Exotic and Conventional Quarkonium Physics Prospects at Belle II

Bianca SCAVINO
bscavino@uni-mainz.de

On behalf of the Belle II collaboration

Bundesministerium für Bildung und Forschung

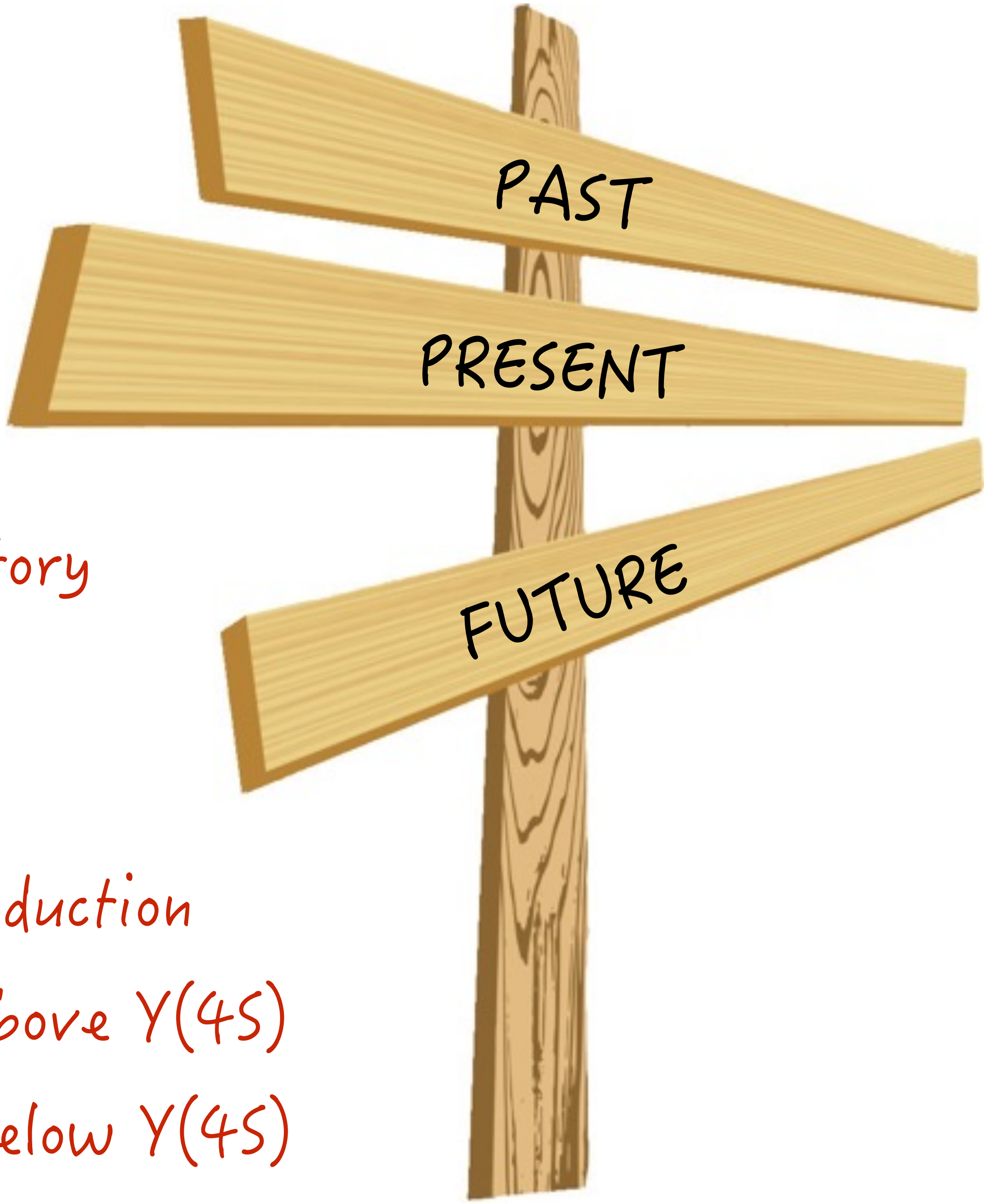
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Contents

- QUARKONIA:
  legacy of 1st generation B-Factories

- BELLE II:
  the next generation B-Factory

- FUTURE PROSPECTS:
  - Charmonium(-like) production
  - Bottomonium(-like): above Υ(4S)
  - Bottomonium(-like): below Υ(4S)

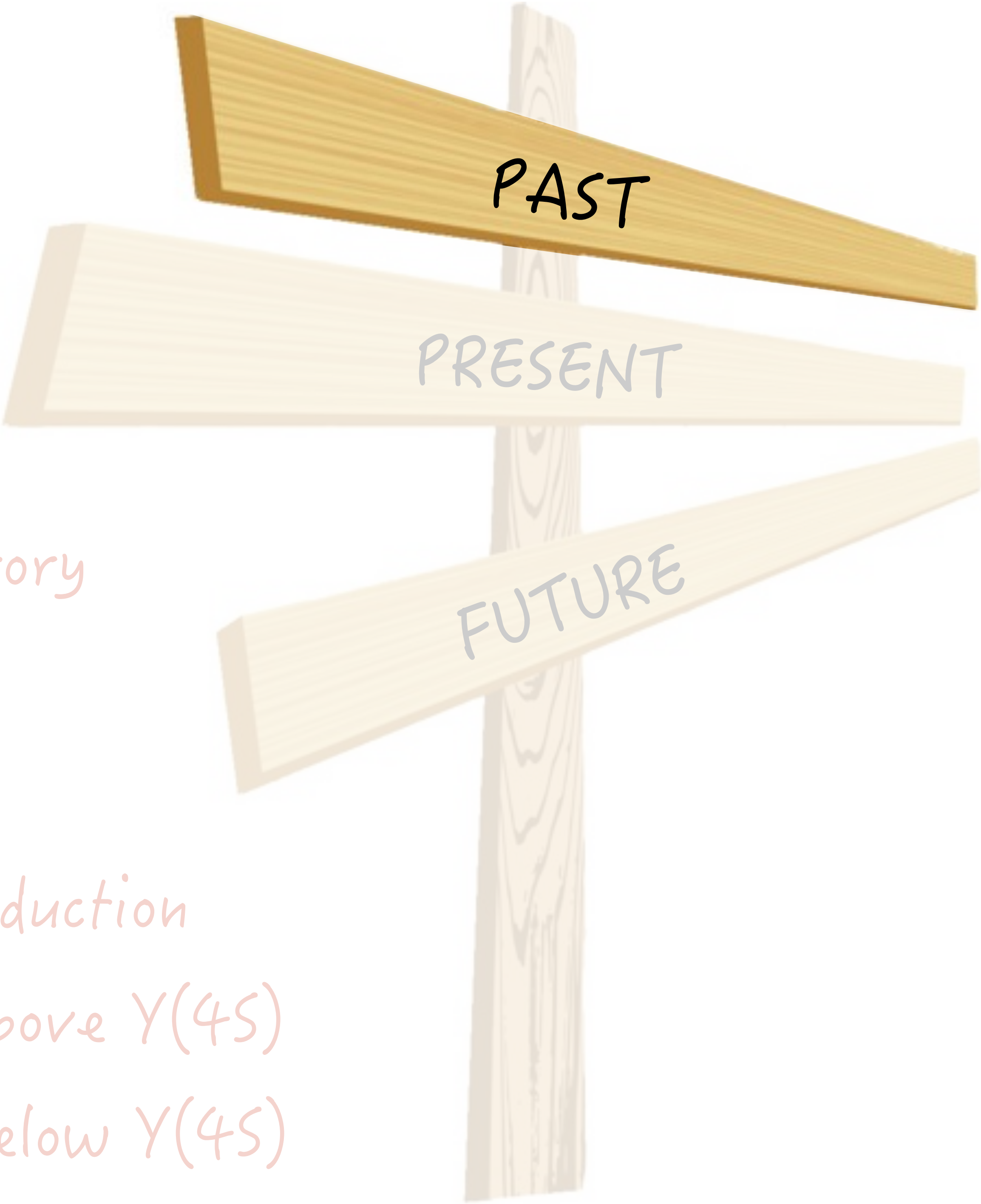


Contents

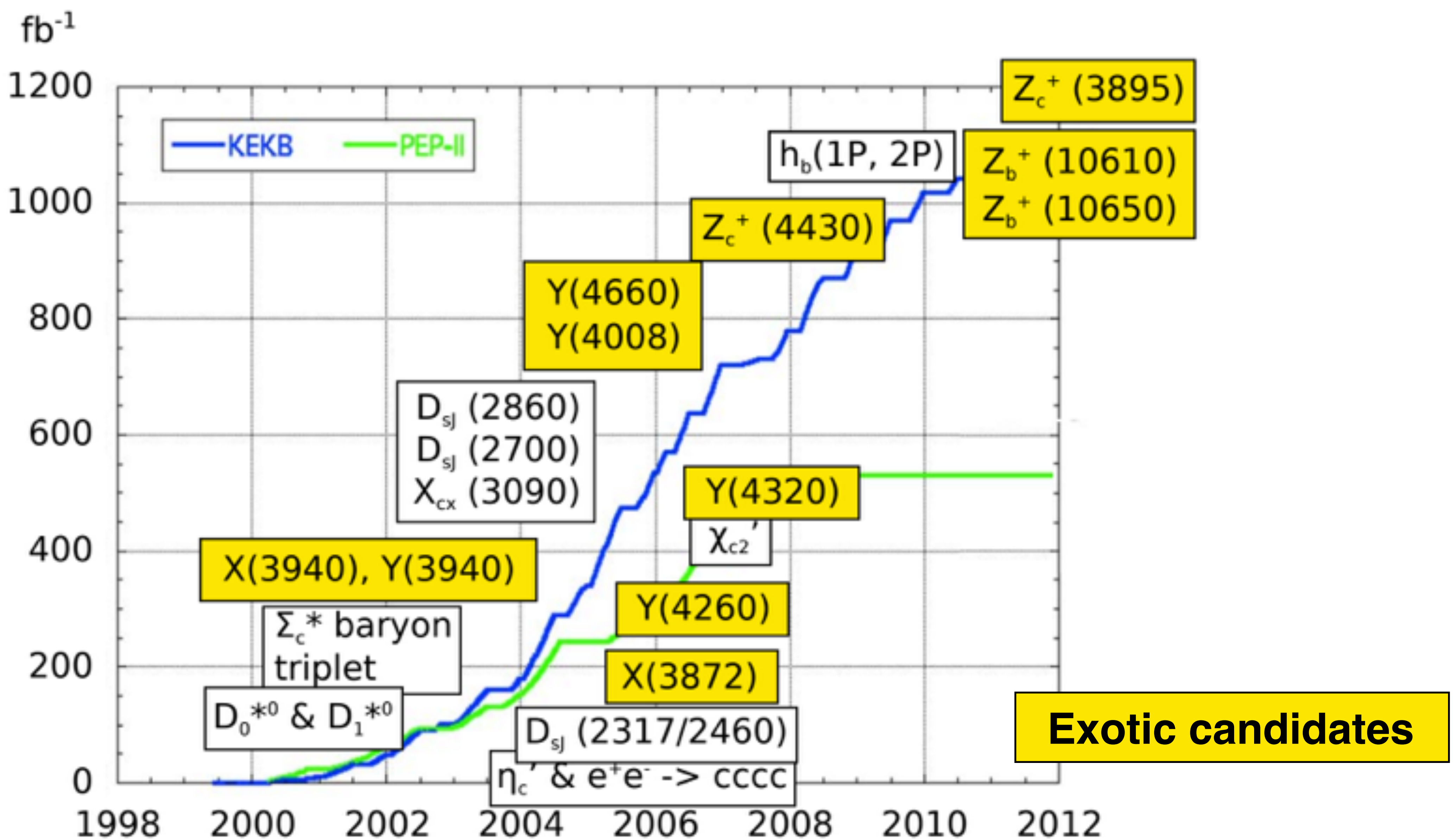
- QUARKONIA: legacy of 1st generation B-Factories

- BELLE II: the next generation B-Factory

- FUTURE PROSPECTS:
  - Charmonium(-like) production
  - Bottomonium(-like): above Υ(4S)
  - Bottomonium(-like): below Υ(4S)

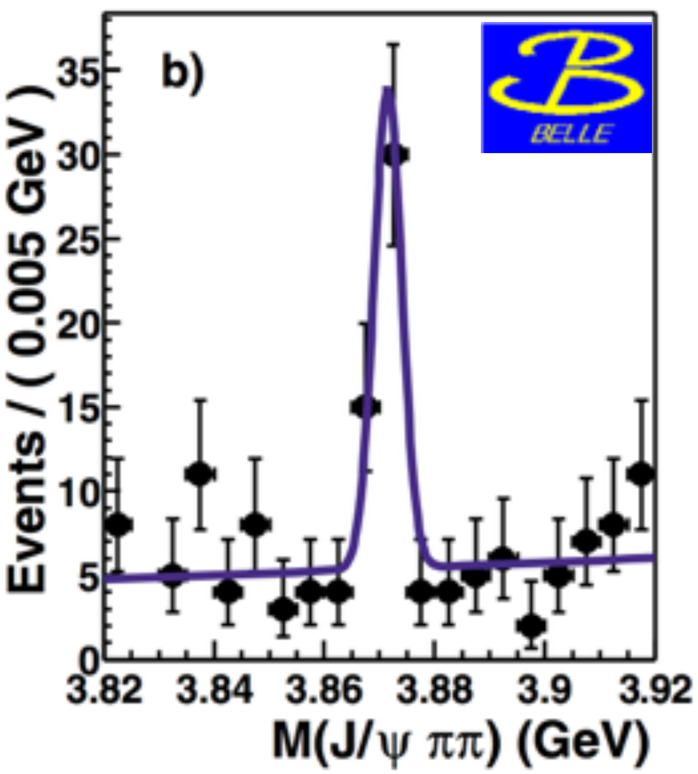


B-Factory: a success story



- The series of discoveries started with the observation of the η_c' meson in B → K η_c' decays
- The first exotic state was X(3872), found in B → K X(3872)

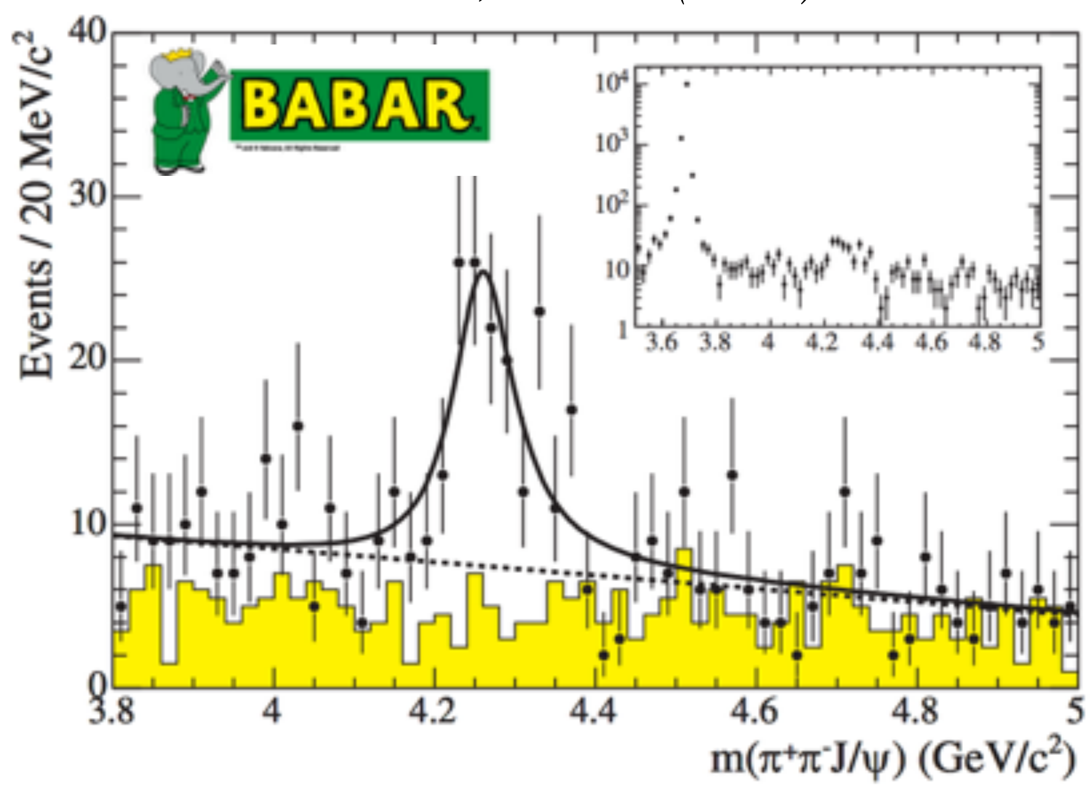
PRL 91, 262001 (2003)



X(3872)

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

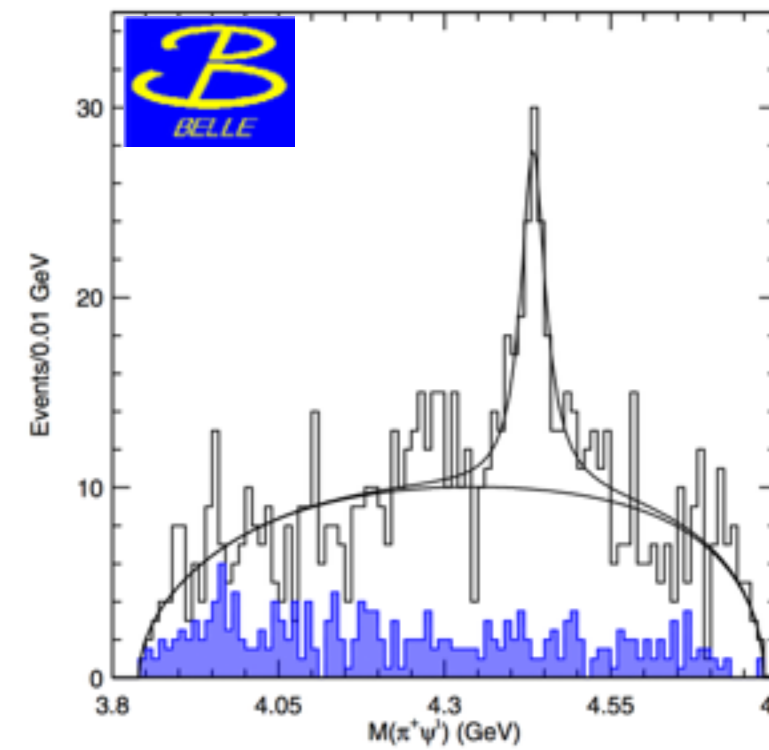
PRL 95, 142001 (2005)



Y(4260)

$e^+ e^- \rightarrow \gamma [\pi^+ \pi^- J/\psi]$

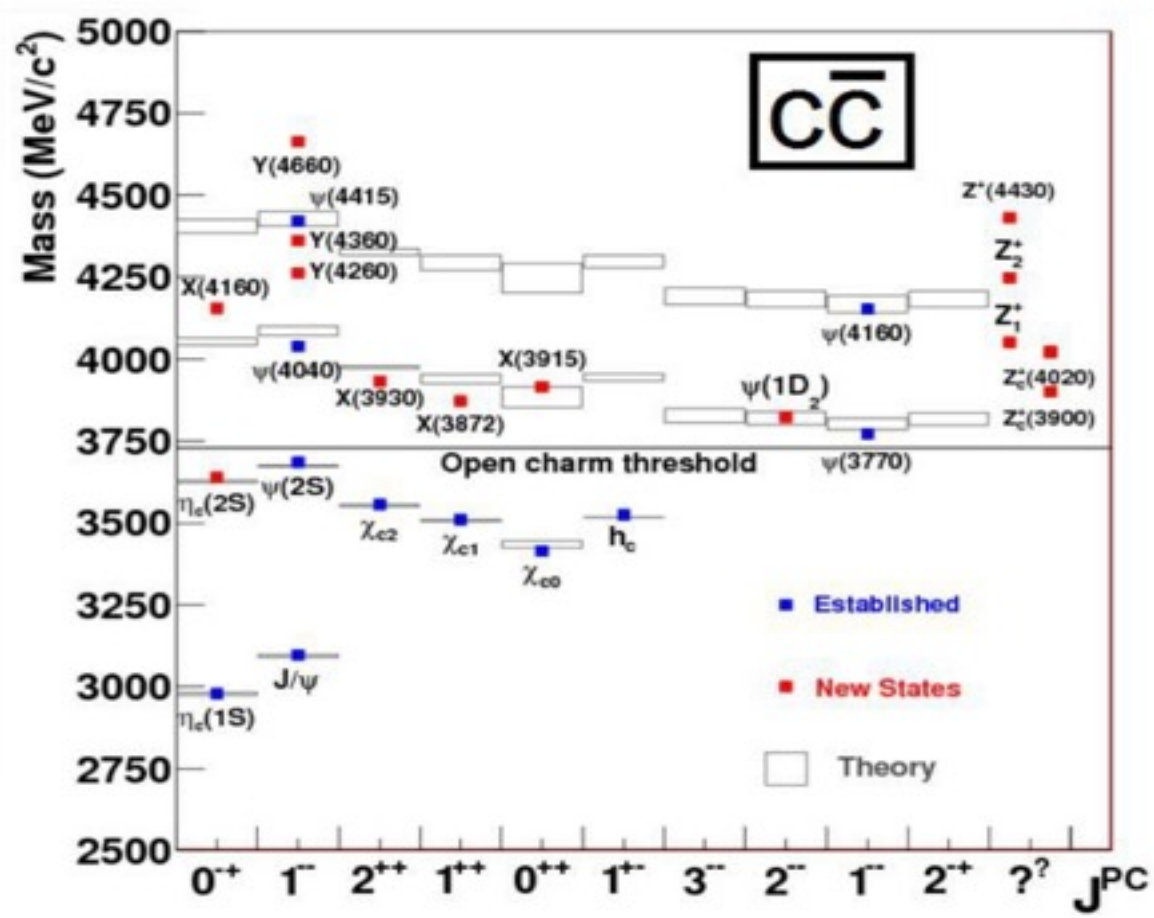
PRL 100, 142001 (2008)

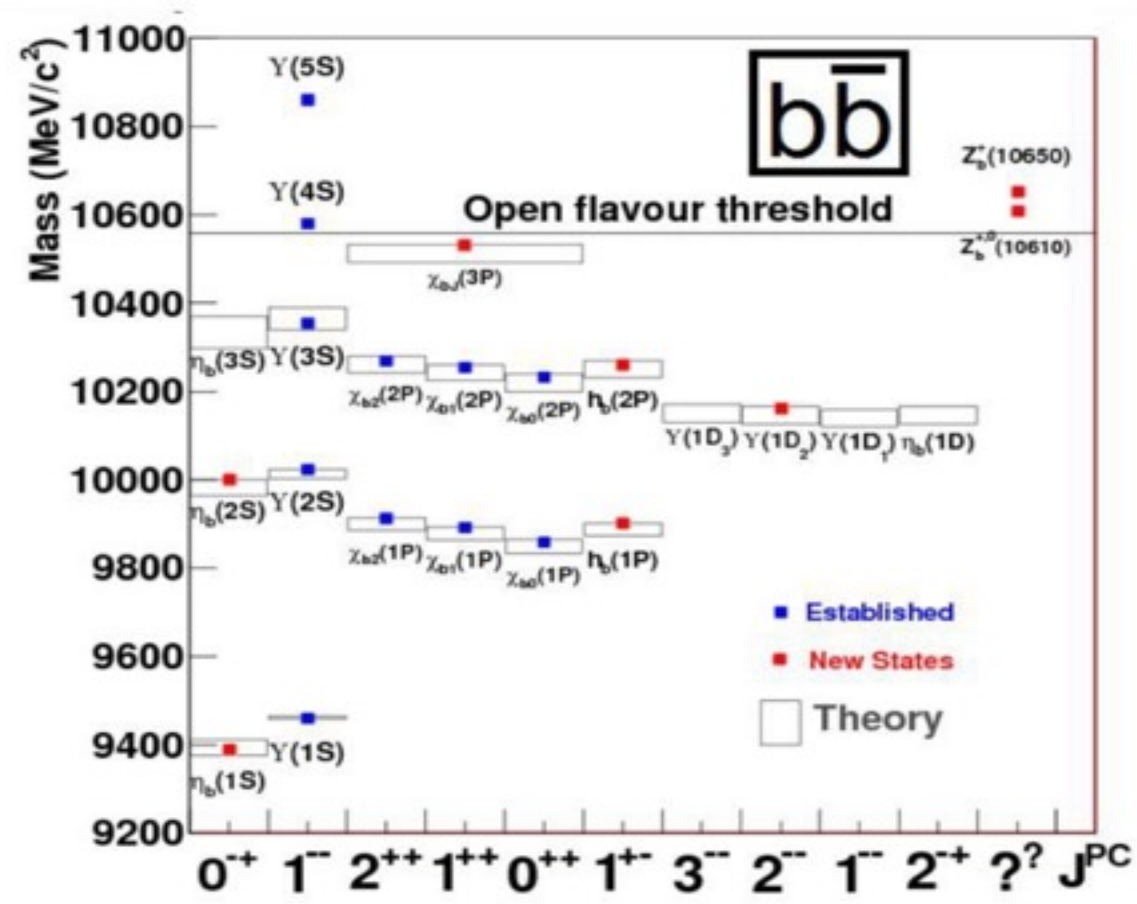


Z(4430)

