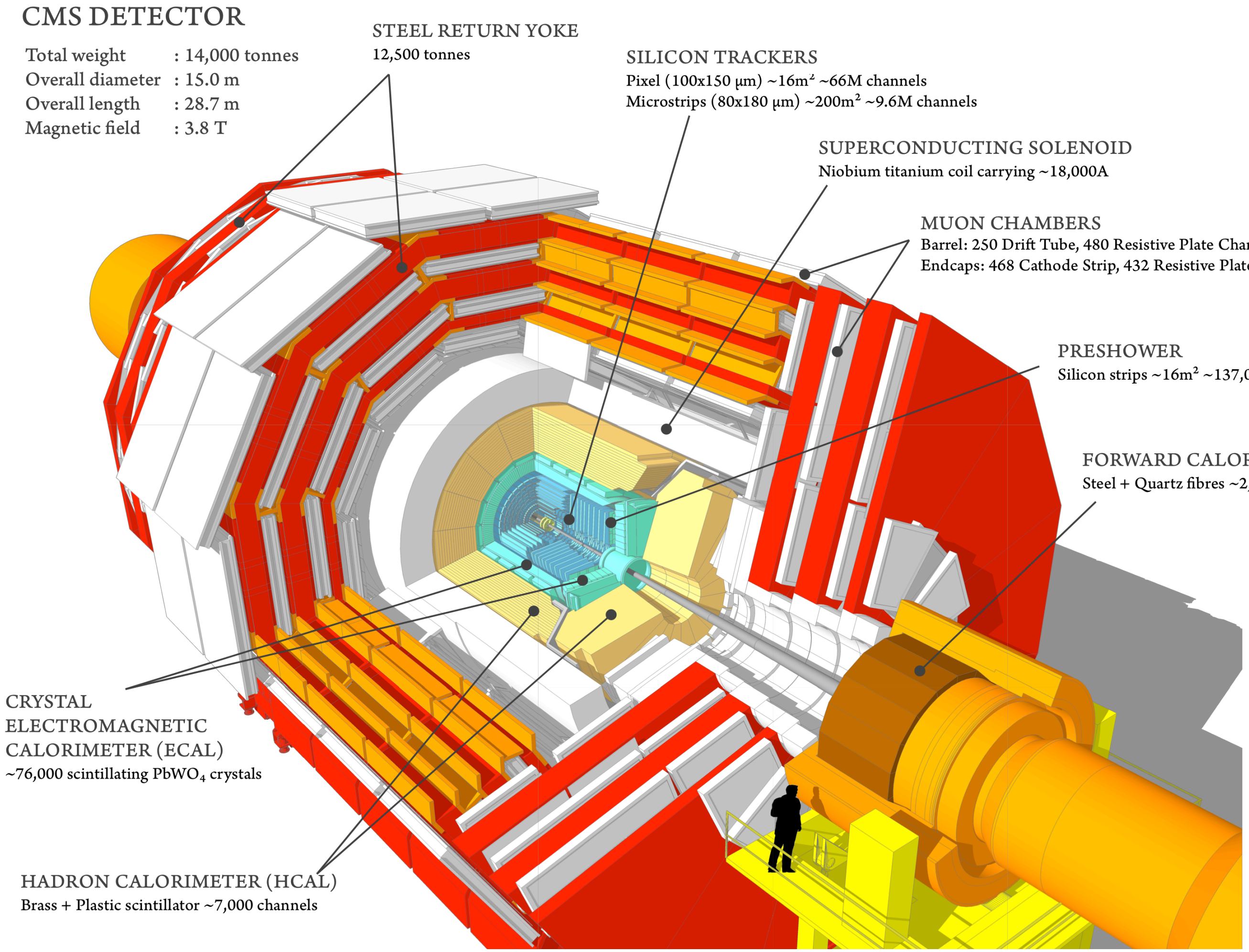
Quarkonium spectroscopy studies at CMS

QWG 2019 – The 13th International Workshop on Heavy Quarkonium 13-17 May 2019 Torino, Italy

Adriano Di Florio on behalf of the CMS collaboration

The CMS Experiment at LHC

The Compact Muon Solenoid (CMS) is a general purpose detector designed for the precision measurement of leptons, photons, and jets, among other physics objects, in proton-proton as well as heavy ion collisions at the CERN LHC facility.



Muon Reconstruction and Triggering

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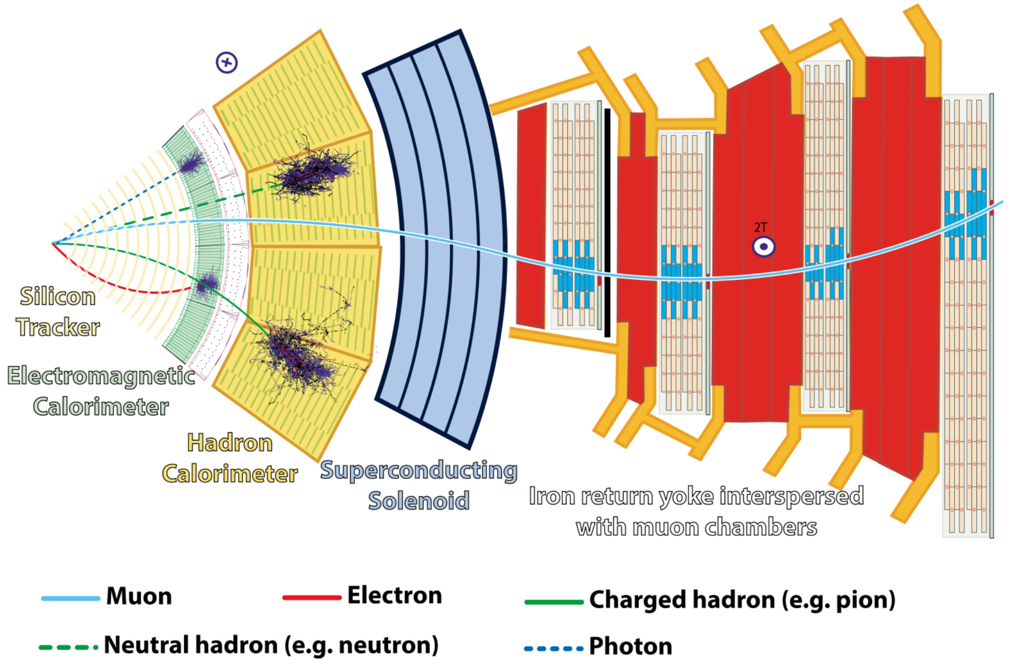
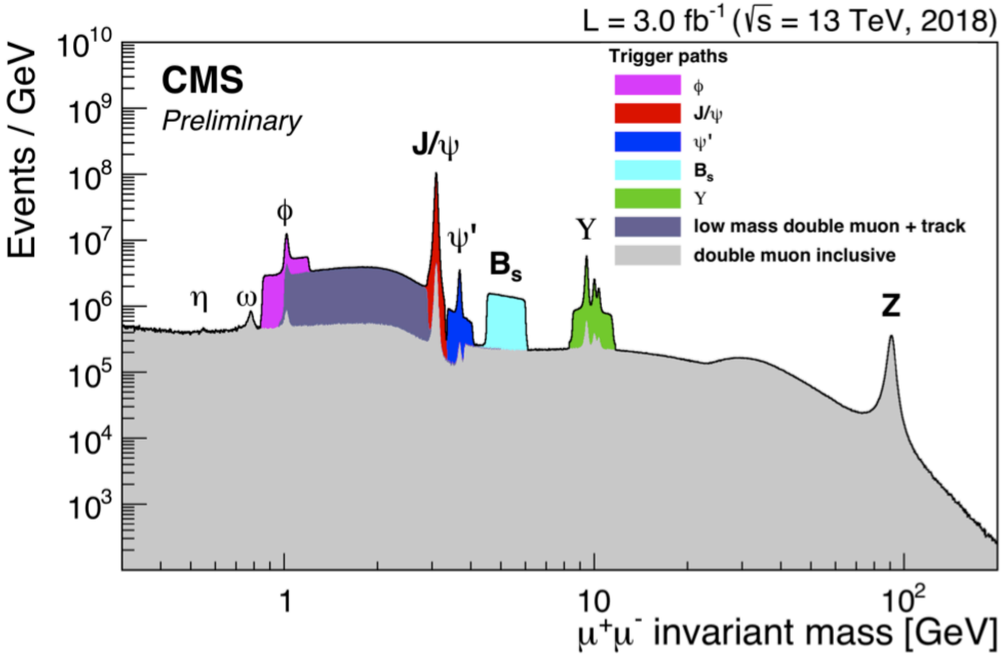
Tracking system

- Good p_T resolution (down to $\Delta p_T / p_T \approx 1\%$ in barrel)
- Tracking efficiency >99% for central muons
- Good vertex reconstruction & impact parameter resolution *O(μm)*





Muon system

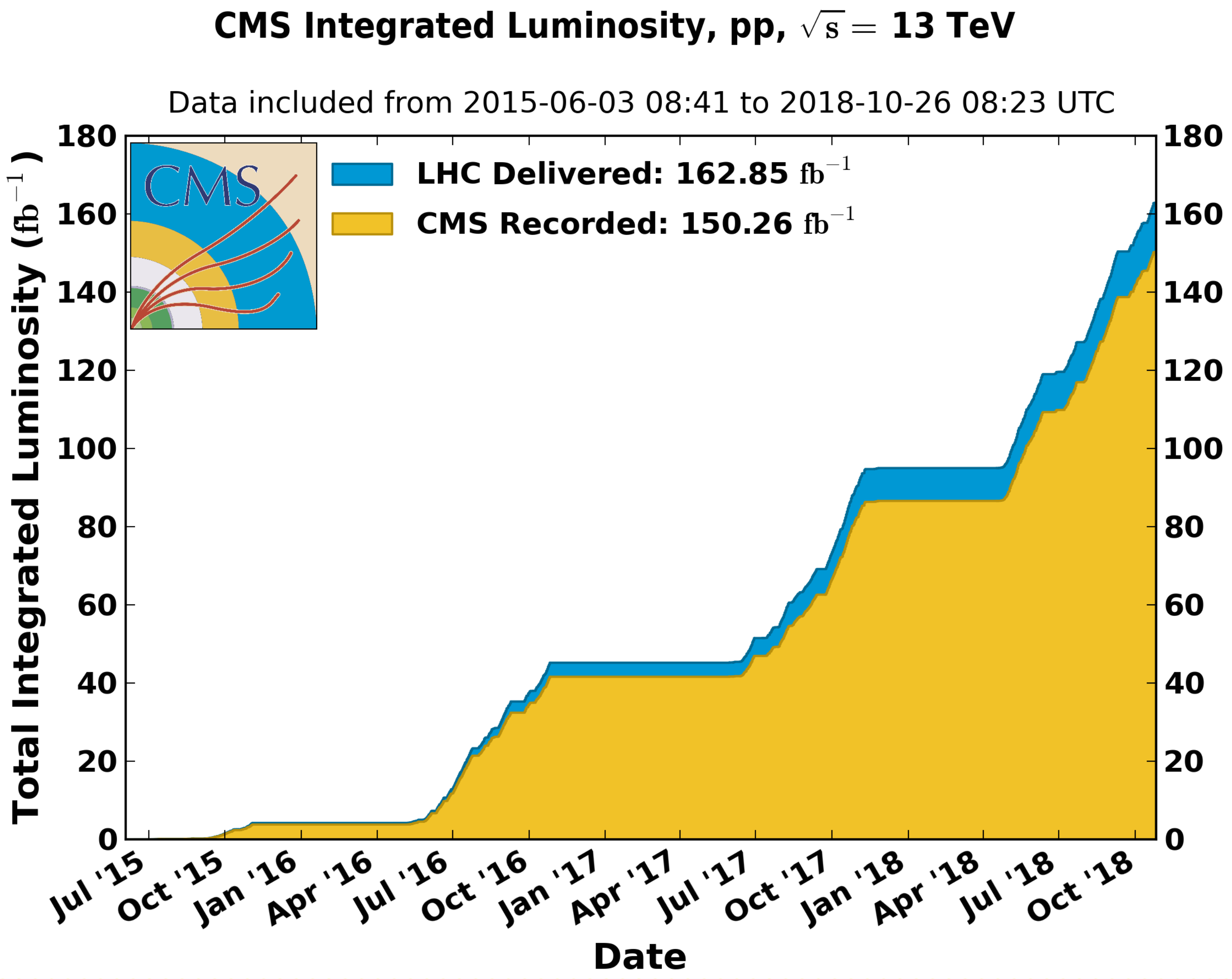
- Muon candidates reconstructed by matching muon segments and a silicon track in a large rapidity coverage ($|\eta| < 2.4$)
- Good dimuon mass resolution ($|\eta|$ dependent):

$$\Delta M / M \approx 0.6 \div 1.5\% \longrightarrow J/\psi : \approx (20 \div 70) MeV$$

