Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Spectroscopy: experimental review

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Interplay with theory

Non-perturbative QCD

Hadroquarkonium

Lattice

NRQCD

Di-quarks

Light cone

Molecules

Experiments

Spectroscopy = Non perturbative QCD

$\rightarrow$ Can't do direct calculation, rely on models approximating QCD

$\rightarrow$ Understand (solve?) QCD in the NP regime

Interplay with theory

Non-perturbative QCD

Hadroquarkonium

Lattice

NRQCD

Di-quarks

Light cone

Molecules

T_{cc}^{+}

Ξ_{cc}^{++}

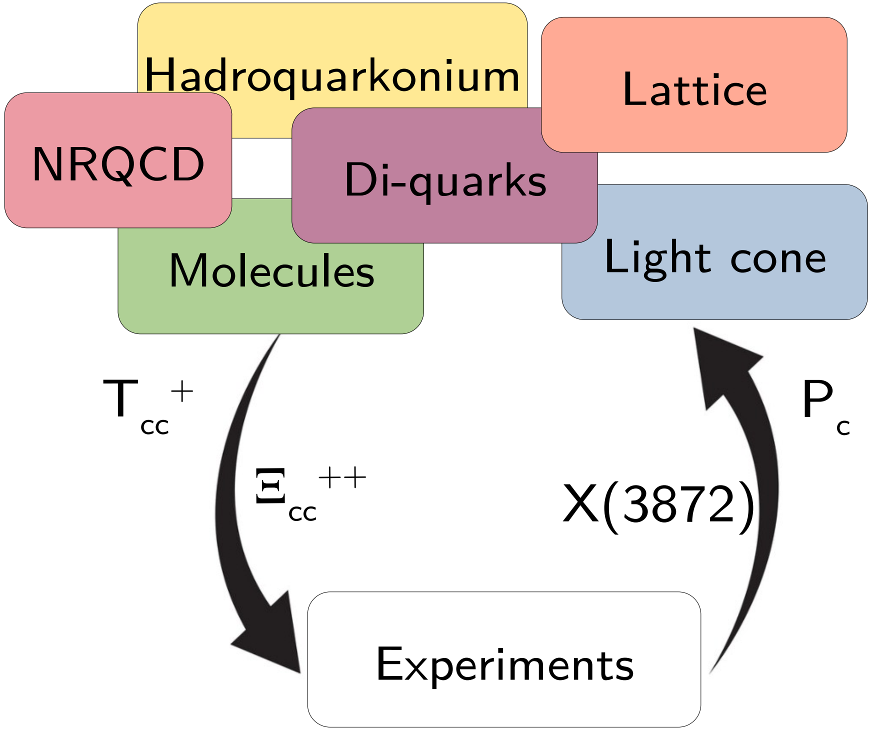
Experiments

Peculiar features

$\rightarrow$ Huge number of theoretical predictions

Interplay with theory

Non-perturbative QCD



Peculiar features

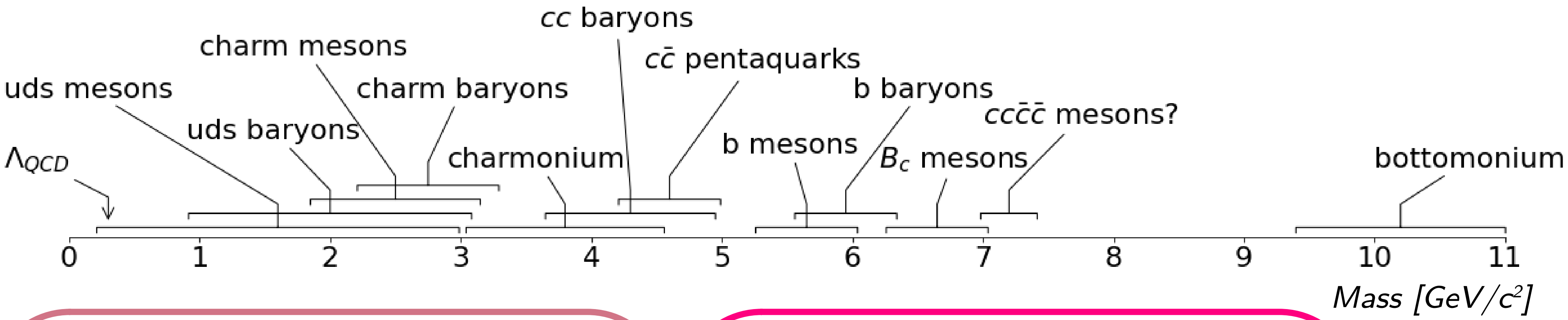
→ Huge number of theoretical predictions

→ feedback loop

→ **We often discover unpredicted features**

→ New knowledge feeds back to theory

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

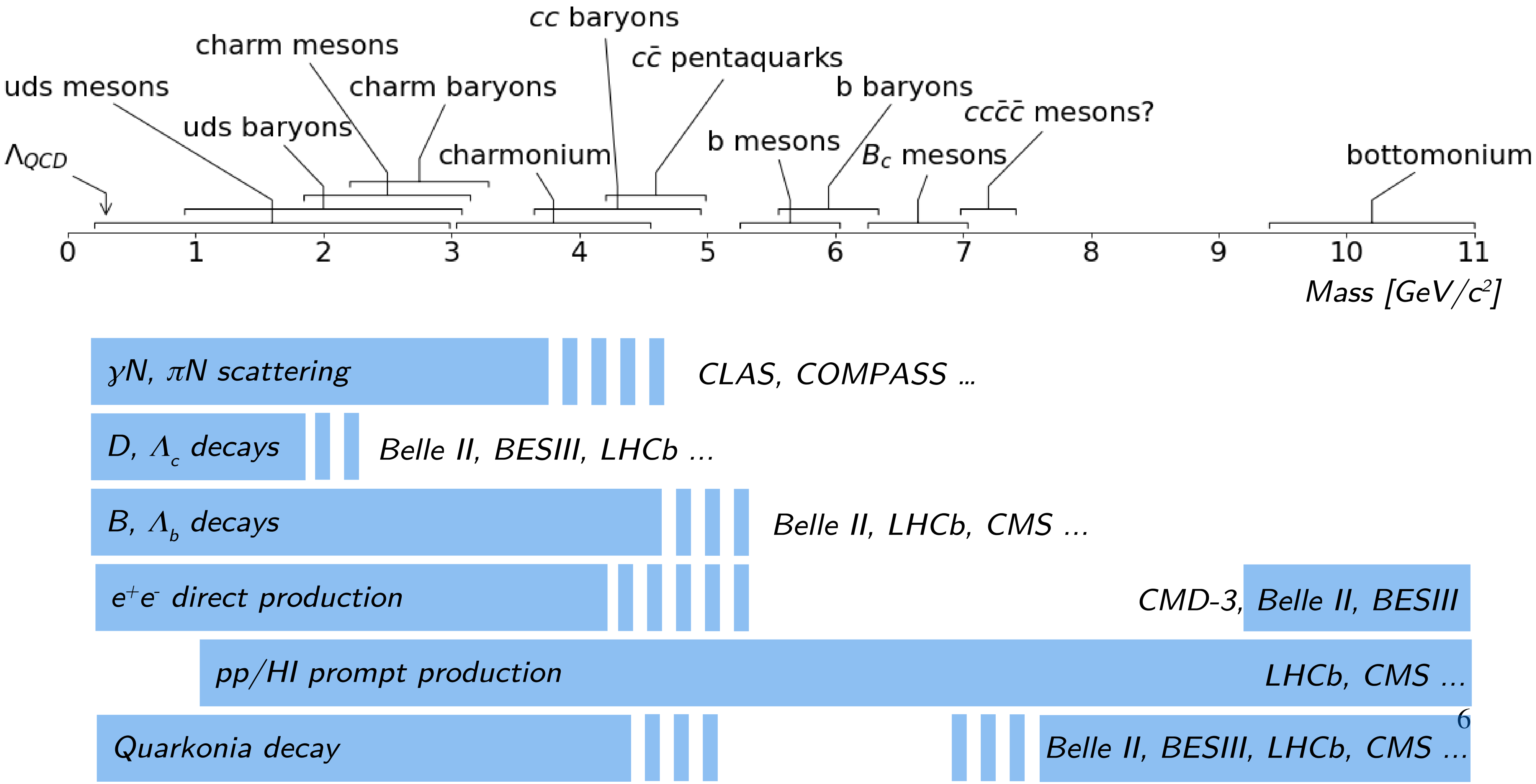
$SU(n)_f$ broken

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

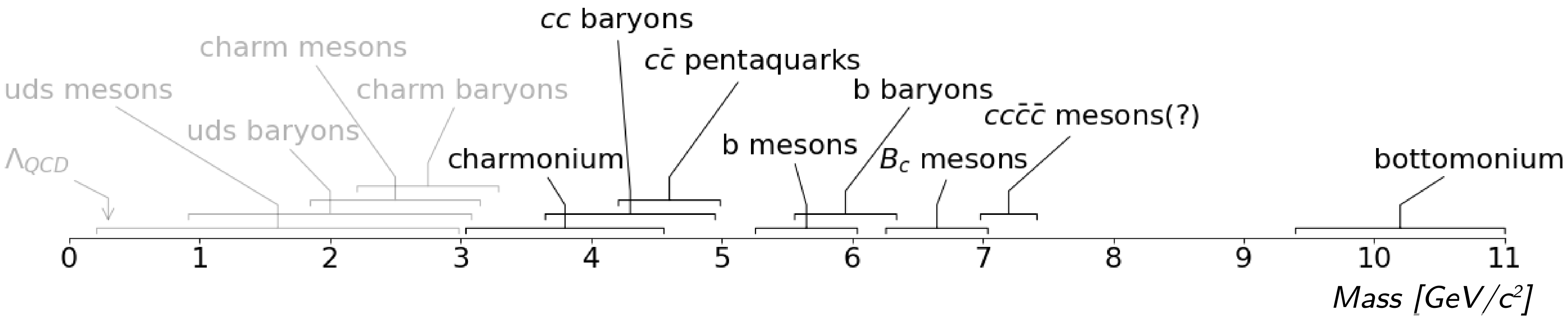
$M(c,b) >> E_{binding}$

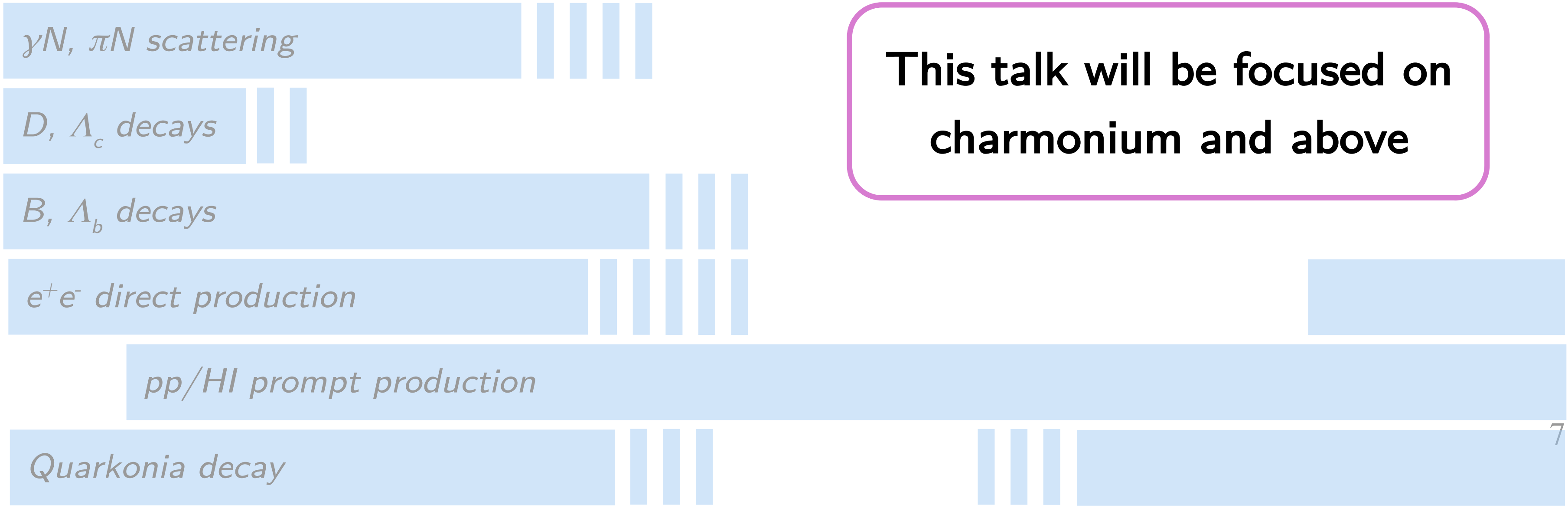
- non-relativistic
- L is good quantum number
- heavy quark spin symmetry

Heavy or light hadrons?



