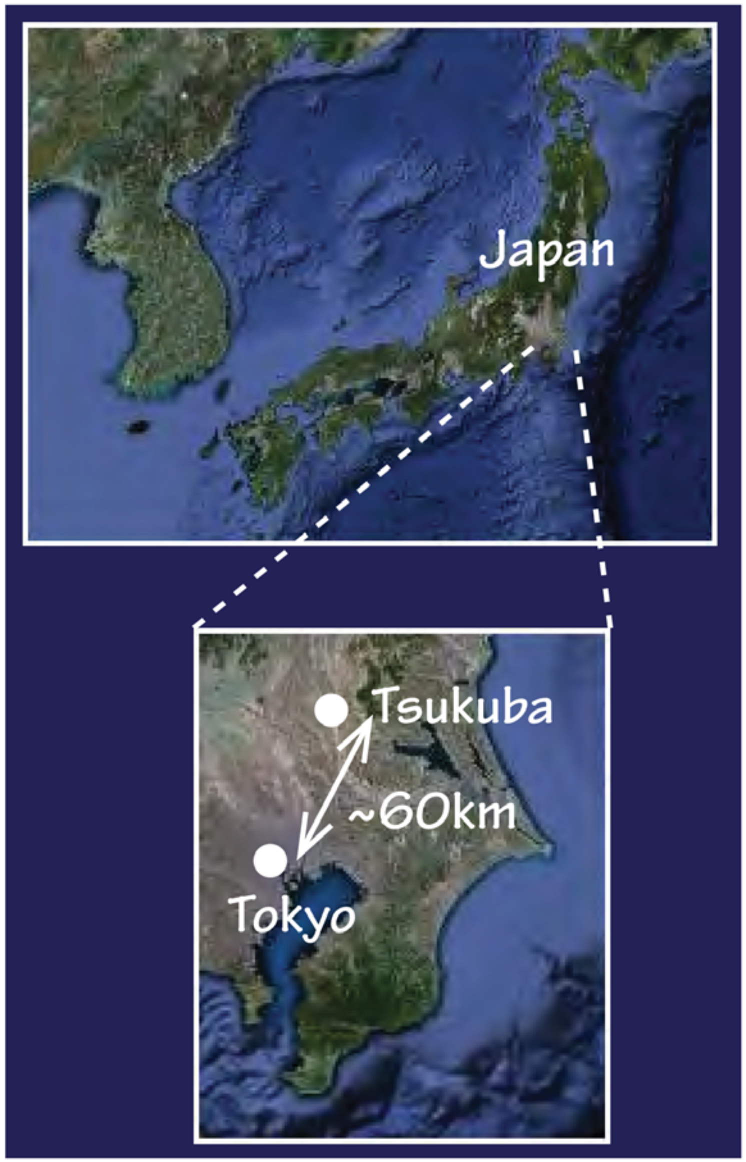
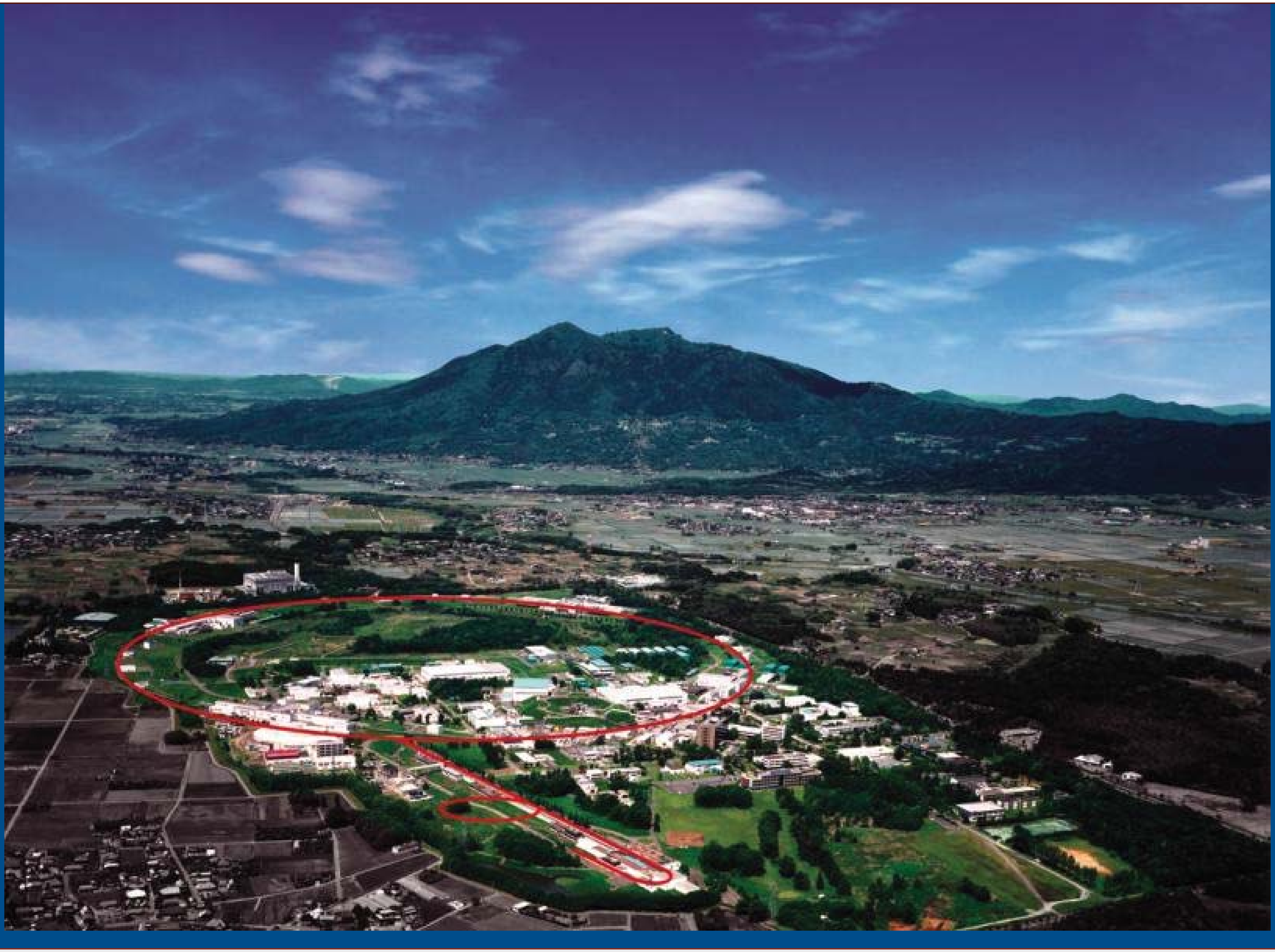
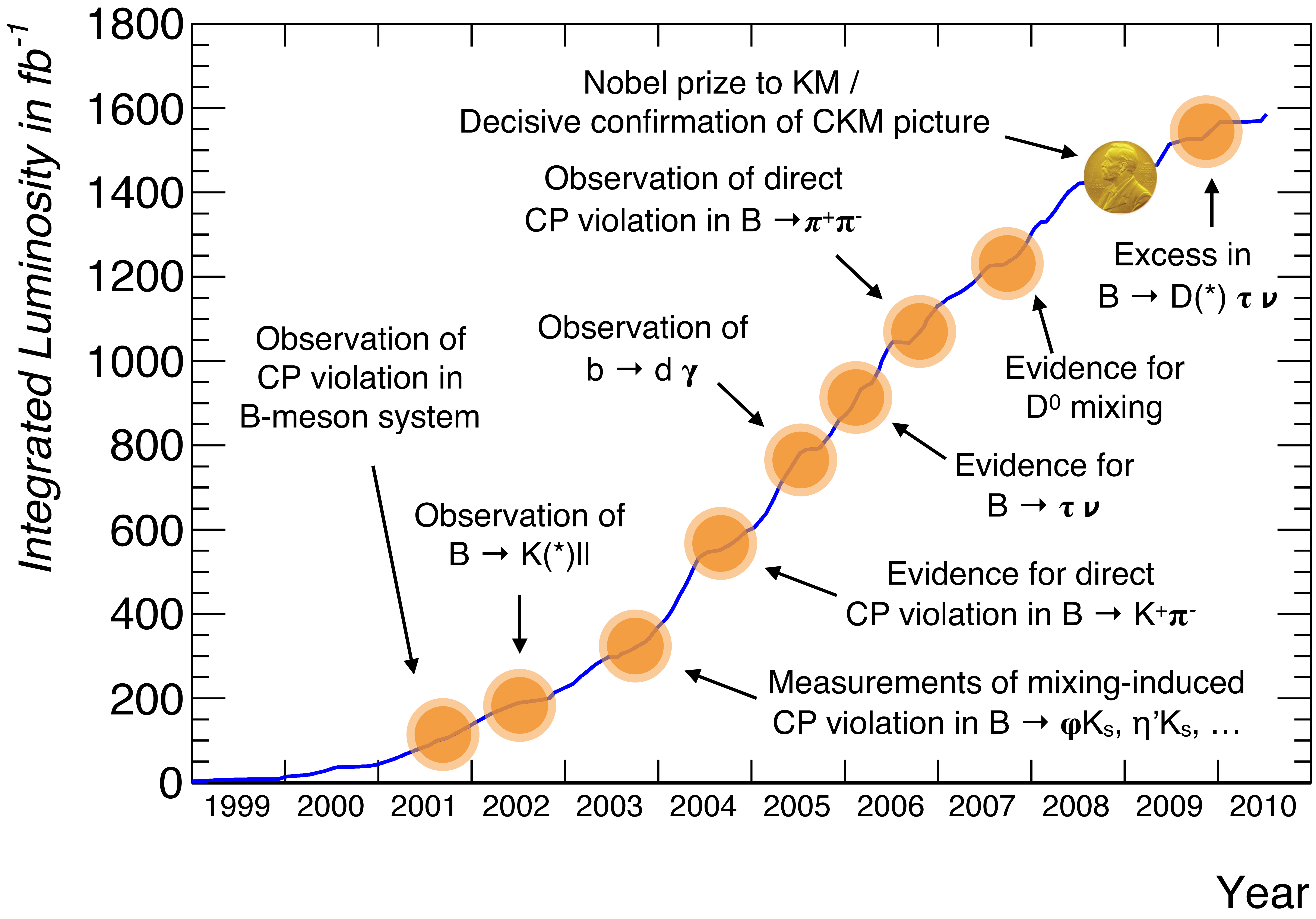
Exotic and Conventional Quarkonium Physics Prospects at Belle II





Vladimir Savinov (University of Pittsburgh), on behalf of Belle II Collaboration



Observation of CP violation in B-meson system

Observation of $B \to K^{(*)}ll$

Measurements of mixing-induced CP violation in $B \to \varphi K_S, \eta' K_S, \ldots$

Evidence for direct CP violation in $B \to K^+\pi^-$

Observation of $b \to d\gamma$

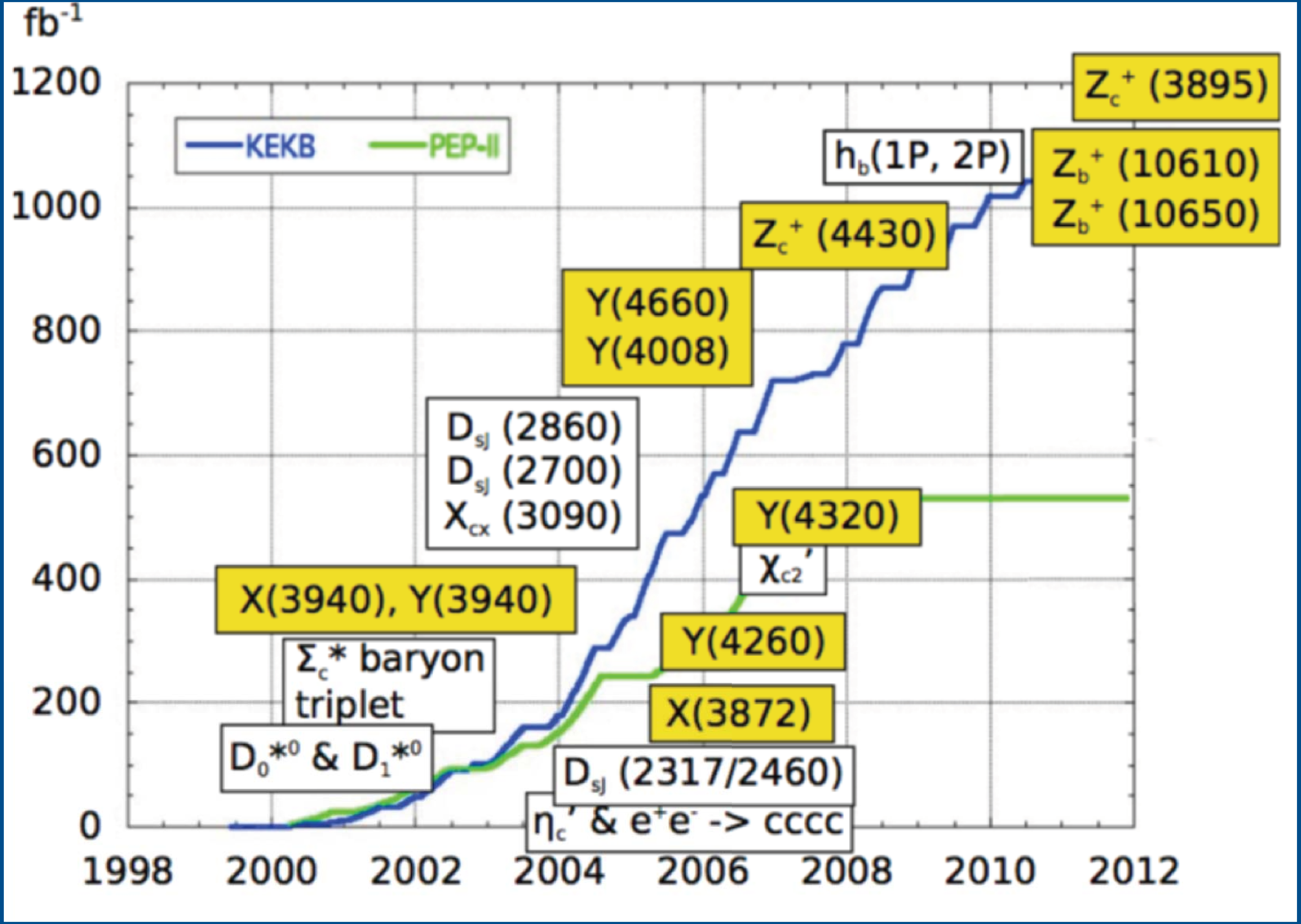
Evidence for $B \to \tau\nu$

Observation of direct CP violation in $B \to \pi^+\pi^-$

Evidence for D^0 mixing

Nobel prize to KM / Decisive confirmation of CKM picture

Excess in $B \to D^{(*)}\tau\nu$


fb^{-1}
1200
1000
800
600
400
200
0
1998
2000
2002
2004
2006
2008
2010
2012
KEKB
PEP-II
Z_c^+ (3895)
h_b(1P, 2P)
Z_b^+ (10610)
Z_b^+ (10650)
Z_c^+ (4430)
Y(4660)
Y(4008)
D_{sJ} (2860)
D_{sJ} (2700)
X_{cx} (3090)
Y(4320)
χ_{c2}'
X(3940), Y(3940)
Σ_c* baryon triplet
Y(4260)
X(3872)
D_0^{*0} & D_1^{*0}
D_{sJ} (2317/2460)
η_c' & e^+e^- -> cccc

The Success of Cornell Potential for Quarkonia

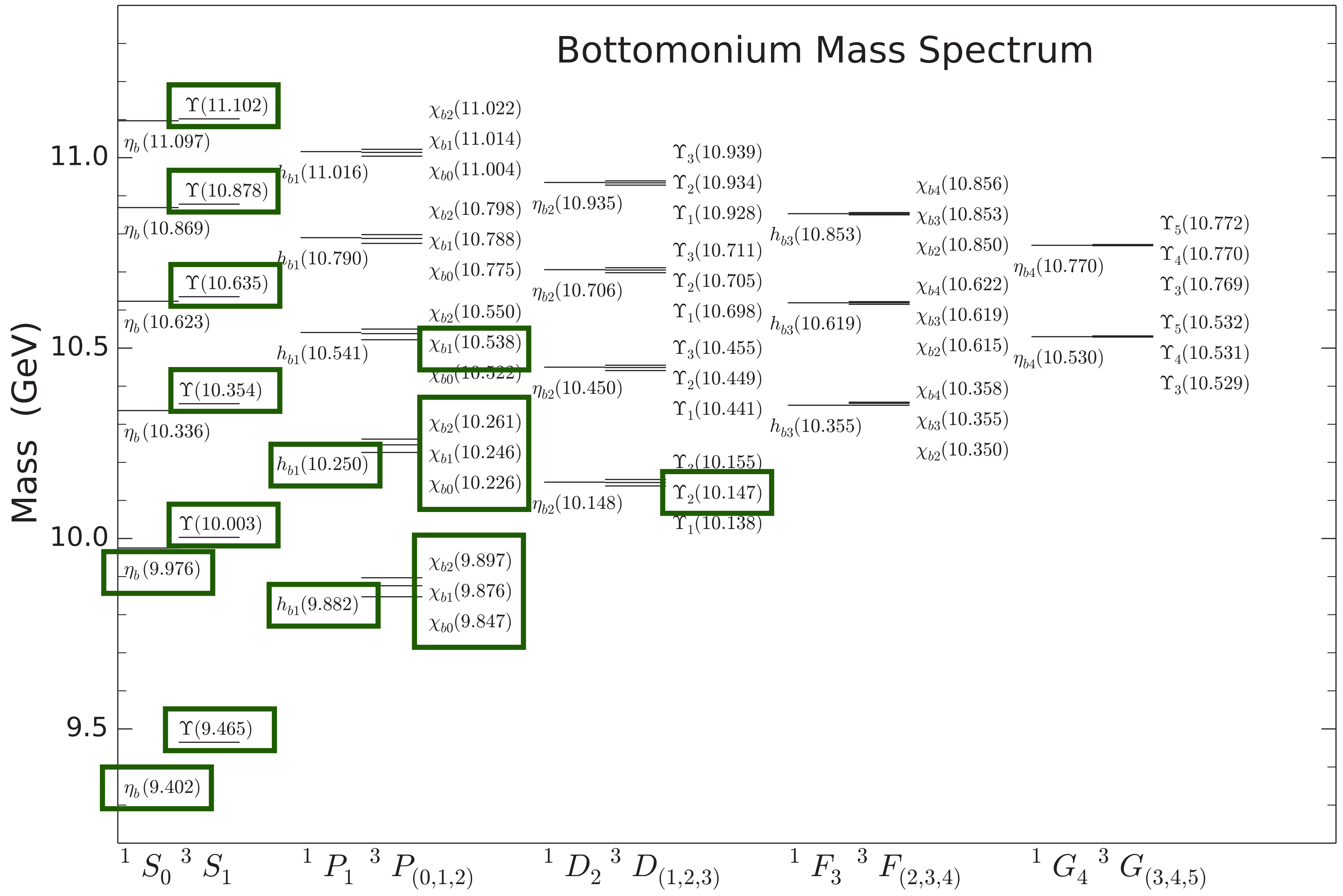
Exotics: Heavy Pentaquarks and Tetraquarks
Ahmed Ali, Jens Soren Lange, and Sheldon Stone
Progress in Particle and Nuclear Physics
Volume 97, November 2017, Pages 123-198

$$V_0^{c\bar{c}}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

$$V_{\alpha_s}^{c\bar{c}}(r) = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

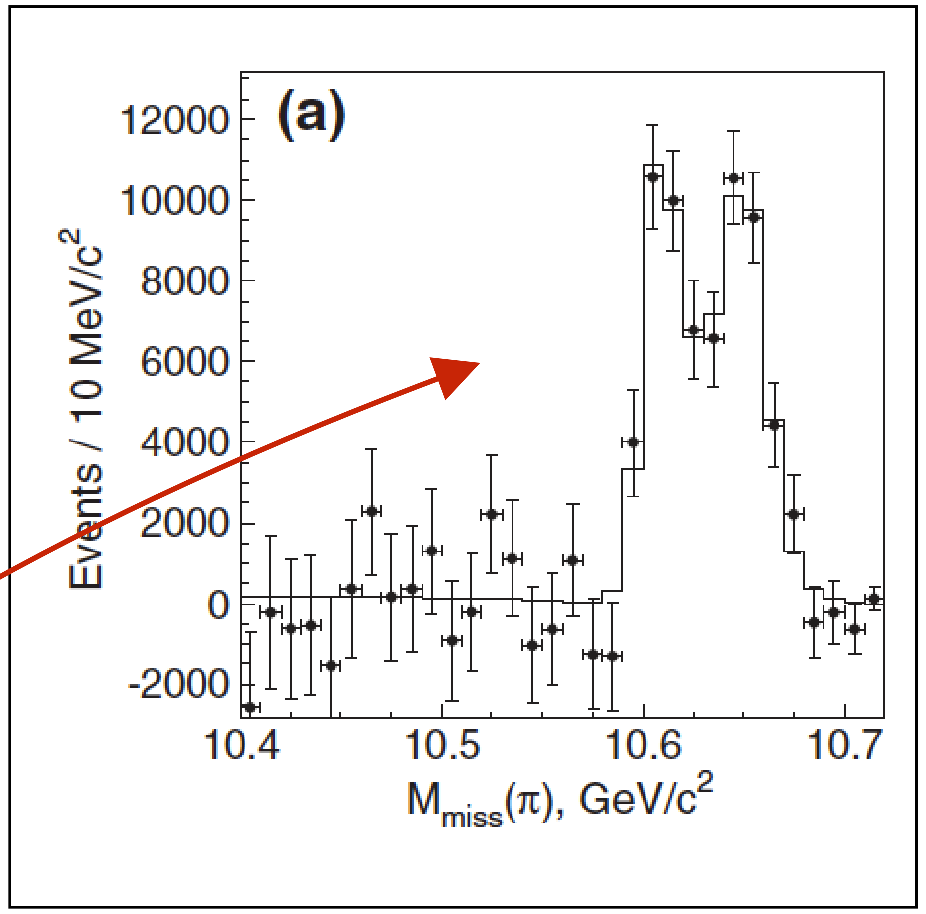
$$\vec{T} \equiv (\vec{S}_c \cdot \hat{r})(\vec{S}_{\bar{c}} \cdot \hat{r}) - \frac{1}{3}\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

T. Barnes, S. Godfrey, E. S. Swanson, Higher charmonia, Phys. Rev. D72 (2005) 054026. `arXiv:hep-ph/0505002`, `doi:10.1103/PhysRevD.72.054026`.



S. Godfrey and K. Moats, Bottomonium mesons and strategies for their observation, Phys. Rev. D 92, 054034 (2015)
S. Godfrey and N. Isgur, Mesons in a relativized quark model with chromodynamics, Phys. Rev. D 32, 189 (1985).

Belle discovered some of the expected quarkonium states and (somewhat) unexpected exotic states / resonances / ?

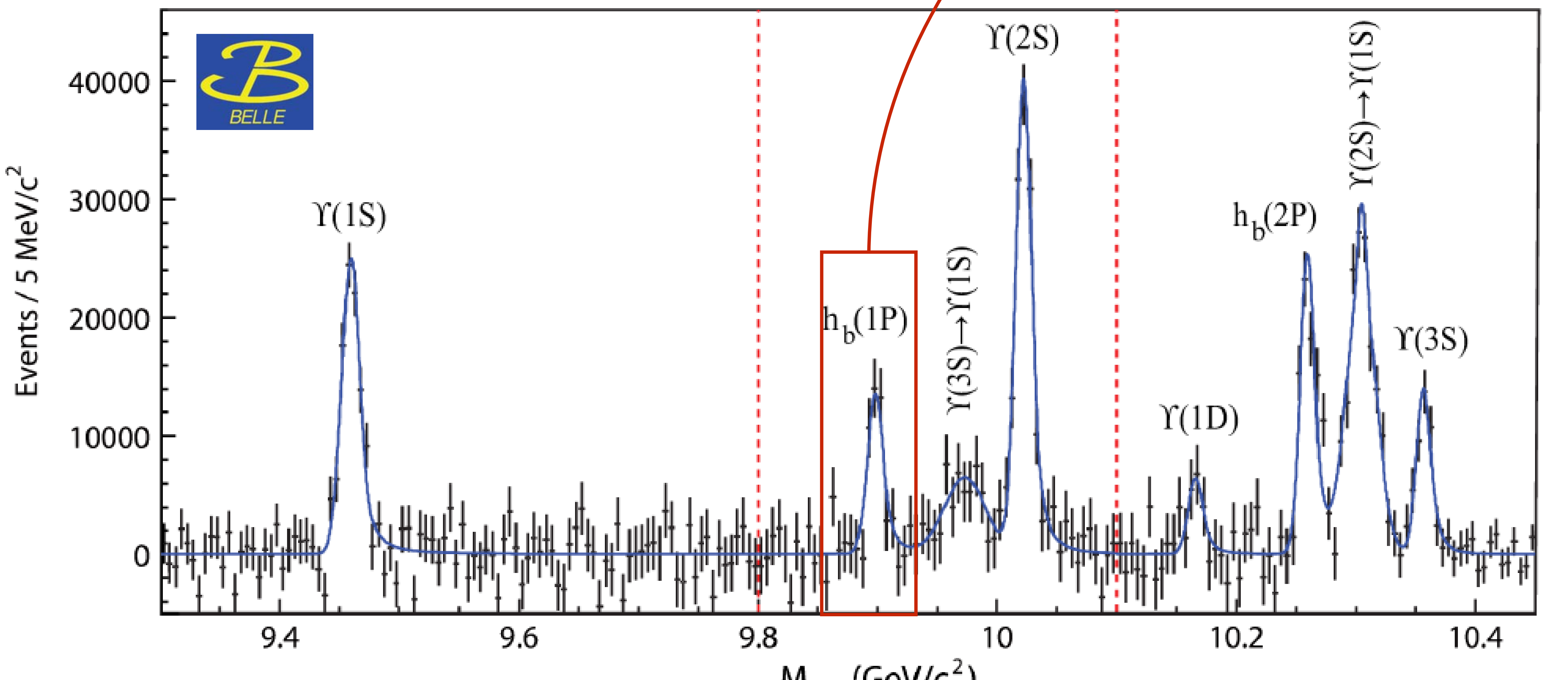


$h_b(1P)\ \pi^+\pi^-$

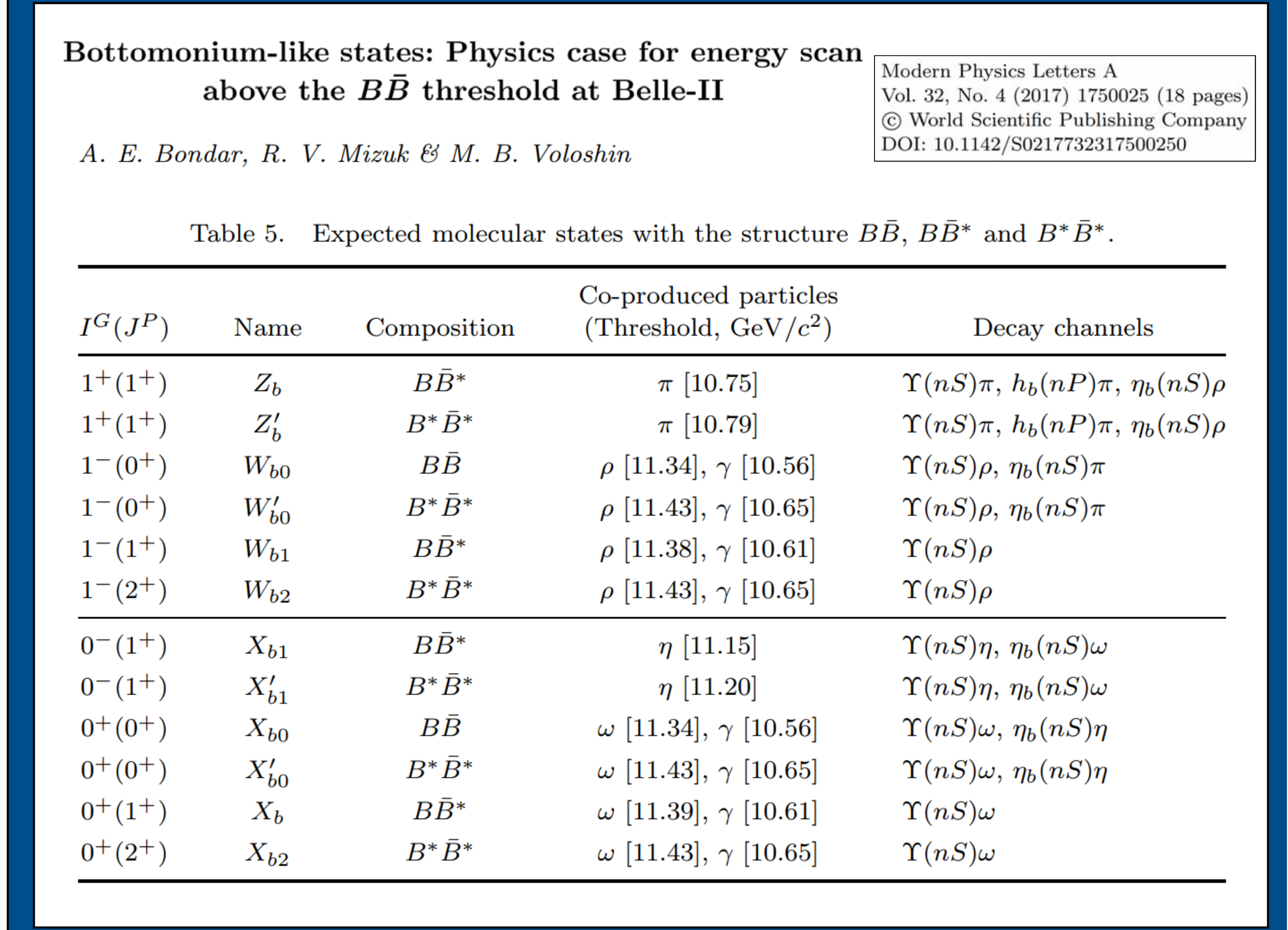
$Z_b(10\,610)$ and $Z_b(10\,650)$

PRL 108, 122001 (2012)

