The Physics Case for Scan Data Taking

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(Belle-II Physics Week, November 30, 2022, Valencia)

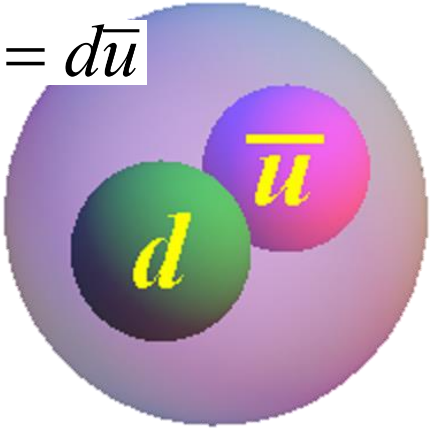
Constituent Quark Model

<u>mesons</u> are bound states of a of quark and anti-quark:

$$\pi^+ = u\bar{d} \qquad \pi^0 = \tfrac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \quad \pi^- = d\bar{u}$$

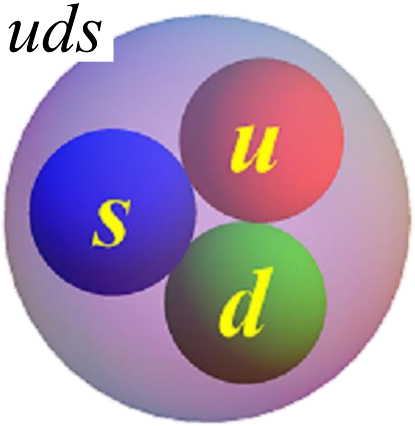
$$K^+ = u\bar{s} \quad K^0 = d\bar{s} \quad \bar{K}^0 = s\bar{d} \quad K^- = s\bar{u}$$

$\pi^- = d\bar{u}$



<u>baryons</u> are bound state of 3 quarks:

$\Lambda = uds$



$$p = uud \qquad n = udd \quad \Lambda = uds$$

$$\bar{p} = \bar{u}\bar{u}\bar{d} \qquad \bar{n} = \bar{u}\bar{d}\bar{d} \qquad \bar{\Lambda} = \bar{u}\bar{d}\bar{s}$$

Quarkonium Basics

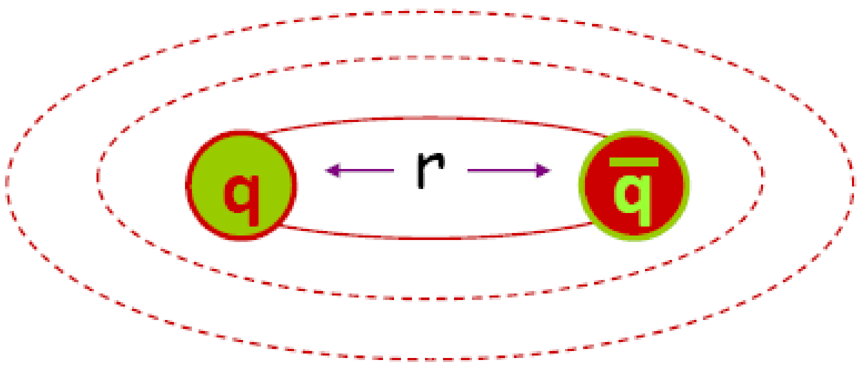
c, b -quarks are heavy:

$m_c \sim 1.5$ GeV $\sim 1.6\, m_p$;

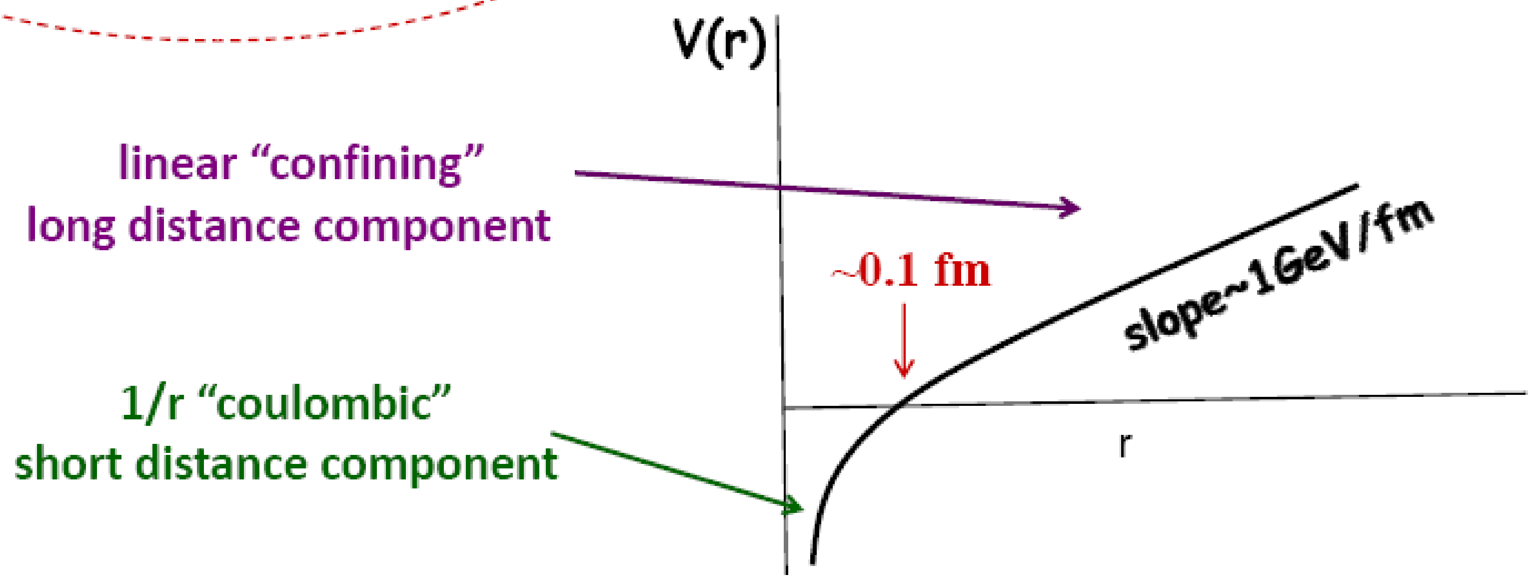
$m_b \sim 4.5$ GeV $\sim 4.8\, m_p$;

velocities are small:

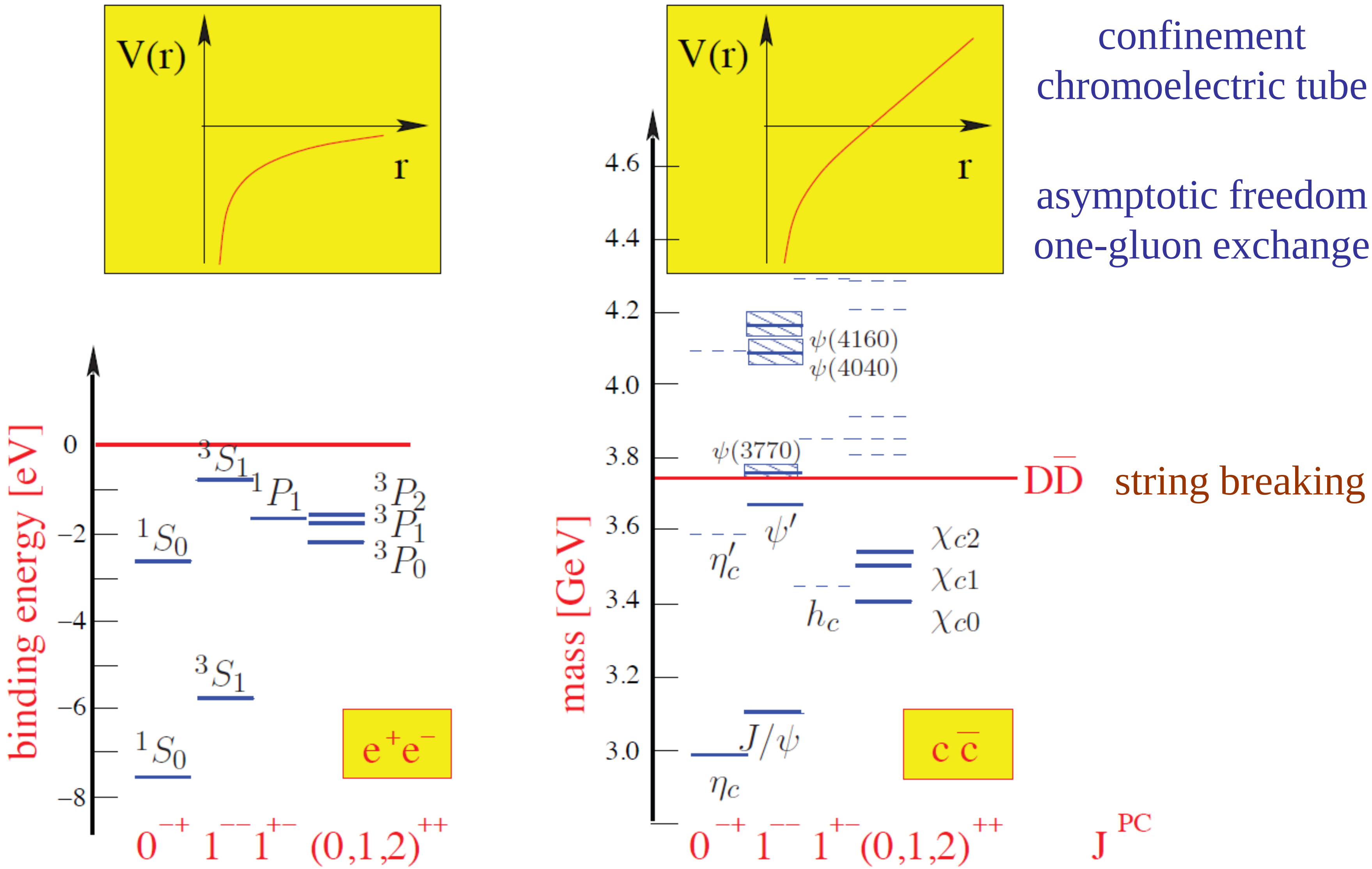
non-relativistic QM applies



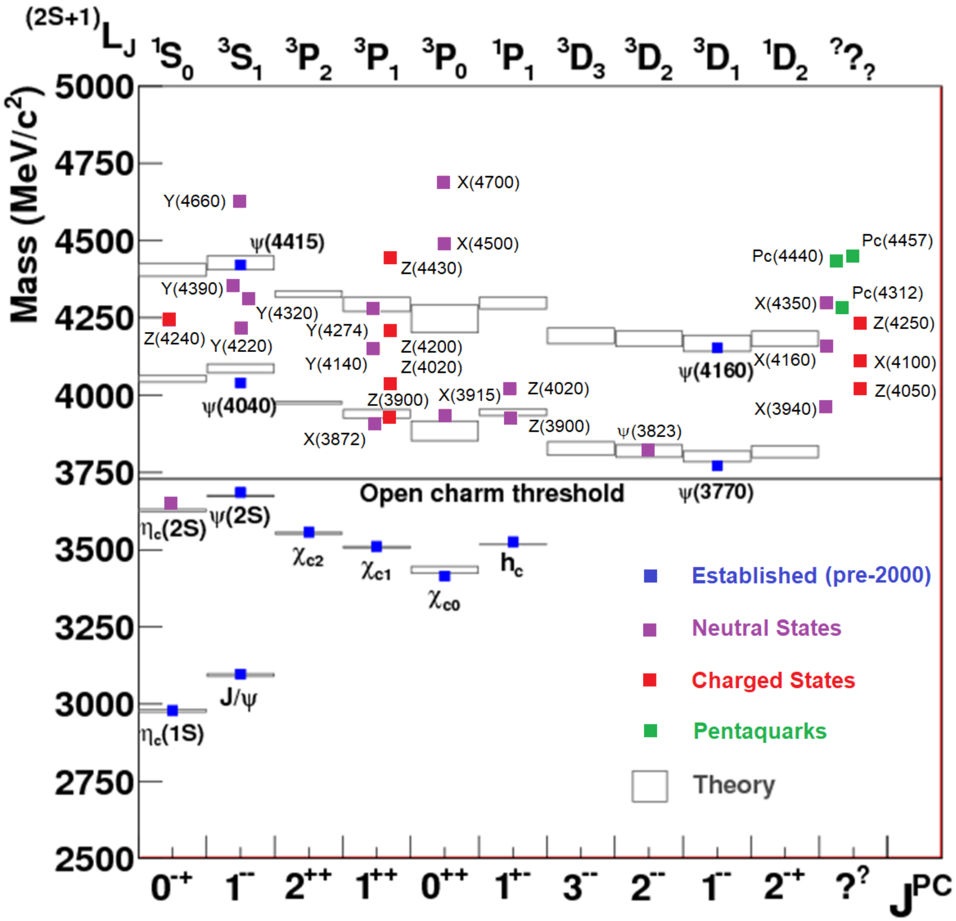
$$-\frac{\hbar^2}{2m}\nabla^2\Psi + V(r)\Psi = E\Psi$$

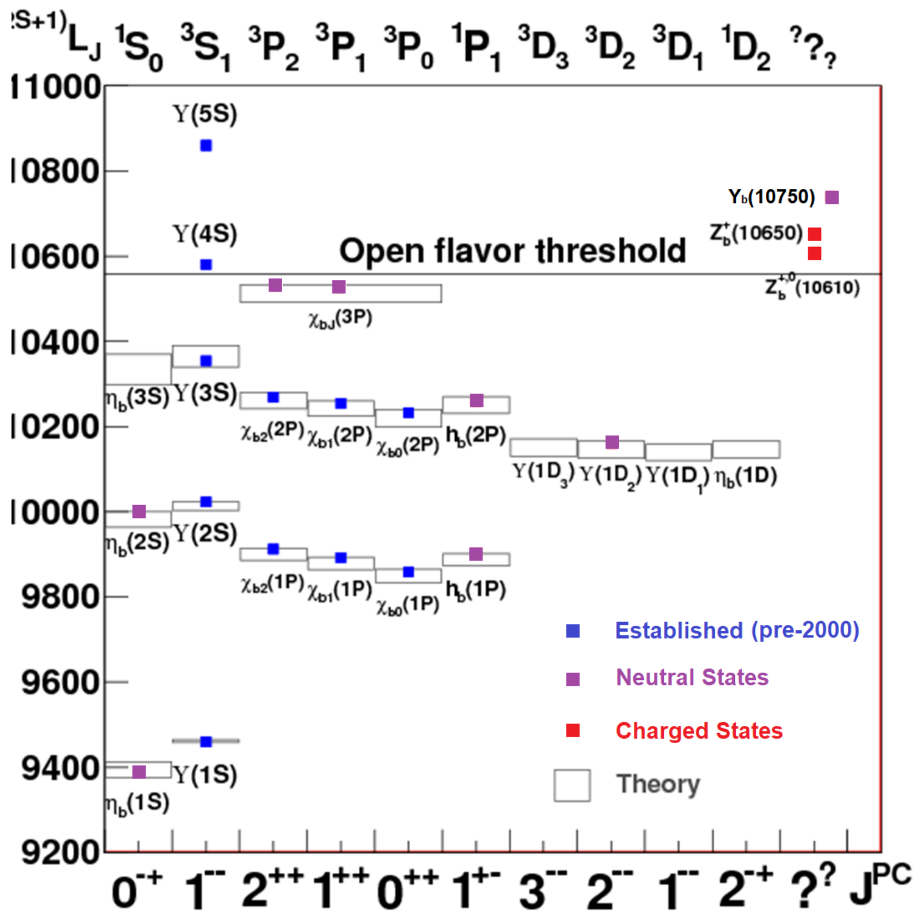


Classification of $c\bar{c}$ and $b\bar{b}$ levels is the same as in positronium: L, S, n_r :

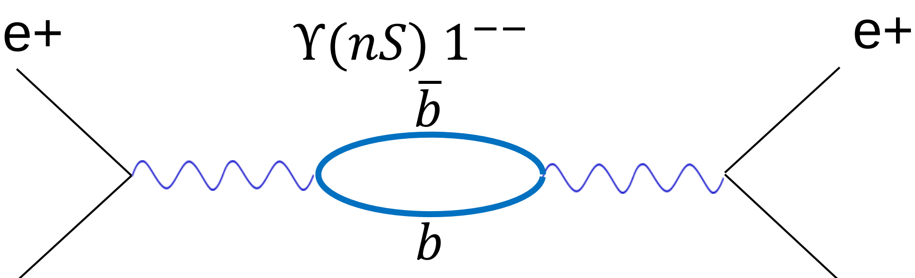


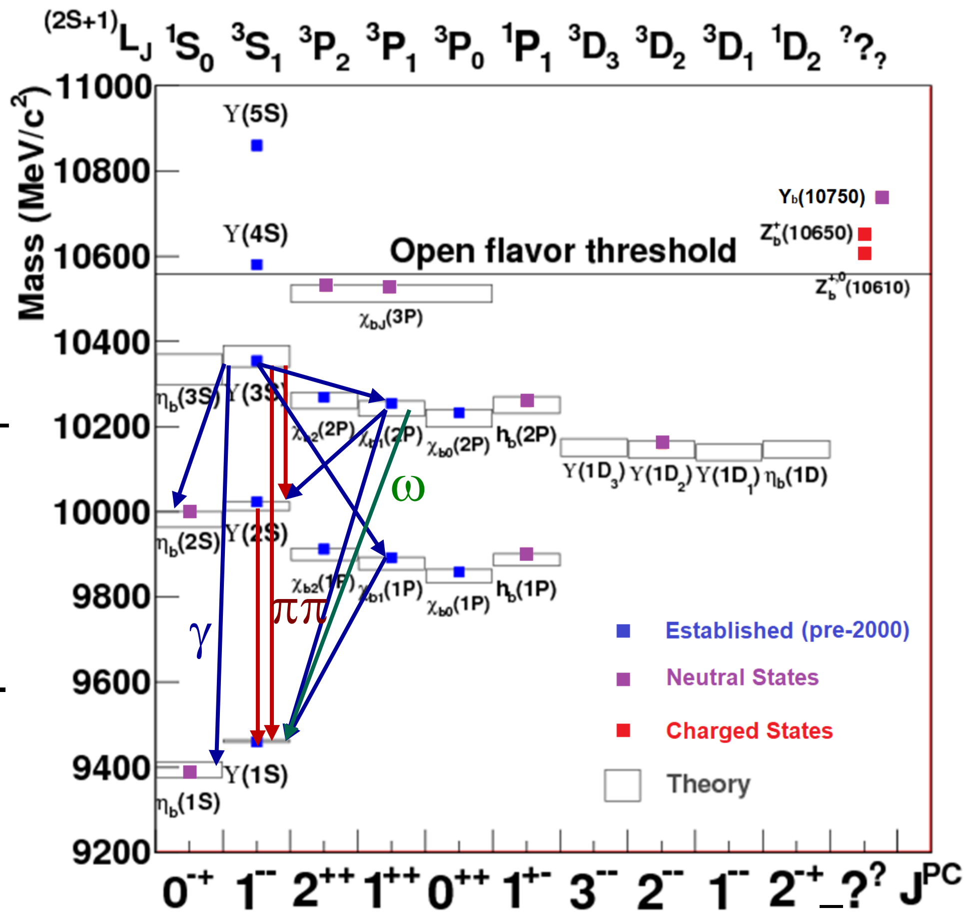
Relativistic effects for low excitations are small

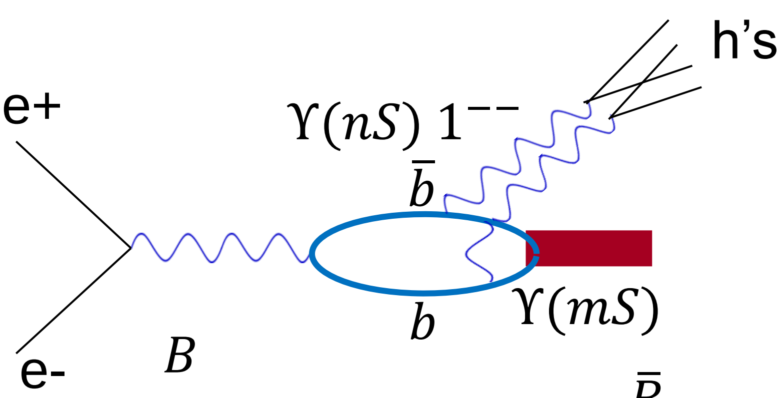

Mass (MeV/c²)
Open charm threshold
Established (pre-2000)
Neutral States
Charged States
Pentaquarks
Theory

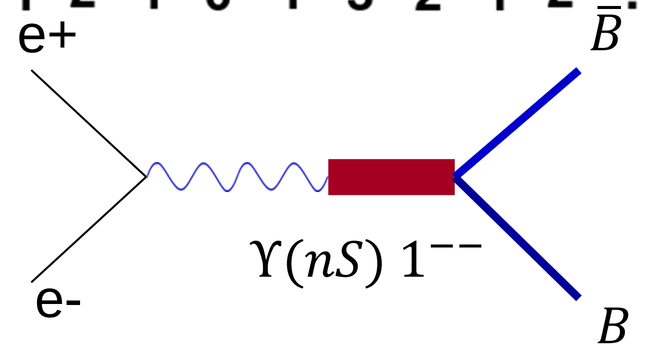

Open flavor threshold
Established (pre-2000)
Neutral States
Charged States
Theory

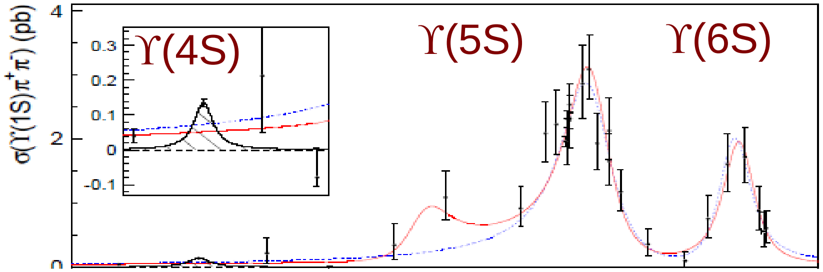
	Γ_f/Γ_{ee}
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	$2. \pm 0.2$
$\Upsilon(3S) \to \Upsilon(2S)\pi^+\pi^-$	1.3 ± 0.26
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	9.3 ± 0.9











JHEP 1910, 220 (2019)

