Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Quarkonia

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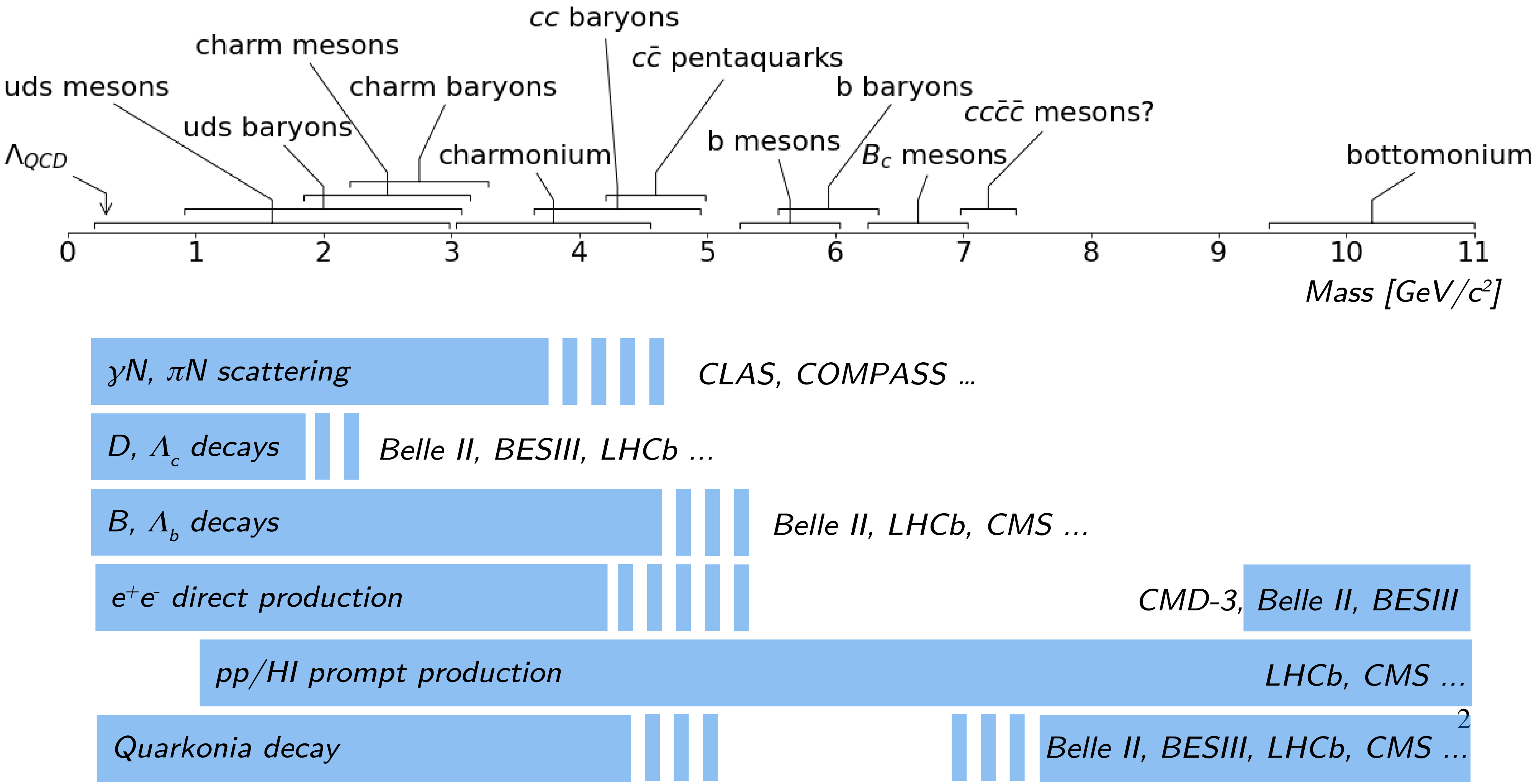
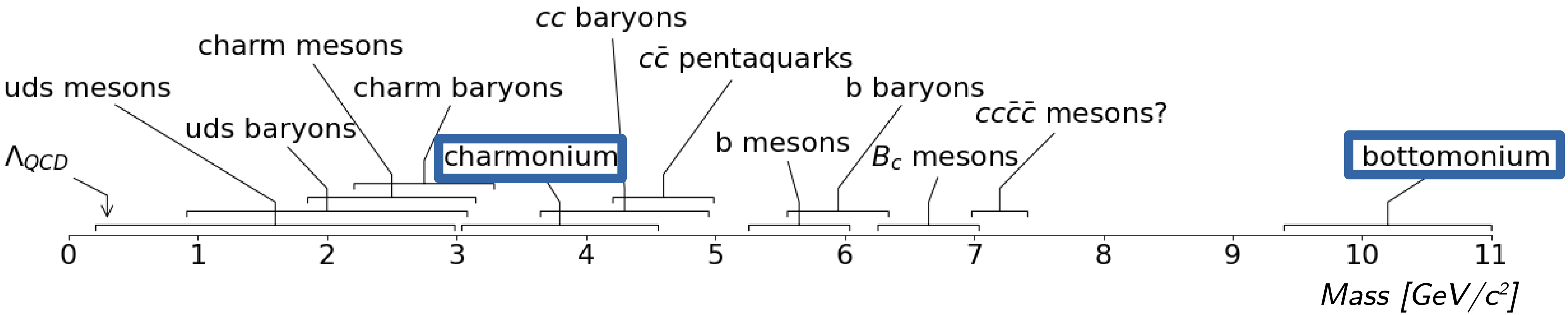
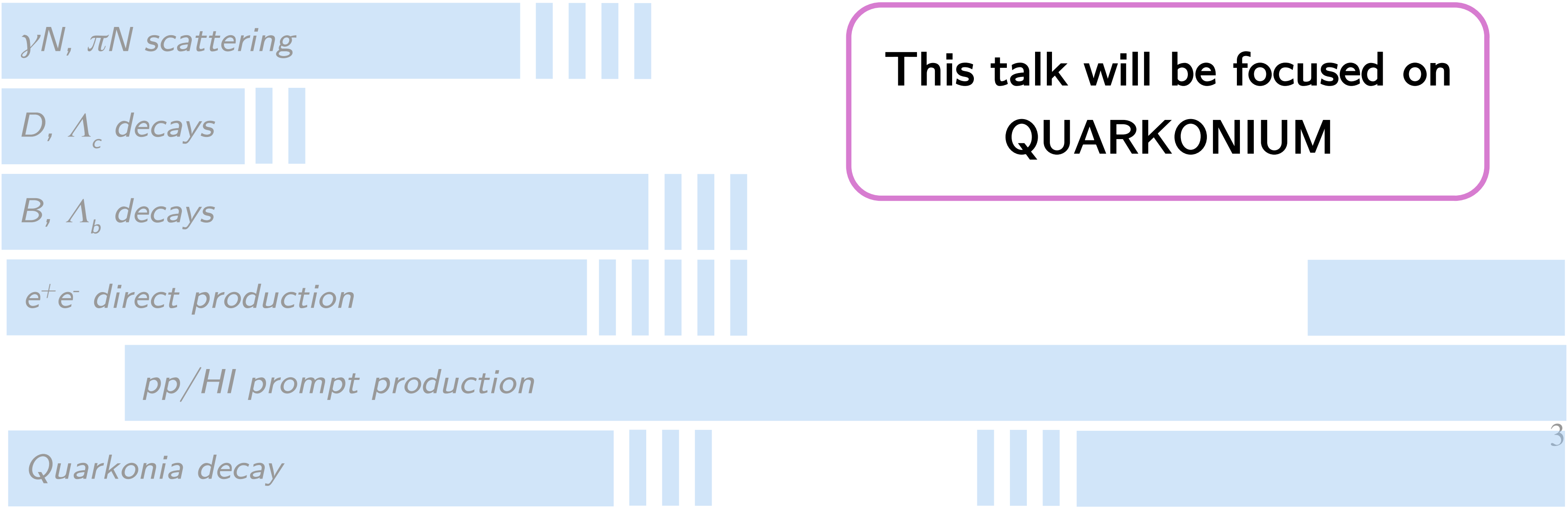
Belle II US summer school
August 3rd 2022

The meson spectrum



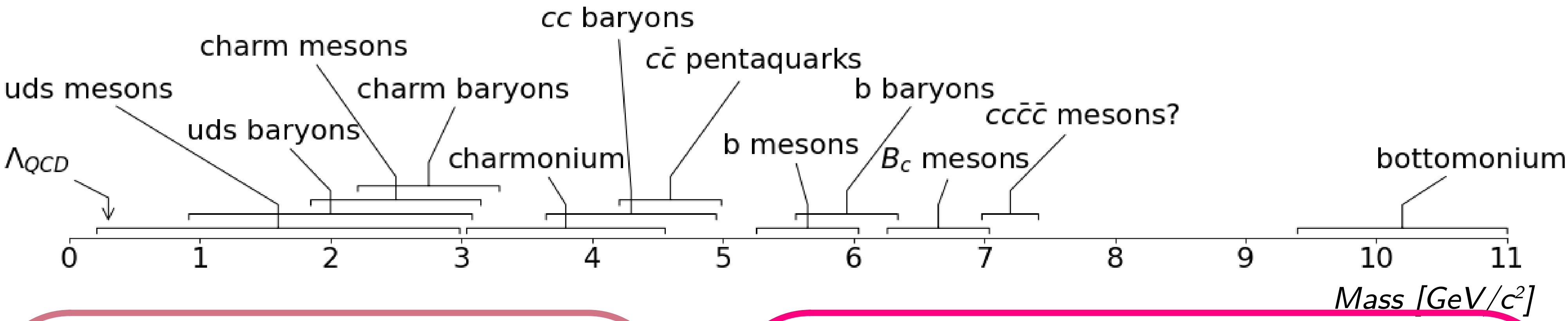
The meson spectrum





This talk will be focused on QUARKONIUM

Heavy or light hadrons?



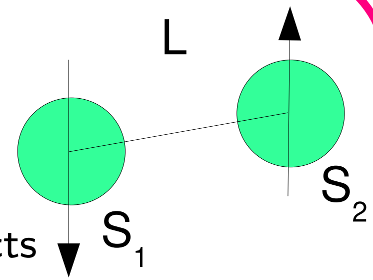
Light hadrons

Large mixing by $SU(3)_f$

$M(q) \sim E_{binding}$

- Relativistic
- L not good quantum number

Heavy hadrons



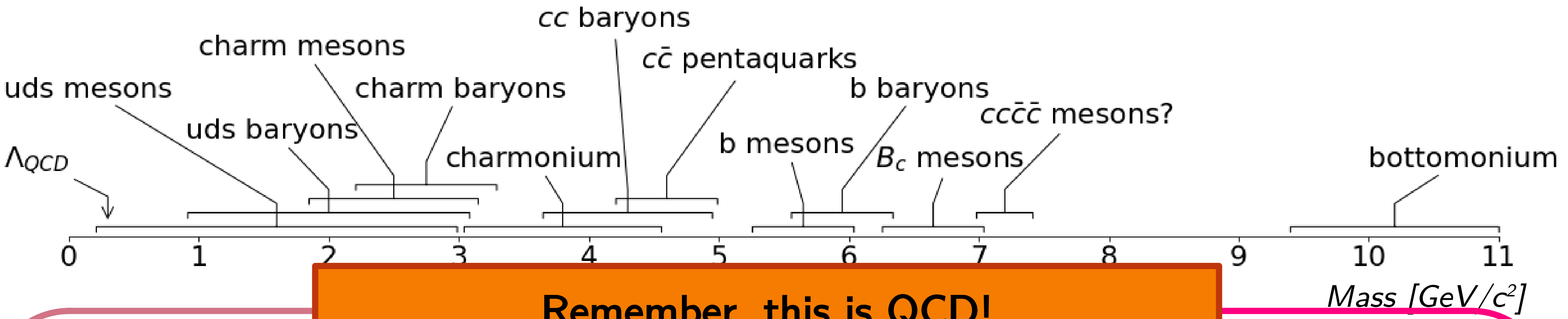
$SU(n)_f$ broken

- c and b hadron don't mix
- tag flavor by decay products

$M(c,b) >> E_{binding}$

- **non-relativistic**
- **L is good quantum number**
- **heavy quark spin symmetry**

Heavy or light hadrons?



Remember, this is QCD!

