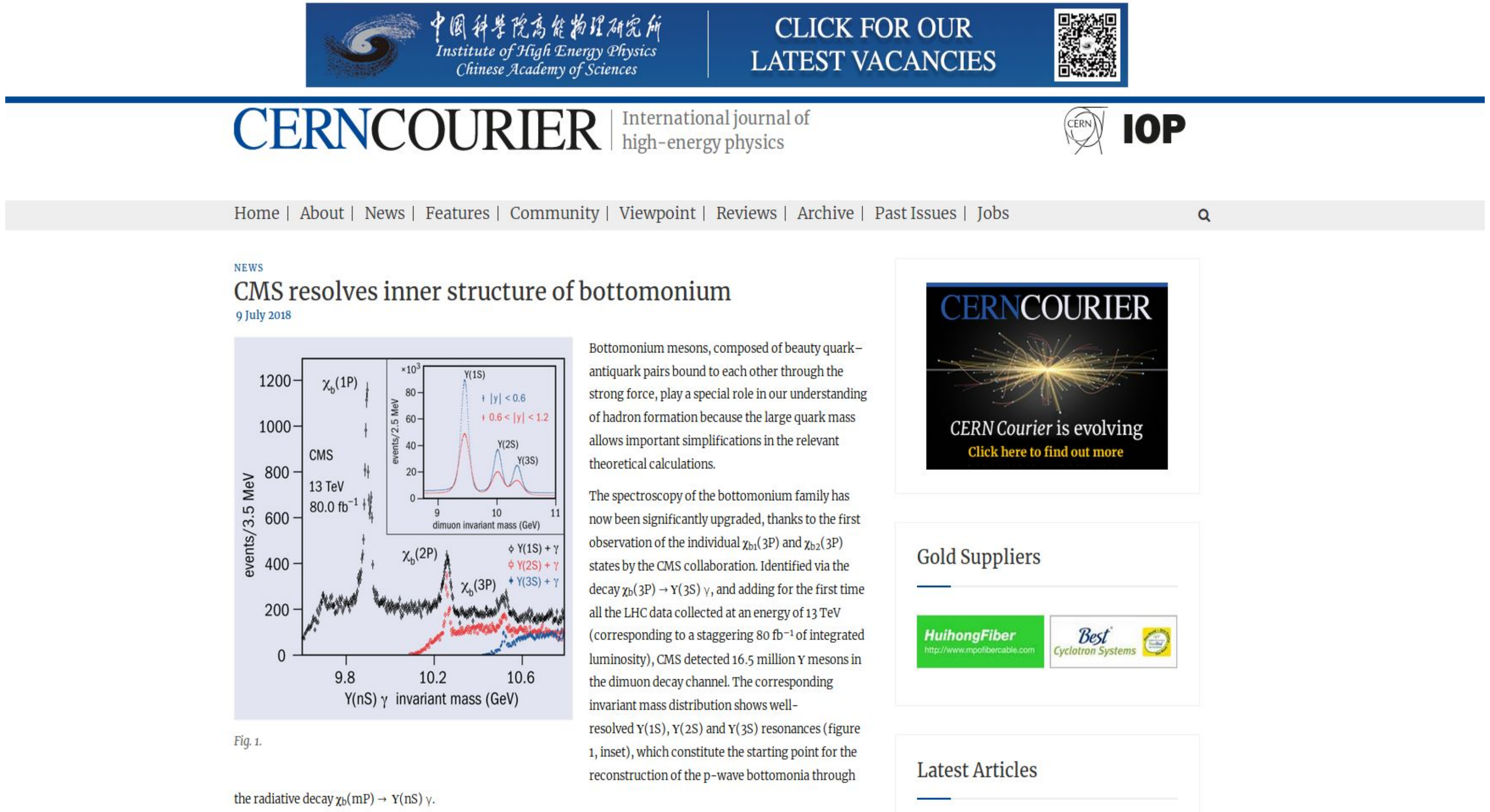
Phys. Rev. Lett. 121, 092002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NEWS

CMS resolves inner structure of bottomonium

9 July 2018

Bottomonium mesons, composed of beauty quark–antiquark pairs bound to each other through the strong force, play a special role in our understanding of hadron formation because the large quark mass allows important simplifications in the relevant theoretical calculations.

The spectroscopy of the bottomonium family has now been significantly upgraded, thanks to the first observation of the individual $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states by the CMS collaboration. Identified via the decay $\chi_b(3P) \to \Upsilon(3S)\,\gamma$, and adding for the first time all the LHC data collected at an energy of 13 TeV (corresponding to a staggering 80 fb^{-1} of integrated luminosity), CMS detected 16.5 million Υ mesons in the dimuon decay channel. The corresponding invariant mass distribution shows well-resolved $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances (figure 1, inset), which constitute the starting point for the reconstruction of the p-wave bottomonia through the radiative decay $\chi_b(mP) \to \Upsilon(nS)\,\gamma$.

Fig. 1.

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Observation of the χb1(3P) and χb2(3P) measurement of their masses using the χbJ(3P) → Υ(3S)γ

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For the CMS collaboration

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The Fifth Latin American Congress of Physics (CLF), October 7 to October 12, 2018, Puebla, Mexico.

Outline

- Motivation
- Experimental setup
- Overview of results by CMS

Observation of the χb1(3P) and χb2(3P) measurement of their masses
CMS-BPH-17-008 ; CERN-EP-2018-134
PRL 121 (2018) 092002

Motivation

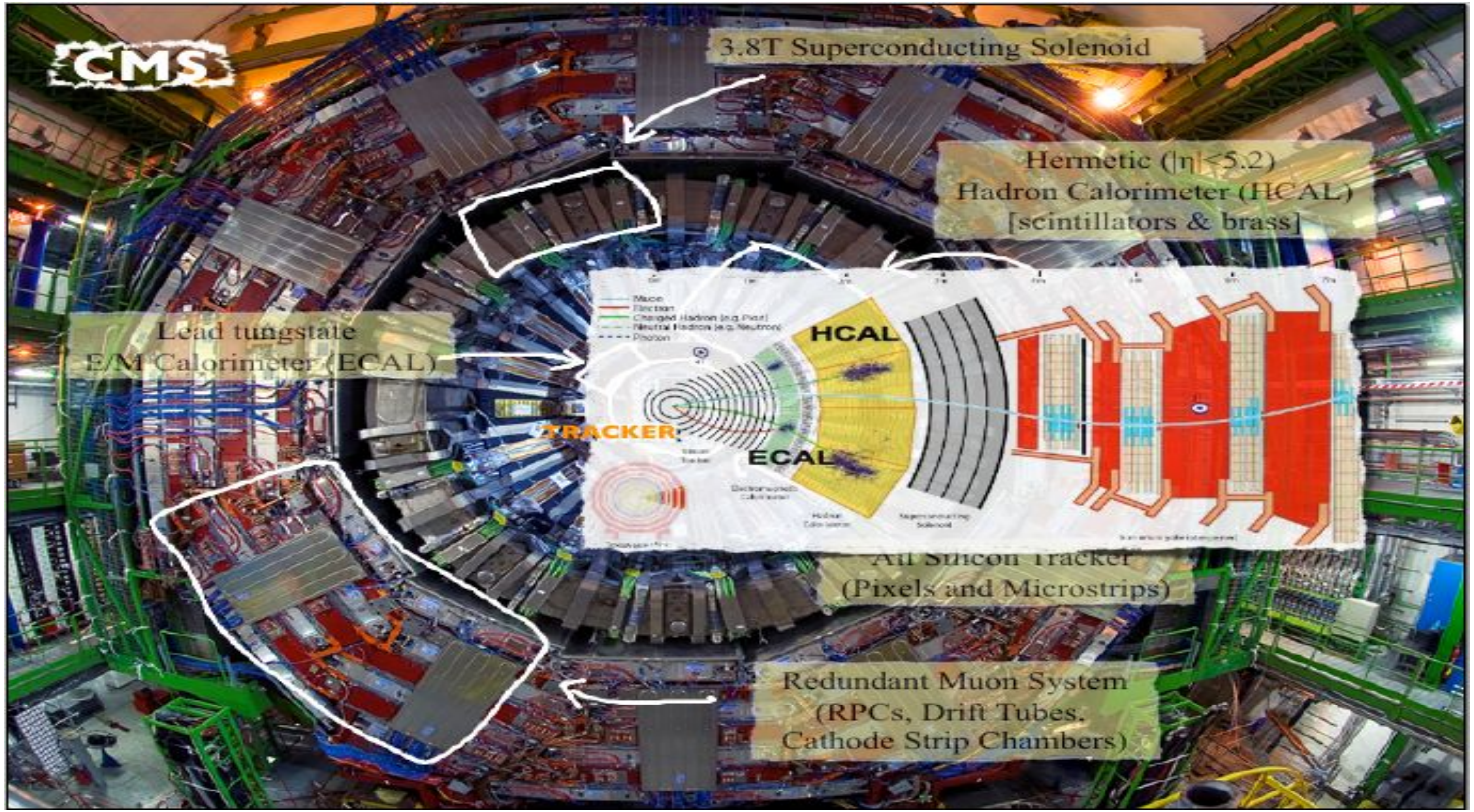
Although quantum chromodynamics (QCD) is well established as the theory of the strong interaction, a complete understanding of the (nonperturbative) processes that lead to the binding of quarks and gluons into hadrons is still lacking.

