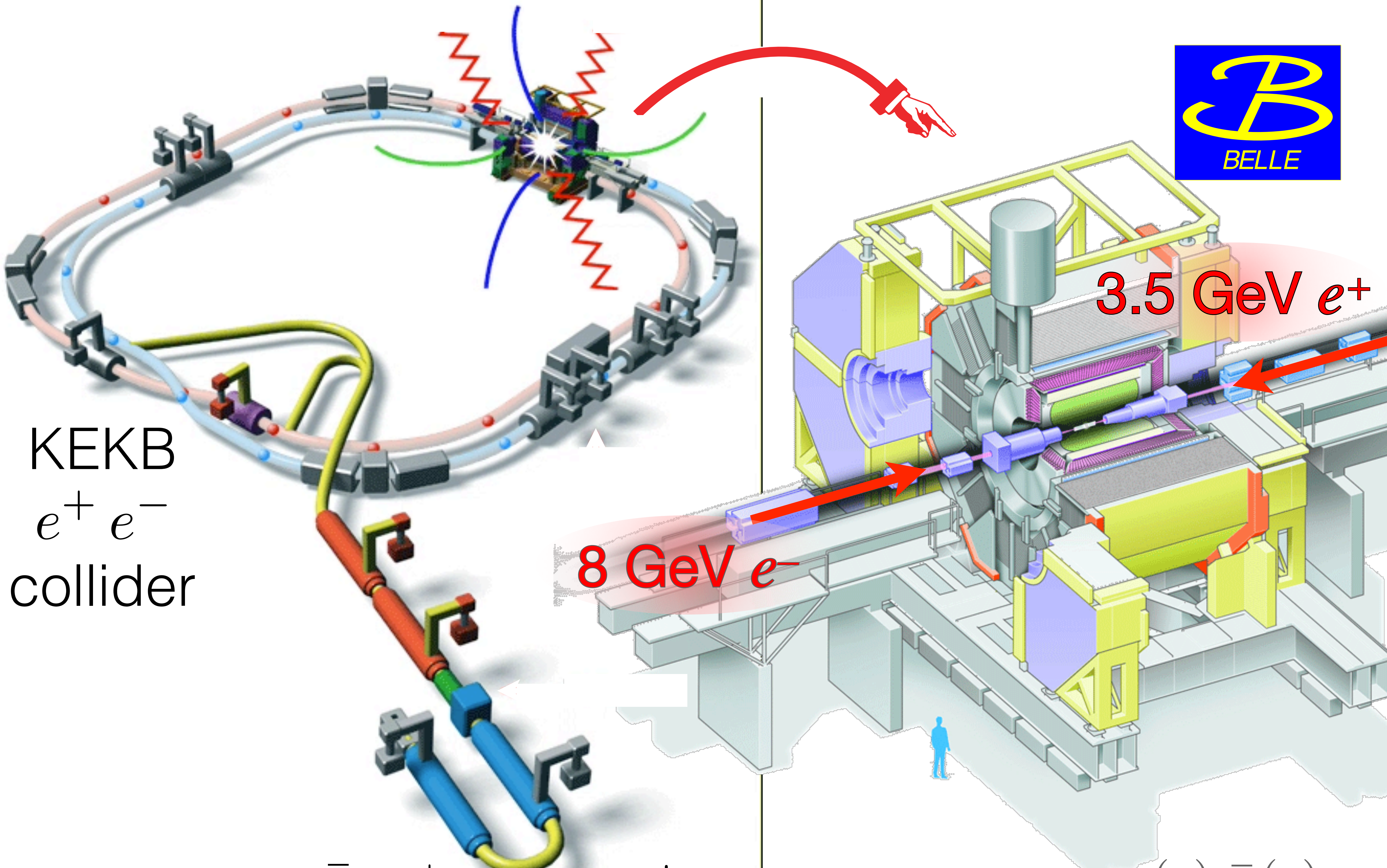
Measurements of B_s and $\Upsilon(5S)$ decays with Belle

Leo Piilonen, Virginia Tech
on behalf of the Belle Collaboration

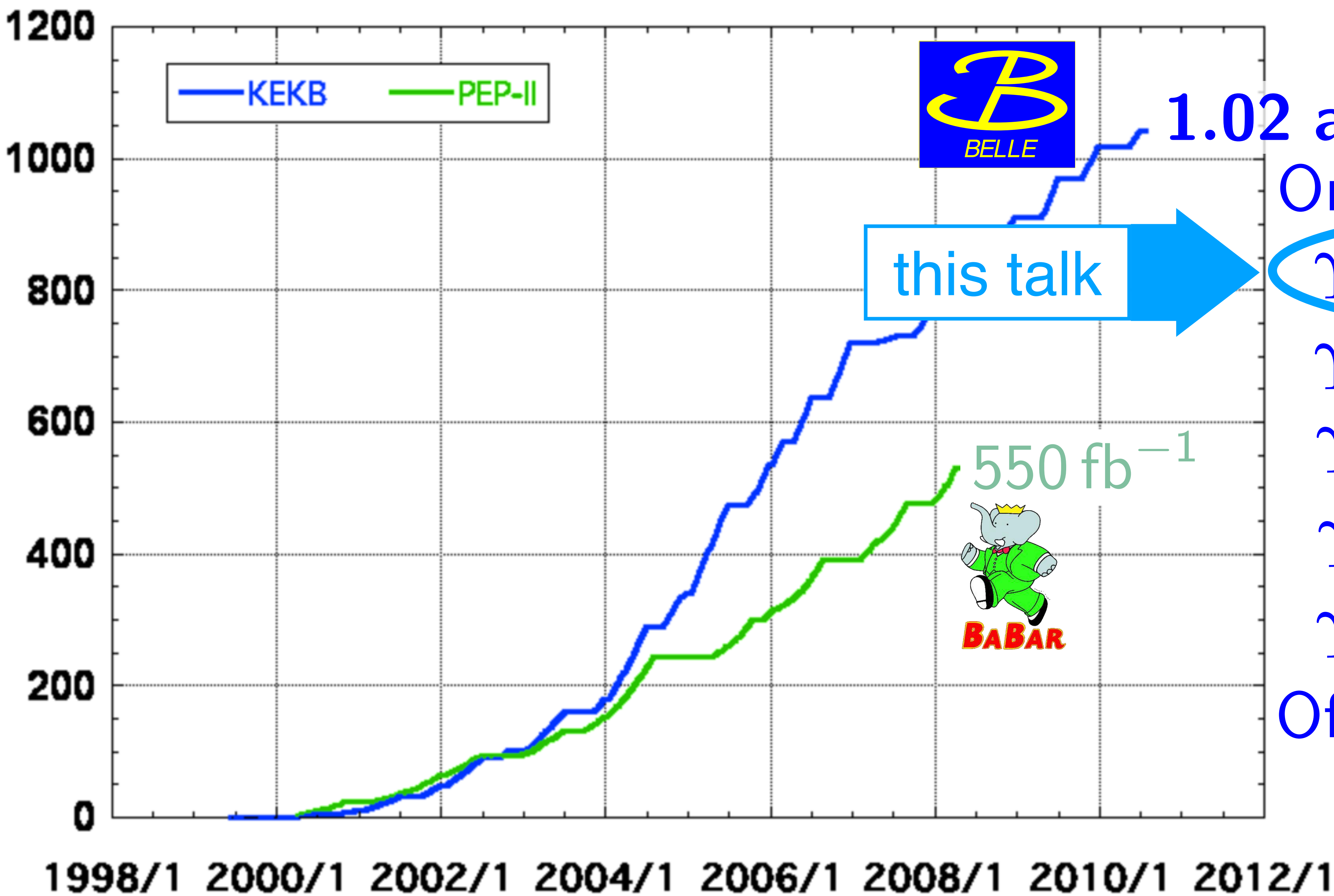
This work supported by U.S. DEPARTMENT OF ENERGY | Office of Science

KEK B Factory and Belle: 1999–2010



$$c\bar{c},\ u\bar{u},\ d\bar{d},\ \ell^+\ell^- \leftarrow \boldsymbol{e^+e^-} \rightarrow \Upsilon(\mathrm{nS}) \rightarrow B^{(*)}\bar{B}^{(*)}$$

Integrated luminosity at the B factories



On resonance:

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

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

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

$\Upsilon(2S)$: 25 fb^{-1}

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

Off resonance/scan:

155 fb^{-1}

From earlier Belle measurements at/near the $\Upsilon(5S)$,

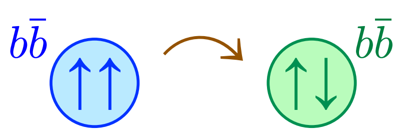
- ✓ hadronic transitions via $\pi^+\pi^-$, η, ω, etc. to lower bottomonia provide useful input for QCD and phenomenological models like Heavy Quark Spin Symmetry *[more on this later]*

- ✓ … and led to the discovery of $h_b(1P)$, $h_b(2P)$, $\eta_b(2S)$, and the exotica $Z_b(10610)^{\pm}$, $Z_b(10650)^{\pm}$, $Z_b(10610)^0$, and $Z_b(10650)^0$

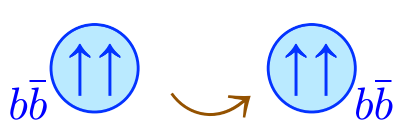
PRL **108**, 032001 (2012), PRL **109**, 232002 (2012), PRL **108**, 122001 (2012), PRD **88**, 052016 (2013)

PRL **108**, 032001 (2012):

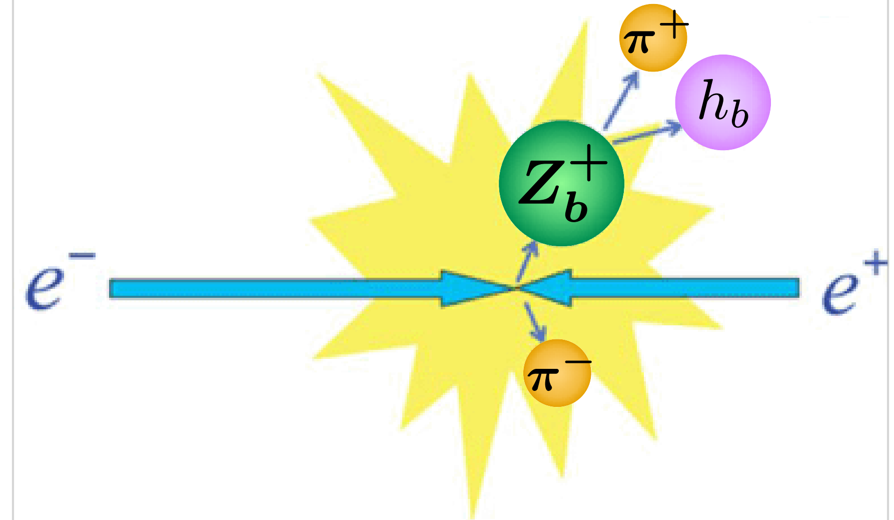
The width of $\Upsilon(5S) \to h_b(\text{nP})\pi^+\pi^-$ is unusually large, given the spin flip of a b quark



$$\frac{\Gamma[\Upsilon(5S) \to h_b(\text{nP})\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-]} = \begin{cases} 0.46 \pm 0.08 \pm ^{0.07}_{0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08 \pm ^{0.22}_{0.17} & \text{for } h_b(2P) \end{cases}$$



It should be suppressed as $\sim (\Lambda_{\text{QCD}}/m_b)^2$

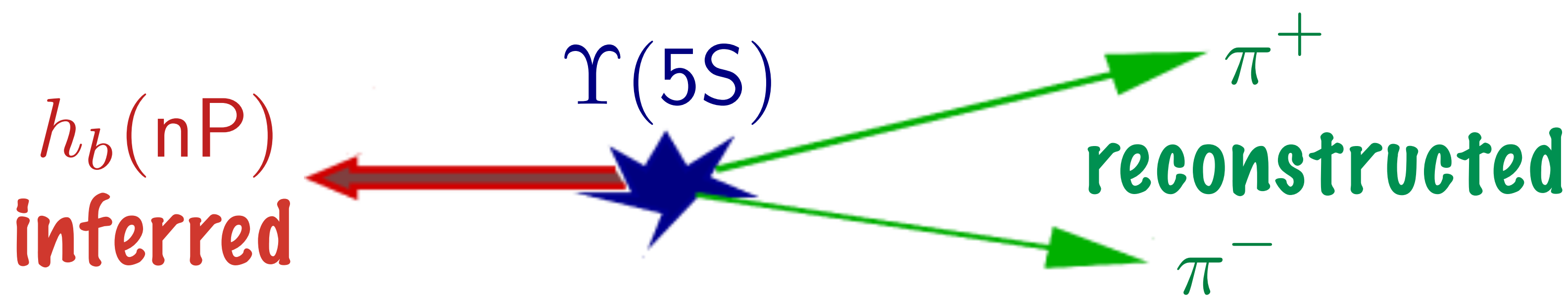


$\Upsilon(5S) \to h_b(\text{nP})\pi^+\pi^-$ proceeds via intermediate charged Z_b states