- P-parity and C-parity are strictly preserved
- Isospin is almost preserved

Light h

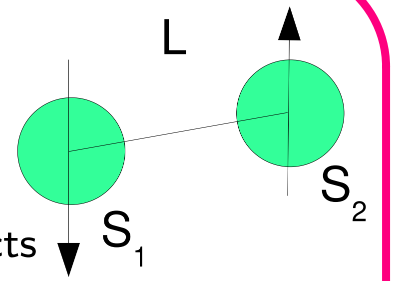
Large mixing by SU

$M(q) \sim E_{binding}$

- Relativistic
- L not good quantum number

x

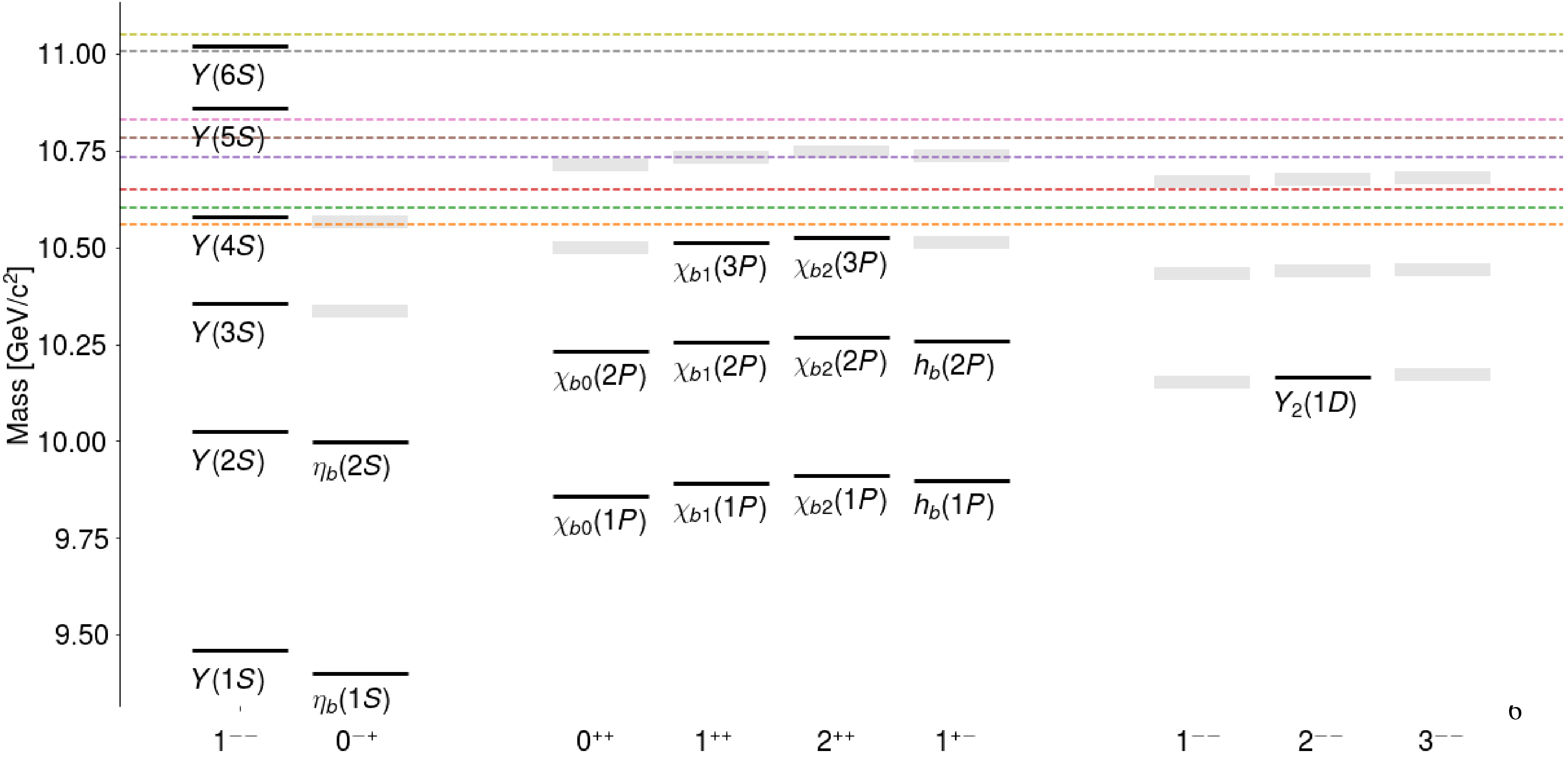
tag flavor by decay products



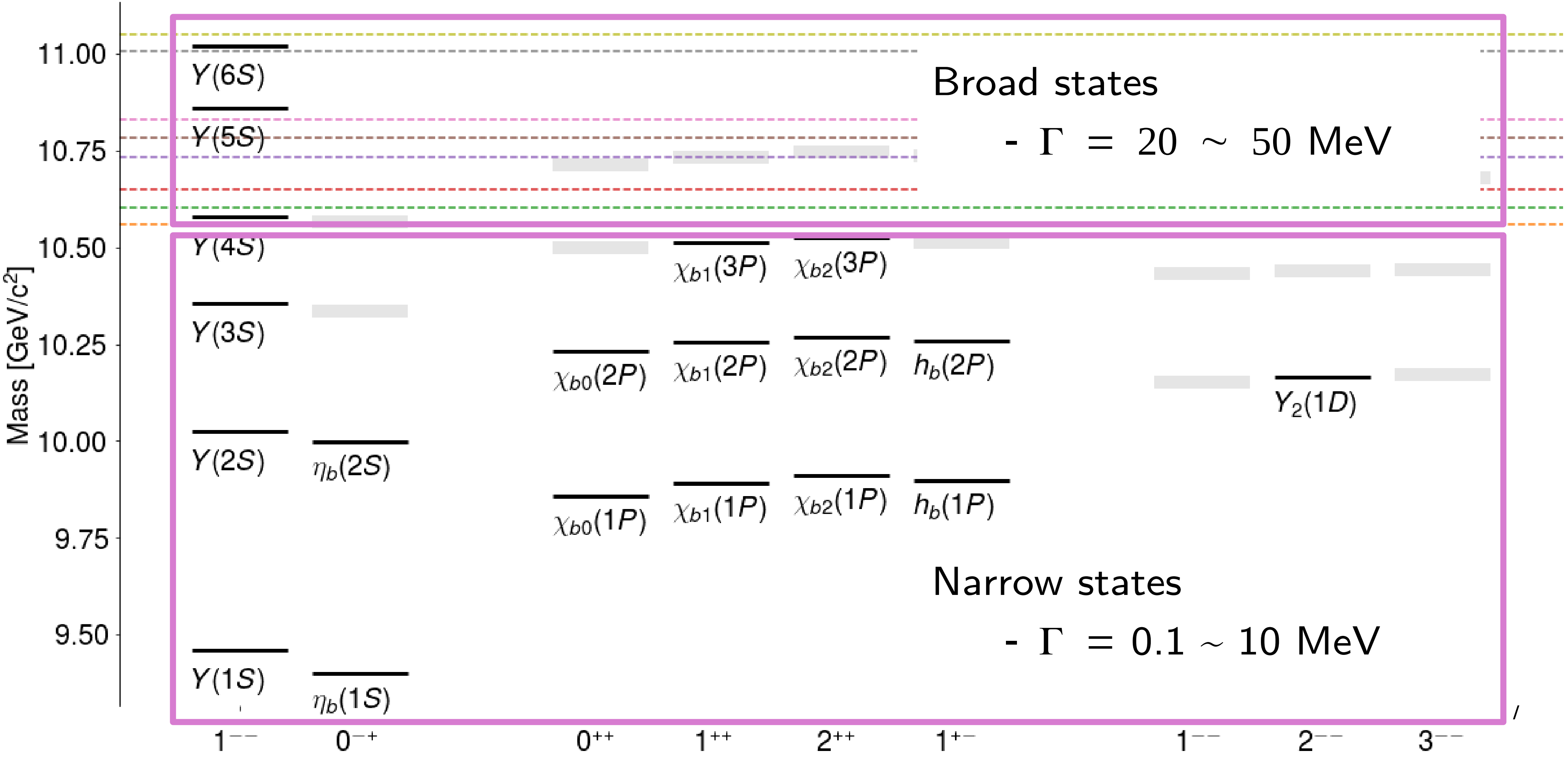
$M(c,b) >> E_{binding}$

- **non-relativistic**
- **L is good quantum number**
- **heavy quark spin symmetry**

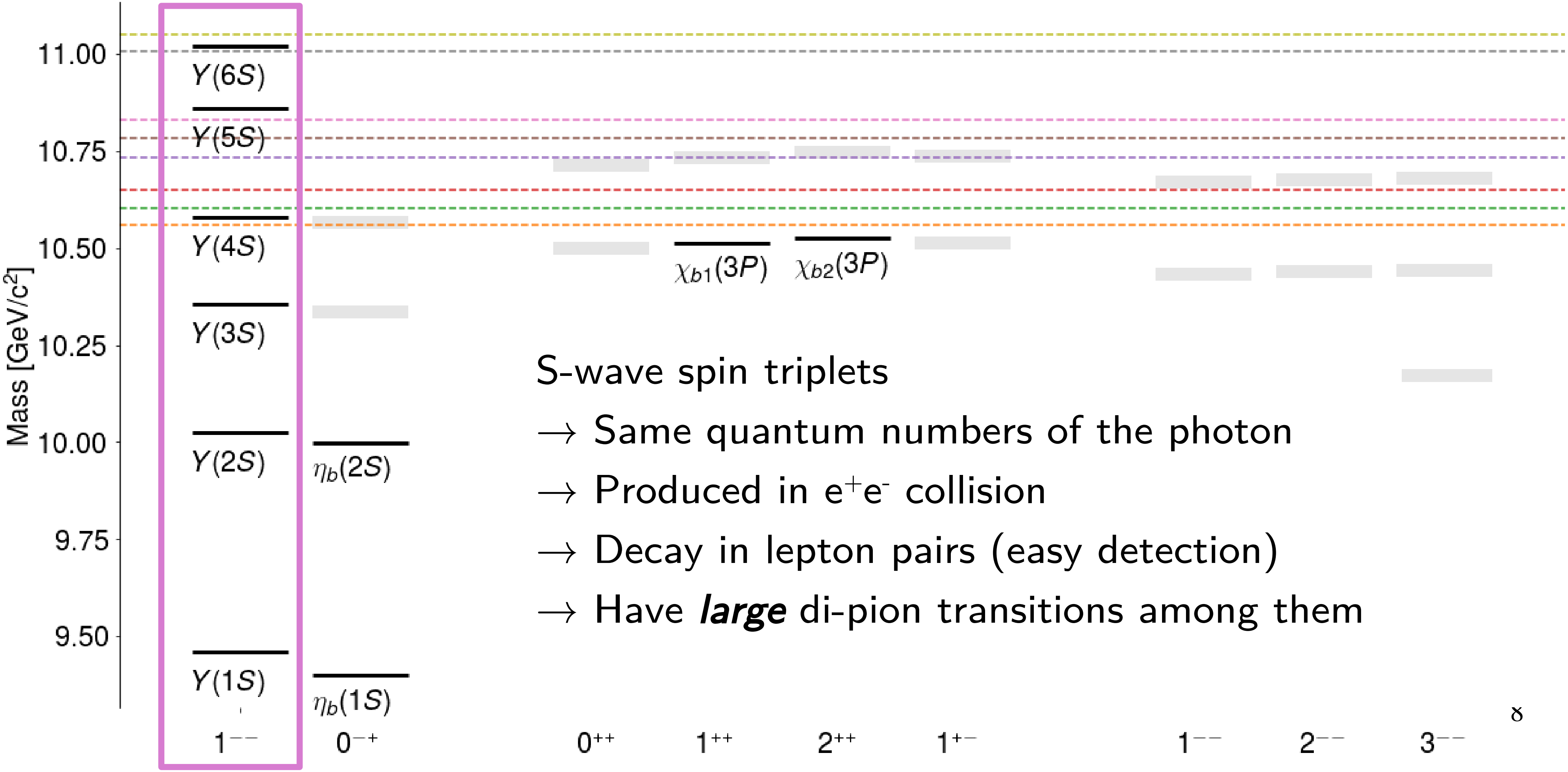
A closer look at bottomonia



A closer look at bottomonia



Selection rules



S-wave spin triplets

→ Same quantum numbers of the photon

→ Produced in e^+e^- collision

→ Decay in lepton pairs (easy detection)

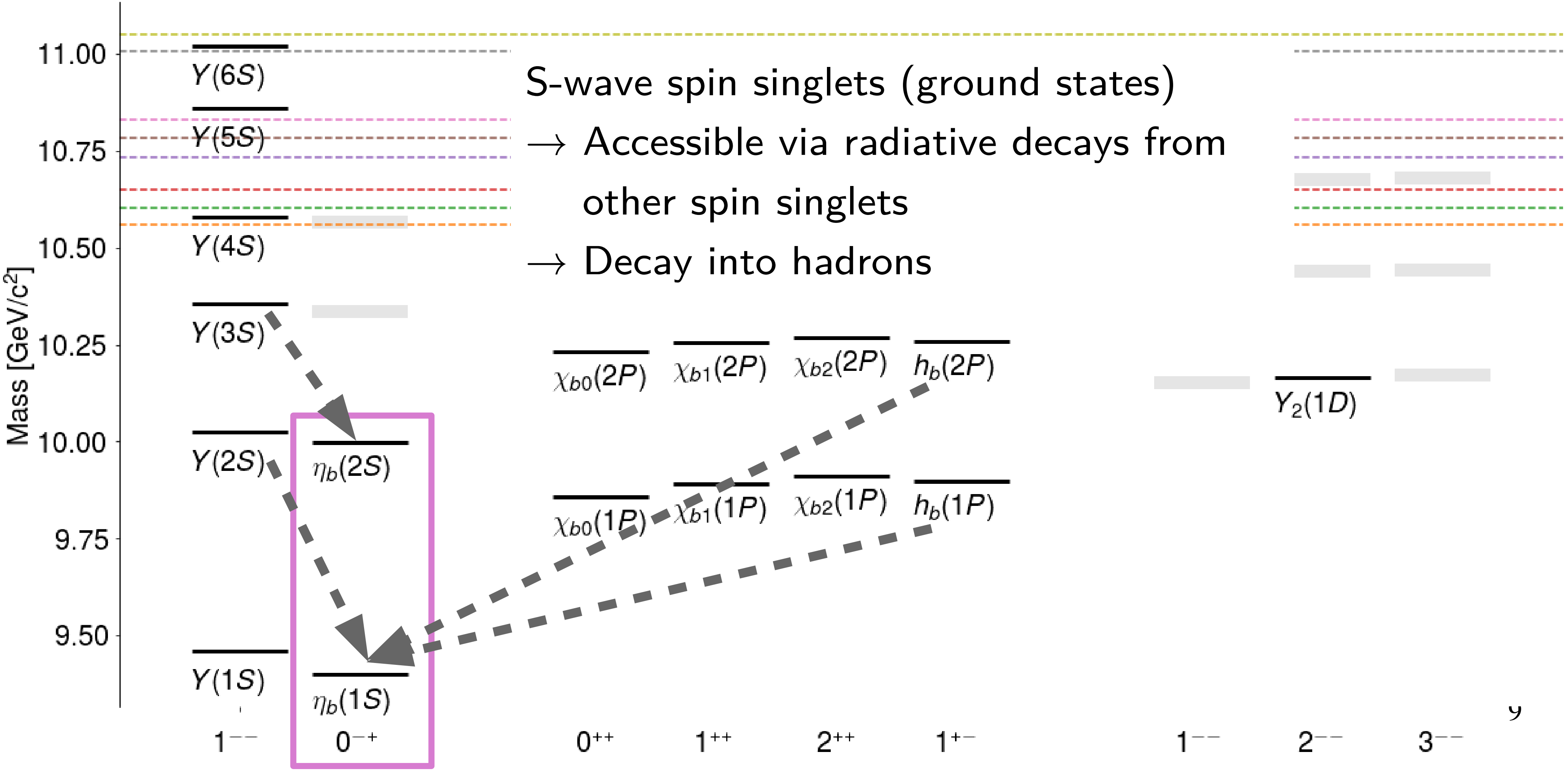
→ Have ***large*** di-pion transitions among them

