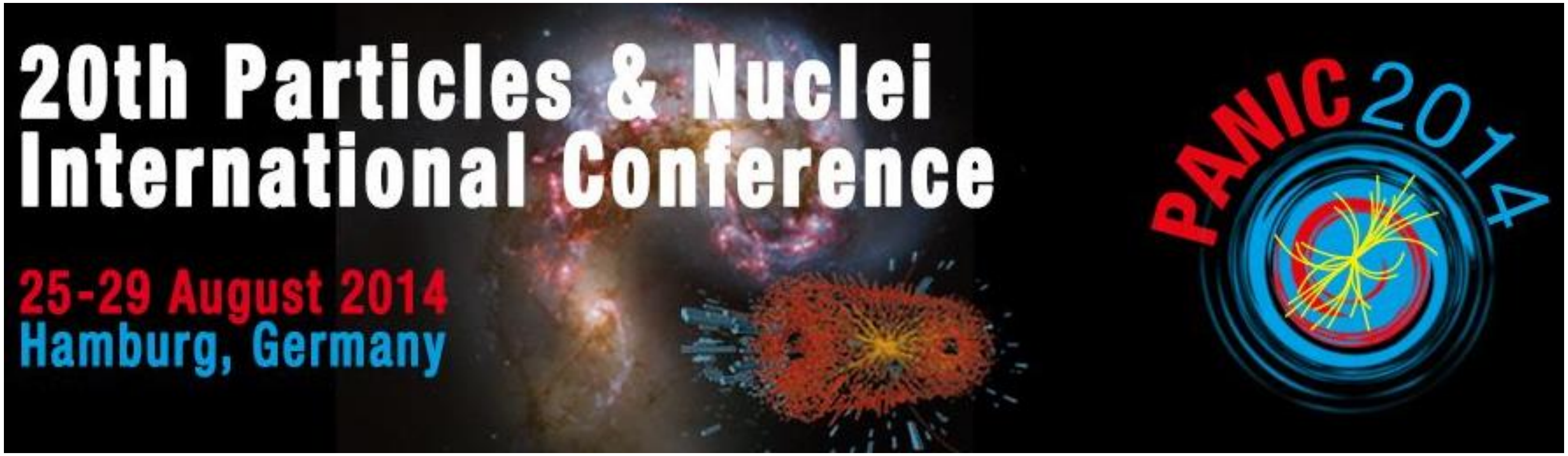
Quarkonia, Resonances and Spectroscopy

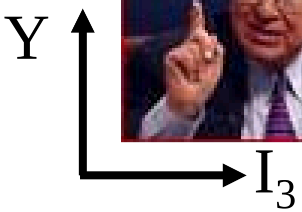
Gagan Mohanty

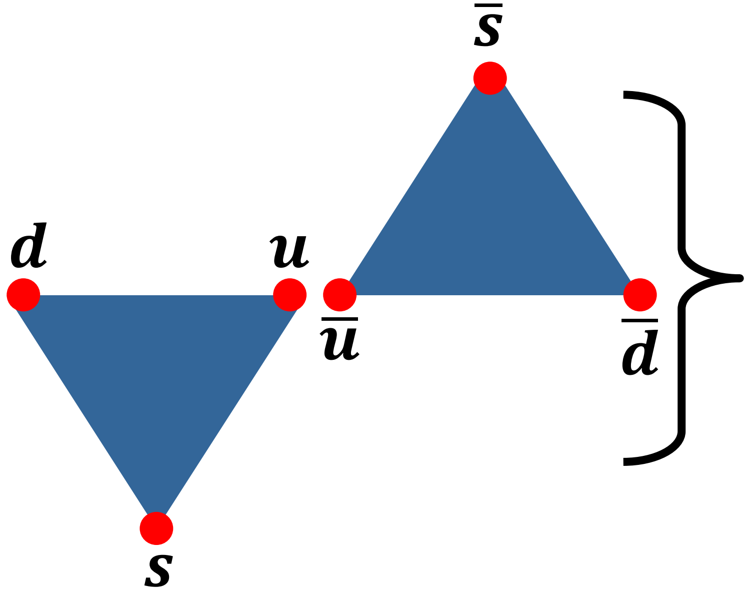
tifr

Mumbai



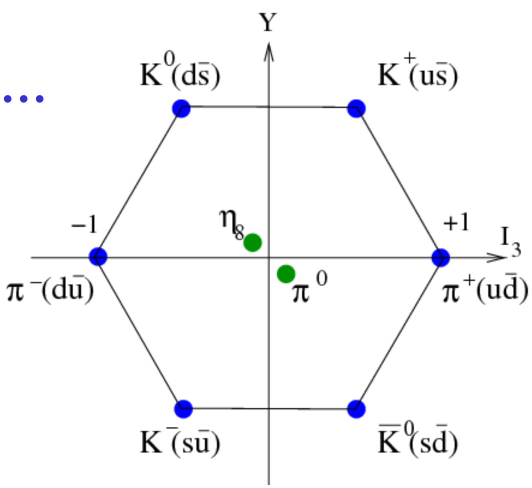
Enter the quark model

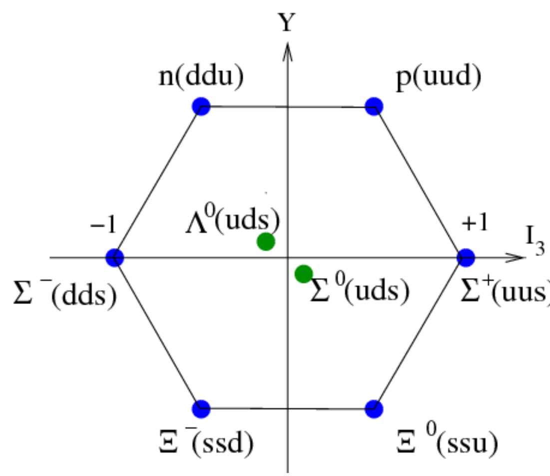




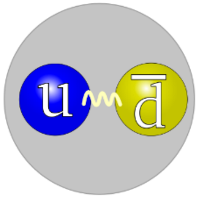
Hadron Spectroscopy

Examples...

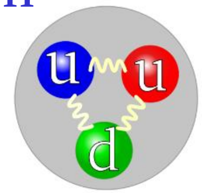




Meson



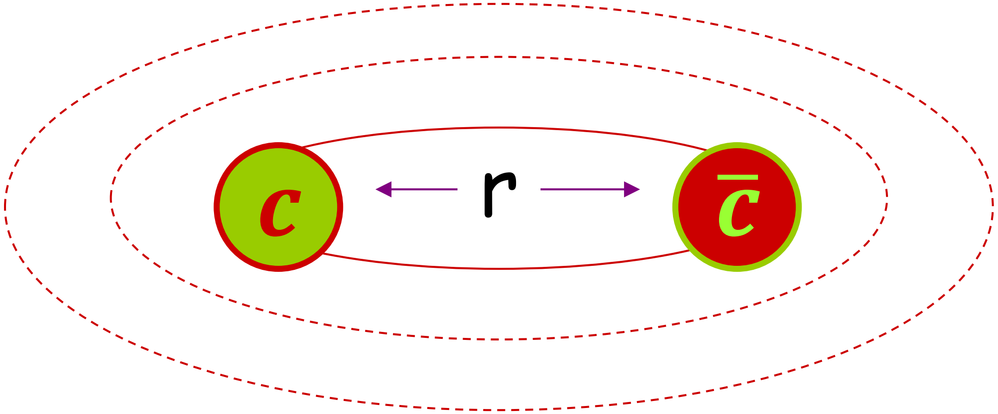
Baryon



Basics of the quarkonia

- Usually refer to charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) states

charm and bottom quarks are heavy: $m_c \sim 1.5$ GeV $\sim 1.6\, m_p$
$m_b \sim 4.5$ GeV $\sim 4.8\, m_p$

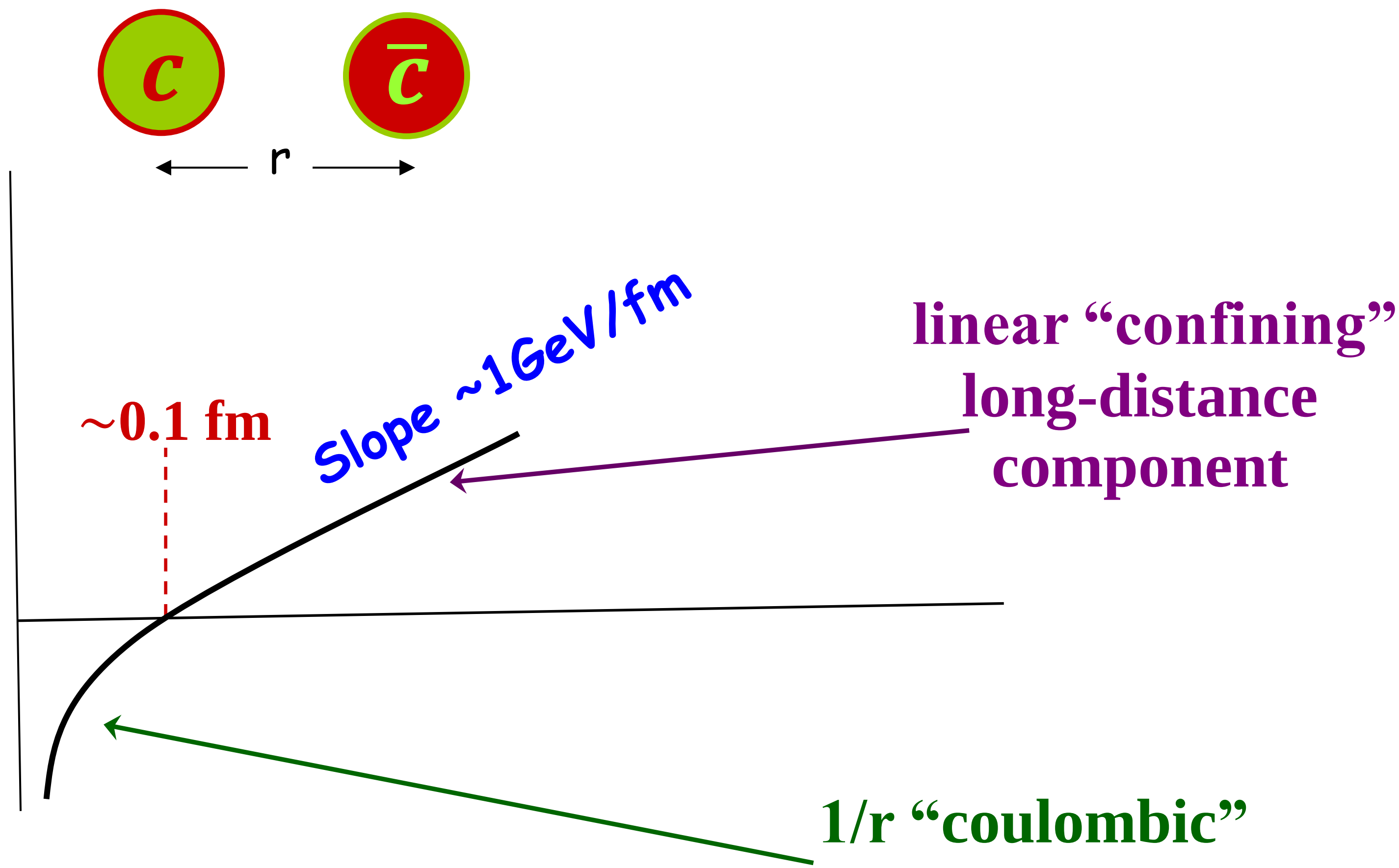


velocities are small: v/c ~ 0.25 for $c\bar{c}$ (~ 0.1 for $b\bar{b}$)
Nonrelativistic Quantum Mechanics is valid

$$-\frac{\hbar^2}{2m_r}\nabla^2\Psi + V(r)\Psi = E\Psi$$

What about V(r)?

Positronium with a twist!



PRD 17, 3090 (1978);
21, 313(E) (1980)

