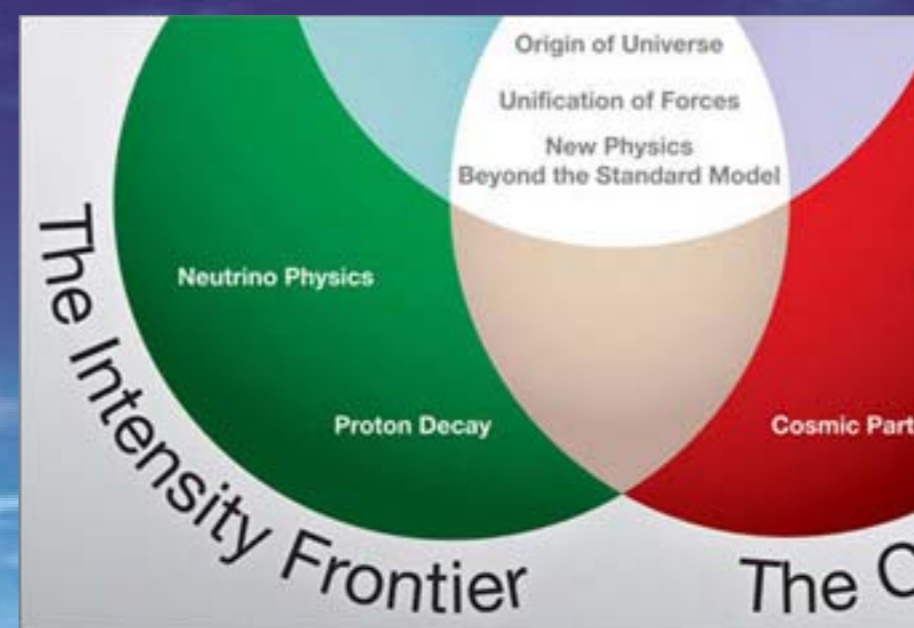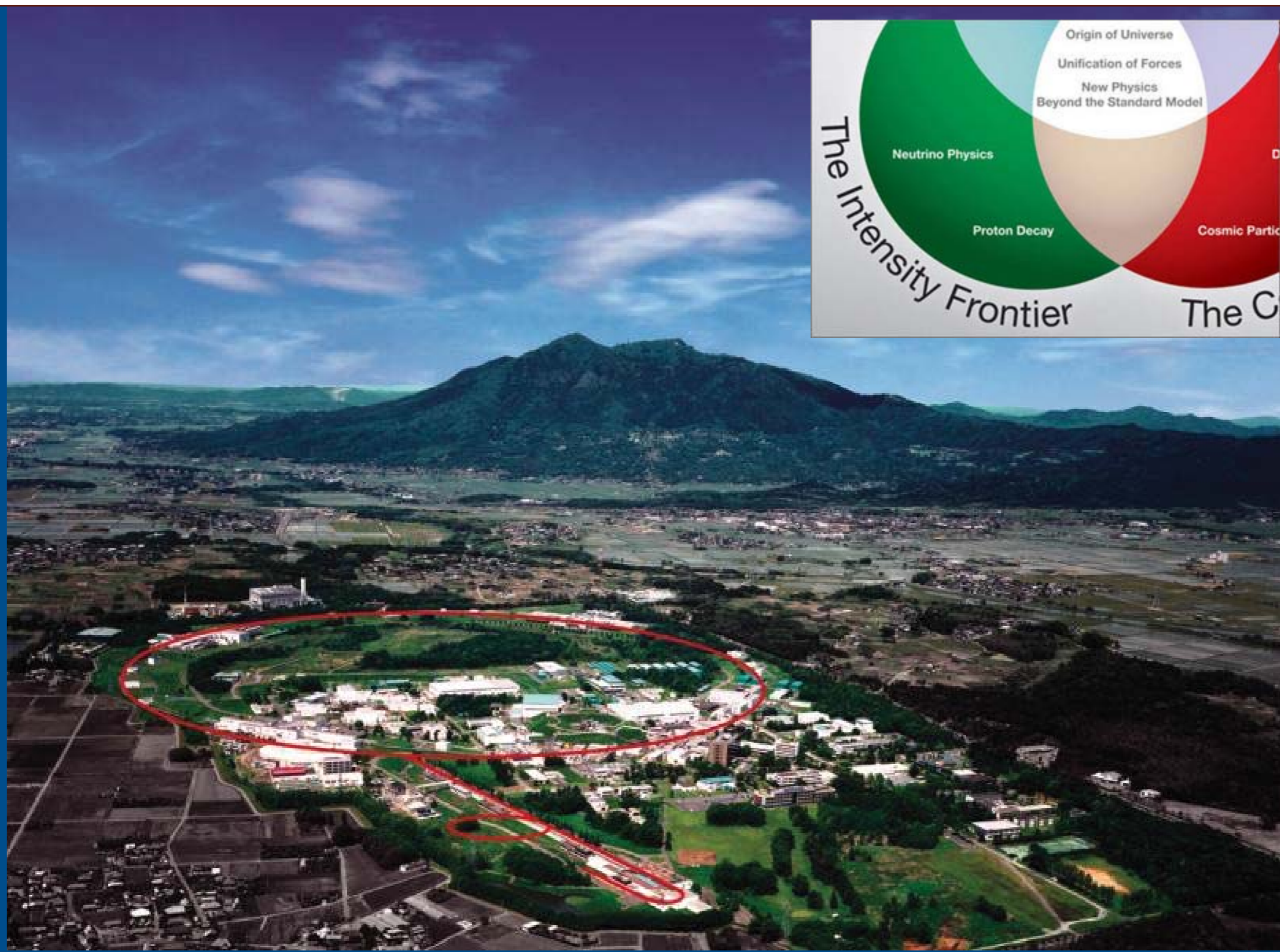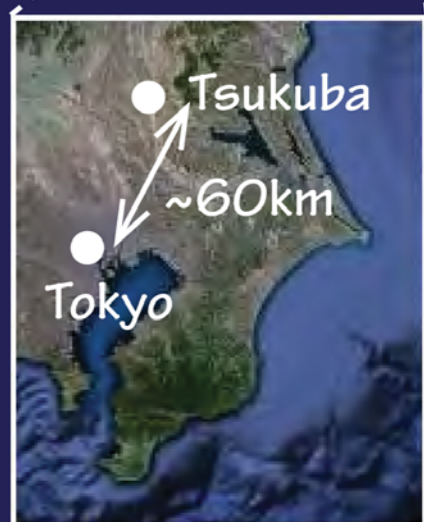# Exotic and Conventional Quarkonium Physics Prospects at Belle II

Vladimir Savinov (University of Pittsburgh), on behalf of Belle II Collaboration
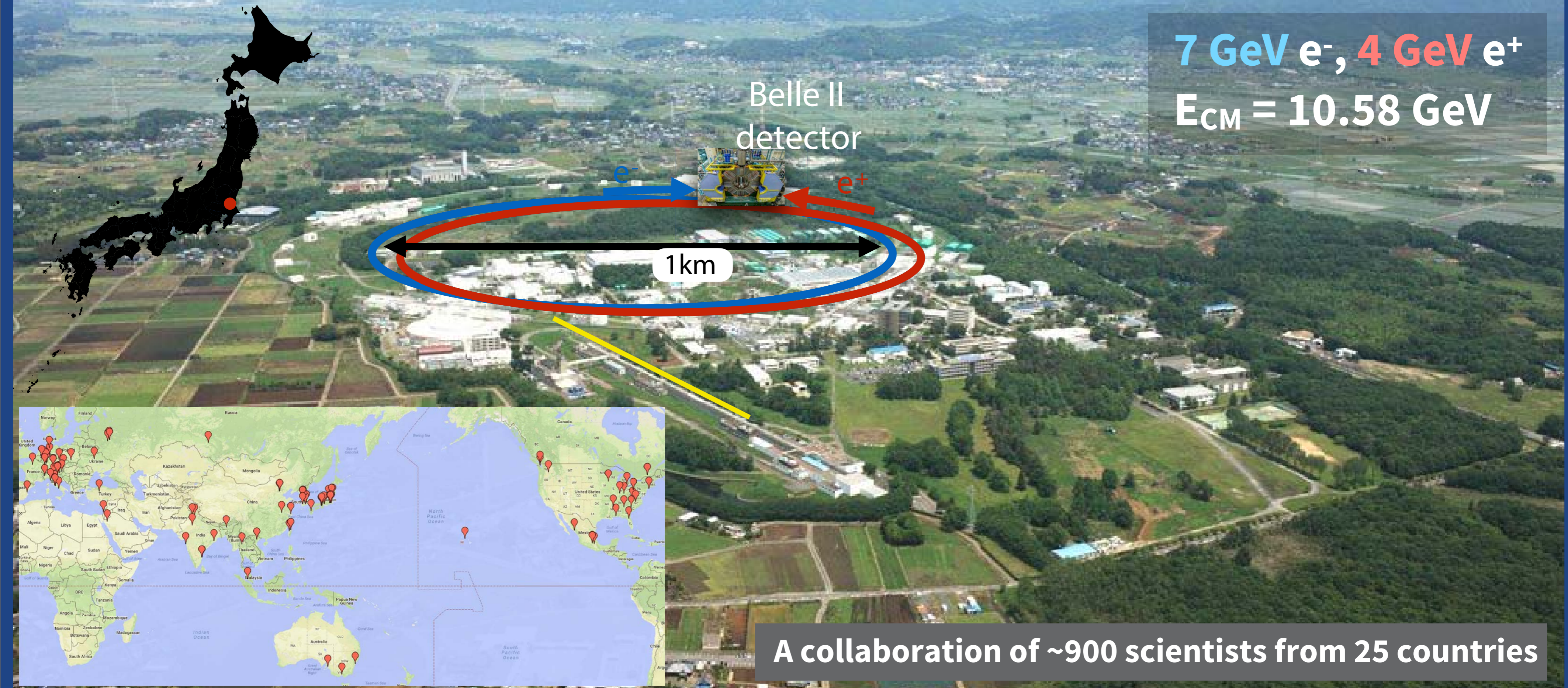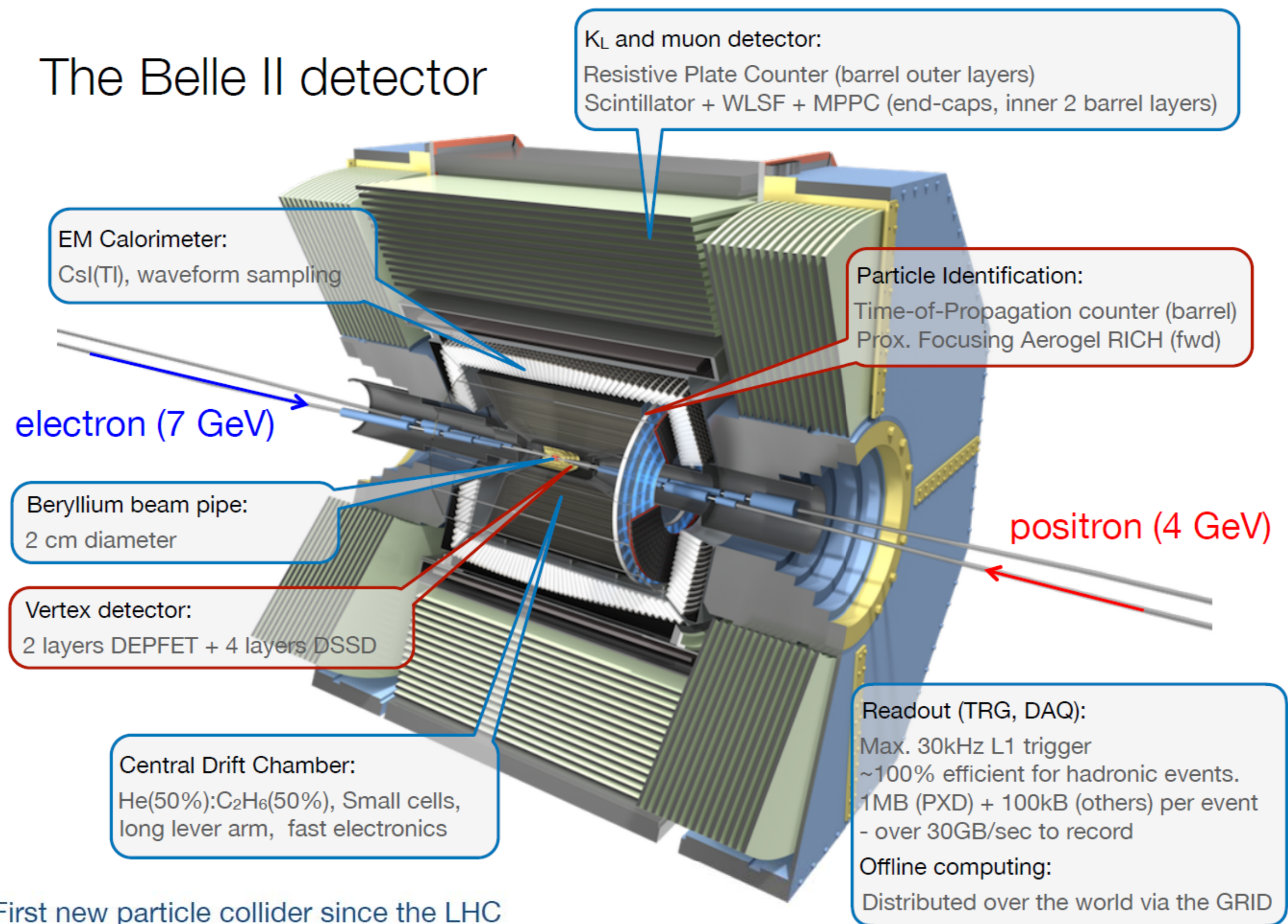
Belle II @ Super-KEKB

Intensity frontier B-factory experiment, successor to Belle @ KEKB (1999-2010)

7 GeV e⁻, 4 GeV e⁺

E_{CM} = 10.58 GeV

Belle II detector

e⁻

e⁺

1km

A collaboration of ~900 scientists from 25 countries

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

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

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

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

arXiv:1011.0352 [physics.ins-det]
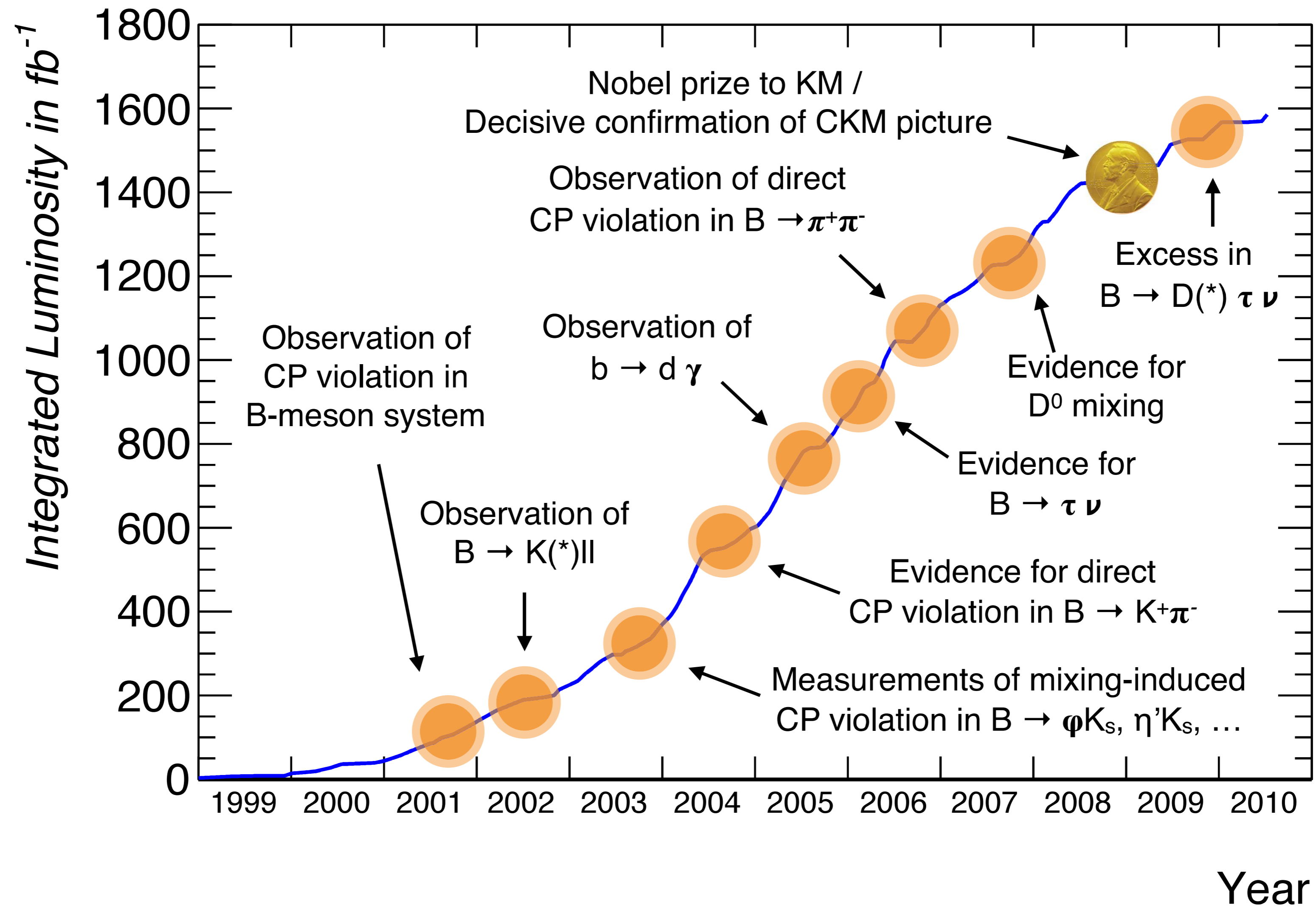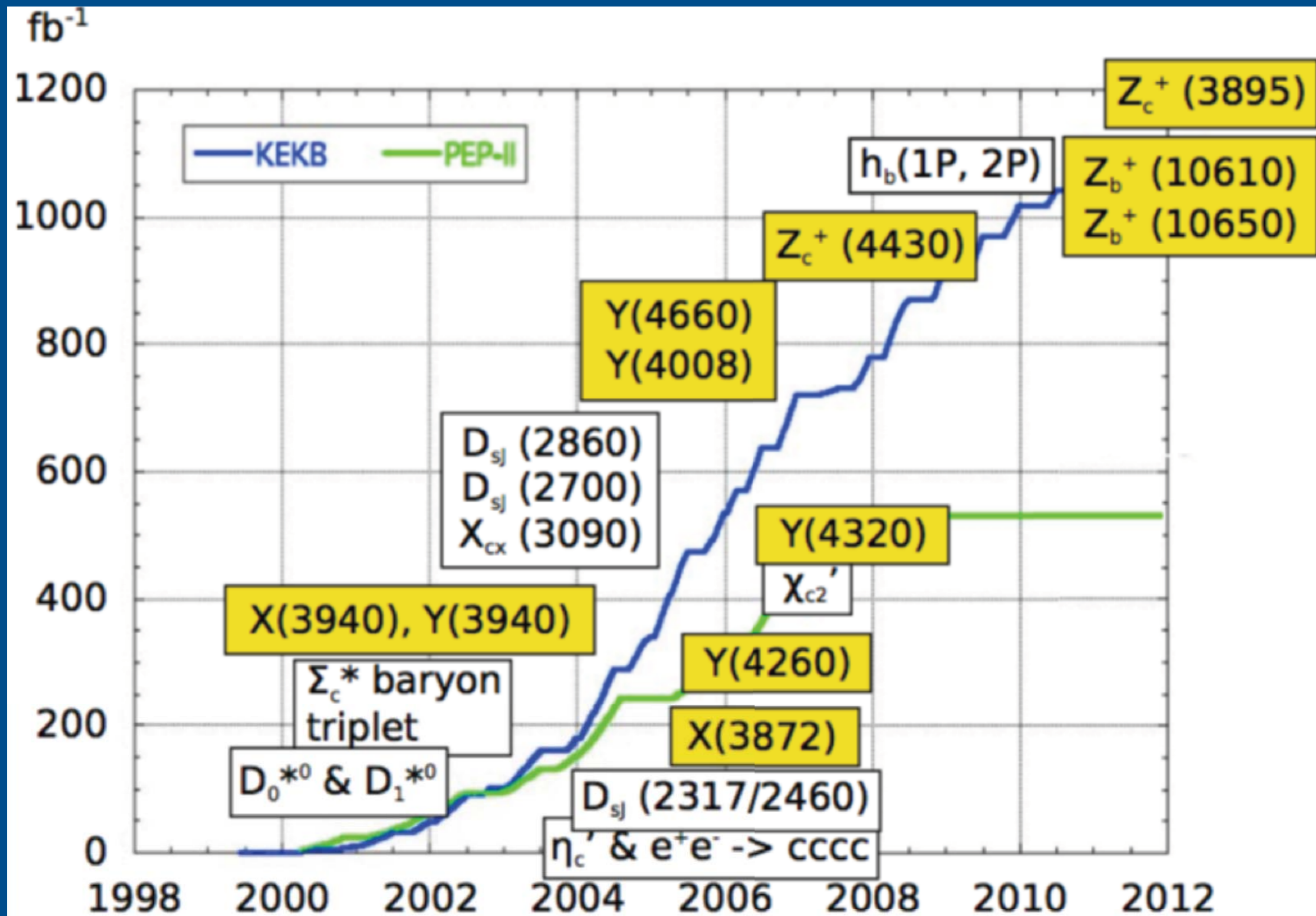
And Now For Something Completely Different

QCD@LHC 2019

Scientific Programme

PQCD/MC

Perturbative QCD and Monte Carlo event generators.

Heavy Flavor/Top

Heavy Flavor and Top quark physics

Higgs/EW/BSM

Higgs Electroweak and BSM physics

PDFs/alpha_S/Soft

Parton Distribution Funcitons, studies of strong coupling and Soft physics

Jets/Substructure/Resummation

Jets their properties and Resummation calculations.

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."

