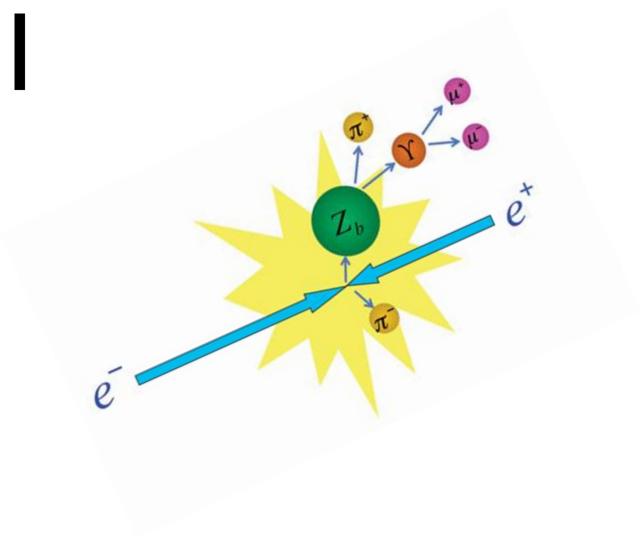
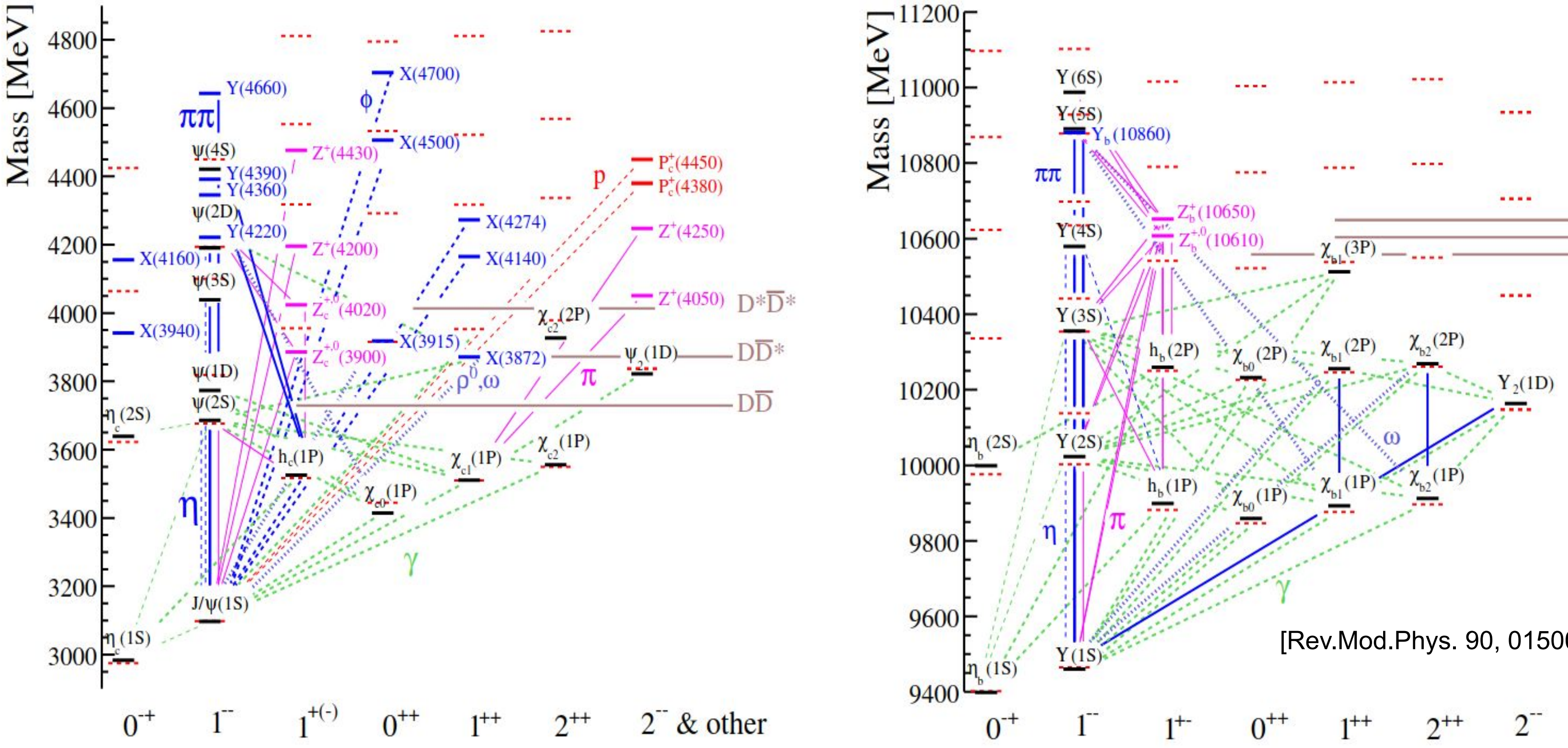
Status and prospects for quarkonium at Belle II



IPA2022 conference, TU Wien
A. Boschetti
(on behalf of the Belle II collaboration)

Heavy quarkonia



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

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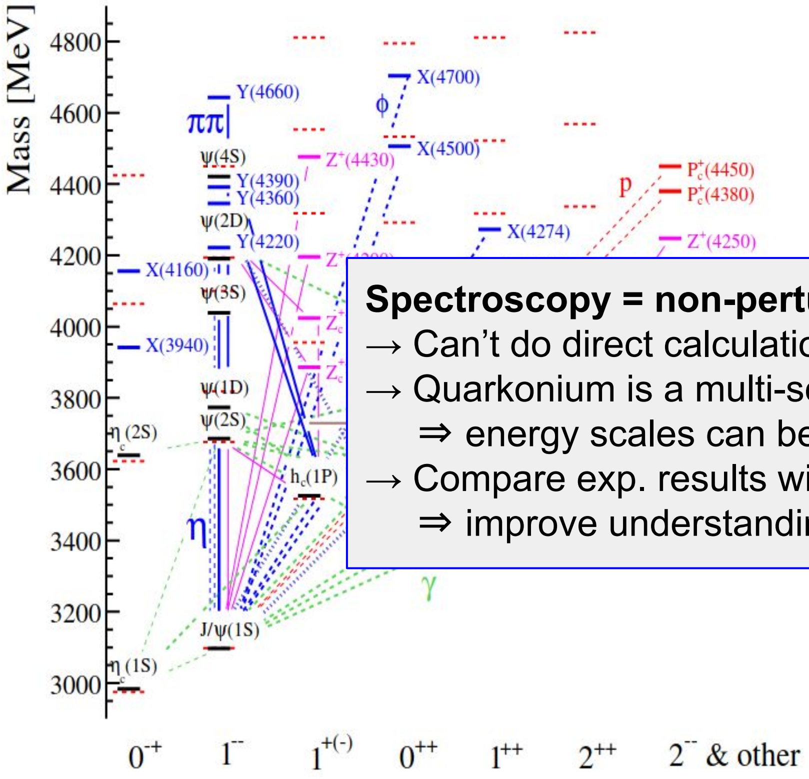
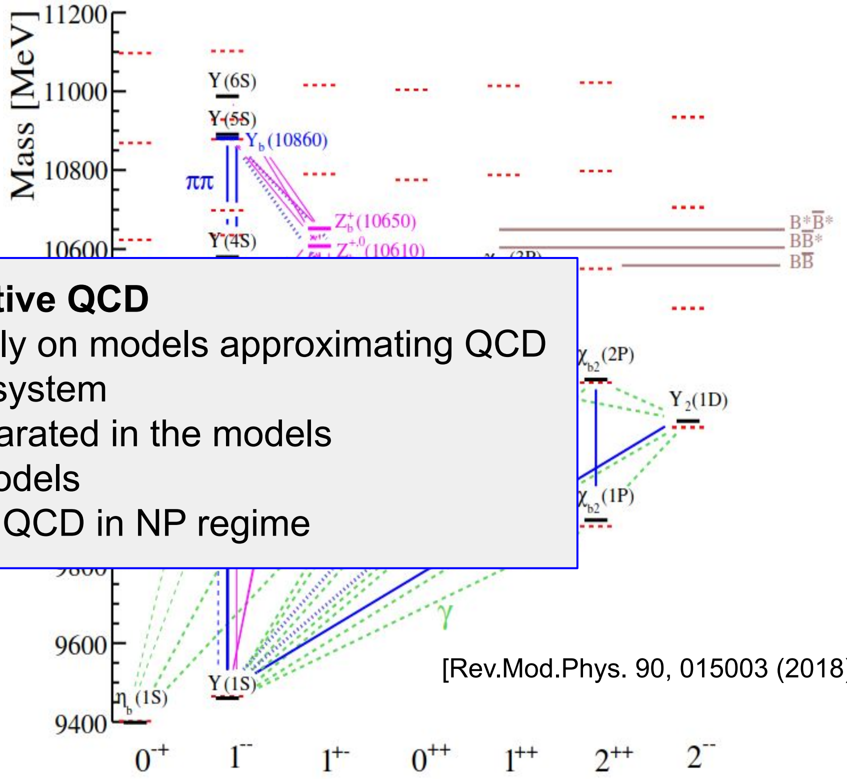
Heavy quarkonia





Spectroscopy = non-perturbative QCD

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

→ Quarkonium is a multi-scale system

⇒ energy scales can be separated in the models

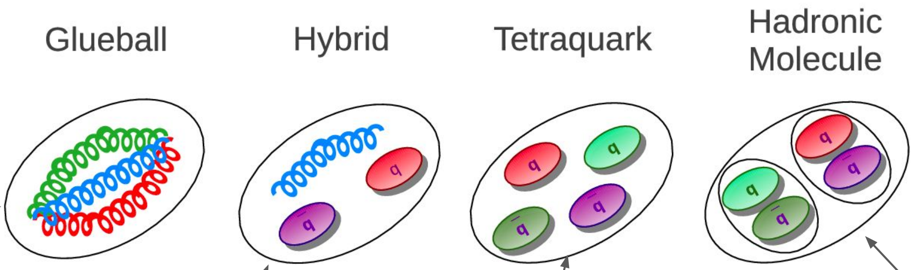
→ Compare exp. results with models

⇒ improve understanding of QCD in NP regime

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

XYZ states

What are they? ⇔ Which partons, how is color arranged?



