Exotic Hadron Spectroscopy at BELLE & Belle II

Roberto Mussa
INFN TORINO

42nd Physics in Collisions

2023/05/17

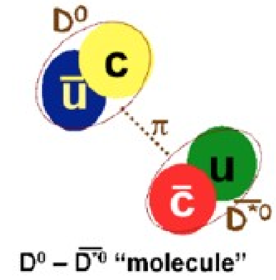
Outline

- High energy scans
- BB cross sections
- Omega chib, Xb
- Omega etab, Omega chib0
- Y pipi
- Double charmonium

What are the XYZ states?

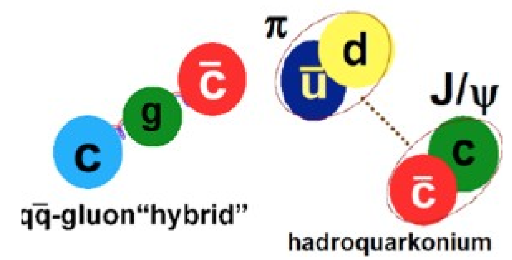
The plethora of new charmonium-like and bottomonium-like states found by B-factories and LHC experiments in the last 20 years has been stimulating very lively debates in the QCD theory community. A short compilation of the various models here:

Meson Molecules (Guo et al, Rev.Mod.Phys.90,015004 (2018))
weakly bound states of two mesons



Tetraquarks (Polosa et al, PRD89, 114010 (2014))
Diquark-antidiquark states bound by the color force

Hybrids (Barnes, PRD 52,5242 (1995)
Meyer and Swanson, Prog.Part.Nucl.Phys. 82, 21 (2015))
colored $Q\overline{Q}$ states with a bound excited gluon



Hadroquarkonium (Dubinskij et al, PLB 666, 344 (2008))
$Q\overline{Q}$ bound state surrounded by a cloud of light quarks

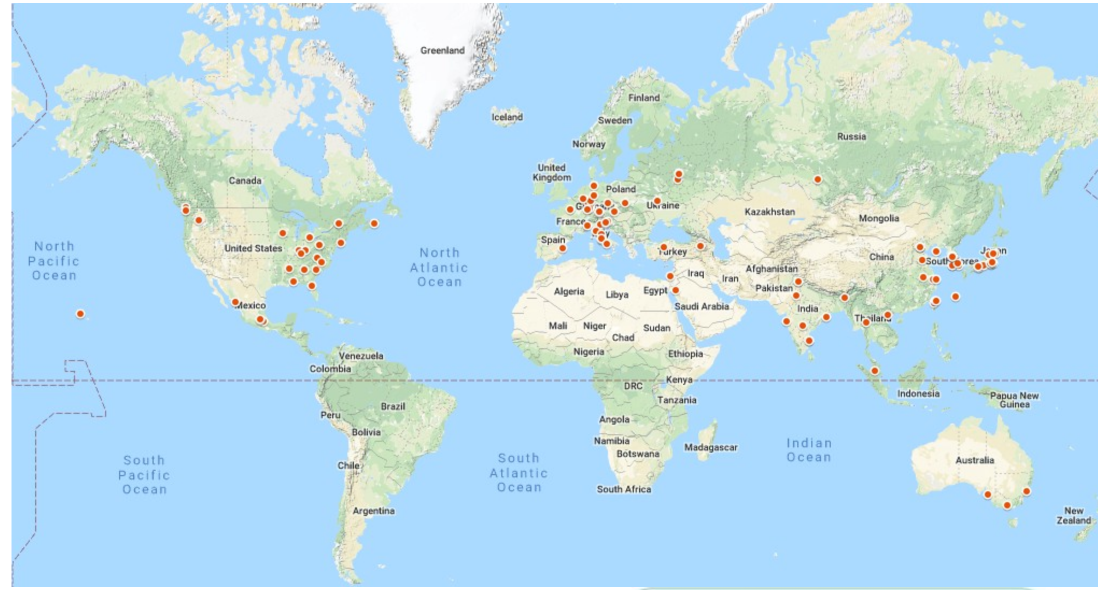
Standard quarkonia (Swanson, PRD 91, 034009 (2015))

Full comprehensive reviews in:
- Brambilla *et al*, Eur.Phys J C(2011)1534
- Olsen *et al*, Rev.Mod.Phys. 90 (2018) 015003

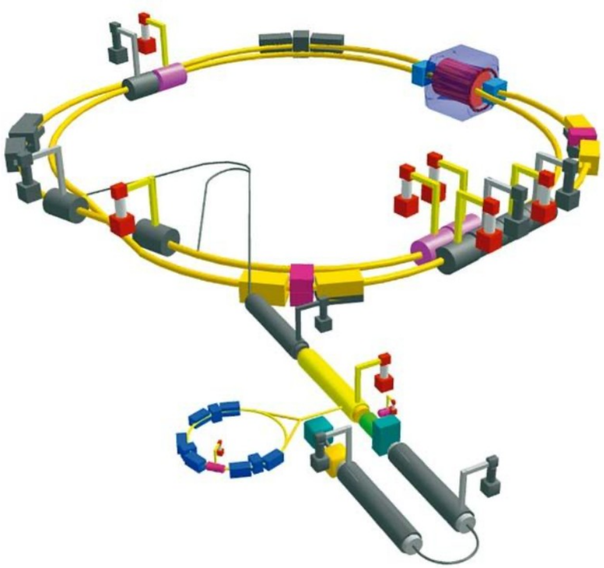
See also: qwg.ph.tum.de

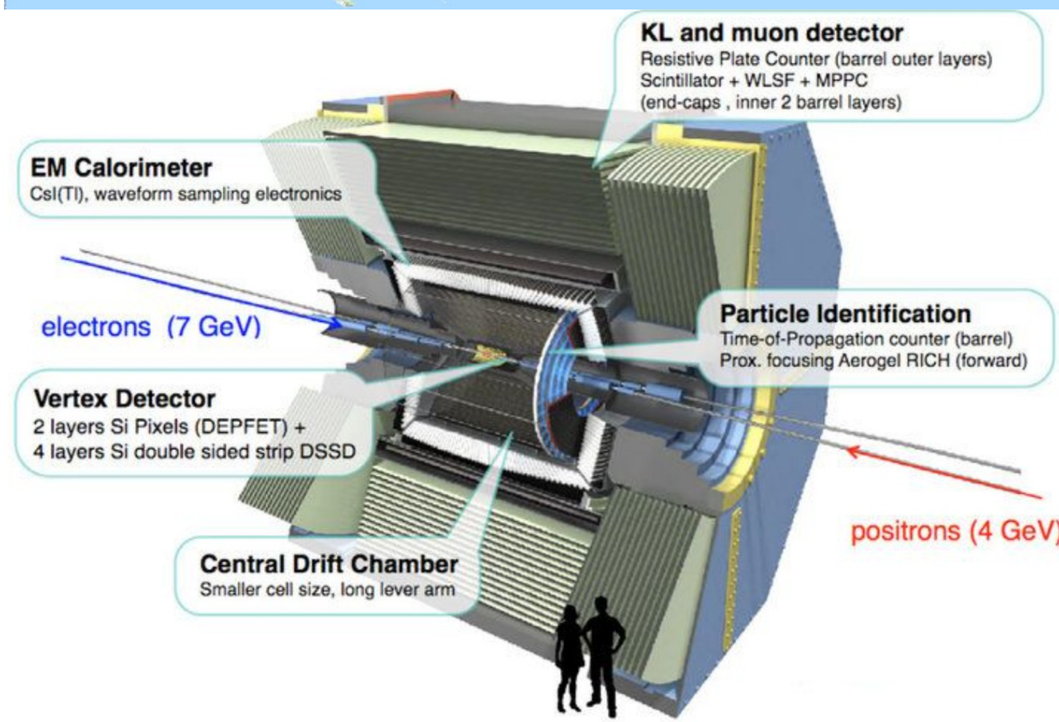
Super-B factory at KEK

1168 active members
123 institutes
27 countries
(as of September 2023)



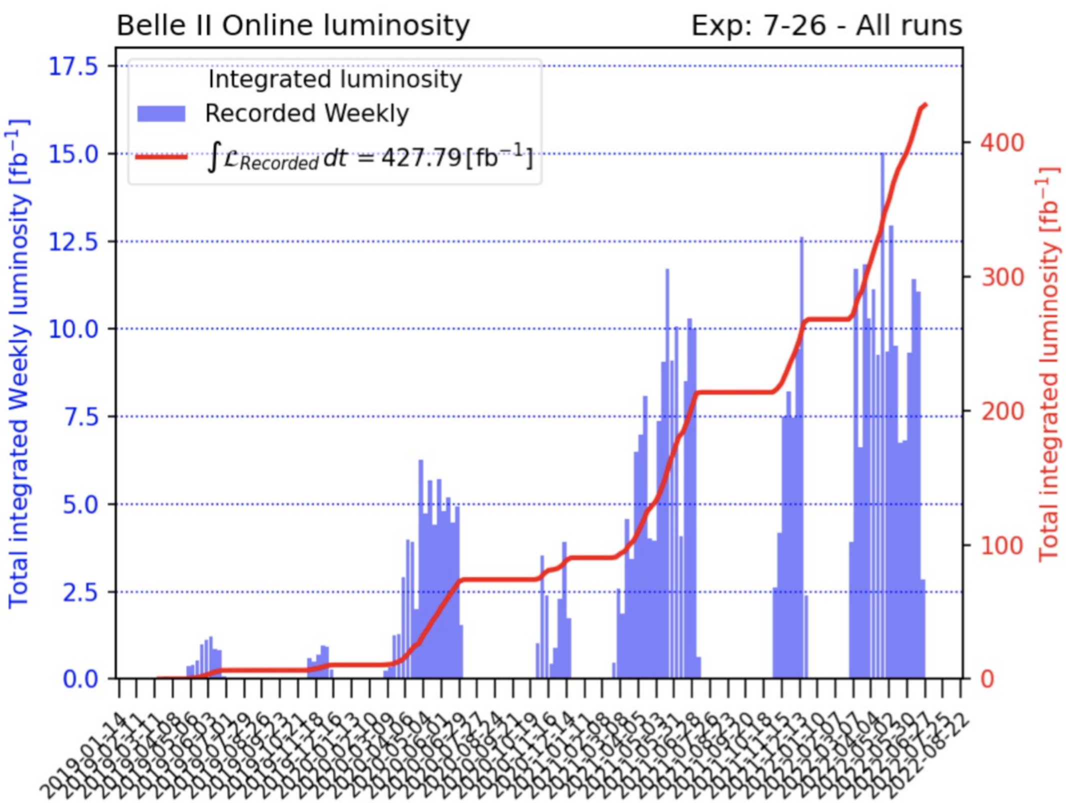
Asymmetric **e$^+$e$^-$ collider**
⇒ **J^{PC}=1^{--}** states directly produced

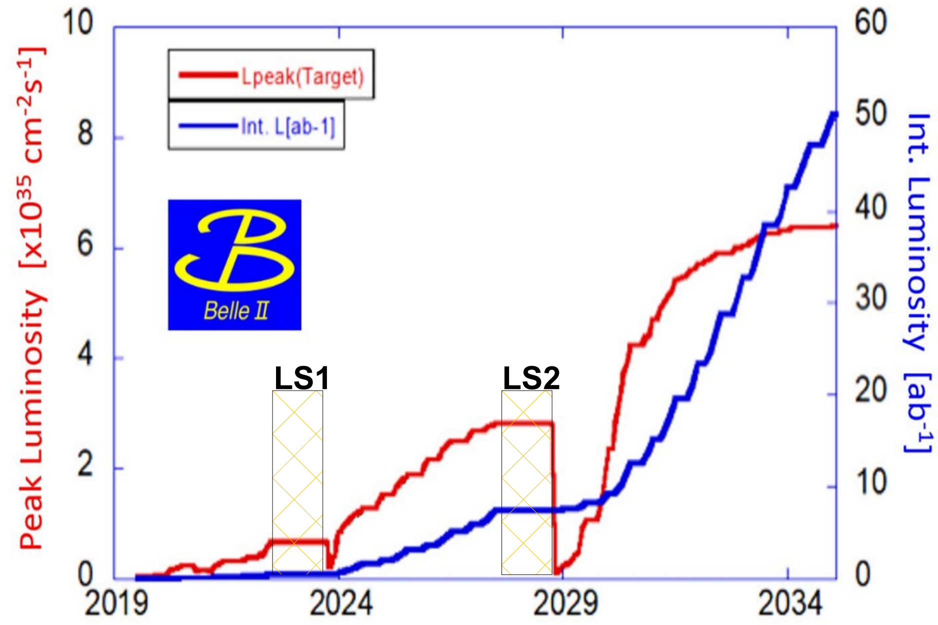




$\sqrt{s} \sim 9 - 11\ GeV$ ⇒ $b\bar{b}$ energy region

Belle-II Luminosity





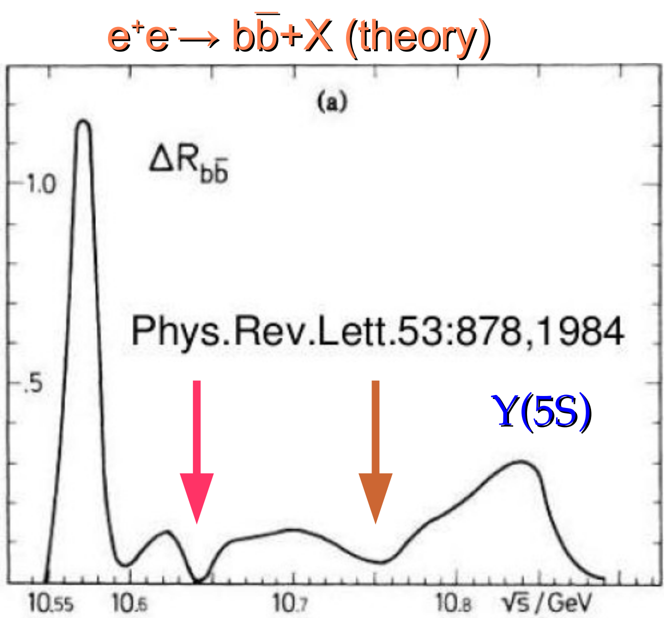
Record instantaneous Luminosity: 4.7x10^{34} cm^{-2} s^{-1}
Integrated Luminosity: 424 fb^{-1}
(362 at 4S peak , 42.4 at E=10.52 GeV, 19.3 in the 4-pt scan)