$B \rightarrow K [\pi^{\pm} \psi']$

- The legacy of 1st generation B-factories is a variety of quarkonium states
- Good agreement with predictions below open flavor threshold
- Many discoveries are difficult to explain with quarkonium model
- Several states have non-zero charge (cannot be $q\bar{q}$ pairs)
- Exotic candidates, XYZ states





➡ Challenge for the new generation B-factories

Contents

QUARKONIA:

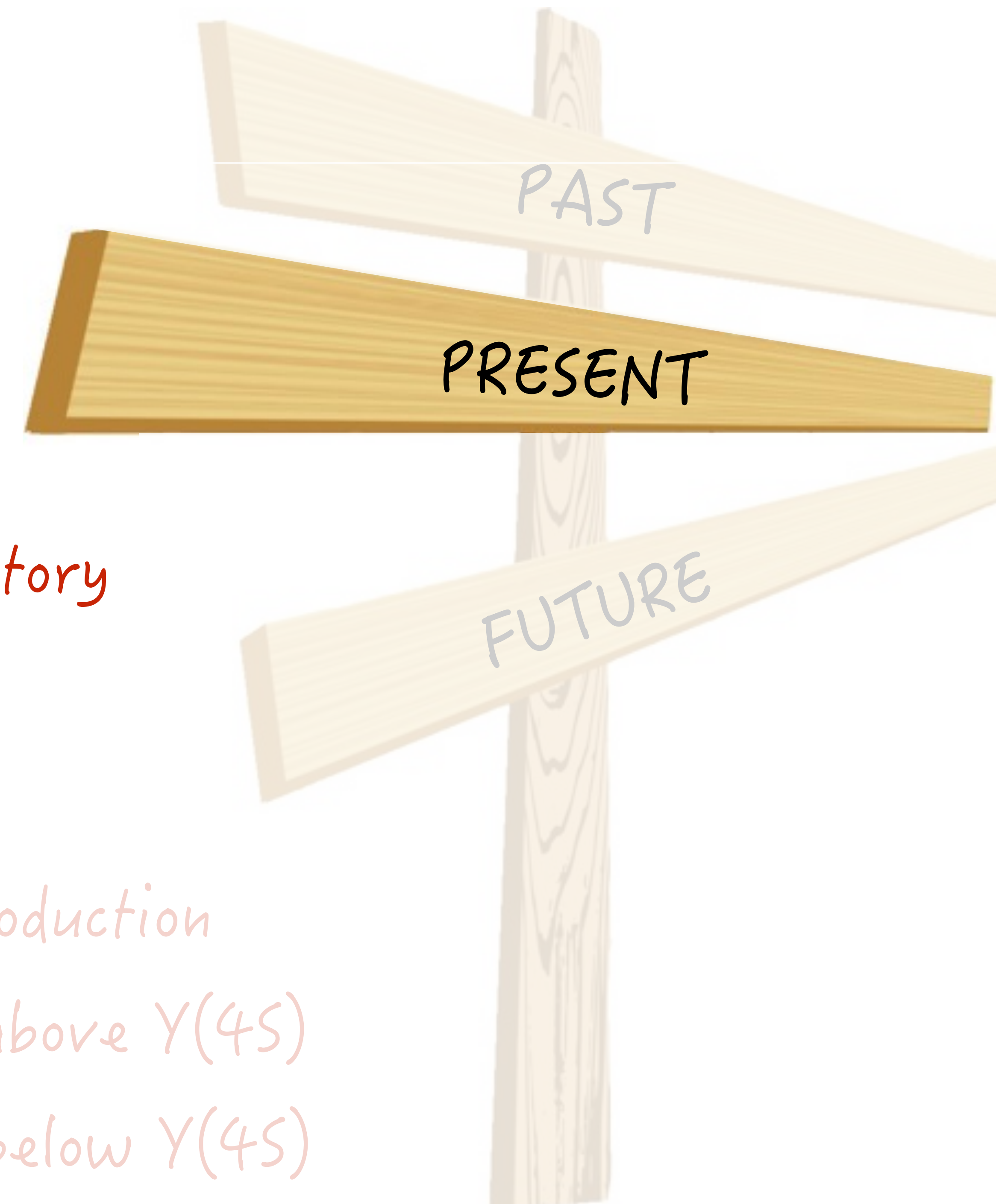
legacy of 1st generation B-Factories

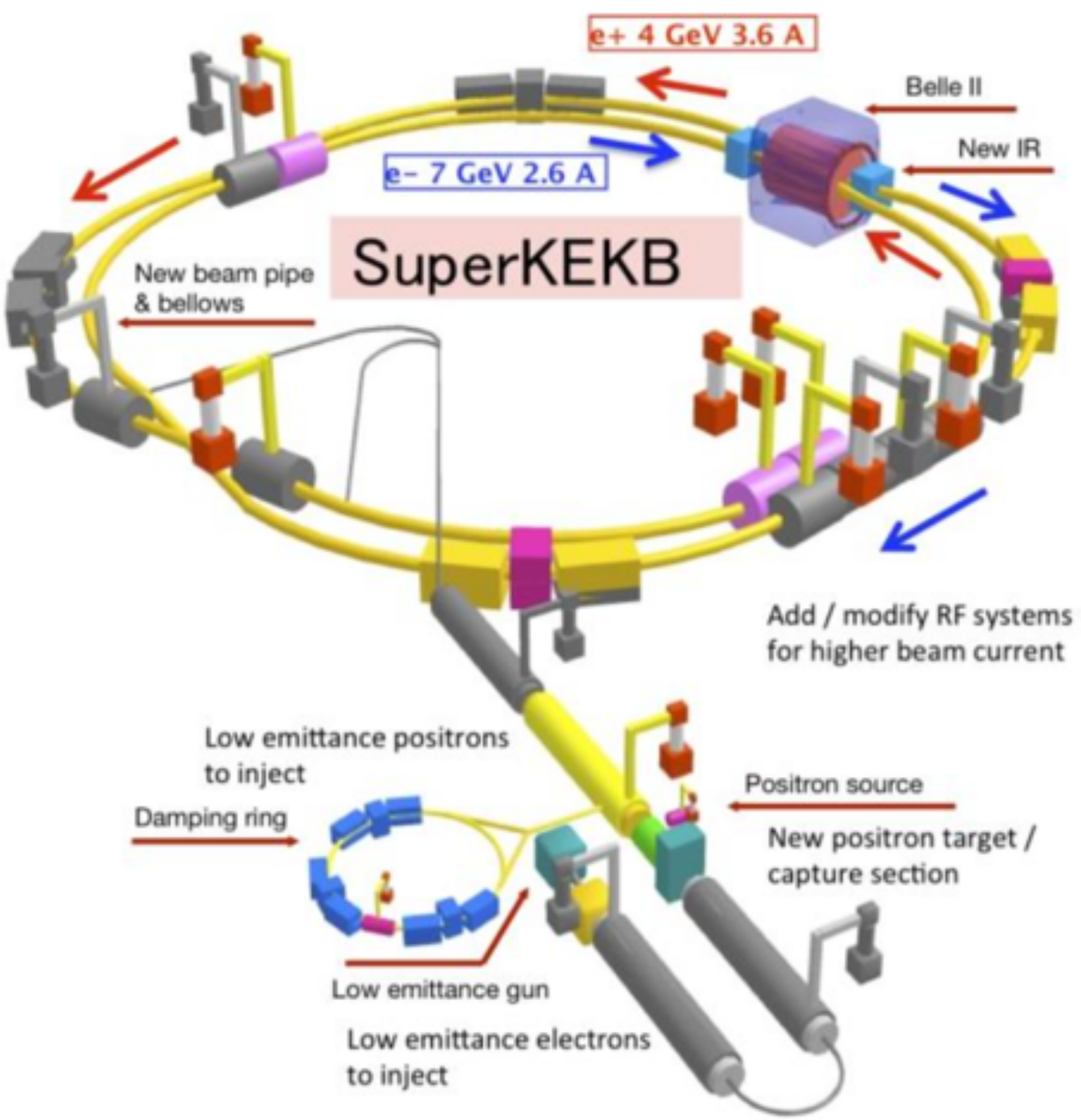
BELLE II:

the next generation B-Factory

FUTURE PROSPECTS:

- Charmonium(-like) production
- Bottomonium(-like): above Υ(4S)
- Bottomonium(-like): below Υ(4S)

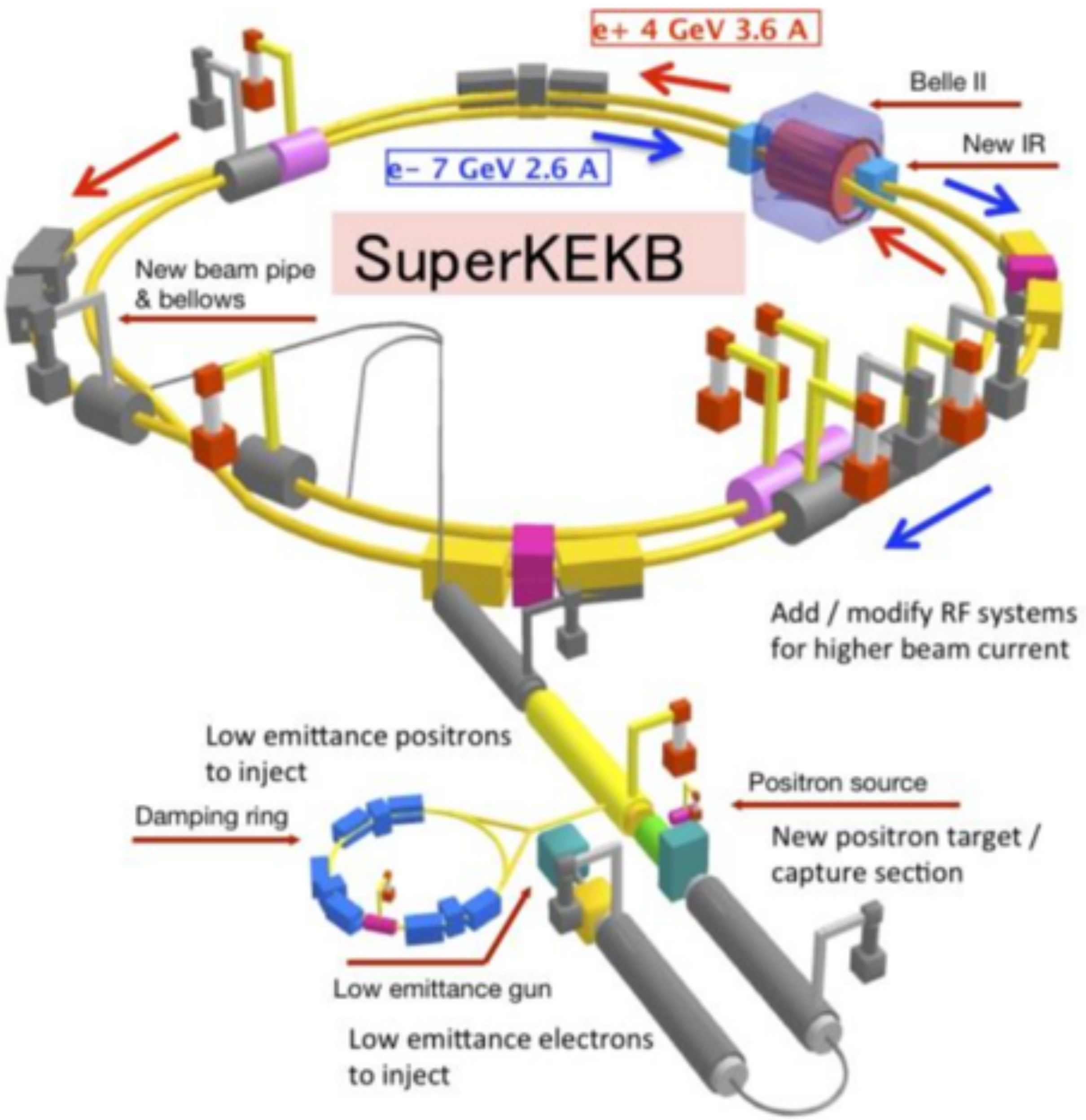




- ➡ **Target integrated luminosity:**
  50 ab^{-1} (x50 Belle)

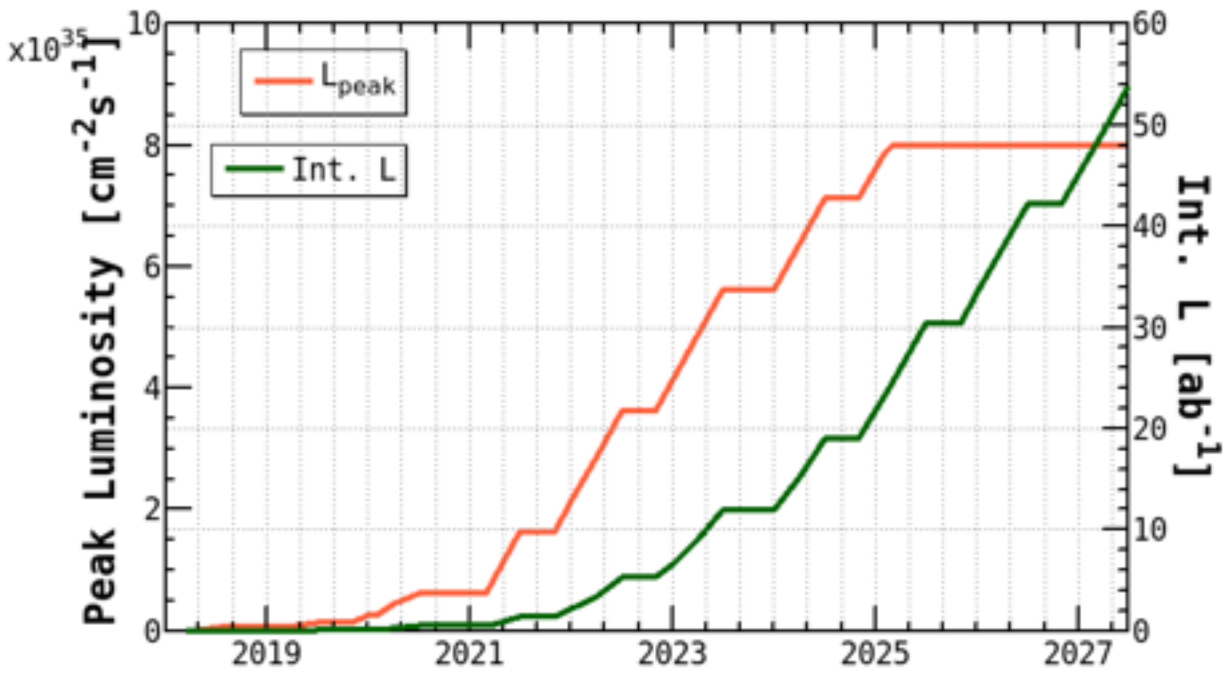
- ➡ **Target peak luminosity:**
  L = 8 x 10^{35} cm^{-2} s^{-1} (x40 Belle)

From KEKB to SuperKEKB



➡ **Target integrated luminosity:**
50 ab^{-1} (x50 Belle)

➡ **Target peak luminosity:**
$L = 8 \times 10^{35}\ cm^{-2}\ s^{-1}$ (x40 Belle)

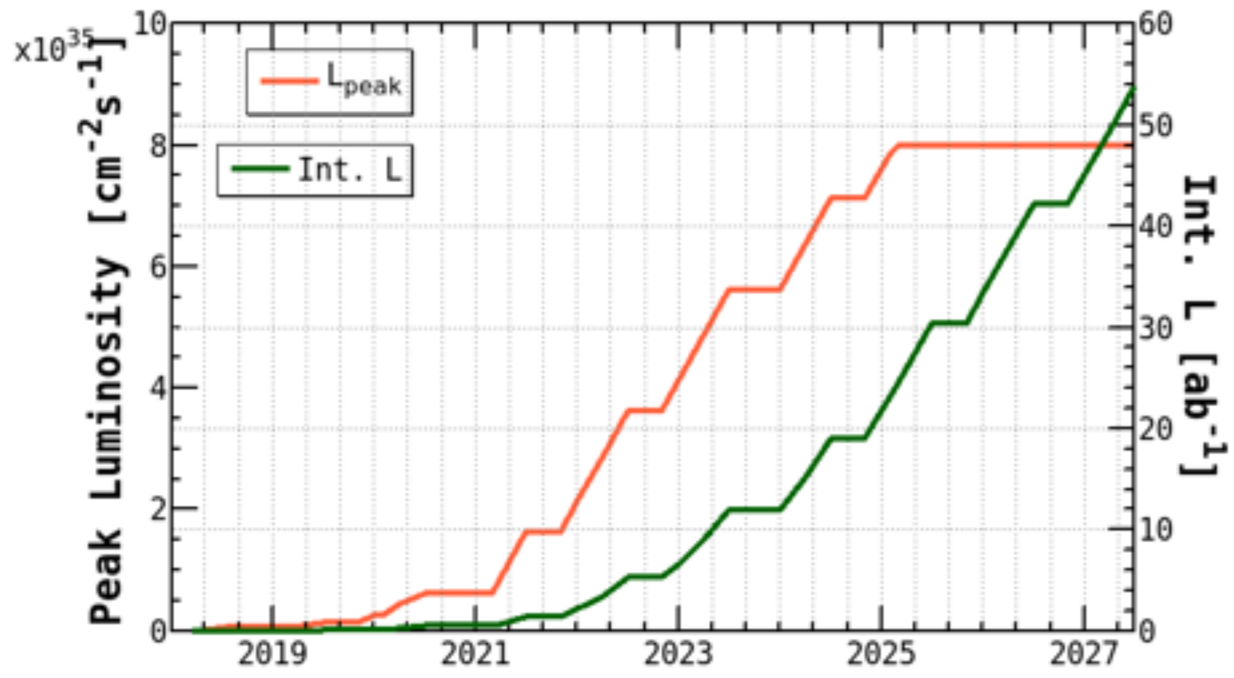


Current samples in fb^{-1} (millions of events)

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			**300(1200)**	**5×10^4(5.4×10^4)**	**1000(300)**	**100+400(scan)**	**3.6%**

- Y(4S) physics program but not only (important especially for the bottomonium physics program)

- In general, a lot can be done in quarkonium field



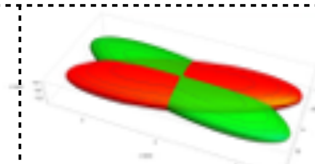
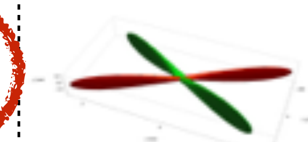
Beam current

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

Beam-beam parameter

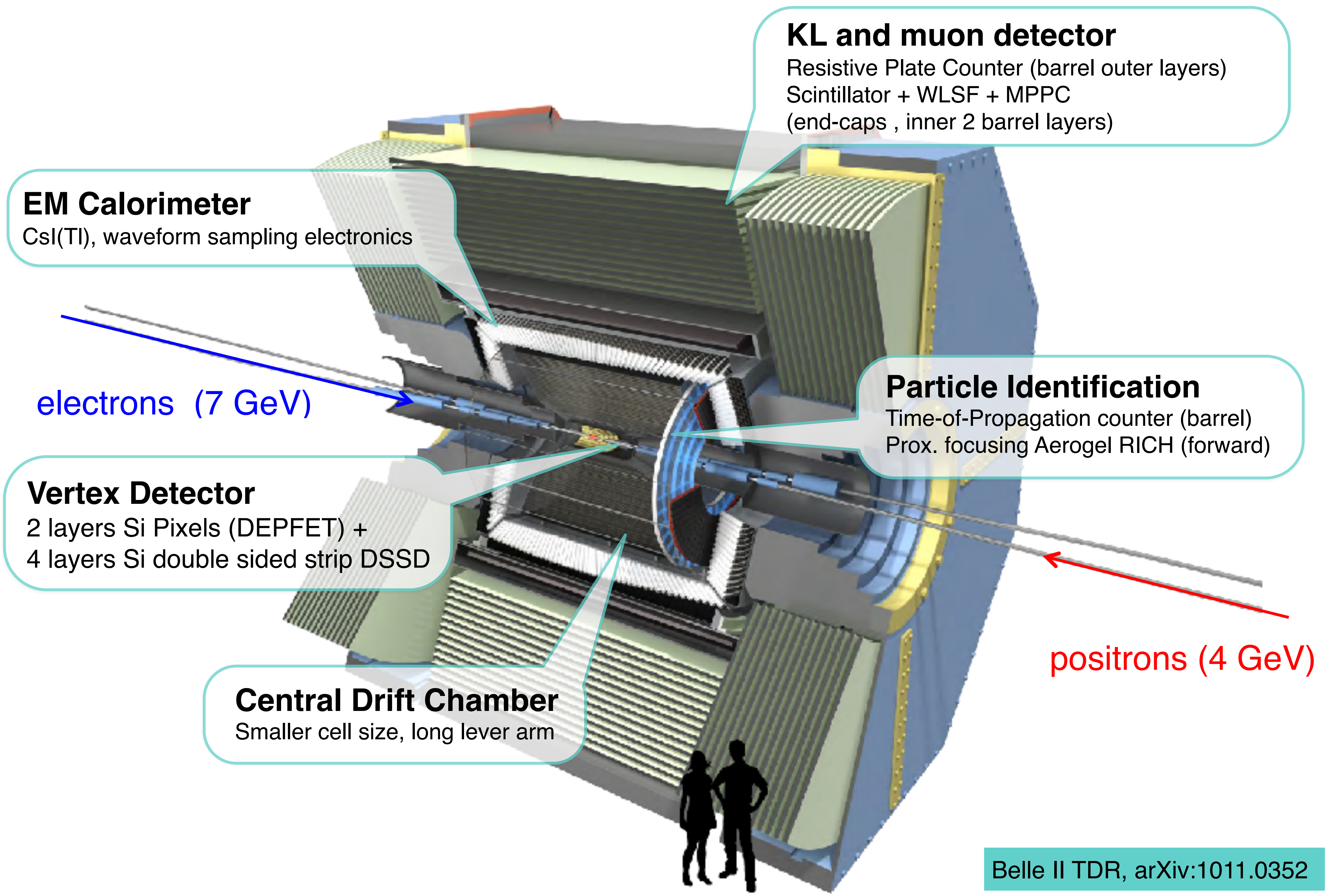
Beam aspect ratio

Vertical beta function @ IP

	E (GeV) LER / HER	β_y^* (cm) LER / HER	β_x^* (mm) LER / HER	Φ (mrad)	I (A) LER / HER	L (cm^{-2} s^{-1})	IP sketch
KEKB	3.5 / 8.0	5.9 / 5.9	120 / 120	11	1.6 / 1.2	2.1 x 10^{34}	
SuperKEKB	4.0 / 7.0	**0.27 / 0.30** **(Factor 20)**	3.2 / 2.5	41.5	**3.6 / 2.6** **(Factor 2)**	**80 x 10^{34}**	

