Bottomonium Spectroscopy: Model Predictions and Experimental Search Strategies

Stephen Godfrey & Ken Moats
Carleton University

S. Godfrey and K. Moats, PRD92, 054034 (2015) [1507.00024]

1. Spectroscopy

Lorentz vector 1-gluon exchange + Lorentz scalar linear confining potential

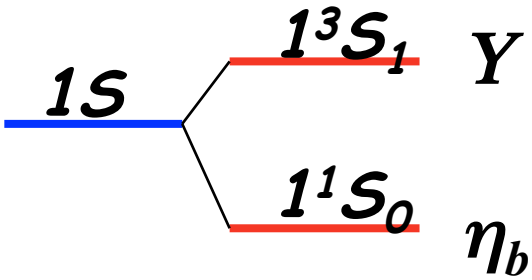
$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + br$$

Relativistic corrections implicitly included in spin-dependent

Spin-spin interactions:

$$H_{ij}^{hyp} = \frac{4\alpha_s(r)}{3m_i m_j}\left\{\frac{8\pi}{3}\vec{S}_i\cdot\vec{S}_j\,\delta^3(\vec{r}_{ij}) + \frac{1}{r_{ij}^3}\left[\frac{3\vec{S}_i\cdot\vec{r}_{ij}\vec{S}_j\cdot\vec{r}_{ij}}{r_{ij}^2} - \vec{S}_i\cdot\vec{S}_j\right]\right\}$$

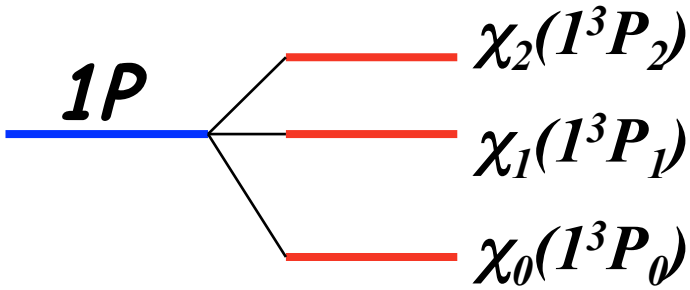
contact tensor



Spin-orbit interactions:

$$H_{ij}^{s.o.(cm)} = \frac{4\alpha_s(r)}{3r_{ij}^3}\left(\frac{1}{m_i}+\frac{1}{m_j}\right)\left(\frac{\vec{S}_i}{m_i}+\frac{\vec{S}_j}{m_j}\right)\cdot\vec{L}$$

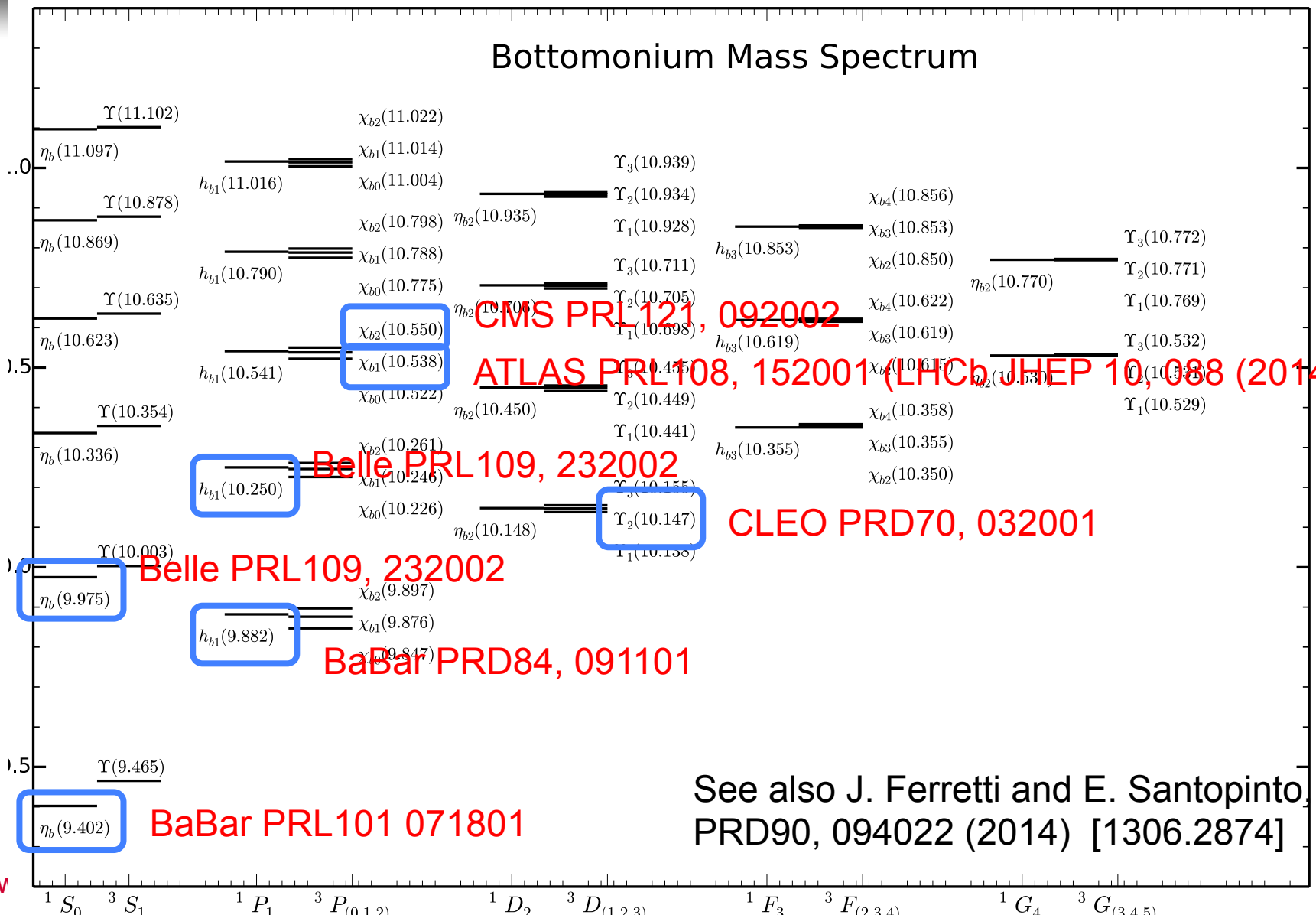
$$H_{ij}^{s.o.(tp)} = \frac{-1}{2r_{ij}}\frac{\partial V(r)}{\partial r_{ij}}\left(\frac{\vec{S}_i}{m_i^2}+\frac{\vec{S}_j}{m_j^2}\right)\cdot\vec{L}$$



For given spin, orbital angular momentum & radial excitations generate spectrum with the meson quantum numbers characterized by given J^{PC}

1. Spectroscopy

SG, K.Moats, PRD92, 054034(2015) [1507.00024]



CMS PRL 121, 092002

ATLAS PRL108, 152001 (LHCb JHEP 10, 088 (2014))

Belle PRL109, 232002

CLEO PRD70, 032001

Belle PRL109, 232002

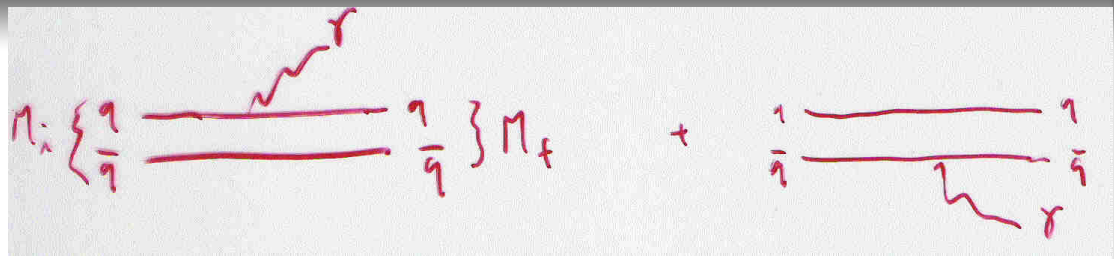
BaBar PRD84, 091101

BaBar PRL101 071801

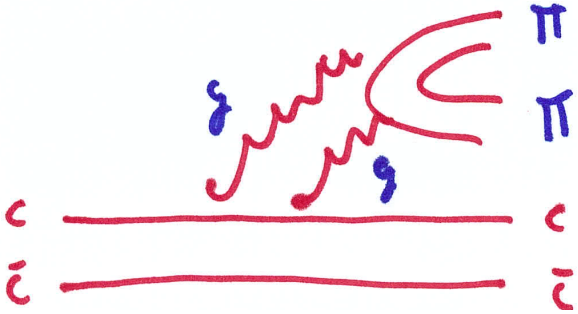
See also J. Ferretti and E. Santopinto, PRD90, 094022 (2014) [1306.2874]

