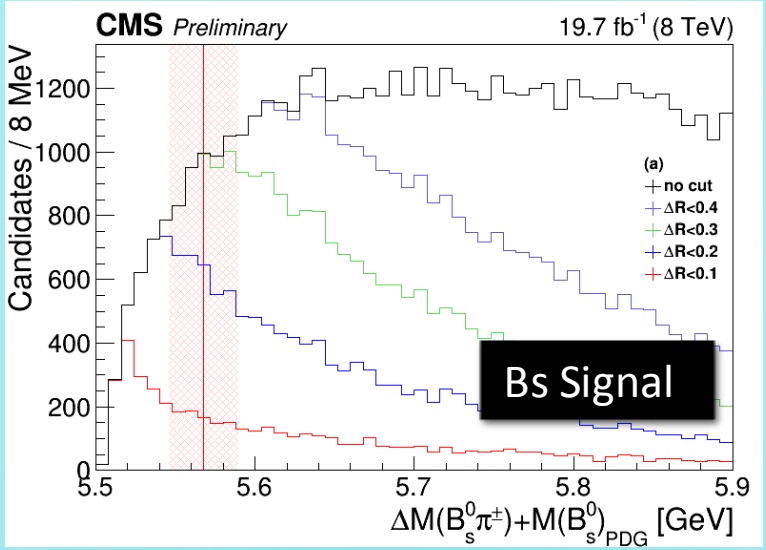


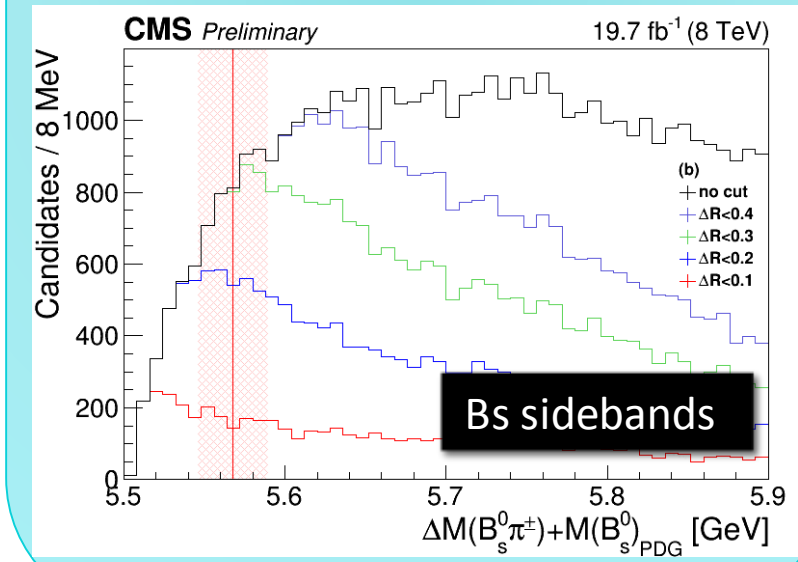
$$\rho_X \equiv \frac{\sigma(pp \to X(5558) + anything) \times B(X(5558) \to B_s\pi^\pm)}{\sigma(pp \to B_s + anything)} = \frac{N_X}{N_{B_s}} \frac{\varepsilon_{B_s}}{\varepsilon_X}$$