- Bottomonium mesons, composed of beauty quark–antiquark pairs bound to each other through the strong force, play a special role in our understanding of hadron formation because the large quark mass allows important simplifications in the relevant theoretical calculations.

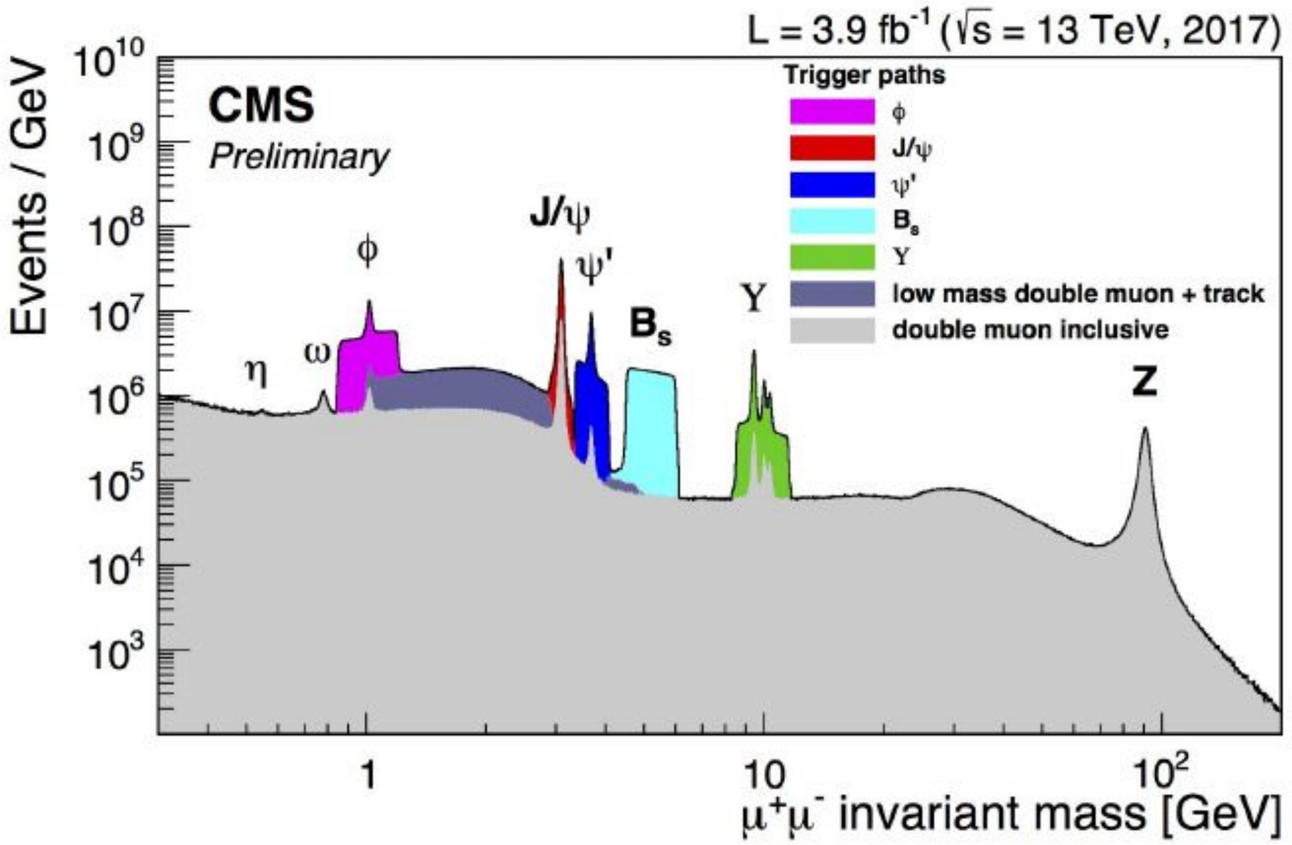
- Studies of the production cross sections and polarizations of the S-wave quarkonium states, such as the J/ψ, the ψ(2S), and the Υ(1S) states, have provided a number of insights into quarkonium production processes and beyond: they address our general understanding of perturbative QCD calculations and their reliability.

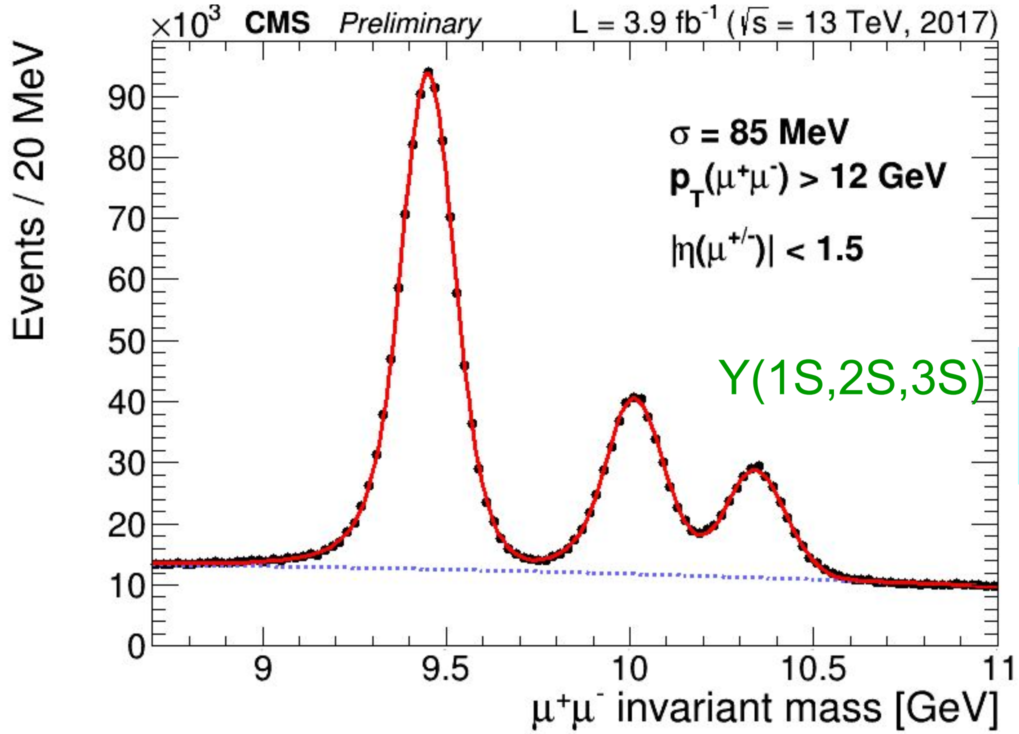
- However, studies of the S-wave states are not sufficient to definitely test the presently existing models of quarkonium production. Much more stringent tests of the models and a quantitative understanding of the mechanisms of quarkonium production imply measurements of P-wave quarkonia, so far much less studied.

Experimental setup



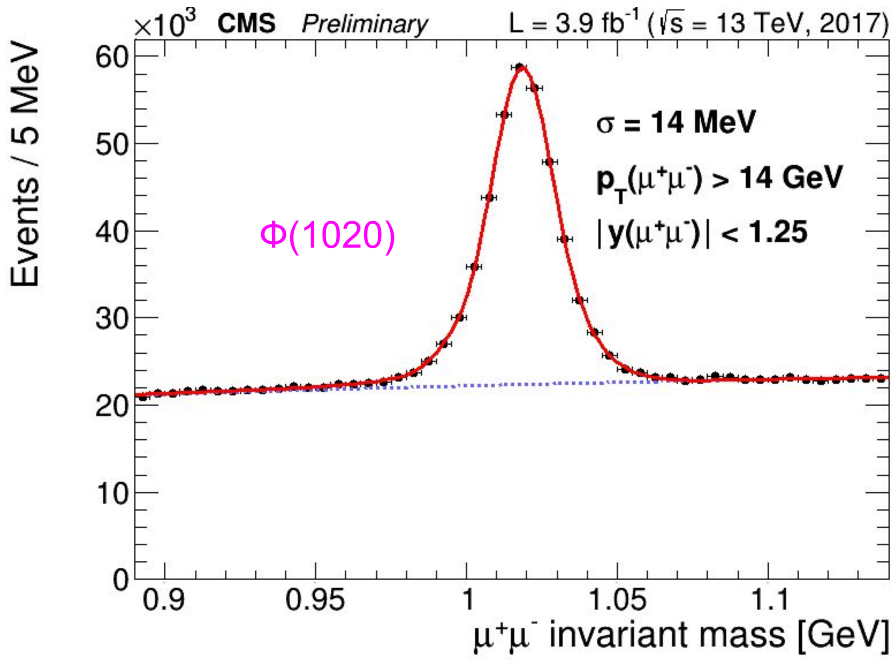
Compact Muon Solenoid: perfect detector for measuring muons

