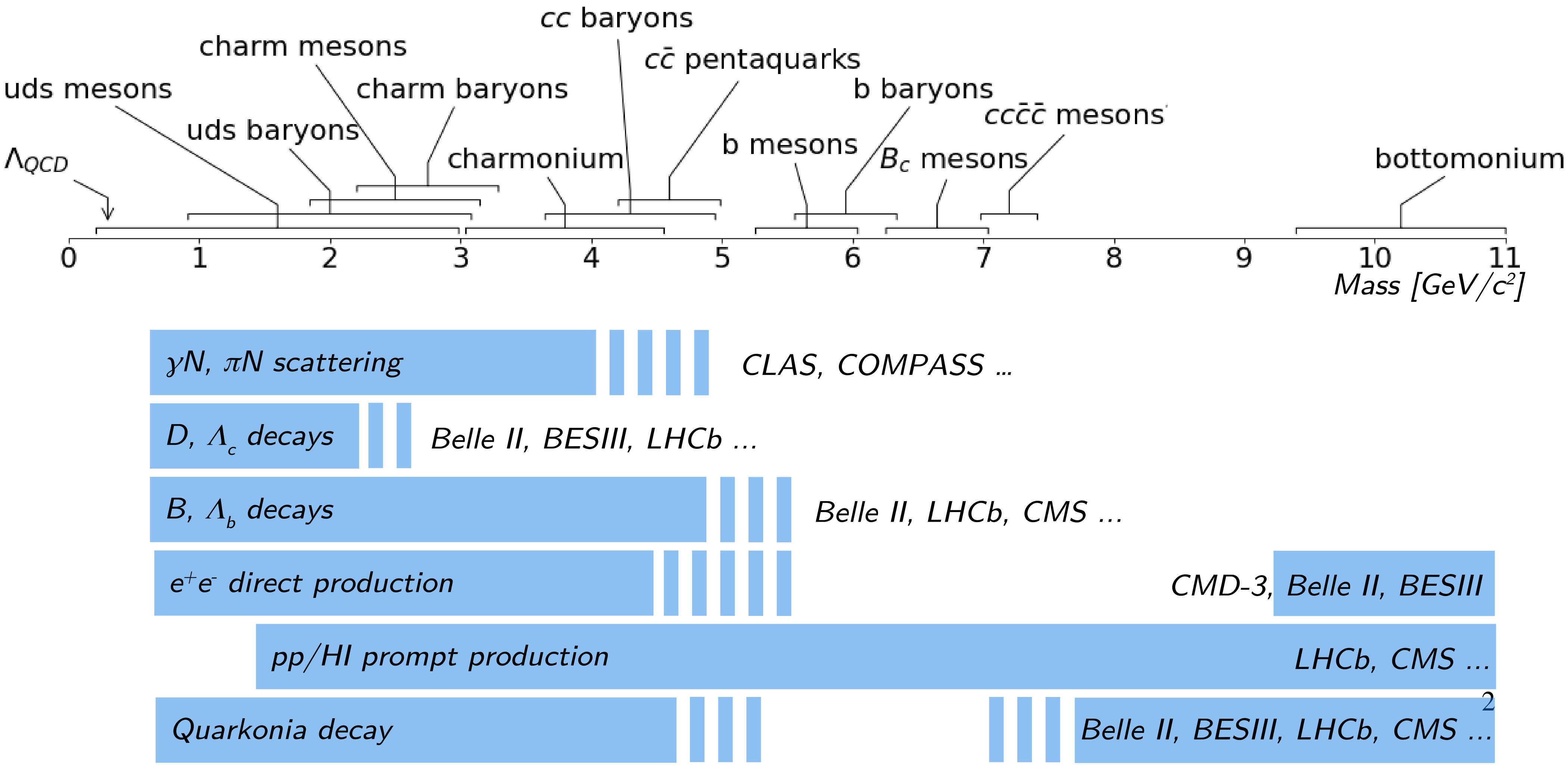
Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Heavy meson review

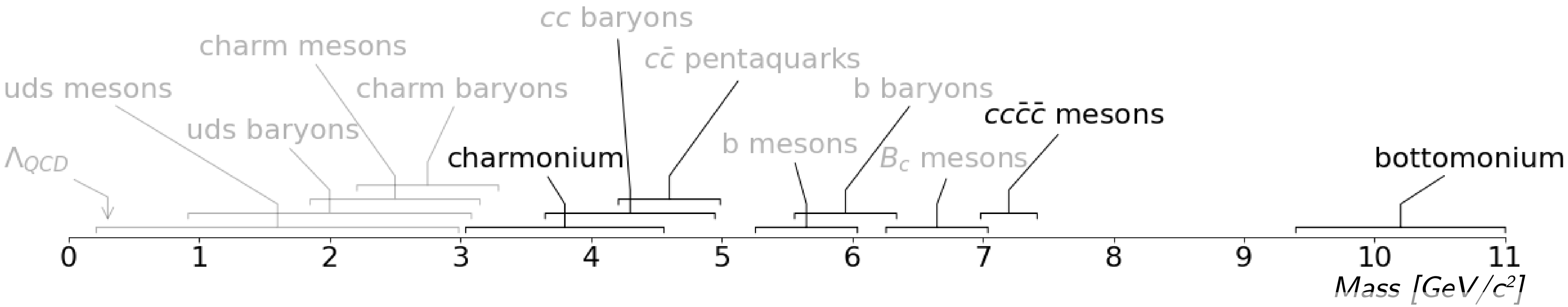
WIFAI 2024
November 13th 2024

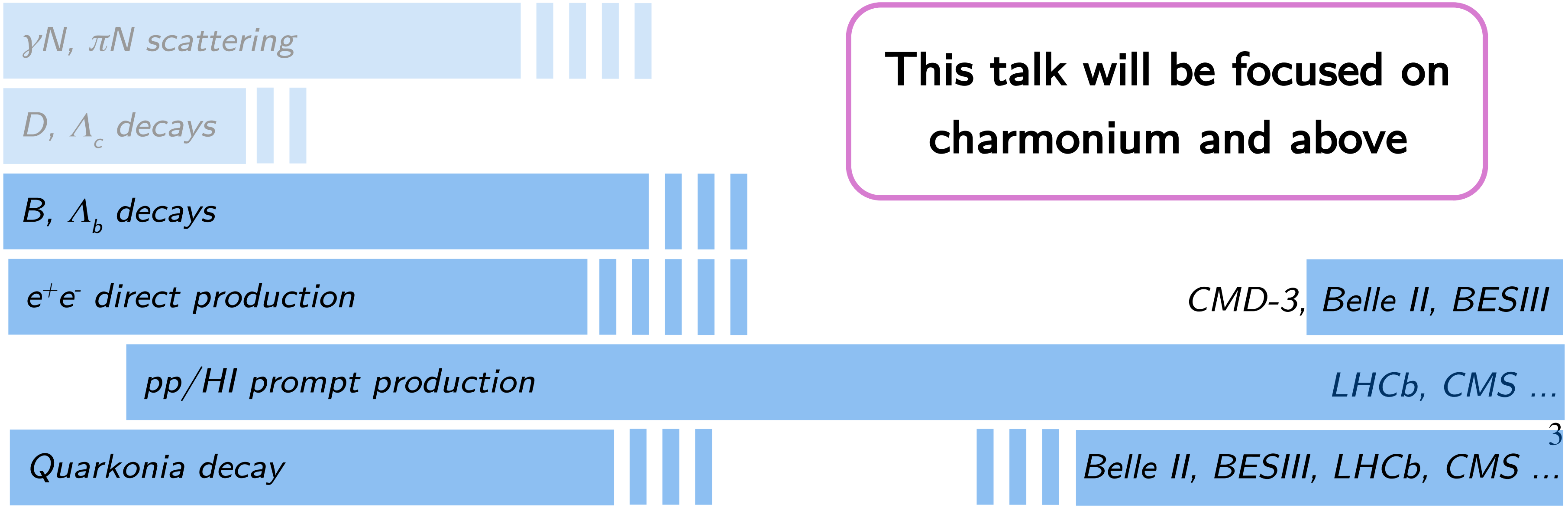
Umberto Tamponi
tamponi@to.infn.it
INFN – Sezione di Torino

Heavy or light hadrons?



Heavy or light hadrons?

