Heavy quarkonia and multiquarks

Roberto Mussa

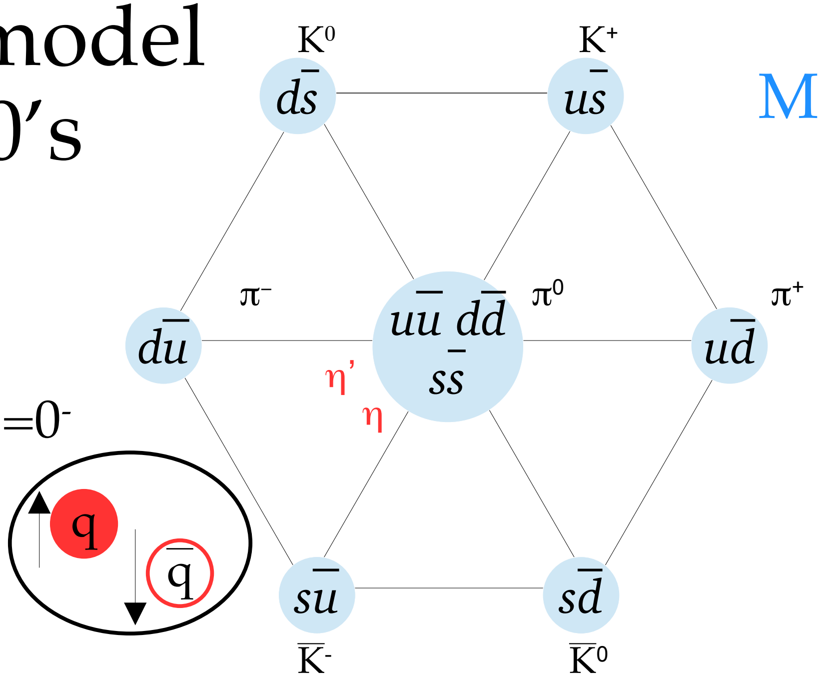
34th Rencontres de Blois

2023/05/17

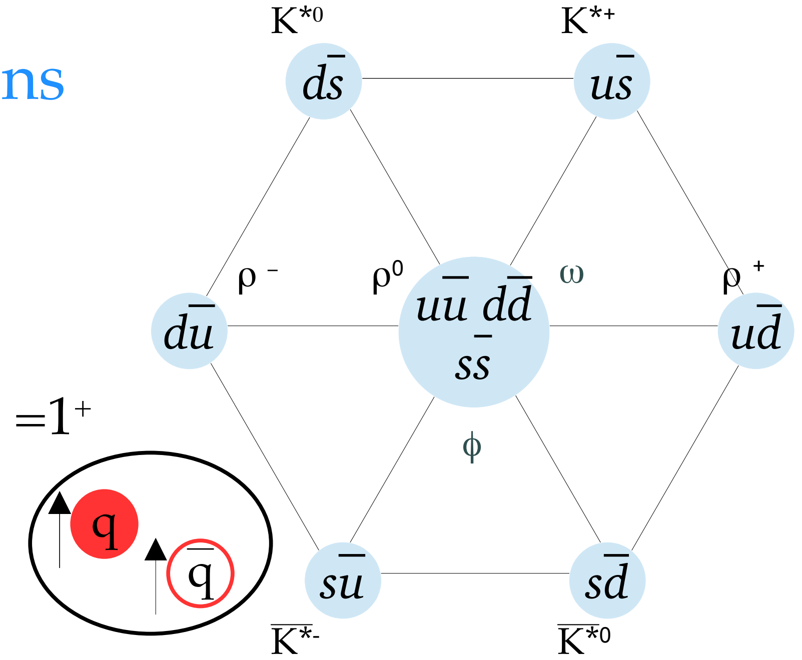
Quark model in the 60's

Mesons

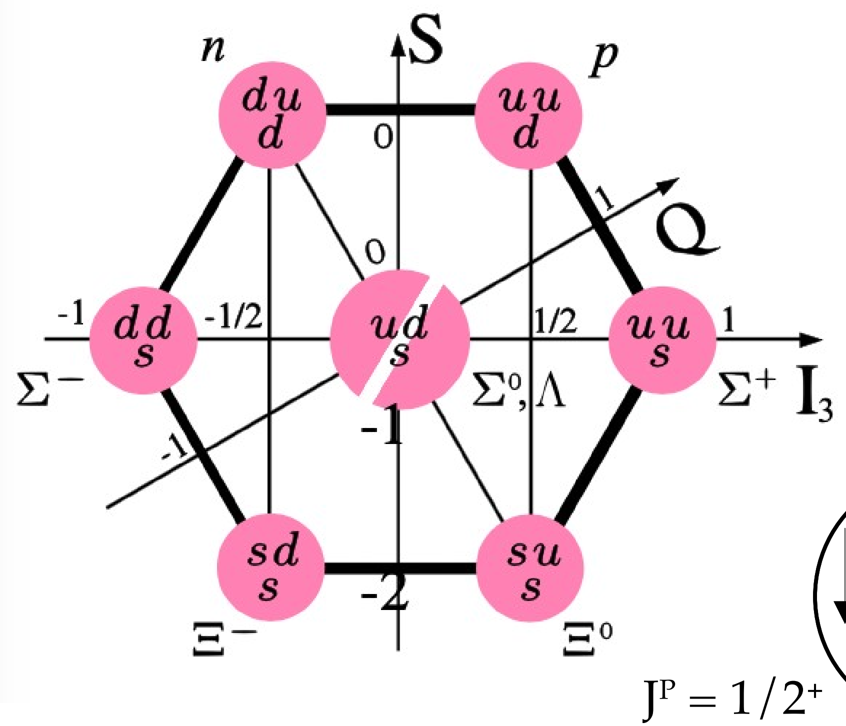
$J^P = 0^-$



$J^P = 1^+$

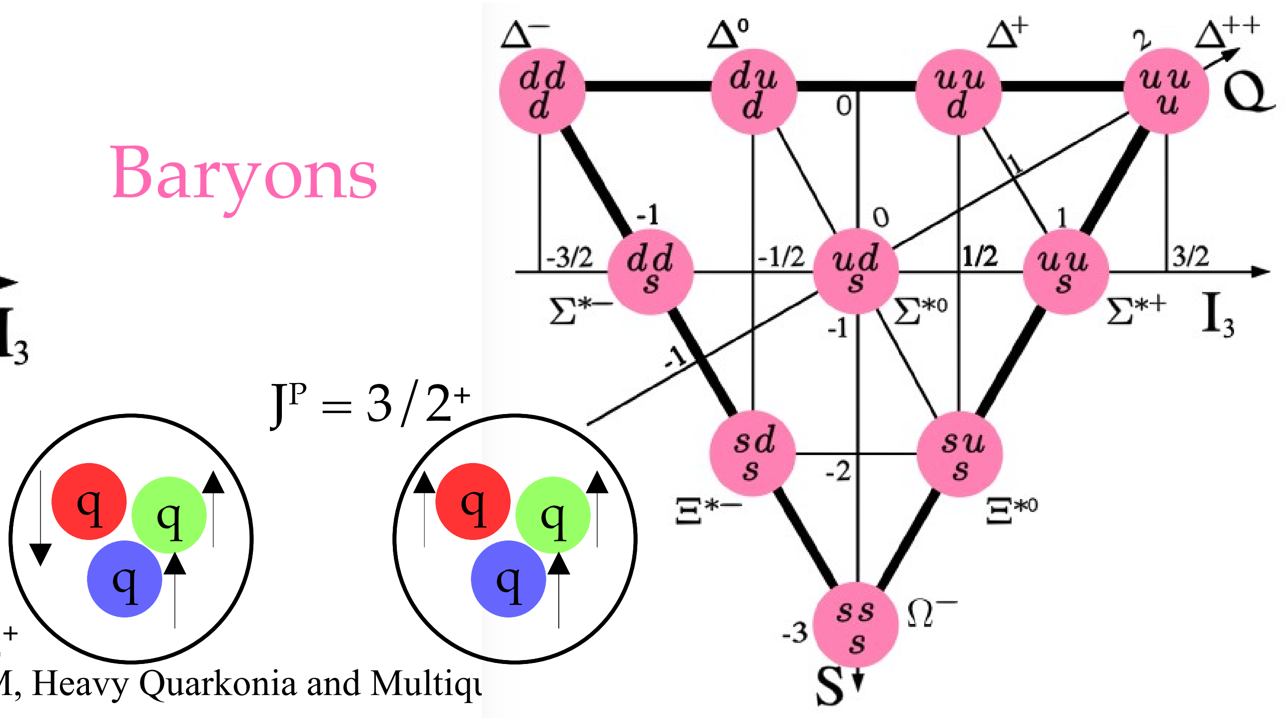


Baryons



$J^P = 1/2^+$

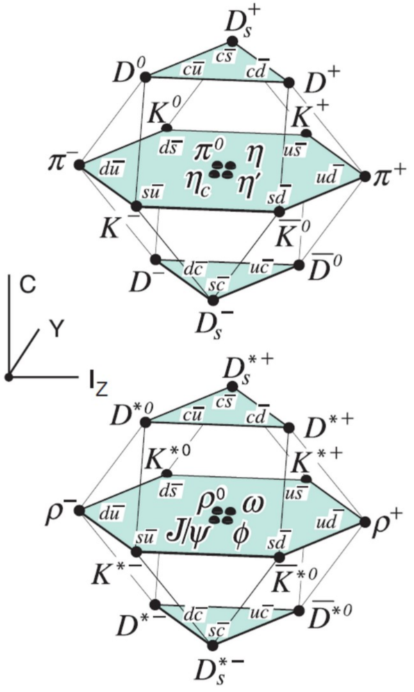
$J^P = 3/2^+$



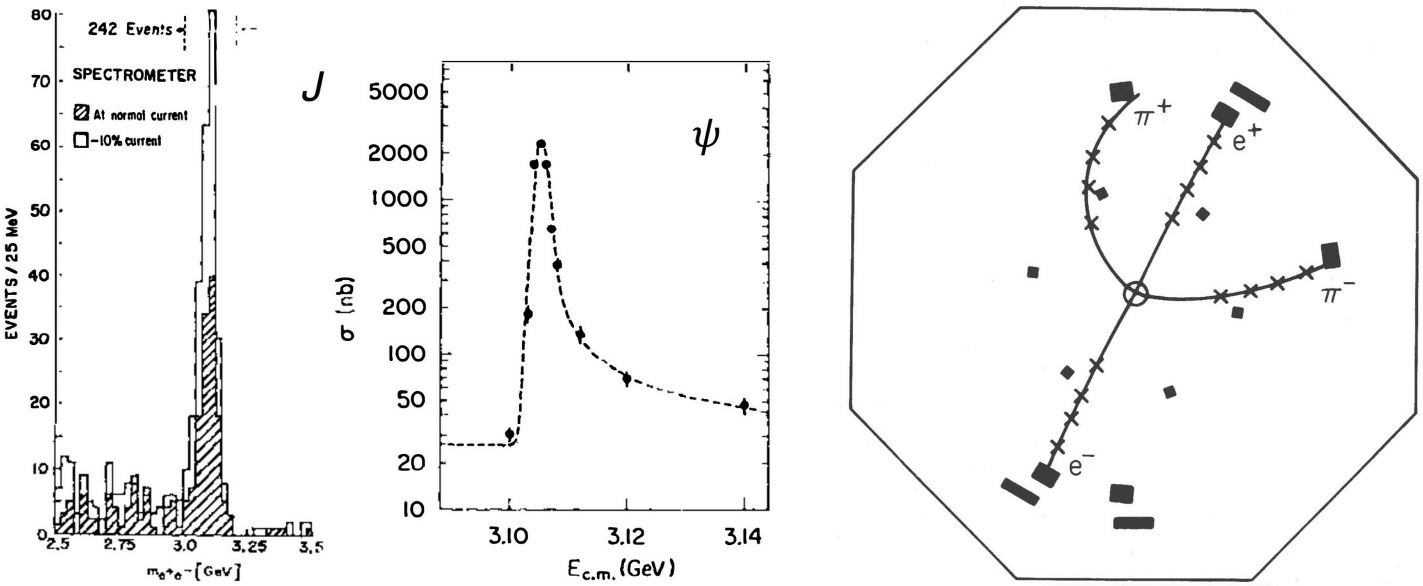
Quark model 1974-81

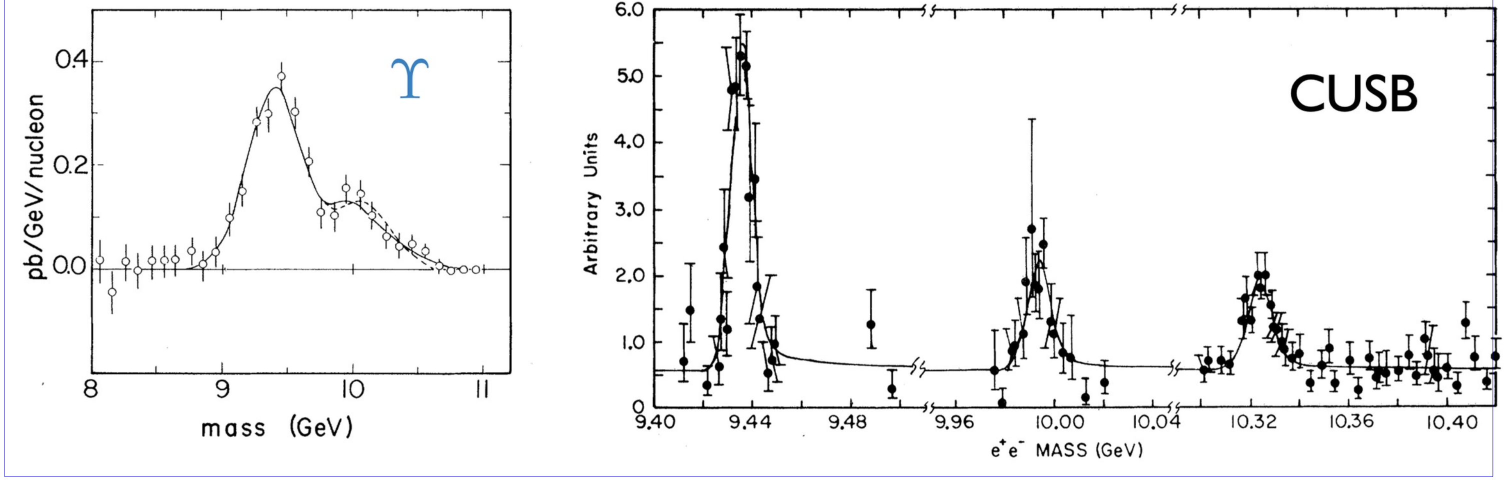
1974 Charm
1976 D mesons

1977 Bottom
1981 B mesons



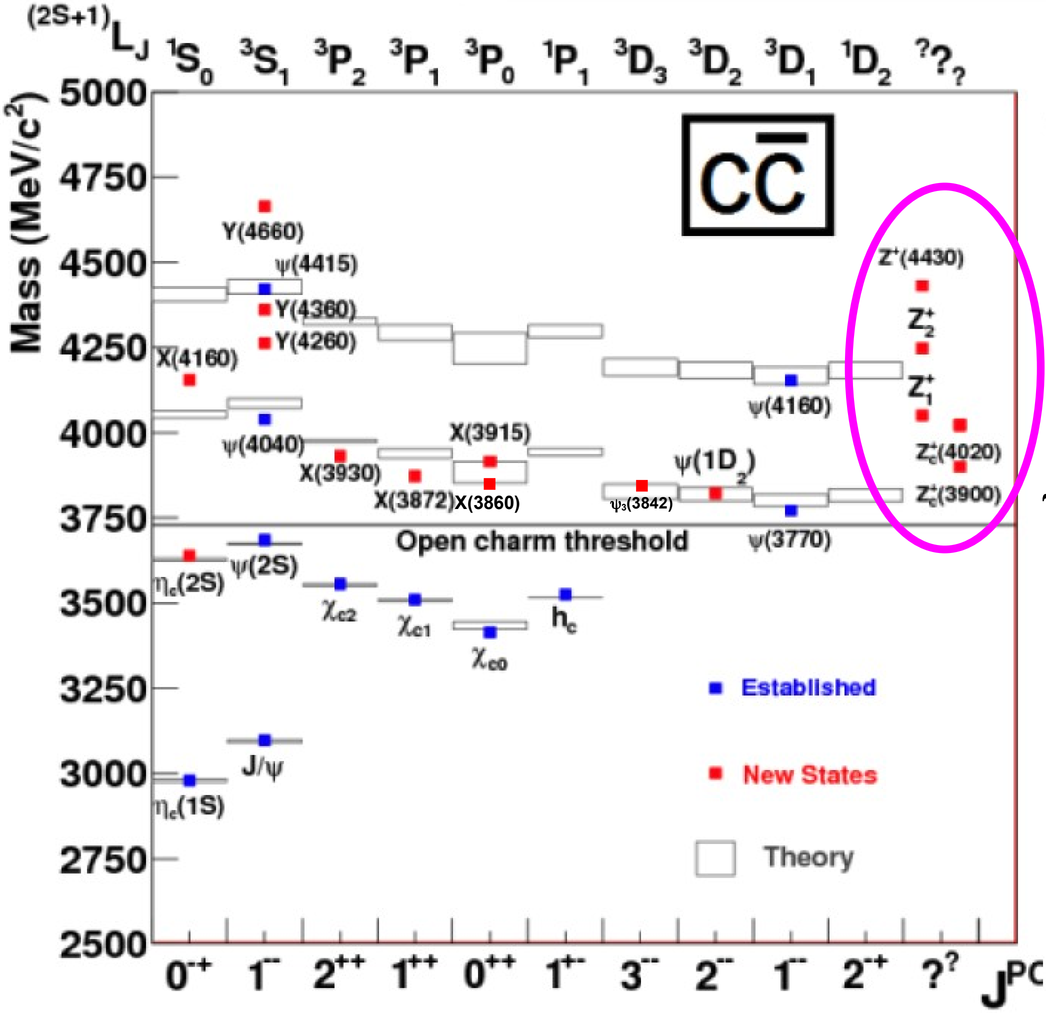
$e^+e^- \to \psi' \to \pi^+\pi^- J/\psi$

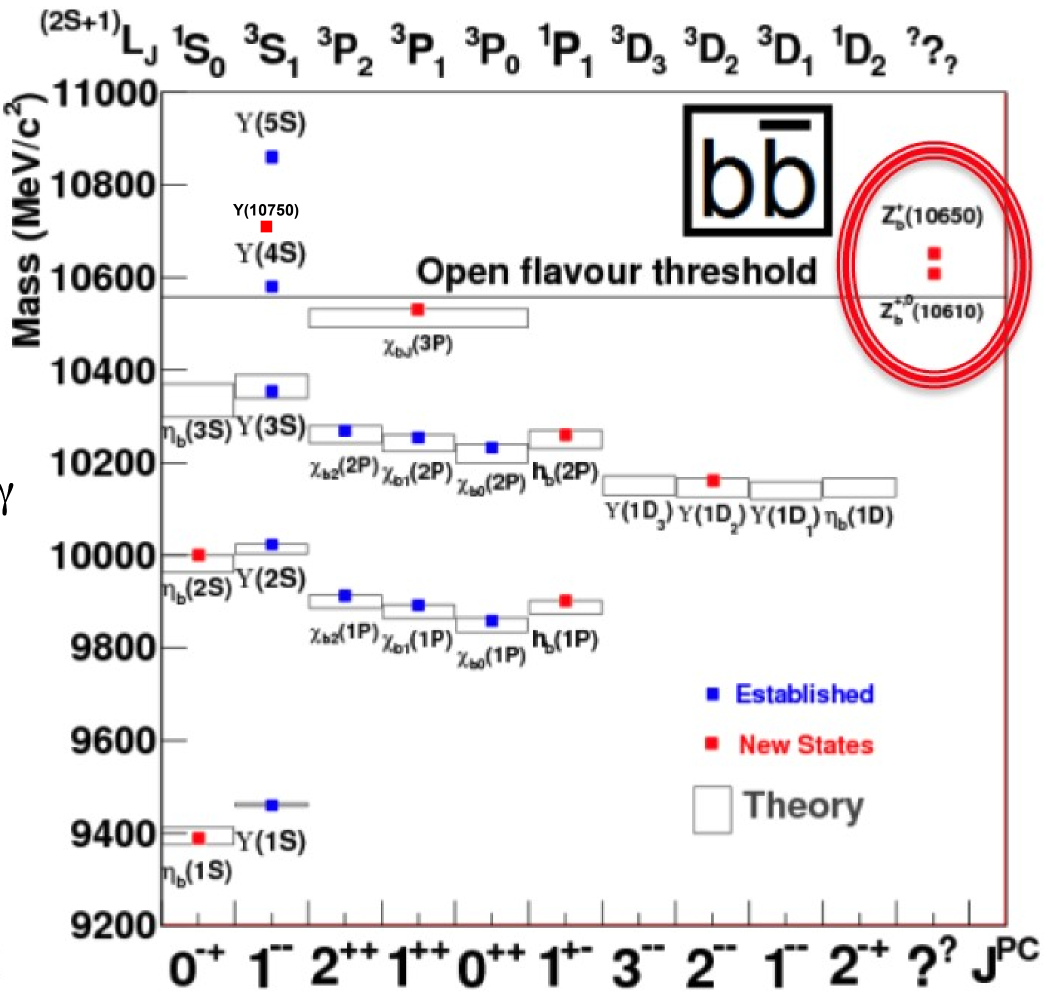




2002-now: beyond Heavy Quarkonia

Besides discovering many missing conventional quarkonium states, the B-factories and BES-III found many meson states not compatible with quarkonium models, dubbed the XYZ states.

