Quarkonium at Belle II

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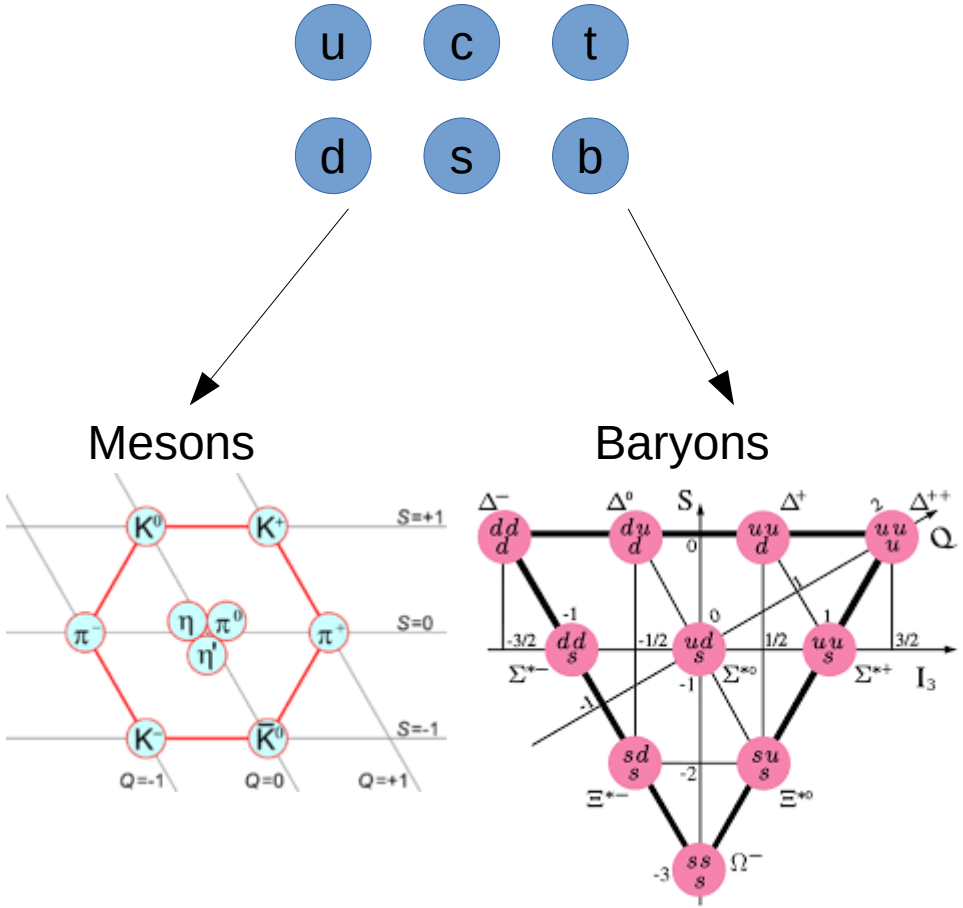
For the Belle II Collaboration

DIS2022 - XXIX Workshop on Deep Inelastic Scattering and Related Subjects

History – I.

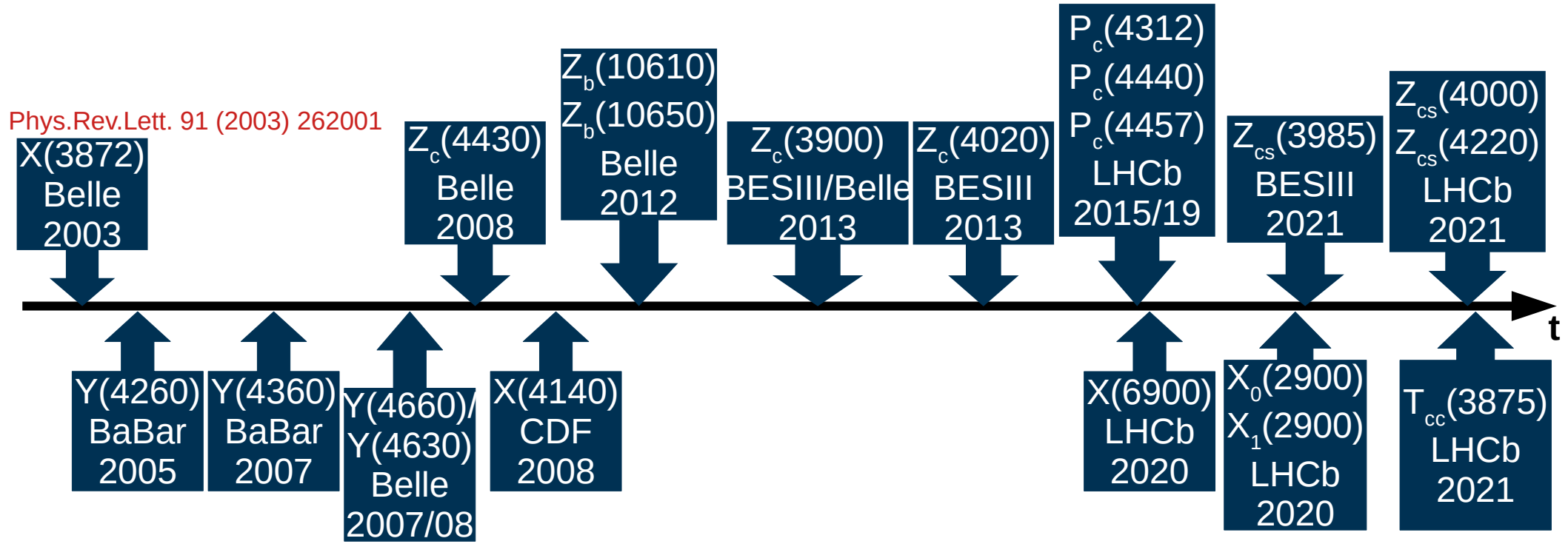
- **In 1963 Gellmann proposed the quark model**
  - Conventional hadrons
    - Mesons : 2 quarks
    - Baryons : 3 quarks

    are described
  - Additionally, also objects of 4 and 5 quarks were predicted
- **Many mesons and baryons were discovered since then**
- **The first „exotic“ object with more than 3 quarks was discovered in 2003 at Belle**



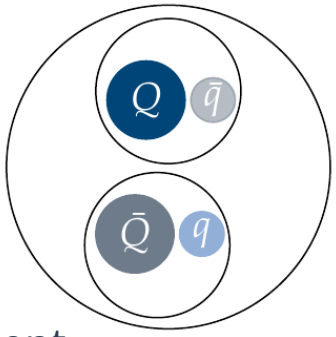
History – II.

- **Until 2003 no evidence for a new, „exotic“ state was found**
  - First exotic state discovered in 2003 at the Belle experiment
  - From there on, many new exotic states were discovered from different experiments
  - Neutrals as well as charged states were found
  - Six theoretical models still compete for the description
  - In most cases, statistics is the limiting factor → Belle II is designed to tackle that problem



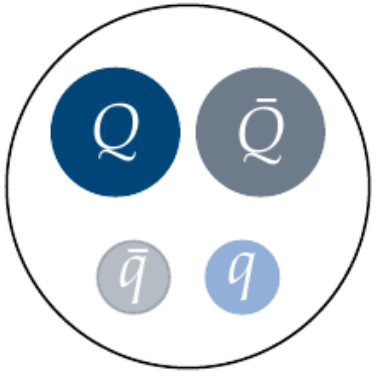
Theoretical models

- **Hadronic Molecules**
  - Two conventional meson bound states
  - Bound by one pion exchange
  - Many new states in good agreement
  - X(3872) most likely a molecular state

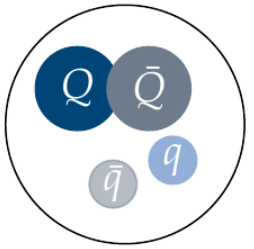


Physics Reports 873 (2020) 1–154

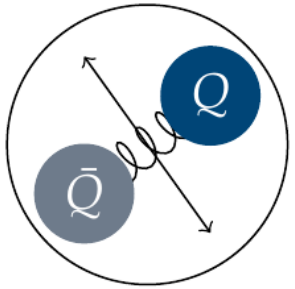
- **Tetraquarks**
  - Internally di-quark system
  - Double-well potential
  - Decay through tunneling of light q
  - Favors open-charm decays