Heavy or light hadrons?



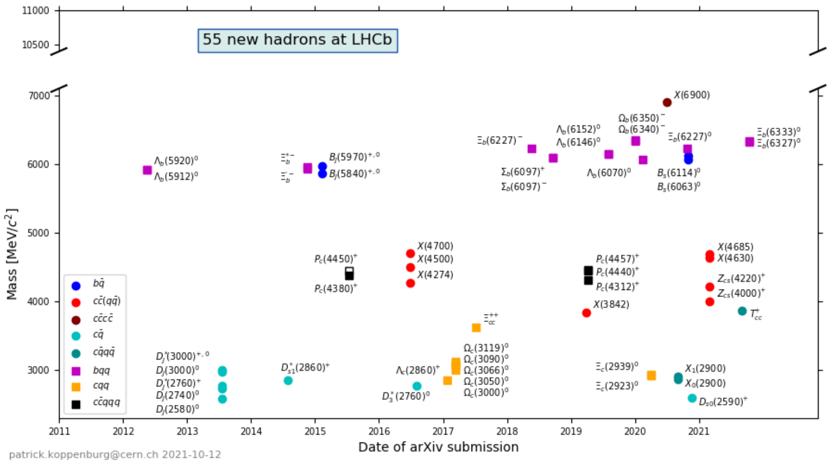


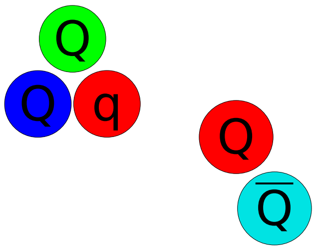
This talk will be focused on charmonium and above

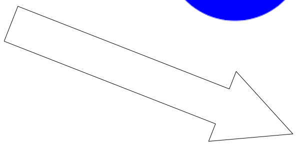
Why heavy mesons

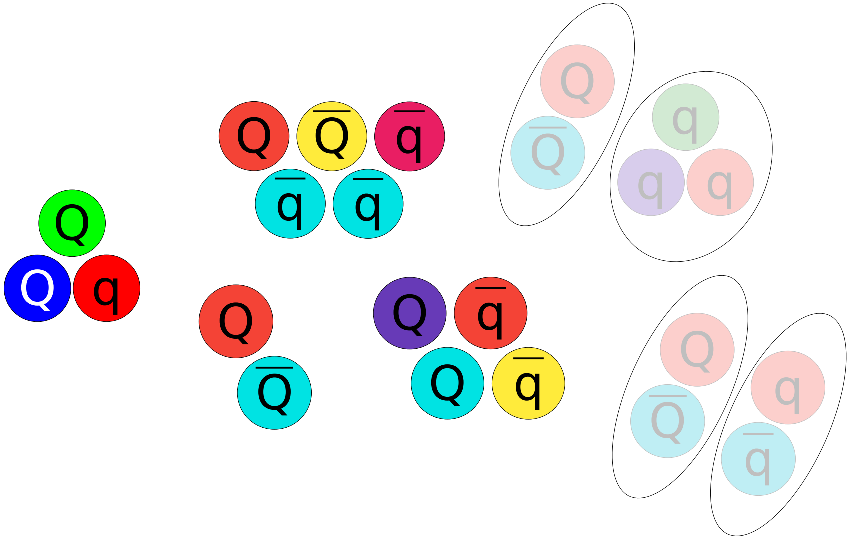
$q\bar{q}$ and qqq are not the only color singlets

- we are now sure there is much more!





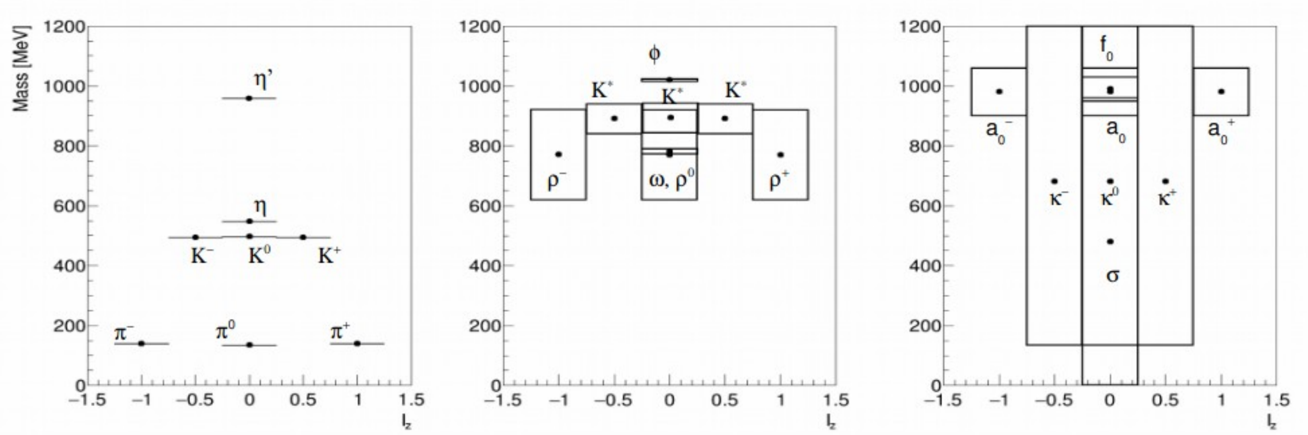




Why heavy mesons

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

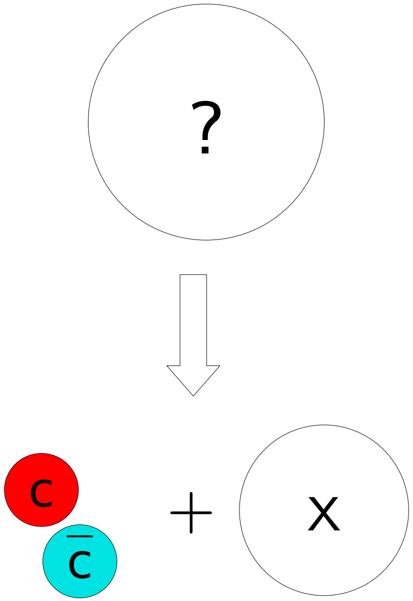
- proposed to describe $a_0(980)$ and $f_0(980)$ *[Baru et al. PLB 586 53-61 (2004)]*
- can explain inverted hierarchy in scalar mesons *[Maiani et al. PRL 93 212002 (2004)]* *['t Hooft et al. PLB 662 424-430 (2008)]*



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

Why heavy mesons

With Heavy mesons separating conventional and exotics is much simpler



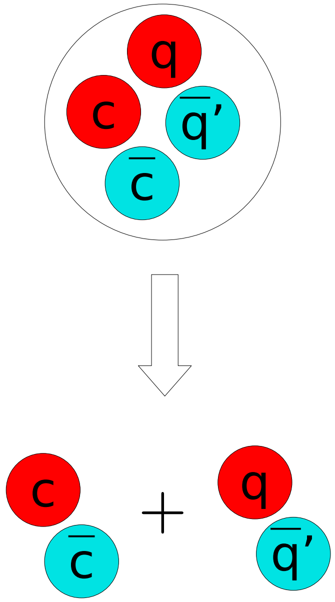
If a state has:

- 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

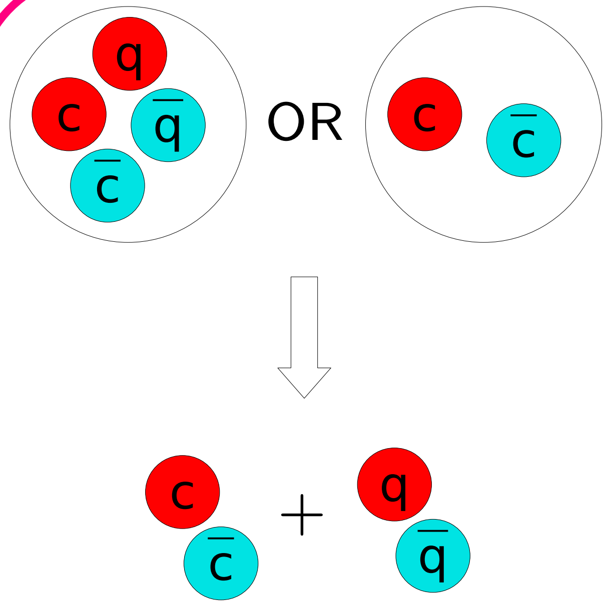
Why heavy mesons

With Heavy mesons separating conventional and exotics is much simpler



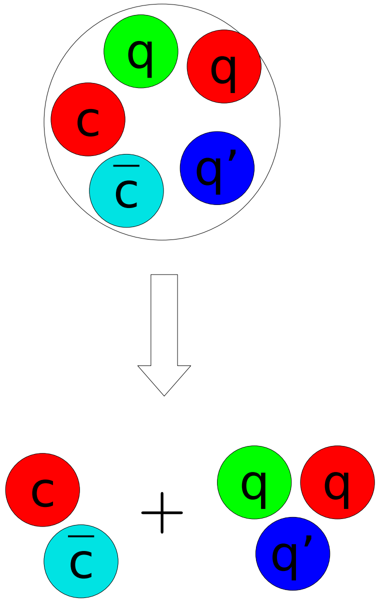
Charged/flavoured $c\bar{c}$-like

- 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

Part I: The news

The first charmed-strange tetraquark

First strange charmonium-like tetraquark …

BESIII *[PRL 126, 102001 (2021)]*

$e^+e^- \rightarrow K^+ Z_{cs}(3985)^- \rightarrow K^+ (D^*D_s^-$ and $D^-D^*_s)$

$c\bar{c}s\bar{u}$

The first charmed-strange tetraquark

… Soon after followed by other 2

BESIII *[PRL 126, 102001 (2021)]*

$e^+e^- \rightarrow K^+ Z_{cs}(3985)^- \rightarrow K^+ (D^*D_s^-$ and $D^-D^*_s)$