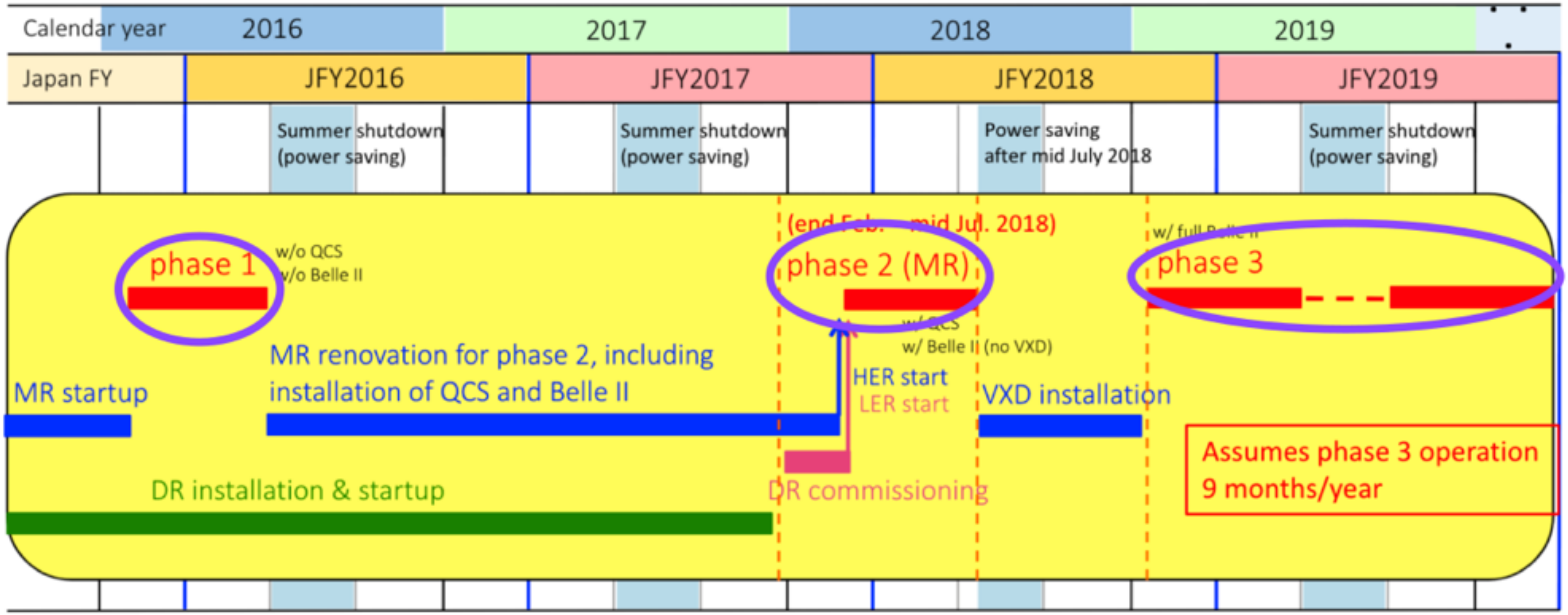
Factor 40

- **Squeeze the beam @ IP by 1 / 20**
- **Double beam currents**



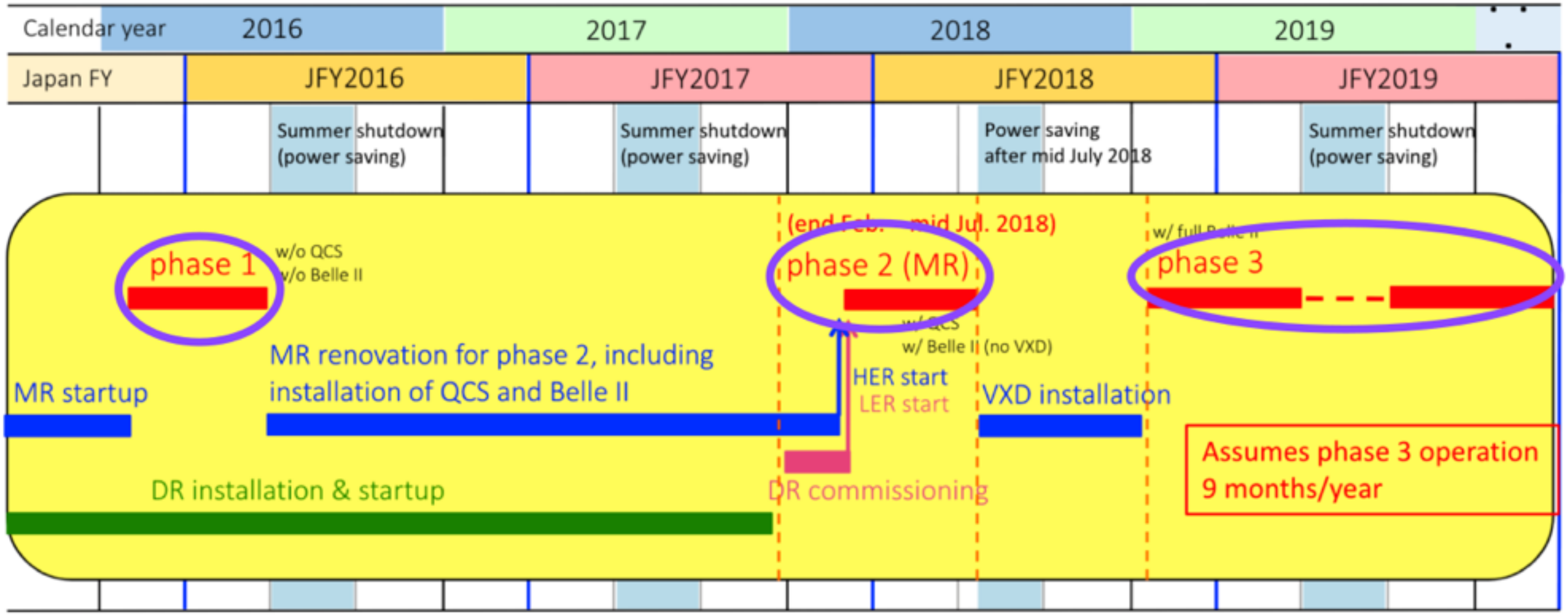
Belle II TDR, arXiv:1011.0352

Belle II status and schedule



- Phase 1: SuperKEKB commissioning (January - June 2016)
- Phase 2: pilot run with limited vertexing (April - July 2018)
- Phase 3: collision data taking with full Belle II detector.

Belle II status and schedule

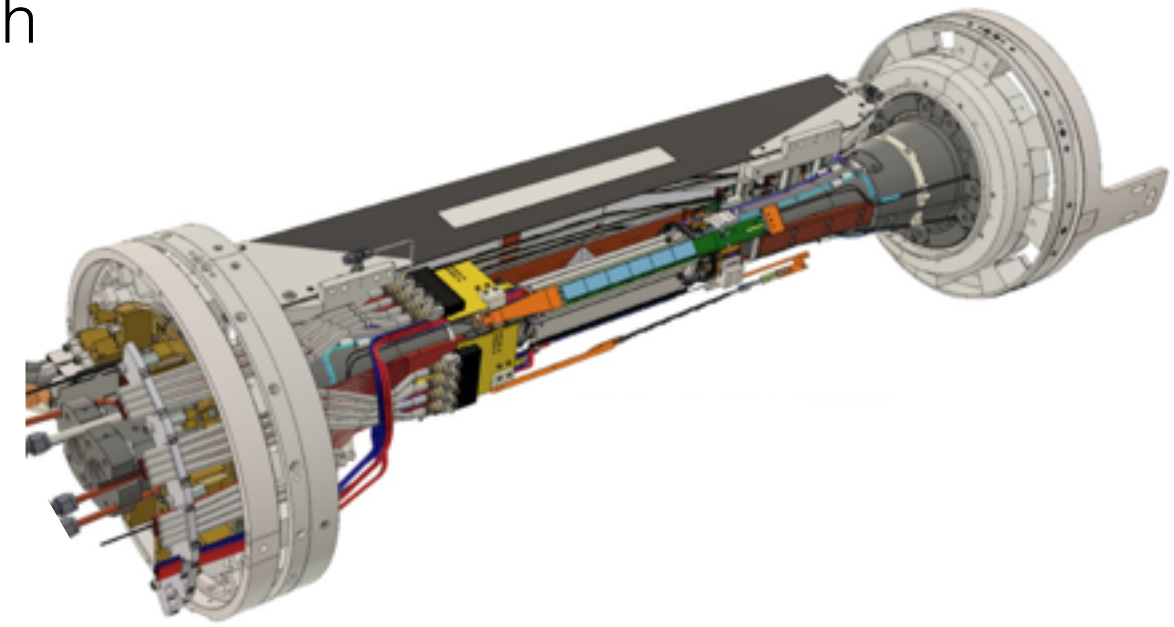


- Phase 1: SuperKEKB commissioning (January - June 2016)
- Phase 2: pilot run with limited vertexing (April - July 2018)
- Phase 3: collision data taking with full Belle II detector. **STARTED MARCH 2019!**

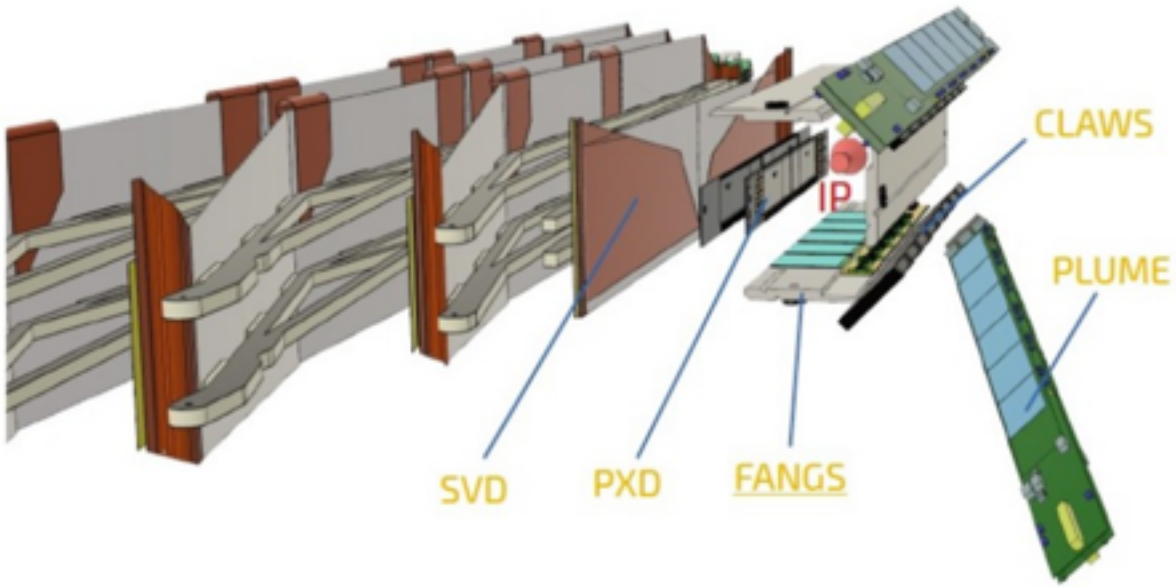
Few more words about Phase 2

- Phase 2 lasted from April 26th to July 17th

- Pilot run with limited vertexing
  - Most of the silicon tracker replaced by background monitor detectors
  - One full octant of PXD + SVD



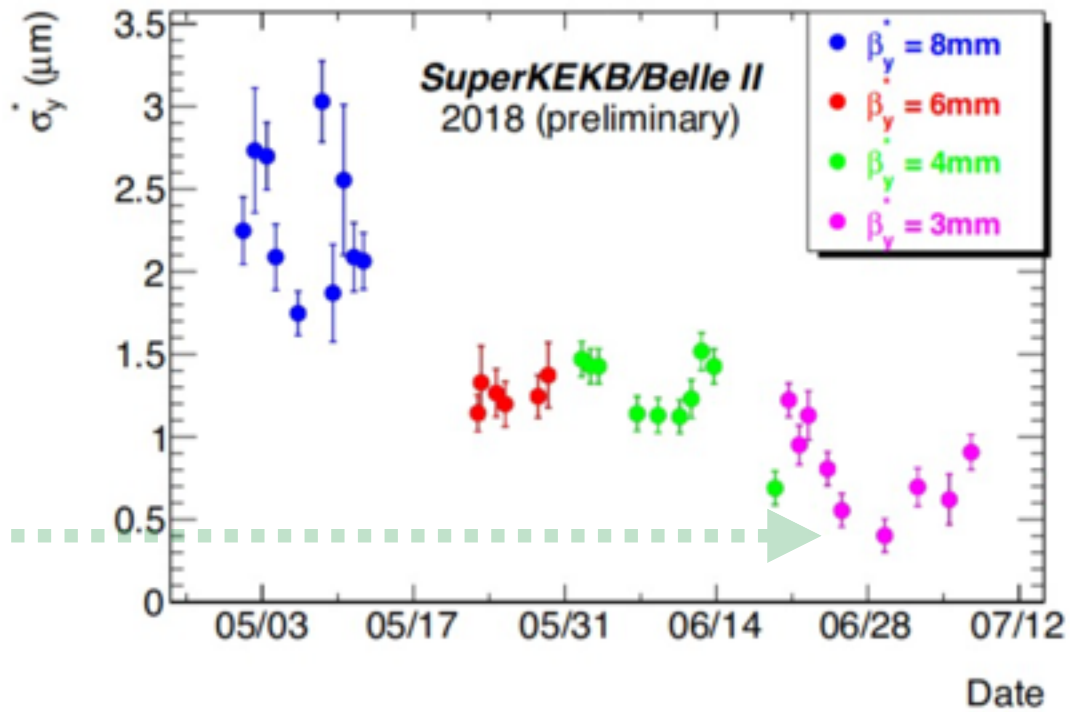
- Luminosity tuning had priority on data taking
  - 5.55 x 10^{33} cm^{-1} s^{-2} maximum luminosity
  - 0.5 fb^{-1} of collisions at Υ(4S)



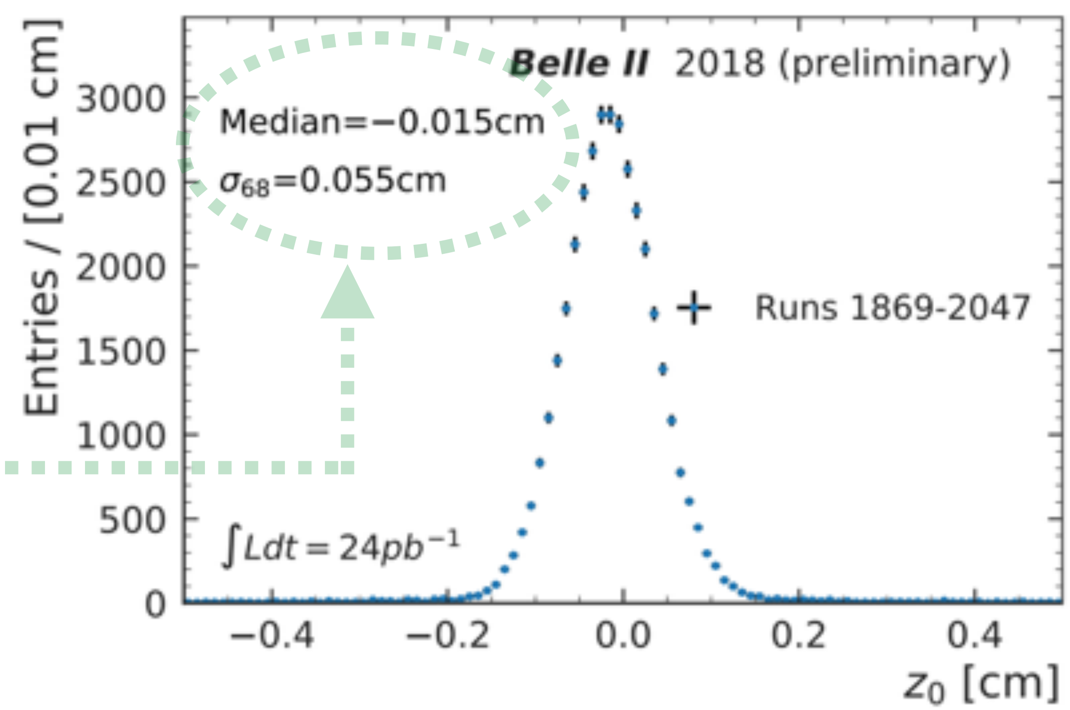
- Goals
  - Verification the nano beam scheme
  - Monitoring of the background
  - Commissioning of the detector
  - Produce some physics results

Phase 2 highlights: beam properties verifications

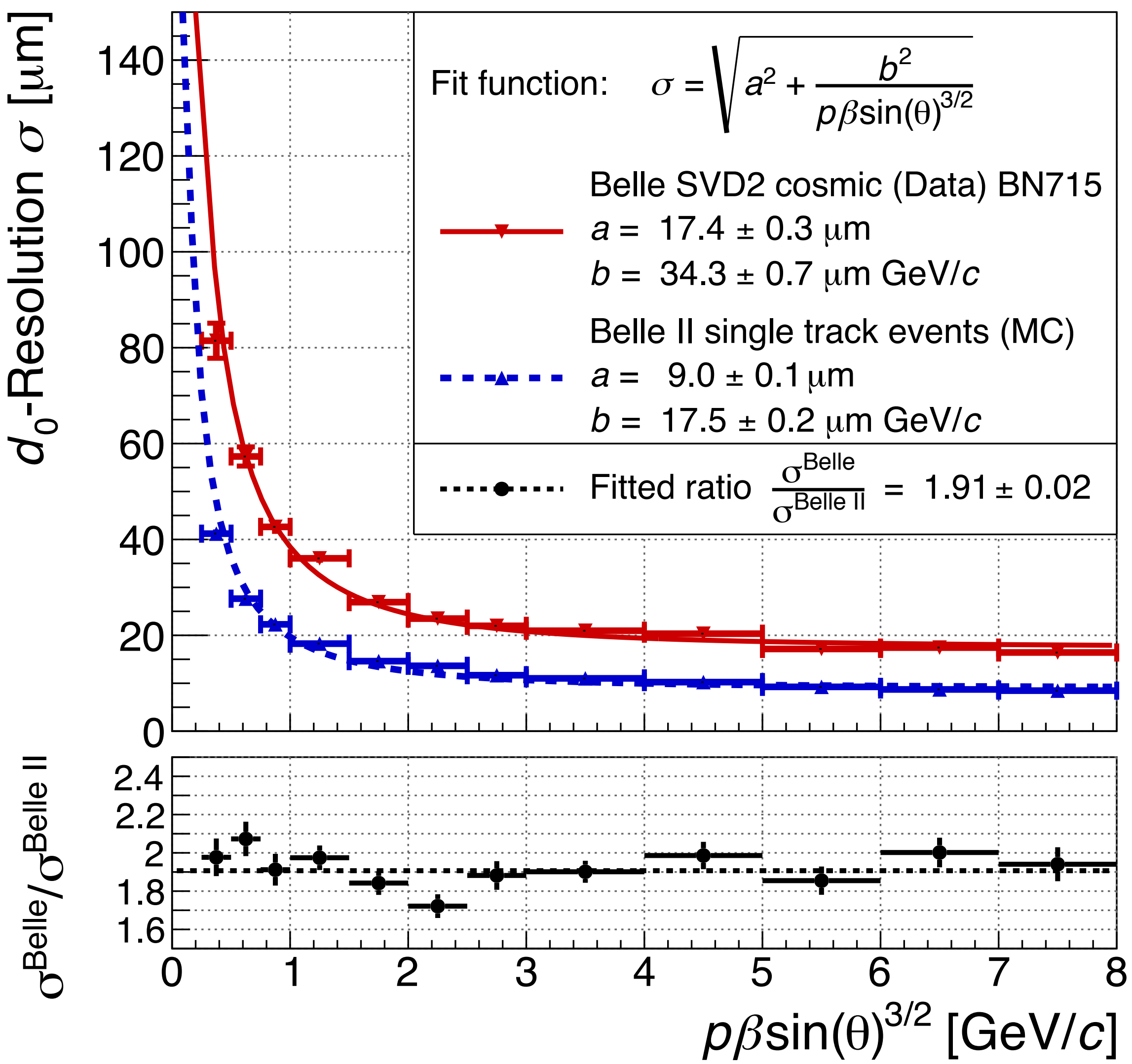
- *Vertical size of the beam (σ_y^*):* obtained using vertical offset scans of the beams at the IP, corresponding to luminosity scans as a function of the vertical offset
(→ *less than 500 nm achieved*)



- *Interaction region size (z_0):* longitudinal component of the interaction vertex estimated using z_0 parameter of single tracks originating from the interaction vertex
(→ Beam spot ~ 10 times smaller than KEKB)

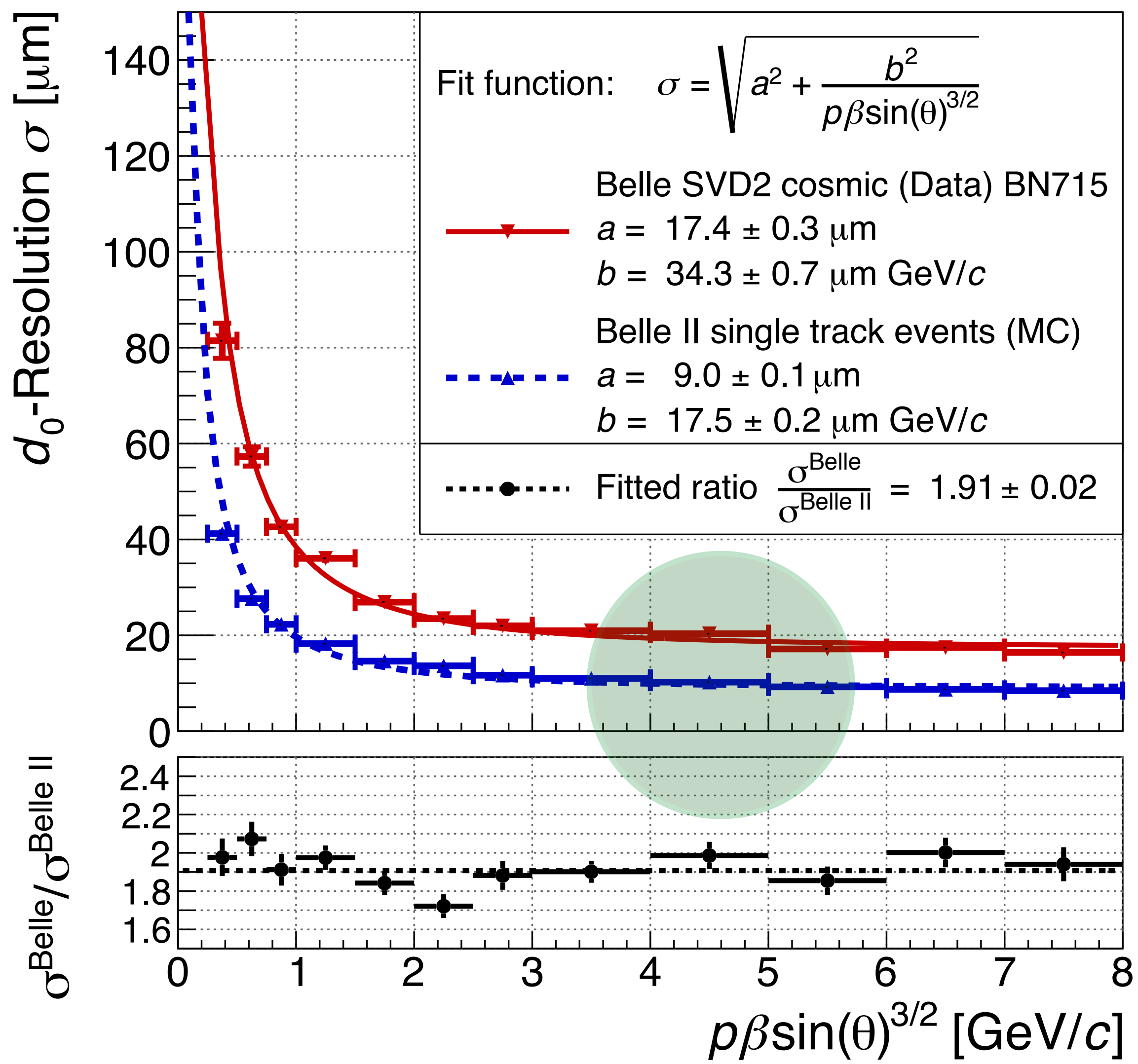


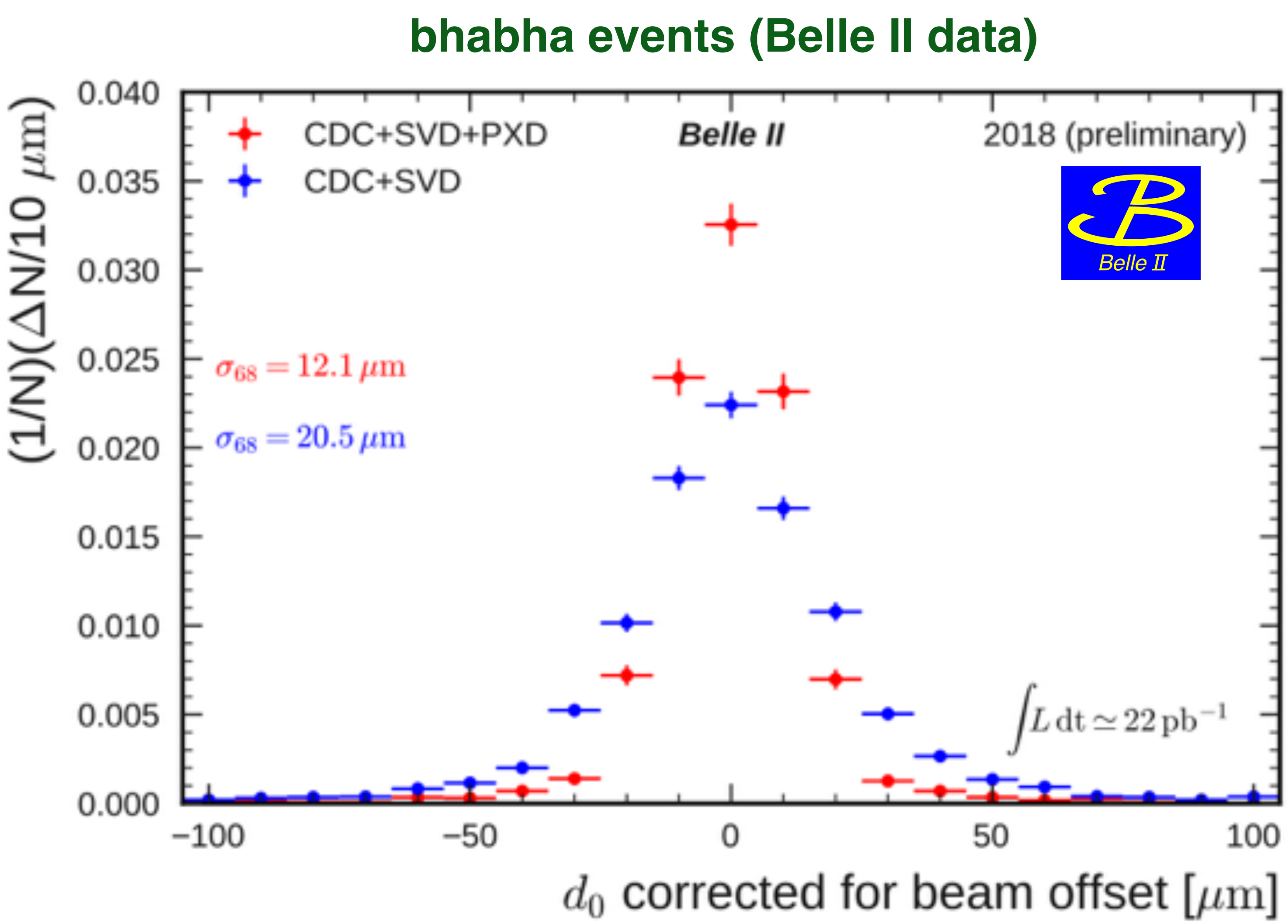
Phase 2 highlights: impact parameter resolution