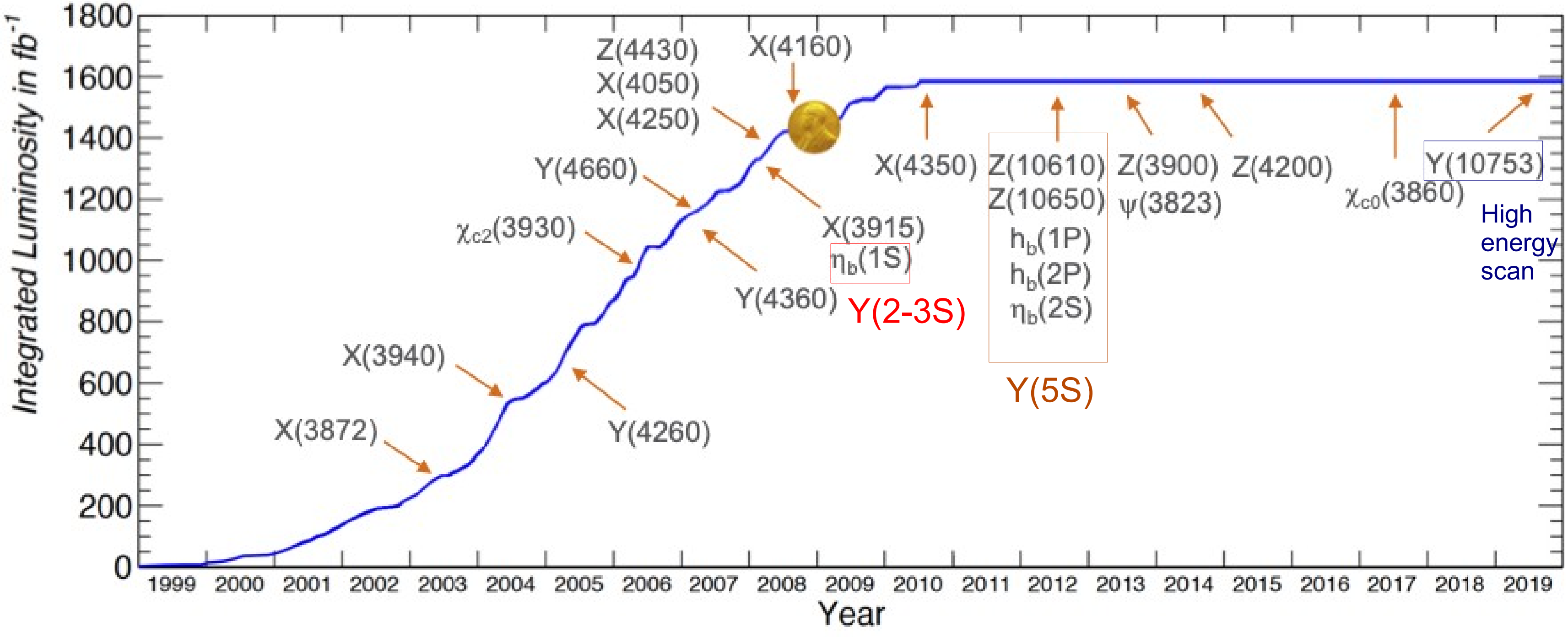




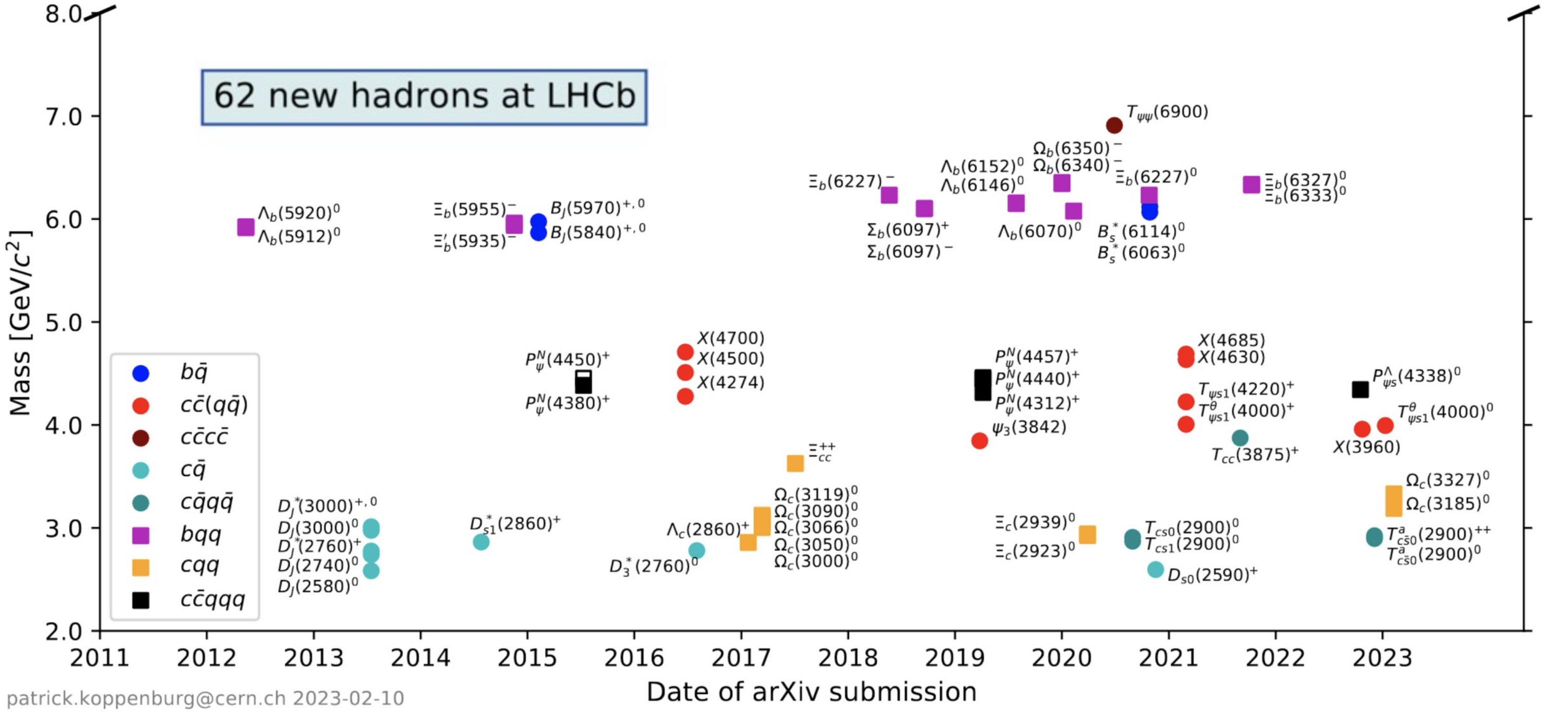
The need to introduce light quark degrees of freedom to describe the XYZ states was finally confirmed with observation of charged charmonium-like (Z_c) and bottomonium-like(Z_b) states.

2002-now: the role of B-factories

e^+e^-



pp



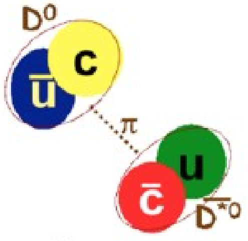
patrick.koppenburg@cern.ch 2023-02-10

QCD: the **WILD SIDE** of the SM

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \overline{\psi}_q (i \not{\partial} - g \not{A} + m) \psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

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:

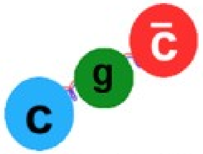


$D^0 - \bar{D}^{*0}$ "molecule"

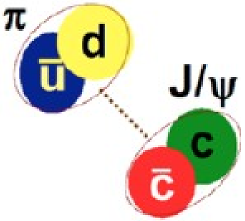
Meson Molecules (Guo et al, Rev.Mod.Phys.90,015004 (2018))
weakly bound states of two mesons

diquark-diantiquark

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



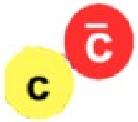
$q\bar{q}$-gluon "hybrid"



hadroquarkonium

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

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



conventional
quarkonium

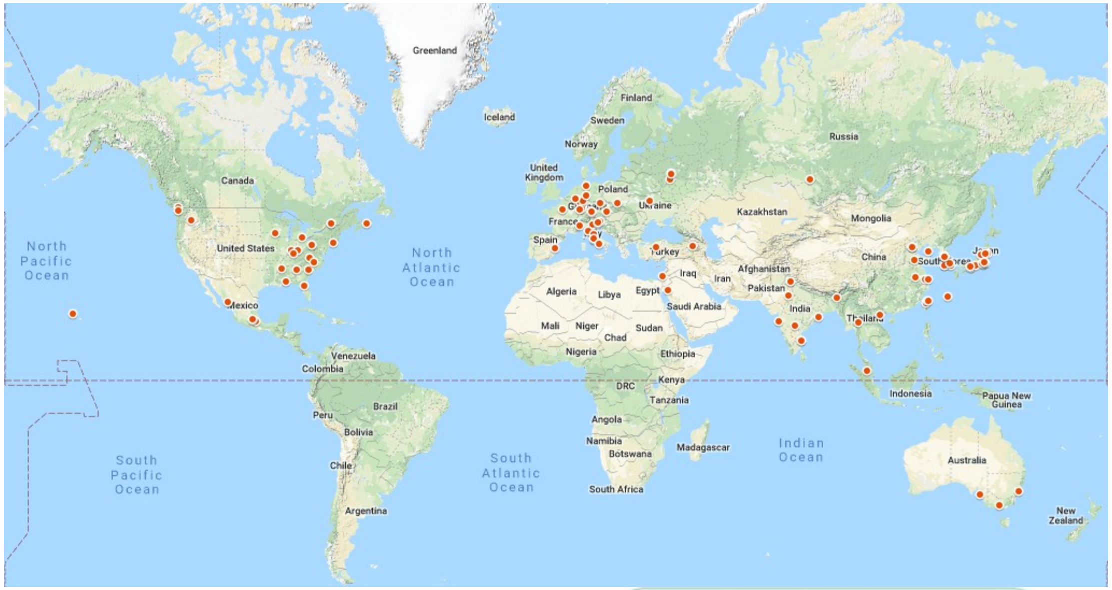
Standard quarkonia (Swanson, PRD 91, 034009 (2015))

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

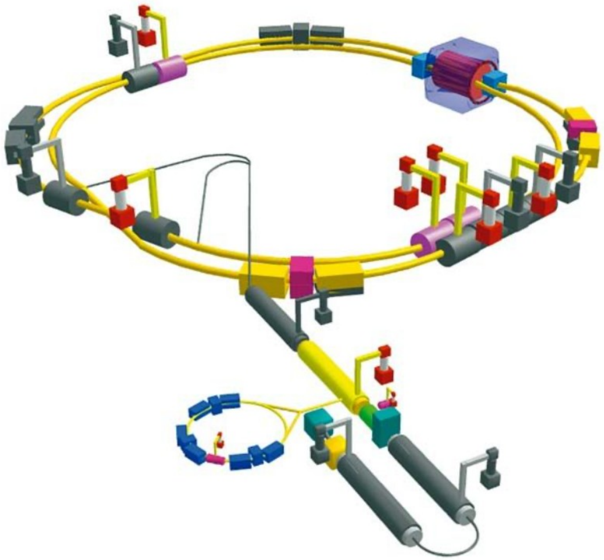
Super-B factory at KEK

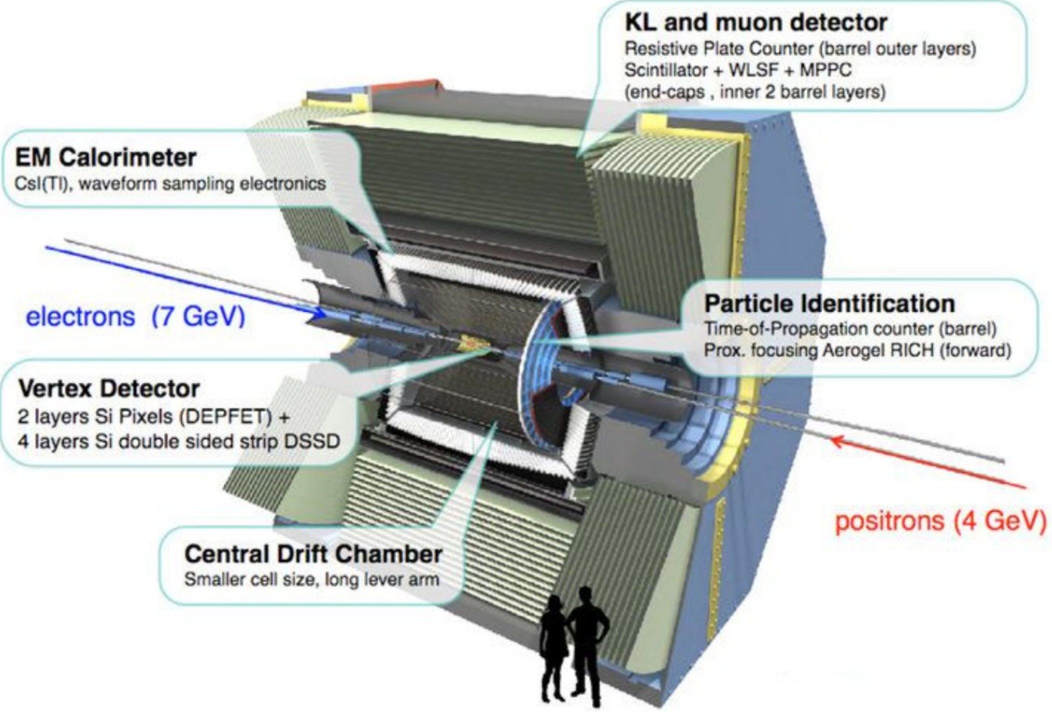
1047 active members
119 institutes
29 countries
(as of June 2020)



Asymmetric **e^+e^- collider**

⇒ **$J^{PC}=1^{--}$** states directly produced





KL and muon detector
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC
(end-caps , inner 2 barrel layers)

EM Calorimeter
CsI(Tl), waveform sampling electronics

electrons (7 GeV)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

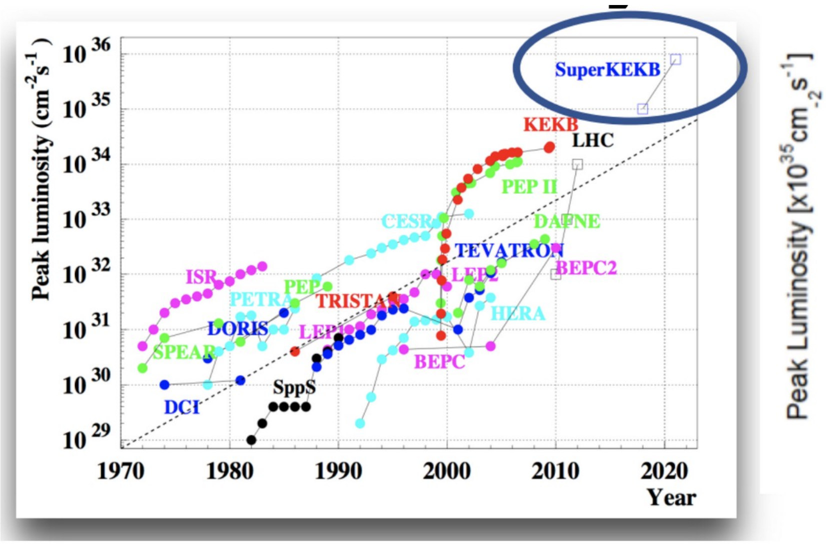
Vertex Detector
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip DSSD

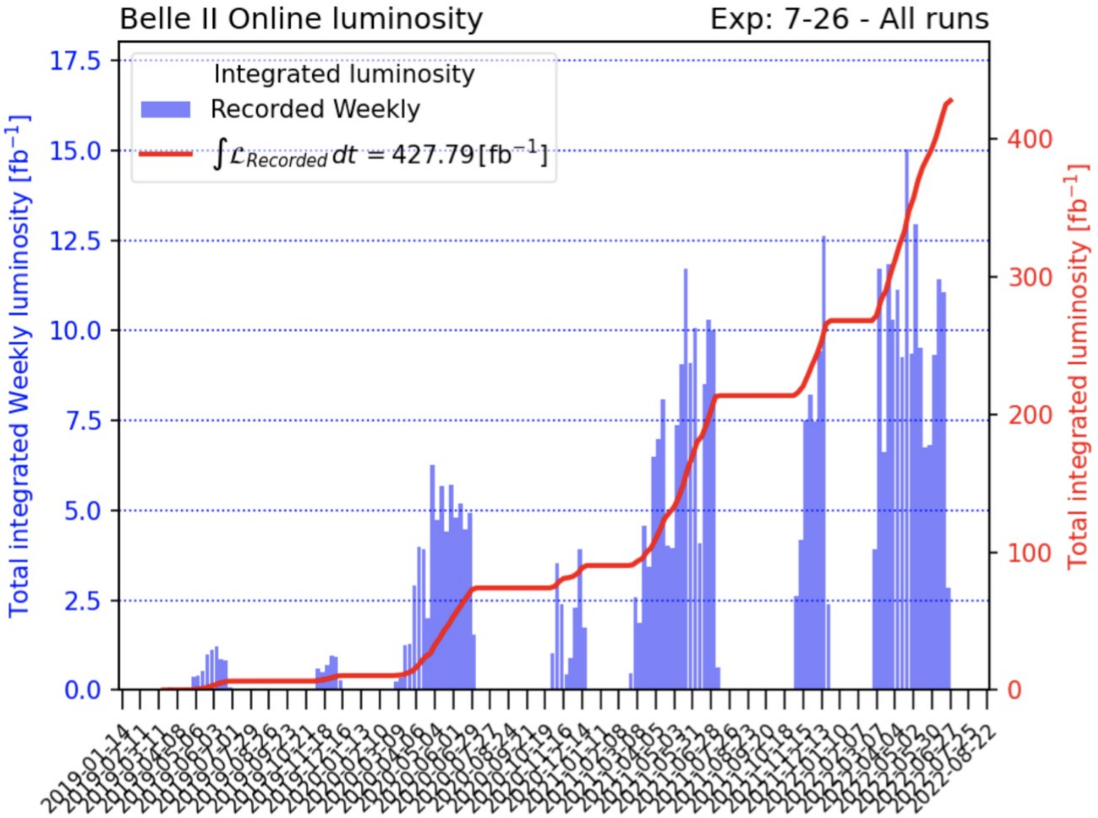
positrons (4 GeV)

Central Drift Chamber
Smaller cell size, long lever arm

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

Belle-II Luminosity





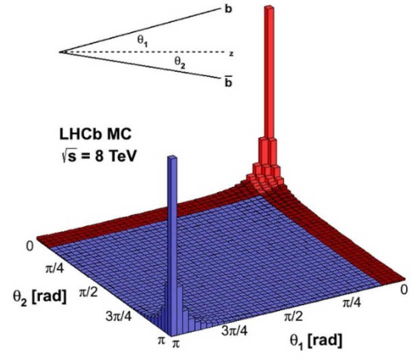
Belle II already achieve the world record instantaneous luminosity: $4.7 \times 10^{34}/cm^2/s$

Integrated luminosity: $427.79\ \mathrm{fb}^{-1}$

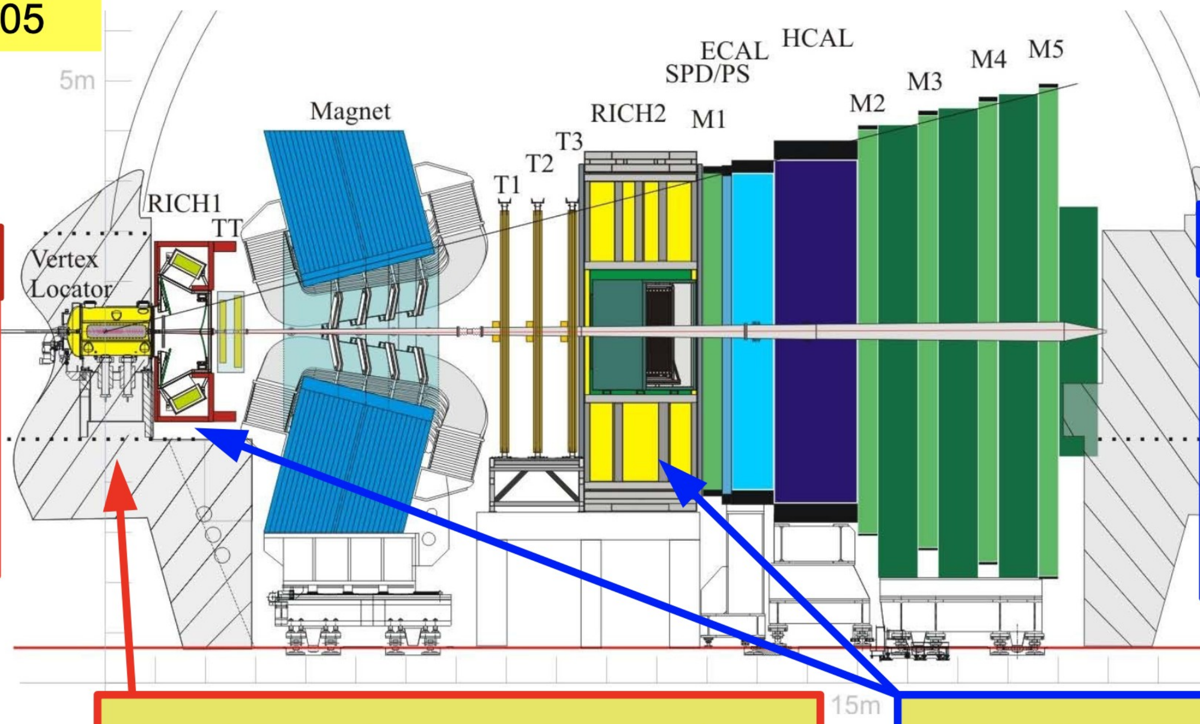
The LHCb detector

(2011-18 edition)

The LHCb Detector
JINST 3 (2008) S08005



VELO silicon strips



Precision primary and secondary vertex measurements

Excellent K/π separation capability

RICH PMTs

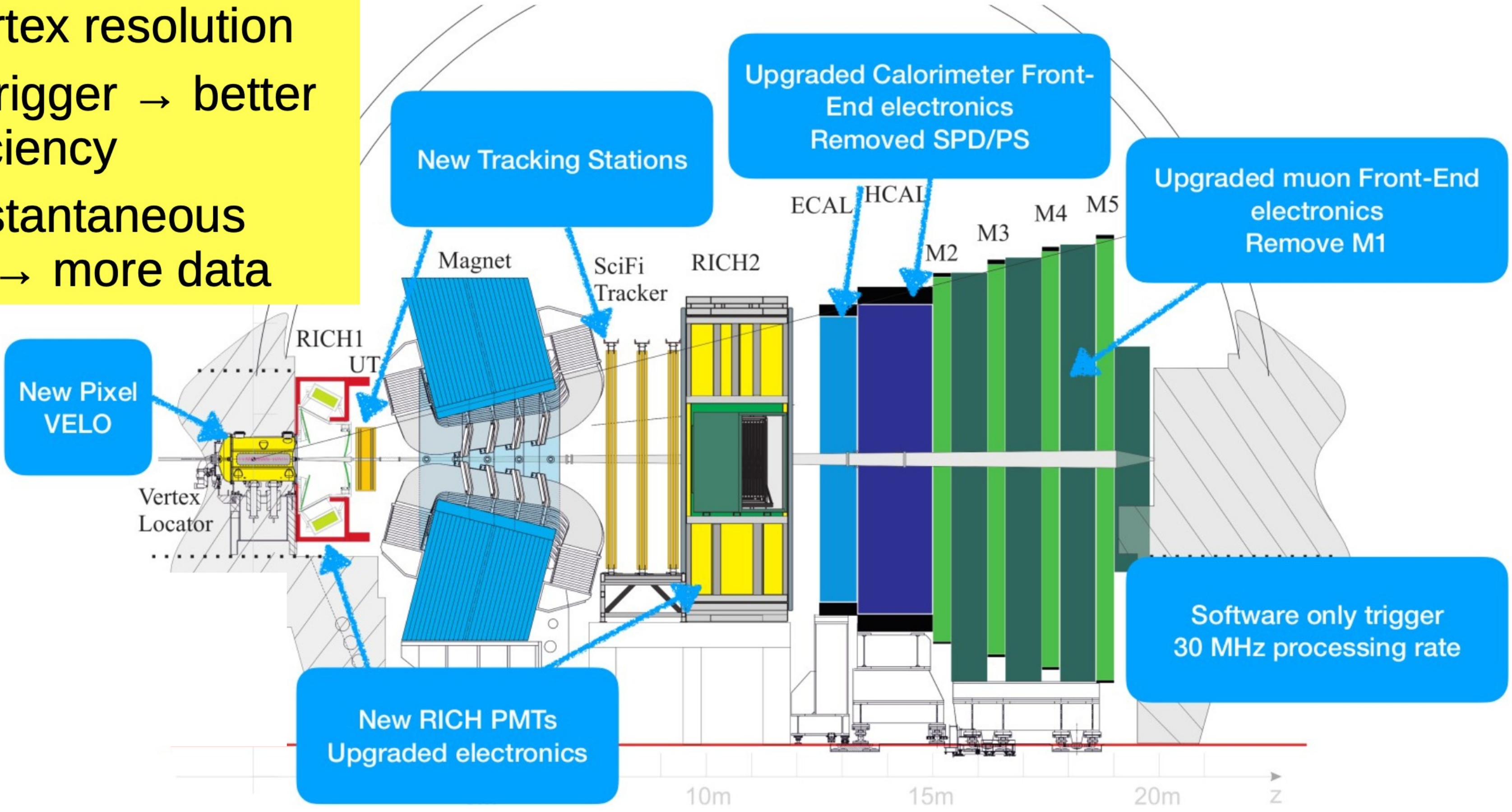
The LHCb detector

(2022-32 edition)