$c\bar{c}s\bar{u}$

LHCb [PRL 127, 082001 (2021)

$B^+ \rightarrow \Phi\ Z_{cs}(4220)^+ \rightarrow \Phi\ (K^+J/\psi)$

$c\bar{c}u\bar{s}$

LHCb [PRL 127, 082001 (2021)]

$B^+ \rightarrow \Phi\ Z_{cs}(4000)^+ \rightarrow \Phi\ (K^+J/\psi)$

$c\bar{c}u\bar{s}$

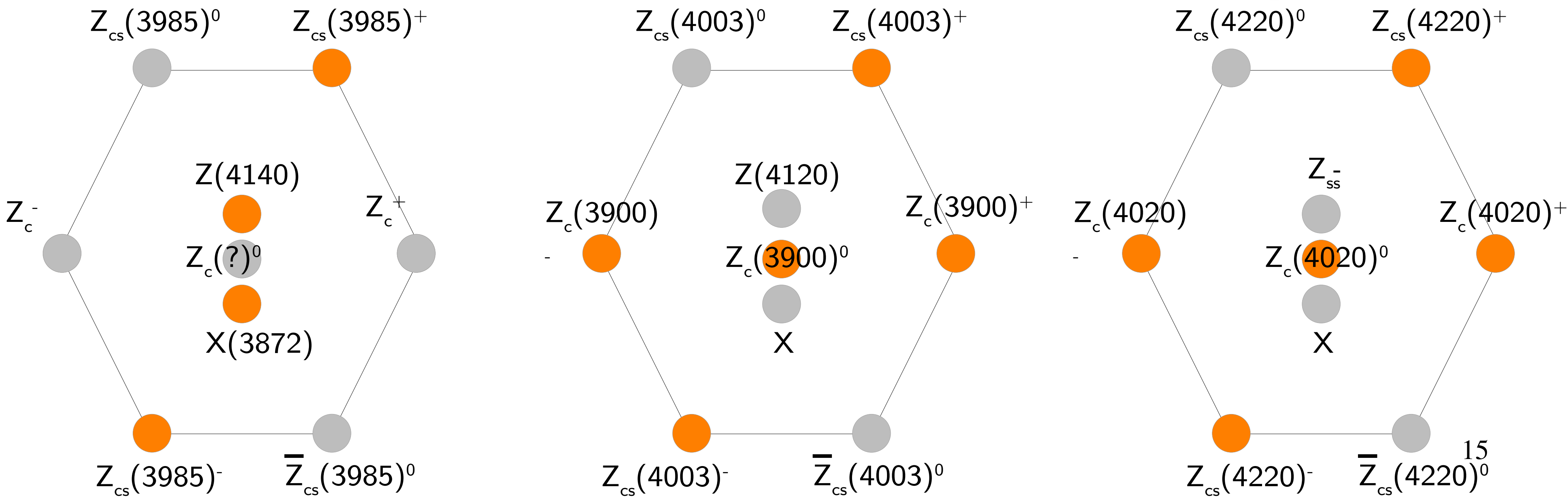
The first charmed-strange tetraquark

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

Di-quarks arrange to produce 3 S-wave nonets

- predictions about the mass of missing states is possible now
- Are we filling up the compact tetraquark nonets?

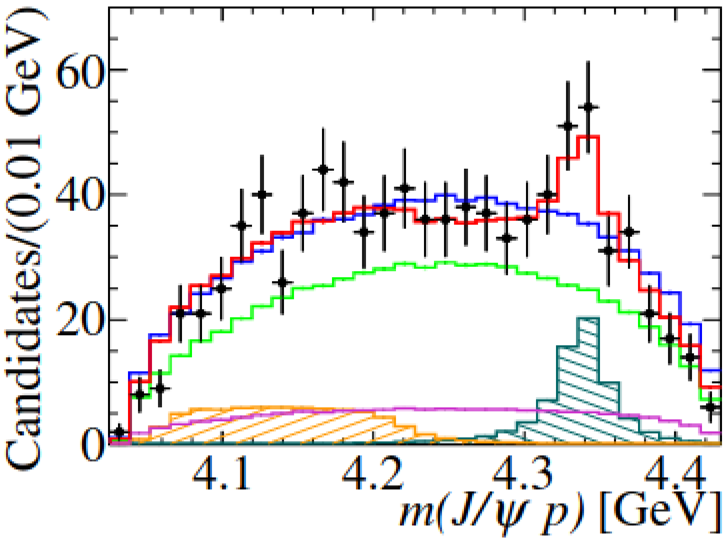
More on this later



New pentaquarks (now with strangeness)

$B_s \rightarrow J/\psi p\bar{p}$

[arXiv:2108.04720]

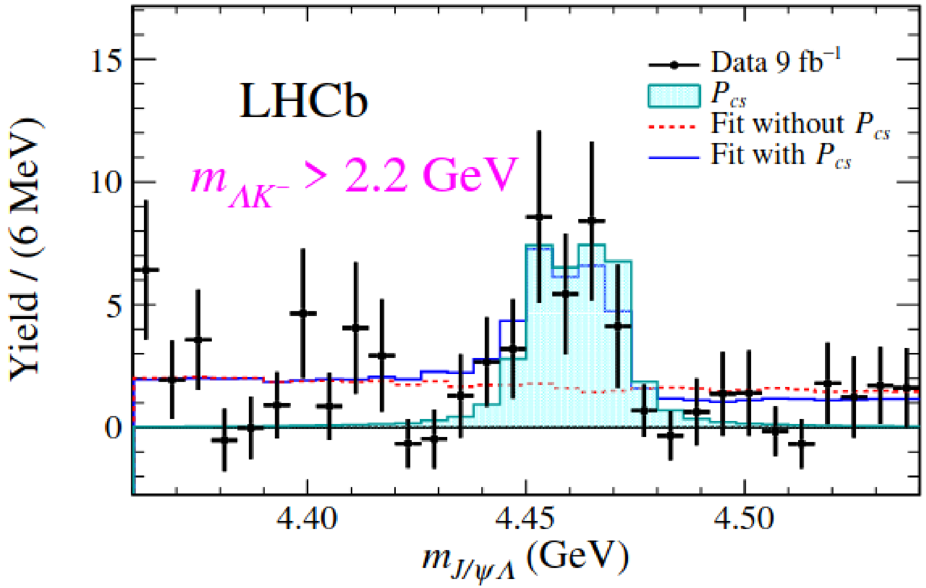


$P_c(4337)$

$J^{PC} = 1/2^+$ (probably)

$\Xi_b \rightarrow J/\psi\ \Lambda\ K$

[Sci.Bull. 66 (2021) 1278-1287]



$P_{cs}(4459)$

J^{PC} = unknown

Fully-heavy states: X(3900)

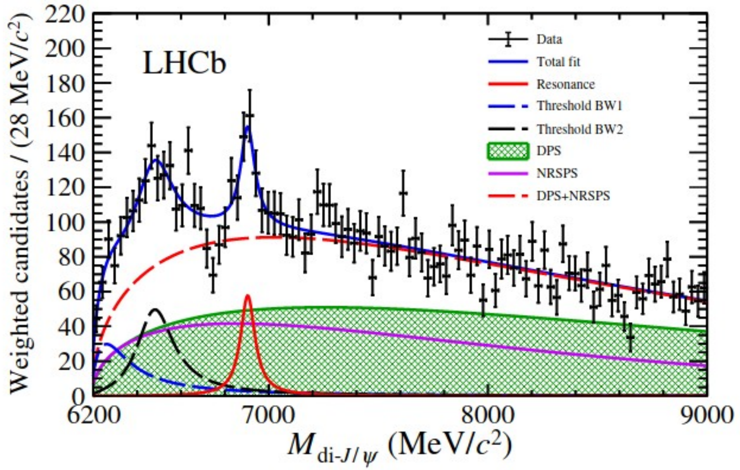
$pp \rightarrow J/\psi\ J/\psi + X$

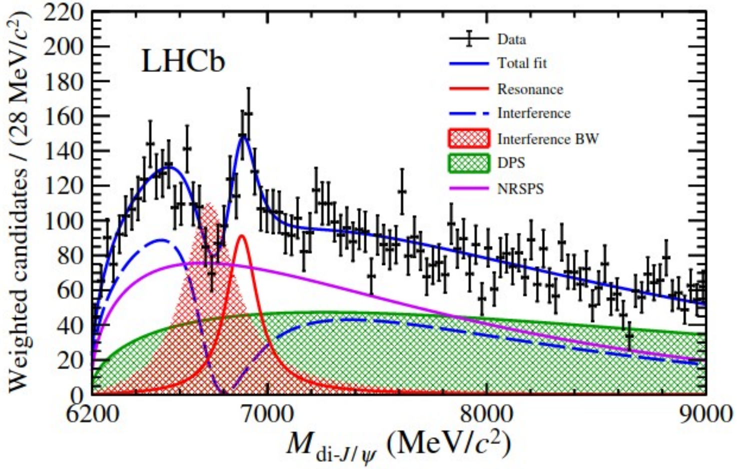
[Sci. Bull. 65 1983 (2020)]

Two structures in $M(J/\psi\ J/\psi)$

- Narrow X(6900)
- Broad enhancement @ threshold

70+ theoretical interpretations





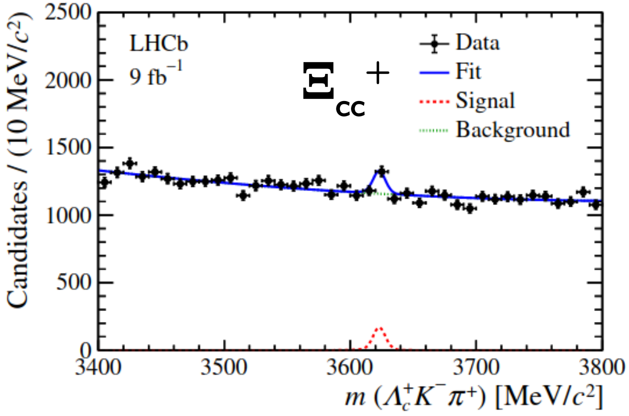
Doubly-charmed objects

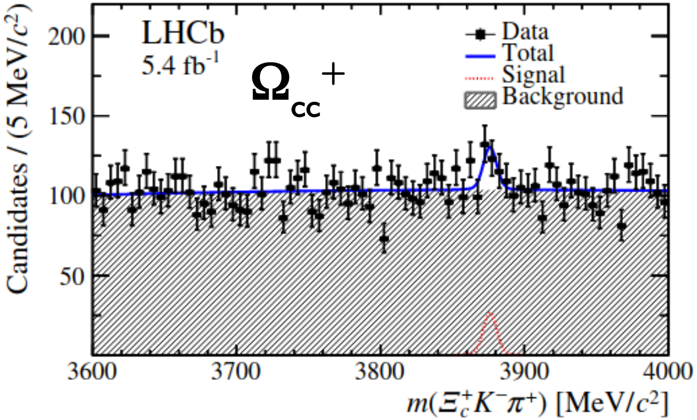
Ξ_{cc}^{++} Observed in 2017

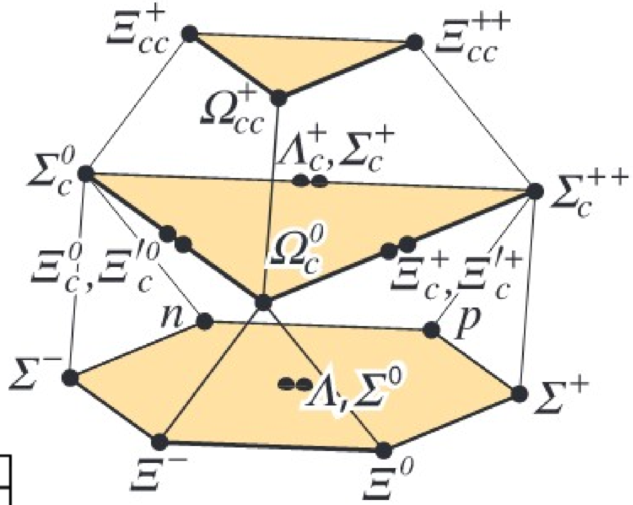
2021: First hints of Ω_{cc}^{+} and Ξ_{cc}^{+}