- Resolution of the transverse impact parameter (d_0)
- Belle II MC events with a single muon tracks compared with results of Belle cosmic events

Phase 2 highlights: impact parameter resolution





- Resolution of the transverse impact parameter (d_0) using bhabha events
  - measured12.1 μm, expected ~10 μm
  - PXD is crucial

Contents

QUARKONIA:

legacy of 1st generation

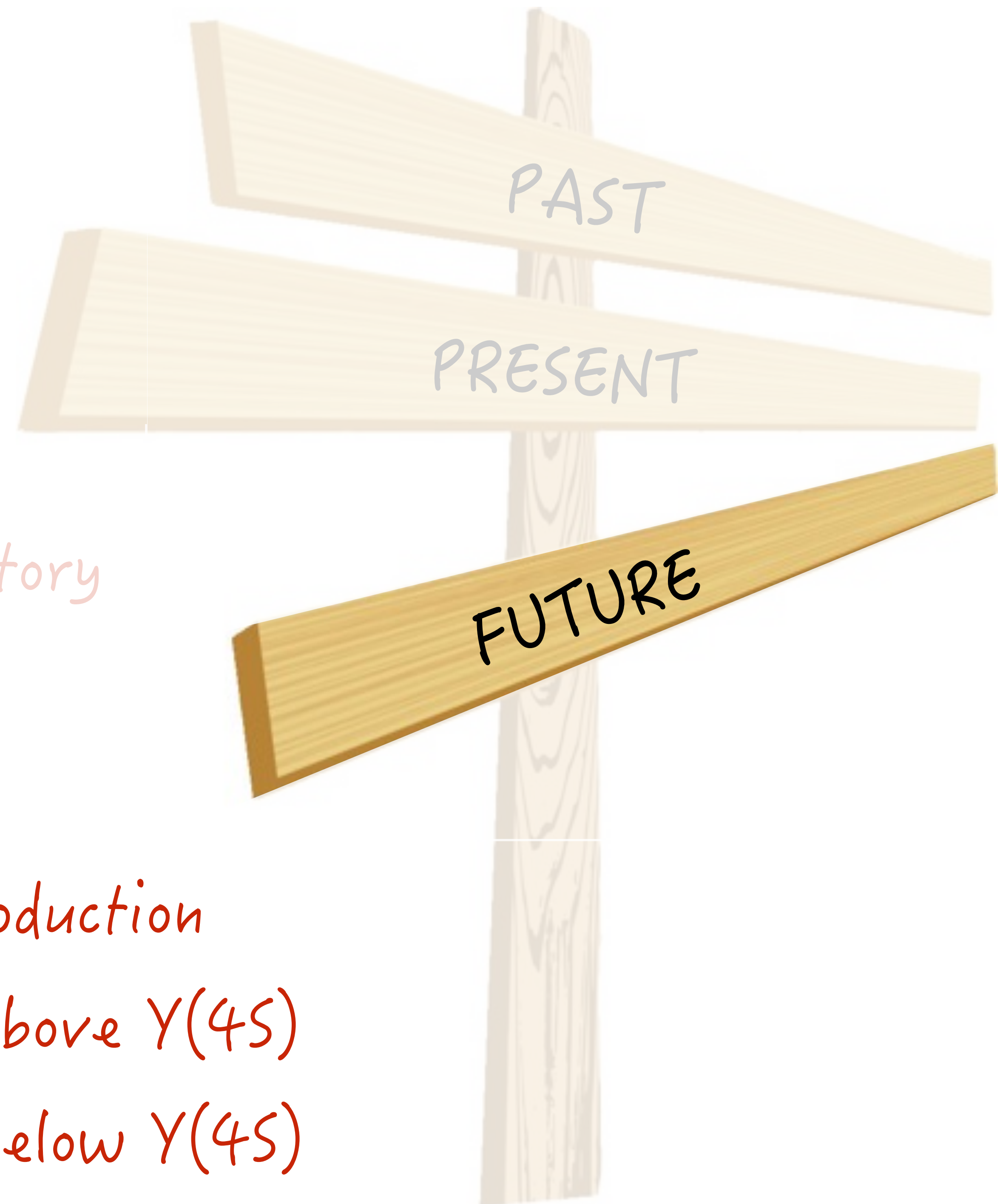
B-Factories

BELLE II:

the next generation B-Factory

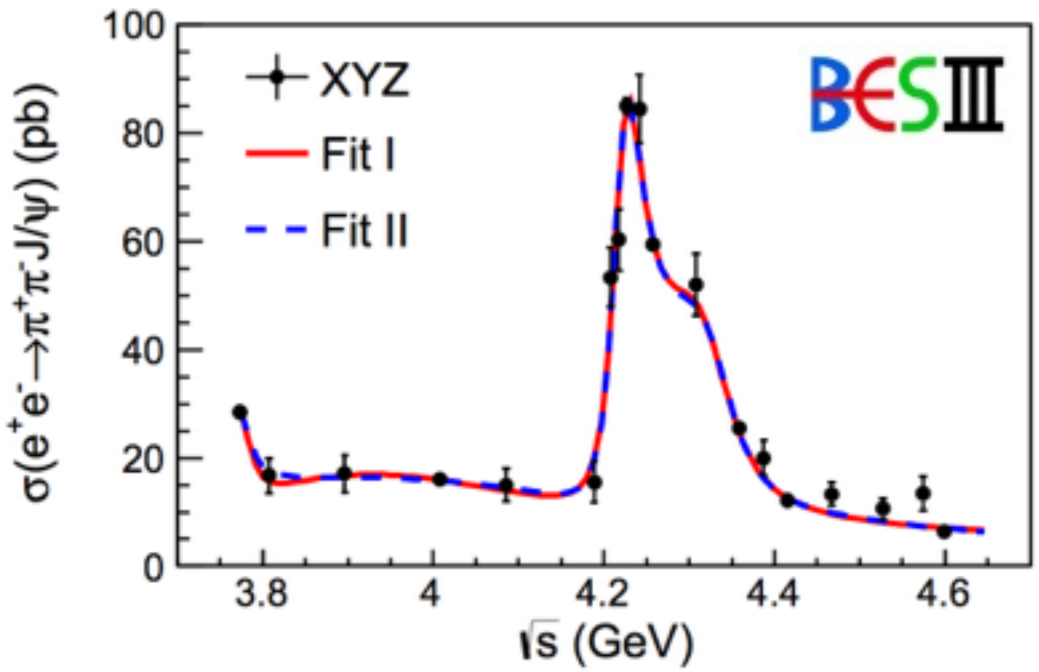
FUTURE PROSPECTS:

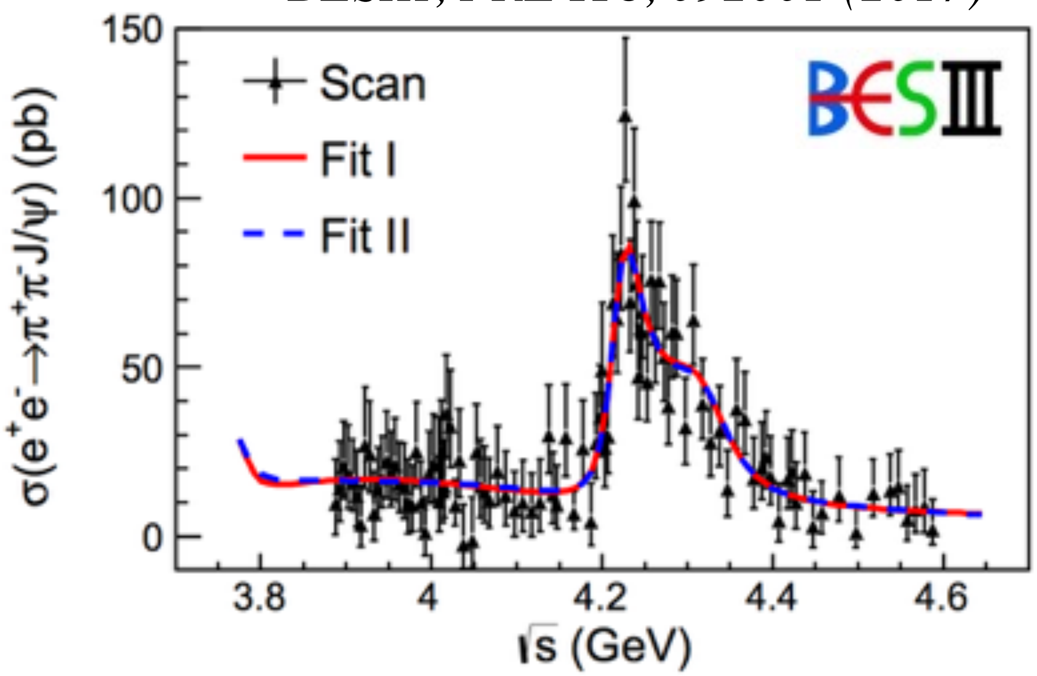
- Charmonium(-like) production
- Bottomonium(-like): above Υ(4S)
- Bottomonium(-like): below Υ(4S)



- Competition from BESIII

BESIII, PRL 118, 092001 (2017)

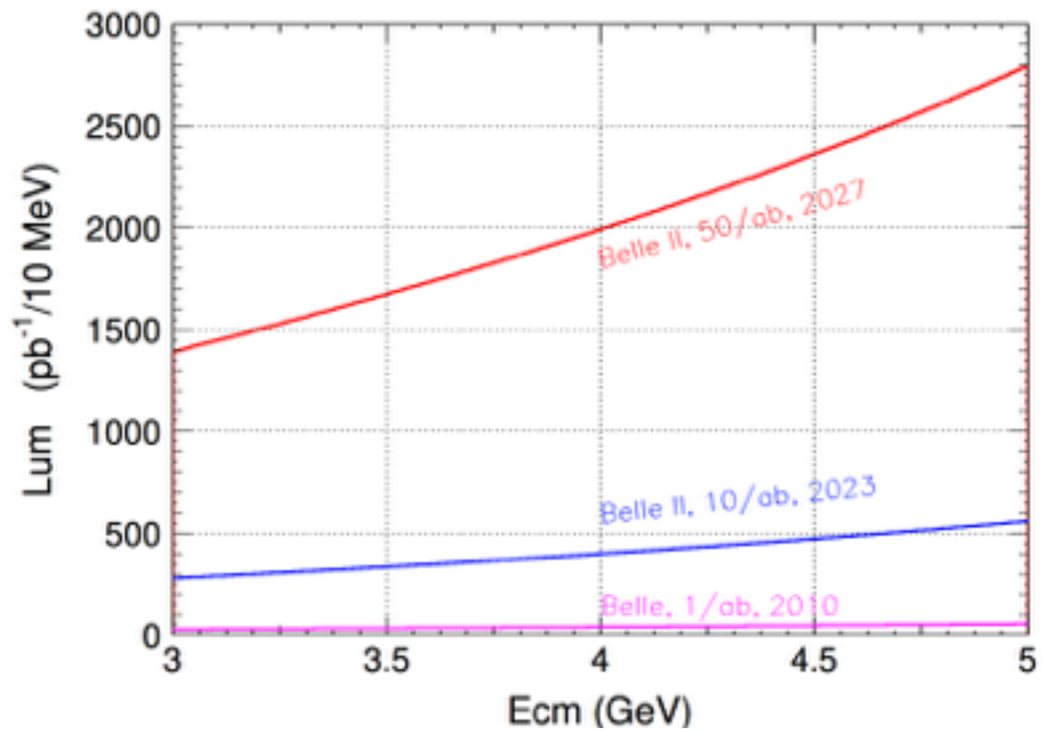




- Recent BESIII scan data show a complex landscape: scan of all decay channels is needed!

➡ **Belle II**

- Higher effective luminosity
- Wider mass range



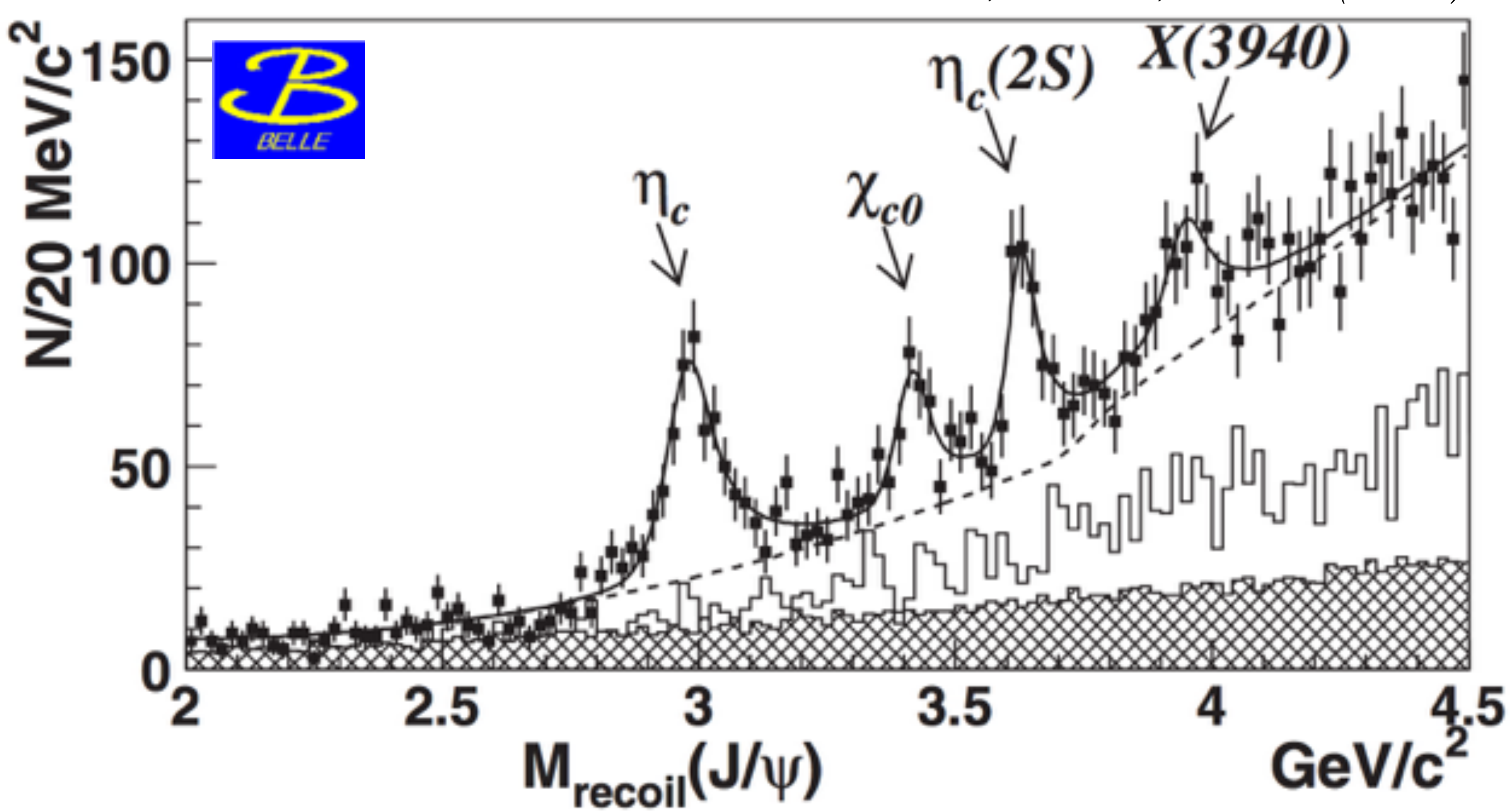
Charmonia: double charmonium production

only at Belle II

- Observed in combinations of J=1 and J=0

  $e^+e^- \to c\bar{c}\ (0+/-)\ c\bar{c}\ (1-/+)$

Belle, PRL 98, 082001 (2005)



