Bottomonium results and prospects at Belle II

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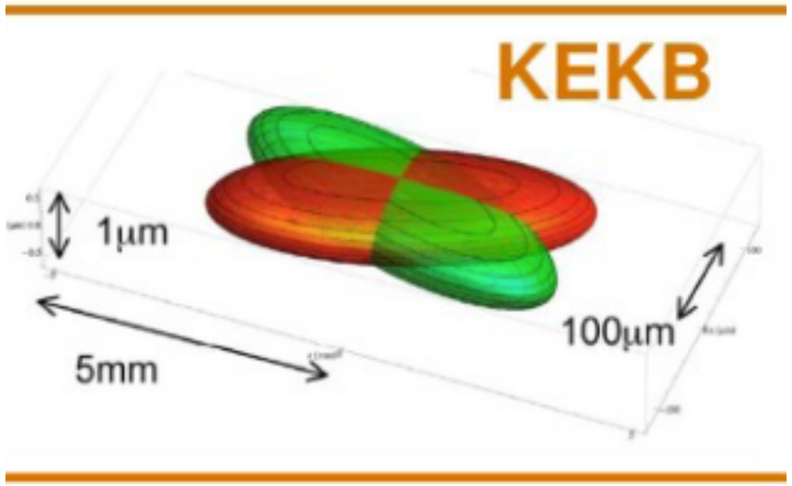
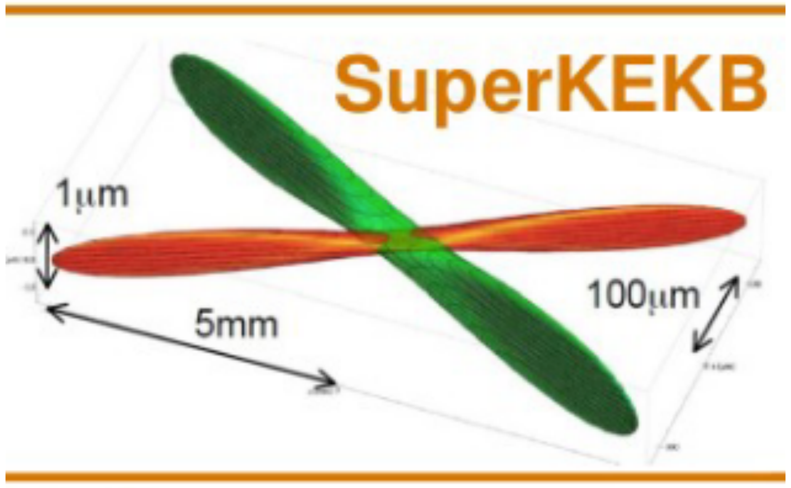
Fairness 2022
23-27 May 2022

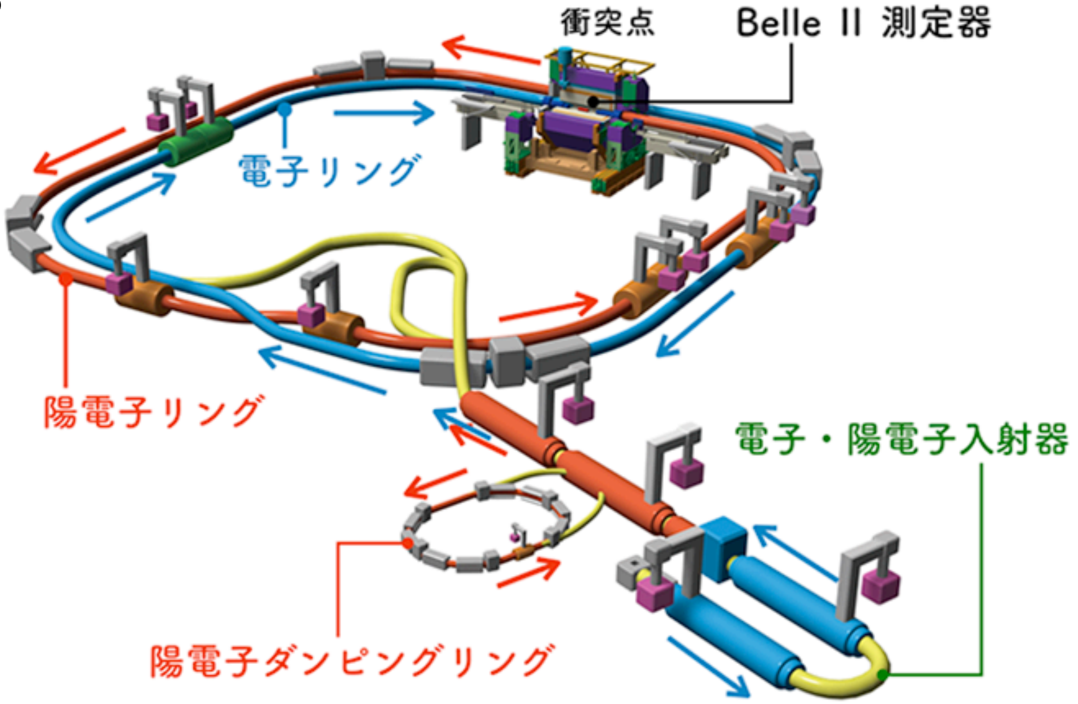
On behalf of the Belle II collaboration

SuperKEKB

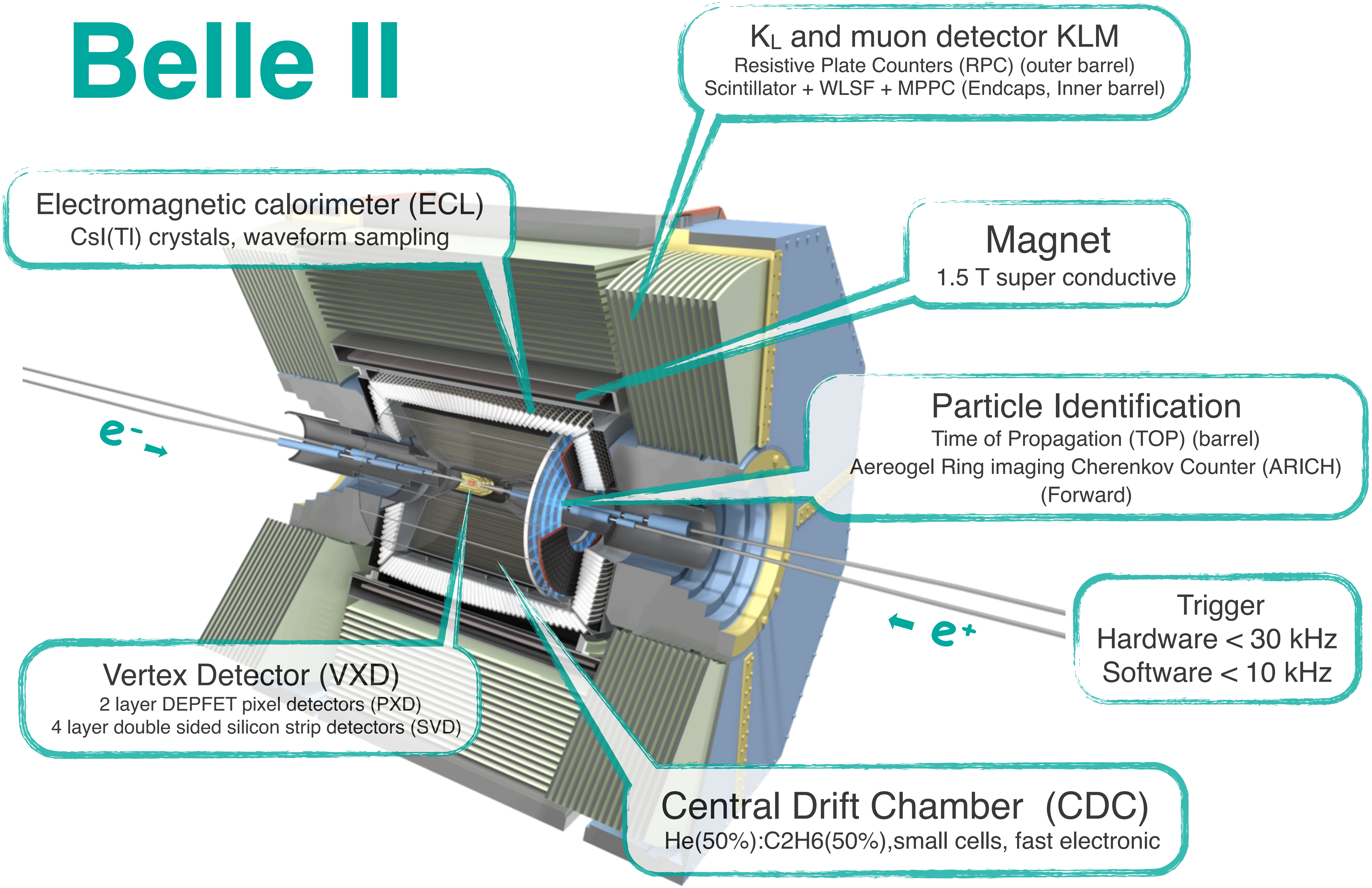
- SuperKEKB is an asymmetric e^+ (4 GeV) e^- (7 GeV) collider at Tsukuba, Japan.
- Energy limit ~11 GeV
- Belle II detector is placed around the IP of SuperKEKB
- SuperKEKB goal: > ~40 × KEKB instantaneous luminosity at cost of $\mathcal{O}(10)$ × higher backgrounds
  - Goal: $\mathscr{L} = 6.5 \times 10^{35}\ cm^{-2}s^{-1}$
- Current world record: $\mathscr{L} = 4.1 \times 10^{34}\ cm^{-2}s^{-1}$
  - May 2022 !!
- First collision physics runs in 2019.





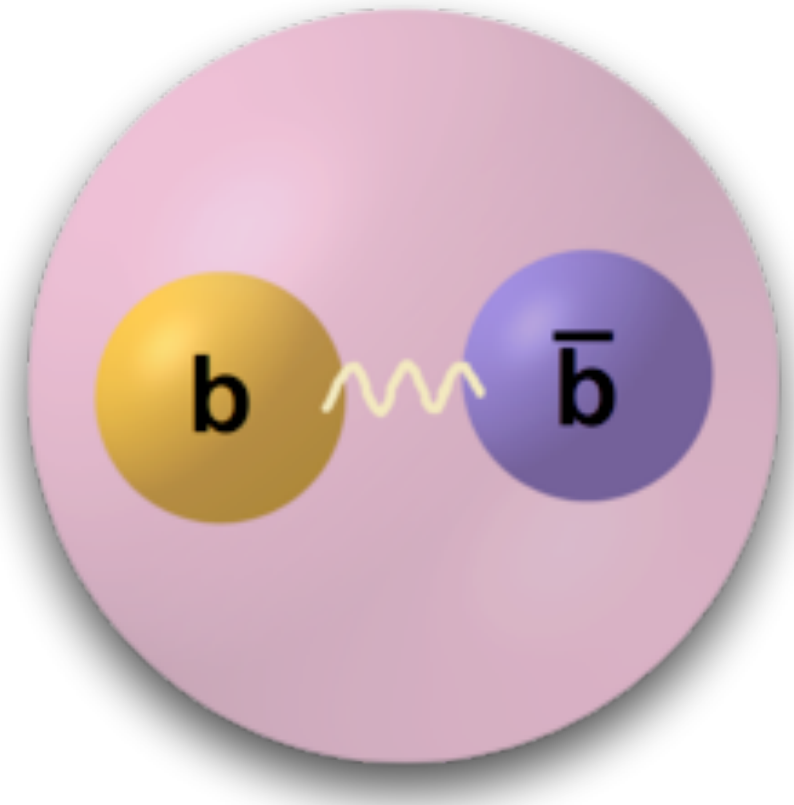


Belle II



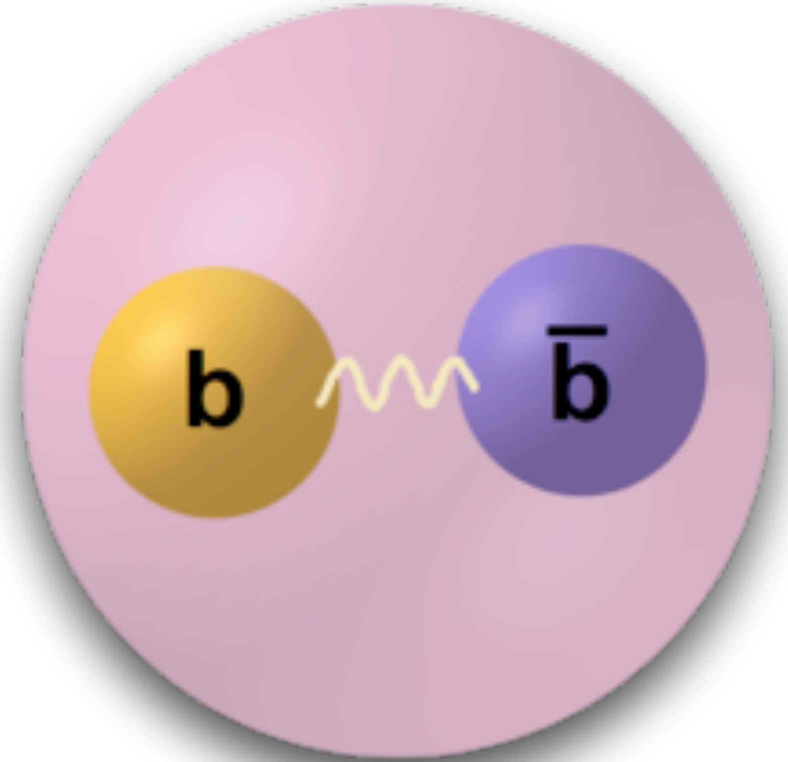
K_L and muon detector KLM
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (Endcaps, Inner barrel)
Electromagnetic calorimeter (ECL)
CsI(Tl) crystals, waveform sampling
Magnet
1.5 T super conductive
Particle Identification
Time of Propagation (TOP) (barrel)
Aereogel Ring imaging Cherenkov Counter (ARICH) (Forward)
e-
e+
Trigger
Hardware < 30 kHz
Software < 10 kHz
Vertex Detector (VXD)
2 layer DEPFET pixel detectors (PXD)
4 layer double sided silicon strip detectors (SVD)
Central Drift Chamber (CDC)
He(50%):C2H6(50%),small cells, fast electronic

Quarkonium



- $Q\bar{Q}$ meson with a heavy quark
  - $b\bar{b}$ Bottomonium
  - $c\bar{c}$ Charmonium
- Simple two body system
- Non-relativistic
  - $v^2_b \sim 0.1$ c , $v^2_c \sim 0.3$ c
- Multiscale system covering all regimes of quantum chromodynamics (QCD)
  - Ideal framework to test Non-perturbative QCD and its interplay with perturbative QCD
- Bottomonium is simpler than charmonium

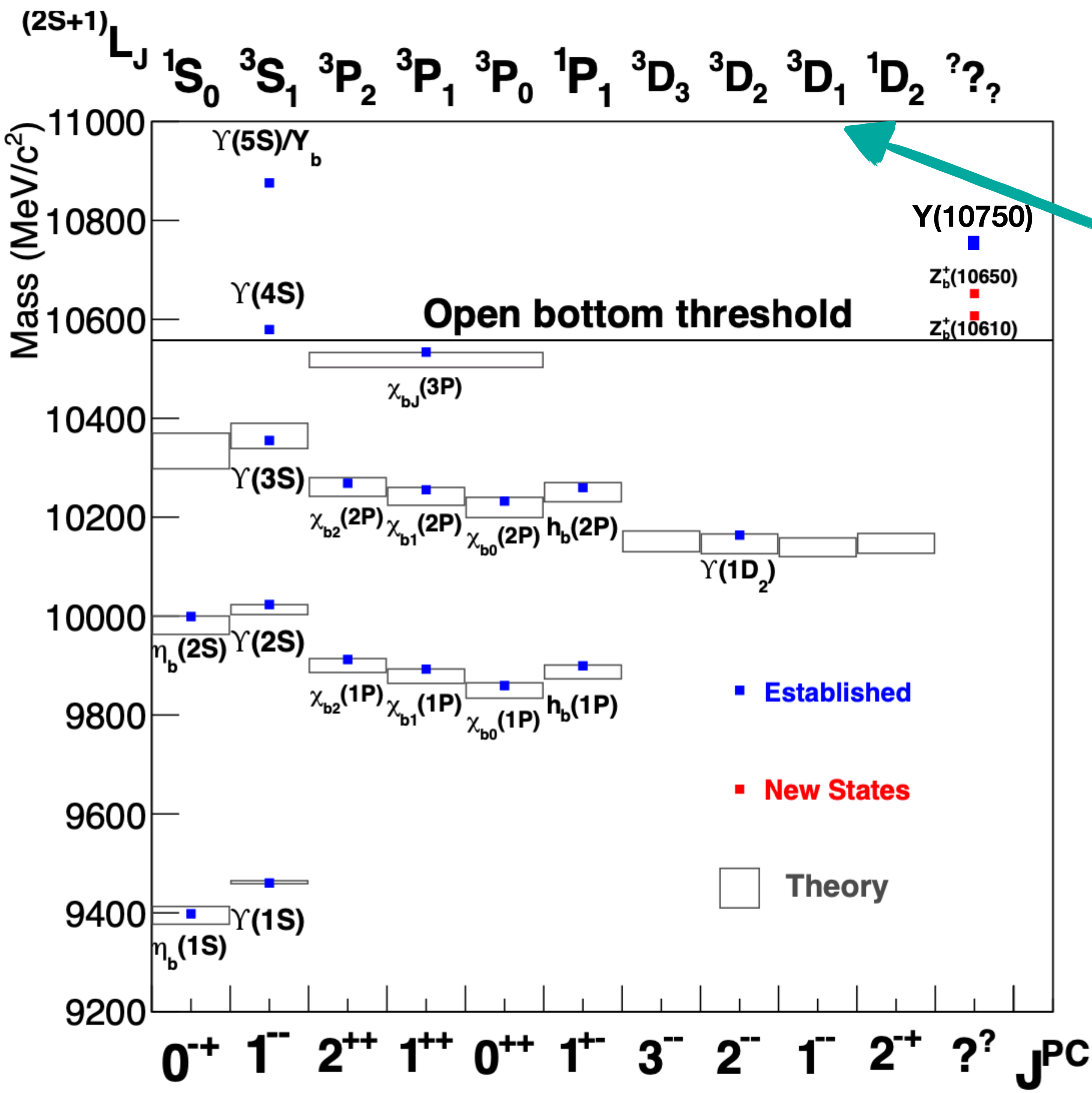
Quarkonium



- $Q\bar{Q}$ meson with a heavy quark
  - $b\bar{b}$ Bottomonium
  - $c\bar{c}$ Charmonium
- Simple two body system
- No…
  - …
- Mu… …CD)
  - … perturbative QCD
- Bottomonium is simpler than charmonium

Exotic quarkonium states, such hybrids, Tetraquark and molecules are usually studied/included in this category

