Tetra-quark from Belle II

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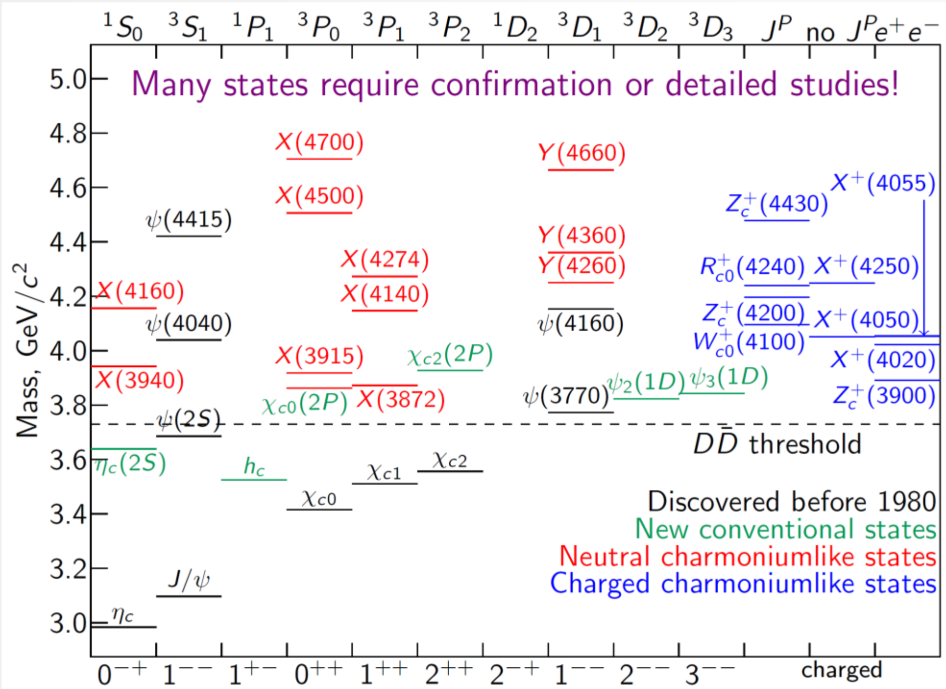
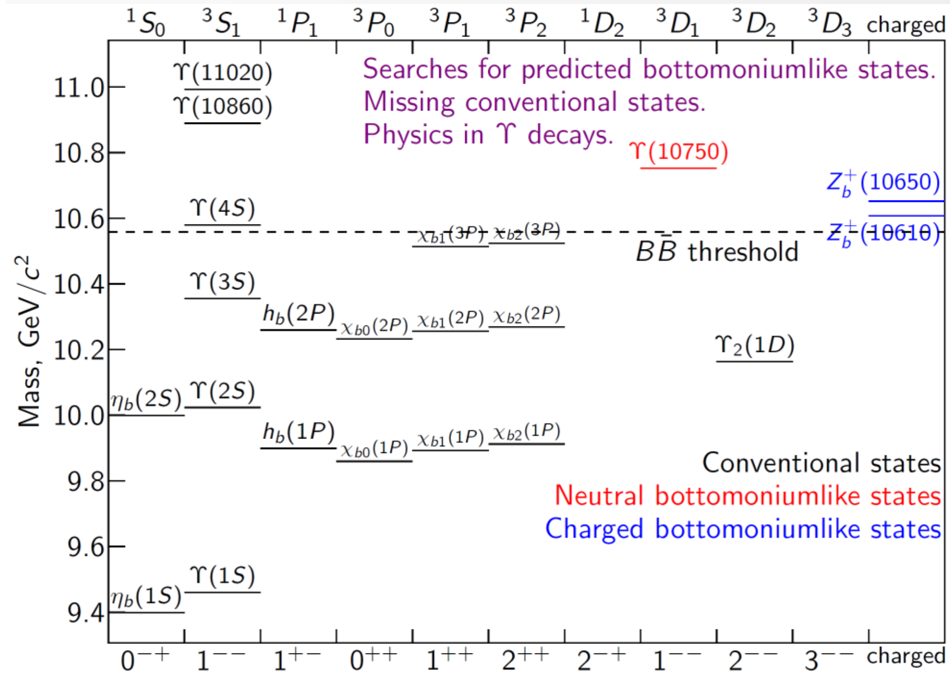
Quarknium and Quarkonium-like exotic hadrons





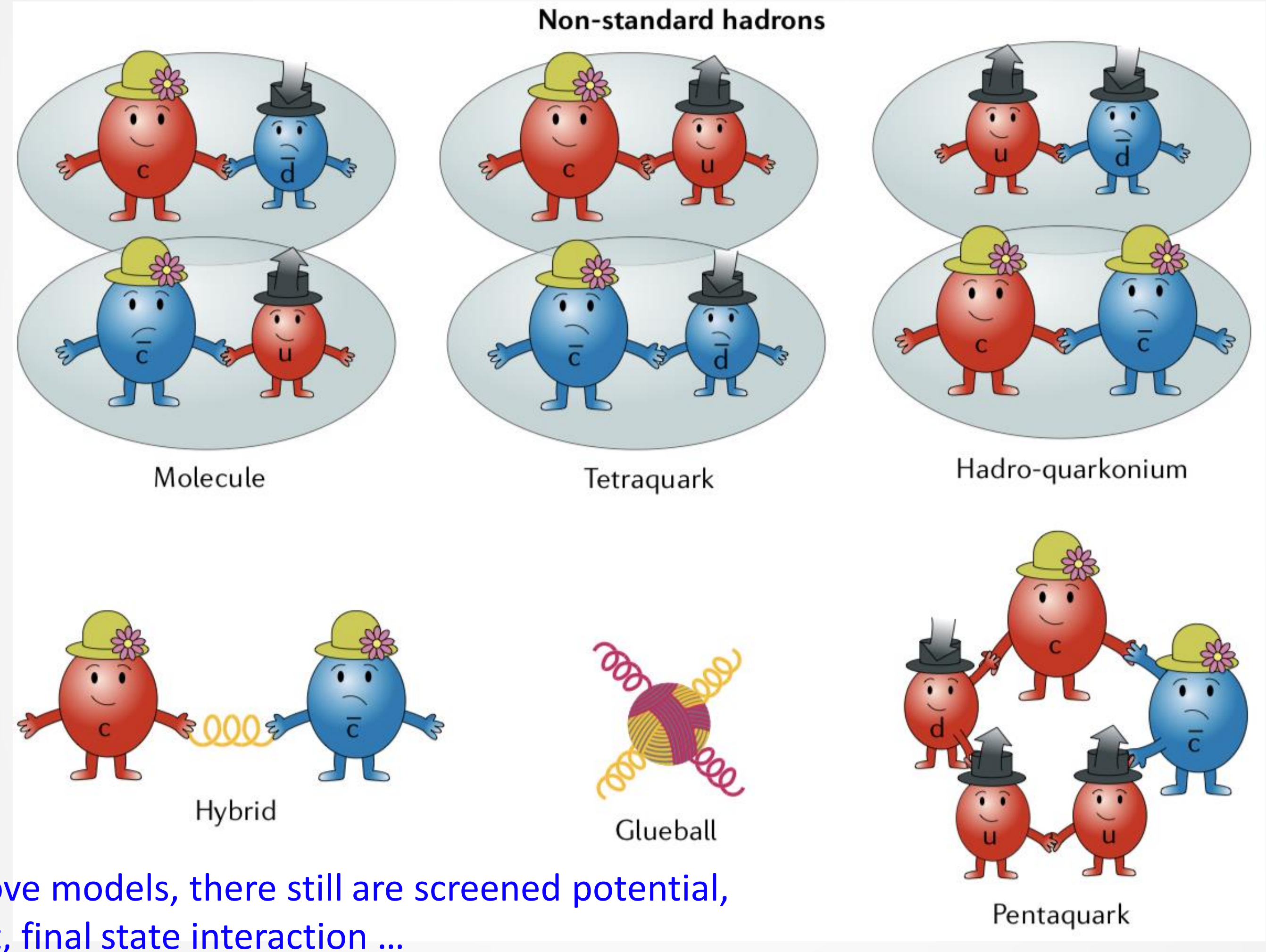
Classification:

- $Q\bar{Q}q\bar{q}$
- $Q\bar{Q}qqq$: P_c^+

X: Neutral, $J^{PC} \neq 1^{--}$; Y: Neutral, $J^{PC} = 1^{--}$; Z: Charged

- Quarkonium: $q\bar{q}$, the simplest system of a hadron.
- Below $D\bar{D}/B\bar{B}$ thresholds – both charmonium and bottomonium are successful stories of QCD.
- But there are many exotic states observed in the past decade, and they are hard to fit in the two families.

Too many models !



Besides above models, there still are screened potential, cusps effect, final state interaction …

Nature Reviews Physics 1, 480 (2019)

High Priority:

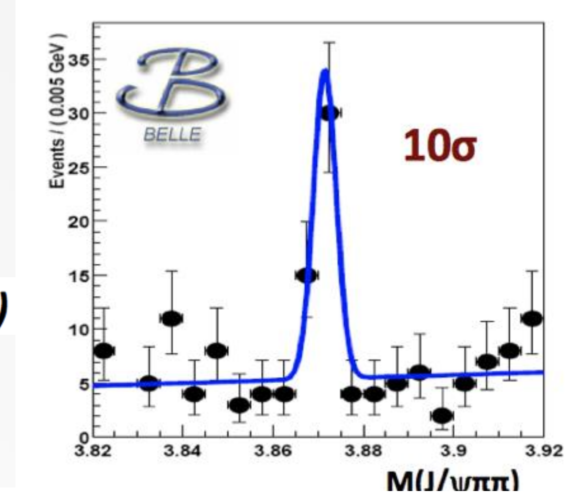
- Identify most prominent component in wave function
- Seek unique picture describing all XYZ states, not state-by-state

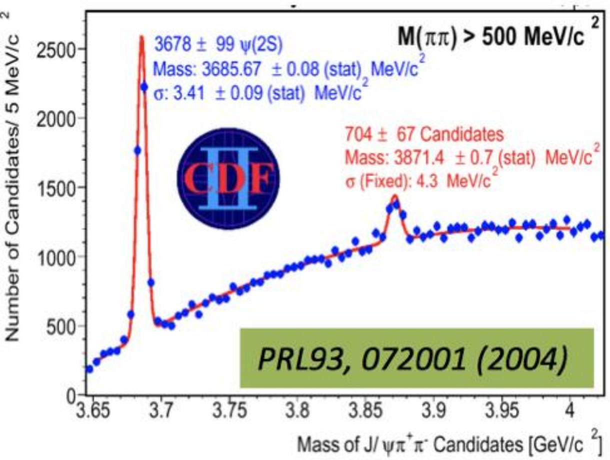
X(3872)→J/ψπ⁺π⁻

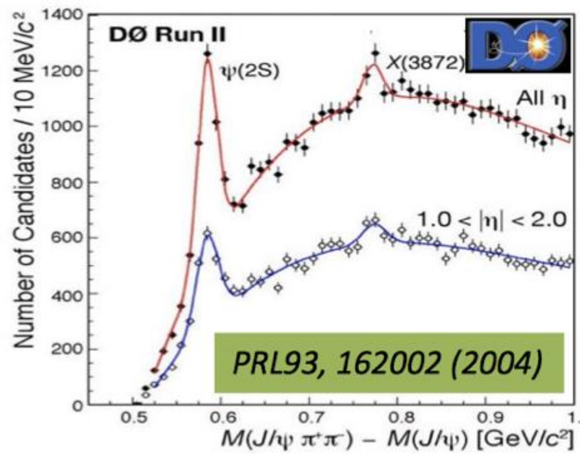
The most-cited article at Belle: 1800+

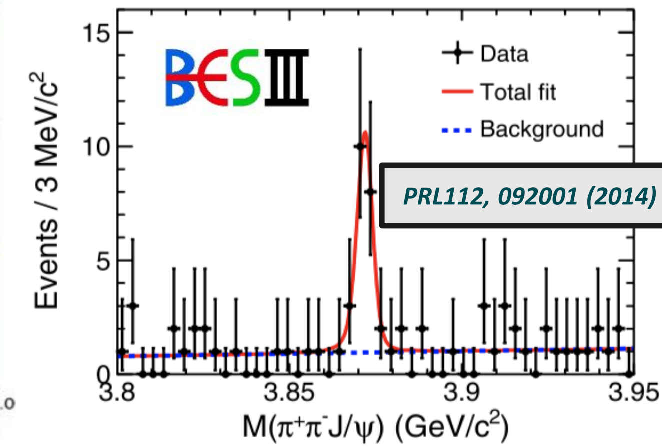
First observed by Belle in $B \to K\, J/\psi\pi^+\pi^-$ ***PRL91, 262001 (2003)***

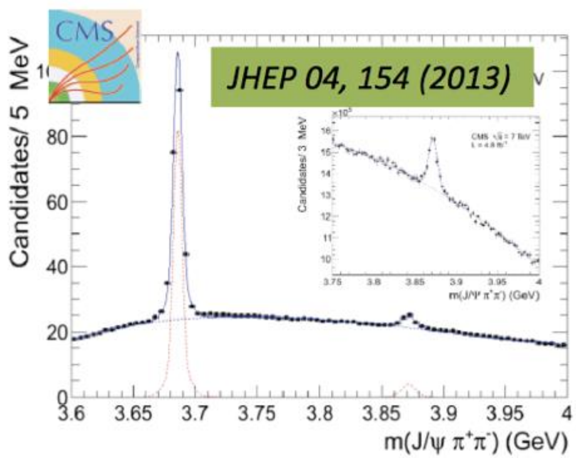
- M_X close to $D^0\bar{D}^{*0}$ threshold M = (3871.68±0.17) MeV
- Surprisingly narrow: $\Gamma_{tot} < 1.2$ MeV at 90% C.L.