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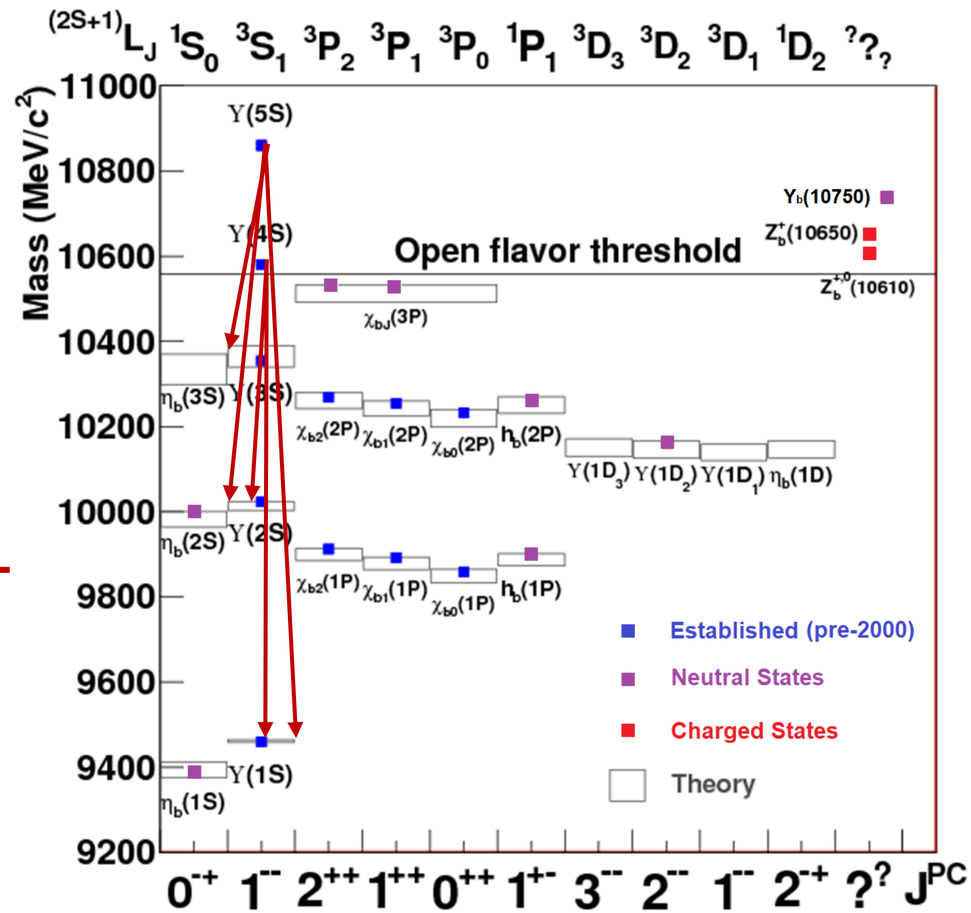
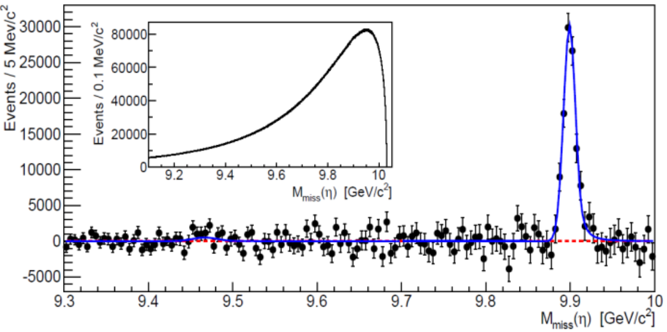
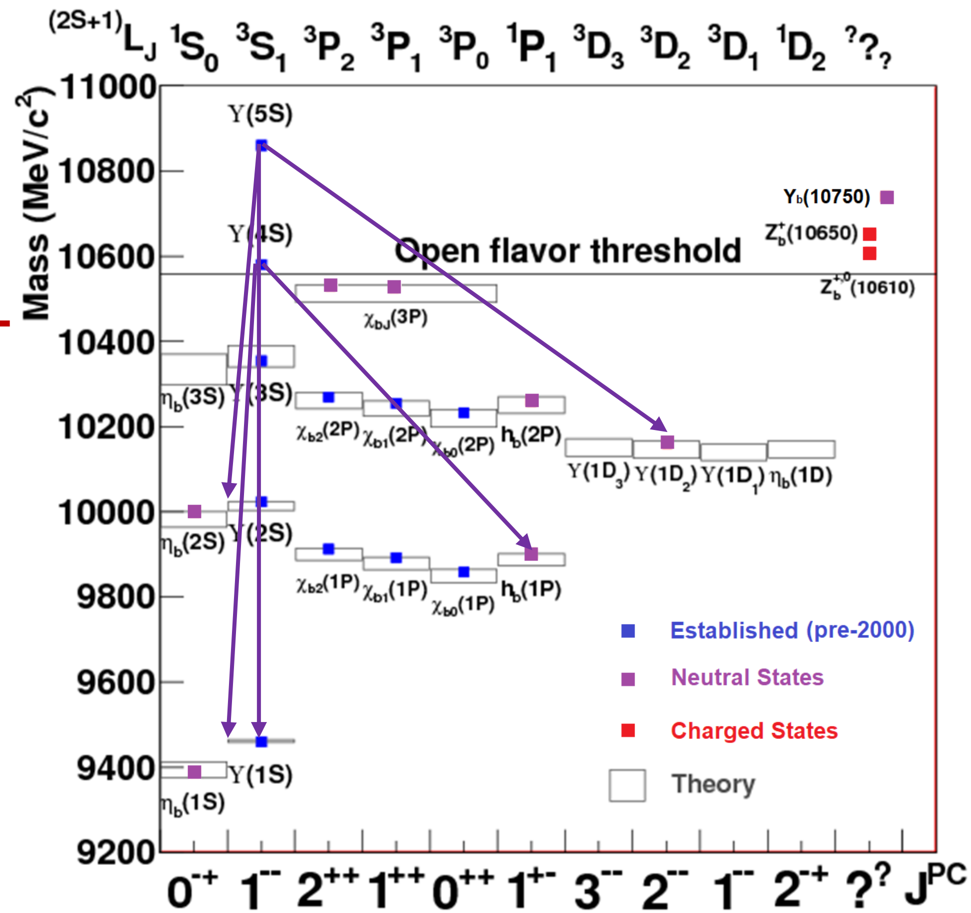
$\Upsilon(3S) \to \Upsilon(2S)\pi^+\pi^-$	1.3 ± 0.26
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	9.3 ± 0.9
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	5.2 ± 0.26
$\Upsilon(4S) \to \Upsilon(2S)\pi^+\pi^-$	5.2 ± 0.52
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	640 ± 160
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	940 ± 230
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	580 ± 150

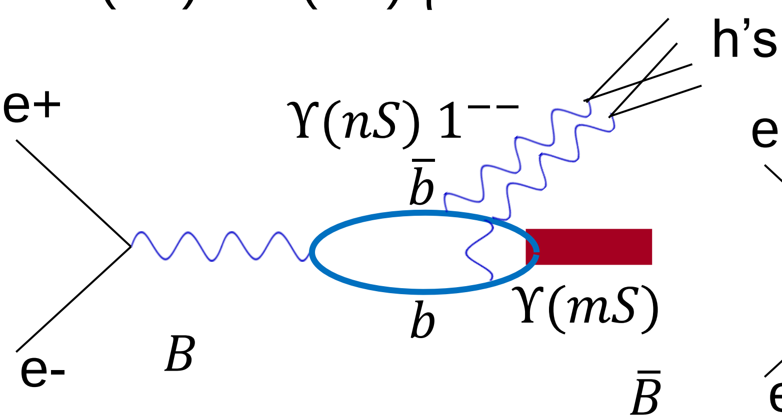


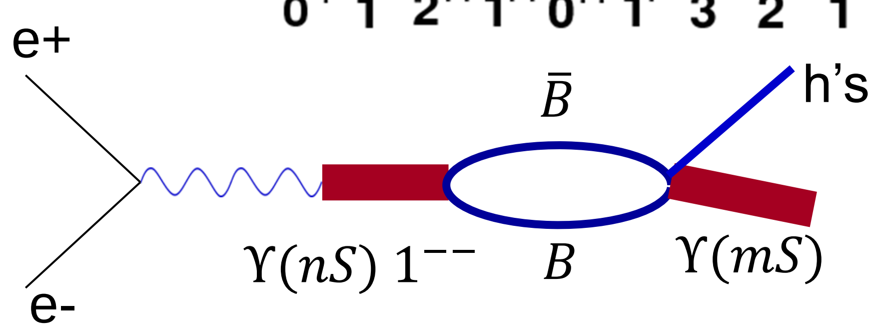


$\Upsilon(4S)\to h_b(1P)\eta$ PRL 115, 142001 (2015)

	Γ_f/Γ_{ee}
$\Upsilon(3S)\to\Upsilon(1S)\eta$	<0.005
$\Upsilon(2S)\to\Upsilon(1S)\eta$	0.015 ± 0.005
$\Upsilon(4S)\to\Upsilon(1S)\eta$	11.5 ± 1.2
$\Upsilon(4S)\to h_b(1P)\eta$	136 ± 114
$\Upsilon(5S)\to\Upsilon(1S)\eta$	100 ± 25
$\Upsilon(5S)\to\Upsilon(2S)\eta$	500 ± 125
$\Upsilon(5S)\to h_b(1P)\eta$	<400
$\Upsilon(5S)\to\Upsilon(1D)\eta$	820 ± 200



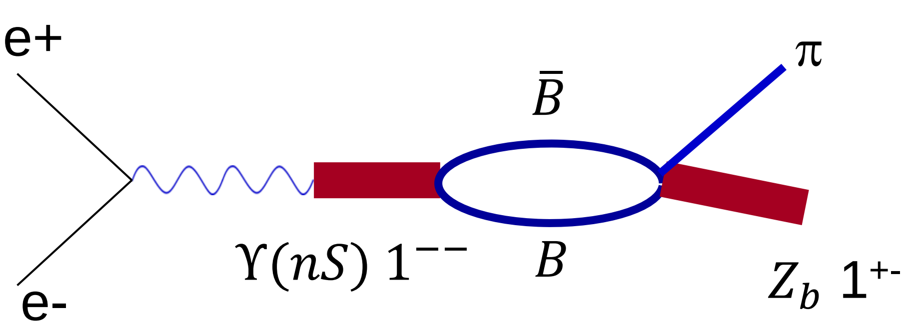


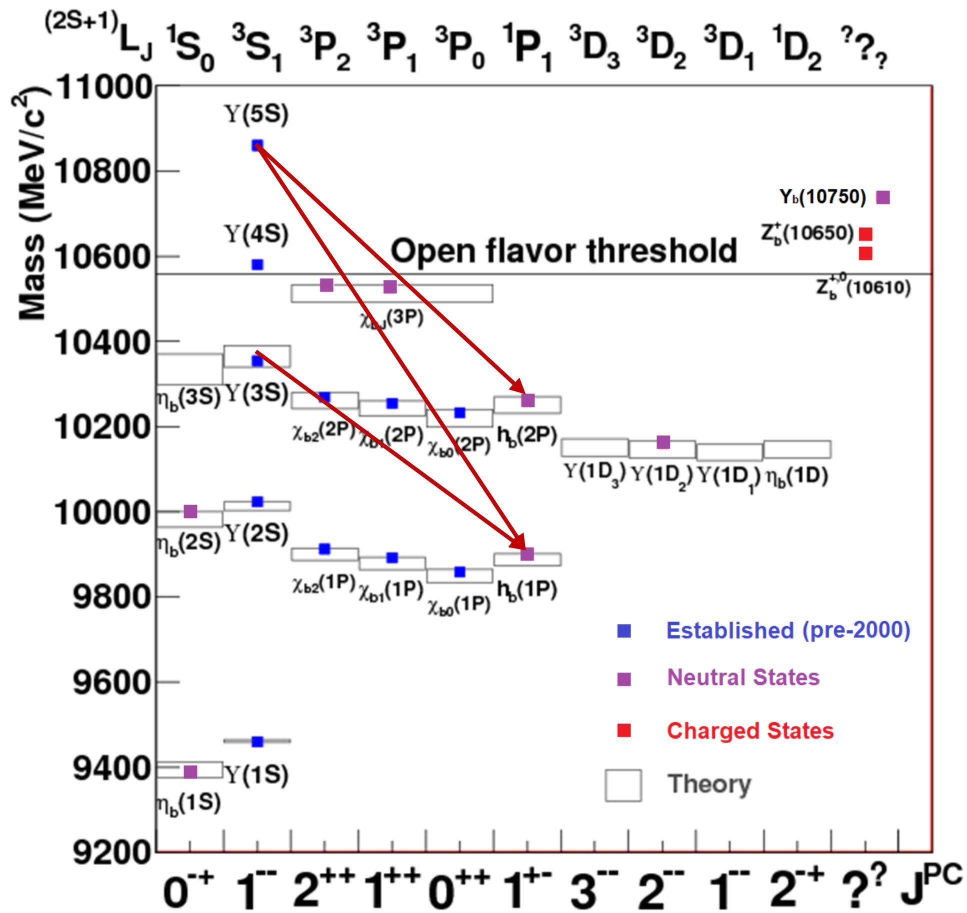


PRL 108, 032001 (2012)

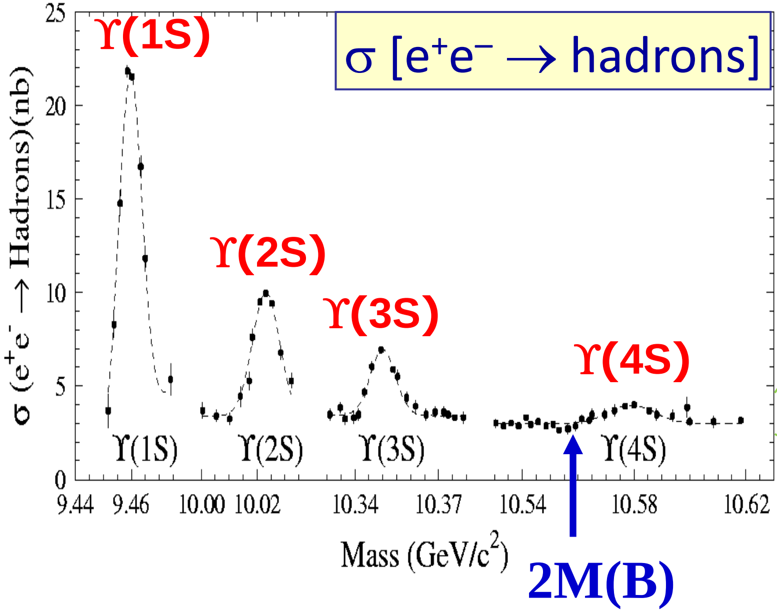
	Γ_f/Γ_{ee}
$\Upsilon(3S) \to h_b(1P)\pi^+\pi^-$	<0.0055

$\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$	420 ± 140
$\Upsilon(5S) \to h_b(2P)\pi^+\pi^-$	690 ± 230

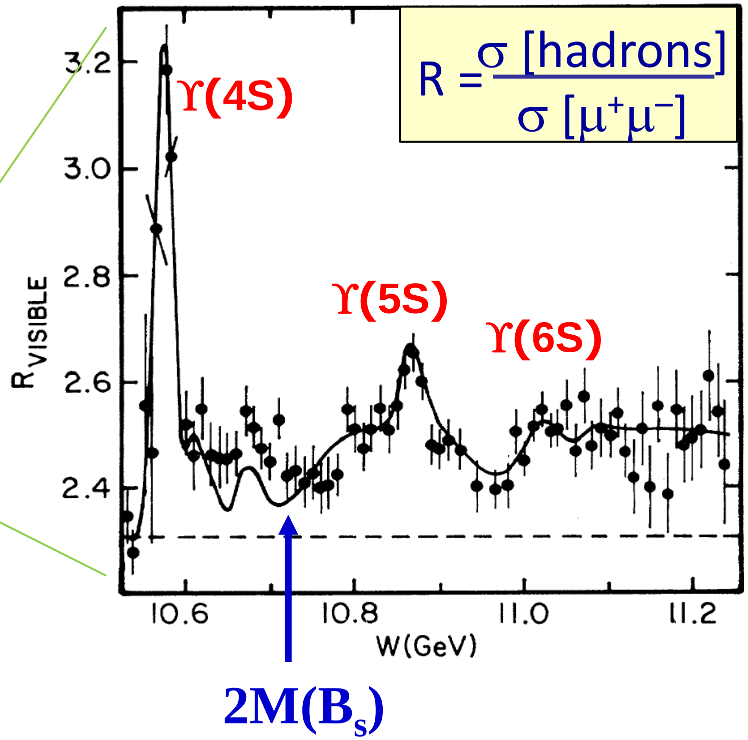




Energy dependence of $\sigma[e^+e^- \to hadrons]$



CUSB PRL54,377(1985)



$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

BaBar 433 fb^{-1} + Belle 711 fb^{-1}

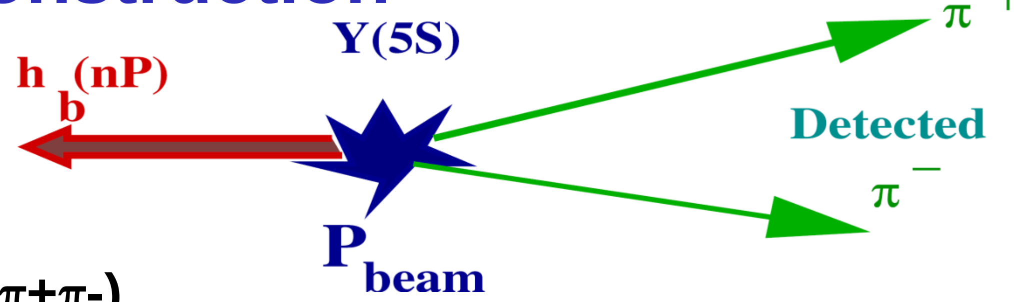
Study rare B decays and CP violation

$e^+e^- \to \Upsilon(5S) \to B\bar{B}, B\bar{B}^*, B^*\bar{B}^*, B\bar{B}^*\pi, B^*\bar{B}^*\pi, B_s^{(*)}\bar{B}_s^{(*)}, \ldots$

Belle 121 fb^{-1}

h_b reconstruction

Missing mass to $\pi\pi$ system



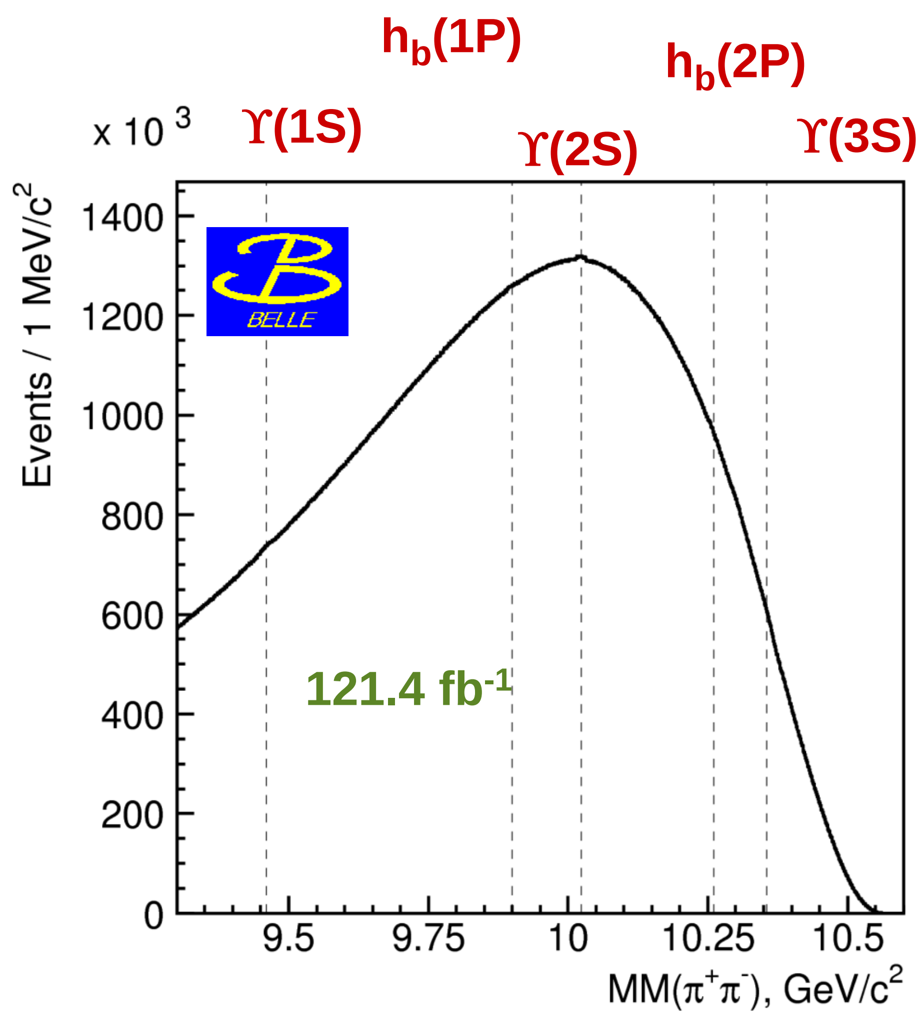
$$M_{hb(nP)} = \sqrt{(P_{\Upsilon(5S)} - P_{\pi+\pi-})^2} \equiv MM(\pi+\pi-)$$

Simple selection :

$\pi^+\pi^-$: good quality, positively identified

Suppression of continuum events
FW R2<0.3

⇒ Search for $h_b(nP)$ peaks in $MM(\pi^+\pi^-)$ spectrum

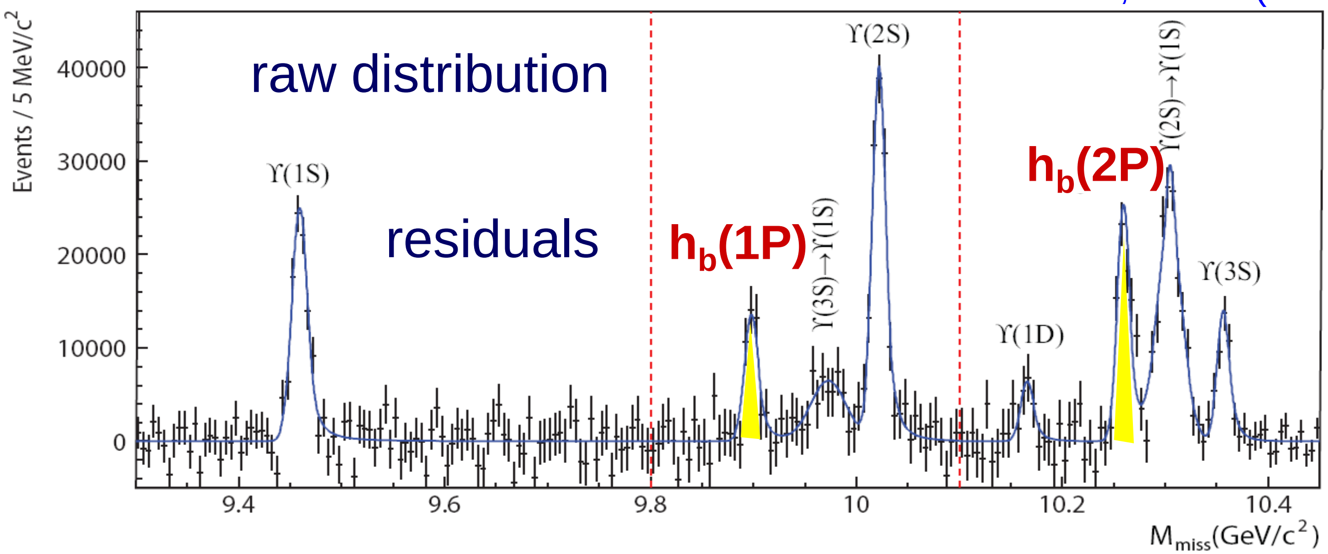


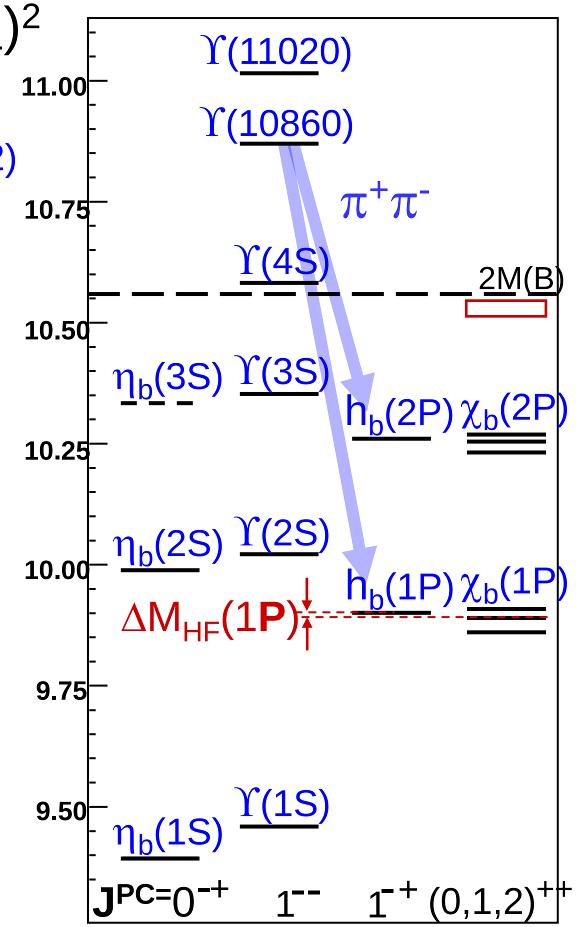
Observation of h_b(1P,2P)