2. Decays

- Electromagnetic Transitions: E1 & M1

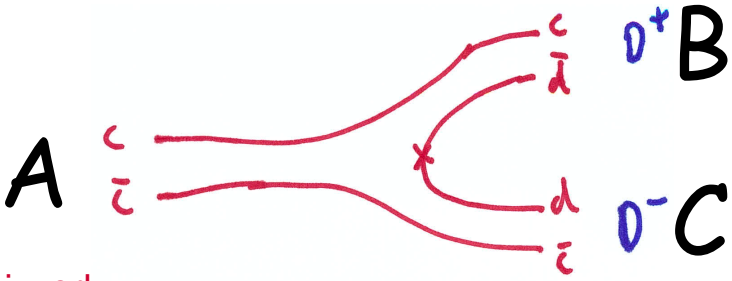


- Hadronic Transitions:



- Annhihilation Decays:

- OZI Allowed Decays:



Putting it all together:

TABLE VI: Partial widths and branching fractions for strong and electromagnetic transitions for $3P$ states. Details of the calculations are given in the text.

Initial state	Final state	M_i (GeV)	M_f (GeV)	$\mathcal{M}$	Predicted Width (keV)	Predicted B.F. (%)	Measured Width (keV)	Measured B.F. (%)
$\chi_{b2}(3^3P_2)$	*glue*	10.528			227	91.6		
	$\gamma\gamma$				1.3×10^{-2}	0.005		
	$\gamma\Upsilon(3^3S_1)$		10.355	2.226	9.3	3.8		
	$\gamma\Upsilon(2^3S_1)$		10.023	0.323	4.5	1.8		
	$\gamma\Upsilon(1^3S_1)$		9.460	0.086	2.8	1.1		
	$\gamma\Upsilon(2^3D_3)$		10.455	-2.568	1.5	0.6		
	$\gamma\Upsilon(2^3D_2)$		10.449	-2.482	0.32	0.1		
	$\gamma\Upsilon(2^3D_1)$		10.441	-2.389	0.027	0.01		
	$\gamma\Upsilon(1^3D_3)$		10.172	0.042	0.046	0.02		
	$\chi_{b2}(1^3P_2)\pi\pi$				1.15	0.5		
	$\chi_{b2}(1^3P_1)\pi\pi$				0.74	0.3		
	$\chi_{b2}(1^3P_0)\pi\pi$				0.33	0.1		
	Total				248	100		
$\chi_{b1}(3^3P_1)$	$q\bar{q}+g$	10.516			101	86.1		
	$\gamma\Upsilon(3^3S_1)$		10.355	2.388	8.5	7.2		
	$\gamma\Upsilon(2^3S_1)$		10.023	0.278	3.1	2.6		
	$\gamma\Upsilon(1^3S_1)$		9.460	0.061	1.3	1.1		
	$\gamma\Upsilon(1S)$							
	$\gamma\Upsilon(2^3D_2)$		10.449	-2.595	1.1	0.9		
	$\gamma\Upsilon(2^3D_1)$		10.441	-2.506	0.47	0.4		
	$\gamma\Upsilon(1^3D_2)$		10.164	0.060	0.080	0.07		
	$\gamma\Upsilon(1^3D_1)$		10.154	0.029	7.0×10^{-3}			
	$\chi_{b2}(1^3P_2)\pi\pi$				1.2	1.0		
	$\chi_{b1}(1^3P_1)\pi\pi$				0.64	0.5		
	$\chi_{b2}(1^3P_0)\pi\pi$				~ 0			
	Total				117	100		

Putting it all together:

TABLE VII: Partial widths and branching fractions for strong and electromagnetic transitions for the $4P$ states. Details of the calculations are given in the text.

Initial state	Final state	M_i (GeV)	M_f (GeV)	$\mathcal{M}$	Width (keV)	B.F. (%)
$\chi_{b2}(4^3P_2)$	*glue*	10.798			248	
	$\gamma\gamma$				1.3×10^{-2}	
	$\gamma\Upsilon(4^3S_1)$		10.579	2.765	28.1	
	$\gamma\Upsilon(3^3S_1)$		10.355	0.427	5.4	1.2×10^{-2}
	$\gamma\Upsilon(2^3S_1)$		10.023	0.063	0.59	1.4×10^{-3}
	$\gamma\Upsilon(1^3S_1)$		9.460	0.056	2.2	5.0×10^{-3}
	$\gamma\Upsilon(3^3D_3)$		10.711	-3.310	4.3	
	$\gamma\Upsilon(3^3D_2)$		10.705	-3.202	0.88	
	$\gamma\Upsilon(3^3D_1)$		10.698	-3.084	0.68	
	BB				8.74 MeV	
	BB^*				28.1 MeV	
	B^*B^*				5.05 MeV	
	B_sB_s				0.593 MeV	
	$B_sB_s^*$				0.833 MeV	
	Total				43.6 MeV	
$\chi_{b1}(4^3P_1)$	$q\bar{q}+g$	10.788			110	
	$\gamma\Upsilon(4^3S_1)$		10.579	2.942	27.7	
	$\gamma\Upsilon(3^3S_1)$		10.355	0.373	3.8	1.3×10^{-2}
	$\gamma\Upsilon(2^3S_1)$		10.023	0.035	0.18	6.0×10^{-4}
	$\gamma\Upsilon(1^3S_1)$		9.460	0.038	1.0	3.3×10^{-3}
	$\gamma\Upsilon(3^3D_2)$		10.705	-3.345	3.4	
	$\gamma\Upsilon(3^3D_1)$		10.698	-3.234	1.4	
	BB^*				20.6 MeV	
	B^*B^*				0.478 MeV	
	$B_sB_s^*$				8.93 MeV	
	Total				30.2 MeV	

Putting it all together:

TABLE X: Partial widths and branching fractions for strong and electromagnetic transitions for $2D$ states. Details of the calculations are given in the text. $\langle f|r|i\rangle$

Initial state	Final state	M_i (GeV)	M_f (GeV)	$\mathcal{M}$	Width (keV)	B.F. (%)
$\Upsilon(2^3D_3)$	$\gamma\chi_{b2}(2^3P_2)$	10.455	10.269	2.445	16.4	65.1
	$\gamma\chi_{b2}(1^3P_2)$	10.455	9.912	0.200	2.6	10.3
	$\gamma\chi_{b4}(1^3F_4)$	10.455	10.358	-1.798	1.7	6.7
	$\gamma\chi_{b3}(1^3F_3)$	10.455	10.355	-1.751	0.16	0.6
	$\gamma\chi_{b2}(1^3F_2)$	10.455	10.350	-1.702	5×10^{-3}	
	$\gamma\eta_{b2}(2^1D_2)$	10.455	10.450	0.999	6.5×10^{-6}	
	$\gamma\eta_{b2}(1^1D_2)$		10.165	-0.033	1.1×10^{-3}	
	ggg					
	ggg	10.455			4.3	17.1
	$\Upsilon(1^3D_3)\pi^+\pi^-$				6.2×10^{-3}	
	$\Upsilon(1^3D_2)\pi^+\pi^-$				2.6×10^{-6}	
	$\Upsilon(1^3D_1)\pi^+\pi^-$				2.6×10^{-7}	
	Total				25.2	100
$\Upsilon(2^3D_2)$	$\gamma\chi_{b2}(2^3P_2)$	10.449	10.269	2.490	3.8	16.8
	$\gamma\chi_{b1}(2^3P_1)$	10.449	10.255	2.359	12.7	56.2
	$\gamma\chi_{b2}(1^3P_2)$	10.449	9.912	0.161	0.4	1.8
	$\gamma\chi_{b1}(1^3P_1)$	10.449	9.893	0.224	2.6	11.5
	$\gamma\chi_{b3}(1^3F_3)$	10.449	10.355	-1.806	1.5	6.6
	$\gamma\chi_{b2}(1^3F_2)$	10.449	10.350	-1.758	0.21	0.9
	$\gamma\eta_{b2}(1^1D_2)$		10.165	-0.047	2.1×10^{-3}	
	ggg	10.449			1.4	6.2
	$\Upsilon(1^3D_3)\pi^+\pi^-$				1.8×10^{-5}	
	$\Upsilon(1^3D_2)\pi^+\pi^-$				6.2×10^{-3}	
	$\Upsilon(1^3D_1)\pi^+\pi^-$				3.2×10^{-6}	
	Total				22.6	100

