Belle II: Status and physics prospects

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On behalf of the Belle II Collaboration

Intensity Frontier in Particle Physics
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Outline

- Motivation for a 50 ab^{-1} e^+e^- B factory
- The SuperKEKB collider
- The Belle II detector
- Performance with early data

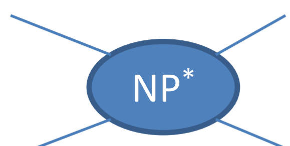
The 1st-generation B factories

- "B factory": High-luminosity, asymmetric-energy e^+e^- collider operating at $\sqrt{s} = 10.59$ GeV to produce $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

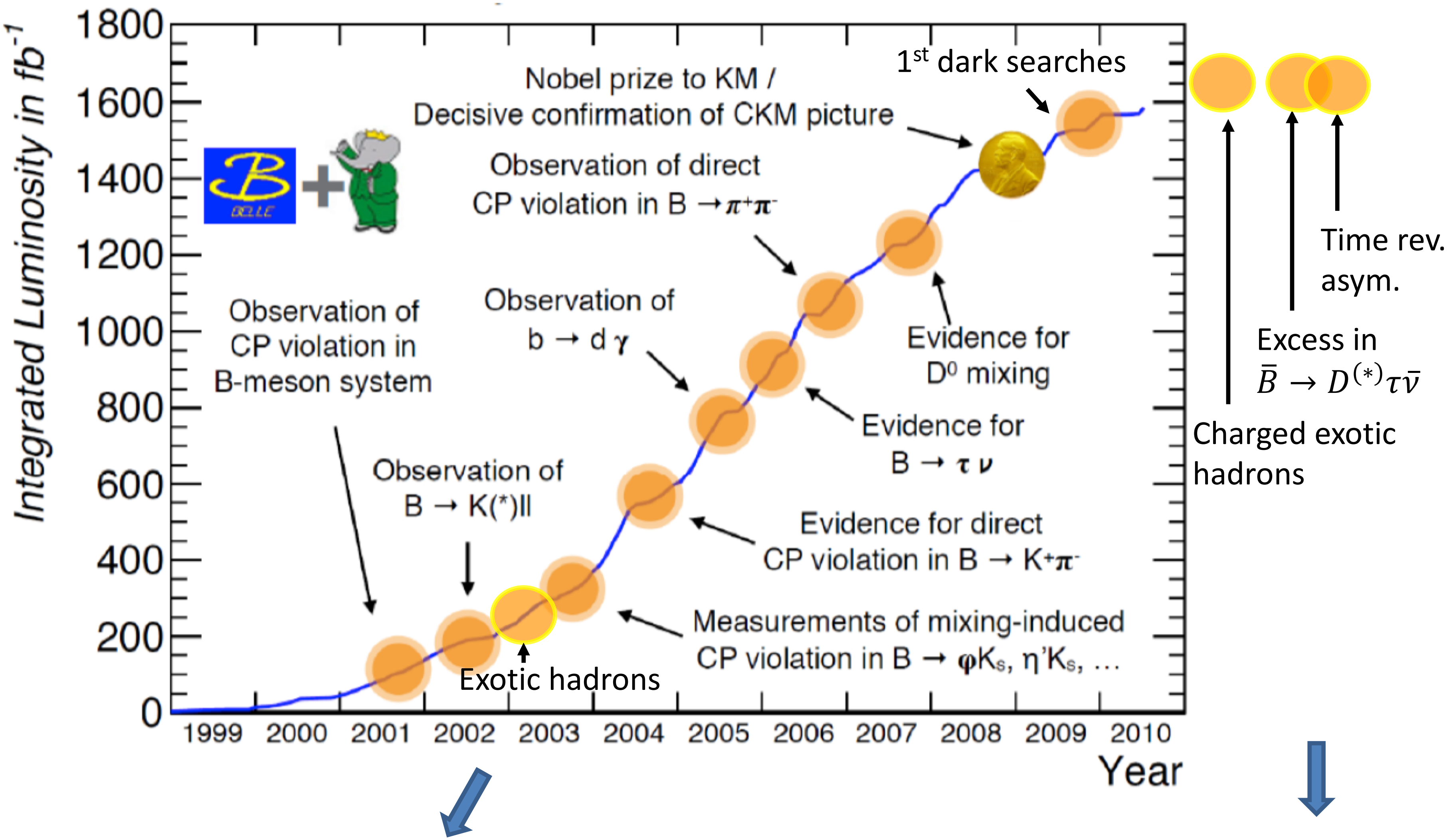
1999-2010
$\sim 1000\ \text{fb}^{-1} = 1\text{ab}^{-1}$

1999-2008
$\sim 500\ \text{fb}^{-1} = 0.5\ \text{ab}^{-1}$

- Built on the success of $\Upsilon(4S)$ experiments ARGUS, CLEO, CUSB
- Initial goal: test the CP-violation mechanism of the SM,
  use virtual probes to study high-scale new physics



