HIRSCHEGG 2024 –
Strong Interaction Physics of Heavy Flavors

Multiquark states –

Recent results in charm-strange and bottomonium spectroscopy

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*new addressed at DFICU (UK) and GHU, AI (UK)

14-20.Jan.2024

Outline

- Introduction
- Status-of-the-art in cs spectroscopy
- $c\bar{c}s\bar{s}$ spectroscopy
- Analyses in the continuum at Belle
- Analyses in the bottomonium sector at Belle and Belle II

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- Introduction
- Status-of-the-art in cs spectroscopy
- $c\bar{c}s\bar{s}$ spectroscopy
- Analyses in the continuum at Belle
- Analyses in the bottomonium sector at Belle a
- Future perspectives
- Summary

This talk is focused on **BELLE & Belle II** results

The CQM Model

- Gell-Mann Zweig idea: Constituent Quark Model (CQM, 1964). Still valid after 60 years

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

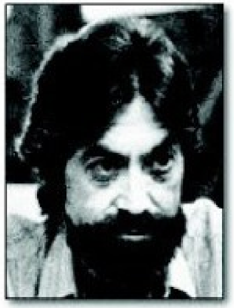
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

sch

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

8182/TH.401
17 January 1964



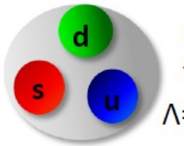
ABSTRACT

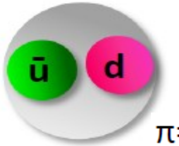
...

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

The CQM Model

- QCD describes the force binding quarks into hadrons
- Perturbation theory: limited applicability at scale corresponding to the separation between quarks inside hadrons
- Many models available to describe spectra and properties of hadrons
- QCD-motivated models predict the existence of hadrons with more complex structures than simple *qq* or *qqq*.
- **<u>Lots of experimental effort to prove it</u>**!





- The study of Charm-*onium*(-like) spectrum ($c\bar{c}$ + xx) and Bottomonium spectrum ($b\bar{b}$ + xx) have uncovered a number of candidates that seem not to conform CQM expectations
- *Exotic states* predicted to exist in the <u>light meson spectrum</u>

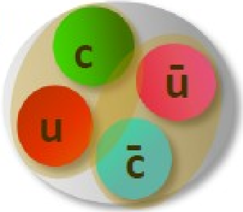
  → difficult to disentangle from the dense background of conventional states
- <u>Charmonium spectrum</u> provide a cleaner environment: $\bar{c}c$ + xx exotics easier to identify

See Belle II talk on Thurday, S. Lange

What are the possibilities?

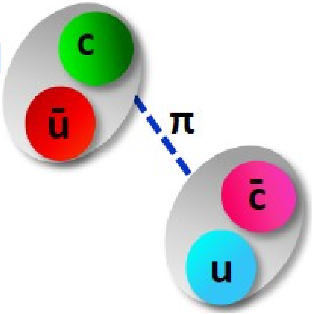
Tetraquark

Tightly bound diquark & anti-diquark

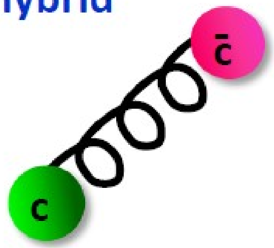


Molecule

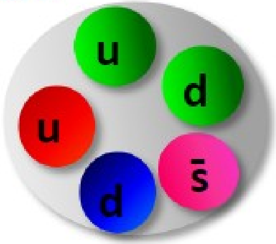
loosely bound meson-antimeson "molecule"



$q\bar{q}$ -gluon hybrid mesons

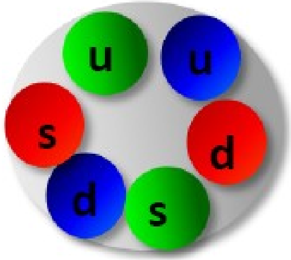


Pentaquark



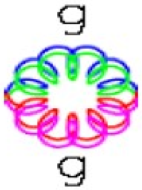
H di-Baryon

Tightly bound 6 quark state



Glueball

Color-singlet multi-gluon bound state



...and superimposition of states. Everything which does not fit CQM!

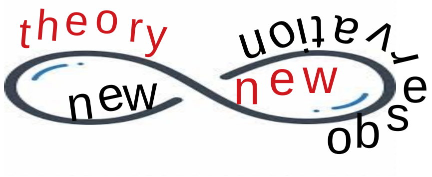
Where to find these new multiquark states?

- Direct production in e^+e^- collisions
- Production in $B \to Kc\bar{c}$
- Photon-photon scattering $\gamma\gamma^* \to (c\bar{c})$
- Double charmonium $e^+e^- \to (c\bar{c})(c\bar{c})$
- Prompt production
- Direct production in $p\bar{p}$ (??)

- How to find multiquark states?

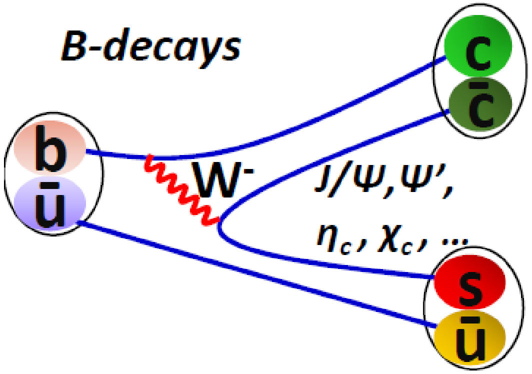
Choose the right detector, make your analysis!

- Interplay between theory-experiments: the infinite loop

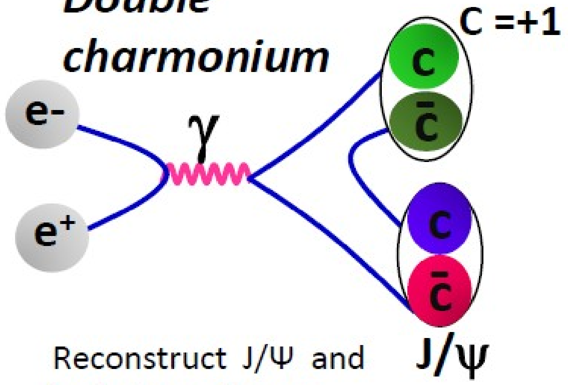


@ B-factories

B-decays

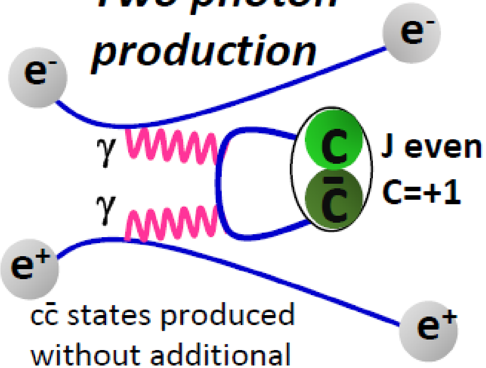


Double charmonium



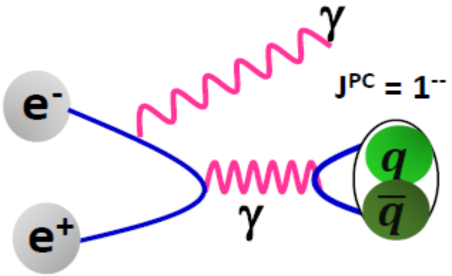
Reconstruct J/Ψ and look at recoil mass

Two photon production



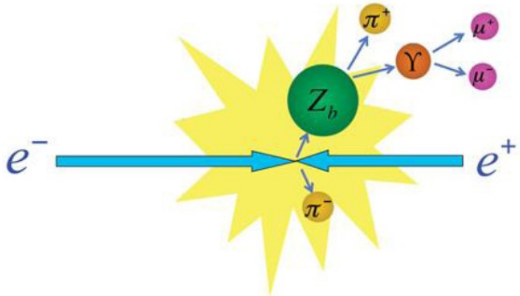
cc̄ states produced without additional hadrons.

Initial state radiation



Annihilation at smaller energy

Quarkonium decay/transitions

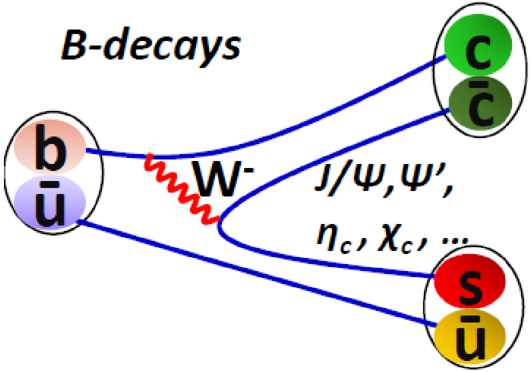


Advantages @ B-factory

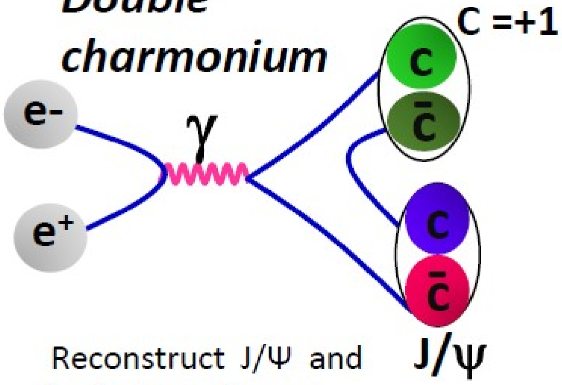
- *"Clean"* events
- Huge data sets available
- Several mechanisms to search for exotics

@ B-factories

B-decays

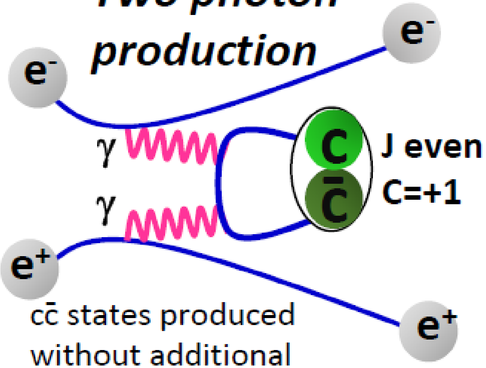


Double charmonium



Reconstruct J/Ψ and look at recoil mass

Two photon production



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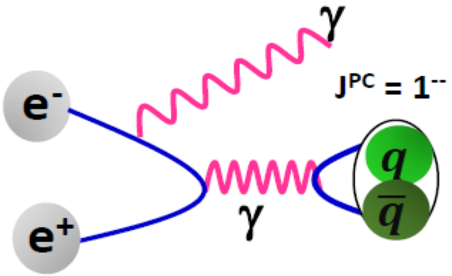

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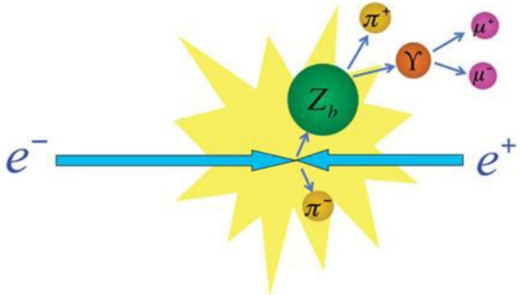
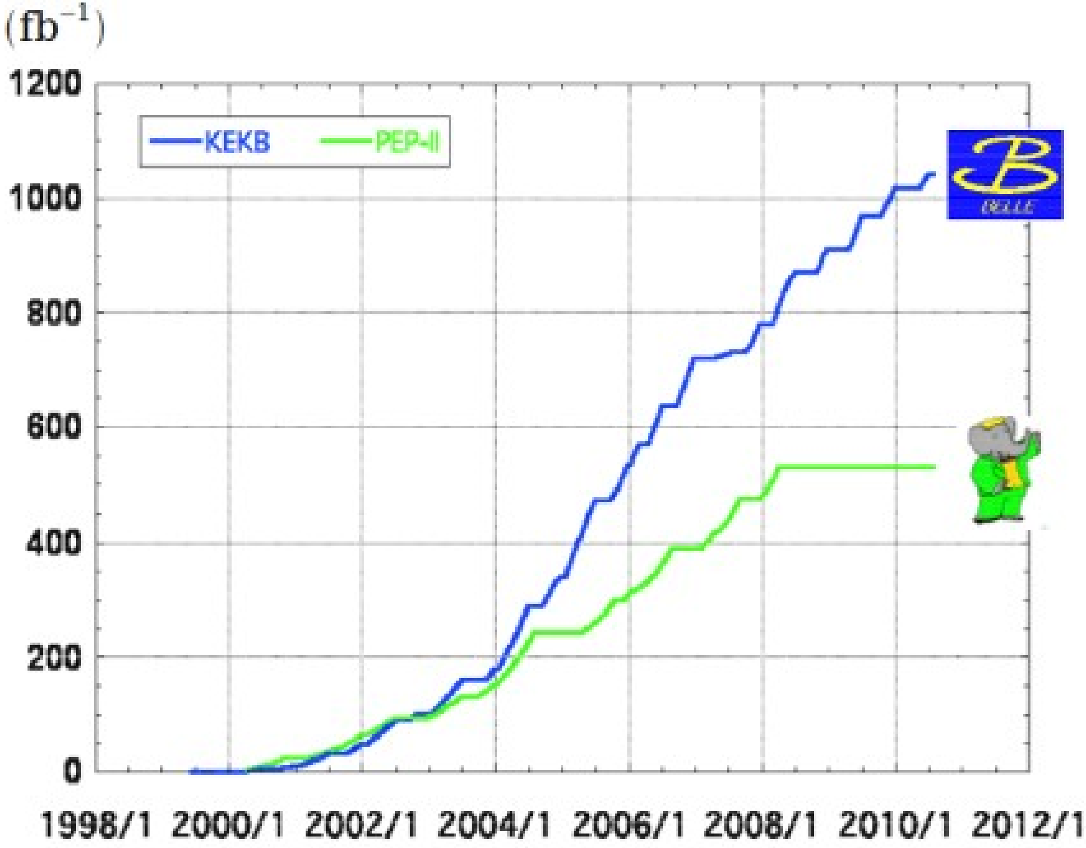


Disadvantages @ B-factory

- No all J^{PC} in production
- Small cross sections



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

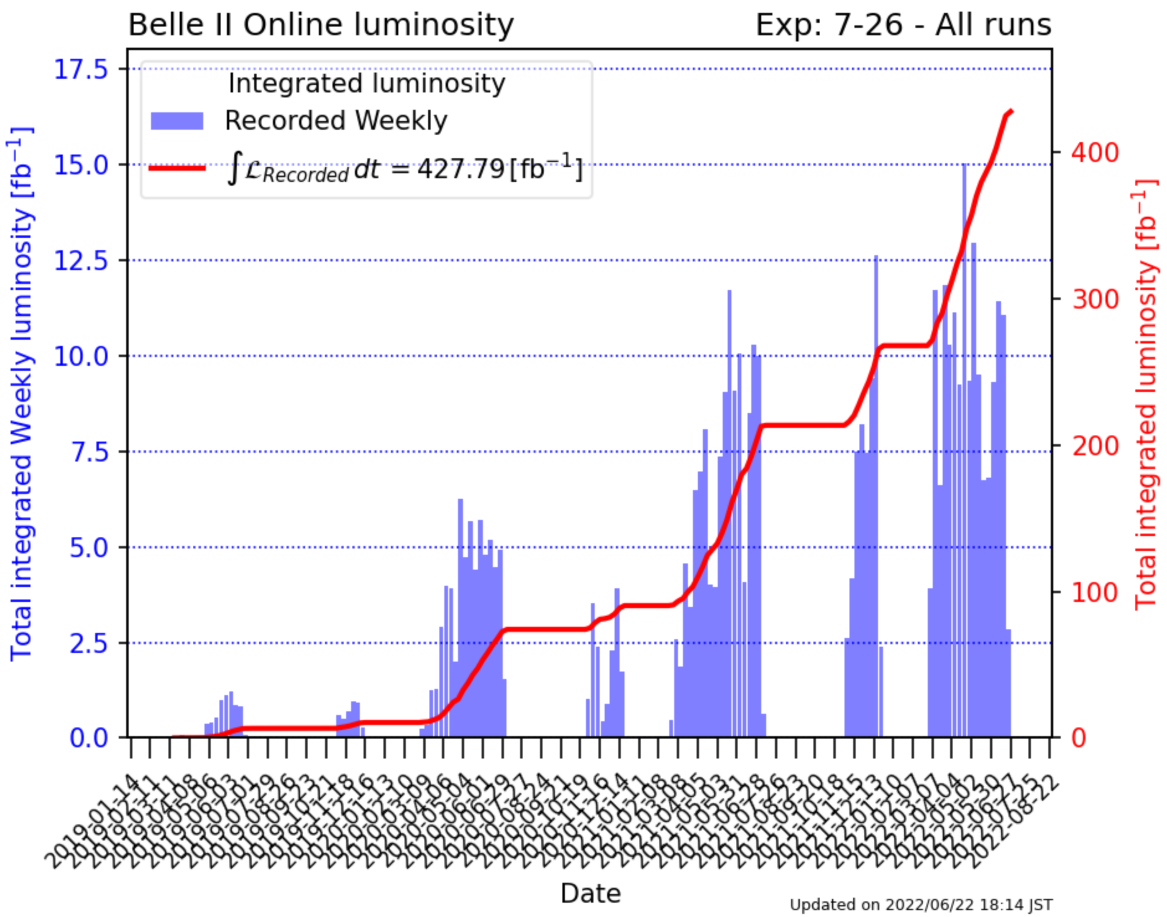
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

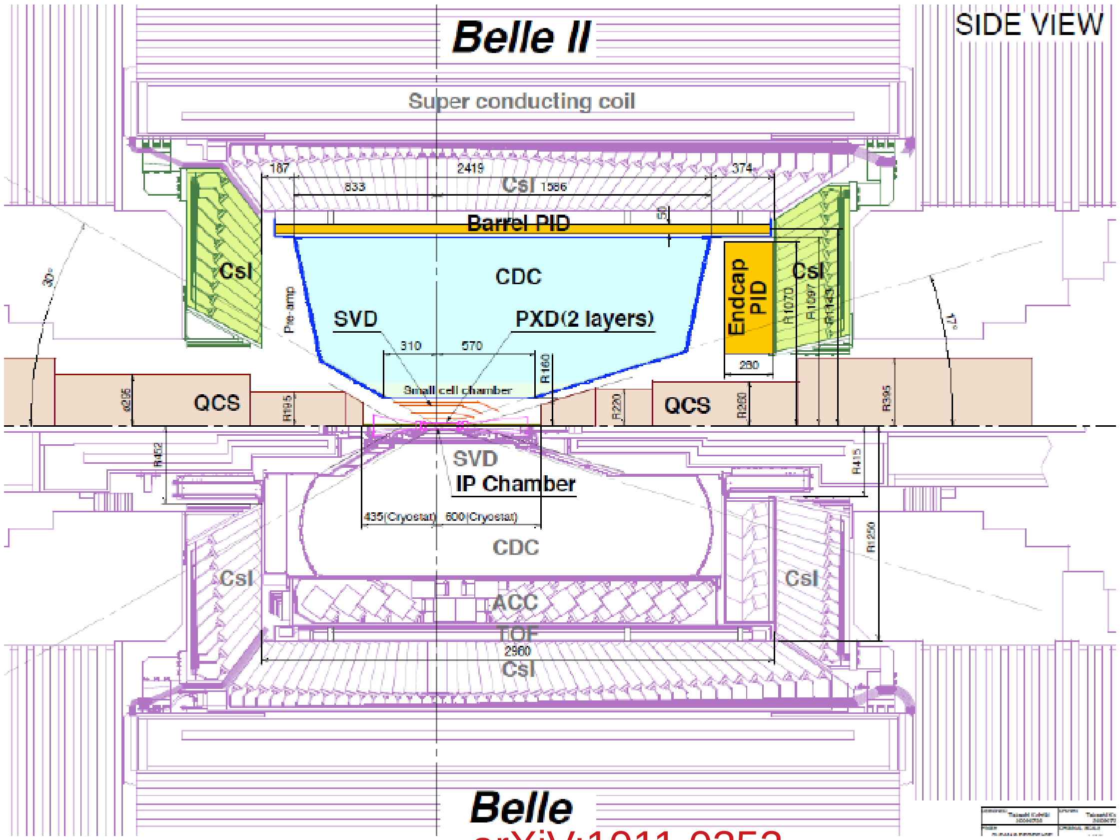
~ 54 fb^{-1}

Resonance	BaBar	Belle
Υ(3S)	121 M	12 M
Υ(2S)	98+(3) M	175 M
Υ(1S)	(23) M	113+(32) M