- **Hadro-Quarkonia**



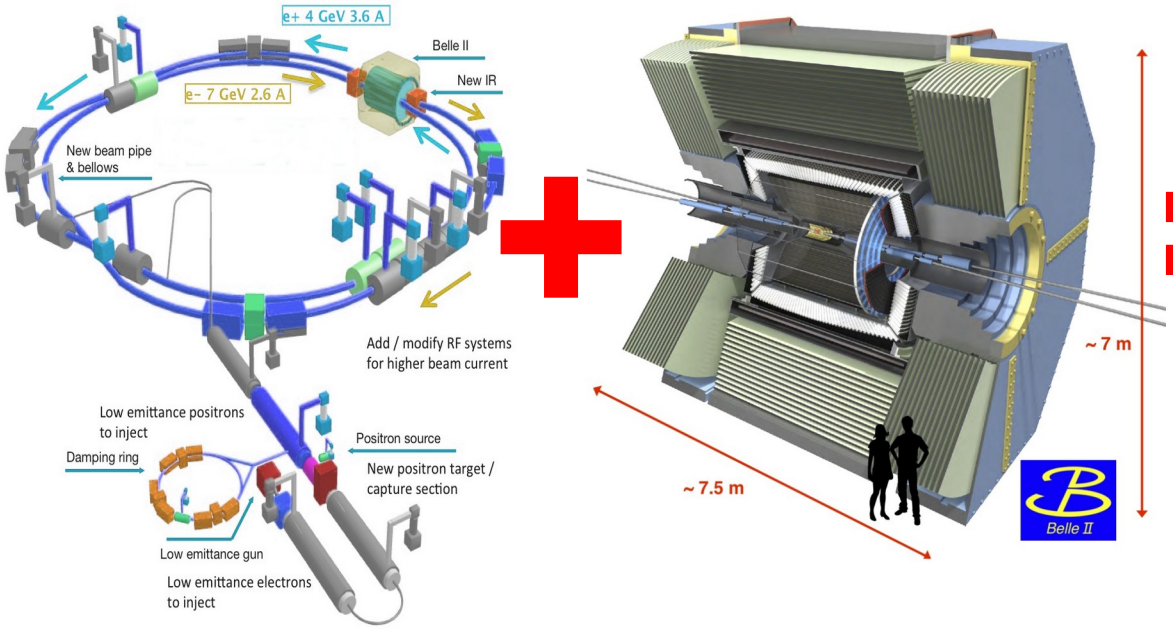
- **Hybrids**

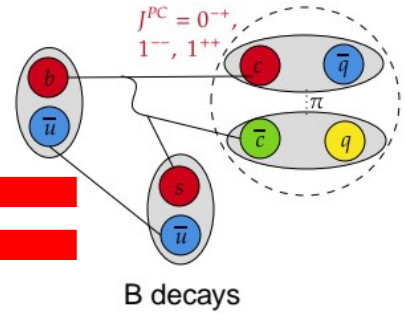


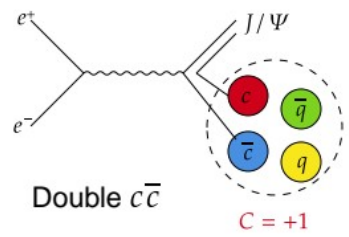
- **Glueballs**

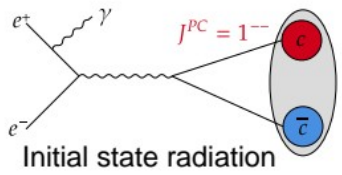
- **Cusps (Threshold Effects)**

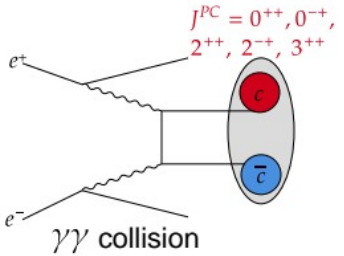
SuperKEKB and Belle II capabilities

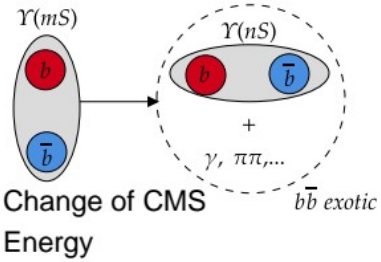








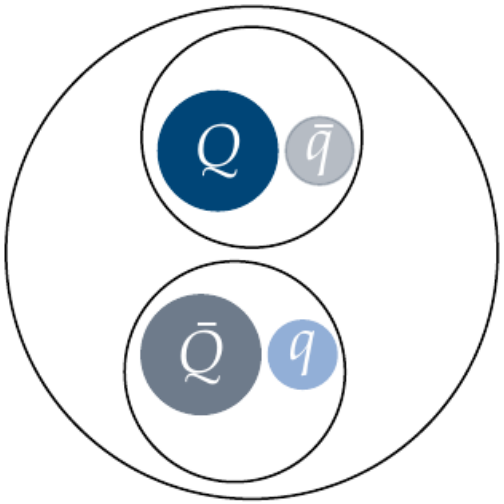




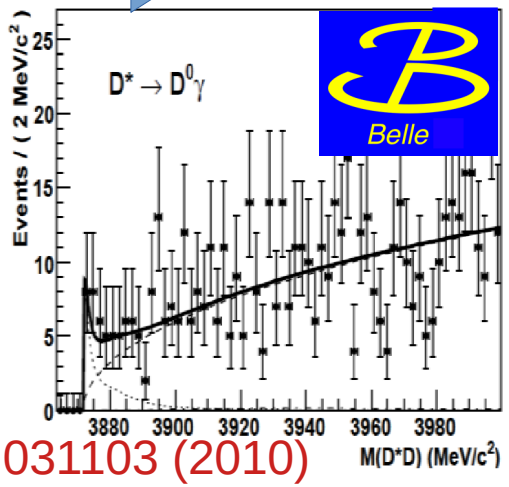
- **Belle II is hosted at the SuperKEKB accelerator**
  - Asymmetric energy e^+e^- (4 & 7 GeV) collider in Tsukuba, Japan
  - Goal for SuperKEKB → 30x KEKB instantaneous luminosity (nano-beam-scheme) : ~6×10^{-35} cm^{-2} s^{-1}
    - 50x integrated Belle luminosity → 50/ab
  - Full event reconstruction, decays with neutral/soft particles
  - Nominal CMS energy 10.58 GeV = M($\Upsilon(4S)$), Y(5S) and Y(6S) also producible
  - So far ~350/fb are collected since April 2018, instantaneous luminosity world record in December 2021

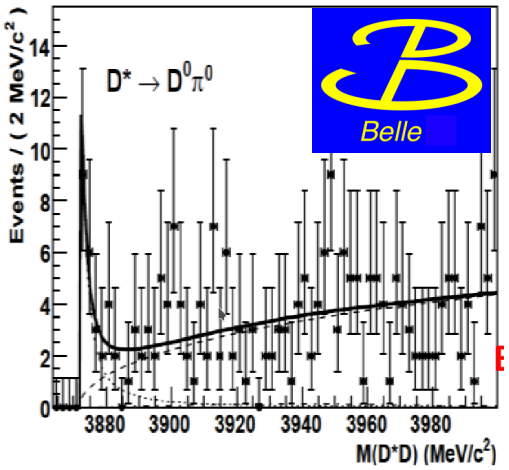
X(3872) – The most concerned particle in the charmonium sector

- **Discovery paper of X(3872) was the highest cited paper of Belle**
- **D^0D^{*0} molecular model is most favored so far, but still not confirmed**
- **Belle II capability**
  - Branching fraction
  - Lineshape measurement
- **Very narrow state, even though it is so close to the D^0D^{*0} threshold**
  - M(X(3872)) = 3871.65 +- 0.06 MeV
  - M(D^0D^{*0}) = 3871.69 +- 0.11 MeV
  - Radius > 5 fm for a molecular hypothesis