Selection rules

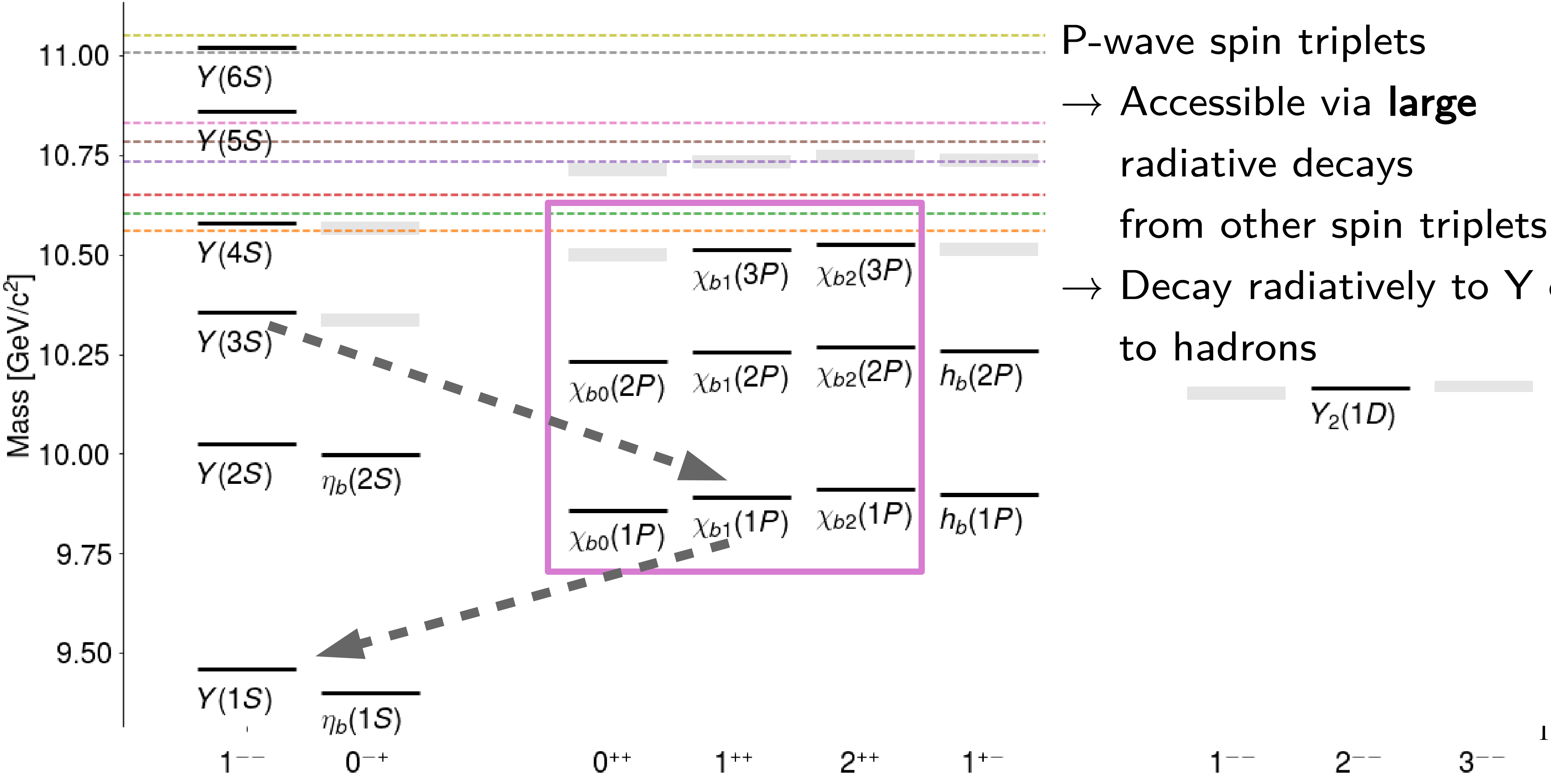
S-wave spin singlets (ground states)

→ Accessible via radiative decays from other spin singlets

→ Decay into hadrons



Selection rules

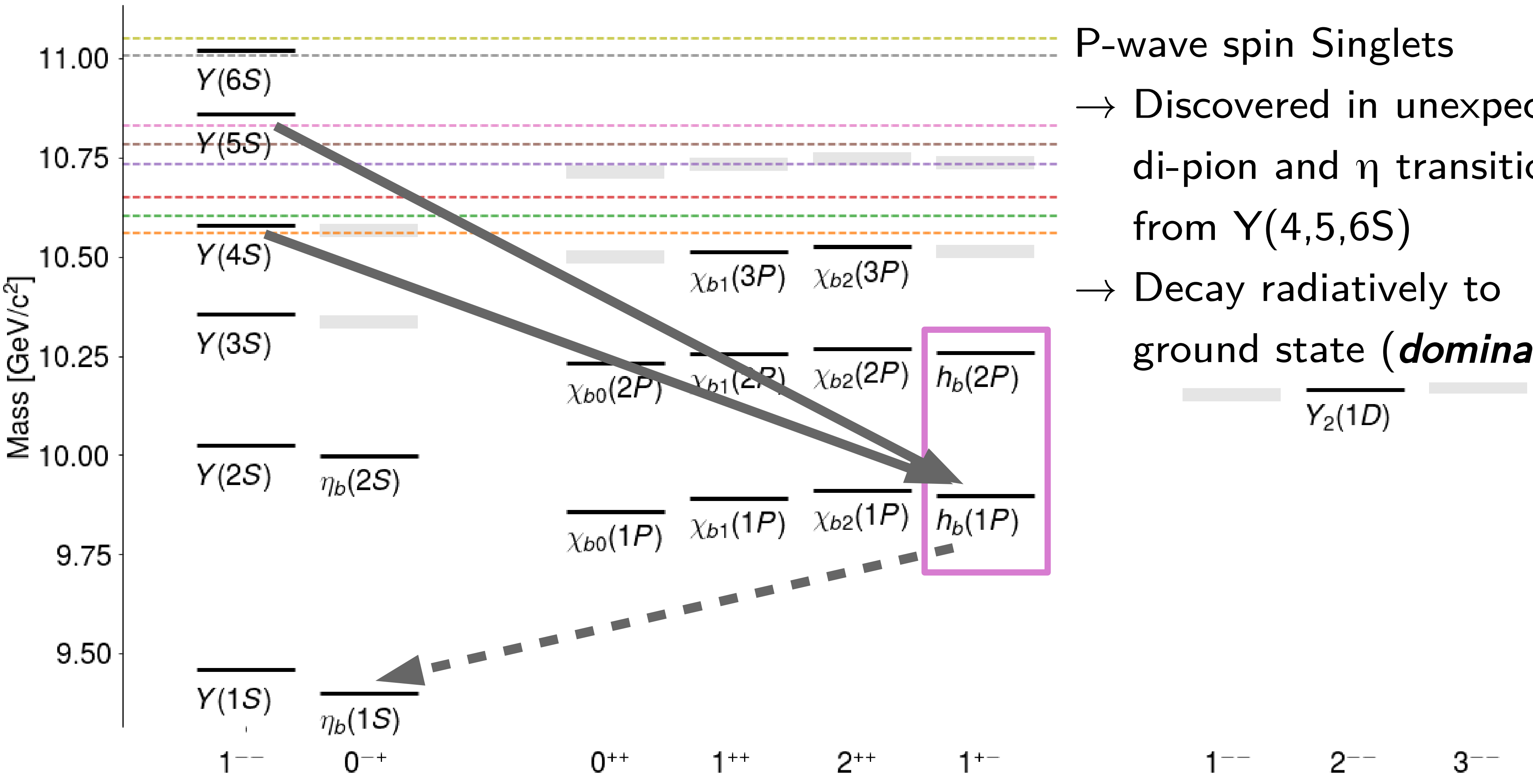


P-wave spin triplets

→ Accessible via **large** radiative decays from other spin triplets

→ Decay radiatively to Υ or to hadrons

Selection rules



P-wave spin Singlets

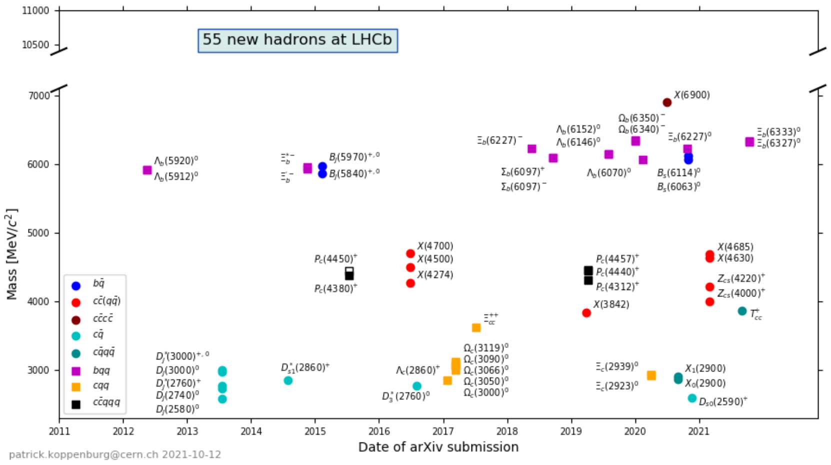
→ Discovered in unexpected di-pion and η transitions from Υ(4,5,6S)

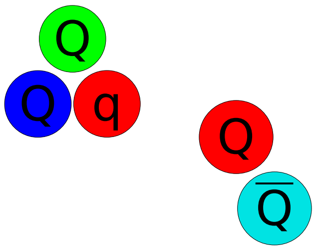
→ Decay radiatively to ground state (***dominant***)

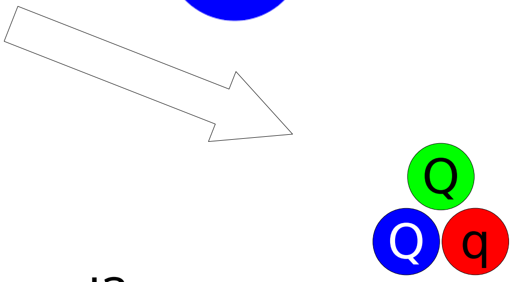
Big questions in spectroscopy

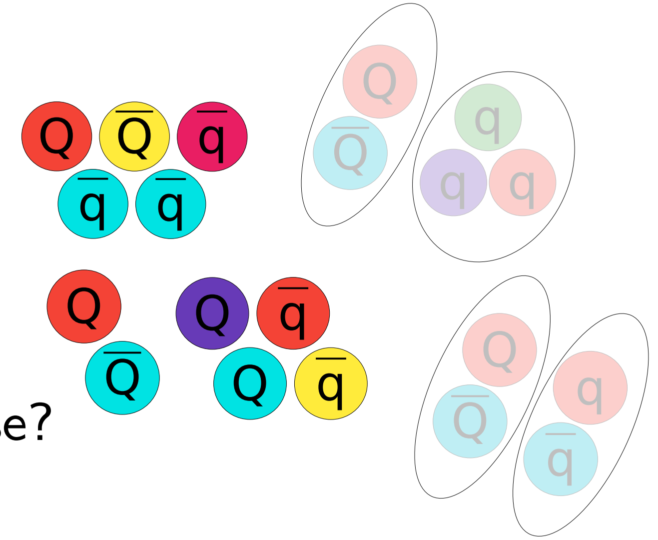
$q\bar{q}$ and qqq are not the only color singlets

- we are now sure there is much more!









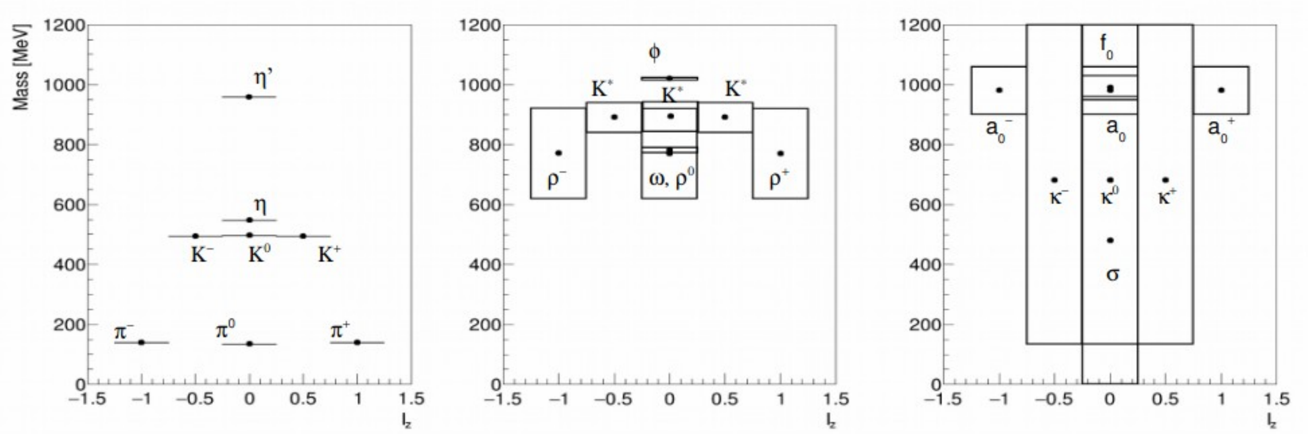
Key question:

- How are the quarks arranged?
- Do we see molecule-like objects or something else?