No quarks

"Excited" flux tube

Compact object, gluon exchange

Bound mesons, π/σ/ω exchange

[Rev.Mod.Phys. 90 (2018) 1, 015003]

+ threshold, cusp effects

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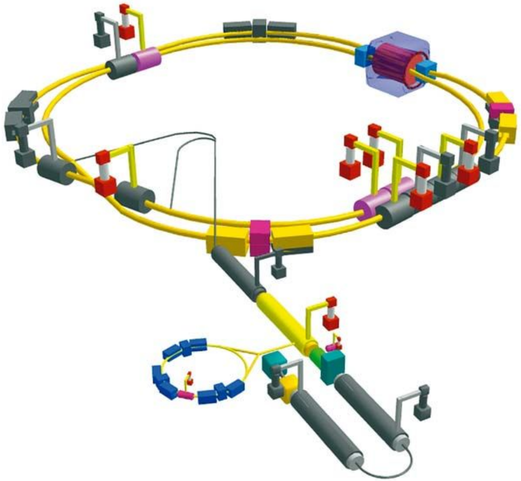
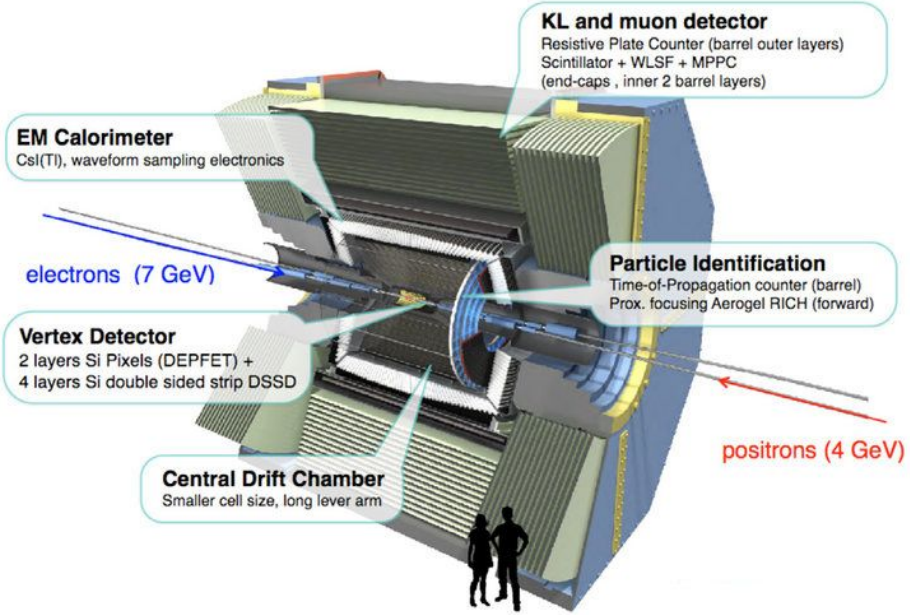
Belle II @SuperKEKB

Asymmetric **e^+e^- collider**
⇒ **$J^{PC}=1^{--}$** states directly produced





$\sqrt{s} \sim 9 - 11\ GeV$ ⇒ $b\bar{b}$ energy region

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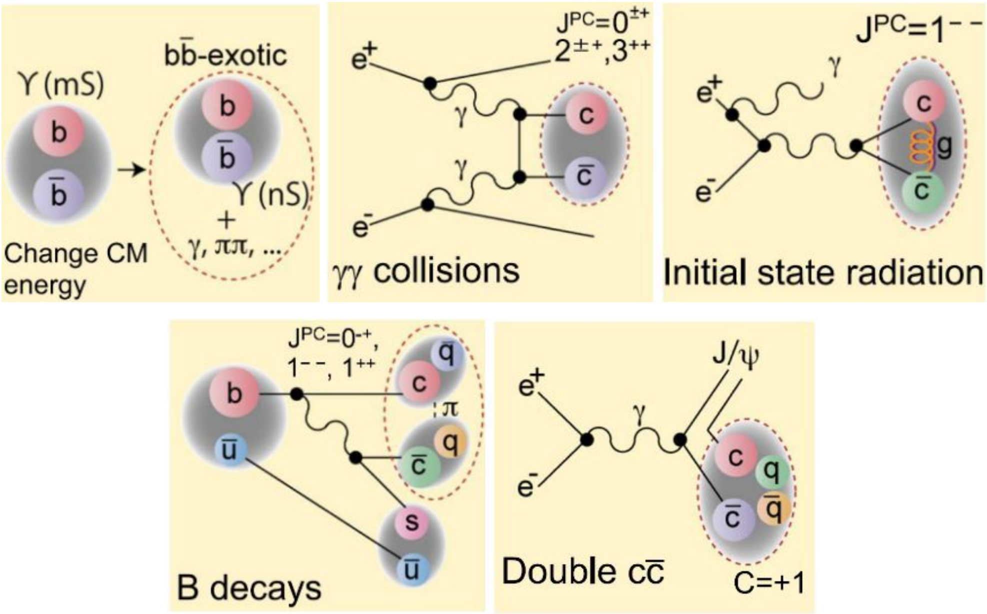
Bottomonium

- Hadronic transitions from ϒ(4S)
- Initial state radiation (ISR)
- Direct production (tunable CM energy)

Charmonium

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



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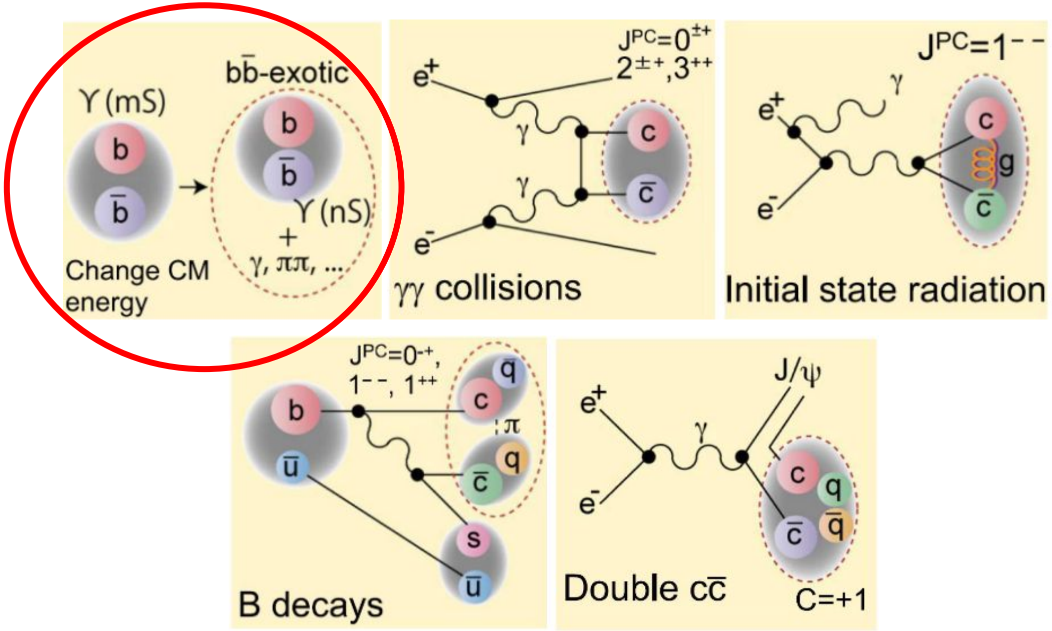
Quarkonium production @SuperKEKB

Bottomonium

- Hadronic transitions from Υ(4S)
- Initial state radiation (ISR)
- Direct production (tunable CM energy)

Charmonium

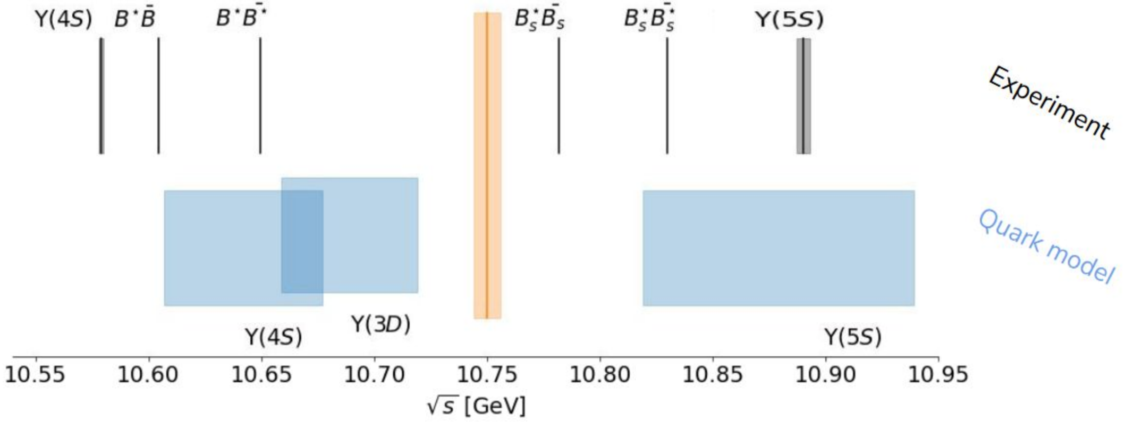
- γγ fusion at Υ(4S)
- B decays via b→c
- ISR