...and the story continues

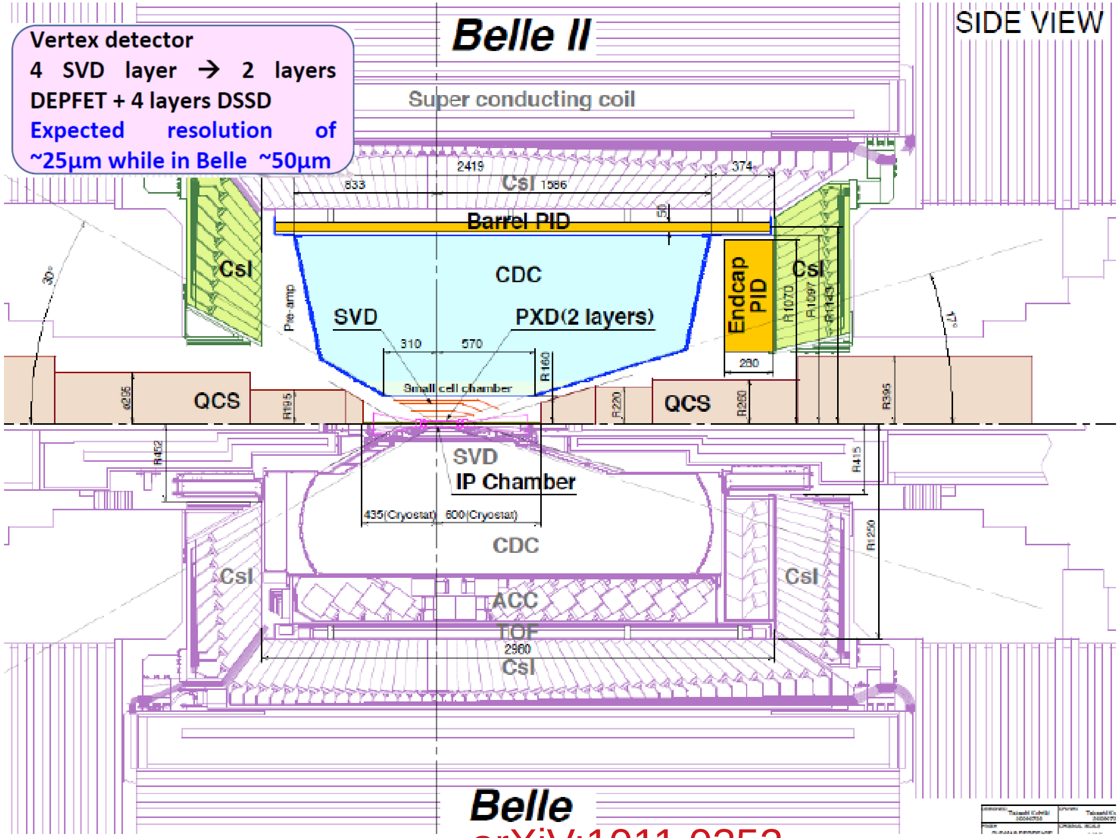


The Belle II Detector



arXiV:1011.0352

The Belle II Detector



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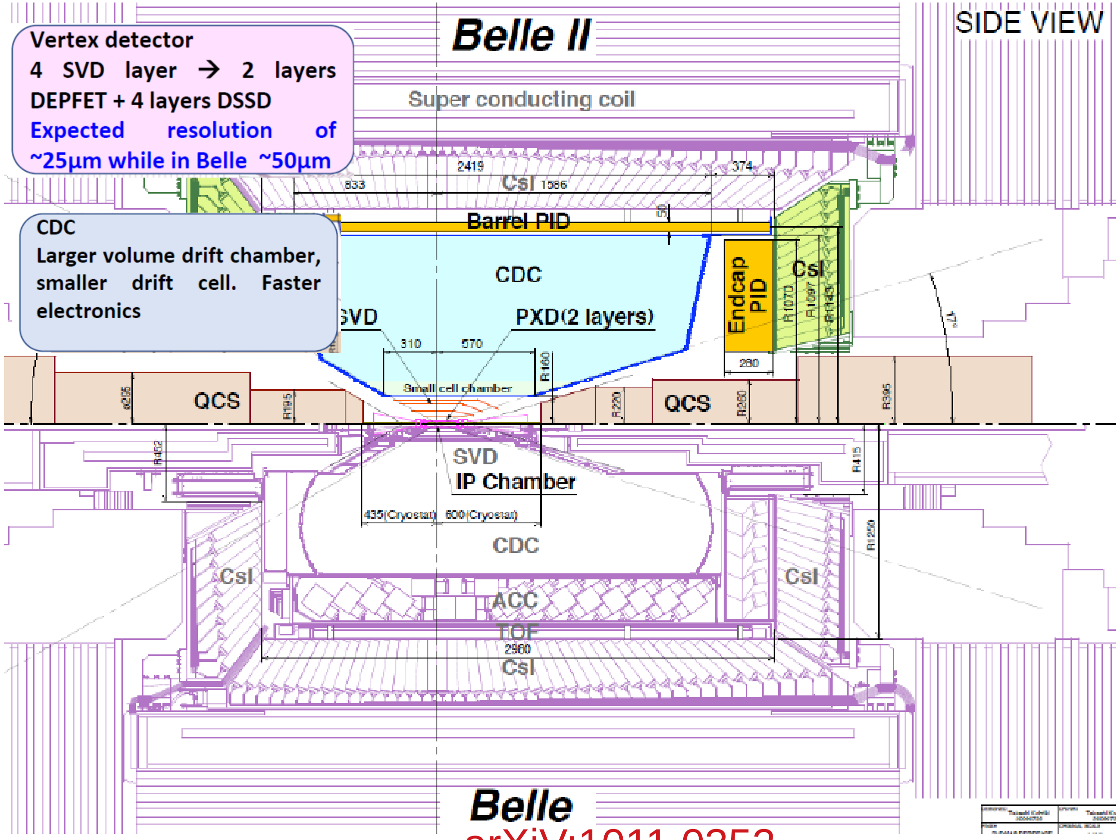

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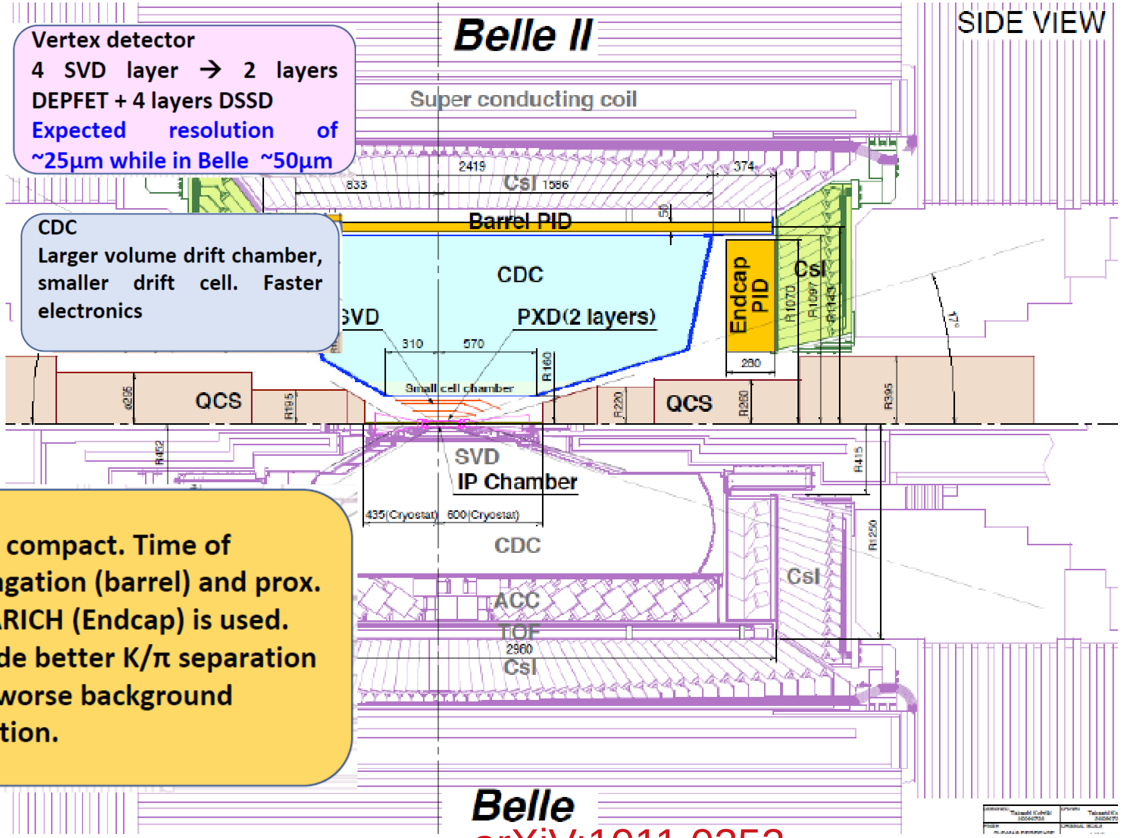
The Belle Detector



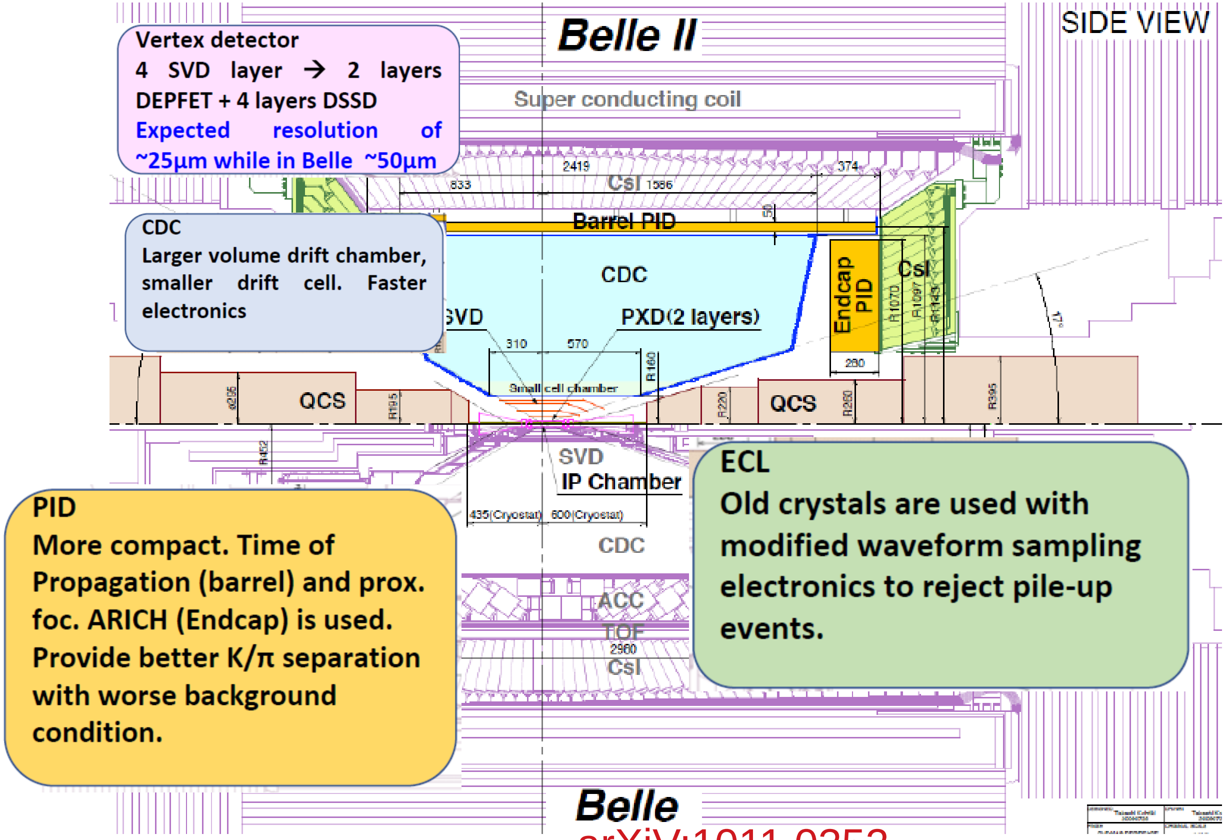
Vertex detector
4 SVD layer → 2 layers DEPFET + 4 layers DSSD
Expected resolution of ~25µm while in Belle ~50µm

CDC
Larger volume drift chamber, smaller drift cell. Faster electronics

PID
More compact. Time of Propagation (barrel) and prox. foc. ARICH (Endcap) is used. Provide better K/π separation with worse background condition.

arXiV:1011.0352

The Belle II Detector



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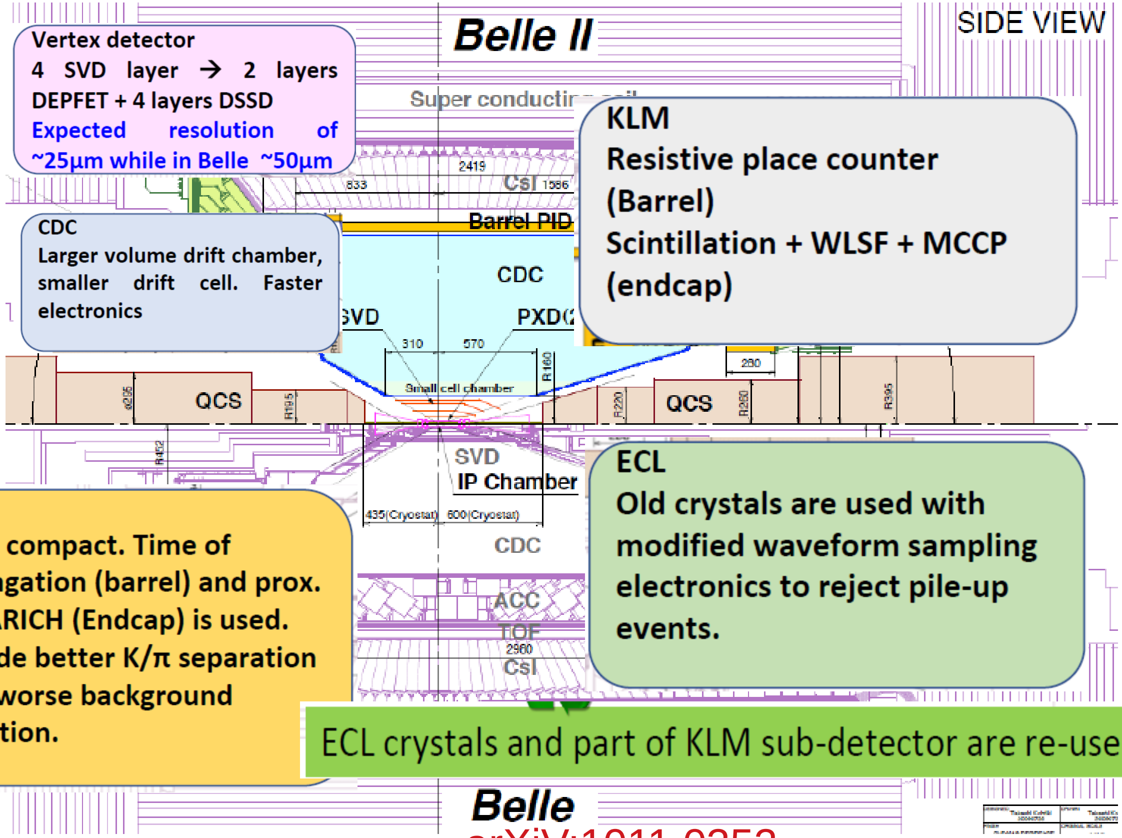
The Belle II Detector



Vertex detector
4 SVD layer → 2 layers DEPFET + 4 layers DSSD
Expected resolution of ~25µm while in Belle ~50µm

CDC
Larger volume drift chamber, smaller drift cell. Faster electronics

KLM
Resistive place counter (Barrel)
Scintillation + WLSF + MCCP (endcap)

ECL
Old crystals are used with modified waveform sampling electronics to reject pile-up events.

PID
More compact. Time of Propagation (barrel) and prox. foc. ARICH (Endcap) is used. Provide better K/π separation with worse background condition.

ECL crystals and part of KLM sub-detector are re-used.

arXiV:1011.0352

Topics of this talk

- Heavy-light systems at Belle and Belle II

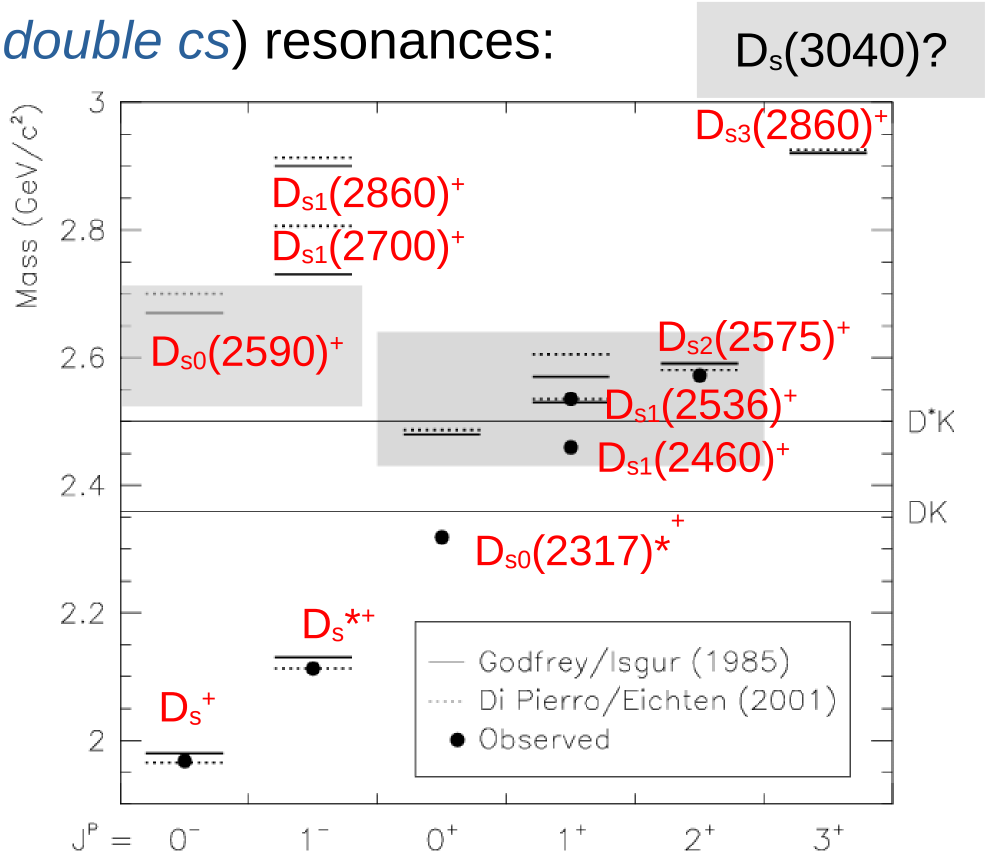
  - $D_s^{(*)} D_{sJ}^{(*)}$ analysis in the continuum

- Pentaquarks search at Belle and Belle II
- Bottomonium at Belle and Belle II

The heavy-light systems

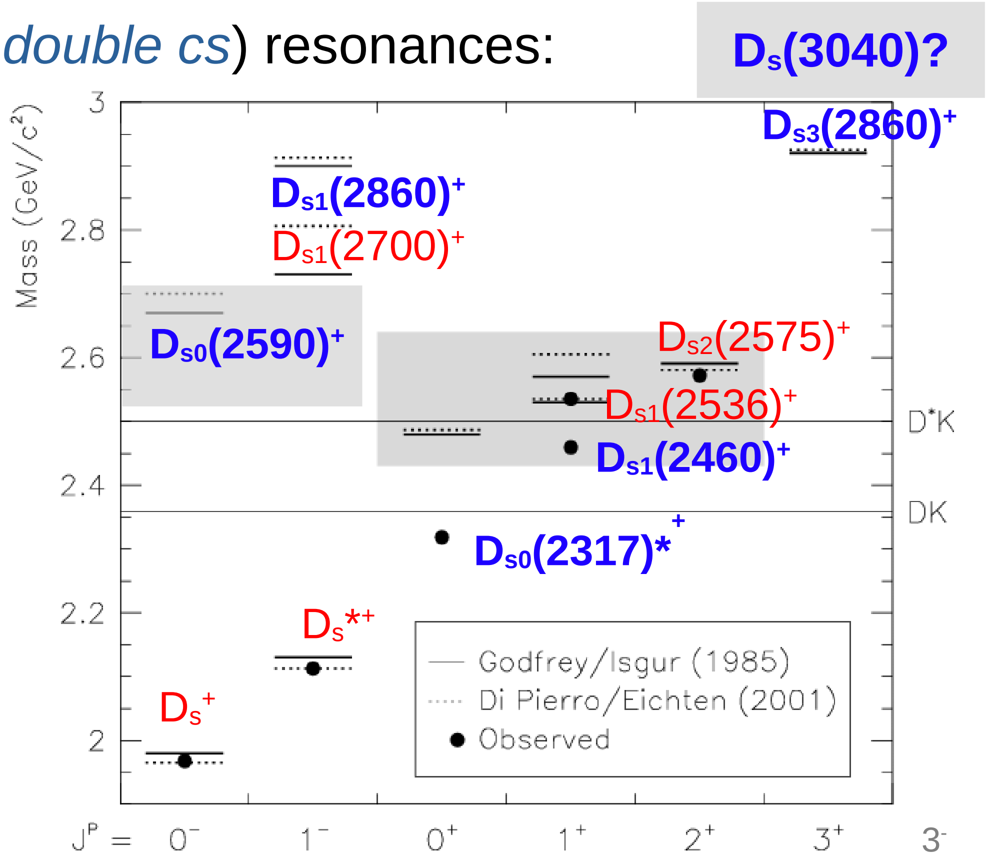
- Recent boost to the search for *cs* (and *double cs*) resonances:
  LHCb and Belle
- Very interesting case:
  s-quark (light) + c-quark (heavy)
- Can we make predictions?

- Perturbative calculations work pretty well for the heavy sector, and should be also in the heavy-light systems: but….



The heavy-light systems

- Recent boost to the search for *cs* (and *double cs*) resonances: LHCb and Belle
- Very interesting case: s-quark (light) + c-quark (heavy)
- Can we make predictions?
- Perturbative calculations work pretty well for the heavy sector, and should be also in the heavy-light systems: but….



How has the cs-story begun?