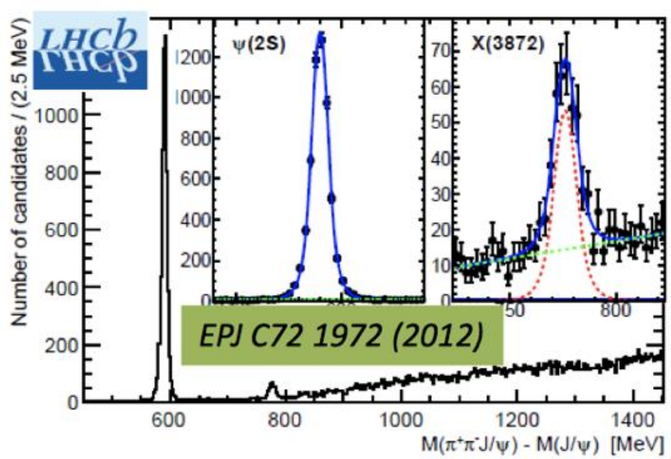












X(3872)→J/ψγ: C-even

Angular analysis:

Belle 2006: $J^{PC} = 1^{++}$ or ≥2

CDF 2008: $J^{PC} = 1^{++}$ or 2^{-+}

Belle 2011: $J^{PC} = 1^{++}$ or 2^{-+}

LHCb 2013: $J^{PC} = 1^{++}$

What is X(3872)?

Decay Modes ▸ Expand all decays

Mode		Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P (MeV/c)
Γ_1	e^+e^-			1936
Γ_2	$\pi^+\pi^- J/\psi(1S)$	> 3.2%		650
Γ_3	$\rho^0 J/\psi(1S)$			-1
Γ_4	$\omega J/\psi(1S)$	> 2.3%		-1
Γ_5	$D^0\overline{D}^0\pi^0$	> 40%		117
Γ_6	$\overline{D}^{*0}D^0$	> 30%		4
Γ_7	$\gamma\gamma$			1936
Γ_8	$D^0\overline{D}^0$			520
Γ_9	D^+D^-			502
Γ_{10}	$\gamma\chi_{c1}$			344
Γ_{11}	$\gamma\chi_{c2}$			303
Γ_{12}	$\pi^0\chi_{c2}$			274
Γ_{13}	$\pi^0\chi_{c1}$	> 2.8%		319
Γ_{14}	$\pi^0\chi_{c0}$			
Γ_{15}	$\gamma J/\psi$	$> 7 \times 10^{-3}$		697
Γ_{16}	$\gamma\psi(2S)$	> 4%		181
Γ_{17}	$\pi^+\pi^-\eta_c(1S)$	not seen		745
Γ_{18}	$\pi^+\pi^-\chi_{c1}$	not seen		218
Γ_{19}	$p\overline{p}$	not seen		1693

Till now, absolute BR(X(3872)→FS) has not been established.

- **Molecular of $D^0\overline{D}^{*0}$**

Various models predict Br(X→ $J/\psi\pi^+\pi^-$) < 10% (PRD 72, 054022 (2005), PRD 69, 054008 (2004), Chin.Phys. C43 12, 124107 (2019))

- **Mixture of $D^0\overline{D}^{*0}$ and $\chi_{c1}(2P)$ bound state**

Br(X→ $J/\psi\pi^+\pi^-$) < 20% (PLB 702, 359 (2011))

- **Tetraquark model**

Br(X→ $J/\psi\pi^+\pi^-$) ~ 50% (PRD 71, 014028 (2005))

- **$\chi_{c1}(2P)$**

Br(X→ $\gamma J/\psi$) ~ 0.6%, Br(X→ $\gamma J/\psi$) ~ 3.5% (PRD 69, 054008 (2004))

Productions of X(3872)

- **B decays**: Belle, BaBar, LHCb

$B \to X(3872)K$, $X(3872) \to$ channel

- **Radiative decay in e^+e^- annihilations**: BESIII

$e^+e^- \to X(3872)\gamma$, $X(3872) \to$ channel

- **Λ_b^0 decays**: LHCb

$\Lambda_b^0 \to X(3872)pK^- \to J/\psi\pi^+\pi^-pK^-$

- **Prompt high energy hadron colliders**: CDF, DØ, CMS

$pp/p\bar{p} \to X(3872)$, $X(3872) \to J/\psi\pi^+\pi^-$

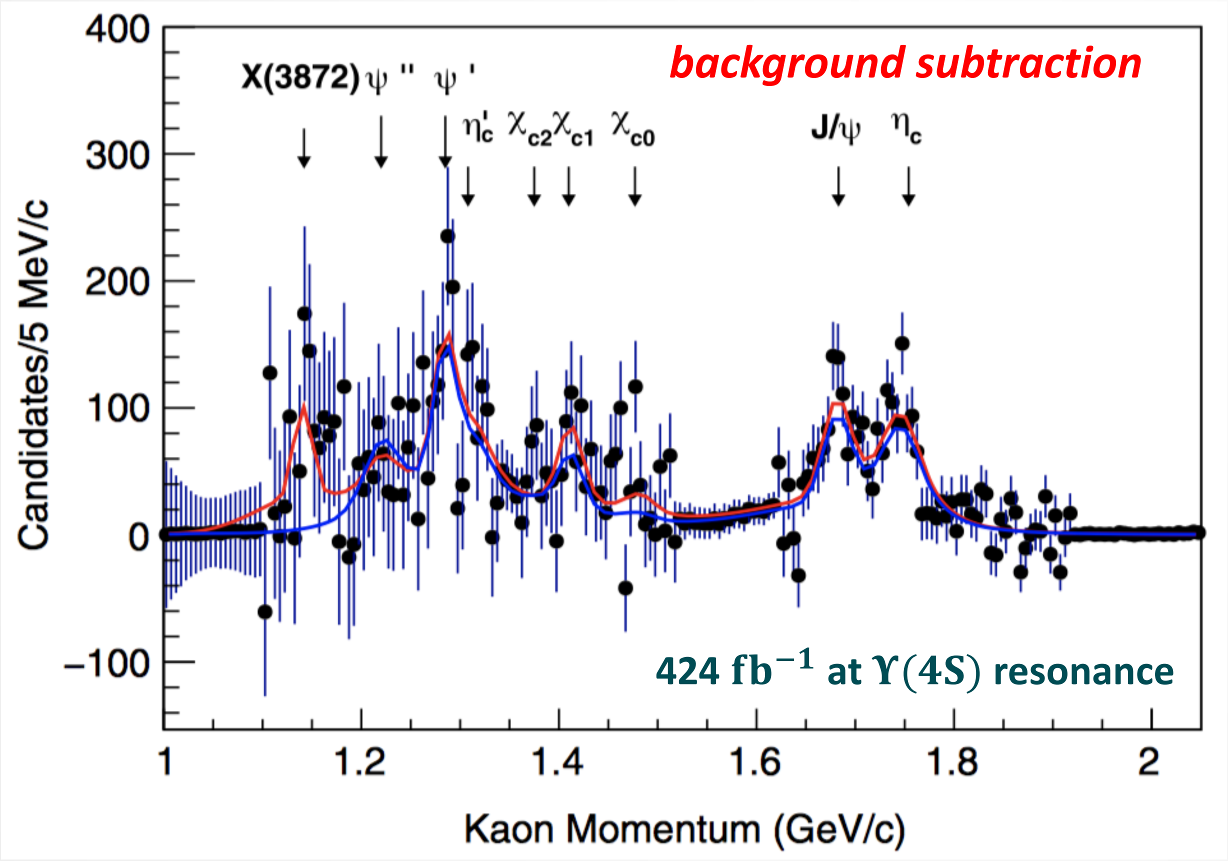
- **Photoproduction reactions**: COMPASS

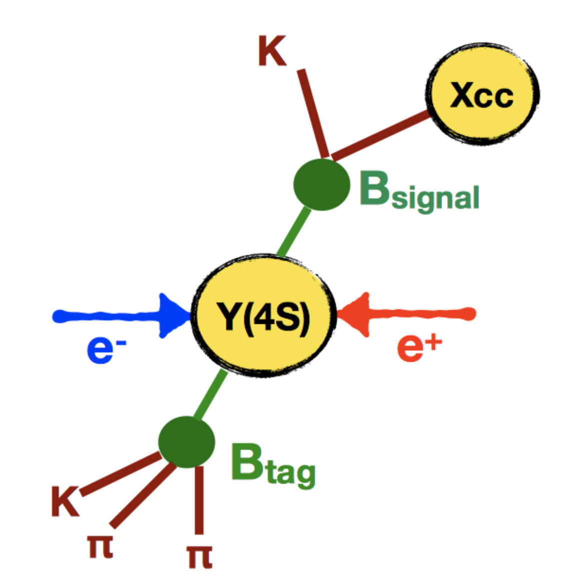
$\mu^+N \to \mu^+J/\psi\pi^+\pi^-\pi^\pm N'$ ($\widetilde{X}(3872)$)

Absolute Brs of X(3872) from BaBar

PRL 124, 152001 (2020)

- If more than one B candidate is found in an event, all candidates are retained to avoid the best one was not the correct one, including those where it belonged to the signal side.
- For the X(3872), the efficiency gains up to a factor of 3.





Absolute Brs of X(3872) from BaBar

PRL 122, 222001 (2019)

Particle	Yield	$\mathcal{B}(10^{-4})$	N_σ
J/ψ Reference mode	2364 ± 189	10.1 ± 0.29 (Ref. [21])	10.4
η_c	2259 ± 188	$9.6 \pm 1.2(\mathrm{stat}) \pm 0.6(\mathrm{syst})$	9.3
χ_{c0}	287 ± 181	$2.0 \pm 1.3(\mathrm{stat}) \pm 0.3(\mathrm{syst})$	1.6
χ_{c1}	1035 ± 193	$4.0 \pm 0.8(\mathrm{stat}) \pm 0.6(\mathrm{syst})$	2.2
χ_{c2}	200 ± 164	< 2.0	1.2
$\eta_c(2S)$	527 ± 271	$3.5 \pm 1.7(\mathrm{stat}) \pm 0.5(\mathrm{syst})$	2.3
ψ'	1278 ± 285	$4.6 \pm 1(\mathrm{stat}) \pm 0.7(\mathrm{syst})$	3.1
$\psi(3770)$	497 ± 308	$3.2 \pm 2.0(\mathrm{stat}) \pm 0.5(\mathrm{syst})$	1.2
$X(3872)$	992 ± 285	$2.1 \pm 0.6(\mathrm{stat}) \pm 0.3(\mathrm{syst})$	3.0

- $\mathcal{B}[X(3872) \rightarrow J/\psi\pi^+\pi^-]$ = **(4.1±1.3)%**
- **The measurement therefore suggests that the X(3872) has a significant molecular component.**

Absolute branching fractions of X(3872) decays

- Globally analyzing the measurements by BESIII, Belle, Babar, LHCb
- The absolute branching fractions of X(3872) is free parameters in the fitting

$$\chi^2(x) = \sum_{i=1}^{25} \frac{(x_i - x)^2}{\sigma_i^2},$$

- Statistical uncertainties are dominant for most measurements.
- Possible correlation between the systematics of different measurements in an experiments is neglected.