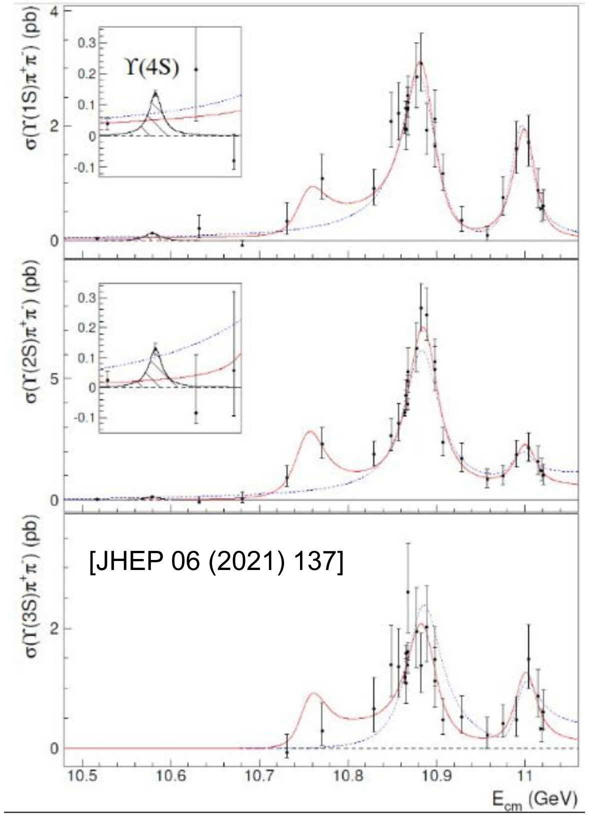


Y(10750)

- Discovered in di-pion transitions to ϒ(nS)
- Far from S-wave threshold ⇒ unlikely hadronic molecule
- No direct matching to conventional states
- In this region we observe a drop in hadronic cross section!

May be 4S-3D mixing, predicted by [PRD 104, 034036 (2021)]





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Υ(10750)

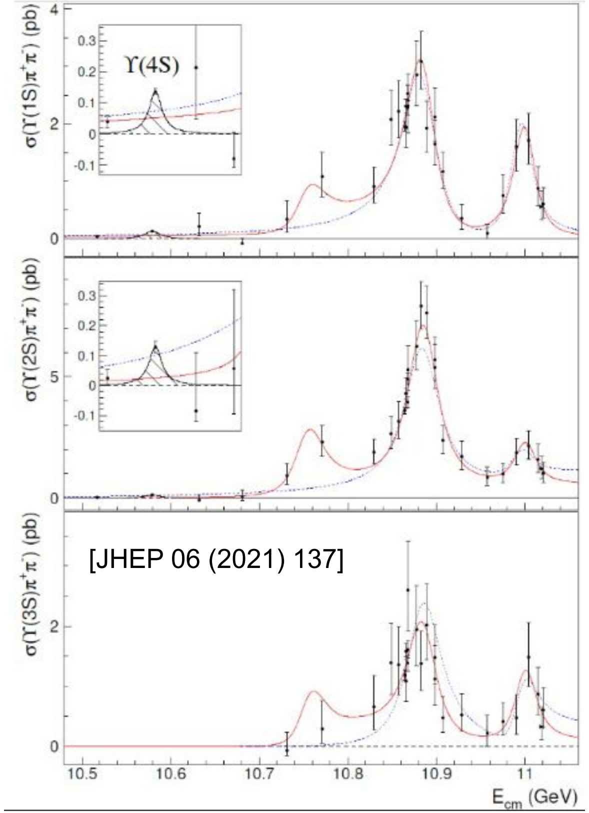
The Υ(10750) state is generating a lot of theoretical interest

Conventional interpretations:

- Chen, Zhang & He, PRD 101, 014020 (2020)
- Li et al., EPJC 80, 59 (2020)
- Liang, Ikeno & Oset, PLB 803, 135340 (2020)

Less conventional interpretations:

- Wang, CPC 43, 123102 (2019)
- Ali, Maiani, Parkhomenko & Wang, PLB 802, 135217 (2020)
- Bicudo, Cardoso & Wagner, arXiv:2008.05605 (2020)
- Giron & Lebed, PRD 102, 014036 (2020)
- …



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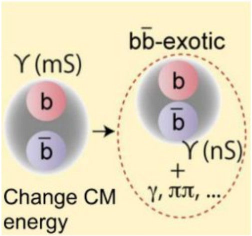
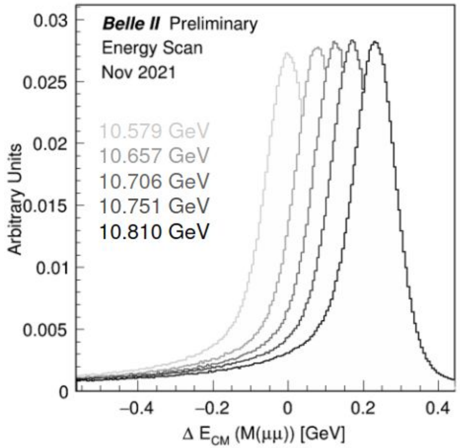
Belle II energy scan above Υ(4S)

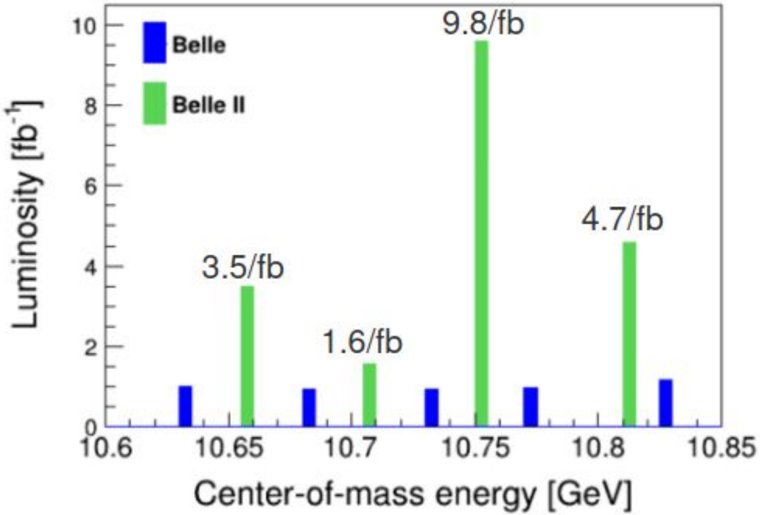


Nov. 2021 →Unique high stat. points between previous Belle energies

First time above Υ(4S) for SuperKEKB ⇒ important test!



E_{CM} change w.r.t. Υ(4S)



Belle II scan dataset is now bigger than Belle's

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Belle II **new result**

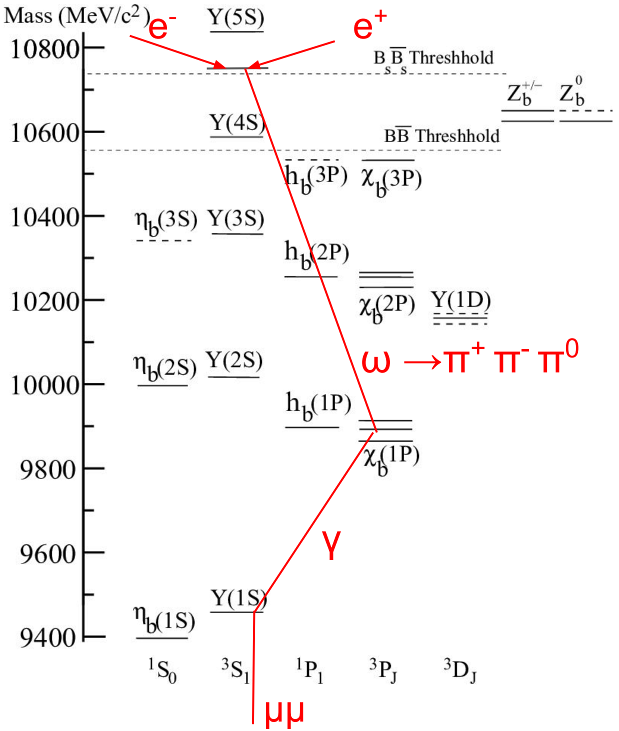
Observation of $e^+e^- \to \omega[\pi^+ \pi^- \pi^0]\ \chi_{bJ}(1P)[\gamma\Upsilon(1S)]$ and search for $X_b \to \omega\Upsilon(1S)$ [arXiv.2208.13189]

Motivation:

- BF[$Y(10750) \to \omega\chi_{bJ}(1P)$] ~ 10^{-3} predicted for 4S-3D mixing [PRD 104,034036 (2021)]
- BESIII: $e^+e^- \to Y(4220) \to \pi\pi J/\psi$, $\gamma X(3872)$, $\omega\chi_{c0}(1P)$, … ⇒ X_b analog of X(3872)?