Search for $X^+(5568) \rightarrow B_s\pi^+$

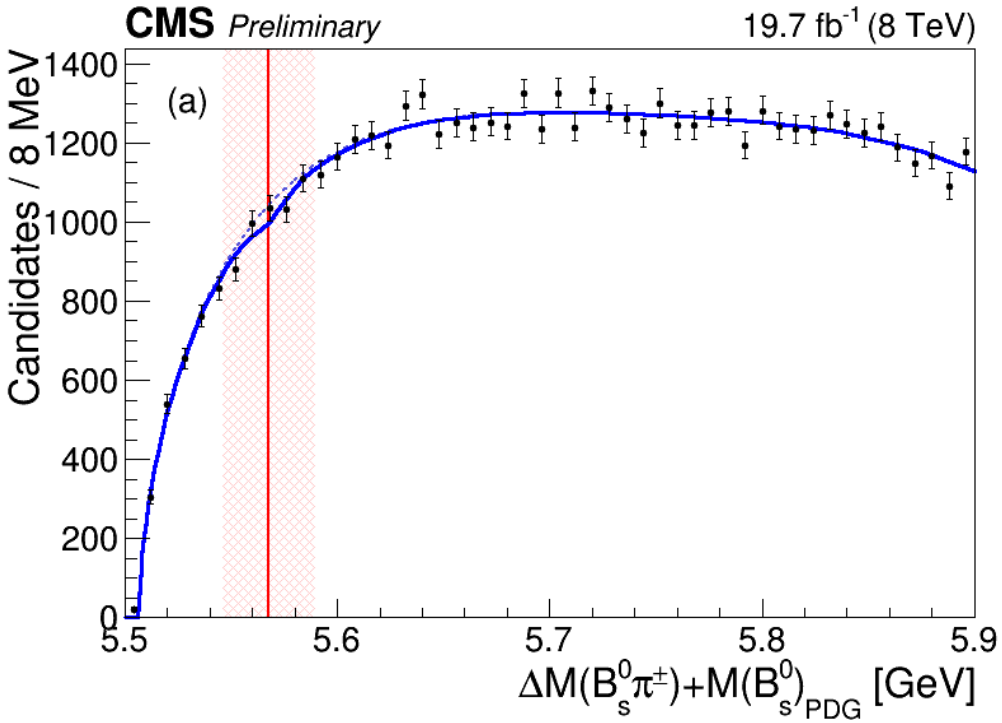


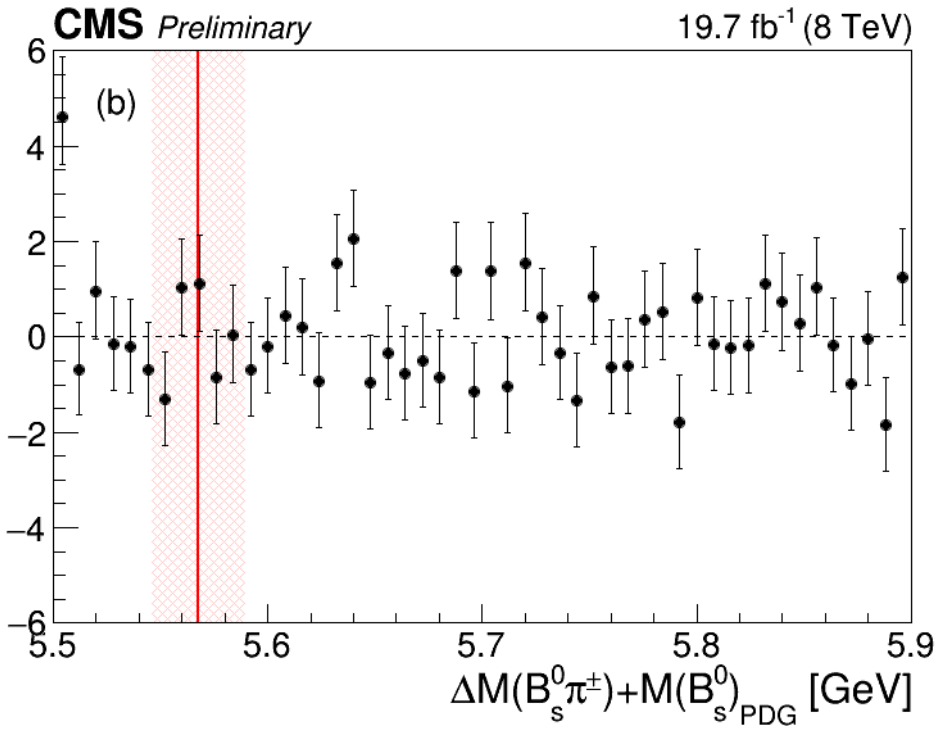
With cone cut





Search for $X^+(5568) \rightarrow B_s\pi^+$

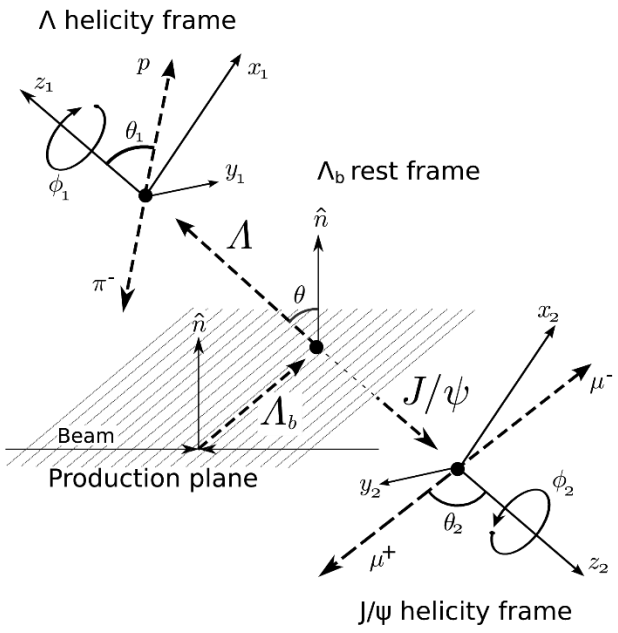


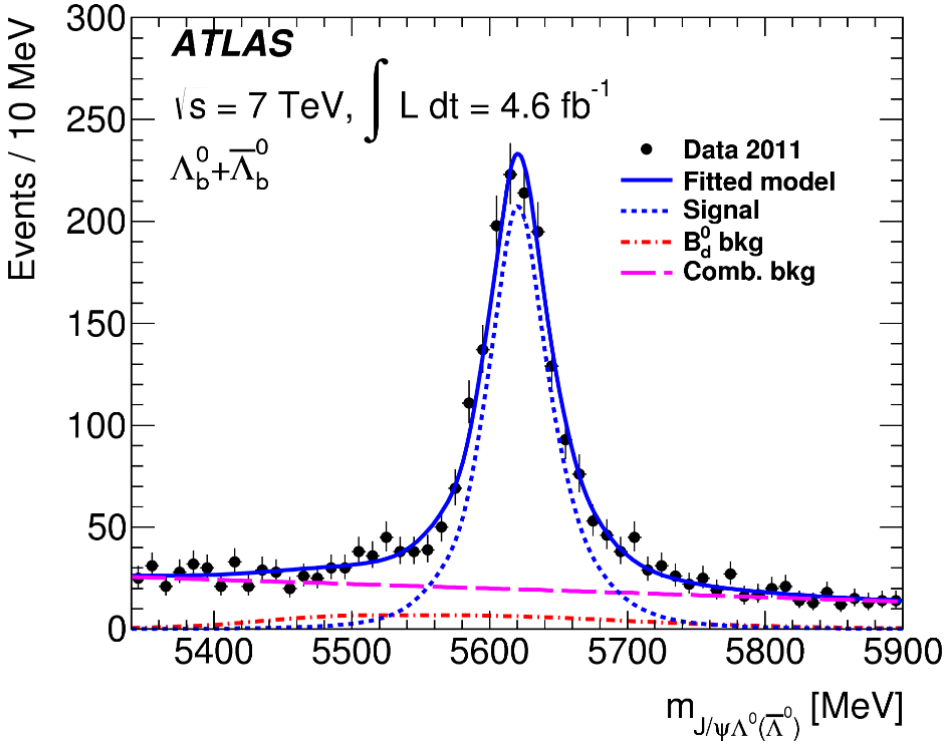


$\rho_X < 3.9\%$ @95% $C.L.$

$\rho_X^{DZero} = 8.6 \pm 1.9\,(stat) \pm 1.4\,(syst.)\ \%$

Helicity study of $\Lambda_b^0 \to J/\phi\ \Lambda$ decays





- Study performed by ATLAS with dataset at 7 TeV
- Requires an angular study
- Assume zero polarization.
- Assume CP conservation.