[Sci. China-Phys. Mech. Astron. 64, 101062 (2021)]

[arXiv:2109.07292]





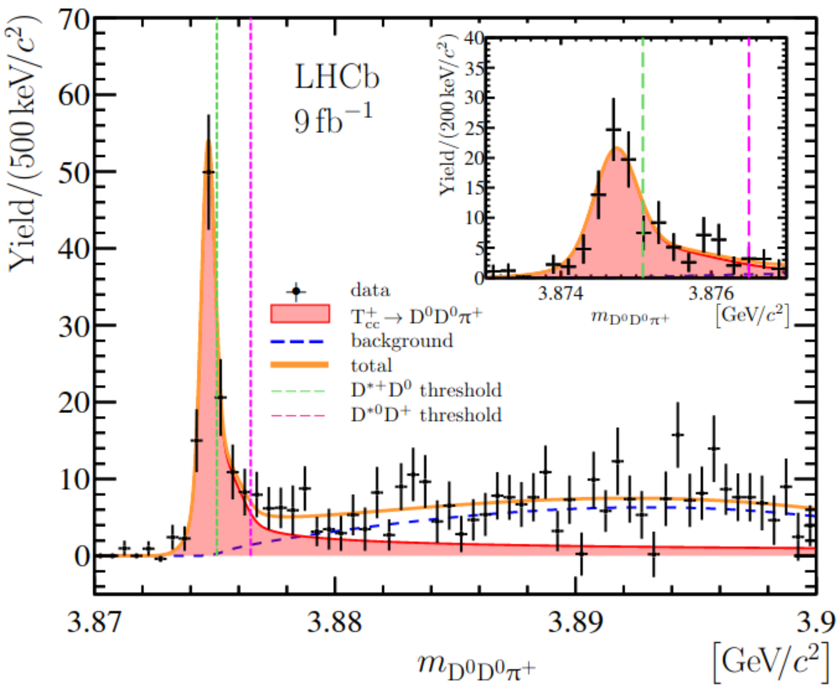


More on this later

The T_{cc}

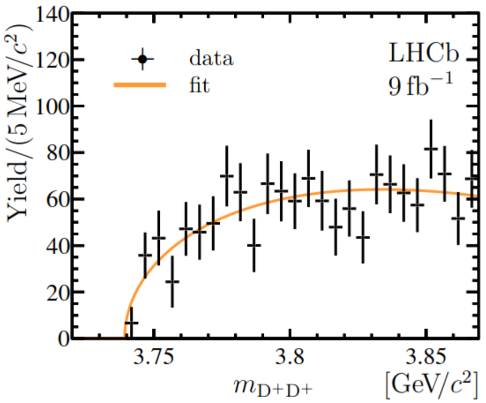
Prompt production of something decaying into $(DD^*)^+$

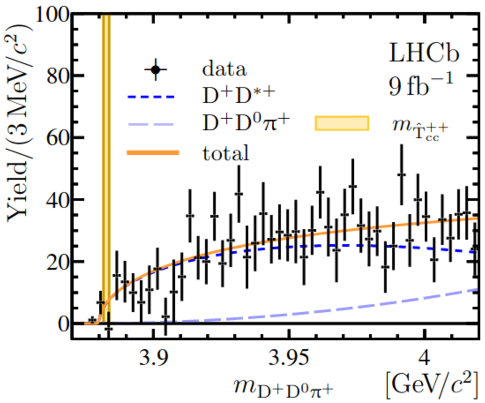
[arXiv:2109:01038 and arXiv:2109:01056]



$J^{PC} = 1^+$ (probably)

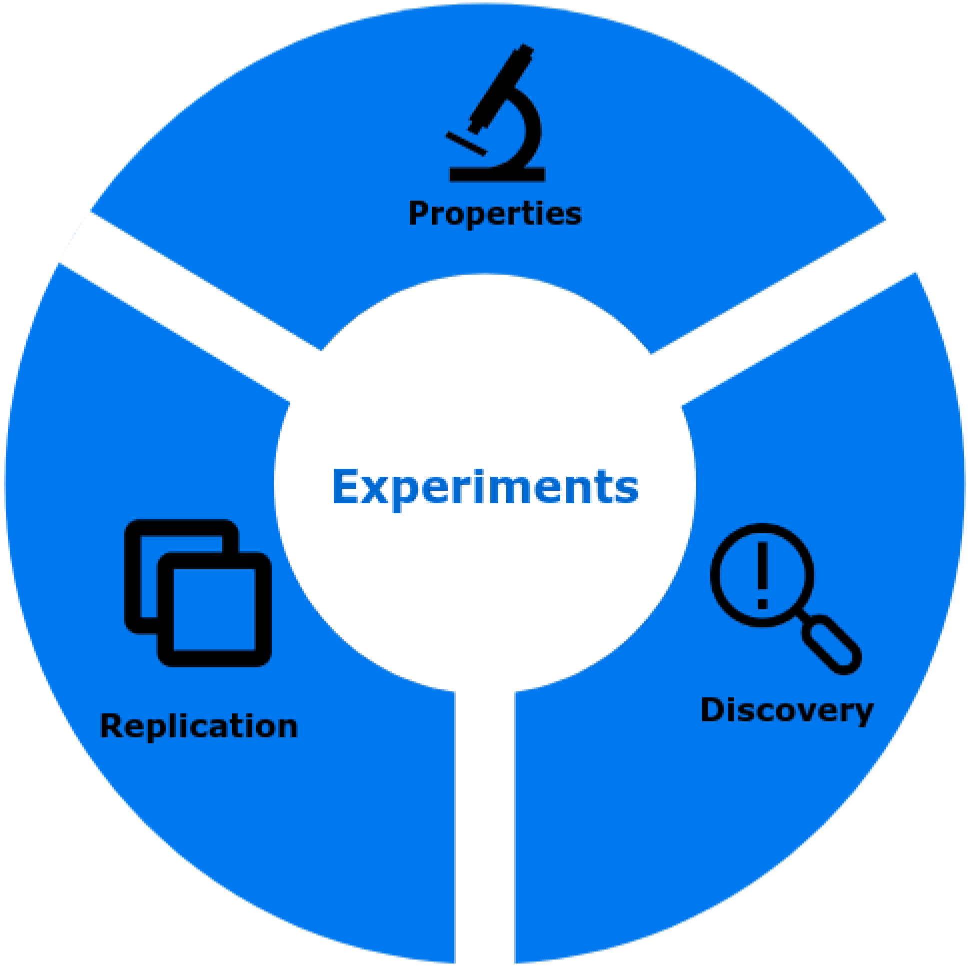
Nothing in the D^+D^+ channel



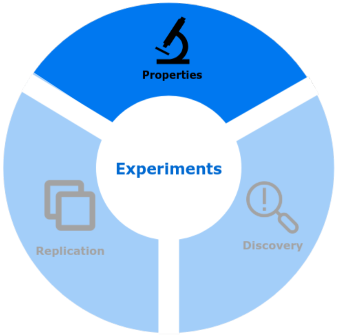


Part II: The path forward

Future challenges



Mapping properties: J^{PC}



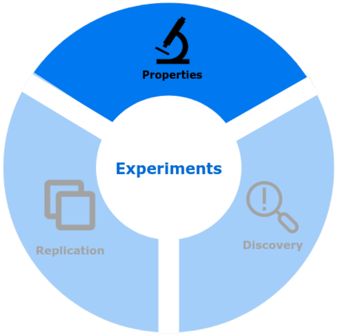
J^{PC} is not directly measured for several of the most recent states

- pentaquarks: 0/5
- charmonium-like: 30/42 (inc. quark model assignments)
- heavy baryons: 28/52 (5/52 excl. quark model assignments)
- heavy mesons: 31/42 (inc. quark model assignments)
- bottomonium-like: 22/22 (inc. quark model assignments)

Task

Determine J^{PC} for all known states

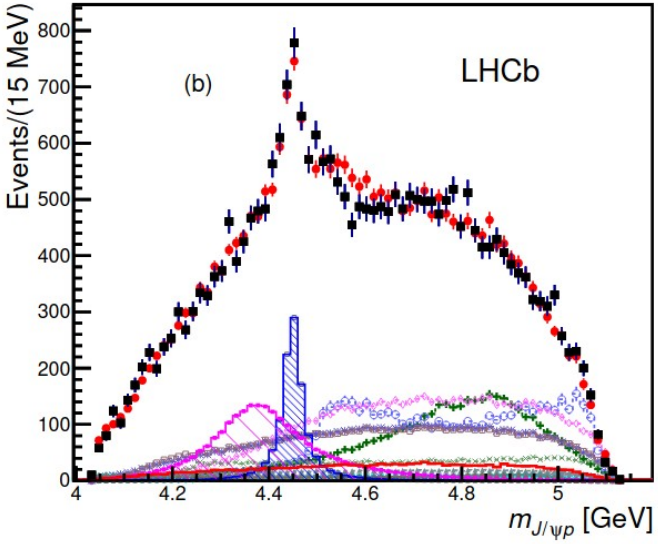
J^{PC} analysis: the pentaquark example



Amplitude analysis is challenging with narrow states

- Cannot neglect the resolution
- Fit computationally very demanding

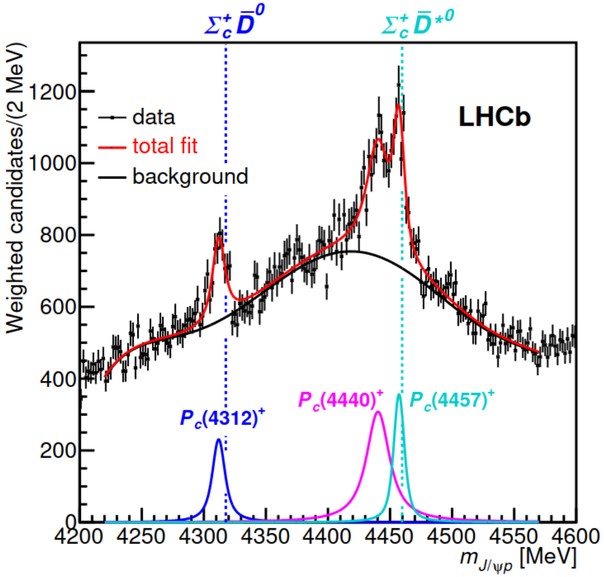
2015: two **broad** states



Assume $\Gamma >> $ resolution

- full fit in the first paper

2019: three **narrow** states



$\Gamma \sim$ resolution

- full fit still ongoing

Same issues in Belle II!
Common shared tools?