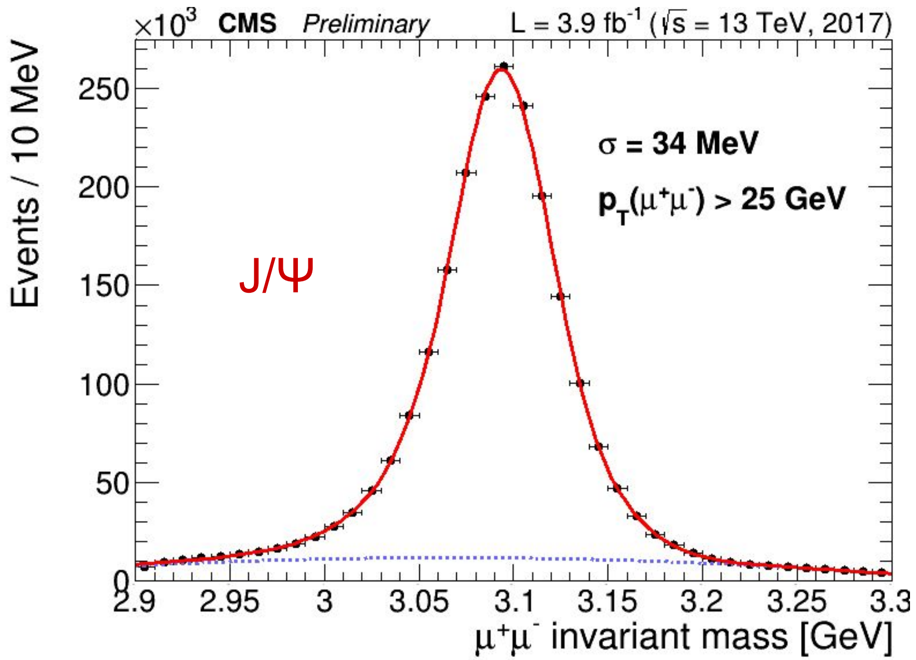


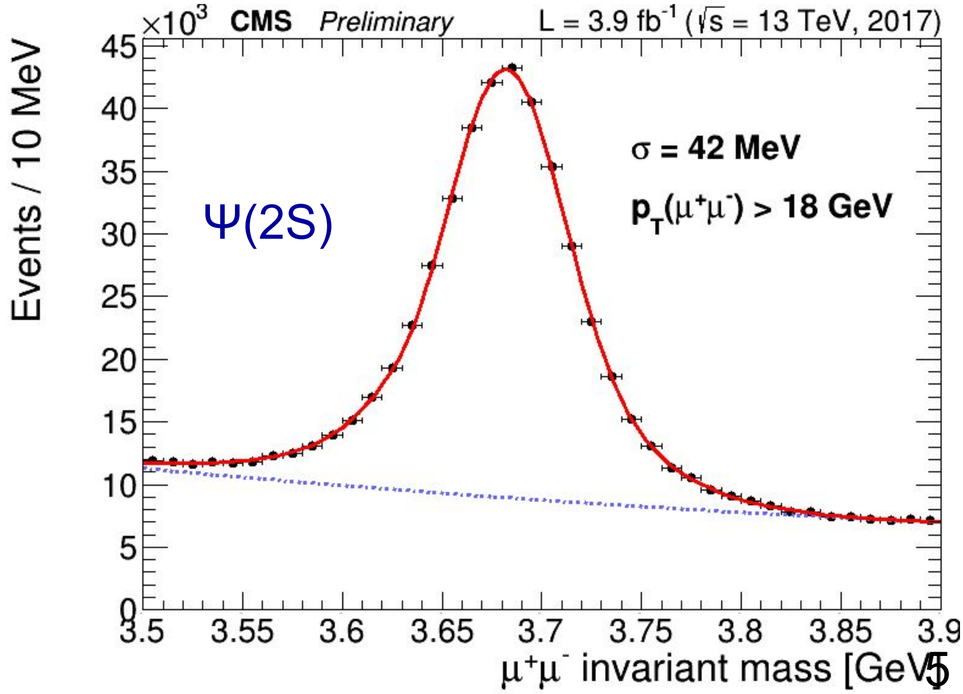


Experimental setup: dedicated HF triggers

Using 2017 data: CMS-DP-2017-029







Overview of the latest HF studies by CMS

- Precision lifetime measurements of b hadrons reconstructed in final states with a J/ψ meson.
  PJC (2018) 78:457
- Search for the X(5568) state in B0s pi+- decays.
  PRL 120 (2018) 202005.
- **Observation of the χb1(3P) and χb2(3P) measurement of their masses**
  PRL 121 (2018) 092002
- Quarkonium production cross sections in pp collisions at √s = 13 TeV.
  PLB 780 (2018) 251
- Measurement of Lambdab polarization and the angular parameters of the decay Lambdab to J/psi Lambda.
  PRD 97 (2018) 072010
- Measurement of the total and differential inclusive B+ hadron cross sections in pp collisions at √s= 13 TeV.
  PLB 771 (2017) 435
- Angular analysis of B+->K+mumu
  arXiv:1806.00636 (sibmited to PRD)
- Search for the Z->Jpsi(->mumu) ll decay
  arXiv:1806.04213 (sibmited to PRL)

CINVESTAV

The analysis in a nutshell

spectroscopy? [*]
The study of excited states of matter through observation of energy emissions

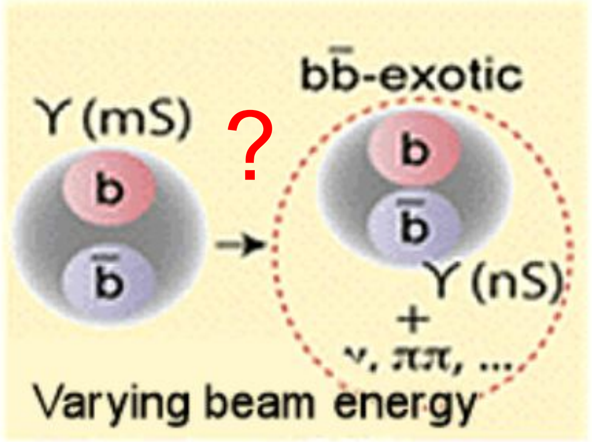
In the 1800s chemists and physicists identified different chemical substances by watching the colour of the flame when they burnt them, using prisms that separated the various **"emission lines"** and made them better measurable. They were looking at spectra of light.

To realize how many collisions correspond to **80 inverse femtobarns**, imagine two protons that bang into one another. Then imagine a billion of these. Well, that's still short by a factor of 10 million!

The number of entries in the histograms is less than 2000, so a pretty wild reduction has taken place in selecting the events of interest