C.H.Li, C.Z.Yuan, Phys.Rev. D100 (2019) 094003

Index (i)	Parameters	Values	Experiments
	$X(3872) \to \pi^+\pi^- J/\psi$	$(\times 10^{-6})$	
1	$B^+ \to X(3872)K^+$	$8.61 \pm 0.82 \pm 0.52$	Belle [14]
2		$8.4 \pm 1.5 \pm 0.7$	BaBar [15]
3	$B^0 \to X(3872)K^0$	$4.3 \pm 1.2 \pm 0.4$	Belle [14]
4		$3.5 \pm 1.9 \pm 0.4$	BaBar [15]
	$X(3872) \to \gamma J/\psi$	$(\times 10^{-6})$	
5	$B^+ \to X(3872)K^+$	$1.78^{+0.48}_{-0.44} \pm 0.12$	Belle [22]
6		$2.8 \pm 0.8 \pm 0.1$	BaBar [23]
7	$B^0 \to X(3872)K^0$	$1.24^{+0.76}_{-0.61} \pm 0.11$	Belle [22]
8		$2.6 \pm 1.8 \pm 0.2$	BaBar [23]
	$X(3872) \to \gamma\psi(3686)$	$(\times 10^{-6})$	
9	$B^+ \to X(3872)K^+$	$0.83^{+1.98}_{-1.83} \pm 0.44$	Belle [22]
10		$9.5 \pm 2.7 \pm 0.6$	BaBar [23]
11	$B^0 \to X(3872)K^0$	$1.12^{+3.57}_{-2.90} \pm 0.57$	Belle [22]
12		$11.4 \pm 5.5 \pm 1.0$	BaBar [23]
	$X(3872) \to D^{*0}\bar{D}^0 + c.c.$	$(\times 10^{-4})$	
13	$B^+ \to X(3872)K^+$	$0.77 \pm 0.16 \pm 0.10$	Belle [16]
14		$1.67 \pm 0.36 \pm 0.47$	BaBar [17]
15	$B^0 \to X(3872)K^0$	$0.97 \pm 0.46 \pm 0.13$	Belle [16]
16		$2.22 \pm 1.05 \pm 0.42$	BaBar [17]
	$X(3872) \to \omega J/\psi$	$(\times 10^{-6})$	
17	$B^+ \to X(3872)K^+$	$6 \pm 2 \pm 1$	BaBar [18]
18	$B^0 \to X(3872)K^0$	$6 \pm 3 \pm 1$	BaBar [18]
	Ratios		
19	$\frac{\mathcal{B}(X(3872)\to\gamma J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	0.79 ± 0.28	BESIII [19]
20	$\frac{\mathcal{B}(X(3872)\to D^{*0}\bar{D}^0+c.c.)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	14.81 ± 3.80	BESIII [19]
21	$\frac{\mathcal{B}(X(3872)\to\omega J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$1.6^{+0.4}_{-0.3} \pm 0.2$	BESIII [20]
22	$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$0.88^{+0.33}_{-0.27} \pm 0.10$	BESIII [21]
23	$\frac{\mathcal{B}(X(3872)\to\gamma\psi(3686))}{\mathcal{B}(X(3872)\to\gamma J/\psi)}$	$2.46 \pm 0.64 \pm 0.29$	LHCb [24]
	$B^+ \to X(3872)K^+$	$(\times 10^{-4})$	
24		$2.1 \pm 0.6 \pm 0.3$	BaBar [27]
25		$1.2 \pm 1.1 \pm 0.1$	Belle [26]

Absolute branching fractions of X(3872) decays

- Fitting results

C.H.Li, C.Z.Yuan, Phys.Rev. D100 (2019) 094003

Parameter index	Decay mode	Branching fraction
1	$X(3872) \to \pi^+\pi^- J/\psi$	$(4.1^{+1.9}_{-1.1})\%$
2	$X(3872) \to D^{*0}\bar{D}^0 + c.c.$	$(52.4^{+25.3}_{-14.3})\%$
3	$X(3872) \to \gamma J/\psi$	$(1.1^{+0.6}_{-0.3})\%$
4	$X(3872) \to \gamma\psi(3686)$	$(2.4^{+1.3}_{-0.8})\%$
5	$X(3872) \to \pi^0\chi_{c1}$	$(3.6^{+2.2}_{-1.6})\%$
6	$X(3872) \to \omega J/\psi$	$(4.4^{+2.3}_{-1.3})\%$
7	$B^+ \to X(3872)K^+$	$(1.9 \pm 0.6) \times 10^{-4}$
8	$B^0 \to X(3872)K^0$	$(1.1^{+0.5}_{-0.4}) \times 10^{-4}$
	$X(3872) \to$ unknown	$(31.9^{+18.1}_{-31.5})\%$

- $X(3872) \to \pi^+\pi^- J/\psi \sim (4.1^{+1.9}_{-1.1})\%$
- $X(3872) \to D^0 D^{*0} \sim (52.4^{+25.3}_{-14.3})\%$
- Unknown decay ~ $(31.9^{+18.1}_{-31.5})\%$

- Statistical uncertainties are dominant.
- At Belle II, we need improve the measurements related with X(3872) decays

Evidence for X(3872)→ $\pi^+\pi^-J/\psi$ produced in single-tag two-photon interactions

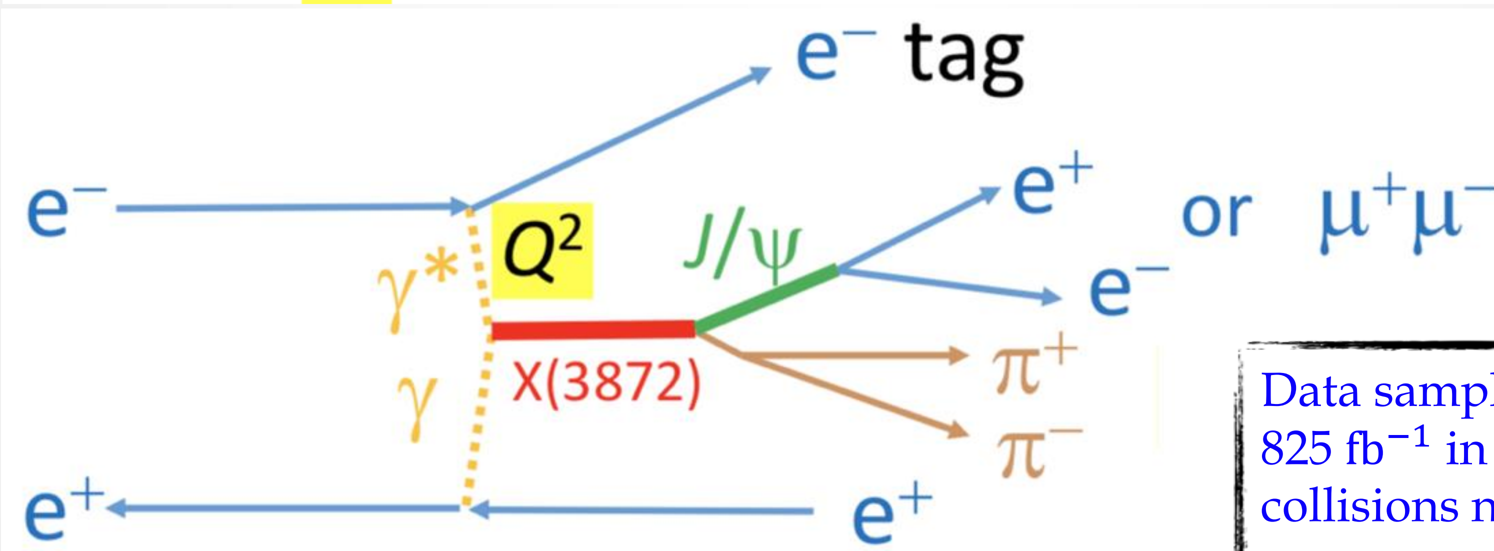
arXiv: 2007.05696 (2020), submitted to PRL

- X(3872) with $J^{PC} = 1^{++}$ could be produced if one or both photons are highly virtual [Nucl. Phys. B 523, 423 (1998)].
- The measurement of X(3872) in two-photon reactions help to understand its internal structure.

X(3872): $J^{PC} = 1^{++}$

$\gamma\gamma \rightarrow X(3872)$ ➡ Not allowed

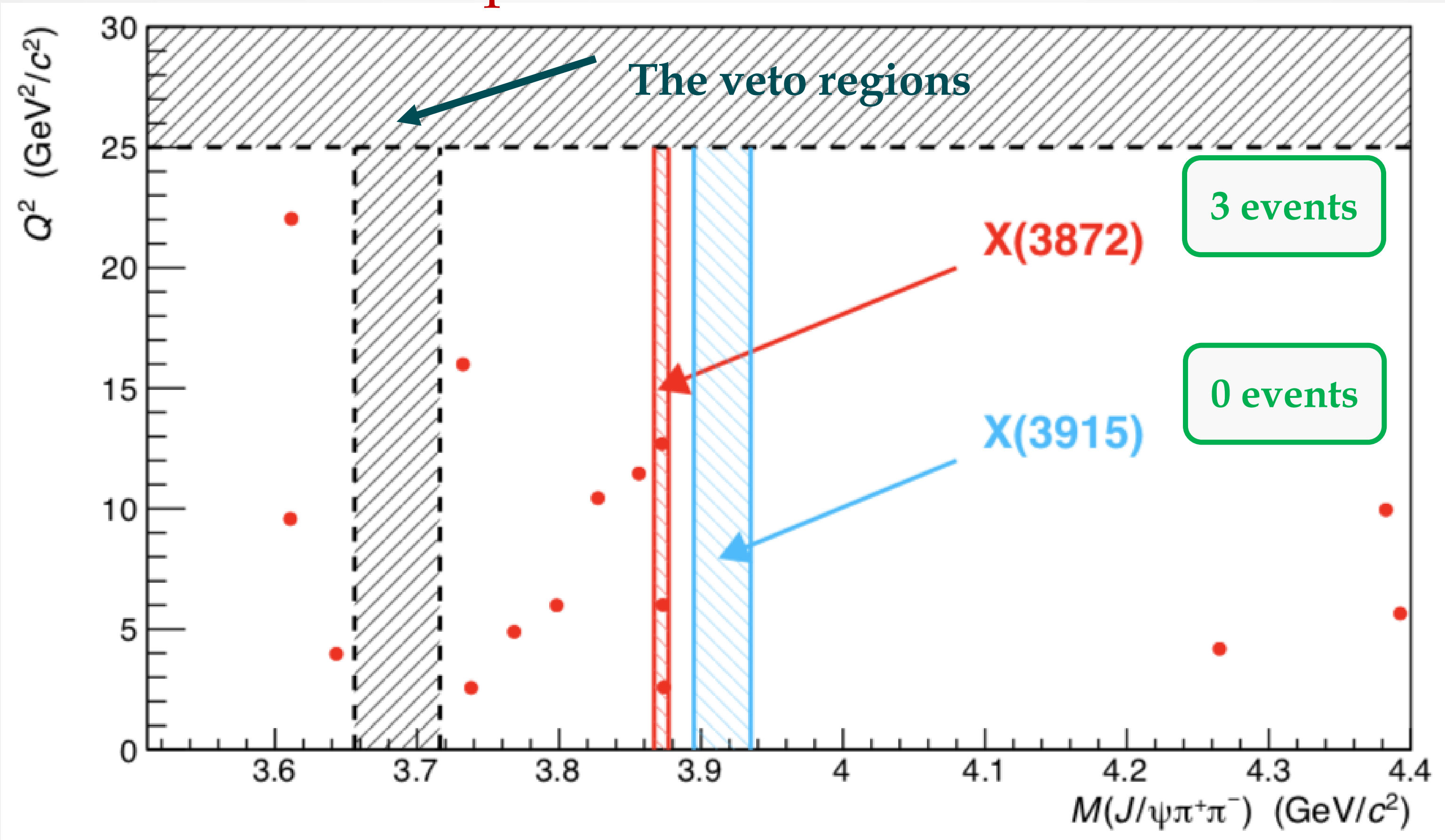
But, $\gamma^*\gamma \rightarrow X(3872)$ ➡ Allowed



Data sample:
825 fb^{-1} in e^+e^- collisions near 10.6 GeV

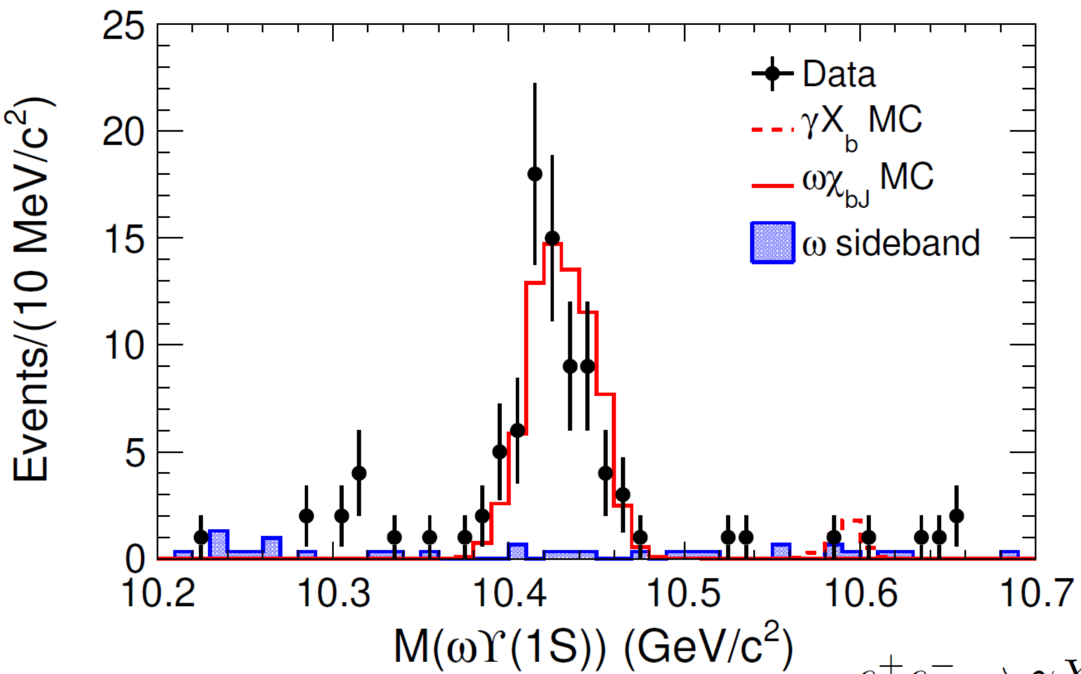
$-Q^2$ is the invariant mass-squared of the virtual photon.