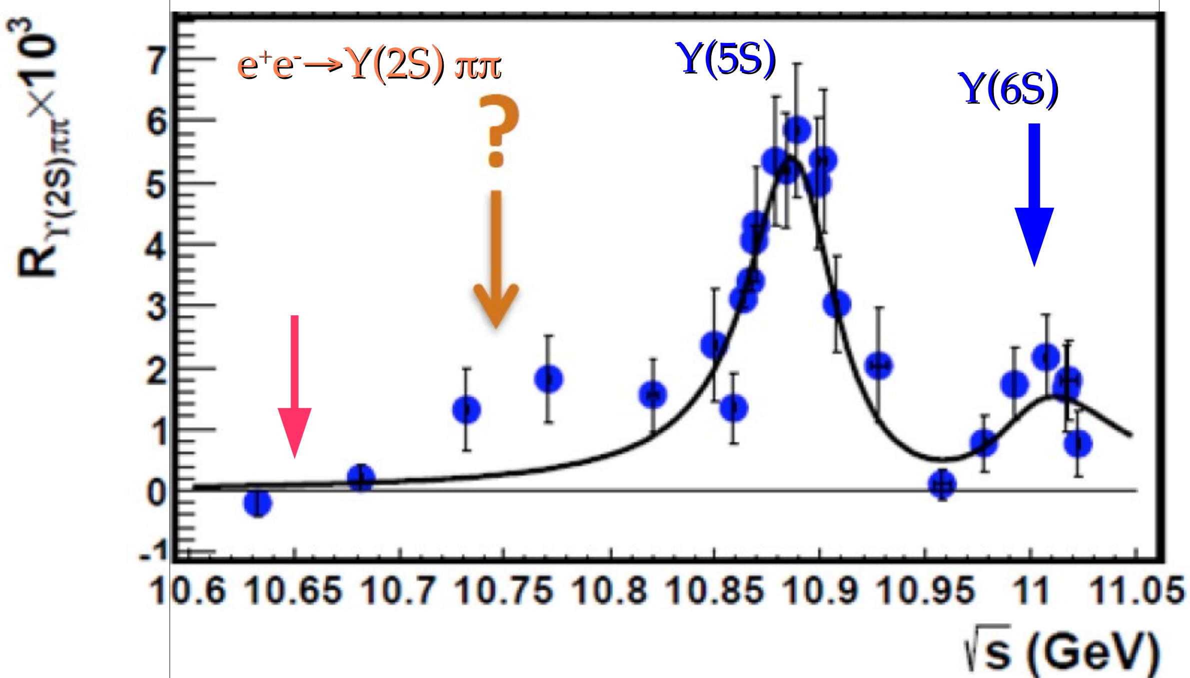
High energy scans

Belle data samples:
- 121.4 fb^{-1} on Υ(5S) peak, √s = 10865 GeV
- 61 points, 50 pb^{-1}, √s = 10.75-11.05 GeV
- 16 points, 1 fb^{-1} , √s = 10.63-11.02 GeV
- continuum data at √s = 10520 GeV

$R_b = \sigma(b\bar{b}+X)/\sigma(\mu\mu)$
Peaks at 10.86, 11 GeV
Dips at 10.65, 10.75 GeV (Tornqvist 84)

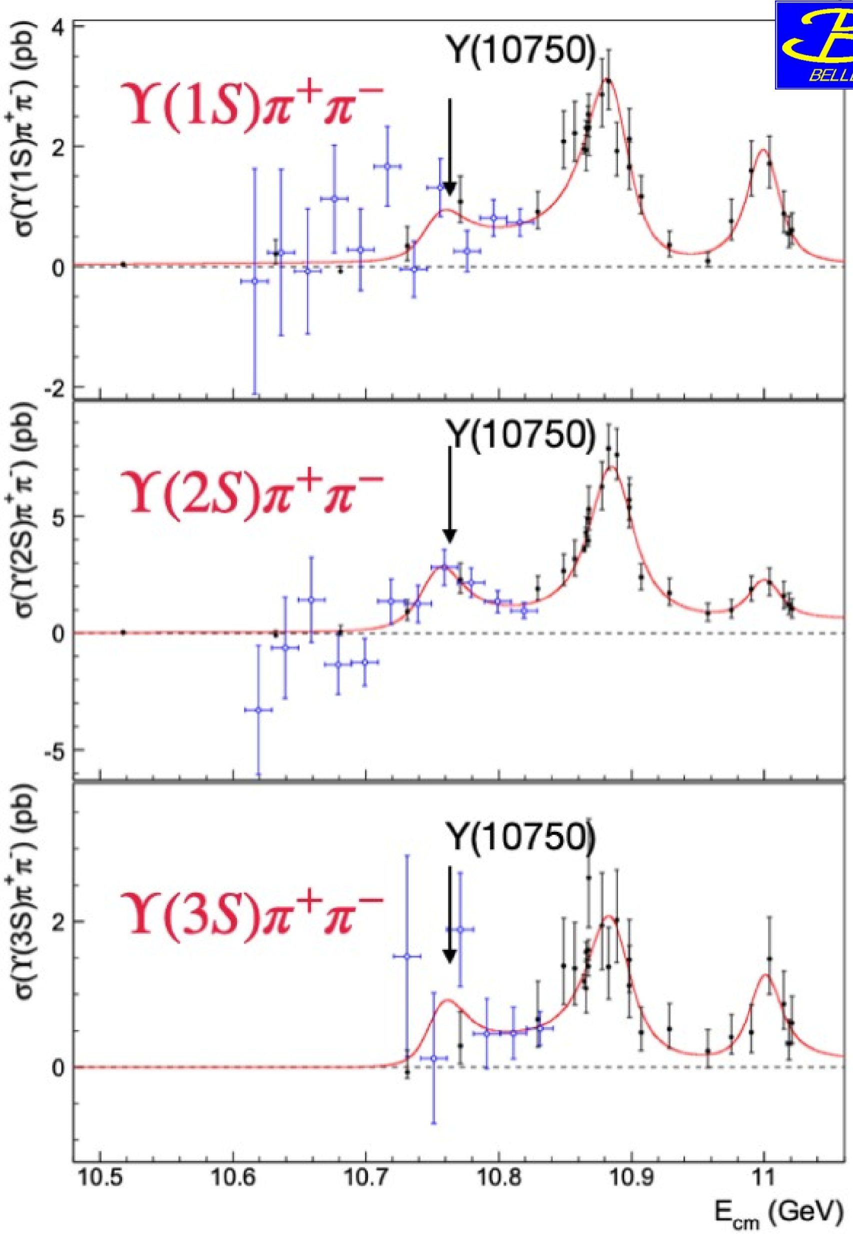
$R_{\Upsilon\pi\pi} = \sigma(\Upsilon\pi\pi)/\sigma(\mu\mu)$
Peaks at 10.89, 11; **bump at 10.75?**





Discovery of Y(10753)

BELLE:JHEP 10 (2019) 220

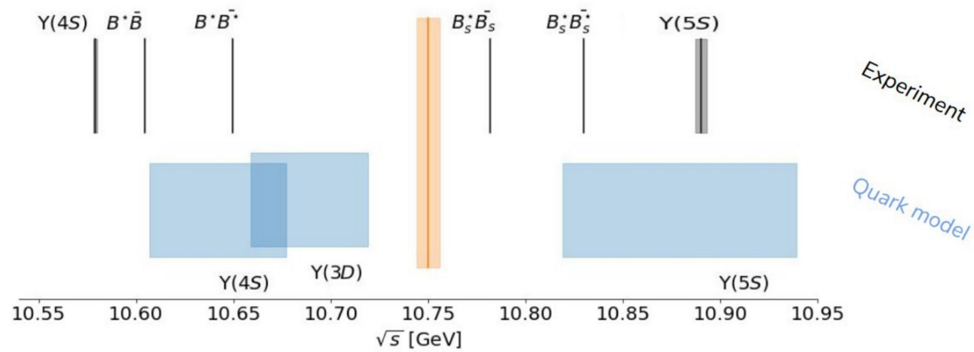


	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0\,+1.0}_{-4.5\,-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5\,+0.5}_{-3.9\,-1.1}$	$23.8^{+8.0\,+0.7}_{-6.8\,-1.8}$	$35.5^{+17.6\,+3.9}_{-11.3\,-3.3}$

A wide variety of interpretations:

Conventional D- or S-D mixed state

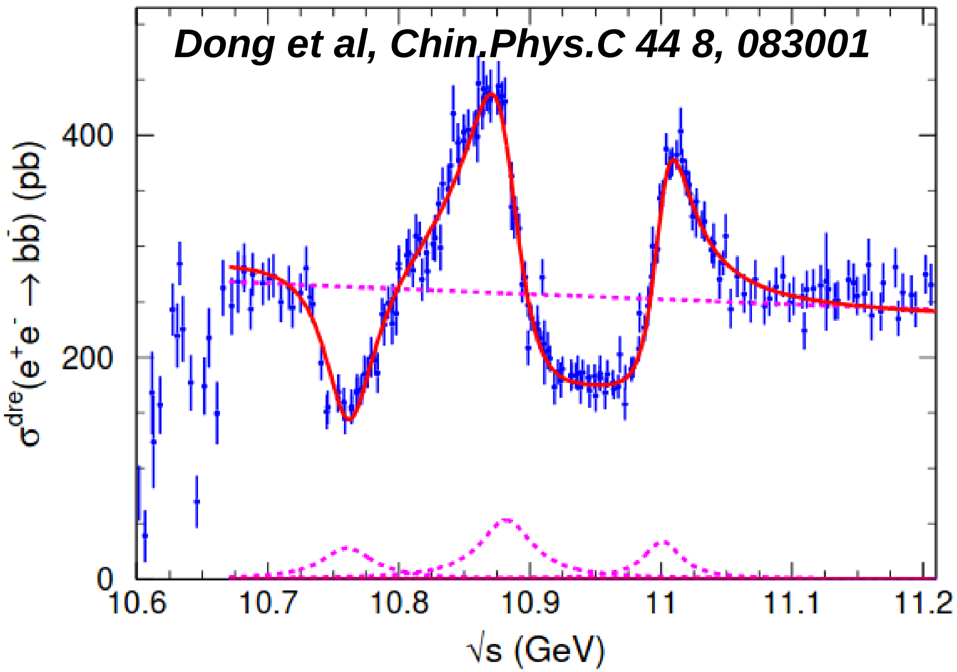
Chen et al., PRD 101 (2020) 1, 014020
Liang et al., PLB 803 (2020) 135340
Li et al., EPJC 80 (2020) 1, 59



Exotic

Bicudo et al., ArXiV:2008.05605 (Dynamic resonance)
Wang, Chin.Phys.C 43 (2019) 12, 123102 (Tetraquark)
Ali et al., PLB 802 (2020) 135217 (Tetraquark)
Giron & Lebed, PRD 102 (2020) 1, 014036 (Y(5S) is 4q)

Evidence of Y(10753) refitting the scans

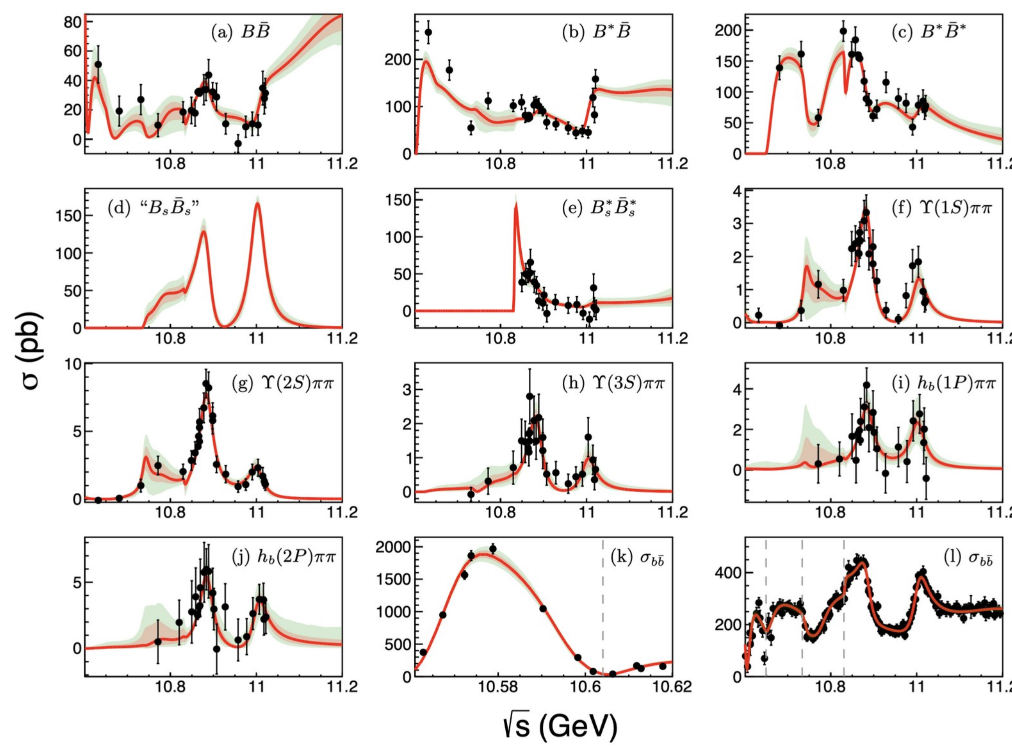


Refit of Babar and Belle data

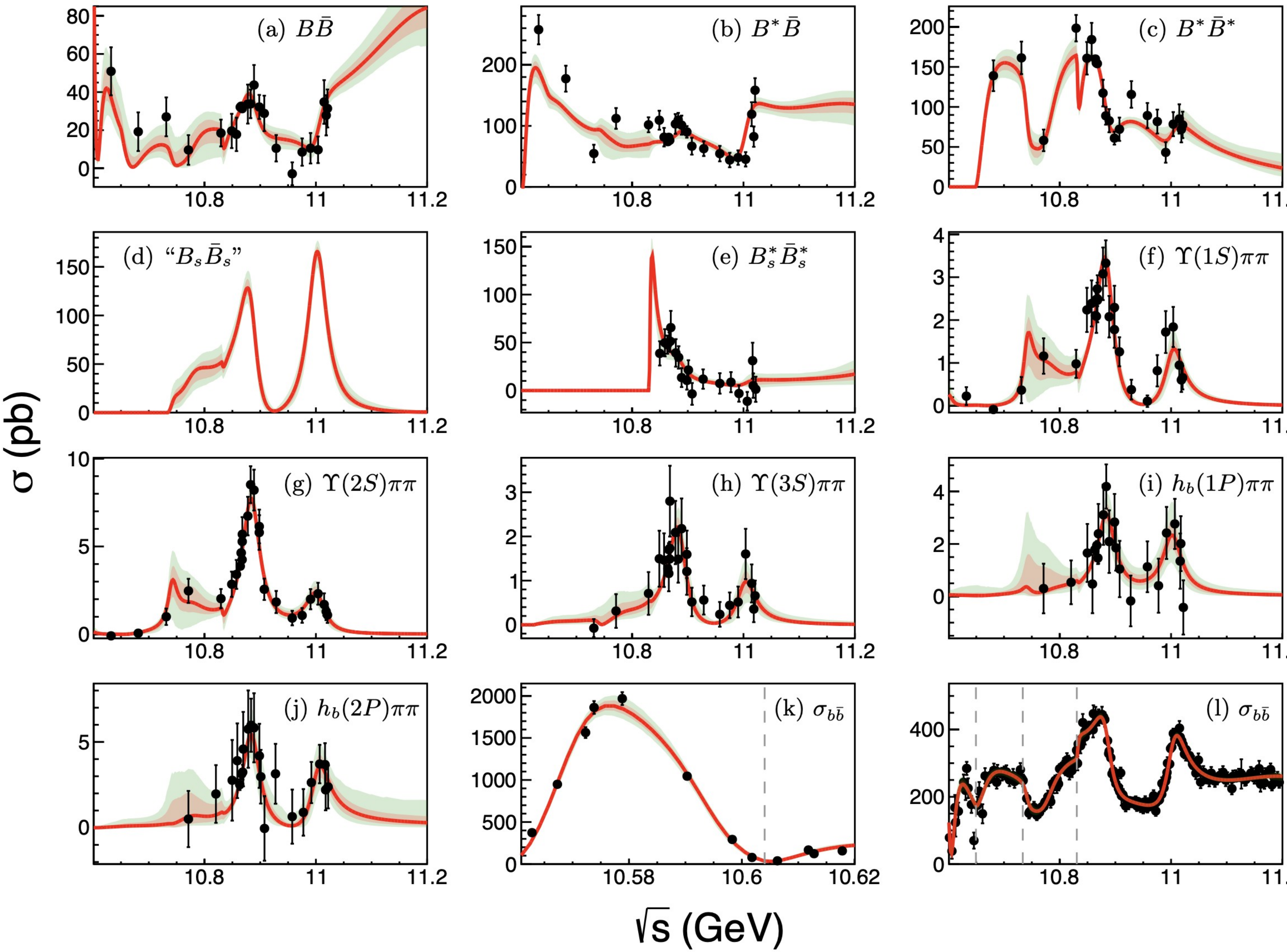
Dip at 10750 generated by destructive interference with the continuum