Reconstruction:

- Events with 4 – 5 tracks
- Exclusive ⇒ low background
- 4C kinematic fit



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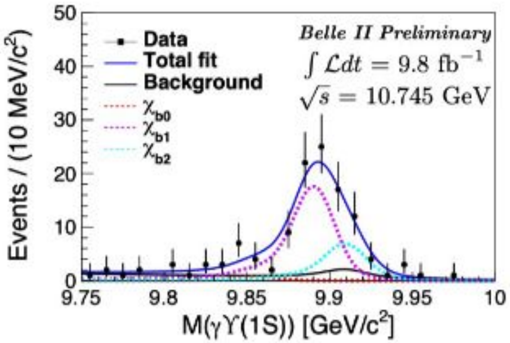
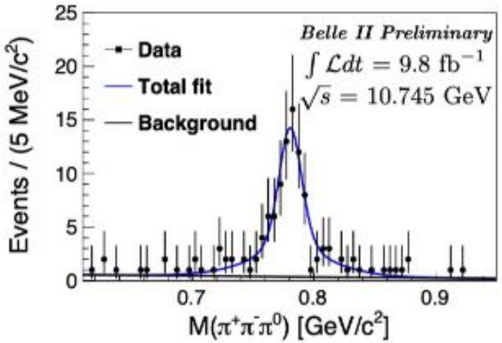
Belle II **new result**

Exclusive analysis ⇒ Very **low background**
Unbinned ML **fits to invariant mass distributions**
→ extract signal yield

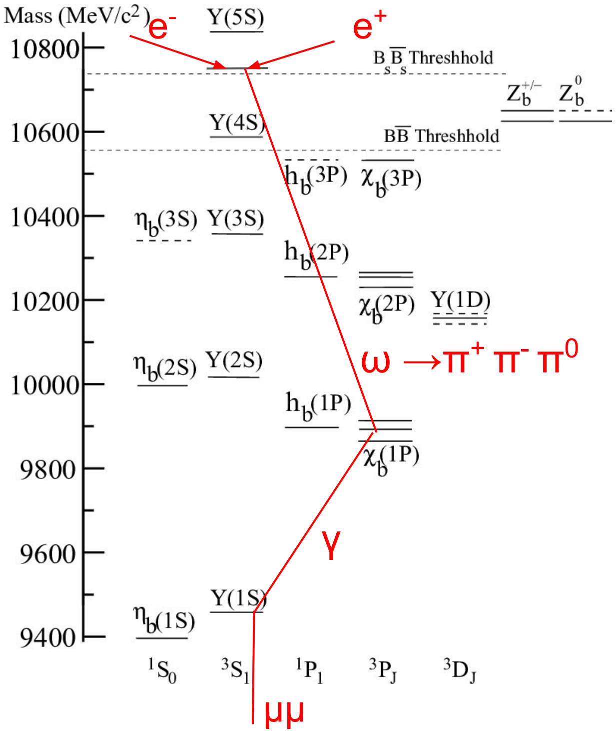
[arXiv.2208.13189]





Peaks on χ_{bJ}**(1P) mass**

Peaks on **ω mass**



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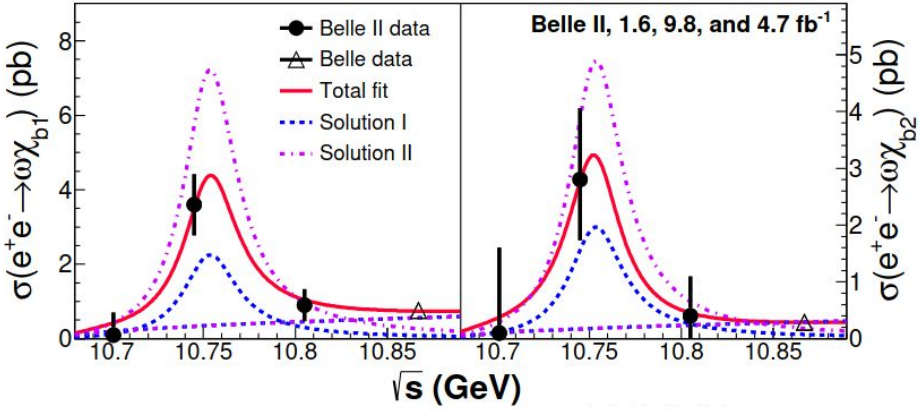
Belle II **new result**



[arXiv.2208.13189]

The Belle Collaboration published an analogous result at 10.867 GeV (triangle in plot).
[PRL 113, 142001 (2014)]

Transition from Y(10860) resonance or tail of the Y(10750) structure?

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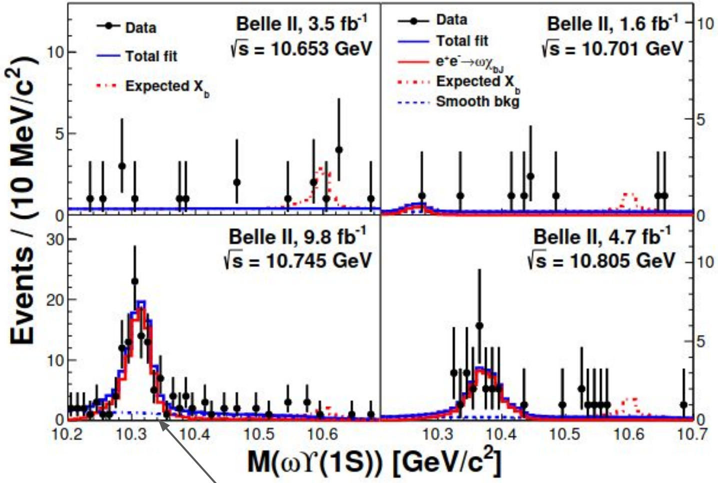
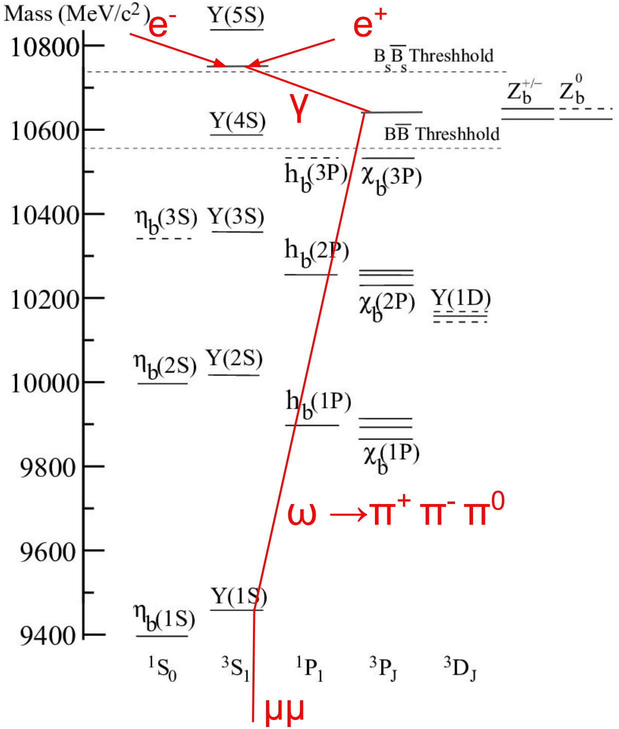
Belle II new result

No evidence for the X_b state



Reflection of $e^+e^- \to \omega\chi_{bJ}(1P)$



Upper limits:

- $\sigma_B(e^+e^- \to \gamma X_b) < 10^{-1}$
- $B[X_b \to \omega\Upsilon(1S)] < 10^{-1}$

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Ongoing analyses

Υ(4S):

- $\Upsilon(4S) \to \eta h_b(1P)$
- $\Upsilon(4S) \to \phi\eta_b(1S)$
- $e^+e^- \to \Upsilon(1S) + X$

Scan:

- $Y_b(10750) \to \pi^+\pi^- h_b(1P)$
- $B\overline{B}$ decomposition w.r.t. $\sqrt{s}$
- $Y_b(10750) \to \omega\eta_b(1S)$
- $e^+e^- \to \pi^+\pi^-\Upsilon_2\,(1D)$
- $e^+e^- \to J/\psi\, X$

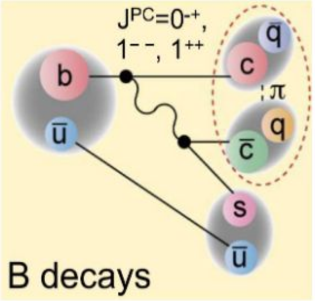
Main goals:

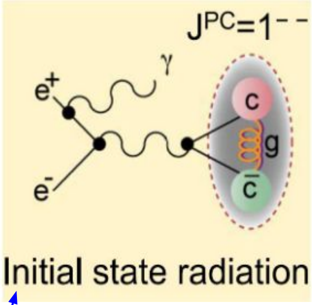
- Improve knowledge on spectrum
- Search for more transitions
- Precise measurement of mass and width of $Y_b(10750)$
- Study of $\pi^+\pi^-$ / ω / η / ϕ transitions ⇒ test NRQCD and other models

Prospects: charmonium(-like) physics

Analysis of unexplored channels

$$B \to J/\psi \eta K$$
$$B \to J/\psi \eta' K$$



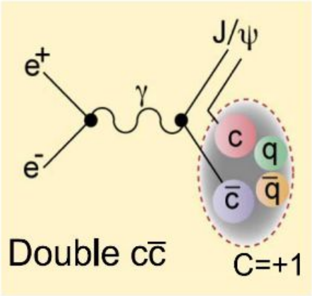


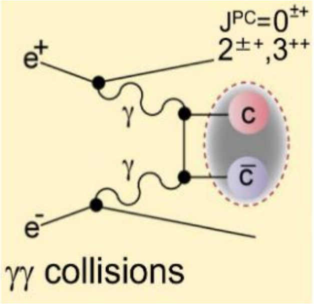
Improve meas. of cross section

$$e^+e^- \to \gamma_{ISR}(c\bar{c})X$$

above 5 GeV

$$e^+e^- \to J/\psi D^*\overline{D}^*$$
$$e^+e^- \to J/\psi D^*\overline{D}$$
$$e^+e^- \to \psi(2S)D^{(*)}\overline{D}^{(*)}$$





$$e^+e^- \to e^+e^- J/\psi \phi$$

Unique to Belle II !

