Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Quarkonium at Belle II

Umberto Tamponi
tamponi@to.infn.it
INFN - Sezione di Torino

On behalf of the Belle II collaboration

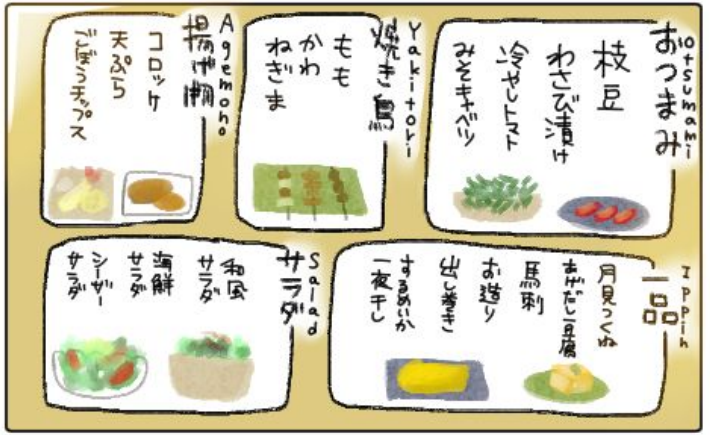
Meson 2021
May 17th 2021

The menu of this talk

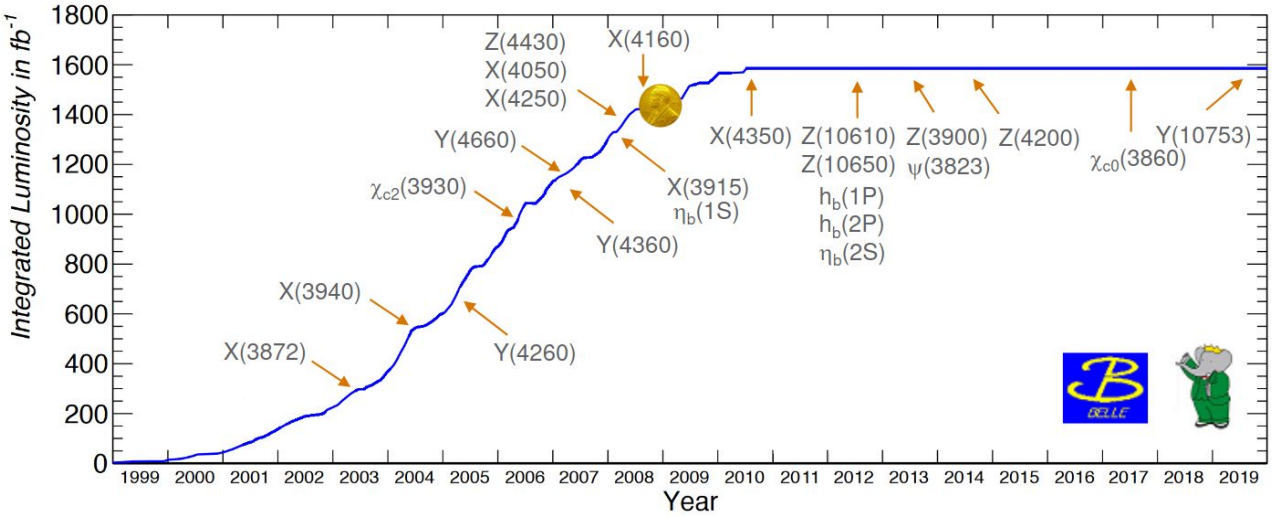
1- An overview of the Belle II experiment

2- Status of the quarkonium physics program

3- Plans for the near and far future



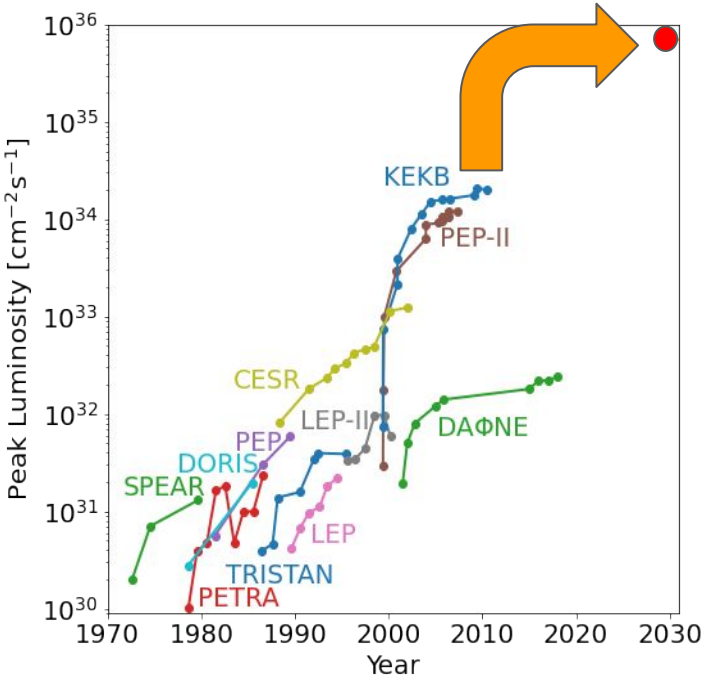
The B-factories legacy



Experiment	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$	$\frac{\Upsilon(nS)}{\Upsilon(4S)}$
CLEO	1.2 (21)	1.2 (10)	1.2 (5)	16 (17.1)	0.1 (0.4)	-	23%
BaBar	-	14 (99)	30 (122)	433 (471)	R_b scan	R_b scan	11%
Belle	6 (102)	25 (158)	3 (12)	711 (772)	121 (36)	5.5	23%
BelleII	-	-	?	5×10^4 (5.4×10^4)	?	?	?

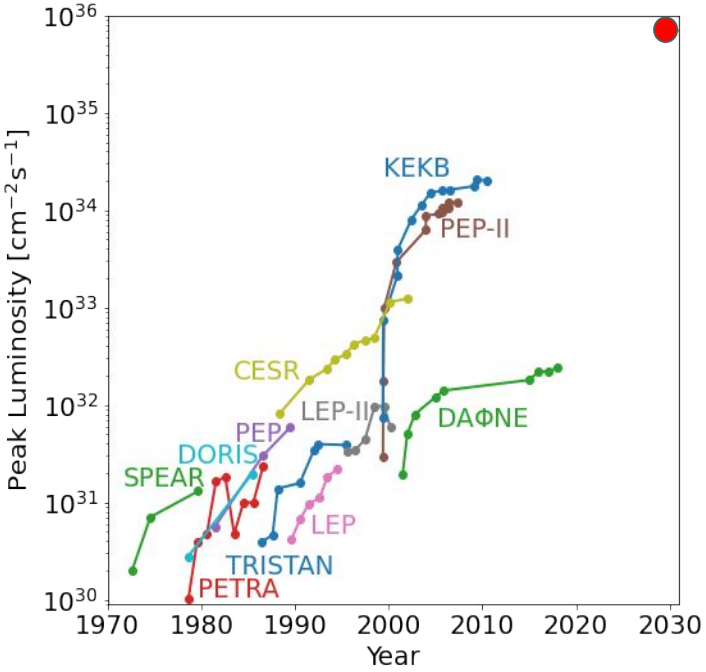
Super-KEKB and the nano-beam scheme

Belle II goal: collect 50 ab^{-1} (~50x Belle data)
Super-KEKB goal: >30x KEKB luminosity



Super-KEKB and the nano-beam scheme

Belle II goal: collect 50 ab^{-1} (~50x Belle data)
Super-KEKB goal: >30x KEKB luminosity



Beam aspect ratio
(flat beam ~ 1-2%)