Evidence for X(3872)→ $\pi^+\pi^-J/\psi$ produced in single-tag two-photon interactions



- M(X(3872)) = (3.8723±0.0012) GeV/c^2
- With 0.11±0.10 background events, **the number of signal events is N_{sig} = $2.9^{+2.2}_{-2.0}$(stat.) ± 0.1(syst.) with a significance of 3.2σ** (Feldman-Cousins method applied [Phys. Rev. D 57, 3873 (1998)]).
- **$\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X(3872) \to \pi^+\pi^-J/\psi) = 5.5^{+4.1}_{-3.8}(\text{stat.}) \pm 0.7(\text{syst.})$ eV** using the Q^2 dependence expected from a $c\bar{c}$ meson model.

Search for X(3872) partner in bottomonium X_b



$e^+e^- \to \gamma X_b,\ X_b \to \omega\Upsilon(1S)$

The peak in $M(\omega\Upsilon(1S))$ comes from $e^+e^- \to \omega\chi_{bJ},\ \chi_{bJ} \to \gamma\Upsilon(1S)$

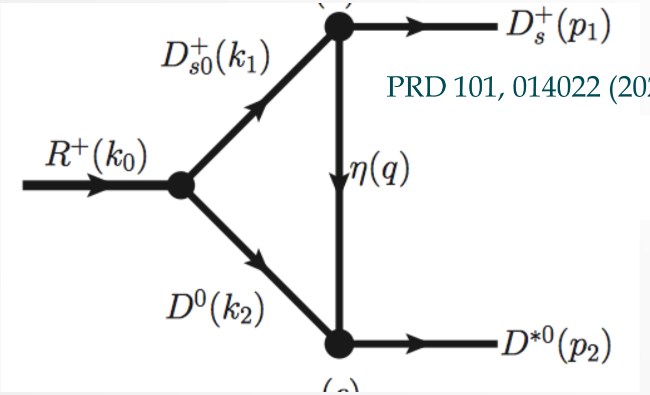
$\mathcal{B}(\Upsilon(10860) \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon(1S)) < (2.6 - 3.8) \cdot 10^{-5}$ btw. 10.55 and 10.65 GeV

X.H. He et al., Phys. Rev. Lett. 113, 142001 (2014)

Search for $R^{++} \to D^+ D_s^{*+}$

Phys. Rev. D 102, 112001 (2020)

- A doubly-charged and doubly-charmed molecule R^{++} decays to $D^+ D_s^{*+}$ with modest rates according to Refs. [PRD 99, 076017 (2019), PRD 101, 014022 (2020)].
- The mass of R++ is predicted to be in the range of 4.13 to 4.17 GeV/c^2; the width is (2.30−2.49) MeV.
- A state decaying to $D^+ D_s^{*+}$ is also a good candidate for a doubly-charged tetraquark according to Ref. [PRL 119, 202001 (2017)].



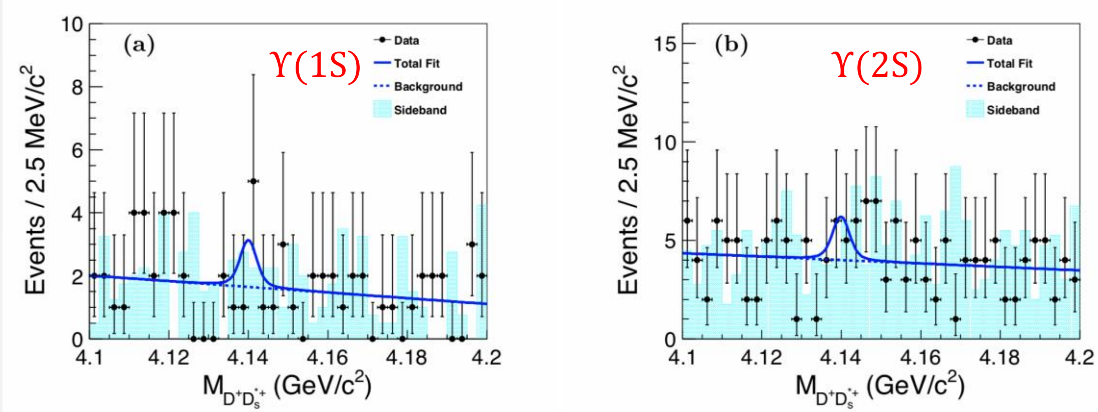
PRD 101, 014022 (2020)

Data samples:

$\sqrt{s}$ (GeV)	Luminosity (fb^{-1})	Events
9.46 [ϒ(1S)]	5.74±0.09	(102±3) million
10.023 [ϒ(2S)]	24.91±0.35	(158±4) million
10.52	89.5±1.3	-
10.58 [ϒ(4S)]	711±10	-
10.867 [ϒ(5S)]	121.4±1.7	-

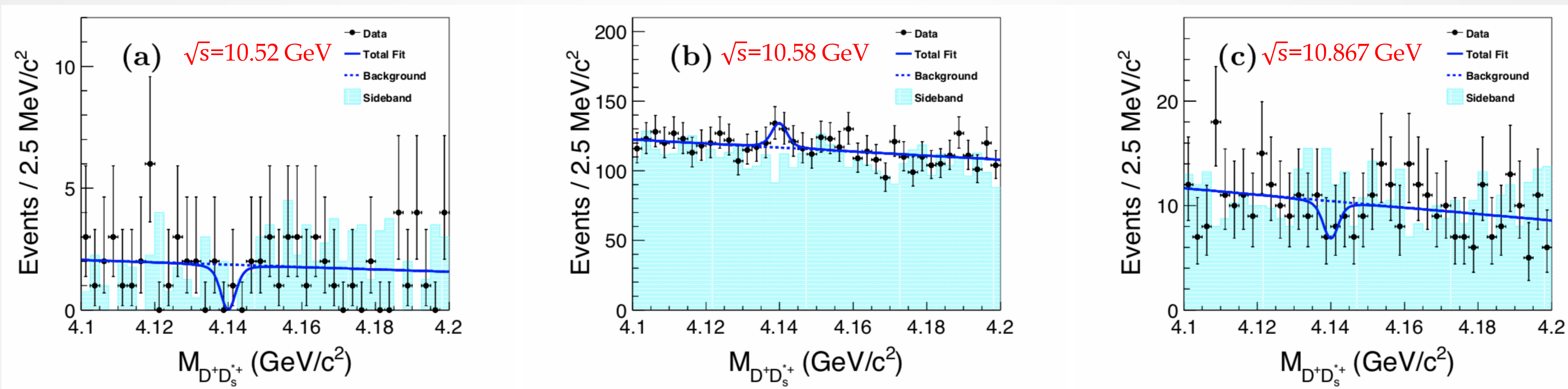
- $D^+ \to K^-\pi^+\pi^- / K_S^0(\to \pi^+\pi^-)\pi^+$
- $D_s^{*-} \to D_s^- \gamma$
- $D_s^- \to \phi\pi^- / \bar{K}^{*0} K^+$

The Punzi parameter S/(3/2+$\sqrt{B}$) [arXiv:physics/0308063] is applied to optimize the mass windows of intermediate states.



The fitted results with the R^{++} mass fixed at 4.14 GeV/c^2 and width fixed at 2 MeV.

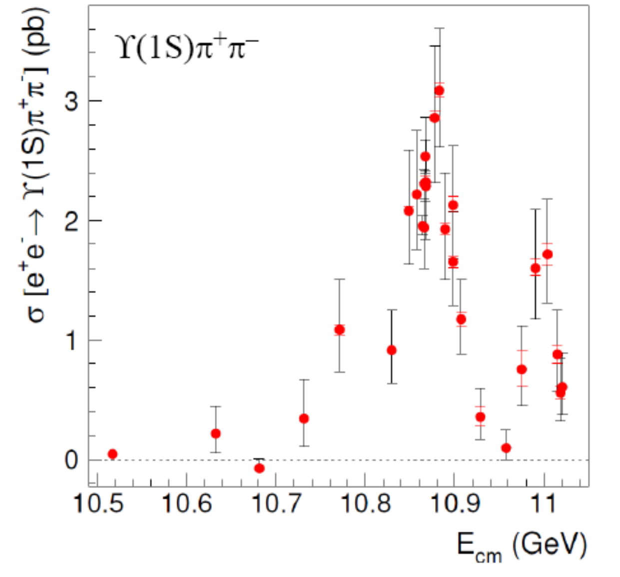
No R^{++} signals are observed.

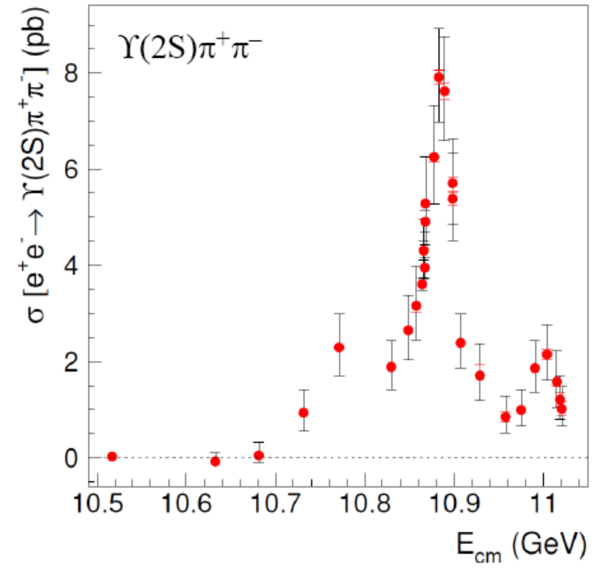


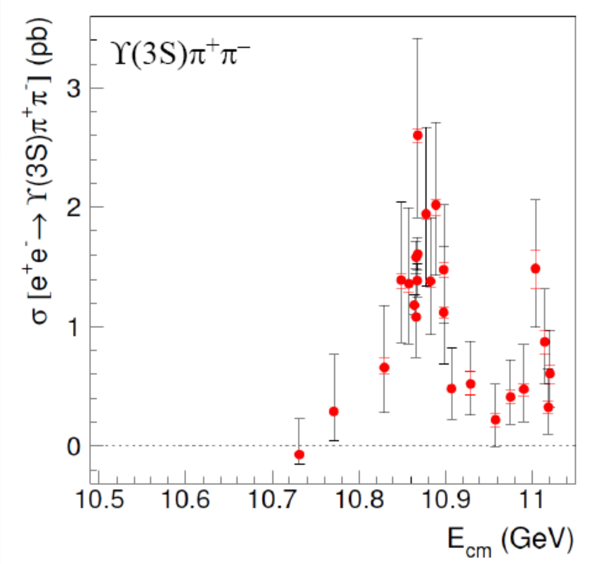
90% C. L. Upper limits [M(R^{++}) varying from 4.13 to 4.17 GeV/c^2, Γ(R^{++}) varying from 0 to 5 MeV]
$\mathcal{B}(\Upsilon(1S) \to R^{++} + \text{anything})\mathcal{B}(R^{++} \to D^+D_s^{*+})$=(11.8 - 54.5)× 10^{-5}
$\mathcal{B}(\Upsilon(2S) \to R^{++} + \text{anything})\mathcal{B}(R^{++} \to D^+D_s^{*+})$=(16.3 - 68.6)× 10^{-5}
$\sigma(e^+e^- \to R^{++} + \text{anything})\mathcal{B}(R^{++} \to D^+D_s^{*+})$ = (202.8 – 880.4) fb at $\sqrt{s}$ = 10.52 GeV
$\sigma(e^+e^- \to R^{++} + \text{anything})\mathcal{B}(R^{++} \to D^+D_s^{*+})$ = (218.9 – 1054.0) fb at $\sqrt{s}$ = 10.58 GeV
$\sigma(e^+e^- \to R^{++} + \text{anything})\mathcal{B}(R^{++} \to D^+D_s^{*+})$ = (346.6 – 1517.6) fb at $\sqrt{s}$ = 10.867 GeV

Update cross sections of $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)$

Belle, JHEP 1910, 220 (2019)







Black error bars: statistical

Red error bars: uncorrelated systematic errors

Structure at 10.75 GeV is more significant

Fits to energy dependent cross sections

$$|\mathrm{BW}^{(n)}_{\Upsilon(5S)} + e^{i\alpha_n}\,\mathrm{BW}^{(n)}_{\Upsilon(6S)} + e^{i\beta_n}\,\mathrm{BW}^{(n)}_{\mathrm{new}} + e^{i\gamma_n}\,\mathrm{BW}^{(n)}_{\Upsilon((n+1)S)}|^2 \otimes \mathrm{Gaussian}$$

$$F_{BW}(s, M, \Gamma, \Gamma^0_{ee} \times \mathcal{B}_f) = \frac{\sqrt{12\pi\,\Gamma\,\Gamma^0_{ee} \times \mathcal{B}_f}}{s - M^2 + iM\Gamma}\sqrt{\frac{\Gamma_f(s)}{\Gamma_f(M^2)}},$$

Simultaneous fit to three channels with some common parameters.