Parameter	$Y(10750)$	$\Upsilon(5S)$	$\Upsilon(6S)$
Mass/(MeV/c^2)	10761 ± 2	10882 ± 1	11001 ± 1
Width/MeV	48.5 ± 3.0	49.5 ± 1.5	35.1 ± 1.2

Coupled channel analysis of high energy scan data using the K-matrix formalism



Hüsken et al, PRD **106** (2022) 9, 094013



(a) $B\bar{B}$
(b) $B^*\bar{B}$
(c) $B^*\bar{B}^*$
(d) "$B_s\bar{B}_s$"
(e) $B_s^*\bar{B}_s^*$
(f) $\Upsilon(1S)\pi\pi$
(g) $\Upsilon(2S)\pi\pi$
(h) $\Upsilon(3S)\pi\pi$
(i) $h_b(1P)\pi\pi$
(j) $h_b(2P)\pi\pi$
(k) $\sigma_{b\bar{b}}$
(l) $\sigma_{b\bar{b}}$
σ (pb)
√s (GeV)

First full BB+BB*+B*B* separation of high energy scan data

JHEP 06 (2021)137

Full Event Interpretation : B meson reconstruction improved using Belle-II new algorithms on Belle high energy data.

B and D decay modes:

$B^+ \to$	$B^0 \to$
$\bar{D}^0\pi^+$	$D^-\pi^+$
$\bar{D}^0\pi^+\pi^+\pi^-$	$D^-\pi^+\pi^+\pi^-$
$\bar{D}^{*0}\pi^+$	$D^{*-}\pi^+$
$\bar{D}^{*0}\pi^+\pi^+\pi^-$	$D^{*-}\pi^+\pi^+\pi^-$
$D_s^+\bar{D}^0$	$D_s^+D^-$
$D_s^{*+}\bar{D}^0$	$D_s^{*+}D^-$
$D_s^+\bar{D}^{*0}$	$D_s^+D^{*-}$
$D_s^{*+}\bar{D}^{*0}$	$D_s^{*+}D^{*-}$
$J/\psi K^+$	$J/\psi K_S^0$
$J/\psi K_S^0\pi^+$	$J/\psi K^+\pi^-$
$J/\psi K^+\pi^+\pi^-$	
$D^-\pi^+\pi^+$	$D^{*-}K^+K^-\pi^+$
$D^{*-}\pi^+\pi^+$	

$D^0 \to$	$D^+ \to$	$D_s^+ \to$
$K^-\pi^+$	$K^-\pi^+\pi^+$	$K^+K^-\pi^+$
$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$	$K^+K_S^0$
$K^-\pi^+\pi^+\pi^-$	$K_S^0\pi^+$	$K^+K^-\pi^+\pi^0$
$K_S^0\pi^+\pi^-$	$K_S^0\pi^+\pi^0$	$K^+K_S^0\pi^+\pi^-$
$K_S^0\pi^+\pi^-\pi^0$	$K_S^0\pi^+\pi^+\pi^-$	$K^-K_S^0\pi^+\pi^+$
K^+K^-	$K^+K^-\pi^+$	$K^+K^-\pi^+\pi^+\pi^-$
$K^+K^-K_S^0$		$K^+\pi^+\pi^-$
		$\pi^+\pi^+\pi^-$

Key variables for analysis are

$$M_{bc} \equiv \sqrt{(E_{beam,CM})^2 - (p_{B,CM})^2}$$

and

$$\Delta E' \equiv \Delta E - M_{bc} + M_B$$

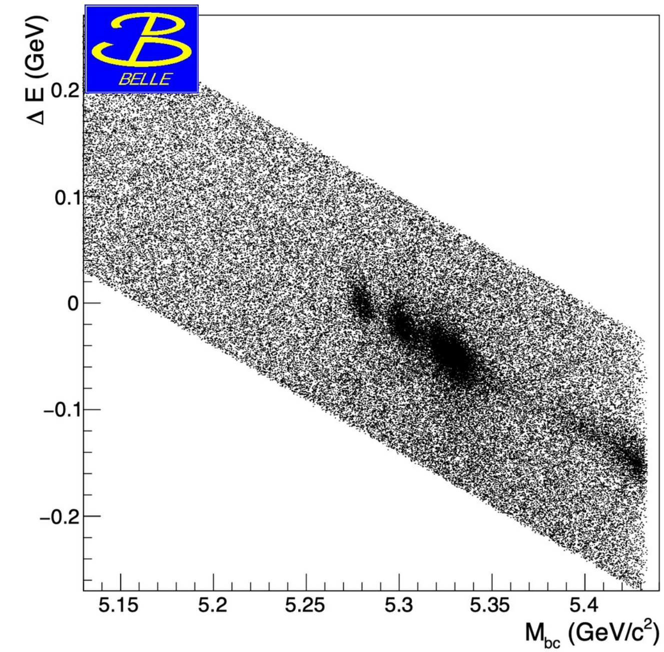
where

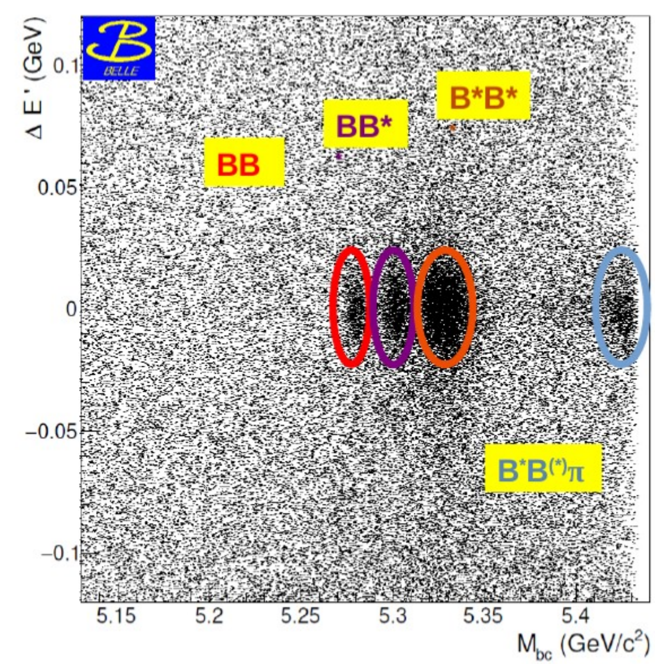
$$\Delta E \equiv E_{B,CM} - E_{beam,CM}$$

This has improved resolution and allows all decays to be selected with a common cut on energy difference.

$\varepsilon = (0.589 \pm 0.012)\times 10^{-3}$

(25.5% higher than in Belle)

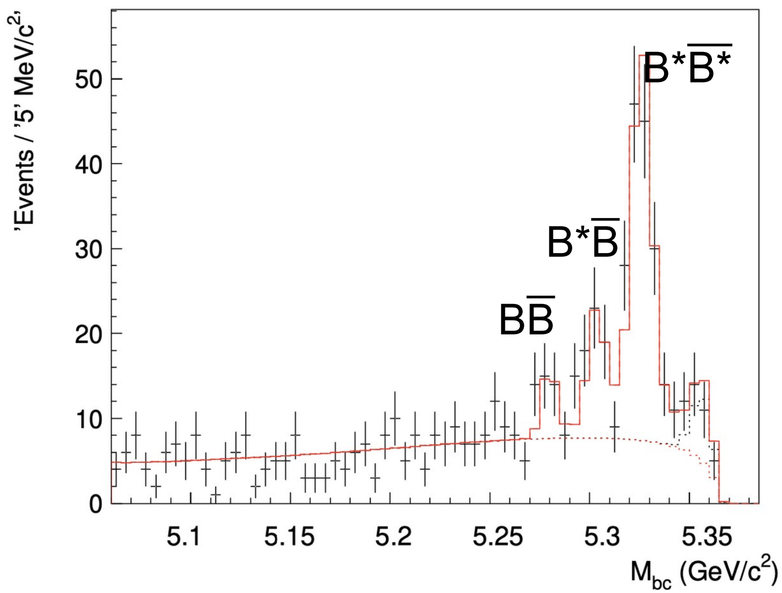


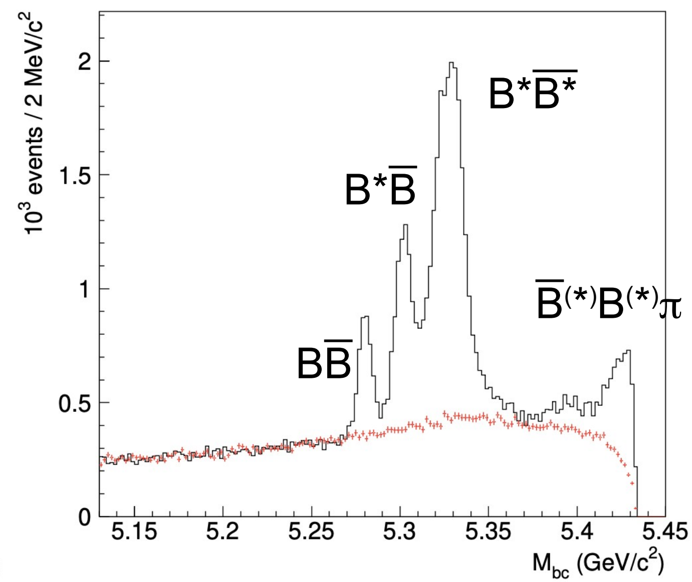


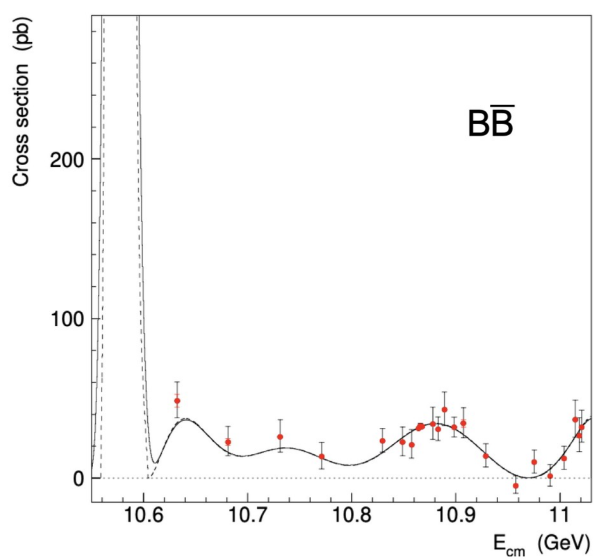
First full BB+BB*+B*B* separation of high energy scan data

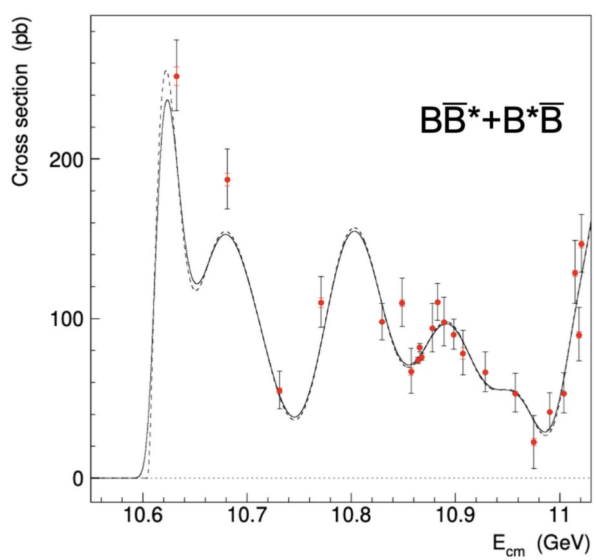
JHEP 06 (2021)137

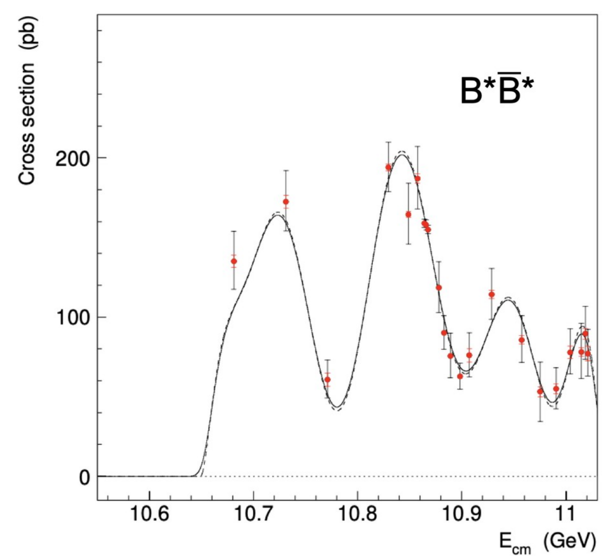
Two body cross sections extracted from the fits of the three peaks at each energy points (right) and fitted with Chebyshev polynomials (below).





