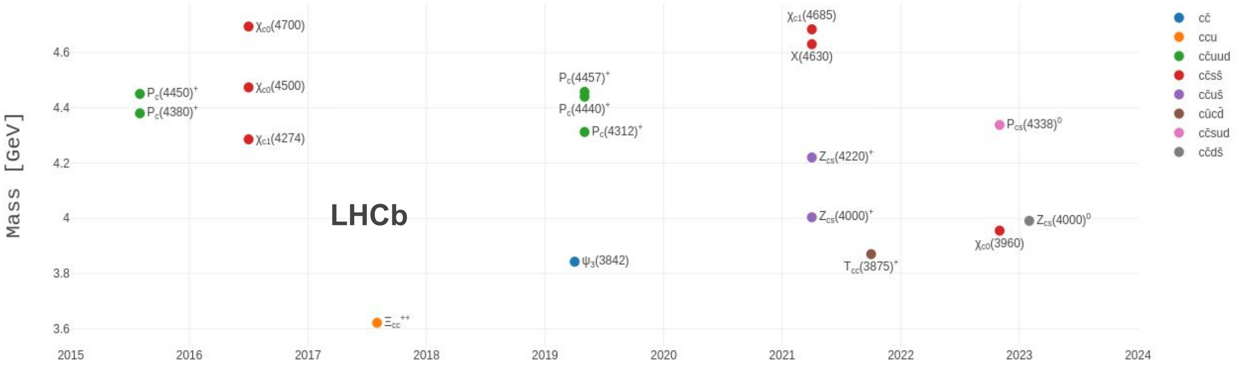
Aci Castello,
22–27 June 2025

Hadron spectroscopy at B factories

A. Boschetti

The rebirth of hadron spectroscopy



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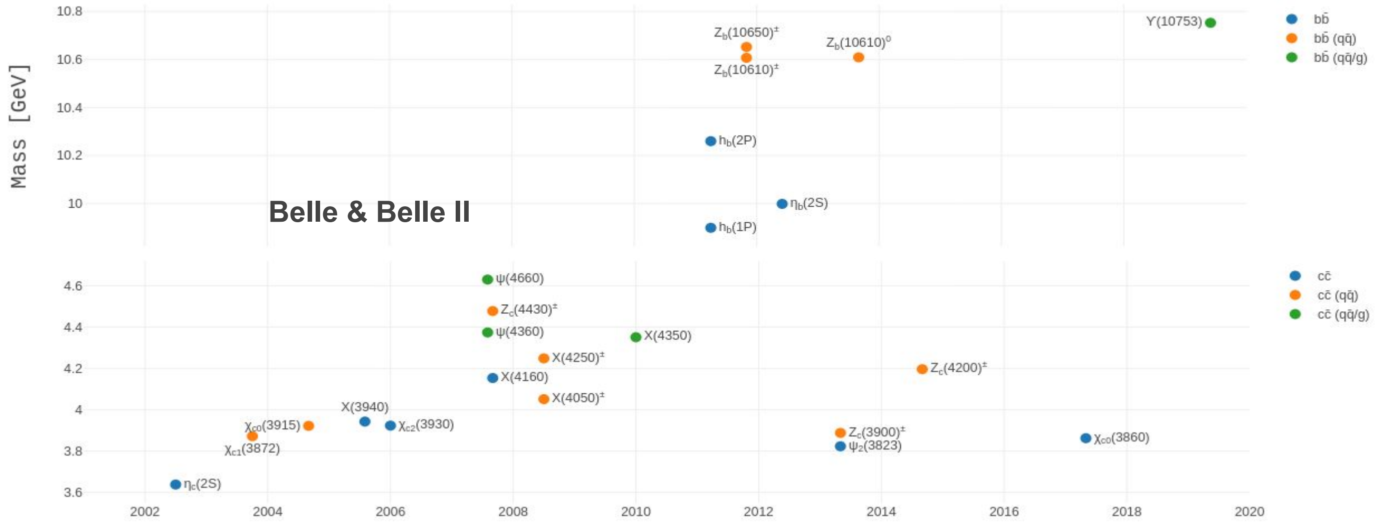
\+



22

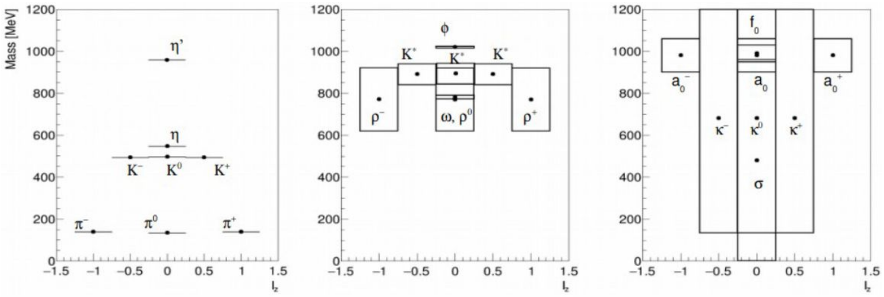
=

40 new states!

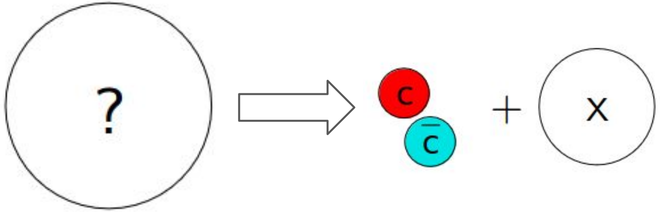
Why heavy quarkonia?

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

However, experimentally challenging to distinguish $q\bar{q}$ from $q\bar{q}q\bar{q}$ in light sector



With heavy quarks separating conventionals and exotics is much simpler, *e.g.*

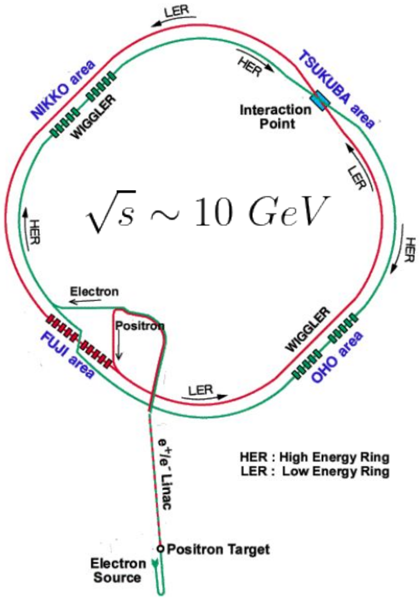


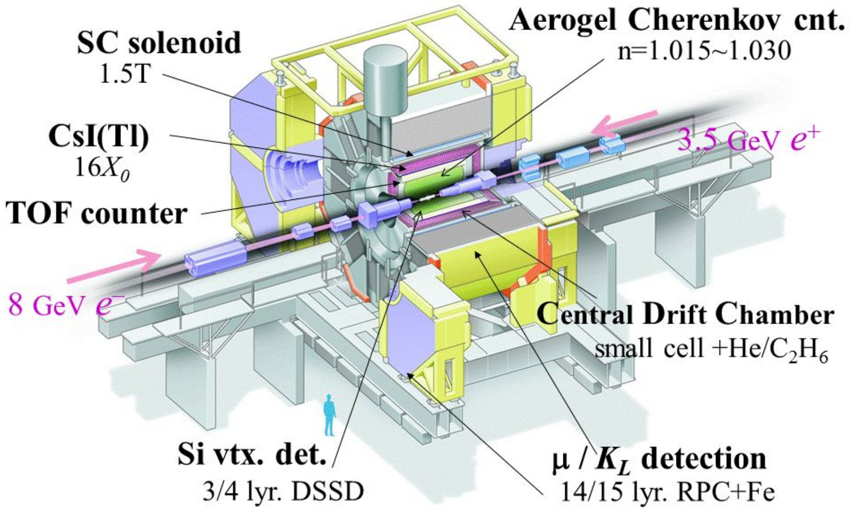
- Mass > 3 GeV/c^2
- Small width ($\Gamma/M < 0.1$)
- Large BF for J/ψ (or $D\bar{D}$) + X decay

⇒ Must contain $c\bar{c}$ pair

Belle at KEKB

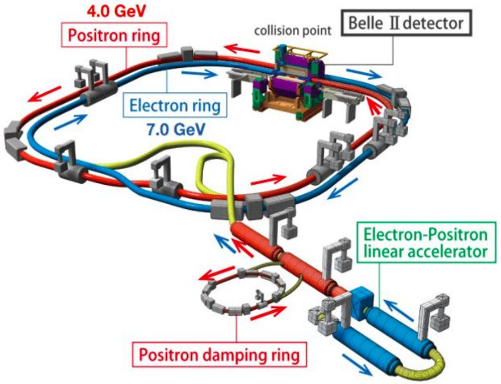
B-factory ⇒ optimized for Υ(4S) production
Quarkonium spectroscopy
⇒ **Tunable beam energy**: from Υ(1S) to Υ(6S)

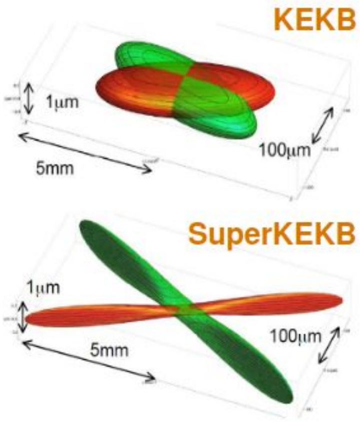


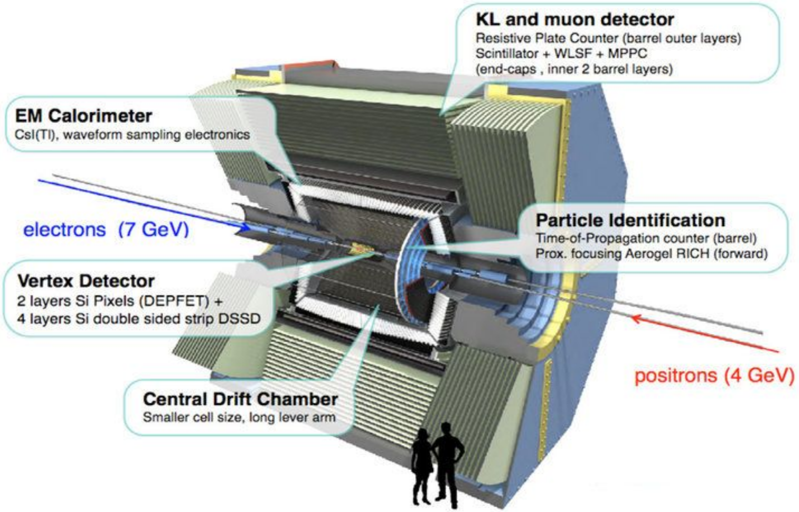


Belle II at SuperKEKB

Improved **tracking** and **PID performance**
Implementation of the **nano-beam** scheme for collisions
⇒ projected **luminosity ~ 30x**Belle



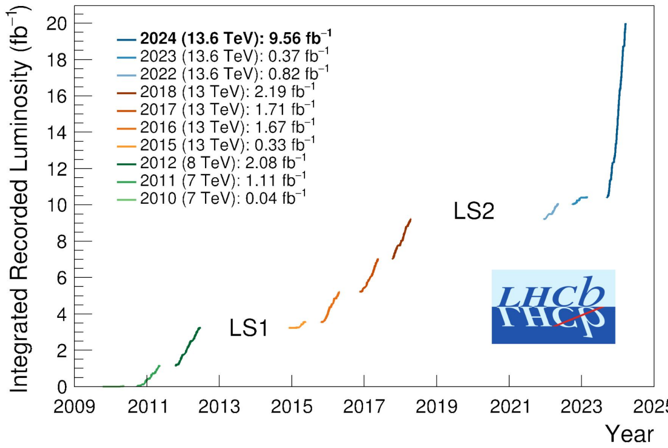


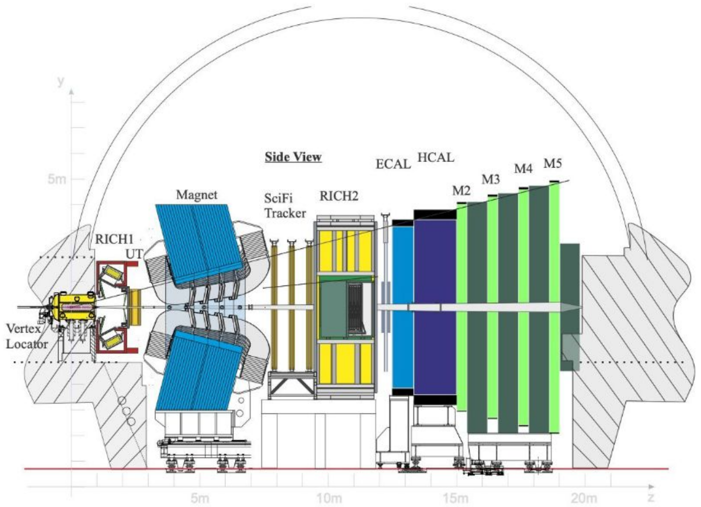


The LHCb detector

Single arm spectrometer (forward)
15 to 300 mrad coverage
Larger cross sections, higher boost, more b hadrons
Large background:

- worse flavor tagging
- difficulties with missing/neutral particles





- Vertex reconstruction:
  - $\Delta IP = (15 + 29/p_T)\ \mu m$
- Momentum resolution:
  - $\Delta p/p$ = ~0.5–1% (from 2 to 200 GeV)
- Hadronic PID:
  - $\varepsilon_{K\to K}$ ~ 95%,
  - $\varepsilon_{K\to\pi}$ ~ 10% (from 2 to 200 GeV)
- Muon trigger efficiency:
  - $\varepsilon > 90\%$

The doubly charmed tetraquark T_{cc}

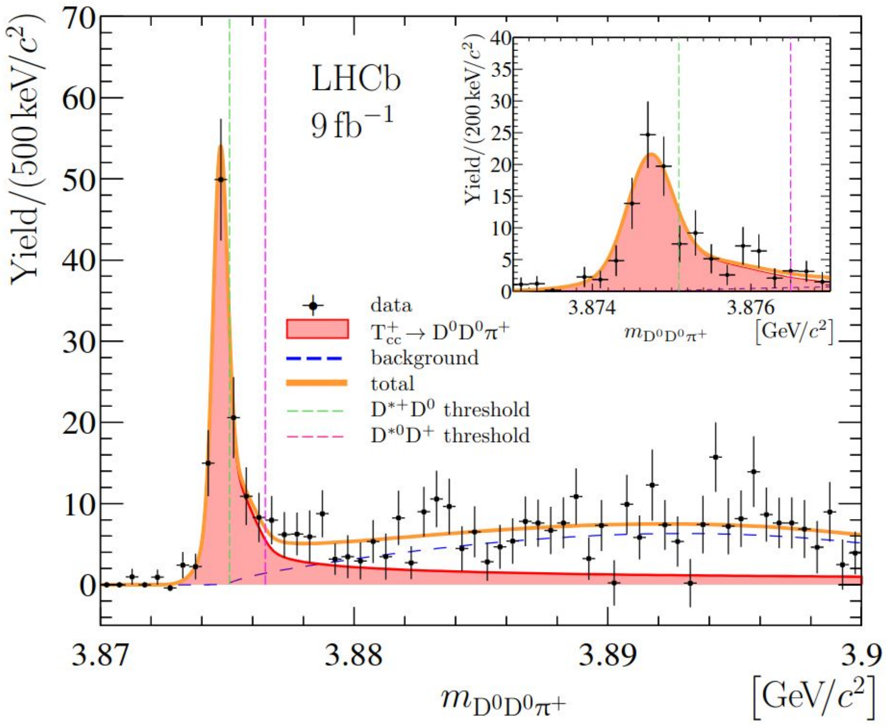
Nat Commun **13**, 3351 (2022)

- Observation of narrow state in $M(D^0D^0\pi^+)$ near D^0D^{*+} threshold
- Minimal quark content $[cc\bar{u}\bar{d}]$
- $J^P = 1^+$

Unitarised model, signal ~ Flatté

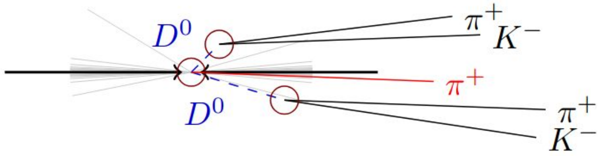
- $\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0}\ \text{keV}/c^2$
- $\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14}\ \text{keV}$
- Excellent description of $M(D^0\pi^+)$
- Absence of signal in $M(D^0D^0)$ and $M(D^+D^0\pi^+)$

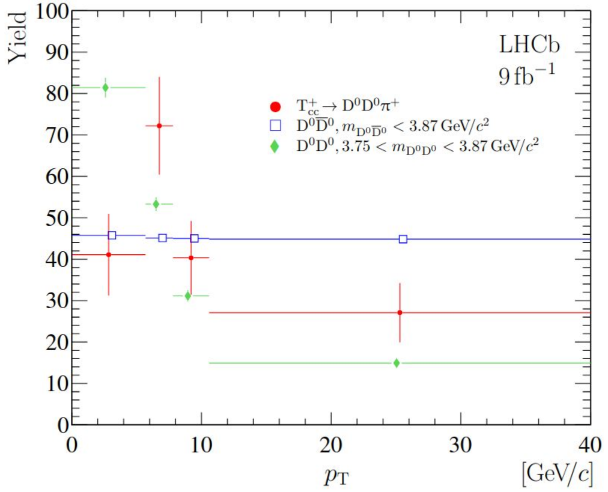
⇒ T_{cc} consistent with isoscalar tetraquark

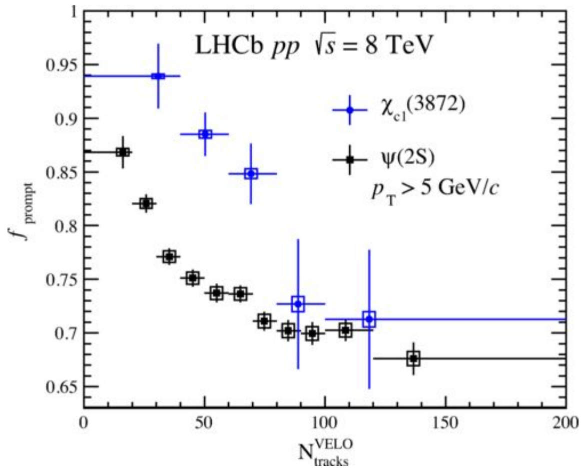


Prompt production

The analysis shows **large <u>prompt</u> production** at high p_T





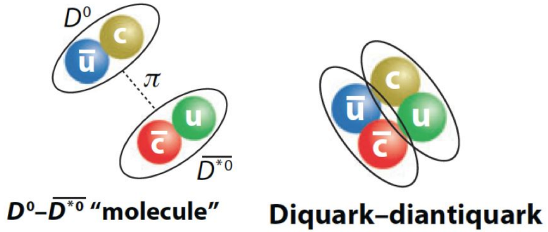


Same property is shared by $\chi_{c1}(3872)$

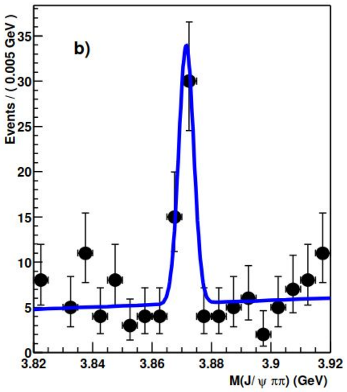
Phys. Rev. Lett. 126, 092001

Large prompt production at high p_T **disfavors molecular interpretation**

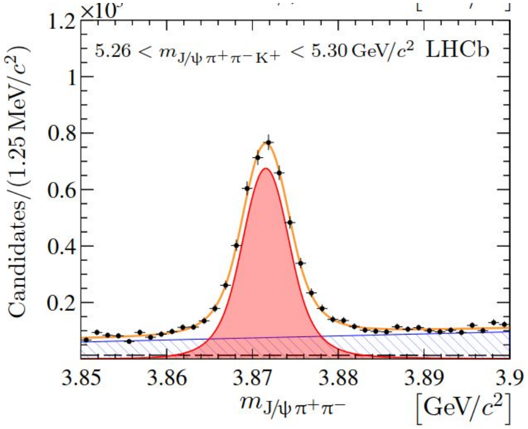
The $\chi_{c1}(3872)$ state



- *$m(\chi_{c1}(3872))$ - $(m(D^0) + m(\bar{D}^{*0}))$* = **-0.07 ± 0.12 MeV**
- *J^{PC}* = 1^{++}
- ***Production***:
  - B decays
  - prompt pp, $p\bar{p}$, pPb, PbPb !
  - $e^+e^- \to \gamma\chi_{c1}(3872)$, $\omega\chi_{c1}(3872)$
- ***Decay:***
  - J/ψππ, J/ψω, $D\bar{D}^*$, ...



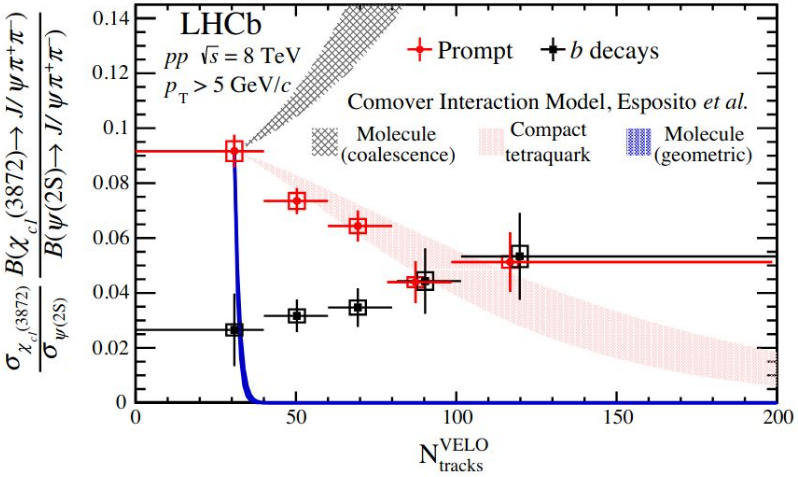
~20 years



Proximity to threshold, dominant decay modes, $J^{PC} = 1^{++}$
⇒ <u>molecular picture is favored</u>

Suppression of χ_{c1}(3872): compact state?

Phys. Rev. Lett. **126**, 092001

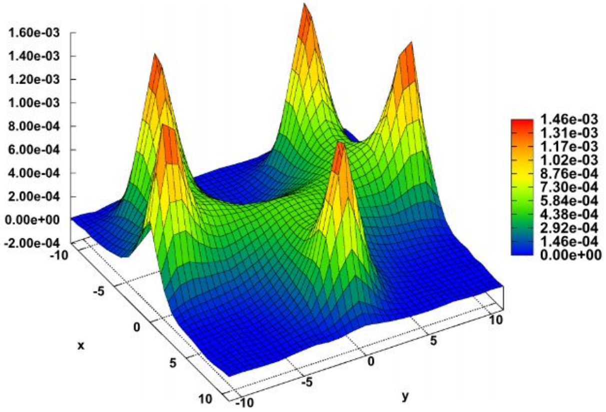


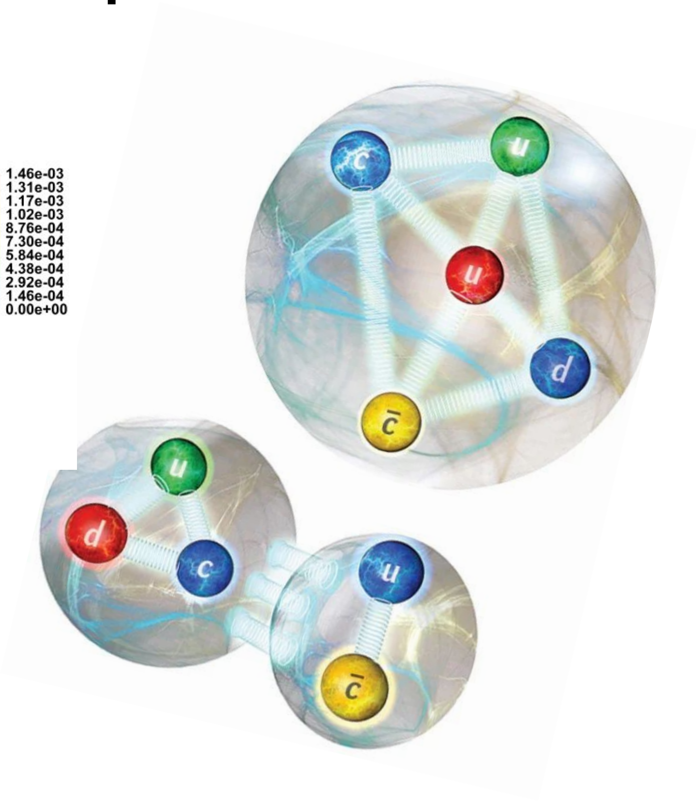
Study behaviour of states immersed in QCD matter ⇒ estimate the spatial size

Comover Interaction Model (CIM)
Eur. Phys. J. C 81, 669 (2021)

- Quarkonia broken by collision with comovers in nuclear medium
  - Breakup cross section depends on radius and binding energy
- Pure molecule:
  - large radius ⇒ quick dissociation
  - reformation by coalescence ⇒ $\sigma_{\chi_{c1}(3872)}/\sigma_{\psi(2S)}$ rises with multiplicity
- Compact state:
  - radius of χ_{c1}(3872) slightly larger than ψ′ ⇒ $\sigma_{\chi_{c1}(3872)}/\sigma_{\psi(2S)}$ decreases

