Exotic and Conventional Quarkonium Physics Prospects at Belle II

QCD@LHC
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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 $\Upsilon(4S)$
  - Bottomonium(-like): below $\Upsilon(4S)$

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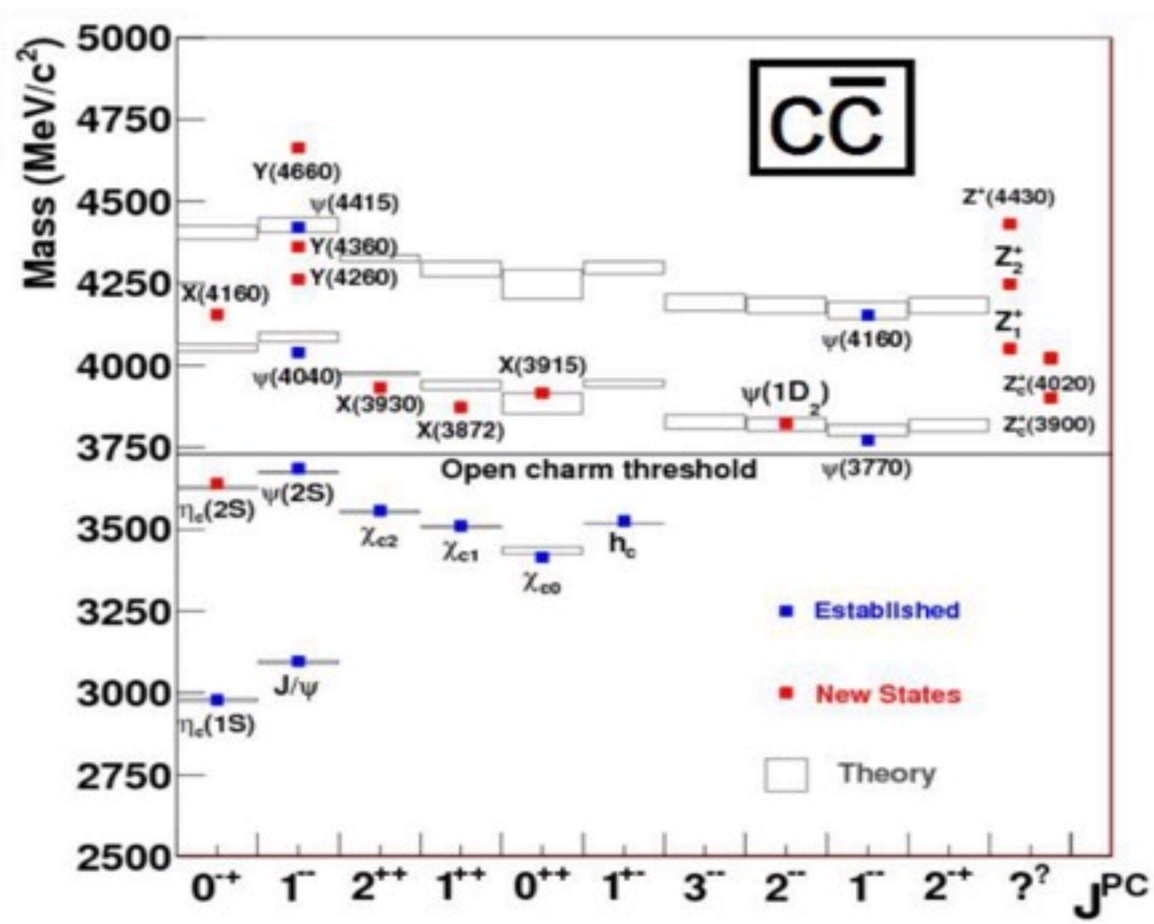
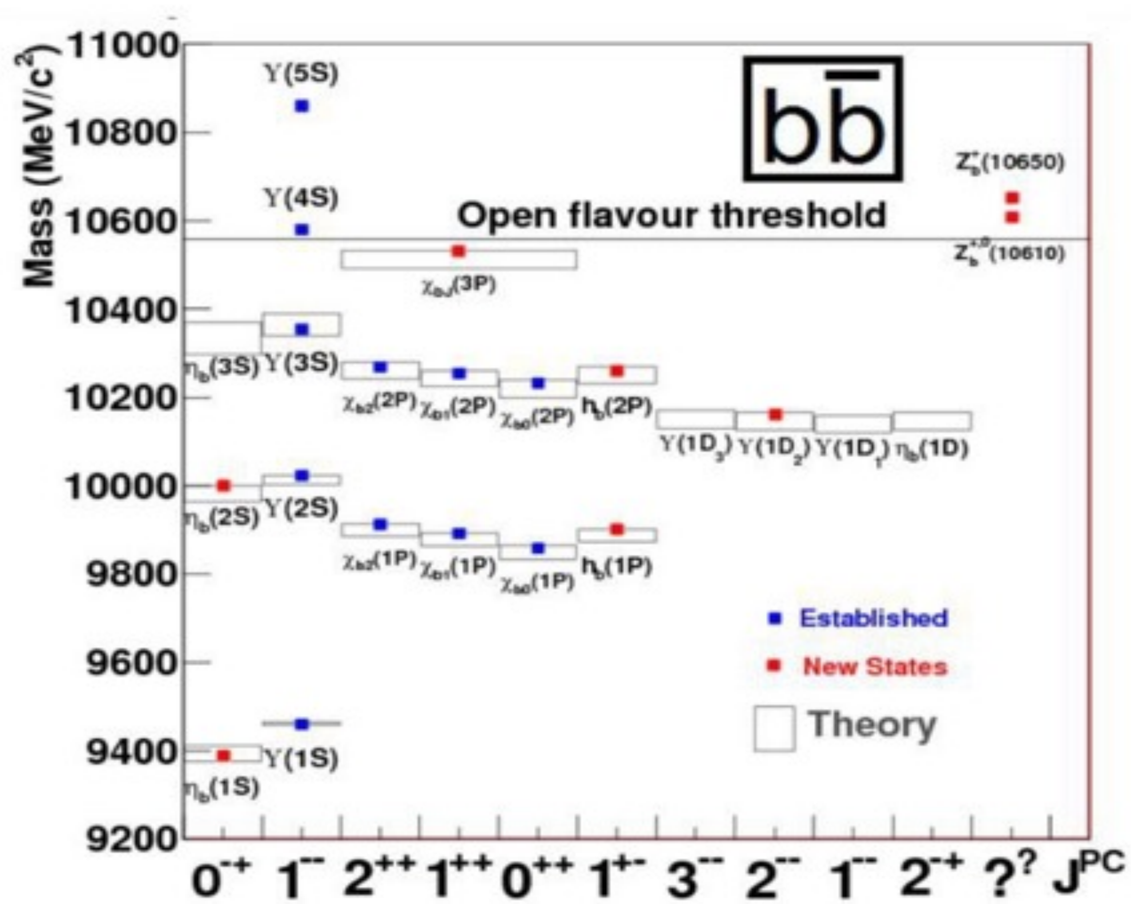
Quarkonium spectroscopy

- 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

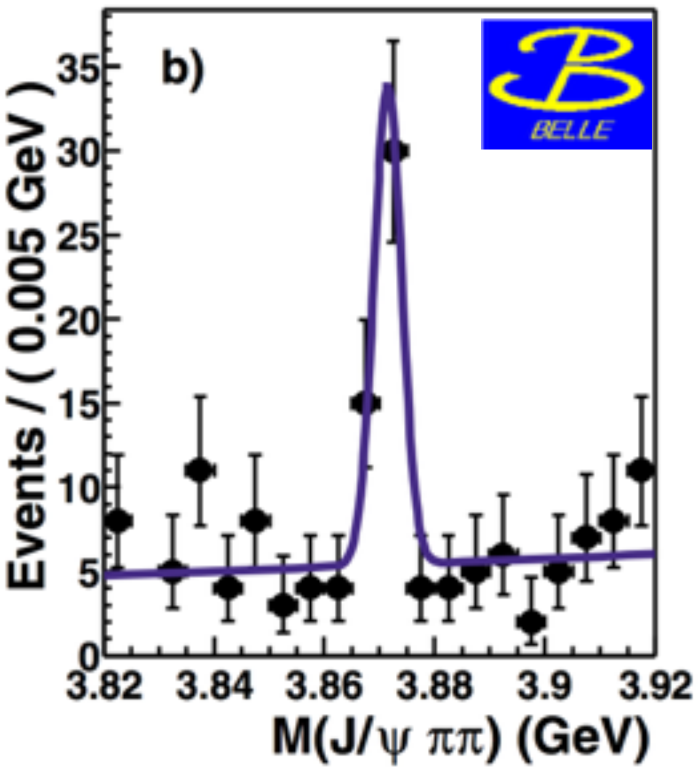




➡ Challenge for the new generation B-factories

B-Factory milestones

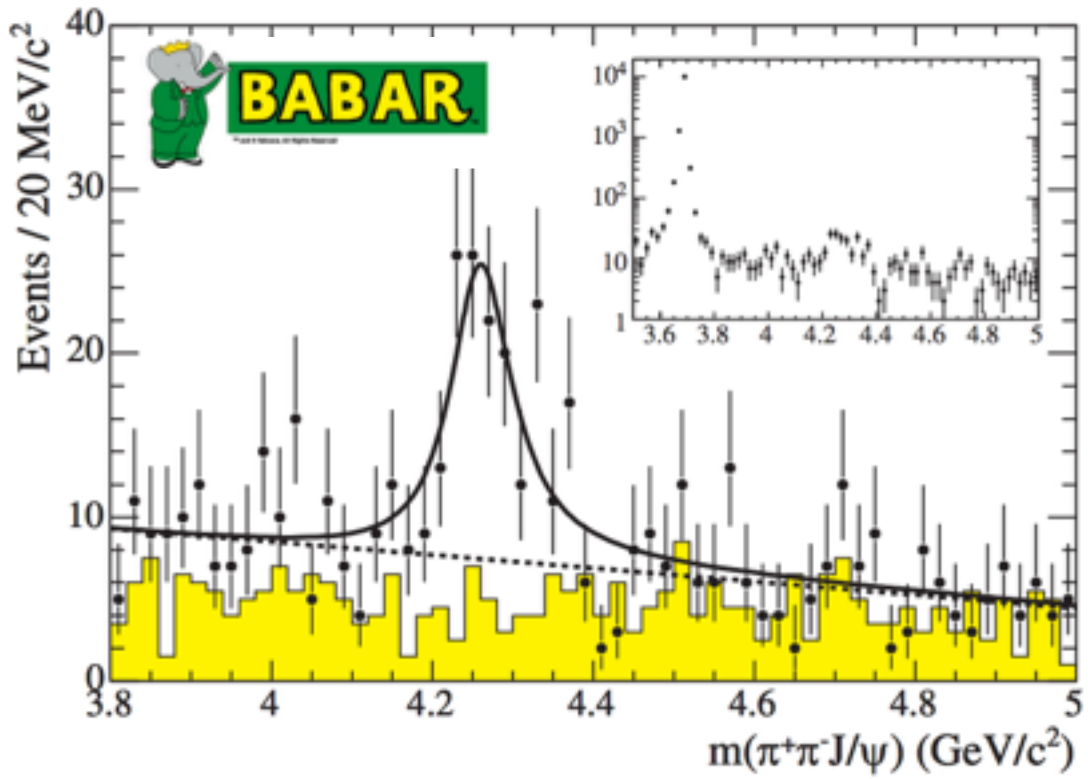
PRL 91, 262001 (2003)



X(3872)

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

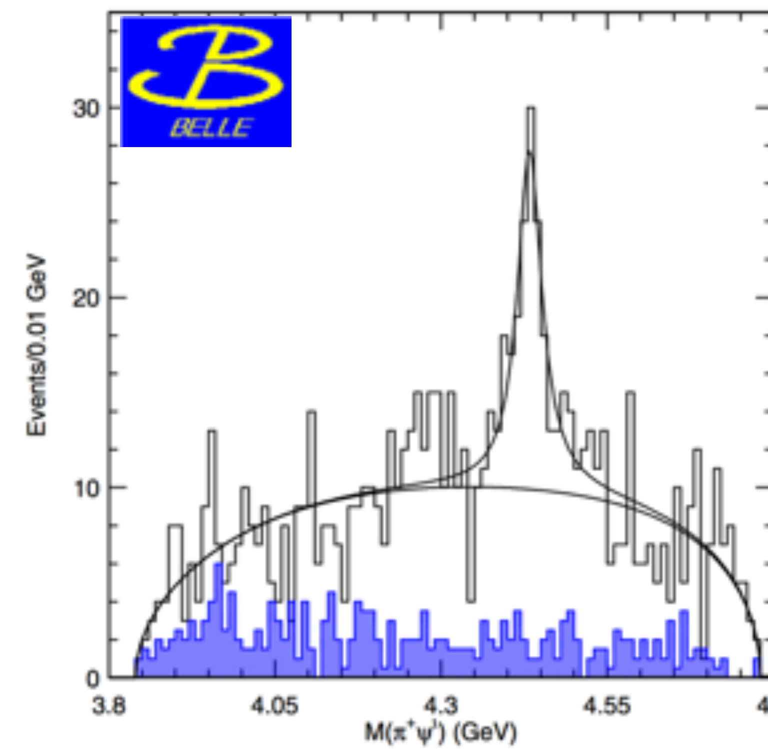
PRL 95, 142001 (2005)



Y(4260)

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

PRL 100, 142001 (2008)



Z(4430)

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

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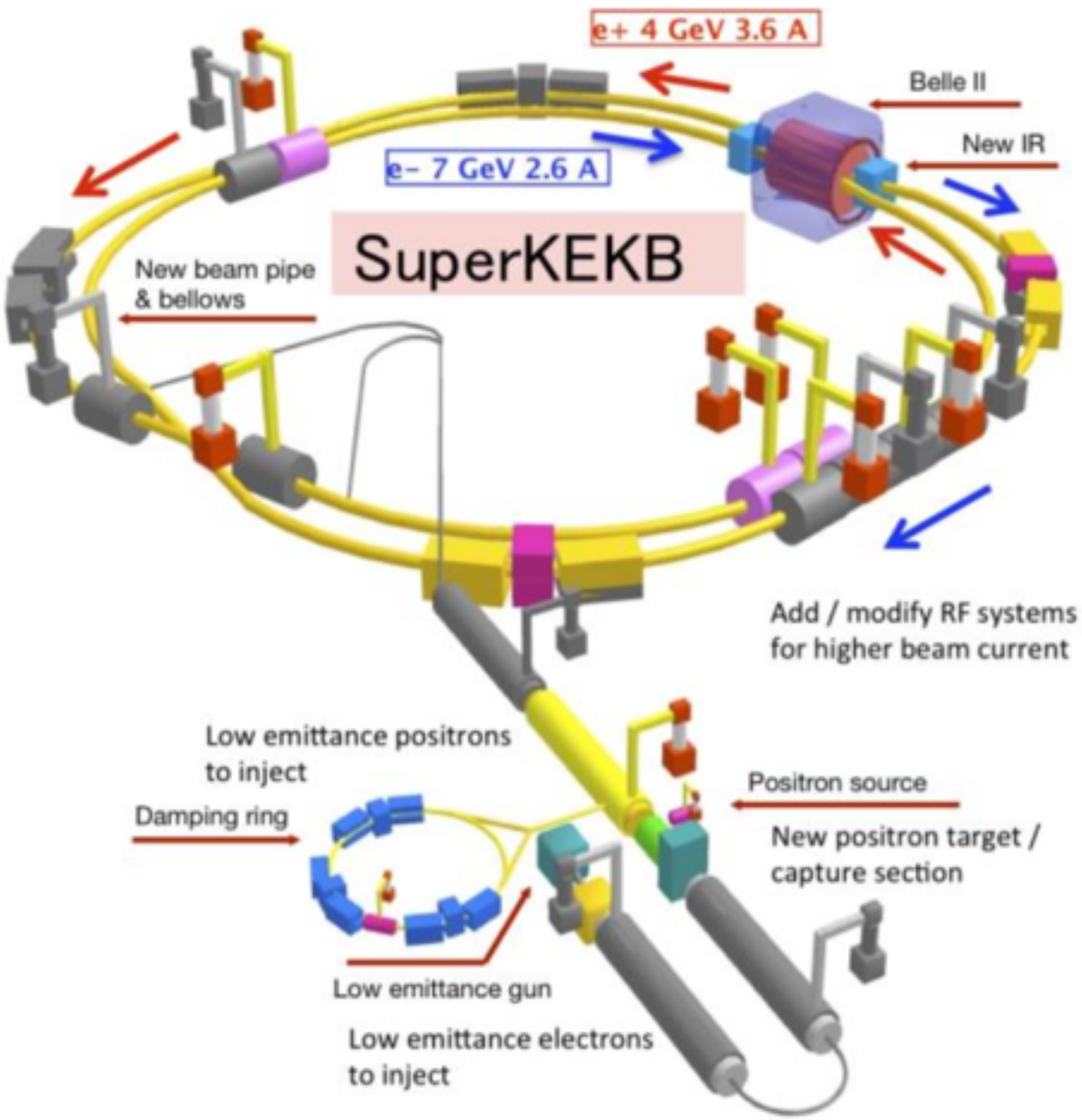