Bottomonia

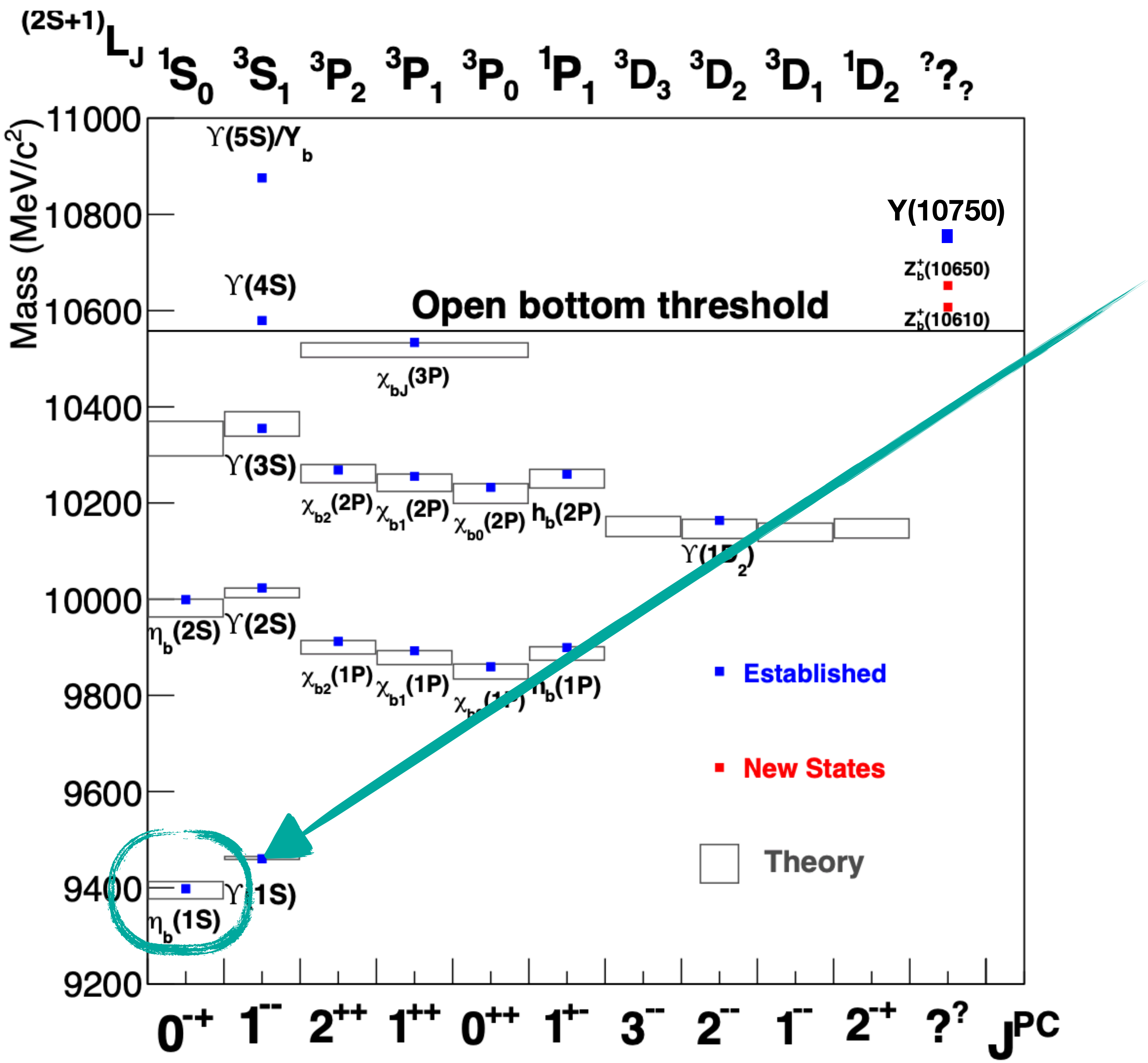


Spectroscopic notation from Schrödinger equation solutions

$$n^{(2S+1)}L_J$$

- **n** radial quantum number
- **S** total spin of $q\bar{q}$ system
- **L** relative orbital ang. momentum
  - **L**= 0,1,2 .. correspond to S,P,D
- **J**=L+S
- Parity **P** = $(-1)^{L+1}$
- Charge Conj. **C** = $(-1)^{L+S}$

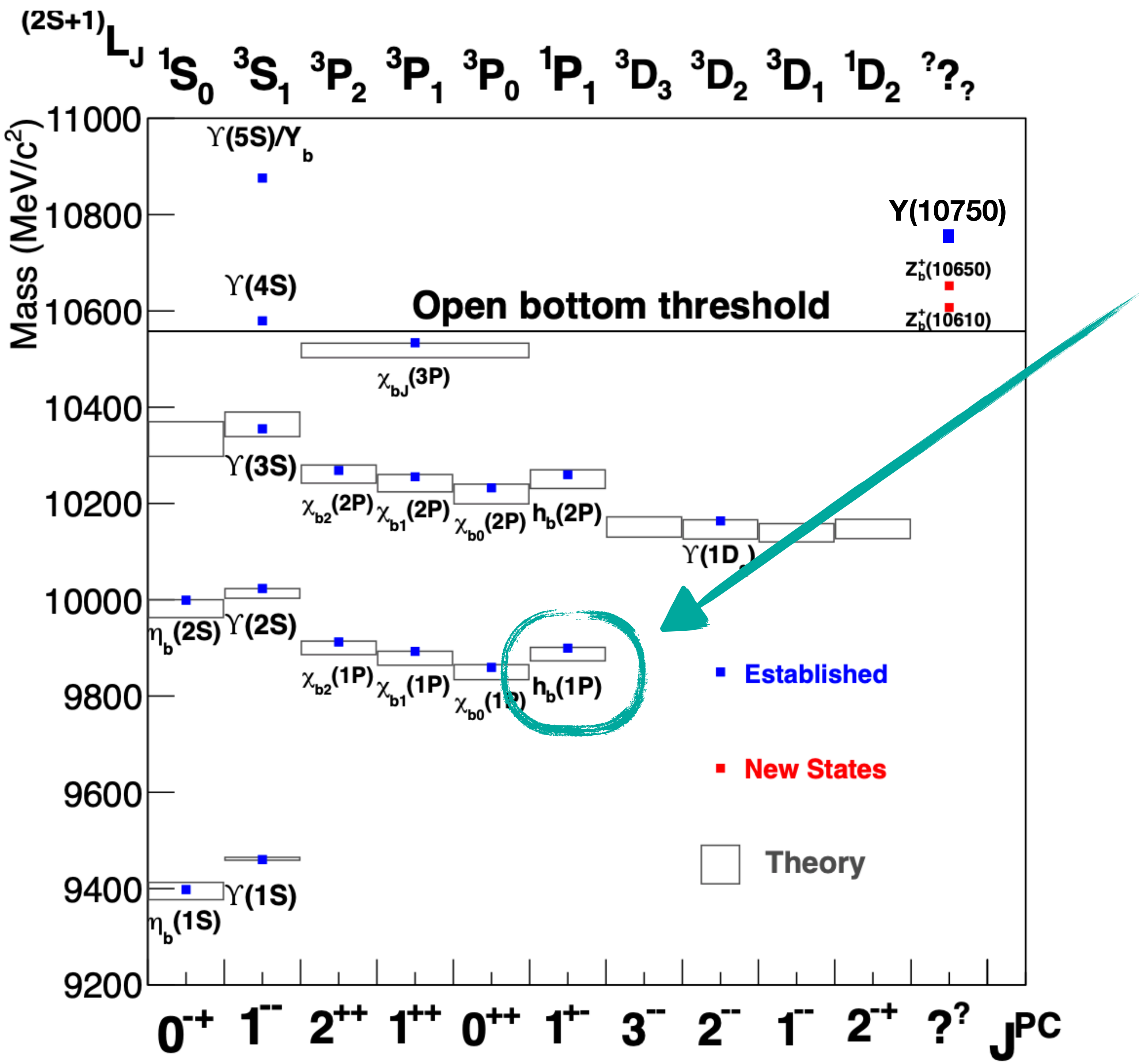
Bottomonia



Ground state
spin singlet S wave

$\eta_b(1S)$

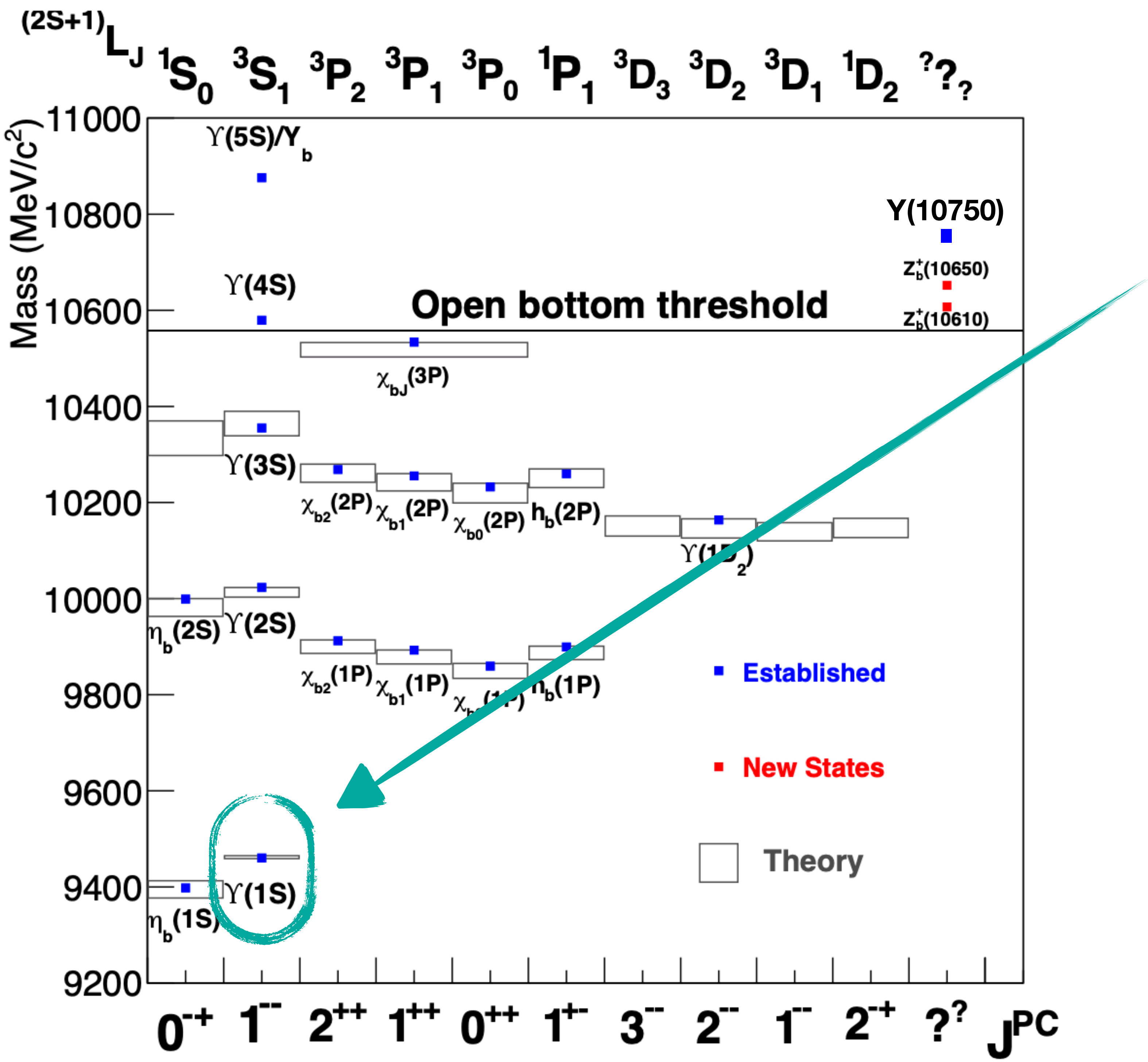
Bottomonia



spin singlet P wave

$h_b(1P)$

Bottomonia



Hyper fine splitting

spin triplet S wave

Υ(1S)

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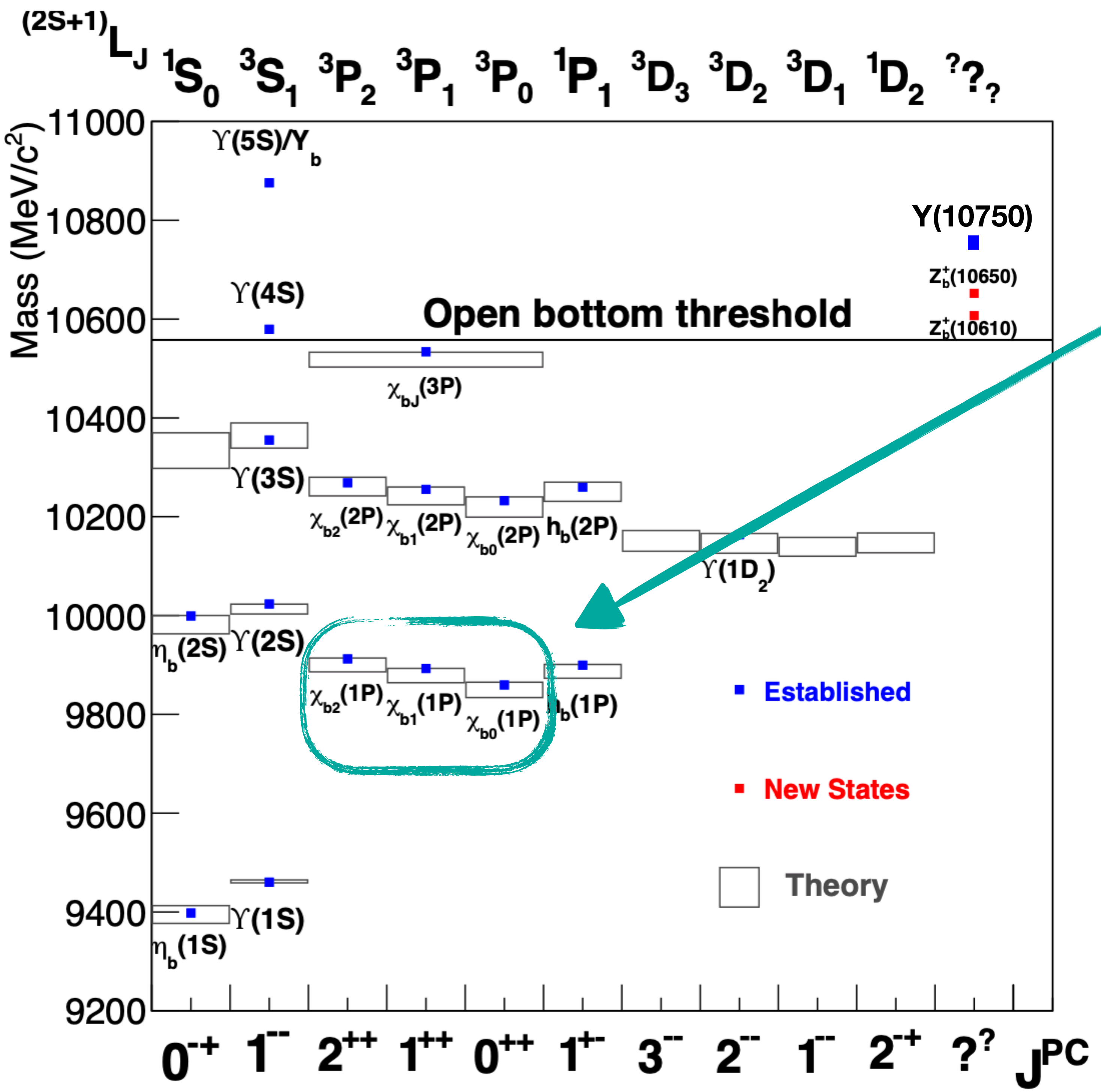

Fine splitting
P wave spin triplet

$\chi_{b1,2,3}$ **(1P)**

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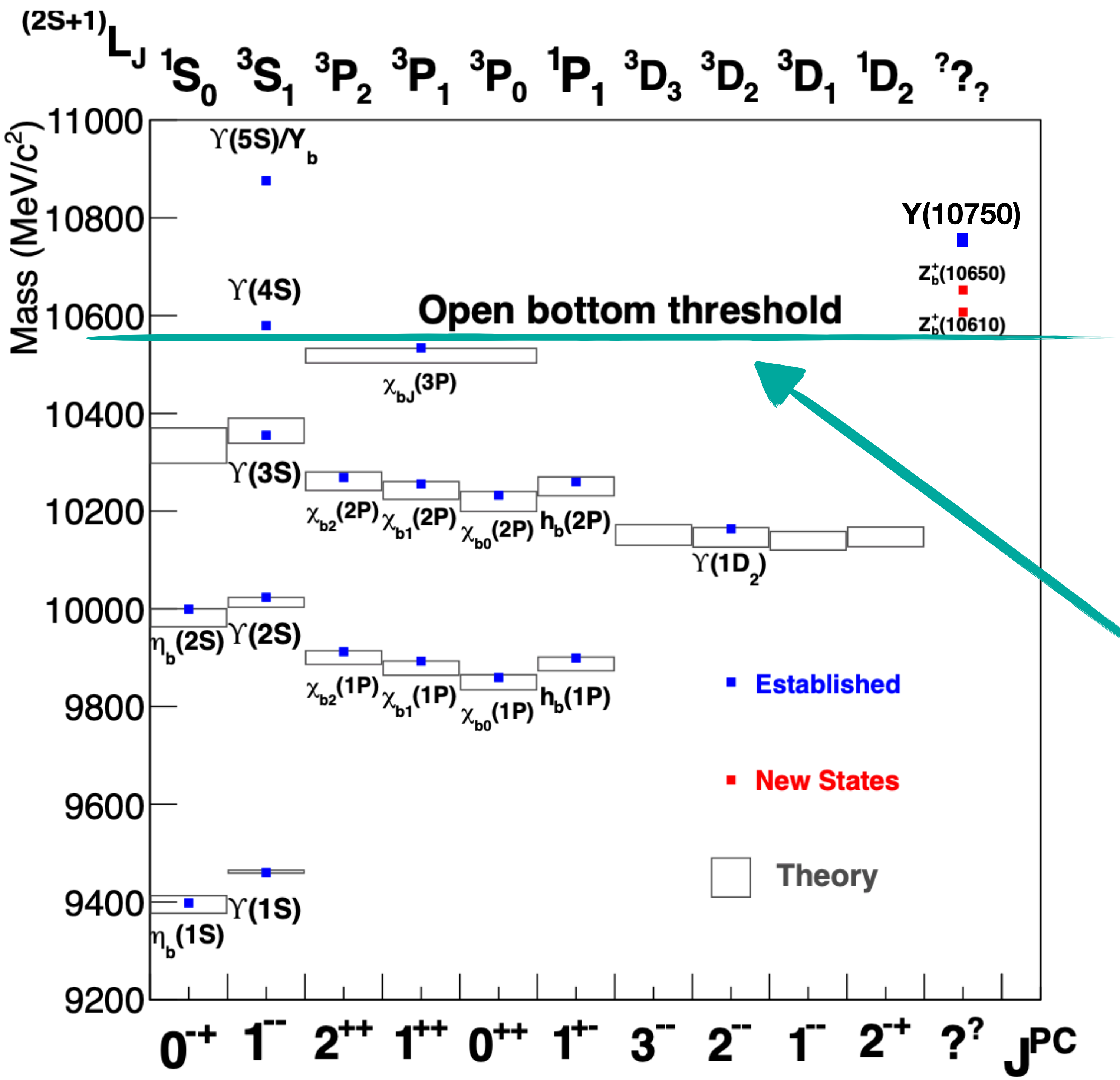

States below open flavour thresholds ($B\bar{B}$) are in good agreement with a simple no relativistic $Q\bar{Q}$ system.