VELO pixels & thinned RF foil → better vertex resolution

All software trigger → better efficiency

Higher instantaneous luminosity → more data



New Tracking Stations

Upgraded Calorimeter Front-End electronics
Removed SPD/PS

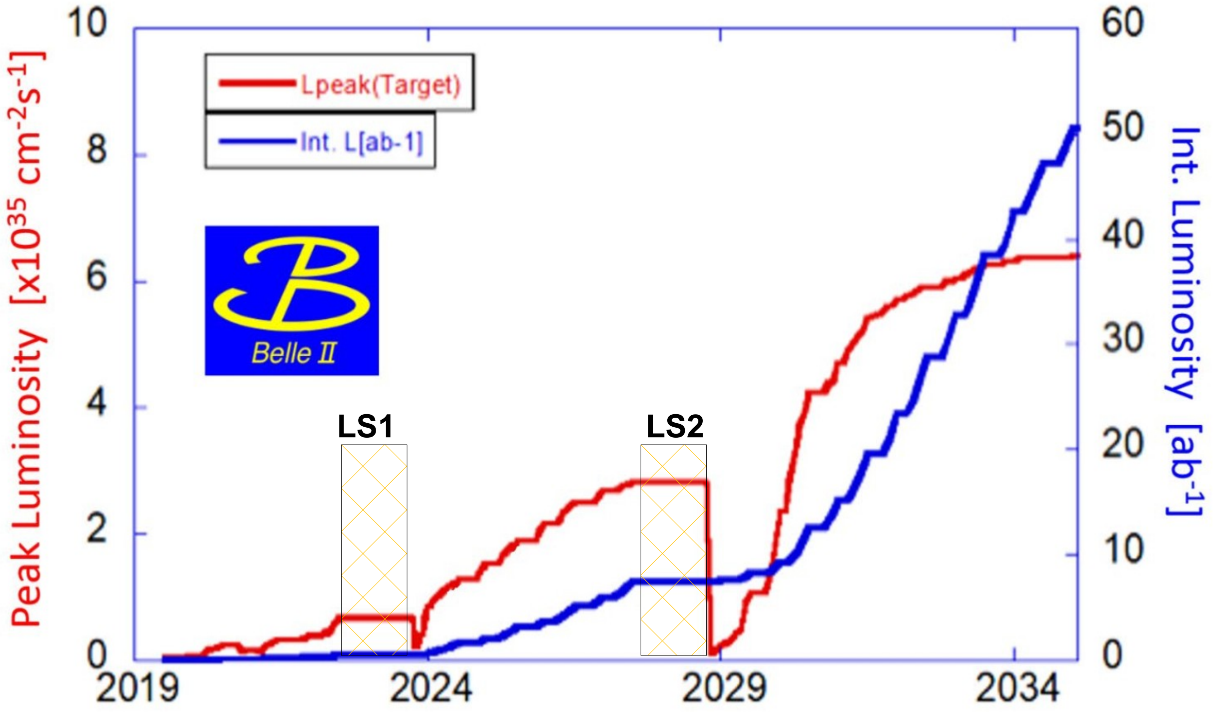
Upgraded muon Front-End electronics
Remove M1

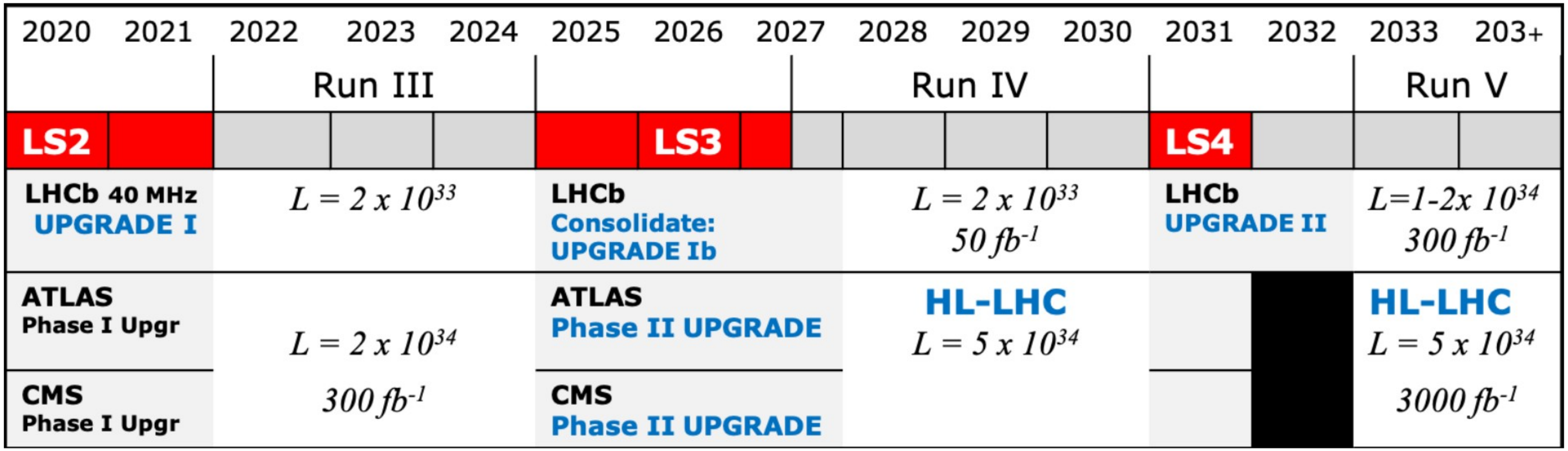
New Pixel VELO

Software only trigger
30 MHz processing rate

New RICH PMTs
Upgraded electronics

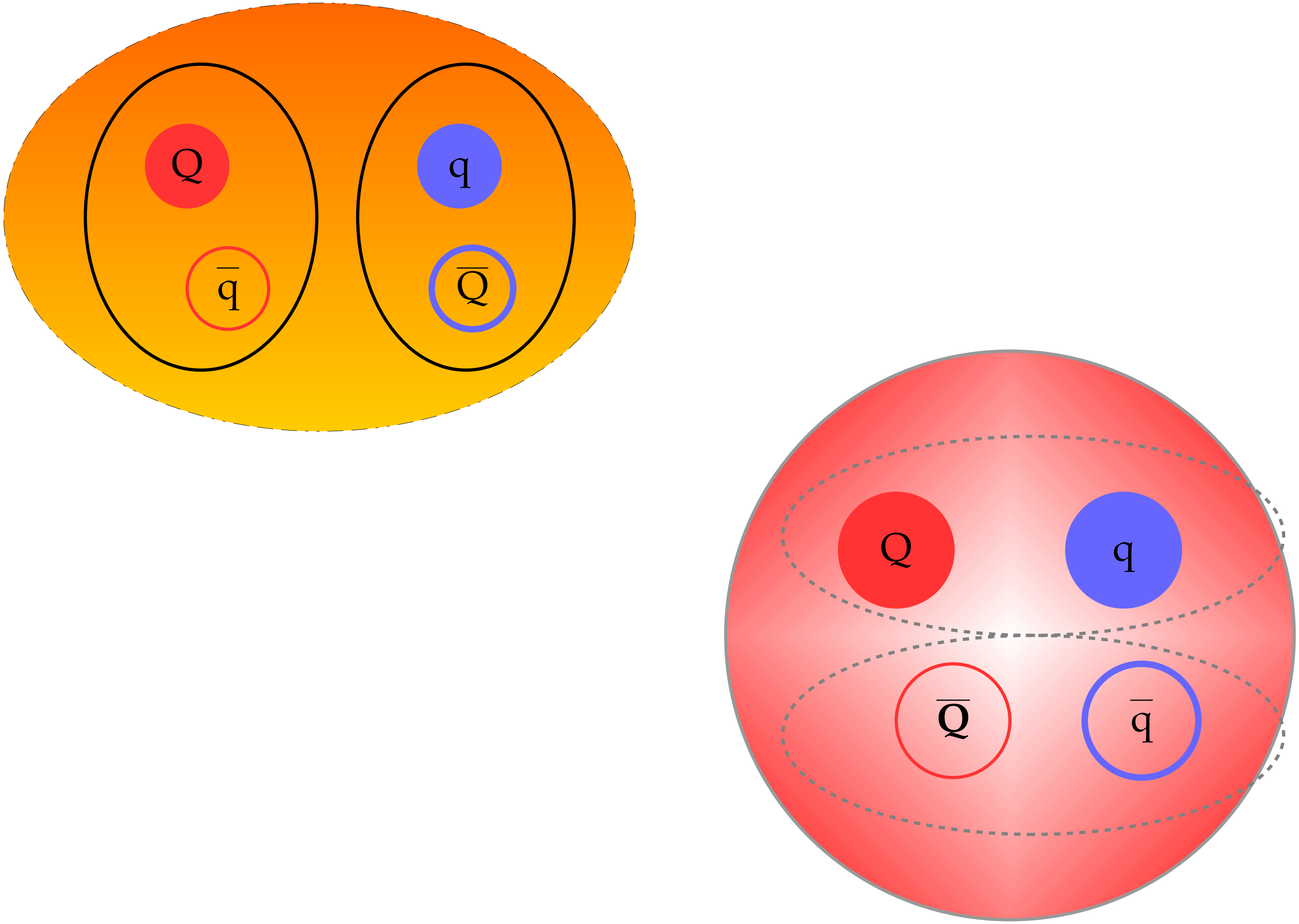
Plans for the 20's



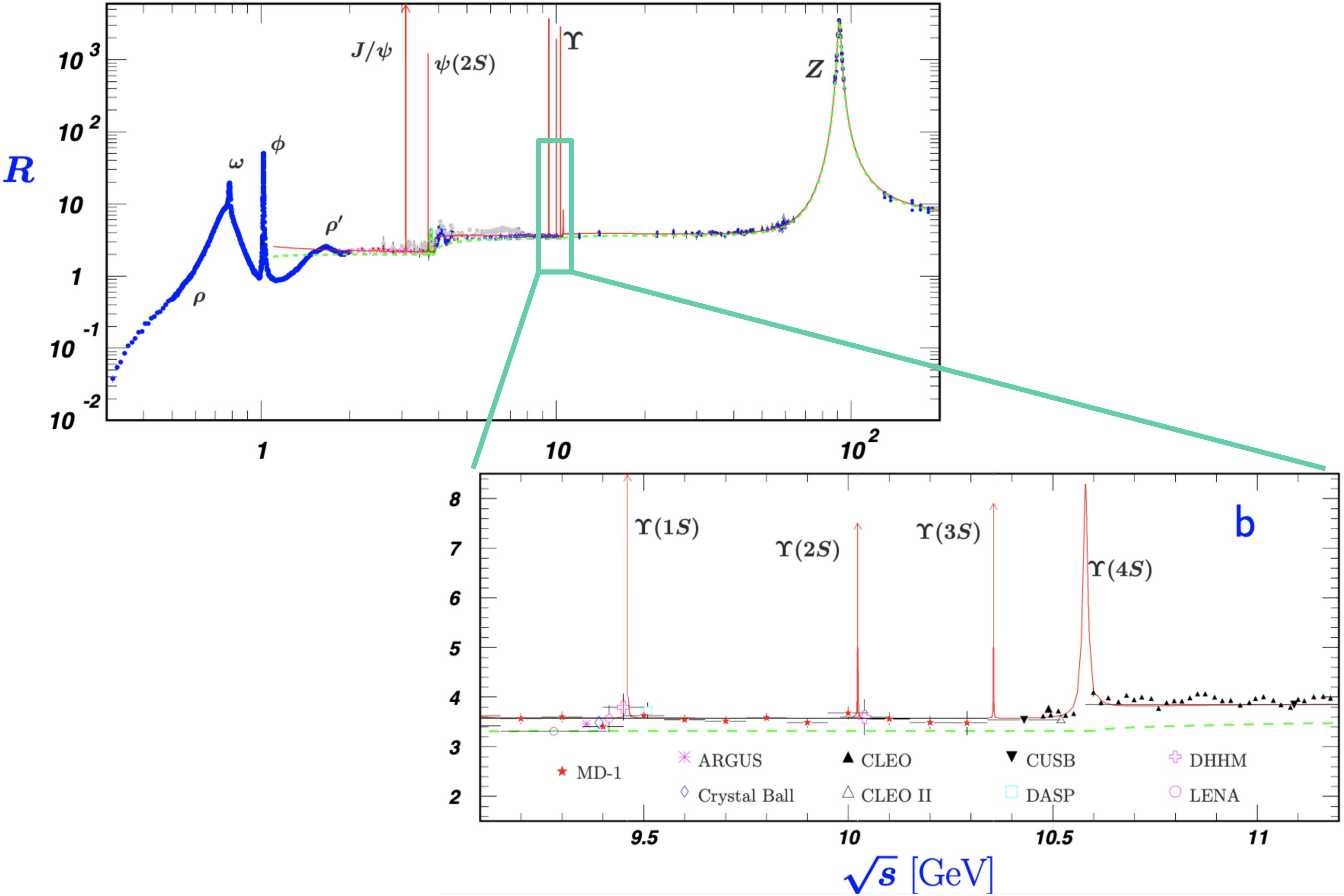


2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	203+
			Run III						Run IV				Run V	
LS2						**LS3**					**LS4**			
LHCb **40 MHz** **UPGRADE I**			$L = 2 \times 10^{33}$		**LHCb** **Consolidate:** **UPGRADE Ib**				$L = 2 \times 10^{33}$ $50\ fb^{-1}$		**LHCb** **UPGRADE II**		$L = 1\text{-}2 \times 10^{34}$ $300\ fb^{-1}$	
ATLAS **Phase I Upgr**			$L = 2 \times 10^{34}$ $300\ fb^{-1}$		**ATLAS** **Phase II UPGRADE**				**HL-LHC** $L = 5 \times 10^{34}$				**HL-LHC** $L = 5 \times 10^{34}$ $3000\ fb^{-1}$	
CMS **Phase I Upgr**					**CMS** **Phase II UPGRADE**									

Vector Tetraquarks



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

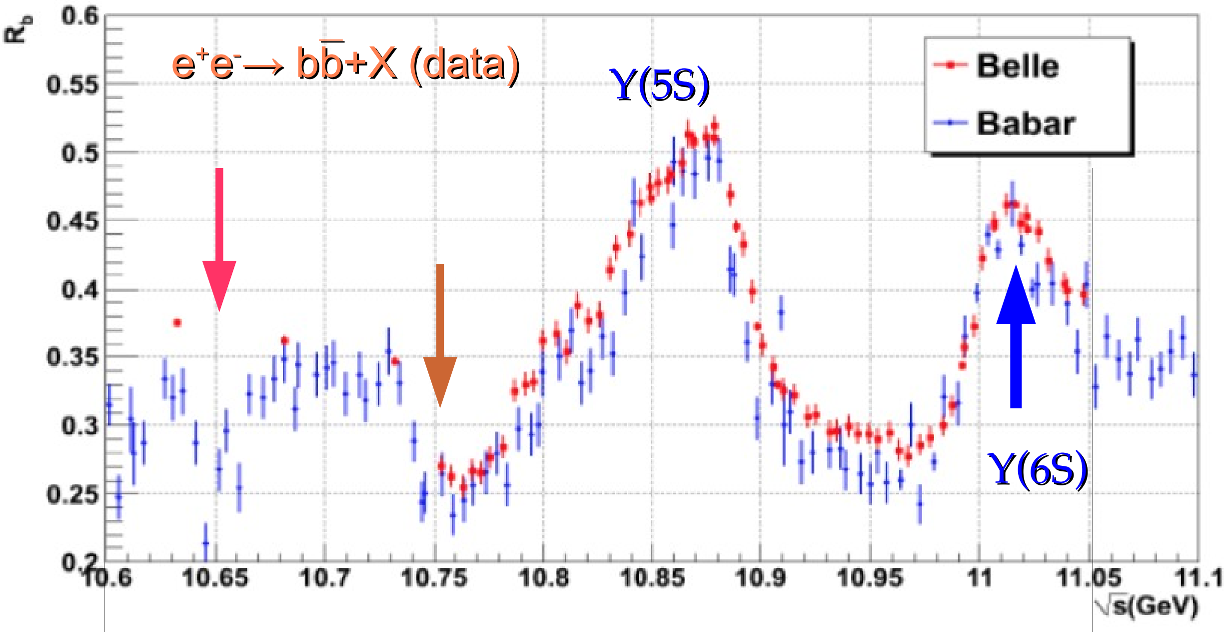


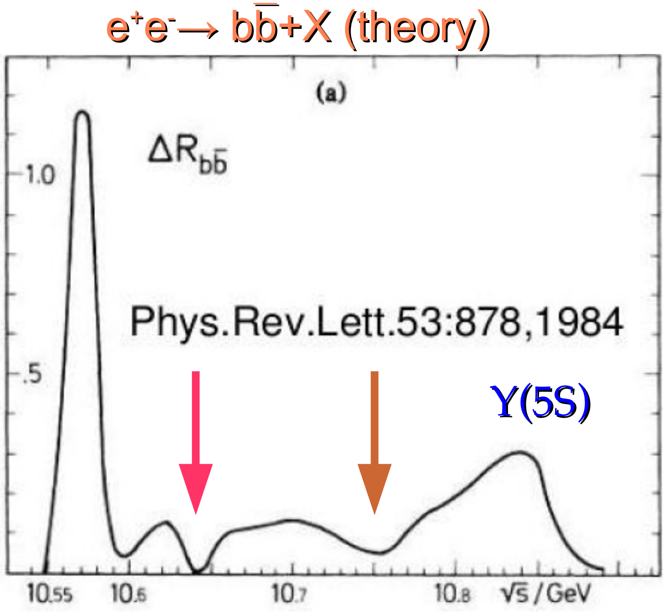
High energy scans

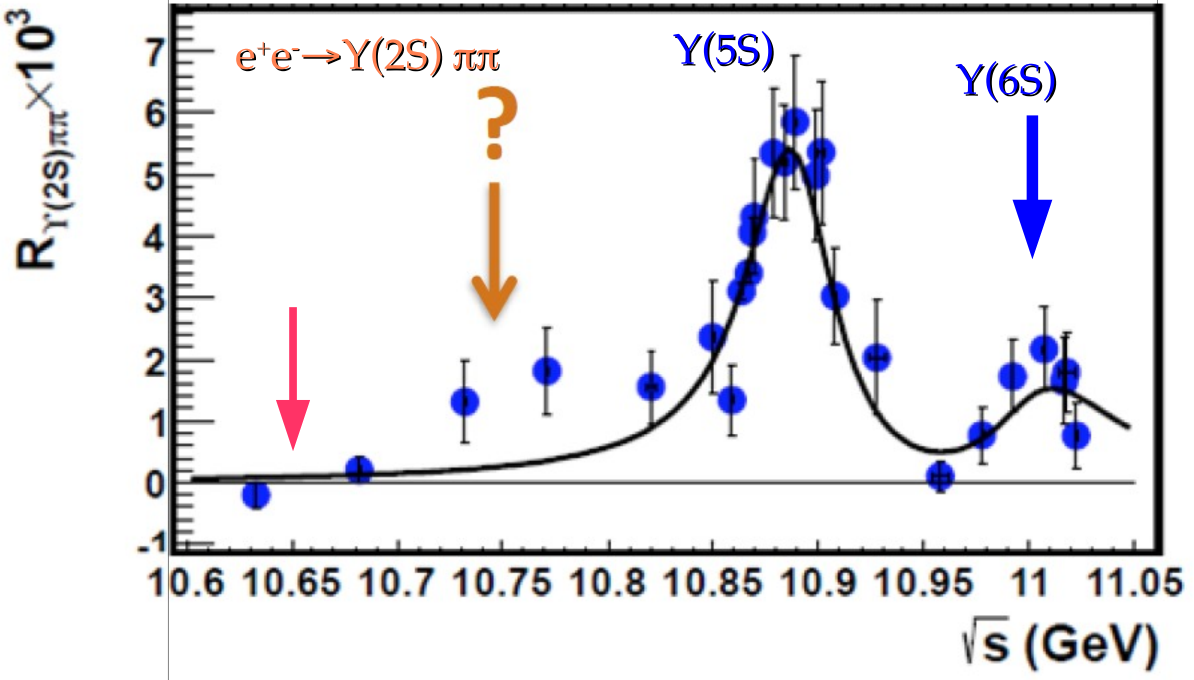
Belle data samples:
- 121.4 fb^{-1} on Υ(5S) peak, √s = 10865 GeV
- 61 points, 50 pb^{-1}, √s = 10.75-11.05 GeV
- 16 points, 1 fb^{-1} , √s = 10.63-11.02 GeV
- continuum data at √s = 10520 GeV

$R_b = \sigma(b\bar{b}+X)/\sigma(\mu\mu)$
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?**

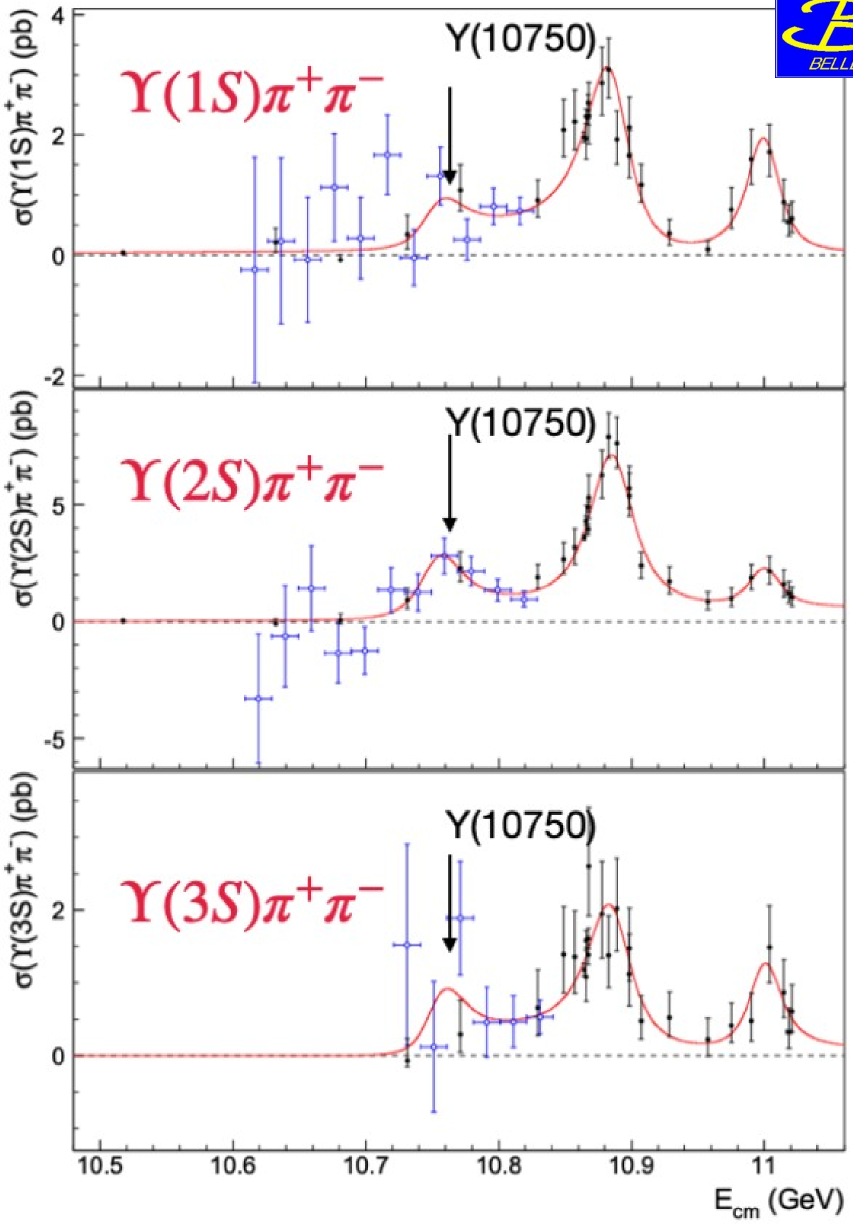






Discovery of Υ(10750)