Beam currents

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

Vertical β function at IP

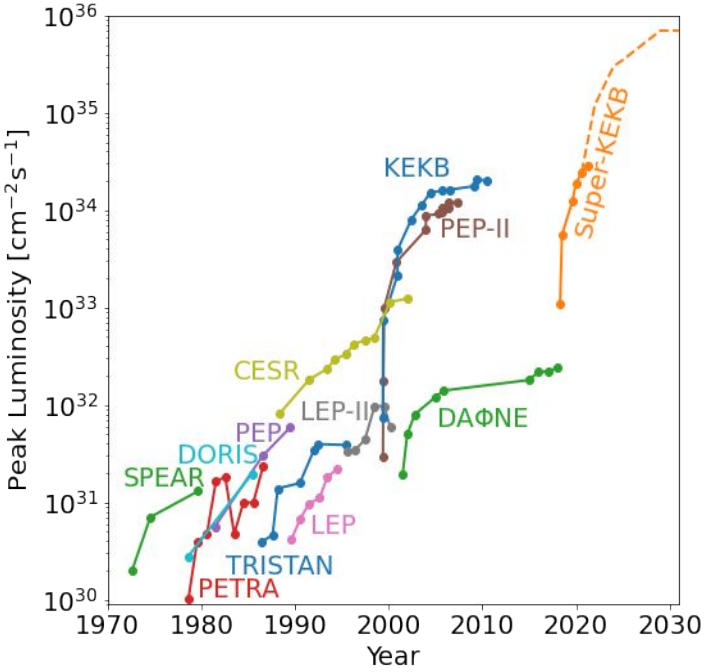
Geometrical corrections

Brute force:
- Current 2 x larger

Nanobeam scheme:
- β_y^* 20 x smaller
- Vertical beam size ~ 50 nm

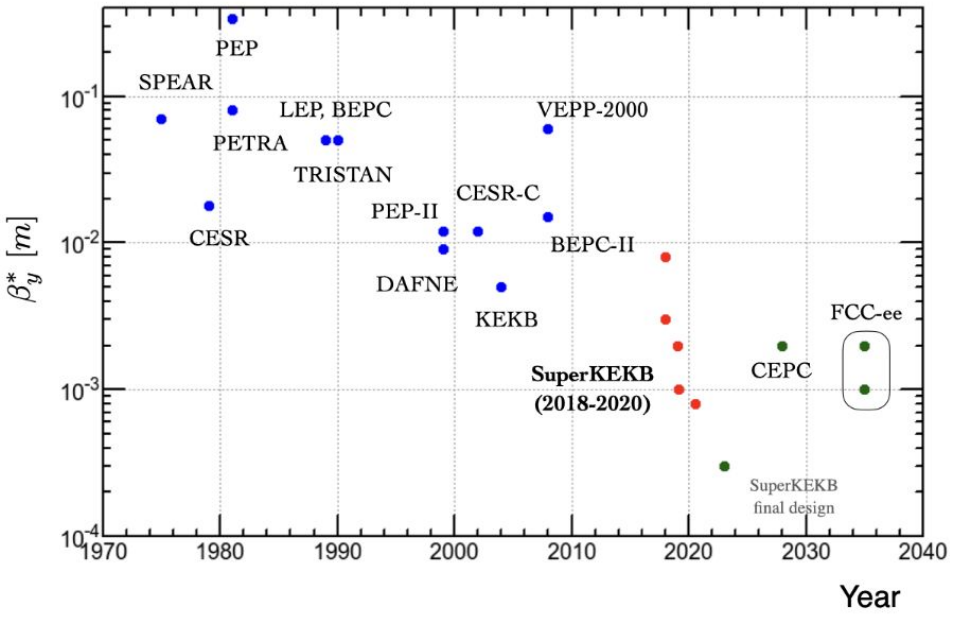
Super-KEKB: how is it going?

Operations started on March 19th 2018



Currently running at

- $L = 2.8 \times 10^{34}\ cm^{-2}s^{-1}$
- $\beta_y^* = 1$ mm
- $L_{int} = 140\ fb^{-1}$ (As of May 12th 2021)



Belle II VS Belle, a matter of backgrounds

[P.Lewis et al, NIM A 914, 69-144 (2019)]

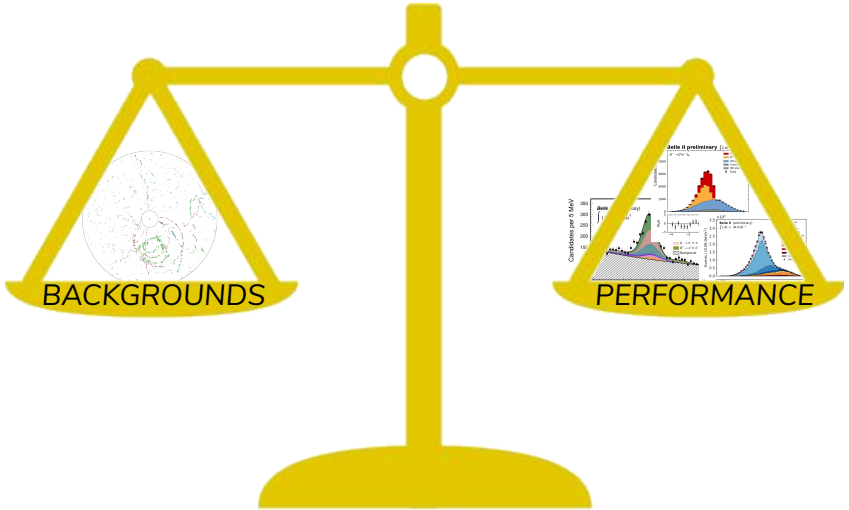
Single beam backgrounds:

- Touschek $\propto I^2 \sigma_y^{-1} n_b^{-1}$ ⬆
- Beam Gas $\propto I$ ⬆
- Synchrotron radiation $\propto I$ ⬆

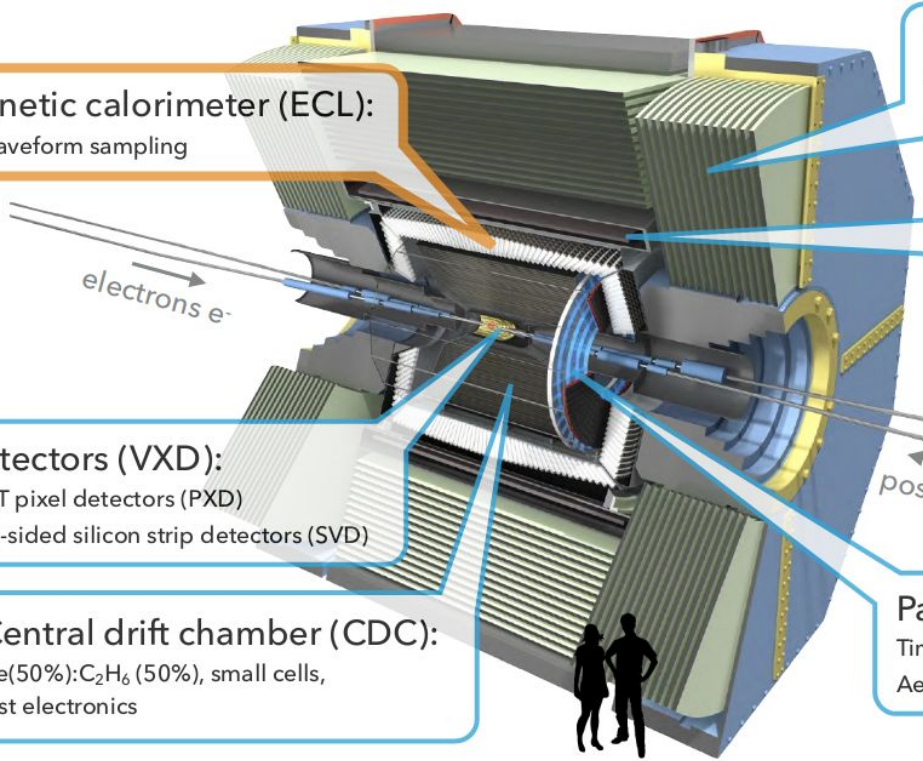
Luminosity backgrounds:

- Radiative Bhabha $\propto L$ ⬆
- Two-photon $\propto L$ ⬆
- Injection ⟺

Belle II is designed to perform as well as or better than Belle with much higher backgrounds!



Belle II



Electromagnetic calorimeter (ECL):
CsI(Tl) crystals, waveform sampling

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting

Trigger:
Hardware: < 30 kHz
Software: < 10 kHz

Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)

Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells,
fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

Belle II performance VS Belle, in broad strokes

Tracking *[Comp. Phys. Comm. 259 (2021) 107610 (Monte Carlo only), in preparation (data)]*

- Better resolution at both low and high p_t
- Better efficiency at low p_t
- 2x better vertexing and decay time resolution

Full event reconstruction *[Comput. Softw. Big Sci* **3,** 6 (2019)*]*

- Better purity and efficiency

Neutrals *[paper in preparation]*

- Better algorithms and electronics
- (Currently) only enough to compensate the increased backgrounds

Particle identification *[paper in preparation]*

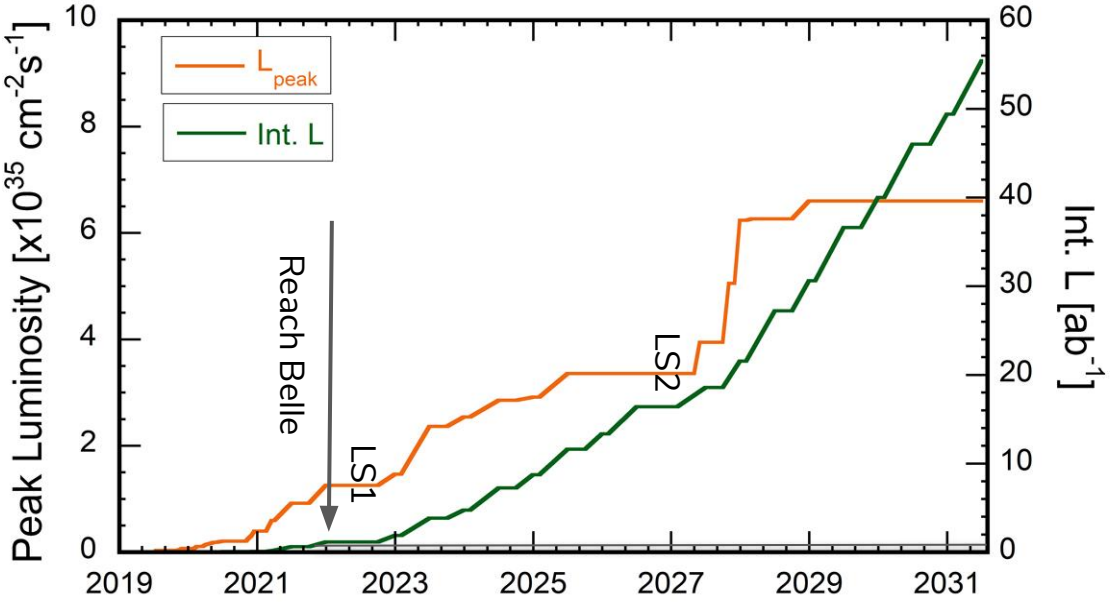
- Better algorithms and new detectors (working on NN-based approaches)
- (Currently) only enough to compensate the increased backgrounds

Belle II road map

Summer 2022: match Belle data set at Y(4S)

2022-2023: Long shutdown: Detector HW replacement and upgrade (LS1)

2026-2027: Long shutdown: Accelerator HW upgrade (LS2)

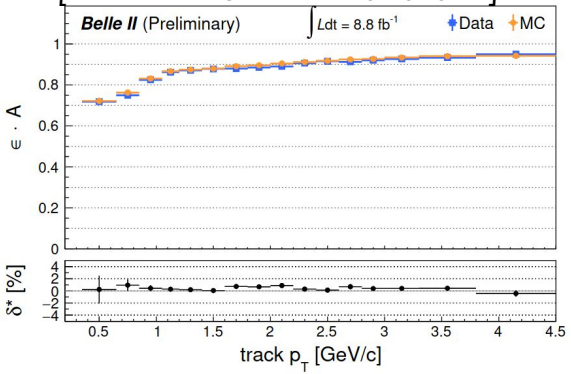


What are we doing right now?