Are generally narrow due to OZI rule
$\Gamma \sim$ 20-50 KeV

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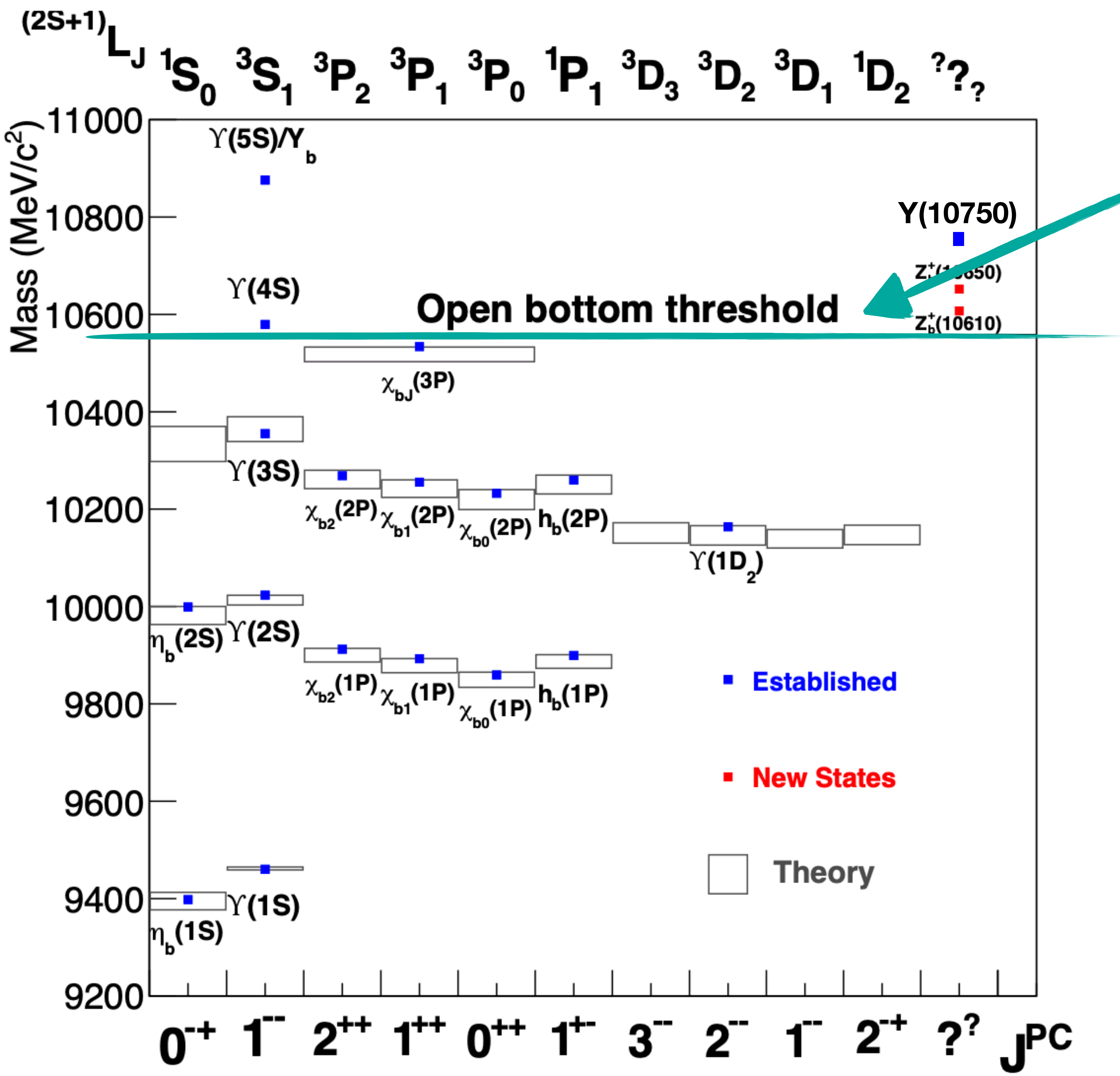

States with masses above open flavour thresholds have properties unexpected for a pure $Q\bar{Q}$ state

Decay mostly to $B^{(*)}B^{(*)}$ and are usually much larger
$\Gamma \sim$ 20-40 MeV

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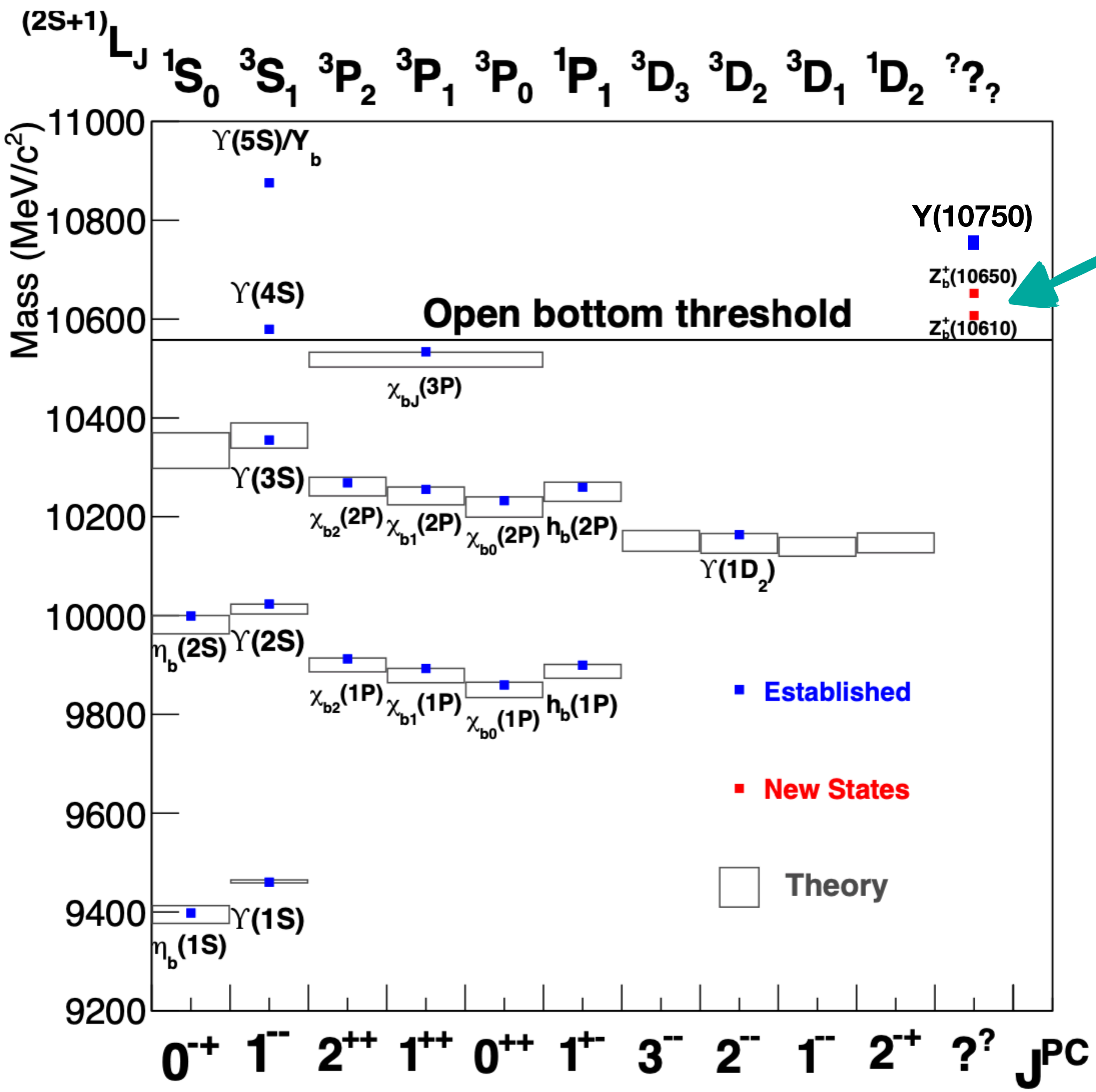
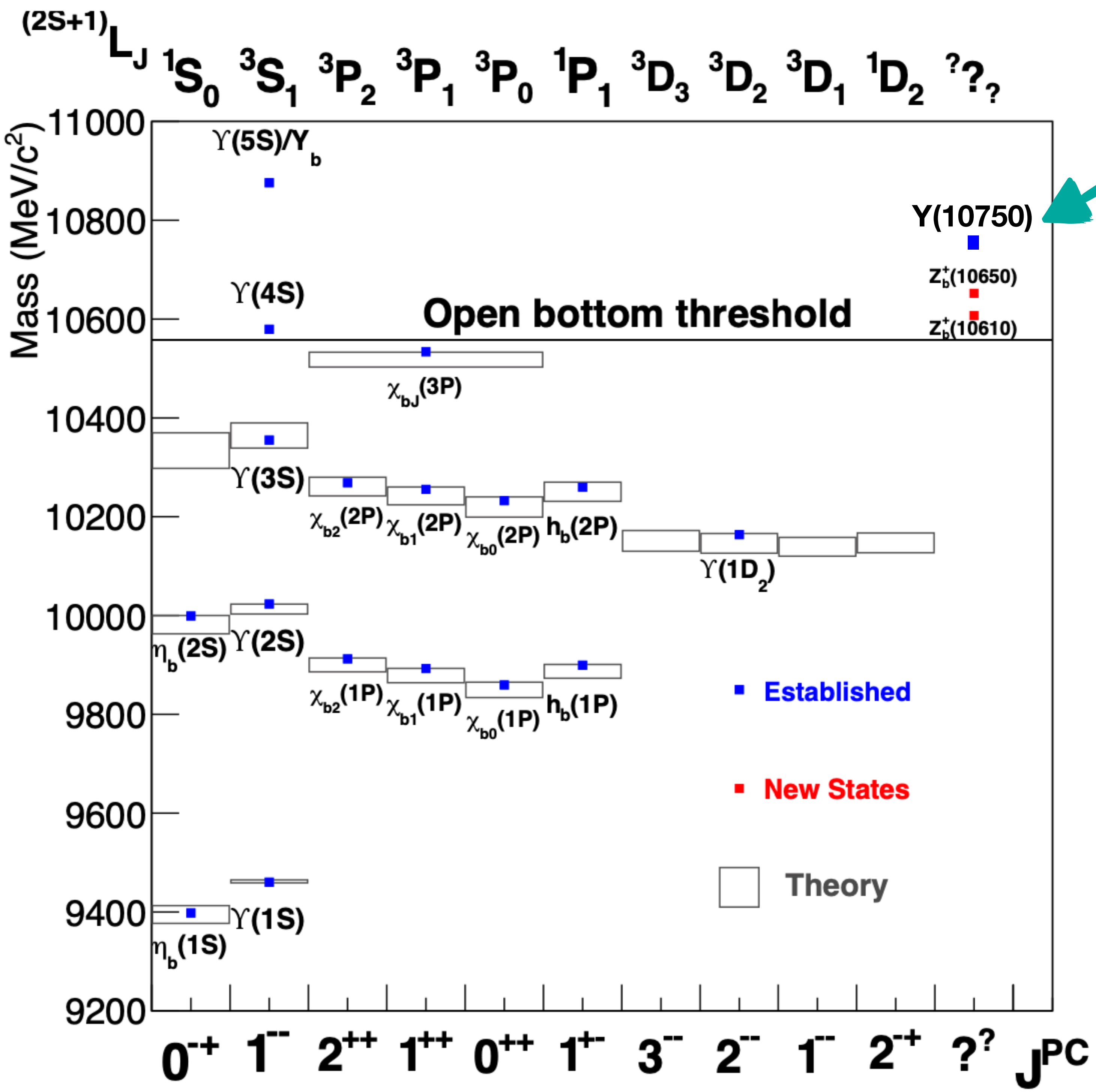


Exotic states

$Z^{\pm}_b$ (10650)

$Z^{\pm}_b$ (10610)

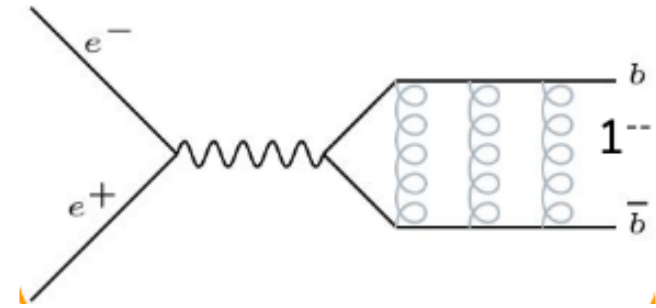
Bottomonia

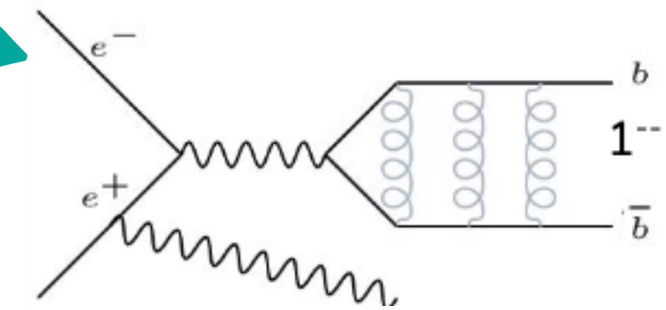


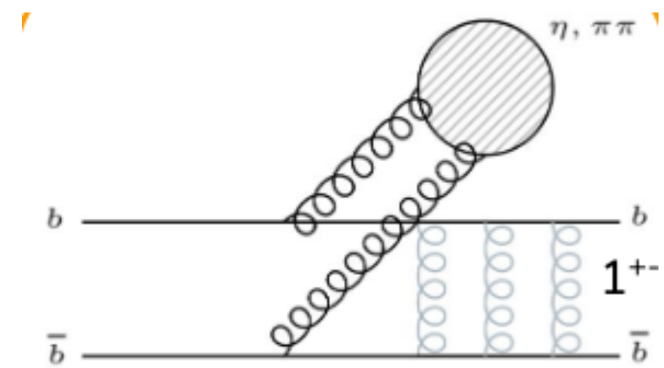
2019 new state with
$J^{PC}=1^{--}$
Details later

How to produce them at e^+e^- collider

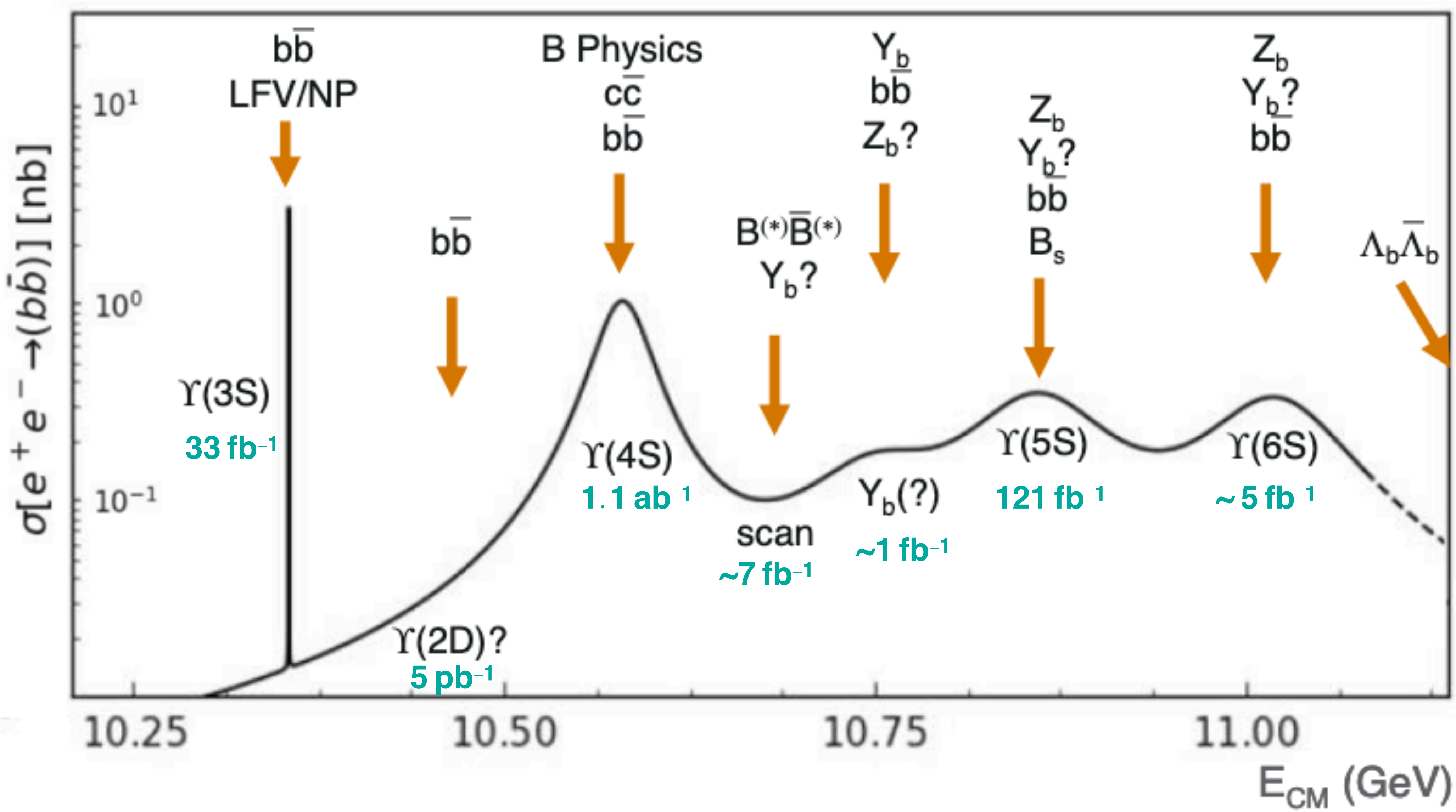
- Directly from e^+e^-
  - Only $J^{PC}=1^{--}$ ($\Upsilon(nS)$)
- ISR production
  - Only $J^{PC}=1^{--}$ ($\Upsilon(nS)$)
- Hadronic transitions from $\Upsilon(nS)$ trough $\eta,\pi\pi$…
  - $J^{PC}=1^{--}$,0^{-+},1^{+-} … ($\Upsilon(nS)$, $h_b(nS)$, $\eta_b(nS)$,..)
- Radiative transitions from $\Upsilon(nS)$
  - $J^{PC} = 0^{++},1^{++},2^{++}$ (χ_{bj})
    - Electric dipole transition (E1)
  - $J^{PC} = 0^{-+}$ (η_b)
    - Magnetic dipole (M1) transitions
- Secondary transition from these states
  - E.g. $h_b(nS) \rightarrow \gamma\eta_b$