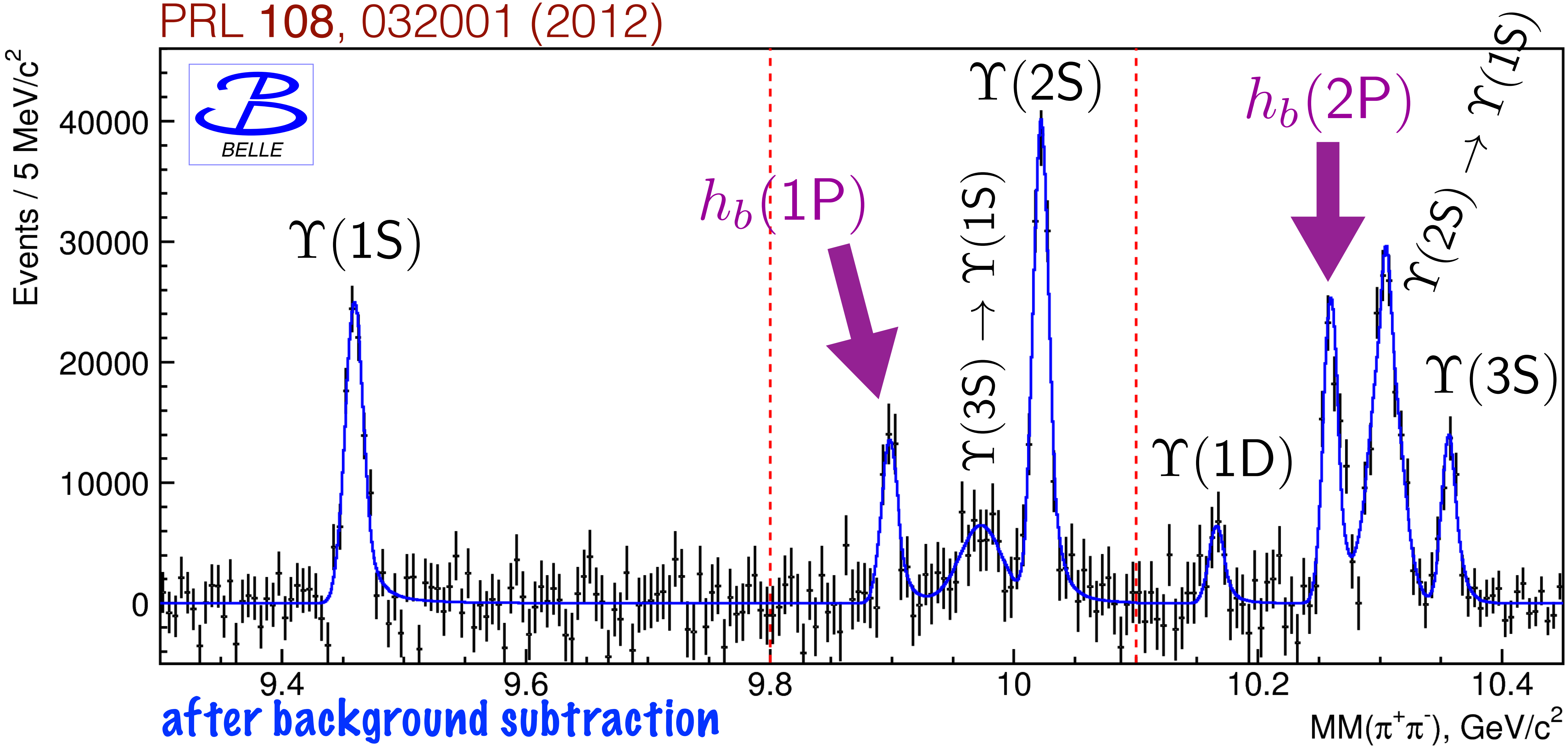
Discoveries of $h_b(\mathrm{1P}),\ h_b(2P),$ $Z_b(10610),\ Z_b(10650)$

(a synopsis)

Use missing-mass technique to find h_b and $h_b(2P)$

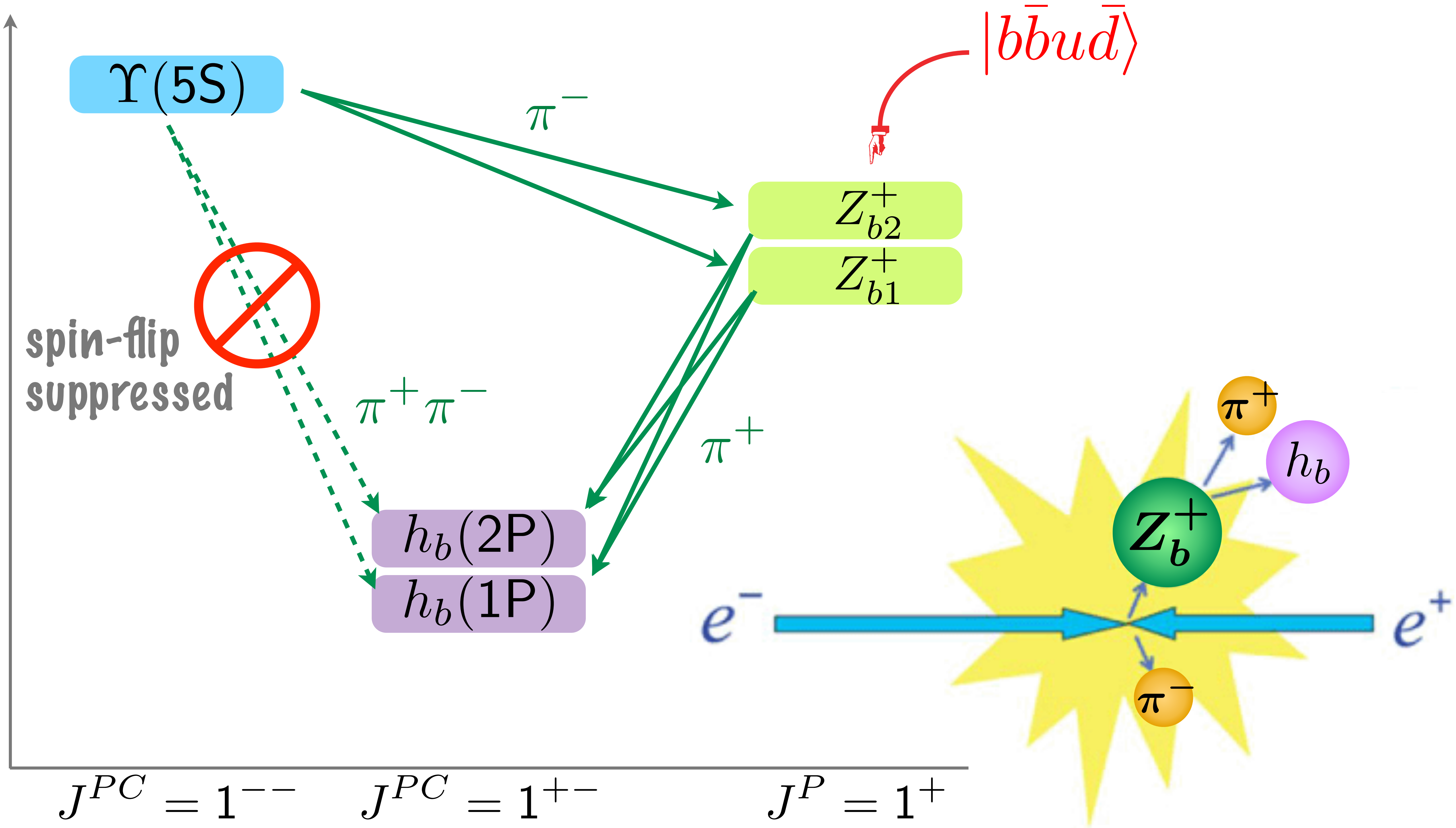


PRL **108**, 032001 (2012)



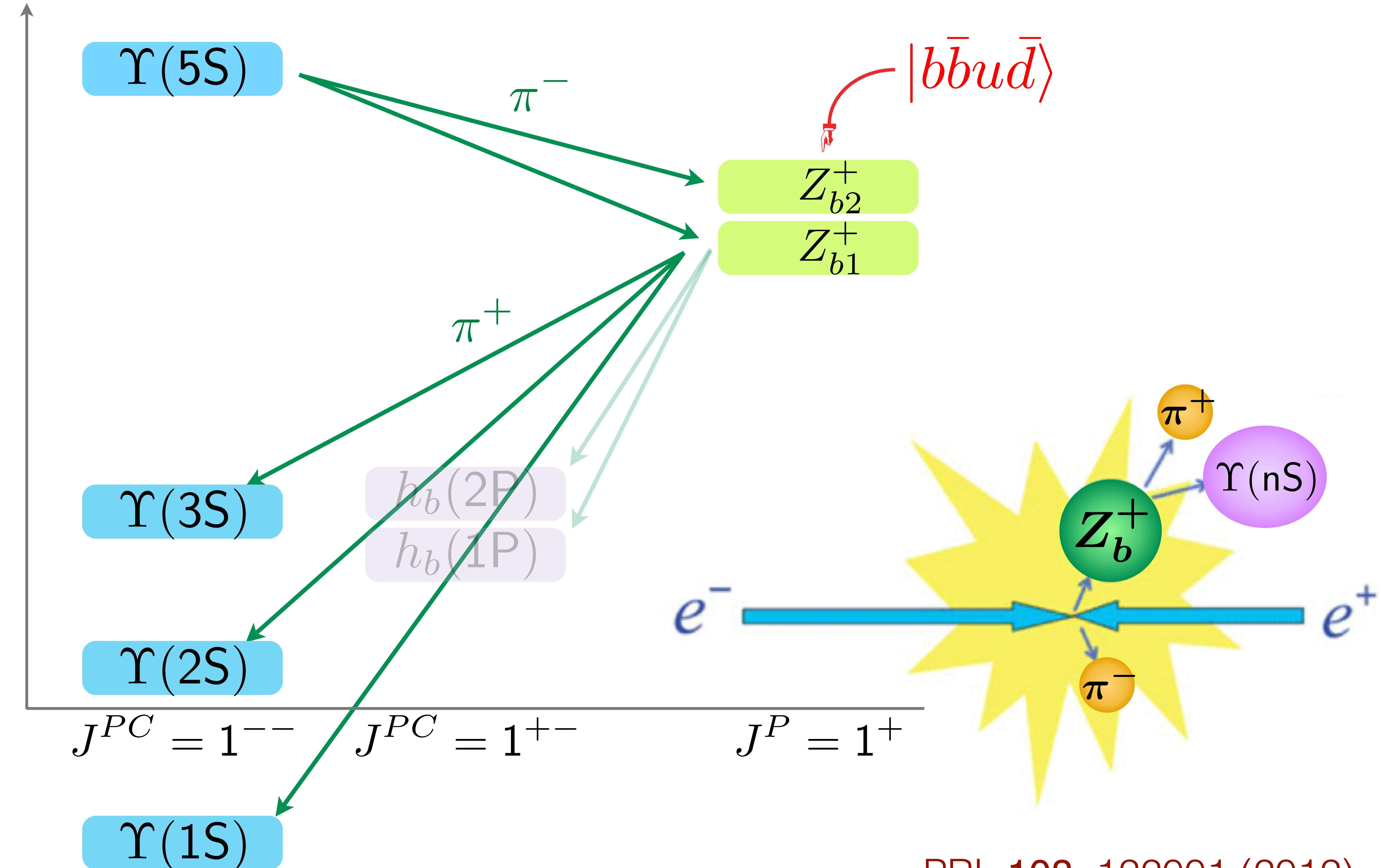
$h_b(nP)$ production should be spin-flip suppressed! *Why not?*

$\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ proceeds via one of two intermediate exotic states, Z_{b1}^+ and Z_{b2}^+