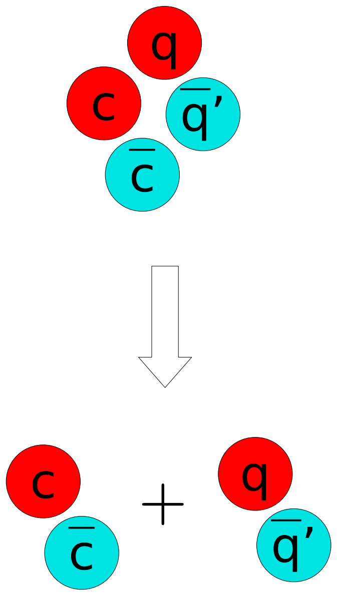




This talk will be focused on charmonium and above

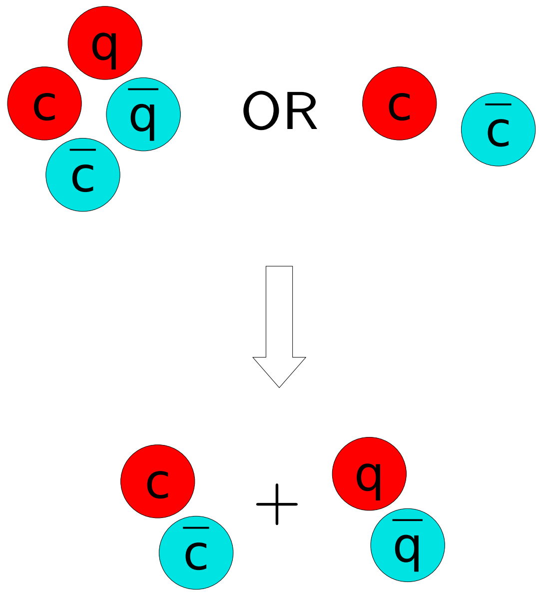
Why heavy hadrons

With heavy quarks separating conventional and exotics is much simpler



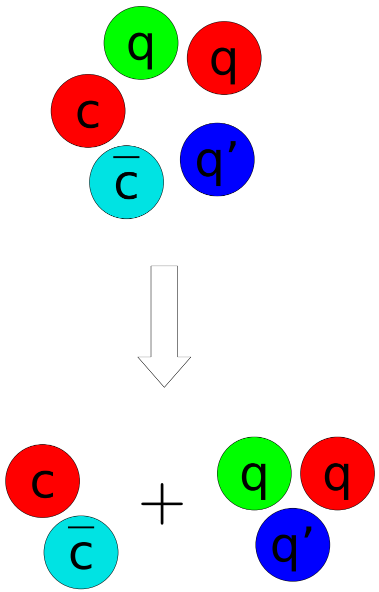
$c\bar{c}$ + charged meson

- must have 4 quarks



$c\bar{c}$ + neutral meson

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

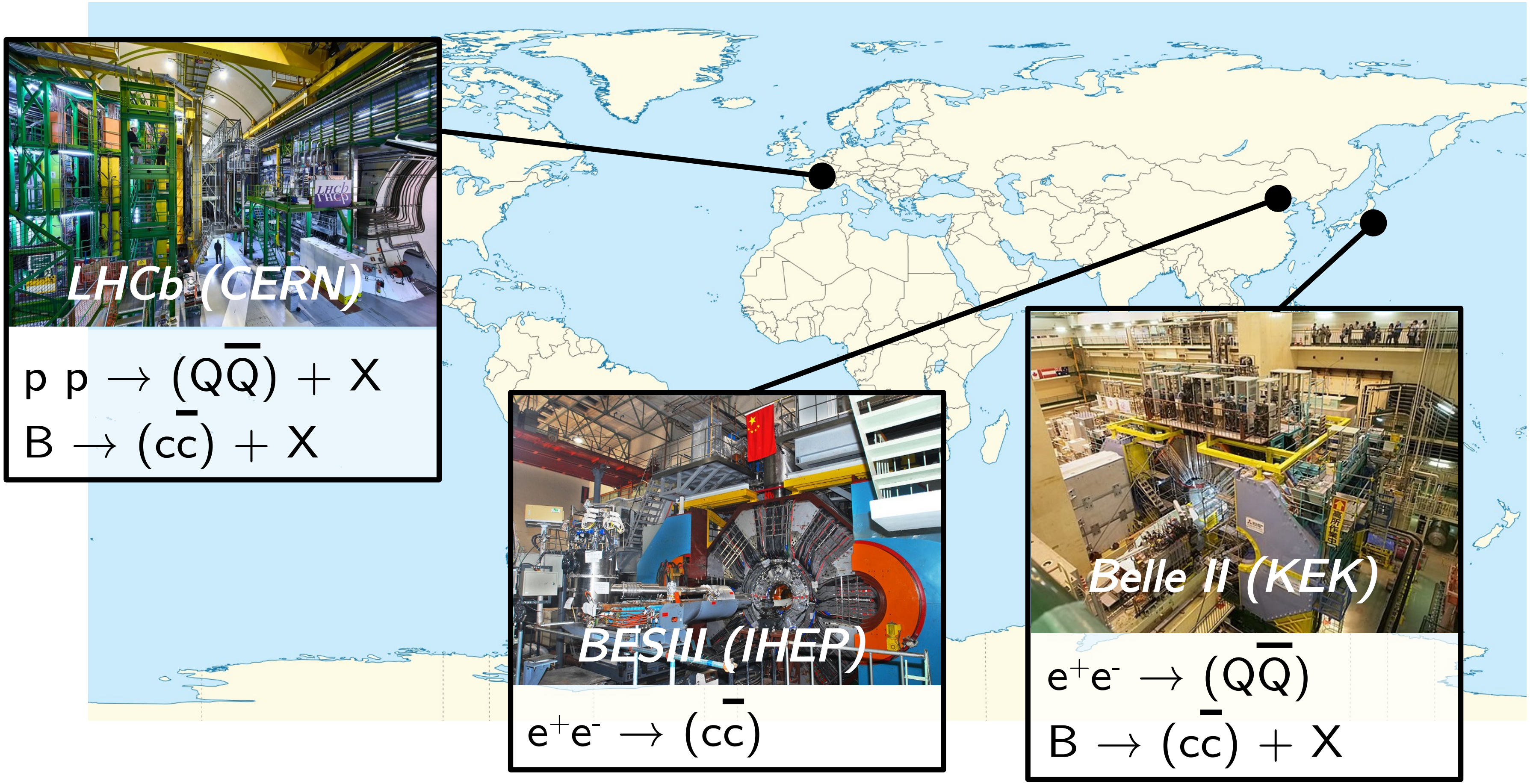


$c\bar{c}$ + baryon

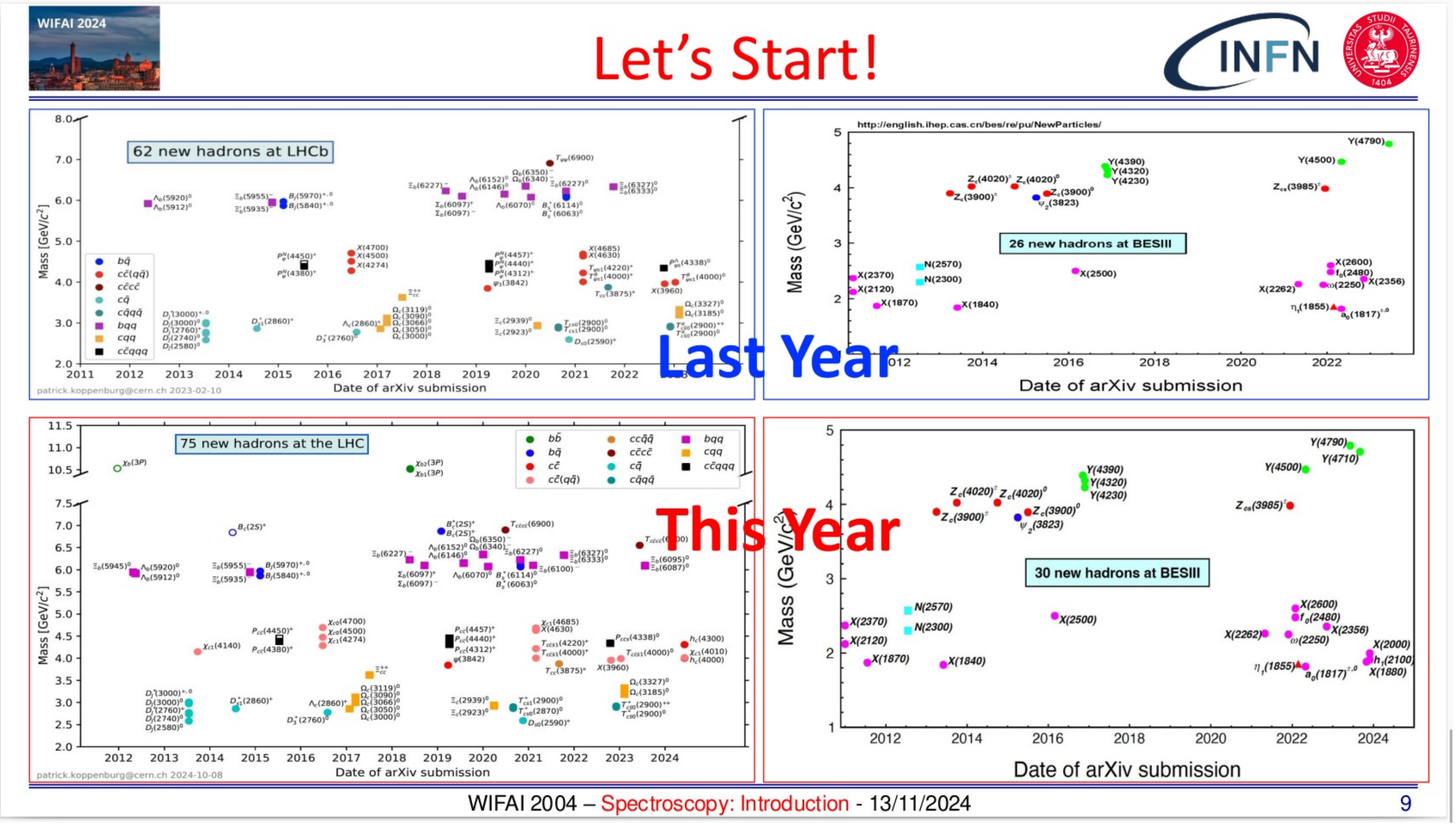
- 5 quarks

Quarkonium at experiments: new generation

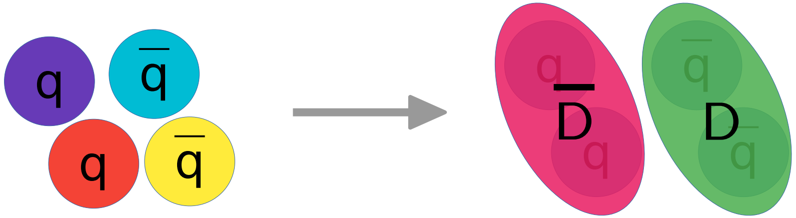
~ 2010 – now: VERY high-statistics, high quality data



The zoo


WIFAI 2024
Let's Start!
INFN
62 new hadrons at LHCb
Mass [GeV/c²]
Date of arXiv submission
patrick.koppenburg@cern.ch 2023-02-10
http://english.ihep.cas.cn/bes/re/pu/NewParticles/
26 new hadrons at BESIII
Mass (GeV/c²)
Date of arXiv submission
Last Year
75 new hadrons at the LHC
Mass [GeV/c²]
Date of arXiv submission
patrick.koppenburg@cern.ch 2024-10-08
This Year
30 new hadrons at BESIII
Mass (GeV/c²)
Date of arXiv submission
WIFAI 2004 – Spectroscopy: Introduction - 13/11/2024
9

Challenging models

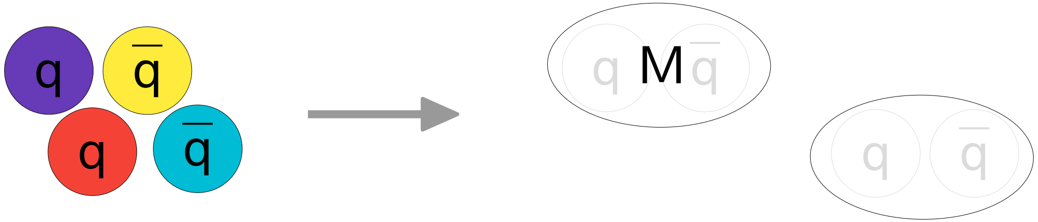


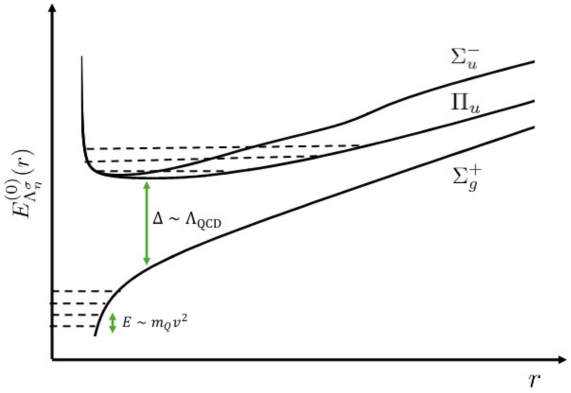
Compact tetraquarks

Prog. Part. Nucl. Phys. 116 (2021) 103835

Meson-meson molecules

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

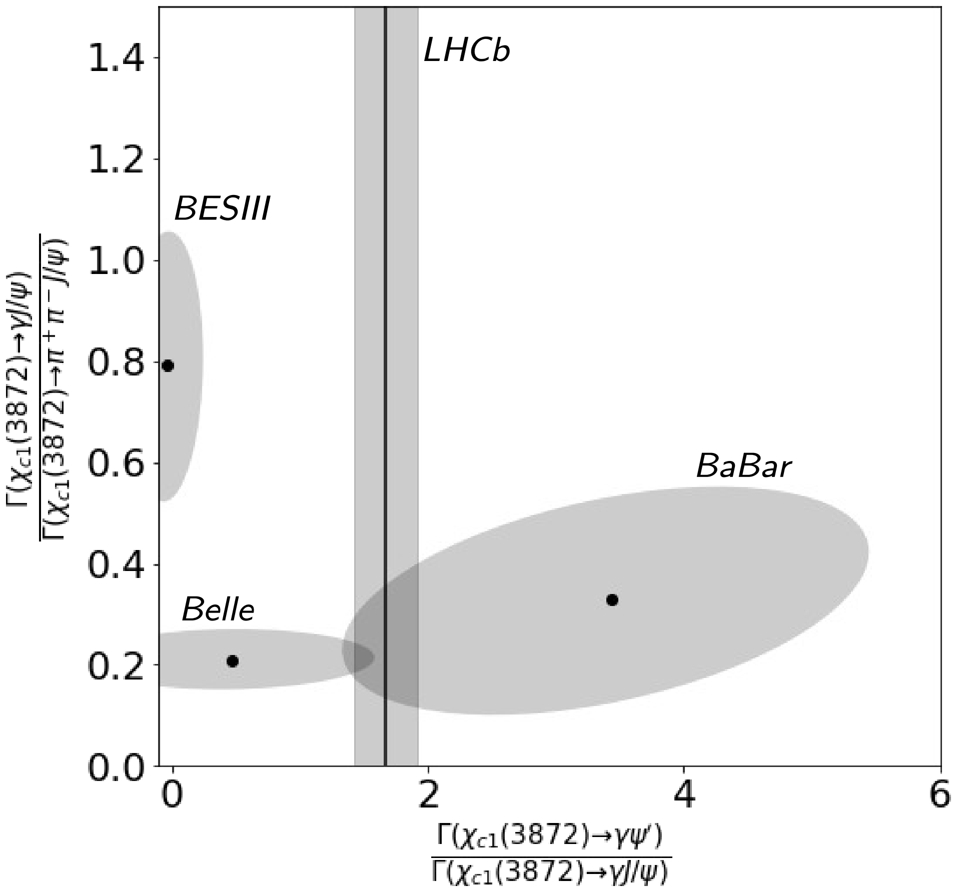




Born-Oppenheimer EFT (BOEFT)