0.04 +- 0.12 MeV binding energy

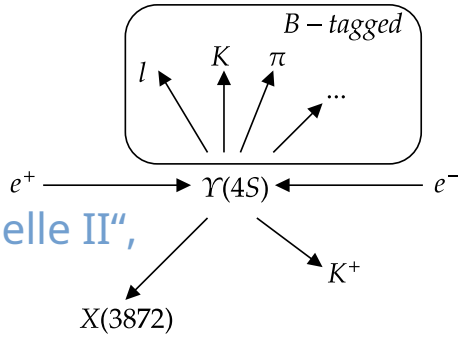


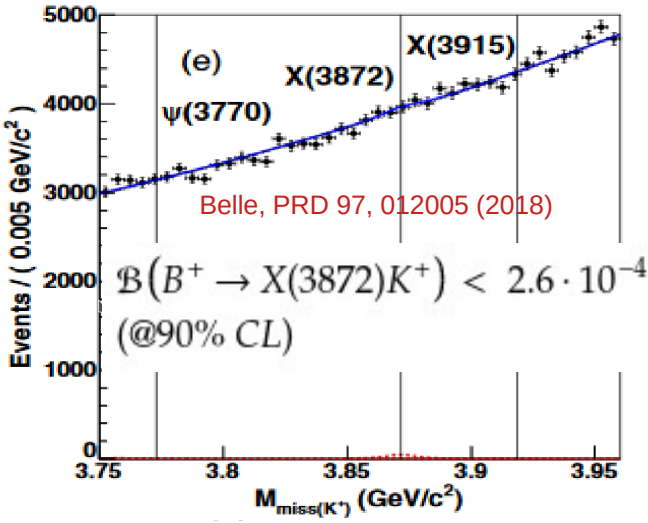


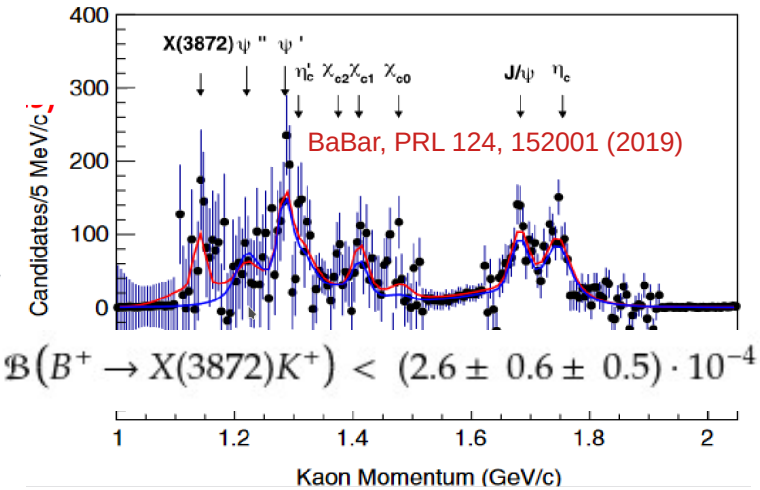
Belle,PRD 81, 031103 (2010)

X(3872) production

- **Measuring absolute branching fraction $\mathcal{B}(B \to X(3872)K^+)$ will help in measuring $\mathcal{B}(X(3872) \to final\ State)$**
  - Only possible at B-factories operating at Y(4S) center of mass energy which decays to $B\overline{B}$
  - Missing mass recoiling against K^+ ,
    - Improve B-tagging efficiency compared to Belle („Results related to anomalies at Belle II“, by Martin Angelsmark Wed. 9:20)
      → Full Event Interpretation (FEI)
      - Reconstruction of ~10000 modes
      - Extensive ML use
      - Semileptonic and hadronic tag modes
      - Up to 50% increase in efficiency and comparable purity



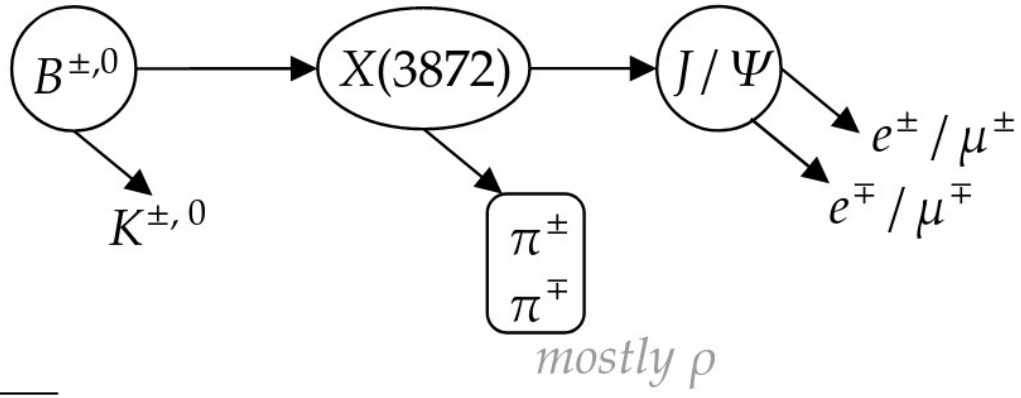


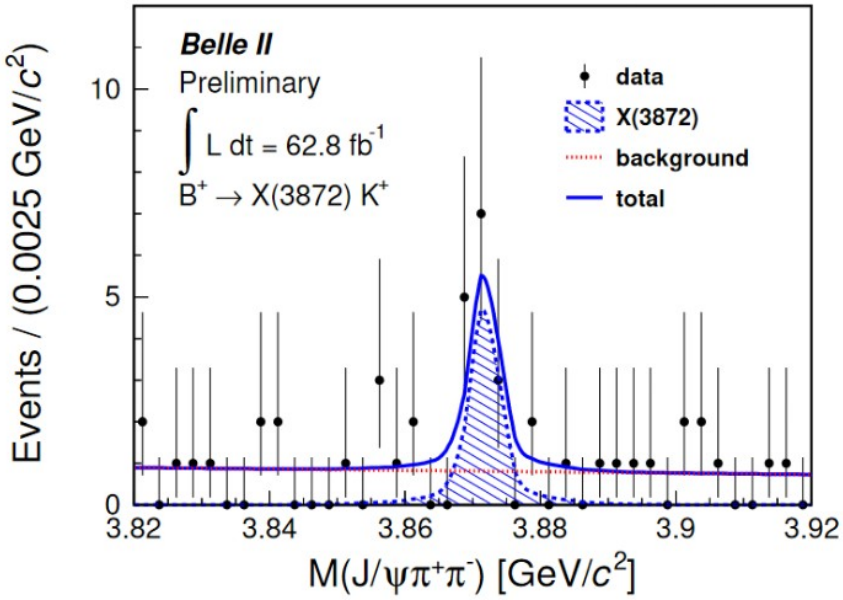


- **Belle II might measure this value not only for X(3872), but also for other states**

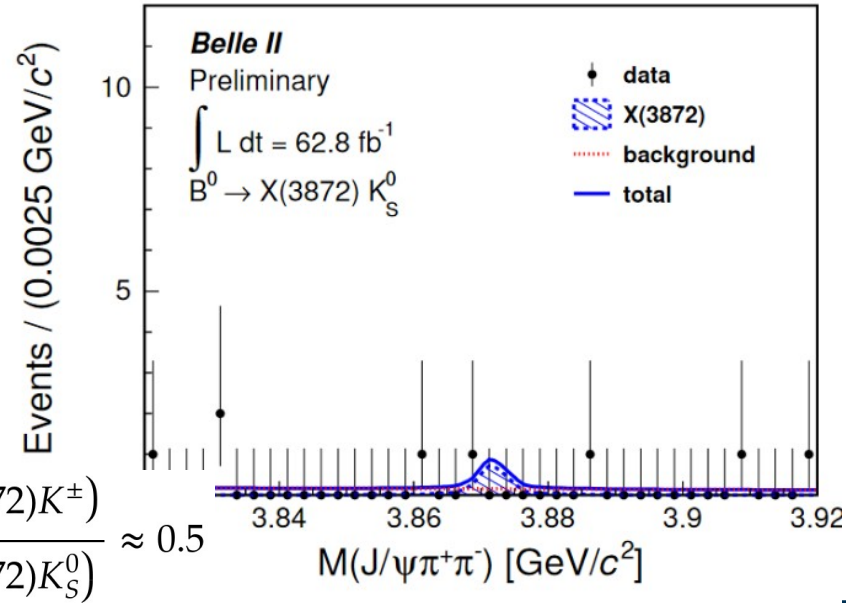
X(3872) rediscovery @BelleII

- **X(3872) was rediscovered @BelleII in** $B^{\pm} \to X(3872)\left(J/\Psi\pi^{+}\pi^{-}\right)K^{\pm}$
  - 14.4 ± 4.6 *signal events* $\to 4.6\sigma$
  - BELLE2-NOTE-PL-2021-002
  - Selection criteria
    - Particle identification
    - Continuum suppression
    - Kinematics criteria: $M_{bc} = \sqrt{\left(\sqrt{s}/2\right)^2 - p_B^2} \cdot \sqrt{s}/2,\ |\Delta E| = E_{beam} - E_B$





$$\frac{\sigma\left(B^{\pm} \to X(3872)K^{\pm}\right)}{\sigma\left(B^{0} \to X(3872)K_S^{0}\right)} \approx 0.5$$