BELLE:JHEP 10 (2019) 220

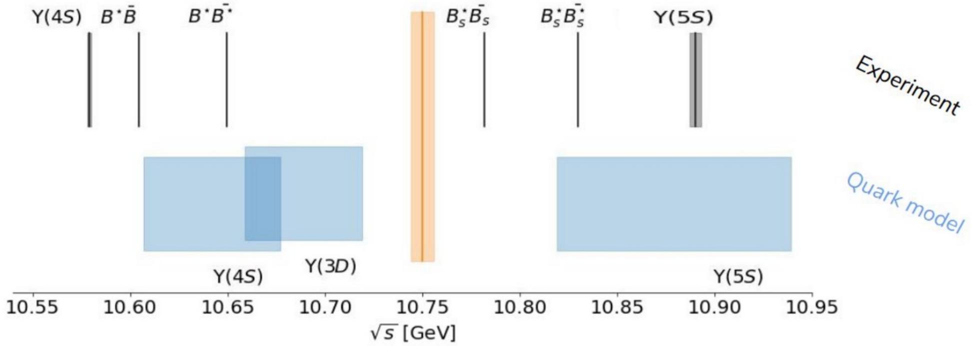


	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$

A wide variety of interpretations:

Conventional D- or S-D mixed state

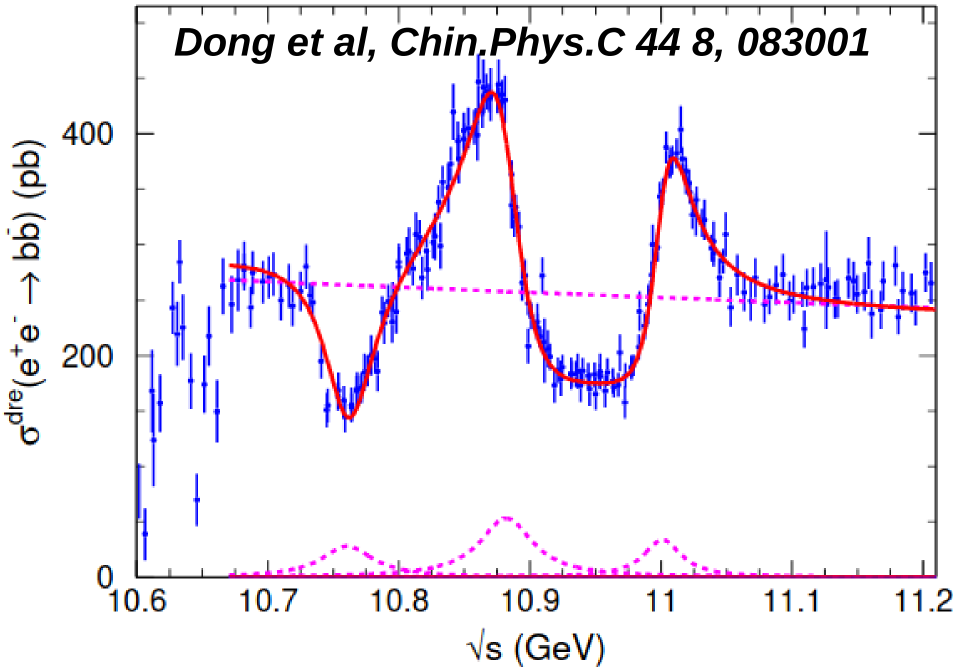
Chen et al., PRD 101 (2020) 1, 014020
Liang et al., PLB 803 (2020) 135340
Li et al., EPJC 80 (2020) 1, 59



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 (Υ(5S) is 4q)

Evidence of Y(10750) refitting the scans

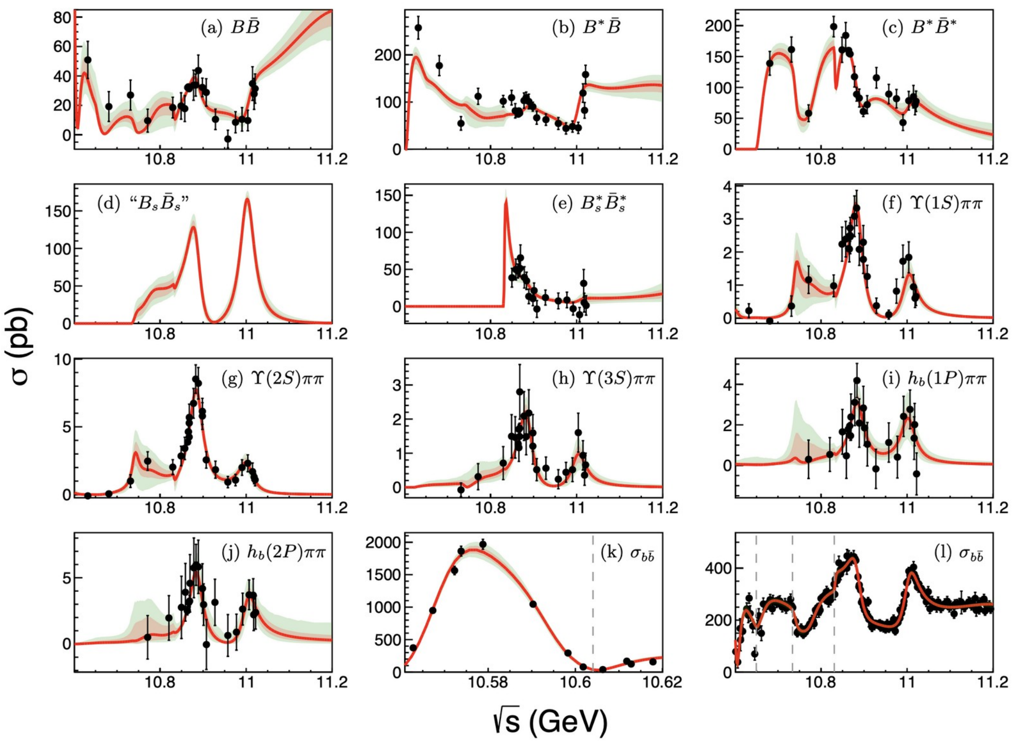


Dong et al, Chin.Phys.C 44 8, 083001

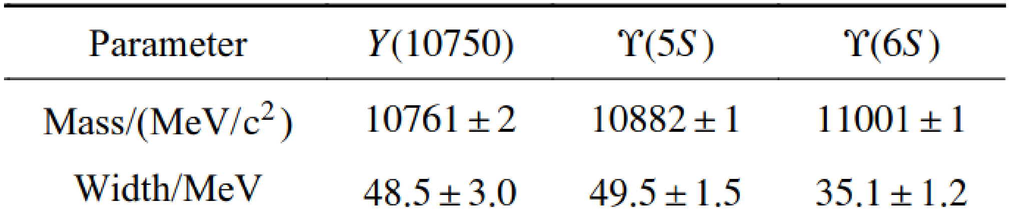
Refit of Babar and Belle data

Dip at 10750 generated by destructive interference with the continuum

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



Husken et al PRD 106 (2022) 9, 094013



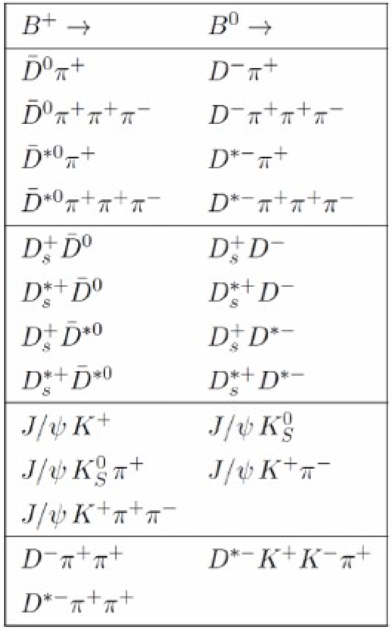
Parameter	$Y(10750)$	$\Upsilon(5S)$	$\Upsilon(6S)$
Mass/(MeV/c^2)	10761 ± 2	10882 ± 1	11001 ± 1
Width/MeV	48.5 ± 3.0	49.5 ± 1.5	35.1 ± 1.2

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

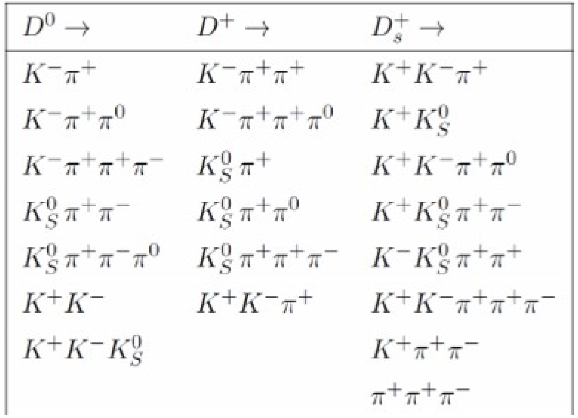
JHEP 06 (2021)137

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

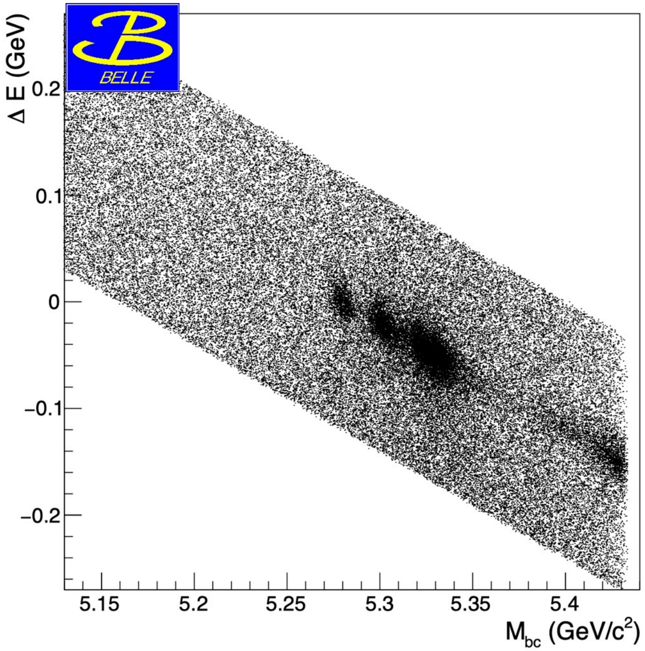
$$\Delta E' \equiv \Delta E - M_{bc} + M_B$$

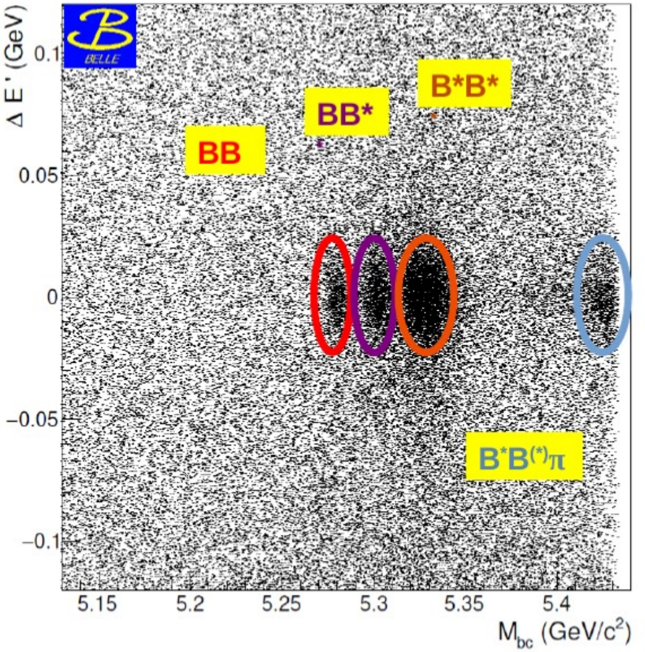
where

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

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

ε = (0.589 ± 0.012) 10–3
(25.5% higher than in Belle)

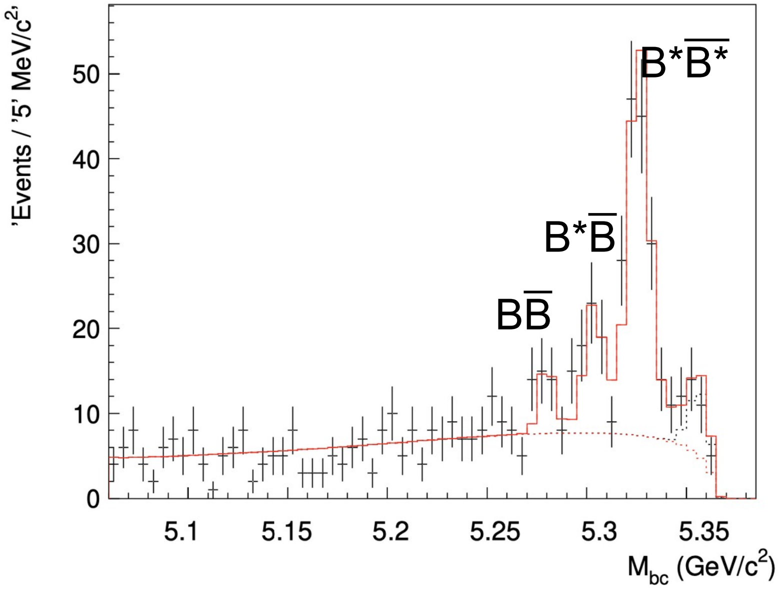


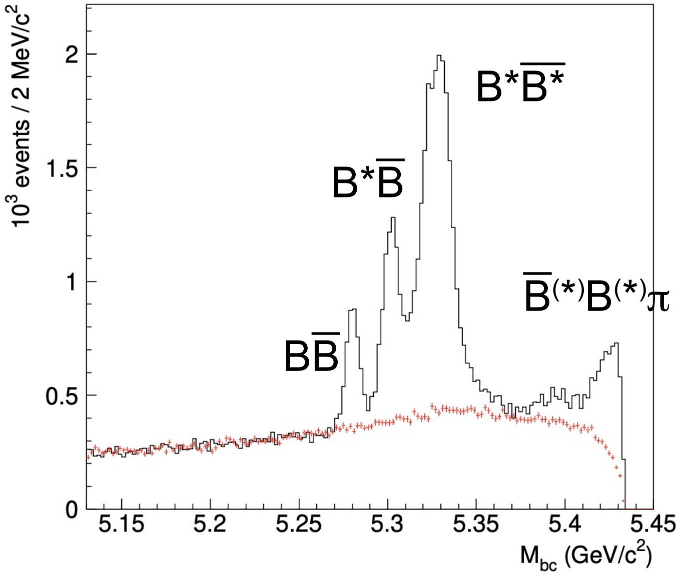


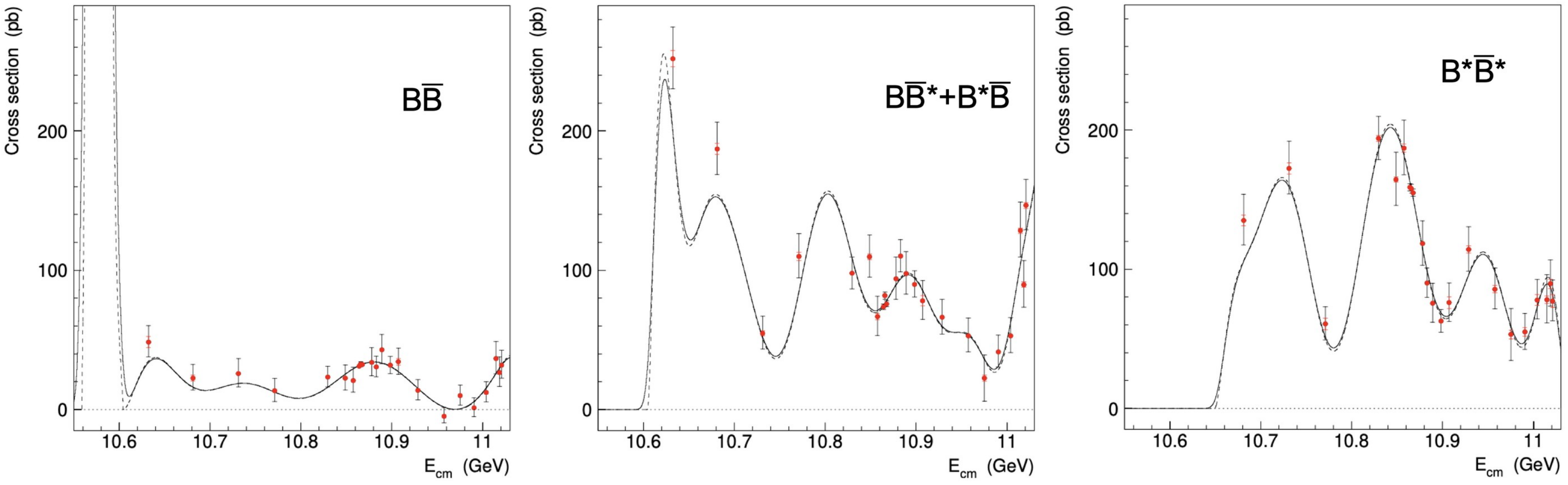
First full BB+BB*+B*B* separation of high energy scan data

JHEP 06 (2021)137

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

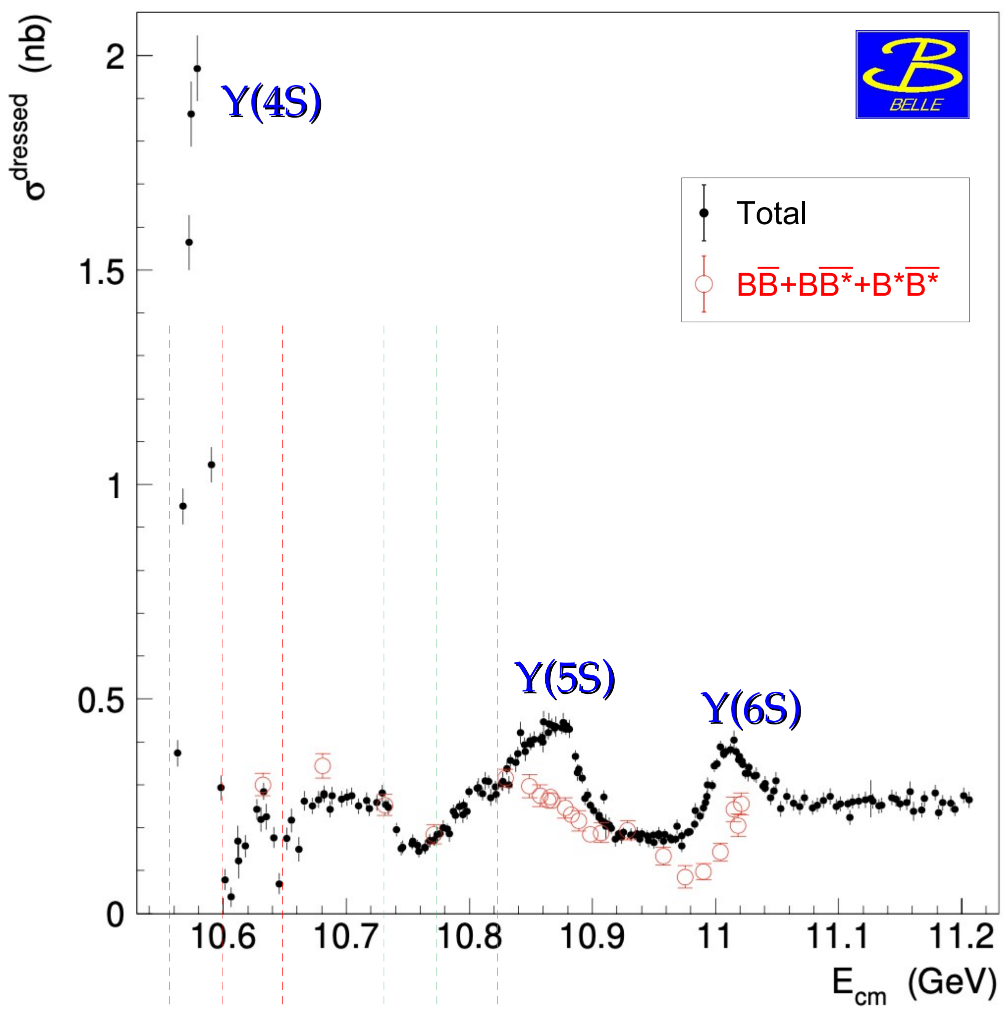


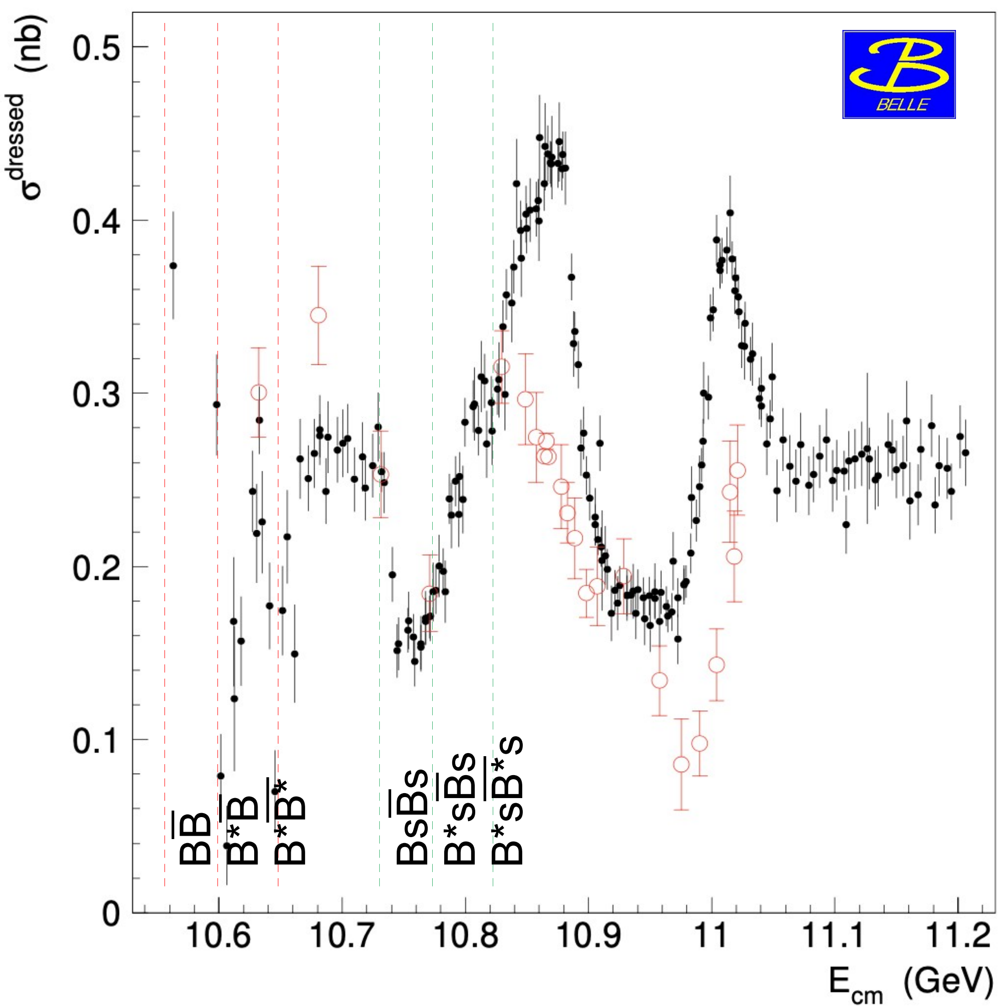




First full BB+BB*+B*B* separation of high energy scan data

JHEP 06 (2021)137



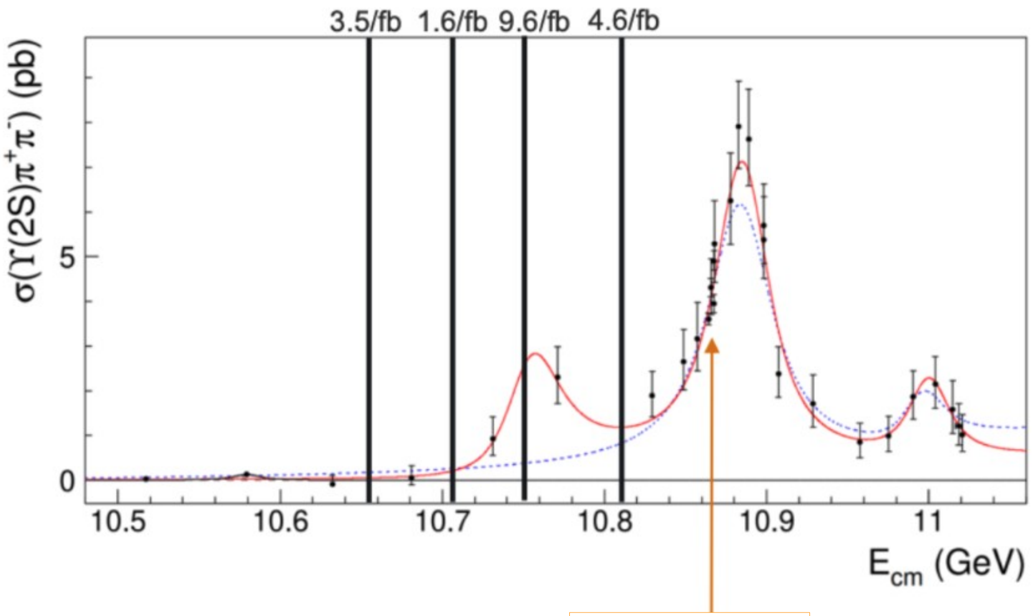


Features of the total cross section:
- dips in correspondance of BB* and B*B* thresholds
- kinks in proximity of BsBs and Bs*Bs* thresholds
- not peaking at the Y(5S) peak energy

Belle-II restarts from Y(10750)

Data taking outside the Y(4S) peak was very fruitful at Belle, with unique record data samples at Y(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 Y(4S) peak was to investigate the nature of the Y(10750): 4 points, 19.3/fb total.