Available datasets before Belle II



- Small dataset outside Υ(4S)
- Even a small data set can make the difference

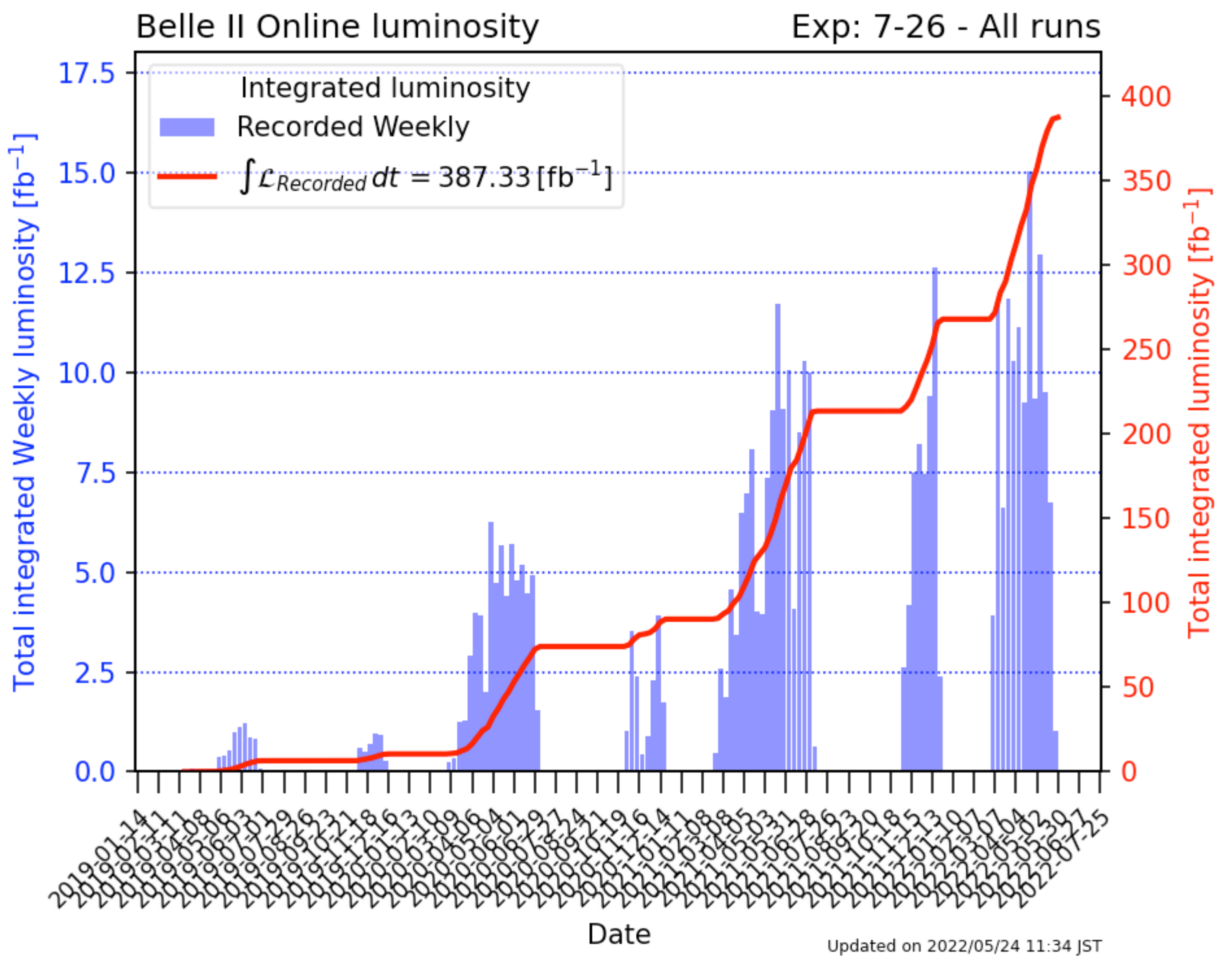
BaBar

CLEO

BELLE

Belle II current status

- Running at $\Upsilon(4S)$
  - Recorded 387 fb^{-1}
    - Many analyses already ongoing, just need more data
    - Rediscovery analyses
      - Thanks to improved analysis techniques may need less data to have competitive/better results
- Early energy scan around 10.751 GeV
    - Recorded ~ 19 fb^{-1}
    - More details later
- Feasibility studies for future analysis

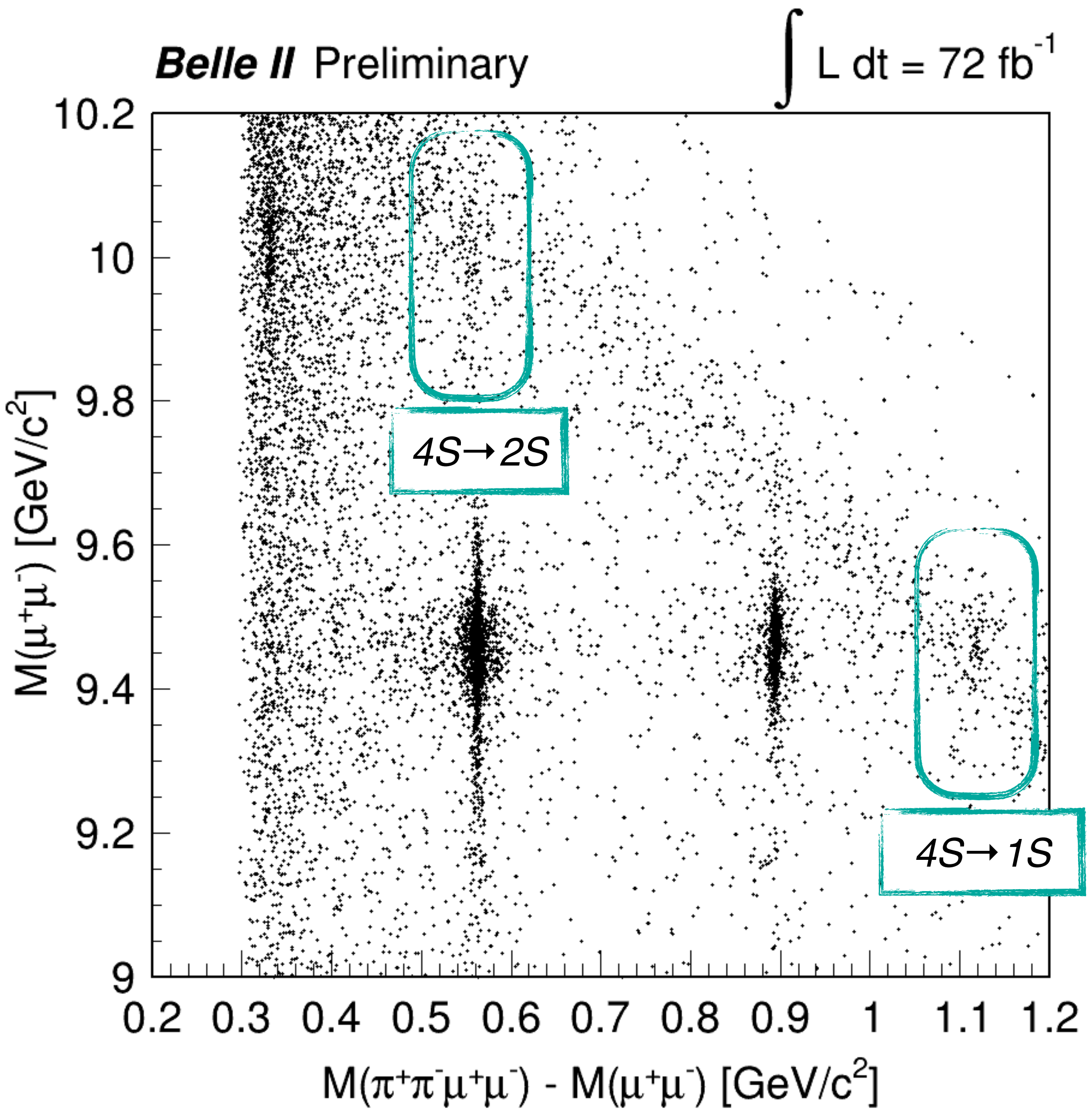


Analyses at $\Upsilon(4S)$

Υ(nS) dipion transitions

BELLE2-NOTE-PL-2021-001

$$\Upsilon(mS) \to \pi^+\pi^-[\Upsilon(nS) \to \mu\mu]$$



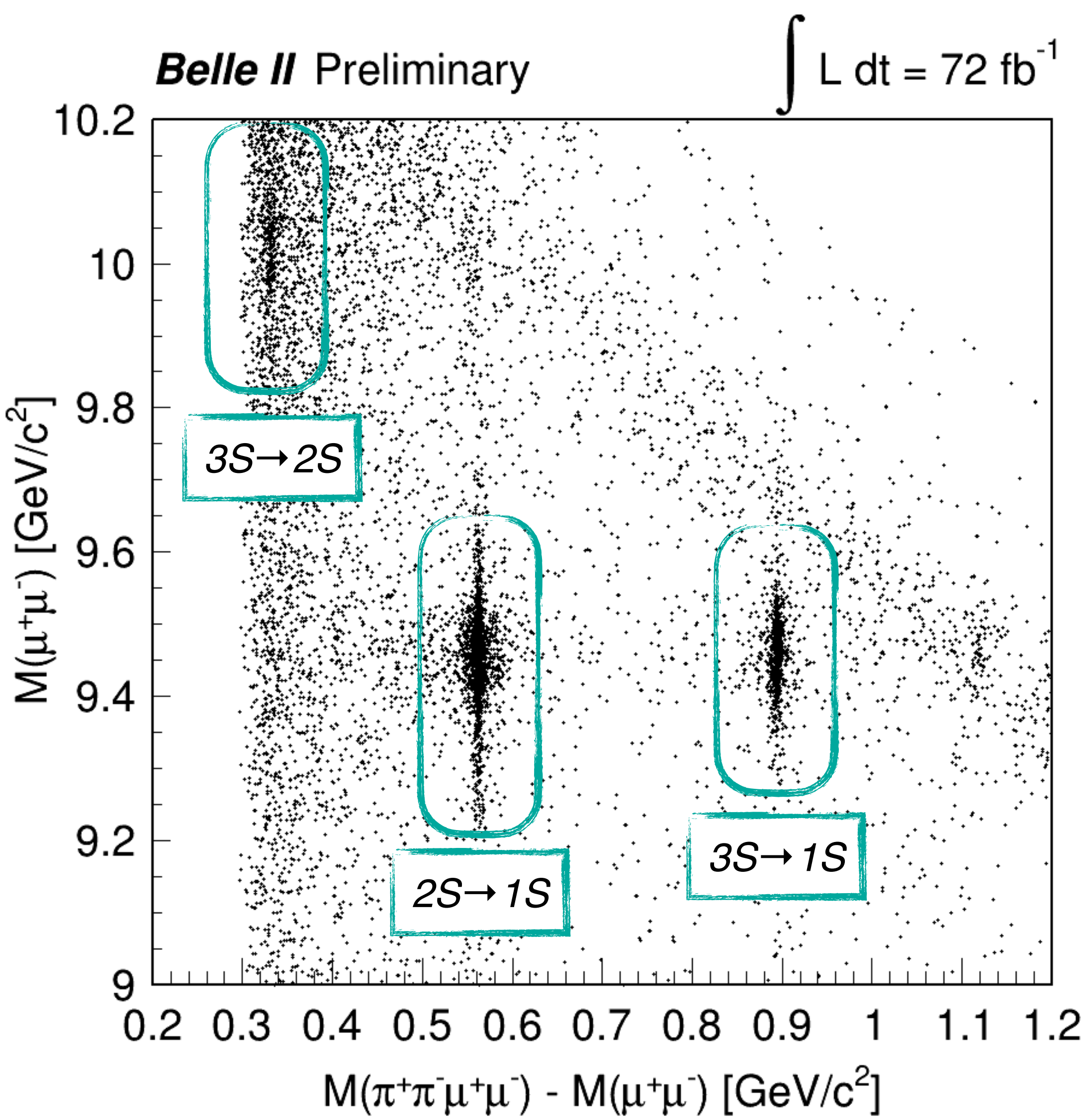
final state: $\pi^+\pi^-\ \mu^+\mu^-$ (+γ undetected)

- Direct transitions:
  - $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S,2S)$

Υ(nS) dipion transitions

BELLE2-NOTE-PL-2021-001

$$\Upsilon(mS) \to \pi^+\pi^-[\Upsilon(nS) \to \mu\mu]$$



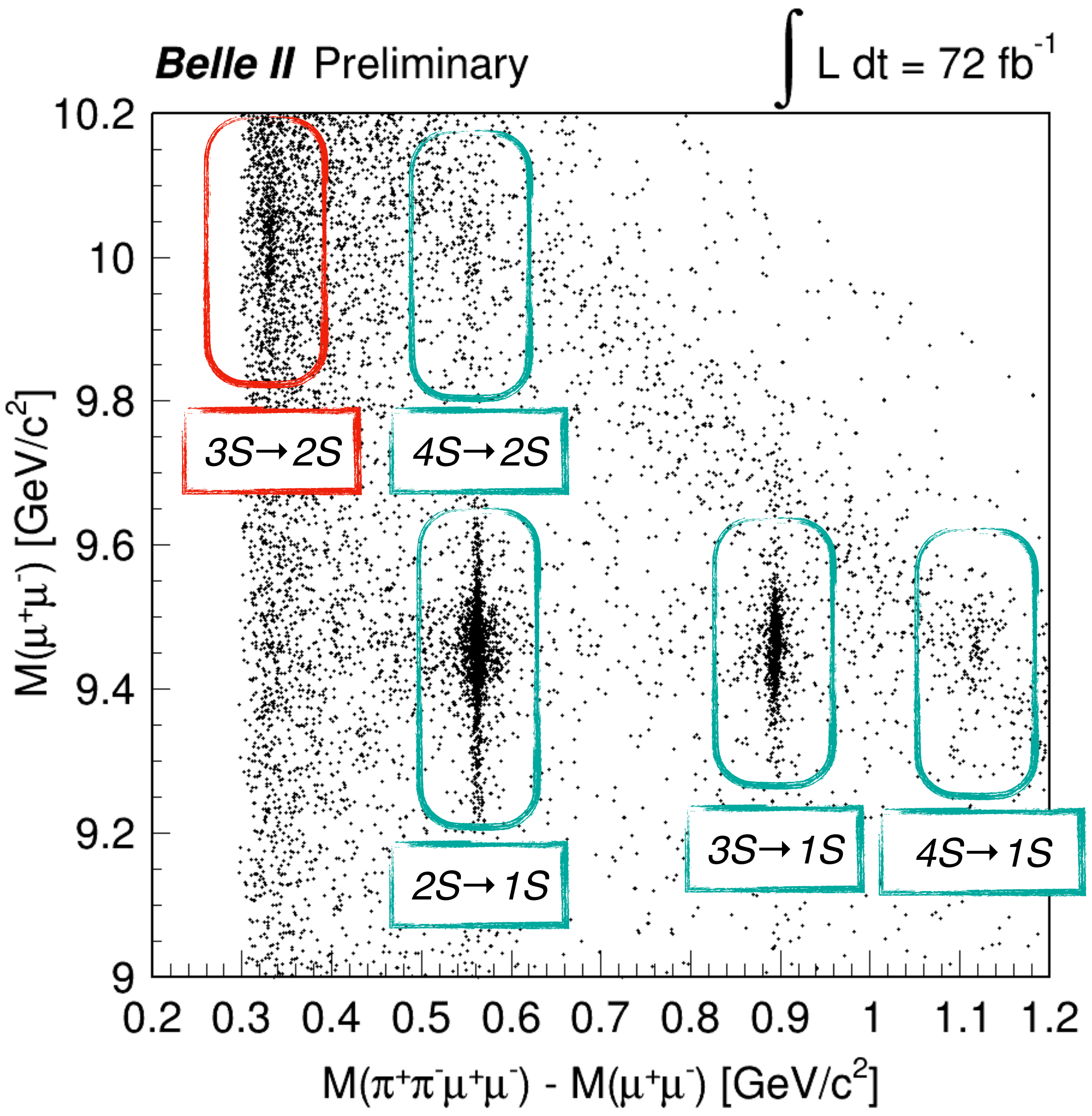
final state: $\pi^+\pi^-$ $\mu^+\mu^-$ (+γ undetected)

- $e^+e^- \to \Upsilon(nS)\ \gamma_{ISR} \to \pi^+\pi^-$ Initial State Radiation (ISR) production:
  - $\gamma_{ISR}\ \Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S,2S)(\ell^+\ell^-)$
  - $\gamma_{ISR}\ \Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)(\ell^+\ell^-)$

Υ(nS) dipion transitions

BELLE2-NOTE-PL-2021-001

$$\Upsilon(mS) \to \pi^+\pi^-[\Upsilon(nS) \to \mu\mu]$$



final state: $\pi^+\pi^-$ $\mu^+\mu^-$ (+γ undetected)

- Done better than Belle analysis
  - 496 fb^{-1}[PRD 96 (2017) 5, 052005]
  - $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)$ was not visible
  - Retention of lower-momentum pion candidates in Belle II compared to Belle.