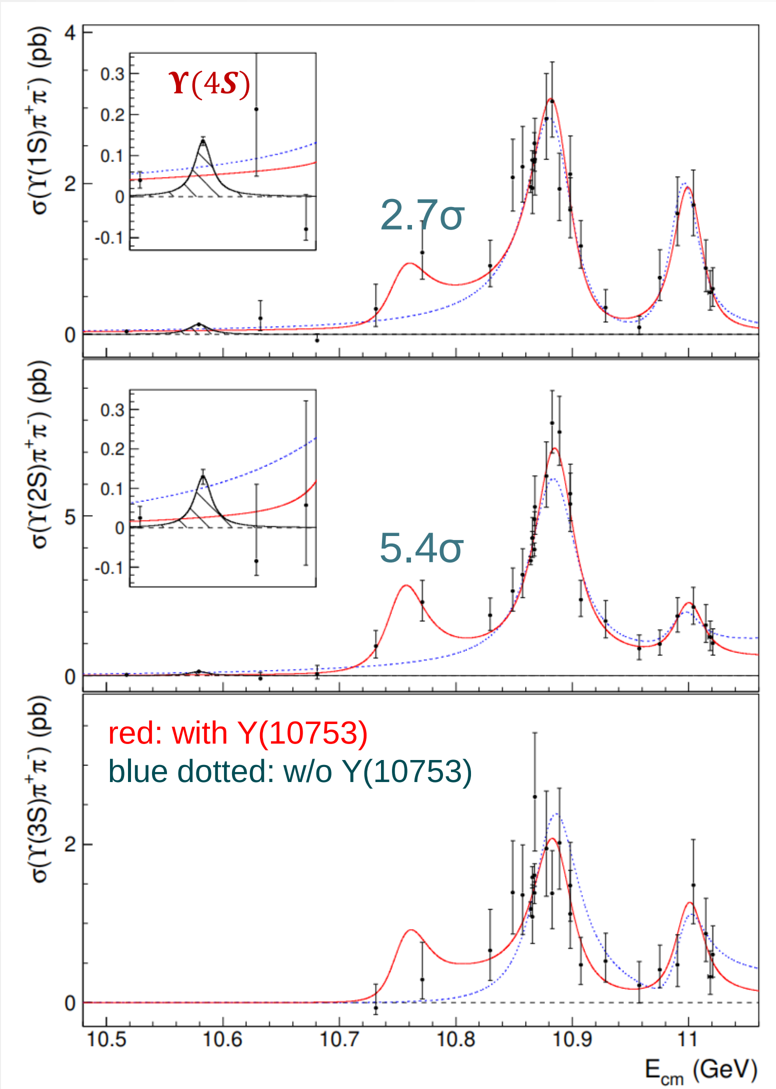
Free parameters: Mass M, width Γ, product of partial width and branching fraction $\Gamma_{ee}B(\pi\pi\Upsilon)$, relative phase ϕ.

Fit results to $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ cross sections

Scan data: 22 points, each point 1fb^{-1}

$\Upsilon(10860)$ on-resonance data: 121 fb^{-1}, between 10.864 and 10.868 GeV

Continuum data at 10.52 GeV, 60 fb^{-1}



	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}{}^{+1.0}_{-1.3}$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}{}^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}{}^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3}$

$\Gamma_{ee} \times \mathcal{B}$ (in eV)

	$\Upsilon(10860)$	$\Upsilon(11020)$	new
$\Upsilon(1S)\pi^+\pi^-$	0.75 – 1.43	0.38 – 0.54	0.12 – 0.47
$\Upsilon(2S)\pi^+\pi^-$	1.35 – 3.80	0.13 – 1.16	0.53 – 1.22
$\Upsilon(3S)\pi^+\pi^-$	0.43 – 1.03	0.17 – 0.49	0.21 – 0.26

a range due to multi-solutions

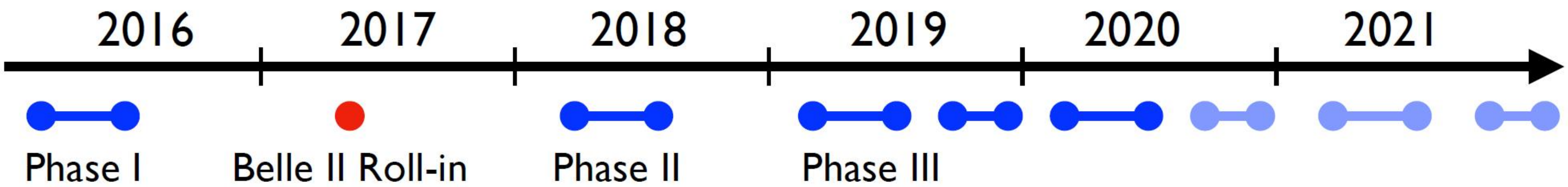
global significance: 6.7σ

- Could there be a Z_b enhancement?
- Could it be Υ(3D) bottomonium or a tetraquark?
- Near B$^{(*)}$B$^*\pi$ threshold regions

Interpretation of the Υ(10750)

- D-wave bottomonium
  - B. Chen, A.L. Zhang, J. He, arXiv:1910.06065, Bottomonium spectrum in the relativistic flux tube model (3D)
  - Q. Li, M.S. Liu, Q.F. Lü, L.C. Gui, X.H. Zhong, arXiv:1905.10344, Canonical interpretation of Y(10750) and Y(10860) in the Υ family (4D)
- $\bar{B}^{(*)}B^{(*)}$ dynamically generated pole
  - P. Bicudo, M. Cardoso, N. Cardoso, M. Wagner, arXiv:1910.04827, Bottomonium resonances with I=0 from lattice QCD correlation functions with static and light quarks
- Hybrid
  - J. T. Castellà, arXiv:1908.05179, Spin Structure of heavy-quark hybrids
- Tetraquark state
  - A. Ali, L. Maiani, A. Y. Parkhomenko, W. Wang, arXiv:1910.07671, Interpretation of Yb (10753) as a tetraquark and its production mechanism
  - Z.G. Wang, arXiv:1905.06610, Vector hidden-bottom tetraquark candidate: Y(10750)

SuperKEKB/Belle II Operation History



Phase 1 (w/o QCS/Belle II)

- Accelerator tuning w/ single beams

Phase 2 (w/ QCS/Belle II but w/o VXD)

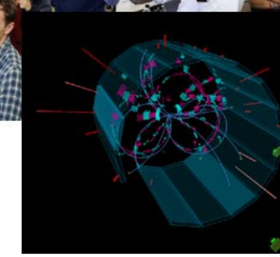
- Verification of nano-beam scheme
- Understand beam background
- Collision data w/o VXD

Phase 3 (w/ full detector)

- Production of physics data

Belle II roll-in (2017.4.17)

1st collision (2018.4.26)



Installation of VXD

Phase 3 physics run (2019.3.25~)

Achievements in 2020 a/b

- Recorded 64 fb^{-1}
  - L_{int} =74 fb^{-1} by adding 2019 data set
- ★ L_{day}^{max} = 1.34 fb^{-1} (June 22)
- ★ L_{peak} = 2.4 x $10^{34}cm^{-2}s^{-1}$ w/ Belle II ON
  - on-resonance
  - HER: 607mA, LER: 712mA, N_b: 978

a factor 2-3 lower currents than KEK

KEKB record

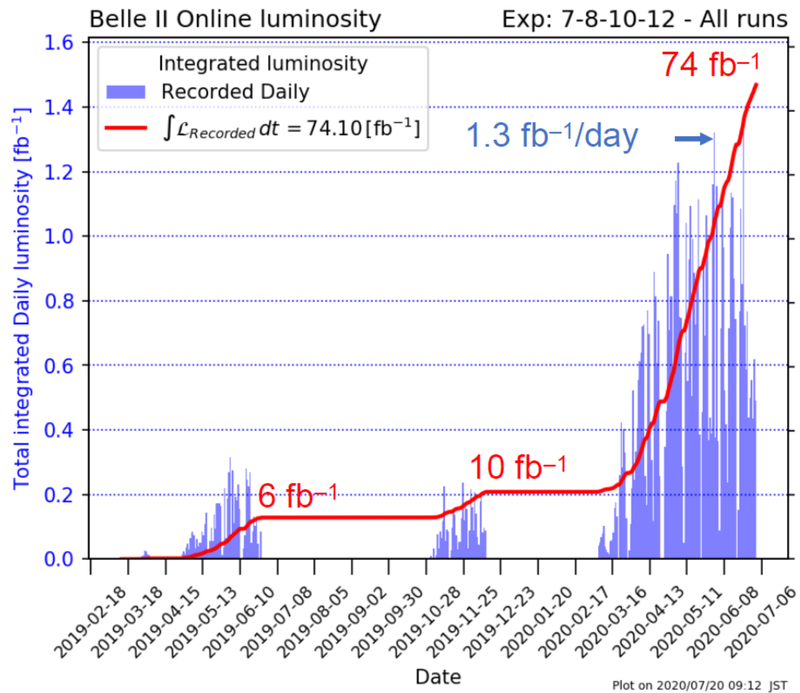
- L_{day}^{max} = 1.48 fb^{-1} (2009.6.14)
- Lpeak = 2.11 x $10^{34}cm^{-2}s^{-1}$

Luminosity world record !

Belle II background (TOP, CDC, PXD) lower than the limit, thanks to many many efforts

Belle II data taking efficiency was improved to 84%.

- less DAQ errors
- Error analysis (ELK)
- Well experienced shifters
- Better controlled injection veto

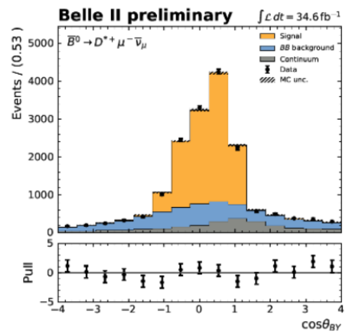


Belle II Summer Results

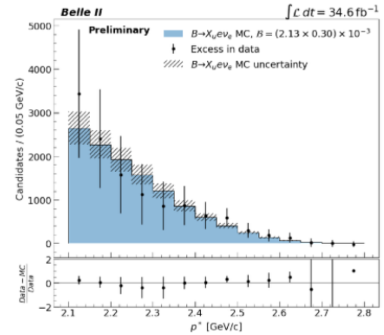
We presented a nice set of results at (virtual) ICHEP 2020:

- 9 conference papers uploaded to the arXiv;
- 13 public documents of rediscoveries and performance on data;
- 3 sensitivity studies based on the simulation;

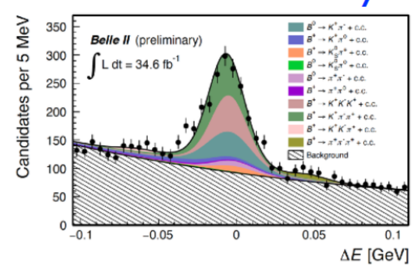
Exclusive B→D*lν



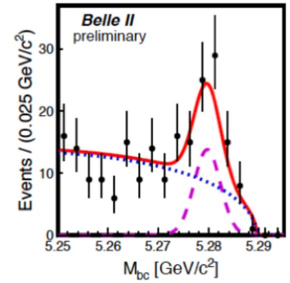
Inclusive b→u



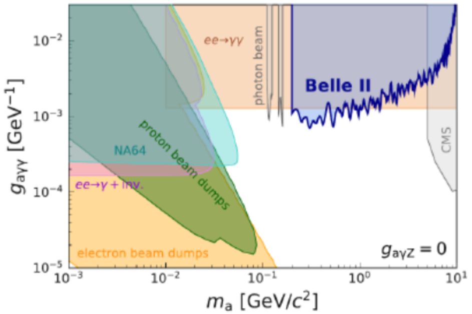
Charmless B decays



B → ΦK(*)