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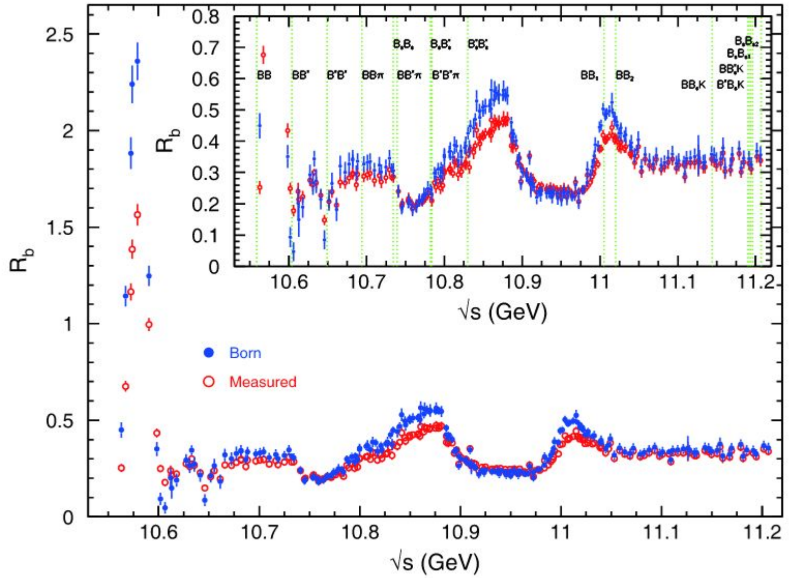
Prospects: bottomonium(-like) physics

The program is much larger, waiting for more data!

QCD goals in the bottomonium region:

- Precise decomposition of the R_b ratio
- Systematic exploration of threshold region

$$R_b = \frac{\sigma(e^+e^- \to b\bar{b} \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



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

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Narrow bottomonia: new physics

Target: collect 1 billion Υ(3S) or Υ(2S)

NP goals:

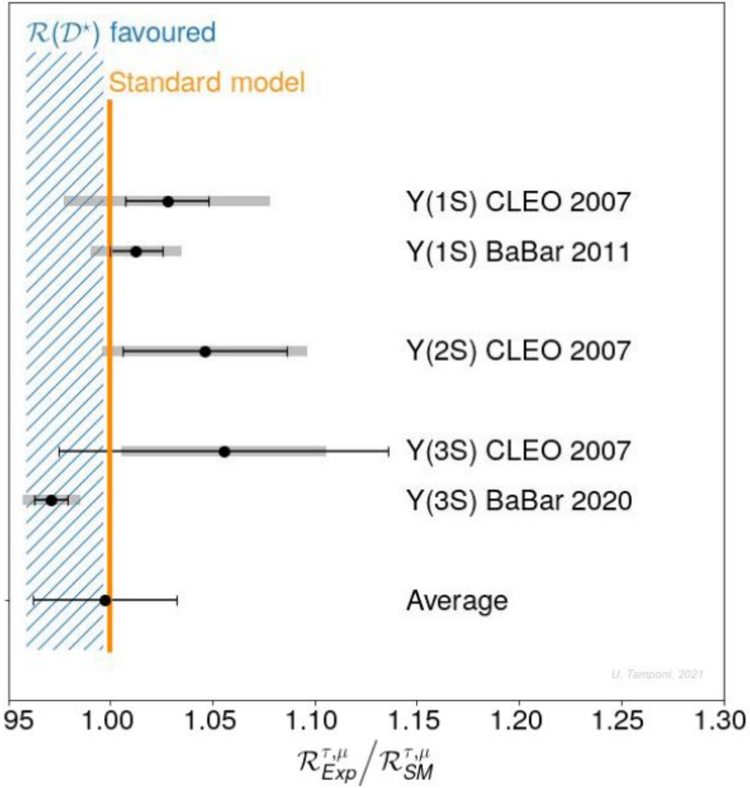
- LFU: < 0.5% precision on Υ(nS) → $\tau^+\tau^-$, Υ(nS) → $\mu^+\mu^-$

  Connection with *R(D*)* [JHEP 06 (2017) 019])

- LFV: maximize sensitivity on

  Υ(nS) → $e\tau$, $\mu\tau$

- Υ(nS) → multi-quark system + X
  - exotic charmonia



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Narrow bottomonia: baryogenesis

$$e^+e^- \to \Upsilon(nS) \to ggg$$

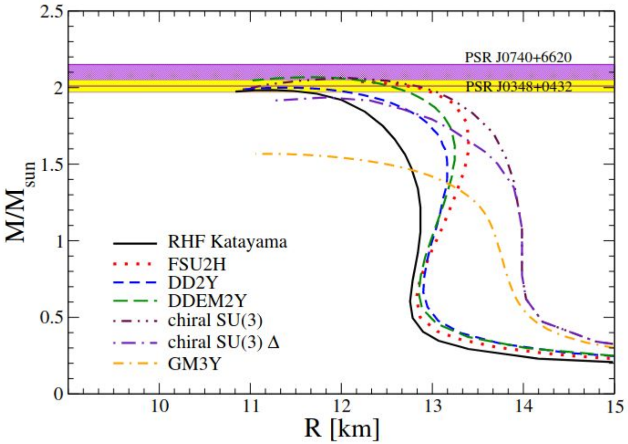
produces nuclei (N) and hyperons (Y)!

We can study N-N, Y-N, Y-Y prod. and interactions in small regions in an unique environment

Case studies:

- Y-Y interaction with **femtoscopy**
  ⇒ constraints on **neutron stars EoS** with hyperons (my PhD project)

- Limits on **H-dibaryion**/exaquark observation
- Scaling in N production



[Universe 2021, 7, 408]

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Summary

We are at the beginning of a long program of quarkonium physics

- ❏ Belle II collected unique data at Υ(10750)
  - ❏ Unique quarkonium production mechanisms at SuperKEKB
  - ❏ $\Upsilon(10750) \to \omega\chi_{bJ}(1P)$ observed for the first time
  - ❏ No evidence for X_b (bottomonium analog of X(3872))
- ❏ Many analyses based on Υ(4S) and scan data
  - ❏ Study of baryon-baryon interactions

High luminosity: goal 50x Belle dataset
⇒ improvements on statistics-dominated analyses

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The end

BACKUP

Belle II **new result**

Observation of $e^+e^- \to \omega[\pi^+ \pi^- \pi^0]\, \chi_{bJ}(1P)[\gamma\Upsilon(1S)]$ and search for $X_b \to \omega\Upsilon(1S)$

Motivation:

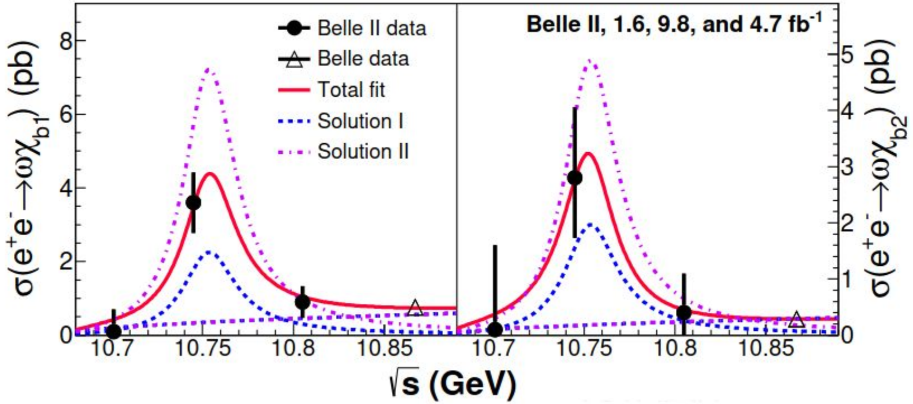
- BF[$\Upsilon(10750) \to \omega\chi_{bJ}(1P)$] ~ 10^{-3} predicted for 4S-3D mixing [PRD 104,034036 (2021)]
- BESIII: $e^+e^- \to Y(4220) \to \pi\pi J/\psi$, $\gamma X(3872)$, $\omega\chi_{c0}(1P)$, … ⇒ X_b analog of X(3872)?

Selection criteria:

- 4 or 5 charged tracks
- standard Belle II PID → 90-95% eff, 1-5% misID
- E_γ > 50 MeV
- 105 < $M(\gamma\gamma)$ < 150 MeV →90% eff.
- 4C kinematic fit
- Best candidate selected based on fit quality
- Data driven corrections and syst. (control samples)

Belle II results:

- **Observation of $e^+e^- \to \omega\chi_{bJ}(1P)[\gamma\Upsilon(1S)]$**
- **No evidence for γX_b**



[arXiv.2208.13189]

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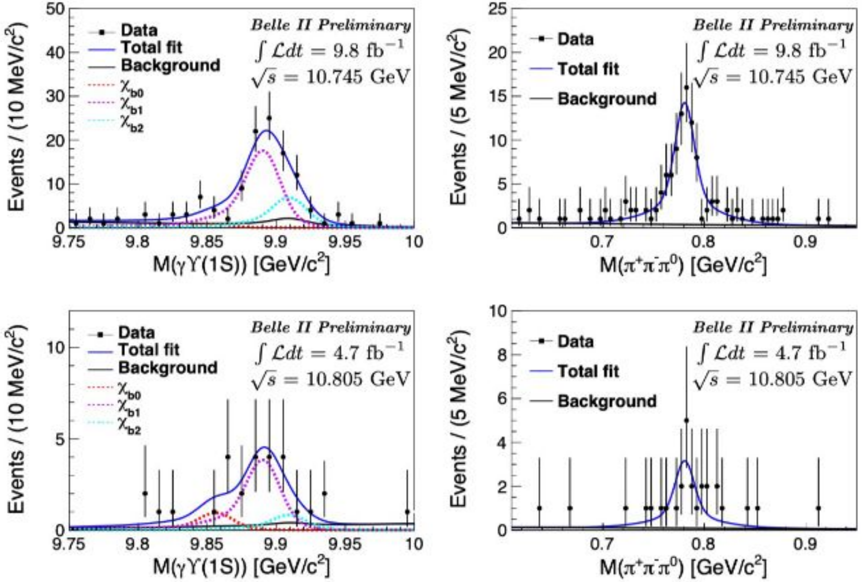
Belle II **new result**



Two dimensional unbinned maximum likelihood fits to the $M(\gamma\Upsilon(1S))$ and $M(\pi^+\pi^-\pi^0)$ distributions.