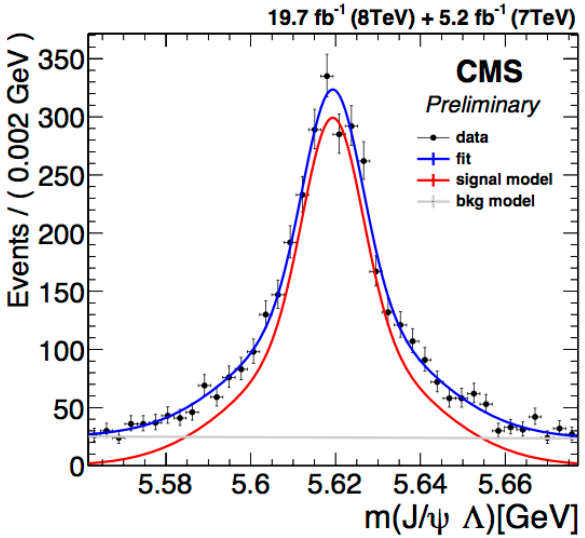
$$\alpha_b = 0.30 \pm 0.16\ (stat) \pm 0.06\ (syst)$$

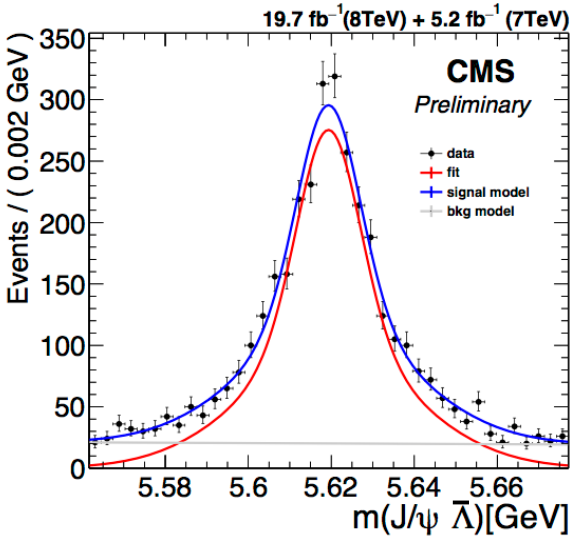
Helicity study of $\Lambda_b^0 \to J/\phi\ \Lambda$ decays

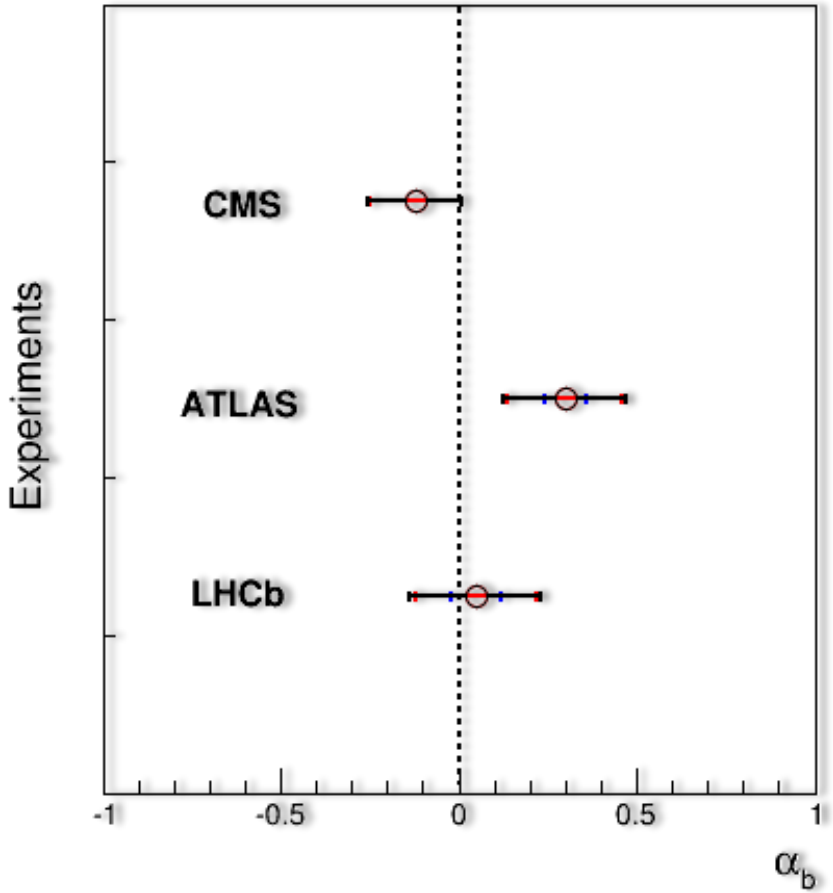
- Study performed by CMS with datasets at 7 TeV and 8 TeV
- Requires an angular study
- Assume CP conservation.

$$P = 0.00 \pm 0.06(stat) \pm 0.02\ (syst)$$

$$\alpha_b = -0.12\ \pm 0.13\ (stat) \pm 0.06\ (syst).$$

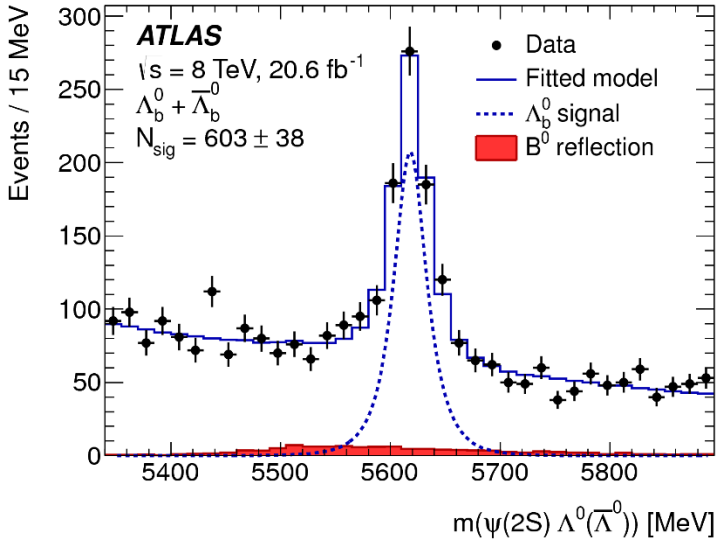






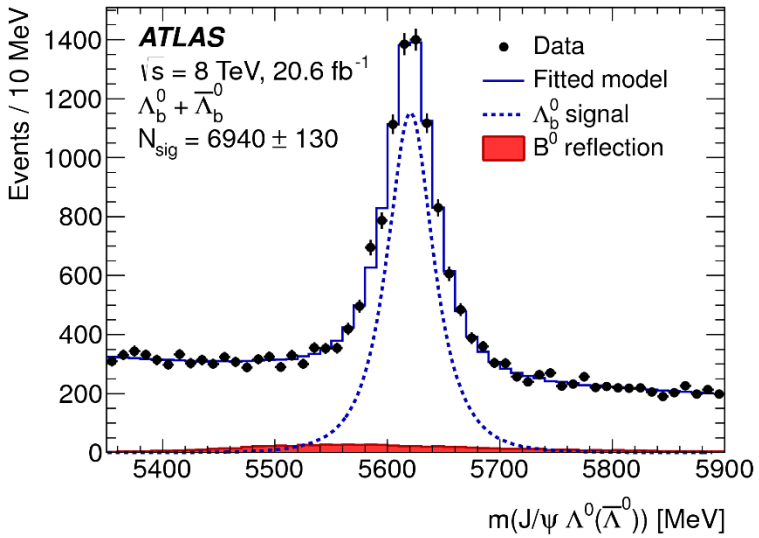
Observation of $\Lambda_b^0 \to \psi(2S)\Lambda^0$