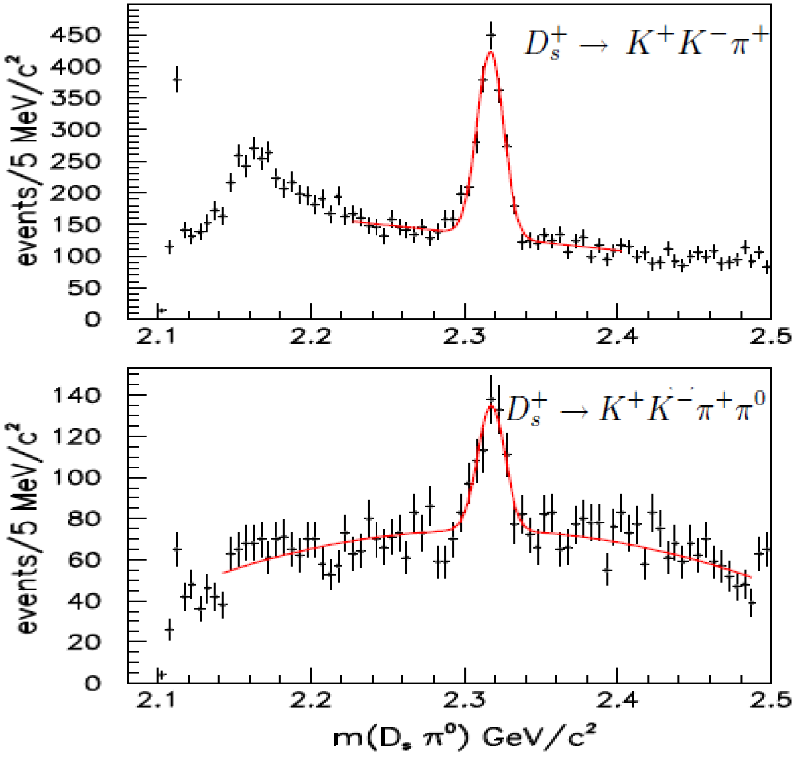
Phys. Rev. Lett. 90 (2003) 242001 BaBar, accepted 17 June 2003

Observation of a Narrow Meson State Decaying to $D^{+}_{s}\pi^{0}$ at a Mass of 2.32 GeV/c^2

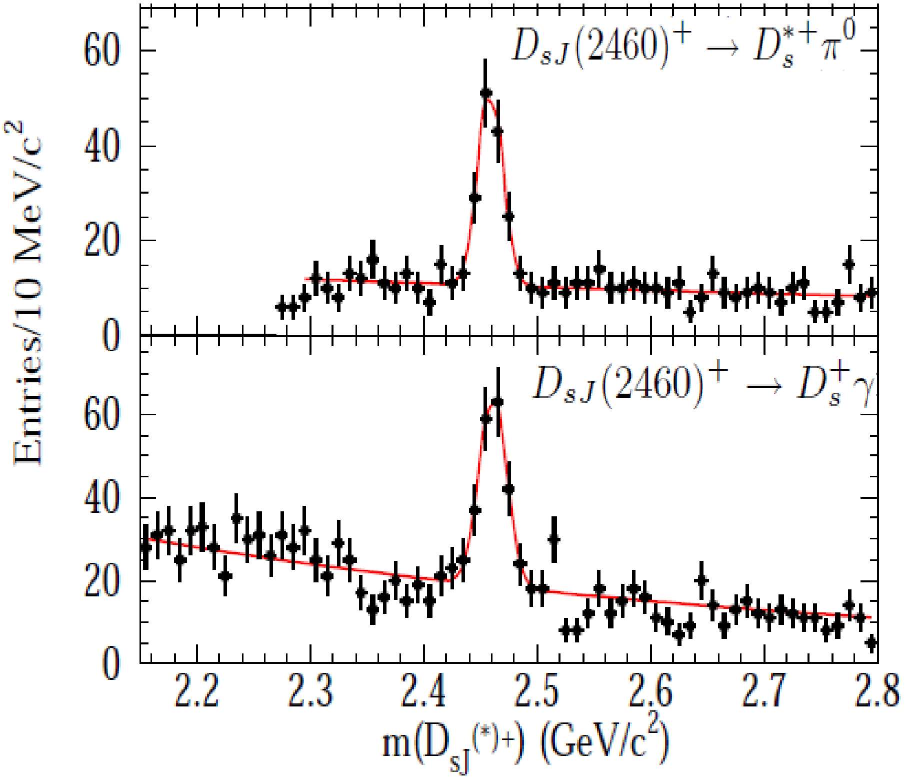
990 citations

The puzzling case of the $D_{s0}(2317)^{*+}$ and $D_{s1}(2460)^{+}$

BABAR, PRL 90 (2003) 242001



BABAR, PRL 93 (2004) 181801

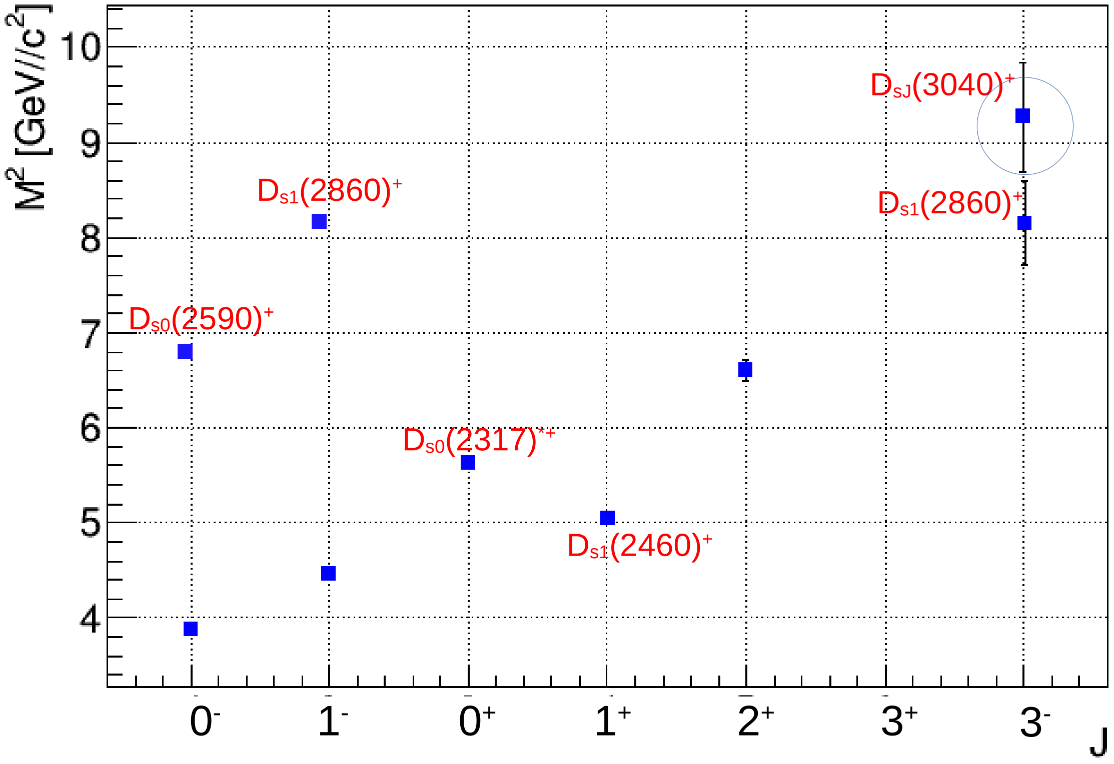


cs meson	Mass (MeV/c^2)	Width (MeV)	$I(J^P)$	Experiment	Match exp/theory
D_s^+	1968.35±0.07		$0(0^-)$	MRK3, CLEO, etc.	✓
D_s^{*+}	2112.2±0.4	< 1.9	$0(?^?)$	MRK3	✓
$D_{s0}(2317)^{*+}$	2371.8±0.5	< 3.8	$0(0^+)$	BABAR, BELLE, BESIII	✗
$D_{s1}(2460)^+$	2459.5±0.6	< 3.5	$0(1^+)$	BABAR, BELLE	✗
$D_{s1}(2536)^+$	2535.11±0.06	0.92±0.05	$0(1^+)$	BESIII, DØ, ALEP	✓
$D_{s1}(2575)^+$	2569.1±0.5	16.9±0.7	$0(2^+)$	BESIII, LHCb	✓
$D_{s0}(2590)^+$	2591±9	89±20	$0(0^-)$	LHCb	✗
$D_{s1}(2700)^+$	2714±5	122±10	$0(1^-)$	BELLE, LHCb	✓
$D_{s1}(2860)^+$	2859±27	159±80	$0(1^-)$	LHCb	✓
$D_{s3}(2860)^+$	2860±7	53±10	$0(3^-)$	BABAR, LHCb	✗
$D_{sJ}(3040)^+$	3044^{+31}_{-9}	239±60	$0(?^?)$	BABAR	✗

Remarks on cs mesons

- Charged particles
- Perturbative calculations cannot explain the whole spectrum: $D_{s0}(2317)^{*+}$ and $D_{s1}(2460)^{+}$ are not isolated cases
- High interest in understanding the cs spectrum: heavy-light systems analyzed as a probe of chiral symmetry
- Analyses in the continuum at B factories offer a useful tool

Regge trajectories for Ds: an experimental view



3-?

Test of chiral symmetry breaking (I)

- $D_{s0}(2317)^{*+}$ and $D_{s1}(2460)^{+}$: many different theoretical interpretations

  - pure cs mesons

  - dynamically-generated molecules

  - four-quark states

  - first chiral partners of hadrons theoretically built out of light (*s*) and heavy (*c*) quarks; etc...

→ they represent rather a pattern of spontaneous breakdown of chiral symmetry than isolated events!

Test of chiral symmetry breaking (II)

- (u, d, s) light quarks; (c, t, b) heavy quarks
- Spontaneous breaking of chiral symmetry characterizes the light sector, while the heavy sector exhibits heavy-quark symmetry
- What happens in the heavy-light systems?
- Assume the limit: light quark massless, heavy quark with infinite mass ⇒

  the spontaneous chiral symmetry breaking yields a mass splitting of the chiral doublers of about **345 MeV/*c*²** (when the pion coupling to the doublers is half its coupling to a free quark)
- This mass splitting never observed in the **B_s sector** ⇒

  this measurement in the D_s sector even more intriguing
- What is the status-of-the-art in the **D_s sector**?

Study of chiral symmetry in the D_s

$m_{Ds} - m_D$	98.69±0.05
$m_{Ds*} - m_{Ds}$	143.8±0.4
$m_{Ds0(2317)*} - m_{Ds}$	349.4±0.5
$m_{Ds1(2460)} - m_{Ds*}$	347.3±0.7
$m_{Ds1(2460)} - m_{Ds}$	481.1±0.6
$m_{Ds1(2536)} - m_{Ds*}$	422.9±0.4
$m_{Ds1(2536)} - m_{D*}$	524.85±0.04
$m_{Ds1(2536)} - m_{D0*}$	528.26±0.05
$m_{Ds2(2575)} - m_{D0}$	704.0±3.2

From PDG 2023

Study of the $c\bar{c}s\bar{s}$ resonances

- Proposal shown at HIRSGHEGG2018 (DFG project https://gepris.dfg.de/gepris/person/324081743):

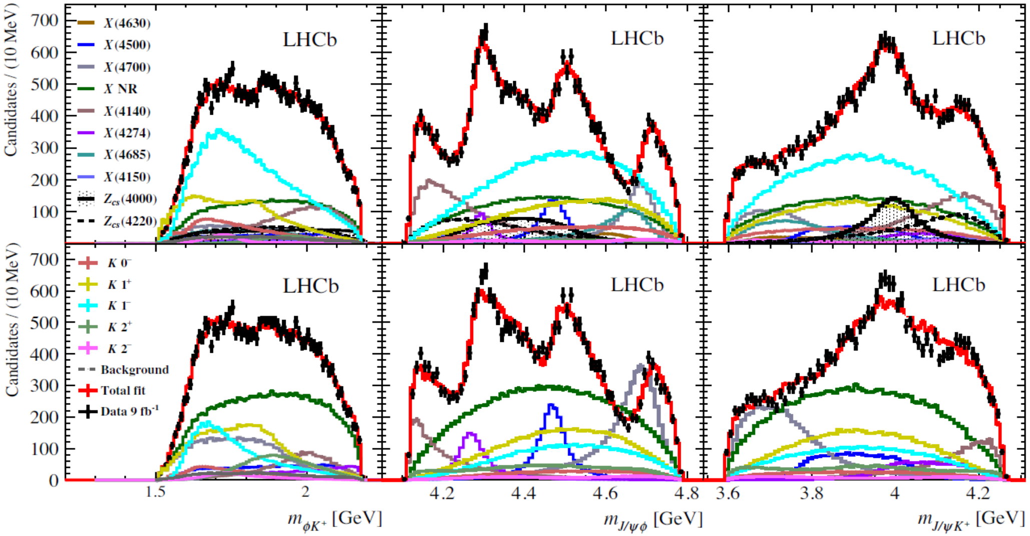
Physics process under study	**Mass Range [GeV/c^2]**
$B \rightarrow J/\psi\phi K$	[4.117-4.78]
Analysis in the continuum: $e^+e^- \rightarrow D_s D_{sJ}^{(*)} A$, $e^+e^- \rightarrow J/\psi\phi A$, A = anything else ($D_{sJ}^{(*)} = D_{s0}(2317)/D_{s1}(2460)$)	[4.117-6.765]
$B_s \rightarrow D_s^{(*)} D_{sJ}^{(*)} \pi^0$	
ISR: $e^+e^- \rightarrow \gamma_{ISR} D_s D_{sJ}^{(*)}$	

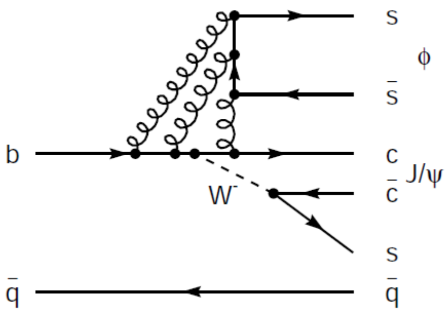
- Many possibilities, in 2018 almost nothing explored!

$B \rightarrow J/\psi\phi K$

Phys. Rev. Lett. 127 (2021) 082001

$B^+ \rightarrow J/\psi\phi K^+$





Full amplitude analysis!

$B \rightarrow J/\psi\phi K$

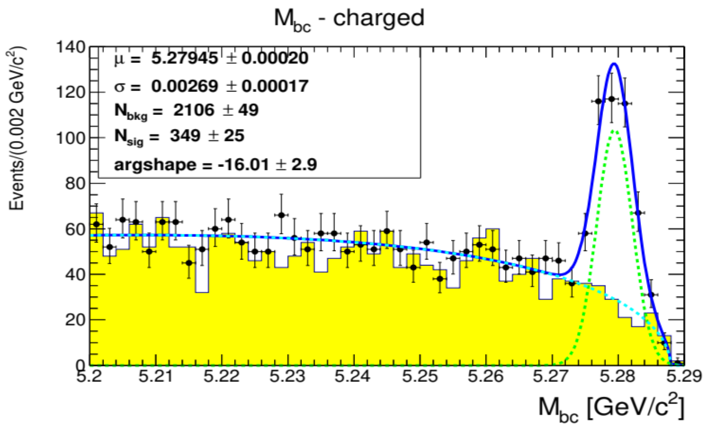
A. Thampi, PhD (2021), Belle

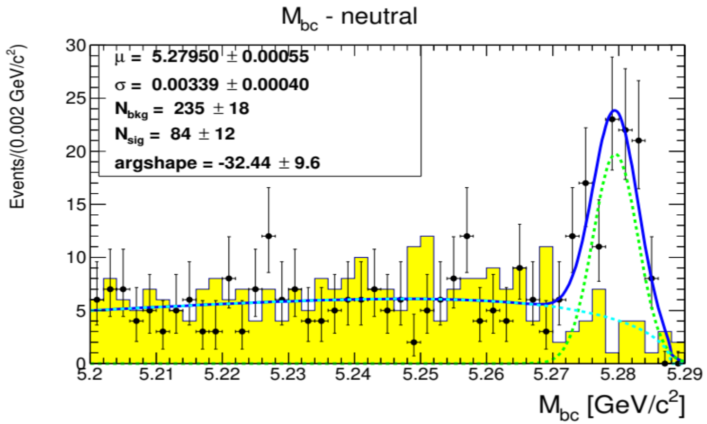
https://hss-opus.ub.ruhr-uni-bochum.de/opus4/frontdoor/deliver/index/docId/8685/file/diss.pdf

$B^{\pm} \rightarrow J/\Psi \Phi K^{\pm}$, $J/\Psi \rightarrow e^+e^-$ or $\mu^+\mu^-$, $\Phi \rightarrow K^+K^-$

$B^0 \rightarrow J/\Psi \Phi K^0_S$, $J/\Psi \rightarrow e^+e^-$ or $\mu^+\mu^-$, $\Phi \rightarrow K^+K^-$, $K^0_S \rightarrow \pi^+\pi^-$

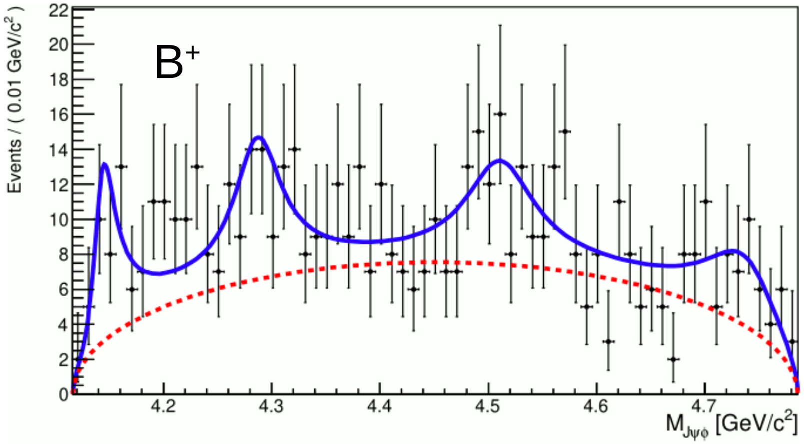
Mode	Efficiency, ϵ (%)	$\mathcal{BF}$ ($\times 10^{-5}$)	PDG value ($\times 10^{-5}$)	Ratio($B^0/B^{\pm}$)
$B^{\pm} \rightarrow J/\psi\phi K^{\pm}$	17.87 ± 0.09	$4.35 \pm 0.31 \pm 0.19$	5.0 ± 0.4	$0.48 \pm 0.10 \pm 0.04$
$B^0 \rightarrow J/\psi\phi K^0_S$	8.94 ± 0.09	$2.10 \pm 0.30 \pm 0.07$	2.4 ± 0.5	



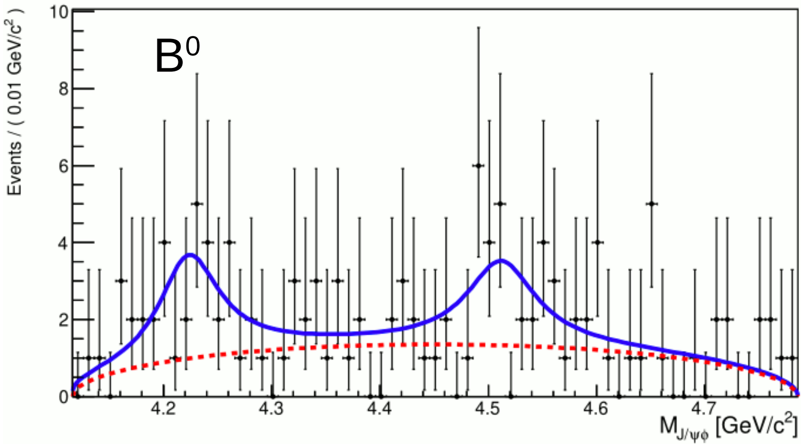


Excellent agreement with former BaBar analysis, PRD 91 (2015) 012003 and PDG.

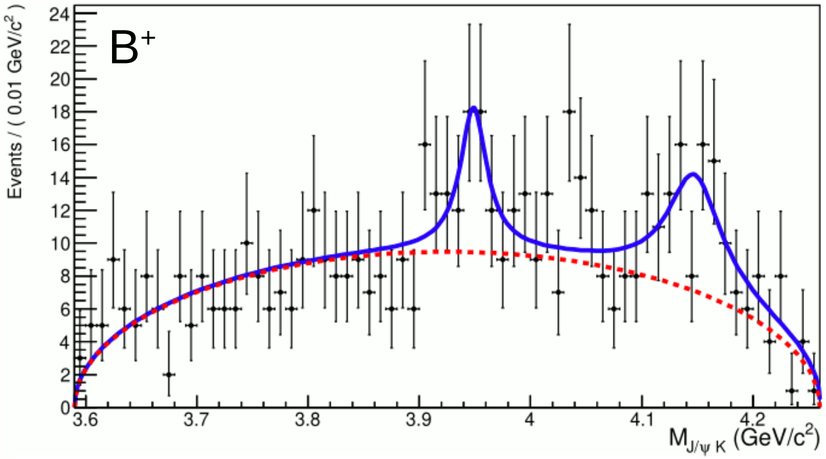
https://hss-opus.ub.ruhr-uni-bochum.de/opus4/frontdoor/deliver/index/docId/8685/file/diss.pdf
(Ashish Thampi PhD thesis)



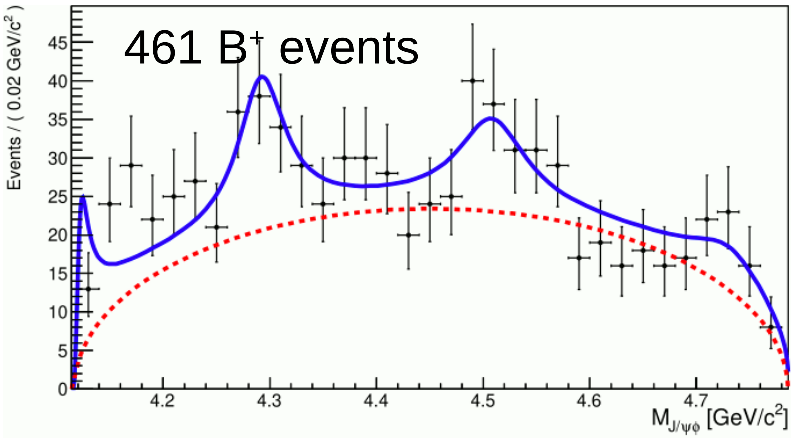
Belle

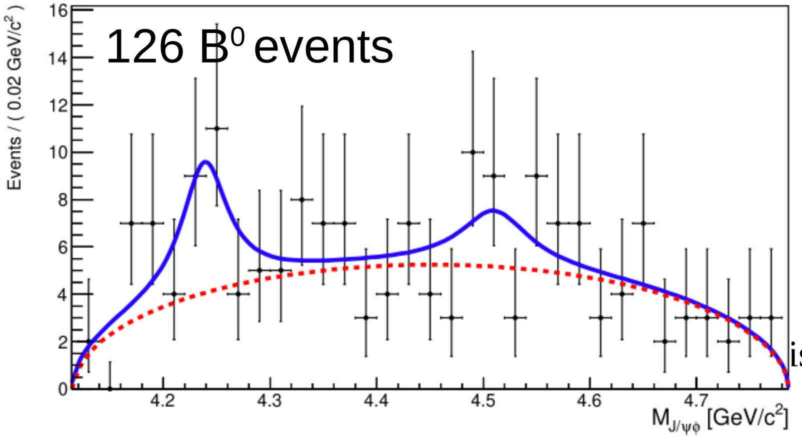


- Main issue found with efficiency: not smooth (problem see in BaBar and Belle data)
- *pdf function* corrected for the efficiency
- Limited statistics: need to perform a full amplitude analysis with full Belle II data



Combining BaBar and Belle data





My homework:

BaBar: Phys.Rev.D 91 (2015) 012003

Belle: https://hss-opus.ub.ruhr-uni-bochum.de/opus4/frontdoor/deliver/index/docId/8685/file/diss.pdf
(Ashish Thampi PhD thesis)

Fit parameters for the X(4140) fixed to:
PRL 127 (2021) 082001

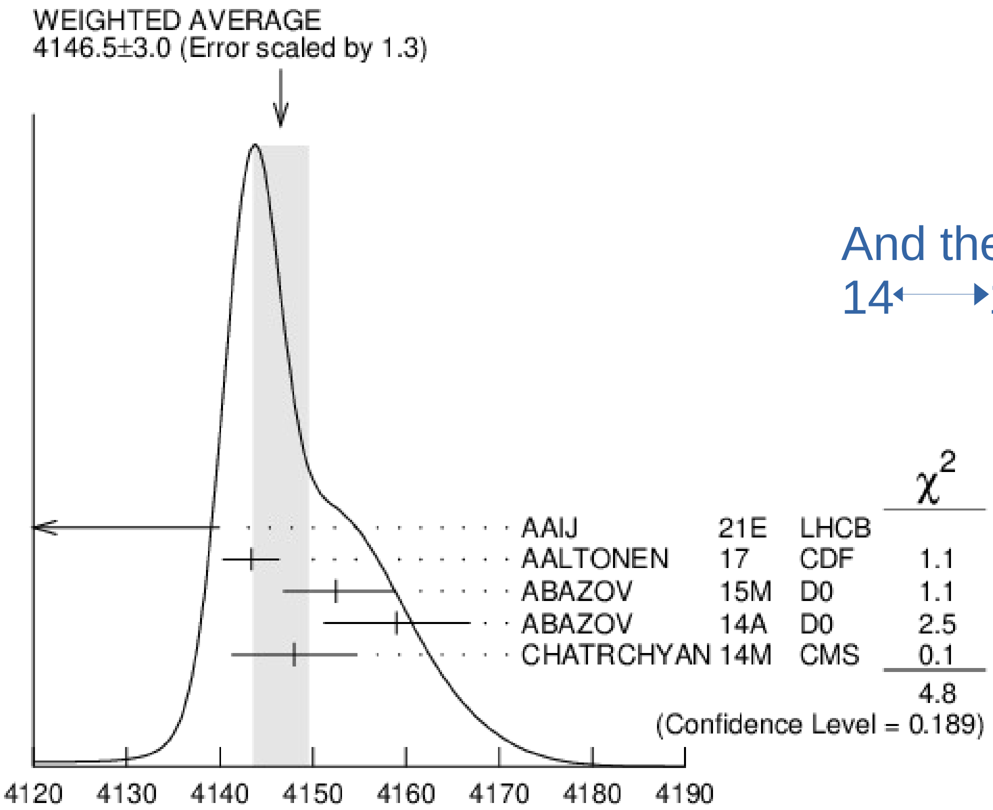
Total luminosity: 711 (BaBar) + 424 (Belle) = 1135 fb^{-1}

Total B^+: 461 events
Total B^0: 126 events

Full amplitude analysis will be performed with Belle II

The infinite saga of the X(4140)

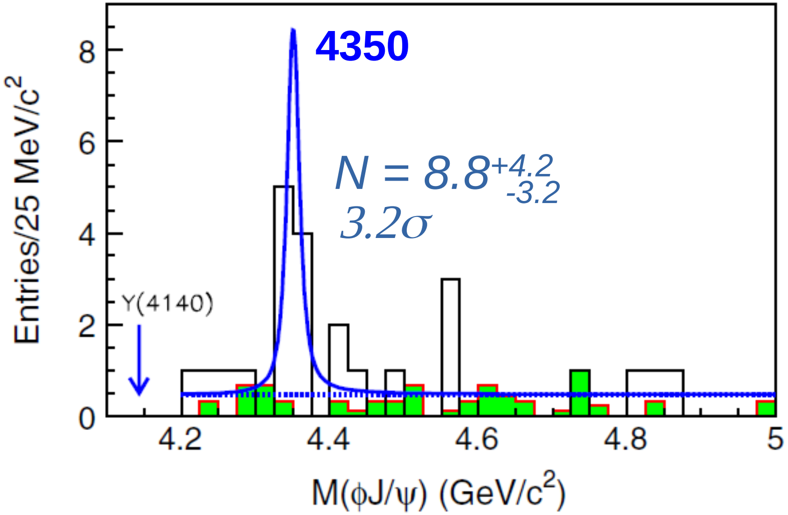
From PDG 2023:



And the width?
14 ⟷ 162 MeV...

