Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Understanding exotic hadrons

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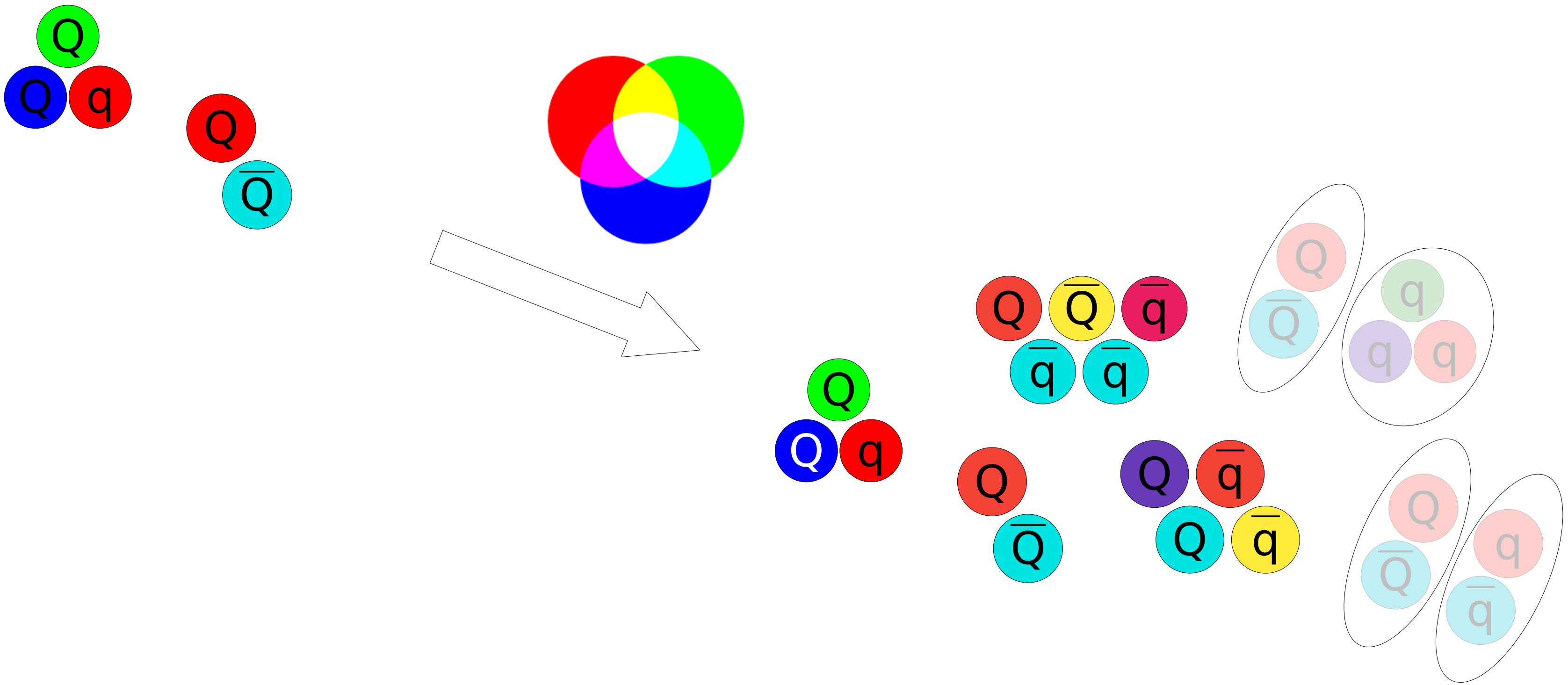
Exotic hadrons

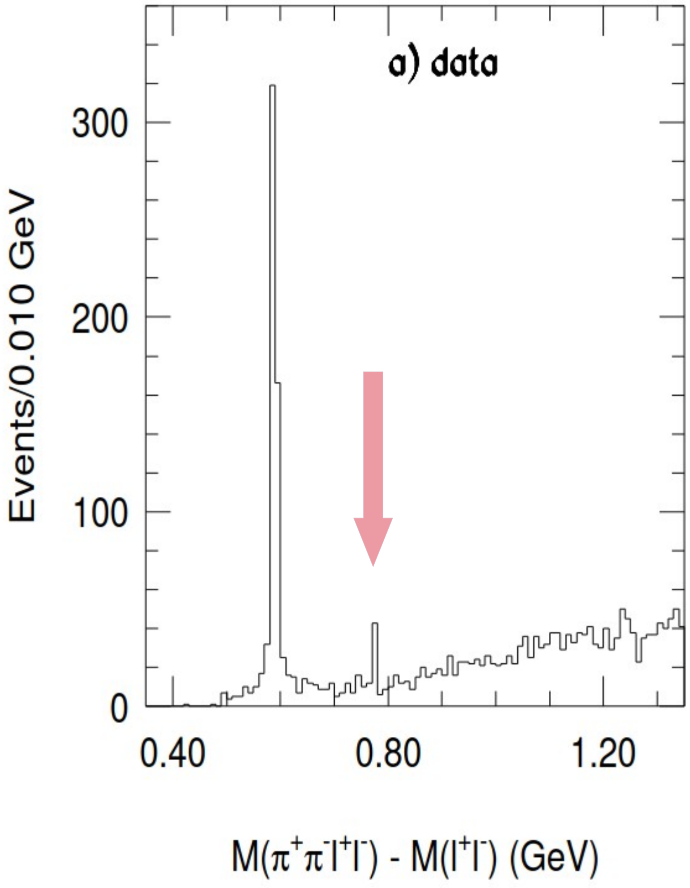
$q\bar{q}$ and qqq are not the only color singlets

- we are now sure there is much more!



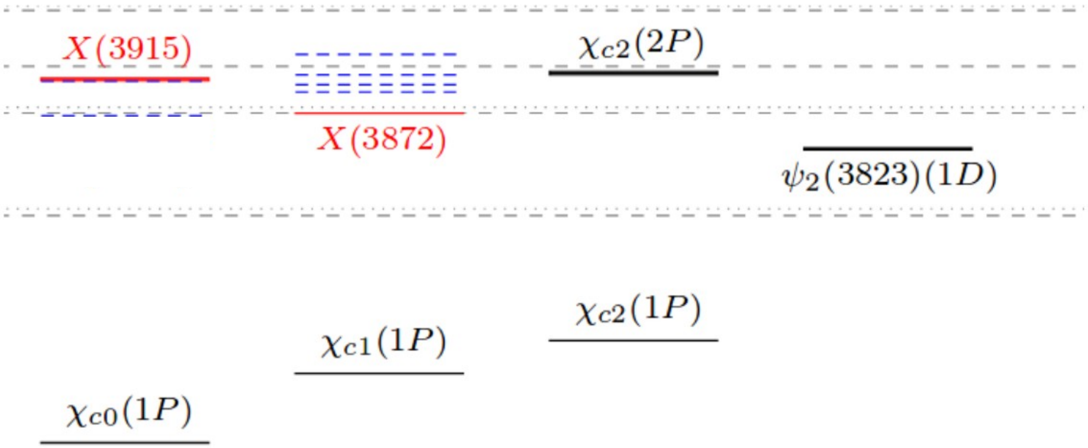
The first (?) Exotic hadron: X(3872)

Belle, PRL 91 262001 (2003)

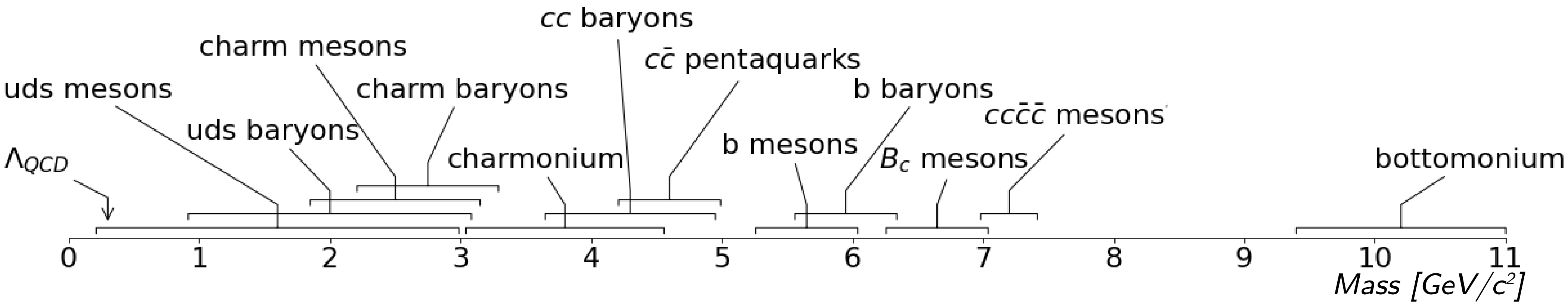


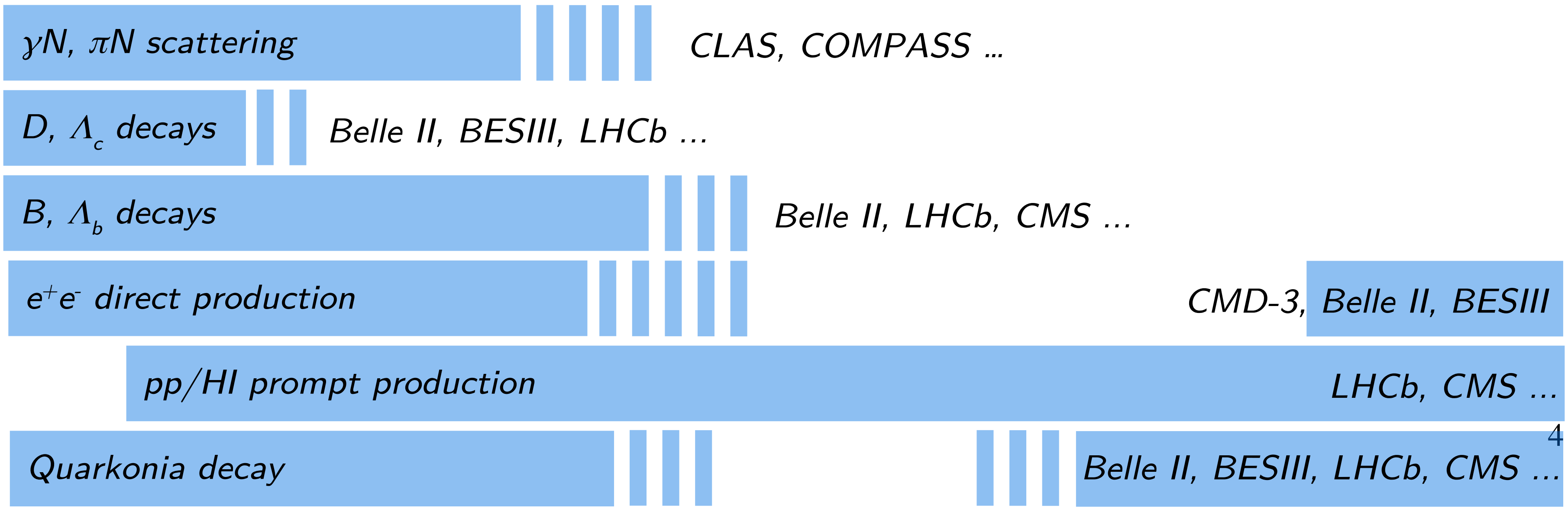
Seen in $B \to K\,\pi\pi\;J/\psi$

- Looks like a $\chi_{c1}(2P)$ but...



Heavy or light hadrons?





Quarkonium in a nutshell

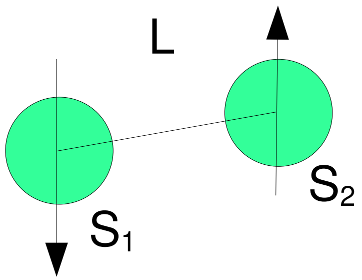
Quarkonia = heavy mesons made of a $c\bar{c}$ or $b\bar{b}$ pair

$\rightarrow$ $m_q \sim$ 3-5 GeV/c^2 $>> \Lambda_{QCD}$

$\rightarrow$ v/c $<<$ 1: **L is a good quantum number**

$\rightarrow$ Narrow resonances $\Gamma < \Delta M << M$

$\rightarrow$ Heavy quark spin symmetry



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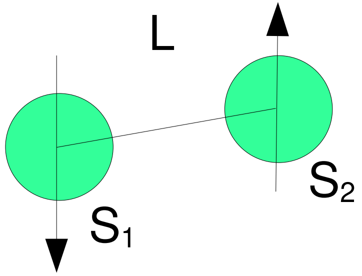
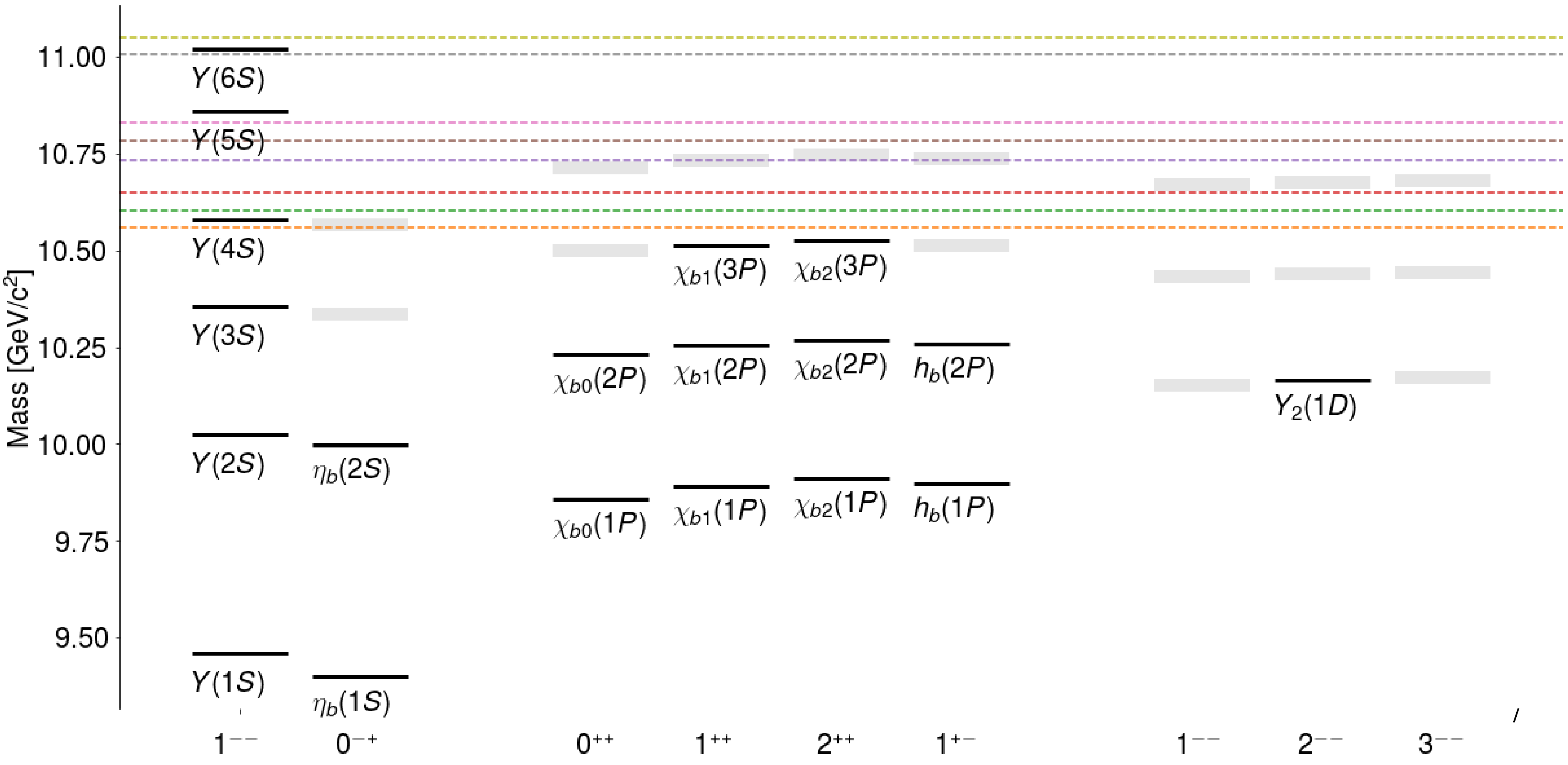


→ $m_c << m_b << m_t$

→ No heavy flavor symmetry

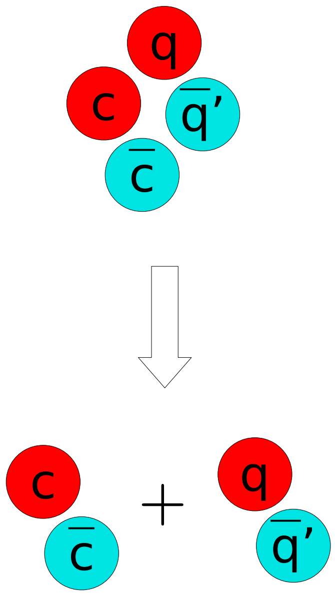
→ All quarkonia are isospin singlets (neutral)