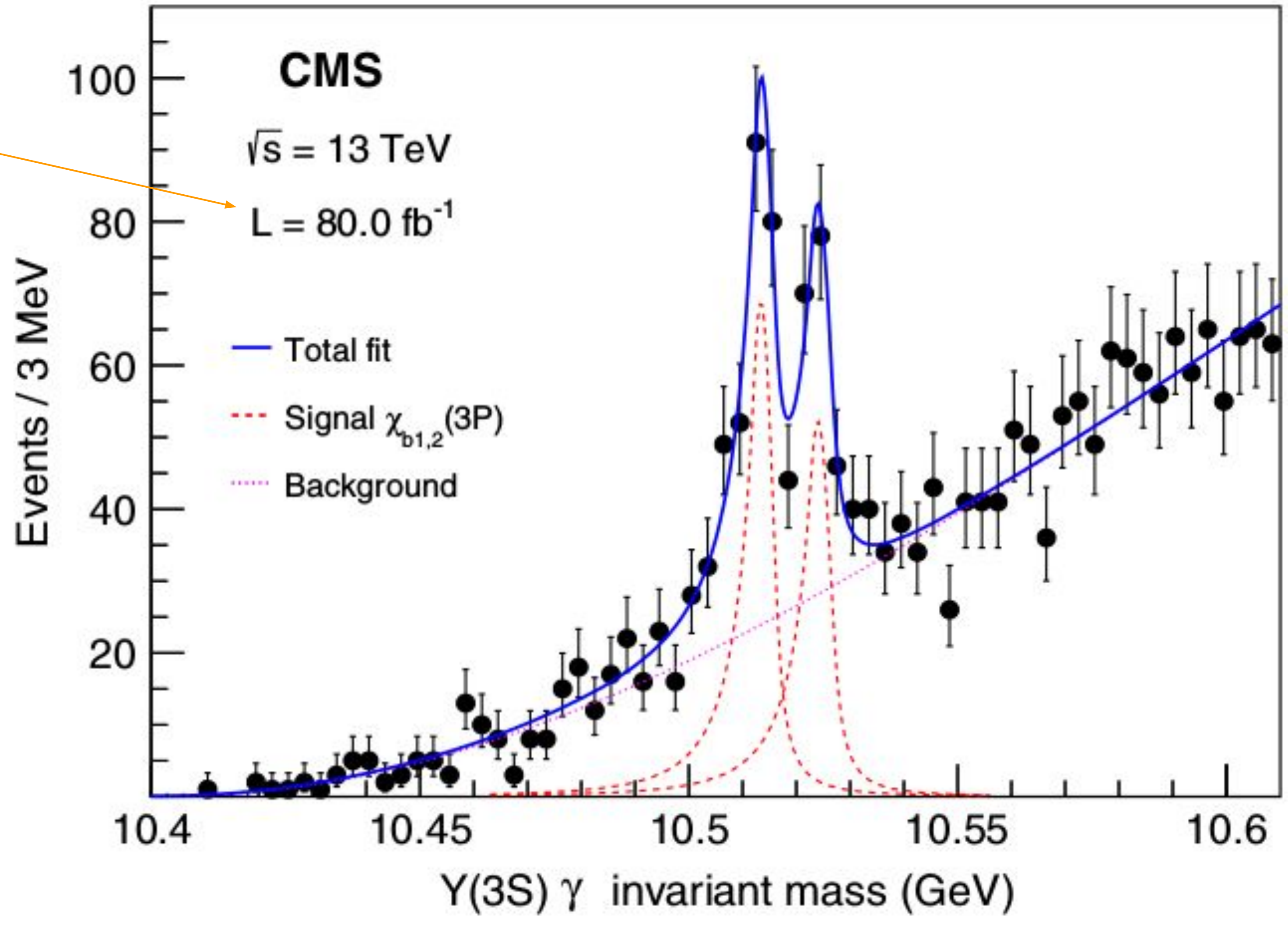
we are very well looking at a spectrum too. Not a colored one, but still a distribution of intensities along an axis describing different energies.

The CMS analysis is remarkable because for the first time it allowed the measurement of two very close resonances



[*] taken from here

The rarity of the processes studied in the recent CMS analysis discussed here is apparent if we uncharacteristically start from the end.



The experimental discovery of the $\chi_b(3P)$ state

The $\chi_b(3P)$ was discovered by ATLAS in 2011

"In addition to the $\chi_b(1P,2P) \to \Upsilon(1S)\,\gamma$,
a new structure centered at

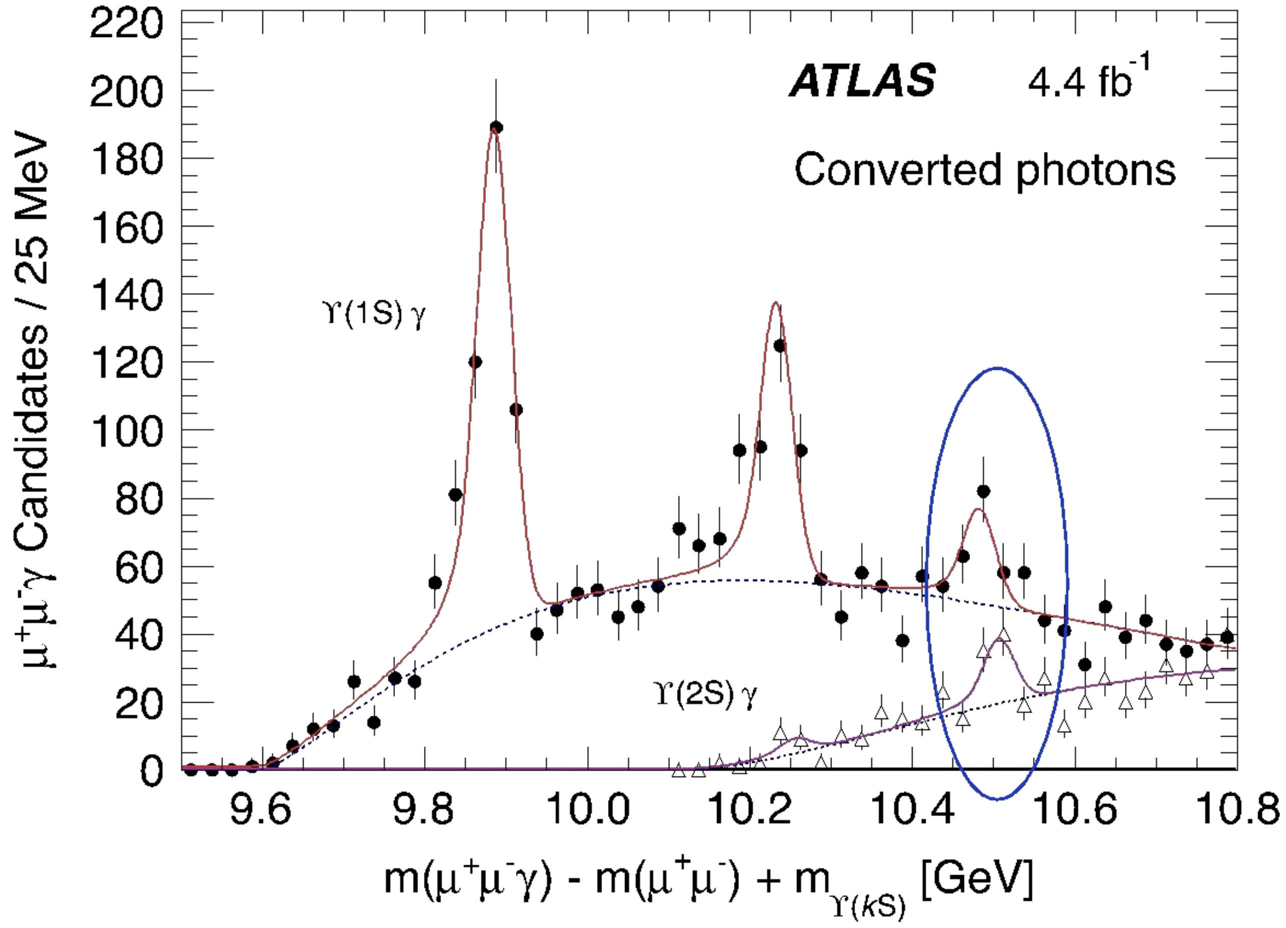
10530 ± 5 (stat) ± 9 (syst) MeV

is also observed,
in the $\Upsilon(1S)\,\gamma$ and $\Upsilon(2S)\,\gamma$ decay modes.

This is interpreted as the $\chi_b(3P)$ system."