$e^+e^- \to \Upsilon(5S) \to X\ \pi^+\pi^-$ ← reconstructed, use $\mathbf{M_{miss}(\pi^+\pi^-)}$

$\sqrt{(P_{e+e-} - P_{\pi+\pi-})^2}$

Belle arxiv:1103.3419 PRL108,032001(2012)





Belle arxiv:1205.6351

ΔM_{HF}(**1P**) = +0.8 ± 1.1 MeV consistent with zero,

ΔM_{HF}(**2P**) = +0.5 ± 1.2 MeV as expected

Large h_b(1,2P) production rates

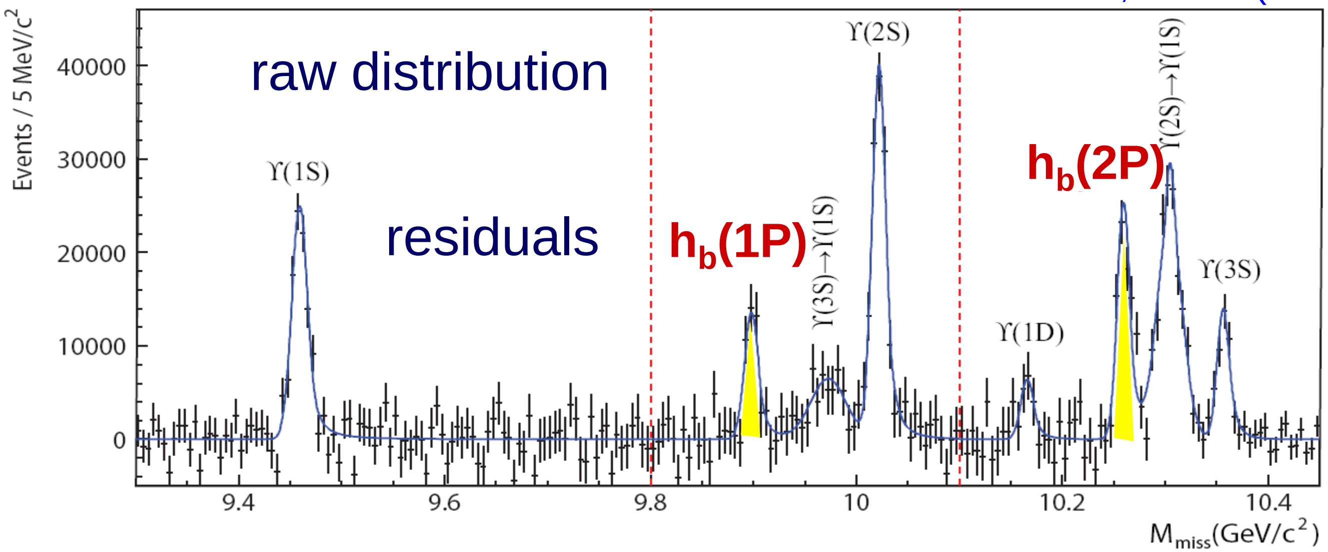
c.f. CLEO $e^+e^- \to \psi(4170) \to h_c\ \pi^+\pi^-$

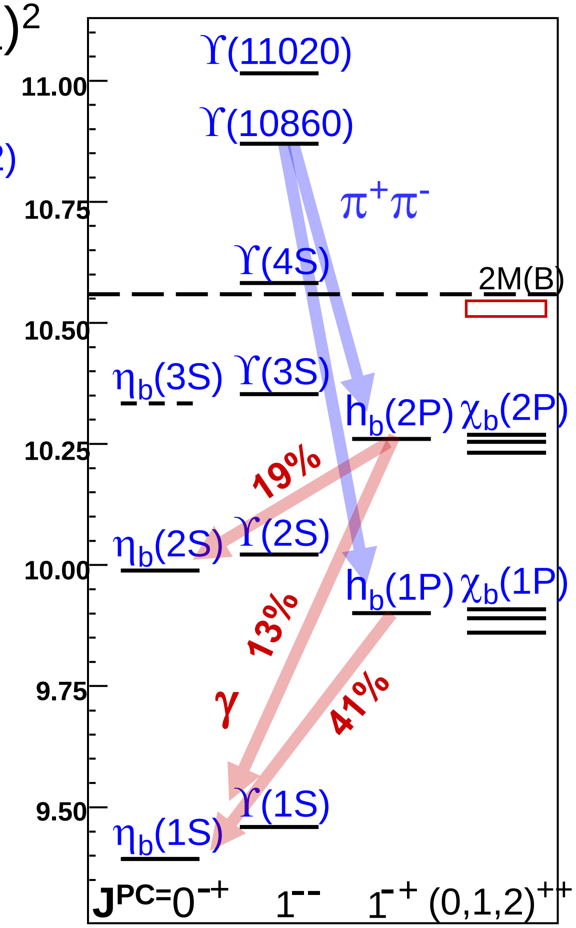
Observation of $h_b(1P,2P)$

$e^+e^- \to \Upsilon(5S) \to h_b(nP)\ \pi^+\pi^-$ ← reconstructed, use $\mathbf{M_{miss}(\pi^+\pi^-)}$

$\sqrt{(P_{e+e-} - P_{\pi+\pi-})^2}$

Belle arxiv:1103.3419 PRL108,032001(2012)





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Large $h_b(1,2P)$ production rates

c.f. CLEO $e^+e^- \to \psi(4170) \to h_c\ \pi^+\pi^-$

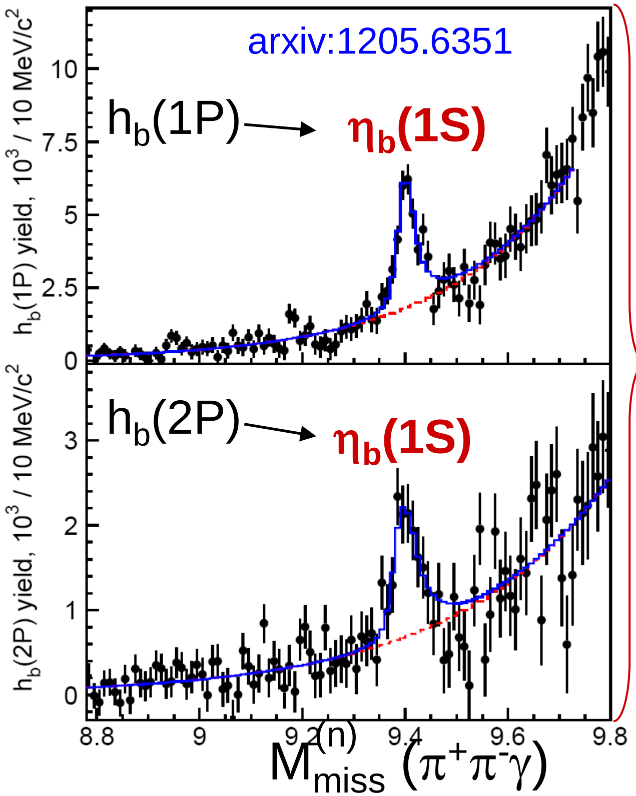
$h_b(nP)$ decays are a source of $\eta_b(mS)$

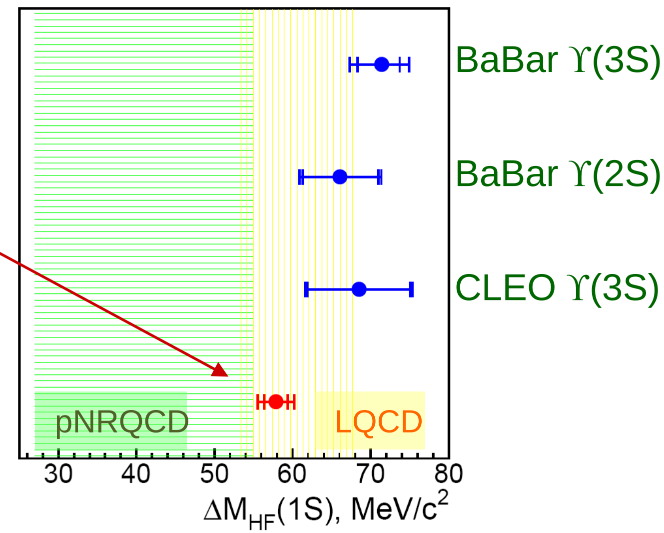
Observation of $h_b(1P,2P) \to \eta_b(1S)\,\gamma$

$e^+e^- \to \Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-$ reconstruct
$\quad \hookrightarrow \eta_b(1S)\,\gamma$

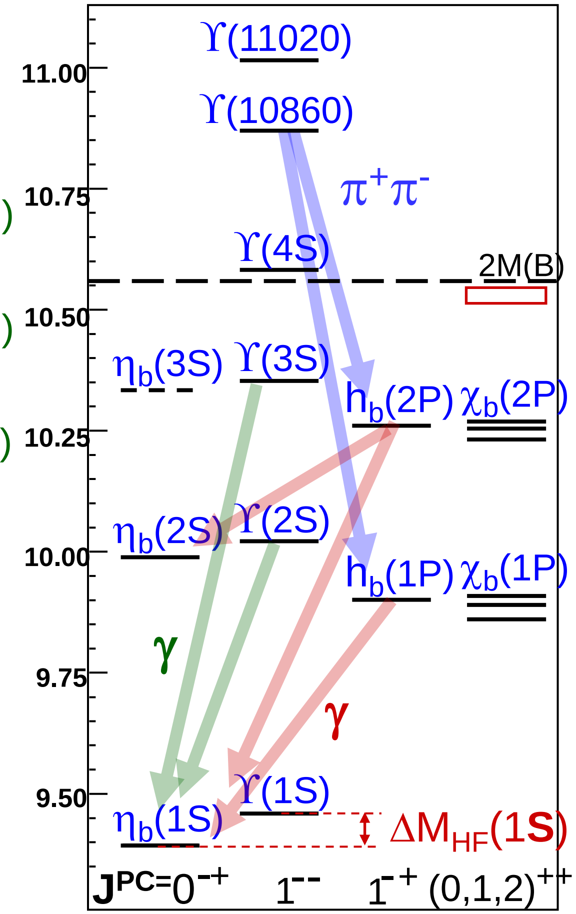
$\Delta M_{HF}(1S)$

Belle : 57.9 ± 2.3 MeV
PDG'12 : 69.3 ± 2.8 MeV
3σ





Kniehl et al, PRL92,242001(2004)
Meinel, PRD82,114502(2010)



Mizuk et al. Belle PRL 109 (2012) 232002

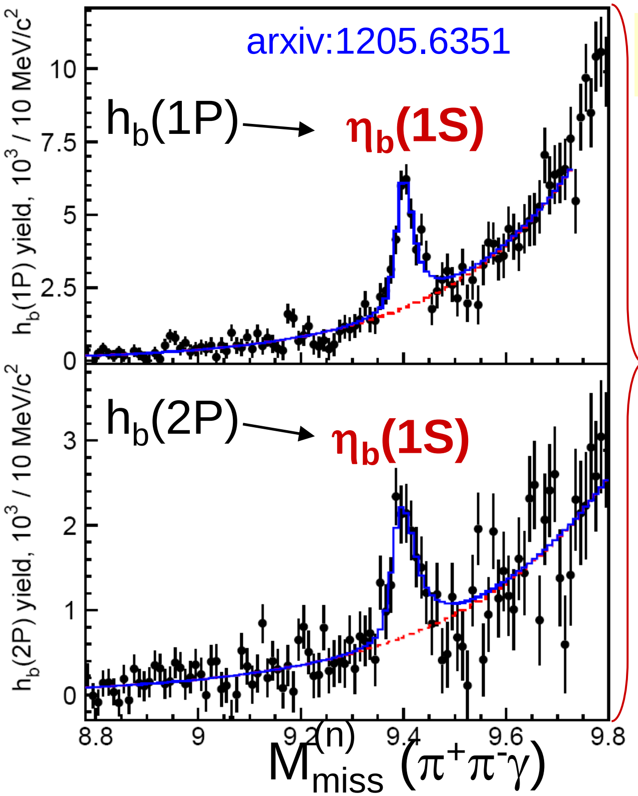
Belle result decreases tension with theory

First measurement $\Gamma = 10.8\,^{+4.0}_{-3.7}\,^{+4.5}_{-2.0}$ MeV
as expected

Observation of $h_b(1P,2P) \to \eta_b(1S)\,\gamma$

$e^+e^- \to \Upsilon(5S) \to h_b(\mathbf{nP})\ \pi^+\pi^-$
$\quad \to \eta_b(\mathbf{1S})\ \gamma$

reconstruct



$\Delta M_{HF}(\mathbf{1S})$

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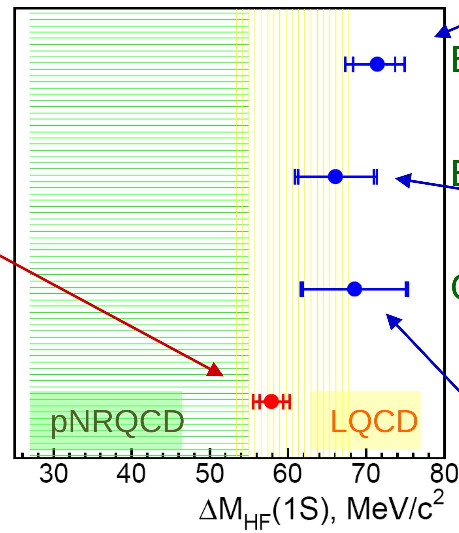
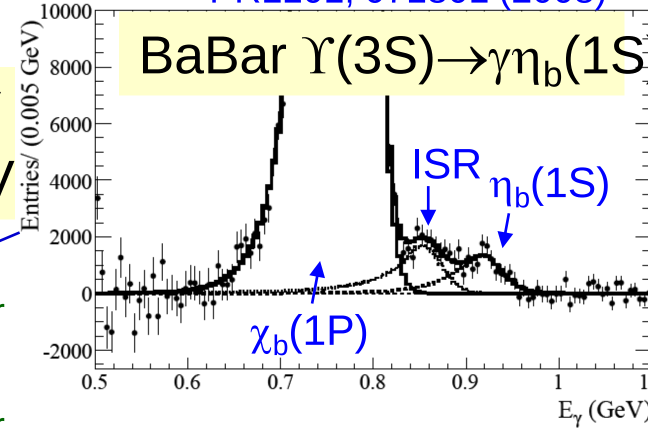
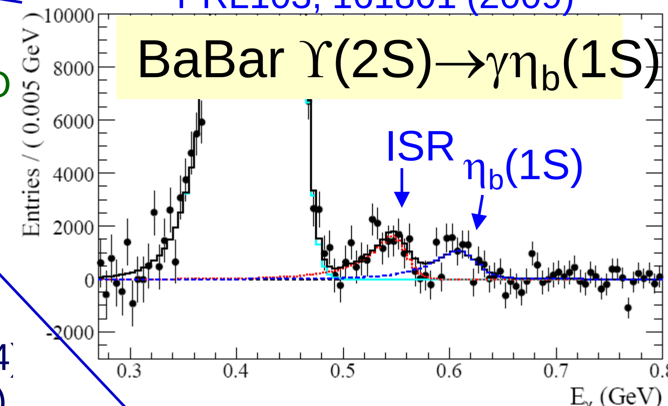


Kniehl et al, PRL92,242001(2004)
Meinel, PRD82,114502(2010)

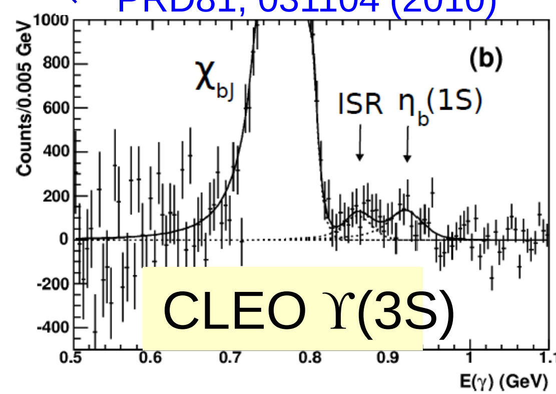
PRL101, 071801 (2008)



PRL103, 161801 (2009)



PRD81, 031104 (2010)



Mizuk et al. Belle PRL 109 (2012) 232002

Belle result decreases tension with theory

First measurement $\Gamma = 10.8\,^{+4.0}_{-3.7}\,^{+4.5}_{-2.0}$ MeV

as expected

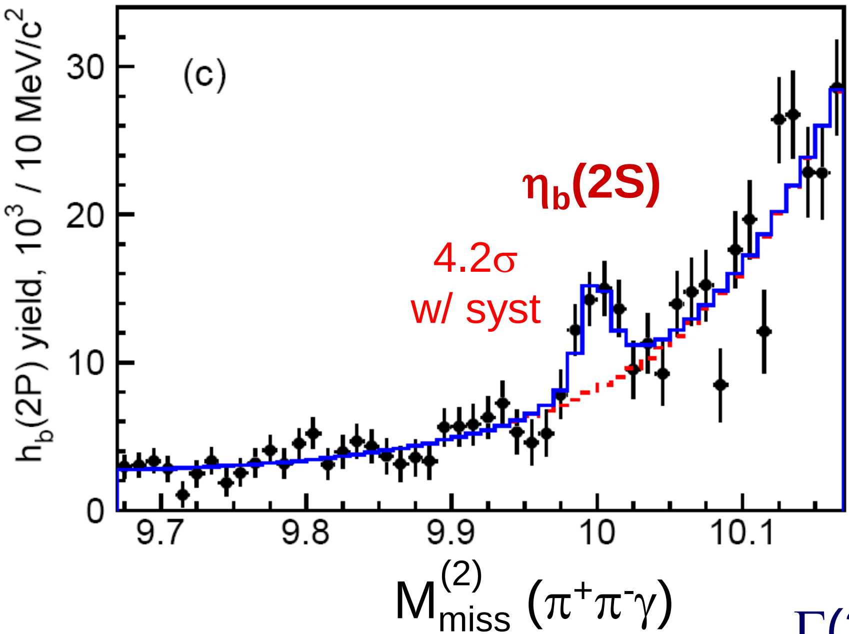
First evidence for $\eta_b(2S)$

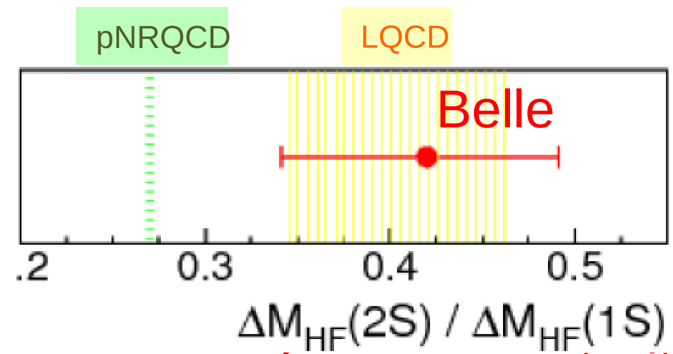
$e^+e^- \to \Upsilon(5S) \to h_b(\mathbf{2P})\ \pi^+\pi^-$
$\hookrightarrow \eta_b(\mathbf{2S})\ \gamma$

Mizuk et al. Belle PRL 109 (2012) 232002

$\Delta M_{HF}(\mathbf{2S}) = 24.3\ ^{+4.0}_{-4.5}$ MeV

First measurement





In agreement with theory

$\Gamma(2S) = 4 \pm 8$ MeV, < 24MeV @ 90% C.L.
expect ~4MeV

Branching fractions

$BF[h_b(1P) \to \eta_b(1S)\ \gamma] = 49.2 \pm 5.7^{+5.6}_{-3.3}$ %

$BF[h_b(2P) \to \eta_b(1S)\ \gamma] = 22.3 \pm 3.8^{+3.1}_{-3.3}$ %

$BF[h_b(2P) \to \eta_b(2S)\ \gamma] = 47.5 \pm 10.5^{+6.8}_{-7.7}$ %

Expectations

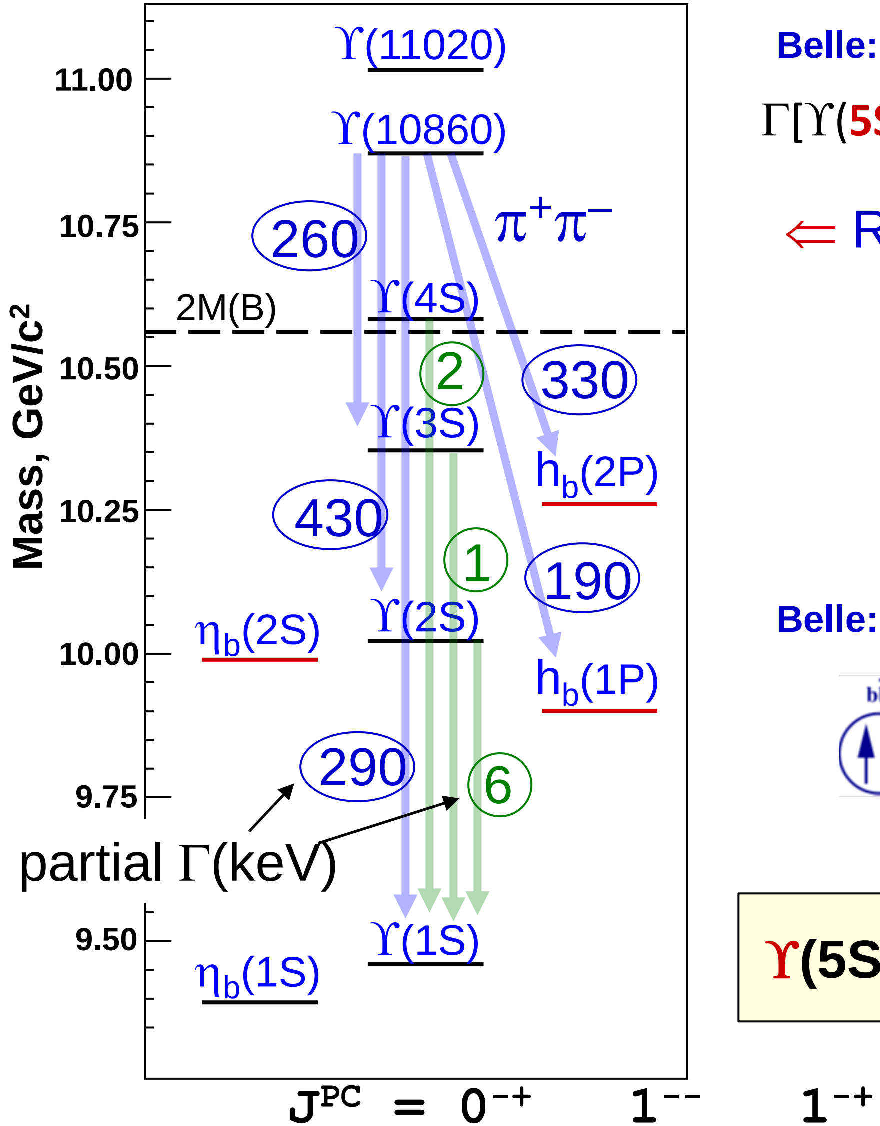
41% Godfrey Rosner PRD66,014012(2002)

13%

19%

c.f. BESIII $BF[h_c(1P) \to \eta_c(1S)\ \gamma] = 54.3 \pm 8.5$ % 39%

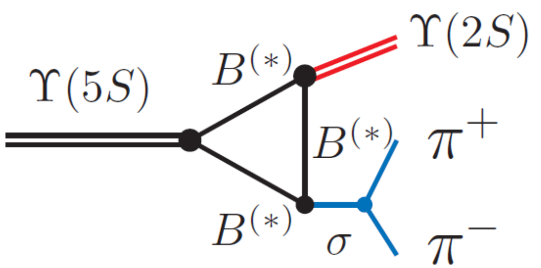
Anomalies in $\Upsilon(5S) \to (b\bar{b})\pi^+\pi^-$ transitions



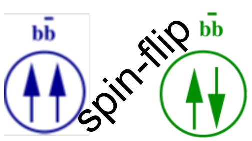
Belle: PRL100, 112001 (2008) ~100

$\Gamma[\Upsilon(5S) \to \Upsilon(1,2,3S)\,\pi^+\pi^-] >> \Gamma[\Upsilon(4,3,2S) \to \Upsilon(1S)\,\pi^+\pi^-]$

⇐ Rescattering of on-shell $B^{(*)}\bar{B}^{(*)}$?