Study of J/ψϕ via two-photon interaction at Belle

J/ψϕ, **PRL 104 (2010) 112004**



- 825 fb^{-1} integrated luminosity (Belle)

$$M = [4350.6^{+4.6}_{-5.1}(\text{stat}) \pm 0.7(\text{syst})]\,\text{MeV}/c^2$$
$$\Gamma = [13^{+18}_{-9}(\text{stat}) \pm 4(\text{syst})]\,\text{MeV}$$

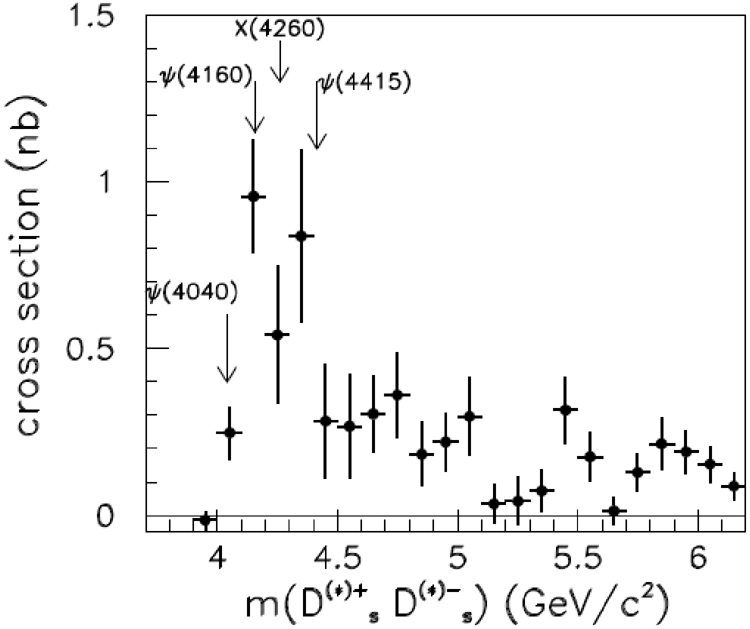
- Need to repeat the analysis with full Belle II data

Today we know that for X(4140) $J^{PC} = 1^{++}$
But what is the X(4350), if confirmed?

- X(4350) mass consistent with predicted $c\bar{c}s\bar{s}$ tetraquark (J. Phys. G37 (2010) 075017)
- Compatibility with $D_s^{*+}D_{s0}^{*}(2317)^-$ molecule state (prediction: CTP 54 (2010) 1075)
- Compatibility with possible χ''_{c2} charmonium state (prediction: PRL 104 (2010) 122001)

$c\bar{c}s\bar{s}$ search via ISR

Phys .Rev. D82 (2010) 052004



Analyzing $e^+e^-\to D_s^+D_s^-$, $e^+e^-\to D_s^{*+}D_s^-$, $e^+e^-\to D_s^{*+}D_s^{*-}$ via ISR BaBar looked for the Y(4260)

$$\frac{\mathcal{B}(Y(4260)\to D_s^+D_s^-)}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 0.7,$$

$$\frac{\mathcal{B}(Y(4260)\to D_s^{*+}D_s^-)}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 44,$$

$$\frac{\mathcal{B}(Y(4260)\to D_s^{*+}D_s^{*-})}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 30$$

If Y(4260) is 1^{--} **charmonium state**, it should decay mostly to open charm

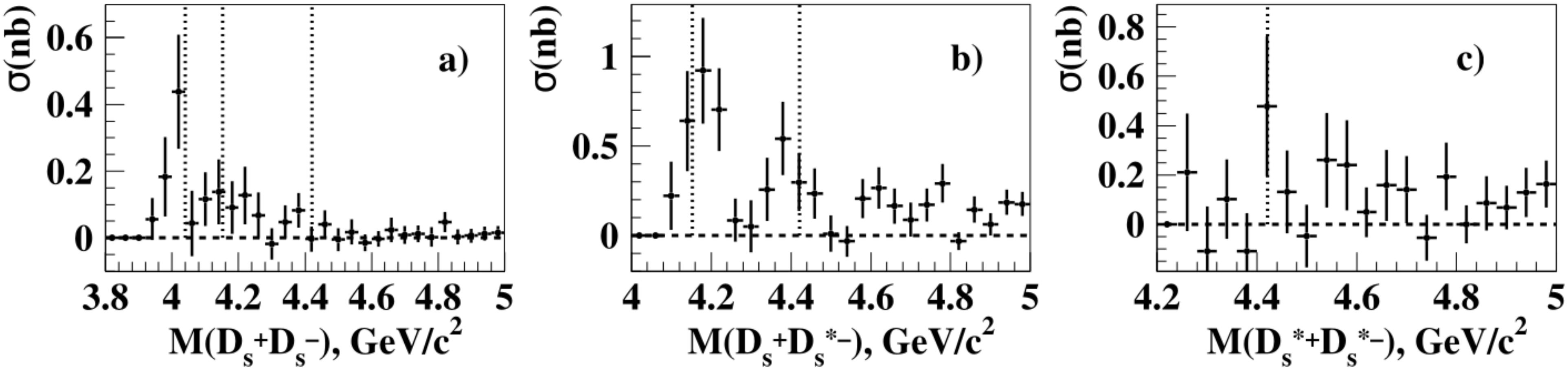
If Y(4260) is a **tetraquark**, it should decay to $D_s^-D_s^+$

it does not happen @95%c.l. with 525 fb^{-1} (BaBar data set)!

$c\bar{c}s\bar{s}$ search via ISR at Belle

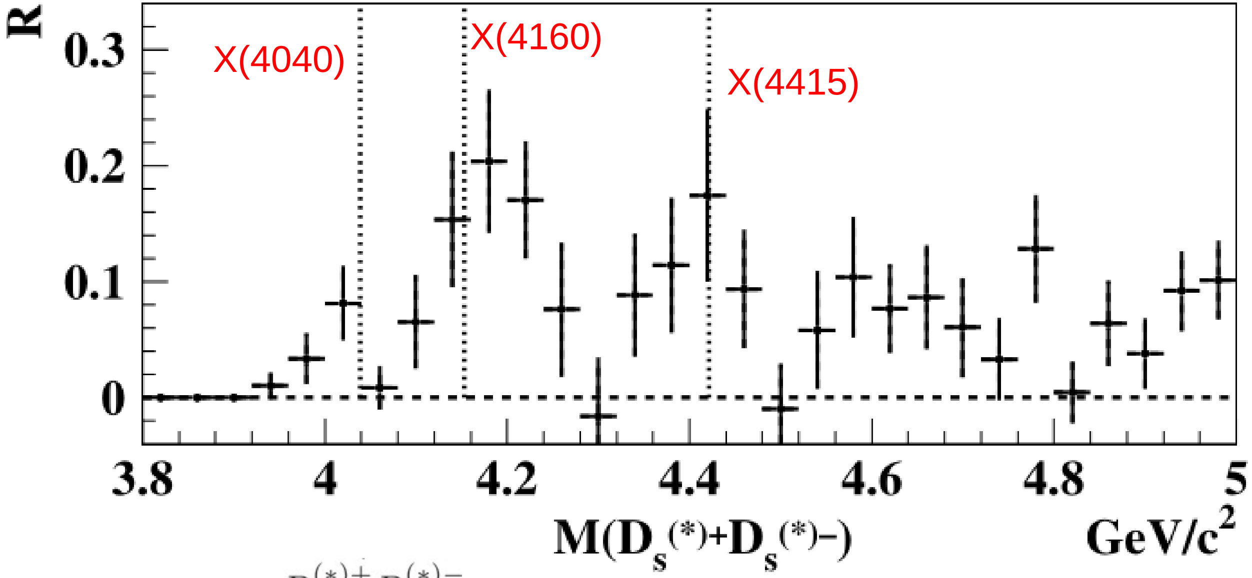
PRD 83 (2011) 011101

Found evidence for the X(4040), X(4160) and X(4415)
Integrated luminosity: 967 fb^{-1}



$c\bar{c}s\bar{s}$ search via ISR at Belle

PRD 83 (2011) 011101



$\rightarrow D_s^{(*)+} D_s^{(*)-}$

$R = \sigma(e^+e^- \rightarrow hadrons)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$

$\sigma(e^+e^- \rightarrow \mu^+\mu^-) = 4\pi\alpha^2/3s$

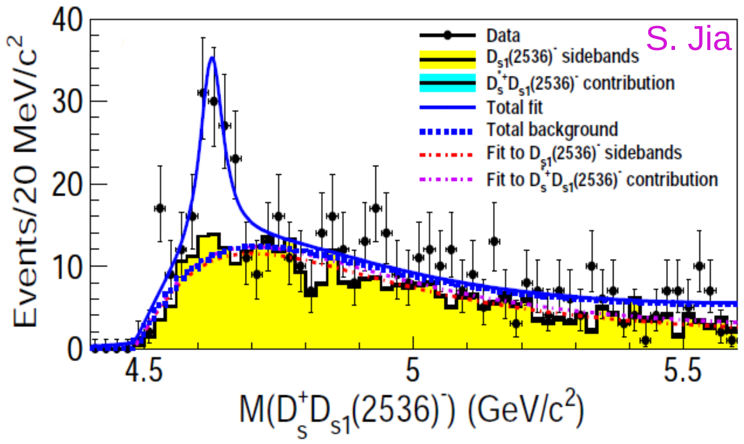
More data are needed!
Belle II will help to solve the puzzle

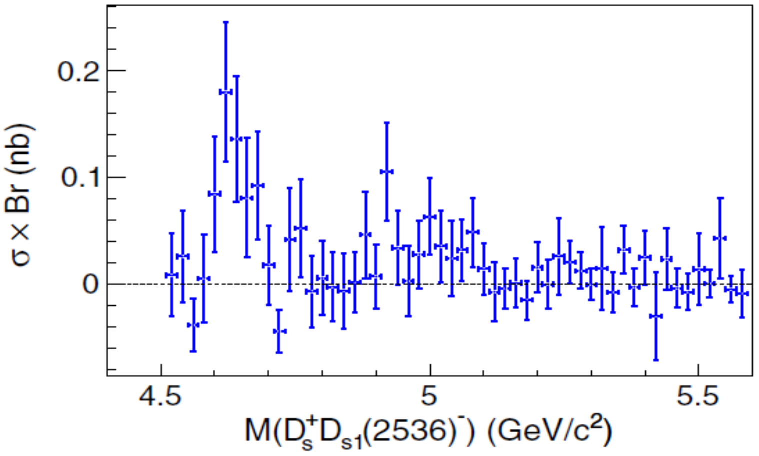
Need to look at the $D_s^{(*)}D_{sJ}^{(*)}$ invariant mass!

Belle and **Belle II**:
excellent calorimeter performance to detect low energy photons (down 48 MeV/c),
essential ingredient for the analysis of the D_{sJ} resonant states below the DK threshold

ISR physics, two-photon interactions and continuum:
unique physics cases at e^+e^- detectors

Results in ISR at Belle: $X \to D_s^+ D_{s1}(2536)^-$





$e^+e^- \to D_s^+ D_{s1}(2536)^-$ via ISR

First observation of the Y(4620)

$J^{PC} = 1^{--}$ compatible with Y(4660)

5.9σ significance

Luminosity: 921.9 fb^{-1}

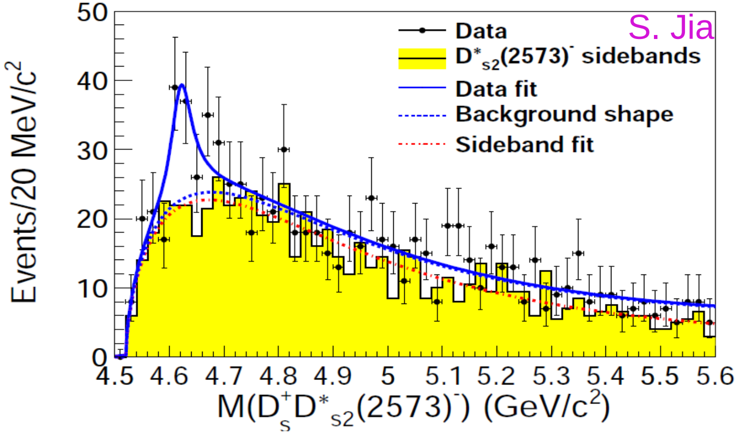
PRD 100 (2019) 111103

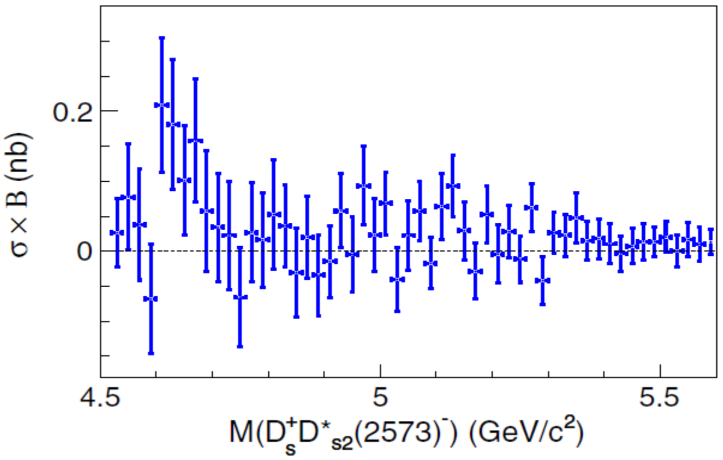
$$M = (4625.9^{+6.2}_{-6.0}(\text{stat}) \pm 0.4(\text{syst}))\ \text{MeV}/c^2$$

$$\Gamma = (49.8^{+13.9}_{-11.5}(\text{stat}) \pm 4.0(\text{syst}))\ \text{MeV}$$

$$\Gamma_{ee} \times \mathcal{B}(Y(4626) \to D_s^+ D_{s1}(2536)^-) \times \mathcal{B}(D_{s1}(2536)^- \to \bar{D}^{*0} K^-)$$
$$= (14.3^{+2.8}_{-2.6}(\text{stat}) \pm 1.5(\text{syst}))\ \text{eV}$$

Results in ISR at Belle: $X \to D_s^+ D_{s1}(2573)^-$





$e^+e^- \to D_s^+ D_{s2}(2573)^-$ via ISR

Evidence of the Y(4620)

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

compatible with Y(4660)

3.4σ significance

Luminosity: 921.9 fb^{-1}

PRD 101 (2020) 091101

$$M = (4619.8^{+8.9}_{-8.0}(\text{stat.}) \pm 2.3(\text{syst.}))\ \text{MeV}/c^2$$

$$\Gamma = (47.0^{+31.3}_{-14.8}(\text{stat.}) \pm 4.6(\text{syst.}))\ \text{MeV}$$

$$\Gamma_{ee} \times \mathcal{B}(Y(4620) \to D_s^+ D_{s2}^*(2573)^-) \times \mathcal{B}(D_{s2}^*(2573)^- \to \bar{D}^0 K^-)$$
$$(14.7^{+5.9}_{-4.5}(\text{stat.}) \pm 3.6(\text{syst.}))\ \text{eV}$$

Analysis in the continuum to search for $c\bar{c}s\bar{s}$ resonant states

- Too little is known
- Huge background, but higher efficiency
- Analyze the invariant mass on the recoil of anything else
- High potential discovery

Observation of cs meson pair production in $\Upsilon(2S)$ at Belle PRD 108 (2023) 112015

Data set: 24.7 fb^{-1} @ Y(2S)

$$\mathcal{B}(\Upsilon(2S) \to D_s^+ D_{s1}(2536)^-)\mathcal{B}(D_{s1}(2536)^- \to K^- D^*(2007)^0) = (1.6 \pm 0.3 \pm 0.2) \times 10^{-5}$$
$$\mathcal{B}(\Upsilon(2S) \to D_s^{*+} D_{s1}(2536)^-)\mathcal{B}(D_{s1}(2536)^- \to K^- D^*(2007)^0) = (1.4 \pm 0.4 \pm 0.2) \times 10^{-5}$$
$$\mathcal{B}(\Upsilon(2S) \to D_s^+ D_{s2}^*(2573)^-)\mathcal{B}(D_{s2}^*(2573)^- \to K^- D^0) = (1.4 \pm 0.4 \pm 0.2) \times 10^{-5}$$
$$\mathcal{B}(\Upsilon(2S) \to D_s^{*+} D_{s2}^*(2573)^-)\mathcal{B}(D_{s2}^*(2573)^- \to K^- D^0) = (0.9 \pm 0.5 \pm 0.2) \times 10^{-5}$$

$$\mathcal{B}(\Upsilon(2S) \to D_s^+ D_{s1}(2536)^-)\mathcal{B}(D_{s1}(2536)^- \to K_S^0 D^*(2010)^-) = (0.84 \pm 0.18 \pm 0.15) \times 10^{-5}$$
$$\mathcal{B}(\Upsilon(2S) \to D_s^{*+} D_{s1}(2536)^-)\mathcal{B}(D_{s1}(2536)^- \to K_S^0 D^*(2010)^-) = (0.82 \pm 0.25 \pm 0.19) \times 10^{-5}$$
$$\mathcal{B}(\Upsilon(2S) \to D_s^+ D_{s2}^*(2573)^-)\mathcal{B}(D_{s2}^*(2573)^- \to K_S^0 D^-) = (0.69 \pm 0.20 \pm 0.22) \times 10^{-5}$$
$$\mathcal{B}(\Upsilon(2S) \to D_s^{*+} D_{s2}^*(2573)^-)\mathcal{B}(D_{s2}^*(2573)^- \to K_S^0 D^-) = (0.54 \pm 0.31 \pm 0.47) \times 10^{-5}$$

Observation of cs meson pair production in $\Upsilon(2S)$ at Belle PRD 108 (2023) 112015

Data set: 24.7 fb-1 @ Y(2S)

$$\sigma^{\text{Born}}(e^+e^- \to D_s^+ D_{s1}(2536)^-)\mathcal{B}(D_{s1}(2536)^- \to K^- D^*(2007)^0) = (67 \pm 8 \pm 6)\ \text{fb}$$

$$\sigma^{\text{Born}}(e^+e^- \to D_s^{*+} D_{s1}(2536)^-)\mathcal{B}(D_{s1}(2536)^- \to K^- D^*(2007)^0) = (84 \pm 11 \pm 11)\ \text{fb}$$

$$\sigma^{\text{Born}}(e^+e^- \to D_s^+ D_{s2}^*(2573)^-)\mathcal{B}(D_{s2}^*(2573)^- \to K^- D^0) = (56 \pm 9 \pm 13)\ \text{fb}$$

$$\sigma^{\text{Born}}(e^+e^- \to D_s^{*+} D_{s2}^*(2573)^-)\mathcal{B}(D_{s2}^*(2573)^- \to K^- D^0) = (106 \pm 17 \pm 12)\ \text{fb}$$

$$\sigma^{\text{Born}}(e^+e^- \to D_s^+ D_{s1}(2536)^-)\mathcal{B}(D_{s1}(2536)^- \to K_S^0 D^*(2010)^-) = (34 \pm 5 \pm 4)\ \text{fb}$$

$$\sigma^{\text{Born}}(e^+e^- \to D_s^{*+} D_{s1}(2536)^-)\mathcal{B}(D_{s1}(2536)^- \to K_S^0 D^*(2010)^-) = (41 \pm 6 \pm 6)\ \text{fb}$$

$$\sigma^{\text{Born}}(e^+e^- \to D_s^+ D_{s2}^*(2573)^-)\mathcal{B}(D_{s2}^*(2573)^- \to K_S^0 D^-) = (27 \pm 6 \pm 5)\ \text{fb}$$

$$\sigma^{\text{Born}}(e^+e^- \to D_s^{*+} D_{s2}^*(2573)^-)\mathcal{B}(D_{s2}^*(2573)^- \to K_S^0 D^-) = (51 \pm 11 \pm 9)\ \text{fb}$$

Recall: $\sigma^{\text{Born}}(e^+e^- \to \mu^+\mu^-) = 0.784\ \text{nb}$ @10.52 GeV

Observation of cs meson pair production in $\Upsilon(2S)$ at Belle

PRD 108 (2023) 112015

Data set: 24.7 fb^{-1} @ Y(2S)

$$\sigma^{\text{Born}}(e^+e^- \to D_s^{(*)+} D_{sJ}^-)/\sigma^{\text{Born}}(e^+e^- \to \mu^+\mu^-) \begin{cases} 9.7 \pm 2.3 \pm 1.1 & D_s^+ D_{s1}(2536)^- \\ 6.8 \pm 2.1 \pm 0.8, & D_s^{*+} D_{s1}(2536)^- \\ 10.2 \pm 3.3 \pm 2.5 & D_s^+ D_{s2}^*(2573)^- \\ 3.4 \pm 2.1 \pm 0.8 & D_s^{*+} D_{s2}^*(2573)^- \end{cases}$$