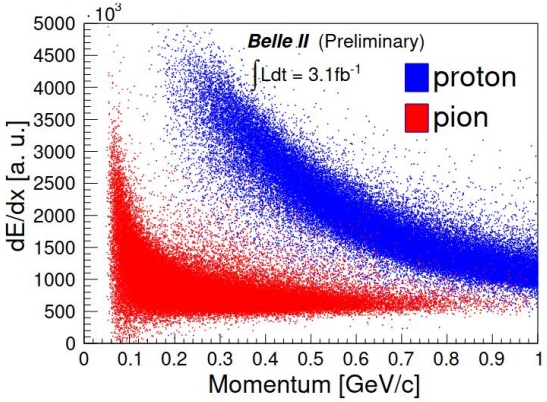
Current data set: 140 fb^{-1} (increasing by 1-1.5 fb^{-1} /day)

- Understand the detector and the performance
  - Check all the results at https://docs.belle2.org/ !

Tracking efficiency
[BELLE2-NOTE-PL-2020-014]

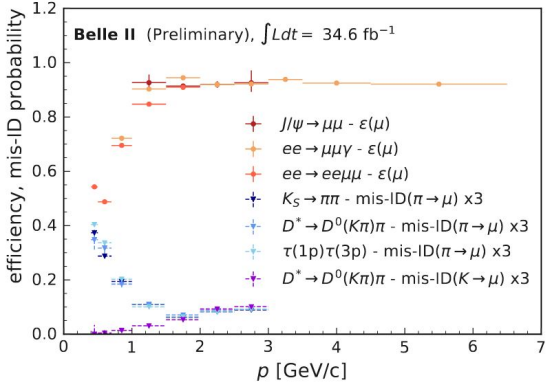


Low-p PID in the SVD
[BELLE2-NOTE-PL-2020-028]

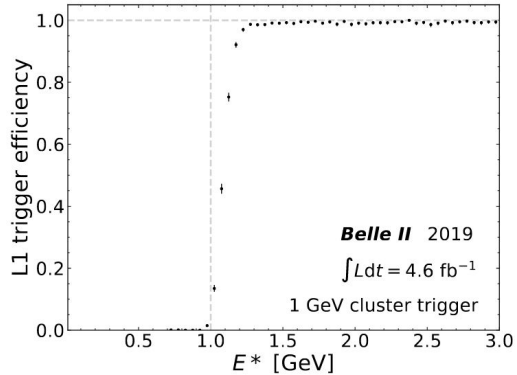


Lepton-ID
[BELLE2-NOTE-PL-2020-027]

0.82 ≤ θ < 1.16 rad, muonID > 0.9



Trigger efficiency
[BELLE2-NOTE-PL-2020-009]



What are we doing right now?

Current data set: 140 fb^{-1} (increasing by 1-1.5 fb^{-1} /day)

- Understand the detector and the performance
- **Exploit new methods**
- **Take advantage of looser triggers for "low" luminosity**

$B^+ \to K^+ \nu\bar{\nu}$ with a new tagging method

[arXiv:2104.12624]

New method

Search for Axion-Like Particles

[Phys.Rev.Lett. 125 (2020) 16, 161806]

Search for an Invisibly Decaying Z' Boson

[Phys.Rev.Lett. 124 (2020) 14, 141801]

Loose triggers

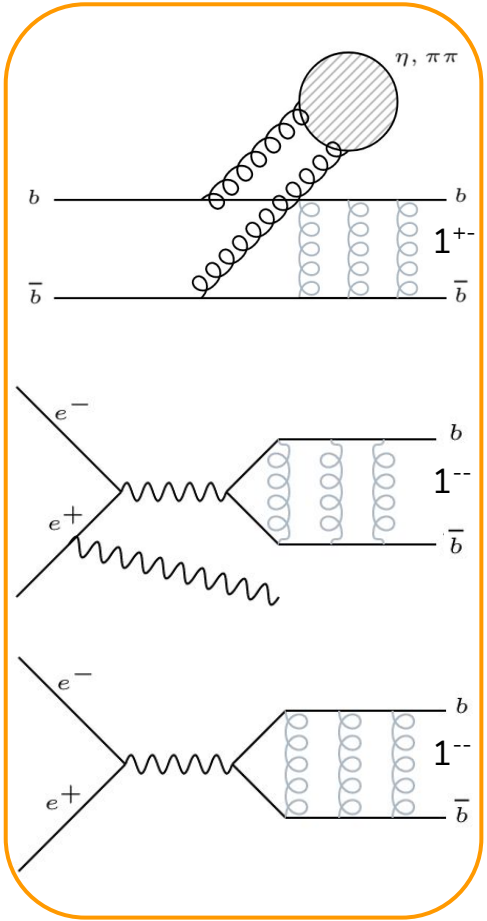
+3 more papers already in internal review!

Quarkonia at Belle II

Quarkonia @ Belle II: how?

Bottomonium

- Hadronic transitions from Υ(4S)
  - Best gateway to $h_b(1P)$ and $\eta_b(1S)$!
- ISR production
- Direct production



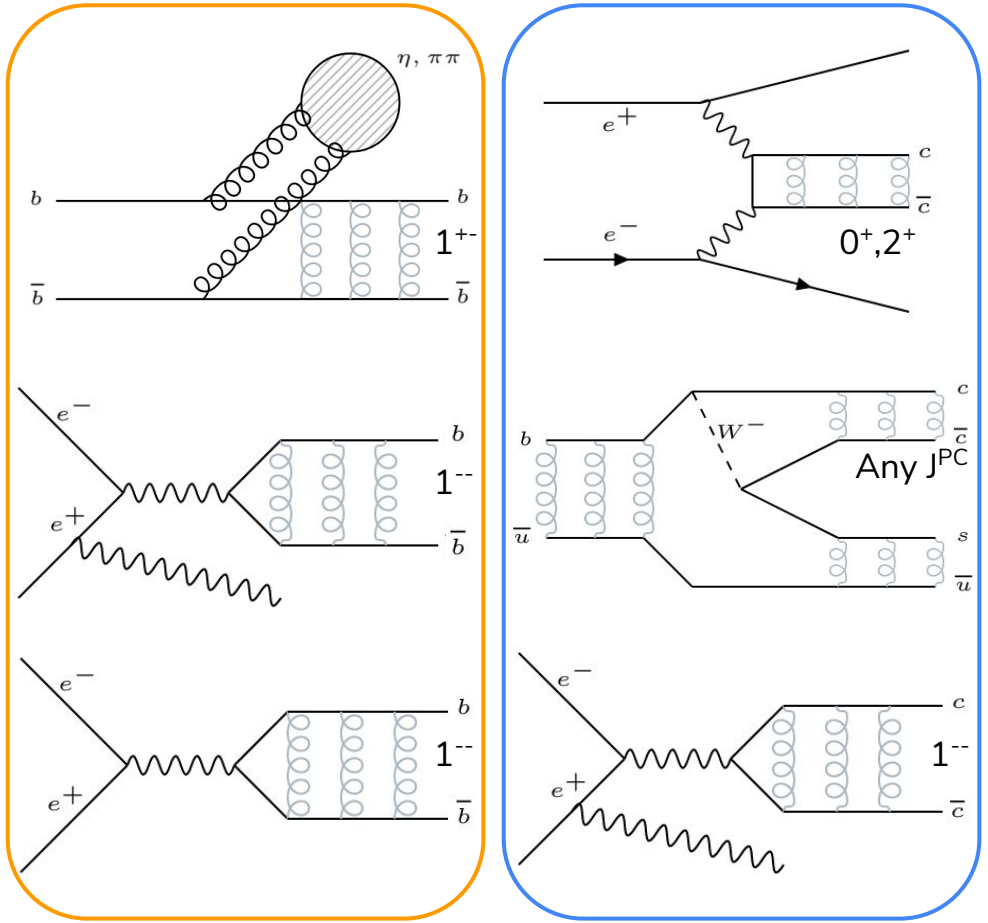
Quarkonia @ Belle II: how?

Bottomonium

- Hadronic transitions from Y(4S)
  - Best gateway to $h_b(1P)$ and $\eta_b(1S)$!
- ISR production
- Direct production

Charmonium

- γγ fusion running at Y(4S)
- B decays via b → c
- ISR production



Quarkonia @ Belle II: when?