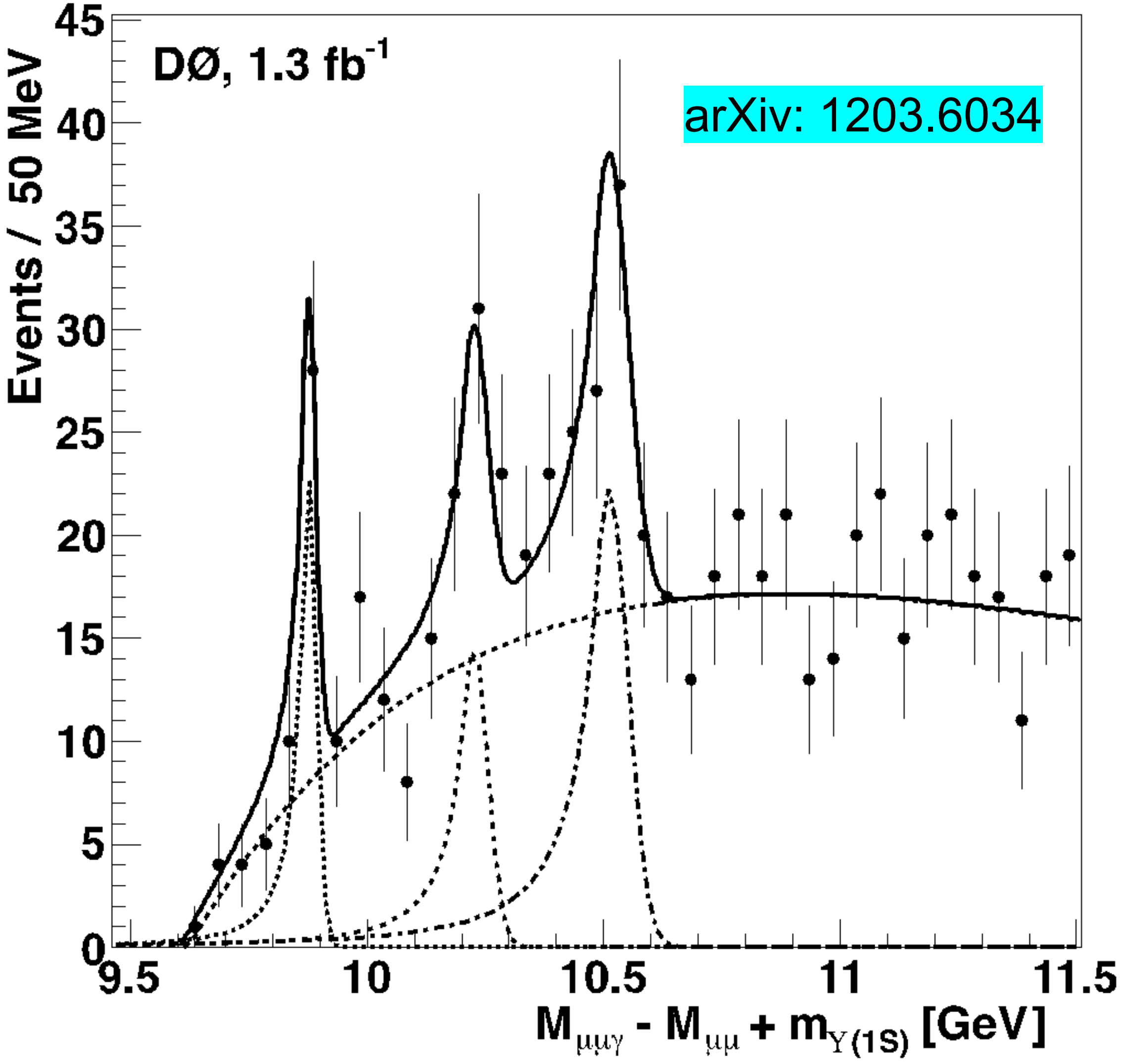
No observation in the $\Upsilon(3S)\,\gamma$ decay mode.

arXiv:1112.5154

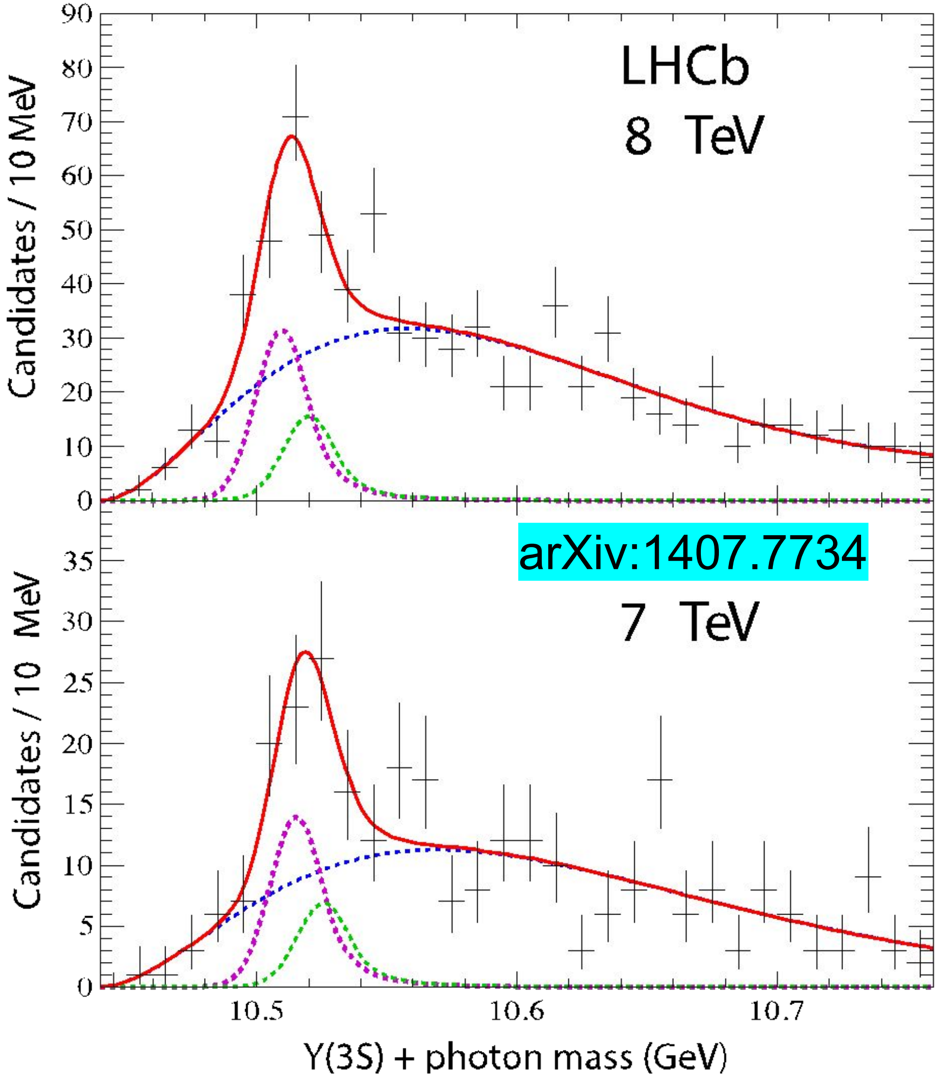


Other experimental measurements: D0 and LHCb

D0 saw the $\chi_b(3P)$
in the $\Upsilon(1S)\,\gamma$ decay channel



LHCb observed the $\chi_b(3P) \rightarrow \Upsilon(3S)\,\gamma$ decay
but could not resolve the J= 1 and 2 doublet

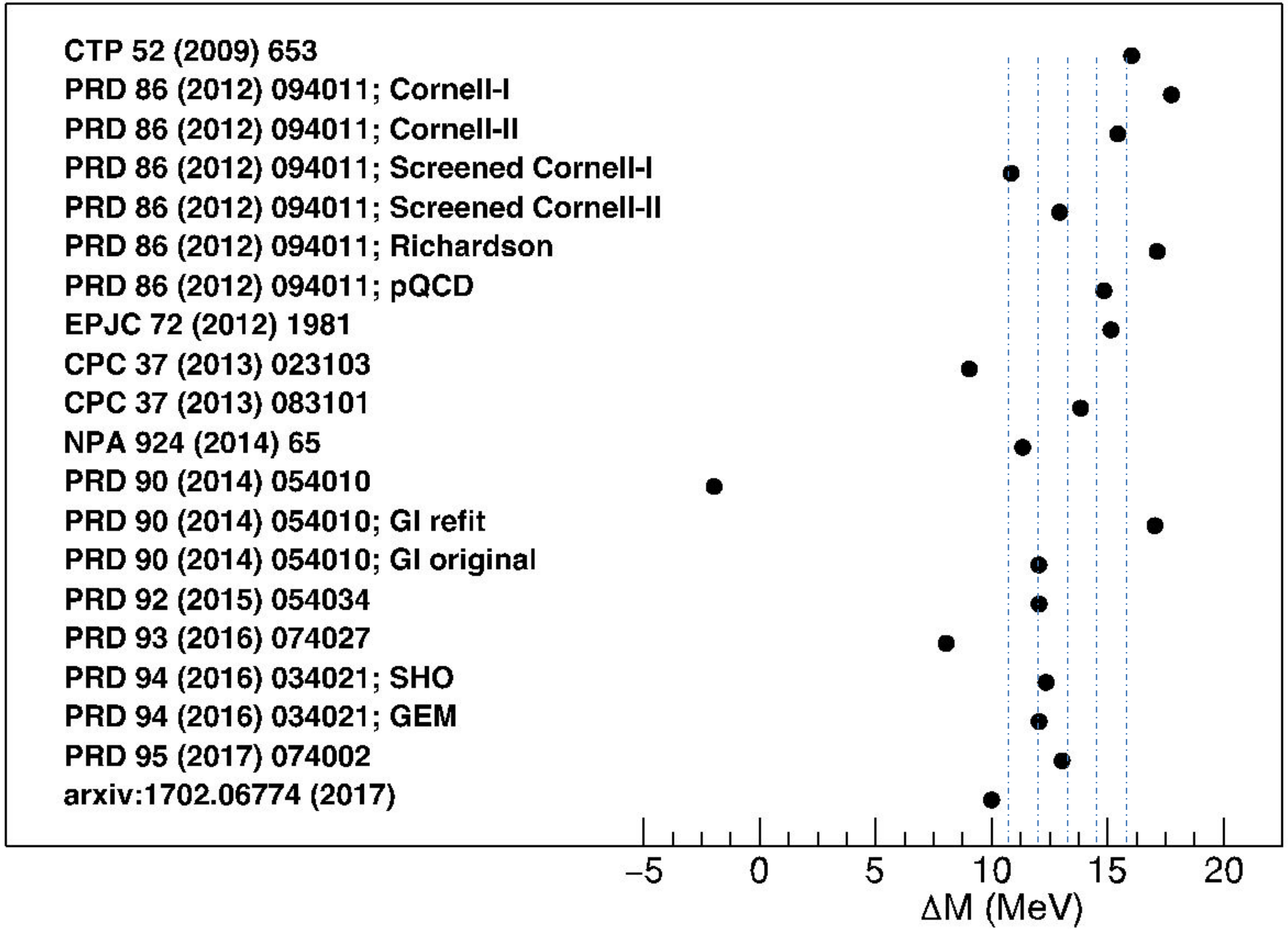


Theory predictions for the $\chi_b(3P)$ mass splitting (ΔM)

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

Out of 20 computations, 14 predict ΔM > 11 MeV

A measurement with a precision around 1 MeV should have a big impact



Context of this analysis

* All publications citing the ATLAS peak take for granted that it is the χb(3P) quarkonium:

"For both the χb2(3P) and χb1(3P) the decay chains to Y(nS) give rise to the largest event rates
and are the simplest to reconstruct so it is not surprising that these were the discovery channels.
Run II should provide sufficient statistics to separately fit the χb2(3P) and χb1(3P) using these decay chains."