Belle: PRL108, 032001 (2012)



expect suppression ~Λ_{QCD}/m_b

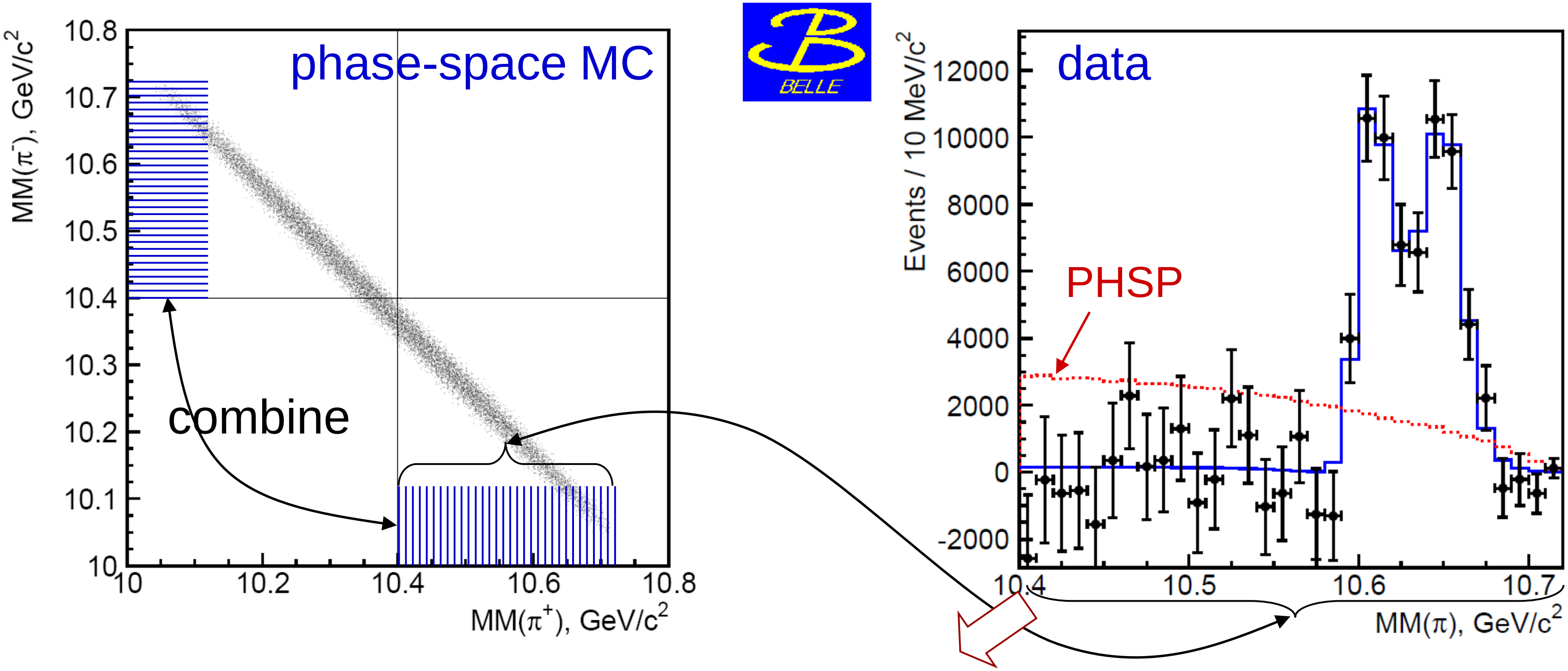
~~Heavy Quark Symmetry~~

$\Upsilon(5S) \to h_b(1,2P)\,\pi^+\pi^-$ are not suppressed

h_b production mechanism? ⇒ Study resonant structure in $h_b(mP)\pi^+\pi^-$

Resonant substructure of $\Upsilon(5S) \to h_b(1P)\,\pi^+\pi^-$

$P(h_b) = P_{\Upsilon(5S)} - P(\pi^+\pi^-)$ $\Rightarrow$ **$M(h_b\pi^+) = MM(\pi^-)$** $\Rightarrow$ ***measure $\Upsilon(5S)\to h_b\pi\pi$ yield in bins of $MM(\pi)$***



[preliminary]

Fit function $|BW(s,M_1,\Gamma_1) + ae^{i\phi}BW(s,M_2,\Gamma_2) + be^{i\psi}|^2\,\frac{qp}{\sqrt{s}}$

Results

$M_1 = 10605.1 \pm 2.2\,^{+3.0}_{-1.0}$ MeV/c² ~$B\bar{B}^*$ threshold

$\Gamma_1 = 11.4\,^{+4.5}_{-3.9}\,^{+2.1}_{-1.2}$ MeV $\quad a = 1.8\,^{+1.0}_{-0.7}\,^{+0.1}_{-0.5}$

$M_2 = 10654.5 \pm 2.5\,^{+1.0}_{-1.9}$ MeV/c² ~$B^*\bar{B}^*$ threshold

$\Gamma_2 = 20.9\,^{+5.4}_{-4.7}\,^{+2.1}_{-5.7}$ MeV $\quad \varphi = 188\,^{+44}_{-58}\,^{+4}_{-9}$ degree

Significances

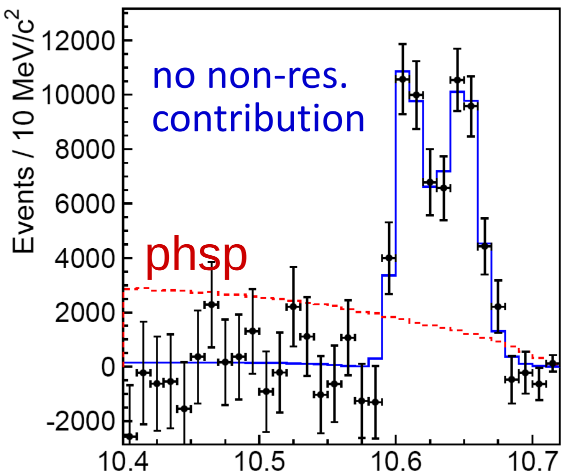
2 vs.1 : 7.4σ (6.6σ w/ syst)

2 vs.0 : 18σ (16σ w/ syst)

non-res. amplitude ~0

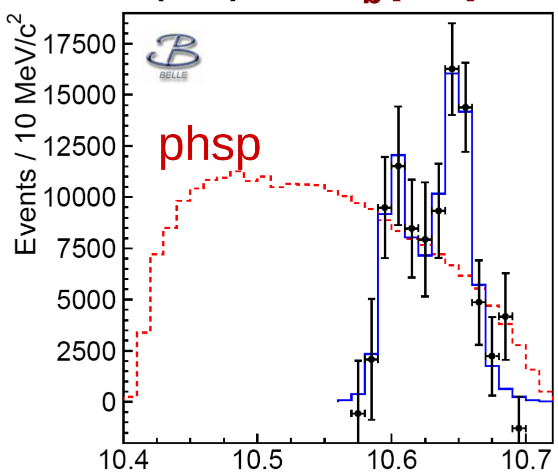
Resonant structure of $\Upsilon(5S) \to (b\bar{b})\pi^+\pi^-$

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



$M[\, h_b(1P)\ \pi^{\pm}\,]$

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



$M[\, h_b(2P)\ \pi^{\pm}\,]$

Two peaks are observed in all modes!

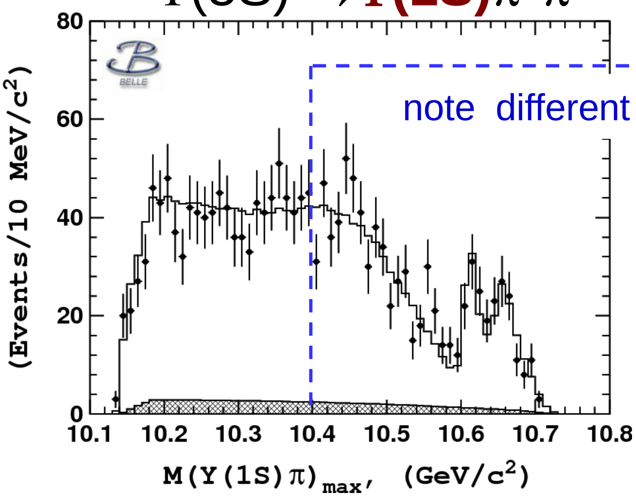
Belle: PRL108, 232001 (2012)

$Z_b(10610)$ and $Z_b(10650)$ should be multiquark states

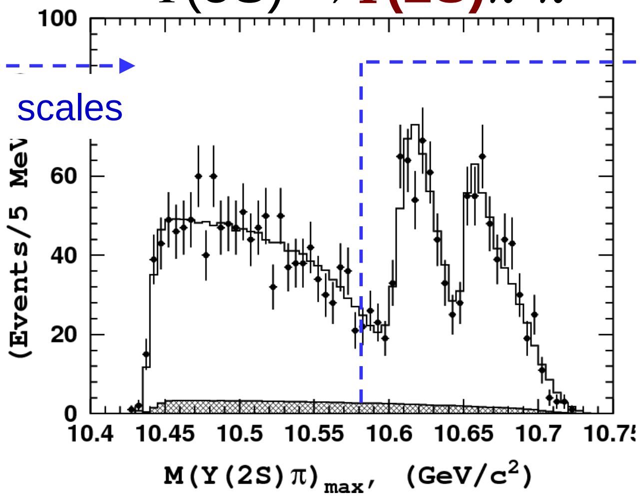
Dalitz plot analysis

note different scales

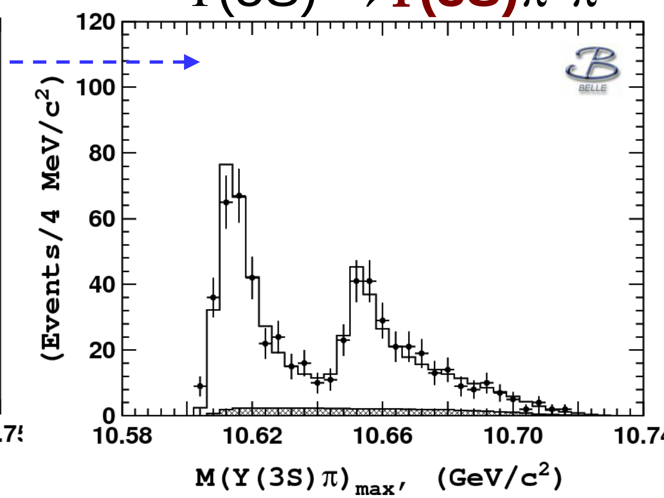
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$



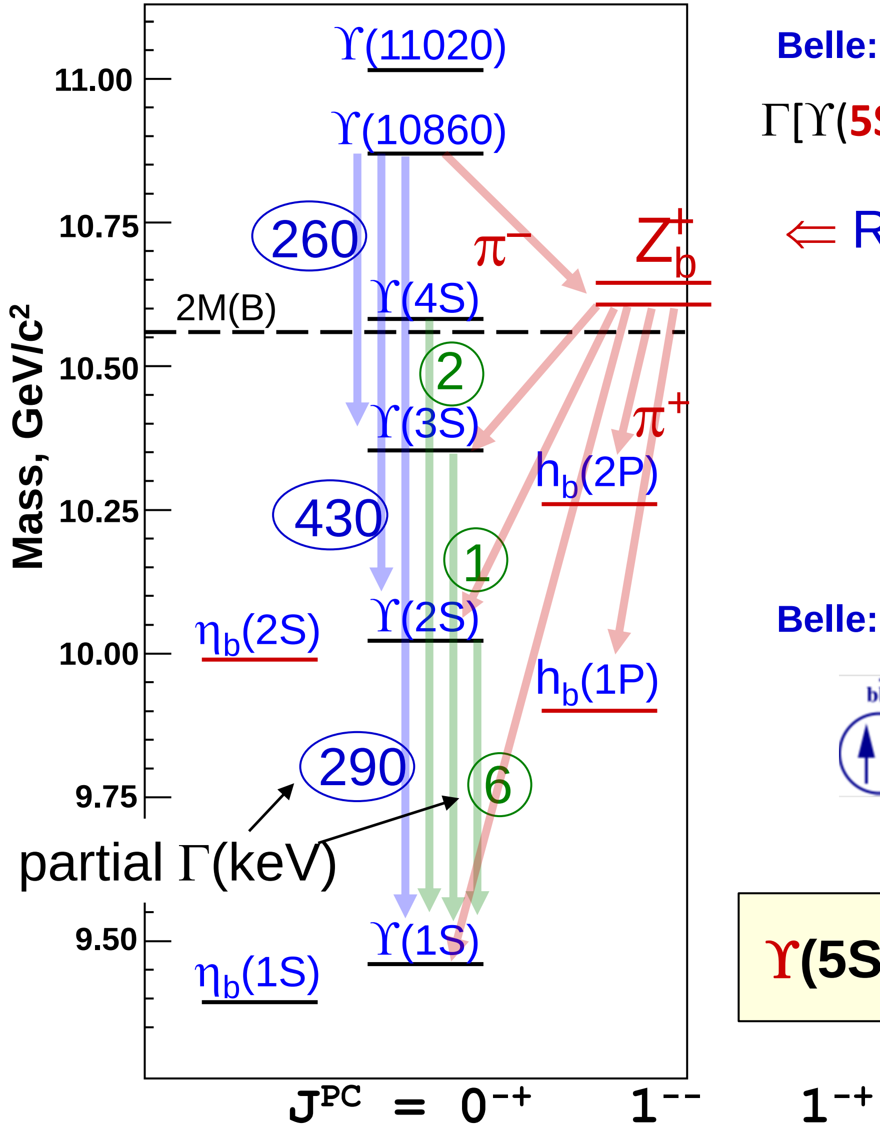
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$



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



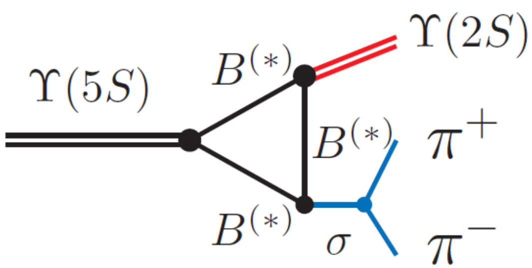
Anomalies in $\Upsilon(5S) \to (b\bar{b})\pi^+\pi^-$ transitions



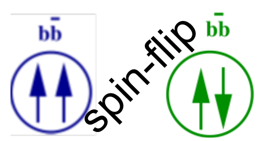
Belle: PRL100, 112001 (2008)

$$\Gamma[\Upsilon(\mathbf{5S}) \to \Upsilon(1,2,3S)\,\pi^+\pi^-] \overset{\sim 100}{>>} \Gamma[\Upsilon(\mathbf{4,3,2S}) \to \Upsilon(1S)\,\pi^+\pi^-]$$

$\Leftarrow$ Rescattering of on-shell $B^{(*)}\bar{B}^{(*)}$?



Belle: PRL108, 032001 (2012)



expect suppression $\sim\Lambda_{QCD}/m_b$

~~Heavy Quark Symmetry~~

Υ(5S) → h_b(1,2P) $\pi^+\pi^-$ are not suppressed

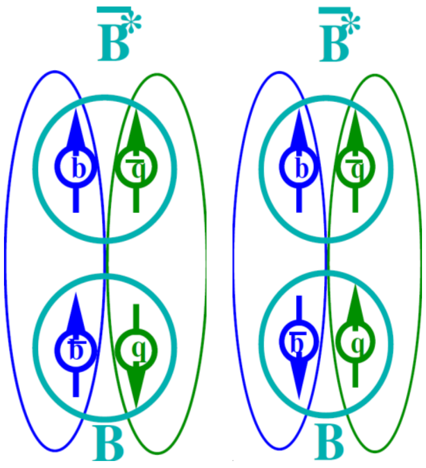
Heavy quark structure in Z_b

A.B. et al. PRD84 054010 (2011)

Wave func. at large distance – B(*)B*

$$|Z_b'\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} - \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$

$$|Z_b\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} + \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$



Explains

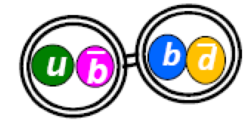
- Why $h_b\pi\pi$ is unsuppressed relative to $\Upsilon\pi\pi$
- Relative phase ~0 for Υ and ~180^0 for h_b
- Production rates of Z_b(10610) and Z_b(10650) are similar
- Widths –"–
- Dominant decays to B(*)B*

Other Possible Explanations

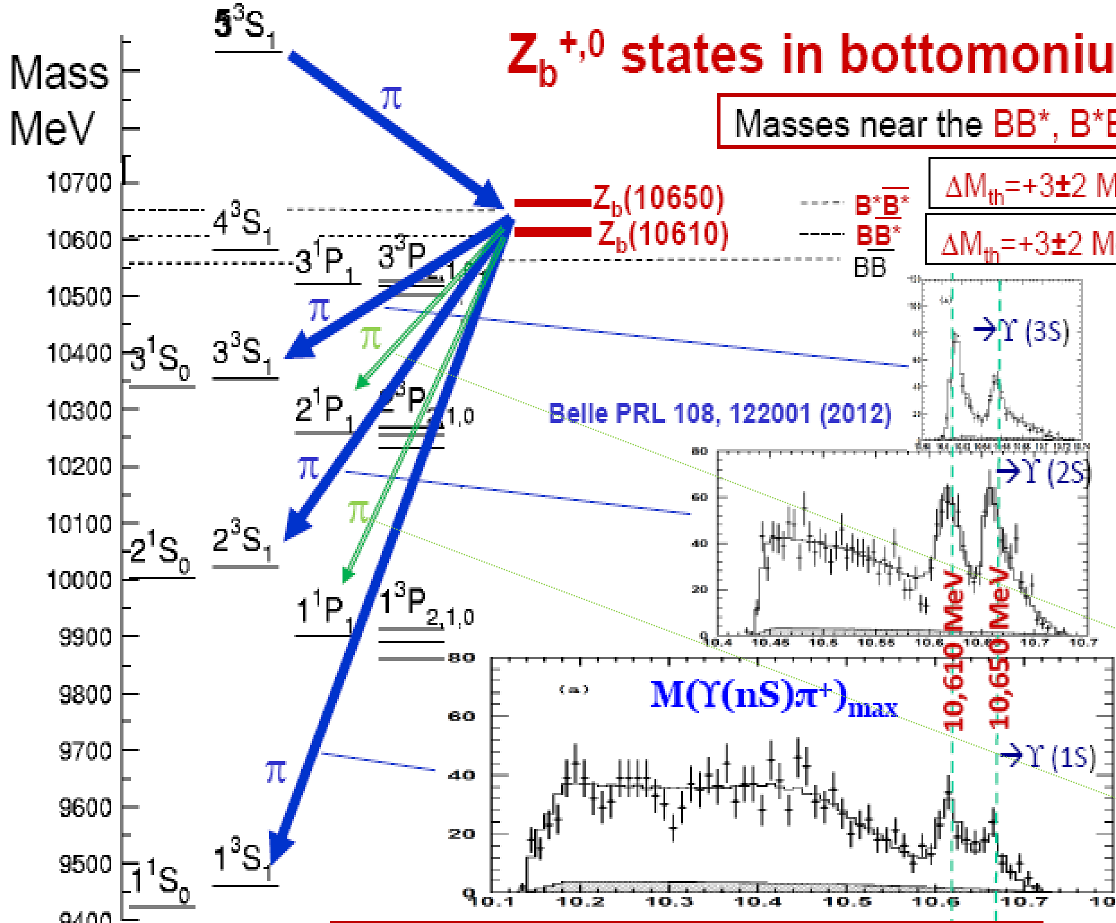
- Coupled channel resonances (I.V.Danilkin et al, arXiv:1106.1552)
- Cusp (D.Bugg Europhys.Lett.96 (2011),arXiv:1105.5492)
- Tetraquark (M.Karliner, H.Lipkin, arXiv:0802.0649)

Charged and neutral

$I^G=1^+$



$Z_b^{+,0}$ states in bottomonium



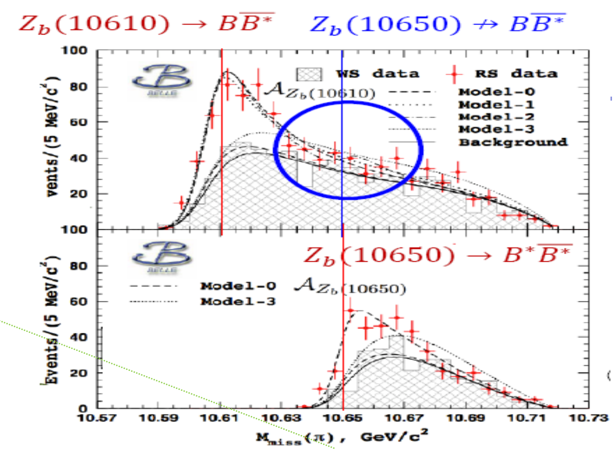
Masses near the $B\bar{B}^*$, $B^*\bar{B}^*$ thresholds