Look for new states

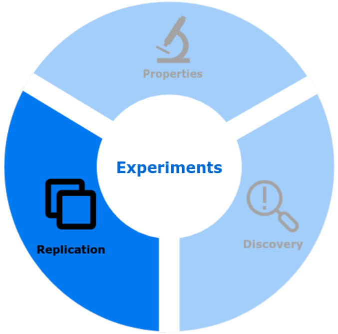
Many states have been seen in either

→ 1 decay mode only

→ 1 production mode only

→ 1 experiment only

Examples: all pentaquarks, T_{cc}, $Z_c(3900)$, Ξ_{cc}^{++}...



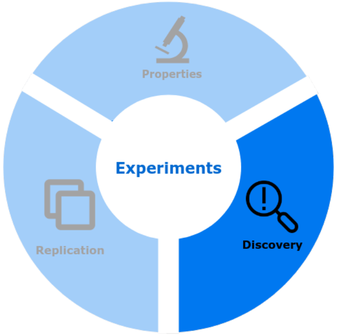
Task

Look for known states where we have not seen them

(more or less) recent ideas to explore:

- Prompt production of exotica (4q/molecule) *[EPJ C81, 669 (2021)]*
- Photo-production of pentaquarks *[PRD 101, 074010 (2020)]*
- 4q in HI peripheral collisions *[PRD 104, 114029 (2021)]*

Look for new states

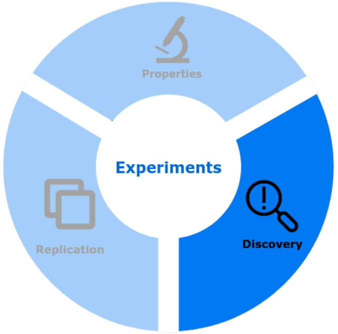


Broad-band, serendipitous searches have been extremely rewarding

Task

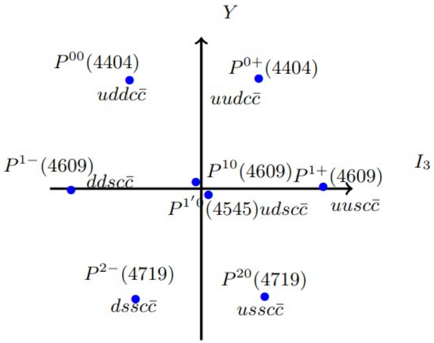
Keep up the good bump hunting!

Look forward to: new pentaquarks



In di-quark models pentaquarks form octets and a decuplet

[PRD 96, 014014 (2017)], [PLB 749, 289-291 (2015)]



Possible discovery modes:

$$\Xi_b(5794) \to K\,(J/\Psi\,\Sigma(1385))$$
$$\Omega_b^-(6049) \to \phi\,(J/\Psi\,\Omega^-(1672))$$
$$\Omega_b^-(6049) \to K\,(J/\Psi\,\Xi(1387))$$

Molecular models also predict several states

[PRL 115, 122001 (2015)]

Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	S-wave J^P	Example of decay mode
$\Sigma_c\bar{D}^*$	1/2	$c\bar{c}qqq'$	4462.4	$1/2^-, 3/2^-$	$J/\psi\, p$
$\Sigma_c B^*$	1/2	$c\bar{b}qqq'$	7779.5	$1/2^-, 3/2^-$	$B_c^+ p$
$\Sigma_b\bar{D}^*$	1/2	$b\bar{c}qqq'$	7823.0	$1/2^-, 3/2^-$	$B_c^- p$
$\Sigma_b B^*$	1/2	$b\bar{b}qqq'$	11139.6	$1/2^-, 3/2^-$	$\Upsilon(nS)p$

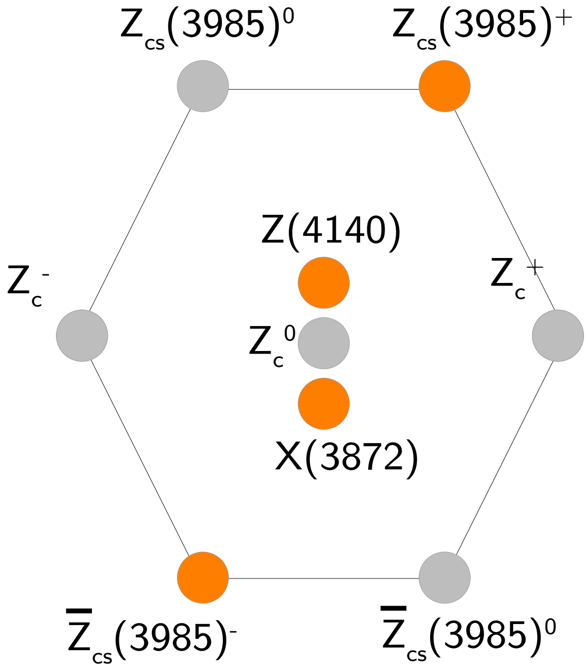
Task

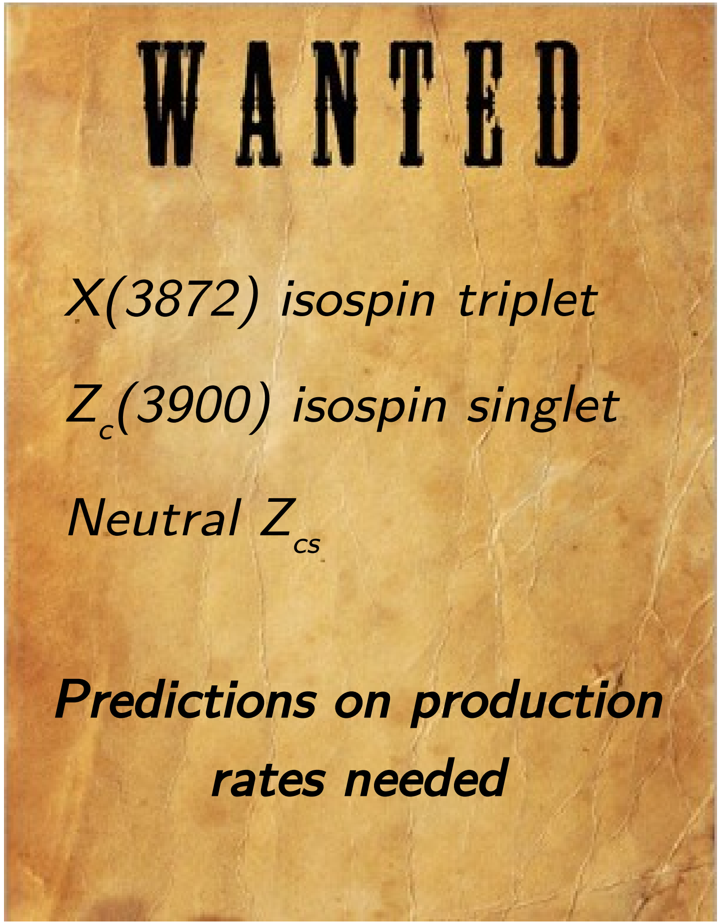
Explore all J/ψ + baryon, B_c+baryon and $\Upsilon(nS)$+baryon spectra

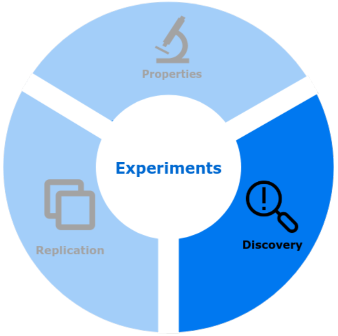
Look forward to: the $c\bar{c}q\bar{q}$ multiplets

Unique prediction of the compact tetraquark model

[J. SCI.B. 2021 04 040 (2021)]







Look forward to: doubly-charmed objects

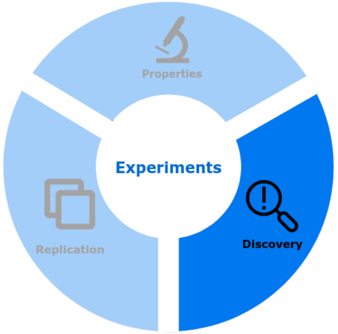
The Ξ_{cc}^{++} is a (simple) benchmark to understand the c-c interaction

→ Can generalize to other cc+q, $\overline{qq}$ hadrons **(predict T_{cc} mass!)**

[Karliner, Rosner, PRL 119, 202001 (2017)]

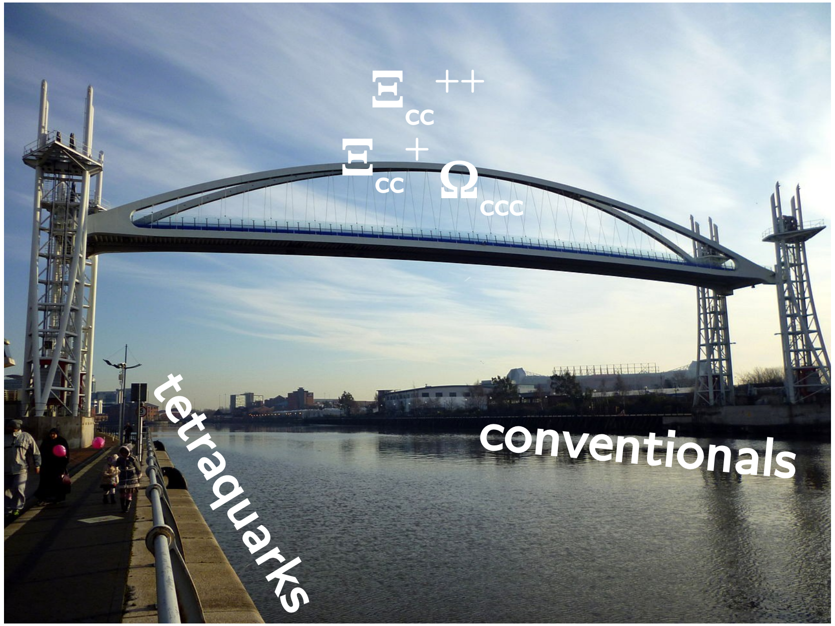
→ Succesfull history of predictions

[Karliner, Rosner, PRD 90, 094007 (2014)]

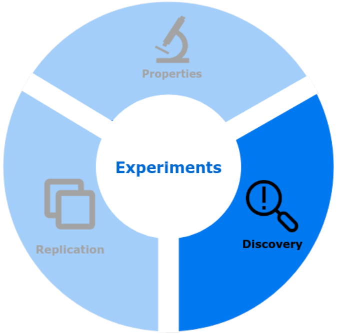


Task

Complete the double-chamed baryons spectra and multiplets, **look for more T_{cc}**



Look forward to: hadrons with beauty



Patterns seen with charm should repeat with b-quark

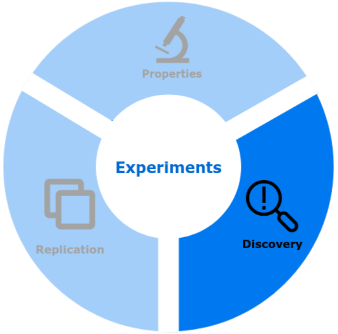
- $\rightarrow$ Smaller relativistic corrections
- $\rightarrow$ Stronger selection rules (Heavy quark spin symmetry…)

Experimentally challenging

- $\rightarrow$ Only prompt production at LHC
  - $\rightarrow$ but $\sigma_{prompt}[pp \rightarrow \Upsilon(1S)] \sim 0.0003 \times \sigma_{prompt}[pp \rightarrow J/\psi]$

- $\rightarrow$ Can produce $\Upsilon(nS)$ 1^{--} states at e^+e^-
  - $\rightarrow$ Strongly depend on the the BF for the $\Upsilon(nS)$ to your state
  - $\rightarrow$ Ecm @ Belle II limited to ~11 GeV (threshold for $T_{bb} \sim$ 19-20 GeV)

Look forward to: hadrons with beauty



Patterns seen with charm should repeat with b-quark

→ Smaller relativistic corrections

→ Stronger selection rules (Heavy quark spin symmetry...)