- First observation of these decay mode
- Dataset of 8 TeV collisions used in the study.
- Production measured relative to the $\Lambda_b^0 \to J/\phi\ \Lambda$ decay mode, to which is expected to be of similar order.
- Kinematic region for the Λ_b^0 of $p_T > 10\ GeV$ and $|\eta| < 2.1$



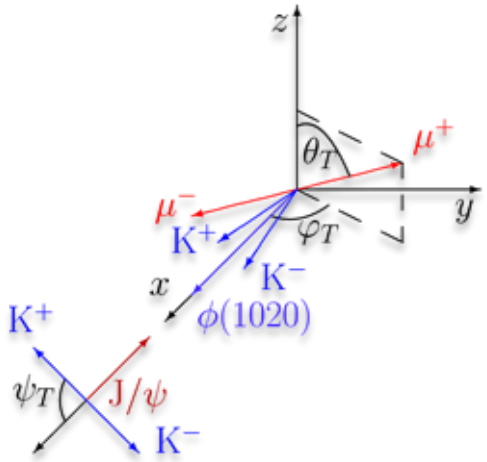
$$\frac{\Gamma(\Lambda_b \to \psi(2S)\ \Lambda)}{\Gamma(\Lambda_b \to J/\psi\ \Lambda)} = 0.501\ \pm 0.033\ (stat) \pm 0.016\ (syst)\ \pm 0.011\ (B)$$

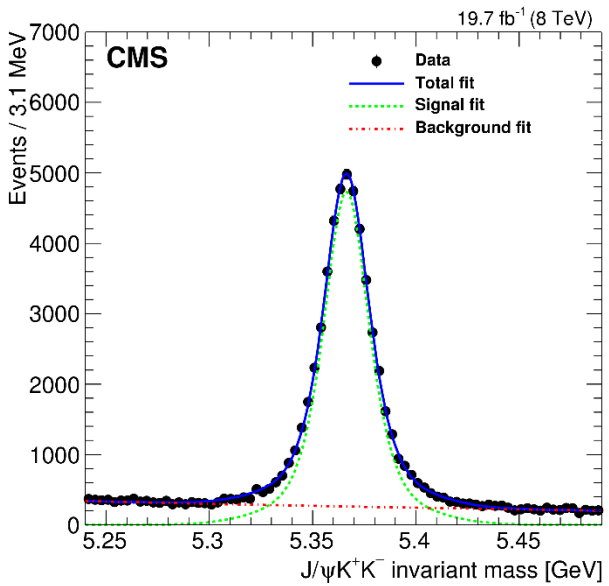
- Last uncertainty (B) is due to the imprecision on the charmonium branching fractions
- Value lower than expected according to the expectation from the covariant quark model: $0.8\ \pm 0.1$



Measure of ϕ_s and $\Delta\Gamma_s$

- CPV phase ϕ_s from interference btw direct and through mixing decays.
- Non-standard particles in loops could change the SM prediction of ϕ_s.
- 3+1 angular-time analysis to disentangle CP-odd/even contributions.





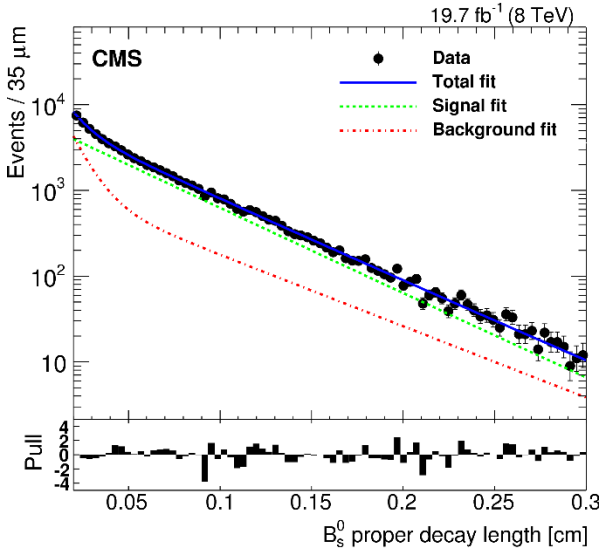
- Using $B_s \to J/\psi\ \phi$ decays in dataset @ 8 TeV.
- Using opposite side tagging to determine the initial flavor probability of the B_s meson.
- Simultaneous fit to mass, proper decay length, and angular distributions.

$$\phi_s = -0.075 \pm 0.097\ (stat) \pm 0.031(syst)\ \ rad$$

$$\Delta\Gamma_s = 0.095 \pm 0.013\ (stat) \pm 0.007\ (syst)\ \ ps^{-1}$$

Results of the fit to the data. Uncertainties are statistical only.