Pentaquarks

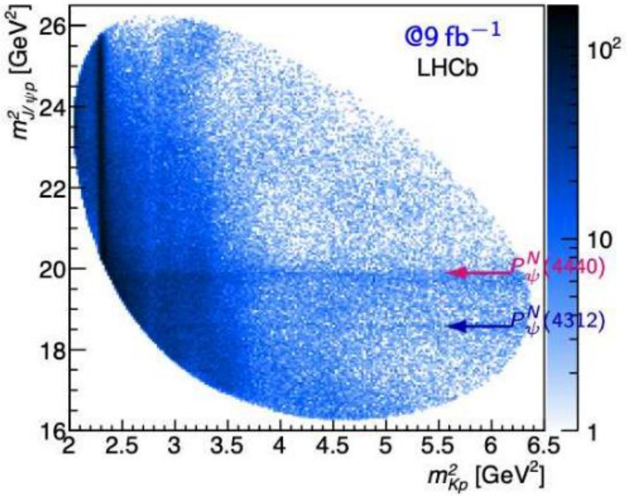




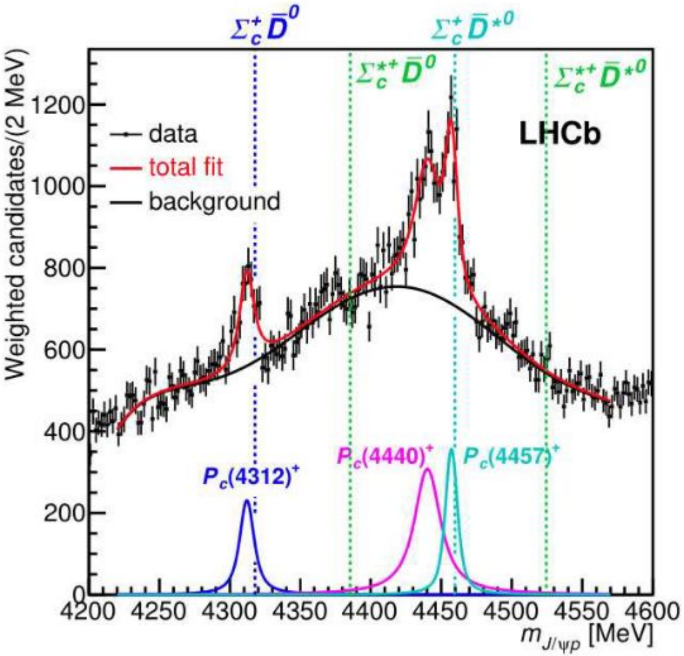
First discovery of pentaquarks

Dalitz plot analysis of

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



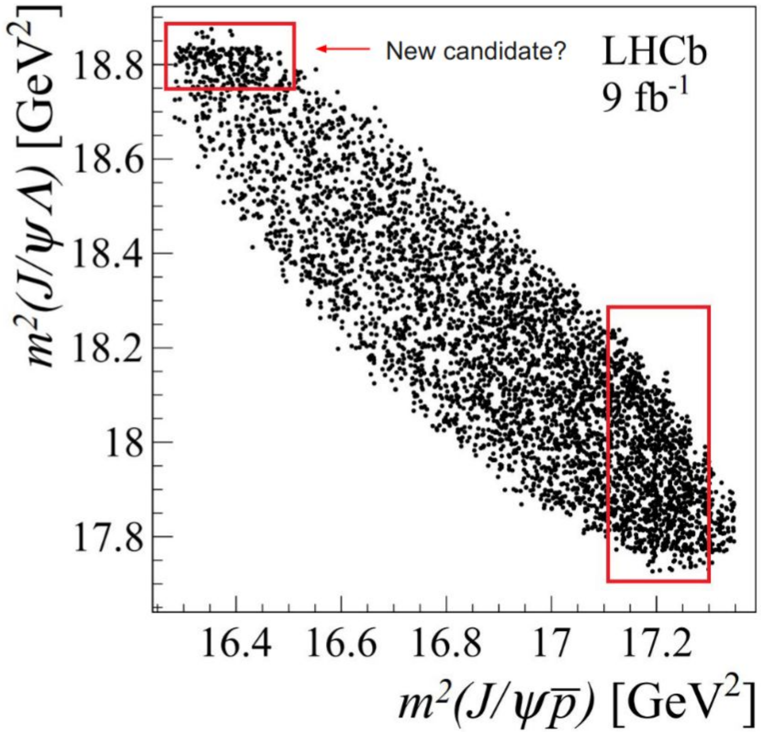
State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$



Phys. Rev. Lett. ***122**, 222001* *(2019)*

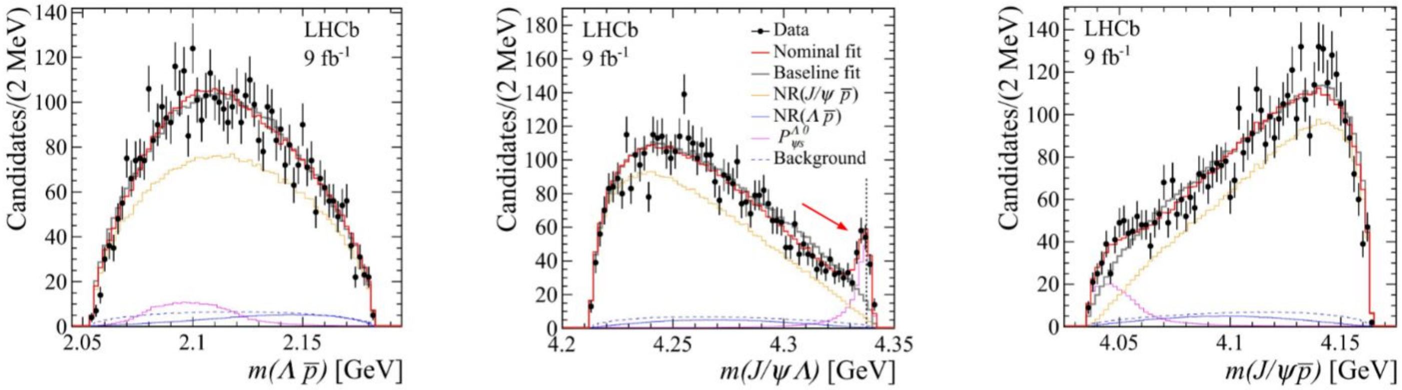
New strange pentaquark candidate $P_{\psi_s}^{\Lambda}$

- Amplitude analysis of $B^- \to J/\psi\Lambda\bar{p}$
  - *pp* collisions, 9 fb^{-1} ⇒ ~4400 events
  - High signal purity (93%)
- Fit model
  - Non-resonant $J/\psi\bar{p}$
  - Non-resonant $\Lambda\bar{p}$
  - Virtual $K_4^*(2045)^-$, $K_2^*(2250)^-$, $K_3^*(2320)^-$
  - Combinatorial background
  - Signal $P_{\psi_s}^{\Lambda} \to J/\psi\Lambda$



Phys. Rev. Lett. ***131****, 031901* *(2023)*

New strange pentaquark candidate $P_{\psi_s}^{\Lambda}$



Results of the fit:

*[Phys. Rev. Lett. **131**, 031901](#) (2023)*

$$m(P_{\psi_s}^{\Lambda}) = 4338.2 \pm 0.7 \pm 0.4\,\mathrm{GeV}$$

$$\Gamma(P_{\psi_s}^{\Lambda}) = 7.0 \pm 1.2 \pm 1.3\,\mathrm{MeV}$$

$$m(\Xi_c^+) + m(D^+) = 4337.2\,\mathrm{MeV}$$

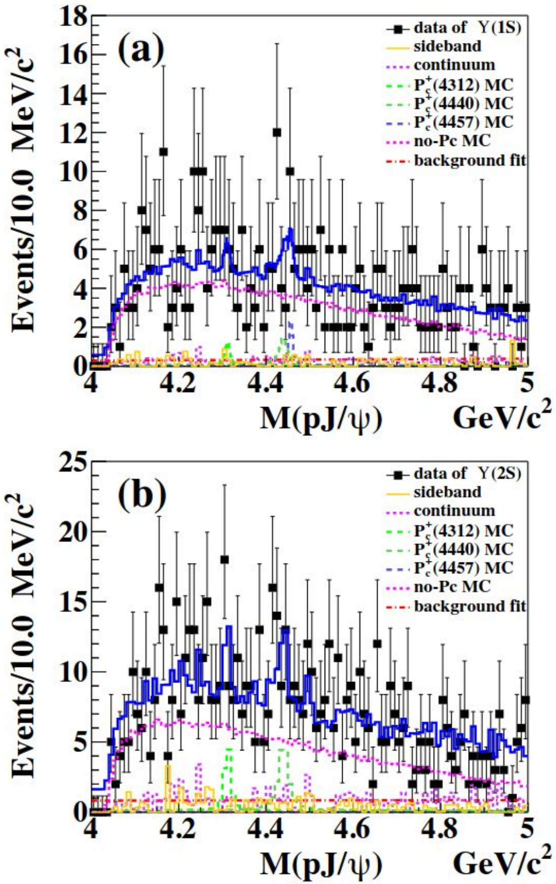
Preferred $J^P = 1/2^-$

Significance > 10σ

First observation of [cc̄uds] pentaquark!

Pentaquarks in Υ decays ?

arXiv:2403.04340 (submitted to JHEP)



Reconstruct inclusive p J/ψ in Υ(1S) & Υ(2S) Belle data

No pentaquark signals found;
only slight excesses at LHC-b masses

Inclusive p J/ψ BF results

$B(\Upsilon(1S) \to pJ/\psi + X) = (4.27 \pm 0.16 \pm 0.20) \times 10^{-5}$

$B(\Upsilon(2S) \to pJ/\psi + X) = (3.59 \pm 0.14 \pm 0.16) \times 10^{-5}$

$\sigma(pJ/\psi + X) = (57.5 \pm 2.1 \pm 2.5)$ fb at 10.52 GeV

Pentaquark Limits:

$$\mathcal{B}[\Upsilon(1S) \to P_c(4312)^+ + anything] \cdot \mathcal{B}[P_c(4312)^+ \to pJ/\psi] < 3.9 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(1S) \to P_c(4440)^+ + anything] \cdot \mathcal{B}[P_c(4440)^+ \to pJ/\psi] < 6.2 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(1S) \to P_c(4457)^+ + anything] \cdot \mathcal{B}[P_c(4457)^+ \to pJ/\psi] < 5.5 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(2S) \to P_c(4312)^+ + anything] \cdot \mathcal{B}[P_c(4312)^+ \to pJ/\psi] < 4.7 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(2S) \to P_c(4440)^+ + anything] \cdot \mathcal{B}[P_c(4440)^+ \to pJ/\psi] < 7.2 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(2S) \to P_c(4457)^+ + anything] \cdot \mathcal{B}[P_c(4457)^+ \to pJ/\psi] < 2.6 \times 10^{-6},$$

Pentaquarks in Υ decays!

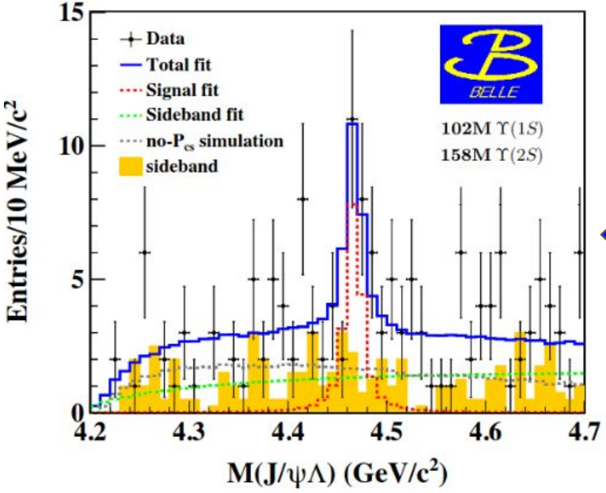
arXiv:2502.09951 (accepted by PRL)

Reconstruct inclusive J/ψ Λ in Υ(1S) & Υ(2S) Belle data

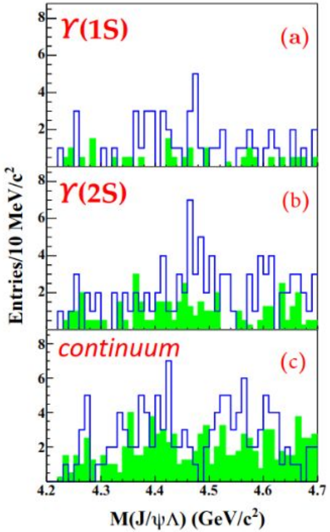
3.3σ evidence for LHCb state
$P_{ccs}(4459)^0 \rightarrow J/\psi\Lambda$