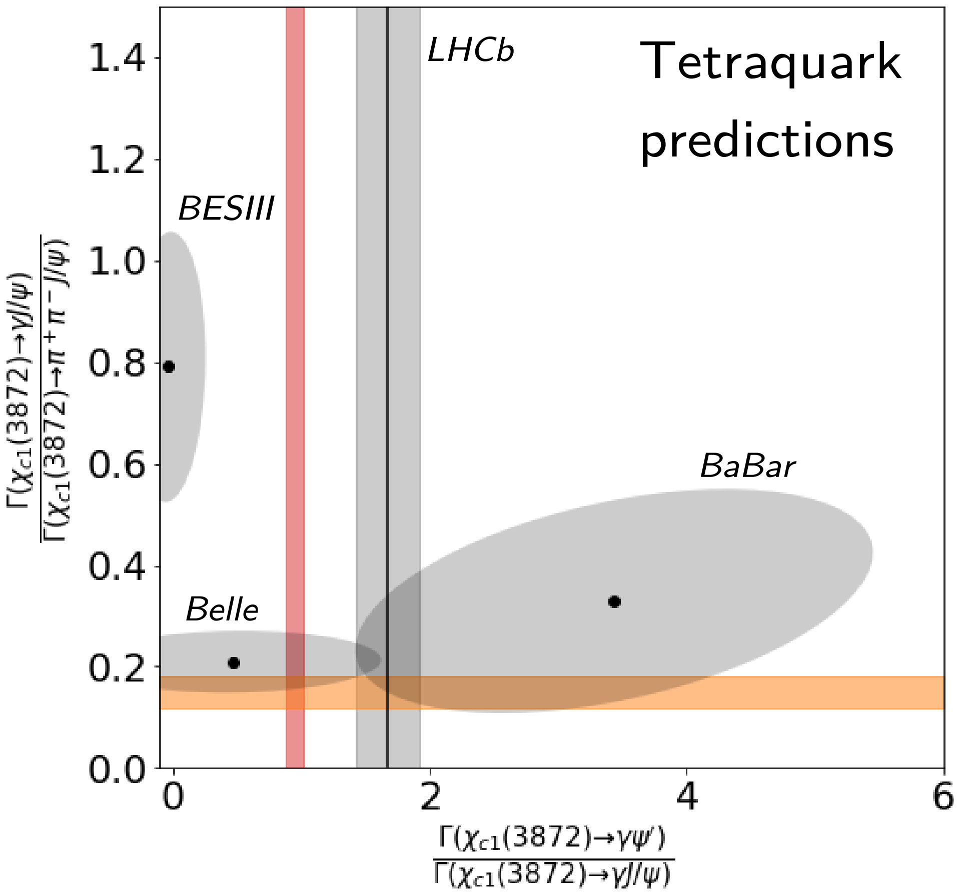
arXiv:2408.04719

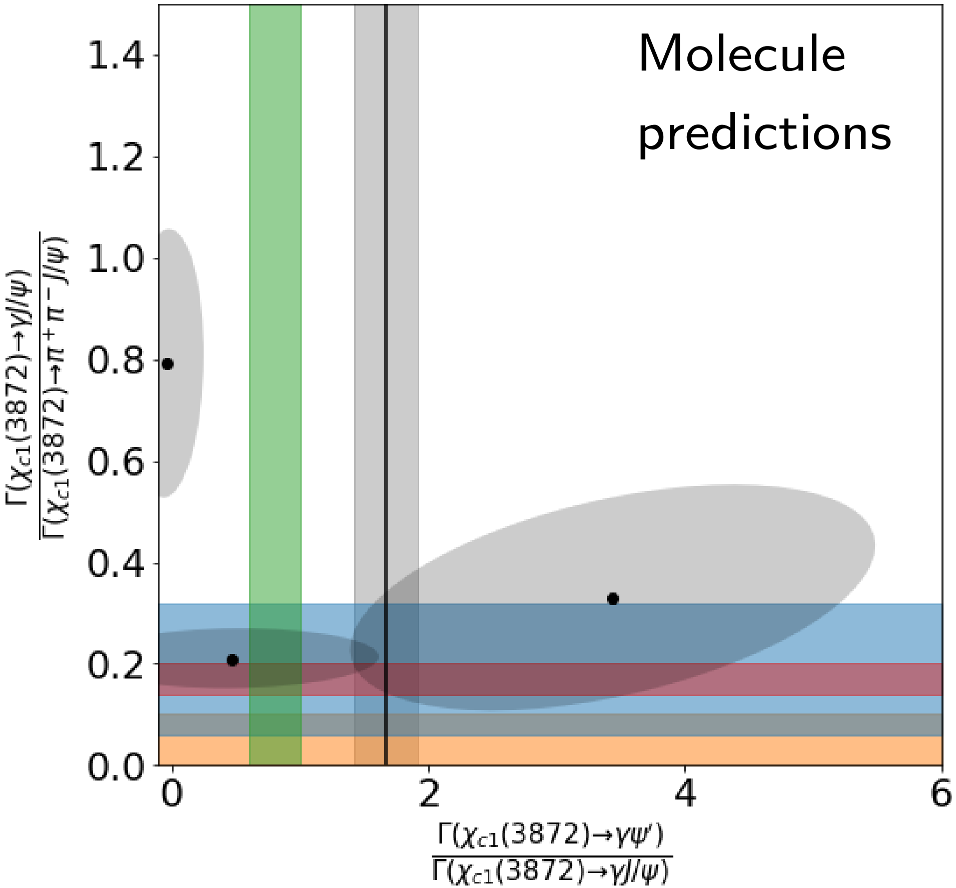
A pathological example



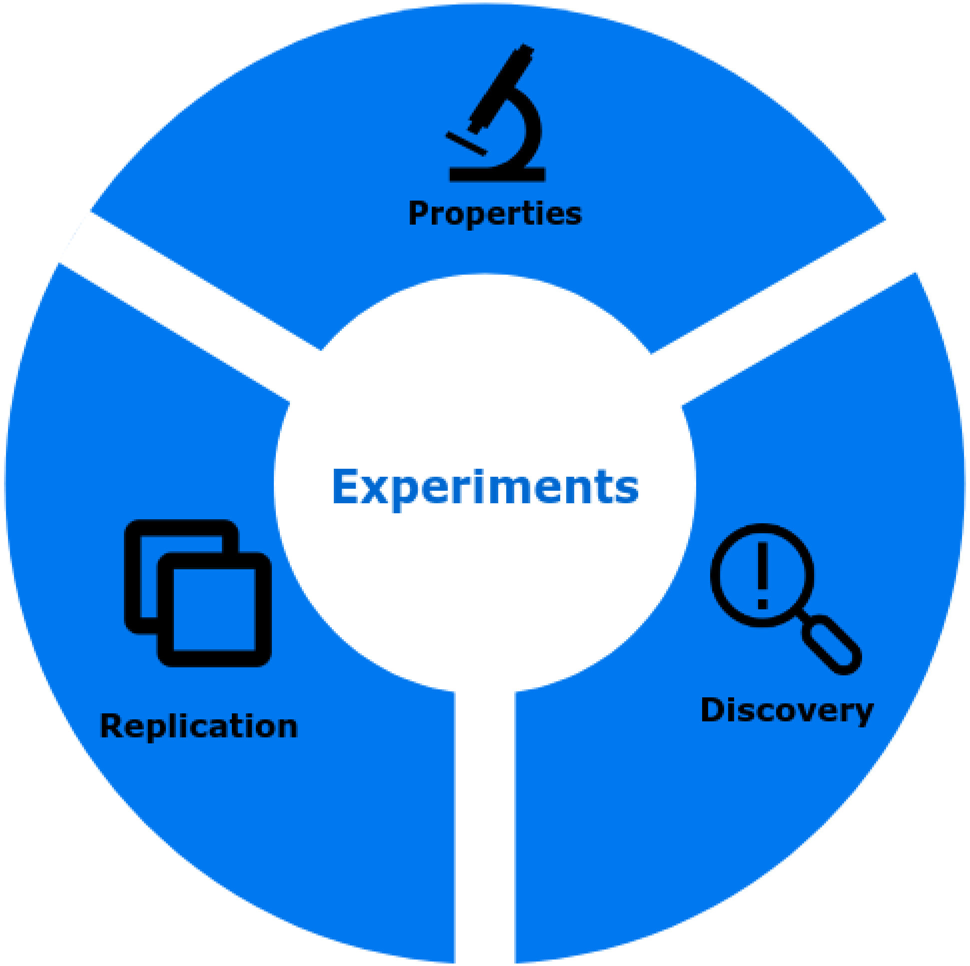
Comparing two radiative decays of X(3872)

A pathological example



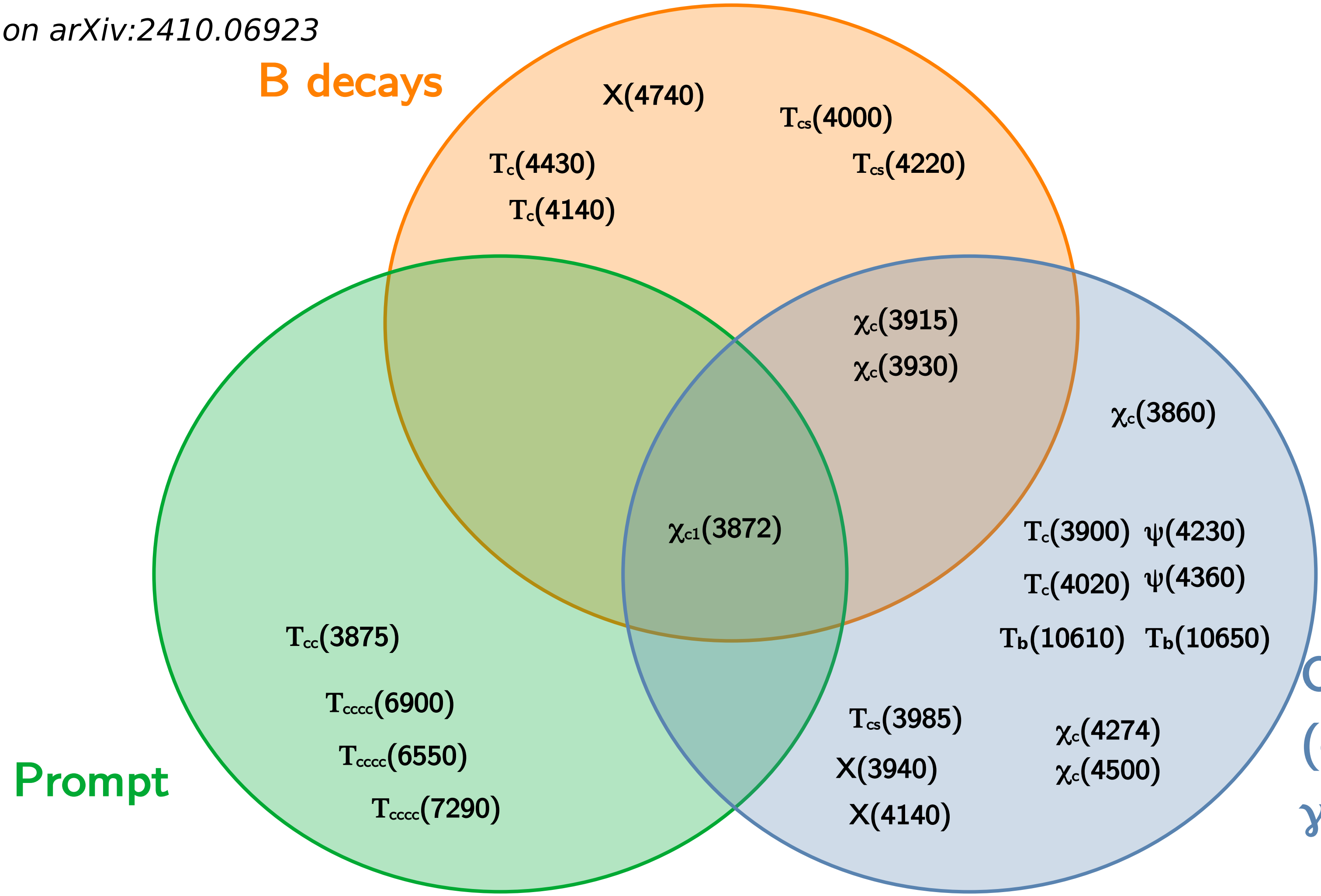


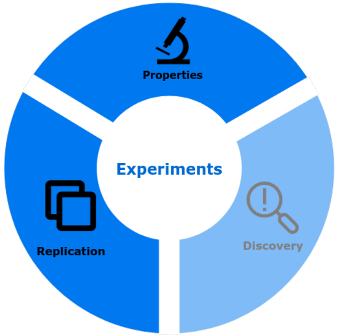
What's to be done



Production

Based on arXiv:2410.06923



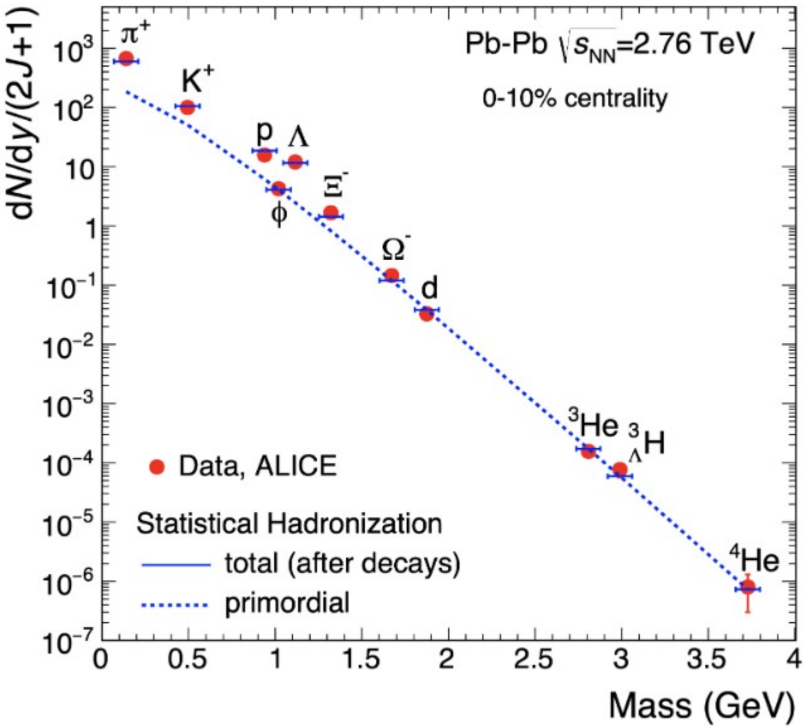


Prompt production of exotica

Naive idea:

- Molecules are weakly bound, they should constantly melt and re-form in dense environment

[Neidig, et al, PLB 827, 136891 (2022)]



(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)]

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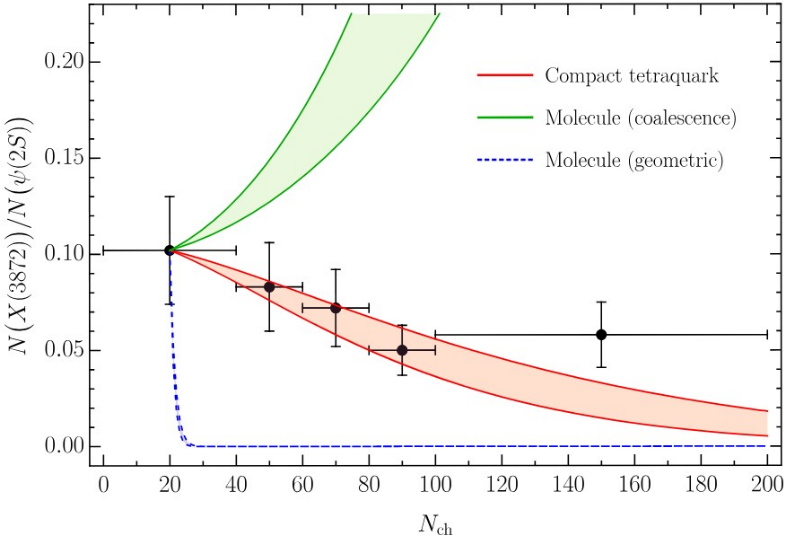
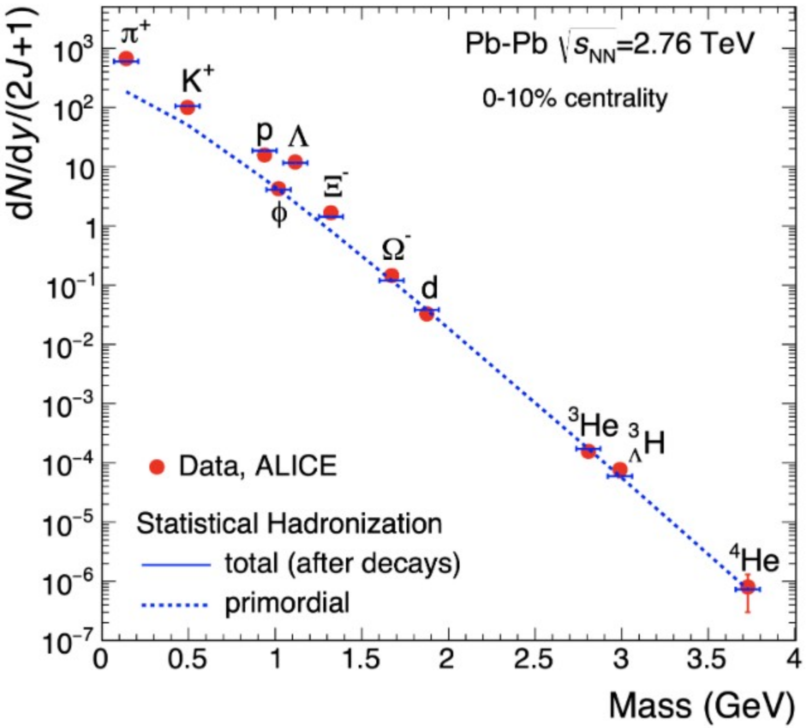




