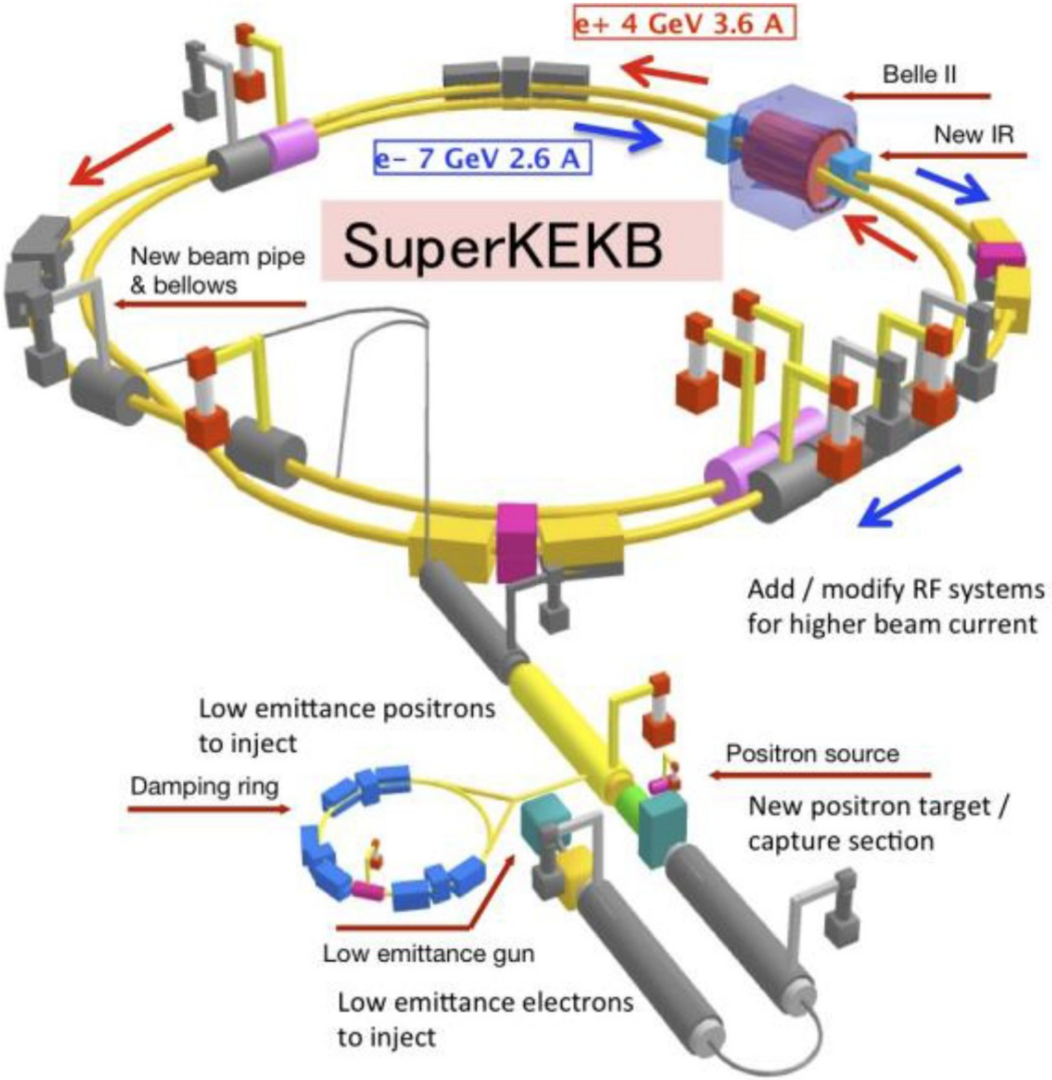
Exotic and Conventional Quarkonium Physics Prospects at

Belle II

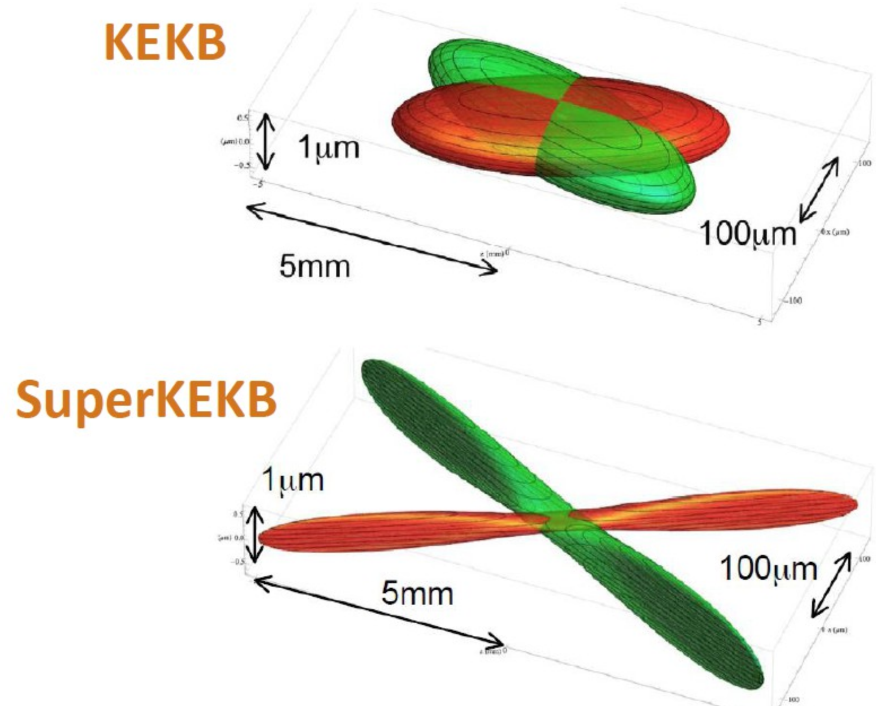
Roberto Mussa
INFN Torino

Confinement XIII , Maynooth University, August 2, 2018

From KEKB to Super-KEKB



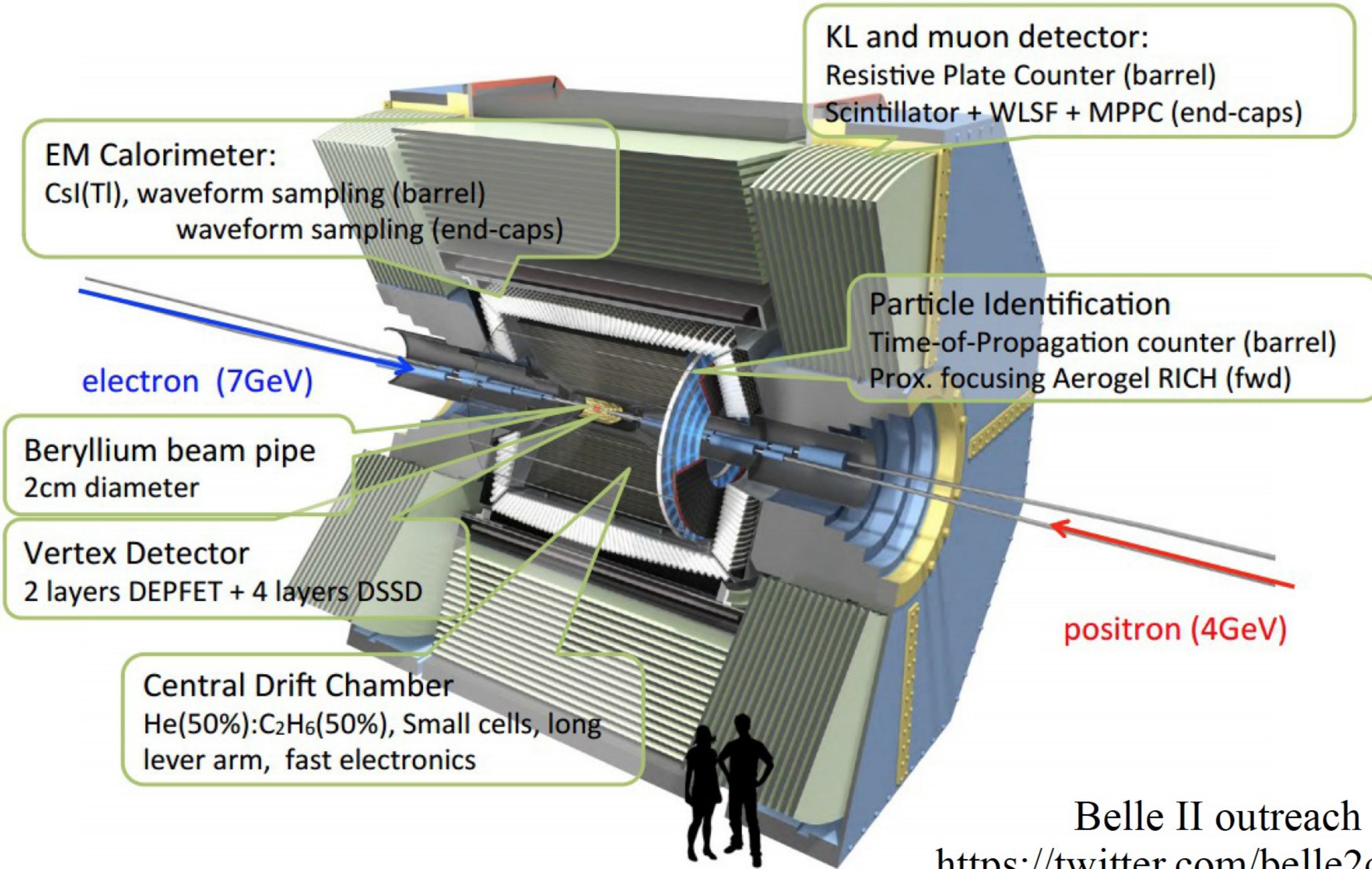
- "Nano-beam" interaction point
- Increase in current
- Factor of 40x increase in luminosity
- Energy: e^- (7 GeV) e^+ (4 GeV)



And almost 2x people!

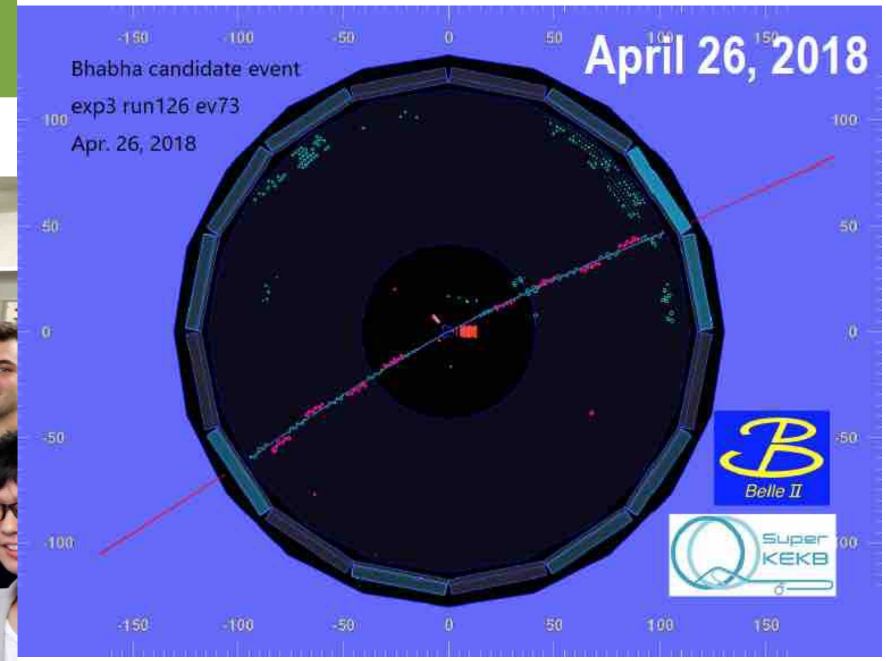
Belle-II Detector

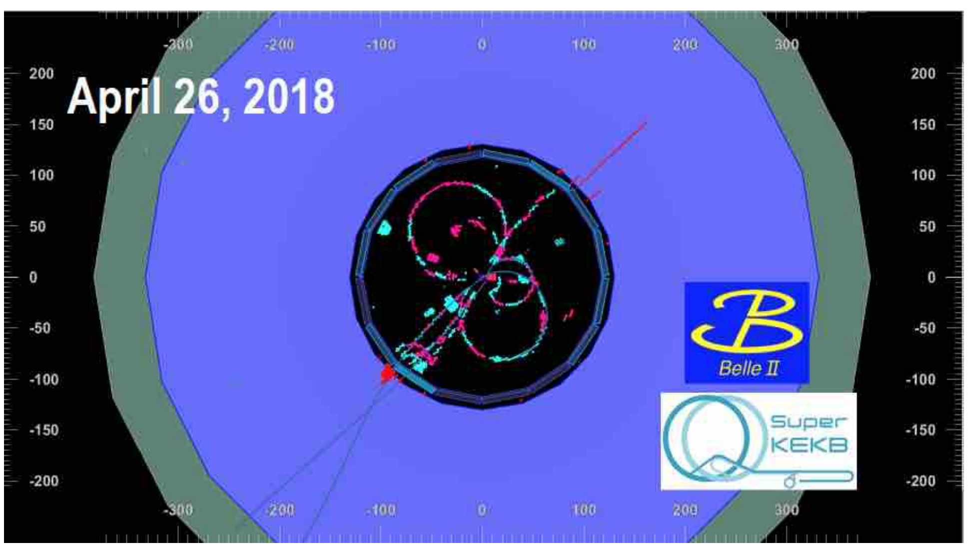
[Belle II TDR, KEK Report 2010-1]

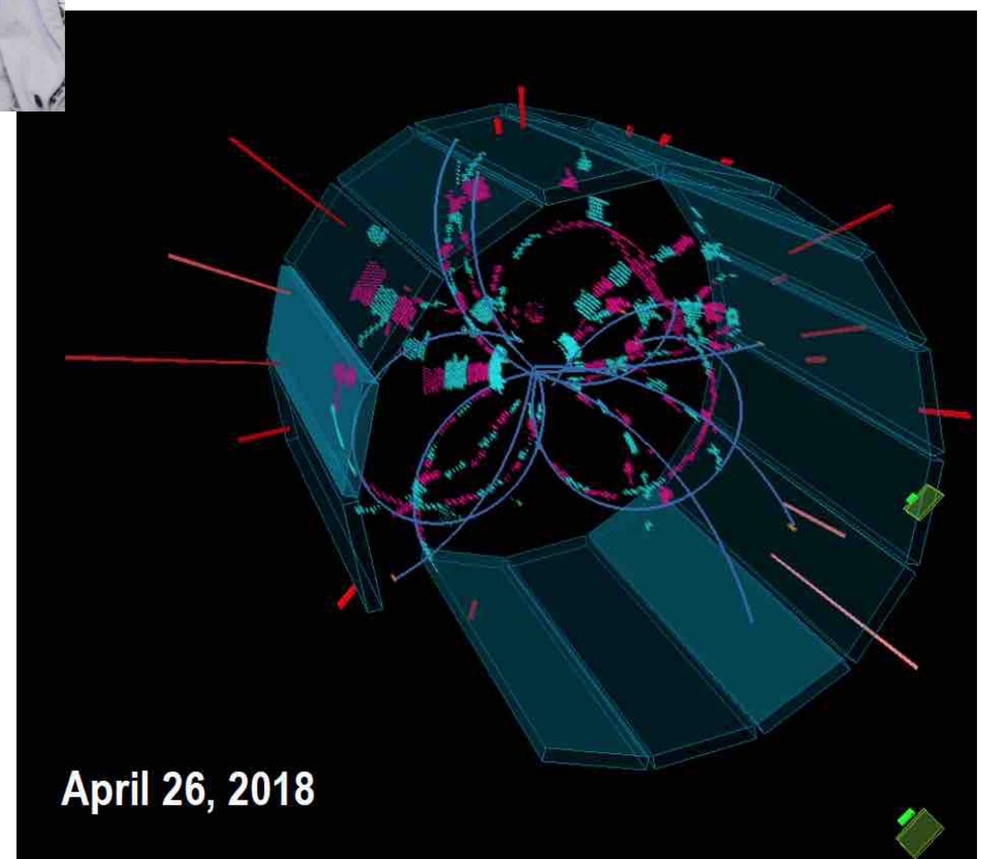


Belle II outreach
https://twitter.com/belle2collab/
https://www.facebook.com/belle2collab/

First collisions (Apr.26)