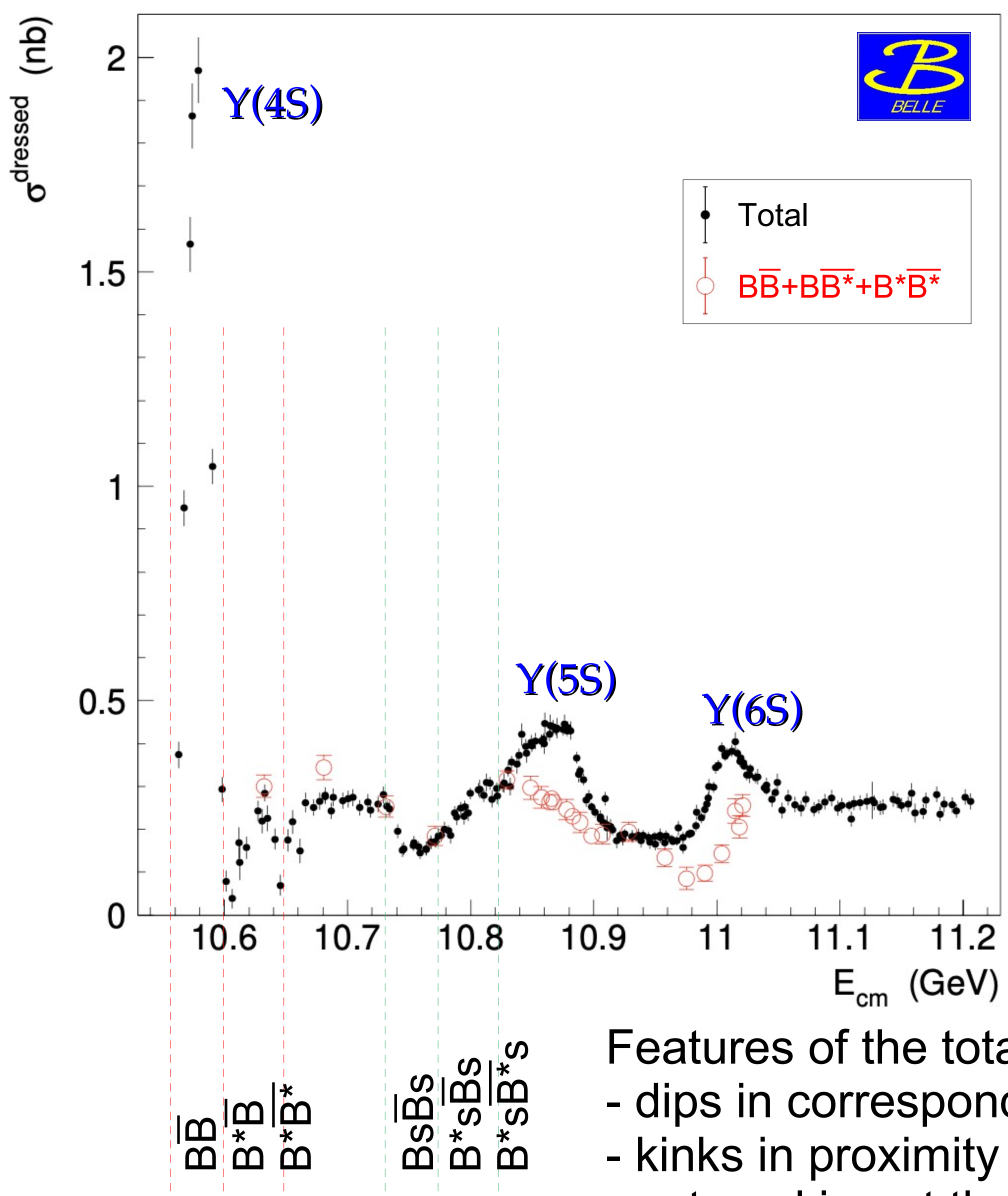


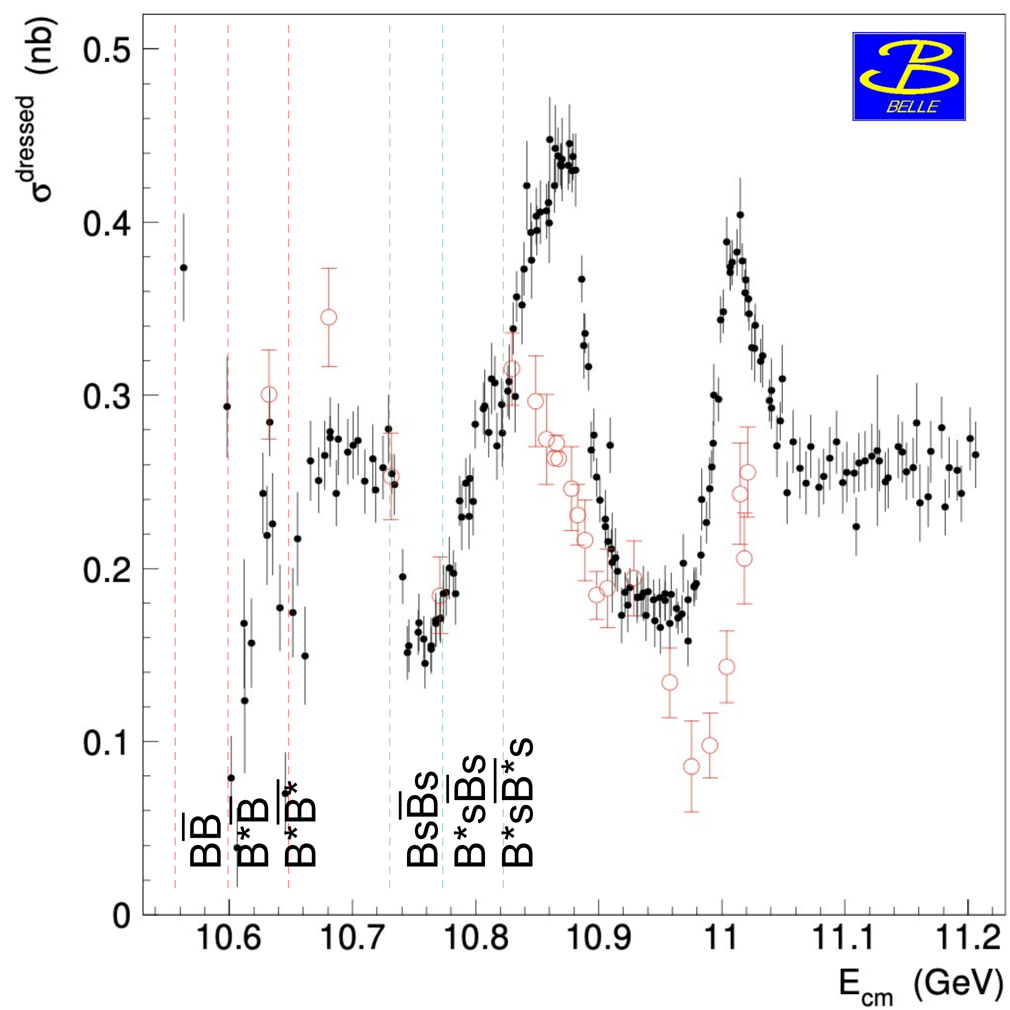




First full BB+BB*+B*B* separation of high energy scan data

JHEP 06 (2021)137



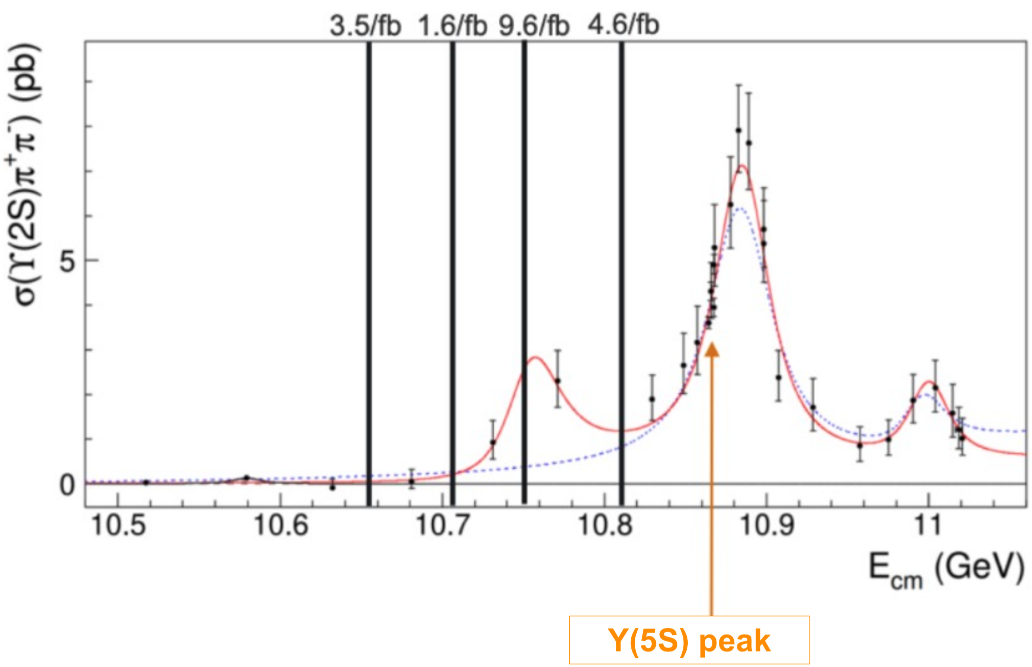


Features of the total cross section:
- dips in correspondance of BB* and B*B* thresholds
- kinks in proximity of BsBs and Bs*Bs* thresholds
- not peaking at the Y(5S) peak energy

Belle-II restarts from Υ(10750)

Data taking outside the Υ(4S) peak was very fruitful at Belle, with unique record data samples at Υ(1,2,5S) peak energies, and the high energy scans just shown, which raised new questions about the possible existence of new vector bottomonium-like states.

Therefore, the first motivation for data taking not at Υ(4S) peak was to investigate the nature of the Υ(10753): 4 points, 19.3/fb total.



Mode	Status @ Belle
BBar decomposition	***JHEP 06 (2021) 137***
$e^+e^- \to \pi\pi\Upsilon(nS)$	***JHEP 10 (2019) 220***
Di-pion Dalitz	Need more data
$\Upsilon(10750) \to \omega\, \eta_b(1S)$	***PRD 102 (2020) 9, 092011(*)***
$\Upsilon(10750) \to \pi\pi\, h_b(nP)$	Need more data
$\Upsilon(10750) \to \eta\, h_b(1P)$	Need more data
$\Upsilon(10750) \to \Upsilon(nS)$ inc.	Need more data
$\Upsilon(10750) \to \omega\, \chi_b(1P)$	In pub / Need more points
$\Upsilon(10750) \to \eta\Upsilon(nS)$	Need more data
$\Upsilon(10750) \to \eta'\Upsilon(nS)$	Need more data

(*) only limits from data at Υ(4S) and Υ(5S) peaks

Many analyses, suggested by recent theory papers are ongoing.

First results from this dataset in the next slides ….

Observation of $\Upsilon(10750) \rightarrow \chi_{bJ}(1P)\,\omega$

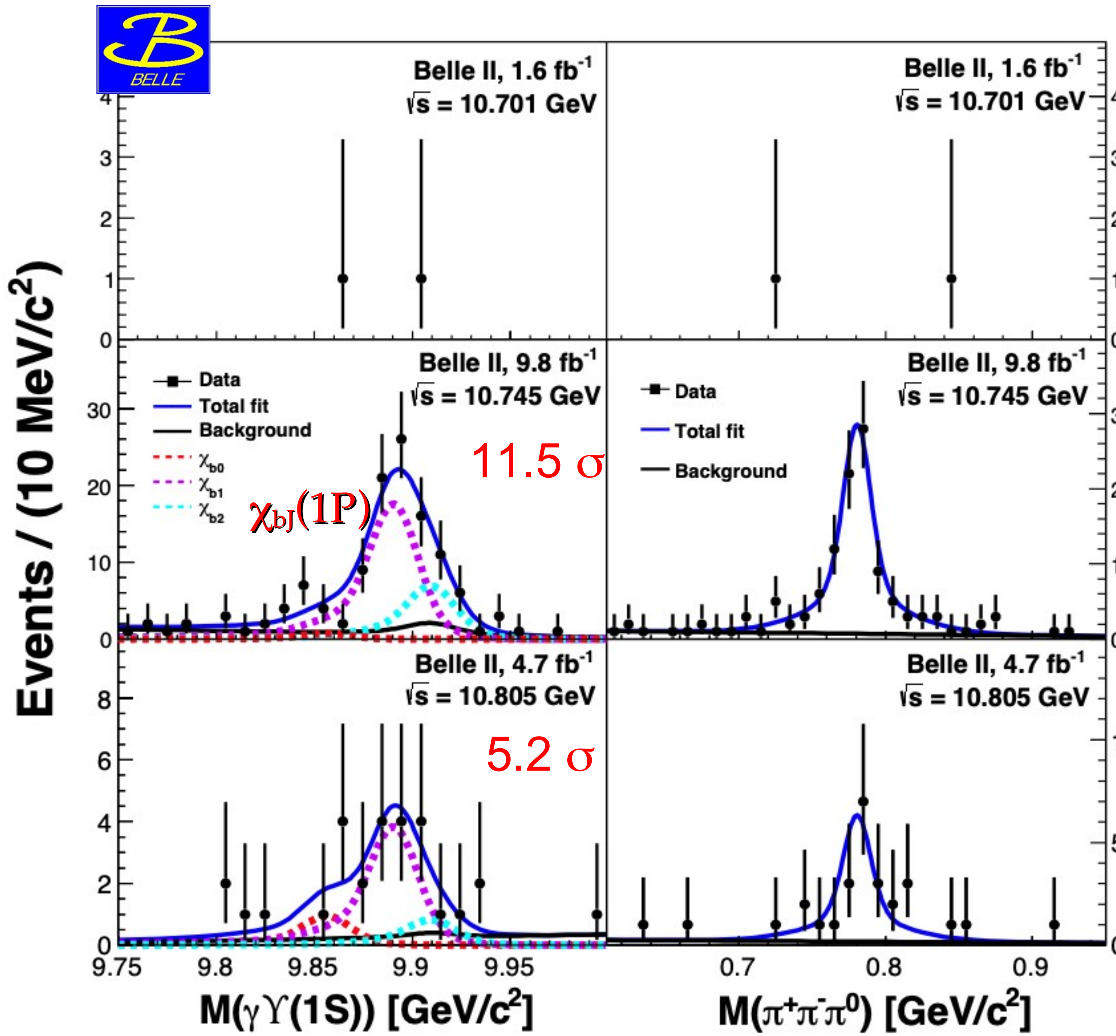
PRL 130, 091902 (2023)

Inspired by decay modes of Y(4220), observed by BES:

- $J/\psi\,\pi^+\pi^-$
- $\chi_{c0}(1P)\,\omega$
- $\gamma X(3872)$

Search for the bottomonium analogue of X(3872), X_b, and the $\omega\chi_{bJ}(1P)$ transition, in the process:

$$e^+e^- \rightarrow (\pi^+\pi^-\pi^0)\,\gamma\,\Upsilon(1S)$$



Observation of $\Upsilon(10753) \to \chi_{bJ}(1P)\,\omega$

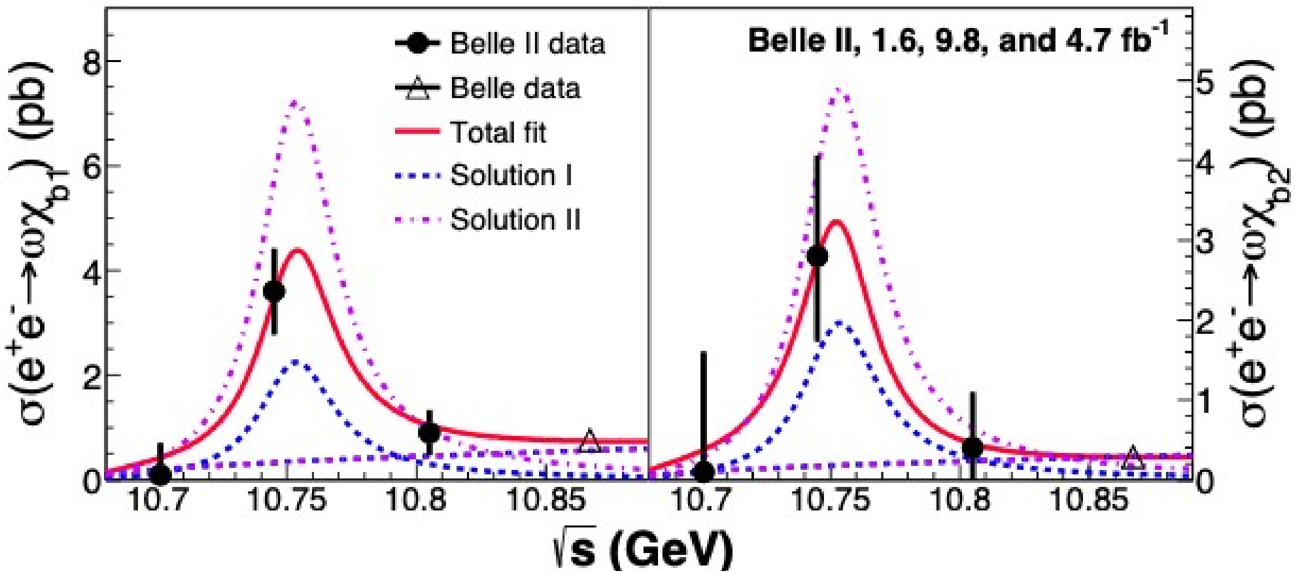
PRL 130, 091902 (2023)

The signal seen is larger than $\Upsilon(10753) \to \Upsilon(2S)\,\pi^+\pi^-$

The signal seen at 5S [1] is probably a TAIL of this.

[1]PRL 113, 142001(2014)

[2]. JHEP 10, 220(2019)



	Solution I	Solution II
$\Gamma_{ee}\,\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b1})$	$(0.63 \pm 0.39 \pm 0.20)$ eV	$(2.01 \pm 0.38 \pm 0.76)$ eV
$\Gamma_{ee}\,\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b2})$	$(0.53 \pm 0.46 \pm 0.15)$ eV	$(1.32 \pm 0.44 \pm 0.55)$ eV

$\Gamma_{ee}BR(\chi_b(1P)\,\omega) \sim$ **1.5** $\Gamma_{ee}BR(\Upsilon(2S)\,\pi^+\pi^-)$ at 10.75

$\Gamma_{ee}BR(\chi_b(1P)\,\omega) \sim$ **0.15** $\Gamma_{ee}BR(\Upsilon(2S)\,\pi^+\pi^-)$ at 10.87 [2]

$$\frac{\sigma(e^+e^-\to\chi_{b1}(1P)\omega)}{\sigma(e^+e^-\to\chi_{b2}(1P)\omega)} = 1.3\pm0.6$$

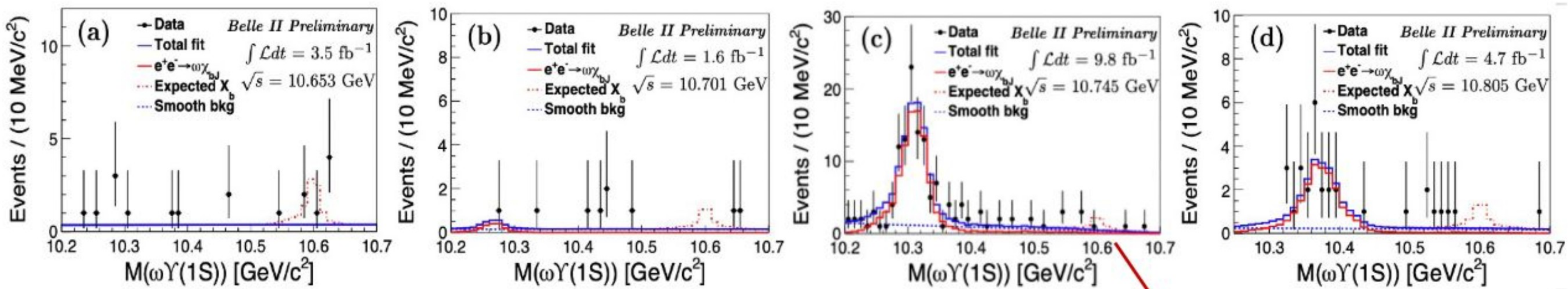
O(10) in 120 MeV for two 1^{--} states indicate different structure of the two states

A pure $\Upsilon(3D)$ state would give **15** *Guo et al, PLB 738 (2014),172*

A mixed 4S-3D state would give **0.18-0.22** , i.e. **1.8 σ smaller** *Li et al. PRD 104 (2021) 034036*

Search for X_b at $\Upsilon(10750)$

PRL 130, 091902 (2023)



From simulated events with $m(X_b) = 10.6$ GeV/c^2
The yield is fixed at the upper limit at 90% C.L.

- No significant X_b signal is observed.
- The peaks are the reflections of $e^+e^- \to \omega\chi_{bJ}$.

Upper limits at 90% C.L. on $\sigma_B(e^+e^- \to \gamma X_b) \cdot \mathcal{B}(X_b \to \omega\Upsilon(1S))$ (pb)	$\sqrt{s}$ (GeV)	10.653	10.701	10.745	10.805
	$m(X_b) = 10.6$ GeV/c^2	0.45	0.33	0.10	0.14
	$m(X_b) = (10.45, 10.65)$ GeV/c^2	(0.14, 0.54)	(0.25, 0.84)	(0.06, 0.14)	(0.08, 0.36)

The bottomonium analogue of X(3872) is still missing …
… we need (a lot) more data

Search for $\Upsilon(10753) \to \chi_{b0}(1P)\,\omega$, $\eta_b(1S)\,\omega$

Motivation

Theory prediction of a strong enhancement of the decay :
$\Upsilon(10753) \to \eta_b(1S)\,\omega$ (30 x $\Upsilon(2S)\,\pi^+\pi^-$) using a compact tetraquark interpretation   CPC 43 (2019)12,123102

Experimental observation (BESIII, PRD99 (2019) 091103) of an enhancement of $\psi(4220) \to \chi_{c0}(1P)\omega$ compared to $\psi(4220) \to \chi_{c1,2}(1P)\omega$

Strategy

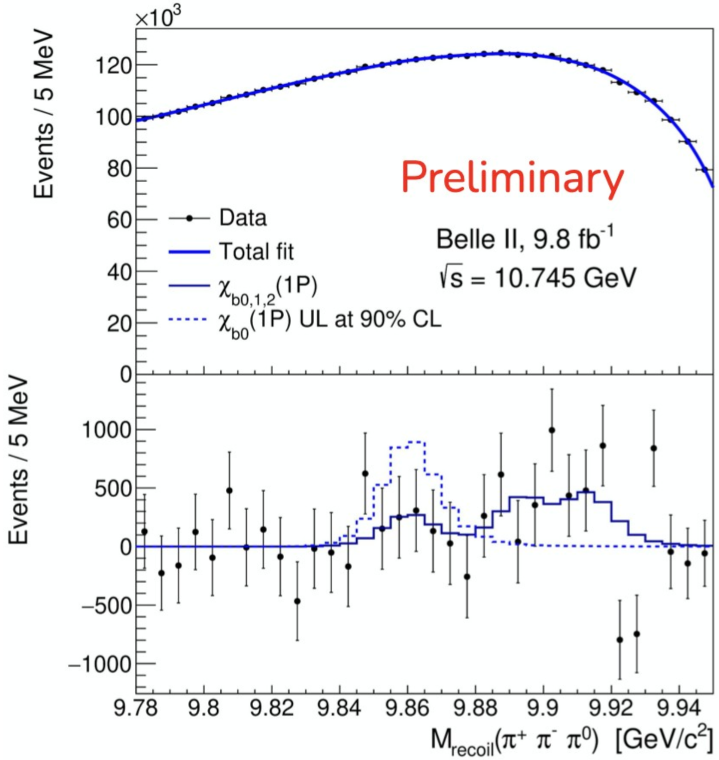
As both $\eta_b(1S)$ and $\chi_{b0}(1P)$ do not have few body decay channels with high branching ratio, an inclusive search is done by calculating the mass recoiling against the ω :

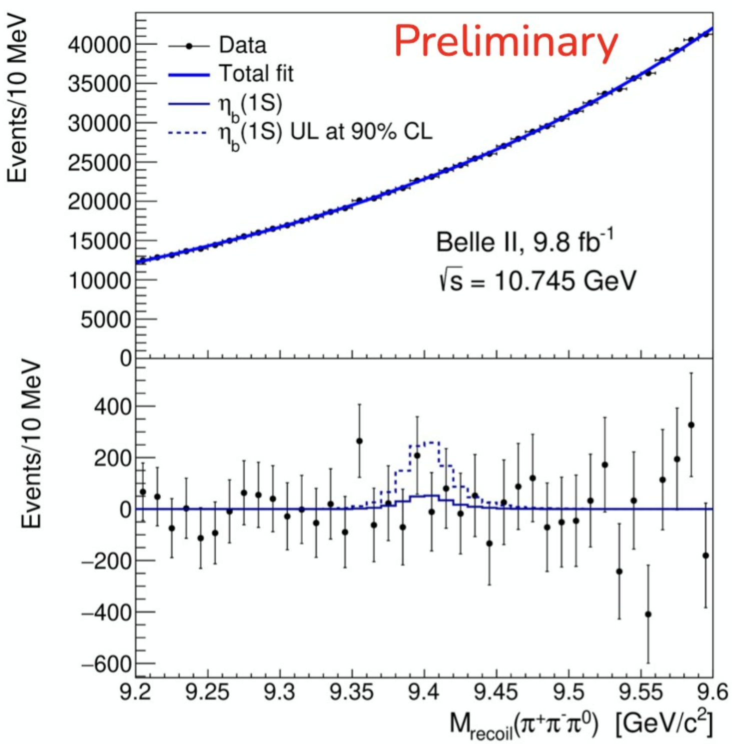
$$M_{\mathrm{recoil}}(\pi^+\pi^-\pi^0) = \sqrt{\left(\frac{E_{\mathrm{c.m.}} - E^*}{c^2}\right)^2 - \left(\frac{p^*}{c}\right)^2}$$

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

Fit to $M_{recoil}(\pi^+\pi^-\pi^0)$

No significant signals are observed and 90% C.L. upper limits are set.



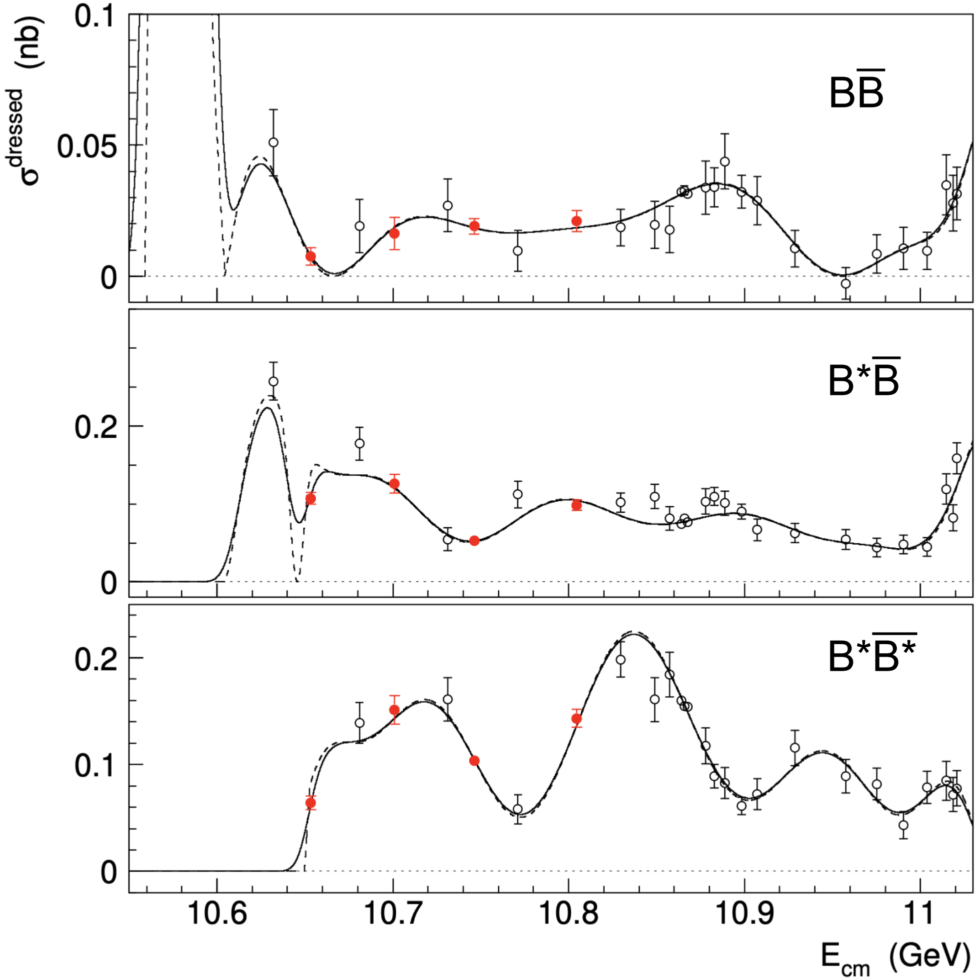


- ❑ $\sigma[e^+e^- \rightarrow \omega\chi_{b0}(1S)] < 8.7$ pb
- ❑ $\sigma[e^+e^- \rightarrow \omega\eta_b(1S)] < 2.5$ pb
- ❑ c.f. $\sigma[e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-] \sim 2.0$ pb (JHEP 10 (2019) 220)