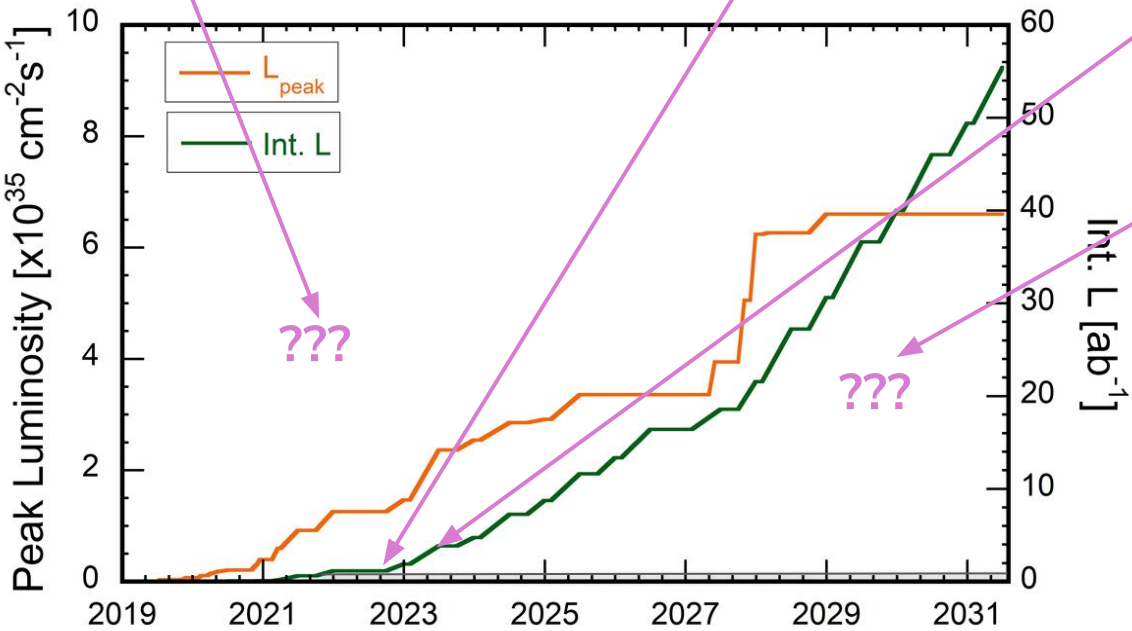
Non-4S runs are not scheduled yet.

Exotic bottomonia: 0.2 ab^{-1} (at CM energy above Y(4S))

Spin-singlet bottomonia from Y(4S): 1 ab^{-1}

Charmonia: 2 ab^{-1}

Narrow bottomonia: 0.2 ab^{-1} (at CM energy below Y(4S))



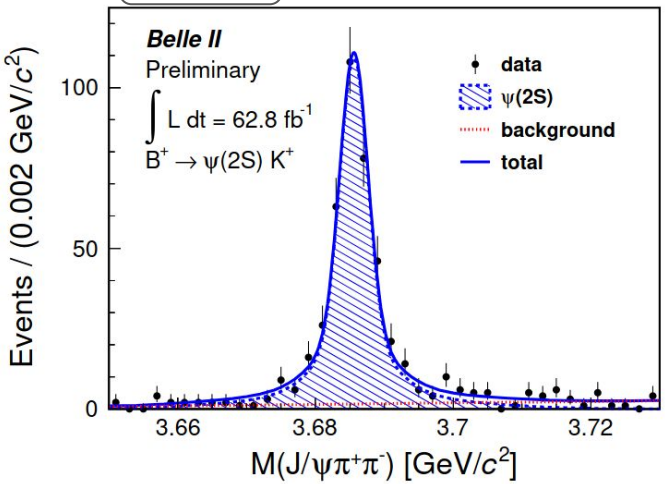
Right now: rediscovery time!

The X(3872) rediscovery

[BELLE2-NOTE-PL-2021-002]

Reconstruct $B^{\pm} \rightarrow K^{\pm}$ $\pi^+\pi^- J/\psi$

$\pi^+\pi^- J/\psi = \psi'$

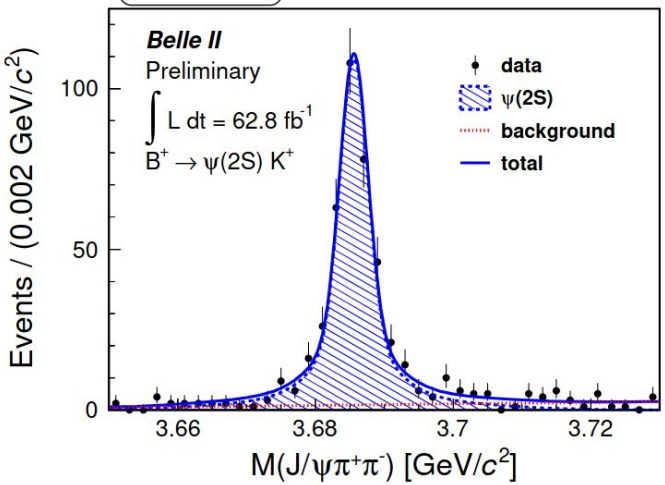


The X(3872) rediscovery

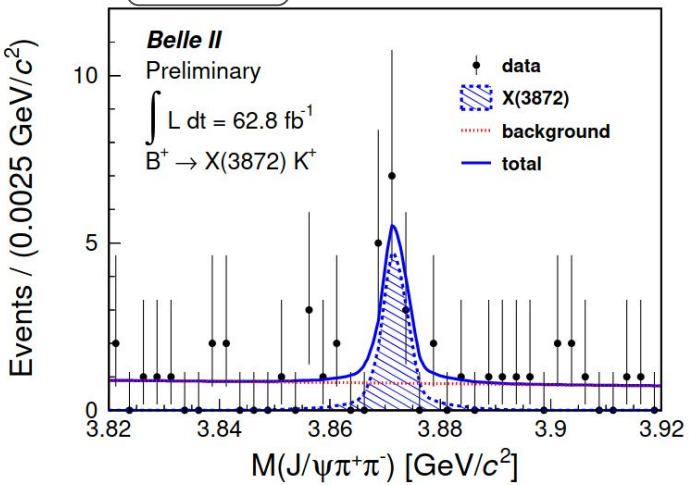
[BELLE2-NOTE-PL-2021-002]

Reconstruct $B^{\pm} \rightarrow K^{\pm}$ $\pi^+\pi^- J/\psi$

$\pi^+\pi^- J/\psi = \psi'$



$\pi^+\pi^- J/\psi = X(3872)$



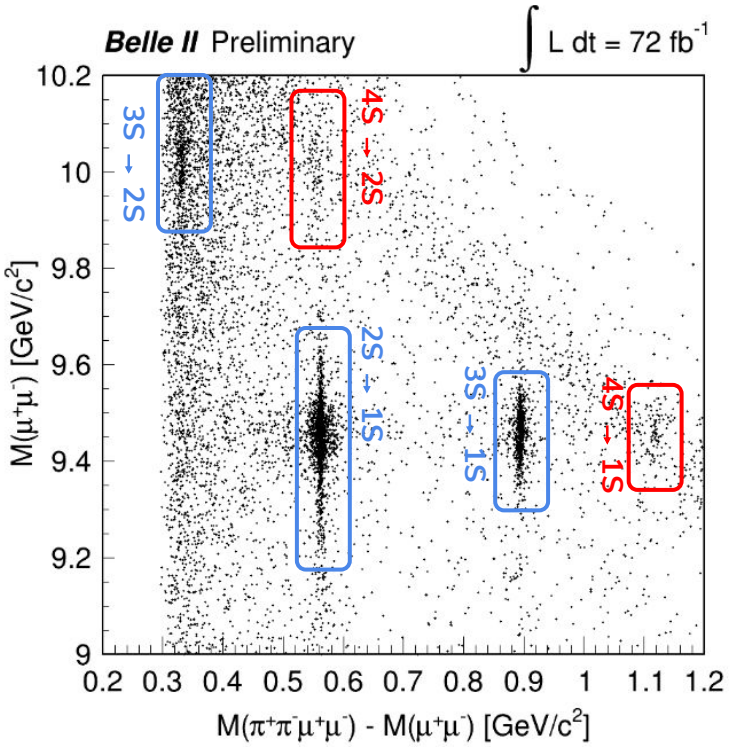
Expected BF : $8.6 \pm 0.8 \times 10^{-6}$

Observed BF : $7.9 \pm 2.5 \times 10^{-6}$

PRELIMINARY

Dipion transitions among bottomonia

[BELLE2-NOTE-PL-2021-001]

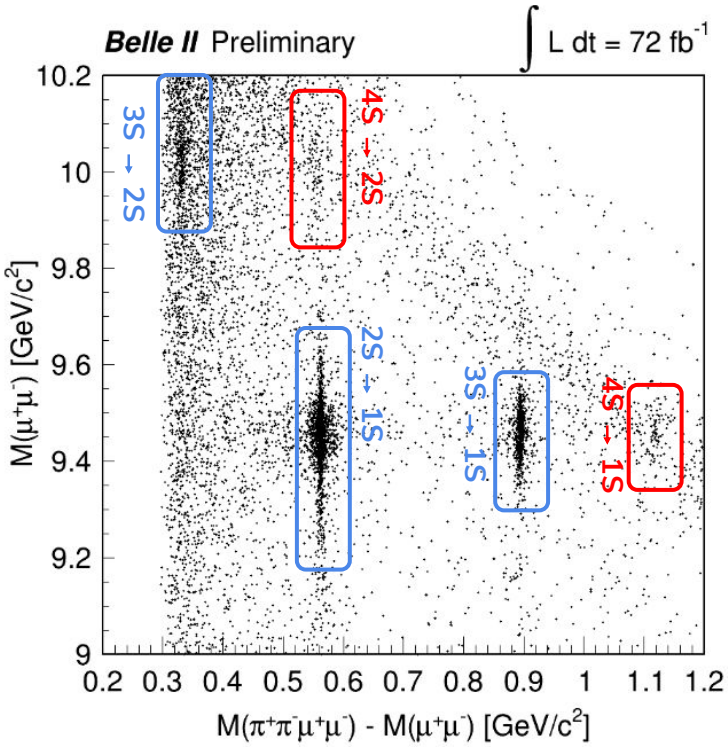


Study $e^+e^- \to \pi^+\pi^-\mu^+\mu^-$ (+γ undetected)