➡ **Goal: x50 Belle integrated luminosity (50 ab^{-1})**

➡ Target luminosity:

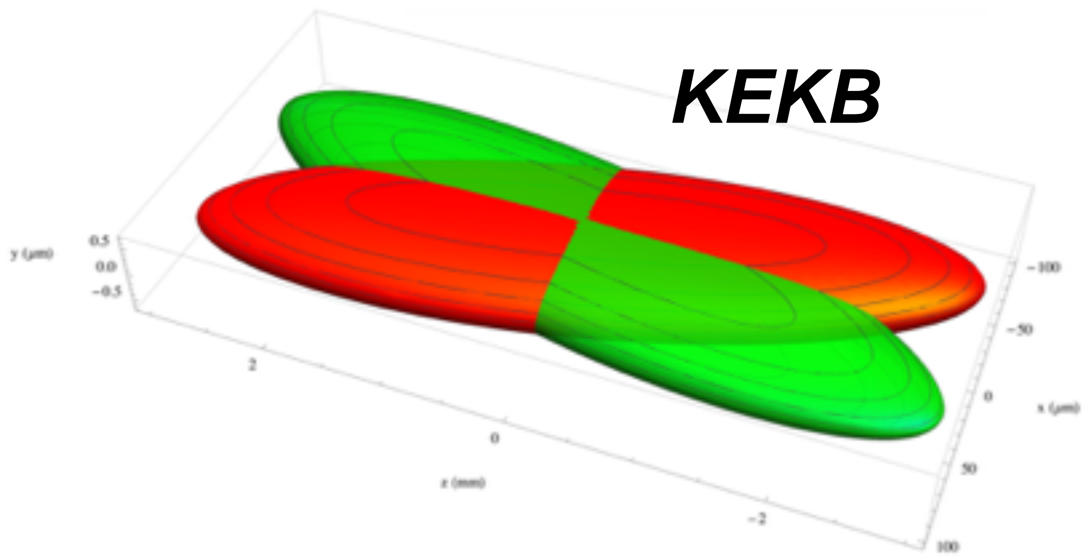
L = 8 x 10^{35} cm^{-2} s^{-1} (x40 Belle)

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

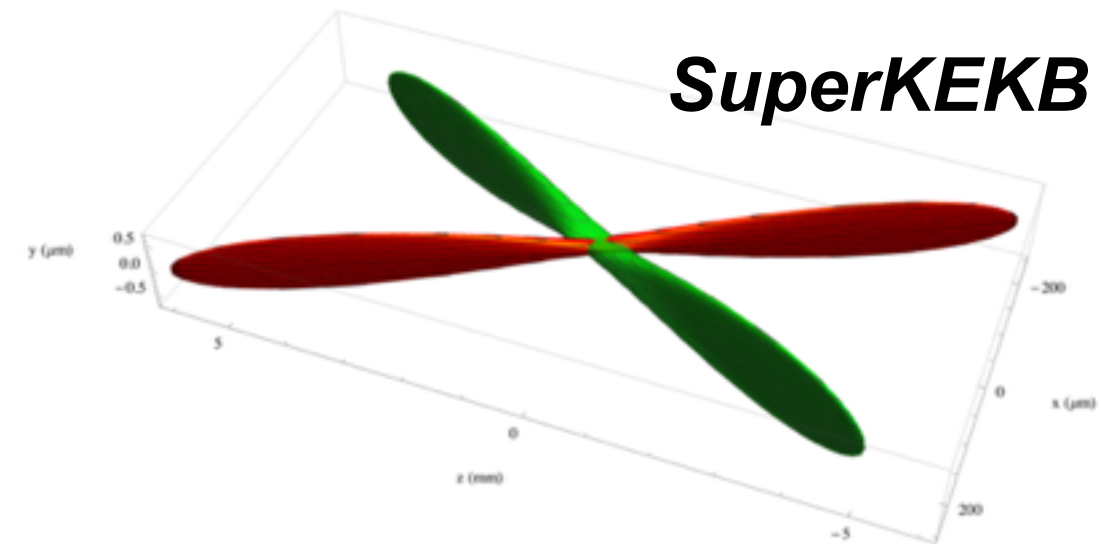
➡ Nano-beam scheme (P. Raimondi for SuperB)

- beam currents x2
- squeeze beam @ IP by 1/20

Nano beam scheme



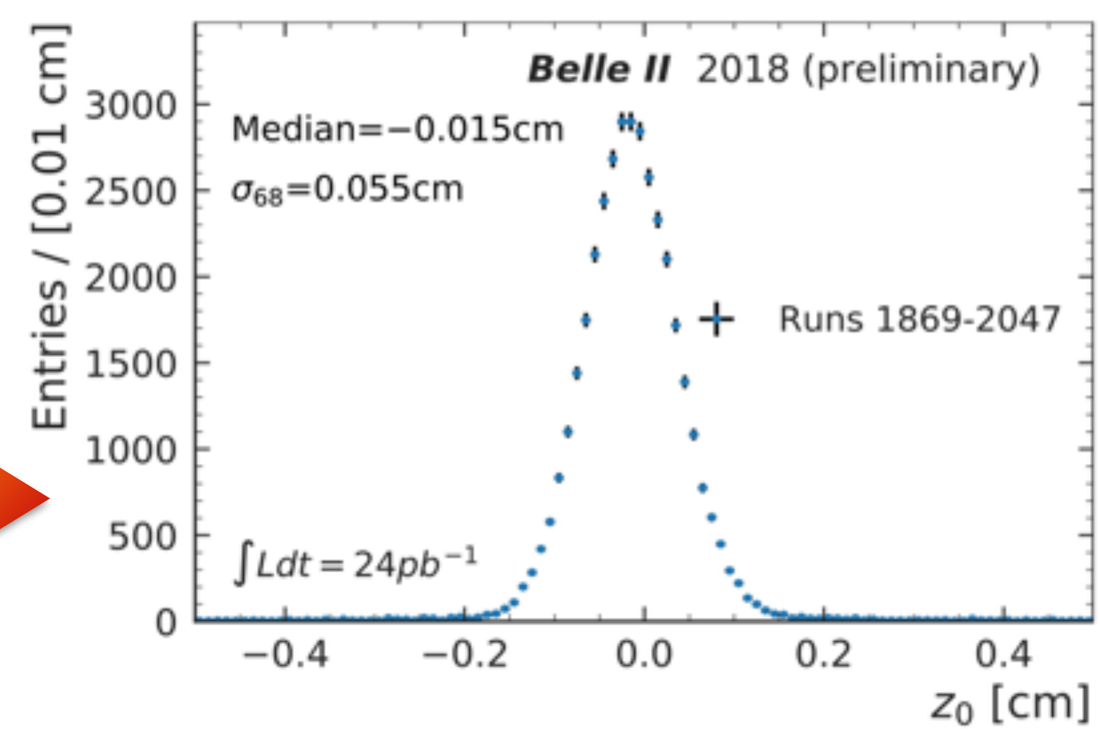
$$\sigma_z = \frac{\sqrt{\epsilon_x \beta_x^*}}{\sqrt{2}\phi_x} = 1 \text{ cm}$$



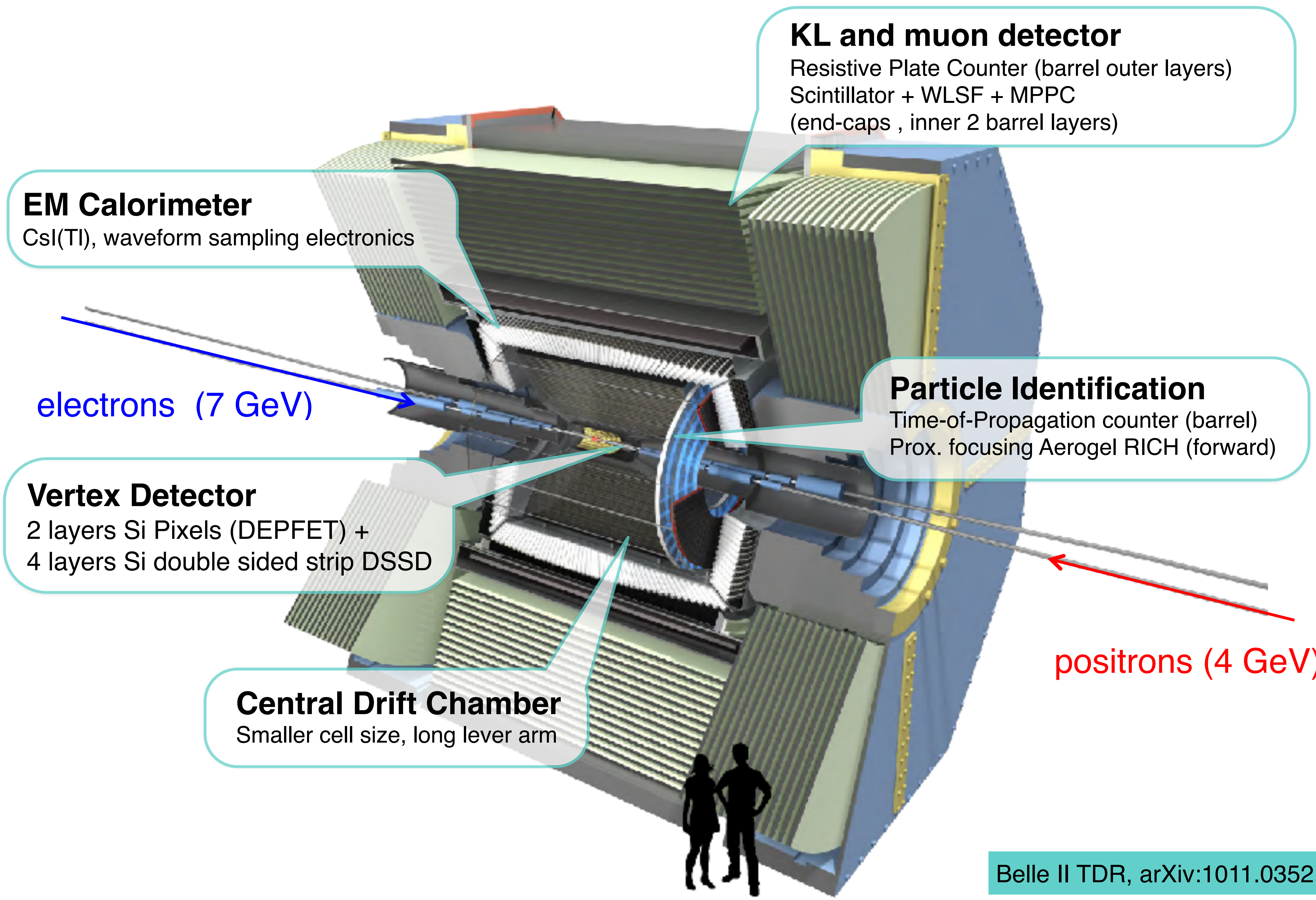
$$\sigma_z = \frac{\sqrt{\epsilon_x \beta_x^*}}{\sqrt{2}\phi_x} = 0.049 \text{ cm}$$

As expected, the effective bunch length is reduced from ~10 mm (KEKB) to ~0.5 mm (SuperKEKB)