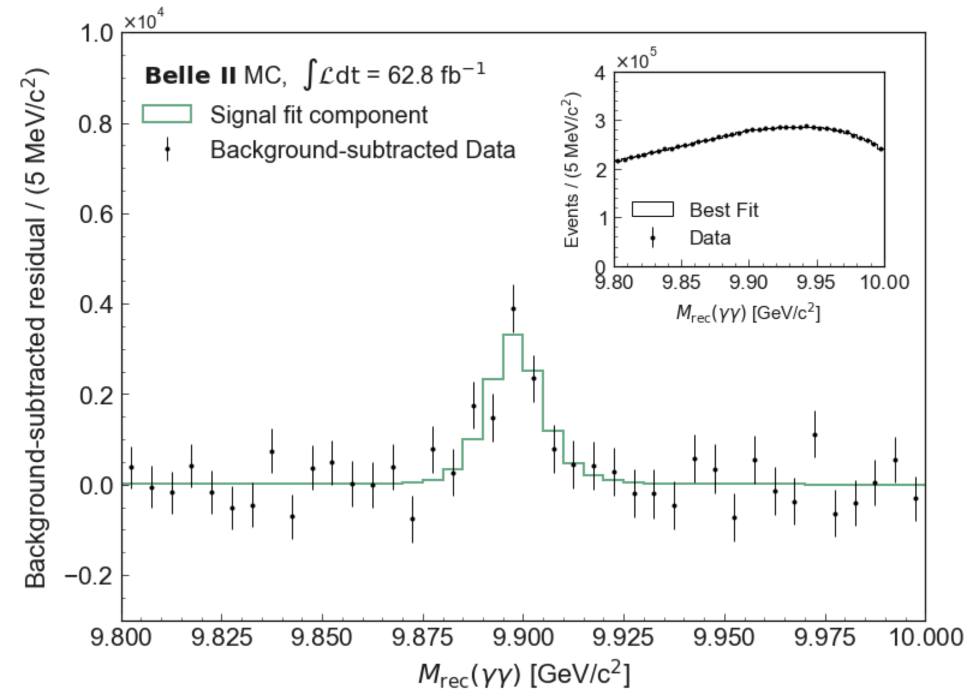
Next step:
Dalitz analysis of $\Upsilon(4S) \to \pi^+\pi^-\ \Upsilon(nS)$
Possible with a ~1ab^{-1} data set

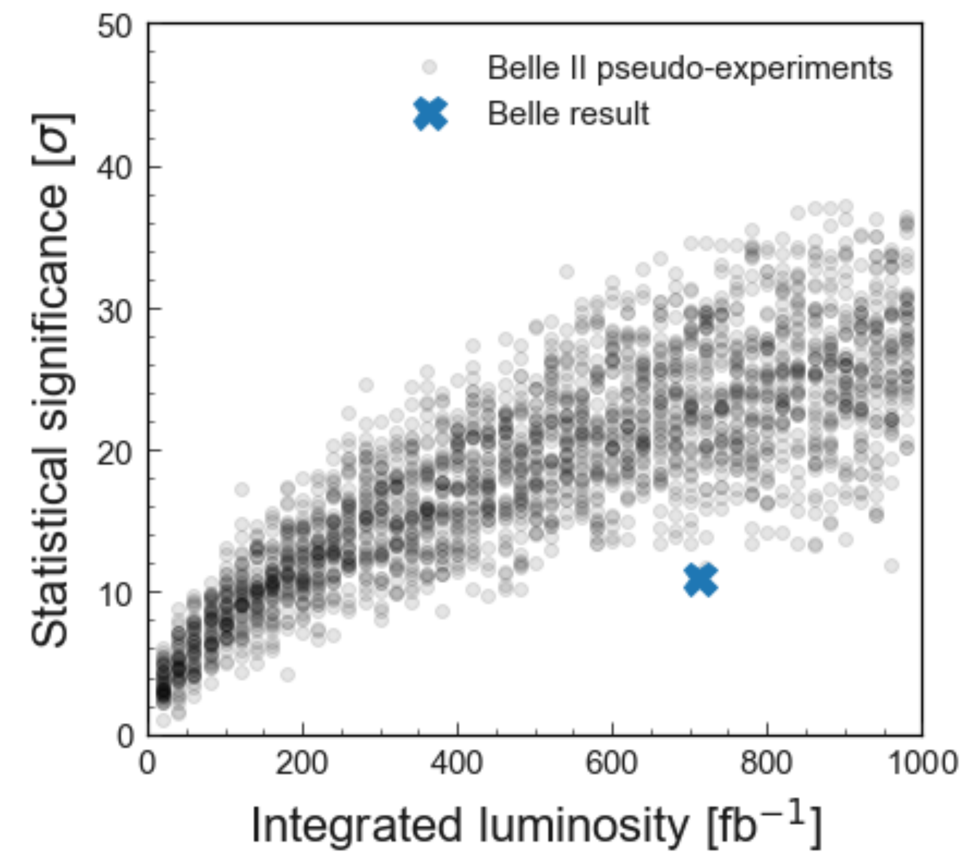
MC study on rediscovery of the Υ(4S)→η h_b(1P) transition

$$\Upsilon(4S) \to \eta\ [\ h_b(1P) \to \gamma\eta_b(1S)\ ]$$

BELLE2-NOTE-PL-2021-007

- η reconstructed in **γγ**
- Signal extracted fitting the recoil mass distribution of the η→**γγ** candidates.
- Belle already measured BR[Υ(4S)→η h_b(1P)] = 2.18×10^{-3}
  - *[Phys. Rev. Lett.115 (2015) 14, 142001]*
- Belle II analysis:
  - Better background reduction
  - 25 % more efficiency
- Belle II should be able to re-observe the process with as little as 50 fb^{-1}

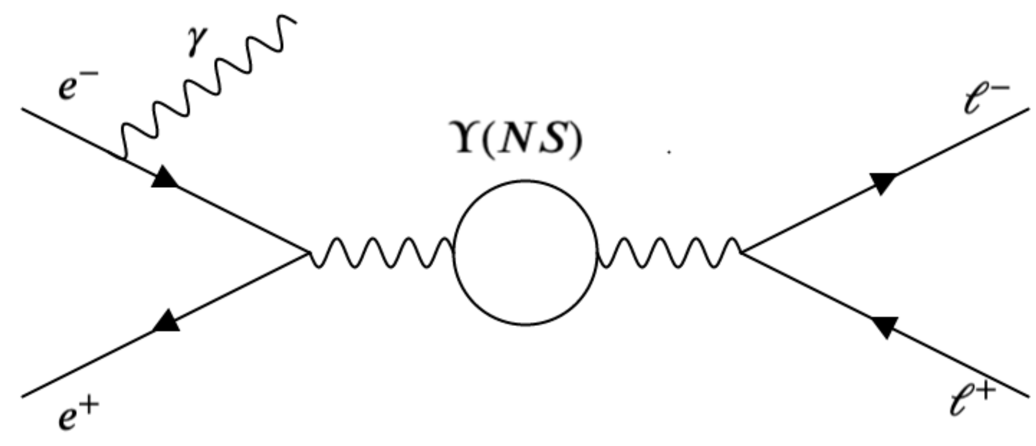




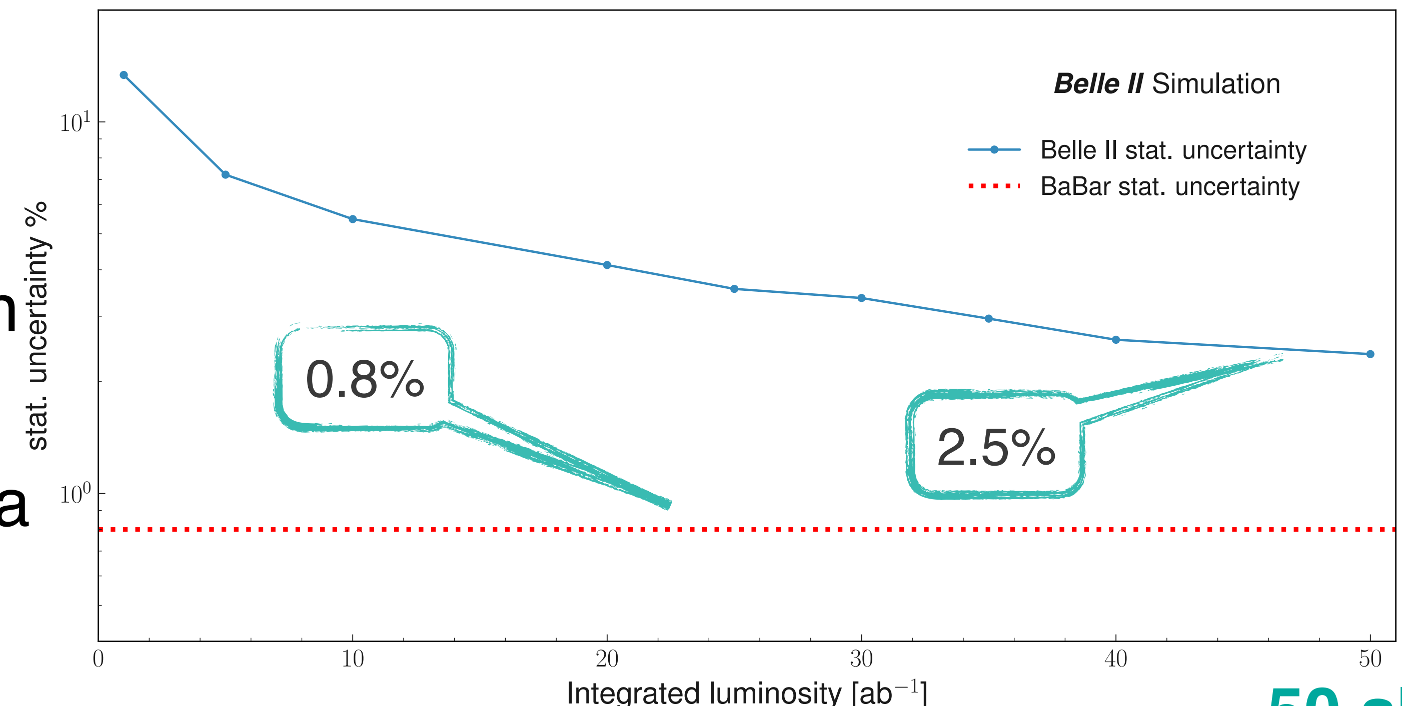
Can we exploit the huge dataset that will be taken at $\Upsilon(4S)$ (50 ab^{-1}) to do physics usually done at lower energies?

Feasibility study on lepton flavour universality

- MC sensitivity studies on the LFU in the channel **$\Upsilon(1,2,3\,S) \to \ell\ell$** via initial-state radiation from run at Υ(4S)
- Potential new physic in $B \to D^{(*)}\ell\nu$ affects also this process
  - *[Aloni et al, JHEP 06 (2017) 019]*
- Measure **$\Upsilon(1S) \to \tau\tau, \mu\mu$** by fitting the ISR peak in the recoil mass distribution
- Measure $R = \dfrac{B(\Upsilon(1S) \to \tau\tau)}{B(\Upsilon(1S) \to \mu\mu)}$
- Check statistical uncertainty as function of integrated luminosity
- More competitive BaBar result with data taken at Υ(3S):
  - *[Phys. Rev. Lett., 125:241801, 2020]*



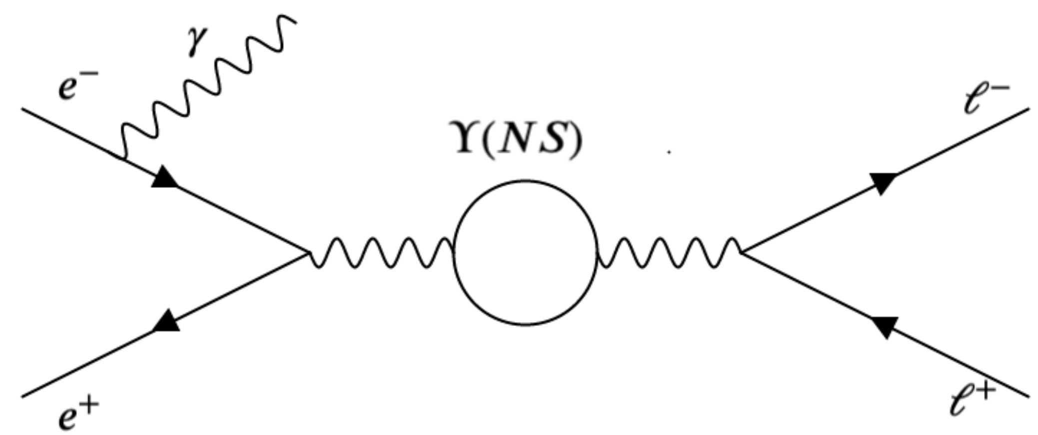
BELLE2-NOTE-PL-2021-006



50 ab^{-1}

Feasibility study on lepton flavour universality

- MC sensitivity studies on the LFU in the channel **Υ(1,2,3 S) → $\ell\ell$** via initial-state radiation from run at Υ(4S)



- Potential new physic in $B \to D^{(*)}\ell\nu$ affects also this process
  - *[Aloni e*

Analysis not feasible with data at Υ(4S)

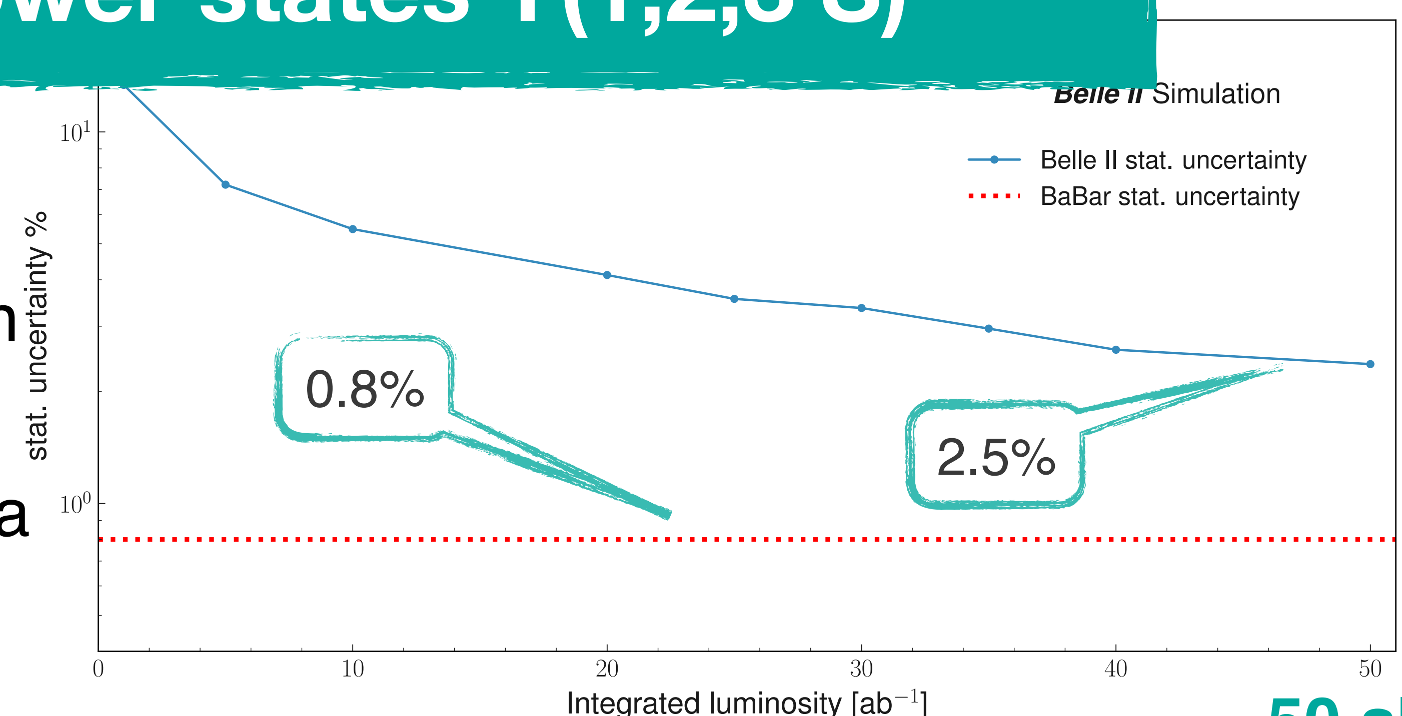
Need data at lower states Υ(1,2,3 S)

- Measure

ISR peak

- Measure $\frac{B(\Upsilon(1S) \to \tau\tau)}{B(\Upsilon(1S) \to \mu\mu)}$

- Check statistical uncertainty as function of integrated luminosity
- More competitive BaBar result with data taken at Υ(3S):
  - *[Phys. Rev. Lett., 125:241801, 2020]*

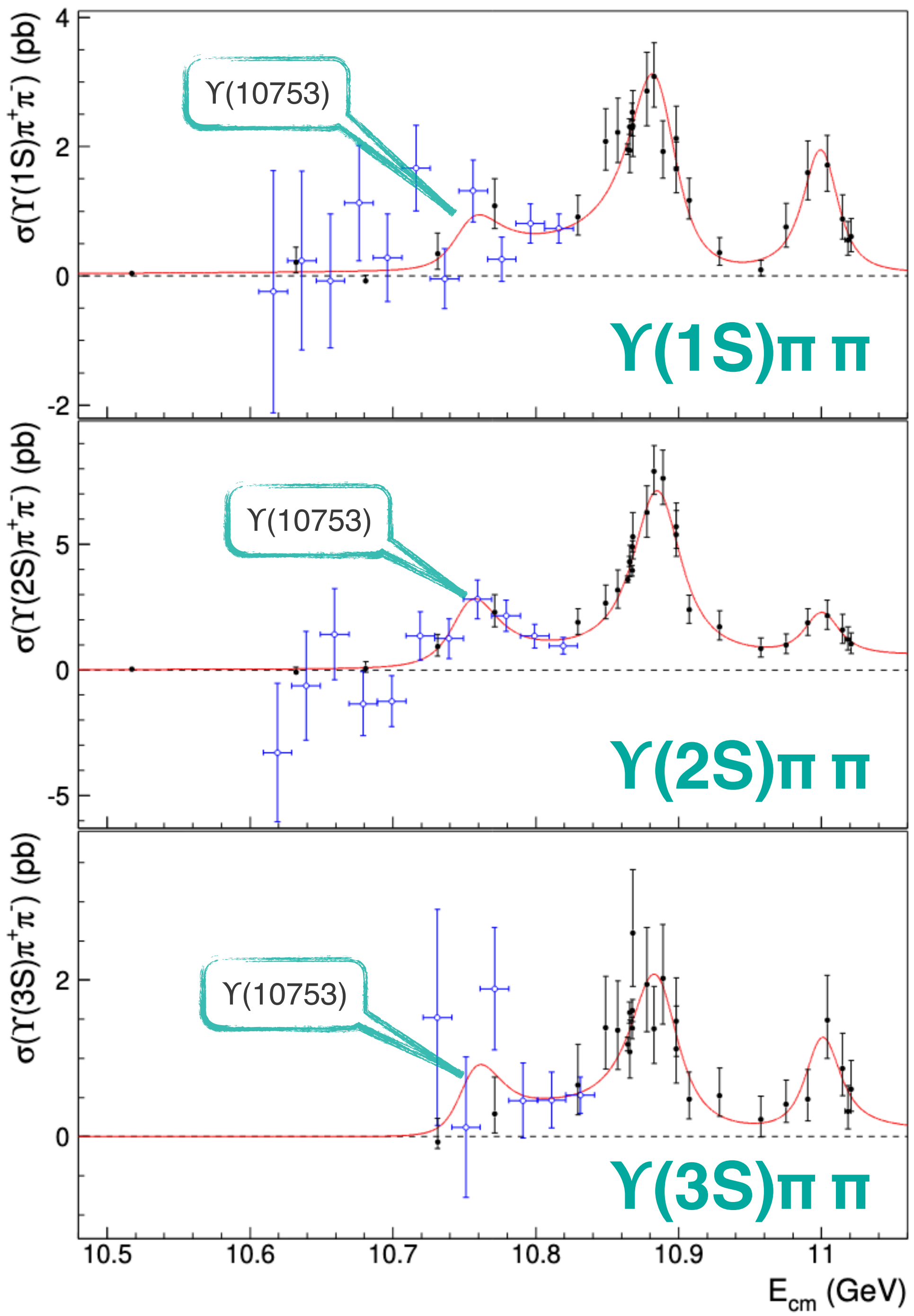


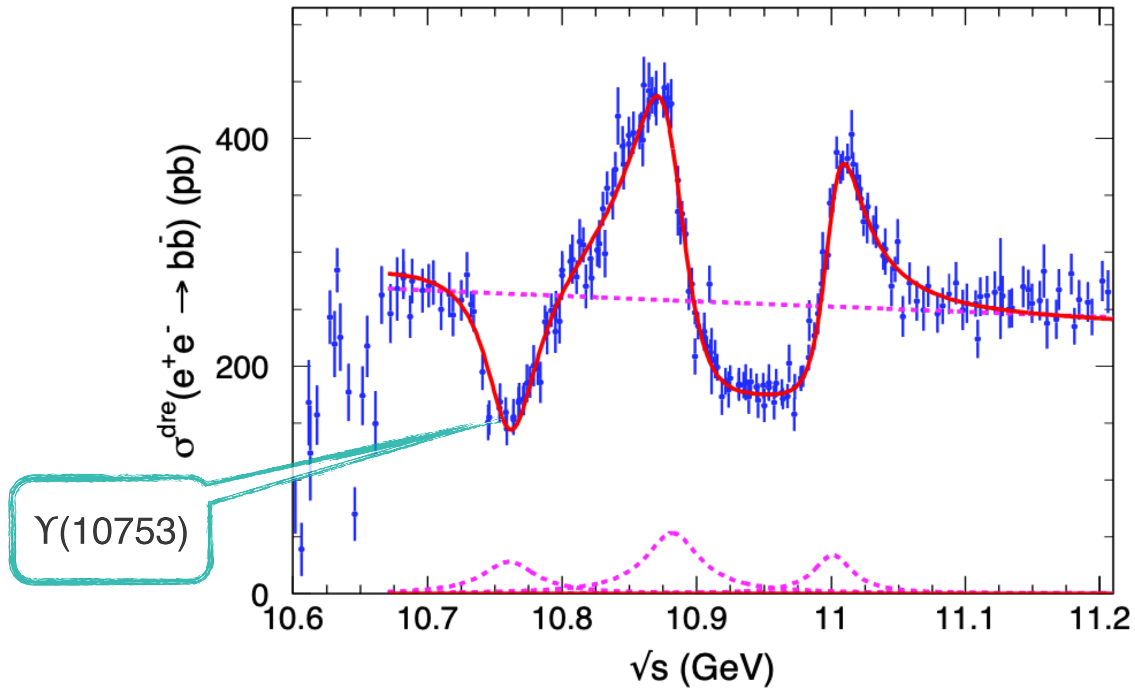
50 ab^{-1}

2021 energy scan around $\Upsilon(10753)$

About Υ(10753)