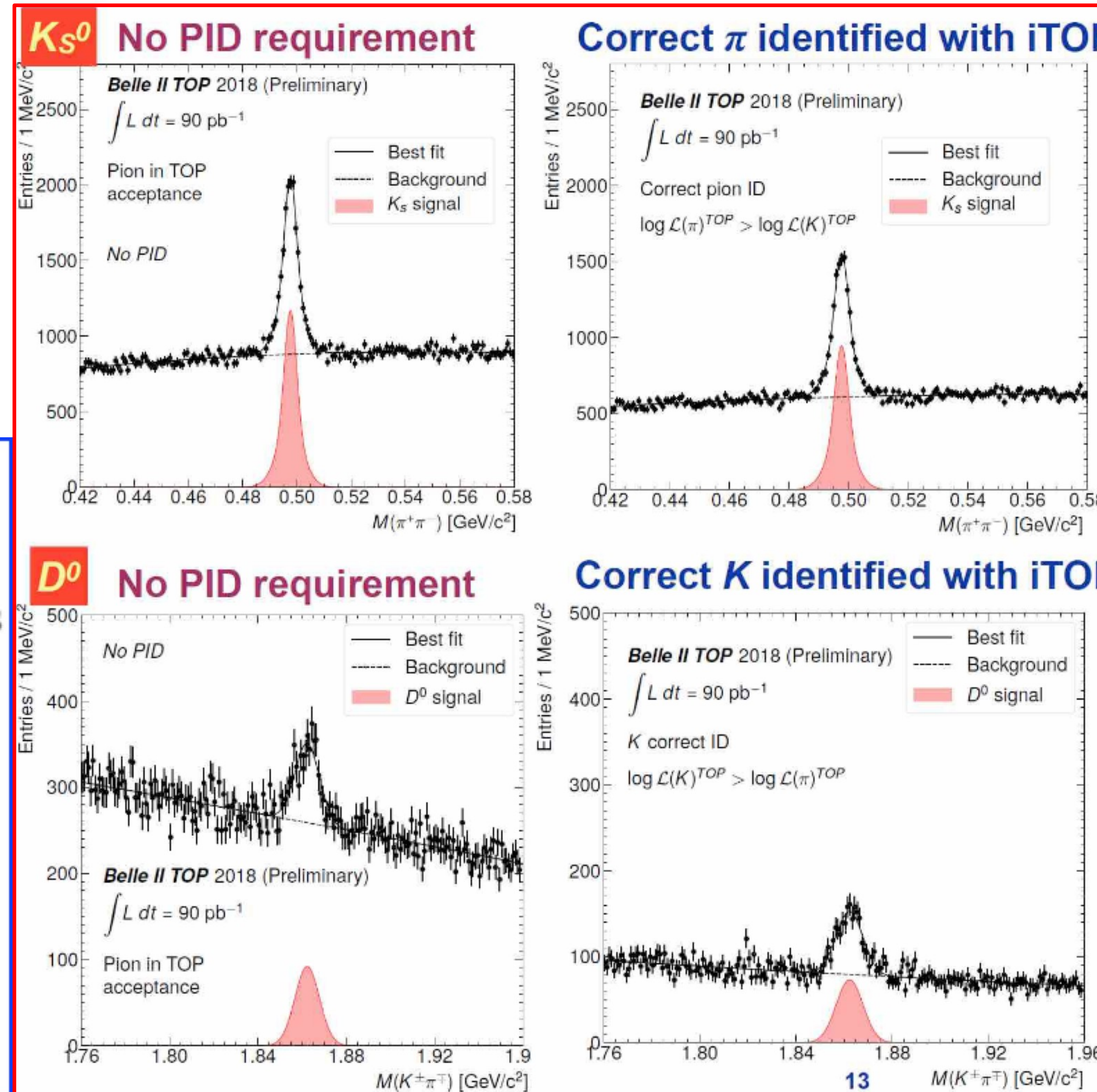


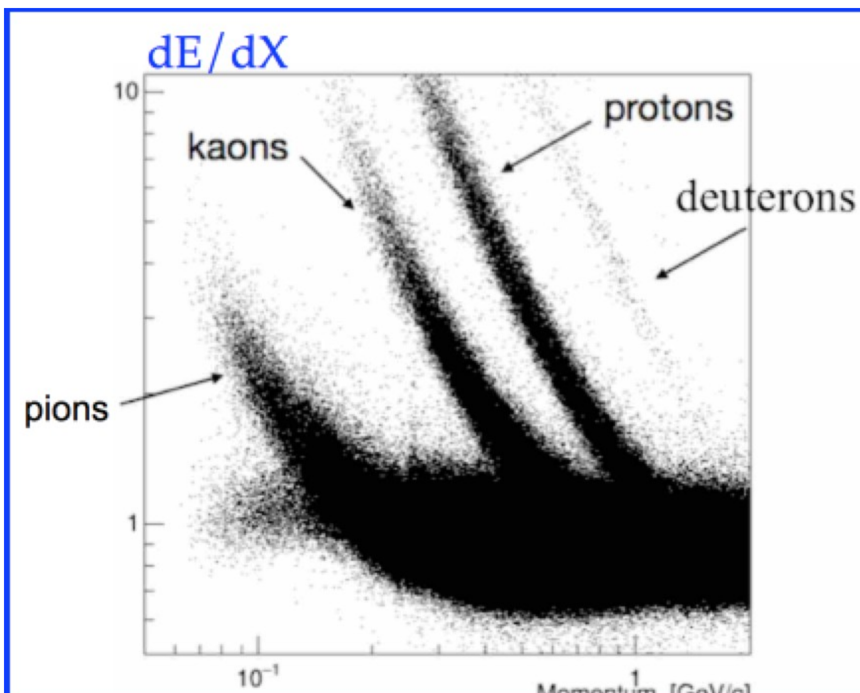


Getting ready for physics

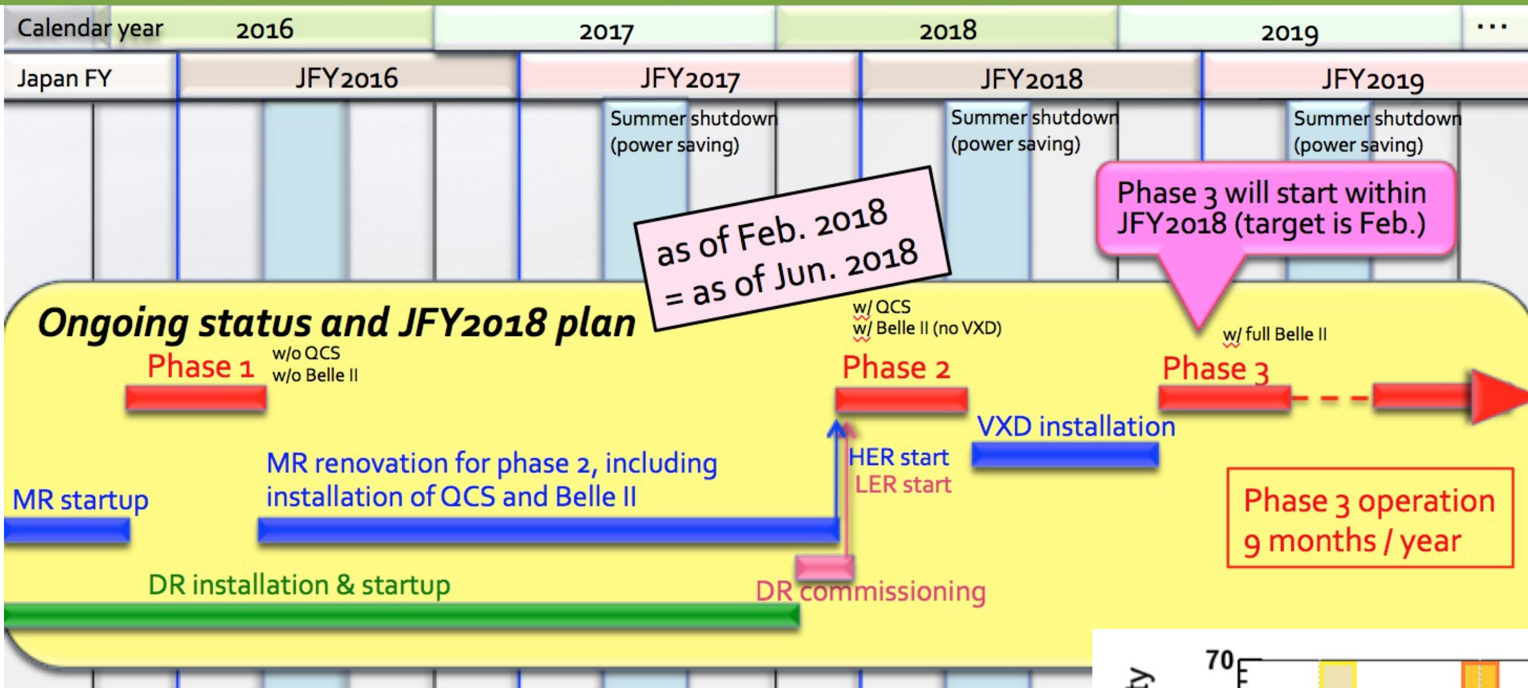
- detectors alignment
- optimization of tracking algorithms and performance
- calibration of particle identification
- calorimeter energy calibration
- DAQ and trigger studies
- re-discovery of most particles

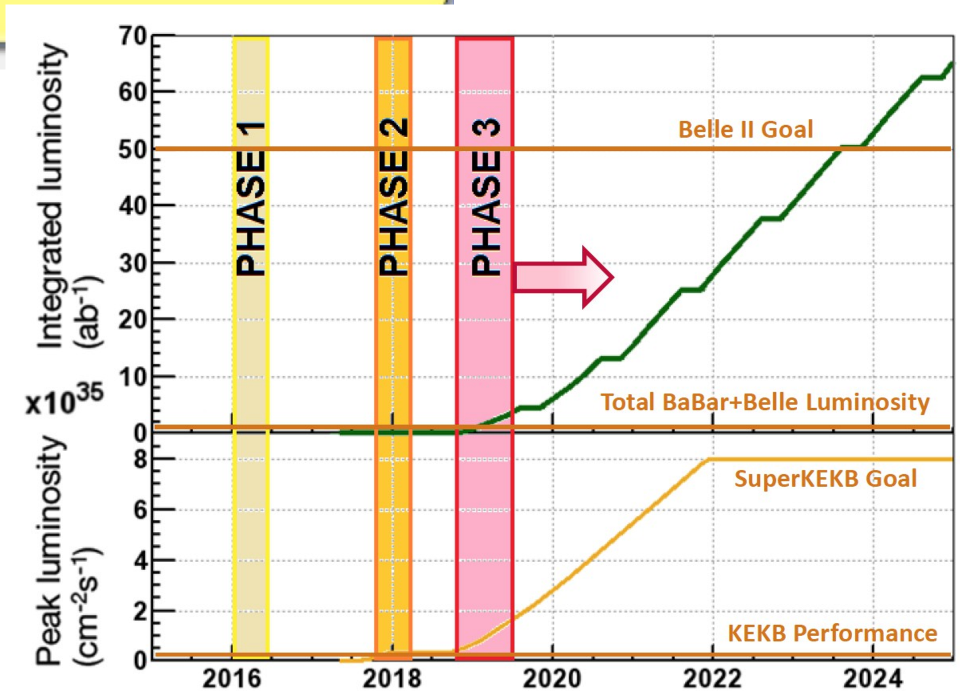
- background studies





Mid and long term plans

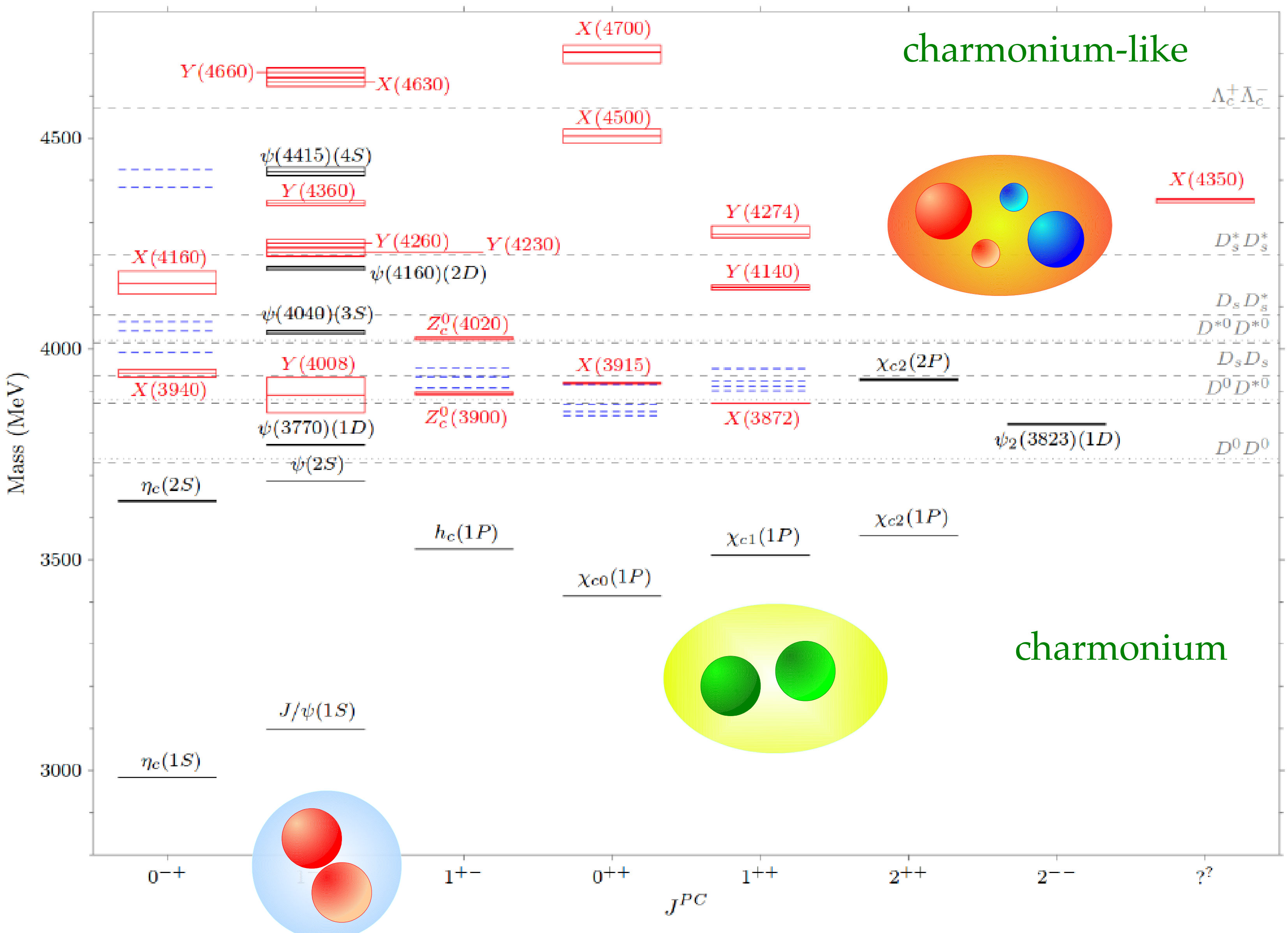




<u>Phase 2:</u>
- Detectors' calibration
- Beam optimization and background minimization, without vertex detectors
- Understanding of the new machine, with the nano beam scheme