First Observation of the *P*-Wave Spin-Singlet Bottomonium States $h_b(1P)$ and $h_b(2P)$



PRL 108, 032001 (2012)



Bottomonium-like states: Physics case for energy scan above the $B\bar{B}$ threshold at Belle-II

Modern Physics Letters A
Vol. 32, No. 4 (2017) 1750025 (18 pages)
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DOI: 10.1142/S0217732317500250

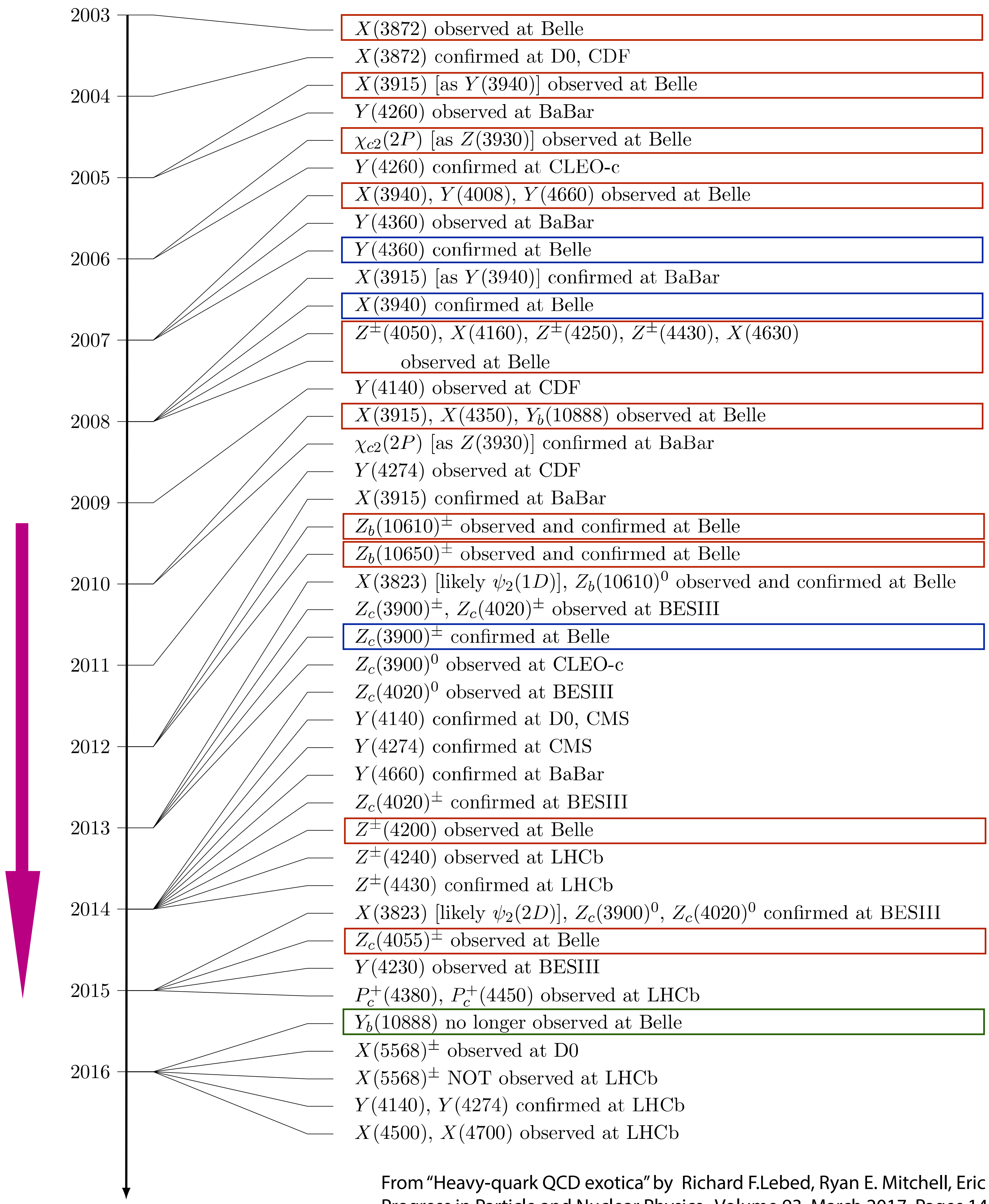
A. E. Bondar, R. V. Mizuk & M. B. Voloshin

Table 5. Expected molecular states with the structure $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$.

$I^G(J^P)$	Name	Composition	Co-produced particles (Threshold, GeV/c^2)	Decay channels
$1^+(1^+)$	Z_b	$B\bar{B}^*$	π [10.75]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^+(1^+)$	Z_b'	$B^*\bar{B}^*$	π [10.79]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^-(0^+)$	W_{b0}	$B\bar{B}$	ρ [11.34], γ [10.56]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(0^+)$	W_{b0}'	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(1^+)$	W_{b1}	$B\bar{B}^*$	ρ [11.38], γ [10.61]	$\Upsilon(nS)\rho$
$1^-(2^+)$	W_{b2}	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$
$0^-(1^+)$	X_{b1}	$B\bar{B}^*$	η [11.15]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^-(1^+)$	X_{b1}'	$B^*\bar{B}^*$	η [11.20]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^+(0^+)$	X_{b0}	$B\bar{B}$	ω [11.34], γ [10.56]	$\Upsilon(nS)\omega$, $\eta_b(nS)\eta$
$0^+(0^+)$	X_{b0}'	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$, $\eta_b(nS)\eta$
$0^+(1^+)$	X_b	$B\bar{B}^*$	ω [11.39], γ [10.61]	$\Upsilon(nS)\omega$
$0^+(2^+)$	X_{b2}	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$

Renaissance of QCD and Hadron Spectroscopy

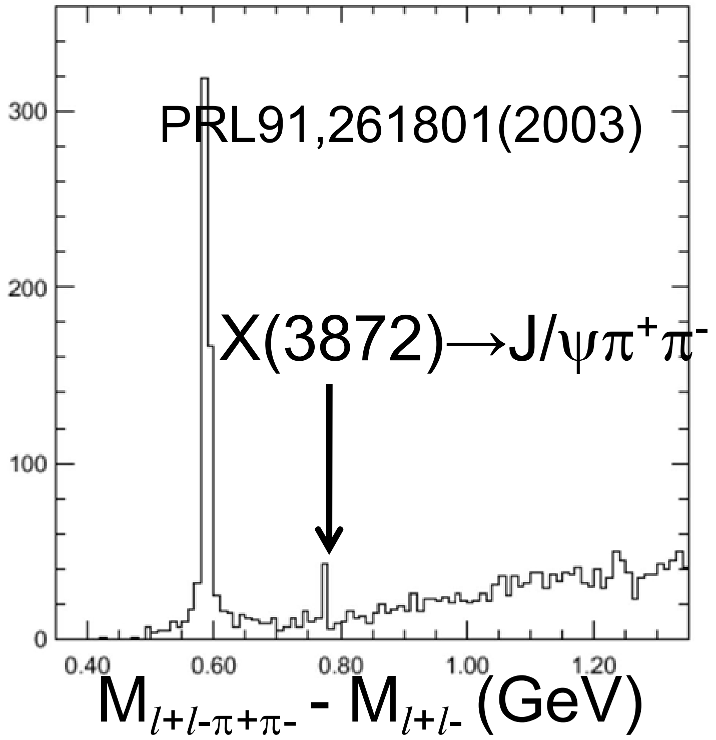
Active data analyysis and discoveries continue!



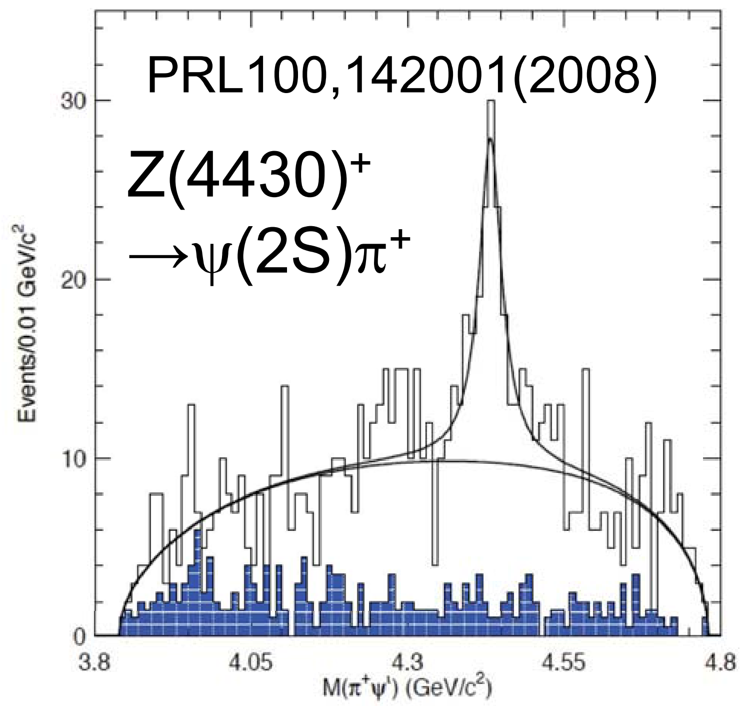
$X(3872)$ observed at Belle
$X(3872)$ confirmed at D0, CDF
$X(3915)$ [as $Y(3940)$] observed at Belle
$Y(4260)$ observed at BaBar
$\chi_{c2}(2P)$ [as $Z(3930)$] observed at Belle
$Y(4260)$ confirmed at CLEO-c
$X(3940)$, $Y(4008)$, $Y(4660)$ observed at Belle
$Y(4360)$ observed at BaBar
$Y(4360)$ confirmed at Belle
$X(3915)$ [as $Y(3940)$] confirmed at BaBar
$X(3940)$ confirmed at Belle
$Z^{\pm}(4050)$, $X(4160)$, $Z^{\pm}(4250)$, $Z^{\pm}(4430)$, $X(4630)$ observed at Belle
$Y(4140)$ observed at CDF
$X(3915)$, $X(4350)$, $Y_b(10888)$ observed at Belle
$\chi_{c2}(2P)$ [as $Z(3930)$] confirmed at BaBar
$Y(4274)$ observed at CDF
$X(3915)$ confirmed at BaBar
$Z_b(10610)^{\pm}$ observed and confirmed at Belle
$Z_b(10650)^{\pm}$ observed and confirmed at Belle
$X(3823)$ [likely $\psi_2(1D)$], $Z_b(10610)^0$ observed and confirmed at Belle
$Z_c(3900)^{\pm}$, $Z_c(4020)^{\pm}$ observed at BESIII
$Z_c(3900)^{\pm}$ confirmed at Belle
$Z_c(3900)^0$ observed at CLEO-c
$Z_c(4020)^0$ observed at BESIII
$Y(4140)$ confirmed at D0, CMS
$Y(4274)$ confirmed at CMS
$Y(4660)$ confirmed at BaBar
$Z_c(4020)^{\pm}$ confirmed at BESIII
$Z^{\pm}(4200)$ observed at Belle
$Z^{\pm}(4240)$ observed at LHCb
$Z^{\pm}(4430)$ confirmed at LHCb
$X(3823)$ [likely $\psi_2(2D)$], $Z_c(3900)^0$, $Z_c(4020)^0$ confirmed at BESIII
$Z_c(4055)^{\pm}$ observed at Belle
$Y(4230)$ observed at BESIII
$P_c^+(4380)$, $P_c^+(4450)$ observed at LHCb
$Y_b(10888)$ no longer observed at Belle
$X(5568)^{\pm}$ observed at D0
$X(5568)^{\pm}$ NOT observed at LHCb
$Y(4140)$, $Y(4274)$ confirmed at LHCb
$X(4500)$, $X(4700)$ observed at LHCb

From "Heavy-quark QCD exotica" by Richard F.Lebed, Ryan E. Mitchell, Eric S.Swanson
Progress in Particle and Nuclear Physics, Volume 93, March 2017, Pages 143-194

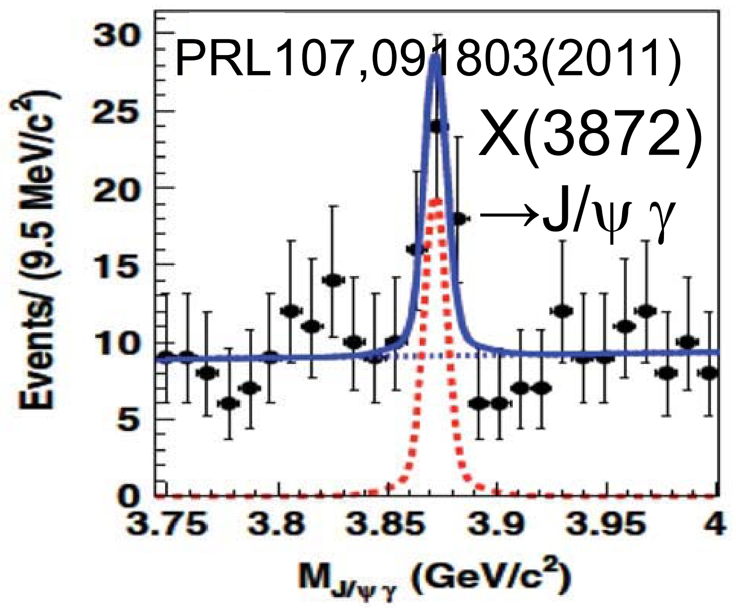
XYZ Discoveries at Belle


PRL91,261801(2003)

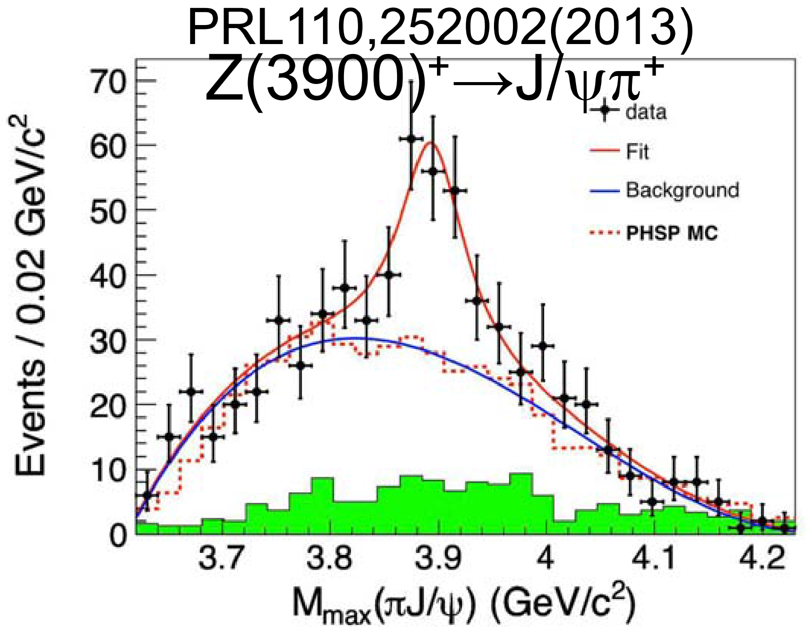
$X(3872)\to J/\psi\pi^+\pi^-$


PRL100,142001(2008)

$Z(4430)^+ \to\psi(2S)\pi^+$

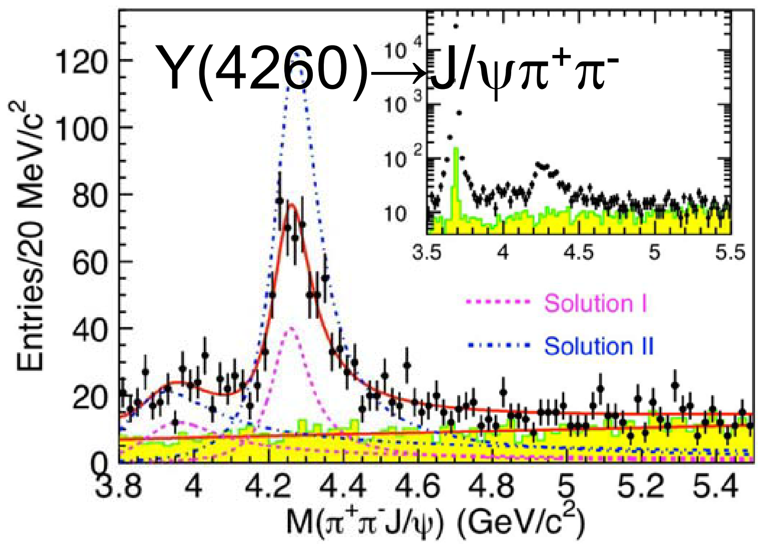

PRL107,091803(2011)

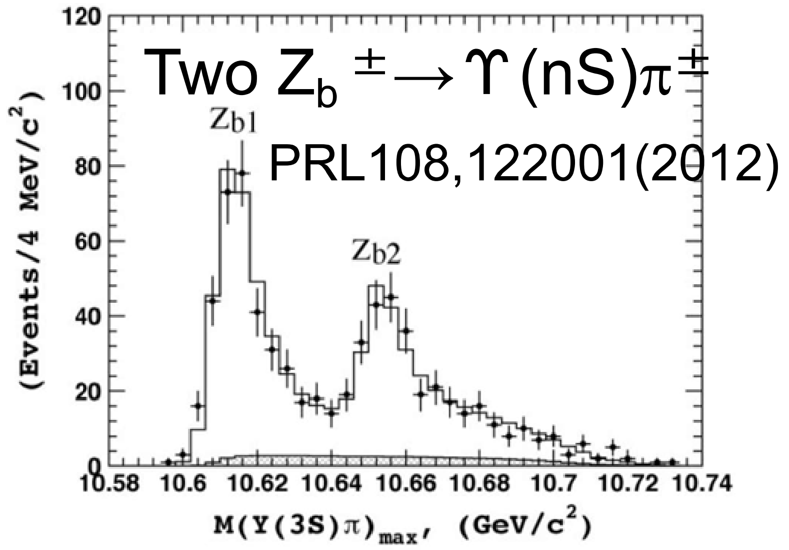
$X(3872) \to J/\psi\,\gamma$


PRL110,252002(2013)

$Z(3900)^+ \to J/\psi\pi^+$

PRL110,252002(2013)


$Y(4260)\to J/\psi\pi^+\pi^-$


Two $Z_b^{\pm} \to \Upsilon(nS)\pi^{\pm}$

PRL108,122001(2012)

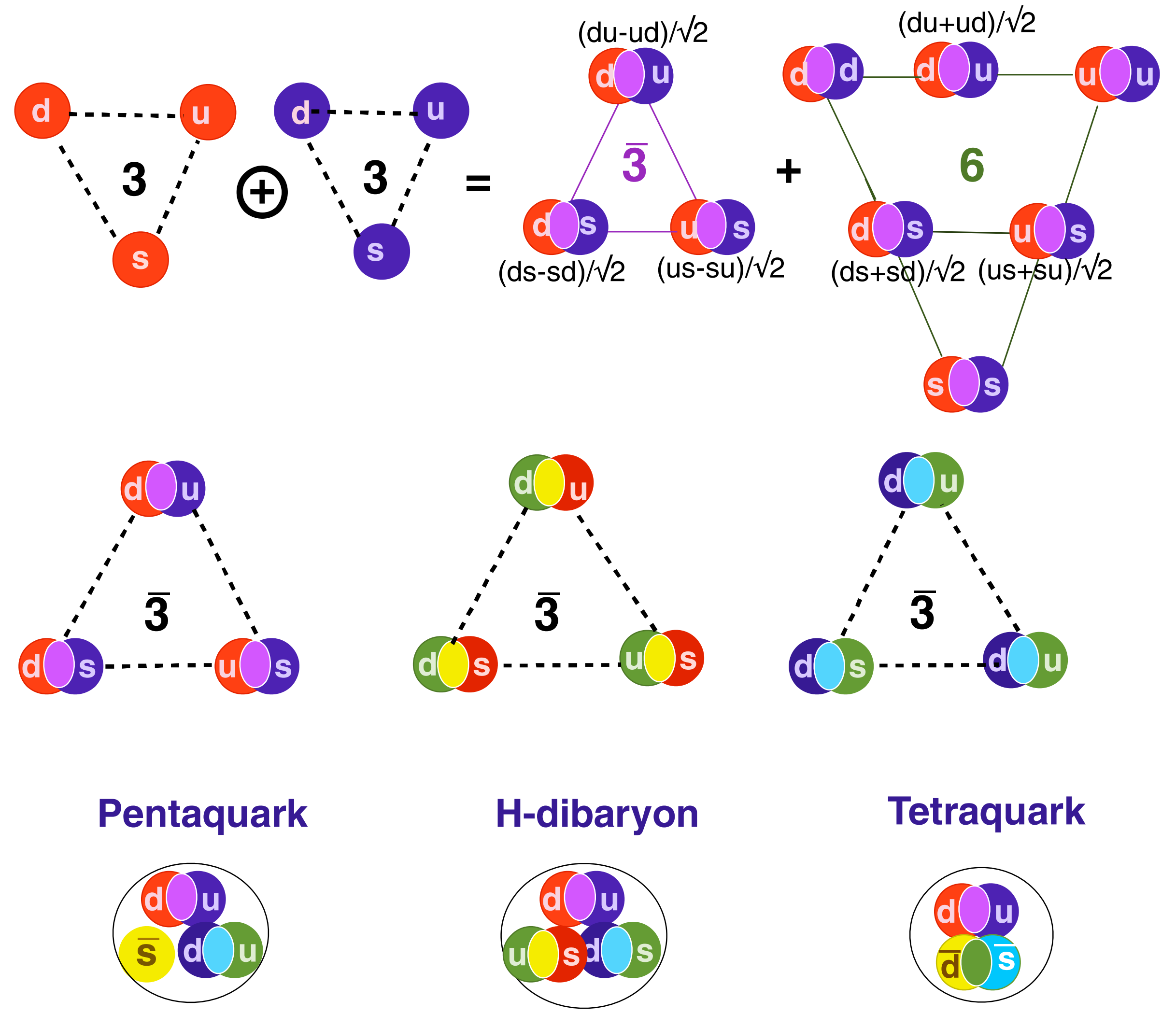
Roses are red
Violets are blue
Quarks and gluons have color
But hadrons have none

MODELS FOR NONSTANDARD HADRONS

(from Olsen, Skwarnicki, and Zieminska, REVIEW OF MODERN PHYSICS, VOLUME 90, JANUARY–MARCH 2018)

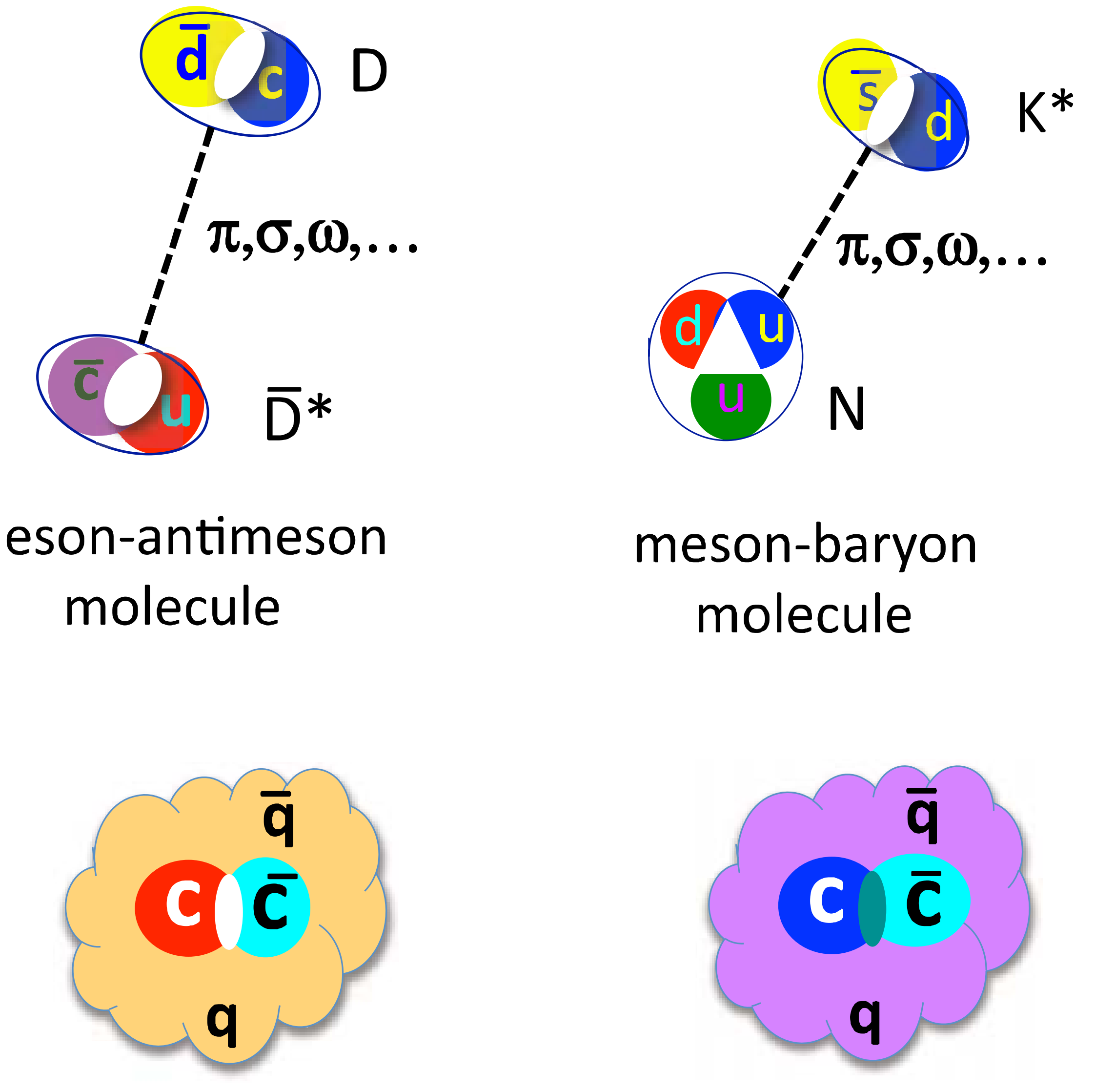
QCD-color-motivated models

QCD diquarks



+QCD hybrids (also glueballs)

Other models



meson-antimeson molecule

meson-baryon molecule

hadrocharmonium

adjoint charmonium

+Kinematically induced resonance-like mass peaks (such as, e.g. threshold cusps)

Lattice QCD should (in principle) be able to predict all colorless states and effects but huge amount of resources would be needed

Currently, none of the models provide a unified description of all the observations

Some states (e.g. X(3872)) are best described by a “mixture of models”

However, it would be of great benefit to have a unified description of data:

REVIEWS OF MODERN PHYSICS, VOLUME 90, JANUARY–MARCH 2018

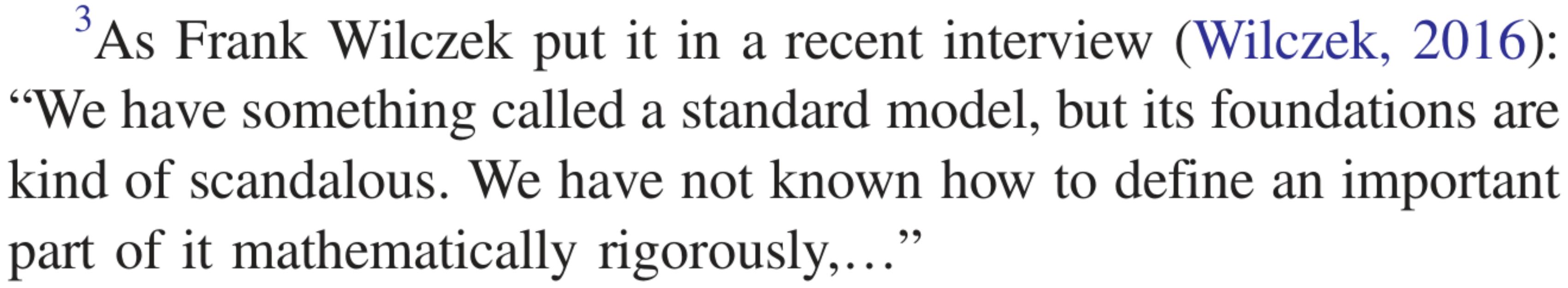
Nonstandard heavy mesons and baryons: Experimental evidence