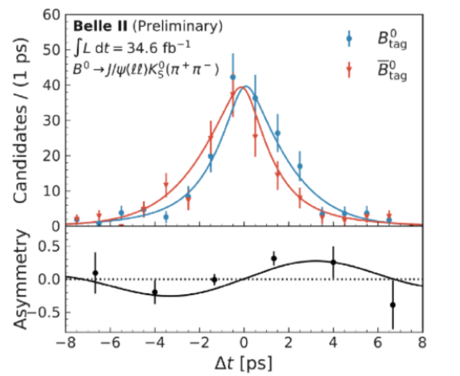


Search for Axion Like Particle (ALP)



2nd physics paper by Belle II
PRL 125 (2020) 16, 161806

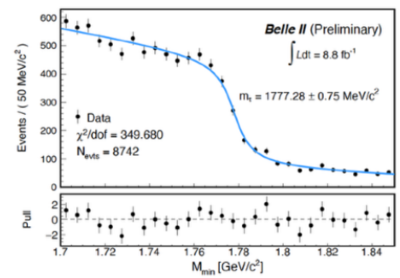
TDCPV (B→J/ψKS0)



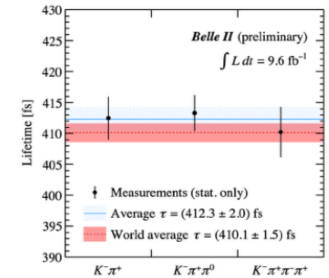
$S_{CP} = 0.55 \pm 0.21(\mathrm{stat.}) \pm 0.04(\mathrm{syst.})$

$S_{\rm PDG} = 0.701 \pm 0.017$

τ mass measurement



D0 lifetime



Belle II Physics results

2 Dark Sector PRL publications on Phase2 data:

- Search for an Invisibly Decaying Z′ Boson at Belle II in $e^+e^- \to \mu^+\mu^-(e^\pm\mu^\mp)$ Plus Missing Energy Final States, PRL 124, 141801 (2020);
- Search for Axionlike Particles Produced in e^+e^- Collisions at Belle II, PRL 125, 161806 (2020);

12 conference papers posted on arXiv:

Spring

- Charmless B decay reconstruction, arXiv:2005.13559 [hep-ex];
- Measurement of the branching fraction B(anti-$B^0 \to D^{*+} l^- \nu_l$), arXiv:2004.09066 [hep-ex];
- Measurement of the B^0 lifetime using fully reconstructed hadronic decays, arXiv:2005.07507 [hep-ex];

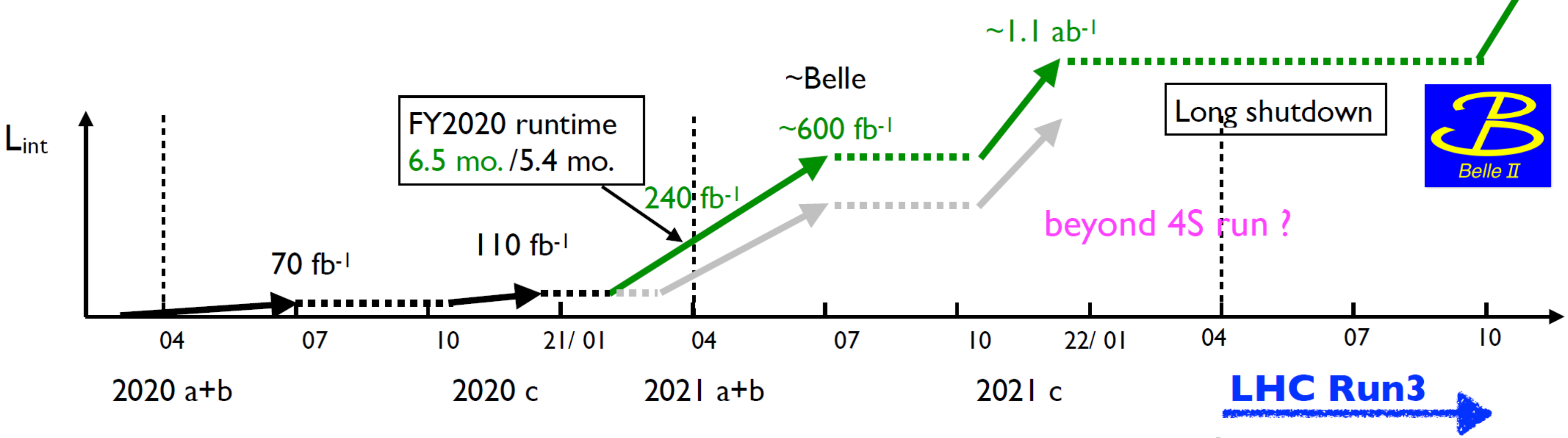
Summer

- Measurement of the branching ratios of $B^0 \to D^{(*)-} l^+ \nu$ (untagged analysis), arXiv:2008.07198 [hep-ex];
- Calibration of the Belle II hadronic Full Event Interpretation (FEI), arXiv:2008.06096 [hep-ex];
- Measurement of the hadronic mass moments of $B \to X_c l^+ \nu$ decays, arXiv:2009.04493 [hep-ex];
- Measurement of the branching ratios of $B^0 \to D^{*-} l^+ \nu$ (using the hadronic FEI), arXiv:2008.10299 [hep-ex];
- Rediscovery of $B^0 \to \pi^- l^+ \nu$ (using the hadronic FEI), arXiv:2008.08819 [hep-ex];
- Calibration of the Belle II B FlavorTagger, arXiv:2008.02707 [hep-ex];
- Rediscovery of $B \to \phi K^{(*)}$ decays, and measurement of the longitudinal polarization fraction of $B \to \phi K^*$, arXiv:2008.03873 [hep-ex];
- Branching ratios and direct CP asymmetries of $B \to$ Charmless decays, arXiv:2009.09452 [hep-ex];
- Measurement of the τ lepton mass, arXiv:2008.04665 [hep-ex];

What we are hoping …

- Belle II is ready to accumulate more data (as endorsed by the BPAC review)
  - Good prospect for 6.5mo. operation in JFY2020
  - Comparable to Belle by 2021 summer
  - >1ab^{-1} target before the long shutdown.

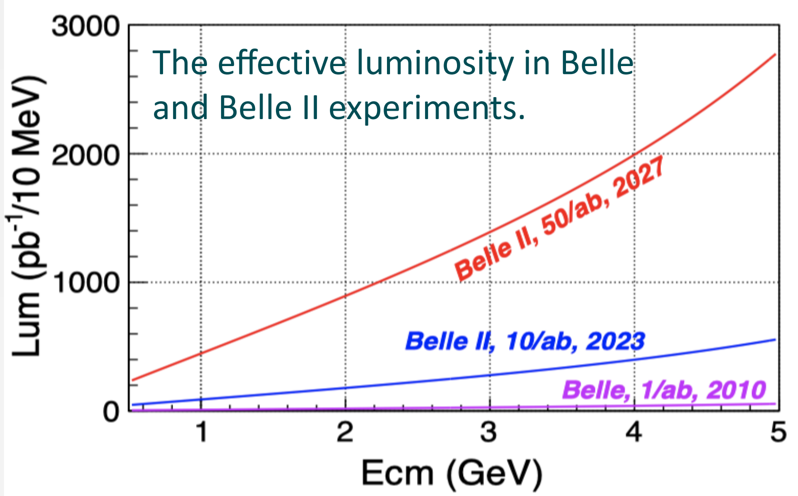
Many many results with "world-leading ***precision****"!*



Longer term LHC schedule

In 2019 the decision was taken to extend Run 3 by a year and for LS3 to start in 2025. Impact of coronavirus pandemic reflected in the extended hardware commissioning and magnet training foreseen for 2021.

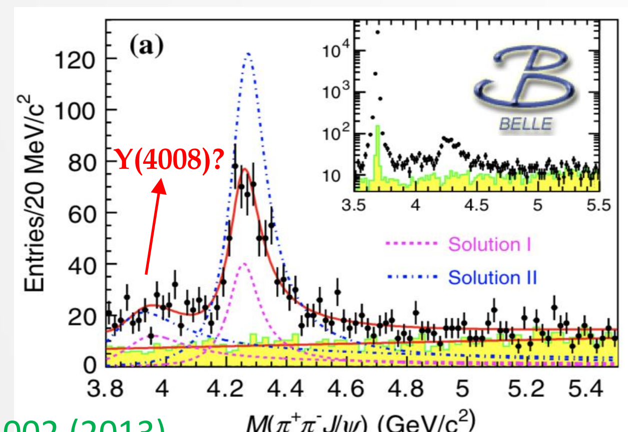
$e^+e^- \to \pi^+\pi^- J/\psi$ via initial-state radiation at Belle II



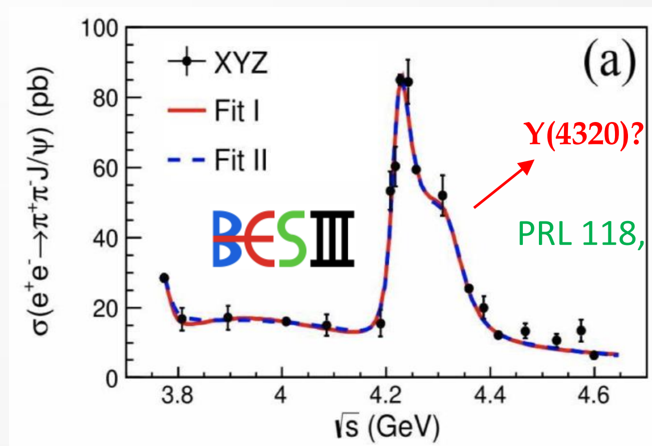
- ISR technique can explore $J^{PC} = 1^{--}$ states far away from e^+e^- collision energy.
- The whole hadron spectrum is visible.
- The effective luminosity and detection efficiency are relatively low.

For $e^+e^- \to \pi^+\pi^- J/\psi(\to \mu^+\mu^-)$ via ISR at Belle II

- Rediscover the first Y state at Belle II
- Identify existences of the Y(4008) and Y(4320) in $M(\pi^+\pi^- J/\psi)$
- Minimize the statistical errors.
- Study the properties of charged charmonium-like state $Z_c(3900)$.



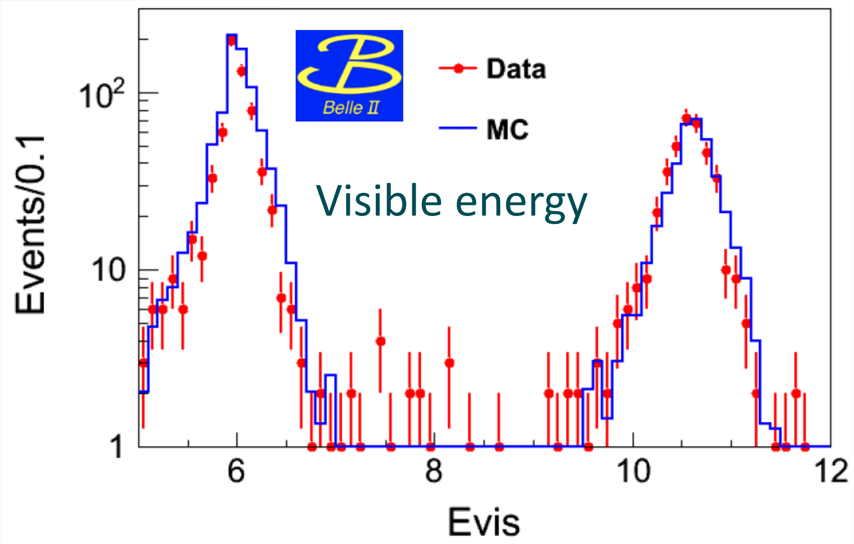
PRL 110, 252002 (2013)

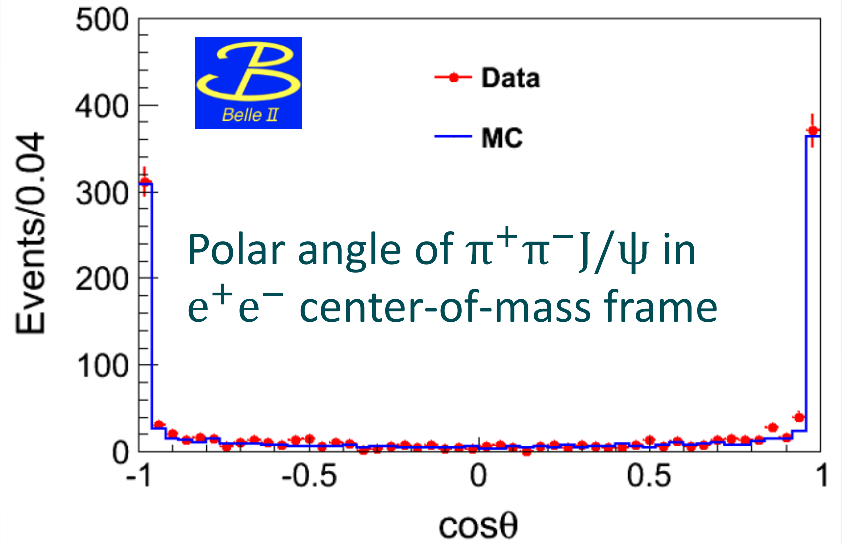


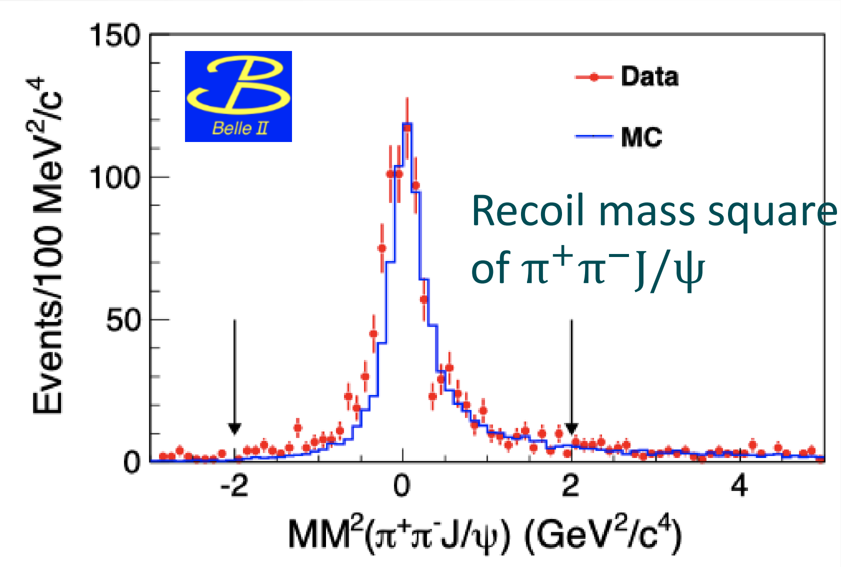
PRL 118, 092001 (2017)

ISR characteristics

The distributions from data and signal MC are compatible, which are all consistent with ISR characteristics.