Putting it all together:

TABLE XI: Partial widths and branching fractions for strong and electromagnetic transitions for $3D$ states. Details of the calculations are given in the text. $\langle f|r|i\rangle$

Initial state	Final state	M_i (GeV)	M_f (GeV)	$\mathcal{M}$	Width (keV)	B.F. (%)
$\Upsilon(3^3D_3)$	$\gamma\chi_{b2}(3^3P_2)$	10.711	10.528	3.022	23.6	1.2×10^{-2}
	$\gamma\chi_{b2}(2^3P_2)$		10.269	0.265	2.5	1.3×10^{-3}
	$\gamma\chi_{b2}(1^3P_2)$		9.912	0.064	0.82	4.1×10^{-4}
	$\gamma\chi_{b4}(2^3F_4)$		10.622	-2.683	3.0	
	$\gamma\chi_{b3}(2^3F_3)$		10.619	-2.617	0.27	
	$\gamma\chi_{b2}(2^3F_2)$		10.615	-2.545	8×10^{-3}	
	ggg				6.6	
	BB				16.2 MeV	
	BB^*				72.9 MeV	
	B^*B^*				109 MeV	
	Total				198 MeV	
$\Upsilon(3^3D_2)$	$\gamma\chi_{b2}(3^3P_2)$	10.705	10.528	3.098	5.6	
	$\gamma\chi_{b1}(3^3P_1)$		10.516	2.919	18.2	
	$\gamma\chi_{b1}(2^3P_2)$		10.269	0.218	0.40	
	$\gamma\chi_{b1}(2^3P_1)$		10.255	0.303	2.5	
	$\gamma\chi_{b1}(1^3P_2)$		9.912	0.043	0.09	
	$\gamma\chi_{b1}(1^3P_1)$		9.893	0.062	0.59	
	$\gamma\chi_{b2}(2^3F_3)$		10.619	-2.698	2.6	
	$\gamma\chi_{b2}(2^3F_2)$		10.615	-2.628	0.36	
	ggg				2.0	
	BB^*				52.4 MeV	
	B^*B^*				76.5 MeV	
	Total				128.9 MeV	

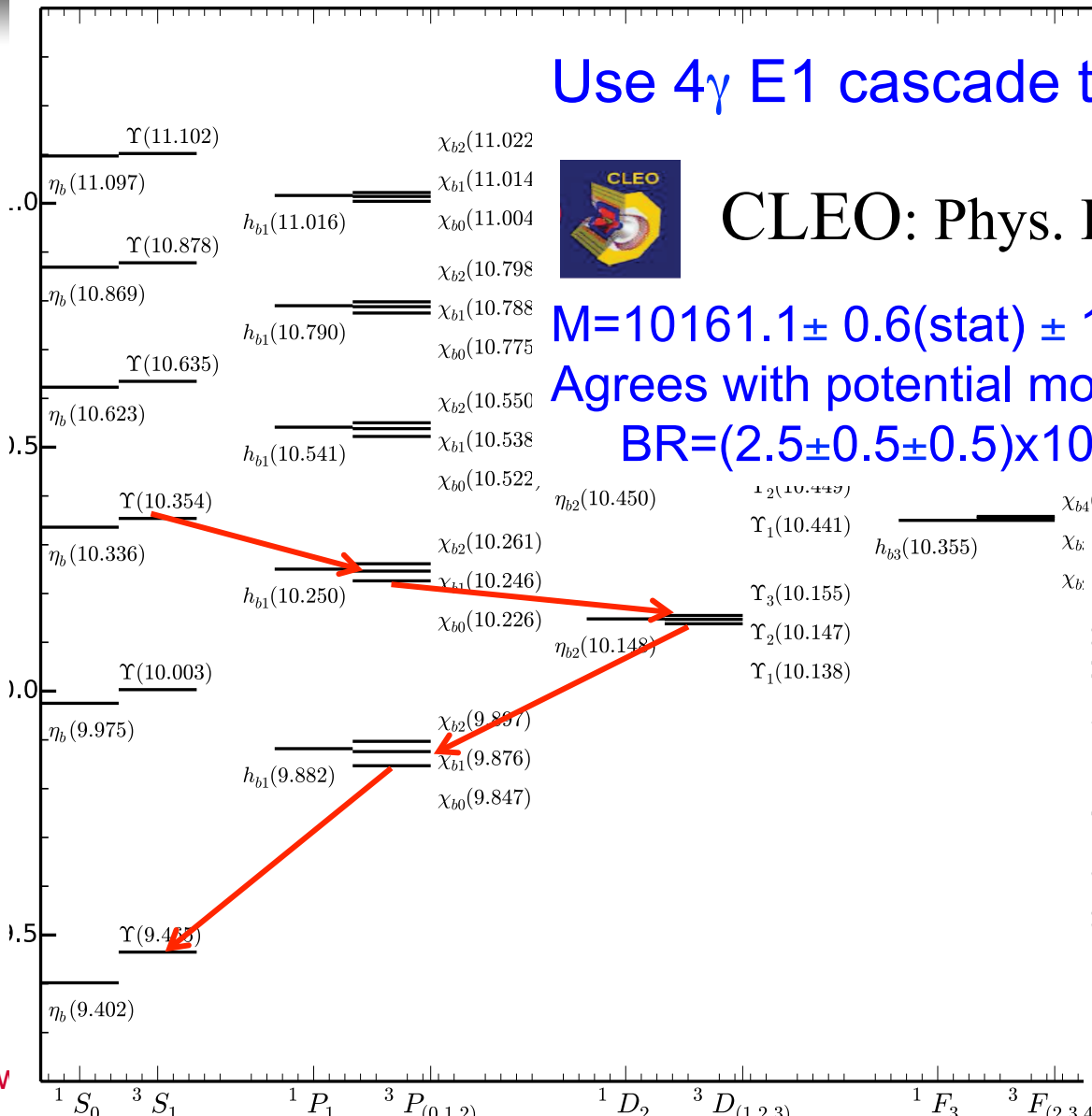
Example 1: 1^3D_J

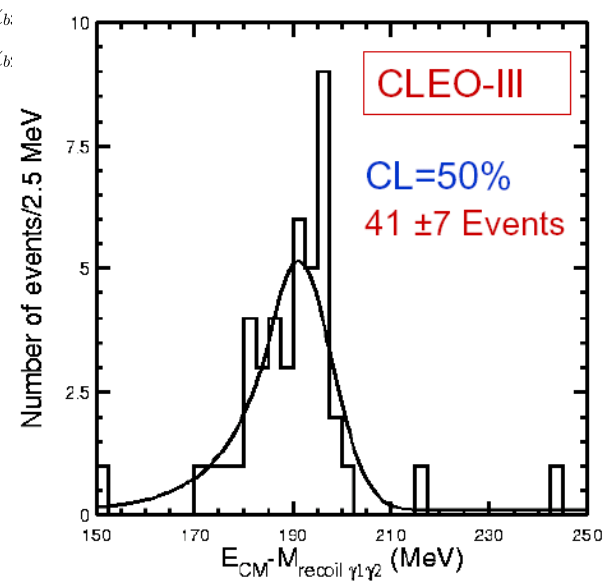
SG & J. Rosner, PRD64, 097501 (2001)
[hep-ph/0105273]