- Excellent muon-ID: $\varepsilon(\mu \mid \pi, K, p) \leq (0.1 \div 0.2)\%$

Run II Data

- The CMS experiment has recorded 150 fb^{-1} at 13 TeV of data of which ~143 fb^{-1} have been certified for physics



Outline

- Observation of $B_c(2S)$ and $B_c^*(2S)$ states

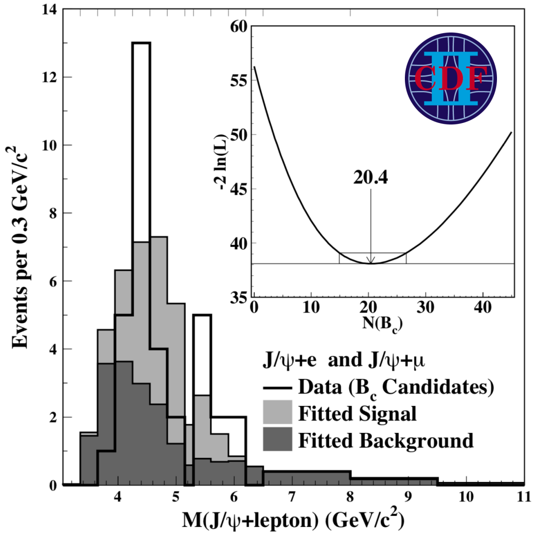
- Observation of $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states

Observation of $B_c(2S)$ and $B_c^*(2S)$ states

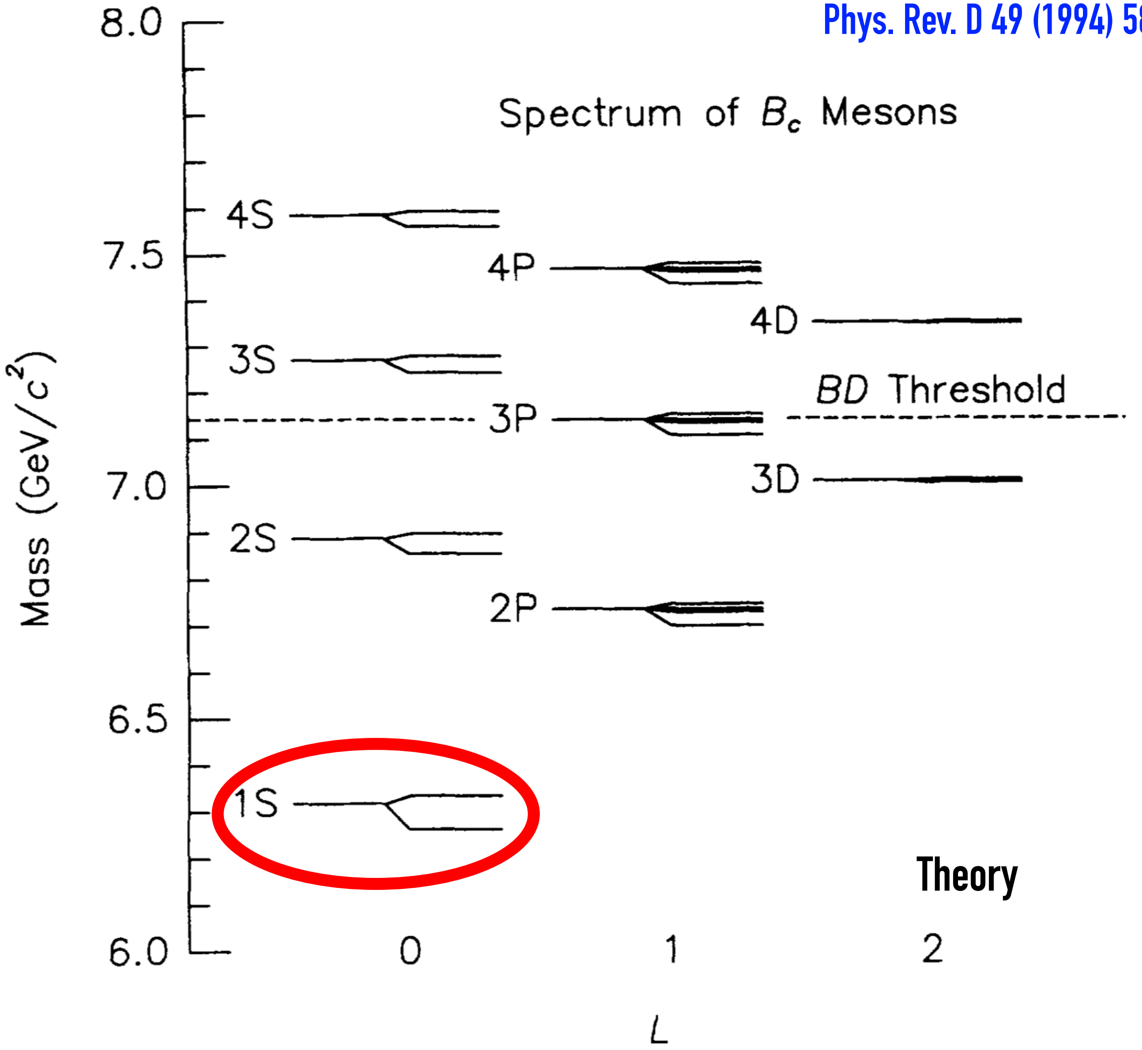
Phys.Rev.Lett. 122, 132001 (2019) arXiv:1902.00571

The B_c family

- The B_c family consists of charged mesons composed of a beauty antiquark and a charm quark (or vice versa). The ground state B_c was discovered in 1998 by the CDF Collaboration in the $B_c \to J/\psi l\nu$ decay channel [PRL 81 (1998) 2432]



Phys. Rev. D 49 (1994) 5845



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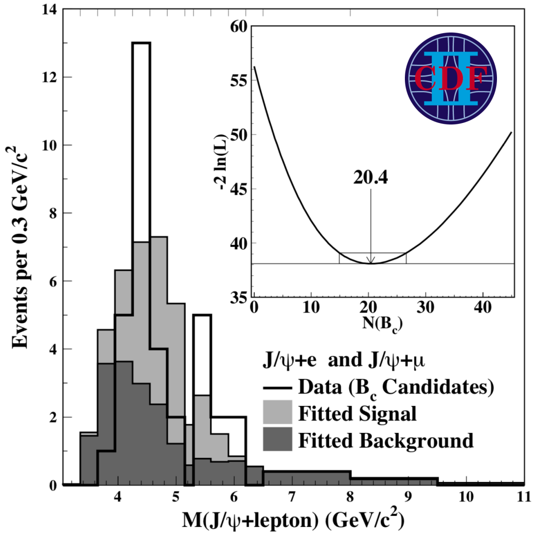

Since the bc mesons cannot annihilate into gluons, the excited states decay to the ground state via the cascade emission of γ or π pairs total widths that are less than a few hundred KeV

Their production yields are extremely low since the bc production cross sections is proportional to the α_s^4 : two pairs of heavy quarks produced

- Nevertheless theoretical preditions on B_c excited states proliferates:

Meson	Predicted Mass (MeV)
B_c	$6247 \div 6286$
B_c^*	$6308 \div 6341$
$B_c(2S)$	$6835 \div 6882$
$B_c^*(2S)$	$6881 \div 6914$

PRD 49 (1994) 5845
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PRL 121 (2018) 202002

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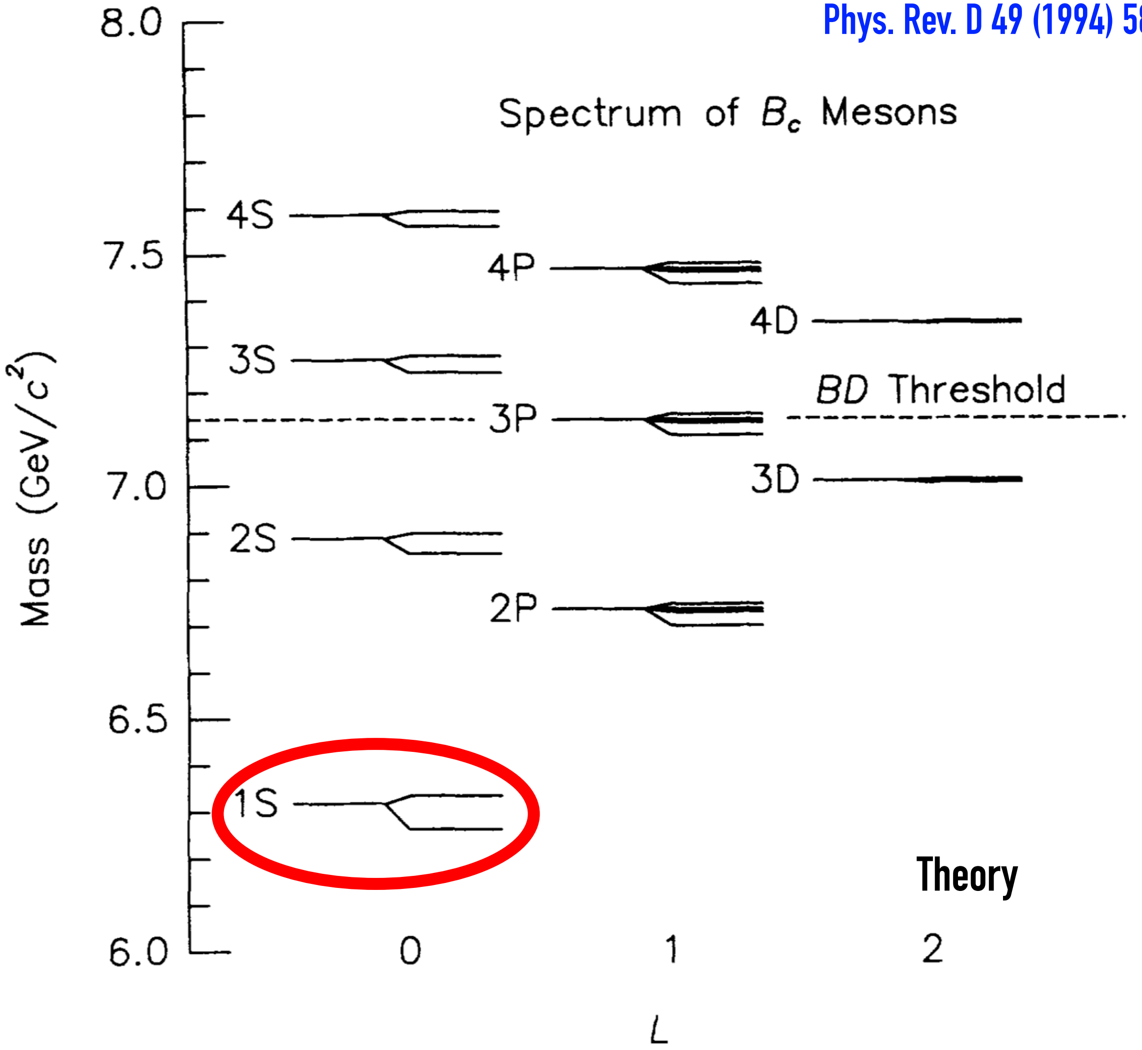

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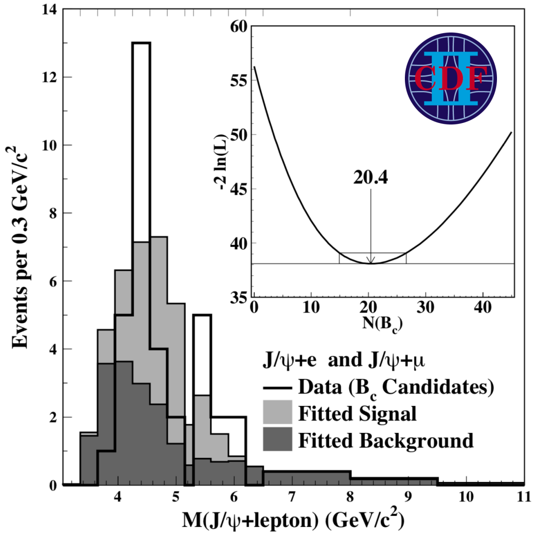