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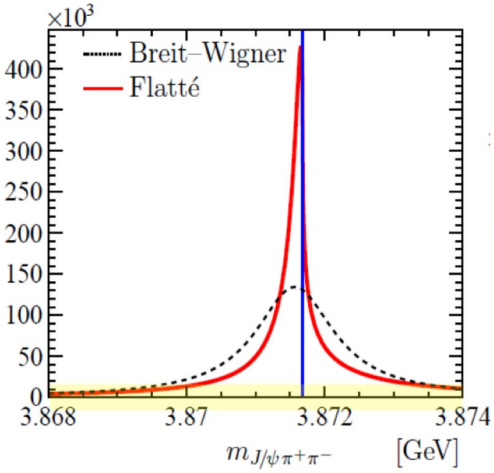
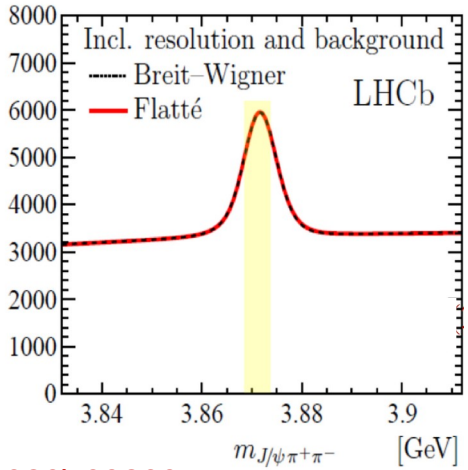
X(3872) – upcoming lineshape study @Belle

Original lineshape



Lineshape with resolution



PRD102 (2020) 092005

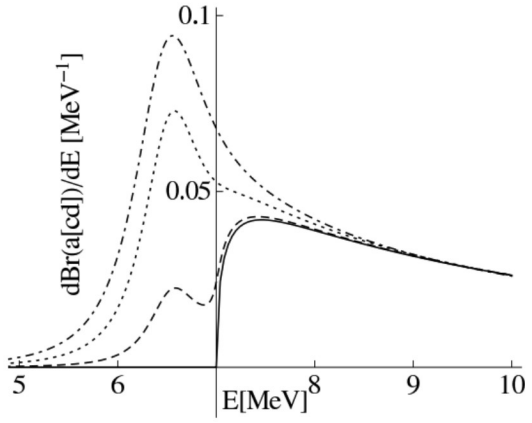
- **LHCb measures mass and width with**

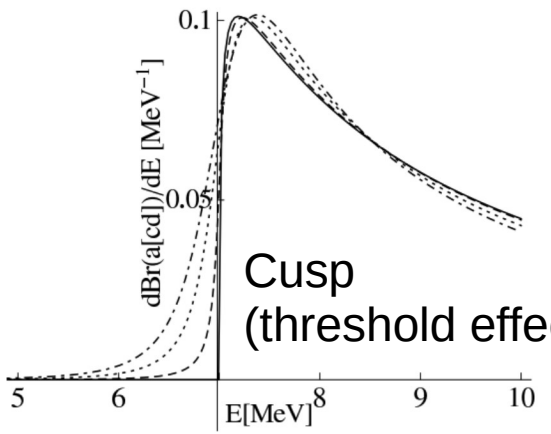
$$X(3872) \to J/\Psi\pi\pi$$

- **Difficult to distinguish BW and Flatté distributions**
  → Lineshape is more sensitive to

$$X(3872) \to D^0\overline{D}^{*0}$$

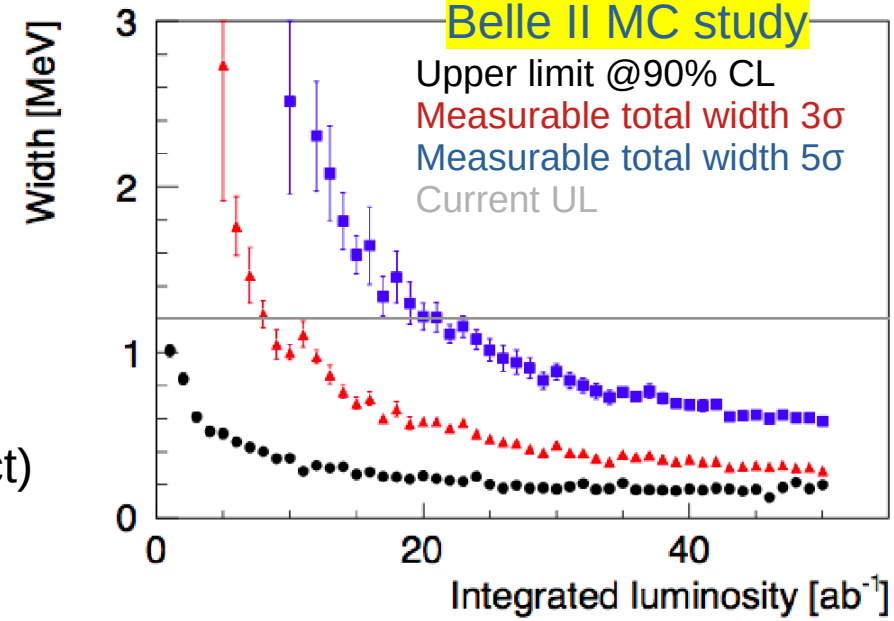
- **Revised study on this also ongoing @Belle**





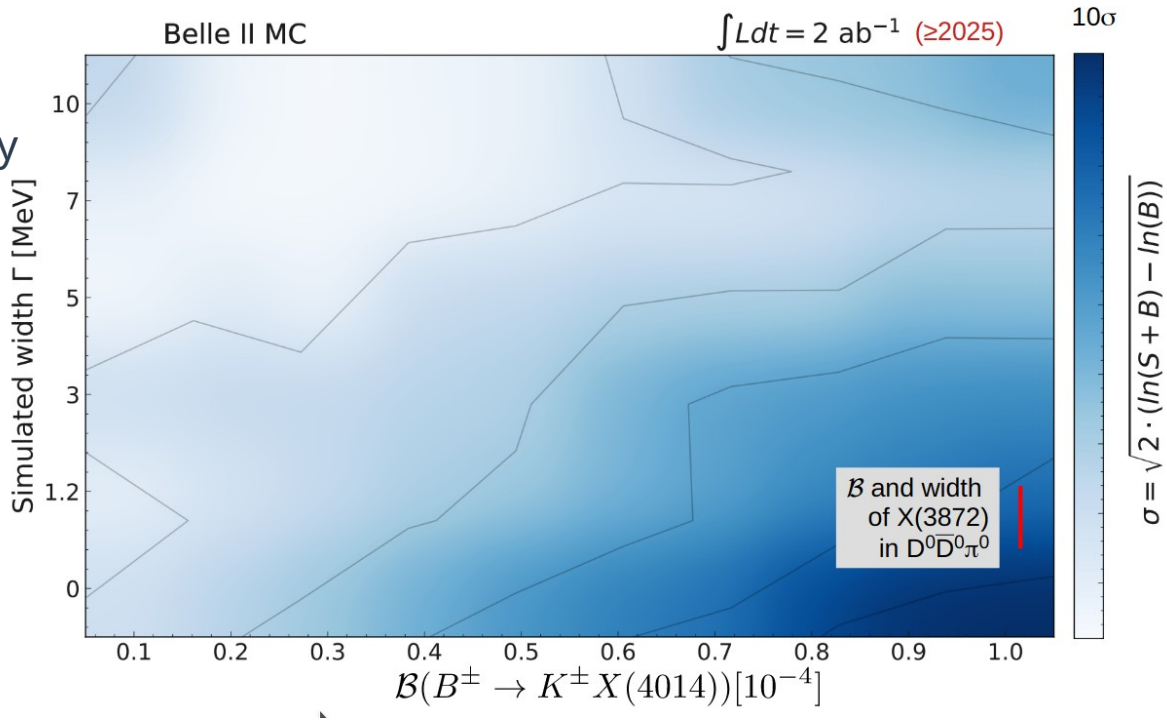
Cusp
(threshold effect)