B-hadrons are much less known than their charmed counterparts

Experimentally ch

→ Only prom

→ but σ_{pro} ... $/\psi]$

→ Can produce Υ(nS) 1^{--} states at e^+e^-

→ Strongly depend on the the BF for the Υ(nS) to your state

→ Ecm @ Belle II limited to ~11 GeV (threshold for T_{bb} ~ 19-20 GeV)

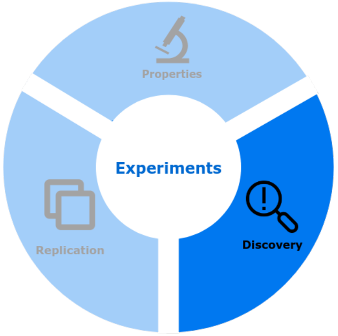
Look forward to: hadrons with beauty

For LHC(b) (run 3?)

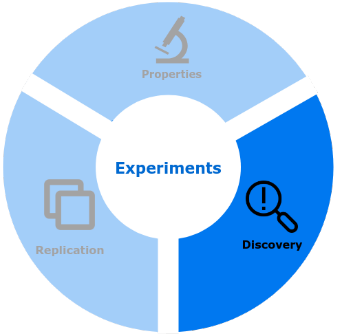
→ The $T_{bb}{}^{+}$ could be stable against strong and EM decays!

[PRL 119, 202001 (2017)] [PRL 119, 202002 (2017)]

→ Doubly-b baryons, 4-b tetraquarks ...



Look forward to: hadrons with beauty



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→ The T_{bb}^{+} could be stable against strong and EM decays!

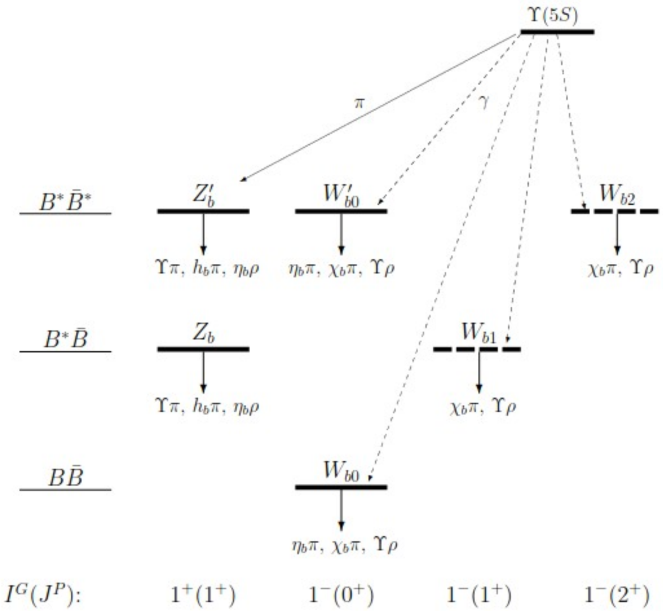
[PRL 119, 202001 (2017)] [PRL 119, 202002 (2017)]

→ Doubly-b baryons, 4-b tetraquarks …

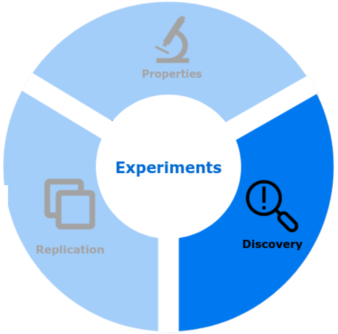
For Belle II

→ 4-q states in Y(5S) radiative decays (2024+)

[PRD 84 031502], [Mod.Phy.Let.A 32, 1750025 (2017)]



Look forward to: hadrons with beauty

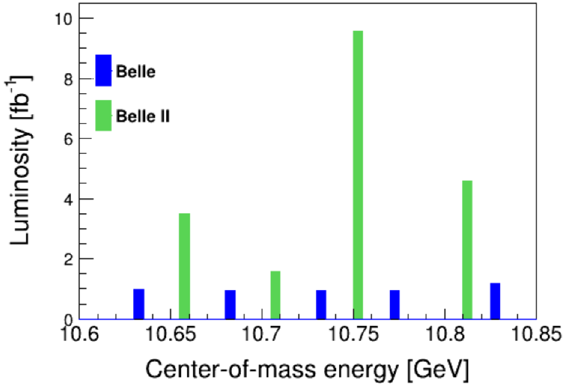


For LHC(b) (run 3?)

→ The T_{bb}^{+} could be stable against strong and EM decays!

[PRL 119, 202001 (2017)] [PRL 119, 202002 (2017)]

→ Doubly-b baryons, 4-b tetraquarks ...

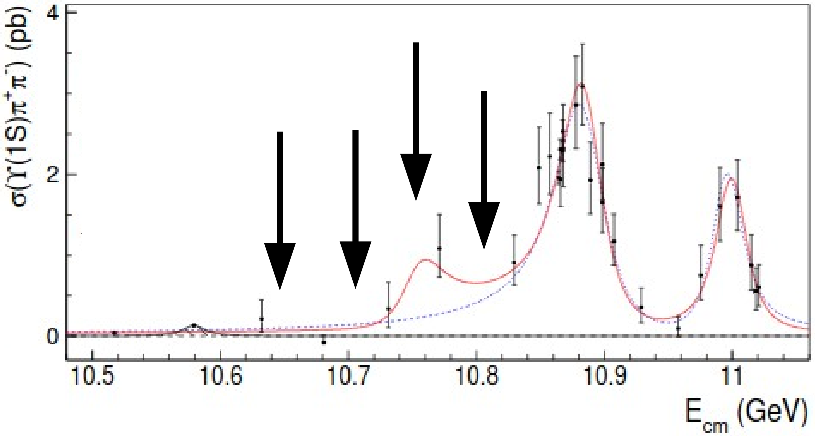


For Belle II

→ 4-q states in Υ(5S) radiative decays (2024+)

[PRD 84 031502], [Mod.Phy.Let.A 32, 1750025 (2017)]

→ **results of the scan at 10.750 GeV (2022!)**

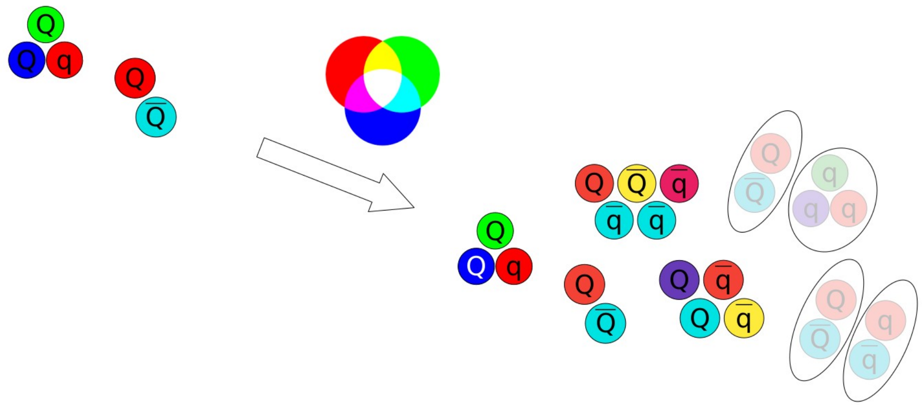


Conclusions

The heavy hadrons gave us solid experimental evidences of exotic states

→ $b\bar{b}$, $c\bar{c}$, and cc 4-quark states

→ $c\bar{c}$, pentaquarks



3(+) experiments are taking data

→ LHCb, Belle II, BES III (CMS, CLAS...)

With more data we can (hopefully!) start constraining the theoretical models

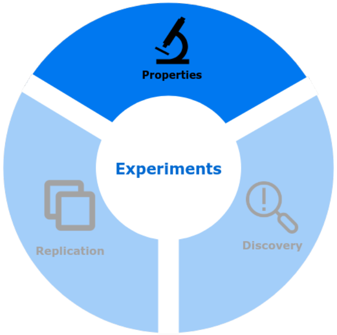
→ Quantum numbers for all known states

→ Doubly-heavy baryons and missing tetraquarks

→ Beauty counterparts of charmed hadrons

Backup

Mapping properties: absolute BFs



When we observe a new state S we access

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

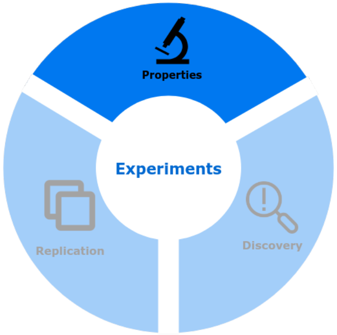
Poorly (or not) constrained by theory

Some (pre, post)dictions usually available

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

	Mode	Fraction ($\Gamma_i\,/\,\Gamma$)
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

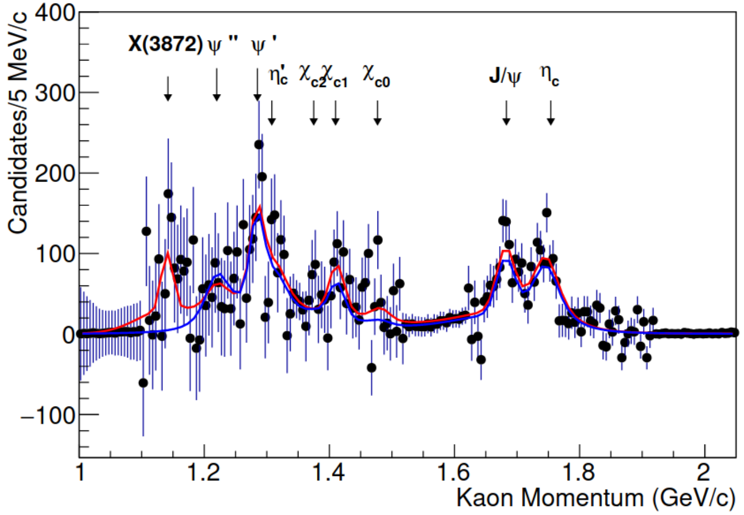


When we observe a new state S we access

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

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

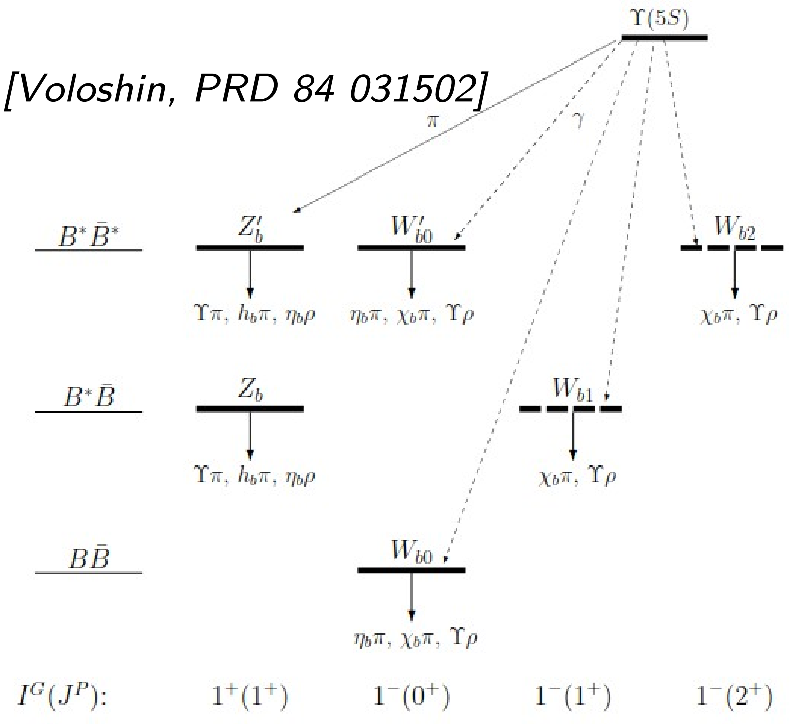
Exotic search with Ecm < 12 GeV are challenging