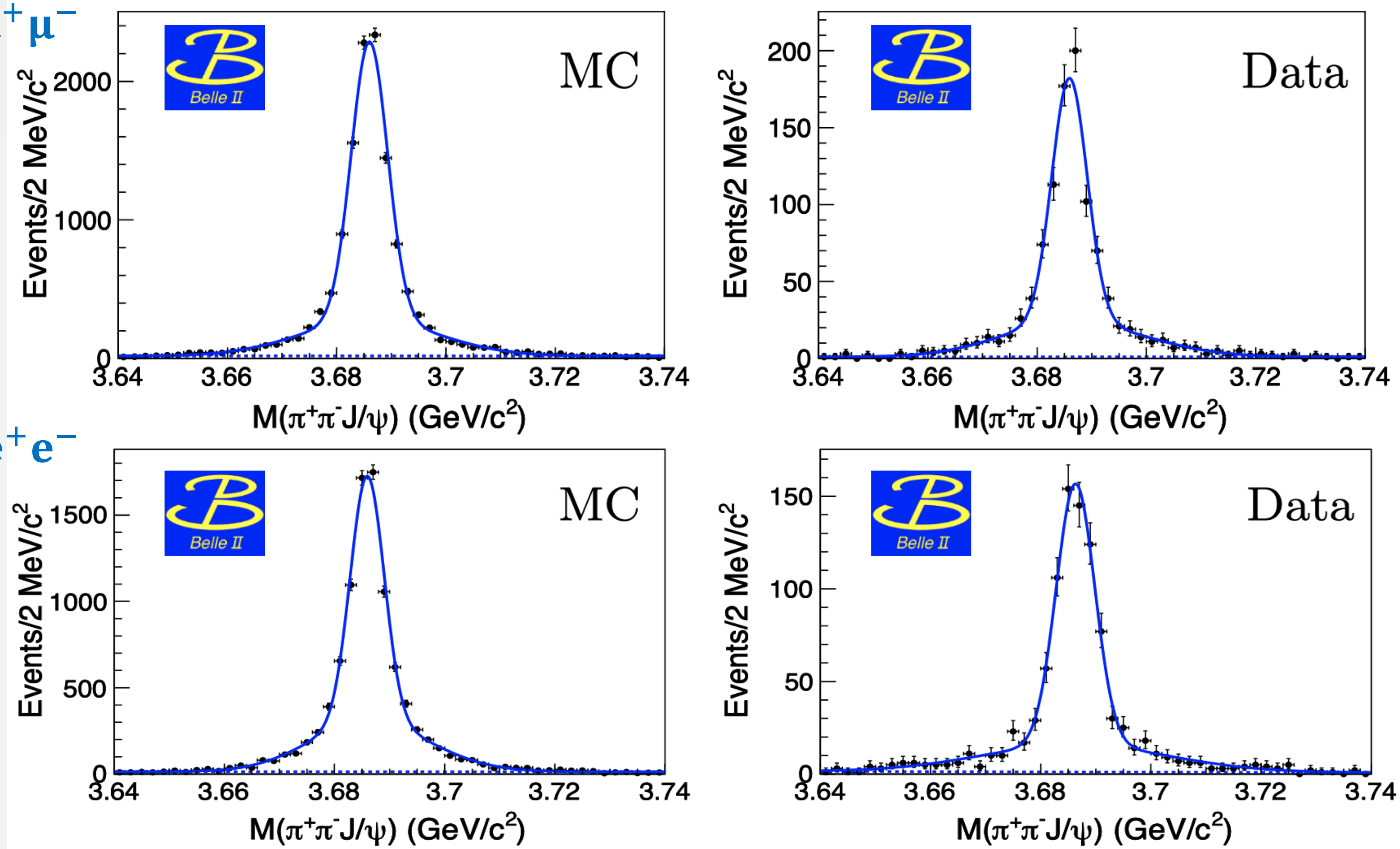
Data sample:
37.8 fb^{-1} in e^+e^- collisions at $\sqrt{s}$ = 10.58 GeV

MC samples:
MC signal samples are generated with Phokhara generator with NLO corrections.

Control samples of $\psi(2S) \to \pi^+\pi^- J/\psi$ via ISR

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

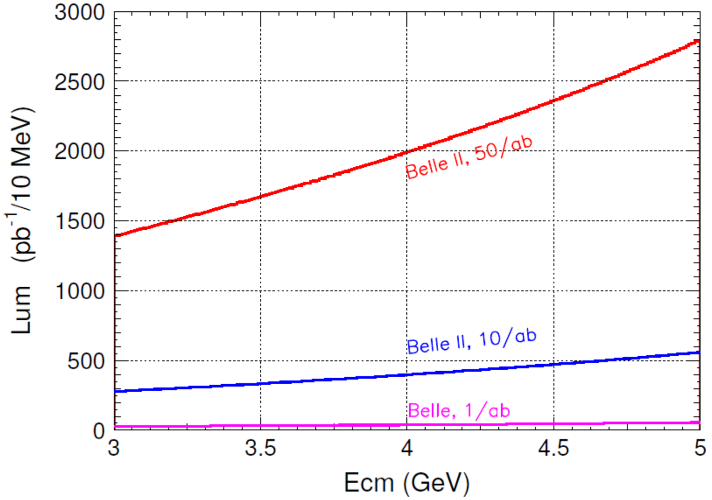
$J/\psi \to e^+e^-$



Mode	Our measurements	Theoretical calculation [Yad. Fiz. 41, 733 (1985)]
$J/\psi \to \mu^+\mu^-$	(12.0 ± 1.2) pb	(14.1 ± 0.3) pb
$J/\psi \to e^+e^-$	(13.0 ± 1.2) pb	

- Further PID and tracking corrections at Belle II are needed.
- The numbers of the expected Y(4260) signal events in data are (12.5 ± 2.3) and (10.6 ± 1.8) for $J/\psi \to \mu^+\mu^-$ and $J/\psi \to e^+e^-$.

Charmonium in ISR: can be done



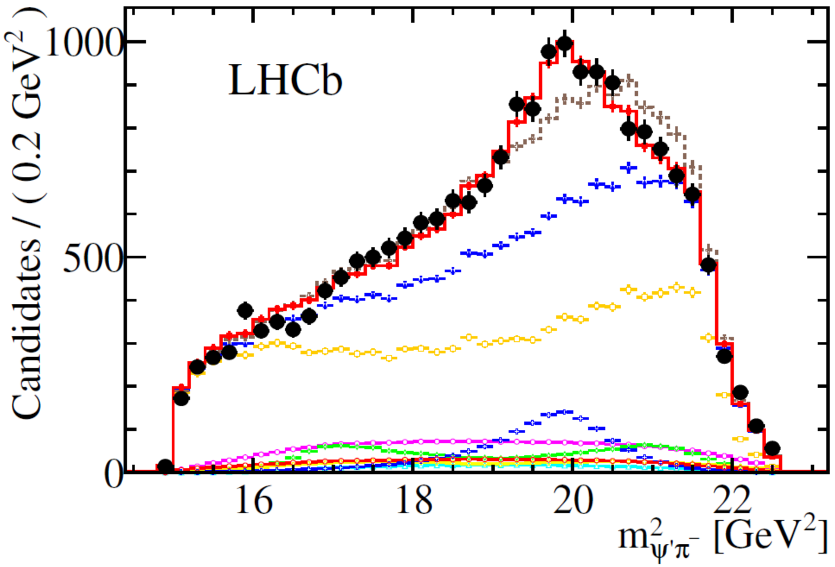
- Comparable samples for e.g. $e^+e^- \to J/\psi\pi^+\pi^-$.
- Access for high-energy region (current limit for BESIII is 4.6 GeV).
- Data are accumulated at the same time for all energies - simplifies lineshape analysis.

1. Improved measurements and fits of $e^+e^- \to \gamma_{\text{ISR}}(c\bar{c})(X)$ cross sections.
2. Improved measurements and fits of the open-charm cross-sections, for example $e^+e^- \to \gamma_{\text{ISR}} D^{(*)}\bar{D}^{(*)}(X)$
3. Measurements of higher mass open-charm channels, for example $e^+e^- \to \gamma_{\text{ISR}}\Sigma_c^+\overline{\Sigma}_c^-$.
4. Analyses of the channels that are currently studied at BESIII only, for example $e^+e^- \to h_c\pi^+\pi^-$ with confirmation of the $Z_c(4020)^+$.

Can be done at Belle II and BESIII with direct production.

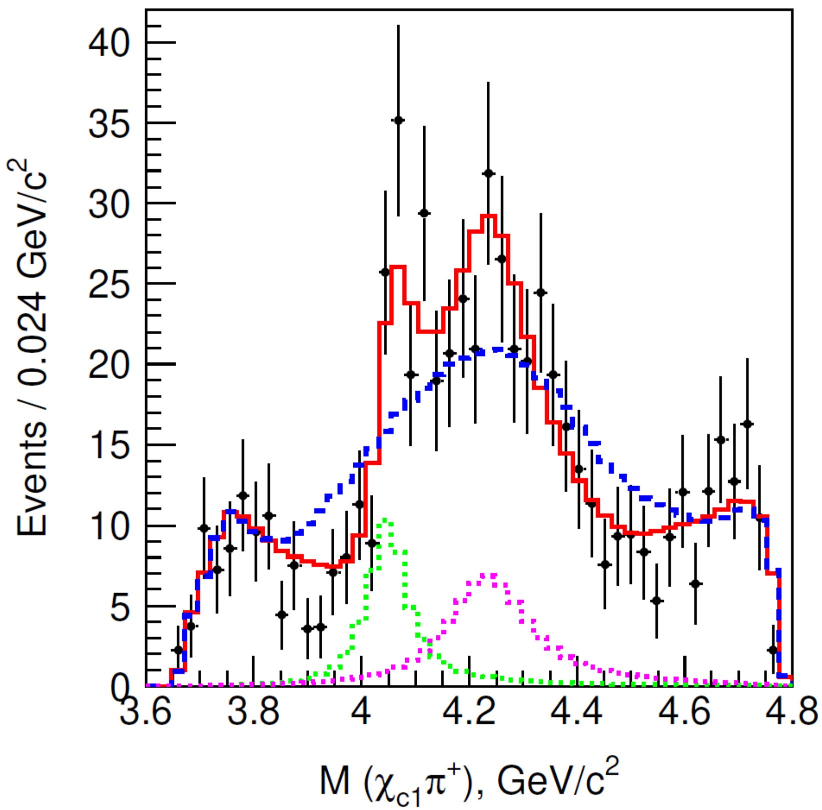
Charged charmoniumlike states: current status

$Z_c(4430)^+$ $(B^0 \to \psi(2S)\pi^- K^+)$
LHCb PRL **112**, 222002 (2014)



Belle (first J^P): PRD **88**, 074026 (2013)
(These analyses are the latest ones; observed by Belle in PRL **100**, 142001 (2008).)