ΔM_{th}=+3±2 MeV

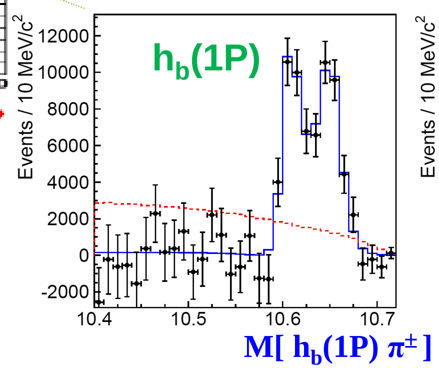
ΔM_{th}=+3±2 MeV

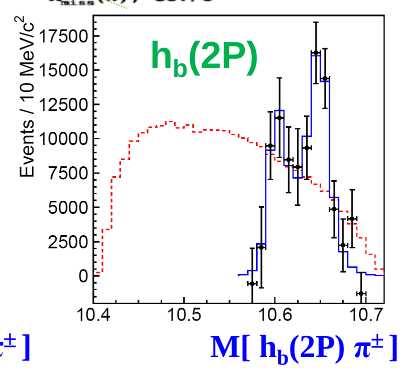
Γ 11.5 ± 2.2, 18.4 ± 2.4 MeV

Both $J^{P(C)}=1^{+(-)}$



Large rate to fall-apart modes observed

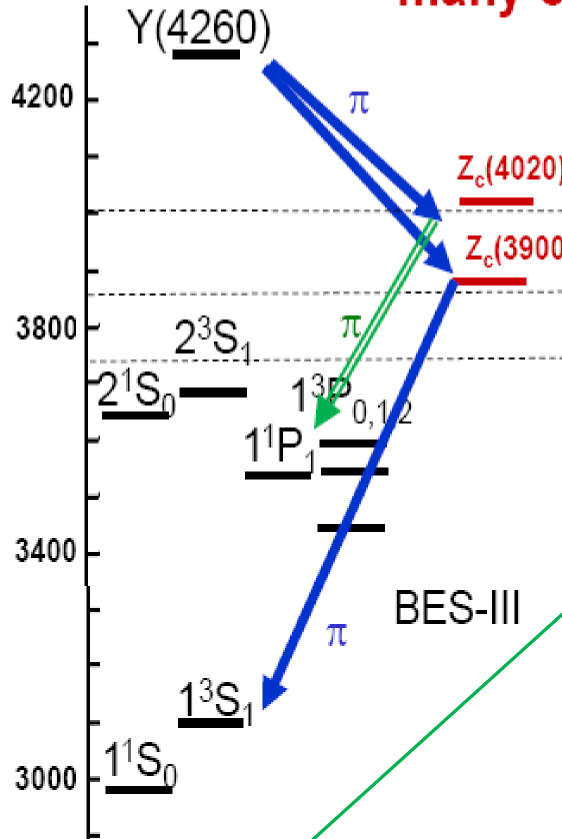




- Likely molecular states of $B\bar{B}^*$, $B^*\bar{B}^*$
- Tightly bound diquark tetraquarks

More near-threshold states: many of $Z_c^{+,0}$ charmonium states

- Expected from Z_b states and Heavy Quark Symmetry



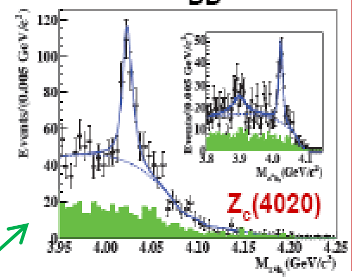
ΔM_{th}=+7±2 MeV

ΔM_{th}=+11±3 MeV

Masses a few MeV above the $D\bar{D}^*$, $D^*\bar{D}^*$ thresholds ✓

Γ 13 ±5 MeV / 28.1± 2.6 ✓

$J^{P(C)}=1^{+(-)}$ (established only for $Z_c(3900)$) ✓

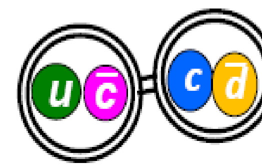


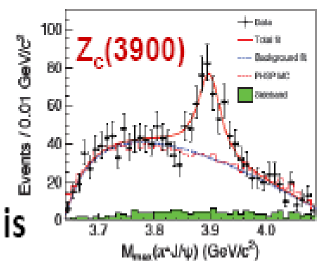
Large rate to fall-apart modes

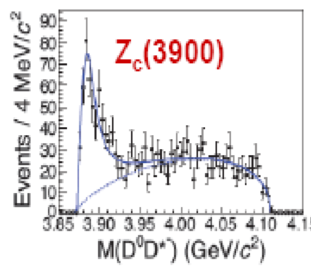
$$\frac{\Gamma[Z_c(4025)\to D^*D^*]}{\Gamma[Z_c(4020)\to \pi h_c]} \sim 9.$$

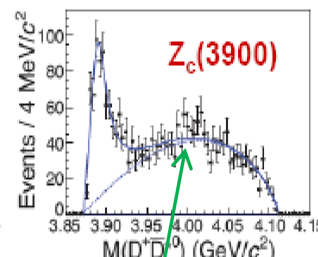
$$\frac{\Gamma[Z_c(3900)\to D\bar{D}^*]}{\Gamma[Z_c(3900)\to \pi J/\psi]} = 6.2 \pm 1.1_{\text{stat}} \pm 2.7_{\text{sys}}$$

✓







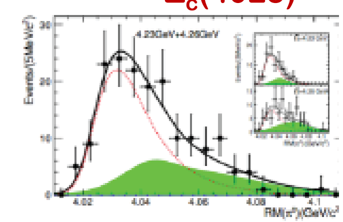


Large non $Z_c\pi$ component is observed in the $Y(4260)\to h_c\pi^+\pi^-$ amplitude.

(also seen by Belle)

Charged and neutral versions detected / $I^G=1^+$

$Z_c(4025)$



Molecular states of $D\bar{D}^*$, $D^*\bar{D}^*$?
Diquark tetraquarks ?

No sign of Zc(4025) decay in DD*

M.Voloshin,

PRD 84 031502 (2011)

$$\left|Z_b^{'}\right\rangle = \frac{1}{\sqrt{2}} 0^-_{bb} \otimes 1^-_{Qq} - \frac{1}{\sqrt{2}} 1^-_{bb} \otimes 0^-_{Qq}$$

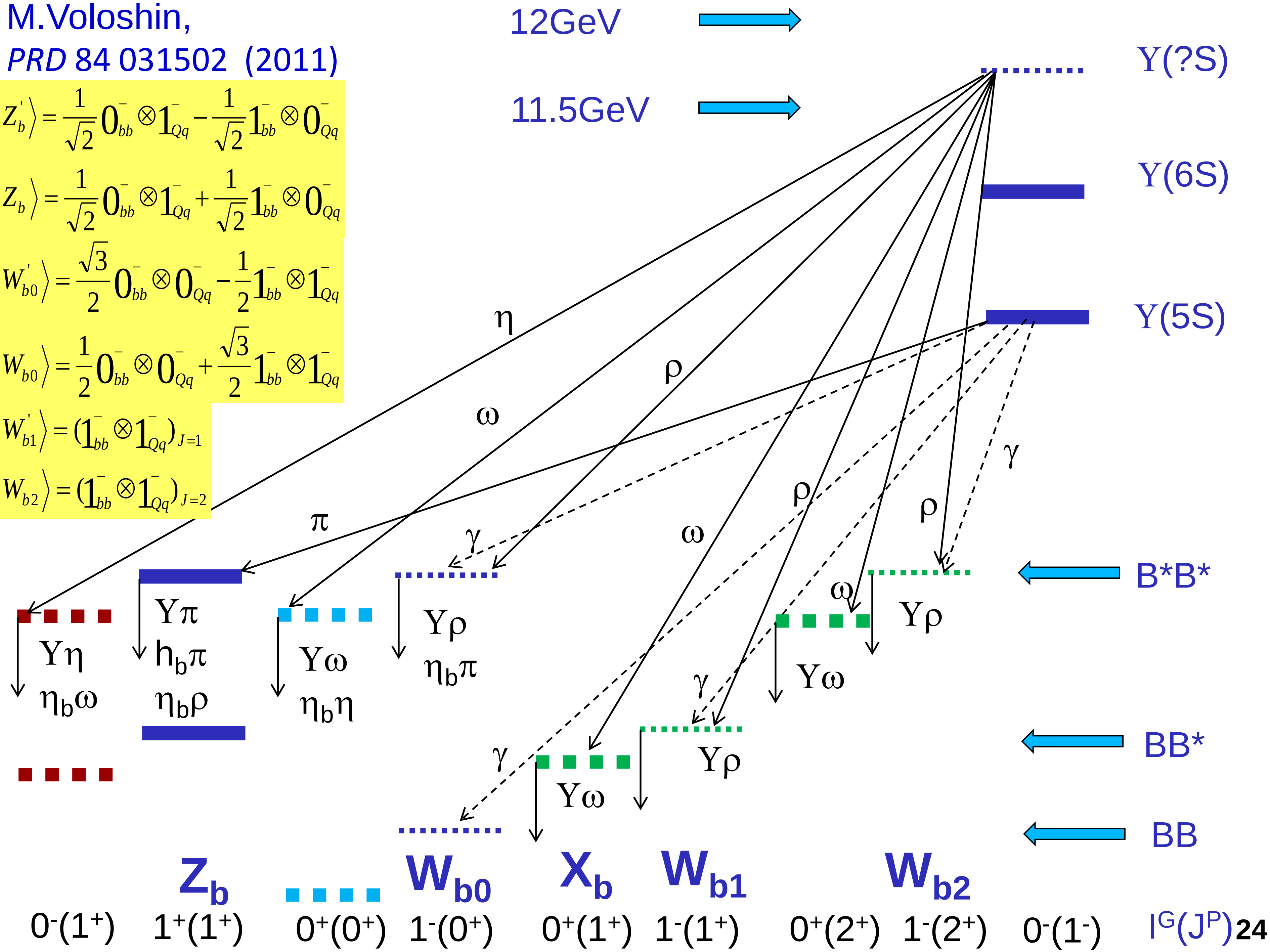
$$\left|Z_b\right\rangle = \frac{1}{\sqrt{2}} 0^-_{bb} \otimes 1^-_{Qq} + \frac{1}{\sqrt{2}} 1^-_{bb} \otimes 0^-_{Qq}$$

$$\left|W_{b0}^{'}\right\rangle = \frac{\sqrt{3}}{2} 0^-_{bb} \otimes 0^-_{Qq} - \frac{1}{2} 1^-_{bb} \otimes 1^-_{Qq}$$

$$\left|W_{b0}\right\rangle = \frac{1}{2} 0^-_{bb} \otimes 0^-_{Qq} + \frac{\sqrt{3}}{2} 1^-_{bb} \otimes 1^-_{Qq}$$

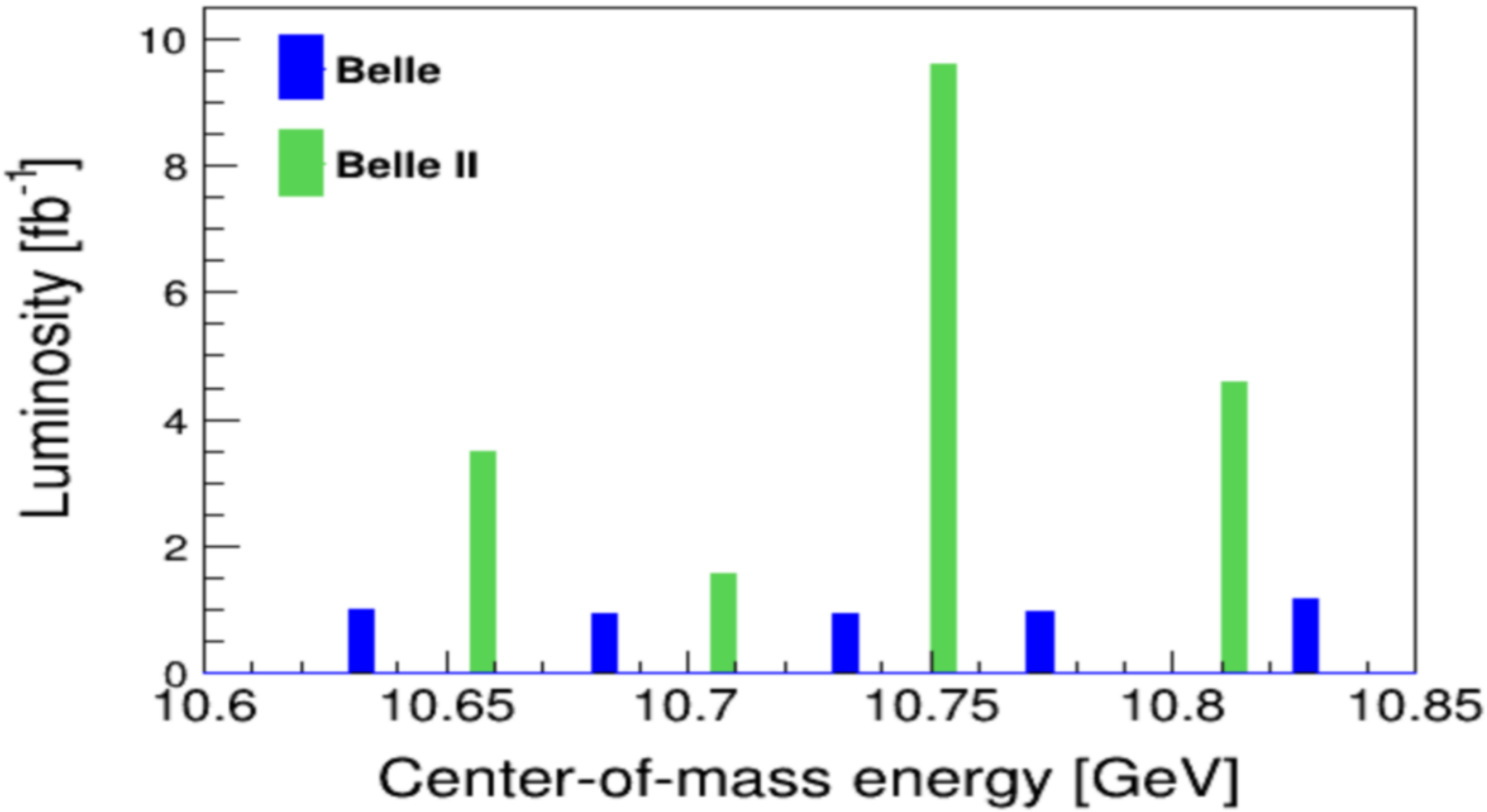
$$\left|W_{b1}^{'}\right\rangle = (1^-_{bb} \otimes 1^-_{Qq})_{J=1}$$

$$\left|W_{b2}\right\rangle = (1^-_{bb} \otimes 1^-_{Qq})_{J=2}$$



Belle's experience showed that the data collected above Υ(4S) is important not only for the study of highly excited bottomonium, but also for the search for exotic states and states of ordinary bottomonium that have not been observed before.

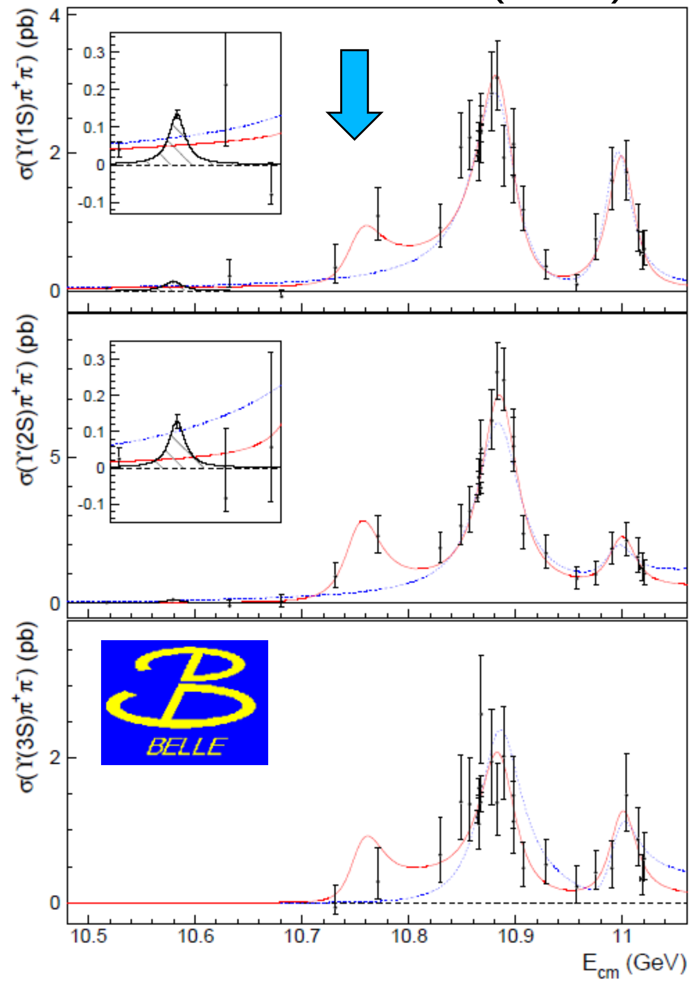
Energy scan took place Nov. 10 –29, 2021



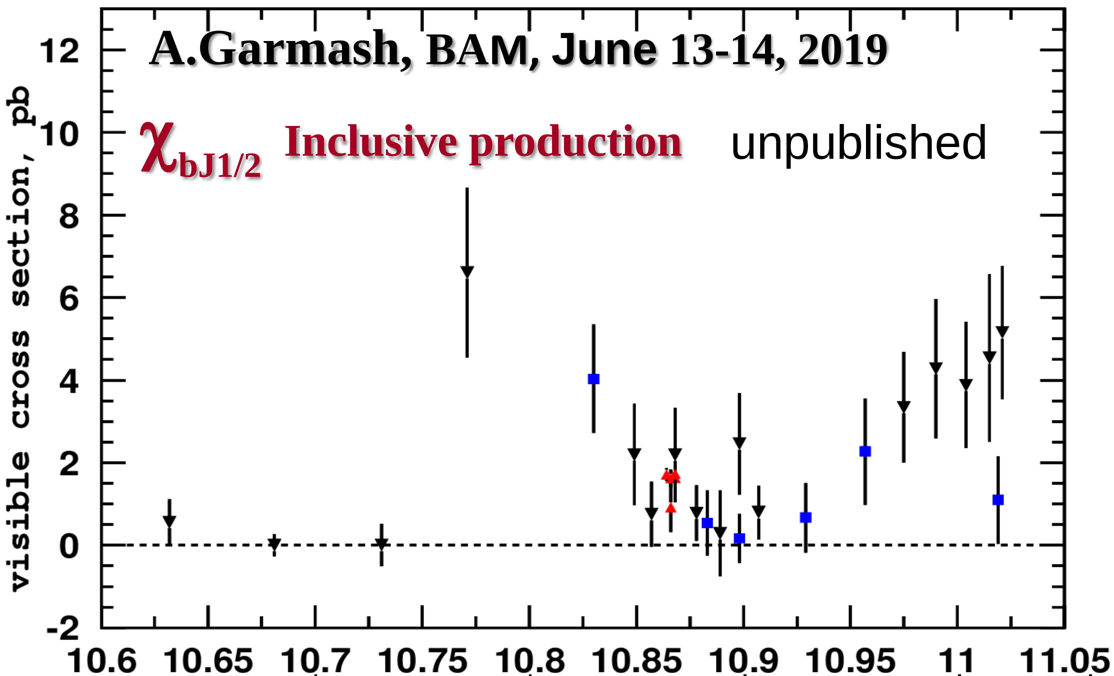
$\Upsilon(10750)$

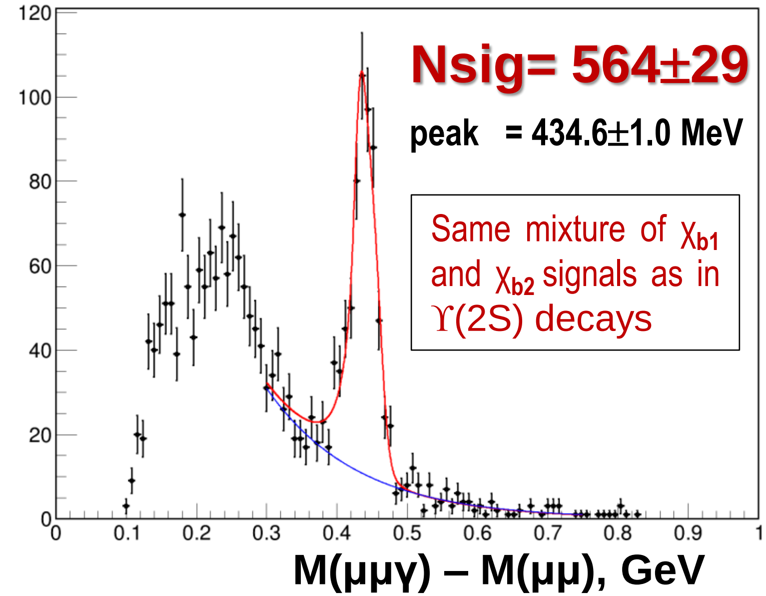
- Scan points: ~1 fb-1 each
- 1 point “on-peak”
- 2-3 points in the region of interest
- Total significance: 5.2s

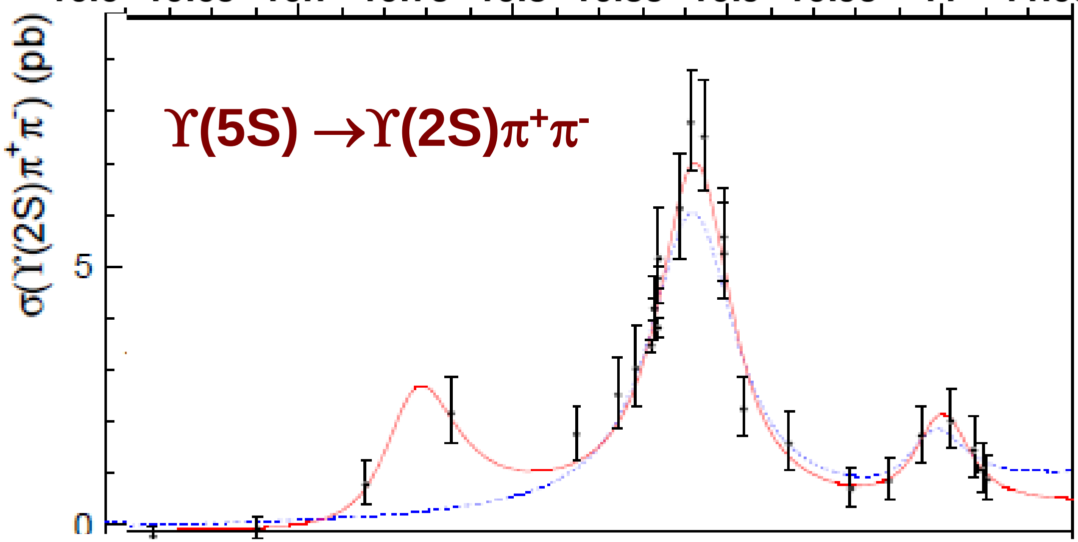
JHEP 1910, 220 (2019)