➡ *We measured it in two track events with early Belle II data*

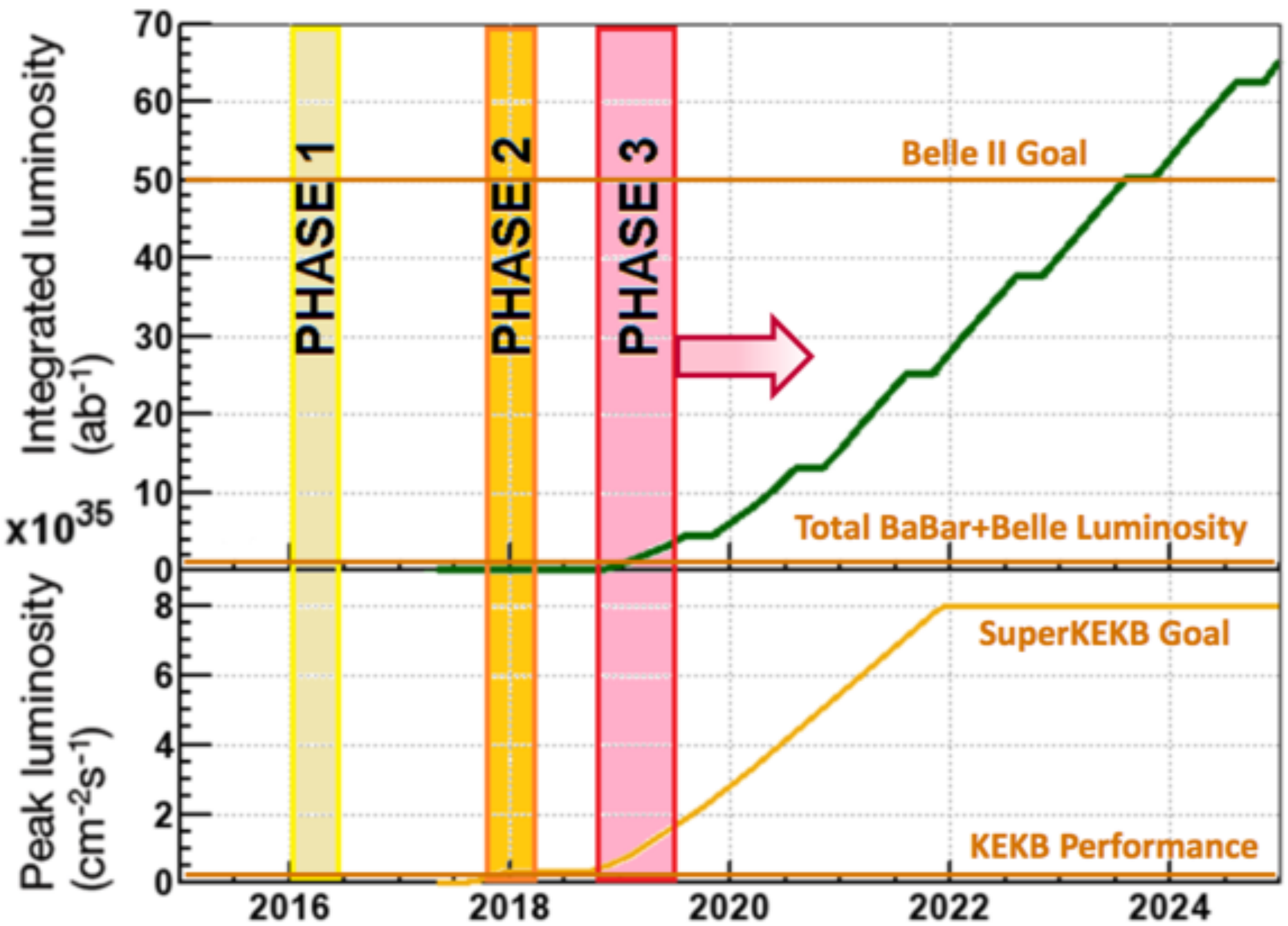


The Belle II detector



Belle II TDR, arXiv:1011.0352

Belle II status and schedule



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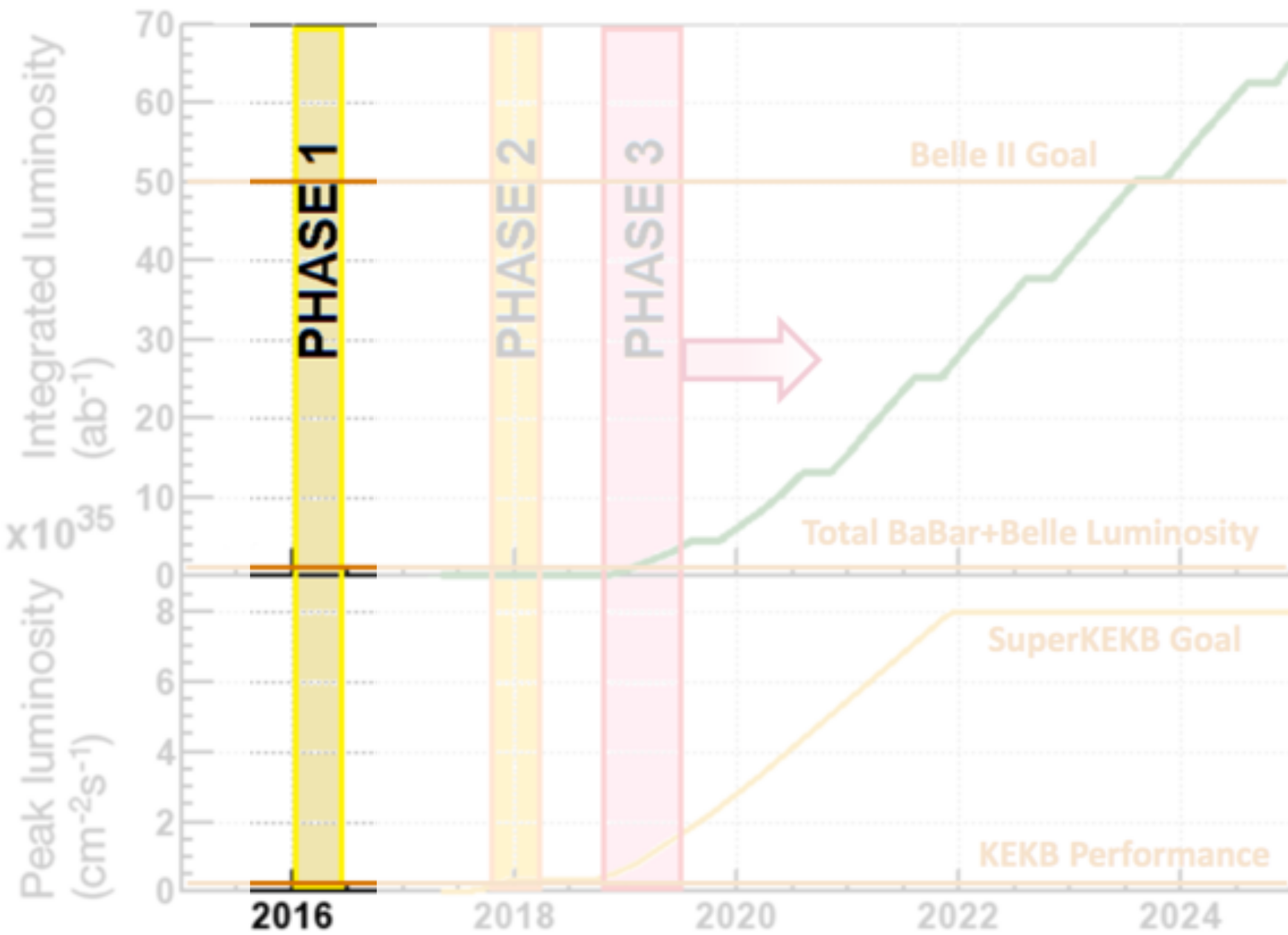
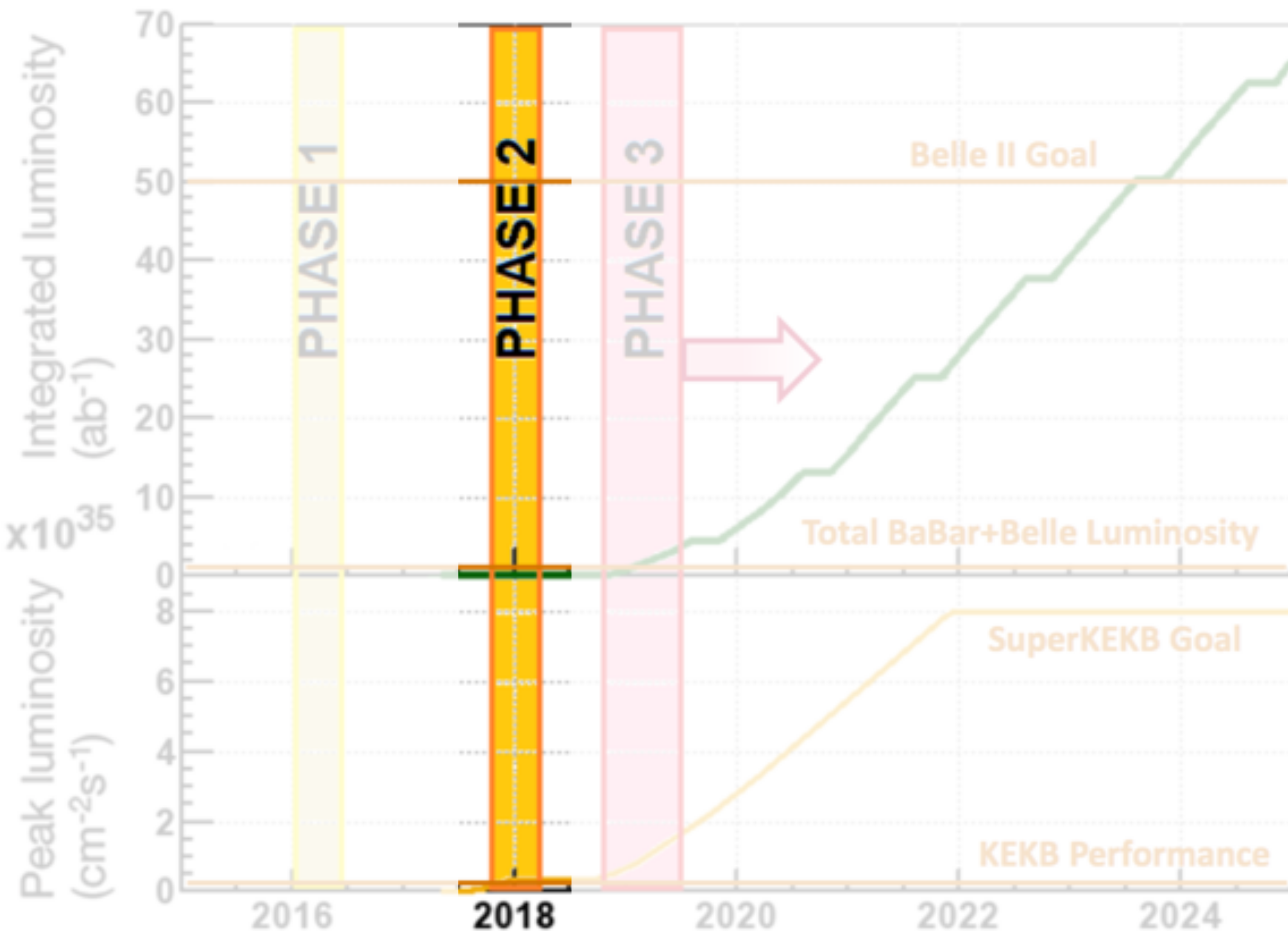


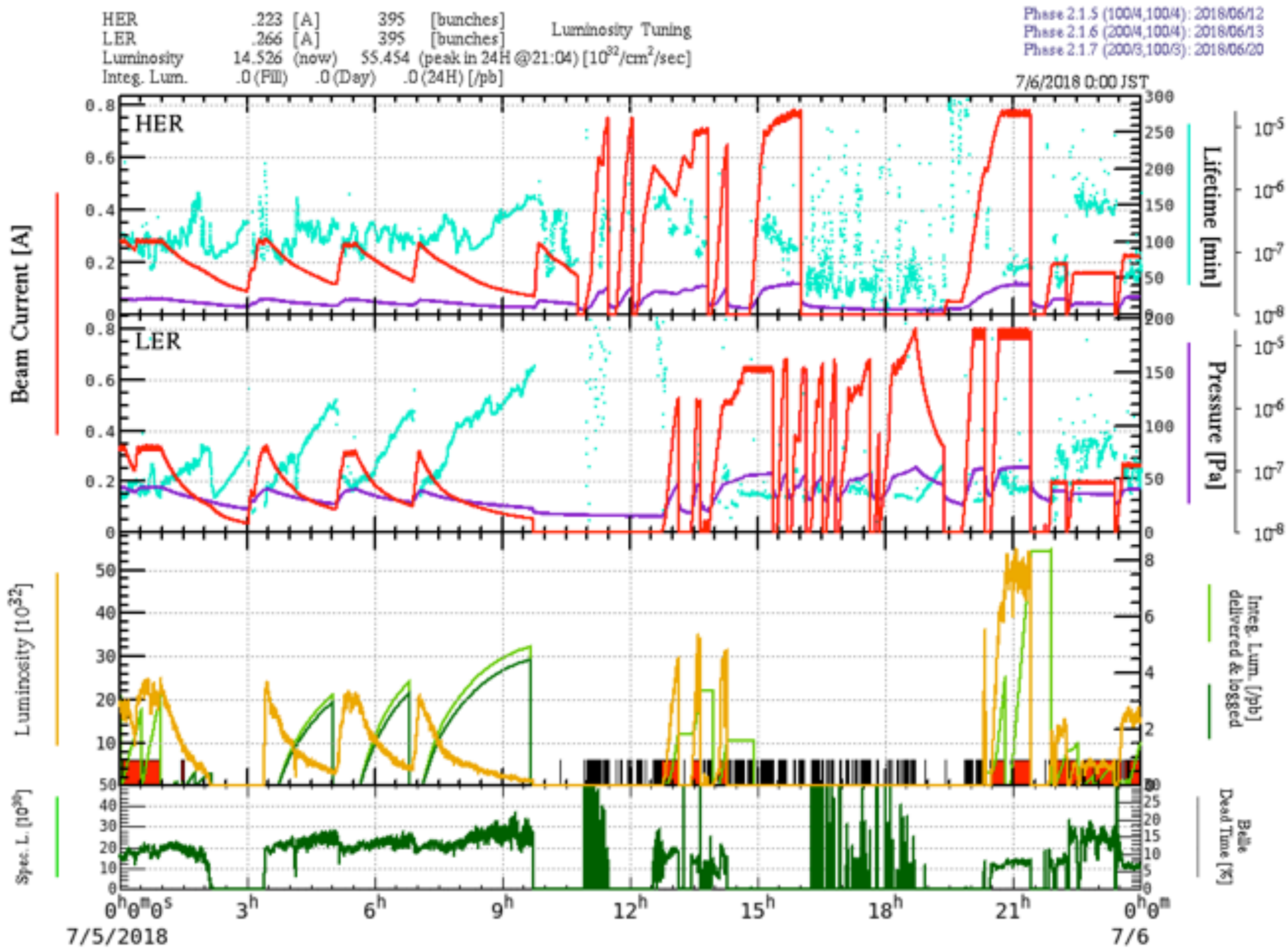
- Phase 1:
  Accelerator commissioning (completed in 2016)
- Detector roll-in (April 2017)

Belle II status and schedule

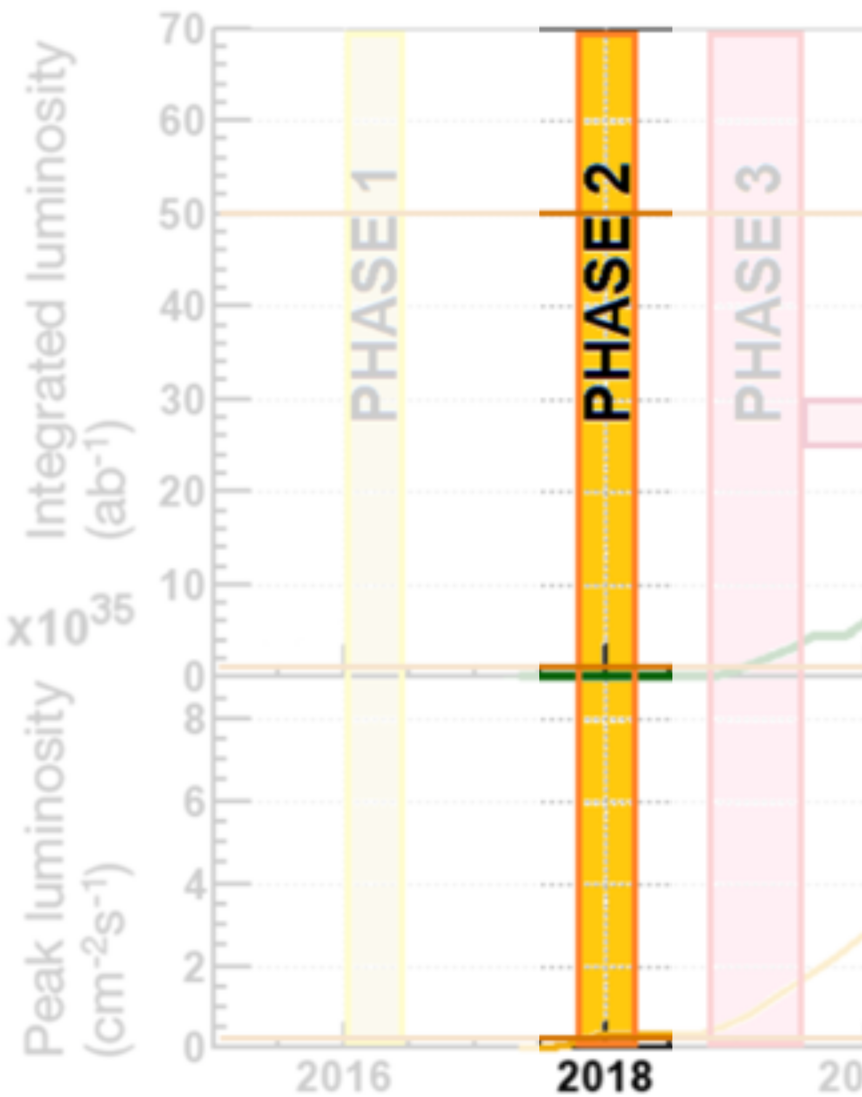


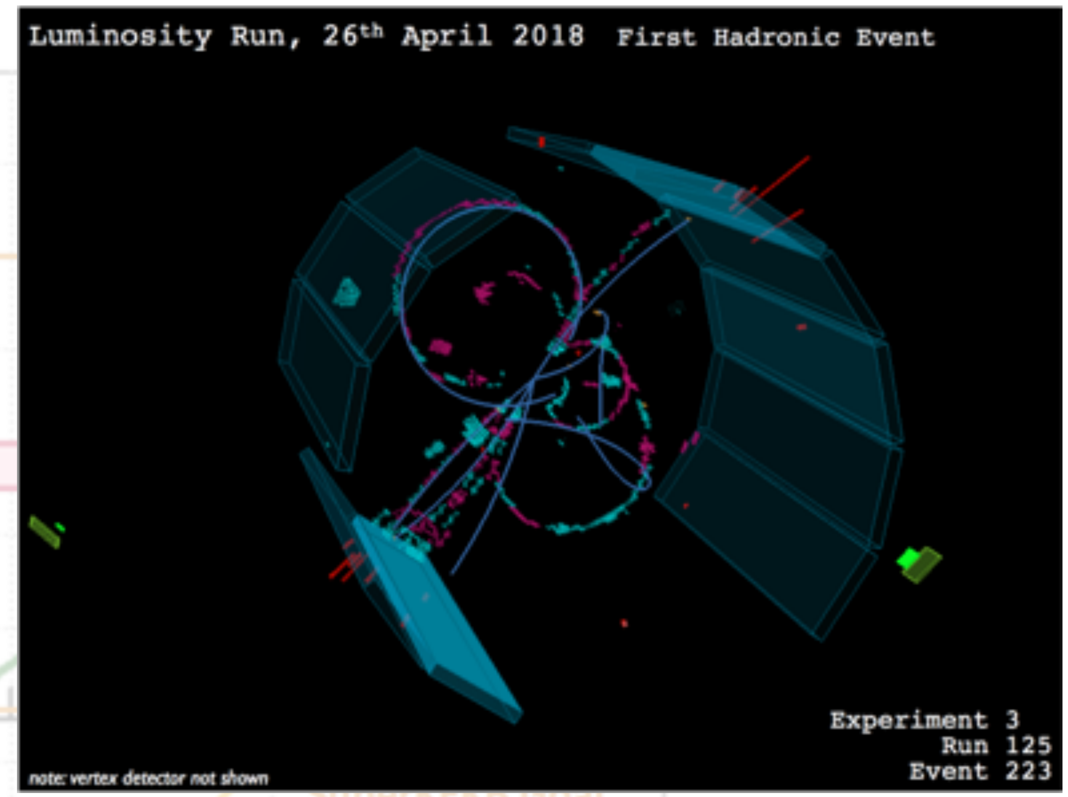
- Phase 2 (ended in July 2018):
  - Beam optimization and background minimization, ~1/10 vertex detector
  - Detector calibration
  - Understanding of the new machine, test of the nano beam scheme
  - First collisions and first data collected