Use 4γ E1 cascade to search $\Upsilon(1^3D_J)$

CLEO: Phys. Rev. D70,032001 (2004)

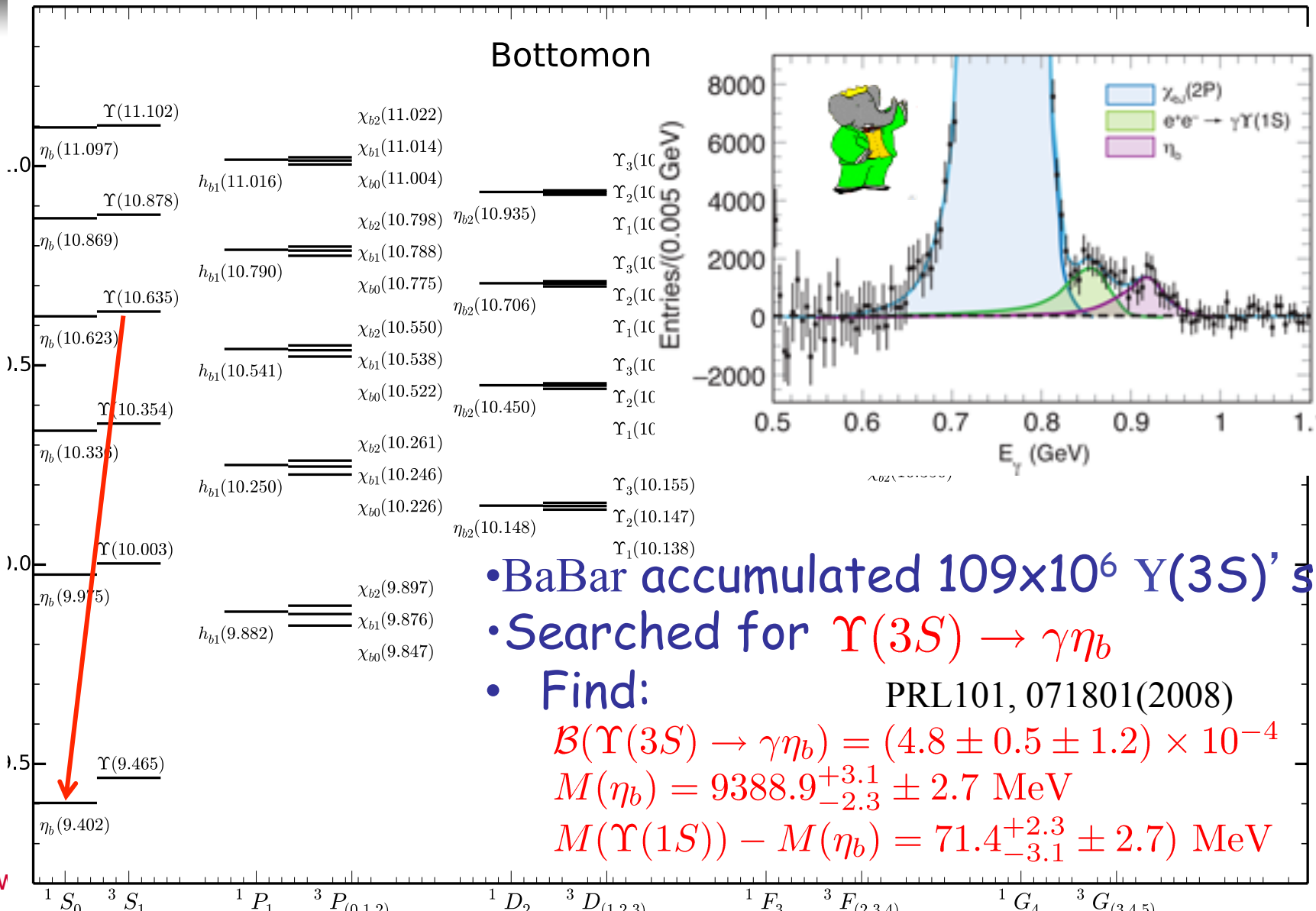
M=10161.1± 0.6(stat) ± 1.6(syst) MeV
Agrees with potential models and Lattice QCD
BR=(2.5±0.5±0.5)x10^{-5} vs 2.6x10^{-5}





Example 2: η_b

S.G. & J. Rosner, PRD64, 074011 (2001)
[hep-ph/0104253]

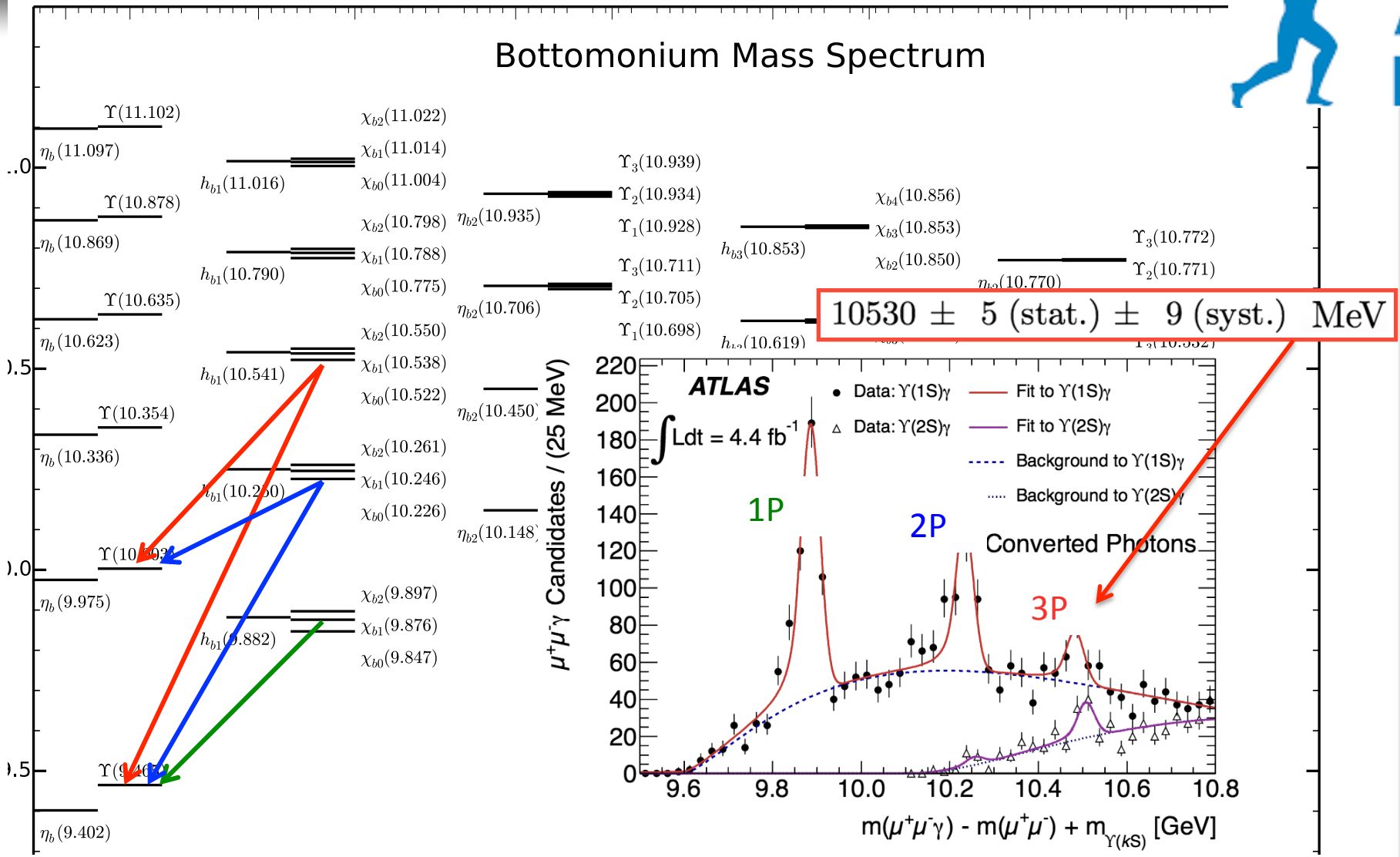


- BaBar accumulated 109×10^6 $\Upsilon(3S)$'s
- Searched for $\Upsilon(3S) \to \gamma\eta_b$
- Find: PRL101, 071801(2008)

$$\mathcal{B}(\Upsilon(3S) \to \gamma\eta_b) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$$
$$M(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7 \text{ MeV}$$
$$M(\Upsilon(1S)) - M(\eta_b) = 71.4^{+2.3}_{-3.1} \pm 2.7) \text{ MeV}$$