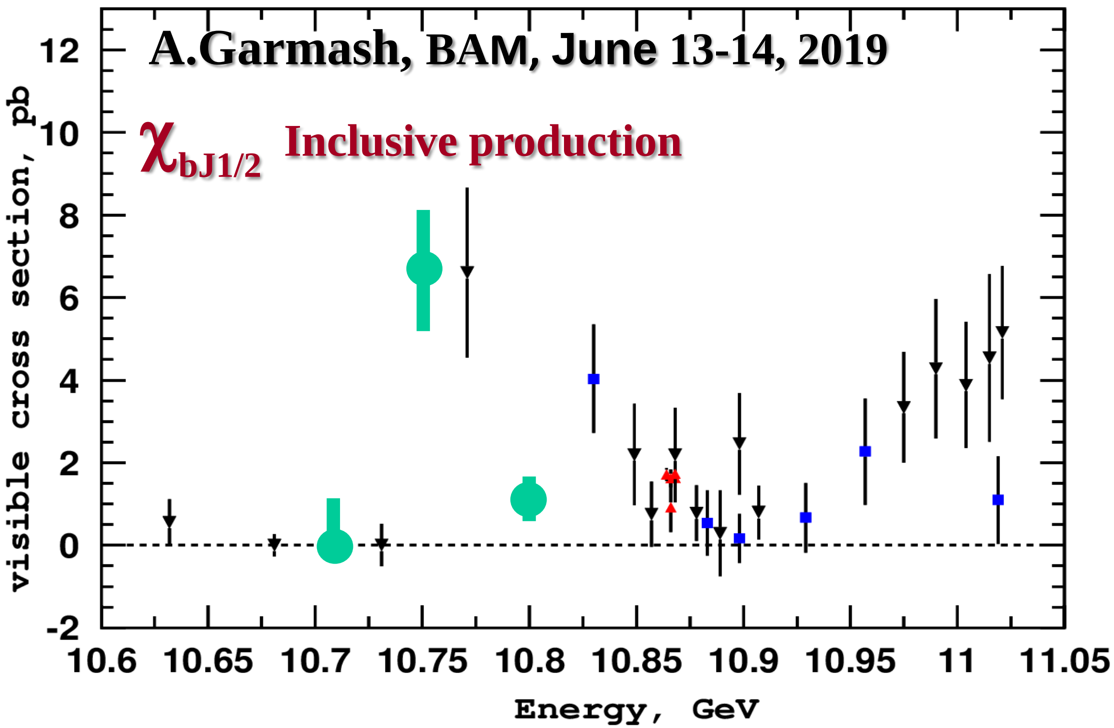
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0\,+1.0}_{-4.5\,-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5\,+0.5}_{-3.9\,-1.1}$	$23.8^{+8.0\,+0.7}_{-6.8\,-1.8}$	$35.5^{+17.6\,+3.9}_{-11.3\,-3.3}$





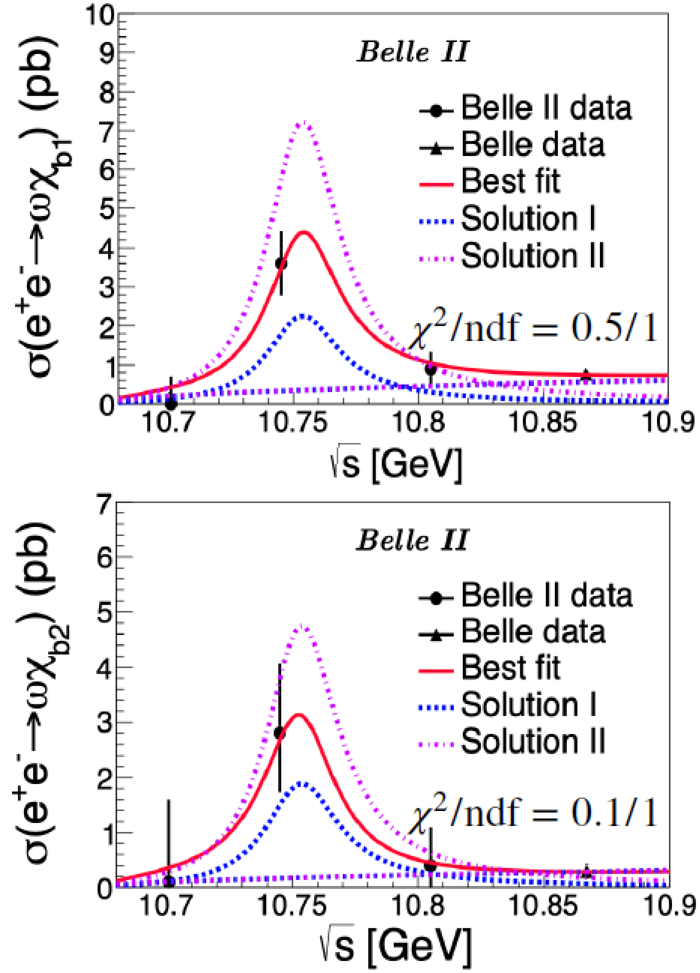


$\Upsilon(1D)\pi^+\pi^-$ and $\chi_b\omega[\pi^+\pi^-\pi^0]$ modes combined can explain no more than 60% of the observed χ_b signal at $\Upsilon(5S)$.



The $e^+e^- \to \omega\chi_{b1/2}$ cross section peak at $\Upsilon(10753)$ while no obvious peak at $\Upsilon(10860)$ is found!

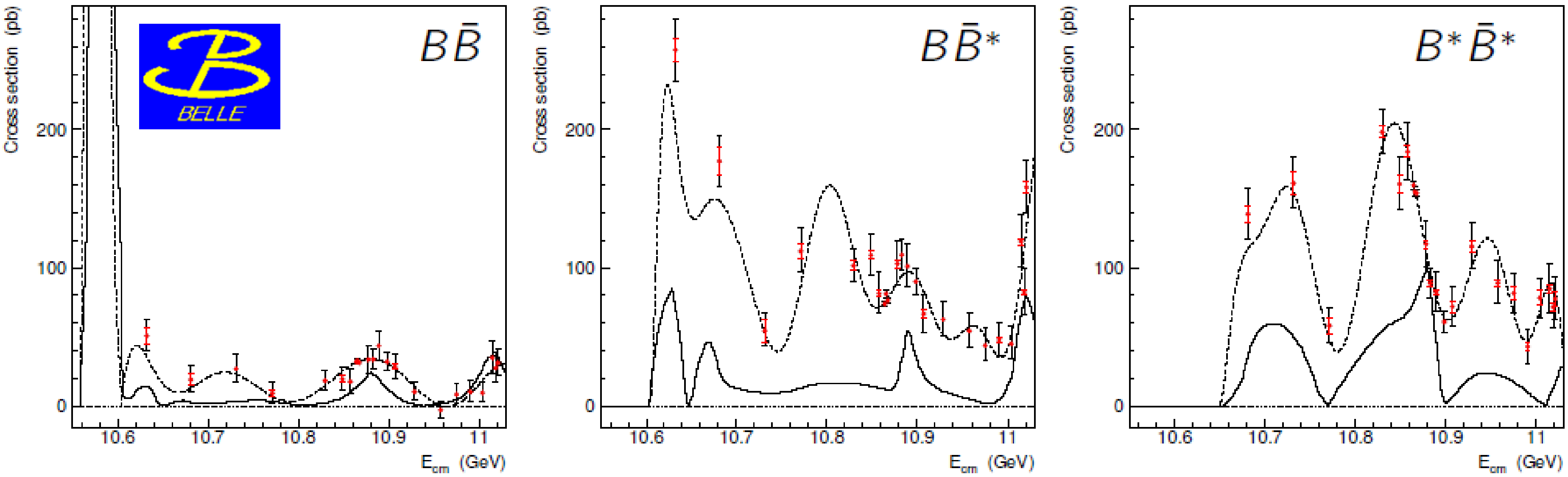
arXiv:2208.13189



Why two neighboring bottomonium (mass difference 110 MeV) with the same quantum numbers are so different in their properties? What distinguishes them in nature?

Belle measurement of $e^+e^- \longrightarrow B^{(*)}\bar{B}^{(*)}$

JHEP 06,137 (2021)

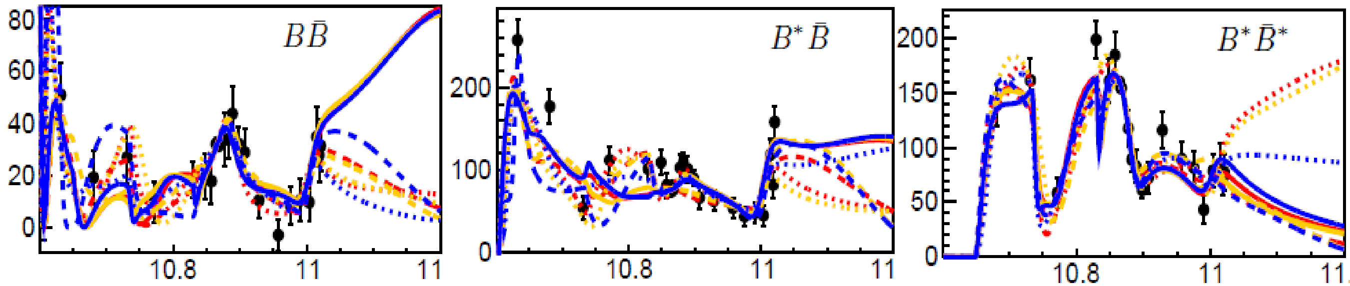


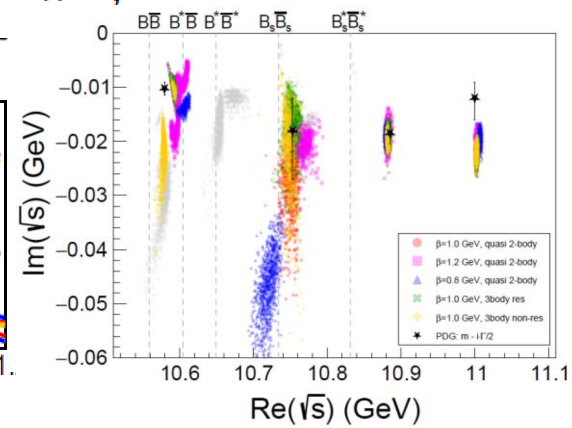
- Oscillatory behavior
- Positions of minima roughly coincide with Unitarized Quark Model prediction: Ono,Sanda,Tornqvist PRD34,186(1986)

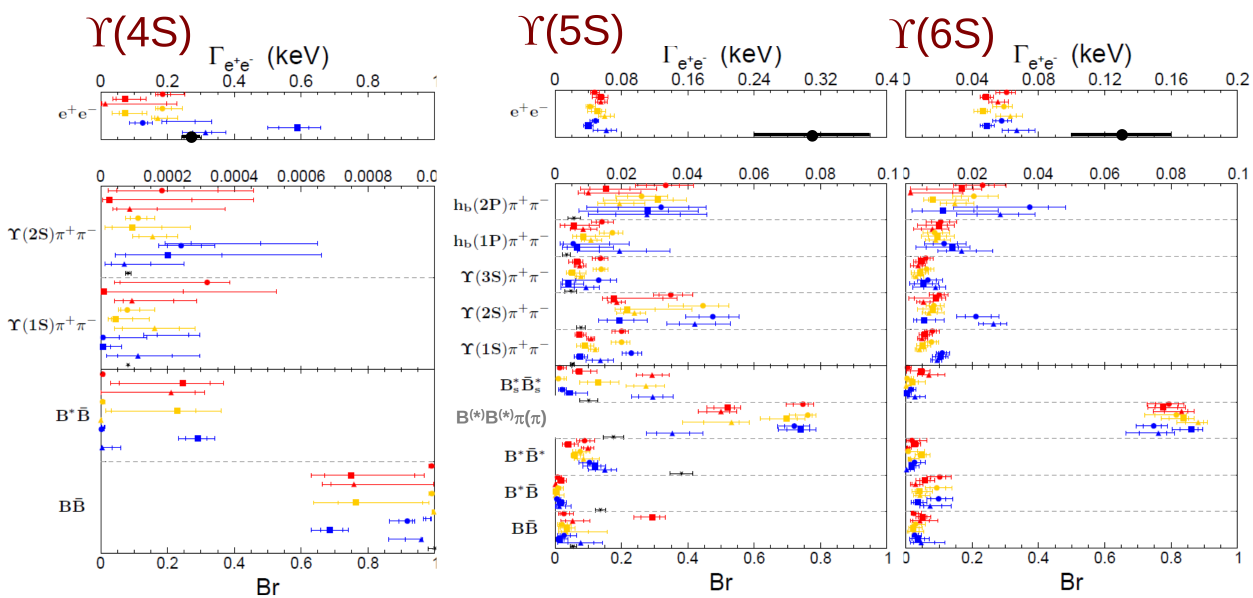
Combined analysis of Belle scan data

Hüsken, Mitchell and Swanson, arXiv:2204.11915

Channels considered: $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$, $B_s^*\bar{B}_s^*$, $\Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, $\Upsilon(3S)\pi^+\pi^-$, $h_b(1P)\pi^+\pi^-$, $h_b(2P)\pi^+\pi^-$







Need 4 poles to describe data: $\Upsilon(4S)$, $\Upsilon(10753)$, $\Upsilon(5S)$, $\Upsilon(6S)$.

Determine

- Pole positions
- Branching fractions
- Electron widths
- Energy dependence of all scattering amplitudes

(—•— - PDG)

Method

$$M_{bc} = \sqrt{E_b^2 - P_B^2}$$

- Reconstruct one B meson using custom FEI.
- Use M_{bc} distributions to identify signals.

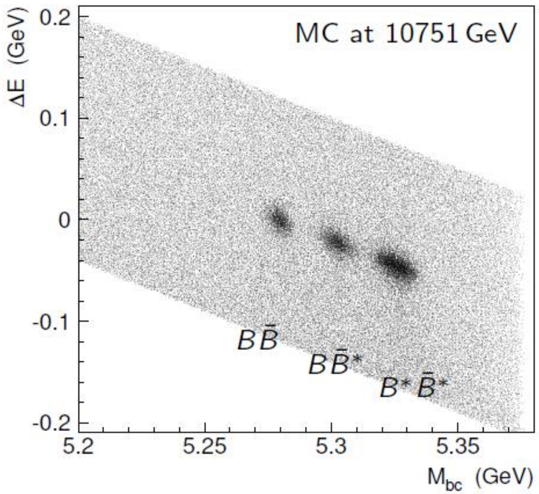
E_b − Beam energy

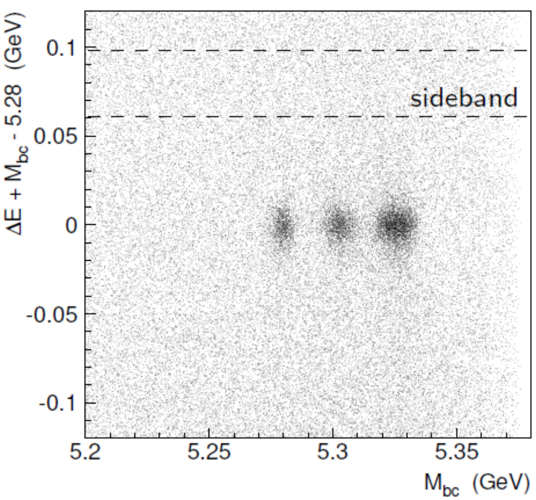
P_B −Measured B meson momentum

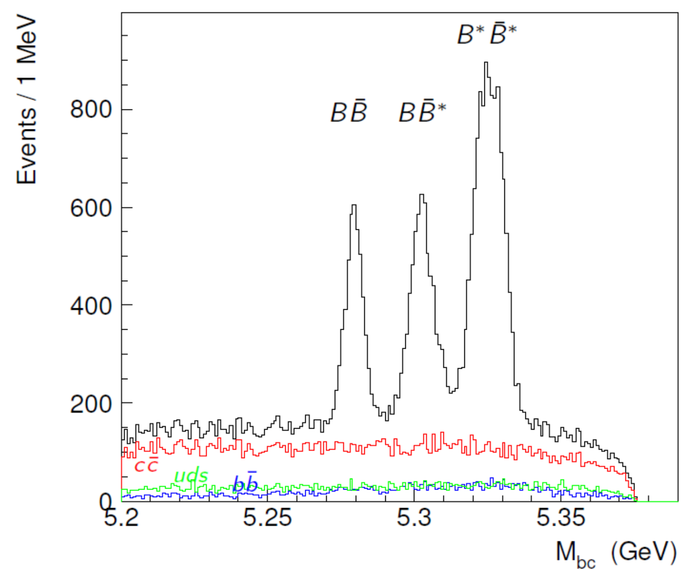
$$\Delta E' = \Delta E + M_{bc} - 5.28(GeV)$$

$$P_B \approx \sqrt{2M(E_b - M)} \qquad B^* \to B\gamma$$

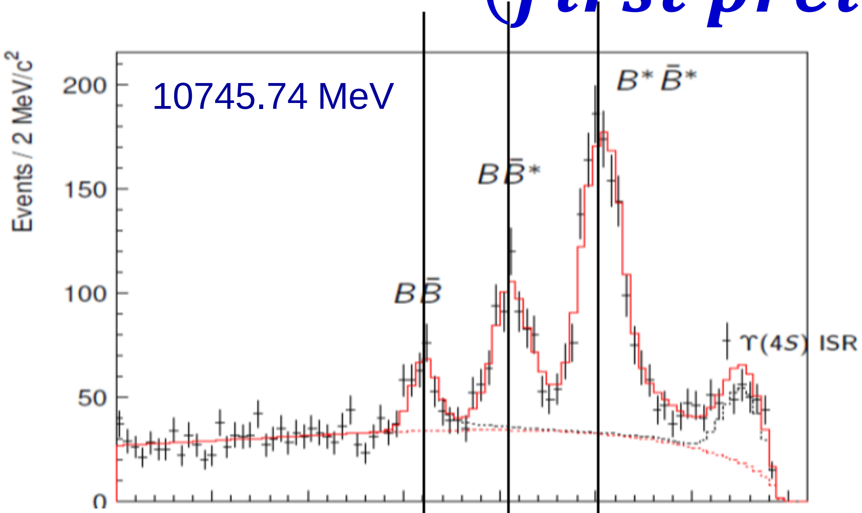
$$\sigma(M_{bc}) = \frac{P_B \cdot \sigma(P_B)}{M_{bc}}$$

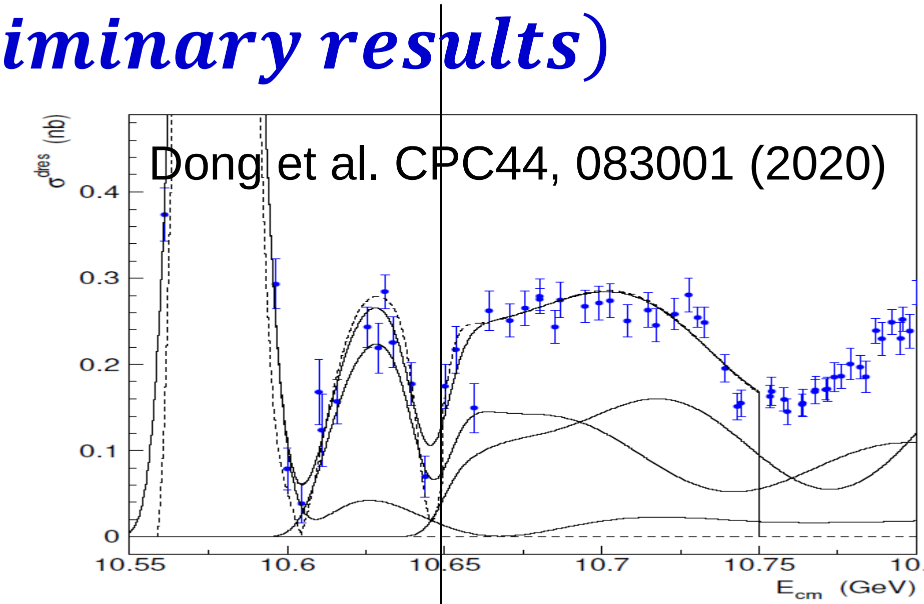


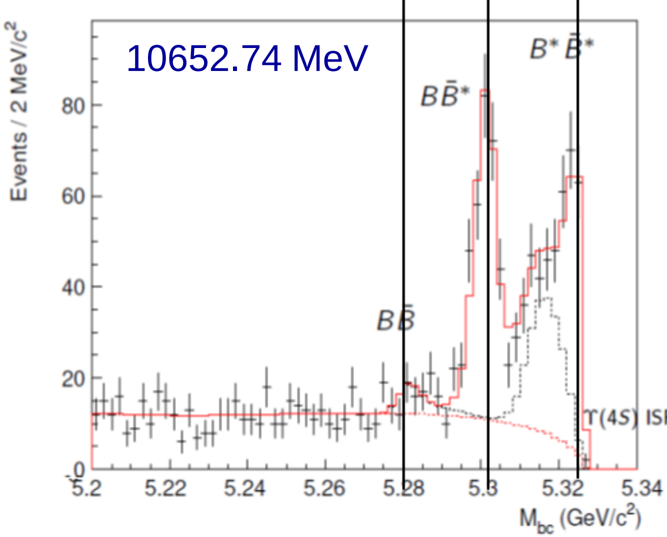


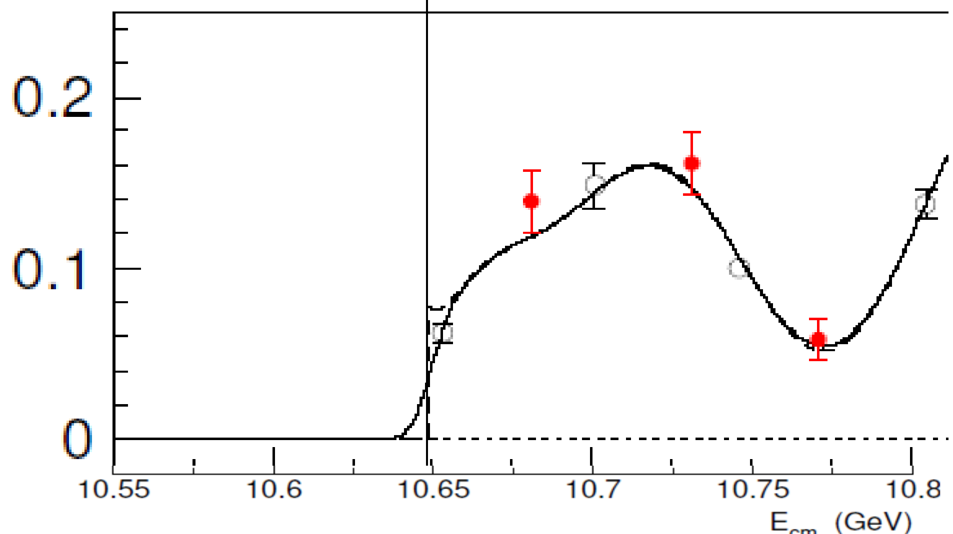


Belle-II $e^+e^- \longrightarrow B^*\bar{B}^*$ measurements
$(first\ preliminary\ results)$

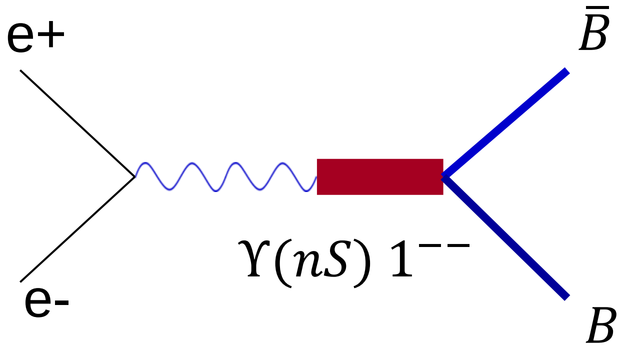








$2M_{B^{*+}} = 10649.4 \pm 0.5 MeV$



Particles scattering with angular momentum ℓ in the rectangular spherical potential hole U(r)=-U, for <a and U(r)=0 for r>a. In our problem BB pair is produced in a state with an orbital angular momentum $\ell = 1$.