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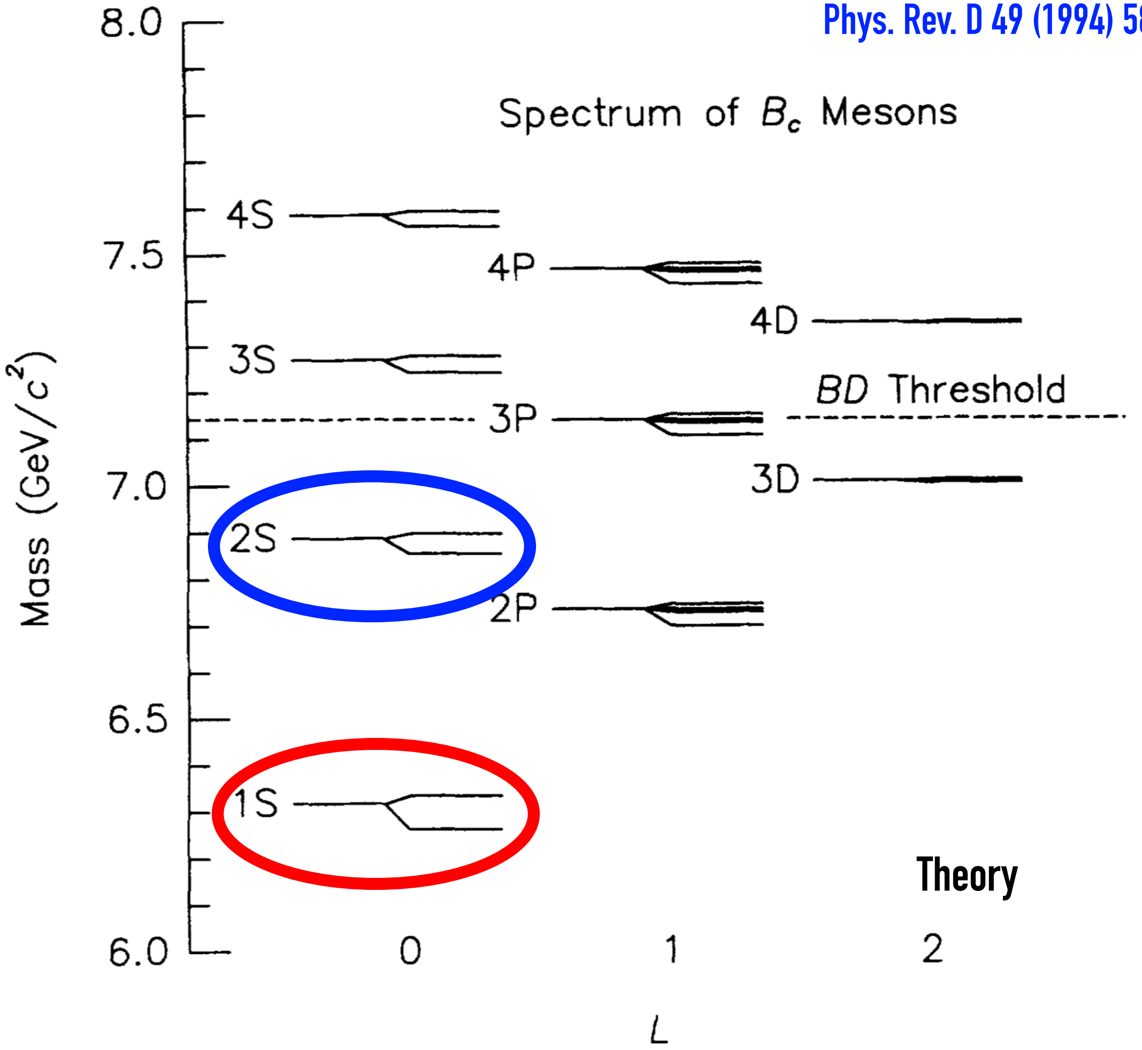

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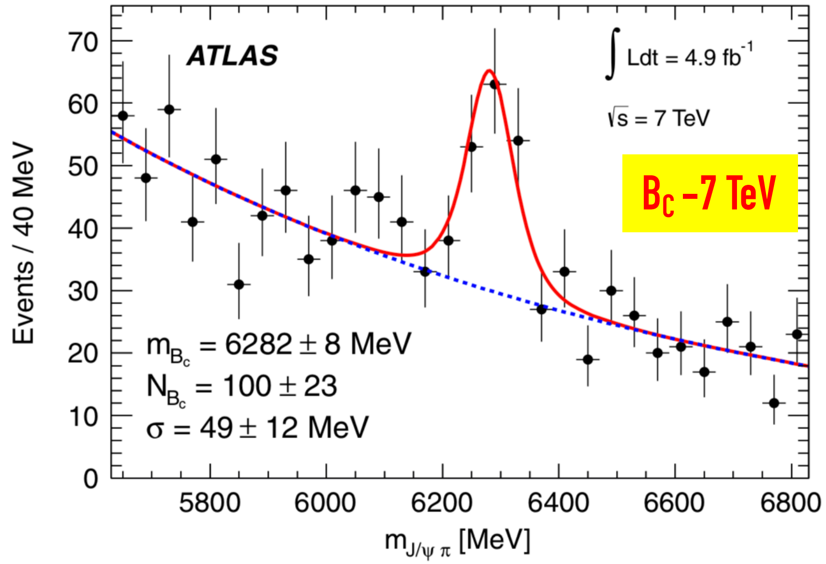
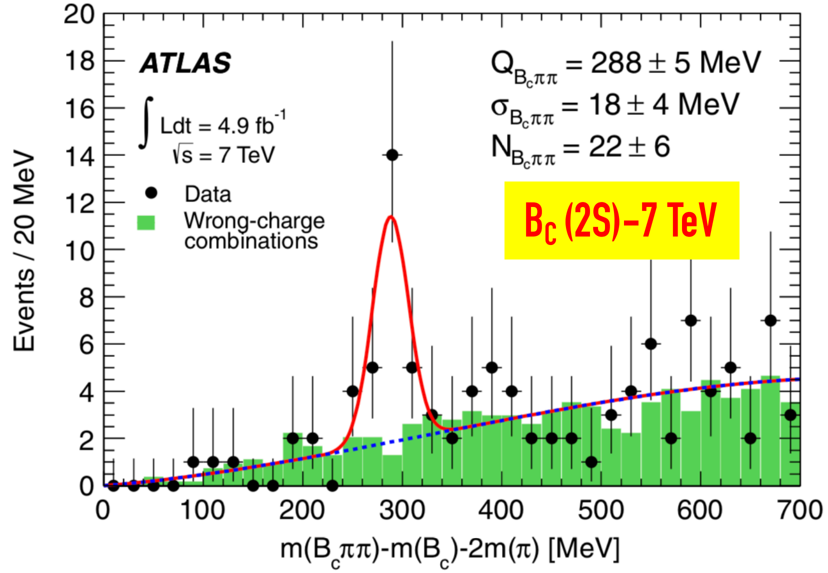
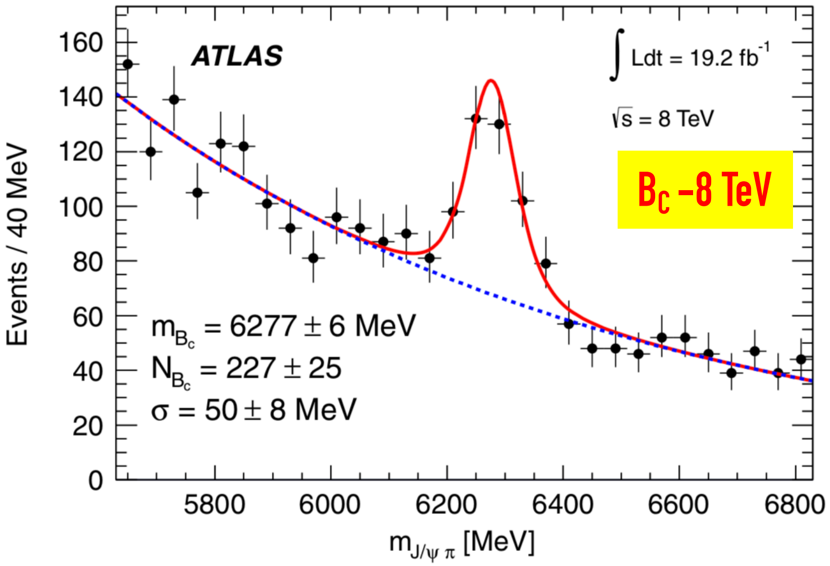
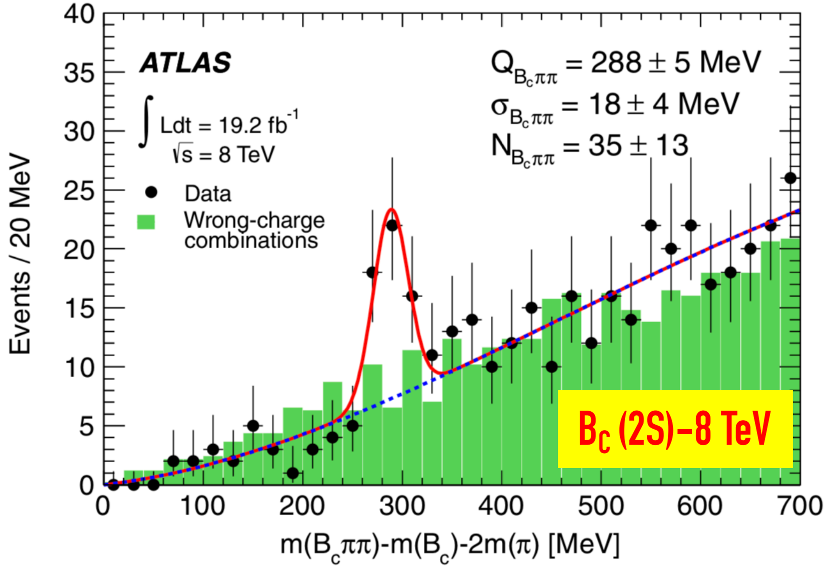
Observation of an excitate B_c^+ meson state by ATLAS









PRL 113 (2014) 212004

Using both 7 TeV and 8 TeV Run I collected data ATLAS collaboration reported the observation of a a new state whose mass is consistent with predictions for the B_c (2S)

- $B_c \to J/\psi\pi$

Data	Signal events	Peak mean [MeV]	Peak width [MeV]
7 TeV	100 ± 23	6282 ± 8	49 ± 12
8 TeV	227 ± 25	6277 ± 6	50 ± 8