Big questions in spectroscopy

Multi-quark systems are possible at any energy *[Jaffe, Wilkez, PRL 91 232003 (2003)]*

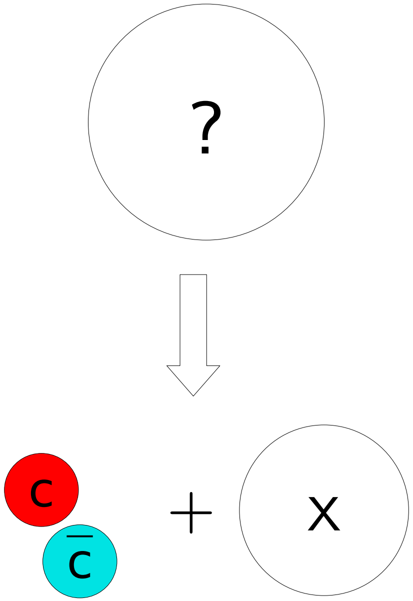
- proposed to describe $a_0(980)$ and $f_0(980)$ *[Baru et al. PLB 586 53-61 (2004)]*
- can explain inverted hierarchy in scalar mesons *[Maiani et al. PRL 93 212002 (2004)]* *['t Hooft et al. PLB 662 424-430 (2008)]*



However, no smocking gun to distinguish $q\bar{q}$ and $qq\bar{q}\bar{q}$ in the light sector

What can we do with heavy hadrons?

With heavy quarks separating conventional and exotics is much simpler



If a state has:

- Mass > 3 GeV/c^2
- Narrow ($\Gamma/M < 0.1$)
- Decaying strongly into J/ψ (or $D\bar{D}$) + something

It must contain a $c\bar{c}$ pair

What can we do with heavy hadrons?

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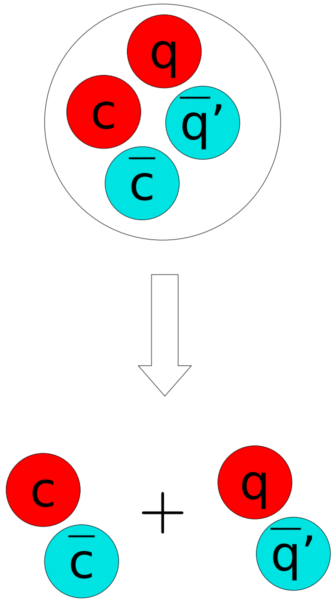
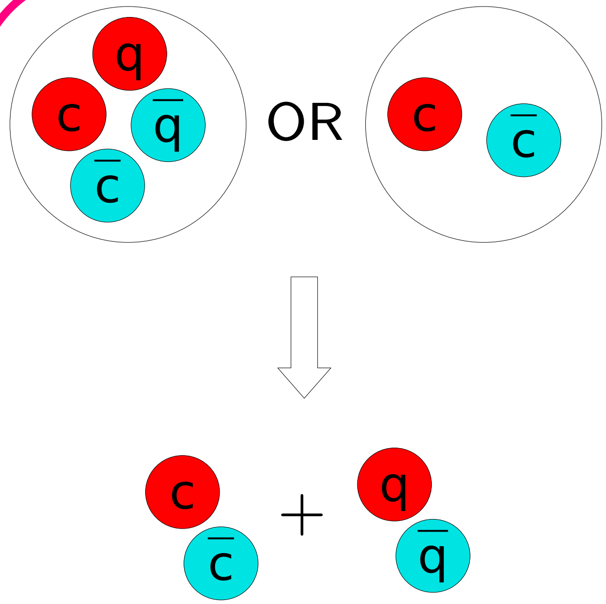
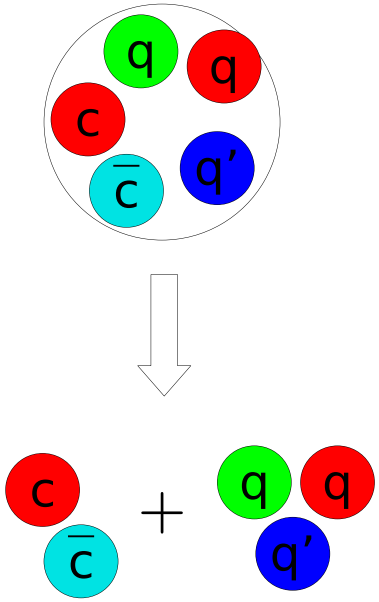


Charged/flavoured $c\bar{c}$-like
- must have 4 quarks



Neutral $c\bar{c}$-like
- 2 or 4 quarks
- check $c\bar{c}$ spectrum



Baryonic $c\bar{c}$-like
- 5 quarks

Intermezzo: Interplay with theory

Non-perturbative QCD

Hadroquarkonium

Lattice

NRQCD

Di-quarks

Light cone

Molecules

Experiments

Spectroscopy = Non perturbative QCD

→ Can't do direct calculation, rely on models approximating QCD

→ Understand (solve?) QCD in the NP regime

Intermezzo: Interplay with theory

Non-perturbative QCD

Hadroquarkonium

Lattice

NRQCD

Di-quarks

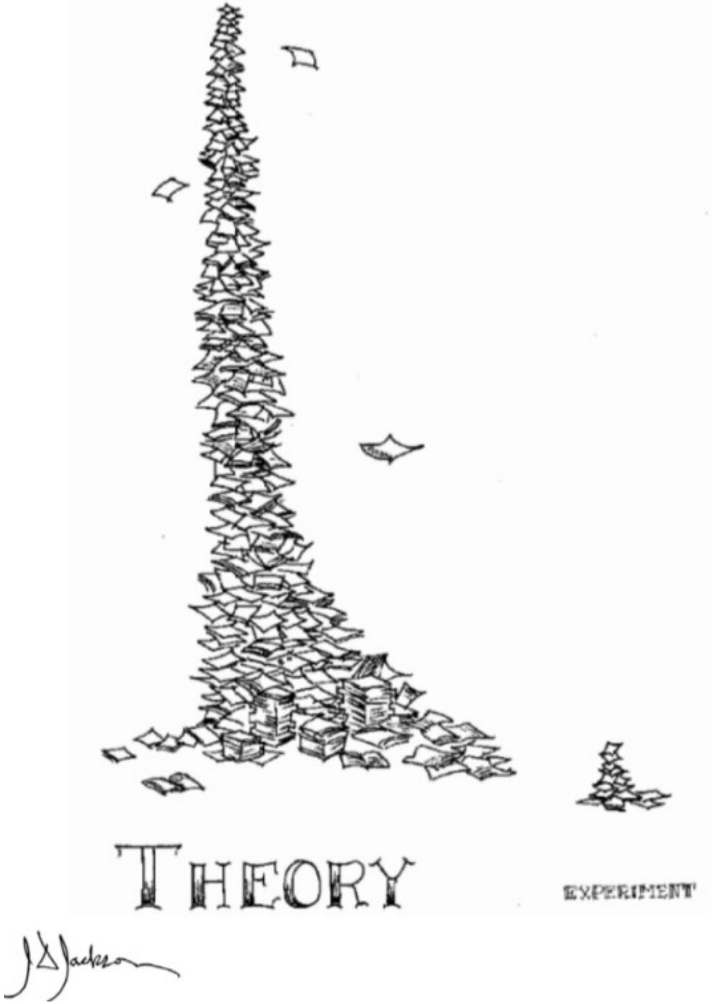
Light cone

Molecules

T_{cc}^{+}

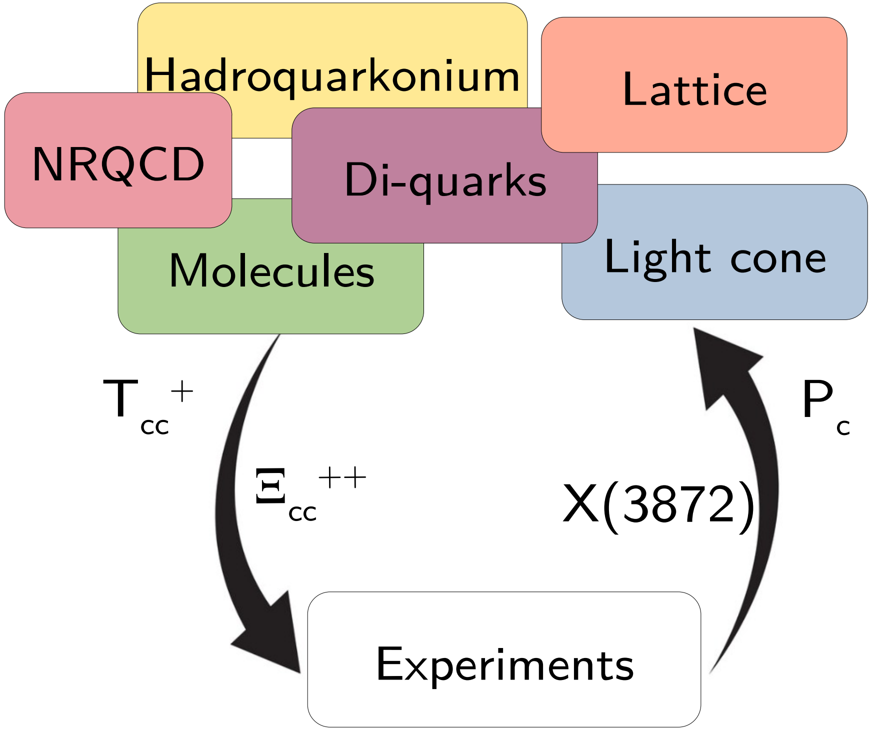
Ξ_{cc}^{++}

Experiments



Intermezzo: Interplay with theory

Non-perturbative QCD



Peculiar features

→ Huge number of theoretical predictions

→ feedback loop

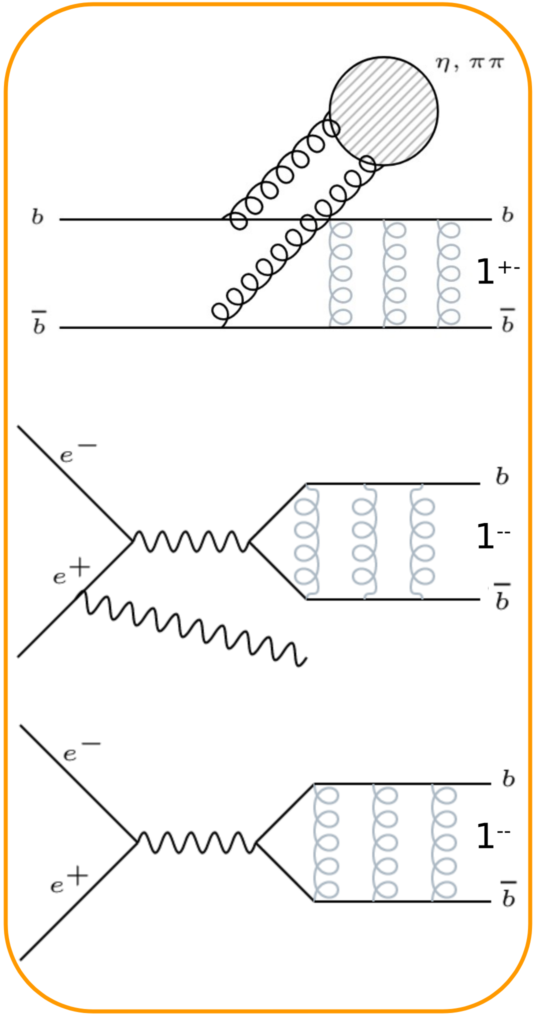
- → **We often discover unpredicted features**
- → New knowledge feeds back to theory and enriches it

Quarkonium spectroscopy at Belle II

Quarkonia at Belle II: how?

Bottomonium

- Hadronic transitions from Υ(4S)
  - Best gateway to $h_b(1P)$ and $\eta_b(1S)$!
- ISR production
- Direct production



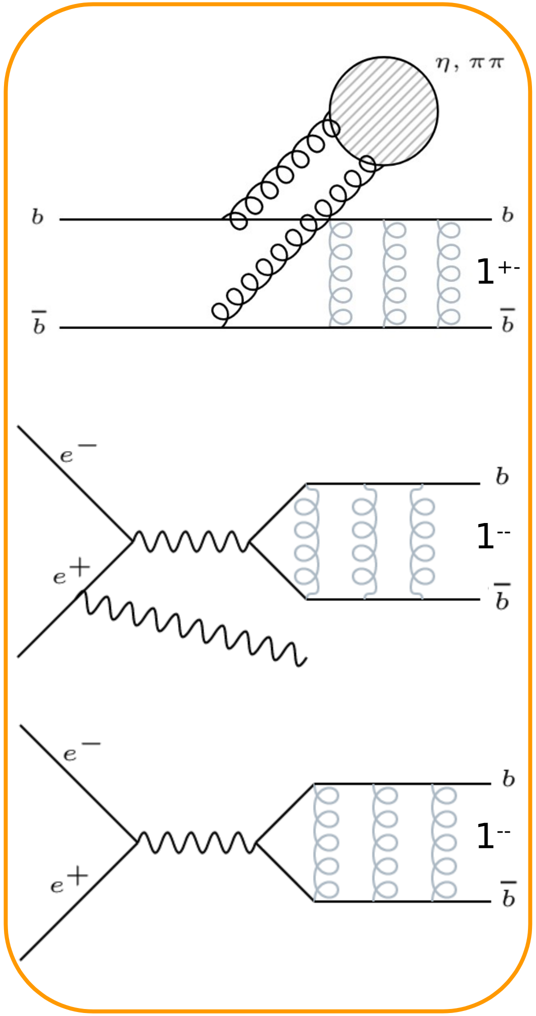
Quarkonia at Belle II: how?