PRD 81 (2010) 094028



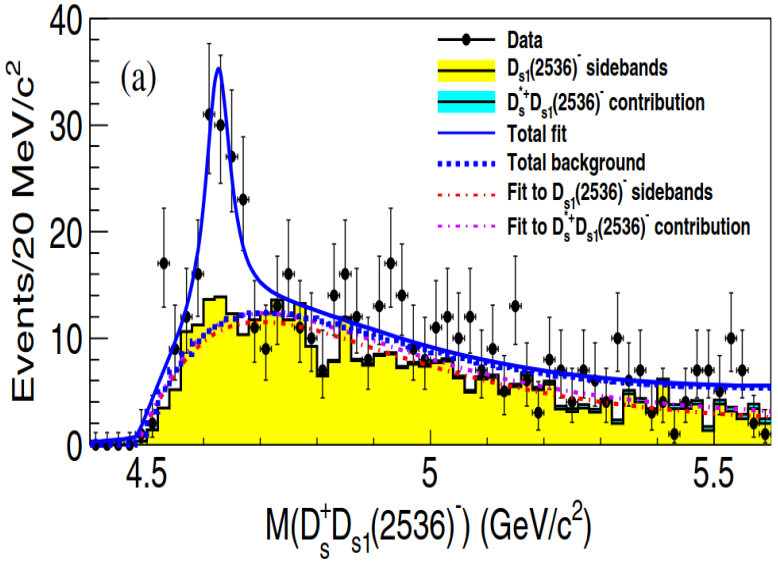
Partner state to the X(3872) at the $D^{*0}D^{*0}$ threshold?

- **If the X(3872) is a hadronic molecular state, it should have a partner state at the $D^{*0}D^{*0}$ threshold**
  - State, predicted already in 1991 by Törnqvist (Phys. Rev. Lett. 67 (1991) 556)
  - Mass prediction around $D^{*0}D^{*0}$ threshold at 4014 MeV
  - Heavy quark spin symmetry partner to X(3872) (Phys. Rev. D88 (2013) 054007)
  - Width up to 10MeV due to D-wave decay to $D^{*0}D^{*0}$
  - First Belle II MC study performed for different scenarios for the width and the branching fraction show discovery potential above 2/ab



Search for exotics using ISR @Belle

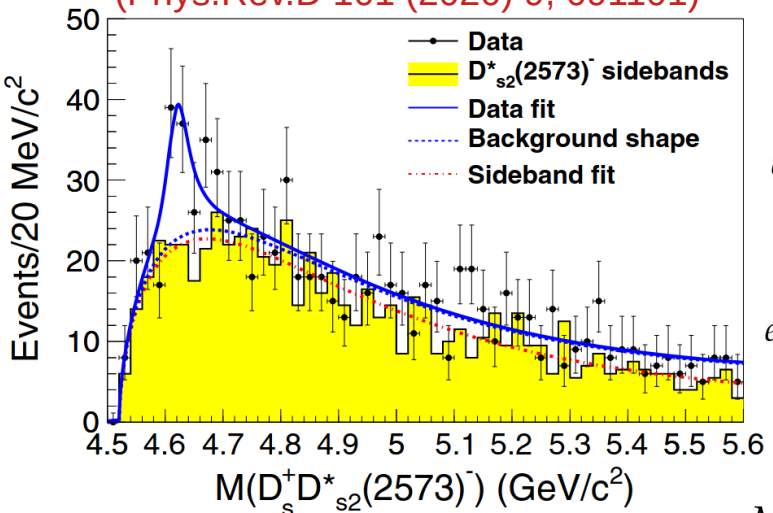
(Phys.Rev.D 100 (2019) 11, 111103)



First observation of a resonant state in $D^+D_{s1}(2536)^-$ + cc with 5.9σ in 921.9/fb

$M = 4625 \pm 0.4\ GeV/c^2$, $\Gamma = 49 \pm 4.0\ MeV$

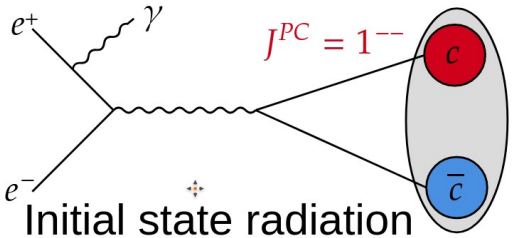
(Phys.Rev.D 101 (2020) 9, 091101)



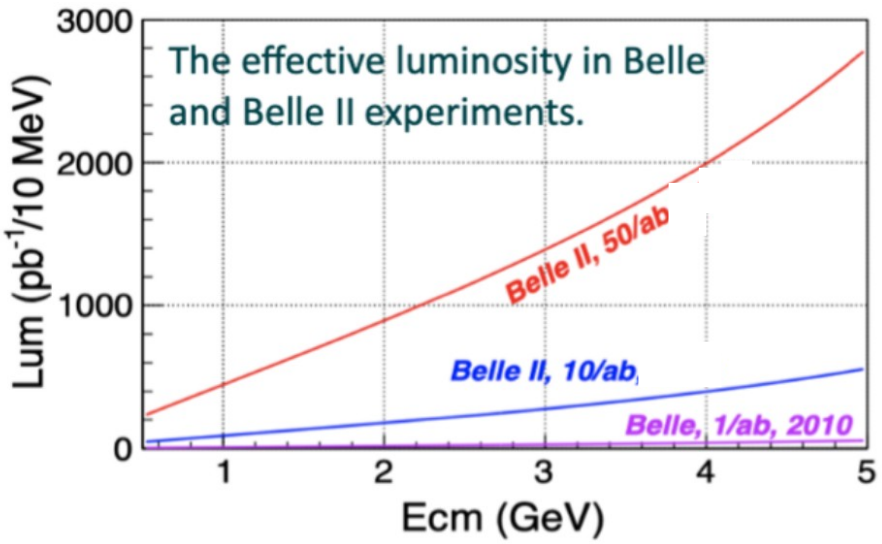
First evidence for a resonant state in $D_s^+D^*_{s2}(2573)^-$ + cc with 3.4σ in 921.9/fb

$M = 4619 \pm 2.3\ GeV/c^2$

$\Gamma = 47 \pm 4.6\ MeV$



- **Explore 1^{--} states far from e^+e^- collision energy**
- **Whole hadron spectrum visible**
- **Effective luminosity and detection efficiency are relatively low**
- **Y(4230), Y(4660) and other results were achieved by the ISR technique at Belle**