- $B_c(2S) \to B_c\pi\pi$

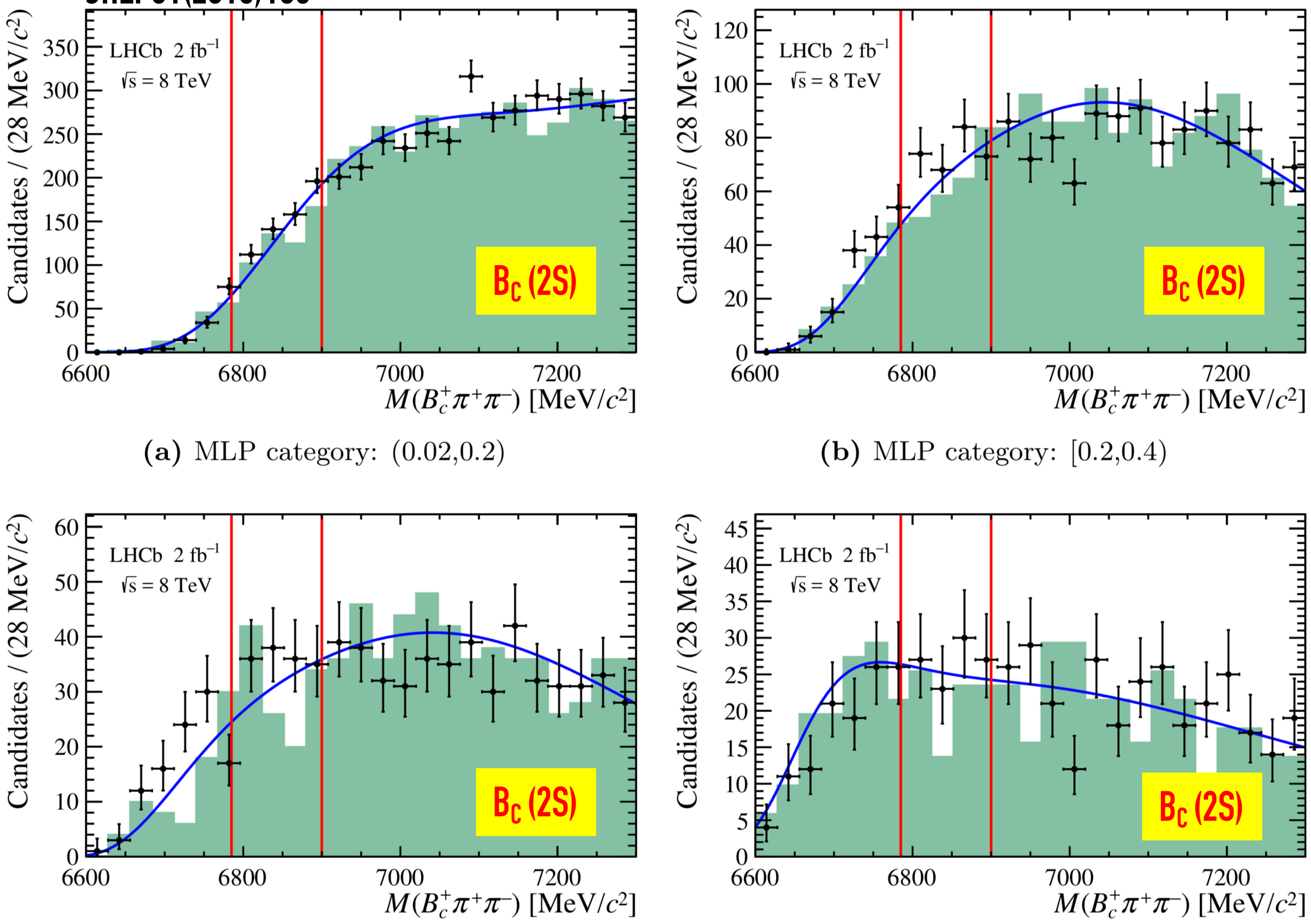
$N_{B_{c(2S)}} = 22 \pm 6$ 7 TeV

$N_{B_{c(2S)}} = 35 \pm 13$ 8 TeV

For the combined 7 and 8 TeV data set the total significance of the observation is found to be 5.2σ (5.4σ local at fixed mass).

Search for excited B_c^+ states by LHCb

JHEP01(2018)138



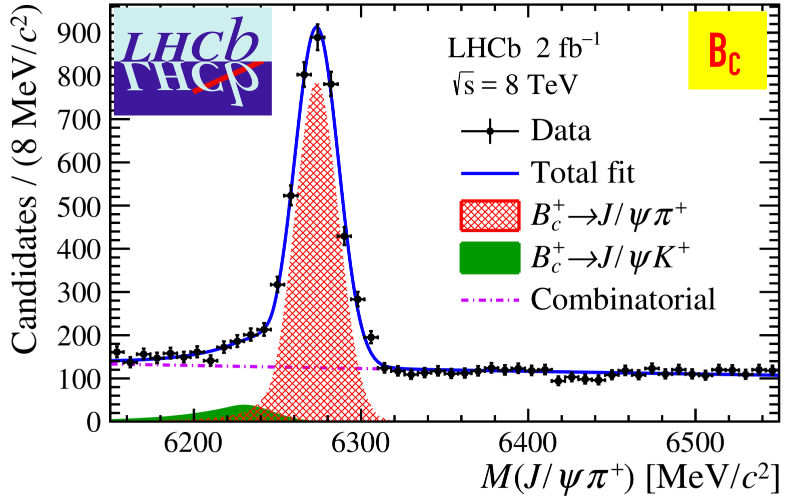
(a) MLP category: (0.02,0.2) **(b)** MLP category: [0.2,0.4)

(c) MLP category: [0.4,0.6) **(d)** MLP category: [0.6,1.0]

- Search sensitivity enhanced by the use of MLP neural network (4 categories)

Using 2.9 fb^{-1} of 8 TeV data LHCb collaborations searched for the B_c (2S) in the same decay channel used by ATLAS

$$B_c(2S) \rightarrow B_c(\rightarrow J/\psi\pi)\pi\pi$$



With much more B_c candidates (3325 ± 73) they found no evidence of B_c (2S) signals and quoted a limit

$$\mathcal{R} = \frac{\sigma_{B_c^{(*)}(2S)^+}}{\sigma_{B_c^+}} \cdot \mathcal{B}(B_c^{(*)}(2S)^+ \rightarrow B_c^{(*)+}\pi^+\pi^-)$$

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
ATLAS	$(0.22 \pm 0.08\,(\text{stat}))/\varepsilon_7$	$(0.15 \pm 0.06\,(\text{stat}))/\varepsilon_8$
LHCb	–	$< [0.04, 0.09]$

$B_c^+(2S)$ and $B_c^{*+}(2S)$ reconstruction

- The $B_c^+(2S)$ decays directly to the B_c^+ ground state :

$$B_c^+(2S) \to B_c^+ \pi^+ \pi^-$$

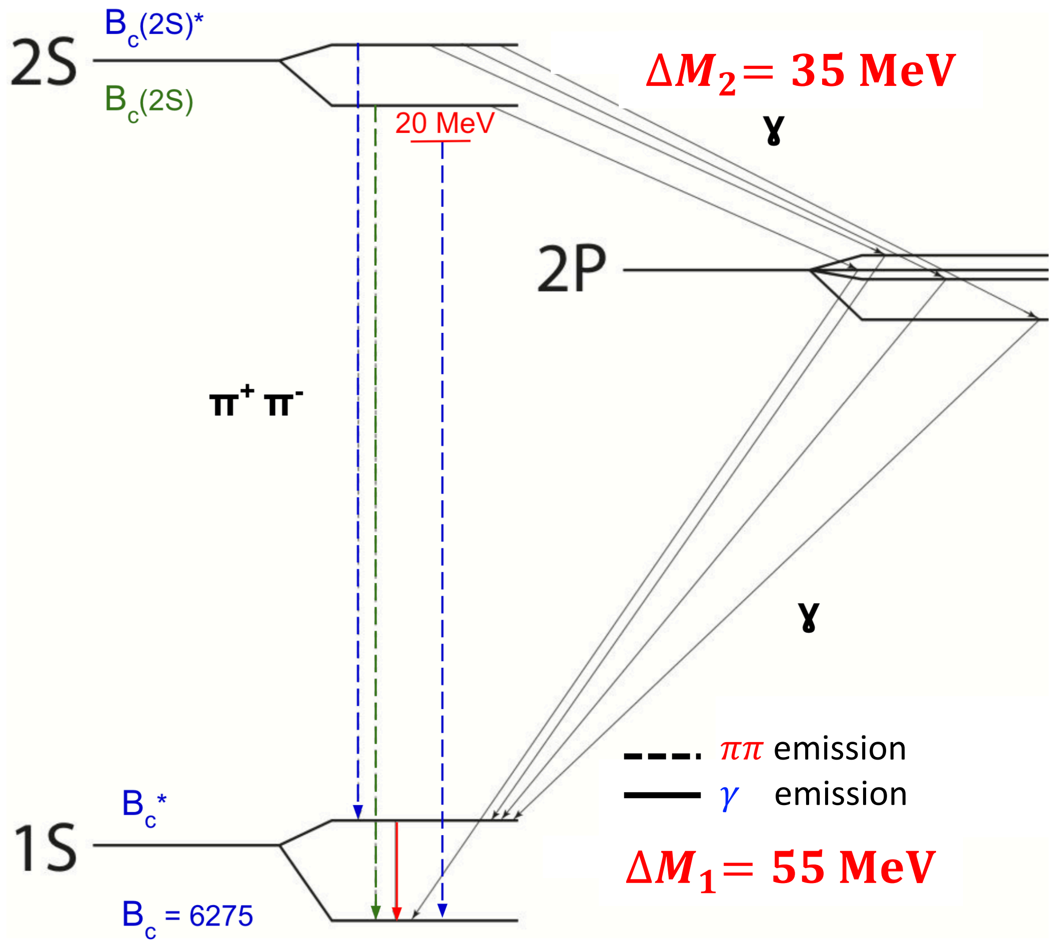
The $B_c^{*+}(2S)$ decays to B_c^{*+} state through $\pi\pi$ emission followed by a radiative decay of B_c^{*+} to the B_c^+ ground state with the emission of a soft γ ($\mathrm{E}{\sim}55\ \mathrm{MeV}$ in rest frame):

$$B_c^{*+}(2S) \to B_c^{*+}(\to B_c^+\ \gamma)\pi^+\pi^-$$

Having the emitted photon a very low energy, its detection is very challenging, and tipically it is lost. Thus:

$$B_c^+(2S) \to B_c^+ \pi^+ \pi^- + E_{miss}$$

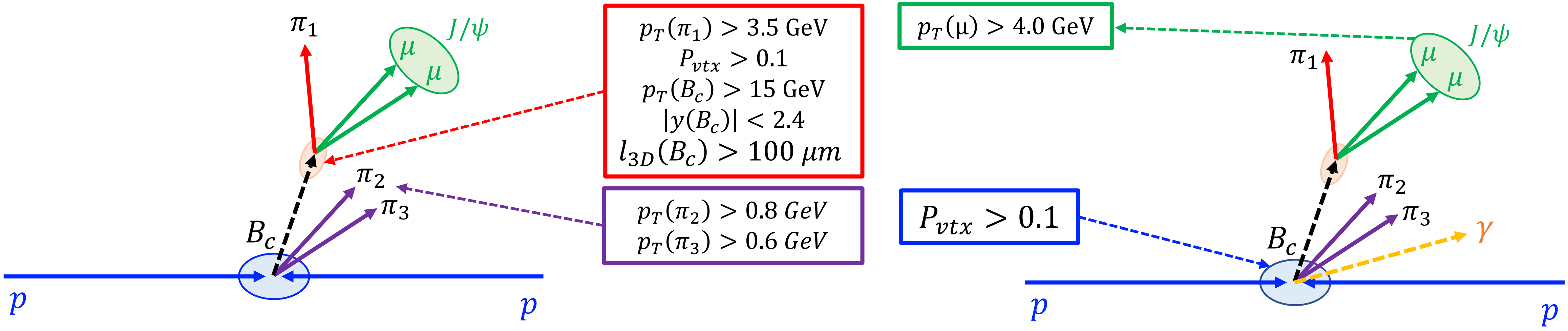
The $B_c^{*+}(2S)$ peak should then appear into $B_c^+\pi^+\pi^-$ mass spectrum at the mass $M(B_c^+(2S)) - \Delta M$ where



$$\Delta M = \Delta M_1 - \Delta M_2 = [M(B_c^*(1S)) - M(B_c(1S))] - [M(B_c^*(2S)) - M(B_c(2S))]$$

which is predicted positive ($\Delta M{\sim}20\mathrm{MeV}$) so that the $B_c^{*+}(2S)$ peak will be at lower masses than the $B_c^+(2S)$ peak.