– OR –

3.8σ for a slightly more massive state
M = 4471.7 ± 4.8 ± 0.6 MeV/c^2
Γ = 21.9 ± 13.1 ± 2.7 MeV



sum of the resonance data



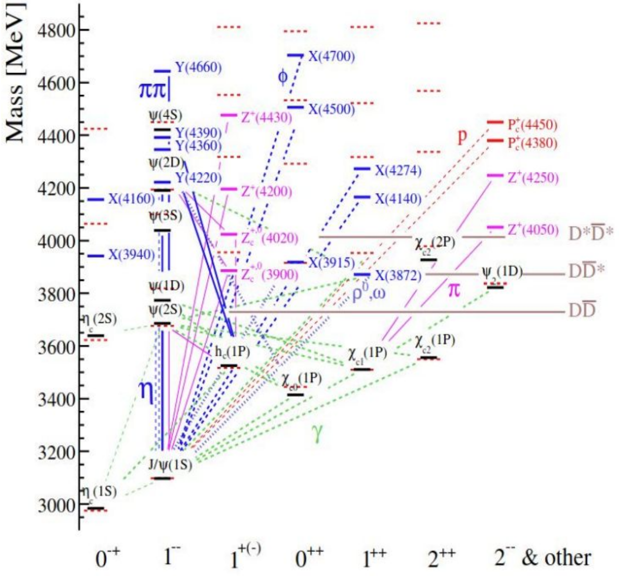
note that LHCb found

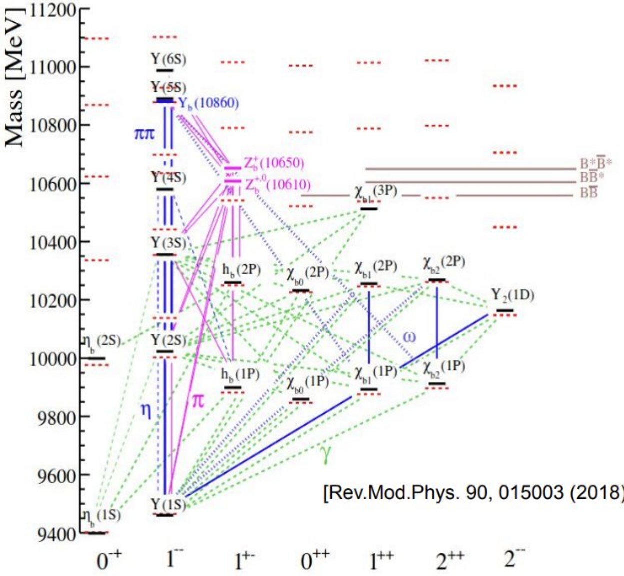
$$M = 4458.8 \pm 2.9^{+4.7}_{-1.1}\ MeV/c^2$$
$$\Gamma = 17.3 \pm 6.5^{+8.0}_{-4.7}\ MeV$$

The $b\bar{b}$ spectrum

QCD is symmetric w.r.t. quark flavor

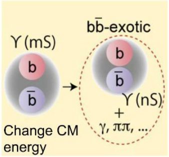
Compact charmonium-like states ⇒ should find **partners in the bottomonium region**





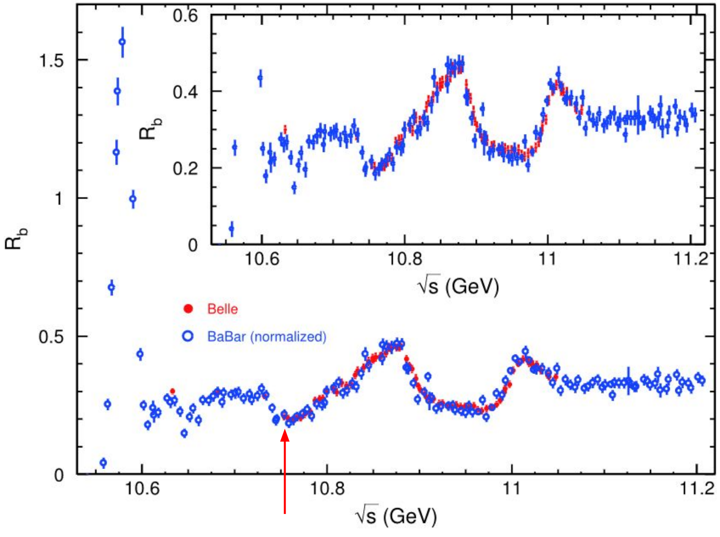
[Rev.Mod.Phys. 90, 015003 (2018)]

Belle: above Υ(4S)



High energy scans @ Belle and BaBar ⇒ R_b

- Peaks at 10.86 and 11.02 GeV ⇒Υ(5S), Υ(6S)
- Dips at 10.65, 10.75 GeV

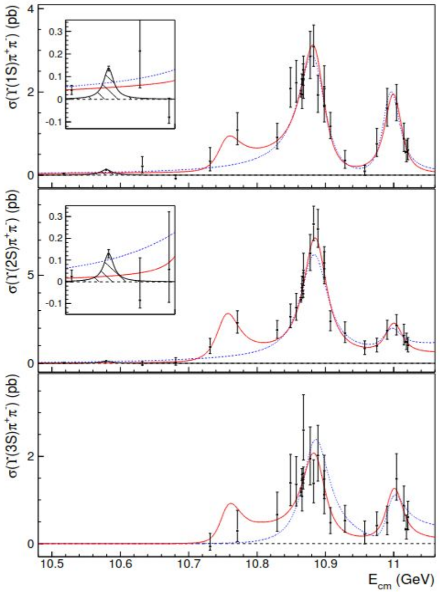


[Dong *et al.*, Chin. Phys. C 44 (2020) 8, 083001]

Discovery of Υ(10753) (ππ transitions)

We want to

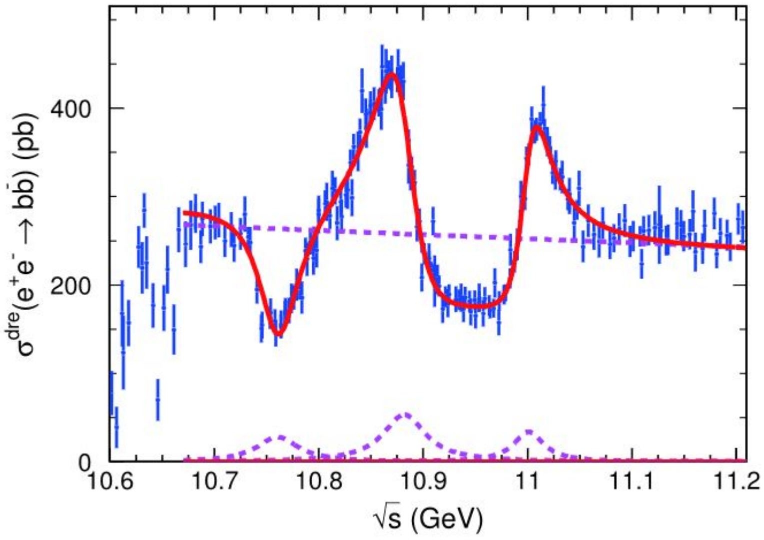
- know more about its nature
- explore transitions to lower states



[Belle, JHEP 10 (2019) 220]

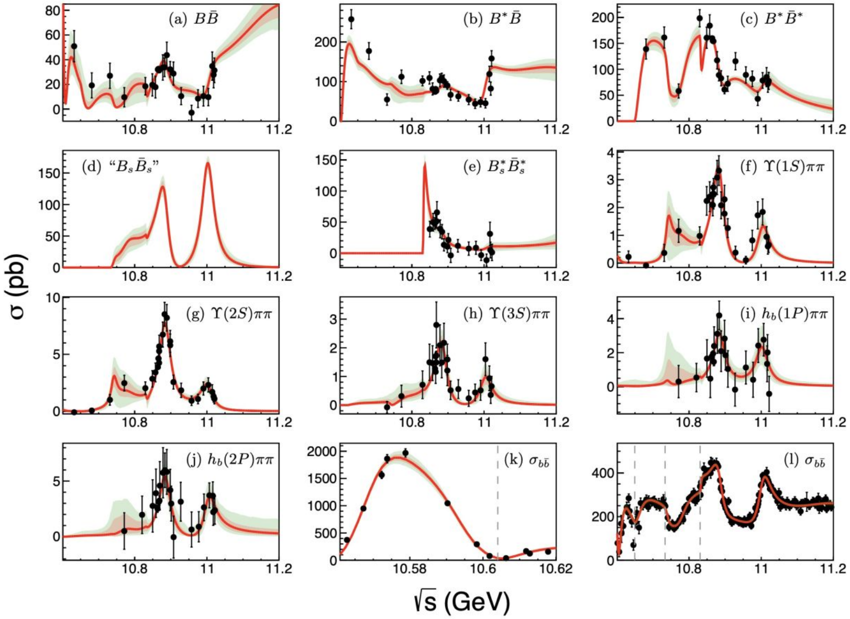
Fitting the R_b scans

Coherent sum of continuum and 3 BW functions
[Dong *et al.*, Chin. Phys. C 44 (2020) 8, 083001]



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

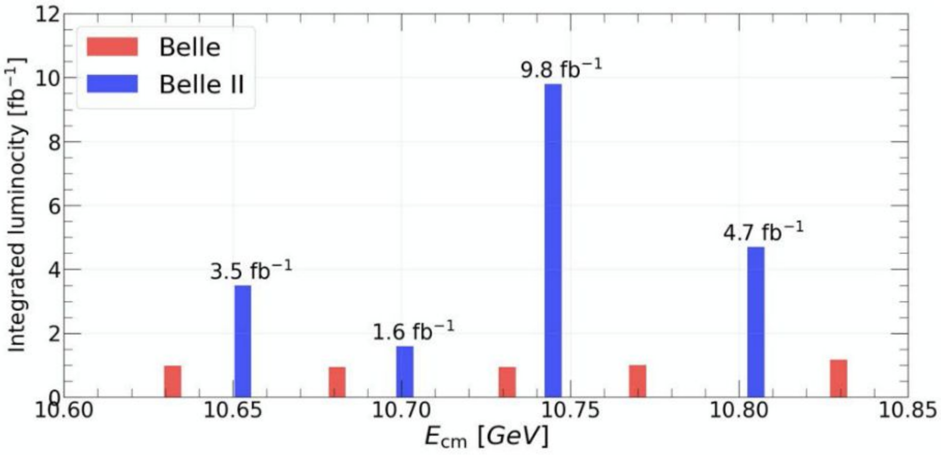
Coupled channel analysis using the K matrix formalism
[Hüsken *et al.*, PRD 106 (2022) 9, 094013]



Belle II: new scan points (Nov. 2021)

Motivations:

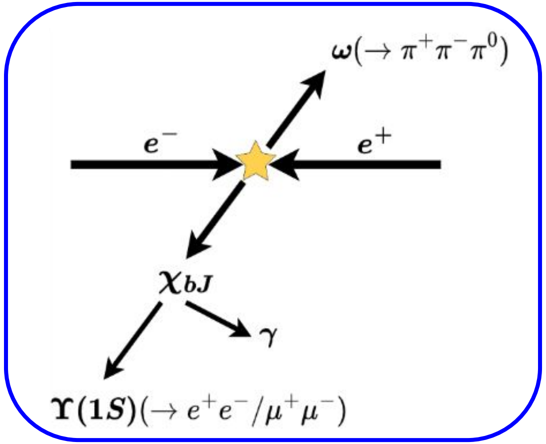
- **confirm** existence and properties of the Υ(10753) state
- update the R_b scan, $e^+e^- \to BB$, $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$
- observe **new transitions** / new **states**!

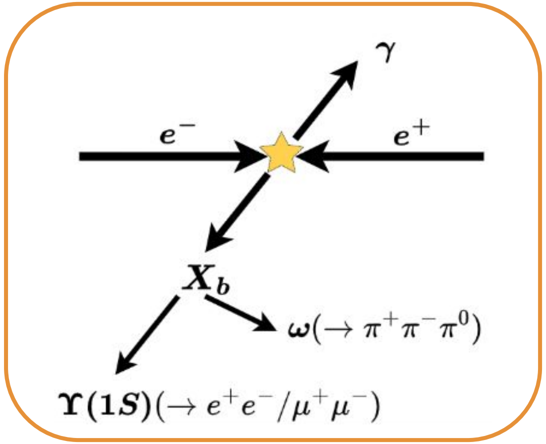


Observation of $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$ and search for X_b