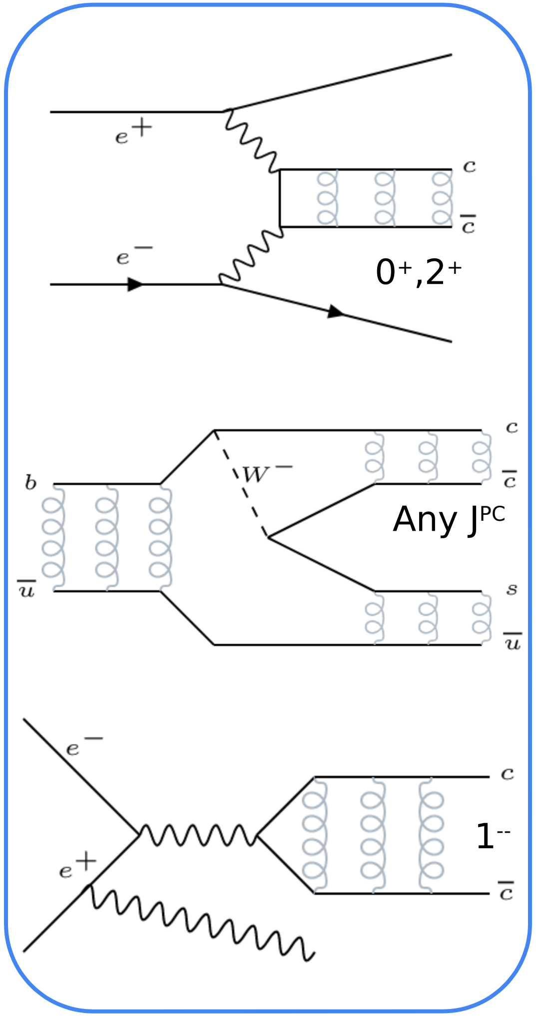
Bottomonium

- Hadronic transitions from Υ(4S)
  - Best gateway to $h_b(1P)$ and $\eta_b(1S)$!
- ISR production
- Direct production

Charmonium

- γγ fusion running at Υ(4S)
- B decays via b → c
- ISR production





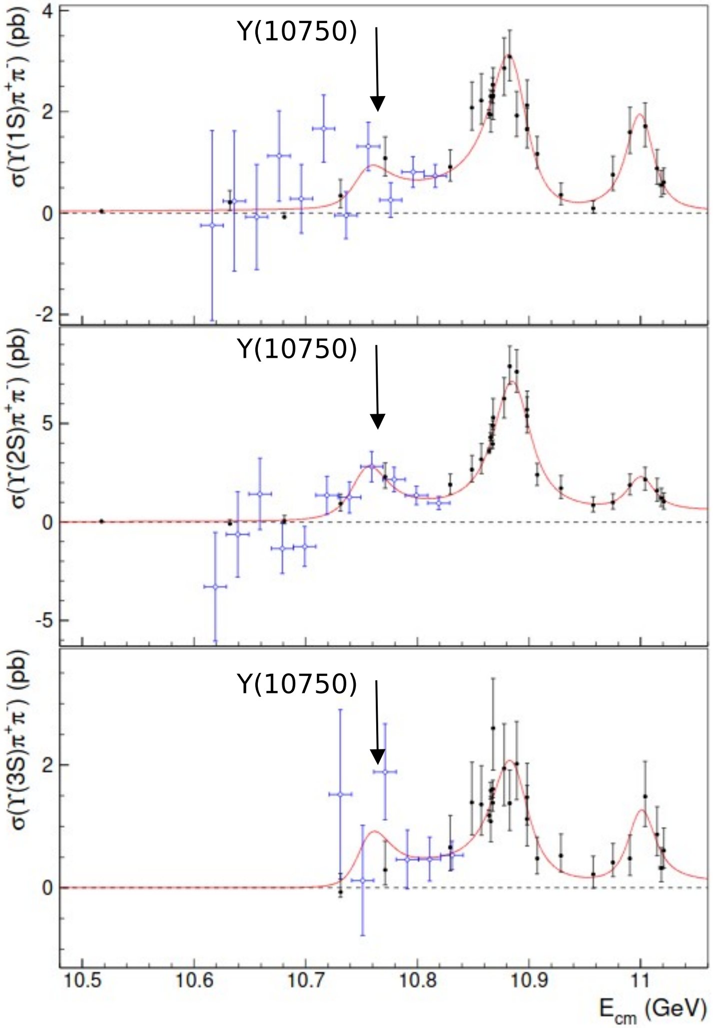
An example: the Y(10750)

JHEP10(2019)220 (*Belle*):

- “High-stat” scan points: 1 fb^{-1} each
- Some resonance appears in the ppY(nS) cross sectior

Parameters:

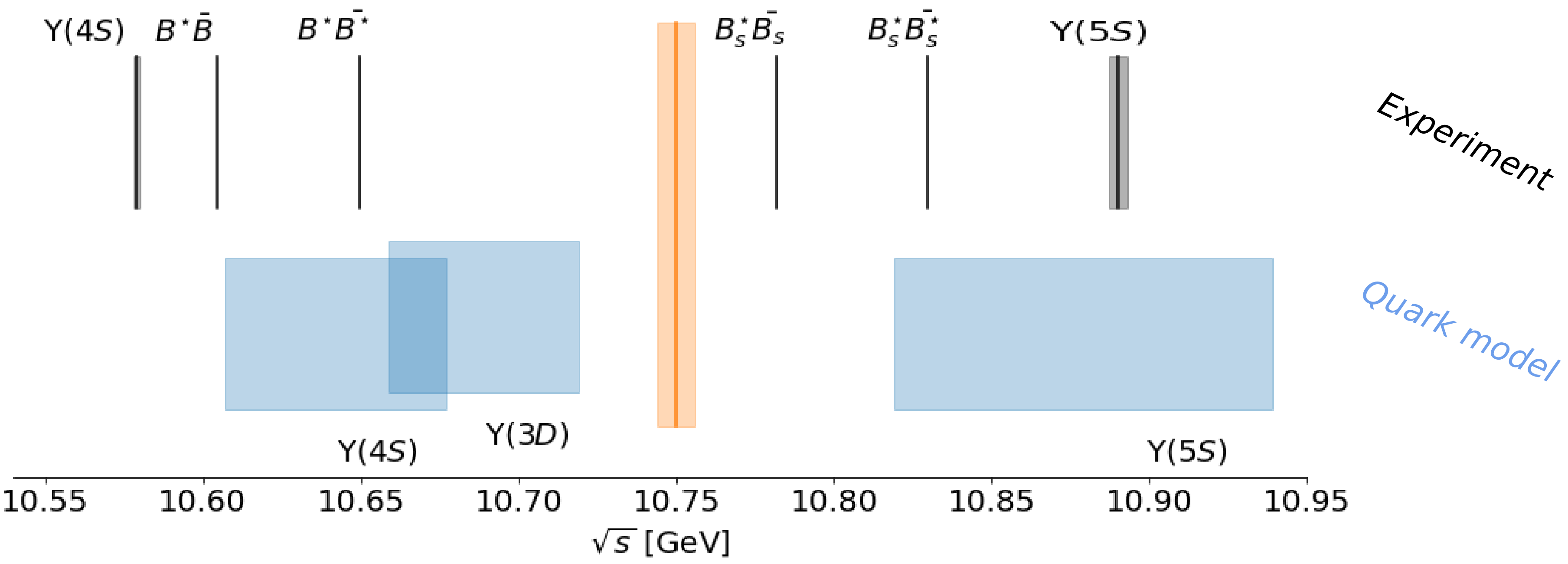
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$



What is it?

Step 1: mass and quantum numbers

- J^{PC} must be 1^{--}
- No direct matching to conventional states (but may be an S-D mixing?)
- **Can it be an exotic?**



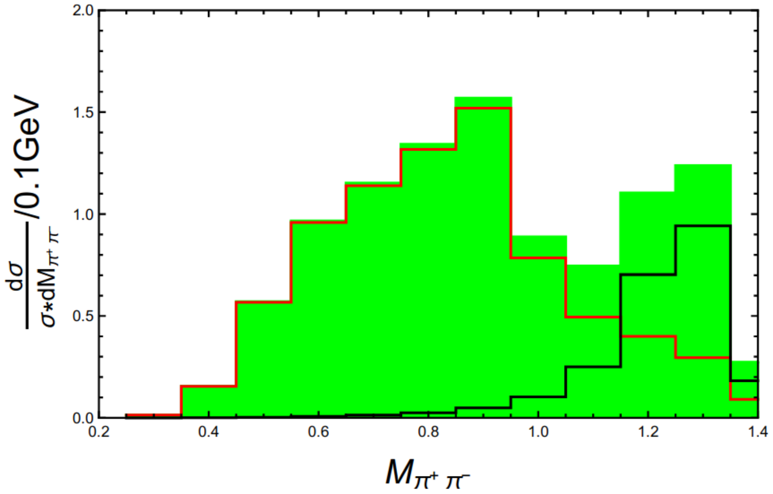
Step 2: Check theory predictions

1) BB : BB* : B*B* ratio is predicted by almost all models

2) $\Upsilon(10750) \to \omega\, \eta_b(1S)$ very large in one tetraquark-based model

3) $M(\pi\pi)$ shape predicted by the tetraquark models

Mode	$\mathcal{B}(4q)$ (%)	$\mathcal{B}(b\bar{b})$ (%)
$B\overline{B}$	$39.3^{+38.7}_{-22.9}$	21.3
$B\overline{B}^*$	$\sim$0.2	14.3
$B^*\overline{B}^*$	$52.3^{+54.9}_{-31.7}$	64.1
$B_s\overline{B}_s$	-	0.3
$\omega\eta_b$	$7.9^{+14.0}_{-5.0}$	-
$f_0(1370)\Upsilon$	$0.2^{+0.6}_{-0.2}$	-
$\omega\Upsilon$	$\sim$0	-



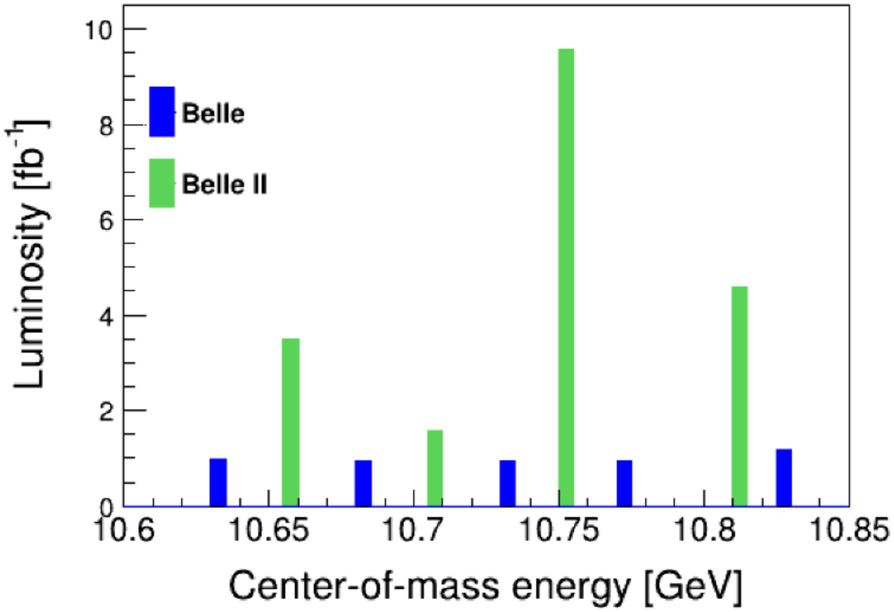
Step 3: take some data!

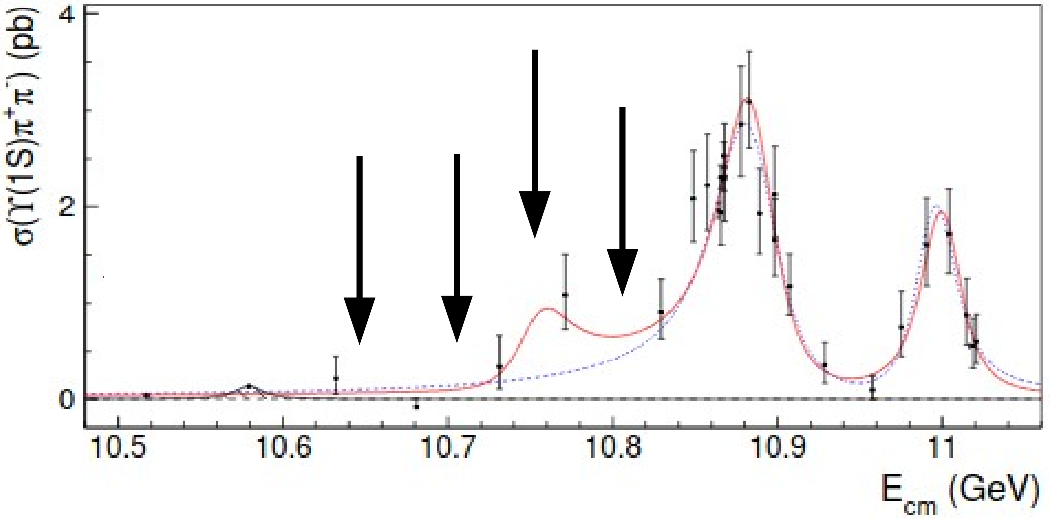
In fall 2021 Belle II took data above the Υ(4S)

→ Goal: study the golden channels to characterize the Υ(10750)

→ Special data taking, lots of discussions and preparation

→ If you have an idea and you like it, don' give up ;)





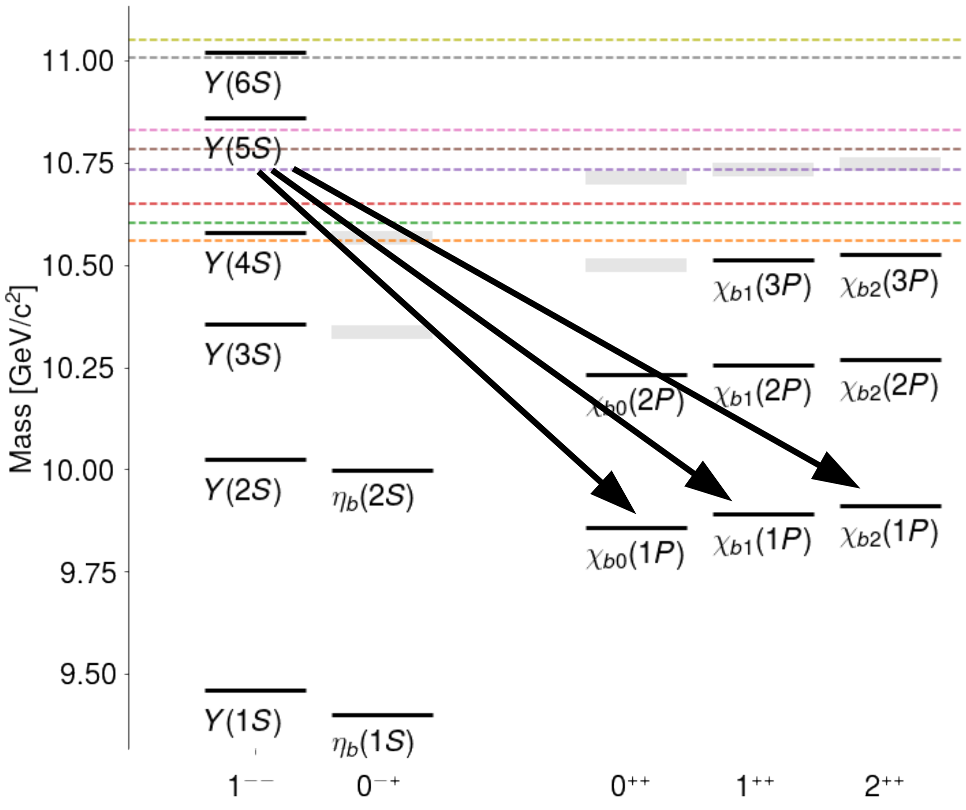
Step 4: First measurements

$\Upsilon(10750) \to \omega\, \chi_b$ in the conventional quarkonium model (S-D mixing state)