Getting familiar with a quarkonium spectrum



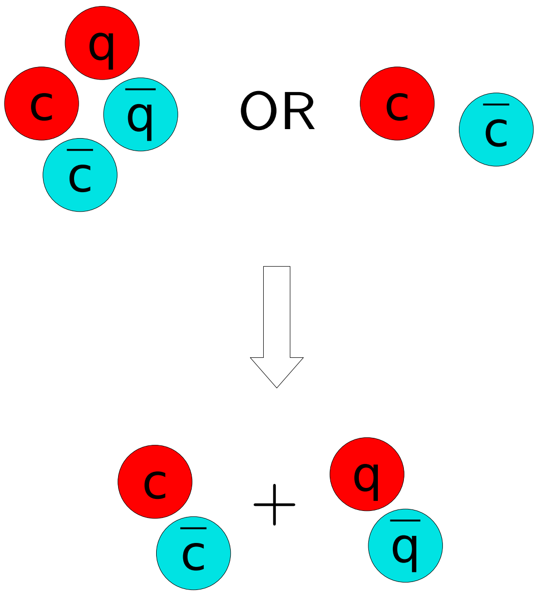
Why heavy hadrons

With heavy quarks separating conventional and exotics is much simpler



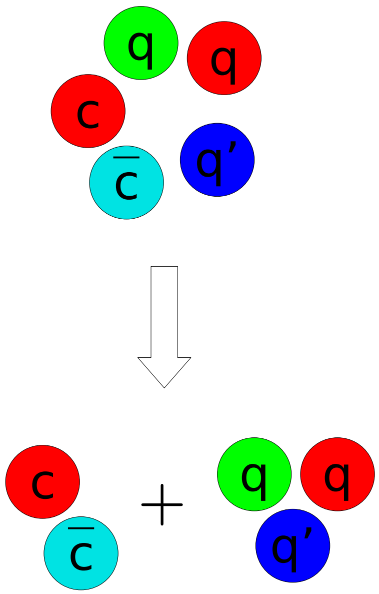
$c\bar{c}$ + charged meson

- must have 4 quarks



$c\bar{c}$ + neutral meson

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

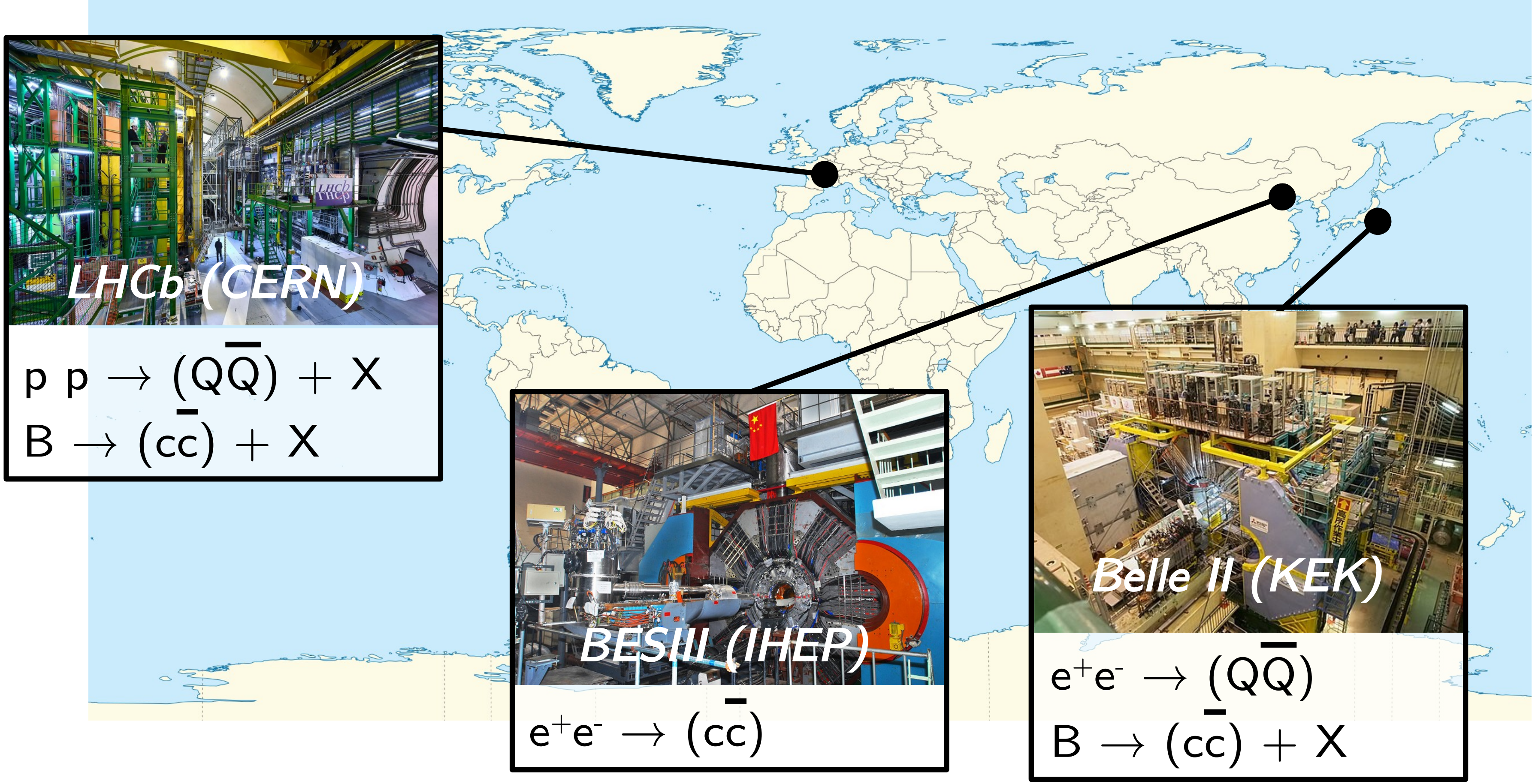


$c\bar{c}$ + baryon

- 5 quarks

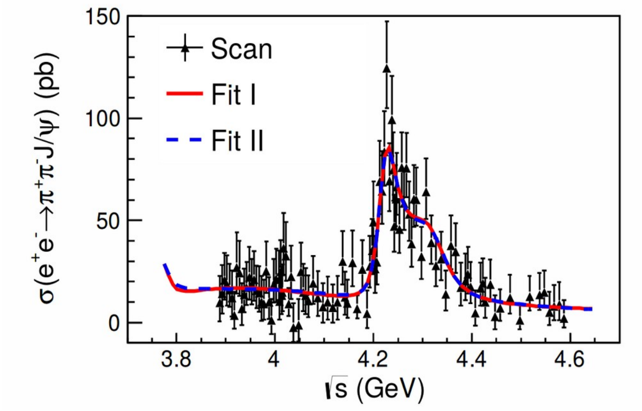
Quarkonium at experiments: new generation

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

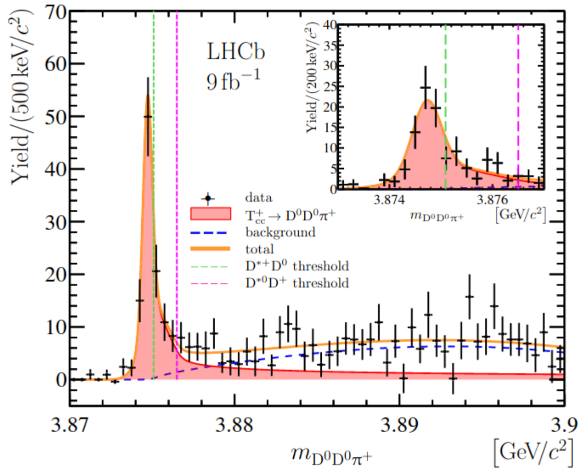


How does an exotic look like?

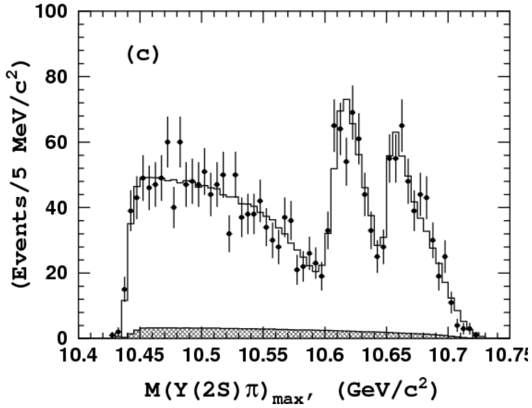
An e$^+$e$^-$ cross section enhancement



A new resonance in hadronic events

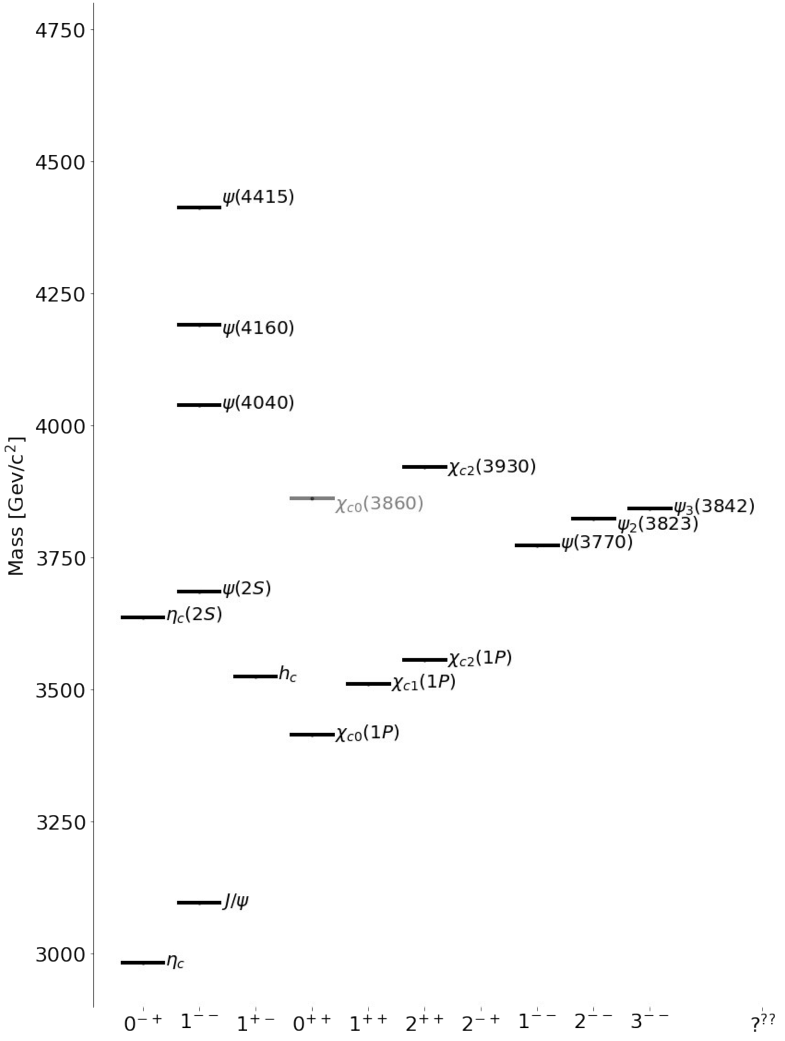


A resonance in a heavier particle decay



Exotica, where are we?

Known, conventional charmonium spectrum



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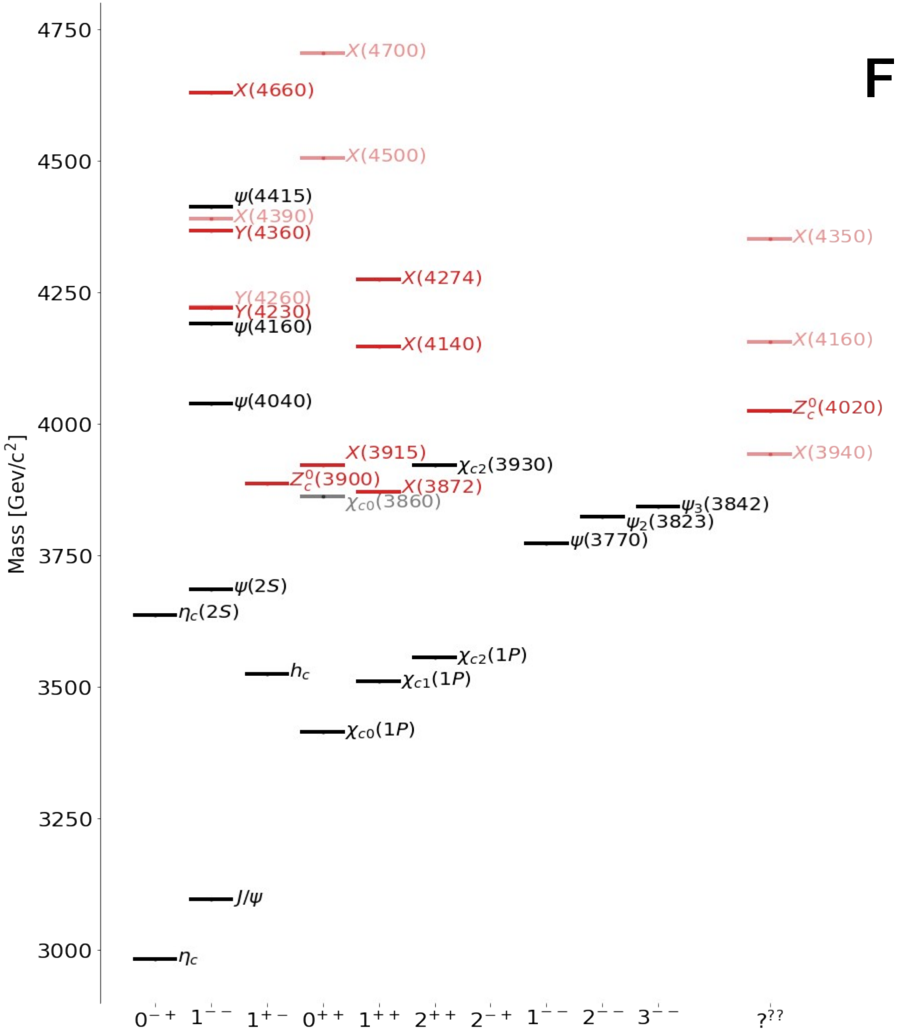


Full, neutral charmonium-like spectrum

In 15 years we discovered:

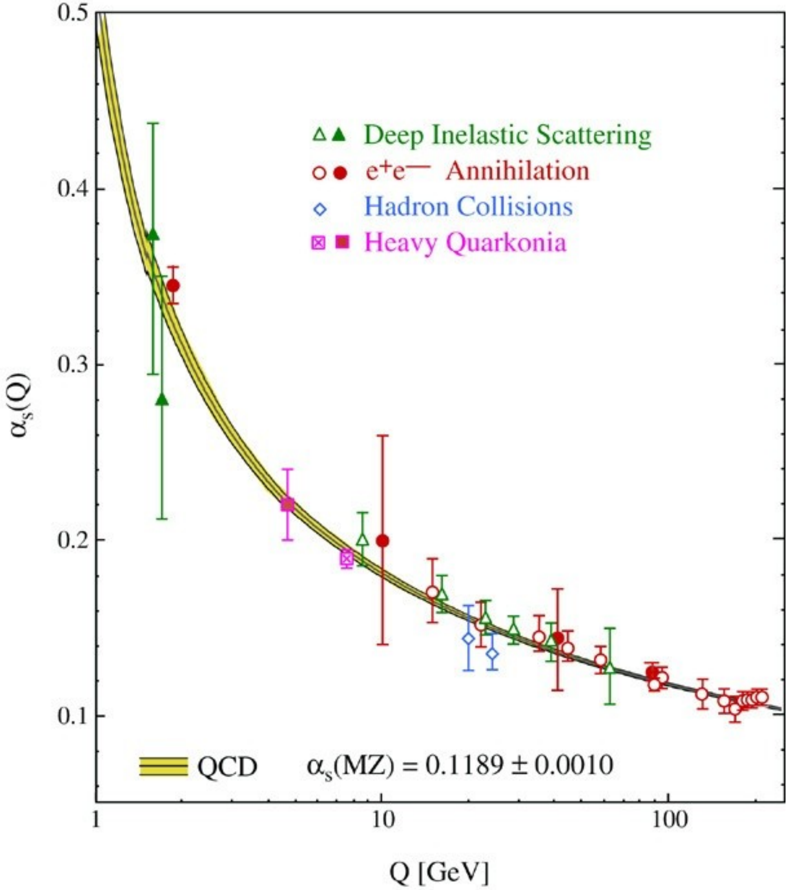
- ~30 exotics in charmonia
- 3 exotics in bottomonium
- 5 pentaquarks

The question is not if they exists, but what they are.

A theoretical summary by a non-theorist

Facing non-perturbative QCD

α_s is not a good expansion parameter to study bound states



Facing non-perturbative QCD

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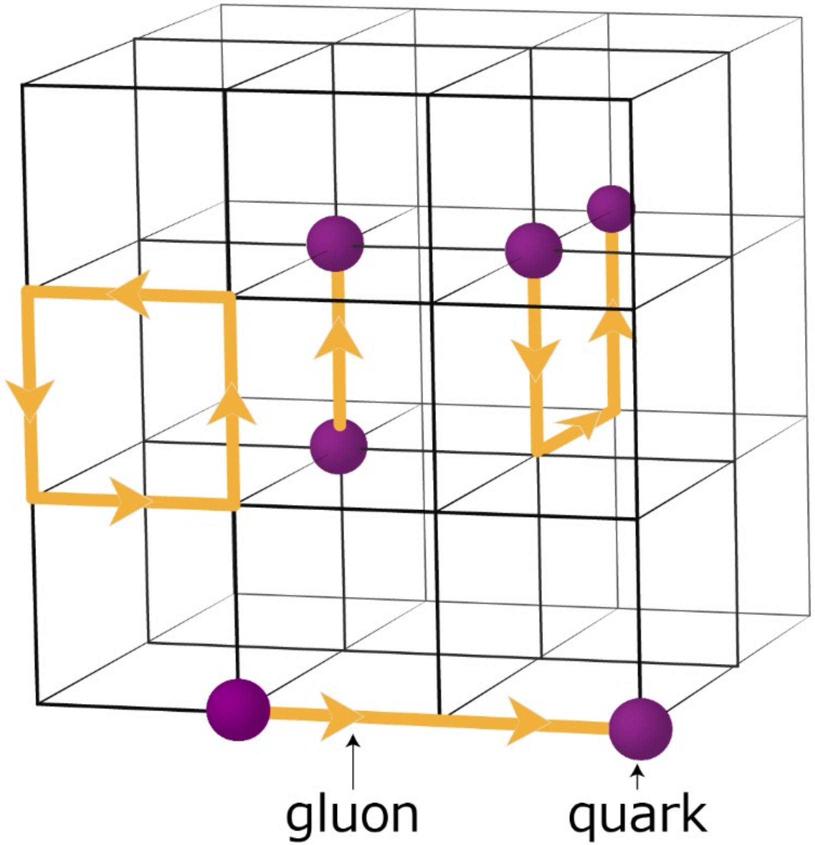
- **Solve QCD numerically (lattice)**

  [See for example Bulava et al., arXiv:2203.03230]



Facing non-perturbative QCD

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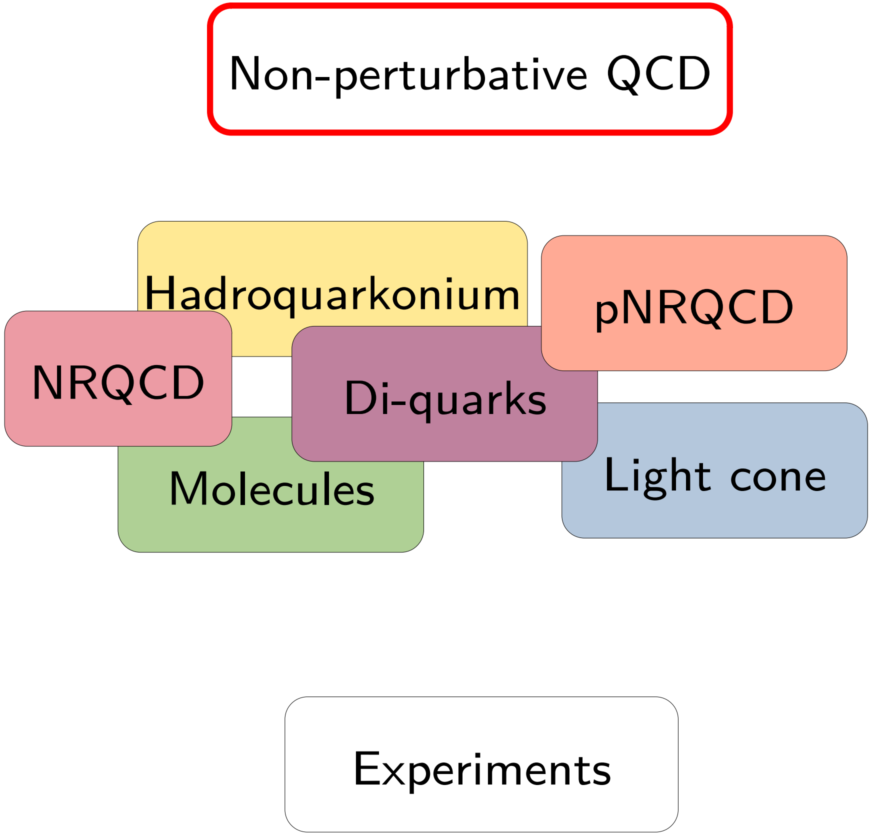
[See for example Bulava et al., arXiv:2203.03230]

- Use effective theories

[See for example Brambilla, arXiv:2111.10788]



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+

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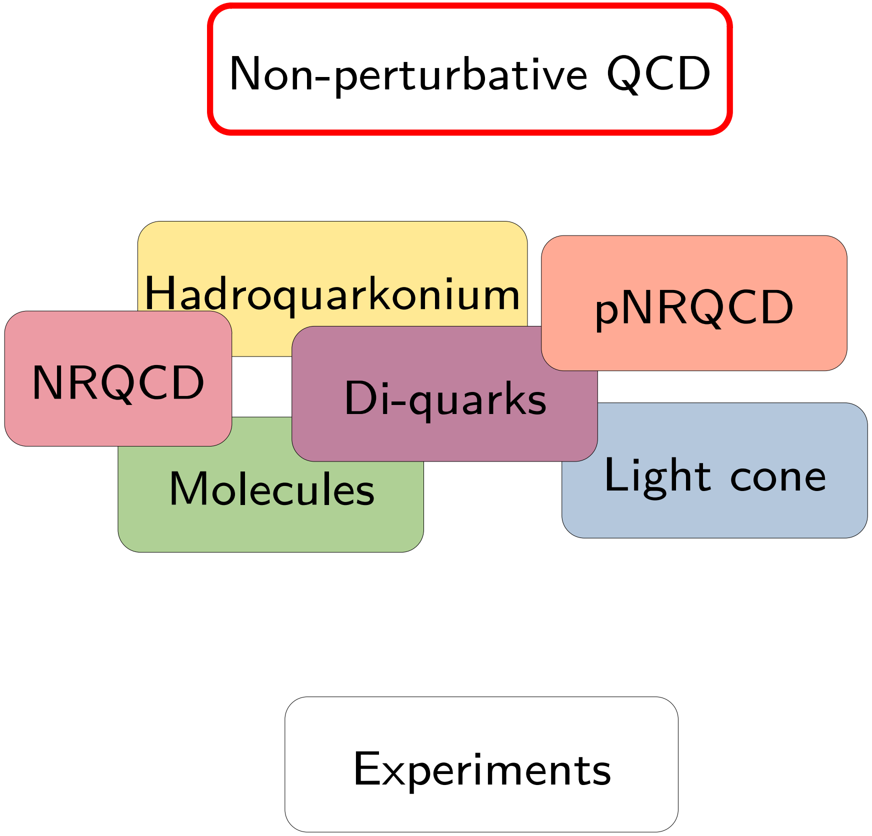
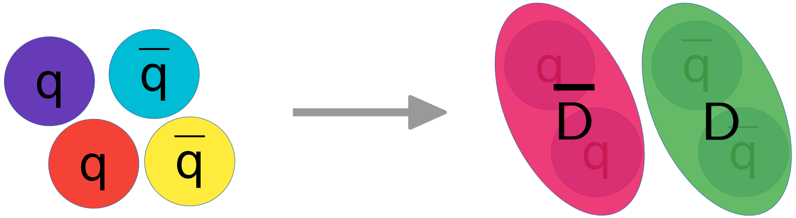