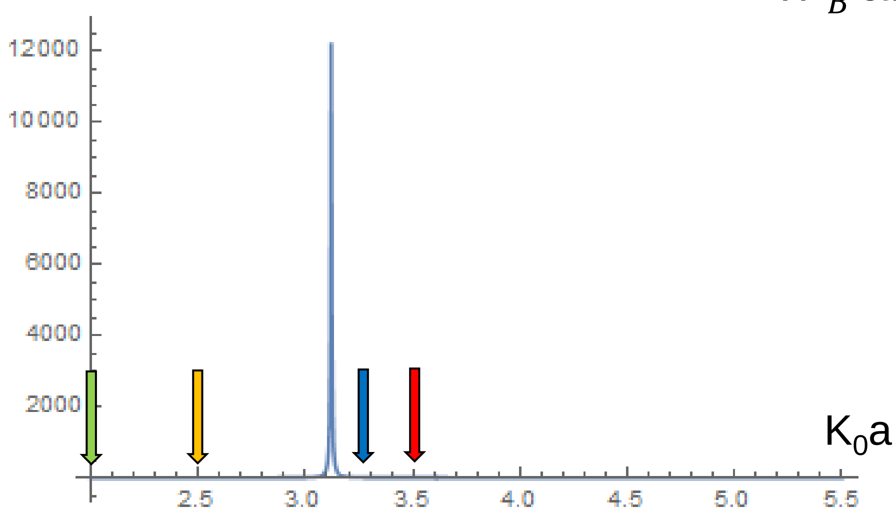
Schrödinger equation inside the potential hole has the form:

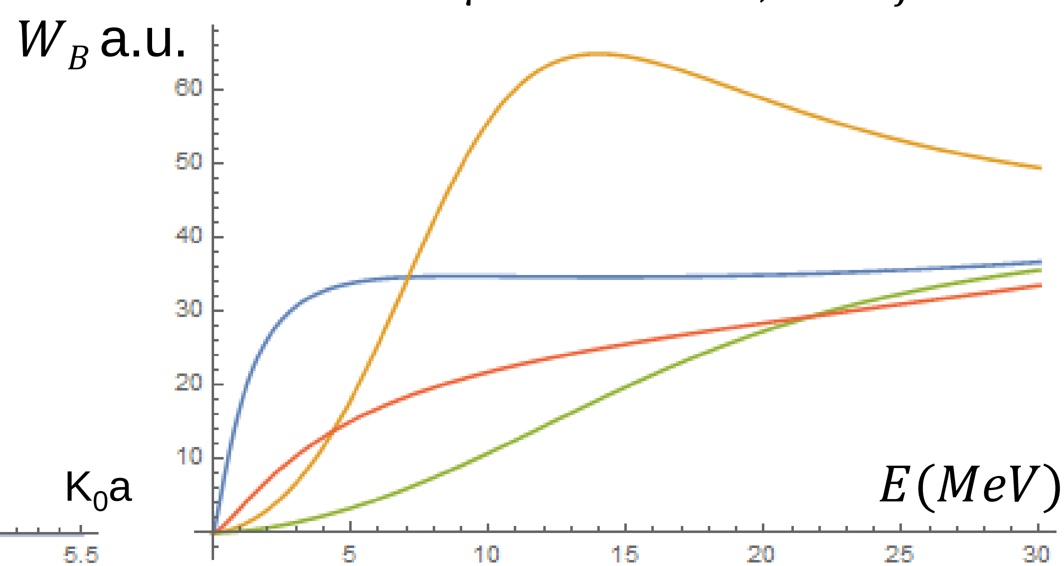
$$\frac{d^2}{dr^2}u(r) + \frac{\mu}{\hbar^2}\left(E - \frac{\hbar^2 l(l+1)}{\mu r^2} - U\right)u(r) = 0, \text{ where } \quad k = \frac{1}{\hbar}\sqrt{\mu E},\ u(r) = kr\Psi$$

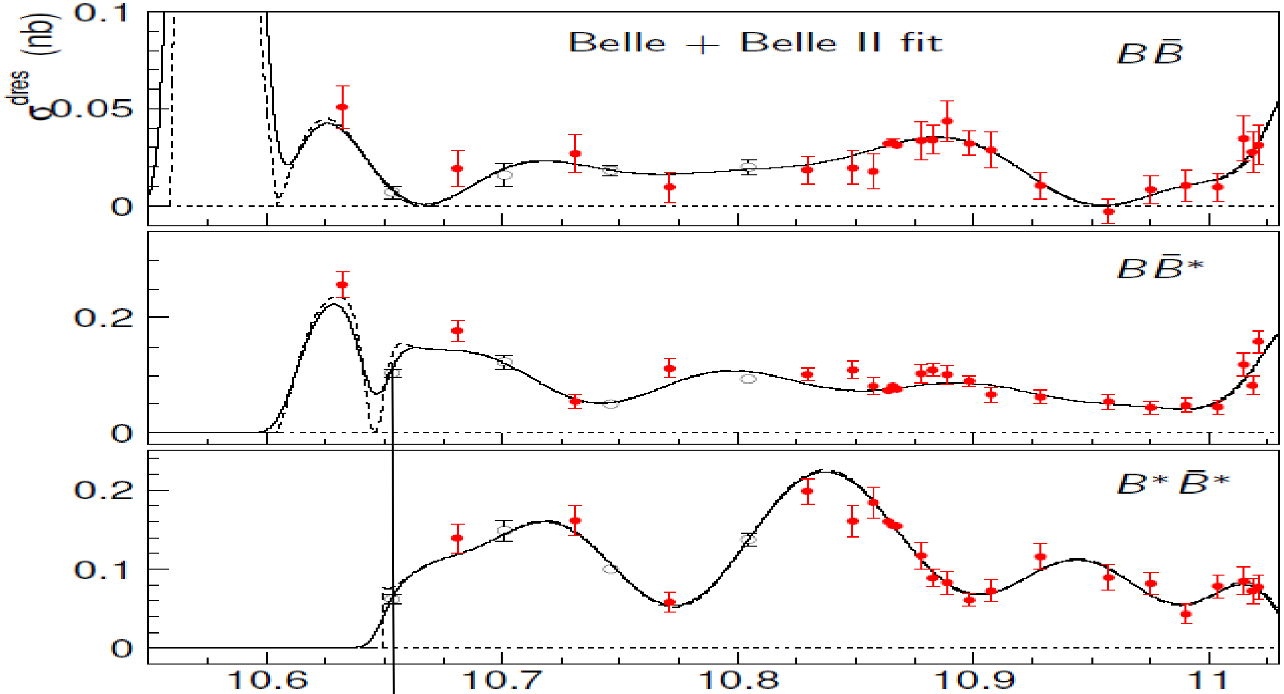
Milstein,A.,Salnikov,S.Phys.Rev.D 104 (2021) 1, 014007

$$W_B \sim k\left|\frac{d\Psi}{dr}\right|^2_{r\to 0} \qquad K = \frac{1}{\hbar}\sqrt{\mu(E+U)} \qquad K_0 = \frac{1}{\hbar}\sqrt{\mu U}$$

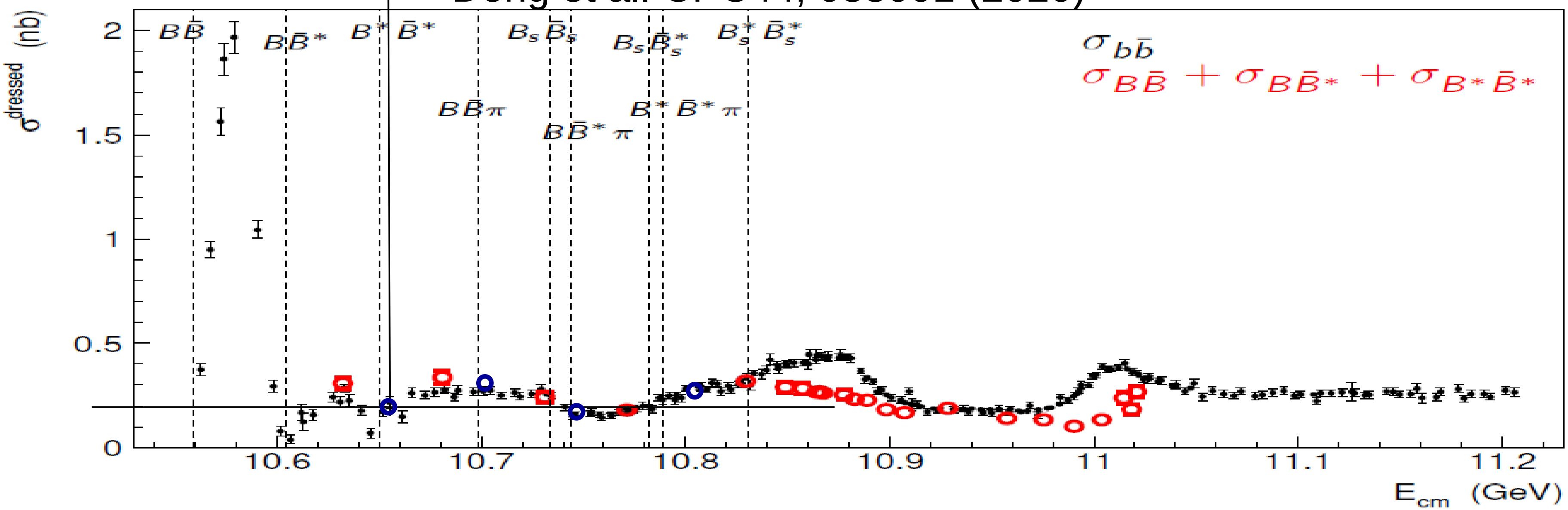
$$\mu = 5300 MeV, a = 1 fm$$







Dong et al. CPC44, 083001 (2020)



To verify the existence of a B*B* bound state near the threshold, a detailed scan must be performed in this energy region. We can also expect a significant violation of isospin in the near-threshold region.

Necessary to look for hadronic transitions to the bottomonium ground states

$\psi_{10} = 1^{--}H \otimes 0^{++}SLB$, $\psi_{11} = 1^{--}H \otimes 1^{++}SLB$, $\psi_{12} = 1^{--}H \otimes 2^{++}SLB$,
and $\psi_{01} = 0^{-+}H \otimes 1^{+-}SLB$ ("SLB" - in the limit of spinless b quark states)

M.Voloshin,
PRD 85 (2012) 034024

State	Decomposition into $b\bar{b}$ spin eigenstates
$B\bar{B}$	$\frac{1}{2\sqrt{3}}\psi_{10} + \frac{1}{2}\psi_{11} + \frac{\sqrt{5}}{2\sqrt{3}}\psi_{12} + \frac{1}{2}\psi_{01}$
$B\bar{B}^*$	$\frac{1}{\sqrt{3}}\psi_{10} + \frac{1}{2}\psi_{11} - \frac{\sqrt{5}}{2\sqrt{3}}\psi_{12}$
$(B^*\bar{B}^*)_{S=0}$	$-\frac{1}{6}\psi_{10} - \frac{1}{2\sqrt{3}}\psi_{11} - \frac{\sqrt{5}}{6}\psi_{12} + \frac{\sqrt{3}}{2}\psi_{01}$
$(B^*\bar{B}^*)_{S=2}$	$\frac{\sqrt{5}}{3}\psi_{10} - \frac{\sqrt{5}}{2\sqrt{3}}\psi_{11} + \frac{1}{6}\psi_{12}$

Spin eigenstate	Expected decays
ψ_{10}	$\Upsilon(nS)\,\pi^+\pi^-$, $\Upsilon(nS)\,K^+K^-$ in S wave
ψ_{11}	$\Upsilon(nS)\,\eta$, $\Upsilon(nS)\,\eta'$
ψ_{11}, ψ_{12}	$\Upsilon(nS)\,\pi^+\pi^-$, $\Upsilon(nS)\,K^+K^-$ in D wave
ψ_{01}	$\eta_b(nS)\,\omega$, $\eta_b(nS)\,\phi$, $h_b(nP)\,\eta$, $h_b(nP)\,\eta'$

$\sigma(B\bar{B})/\sigma(B\bar{B}^*)/\sigma(B^*\bar{B}^*{}_{s=0})/\sigma(B^*\bar{B}^*{}_{s=2}) = 1:4:\frac{1}{3}:\frac{20}{3}$

Mixing $(B^*\bar{B}^*{}_{s=0})/(B^*\bar{B}^*{}_{s=2})$? ->

$\frac{d}{d\cos\theta}\sigma(B^*\bar{B}^*{}_{s=0}) = 1-(\cos\theta)^2$, $\frac{d}{d\cos\theta}\sigma(B^*\bar{B}^*{}_{s=2}) = 1-\frac{1}{7}(\cos\theta)^2$

It is necessary to measure the angular distribution of B* production near the threshold

It can be concluded that at present the physics of heavy quarkonium is poorly understood and additional experimental data are required at energies above Y(4S) up to the maximum achievable by KEKB

The experimental data obtained by Belle and Belle-II above the Y(4S) resonance have already provided interesting results

What tasks can be formulated today for this area of research?

- Measurement of the Energy Dependence of processes with the emission of Light Hadrons and the transition to Light Bottomonium States
- Detailed study of the properties of Y(10750), Y(5S), Y(6S), $Z_b(10610)$, $Z_b(10650)$
- Search for G-odd partners of Zb(10610), Zb(10650)
- Search for a bottomonium partner of X(3872)
- Detailed study of all processes near two-particle thresholds, especially $B^{(*)}B^{(*)}$, B_1B, B_0B^* and $B_s^{(*)}B_s^{(*)}$
- Search for P-wave J=1/2 states of B and B_s mesons
- And many others…

A more detailed discussion of the physical program for the energy region above Y(4S) can be found in AB, R.Mizuk, M.Voloshin Mod.Phys.Lett.A 32 (2017) 04, 1750025, but even now one can see problems not covered in this article

Conclusion

The understanding of the physics of highly excited heavy quarkonium is very incomplete.

New data are needed to search for patterns that may indicate possible theoretical solutions.

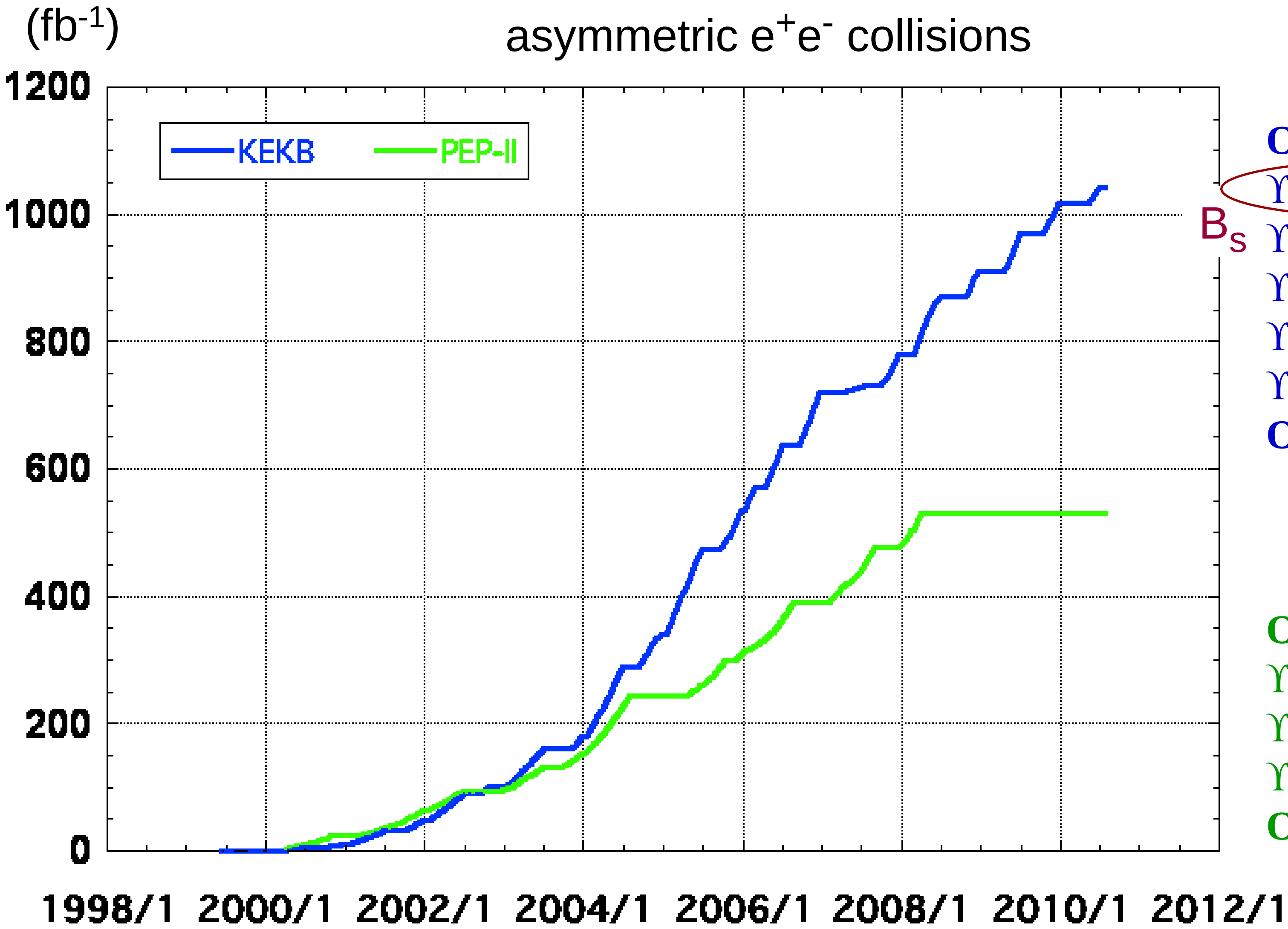
Bottomonium is a good object for detailed study.

KEKB is a unique experimental facility in which the phenomena discussed can be studied under well controlled conditions.

Thank you for your attention!

Back up slides

Integrated Luminosity at B-factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 24 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan :

~100 fb-1

530 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

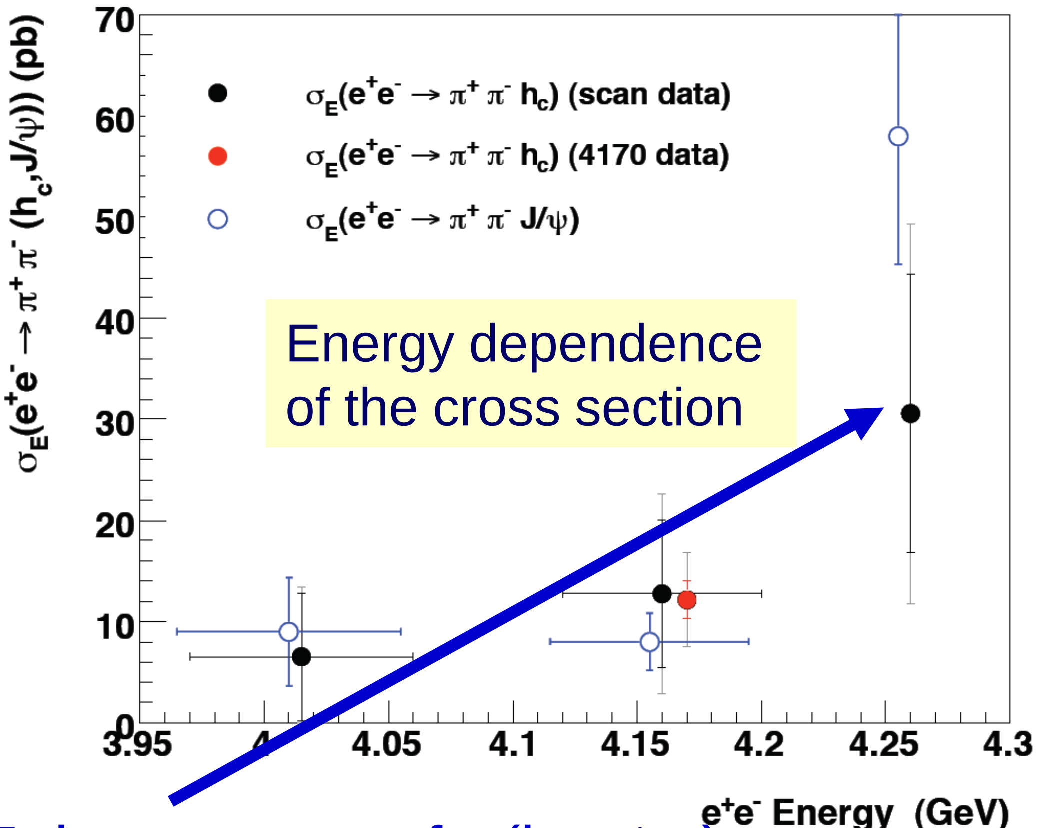
Off reson./scan :

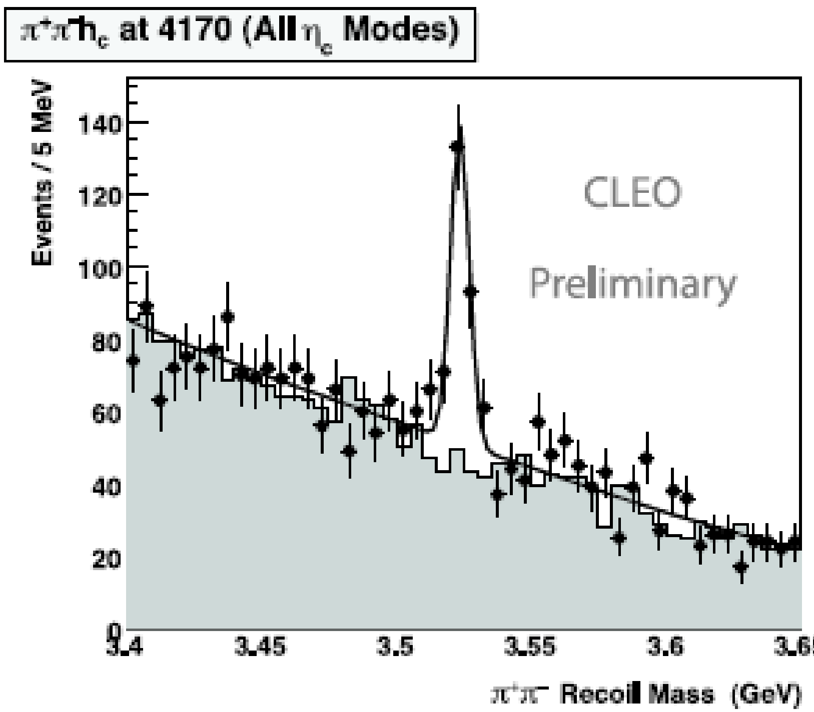
~54 fb-1

Motivation

Observation of $e^+e^- \to \pi^+\pi^- h_c$ by CLEO arxiv:1104.2025 PRL107,04803(2011)

Ryan Mitchell @ CHARM2010





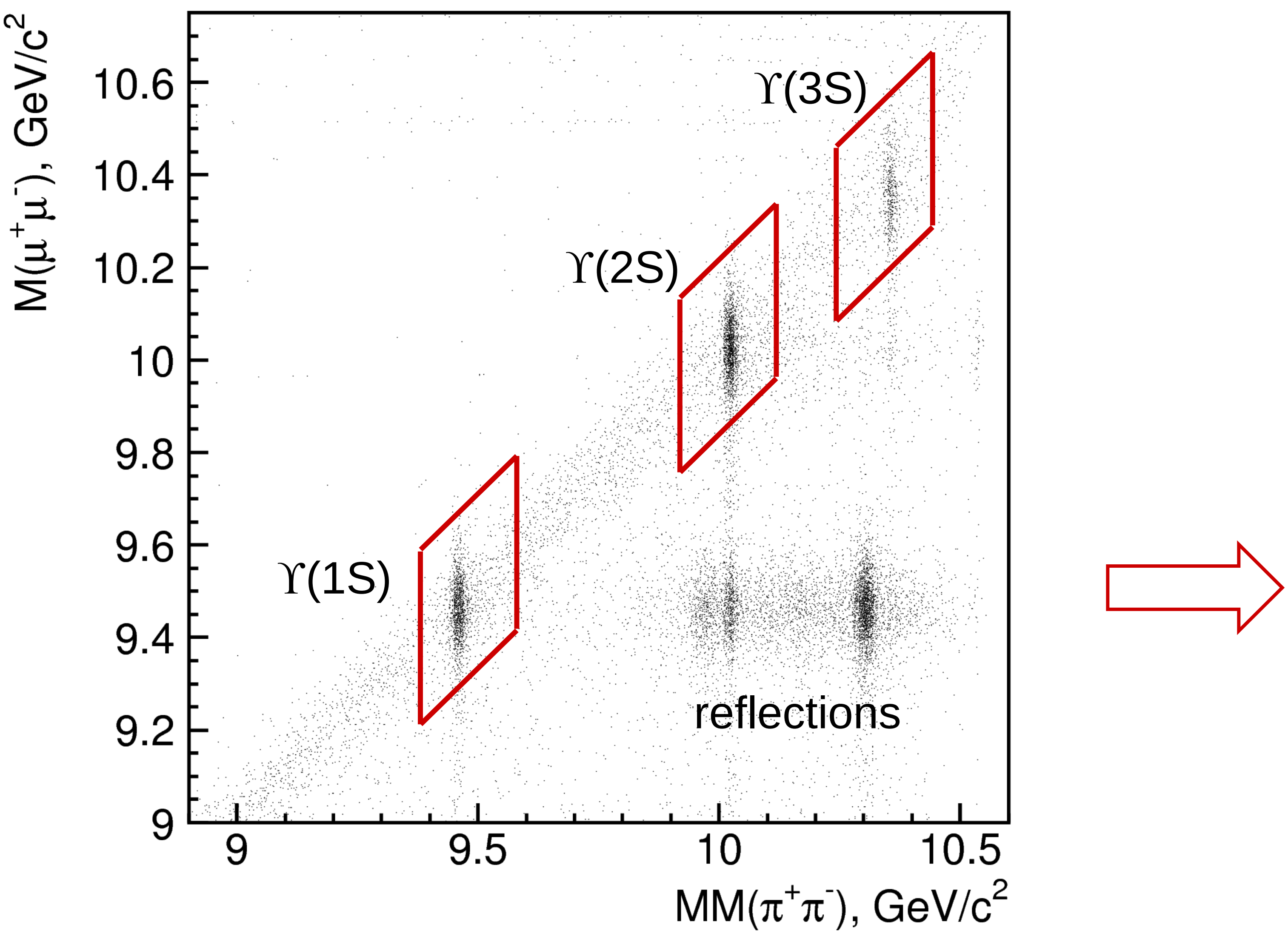
Enhancement of $\sigma(h_c\, \pi^+\pi^-)$ @ Y(4260) ⇒ $\sigma(h_b\, \pi^+\pi^-)$ is enhanced @ Y_b?