Parameter	Fit result
ϕ_s [rad]	-0.075 ± 0.097
$\Delta\Gamma_s$ [ps^{-1}]	0.095 ± 0.013
$\lvert A_0\rvert^2$	0.510 ± 0.005
$\lvert A_S\rvert^2$	$0.012^{+0.009}_{-0.007}$
$\lvert A_\perp\rvert^2$	0.243 ± 0.008
$\delta_\parallel$ [rad]	$3.48^{+0.07}_{-0.09}$
$\delta_{S\perp}$ [rad]	$0.37^{+0.28}_{-0.12}$
$\delta_\perp$ [rad]	2.98 ± 0.36
$c\tau$ [μm]	447.2 ± 2.9

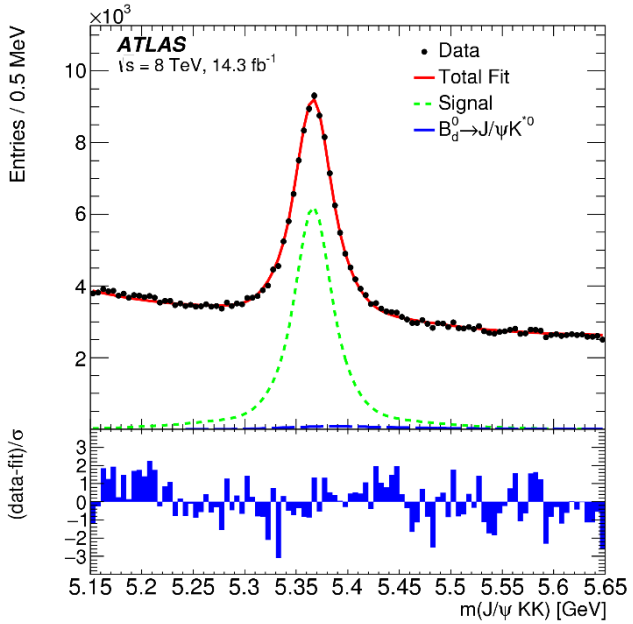


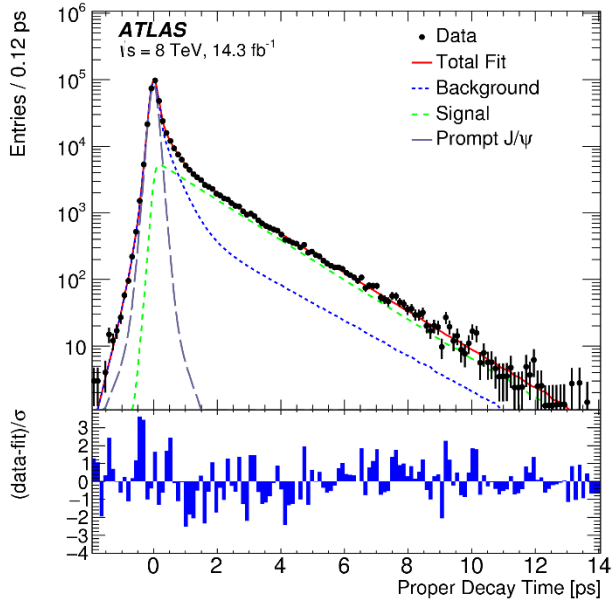
Measure of ϕ_s and $\Delta\Gamma_s$

- Using $B_s \to J/\psi\ \phi$ decays in dataset @ 8 TeV.
- Using opposite side tagging to determine the initial flavor probability of the B_s meson.
- Simultaneous fit to mass, proper decay length, and angular distributions.
- Combined with 7 TeV results to find:

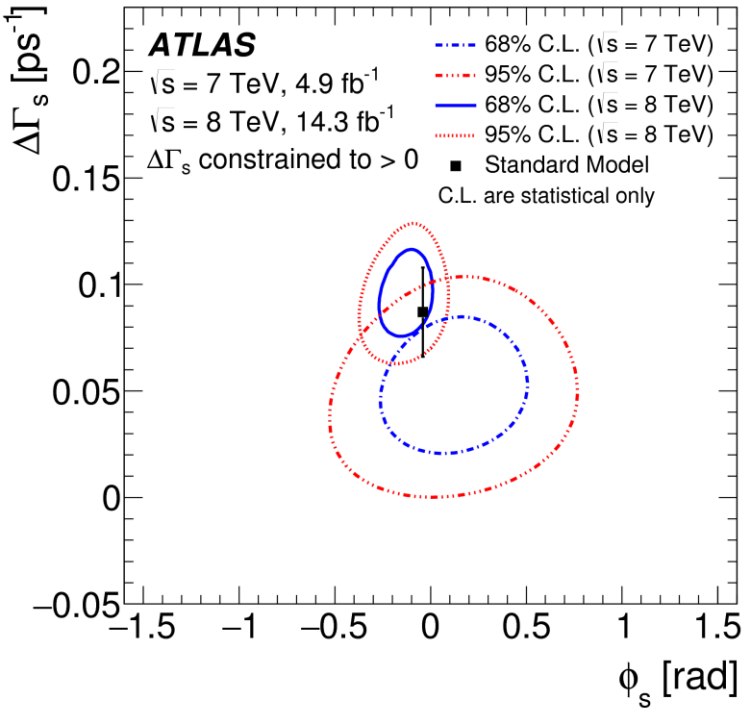
$$\phi_s = -0.098\ \pm 0.084\ (stat) \pm 0.040(syst)\ \ rad$$

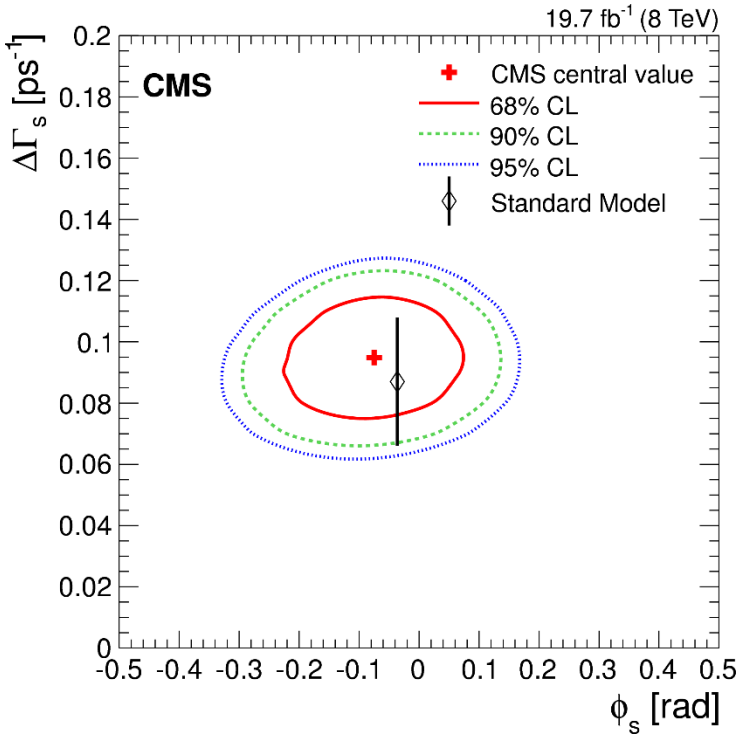
$$\Delta\Gamma_s = 0.083\ \pm 0.011\ (stat) \pm 0.007\ (syst)\ \ ps^{-1}$$