<u>Phase 3:</u>
- Physics Run: 5 ab^{-1} by 2020,
  50 ab^{-1} in 2024

The legacy of 1st generation B-factories…



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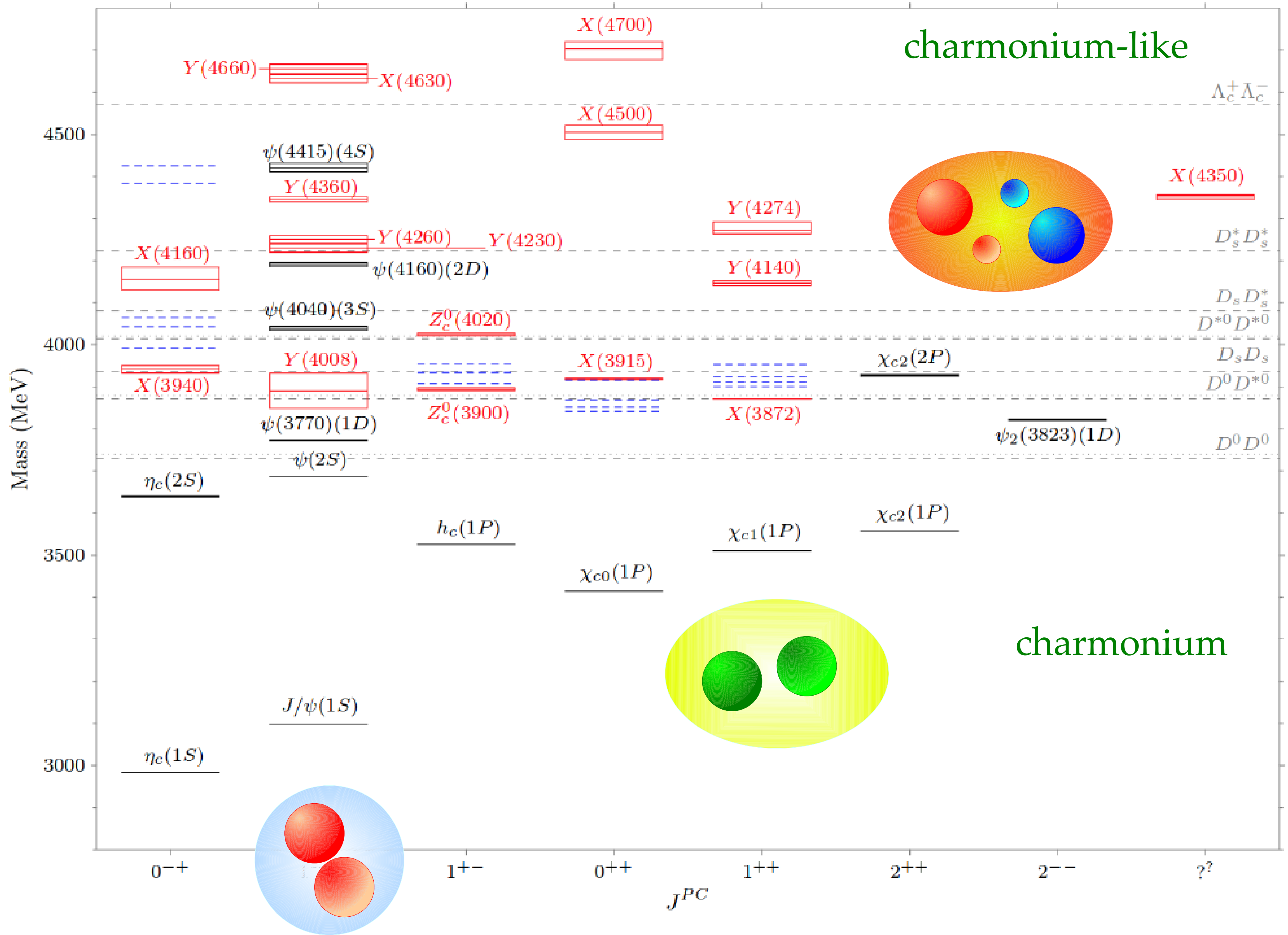
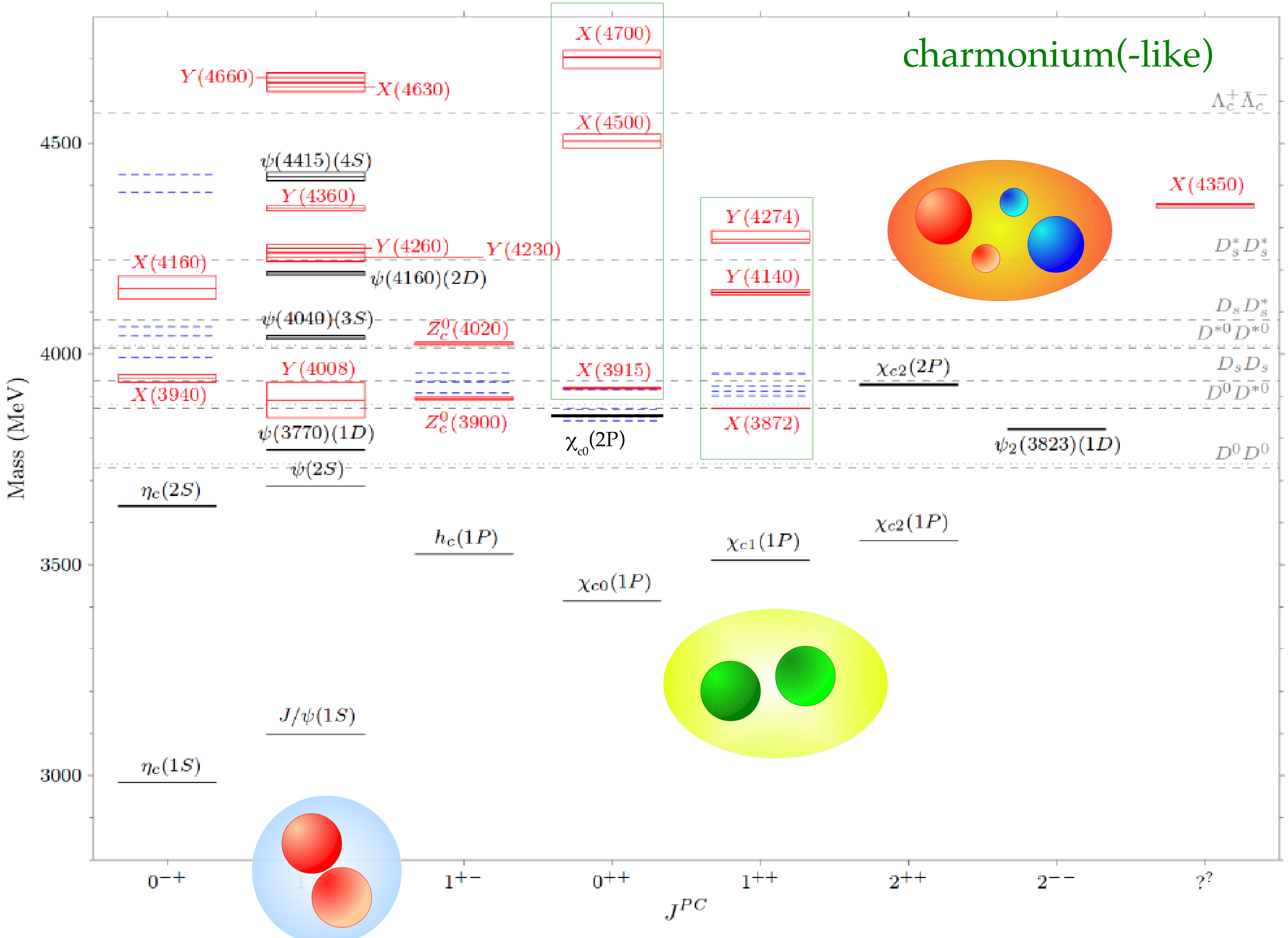
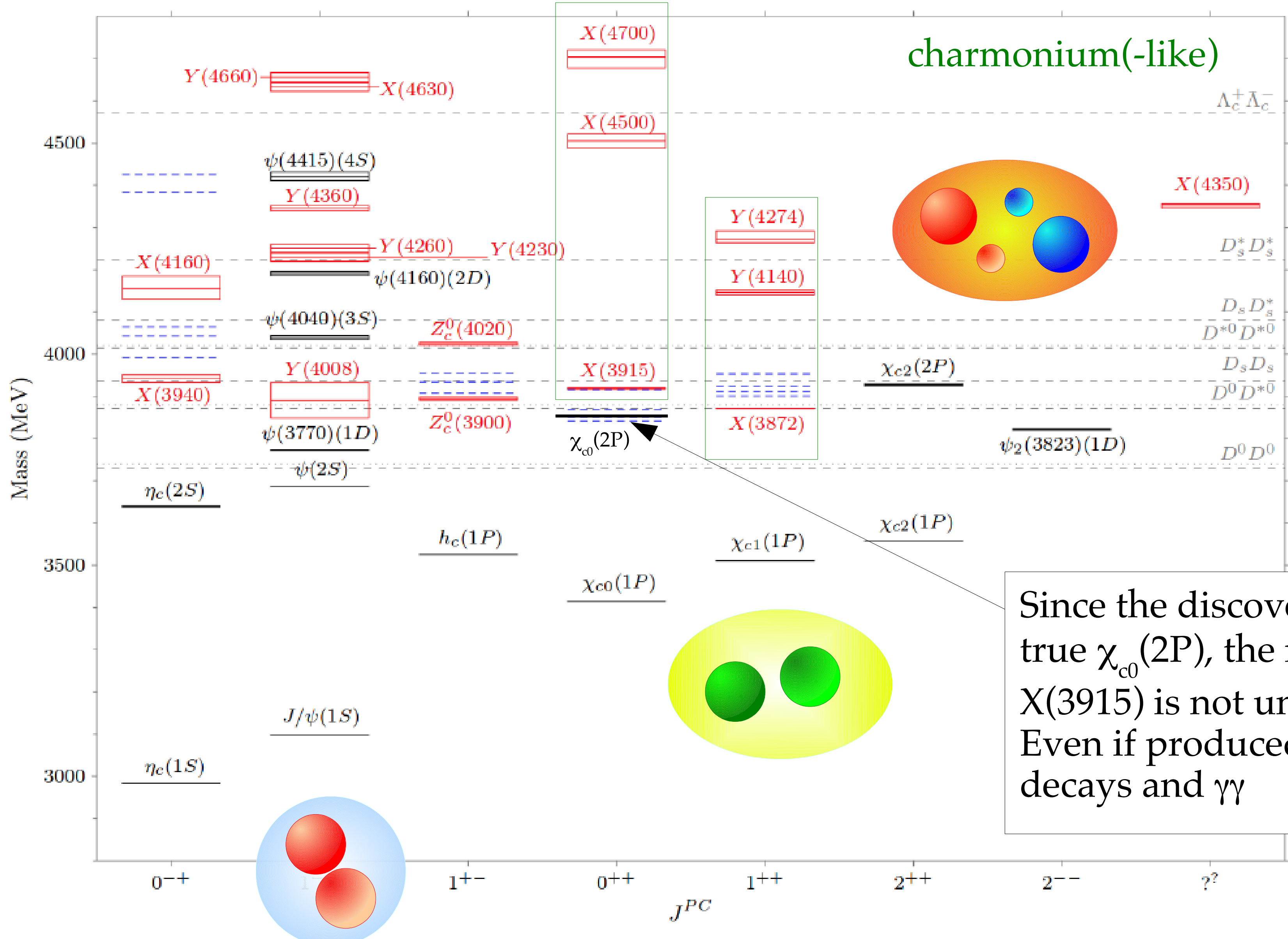


Challenge for the new generation: sort this mess…

Υ(4S) running : B to K($c\bar{c}$)

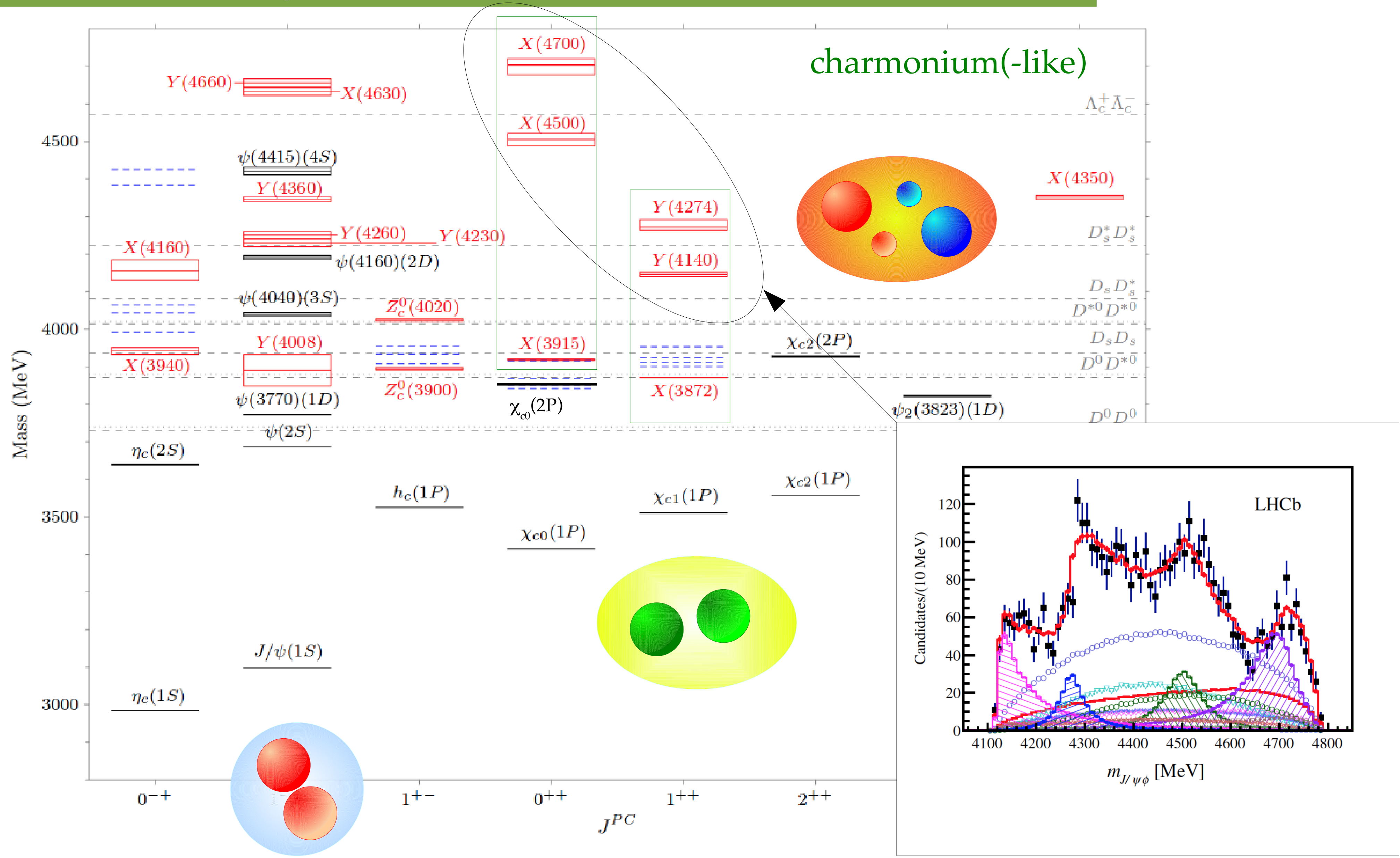


Y(4S) running : B to K($c\bar{c}$)



Since the discovery of the true χ_{c0}(2P), the nature of X(3915) is not understood … Even if produced both in B decays and γγ

Y(4S) running : B to K(cc̄)



Y(4S) running : B to K($c\bar{c}$)

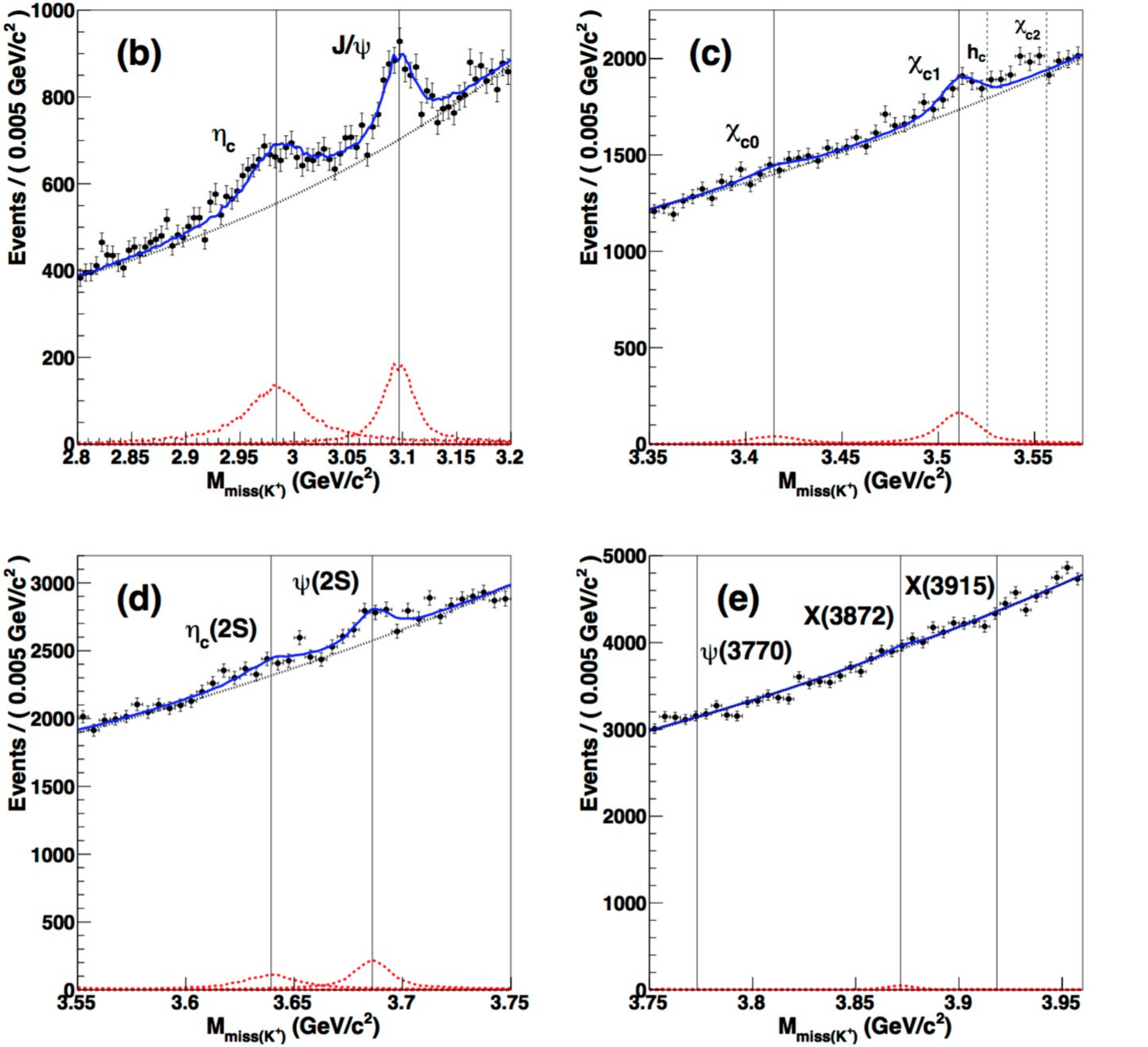
PRD 97, 012005 (2018)

Uniquely done in e^+e^- B-factories:

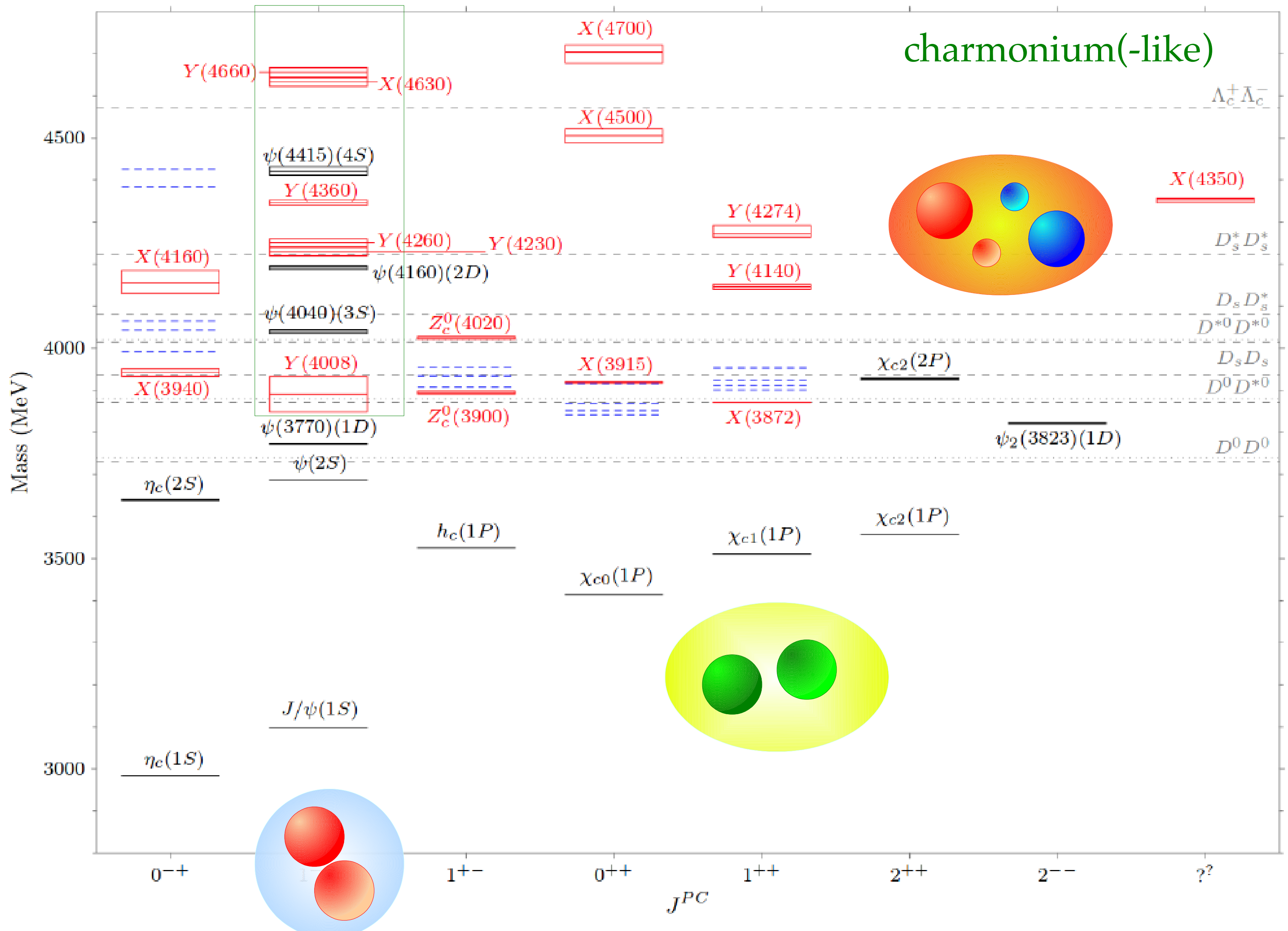
Full reconstruction of one B and inclusive reconstruction of what recoils against a K in the decay of the opposite B meson
Allows to calculate absolute BR:
$BR > 3.2\% = 8.6\times10^{-6} / 2.6\times10^{-4}$

Competitive with LHCb exclusive reconstruction only for:
- hadronic transitions with π^0,η,ω in final state;
- states decaying with large multiplicities

Further developments:
- $K\gamma$ recoils (search for the spin singlet 1^1D_2 state)
- Comprehensive study of:
$K D^{(*)}\bar{D}^{(*)}$, and $K D^{(*)}\bar{D}^{**}$



The vector landscape in charmonium



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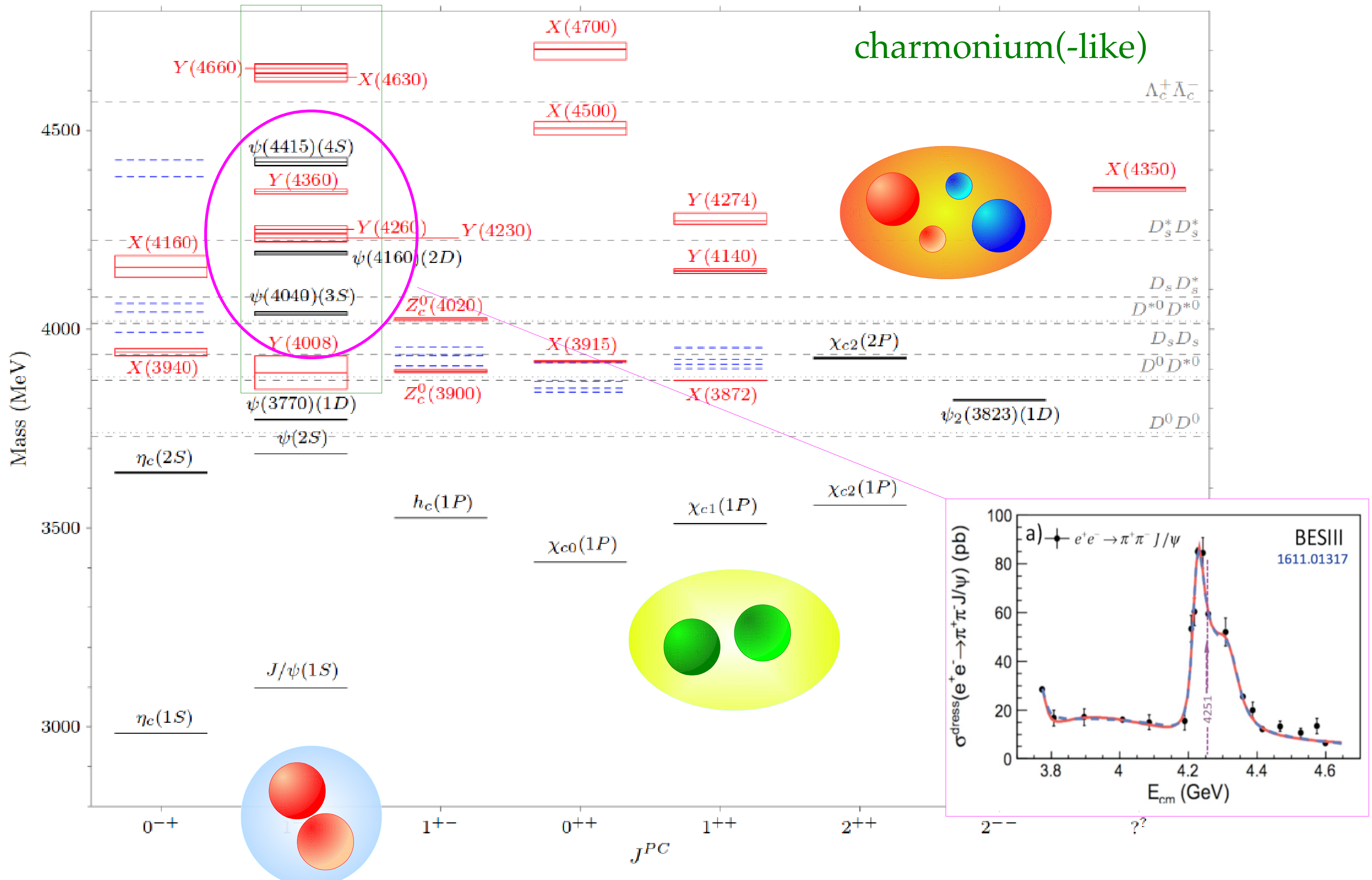
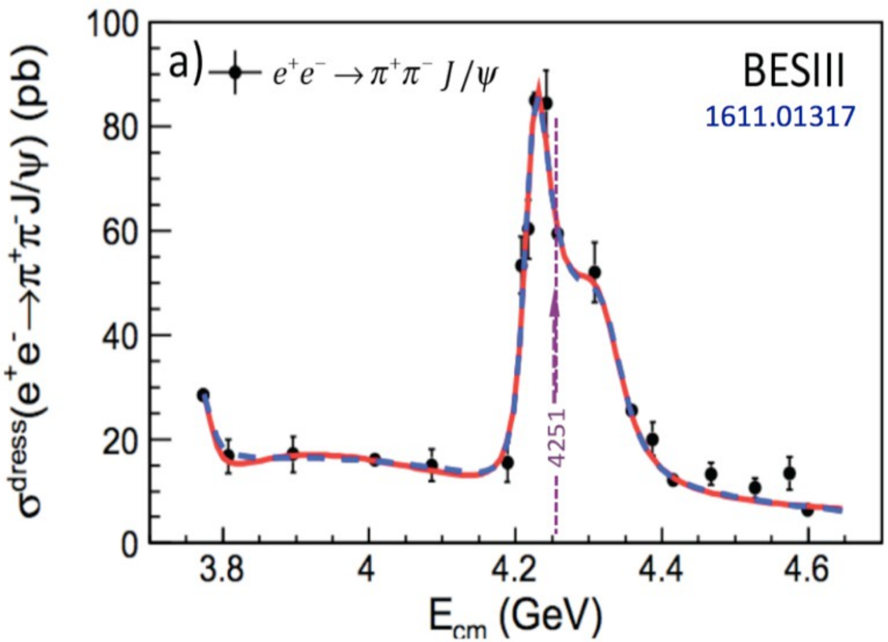
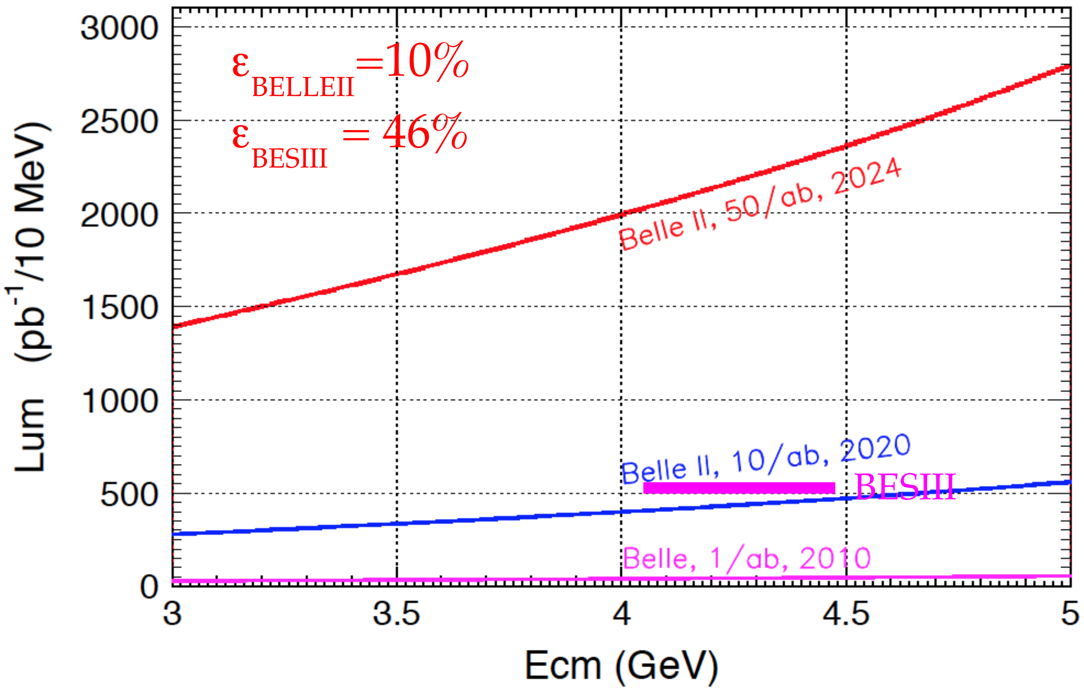


ISR luminosity

Recent BES-III scan data show a complex landscape
Scan of all decay channels is needed





Statistical sensitivities for 10(50) ab^{-1} are given below:

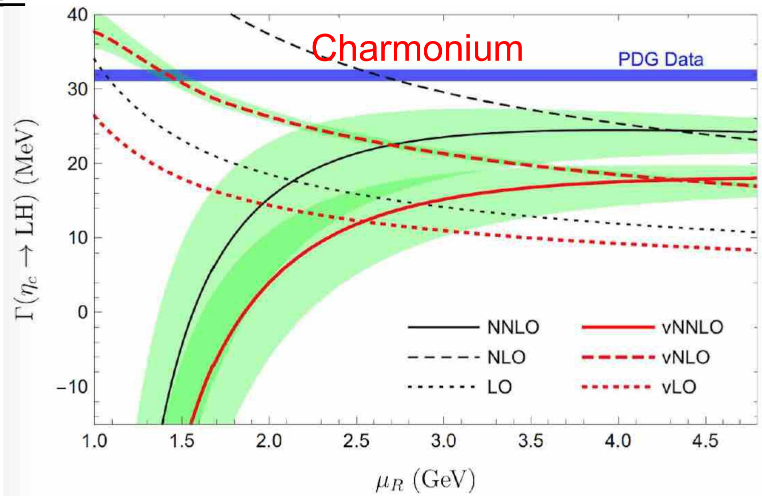
Golden Channels	$E_{c.m.}$ (GeV)	Statistical error (%)	Related XYZ states
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	$Y(4008)$, $Y(4260)$, $Z_c(3900)$
$\pi^+\pi^- \psi(2S)$	4.36	12 (5.0)	$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	$Y(4220)$, $Y(4390)$, $Z_c(4020)$, $Z_c(4025)$
$\omega\chi_{c0}$	4.23	35 (15)	$Y(4220)$

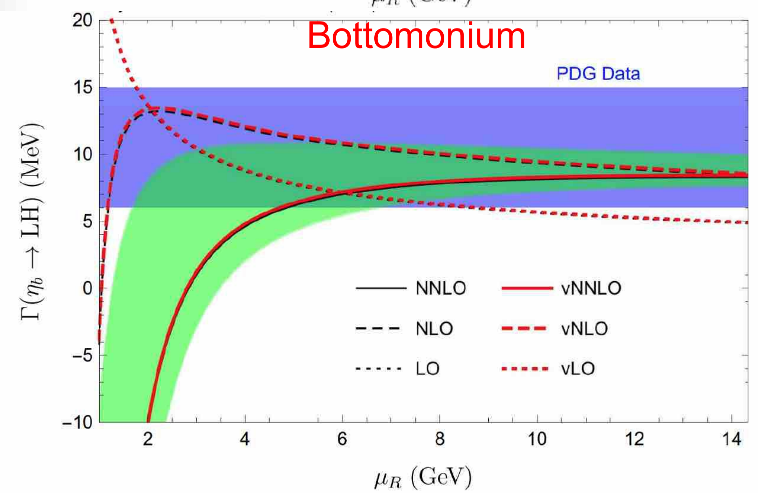
Ground states: 2-gluon and 2-photon widths

NRQCD calculation at vNNLO order
- 1700 three-loop diagrams
- 10^5 hours of CPU in Tianhe Supercomputer

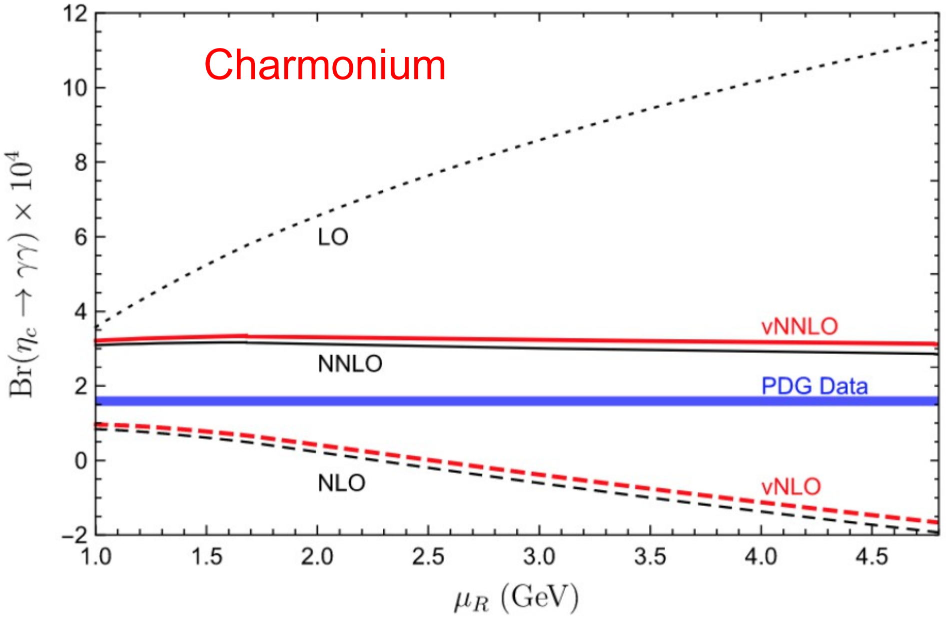
Yu Jia et al, Phys. Rev. Lett. 119, 252001 (2017)