Example 3

3^3P_1 state was discovered at LHC by ATLAS [ATLAS, PRL 108, 152001 (2012)],



Sr confirmed by LHCb [LHCb-CONF-2012-020] and CMS PRL121, 092002

3. Bottomonium searches at the LHC and in e^+e^-

- LHC and Belle II can discover missing excited bottomonium states
- Use model predictions to propose search strategies

- For LHC estimate by rescaling LHCb event numbers:
  - Expect production cross section to roughly double going from 8 to 13 TeV
  - Expect order of magnitude increase in luminosity

- Focus on states below threshold ($B\overline{B}$)
  - Relatively narrow widths and high BR via radiative transitions
  - Use NRQCD to estimate production cross sections
  - Production of high L states suppressed:

$$\sigma(H) = \sum_n \sigma_n(\Lambda)\langle \mathcal{O}_n^H(\Lambda)\rangle \qquad \langle \mathcal{O}(^{2S+1}L_J)\rangle \propto (2J+1)\frac{|R_{nL}^{(L)}(0)|^2}{M^{2L+2}}$$

- Focus on radiative transitions
  - Cleaner backgrounds and easier to reconstruct than hadronic decays

Search strategies via 3S states

pp: LHCb 13 TeV, producing 3.1×10^8 $\Upsilon(3S)$, 1.4×10^8 $\eta_b(3S)$

e^+e^-: Belle II, producing 10^9 $\Upsilon(3S)$, assuming 250 fb^{-1}

- S-wave states have largest cross sections
- Interested in h_b and D-waves in decay chains

Interested in $\Upsilon(3S)$ decay chains via unobserved 1D states

Interested in $\eta_b(3S)$

Parent	Decay chain	Combined BR	Events pp	Events e^+e^-
3^3S_1	$\xrightarrow{13.1\%} 2^3P_2\gamma(86.2) \xrightarrow{1.2\%} 1^3D_3\gamma(96.5) \xrightarrow{91.0\%} 1^3P_2\gamma(256.0) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	6.8×10^{-6}	2100	6800
	$\xrightarrow{13.1\%} 2^3P_2\gamma(86.2) \xrightarrow{0.2\%} 1^3D_2\gamma(104.4) \xrightarrow{22\%} 1^3P_2\gamma(248.4) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	2.7×10^{-7}	84	270
	$\xrightarrow{13.1\%} 2^3P_2\gamma(86.2) \xrightarrow{0.2\%} 1^3D_2\gamma(104.4) \xrightarrow{74.7\%} 1^3P_1\gamma(267.3) \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	1.6×10^{-6}	500	1600
	$\xrightarrow{13.1\%} 2^3P_2\gamma(86.2) \xrightarrow{0.02\%} 1^3D_1\gamma(78.0) \xrightarrow{1.6\%} 1^3P_2\gamma(239.1) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	2.0×10^{-9}	0.6	2
	$\xrightarrow{13.1\%} 2^3P_2\gamma(86.2) \xrightarrow{0.02\%} 1^3D_1\gamma(78.0) \xrightarrow{28\%} 1^3P_1\gamma(258.0) \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	6.2×10^{-8}	19	62
	$\xrightarrow{13.1\%} 2^3P_2\gamma(86.2) \xrightarrow{0.02\%} 1^3D_1\gamma(78.0) \xrightarrow{47.1\%} 1^3P_0\gamma(290.5) \xrightarrow{1.76\%} 1^3S_1\gamma(391.1) \xrightarrow{2.48\%} \mu^+\mu^-$	5.4×10^{-9}	2	5
	$\xrightarrow{13.1\%} 2^3P_2\gamma(86.2) \xrightarrow{0.02\%} 1^3D_1\gamma(78.0) \xrightarrow{0.00393\%} \mu^+\mu^-$	1.0×10^{-9}	0.3	1
	$\xrightarrow{12.6\%} 2^3P_1\gamma(99.3) \xrightarrow{1.9\%} 1^3D_2\gamma(91.3) \xrightarrow{22\%} 1^3P_2\gamma(248.4) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	2.5×10^{-6}	780	2500
	$\xrightarrow{12.6\%} 2^3P_1\gamma(99.3) \xrightarrow{1.9\%} 1^3D_2\gamma(91.3) \xrightarrow{74.7\%} 1^3P_1\gamma(267.3) \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	1.5×10^{-5}	4650	15,000
	$\xrightarrow{12.6\%} 2^3P_1\gamma(99.3) \xrightarrow{0.80\%} 1^3D_1\gamma(100.8) \xrightarrow{1.6\%} 1^3P_2\gamma(239.1) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	7.6×10^{-8}	24	76
	$\xrightarrow{12.6\%} 2^3P_1\gamma(99.3) \xrightarrow{0.80\%} 1^3D_1\gamma(100.8) \xrightarrow{28\%} 1^3P_1\gamma(258.0) \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	2.4×10^{-6}	740	2400
	$\xrightarrow{12.6\%} 2^3P_1\gamma(99.3) \xrightarrow{0.80\%} 1^3D_1\gamma(100.8) \xrightarrow{47.1\%} 1^3P_0\gamma(290.5) \xrightarrow{1.76\%} 1^3S_1\gamma(391.1) \xrightarrow{2.48\%} \mu^+\mu^-$	2.1×10^{-7}	65	210
	$\xrightarrow{5.9\%} 2^3P_0\gamma(122.0) \xrightarrow{0.4\%} 1^3D_1\gamma(78.0) \xrightarrow{1.6\%} 1^3P_2\gamma(239.1) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	1.8×10^{-8}	6	18
	$\xrightarrow{5.9\%} 2^3P_0\gamma(122.0) \xrightarrow{0.4\%} 1^3D_1\gamma(78.0) \xrightarrow{28\%} 1^3P_1\gamma(258.0) \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	5.6×10^{-7}	170	560
	$\xrightarrow{5.9\%} 2^3P_0\gamma(122.0) \xrightarrow{0.4\%} 1^3D_1\gamma(78.0) \xrightarrow{47.1\%} 1^3P_0\gamma(290.5) \xrightarrow{1.76\%} 1^3S_1\gamma(391.1) \xrightarrow{2.48\%} \mu^+\mu^-$	4.8×10^{-8}	15	48
3^1S_0	$\xrightarrow{1.8\times10^{-6}} 2^3S_1\gamma(309.2) \xrightarrow{1.93\%} \mu^+\mu^-$	3.4×10^{-8}	5	NA
	$\xrightarrow{1.5\times10^{-5}} 1^3S_1\gamma(840.0) \xrightarrow{2.48\%} \mu^+\mu^-$	3.7×10^{-7}	52	NA