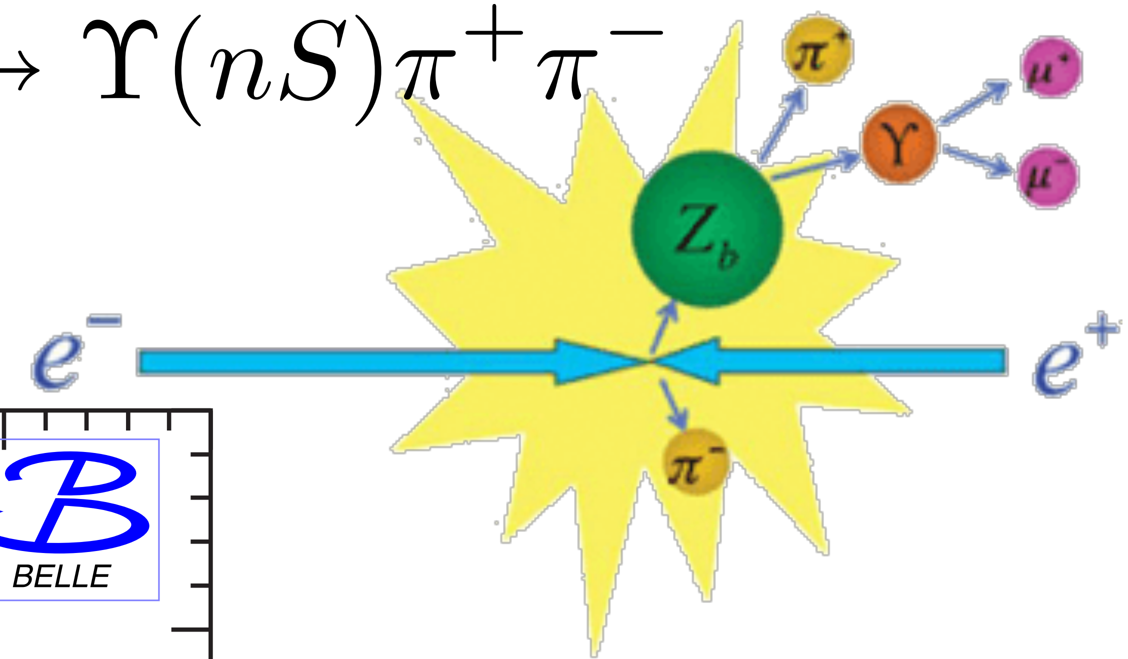
PRL **108**, 032001 (2012)

$\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ can also proceed via the two intermediate exotic states, Z_{b1}^+ and Z_{b2}^+

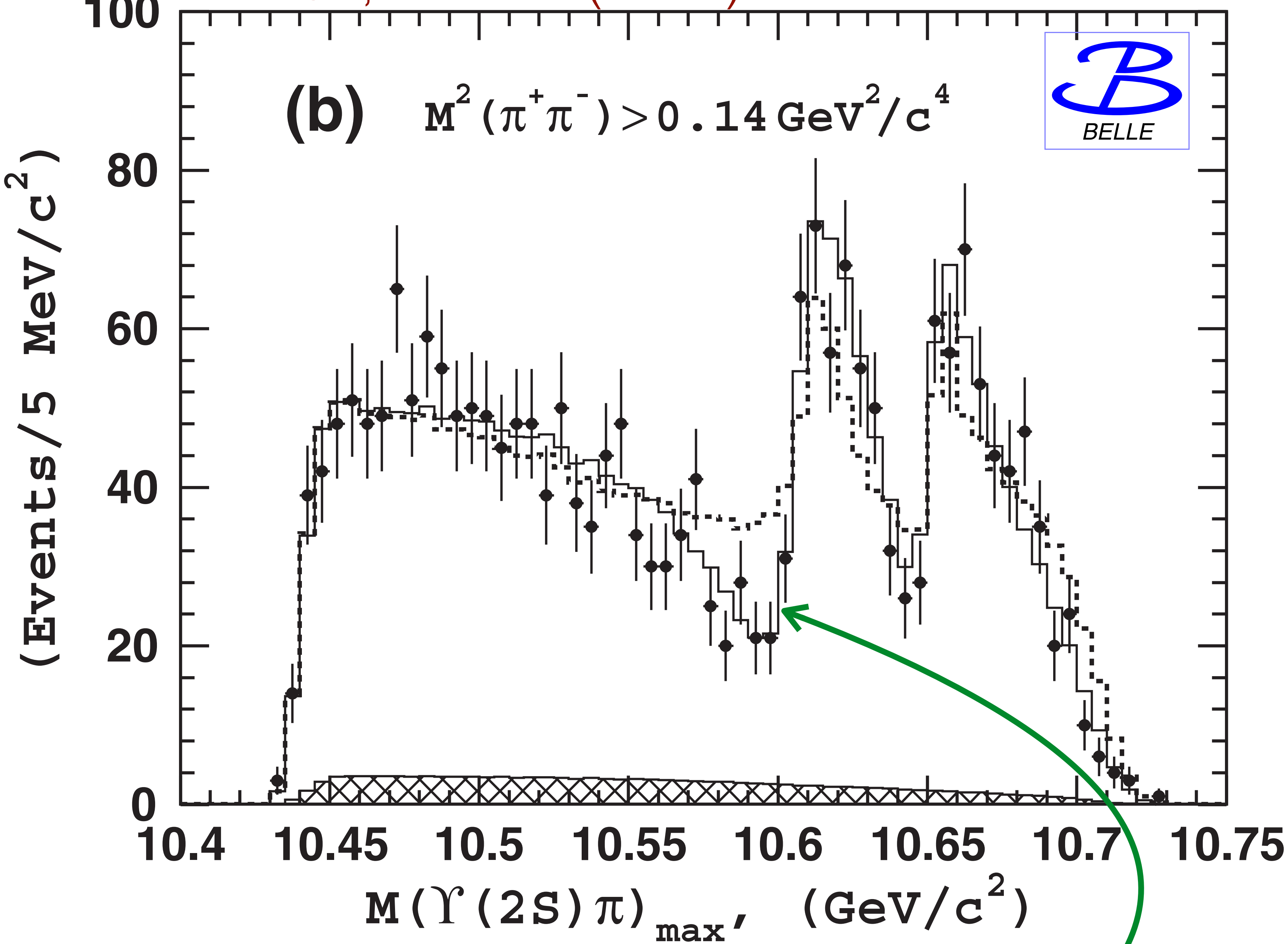


PRL **108**, 122001 (2012)

Amplitude analysis of $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ prefers $J^P = 1^+$ for Z_b



PRD **91**, 072003 (2015)

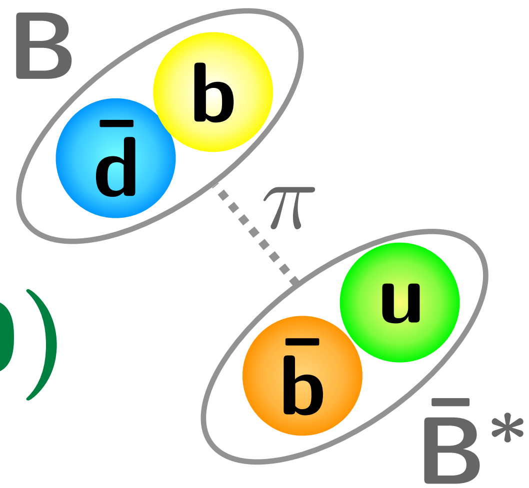


nominal model: $J^P = 1^+$ for both Z_b states (solid)

comparison: $J^P = 2^+$ for both Z_b states (dashed)

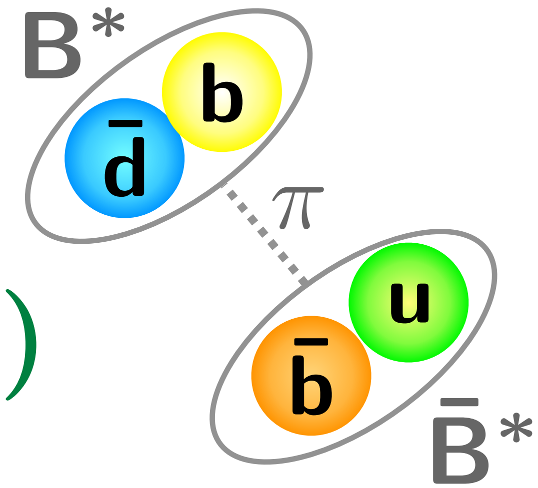
Are these molecular states?

$Z_b^+(10610)$



B–B̄* “molecule”

$Z_b^+(10650)$

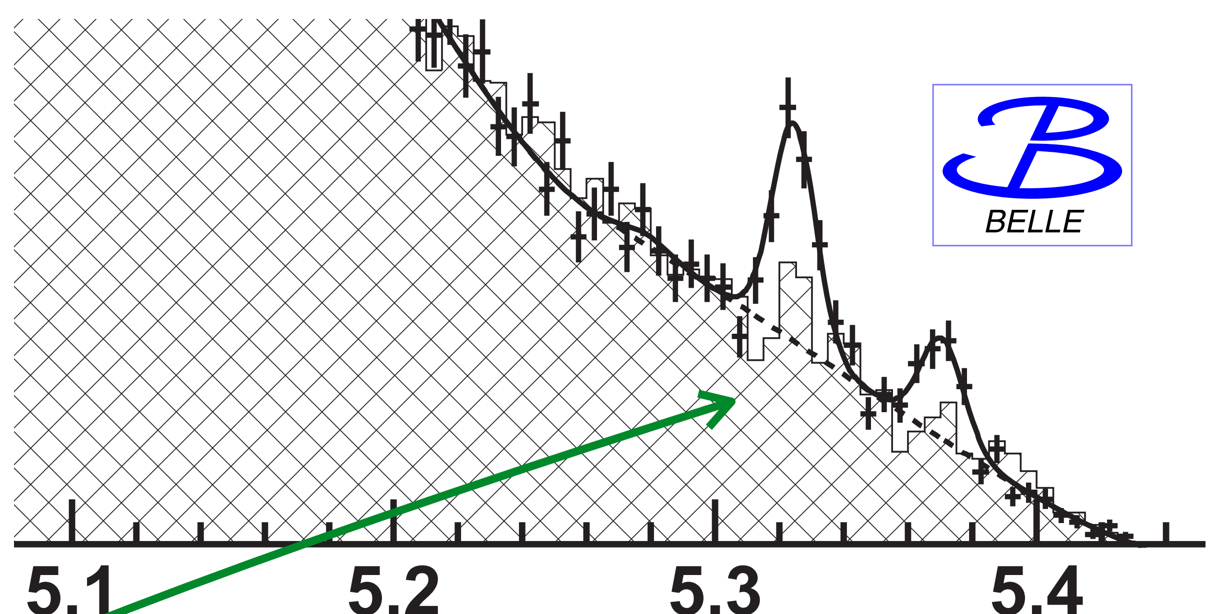


B*–B̄* “molecule”

$$M_{Z_b(10610)} - (M_B + M_{B^*}) = +2.7 \pm 1.8\,\text{MeV}$$

$$M_{Z_b(10650)} - 2M_{B^*} = +2.0 \pm 1.8\,\text{MeV}$$

- ✓ Study resonant substructure in $\Upsilon(5S) \to (B\bar{B}^* + c.c.)\pi$ and $\Upsilon(5S) \to B^*\bar{B}^*\pi$
- ✓ Reconstruct one B in $J/\psi\, K^{(*)}$ or $D^{(*)}\pi^+$
- ✓ Look at recoil mass against $B\pi$
- ✓ Select events in each peak



$M^*_{\text{miss}}(B\pi) \equiv M_{\text{miss}}(B\pi) + M(B) - m_B$

PRL **116**, 212001 (2016)

$Z_b^{\pm}$ states discovered in $h_b\,\pi^{\pm}$ and then $\Upsilon\,\pi^{\pm}$,
but they prefer to decay to $B^{(*)}\bar{B}^*$

Assuming Z_b decays to $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and $B^{(*)}B^*$ only:

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.60 \pm 0.17 \pm 0.07$	$0.17 \pm 0.06 \pm 0.02$
$\Upsilon(2S)\pi^+$	$4.05 \pm 0.81 \pm 0.58$	$1.38 \pm 0.45 \pm 0.21$
$\Upsilon(3S)\pi^+$	$2.40 \pm 0.58 \pm 0.36$	$1.62 \pm 0.50 \pm 0.24$
$h_b(1P)\pi^+$	$4.26 \pm 1.28 \pm 1.10$	$9.23 \pm 2.88 \pm 2.28$
$h_b(2P)\pi^+$	$6.08 \pm 2.15 \pm 1.63$	$17.0 \pm 3.74 \pm 4.1$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$82.6 \pm 2.9 \pm 2.3$	$-$
$B^{*+}\bar{B}^{*0}$	$-$	$70.6 \pm 4.9 \pm 4.4$

… strong evidence for molecular structure

BELLE

PRL **116**, 212001 (2016)