[Y.S. Li, et al., PRD 104, 034036 (2021)]

$$\mathcal{B}[\Upsilon(10753) \to \chi_{b0}\omega] = (0.73\text{–}6.94) \times 10^{-3},$$
$$\mathcal{B}[\Upsilon(10753) \to \chi_{b1}\omega] = (0.25\text{–}2.16) \times 10^{-3},$$
$$\mathcal{B}[\Upsilon(10753) \to \chi_{b2}\omega] = (1.08\text{–}11.5) \times 10^{-3}.$$

$$R_{12} = \frac{\mathcal{B}[\Upsilon(10753) \to \chi_{b1}\omega]}{\mathcal{B}[\Upsilon(10753) \to \chi_{b2}\omega]} = (0.18\text{–}0.22)$$



Step 4: First measurements

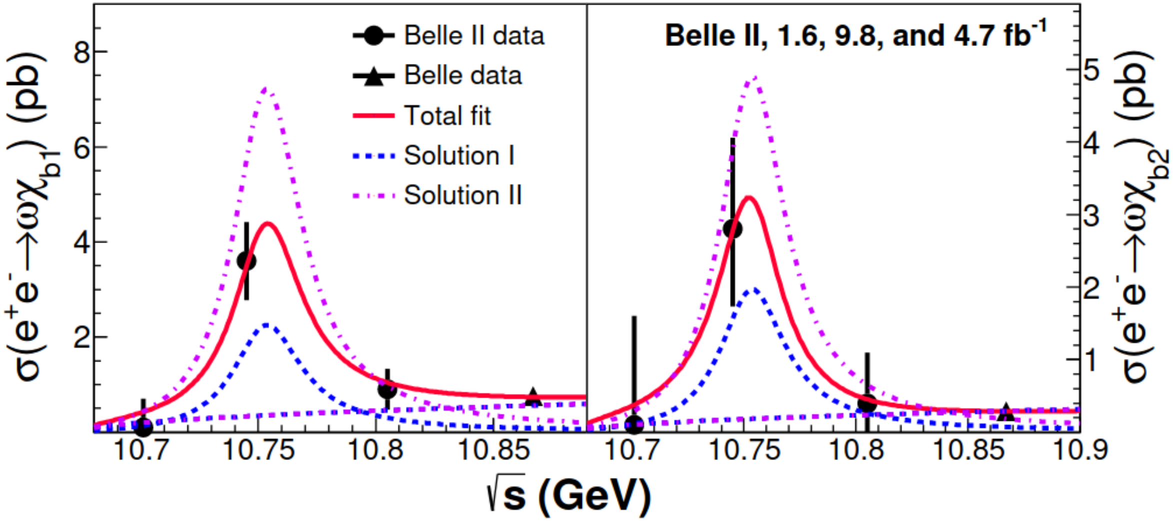
We can measure a cross section for $e^+e^- \to \omega\,\chi_b$

can't measure this without Γ_{ee}

$\mathcal{B}[\Upsilon(10753) \to \chi_{b0}\omega] =$ [illegible] $) \times 10^{-3}$,

$\mathcal{B}[\Upsilon(10753) \to$ [illegible] $–2.16) \times 10^{-3}$,

$\mathcal{B}[\Upsilon($ [illegible] $\omega] = (1.08–11.5) \times 10^{-3}$.



$$R_{12} = \frac{\mathcal{B}[\Upsilon(10753) \to \chi_{b1}\omega]}{\mathcal{B}[\Upsilon(10753) \to \chi_{b2}\omega]} = (0.18–0.22)$$

Our measurement: 1-4

Feed back to theory!

A summary

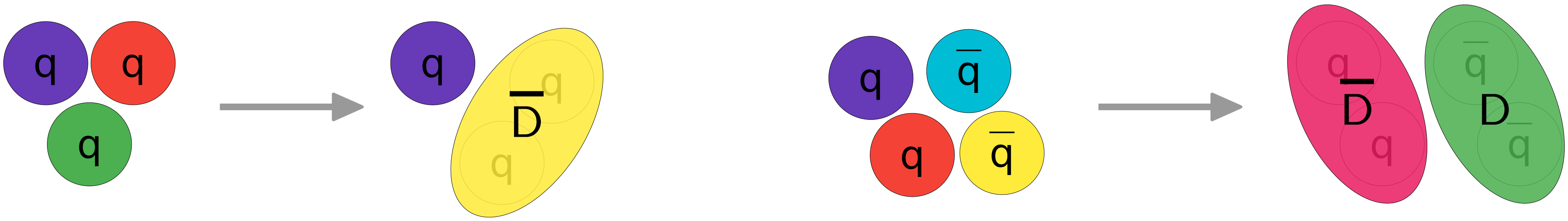
- Hadron spectroscopy is <u>one</u> way to study non-perturbative QCD
- The open problem in hadron spectroscopy is the understanding of the quark-level structure of the multi-quark particles
- Heavy hadrons offer very clear signatures
- Belle II is a key player for the upcoming years

Backup

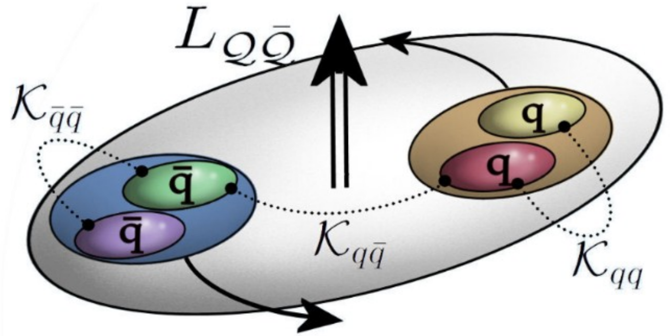
Competing models: compact tetraquarks

Maiani et al, Phys.Rev.Lett. 93 (2004) 212002
t'Hooft et al, Phys.Lett. B662 (2008) 424430

A qq pair belongs behaves (color-wise) exactly like a $\bar{q}$



Structure determined by both
→ q-q Interaction within di-quarks
→ q-$\bar{q}$ Interaction across diquark



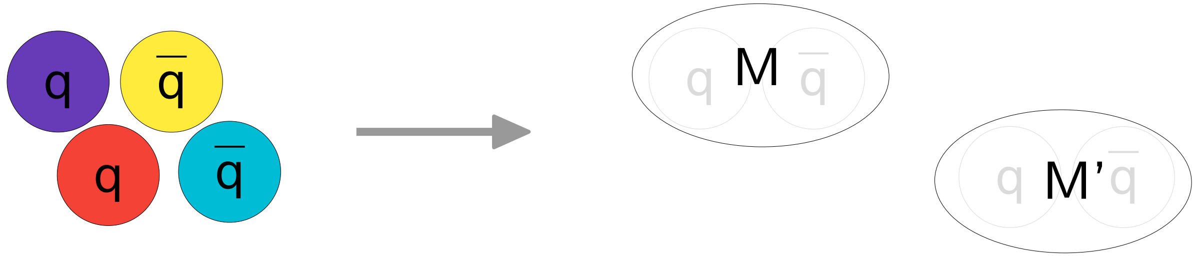
Good review about di-quarks: *Prog. Part. Nucl. Phys. 116 (2021) 103835*

Competing models: molecules

Guo et al, Rev. Mod. Phys. 90, 015004 (2018)

Several exotics lay very close to a DD threshold

$\rightarrow$ cold be loosely bound meson-meson bound states

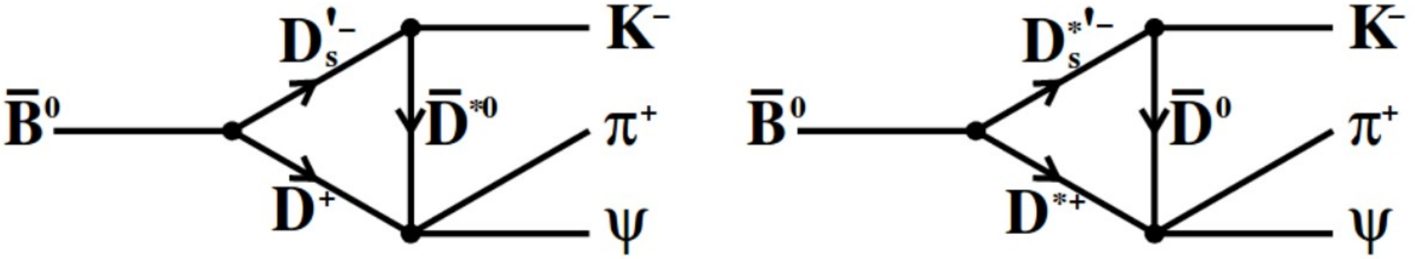


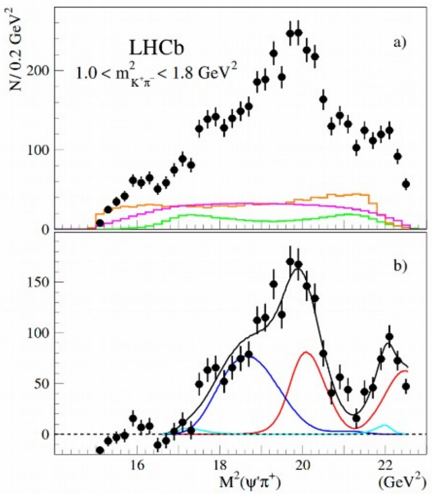
Molecules should always be close (or better below...) the threshold

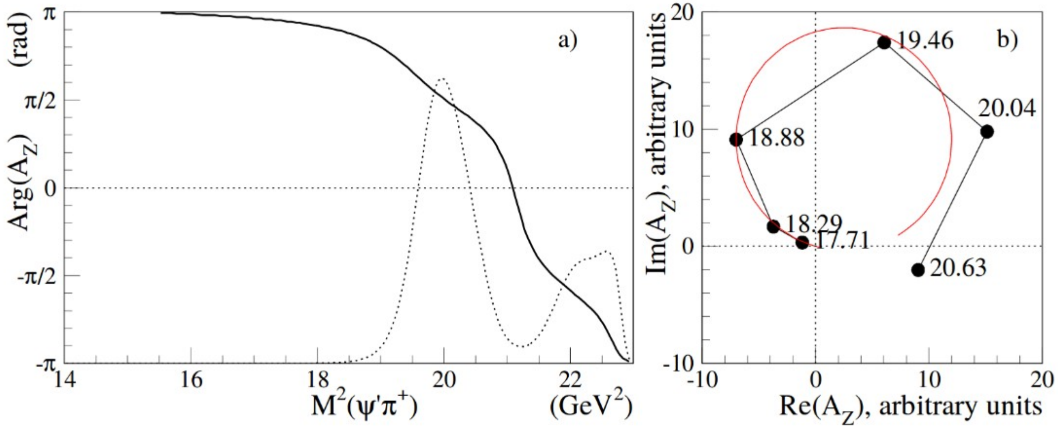
Competing models: others

Phys. Lett. B748 (2015) 183186

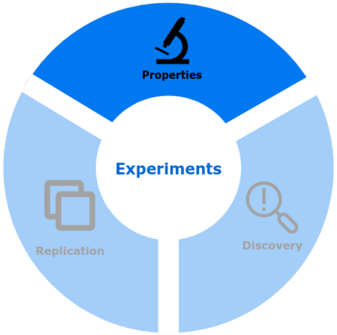
Also "dynamic" effects can produce resonance-like stuctures







Mapping properties: absolute BFs



When we observe a new state S we access

$$\text{Rate} = \sigma_{\text{production}}(S) \times \text{BF}(S \to \text{final state})$$

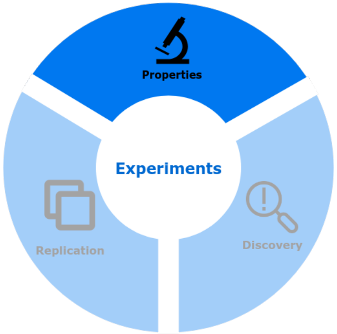
Poorly (or not) constrained by theory

Some (pre, post)dictions usually available

$Z_c(3900)$ **Decay Modes**

	Mode	Fraction (Γ_i / Γ)
Γ_1	$J/\psi\pi$	seen
Γ_2	$h_c\pi^\pm$	not seen
Γ_3	$\eta_c\pi^+\pi^-$	not seen
Γ_4	$\eta_c(1S)\rho(770)^\pm$	
Γ_5	$(D\overline{D}^*)^{+-}$	seen
Γ_6	D^0D^{*-} + c.c.	seen
Γ_7	D^-D^{*0} + c.c.	seen
Γ_8	$\omega\pi^\pm$	not seen
Γ_9	$J/\psi\eta$	not seen
Γ_{10}	D^+D^{*-} + c.c	seen
Γ_{11}	$D^0\overline{D}^{*0}$ + c.c	seen