Same final state $\gamma\omega\Upsilon(1S)$

$\omega \to \pi^+\pi^-\pi^0$, $\Upsilon(1S) \to l^+l^-$





Inspired by observations at **BESIII**

$Y(4230) \to \chi_{c0}(1P)\omega$

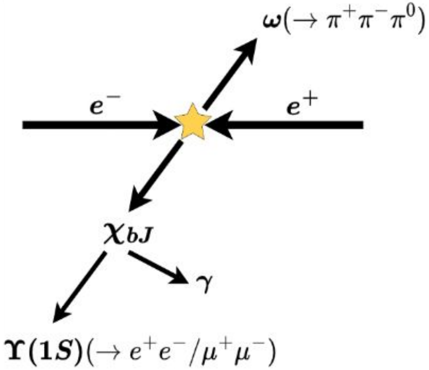
$Y(4230) \to \gamma X(3872)$

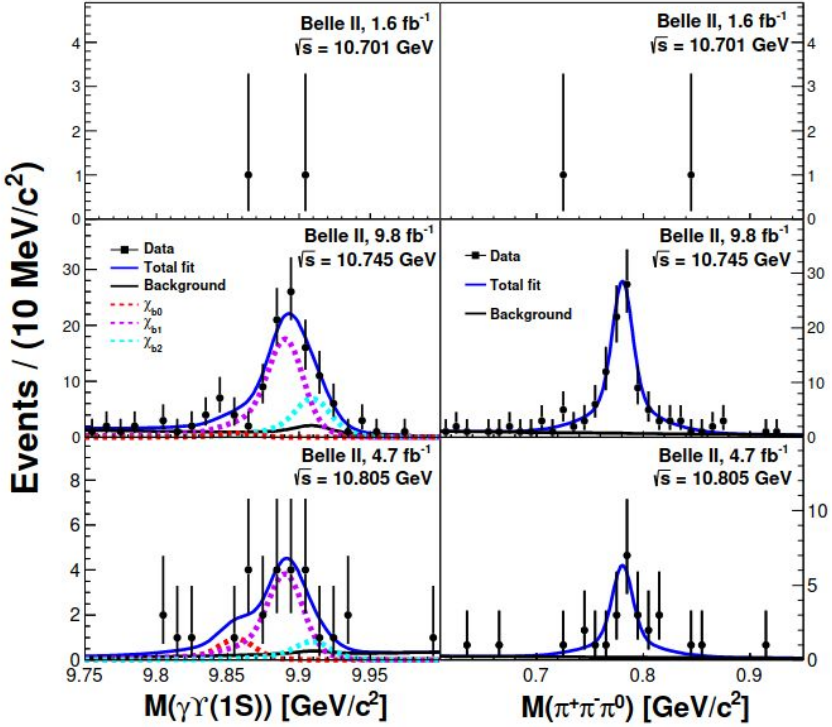
Observation of Υ(10753) → $\omega\chi_{bJ}$(1P)

Prediction for S–D mixed state
[PRD 104 034036 (2021)]

BR comparable with
$Y_b \rightarrow \pi^+ \pi^- Y(nS)$

$$\frac{\mathcal{B}(\omega\chi_{b1})}{\mathcal{B}(\omega\chi_{b2})} \sim \frac{1}{5}$$

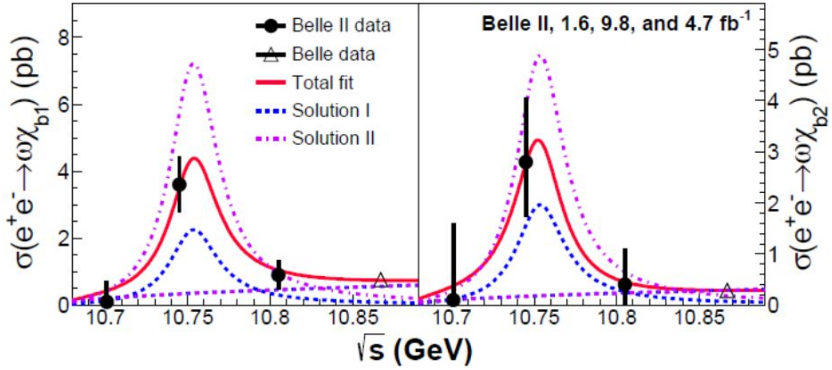




PRL 130, 091902 (2023)

Observation of Υ(10753) → $\omega\chi_{bJ}$(1P)

Signal is larger than in Υ(10753) → Υ(2S)$\pi^+\pi^-$



Signal at Υ(5S) (Belle △) is likely a **tail**

PRL 130, 091902 (2023)

Two J^{PC} = **1**$^{--}$ states, ΔM = 120 MeV, 1 order of magnitude diff in σ ⇒ hints at **different structure**

$$\frac{\sigma(e^+e^-\to\chi_{b1}(1P)\omega)}{\sigma(e^+e^-\to\chi_{b2}(1P)\omega)} = 1.3\pm0.6$$

Pure Υ(3D) would give **15** [Guo *et al.*, PLB 738 (2014), 172]
Slight tension with mixed 4S-3D state
[Li *et al.*, PRD 104 (2021) 034036]

Search for X_b

Bottomonium analogue of X(3872)

Existence predicted in both molecular and tetraquark models

- **Molecule** ⇒ M close to $B\bar{B}^*$ threshold
- **Tetraquark** ⇒ $10 < M < 11$ GeV/c^2

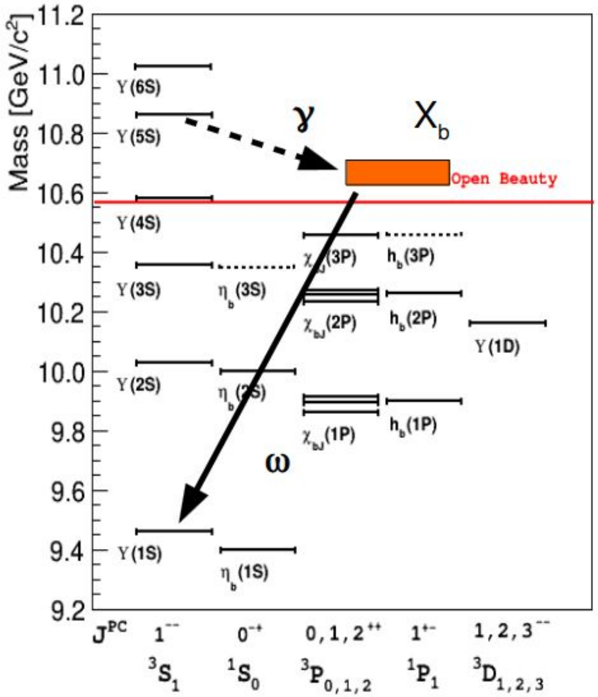
Dynamical effect (cusp)?

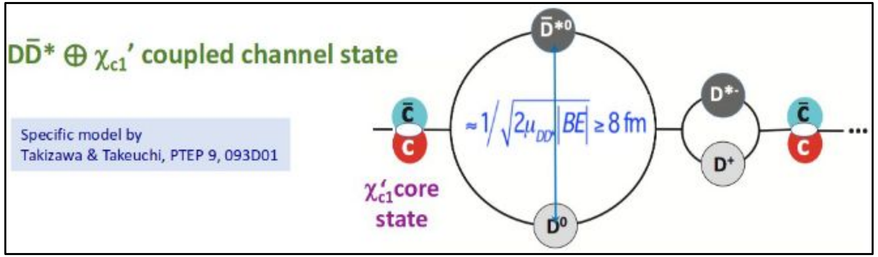
No χ_b near $B\bar{B}^*$ threshold ⇒ No X_b?

Strong UL on σ ⇒ exclude tetraquark hypothesis

Negligible isospin breaking for X_b

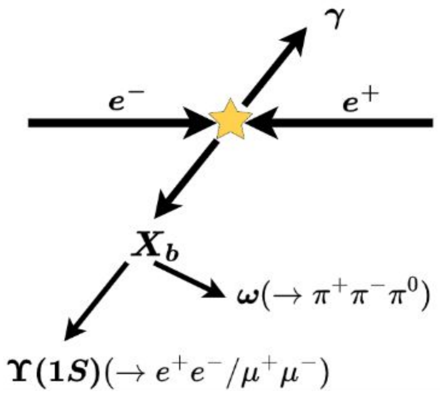
⇒ **3π mode enhanced** wrt 2π



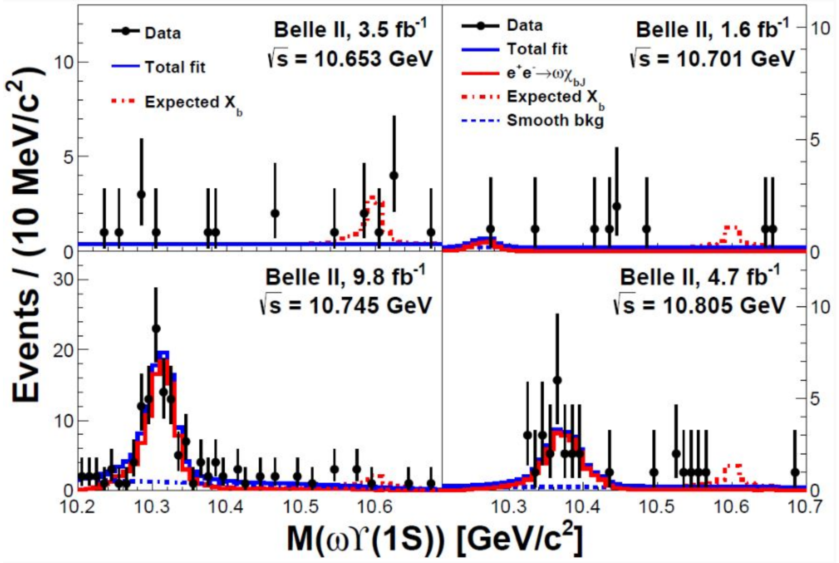


Search for X_b

- Same Υ(1S) $\pi^+\pi^-\pi^0$ γ final state
- Search for resonances in **M(Υ(1S)ω)**
- Reflection from Υ(10753) → $\omega\chi_{bJ}$(1P)
- **No evidence** for X_b signal



$\sqrt{s}$ (GeV)	M_{X_b} (GeV)	$\sigma^{UL}_{X_b}$ (pb)
10.653	10.59	0.55
10.701	10.45	0.84
10.745	10.45	0.14
10.805	10.53	0.47



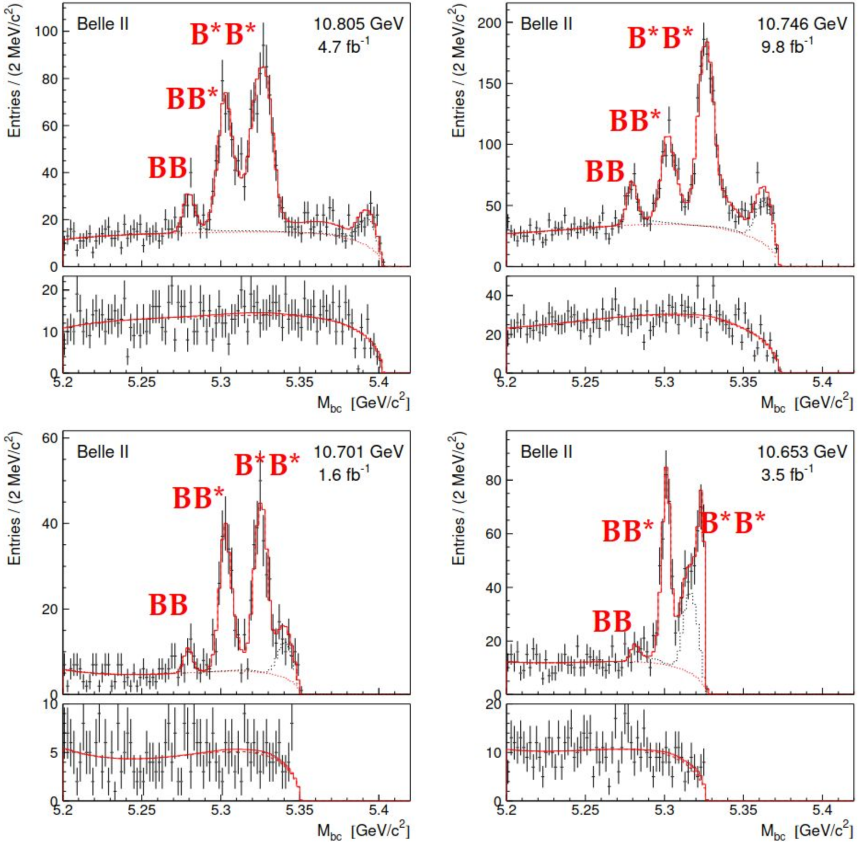
PRL 130, 091902 (2023)

$e^+e^- \to B\bar{B} + B\bar{B}^* + B^*\bar{B}^*$ cross sections

Method

- FEI: fully reconstruct one B [Comput.Softw.Big Sci. 3 (2019) 1, 6]
- Identify signals with M_{bc}
- Combine with Belle measurement [JHEP 06, 137 (2021)]

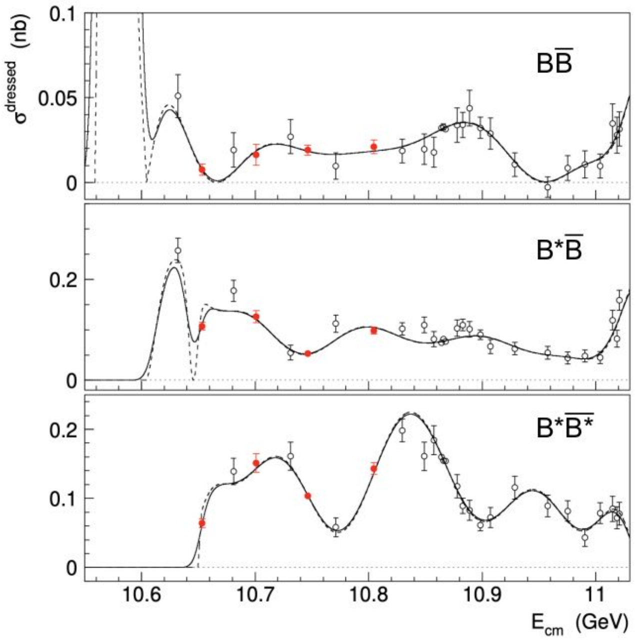
$$M_{bc} = \sqrt{(E_{cm}/2)^2 - p_B^2}$$