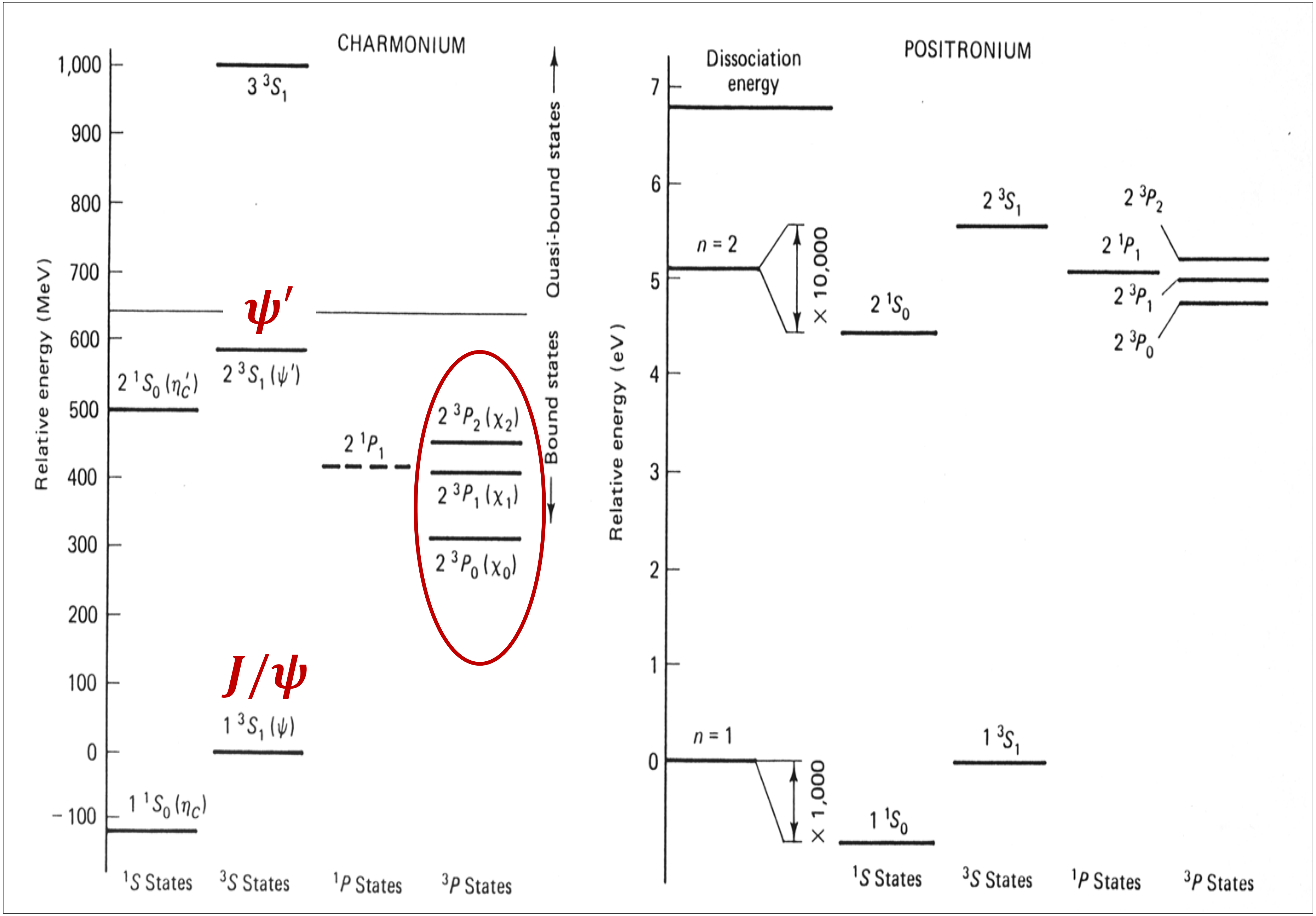
Cornell potential

Two parameters:
slope and intercept

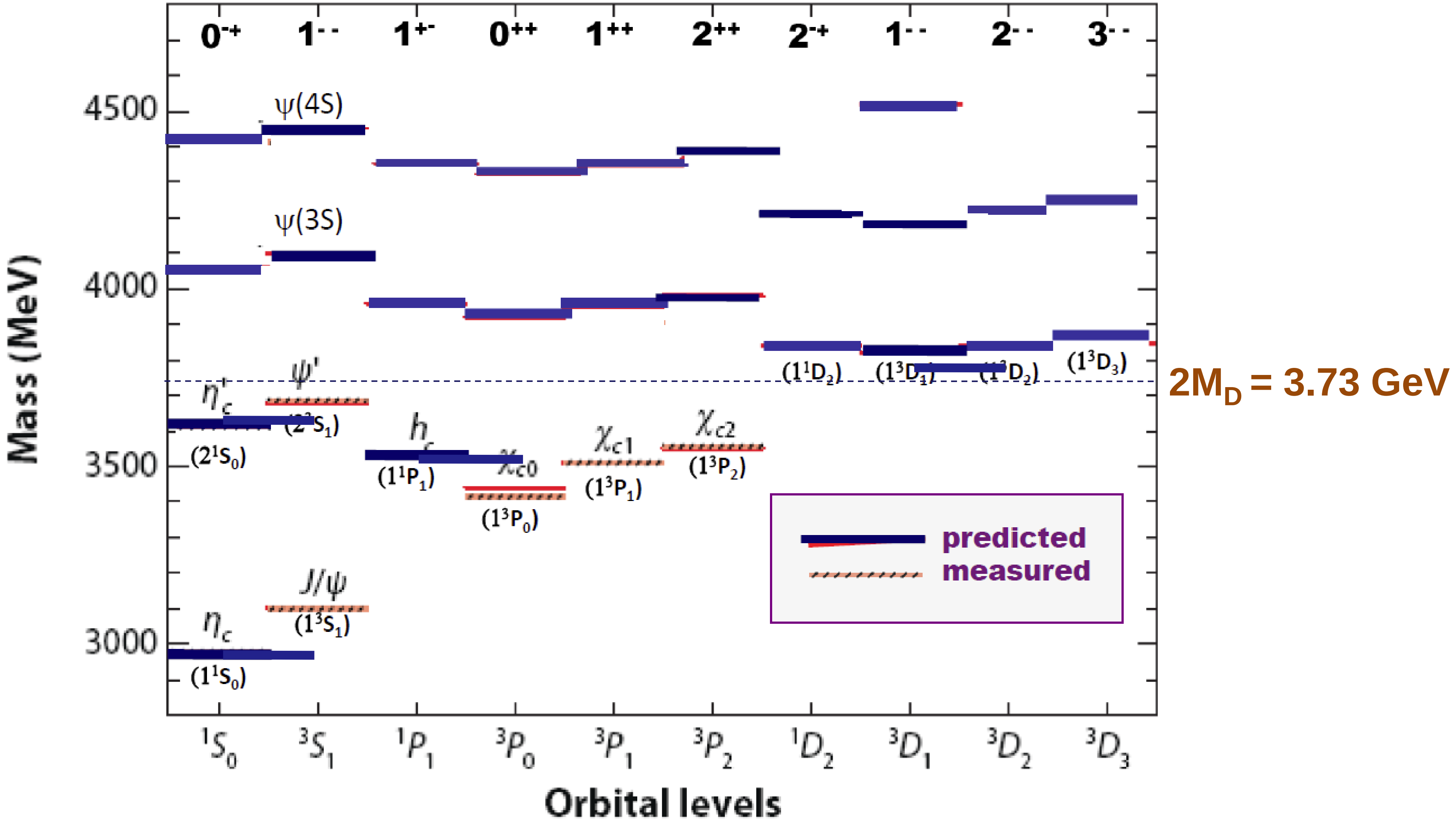
- Same V(r) works both for charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$)

Side-by-side comparison

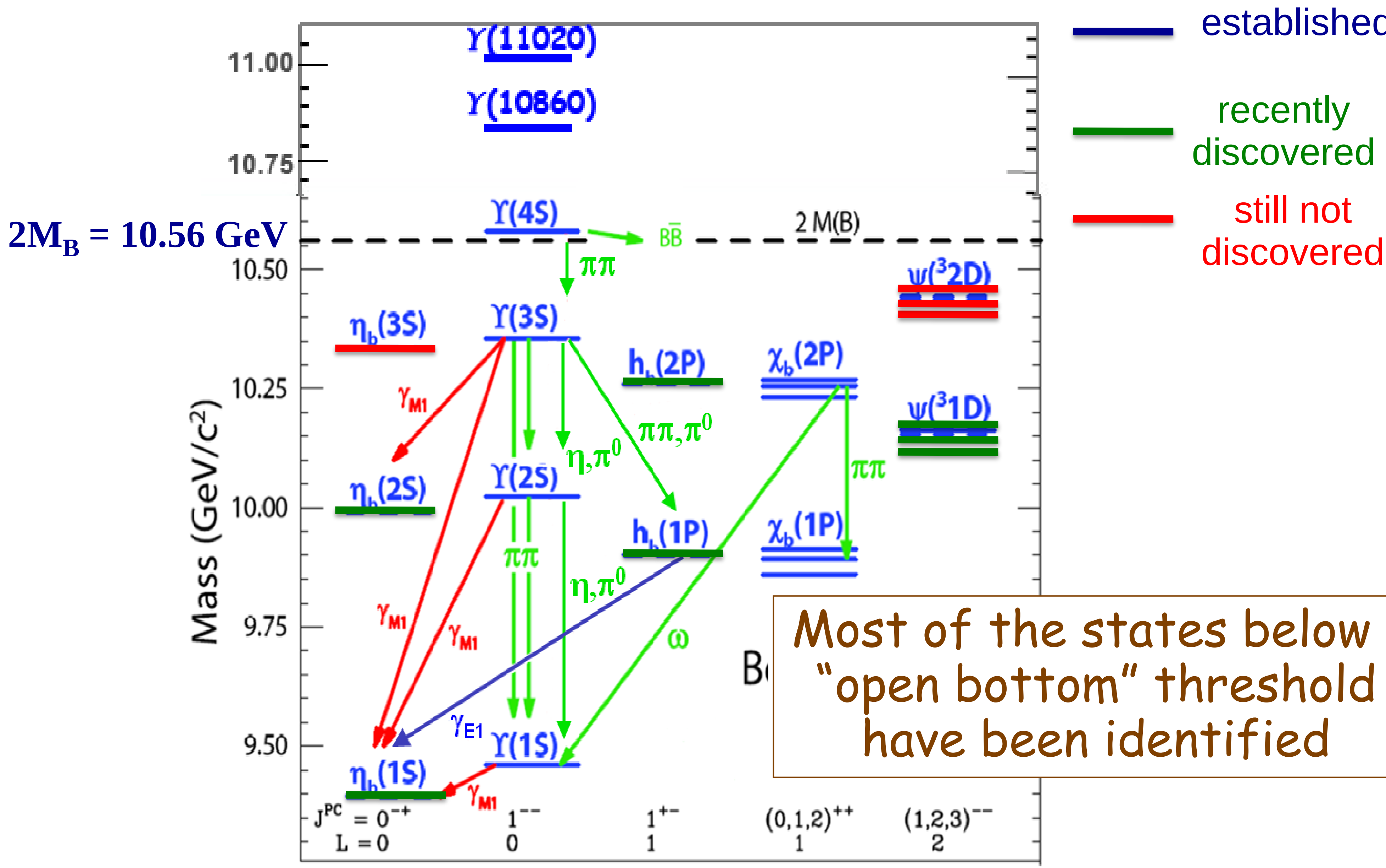
Charmonium ($c\bar{c}$) **Positronium (e^+e^-)**



All states below the “open charm” threshold are identified



Bottomonium spectra circa 2014



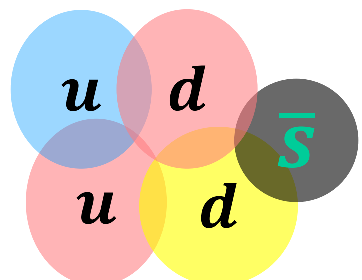
Most of the states below "open bottom" threshold have been identified

What about other varieties?

No *a priori* reason for mesons to exist only in $q\bar{q}$ configurations, or baryons to occur with only qqq structures

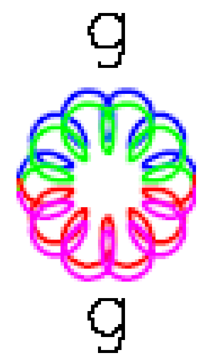
Pentaquark:

e.g. an S=+1 baryon

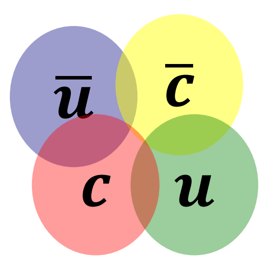


Glueball:

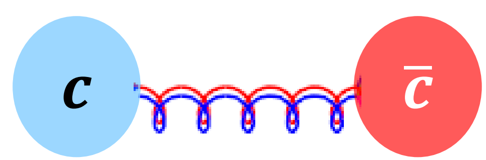
bundling gluons into a color singlet state



Tetraquark state:

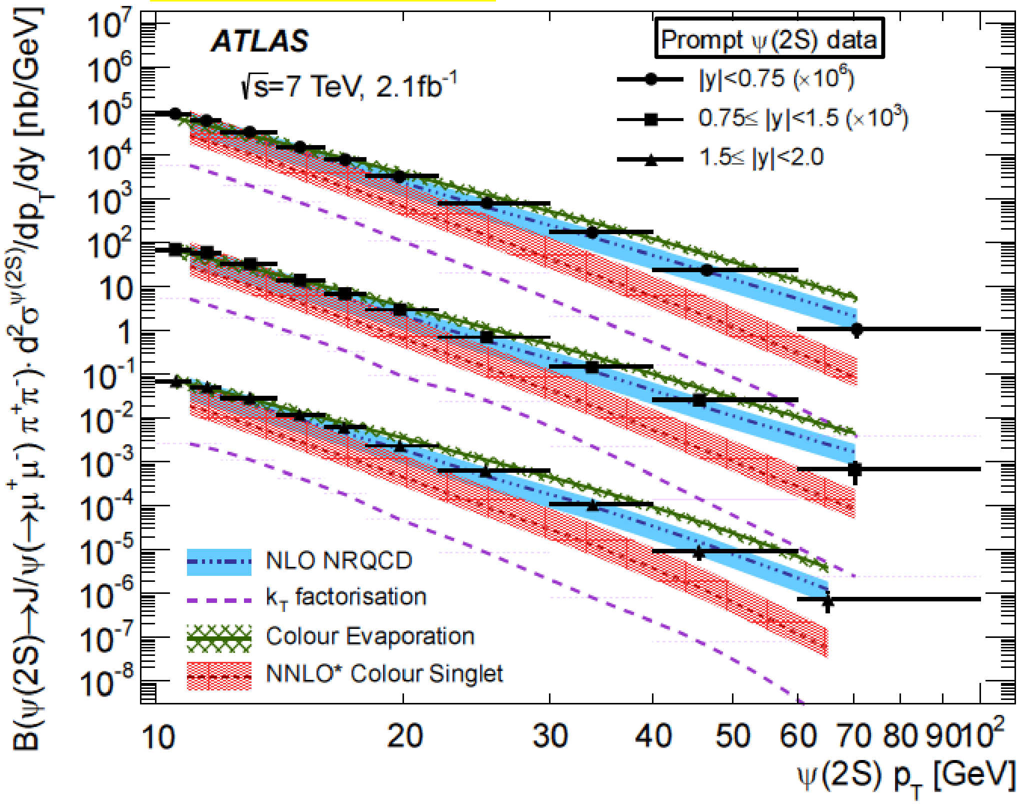


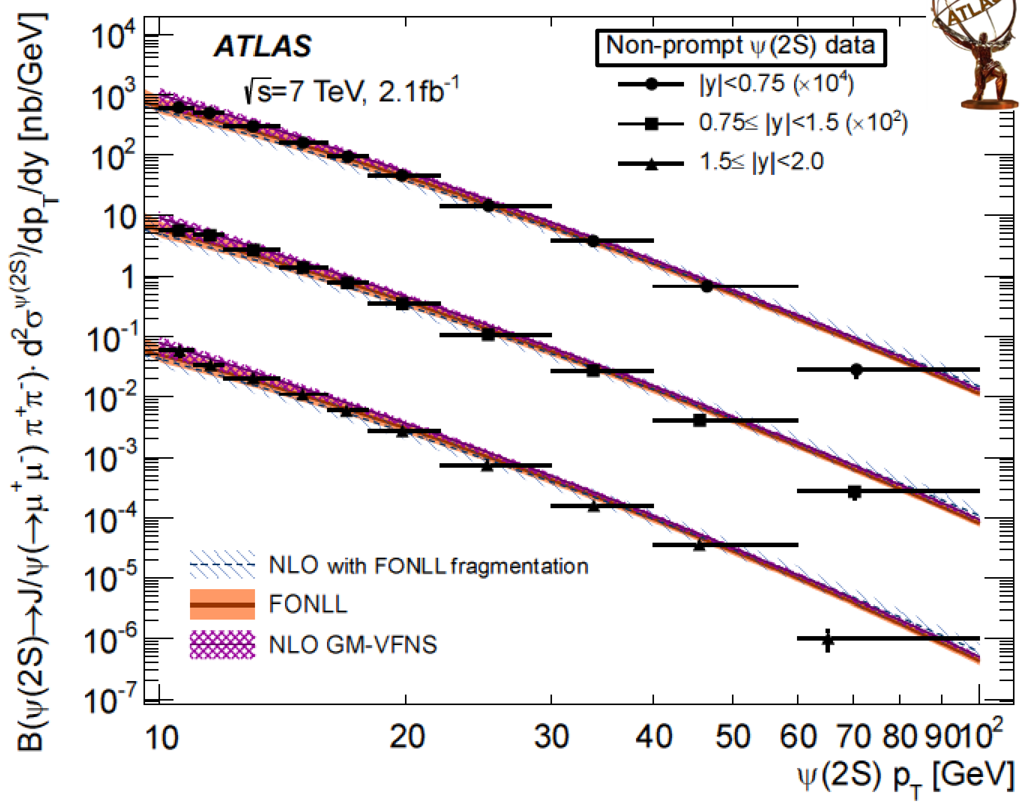
$q\bar{q}$-gluon hybrid meson:



Production of $\psi(2S) \to J/\psi\pi^+\pi^-$ in pp collisions

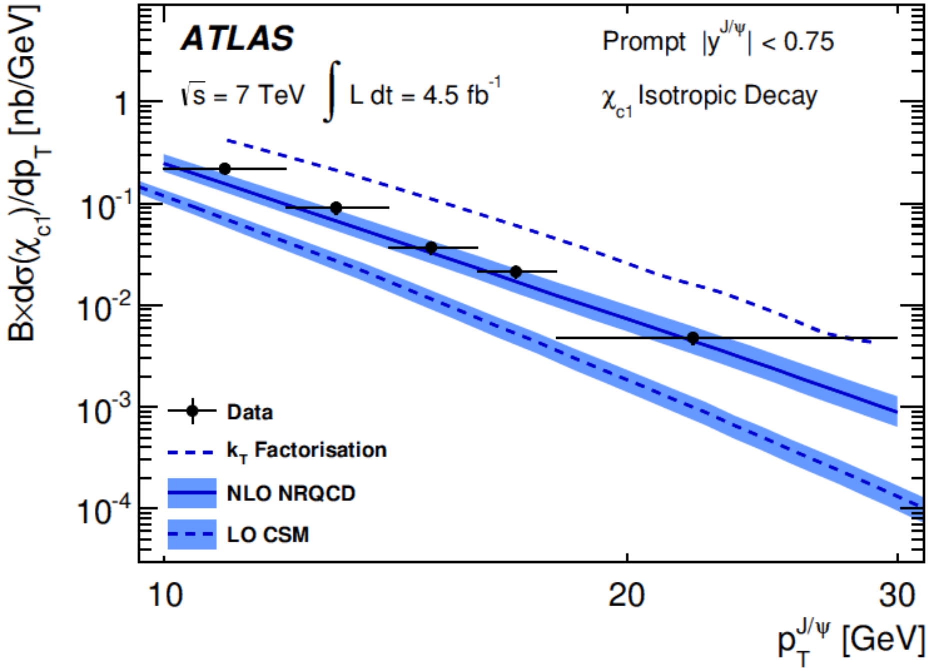
arXiv:1407.5532

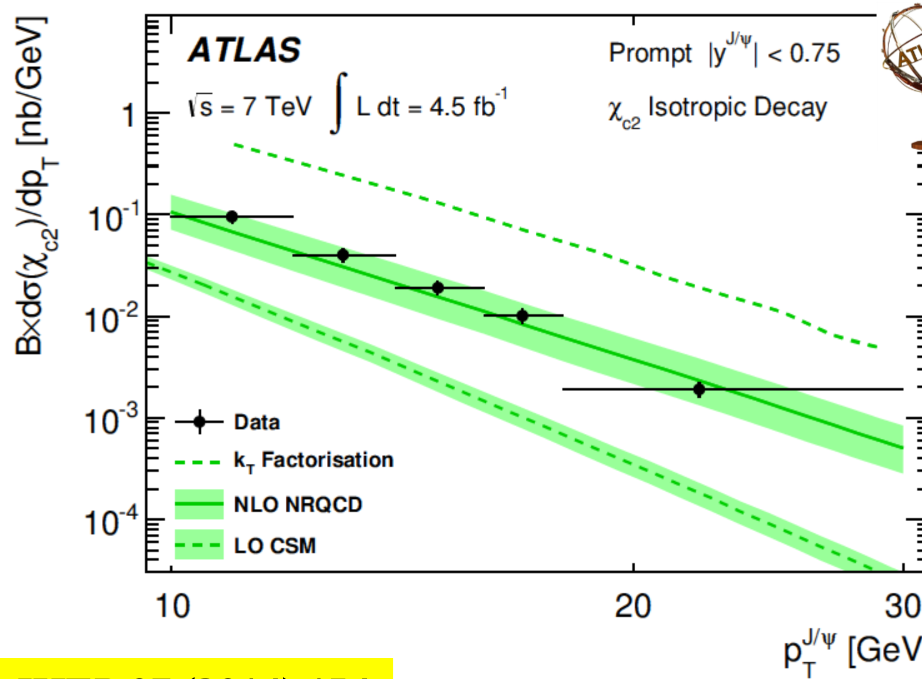


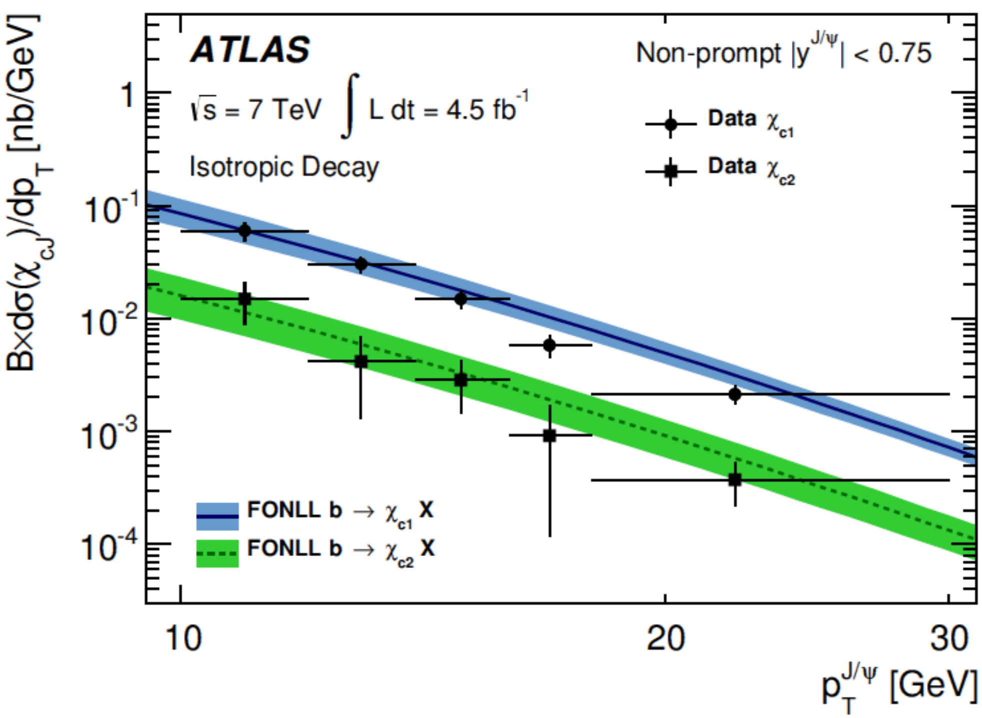


- For the prompt $\psi(2S)$ production, NLO NRQCD predictions describe the data satisfactorily while the colour evaporation model is not that good at highest p_T regions and NNLO* colour-singlet fails throughout ➡ fine-tuning required
- In the non-prompt case, NLO GM-VFNS and FONLL calculations do pretty good job although a peculiar tendency is observed for the theory to predict a slightly harder p_T spectrum than that in data

Productions of χ_{c1} and χ_{c2} in pp collisions





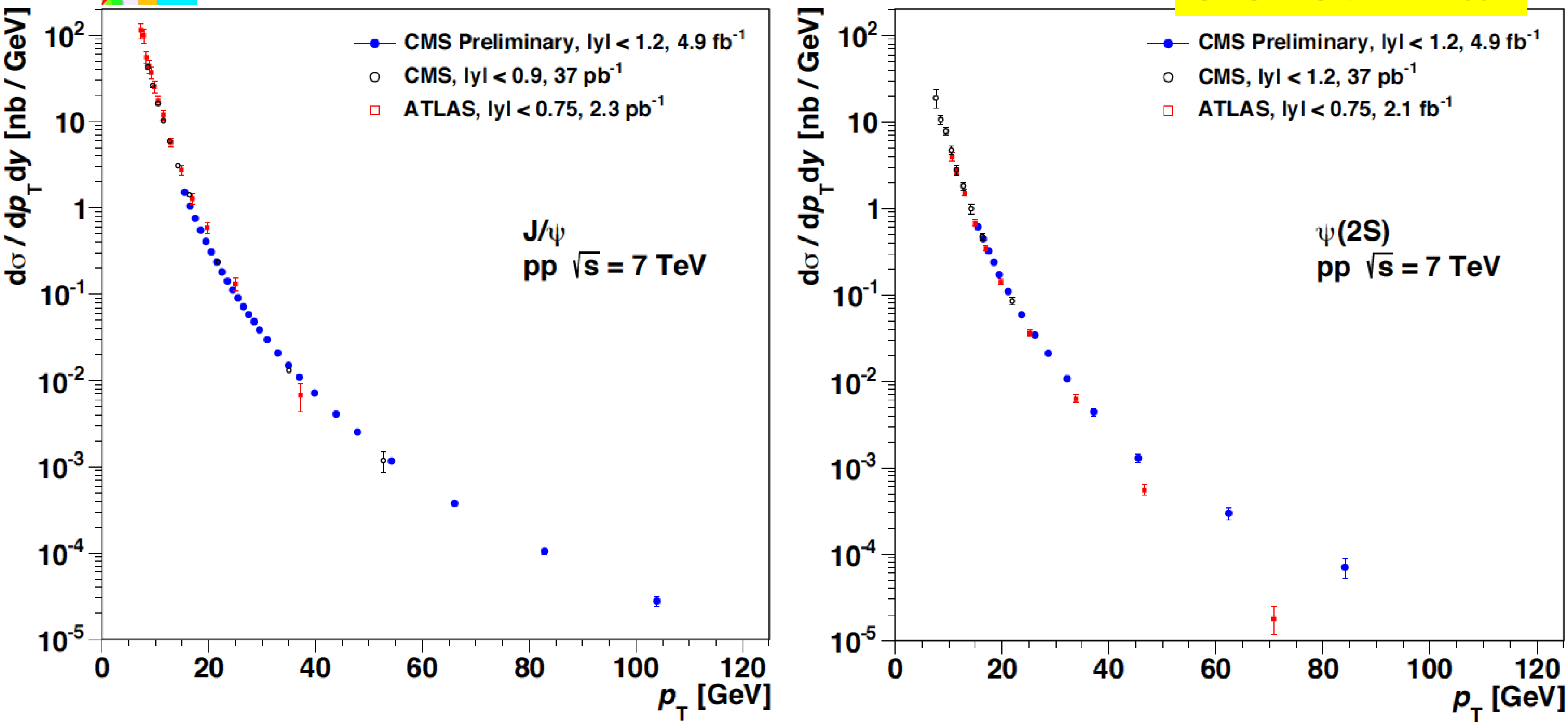


JHEP 07 (2014) 154

- NRQCD describes prompt χ_{c1} data rather well and the k_T factorisation (CSM) significantly overestimates (underestimates) the data
- Non-prompt χ_c productions generally agree with predictions based upon the FONLL approach

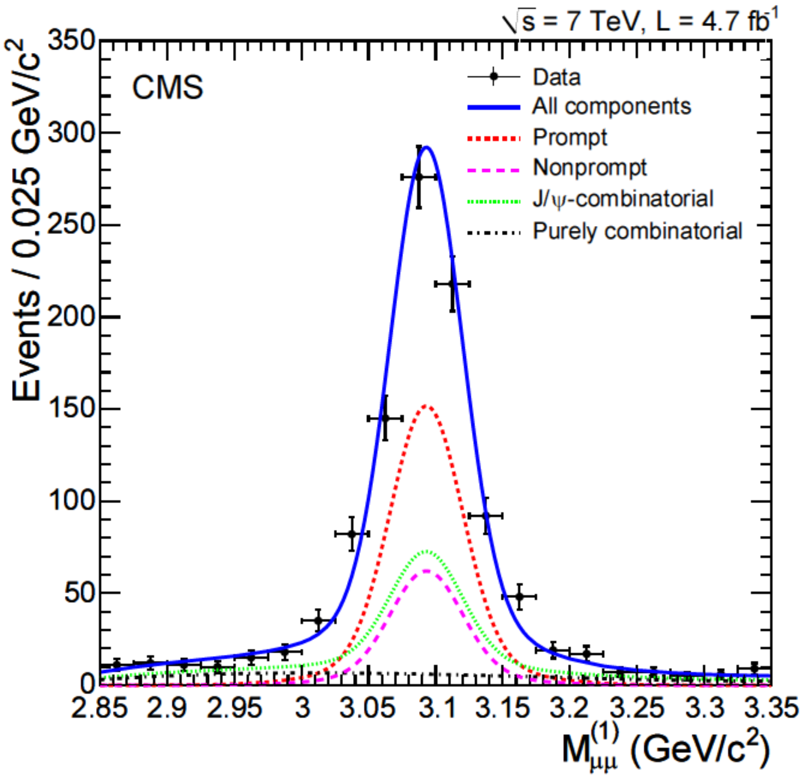
Double-differential cross sections of prompt J/ψ and $\psi(2S)$

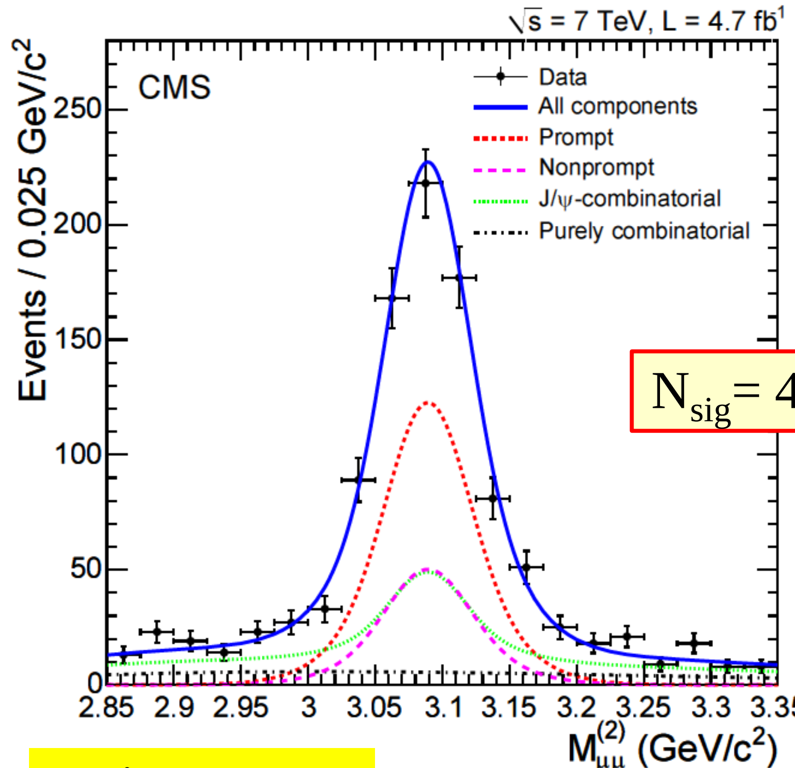
CMS PAS BPH-14-001



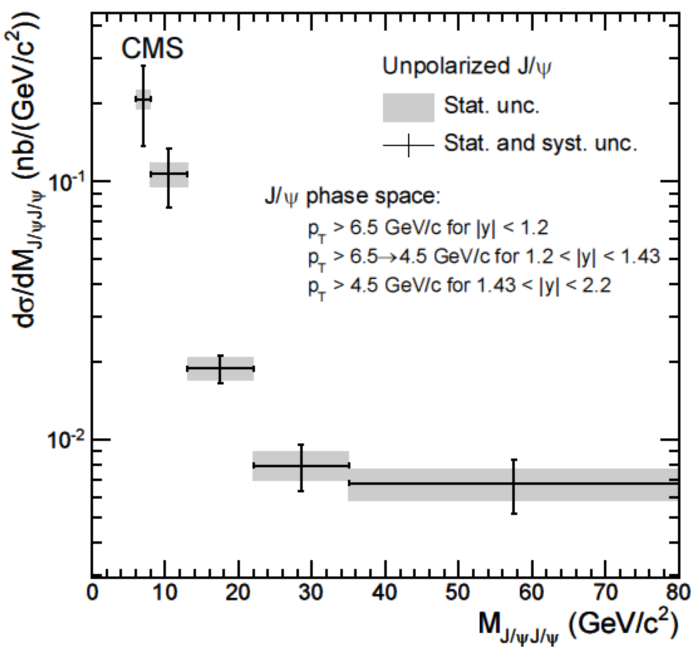
- Constitute a significant improvement over the previous results both in terms of accuracy and p_T reach ($\geq$ 100 GeV)
- Will contribute towards an improved understanding of quarkonium production in the scope of NRQCD or other theoretical approaches

Prompt J/ψ pair production in pp collisions





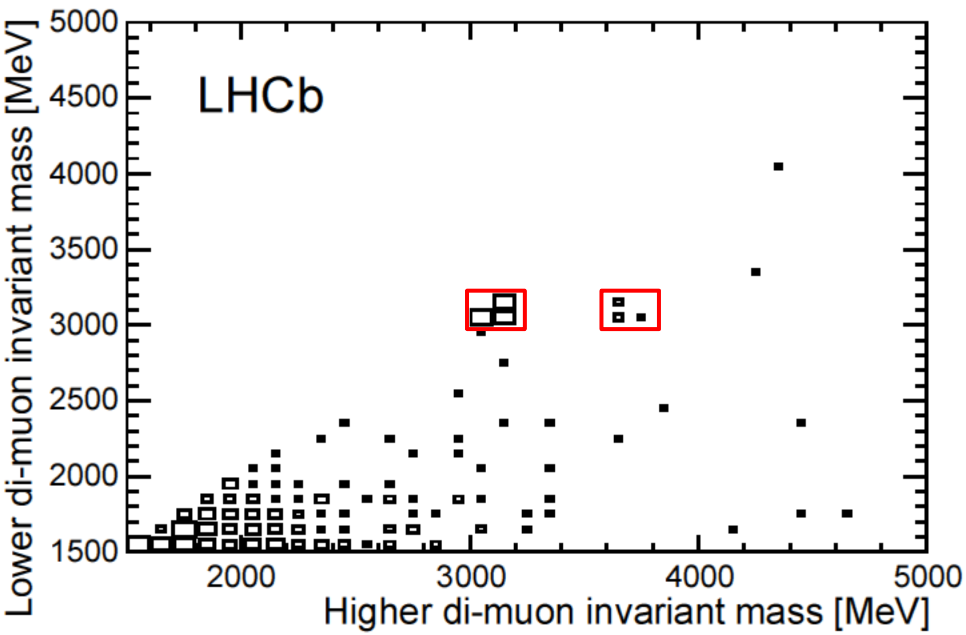
$N_{sig} = 446 \pm 23$

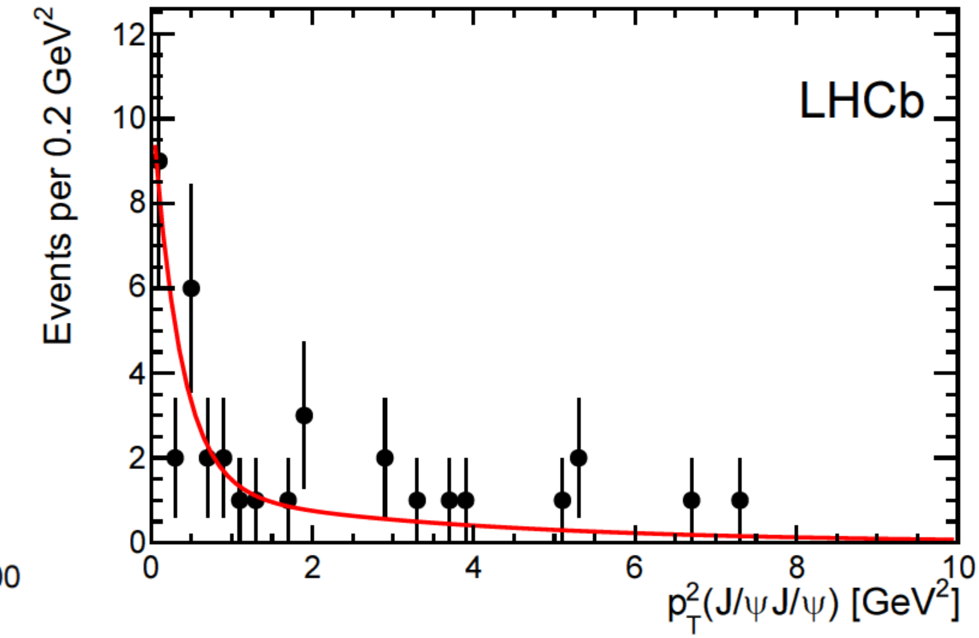


arXiv:1406.0484

- The cross section of prompt J/ψ pair production is measured to be [1.49 ± 0.07(stat.) ± 0.13(syst.)] nb
- Probes J/ψ pair production at higher J/ψ p_T and more central rapidity than the LHCb measurement **PLB 707 (2012) 52**
- No evidence for the η_b state in the J/ψ pair invariant-mass distribution