$\rightarrow$ 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]

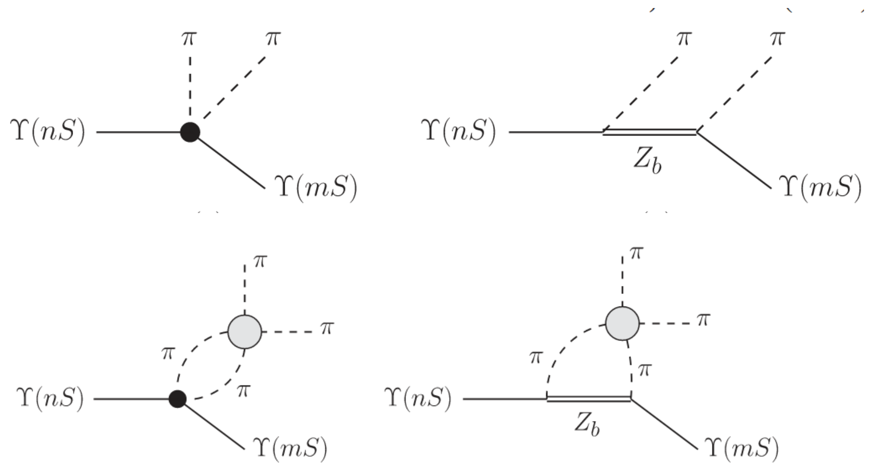


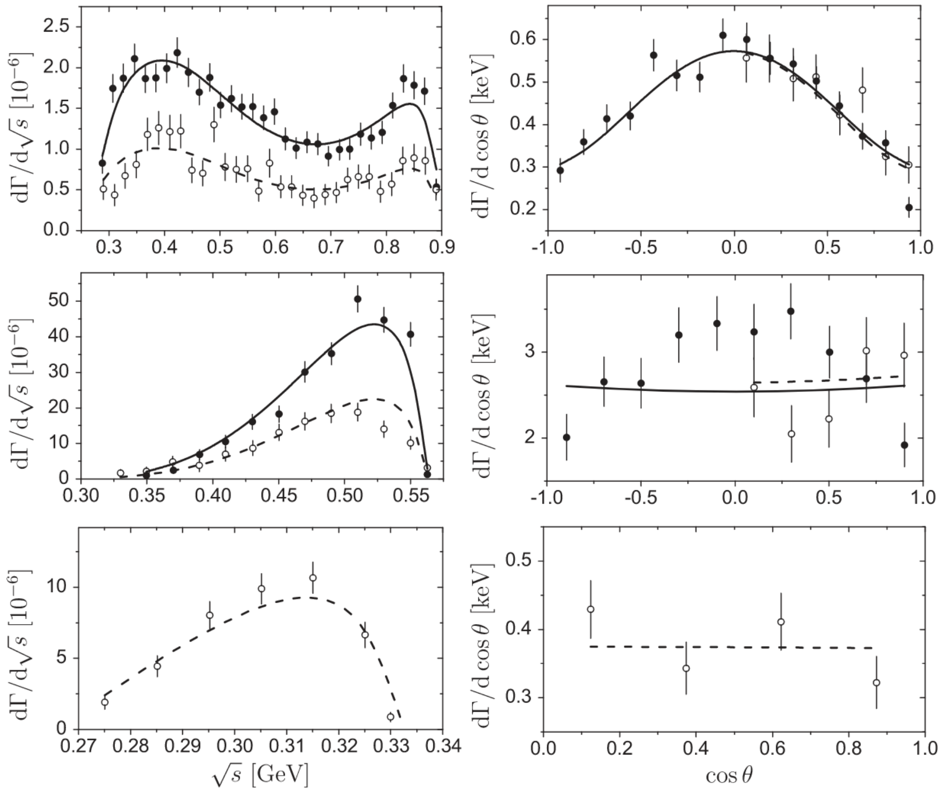
Bottomonium: alternative approaches

Exotic stats contribute to the transitions from narrow quarkonia?

$\rightarrow$ new (?) approach to heavy spectroscopy

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





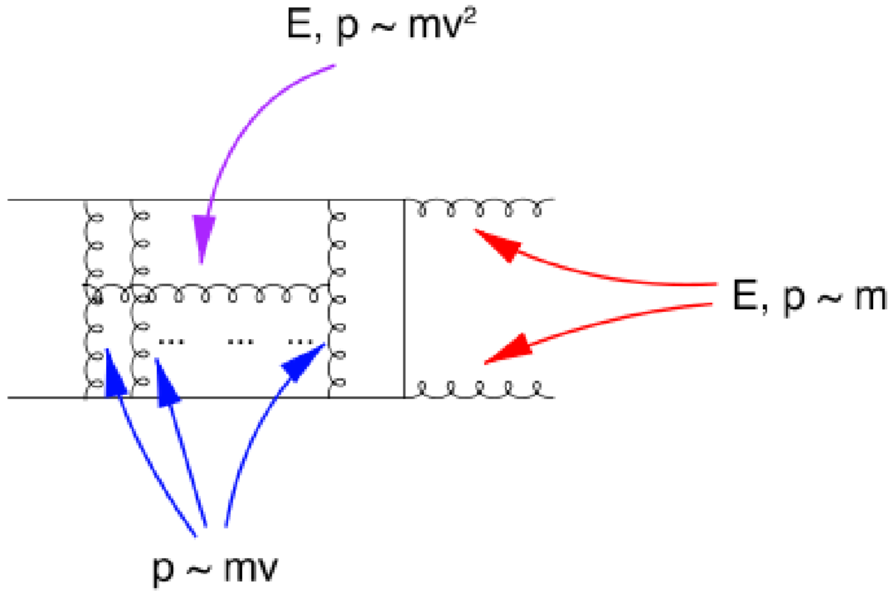
Why is bottomonium so special?

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 $B \to K\, c\bar{c}$

→ 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 $p\bar{p}$ (???)

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

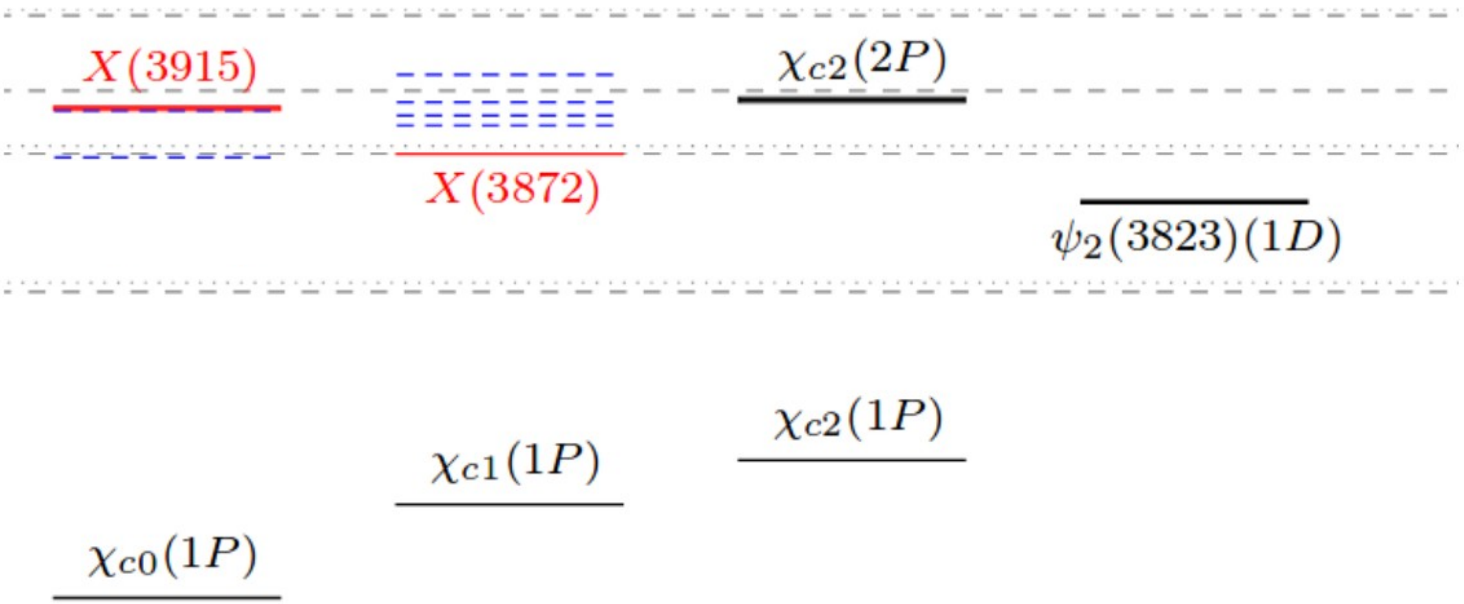
Bottom line: after Belle II, bottomonium studies will havestrong limitations

Look for more patterns: the X(3872)