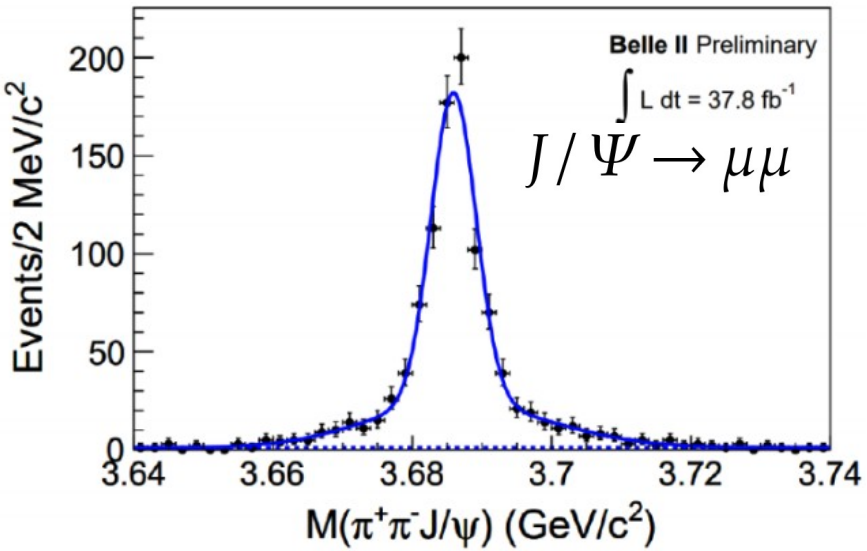


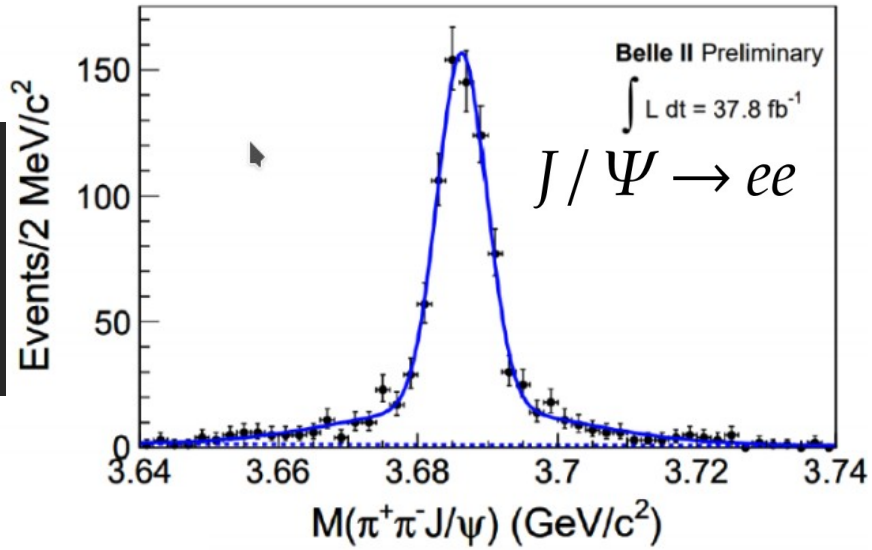
Preliminary ISR results @BelleII

- $e^+e^-\gamma_{ISR} \rightarrow J/\Psi(l^+l^-)\,\pi^+\pi^-$
  - Nominal PID requirements
  - |M(J/Ψ) – M(PDG)| < 75 MeV
  - ISR photon NOT required (higher efficiency)
  - |missingM²(ππ J/Ψ)| < 2 GeV²
- **Clear observation of ISR Ψ(2S) signals**
  - Cross sections compatible with theoretical calculations

Mode	Our measurement	Theoretical Prediction (Yad. Fit. 41, 733 (1985))
$J\Psi \rightarrow \mu^+\mu^-$	(12.0 ± 1.2) pb	(14.1 ± 0.3) pb
$J\Psi \rightarrow e+e^-$	(13.0 ± 1.2) pb	(14.1 ± 0.3) pb

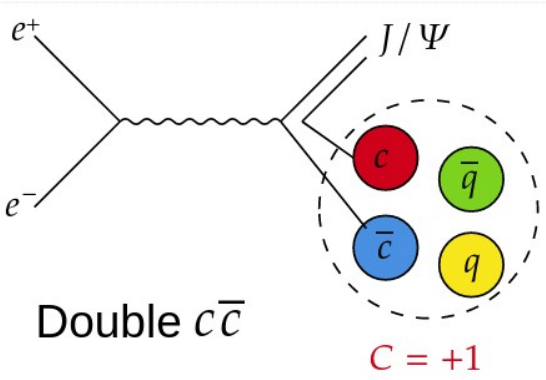
- **Next → Y(4260) rediscovery**
  - Expected are ~60 events @100/fb

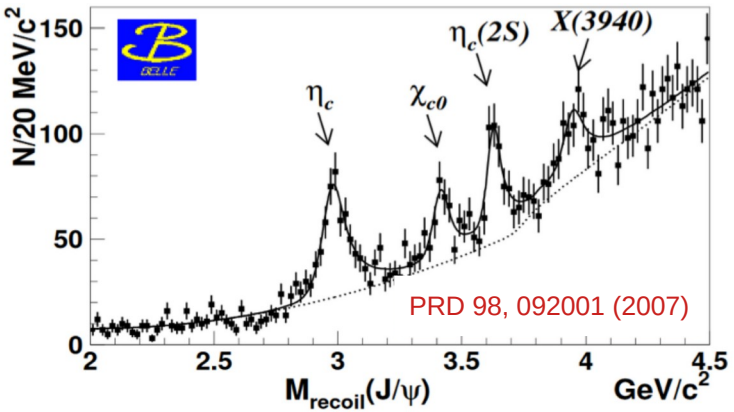




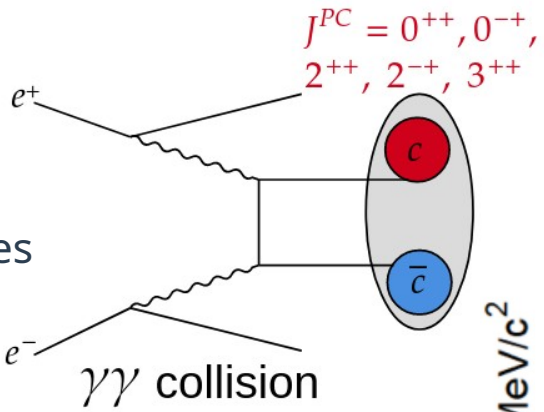
Other productions

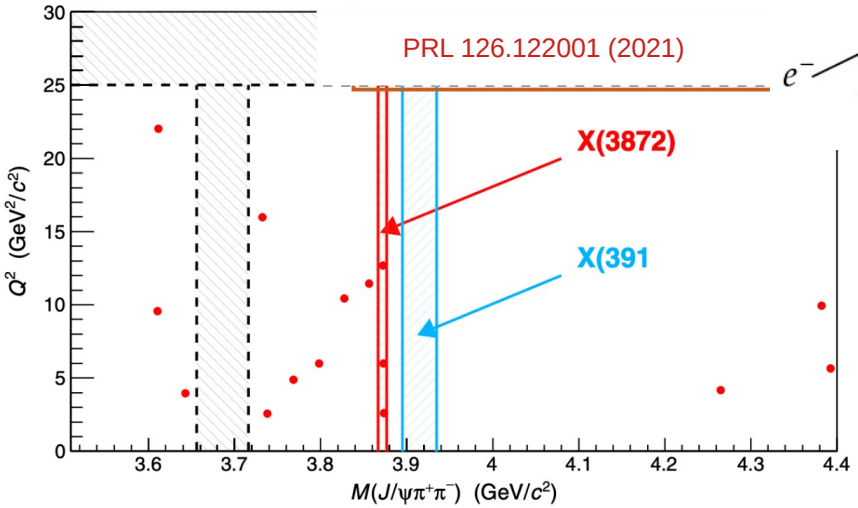
- **Double charmonium production**
  - Discovery of X(3940), $\chi_{c0}(2P)$
  - Expand for other cc states
  - Search for new states



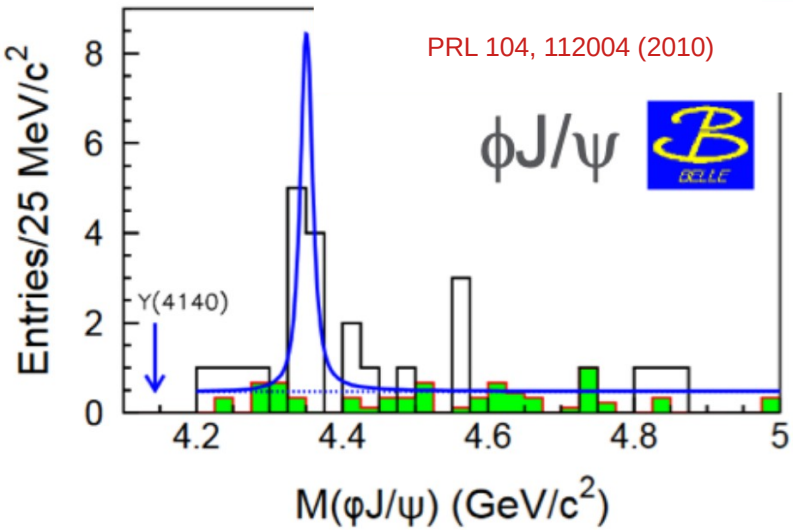


- **Two photon production**
  - J^{PC} of X(3915)
  - Confirm $\phi J/\Psi$ and X(3872) states



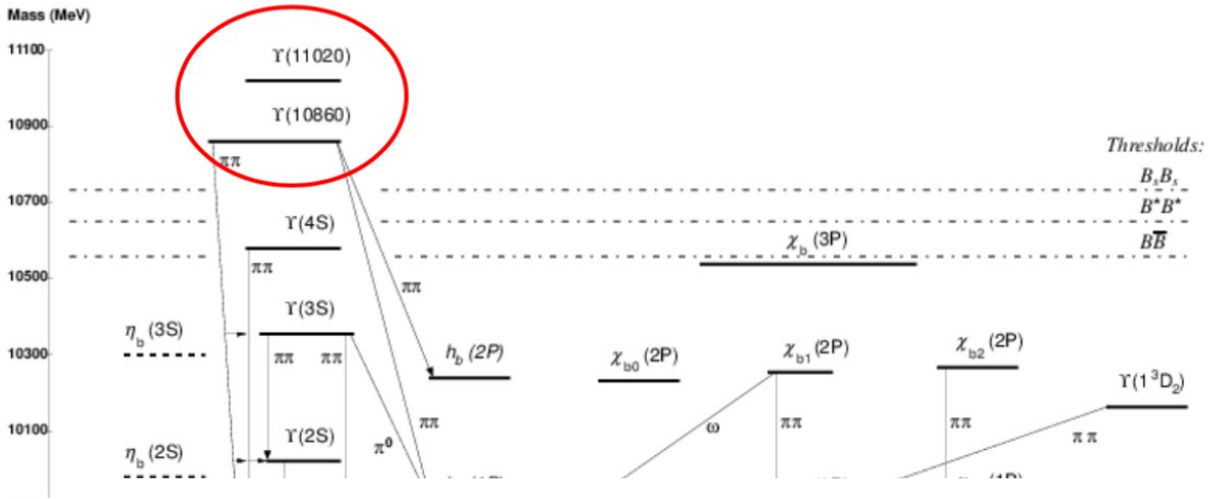


$$Belle\ Data: \int \mathcal{L}\, dt = 825\ fb^{-1}$$
$$\Rightarrow 3.2\,\sigma$$