Observation of exclusive charmonium pairs



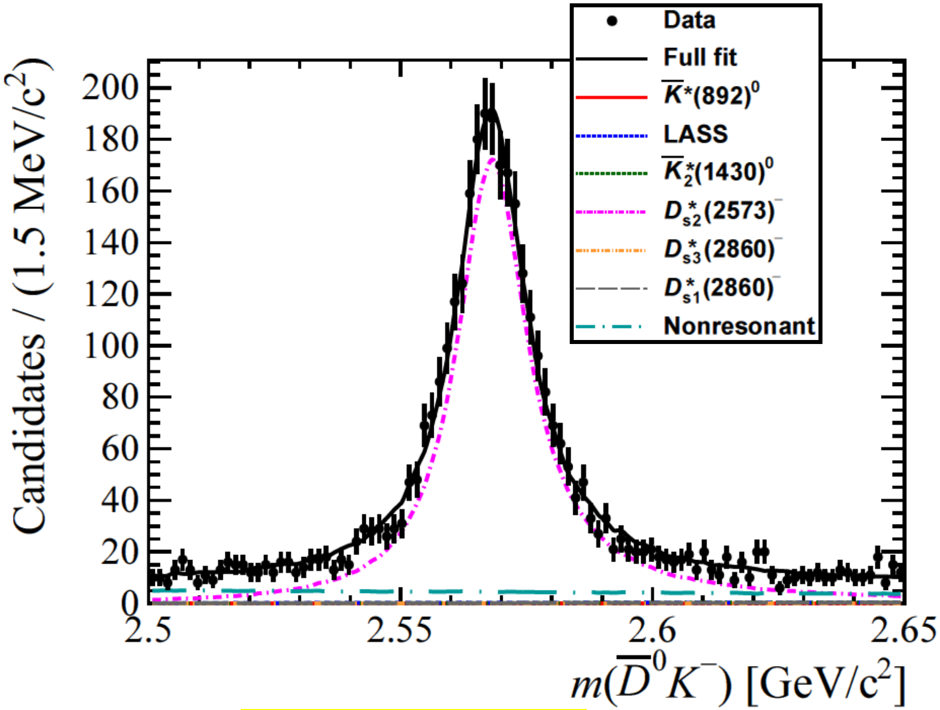


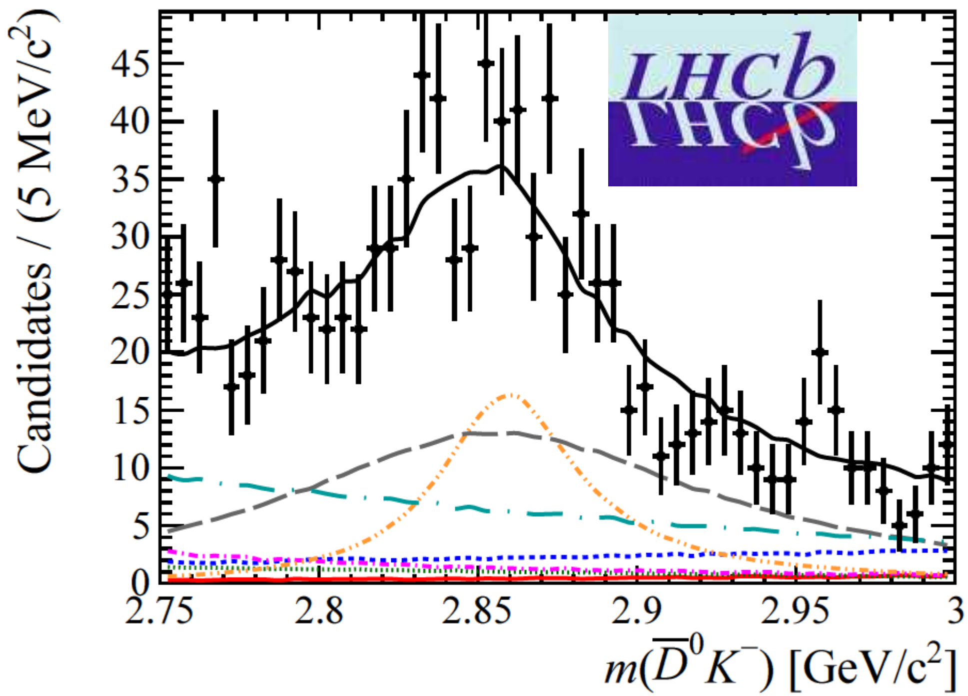
arXiv:1407.5973

$$
\begin{aligned}
\sigma^{J/\psi\, J/\psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{syst})\,\text{pb},\\
\sigma^{J/\psi\, \psi(2S)} &= 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\,\text{pb},\\
\sigma^{\psi(2S)\psi(2S)} &< 237\,\text{pb},\\
\sigma^{\chi_{c0}\chi_{c0}} &< 69\,\text{nb},\\
\sigma^{\chi_{c1}\chi_{c1}} &< 45\,\text{pb},\\
\sigma^{\chi_{c2}\chi_{c2}} &< 141\,\text{pb},
\end{aligned}
$$

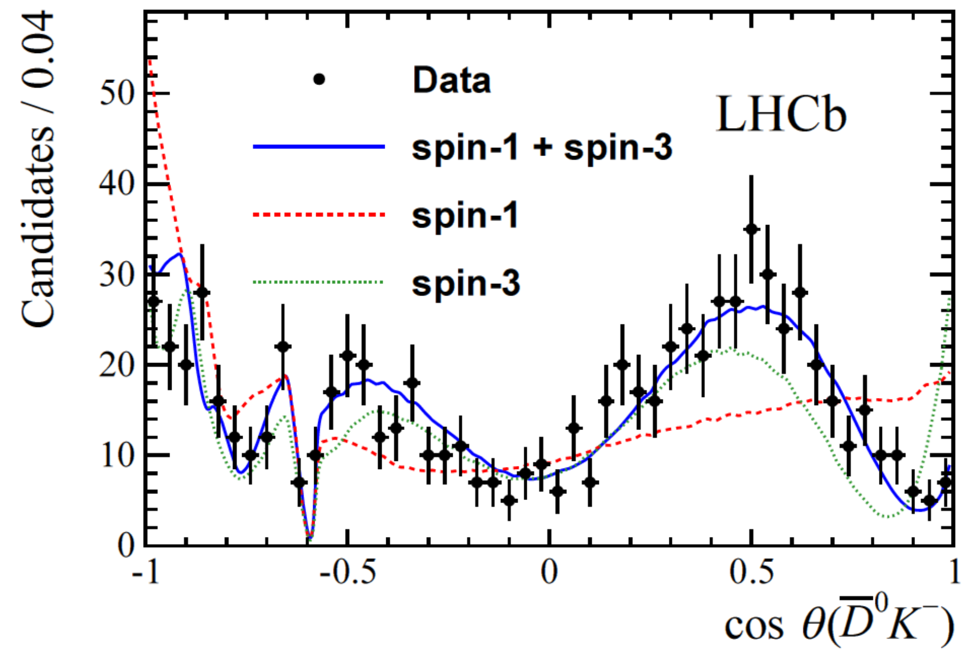
- First observation of the central exclusive production of pairs of charmonia
- Measurements of individual cross section of $J/\psi J/\psi$ and $J/\psi\psi(2S)$ and their ratio are in agreement with preliminary theory predictions
- No signal for the production of pairs of P-wave charmonia

Resonant substructures in $B_s^0 \to \overline{D}^0 K^- \pi^+$





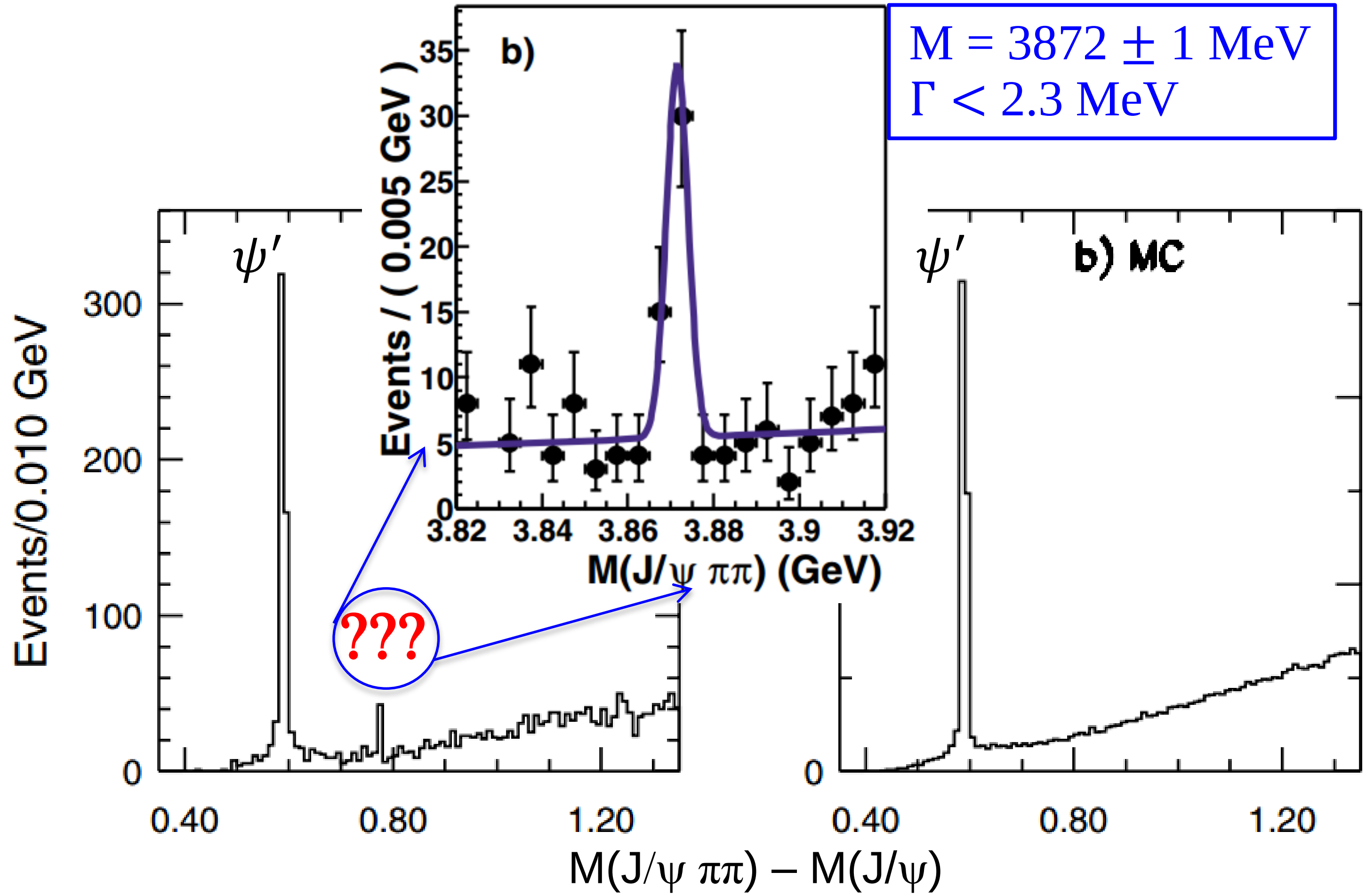
arXiv:1407.7574



- Precise measurement of $D_{s2}^{\star}(2573)^-$ mass and width
- An excess of events near 2.86 GeV is found in m($\overline{D}^0 K^-$) spectrum
- To describe the data well, we need an admixture of spin-1 and spin-3 states
- This is the first observation of a heavy flavoured spin-3 resonance

X(3872): Belle observed in $B \to (J/\psi\pi^+\pi^-)K$

Steve with a big fish!

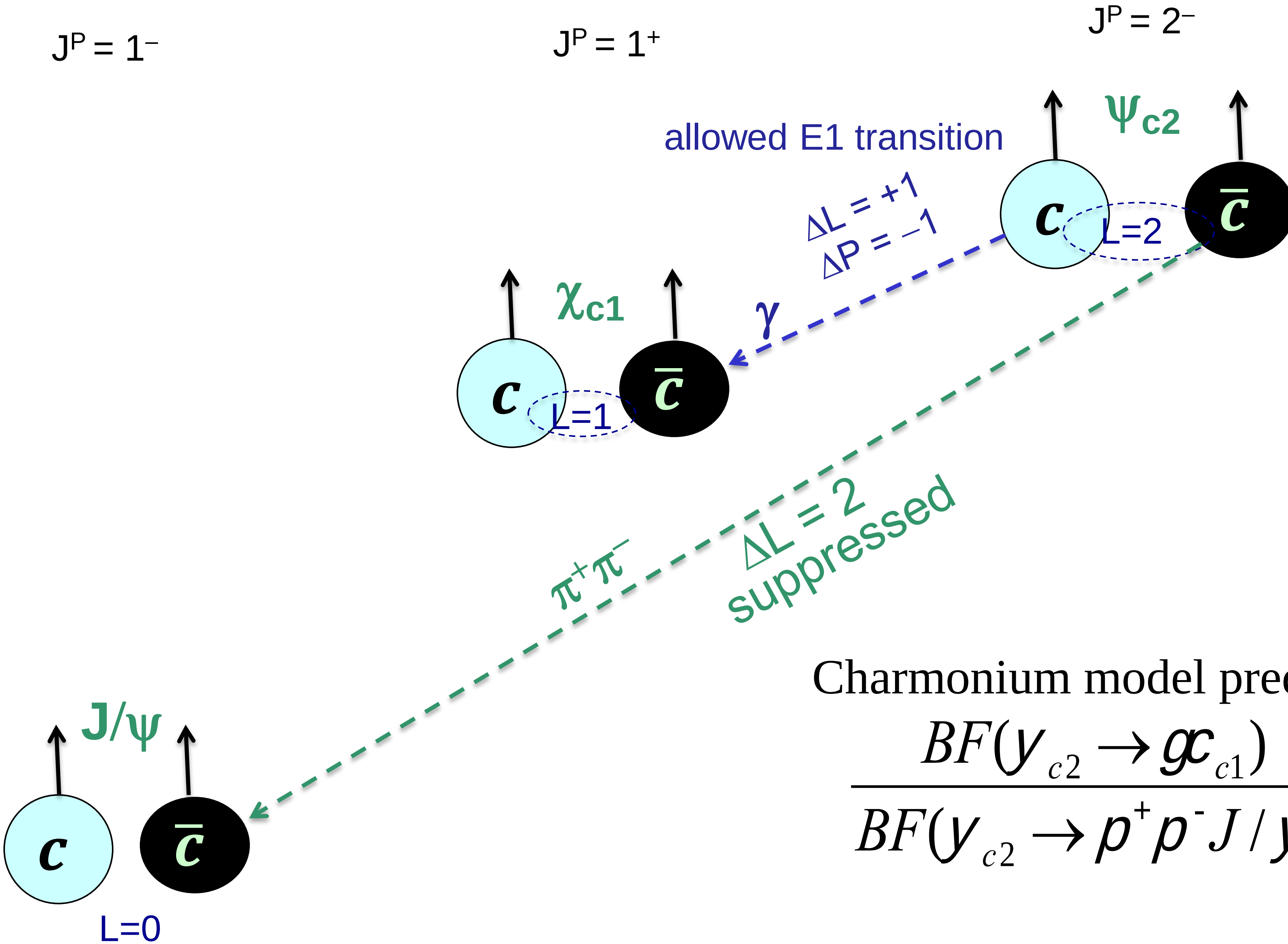


PRL 91 (2003) 262001

Confirmed by many other experiments:

- in exclusive B decays by BABAR and LHCb
- in high-energy $p\bar{p}$ (CDF and D0) and pp collisions (CMS, LHCb)

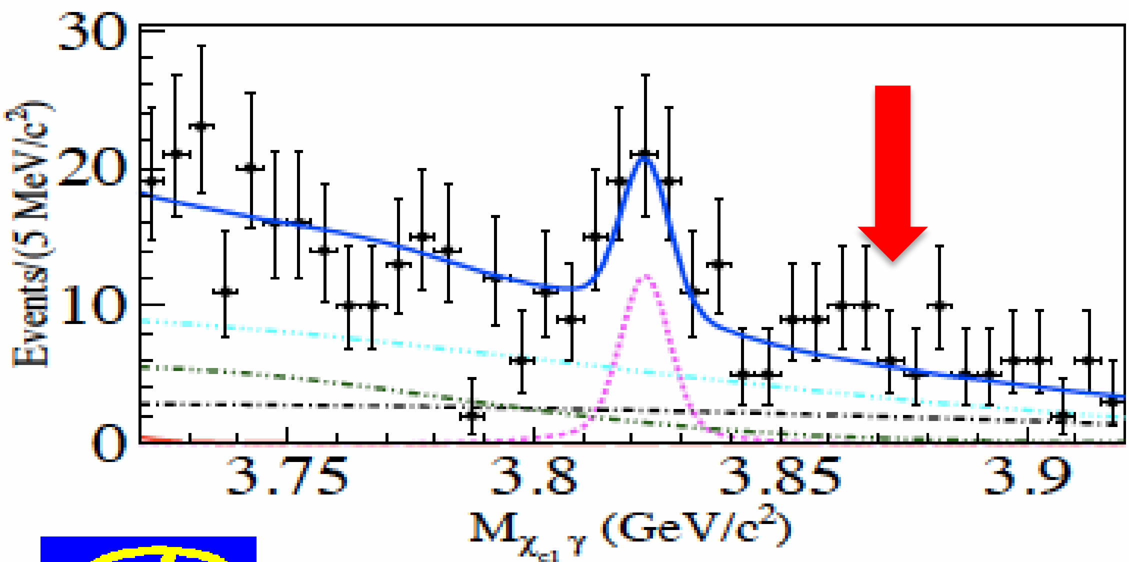
Is it the conventional ψ_{c2}?