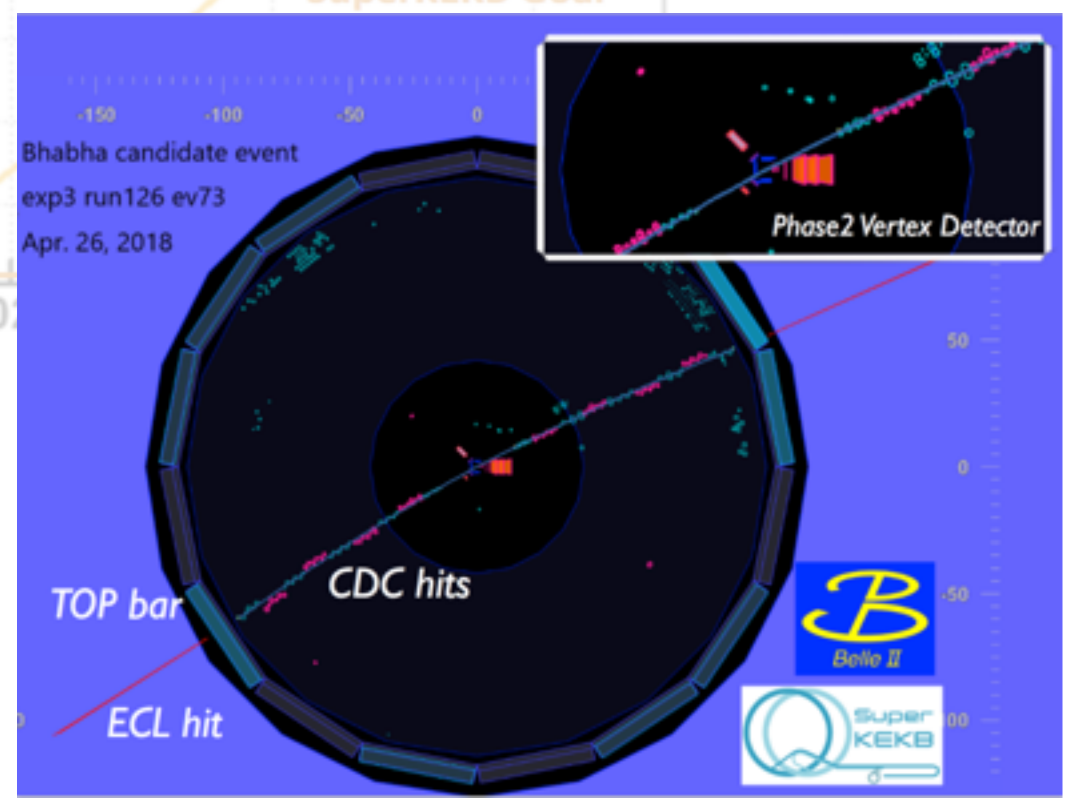
- In Phase 2 luminosity tuning had priority over data taking



$L_{peak} = 5.5 \times 10^{33}\ cm^{-2}\ s^{-1}$







First collisions (April 26th)

~0.5 fb^{-1} data collected until July

Getting ready for physics

- Optimization of tracking algorithms and performance
- "Re-discovery" of most particles
- Calorimeter energy calibration
- Detector alignment
- Calibration of PID
- Background studies

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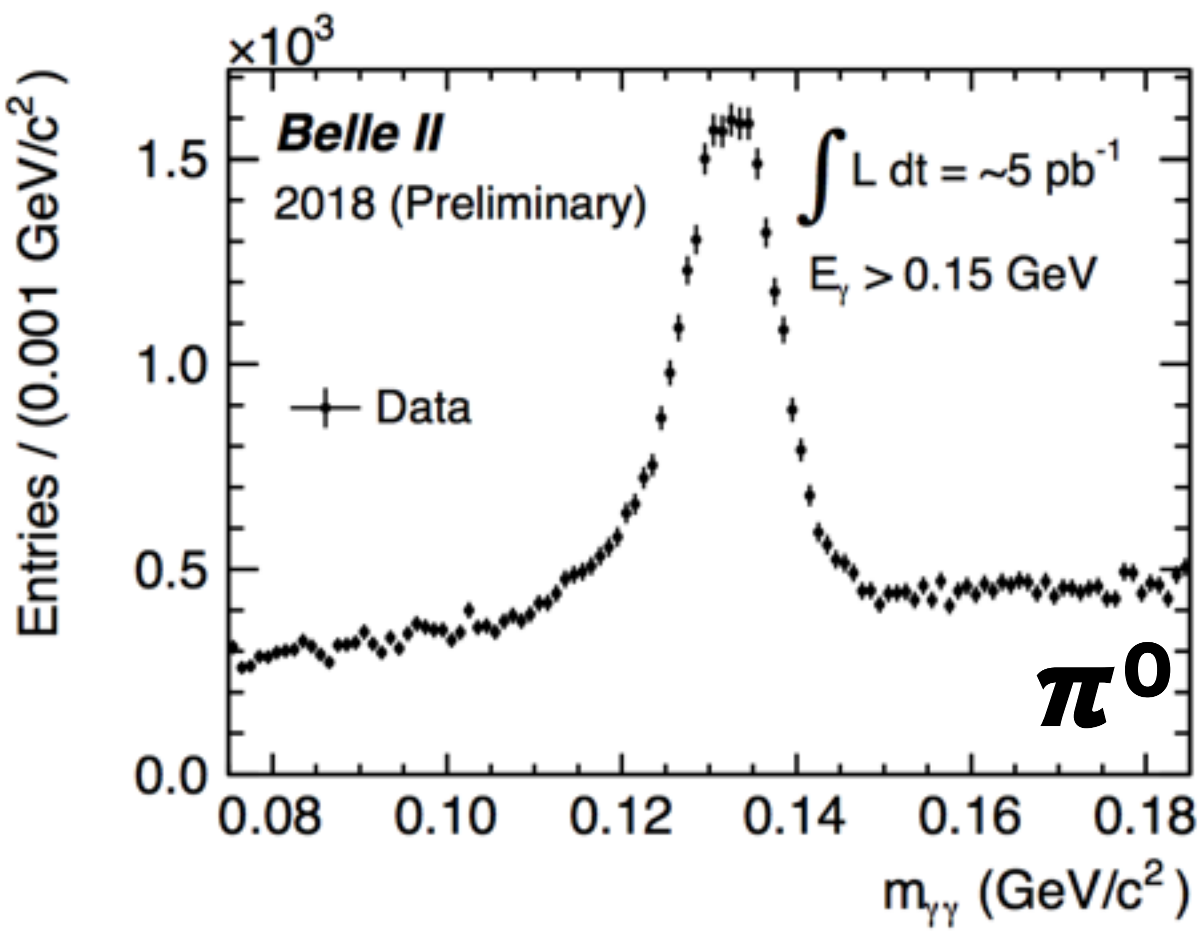
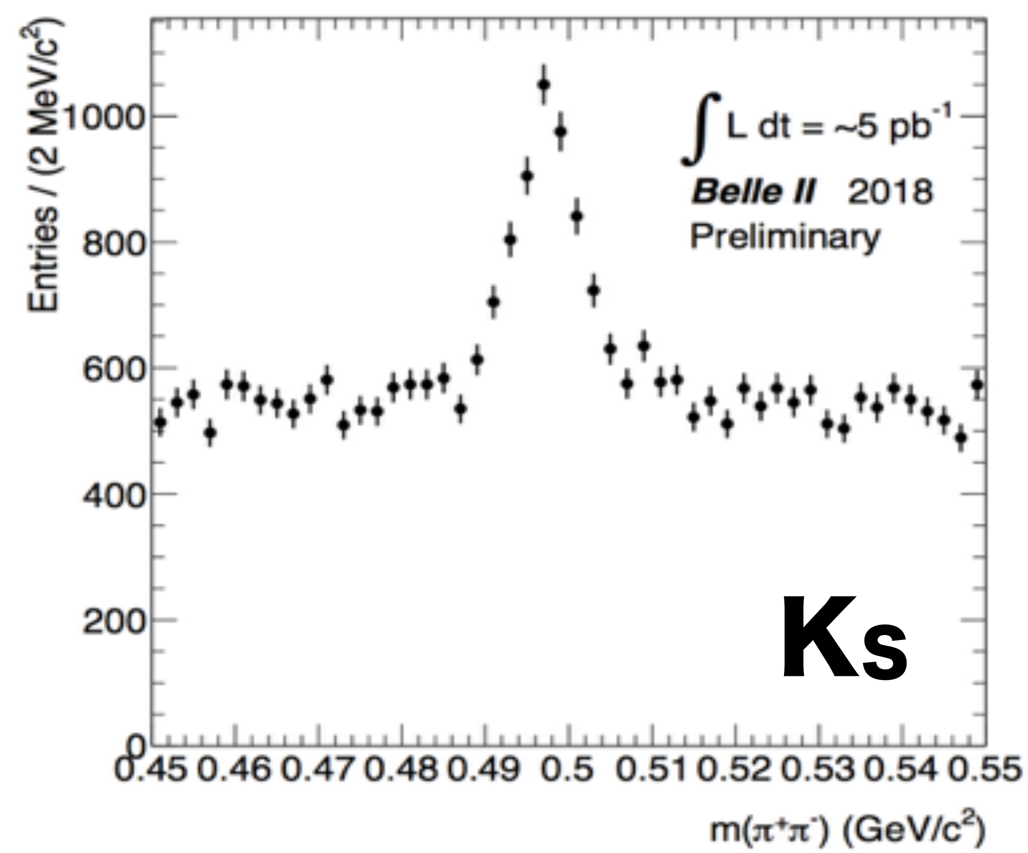
1 week after the first collisions!

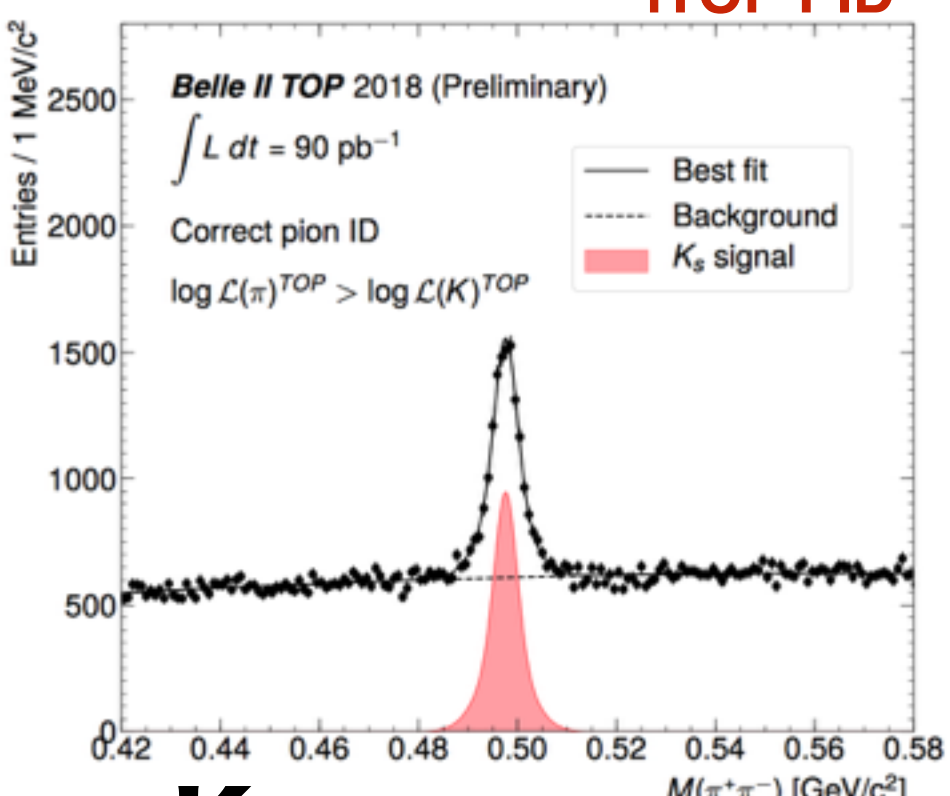




Getting ready for physics

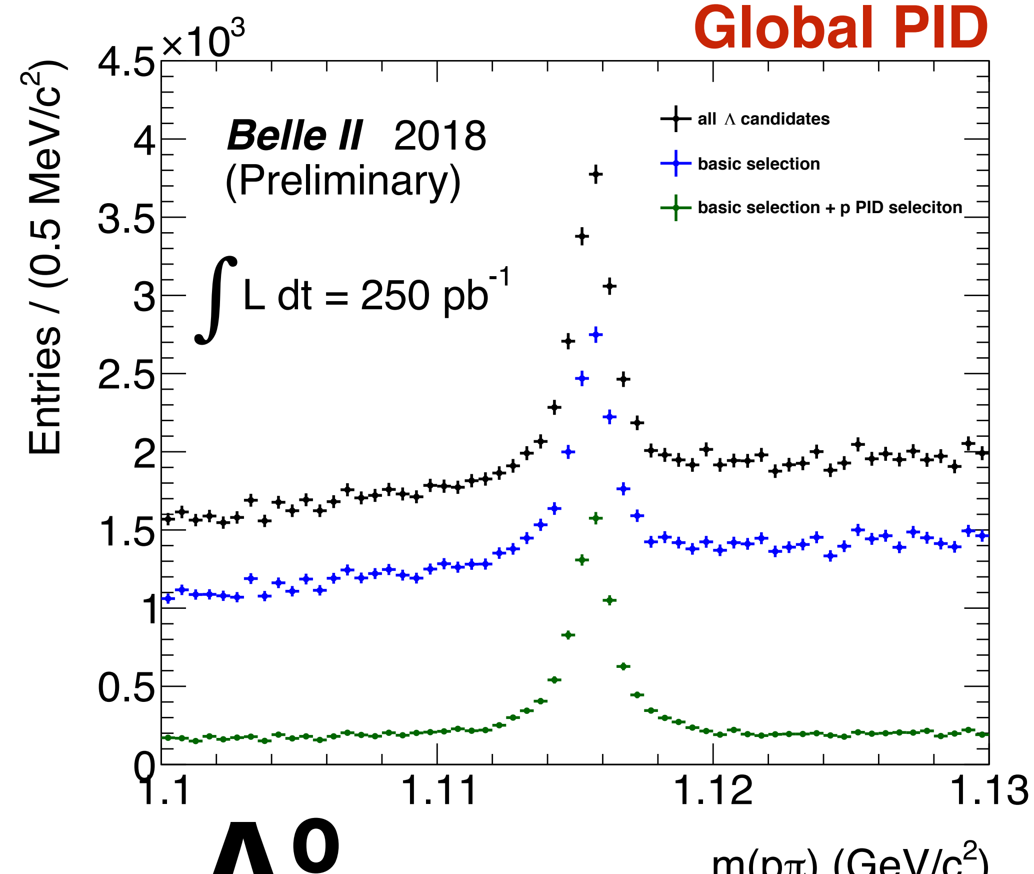
- Optimization of tracking algorithms and performance
- "Re-discovery" of most particles
- Calorimeter energy calibration
- Detector alignment
- **Calibration of PID**
- Background studies