Y(5S) peak

Mode	Status @ Belle
BBar decomposition	***JHEP 06 (2021) 137***
e^+e^- → ππY(nS)	***JHEP 10 (2019) 220***
Di-pion Dalitz	Need more data
Y(10750) → ω η_b(1S)	***PRD 102 (2020) 9, 092011(*)***
Y(10750) → ππ h_b(nP)	Need more data
Y(10750) → η h_b(1P)	Need more data
Y(10750) → Y(nS) inc.	Need more data
Y(10750) → ω χ_b(1P)	In pub / Need more points
Y(10750) → ηY(nS)	Need more data
Y(10750) → η'Y(nS)	Need more data

(*) only limits from Y(4S) and Y(5S) peaks

Many analyses, suggested by recent theory papers are ongoing.

First results from this dataset in the next slides ….

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

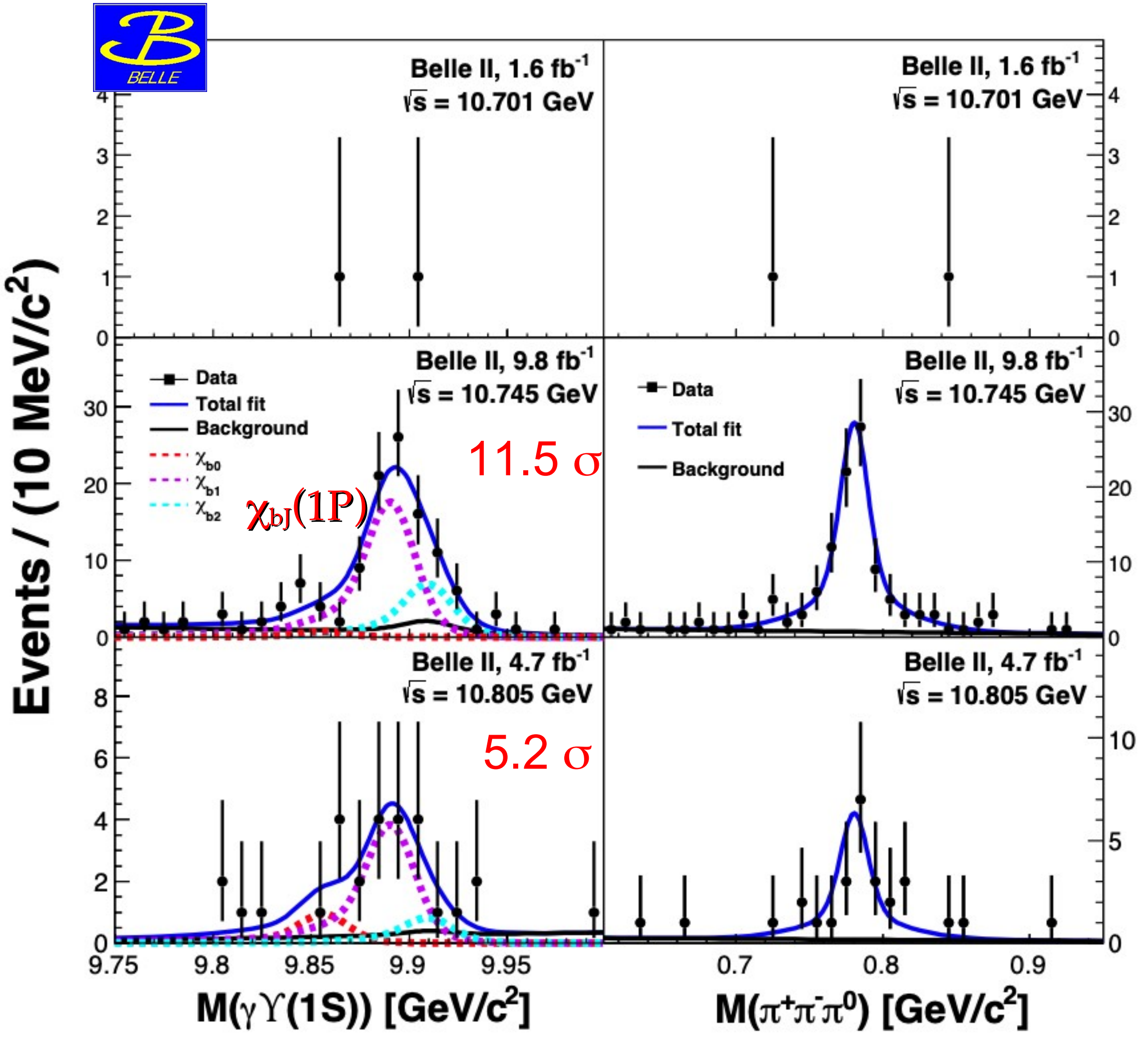
PRL 130, 091902 (2023)

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

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

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

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



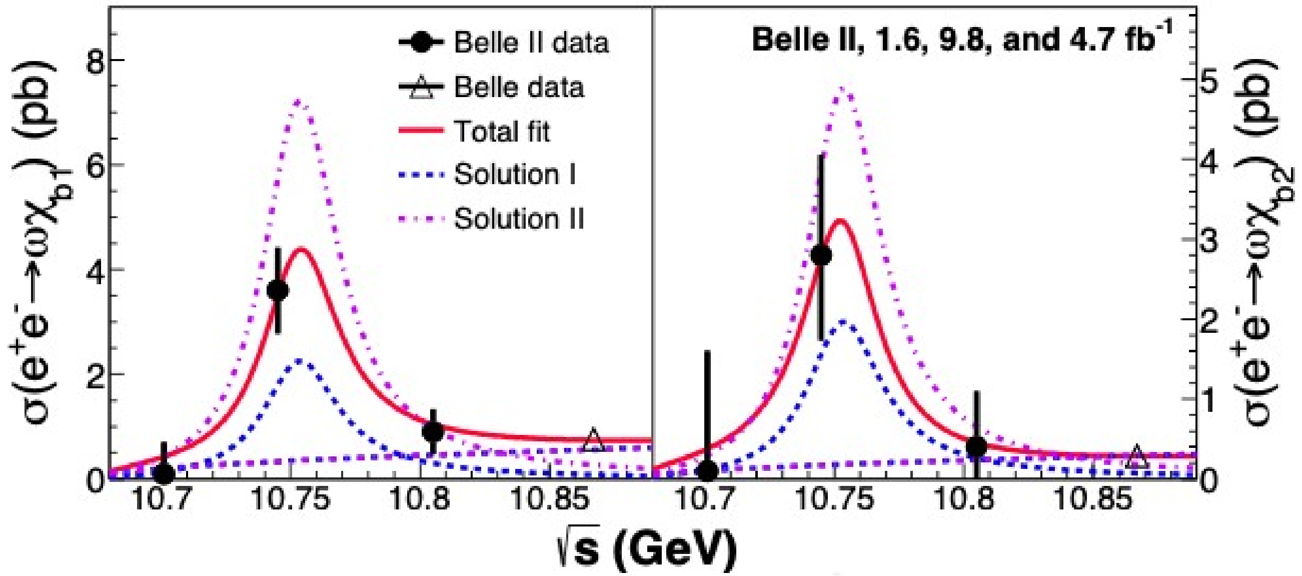
Observation of $\Upsilon(10750) \rightarrow \chi_{bJ}(1P)\,\omega$

PRL 130, 091902 (2023)

The signal seen is larger than $\Upsilon(10750) \rightarrow \Upsilon(2S)\,\pi^+\pi^-$

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

[1]PRL 113, 142001(2014)



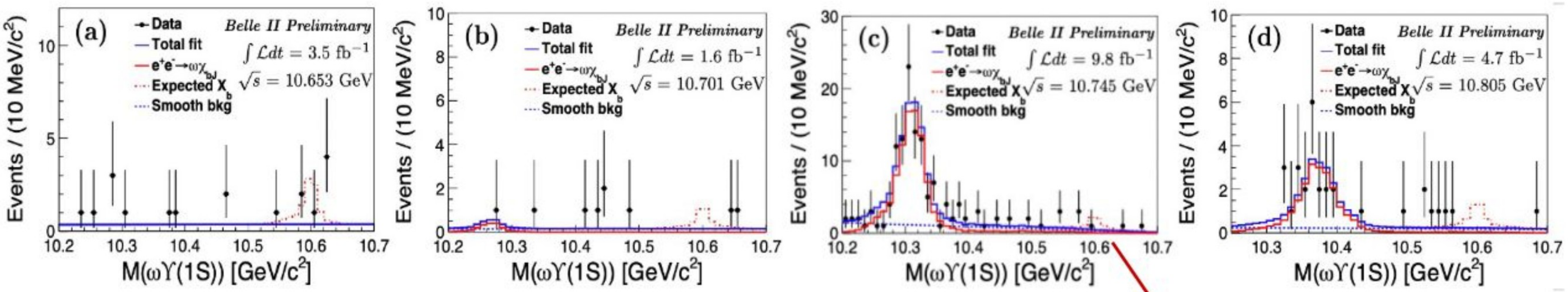
$\Gamma_{ee}\mathcal{B}_f$	Solution I	Solution II
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \rightarrow \omega\chi_{b1})$	$(0.63 \pm 0.39 \pm 0.20)$ eV	$(2.01 \pm 0.38 \pm 0.76)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \rightarrow \omega\chi_{b2})$	$(0.53 \pm 0.46 \pm 0.15)$ eV	$(1.32 \pm 0.44 \pm 0.55)$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

- $\dfrac{\Gamma_{ee}\mathcal{B}(\omega\chi_{b1/2})}{\Gamma_{ee}\mathcal{B}(\pi^+\pi^-\Upsilon(2S))^{[2]}} \sim 1.5$ for $\Upsilon(10753)$ and ~ 0.1 for $\Upsilon(10870)$

[2]. JHEP 10, 220(2019)

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.

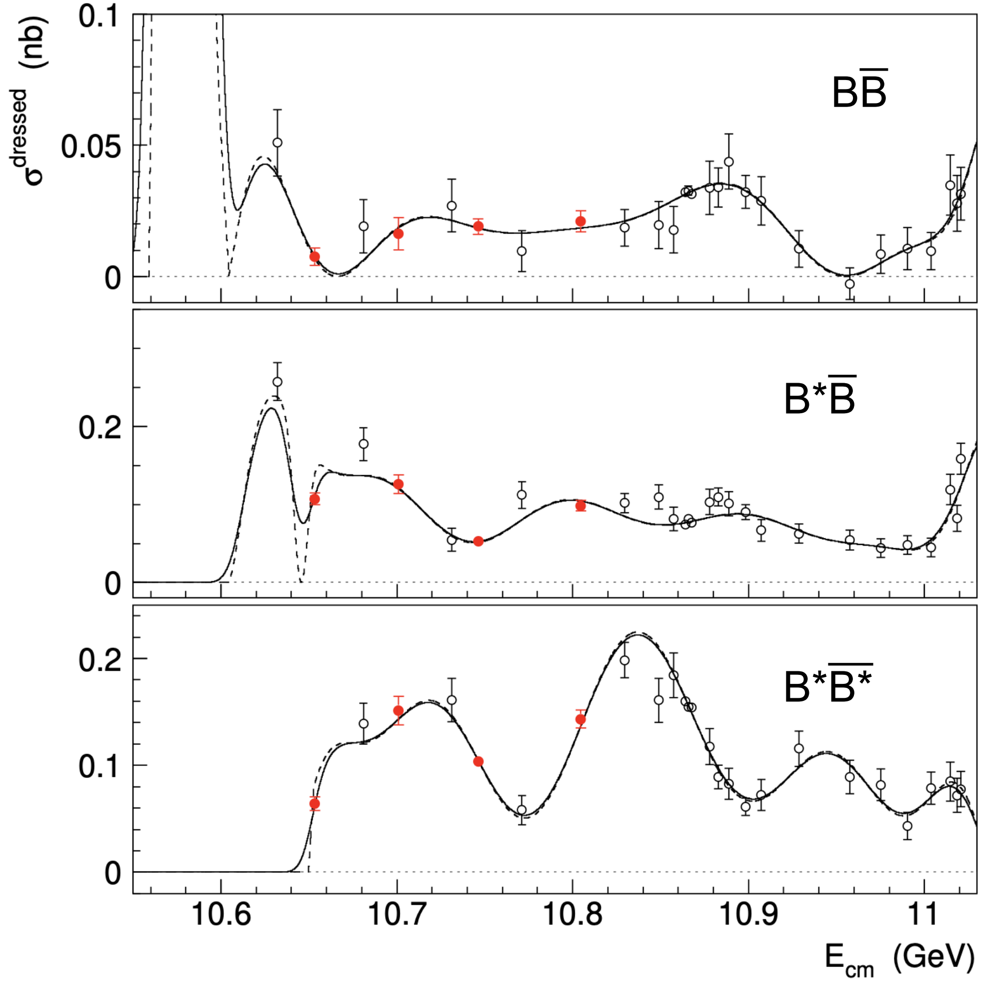
- No significant X_b signal is observed.
- The peaks are the reflections of $e^+e^- \to \omega\chi_{bJ}$.

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)

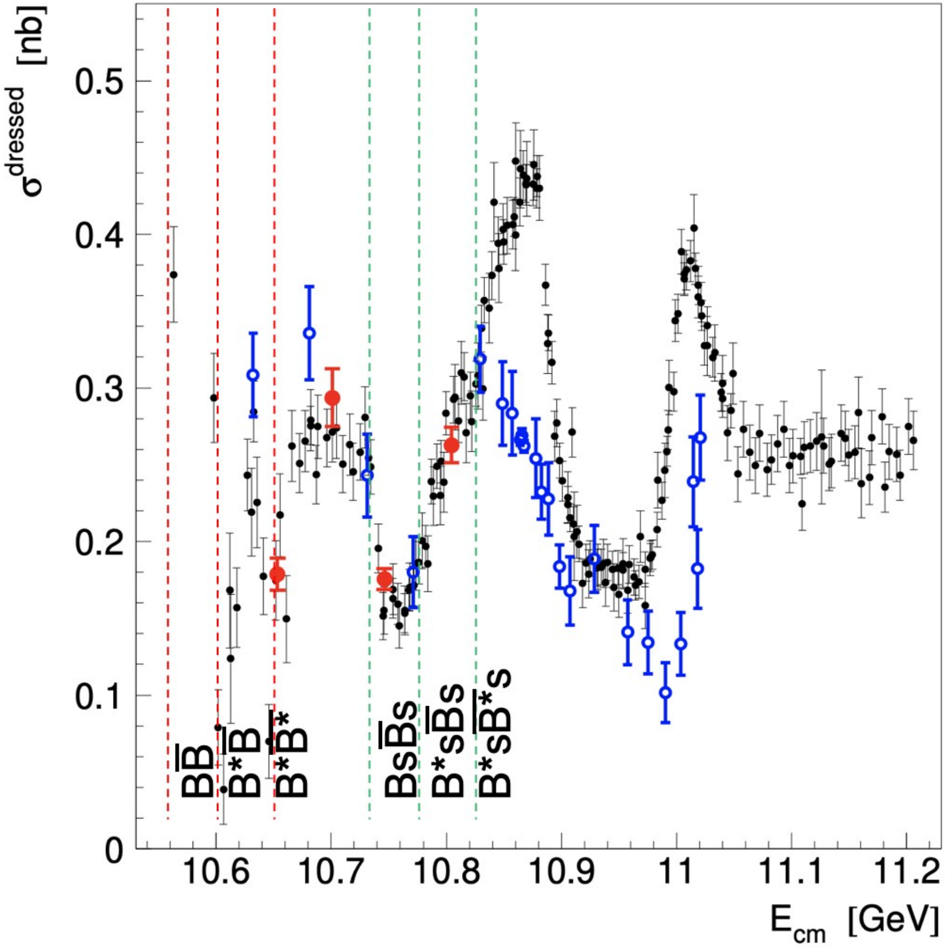
The bottomonium analogue of X(3872) is still missing ...

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

Shown at Moriond QCD 2023, submitted to JHEP



Individual 2-body cross sections fitted with Chebychev polinomials

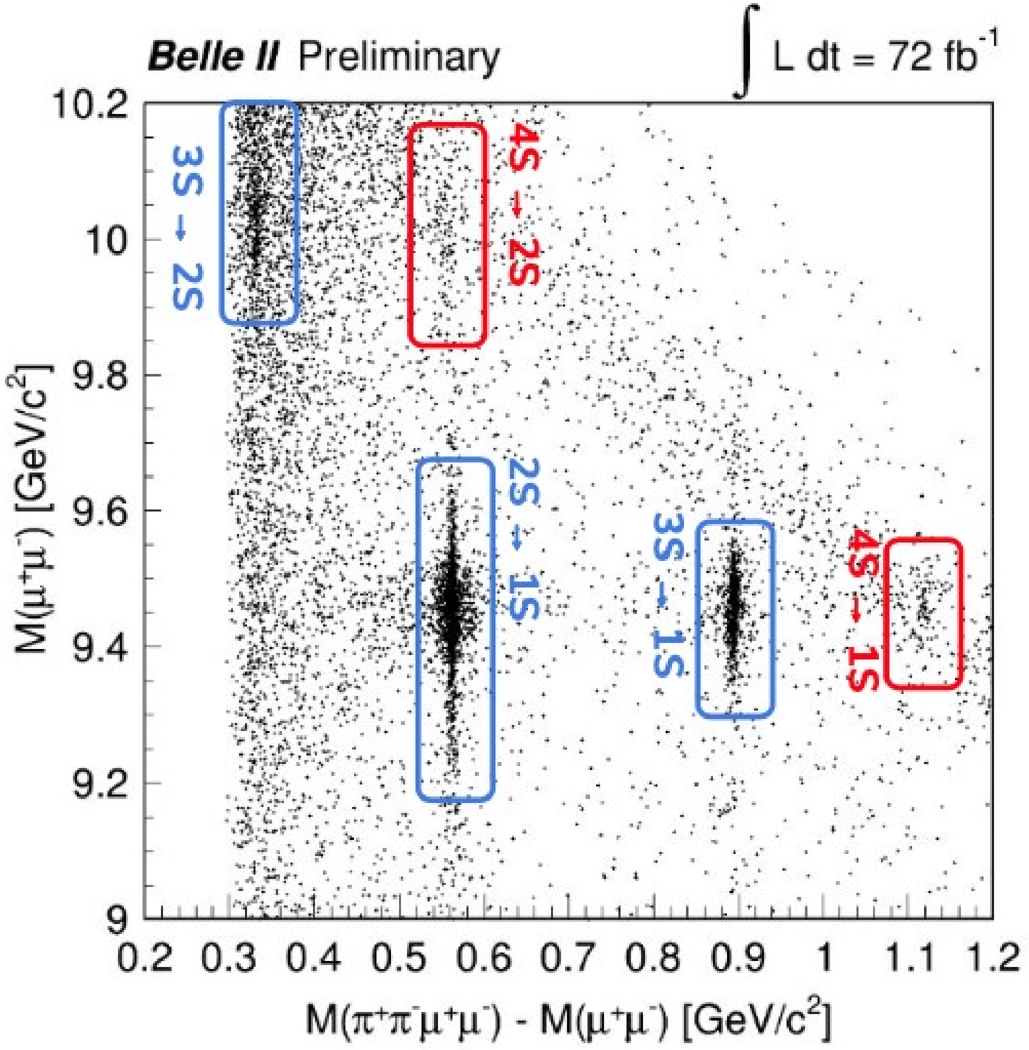


Total cross section: the four new points are in red.

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

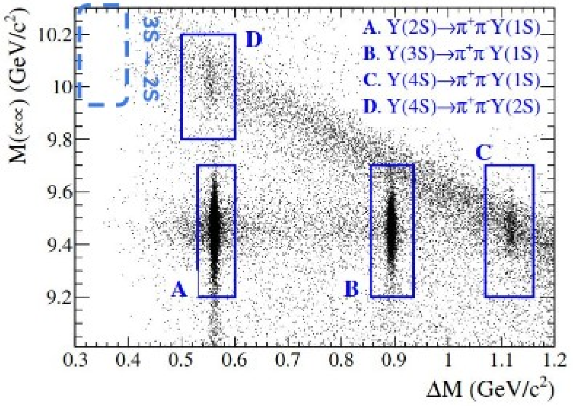


Study $e^+e^- \to \pi^+\pi^-\mu^+\mu^-$ (+γ undetected)

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

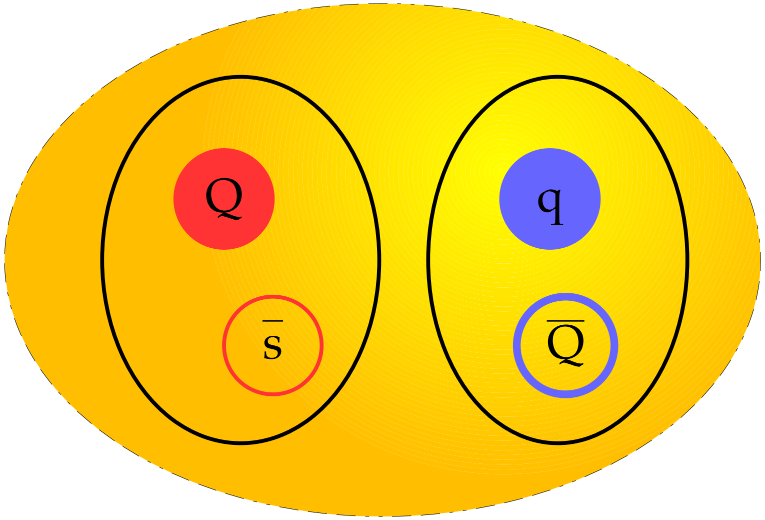
Compare with Belle, 496 fb^{-1} [PRD 96 (2017) 5, 052005]

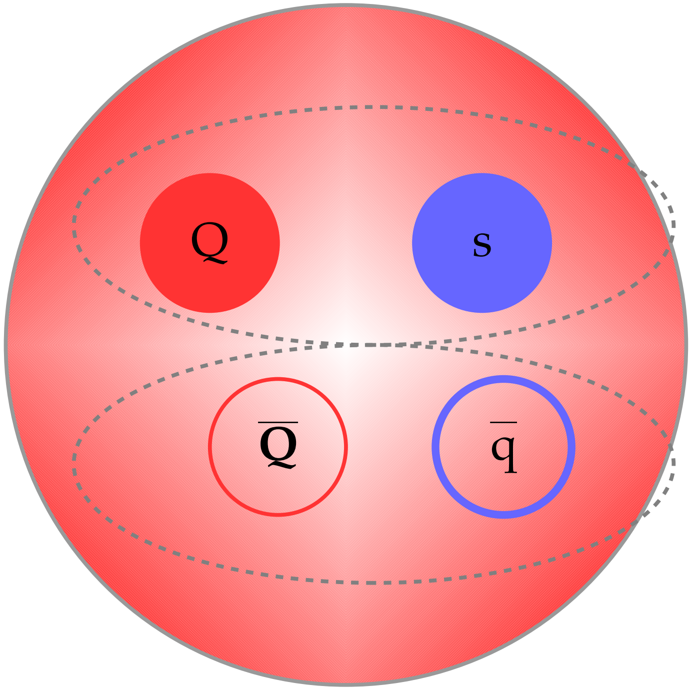
- Improved low momentum tracking



Stay tuned !