Stephen Lars Olsen*
Center for Underground Physics, Institute for Basic Science, Daejeon 34126 Korea

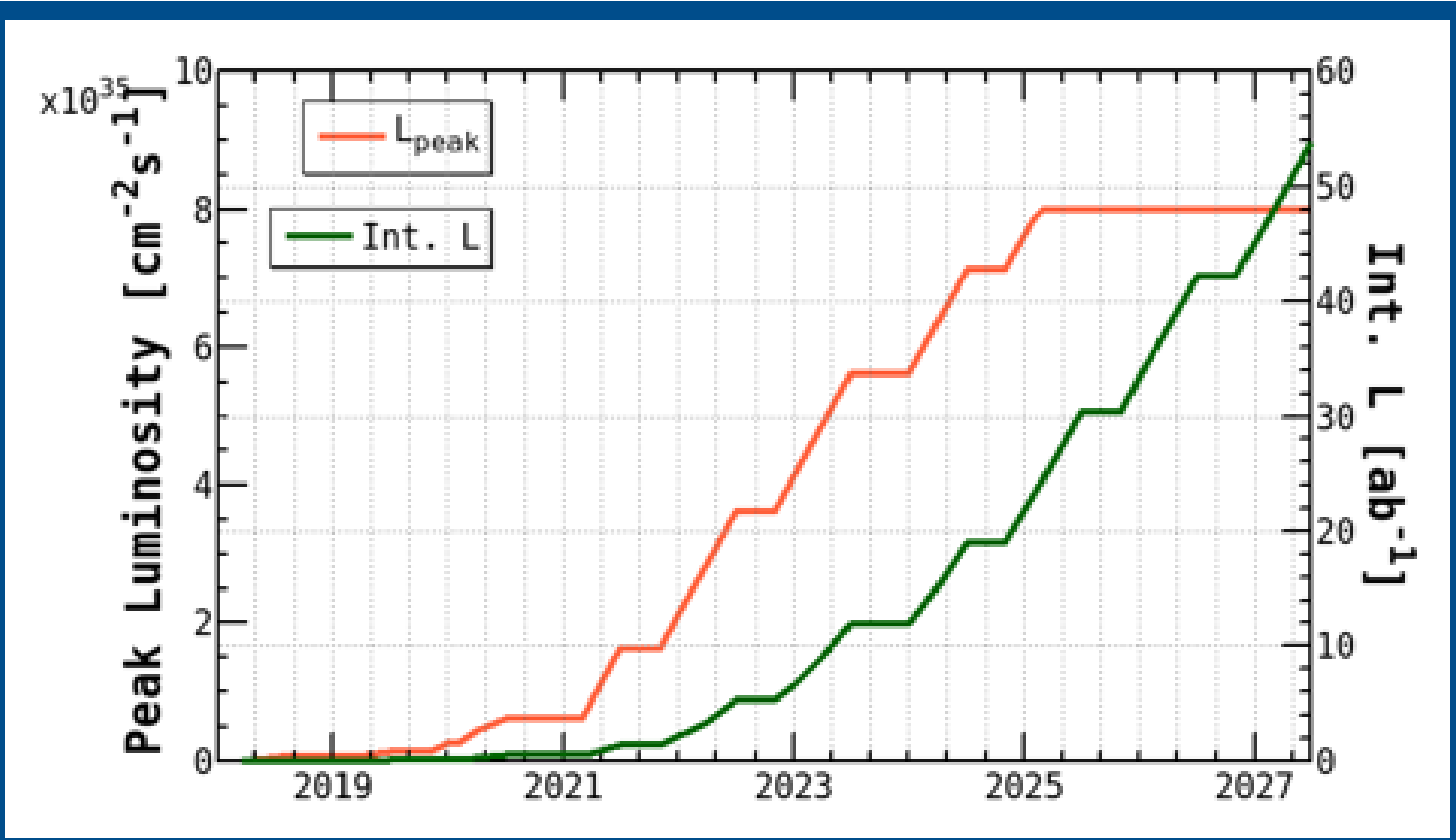
Tomasz Skwarnicki†
Department of Physics, Syracuse University, Syracuse, New York 13244, USA

Daria Zieminska‡
Department of Physics, Indiana University, Bloomington, Indiana 47405-71055, USA

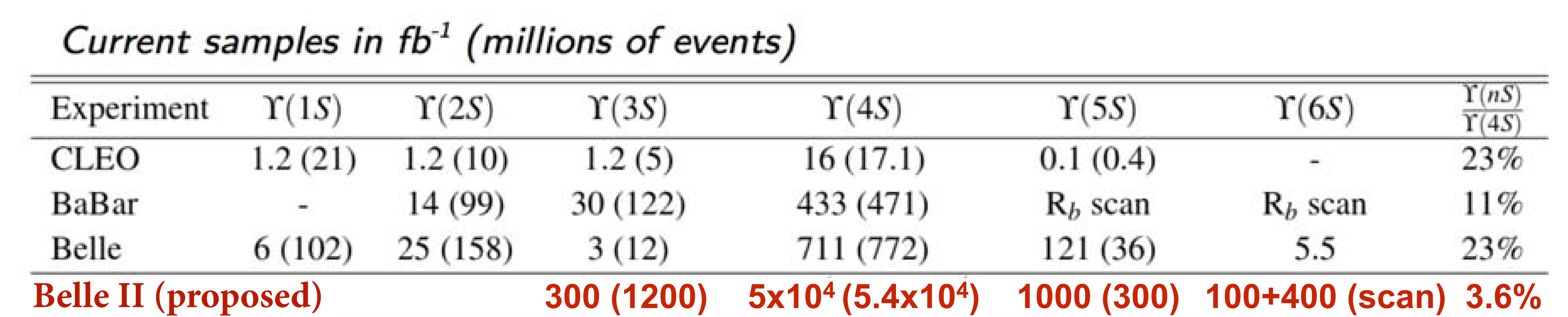
“This nearly total disconnect between the hadrons that we observe in experiments and the quarks and gluons that appear in the theory is a problem of large proportions in particle physics.[3] This is what we refer to as the “QCD dilemma.” In addition to the intellectual dissatisfaction with a theory that is not directly applicable to the particles that are used and detected in experiments, there is also a practical problem in that many SM tests and searches for new physics (NP) involve strongly interacting hadrons in the initial and/or final states of the associated measurements.”



[3] As Frank Wilczek put it in a recent interview (Wilczek, 2016): “We have something called a standard model, but its foundations are kind of scandalous. We have not known how to define an important part of it mathematically rigorously,…”

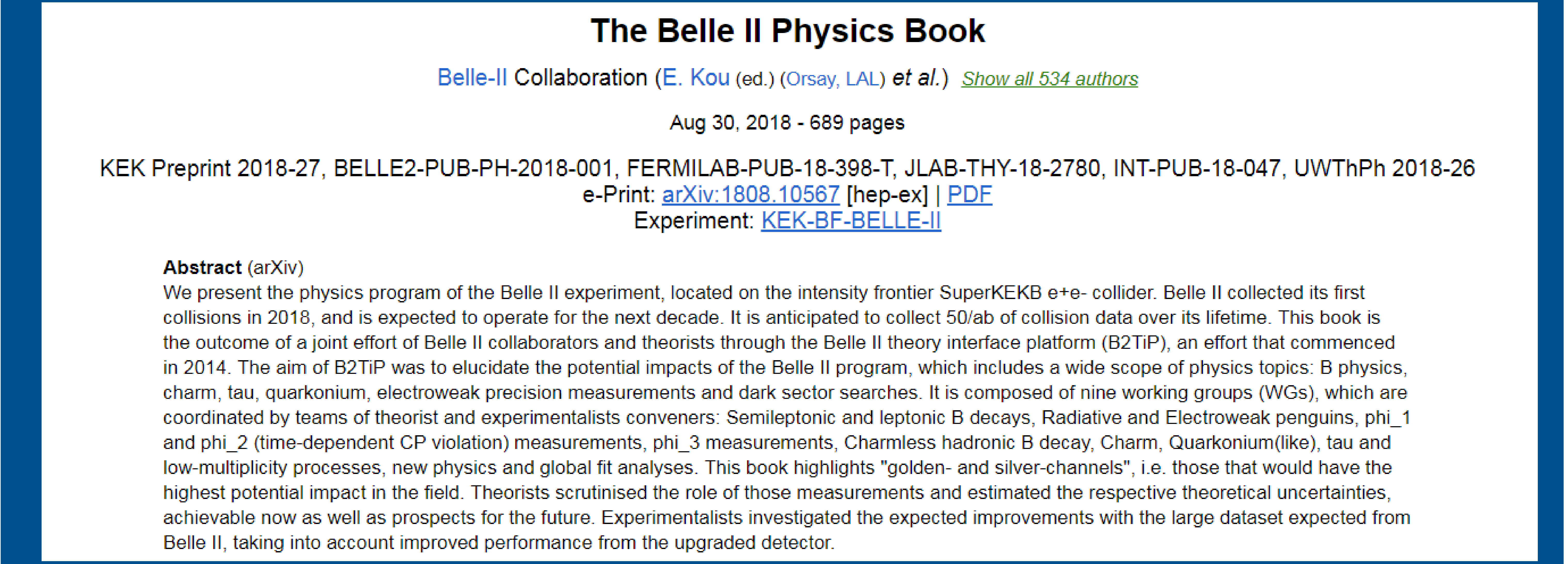


- Belle: 1 ab^{-1}
- Belle II:
  - 5 ab^{-1} by 2023
  - 50 ab^{-1} by 2028



Current samples in fb^{-1} (millions of events)

Experiment	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$	$\frac{\Upsilon(nS)}{\Upsilon(4S)}$
CLEO	1.2 (21)	1.2 (10)	1.2 (5)	16 (17.1)	0.1 (0.4)	-	23%
BaBar	-	14 (99)	30 (122)	433 (471)	R_b scan	R_b scan	11%
Belle	6 (102)	25 (158)	3 (12)	711 (772)	121 (36)	5.5	23%
Belle II (proposed)			**300 (1200)**	**5x10^4 (5.4x10^4)**	**1000 (300)**	**100+400 (scan)**	**3.6%**



The Belle II Physics Book

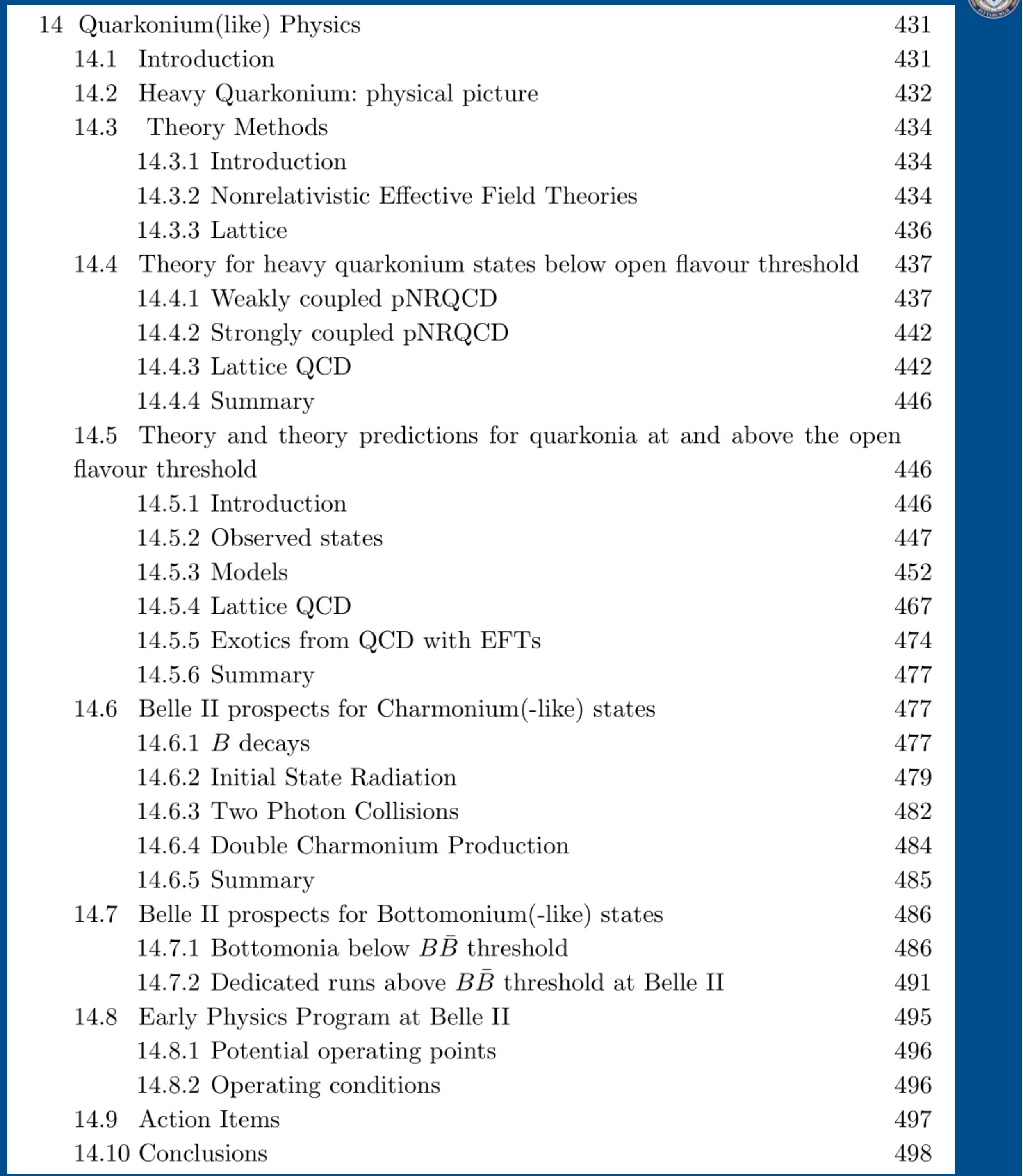
Belle-II Collaboration (E. Kou (ed.) (Orsay, LAL) *et al.*) Show all 534 authors

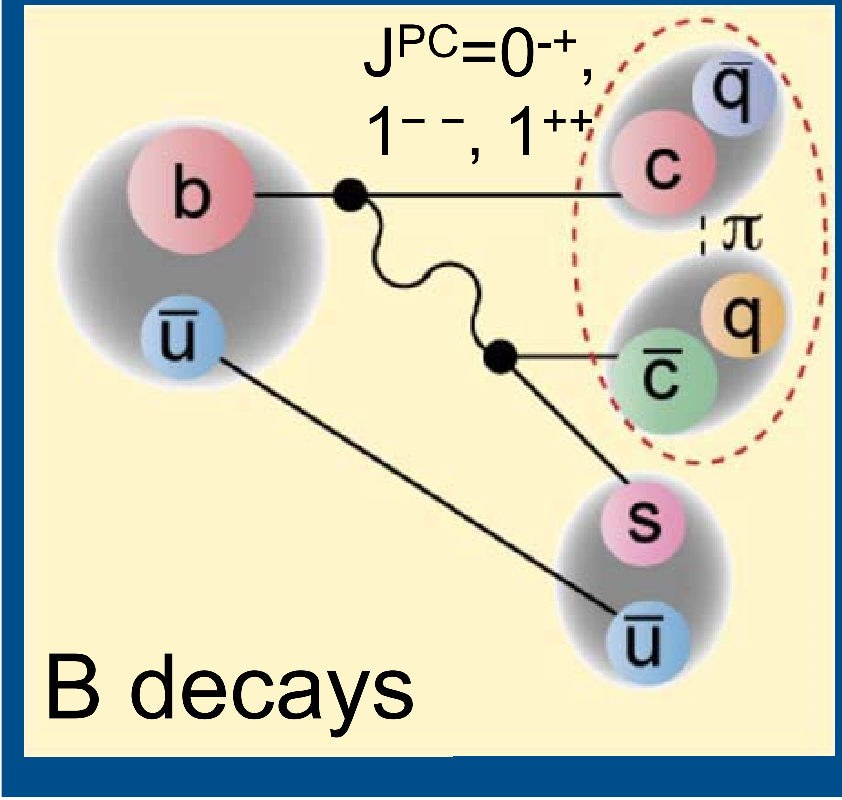
Aug 30, 2018 - 689 pages

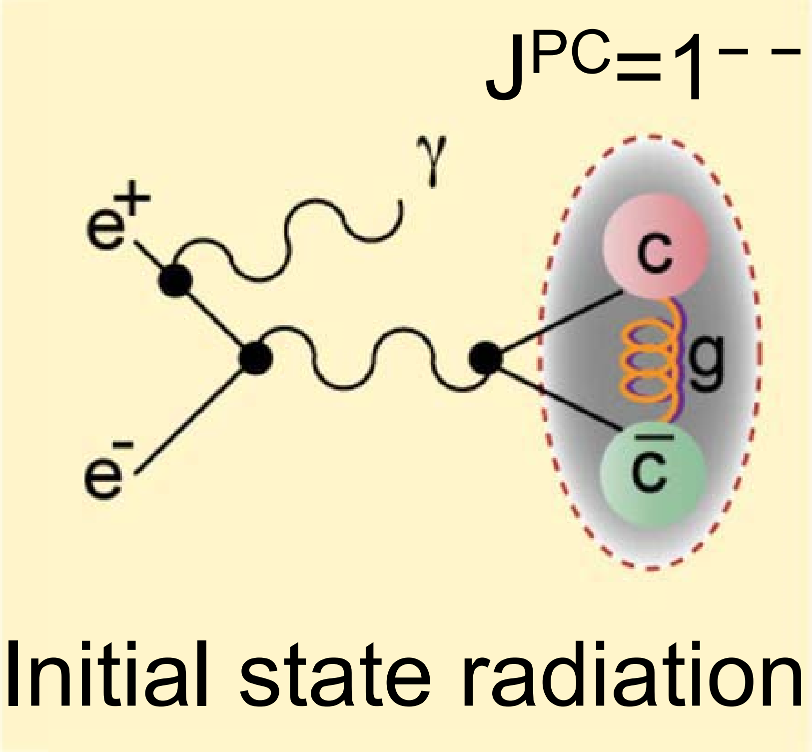
KEK Preprint 2018-27, BELLE2-PUB-PH-2018-001, FERMILAB-PUB-18-398-T, JLAB-THY-18-2780, INT-PUB-18-047, UWThPh 2018-26
e-Print: arXiv:1808.10567 [hep-ex] | PDF
Experiment: KEK-BF-BELLE-II

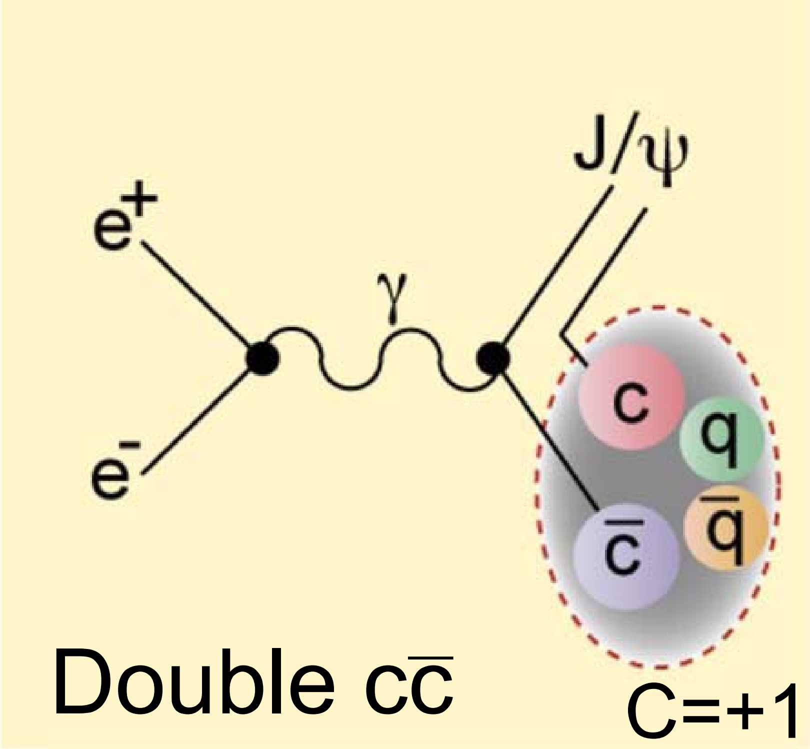
Abstract (arXiv)

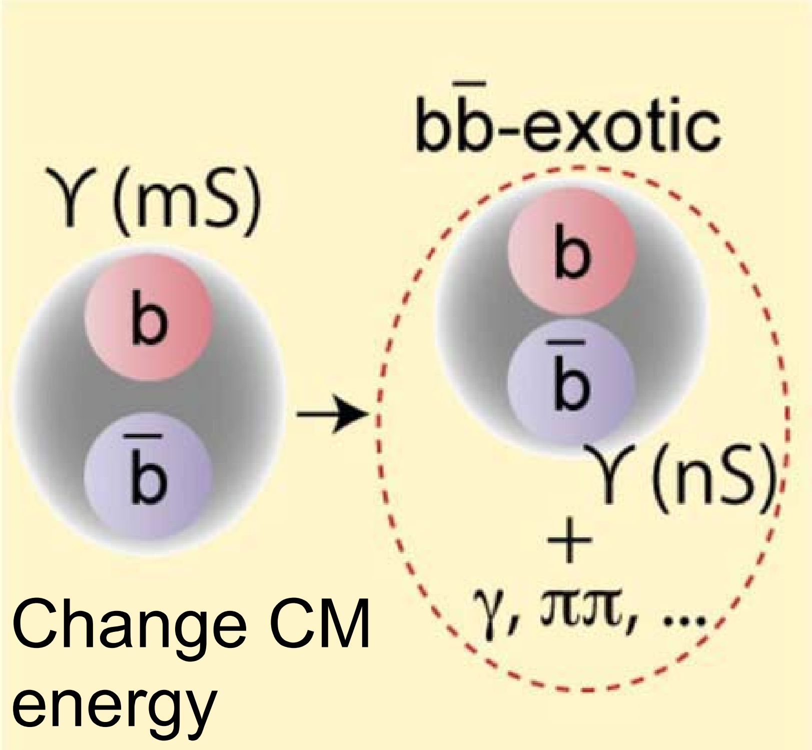
We present the physics program of the Belle II experiment, located on the intensity frontier SuperKEKB e+e- collider. Belle II collected its first collisions in 2018, and is expected to operate for the next decade. It is anticipated to collect 50/ab of collision data over its lifetime. This book is the outcome of a joint effort of Belle II collaborators and theorists through the Belle II theory interface platform (B2TiP), an effort that commenced in 2014. The aim of B2TiP was to elucidate the potential impacts of the Belle II program, which includes a wide scope of physics topics: B physics, charm, tau, quarkonium, electroweak precision measurements and dark sector searches. It is composed of nine working groups (WGs), which are coordinated by teams of theorist and experimentalists conveners: Semileptonic and leptonic B decays, Radiative and Electroweak penguins, phi_1 and phi_2 (time-dependent CP violation) measurements, phi_3 measurements, Charmless hadronic B decay, Charm, Quarkonium(like), tau and low-multiplicity processes, new physics and global fit analyses. This book highlights "golden- and silver-channels", i.e. those that would have the highest potential impact in the field. Theorists scrutinised the role of those measurements and estimated the respective theoretical uncertainties, achievable now as well as prospects for the future. Experimentalists investigated the expected improvements with the large dataset expected from Belle II, taking into account improved performance from the upgraded detector.

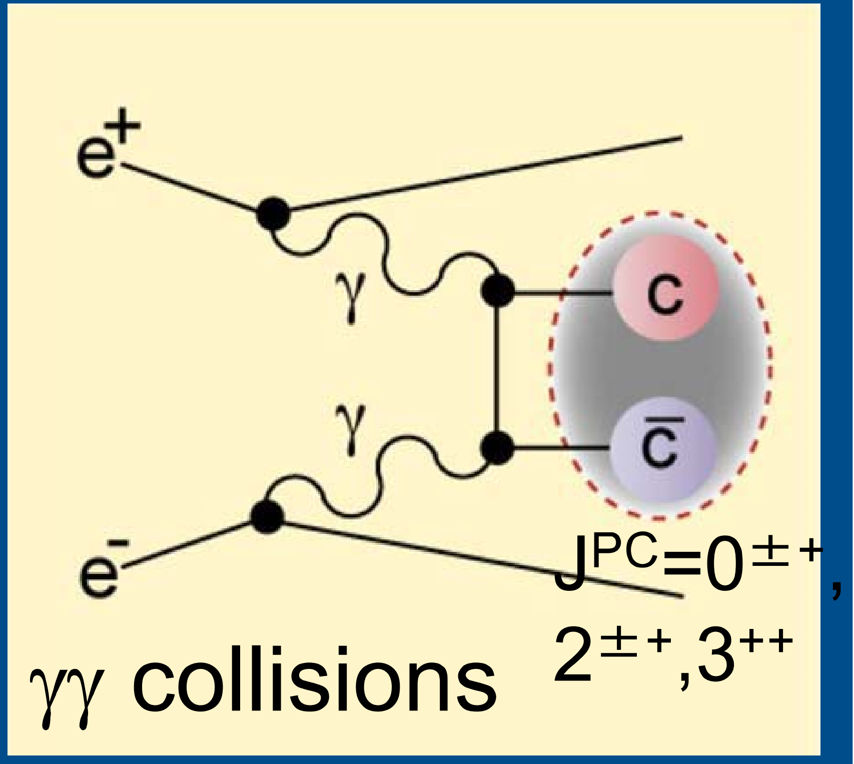






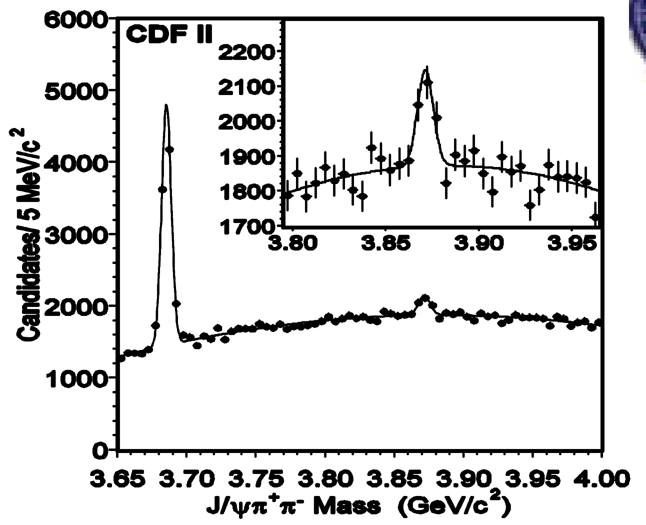




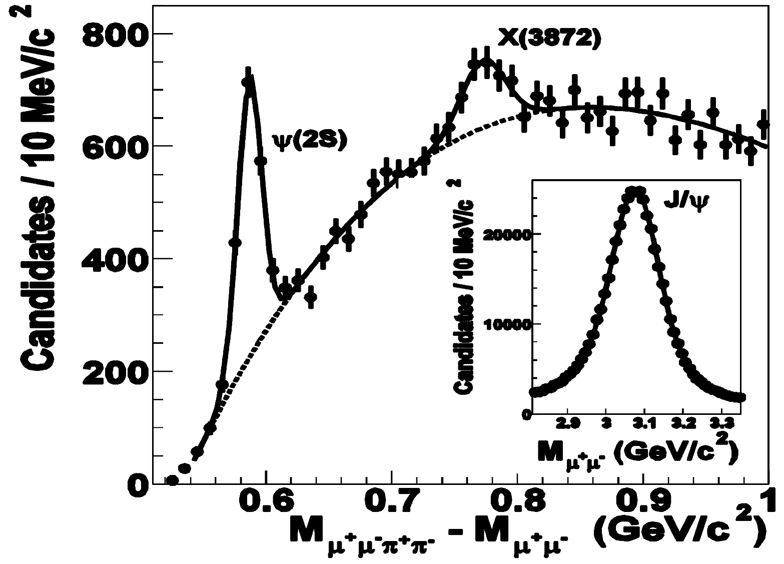


The status of X(3872): the most enigmatic of all the exotic states, most cited Belle publication