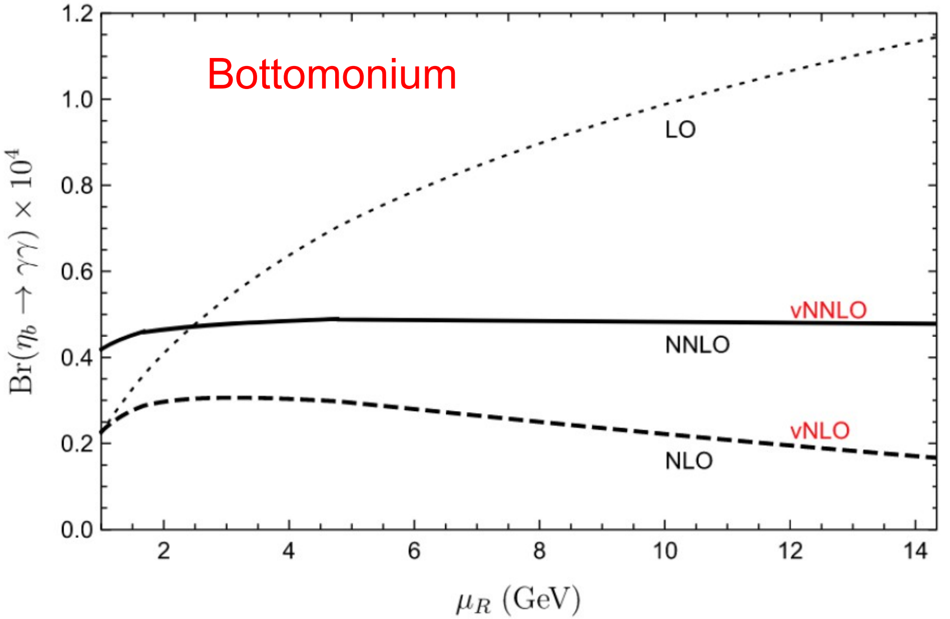
Total widths





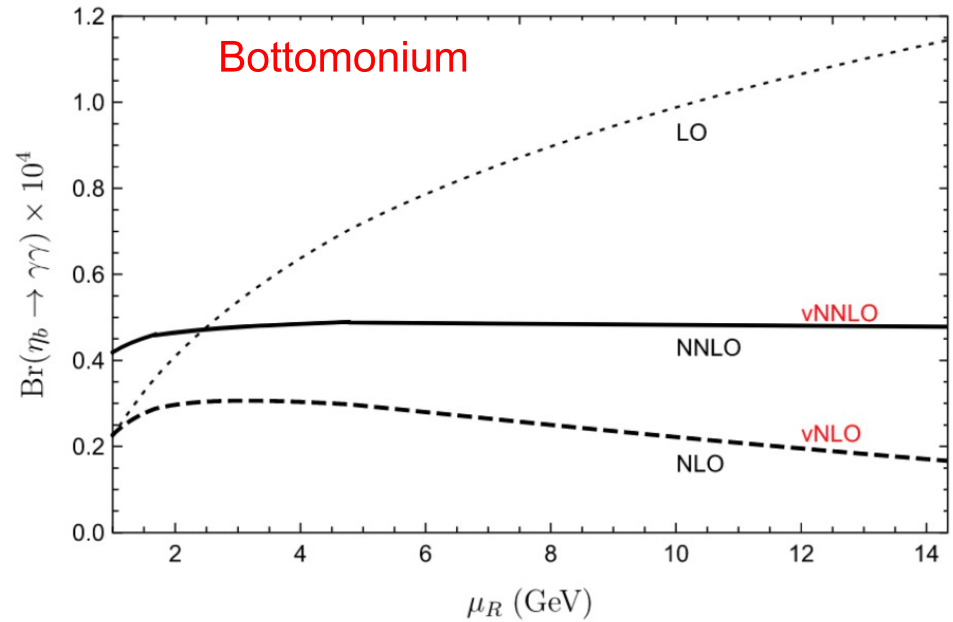
Branching ratios





Ground states: 2-gluon and 2-photon widths

Belle II trigger strategy:
All neutral final state : trigger on $\gamma\gamma_{hard}$
is not possible due to the $e^+e^- \to \gamma\gamma$ QED background:



$\Upsilon(4S) \to \eta\, h_b(1P) \to \gamma\, \eta_b(1S)$; $\eta \to \gamma\gamma_{soft}$; $\eta_b(1S) \to \gamma\gamma_{hard}$

Trigger on soft dipion pair AND hard $\gamma\gamma$ is the solution

$\Upsilon(4S) \to \eta\, h_b(1P) \to \gamma\, \eta_b(1S)$; $\eta \to \pi^+\pi^-\pi^0$; $\eta_b(1S) \to \gamma\gamma_{hard}$

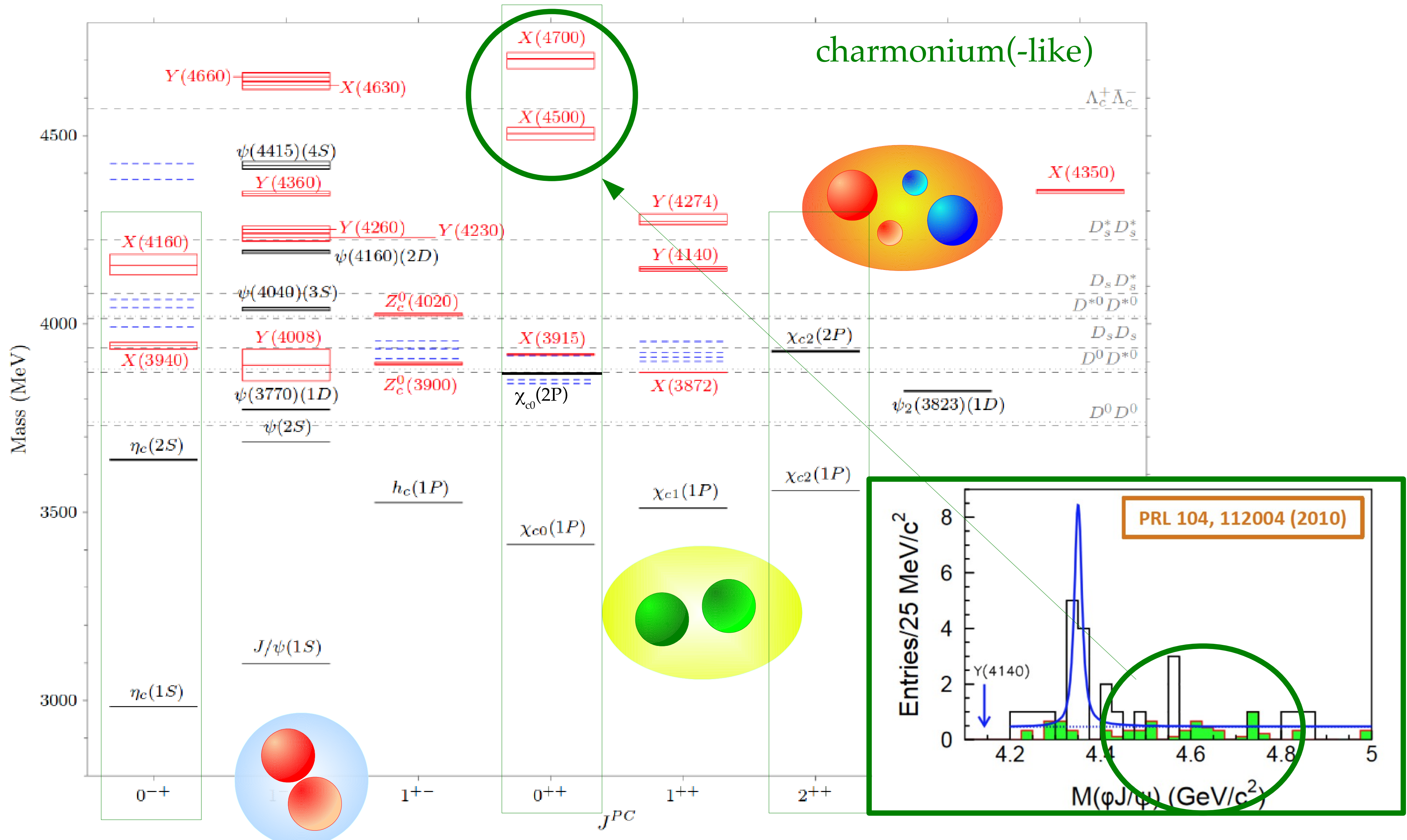
~0.5 Millions $\eta_b(1S)$ ($\eta \to \pi^+\pi^-\pi^0$)
In 50 ab^{-1} at $\Upsilon(4S)$ peak
~ 15 fully reconstructed $\eta_b(1S) \to \gamma\gamma$

$\Upsilon(5S) \to \pi^+\pi^-\, h_b(1,2P) \to \gamma\, \eta_b(1.2S)$; $\eta_b \to \gamma\gamma_{hard}$

~0.5 Millions $\eta_b(1,2S)$
In 2 ab^{-1} at $\Upsilon(5S)$ peak
~ 20 fully reconstructed $\eta_b(1S,2S) \to \gamma\gamma$

Belle II's goal is to make a 15% precision measurement with full statistics

Two photons physics



We need >10 ab^{-1} to confirm the scalar states found by LHCB

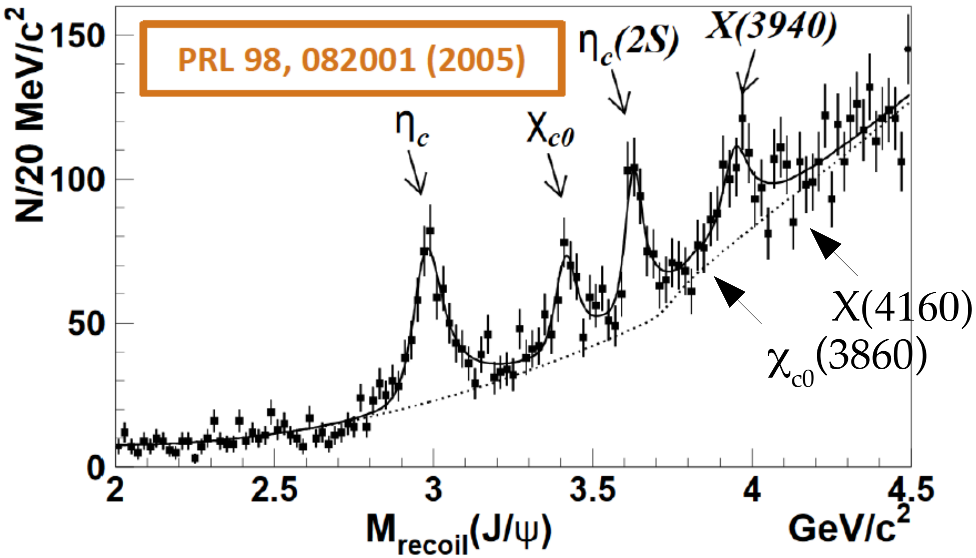
Double charmonium

The legacy of previous generation (mostly Belle) :

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

$\longrightarrow J/\psi, \psi'$ recoils

Most recent result: the discovery of $\chi_{c0}(2P)$
(studying the J/ψ D recoil)
Chilikin et al., Phys.Rev. D95 (2017) 112003

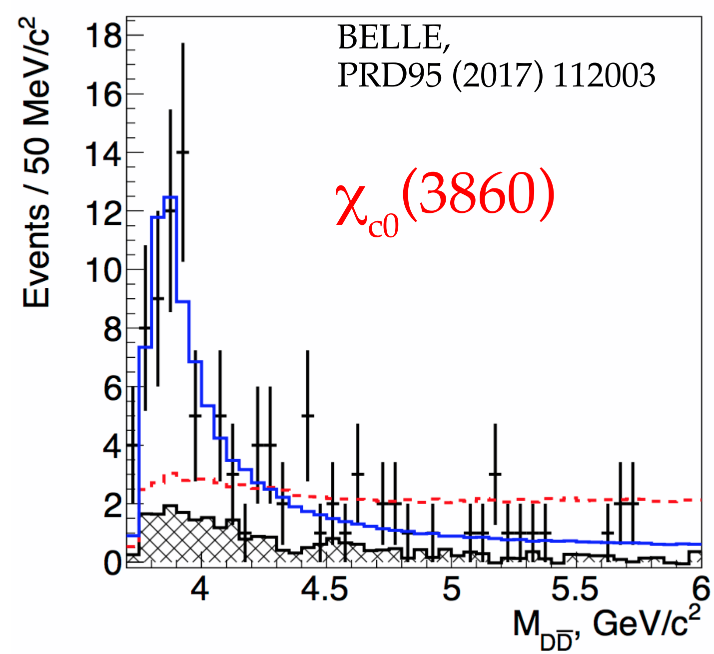


Future prospects, with larger statistics (>5 ab^{-1}):

$e^+e^- \rightarrow c\bar{c}\ (0^{\pm})$ $c\bar{c}(1^-$ or $1^+)$

$\longrightarrow \eta_c$ or χ_{c0} recoils

- study of angular distributions:
  - to decouple overlapping states
  - to do cross checks on J^{PC}
- study on double charmonium from Υ(3S)
  * Belle has evidence of $J/\psi, \chi_{c1}$ from Υ(1,2S) [PRD90,112008(2014)]



Motivations for non-Υ(4S) running

Current samples in fb^{-1} (millions of events), and the proposal for BelleII

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%
BelleII	-	-	300 (1200)	5×10^4 (5.4×10^4)	1000 (300)	100+400(scan)	3.6%

Motivations for non-Y(4S) running

Current samples in fb^{-1} (millions of events), and the proposal for BelleII

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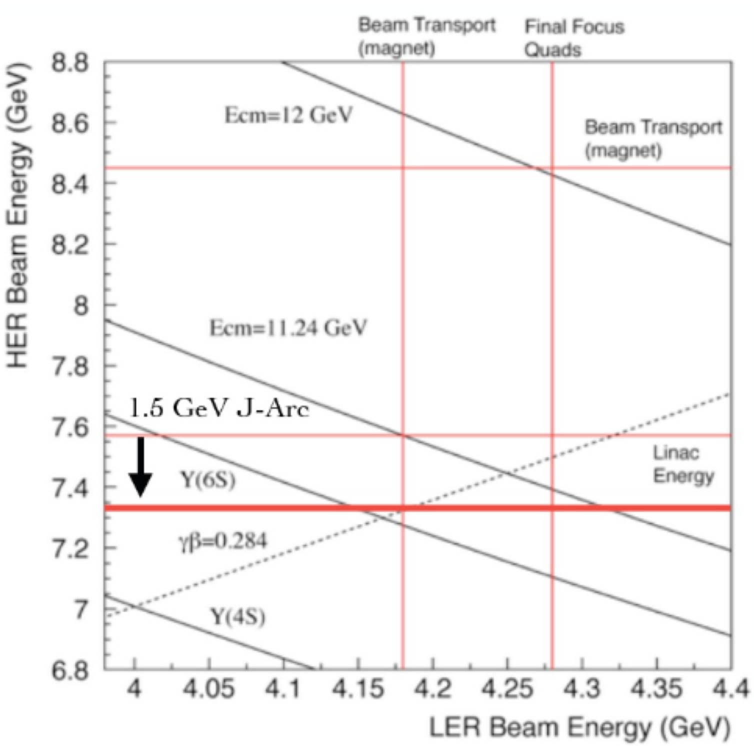
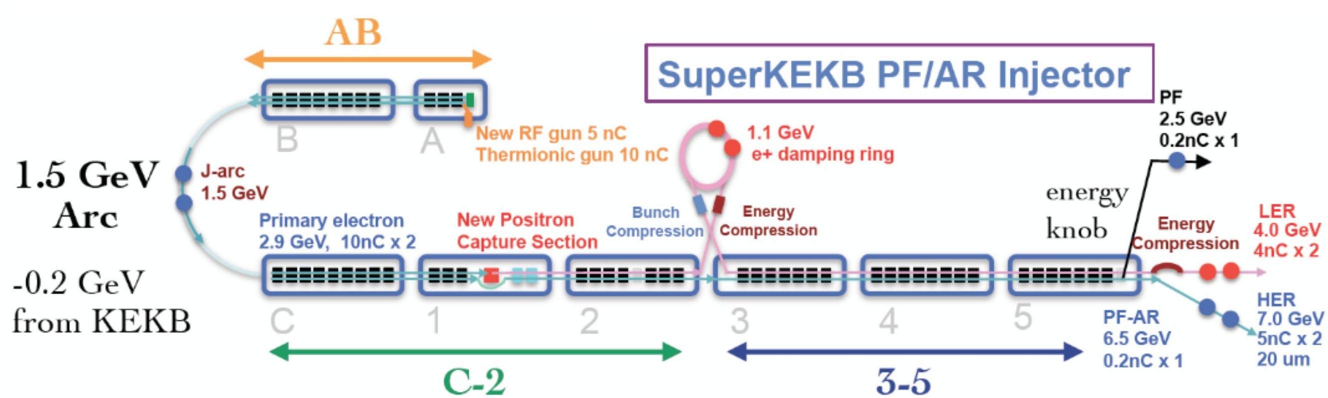


Current machine limits:
- not enough spare cavities to run safely at Y(6S)
- major modifications required for running above 6S
- beam energy spread at 3S at high lumi: unknown



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Spectroscopy of narrow states
Exotica in virtual loops
Precision NRQCD tests
BSM: DM, light Higgs
Hadronic and Radiative Transitions
Baryon correlations
Production of Antinuclei
Gluon fragmentation
Inclusive Charmonium(-like)
$D\overline{D}$ correlations

Bs physics
Exotica discovery
Precision Zb measurements
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Light meson spectroscopy