Channel	$\sqrt{s}$ (GeV)	N^{sig}	$\sigma^{(UL)}_{Born}$ (pb)
$\omega\chi_{b1}$	10.745	$68.9^{+13.7}_{-13.5}$	$3.6^{+0.7}_{-0.7} \pm 0.4$
$\omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	$2.8^{+1.2}_{-1.0} \pm 0.5$
$\omega\chi_{b1}$	10.805	$15.0^{+6.8}_{-6.2}$	1.6 @90% C.L.
$\omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	1.5 @90% C.L.

The total χ_{bJ} signal significances are 11.5σ and 5.2σ at $\sqrt{s}$ = 10.745 and 10.805 GeV.

Note that the $\sigma_{Born}(e^+e^- \to \omega\chi_{b1}/\omega\chi_{b2})$ is only (0.76±0.11±0.11)/(0.29±0.11±0.08) pb at $\sqrt{s}$ = 10.867 GeV [PRL 113, 142001(2014)].

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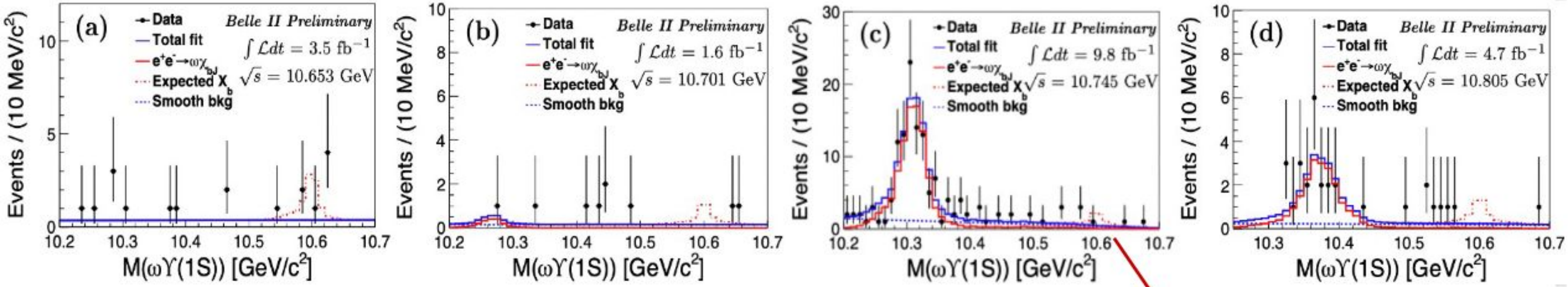
Belle II **new result**



From simulated events with $m(X_b)$ = 10.6 GeV/c^2
The yield is fixed at the upper limit at 90% C.L.

- No significant X_b signal is observed.
- The peaks are the reflections of $e^+e^- \to \omega\chi_{bJ}$.

Upper limits at 90% C.L. on $\sigma_B(e^+e^- \to \gamma X_b) \cdot \mathcal{B}(X_b \to \omega\Upsilon(1S))$ (pb)	$\sqrt{s}$ (GeV)	10.653	10.701	10.745	10.805
	$m(X_b)$ = 10.6 GeV/c^2	0.45	0.33	0.10	0.14
	$m(X_b)$ = (10.45, 10.65) GeV/c^2	(0.14, 0.54)	(0.25, 0.84)	(0.06, 0.14)	(0.08, 0.36)

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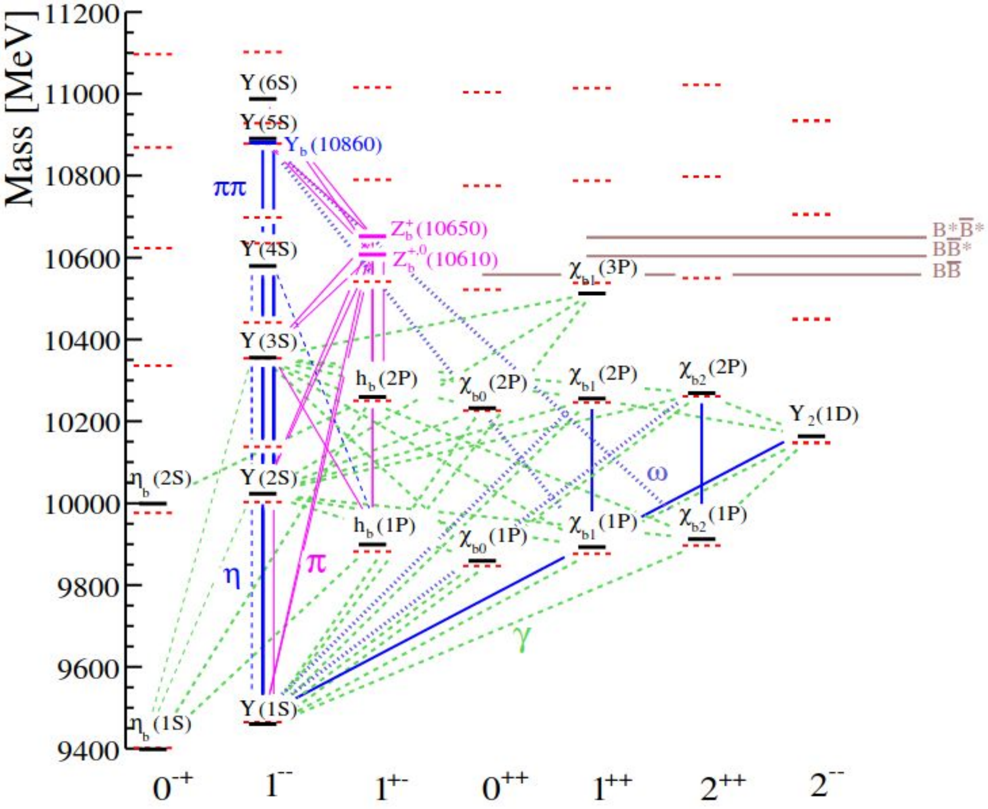
Transitions and decays



Above threshold: $B\overline{B}, D\overline{D}$ dominate

Below threshold:

- transitions
  - hadronic
  - radiative
- decays to
  - hadrons
  - lepton pairs
  - photons

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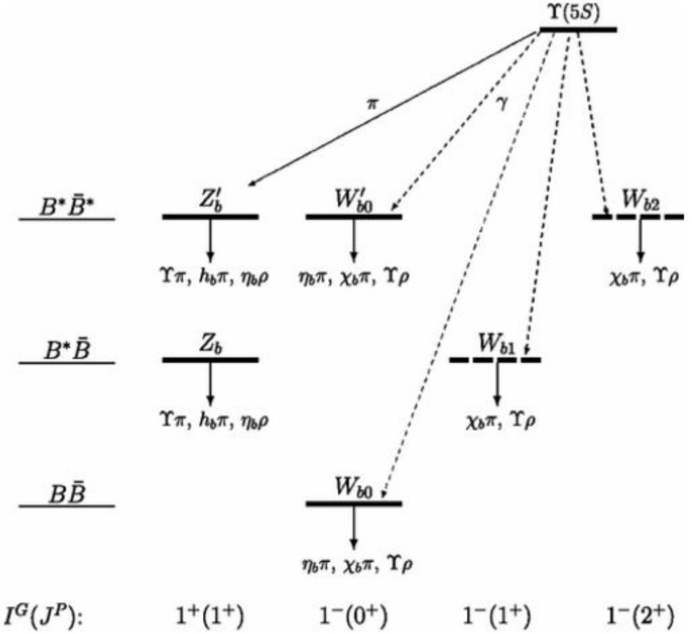
Υ(5S) and Υ(6S): new exotica

If Z_b's are loosely bound molecules, then others must appear



[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]	$\Upsilon(nS)\omega$

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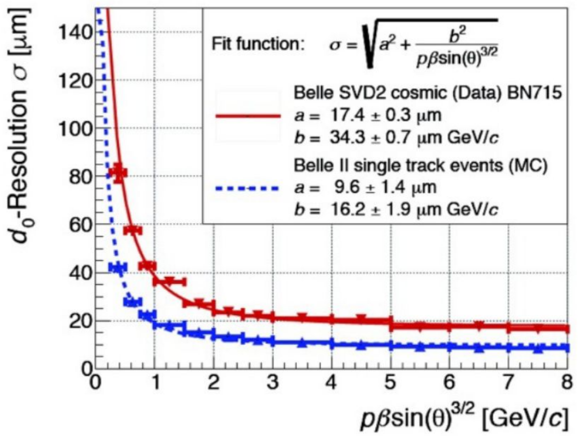
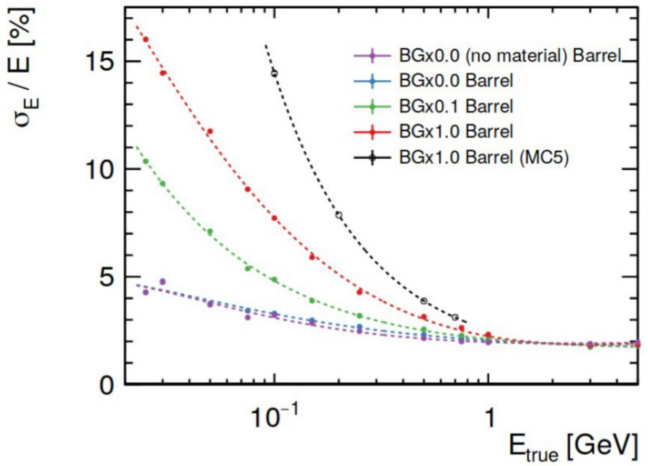
Belle VS Belle II