iTOP PID

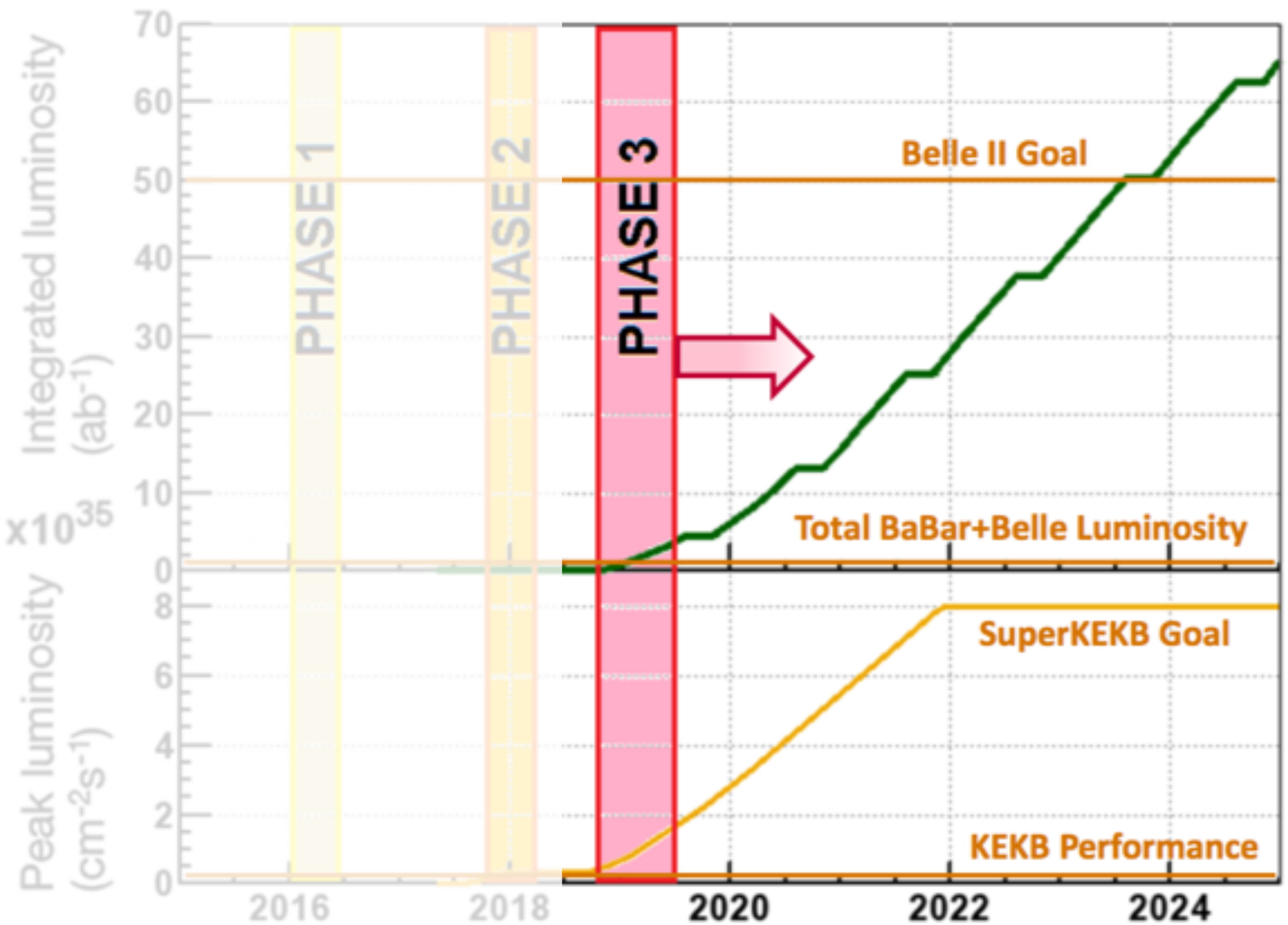


Ks

Global PID

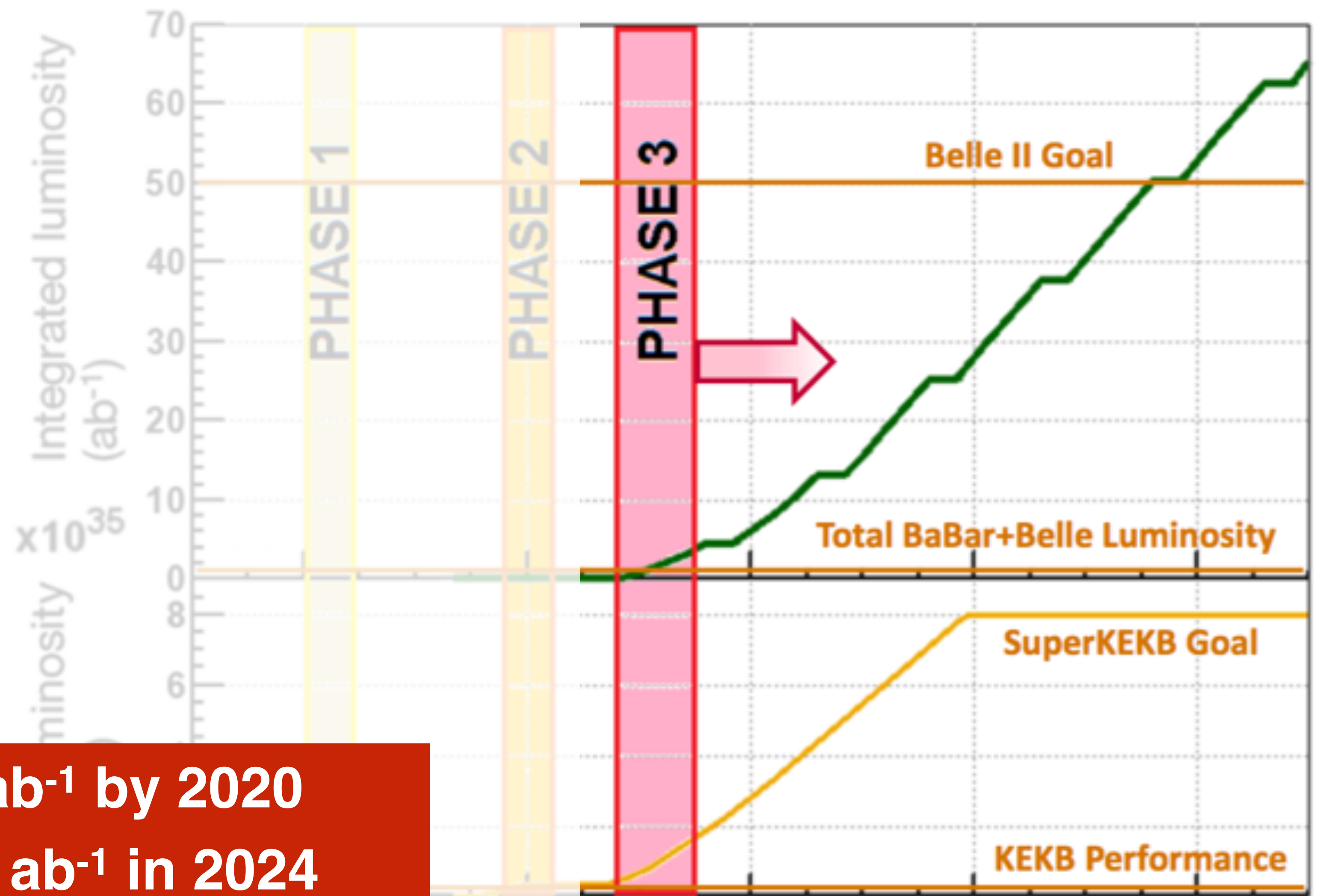


Λ⁰



- Phase3 (early 2019):
  Full Belle II detector (vertex detector), physics run

Belle II status and schedule



- 5 ab^{-1} by 2020
- 50 ab^{-1} in 2024

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%**

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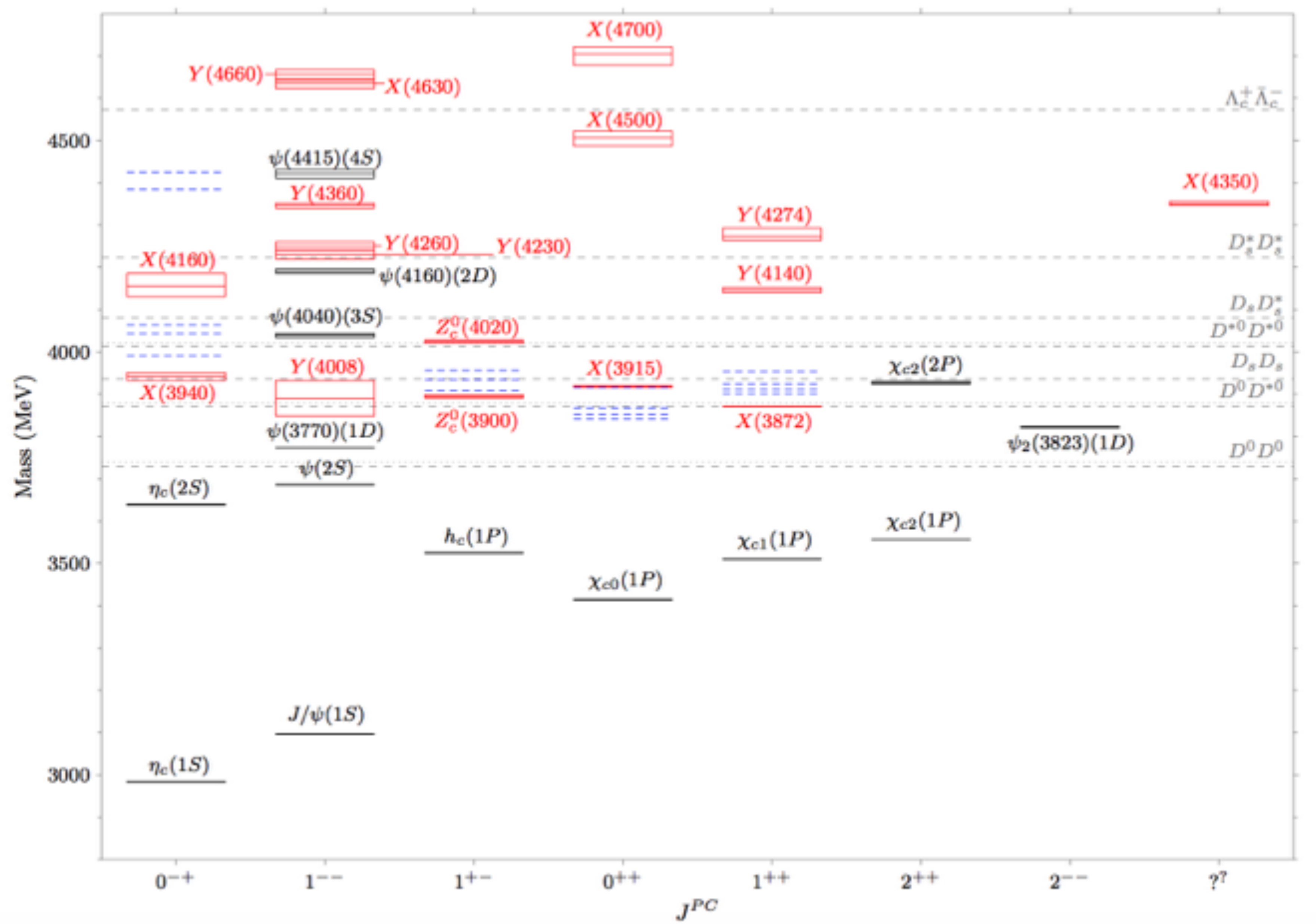
Charmonia: overview



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

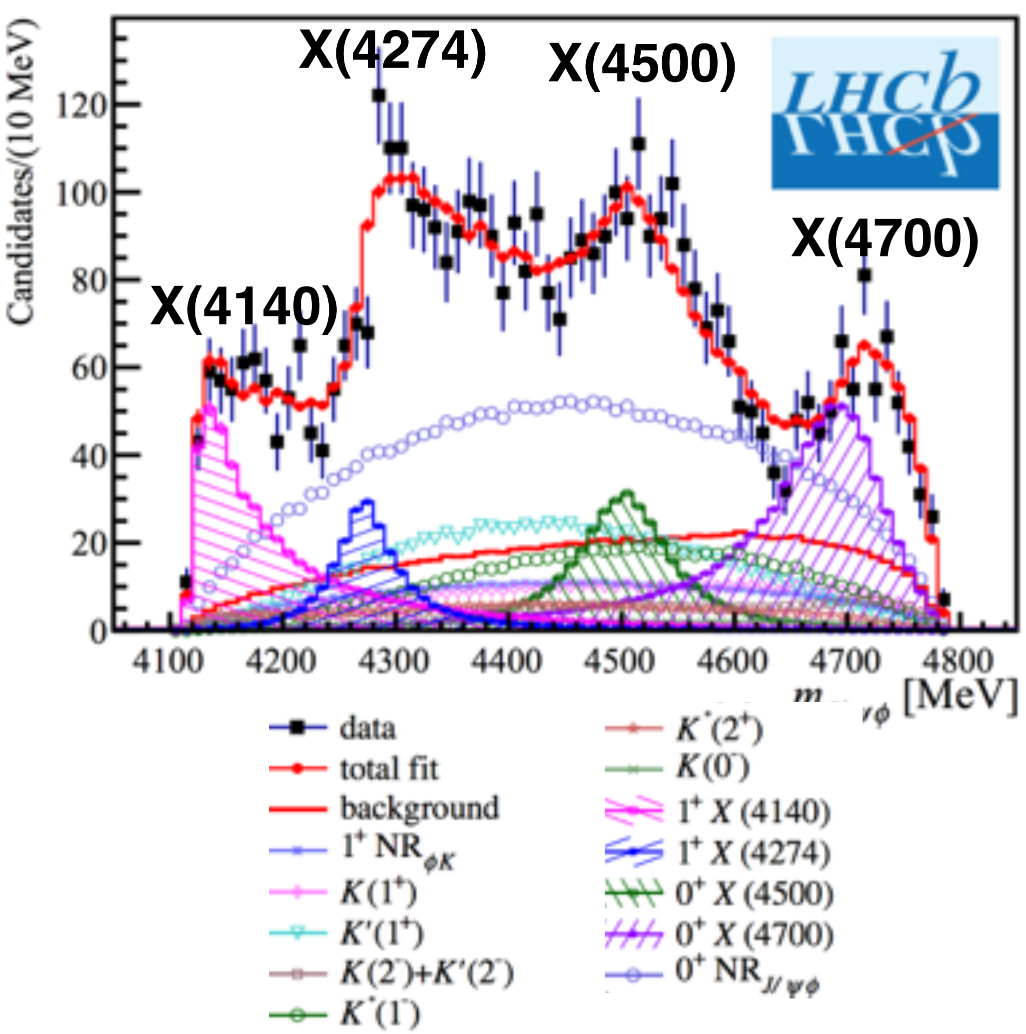
Charmonia: B decay

- Competition from LHCb

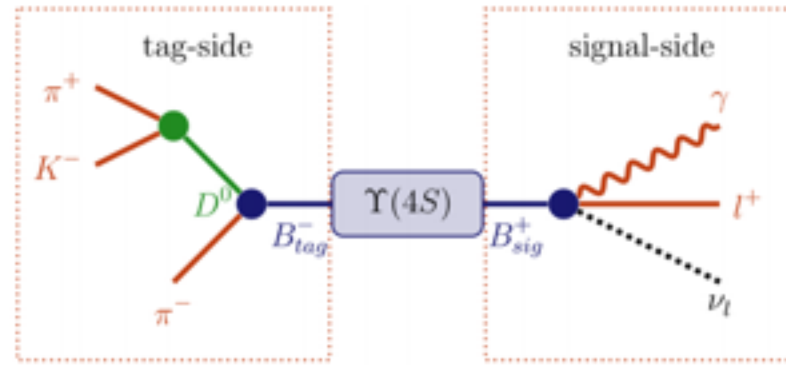
Phys. Rev. Lett. 118, 022003 (2017)

Phys. Rev. D 95, 012002 (2017)