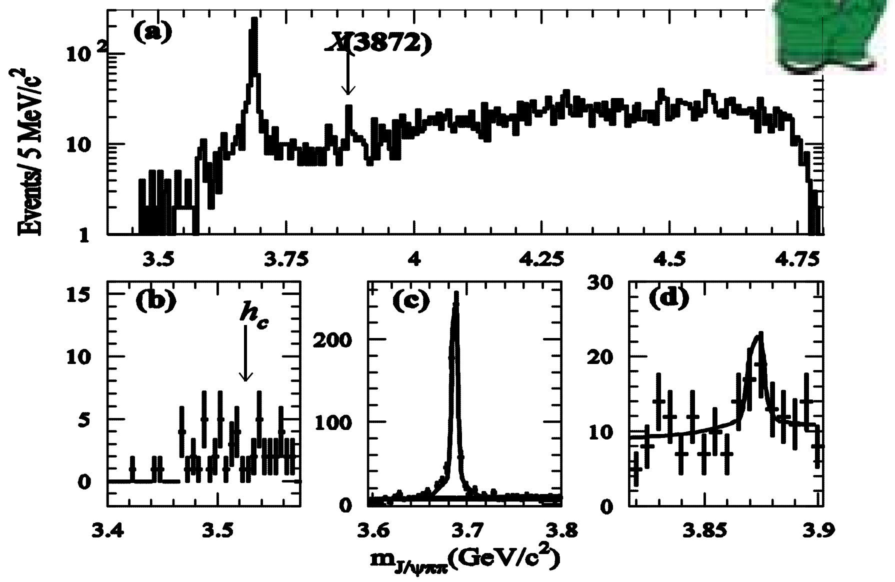
PRL.93.072001 (2004)

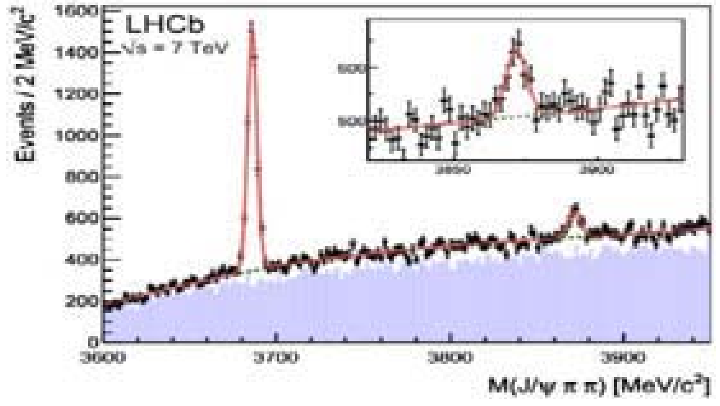


PRL.93.162002 (2004)

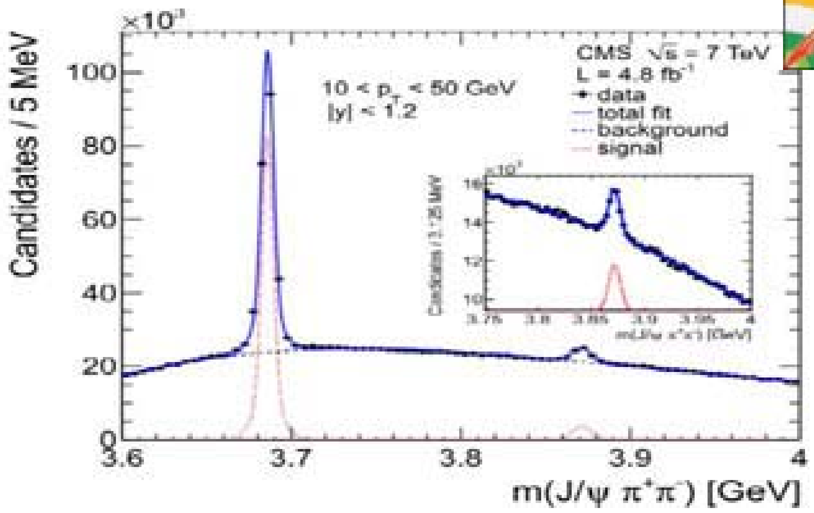


PRD.71.071103 (2005)

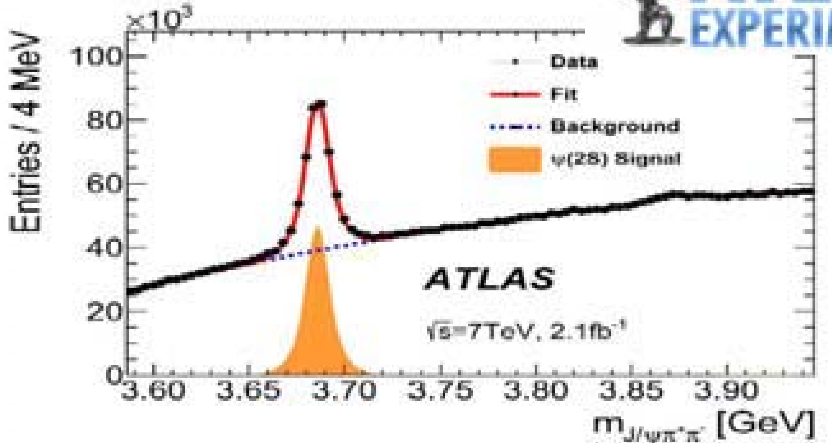




EPJC.72.1972 (2012)



JHEP.04.154 (2013)

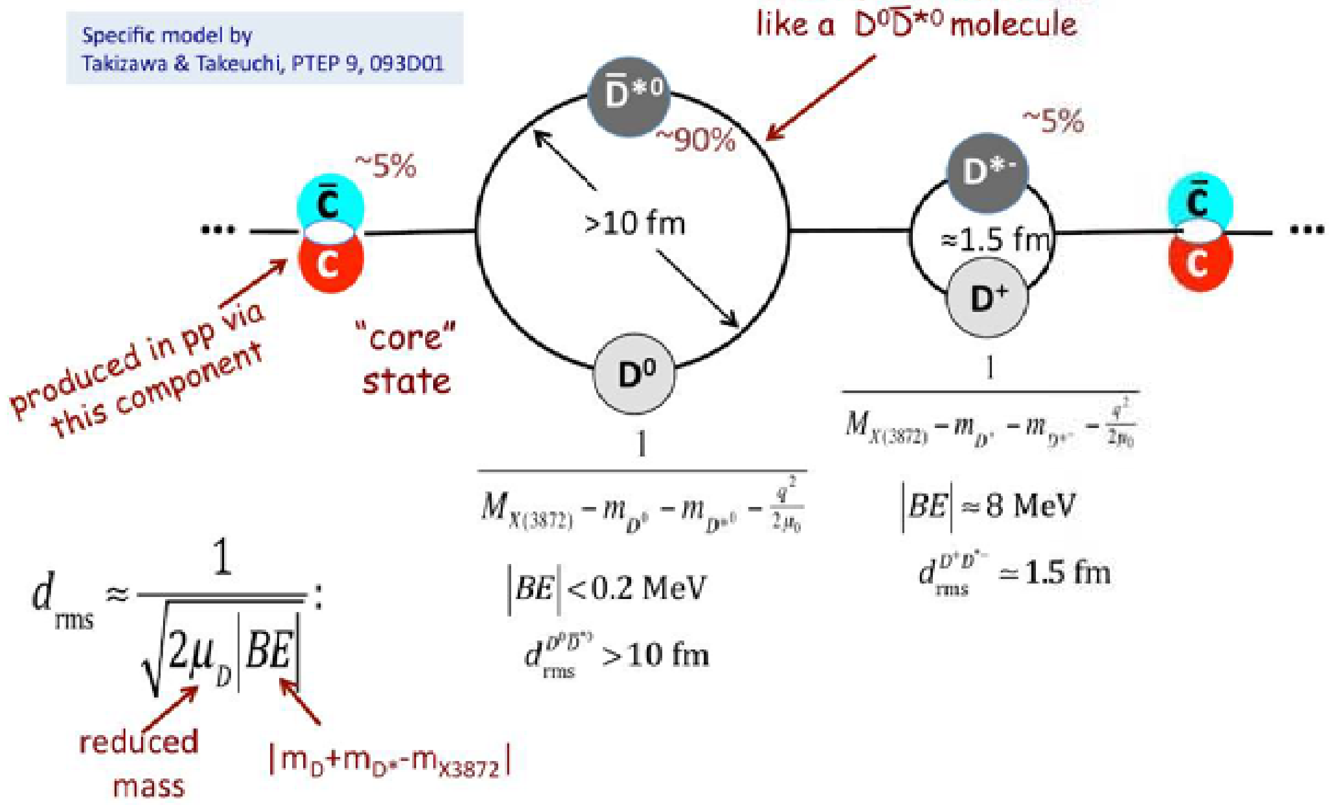


JHEP.79.2014 (2014)

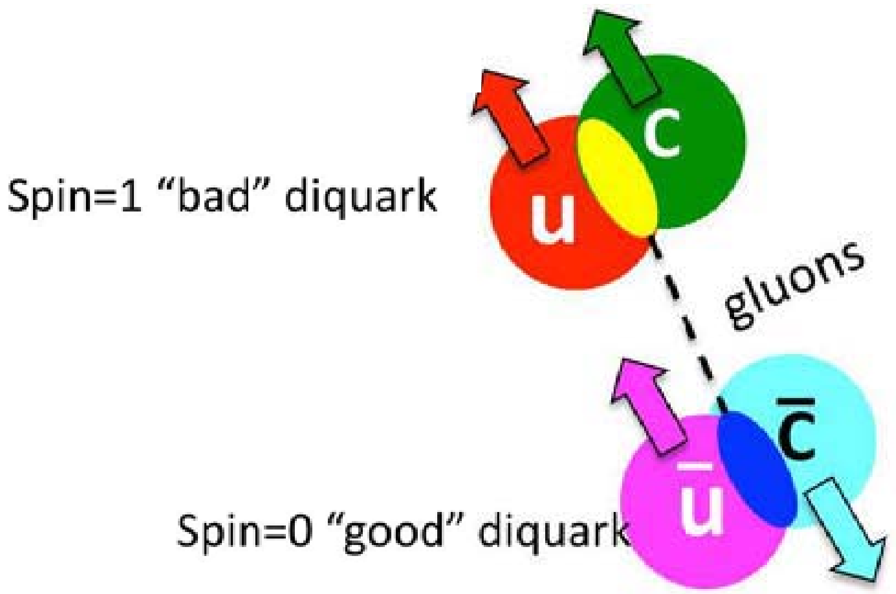
- No quark model prediction in this mass region
- Mass is consistent with DD* with O(0.1) MeV precision suggesting DD* molecular state
- Differential cross section for “prompt production” (not from a B meson decay) is measured by LHC, though this should be suppressed for molecular state!
- Suggests X(3872) is superposition of molecular and $c\bar{c}$ state
- Precise measurements of production and decay processes are essential to understand the exotic nature

The status of X(3872): important details, models, interpretation etc

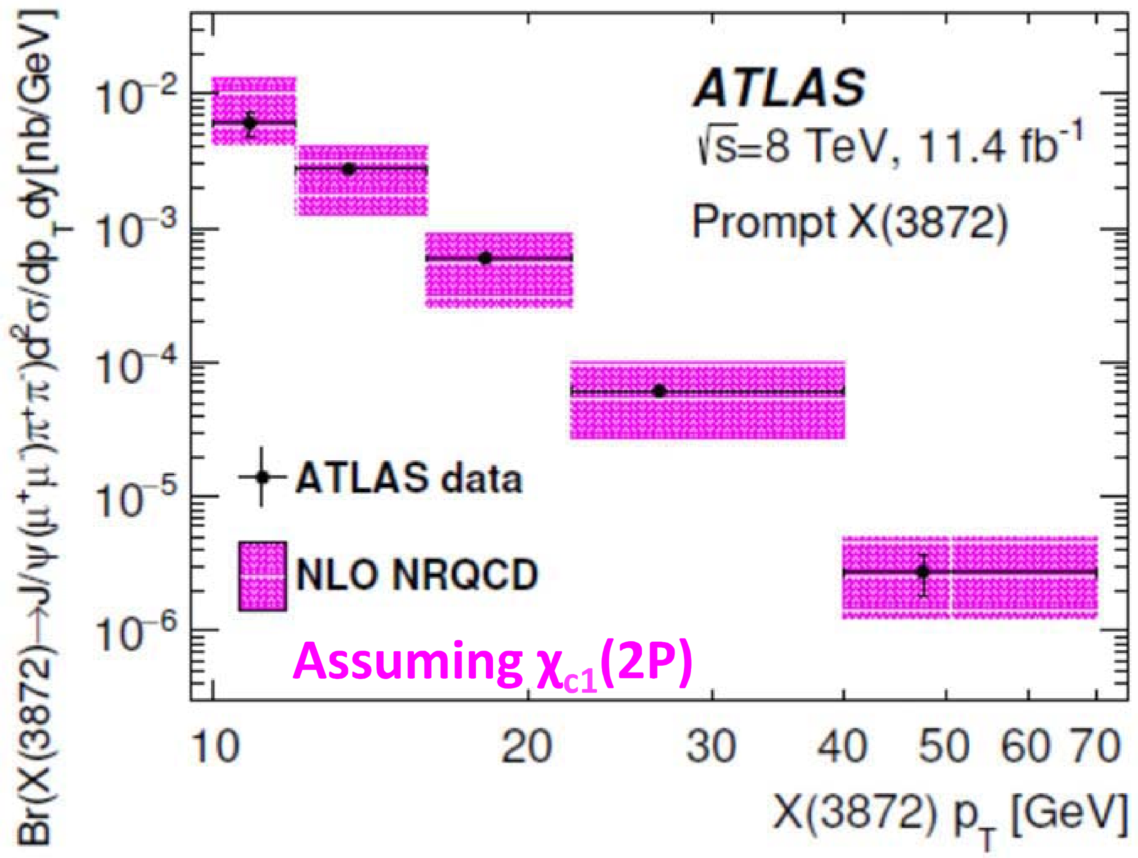
- $J^{PC} = 1^{++}$
- Strong coupling to DD*
- No charged or neutral partner observed
  - Coupled channel, good description
    - PTEP9, 093D01(2013)



- Or QCD diquark-diantiquark
  - Maiani et al., PRD71, 014028(200
  - No 1^{++} partner state seen



Cross section of prompt X(3872) in pp-collision (LHC experiment)



(JHEP01(2017)117)

Inconsistent with pure molecular interpretation

- Support $D\bar{D}^* - \chi_{c1}(2P)$ mixture state.

→ Need further information about production and decay

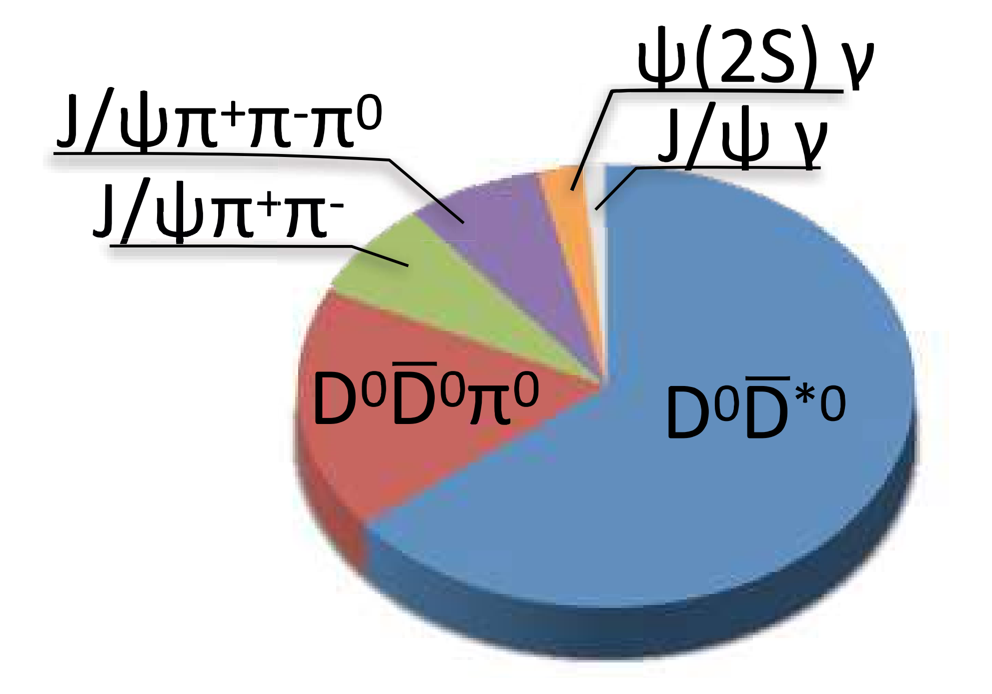
- Current X(3872) total width:

$$\Gamma_{\mathrm{tot}} < 1.2 \text{ MeV}$$

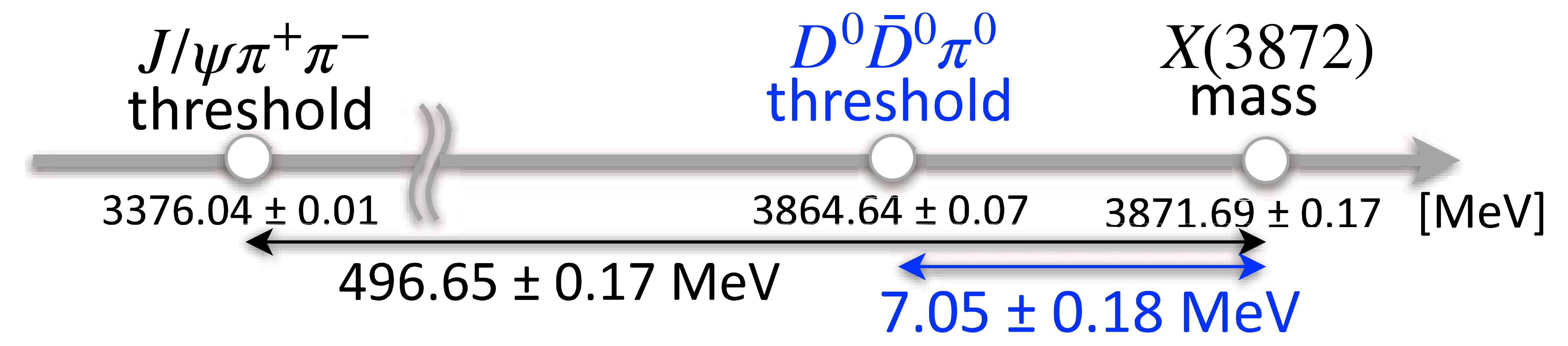
Want to measure total width (which is related to partial widths):

$$\Gamma(X(3872) \to f) = \frac{\mathrm{Br}(B^\pm \to K^\pm X(3872)) \times \mathrm{Br}(X(3872) \to f)}{\mathrm{Br}(B^\pm \to K^\pm X(3872))} \times \Gamma_{\mathrm{tot}}$$

The status of X(3872): the most enigmatic of all the exotic states, most cited Belle publication



X(3872) Decays



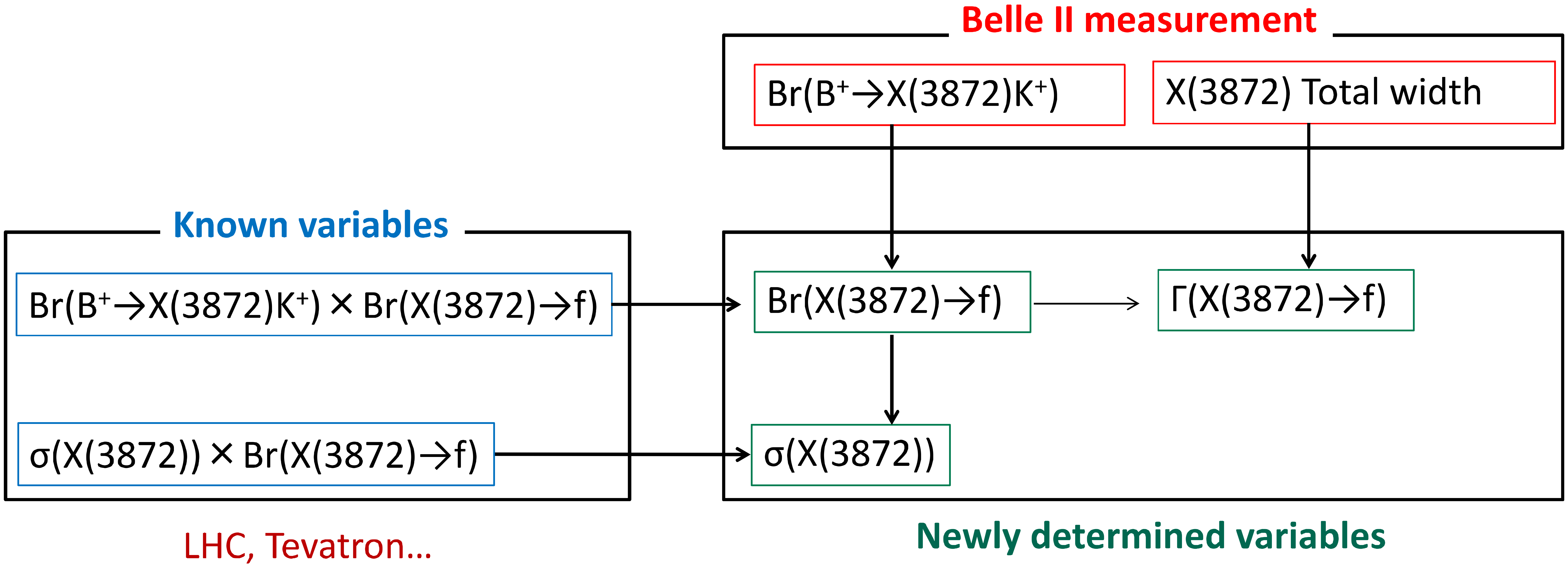
- Previous study (Phys. Rev. D 84, 052004 (2011))
  - Used $X(3872) \to J/\psi\pi^+\pi^-$ mode
  - Used a Breit-Wigner (convolved with resolution) fit to mass spectrum

Γ_{tot} < 1.2 MeV (90% C.L.) < Mass resolution 1.86 ± 0.01 MeV/c^2

Improvement of mass resolution is essential

The Nature of X(3872): Prospects with Belle II

- Many decay modes have been observed: $J/\psi\ \rho$, $J/\psi\ \omega$, $J/\psi\ \gamma$, $\psi(2S)\ \gamma$, DD^*, $DD\pi^0$. etc.
- Branching fractions and decay widths not known
  - Essential dynamic information!
- Belle II can contribute to a deeper understanding of this state!



Belle II measurement

$Br(B^+ \to X(3872)K^+)$

X(3872) Total width

Known variables

$Br(B^+ \to X(3872)K^+) \times Br(X(3872) \to f)$

$\sigma(X(3872)) \times Br(X(3872) \to f)$

$Br(X(3872) \to f)$

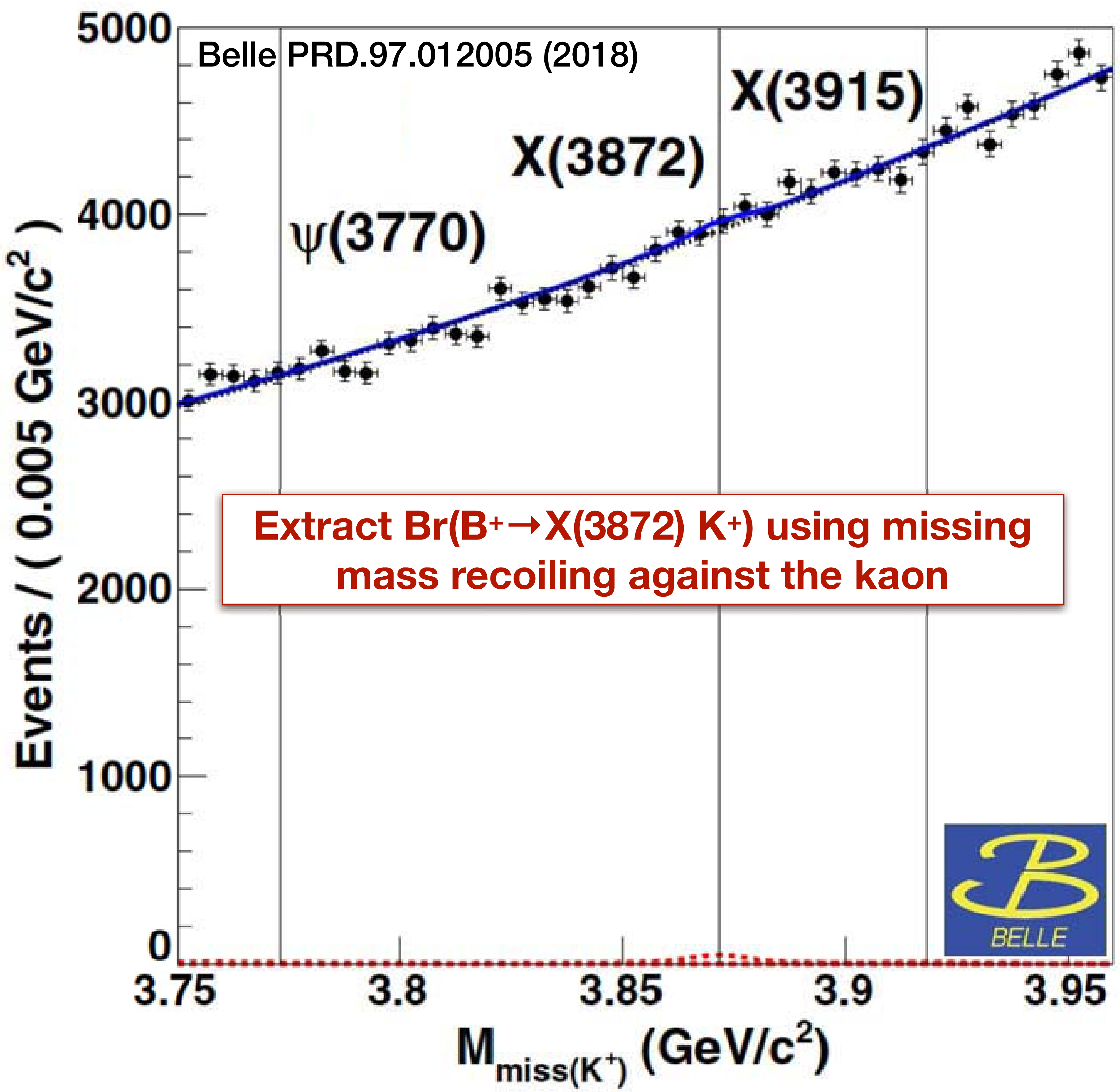
$\Gamma(X(3872) \to f)$

$\sigma(X(3872))$

LHC, Tevatron…

Newly determined variables

Toward X(3872) Total and Partial Widths Measurements with Belle II



Extract Br($B^+ \rightarrow X(3872)\ K^+$) using missing mass recoiling against the kaon

Mass resolution for $D\bar{D}\pi^0$ is ~680 keV: ~3 times better than $J/\psi\pi^+\pi^-$ Previously unmeasured due to low statistics