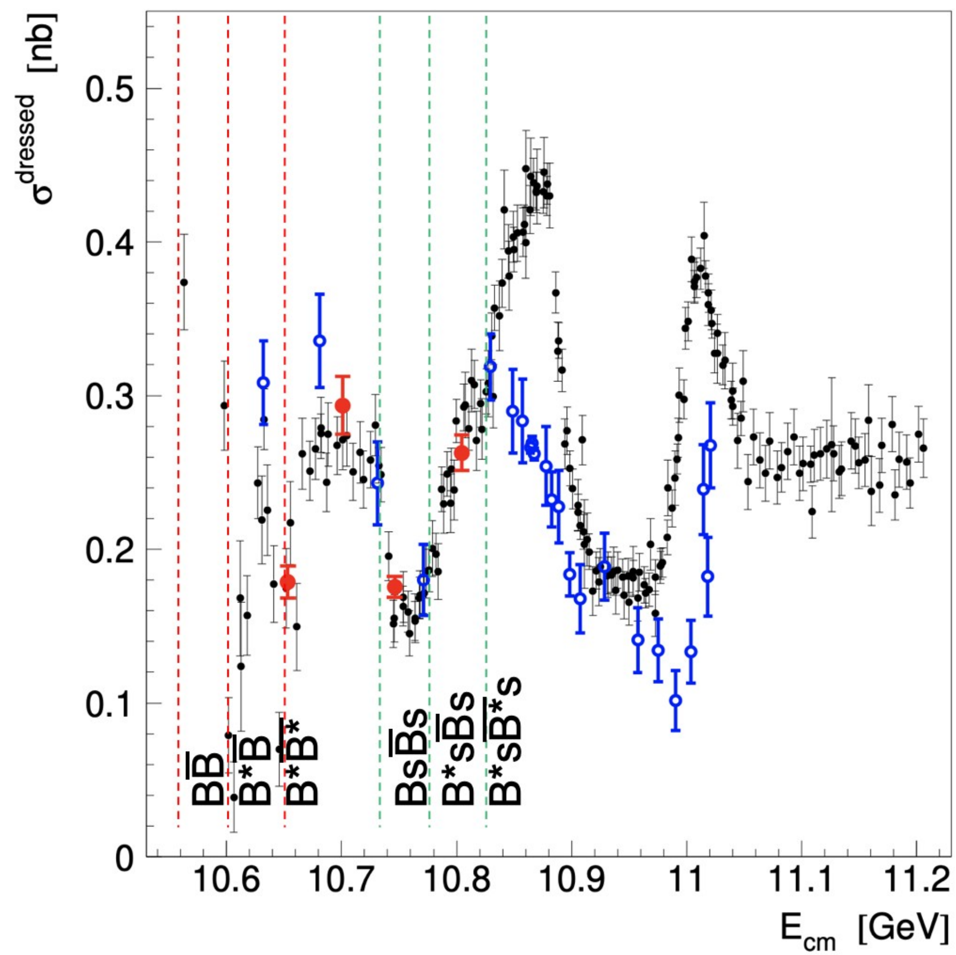
This result does not support the prediction of the tetraquark model in CPC 43 (2019) 12, 123102

BB+BB*+B*B* cross sections in the 10.65-10.8 GeV region

Sci.Bull. 65 (2020) 23, 1983



Shown at Moriond QCD 2023, to appear on JHEP



Individual 2-body cross sections fitted with Chebychev polinomials

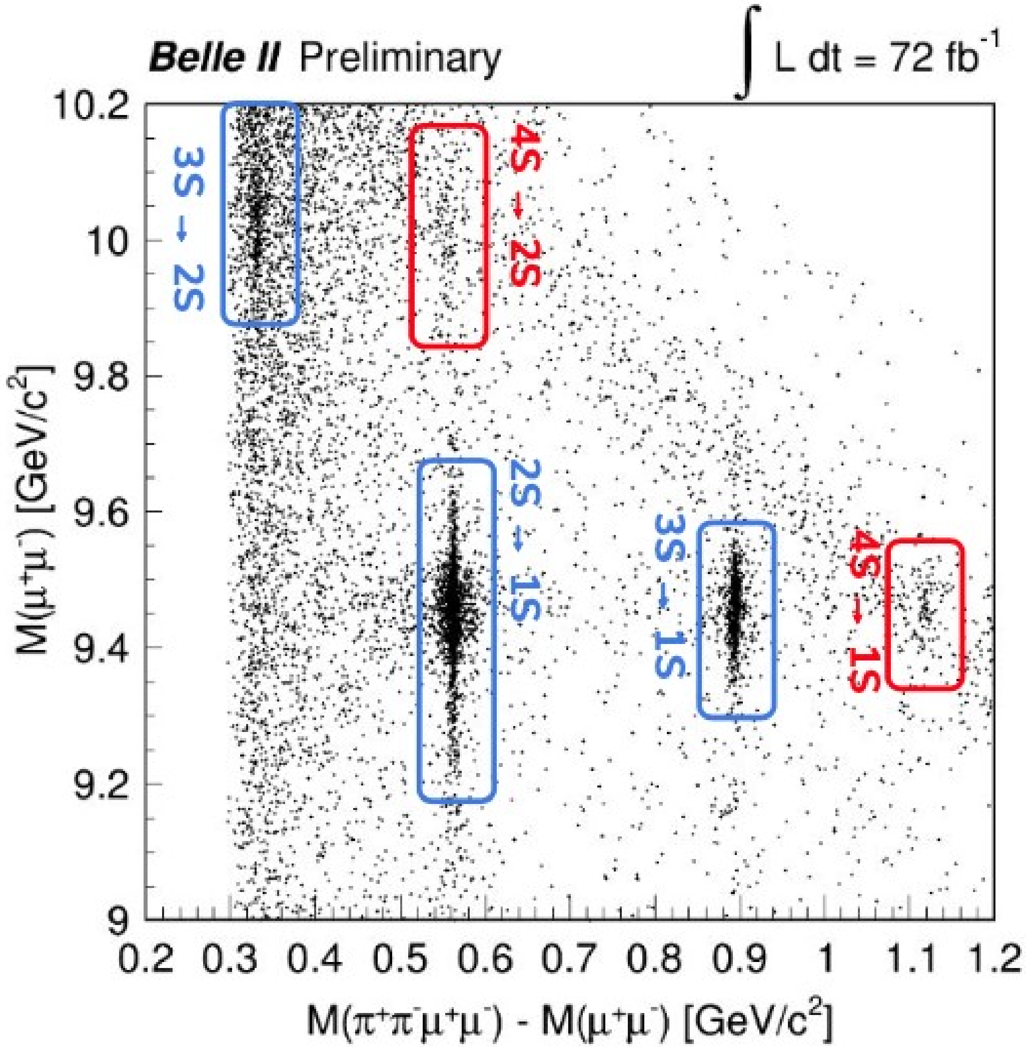
The steep rise of B*B̄* cross section suggest the existence of a molecular state at threshold

Total cross section: the four new points are in red.

Dipion transitions from 4S

Control channel to prepare unblinding of data taken at 10.6-10.85 GeV

Searched in $\mu\mu\pi\pi$ mode, asking for Ntracks=4,5.
Recoil mass cuts to isolate ISR production
$|M_{\mu\mu} - M(\Upsilon(1S))| < 50$ MeV/c^2

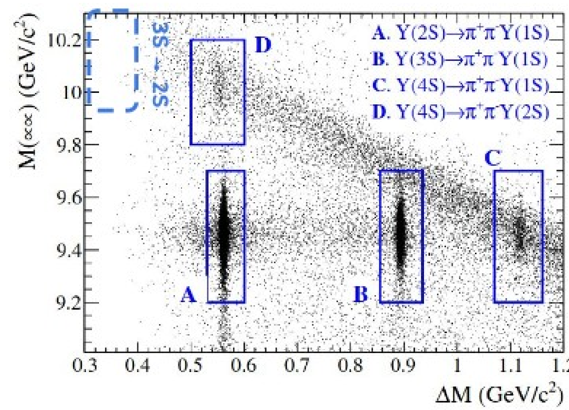


Study $e^+e^- \to \pi^+\pi^-\mu^+\mu^-$ (+γ undetected)

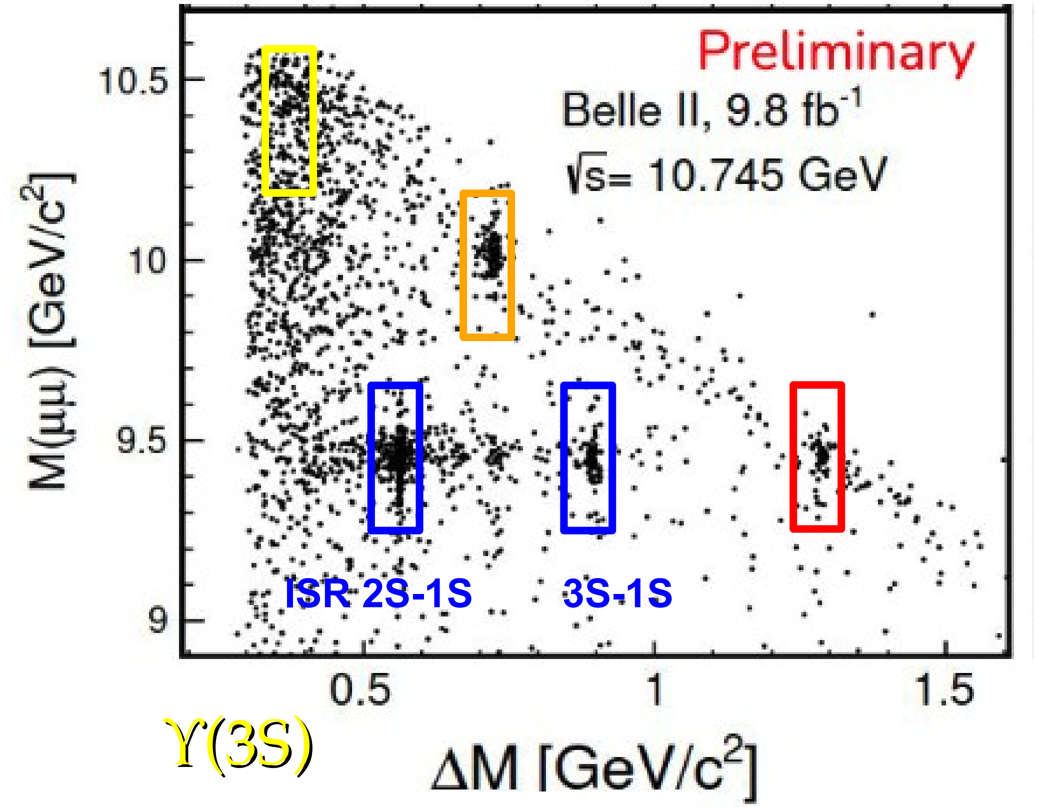
- $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(nS)$
- $e^+e^- \to \gamma_{ISR}\Upsilon(mS)$, $\Upsilon(mS) \to \pi^+\pi^-\Upsilon(nS)$

Compare with Belle, 496 fb^{-1} [PRD 96 (2017) 5, 052005]