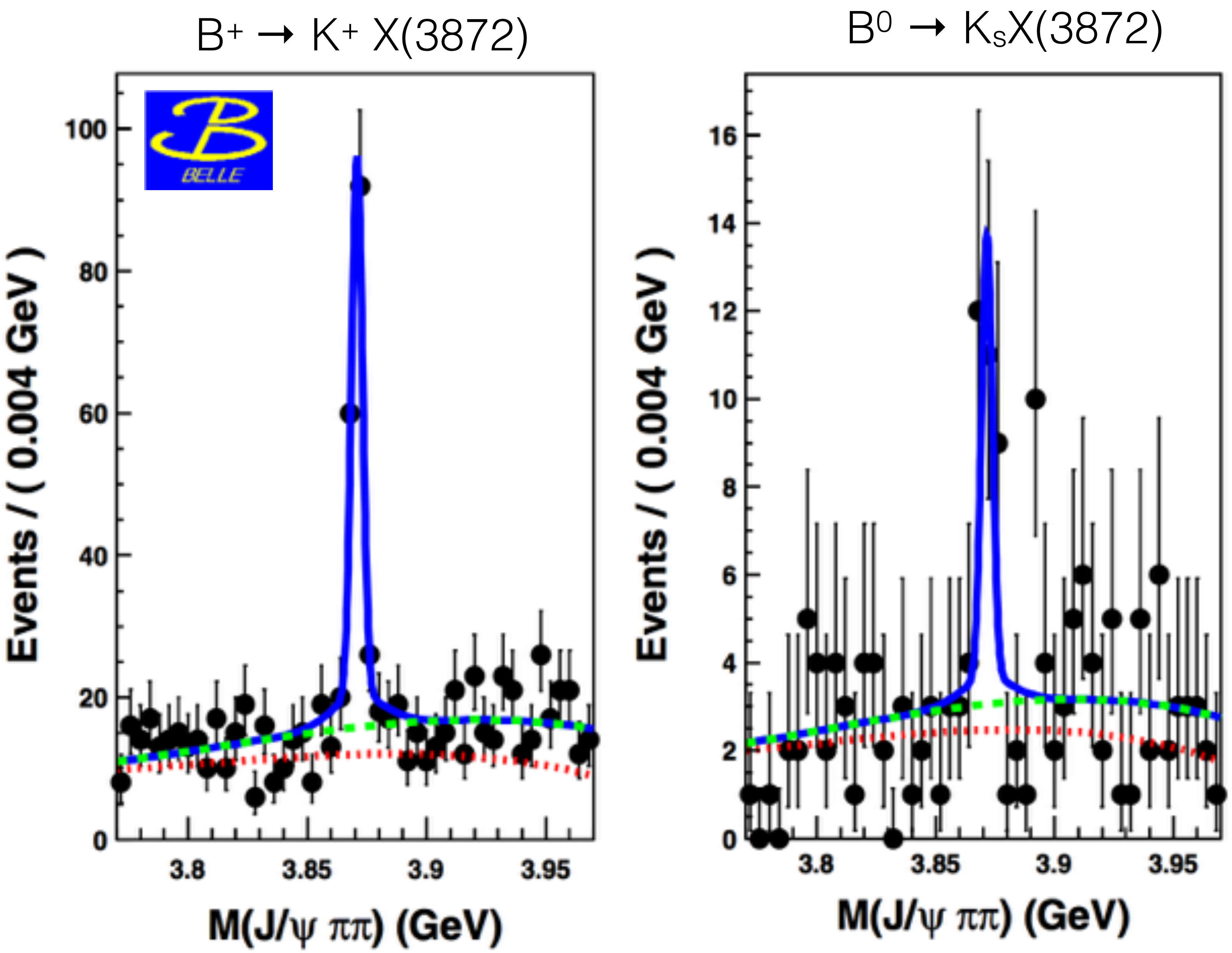
➡ **Belle II**

- angular distributions, production
- probe for new states

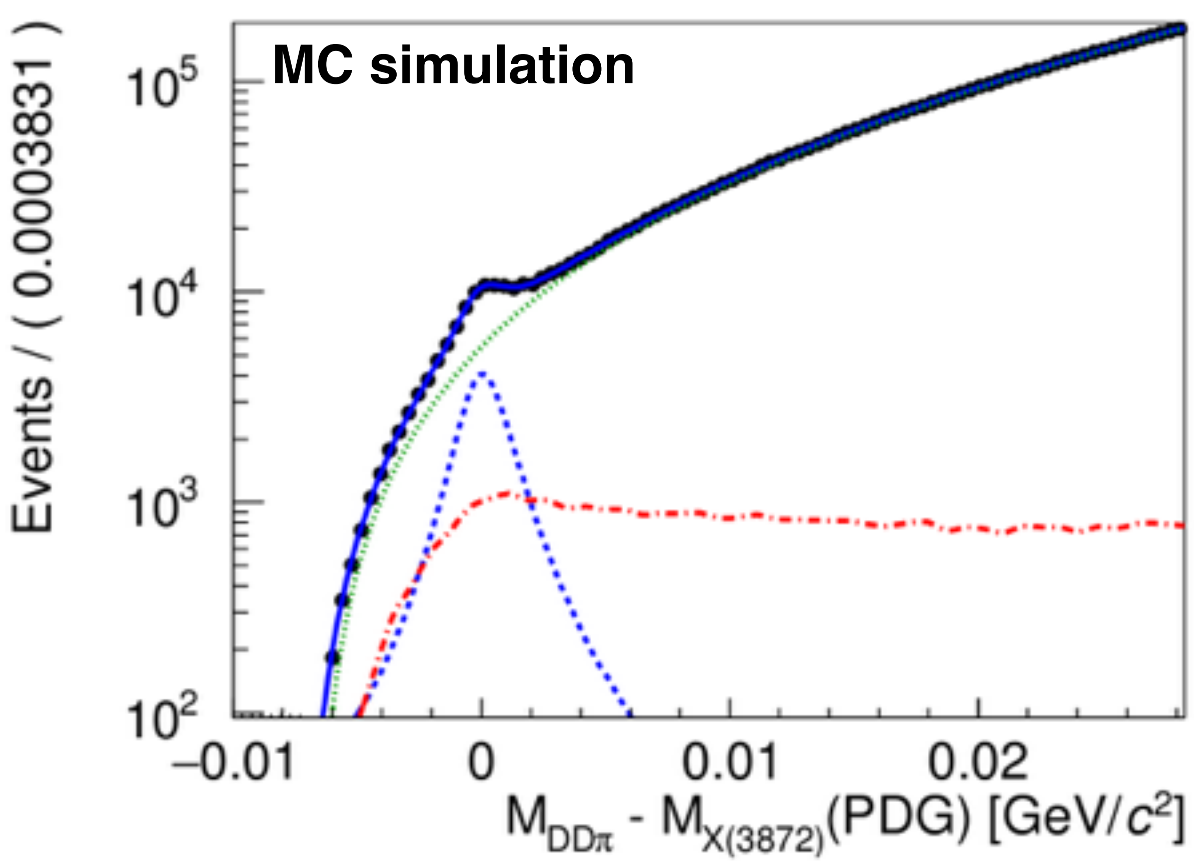
Charmonia: X(3872) width

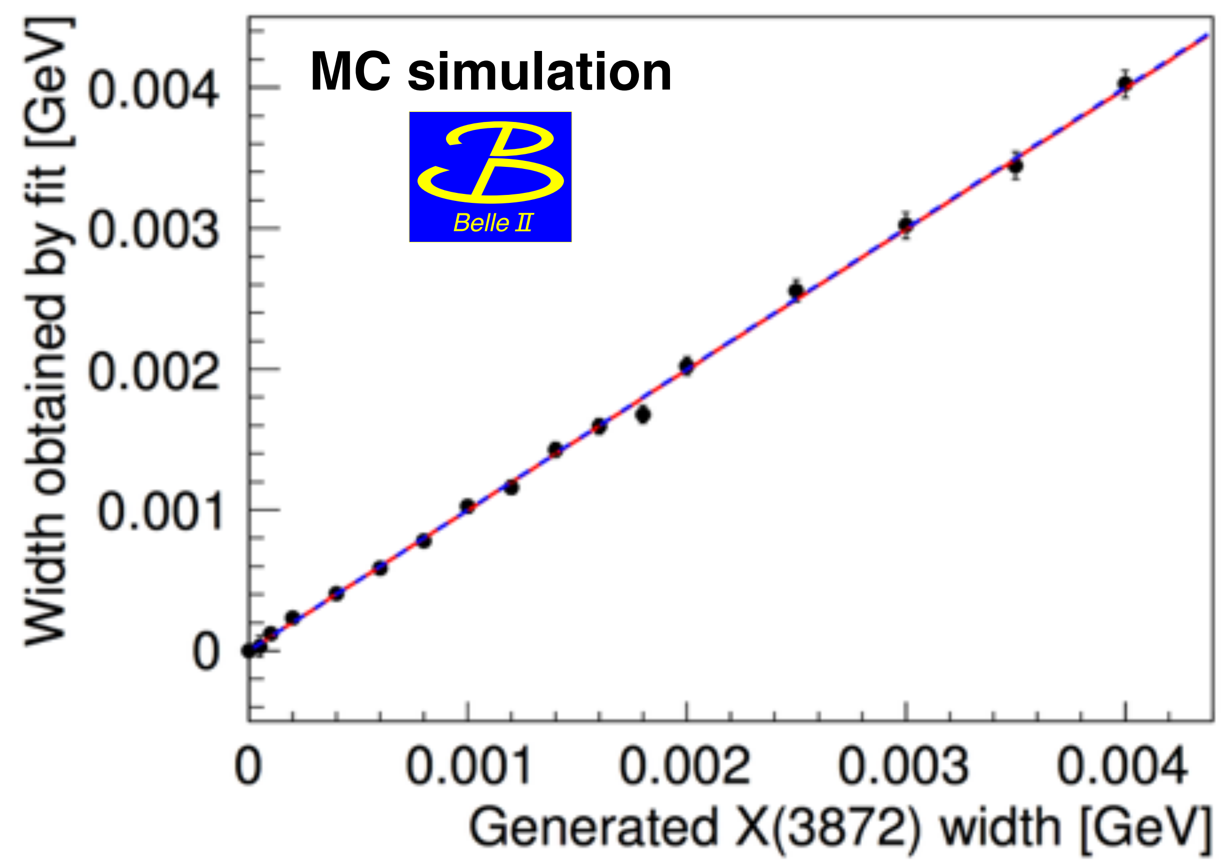
- The current upper limit on the width of the X(3872) width is the 90% C.L. of $\Gamma_{X(3872)} < 1.2$ MeV, obtained using the mode $B \to J/\psi\, \pi^+\pi^- K$

Belle, PRD 84, 052004 (2011)



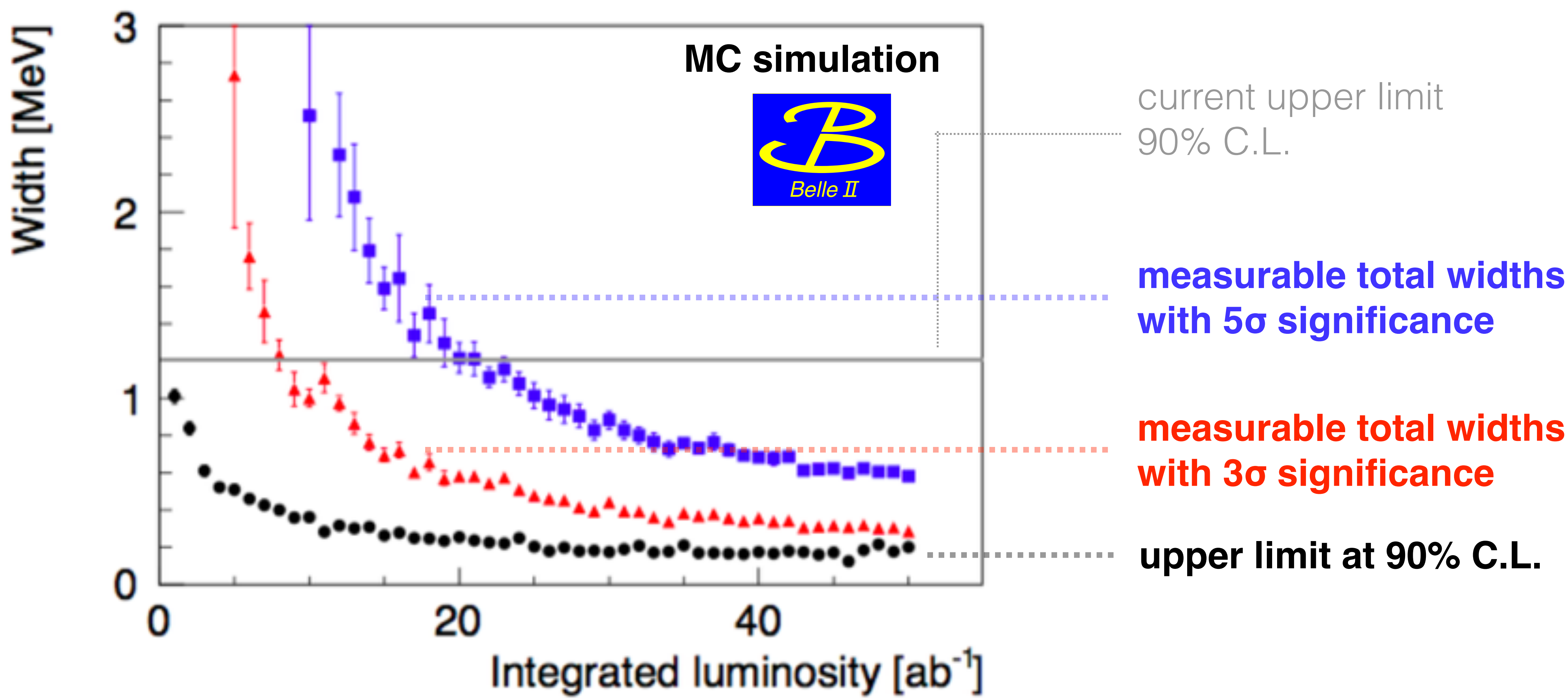
- A way to improve the sensitivity of the X(3872) total width is to improve the mass resolution
- $B \to D^0 D^0 \pi^0$ good mode to improve the mass resolution
- The sensitivity has been estimated on MC (H. Hirata, master thesis, 2019)





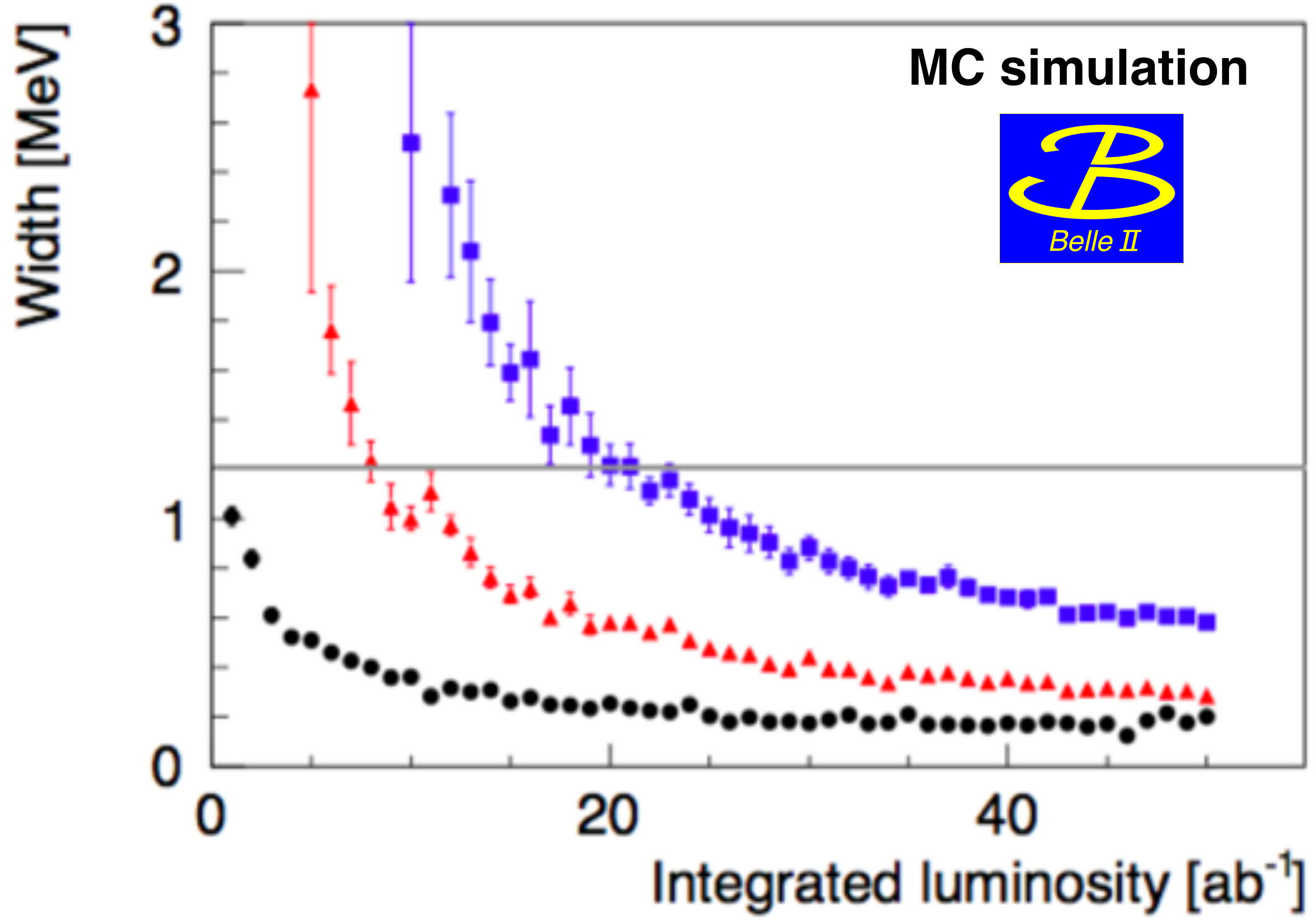
Charmonia: X(3872) width

- A way to improve the sensitivity of the X(3872) total width is to improve the mass resolution
- $B \to D^0 D^0 \pi^0$ good mode to improve the mass resolution
- The sensitivity has been estimated on MC (H. Hirata, master thesis, 2019)



Charmonia: X(3872) width

- A way to improve the sensitivity of the X(3872) total width is to improve the mass resolution
- B → $D^0 D^0 \pi^0$ good mode to improve the mass resolution
- The sensitivity has been estimated on MC (H. Hirata, master thesis, 2019)



- With the full Belle II data sample (50 ab-1):

90% C.L.: ~ 180 KeV

3s significance: ~280 KeV

5s significance: ~570 KeV

Bottomonia: motivation for non-Y(4S) running

➡ **above Y(4S):**

- conventional state search
- exotica discovery
- precision Z_b mass measurement

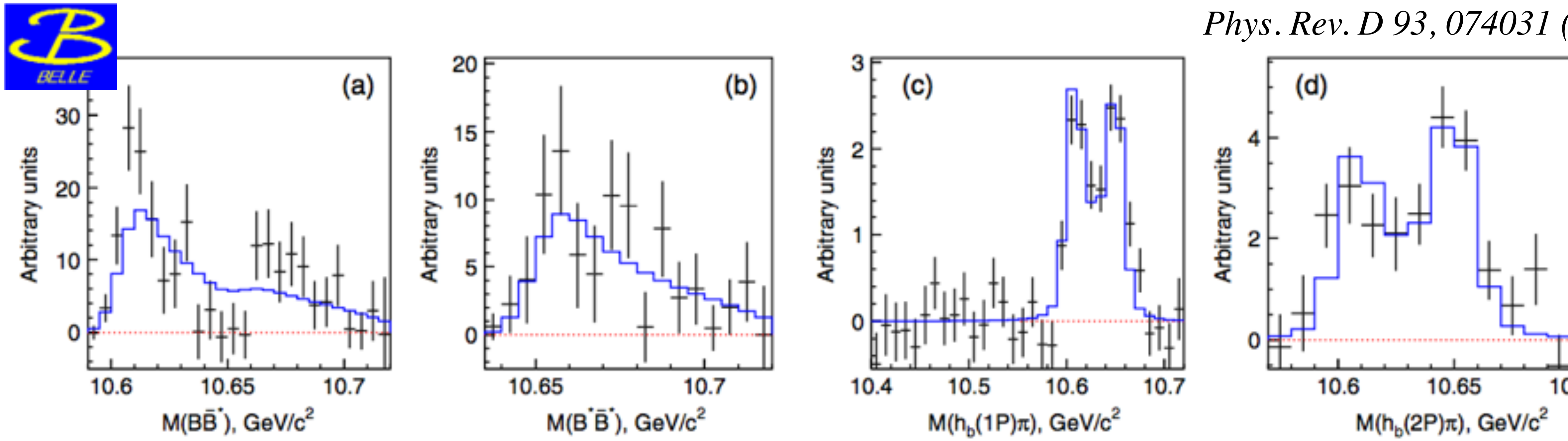
- 1 ab^{-1} @Y(5S): also B_s physics
- 100 fb^{-1}@Y(6S) + ~400 fb^{-1} scan

Current samples in fb^{-1} (millions of events)

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			**300(1200)**	**$5x10^4(5.4x10^4)$**	**1000(300)**	**100+400(scan)**	**3.6%**

- open question: are Z_b masses below or above $B^{(*)}B^*$ thresholds?
- fundamental question to understand their nature

Phys. Rev. D 93, 074031 (2016)



➡ **Belle II**

- 1 ab^{-1} @ Υ(5S): determine if they are located above or below the open threshold

estimate of the Z_b location with respect to the thresholds:

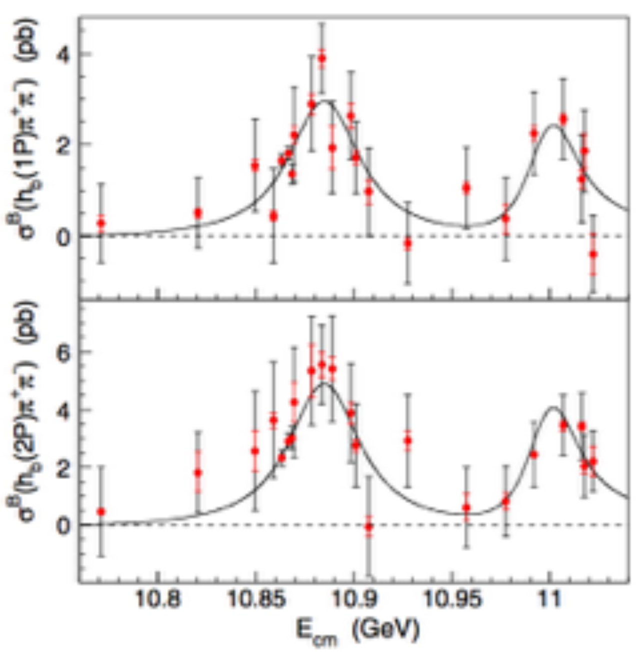
$$\epsilon_B(Z_b) = (0.60^{+1.40}_{-0.49} \pm i0.02^{+0.02}_{-0.01})\ \text{MeV},$$
$$\epsilon_B(Z_b') = (0.97^{+1.42}_{-0.68} \pm i0.84^{+0.22}_{-0.34})\ \text{MeV},$$

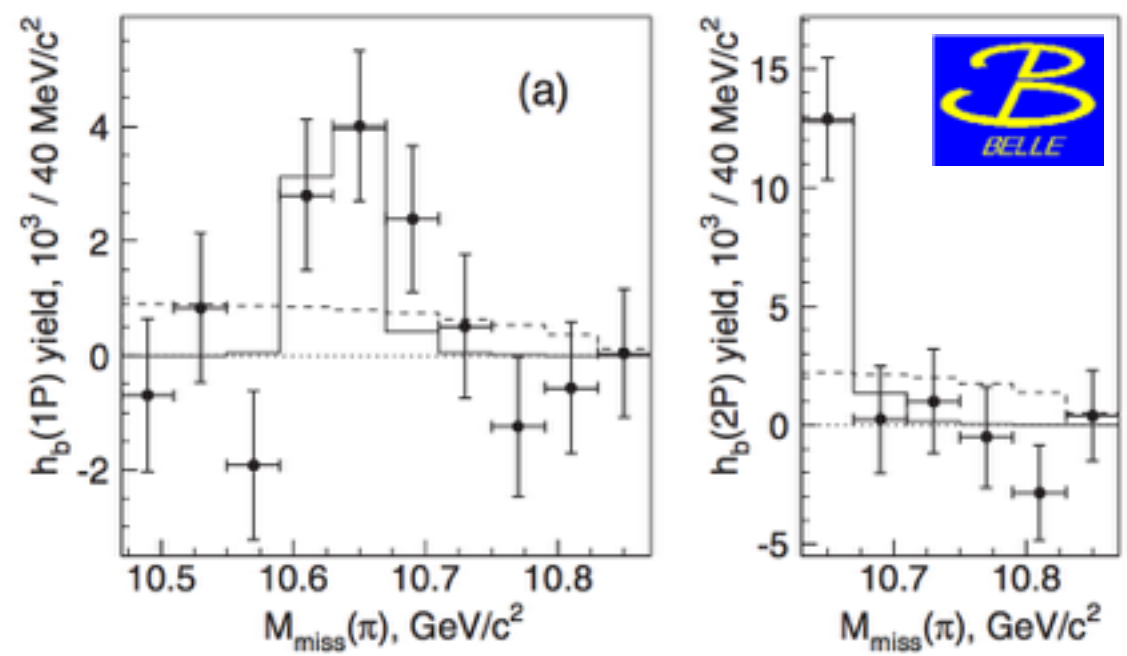
$$\epsilon_B(Z_b) \equiv M(B\bar{B}^*) - M(Z_b),$$
$$\epsilon_B(Z_b') \equiv M(B^*\bar{B}^*) - M(Z_b'),$$

High energy scans: resolve new states ($Z_b^{\pm}$)

PRL 117, 142001 (2016)

- Belle energy scan, search for $\Upsilon(6S) \rightarrow \pi^+ \pi^- h_b(1P,2P)$ decay
- observation of $Z_b(106XX)$ state, but unable to resolve them





➡ **Belle II**

- Understand $\Upsilon(6S) \rightarrow Z_b$ decay
  - $\Upsilon(6S) \rightarrow \pi^+ \pi^- h_b(1P,2P)$
  - $\Upsilon(6S) \rightarrow \pi^+ \pi^- \Upsilon(1S,2S,3S)$

Bottomonia: motivation for non-Y(4S) running

➡ **below Y(4S):**

- bottomonium studies/searches
- new physics in decays (DM / light Higgs)
- anti nucleon production (possible DM application)
- baryon physics

- 300 fb^{-1} @Y(3S): order of magnitude increase

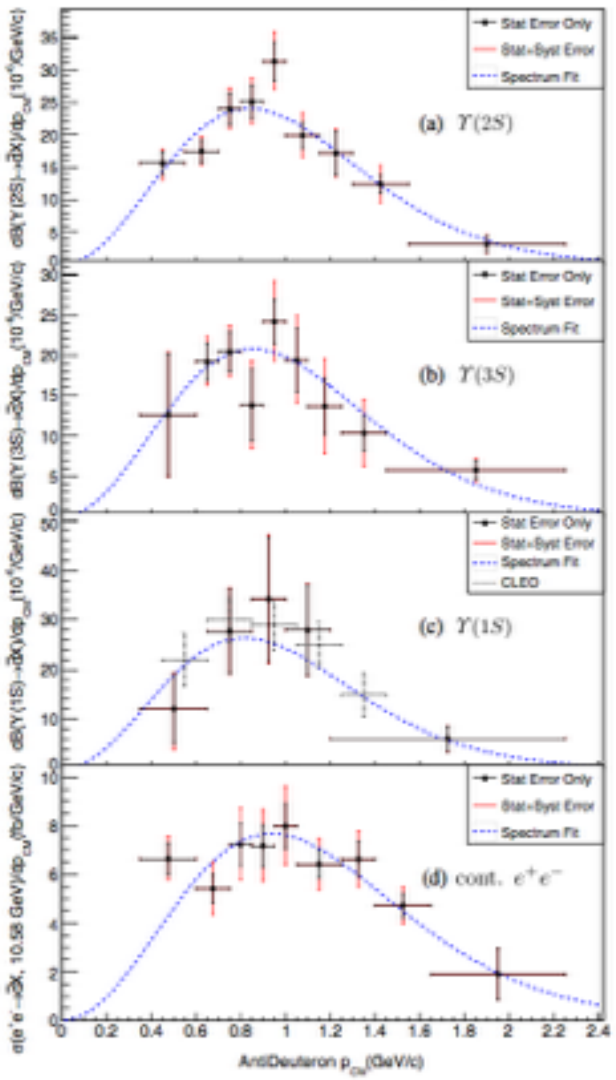
Current samples in fb^{-1} (millions of events)

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			**300(1200)**	**$5\times10^4(5.4\times10^4)$**	**1000(300)**	**100+400(scan)**	**3.6%**

$\Upsilon(3S)$ runs: (Anti)deuteron

PRD 62, 043003 (2000)

Phys. Rev. D89 (2014) no.11, 111102



Process	Rate
$\mathcal{B}(\Upsilon(3S) \to \bar{d}X)$	$(2.33 \pm 0.15^{+0.31}_{-0.28}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(2S) \to \bar{d}X)$	$(2.64 \pm 0.11^{+0.26}_{-0.21}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(1S) \to \bar{d}X)$	$(2.81 \pm 0.49^{+0.20}_{-0.24}) \times 10^{-5}$
$\sigma(e^+e^- \to \bar{d}X)$ [$\sqrt{s} \approx 10.58$ GeV]	$(9.63 \pm 0.41^{+1.17}_{-1.01})$ fb
$\frac{\sigma(e^+e^- \to \bar{d}X)}{\sigma(e^+e^- \to \text{Hadrons})}$	$(3.01 \pm 0.13^{+0.37}_{-0.31}) \times 10^{-6}$

- $\bar{d}$ in cosmic rays have long been considered a probe for supersymmetric relics in the galactic halo
- $\bar{d}$ production described with coalescence models tuned on HEP data
- need to further constrain in the production model

➡ CLEO and Babar measured the $\bar{d}$ spectrum (no dedicated PID or tracking)