Charmonium model prediction:

$$\frac{BF(\psi_{c2} \to \gamma\chi_{c1})}{BF(\psi_{c2} \to \pi^+\pi^- J/\psi)} > 5$$

Does the X(3872) decay to $\gamma\chi_{c1}$?

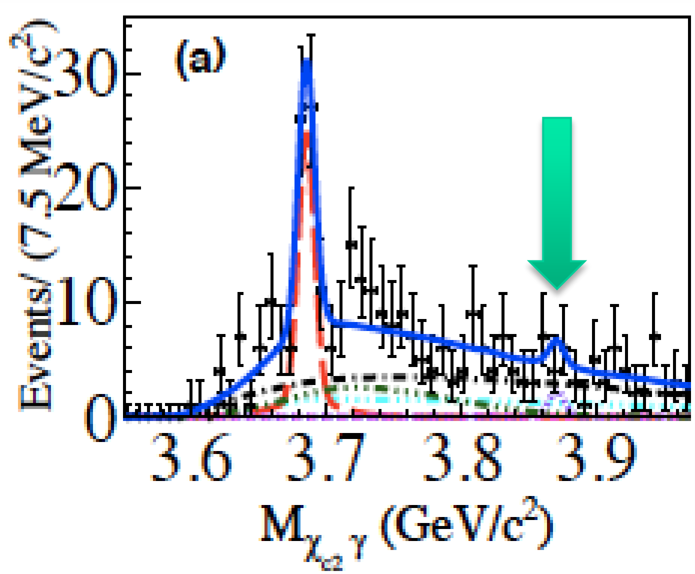


$B \to KX(3872) \to \gamma\chi_{c1}$?

(The peak near 3823 MeV/c² is the conventional triplet D-wave charmonium state, ψ_2)

No X(3872) signal

$B \to K\psi' \to \gamma\chi_{c2}$

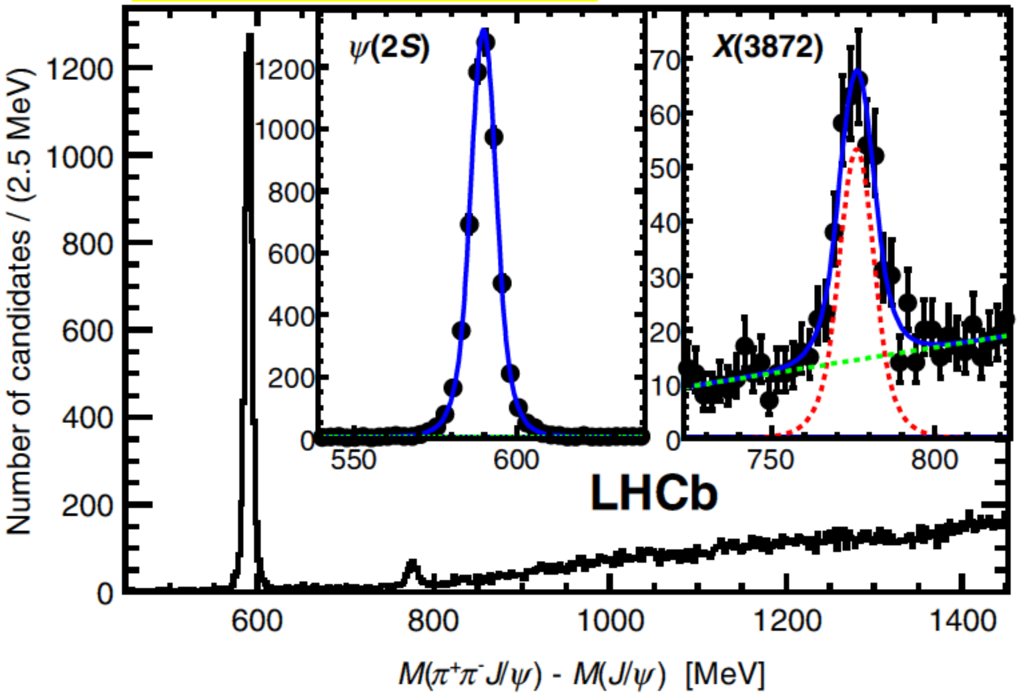


$$\frac{BF(\psi_{c2} \to \gamma\chi_{c1})}{BF(\psi_{c2} \to \pi^+\pi^- J/\psi)} < 0.25$$

PRL 111 (2013) 032001

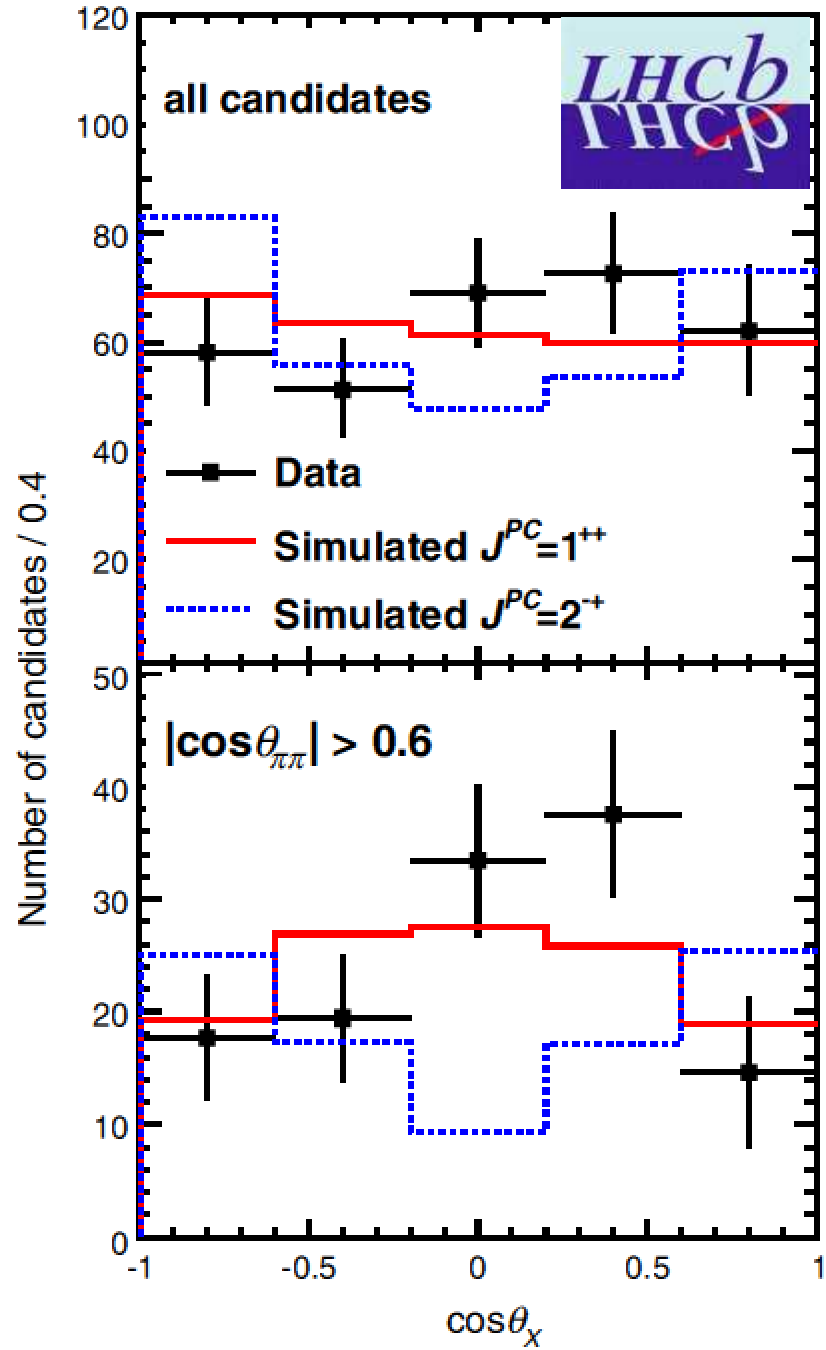
J^{PC} of the X(3872)

PRL 110 (2013) 222001

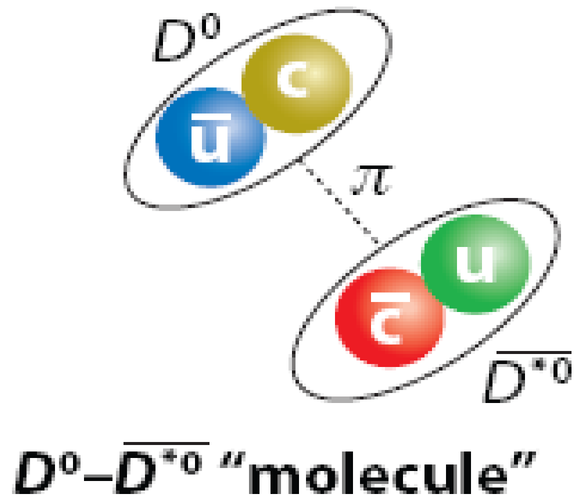


- Multidimensional angular analysis involving $\cos\theta_X$, $\cos\theta_{\pi\pi}$, $\Delta\phi_{X,\pi\pi}$, $\cos\theta_{J/\psi}$ and $\Delta\phi_{X,J/\psi}$
- Data favour the 1^{++} over the 2^{-+} hypothesis for the X(3872) at $> 8\sigma$ significance

➢ Closes the door for conventional $c\bar{c}$ meon assignment



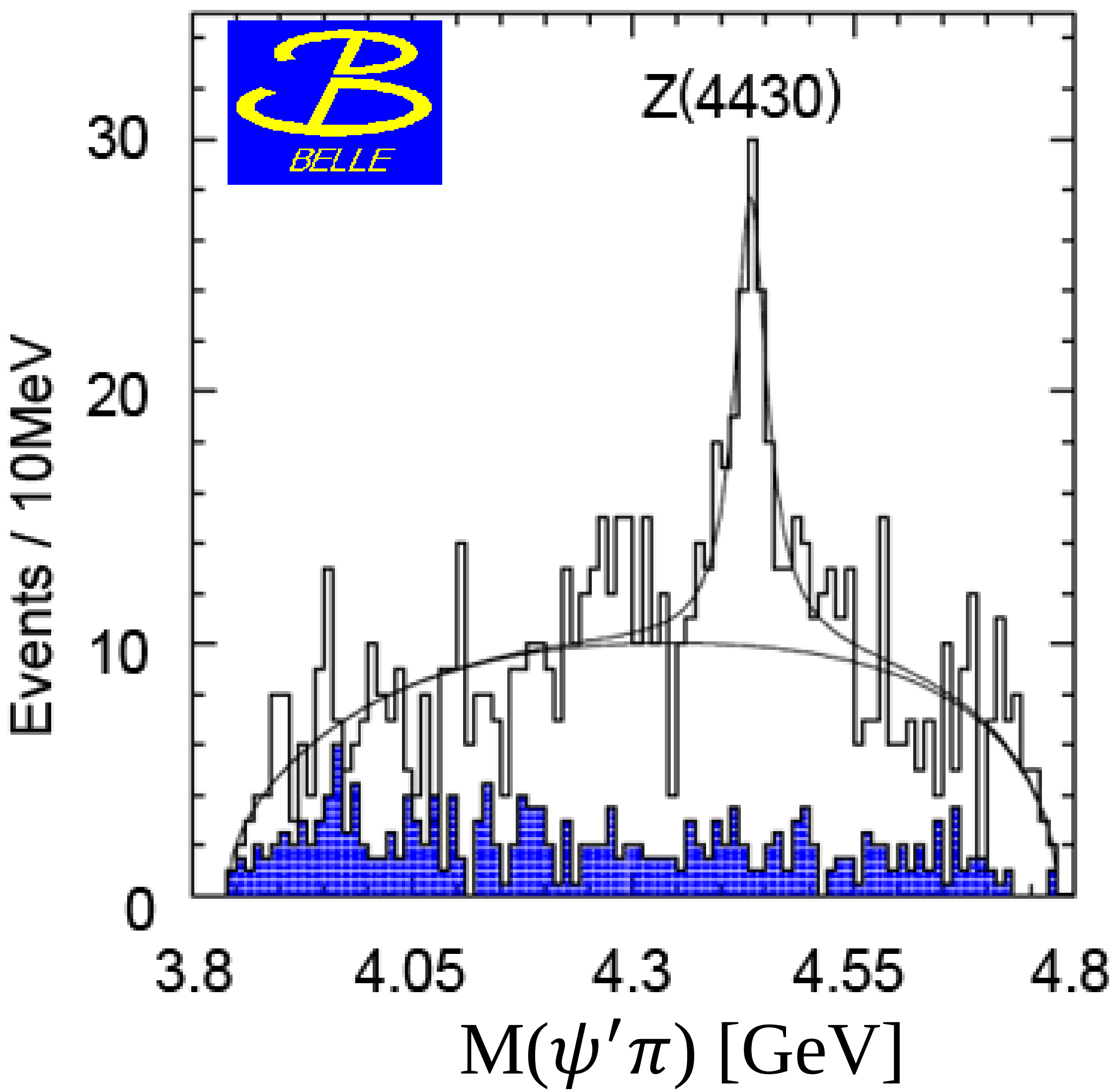
X(3872) looks like a $D^{\star 0}\overline{D}^0$ molecule



Predicted by N.A. Törnqvist: Z Phys C **61,** 525 (1994)

Caveat: It is still possible that "either/or" is not the correct hypothesis. The X(3872) could be a linear combination of a molecule and a charmonium state, in which the molecular component is dominant.

Observation of $Z^+(4430)$ in $B \to K\psi'\pi$ decays



PRL 100 (2008) 142001

$M = 4433 \pm 4(\text{stat}) \pm 2(\text{syst})$ MeV

$\Gamma = 45\,^{+18}_{-13}(\text{stat})\,^{+30}_{-13}(\text{syst})$ MeV

with a product branching fraction

$[4.1 \pm 1.0(\text{stat}) \pm 1.4(\text{syst})]\times 10^{-5}$

- The first candidate for an exotic, charged charmonium-like state

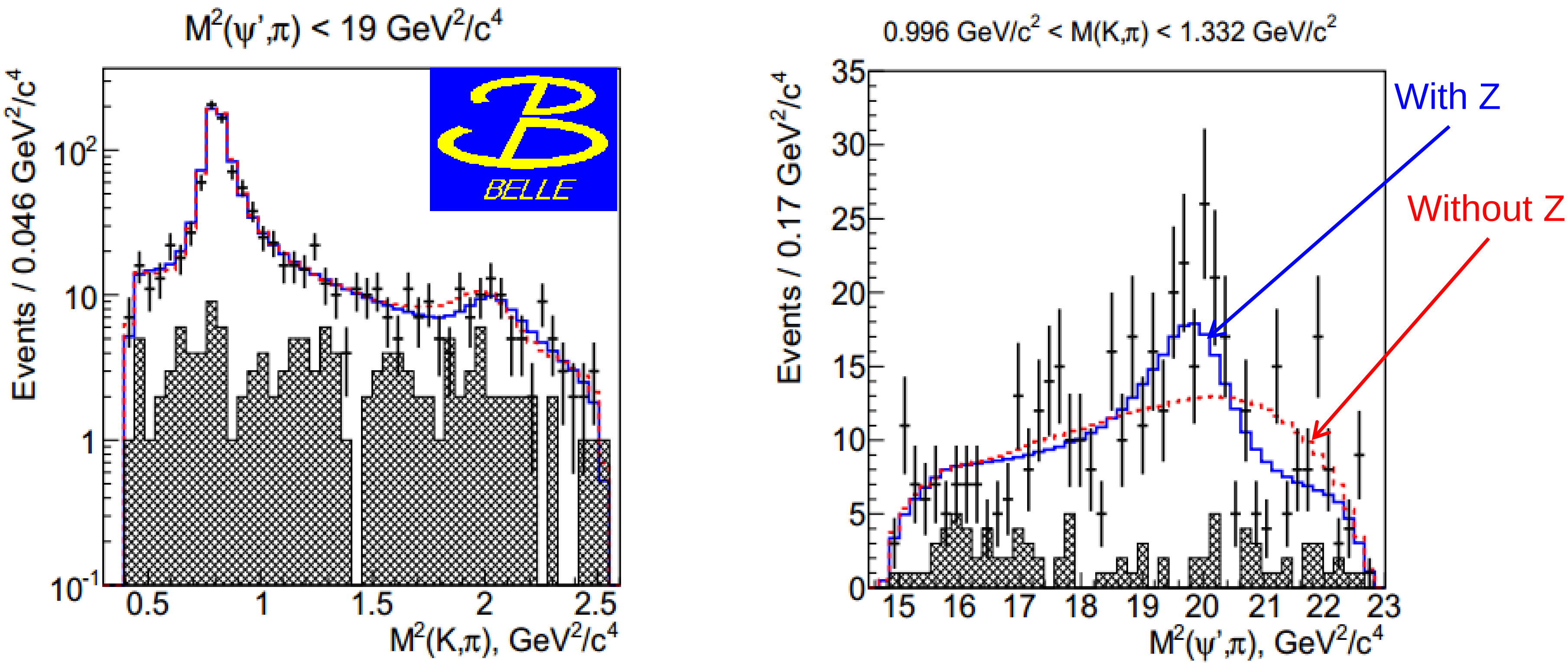
Veto $K^\star$ and $K^{\star\star}$ resonances in the study

- Important technical objection: Could higher $K^{\star\star}$ resonances & interference effects produce such structure?