Effective models for exotica

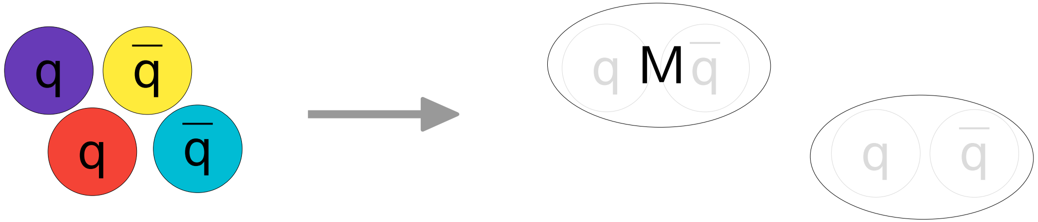


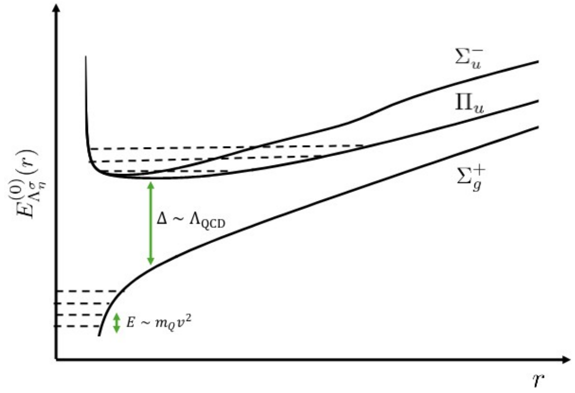
Compact tetraquarks

Esposito et al, IJMP A 30, No. 04n05, 1530002 (2015)

Meson-meson molecules

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





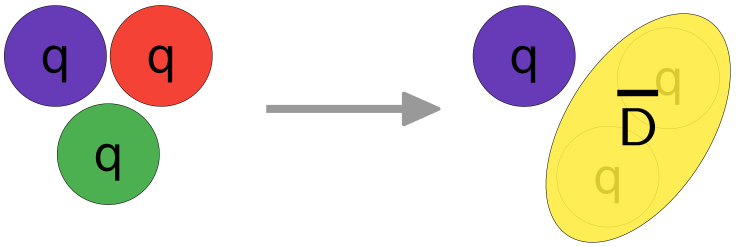
Born-Oppenheimer EFT (BOEFT)

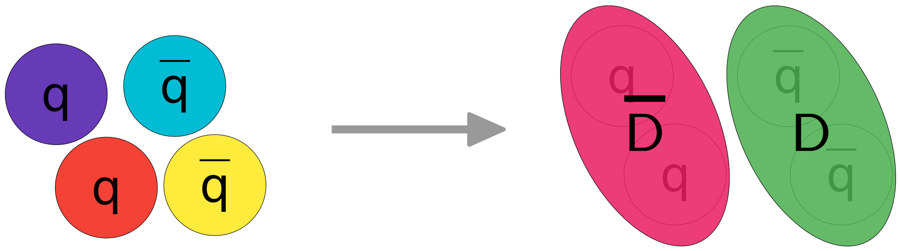
Berwein et al. arXiv:2408.04719

Competing models: compact tetraquarks

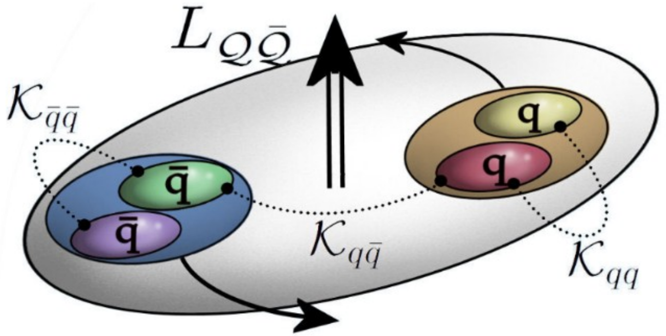
Maiani et al, Phys.Rev.Lett. 93 (2004) 212002
t'Hooft et al, Phys.Lett. B662 (2008) 424430

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



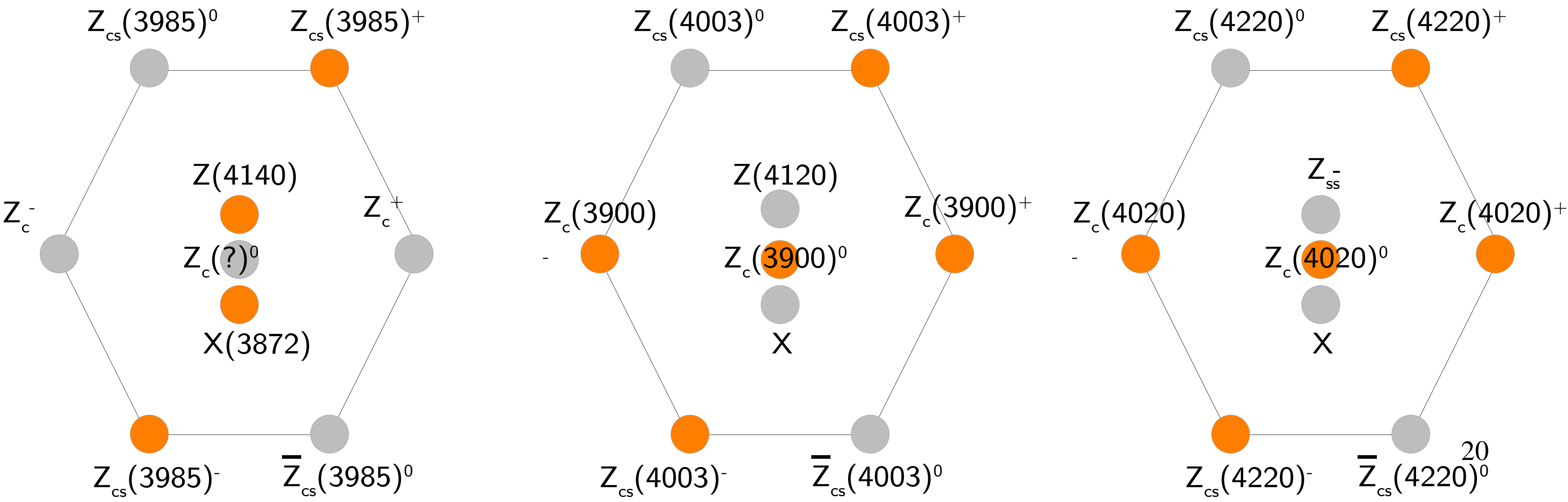
Good review about di-quarks: *Prog. Part. Nucl. Phys. 116 (2021) 103835*

Tetraquark multiplets

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

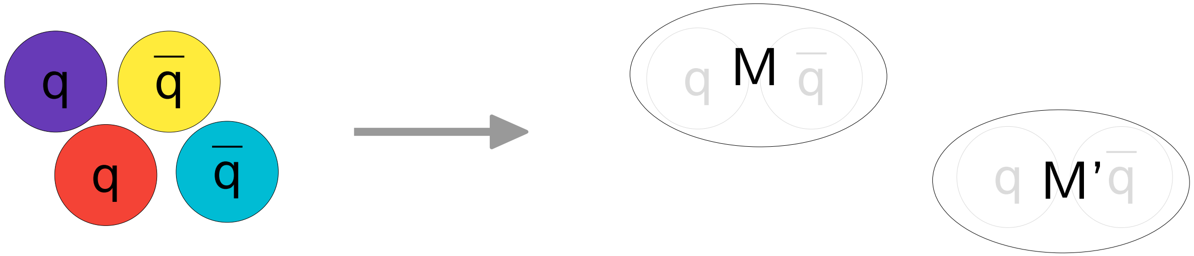


Competing models: molecules

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

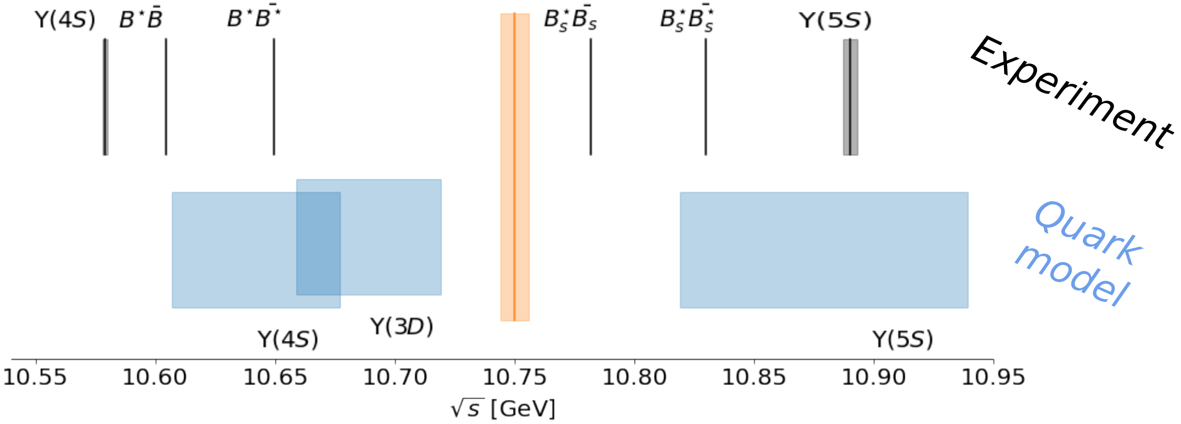


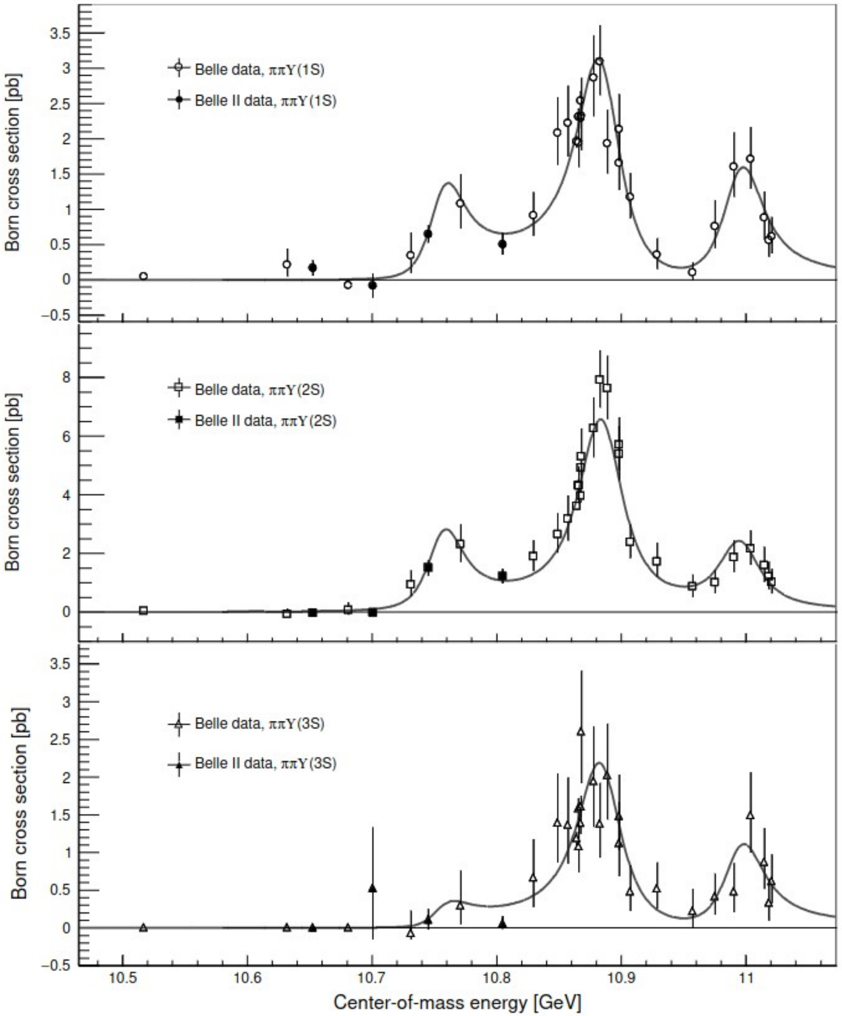
Molecules should always be close (or better below...) the threshold

Theory struggles

An example: the Υ(10753)

Unexpected vector state around 10.750 GeV





Optimal situation:

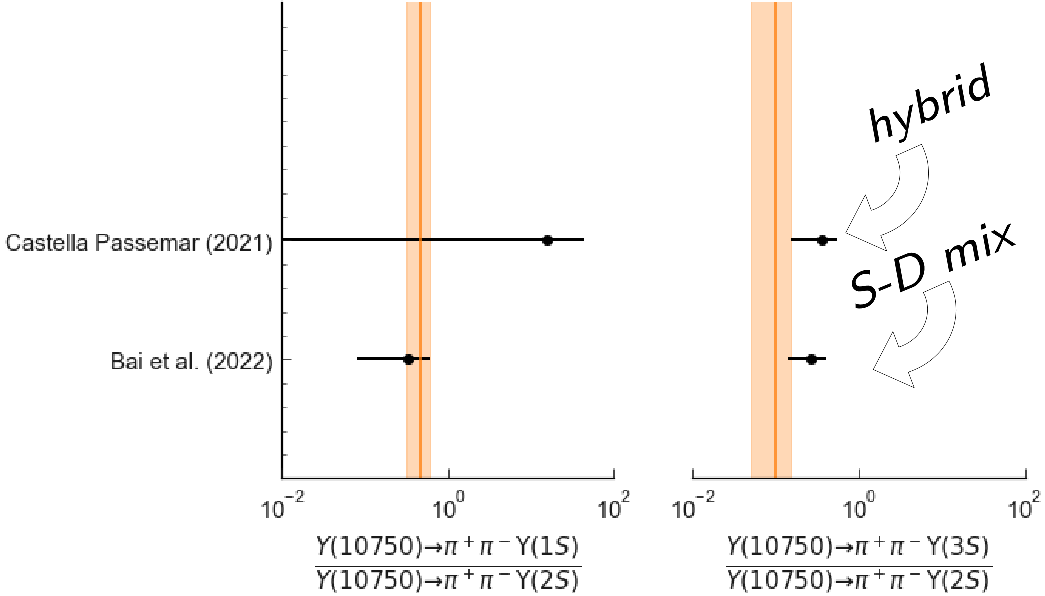
→ First discovery

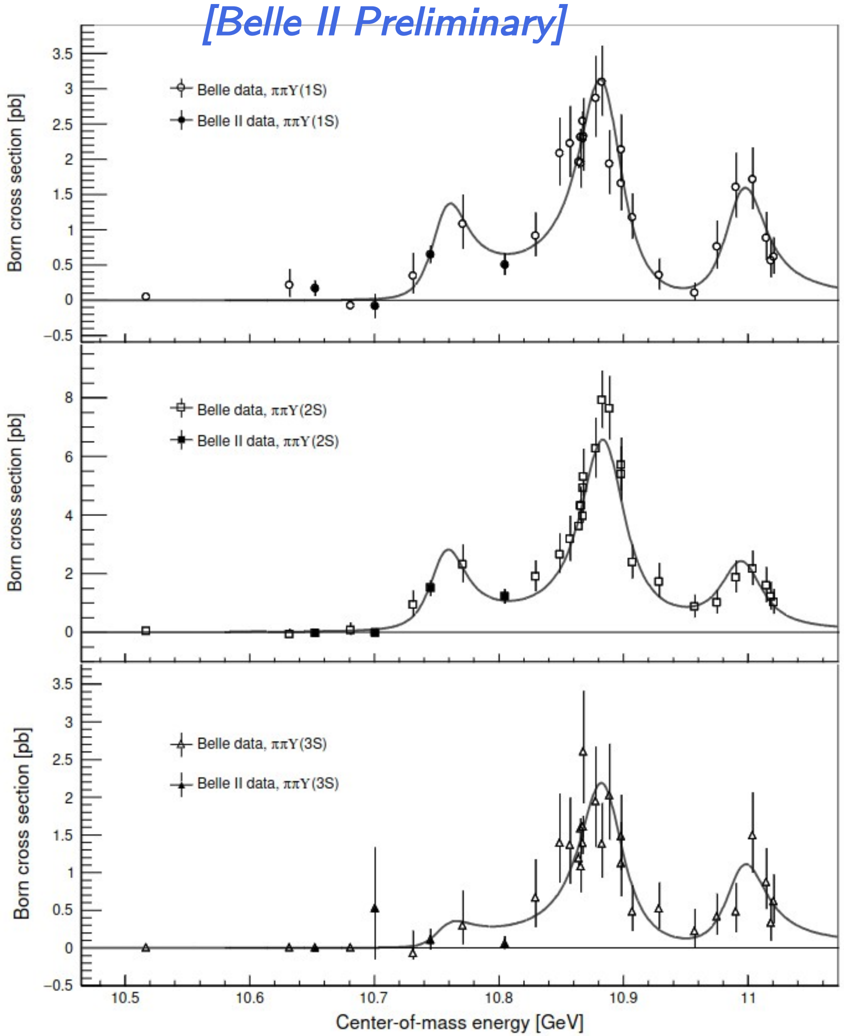
→ ~30 theoretical predictions

→ More data, more studies

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

Conventional	✓
Tetraquark	---
Hybrid	✓



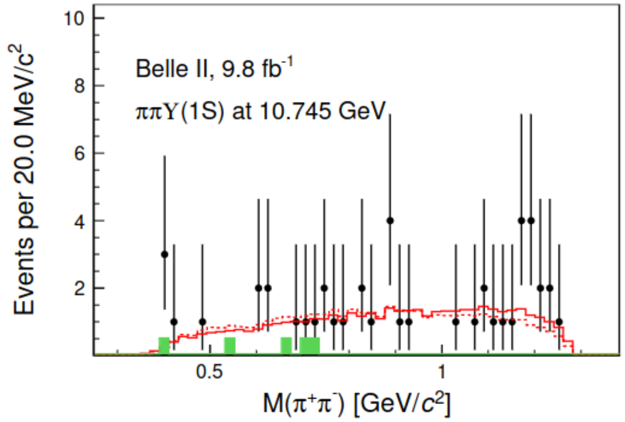


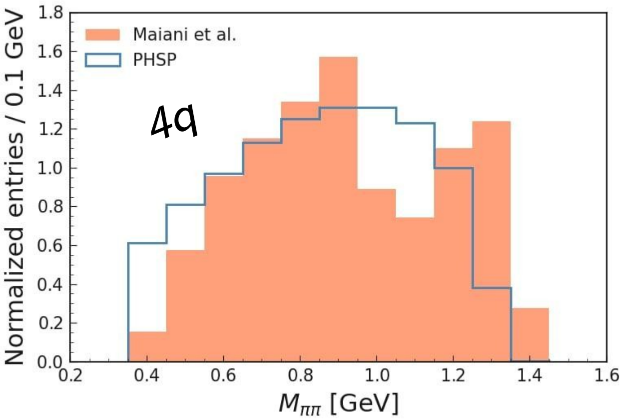
Theory VS experiment: $e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