➡ **Belle II:**

- dedicated tracking and PID
- collect ~3x10^4 $\bar{d}$ in 300 fb^{-1}
- world's best estimate of coalescence parameter
- search for excited nucleons (d*)
- d$\bar{d}$ associated production

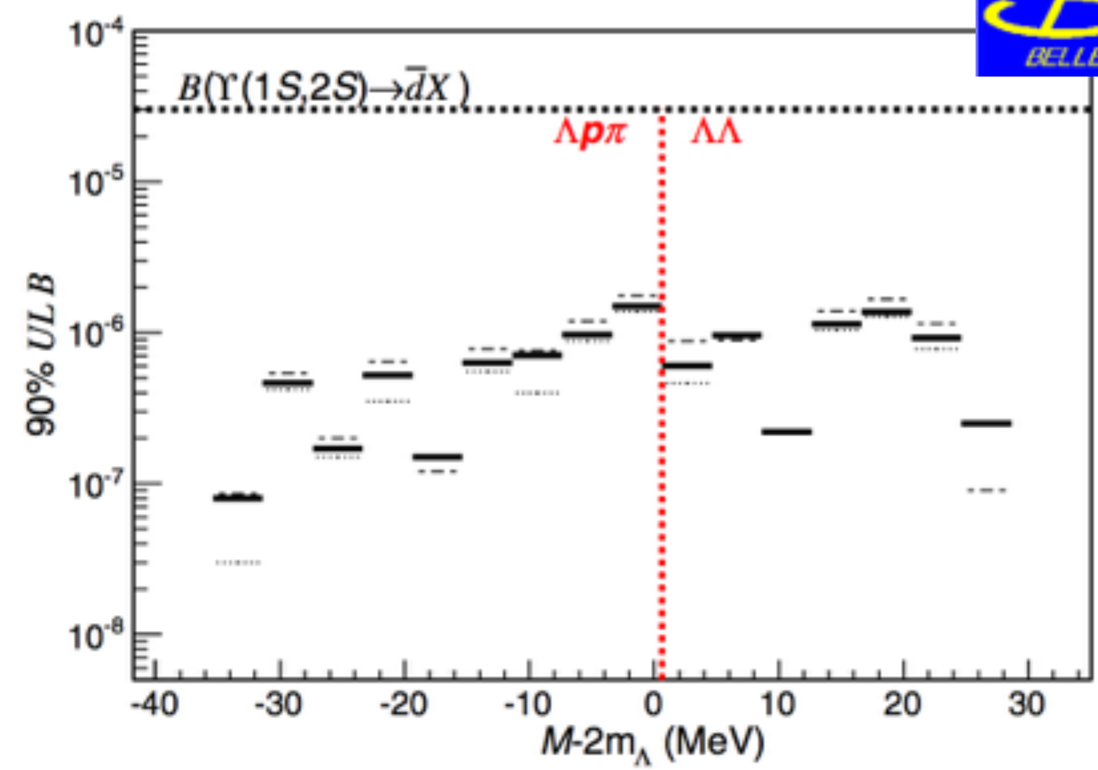
Υ(3S) runs: Λ-Λ interaction

➡ From Belle:

- No sign of weakly bound H dibaryon

- Near threshold enhancement in exclusive annihilations
  Υ(1S,2S) → Λ $\bar{\Lambda}$ X (still not published)

Phys. Rev. Lett. 110, 222002



➡ **Belle II**

- search for H dibaryon in missing mass (Υ(3S) → Λ $\bar{\Lambda}$ H + hadrons)
- high statistics study near threshold

Rough extrapolation to 300 fb^{-1} Υ(3S)
~60 Million events with one Λ or $\bar{\Lambda}$
~3 Million events with one Λ $\bar{\Lambda}$ pair

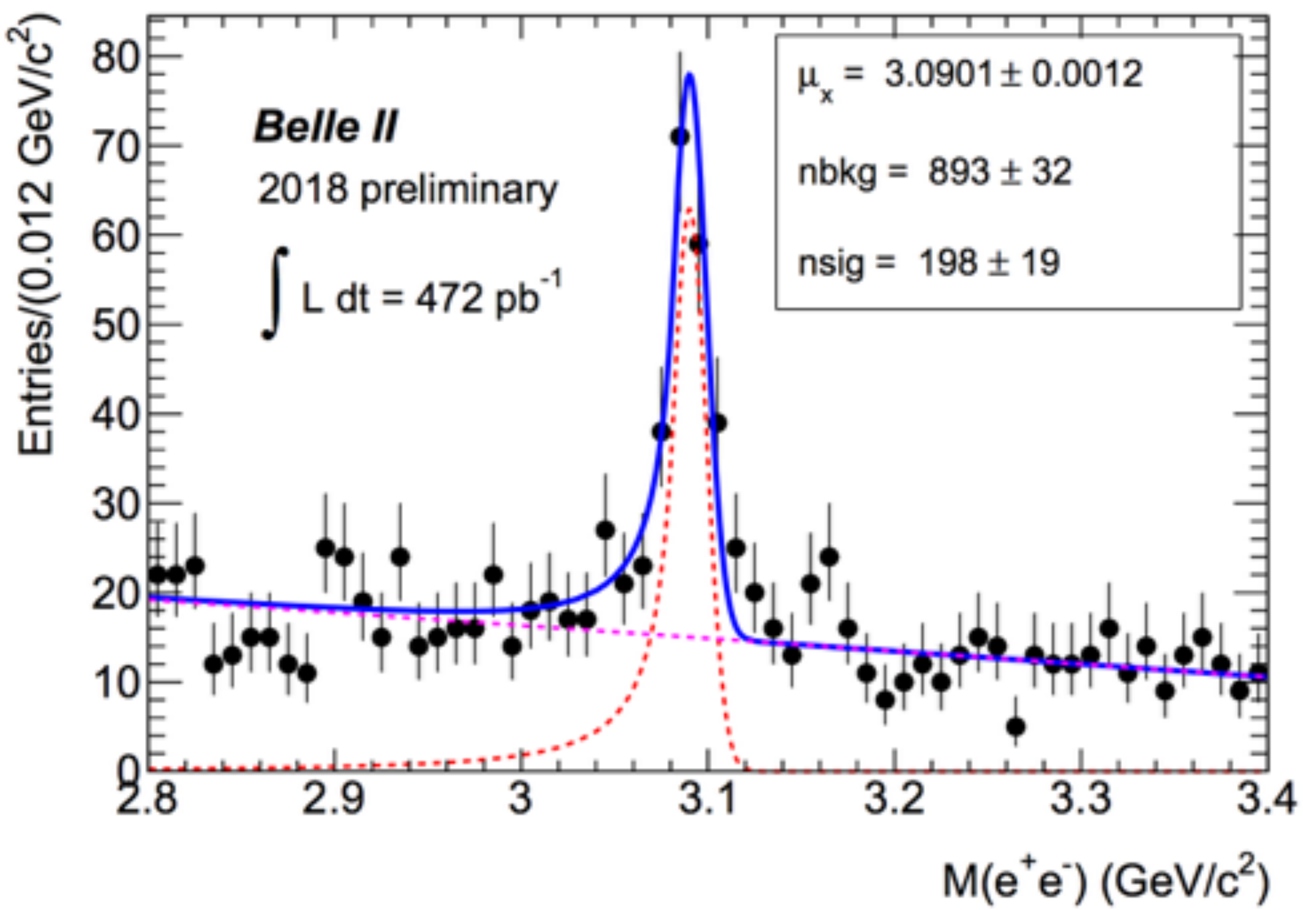
Summary

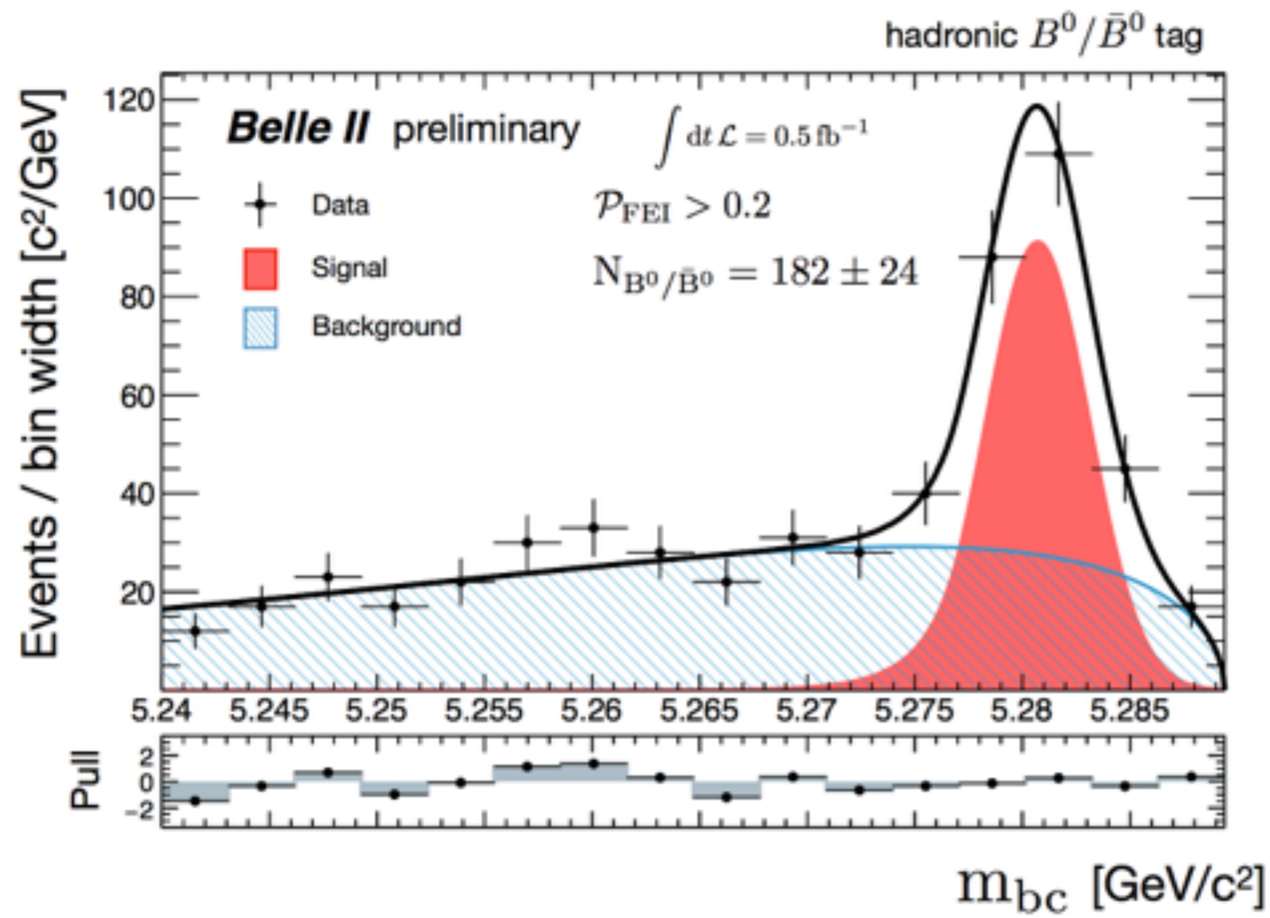
- We have entered the post B-factory era:
  - Variety of states in the quarkonium spectroscopy
  - Exotic states
- Belle II will collect 50 times more statistics than Belle, mainly but not only @ the Y(4S) resonance
- Belle II ended a successful Phase 2 commissioning run and just entered in the physics run era
- A variety of quarkonium studies will be possible, and among theme some unique topics:
  - charmonium: double charmonium
  - bottomonium: Belle II is in a unique position to address the open topics in this field

For further details about Belle II physics prospects

see the Belle II Physics Book

arXiv:1808.10567 [hep-ex]





BACKUP

KEKB VS SuperKEKB

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
beam energy	E_b	3.5	8	4	7	GeV
CM boost	$\beta\gamma$	0.425		0.28		
half crossing angle	φ	11		41.5		mrad
horizontal emittance	ε_x	18	24	3.2	4.6	nm
emittance ratio	κ	0.88	0.66	0.37	0.40	%
beta-function at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam parameter	ξ_y	129	90	0.0881	0.0807	
beam size at IP	σ_x^*/σ_y^*	100/2		10/0.059		μm
Luminosity	$\mathscr{L}$	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

Nano beam scheme

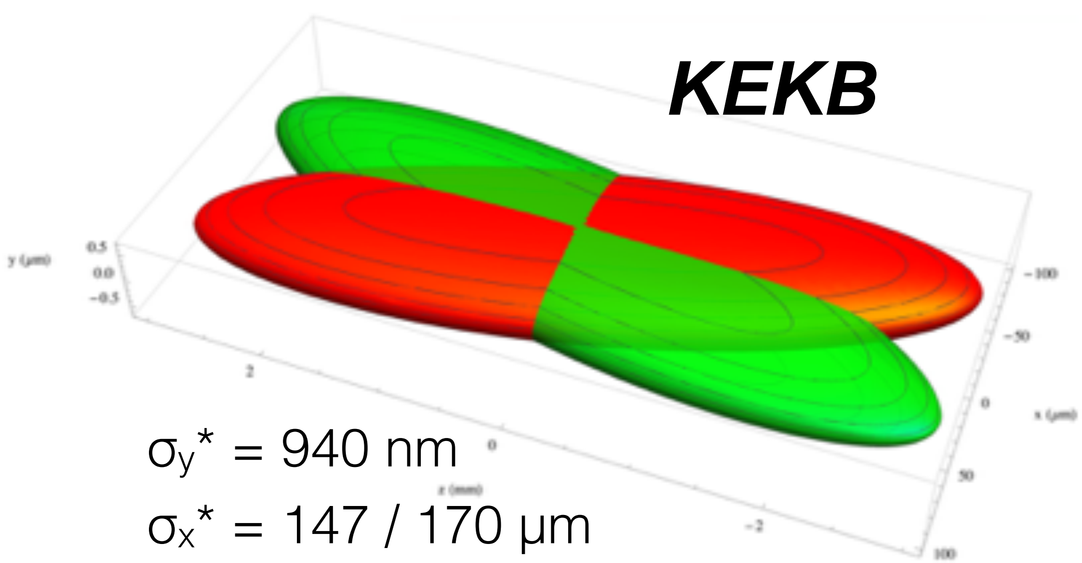
$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\cdot\xi_{y,e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Beam current

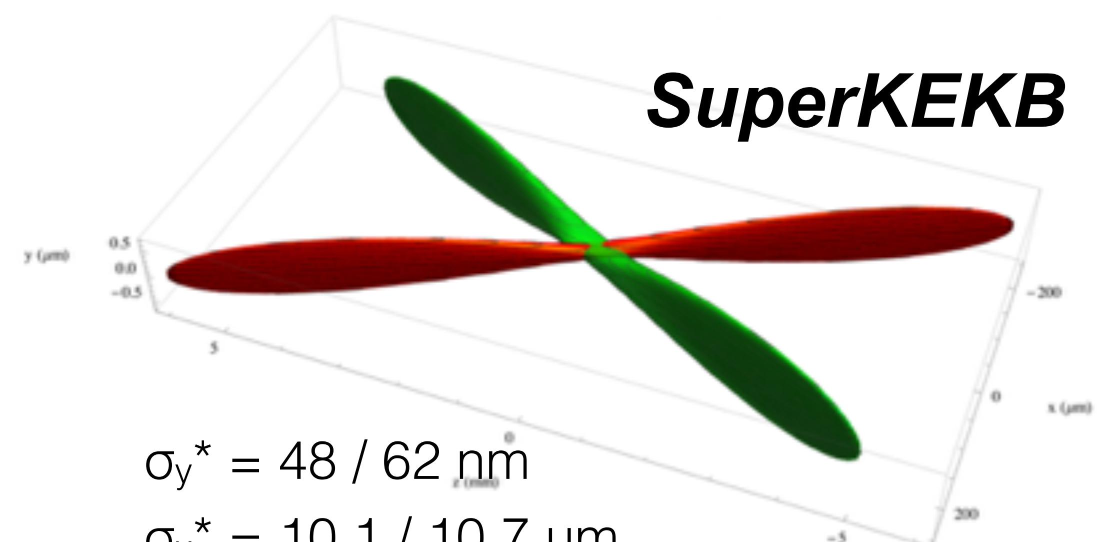
Beam aspect ratio

Beam-beam parameter

Vertical beta function @ IP

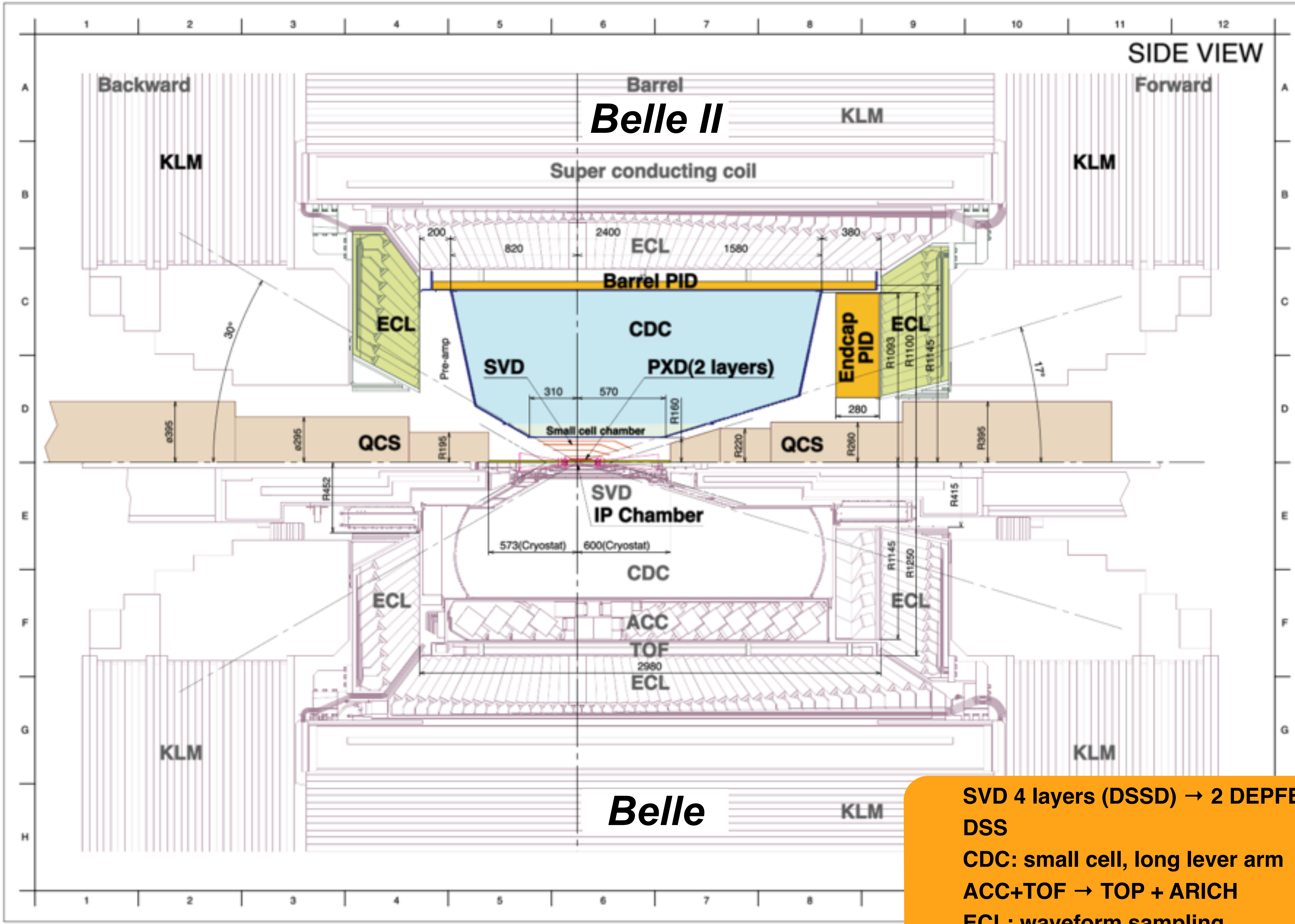


σ_y^* = 940 nm
σ_x^* = 147 / 170 µm
β_y^* = 5.9 mm



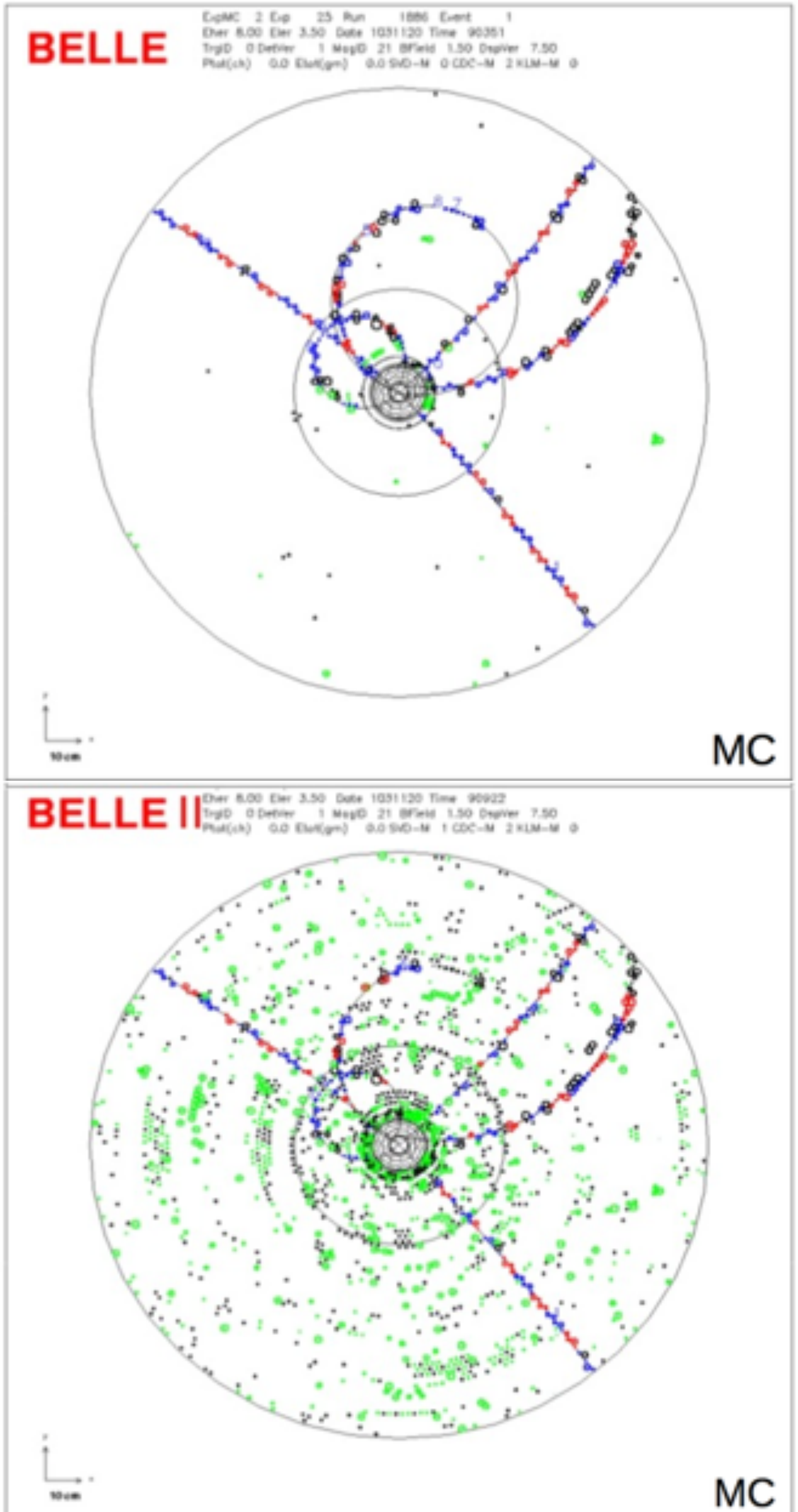
σ_y^* = 48 / 62 nm
σ_x^* = 10.1 / 10.7 µm
β_y^* = 0.27 / 0.3 mm

From Belle to Belle II



SVD 4 layers (DSSD) → 2 DEPFET + 4 DSSD
CDC: small cell, long lever arm
ACC+TOF → TOP + ARICH
ECL: waveform sampling
KLM: RPC → Scintillator+SiPM