QCD Dynamics in $\Upsilon(5S) \to \eta\Upsilon_J(1D)$

$J = 1,\ 2,\ 3$

arXiv:1803.03225, submitted to EPJC

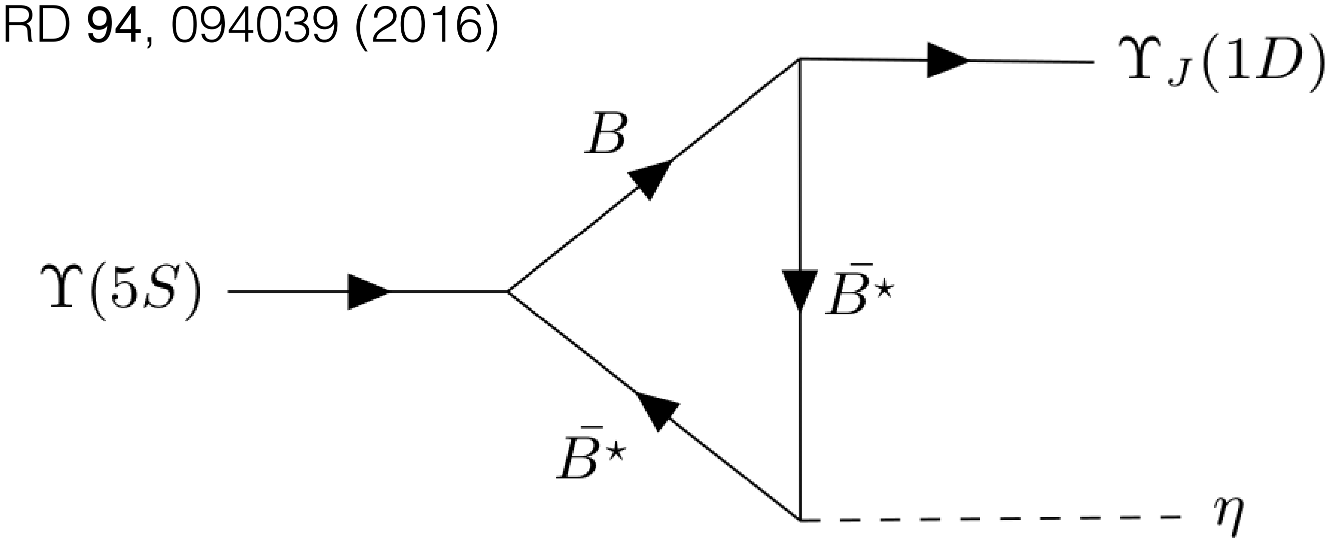
Reminder: see slide #6 for $\Upsilon(5S) \to \pi^+\pi^-\Upsilon_J(1D)$

QCD: $\Upsilon(5S) \to \eta\Upsilon(1D)$ should be suppressed by $\approx 10^{-3}$ relative to $\pi\pi\Upsilon(1D)$ due to spin flip

Kuang, Front. Phys. China **1**, 19 (2006); Voloshin, Prog. Part. Nucl. Phys. **61**, 455 (2008).

but can be enhanced via $B^{(*)}$–loop rescattering:

Wang, Chen and Liu, PRD **94**, 094039 (2016)

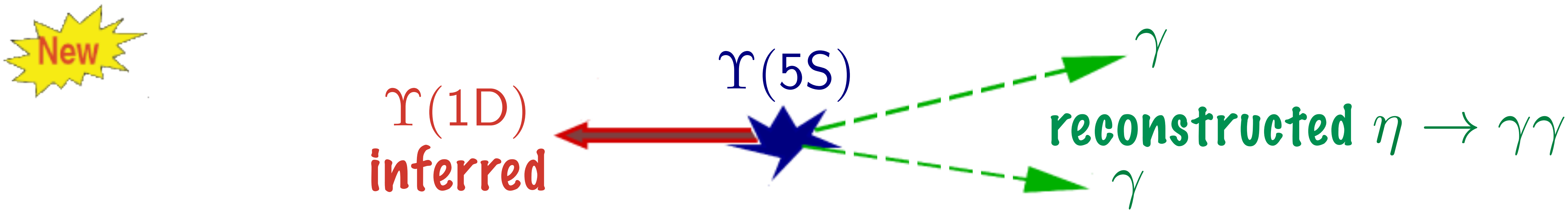


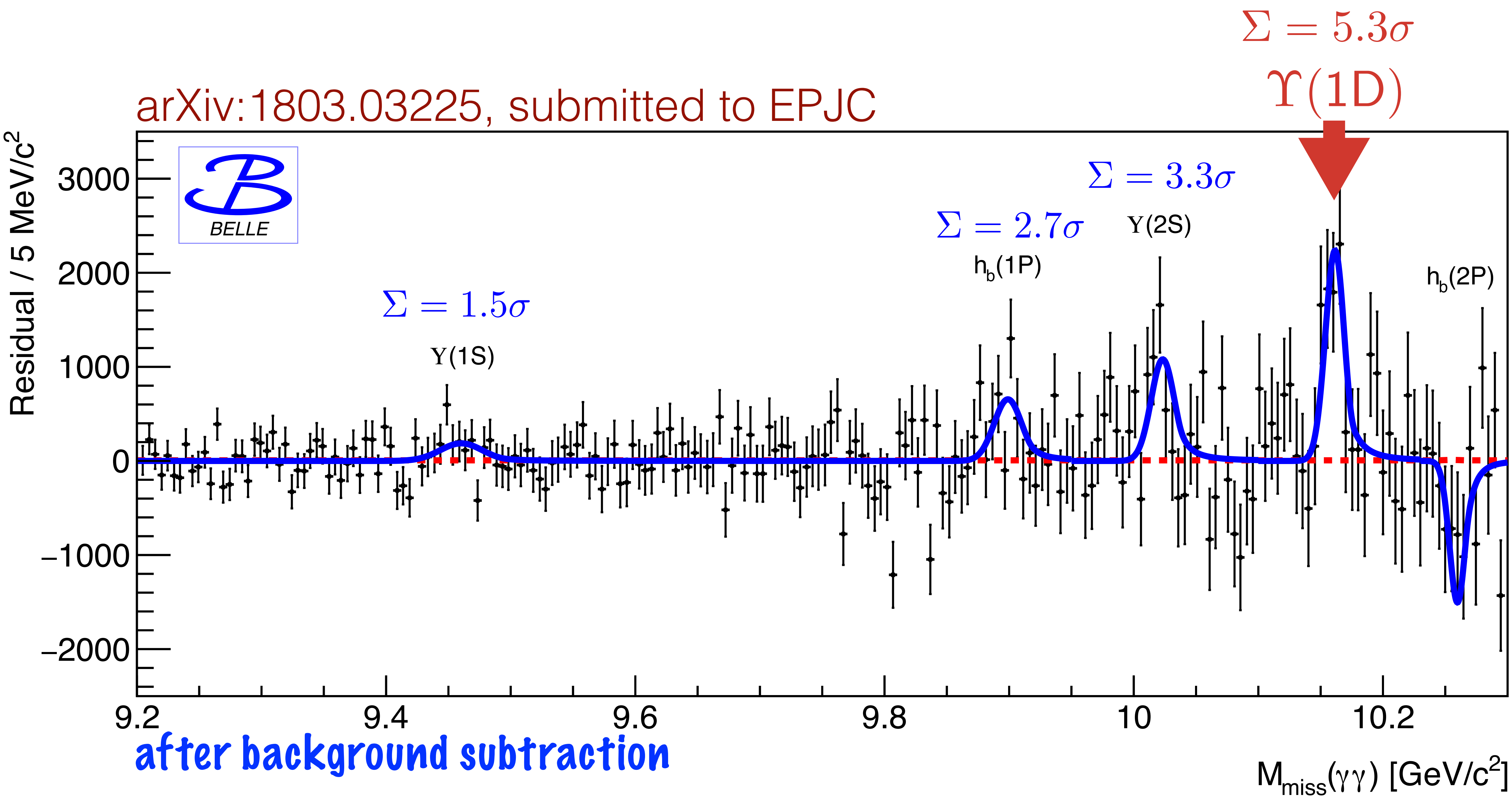
with expected triplet fractions (J = 1, 2, 3) of

$$f_1 = \frac{\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon_1(1D)]}{\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon(1D_2)]} = 0.68$$

$$f_3 = \frac{\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon_3(1D)]}{\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon(1D_2)]} = 0.13$$

Use missing-mass technique for $\Upsilon(5S) \to \eta\Upsilon(1D)$





Measured triplet fractions for $\Upsilon(5S) \to \eta\Upsilon(1D)$ are compatible with zero … and with predictions of Wang *et al*

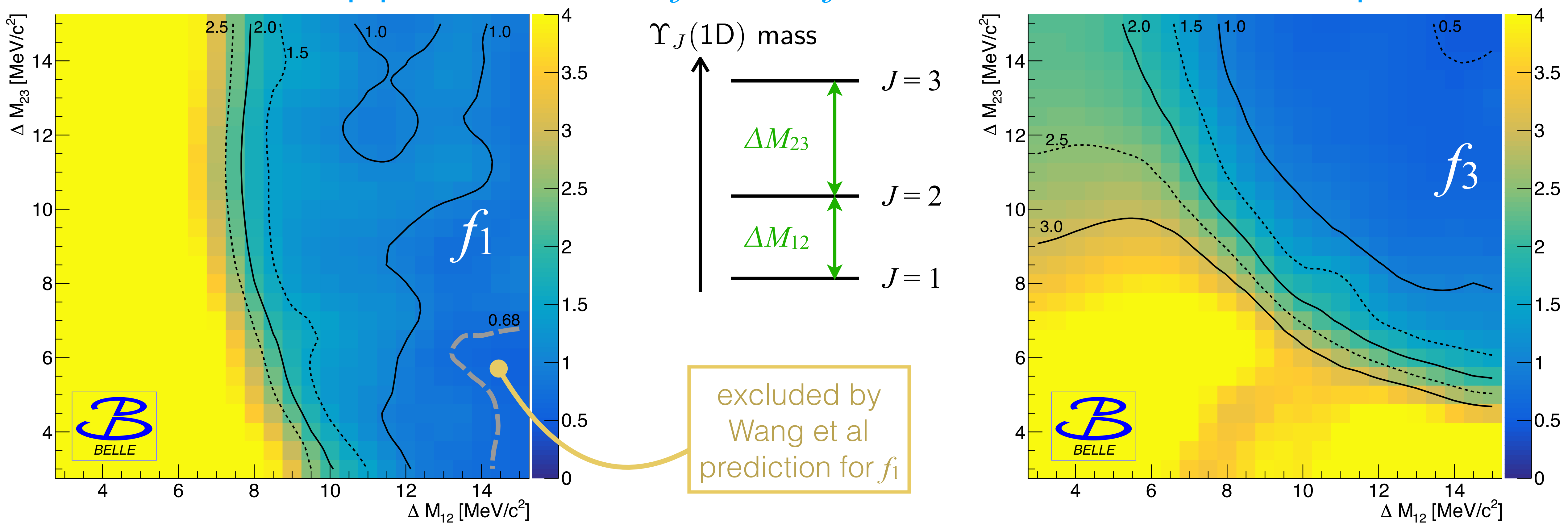
New

(see slide 13)

$f_1 = 0.23 \pm 1.42$ — *0.68 predicted*

$f_3 = -0.31 \pm 0.53$ — *0.13 predicted*

90% C.L. upper limits on f_1 and f_3 in the ΔM_{23} vs ΔM_{12} plane



Branching fraction:

$$\mathcal{B}\left[\Upsilon(5S) \to \eta\Upsilon_J(1D)\right] = (4.82 \pm 0.92 \pm 0.67) \cdot 10^{-3}$$

arXiv:1803.03225, submitted to EPJC

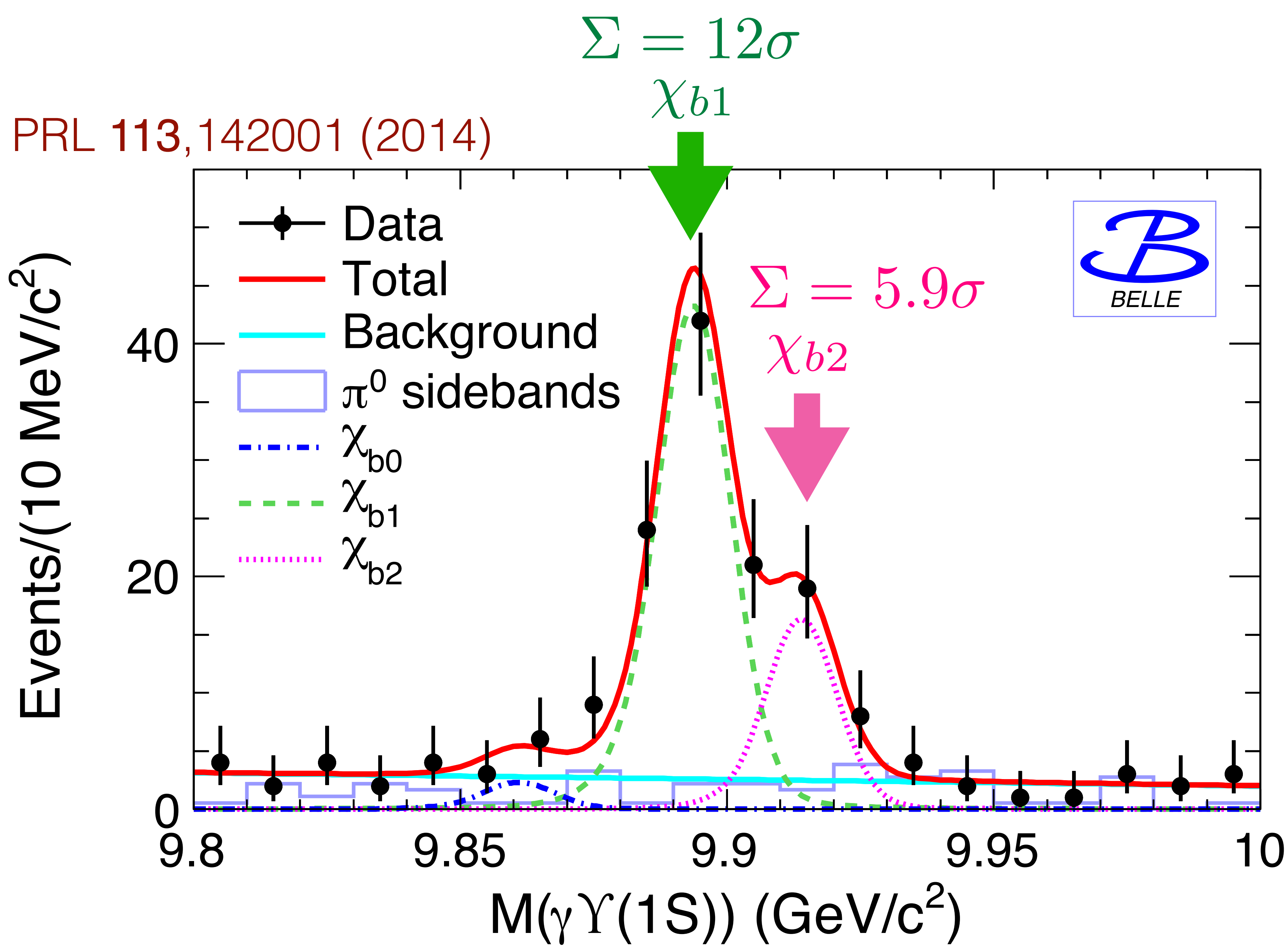
QCD Dynamics in $\Upsilon(5\text{S},6\text{S}) \to \pi^+\pi^-\pi^0\chi_{b1,2}$ and $\Upsilon(6\text{S}) \to \phi\chi_{bJ}$

New

arXiv:1806.06203, submitted to PRL

First, some background . . .