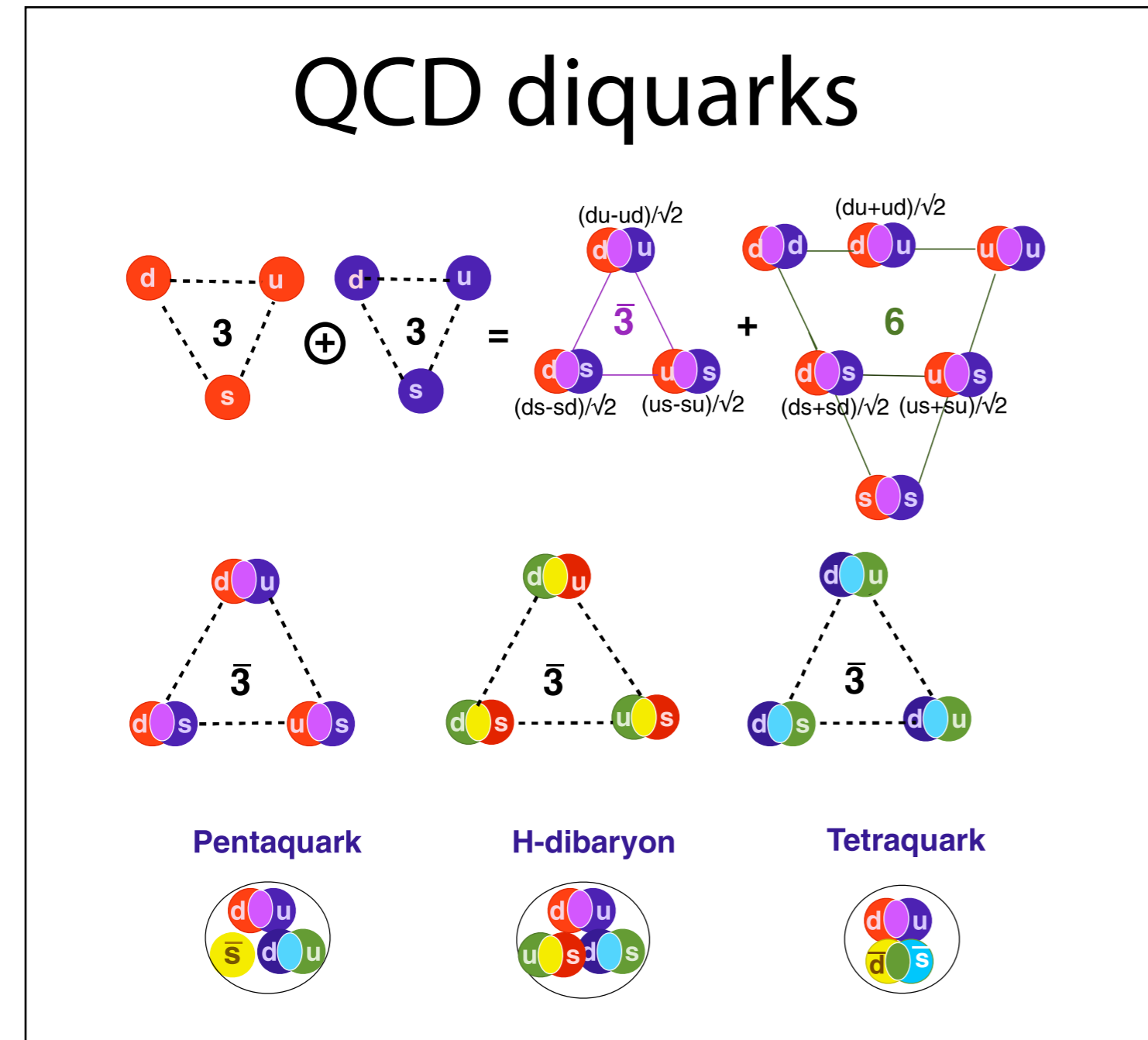_____

[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,…"

MODELS FOR NONSTANDARD HADRONS

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

QCD-color-motivated models

QCD diquarks

Pentaquark   H-dibaryon   Tetraquark

+QCD hybrids (also glueballs)

Other models

meson-antimeson molecule

meson-baryon molecule

hadrocharmonium

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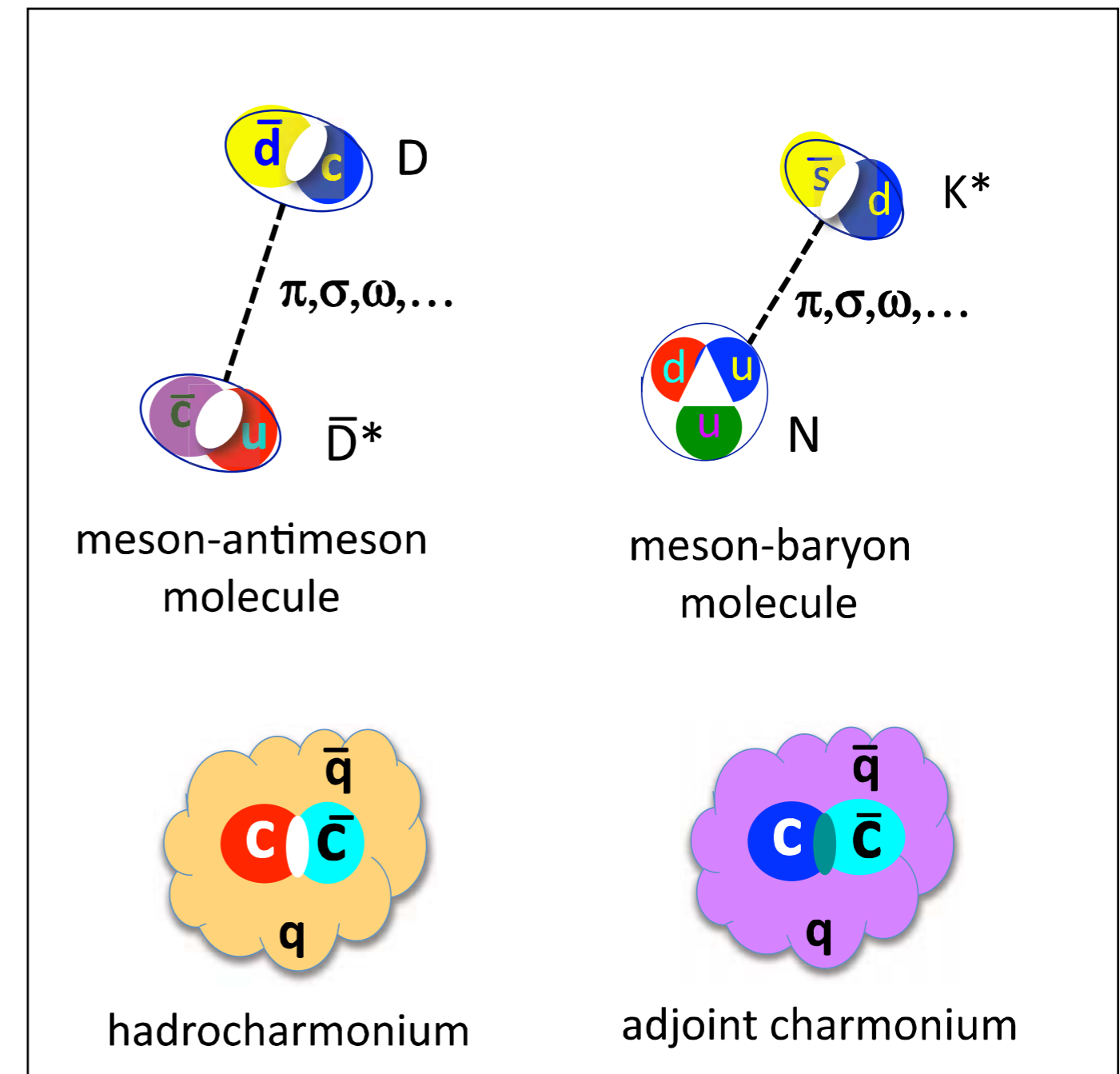
+Kinematically induced resonance-like mass peaks (such as, e.g. threshold cusps)

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

Still Crazy (about non-perturbative QCD) After All These Years

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

Some states (e.g. famous X(3872)) are best described by a "mixture of models"
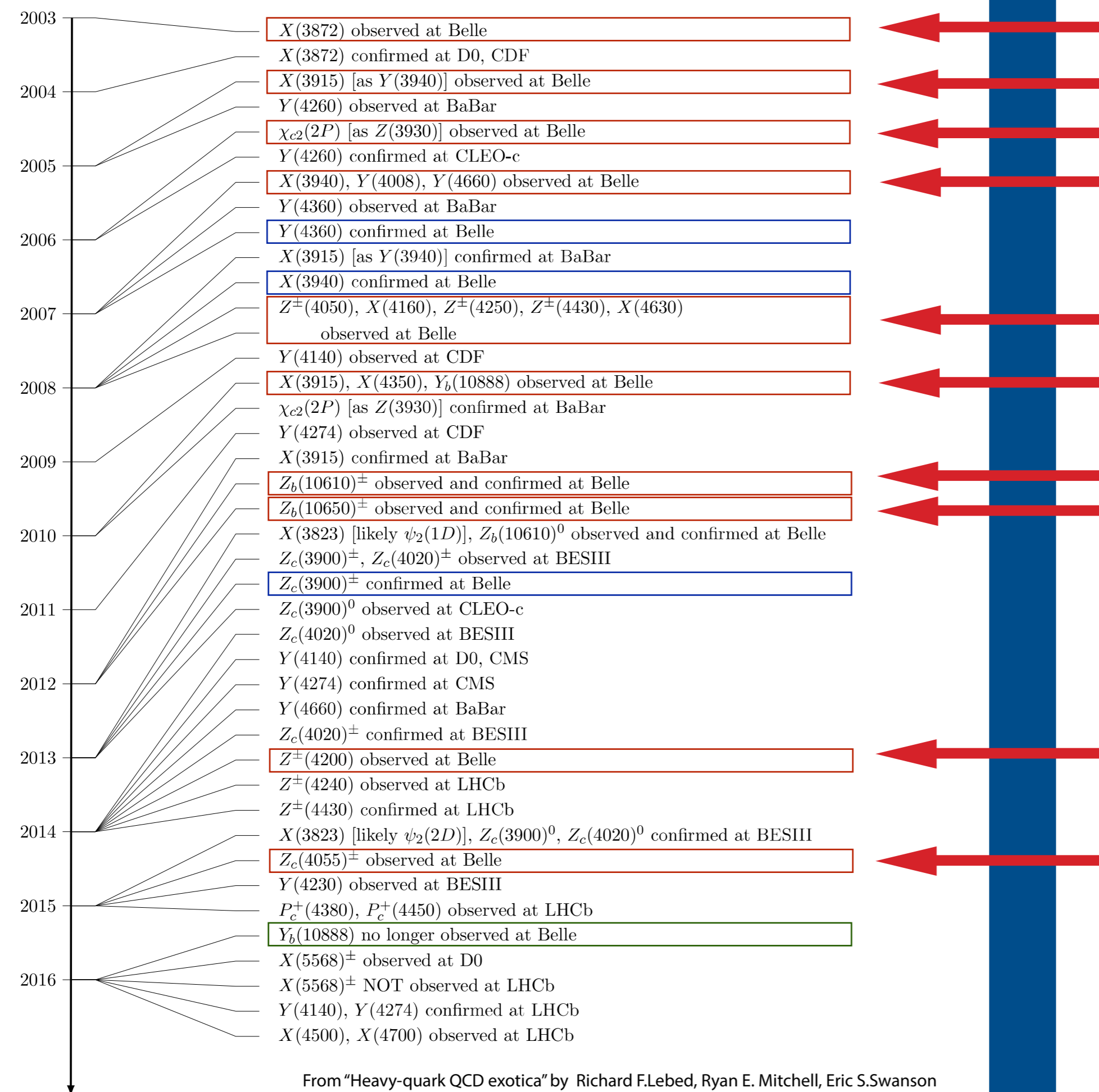
One of Belle II goals is to provide high-statistics data on hadronic resonances to help theoretical community to develop a unified description of data

A better understanding of non-perturbative QCD remains to be important, topical and necessary after all these years
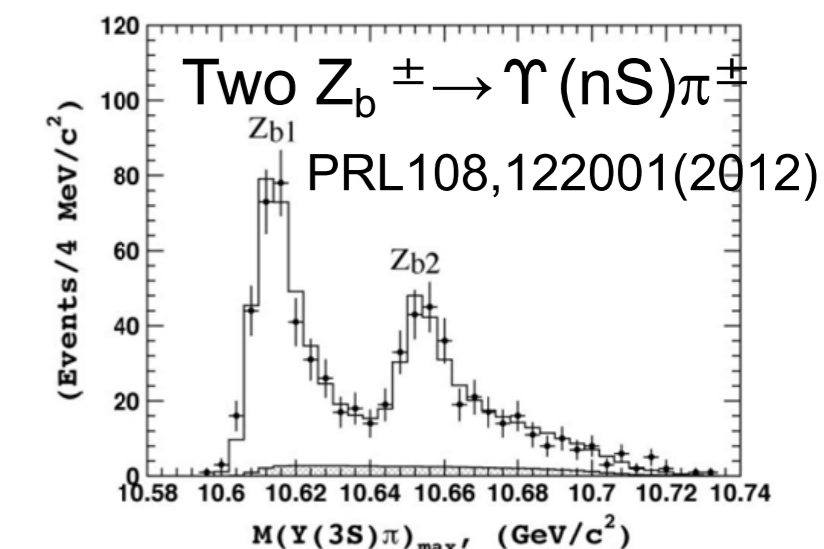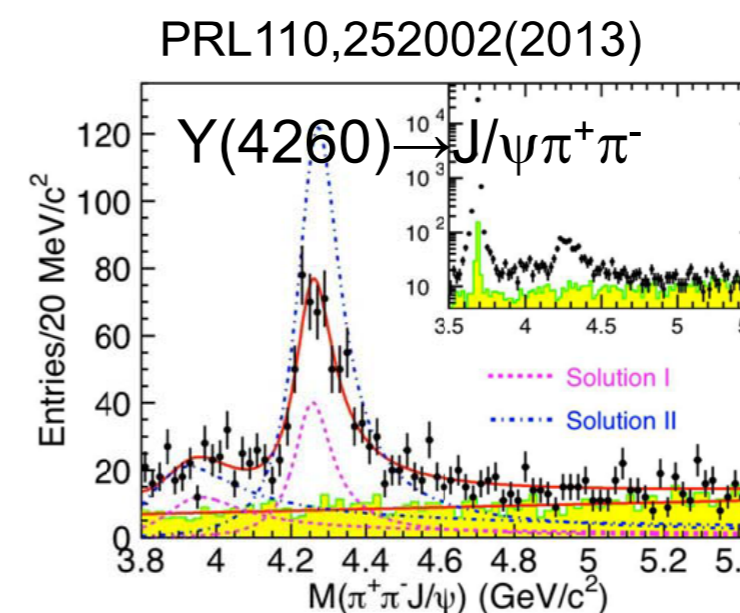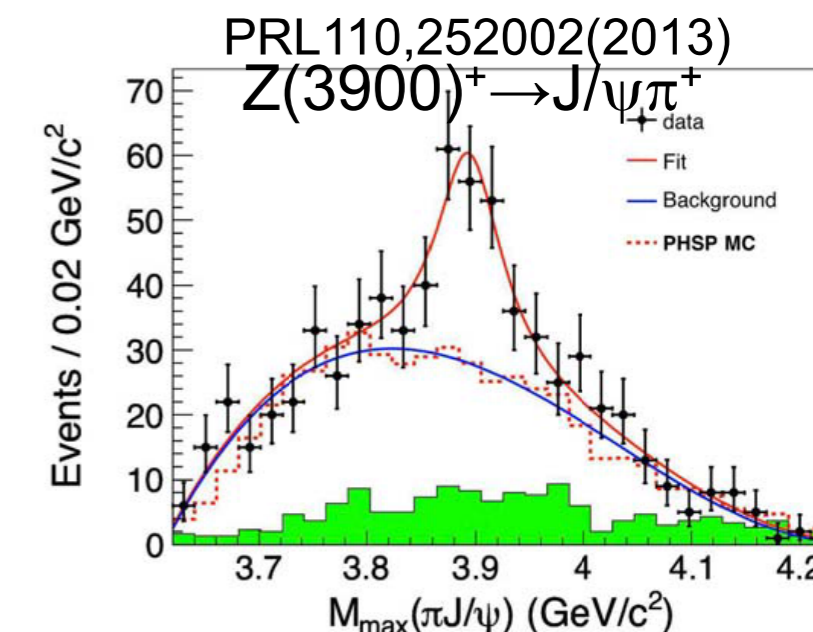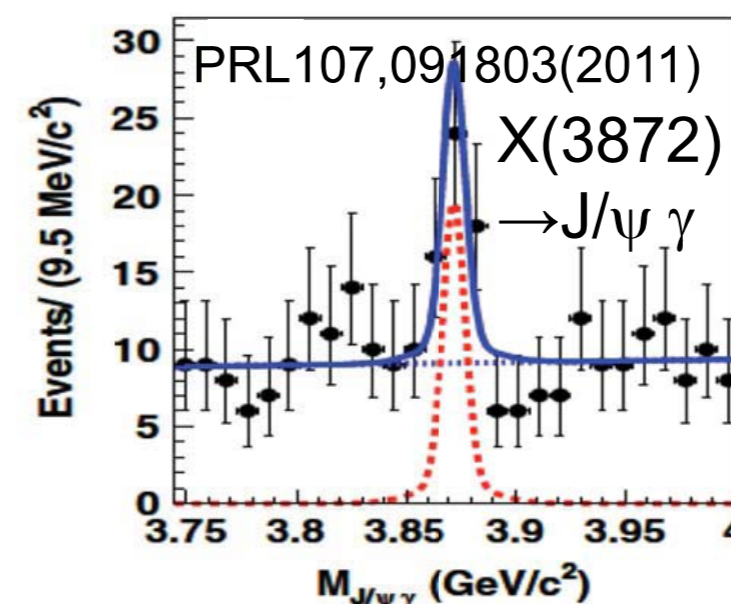
Active data analysis and discoveries continue!

Year	Event
2003	$X(3872)$ observed at Belle
	$X(3872)$ confirmed at D0, CDF
2004	$X(3915)$ [as $Y(3940)$] observed at Belle
	$Y(4260)$ observed at BaBar
	$\chi_{c2}(2P)$ [as $Z(3930)$] observed at Belle
2005	$Y(4260)$ confirmed at CLEO-c
	$X(3940)$, $Y(4008)$, $Y(4660)$ observed at Belle
	$Y(4360)$ observed at BaBar
2006	$Y(4360)$ confirmed at Belle
	$X(3915)$ [as $Y(3940)$] confirmed at BaBar
	$X(3940)$ confirmed at Belle
2007	$Z^{\pm}(4050)$, $X(4160)$, $Z^{\pm}(4250)$, $Z^{\pm}(4430)$, $X(4630)$ observed at Belle
	$Y(4140)$ observed at CDF
2008	$X(3915)$, $X(4350)$, $Y_b(10888)$ observed at Belle
	$\chi_{c2}(2P)$ [as $Z(3930)$] confirmed at BaBar
	$Y(4274)$ observed at CDF
2009	$X(3915)$ confirmed at BaBar
	$Z_b(10610)^{\pm}$ observed and confirmed at Belle
	$Z_b(10650)^{\pm}$ observed and confirmed at Belle
2010	$X(3823)$ [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
2011	$Z_c(3900)^0$ observed at CLEO-c
	$Z_c(4020)^0$ observed at BESIII
	$Y(4140)$ confirmed at D0, CMS
2012	$Y(4274)$ confirmed at CMS
	$Y(4660)$ confirmed at BaBar
	$Z_c(4020)^{\pm}$ confirmed at BESIII
2013	$Z^{\pm}(4200)$ observed at Belle
	$Z^{\pm}(4240)$ observed at LHCb
	$Z^{\pm}(4430)$ confirmed at LHCb
2014	$X(3823)$ [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
2015	$P_c^+(4380)$, $P_c^+(4450)$ observed at LHCb
	$Y_b(10888)$ no longer observed at Belle
2016	$X(5568)^{\pm}$ 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

PRL91,261801(2003)

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

$M_{l+l-\pi+\pi-} - M_{l+l-}$ (GeV)

PRL100,142001(2008)

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

PRL107,091803(2011)

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

PRL110,252002(2013)

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

PRL110,252002(2013)

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

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

PRL108,122001(2012)
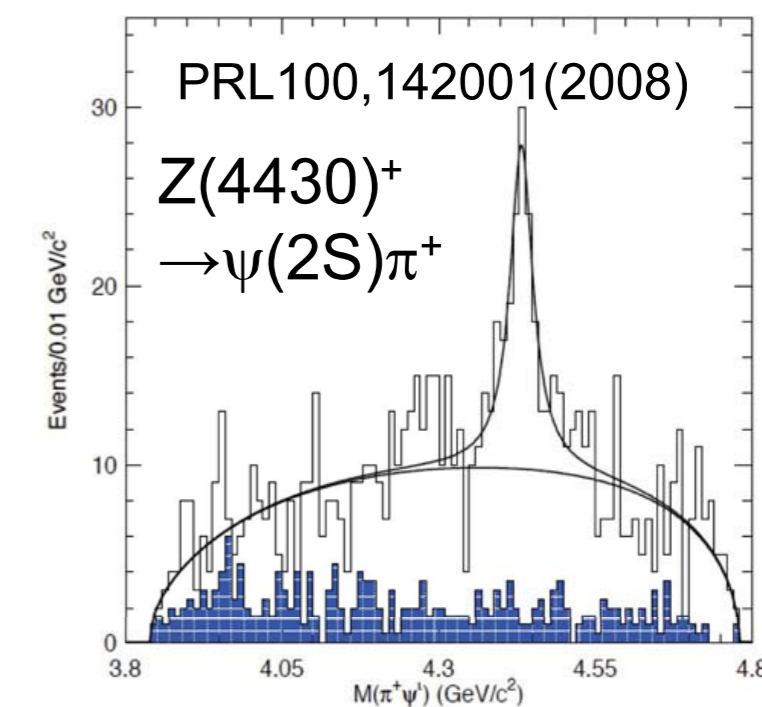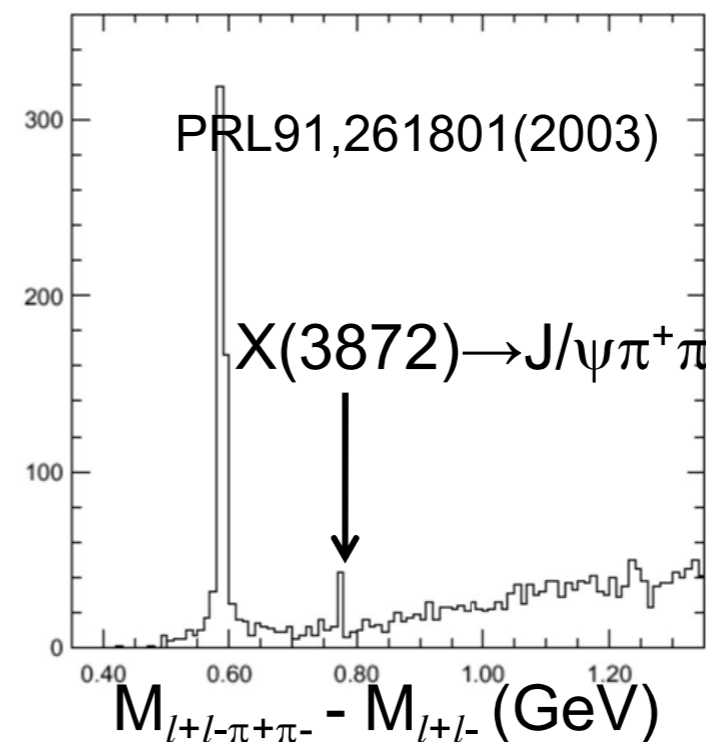
The Belle II Physics Book

Belle-II Collaboration (E. Kou (ed.) (Orsay, LAL) *et al.*) _Show all 534 authors_
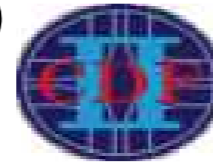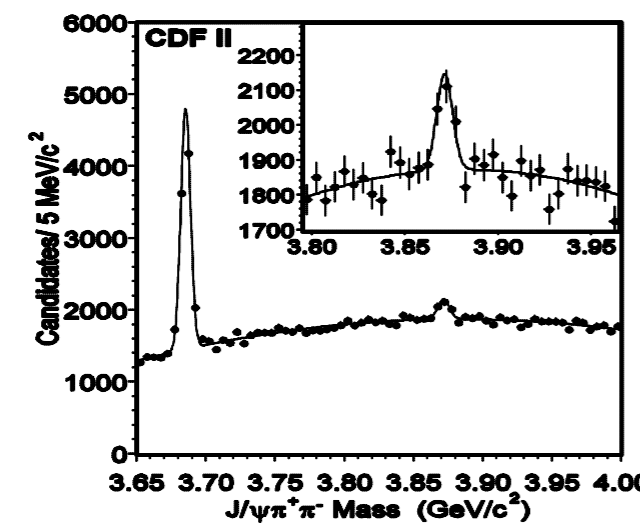
Aug 30, 2018 - 689 pages

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.