New challenges

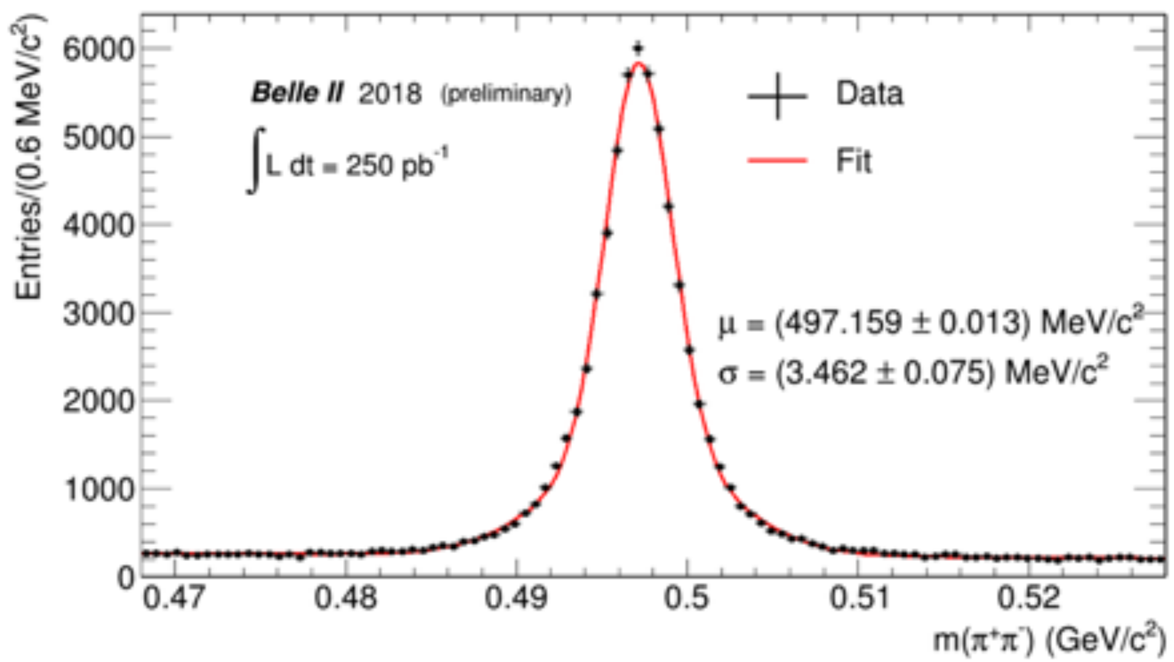


➡ x40 luminosity:

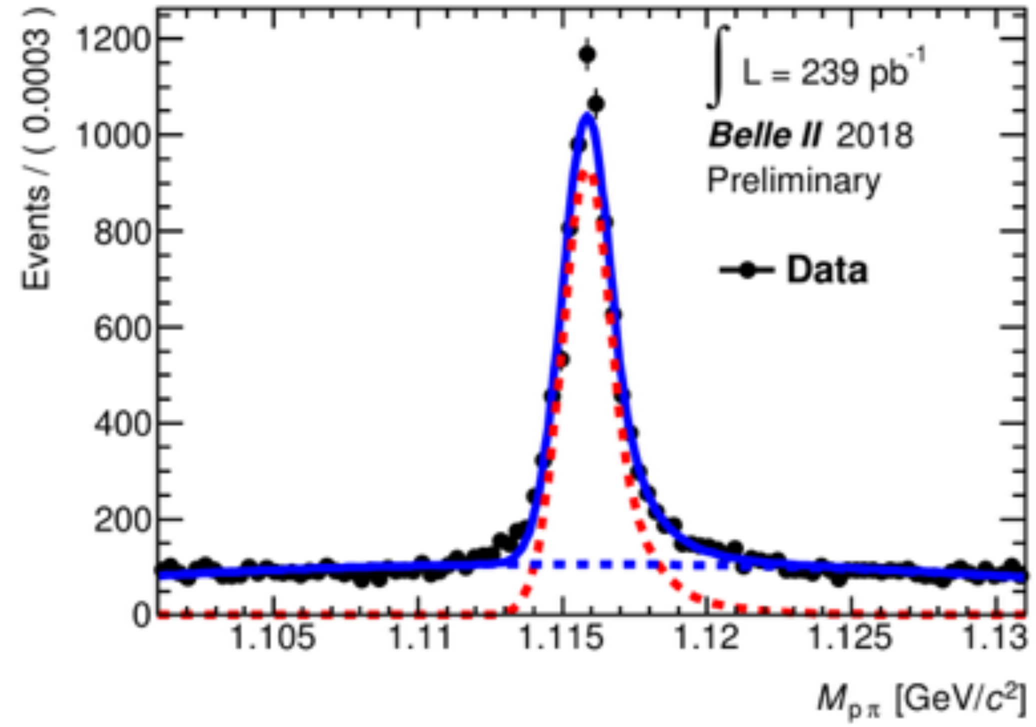
- x40 produced signal events
- Higher background (detector occupancy, fake hits, radiation damage)
- Higher event rate (trigger rate,DAQ, computing)

➡ Important to have a dedicated phase for background studies, detector response and alignment

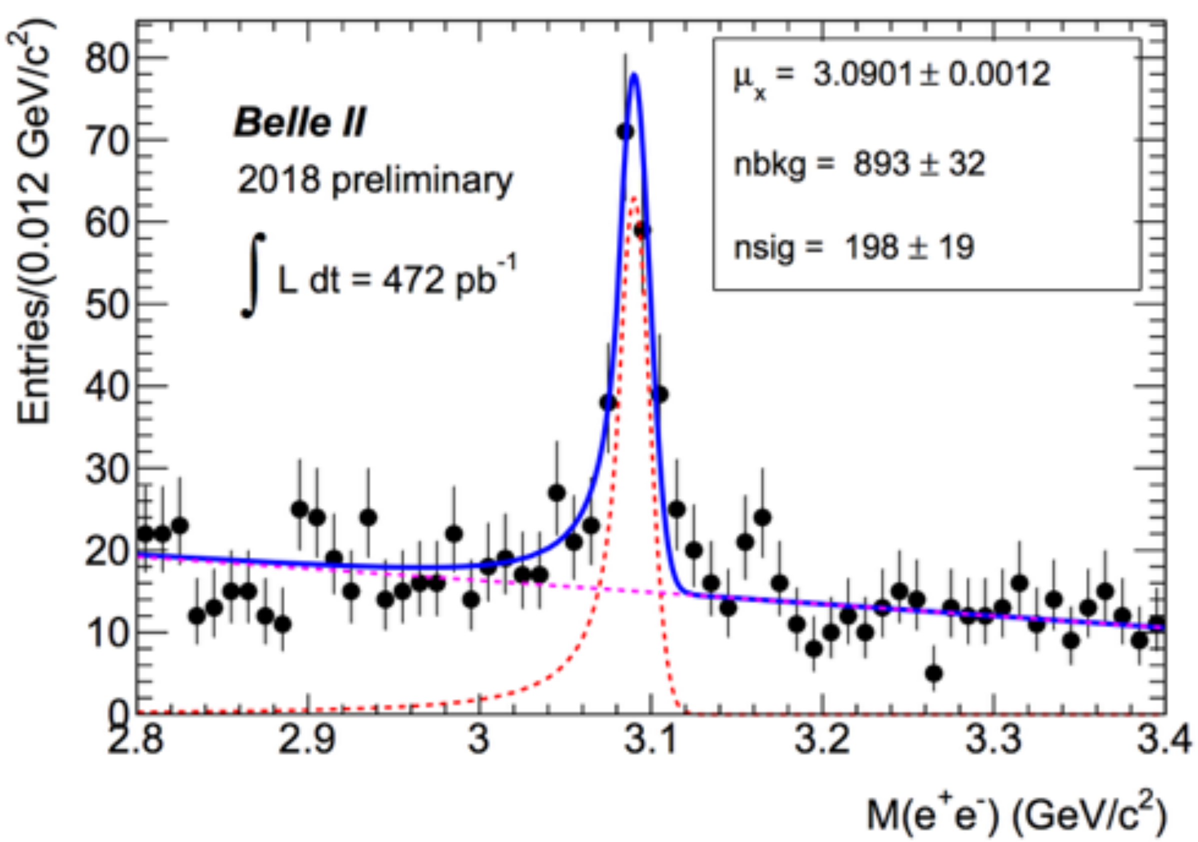
Tracking



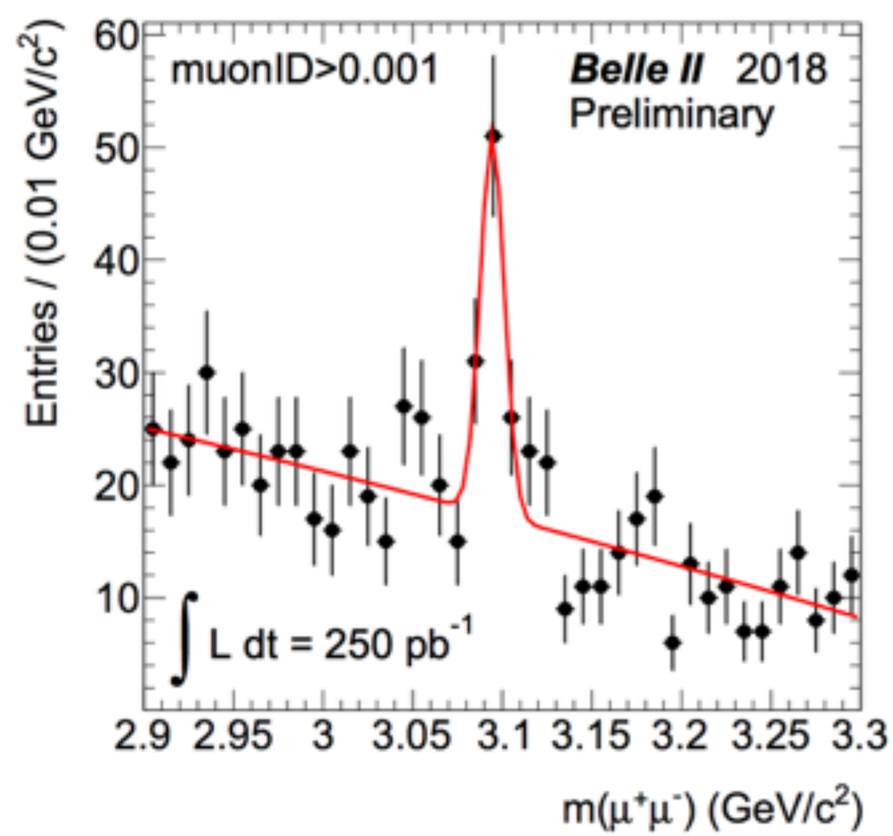
Belle II 2018 (preliminary)
∫L dt = 250 pb⁻¹
Data
Fit
μ = (497.159 ± 0.013) MeV/c²
σ = (3.462 ± 0.075) MeV/c²
Entries/(0.6 MeV/c²)
m(π⁺π⁻) (GeV/c²)



∫ L = 239 pb⁻¹
Belle II 2018
Preliminary
Data
Events / (0.0003)
M_pπ [GeV/c²]

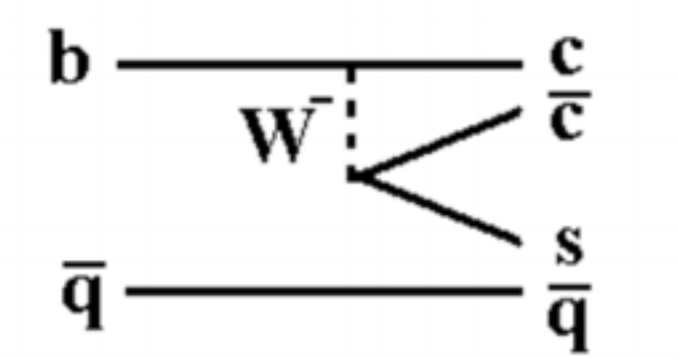


Belle II
2018 preliminary
∫ L dt = 472 pb⁻¹
μ_x = 3.0901 ± 0.0012
nbkg = 893 ± 32
nsig = 198 ± 19
Entries/(0.012 GeV/c²)
M(e⁺e⁻) (GeV/c²)

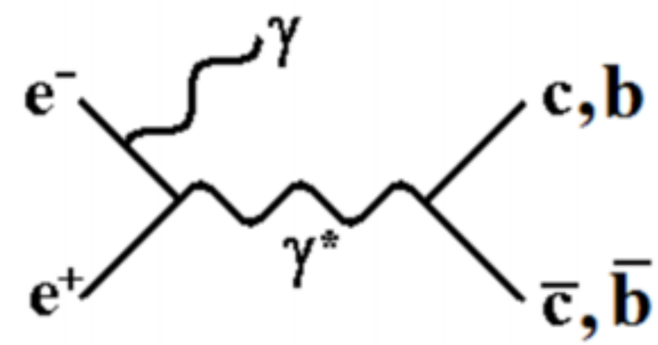


muonID>0.001
Belle II 2018
Preliminary
∫ L dt = 250 pb⁻¹
Entries / (0.01 GeV/c²)
m(μ⁺μ⁻) (GeV/c²)

B decays

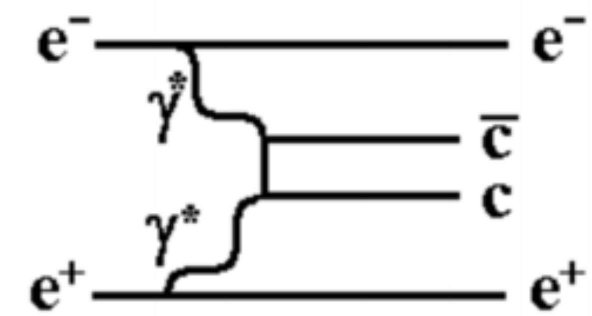


Initial State Radiation(ISR)



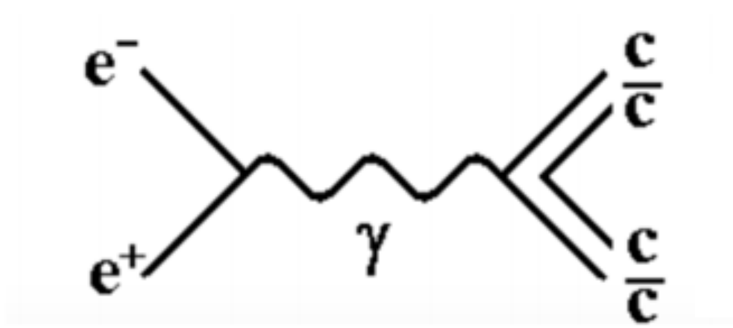
$J^{PC}=1^{--}$

Two γ interaction



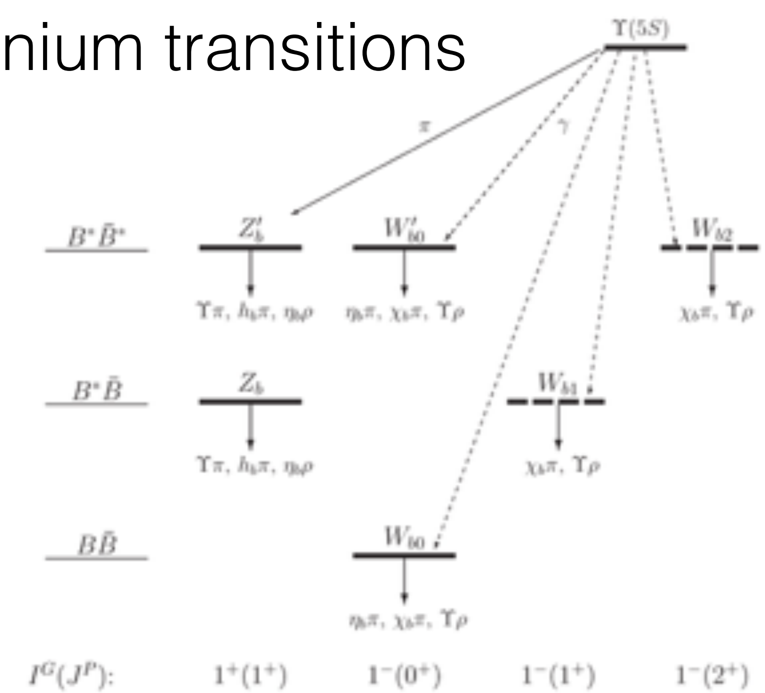
$J^{PC}=0^{-+}, 0^{++}, 2^{++}$

Double charmonium production

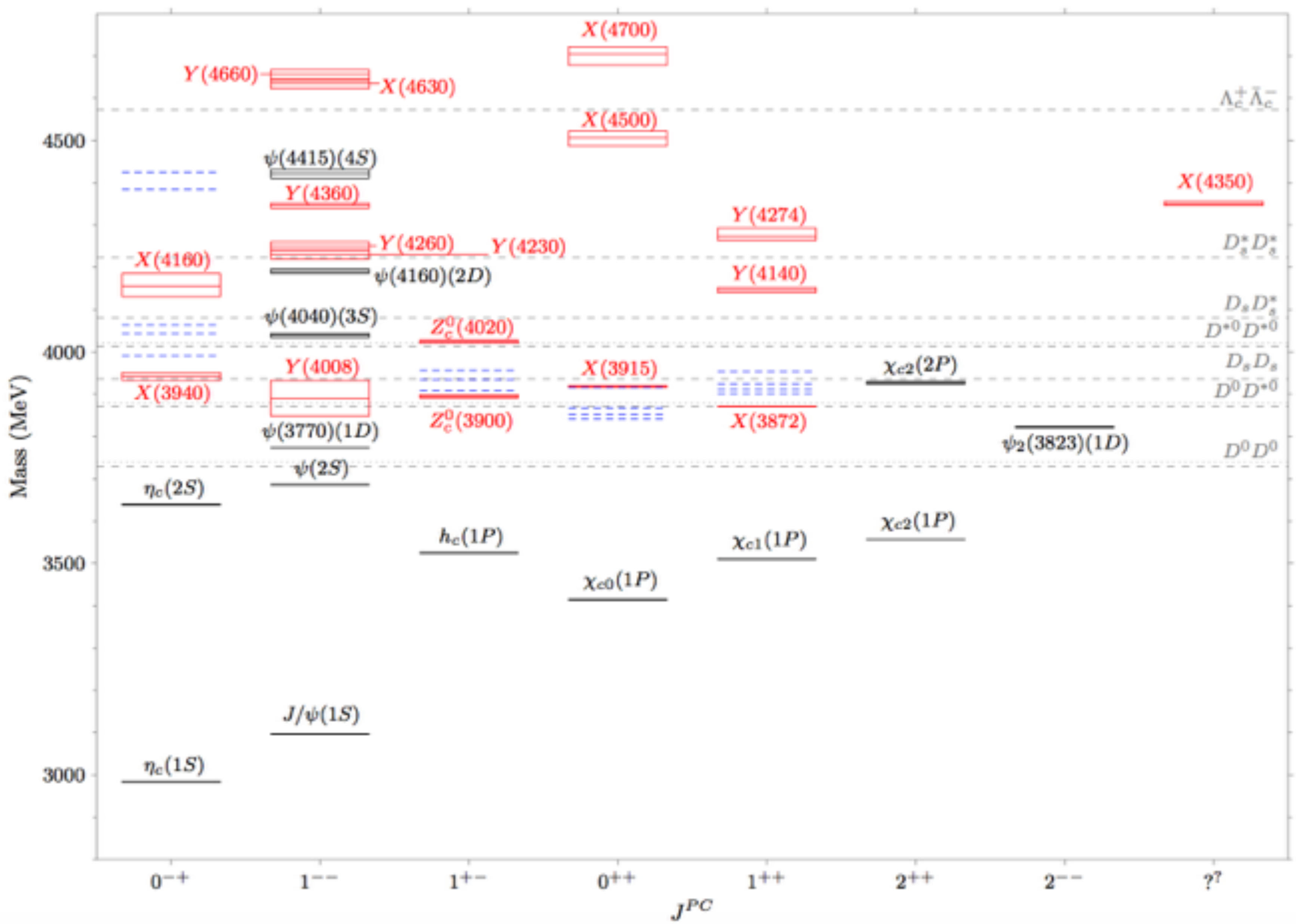


$J^{PC}=1^{--}$ (J/Ψ, $\Psi(2S)$) & J=0

Quarkonium transitions



Charmonia: overview



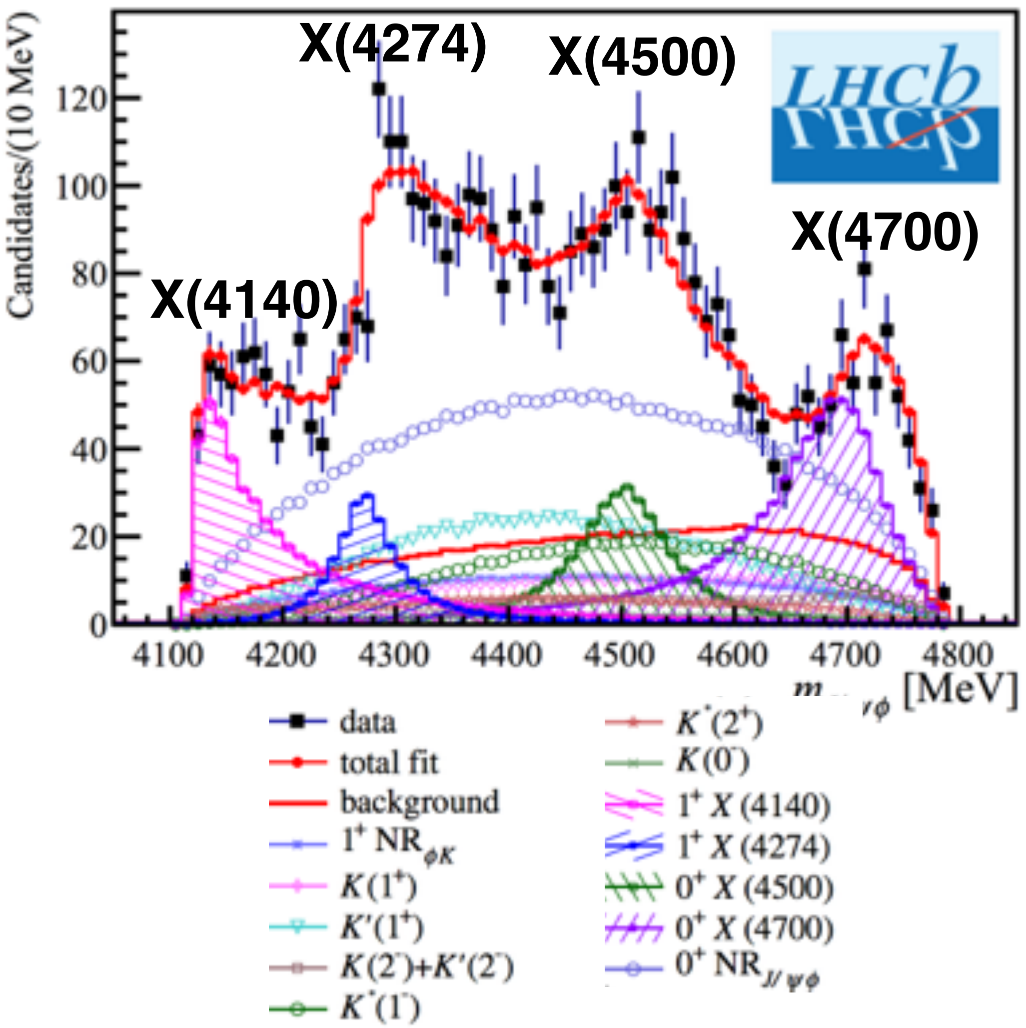
- Competition from LHCb (B decays) and BESIII (scans for 1^{--} states)
- Exploit different production methods

- Competition from LHCb

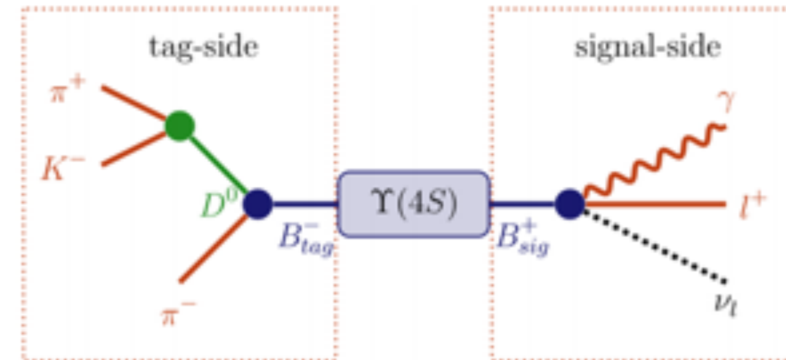
Phys. Rev. Lett. 118, 022003 (2017)

Phys. Rev. D 95, 012002 (2017)