Analysis of the di-pion mass spectrum

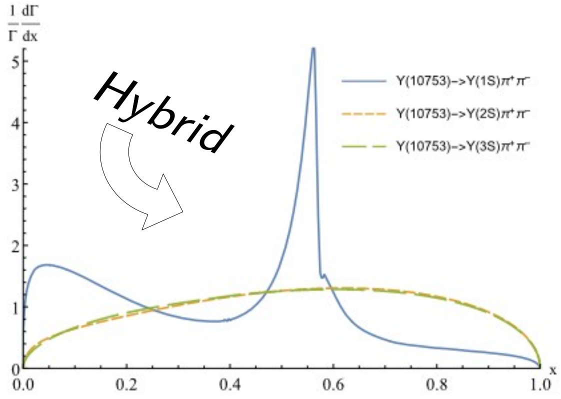
Conventional	✓	✗
Tetraquark	---	✓
Hybrid	✓	✗

[Belle II Preliminary]

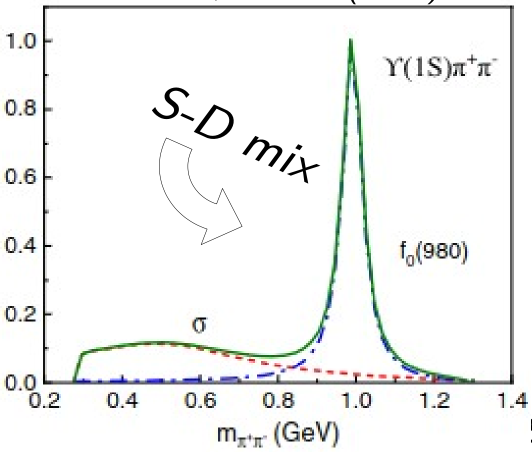




PRD 104, 0340 (2022)



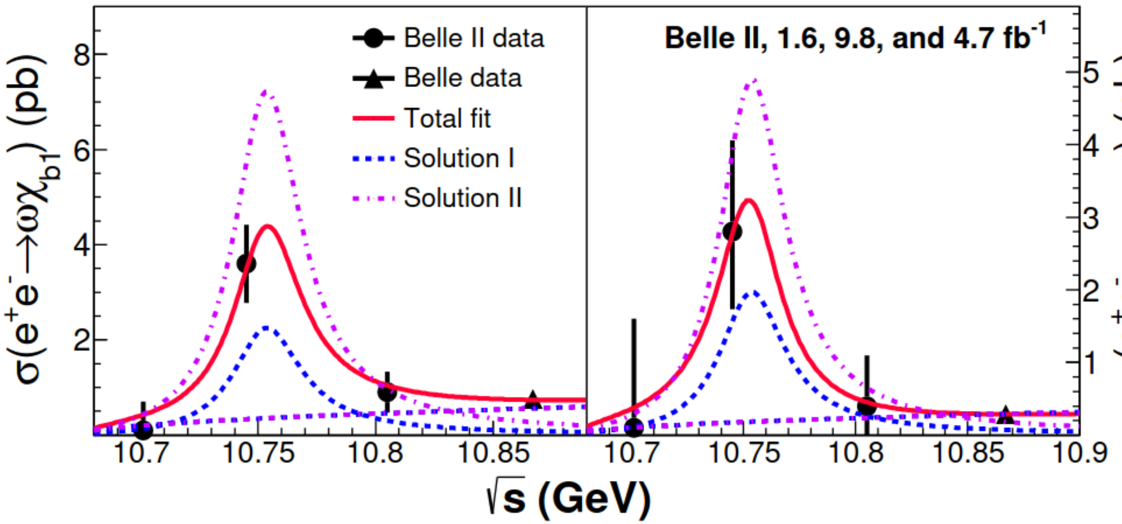
PRD 105, 074007 (2022)

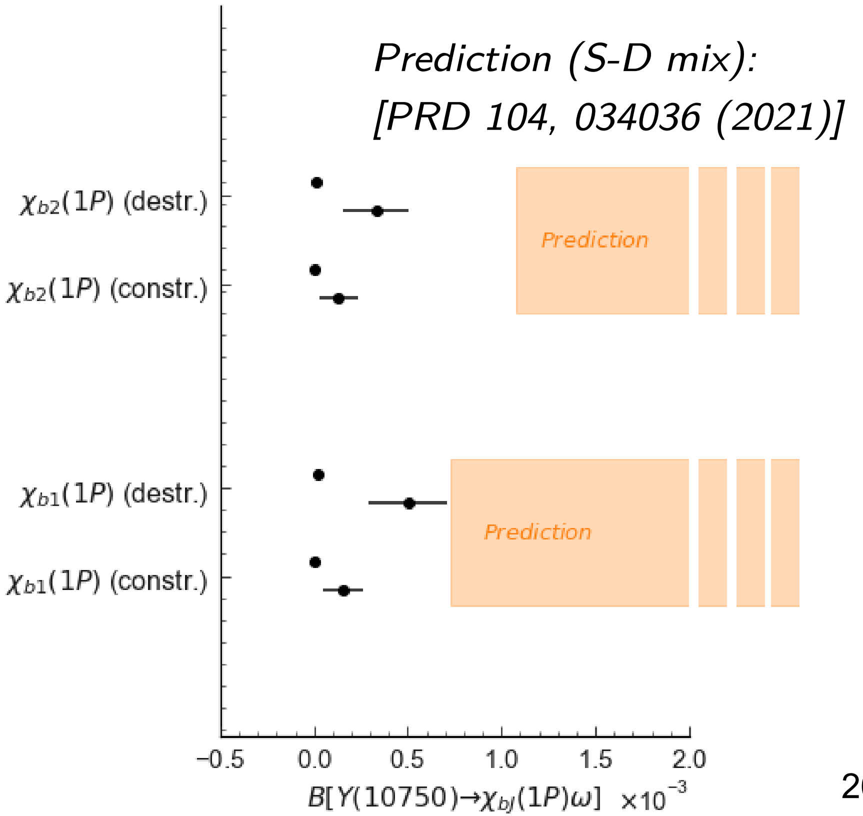


Theory VS experiment: $e^+e^- \rightarrow \chi_{b1,2}(1P)\,\omega$

[PRL 130, 091902 (2023)]

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



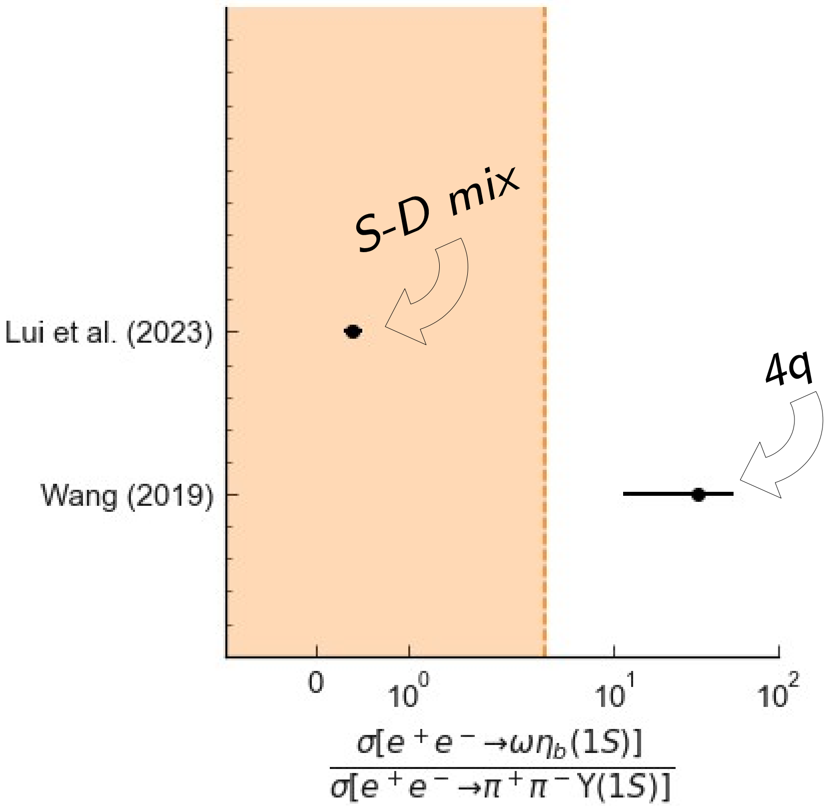


Theory VS experiment: $e^+e^- \to \eta_b(1S)\,\omega$

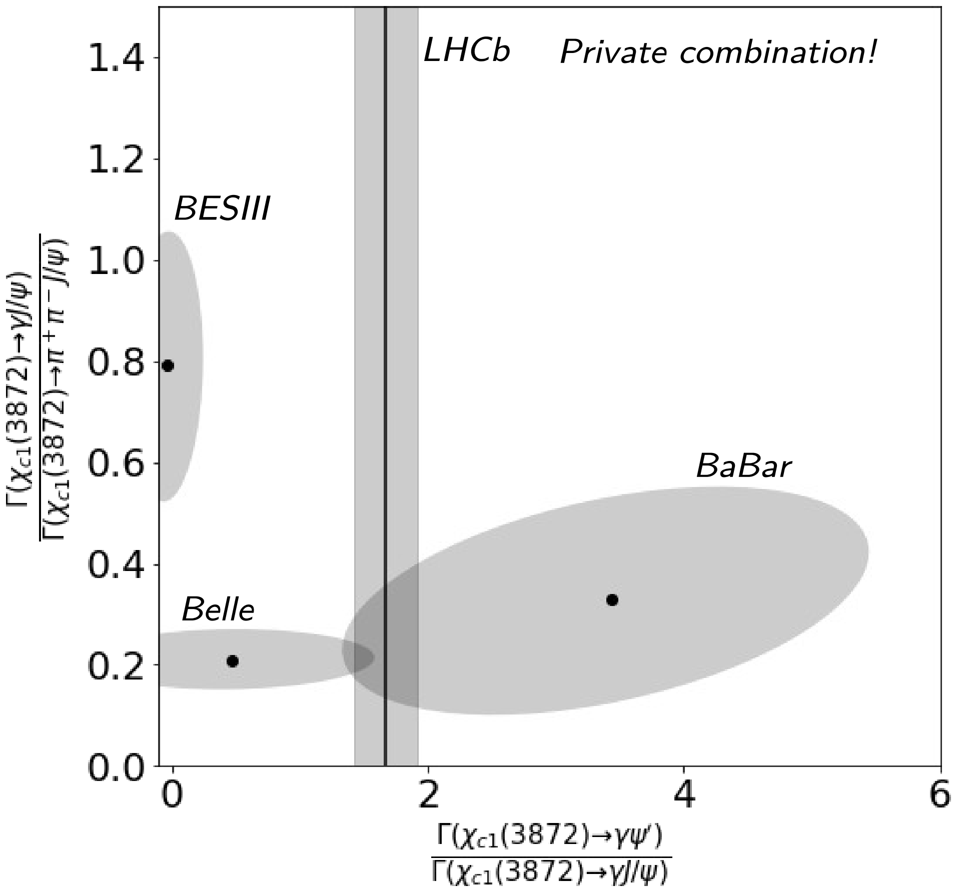
[arxiv:2312.13043]

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

So the Y(10753) is...

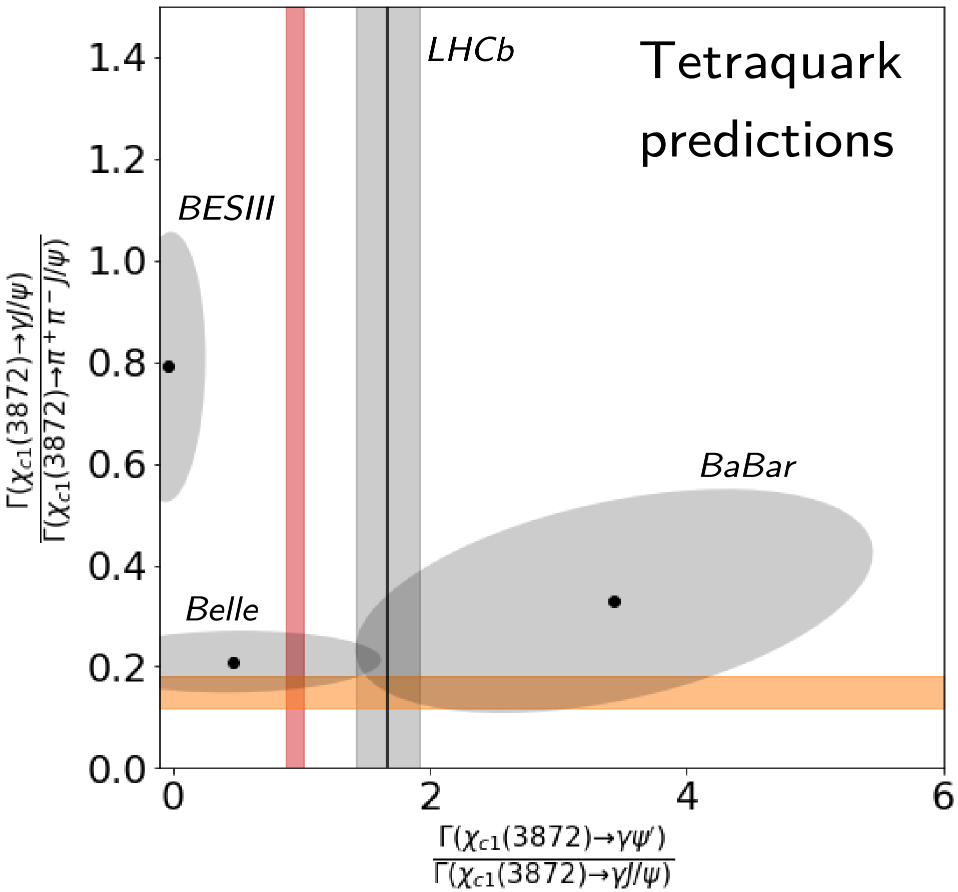


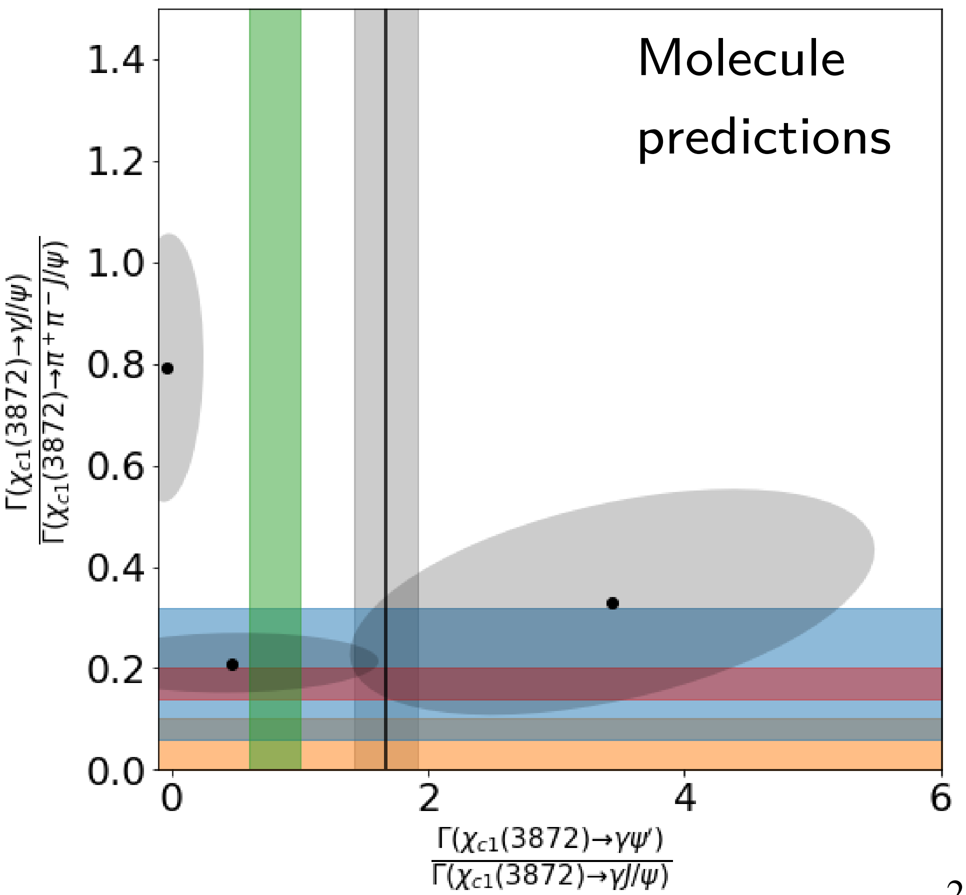
A pathological example: double struggle



Comparing two radiative decays of X(3872)

A pathological example: double struggle

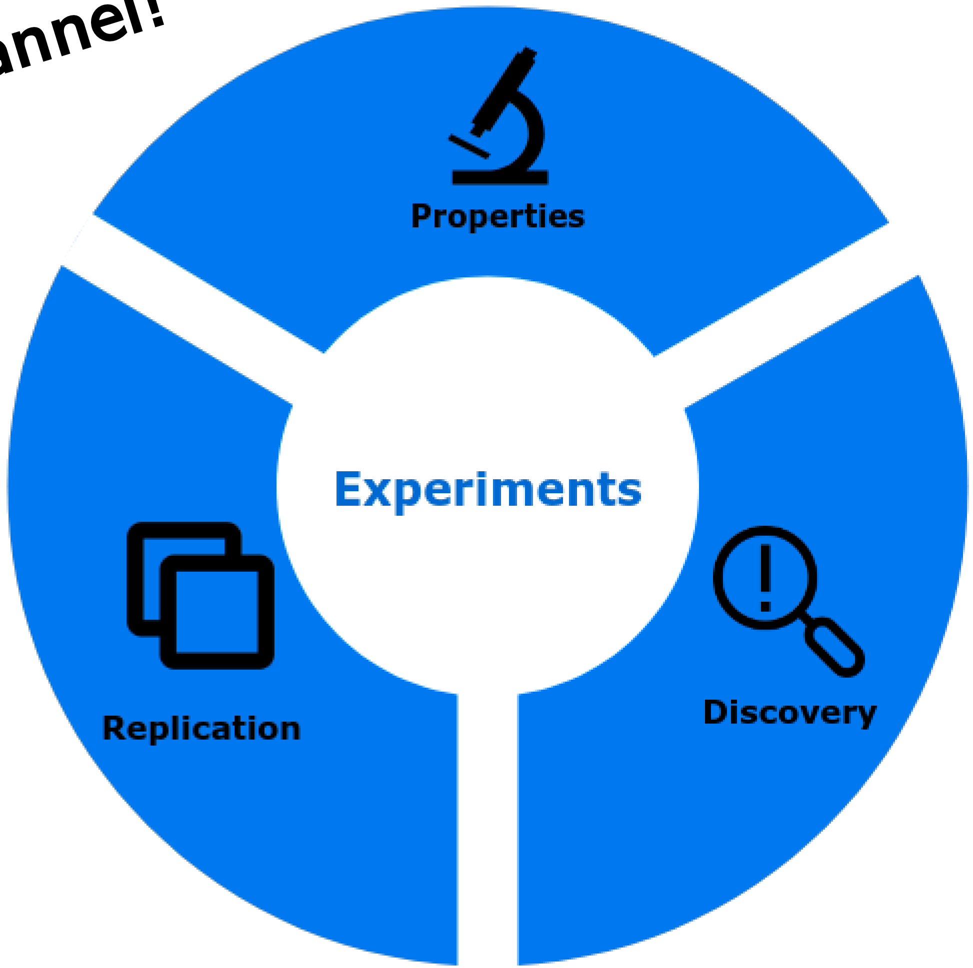




How to get out of there

What’s to be done

No golden channel!



A very personal recipe

Task 0
Replicate results!!