→ Strong decays dominate in the $\Upsilon(2S) \to D_s^{(*)+} D_{sJ}^-$ process

$$\mathcal{B}(D_{s1}(2536)^- \to K_S^0 D^*(2010)^-)/\mathcal{B}(D_{s1}(2536)^- \to K^- D^*(2007)^0) = 0.48 \pm 0.07 \pm 0.02$$

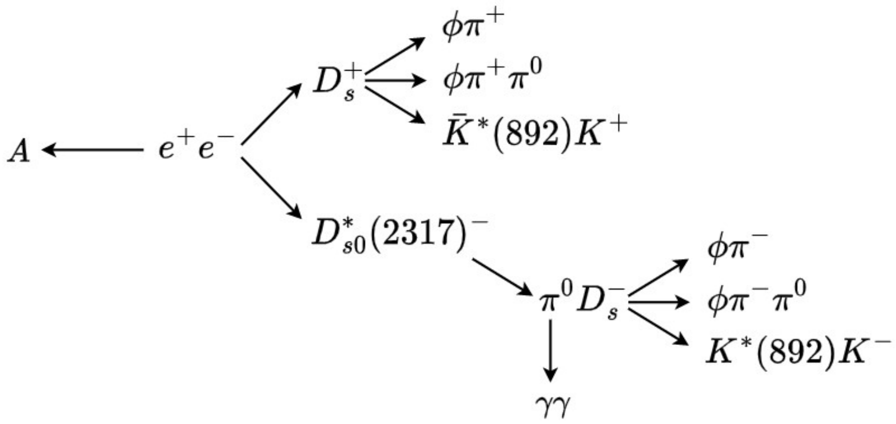
$$\mathcal{B}(D_{s2}^*(2573)^- \to K_S^0 D^-)/\mathcal{B}(D_{s2}^*(2573)^- \to K^- D^0) = 0.49 \pm 0.10 \pm 0.02$$

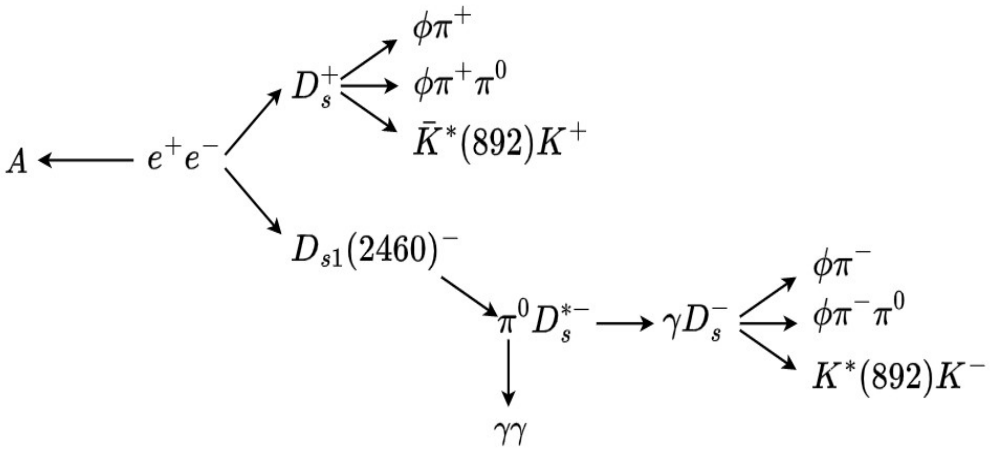
First measurement

→ Isospin symmetry

Study of the $e^+e^- \rightarrow D_s^+ D_{s0}(2317)^{*-} A$ and $e^+e^- \rightarrow D_s^+ D_{s1}(2460)^- A$ in the continuum at Belle

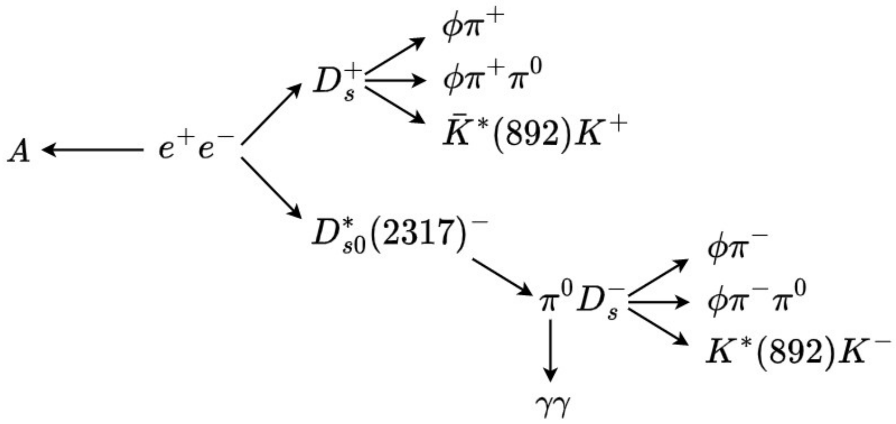
FIRST MEASUREMENT
PRELIMINARY

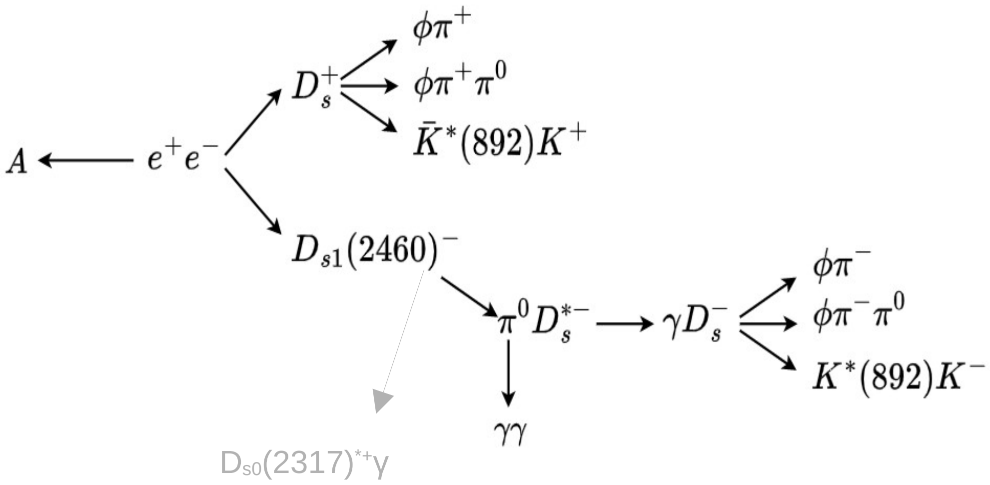




Study of the $e^+e^- \to D_s^+ D_{s0}(2317)^{*-} A$ and $e^+e^- \to D_s^+ D_{s1}(2460)^- A$ in the continuum at Belle

FIRST MEASUREMENT
PRELIMINARY



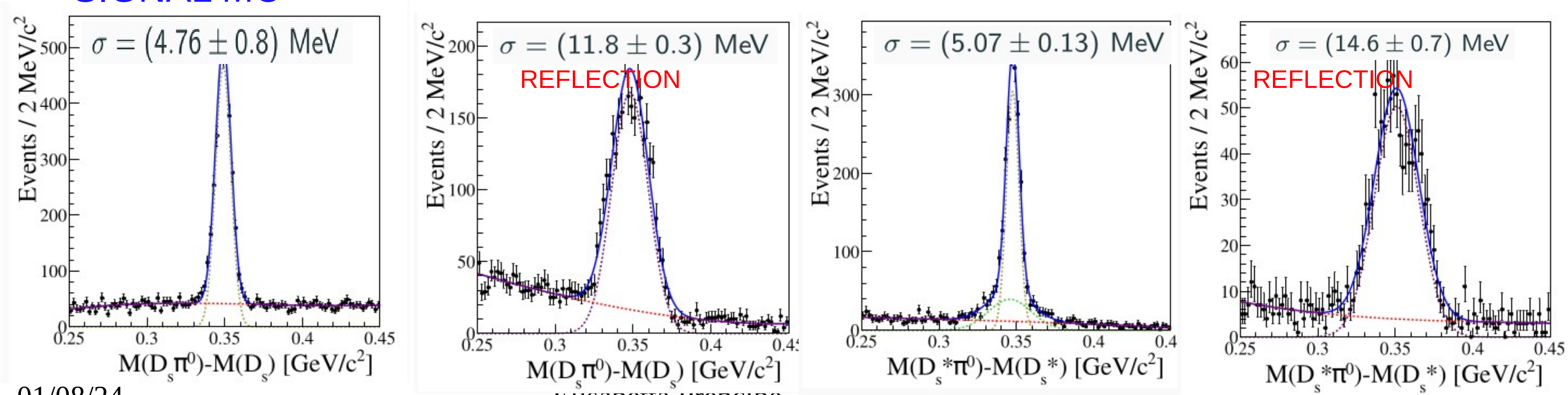


Study of the $e^+e^- \to D_s^+ D_{s0}(2317)^{*-} A$ and $e^+e^- \to D_s^+ D_{s1}(2460)^- A$ in the continuum at Belle

FIRST MEASUREMENT
PRELIMINARY

- Complicated cross-feed background to study
- Poor knowledge from theory: MC model not appropriate
- Still limited statistics with Belle, but...

SIGNAL MC



Study of the $e^+e^- \to D_s^+ D_{s0}(2317)^{*-} A$ and $e^+e^- \to D_s^+ D_{s1}(2460)^- A$ in the continuum at Belle

FIRST MEASUREMENT
PRELIMINARY

Topology type	μ, [MeV]	σ, [MeV]	N
True $D^*_{s0}(2317)$ signal	349.3 ± 0.2	5.97 ± 0.25	$3{,}797 \pm 137$
Feed-down background	345.1 (fixed)	13.5 (fixed)	$0.3297 \cdot N_2$
True $D_{s1}(2460)$ signal	347.1 ± 0.5	5.46 ± 0.60	811 ± 155
Feed-up background	352.0 (fixed)	13.9 (fixed)	$3.042 \cdot N_1$
$D_{s1}(2460)$	346.7 (fixed)	22.7 (fixed)	$1.189 \cdot N_2$

$N_1 = 3{,}843 \pm 67,\ \mu = 348.9 \pm 0.1,\ \sigma = 6.20 \pm 0.10$

$N_2 = 835 \pm 31,\ \mu = 347.1 \pm 0.2,\ \sigma = 5.80 \pm 0.20$

Fit functions:

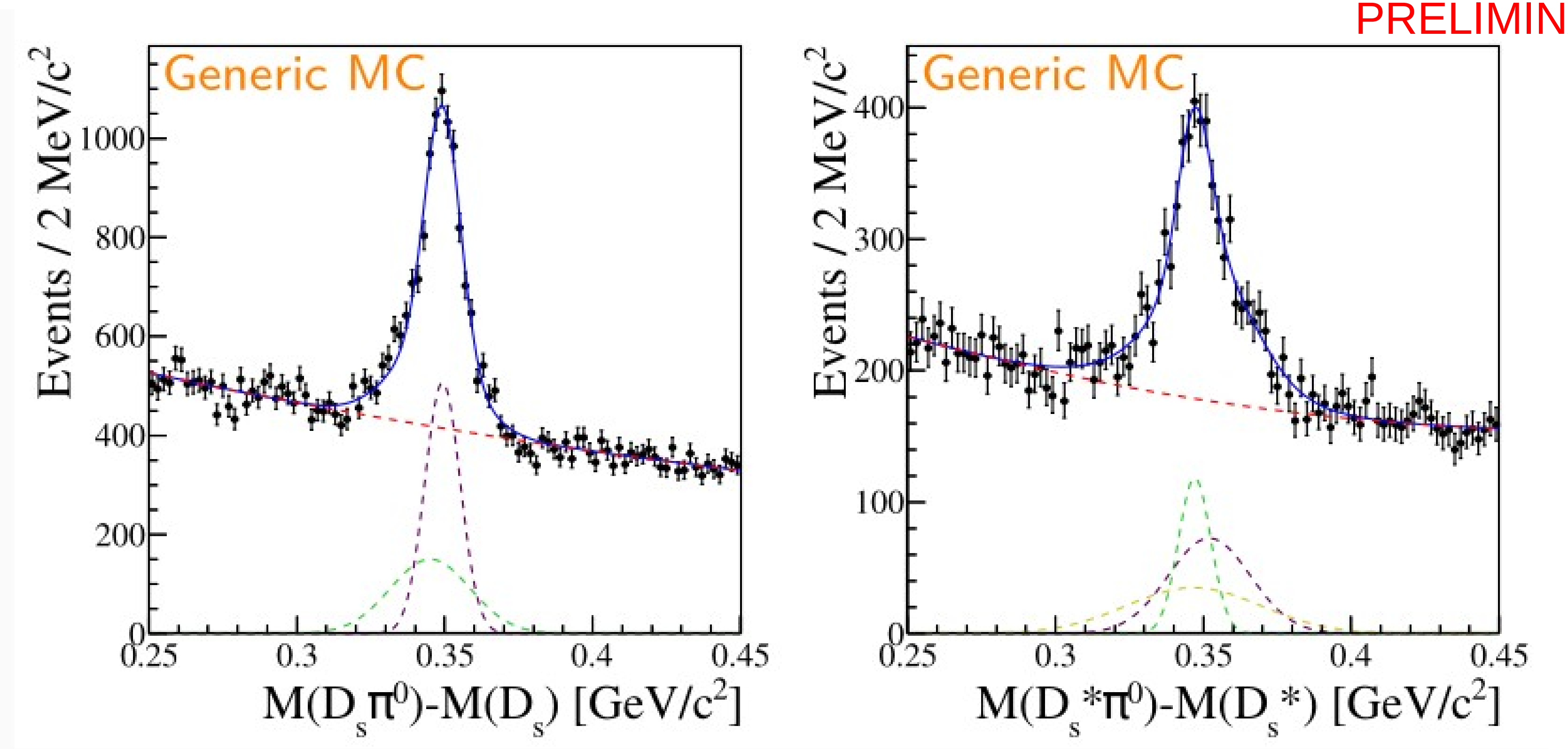
$$\Delta M(D_s\pi^0) = N_1 G(\mu_1, \sigma_1) + f^{down} N_2 G(\mu^{down}, \sigma^{down})$$

$$\Delta M(D_s^*\pi^0) = N_2 G(\mu_2, \sigma_2) + f^{up} N_1 G(\mu^{up}, \sigma^{up}) + f^{broken} N_2 G(\mu^{broken}, \sigma^{broken})$$

Study of the $e^+e^- \rightarrow D_s^+D_{s0}(2317)^{*-}A$ and $e^+e^- \rightarrow D_s^+D_{s1}(2460)^-A$ in the continuum at Belle

FIRST MEASUREMENT

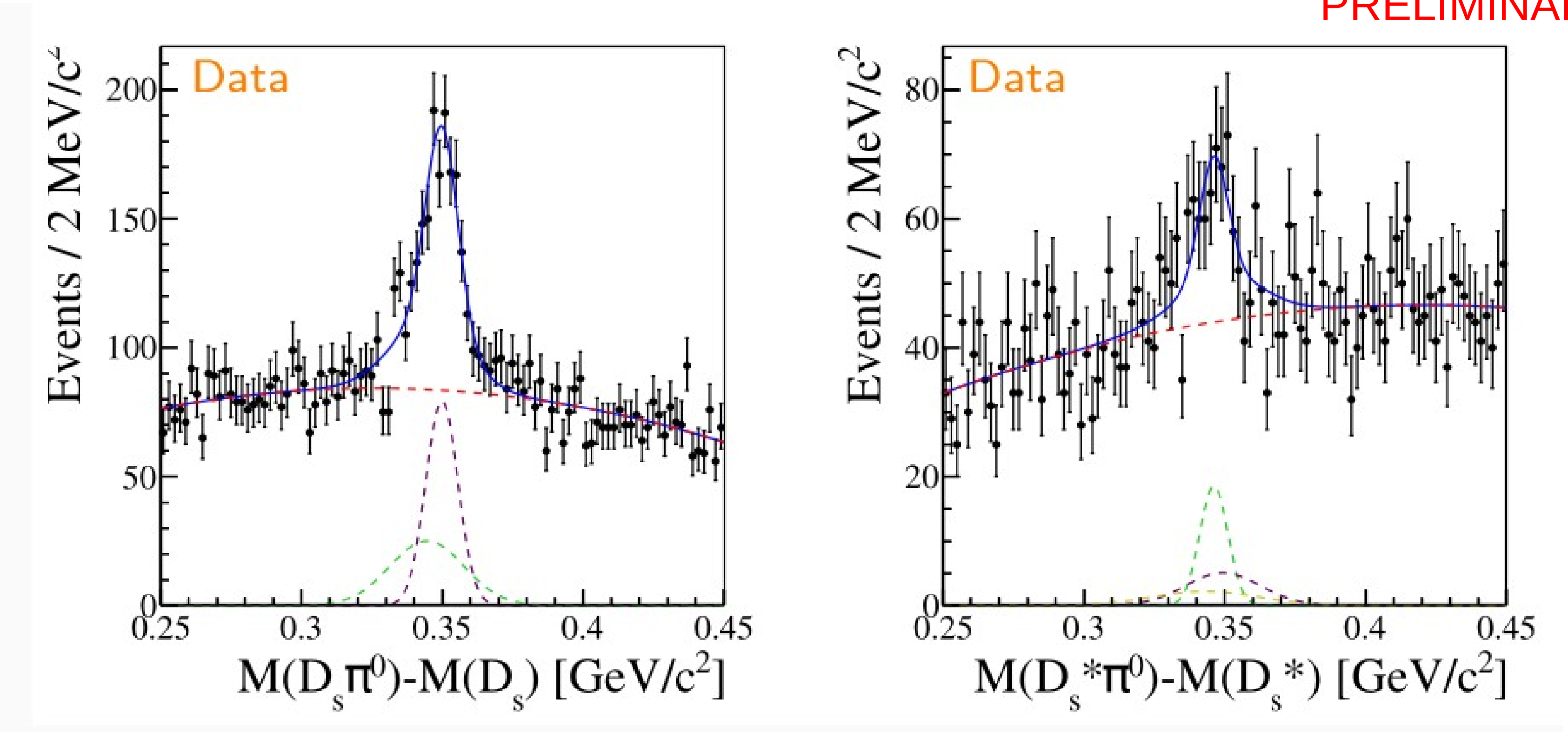
PRELIMINARY



Study of the $e^+e^- \rightarrow D_s^+ D_{s0}(2317)^{*-} A$ and $e^+e^- \rightarrow D_s^+ D_{s1}(2460)^{-} A$ in the continuum at Belle

FIRST MEASUREMENT

PRELIMINARY



Study of the $e^+e^- \rightarrow D_s^+ D_{s0}(2317)^{*-} A$ and $e^+e^- \rightarrow D_s^+ D_{s1}(2460)^- A$ at Belle

FIRST MEASUREMENT

PRELIMINARY

DATA

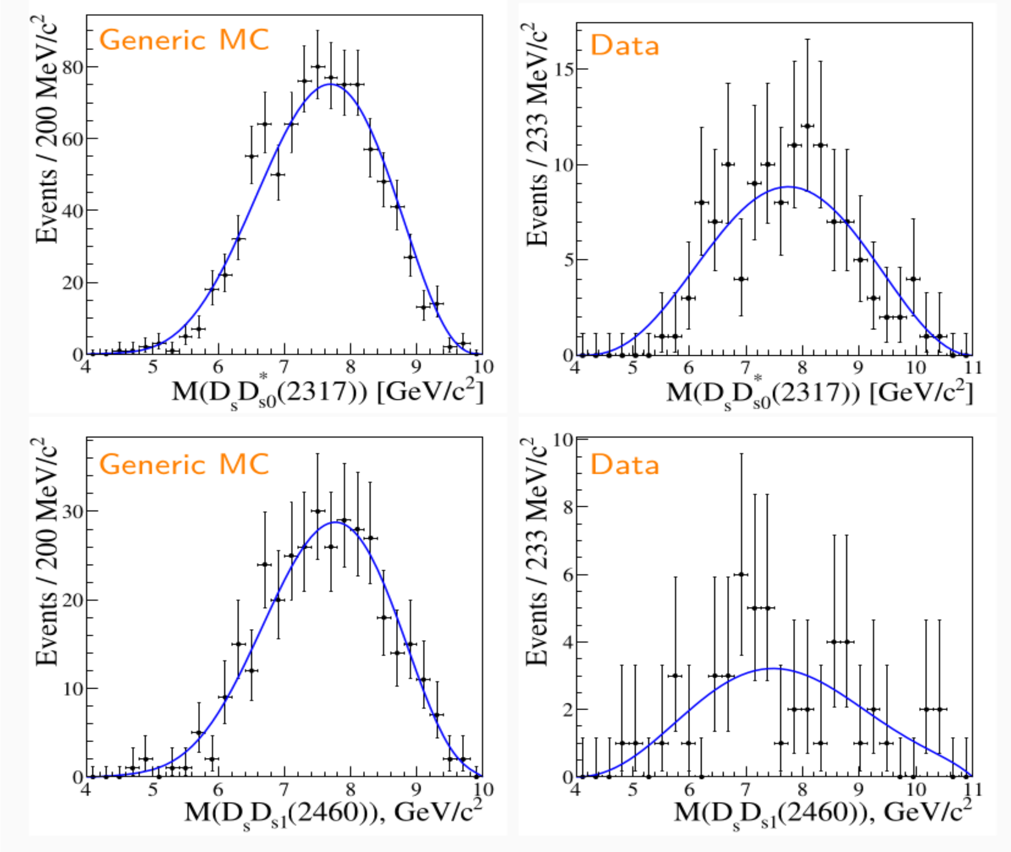
Topology type	μ, [MeV]	σ, [MeV]	N
True $D_{s0}^*(2317)$ signal	349.6 ± 0.5	7.16 ± 0.59	792 ± 62
Feed-down background	344.0 (fixed)	13.4 (fixed)	$0.170 \cdot N_2$
True $D_{s1}(2460)$ signal	347.3 ± 1.8	6.98 ± 1.72	137 ± 36
Feed-up background	349.6 (fixed)	14.6 (fixed)	$2.097 \cdot N_1$
$D_{s1}(2460)$ broken signal	345.5 (fixed)	17.0 (fixed)	$0.231 \cdot N_2$

NN-analysis performed: a factor 2 gain compared to a cut-based analysis!