Production at the LHC: 3^3P_1

LHCb 13 TeV, producing 7.9×10^6 $\chi_b(3^3P_1)$

Parent	Decay chain	Combined BR	Events
3^3P_2	$\xrightarrow{3.8\%} 3^3S_1\ \gamma(171.6) \xrightarrow{2.18\%} \mu^+\mu^-$	8.3×10^{-4}	8,240
	$\xrightarrow{1.8\%} 2^3S_1\ \gamma(492.9) \xrightarrow{1.93\%} \mu^+\mu^-$	3.5×10^{-4}	3,460
	$\xrightarrow{1.1\%} 1^3S_1\ \gamma(1013.8) \xrightarrow{2.48\%} \mu^+\mu^-$	2.7×10^{-4}	2,710
	$\xrightarrow{0.28\%} 1^3P_2\pi\pi \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	1.3×10^{-5}	132
	$\xrightarrow{0.21\%} 1^3P_1\pi\pi \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	1.8×10^{-5}	173
	$\xrightarrow{0.61\%} 2^3D_3\ \gamma(72.7) \xrightarrow{65.1\%} 2^3P_2\gamma(185.0) \xrightarrow{10.6\%} 2^3S_1\gamma(242.5) \xrightarrow{1.93\%} \mu^+\mu^-$	8.1×10^{-6}	80
	$\xrightarrow{0.61\%} 2^3D_3\ \gamma(72.7) \xrightarrow{65.1\%} 2^3P_2\gamma(185.0) \xrightarrow{7.0\%} 1^3S_1\gamma(776.5) \xrightarrow{2.48\%} \mu^+\mu^-$	6.9×10^{-6}	68
	$\xrightarrow{0.61\%} 2^3D_3\ \gamma(72.7) \xrightarrow{10\%} 1^3P_2\gamma(529.0) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	2.9×10^{-6}	29
	$\xrightarrow{0.61\%} 2^3D_3\ \gamma(72.7) \xrightarrow{6.7\%} 1^3F_4\gamma(96.7) \xrightarrow{100\%} 1^3D_3\gamma(200.9) \xrightarrow{91.0\%} 1^3P_2\gamma(256.0)$		
3^3P_1	$\xrightarrow{7.2\%} 3^3S_1\ \gamma(159.8) \xrightarrow{2.18\%} \mu^+\mu^-$	1.6×10^{-3}	12,360
	$\xrightarrow{2.6\%} 2^3S_1\ \gamma(481.4) \xrightarrow{1.93\%} \mu^+\mu^-$	5.0×10^{-4}	3,950
	$\xrightarrow{1.1\%} 1^3S_1\ \gamma(1003.0) \xrightarrow{2.48\%} \mu^+\mu^-$	2.7×10^{-4}	2,150
	$\xrightarrow{0.75\%} 1^3P_2\pi\pi \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	3.5×10^{-5}	278
	$\xrightarrow{0.48\%} 1^3P_1\pi\pi \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	4.0×10^{-5}	317
	$\xrightarrow{0.40\%} 2^3D_1\ \gamma(74.7) \xrightarrow{5.3\times10^{-3}\%} \mu^+\mu^-$	2.1×10^{-7}	2
	$\xrightarrow{0.94\%} 2^3D_2\ \gamma(66.8) \xrightarrow{17\%} 2^3P_2\gamma(178.6) \xrightarrow{10.6\%} 2^3S_1\gamma(242.5) \xrightarrow{1.93\%} \mu^+\mu^-$	3.3×10^{-6}	26
	$\xrightarrow{0.94\%} 2^3D_2\ \gamma(66.8) \xrightarrow{17\%} 2^3P_2\gamma(178.6) \xrightarrow{7.0\%} 1^3S_1\gamma(776.5) \xrightarrow{2.48\%} \mu^+\mu^-$	2.8×10^{-6}	22
	$\xrightarrow{0.94\%} 2^3D_2\ \gamma(66.8) \xrightarrow{56.2\%} 2^3P_1\gamma(191.6) \xrightarrow{19.9\%} 2^3S_1\gamma(229.6) \xrightarrow{1.93\%} \mu^+\mu^-$	2.0×10^{-5}	158
	$\xrightarrow{0.94\%} 2^3D_2\ \gamma(66.8) \xrightarrow{56.2\%} 2^3P_1\gamma(191.6) \xrightarrow{9.2\%} 1^3S_1\gamma(764.3) \xrightarrow{2.48\%} \mu^+\mu^-$	1.2×10^{-5}	95
	$\xrightarrow{0.94\%} 2^3D_2\ \gamma(66.8) \xrightarrow{2\%} 1^3P_2\gamma(522.8) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	8.9×10^{-7}	7
	$\xrightarrow{0.94\%} 2^3D_2\ \gamma(66.8) \xrightarrow{12\%} 1^3P_1\gamma(541.2) \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	1.1×10^{-5}	87
	$\xrightarrow{0.94\%} 2^3D_2\ \gamma(66.8) \xrightarrow{6.6\%} 1^3F_3\gamma(93.7) \xrightarrow{89.3\%} 1^3D_2\gamma(189.2) \xrightarrow{74.7\%} 1^3P_1\gamma(267.3)$		

Large event rate for 3^3P_1
Not surprising it was discovered first in LHC Run 1

Production at the LHC: $h_b(3^1P_1)$

Missing 3^1P_1 state may be observed via hadronic decays, depending on reconstruction efficiency

LHCb 13 TeV, producing 7.3×10^6 $h_b(3^1P_1)$

	BR	events
$3^1P_1 \xrightarrow{4.3\%} 1^1S_0\,\gamma\,(1081.0) \xrightarrow{100\%} gg$	4.3×10^{-2}	3.1×10^5
$\xrightarrow{1.7\%} 1^1P_1\pi\pi \xrightarrow{49\%} 1^1S_0\,\gamma\,(488.3) \xrightarrow{100\%} gg$	8.3×10^{-3}	6.0×10^4

Production at the LHC: 2P

TABLE XXVIII. The $2P$ decay chains, branching ratios and event estimates for LHCb Run II. These are based on producing 1.0×10^7 $\chi_{b2}(2P)$'s, 9.1×10^6 $\chi_{b1}(2P)$'s, 4.7×10^6 $\chi_{b0}(2P)$'s and 7.4×10^6 $h_b(2P)$'s as described in the text.

Parent	Decay chain	Combined BR	Events
2^3P_2	$\xrightarrow{1.2\%} 1^3D_3\gamma(96.5) \xrightarrow{91.0\%} 1^3P_2\gamma(256.0) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	5.2×10^{-5}	517
	$\xrightarrow{0.2\%} 1^3D_2\gamma(104.4) \xrightarrow{22\%} 1^3P_2\gamma(248.4) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	2.1×10^{-6}	21
	$\xrightarrow{0.2\%} 1^3D_2\gamma(104.4) \xrightarrow{74.7\%} 1^3P_1\gamma(267.3) \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	1.2×10^{-5}	124
2^3P_1	$\xrightarrow{1.9\%} 1^3D_2\gamma(91.3) \xrightarrow{22\%} 1^3P_2\gamma(248.4) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	2.0×10^{-5}	180
	$\xrightarrow{1.9\%} 1^3D_2\gamma(91.3) \xrightarrow{74.7\%} 1^3P_1\gamma(267.3) \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	1.2×10^{-4}	1100
	$\xrightarrow{0.80\%} 1^3D_1\gamma(100.8) \xrightarrow{1.6\%} 1^3P_2\gamma(239.1) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	6.1×10^{-7}	6
	$\xrightarrow{0.80\%} 1^3D_1\gamma(100.8) \xrightarrow{28\%} 1^3P_1\gamma(258.0) \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	1.9×10^{-5}	174
	$\xrightarrow{0.80\%} 1^3D_1\gamma(100.8) \xrightarrow{47.1\%} 1^3P_0\gamma(290.5) \xrightarrow{1.76\%} 1^3S_1\gamma(391.1) \xrightarrow{2.48\%} \mu^+\mu^-$	1.6×10^{-6}	15
2^3P_0	$\xrightarrow{0.4\%} 1^3D_1\gamma(78.0) \xrightarrow{1.6\%} 1^3P_2\gamma(239.1) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	3.0×10^{-7}	1
	$\xrightarrow{0.4\%} 1^3D_1\gamma(78.0) \xrightarrow{28\%} 1^3P_1\gamma(258.0) \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	9.4×10^{-6}	44
2^1P_1	$\xrightarrow{2.0\%} 1^1D_2\gamma(111.4) \xrightarrow{91.5\%} 1^1P_1\gamma(262.5) \xrightarrow{49\%} 1^1S_0\gamma(488.3) \xrightarrow{100\%} gg$	9.0×10^{-3}	6.6×10^4
	$\xrightarrow{48\%} 2^1S_0\ \gamma(257.7) \xrightarrow{100\%} gg$	0.48	3.6×10^6
	$\xrightarrow{22\%} 1^1S_0\ \gamma(825.8) \xrightarrow{100\%} gg$	0.22	1.6×10^6

Production at the LHC 1D

TABLE XXXI. The $1D$ decay chains, branching ratios and event estimates for LHCb Run II and Belle II. For the pp column these are based on producing 2.0×10^4 $\Upsilon_3(1D)$'s and $\Upsilon_2(1D)$'s, 1.6×10^4 $\Upsilon_1(1D)$'s and 1.9×10^4 $\eta_{b2}(1D)$'s as described in the text. For the e^+e^- column these are based on 1.3×10^6 $\Upsilon_1(1D)$'s produced assuming $\sigma = 13$ pb and 100 fb^{-1} integrated luminosity.