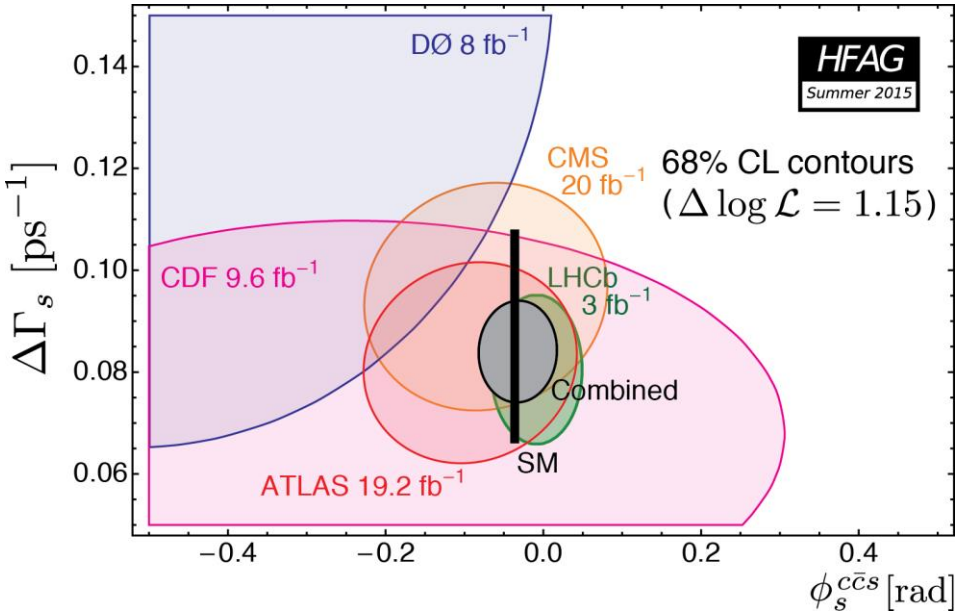




Measure of ϕ_s and $\Delta\Gamma_s$



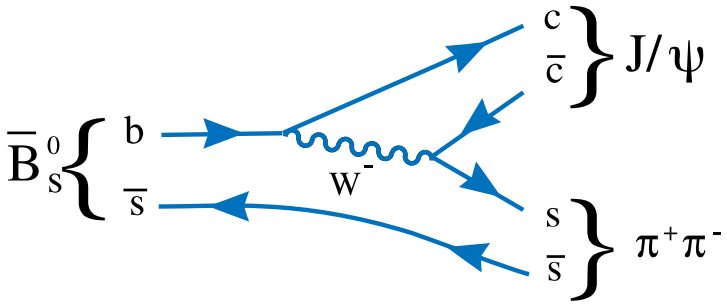




$B^0_s \to J/\psi\ \phi$: ATLAS, CDF, CMS, D0.
$B^0_s \to J/\psi KK$: LHCb.
$B^0_s \to J/\psi \pi\pi$: LHCb.
$B^0_s \to J/\psi\ D_s D_s$: LHCb.
[Refs. in http://www.slac.stanford.edu/xorg/hfag/osc/summer_2015/HFAG_phis_inputs.pdf]

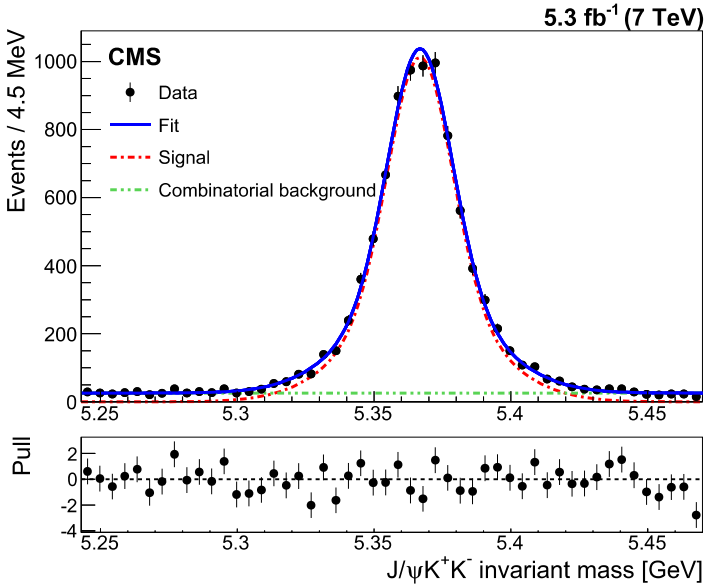
Results very consistent between both experiments

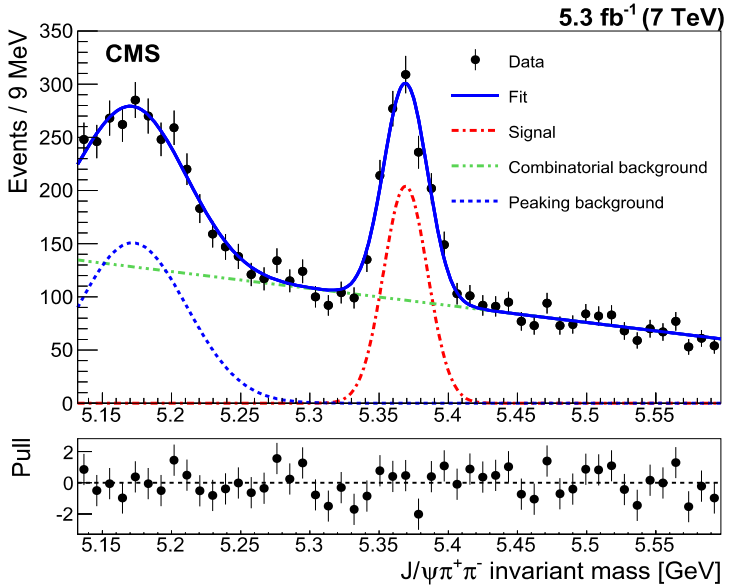
$B^0_s \to J/\psi\, f_0(980)$



$$R_{f_0/\phi} = \frac{\mathcal{B}(B^0_s \to J/\psi f_0)\,\mathcal{B}(f_0 \to \pi^+\pi^-)}{\mathcal{B}(B^0_s \to J/\psi \phi)\,\mathcal{B}(\phi \to K^+K^-)} = \frac{N^{f_0}_{obs}}{N^{\phi}_{obs}}\,\epsilon^{\phi/f_0}_{reco}$$