BaBar was able to describe the structure purely in terms of reflections of higher $K^\star$ states although did not contradict the above observation

PRD 79 (2009) 112001

DP analysis with interference and K* resonances

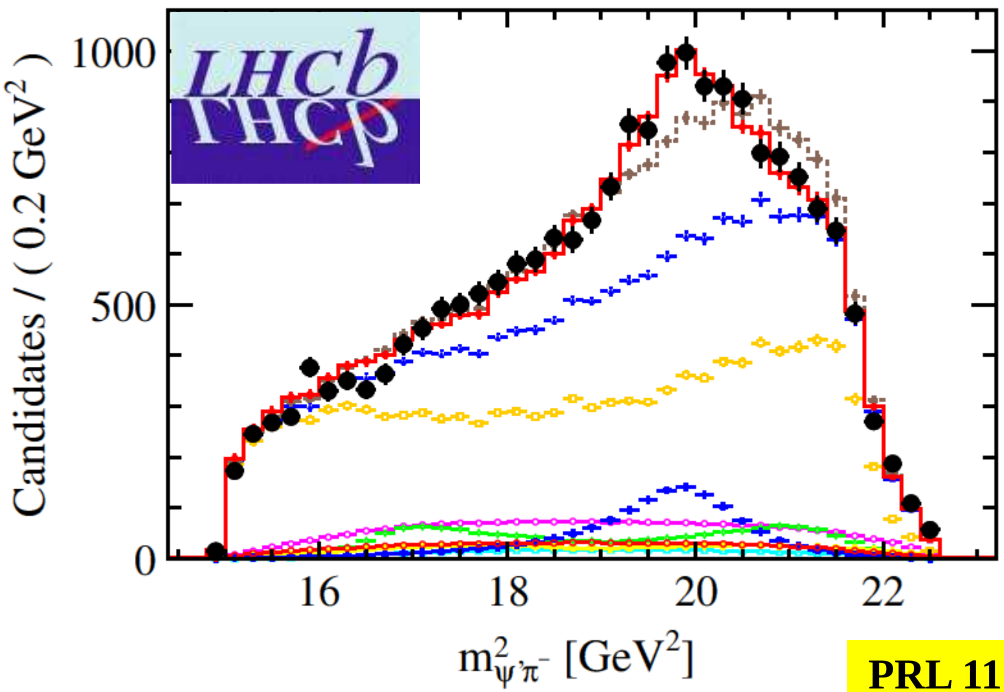


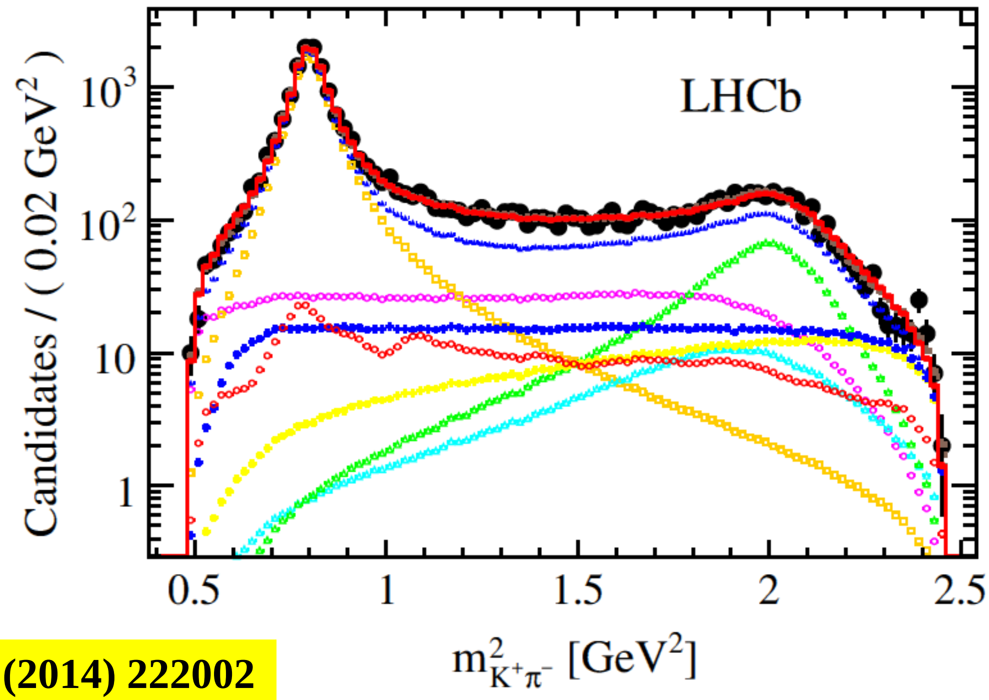
PRD 88 (2013) 074026

- Recent Dalitz plot analysis from Belle still finds a signal of 5σ significance
- A spin parity assignment of 1^+ is found to be preferred over 0^- at 2.9σ level while all other are ruled out with greater than 4.3σ significance

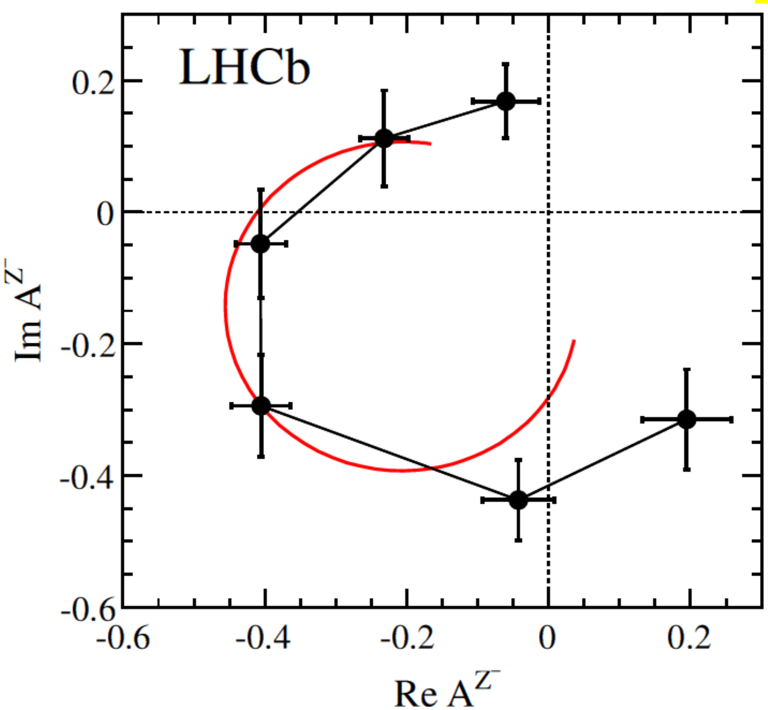
Any news from LHCb or other?

Observation of the resonant nature of Z(4430)





PRL 112 (2014) 222002



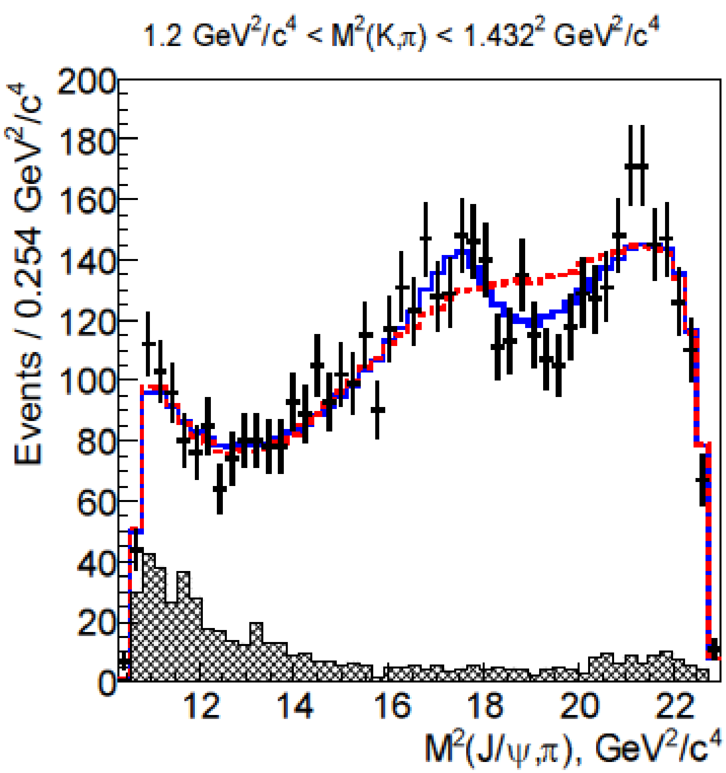
- ❑ 4D fit to the decay amplitude reveals that the data cannot be described with the (Kπ) resonances alone
- ❑ The same is corroborated by a model-independent approach

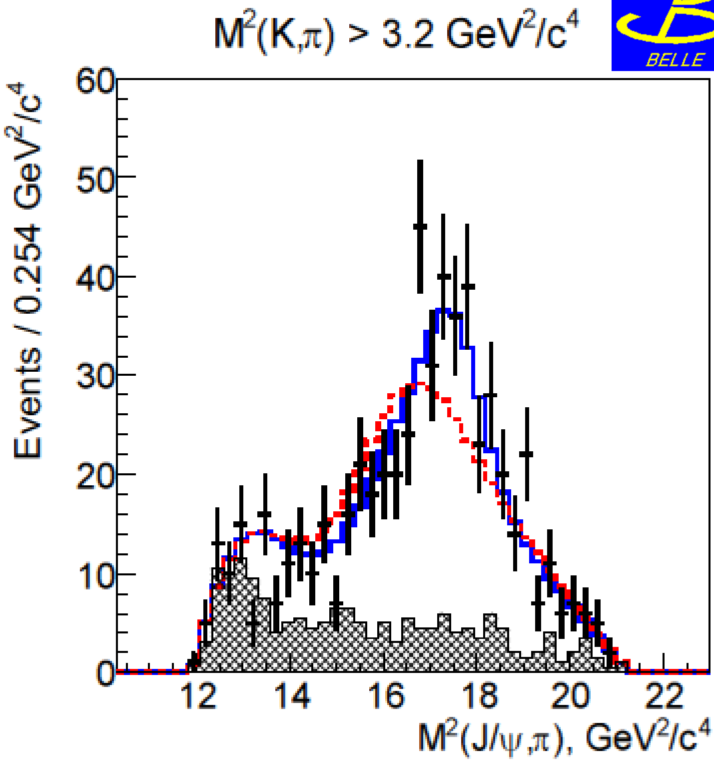
➢ A highly significant signal for the $Z^+(4430)$ resonance is obtained with an unambiguous determination J^P as 1^+

Amplitude analysis of $B \to J/\psi K\pi$

- Look for possible exotic, charmonium-like resonances in the $J/\psi\pi$ system

- 4D amplitude analysis comprising $(M^2_{K\pi}, M^2_{J/\psi\pi}, \cos\theta, \phi)$, where θ is the J/ψ helicity angle and ϕ is the angle between the two planes containing $J/\psi(\ell^+\ell^-)$ and $K\pi$ systems in the B rest frame
- Resonances: 10 $K^\star$ resonances and the $Z_c(4430)^+$state for the $J/\psi\pi$ system; additional Z_c^+ states are used for cross-check
- Tried out five spin-parity hypotheses: $0^-, 1^+, 1^-, 2^+, 2^-$ for the $Z_c^+(J^P = 0^+$ is forbidden due to parity conservation)





arXiv:1408.6457

- Blue solid lines are projections of the $J/\psi\pi$ invariant mass including a new Z_c^+ state along with the $Z_c(4430)^+$
- Red dashed lines are for the $Z_c(4430)^+$ only

Observation of a new state in $B \to J/\psi K\pi$

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4318 ± 48	4315 ± 40	4196^{+31}_{-29}	4209 ± 14	4203 ± 24
Width, MeV	720 ± 254	220 ± 80	370 ± 70	64 ± 18	121 ± 53
Significance (Wilks)	3.9σ	2.3σ	8.2σ	3.9σ	1.9σ

- A new Z_c^+ state [$Z_c(4200)^+$] with $J^P = 1^+$ is found with 6.2σ significance

$$M = 4196^{+31+17}_{-29-13}\ \mathrm{MeV}/c^2,\ \Gamma = 370^{+70+70}_{-70-132}\ \mathrm{MeV}$$

- Other J^P hypotheses are excluded: $0^-(6.1\sigma), 1^-(7.4\sigma), 2^-(4.4\sigma), 2^+(7.0\sigma)$
- Evidence for the $Z_c(4430)^+$ at the 4.0σ significance level

BELLE arXiv:1408.6457

$$\mathcal{B}(\bar{B}^0 \to J/\psi K^-\pi^+) = (1.15 \pm 0.01 \pm 0.05) \times 10^{-3}$$

$$\mathcal{B}(\bar{B}^0 \to J/\psi K^*(892)) = (1.19 \pm 0.01 \pm 0.08) \times 10^{-3}$$

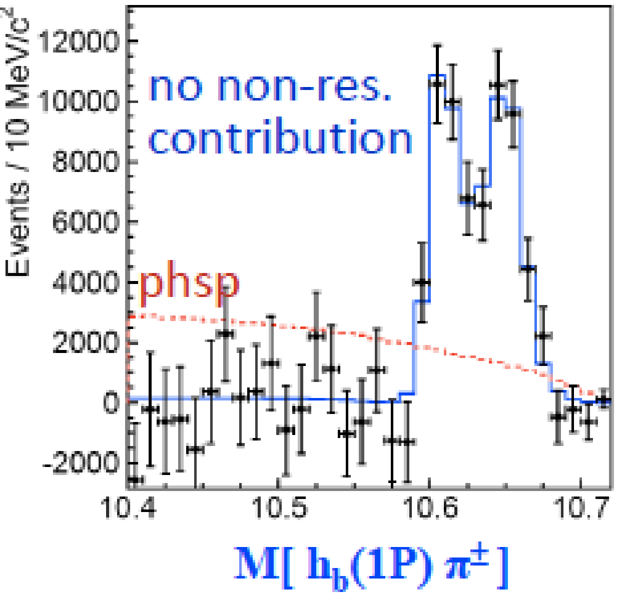
$$\mathcal{B}(\bar{B}^0 \to Z_c(4430)^+K^-) \times \mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+) = (5.4^{+4.0+1.1}_{-1.0-0.9}) \times 10^{-6}$$

$$\mathcal{B}(\bar{B}^0 \to Z_c(4200)^+K^-) \times \mathcal{B}(Z_c(4200)^+ \to J/\psi\pi^+) = (2.2^{+0.7+1.1}_{-0.5-0.6}) \times 10^{-5}$$

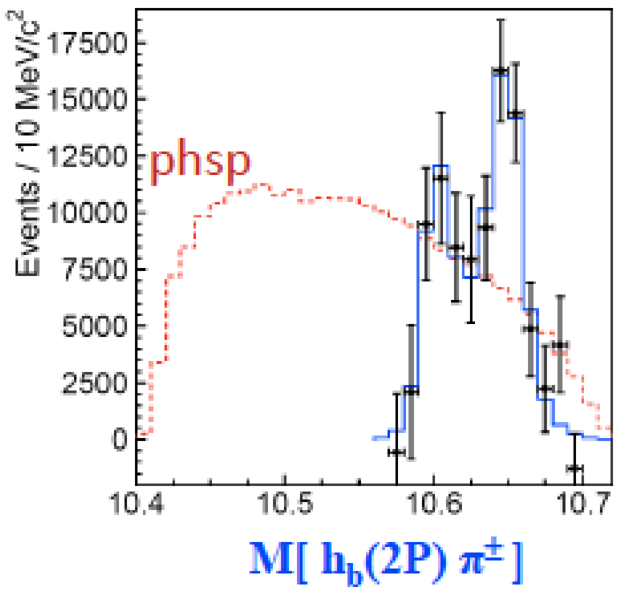
Resonant structure of $\Upsilon(5S) \to (b\bar{b})\,\pi^+\pi^-$