Stephen Godfrey and Kenneth Moats, Phys. Rev. D 92 (2015) 054034

** One paper mentions the Xb, the bottomonium counterpart of X(3872) :

"As the decays χb(3P) $\rightarrow$ Y(1S, 2S) g have been observed,
and the Xb is expected to mix strongly with the χb1(3P),
it is worthwhile to examine the Y(1S, 2S) g mass spectra
for any departures from single Breit-Wigner behavior."

Marek Karliner and Jonathan L. Rosner, Phys. Rev. D 91 (2015) 014014

*** One unpublished 3-year old paper, arXiv:1502.07011, mentions another option:

"We study the possibility that this boson is the light Higgs boson h0(0+)"

Reconstruction of the χ_b candidates

The mass of the $\chi_b(3P)$ candidate is computed through a dimuon-photon kinematic vertex fit

Note: the result is almost identical to $m(\mu\mu\gamma) - m(\mu\mu) + M(Y3S)$

The fit is performed with the following conditions:

- the masses of the muons and electrons are fixed to their PDG values
- the mass of the dimuon is fixed to the Y(3S) PDG mass
- the mass of the electron-positron pair is fixed to zero
- the electron and the positron are constrained to have a common vertex
- the dimuon and the photon are constrained to have a common vertex

The $\chi_b(3P)$ candidate is kept if the χ^2 probability of the kinematic fit exceeds 1%

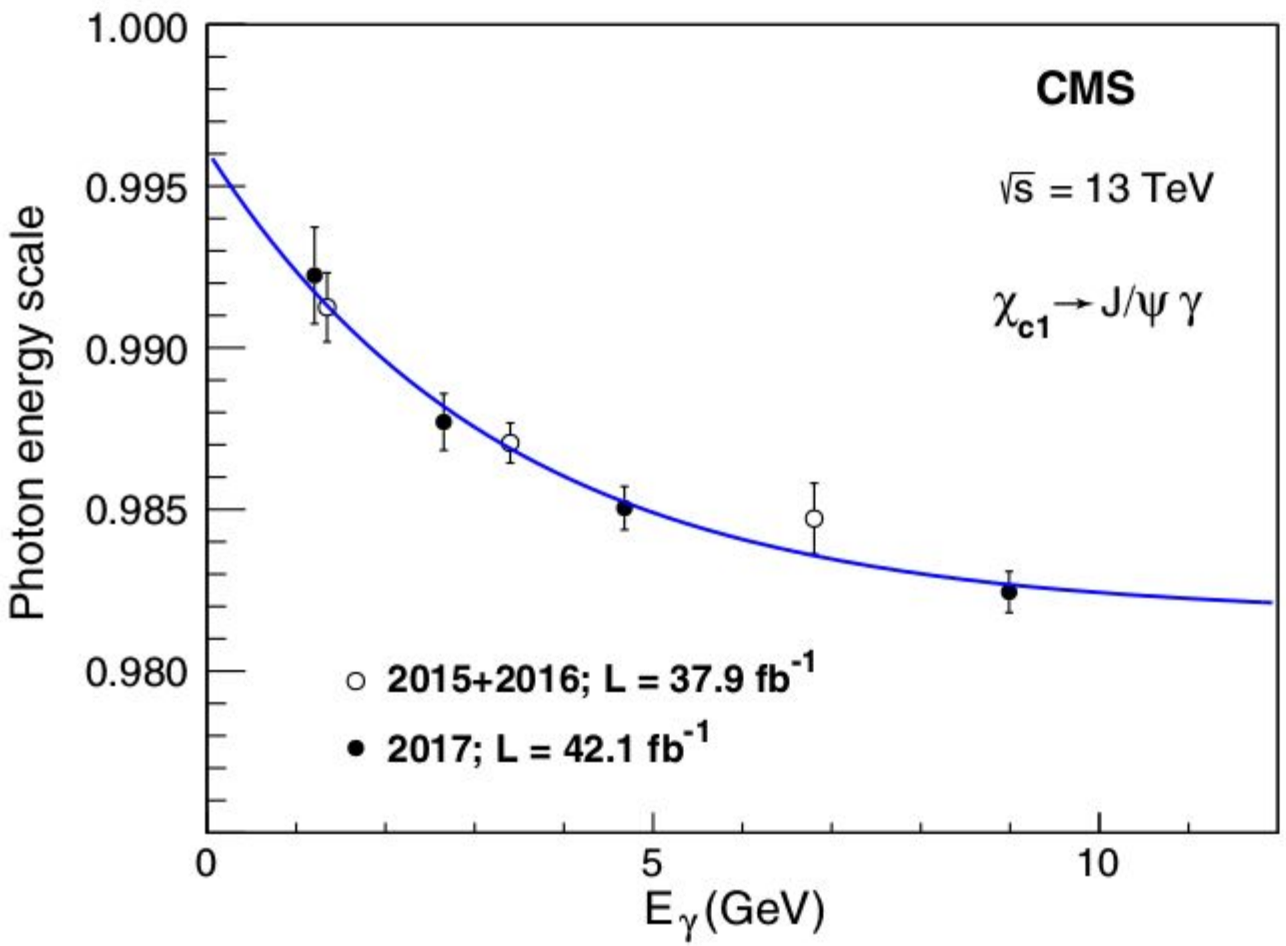
If several candidates are found in the same event, only the one with the best vertex fit is kept

Determination of the photon energy scale (PES)

The measured photon energy might differ from the true value: $E_{true} = E_{rec} / PES$

The PES is computed using $\chi_{c1} \rightarrow J/\psi\ \gamma$ events, comparing the measured and PDG χ_{c1} masses

The $J/\psi\ \gamma$ events were collected in the same runs, with similar dimuon triggers, and processed in the same way as the Upsilon events



The correction is very small for the $\chi_b(3P) \rightarrow \Upsilon(3S)\ \gamma$ decay (small photon energies)