⇒ Belle search for h_b in $\Upsilon(5S)$ data

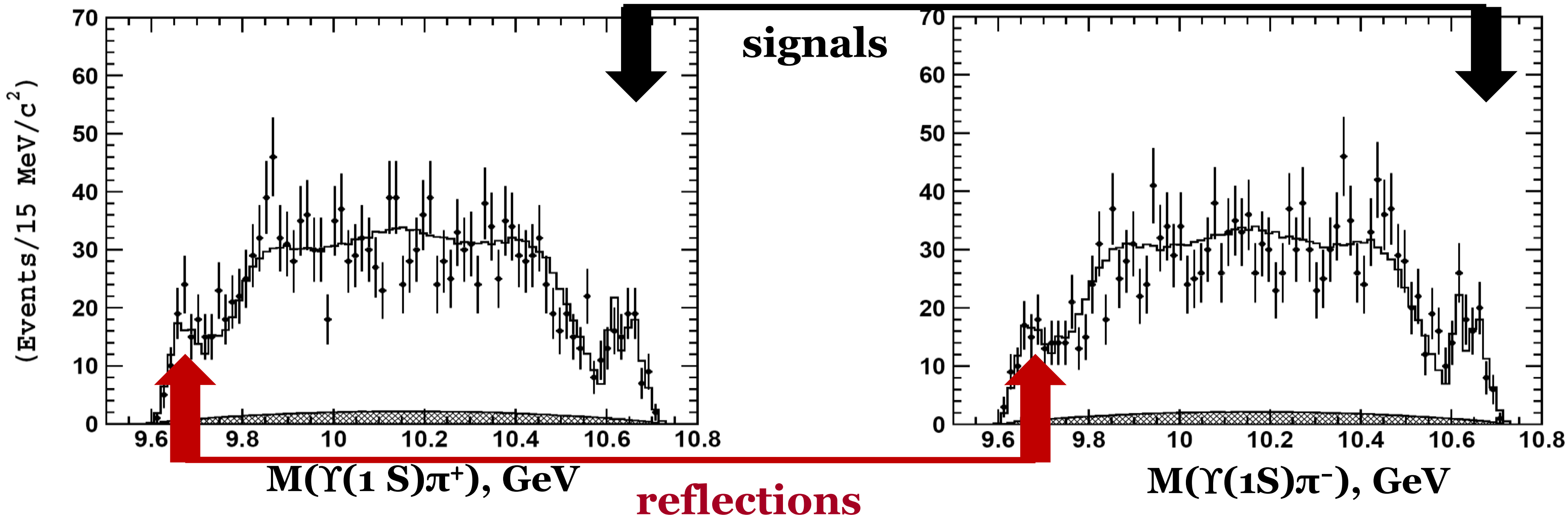
Exclusive $\Upsilon(5S) \to \Upsilon(nS)\ \pi^+\pi^-$

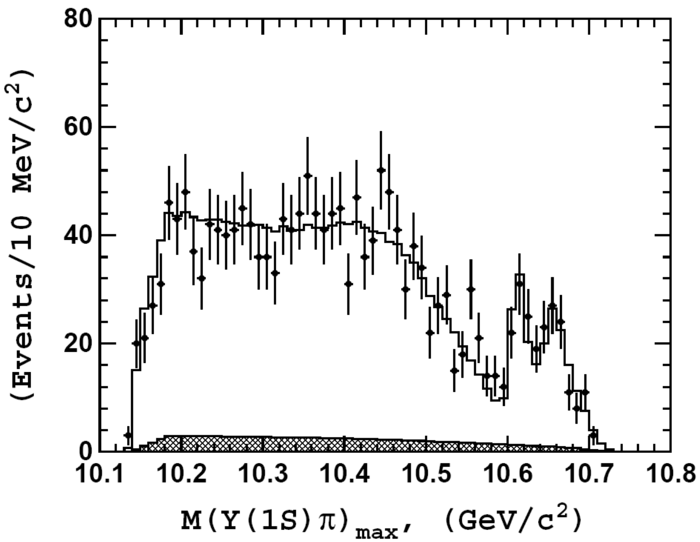
$\Upsilon(5S) \to \Upsilon(nS)\ \pi^+\pi^-$ (n = 1,2,3)

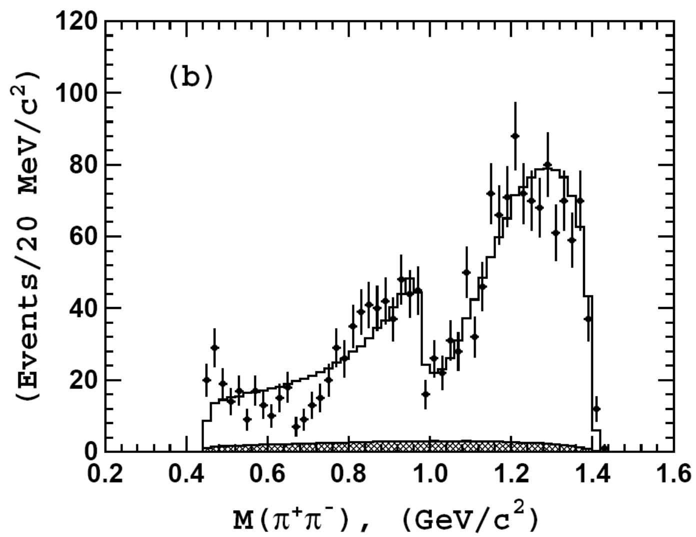
$\Upsilon(nS) \to \mu^+\mu^-$



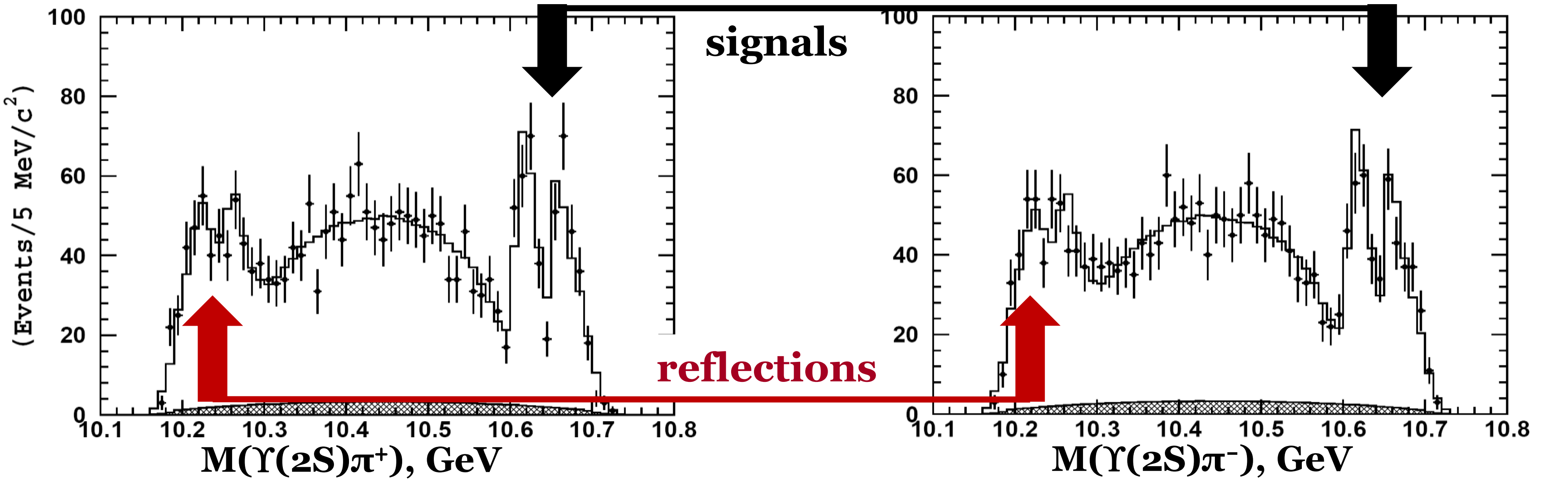
Results: $\Upsilon(1S)\pi^+\pi^-$

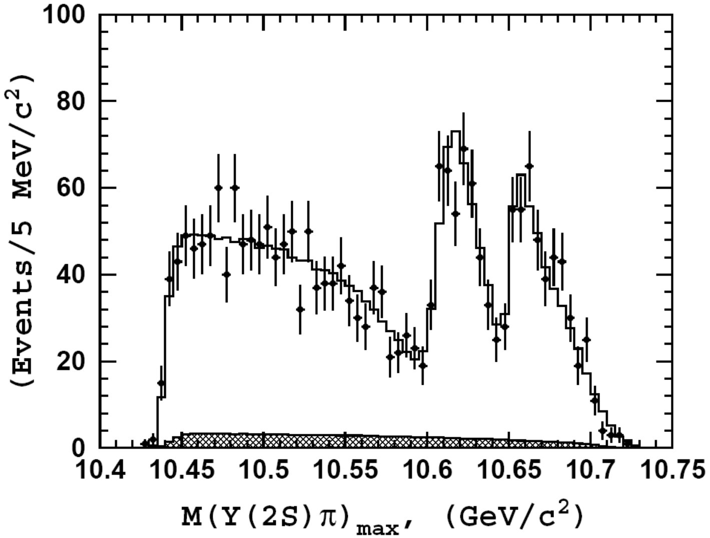


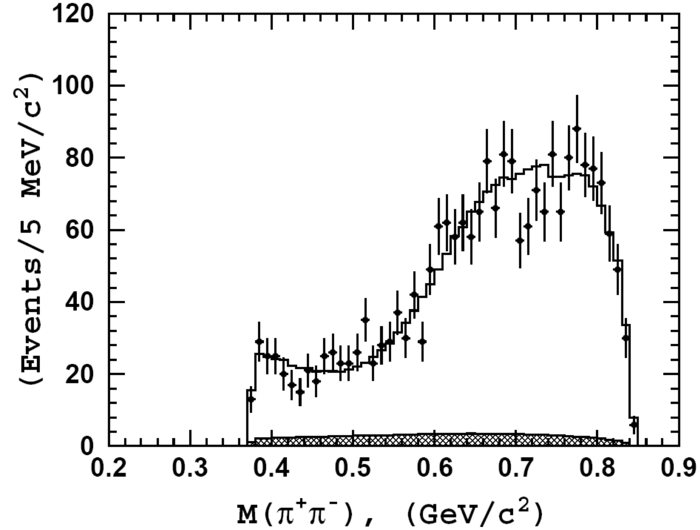




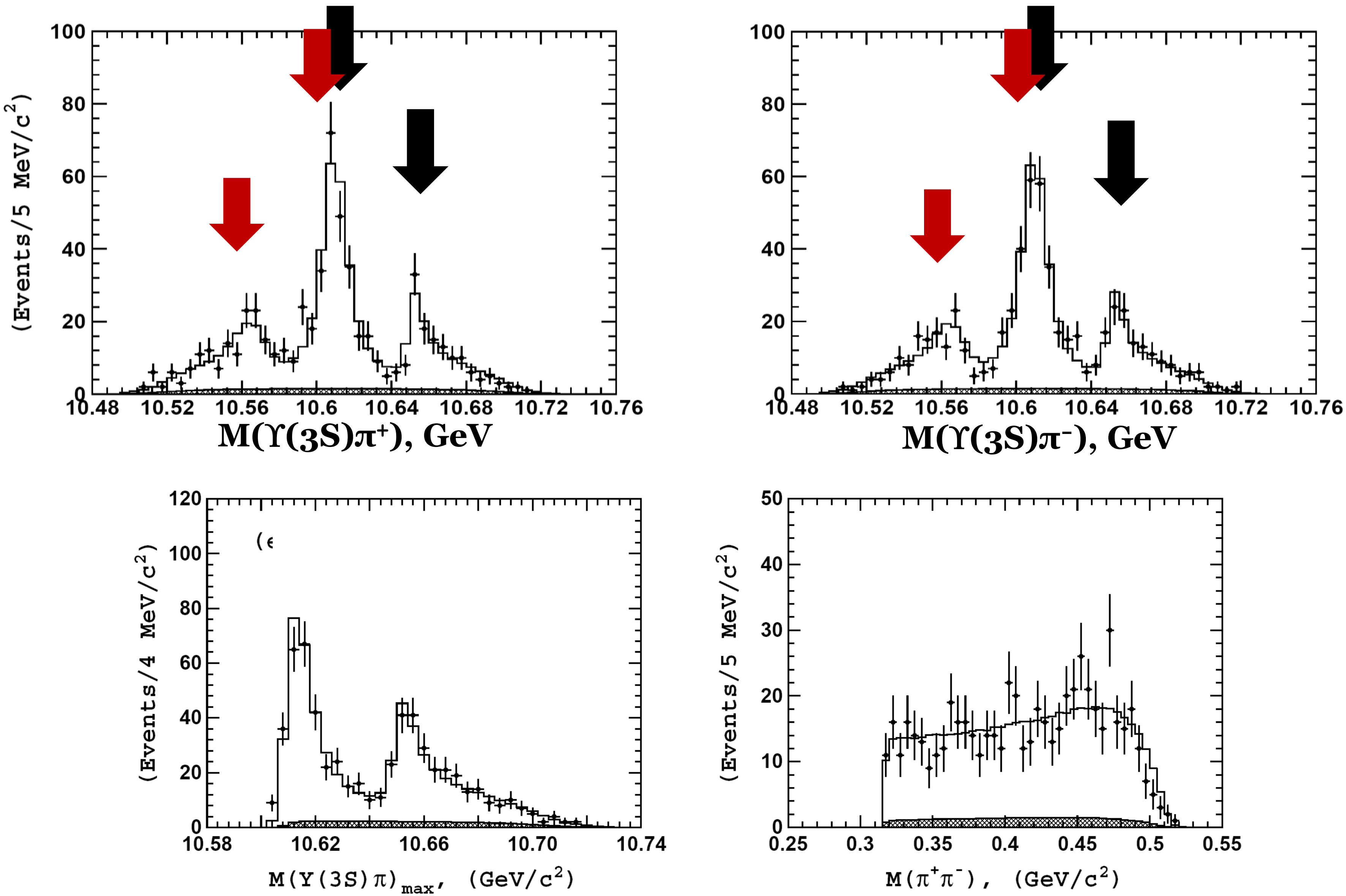
Results: $\Upsilon(2S)\pi^+\pi^-$







Results: $\Upsilon(3S)\pi^+\pi^-$

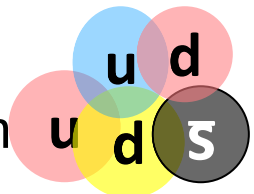


What about other color-singlet combinations?

Other possible "white" combinations of quarks & gluons:

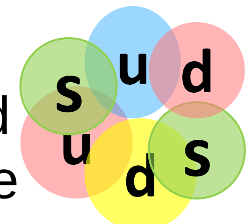
Pentaquark:

S=+1 Baryon



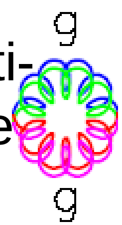
H-diBaryon

tightly bound
6-quark state



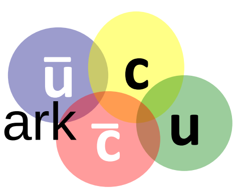
Glueball

Color-singlet multi-
gluon bound state

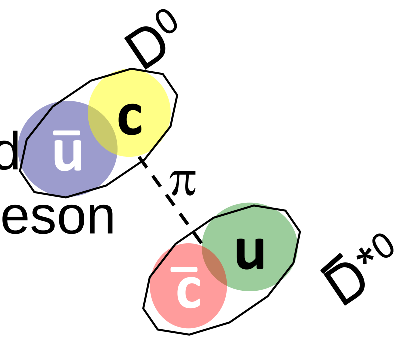


Tetraquark mesons

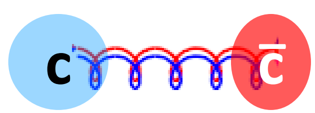
tightly bound
diquark-diantiquark



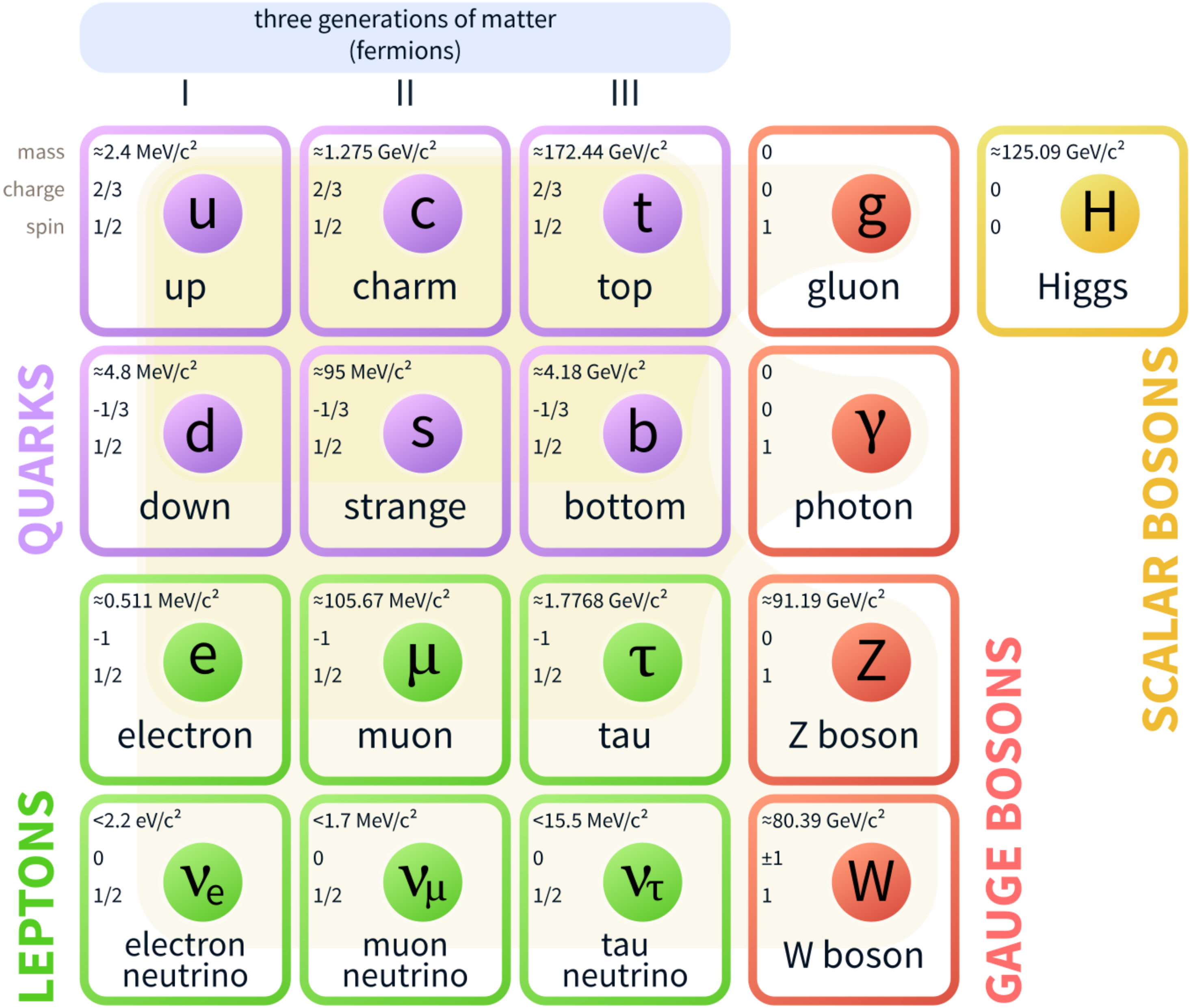
loosely bound
meson-antimeson
"molecule"



q$\bar{q}$-gluon hybrid mesons



Standard Model of Elementary Particles



- Heavy quark mass → non-relativistic bound state
- Analogous to positronium (e^+e^-)
- NRQCD potential based on one gluon exchange:

HQET color magnetic moment ~$1/m_Q$

$$V(r) \sim \frac{-4}{3}\frac{\alpha_s}{r} \quad \text{for} \quad r << \frac{1}{\Lambda}$$

$$\begin{aligned} V_{spin}(r) \;=\; & \left(\frac{1}{2m_1^2}\vec{L}\cdot\vec{S}_1 + \frac{1}{2m_2^2}\vec{L}\cdot\vec{S}_2\right)\frac{1}{r}\frac{d}{dr}\left(V(r) + 2V_1(r)\right) \\ & + \frac{1}{m_1 m_2}\vec{L}\cdot(\vec{S}_1 + \vec{S}_2)\frac{1}{r}\frac{dV_2(r)}{dr} \\ & + \frac{1}{m_1 m_2}(\hat{r}\cdot\vec{S}_1\ \hat{r}\cdot\vec{S}_2 - \frac{1}{3}\vec{S}_1\cdot\vec{S}_2)V_3(r) + \frac{1}{3m_1 m_2}\vec{S}_1\cdot\vec{S}_2\ V_4(r) \end{aligned}$$

- Modern descriptions: EFT and lattice QCD
- Predictions: mass, width, J^{PC}, production, decay