Exotica discovery
5S vs 6S Properties
Hadronic and Radiative Transitions

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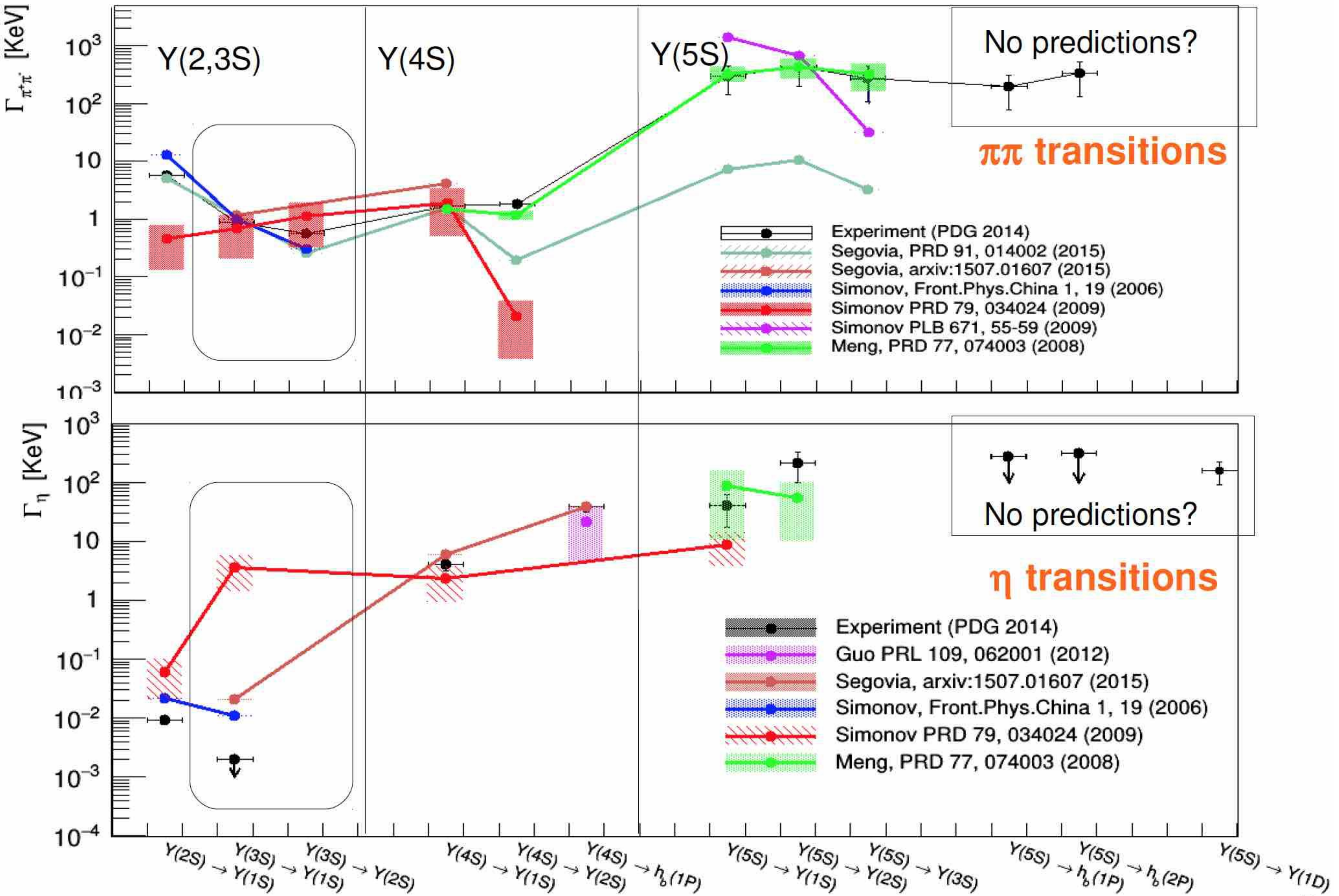
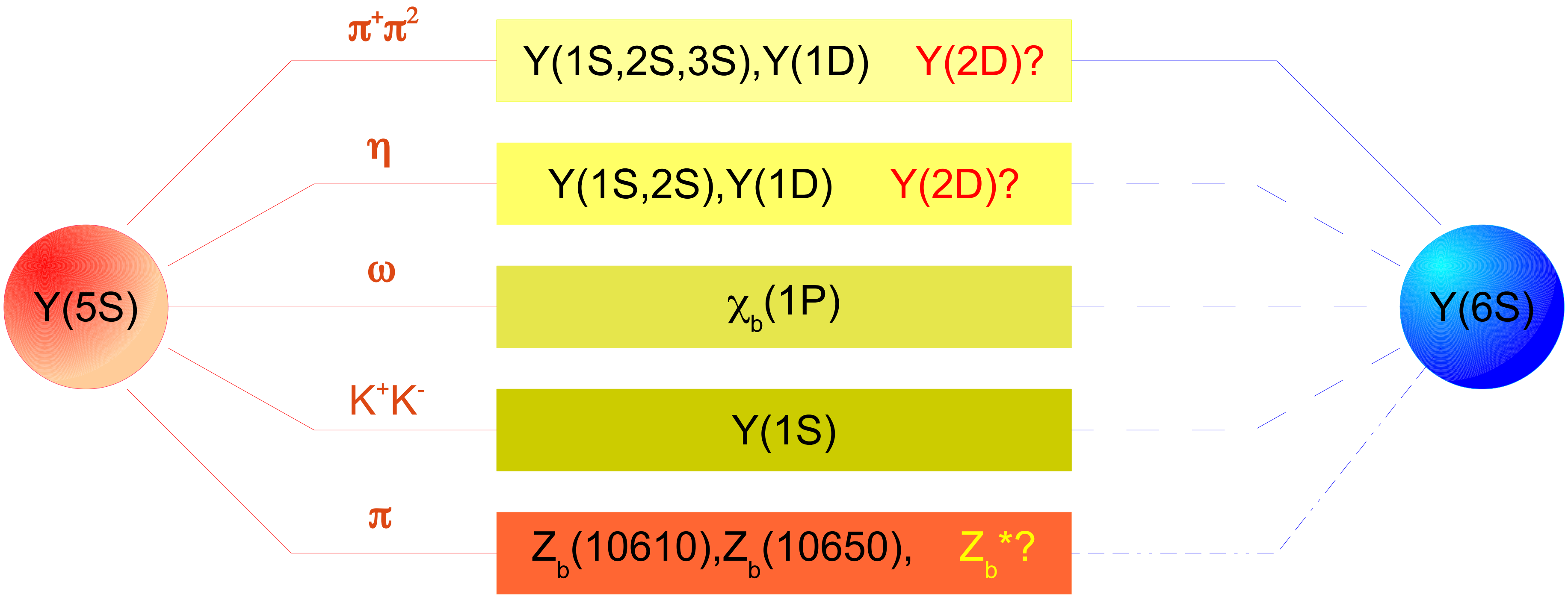
The puzzle of eta / dipion transitions in bottomonium



Υ(6S) vs Υ(5S): hadronic transitions

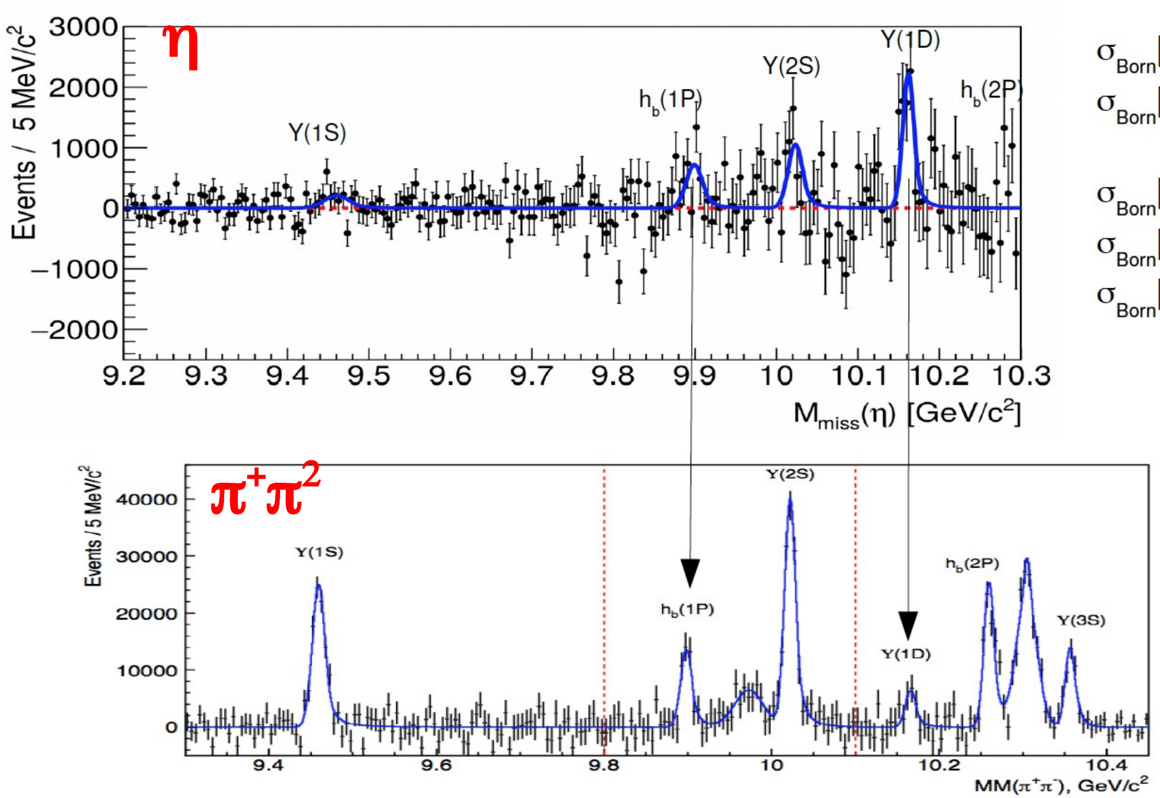


Comparison of the decay rates will allow to better understand the nature of the Υ(5,6S) states.

Search for missing narrow bottomonia :
* Υ(2D), via either dipion or eta transition
* h_b(3P) , via some new Z_b* state?

Y(6S): searches for more η, $\pi^+\pi^2$ transitions

Eta vs dipion transitions with 120 fb^{-1} at Y(5S)



$\sigma_{Born}[e^+e^- \to \eta\, \Upsilon_{1,2}(1D)] = (1.50 \pm 0.30 \pm 0.20)$ pb

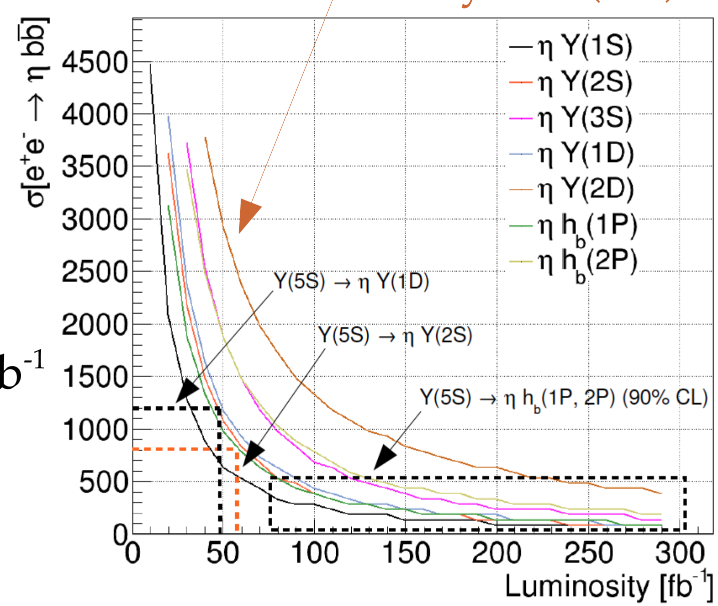
$\sigma_{Born}[e^+e^- \to \eta\, \Upsilon(2S)] = (0.97 \pm 0.31 \pm 0.19)$ pb

$\sigma_{Born}[e^+e^- \to \eta\, \Upsilon(1S)] < 0.61$ pb

$\sigma_{Born}[e^+e^- \to \eta\, h_b(1P)] < 0.92$ pb

$\sigma_{Born}[e^+e^- \to \eta\, h_b(2P)] < 0.69$ pb

5 σ level for discovery of Y(2D)



- Y(6S) running will be staged: first 10 fb^{-1} , ..30 fb^{-1}, .. 100 fb^{-1}

- Dipion transitions main discovery tool for charged bottomonia (more Z_b's?)

- Eta transitions : best pathway to Y(2D)?

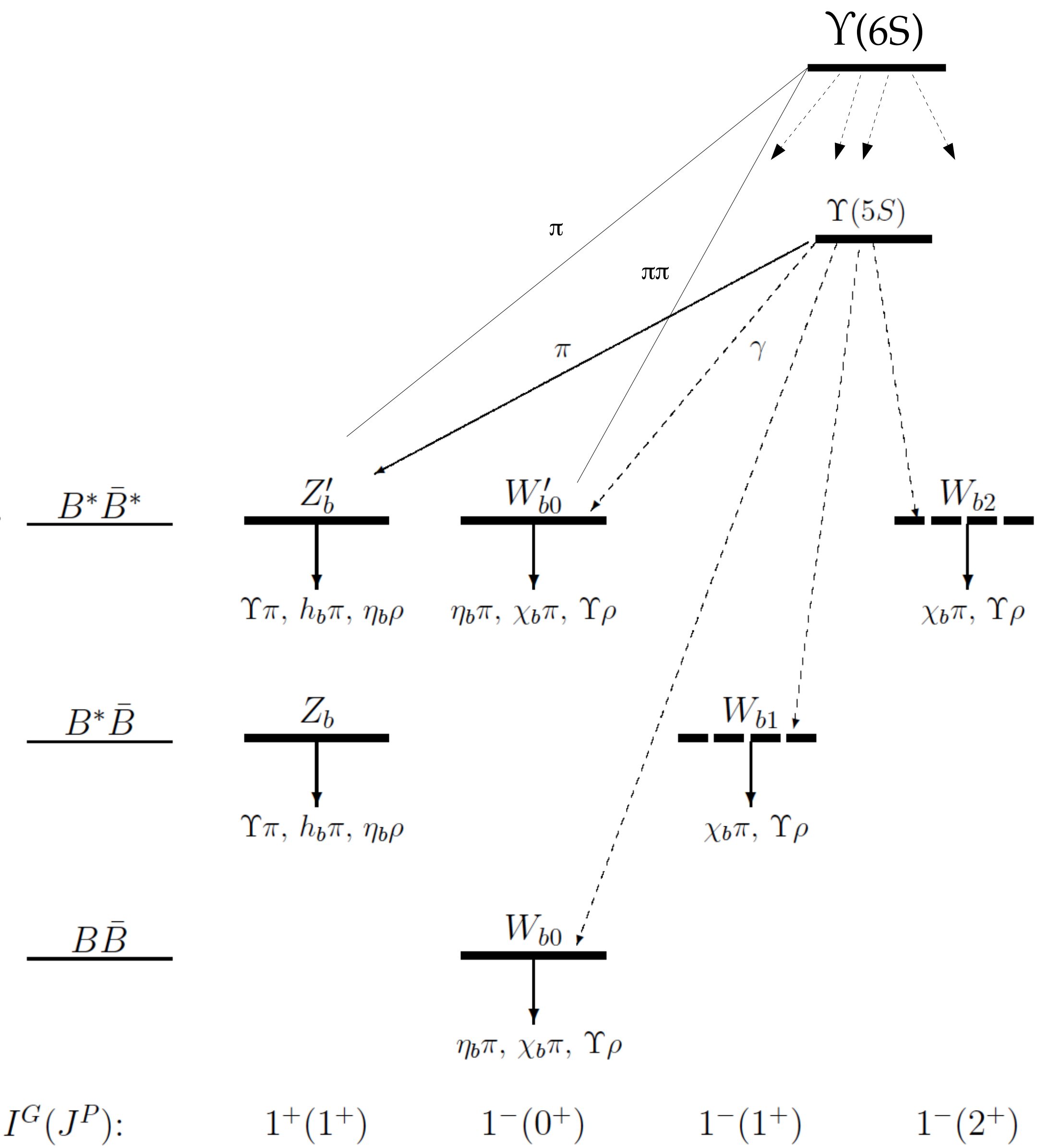
Υ(6S): searches for more 4 quark states

Voloshin, PRD 84, 031502 (2011)

The molecular model of the Z_b states predicts neutral partners (W_b) with J=0,1,2 which are expected on the same energy range, and should be reachable from Υ(5,6S) via radiative transitions.

Further hadronic transitions to W_b states are expected above 11.3, GeV, unreachable at present.

The tetraquark model predicts two states split by less than 10 MeV at the energy peak of the Υ(6S)



High energy scans

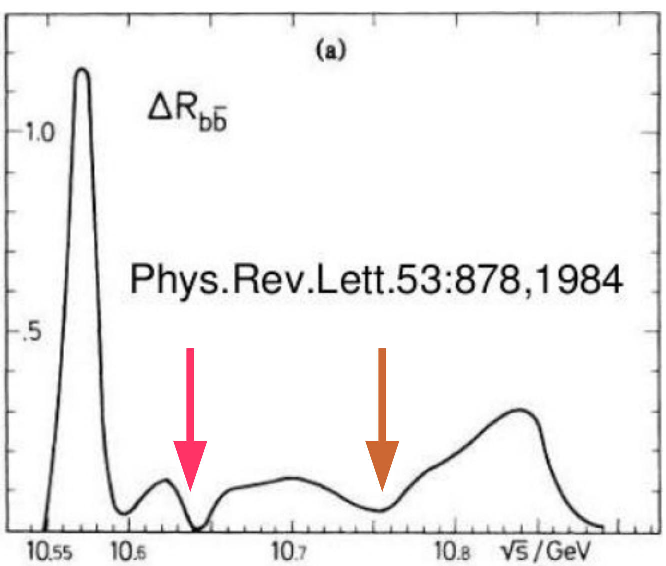
Bondar, Mizuk, Voloshin,
Mod.Phys.Lett. A32 (2017) no.04, 1750025

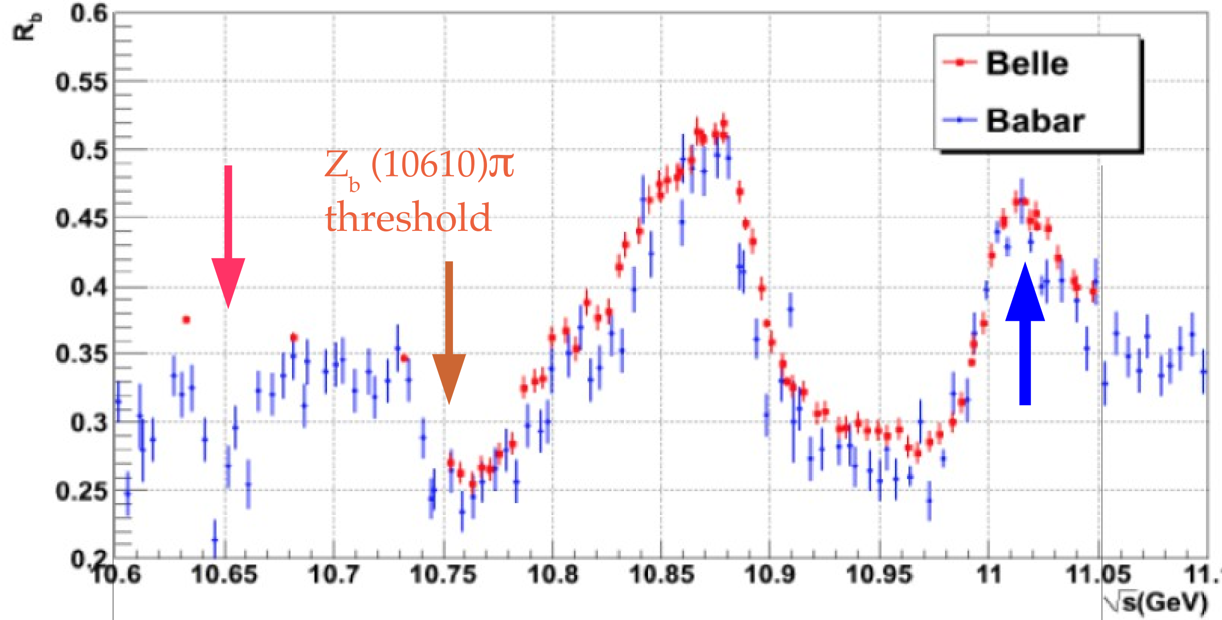
A high intensity scan has been proposed:

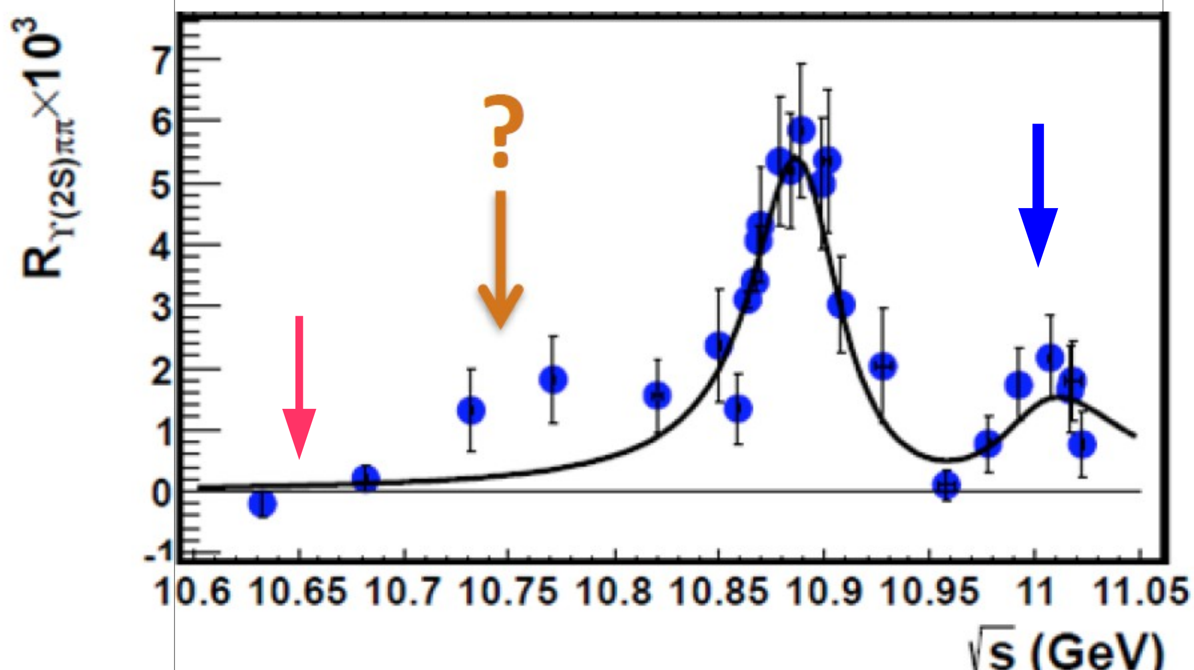
- 400 fb^{-1}, 10 fb^{-1}/point, 10 MeV steps: at L = $2x10^{34}$, 1 point/week, at L = 10^{35}, 1 point/day

- E = 10.62 to 11.02 GeV

Note: features predicted by theory (coupled channel model)



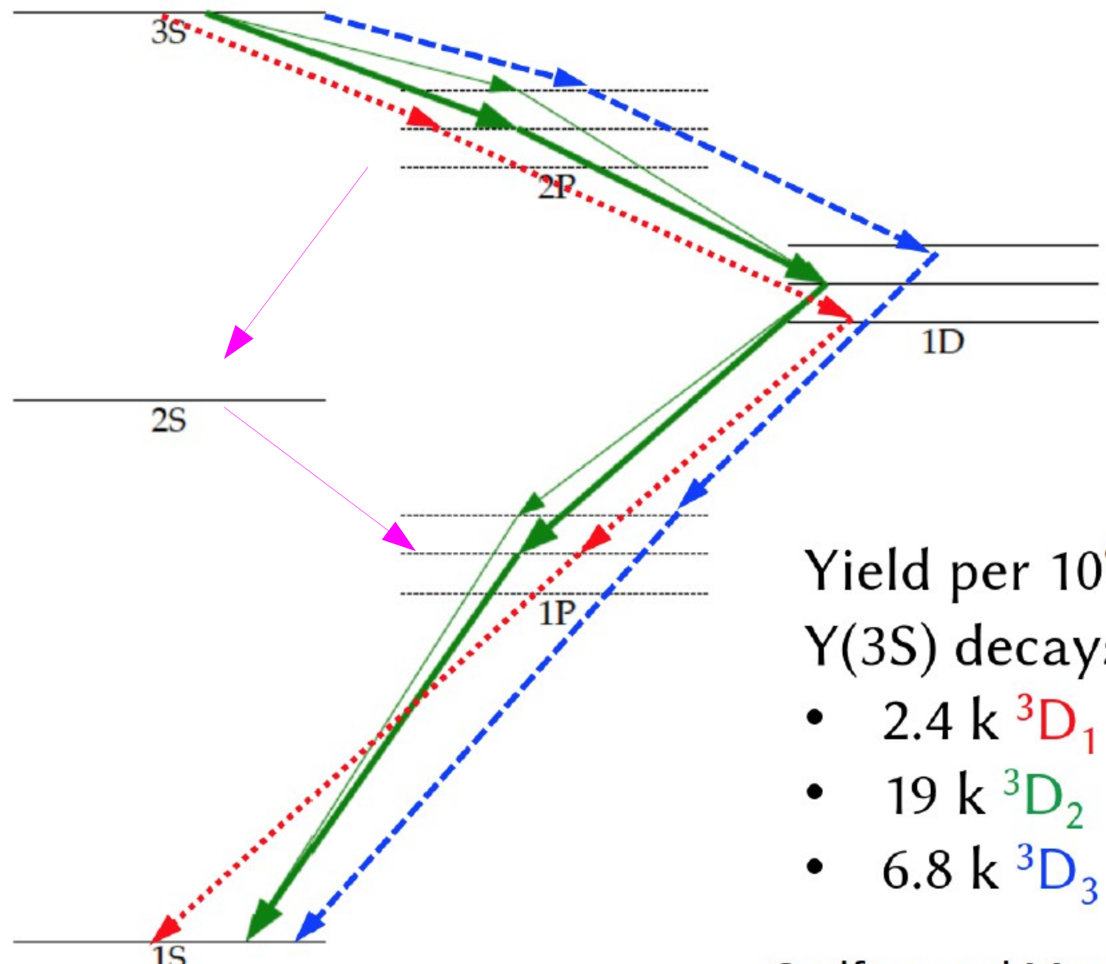




(*) At 6S: 6pt scan (1 fb^{-1} each) in Belle-I

Υ(3S) runs: splitting the 1D multiplet

The Υ(1D) multiplet is still unresolved: the J=2 state is around 10.18 GeV. We plan to study it through both γγππ and 4γ transitions (background: same via 2S)

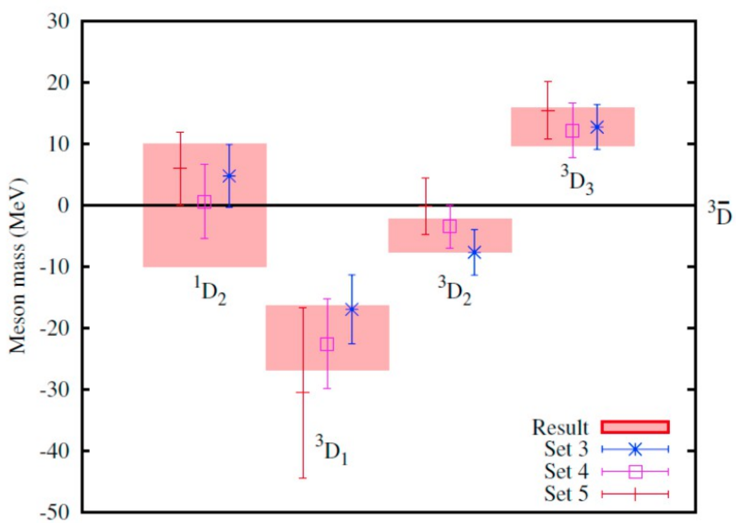


Yield per 10^9 Υ(3S) decays

- 2.4 k $^3D_1$
- 19 k $^3D_2$
- 6.8 k $^3D_3$

Godfrey and Moats, PRD 92, 054034 (2015)

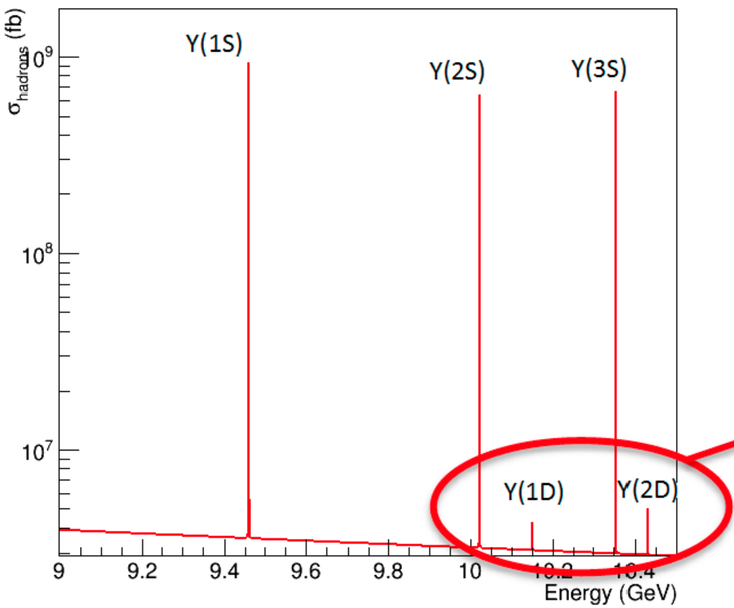
Lattice predictions on 1D splittings: Daldrop et al., PRL 108, 102003 (2012)

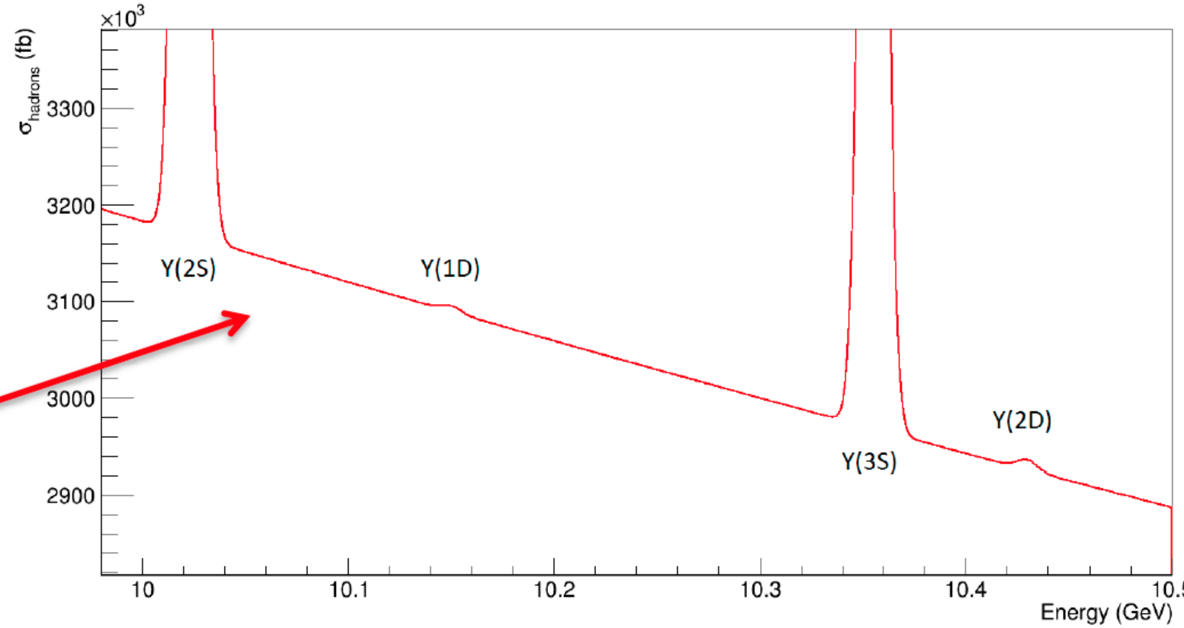


Scanning $\Upsilon(1,2^3D_1)$?

Observable : e+e- to hadrons

Continuum cross section: $\sigma = N_c Q_f^2 \frac{86.8 \text{ nb}}{s\,(\text{GeV}^2)}$



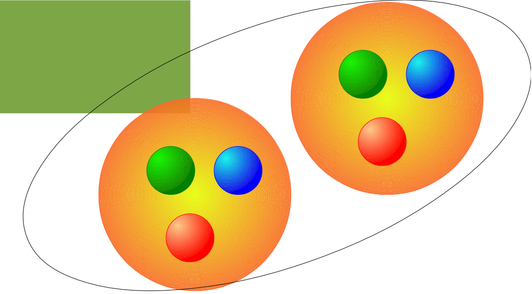


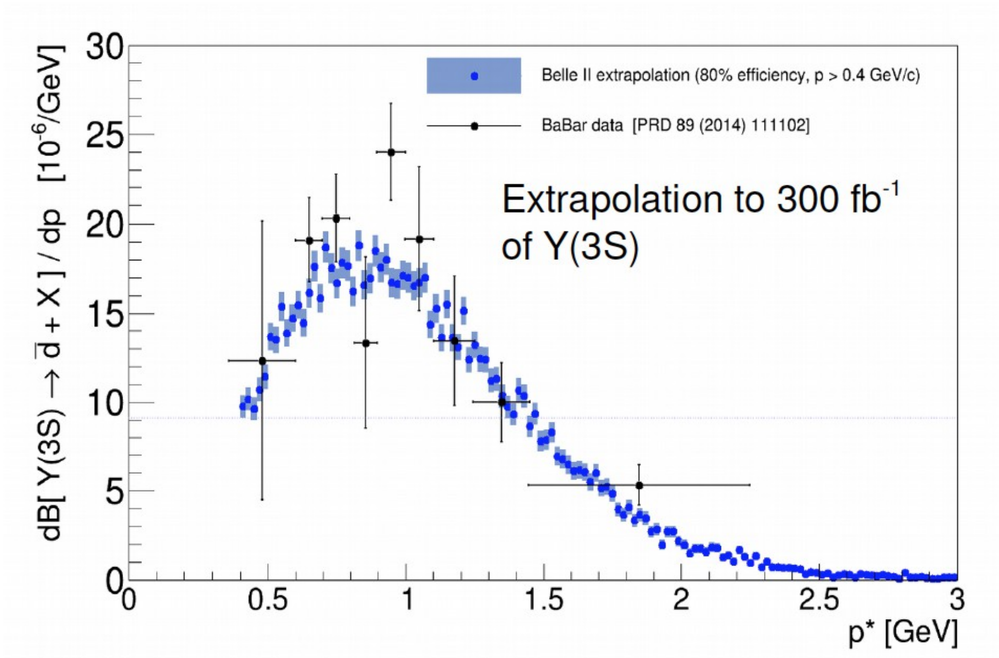
Search for 1D: 7 point scan (5 MeV steps) around 10.15 GeV

Search for 2D: 7 point scan (5 MeV steps?) around 10.43 GeV

IF the 2D scan is successful, we may envisage a longer run on 2D peak and search for 1F states (single photon spectrum, probably large background from ISR Υ(3S))

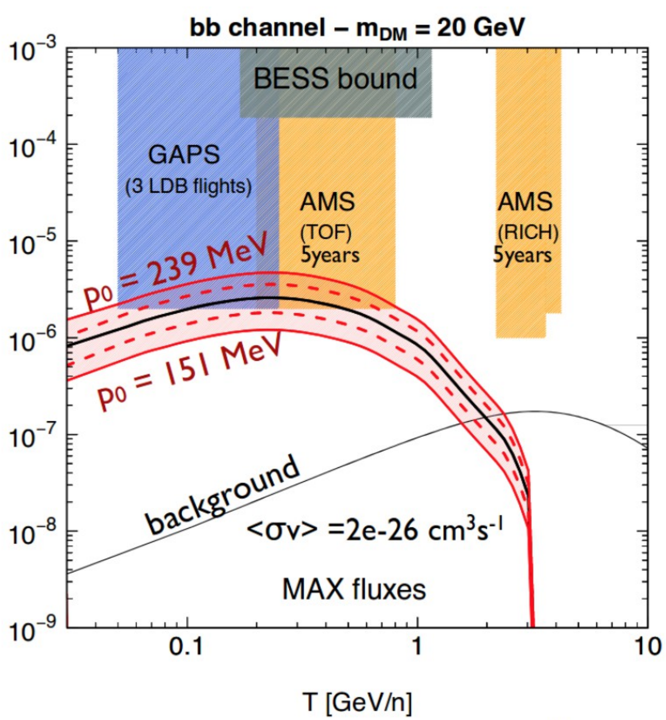
Y(3S) runs: antinuclei production





BABAR results :

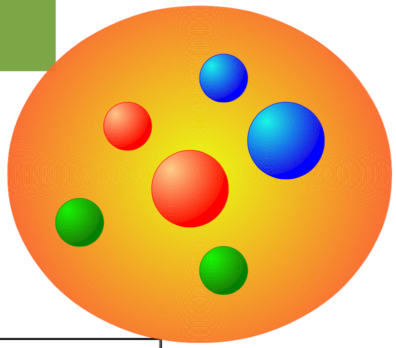
Process	Rate
$\mathcal{B}(\Upsilon(3S) \to \bar{d}X)$	$(2.33 \pm 0.15^{+0.31}_{-0.28}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(2S) \to \bar{d}X)$	$(2.64 \pm 0.11^{+0.26}_{-0.21}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(1S) \to \bar{d}X)$	$(2.81 \pm 0.49^{+0.20}_{-0.24}) \times 10^{-5}$
$\sigma(e^+e^- \to \bar{d}X)$ [$\sqrt{s} \approx 10.58$ GeV]	$(9.63 \pm 0.41^{+1.17}_{-1.01})$ fb
$\dfrac{\sigma(e^+e^- \to \bar{d}X)}{\sigma(e^+e^- \to \text{Hadrons})}$	$(3.01 \pm 0.13^{+0.37}_{-0.31}) \times 10^{-6}$



Questions:
- Production mechanism still unclear: coalescence?
- Associated $d\bar{d}$ production not checked by Babar
- Astroparticle: AMS observes 8 $^3\overline{He}$, $^3\overline{He}/^3He$=2x10^{-8}
  Production mechanism of $\bar{d}$ unknown, DM?