- JHEP10(2019)220 (Belle)
  - $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$
    - $\Upsilon(nS) \to e^+e^-$, $\mu^+\mu^-$
    - n= 1,2,3
  - High-stat scan points: 1 fb^{-1} each (**black**)
  - + ISR process at the Υ(10860) [Υ(5S)] (**blue**)
  - **Found new $J^{PC}=1^{--}$ structure**
    - significance of 5.2 σ





- Chin.Phys.C 44 8, 083001 (2020):
  - Refit the Belle + BaBar R_b scan
  - Evidence of Υ(10753) in interference

Possible interpretations

- Followed several Belle analyses:
  - $B\bar{B}$, $B^*\bar{B}$, $B^*\bar{B}^*$ cross sections study, $\Upsilon(10750) \to \omega\eta_b(1S)$ (Not published), …
  - Results inconclusive
  - Need more data

Conventional D- or S-D mixed state:

- Phys.Rev.D 101 (2020) 1, 014020
- Phys.Lett.B 803 (2020) 135340
- Eur.Phys.J.C 80 (2020) 1, 59
- arXiv:2106.14123v1 (2021)

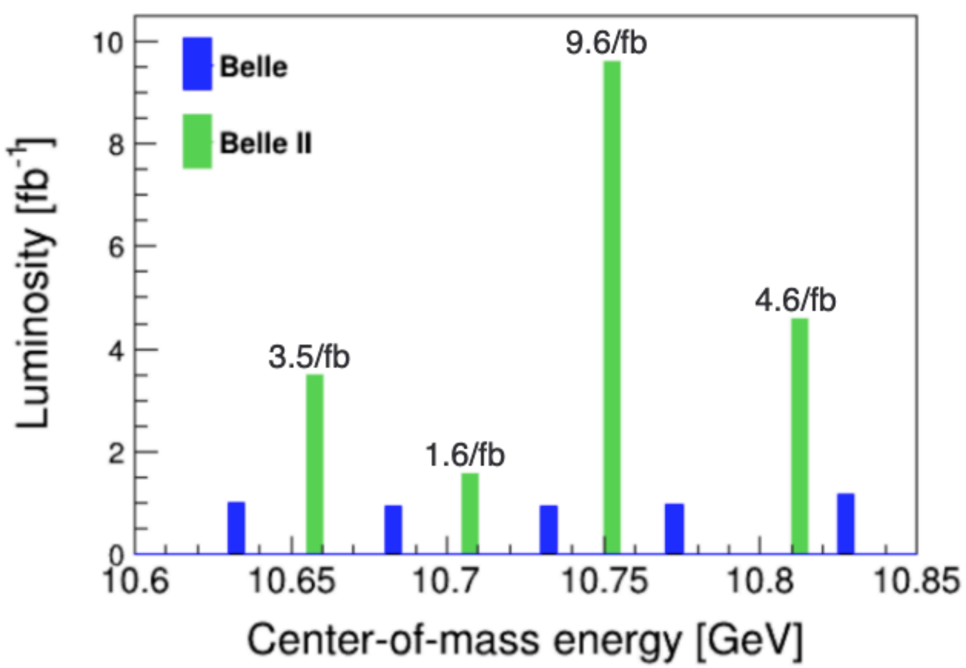
Exotic:

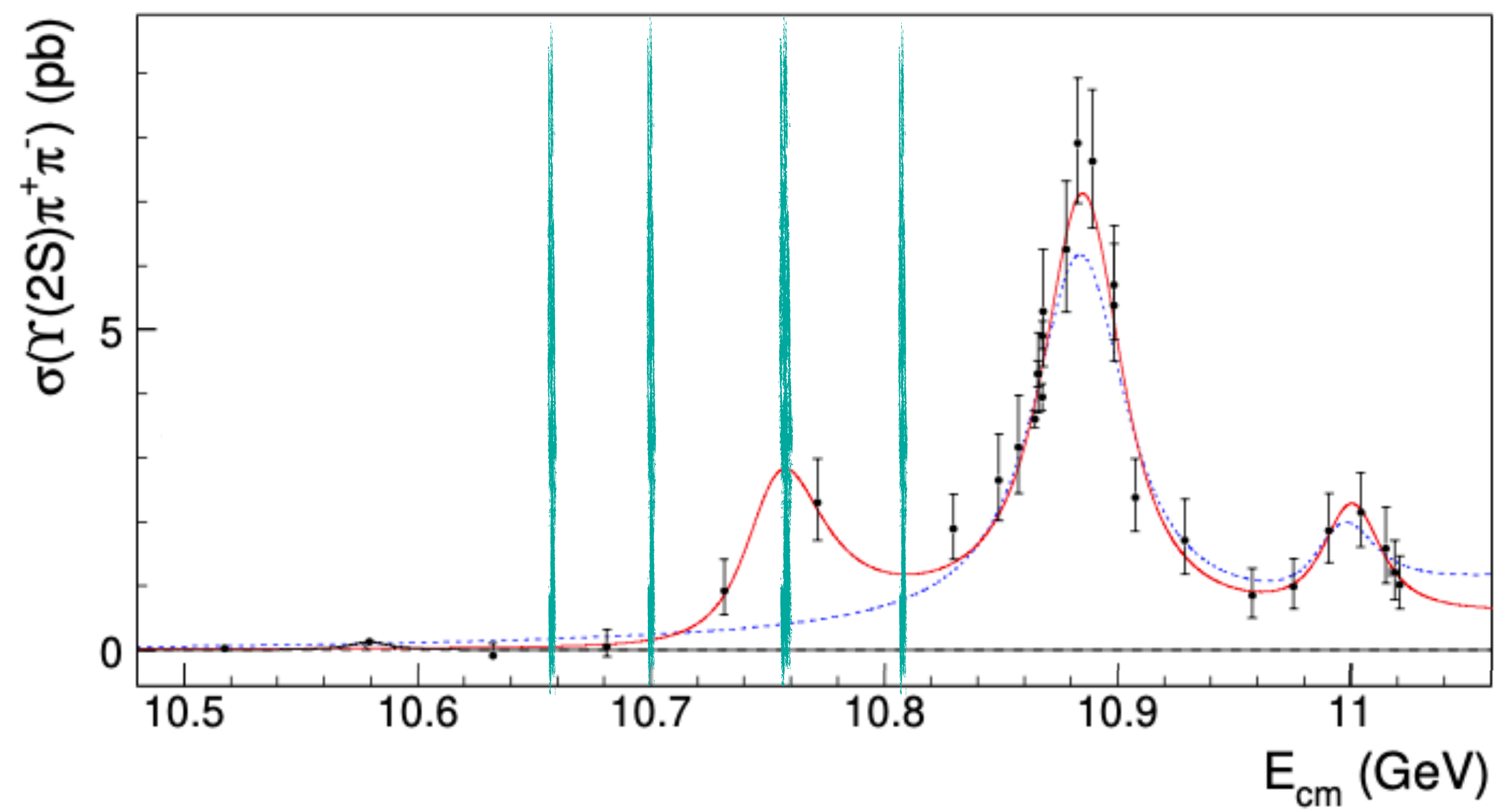
- Arxiv:2008.05605 (Dynamic resonance)
- Chin.Phys.C 43 (2019) 12, 123102 (Tetraquark)
- Phys.Lett.B 802 (2020) 135217 (Tetraquark)
- Phys.Rev.D 102 (2020) 1, 014036 (Υ(5S) is 4q)

2021 Energy scan

3 weeks in November 2021

- 10.751 GeV (9.6 fb^{-1})(on resonance?)
- 3 scan point for energy-dependent $B\bar{B}$, $B^*\bar{B}$, $B^*\bar{B}^*$ cross sections study:
  - 10.657 GeV (3.5 fb^{-1})
  - 10.706 GeV (1.6 fb^{-1})
  - 10.810 GeV (4.6 fb^{-1})
- BELLE2-NOTE-PL-2022-001





Υ(10753) analyses

- No public results yet

Mode	Belle Status	Belle II Outcome
Golden Modes		
$e^+e^- \to \pi^+\pi^-\Upsilon(pS)(\to \ell^+\ell^-)$	Published	B+BII combined
$B\overline{B}$ decomposition	Published	B+BII combined
$\pi^+\pi^-$ Dalitz	Needs data	First result
$Y_b \to \omega\eta_b(1S)$	Ongoing	B+BII or BII update
$Y_b \to \omega\chi_{bJ}(1P)$	In pub./needs data/points	B+BII combined
Silver Modes		
$Y_b \to \pi^+\pi^- X$ (inclusive)	Needs data	First result
$Y_b \to \eta X$ (inclusive)	Needs data	First result
$Y_b \to \eta\Upsilon(1S, 2S)(\to \ell^+\ell^-)$	Needs data	First search
$Y_b \to \eta'\Upsilon(1S)(\to \ell^+\ell^-)$	Needs data	First search
$Y_b \to \Upsilon(1S)$ (inclusive)	Needs data	First result
Bronze Modes		
$Y_b \to \gamma X_b$	Needs data	First search
$Y_b \to \pi^0\pi^0\Upsilon(pS)(\to \ell^+\ell^-)$	Needs data	First search
$Y_b \to KK(\phi)\Upsilon(pS)(\to \ell^+\ell^-)$	Needs data	First search
$Y_b \to \pi^0\pi^0 X$ (inclusive)	Needs data	First search
$Y_b \to \pi^0 X$ (incl. or excl.)	Needs data	First search
...		

BELLE II POTENTIAL

Far future

- Run at Υ(6S) and Υ(5S) and high energy scan
  - Search for new, predicted, resonances such missing bottomonia, exotic states, etc..
  - Improve precision of already known process and states.
    - Z_b states were only found so far in Υ(5S) decays.
  - Measure the effect of the coupled channel contribution.
  - Study $B^{(*)}\bar{B}^{(**)}$ and $B_s^{(*)}\bar{B}_s^{(**)}$ threshold regions.
    - Maybe challenging for SuperKEKB

Above Υ(4S)

- Run at Υ(3S), Υ(2S) and Υ(1S)
  - Search for missing ππ/η transitions to constrain further theoretical models.
  - Search for new physics:
    - Lepton flavour universality, Lepton flavour violation, new scalars…

BELLE II POTENTIAL

Far future

- Run at $\Upsilon(6S)$ and $\Upsilon(5S)$ and high energy scan
  - Search for new, predicted, resonances such missing bottomonia, exotic states, etc..
  - Improve precision of already known process and states.
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Below $\Upsilon(4S)$

- Run at $\Upsilon(3S)$, $\Upsilon(2S)$ and $\Upsilon(1S)$
  - Search for missing $\pi\pi/\eta$ transitions to constrain further theoretical models.
  - Search for new physics:
    - Lepton flavour universality, Lepton flavour violation, new scalars…

Summary

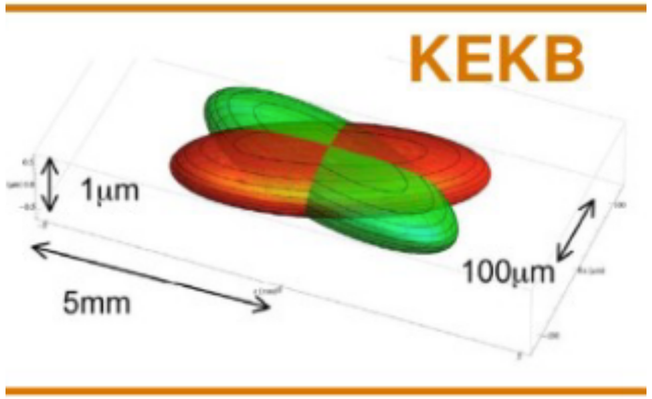
- Currently taking data at $\Upsilon(4S)$
  - Rediscovery analyses going on
    - Shown results with only a small part of accumulated luminosity.
  - Feasibility studies shows how it's important to take data below the $\Upsilon(4S)$ to perform studies on physic beyond standard model
- Took energy scan around 10.751 GeV
  - New structure studies going on
- Possible run at $\Upsilon(6S)$, $\Upsilon(5S)$, $\Upsilon(3S)$, $\Upsilon(2S)$ and $\Upsilon(1S)$
  - Plans are under discussion

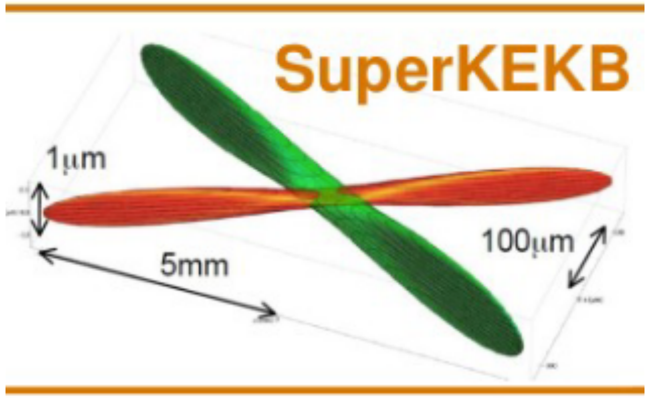
Together with the capability of SuperKEKB, Belle II has a unique opportunity to study quarkonium(-like) particles and make an impact in this sector in the years to come.

Backup slides

SuperKEKB Luminosity

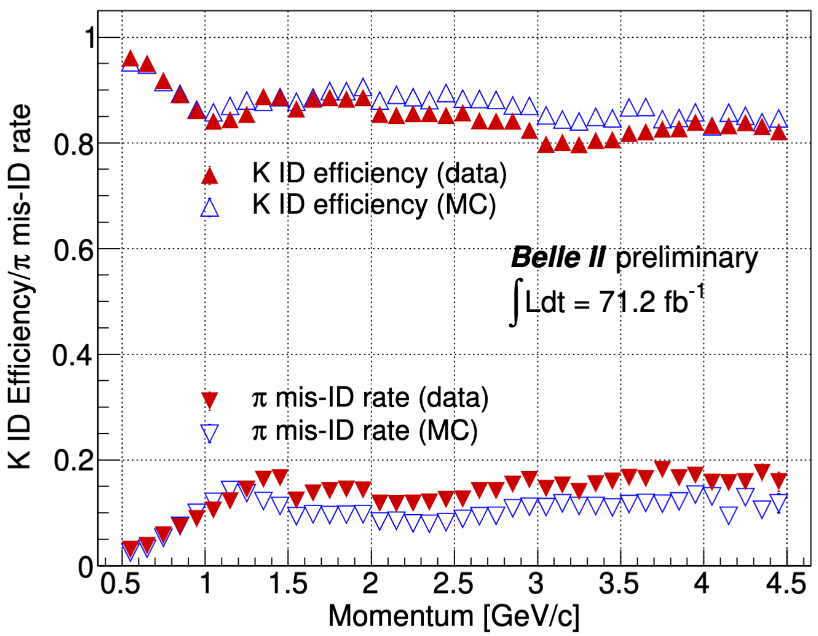
- SuperKEKB goal: > ~40 × KEKB instantaneous luminosity
  - $\mathscr{L} = 6.5\times10^{35}$ cm^{-2}s^{-1}
  - Current world record: $\mathscr{L} = 3.9\times10^{34}$ cm^{-2}s^{-1} (May 2022)
- How to achieve that?
  - Beam current:
    - 1.64/1.19 A (Belle) → 2.5/1.8 A (Belle II) for e^- /e^+ beam.
  - Beta function at IP ($\beta^{+-*}y$):
    - 5.9/5.9 mm (Belle) → 0.27/0.30 mm (Belle II).