B decays — $J^{PC}=0^{-+}, 1^{--}, 1^{++}$

Initial state radiation — $J^{PC}=1^{--}$

Double $c\bar{c}$ — C=+1

Change CM energy — $b\bar{b}$-exotic

$\gamma\gamma$ collisions — $J^{PC}=0^{\pm+}, 2^{\pm+}, 3^{++}$

PRL.93.072001 (2004)

PRL.93.162002 (2004)
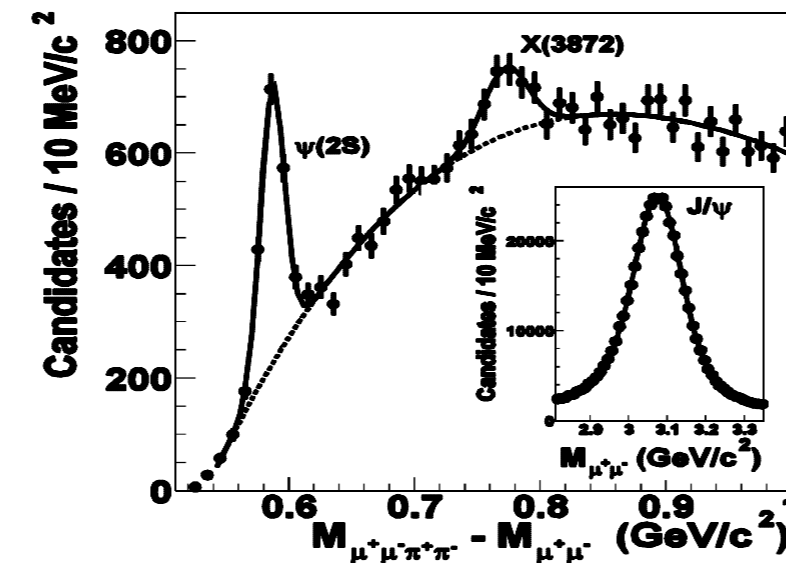
PRD.71.071103 (2005)
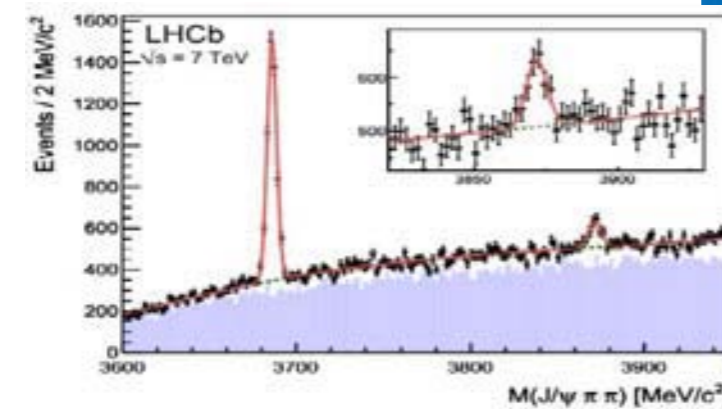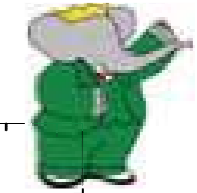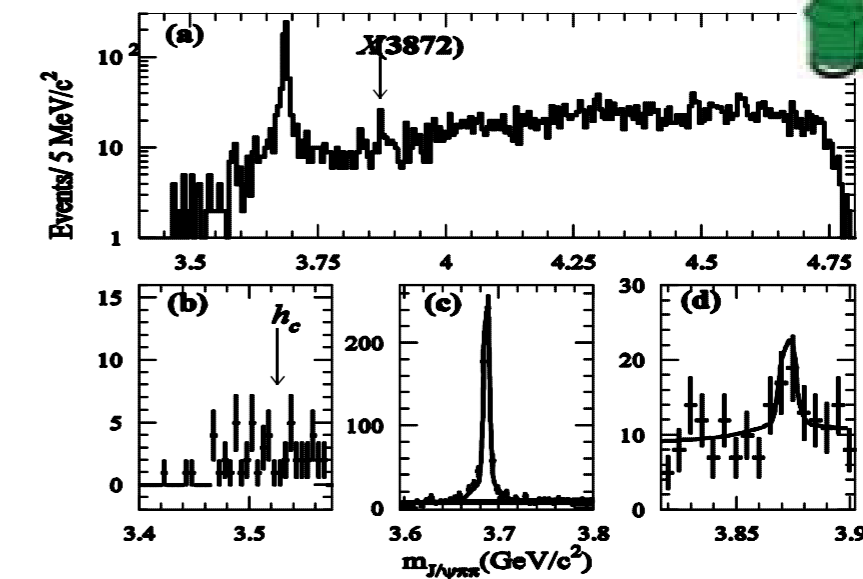
EPJC.72.1972 (2012)
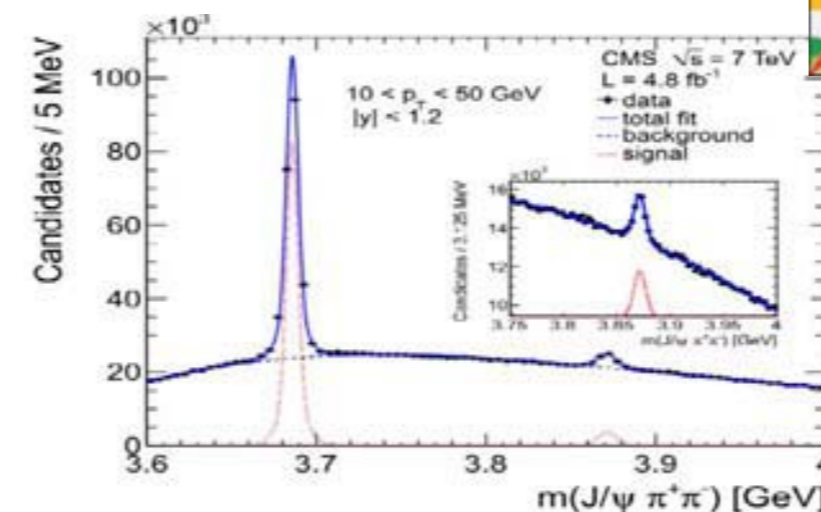
JHEP.04.154 (2013)
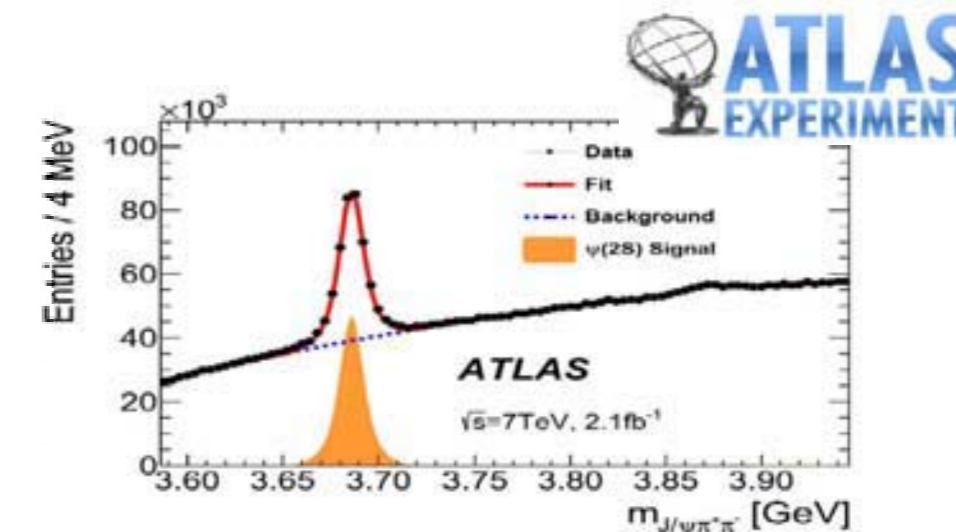
JHEP.79.2014 (2014)

- 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 cc̄ state
- Precise measurements of production and decay processes are essential to understand the exotic nature

- $J^{PC} = 1^{++}$

- Strong coupling to DD*

- No charged or neutral partner observed

  - Coupled channel, good description

    - PTEP9, 093D01(2013)

Specific model by Takizawa & Takeuchi, PTEP 9, 093D01

most of the time looks like a $D^0\bar{D}^{*0}$ molecule

~5%   ~90%   >10 fm   ≈1.5 fm   ~5%

"core" state

$|BE| \approx 8$ MeV
$d_{rms}^{D^+D^{*-}} \approx 1.5$ fm

$\dfrac{1}{M_{X(3872)} - m_{D^0} - m_{\bar{D}^{*0}} - \frac{q^2}{2\mu_0}}$

$|BE| < 0.2$ MeV
$d_{rms}^{D^0\bar{D}^{*0}} > 10$ fm

$d_{rms} \approx \dfrac{1}{\sqrt{2\mu_D |BE|}}$:

reduced mass $|m_D + m_{D^*} - m_{X3872}|$

produced in pp via this component
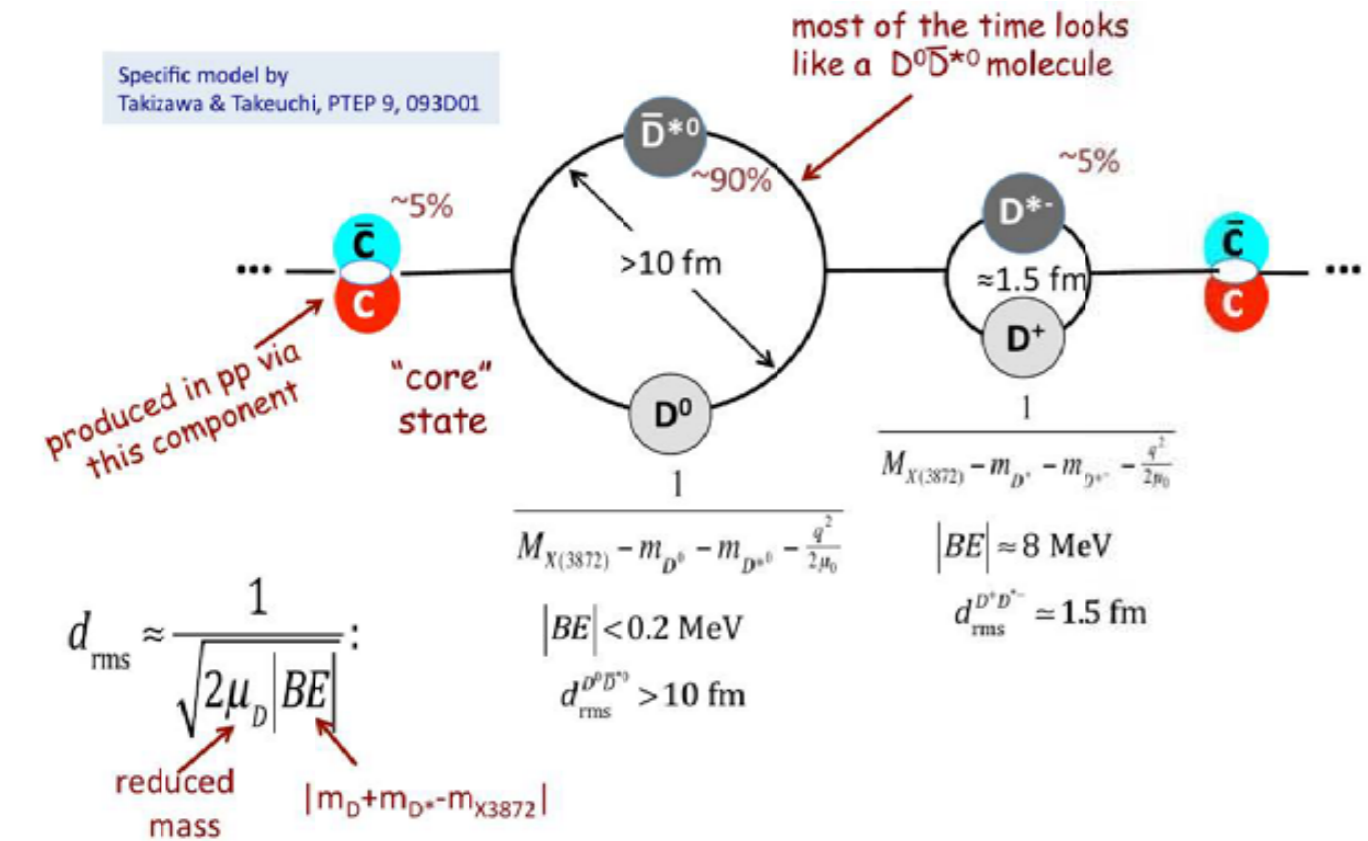
- Or QCD diquark-diantiquark

  - Maiani et al., PRD71, 014028(200

  - No 1^{++} partner state seen

Spin=1 "bad" diquark

gluons

Spin=0 "good" diquark

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

ATLAS
$\sqrt{s}$=8 TeV, 11.4 fb^{-1}
Prompt X(3872)

+ ATLAS data
NLO NRQCD

Assuming χ_{c1}(2P)

Br(X(3872)$\to$J/$\psi(\mu^+\mu^-)\pi^+\pi^-$)d$^2\sigma$/dp$_T$ dy[nb/GeV]

X(3872) p$_T$ [GeV]

(JHEP01(2017)117)
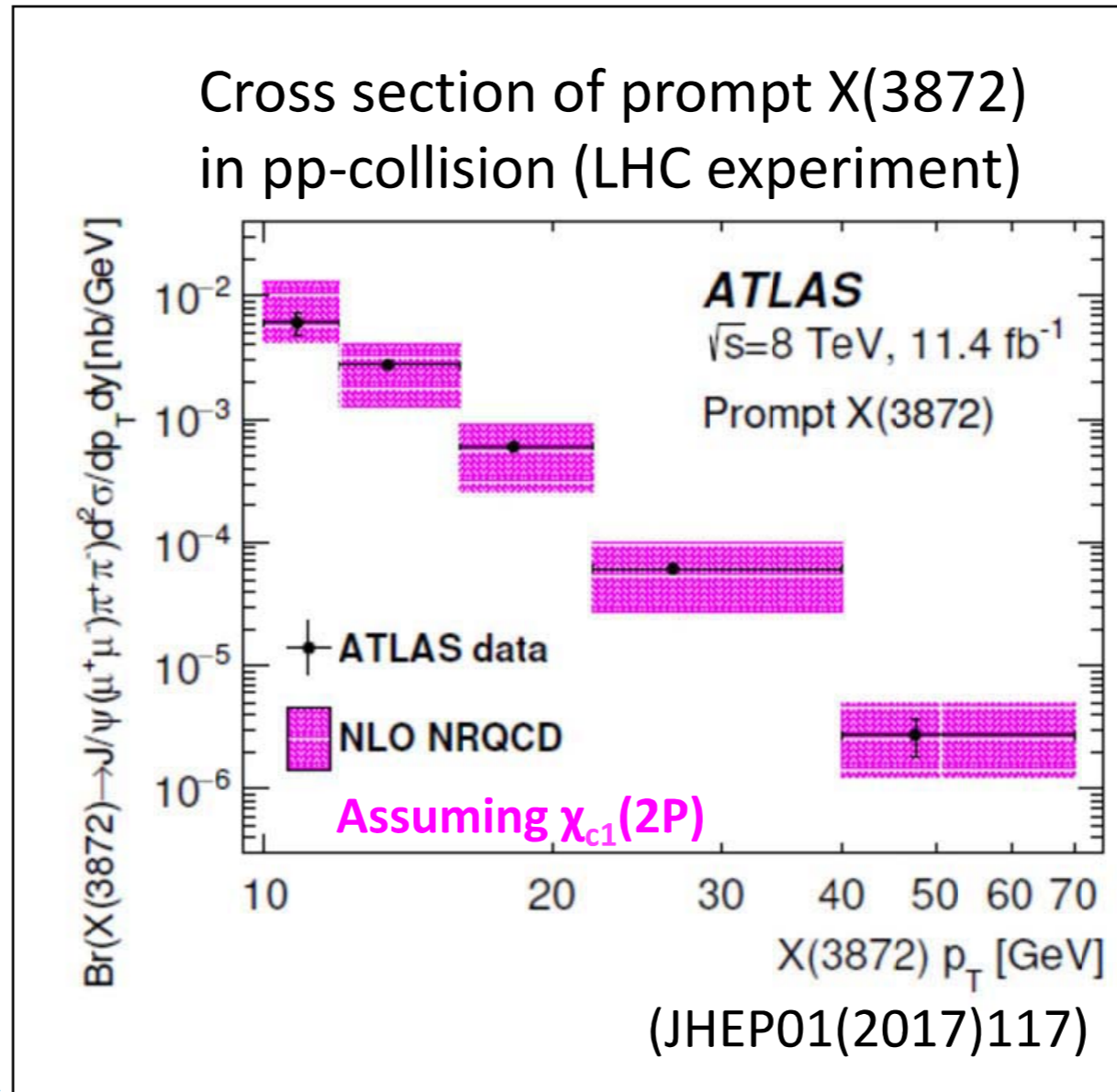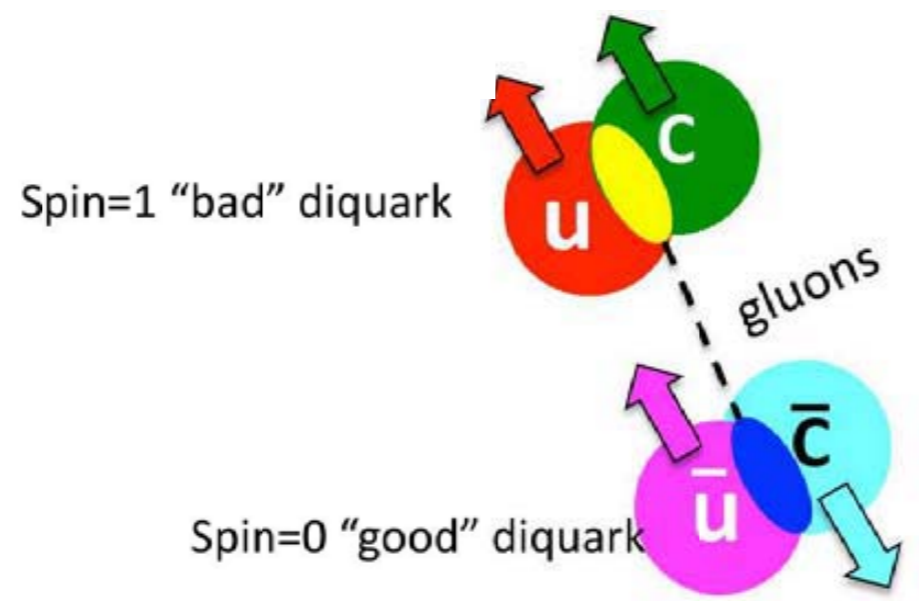
Inconsistent with pure molecular interpretation

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

  $\to$ Need further information about production and decay

- Current X(3872) total width:

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

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

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

X(3872) Decays

$J/\psi\pi^+\pi^-$ threshold

$D^0\bar{D}^0\pi^0$ threshold

$X(3872)$ mass

3376.04 ± 0.01

3864.64 ± 0.07

3871.69 ± 0.17 [MeV]

496.65 ± 0.17 MeV

7.05 ± 0.18 MeV
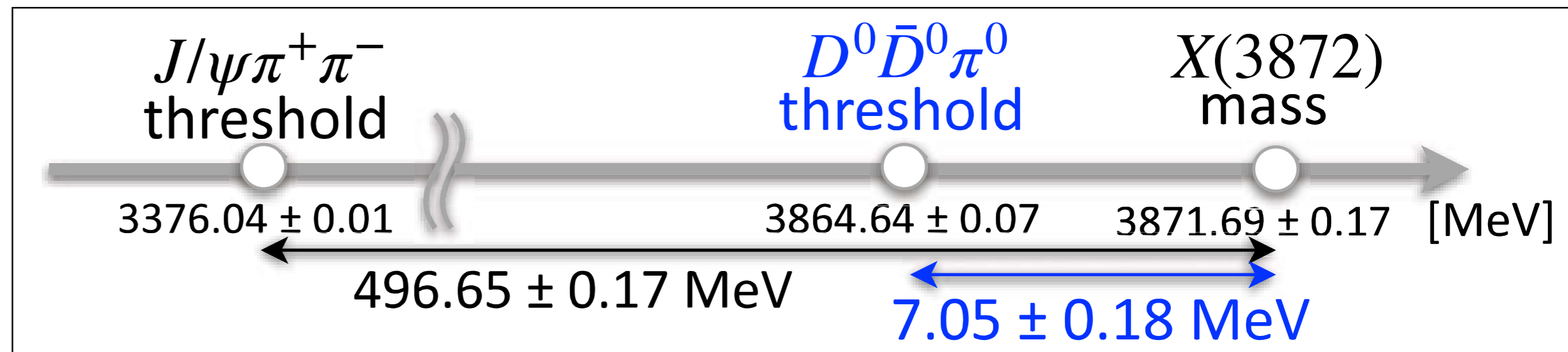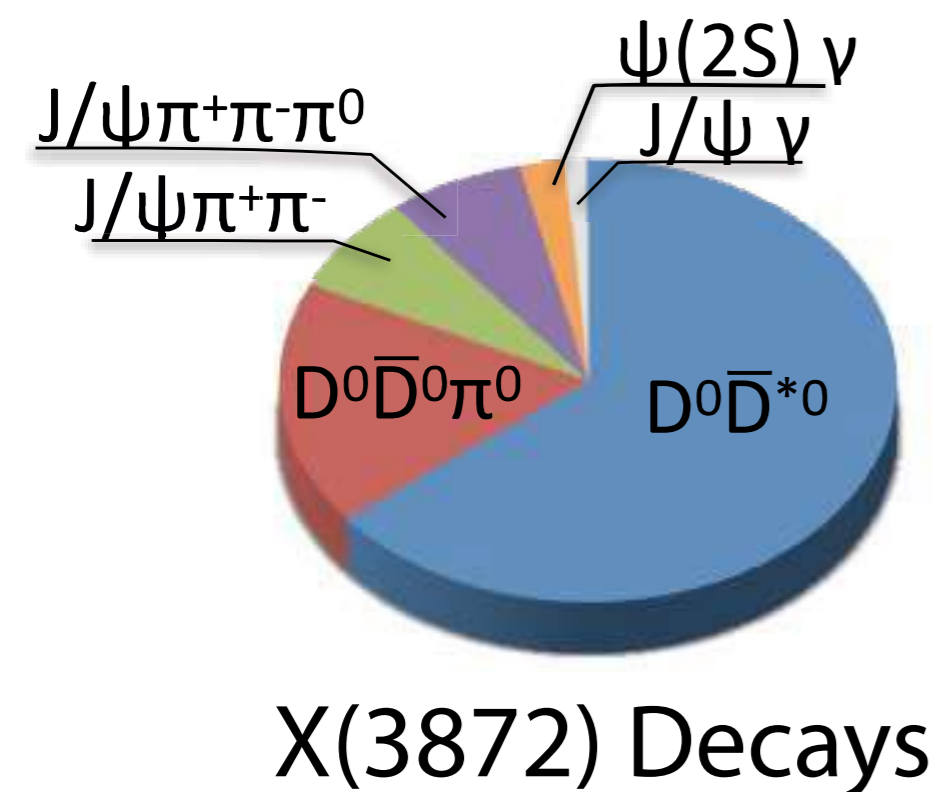
- **Previous study** (Phys. Rev. D 84, 052004 (2011))

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

- Many decay modes have been observed: J/ψ ρ, J/ψ ω, J/ψ γ, ψ(2S) γ, DD*, DDπ^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$^+$→X(3872)K$^+$)	X(3872) Total width

Known variables

Br(B$^+$→X(3872)K$^+$) × Br(X(3872)→f)

σ(X(3872)) × Br(X(3872)→f)

Br(X(3872)→f)   →   Γ(X(3872)→f)

σ(X(3872))

LHC, Tevatron…

Newly determined variables

Belle PRD.97.012005 (2018)

ψ(3770)

X(3872)

X(3915)

Extract Br(B+→X(3872) K+) using missing mass recoiling against the kaon
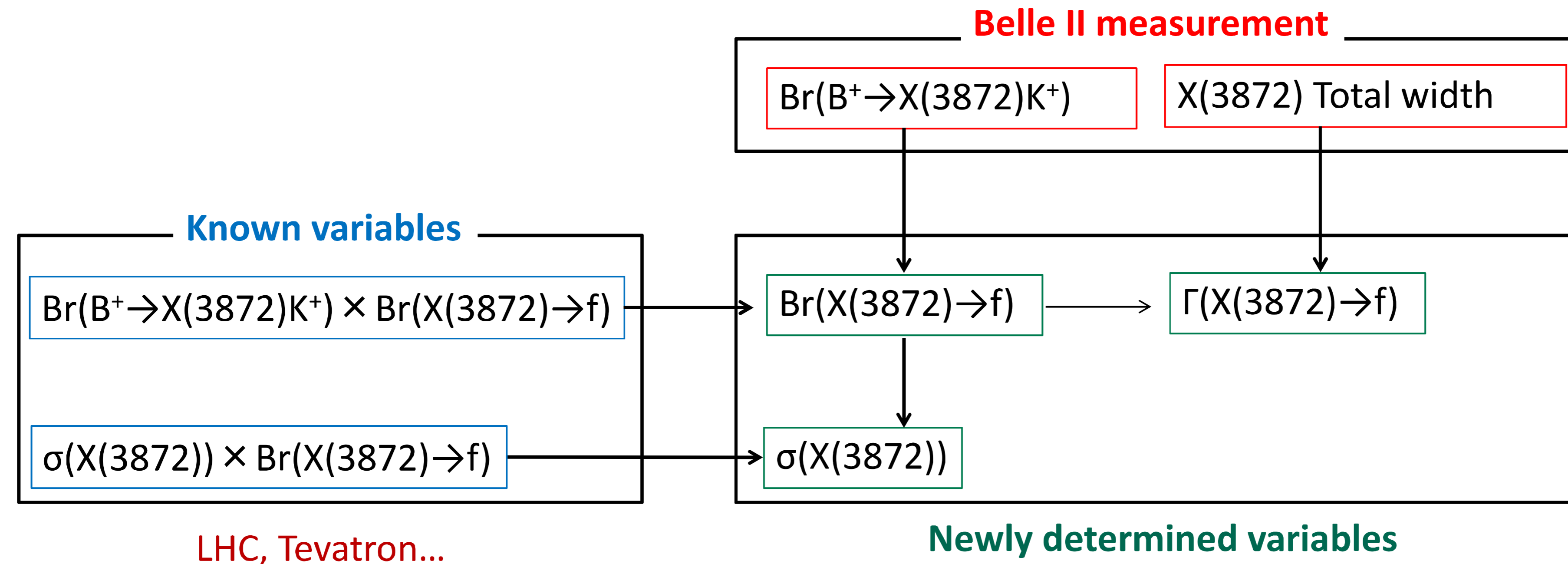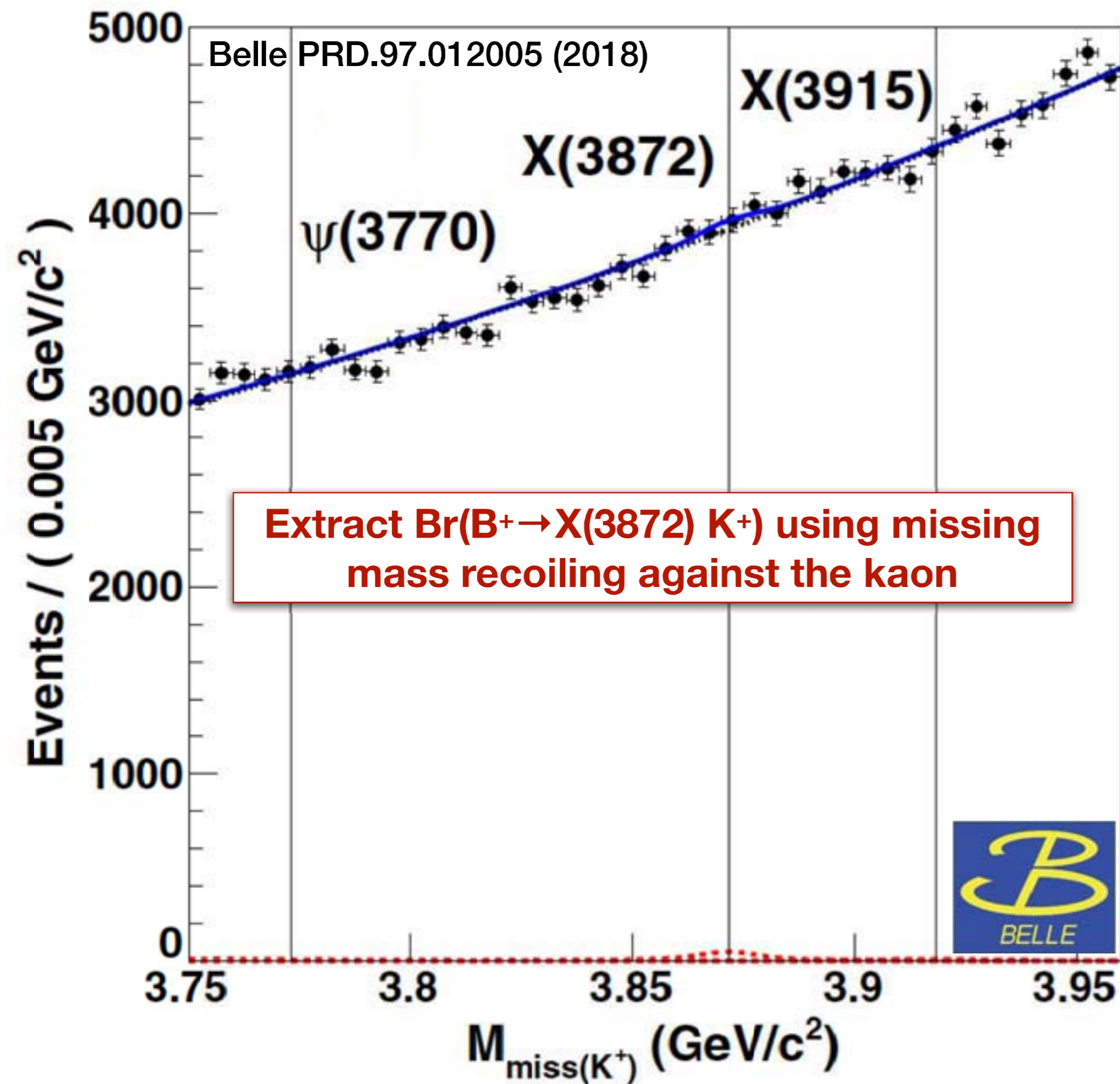
**Mass resolution for DD̄π⁰ is ~680 keV:
~3 times better than J/ψπ⁺π⁻
Previously unmeasured due to low statistics**

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.