- **$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(nS)$**
- $e^+e^- \to \gamma_{ISR}\,\Upsilon(mS)$, **$\Upsilon(mS) \to \pi^+\pi^-\Upsilon(nS)$**

Dipion transitions among bottomonia

[BELLE2-NOTE-PL-2021-001]

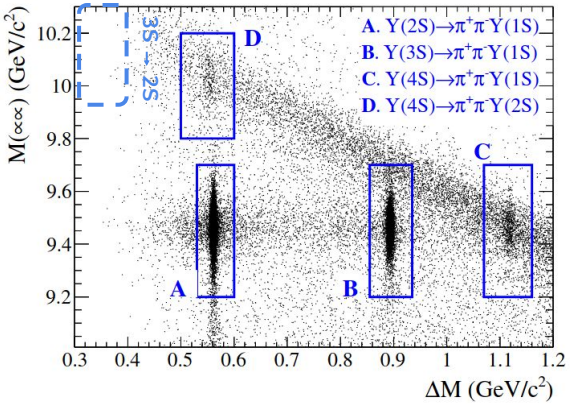


Study $e^+e^- \to \pi^+\pi^- \mu^+\mu^-$ (+γ undetected)

- **$\Upsilon(4S) \to \pi^+\pi^- \Upsilon(nS)$**
- $e^+e^- \to \gamma_{ISR}\, \Upsilon(mS)$, **$\Upsilon(mS) \to \pi^+\pi^- \Upsilon(nS)$**

Compare with Belle, 496 fb^{-1} [*PRD* 96 (2017) 5, 052005]

- Improved low momentum tracking



Near-term plans and projects

Quarkonium physics with the 2022 dataset

By 2022 Belle II should have as much Y(4S) as Belle. Analysis results from 2023!

Many analysis already ongoing, just waiting for more data!

Charmonium

- X(3872) lineshape combining Belle and Belle II dataset
- Full amplitude analysis of B → charmonium modes
- Inclusive B → K ($c\bar{c}$)

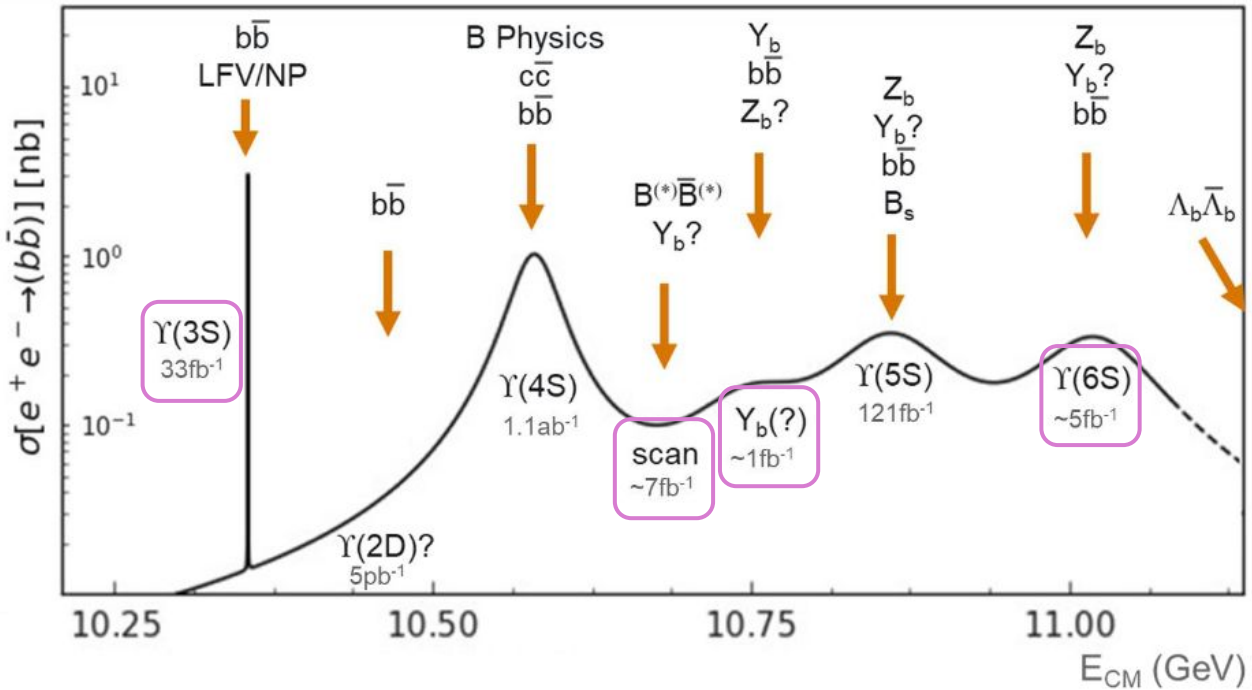
Bottomonium sector

- Dalitz analysis of Y(4S) → $\pi^+\pi^-$ Y(nS)
- h_b(1P) and η_b(1S) exclusive decays

A non-4S early run?

Outside Υ(4S) even small data sets can make a difference

Currently available data sets in the bottomonium region



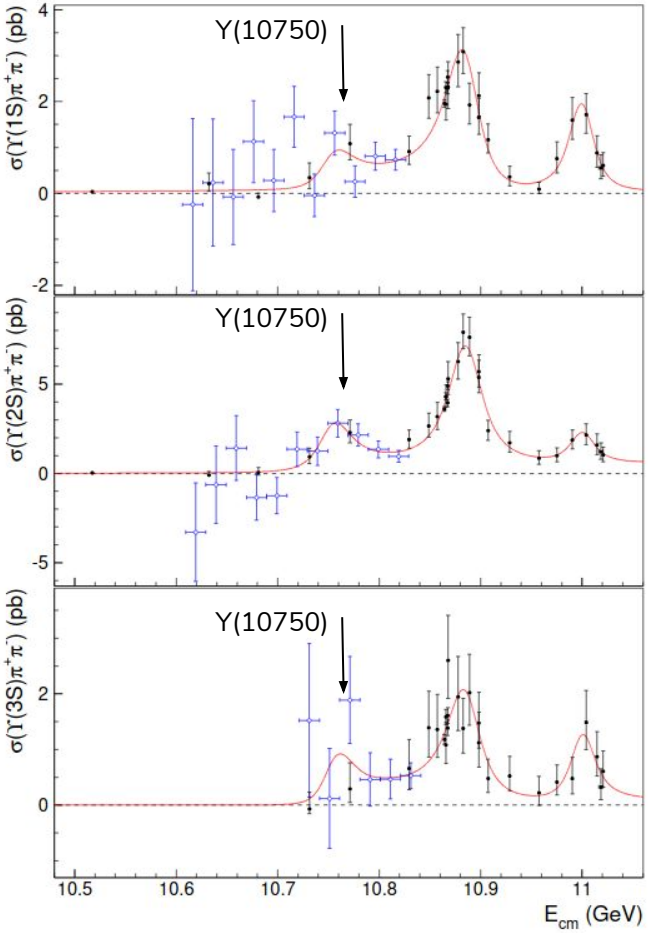
What's special about 10.750 GeV?

JHEP10(2019)220 (*Belle*):

- "High-stat" scan points: 1 fb^{-1} each
- 1 point "on resonance"
- 2-3 points in the region of interest
- Significance: 5.2 σ

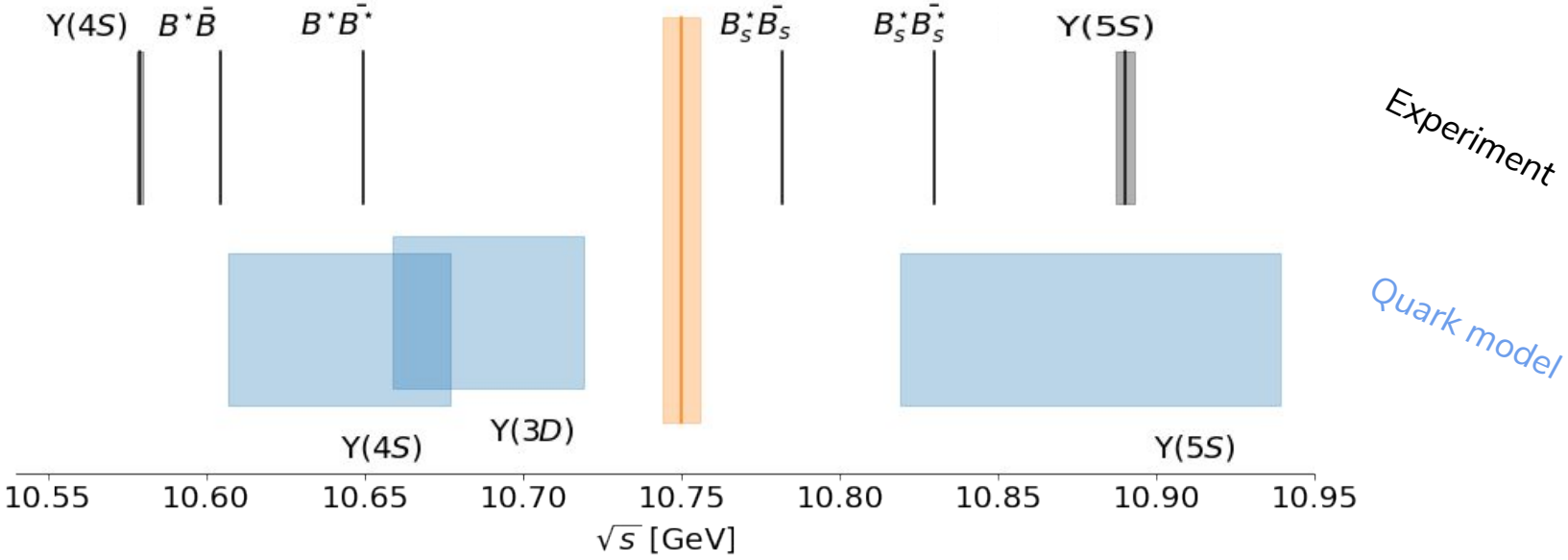
Parameters:

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



Why is the Y(10750) important?