Parent	Decay chain	Combined BR	Events pp	Events e^+e^-
1^3D_3	$\xrightarrow{91.0\%} 1^3P_2\gamma(256.0) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	4.3×10^{-3}	87	NA
	$\xrightarrow{0.74\%} 1^3S_1\pi^+\pi^- \xrightarrow{2.48\%} \mu^+\mu^-$	1.8×10^{-4}	4	NA
1^3D_2	$\xrightarrow{22\%} 1^3P_2\gamma(248.4) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	1.0×10^{-3}	20	NA
	$\xrightarrow{74.7\%} 1^3P_1\gamma(267.3) \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	6.3×10^{-3}	126	NA
	$\xrightarrow{0.66\%} 1^3S_1\pi^+\pi^- \xrightarrow{2.48\%} \mu^+\mu^-$	1.6×10^{-4}	3	NA
1^3D_1	$\xrightarrow{1.6\%} 1^3P_2\gamma(239.1) \xrightarrow{19.1\%} 1^3S_1\gamma(441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	7.6×10^{-5}	1	99
	$\xrightarrow{28\%} 1^3P_1\gamma(258.0) \xrightarrow{33.9\%} 1^3S_1\gamma(423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	2.4×10^{-3}	38	3120
	$\xrightarrow{47.1\%} 1^3P_0\gamma(290.5) \xrightarrow{1.76\%} 1^3S_1\gamma(391.1) \xrightarrow{2.48\%} \mu^+\mu^-$	2.0×10^{-4}	3	260
	$\xrightarrow{0.40\%} 1^3S_1\pi^+\pi^- \xrightarrow{2.48\%} \mu^+\mu^-$	9.9×10^{-5}	2	129
	$\xrightarrow{3.93\times10^{-3}\%} \mu^+\mu^-$	3.9×10^{-5}	1	50
1^1D_2	$\xrightarrow{91.5\%} 1^1P_1\gamma(262.5) \xrightarrow{49\%} 1^1S_0\gamma(488.3) \xrightarrow{100\%} gg$	0.45	8550	NA
	$\xrightarrow{1.3\%} 1^1S_0\pi^+\pi^- \xrightarrow{100\%} gg$	1.3×10^{-2}	247	NA

- Largest contribution to D-wave production comes from decays originating from 3S then from 2P
- Expect sizeable production of D-waves so might be observable

Search Strategies: 4P & 5P states

LHCb 13 TeV, producing 9.7×10^6 4^3P_2, 7.4×10^6 4^3P_1, 3.1×10^6 4^3P_0
8.2×10^6 5^3P_2, 5.7×10^6 5^3P_1, 2.2×10^6 5^3P_0

Above $B\bar{B}$ threshold, so small radiative BR.

Possible to observe some 4P states in simple $\gamma\mu^+\mu^-$ final states at LHC Run II

May even be able to see the 5^3P_2 state

Parent	Decay chain	Combined BR	Events
4^3P_2	$\xrightarrow{0.012\%} 3^3S_1\ \gamma\ (433.9) \xrightarrow{2.18\%} \mu^+\mu^-$	2.6×10^{-6}	25
	$\xrightarrow{1.4\times10^{-3}\%} 2^3S_1\ \gamma\ (747.2) \xrightarrow{1.93\%} \mu^+\mu^-$	2.6×10^{-7}	3
	$\xrightarrow{5.0\times10^{-3}\%} 1^3S_1\ \gamma\ (1255.1) \xrightarrow{2.48\%} \mu^+\mu^-$	1.3×10^{-6}	12
4^3P_1	$\xrightarrow{0.013\%} 3^3S_1\ \gamma\ (424.3) \xrightarrow{2.18\%} \mu^+\mu^-$	2.7×10^{-6}	20
	$\xrightarrow{6.0\times10^{-4}\%} 2^3S_1\ \gamma\ (737.9) \xrightarrow{1.93\%} \mu^+\mu^-$	1.1×10^{-7}	1
	$\xrightarrow{3.3\times10^{-3}\%} 1^3S_1\ \gamma\ (1003.0) \xrightarrow{2.48\%} \mu^+\mu^-$	8.2×10^{-7}	6
4^3P_0	$\xrightarrow{6.4\times10^{-3}\%} 3^3S_1\ \gamma\ (411.8) \xrightarrow{2.18\%} \mu^+\mu^-$	1.4×10^{-6}	4
	$\xrightarrow{6.1\times10^{-4}\%} 1^3S_1\ \gamma\ (1234.8) \xrightarrow{2.48\%} \mu^+\mu^-$	1.5×10^{-7}	0.5
5^3P_2	$\xrightarrow{1\times10^{-4}\%} 3^3S_1\ \gamma\ (646.8) \xrightarrow{2.18\%} \mu^+\mu^-$	2.1×10^{-8}	0.2
	$\xrightarrow{2.5\times10^{-3}\%} 2^3S_1\ \gamma\ (953.7) \xrightarrow{1.93\%} \mu^+\mu^-$	4.8×10^{-7}	4
	$\xrightarrow{3.4\times10^{-3}\%} 1^3S_1\ \gamma\ (1451.3) \xrightarrow{2.48\%} \mu^+\mu^-$	8.4×10^{-7}	7
5^3P_1	$\xrightarrow{1.3\times10^{-3}\%} 2^3S_1\ \gamma\ (946.4) \xrightarrow{1.93\%} \mu^+\mu^-$	2.5×10^{-7}	1
	$\xrightarrow{1.4\times10^{-3}\%} 1^3S_1\ \gamma\ (1444.4) \xrightarrow{2.48\%} \mu^+\mu^-$	3.5×10^{-7}	2
5^3P_0	$\xrightarrow{3.0\times10^{-4}\%} 3^3S_1\ \gamma\ (629.9) \xrightarrow{2.18\%} \mu^+\mu^-$	6.5×10^{-8}	0.1
	$\xrightarrow{6.7\times10^{-4}\%} 2^3S_1\ \gamma\ (937.3) \xrightarrow{1.93\%} \mu^+\mu^-$	1.3×10^{-7}	0.3
	$\xrightarrow{4.1\times10^{-4}\%} 1^3S_1\ \gamma\ (1435.7) \xrightarrow{2.48\%} \mu^+\mu^-$	1.0×10^{-7}	0.2