Systematic uncertainties need to be understood

Belle II simulation

- 90 % C.L.
- 3σ significance
- 5σ significance

Current upper limit (90% C.L.)
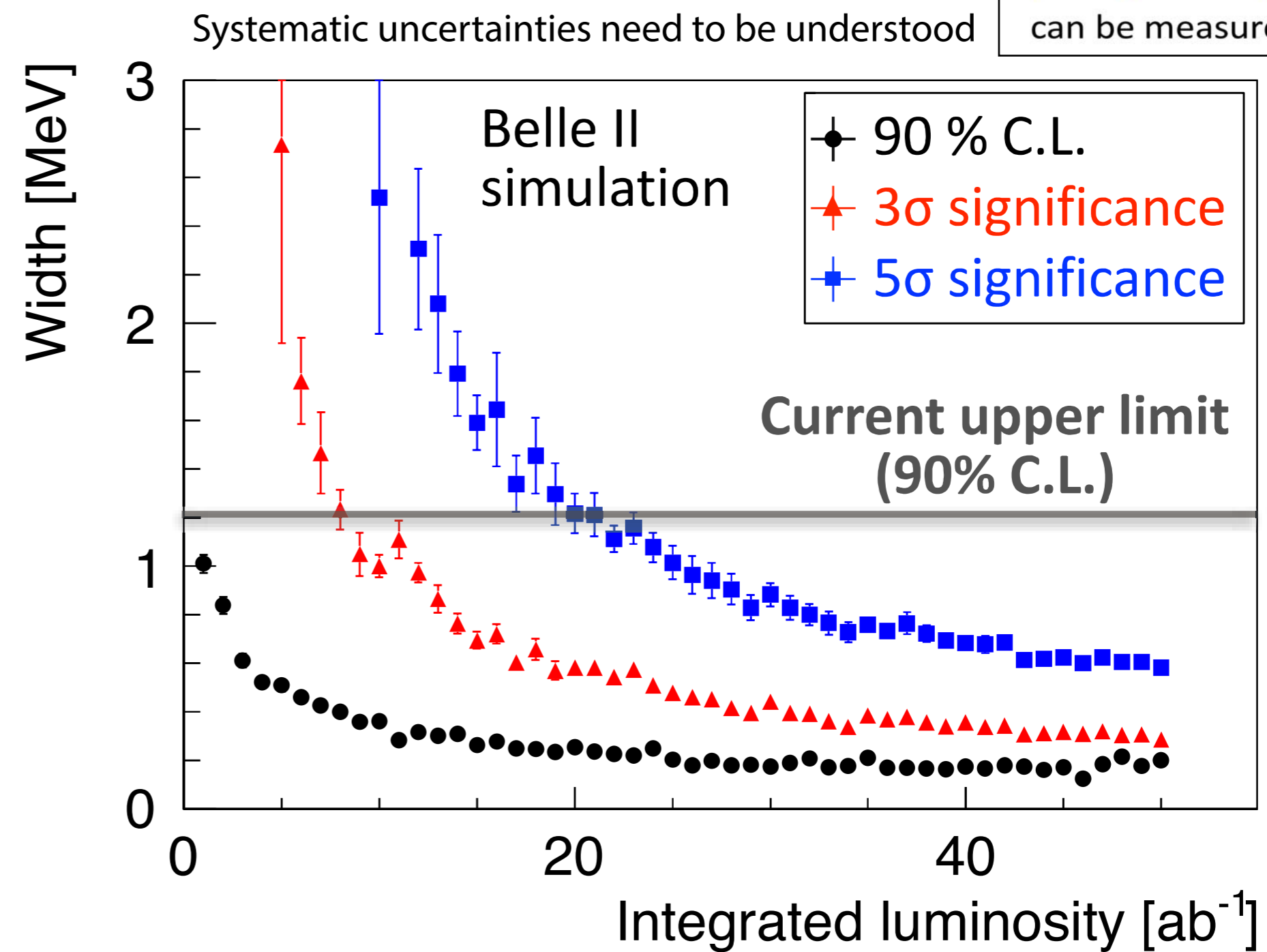
Master thesis of H. Hirata (KMI / Nagoya University)

$Y(4260)$ 4221.1 ± 2.5 47.7 ± 4.0 1^{--}

$e^+ e^-$	$(\pi^+ \pi^- J/\psi)$	BaBar [1191, 1192] (8), CLEO [1193, 1194] (11),	2005	Ok
		Belle [1140, 1195] (15), BESIII [1139, 1196] (np)		
$e^+ e^-$	$(\pi^0 \pi^0 J/\psi)$	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

Table (inset):

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^{++}	$B^+ \quad K^+(\phi J/\psi)$	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}	$0/2^{?+}$	$e^+ e^- \quad e^+ e^-(\phi J/\psi)$	Belle [1199] (3.2)	2009	NC!
$Y(4360)$	4341.2 ± 5.4	101.9 ± 9.3	1^{--}	$e^+ e^- \quad (\pi^+ \pi^- \psi(2S))$	Belle [1148, 1200] (8), BaBar [1201] (np)	2007	Ok
				$e^+ e^- \quad (\pi^+ \pi^- J/\psi)$	BESIII [1196] (7.6)	2016	NC!
				$e^+ e^- \quad (\pi^+ \pi^- \psi_2(3823))$	BESIII [1165] (np)	2015	NC!
				$e^+ e^- \quad (\pi^0 Z_c(3900)^0)$	BESIII [1142] (np)	2015	NC!
				$e^+ e^- \quad (\pi^- Z_c(4020)^+)$	Belle [1148] (3.5), BESIII [1149] (9.2)	2014	NC!
$Y(4390)$	4391.6 ± 6.4	139.5 ± 16.1	1^{--}	$e^+ e^- \quad (\pi^+ \pi^- h_c)$	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^{--}	$e^+ e^- \quad$ (hadrons)	PDG [70]	1976	Ok
				$e^+ e^- \quad (\eta J/\psi)$	Belle [1176] (np), BESIII [1189] (>5)	2013	NC!
				$e^+ e^- \quad (\omega \chi_{c2})$	BESIII [1202] (10.4)	2015	NC!
				$e^+ e^- \quad (D \bar{D}_2^*(2460))$	Belle [1203] (10)	2007	NC!
$Z(4430)^+$	4478^{+15}_{-18}	181 ± 31	1^{+-}	$\bar{B}^0 \quad K^-(\pi^+ \psi(2S))$	Belle [1204–1206] (6.4), BaBar [1207] (2.4), LHCb [1208, 1209] (13.9)	2007	Ok
				$\bar{B}^0 \quad K^-(\pi^+ J/\psi)$	Belle [1190] (4.0)	2014	NC!
$X(4500)$	4506^{+16}_{-19}	92^{+30}_{-29}	0^{++}	$B^+ \quad K^+(\phi J/\psi)$	LHCb [1186, 1187] (6.1)	2016	NC!
$Y(4660)$	4643 ± 9	72 ± 11	1^{--}	$e^+ e^- \quad (\pi^+ \pi^- \psi(2S))$	Belle [1148, 1200] (5.8), BaBar [1201] (5)	2007	Ok
				$e^+ e^- \quad (\Lambda_c^+ \bar{\Lambda}_c^-)$	Belle [1210] (8.2)	2007	NC!
$X(4700)$	4704^{+17}_{-26}	120^{+52}_{-45}	0^{++}	$B^+ \quad K^+(\phi J/\psi)$	LHCb [1186, 1187] (5.6)	2016	NC!
$\Upsilon(4S)$	10579.4 ± 1.2	20.5 ± 2.5	1^{--}	$e^+ e^- \quad$ (hadrons)	PDG [70]	1985	Ok
				$e^+ e^- (\pi^+ \pi^- \Upsilon(1S,2S))$	BaBar [1211, 1212] (>10), Belle [1213, 1214] (11.2)	2006	Ok
				$e^+ e^- \quad (\eta \Upsilon(1S))$	BaBar [1212] (>11)	2008	Ok
				$e^+ e^- \quad (\eta h_b(1P))$	Belle [1092] (11)	2015	Ok
$\Upsilon(10860)$	10891 ± 4	54 ± 7	1^{--}	$e^+ e^- \quad$ (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
				$e^+ e^- \quad (f_0(980) \Upsilon(1S))$	Belle [1153–1155] (>8)	2011	Ok
				$e^+ e^- \quad (f_2(1275) \Upsilon(1S))$	Belle [1153–1155] (np)	2011	NC!
				$e^+ e^- \quad (\eta \Upsilon(1S,2S))$	Belle [10]	2012	NC!
				$e^+ e^- \quad (K^+ K^- \Upsilon(1S))$	Belle [1215] (4.9)	2007	NC!
				$e^+ e^- \quad (\omega \chi_{b1,2}(1P))$	Belle [1216] (12)	2014	Ok
				$e^+ e^- ((\pi^+ \pi^- \pi^0)_{non-\omega} \chi_{b1,2}(1P))$	Belle [1216] (4.9)	2014	NC!
				$e^+ e^- \quad (\pi^+ \pi^- \Upsilon_J(1D))$	Belle [9]	2012	NC!
				$e^+ e^- \quad (\eta \Upsilon_J(1D))$	Belle [np]	2014	NC!
				$e^+ e^- (\pi Z_b(10610, 10650))$	Belle [1153, 1155] (>10)	2011	Ok
				$e^+ e^- \quad (B_s^* \bar{B}_s^*)$	Belle [1217] (np)	2016	NC!
$\Upsilon(11020)$	$10987.5^{+11.0}_{-3.4}$	61^{+9}_{-28}	1^{--}	$e^+ e^- \quad$ (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
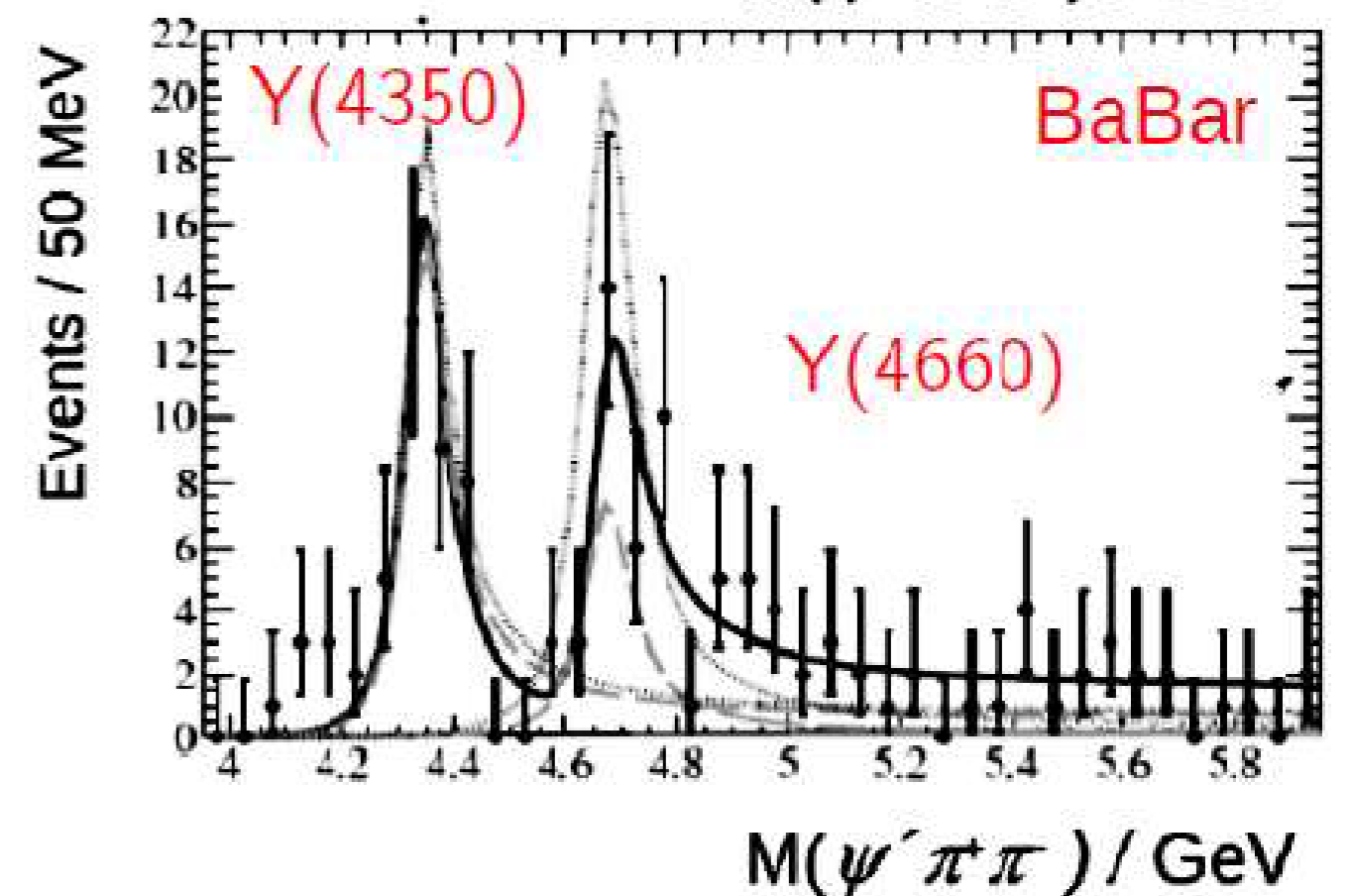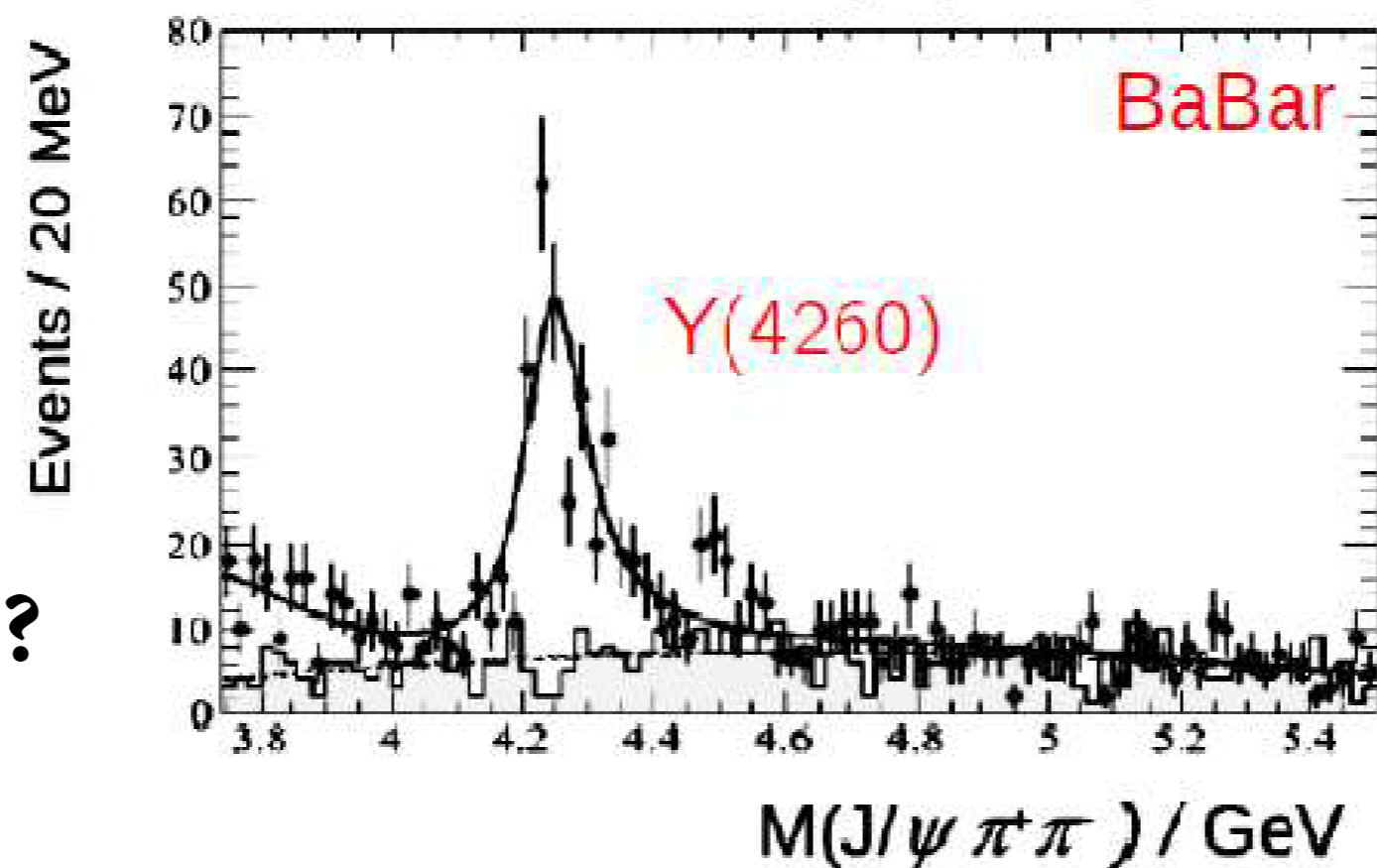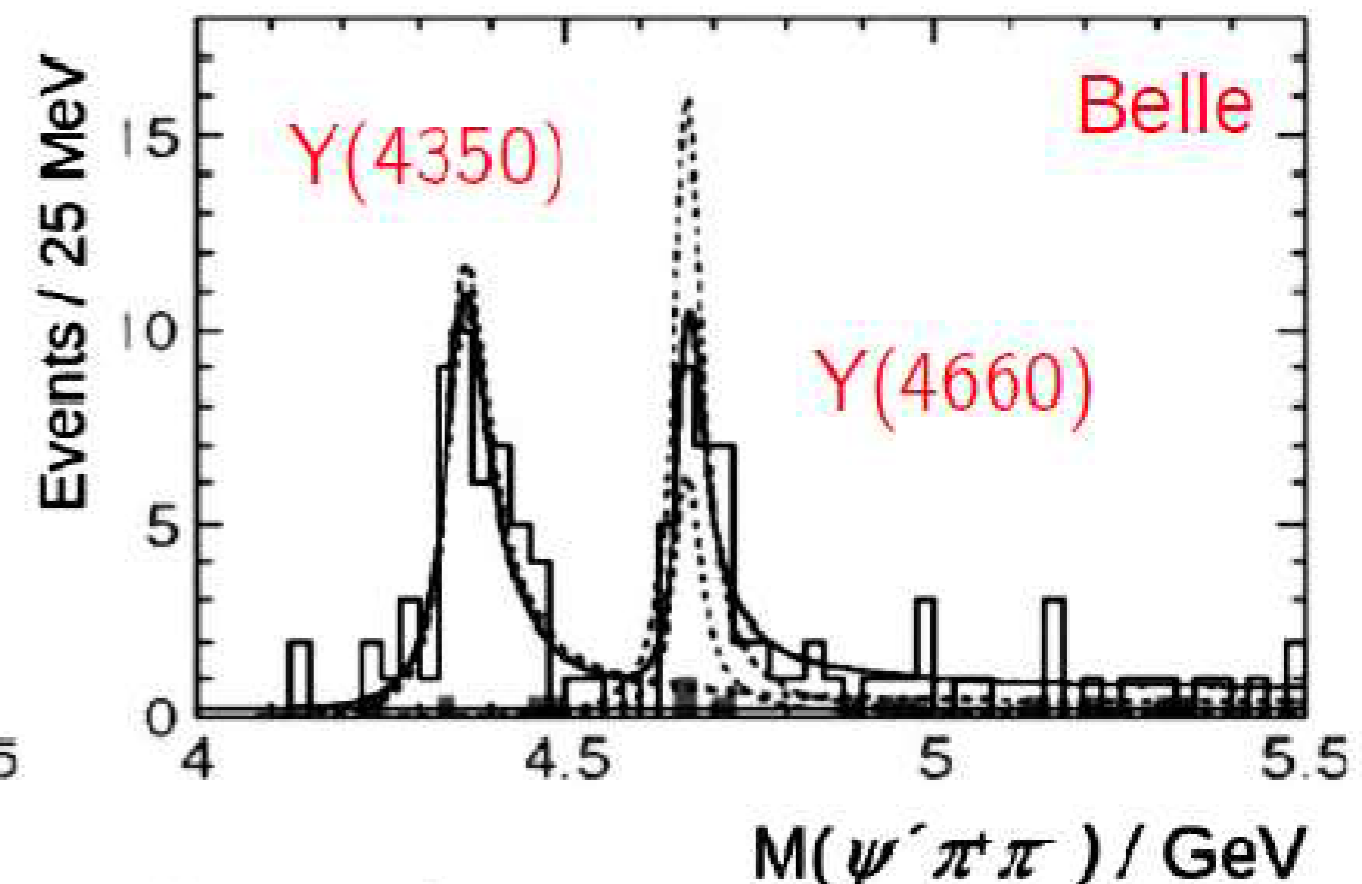
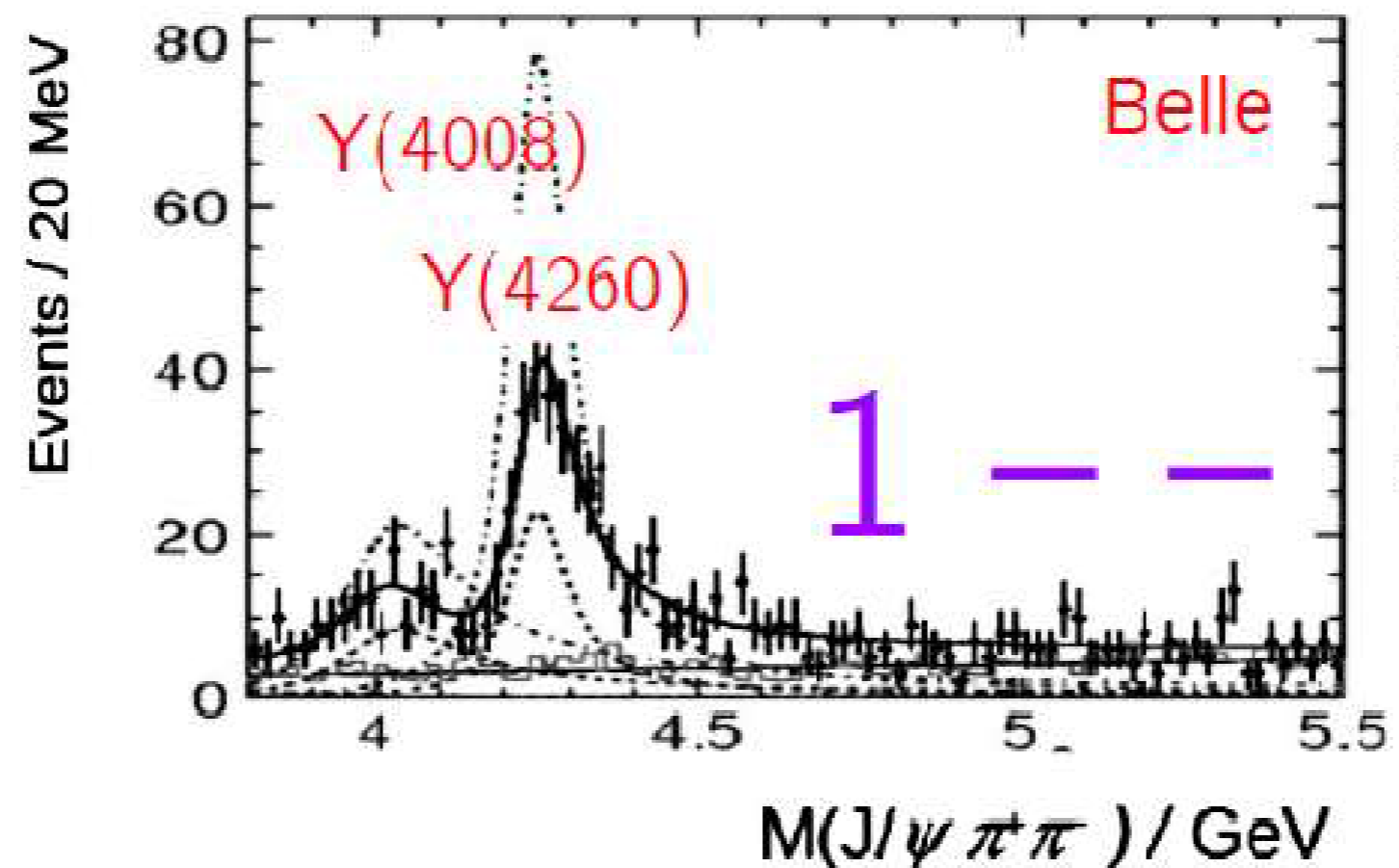**The Belle II Physics Book, arXiv:1808.10567 [hep-ex]**

Y(4260):

Why such state(s)?