Striking (?) differences in the production of compact or loose states

[EPJ C81, 669 (2021)] [arXiv:2302.03828]

Prompt production of exotica

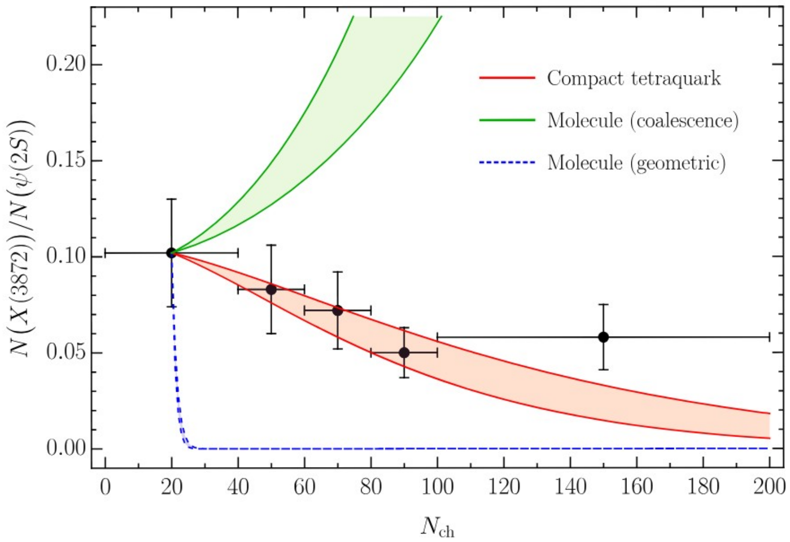
Naive idea:

- Molecules are weakly bound, they should constantly melt and re-form in dense environment

[Neidig, et al, PLB 827, 136891 (2022)]

Tasks

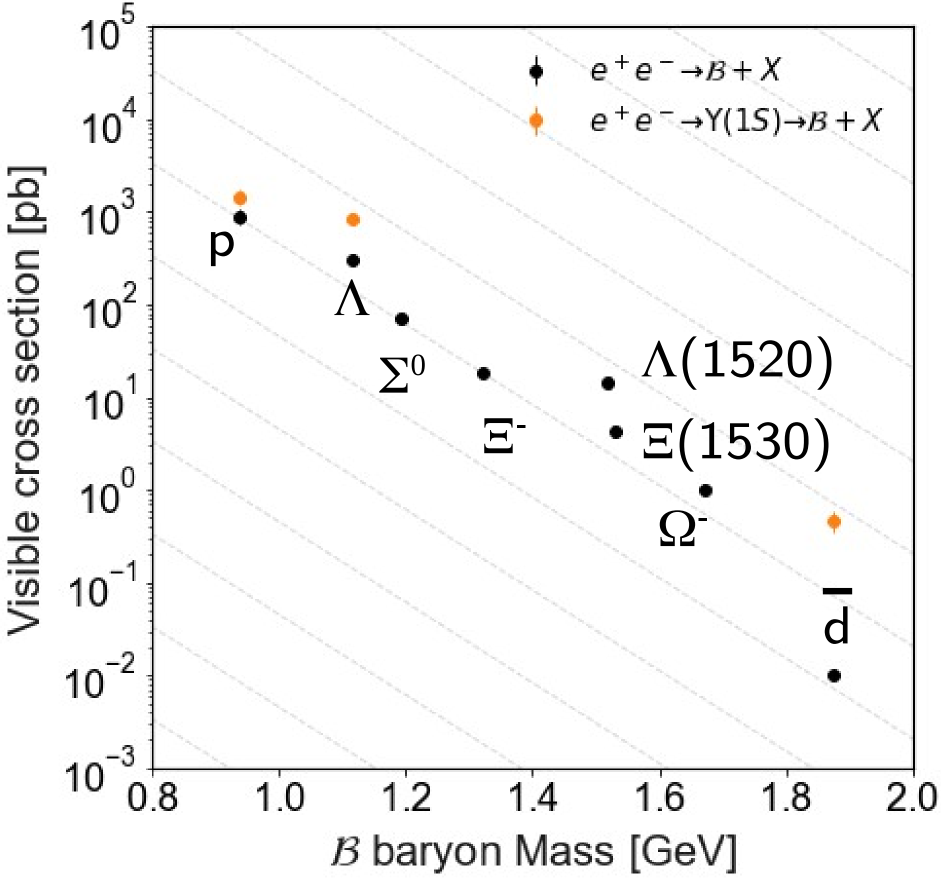
Systematic study of exotica in prompt

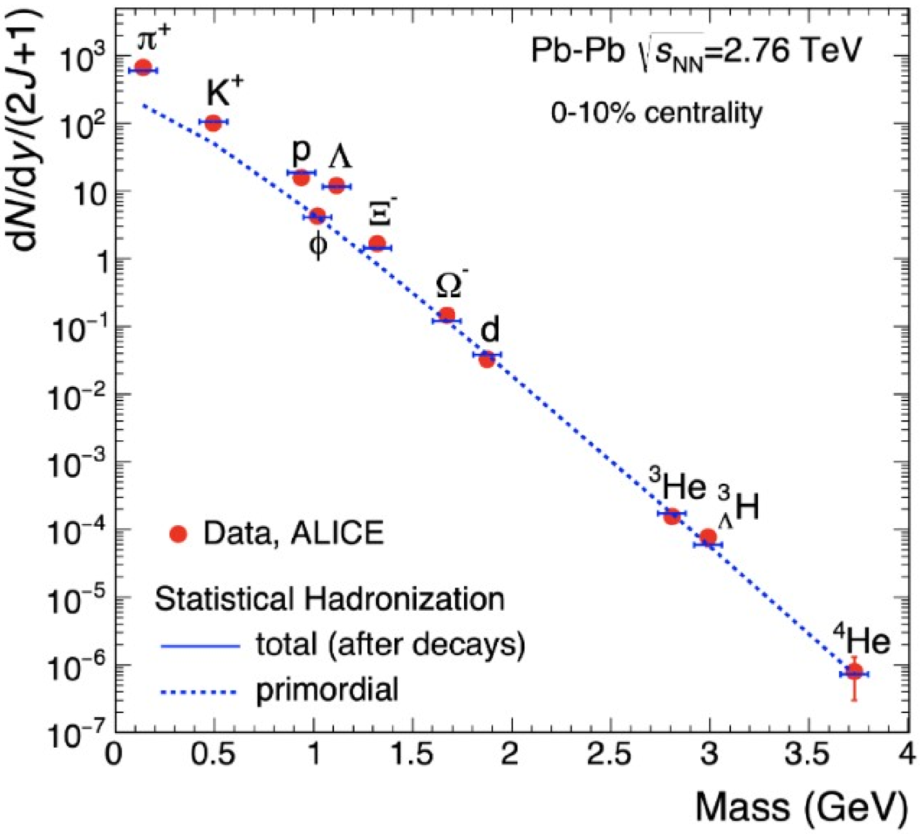


(more or less) recent ideas to explore:

- 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)]*

Other ideas: prompt production in bottomonium





*) piecing together many measurements

Existing measurements: Υ(1S) → exotica

Heavy Exotica

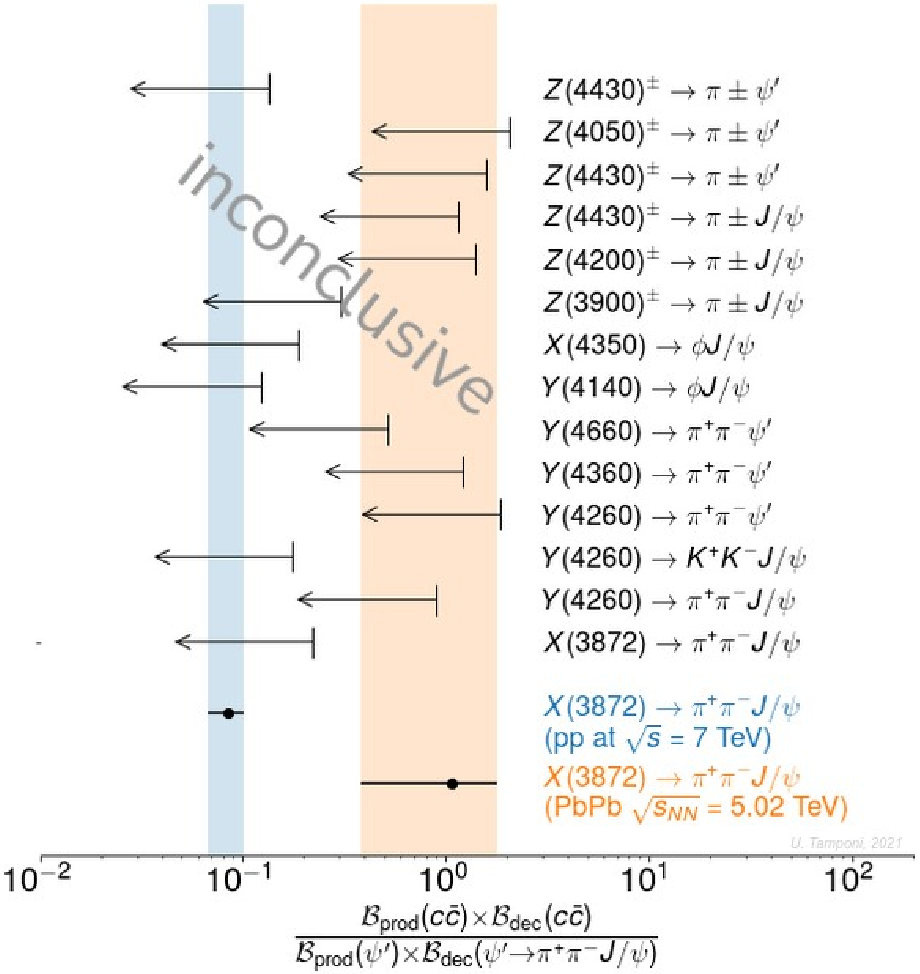
→ Searched in Υ(1S)

→ None observed, not even X(3872)

Tasks

-More quarkonium data

-Predictions!



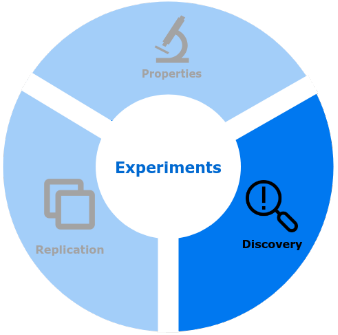
Moving to bottomonium

Patterns seen with charm should repeat with b-quark

$\rightarrow$ Smaller relativistic corrections

$\rightarrow$ Stronger selection rules (Heavy quark spin symmetry…)

$\rightarrow$ Only 2 (3?) exotica known there!



Experimentally challenging

$\rightarrow$ Only prompt production at LHC

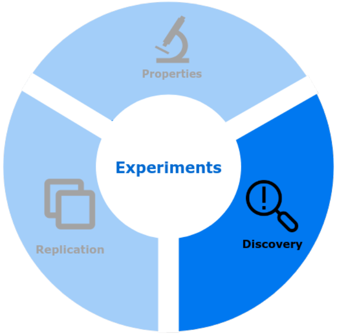
$\rightarrow$ but $\sigma_{prompt}[pp \rightarrow \Upsilon(1S)] \sim 0.0003 \times \sigma_{prompt}[pp \rightarrow J/\psi]$

$\rightarrow$ 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)

Moving to bottomonium



Patterns seen with charm should repeat with b-quark

→ Smaller relativistic corrections

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

→ **Only 2 (3?**

Experimentally ch

→ Only prom

→ but σ_{pro} ... /ψ]

B-hadrons are much less known than their charmed counterparts

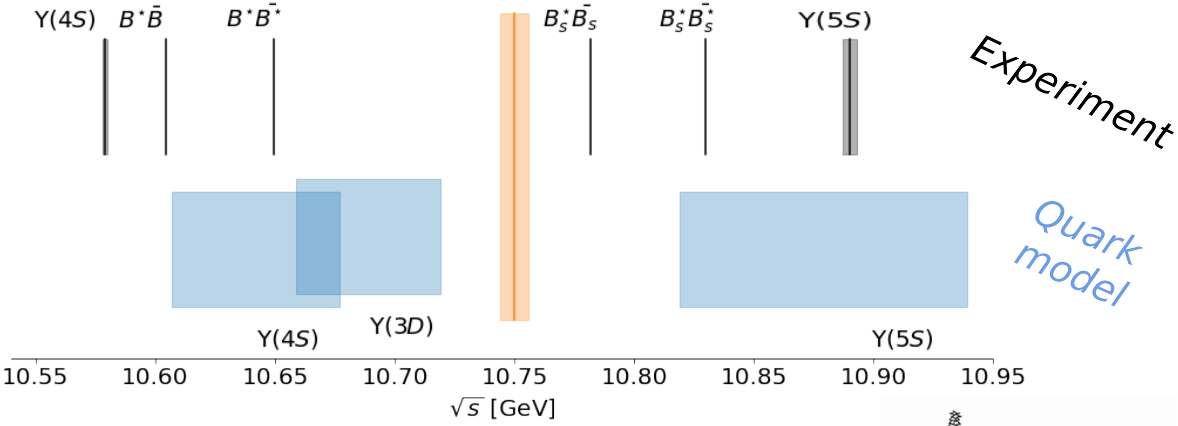
→ Can produce Υ(nS) 1^{--} states at e^+e^-