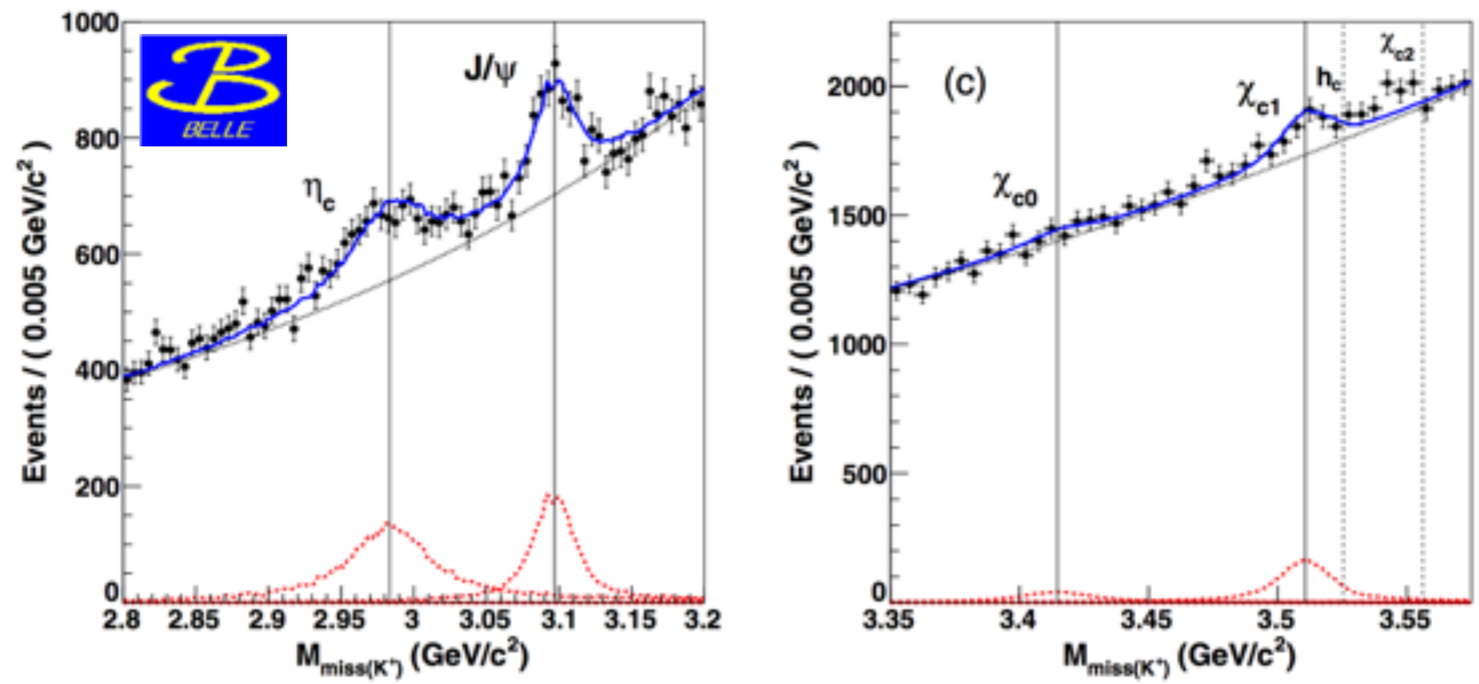
LHCb amplitude analysis of B ➔ J/ψ ϕ K



- e+e- B-factories only: ➡ **Belle II**



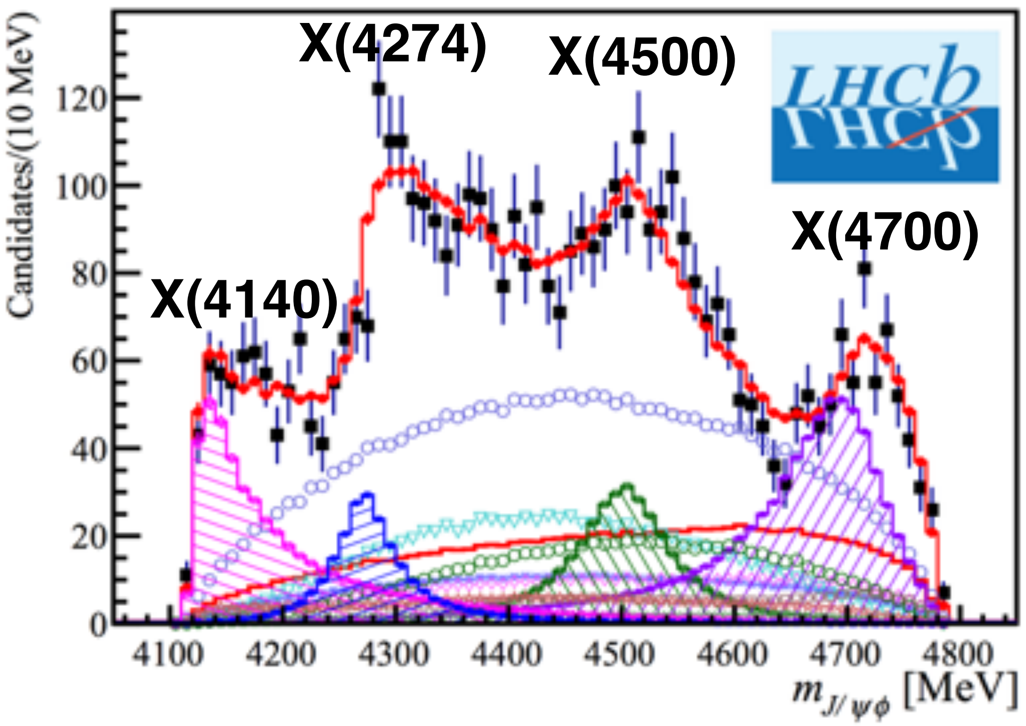
PRD 97, 012005 (2018)



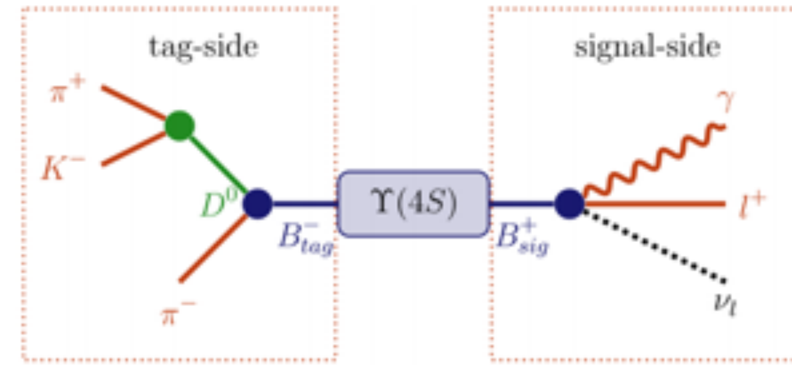
- Competition from LHCb

Phys. Rev. Lett. 118, 022003 (2017)
Phys. Rev. D 95, 012002 (2017)

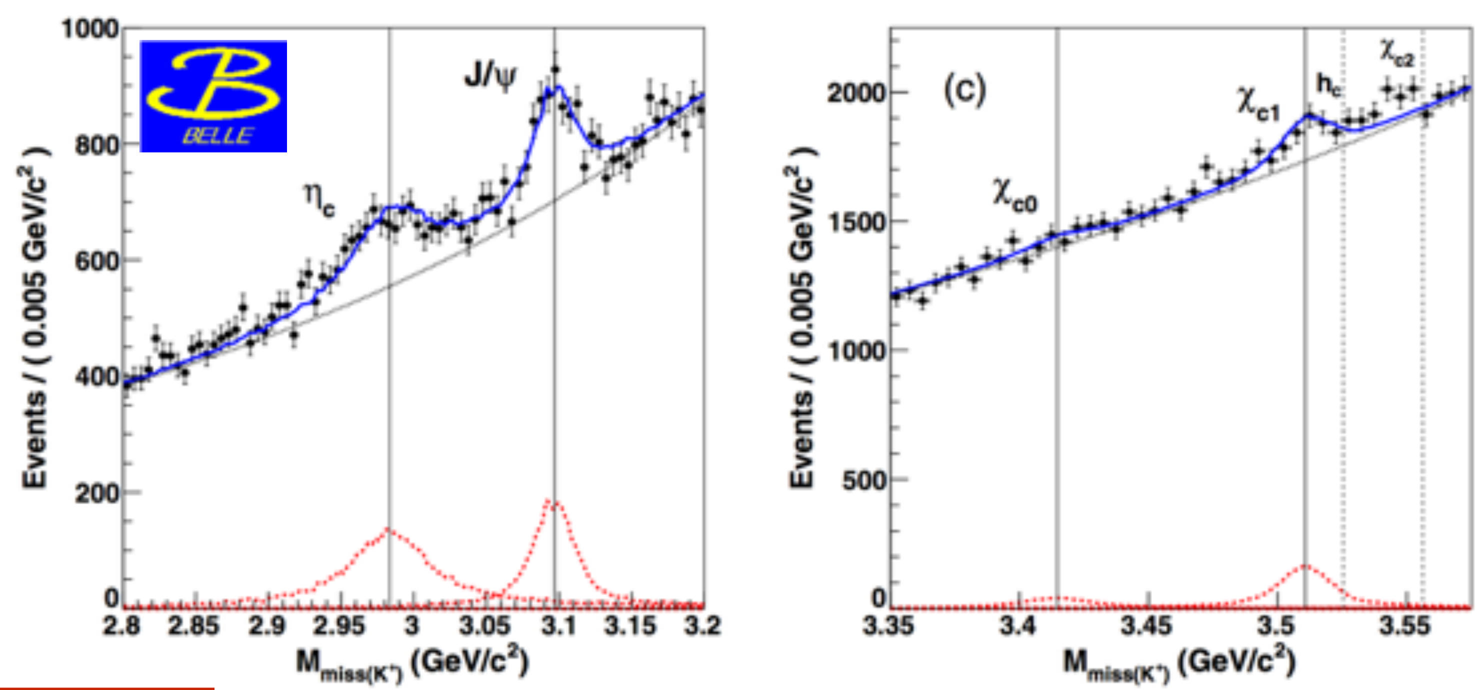
LHCb amplitude analysis of B ➔ J/ψ ϕ K



- e^+e^- B-factories only: ➡ **Belle II**



PRD 97, 012005 (2018)

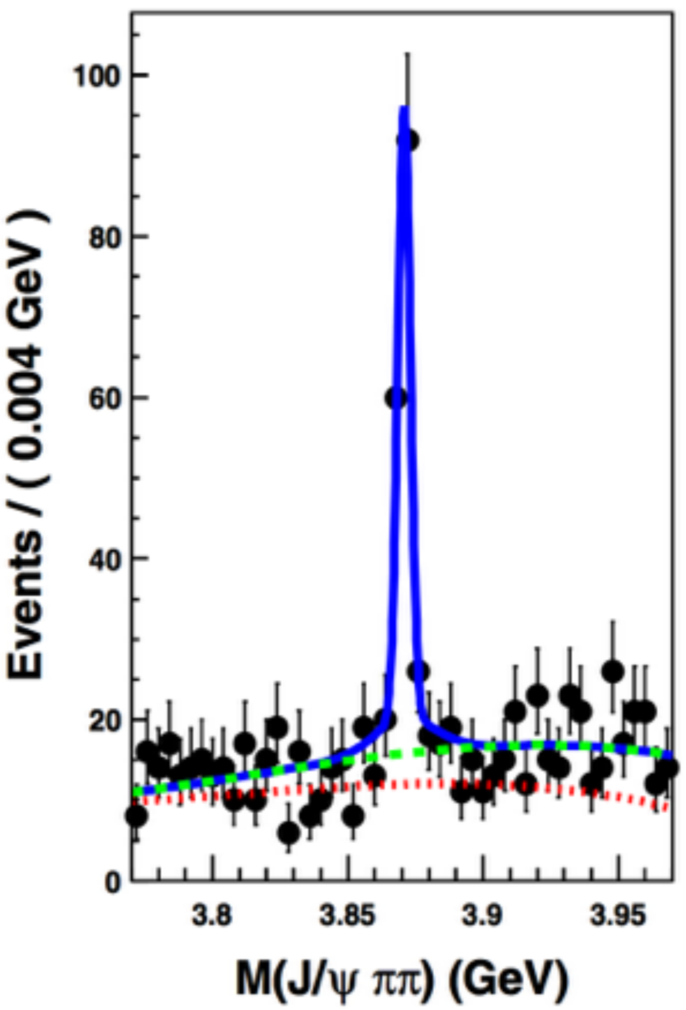


Competitive with LHCb exclusive reconstruction only for:
- hadronic transitions with π^0,η,ω in final state
- states decaying with large multiplicities

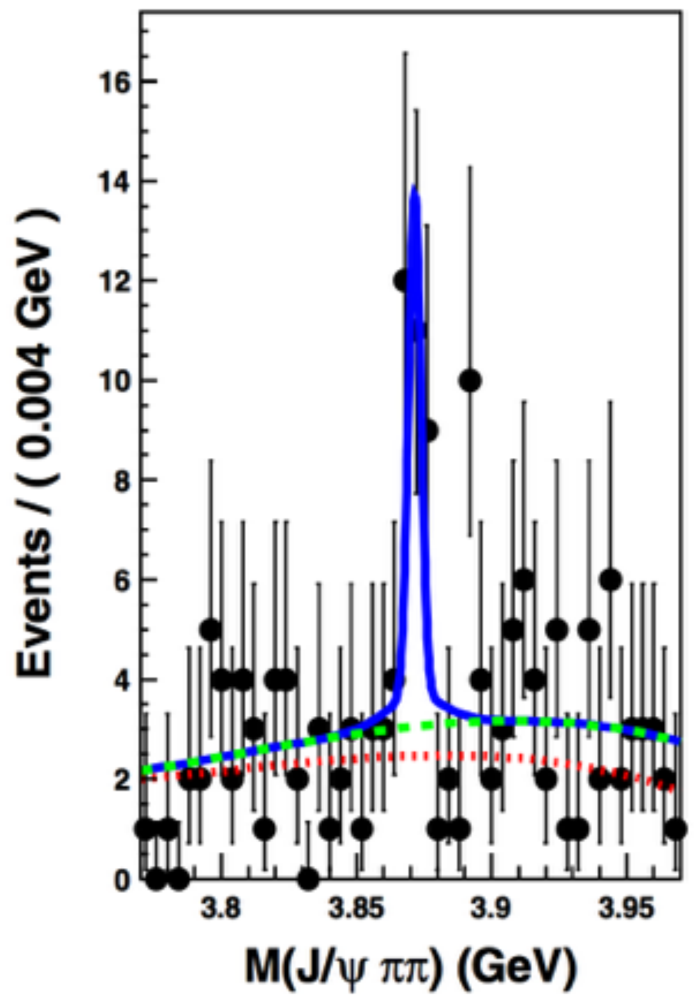
Charmonia: X(3872) width

- The current upper limit on the width of the X(3872) width is the 90% C.L. of $\Gamma_{X(3872)} < 1.2$ MeV, obtained using the mode $B \rightarrow J/\psi\, \pi^+\pi^- K$

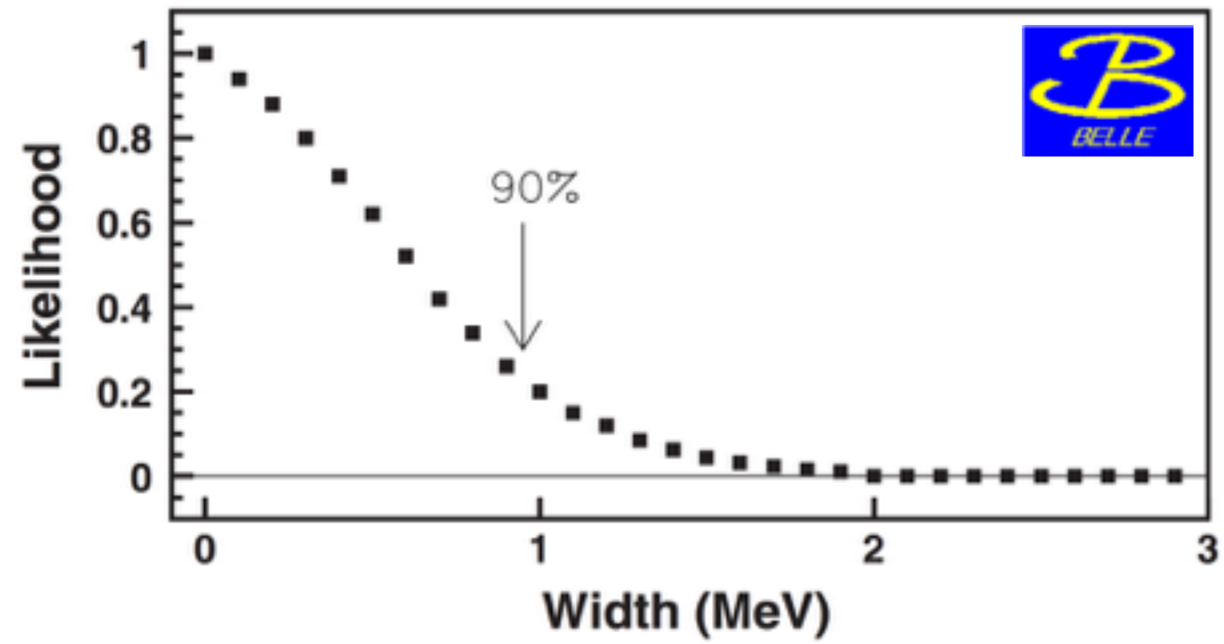
$B^+ \rightarrow K^+$ X(3872)



$B^0 \rightarrow K_S$X(3872)



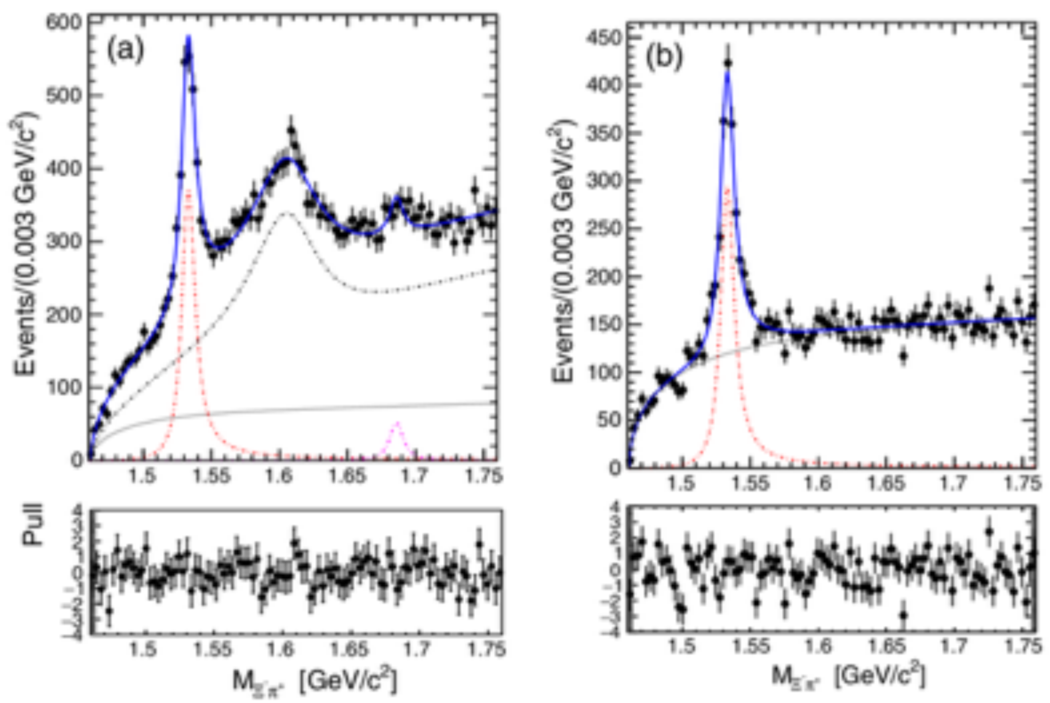
Belle, PRD 84, 052004 (2011)



Prospects in baryon spectroscopy

- Baryon spectroscopy is in general more complicated than quarkonia but exotic candidates exists even in the first excited states
- Excited spectrum is not well understood
- Belle still actively publishing

Belle, PRL 9122, 072501 (2019)



➡ **Belle II**

- measure quantum numbers for excited charmed baryons
- search for excited baryons in charmed baryon decays
- search for exotic candidate states

Coalescence model for anti-deuteron production

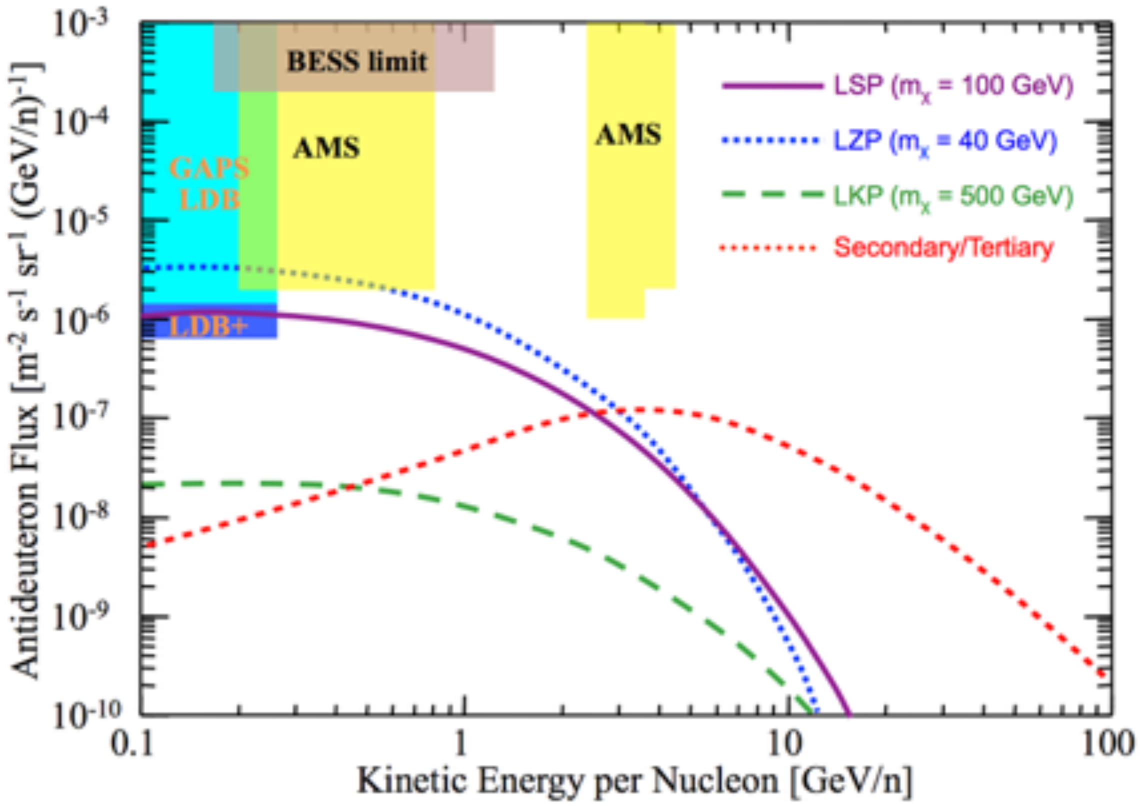
Donato, Fornengo, Salati, PRD 62, 043003 (2000)

Aramaki et al. Phys. Rept. 618 (2016) 137

Anti-deuteron production is described by p-n coalescence models tuned on the HEP data

Most recent data are from Alice

- Large final state
- MC-driven correction



$$\frac{dN_{\bar{d}}}{dT_{\bar{d}}} = \frac{p_0^3}{6k_{\bar{d}}} \frac{m_{\bar{d}}}{m_{\bar{p}} m_{\bar{n}}} \left.\frac{dN}{dT_{\bar{p}}}\right|^{**} \left.\frac{dN}{dT_{\bar{n}}}\right|^{**}$$

where $T_i = E_i - m_i$ is the kinetic energy of $i = \bar{d}, \bar{p}, \bar{n}$ and the $|^{**}$ notation recalls that the $\bar{p}$ and $\bar{n}$ spectra must be evaluated at $T_{\bar{p}} = T_{\bar{d}}/2$ and $T_{\bar{n}} = T_{\bar{d}}/2$, respectively (as dictated by Eq. (2.14)). In deriving Eq. (2.19), we have clearly assumed $m_{\bar{p}} = m_{\bar{n}} = m_{\bar{d}}/2$.