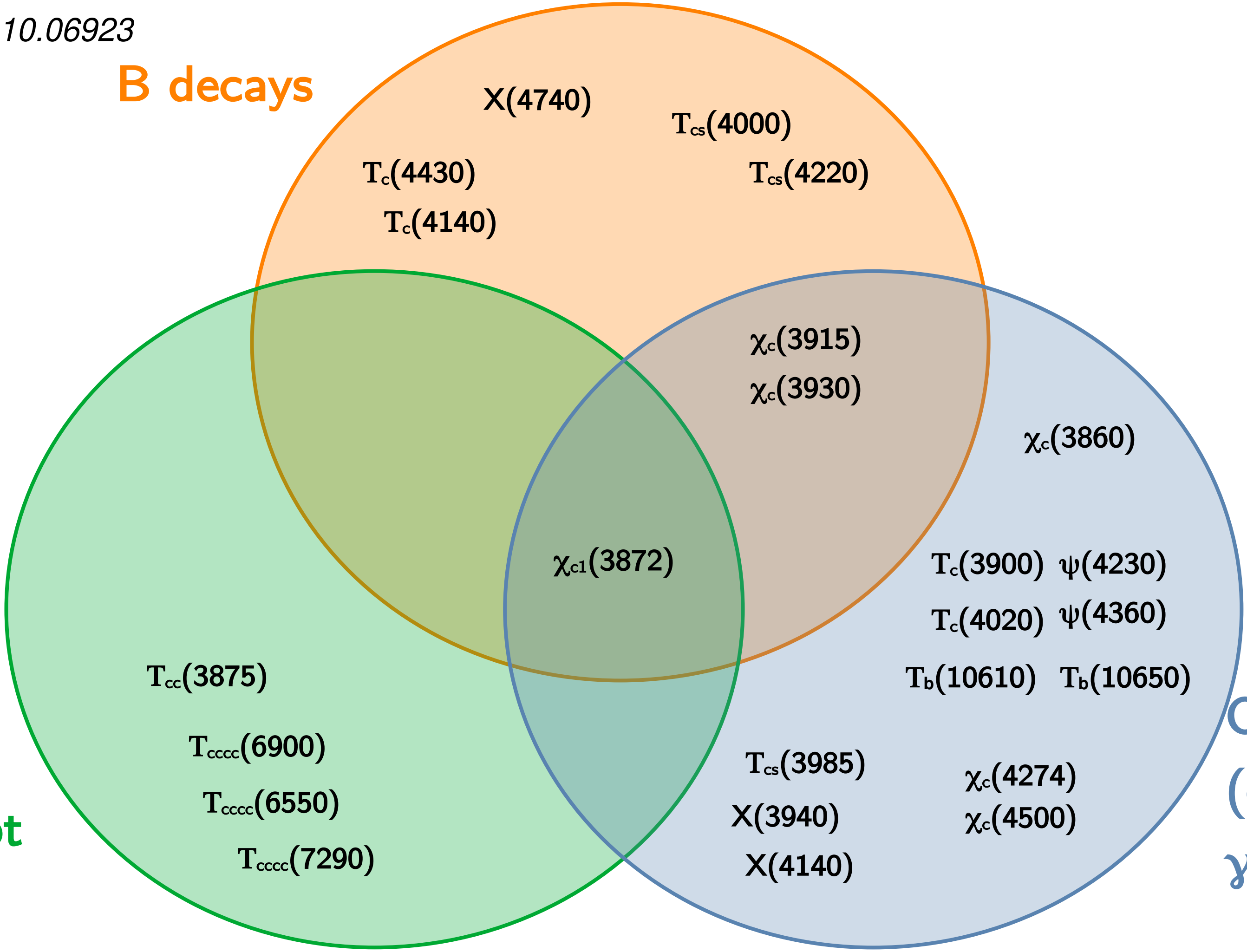
Task 1
Determine J^{PC} for all known states

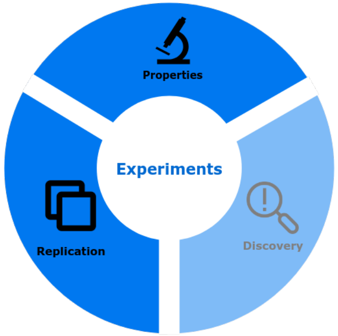
Task 2
Systematic measurement of production rates

Task 3
Exploit flavour invariance: Look at c- and b- hadrons together

Production and replication

Based on arXiv:2410.06923





The single-observation nightmare

Many states have been seen in either

$\rightarrow$ 1 decay mode only

$\rightarrow$ 1 production mode only

$\rightarrow$ 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)]*

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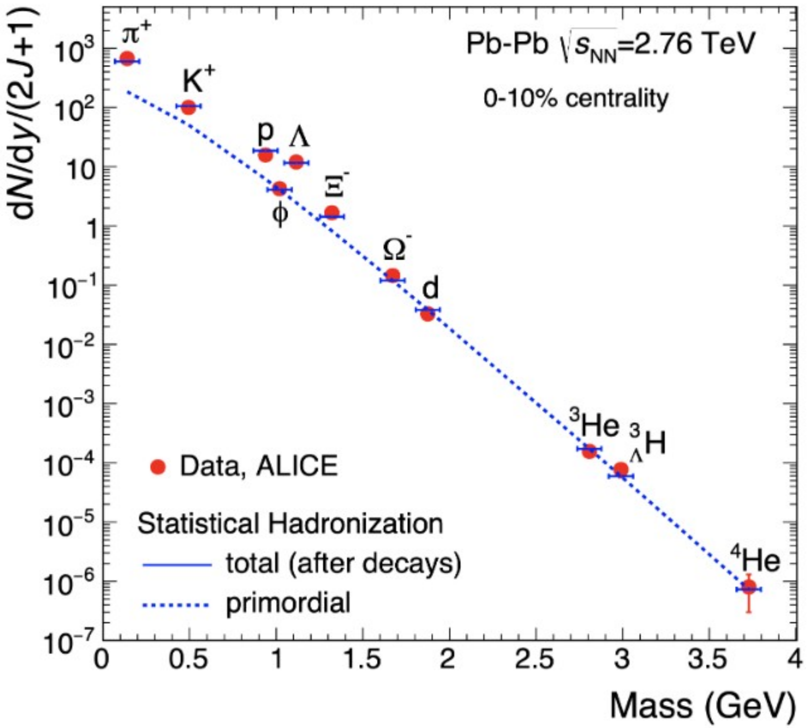
Prompt production of molecules

Deuteron has been observed in heavy ion collisions

$\rightarrow$ How can it survive such a hot environment?

$\rightarrow$ Melting and recombination?

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



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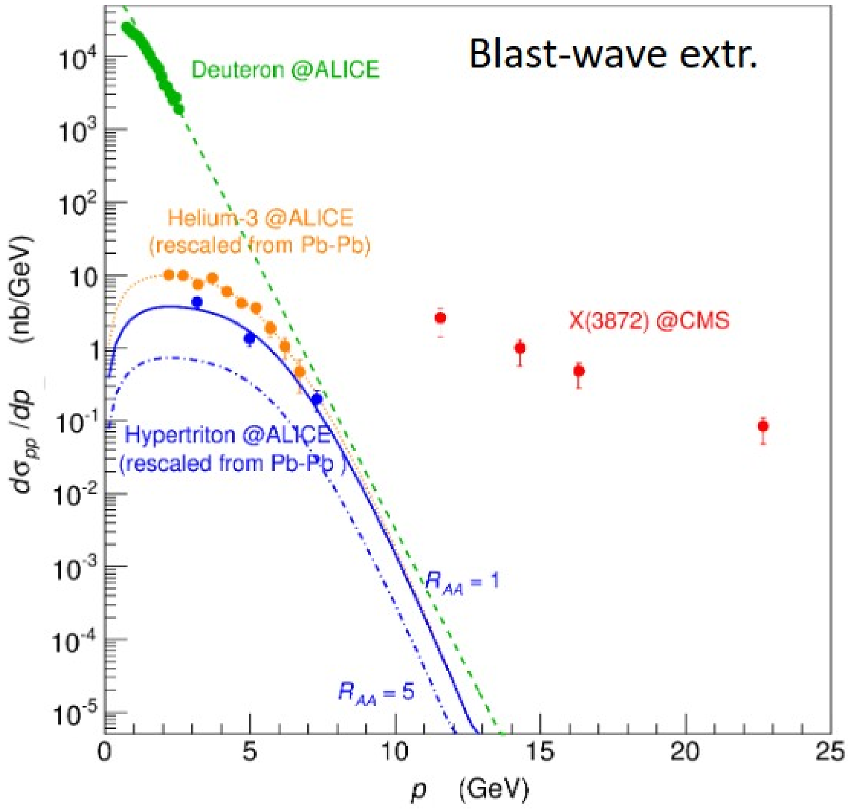
Heavy exotica: never observed (except for X3872)

→ Why we don't see prompt exotica?

→ Why is the rate of X(3872) so different from other molecules?



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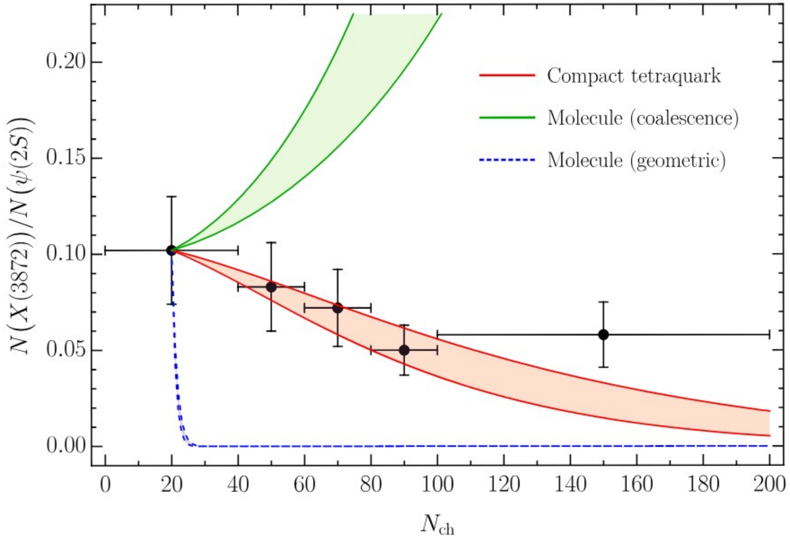
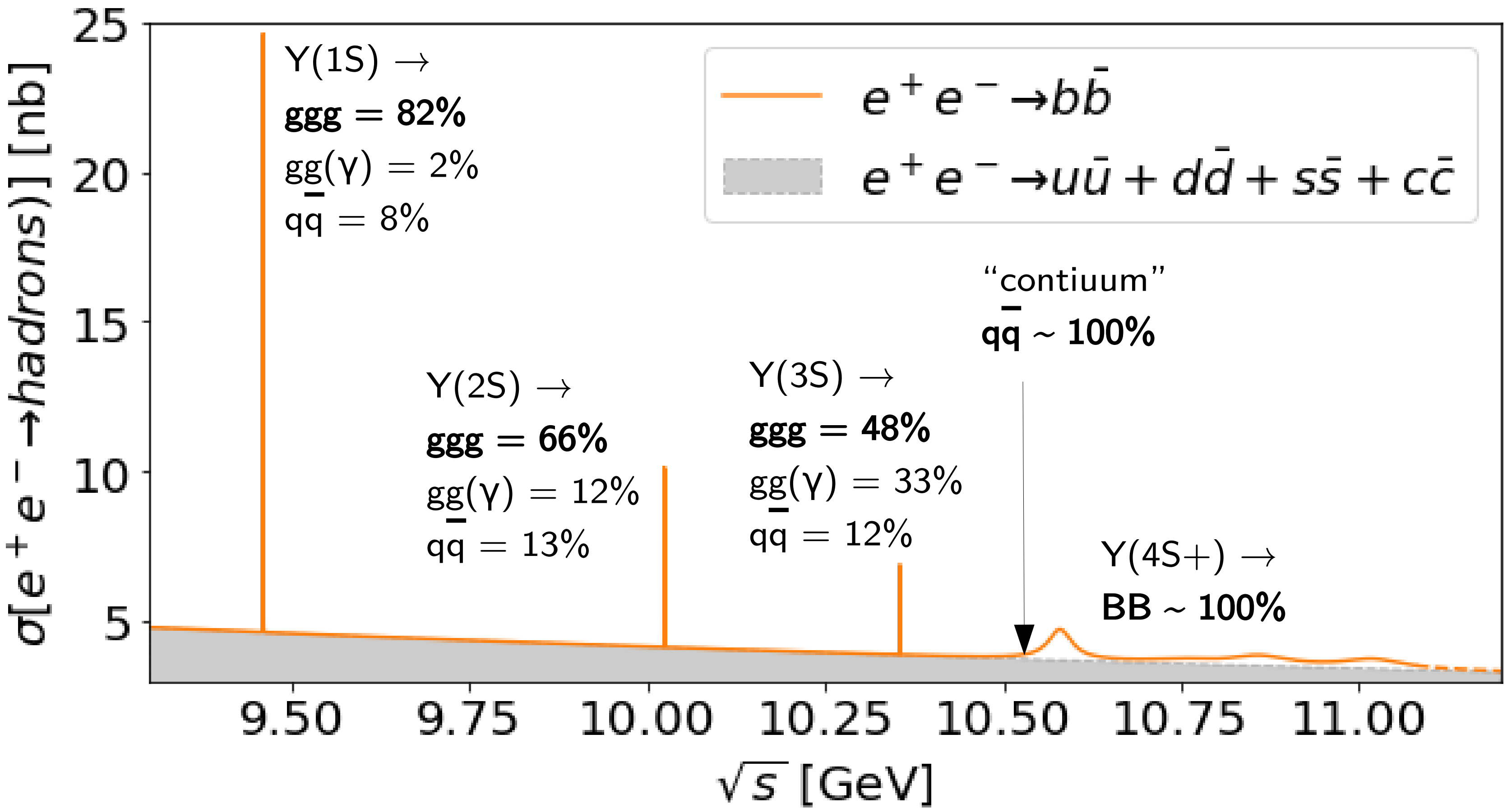


Striking (?) differences in the production of compact or loose states *[EPJ C81, 669 (2021)] [arXiv:2302.03828]*

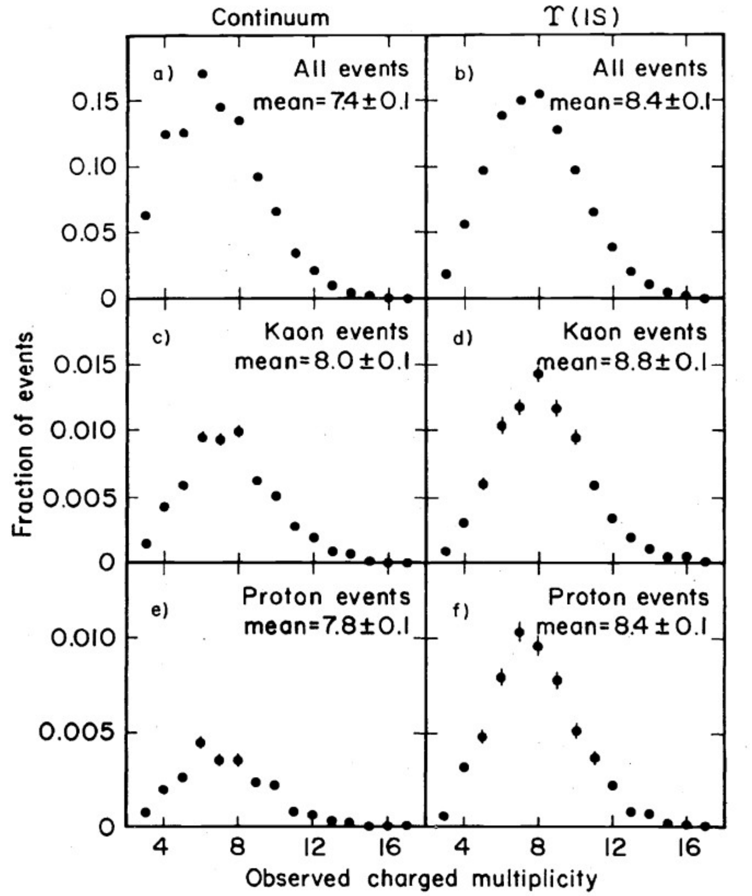
e^+e^- collisions energies



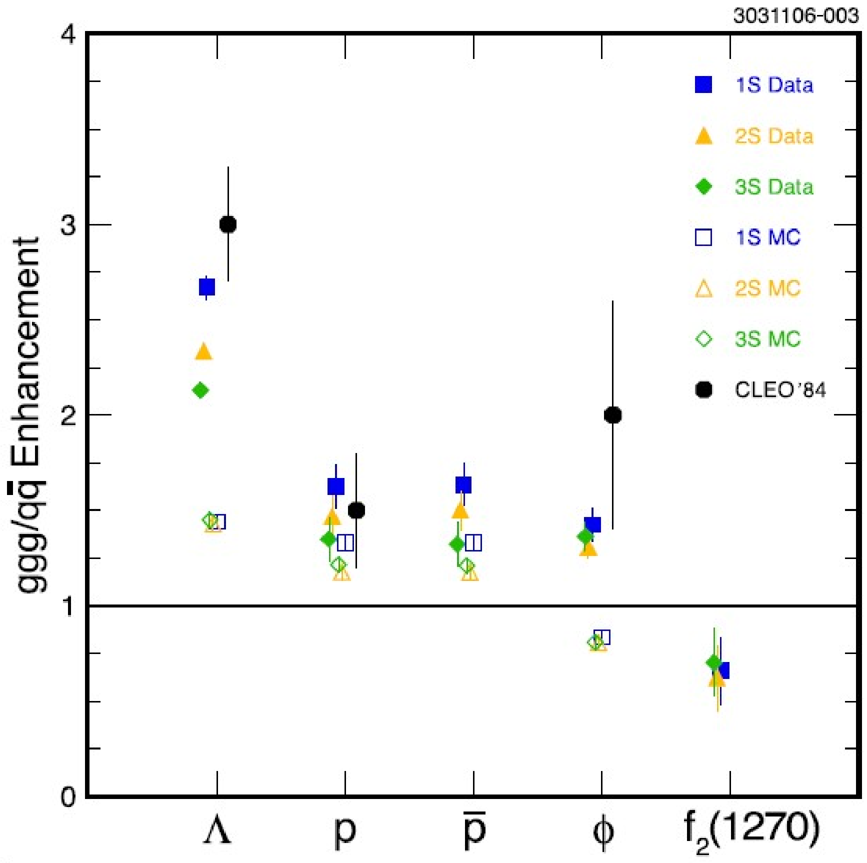
σ = 1 nb → 1-2 Million events/day @ current Belle II luminosity

$e^+e^- \to ggg/q\bar{q}$ environments

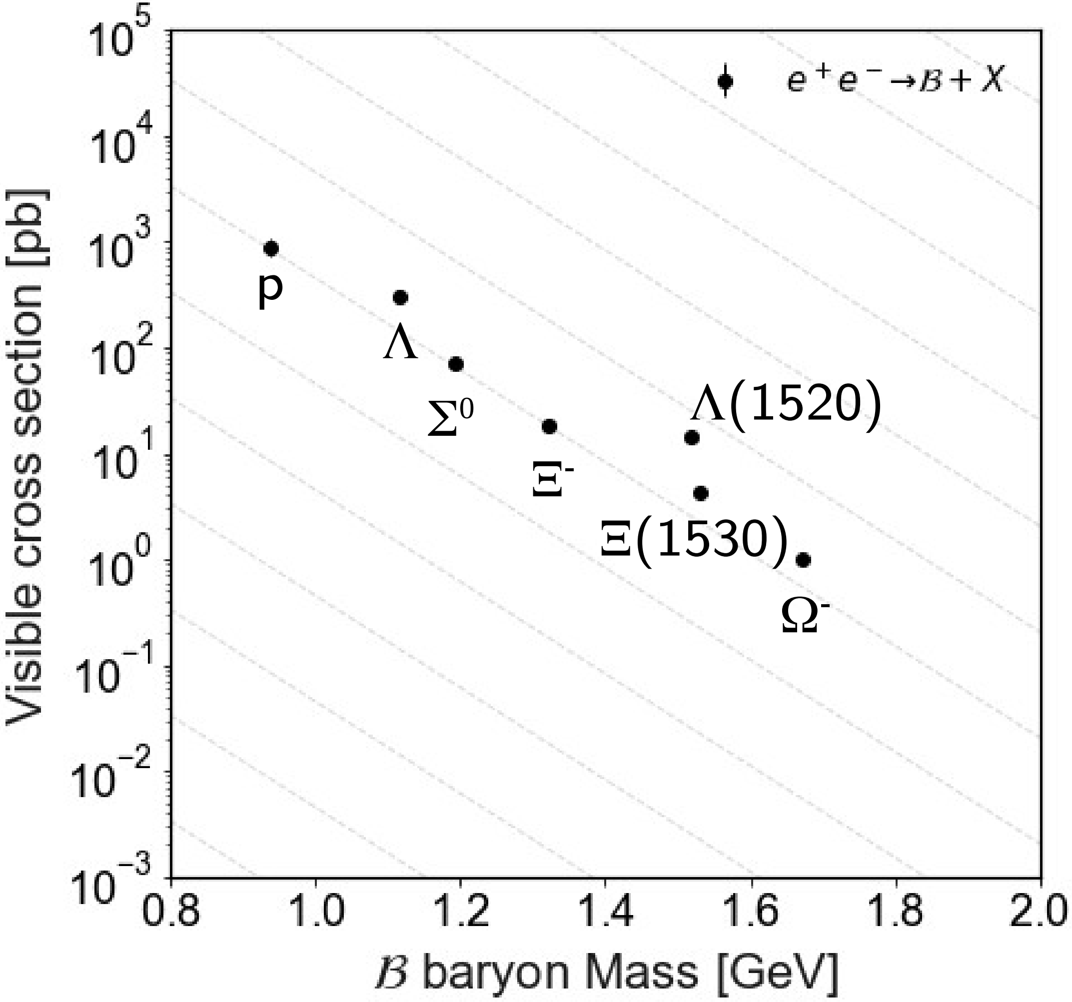
[PRD 31, 2161 (1985)]



[PRD76 012005 (2007)]



A laboratory for hadron coalescence?