Trigger preselection: two μ from J/ψ plus a track, with common vertex displaced from interaction point ($L_{xy}/\sigma_{L_{xy}} > 3.0$)



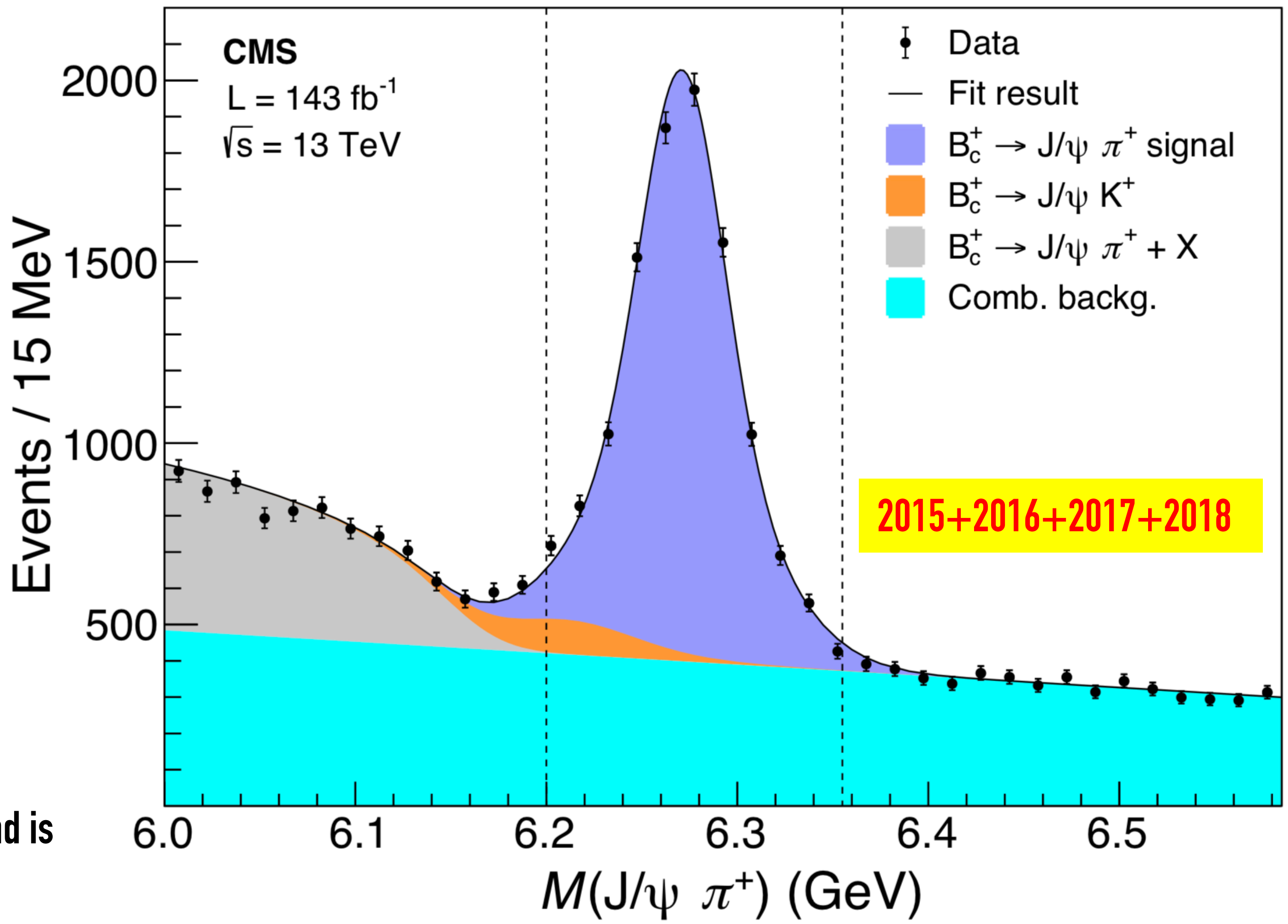
$B_c^+(2S) \rightarrow B_c^+\pi^+\pi^-$

$B_c^{*+}(2S) \rightarrow B_c^{*+}\pi^+\pi^-$

- B_c^+ meson momentum required to point to PV in xy plane
- $6.2GeV < M(B_c) < 6.35$GeV
- The PV is re-fitted excluding the three B_c decay tracls ($\mu\mu\pi_1$)
- Tracks and muons satisfy high-quality requirements
- Among multiple $B_c^+\pi^+\pi^-$ candidates the highest p_T one is kept
- π_2 and π_3 are tracks from the refitted PV

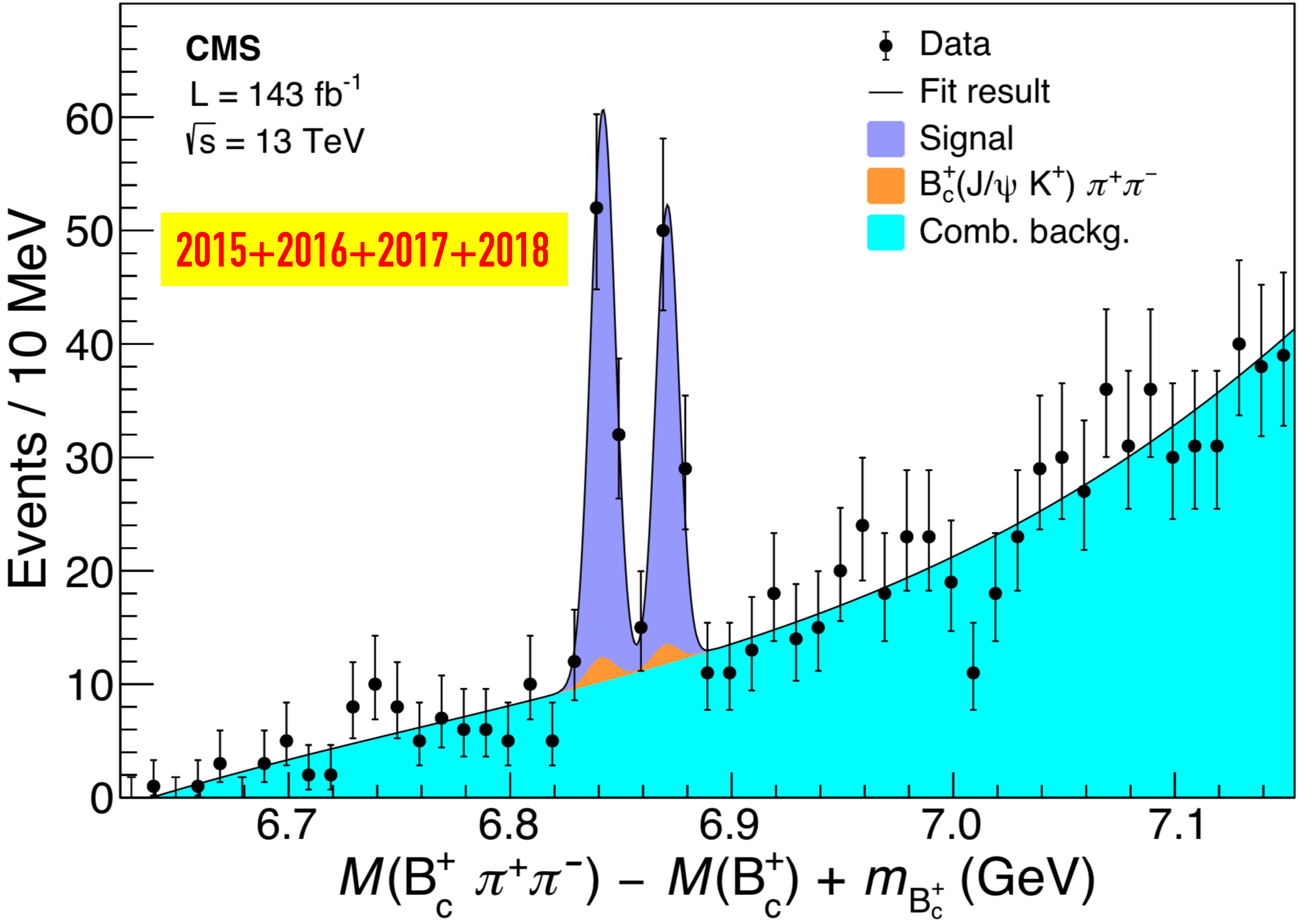
B_c^+ reconstruction in Run II data

- Unbinned ML fit
- Signal modelled using a double gaussian
- Combinatorial background: first-order Chebyshev polynomial function
- $B_c^+ \to J/\psi K^+$ background: shape determined from simulation studies and a normalization fixed relative to the $B_c^+ \to J/\psi\pi^+$ yield
- $B_c^+ \to J/\psi\pi^+ + X$ background: relevant only below $6.2GeV$ and is described by a ARGUS function convolved with a Gaussian resolution



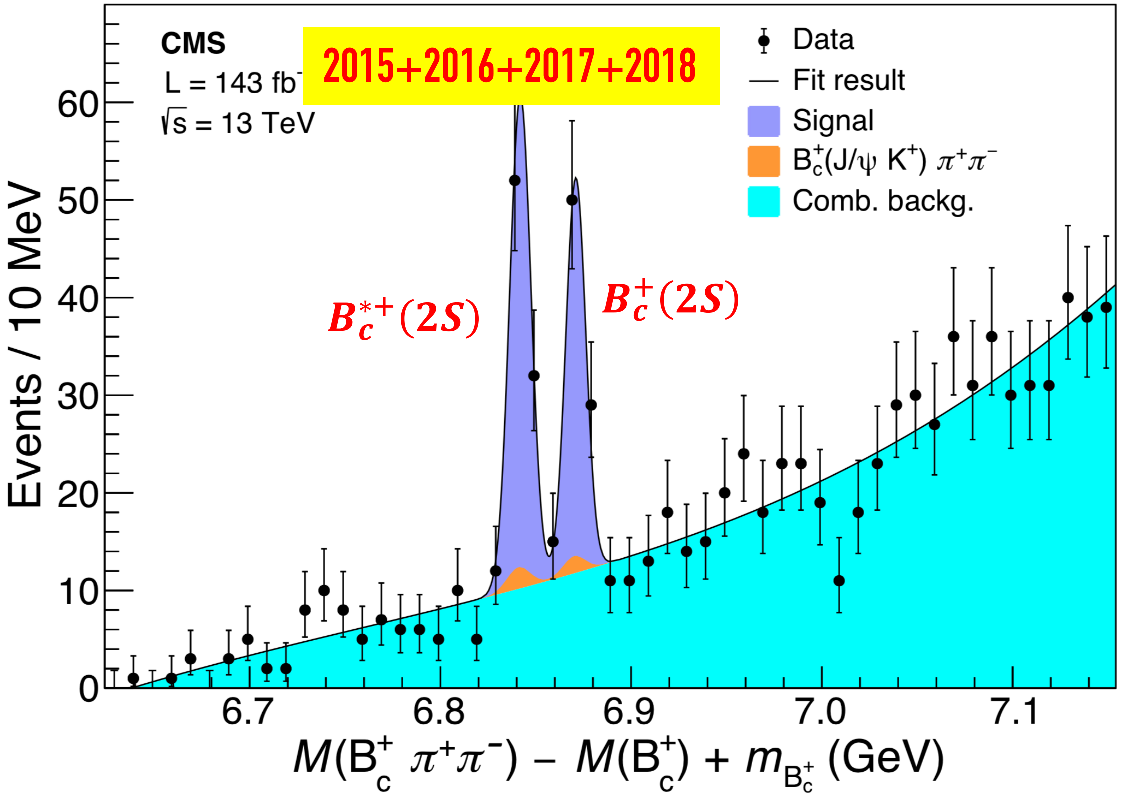
$N_{B_c^+} = 7629 \pm 225$ $M(B_c^+) = 6371.1 \pm 0.5\text{MeV}$ $\sigma(B_c^+) = 33.5 \pm 2.5\text{MeV}$ $\chi^2_{fit} = 35\ (d.o.f. = 30)$

$B_c(2S)$ and $B_c^*(2S)$ observation



$B_c(2S)$ and $B_c^*(2S)$ observation

- The $M(B_c\pi\pi) - M(B_c) + m_{PDG}(B_c)$ distribution is fitted with Gaussian functions for the peaks and a 3rd order Chebyshev polynomial for the background.
- Mass resolution agrees with MC expectations (~6MeV) and is much lower than ΔM thus allowing a two-peak structure to be observed.



- Measured two peaks' mass difference:

$$\Delta M = 29.1 \pm 1.5\ (stat)\text{MeV}$$

Given the predicted mass splitting ($\Delta M_1 - \Delta M_2 > 0$), $B_c^+(2S)$ is assumed to be the right-most peak

$$M(B_c(2S)) = 6871.0 \pm 1.2\ (stat)\text{MeV}$$

From MC studies: the low-energy γ emitted in the $B_c^{*+}(2S)$ decay has a very small reconstruction efficiency, of order 1% . The photon is not detected and the mass of the $B_c^*(2S)$ cannot be measured.

- Local significance exceeding 6.5σ for observing two peaks rather than one. For both single peaks significance is above 5σ

- When fitting each signal with a Breit-Wigner convolved with the gaussian resolution function the natural width (predicted $50 \div 90$ KeV) is consistent with zero: natural widths are much smaller than resolution.