And what is it / are they?

Charmonium?

Four-quark state?

Molecule?

A superposition of all of these?

BaBar PRL.95.142001 (2005)

BaBar PRD.73.011101(R) (2006)

Belle arXiv:1901.06470
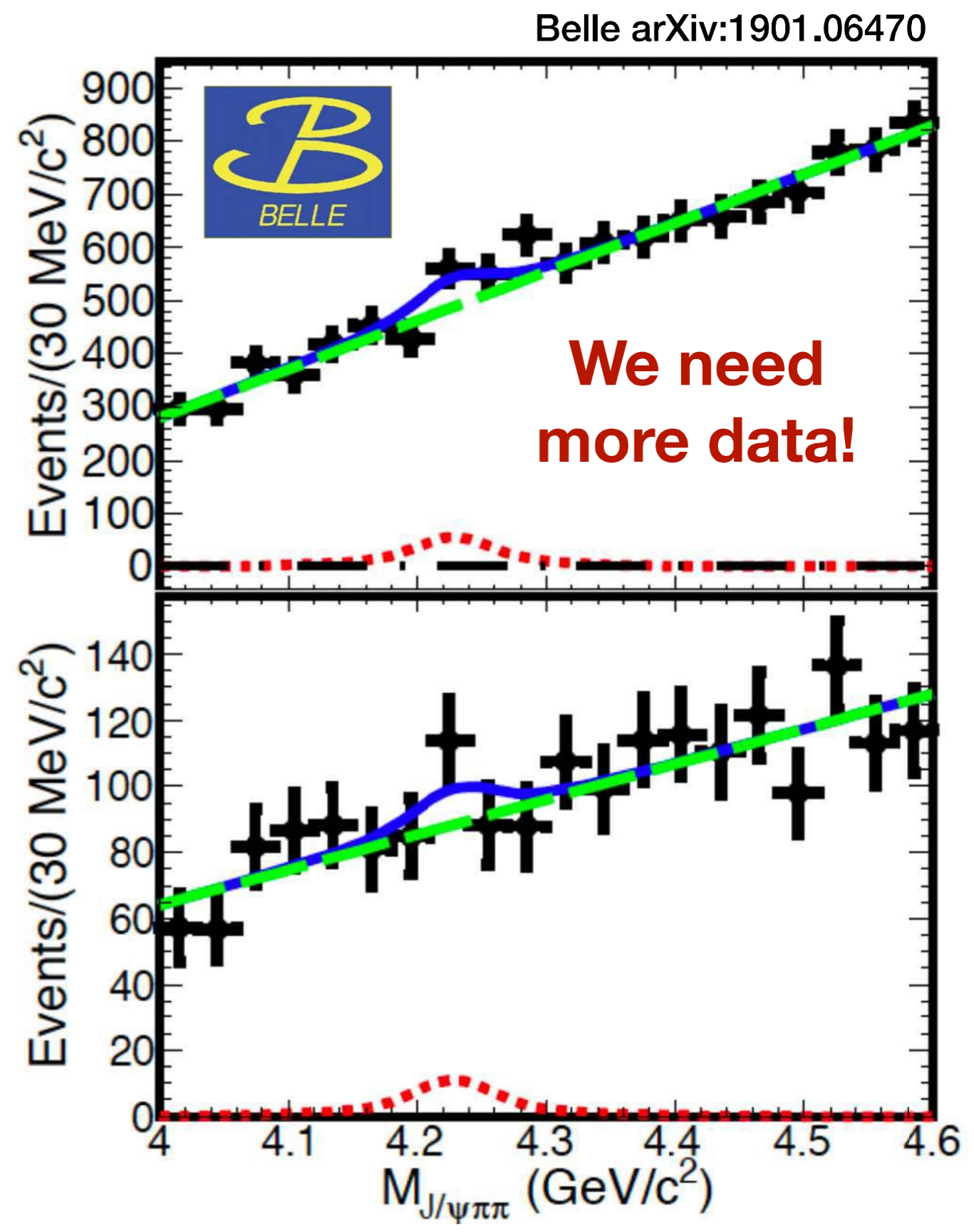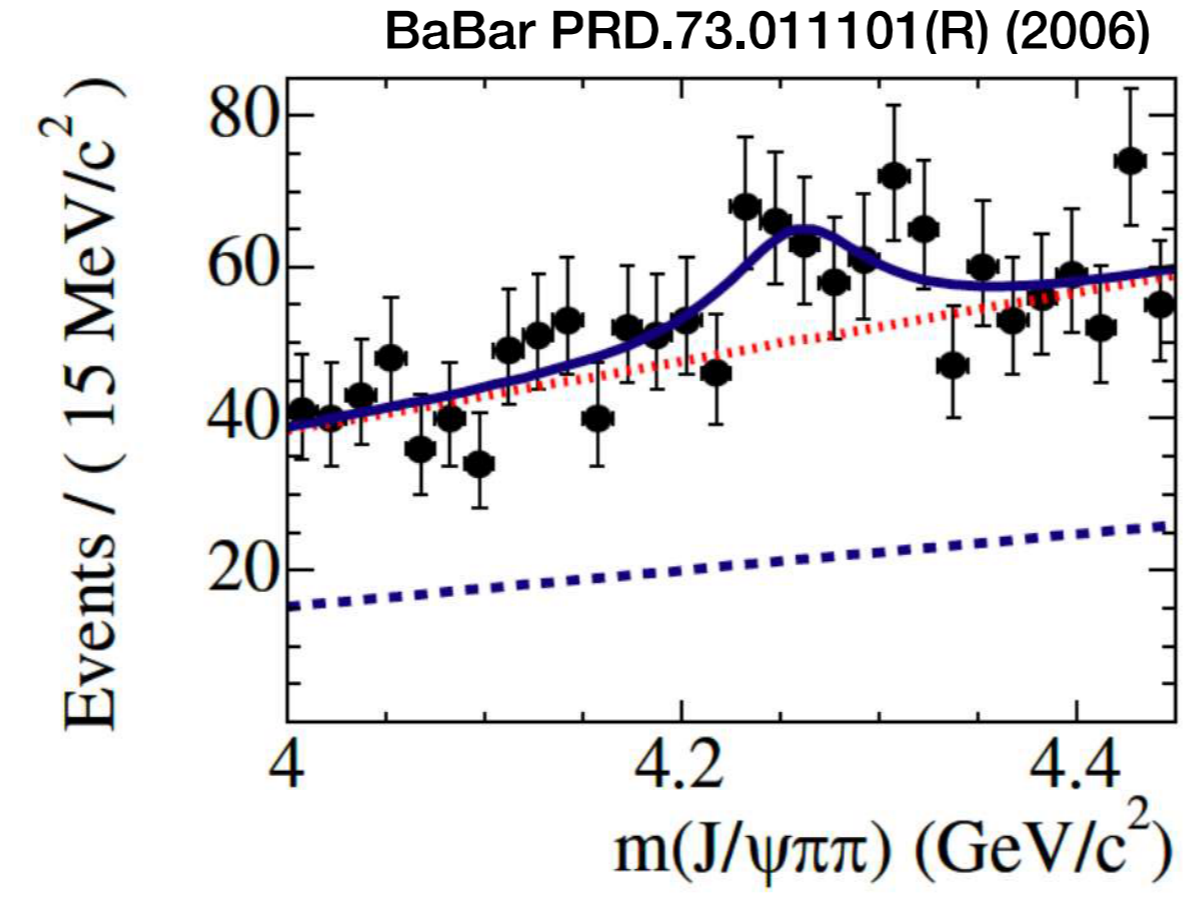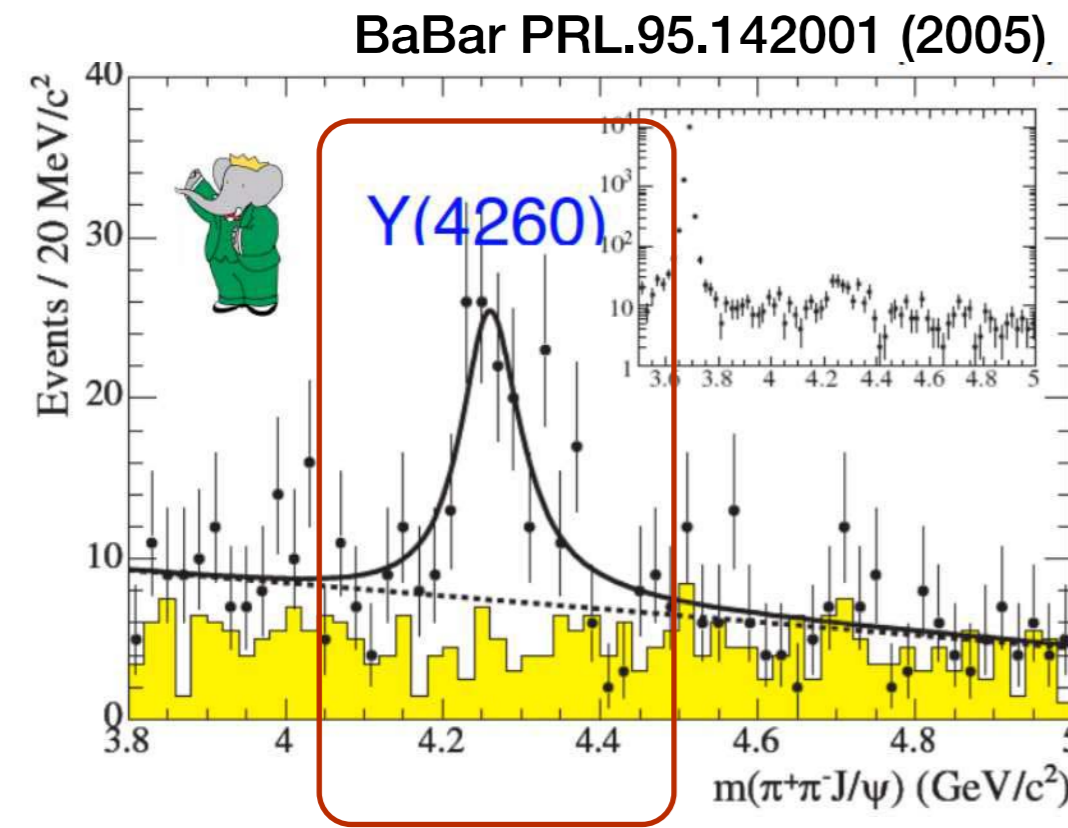
Y(4260)

How many states?

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

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 $3.0 \times 10^{-8} - 1.8 \times 10^{-6}$
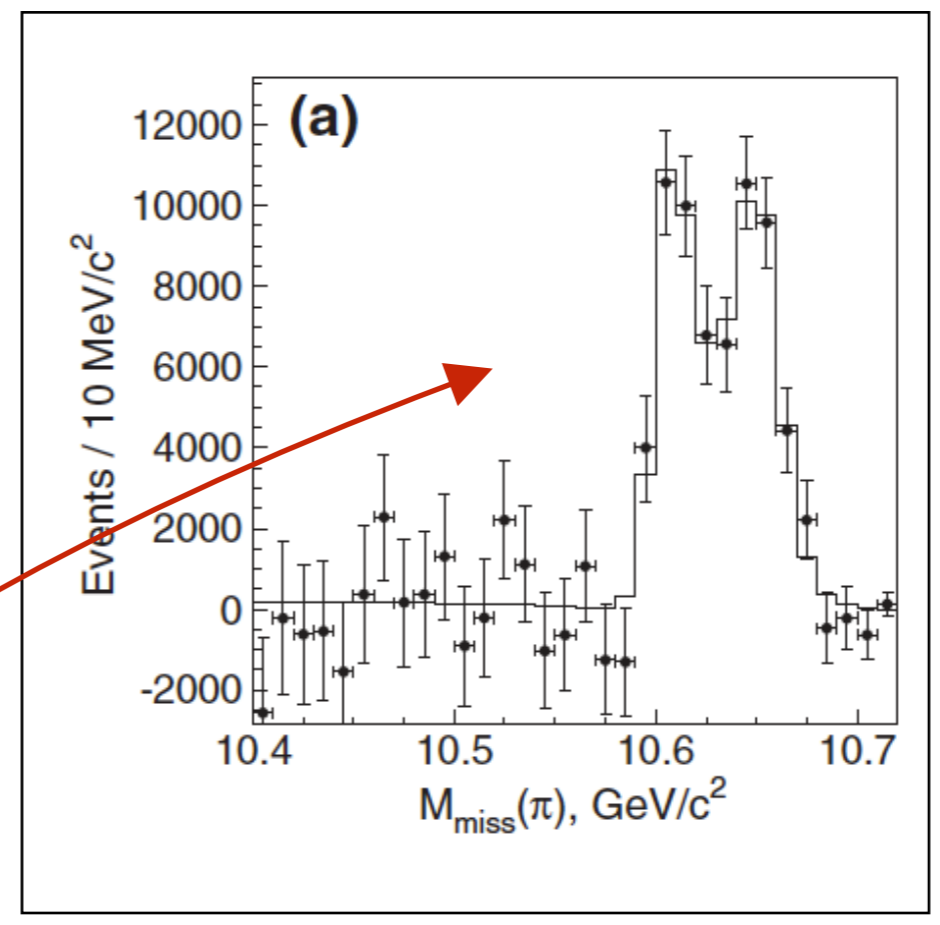
Improved by factor of 2

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

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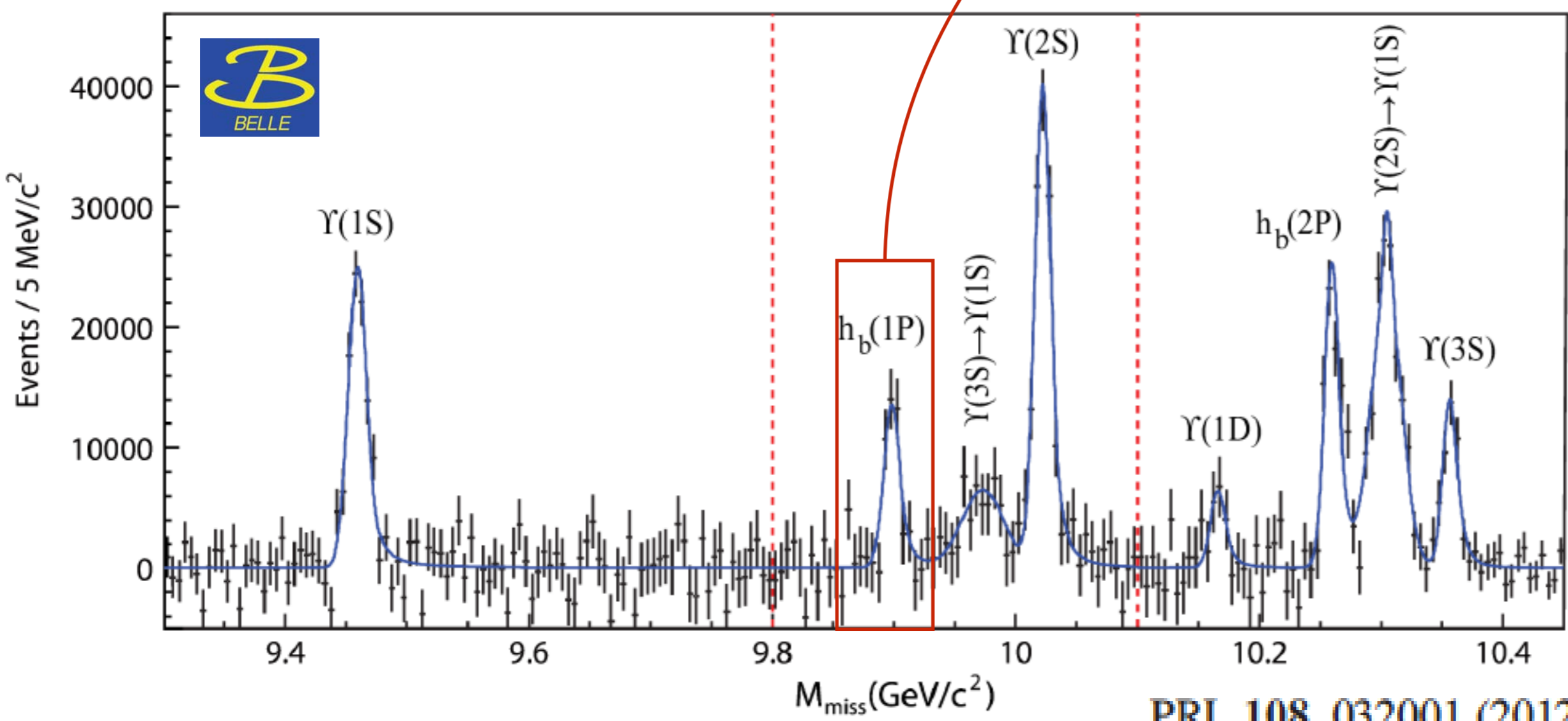
New upper limit

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)

(a)
Events / 10 MeV/c^2
$M_{miss}(\pi)$, GeV/c^2

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

Events / 5 MeV/c^2

$\Upsilon(1S)$
$h_b(1P)$
$\Upsilon(3S)\rightarrow\Upsilon(1S)$
$\Upsilon(2S)$
$\Upsilon(1D)$
$h_b(2P)$
$\Upsilon(2S)\rightarrow\Upsilon(1S)$
$\Upsilon(3S)$

$M_{miss}(GeV/c^2)$

PRL 108, 032001 (2012)

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

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]	$\Upsilon(nS)\omega$

# 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

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

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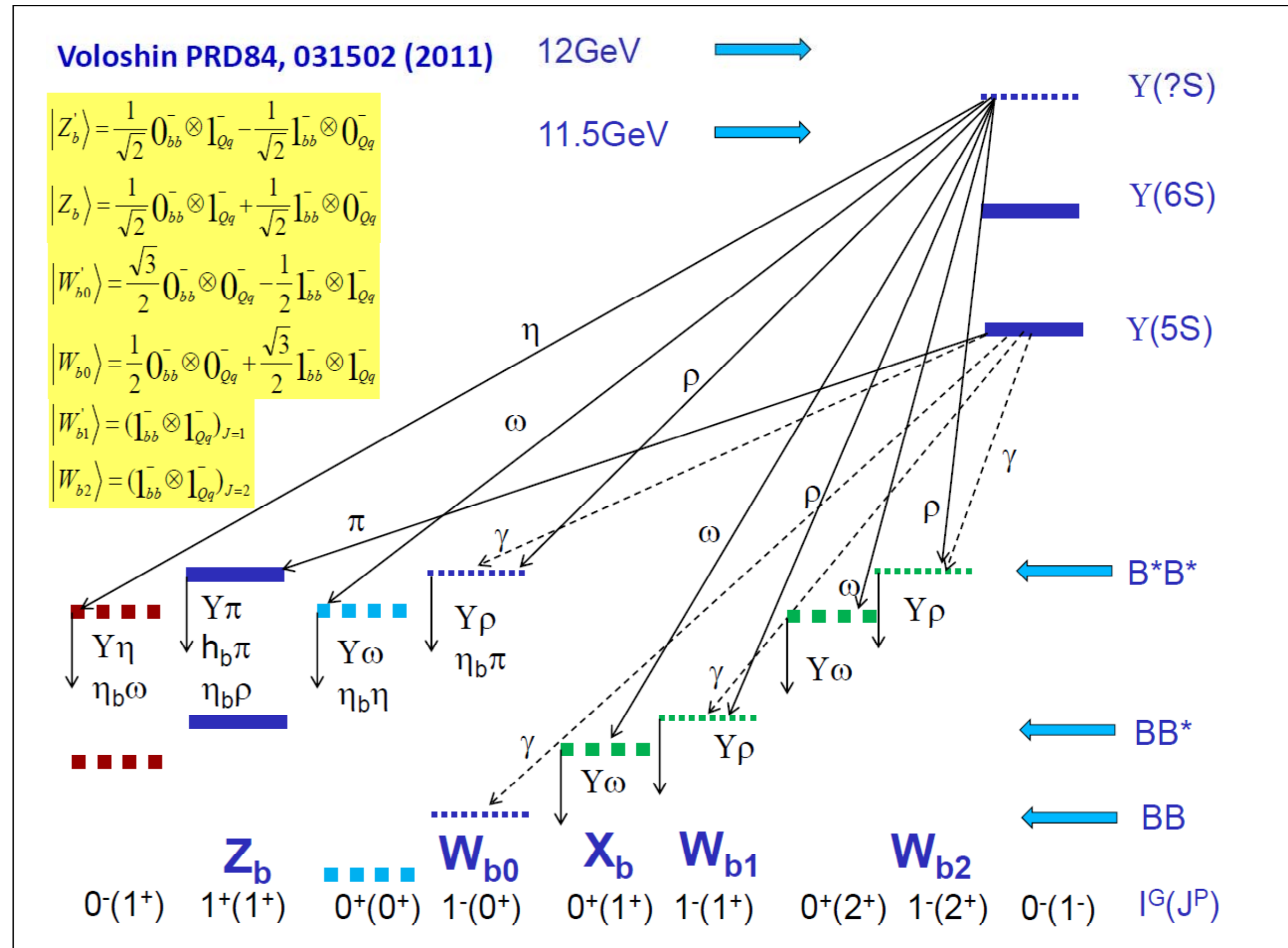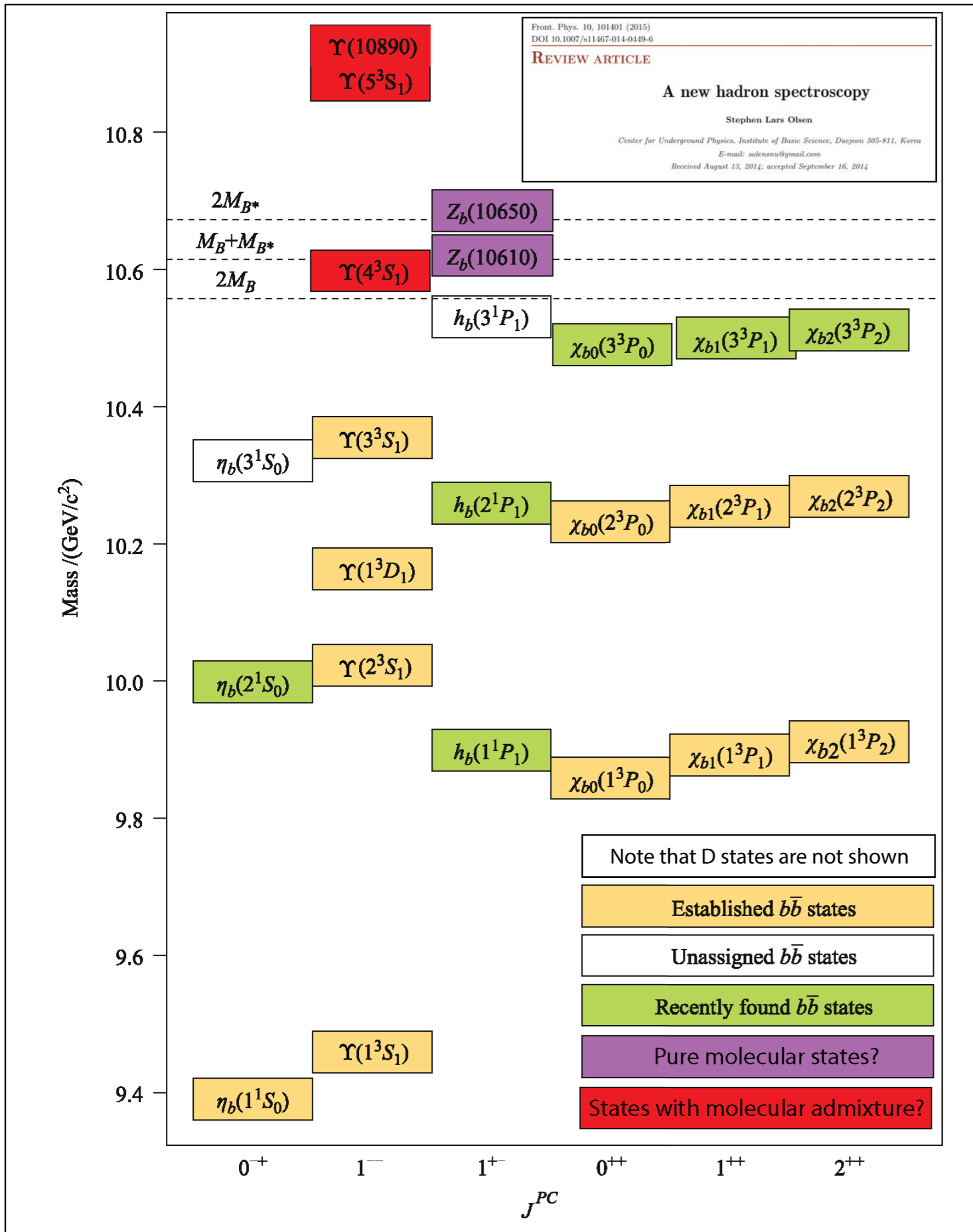
$$\vec{T} \equiv (\vec{S}_c \cdot \hat{r})(\vec{S}_{\bar{c}} \cdot \hat{r}) - \frac{1}{3}\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