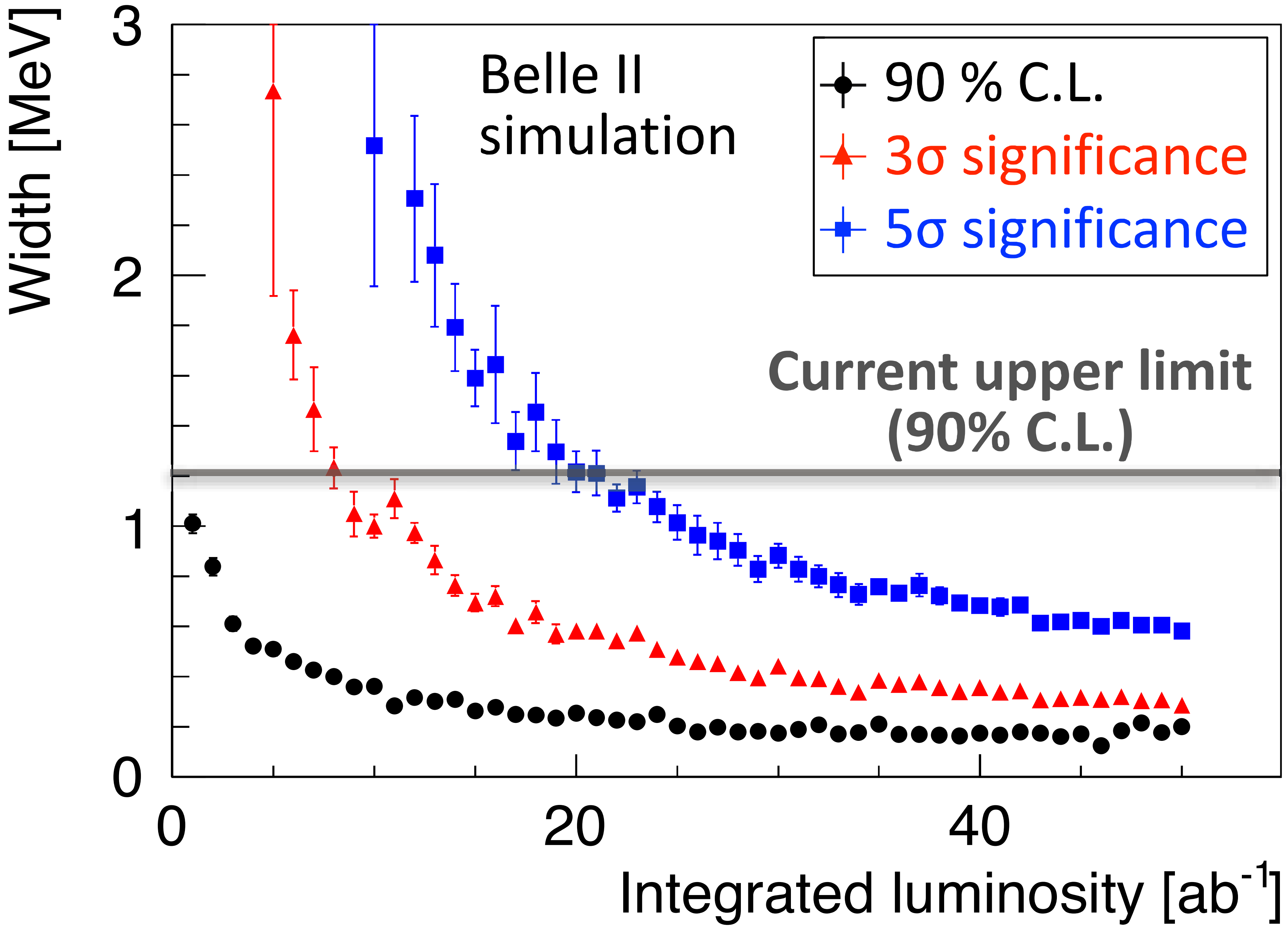
With the full data sample of Belle II (50 ab^{-1}), total width with values up to

[90% C.L.] ~ 180 keV

[3σ significance] ~ 280 keV

[5σ significant] ~ 570 keV

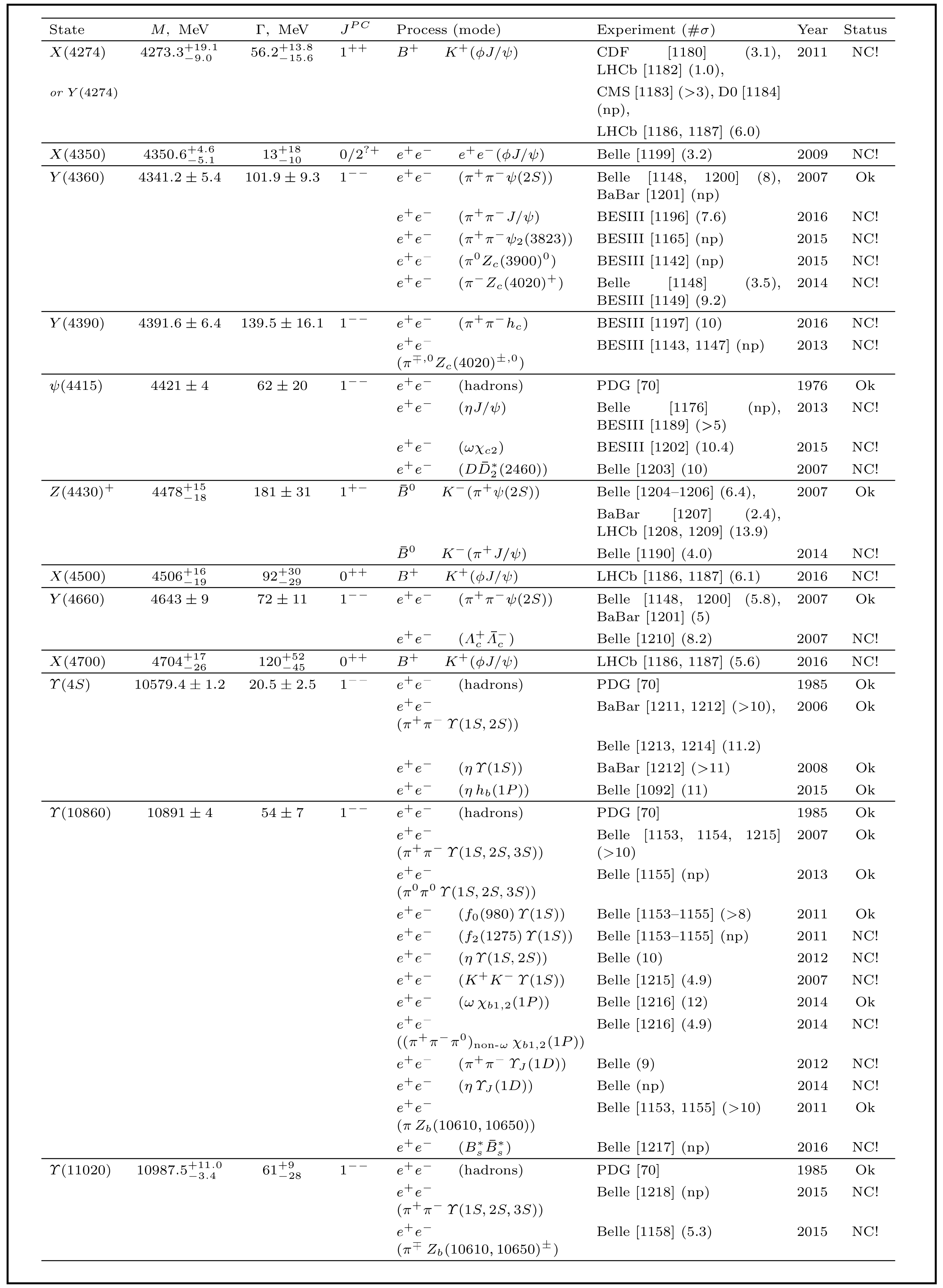
can be measured.



Master thesis of H. Hirata (KMI / Nagoya University)

The status of Y(4260) (and some other “Why?” states)

$Y(4260)$	4221.1 ± 2.5	47.7 ± 4.0	1^{--}	e^+e^-	$(\pi^+\pi^- J/\psi)$	BaBar [1191, 1192] (8), CLEO [1193, 1194] (11), Belle [1140, 1195] (15), BESIII [1139, 1196] (np)	2005	Ok
				e^+e^-	$(\pi^0\pi^0 J/\psi)$	CLEO [1193] (5.1), BESIII [1142] (np)	2006	Ok
				e^+e^-	$(K^+K^- J/\psi)$	CLEO [1193] (3.7)	2006	NC!
				e^+e^-	$(f_0(980) J/\psi)$	BaBar [1192] (np), Belle [1140] (np)	2012	Ok
				e^+e^-	$(\pi^+\pi^- h_c)$	BESIII [1143, 1197] (10)	2013	NC!
				e^+e^-	$(\pi^0\pi^0 h_c)$	BESIII [1147] (np)	2014	NC!
				e^+e^-	$(\omega\chi_{c0})$	BESIII [1198] (>9)	2014	NC!
				e^+e^-	$(\gamma X(3872))$	BESIII [1129] (6.3)	2013	NC!
				e^+e^-	$(\pi^- Z_c(3900)^+)$	BESIII [1139, 1145] (>8), Belle [1140] (5.2)	2013	Ok
				e^+e^-	$(\pi^0 Z_c(3900)^0)$	BESIII [1142, 1146] (10.4)	2015	Ok
				e^+e^-	$(\pi^{\mp,0} Z_c(4020)^{\pm,0})$	BESIII [1143, 1147, 1150, 1151] (>10)	2013	Ok



State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(4274)$ *or* $Y(4274)$	$4273.3^{+19.1}_{-9.0}$	$56.2^{+13.8}_{-15.6}$	1^{++}	B^+ $K^+(\phi J/\psi)$	CDF [1180] (3.1), LHCb [1182] (1.0), CMS [1183] (>3), D0 [1184] (np), LHCb [1186, 1187] (6.0)	2011	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	e^+e^- $e^+e^-(\phi J/\psi)$	Belle [1199] (3.2)	2009	NC!
$Y(4360)$	4341.2 ± 5.4	101.9 ± 9.3	1^{--}	e^+e^- $(\pi^+\pi^-\psi(2S))$	Belle [1148, 1200] (8), BaBar [1201] (np)	2007	Ok
				e^+e^- $(\pi^+\pi^- J/\psi)$	BESIII [1196] (7.6)	2016	NC!
				e^+e^- $(\pi^+\pi^-\psi_2(3823))$	BESIII [1165] (np)	2015	NC!
				e^+e^- $(\pi^0 Z_c(3900)^0)$	BESIII [1142] (np)	2015	NC!
				e^+e^- $(\pi^- Z_c(4020)^+)$	Belle [1148] (3.5), BESIII [1149] (9.2)	2014	NC!
$Y(4390)$	4391.6 ± 6.4	139.5 ± 16.1	1^{--}	e^+e^- $(\pi^+\pi^- h_c)$	BESIII [1197] (10)	2016	NC!
				e^+e^- $(\pi^{\mp,0} Z_c(4020)^{\pm,0})$	BESIII [1143, 1147] (np)	2013	NC!
$\psi(4415)$	4421 ± 4	62 ± 20	1^{--}	e^+e^- (hadrons)	PDG [70]	1976	Ok
				e^+e^- $(\eta J/\psi)$	Belle [1176] (np), BESIII [1189] (>5)	2013	NC!
				e^+e^- $(\omega\chi_{c2})$	BESIII [1202] (10.4)	2015	NC!
				e^+e^- $(D\bar{D}_2^*(2460))$	Belle [1203] (10)	2007	NC!
$Z(4430)^+$	4478^{+15}_{-18}	181 ± 31	1^{+-}	$\bar{B}^0$ $K^-(\pi^+\psi(2S))$	Belle [1204–1206] (6.4), BaBar [1207] (2.4), LHCb [1208, 1209] (13.9)	2007	Ok
				$\bar{B}^0$ $K^-(\pi^+ J/\psi)$	Belle [1190] (4.0)	2014	NC!
$X(4500)$	4506^{+16}_{-19}	92^{+30}_{-29}	0^{++}	B^+ $K^+(\phi J/\psi)$	LHCb [1186, 1187] (6.1)	2016	NC!
$Y(4660)$	4643 ± 9	72 ± 11	1^{--}	e^+e^- $(\pi^+\pi^-\psi(2S))$	Belle [1148, 1200] (5.8), BaBar [1201] (5)	2007	Ok
				e^+e^- $(\Lambda_c^+\bar{\Lambda}_c^-)$	Belle [1210] (8.2)	2007	NC!
$X(4700)$	4704^{+17}_{-26}	120^{+52}_{-45}	0^{++}	B^+ $K^+(\phi J/\psi)$	LHCb [1186, 1187] (5.6)	2016	NC!
$\Upsilon(4S)$	10579.4 ± 1.2	20.5 ± 2.5	1^{--}	e^+e^- (hadrons)	PDG [70]	1985	Ok
				e^+e^- $(\pi^+\pi^-\Upsilon(1S,2S))$	BaBar [1211, 1212] (>10), Belle [1213, 1214] (11.2)	2006	Ok
				e^+e^- $(\eta\Upsilon(1S))$	BaBar [1212] (>11)	2008	Ok
				e^+e^- $(\eta h_b(1P))$	Belle [1092] (11)	2015	Ok
$\Upsilon(10860)$	10891 ± 4	54 ± 7	1^{--}	e^+e^- (hadrons)	PDG [70]	1985	Ok
				e^+e^- $(\pi^+\pi^-\Upsilon(1S,2S,3S))$	Belle [1153, 1154, 1215] (>10)	2007	Ok
				e^+e^- $(\pi^0\pi^0\Upsilon(1S,2S,3S))$	Belle [1155] (np)	2013	Ok
				e^+e^- $(f_0(980)\Upsilon(1S))$	Belle [1153–1155] (>8)	2011	Ok
				e^+e^- $(f_2(1275)\Upsilon(1S))$	Belle [1153–1155] (np)	2011	NC!
				e^+e^- $(\eta\Upsilon(1S,2S))$	Belle (10)	2012	NC!
				e^+e^- $(K^+K^-\Upsilon(1S))$	Belle [1215] (4.9)	2007	NC!
				e^+e^- $(\omega\chi_{b1,2}(1P))$	Belle [1216] (12)	2014	Ok
				e^+e^- $((\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{b1,2}(1P))$	Belle [1216] (4.9)	2014	NC!
				e^+e^- $(\pi^+\pi^-\Upsilon_J(1D))$	Belle (9)	2012	NC!
				e^+e^- $(\eta\Upsilon_J(1D))$	Belle (np)	2014	NC!
				e^+e^- $(\pi Z_b(10610,10650))$	Belle [1153, 1155] (>10)	2011	Ok
				e^+e^- $(B_s^*\bar{B}_s^*)$	Belle [1217] (np)	2016	NC!
$\Upsilon(11020)$	$10987.5^{+11.0}_{-3.4}$	61^{+9}_{-28}	1^{--}	e^+e^- (hadrons)	PDG [70]	1985	Ok
				e^+e^- $(\pi^+\pi^-\Upsilon(1S,2S,3S))$	Belle [1218] (np)	2015	NC!
				e^+e^- $(\pi^{\mp} Z_b(10610,10650)^{\pm})$	Belle [1158] (5.3)	2015	NC!

Many other XYZ states will also be investigated at Belle II

The Belle II Physics Book, arXiv:1808.10567 [hep-ex]

The status of Y(4260) (and some other “Why?” states)

Y(4260):

Why such state(s)?

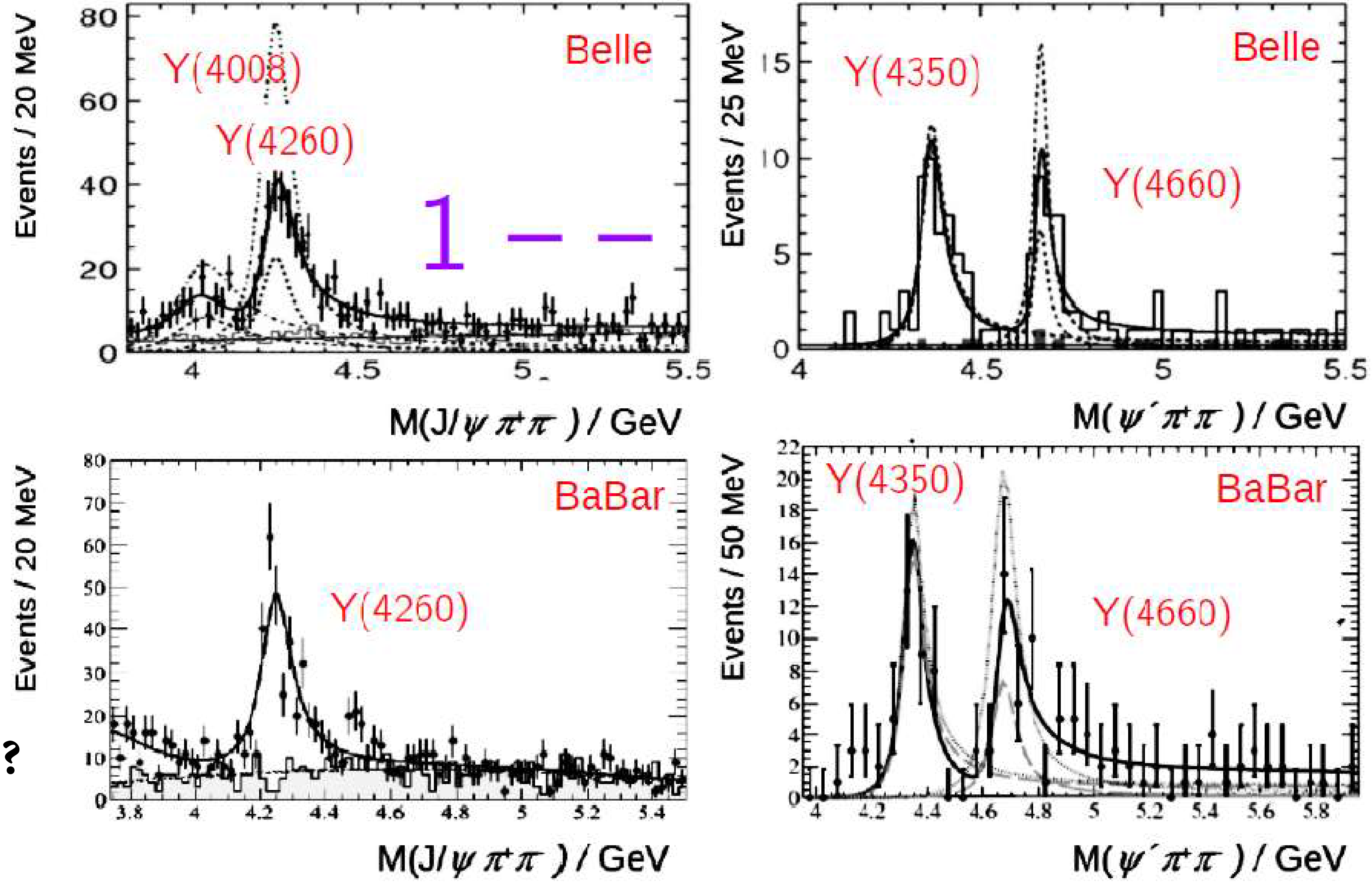
And what is it / are they?

Charmonium?

Four-quark state?

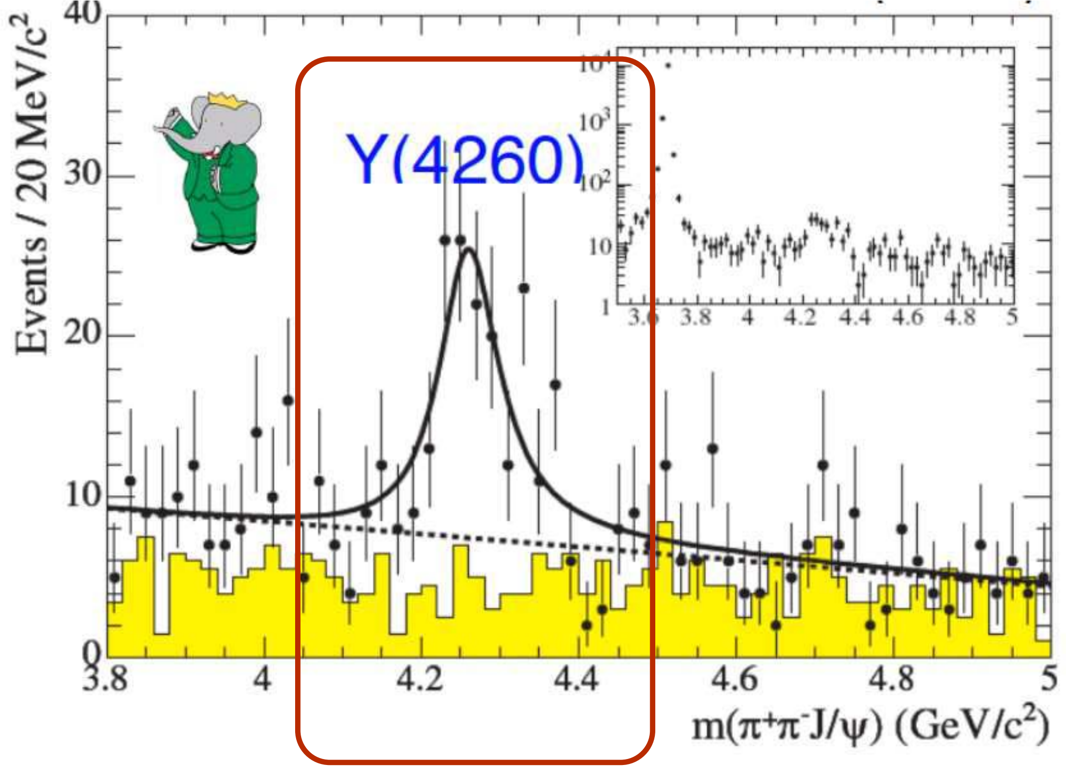
Molecule?

A superposition of all of these?



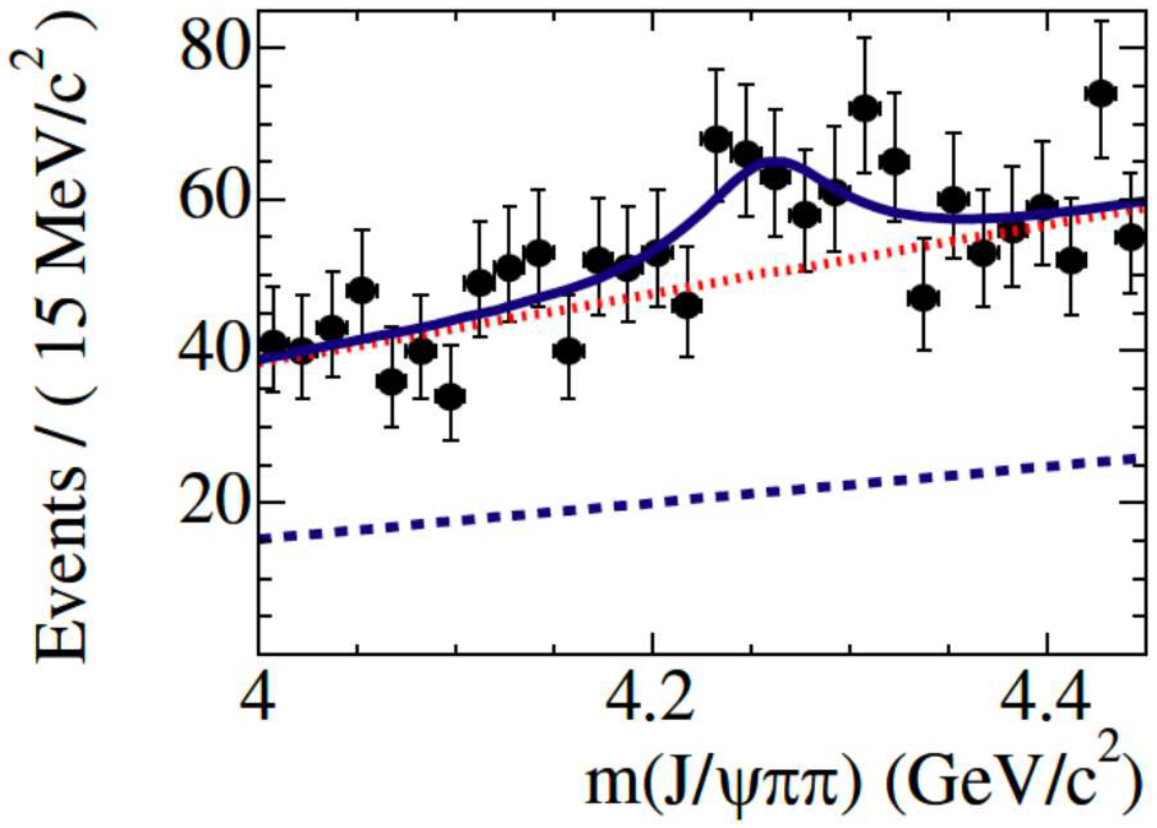
Enigmatic Y(4260) (discovered by BaBar in ISR, searched for in B decays)

BaBar PRL.95.142001 (2005)



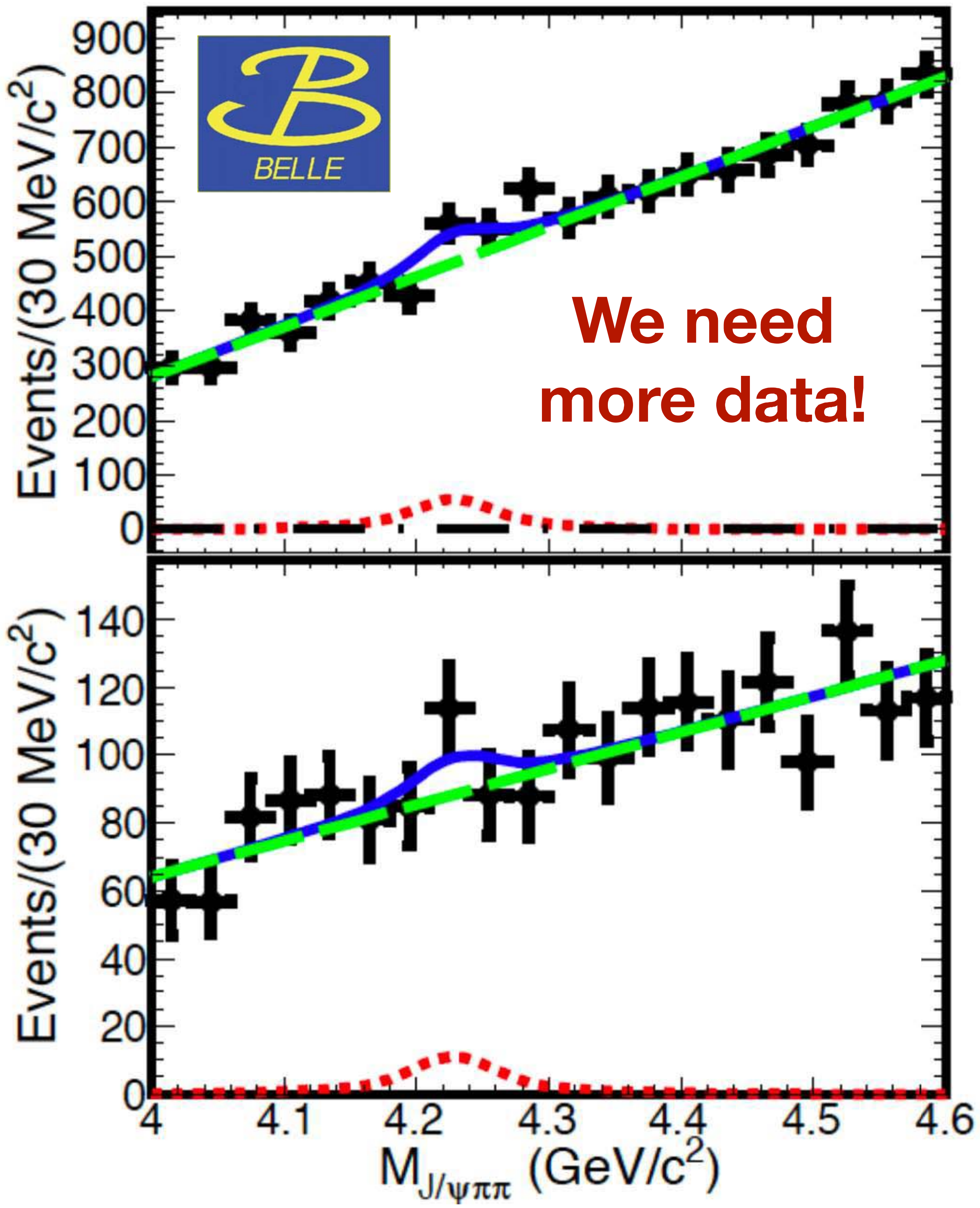
How many states?

BaBar PRD.73.011101(R) (2006)



$$\mathcal{B}(B^- \to Y(4260)K^-, Y(4260) \to J/\psi\pi^+\pi^-) < 2.9 \times 10^{-5}$$

Belle arXiv:1901.06470



We need more data!