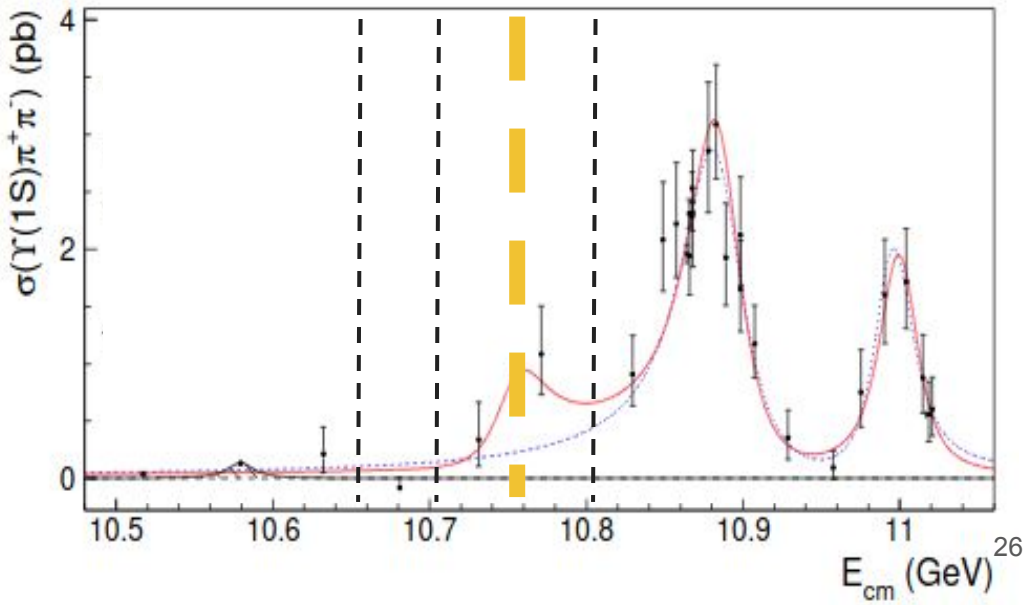
- Unlikely to be a molecule as it's far from any S- threshold
- No direct matching to conventional states (but may be an S-D mixing?)



The early Y(10750) run

Proposal under discussion to take before the 2022 shutdown:

- 10.751 GeV: 10 fb^{-1} to study the Y(10750) on-peak
- **10.657, 10.706, 10.810 (1+2+3 fb^{-1})** ancillary points for the BBbar decomposition
- **Total: 10 + 6 fb^{-1}**



Under discussion within the collaboration

Long-term plans and projects

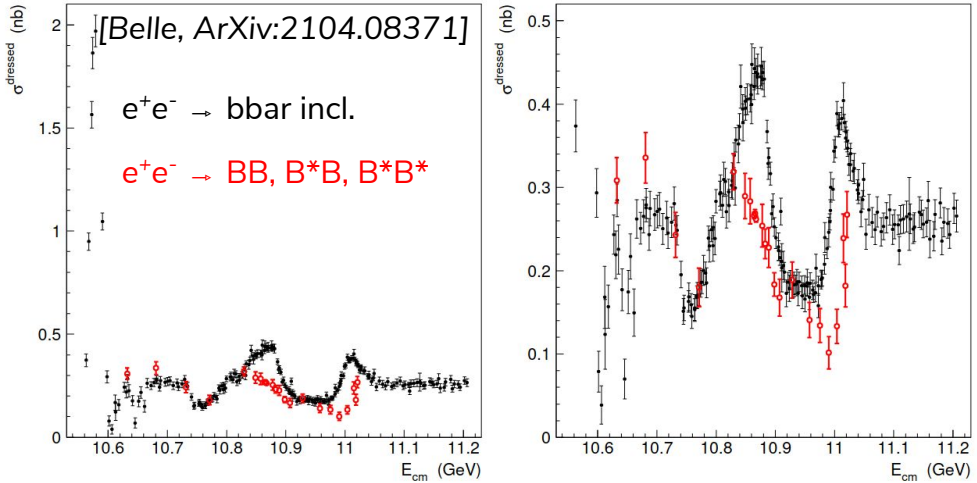
2024+ planes: above-4S scan

The wish: 0.5 ab^{-1} scan between Y(4S) and at least 11.02 GeV

[Bondar, Mizuk, Voloshin; Mod. Phys. A 32, 04, 1750025 (2017)]

QCD goals:

- Precise decomposition of the R-ratio
  and systematic exploration of the threshold region



When?

- Challenging for the accelerator operations

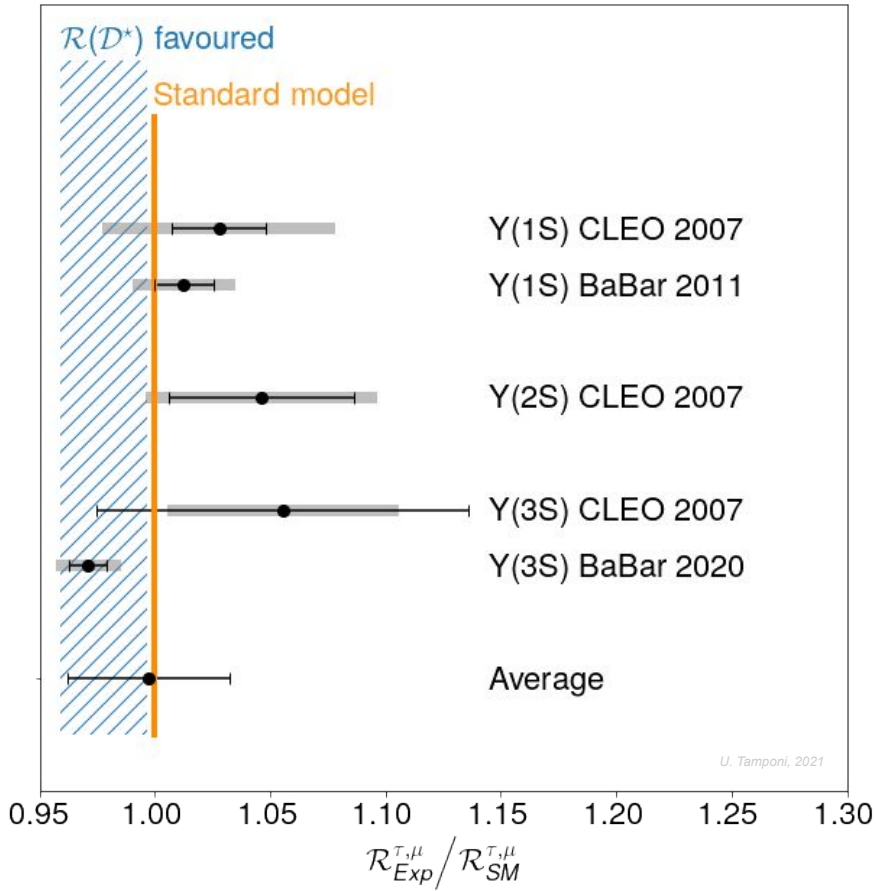
2024+ planes: narrow bottomonium run

The wish: **collect 1 Billion Y(3S) or Y(2S)**

NP goals:

- LFU: < 0.5% precision on
  Y(nS) → $\tau^+\tau^-$ / Y(nS) → $\mu^+\mu^-$
  - *Connection with R(D*)*
    [Aloni et al, JHEP 06 (2017) 019]

- LFV: push as much as possible
  the sensitivity on Y(nS) → eτ, $\mu\tau$
  - *Best sensitivity to EFT Wilson coefficients*
    [Hazard, Petrov; Phys. Rev. D 94, 074023]