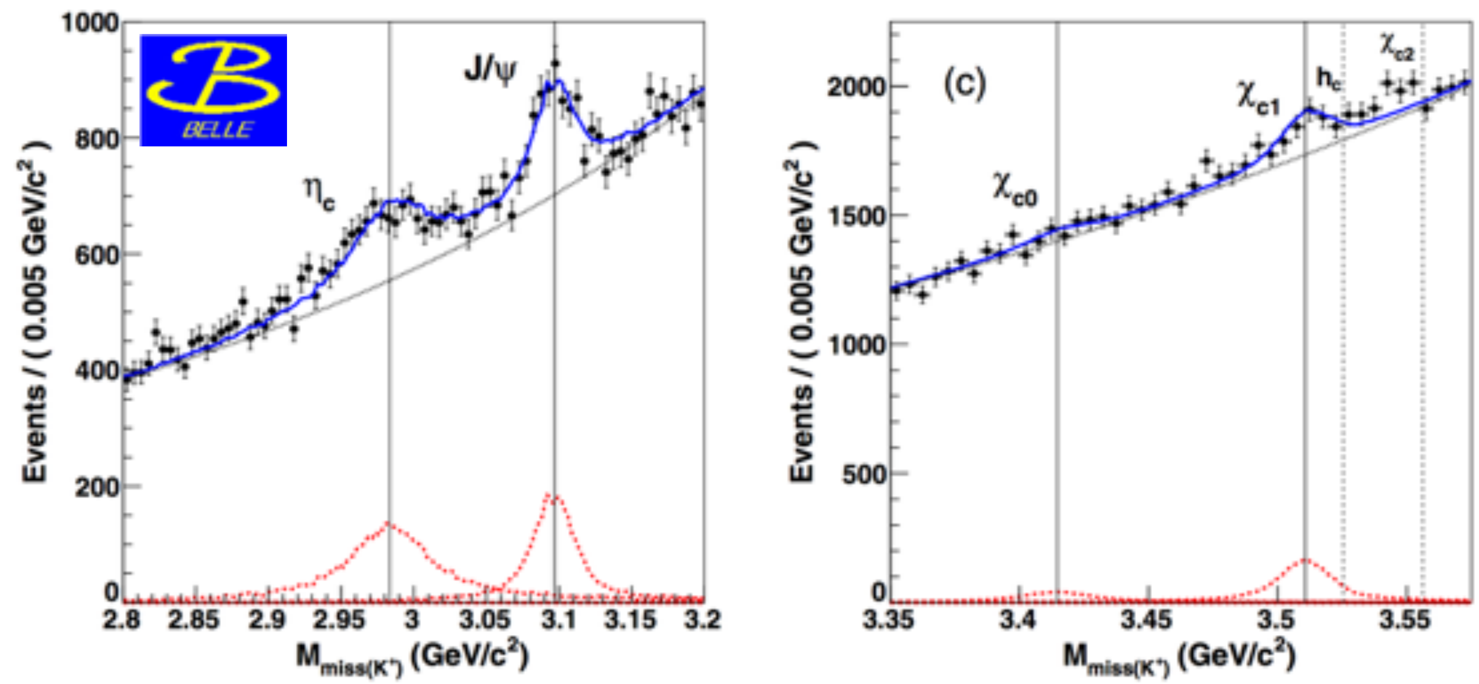
LHCb amplitude analysis of B ➔ J/ψ ϕ K



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



PRD 97, 012005 (2018)



- Competition from LHCb

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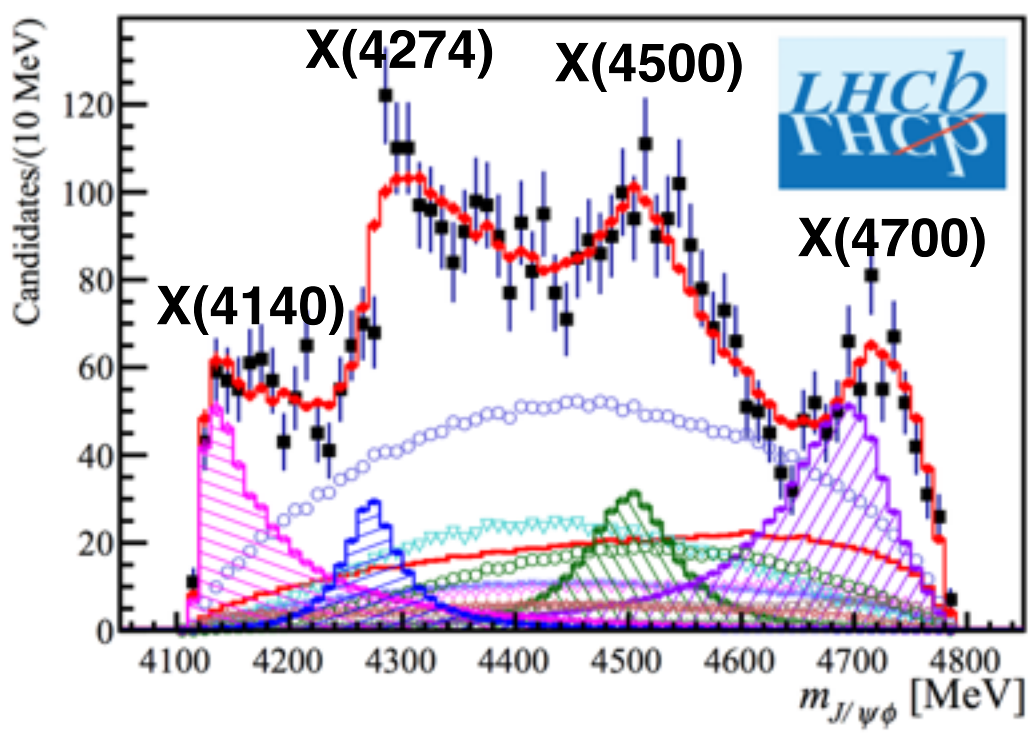
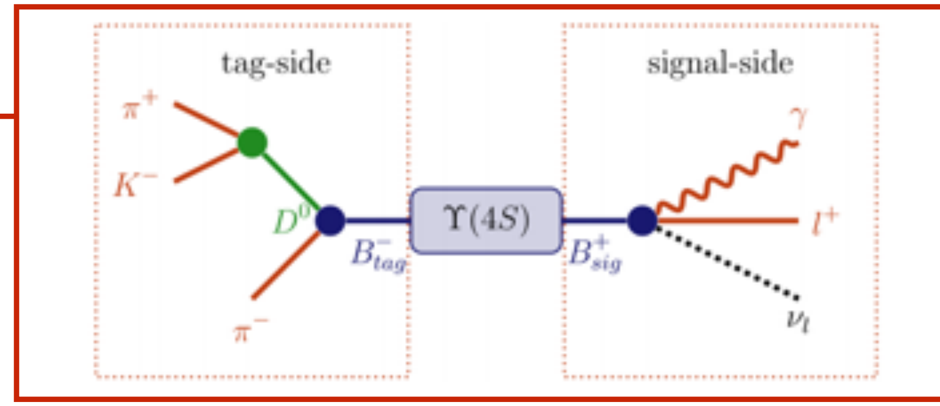
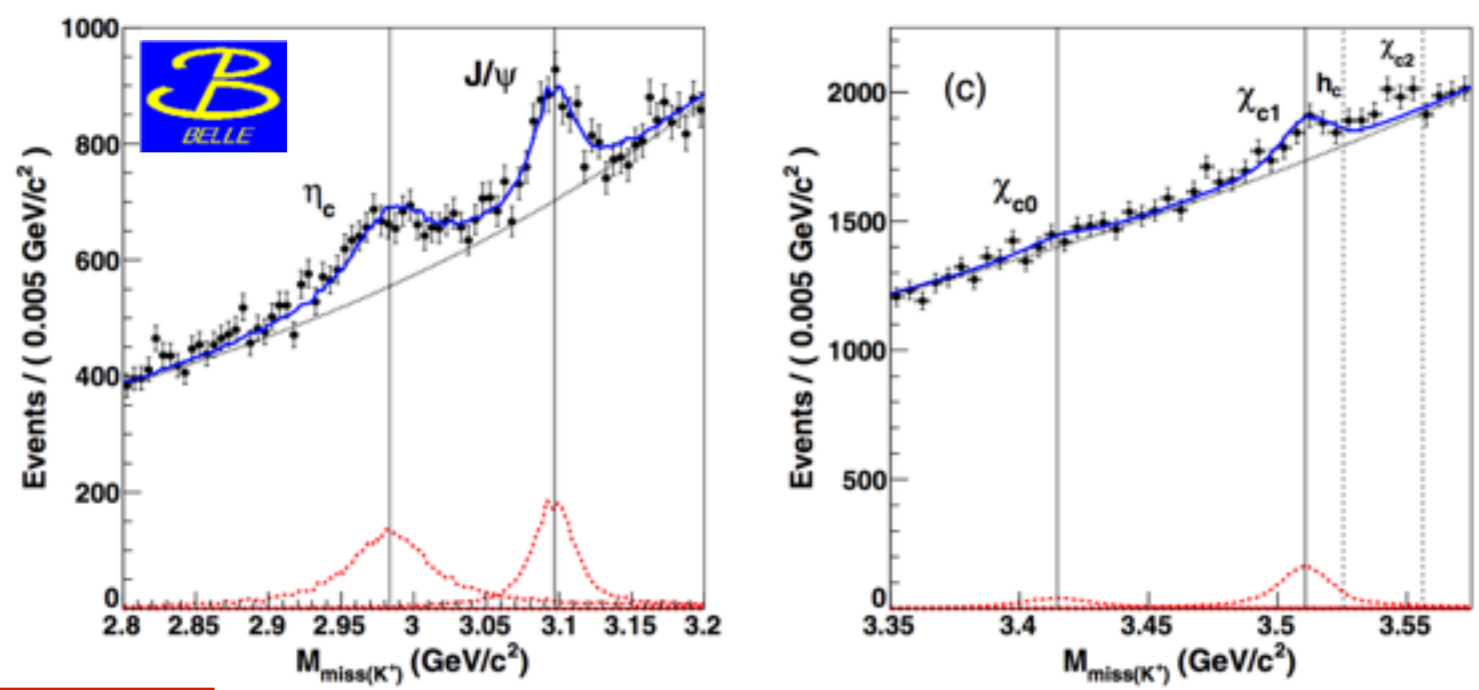


- e^+e^- B-factories only: ➡ **Belle II**



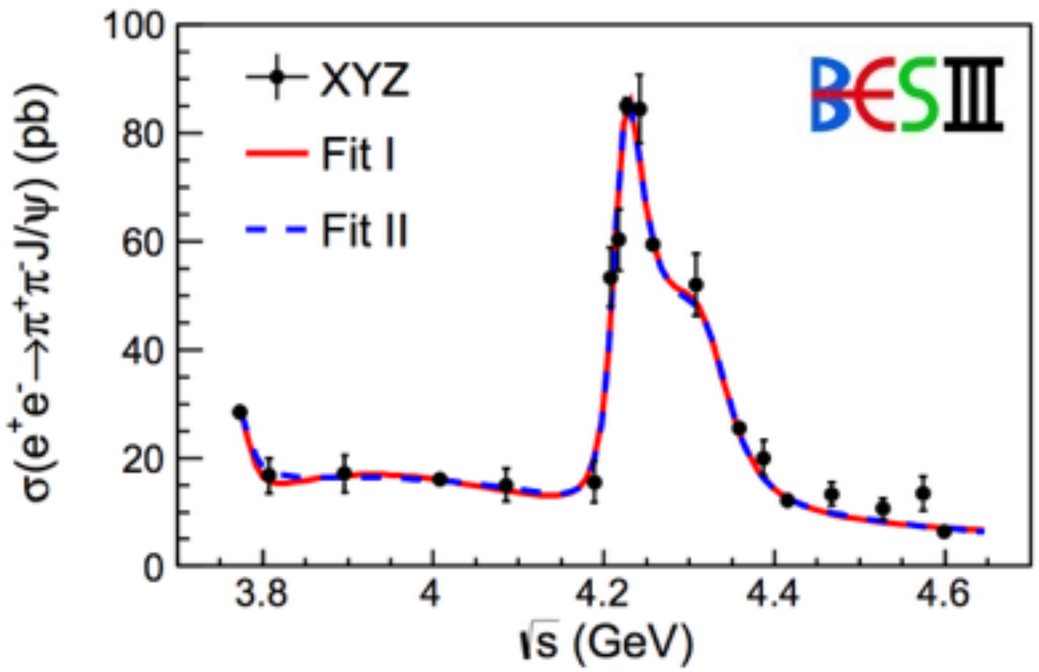
PRD 97, 012005 (2018)

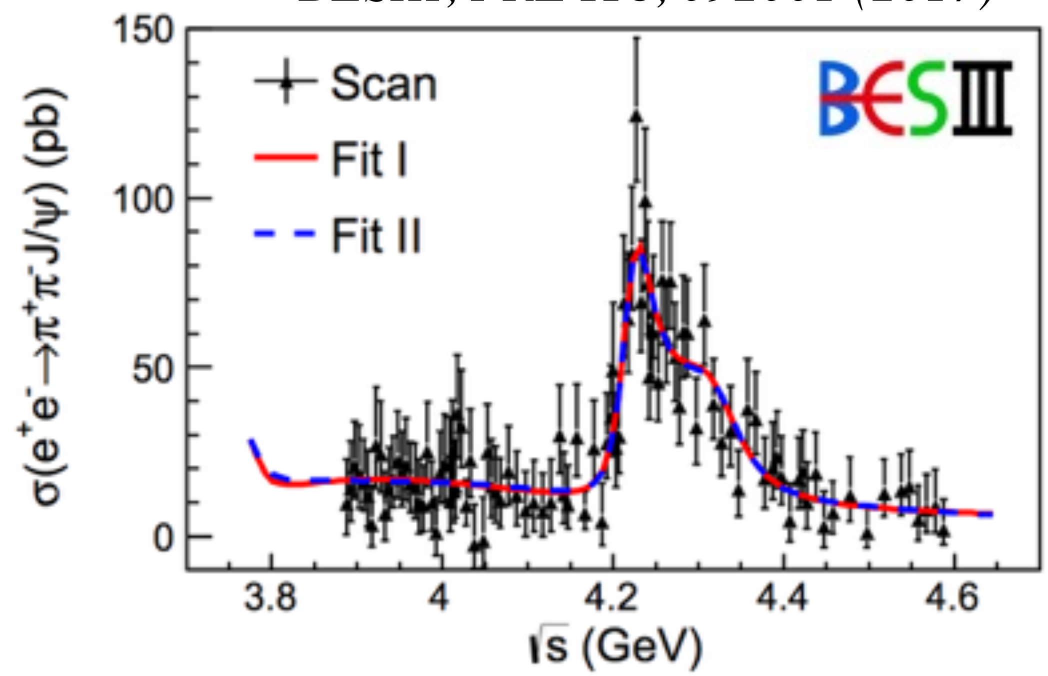


Competitive with LHCb exclusive reconstruction only for:
- hadronic transitions with π^0,η,ω in final state
- states decaying with large multiplicities

- Competition from BESIII

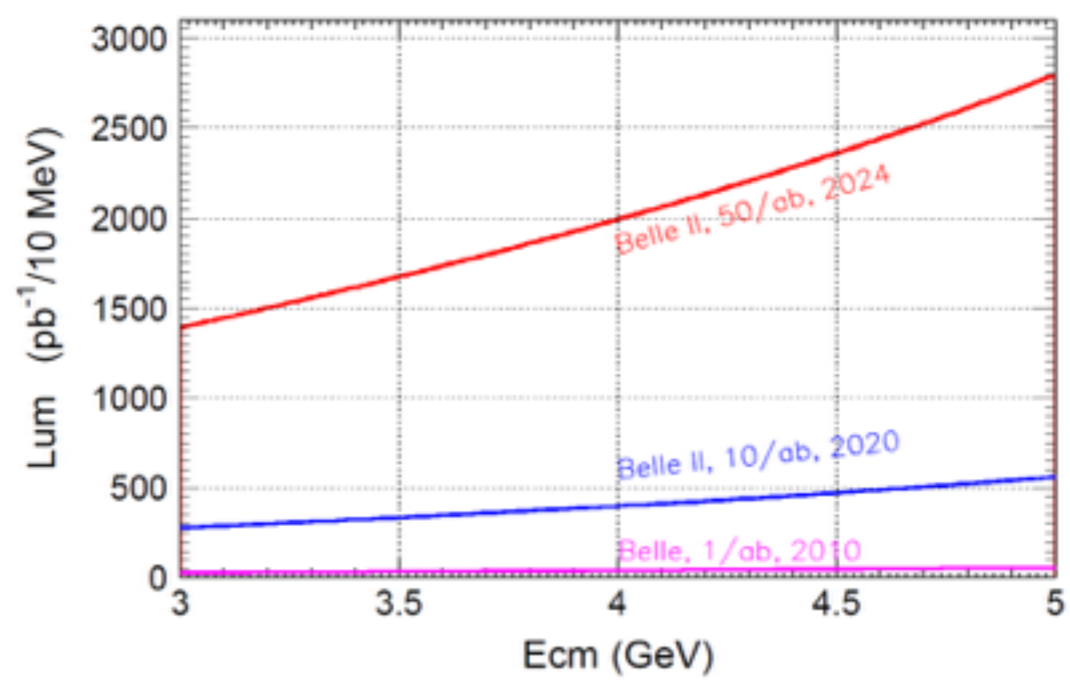
BESIII, PRL 118, 092001 (2017)