Study of the $e^+e^- \to D_s^+ D_{s0}(2317)^{*-}A$ and $e^+e^- \to D_s^+ D_{s1}(2460)^{-}A$ in the continuum at Belle

FIRST MEASUREMENT

PRELIMINARY



No evidence for resonant states found up to 980.15 fb^{-1}

$$\frac{Br(D_{s1}(2460) \to D_s^* \pi^0)}{Br(D_{s0}^*(2317) \to D_s \pi^0)} \times \frac{\sigma(D_{s1}(2460), p^* > 3.5\ \ \mathrm{GeV/c})}{\sigma(D_{s0}^*(2317), p^* > 3.5\ \ \mathrm{GeV/c})} =$$

$$0.33 \pm 0.09(\mathrm{stat}) \pm 0.01(\mathrm{syst})$$

a factor 10 lower than the theory predicts

Study of the $e^+e^- \rightarrow D_s^+ D_{s0}(2317)^{*-} A$ and $e^+e^- \rightarrow D_s^+ D_{s1}(2460)^- A$ in the continuum at Belle

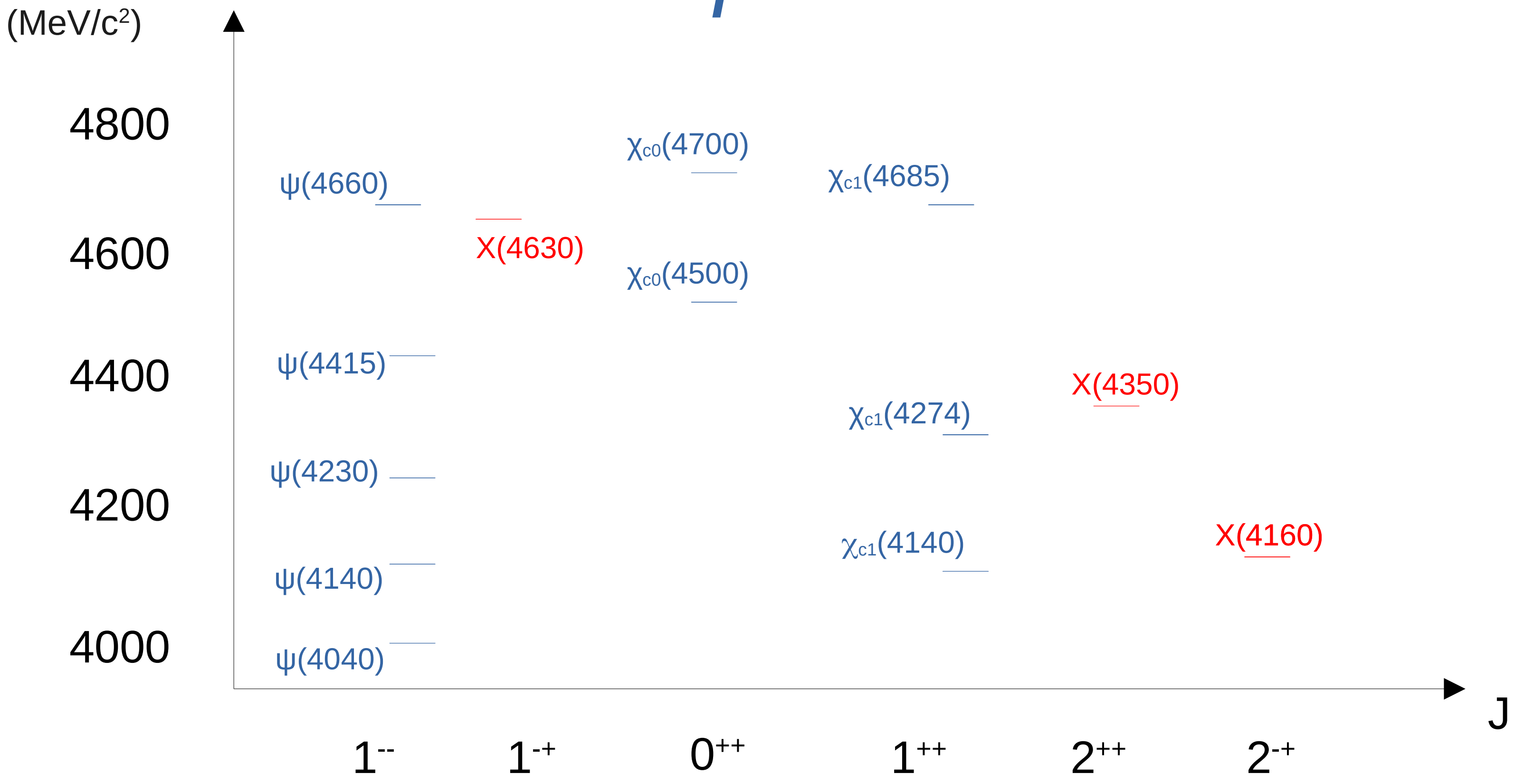
FIRST MEASUREMENT

PRELIMINARY

Upper limits determined on the resonant states seen in J/ψϕ mass via B decays

Mode	N^{UL}	Tot. err. [%]	$\sigma^{UL} \times \mathcal{B}(X \to D_s D_{sJ}^{(*)})$ [fb]
$e^+e^- \to X(4274)A$	2.4	10.1	99.1
$e^+e^- \to X(4685)A$	1.9	11.2	78.1
$e^+e^- \to X(4630)A$	1.9	14.9	153.2
$e^+e^- \to X(4500)A$	2.3	14.7	189.3
$e^+e^- \to X(4700)A$	2.1	15.3	171.3

Summary of the $c\bar{c}s\bar{s}$ states: an experimental view



Search for pentaquarks at Belle

Search for a penta-quark state in pJ/ψ final state from the ϒ(1, 2S) inclusive decays at Belle

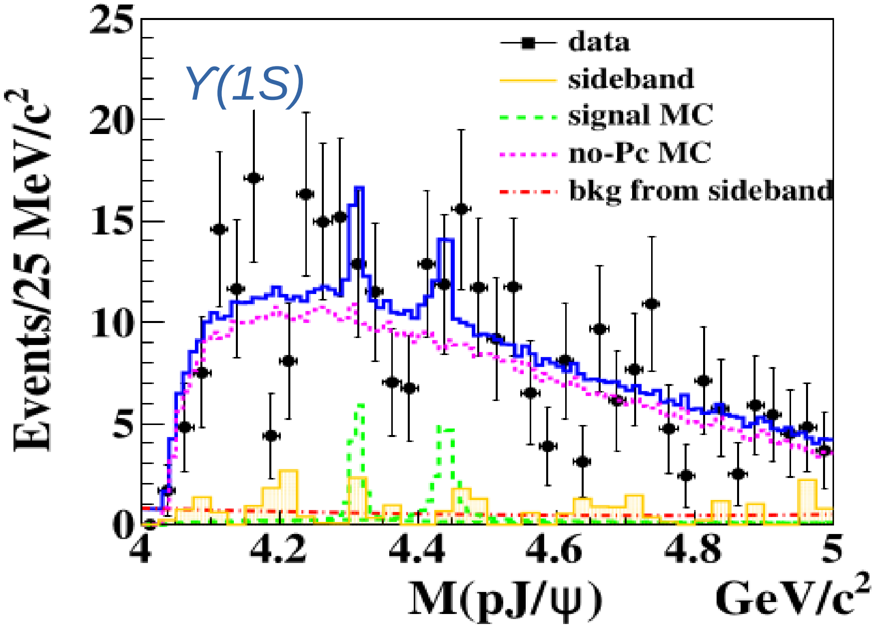
PRELIMINARY

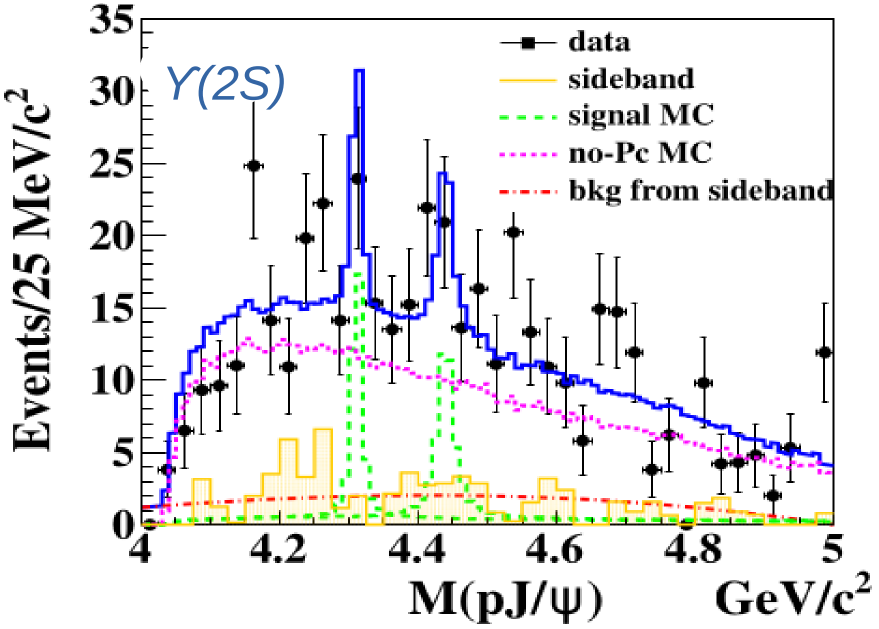
- Total integrated luminosity used: ϒ(1S) + ϒ(2S) = 30.5 fb^{-1}
- Inclusive analysis = reconstruction of Pc candidates on the recoil of anything else
- Use also 89 fb^{-1} data @60 MeV below the ϒ(4S) peak → analysis in the continuum
- Eliminate Bhabha bkg and reflection peak imposing M^2 (pJ/ψ)>10 GeV^2/c^4

Search for a penta-quark state in pJ/ψ final state from the Y(1, 2S) inclusive decays at Belle

PRELIMINARY

- No clear signal found for $P_c^+(4312)$, $P_c^+(4440)$, $P_c^+(4457)$





Search for a penta-quark state in pJ/ψ final state from the $Y(1, 2S)$ inclusive decays at Belle

PRELIMINARY

$$\mathcal{B}[\Upsilon(1S) \to pJ/\psi + any] = (4.43 \pm 0.25 \pm 0.17) \times 10^{-5}$$
$$\mathcal{B}[\Upsilon(2S) \to pJ/\psi + any] = (3.82 \pm 0.20 \pm 0.16) \times 10^{-5}$$
$$\sigma(e^+e^- \to pJ/\psi + any) = (67 \pm 2 \pm 2) \text{ fb at } \sqrt{s} = 10.52 \text{ GeV}$$

$$\mathcal{B}^{\mathrm{UL}}[\Upsilon(1S) \to P_c(4312)^+ + any] \cdot \mathcal{B}[P_c(4312)^+ \to pJ/\psi] < 4.5 \times 10^{-6}$$
$$\mathcal{B}^{\mathrm{UL}}[\Upsilon(1S) \to P_c(4440)^+ + any] \cdot \mathcal{B}[P_c(4440)^+ \to pJ/\psi] < 6.8 \times 10^{-6}$$
$$\mathcal{B}^{\mathrm{UL}}[\Upsilon(1S) \to P_c(4457)^+ + any] \cdot \mathcal{B}[P_c(4457)^+ \to pJ/\psi] < 4.9 \times 10^{-6}$$
$$\mathcal{B}^{\mathrm{UL}}[\Upsilon(2S) \to P_c(4312)^+ + any] \cdot \mathcal{B}[P_c(4312)^+ \to pJ/\psi] < 5.3 \times 10^{-6}$$
$$\mathcal{B}^{\mathrm{UL}}[\Upsilon(2S) \to P_c(4440)^+ + any] \cdot \mathcal{B}[P_c(4440)^+ \to pJ/\psi] < 7.2 \times 10^{-6}$$
$$\mathcal{B}^{\mathrm{UL}}[\Upsilon(2S) \to P_c(4457)^+ + any] \cdot \mathcal{B}[P_c(4457)^+ \to pJ/\psi] < 2.4 \times 10^{-6}$$

Bottomonium physics at Belle and Belle II

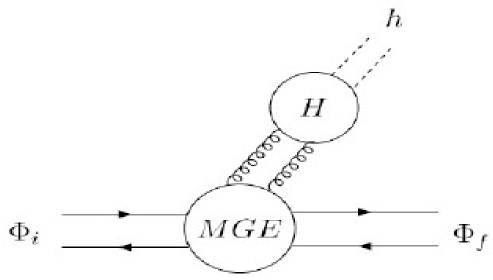
Unique physics case at Belle II

Bottomonium

- Hadronic transitions between heavy quarkonium states can be described with the QCD multiple expansion model (*QCDME*) PRD 24, 2874 (1981)

☑ in analogy with electromagnetism, it is possible to expand in terms of *(ak)* gluon radiation if the radius *a* of the bound *qq* state is much smaller than the wavelenght *1/k*

☑ vicinity to threshold opening can modify **QCDME** predictions



$m^3S^1 \rightarrow \pi\pi$ n^3S^1 (E1E1)

$m^3S^1 \rightarrow \eta$ n^3S^1 (E1M2 or M1M1)

- When/how did the *bottomonium story* begin?

Bottomonium: how it started

- From Belle, PRL 100 (2008) 112001:

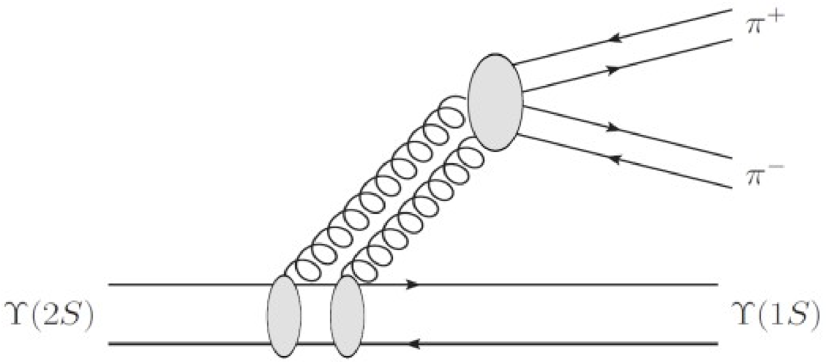
Observation of anomalous ϒ(1S)π⁺π- and ϒ(2S)π⁺π⁻ production near the ϒ(5S) resonance

- First observation of $e^+e^- \to \Upsilon(1S)\pi^+\pi^-$ and $e^+e^- \to \Upsilon(2S)\pi^+\pi^-$
- First evidence for $e^+e^- \to \Upsilon(3S)\pi^+\pi^-$ and $e^+e^- \to \Upsilon(1S)K^+K^-$ ~ϒ(5S)

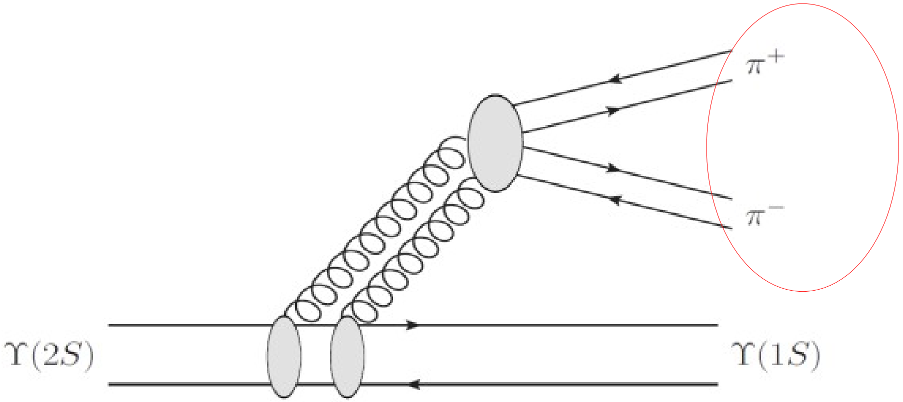
$$\Gamma(\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-) = 0.59\pm0.04(\mathrm{stat})\pm0.09(\mathrm{syst})\ \mathrm{MeV}$$
$$\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-) = 0.85\pm0.07(\mathrm{stat})\pm0.16(\mathrm{syst})\ \mathrm{MeV}$$

- From BaBar, PRD 78 (2008) 112022: $\frac{\Gamma(\Upsilon(4S)\to\Upsilon(1S)\eta)}{\Gamma(\Upsilon(4S)\to\Upsilon(1S)\pi^+\pi^-)} = 2.4 \pm 0.4$

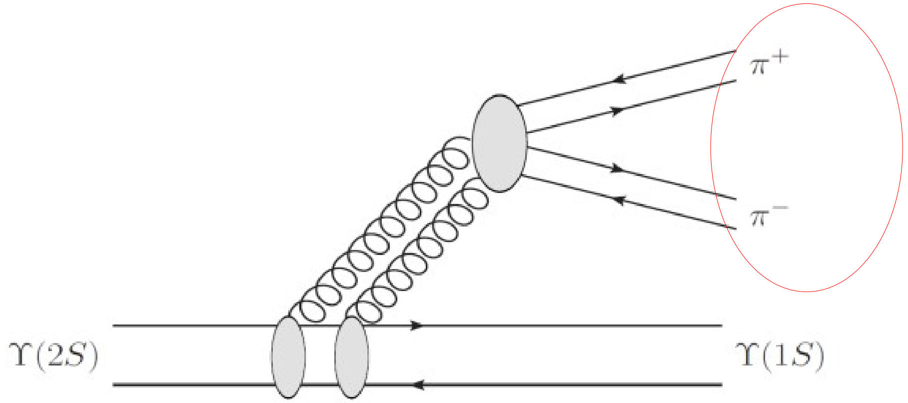
Hadronic transition in Bottomonium



Hadronic transition in Bottomonium



Hadronic transition in Bottomonium



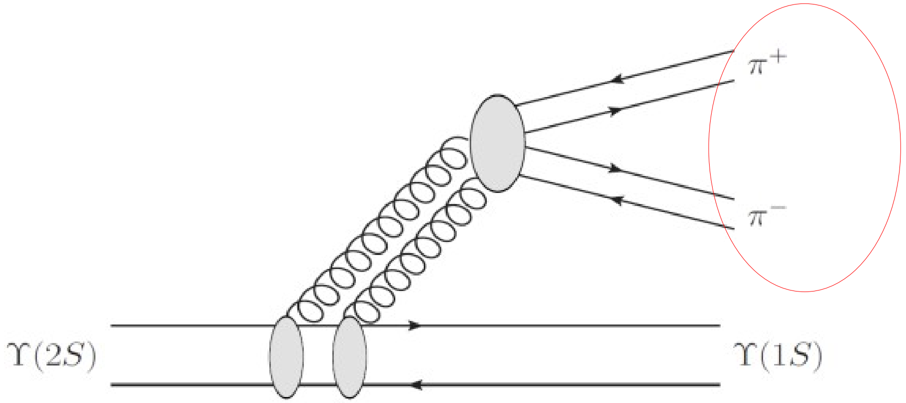
$\pi^+\pi^-$: $E1E1$ gluons

$$\Gamma(\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-) = 5.7 \pm 0.5\,\mathrm{keV}$$
$$\Gamma(\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-) = 0.89 \pm 0.08\,\mathrm{keV}$$
$$\Gamma(\Upsilon(3S) \to \Upsilon(2S)\pi^+\pi^-) = 0.57 \pm 0.06\,\mathrm{keV}$$

partial widths are small

$\Gamma(\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-) \sim 1\ MeV$

Hadronic transition in Bottomonium



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partial widths are small

$\Gamma(\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-) \sim 1\ MeV$

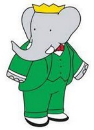
η : $E1M2$ gluons

Amplitude $\propto$ chromomagnetic moment of b quark $\propto$ $1/m_b$

$$\Gamma(\Upsilon(2S) \to \Upsilon(1S)\eta) = (9.3 \pm 1.5) \times 10^{-3}\,\text{keV}$$
$$\Gamma(\Upsilon(3S) \to \Upsilon(1S)\eta) < 2 \times 10^{-3}\,\text{keV}$$

additional suppression

$$\frac{\Gamma(\Upsilon(4S) \to \Upsilon(1S)\,\eta)}{\Gamma(\Upsilon(4S) \to \Upsilon(1S)\,\pi^+\pi^-)} = 2.4 \pm 0.4$$

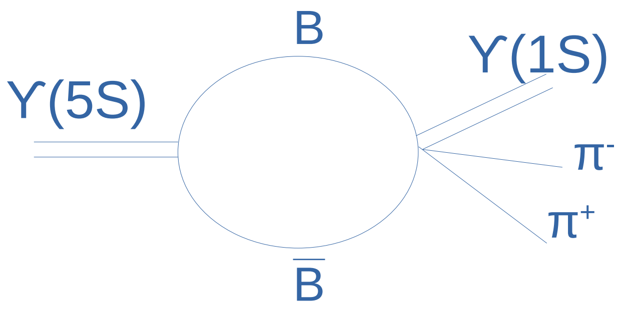


How that can happen?

- Alternative explanation is that the transitions $\Upsilon(nS) \rightarrow \Upsilon(mS)$ proceed via exotic admixture
- The decay into constituents dominates
- If p_B is high enough, rescattering is suppressed
- Then: $\Upsilon(4S)$ $|B\bar{B}>$,

  $\Upsilon(5S)$ $|B_s{}^*\bar{B}_s{}^*>$ $|B_s{}^*B^0>$?

  $\Upsilon(6S)$ $|B_1\bar{B}>$



- New decay mechanism : exotic admixture
- Possibilities: hadroquarkonium, compact tetraquark, hybrids

  $|\Upsilon(2S)\ f_0>$ $|bq\ \bar{b}\bar{q}>$ $|b\bar{b}\ g>$

Angular momentum wave functions

PRD 85, 034024 (2012)

$$
\begin{aligned}
|B\bar{B}\rangle \quad &\equiv \quad |S_{b\bar{q}}=0, L_{b\bar{q}}=0, S_{\bar{b}q}=0, L_{\bar{b}q}=0, L=1\rangle \\
&= \frac{1}{2\sqrt{3}} \quad |S_{b\bar{b}}=1, J_{q\bar{q}}=0\rangle \rightarrow \Upsilon(1S)\,\pi^+\pi^- \text{ in S wave} \\
&+ \frac{1}{2} \quad |S_{b\bar{b}}=1, J_{q\bar{q}}=1\rangle \rightarrow \Upsilon(1S)\,\eta \\
&+ \frac{\sqrt{5}}{2\sqrt{3}} \quad |S_{b\bar{b}}=1, J_{q\bar{q}}=2\rangle \rightarrow \Upsilon(1S)\,\pi^+\pi^- \text{ in D wave} \\
&+ \frac{1}{2} \quad |S_{b\bar{b}}=0, J_{q\bar{q}}=1\rangle \rightarrow h_b(1P)\,\eta
\end{aligned}
$$

Rescattering ⇒ many transitions are allowed

Transition	Partial width (keV)
$\Upsilon(4S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	1.7 ± 0.2
$\Upsilon(1S)\,\eta$	4.0 ± 0.8
$\Upsilon(2S)\,\pi^+\pi^-$	1.8 ± 0.3
$h_b(1P)\,\eta$	45 ± 7
$\Upsilon(5S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	238 ± 41
$\Upsilon(1S)\,\eta$	39 ± 11
$\Upsilon(1S)\,K^+K^-$	33 ± 11
$\Upsilon(2S)\,\pi^+\pi^-$	428 ± 83
$\Upsilon(2S)\,\eta$	204 ± 44
$\Upsilon(3S)\,\pi^+\pi^-$	153 ± 31
$\chi_{b1}(1P)\,\omega$	84 ± 20
$\chi_{b1}(1P)\,(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$	28 ± 11
$\chi_{b2}(1P)\,\omega$	32 ± 15
$\chi_{b2}(1P)\,(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$	33 ± 20
$\Upsilon_J(1D)\,\pi^+\pi^-$	~ 60
$\Upsilon_J(1D)\,\eta$	150 ± 48
$Z_b(10610)^\pm\pi^\mp$	2070 ± 440
$Z_b(10650)^\pm\pi^\mp$	1200 ± 300
$\Upsilon(6S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	137 ± 32
$\Upsilon(2S)\,\pi^+\pi^-$	183 ± 43
$\Upsilon(3S)\,\pi^+\pi^-$	77 ± 28
$Z_b(10610, 10650)^\pm\pi^\mp$	$1300 - 6600$

Bondar, RM, Voloshin MPLA 32, 1750025 (2017)

So variety of transitions support the interpretation as molecular admixture

How to perform Bottomonium analysis?