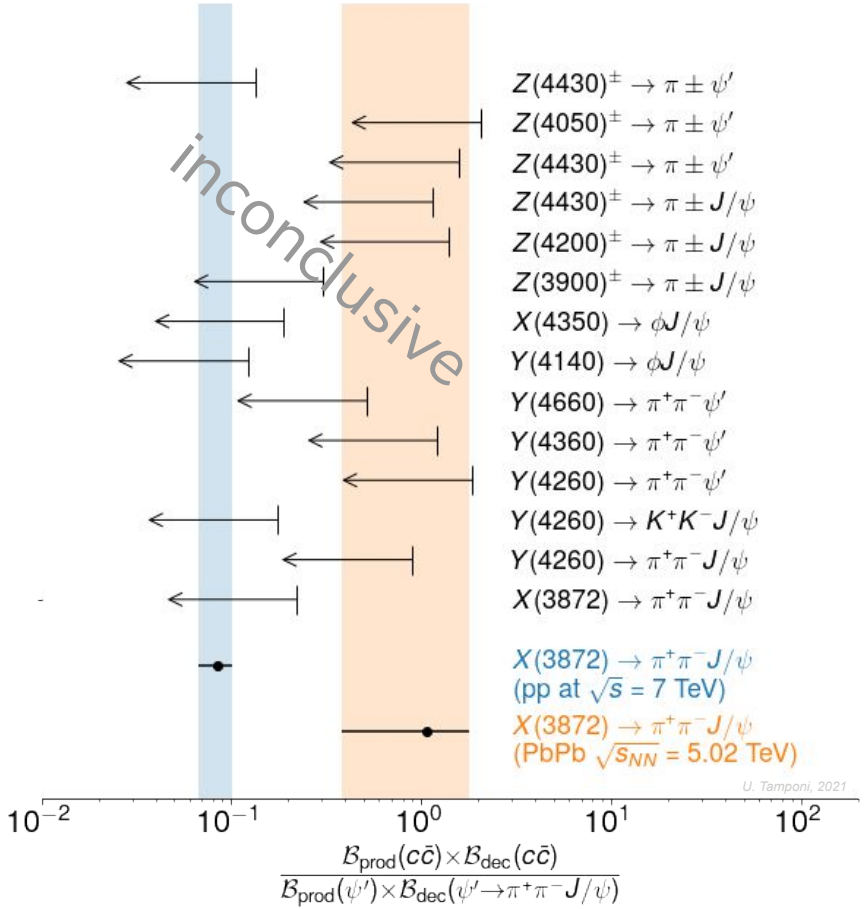


2024+ planes: narrow bottomonium run

The wish: **collect 1 Billion Y(3S) or Y(2S)**

(A personal favourite) QCD goals:

- Y(nS) → multi-quark system + X
  - *Exotic charmonia*
    [Phys. Rev. D 93, 112013 (2016)]



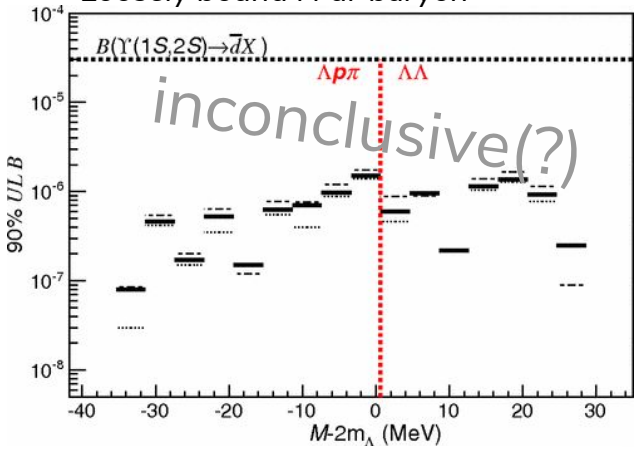
2024+ planes: narrow bottomonium run

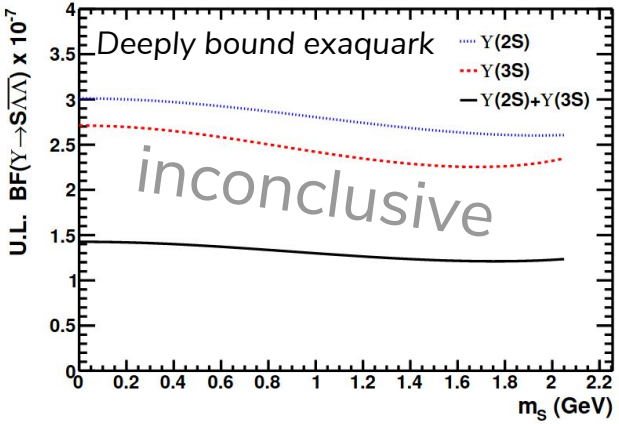
The wish: **collect 1 Billion Y(3S) or Y(2S)**

(A personal favourite) QCD goals:

- Y(nS) → multi-quark system + X
  - *Exotic charmonia*
    [Phys. Rev. D 93, 112013 (2016)]
  - *Di-baryons*
    - *Loosely-bound*
      [Phys. Rev. Lett. 110 (2013), 222002]
    - *Deeply-bound*
      [Phys. Rev. Lett. 122 (2019) 7, 072002]

Loosely bound H di-baryon





Summary

Belle II and SuperKEKB have fully entered the physics data taking phase

Detector performances are good

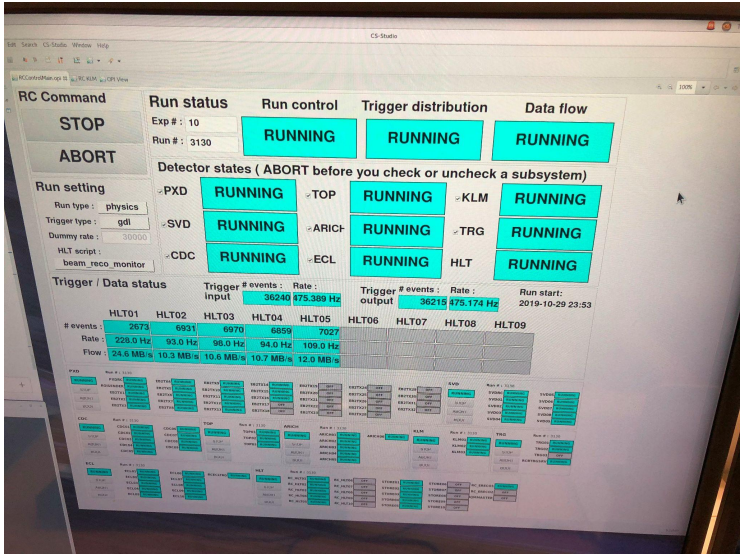
- First performance publications in fall 2021

Belle II is providing the first physics results

- Mostly low-multiplicity, NP channels

First quarkonium results from 2023!

- Bottomonium-related plans are under discussion



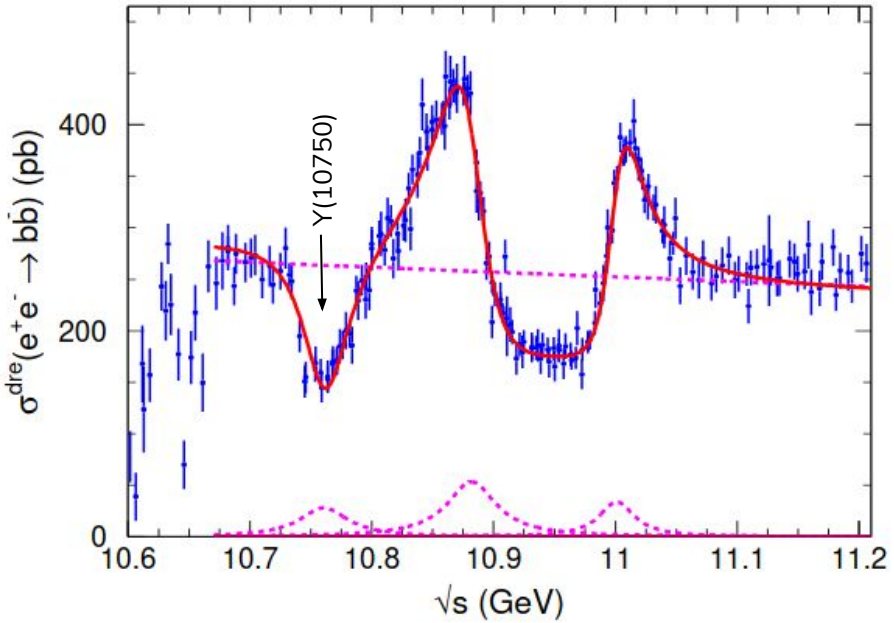
Backup

Y(10750): further evidences

Chin.Phys.C 44 8, 083001:

- Refit the BaBar R_b scan
- Further evidence of Y(10750) in interference

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



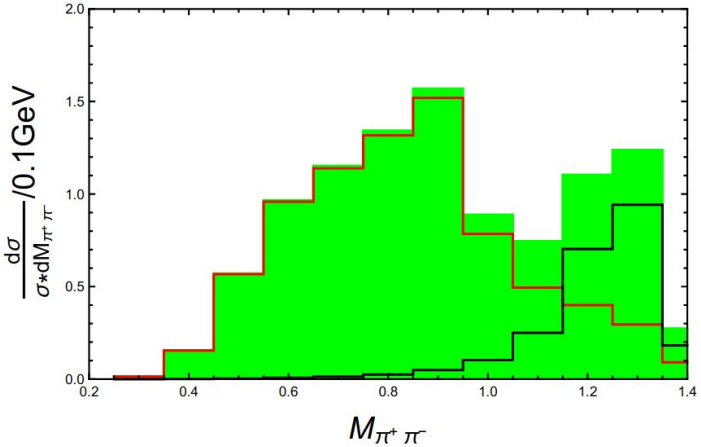
The (theoretical) golden modes at Y(10750)