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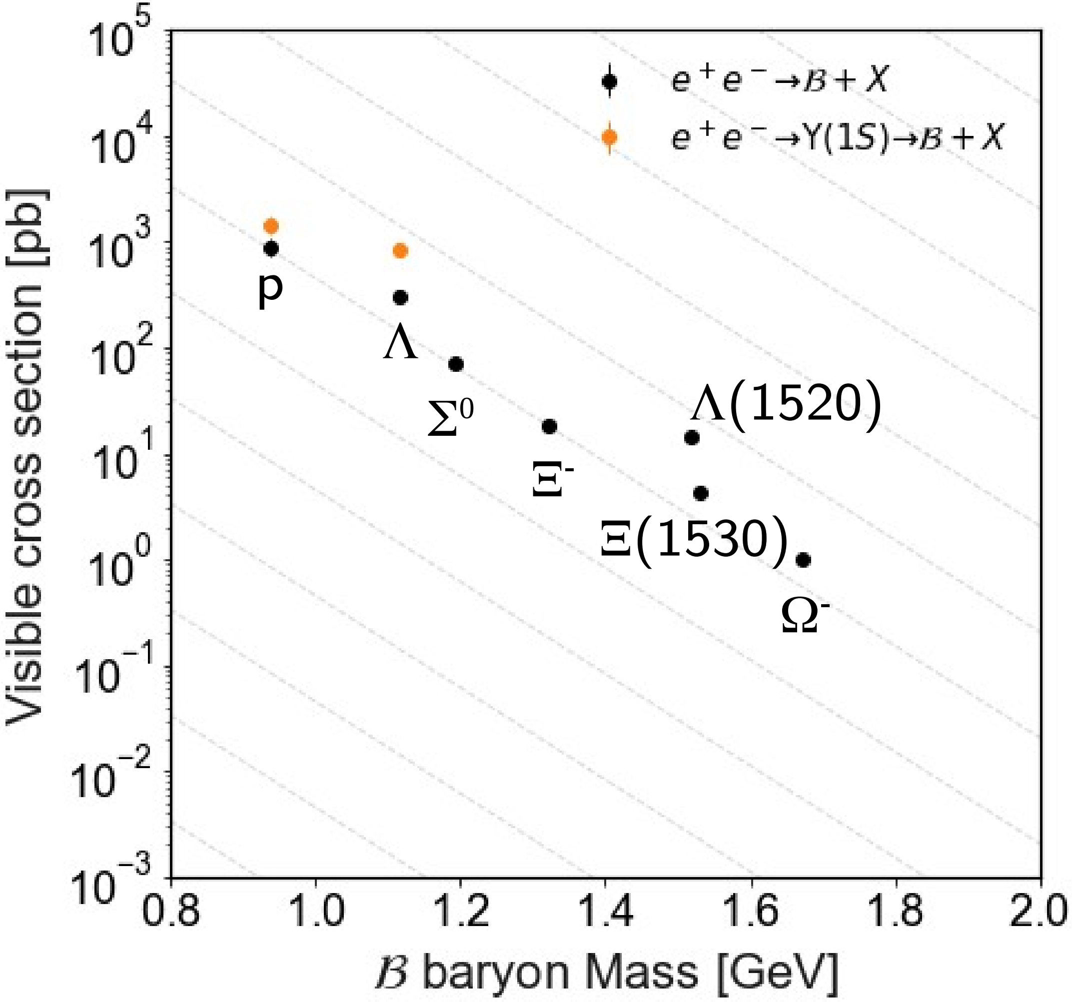
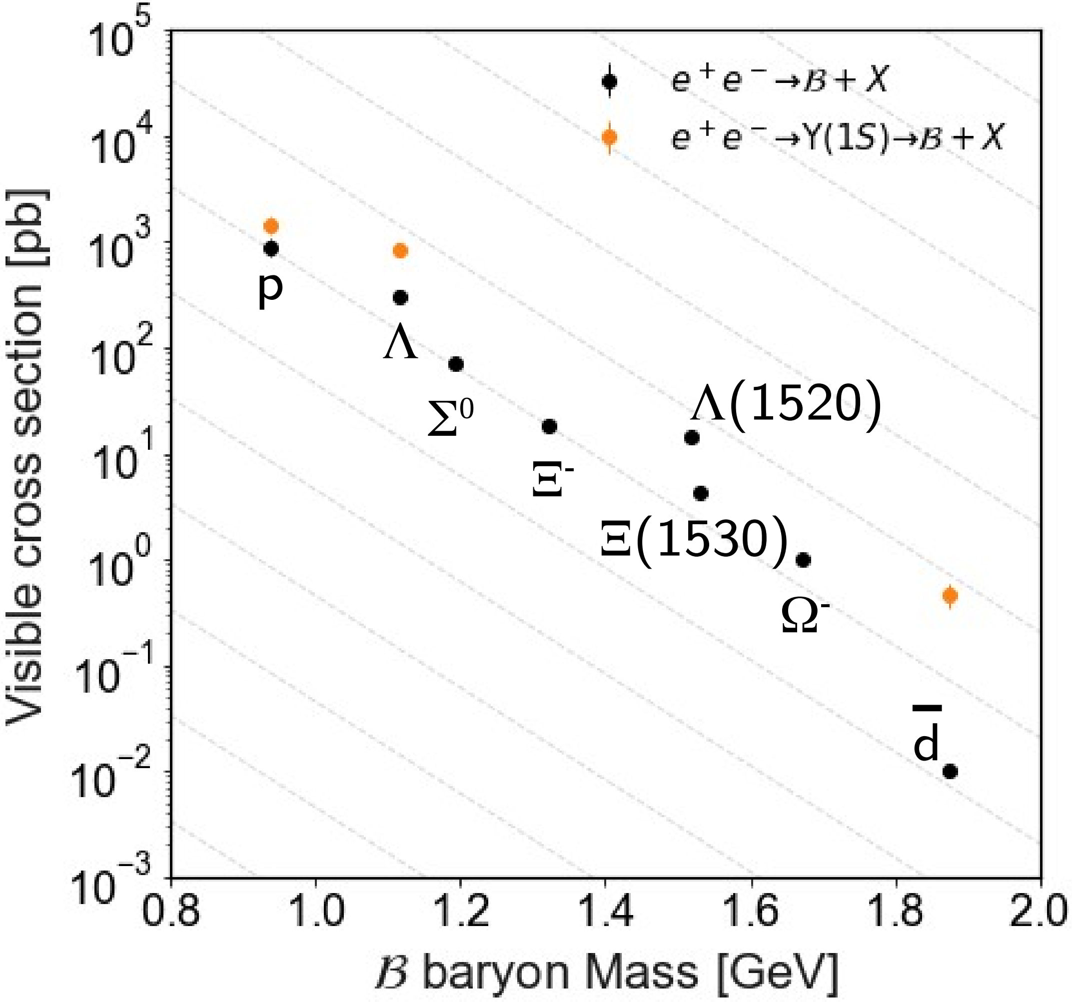


*) piecing together many measurements

A laboratory for hadron coalescence?



p → d Penalty factors:

∼ 30000 in continuum

∼ 1000 in Y(1S)

Explained (mostly) by kinematic effects (2-jet VS spherical events)

*) piecing together many measurements

Predicting a molecule production rate

Coalescence: the molecule is created by **merge of its constituents**

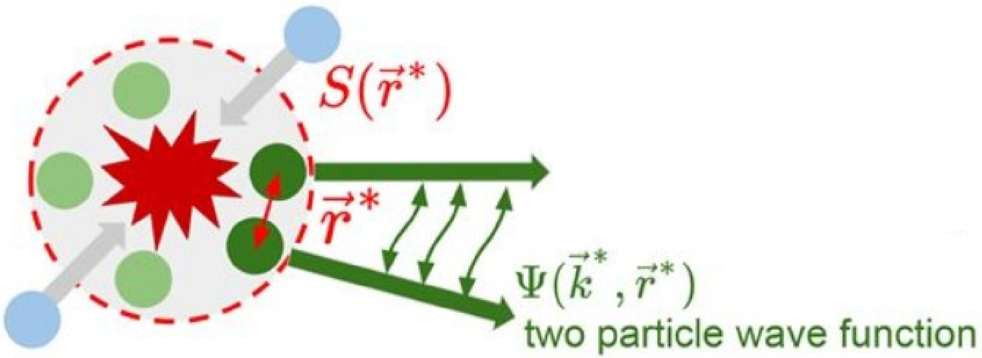
We need three ingredients to calculate the coalescence probability:

- The spatial size of the emitting source

- The molecule's wave function

- The kinematic of its components

In QGP: take also into account dissociation and recombination...



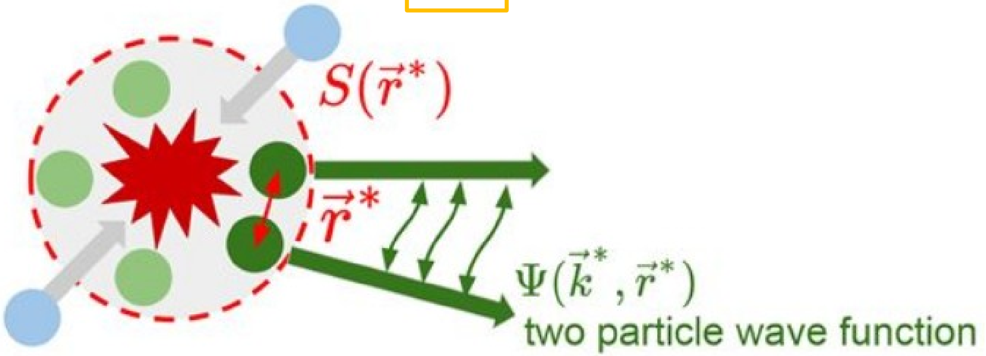
Predicting a molecule production rate

Coalescence: the molecule is created by **merge of its constituents**

We need three ingredients to calculate the coalescence probability at Belle II:

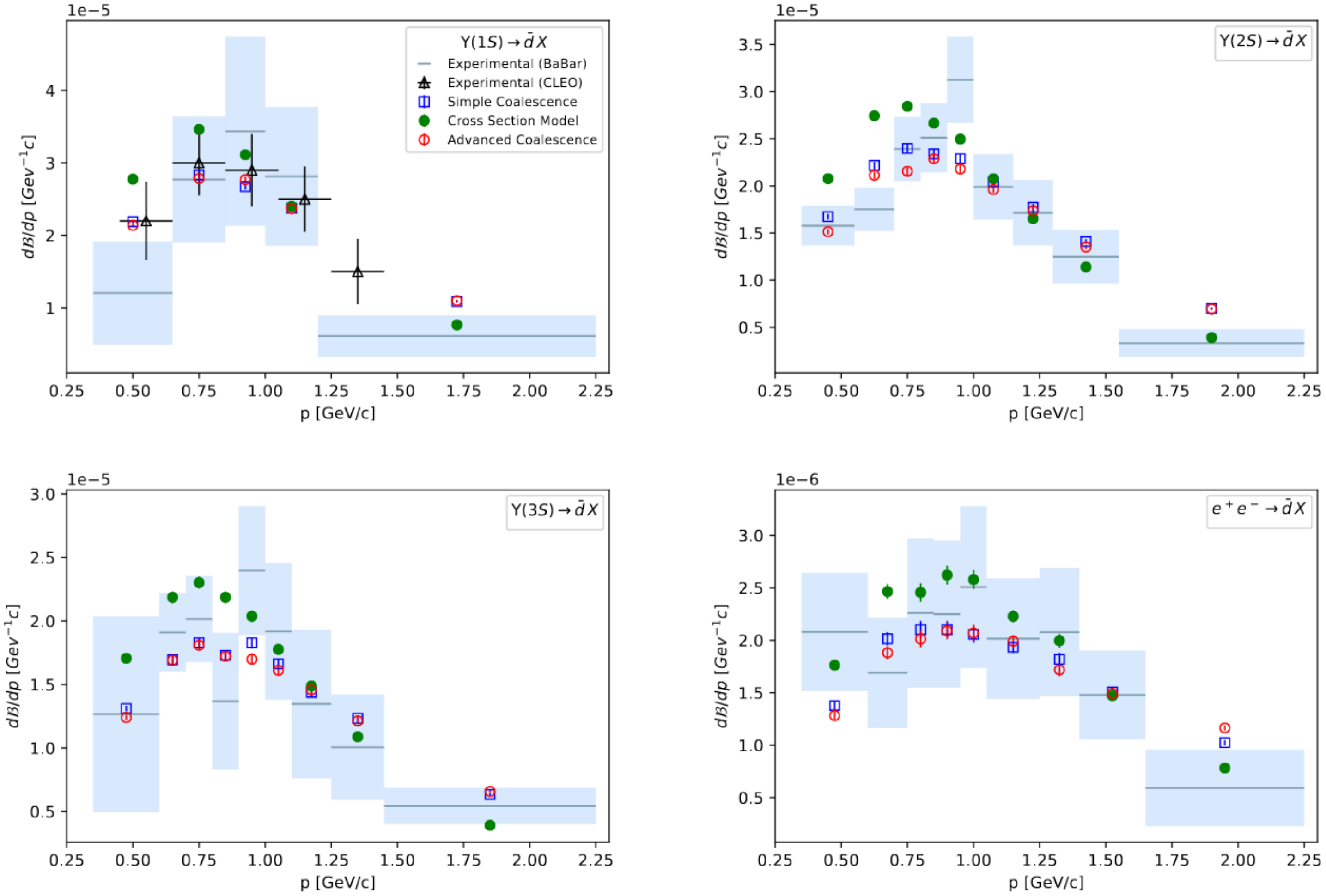
- The spatial size of the emitting source :-(
- The molecule's wave function :-)
- The kinematic of its components :-|

~~In QGP: take also into account dissociation and recombination...~~



Benchmarks: anti-deuteron

[Marietti, Pilloni, UT, PRD 106 (2022) 9, 094040]



- All models describe the data
- Overshoot by the cross-section-based model?

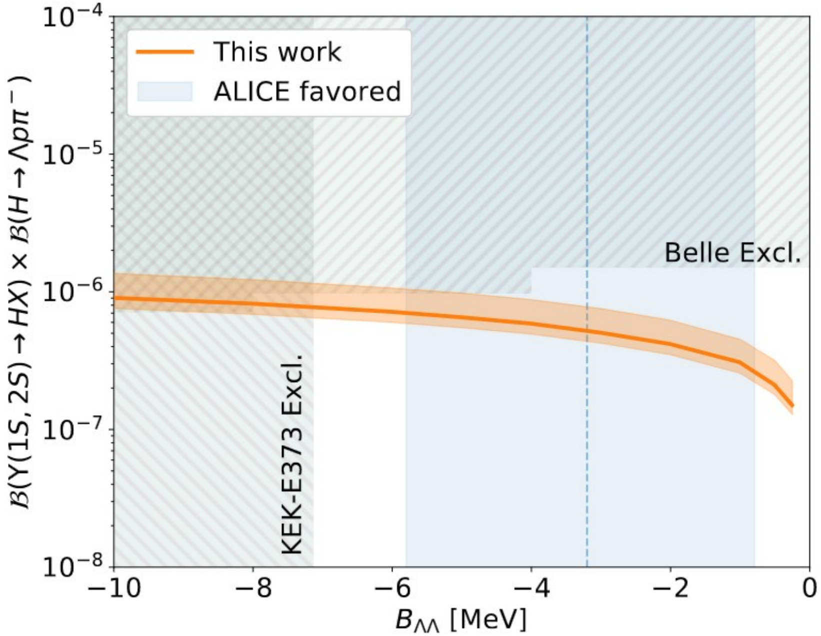
Existing measurements: $\Upsilon(1S) \to$ exotica

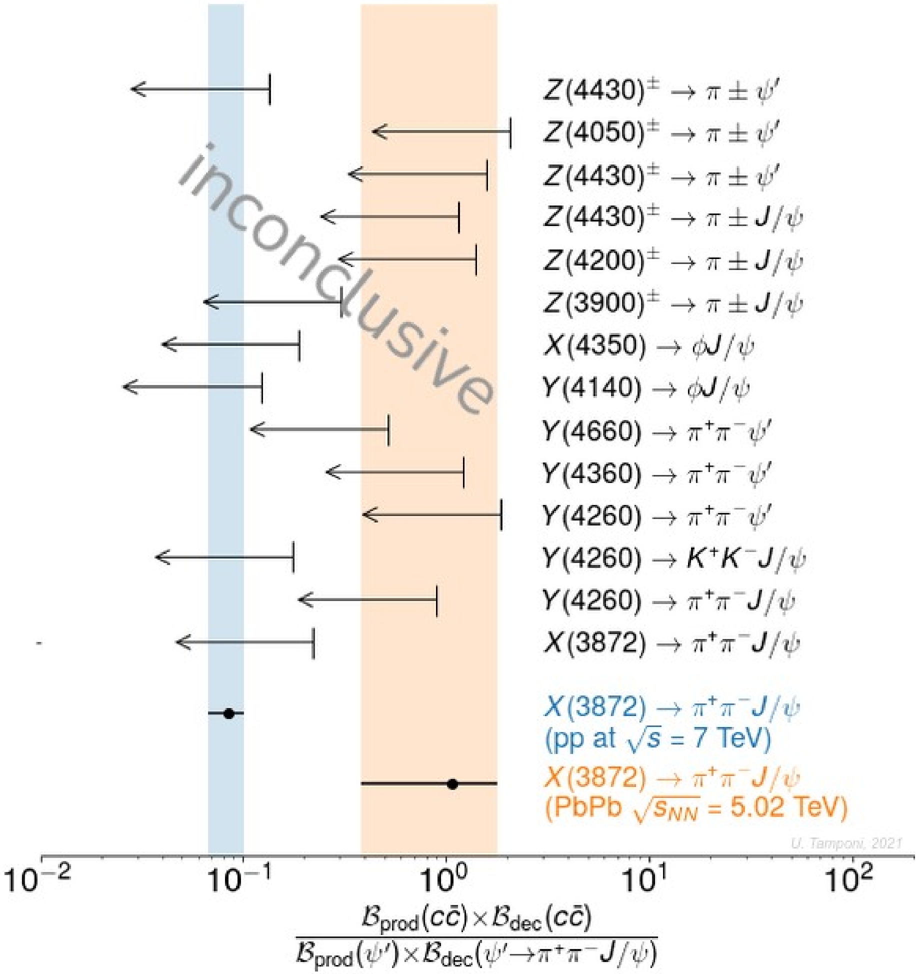
Heavy Exotica

→ Searched in Υ(1S)

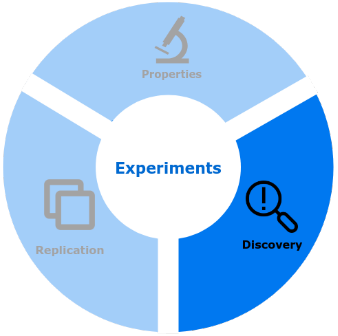
→ None observed, not even X(3872)

[Marietti, Pilloni, UT, PRD 106 (2022) 9, 094040]