$Z_c(4050)^+$, $Z_c(4250)^+$
$(B^0 \to \chi_{c1}\pi^- K^+)$
Belle PRD **78**, 072004 (2008)



Only the $Z_c(4430)^+$ is confirmed (seen by Belle and LHCb), it is studied relatively well now. Other charged charmoniumlike states observed in B decays are not confirmed; the analyses were performed either only at Belle or only at LHCb.

Charged charmoniumlike states: can be done

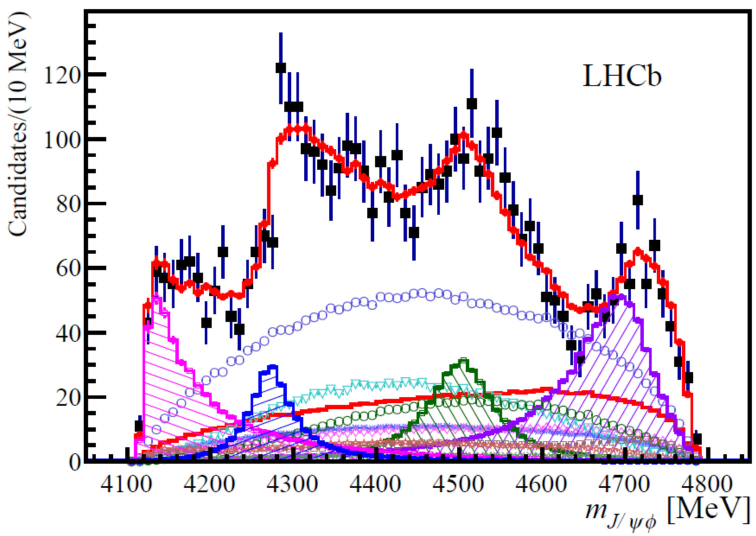
1. Updated amplitude analysis of $\bar{B}^0 \to \psi(2S)\pi^+K^-$: confirmation of the LHCb observation of the resonant character of the $Z_c(4430)^+$, confirmation of the $Z_c(4240)^+$ / $R_{c0}(4240)^+$.
2. Confirmation of the $W_{c0}(4100)^+$ in $\bar{B}^0 \to \eta_c\pi^+K^-$
3. Amplitude analysis of $\bar{B}^0 \to \chi_{c1}\pi^+K^-$, measurement of the $Z_c(4050)^+$ and $Z_c(4250)^+$ quantum numbers.
4. Search for the neutral partners of all charged charmoniumlike states observed in B decays.
5. Amplitude analyses of unexplored channels, for example $\bar{B}^0 \to X(3872)\pi^+K^-$.
6. Search for the $Z_c(3900)^+$ in $\bar{B}^0 \to J/\psi\pi^+\pi^-K^+$.
7. Search for decays of charged charmoniumlike states to $D^{(*)}\bar{D}^{(*)}$ in $B \to D^{(*)}\bar{D}^{(*)}K$.

Can be done at Belle II and LHCb.

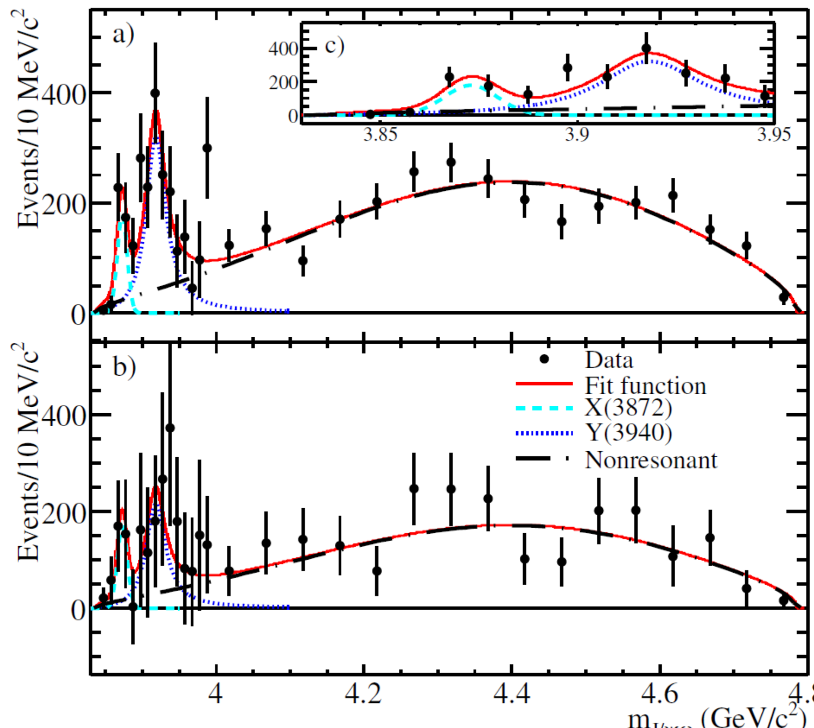
Belle II has a good sensitivity for neutral partners.

Neutral charmoniumlike states: current status

$B^+ \to J/\psi\phi K^+$
LHCb PRL **118**, 022003 (2017)
(amplitude analysis)



$B \to J/\psi\omega K$
BaBar PRD **82**, 011101 (2010)



While the $X(4140)$ and $X(4274)$ are seen by many experiments, the only amplitude analysis (and observation of two other states), has been performed by LHCb. The $X(3915)$ is also seen by Belle and BaBar, but the amplitude analysis of the decay $B \to J/\psi\omega K$ has never been performed.

Neutral charmoniumlike states: can be done

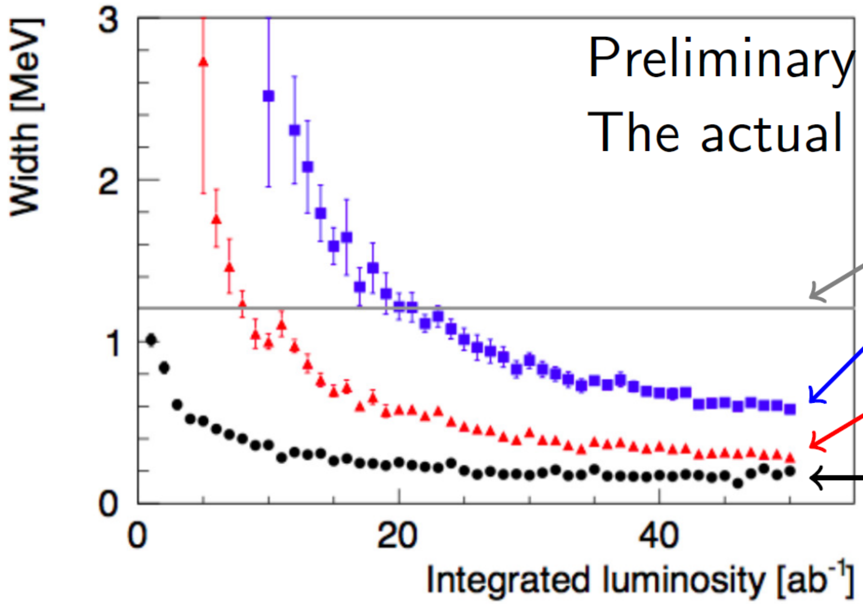
1. Amplitude analysis of $B \to J/\psi \phi K$, confirmation of 4 states observed by LHCb.
2. Amplitude analysis of $B \to J/\psi \omega K$, measurement of the $X(3915)$ quantum numbers in B decays.
3. Updated search for $B \to Y(4260)(\to J/\psi \pi^+\pi^-)K$ and other $J^{PC} = 1^{--}$ charmoniumlike states.
4. Amplitude analyses of unexplored channels with a J/ψ such as $B \to J/\psi \eta K$ or $B \to J/\psi \eta' K$.
5. Analyses of the above channels with K_S^0.
6. Search for decays of known charmoniumlike states to other final states, for example, $X(3915) \to \eta_c \eta$ ($X(3915)$ should decay to this channel if it is a $c\bar{c}s\bar{s}$ state).
7. Absolute branching fractions for $B \to X(3872)K$, $B \to X(3915)K$.

Can be done at Belle II and LHCb.

Absolute branching fractions are unique for Belle II!

The $X(3872)$ width: sensitivity

- The current upper limit on the $X(3872)$ width is 1.2 MeV at 90% C. L (Belle PRD **84**, 052004 (2011), from $B \to J/\psi\pi^+\pi^-K$ data).
- Using the $B \to (D^0\bar{D}^0\pi^0)K$ data can significantly improve the mass resolution (near-threshold decay), and, consequently, the total-width sensitivity.
- The sensitivity has been estimated on MC (H. Hirata, master thesis, 2019), the expectation is shown below.



Preliminary and the error is statistical only.
The actual limit should be larger.

Current limit: 1.2 MeV at 90% C. L.

Measureable width (5σ)

Measureable width (3σ)

Limit (90%C.L.) if $\Gamma = 0$ MeV
About 180 keV for full data sample

Bottomonium: $\Upsilon(3S)$ data

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

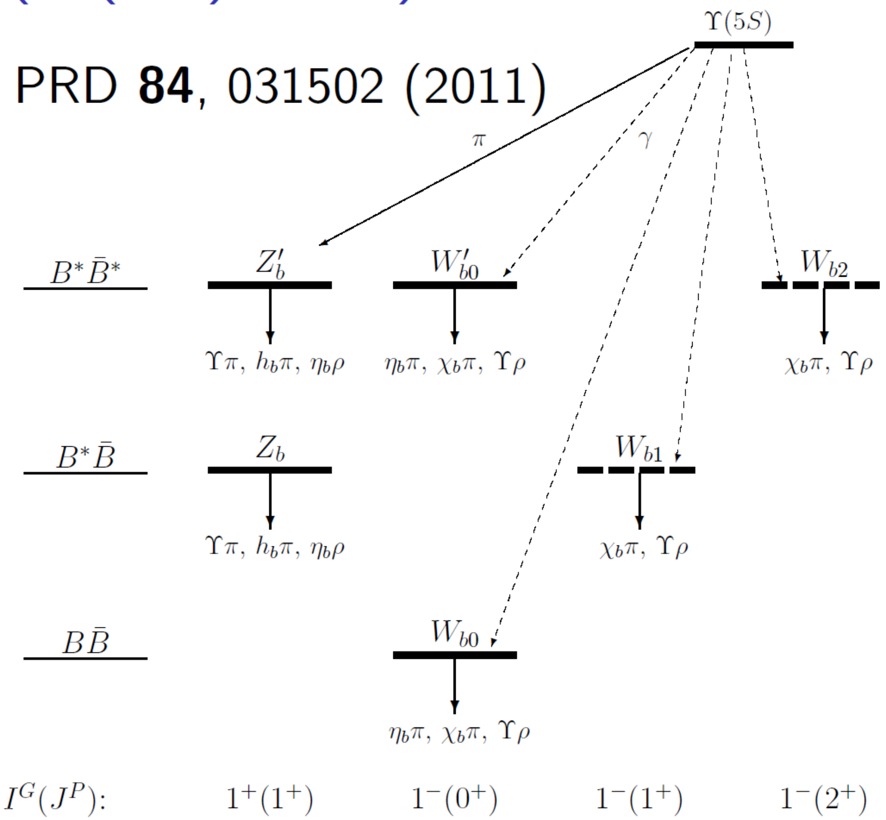
Experiment	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$	$\frac{\Upsilon(nS)}{\Upsilon(4S)}$
CLEO	1.2 (21)	1.2 (10)	1.2 (5)	16 (17.1)	0.1 (0.4)	-	23%
BaBar	-	14 (99)	30 (122)	433 (471)	R_b scan	R_b scan	11%
Belle	6 (102)	25 (158)	3 (12)	711 (772)	121 (36)	5.5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

1. Inclusive production of charmonium(-like) states in $\Upsilon(nS)$ decays.
2. Double production of charmonium(-like) states in $\Upsilon(nS)$ decays.
3. Amplitude analyses of $\Upsilon(3S) \to \Upsilon(1S, 2S)\pi^+\pi^-$ (possible contribution from bottomonium states).
4. Search for missing $\pi\pi$ and η transitions to lower-mass bottomonium states, suppressed radiative transitions.
5. Study of baryons in bottomonia decays.
6. Correlation in $D\bar{D}^*$ production.
7. Study of deutron production.

Can be done at Belle and (some topics) LHC experiments.

Bottomonium ($\Upsilon(5S)$ data): can be done

M. Voloshin PRD **84**, 031502 (2011)



Molecular states with quantum numbers other than $I^G = 1^+$, $J^P = 1^+$ are expected to exist. The transitions to such states are radiative and they are consequently suppressed by $\sim \alpha$. However, using the high statistics their observation might be possible.

Unique for Belle II!

Summary

- The expected Belle II data sample of 50 ab^{-1} will provide a lot of new opportunities for physics analyses in the area of exotic states
- Some of them, for example, double charmonium production, charmonium in two-photon processes, or bottomonium physics, are unique for Belle II.
- Several quarkonium states and exclusive B decays to charmonium and other particles were \rediscovered" using the currently available data.

Thanks a lot!

Thanks for your attention

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