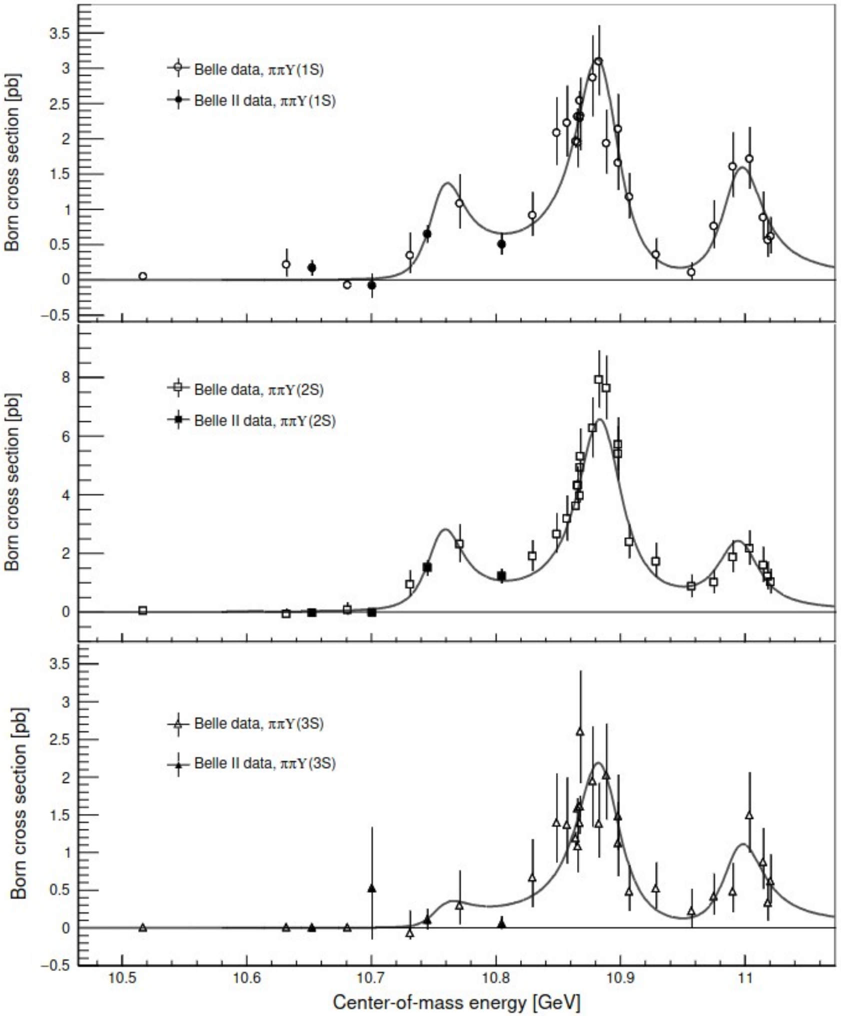
→ Strongly depend on the the BF for the Υ(nS) to your state

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

An example: the Y(10753)

Unexpected vector state around 10.750 GeV





Optimal situation:

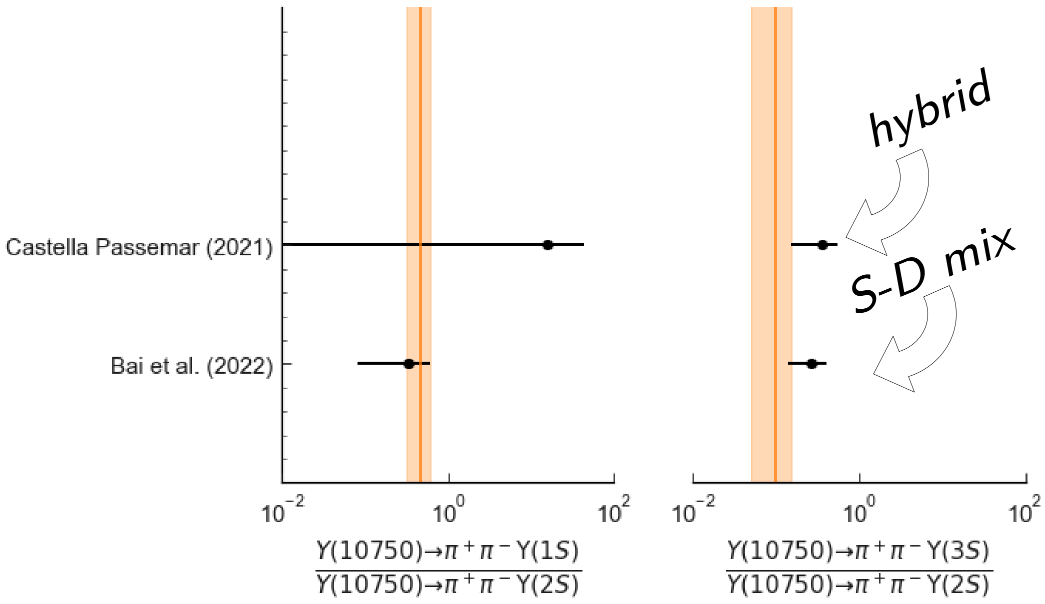
→ First discovery

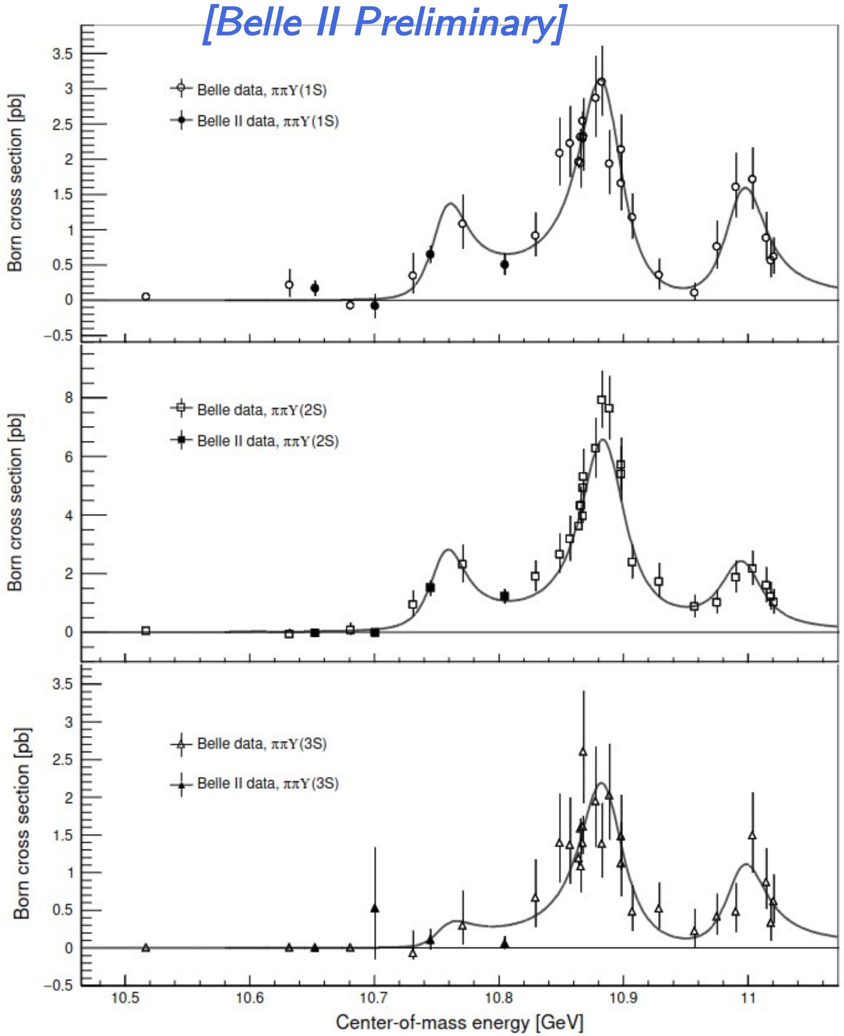
→ ~30 theoretical predictions

→ More data, more studies

Theory VS experiment: $e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

Conventional	✓
Tetraquark	---
Hybrid	✓



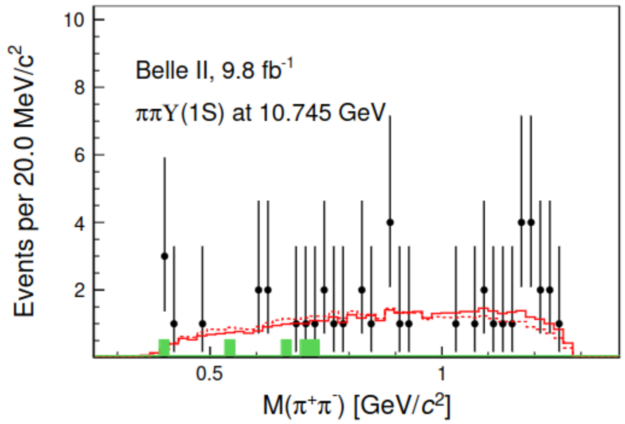


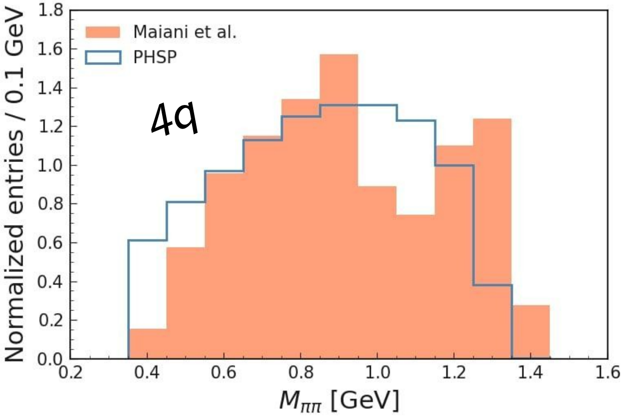
Theory VS experiment: $e^+e^- \rightarrow \Upsilon(nS)\,\pi^+\pi^-$

Analysis of the di-pion mass spectrum

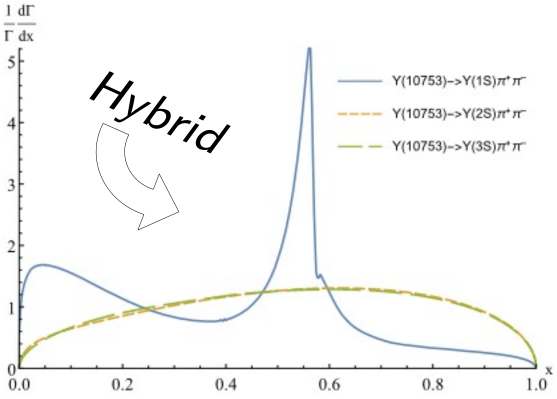
Conventional	✓	✗
Tetraquark	---	✓
Hybrid	✓	✗

[Belle II Preliminary]

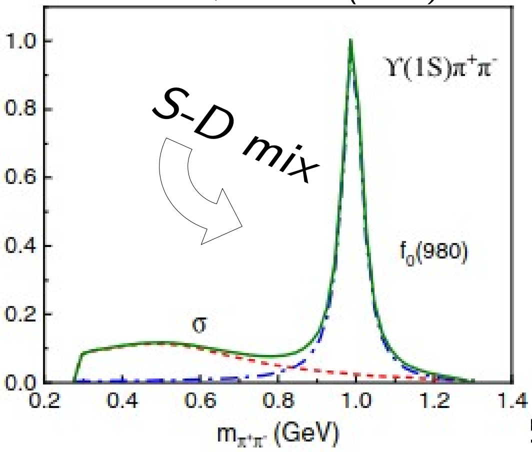




PRD 104, 0340 (2022)



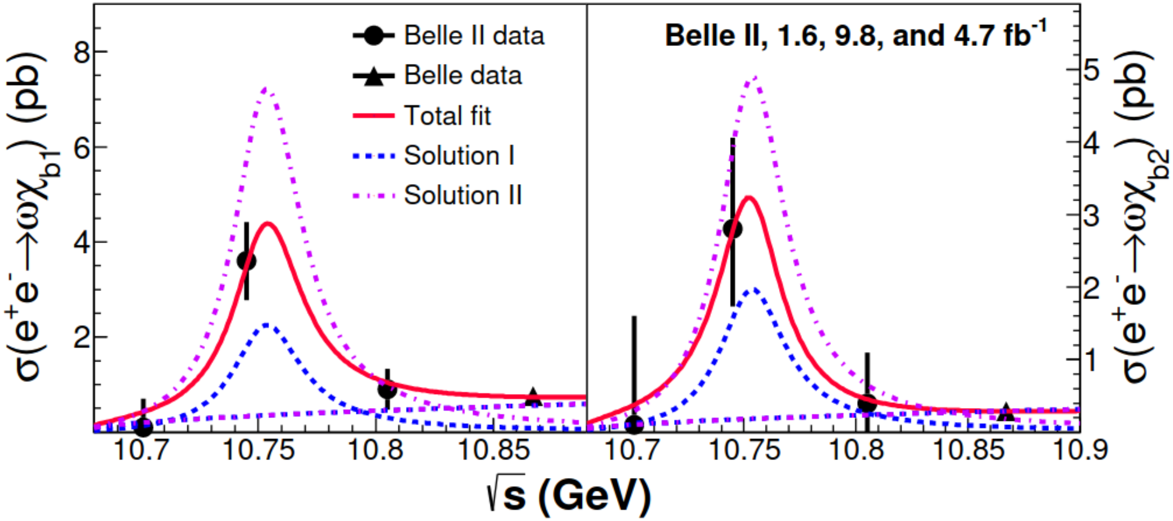
PRD 105, 074007 (2022)