1) BB : BB* : B*B* ratio is predicted by almost all models

2) Y(10750) → ω η_b(1S) very large in one tetraquark-based model

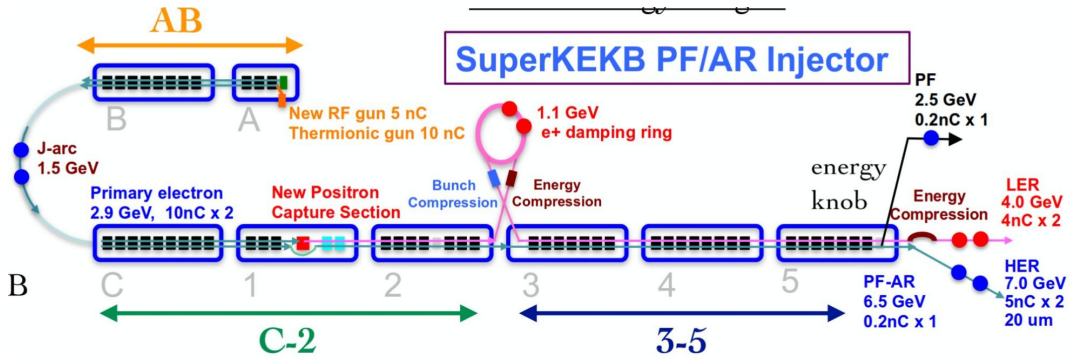
Mode	$\mathcal{B}(4q)$ (%)	$\mathcal{B}(b\bar{b})$ (%)
$B\overline{B}$	$39.3^{+38.7}_{-22.9}$	21.3
$B\overline{B}^*$	~ 0.2	14.3
$B^*\overline{B}^*$	$52.3^{+54.9}_{-31.7}$	64.1
$B_s\overline{B}_s$	-	0.3
$\omega\eta_b$	$7.9^{+14.0}_{-5.0}$	-
$f_0(1370)\Upsilon$	$0.2^{+0.6}_{-0.2}$	-
$\omega\Upsilon$	~ 0	-

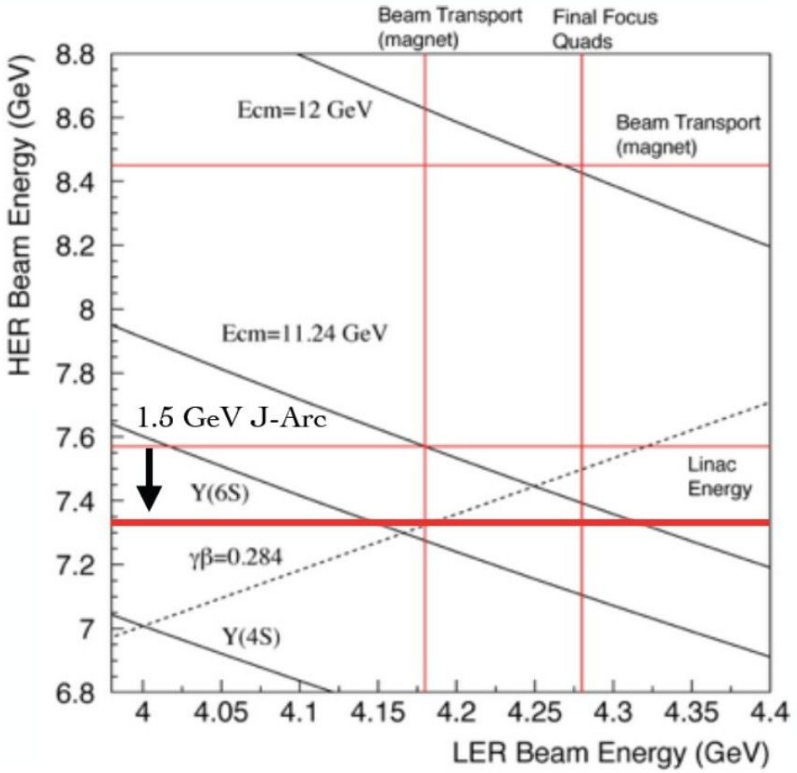
3) M(ππ) shape predicted by the tetraquark models



The (theoretical) golden modes at Y(10750)

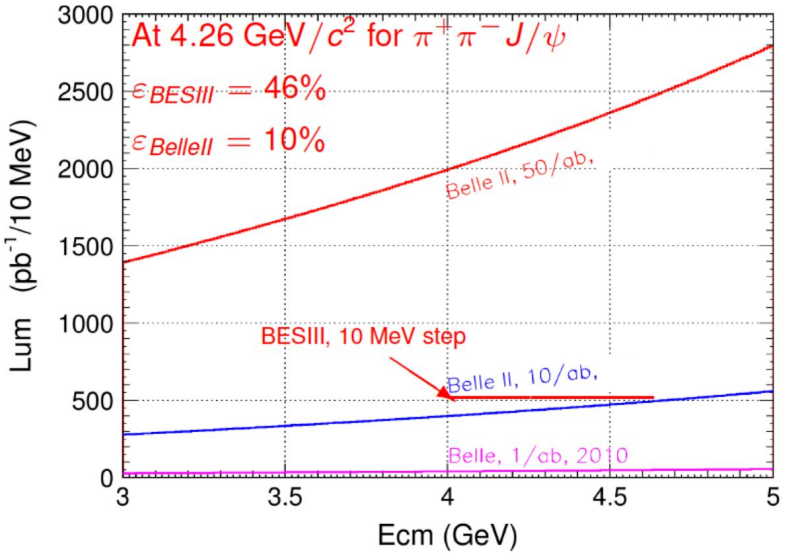
Current energy limit: E_{cm} = 11.02 GeV





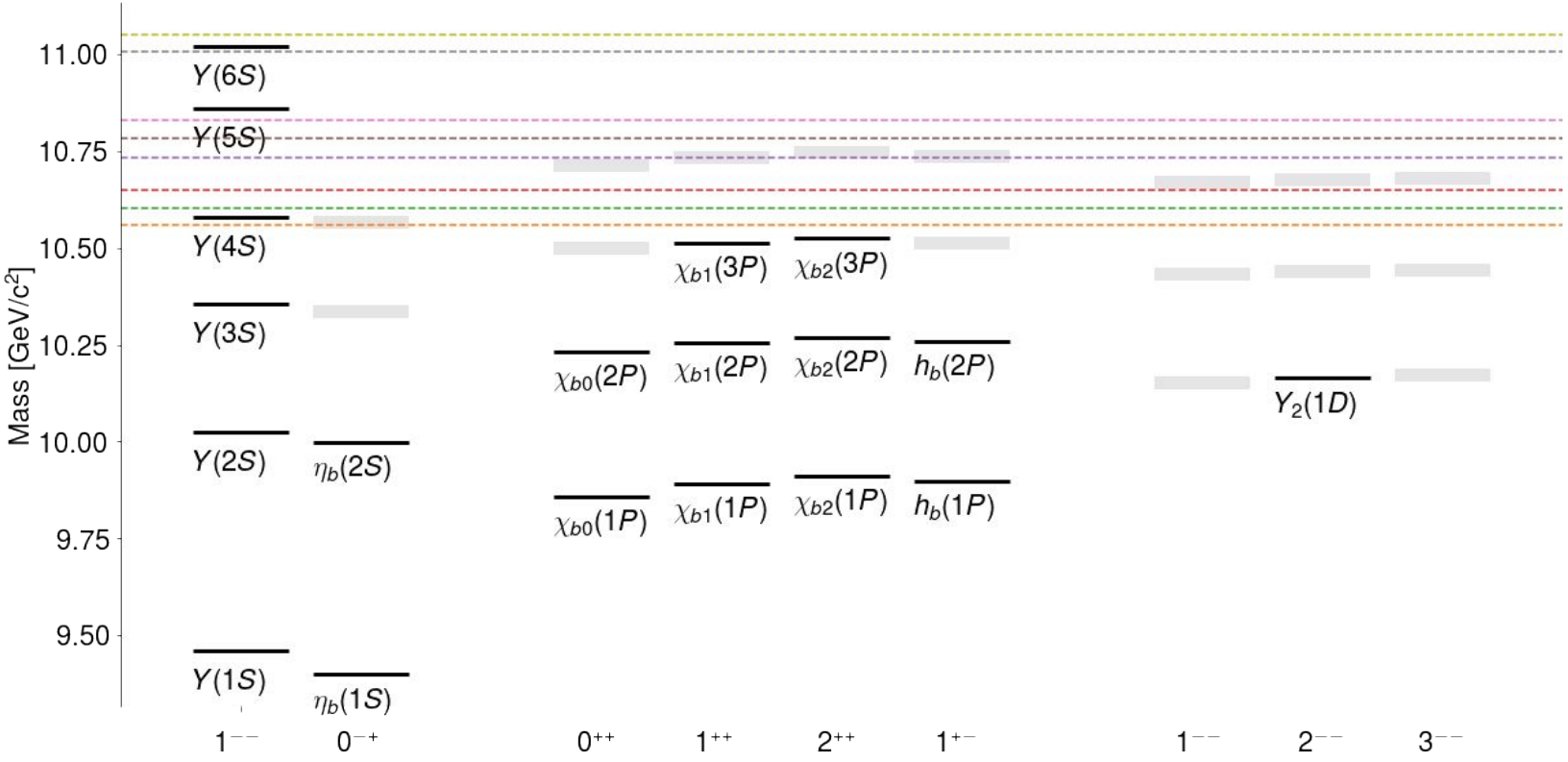
ISR: Belle II VS Belle

Golden Channels	$E_{c.m.}$ (GeV)	Statistical error (%)	Related XYZ states
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	$Y(4008)$, $Y(4260)$, $Z_c(3900)$
$\pi^+\pi^- \psi(2S)$	4.36	12 (5.0)	$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	$Y(4220)$, $Y(4390)$, $Z_c(4020)$, $Z_c(4025)$
$\omega\chi_{c0}$	4.23	35 (15)	$Y(4220)$



Same sensitivity as BESIII with ~10 ab^{-1}

Bottomonium spectrum



Charmonium spectrum