- Measurement at a single energy can:

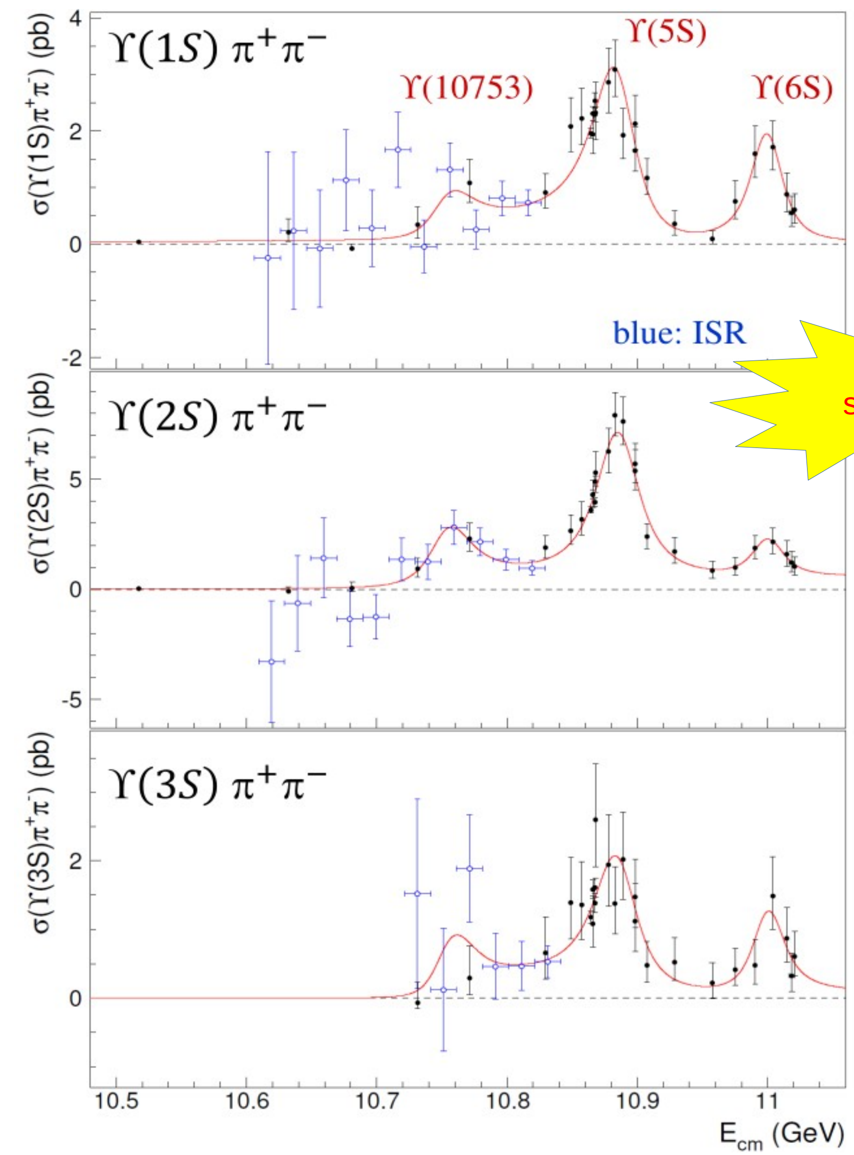
  - show non-resonant contribution

  - reveal other resonances

- Energy scan is needed!

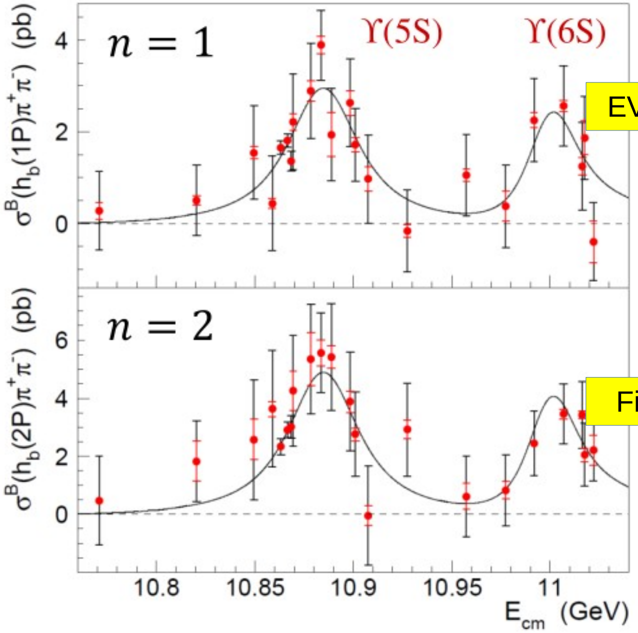
Bottomonium at Belle

PRL 117 (2016) 142001
JHEP 10 (2019) 220



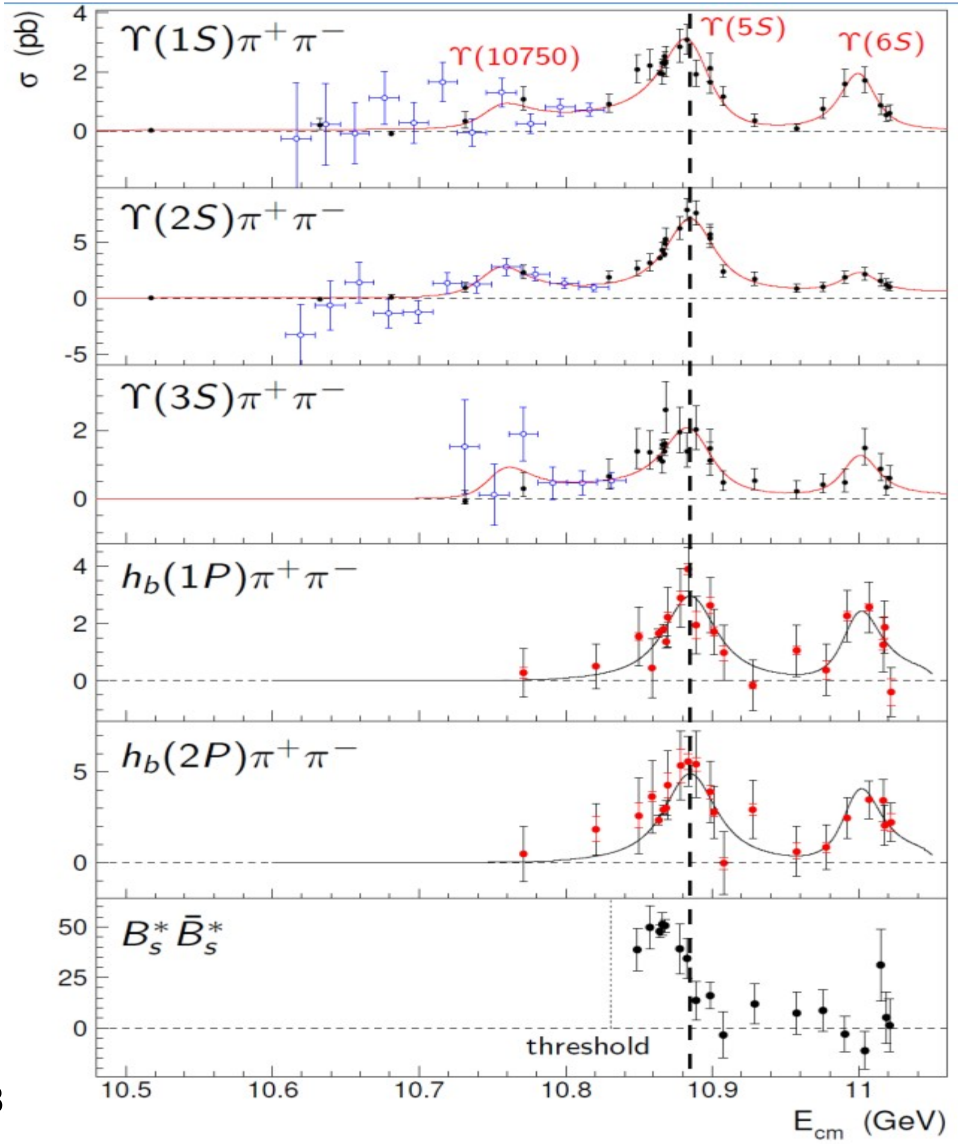
New structure

$Z_b^+\pi^- \to h_b(nP)\,\pi^+\pi^-$



EVIDENCE

FiIRST OBS.



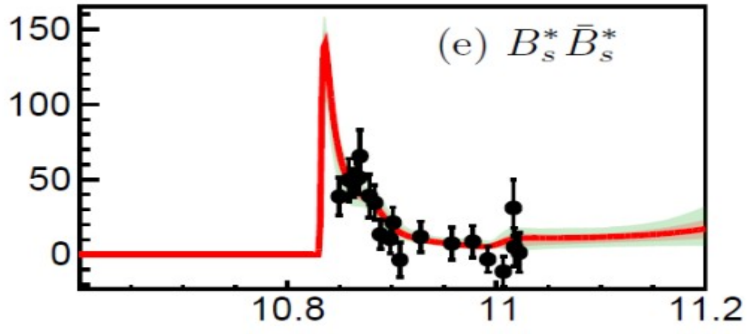
PRL 117 (2016) 142001
JHEP 10 (2019) 220

$\Upsilon(5S)$ peak in $B_s^* \bar{B}_s^*$ channel is shifted by 20 MeV w.r.t. bottomonium channels.

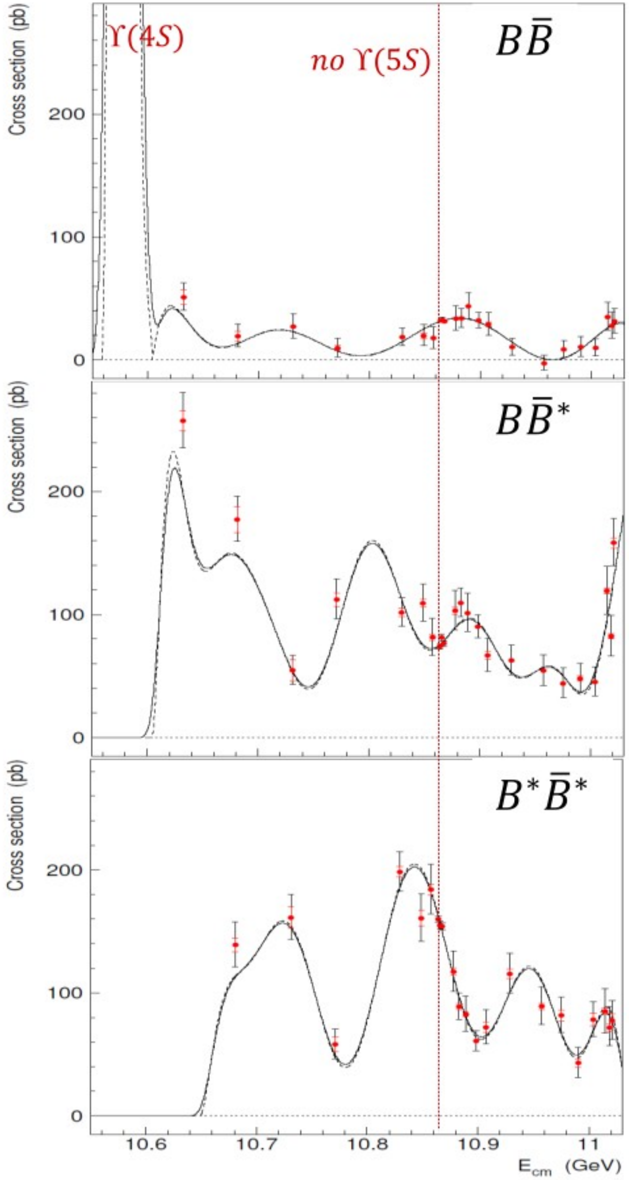
Two states near $\Upsilon(5S)$?

Hüsken, Mitchell, Swanson, PRD 106, 094013 (2022)

Coupled-channel analysis:

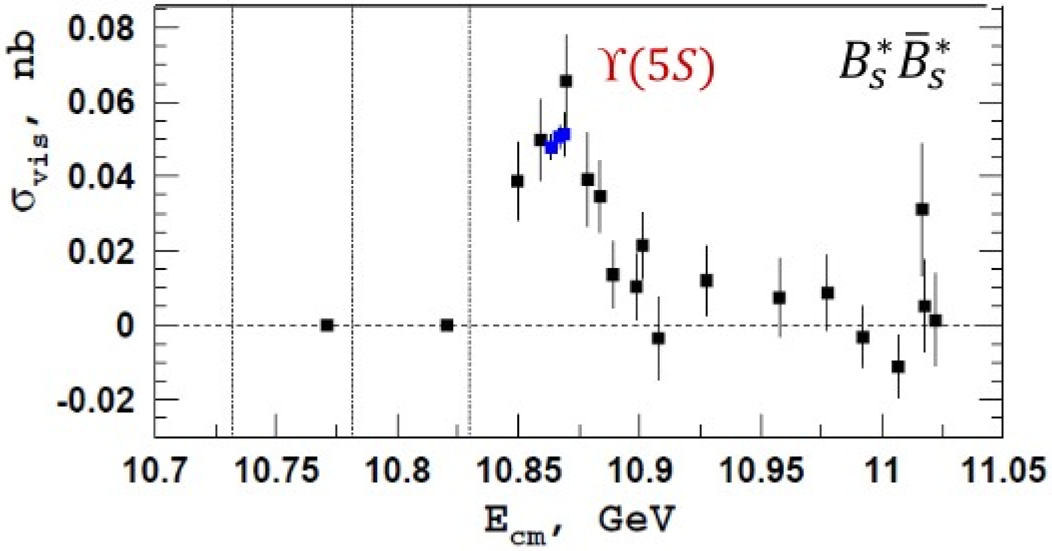


$\Rightarrow$ Improve accuracy in $B_s^* \bar{B}_s^*$



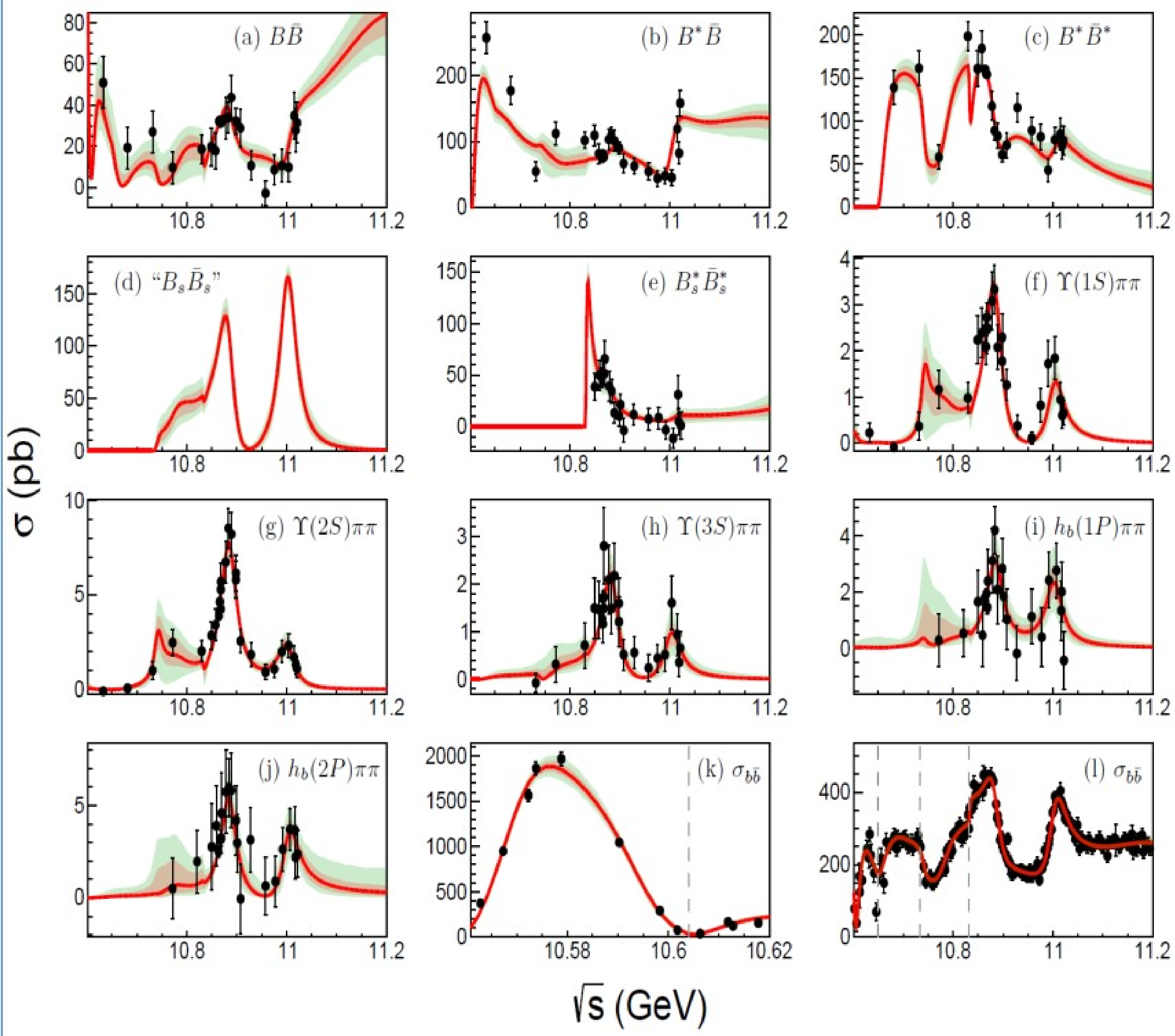
Bottomonium at Belle

JHEP 06 (2021) 137



No clear Υ(5S) peak:
''oscillatory'' non-resonant contribution?

A note about Coupled-channel analysis:

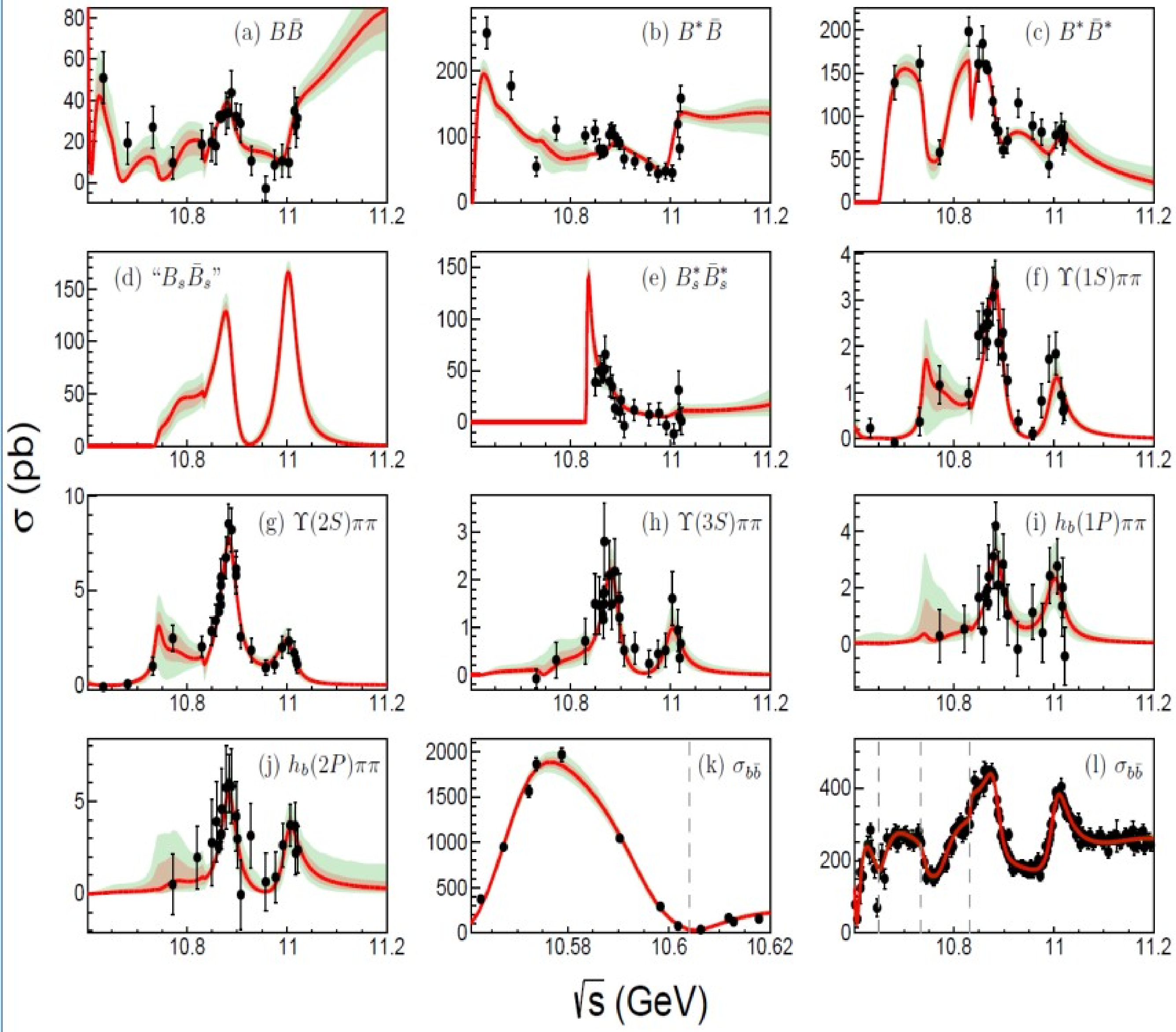


Husken, Mitchell, Swanson, PRD 106 (2022) 094013

- Assume ϒ(10753) is a 4S-3D mixture

- All available scan data
- Global and unitary analysis of $e^+e^- \to b\bar{b}$ cross section
- Pole positions are determined for ϒ(4S), ϒ(10753), ϒ(5S), and ϒ(6S)
- Strong evidence for the new ϒ(10753)

Accuracy above ϒ(6S) and near ϒ(10753) needs improvement.