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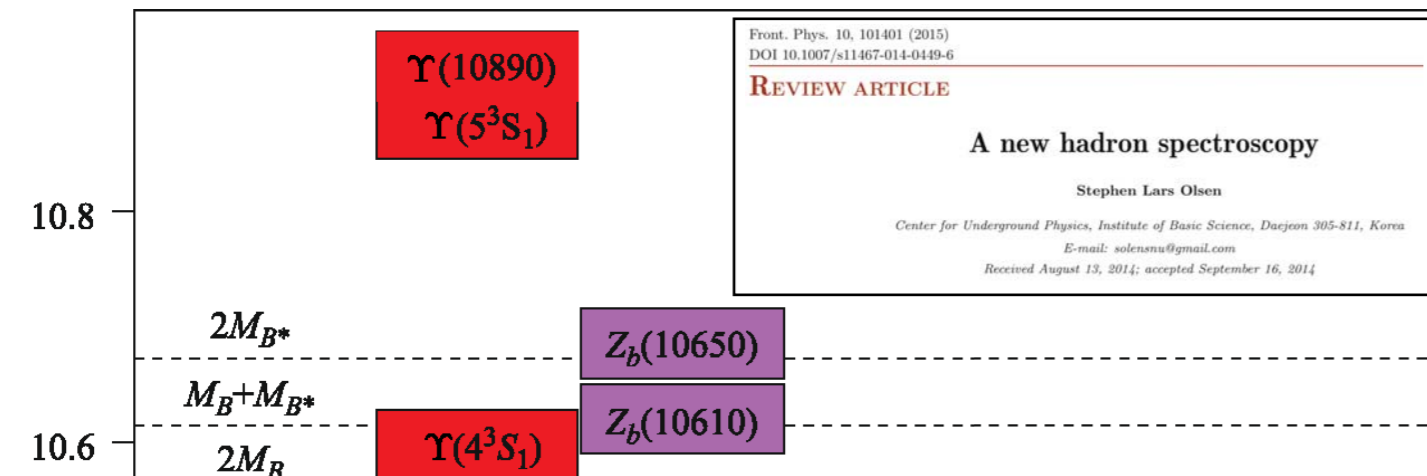

Bottomonium Mass Spectrum
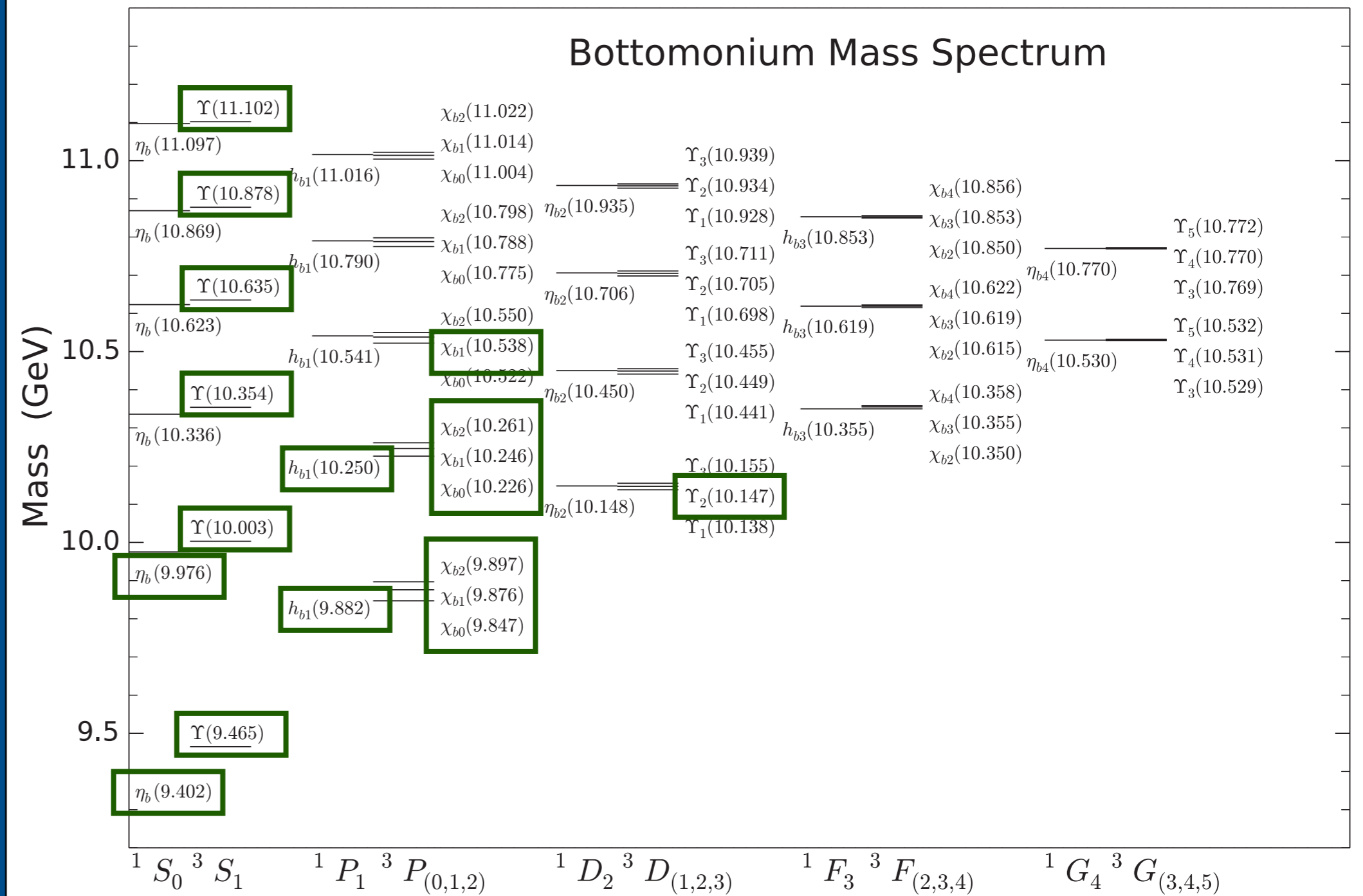
S. Godfrey and K. Moats, Bottomonium mesons and strategies for their observation, Phys. Rev. D 92, 054034 (2015)
S. Godfrey and N. Isgur, Mesons in a relativized quark model with chromodynamics, Phys. Rev. D 32, 189 (1985).

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

$I^G(J^P)$: $1^+(1^+)$ $1^-(0^+)$ $1^-(1^+)$ $1^-(2^+)$

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]

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]

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).

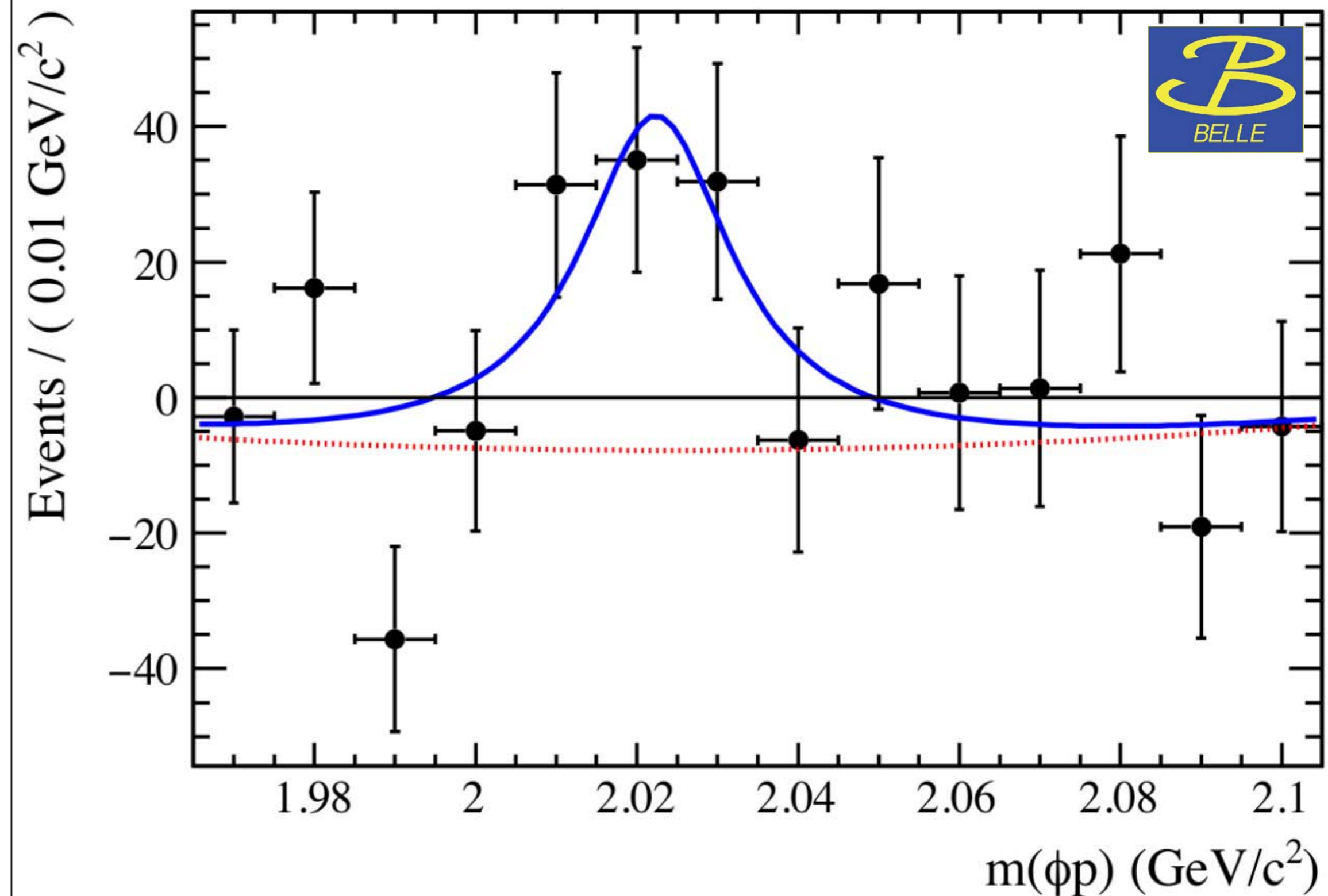**From 2D fit with three components in each bin of shown invariant mass**

Hidden charm

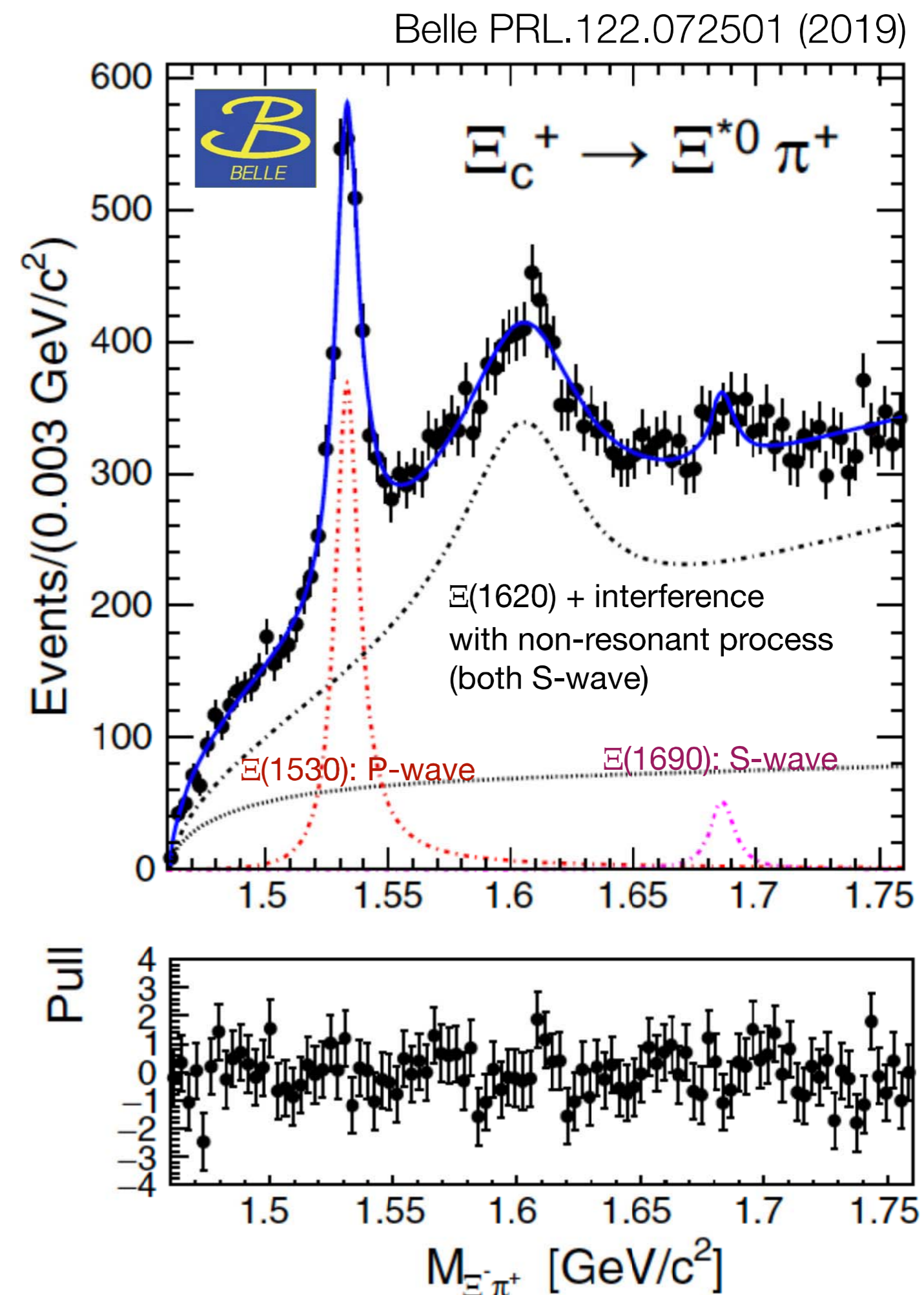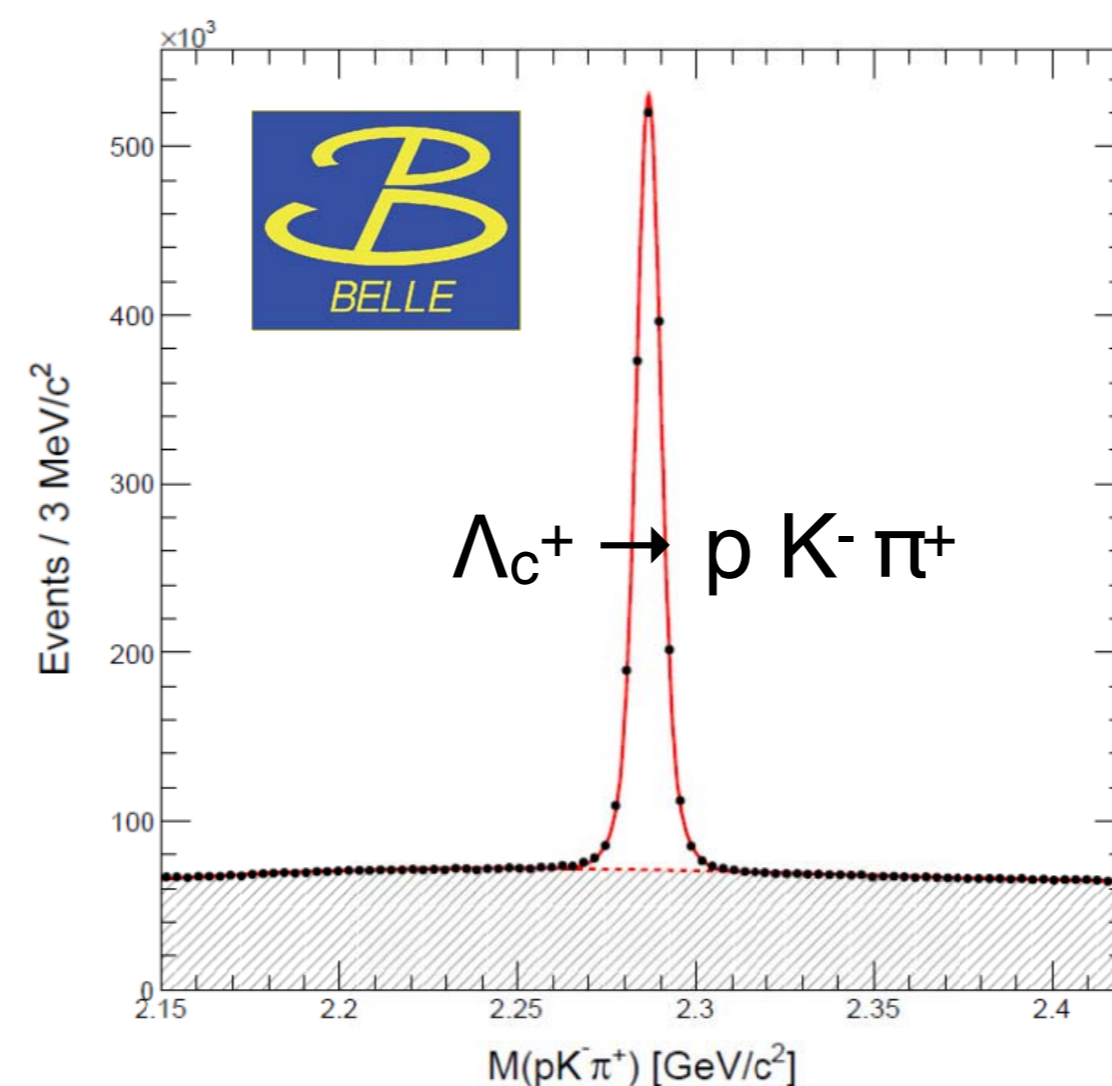**Hidden strangeness**

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

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

- 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)

$\Xi_c^+ \to \Xi^{*0}\pi^+$

Ξ(1620) + interference
with non-resonant process
(both S-wave)

Ξ(1530): P-wave

Ξ(1690): S-wave

$M_{\Xi^-\pi^+}$ [GeV/c^2]

$\Lambda_c^+ \to p\,K^-\,\pi^+$

M(pK$^-\pi^+$) [GeV/c^2]

$$\int L\,dt = 472\ pb^{-1}$$

Belle II 2018

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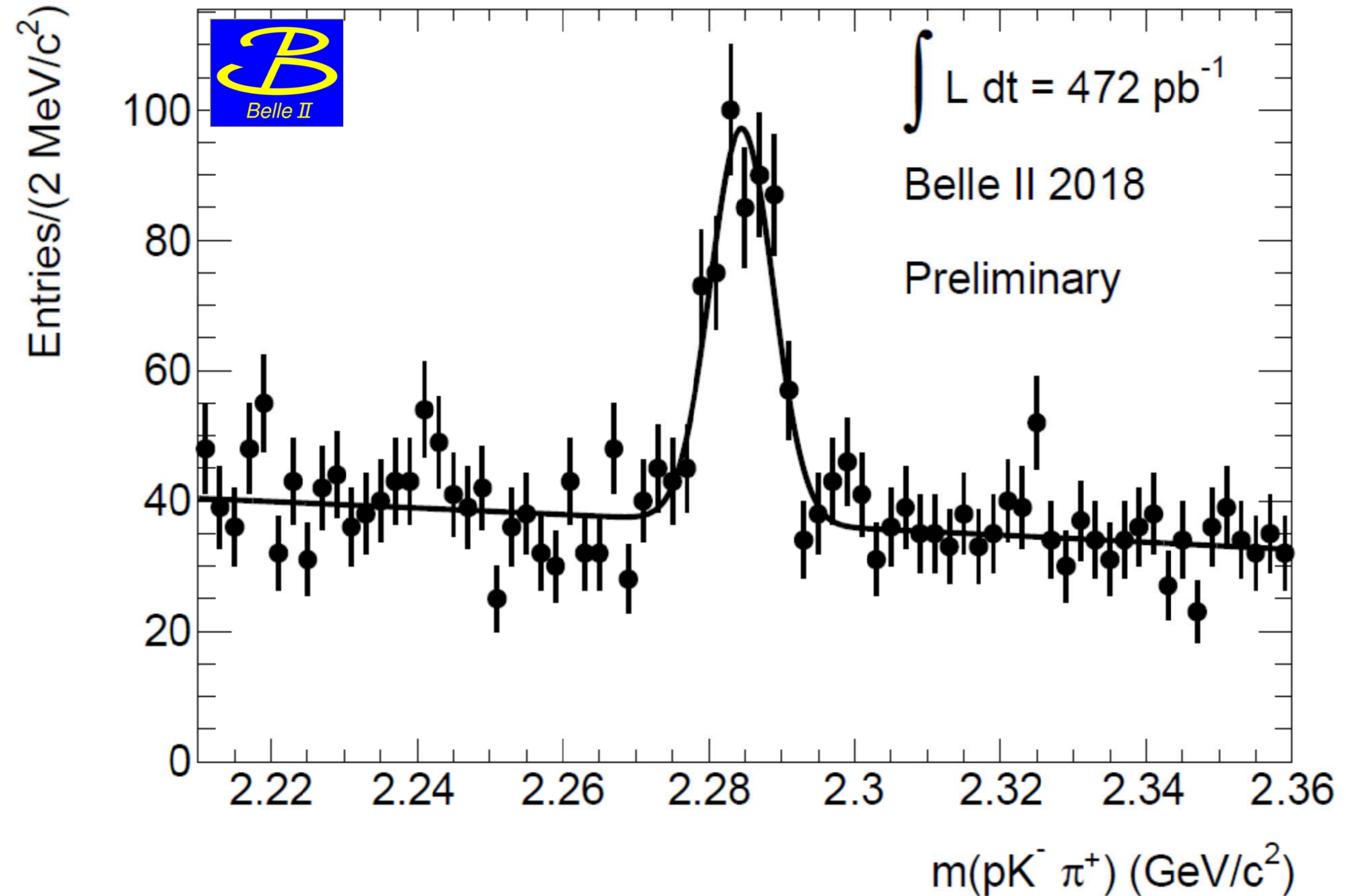
- Observed in combinations of J=1 and J=0

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

➡ **Belle II**

- angular distributions, production
- probe for new states

Belle, PRL 98, 082001 (2005)
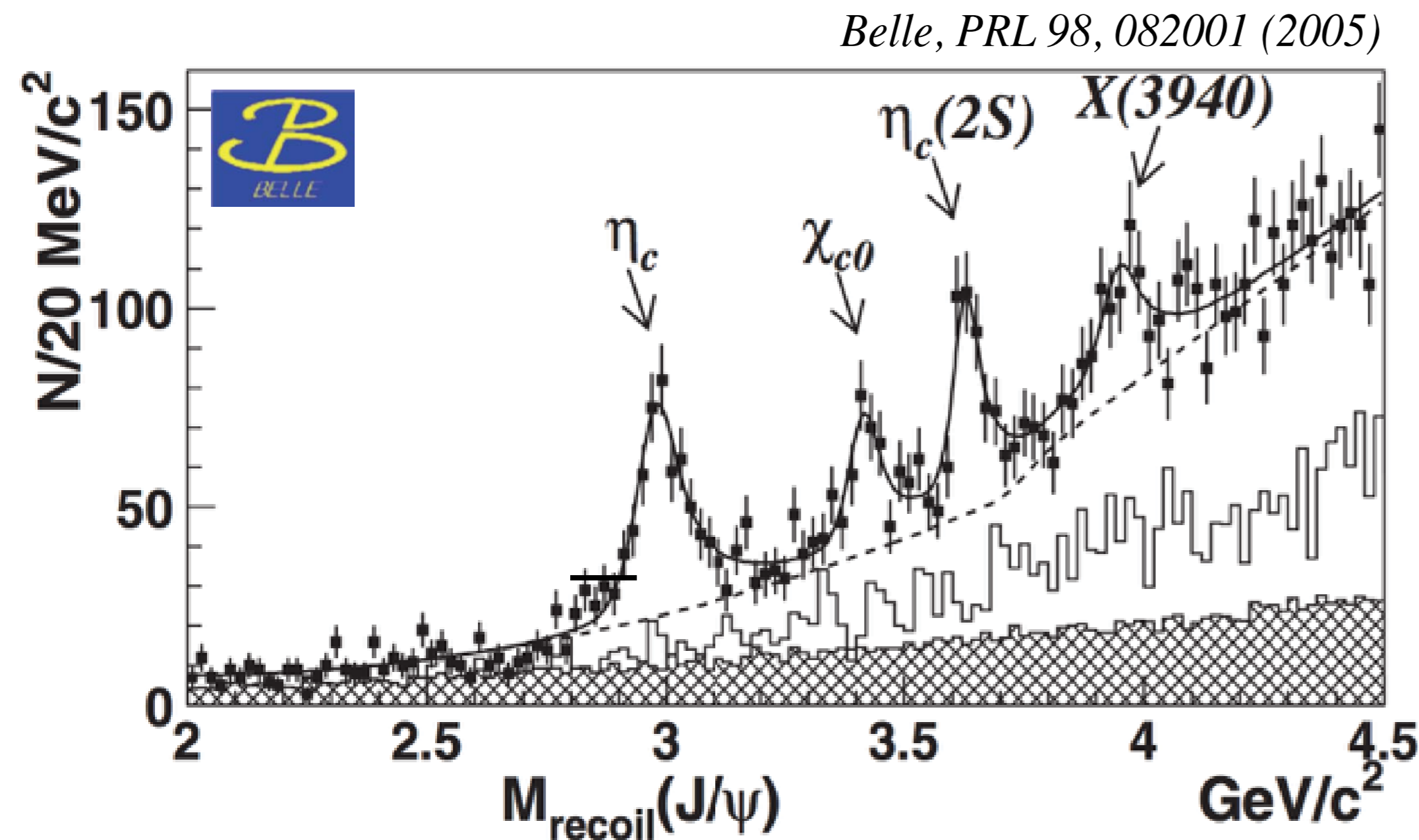
Also, from Belle II Physics Book (arXiv:1808.10567 [hep-ex]):

The discovery of a number of double-charmonium production processes in e^+e^- annihilation at B-factories was initiated by the observation of $e^+e^- \rightarrow J/\psi X$, 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 $e^+e^- \rightarrow J/\psi \eta_c$ 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.