Strange Tetraquarks





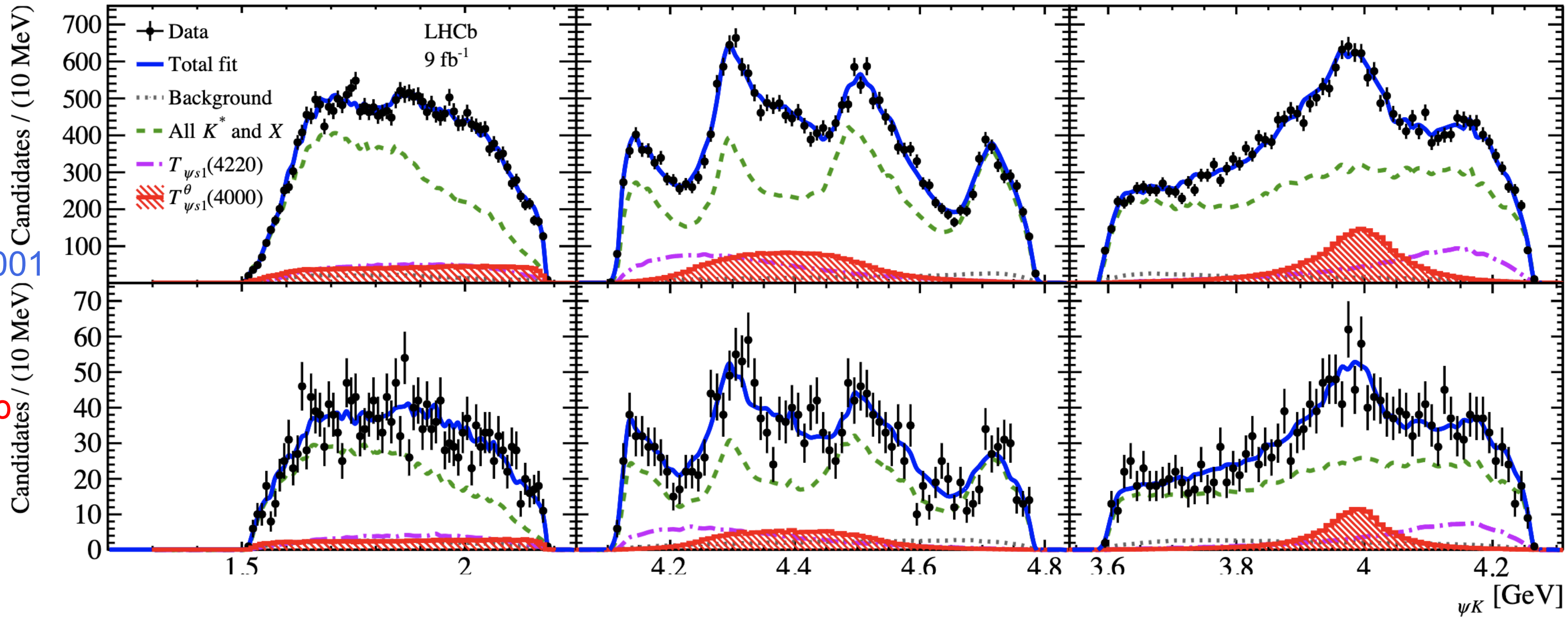
New charmed strange tetraquarks from LHCb

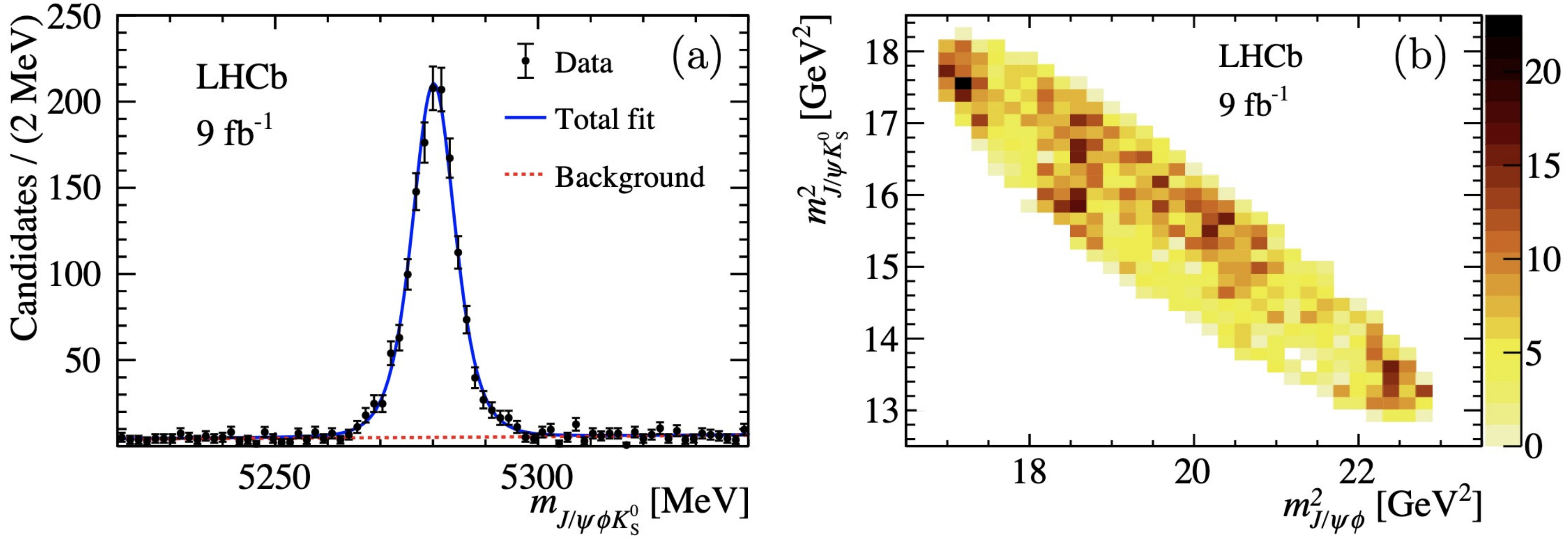
B± → $J/\psi\ \phi\ K^{\pm}$

PRL127(2021)082001

$B^0 \to J/\psi\ \phi\ K_s^0$

ArXiV:2301.04899





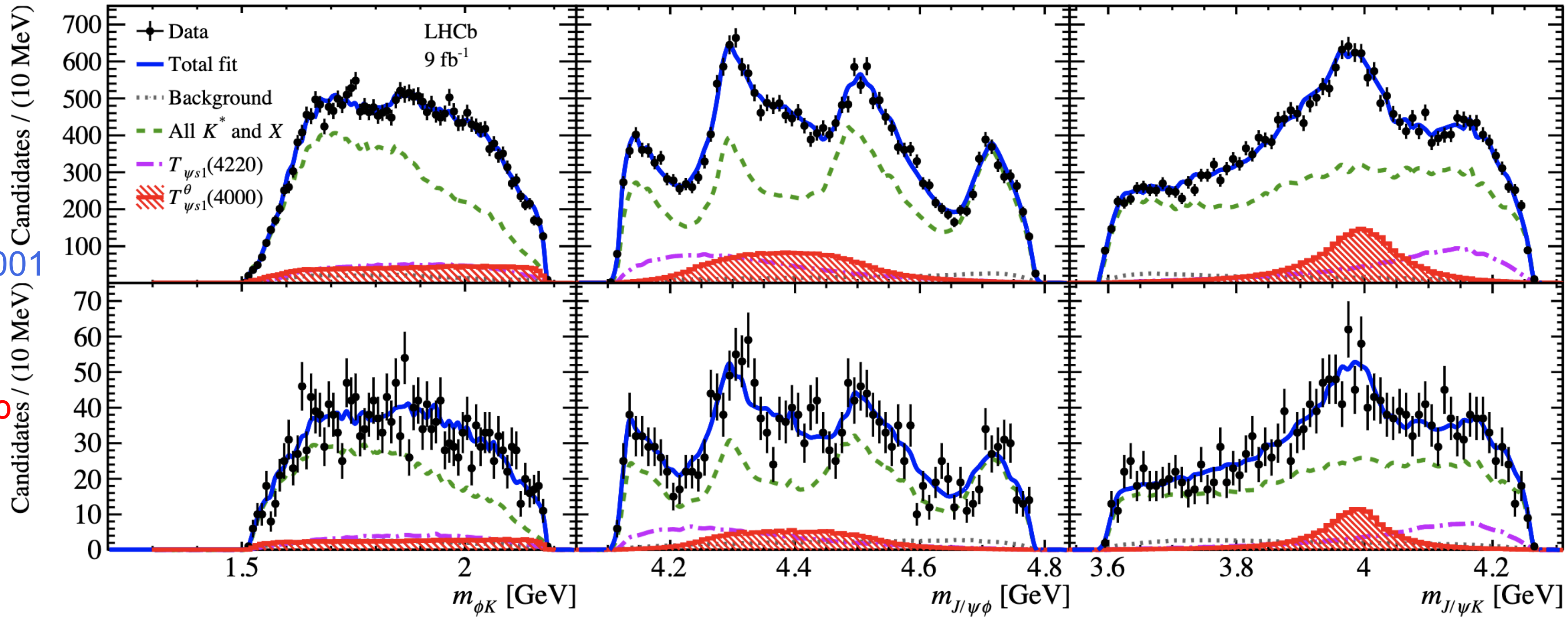
New charmed strange tetraquarks from LHCb

$B^{\pm} \rightarrow J/\psi\, \phi\, K^{\pm}$

PRL127(2021)082001

$B^{o} \rightarrow J/\psi\, \phi\, K_s^{o}$

ArXiV:2301.04899



Independent measurement of mass and width of the neutral partner of $T^2_{c\bar{c}s}(4000)^+$

$$M(T^{\theta}_{\psi s1}(4000)^0) = 3991\,^{+12}_{-10}\,^{+\ 9}_{-17}\ \mathrm{MeV}$$

$$\Gamma(T^{\theta}_{\psi s1}(4000)^0) = \ 105\,^{+29}_{-25}\,^{+17}_{-23}\ \mathrm{MeV}$$

Isospin partner mass splitting:

$$\Delta M = -12\,^{+11}_{-10}\,^{+6}_{-4}\ \mathrm{MeV}$$

$T^2_{c\bar{c}s}(4220)^0$ mass and width fixed to the values of the isospin partner $T^2_{c\bar{c}s}(4220)^+$

Most likely spin assignment for both J/ψ K resonances :

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

(*) $T^2_{c\bar{c}s}$(PDG) = $T^2_{\psi s1}$(LHCb)

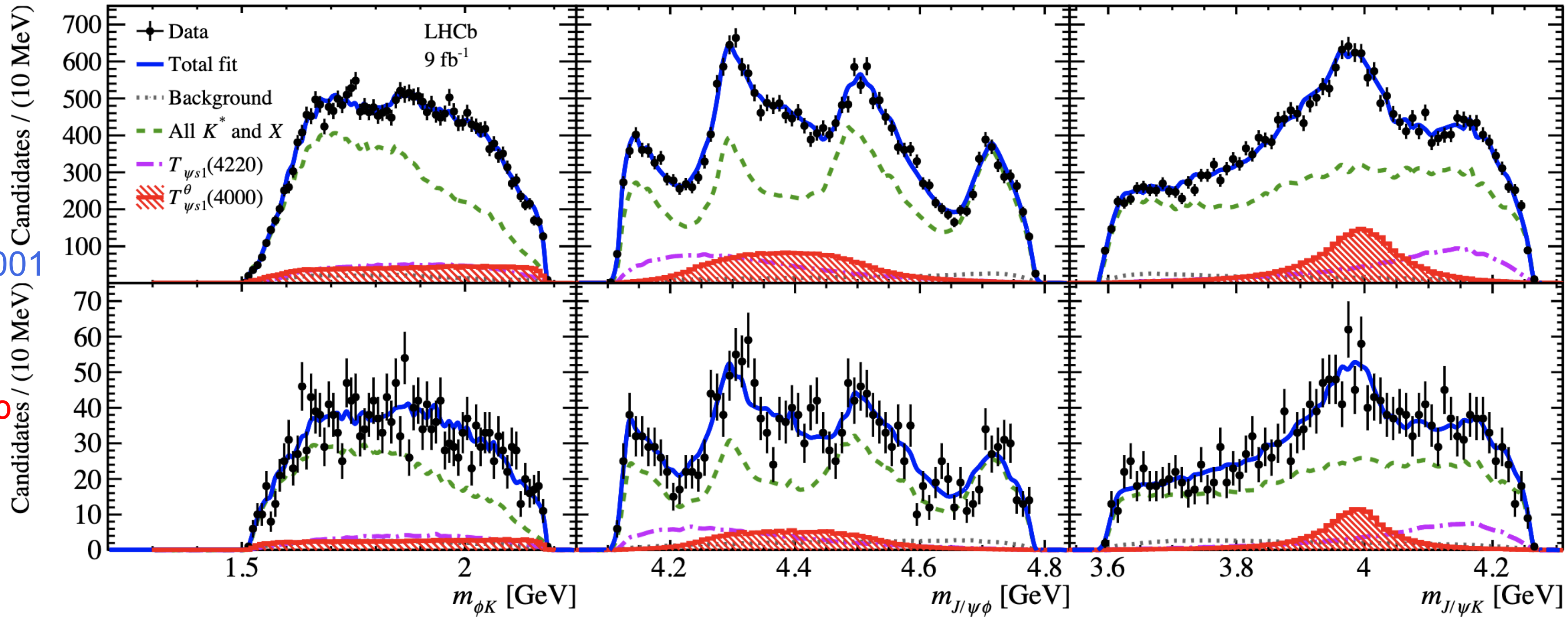
New charmed strange tetraquarks from LHCb

$B^\pm \to J/\psi\ \phi\ K^\pm$

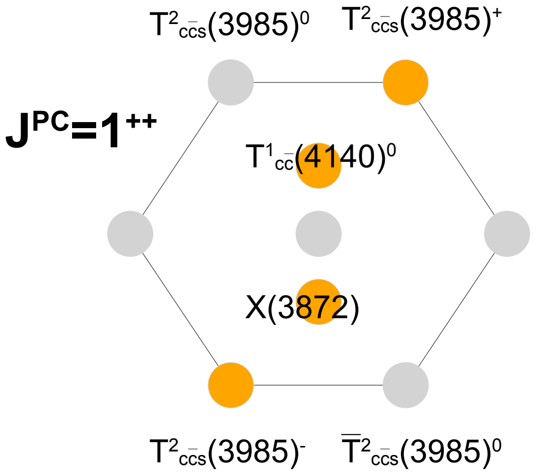
PRL127(2021)082001

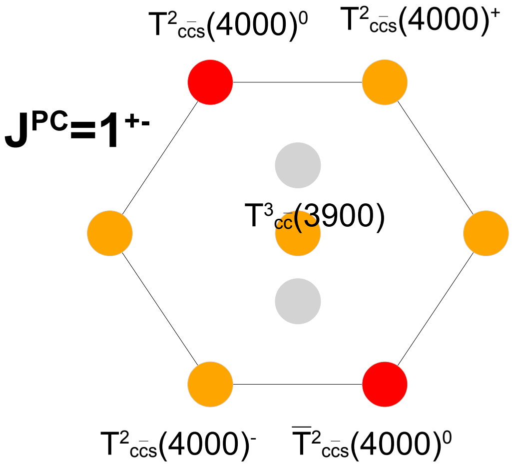
$B^0 \to J/\psi\ \phi\ K_s^0$

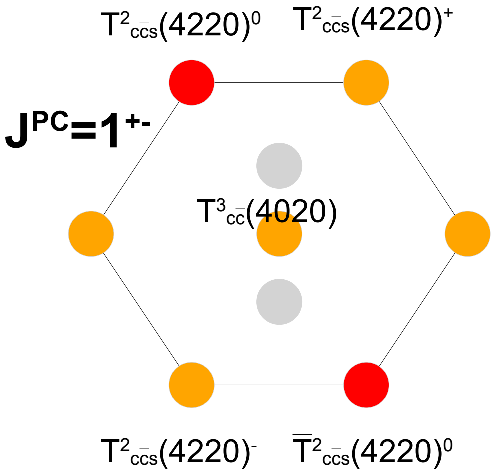
ArXiV:2301.04899



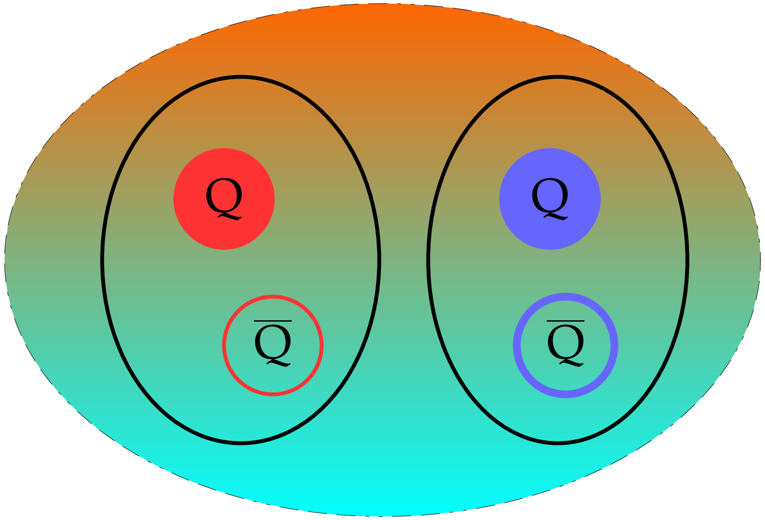
Maiani et al, J. SCI.B. 2021 04 040 (2021)

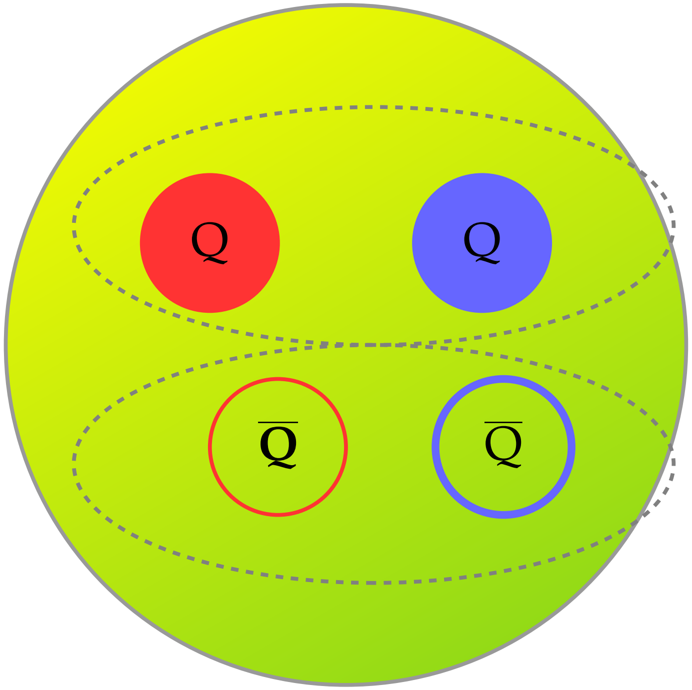






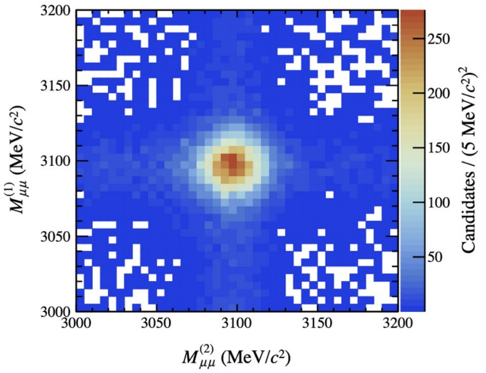
Doubly heavy Tetraquarks

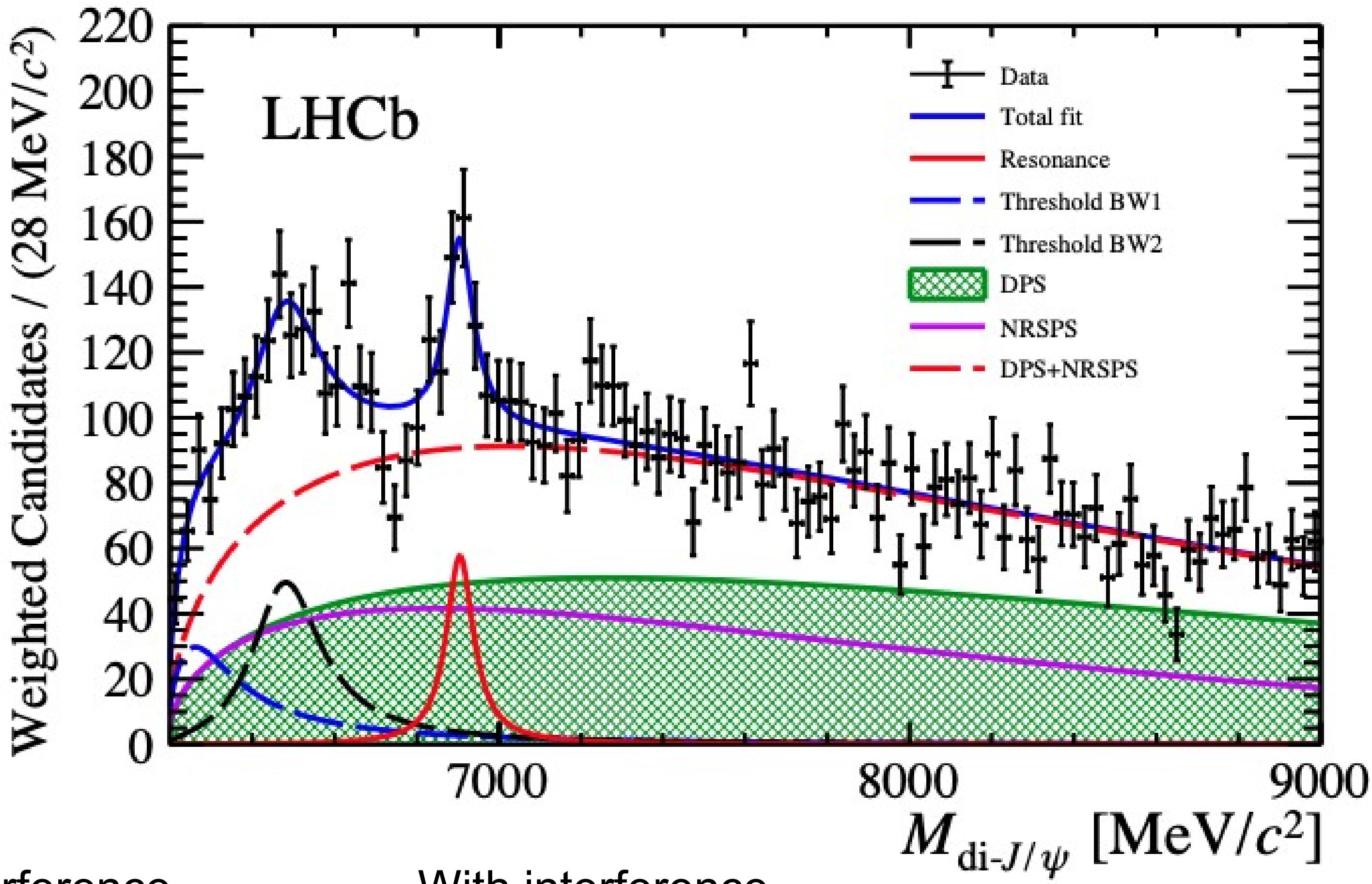




Discovery of Double J/ψ at LHCb

Sci.Bull. 65 (2020) 23, 1983





Simple BW without interference

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\mathrm{MeV}/c^2$$

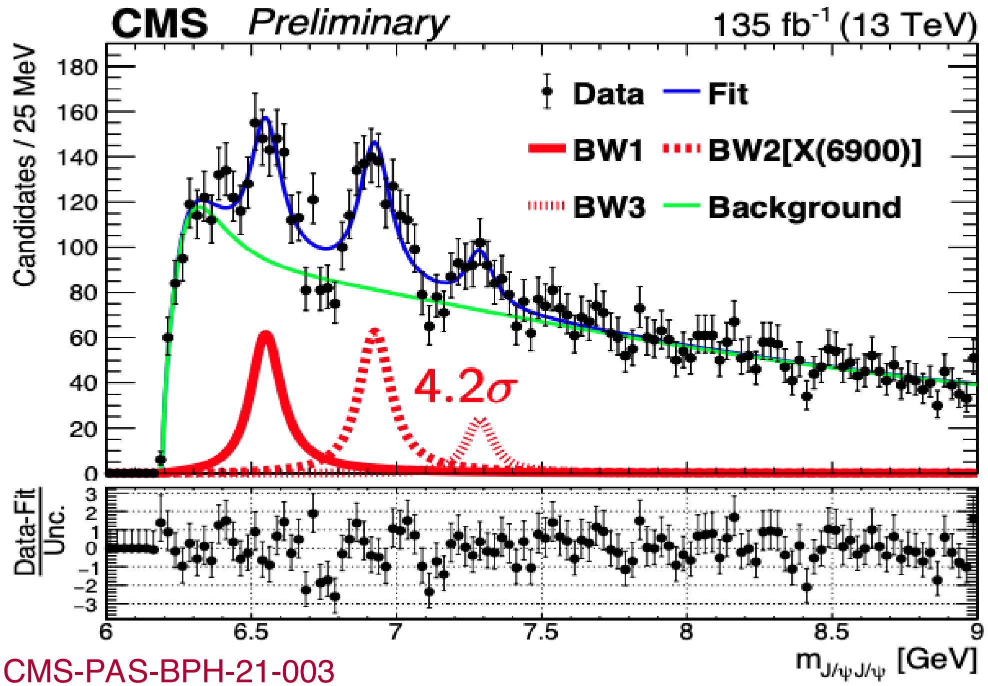
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\mathrm{MeV},$$