Reconstruct the decay $\Upsilon(5S) \rightarrow \pi^+\pi^-\pi^0\gamma\Upsilon(1S)$

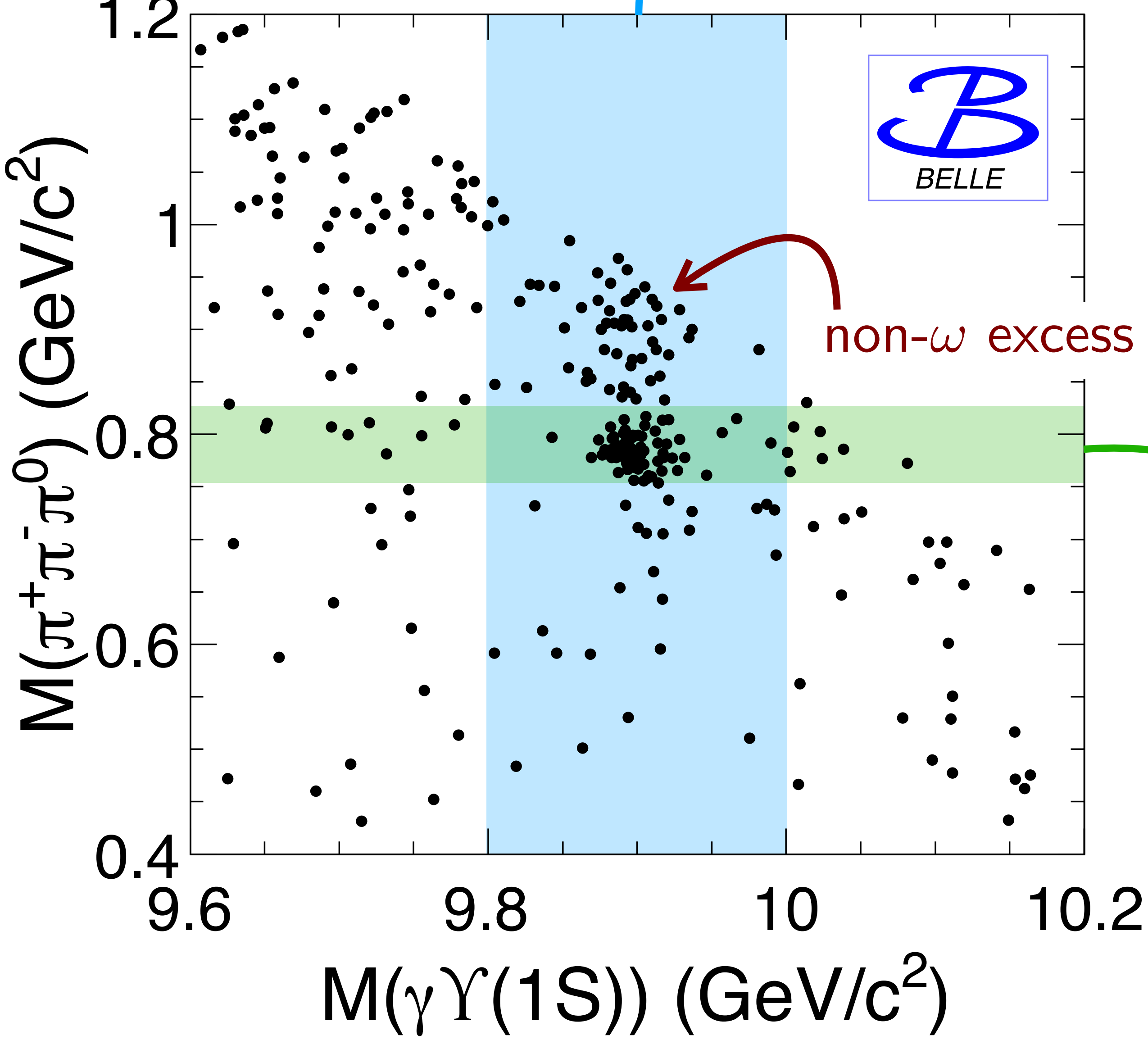


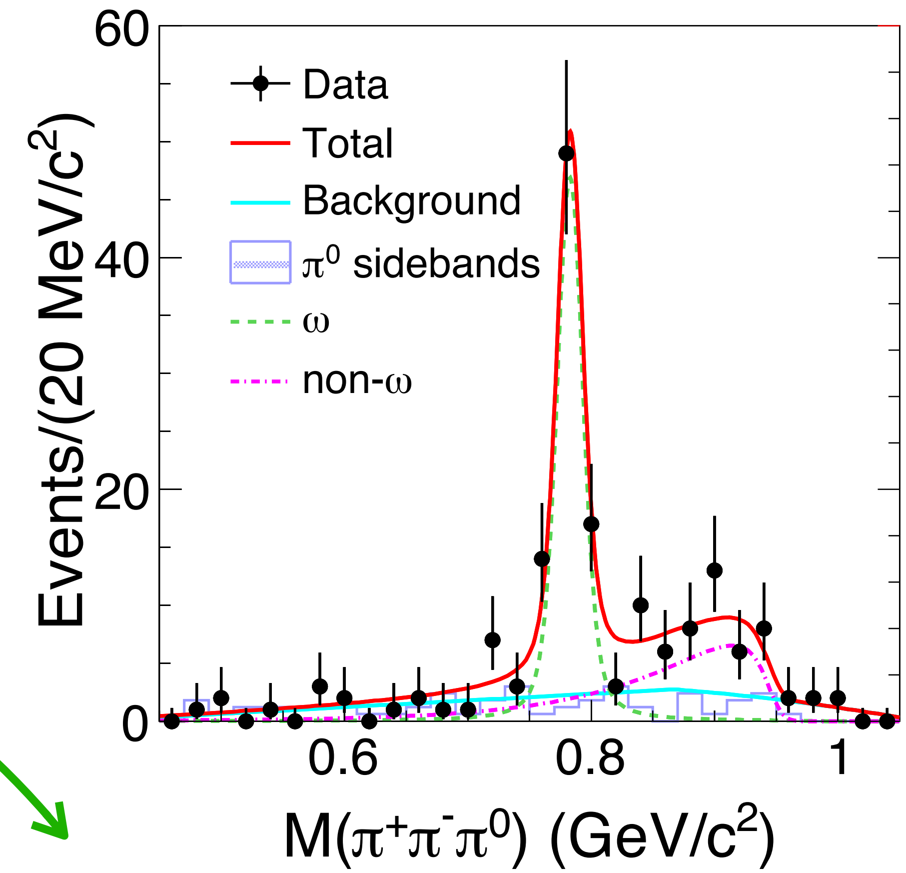
$$\mathcal{B}\left[\Upsilon(5S) \rightarrow \pi^+\pi^-\pi^0\chi_{b1}\right] = (1.85 \pm 0.23 \pm 0.23) \cdot 10^{-3}$$

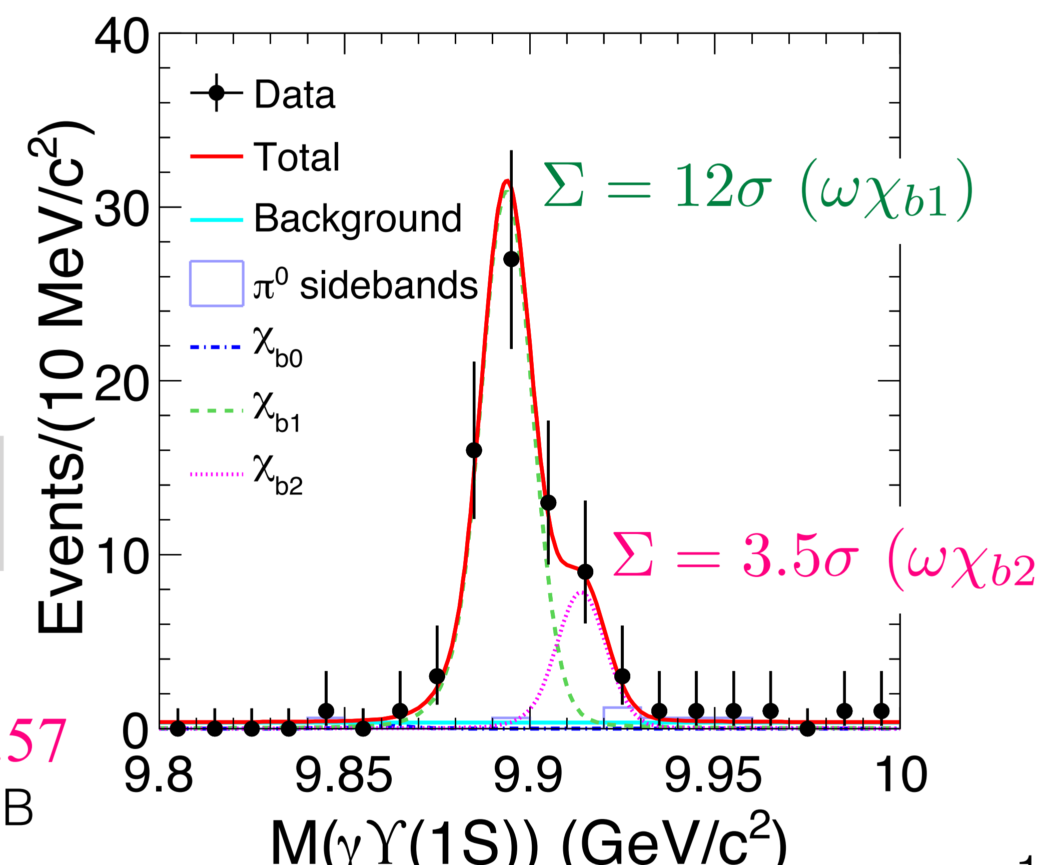
$$\mathcal{B}\left[\Upsilon(5S) \rightarrow \pi^+\pi^-\pi^0\chi_{b2}\right] = (0.57 \pm 0.13 \pm 0.08) \cdot 10^{-3}$$

Dalitz plot of $\Upsilon(5S) \to \pi^+\pi^-\pi^0\,\gamma\Upsilon(1S)$

PRL **113**,142001 (2014)







$$\mathcal{B}\left[\Upsilon(5S) \to \omega\chi_{b1}\right] = (1.57 \pm 0.22 \pm 0.21) \cdot 10^{-3}$$

$$\mathcal{B}\left[\Upsilon(5S) \to \omega\chi_{b2}\right] = (0.29 \pm 0.11 \pm 0.08) \cdot 10^{-3}$$