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 $10\,\text{fb}^{-1}$ 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.

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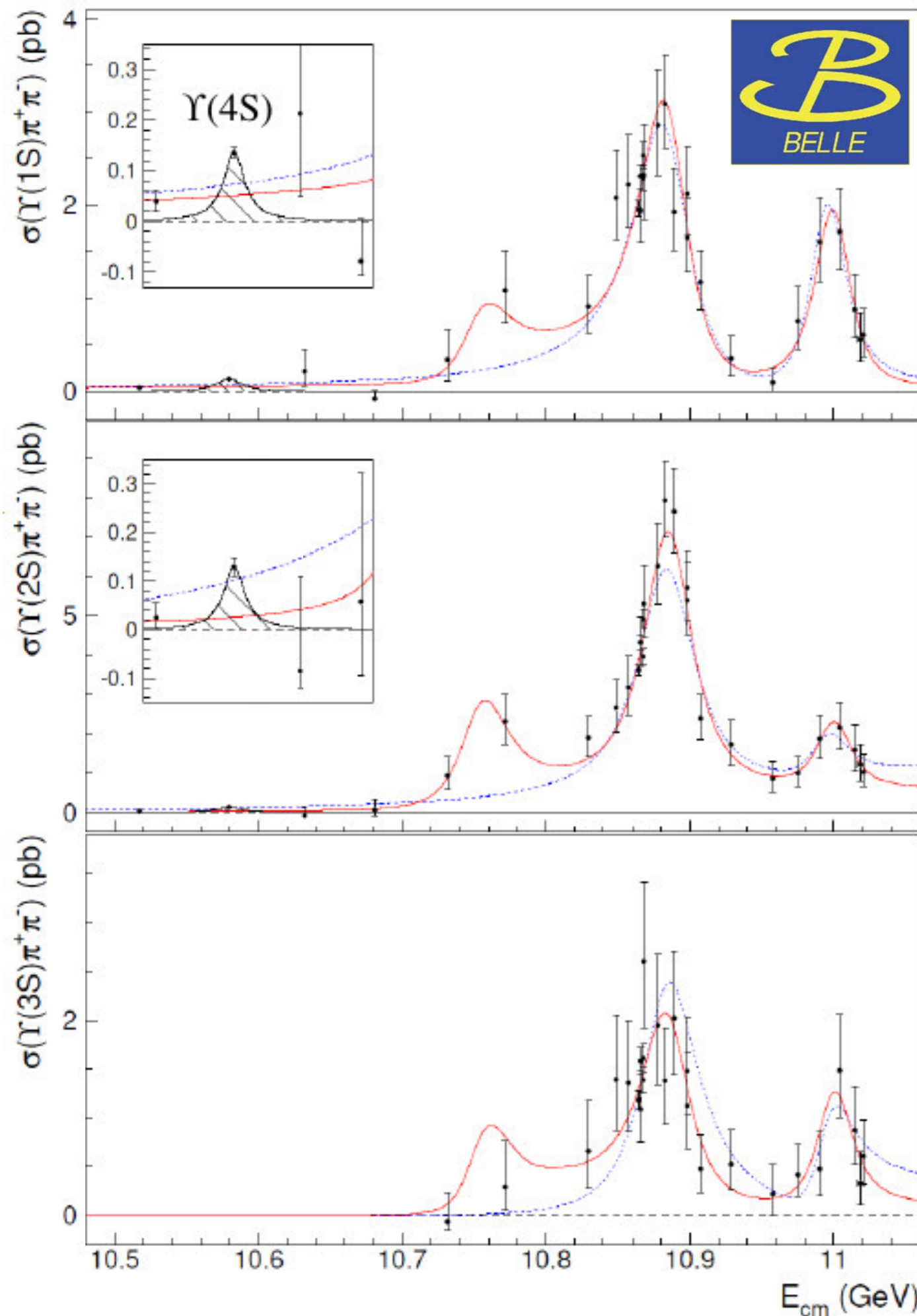
$$e^+ e^- \to \Upsilon(nS)\pi^+\pi^- \quad (n = 1, 2, 3)$$

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

- Maximal energy of SuperKEKB is expected to be $11.24\,\text{GeV}$. The region above this energy is previously unexplored and it is of paramount importance to increase the energy. There is a $\Lambda_b\bar{\Lambda}_b$ threshold at $11.24\,\text{GeV}$ with potentially interesting baryon-antibaryon dynamics and more promising thresholds all the way up to $12\,\text{GeV}$. 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 $11.5\,\text{GeV}$.

- 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.

- 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.

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}x40

Beam current: ×2 (higher RF power); upgraded components shown in color

Beam size: 1/20 (low emittance, compact and strong focusing quads)

Belle II

e$^+$ 4GeV 3.6 A

e$^-$ 7GeV 2.6 A

LINAC

Positron source

Damping ring

KEKB

Super-KEKB

22mrad

1μm

5mm

100μm

~50nm

83mrad

1μm

5mm

100μm
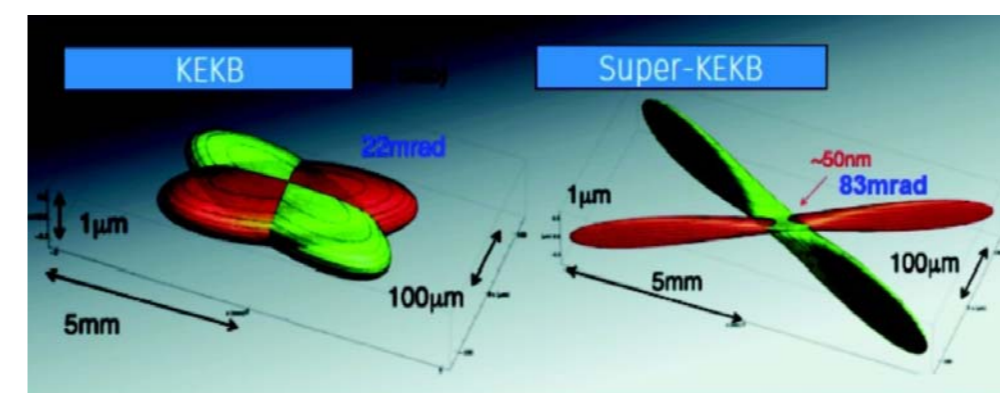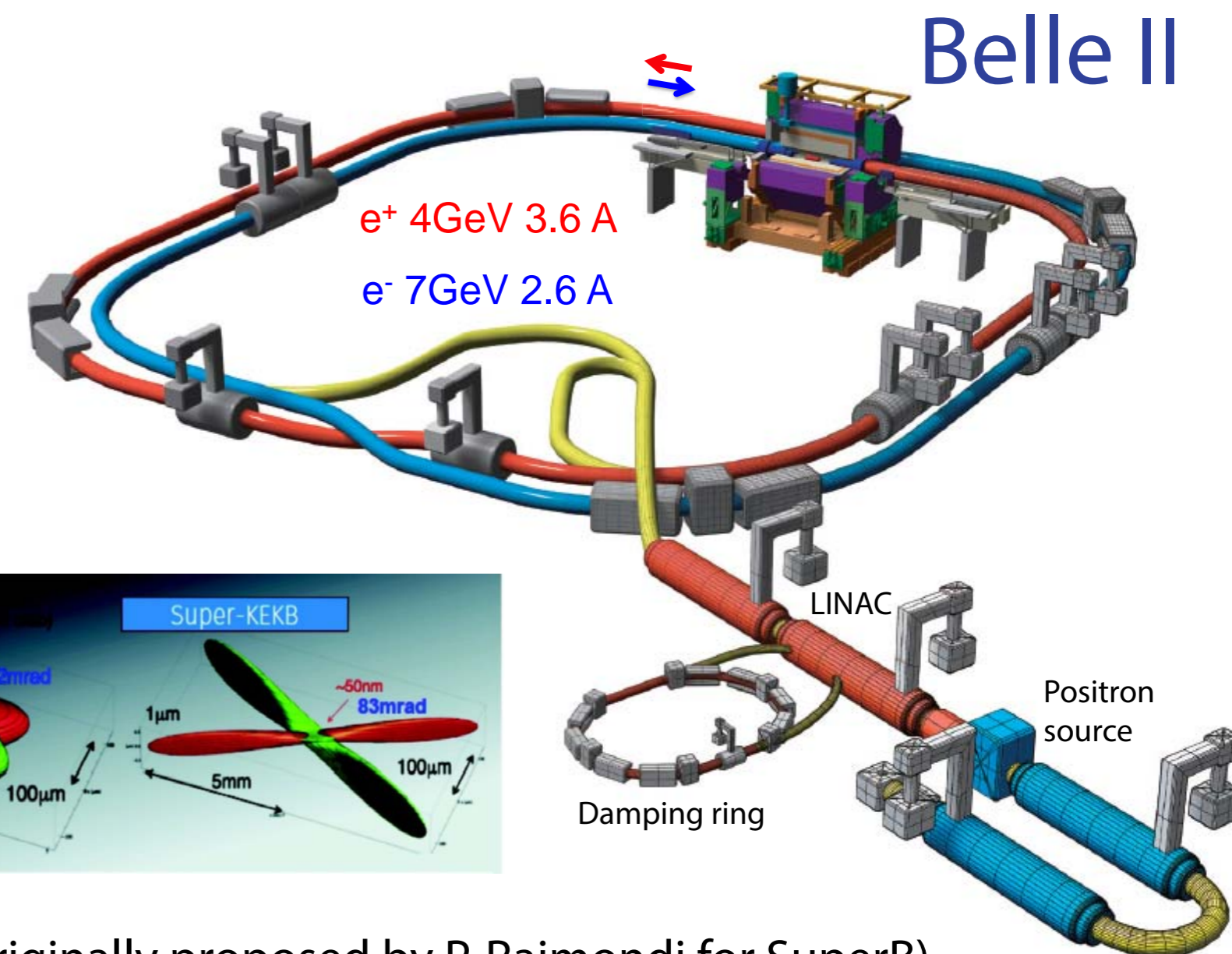
Nanobeams (originally proposed by P. Raimondi for SuperB)
new positron target, reinforced RF cavities, redesigned lattices for LER & HER,
LER: dipoles magnets replaced by longer ones,
TiN-coated LER beampipe with antechambers,
new superconducting focusing quadrupole magnets near IP

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.

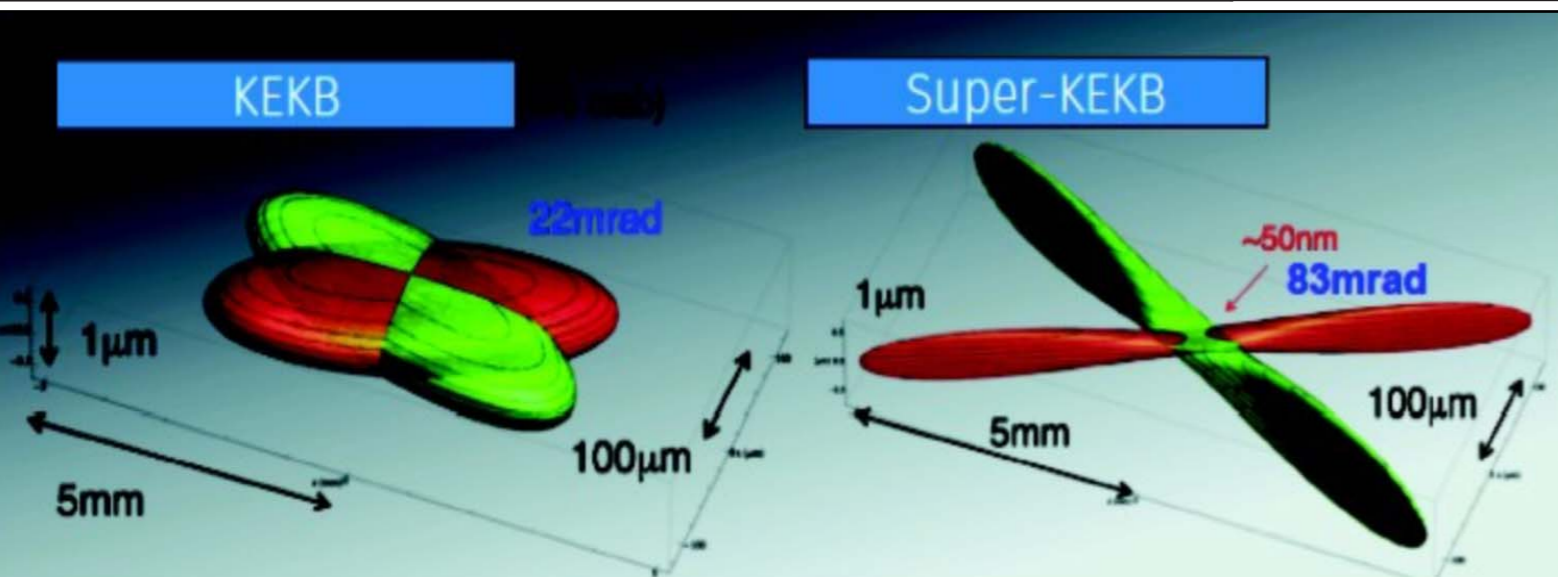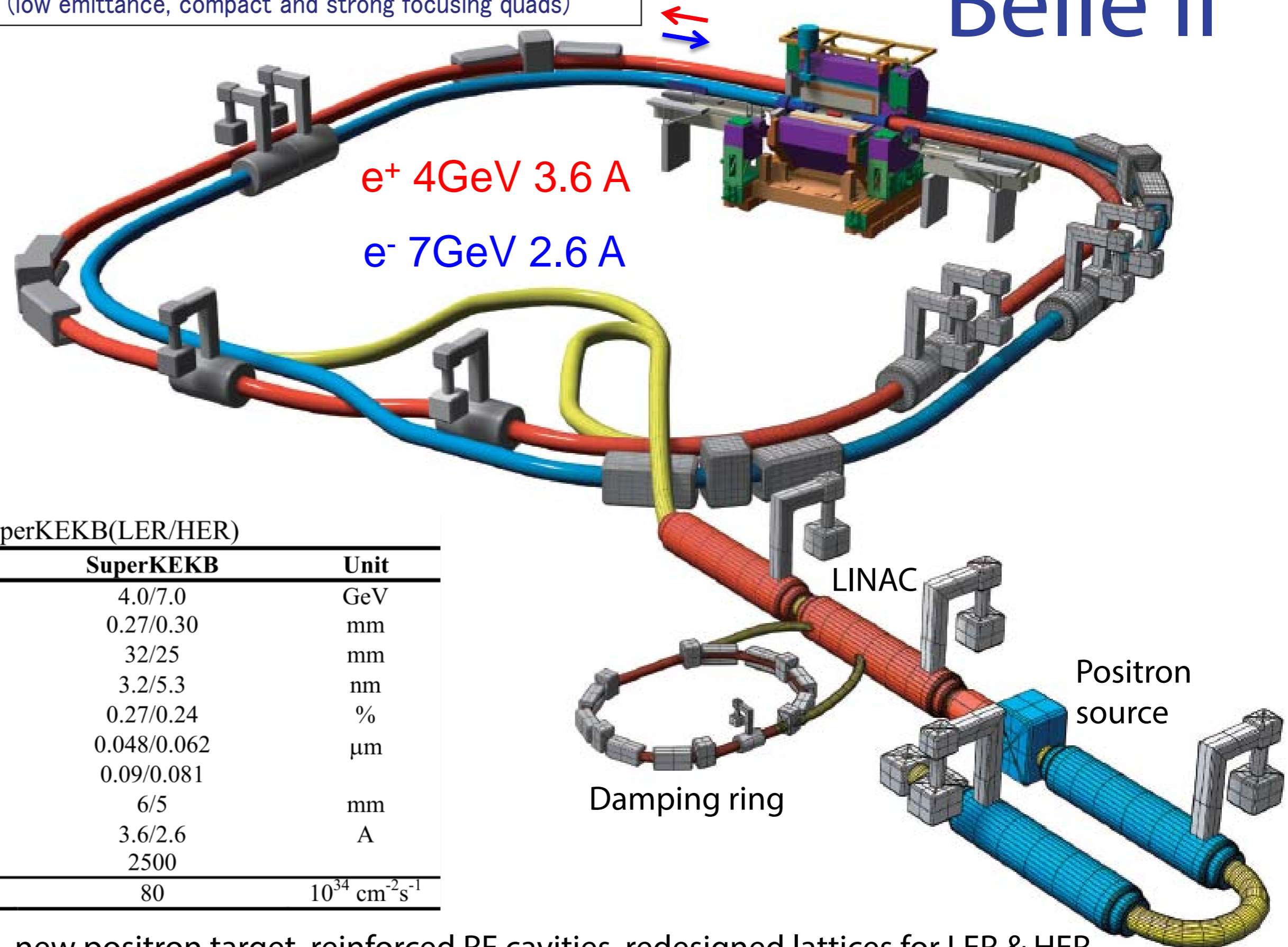- ● The mixing of exotic states with regular quarkonia needs to be investigated.

○ Action items for 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 $X(3872)$.

Target: $L = 8 \times 10^{35}/\text{cm}^2/\text{s}$ = $L_{KEKB} \times 40$

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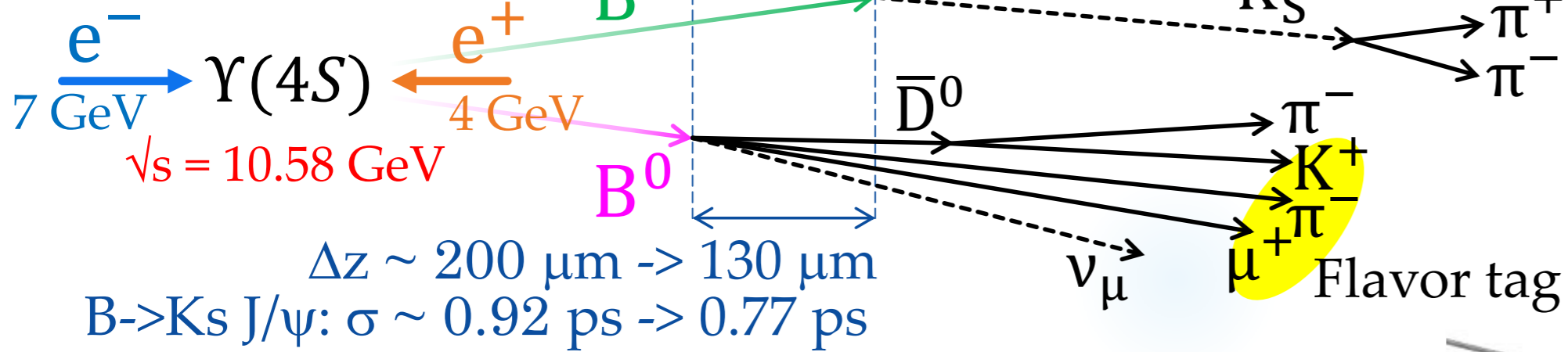
Belle II

KEKB / Super-KEKB

$$L = \frac{\gamma_\pm}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\right)\left(\frac{R_L}{R_{\xi y}}\right) \propto \frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}$$

e^+ 4GeV 3.6 A

e^- 7GeV 2.6 A

LINAC

Positron source

Damping ring

Table 1: Machine parameters of KEKB (LER/HER) and SuperKEKB(LER/HER)

	KEKB design	KEKB Achieved: with crab	SuperKEKB	Unit
Energy	3.5/8.0	3.5/8.0	4.0/7.0	GeV
β_y^*	10/10	5.9/5.9	0.27/0.30	mm
β_x^*	330/330	1200/1200	32/25	mm
ε_x	18/18	18/24	3.2/5.3	nm
x-y coupling ($\varepsilon_y/\varepsilon_x$)	1	0.85/0.64	0.27/0.24	%
σ_y^*	1.9	0.94	0.048/0.062	μm
ξ_y	0.052	0.129/0.090	0.09/0.081	
σ_z	4	6-7	6/5	mm
I	2.6/1.1	1.64/1.19	3.6/2.6	A
N_{bunch}	5000	1584	2500	
Luminosity	1	2.11	80	$10^{34}\ \text{cm}^{-2}\text{s}^{-1}$

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

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

e^- $\Upsilon(4S)$ e^+
7 GeV 4 GeV
$\sqrt{s} = 10.58$ GeV

$\overline{B}^0$
B^0

J/Ψ μ^+
μ^-
K_S π^+
π^-

$\overline{D}^0$ π^-
K^+
π^-
ν_μ μ^+ Flavor tag

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

Beryllium beam pipe in the interaction region: diameter decreased from 3cm to 2cm

Vertex detector (VXD): two layers of pixels followed by four double-layered silicon strips

Center drift chamber: smaller cells (than @Belle), faster electronics, improved triggering capabilities

PID: compact Time-of-Propagation (TOP) barrel and proximity focusing aerogel endcap Cherenkov detectors
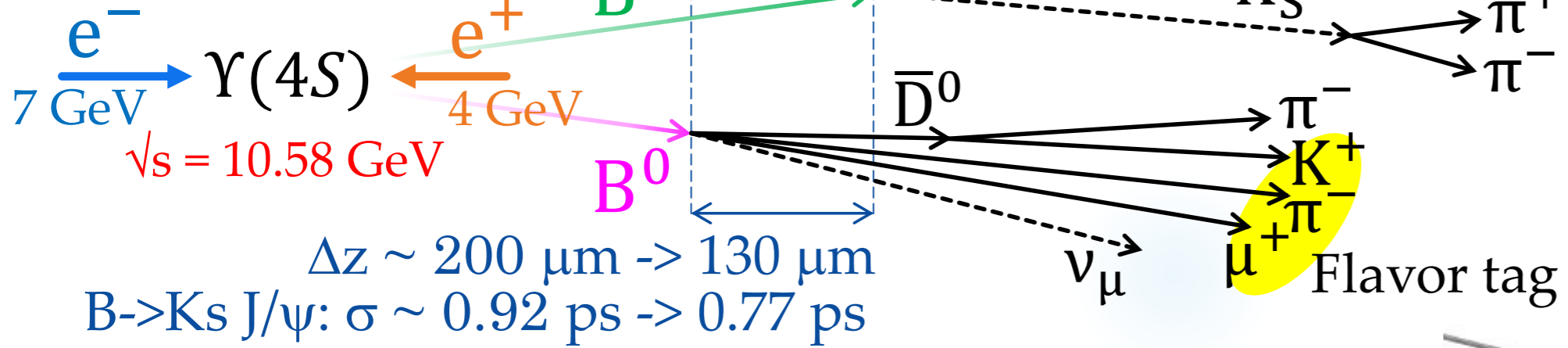
EM calorimeter: Same CsI(Tl) crystals, upgraded electronics (shaper based on digital signal processing)