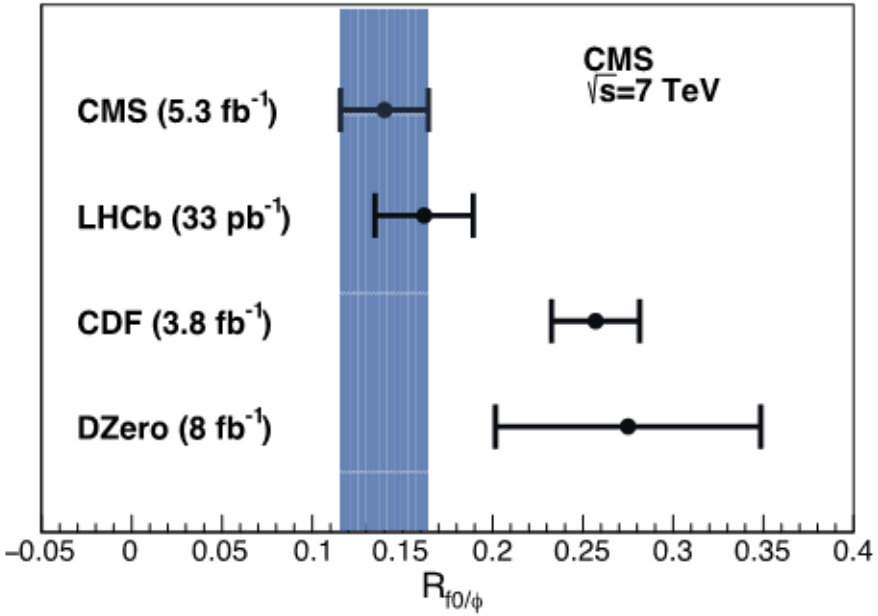
- CPV analysis is simplified using $B^0_s \to J/\psi\, f_0(\pi^+\pi^-)$ wrt $B^0_s \to J/\psi\phi(K^+K^-)$ decays. It is also a pure CP-odd eigenstate.
- It is important first to measure its production relative to $B^0_s \to J/\psi\phi(1020)$:





$\mathcal{B}(B^0_s \to \psi f_0(\pi\pi))/\mathcal{B}(B^0_s \to \psi\varphi(KK))$

$$R_{f_0/\phi}\,|_{|M_{\pi^+\pi^-}-974\ \mathrm{MeV}|<50\ \mathrm{MeV}} = 0.140 \pm 0.008\ (\mathrm{stat})\ \pm 0.023\ (\mathrm{syst})$$



Other experiments measure ratio in different $M(\pi^+\pi^-)$ ranges:

$$R_{f_0/\phi}\,|_{|M_{\pi^+\pi^-}-974\ \mathrm{MeV}|<90\ \mathrm{MeV}} = 0.162 \pm 0.022\ (\mathrm{stat})\ \pm 0.016\ (\mathrm{syst})$$

LHCb [PLB 698 (2011) 115–122]

$$R_{f_0/\phi}\mathcal{B}(\phi \to K^+K^-) = 0.139 \pm 0.006\ (\mathrm{stat})\ \pm\ ^{0.025}_{0.012}\ (\mathrm{syst})$$

LHCb [PRD 86, 052006 (2012)]*

$$R_{f_0/\phi}\,|_{0.85<M_{\pi^+\pi^-}<1.2} = 0.257 \pm 0.020\ (\mathrm{stat})\ \pm 0.014\ (\mathrm{syst})$$

CDF (PRD 84, 052012 (2011))

$$R_{f_0/\phi}\,|_{0.91<M_{\pi^+\pi^-}<1.05} = 0.275 \pm 0.041\ (\mathrm{stat})\ \pm 0.061\ (\mathrm{syst})$$

D0 [PRD 85, 011103(R) (2012)]

Consistent with theoretical expectation of $R_{f_0/\phi} \approx 0.2$ [Stone & Zhang, PRD 79, 074024 (2009)].

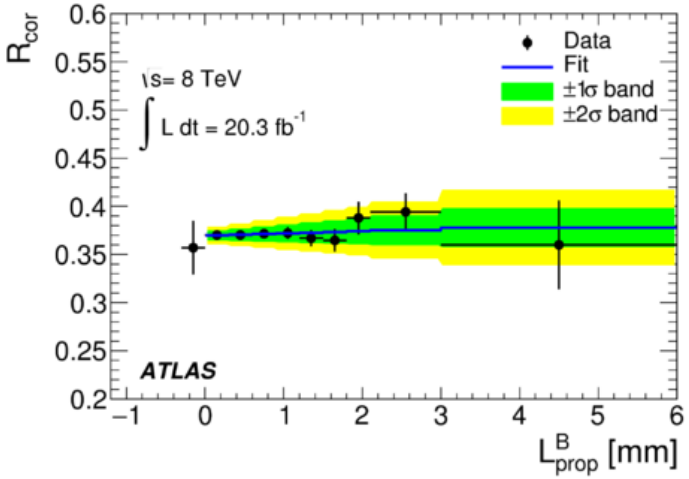
$*\mathcal{B}(\phi \to K^+K^-) = (48.9 \pm 0.5)\%$

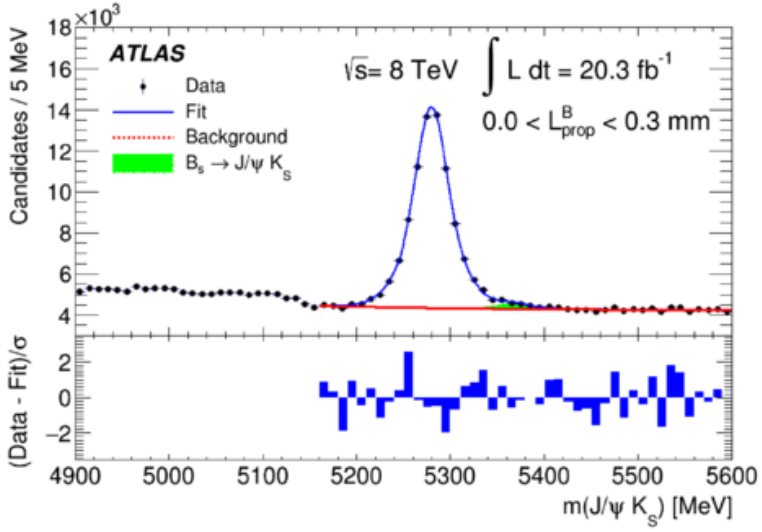
$\Delta\Gamma_d/\Gamma_d$ of the $B^0 - \bar{B}^0$ system