Bottomonia - I

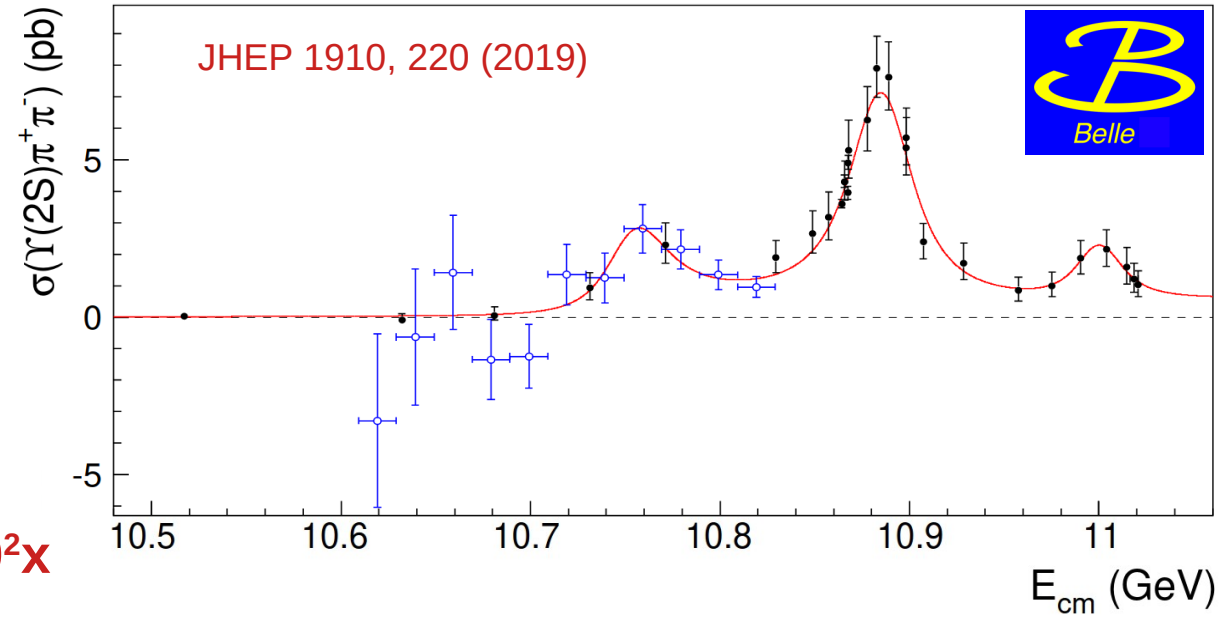
- **Unique Study in Belle & Belle II**
- **Y(5S), Y(6S)**
  - Study of Z branching ratios and decays
  - Search for new resonances (predicted / unpredicted)
  - Y(2,3,4S) / Y(5S) transitions are different
    - Hint for non-bb nature
  - Extra resonance around 10.75 GeV?



PRL 100, 112001 (2008)

	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

>10^2x

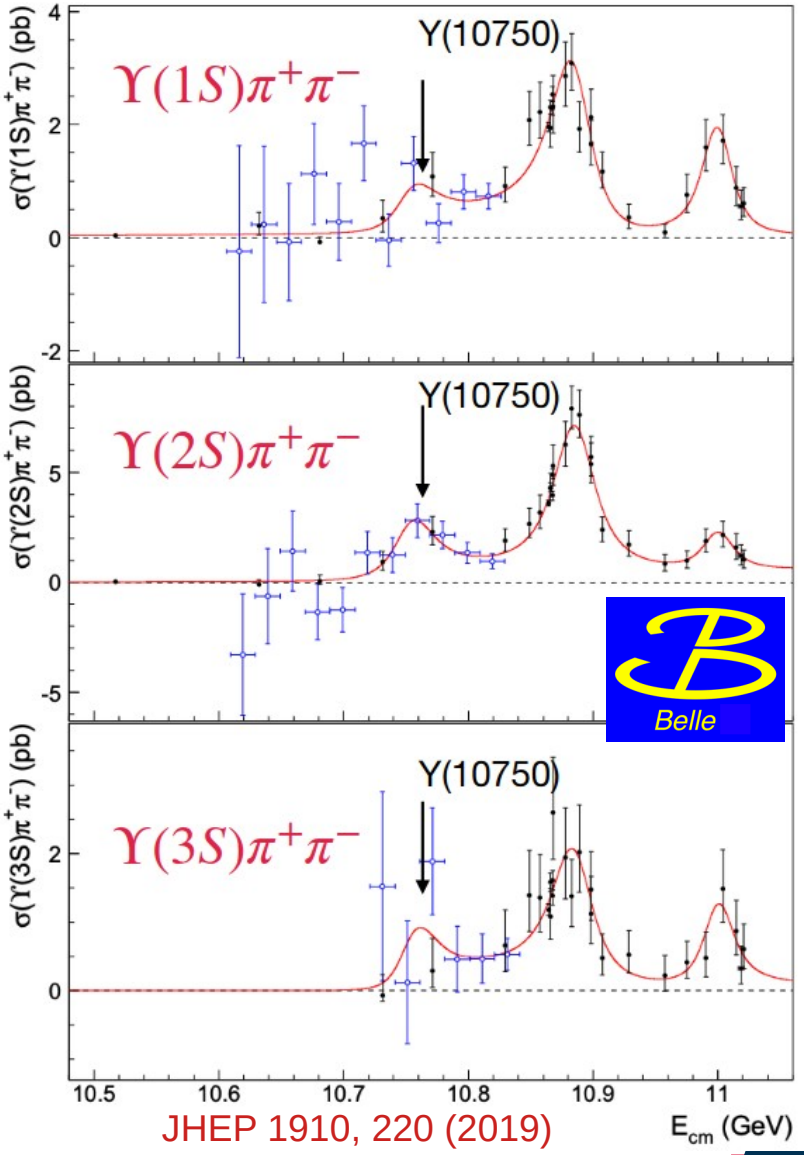


Bottomonia - II

- **Scan data sample at 22 points with 1/fb at each point**
  - In addition, 121/fb at Y(10860) on-resonance and 60/fb continuum sample at 10.52 GeV
- **In the final state of Y(1,2,3S)$\pi^+\pi^-$ a resonant structure is observed with 5.2σ**
  - Test this also with new Belle II data

	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}{}^{+1.0}_{-1.3}$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}{}^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}{}^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3}$

- **Many models on the nature of the Y(10750) have emerged**
  - None of them confirmed so far => more data needed
  - D-wave bottomonium (arXiv:1910.06065),
    BB dynamically generated pole (arXiv:1910.04827),
    Hybrid (arXiv:1908.05179),
    Tetraquark state (arXiv:1905.06610)