Belle PRL108,122001(2012)

$\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$



$\Upsilon(5S) \to h_b(2P)\pi^+\pi^-$



Two peaks in all 5 modes

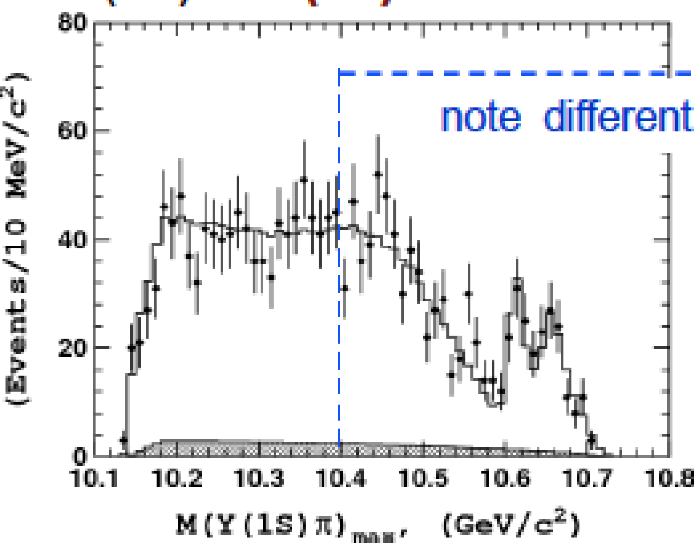
minimal quark content

$| b\bar{b}u\bar{d} \rangle$

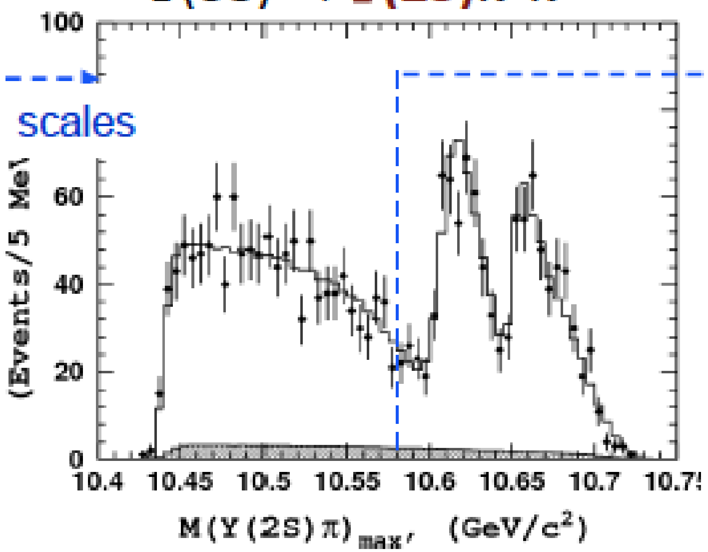
flavor-exotic states

Dalitz plot analysis

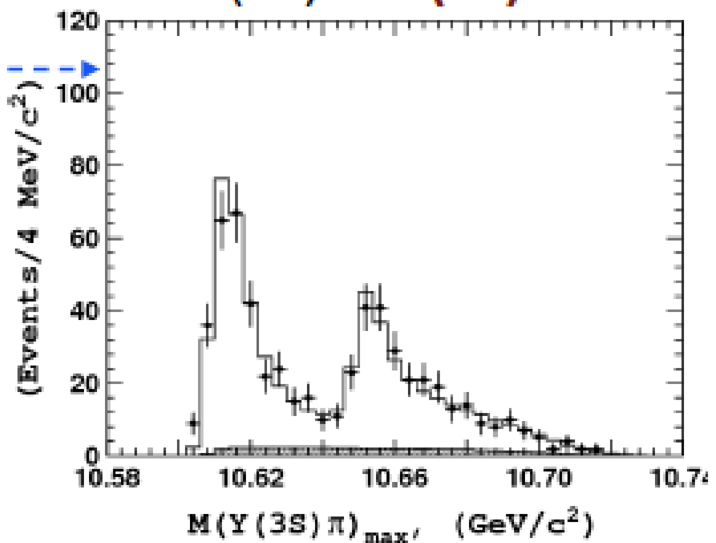
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$



$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$



$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$

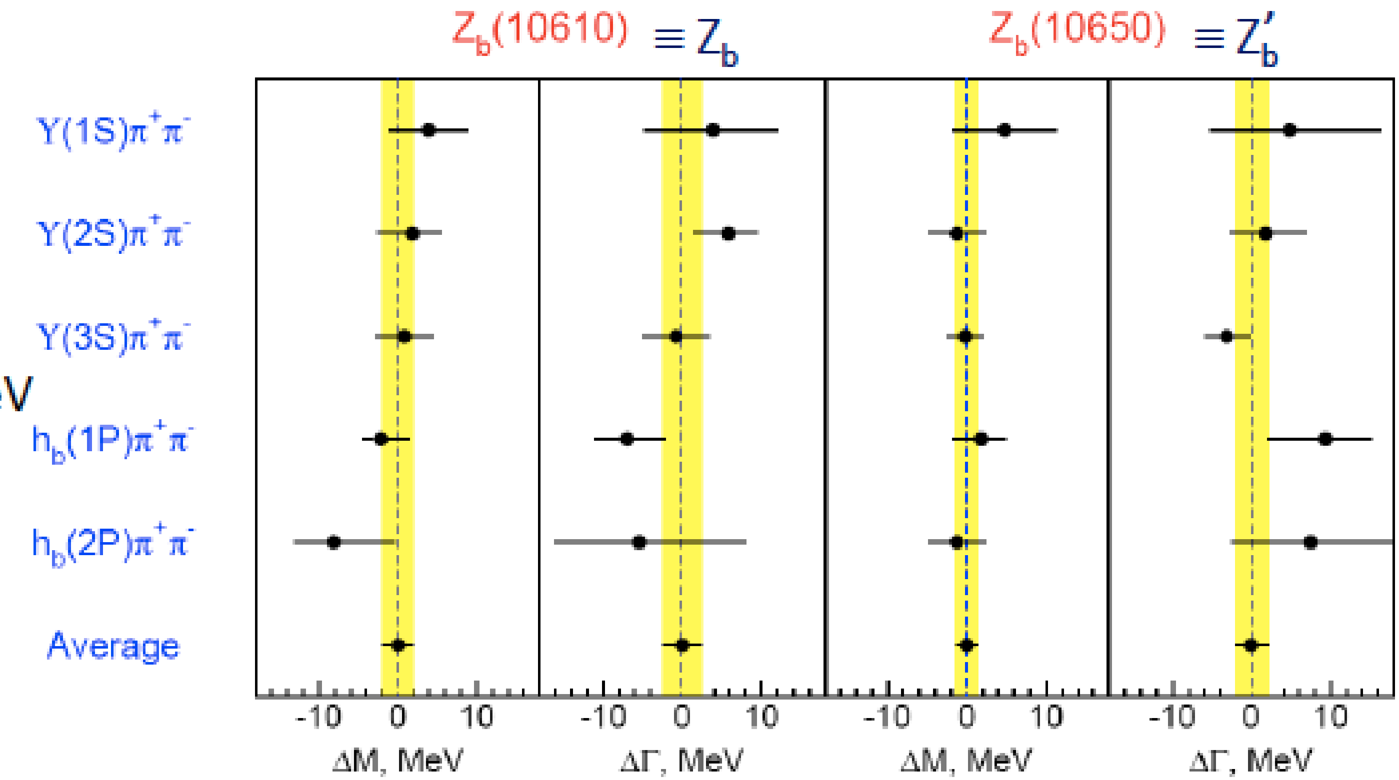


Fit results

Average over 5 channels

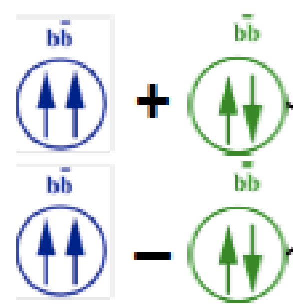
$$\mathbf{M_1 = 10607.2 \pm 2.0\ MeV}$$
$$\mathbf{\Gamma_1 = 18.4 \pm 2.4\ MeV}$$
$M_{Zb} - (M_B + M_{B*}) = +2.6 \pm 2.1$ MeV

$$\mathbf{M_2 = 10652.2 \pm 1.5\ MeV}$$
$$\mathbf{\Gamma_2 = 11.5 \pm 2.2\ MeV}$$
$M_{Zb'} - 2M_{B*} = +1.8 \pm 1.7$ MeV



Angular analysis ⇒ both states are $\mathbf{J^P = 1^+}$ Decays ⇒ $\mathbf{I^G = 1^+}$ (C= – for Z_b^0)

Proximity to thresholds favors molecule over tetraquark

$Z_b \sim |B\ B^*\rangle = |$  $\rangle$ → $h_b(mP)\pi$ not suppressed

S-wave

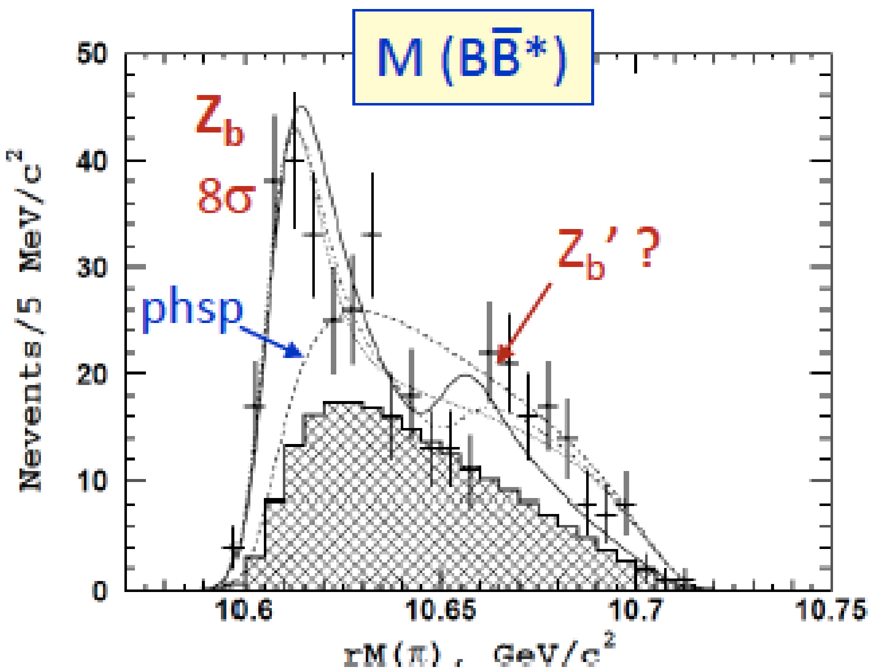
$Z_b' \sim |B^* B^*\rangle = |$ ... − ... $\rangle$

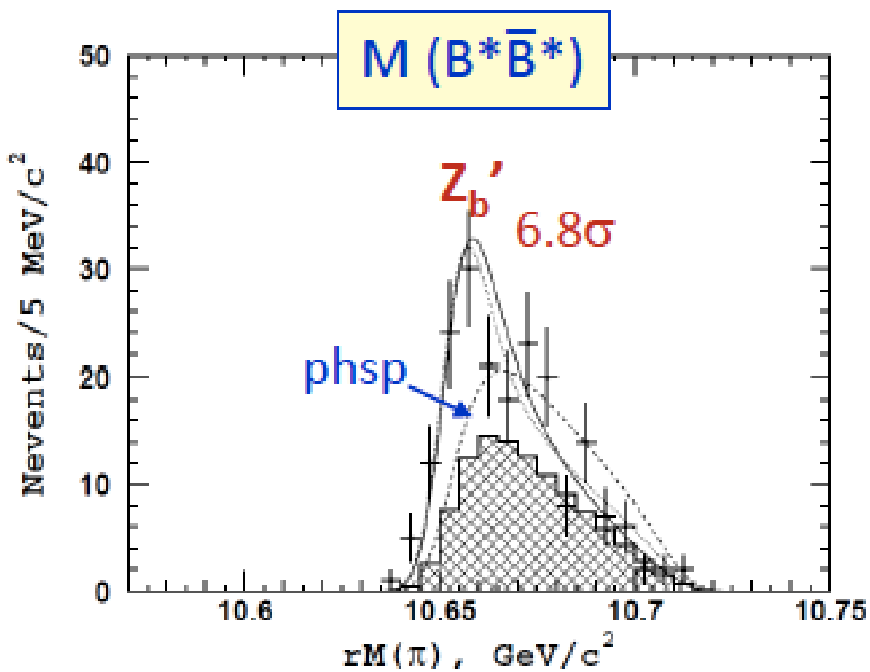
Bondar et al, PRD84,054010(2011)

Phase btw Z_b and Z_b' amplitudes is ~0° for $\Upsilon(nS)\pi\pi$ and ~180° for $h_b(mP)\pi\pi$

Observation of $Z_b \to B\bar{B}^*$ and $Z_b' \to B^*\bar{B}^*$

arXiv:1209.6450





Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

$BF[Z_b' \to B\bar{B}^*] = (25 \pm 10)\%$ insignificant

If included, other fractions of Z_b' are reduced by 1.33.

$Z_b' \to B\bar{B}^*$ is suppressed w.r.t. $B^*\bar{B}^*$ despite much larger PHSP.

Explanations:

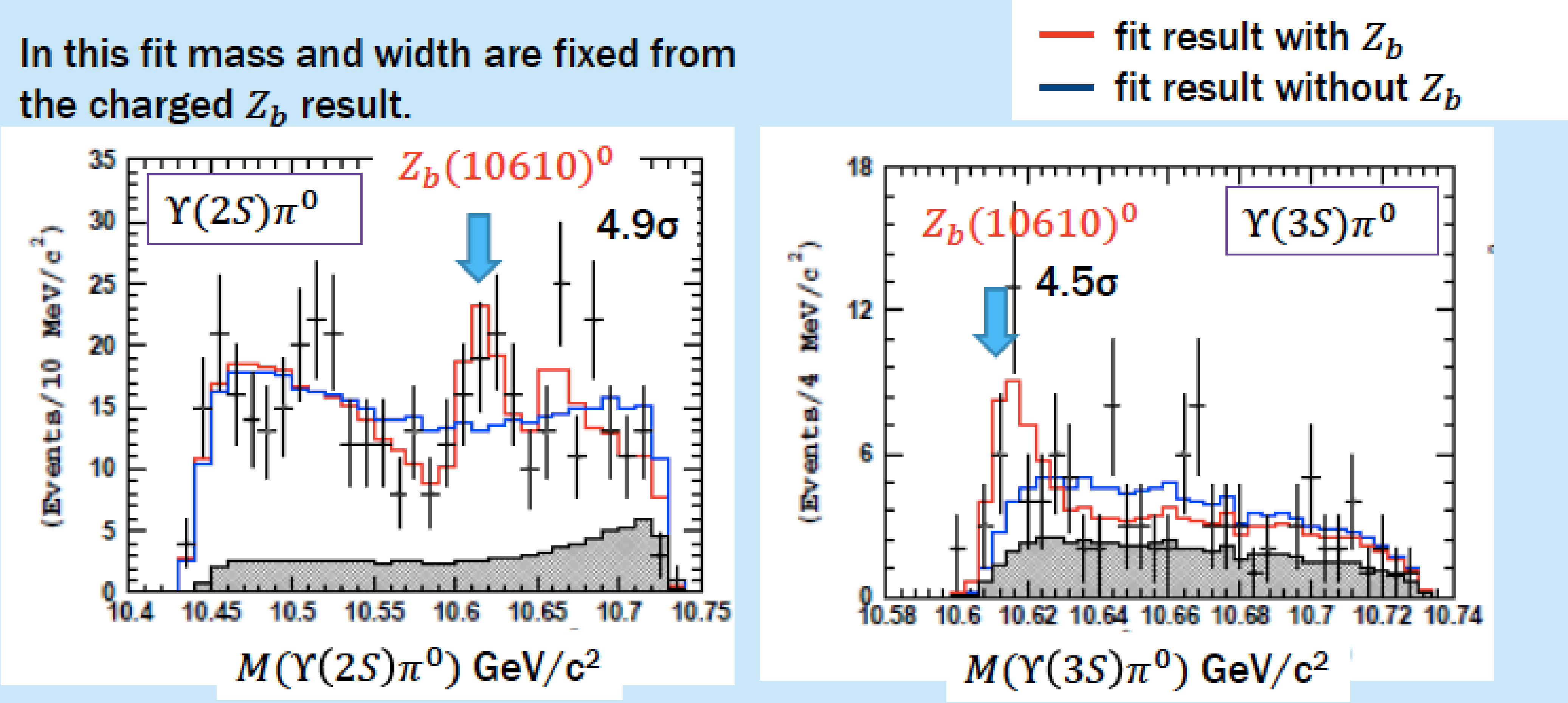
Molecule ⇒ admixture of $B\bar{B}^*$ in Z_b' is small.
Challenging for tetraquark?