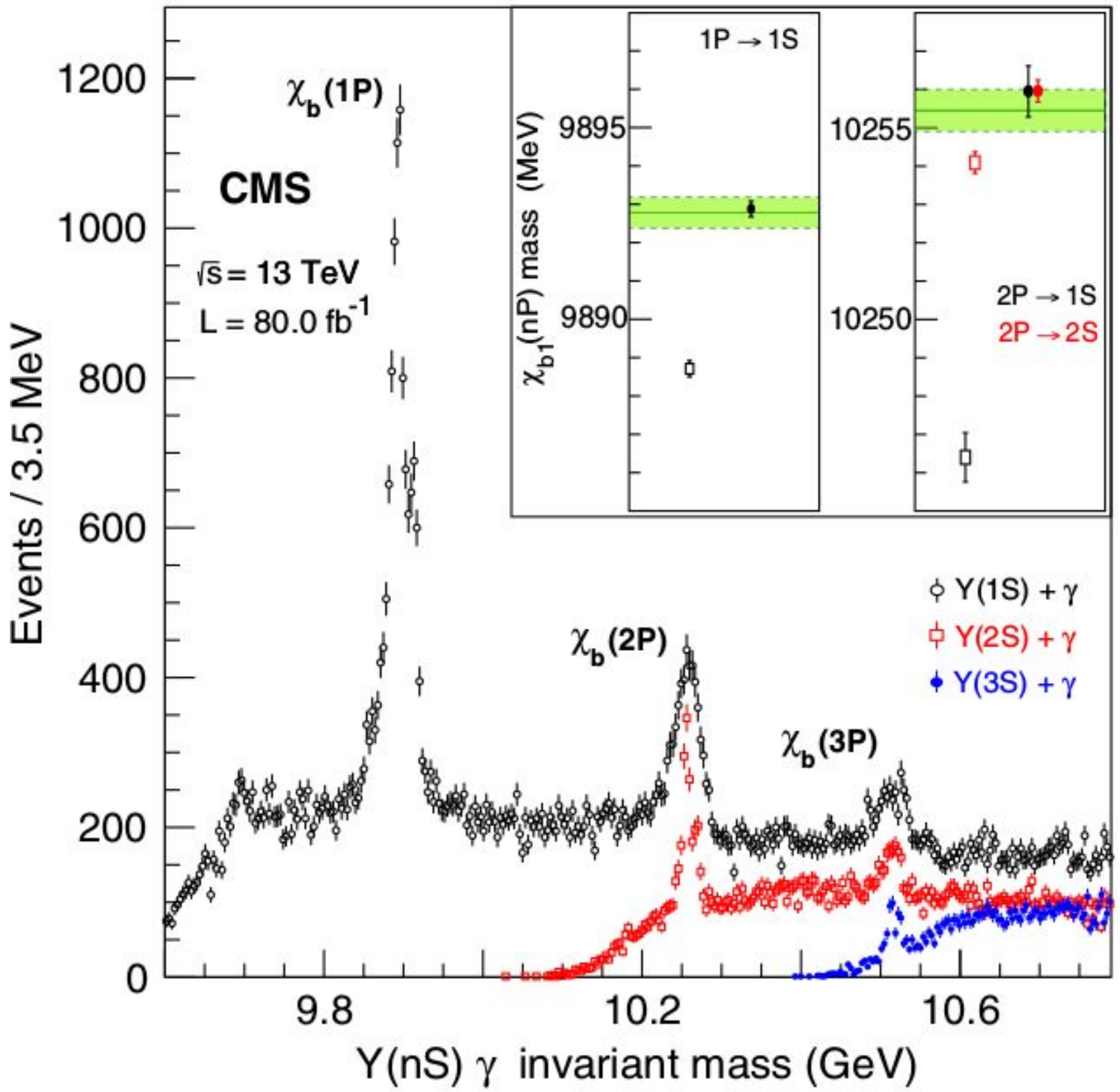
Validation of the photon energy scale

After PES correction,
the measured $\chi_{b1}(1P)$ and $\chi_{b1}(2P)$ masses agree well with the PDG values

The three $\chi_b(3P)$ peaks are also well aligned with each other

The $\chi_b(3P) \to \Upsilon(3S)\,\gamma$ decay is the least affected by the PES

	Rec.	Corr.	PDG
$M(\chi_{b1}(1P))$ in $\Upsilon(1S)+\gamma$	$9888.71^{+0.21}_{-0.21}$	$9892.88^{+0.20}_{-0.21}$	$9892.78 \pm 0.26 \pm 0.31$
$M(\chi_{b1}(2P))$ in $\Upsilon(1S)+\gamma$	$10246.41^{+0.64}_{-0.64}$	$10255.95^{+0.66}_{-0.67}$	$10255.46 \pm 0.22 \pm 0.50$
$M(\chi_{b1}(2P))$ in $\Upsilon(2S)+\gamma$	$10254.10^{+0.28}_{-0.28}$	$10255.96^{+0.28}_{-0.29}$	
$M(\chi_{b1}(3P))$ in $\Upsilon(1S)+\gamma$	$10498.77^{+2.01}_{-2.11}$	$10512.88^{+1.92}_{-1.99}$	10512.1 ± 2.3
$M(\chi_{b1}(3P))$ in $\Upsilon(2S)+\gamma$	$10506.85^{+1.18}_{-1.18}$	$10511.48^{+1.23}_{-1.18}$	
$M(\chi_{b1}(3P))$ in $\Upsilon(3S)+\gamma$	$10512.26^{+0.40}_{-0.43}$	$10513.42^{+0.41}_{-0.42}$	unpublished

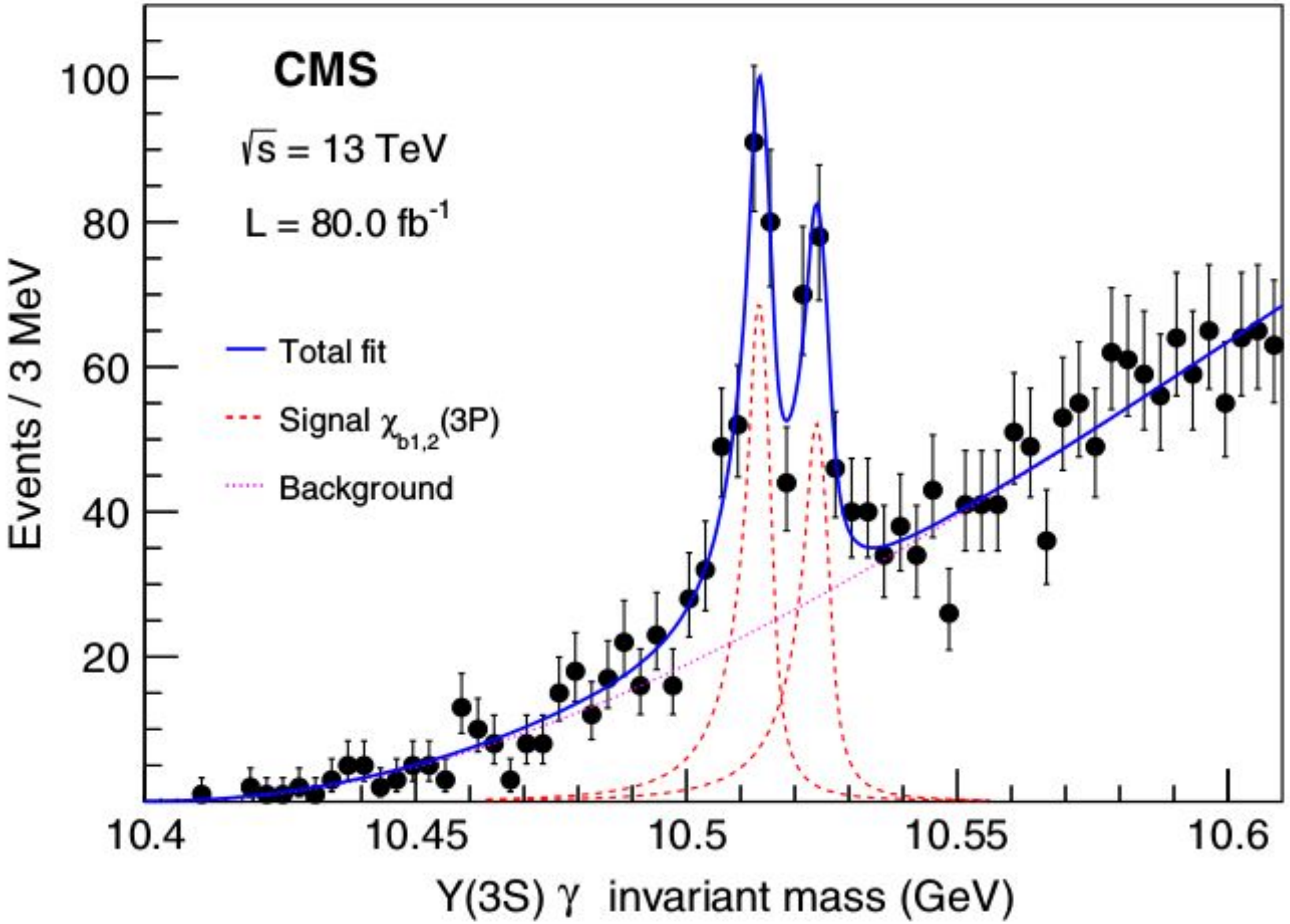


Fit of the measured mass distribution

The measured distribution of the χb(3P) candidate mass distribution is well fitted by two DCB functions on the top of a smooth continuum from uncorrelated dimuon-photon pairs

$$F_{\mathrm{Bg}}(m) = (m - q_0)^{\lambda} \cdot \exp\left[\nu(m - q_0)\right]$$

An extended unbinned max. likelihood fit, made in RooFit with the “Minos” option, provides stable results



Systematic uncertainties

Background fit model: replace by power-law or Chebychev polynomial of second order

Selection criteria:

- vary photon p_T cut between 400 and 600 MeV
- vary dimuon p_T cut between 12 and 16 GeV
- use a broader Υ(3S) mass window: $M(\Upsilon(3S)) \pm 2.5\,\sigma_m(y)$
- use dimuon-photon 4-track vertex-fit χ^2 probability > 1.5%

Source of uncertainty	ΔM	$M(\chi_{b1}(3P))$
Fit Model	0.05	0.05
PES correction	0.16	0.17

PES correction: used a constant PES, the average of the two measurements with $E_\gamma < 2$ GeV: 0.9916
Also generated 400 PES functions by drawing new p_0, p_1, and p_2 parameters from Gaussian functions with nominal means and standard deviations respecting the covariance matrix

Given the absence of significant changes in the results, the systematic uncertainty related to the selection criteria is considered negligible. There is also no significant change in the results if the σ2/σ1 ratio is left free in the fit.