With interference

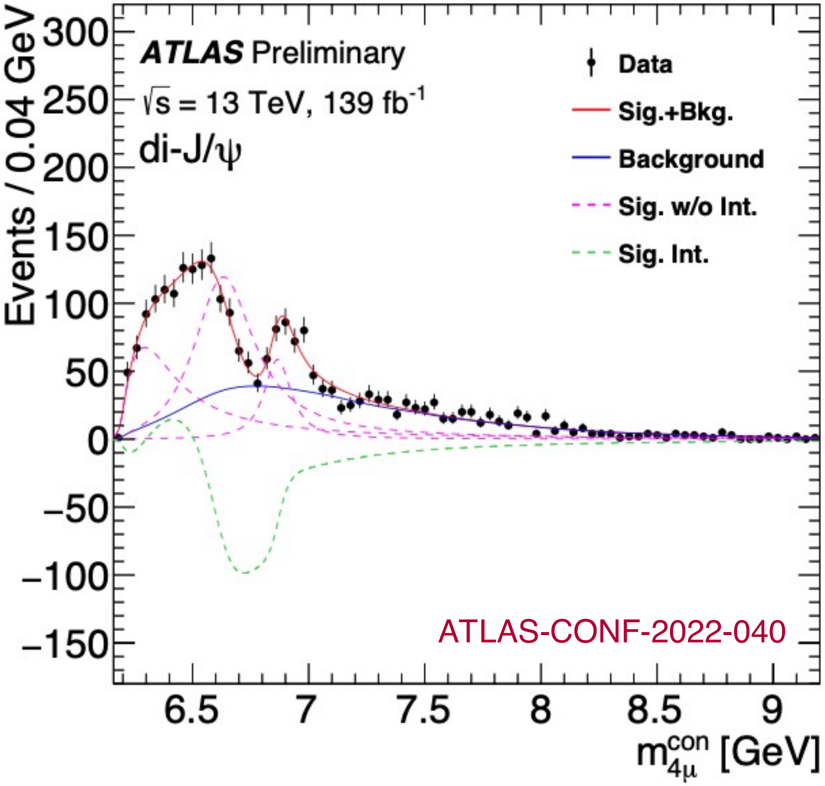
$$m[X(6900)] = 6886 \pm 11 \pm 11\,\mathrm{MeV}/c^2$$

$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\mathrm{MeV}.$$

Double J/ψ peaks confirmed by CMS and ATLAS



CMS-PAS-BPH-21-003

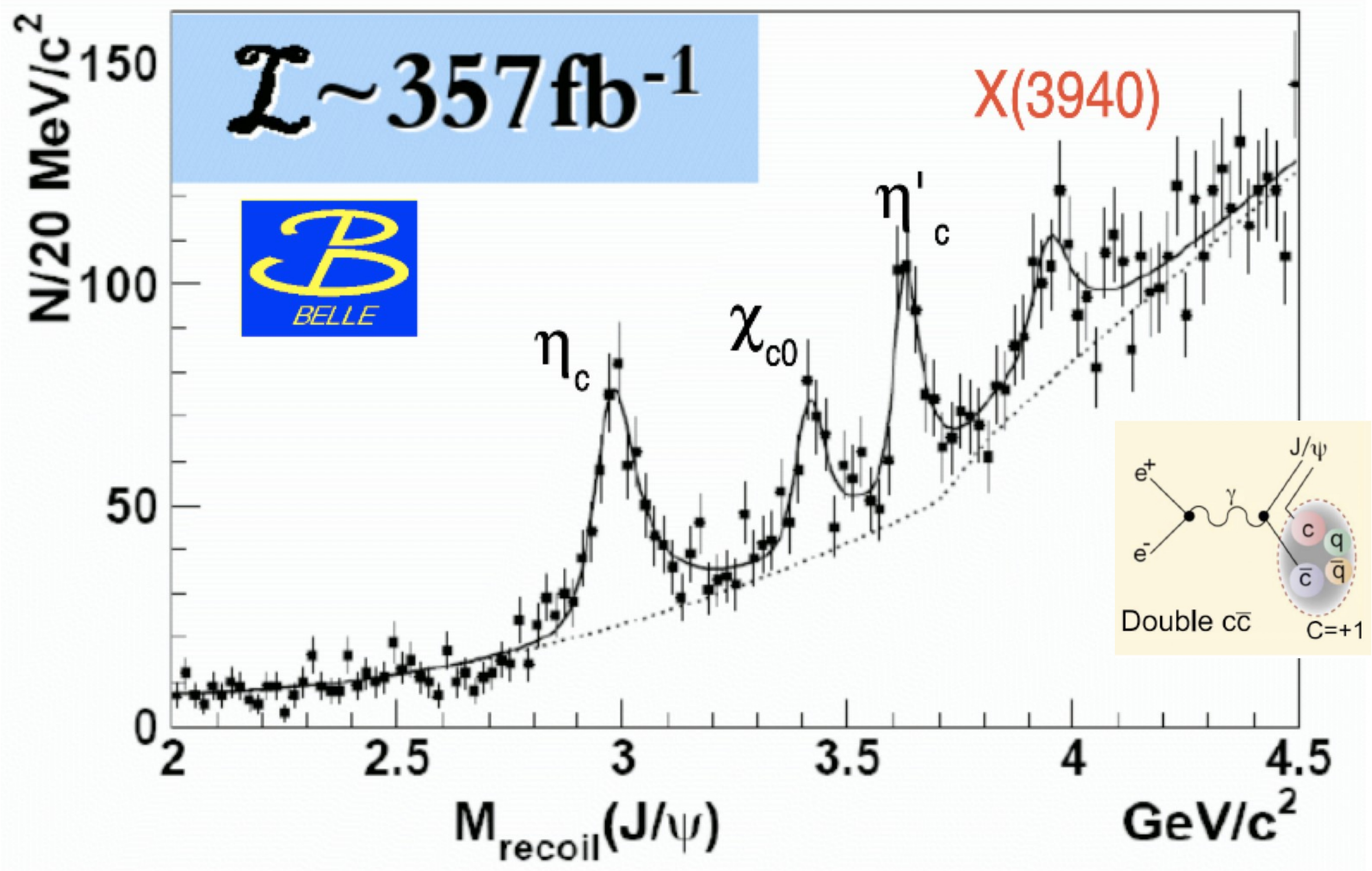


ATLAS-CONF-2022-040

	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
N	474 ± 113	492 ± 75	156 ± 56

Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24
LHCb [15]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

2002 : double charmonium at Belle



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

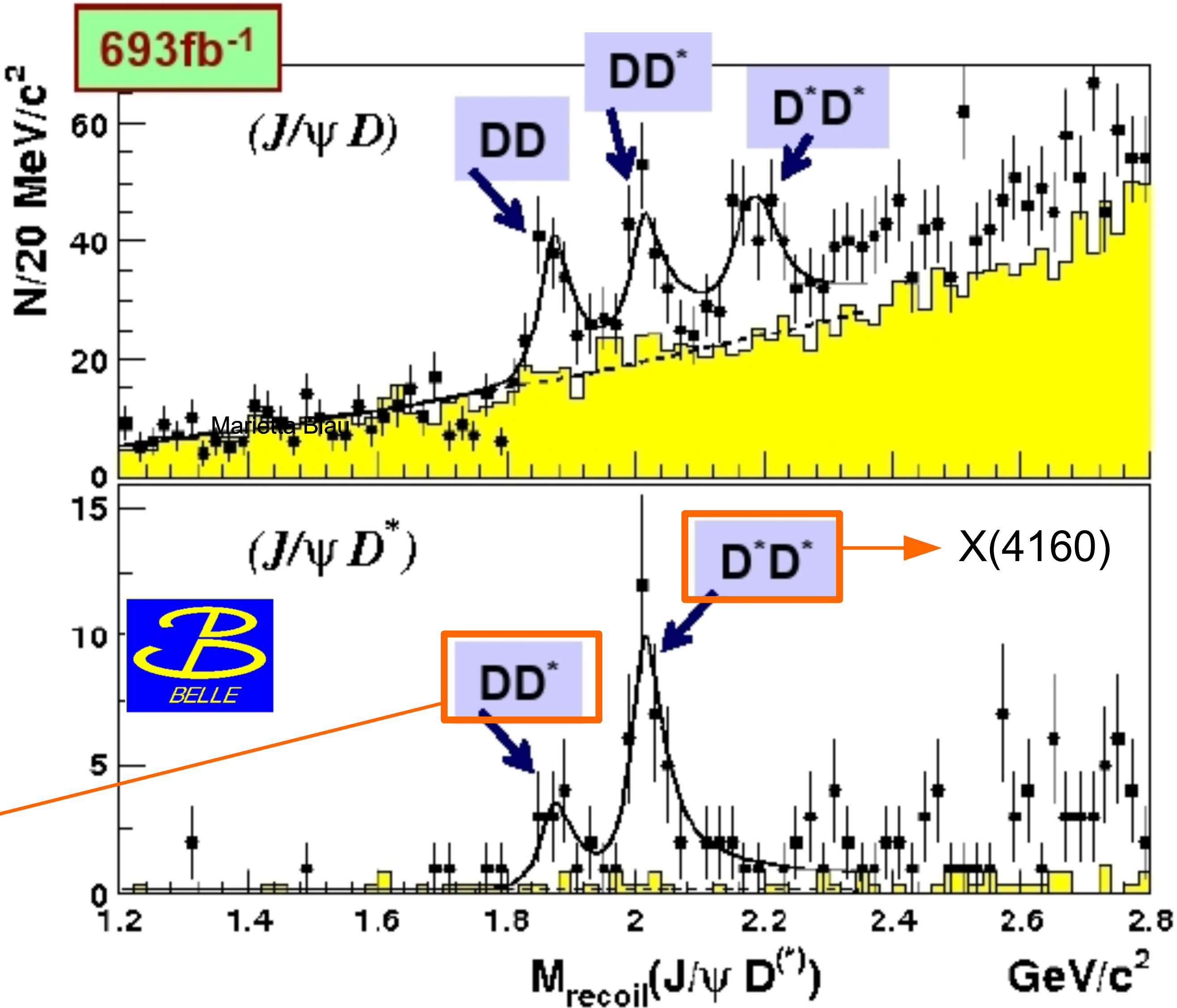
2002 : double charmonium at Belle

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^- , $K^-\pi^+\pi^-\pi^+$,
$K_S^0\pi^+\pi^-$, $K^+K^-\pi^0$



X(4160)

X(3940)

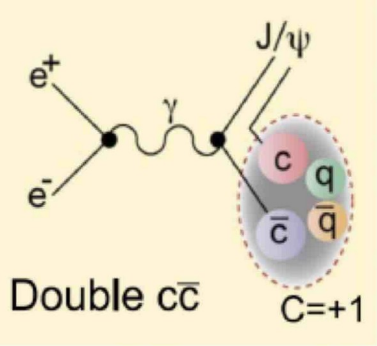
Prospects for double charmonium in Belle-II

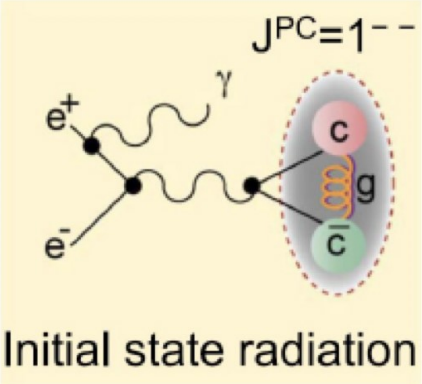
With J/ψ and ψ’ recoil we only explored C=+1 charmonium-like states

- In continuum, spectra are dominated by J=0 states
- In Y decays, though, we observe decay to $\psi\chi_{c1}$
  → Three gluon annihilation to double $c\bar{c}$ is different from EM production

With more statistics, we can reconstruct:
- J/ψ+photons from χ_c transitions
- final products of η_c decays

to explore C= -1 charmonium(like) spectrum



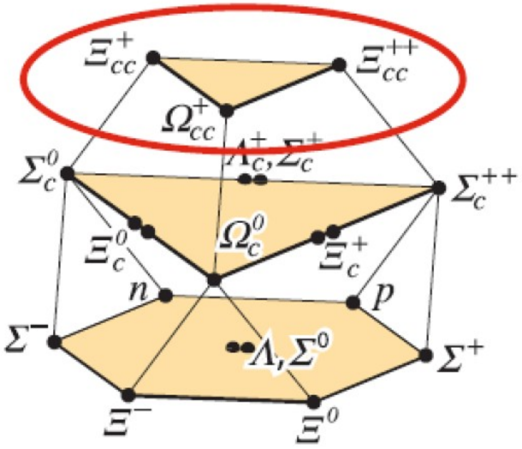


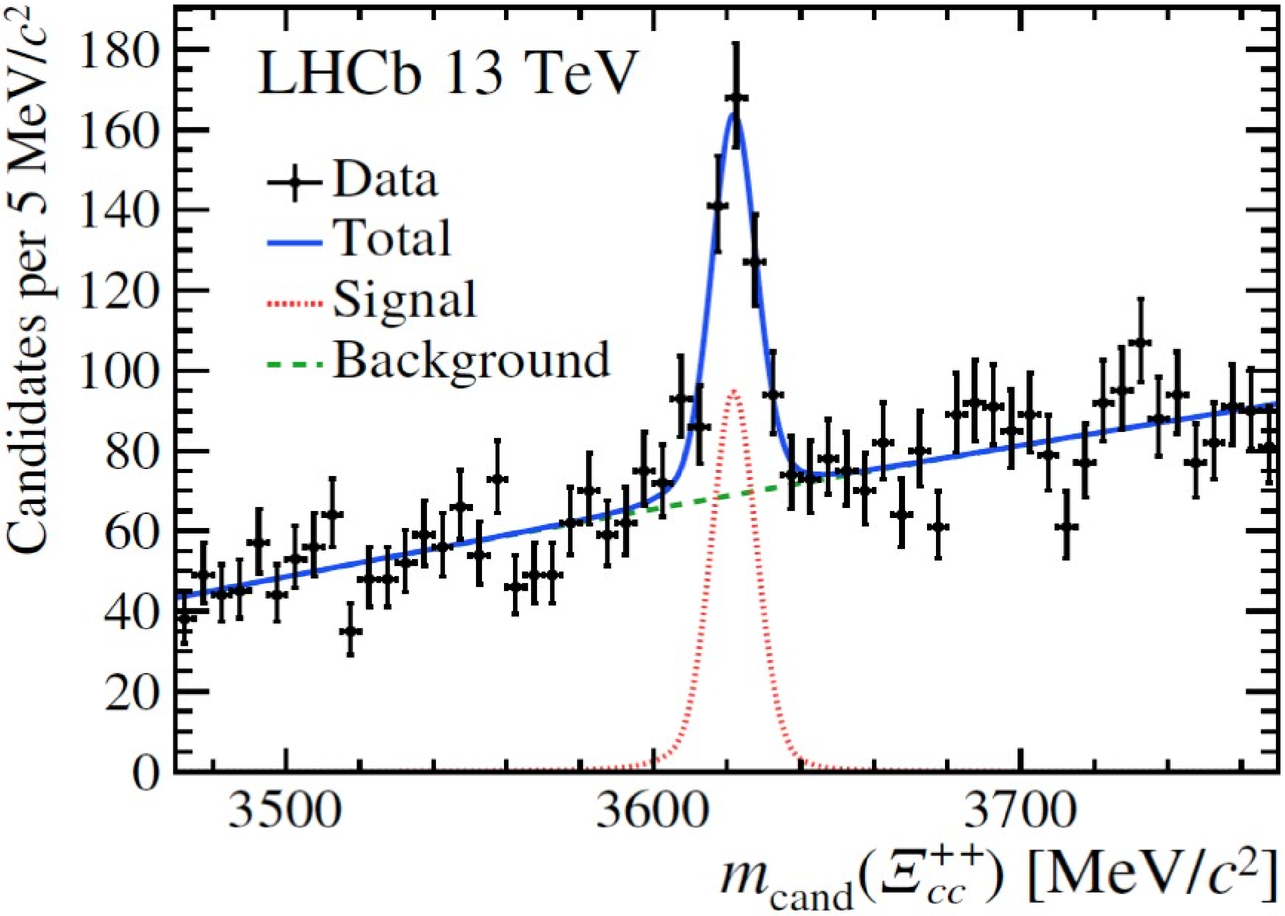
Reconstructing J/ψ and ISR photon we can :
- search for peaks in the J/ψ $c\bar{c}$ cross section, from 6 to 9 GeV

Stay tuned !

Discovery of Double Charm Baryons

Phys. Rev. Lett. 119, (2017) 112001





Narrow structure in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum.

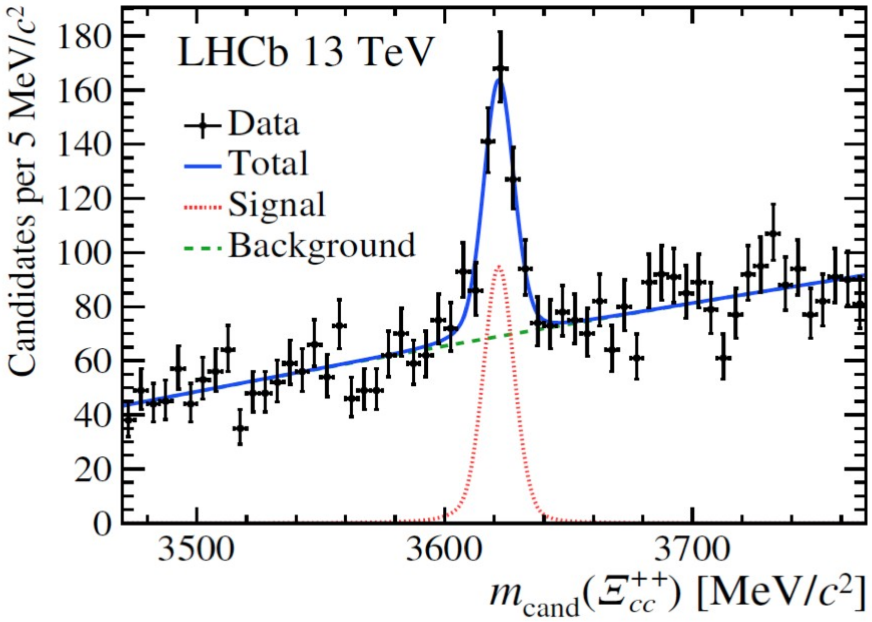
Significant displacement consistent with a weakly decaying particle.

Observed in two LHCb data sets.

Consistent with Ξ_{cc}^{++} (ccu).

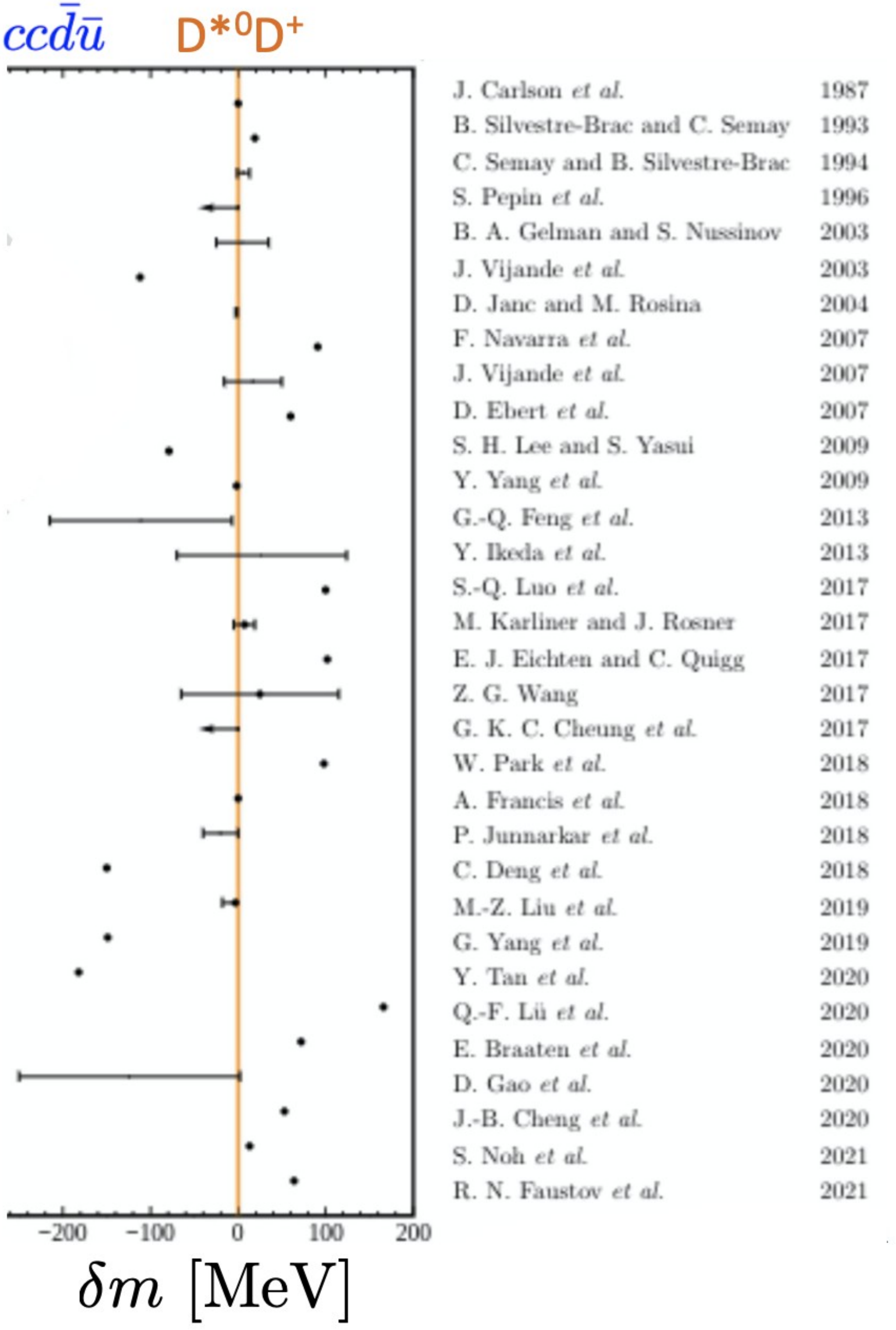
Mass: $m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14(\Lambda_c^+)\,\text{MeV}$

DCB discovery implies...