Ratio (b_2/b_1) is $0.38 \pm 0.16 \pm 0.09$; QCD HQSS expects 1.57

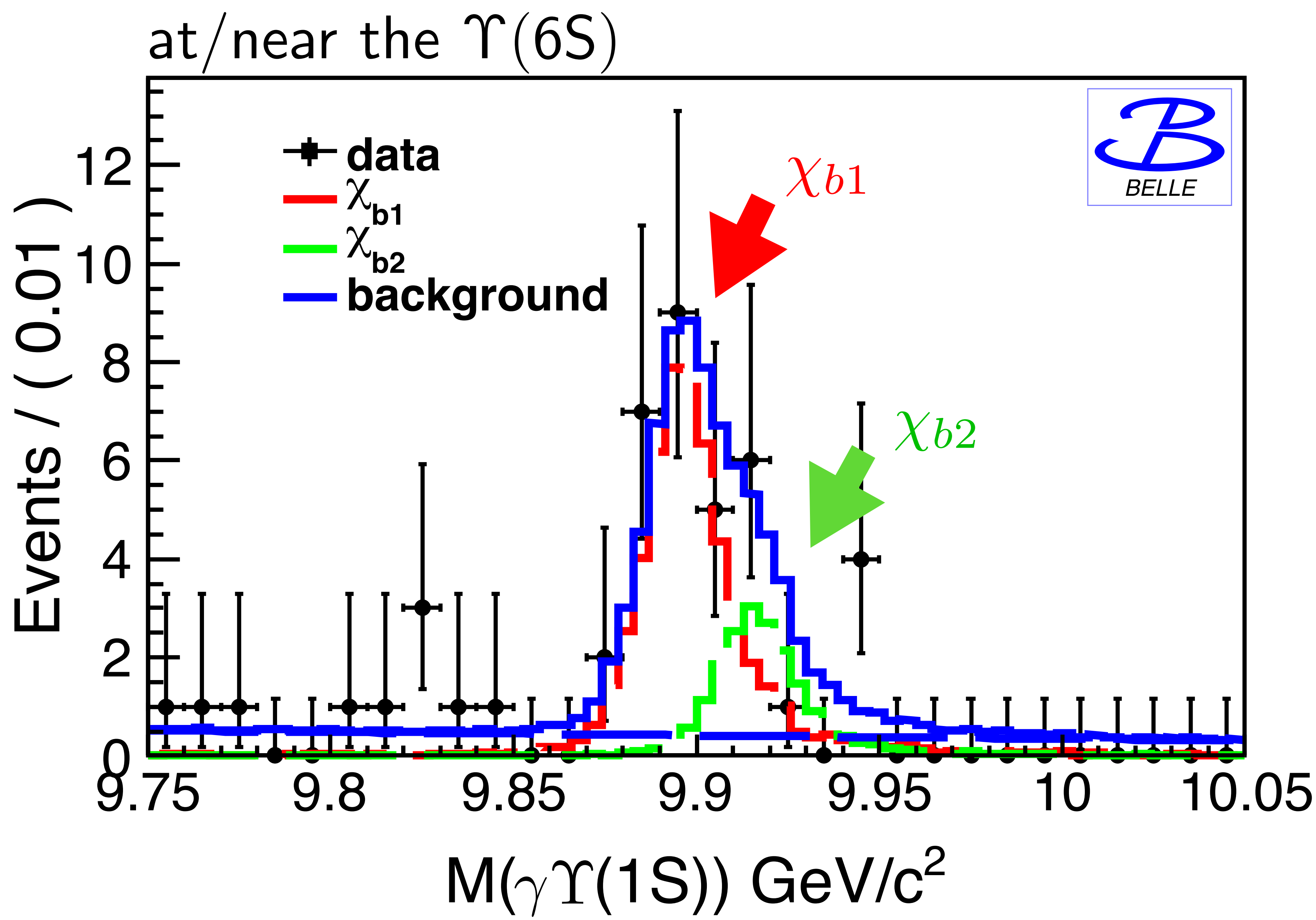
Casabuoni *et al*, Phys. Rept. **281**, 145 (1997); Cho & Wise, Phys. Lett. B **346**, 129 (1995); Guo *et al*, Phys. Lett. B **738**, 172 (2014).

Repeat for the decay $\Upsilon(6S) \to \pi^+\pi^-\pi^0\gamma\Upsilon(1S)$

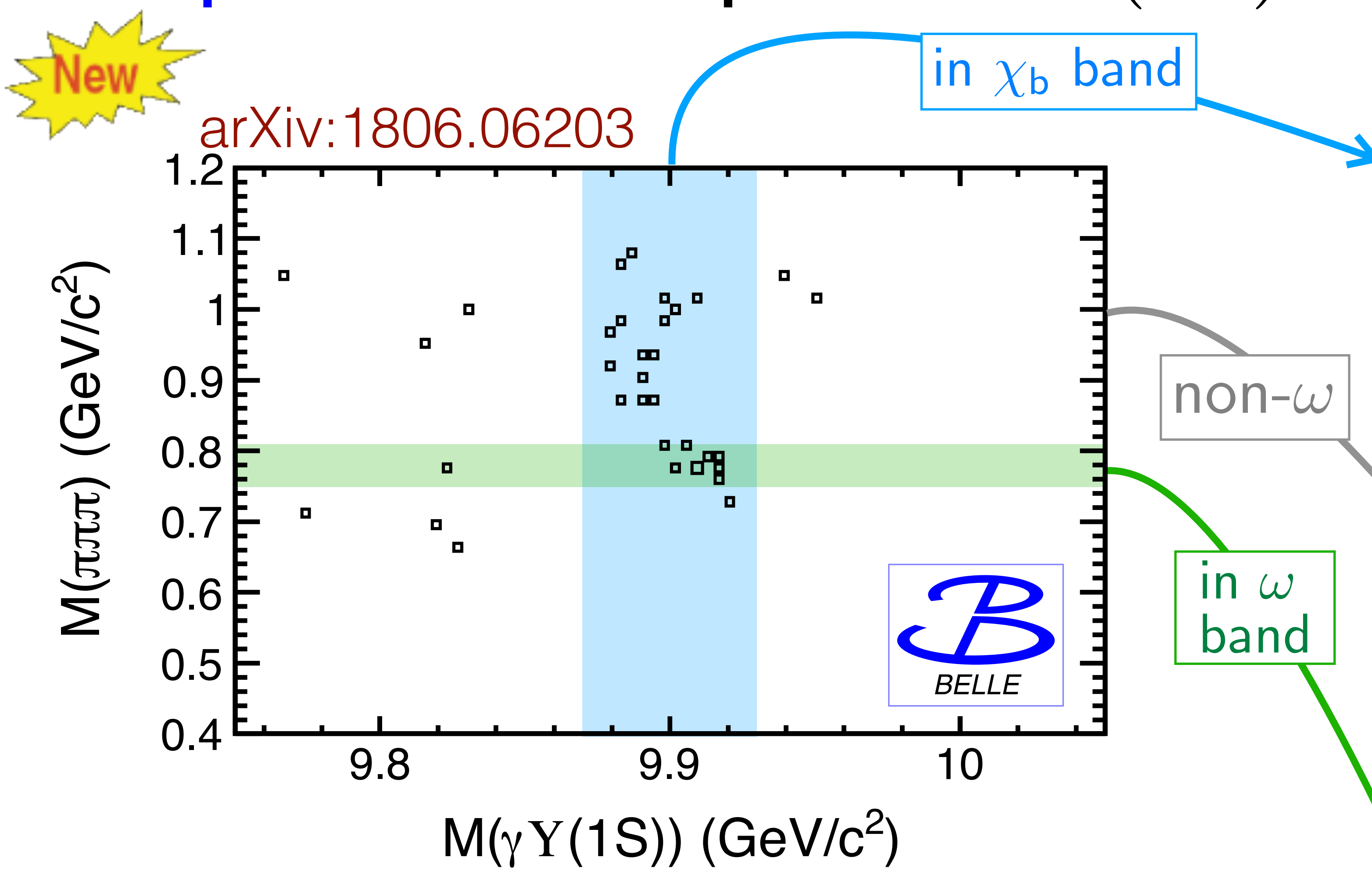
and other energies in the vicinity of $\Upsilon(5S)$ and $\Upsilon(6S)$

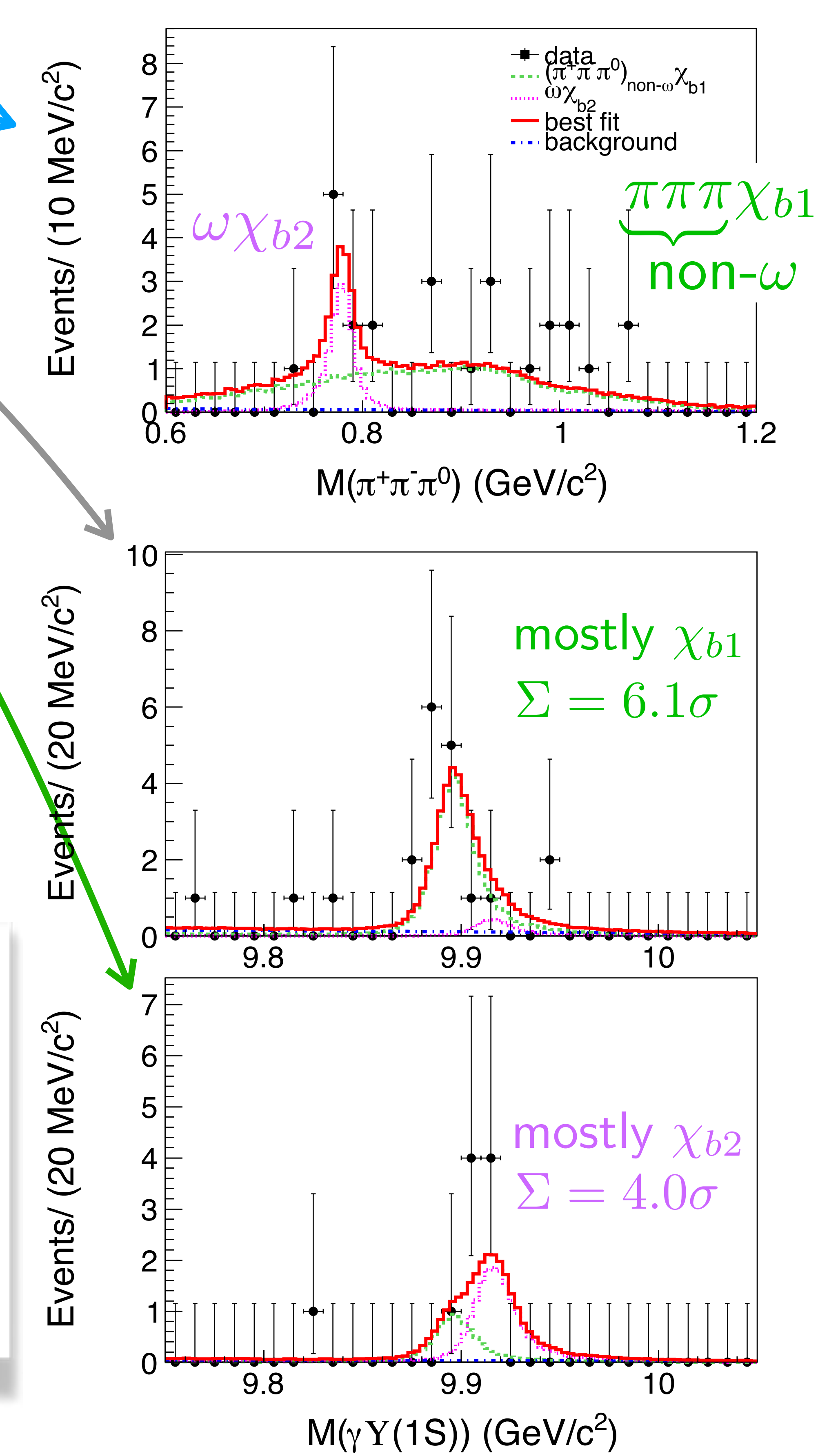
New arXiv:1806.06203, submitted to PRL

$E_{c.m.}$ (GeV)	$\mathcal{L}(\text{ fb}^{-1})$
10.7711	0.955
10.8203	1.164
10.8497	0.989
10.8589	0.989
10.8633	47.648
10.8667	45.553
10.8686	22.938
10.8695	0.978
10.8785	0.978
10.8836	1.230
10.8889	0.989
10.8985	0.983
10.9011	0.873
10.9077	0.980
10.9275	0.667
10.9575	0.851
10.9775	0.999
10.9919	0.986
11.0068	0.976
11.0164	0.771
11.0175	0.849
11.0220	0.982



Repeat: Dalitz plot of $\Upsilon(6S) \to \pi^+\pi^-\pi^0\gamma\Upsilon(1S)$





Combined χ_{b1} and χ_{b2} (with $\Upsilon(5S)$ re-measurement):

$$\mathcal{B}\left[\Upsilon(5S) \to 3\pi\chi_{bJ}\right] = (2.5 \pm 0.6 \pm 2.0 \pm 0.7) \cdot 10^{-3}$$