- Improved low momentum tracking

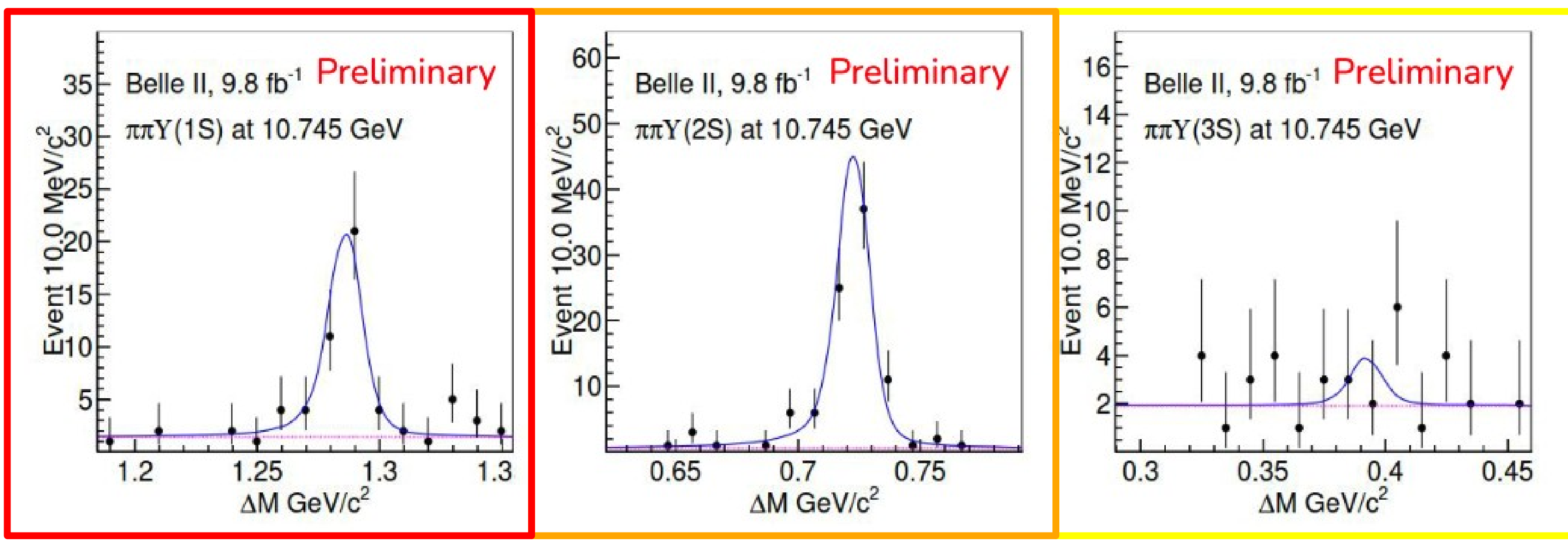


Signals from Ecm = 10.745 GeV

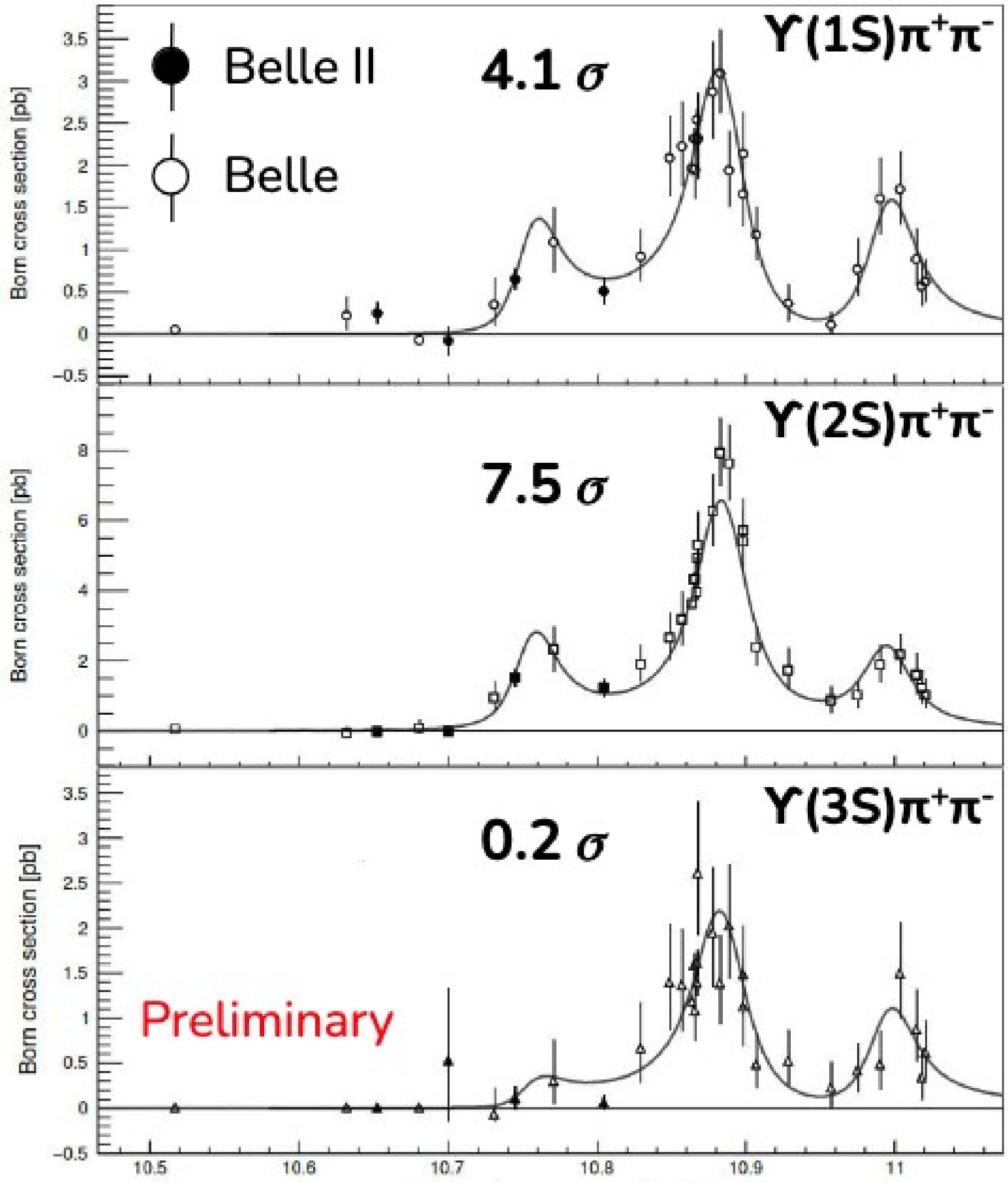


Dipion transitions from 10.745 to:

$\Upsilon(1S)$ $\Upsilon(2S)$ $\Upsilon(3S)$



Signals vs Ecm



We confirm the Belle result

Cross section fit of 10.75 peak:
BW+gaussian to account for Ecm spread

Mass: 10756.3 2.7 stat 0.6 syst MeV/c2
Width: 29.7 8.5 stat 1.1 syst MeV

...but …
We should have taken data at 10.750, not 10.745

Dalitz Plot projections

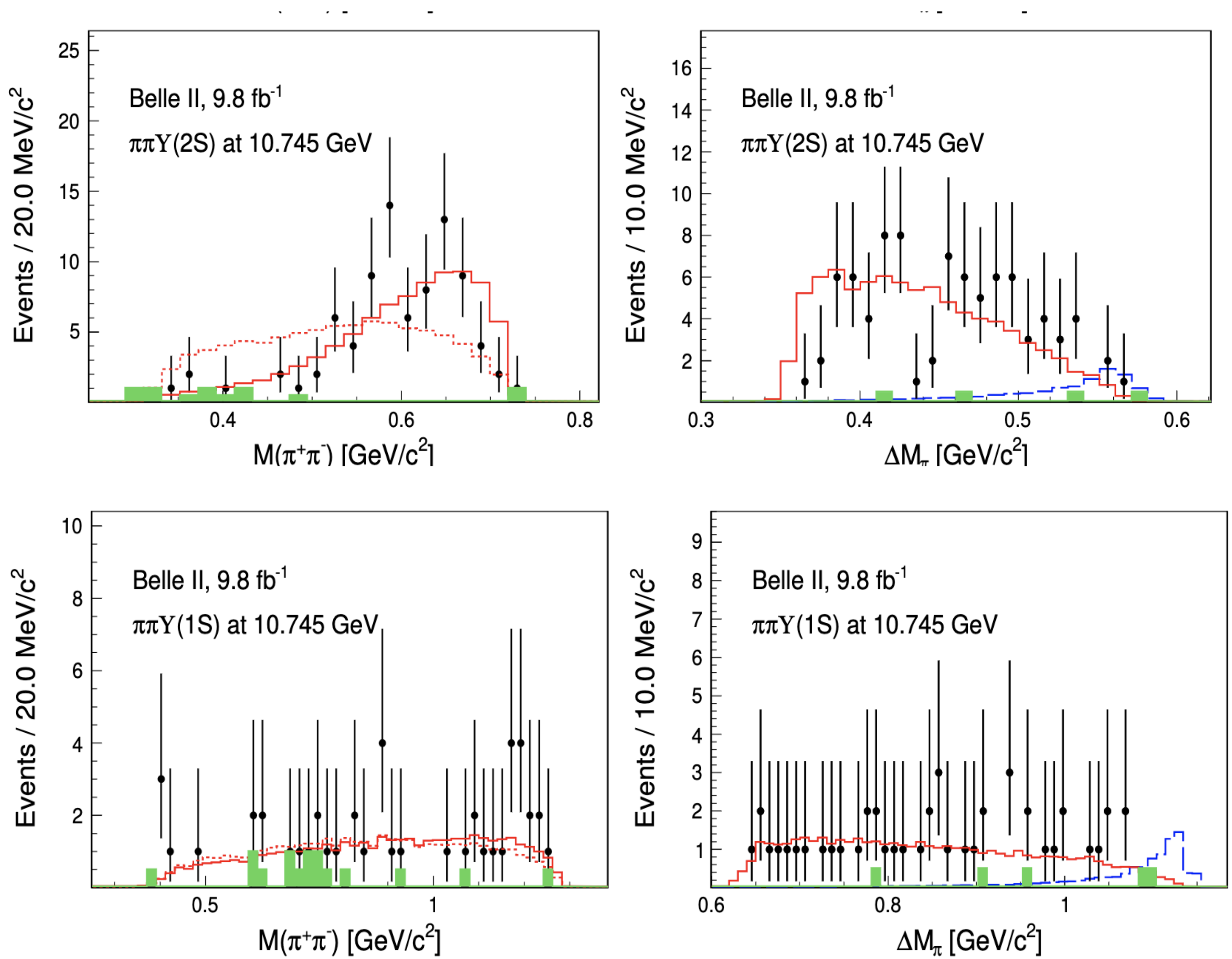
Y(10753) to Y(2S) similar to Y(2S) to Y(1S)

Fitted with Cleo parametrization assuming the spin-flip term C=0.

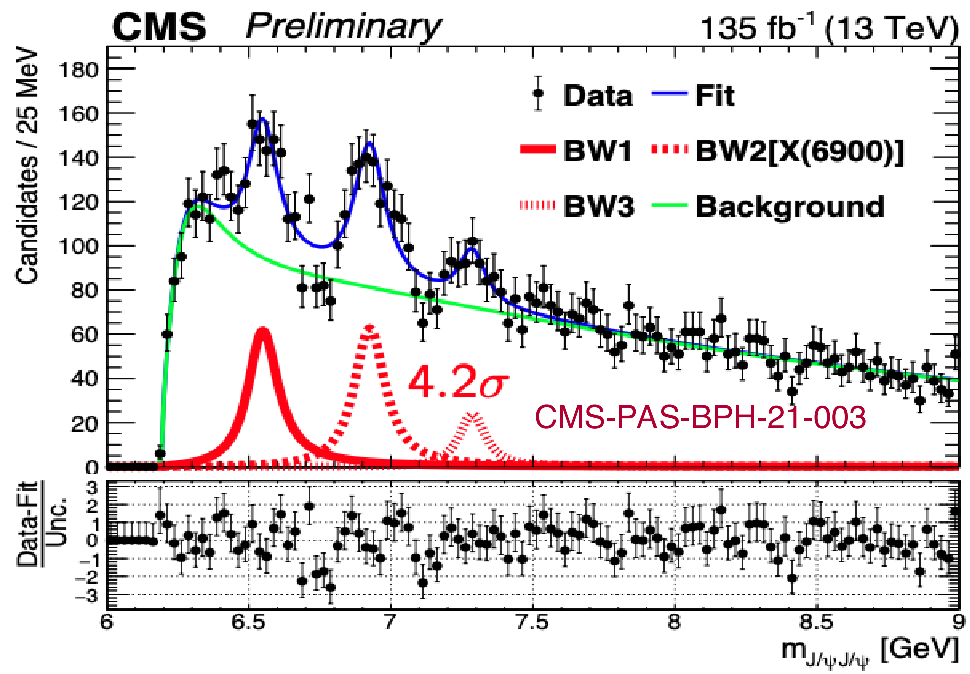
More statistics is needed to test HQSS violations.

Despite low efficiency in the high deltaMpi region, we can exclude strong Zb contributions.

Y(1S) transition still consistent with phase space, needs nore statistics.



Double charmonium resonances



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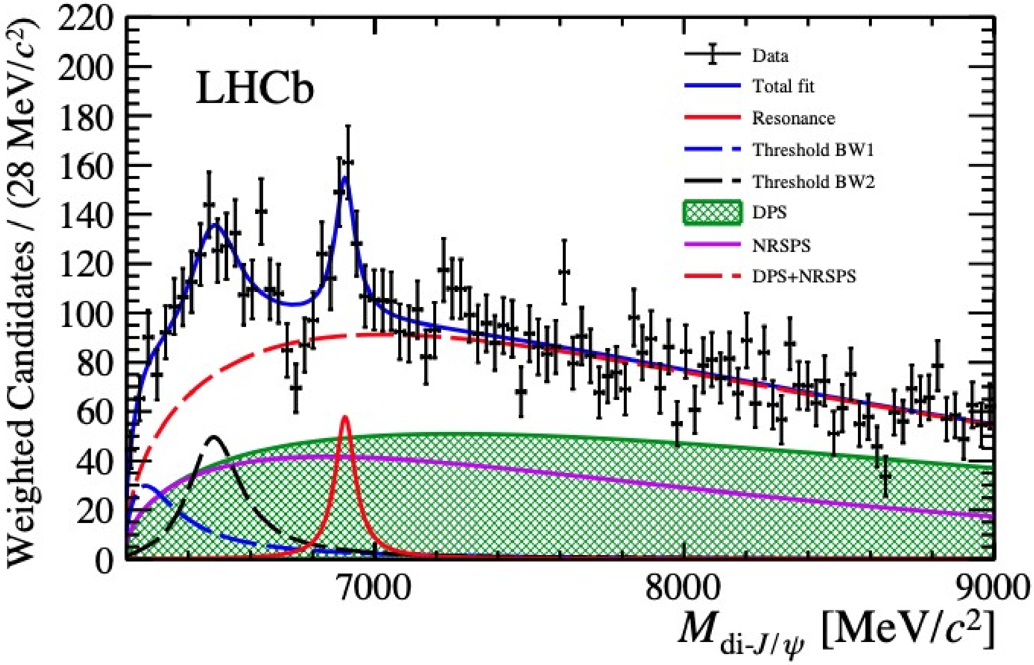
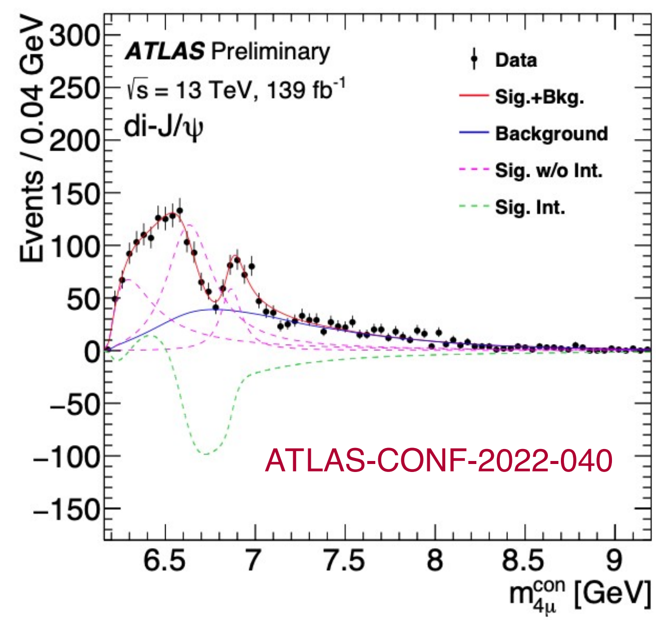
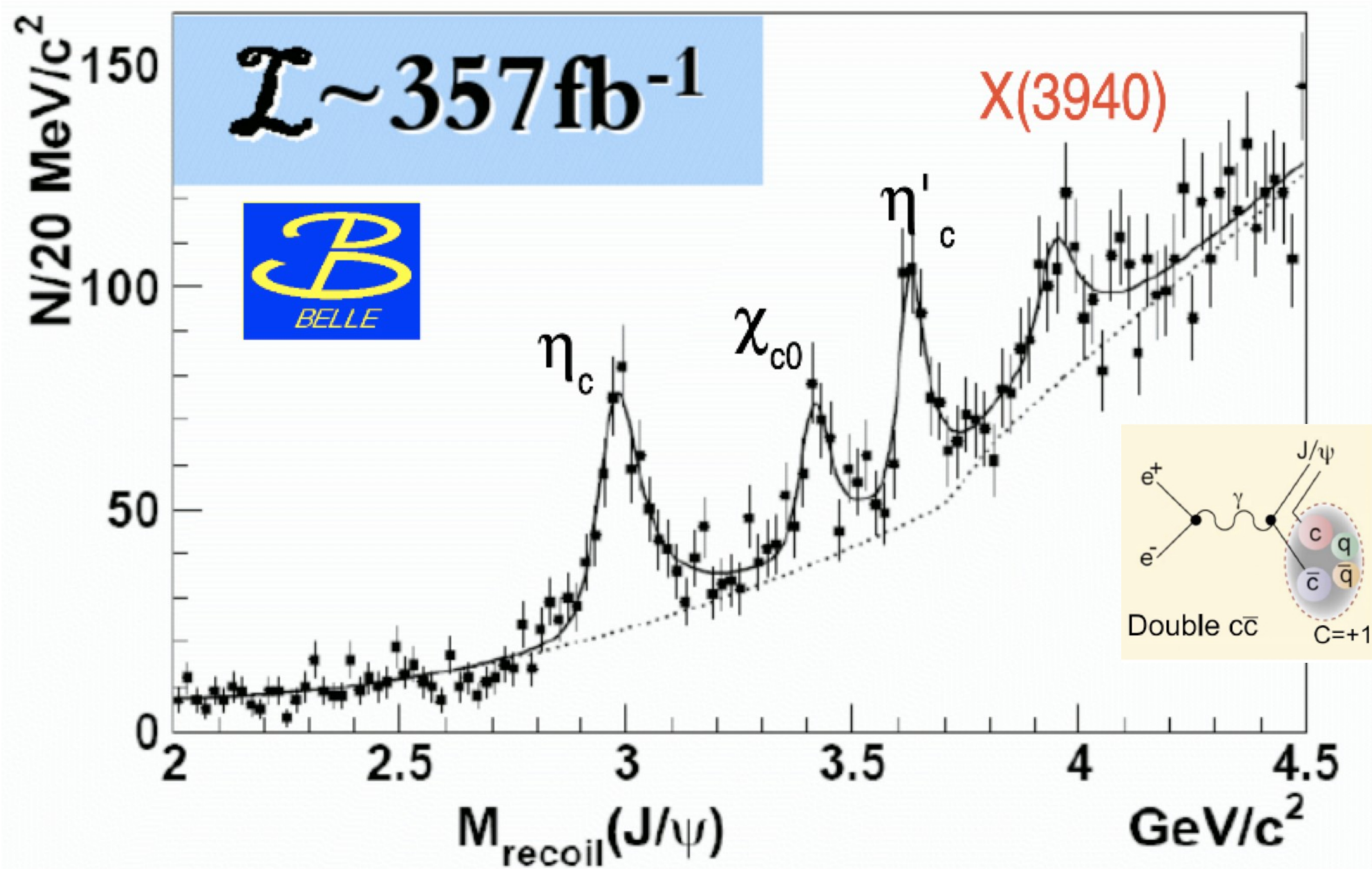


y at Belle I&II



2002 : double charmonium at Belle



Clean observation of J=0 charmonium peaks … AND an unexpected discovery : the X(3940)