Exploit bottomonium



Patterns seen with charm should repeat with b-quark

→ Smaller relativistic corrections

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

→ **Only 2 (3?) exotica known there!**

Experimentally challenging

→ Only prompt production at LHC

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

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

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

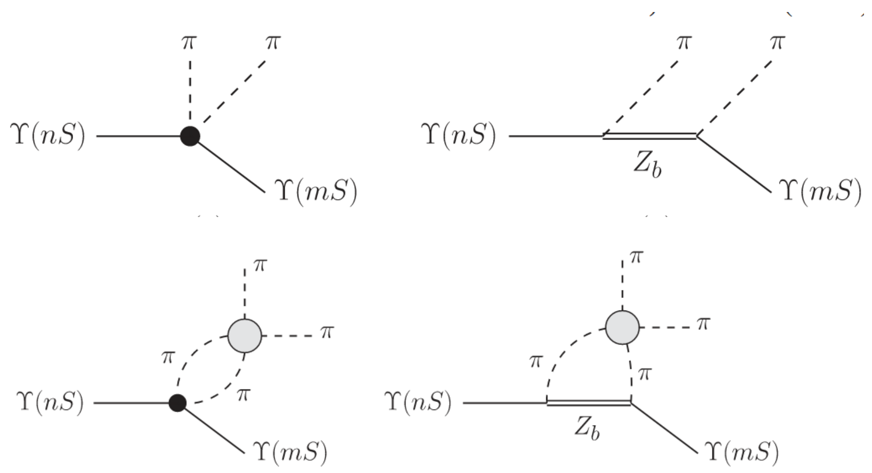
→ Ecm @ Belle II limited to ~11 GeV (threshold for T_{bb} ~ 19-20 GeV)

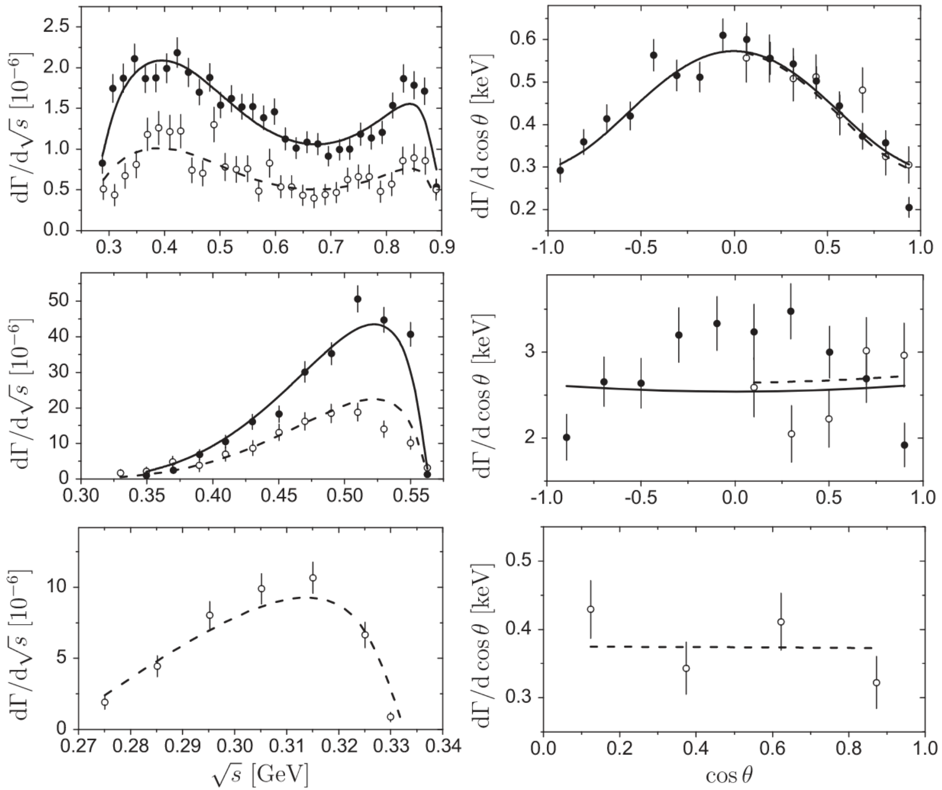
Hidden exotica

Exotic stats contribute to the transitions from narrow quarkonia?

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

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





Bottomonium exotica

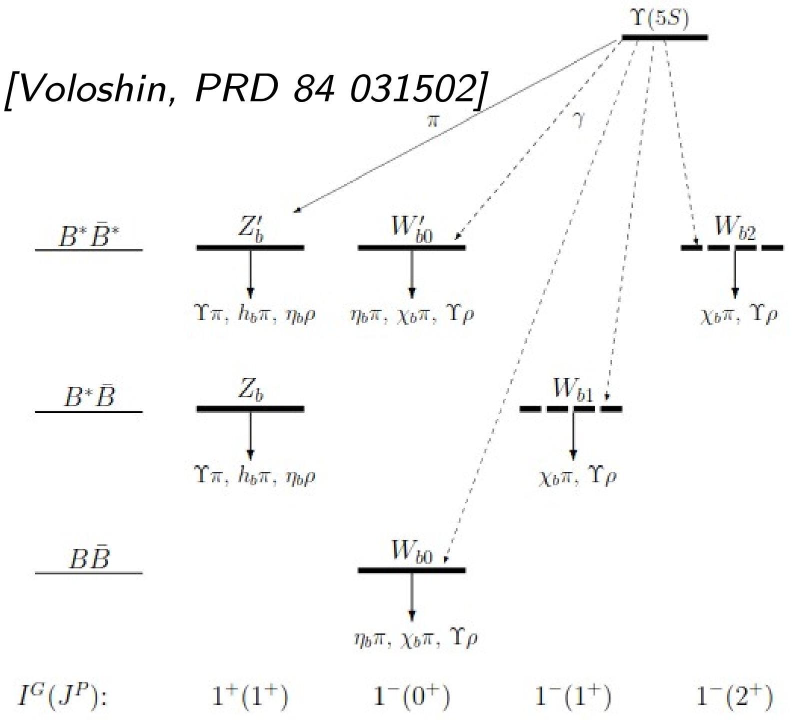
Exotic search with Ecm < 12 GeV are challenging

→ rely on rare, soft EM transitions

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

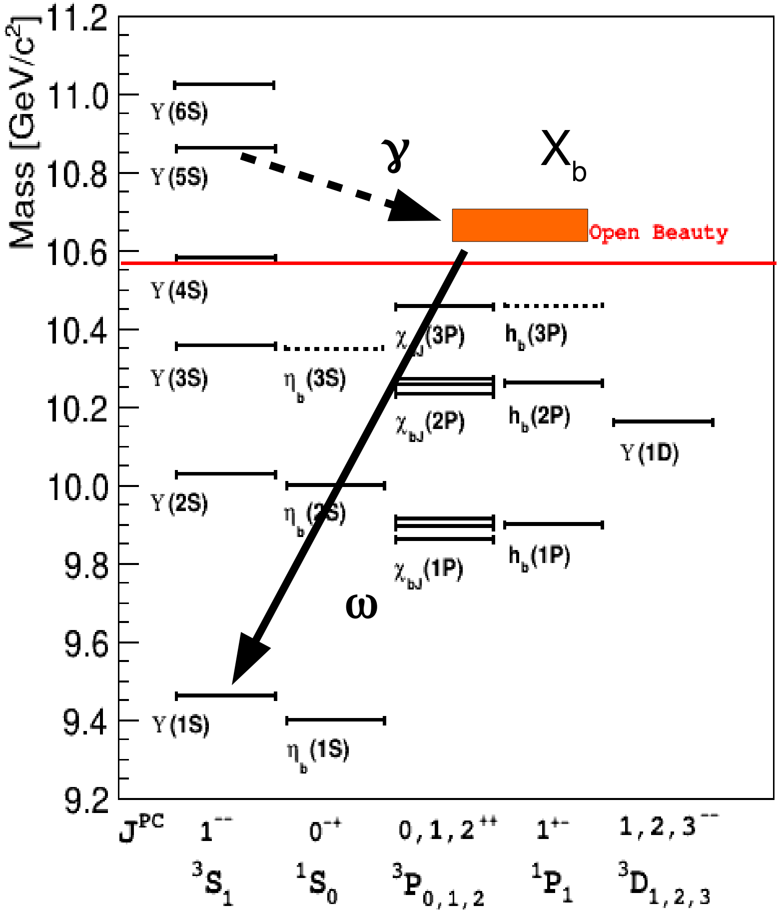
Label	J^{PC}	charmonium-like State	charmonium-like Mass [MeV]	bottomonium-like State	bottomonium-like Mass [MeV]
X_0	0^{++}	—	3756	—	10562
X_0'	0^{++}	—	4024	—	10652
X_1	1^{++}	$X(3872)$	3890	—	10607
Z	1^{+-}	$Z_c^+(3900)$	3890	$Z_b^{+,0}(10610)$	10607
Z'	1^{+-}	$Z_c^+(4020)$	4024	$Z_b^+(10650)$	10652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



Another production-like problem

Both tetraquark and pure molecule predict a counterpart (X_b)



Another production-like problem

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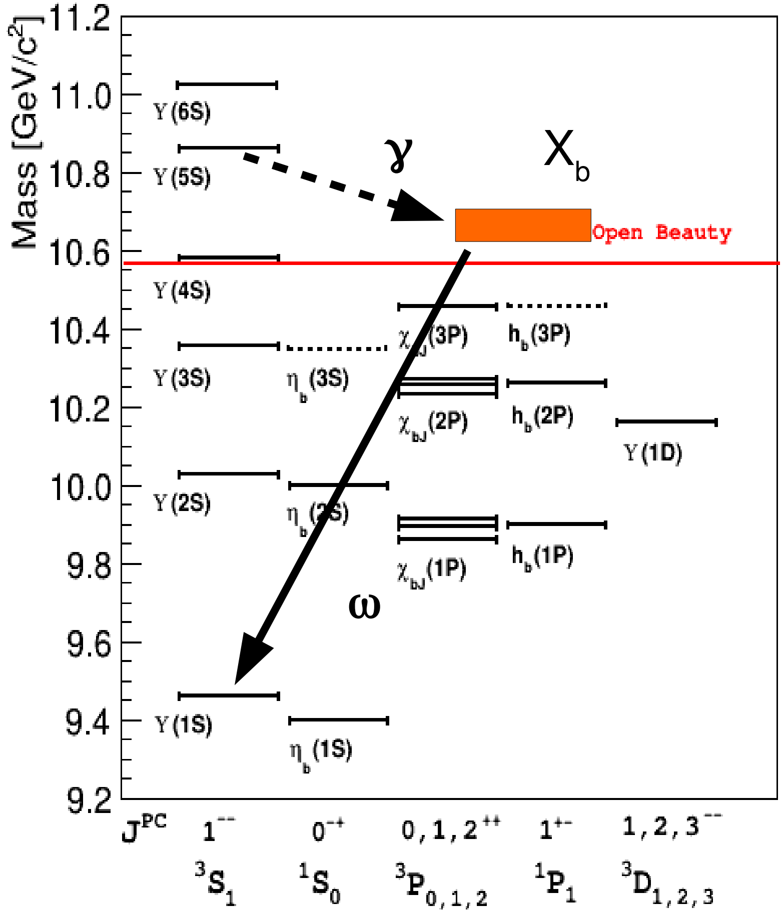
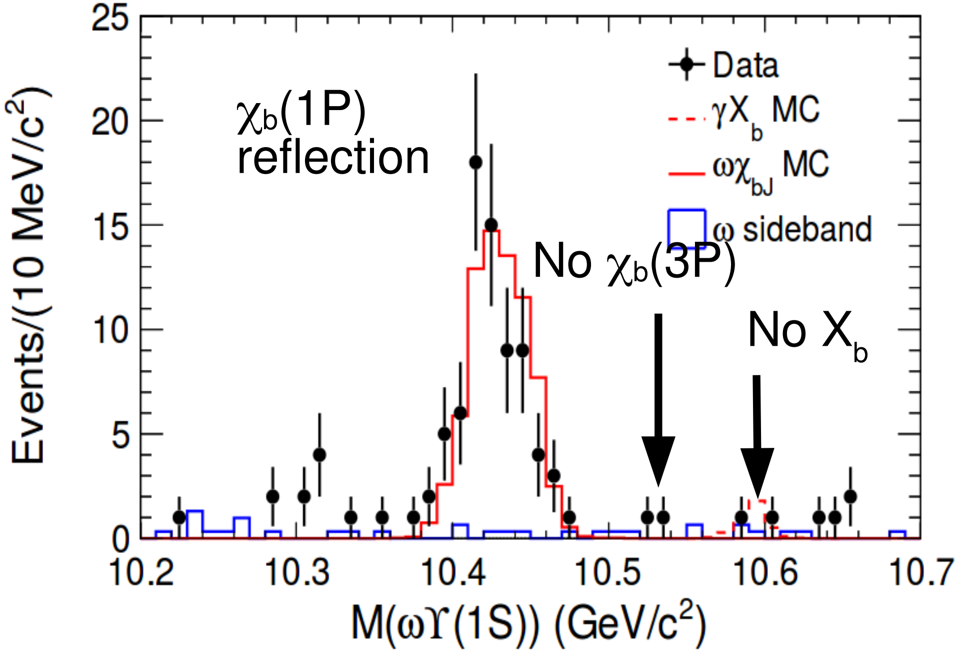


Without predictions on the Production Bfs we can't Interpret upper limits



Conclusions

Understanding heavy quarkonia is like mapping a forest we have to cross

→ You need to explore all paths and look at the bigger picture

→ Sometimes it's a good path, sometimes it's a Holzwege.

You'll still get some understanding of the forest out of it!

Summary

Understanding heavy quarkonia is like mapping a forest we have to cross

→ You need to explore all paths and look at the bigger picture

→ Sometimes it's a good path, sometimes it's a Holzwege.
You'll still get some understanding of the forest out of it!

New discoveries 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!)

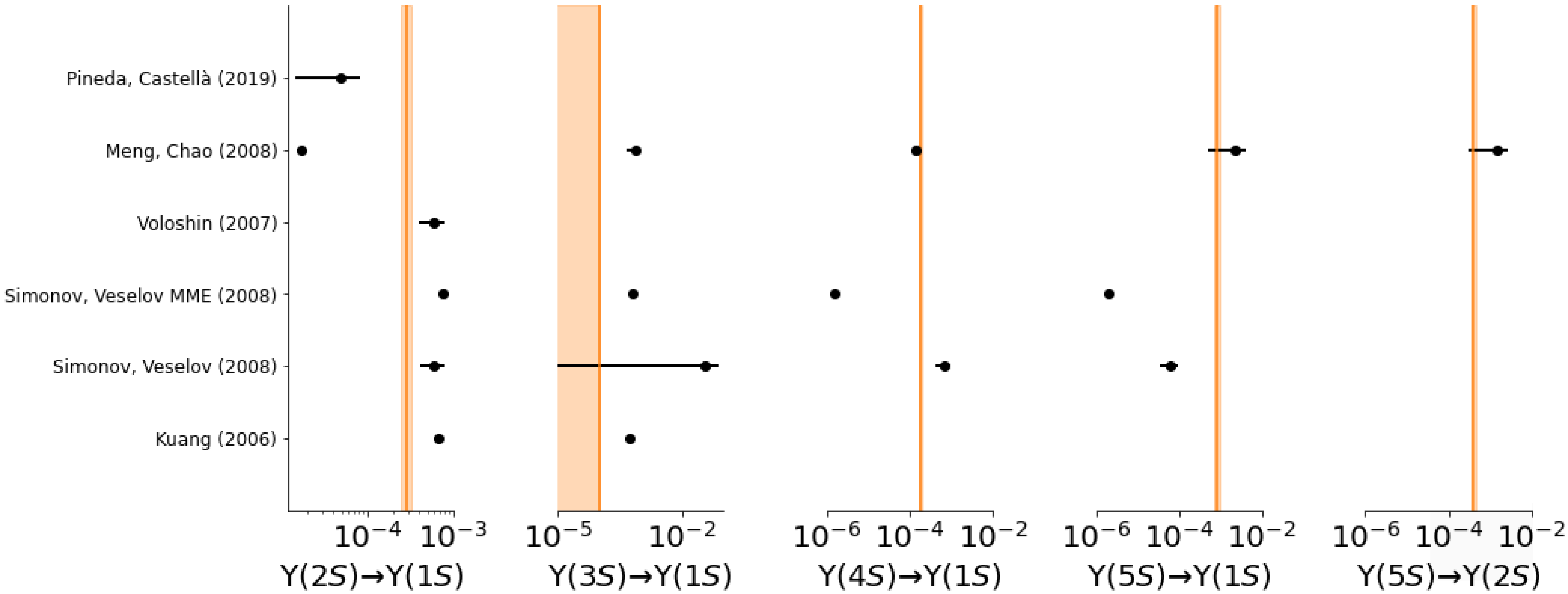
→ Measure J^{PC} of all states!

Thank you

Theory troubles: η transitions updated

No solid prediction on simple transitions like single η

$\rightarrow$ Exotic contributions?



Theory troubles: η transitions updated

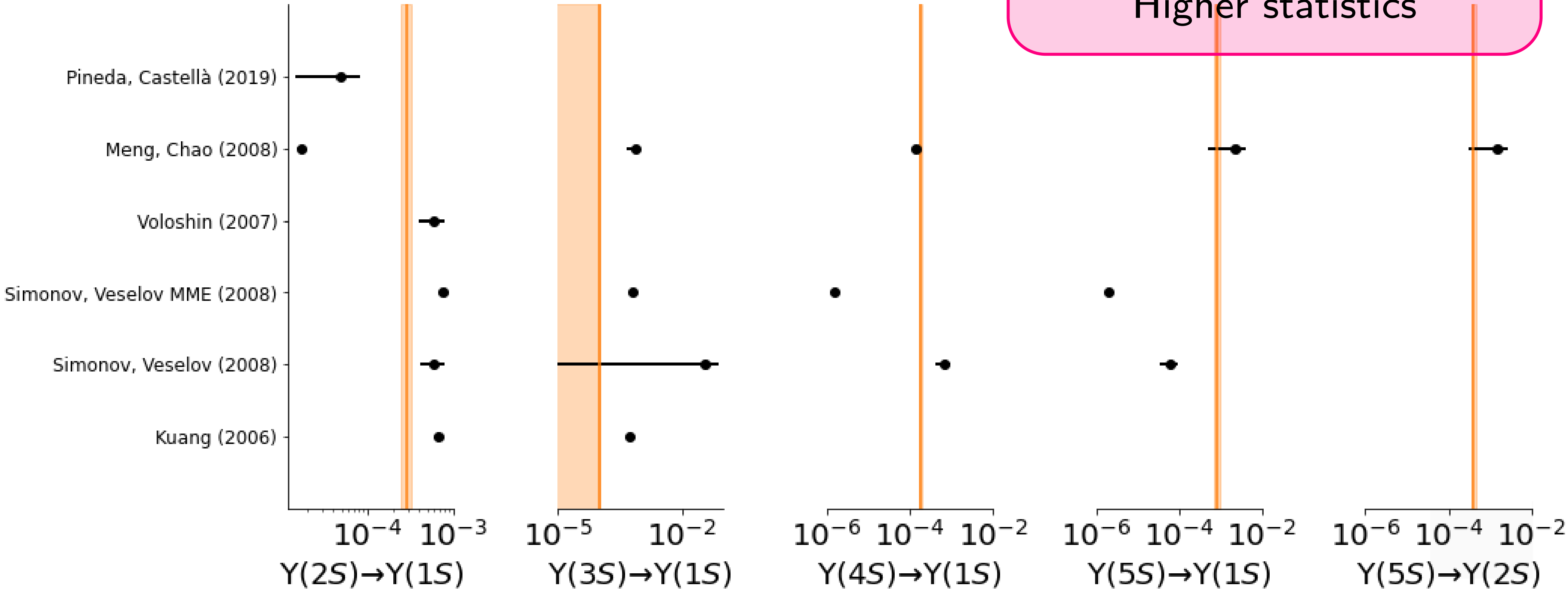
No solid prediction on simple transitions like single η

$\rightarrow$ Exotic contributions?