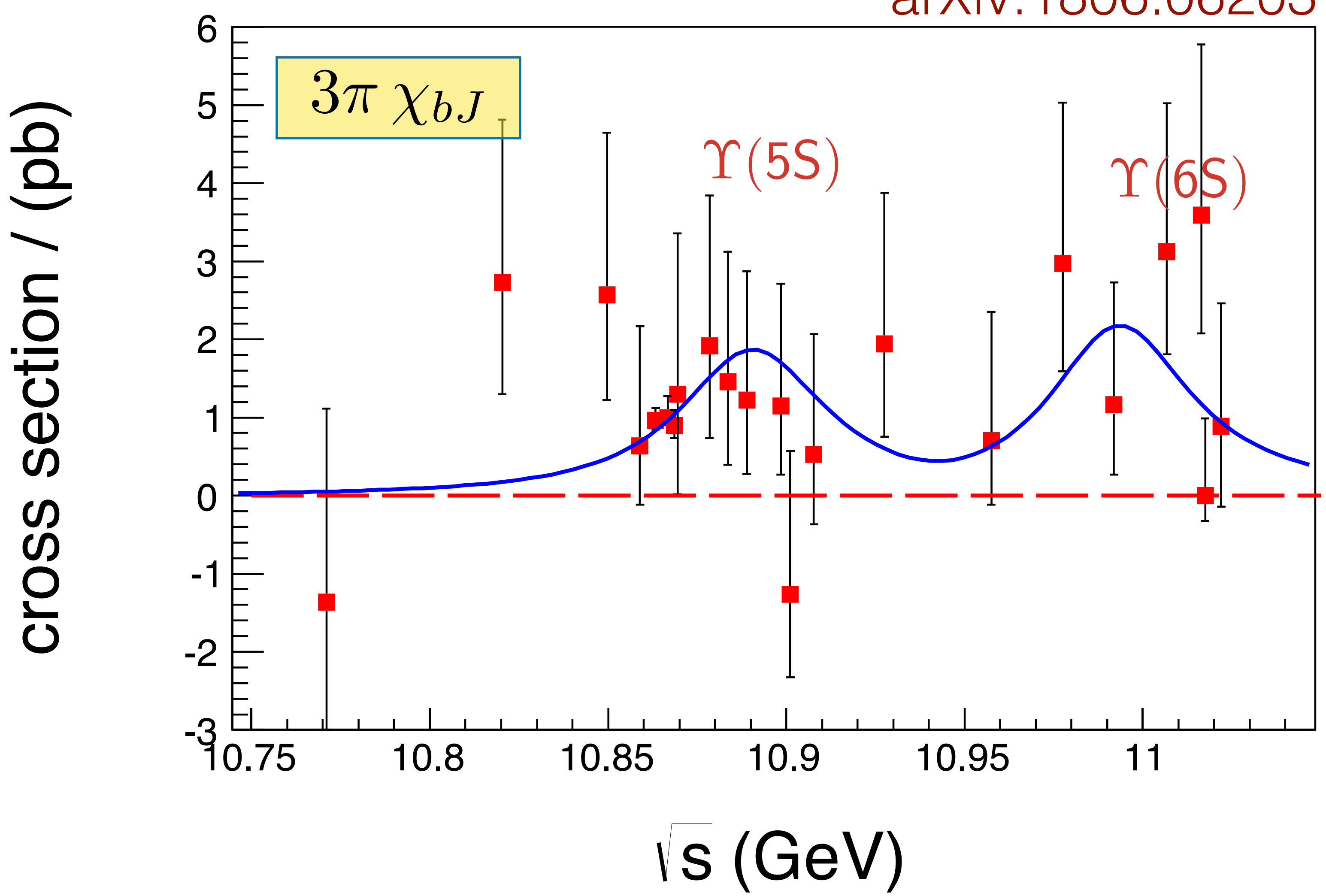
$$\mathcal{B}\left[\Upsilon(6S) \to 3\pi\chi_{bJ}\right] = (8.7 \pm 4.3 \pm 6.1 \pm ^{4.5}_{2.5}) \cdot 10^{-3}$$

Energy scan near $\Upsilon(5S)$ / $\Upsilon(6S)$ for $e^+e^- \to \pi^+\pi^-\pi^0\,\chi_{bJ}$

BELLE

New

arXiv:1806.06203



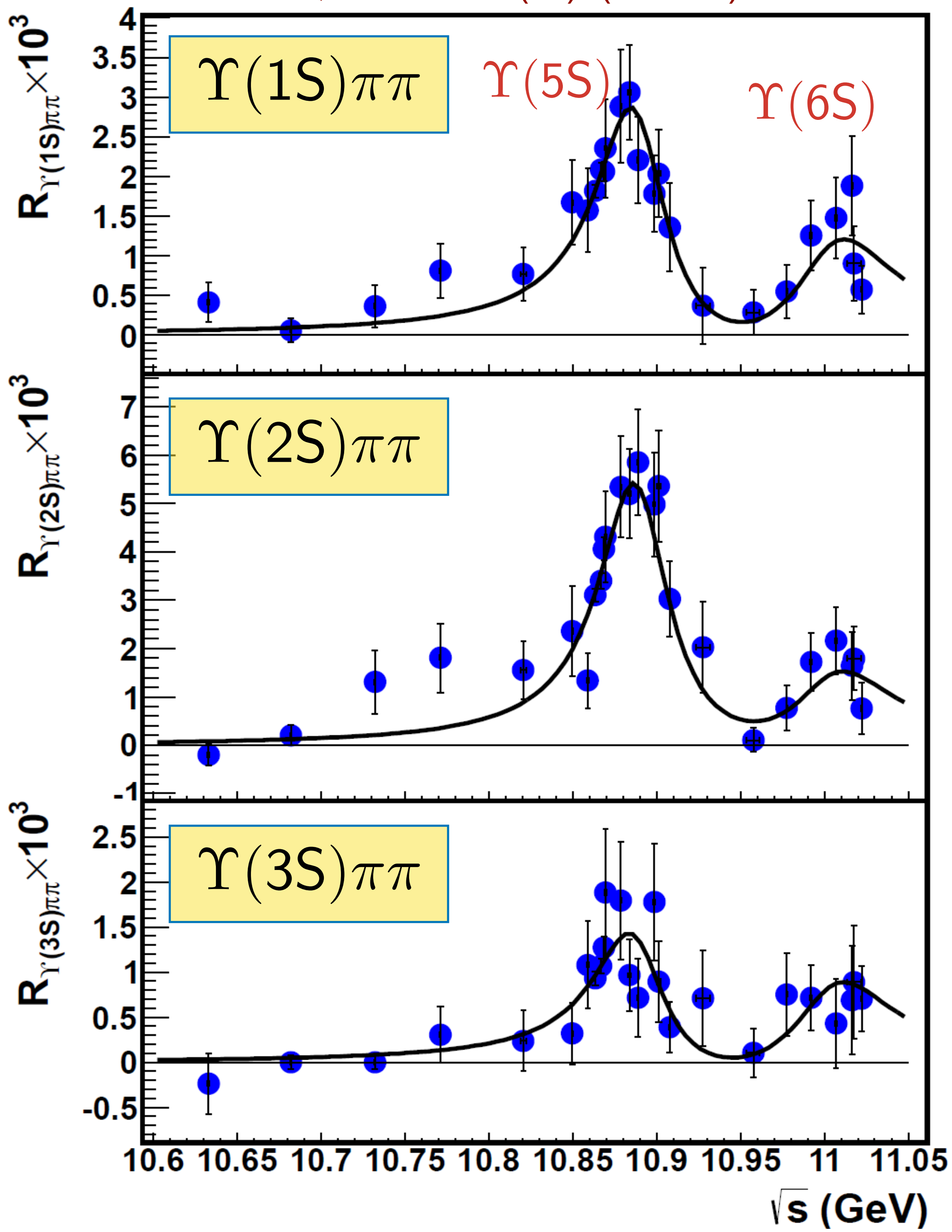
- **statistics-limited:** cannot determine conclusively the relative contributions from bottomonium decay and continuum 😐
- assuming only bottomonium decay,

$$\mathcal{B}\left[\Upsilon(5S) \to 3\pi\,\chi_{bJ}\right] = (2.5 \pm 0.6 \pm 2.0 \pm 0.7) \cdot 10^{-3}$$

$$\mathcal{B}\left[\Upsilon(6S) \to 3\pi\,\chi_{bJ}\right] = (8.7 \pm 4.3 \pm 6.1 \pm {}^{4.5}_{2.5}) \cdot 10^{-3}$$

Comparison #1: energy scan near $\Upsilon(5S)$ / $\Upsilon(6S)$ for $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$

PRD **93**, 011101(R) (2016)



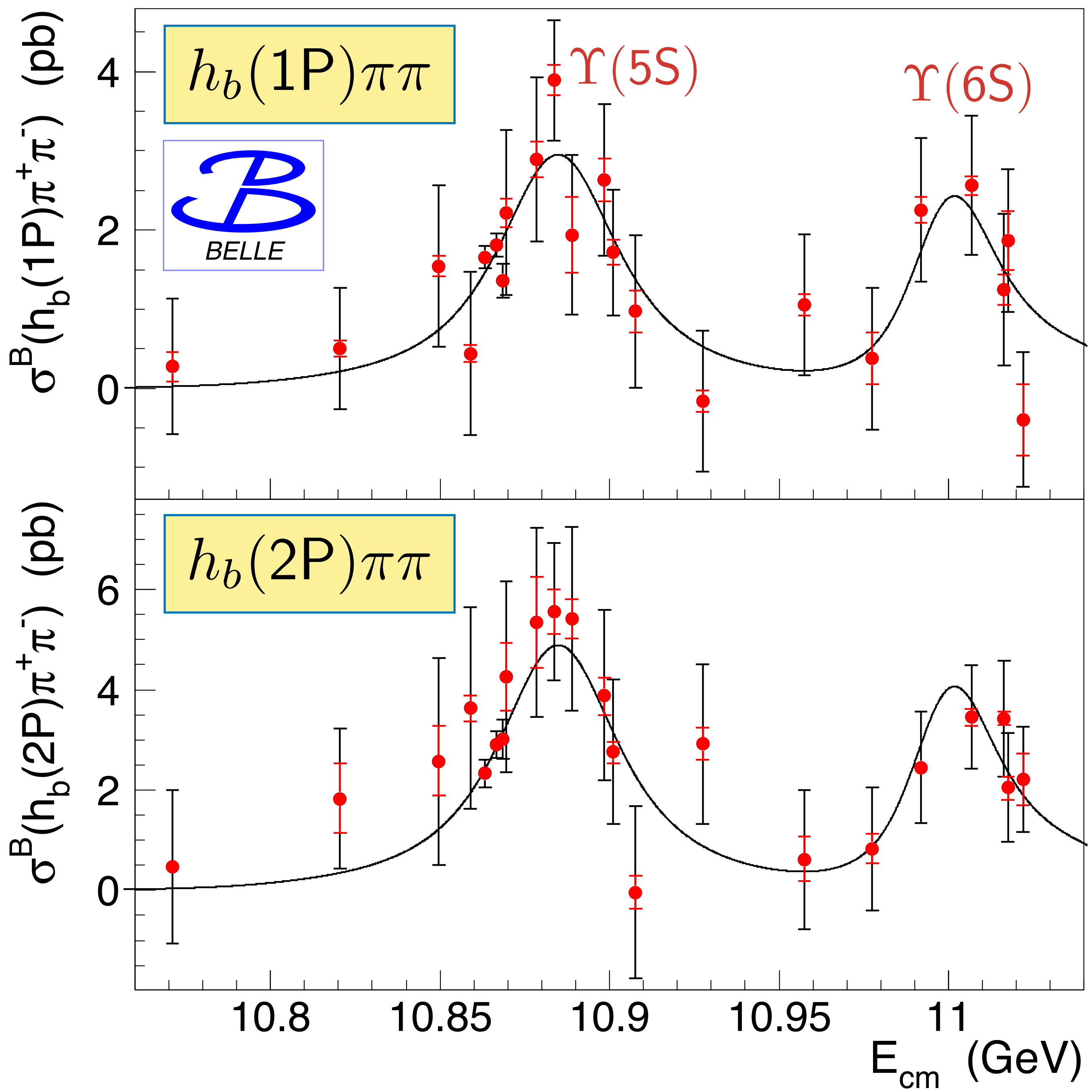
- ✓ higher statistics 😀
- ✓ essentially no continuum contribution
- ✓ interference between $\Upsilon(5S)$ and $\Upsilon(6S)$ is included in the fit:

$$\mathcal{F}'_n = \Phi_n(\sqrt{s}) \cdot \Big\{ |A_{5S,n}\, f_{5S}|^2 + |A_{6S,n}\, f_{6S}|^2 + 2k_n\, A_{5S,n}\, A_{6S,n}\, \Re\big[e^{i\delta_n} f_{5S}\, f_{6S}\big] \Big\}$$

Measure resonance parameters of $\Upsilon(5S)$ and $\Upsilon(6S)$ using this cross section.