$N_{B_c^{*+}(2S)} = 67 \pm 10$ $\quad$ $N_{B_c^+(2S)} = 51 \pm 10$ $\quad$ $\chi^2_{fit} = 42\ (d.o.f. = 39)$

Systematic Uncertainties

Partially reconstructed decays

The low-mass edge of signal mass window was varied from 6.2 to 6.1, to increase this contamination; the variations in the results are negligible : no systematic uncertainty is considered

Alignment of the detector

The possible misalignment of detector biases the measured masses, however for studies with major detector changes (2016 vs 2017), was found to be negligible

$J/\psi K$ background contamination:

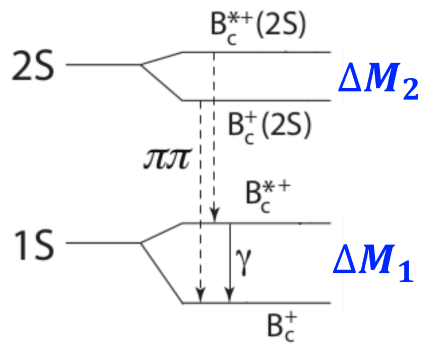
Difference seen when normalisation increased by a factor 2: the difference is negligible

$B_c\ (2S)$ fit modeling

Alternative functions for the signal and the backgrounds

- Signal : changed from two Gaussians to two Breit-Wigner functions
- Background: changed from a polynomials to a threshold function

Observed differences in M and ΔM are quoted as systematic uncertainties: 0.8 and 0.7 MeV respectively



$$\Delta M = \Delta M_1 - \Delta M_2 = 29.1 \pm 1.5\ (stat) \pm 0.7\ (sys)\ MeV$$

$$M(B_c(2S)) = 6871.0 \pm 1.2\ (stat) \pm 0.8\ (sys) \pm 0.8\ (B_c)\ MeV$$

$m_{PDG}(B_c)$
world average uncertainty

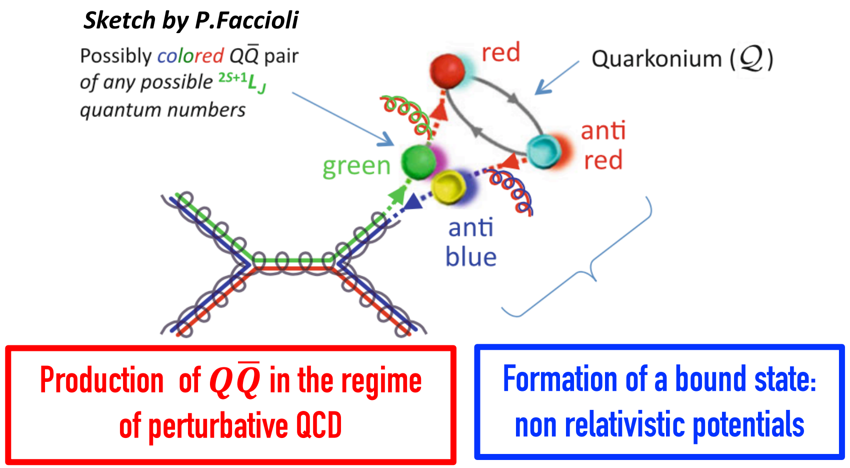
Observation of $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states

Phys. Rev. Lett. 121, 092002 (2018) arXiv:1805.11192

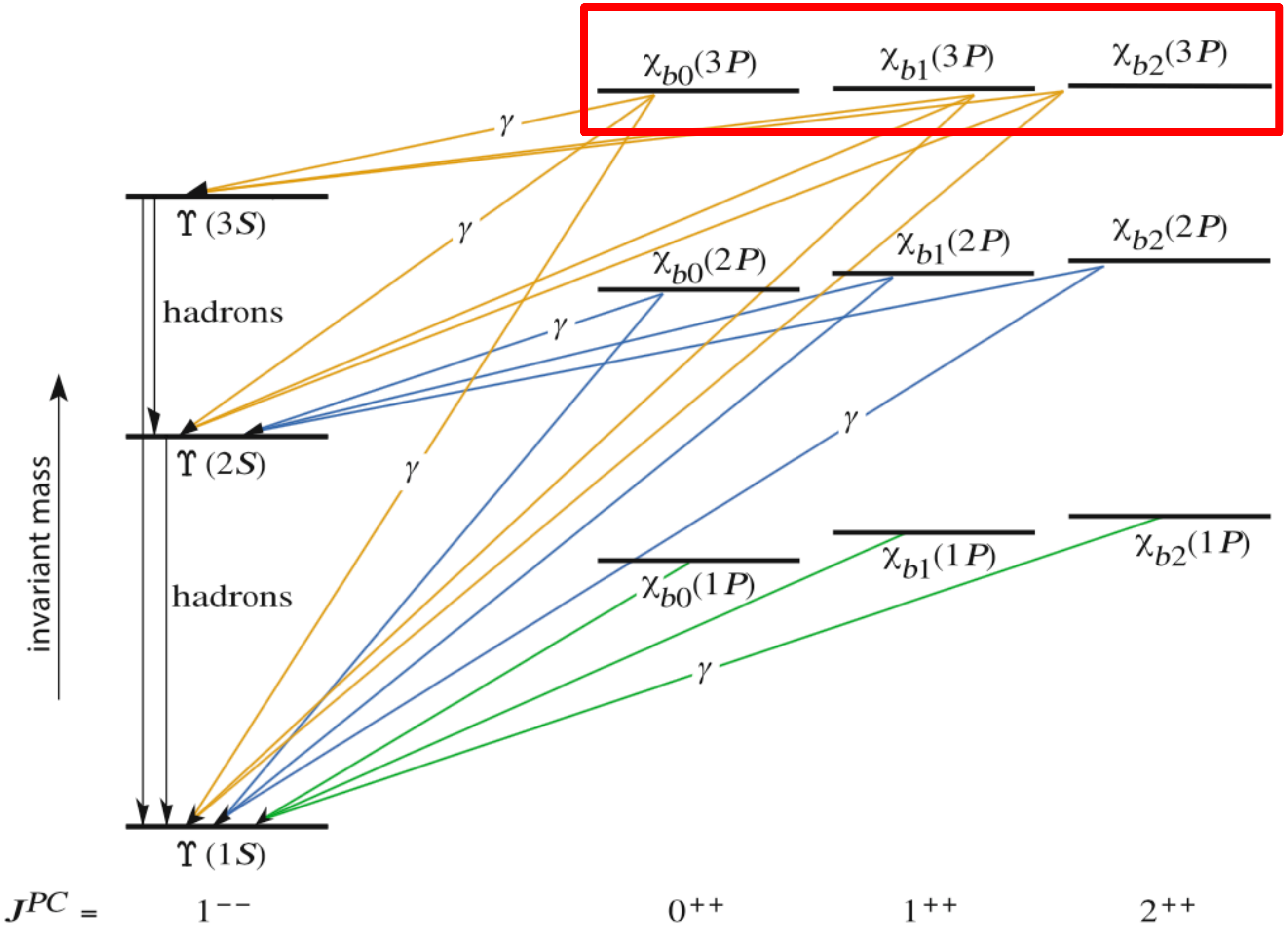
The bottomonium family

- The bottomonium family ($b\bar{b}$) plays a special role in understanding how the strong force binds quarks because, due to the high quark mass, allows two important theoretical simplifications

1. the hard-scattering production of a proto-quarkonium quark-antiquark pair can be described in perturbation theory
2. the binding of the quark-antiquark pair can be described in terms of lattice-calculable nonrelativistic potentials

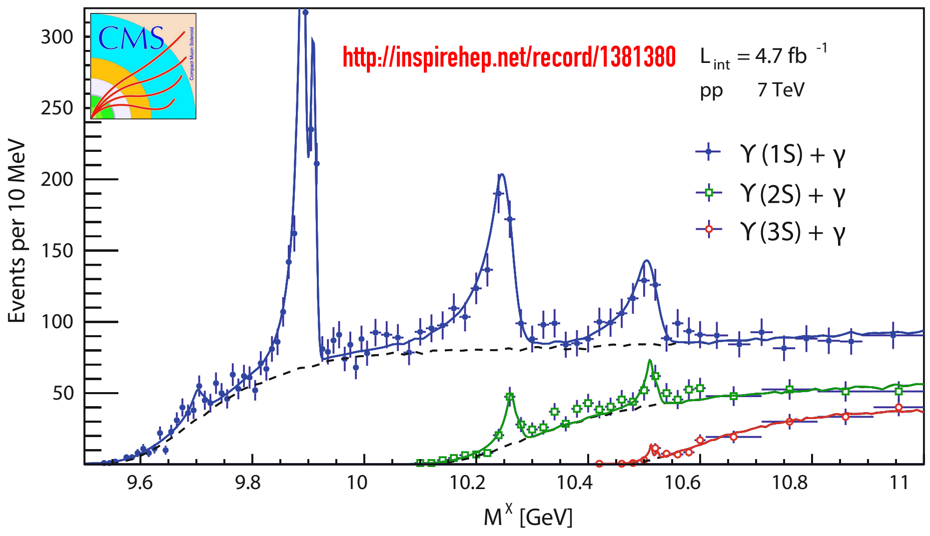


The measurements of the masses of the $\chi_{bJ}(3P)$ triplet states ($J = 0,1,2$) is especially interesting to probe details of the $b\bar{b}$ interaction in proximity of open-beauty threshold



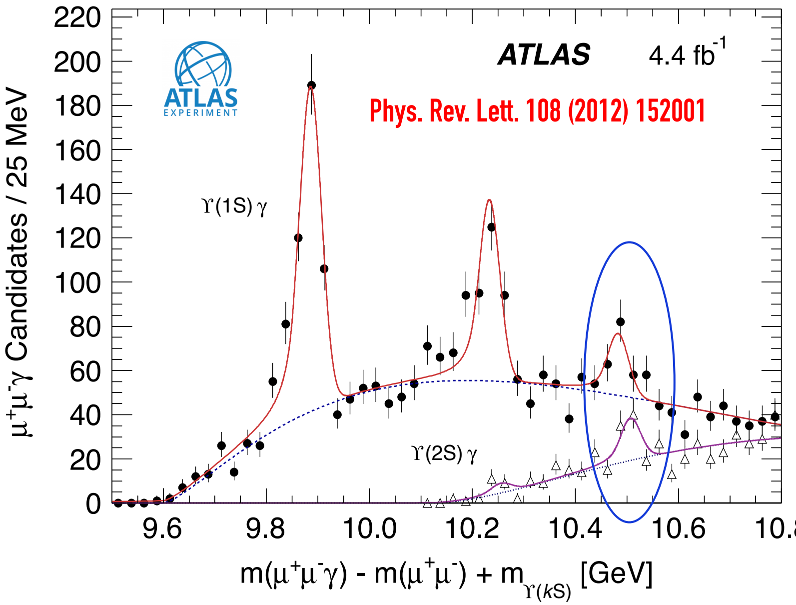
Picture from : V. Knünz, Measurement of Quarkonium Polarization to Probe QCD - *DOI 10.1007/978-3-319-49935-2_2*

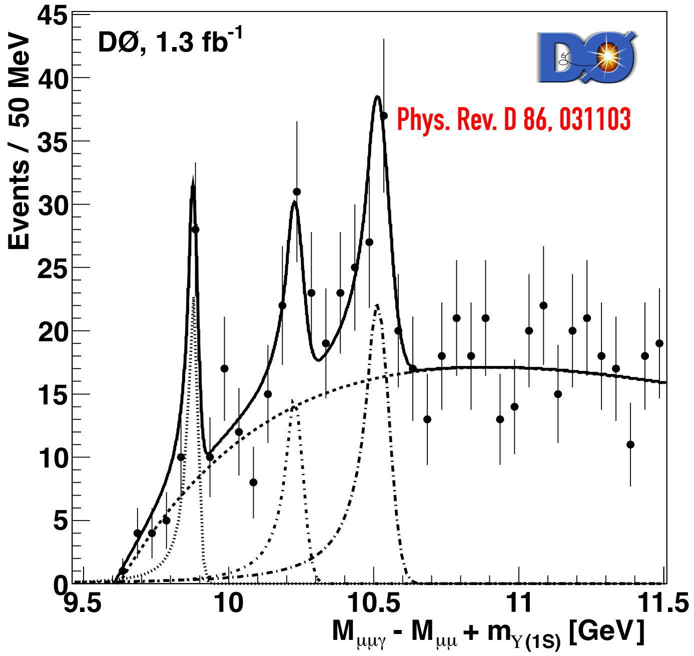
The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states



The $\chi_b(3P)$ was observed by ATLAS in 2011 as a new structure in the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ decay modes

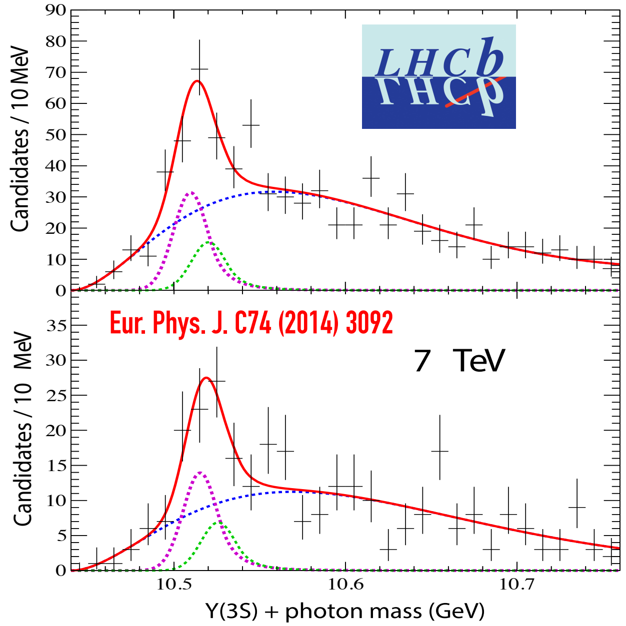
CMS saw the $\chi_b(3P)$ in the $\Upsilon(nS)$ radiative decays, in the 7 TeV data





DØ observed the $\chi_b(3P) \rightarrow \Upsilon(1S)\gamma$ decay channel.