- Y(4260) discovered in $e^+e^+ \to \gamma_{ISR}\pi^+\pi^-J/\psi$
  - Overpopulation of charmonium states!
  - Molecular ($D_1\bar{D}$), hybrid, tetraquark all offer viable descriptions
- Some predictions (e.g. mixed-state model based upon QCD sum rules), suggest $B^+ \to Y(4260)K^+$ with $Y(4260) \to \pi^+\pi^-J/\psi$ may have a branching fraction in the range $3.0 \times 10^{-8} – 1.8 \times 10^{-6}$

Improved by factor of 2

$$\mathcal{B}(B^+ \to Y(4260)K^+) \times \mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-) < 1.4 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to Y(4260)K^0) \times \mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-) < 1.7 \times 10^{-5}$$

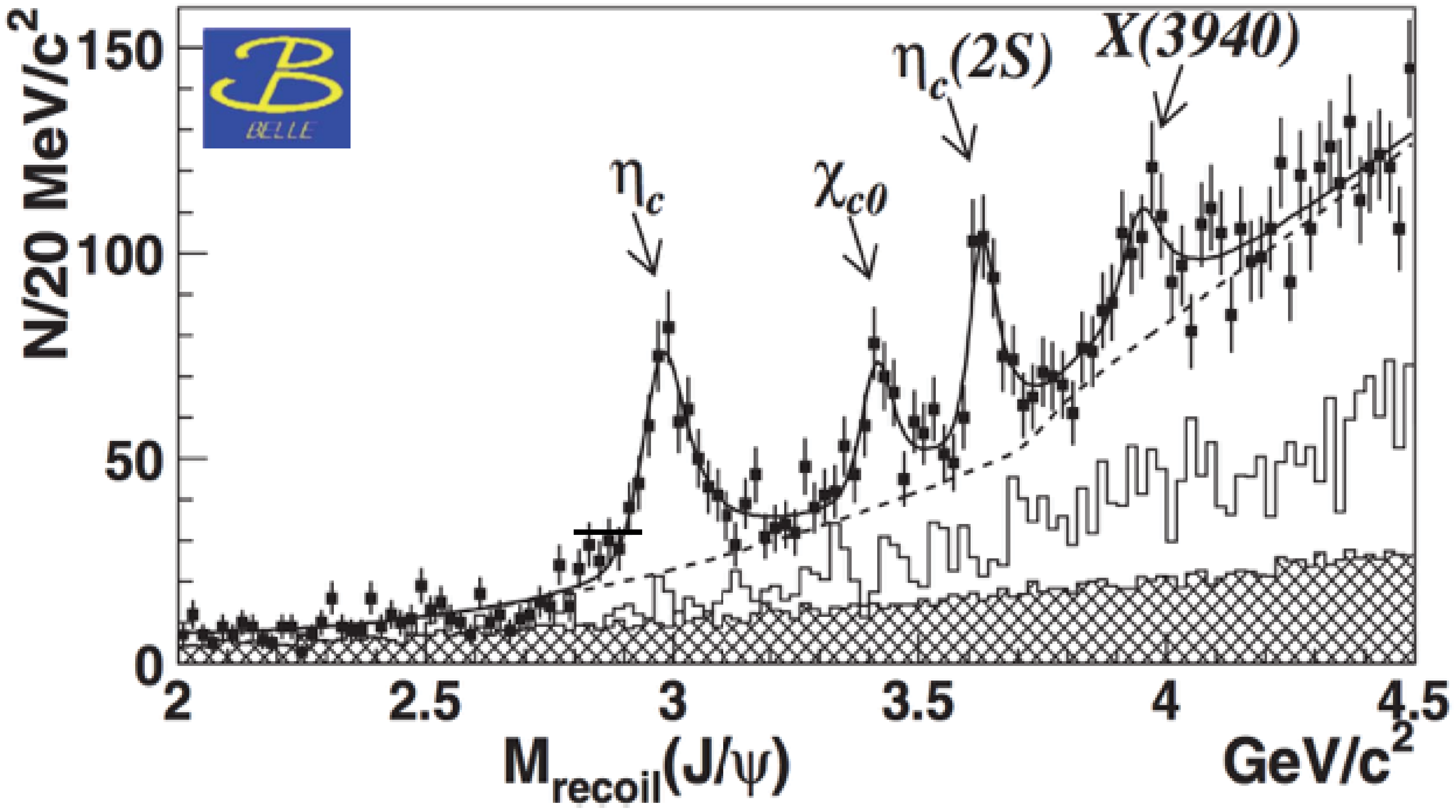
New upper limit

Double Charmonium Production at Belle (II)

- Observed in combinations of J=1 and J=0

  $e^+e^- \to c\bar{c}\ (0+/-)\ c\bar{c}\ (1-/+)$

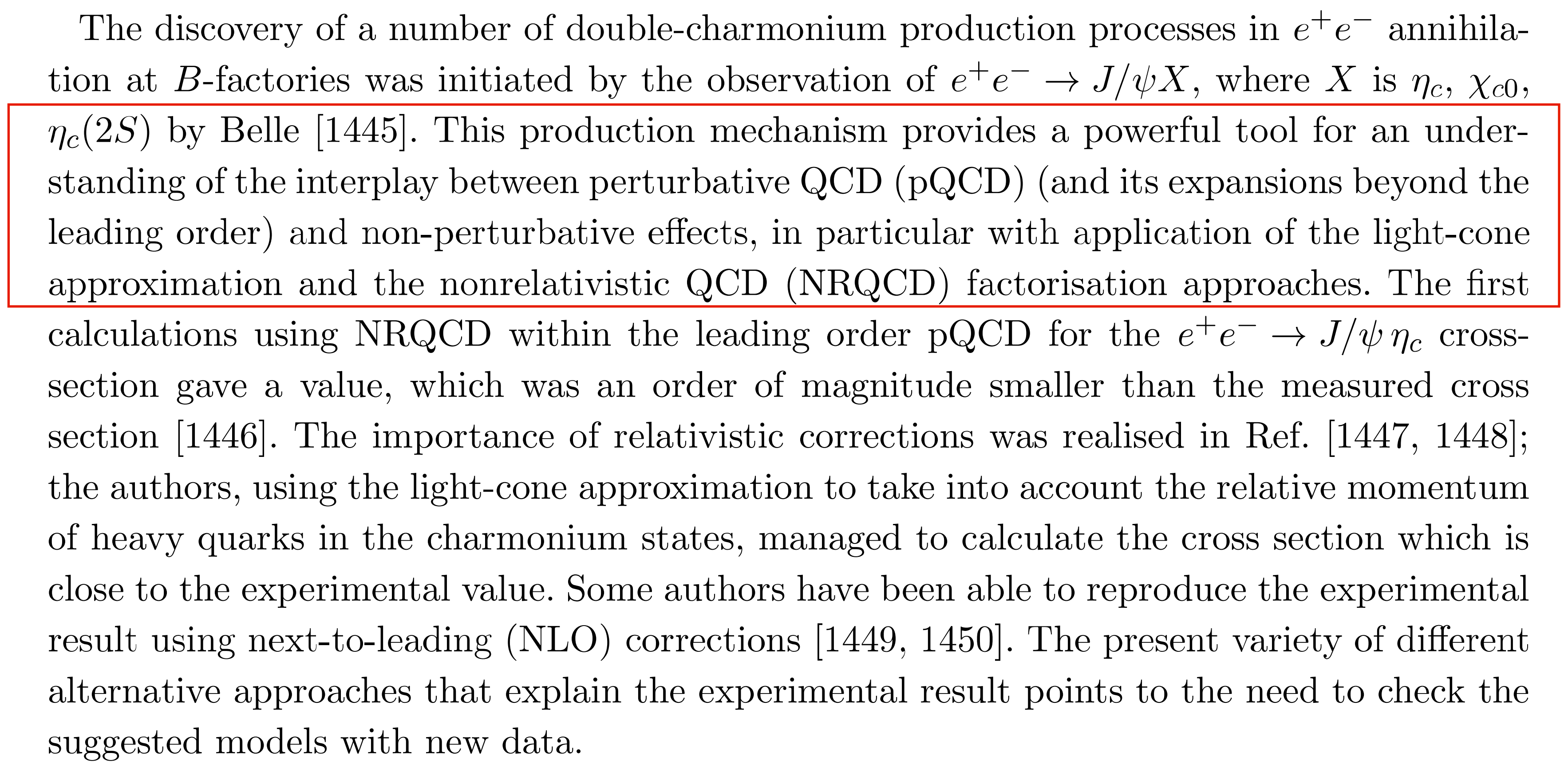
Belle, PRL 98, 082001 (2005)



➡ **Belle II**

- angular distributions, production
- probe for new states

Also, from Belle II Physics Book (arXiv:1808.10567 [hep-ex]):

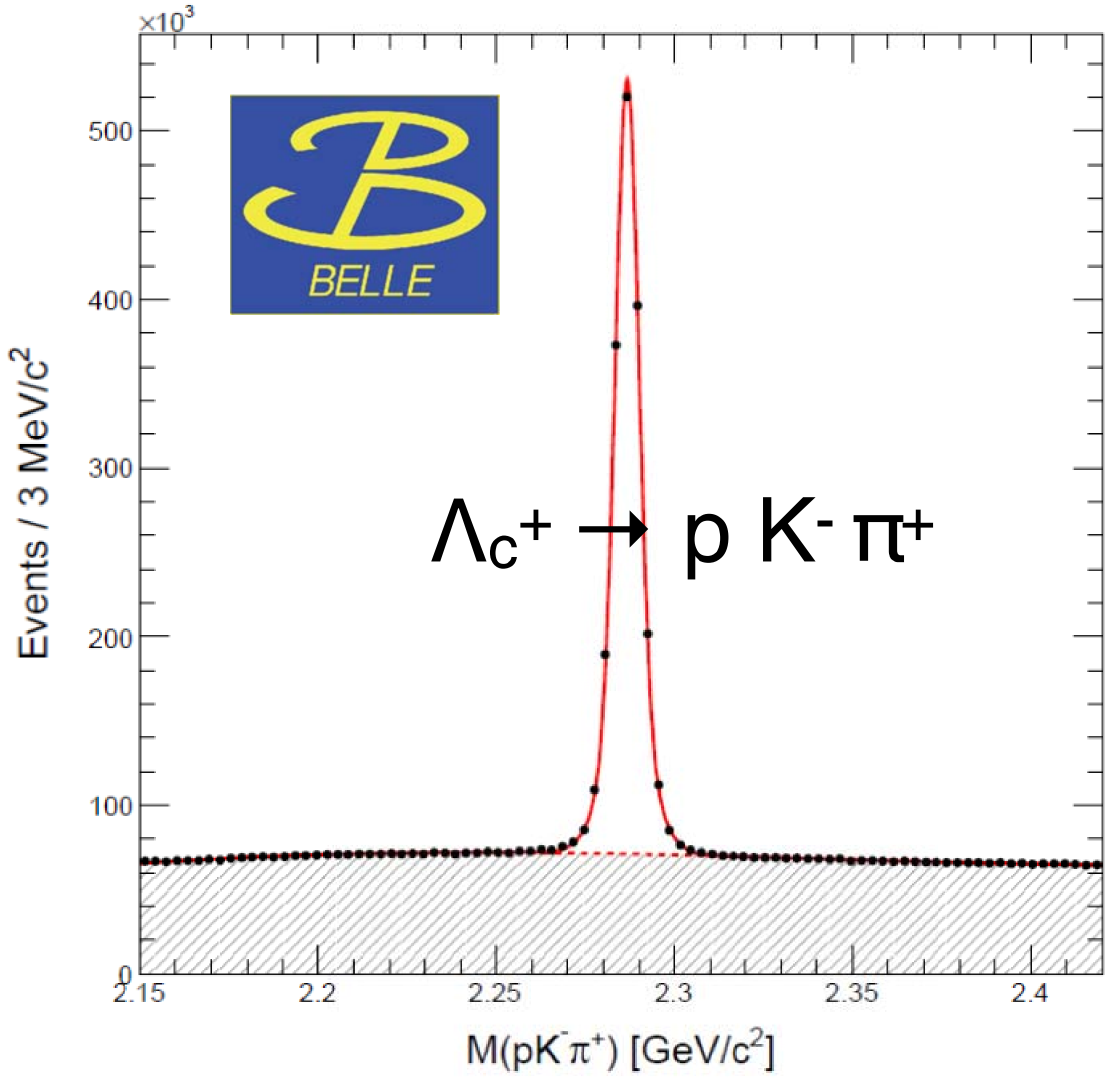


The discovery of a number of double-charmonium production processes in e^+e^- annihilation at B-factories was initiated by the observation of $e^+e^- \to J/\psi X$, where X is η_c, χ_{c0}, $\eta_c(2S)$ by Belle [1445]. This production mechanism provides a powerful tool for an understanding of the interplay between perturbative QCD (pQCD) (and its expansions beyond the leading order) and non-perturbative effects, in particular with application of the light-cone approximation and the nonrelativistic QCD (NRQCD) factorisation approaches. The first calculations using NRQCD within the leading order pQCD for the $e^+e^- \to J/\psi\,\eta_c$ cross-section gave a value, which was an order of magnitude smaller than the measured cross section [1446]. The importance of relativistic corrections was realised in Ref. [1447, 1448]; the authors, using the light-cone approximation to take into account the relative momentum of heavy quarks in the charmonium states, managed to calculate the cross section which is close to the experimental value. Some authors have been able to reproduce the experimental result using next-to-leading (NLO) corrections [1449, 1450]. The present variety of different alternative approaches that explain the experimental result points to the need to check the suggested models with new data.

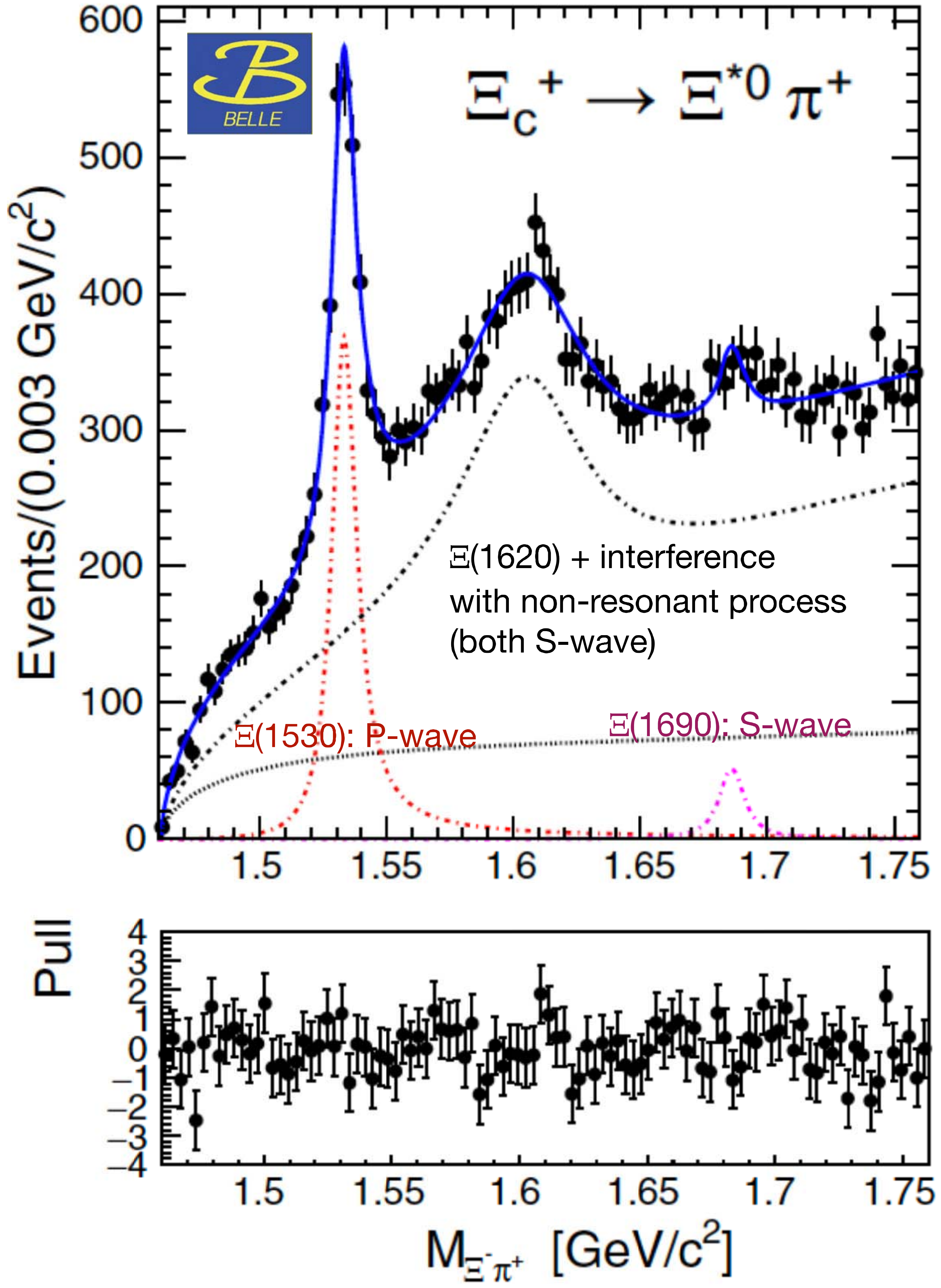
(Selected) Prospects in Baryon Spectroscopy

- Mesons get all the attention…
- Baryon spectrum is much more complicated than quarkonia but exotic candidates exist even in the first excited states
  - Notable examples include the Λ(1405) and N(1440)
- Excited spectrum not well understood
  - Many missing states
  - Multiple candidates for known states
  - Few quantum number determinations for baryons containing c or b quarks
- Belle still actively publishing

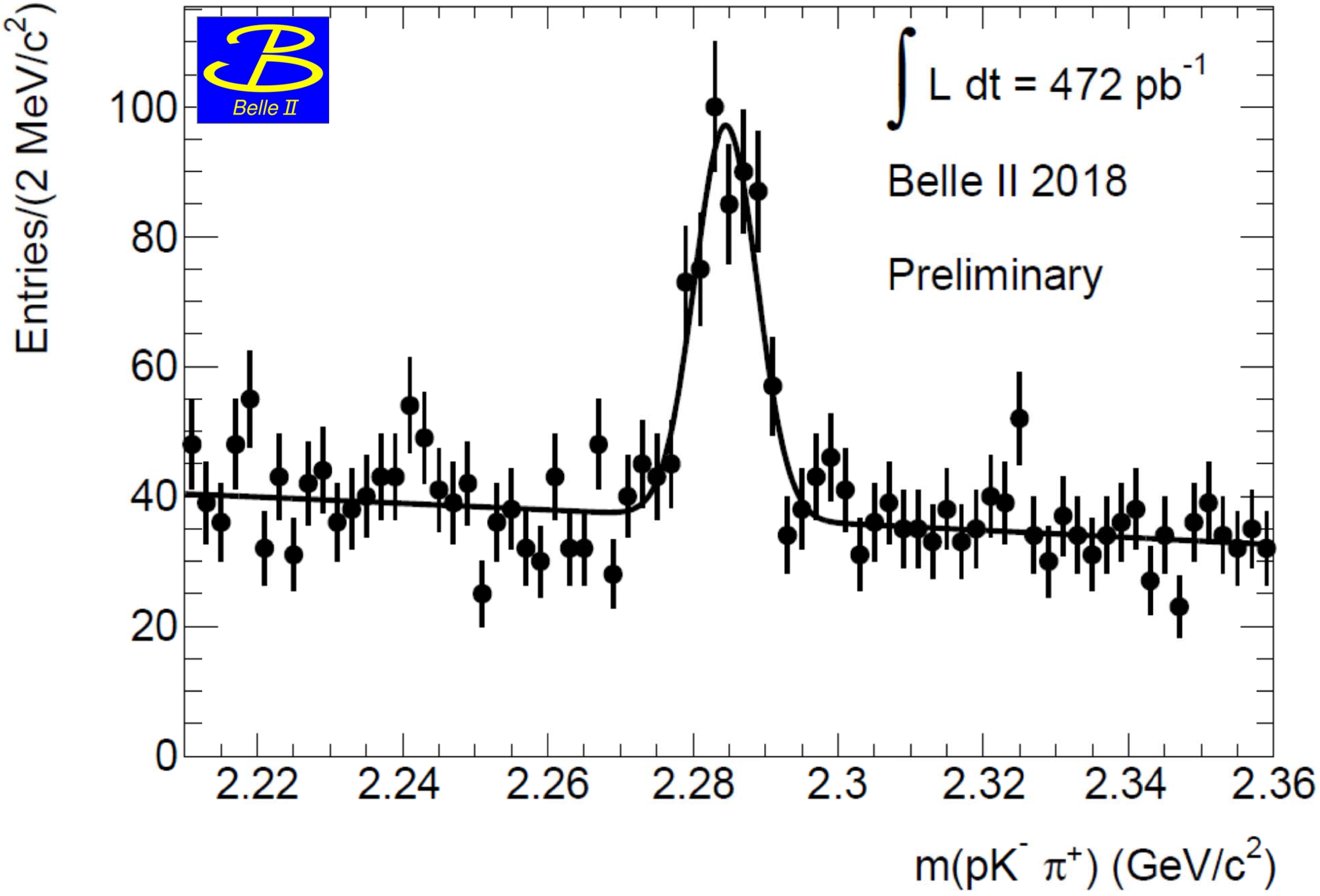
- Belle II can
  - measure quantum numbers for excited charmed baryons
  - search for excited baryons in charmed baryon decays
  - search for exotic candidate states



Belle PRL.122.072501 (2019)

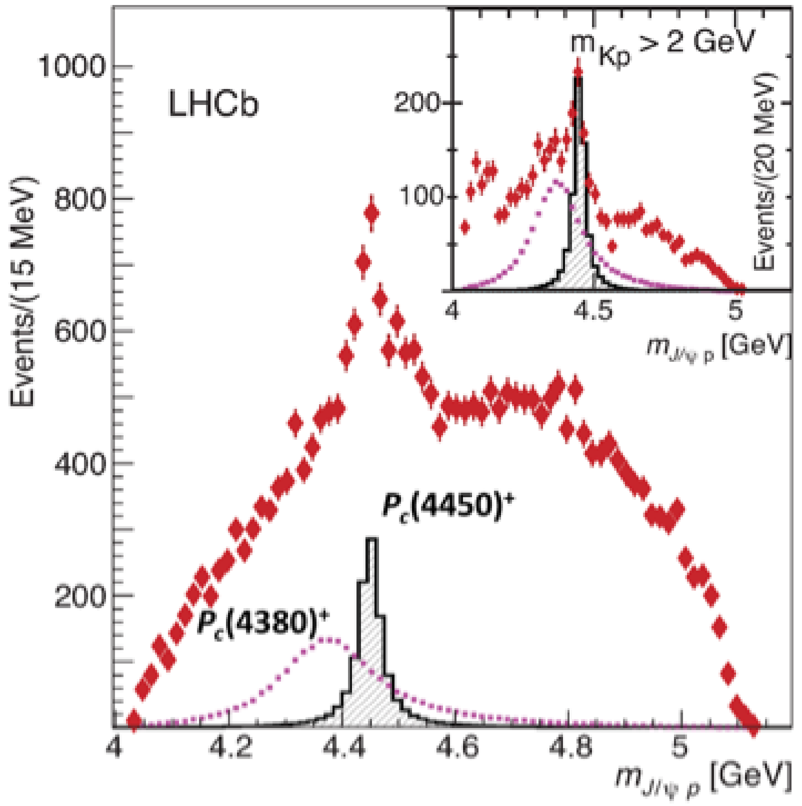


Belle II Λ_c Observation in 2018 Data



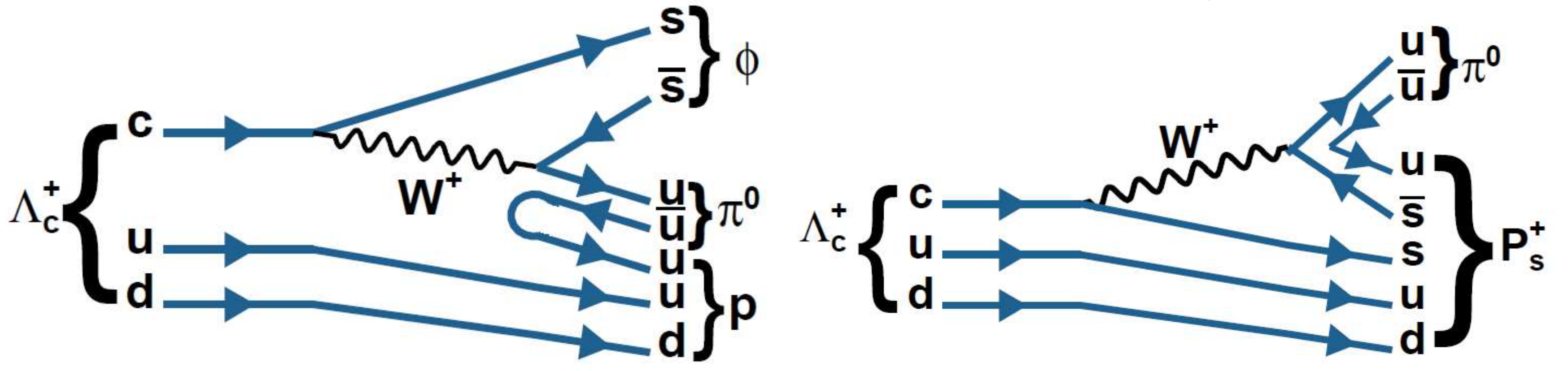
Search for the P_s^+ pentaquark (motivated by LHCb discoveries)

R. Aaij *et al.* (LHCb Collaboration), Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays, Phys. Rev. Lett. **115**, 072001 (2015).

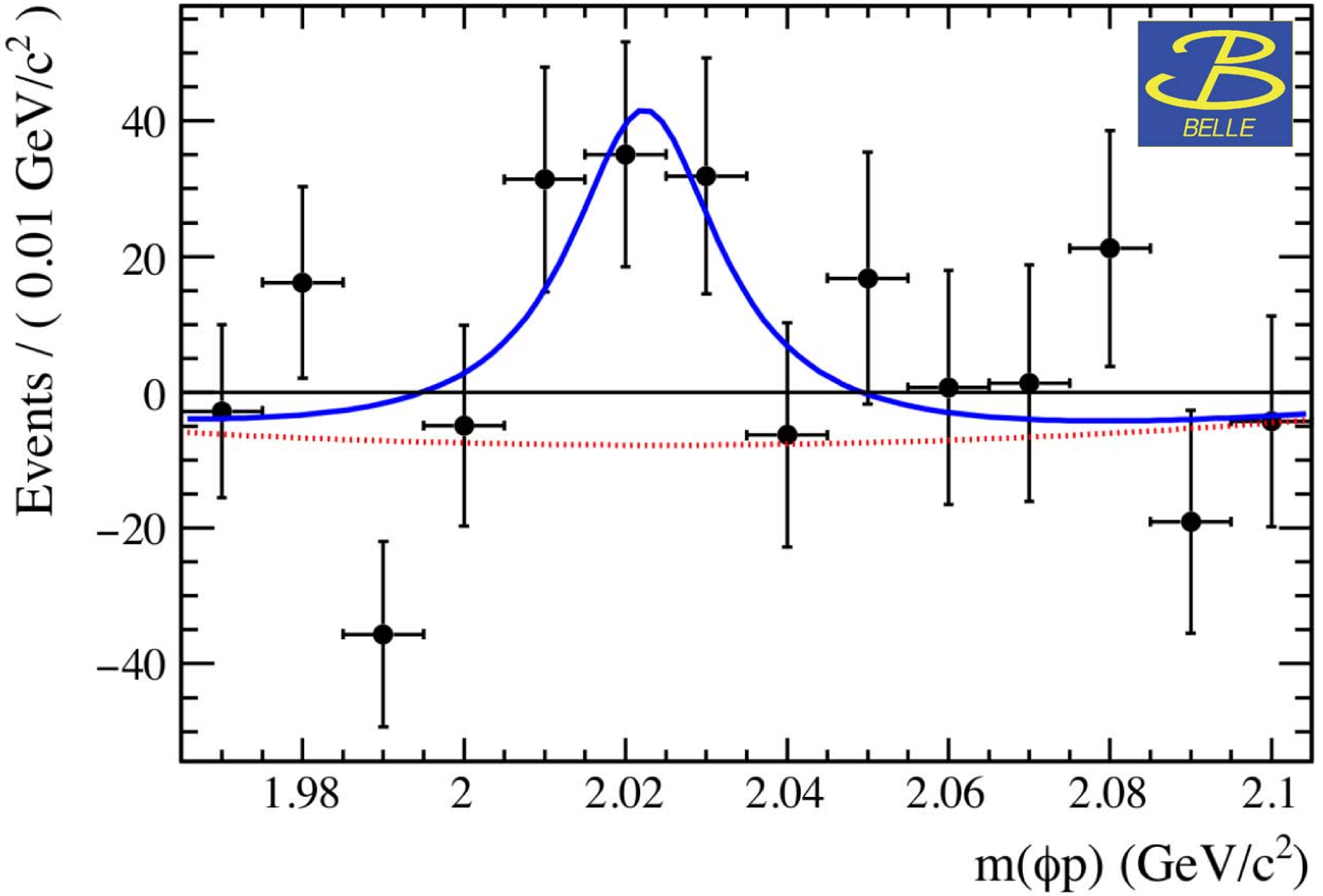


Hidden charm

Hidden strangeness



From 2D fit with three components in each bin of shown invariant mass



$$\mathcal{B}(\Lambda_c^+ \to P_s^+\pi^0) \times \mathcal{B}(P_s^+ \to \phi p) \; < \; 8.3 \times 10^{-5}$$

B. Pal, A. J. Schwartz, et al. (Belle Collaboration), Phys. Rev. **D96**, 051102 (2017).

Search for Missing Conventional Bottomonia

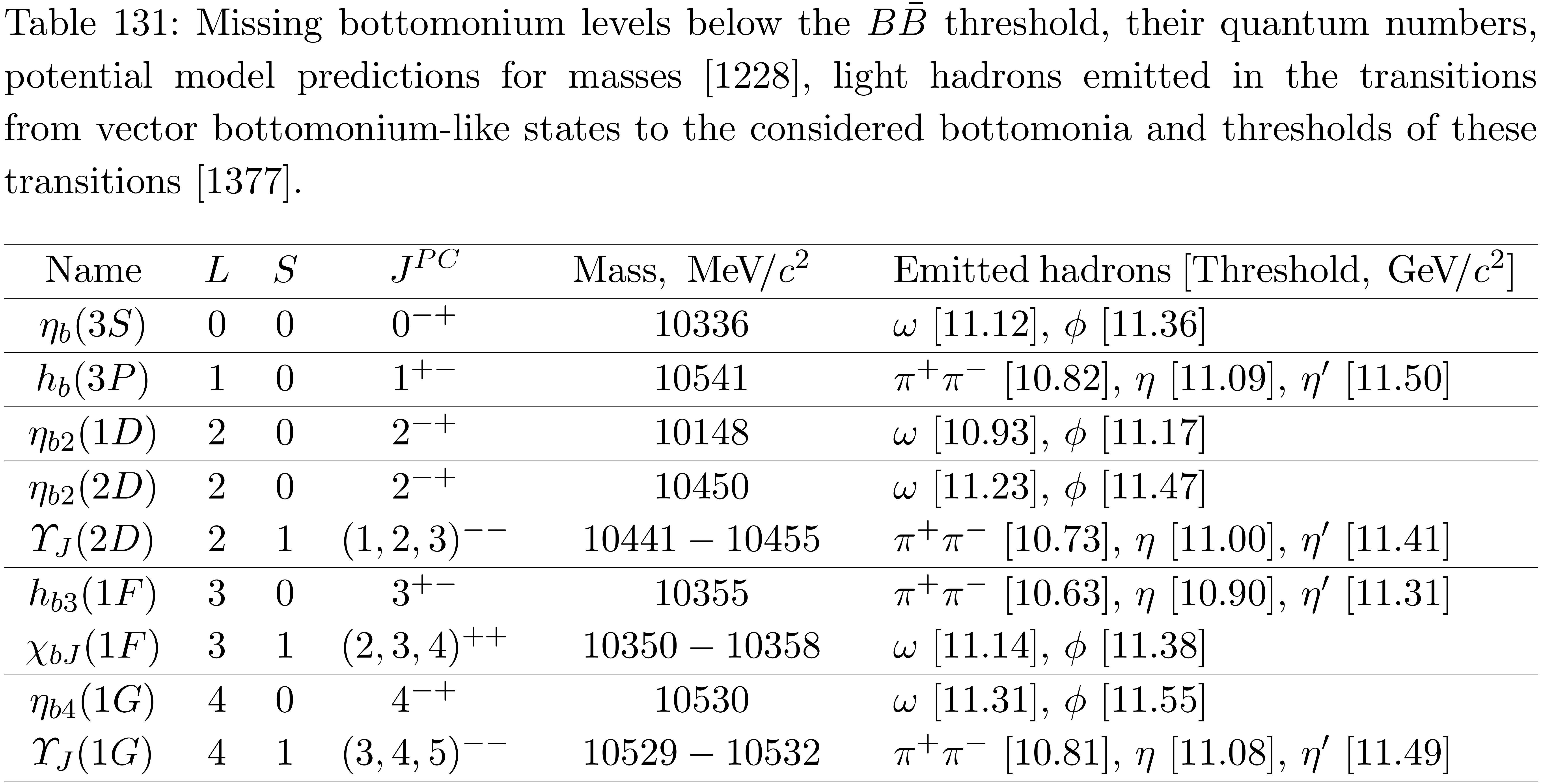


Table 131: Missing bottomonium levels below the $B\bar{B}$ threshold, their quantum numbers, potential model predictions for masses [1228], light hadrons emitted in the transitions from vector bottomonium-like states to the considered bottomonia and thresholds of these transitions [1377].