K_L and µ identification: RPCs replaced by scintillators in the endcap and two inner barrel layers, new electronics, triggering

electron beam (7GeV)

positron beam (4GeV)
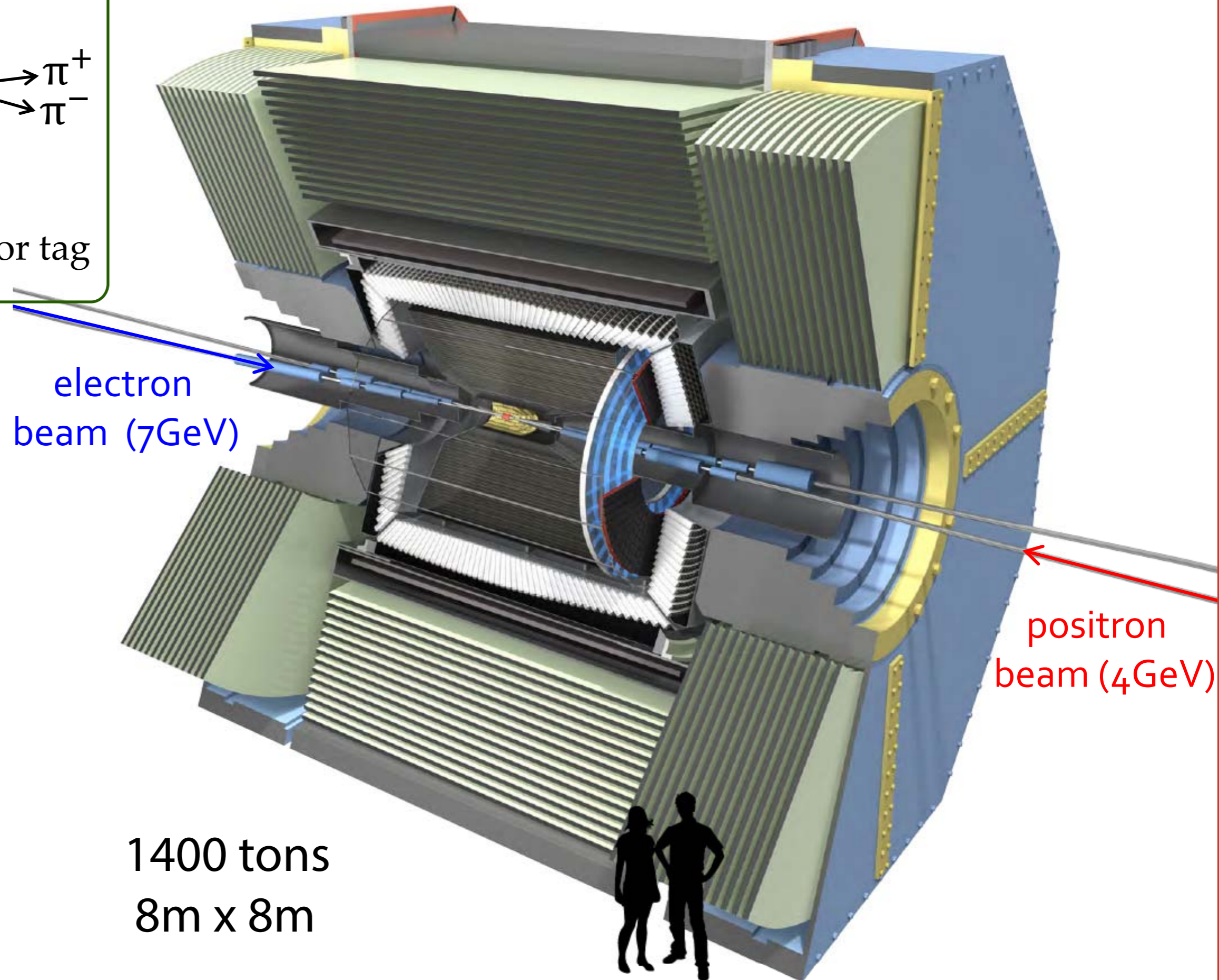
1400 tons
8m x 8m

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

$\overline{B}^0$

e^- $\xrightarrow{}$ $\Upsilon(4S)$ $\xleftarrow{}$ e^+
7 GeV $\qquad\qquad$ 4 GeV
$\sqrt{s} = 10.58$ GeV

B^0

$J/\Psi \to \mu^+ \mu^-$

$K_S \to \pi^+ \pi^-$

$\overline{D}^0 \to \pi^- K^+ \pi^-$

$\mu^+ \pi^-$ Flavor tag

ν_μ

$\Delta z \sim 200\ \mu m \to 130\ \mu m$
$B \to K_S\ J/\psi$: $\sigma \sim 0.92$ ps $\to 0.77$ ps

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K_L **and μ identification:** RPC replaced by scintillators in the endcap and two inner barrel layers, new electronics, triggering

VXD: beam-related background tolerant

Improved impact parameter resolution

Better z vertex resolution

Approx. 30% better inv. mass resolution

~30% increase in K_S efficiency

Improved K / π separation

Decreased π fake rate by the factor of ~2.5

Improved slow (~100MeV/c) π reconstruction

Improved π^0 reconstruction

electron beam (7GeV)

positron beam (4GeV)

1400 tons
8m x 8m
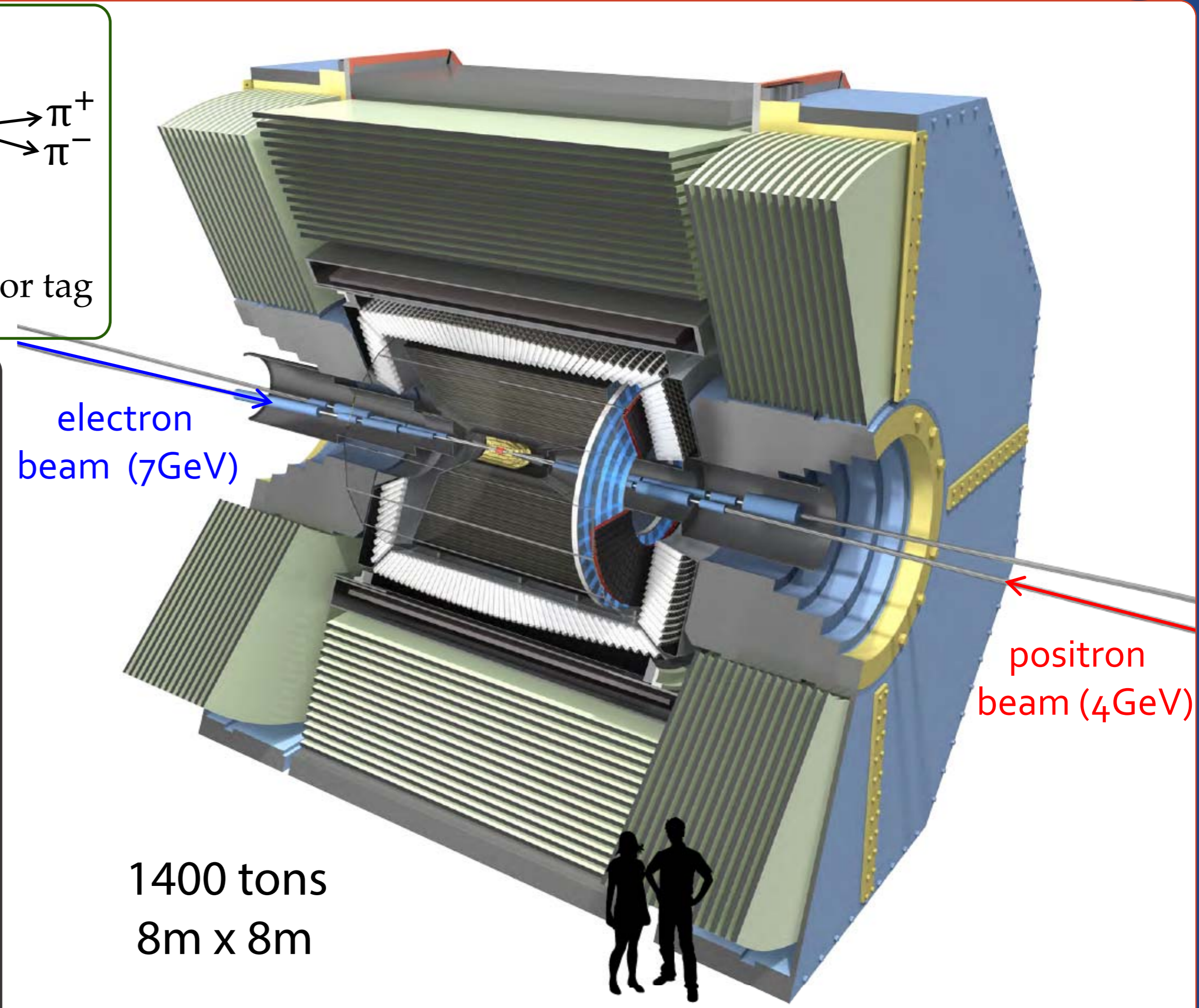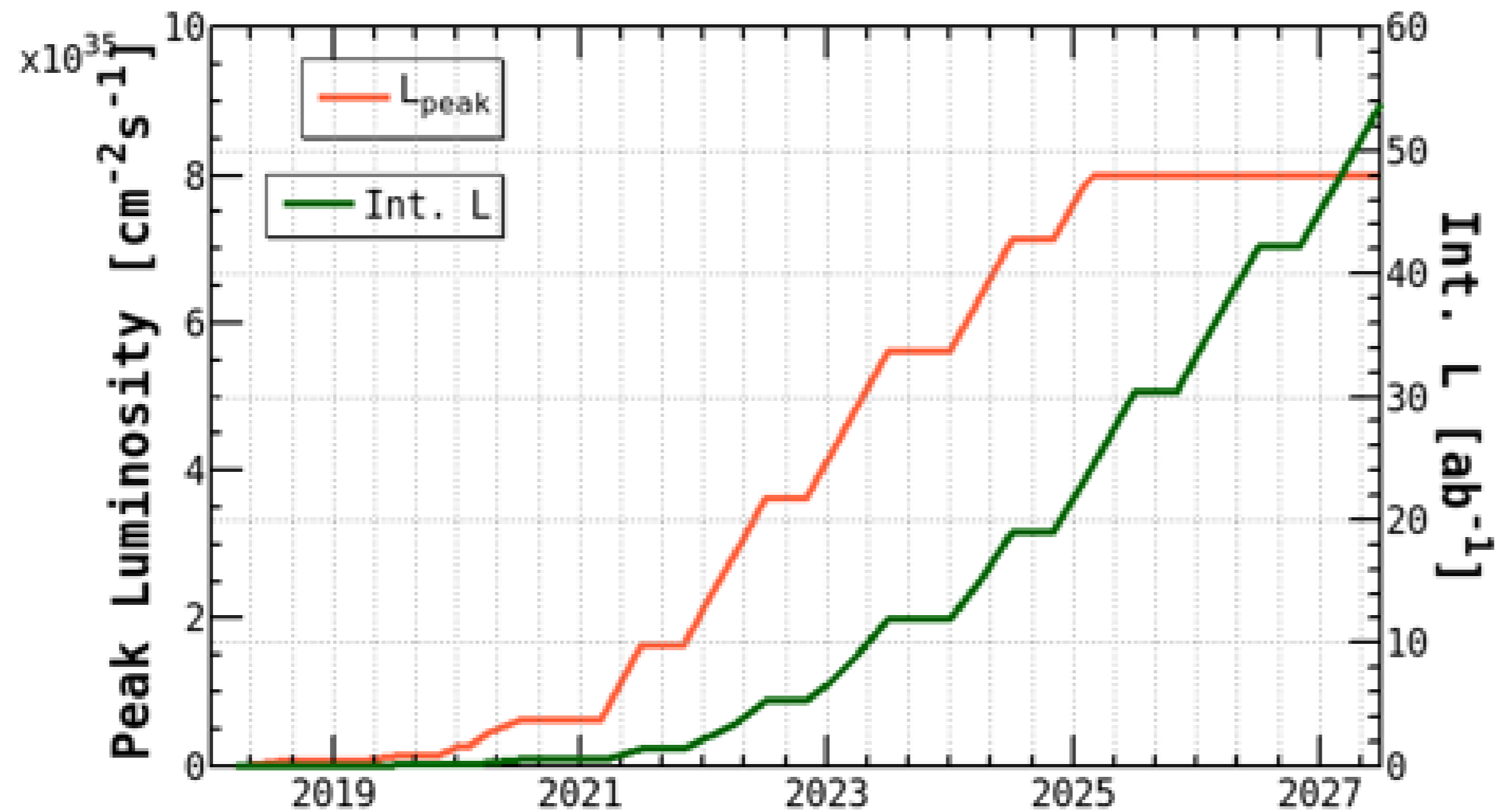
Belle: 1 ab⁻¹

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)**	**5×10^4 (5.4×10^4)**	**1000 (300)**	**100+400 (scan)**	**3.6%**

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., Y(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)
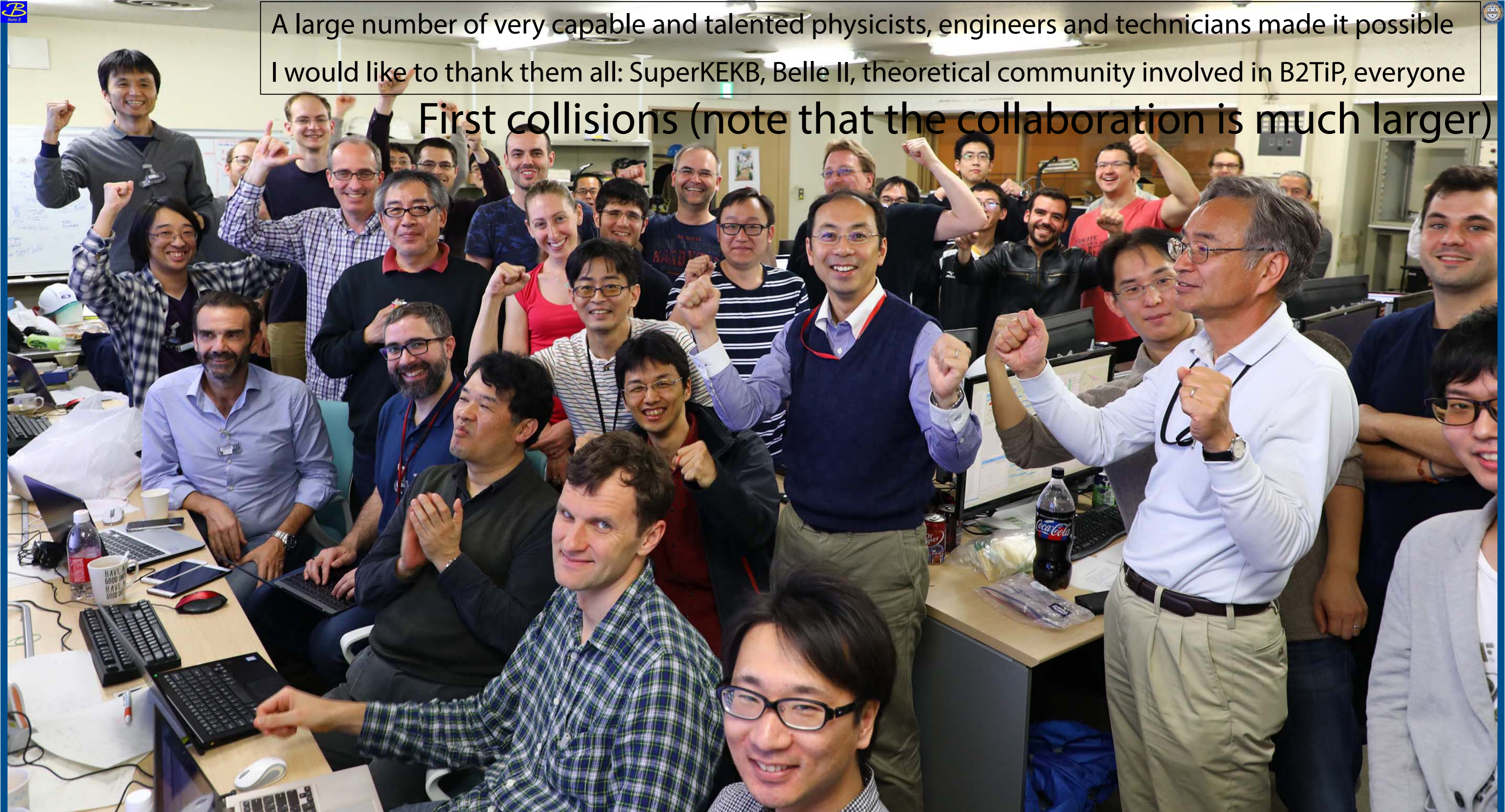
BACKUP slides
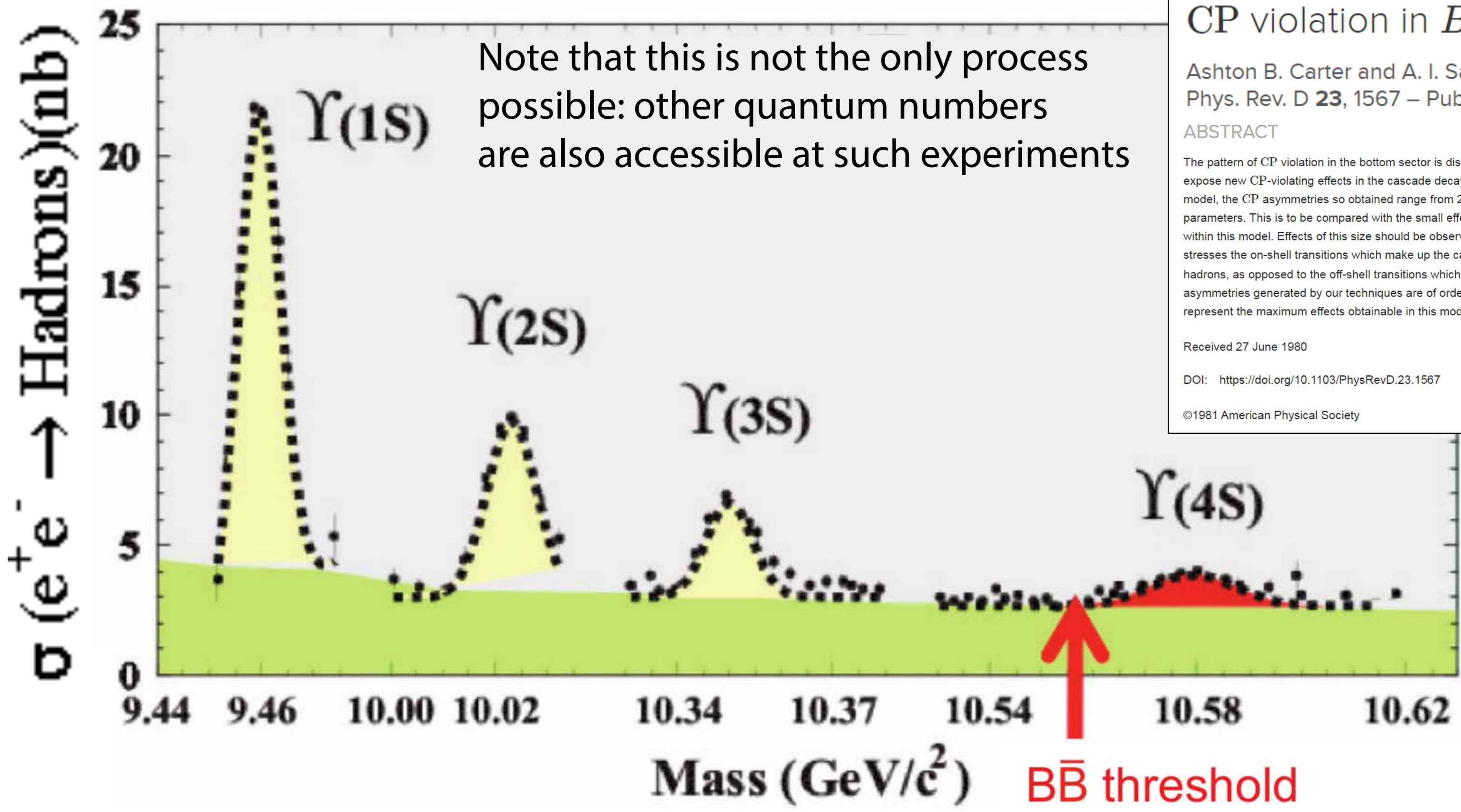
Note that this is not the only process possible: other quantum numbers are also accessible at such experiments
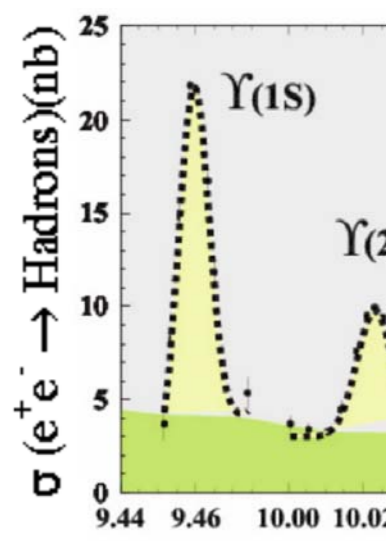
Asymmetry between the energies of the beams increases

the distance between the decay vertices of the two B mesons

therefore making the measurement of oscillations possible

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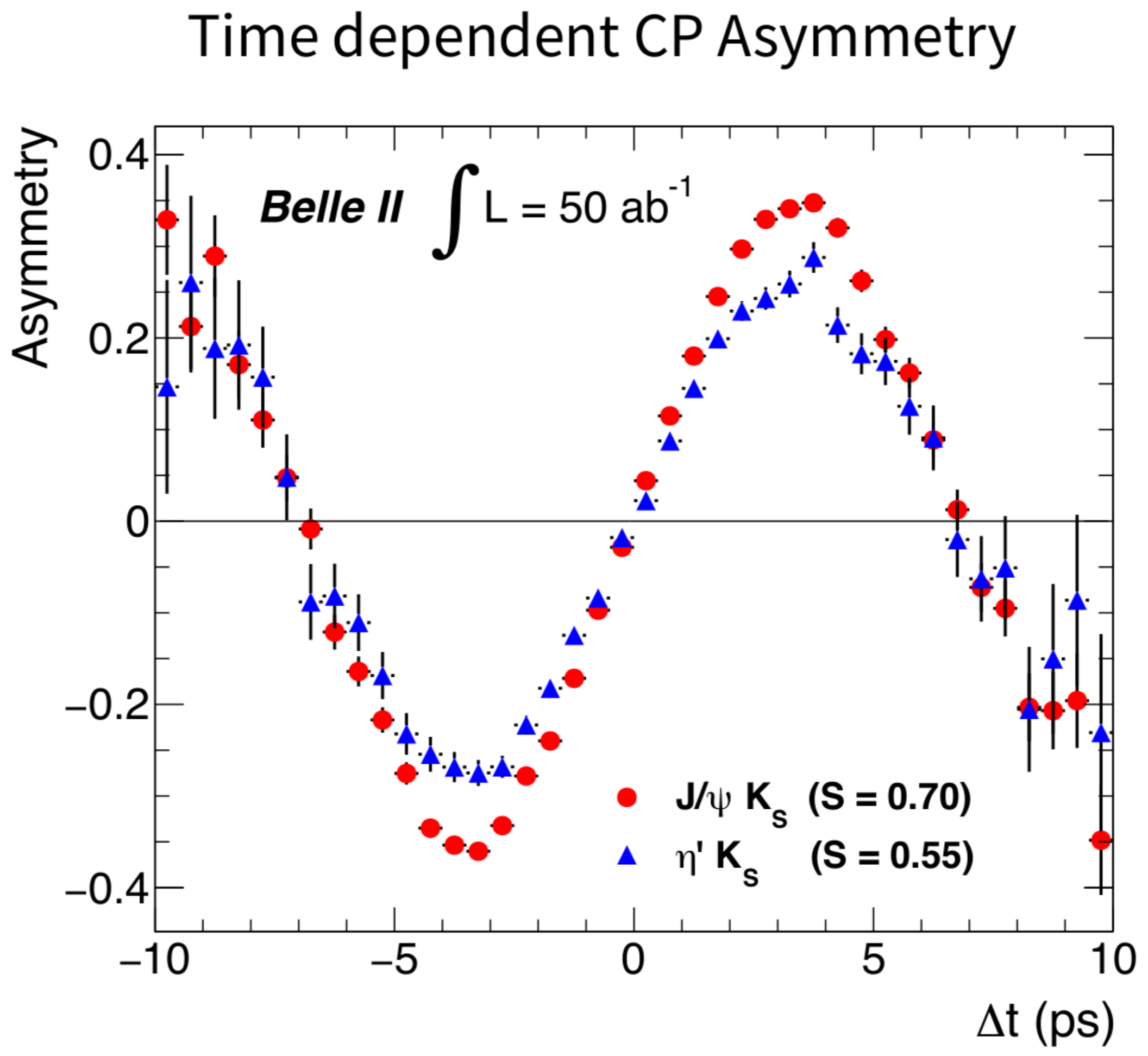SuperKEKB: $\beta\gamma = 0.28$

e^-
7 GeV

$\Upsilon(4S)$

e^+
4 GeV

$\sqrt{s} = 10.58$ GeV

$\overline{B}^0$

B^0

J/Ψ

μ^+

μ^-

K_S

π^+

π^-

$\overline{D}^0$

π^-

K^+

π^-

μ^+

ν_μ

Flavor tag

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

Time dependent CP Asymmetry

Belle II $\int L = 50\ ab^{-1}$

- ● $J/\psi\ K_S$ (S = 0.70)
- ▲ $\eta'\ K_S$ (S = 0.55)

Δt (ps)