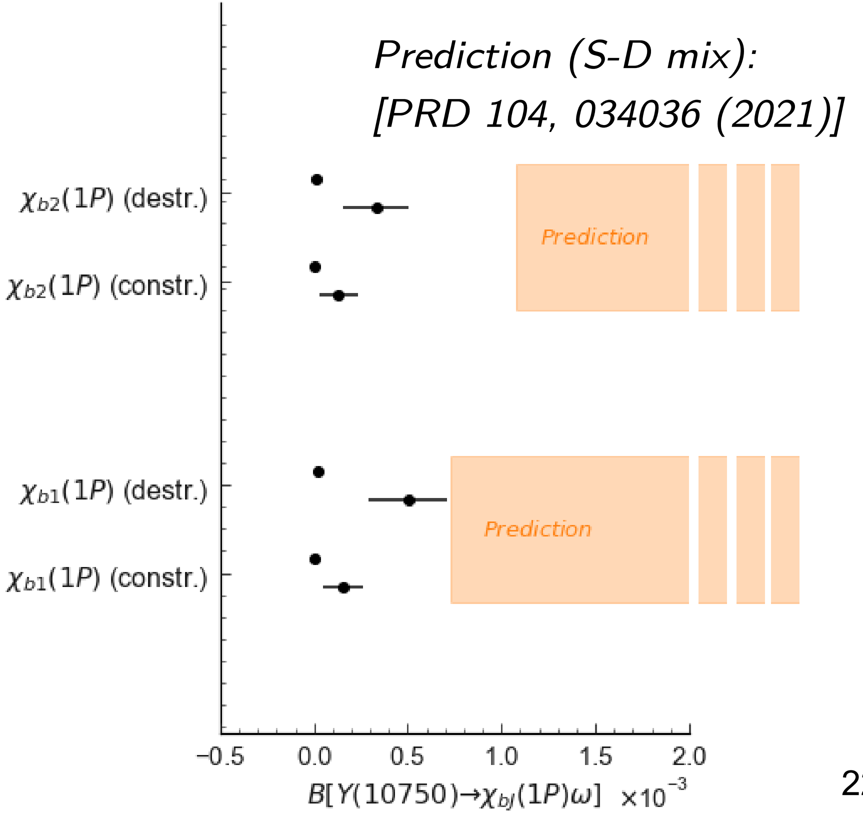


Theory VS experiment: $e^+e^- \to \chi_{b1,2}(1P)\,\omega$

[PRL 130, 091902 (2023)]

Conventional	✓	✗	✗
Tetraquark	---	✓	---
Hybrid	✓	✗	---





Theory VS experiment: $e^+e^- \rightarrow \eta_b(1S)\ \omega$

[arxiv:2312.13043]

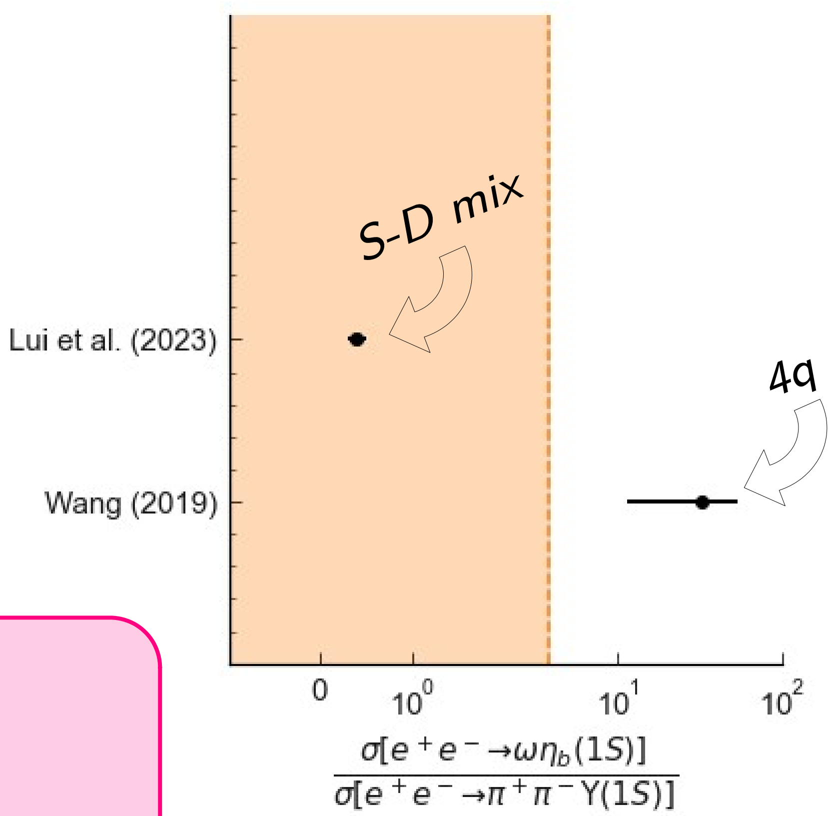
Conventional	✓	✗	✗	✓
Tetraquark	---	✓	---	✗
Hybrid	✓	✗	---	---

So the Y(10753) is…

Tasks

-More data

-Comprehensive Predictions!

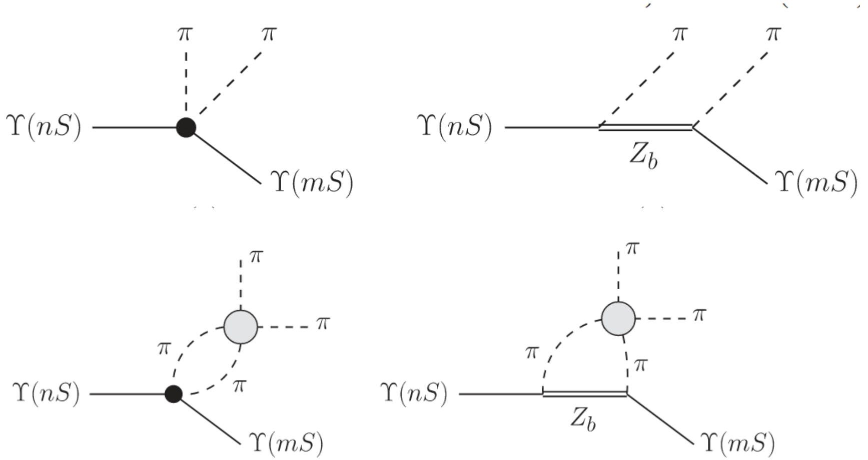


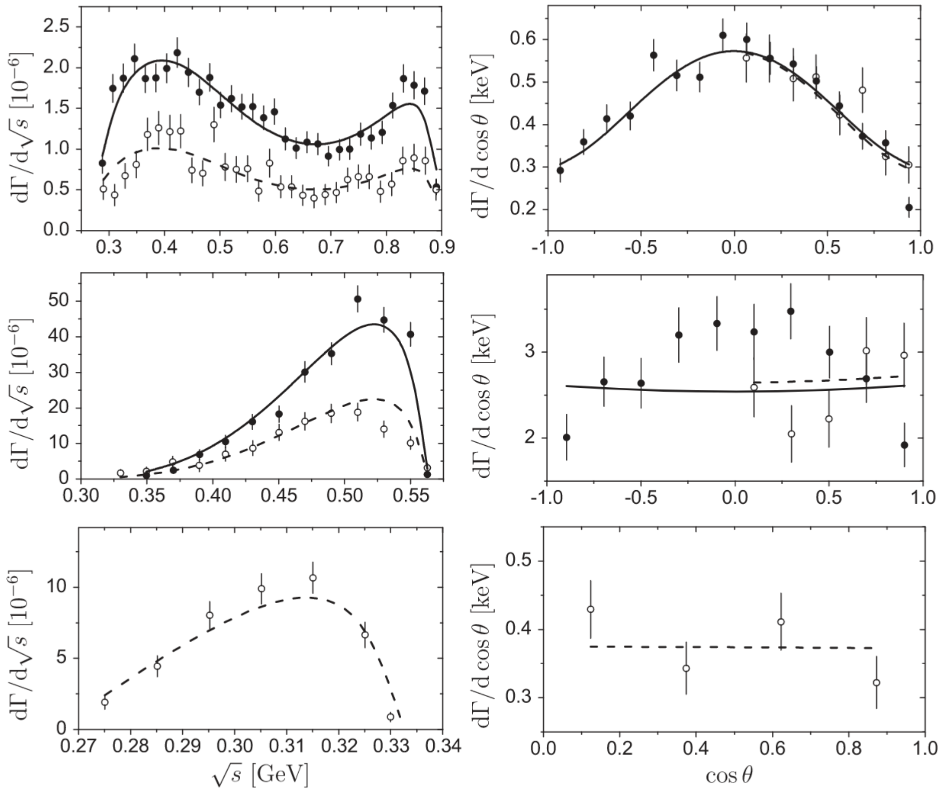
Bottomonium: alternative approaches

Exotic stats contribute to the transitions from narrow quarkonia?

→ new (?) approach to heavy spectroscopy

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

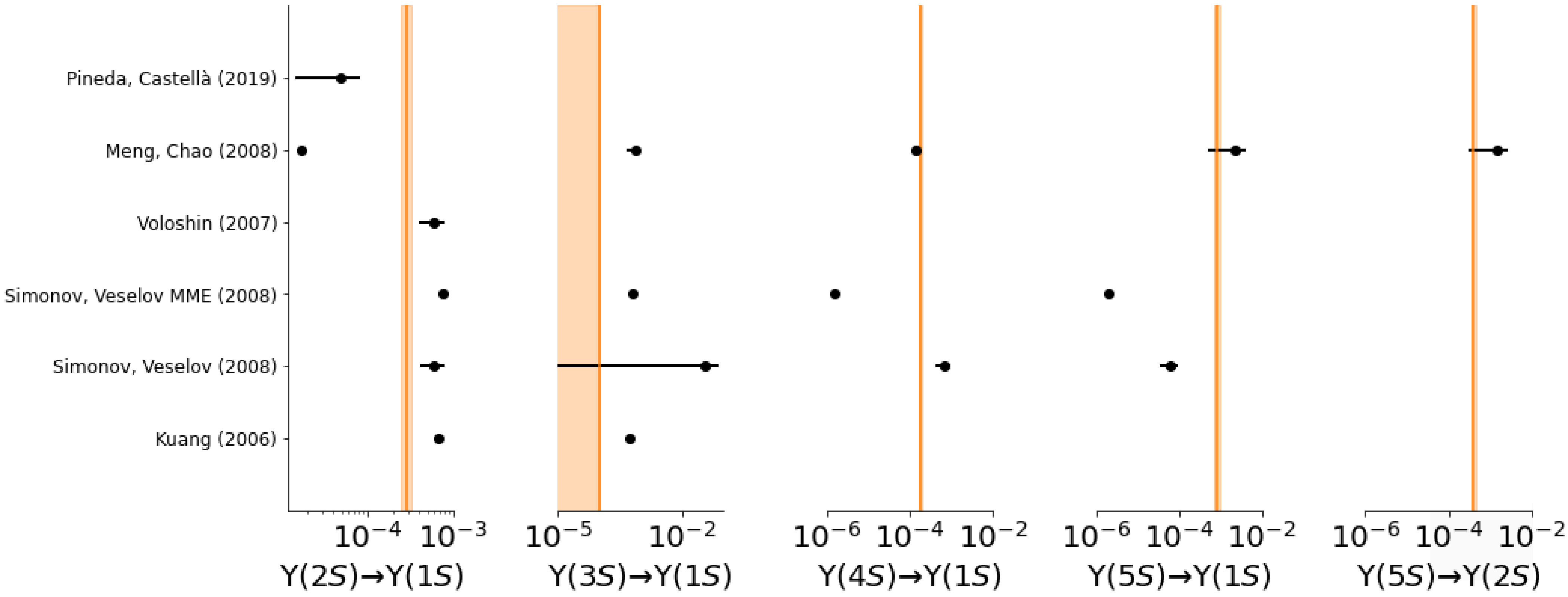




Theory troubles: η transitions updated

No solid prediction on simple transitions like single η

→ Exotic contributions?



Theory troubles: η transitions updated

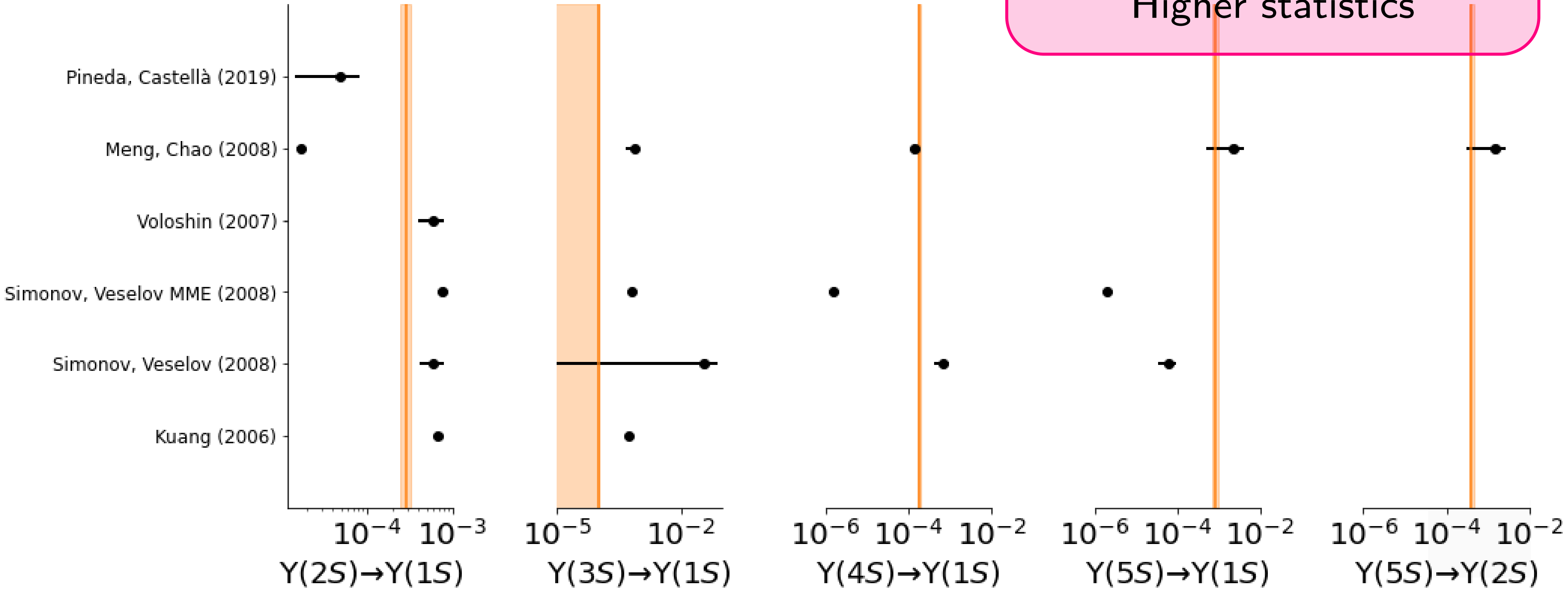
No solid prediction on simple transitions like single η

$\rightarrow$ Exotic contributions?