Name	L	S	J^{PC}	Mass, MeV/c^2	Emitted hadrons [Threshold, GeV/c^2]
$\eta_b(3S)$	0	0	0^{-+}	10336	ω [11.12], ϕ [11.36]
$h_b(3P)$	1	0	1^{+-}	10541	$\pi^+\pi^-$ [10.82], η [11.09], η' [11.50]
$\eta_{b2}(1D)$	2	0	2^{-+}	10148	ω [10.93], ϕ [11.17]
$\eta_{b2}(2D)$	2	0	2^{-+}	10450	ω [11.23], ϕ [11.47]
$\Upsilon_J(2D)$	2	1	$(1,2,3)^{--}$	10441 – 10455	$\pi^+\pi^-$ [10.73], η [11.00], η' [11.41]
$h_{b3}(1F)$	3	0	3^{+-}	10355	$\pi^+\pi^-$ [10.63], η [10.90], η' [11.31]
$\chi_{bJ}(1F)$	3	1	$(2,3,4)^{++}$	10350 – 10358	ω [11.14], ϕ [11.38]
$\eta_{b4}(1G)$	4	0	4^{-+}	10530	ω [11.31], ϕ [11.55]
$\Upsilon_J(1G)$	4	1	$(3,4,5)^{--}$	10529 – 10532	$\pi^+\pi^-$ [10.81], η [11.08], η' [11.49]

The Belle II Physics Book, arXiv:1808.10567 [hep-ex]

Search for Additional Molecular States at BB Thresholds

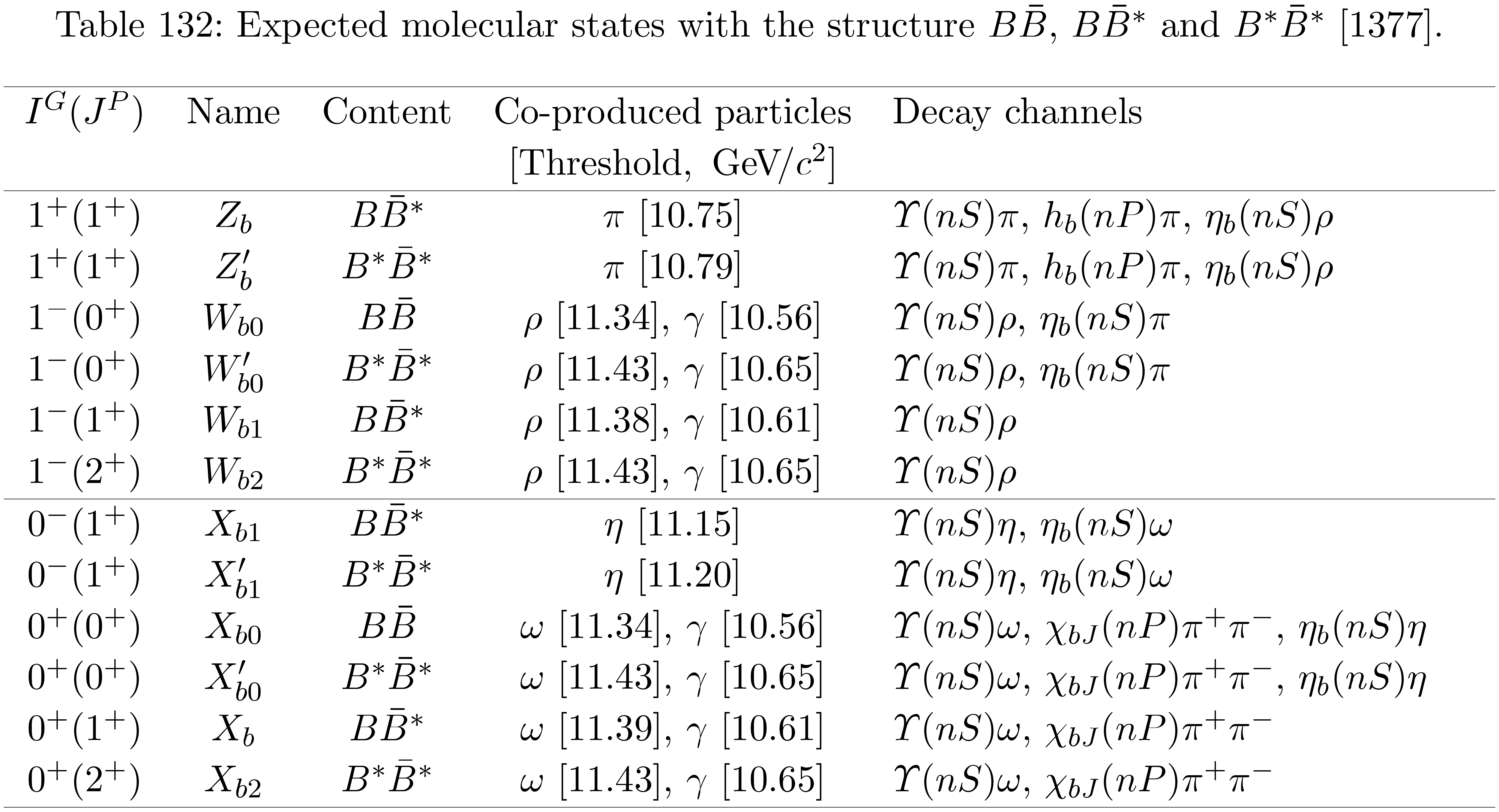
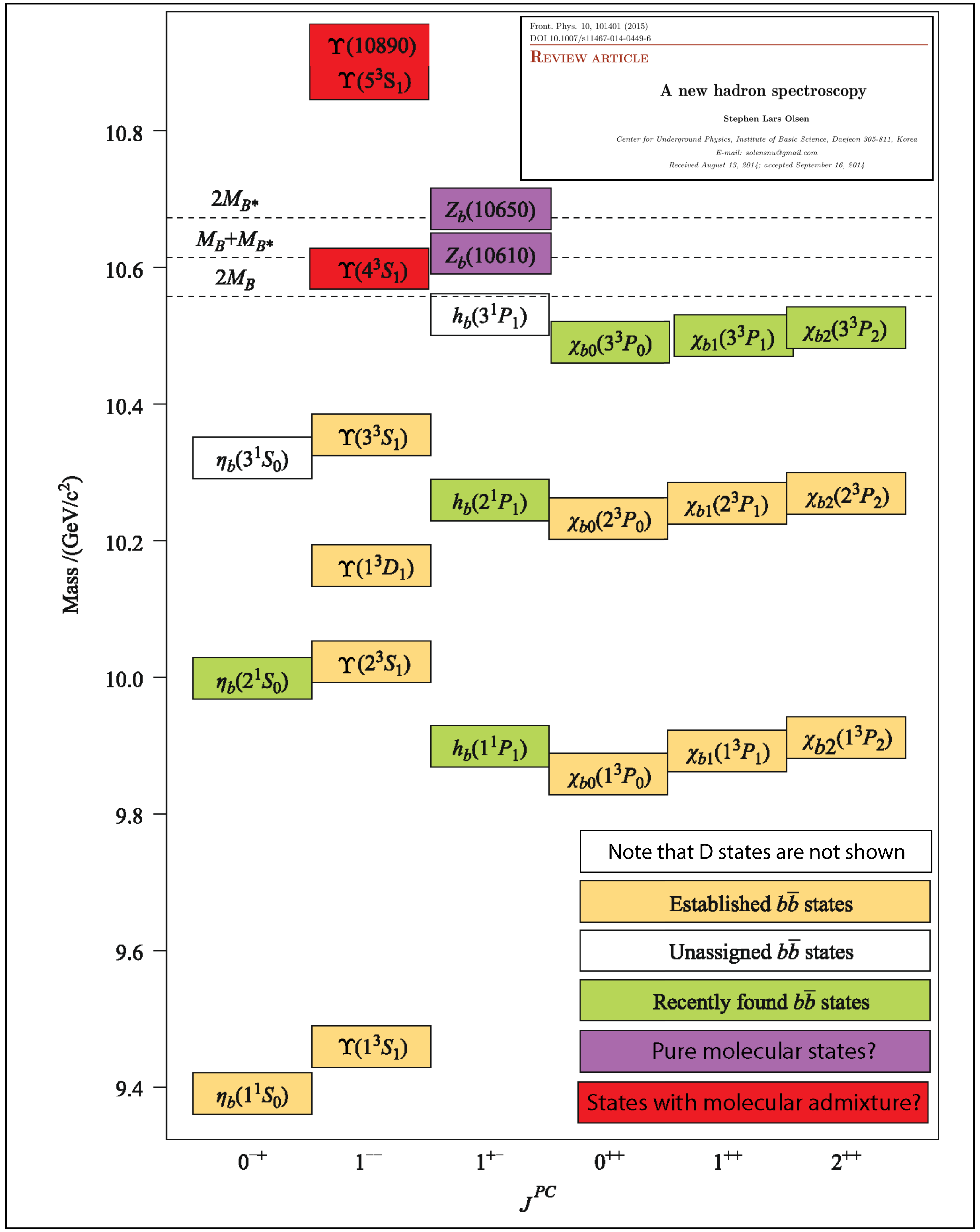


Table 132: Expected molecular states with the structure $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ [1377].

$I^G(J^P)$	Name	Content	Co-produced particles [Threshold, GeV/c^2]	Decay channels
$1^+(1^+)$	Z_b	$B\bar{B}^*$	π [10.75]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^+(1^+)$	Z'_b	$B^*\bar{B}^*$	π [10.79]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^-(0^+)$	W_{b0}	$B\bar{B}$	ρ [11.34], γ [10.56]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(0^+)$	W'_{b0}	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(1^+)$	W_{b1}	$B\bar{B}^*$	ρ [11.38], γ [10.61]	$\Upsilon(nS)\rho$
$1^-(2^+)$	W_{b2}	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$
$0^-(1^+)$	X_{b1}	$B\bar{B}^*$	η [11.15]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^-(1^+)$	X'_{b1}	$B^*\bar{B}^*$	η [11.20]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^+(0^+)$	X_{b0}	$B\bar{B}$	ω [11.34], γ [10.56]	$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$, $\eta_b(nS)\eta$
$0^+(0^+)$	X'_{b0}	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$, $\eta_b(nS)\eta$
$0^+(1^+)$	X_b	$B\bar{B}^*$	ω [11.39], γ [10.61]	$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$
$0^+(2^+)$	X_{b2}	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$

The Belle II Physics Book, arXiv:1808.10567 [hep-ex]

Additional Molecular States in Bottomonium-like Spectroscopy



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DOI 10.1007/s11467-014-0449-6

REVIEW ARTICLE

A new hadron spectroscopy

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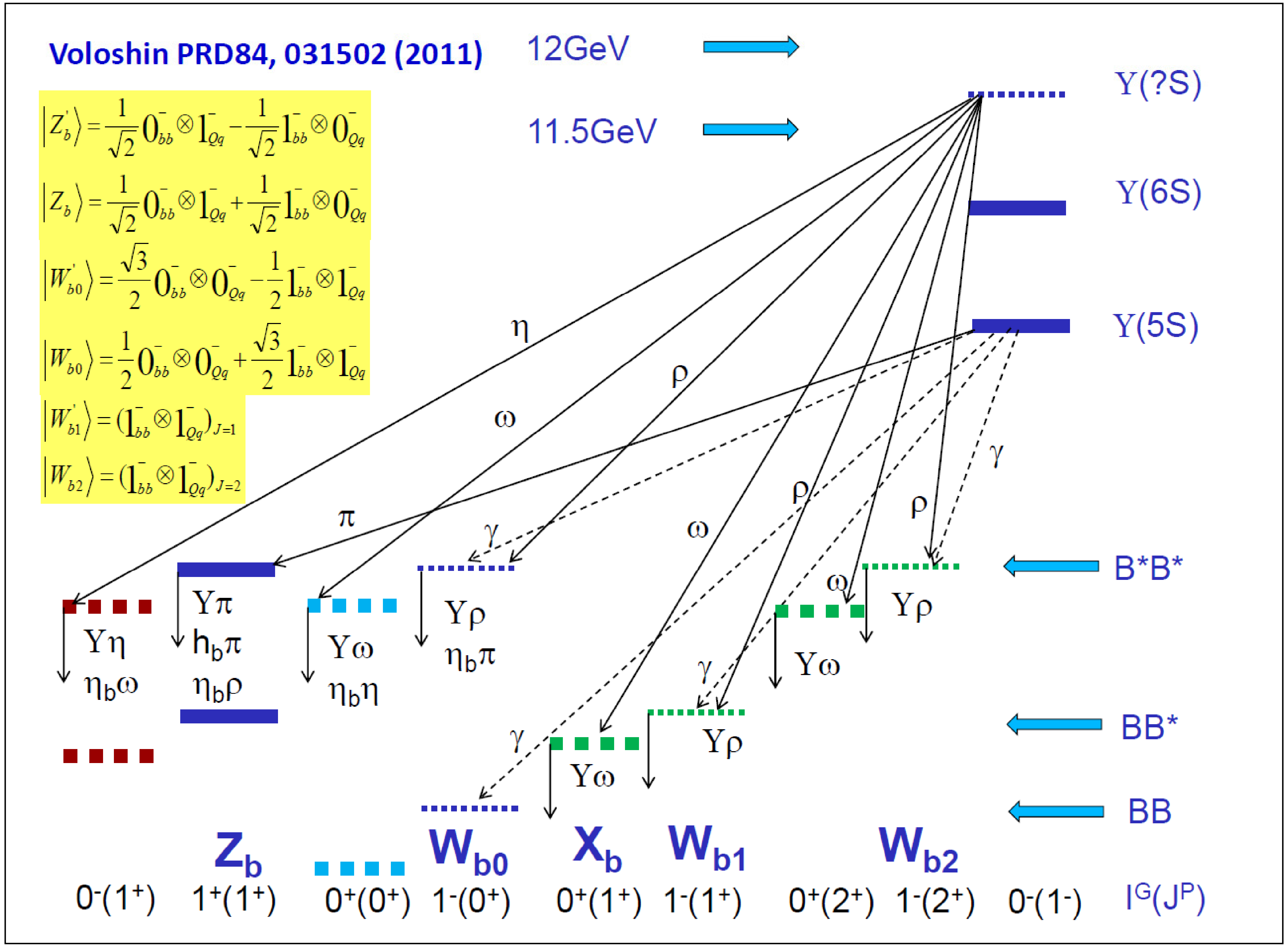


Voloshin PRD84, 031502 (2011)

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

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

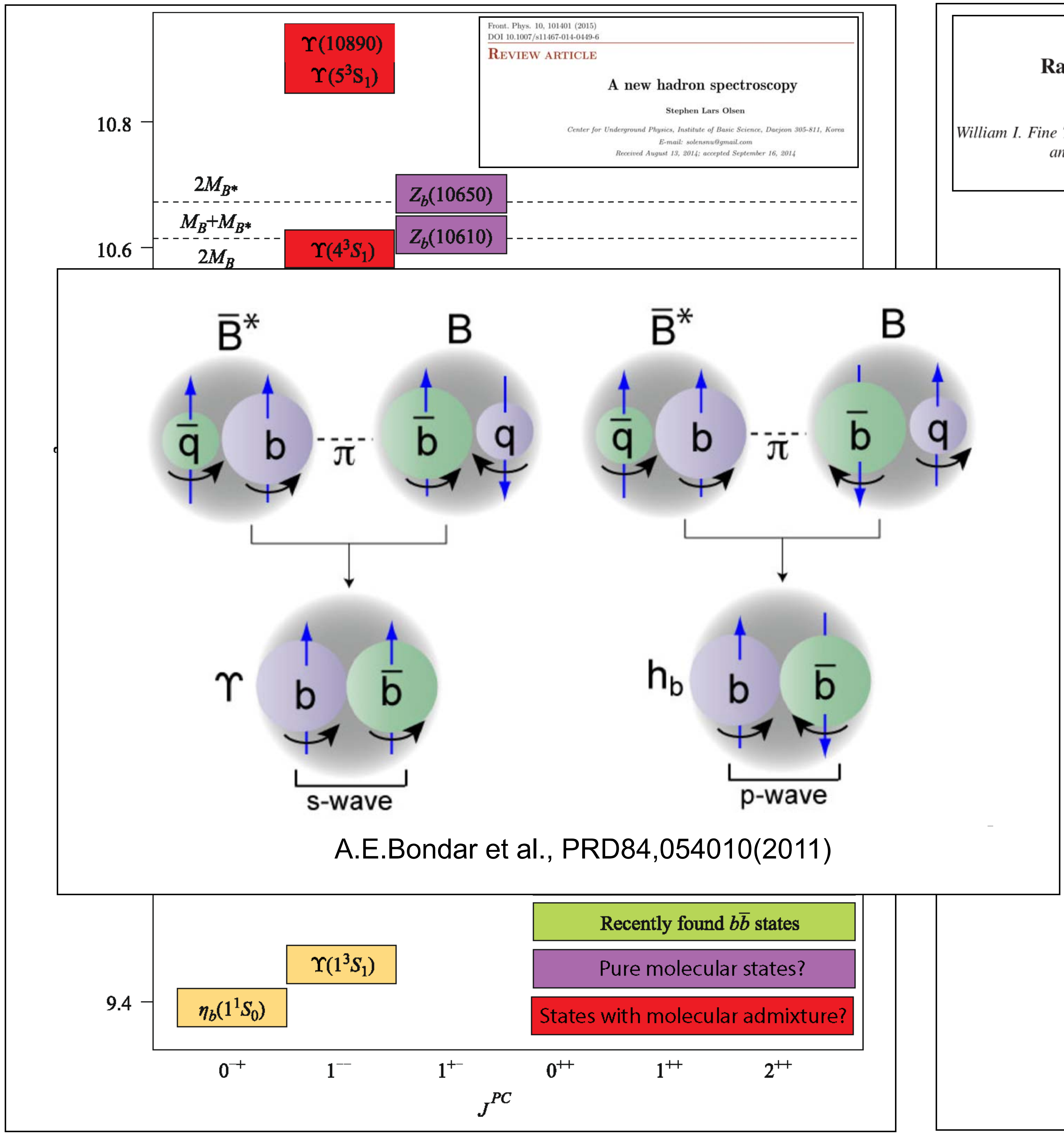
$$|W'_{b0}\rangle = \frac{\sqrt{3}}{2} 0^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}} - \frac{1}{2} 1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}}$$

$$|W_{b0}\rangle = \frac{1}{2} 0^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}} + \frac{\sqrt{3}}{2} 1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}}$$

$$|W'_{b1}\rangle = (1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}})_{J=1}$$

$$|W_{b2}\rangle = (1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}})_{J=2}$$

Additional Molecular States in Bottomonium-like Spectroscopy



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REVIEW ARTICLE

A new hadron spectroscopy

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A.E.Bondar et al., PRD84,054010(2011)

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Radiative transitions from Υ(5*S*) to molecular bottomonium

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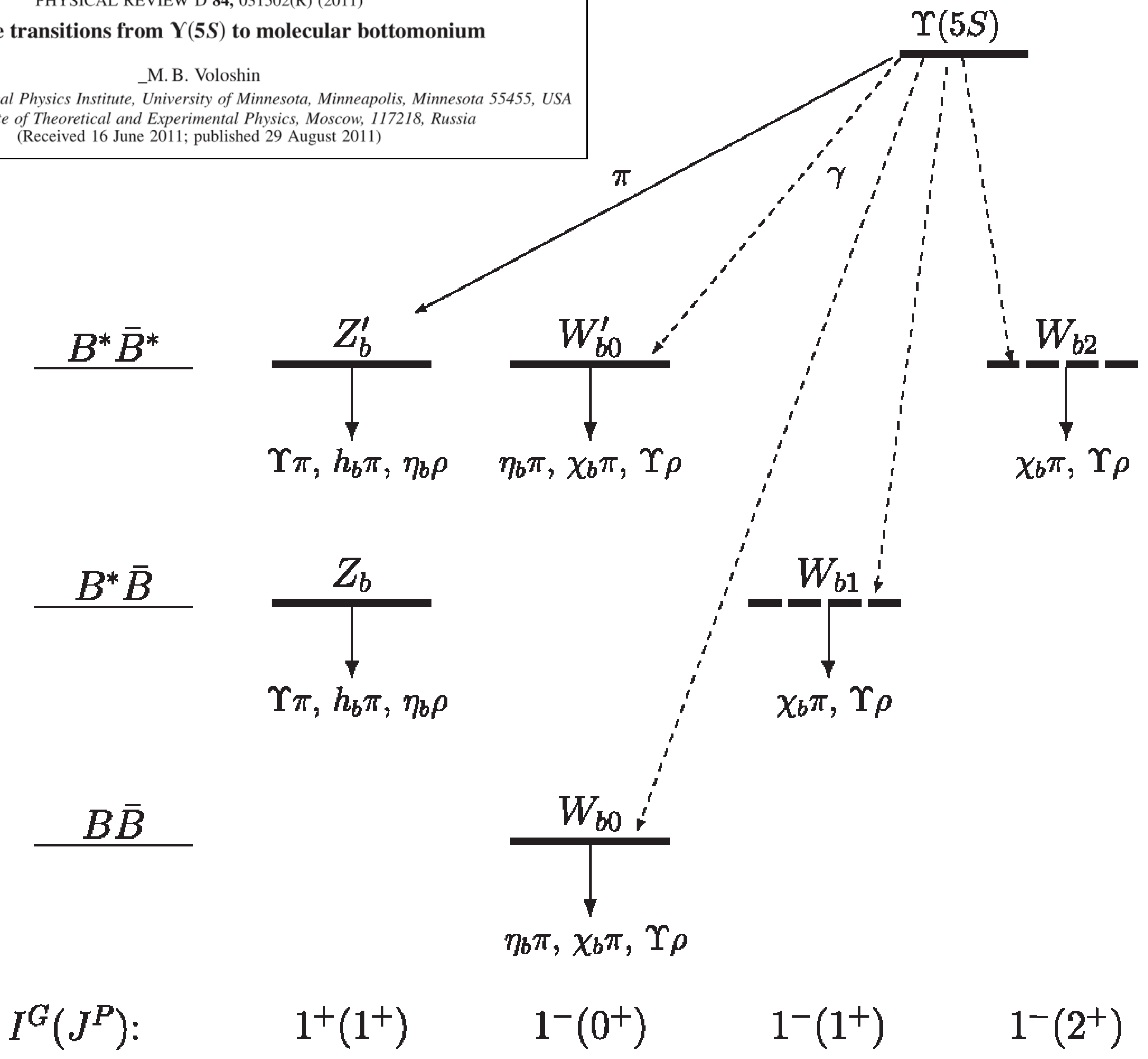


Action Items for Belle II (directly from Belle II Physics Book)

- It is important to perform an energy scan from the $B\bar{B}$ threshold up to the highest possible energy with about $10\,\mathrm{fb}^{-1}$ per point, and to measure energy dependence of exclusive open flavour ($B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$, $B^{(*)}\bar{B}^{(*)}\pi$, $B_s\bar{B}_s$ etc) and hidden flavour ($\Upsilon(nS)\pi^+\pi^-$, $h_b(nP)\pi^+\pi^-$, $\Upsilon(nS)\eta$, etc.) cross sections. This information is crucial for understanding vector bottomonium-like states. ①
- Collect data at $\Upsilon(6S)$ and at any new peak observed in the energy scan. These data will allow investigation of the decay mechanism of bottomonium-like states, search for missing conventional bottomonia, predicted bottomonium-like states and missing P-wave excitations of B_s mesons. ②

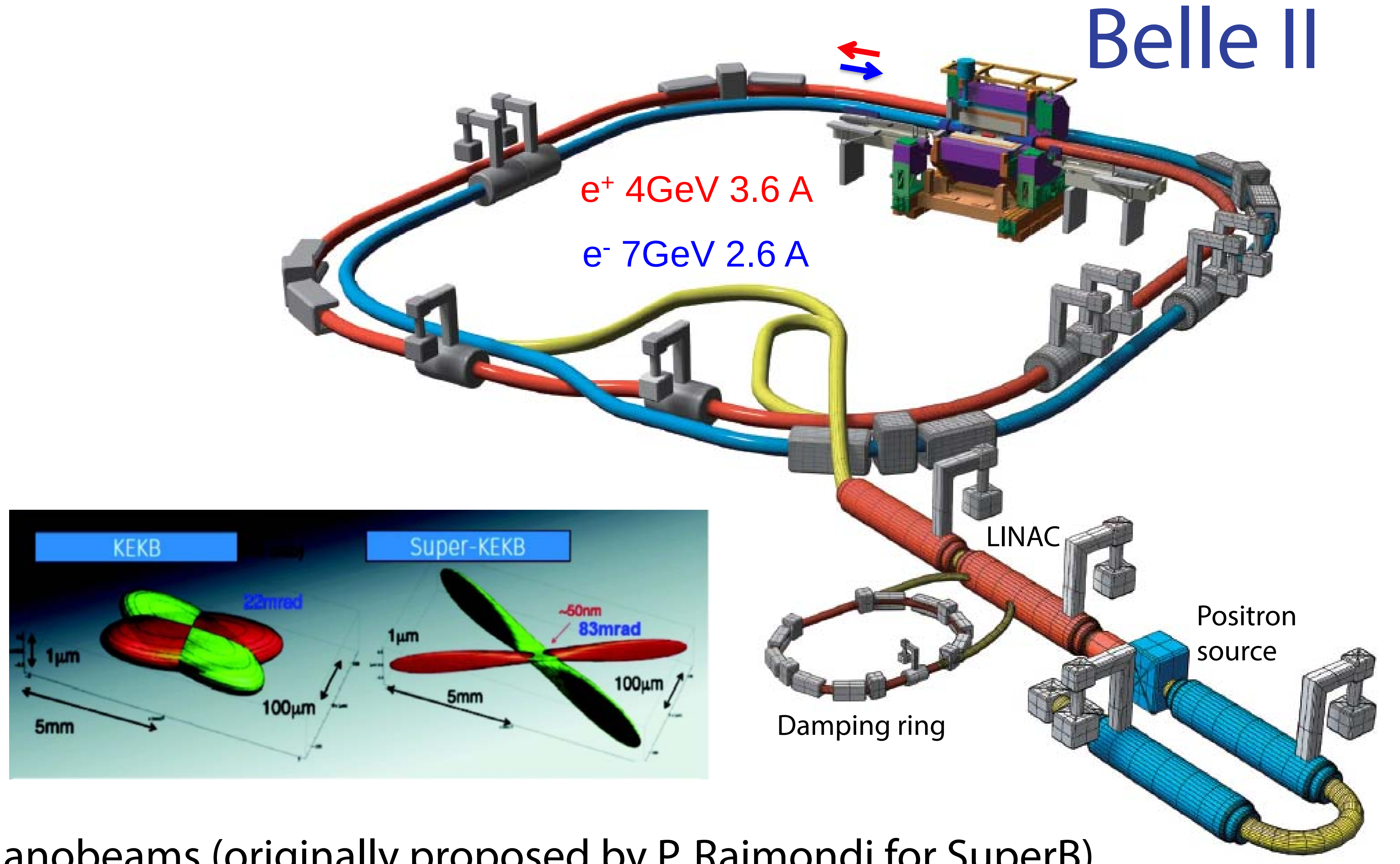
Production Thresholds for Narrow S and P wave Mesons and Baryons