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

➡ **Belle II**
- Higher effective luminosity
- Wider mass range

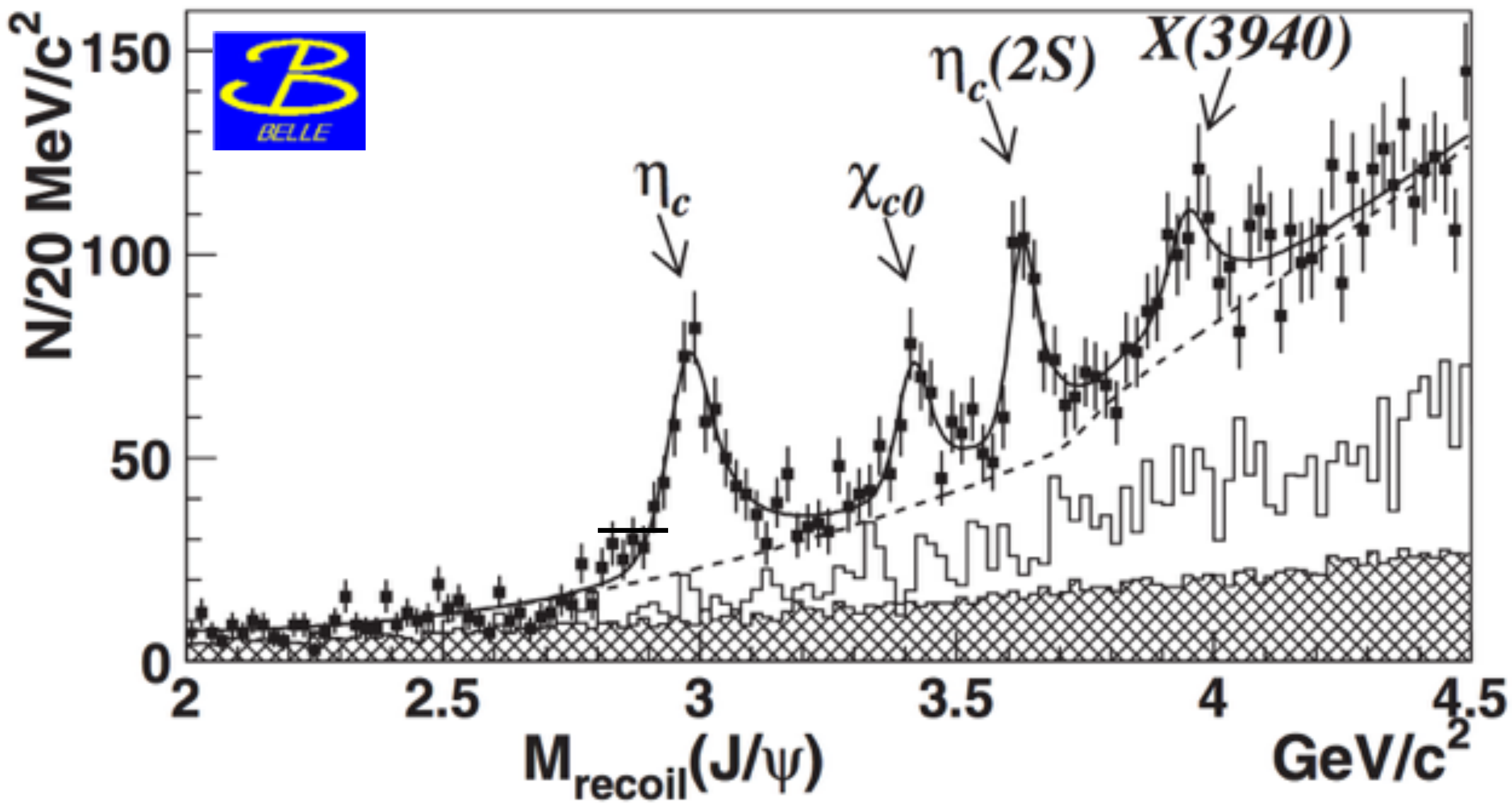


Charmonia: double charmonium production

only at Belle II

- Observed in combinations of J=1 and J=0
  $e^+e^- \rightarrow c\bar{c}\,(0+/-)\,c\bar{c}\,(1-/+)$

Belle, PRL 98, 082001 (2005)



➡ **Belle II**
- angular distributions, production
- probe for new states

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	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$	$\frac{\Upsilon(nS)}{\Upsilon(4S)}$
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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)

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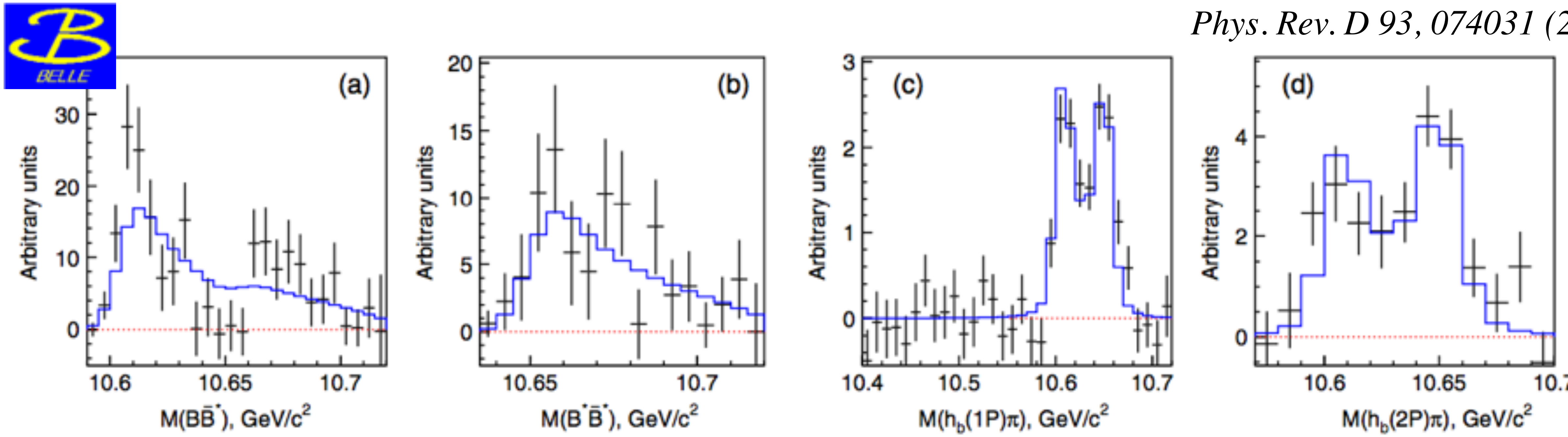
Υ(5S) runs: Z_b masses (precision study)

- 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

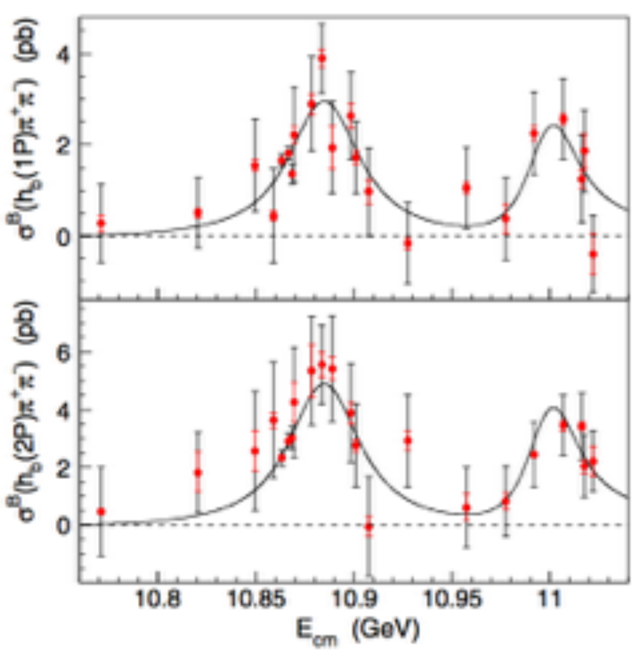
estimate of the Z_b location with respect to the thresholds:

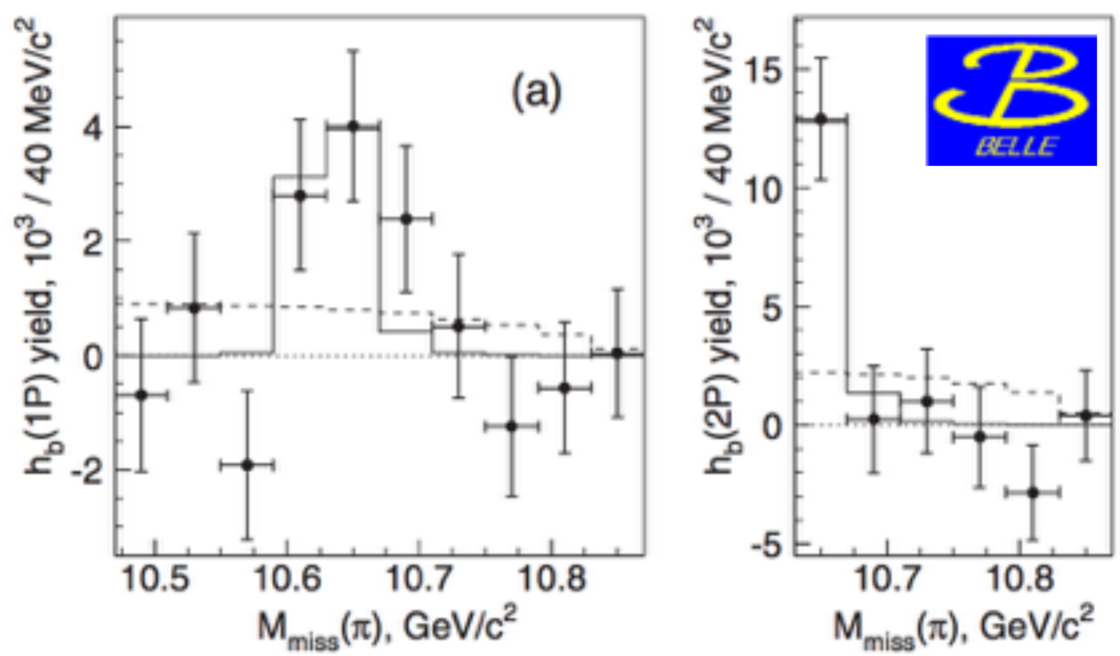
$$\epsilon_B(Z_b) = (0.60^{+1.40}_{-0.49} \pm i0.02^{+0.02}_{-0.01})\ \text{MeV},$$
$$\epsilon_B(Z_b') = (0.97^{+1.42}_{-0.68} \pm i0.84^{+0.22}_{-0.34})\ \text{MeV},$$

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

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





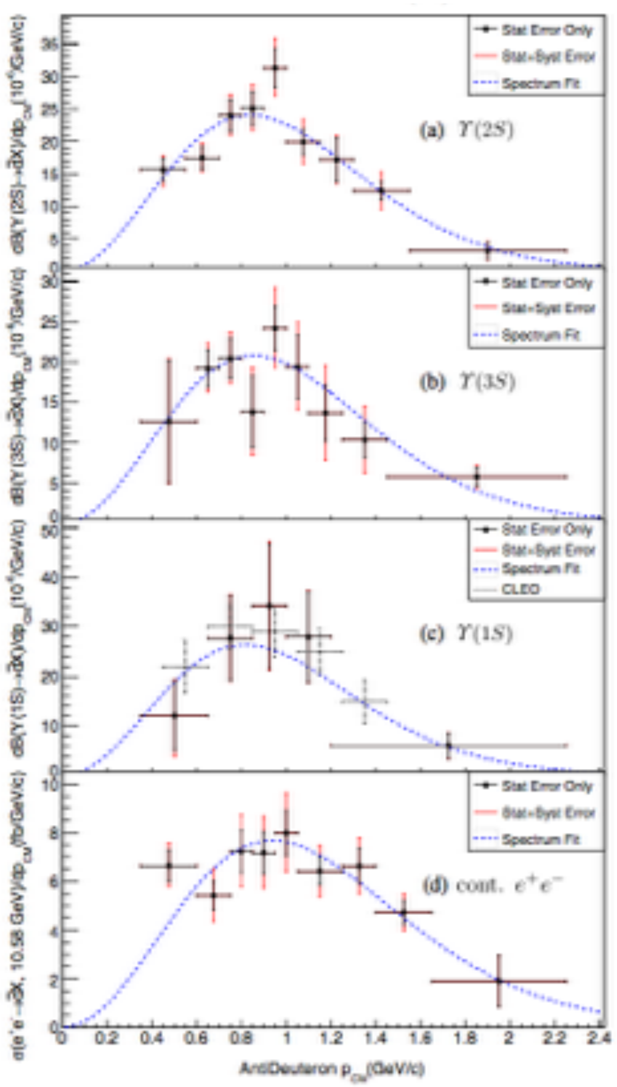
➡ **Belle II**

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

Υ(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:**

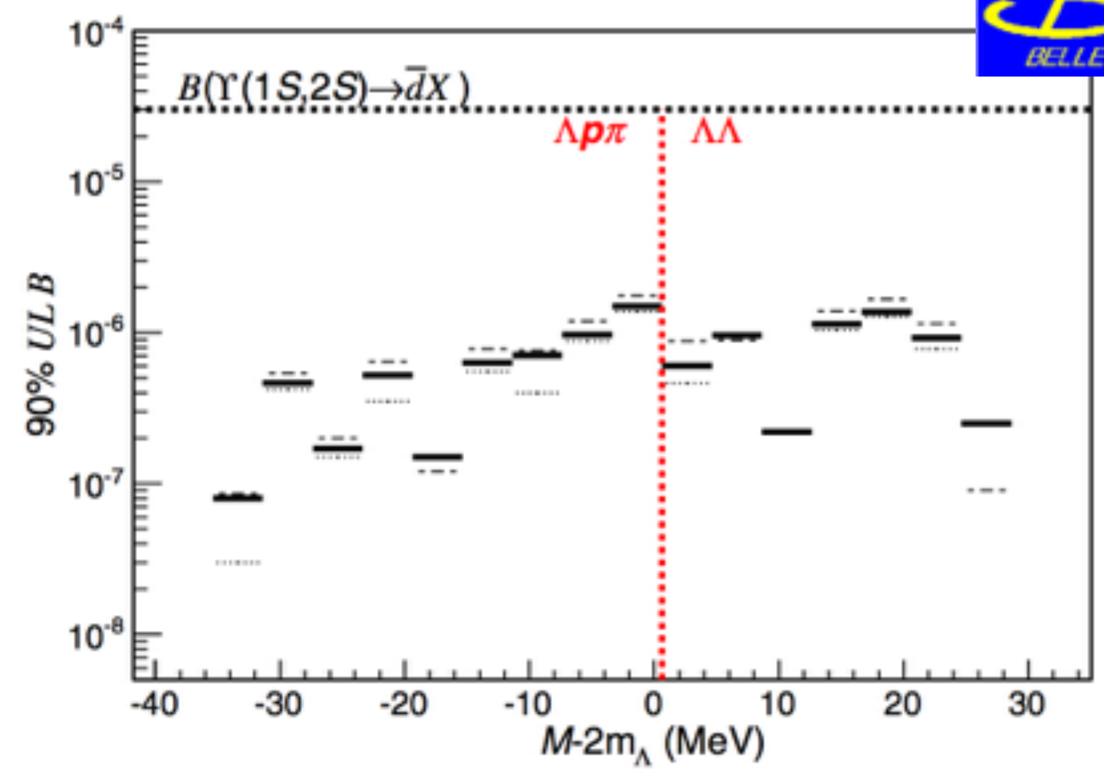
- dedicated tracking and PID
- collect ~3x10^4 $\bar{d}$ in 300 fb^{-1}
- world's best estimate of coalescence parameter
- search for excited nucleons (d*)
- $d\bar{d}$ associated production

Υ(3S) runs: Λ-Λ interaction

➡ From Belle:

- No sign of weakly bound H dibaryon
- Near threshold enhancement in exclusive annihilations
  $\Upsilon(1S,2S) \rightarrow \Lambda\bar{\Lambda} X$ (still not published)

Phys. Rev. Lett. 110, 222002



➡ Belle II

- search for H dibaryon in missing mass ($\Upsilon(3S) \rightarrow \Lambda\bar{\Lambda}$ 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 $\Lambda\bar{\Lambda}$ 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 II
- Belle II just ended Phase 2 commissioning run:
    - Effort to understand machine and the backgrounds, detector response, and test the software
    - First collision data
- Physics run will start at the beginning of 2019
- A variety of quarkonium studies will be possible