Tasks

Theoretical modeling

Higher statistics

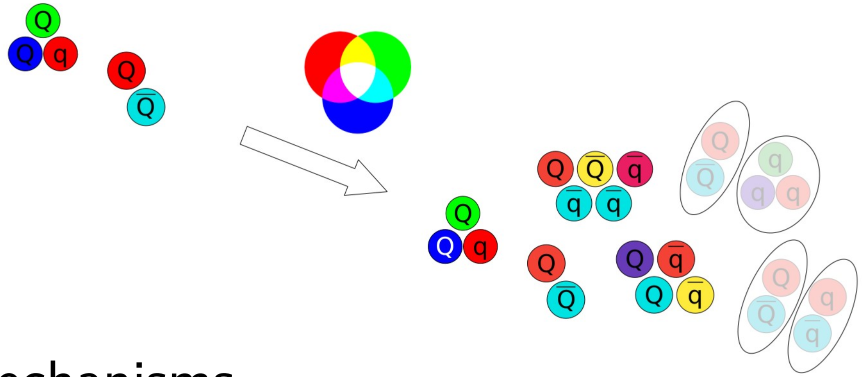


Summary

The heavy hadrons gave us solid experimental evidences of exotic states

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

→ More states than what we can understand



New discoveries in charmonium are not everything:

→ Search for exotica in multiple production mechanisms

→ Systematic study of production in high-multiplicity environments

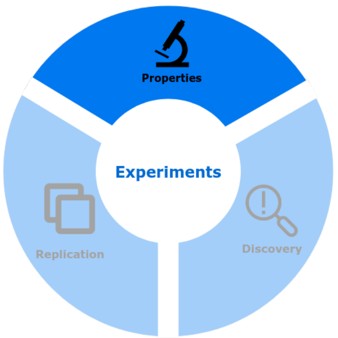
→ Prompt production in bottomonium decays

→ Look for exotica hidden in the transitions (for bottomonium!)

→ Measure J^{PC} of all states!

Backup

Mapping properties: absolute BFs



When we observe a new state S we access

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

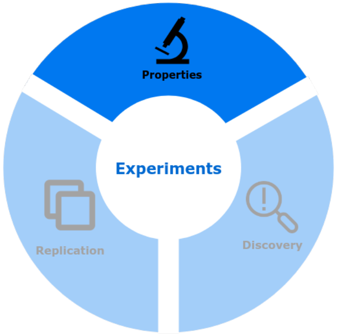
Poorly (or not) constrained by theory

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

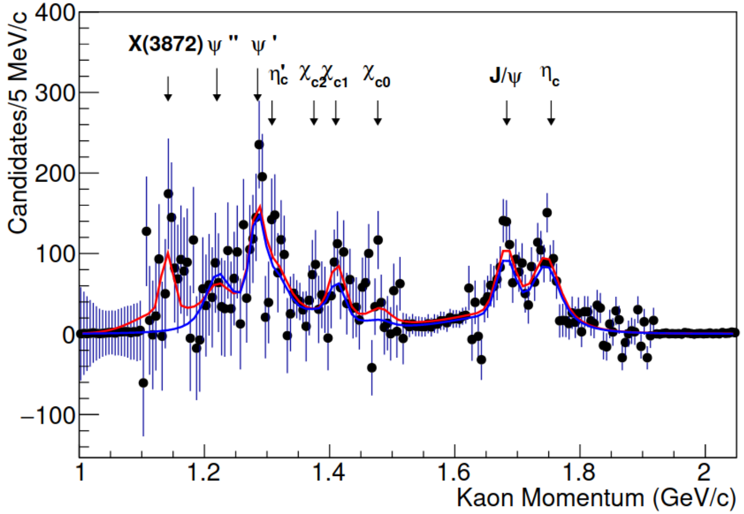


When we observe a new state S we access

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

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

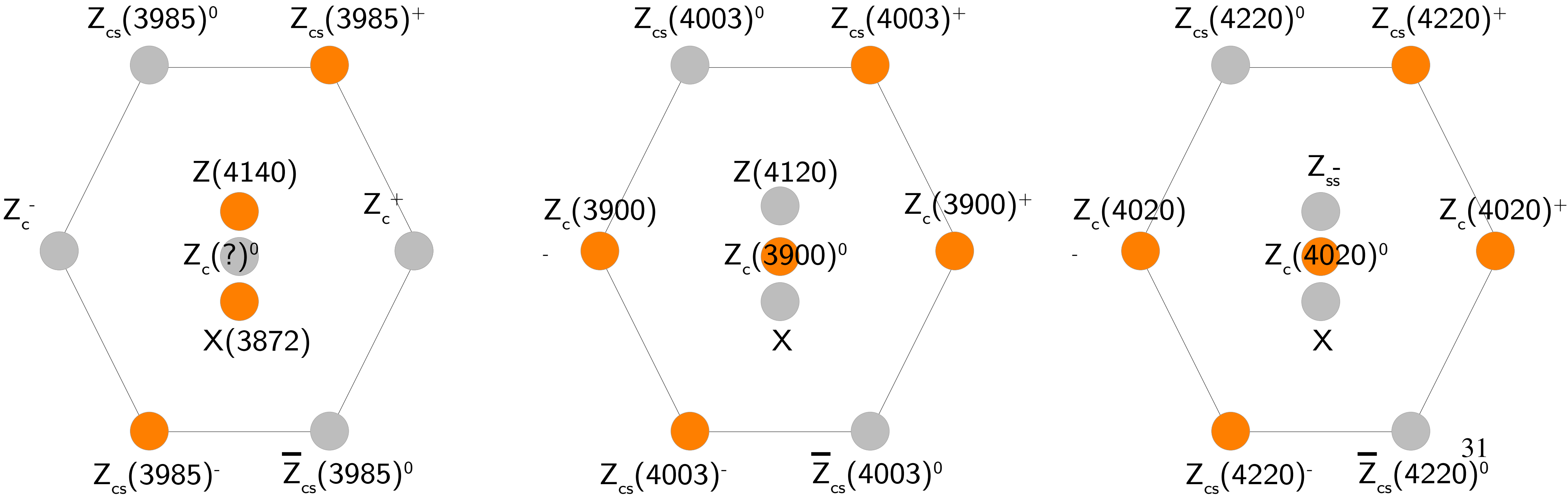
The first charmed-strange tetraquark

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



Fully-heavy states: X(3900)

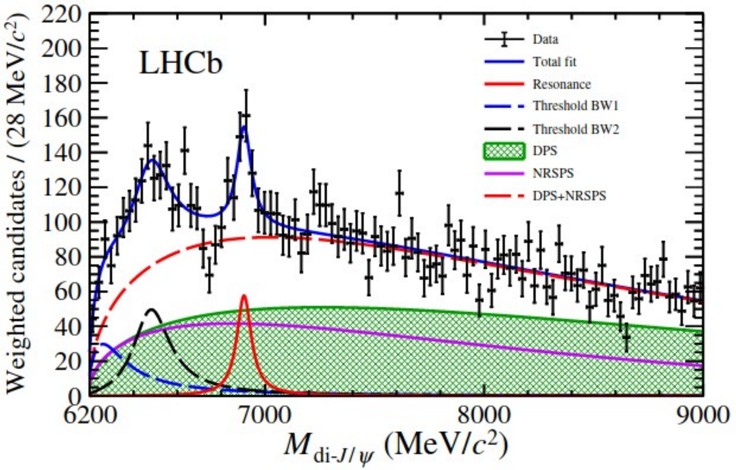
pp → J/ψ J/ψ + X

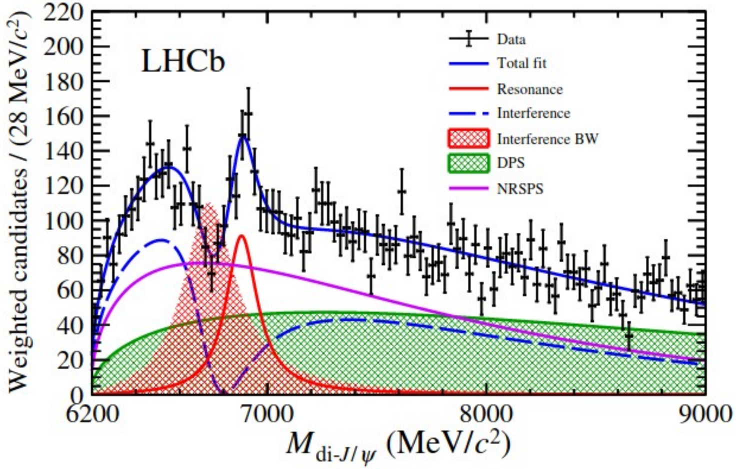
[Sci. Bull. 65 1983 (2020)]

Two structures in M(J/ψ J/ψ)

- Narrow X(6900)
- Broad enhancement @ threshold

70+ theoretical interpretations



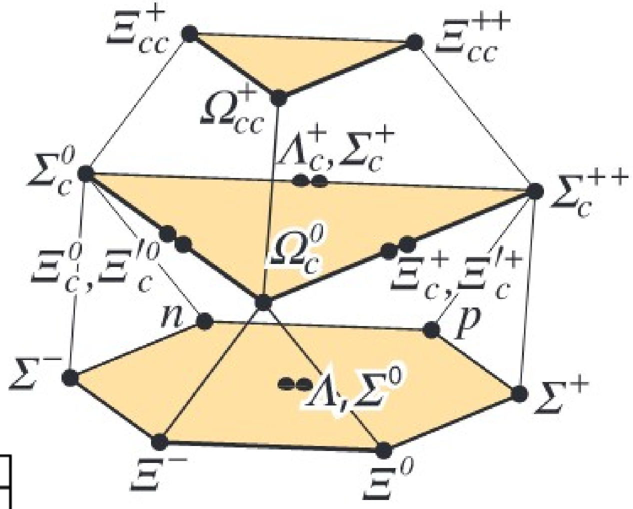


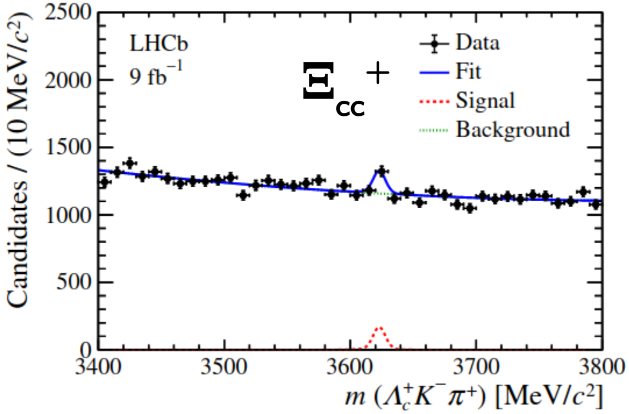
Doubly-charmed objects

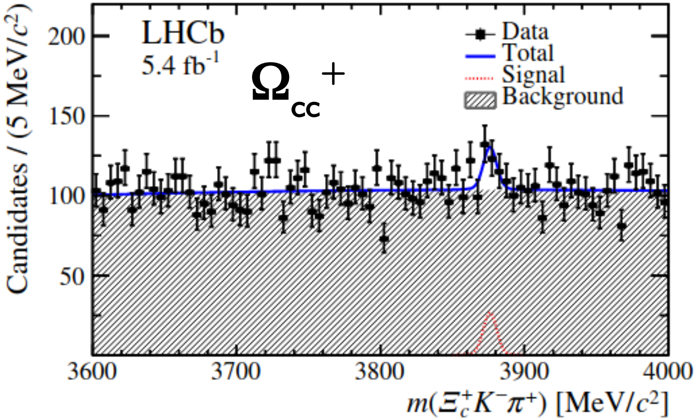
Ξ_{cc}^{++} Observed in 2017

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

[Sci. China-Phys. Mech. Astron. 64, 101062 (2021)]
[arXiv:2109.07292]



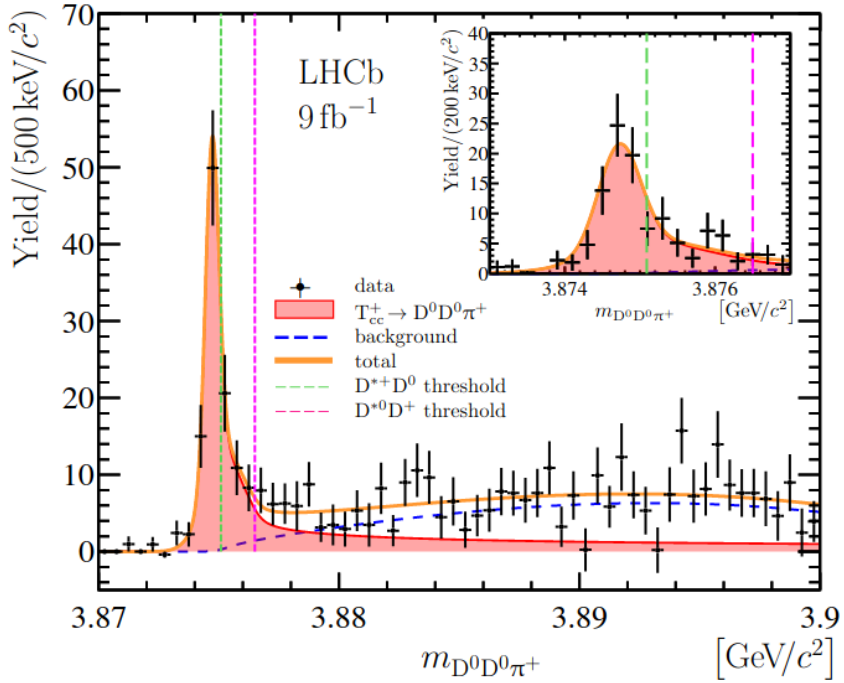




The T_{cc}

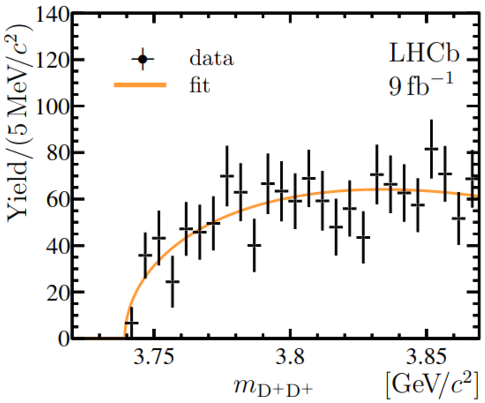
Prompt production of something decaying into $(DD^*)^+$