Husken, Mitchell, Swanson, PRD 106 (2022) 094013

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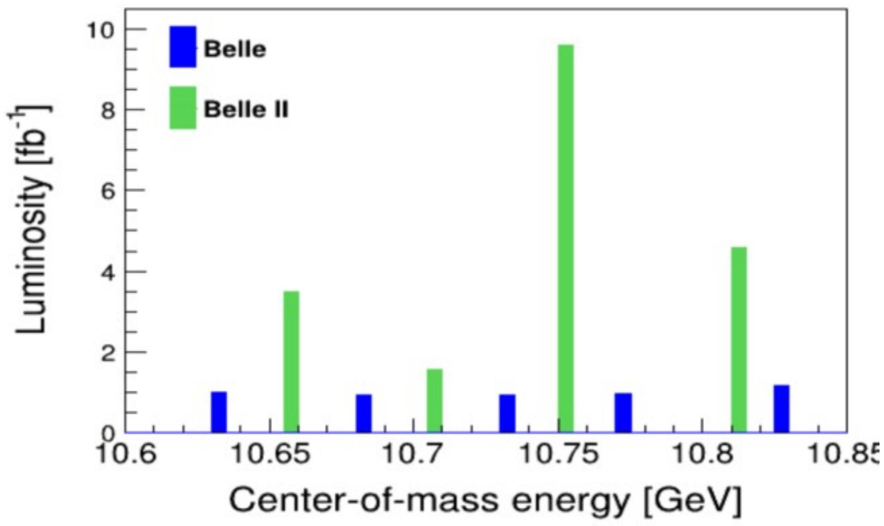
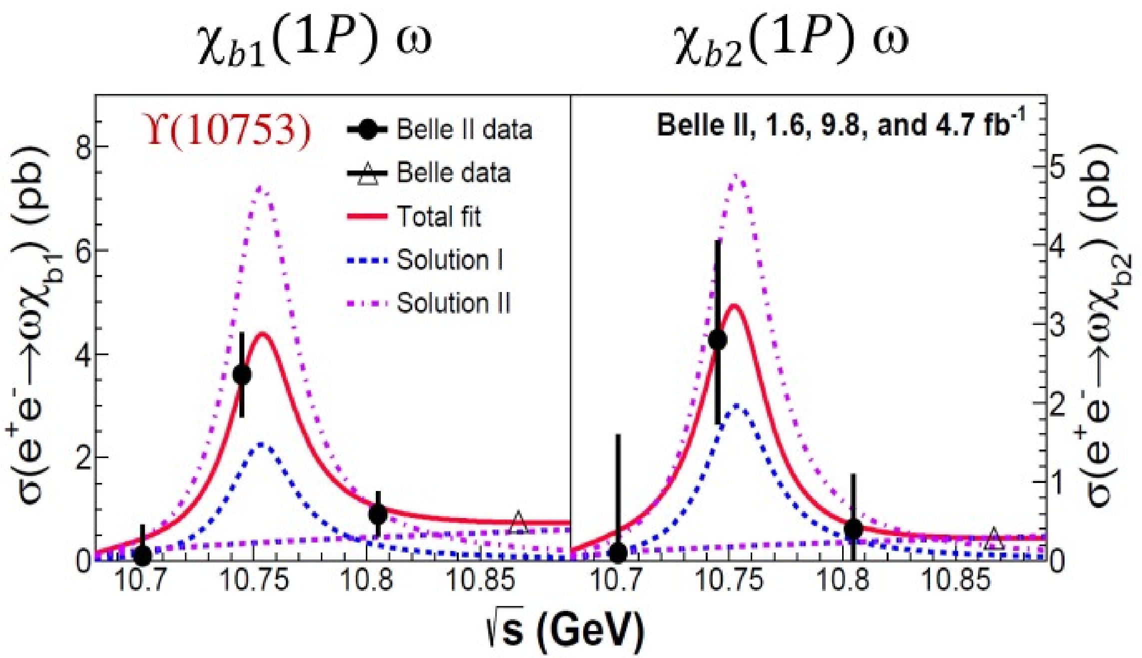
Plan in Belle II to run @ ϒ(6S)

Belle II energy scan

PRL 130 (2023) 091902

- Luminosity: 20 fb^{-1} (Nov 2021)
- Goal: study ϒ(10753) and $B^*\bar{B}^*$ threshold region
- Found: ϒ(10753) and ϒ(5S) have different pattern: different structure?





$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

PRELIMINARY

Full reconstruction: $\Upsilon(nS) \to \mu^+\mu^-$

$\Upsilon(10753)$ significance:

	Belle	Belle + Belle II
$\Upsilon(1S)\,\pi^+\pi^-$	2.7σ	4.1σ
$\Upsilon(2S)\,\pi^+\pi^-$	5.4σ	7.5σ

$\Upsilon(10753)$ parameters:

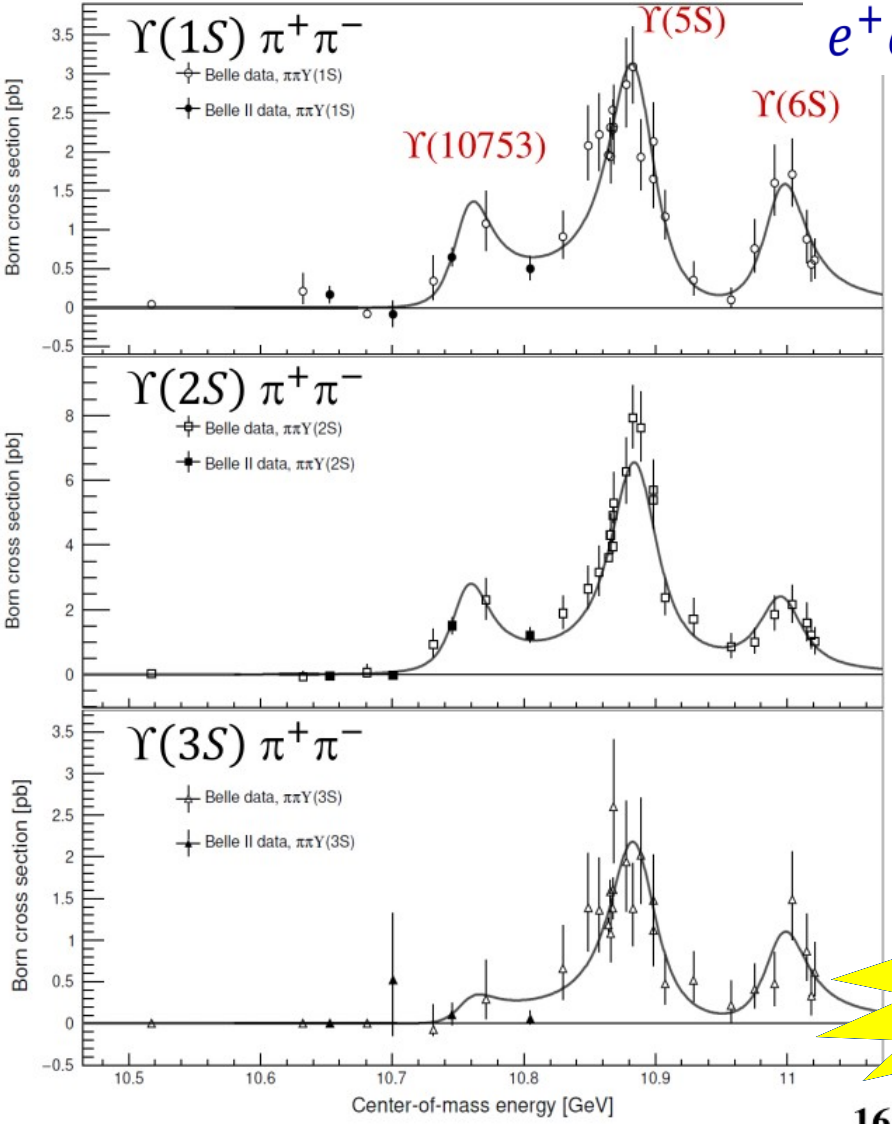
$$M = (10756.3 \pm 2.7 \pm 0.6)\ MeV$$

$$\Gamma = (29.7 \pm 8.5 \pm 1.1)\ MeV$$

c.f. Belle

$$M = (10752.7 \pm 5.9^{+0.7}_{-1.1})\ MeV$$

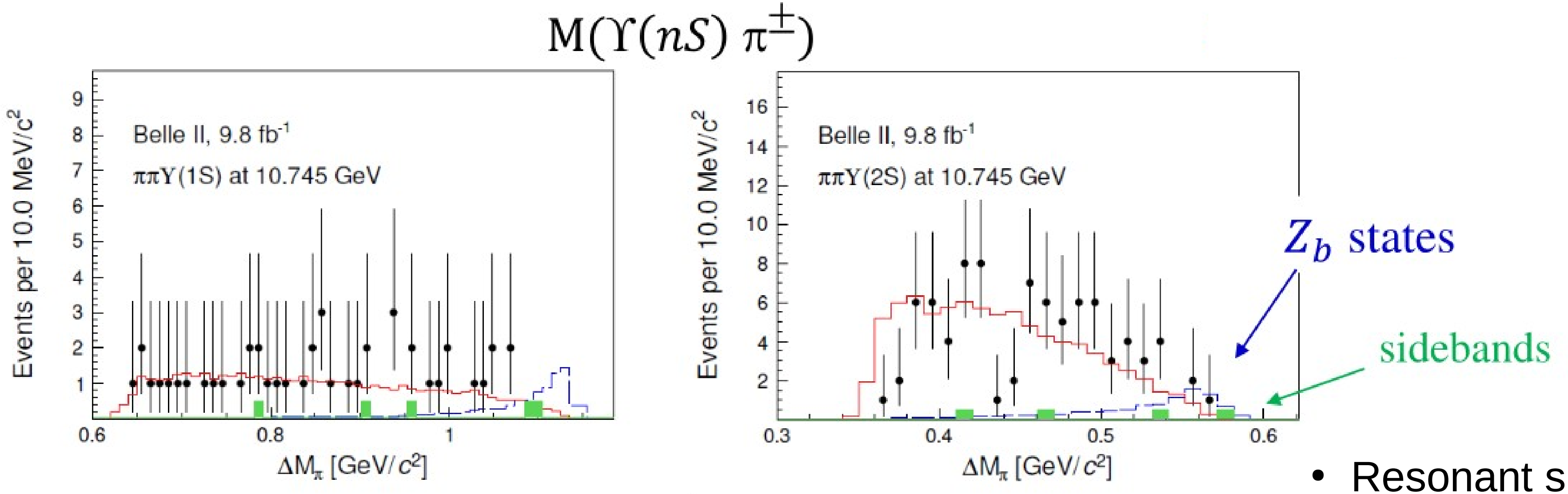
$$\Gamma = (35.5^{+17.6}_{-11.3}\ {}^{+3.9}_{-3.3})\ MeV$$



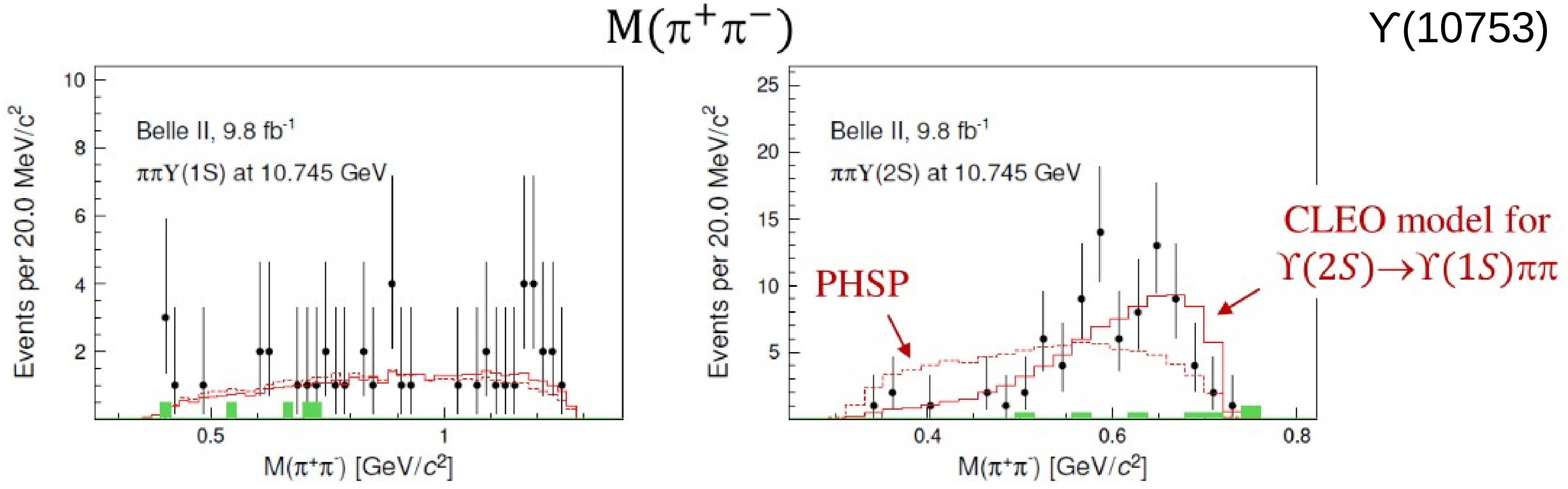
16

Very good agreement

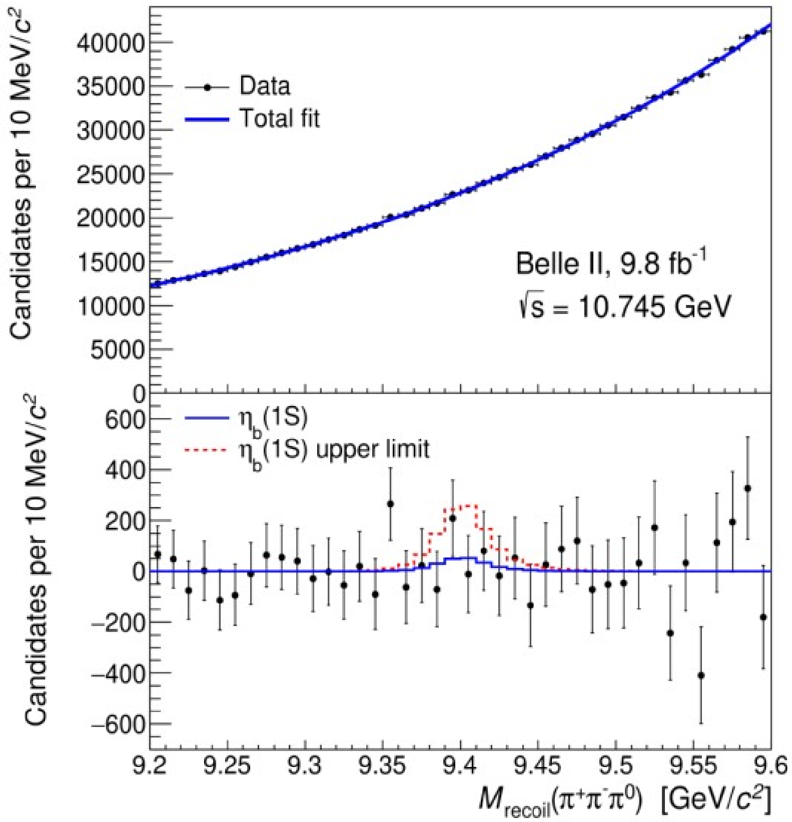
PRELIMINARY



- Resonant substructure of $\Upsilon(10753) \rightarrow \Upsilon(nS)\pi^+\pi^-$



Testing tetraquark model for the $\Upsilon(10753)$ at Belle II



PRELIMINARY

$\Upsilon(10753) \rightarrow \eta_b(1S)\omega \,/\, \chi_{b0}(1P)\omega$

- Predicted for the tetraquark model
- No signal found

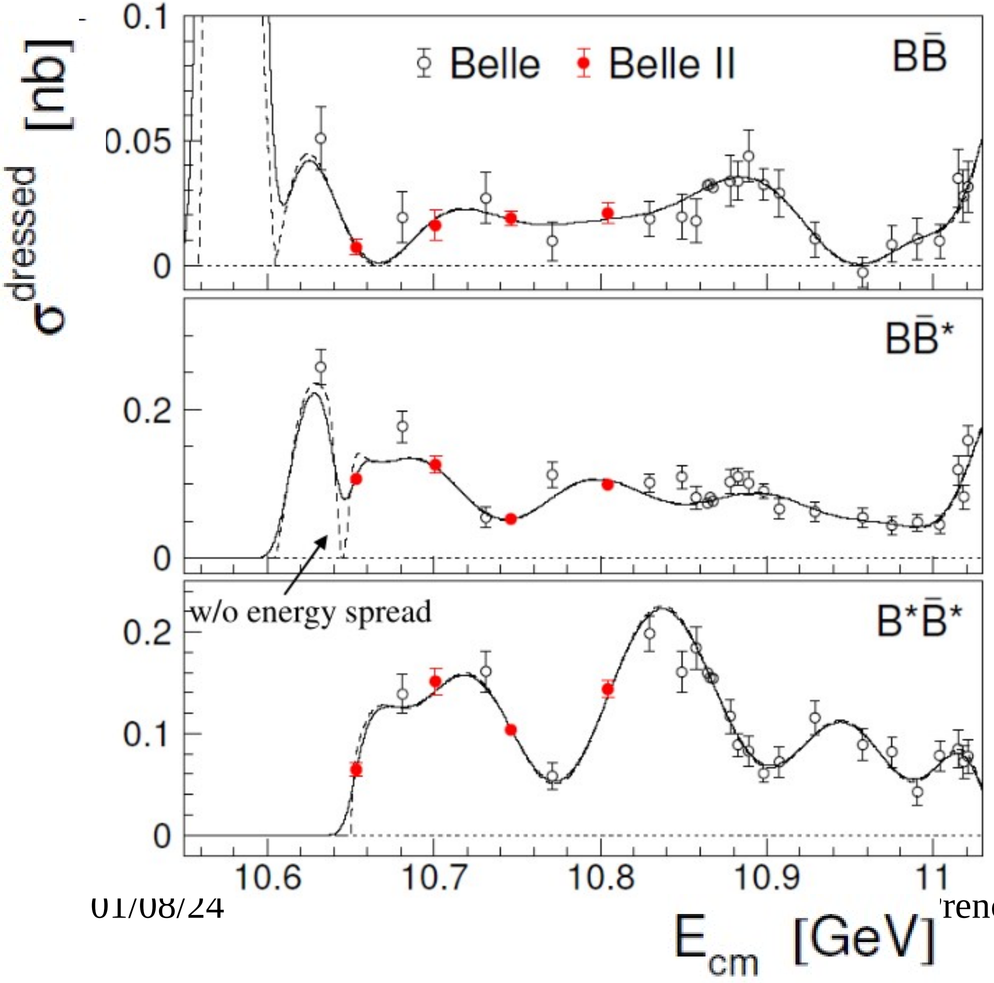
$$\sigma(e^+e^- \rightarrow \eta_b(1S)\ \omega) < 2.5\ pb \quad 90\%\ \mathrm{CL}$$

$$\text{c.f.} \quad \sigma(e^+e^- \rightarrow \Upsilon(1,2S)\pi^+\pi^-) = (1-3)\ pb$$

$$\sigma(e^+e^- \rightarrow \chi_{b0}(1P)\ \omega) < 7.8\ pb$$

$$\text{c.f.} \quad \sigma(\chi_{b1}(1P)\omega \,/\, \chi_{b2}(1P)\omega) = (3.6 \,/\, 2.8)\ pb$$

Study of $e^+e^- \to B\bar{B}, B\bar{B}^*, B^*\bar{B}^*$ at Belle II



- Reconstruct B meson in 1000 final states

PRELIMINARY

- Rapid rise of the $B^*\bar{B}^*$ cross section close to threshold: hint for molecular state?

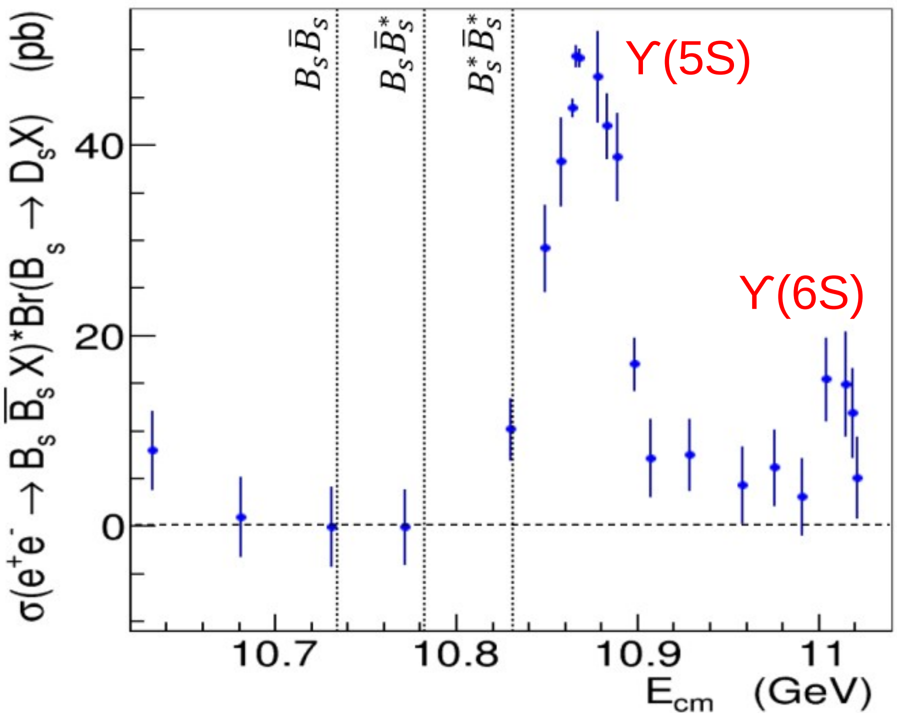
Study of $e^+e^- \rightarrow B_s\overline{B}_sX$ at Belle II

JHEP 08 (2023) 131

- Inclusive analysis

$$\frac{Br(B_s \rightarrow D^0 X)}{Br(B_s \rightarrow D_s X)} = 0.415 \pm 0.094$$

- Clear ϒ(5S) peak, seen also ϒ(6S)



$\sigma(B_s\bar{B}_sX) = \sigma(B_s^{(*)}\bar{B}_s^{(*)})$ – up to the $B_s\bar{B}_s\pi^0\pi^0$ threshold at 11.004 GeV

Summary

- Belle shut down: 2010. After 14 years still great physics results show up with Belle data sets!
- Most of the interesting results use the whole Belle luminosity: update with Belle II is planned
- A remarkable fraction of data taking @Belle II will be above/below $\Upsilon(4S)$ c.m. energy
- Great potential in the continuum and ISR physics
- Amplitude analysis to search for $c\bar{c}s\bar{s}$ resonances and more
- Bottomonium physics: unique at Belle and Belle II
- Belle II is in excellent shape: already collected ~BaBar luminosity (424 fb^{-1} in 2022)
- Analysis plan: combining Belle + Belle II data sets (~1.5 ab^{-1})
- Data taking at Belle II: 50 ab^{-1} by 2035
- Pentaquark search: so far no results with Belle data set. More investigation is ongoing

STAY tuned!