Belle II targets :
Study associated $d\bar{d}$ production
Study $\bar{d}$ spectrum at Y(3S)
Search for $^3\overline{He}$, and $^3\overline{H}$ in Y(3S) decays
Study $\bar{d}$ spectrum in continuum (from Y(4S))

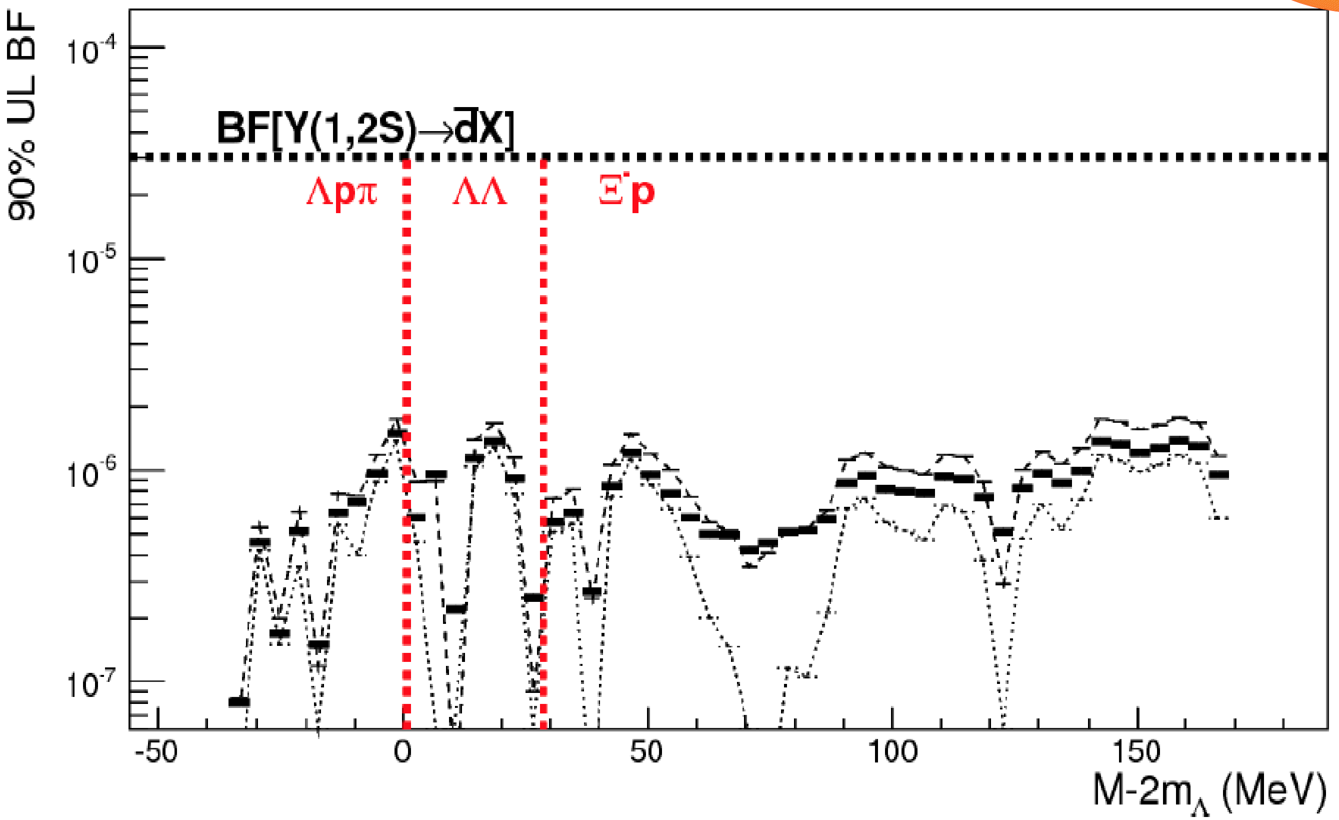
Υ(3S) runs: further dibaryons / exaquarks



Belle has extensively searched for the weakly bound Jaffe's H-dibaryon in Υ(1,2S) in a broad mass range, setting limits at $O(10^{-1})$ the measured deuteron production

With 300 fb'1 we expect:

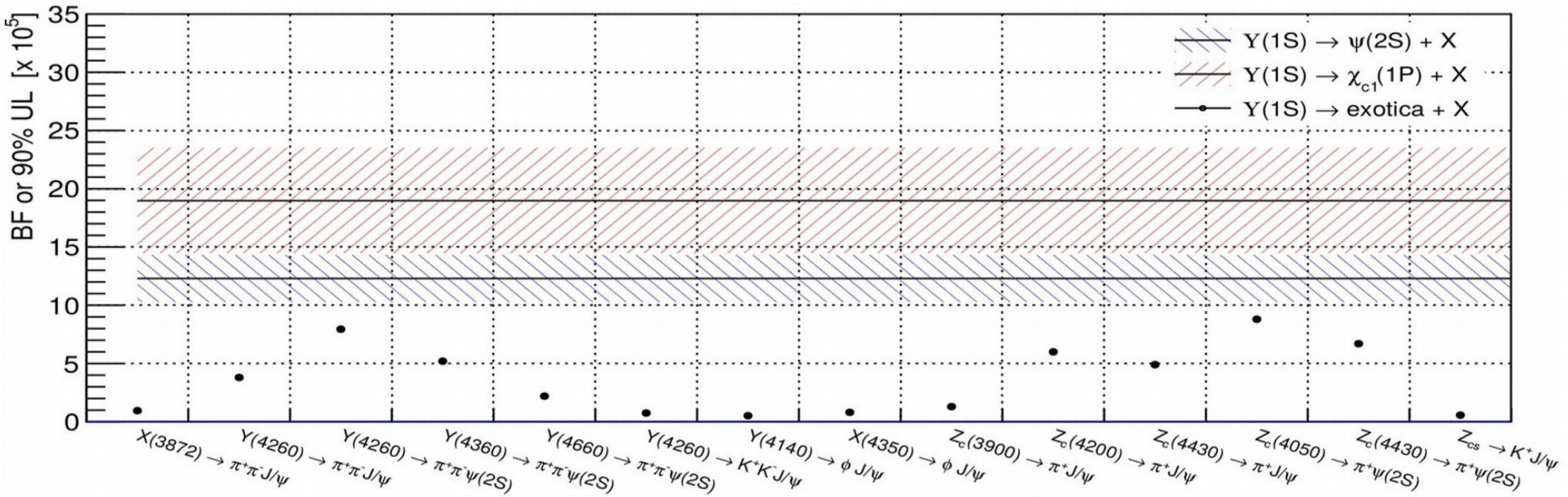
* 60 M events with one Λ or $\overline{\Lambda}$
3 M events with one $\Lambda\overline{\Lambda}$ pair



Belle-II will further investigate these channels, both with fully reconstructed final modes, and in missing mass. We plan also to search for non strange dibaryons, such as the d*(2380) (see Clement, Prog Part. Nucl. Phys. 93 (2017), 195) in $d\pi\pi$ final state.

Υ(3S) runs: transitions to XYZ states

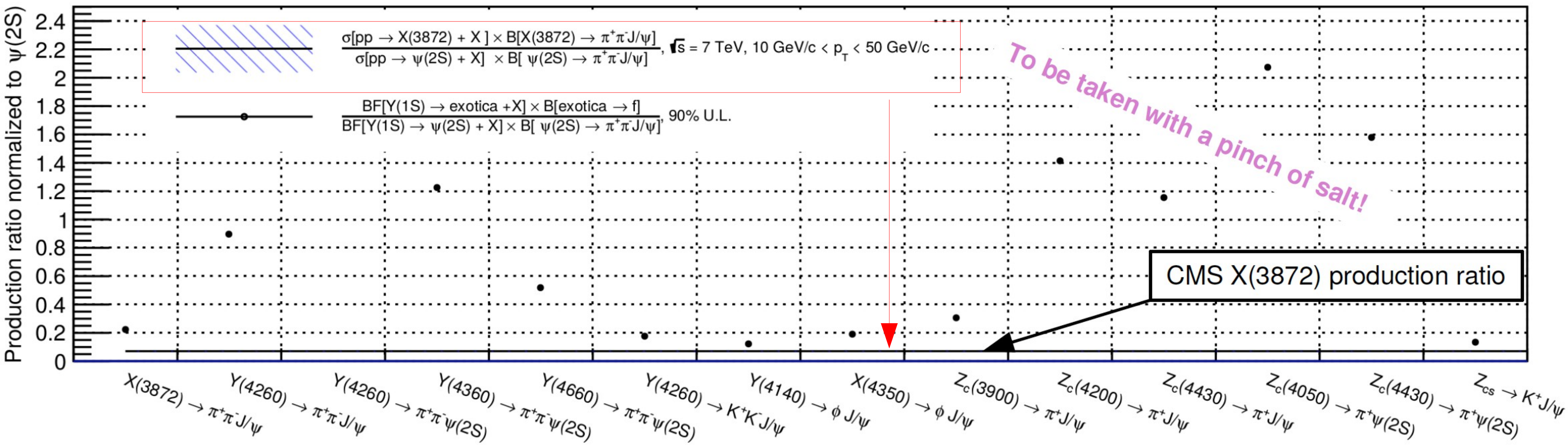
If narrow bottomonia are fertile sources of bound multiquarks , inclusive production of X,Y,Z states should be enhanced: Belle has put various upper limits on these processes [PRD82, 051504(R) (2010) PRD84,071107(R) (2014),   PRD96,112002(2017),   PRD97,112004(2018)]



Here we compare the current limits on inclusive production of XYZ states with measurements of inclusive production of known charmonia

Y(3S) runs: transitions to XYZ states

If we normalize BELLE and CMS results on charmoniumlike to the production of ψ', the first generation was just on the top of an iceberg :



With 300 fb^{-1} on the Y(3S) peak, Belle II can increase:

- by a factor 3 to 5 the sensitivity to production of inclusive charmoniumlike states ,
- by 10 to 15 times the sensitivity to double charmonium(like)

Wrapping it up ....

Belle II

Belle II is starting to take data ! Since Apr.26, the upgraded detector is seeing collisions at Υ(4S) peak. On July 17th, phase II has stopped to allow installation of vertex detectors. We'll start the physics program with full detector in Spring 2019. The goal is to integrate 50x Belle data by 2024.

Less than 5% of data taking is expected to give a wide variety of new results on bottomonium physics above and below the 4S:

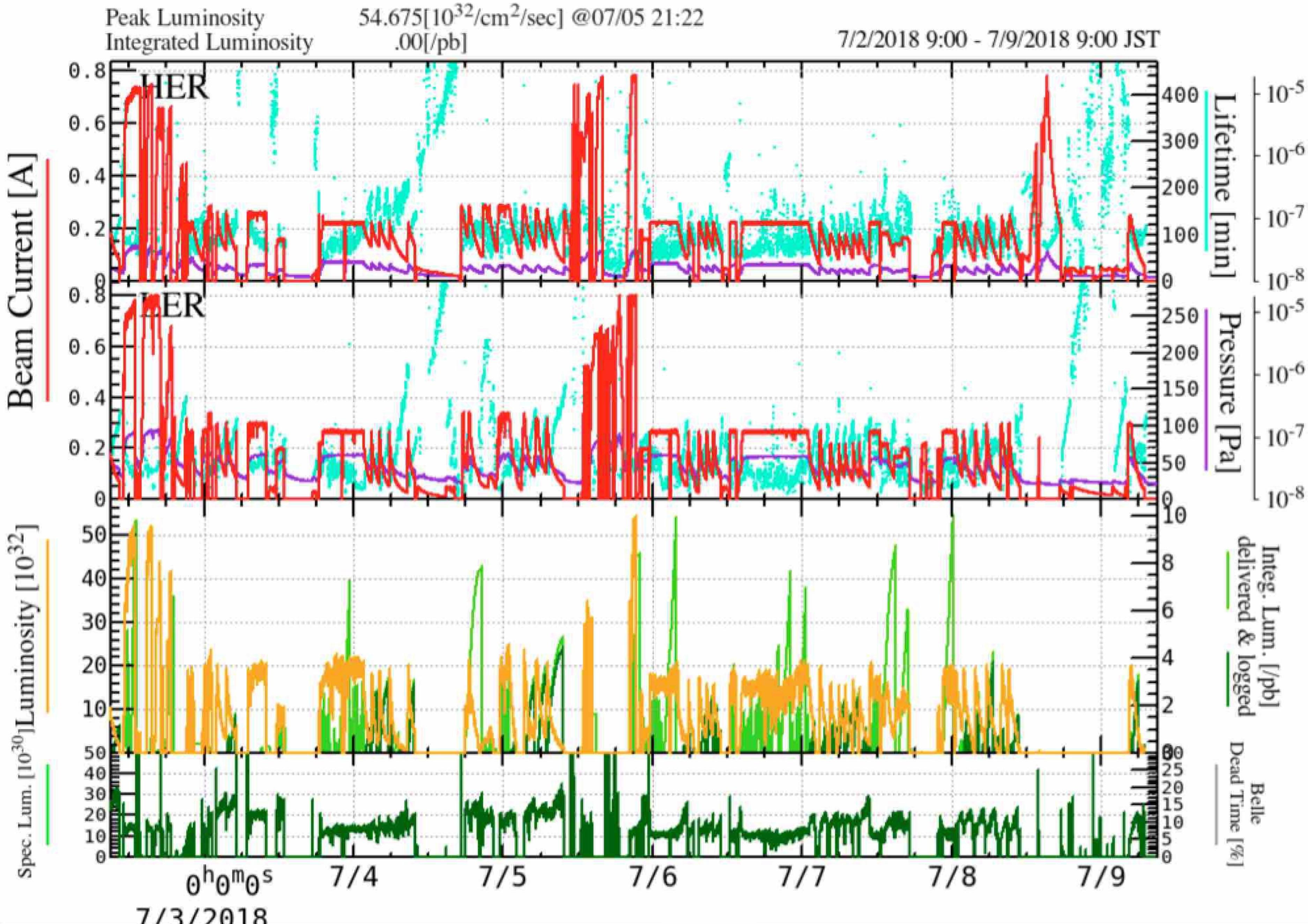
Υ(6S) peak: a pilot run of 10 fb^{-1} , then up to 100 fb^{-1}
Υ(5S) peak: at least 1ab^{-1} is envisaged, to have impactful new results
Scan of the high energy region (10.5 to 11 GeV): 400 fb^{-1} (2021?)
Υ(3S) peak: if high lumi running does not spoil the beam energy spread, at least 300 fb^{-1} data taking , yielding 1.2 G decays) is planned
Mini scans (10-20 fb^{-1}) will precisely determine the Υ(1,2D) vector masses

A wide variety of bottomonium and charmonium studies are in preparation:

Looking forward showing first results from Belle II in end 2019. Stay tuned !

Go raibh maith agaibh

Istantaneous Luminosity towards $L=10^{34}$ $cm^{-2}s^{-1}$ (but not yet)



5.55 x 10^{33}/cm^2/s (βy*3mm, LER: 800mA, HER: 780mA, 1576 bunches/beam July 5th)
2.29 x 10^{33}/cm^2/s (βy*3mm, LER: 270mA, HER: 225mA, 394 bunches/beam July 3rd)

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52±0.20	1.3±0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)		
				$B \to K(\gamma\psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28±10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (...)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108±14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96±42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007	NC!
$Y_b(10888)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

C

Missing pieces of spectrum below threshold

Below threshold:

* 3S: $\eta_b(3S)$ not yet observed by anyone, maybe reachable from $h_b(3P)$?
* 3P: $\chi_b(3P)$ discovered at LHC, not yet resolved, can we see them from 4S?
  $h_b(3P)$: too high to be reached from 5S via Z_b, maybe from 6S? How?

* 1D states : triplet states BEST STUDIED from 3S, singlet (2^{-+}) *maybe* reachable from $h_b(2P)$.We plan to scan the 1^{--} region.

* 2D, 1F, 1G: totally unknown

We propose to search for the lowest member of the 2D triplet with a scan. The others *may* be reached from 6S.

The 1F triplet $2,3,4^{++}$ is very close in mass to Y3S, but may be reached from the 2D triplet via E1 radiative transitions.