The PDG Υ(3S) mass has an uncertainty of 0.5 MeV, which affects our $\chi_{b1}(3P)$ mass measurement :

$$M(\chi_{b1}(3P)) \sim m(\mu\mu\gamma) - m(\mu\mu) + M(Y3S)$$

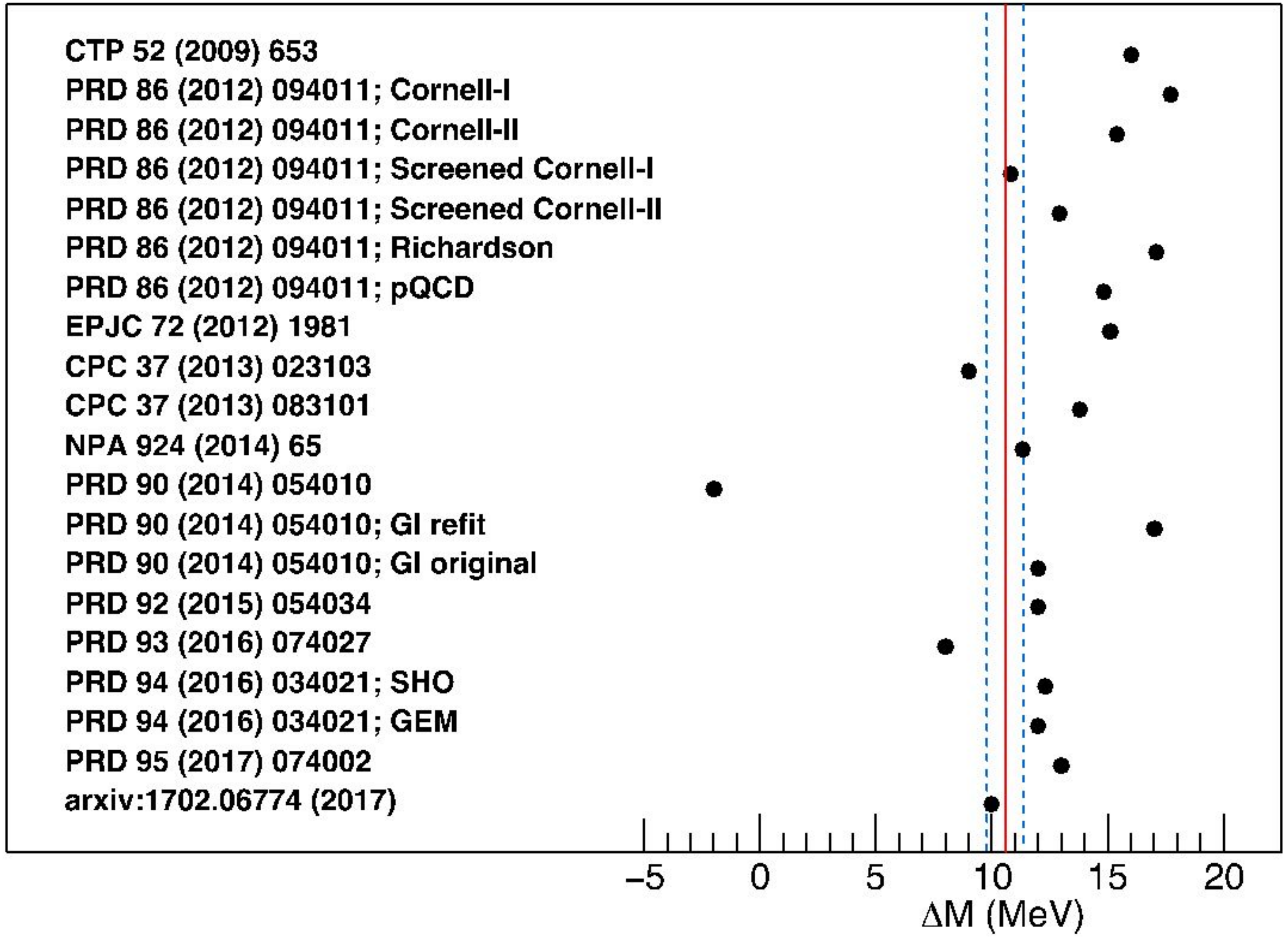
Measured vs. predicted $\chi_{b2}(3P)$ - $\chi_{b1}(3P)$ mass difference

Our measurement

10.61 ± 0.64 (stat) ± 0.17 (syst) MeV

has a very good precision
in comparison to the spread of
values reported in theory papers

It is an important contribution
to constrain and improve
the models calculating
quarkonium spectroscopy levels



Summary

Using 80 fb^{-1} of data collected in pp collisions at 13 TeV in 2015, 2016 and 2017, we have seen well-resolved J = 1 and J = 2 states in the $\chi_{bJ}(3P) \rightarrow \Upsilon(3S)\,\gamma$ decay channel

The mass difference between the two states is

$$M[\chi_{b2}(3P)] - M[\chi_{b1}(3P)] = 10.66 \pm 0.64\ (\text{stat}) \pm 0.17\ (\text{syst})\ \text{MeV}$$

The mass of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states are

$$M[\chi_{b1}(3P)] = 10513.42 \pm 0.41\ (\text{stat}) \pm 0.18\ (\text{syst}) \pm 0.5\ (\Upsilon 3S)\ \text{MeV}$$

$$M[\chi_{b1}(3P)] = 10524.02 \pm 0.57\ (\text{stat}) \pm 0.18\ (\text{syst}) \pm 0.5\ (\Upsilon 3S)\ \text{MeV}$$

Summary

The new measurement is a step forward in completing the spin-dependent bottomonium spectroscopy diagram, and should significantly contribute to an improved understanding of the non-perturbative QCD processes that lead to the binding of quarks and gluons into hadrons.

The measured mass splitting, 10.66 ± 0.64 (stat) ± 0.17 (syst) MeV, can be used to improve the theoretical calculations, which currently predict values between 8 and 18 MeV depending on the potentials describing the quark–antiquark non-perturbative interaction. The only exception predicts a value of –2 MeV, the negative sign meaning that the χb2(3P) has a mass smaller than the χb1(3P).

"A major highlight for CMS at LHCP is the first observation of well-resolved chi_b1(3P) and chi_b2(3P) signals, and a measurement of their masses, using Y(3S)+photon decays reconstructed from 80 fb-1 of pp data collected at 13 TeV. The photons interact in the material of the CMS tracker and convert to electron-positron pairs whose momentum is measured in CMS magnetic spectrometer, providing the superb resolution needed to separate the two states whose mass differs by only 10 MeV. Measurements of the chi_bJ(3P) triplet states, with total angular momentum J=0,1, and 2, probe details of the bbbar interaction and contribute to an improved understanding of quarkonium spectroscopy and hadron formation."

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The CMS collaboration continues with its rich harvesting of the large Run 2 dataset with 21 new results presented at the LHCP 2018 conference in Bologna, Italy. The results cover a wide assortment of topics and range from precision measurements of the Higgs boson and Standard Model (SM) processes to searches for rare decays and exotic phenomena.

A recent highlight from CMS has been the first observation of the associated production of a Higgs boson with a top quark-antiquark pair or "ttH production". This measurement, first reported in April 2018 and now published in the journal Physical Review Letters [Phys. Rev. Lett. 120, 231801 (2018)], establishes the tree-level coupling of the Higgs boson to the top quark and is a major milestone towards the measurement of the Higgs boson coupling to fermions. CMS has now extended this exploration of Higgs couplings and presents at LHCP a new analysis that studies in a more general way the coupling of the Higgs boson to the top quark by searching for Higgs boson production in association with a single top quark (tH). CMS also presents measurements of the properties of the Higgs boson using the latest dataset collected in 2017 and the H -> ZZ -> 4l (l=e, μ) decay channel. The results have been combined with the 2016 dataset and are found to be consistent, within their uncertainties, with the expectations for the SM Higgs Boson.

A major highlight for CMS at LHCP is the first observation of well-resolved chi_b1(3P) and chi_b2(3P) signals, and a measurement of their masses, using Y(3S)+photon decays reconstructed from 80 fb^{-1} of pp data collected at 13 TeV. The photons interact in the material of the CMS tracker and convert to electron-positron pairs whose momentum is measured in CMS magnetic spectrometer, providing the superb resolution needed to separate the two states whose mass differs by only 10 MeV. Measurements of the chi_bJ(3P) triplet states, with total angular momentum J=0,1, and 2, probe details of the bbbar interaction and contribute to an improved understanding of quarkonium spectroscopy and hadron formation.