$e^+e^- \to B\bar{B} + B\bar{B}^* + B^*\bar{B}^*$ cross sections

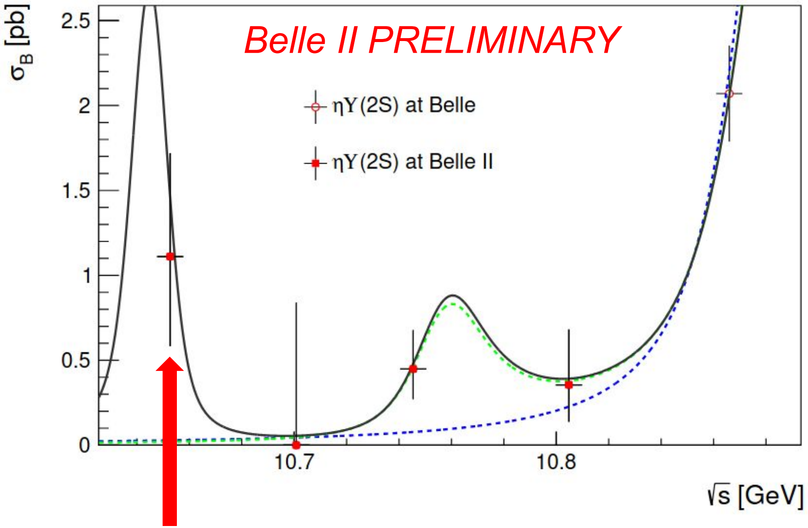
2-body cross sections fit with Chebychev polynomials

Steep rise of the $B^*\bar{B}^*$ cross section at threshold
⇒ hint at existence of **bound state**



JHEP 10 (2024) 114

Search for $e^+e^- \to \eta\Upsilon(1, 2S)$ near $\Upsilon(10753)$



— $B^*\bar{B}^*$ bound state near threshold

- - - Fit with Υ(5S) and Υ(10753)

- - - Fit with Υ(5S) only

Belle II PRELIMINARY

Mode	$N_{signal}/\mathcal{B}\epsilon$	$\mathcal{L}$ (pb^{-1})	$(1+\delta)$	$\lvert 1-\Pi \rvert^2$	σ_B (pb)
(10653.30 ± 1.14) MeV					
$\eta\Upsilon(2S)$	$(3.71^{+1.6}_{-1.3}) \times 10^3$	3521	0.881	0.929	$1.11^{+0.49}_{-0.39} \pm 0.36$
$\eta\Upsilon(1S)$	$< 0.4 \times 10^3$	3521	0.895	0.929	< 0.10
γX_b	$< 0.3 \times 10^3$	3521	0.784	0.929	< 0.14
(10700.90 ± 0.63) MeV					
$\eta\Upsilon(2S)$	$(0.00^{+1.0}_{-0.0}) \times 10^3$	1632	1.832	0.928	$0.00^{+0.31}_{-0.00} \pm 0.53$
$\eta\Upsilon(1S)$	$< 0.4 \times 10^3$	1632	0.901	0.928	< 0.22
γX_b	$< 0.1 \times 10^3$	1632	0.803	0.928	< 0.09
(10746.30 ± 0.48) MeV					
$\eta\Upsilon(2S)$	$(3.25^{+1.6}_{-1.2}) \times 10^3$	9818	0.687	0.930	$0.45^{+0.22}_{-0.17} \pm 0.05$
$\eta\Upsilon(1S)$	$< 0.9 \times 10^3$	9818	0.906	0.930	< 0.09
γX_b	$< 1.4 \times 10^3$	9818	0.817	0.930	< 0.17
(10804.50 ± 0.70) MeV					
$\eta\Upsilon(2S)$	$(1.52^{+1.4}_{-0.9}) \times 10^3$	4690	0.848	0.931	$0.36^{+0.32}_{-0.21} \pm 0.04$
$\eta\Upsilon(1S)$	$< 0.4 \times 10^3$	4690	0.912	0.931	< 0.08
γX_b	$< 1.3 \times 10^3$	4690	0.833	0.931	< 0.32

Also search for

$X_b \to \pi^+\pi^-\chi_{b1,2}(1P)$, $\chi_{b1,2} \to \gamma\Upsilon(1S)$

No signal ⇒ UL on σ_B are set

Conclusion and prospects

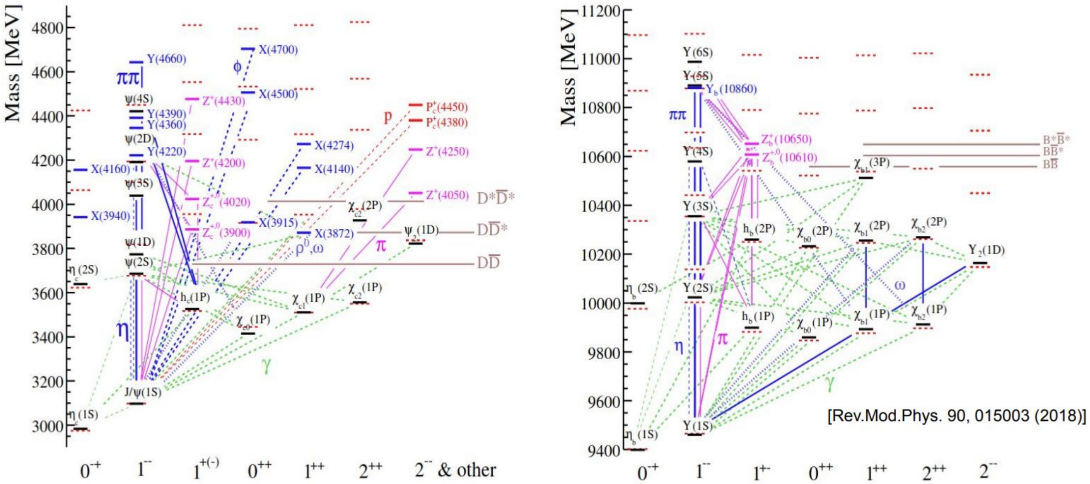
- The advent of B factories has led to a renaissance of hadron spectroscopy
  - Tens of new state discovered, more are expected to come
- Properties of T_{cc} are being studied in detail at LHCb
  - Belle II could be able to produce T_{cc} in double charmonium production with larger statistics
- Pentaquarks have been discovered in beauty hadron decays, but we are seeing the first evidence of inclusive production of these states also in Υ(nS) decays
- The nature of the recently discovered vector bottomonium-like state Υ(10750) still unclear
  - The recent **scan data** above Υ(4S) is showing interesting results
- Implementing femtoscopy in $e^+e^- \to \Upsilon(nS) \to ppX$ at Belle

Stay tuned!

Backup

The rebirth of hadron spectroscopy

- Lots of unexpected, puzzling experimental results
  - especially in **heavy quarkonium** sector
- Difficulties in QCD calculations hinder accurate predictions for spectra
- Interplay of **experimental results** and **effective models/LQCD** is needed



[Rev.Mod.Phys. 90, 015003 (2018)]

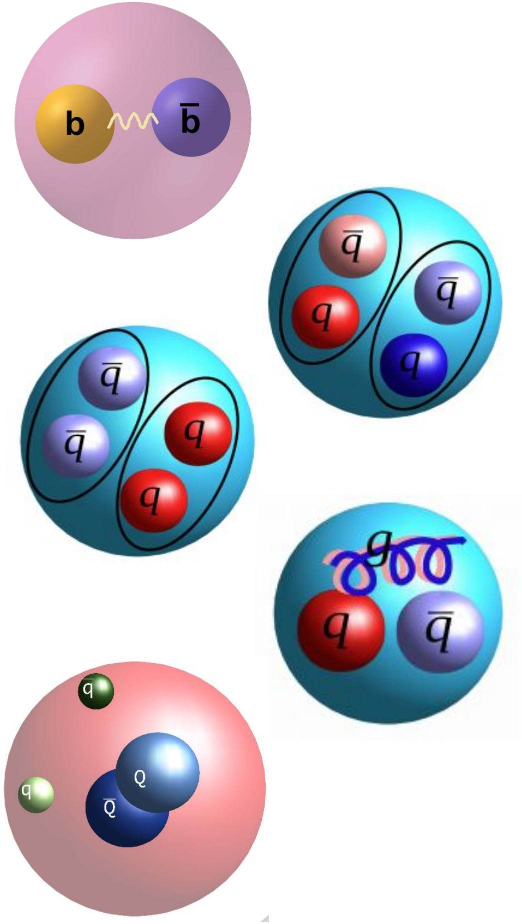
Exotic heavy quarkonia

What are they? Competition between several models:

- **Standard quarkonia** [Swanson, PRD 91, 034009 (2015)]
- **Meson molecules**: shallow bound states of two mesons [Guo *et al.*, Rev.Mod.Phys.90,015004 (2018)]
- **Compact tetraquarks**: diquark-antidiquark states bound by the color force [Polosa *et al.*, PRD89, 114010 (2014)]
- **Hybrids**: colored QQbar states with bound excited gluon [Meyer and Swanson, Prog.Part.Nucl.Phys. 82, 21 (2015)]
- **Hadroquarkonium**: QQbar state surrounded by a cloud of light quarks [Dubinskij *et al.*, PLB 666, 344 (2008)]

<u>Comprehensive reviews</u>:

- Brambilla *et al.*, Eur. Phys. J. C (2011) 1534
- Olsen *et al.*, Rev. Mod. Phys. 90 (2018) 015003

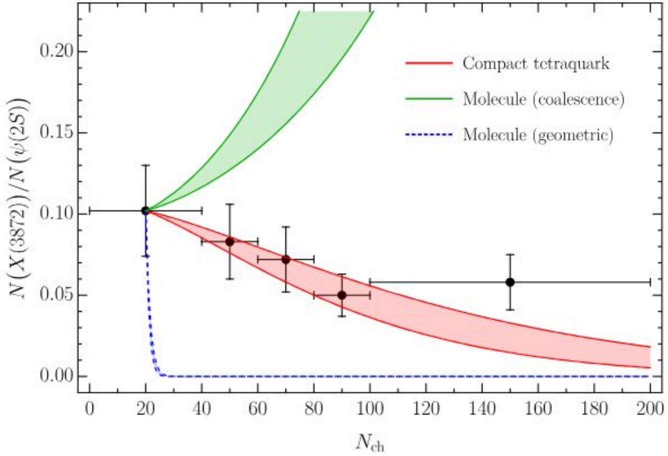


Suppression of $\chi_{c1}(3872)$

Study behaviour of states immersed in QCD matter ⇒ estimate the spatial size

Comover Interaction Model (CIM):

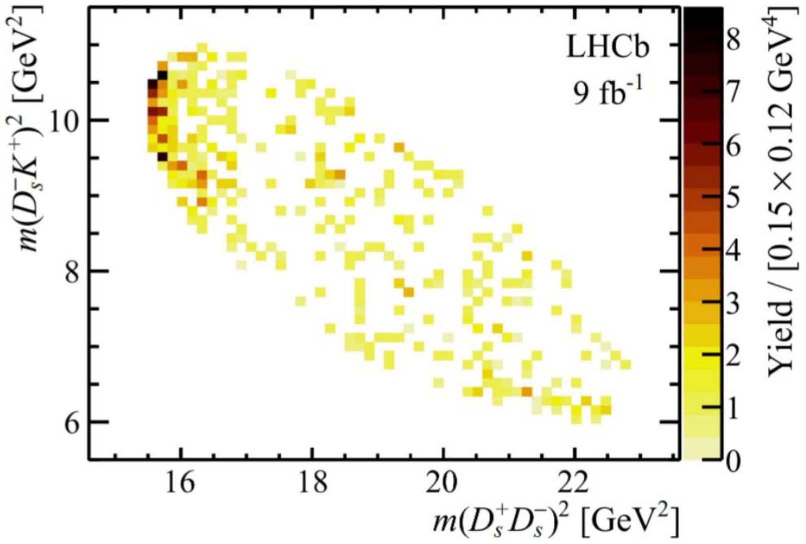
- Quarkonia broken by collision with comovers in nuclear medium
- Breakup cross section depends on radius and binding energy
- Pure molecules:
  - large radius ⇒ quick dissociation
  - reformation by coalescence ⇒ σ increases



Modeling (3872) as a compact tetraquark (r=1.3 fm) well reproduces experimental data [arXiv:2006.15044]