The discovery has triggered a large number of predictions for a stable state with $cc\overline{ud}$ content very close to D*D+ threshold …

AND a deeply (200 MeV) bound T_{bb} state!



Theoretical predictions for T_{cc} mass (I=0, $J^P=1^+$)

Double charm tetraquark: Tcc !

Nature Phys. 18 (2022) 7, 751

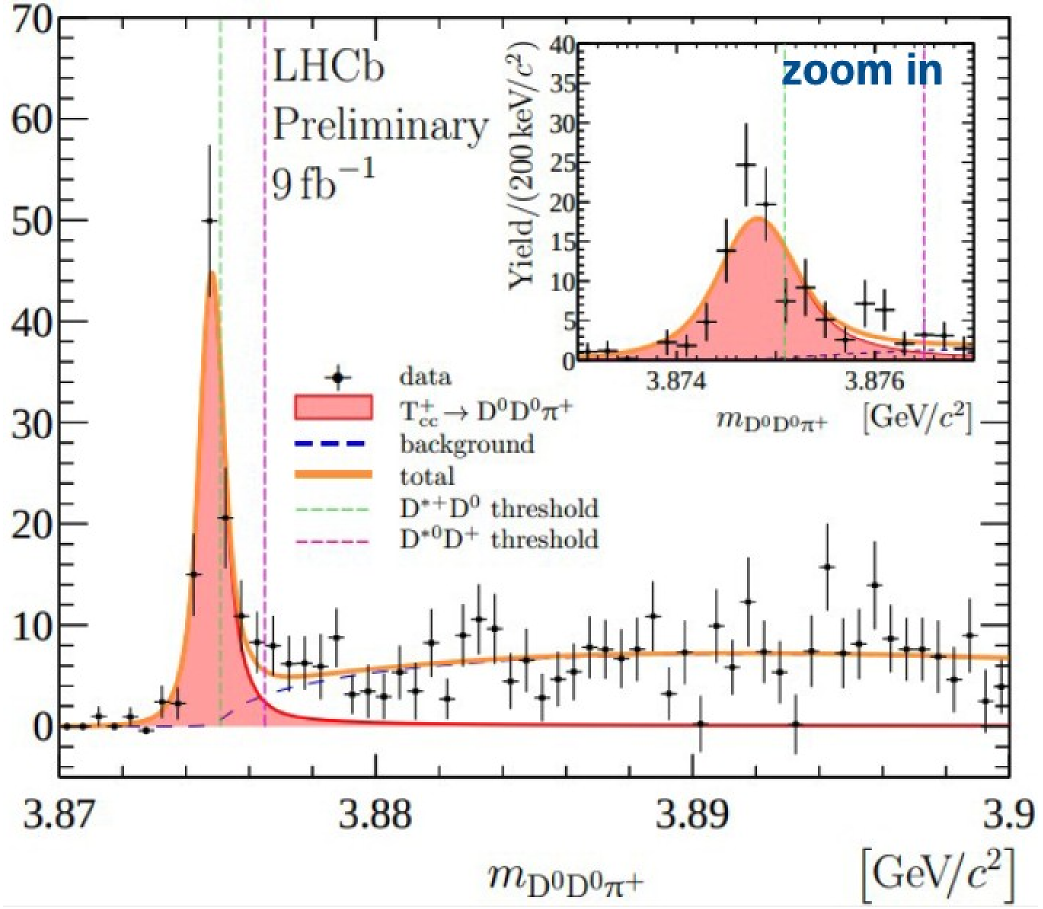
Very narrow state in $D^0 D^0 \pi^+$ spectrum
Very close to DD* thresholds
Consistent with $cc\bar{u}\bar{d}$ quark content

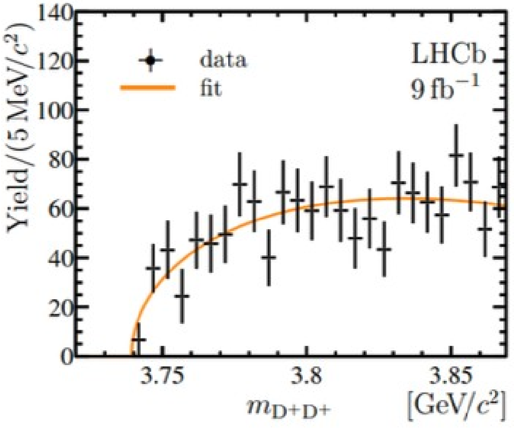
Visible characteristics:

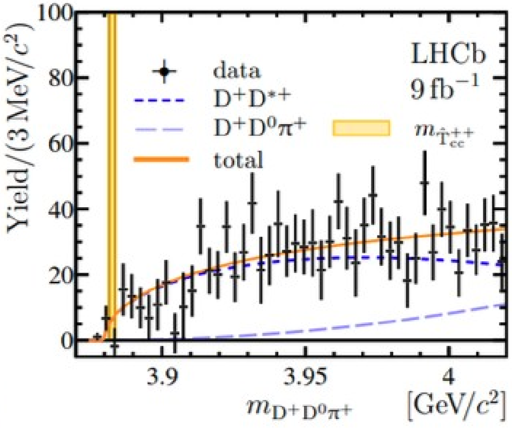
- Peak position: $-359 \pm 40\,\mathrm{keV}$
- FWHM: $47.8 \pm 1.9\,\mathrm{keV}$,
- Lifetime: $\tau \approx 10^{-20}$ s.

J^P consistent with 1^+

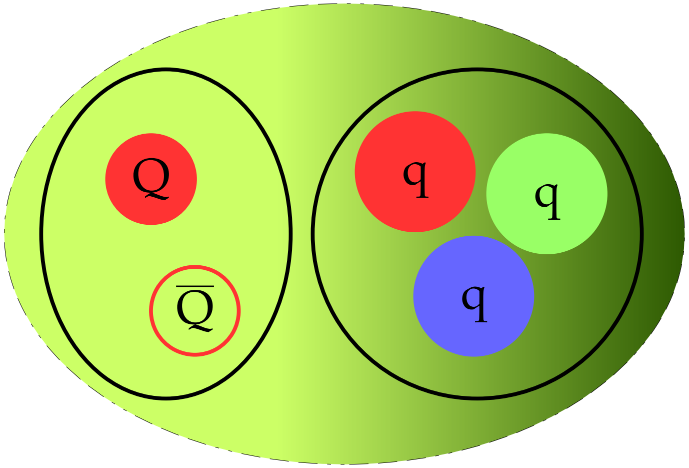
No peaks seen in the D^+D^+ channel

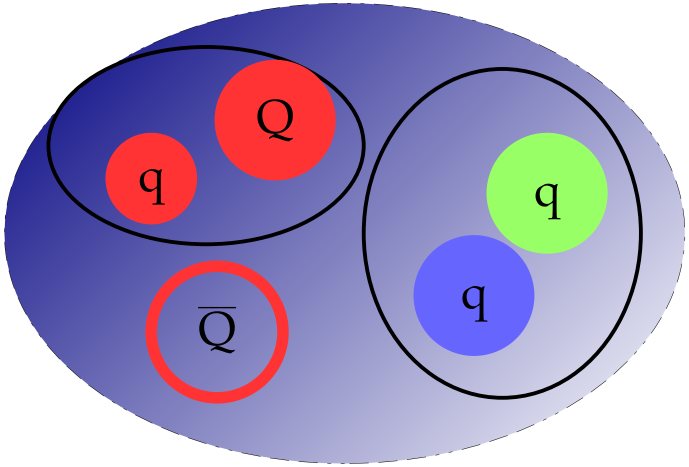






Pentaquarks



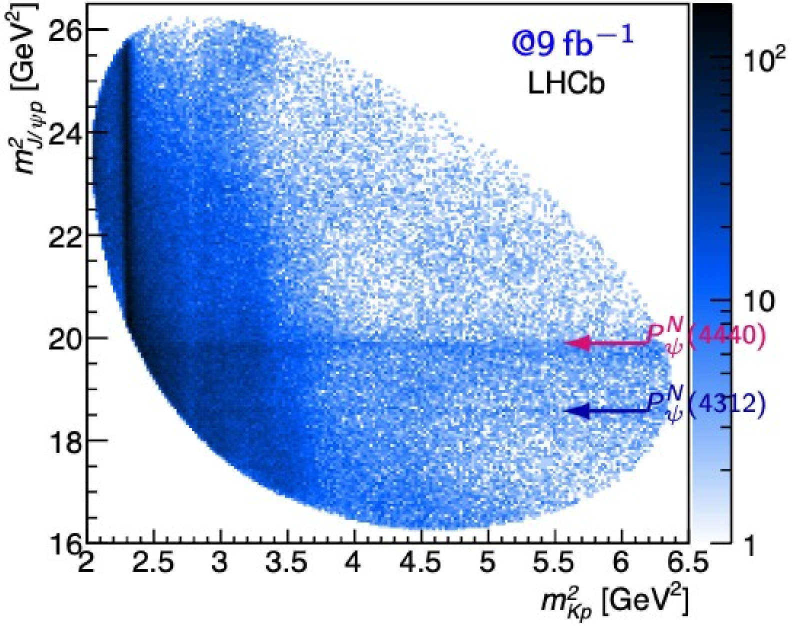


Discovery of the Pentaquark

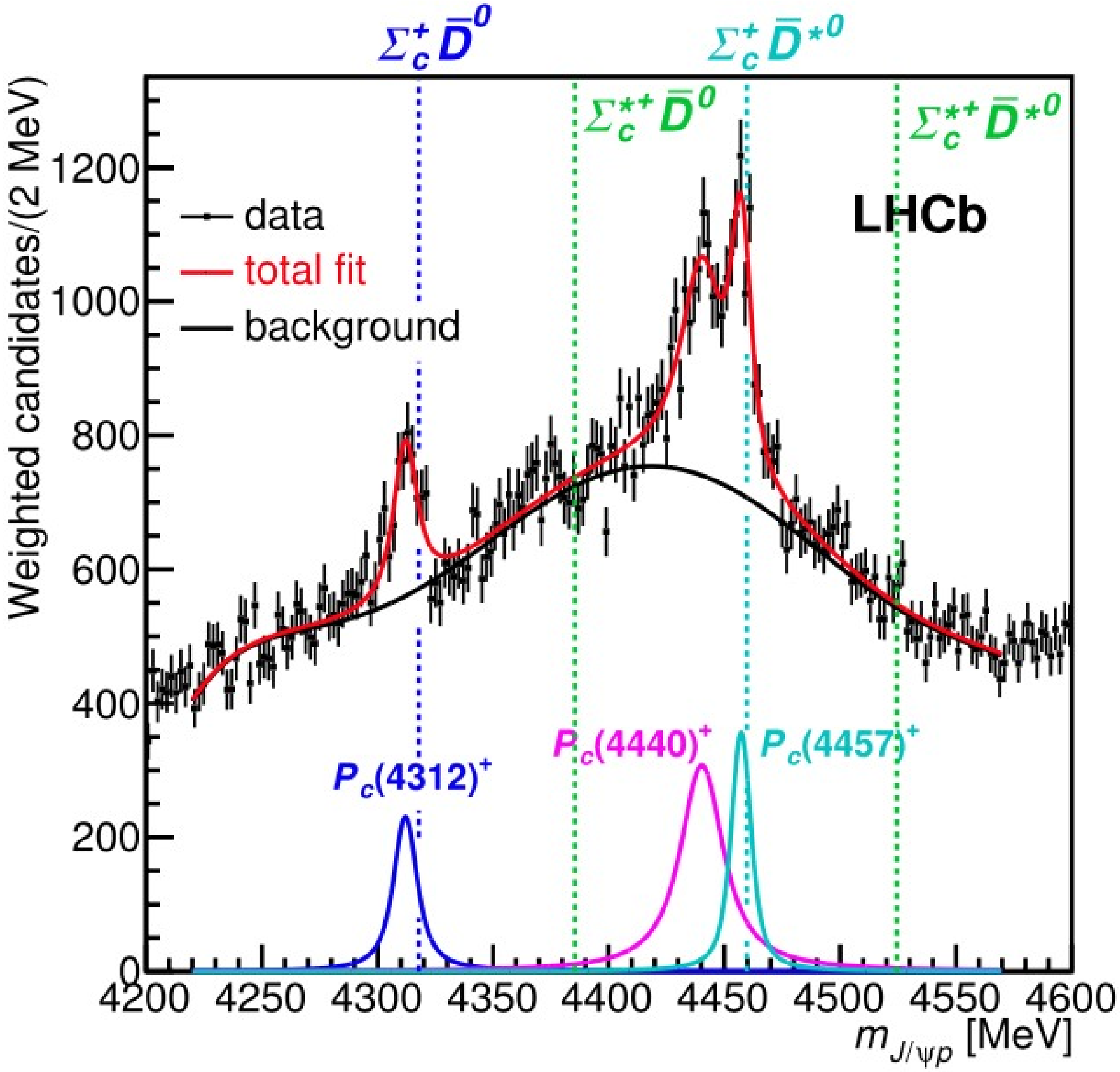
Dalitz plot analysis of

$\Lambda_b \rightarrow K^- p \; J/\psi$

LHCb : PRL 122 (2019) 22, 222001
(491 citations)



State	M [MeV]	Γ [MeV
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	9.8 ± 2.7
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$



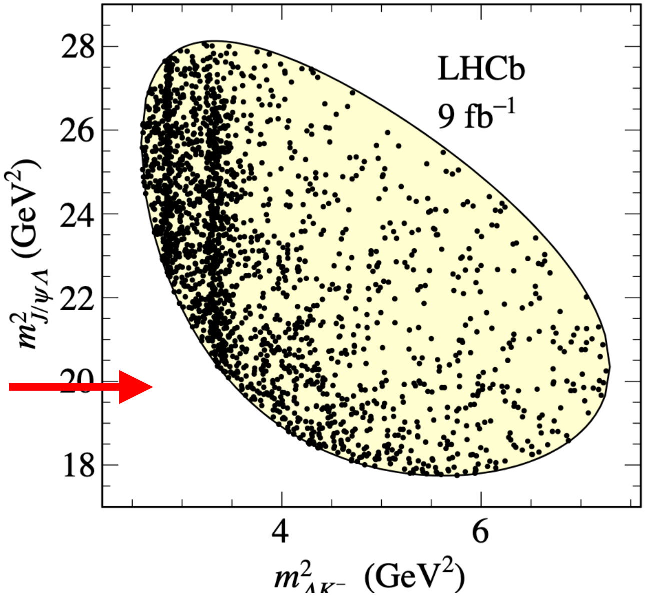
States found close to the $\Sigma_c D^{(*)}$ thresholds,
but not to the $\Sigma^*_c D^{(*)}$ ones

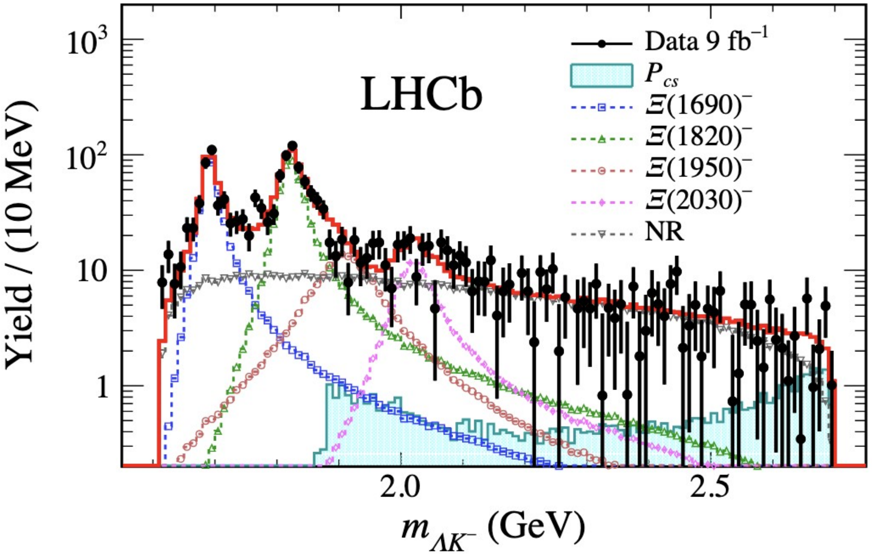
More Pentaquarks

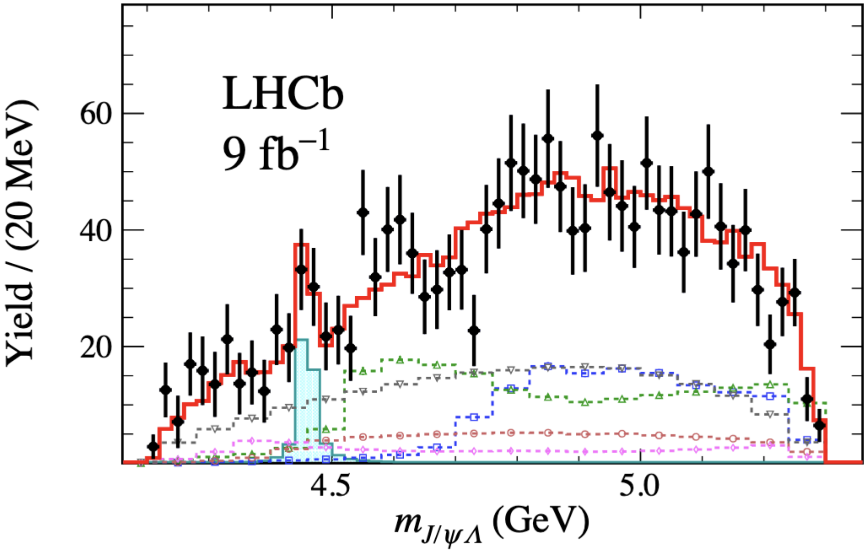
Dalitz plot analysis of

$\Xi_b^- \to \Lambda\ J/\psi\ K^-$

Sci.Bull. 66 (2021) 1278





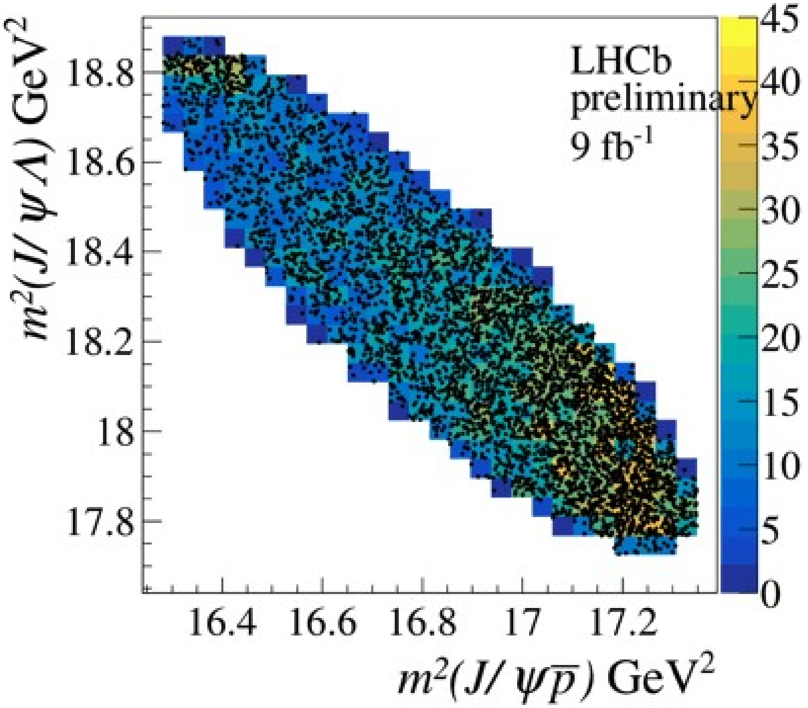


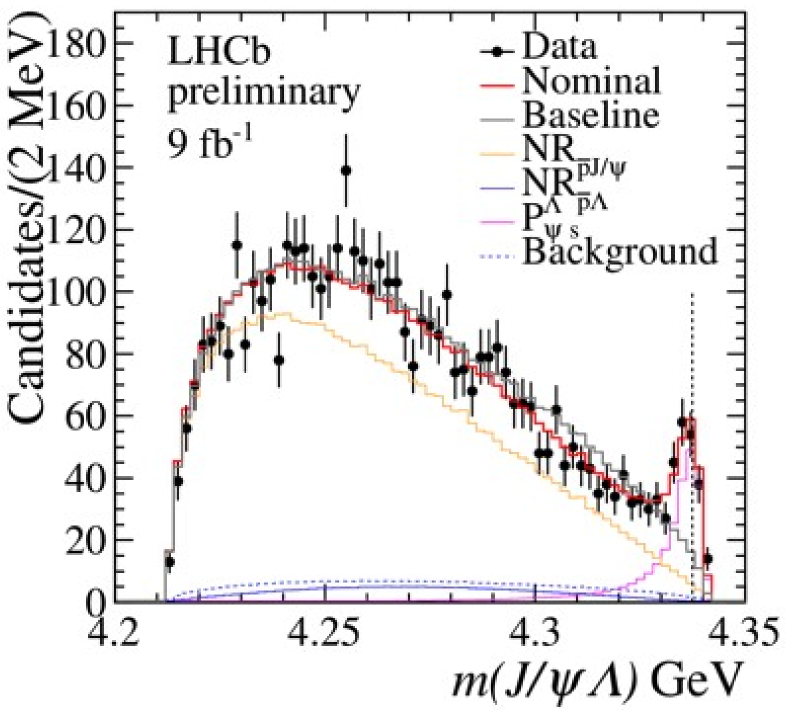
State	M_0 (MeV)	Γ_0 (MeV)	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$	$22.1\,^{+6.2}_{-2.6}\,^{+6.7}_{-8.9}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$	$32.9\,^{+3.2}_{-6.2}\,^{+6.9}_{-4.1}$
$\Xi(1950)^-$	1910.6 ± 18.4	105.7 ± 23.2	$11.5\,^{+5.8}_{-3.5}\,^{+49.9}_{-\ 9.4}$
$\Xi(2030)^-$	2022.8 ± 4.7	68.2 ± 8.5	$7.3\,^{+1.8}_{-1.8}\,^{+3.8}_{-4.1}$
NR	–	–	$35.8\,^{+4.6}_{-6.4}\,^{+10.3}_{-11.2}$

More Pentaquarks

LHCB-PAPER-2022-031
ArXiV:2210.10346

Dalitz plot analysis of $B^- \rightarrow \Lambda\ J/\psi\ \overline{p}$





- Amplitudes:
  - NR($J/\psi p$), $84.0 \pm 2.2\%$
  - NR($\Lambda\overline{p}$), $11.3 \pm 1.3\%$
  - New $P^{\Lambda}_{\psi s}$, $12.5 \pm 0.7\%$,
  - with parameters
    - $m(P^{\Lambda}_{\psi s}) = 4338.2 \pm 0.7\,\mathrm{MeV}$
    - $\Gamma(P^{\Lambda}_{\psi s}) = 7.0 \pm 1.2\,\mathrm{MeV}$

- $J^P = 1/2^-$ is preferred
- BW mass is close to $\Xi_c \bar{D}$ thresholds:
  - $0.8\,\mathrm{MeV}$ above $\Xi_c^+ D^-$
  - $2.9\,\mathrm{MeV}$ above $\Xi_c^0 \overline{D}^0$

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.

The discovery of double charm baryons has led to very solid predictions on the T_{cc} tetraquark, confirmed by its discovery in 2021. Next big search: the T_{bb}...

Pentaquarks have been discovered by LHCb in 2019 and their number is increasing every year, both from decays of B baryons and B mesons: wait for more!

Thanks for your attention !

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