Production in e^+e^- collisions

For $\Upsilon(4S)$ 10 ab^{-1} yields 10^{10} $\Upsilon(4S)$

Parent	Decay chain	Combined BR	Events pp	Events e^+e^-
4^3S_1	$\xrightarrow{1.57\times10^{-5}} \mu^+\mu^-$	1.6×10^{-5}	3680	1.6×10^5
	$\xrightarrow{3.7\times10^{-5}} 3^3P_2\gamma(50.8)\xrightarrow{3.8\%}3^3S_1\ \gamma(171.6)\xrightarrow{2.18\%}\mu^+\mu^-$	3.1×10^{-8}	7	310
	$\xrightarrow{3.7\times10^{-5}} 3^3P_2\gamma(50.8)\xrightarrow{1.8\%}2^3S_1\ \gamma(492.9)\xrightarrow{1.93\%}\mu^+\mu^-$	1.3×10^{-8}	3	130
	$\xrightarrow{3.7\times10^{-5}} 3^3P_2\gamma(50.8)\xrightarrow{1.1\%}1^3S_1\ \gamma(1013.8)\xrightarrow{2.48\%}\mu^+\mu^-$	1.0×10^{-8}	2	100
	$\xrightarrow{3.7\times10^{-5}} 3^3P_2\gamma(50.8)\xrightarrow{3.8\%}3^3S_1\ \gamma(171.6)\xrightarrow{2.82\%}2^3S_1\pi^+\pi^-\xrightarrow{1.93\%}\mu^+\mu^-$	7.7×10^{-10}	0.2	8
	$\xrightarrow{3.7\times10^{-5}} 3^3P_2\gamma(50.8)\xrightarrow{3.8\%}3^3S_1\ \gamma(171.6)\xrightarrow{4.37\%}1^3S_1\pi^+\pi^-\xrightarrow{2.48\%}\mu^+\mu^-$	1.5×10^{-9}	0.3	15
	$\xrightarrow{3.7\times10^{-5}} 3^3P_2\gamma(50.8)\xrightarrow{1.8\%}2^3S_1\ \gamma(492.9)\xrightarrow{17.85\%}1^3S_1\pi^+\pi^-\xrightarrow{2.48\%}\mu^+\mu^-$	2.9×10^{-9}	0.7	29
	$\xrightarrow{3.7\times10^{-5}} 3^3P_2\gamma(50.8)\xrightarrow{0.61\%}2^3D_3\ \gamma(72.7)\xrightarrow{65.1\%}2^3P_2\gamma(185.0)\xrightarrow{10.6\%}2^3S_1\gamma(242.5)\xrightarrow{1.93\%}\mu^+\mu^-$	3.0×10^{-10}	0.07	3
	$\xrightarrow{3.7\times10^{-5}} 3^3P_2\gamma(50.8)\xrightarrow{0.61\%}2^3D_3\ \gamma(72.7)\xrightarrow{65.1\%}2^3P_2\gamma(185.0)\xrightarrow{7.0\%}1^3S_1\gamma(776.5)\xrightarrow{2.48\%}\mu^+\mu^-$	2.6×10^{-10}	0.06	3
	$\xrightarrow{3.7\times10^{-5}} 3^3P_2\gamma(50.8)\xrightarrow{0.61\%}2^3D_3\ \gamma(72.7)\xrightarrow{10\%}1^3P_2\gamma(529.0)\xrightarrow{19.1\%}1^3S_1\gamma(441.6)\xrightarrow{2.48\%}\mu^+\mu^-$	1.1×10^{-10}	0.03	1
	$\xrightarrow{3.7\times10^{-5}} 3^3P_2\gamma(50.8)\xrightarrow{0.61\%}2^3D_3\ \gamma(72.7)\xrightarrow{6.7\%}1^3F_4\gamma(96.7)$ $\xrightarrow{100\%}1^3D_3\gamma(200.9)\xrightarrow{91.0\%}1^3P_2\gamma(256.0)\xrightarrow{19.1\%}1^3S_1\gamma(441.6)\xrightarrow{2.48\%}\mu^+\mu^-$	6.5×10^{-11}	0.01	0.6

Production in e^+e^- collisions

For n^3D_1 take ratio of nD/2S BR to e^+e^- x 2^3S_1 cross section

For 100 fb^{-1} this gives 1.3 x 10^6 1^3D_1 's produced

1^3D_1	$\xrightarrow{1.6\%} 1^3P_2\gamma\ (239.1)$	$\xrightarrow{19.1\%} 1^3S_1\gamma\ (441.6)$	$\xrightarrow{2.48\%} \mu^+\mu^-$	7.6×10^{-5}	99
	$\xrightarrow{28.0\%} 1^3P_1\gamma\ (258.0)$	$\xrightarrow{33.9\%} 1^3S_1\gamma\ (423.0)$	$\xrightarrow{2.48\%} \mu^+\mu^-$	2.4×10^{-3}	3120
	$\xrightarrow{47.0\%} 1^3P_0\gamma\ (290.5)$	$\xrightarrow{1.76\%} 1^3S_1\gamma\ (391.1)$	$\xrightarrow{2.48\%} \mu^+\mu^-$	2.0×10^{-4}	260
	$\xrightarrow{3.9\times10^{-3}\%} \mu^+\mu^-$			3.9×10^{-5}	50

Production in e^+e^- collisions

Similarly:

- For 100 fb^{-1} this gives 2 x 10^6 2^3D_1 's produced

2^3D_1	$\xrightarrow{3.9\times10^{-3}\%} \mu^+\mu^-$	3.9×10^{-5}	1
	$\xrightarrow{17.2\%} 2^3P_1\gamma\ (183.9) \xrightarrow{19.9\%} 2^3S_1\gamma\ (229.6) \xrightarrow{1.93\%} \mu^+\mu^-$	6.6×10^{-4}	16
	$\xrightarrow{28.1\%} 2^3P_0\gamma\ (206.4) \xrightarrow{4.6\%} 2^3S_1\gamma\ (207.1) \xrightarrow{1.93\%} \mu^+\mu^-$	2.5×10^{-4}	6
	$\xrightarrow{28.1\%} 2^3P_0\gamma\ (206.4) \xrightarrow{9.0\%} 1^3S_1\gamma\ (743.1) \xrightarrow{2.48\%} \mu^+\mu^-$	6.3×10^{-4}	15
	$\xrightarrow{4.2\%} 1^3F_2\gamma\ (90.5) \xrightarrow{1.6\%} 1^3D_2\gamma\ (184.3) \xrightarrow{78.0\%} 1^3P_1\gamma\ (267.3) \xrightarrow{33.9\%} 1^3S_1\gamma\ (423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	3.7×10^{-5}	1

- Can rescale these numbers to reflect actual cross sections and integrated luminosity

- Do not expect to see the 3^3D_1 or 4^3D_1 this way because they are much broader but maybe in BB final state?

Some theory comments:

- Include virtual meson loops into calculations
- Threshold effects
- Non qq content:
  - Hybrids
  - Multiquarks:
    - molecules
    - tetraquarks

Summary

- Performed extensive calculation of bottomonium properties

- The object was to make predictions that can be used by experimentalists find missing states and measure their properties

- LHCb will see 3P, 4P and $h_b(3S)$ events in $\gamma + \mu^+\mu^-$
  and 1D and 2D events in $\gamma\gamma + \mu^+\mu^-$
- e^+e^- will see large numbers of 1^3D_J in $\Upsilon(3S)$ decays
  - sitting on the 4S will see $3^3P_{1,2}$
  - should be able to see the 1^3D_1 and 2^3D_1
  - Maybe the 1^3F_2 in radiative transitions of the 2^3D_1

22 December 2011 Last updated at 05:59 ET

4.3K Share

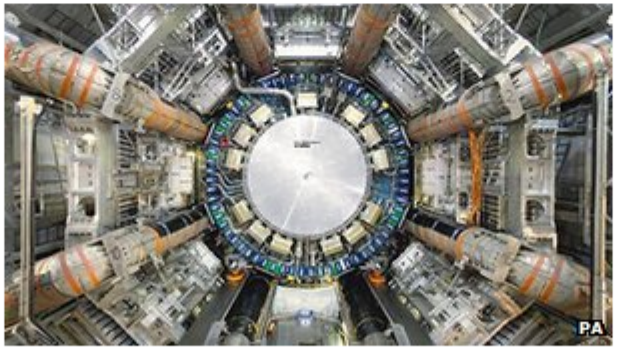
LHC reports discovery of its first new particle

By Jonathan Amos
Science correspondent, BBC News

The Large Hadron Collider (LHC) on the Franco-Swiss border has made its first clear observation of a new particle since opening in 2009.

It is called Chi_b (3P) and will help scientists understand better the forces that hold matter together.

The as-yet unpublished discovery is **reported on the Arxiv pre-print server**.



The LHC has been built to investigate the fundamental building blocks of nature

The LHC is exploring some of the fundamental questions in "big physics" by colliding proton particles together in a huge underground facility.

Related Stories