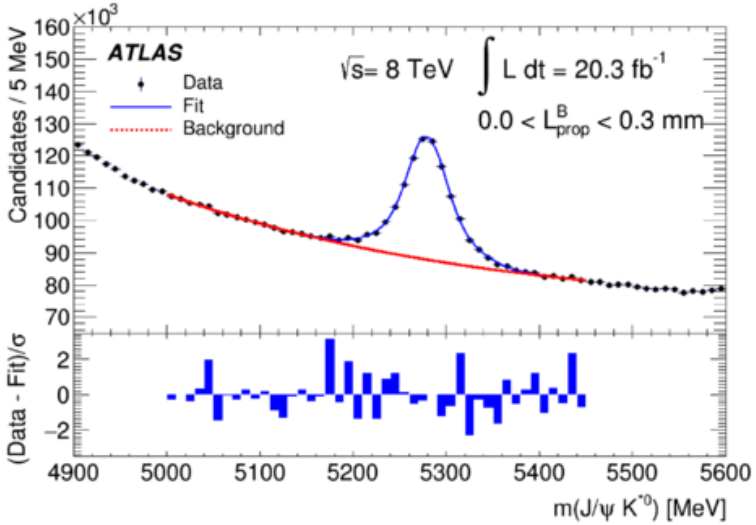
- Determined by comparing the decay time distributions of $B^0 \to J/\psi\, K_S$ and $B^0 \to J/\psi\, K^{*0}$ decays (10 bins)
- Takes into account the production asymmetry in the calculation of expected events of each decay per bin.

$$\frac{\Delta\Gamma_d}{\Gamma_d} = (-0.1 \pm 1.1\,(stat) \pm 0.9\,(syst)) \times 10^{-2}$$

Source	$\delta(\Delta\Gamma_d/\Gamma_d)$, 2011	$\delta(\Delta\Gamma_d/\Gamma_d)$, 2012
K_S decay length	0.21×10^{-2}	0.16×10^{-2}
K_S pseudorapidity	0.14×10^{-2}	0.01×10^{-2}
$B_d^0 \to J/\psi K_S$ mass range	0.47×10^{-2}	0.59×10^{-2}
$B_d^0 \to J/\psi K^{*0}$ mass range	0.30×10^{-2}	0.15×10^{-2}
Background description	0.16×10^{-2}	0.09×10^{-2}
$B_s^0 \to J/\psi K_S$ contribution	0.11×10^{-2}	0.08×10^{-2}
L^B_{prop} resolution	0.29×10^{-2}	0.29×10^{-2}
Fit bias (Toy MC)	0.07×10^{-2}	0.07×10^{-2}
B_d^0 production asymmetry	0.01×10^{-2}	0.01×10^{-2}
MC sample	1.54×10^{-2}	0.45×10^{-2}
Total uncertainty	1.69×10^{-2}	0.84×10^{-2}







Conclusion and prospects

- Many results based on 7 TeV and 8 TeV datasets have been presented. Most f them finalized during the long LHC shutdown.
- With the restart of the LHC, the analysis of data at 13 TeV have started, some of the preliminary results have been presented and soon we will have more results at this energy.
- ATLAS and CMS have oriented their trigger on dimuons, suitable for studies on rare decays of b-hadrons, so new results on that line will come soon, in addition to properties and other observations.
- CMS can not confirm the peaking structure observed by Dzero. ATLAS is working on that.
- Both experiments, ATLAS and CMS have a strong opportunities on the study of heavy hadron.
- ATLAS and CMS has produced much more results than what can fit in this talk.

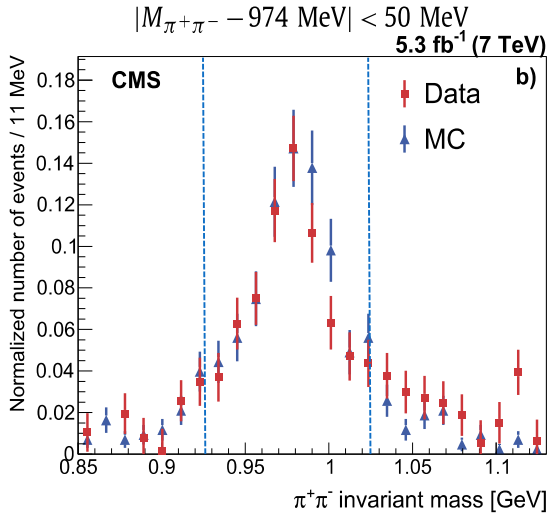
Backups

Analysis around the $f_0(980)$ state

- Di-pion mass around Δ = 50 MeV ~ $\Gamma^{(BW)}_{f0(980)}$ of the fitted mass in data.
- Region around the $f_0(980)$ is pure enough to be used to measure $\tau(B^0_s)_{CP\text{-}odd}$ and ϕ_s.

- MC ($\Gamma^{(BW)}_{f0(980)} \equiv$ 50 MeV) describes data well in the selected region:
  - No significant deviation from BW model found. Flatté model also tested.
  - Interferences effects on $\epsilon^{\varphi/f0}_{reco}$ are estimated small by comparing the fitted model by LHCb for different f_0 fraction scenarios* and the simple BW.
  - Other Res. or Non-Res. contaminations are suppressed; effects estimated to be small.

* PRD 86, 052006 (2012)



Systematic sources	%
B^0_s fit variant	2.1
Decay models in MC	6.2
f_0 width in MC (±10 MeV)	8.6
BW vs Flatté models in MC	5.8
Finite MC sample	7.1
R or NR contaminations (Δ = 100 MeV)	6.4
Interferences	5.6
Total uncertainty	**16.5**