Z_b states seems to have neutral partners

PRD 88 (2013) 052016

$\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ decay

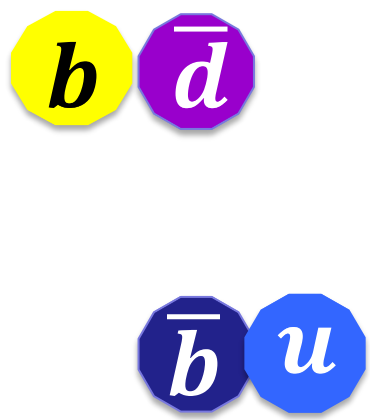
In this fit mass and width are fixed from the charged Z_b result.



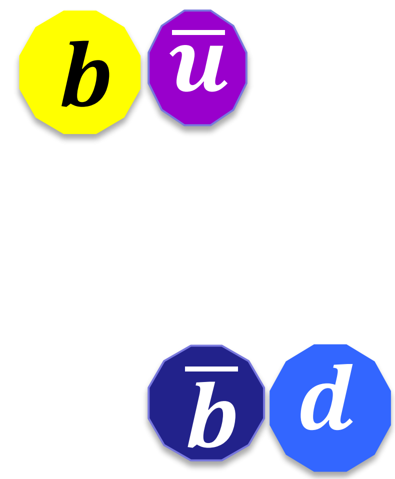
Combined significance for the two modes is 6.5σ

$Z_b^{\pm}$ cannot be standard $b\bar{b}$ states

Z^+ =



Z^- =

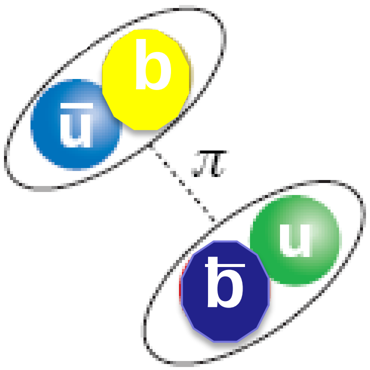


Decays to h_b(nP) or Υ(nS) ➔must contain a $b\bar{b}$ pair

Has electric charge ➔ must contain u and d quarks

$B\bar{B}^*$ and $B^*\bar{B}^*$ molecules ?

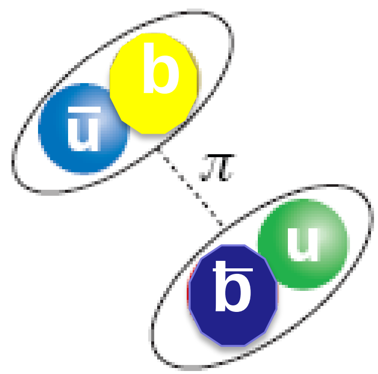
$Z_b(106010)^{\pm}$



B-B* “molecule”

$M_{Z_b(106010)} - (M_B + M_{B^*}) = +3.9 \pm 2.1$ MeV

$Z_b(106050)^{\pm}$



B*-B* “molecule”

$M_{Z_b(106010)} - 2M_{B^*} = +3.2 \pm 1.6$ MeV

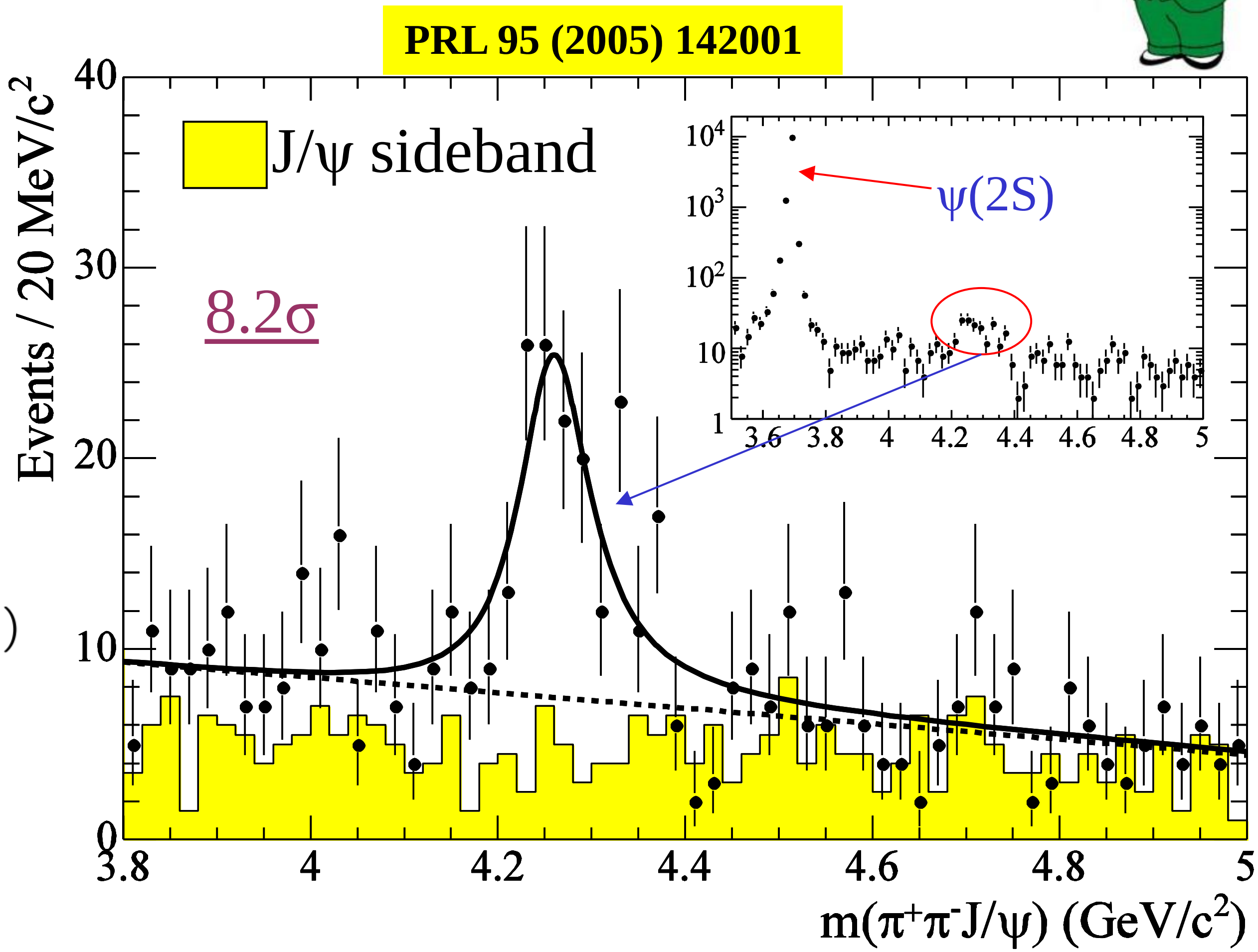
Slightly unbound threshold resonances??

Back to charmonium: Y(4260) in ISR

- No *X*(3872)
- Observed *Y*(4260)

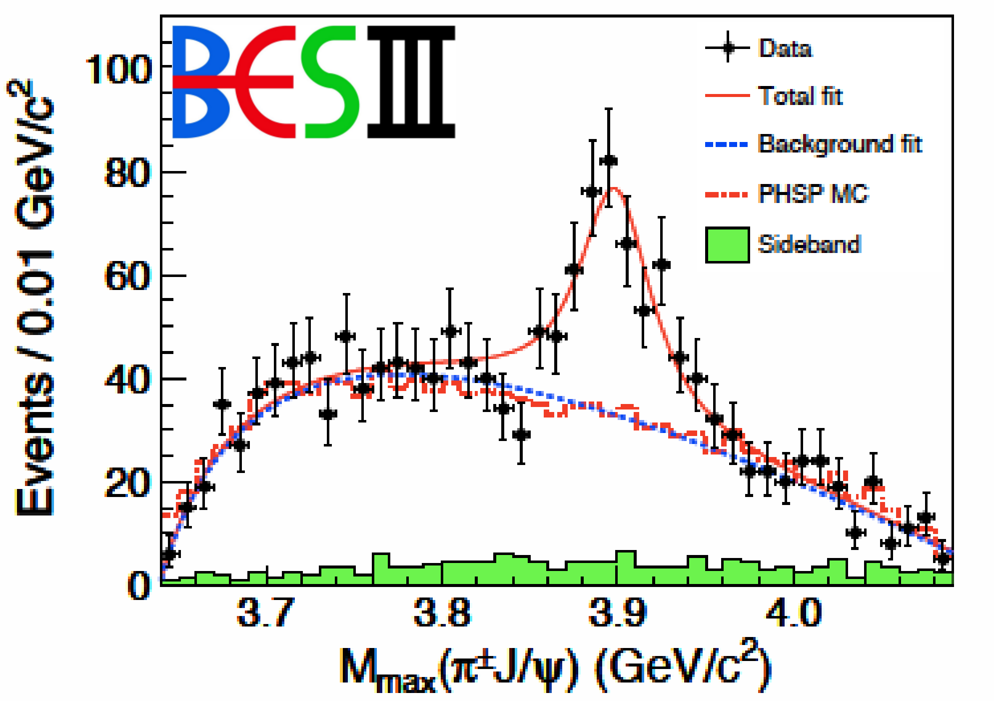
From single-resonance fit:

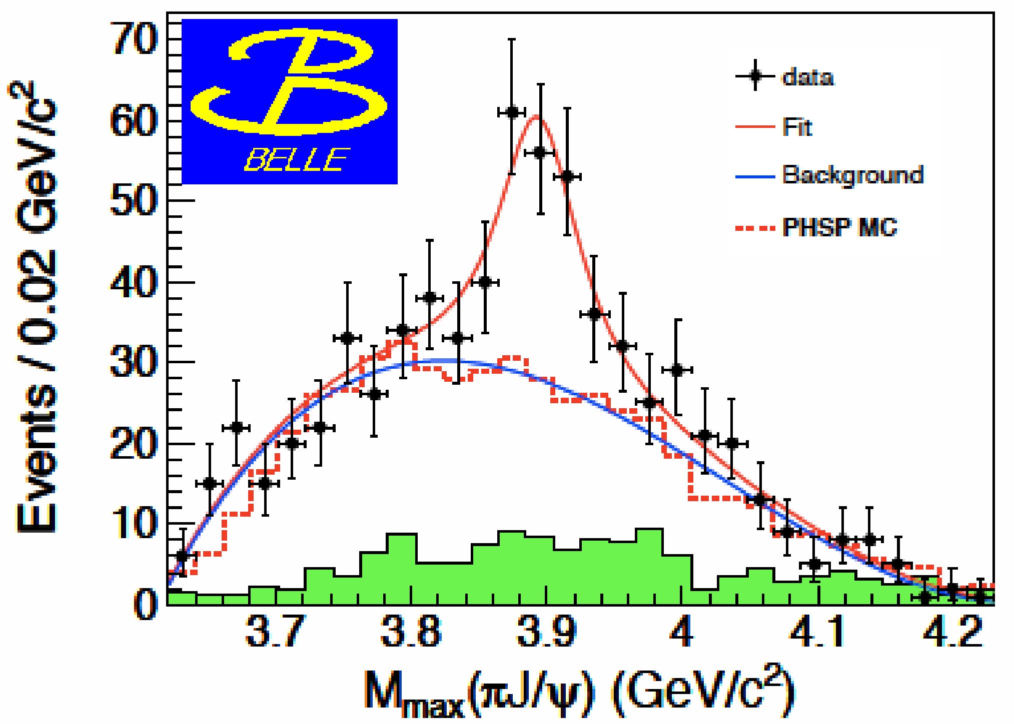
- $N = 125 \pm 23$
- $M = 4259 \pm 8^{+2}_{-6}\ \text{MeV}/c^2$
- $\Gamma = 88 \pm 23^{+6}_{-4}\ \text{MeV}$
- $\Gamma(Y \to e^+e^-) \cdot \mathcal{B}(Y \to J/\psi\pi^+\pi^-)$
  $= 5.5 \pm 1.0^{+0.8}_{-0.7}\ \text{eV}$
- $J^{PC} = 1^{--}$ (ISR production)



Observation of $Z^+(3900)$ state in $\pi J/\psi$ spectra

Charged ➔ Cannot be a conventional charmonium state, must contain 4 quarks





$M = 3899 \pm 3.6 \pm 4.9 MeV$

G$= 46 \pm 10 \pm 20 MeV$

Produced by running at the energy of Y(4260)

PRL 110 (2013) 252001

$M = 3894 \pm 6.6 \pm 4.5 MeV$

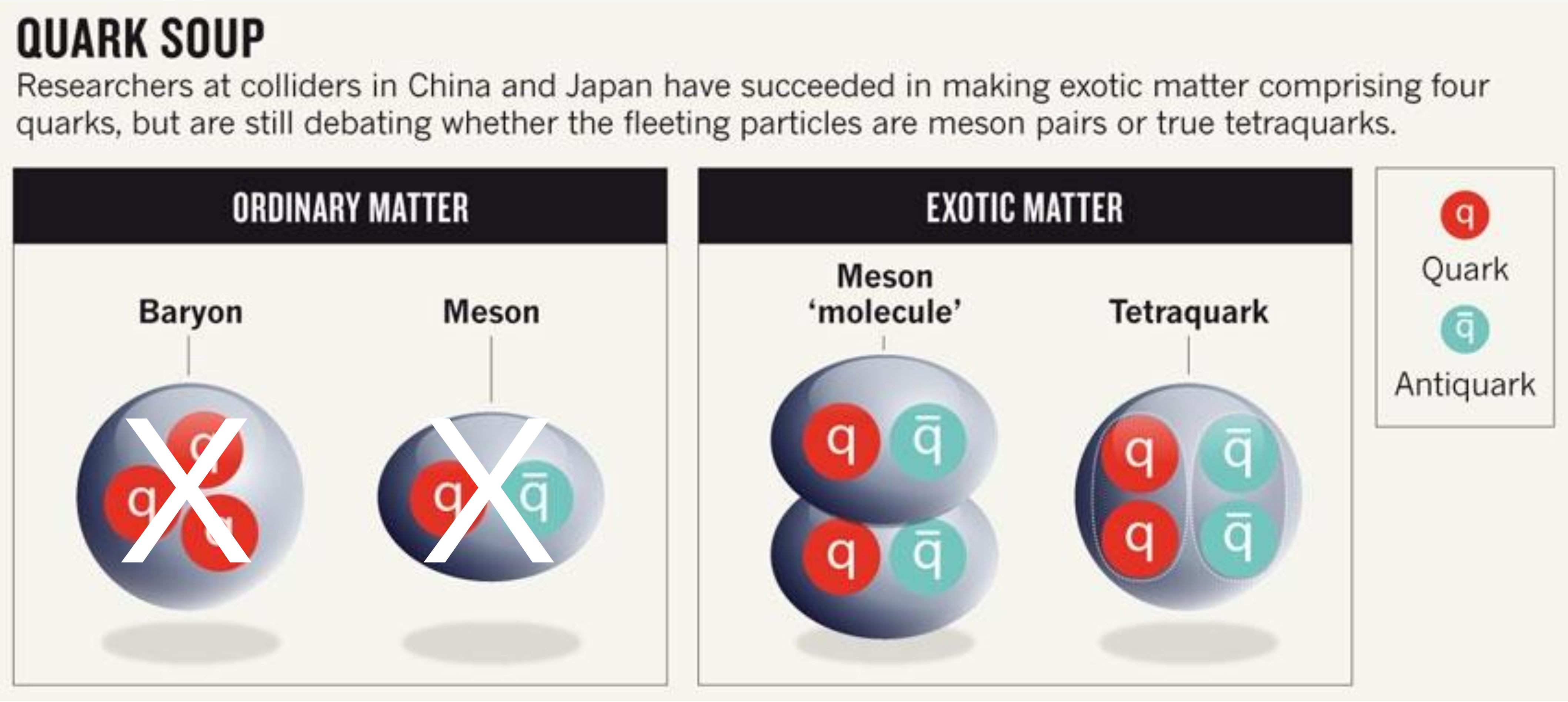
G$= 63 \pm 24 \pm 26 MeV$

Using Y(4260) decays in ISR

PRL 110 (2013) 252002

New Particle scorecard:

$Z_b(106010)^{\pm}$ **$Z_b(106050)^{\pm}$** **$Z_c(3900)^{\pm}$**



Summary and Outlook

❑ Hadron spectroscopy is one of most exciting and pursued areas by the e^+e^- flavour factories and hadron collider experiments

❖ Some of the selected charmonium and bottomonium states are presented here that look very much exotic in nature

➢ These recent discoveries have created a renewed interest in the quarkonium sector and are pushing our friends over the corridor to the extreme(!)

➢ Look for more such results from LHC, especially LHCb, the upcoming Belle-II and other experiments (PANDA…)

Thank you very much for your attention