Mapping properties: absolute BFs

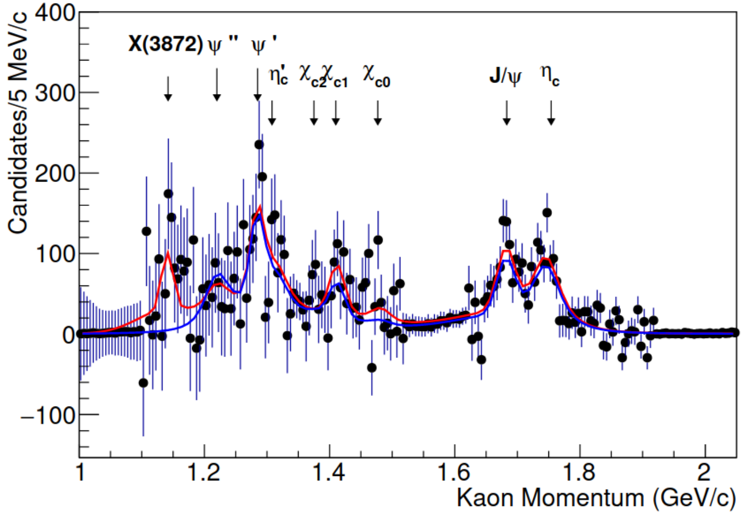


When we observe a new state S we access

$$\text{Rate} = \boxed{\sigma_{\text{production}}(S)} \times \boxed{\text{BF}(S \to \text{final state})}$$

Workaround: measure inclusive production BF from B mesons

[BaBar, PRL 124, 152001 (2020)]



$B^+ \to K^+ X$

- X not reconstructed. Use K^+ recoil
- Measure production BF

Next generation b-factories: use this method as much as possible

Future challenges: hadrons with beauty

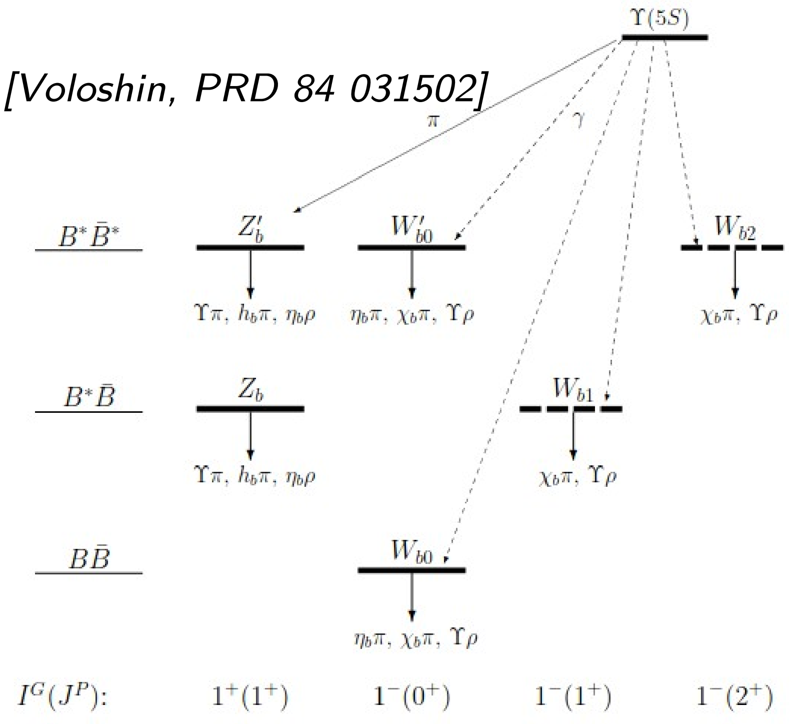
Exotic search with Ecm $<$ 12 GeV are challenging

$\rightarrow$ rely on rare, soft EM transitions

[Ali et. Al., Prog. Part. Nucl. Phys. 97 (2017) 123-198]

Label	J^{PC}	charmonium-like State	charmonium-like Mass [MeV]	bottomonium-like State	bottomonium-like Mass [MeV]
X_0	0^{++}	—	3756	—	10562
X_0'	0^{++}	—	4024	—	10652
X_1	1^{++}	$X(3872)$	3890	—	10607
Z	1^{+-}	$Z_c^+(3900)$	3890	$Z_b^{+,0}(10610)$	10607
Z'	1^{+-}	$Z_c^+(4020)$	4024	$Z_b^+(10650)$	10652
X_2	2^{++}	—	4024	—	10652
Y_1	1^{--}	$Y(4008)$	4024	$Y_b(10890)$	10891
Y_2	1^{--}	$Y(4260)$	4263	$\Upsilon(11020)$	10987
Y_3	1^{--}	$Y(4290)$ (or $Y(4220)$)	4292	—	10981
Y_4	1^{--}	$Y(4630)$	4607	—	11135
Y_5	1^{--}	—	6472	—	13036

[Voloshin, PRD 84 031502]

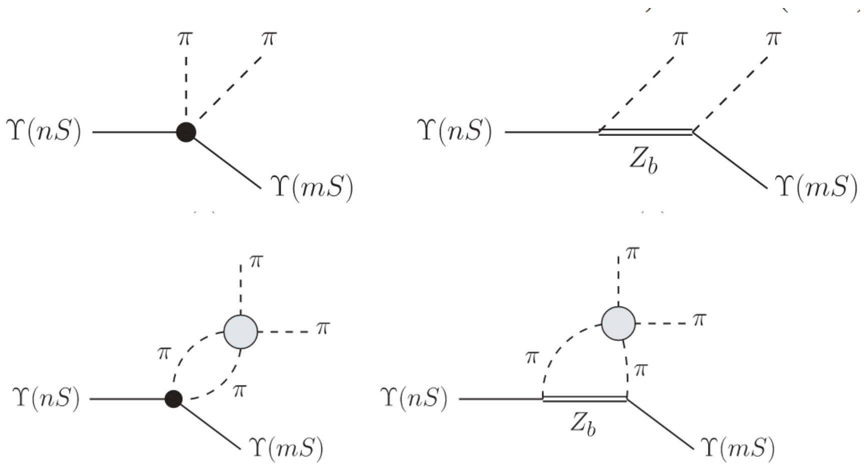


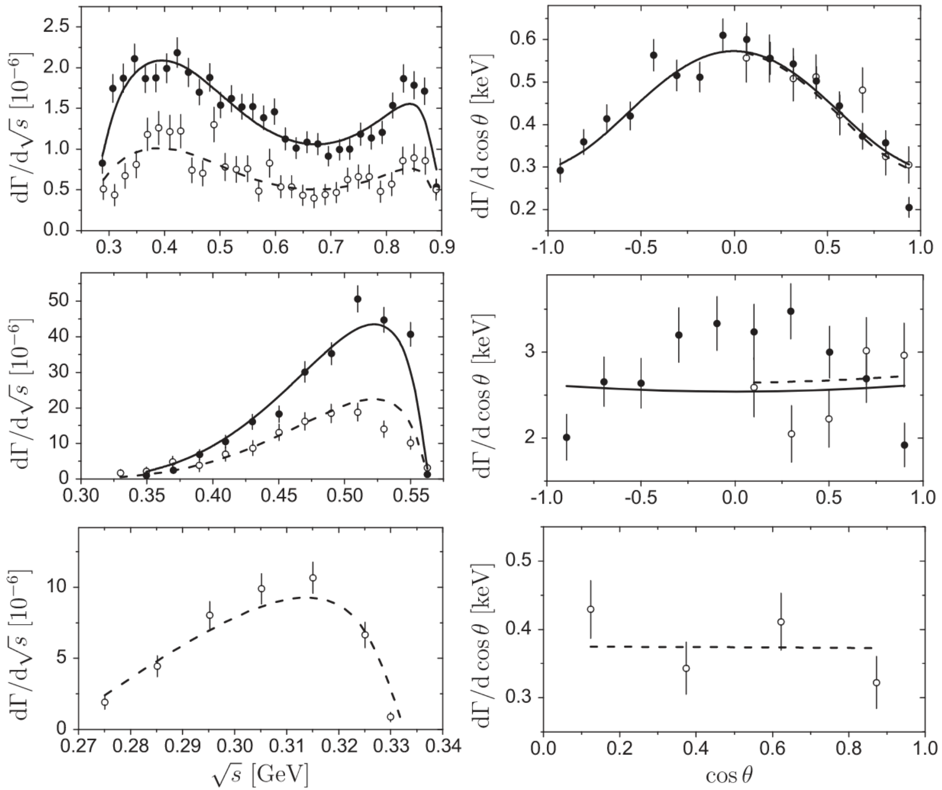
Bottomonium: alternative approaches

Exotic stats contribute to the transitions from narrow quarkonia?

→ new (?) approach to heavy spectroscopy

Y.H. Chen et al, PRD93 (2016) 034030





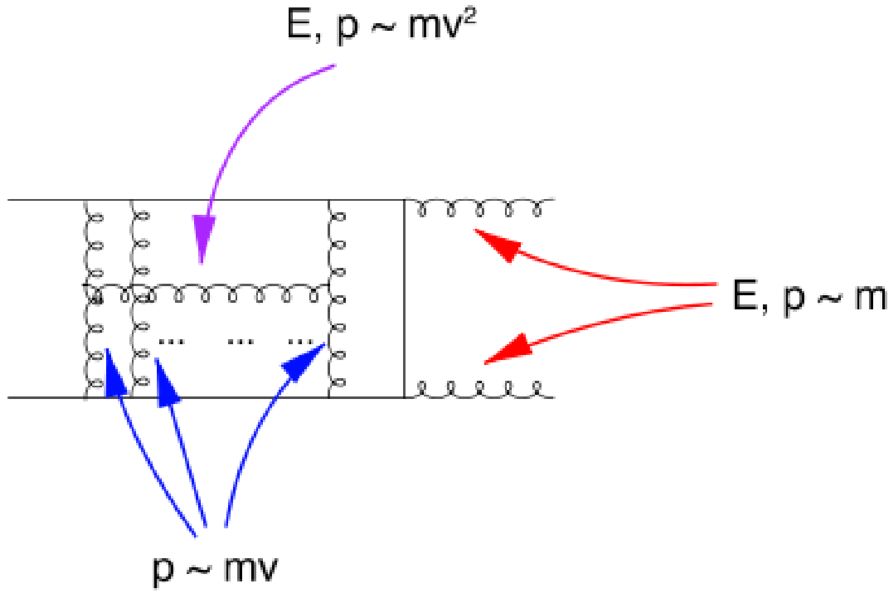
Why is bottomonium so special?

A clean spectrum is not the only distincitve feature

→ **A QCD multi-scale system**

→ each feature is controlled by a different scale

→ From perturbative to non-perturbative in one system!



→ **A lepton-pair factory**

→ BF(Y → ll) ~ 2.5%

→ (almost) purely EM process

Charmonium at experiments

Charmonium is experimentally easy and accessible

→ Direct production in e^+e^- collisions

→ Production in B → K $c\bar{c}$

→ Photon-photon scattering $\gamma\gamma^*$ → $(c\bar{c})$

→ Double Charmonium e^+e^- → $(c\bar{c})(c\bar{c})$

→ Prompt production

→ Direct production in $p\bar{p}$ (???)

Bottom line: Charmonium will still be fully covered in the next 15 yrs.

Bottomonium at experiments

Bottomonium is much less accessible

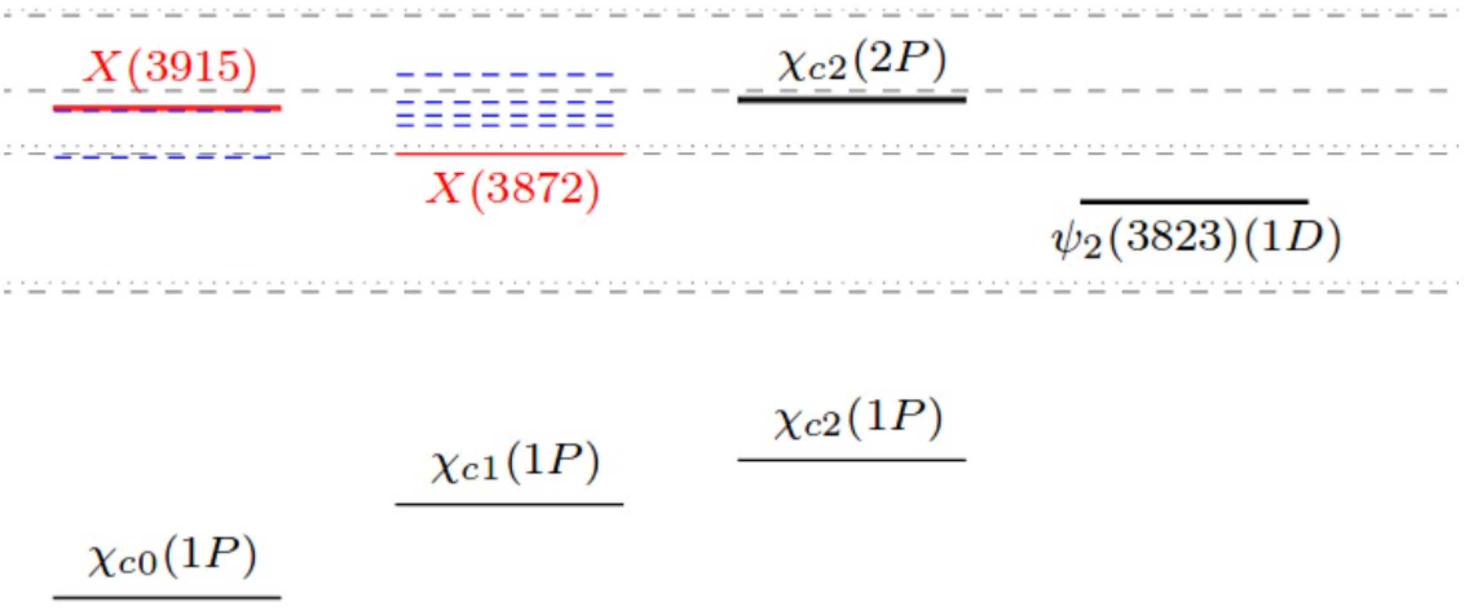
→ Direct production in e^+e^- collisions