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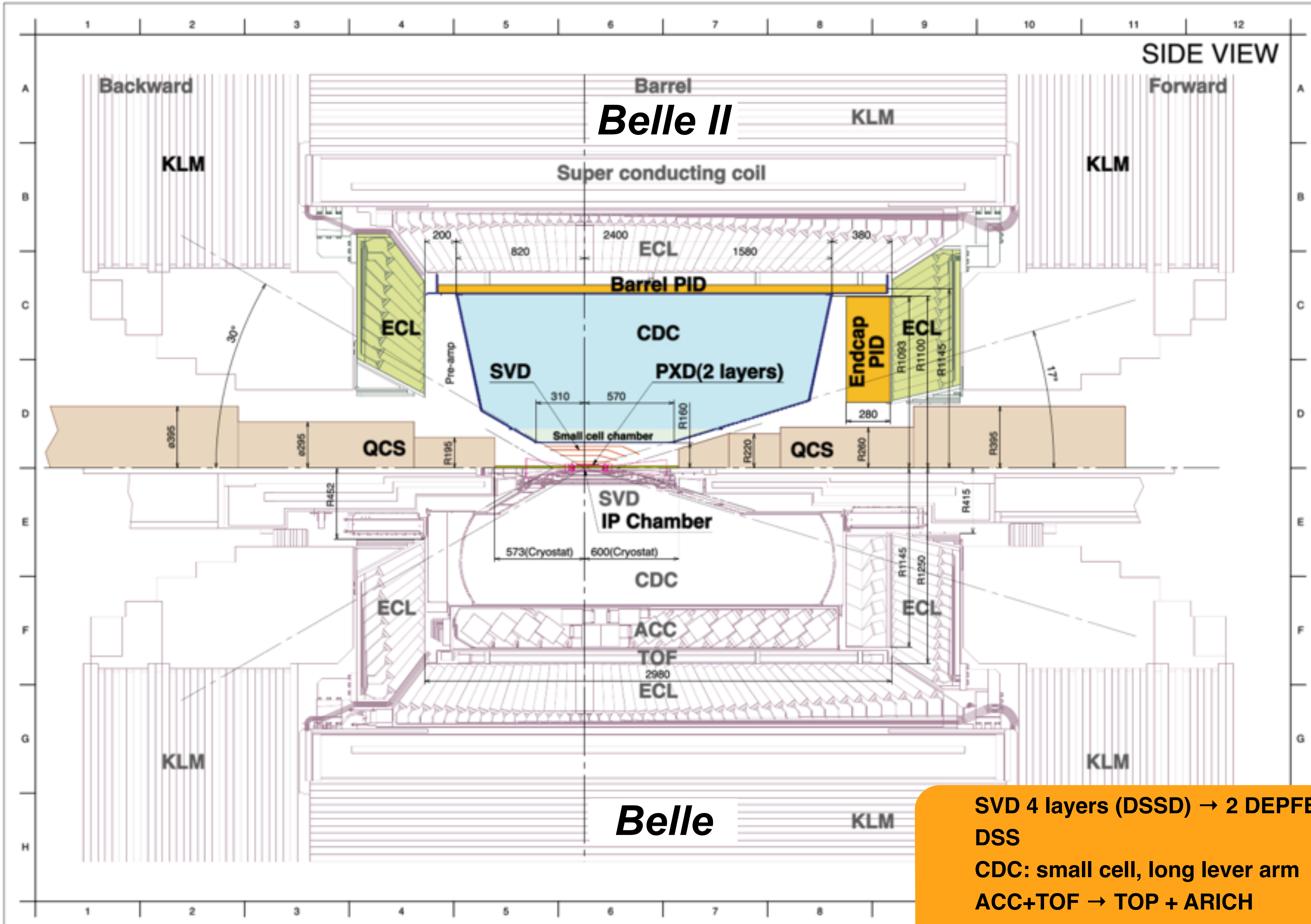
Thanks for the attention and.. stay tuned!

BACKUP

KEKB VS SuperKEKB

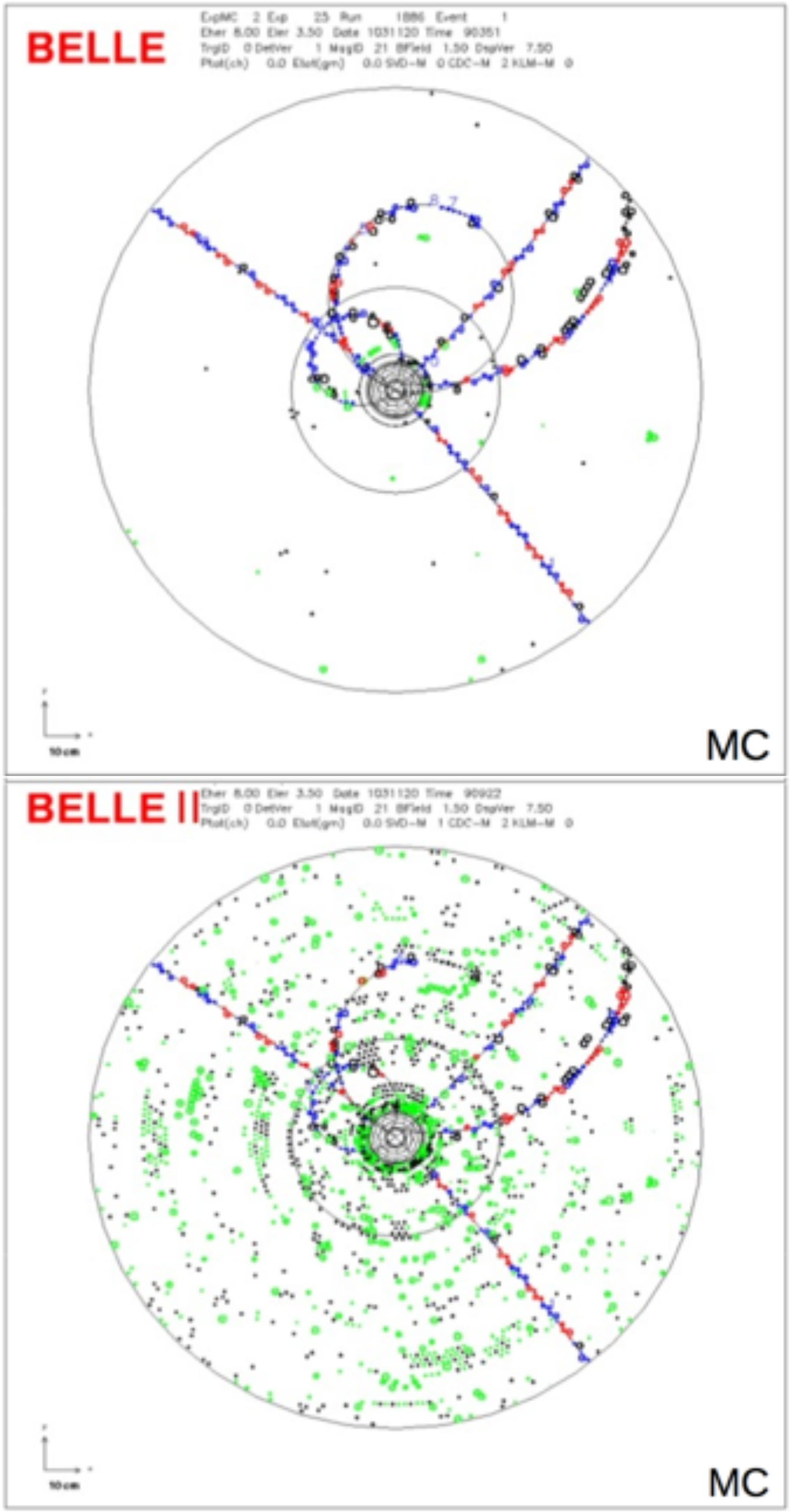
parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
beam energy	E_b	3.5	8	4	7	GeV
CM boost	$\beta\gamma$	0.425		0.28		
half crossing angle	φ	11		41.5		mrad
horizontal emittance	ε_x	18	24	3.2	4.6	nm
emittance ratio	κ	0.88	0.66	0.37	0.40	%
beta-function at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
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}		$cm^{-2}s^{-1}$

From Belle to Belle II



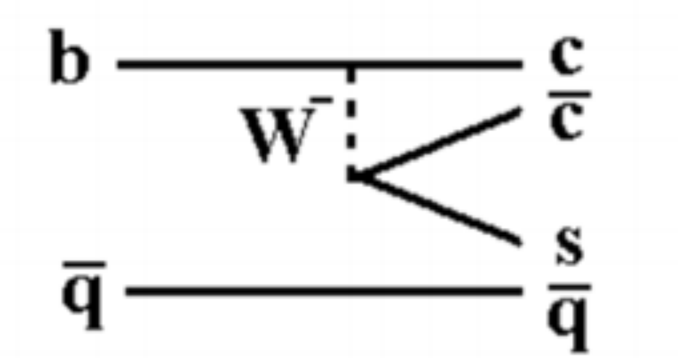
SVD 4 layers (DSSD) → 2 DEPFET + 4 DSS
CDC: small cell, long lever arm
ACC+TOF → TOP + ARICH
ECL: waveform sampling
KLM: RPC → Scintillator+SiPM

New challenges

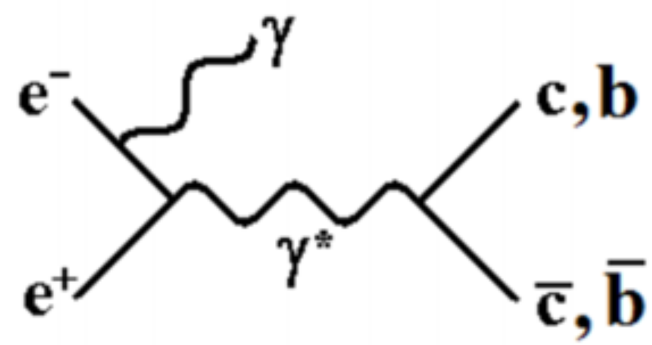


- ➡ x40 luminosity:
  - x40 produced signal events
  - Higher background (detector occupancy, fake hits, radiation damage)
  - Higher event rate (trigger rate,DAQ, computing)
- ➡ Important to have a dedicated phase for background studies, detector response and alignment

B decays

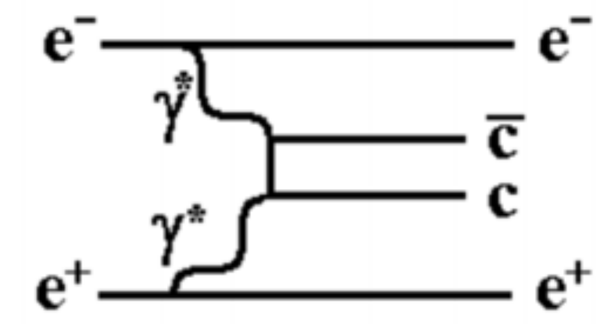


Initial State Radiation(ISR)



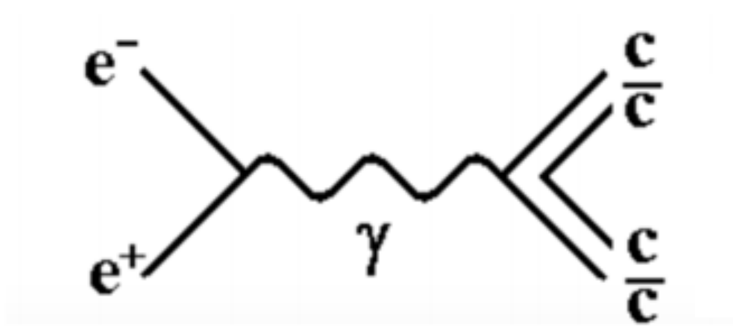
$J^{PC}=1^{--}$

Two γ interaction



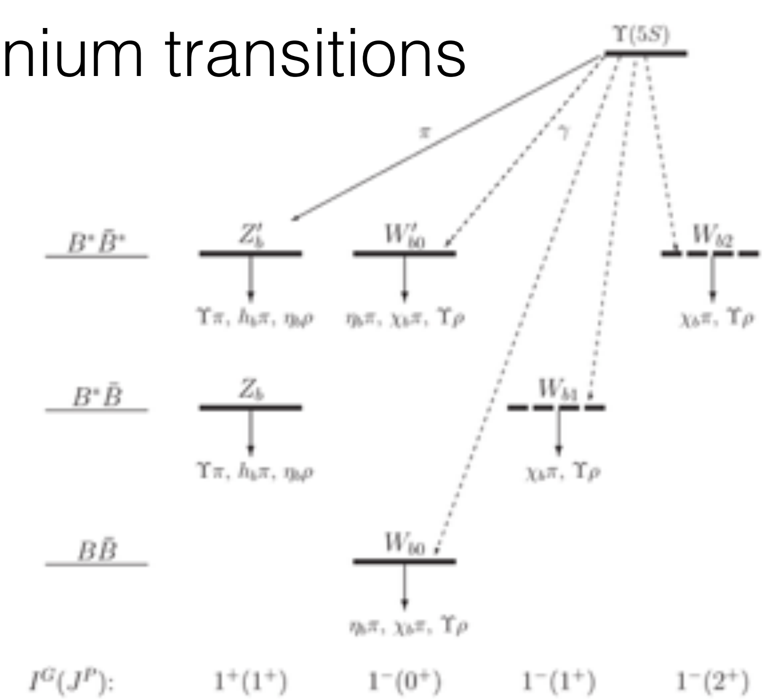
$J^{PC}=0^{-+}$, 0^{++}, 2^{++}

Double charmonium production



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

Quarkonium transitions

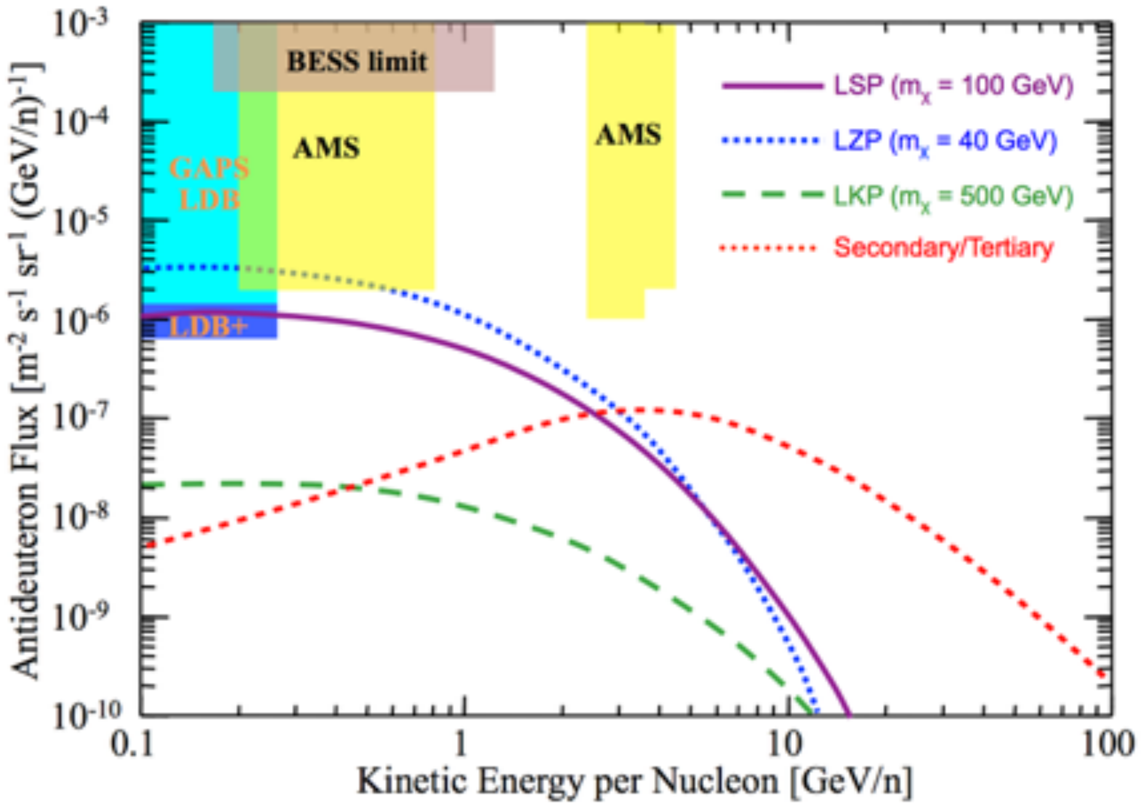


Coalescence model for anti-deuteron production

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 $m_{\bar{p}} = m_{\bar{n}} = m_{\bar{d}}/2$.