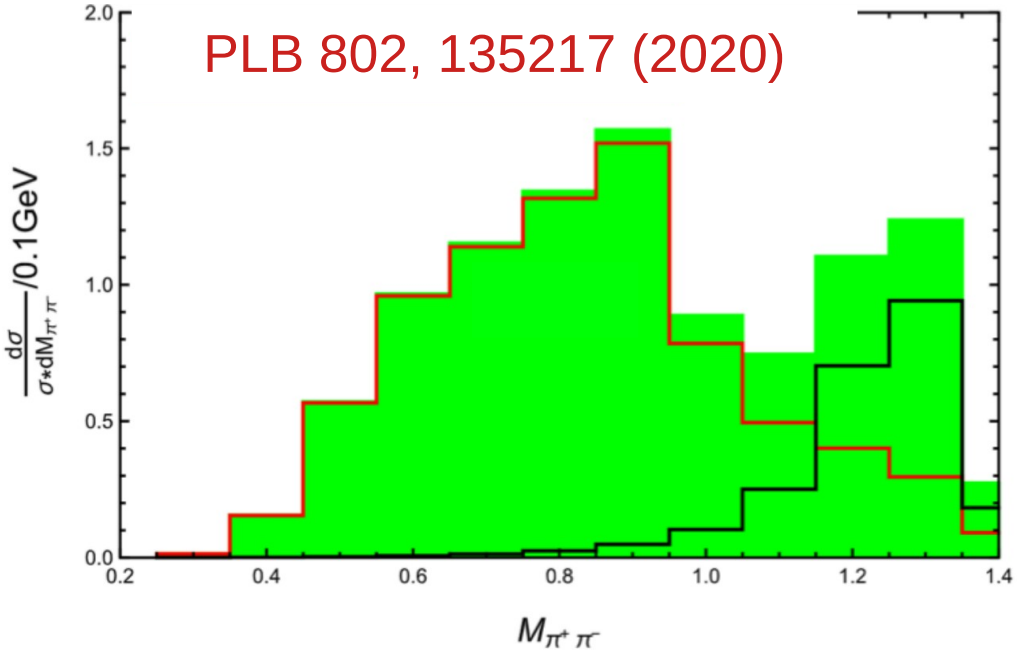
JHEP 1910, 220 (2019)

Interpretations of the Y(10750) → More data needed!!

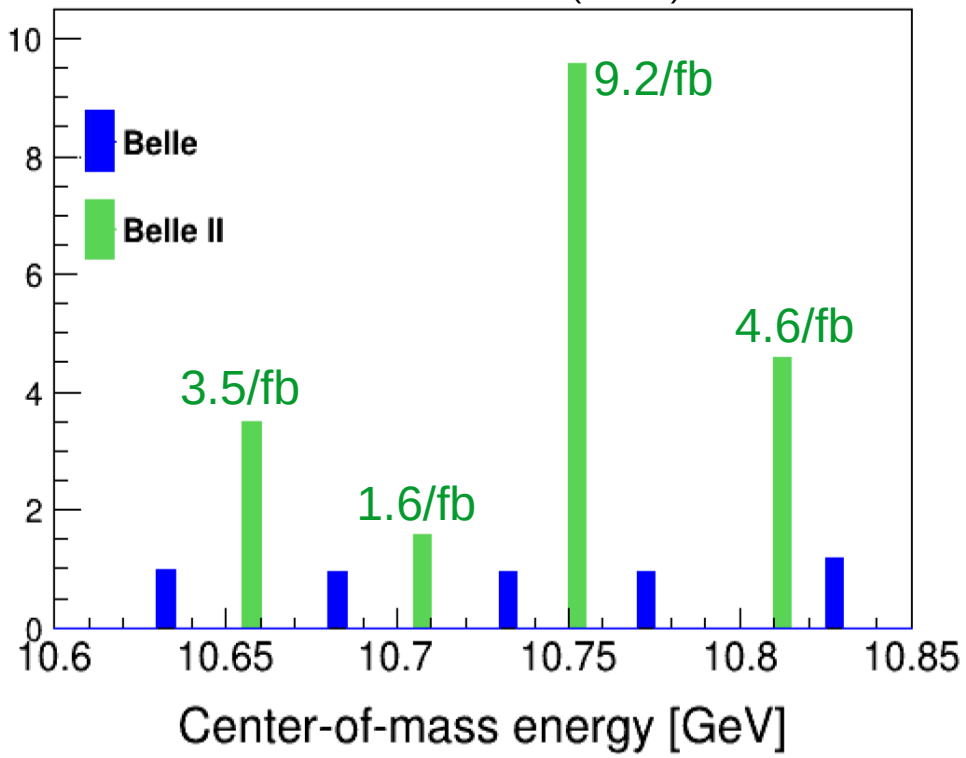
- **Belle II collected data at 4 energy points around 10.75 GeV, more is needed!**
- **Physics goal: understand the nature of the Y(10750) energy region**
- **The mechanism of Y(10750) → ππ Y(1S) in the tetraquark interpretation**
  - $J^{PC} = 1^{--}$ state with dominant tetraquark component

- Quarkonium spectrscopy (conventional and exotic)
- Hadronic and radiative transitions
- Annihilations in exclusive final states
- Precision study of the vector states using ISR
- New Physics in Bottomonia (rare and forbidden decay, LUV, LFV, invisible decays)
- Cross section for hyperon production
- Dynamic correlations in hyperon pair production
- Search for di-baryons and anti-nuclei production

Normalized resonant $M(\pi^+\pi^-)$ distribution for
$e^+e^- \to Y(10750) \to Y(1S)\pi^+\pi^-$
f0(500) and f0(980) scalars component
f2(1270) component

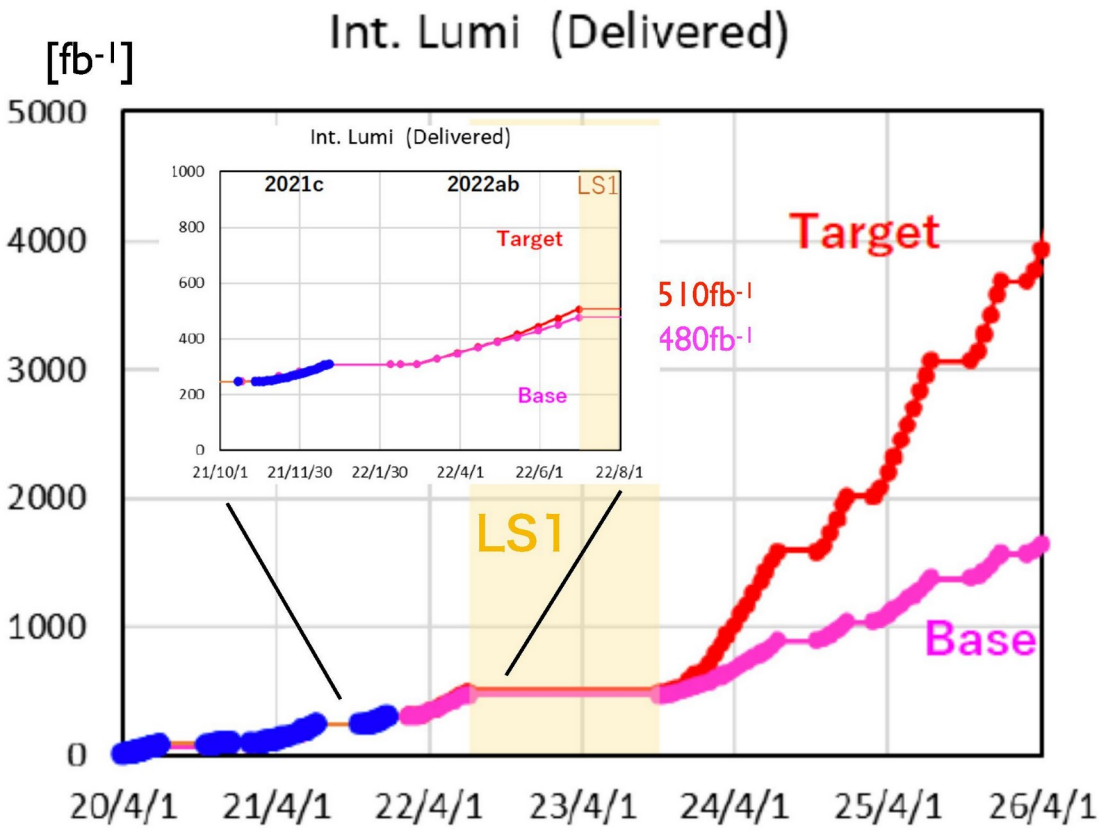


Accumulated luminosities around the Y(10750) as of November 21



Summary

- **Belle II is at the beginning of a long-term quarkonium journey**
  - Many opportunities for world leading physics
- **Early measurements display the foundations we will build upon**



- **Expectations of great achievements in hadronic spectroscopy**
  - Dedicated study of unknown XYZ states
  - Determination of the X(3872) nature from the many models available
  - Search for new particles via ISR, two photon production, double charmonium production…
  - Bottomonium search through Υ(nS)

Extrapolation from 2021 including expected improvements

Conservative extrapolation from SuperKEKB parameters of 2021

Thank You!