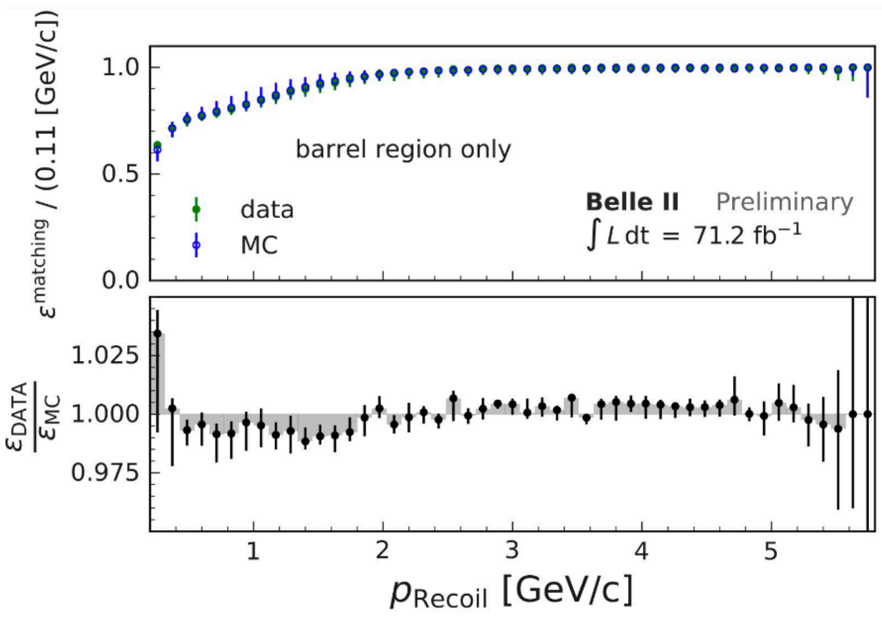


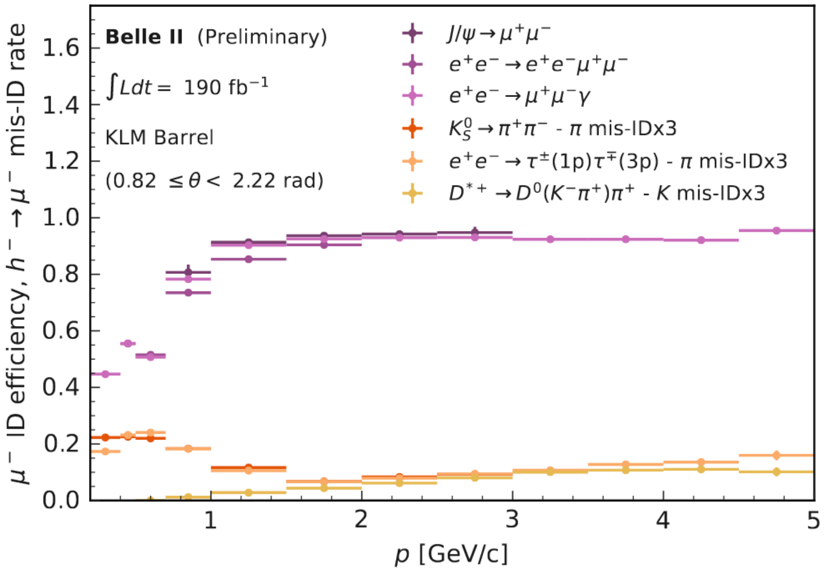


$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y\pm}}\right)$$

Belle II performance







K π identification

BELLE2-NOTE-PL-2020-024

Photon matching efficiency

BELLE2-NOTE-TE-2020-026

μ e identification

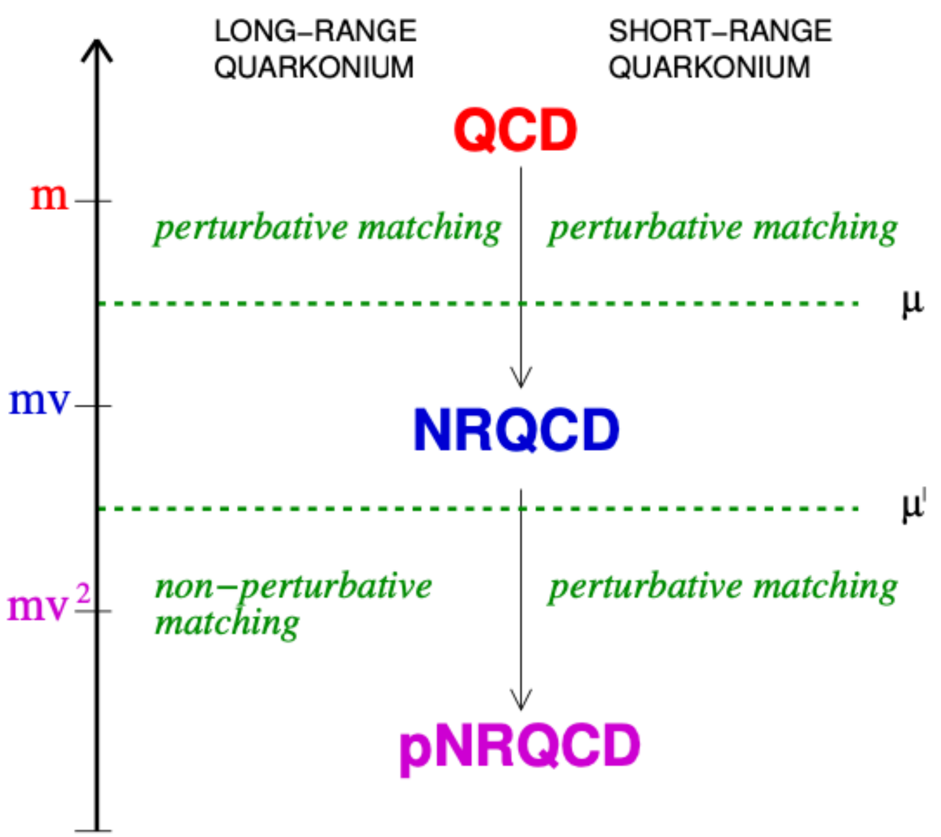
BELLE2-CONF-PH-2022-003

Potential models

- Use of stationary non-relativistic Schrödinger equation with appropriate potential:
  - Cornell potential $V = -\frac{a}{r} + br + c$
  - $-\frac{a}{r}$ coincides with the QCD one-gluon exchange Coulomb potential
  - $+br$ incorporates confinement
- Non relativistic potential model justified by the fact that the bottom and, to a lesser extent, the charm masses are large in comparison to Λ_{QCD}
- Add extra terms to include relativistic effect, fine and hyper fine structure…
- Above two heavy-light meson threshold extra degrees of freedom are needed to account for possible mixing effects.
- Purely phenomenological, with no way to link the model parameters to QCD.

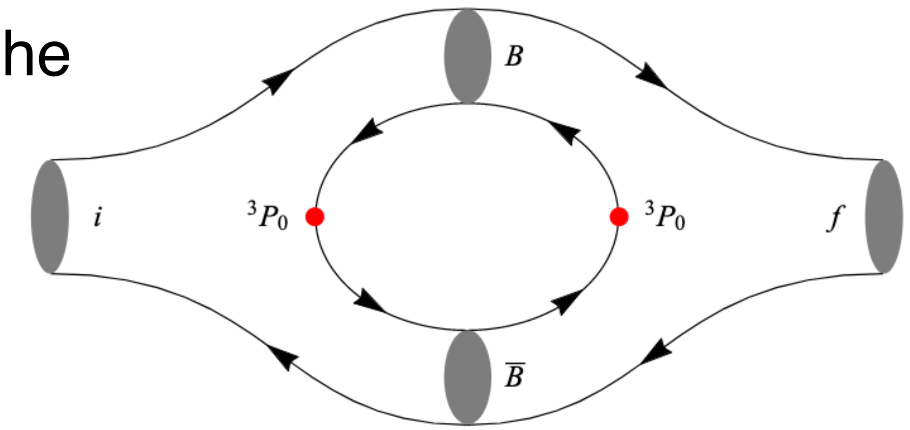
Multiscale system

- Hard scale (the mass m of the heavy quarks)
  - Can be described in perturbation theory.
  - Quarkonium annihilation and production take place at the scale **m**
- Soft scale (the relative momentum of the heavy-quark–antiquark **p ~ mv**)
  - Quarkonium binding
- Ultra soft scale (the typical kinetic energy **E ~ mv²** of the heavy quark and antiquark)
  - Very low-energy gluons and light quarks (also called ultrasoft degrees of freedom) live long enough that a bound state has time to form
- The description of the systems depends on the relation of Λ_{QCD} to the scales.

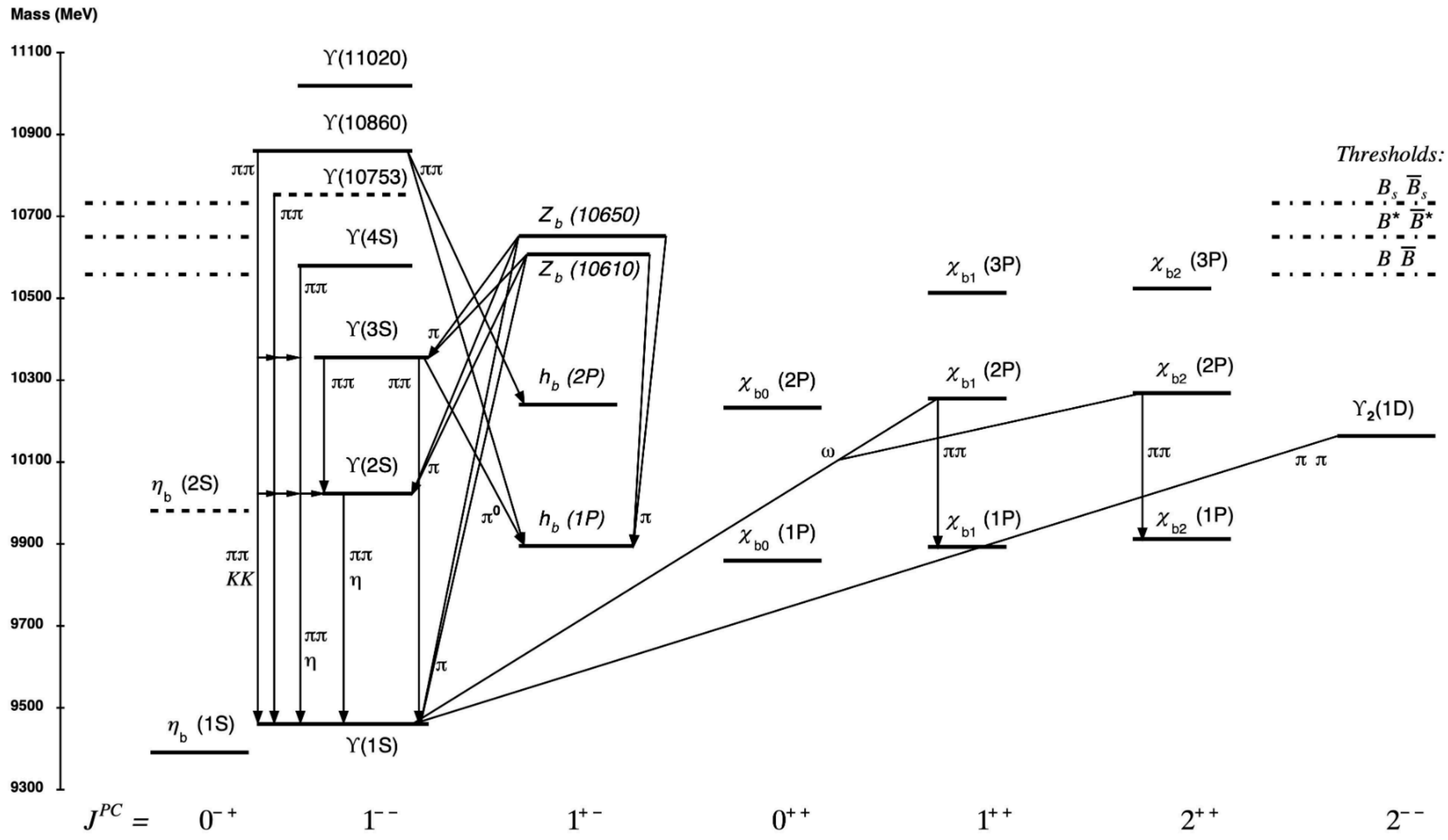


Couple channel effect

- Framework used to describe the nature of the properties unexpected for a pure $q\bar{q}$ state.
- Generate quark-antiquark pairs which enlarge the Fock space of the initial state.
- This formalism incorporate intermediate heavy mesons within hadrons.
- These multiquark components will change the Hamiltonian of the potential model:
  - Mass shift
  - Mixing between states with the same quantum numbers
  - Directly contribution to open channel strong decay if the initial state is above threshold.
- Above the BB threshold the states such 4S, 5S and Y6S are more affected.
  - These states can be modelled as mixture of $q\bar{q}$ with two-meson continuum in a form of hadronic loop.

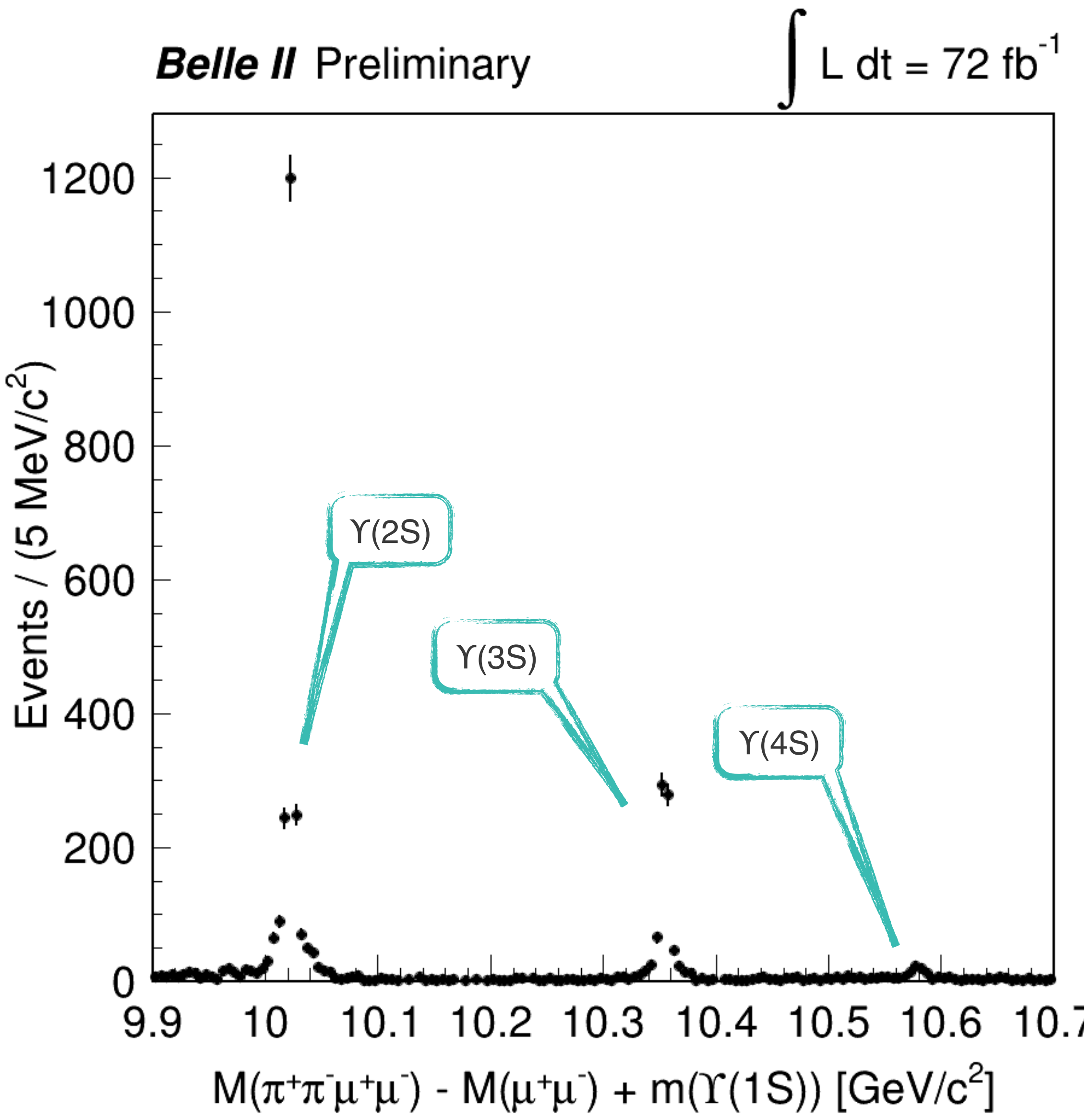


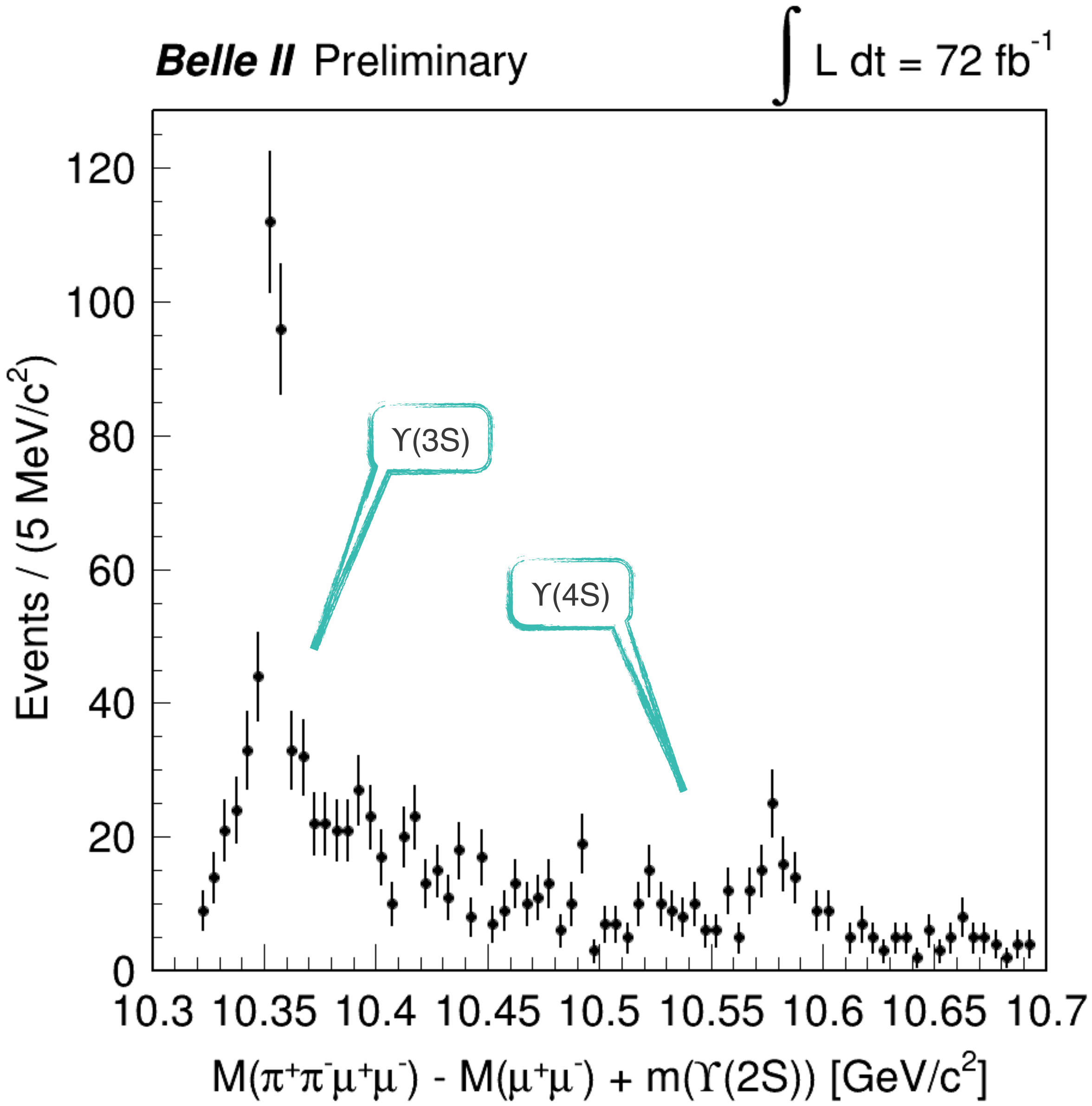
Transitions



Υ(nS) dipion transitions

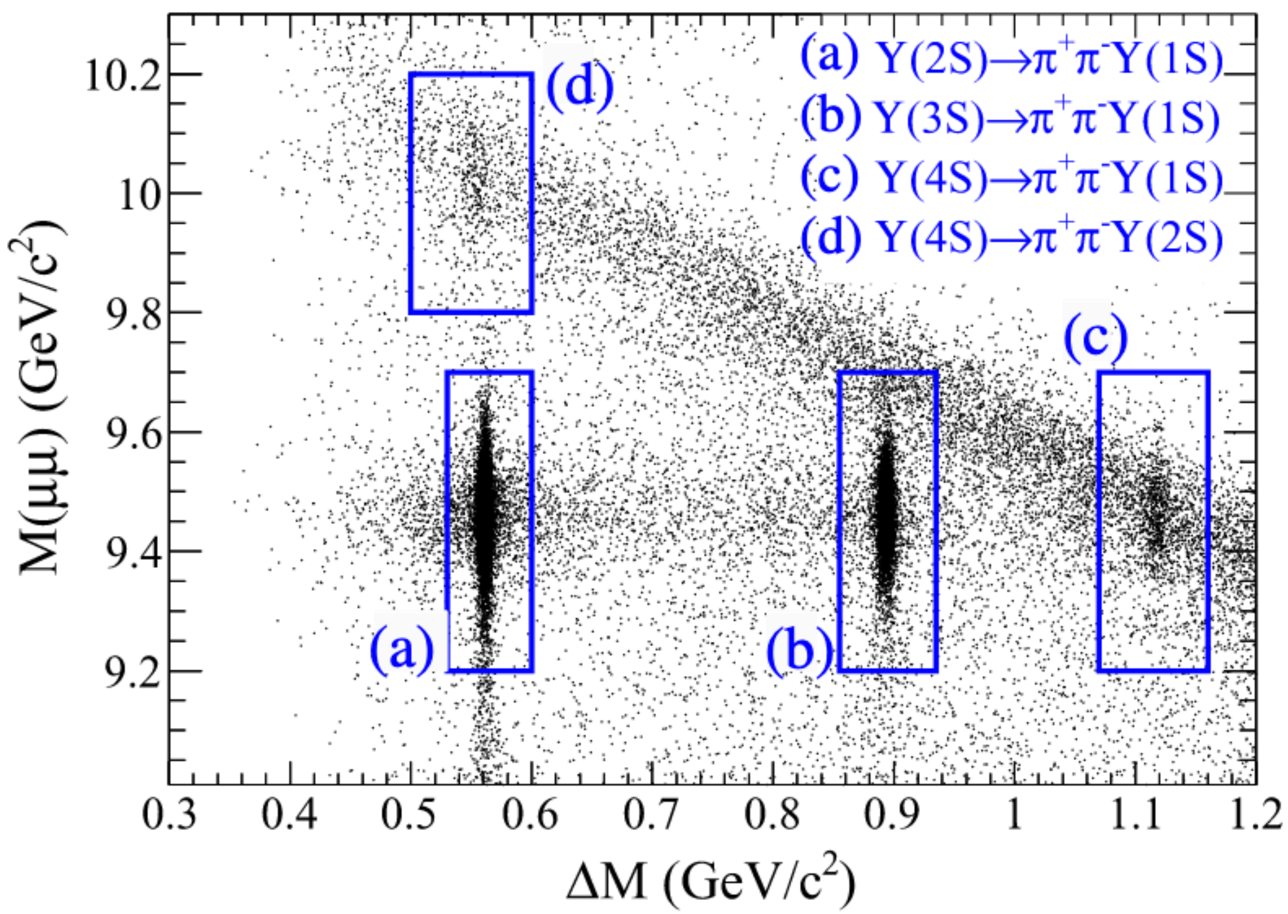
- Variable of interest: $\Delta M = M(\pi\pi\ell\ell) - M(\ell\ell) + M(PDG)$
  - M(PDG) = mass of the daughter