Tracking and **vertexing** → more precise



Calorimetry → Better reconstruction, more bkg



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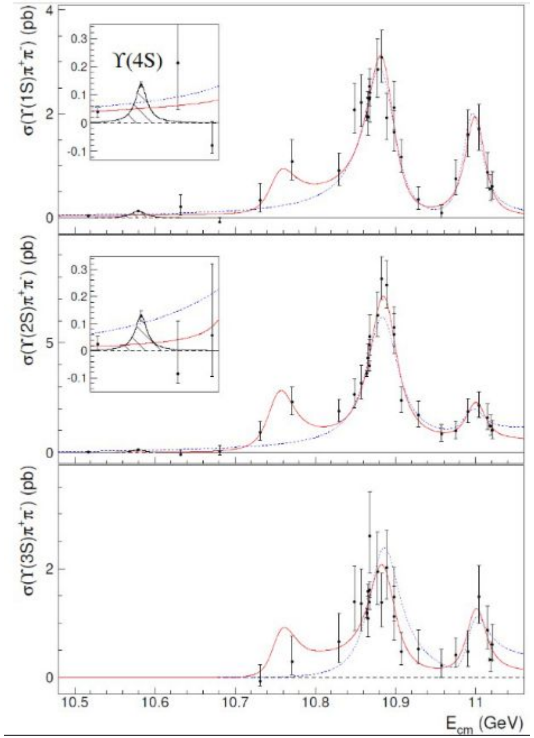
Dataset of the B-factories

B-factories took also **non-4S** data



Some related discoveries:

- Belle @ $\Upsilon(5S)$: $h_b(1,2P)$, $\eta_b(2S)$, $Z_b(10610, 10650)$
- Belle energy scan: $\mathbf{Y_b(10750)}$

	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c²)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$

[JHEP 06 (2021) 137]

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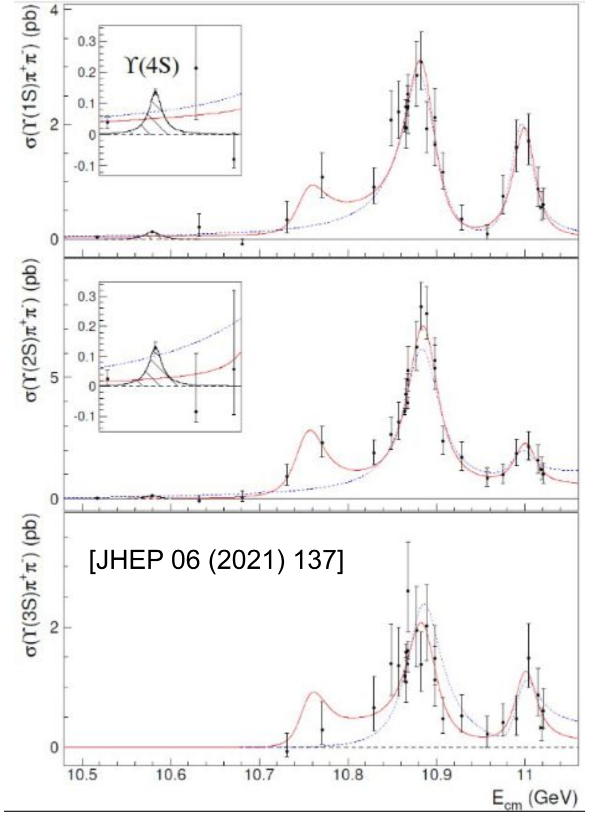
Bottomonium(-like) physics

Belle II advantages

- Tunable beam energy
- Main possibility to study ϒ, Y_b and Z_b states
- Understanding relationship between c- and b-sector spectroscopy

Ability to run at non-4S energies:

- Revisit ϒ(6S) with 10x+ statistics
- Higher statistics scan of entire region and ϒ(5S)



[JHEP 06 (2021) 137]

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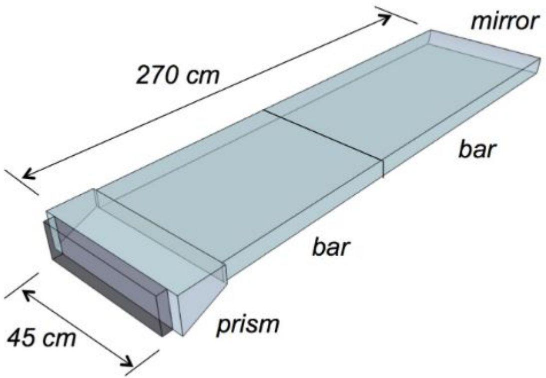
PID with the TOP counter

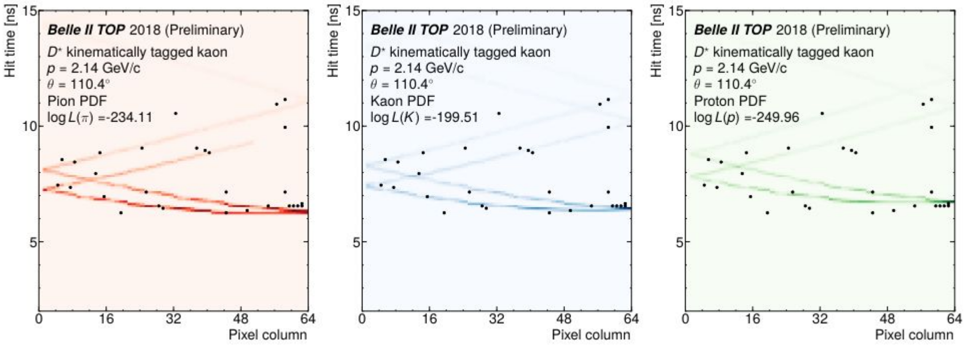
Particle identification → much more powerful

A key improvement is due to the **TOP** counter

The TOP is a “DIRC in the time domain”

- Cherenkov light trapped and propagated to the readout in bar of fused silica
- Cherenkov angle measured by the **time of propagation**





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Femtoscopy in bottomonium decays

Two-particle **dynamic correlations** bring information about

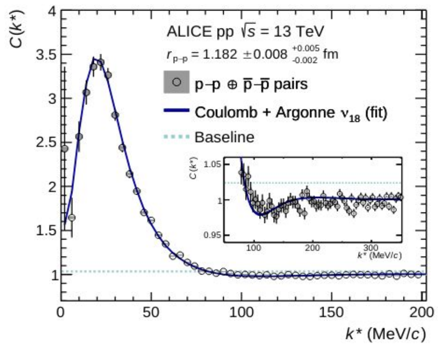
- Interactions between them
- Geometry of the emitting source

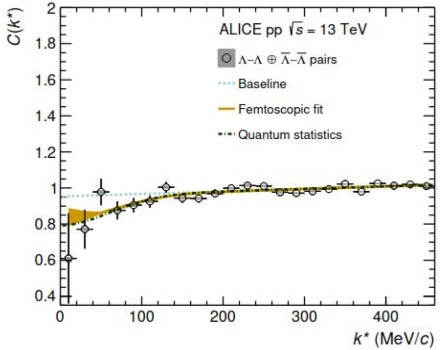
e.g. is X(3872) a $D\overline{D}$ molecule? (attractive interaction)

⇒ we could see correlations between reconstructed $D, \overline{D}$ momenta

- Method already used at ALICE (mixed event technique)
- We will develop analogous method, in cleaner exp. environment

$$C(k^*) \propto \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$





[PLB 797, 134822 (2019)]

Femtoscopy in bottomonium decays

Two-particle **dynamic correlations** bring information about

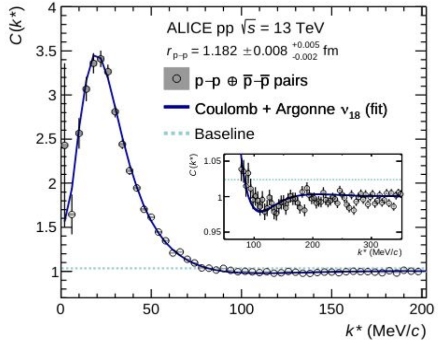
- Interactions between them
- Geometry of the emitting source

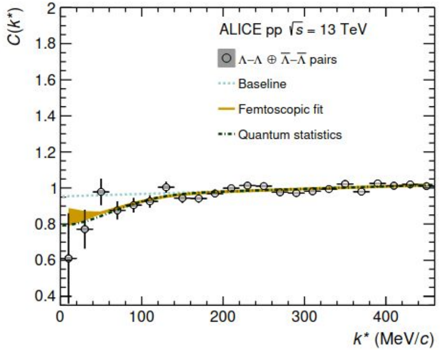
Search for $\Lambda\Lambda$ interactions using **femtoscopy**

- Method already used at ALICE (mixed event technique)
- We will develop analogous method, in cleaner exp. environment

Applications: neutron star EoS, nuclear force, H-dybarion, …

$$C(k^*) \propto \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$





[PLB 797, 134822 (2019)]

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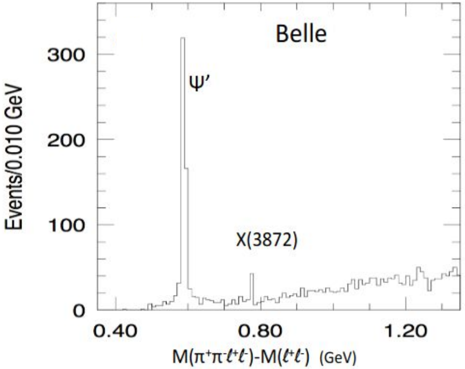
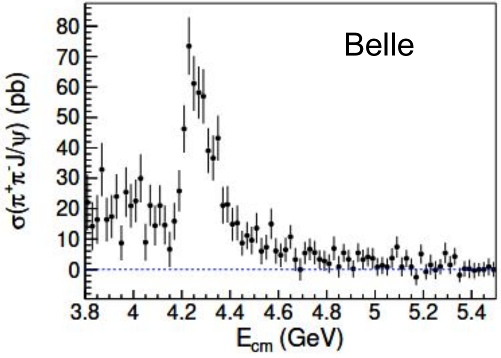
XYZ states