→ Prompt production

Bottom line: after Belle II, bottomonium studies will havestrong limitations

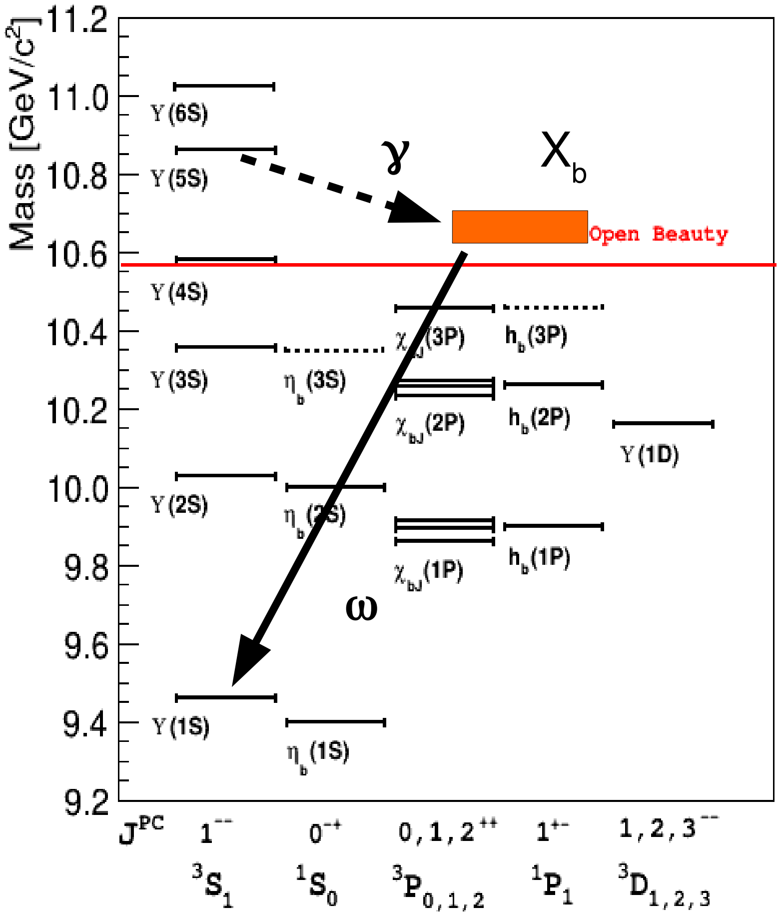
Look for more patterns: the X(3872)

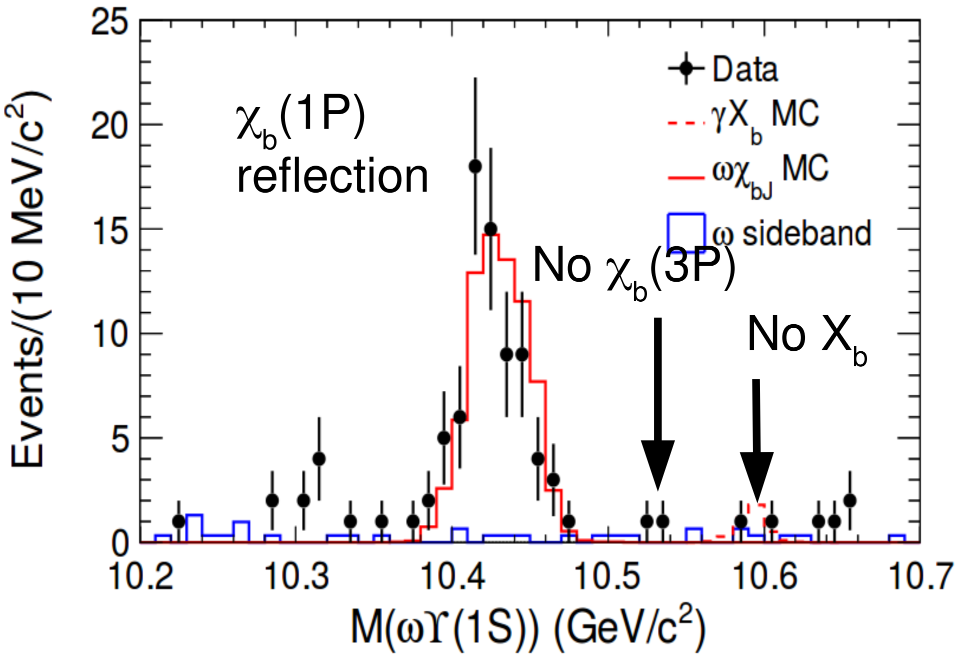
- → The only exotica to have been observed in several different conditions
- → A narrow peak ~ at the DD* threshold
- → Same quantum numbers as a χ_{c1}(2P), completely different properties



Is there an X(3872) counterpart?

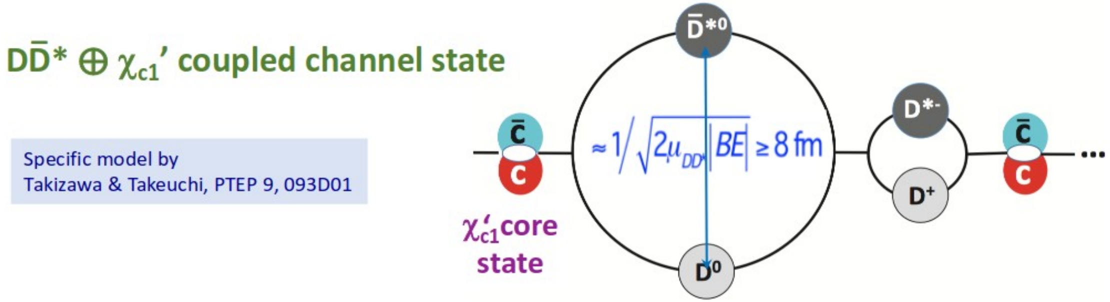
Both tetraquark and pure molecule predict a counterpart (X_b)

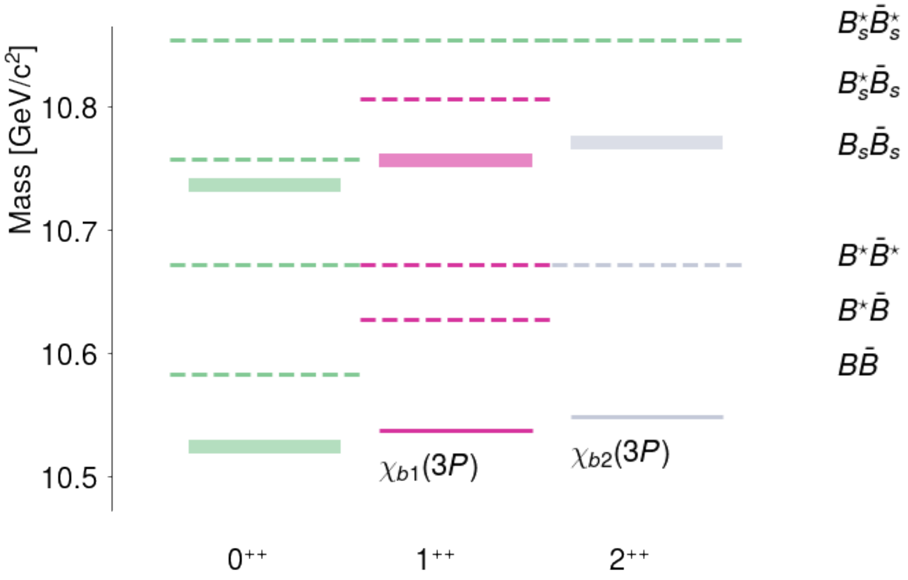




Why no X_b ?

The X(3872) may generated by a peculiar coincidence

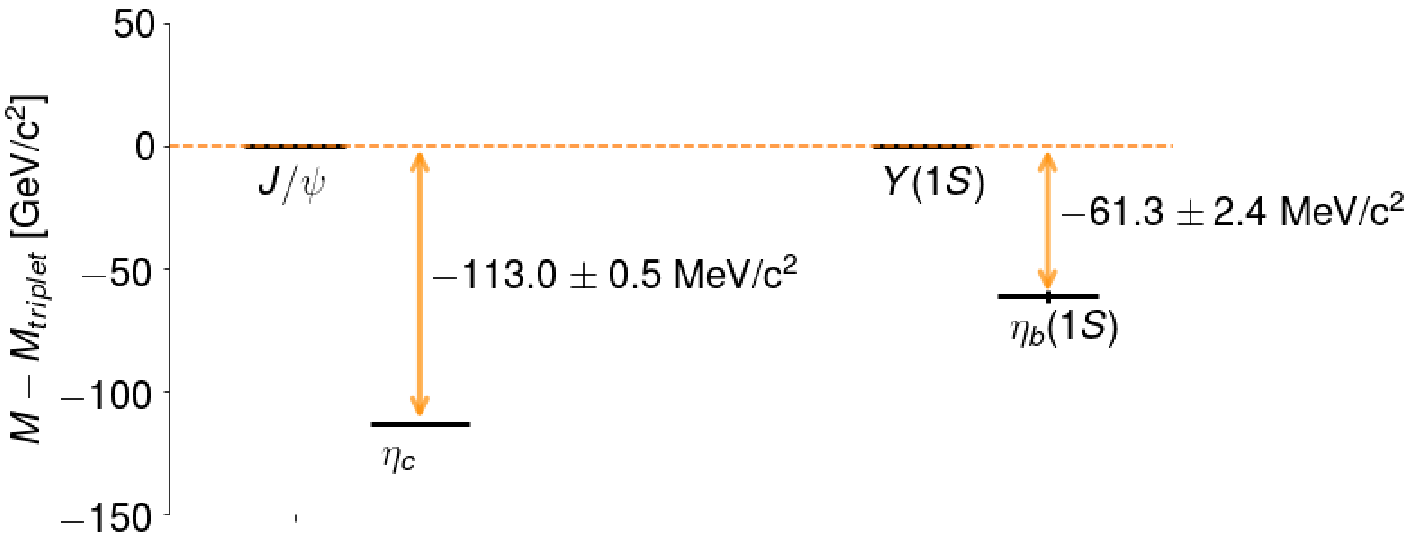




No χ_b is near the BB* threshold, no X_b

Statistics in bottomonium is still too limited. **Need to set a stronger UL to rule out the X_b tetraquark hypothesis**

The ground states

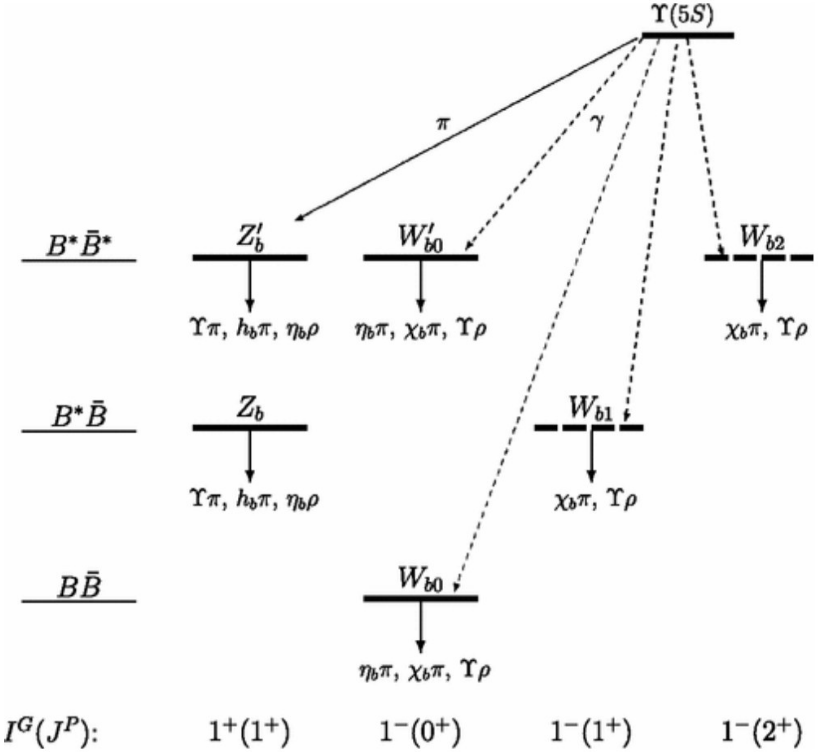


$$
\begin{aligned}
V_{spin}(r) \quad &= \quad \left(\frac{1}{2m_1^2}\vec{L}\cdot\vec{S}_1 + \frac{1}{2m_2^2}\vec{L}\cdot\vec{S}_2\right)\frac{1}{r}\frac{d}{dr}\left(V(r) + 2V_1(r)\right) \\
&\quad + \frac{1}{m_1 m_2}\vec{L}\cdot(\vec{S}_1 + \vec{S}_2)\frac{1}{r}\frac{dV_2(r)}{dr} \\
&\quad + \frac{1}{m_1 m_2}(\hat{r}\cdot\vec{S}_1\,\hat{r}\cdot\vec{S}_2 - \frac{1}{3}\vec{S}_1\cdot\vec{S}_2)V_3(r) + \boxed{\frac{1}{3m_1 m_2}\vec{S}_1\cdot\vec{S}_2\;V_4(r)}
\end{aligned}
$$

Y(5S) and Y(6S): new exotica

→ If the Z_b is a loosely bound state, then several other molecules must appear

→ No predictions on the production rates



Mod. Phys. Lett. A 32, 1750025 (2017)

$I^G(J^P)$	Name	Composition	Co-produced particles [Threshold, GeV/c^2]	Decay channels
$1^+(1^+)$	Z_b	$B\bar{B}^*$	π [10.75]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^+(1^+)$	Z_b'	$B^*\bar{B}^*$	π [10.79]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^-(0^+)$	W_{b0}	$B\bar{B}$	ρ [11.34], γ [10.56]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(0^+)$	W_{b0}'	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(1^+)$	W_{b1}	$B\bar{B}^*$	ρ [11.38], γ [10.61]	$\Upsilon(nS)\rho$
$1^-(2^+)$	W_{b2}	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$
$0^-(1^+)$	X_{b1}	$B\bar{B}^*$	η [11.15]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^-(1^+)$	X_{b1}'	$B^*\bar{B}^*$	η [11.20]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^+(0^+)$	X_{b0}	$B\bar{B}$	ω [11.34], γ [10.56]	$\Upsilon(nS)\omega$, $\eta_b(nS)\eta$
$0^+(0^+)$	X_{b0}'	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$, $\eta_b(nS)\eta$
$0^+(1^+)$	X_b	$B\bar{B}^*$	ω [11.39], γ [10.61]	$\Upsilon(nS)\omega$
$0^+(2^+)$	X_{b2}	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$