LHCb observed the $\chi_b(3P) \rightarrow \Upsilon(3S)\gamma$ decay channel



The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ reconstruction – $\Upsilon(3S)$ selection

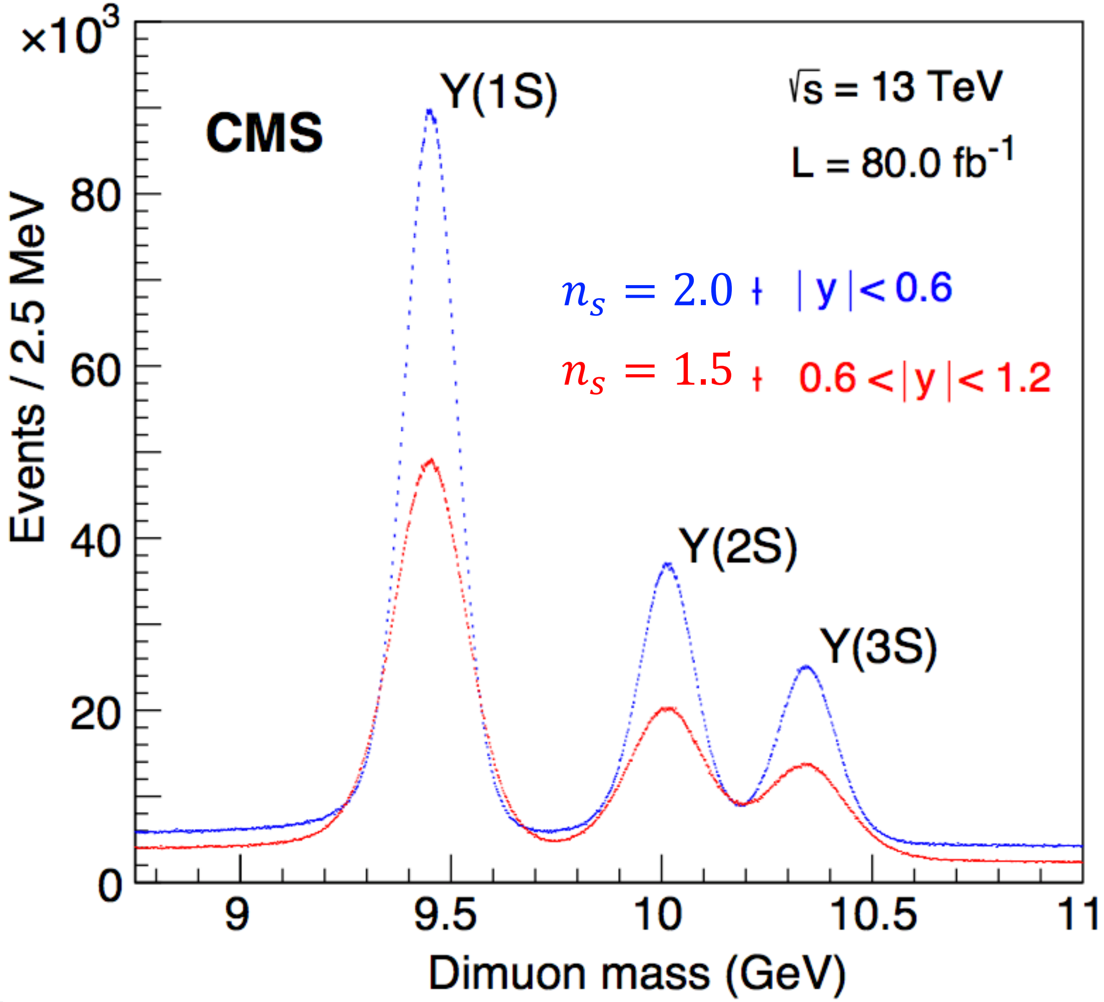
Based on pp data, collected from 2015 to 2017 at $\sqrt{s} = 13$ TeV and corresponding to $\mathcal{L}_{int} = 80 fb^{-1}$, CMS reported the first observation of resolved $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states and the measurement of their masses through the decay channel :

$$\chi_b(3P) \rightarrow \Upsilon(3S)\gamma$$

- $\Upsilon(3S) \rightarrow \mu\mu$ decay triggering the event with a μμ pair with two opposite sign μ coming from a common vertex
- Υ candidate: $p_T > 14\ GeV\ |y| < 1.2$
- High purity $\Upsilon(3S)$ sample achieved with tight mass cuts:

$$M(\Upsilon(3S)) - n_s\sigma_m(y) < M(\mu\mu) < M(\Upsilon(3S)) + 2.5\sigma_m(y)$$

low $\Upsilon(2S)$ contamination $S/B > 0.5$



The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ reconstruction – γ selection

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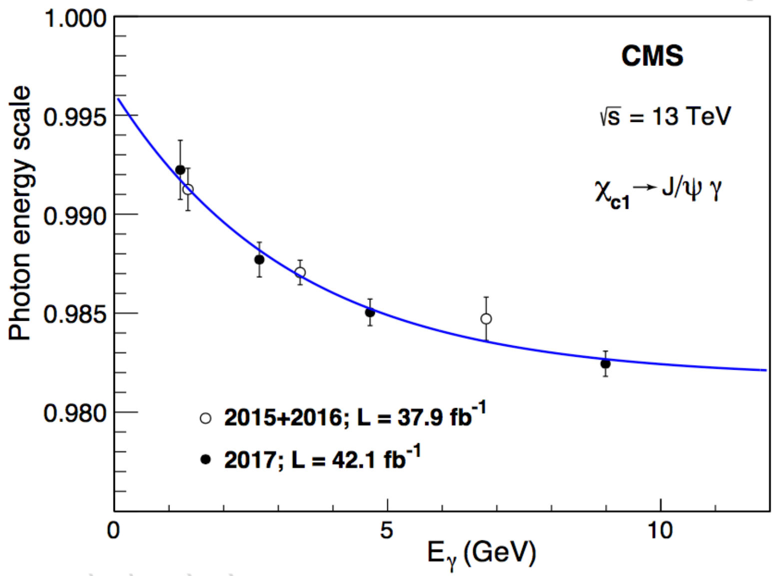
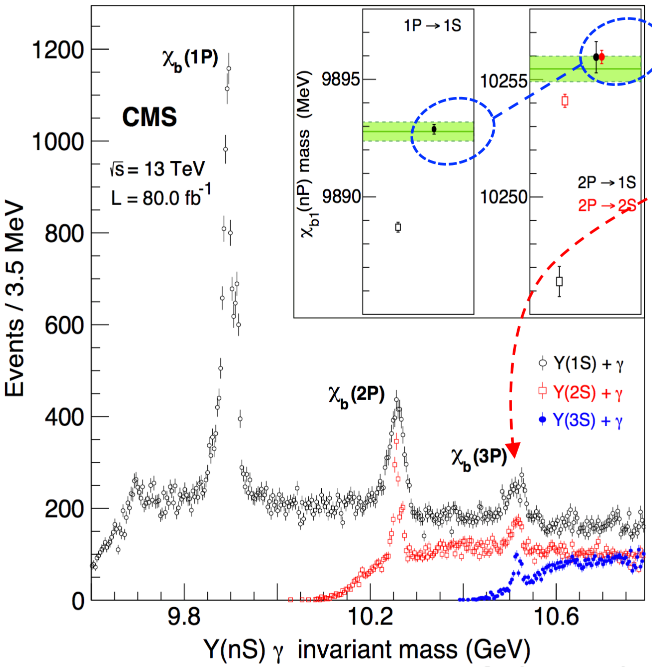


- $\gamma \rightarrow ee$ converted photon with $|\eta| < 1.2$ and $p_T > 500\ MeV$
- For an higher resolution, at the cost of a reduced yield (w.r.t. calorimetric energy measurements), only $e^+ e^-$ from a conversion in the beam pipe or in the tracker are considered

see arXiv:1210.0875 & arXiv:1409.5761



N.B. the measured low mass peak resolution :
- 2.18 ± 0.32 MeV in $\Upsilon(3S)\gamma$ mass distribution
- 7 MeV and 15 MeV in $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$

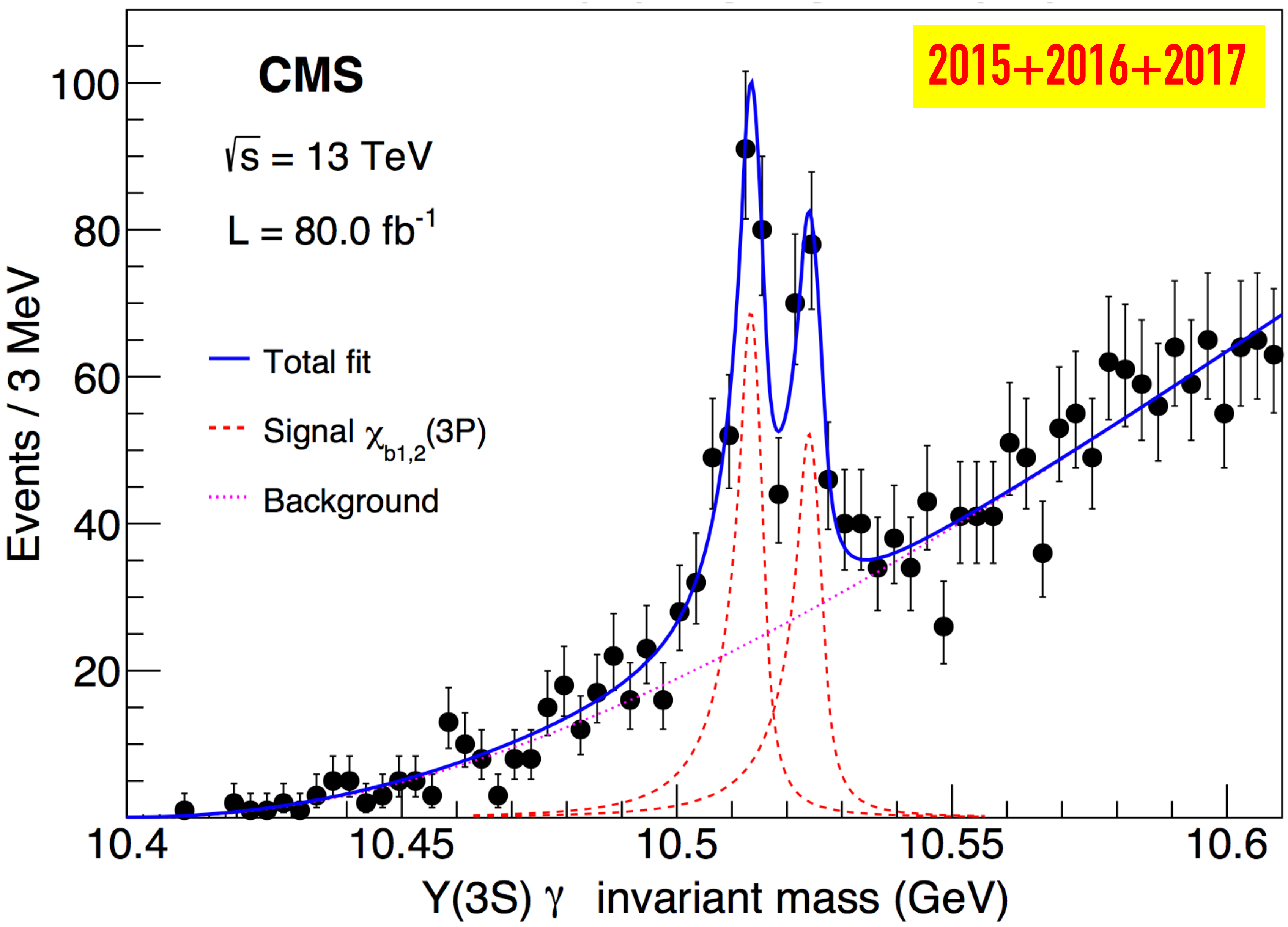
- For a more accurate measure the photon energy scale is calibrated through a $\chi_{c1} \rightarrow J/\psi(\rightarrow \mu\mu)\gamma$ sample:

$$P.E.S. = \frac{m^2_{\mu\mu\gamma} - m^2_{\mu\mu}}{M(\chi_{c1})^2 - M(J/\psi)^2}$$