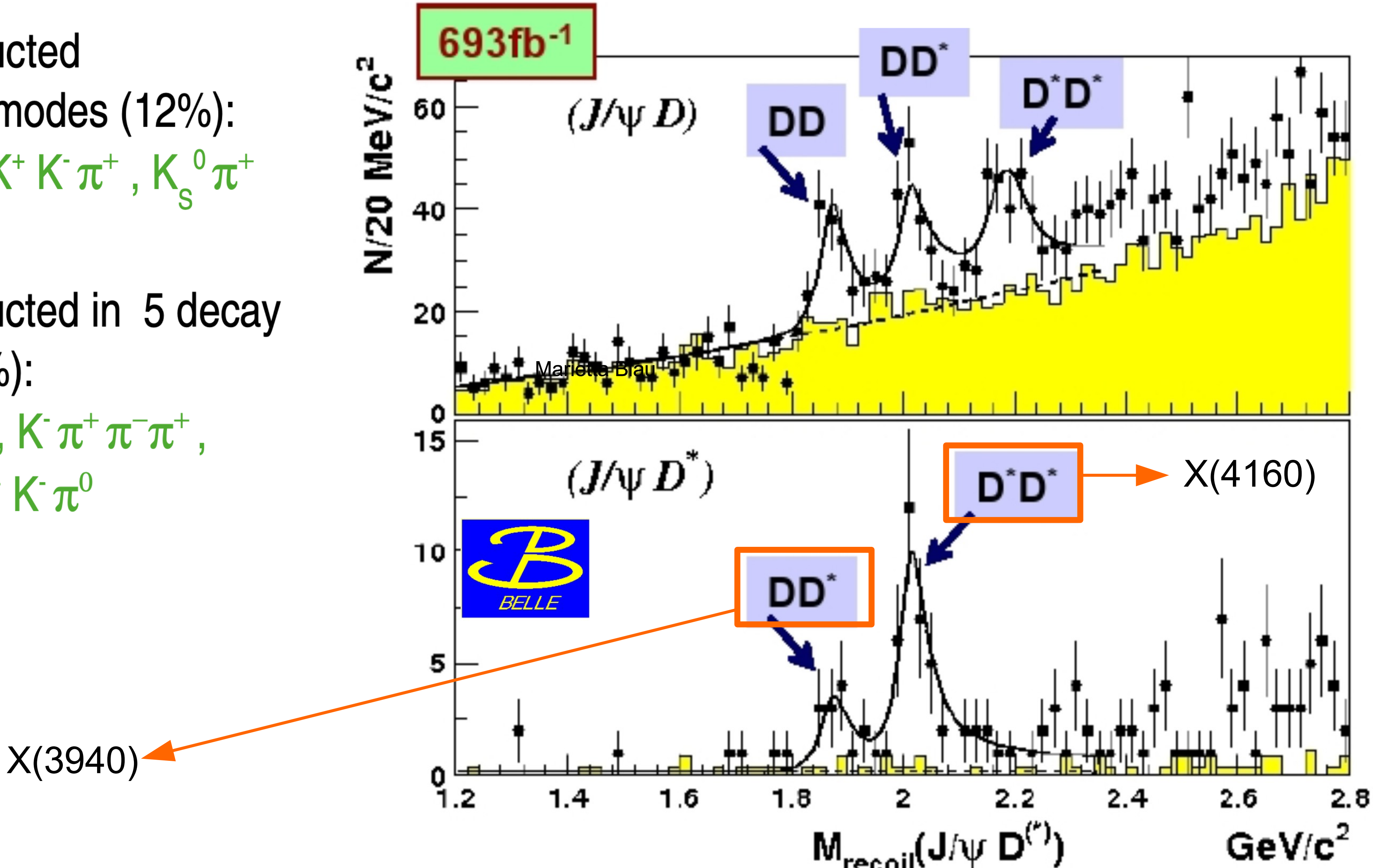
2002 : double charmonium at Belle

Mass spectrum of what recoils against a D(*) meson and a J/ψ

Another development:

D^+ reconstructed in 3 decay modes (12%):
$K^-\pi^+\pi^-$, $K^+K^-\pi^+$, $K_S^0\pi^+$

D^0 reconstructed in 5 decay modes (29%):
$K^-\pi^+$, K^+K^- , $K^-\pi^+\pi^-\pi^+$, $K_S^0\pi^+\pi^-$, $K^+K^-\pi^0$



Double charmonium vs Ecm in Belle

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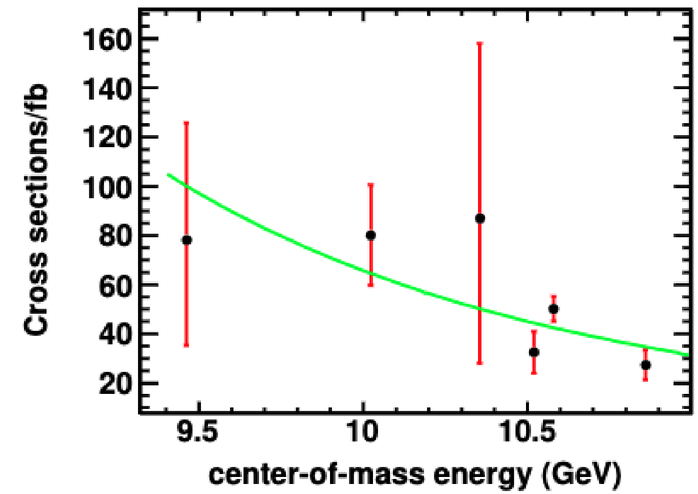
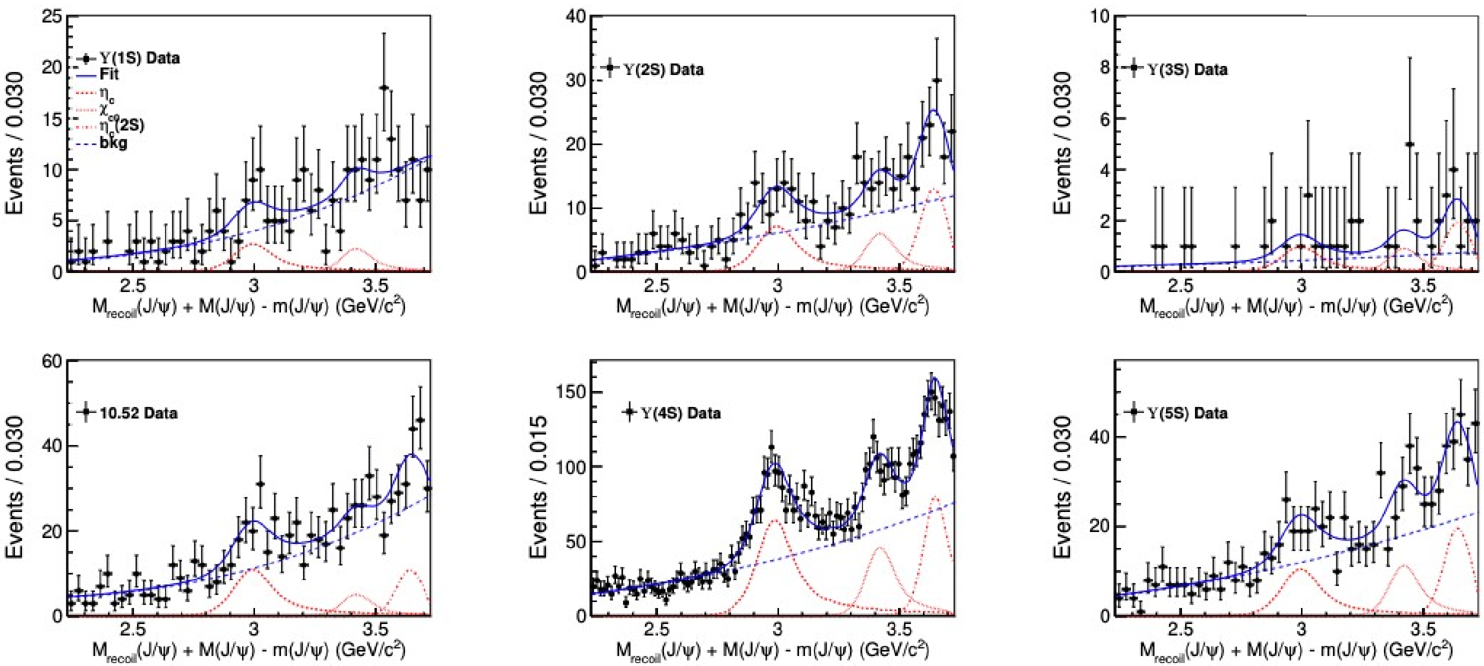
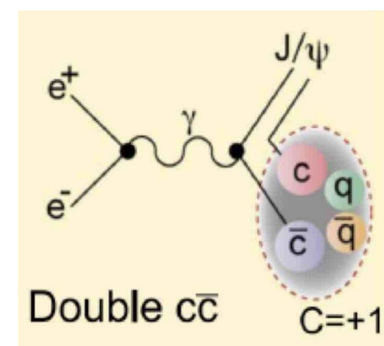


Data sample : 955 fb-1 integrated at Υ(1,2,3,4,5S) and at 10.52 GeV.

Inclusive search: reconstruction of J/psi in ee,mm and study of the recoil mass

Plot of the etac J/psi cross section vs Ecm



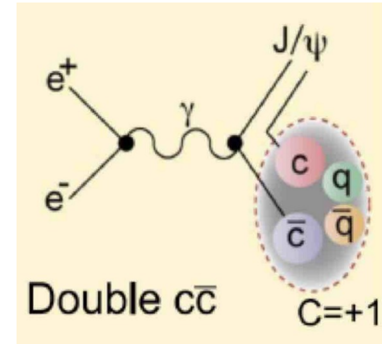


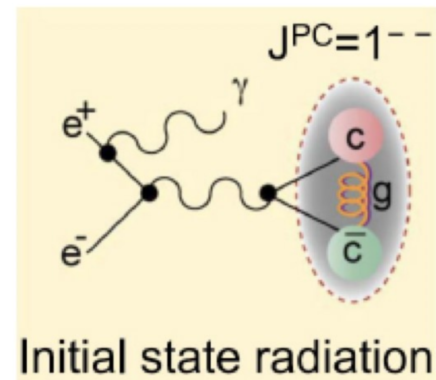
Double charmonium vs Ecm in Belle

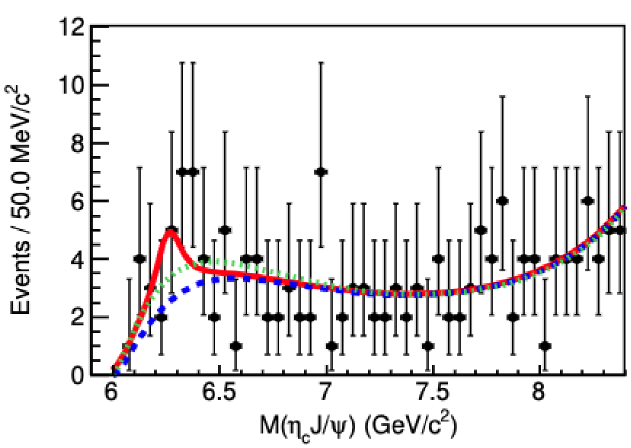
Data sample : 980 fb-1, full Belle dataset

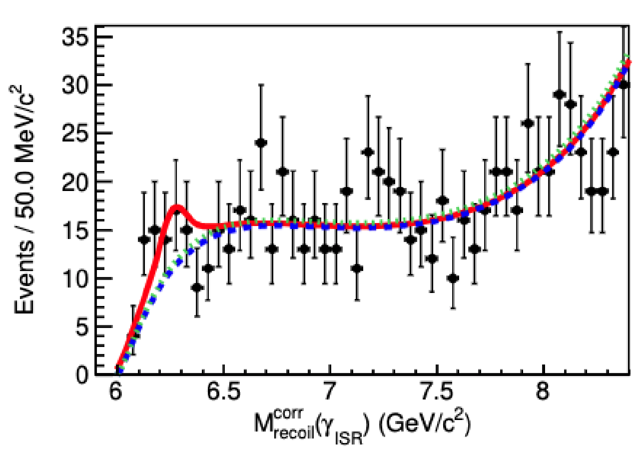
Two reconstruction methods:

1) Inclusive reconstruction of J/psi and the ISR photon, and inclusive search for peaks in the recoil mass
2) Full Exclusive reconstruction, etac in 6 decay modes (), and study of the etac+jpsi invariant mass distribution. Recoil mass squaredof etac+jpsi in [-1,2]GeV2 range









3.3 sigma evidence of threshold enhancement , need more data at Belle-II

In conclusion …

The advent of B factories have led to a renaissance of hadron spectroscopy .
All sort of more complex ensembles of quarks have been seen and more results are expected for the coming years.

Above the open flavor thresholds, bottomonium and charmonium-like states exhibit analogies and differences, which are still not completely understood:
The first scan of the 10.6-10.8 GeV region at Belle-II is starting to produce interesting results, analogue to the 4.2-4.4 GeV region in charmonium, pioneered by Babar and Belle, and now intensively studied by BES-III.

Structures seen at LHC in double charmonium may lead to a whole new spectroscopy with fully heavy tetraquarks: radiative return may allow similar studies at Super-KEKB.

Thanks for your attention !