Promising energy regions

Particles	Threshold, GeV/c^2
$B^{(*)}\bar{B}^{**}$	11.00 – 11.07
$B_s^{(*)}\bar{B}_s^{**}$	11.13 – 11.26
$\Lambda_b\,\bar{\Lambda}_b$	11.24
$B^{**}\bar{B}^{**}$	11.44 – 11.49
$B_s^{**}\bar{B}_s^{**}$	11.48 – 11.68
$\Lambda_b\,\bar{\Lambda}_b^{**}$	11.53 – 11.54
$\Sigma_b^{(*)}\,\bar{\Sigma}_b^{(*)}$	11.62 – 11.67
$\Lambda_b^{**}\,\bar{\Lambda}_b^{**}$	11.82 – 11.84

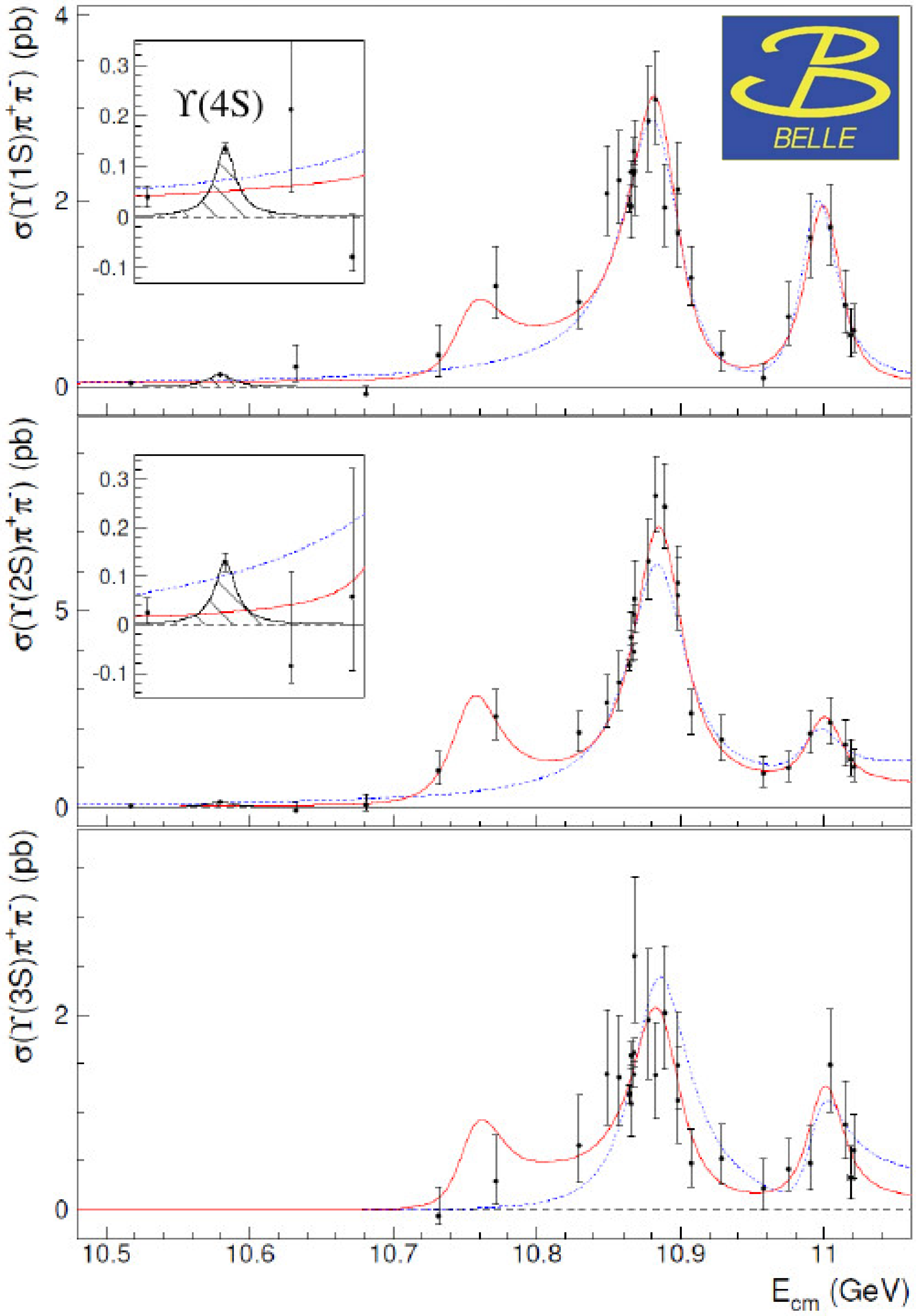
Target: L = 8×10^{35}/cm^2/s = $L_{KEKB}\times40$

Beam current: ×2 (higher RF power); upgraded components shown in color
Beam size: 1/20 (low emittance, compact and strong focusing quads)



Nanobeams (originally proposed by P. Raimondi for SuperB)
new positron target, reinforced RF cavities, redesigned lattices for LER & HER,
LER: dipoles magnets replaced by longer ones,
TiN-coated LER beampipe with antechambers,
new superconducting focusing quadrupole magnets near IP

Observation of a New Structure in Energy Scan Between 10.52 and 11.02 GeV



arXiv:1905.05521v1 [hep-ex] 14 May 2019

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

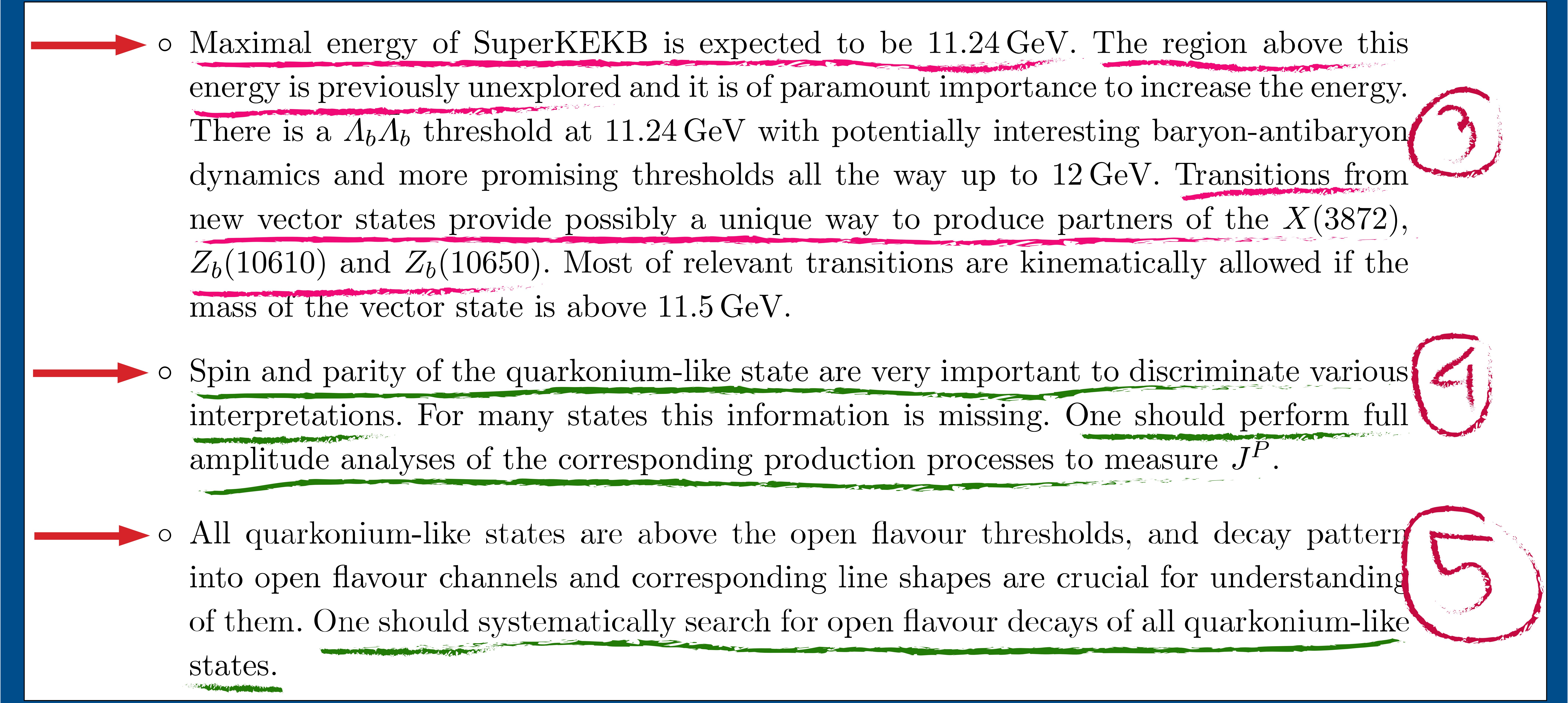
The new structure could have a resonant origin and correspond to a signal for the not yet observed $\Upsilon(3D)$ state provided $S-D$ mixing is enhanced [8], or an exotic state, e.g. a compact tetraquark [9] or hadrobottomonium [10]. It could also be a non-resonant effect due to some complicated rescattering. Information on the cross section energy dependence for more channels, with both hidden and open b flavor, is needed to clarify the nature of the new structure.

Can be done:

1. A study with higher statistics will be possible.
2. Study of $\Upsilon(5S)$ and $\Upsilon(6S)$ lineshapes in other channels

Belle II

Action Items for Belle II (directly from Belle II Physics Book)

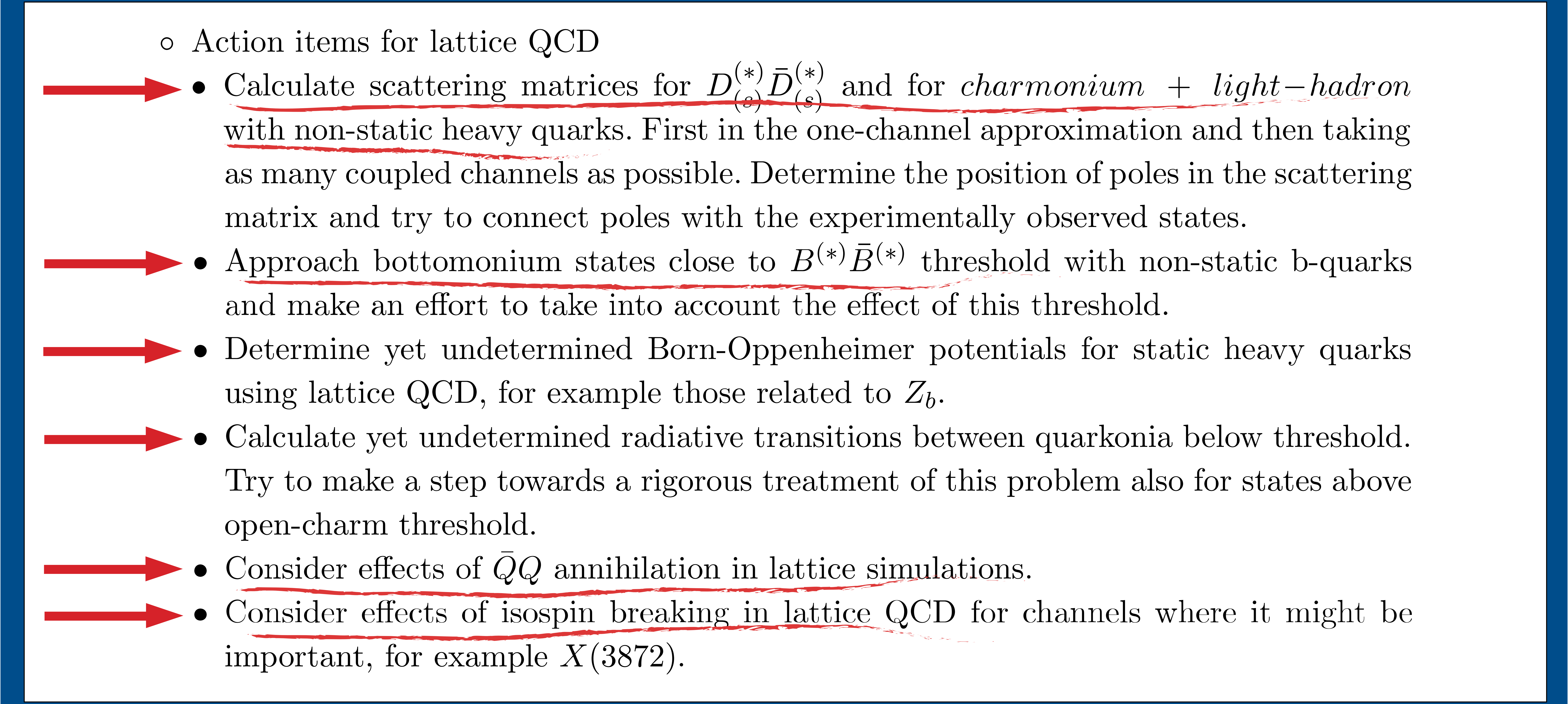


- Maximal energy of SuperKEKB is expected to be 11.24 GeV. The region above this energy is previously unexplored and it is of paramount importance to increase the energy. There is a $\Lambda_b \Lambda_b$ threshold at 11.24 GeV with potentially interesting baryon-antibaryon dynamics and more promising thresholds all the way up to 12 GeV. Transitions from new vector states provide possibly a unique way to produce partners of the $X(3872)$, $Z_b(10610)$ and $Z_b(10650)$. Most of relevant transitions are kinematically allowed if the mass of the vector state is above 11.5 GeV. ③
- Spin and parity of the quarkonium-like state are very important to discriminate various interpretations. For many states this information is missing. One should perform full amplitude analyses of the corresponding production processes to measure J^P. ④
- All quarkonium-like states are above the open flavour thresholds, and decay pattern into open flavour channels and corresponding line shapes are crucial for understanding of them. One should systematically search for open flavour decays of all quarkonium-like states. ⑤

Action Items for theory (directly from Belle II Physics Book)

- Action items for phenomenological approaches
  - Within all approaches to QCD exotics predictions should be provided for states with quantum numbers not yet observed. This could be done, *e.g.*, employing the heavy quark spin symmetry. At Belle those could be searched for in the decay chains of heavy vector states.
  - For all predicted states quantitative statements about partial decay widths or at least branching ratios should be provided, not only allowing one to identify potential discovery modes but also as stringent test of the assumed dynamics.
  - Predictions also for the bottom sector are necessary again for various quantum numbers.
  - The mixing of exotic states with regular quarkonia needs to be investigated.

Action Items for theory (directly from Belle II Physics Book)



- Action items for lattice QCD
  - Calculate scattering matrices for $D^{(*)}_{(s)}\bar{D}^{(*)}_{(s)}$ and for $charmonium + light{-}hadron$ with non-static heavy quarks. First in the one-channel approximation and then taking as many coupled channels as possible. Determine the position of poles in the scattering matrix and try to connect poles with the experimentally observed states.
  - Approach bottomonium states close to $B^{(*)}\bar{B}^{(*)}$ threshold with non-static b-quarks and make an effort to take into account the effect of this threshold.
  - Determine yet undetermined Born-Oppenheimer potentials for static heavy quarks using lattice QCD, for example those related to Z_b.
  - Calculate yet undetermined radiative transitions between quarkonia below threshold. Try to make a step towards a rigorous treatment of this problem also for states above open-charm threshold.
  - Consider effects of $\bar{Q}Q$ annihilation in lattice simulations.
  - Consider effects of isospin breaking in lattice QCD for channels where it might be important, for example $X(3872)$.

Conclusions / Summary

Significant increase in luminosity at Belle II will allow us to do an even better job than with Belle

There are many puzzles to solve, many states to search for and analyze, a large body of work to do

The Belle II Physics Book (arXiv:1808.10567) provides a roadmap of important studies to carry out

Future high precision measurements require close collaborations of experimentalists and theorists

Distinguishing between the models is cool, but our goals also include to provide data which could be used to develop a unified theoretical approach to long-distance strong-interaction physics →

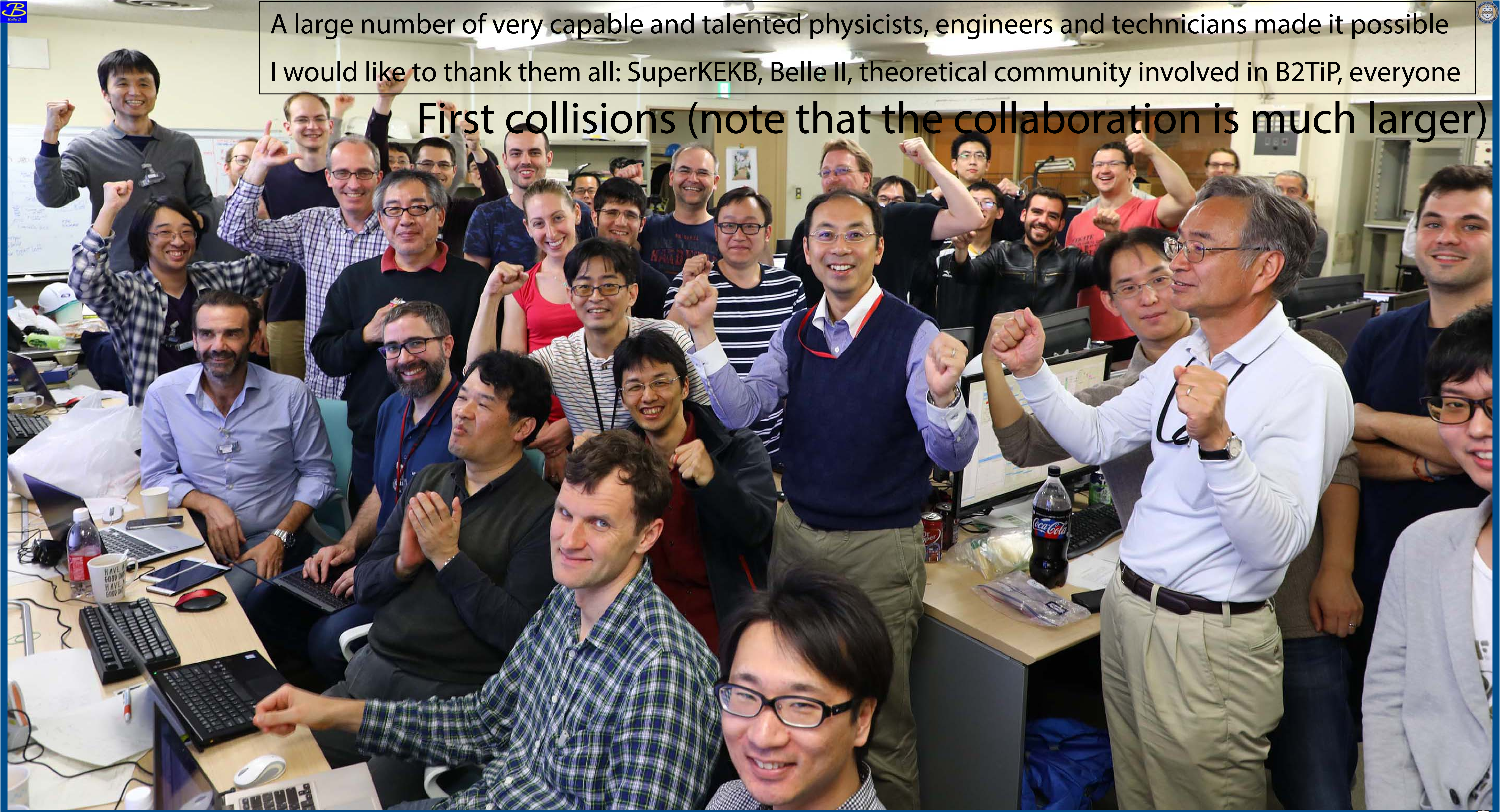
This would facilitate theoretical progress in extracting NP from processes where QCD is involved

(please note that I omitted (without prejudice) some of the topics (e.g., Υ(3S) physics) from my slides)

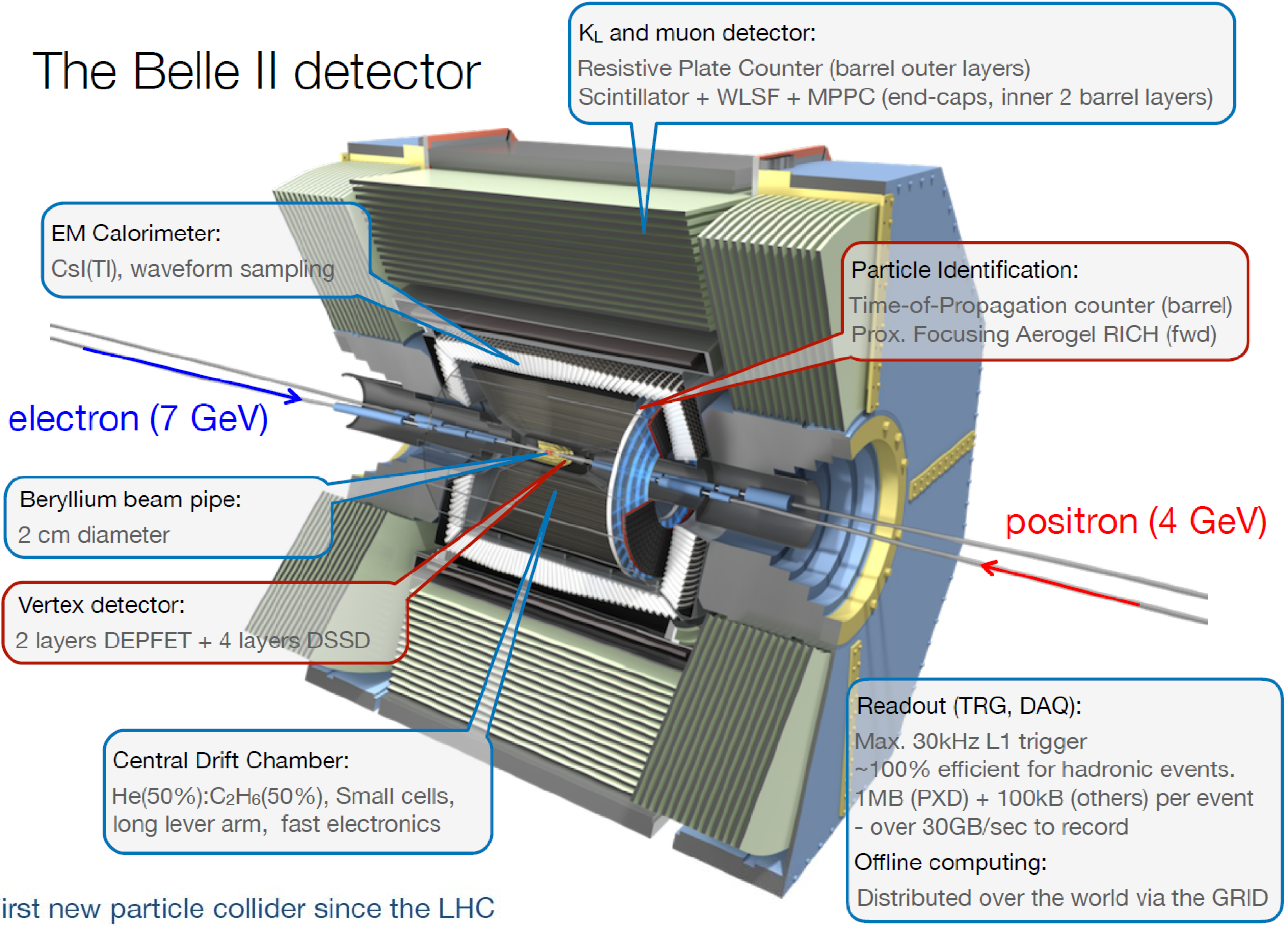
A large number of very capable and talented physicists, engineers and technicians made it possible

I would like to thank them all: SuperKEKB, Belle II, theoretical community involved in B2TiP, everyone

First collisions (note that the collaboration is much larger)



The Belle II detector



K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling

Particle Identification:
Time-of-Propagation counter (barrel)
Prox. Focusing Aerogel RICH (fwd)

electron (7 GeV)

positron (4 GeV)

Beryllium beam pipe:
2 cm diameter

Vertex detector:
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber:
He(50%):C_2H_6(50%), Small cells,
long lever arm, fast electronics

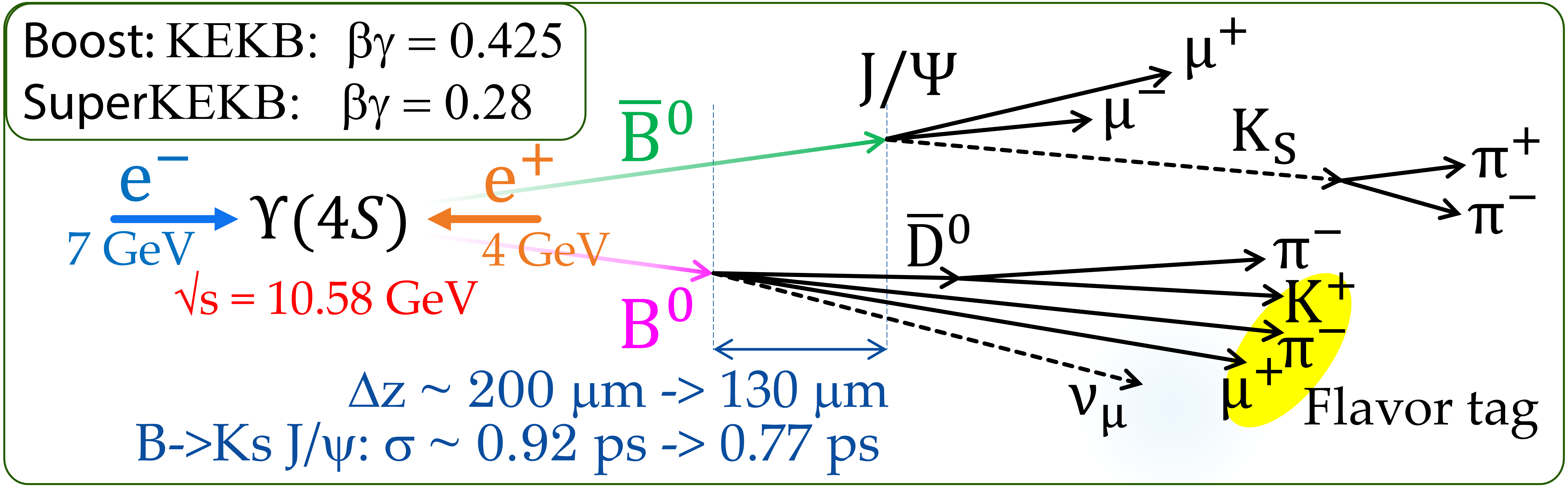
Readout (TRG, DAQ):
Max. 30kHz L1 trigger
~100% efficient for hadronic events.
1MB (PXD) + 100kB (others) per event
- over 30GB/sec to record

Offline computing:
Distributed over the world via the GRID

First new particle collider since the LHC
(intensity rather than energy frontier; e^+e^- rather than pp)

arXiv:1011.0352 [physics.ins-det]

Boost: KEKB: $\beta\gamma = 0.425$
SuperKEKB: $\beta\gamma = 0.28$



$\Delta z \sim 200\ \mu m$ -> $130\ \mu m$
B->Ks J/ψ: $\sigma \sim 0.92$ ps -> 0.77 ps