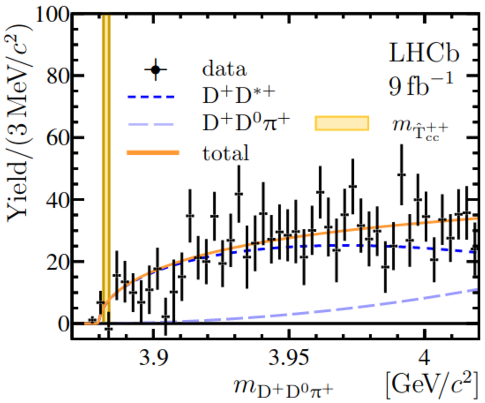
[arXiv:2109:01038 and arXiv:2109:01056]



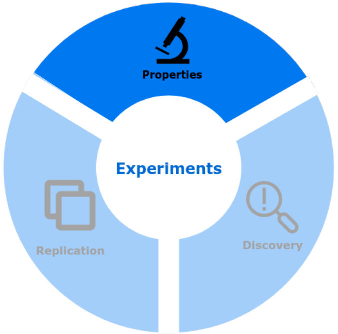
$J^{PC} = 1^+$ (probably)

Nothing in the D^+D^+ channel





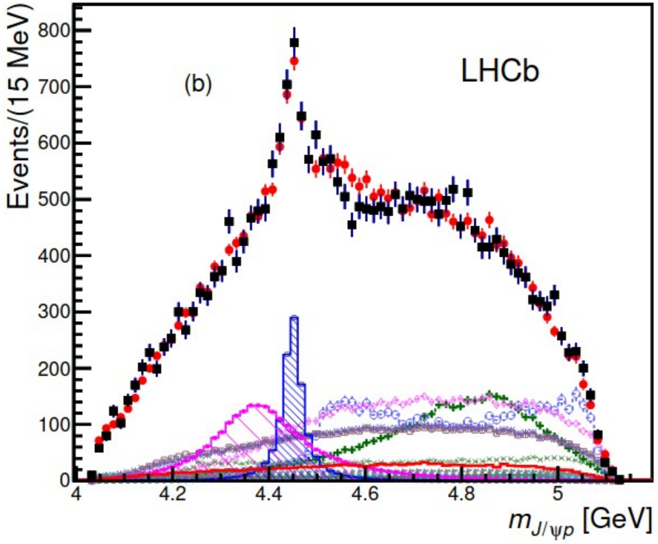
J^{PC} analysis: the pentaquark example



Amplitude analysis is challenging with narrow states

- Cannot neglect the resolution
- Fit computationally very demanding

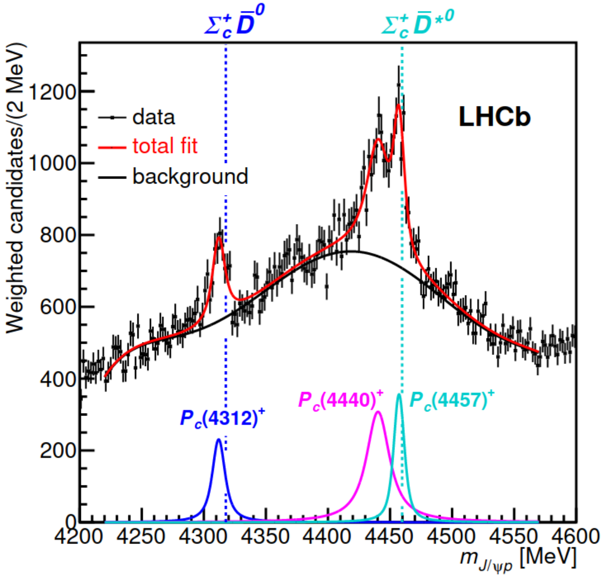
2015: two **broad** states



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?

Future challenges: hadrons with beauty

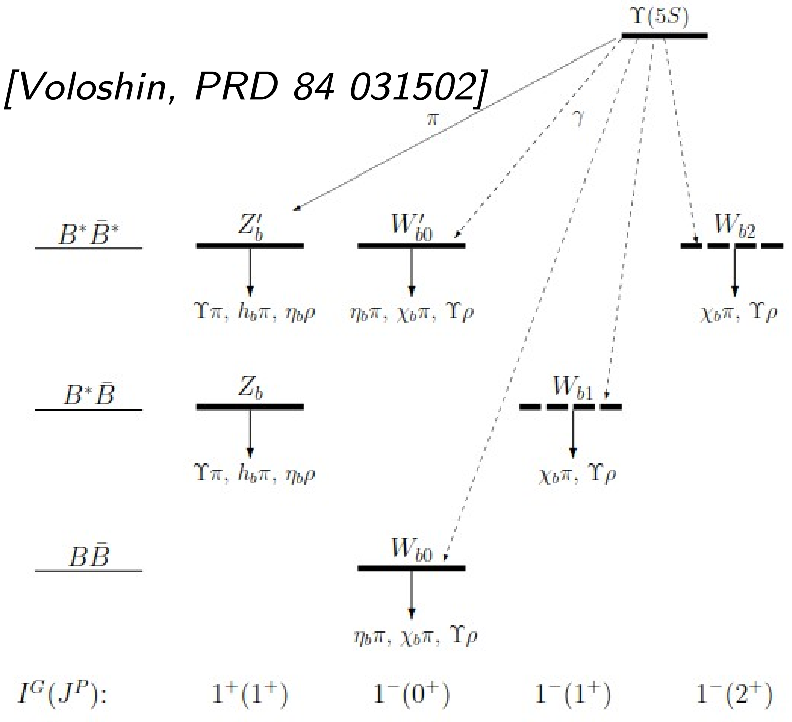
Exotic search with Ecm $<$ 12 GeV are challenging

$\rightarrow$ rely on rare, soft EM transitions

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

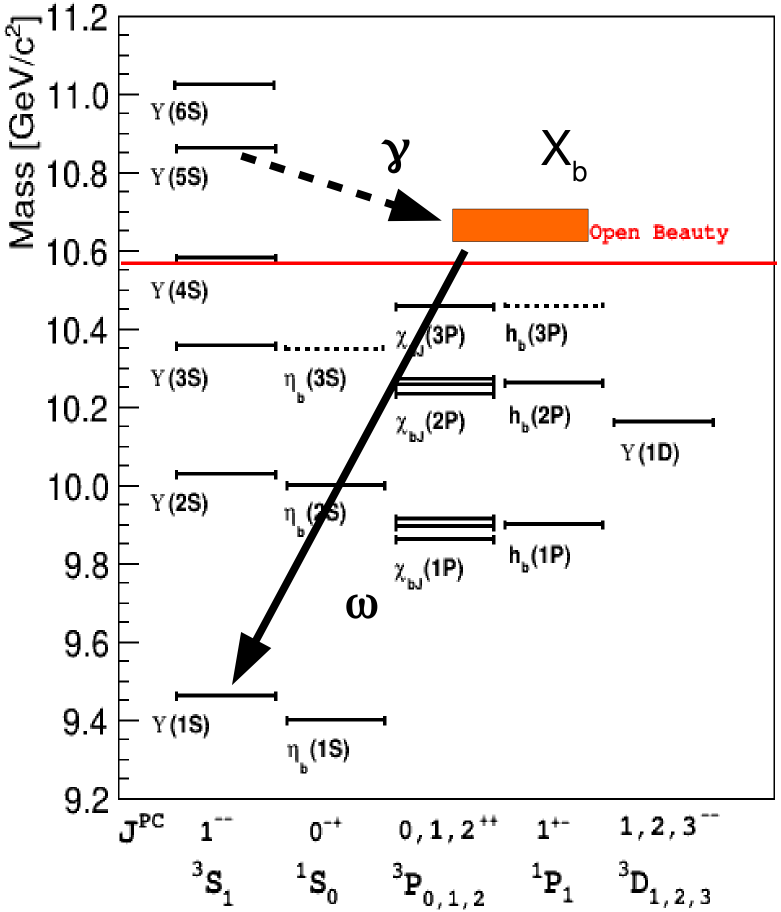
Label	J^{PC}	charmonium-like State	Mass [MeV]	bottomonium-like State	Mass [MeV]
X_0	0^{++}	—	3756	—	10562
X_0'	0^{++}	—	4024	—	10652
X_1	1^{++}	$X(3872)$	3890	—	10607
Z	1^{+-}	$Z_c^+(3900)$	3890	$Z_b^{+,0}(10610)$	10607
Z'	1^{+-}	$Z_c^+(4020)$	4024	$Z_b^+(10650)$	10652
X_2	2^{++}	—	4024	—	10652
Y_1	1^{--}	$Y(4008)$	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

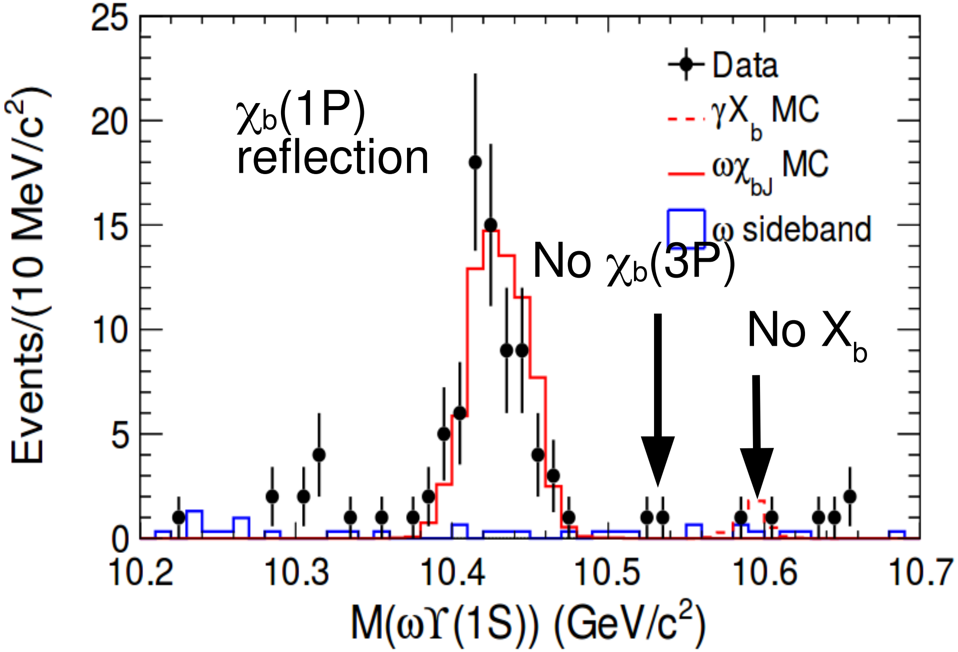
[Voloshin, PRD 84 031502]



Is there an X(3872) counterpart?

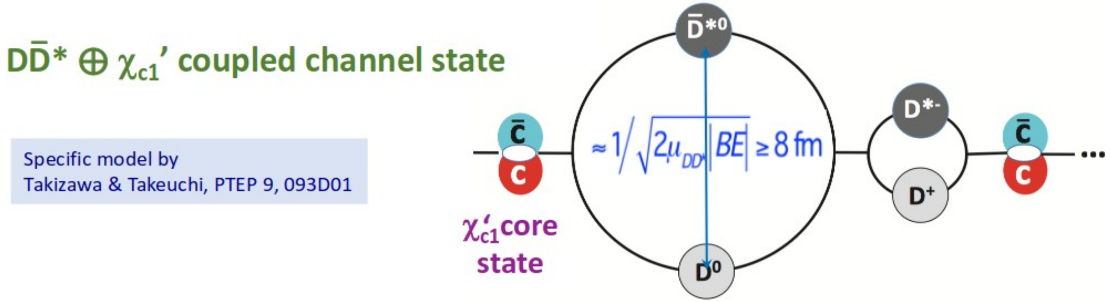
Both tetraquark and pure molecule predict a counterpart (X_b)

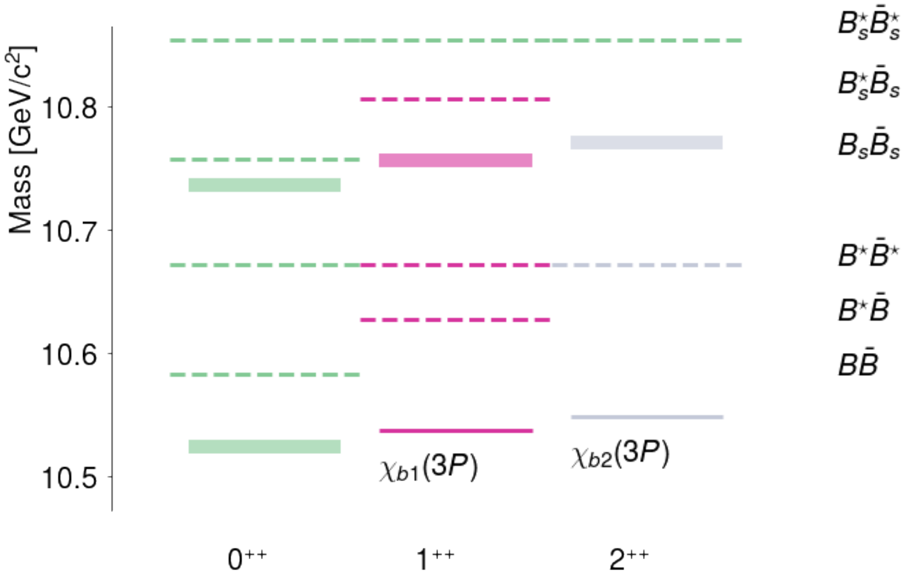




Why no X_b ?

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**