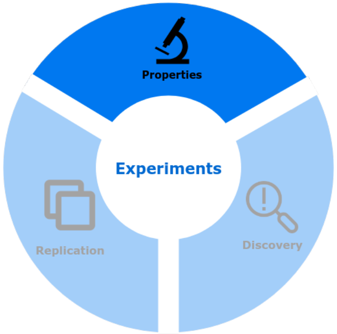
Tasks

Theoretical modeling

Higher statistics



Mapping properties: absolute BFs



When we observe a new state S we access

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

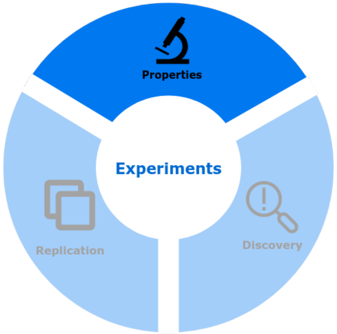
Poorly (or not) constrained by theory (for $\sigma_{\text{production}}(S)$)

Some (pre, post)dictions usually available (for $\text{BF}(S \to \text{final state})$)

$Z_c(3900)$ **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	$D^0 D^{*-}$ + 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

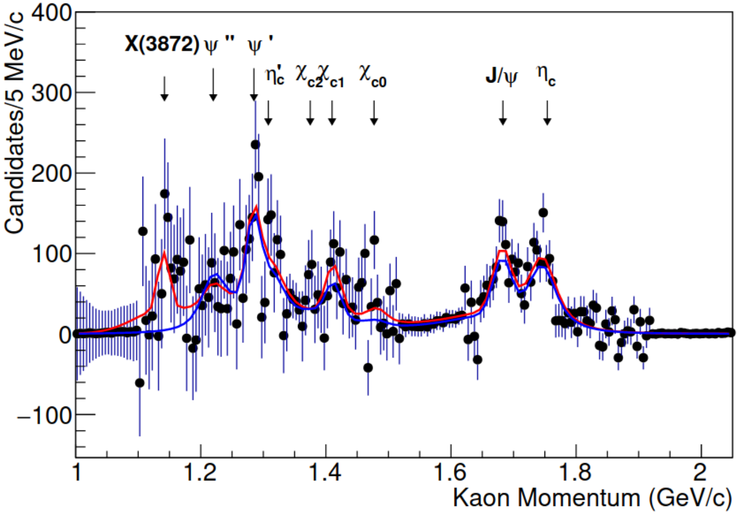


When we observe a new state S we access

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

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

Fully-heavy states: X(3900)

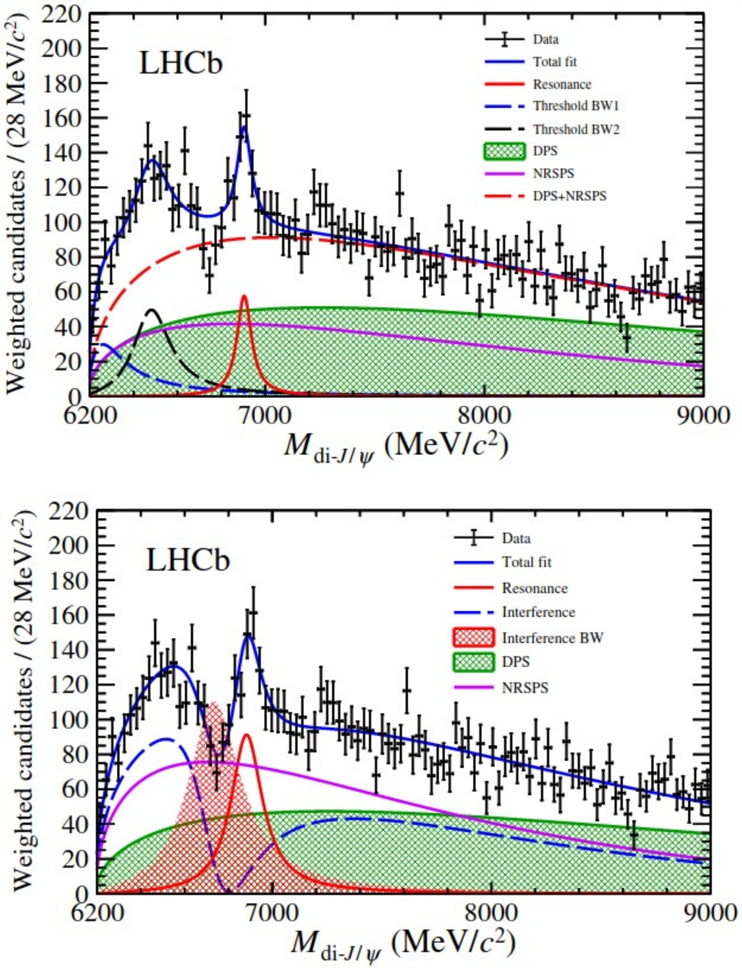
$pp \to J/\psi\ J/\psi + X$

[Sci. Bull. 65 1983 (2020)]

Two structures in M(J/ψ J/ψ)

- Narrow X(6900)
- Broad enhancement @ threshold

70+ theoretical interpretations



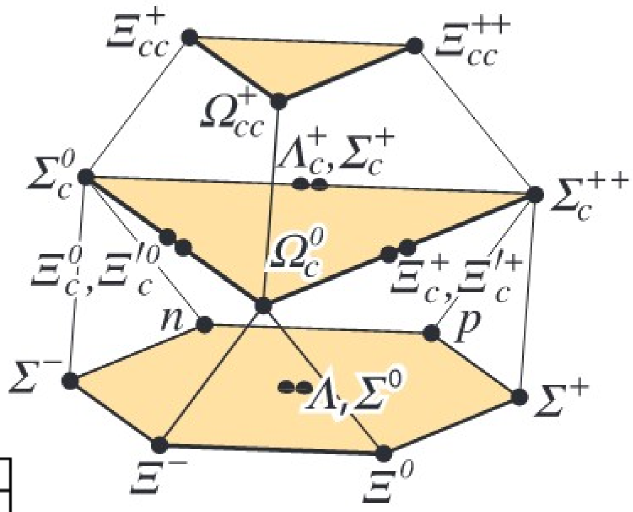
Doubly-charmed objects

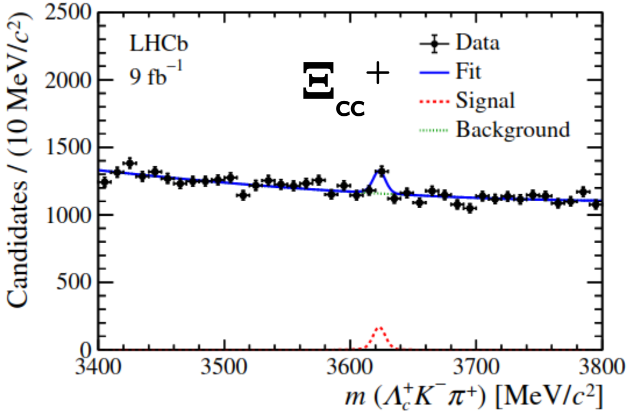
Ξ_{cc}^{++} Observed in 2017

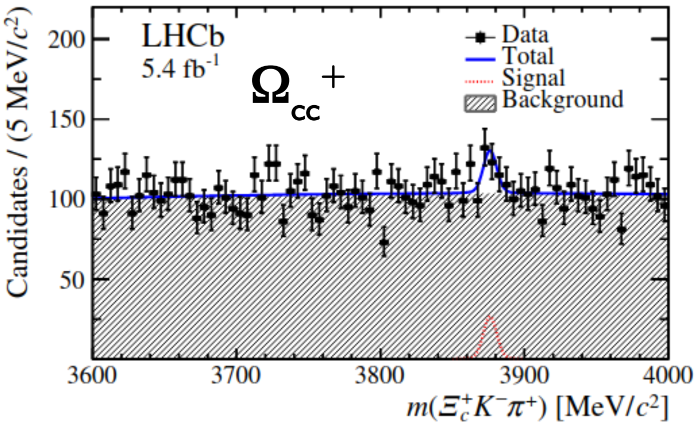
2021: First hints of Ω_{cc}^{+} and Ξ_{cc}^{+}

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

[arXiv:2109.07292]







More on this later

Going further: femtoscopy at e^+e^- colliders

[Fabbietti, Mantivani Sarti, Doce, Annu. Rev. Nucl. Part. Sci. (2021) 71:377-402]

Pairs from the same event

$$C(k^*) = \int S(\mathbf{r}^*)|\psi(\mathbf{r}^*, \mathbf{k}^*)|^2 \mathrm{d}^3 r = \xi(k^*) \cdot \frac{N_{\mathrm{SE}}(k^*)}{N_{\mathrm{ME}}(k^*)}$$

Source distribution

Experimental corrections

Two-particle wave function

K* = relative momentum

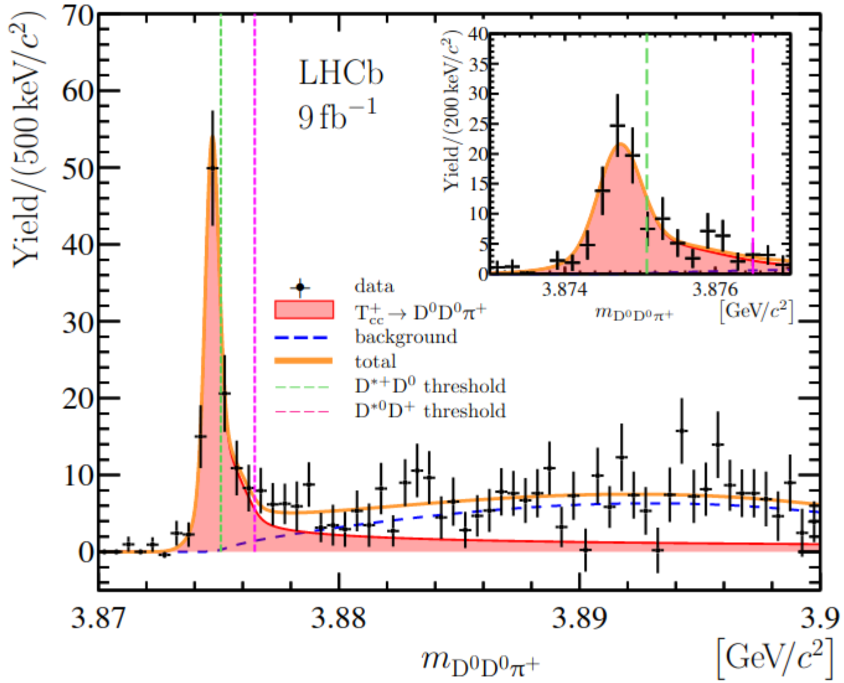
r* = relative distance

Pairs from different events

The T_{cc}

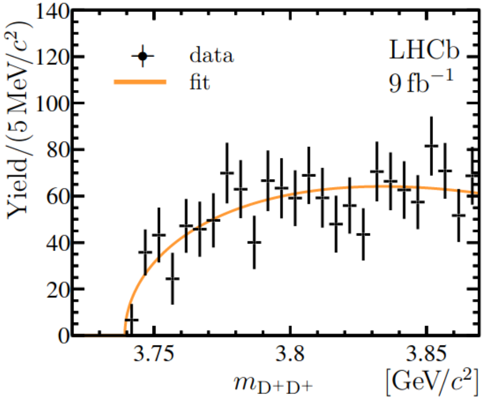
Prompt production of something decaying into $(DD^*)^+$

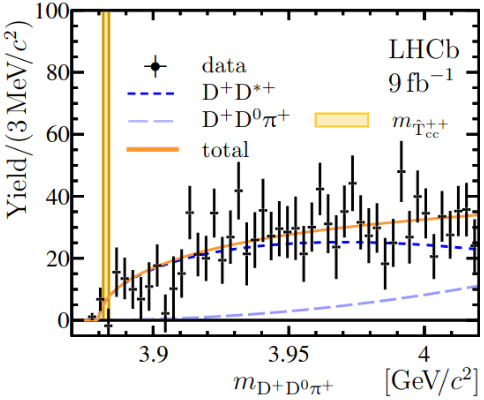
[arXiv:2109:01038 and arXiv:2109:01056]



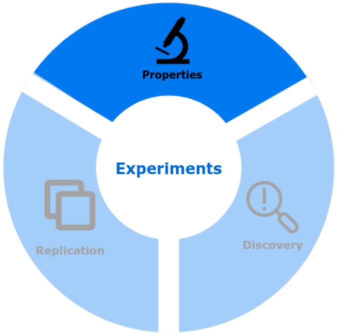
$J^{PC} = 1^+$ (probably)

Nothing in the D^+D^+ channel





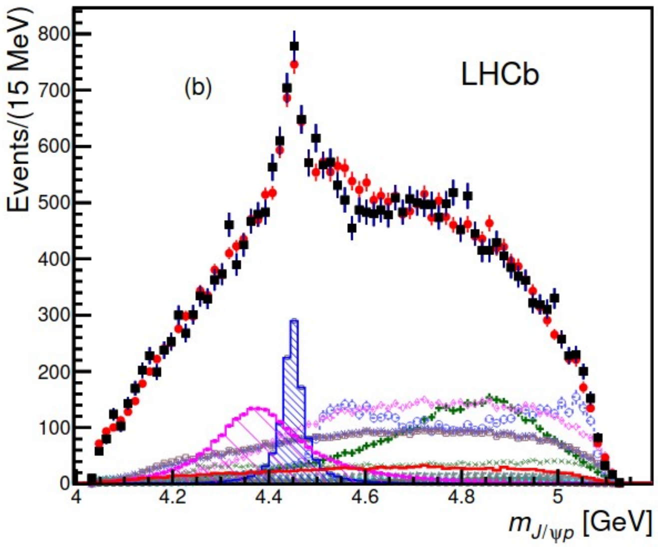
J^{PC} analysis: the pentaquark example



Amplitude analysis is challenging with narrow states

- Cannot neglect the resolution
- Fit computationally very demanding

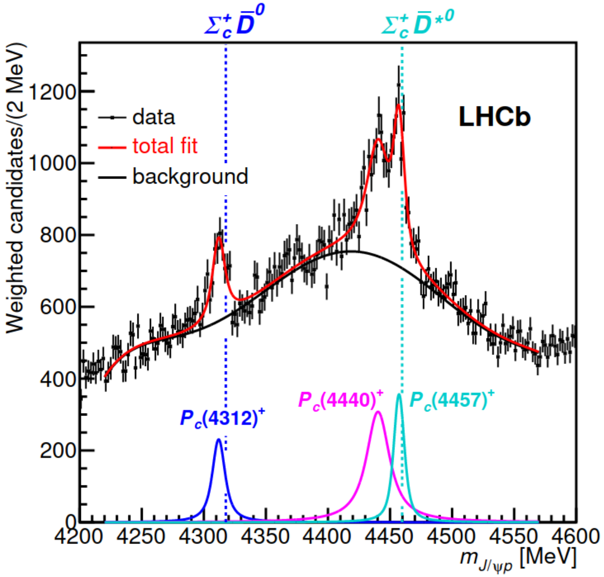
2015: two **broad** states



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?

Predictions on the H dibaryon

[Marietti, Pilloni, UT, PRD 106 (2022) 9, 094040]

$$(2k_{cut})^3 = \frac{36}{\sqrt{\pi}}\sigma^{-2}\sqrt{m_p B_d}$$

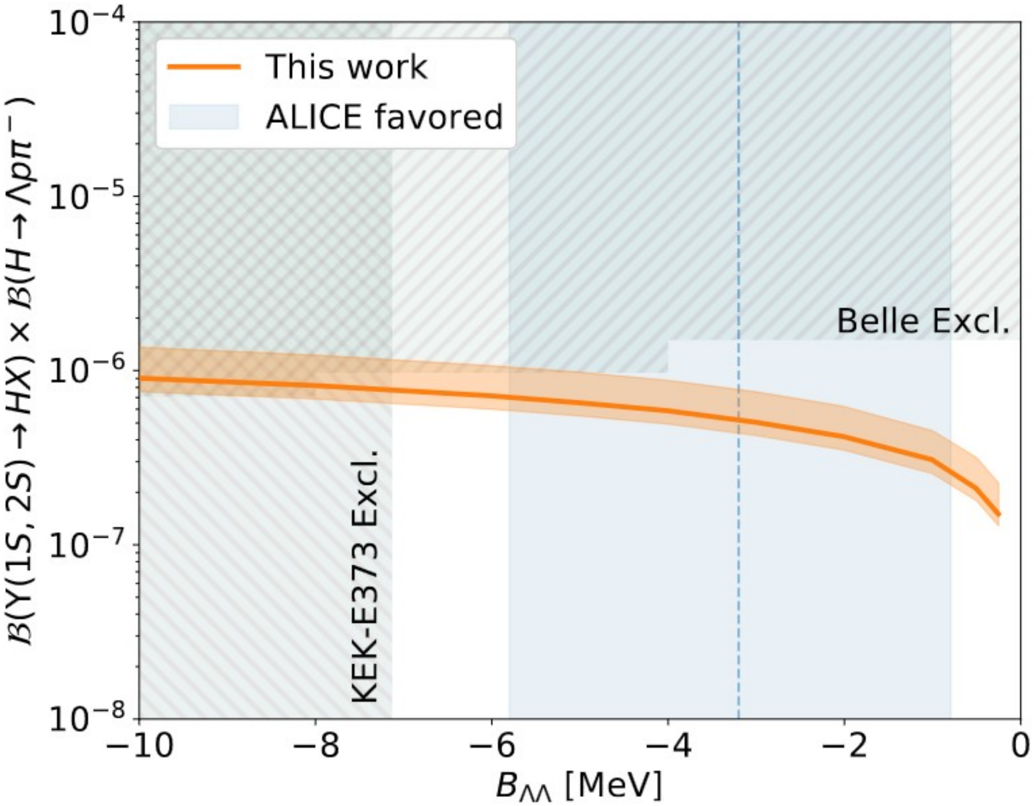
Gustafson and Hakkinen 1994 (Z.Phys.C 61 (1994) 683-688)

→ Fit σ from deuteron data

→ Calculate k for any other molecule

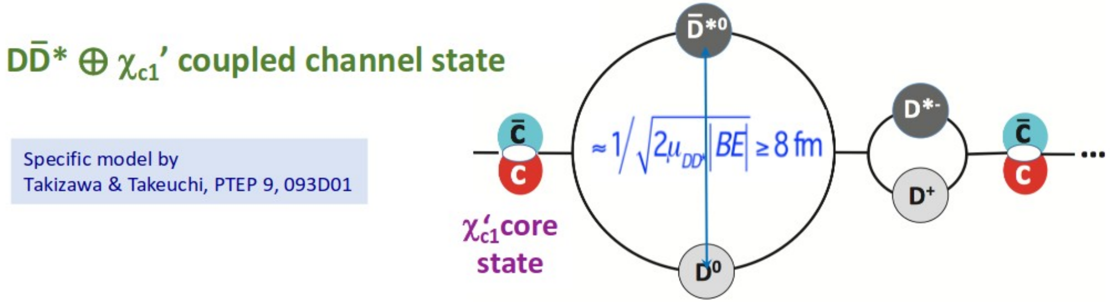
Attempt with loosely-bound H dibaryon

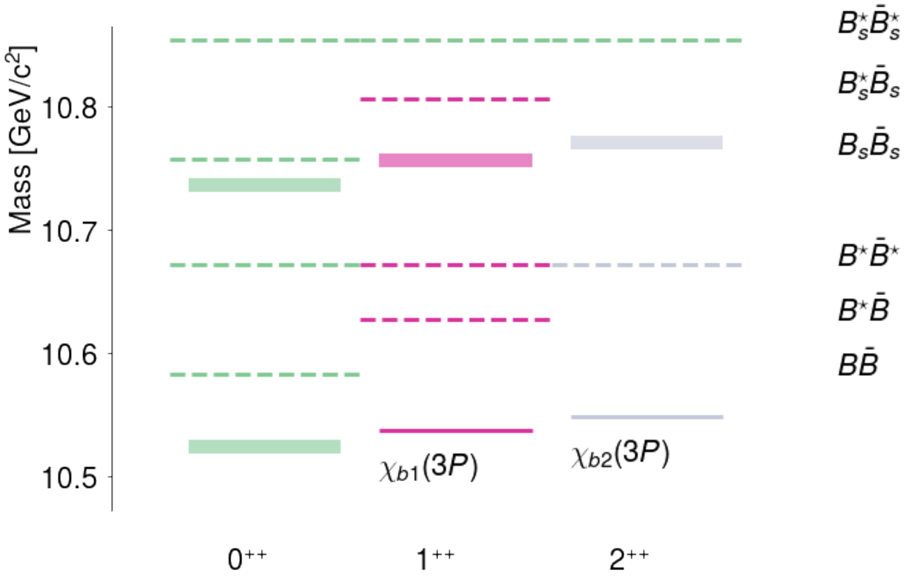
($\Lambda\Lambda$ spectrum from tuned MC)



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**