Comparison #2: energy scan near $\Upsilon(5S)$ / $\Upsilon(6S)$ for $e^+e^- \to h_b(nP)\pi^+\pi^-$

PRL **117**, 142001 (2016)

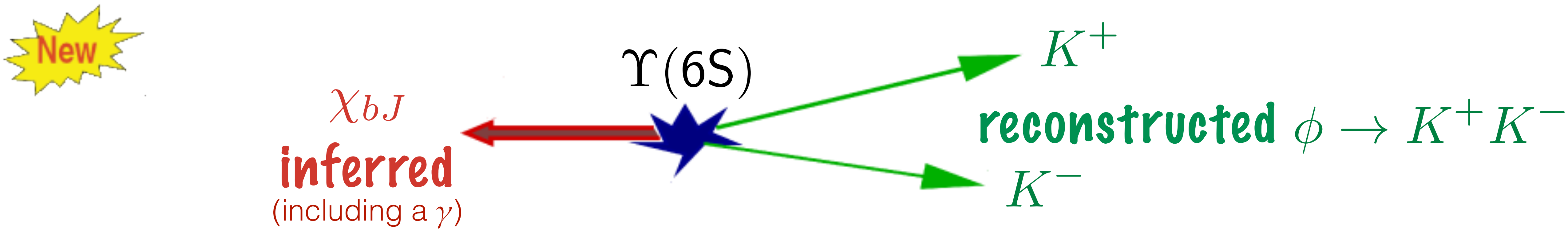


~Same pattern here as in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$:
two resonances and
≈no continuum background

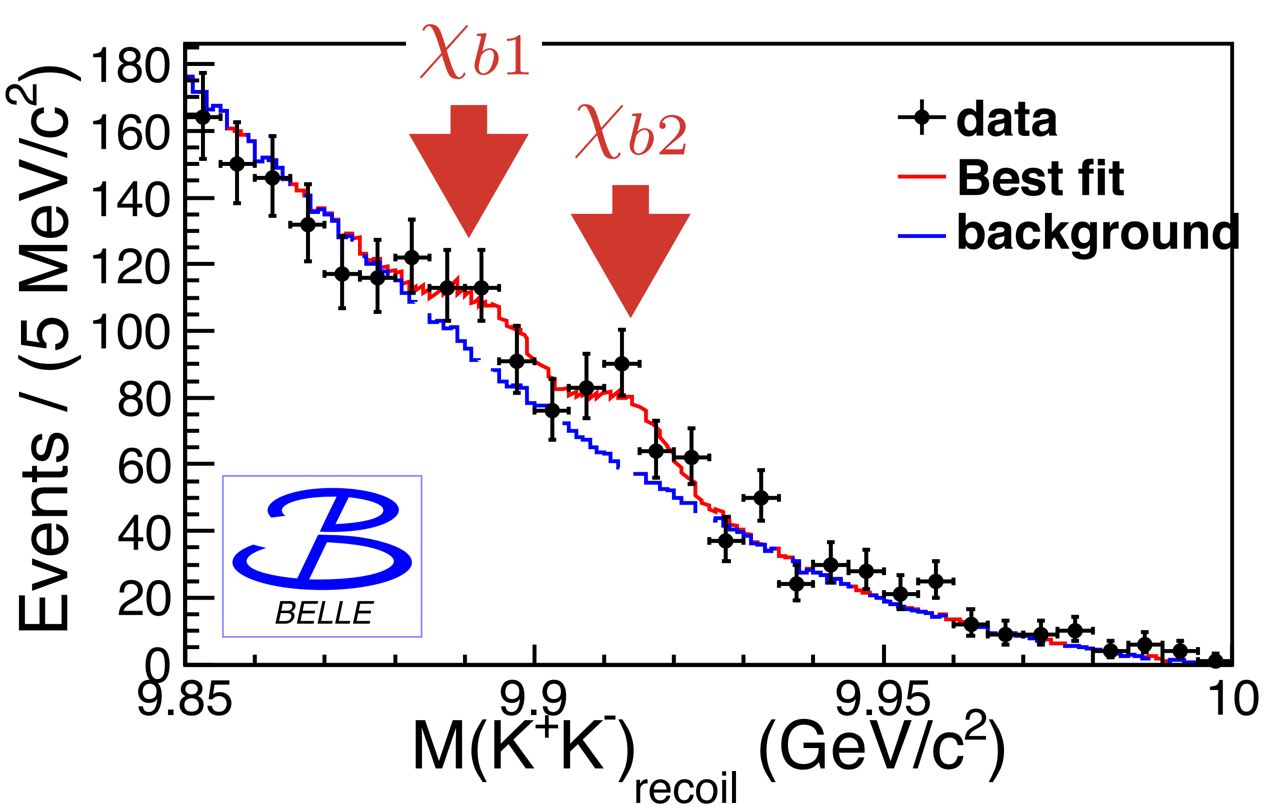
✓ First evidence ($\mathcal{S} = 3.5\sigma$) for $\Upsilon(6S) \to h_b(1P)\pi^+\pi^-$

✓ First observation ($\mathcal{S} = 5.3\sigma$) of $\Upsilon(6S) \to h_b(2P)\pi^+\pi^-$

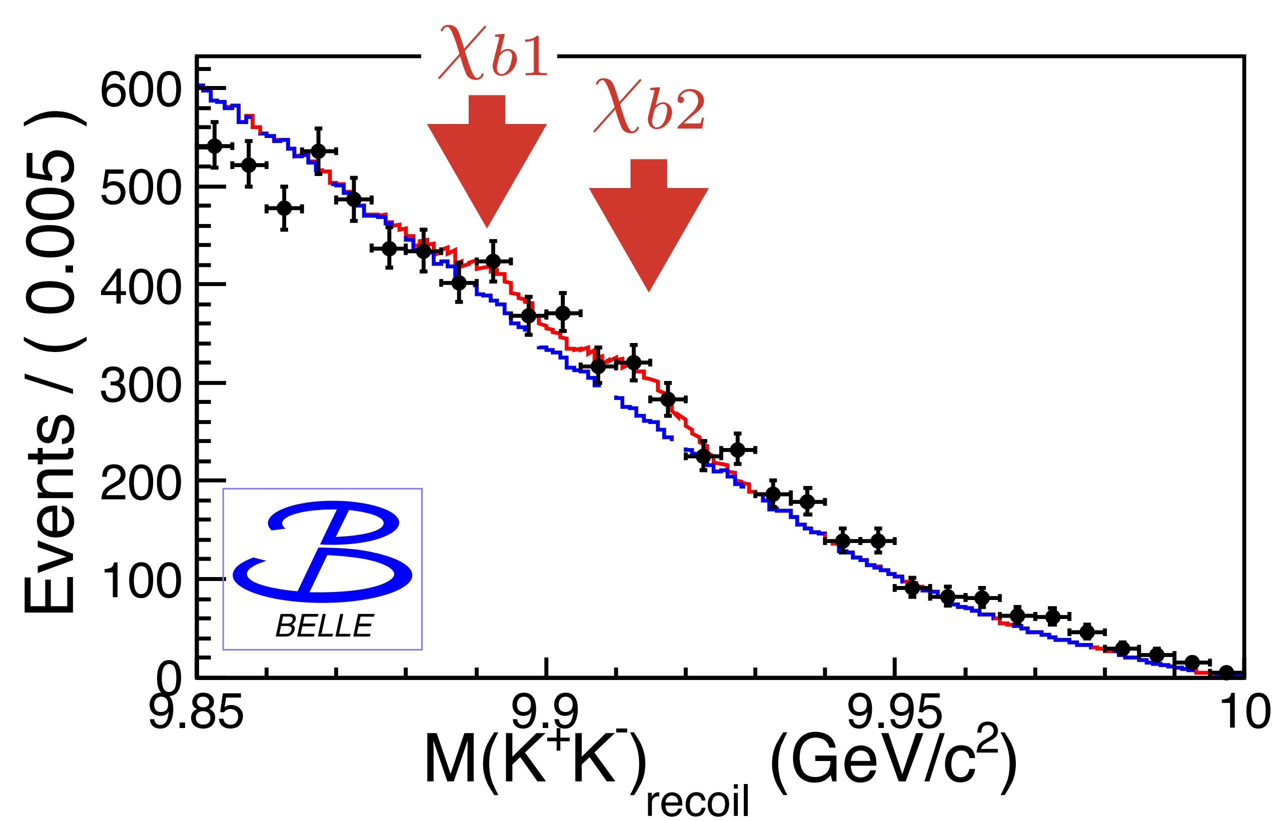
Use missing-mass technique for $\Upsilon(6S) \to \phi\chi_{bJ}$



for events with γKK in the $\Upsilon(1S)$ window



for events with γKK outside $\Upsilon(1S)$ window

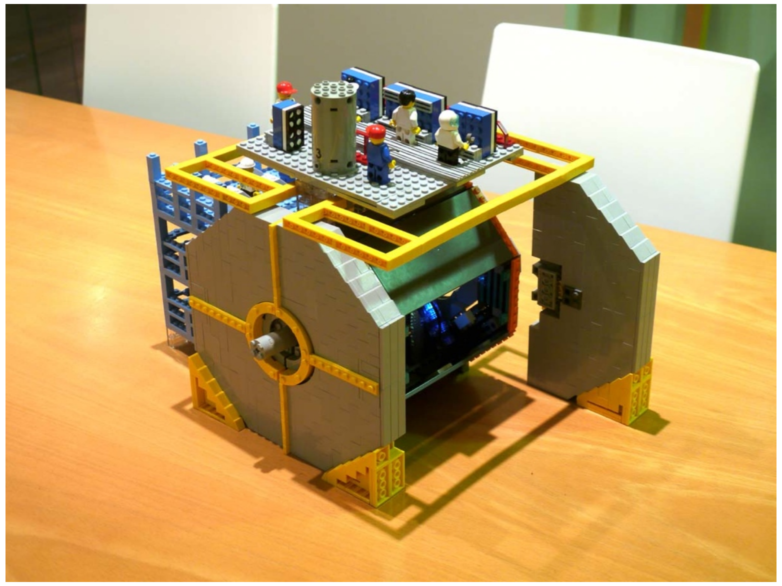


χ_{b1}: $\Sigma = 2.6\sigma \Rightarrow \sigma_{\text{Born}}\left(e^+e^- \to \phi\chi_{b1}\right) < 0.6\,\text{pb}\ (90\%\ \text{C.L.})$

χ_{b2}: $\Sigma = 2.1\sigma \Rightarrow \sigma_{\text{Born}}\left(e^+e^- \to \phi\chi_{b2}\right) < 1.0\,\text{pb}\ (90\%\ \text{C.L.})$

… three orders of magnitude above QCD expectation (Huang et al, EPJC **77**, 165 (2017)

$\Upsilon(5S, 6S)$ Summary



- ✓ Synopsis of prior Belle results at $\Upsilon(5S)$
- ✓ Measurement of $\Upsilon(5S) \to \eta\Upsilon(1D)$
  New arXiv:1803.03225, submitted to EPJC
- ✓ Measurement of $\Upsilon(5S, 6S) \to \pi^+\pi^-\pi^0\chi_{bJ}$ with evidence for $\omega\chi_{bJ}$ and upper limits for $\phi\chi_{bJ}$ final states
  New arXiv:1806.06203, submitted to PRL
- ✓ Statistics-limited results … Expect new data from Belle II.

Other Belle talks at ICHEP:

• **P Urquijo: CPV and CKM in the quark sector**	**PLENARY July 10 at 13:40**
• **E Won:** Dark Particles and Dark Sector	BeyondStandardModel July 6 at 14:15
• **K Matsuoka:** New results on R(D) and R(D*)	BeyondStandardModel July 7 at 14:30
• **B Fulsom:** Y(4S) $\to \eta'$ Y(1S) and Y(2S) $\to \gamma\ \eta_b$(1S)	StrongInt+Hadrons July 5 at 14:20
• **R Seidl:** Inclusive di-hadrons, hyperons and charmed baryons	StrongInt+Hadrons July 6 at 11:15
• **N Gabyshev:** Charmed baryons	StrongInt+Hadrons July 7 at 11:15
• **P Krokovny:** Charmonium(-like) states, pentaquark search	StrongInt+Hadrons July 7 at 14:50
• **Q Xu:** K_S pairs, η_c(1S), η_c(2S) + non-res $\eta'\pi\pi$ in two-γ collisions	StrongInt+Hadrons July 7 at 17:15
• **A Ishikawa:** Radiative *B* Decays	QuarkLeptonFlavor July 5 at 9:20
• **M Purohit:** Electroweak Penguin *B* Decays	QuarkLeptonFlavor July 5 at 11:20
• **E Waheed:** Semileptonic *B* decays and CKM $\|V_{ub}\|$ and $\|V_{cb}\|$	QuarkLeptonFlavor July 5 at 16:50
• **V Vorobyev:** cos2β [= cos2ϕ_1] in $B^0 \to D^{(*)0} h^0$ (Belle + BaBar)	QuarkLeptonFlavor July 6 at 9:20
• **IS Lee:** Time-dependent CP violation in charmless *B* decays	QuarkLeptonFlavor July 6 at 10:00
• **CL Hsu:** Direct CP violation in *B* decays	QuarkLeptonFlavor July 6 at 15:20
• **YT Lai:** CP violation and rare decays in charm sector	QuarkLeptonFlavor July 6 at 18:10
• **K Hayasaka:** Lorentz structure of τ decays and rare τ decays	QuarkLeptonFlavor July 7 at 16:50