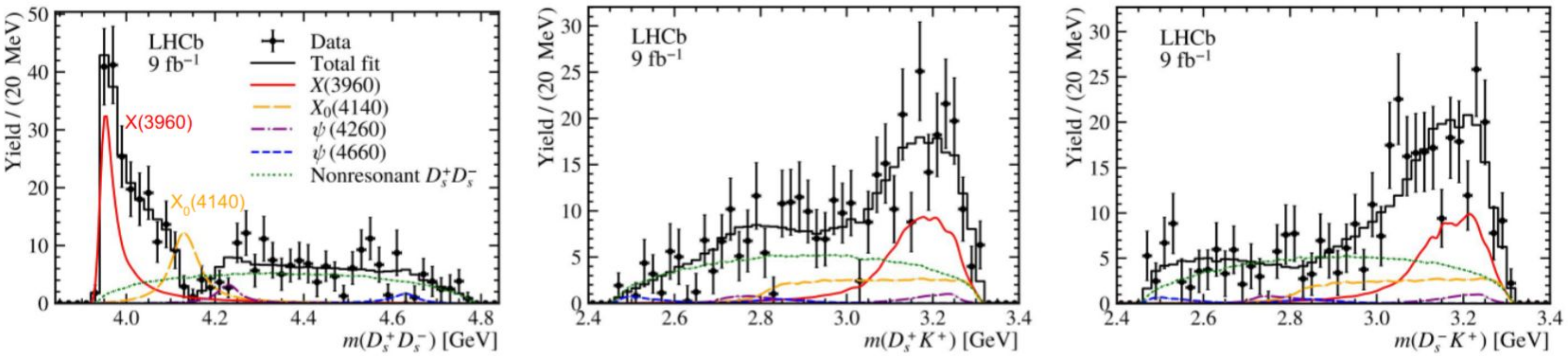
Observation of X(3960) and search for X(4140)

- Amplitude analysis of B+ → Ds+ Ds- K+
  - 360 events
  - Enhancement close to threshold in M(Ds+Ds-)2
- Fit model
  - ψ(4260), ψ(4660) contributions
  - Non-resonant Ds+Ds-K+ component
  - X(3960), X(4140) signals



[Phys. Rev. Lett. 131, 071901 (2023)]

Observation of X(3960) and search for X(4140)

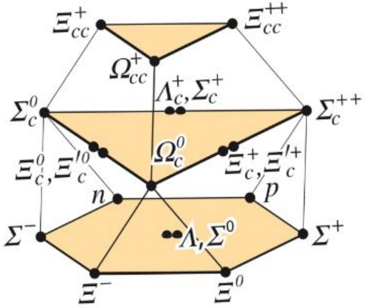


- X(3960)
  - Significance > 12σ
  - M = 3956 ± 5 ± 10 MeV, Γ = 43 ± 13 ± 8 MeV
  - Minimal quark content [ccss]
- X(4140)
  - Significance = 3.9σ
  - Dip around 4140 MeV: X(4140) or J/ψ → Ds+Ds- rescattering?
- Both states with preferred $J^{PC} = 0^{++}$

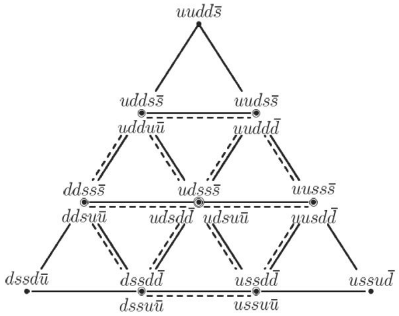
Compact objects?

If so, symmetry should imply existence of tetra- and penta-quark multiplets

e.g. can we find partners of $\mathbf{T_{cc}}$?



Spin 1/2 SU(4)$_f$ multiplet



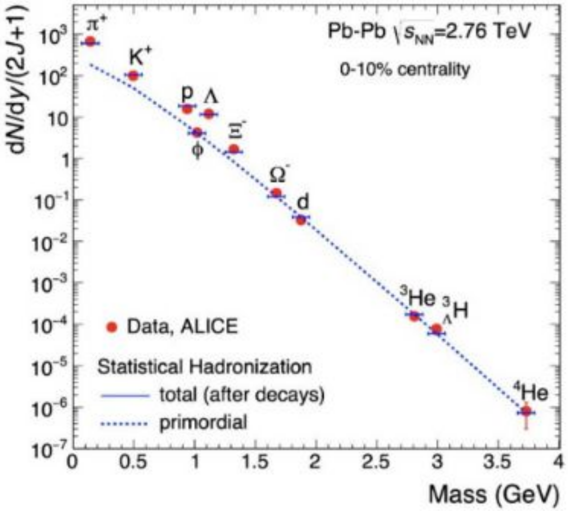
Light pentaquark multiplet

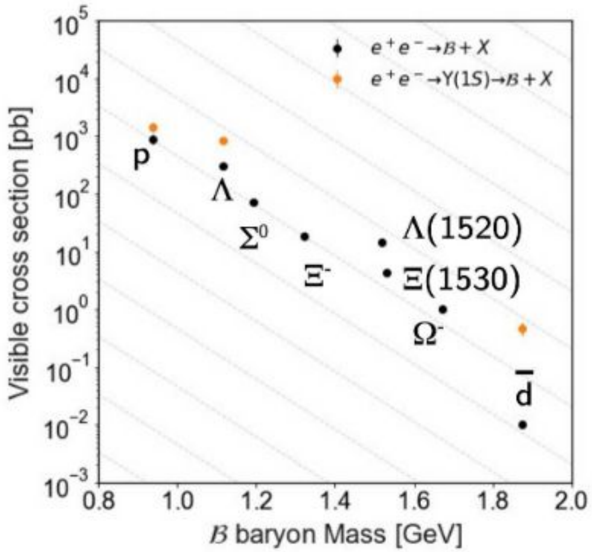
[2411.08429]

Heavy quarkonia: **non-perturbative QCD**: rely on EFTs / lattice / potential models

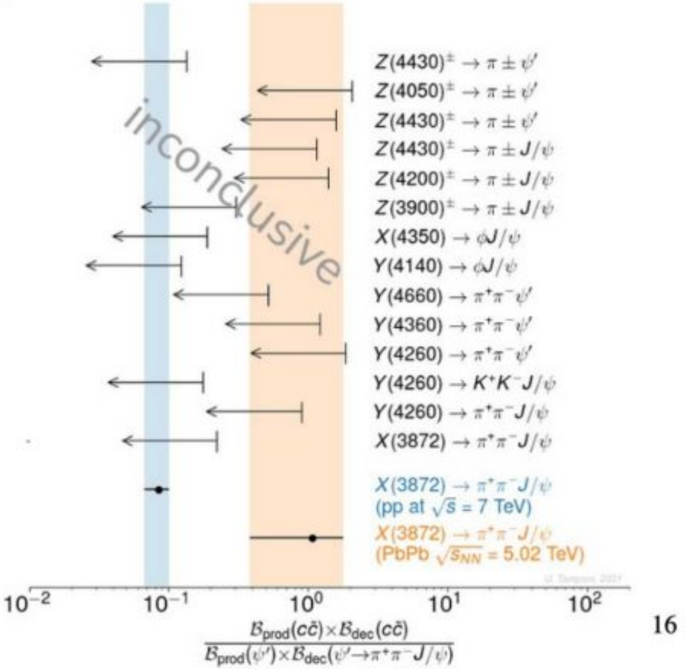
Production of exotica in Y decays at Belle

ALICE has been doing many studies on scaling laws to describe inclusive production of hadrons in heavy ion collisions.





Enhanced production of hyperons and even nuclei in bottomonium decays is known since ARGUS times and has been exploited by B factories to search for dibaryons.



BELLE has been searching for inclusive production of many tetraquarks in Y decays, but further data are needed to reach solid conclusions.
What about pentaquarks in Y decays?

The $\chi_{c1}(3872)$ state

N. Hüsken, E. S. Norella, I. Polyakov

4.2. *The $\chi_{c1}(3872)$* *(also known as $X(3872)$)*

MESON-LIKE/HIDDEN CHARM/ISOSCALAR

quantum numbers: $I^G(J^{PC}) = 0^+(1^{++})$

minimal quark content: $[c\bar{c}]$, more likely $[c\bar{c}(u\bar{u} + d\bar{d})]$

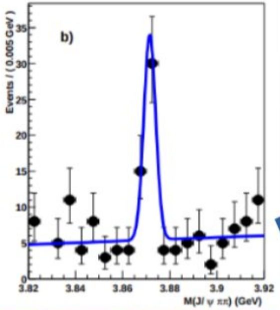
experiments: Belle, CDF, D0, BaBar, LHCb, CMS, ATLAS, BESIII (and potentially E705, COMPASS)

production: B^+, B^0, B^0_s and Λ^0_b decays, prompt pp, $p\bar{p}$, pPb (Pbp) and PbPb collisions, $e^+e^- \to \gamma\chi_{c1}(3872)$, $\omega\chi_{c1}(3872)$ potentially via ψ- or χ_c-like states

decay modes: $\pi^+\pi^- J/\psi$, $\omega J/\psi$, $D^{*0}\bar{D}^0$, $\pi^0\chi_{c1}(1P)$, $\gamma J/\psi$, $\gamma\psi(2S)$

nearby threshold: $D^{*0}\bar{D}^0$

width: 1.19 ± 0.21 MeV *(Breit-Wigner)*

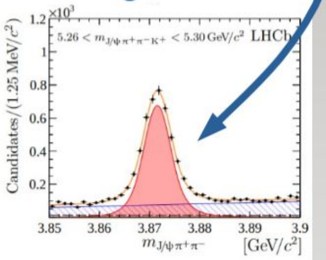


Belle, PRL 91 (2003) 262001

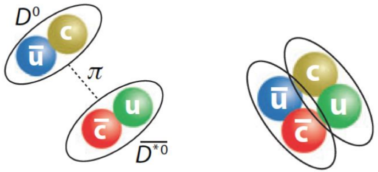
$36 \to 20\text{x}10^3$ signal events

$m(\chi_{c1}(3872)) - m(D^0\bar{D}^{*0}) = -0.07 \pm 0.12$ MeV

LHCb, JHEP 08 (2020) 123



LHCb, JHEP 08 (2020) 123



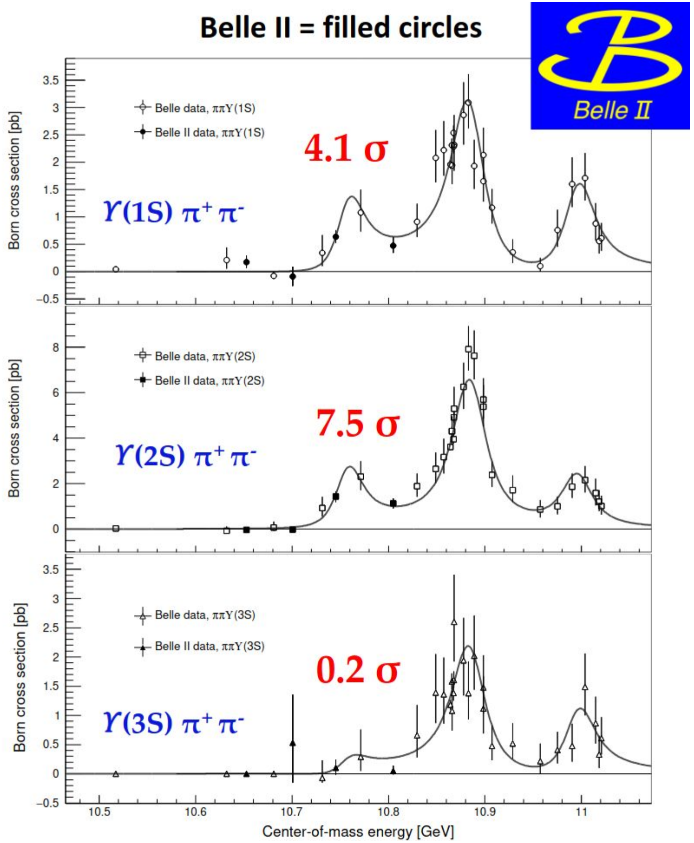
D^0–$\overline{D}^{*0}$ "molecule" **Diquark–diantiquark**

Proximity to threshold, dominant decay modes, $J^{PC} = 1^{++}$

⇒ molecular picture is favored

Di-pion transitions

$\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$, n=1,2,3



Analysis of di-pion transitions: excellent confirmation of Υ(10753) properties

M = 10756.6 ± 2.7 ± 0.9 MeV
Γ = 29.0 ± 8.8 ± 1.2 MeV

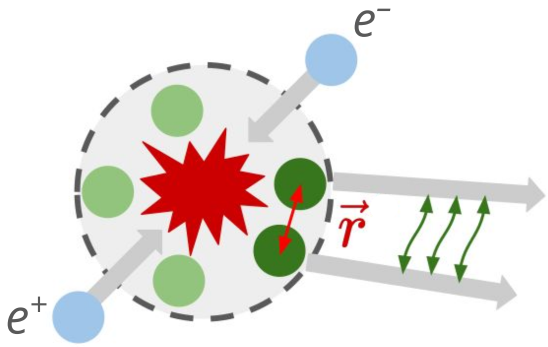
[JHEP 07, 116 (2024)]

Femtoscopy

Method to probe **geometric** and **dynamic** properties of a **source of hadrons**

They are affected by

- quantum statistics
- interaction potential
- hadronization process



Key observable: 2-particle correlation function C(k*)