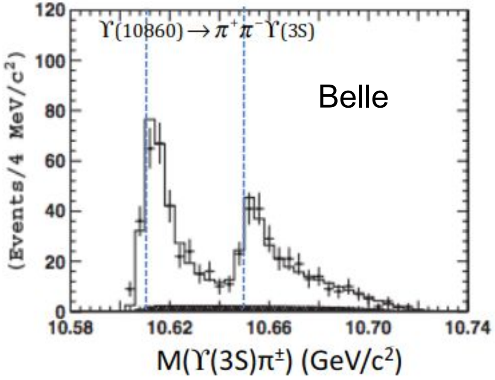
X(3872)



Y(4260)

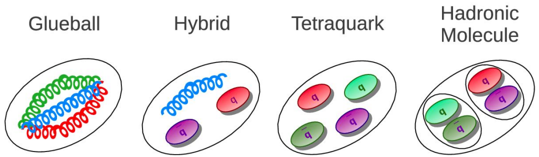


$Z_b(10610, 10650)^{\pm}$



And many more in charmonium sector: X(3915), Z_c(3900), Z_c(4430), …

What are they?
Many possible interpretations:



+ threshold, cusp effects

[Rev.Mod.Phys. 90 (2018) 1, 015003]

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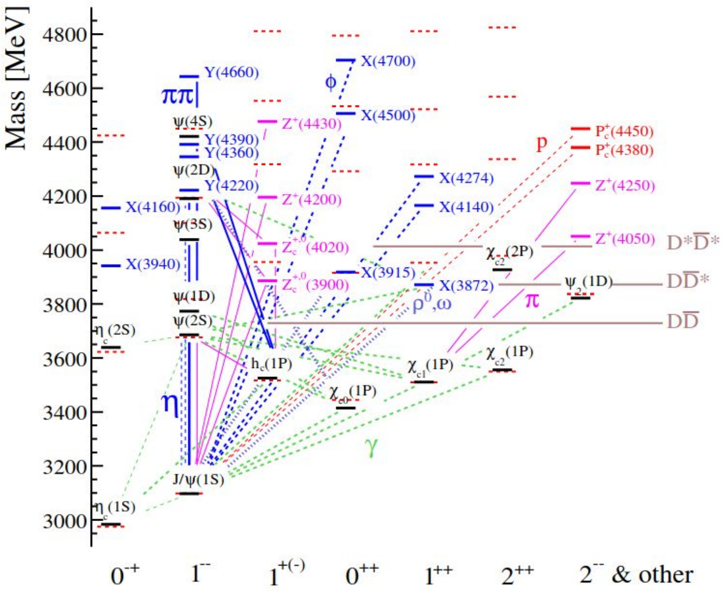
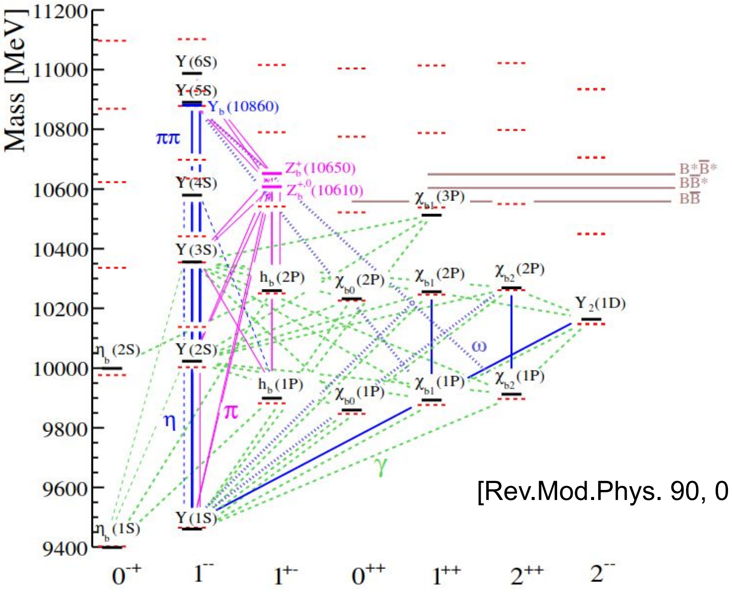
Heavy quarkonia





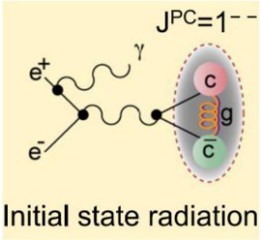
[Rev.Mod.Phys. 90, 015003 (2018)]

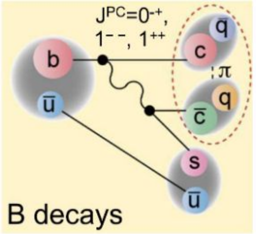
- Conventional states → $c\bar{c}, b\bar{b}$
- Neutral exotics
- Charged exotics
- Pentaquark candidates

(Neutral exotics, Charged exotics, Pentaquark candidates) → non $q\bar{q}$

Spectroscopy = non-perturbative QCD
→ Can't do direct calculation, rely on models approximating QCD
→ Understand (solve?) QCD in NP regime

Charmonium(-like) physics





Improve stat. for observation of

$Z_c(3900)^+ \to J/\psi\pi^+$ [PRL 110, 252002 (2013)]

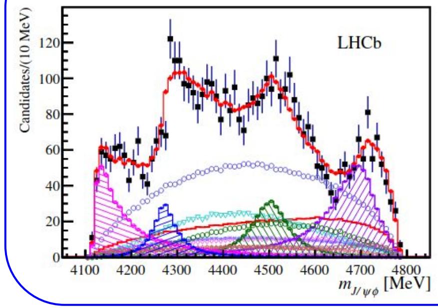
Improve meas. of cross section

$e^+e^- \to \gamma_{ISR}(c\bar{c})X$

Above 5 GeV

Amplitude analyses:

$B \to J/\psi\,\phi\,K$



PRL 118, 022003 (2017)

(confirm LHCb results)

Analysis of unexplored channels

$B \to J/\psi\eta K$ $\quad B \to J/\psi\eta' K$

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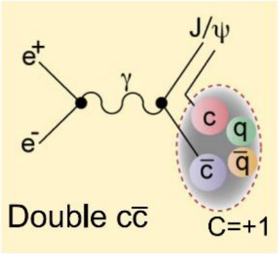
Charmonium(-like) physics

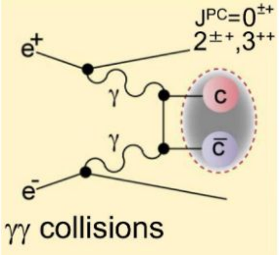


$$e^+e^- \to J/\psi D^*\overline{D}^*$$ X(3940)

$$e^+e^- \to J/\psi D^*\overline{D}$$ X(4160)

$$e^+e^- \to \psi(2S)D^{(*)}\overline{D}^{(*)}$$

X*(3860), X(3940), X(4160)



Conventional states:

- χ_{c2}(2P)
- search for states decaying to open charm

Exotic

$$e^+e^- \to e^+e^- J/\psi\phi$$

→ establish X(4350) ?

Unique to Belle II !

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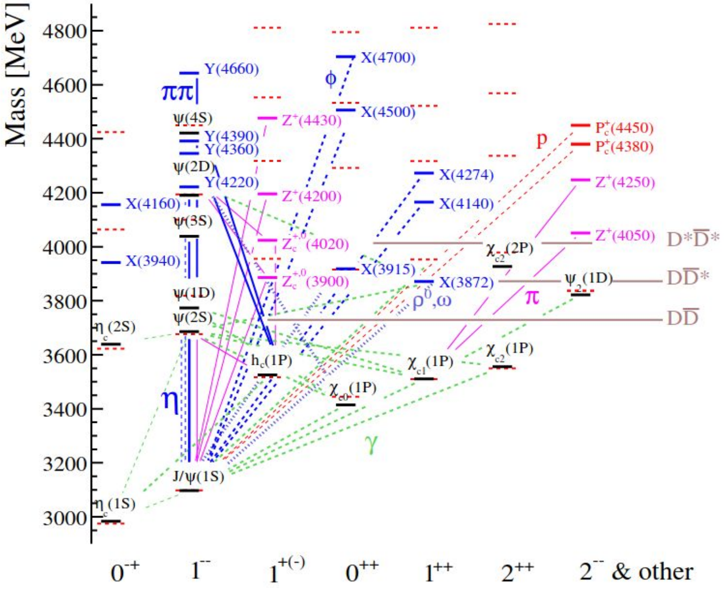
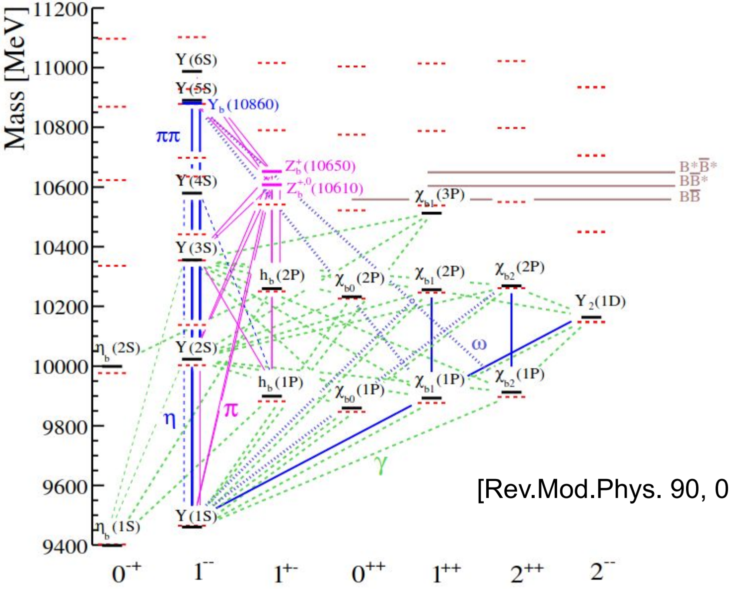
Heavy quarkonia





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

Spectroscopy = non-perturbative QCD
→ Can't do direct calculation, rely on models approximating QCD
→ Compare exp. results with models
⇒ improve understanding of QCD in NP regime

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