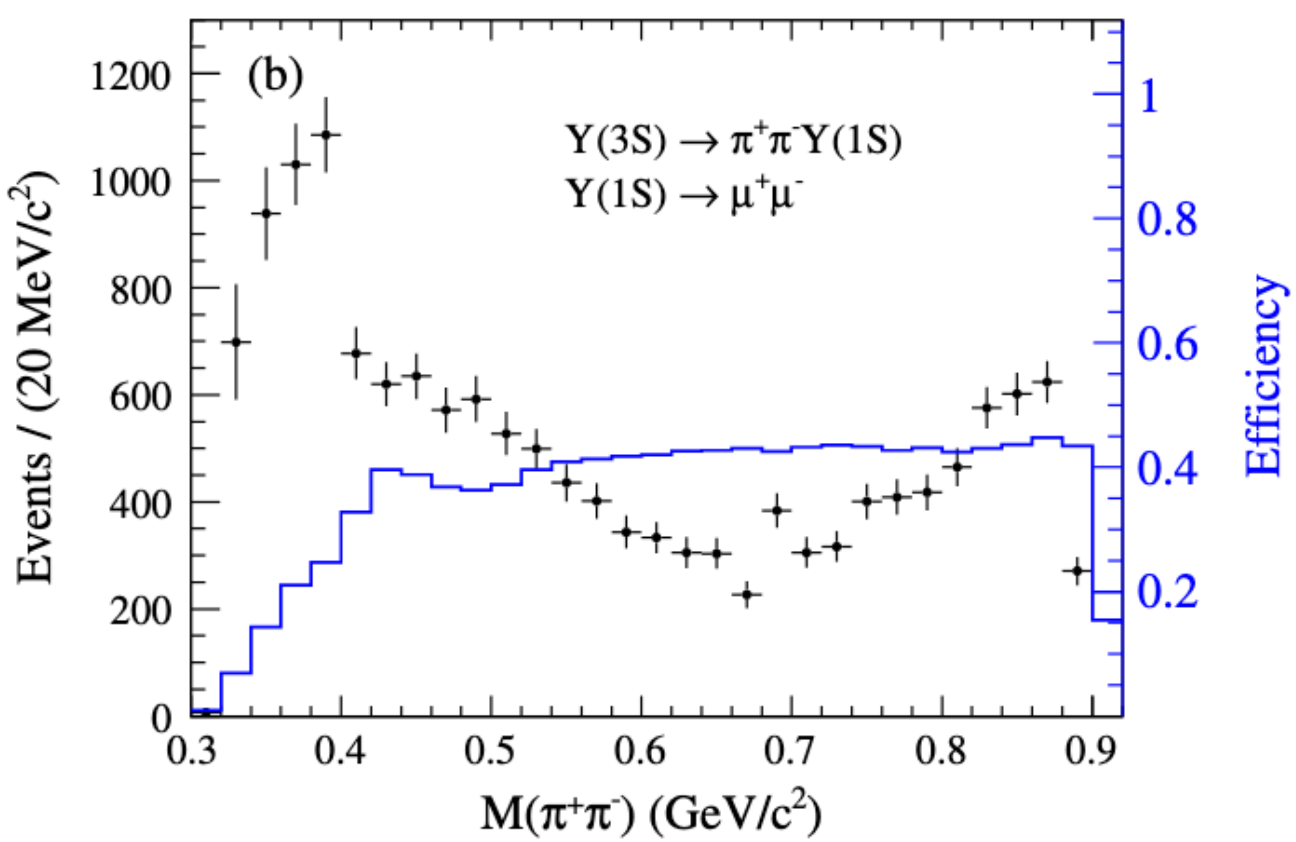




Dipion transion at Belle

- $\Upsilon(3S)\rightarrow\pi+\pi-\Upsilon(2S)$ not visible
- Not yet understood behaviour of $m_{\pi+\pi-}$ distributions

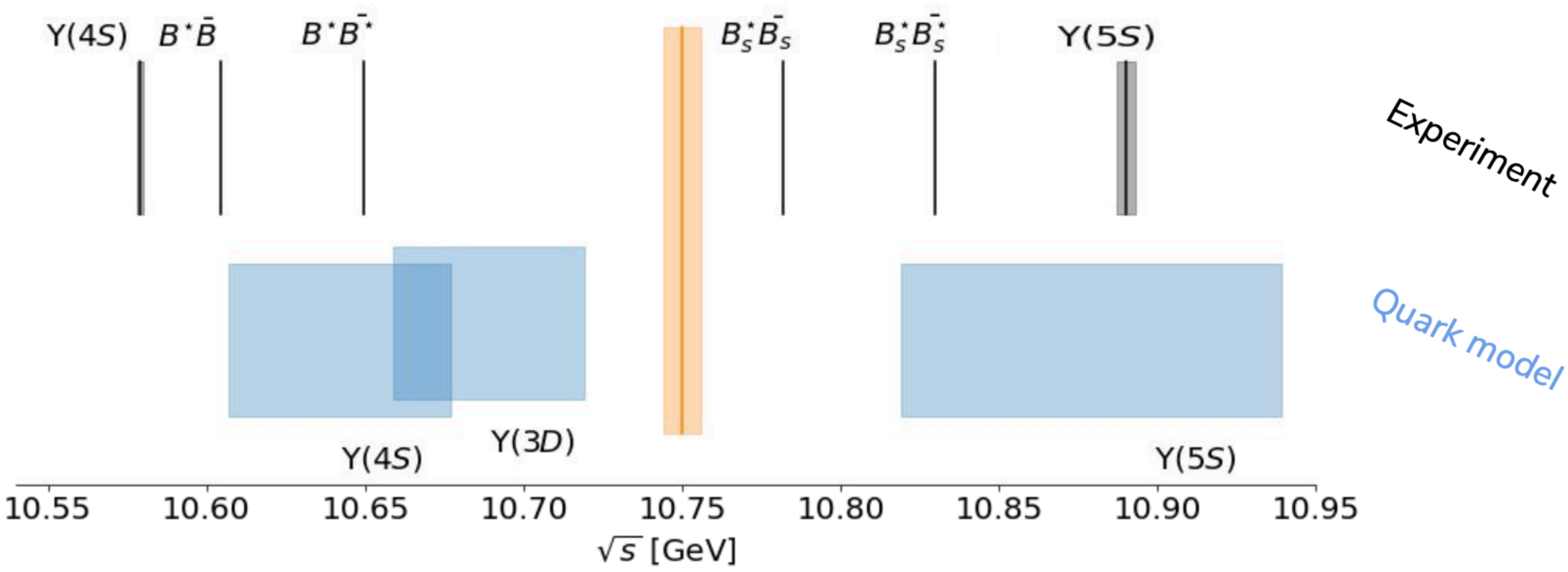




Υ(10753)

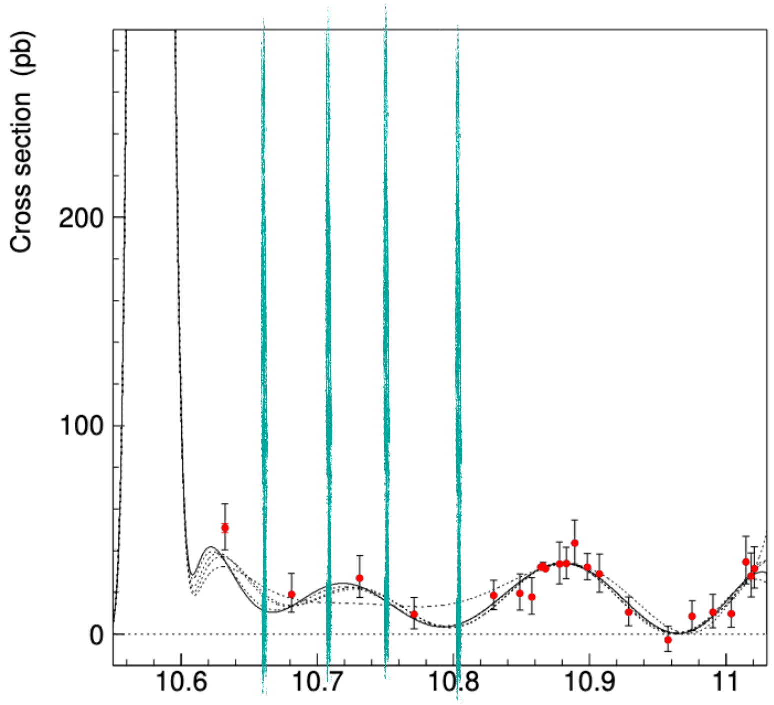
- Unlikely to be a molecule as it's far from any S- threshold

- No direct matching to conventional states (but may be an S-D mixing?)

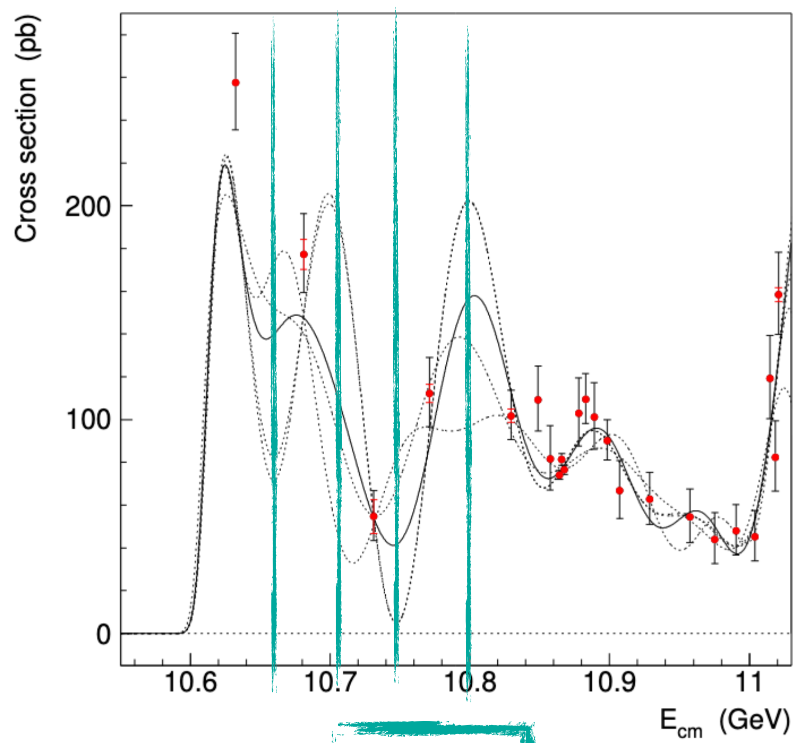


$B\bar{B}$ Decomposition in energy scan

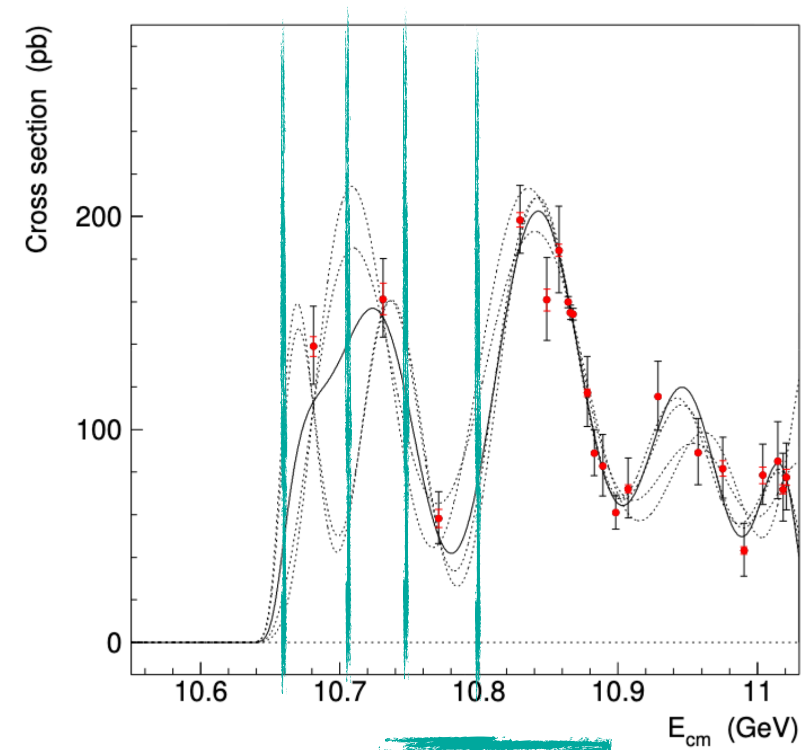
- $B\bar{B}$, $B^*\bar{B}$, $B^*\bar{B}^*$ cross section at various energies
- Higher statistic to improve fits
- JHEP06(2021)137



$B\bar{B}$

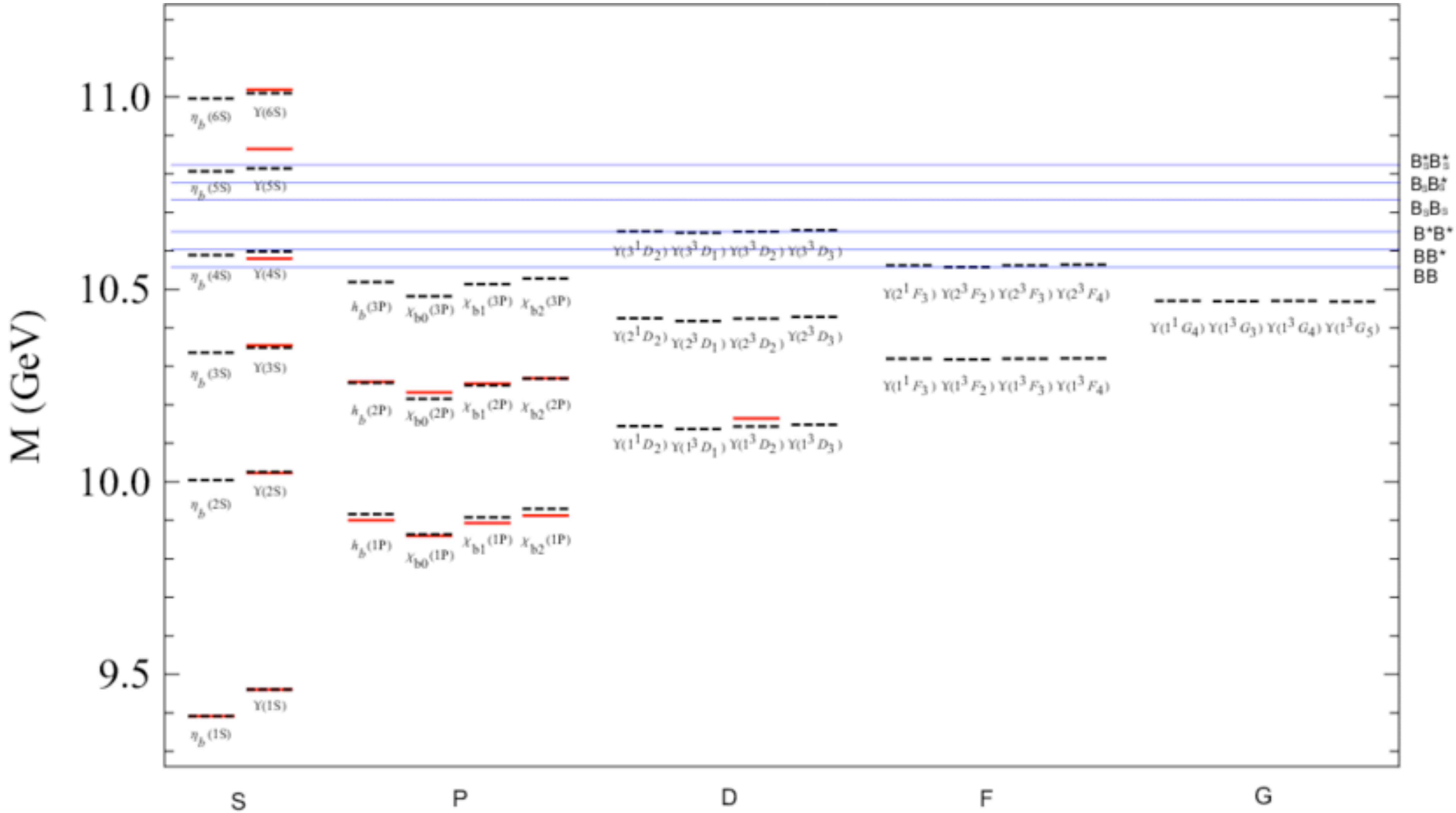


$B^*\bar{B}$



$B^*\bar{B}^*$

B(*)B(*) thresholds



Exotic states

- Many other possible states beyond Zb states are expected

Re-elaborated from Mod. Phys. Lett. A 32, 1750025 (2017)