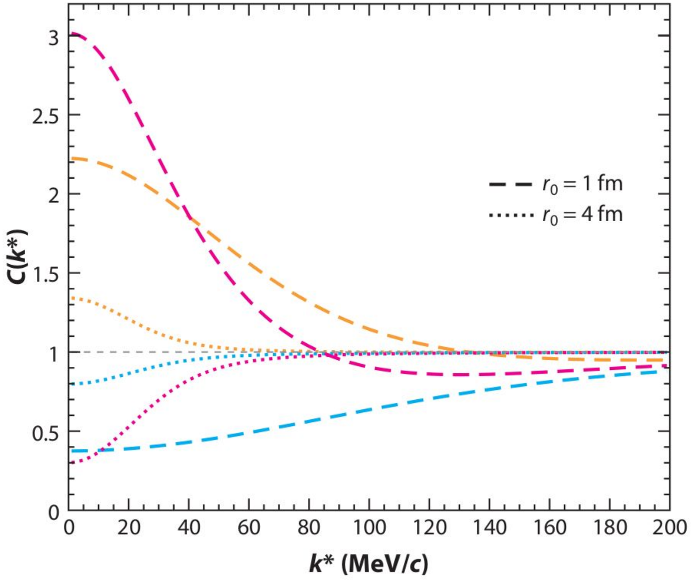
(k* = relative momentum) $$C(k^*) = \int S(r)\,|\,\Psi(\vec{k}^*,\vec{r})\,|^2\,\mathrm{d}^3r$$

- known interaction ⇒ study source geometry
- known source ⇒ study the interaction

Correlation function

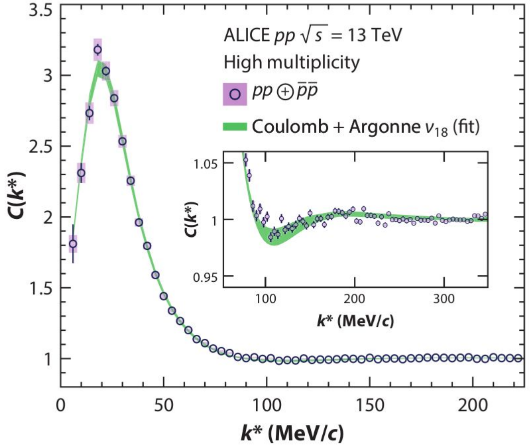
$$C(k^*) = \int S(r) \mid \Psi(\vec{k^*}, \vec{r}) \mid^2 \mathrm{d}^3 r$$

Expectations from theory for 2 different **source sizes (r_0)**



[*Phys. Atom. Nucl.* 71 (2008) 1572-1578]

- Orange: attractive potential
- Blue: repulsive potential
- Magenta: shallow bound state

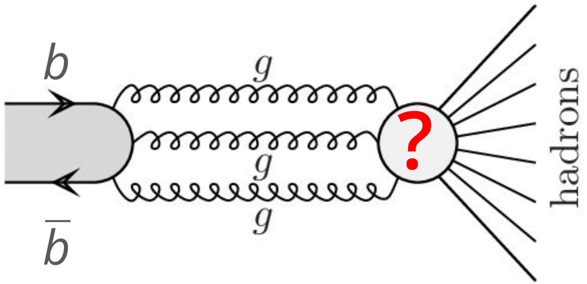


[*Phys.Lett.B* 805 (2020) 135419]

Goal of the analysis

The *pp* interaction potential is well known (Coulomb + Argonne v_{18})

But we know nothing about the **source geometry**



Idea: <u>select protons with **high purity**</u>

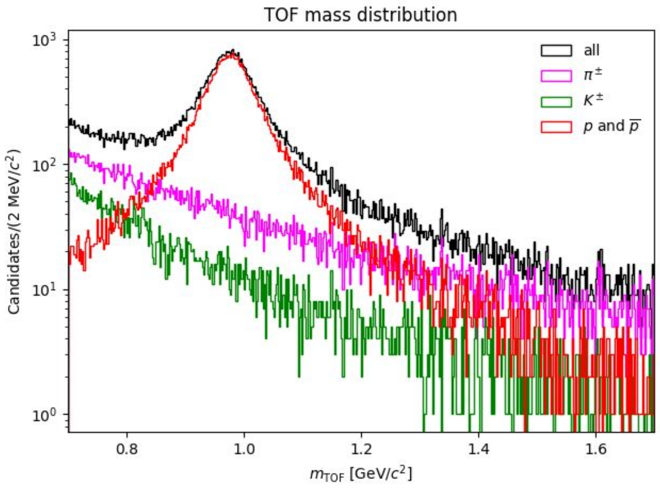
Then build $C_{\text{exp}}(k^*) = \mathcal{N} \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$

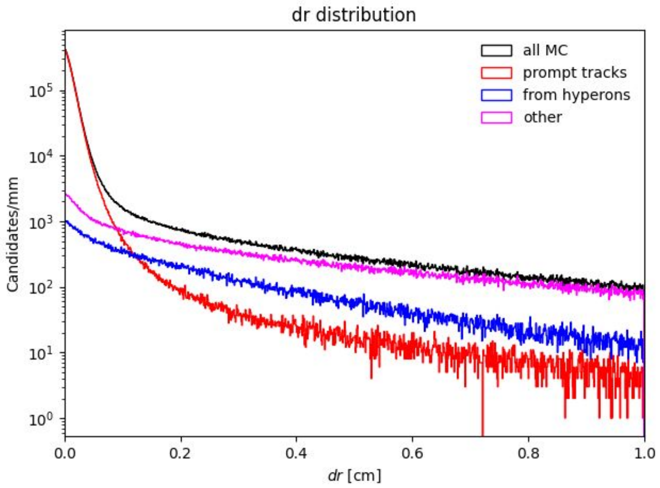
Fit to $C(k^*) = \int S(r) \, | \, \Psi(\vec{k}^*, \vec{r}) \, |^2 \, \mathrm{d}^3 r$ with **known Ψ**

Get **source size**

Using this technique in $\boldsymbol{e^+e^- \to \Upsilon(nS) \to} ggg$ for **1st time**!

Identifying prompt protons





Fit ⇒ **proton** fraction

Fit ⇒ **prompt** tracks fraction

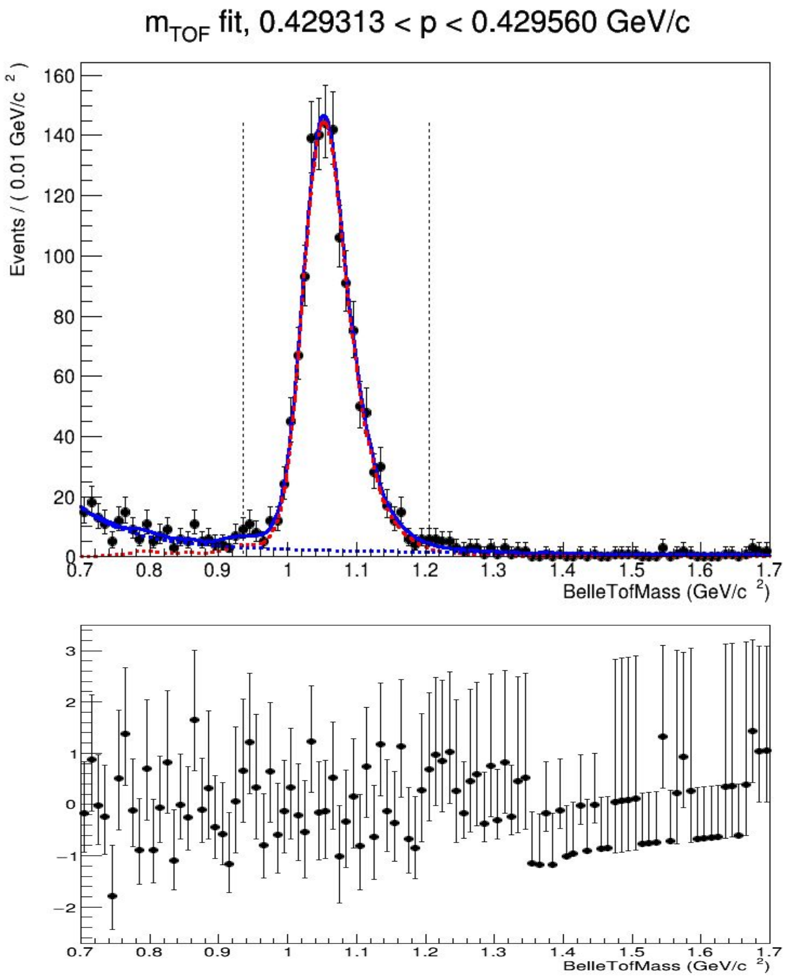
m_{TOF} fits

Extended binned ML

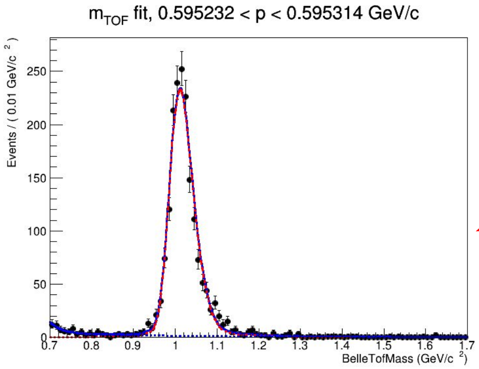
$$f(m) = n_S \mathrm{T}_{\mathrm{MC}} * \mathcal{SN}(\mu, \sigma_L, \sigma_R) + \\ + n_B \left(f_\pi \mathrm{Exp}(\lambda_\pi m) + f_K \mathrm{Exp}(\lambda_K m)\right)$$

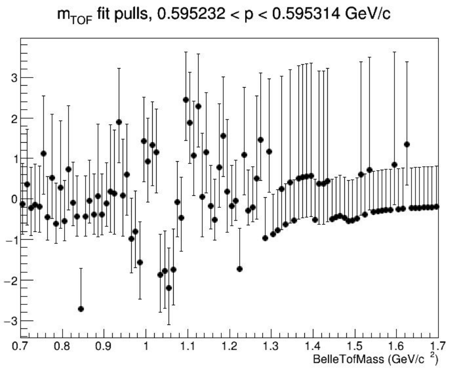
After convergence:

- get signal mode and FWHM
- take **(-2*FWHM, +2.5*FWHM)** range
- get sig and bg p.d.f.'s integrals inside range
- multiply integrals by n_S and n_B

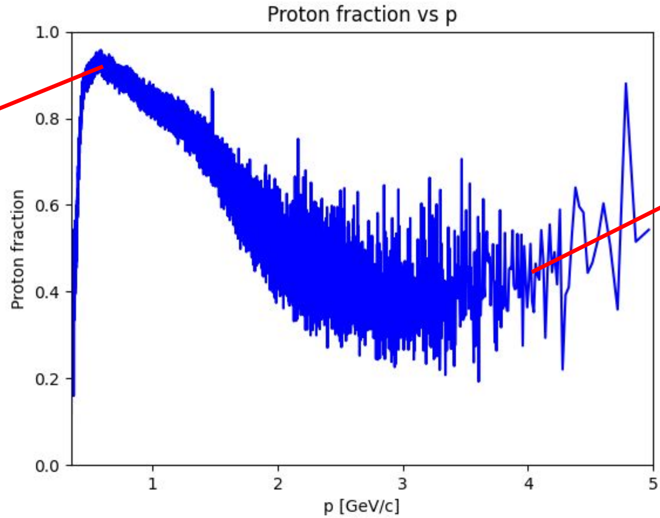


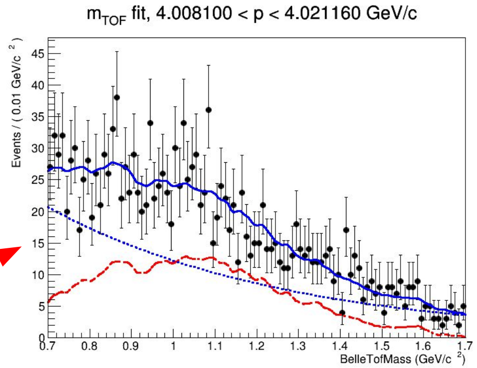
Measured (anti-)proton fraction vs *p*

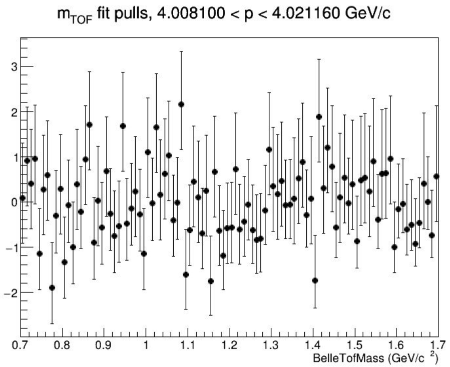




Y(2S) data (good)







These values are put into a lookup table for proton identification

Mixed event technique

We build k* distributions for pairs reconstructed in both **same** and **mixed** events

Mixed events: have to be similar

- N_{tracks} bins: [2, 4, 6, 10, 15, 20, 25, 30, 50]
- R_2 bins: [0.0 ,0.1, 0.2, 0.3, ... , 1.0]

$$C_{\text{exp}}(k^*) = \mathcal{N}\frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$