Large data sample in the same running periods

and is used for the event-by-event correction of the photon energy in the computation of the $\Upsilon(3S)\gamma$ invariant mass

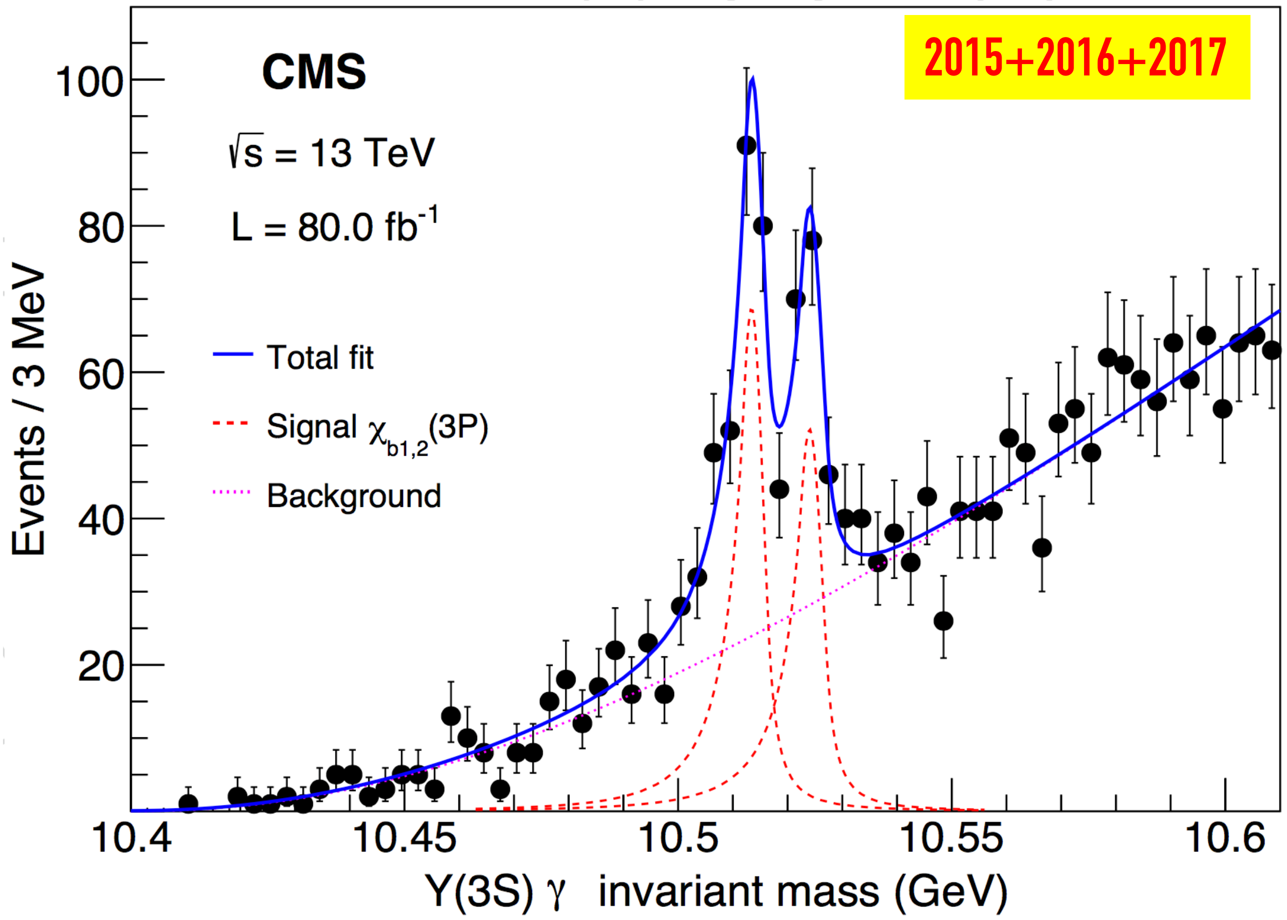
The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ mass spectrum



The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ mass spectrum

- Unbinned ML fit
- Signal modelled using a double gaussian
- Combinatorial background: exponential function
- Total (two peaks) yield is 372 ± 36
- The two masses:

$$M(\chi_{b1}(3P)) = 10513.42 \pm 0.41(\text{stat}) \pm 0.18(sys)\text{MeV}$$
$$M(\chi_{b2}(3P)) = 10524.02 \pm 0.57(\text{stat}) \pm 0.18(sys)\text{MeV}$$



- The mass difference between the J = 1,2 states is measured to be:

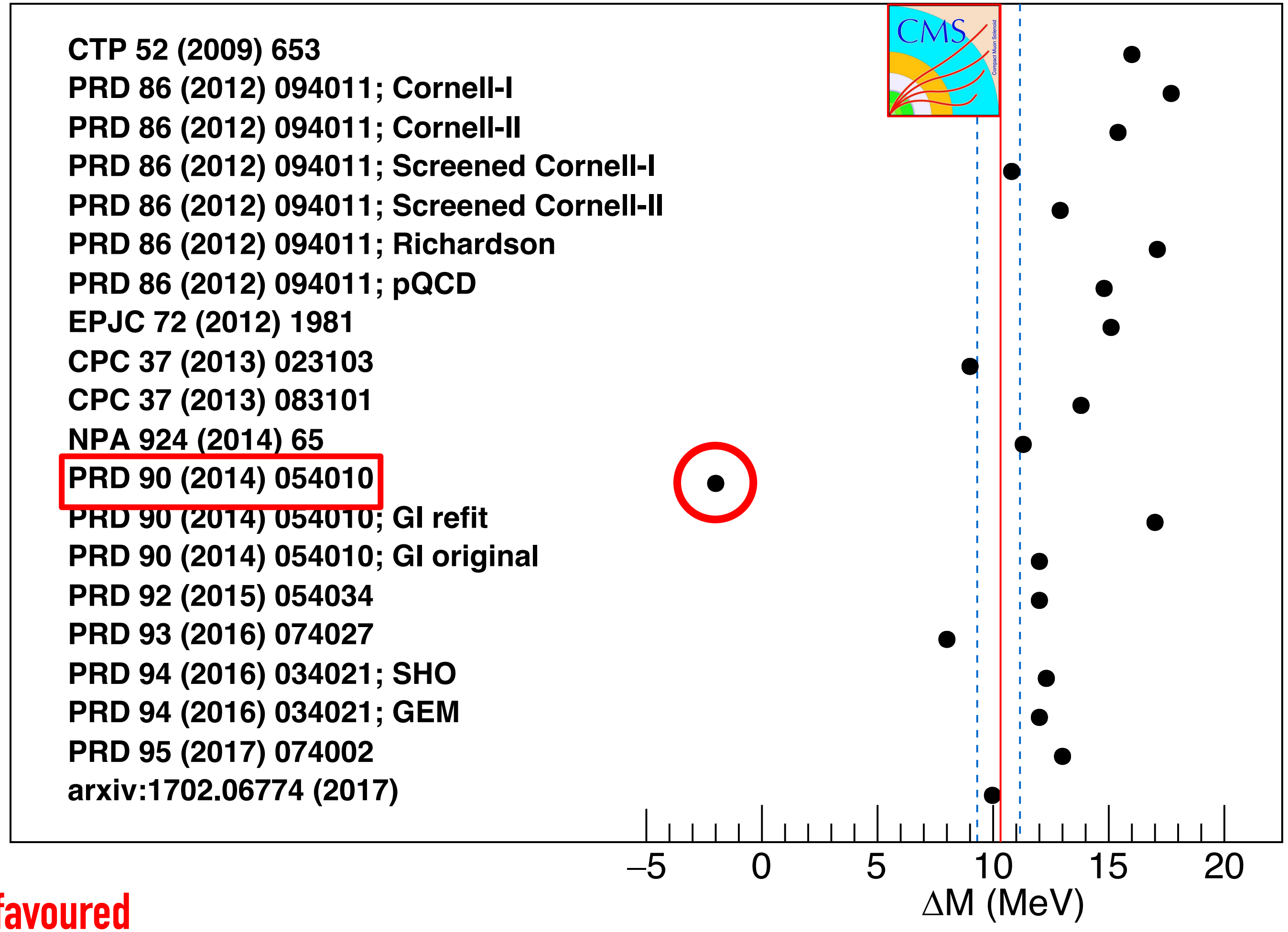
$$\Delta M = M(\chi_{b2}(3P)) - M(\chi_{b1}(3P)) =$$
$$= 10.60 \pm 0.64(stat) \pm 0.17(sys)\text{MeV}$$

Main systematic uncertainties:
- PES fit function (0.16 MeV)
- Fit functions (0.05 MeV)
- $\Upsilon(3S)$ mass uncertainty cancels out

Mass splitting: comparison to theoretical predictions

There is a large number of theory predictions for the ΔM mass spliting between the $J = 1$ and $J = 2$ $\chi_{bJ}(3P)$ states

- Out of 20 predictions:
  - 19 range from 8 to 18 MeV
  - 1 prediction is –2 MeV



- CMS measurement

$$\Delta M = 10.60 \pm 0.64(\text{stat}) \pm 0.17(\text{sys})\text{MeV}$$

has sufficient precision to provide an important constraint to the theory models calculating quarkonium spectroscopy levels

1) most of the predictions may be ruled out

2) breaking of the conventional pattern of splittings strongly disfavoured

Summary and Conclusions – II

Observation of $B_c(2S)$ and $B_c^*(2S)$ states

- Signals consistent with the $B_c(2S)$ and $B_c^*(2S)$ states have been separately observed for the first time by investigating the $B_c\pi\pi$ invariant mass spectrum measured by CMS experiment. ΔM and $M(B_c(2S))$ have been measured while the mass of the $B_c^*(2S)$ state remains unknown because the B_c^* decays to $B_c\gamma$ and the γ is not reconstructed
- This analysis is first LHC result based on the full usable Run 2 data of proton-proton collisions at $\sqrt{s} = 13\text{TeV}$, corresponding to a total integrated luminosity of 143 fb^{-1}
- Both peaks have local significance exceeding 5σ, the significance of two peaks with respect to observing only one peak is 6.5σ

Observation of $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states

- Signals consistent with the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states have been separately observed for the first time by investigating the $\Upsilon(3S)\gamma$ invariant with the photon converting ($\rightarrow ee$) in the beam pipe or in the tracker to enhance the mass resolution
- ΔM , $M(\chi_{b1}(3P))$ and $M(\chi_{b2}(3P))$have been measured with sufficient precision to highly support the standard mass hierarchy
- Two peaks local significance exceeds 5σ

Both these measurements contribute significantly provide a rich source of information on the non-perturbative QCD processes that bind heavy quarks

Thank You

"I am putting myself to the fullest possible use, which is all I think that any conscious entity can ever hope to do"

Back Up

B_c example event display