→ The only exotica to have been observed in several different conditions

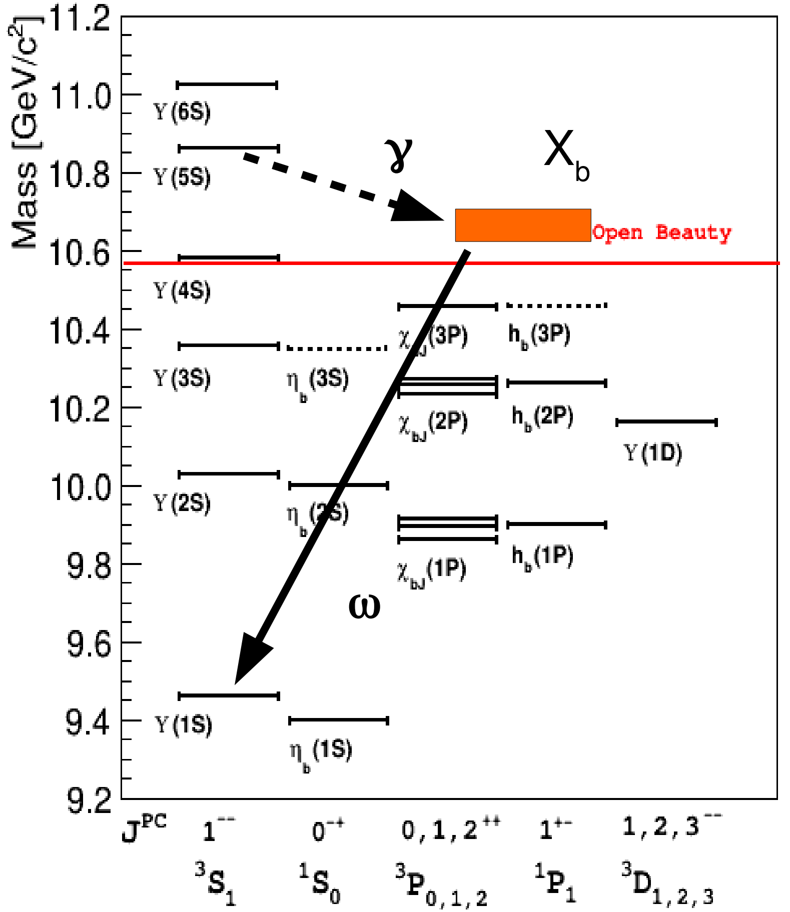
→ A narrow peak ~ at the DD* threshold

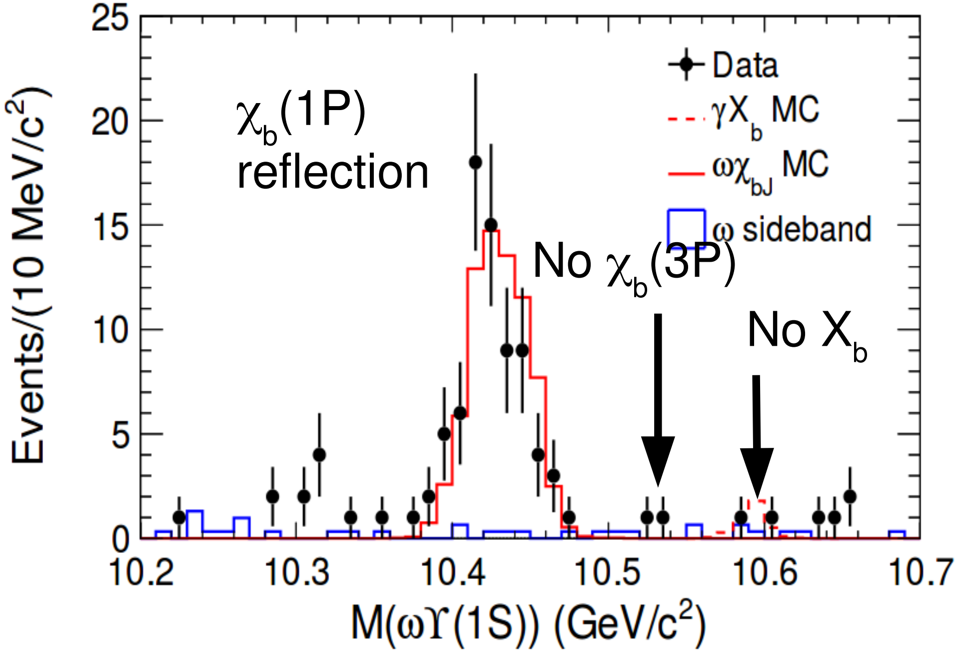
→ Same quantum numbers as a $\chi_{c1}(2P)$, completely different properties



Is there an X(3872) counterpart?

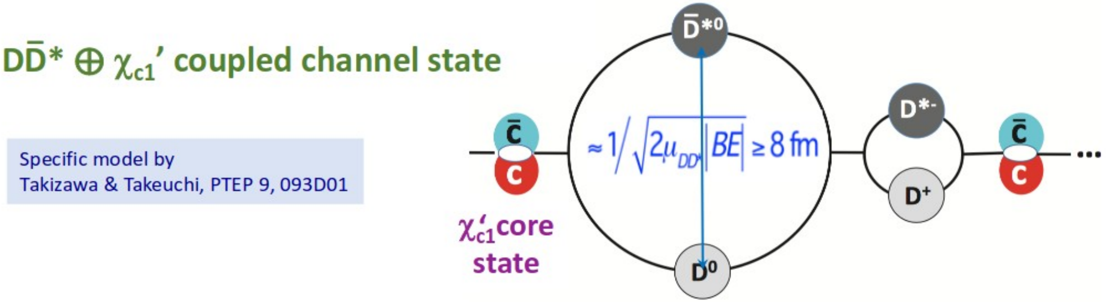
Both tetraquark and pure molecule predict a counterpart (X_b)

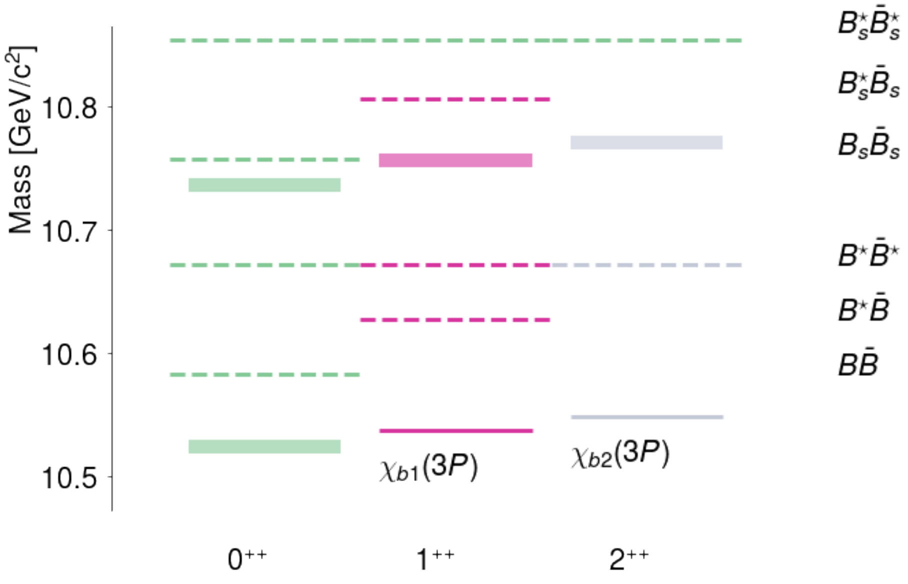




Why no X_b ?

The X(3872) may generated by a peculiar coincidence

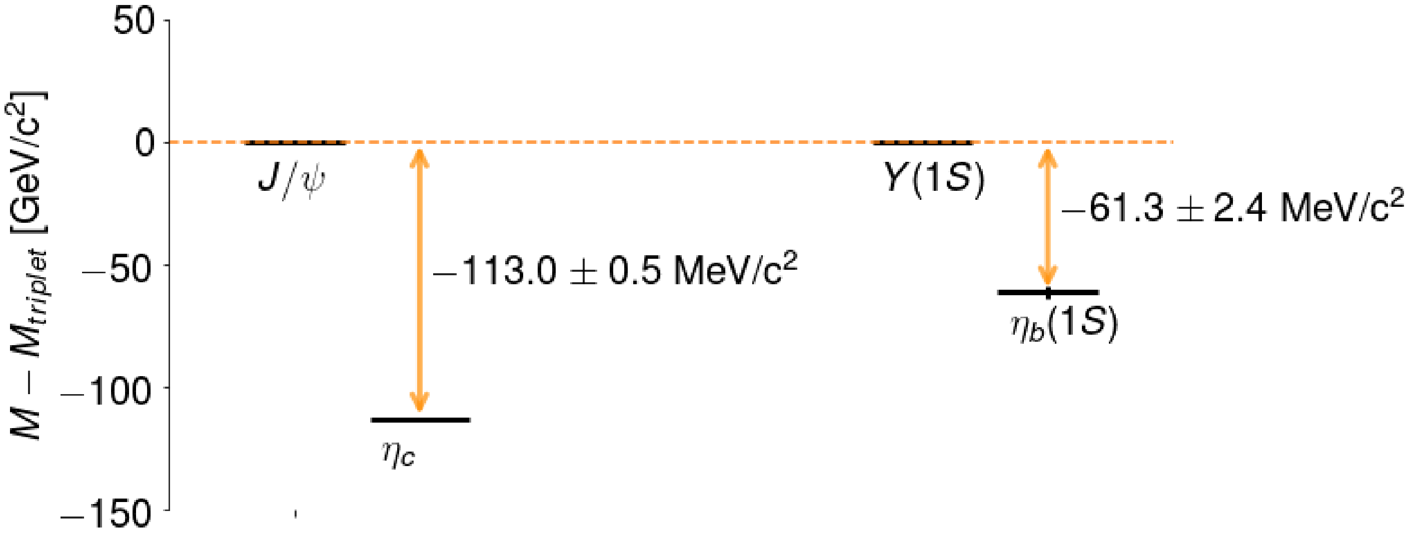




No χ_b is near the BB* threshold, no X_b

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

The ground states

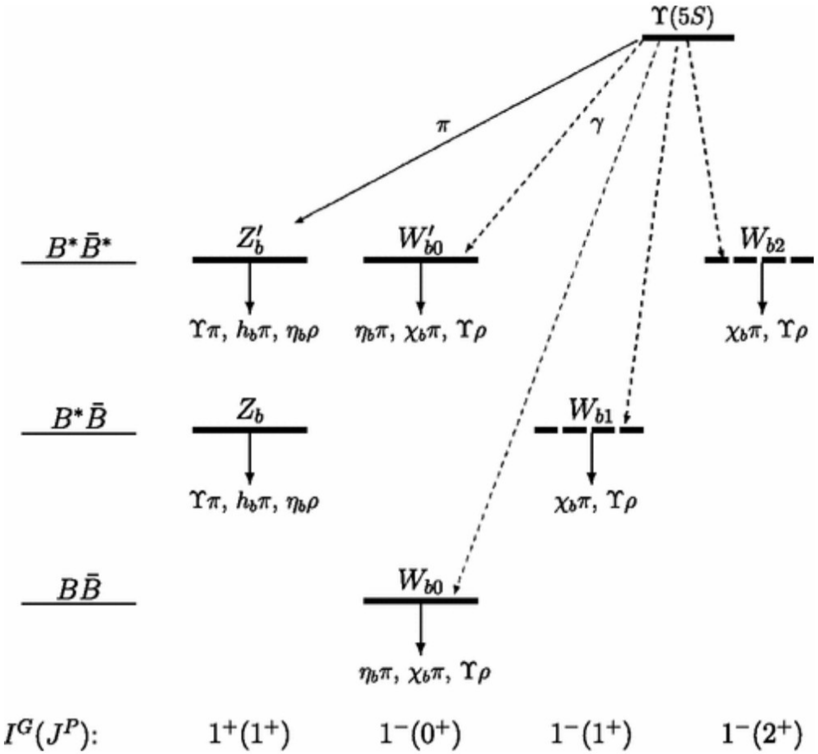


$$
\begin{aligned}
V_{spin}(r) \quad &= \quad \left(\frac{1}{2m_1^2}\vec{L}\cdot\vec{S}_1 + \frac{1}{2m_2^2}\vec{L}\cdot\vec{S}_2\right)\frac{1}{r}\frac{d}{dr}\left(V(r) + 2V_1(r)\right) \\
&\quad + \frac{1}{m_1 m_2}\vec{L}\cdot(\vec{S}_1 + \vec{S}_2)\frac{1}{r}\frac{dV_2(r)}{dr} \\
&\quad + \frac{1}{m_1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

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]	$\Upsilon(nS)\omega$

Charmonium in bottomonium

Lots of observation of exotica, but quite few completely independent confirmations
→ Only X(3872) has been seen in prompt production (in $p\bar{p}$ and pp collisions)

Based on Phys. Rev. D 93, 112013 [Belle]