Some B-factory physics milestones



>100 unique CPV results

~350 papers published after shutdown, 30 in 2018

Motivation for >×30 integrated luminosity

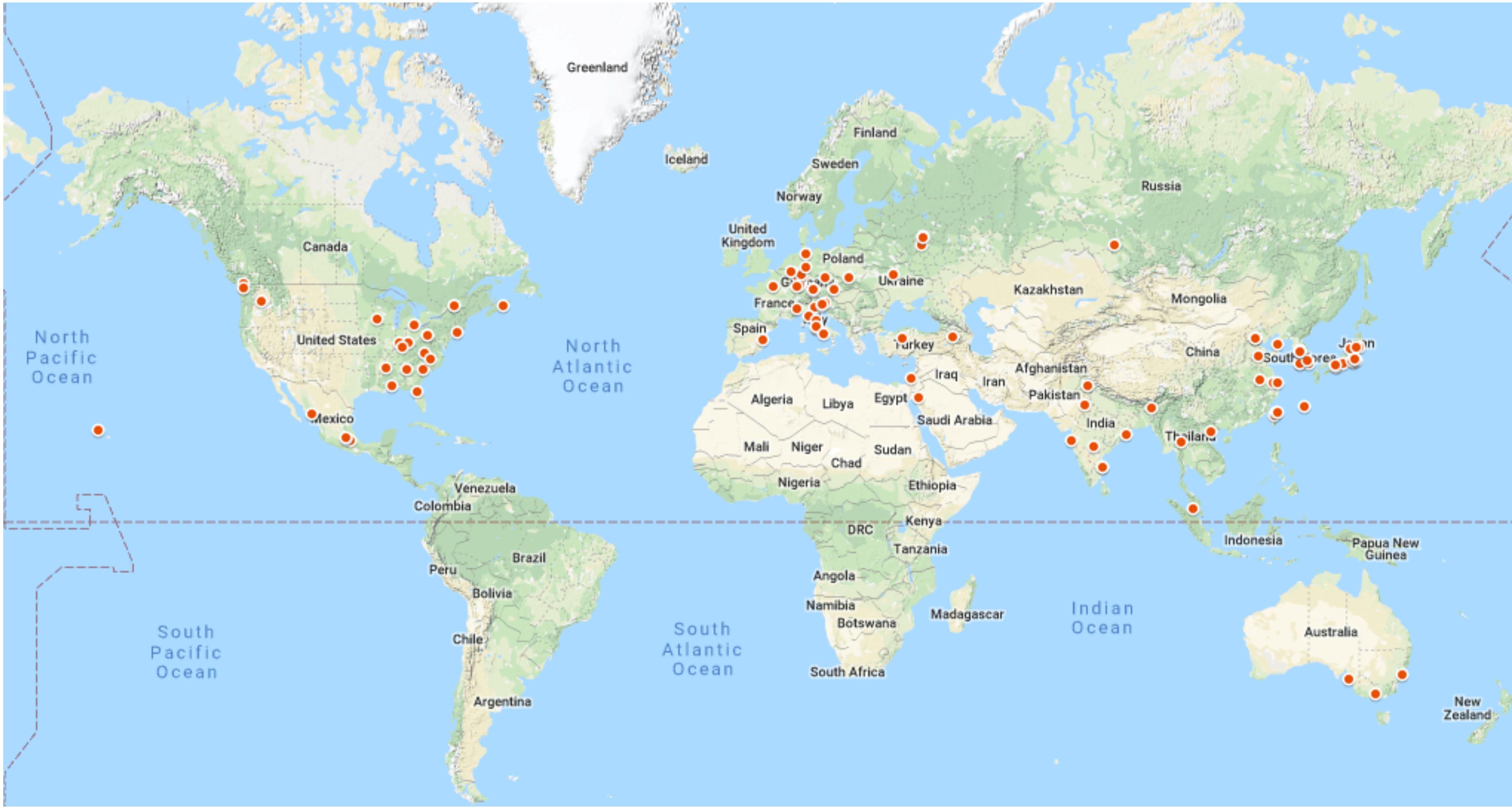
- BABAR and Belle:
  - Established SM flavor-physics picture,
    particularly the Kobayashi-Maskawa mechanism of CP violation
  - Constrained NP at scales >> direct searches at LHC
  - Discovered exotic (non-$q\bar{q}/qqq$) hadrons
  - Provided precision input for lattice, $(g-2)_\mu$
  - Conducted direct searches for light new physics
- This success sets the stage for the physics of Belle II:
  - Stress-testing the SM and sensitively probing new physics via, e.g.,
    - Precision flavor physics: CP violation, meson mixing, decay rates → Talk by A. Gaz
    - Rare processes, e.g., flavor-changing neutral currents → Talk by A. Ishikawa
    - SM-forbidden processes, e.g., lepton-flavor non-universality,
      Lepton number/flavor violation
    - Direct searches for light new states

Checkout the Belle II Physics Book: https://arxiv.org/abs/1808.10567

Belle II and LHCb: competition and complementarity

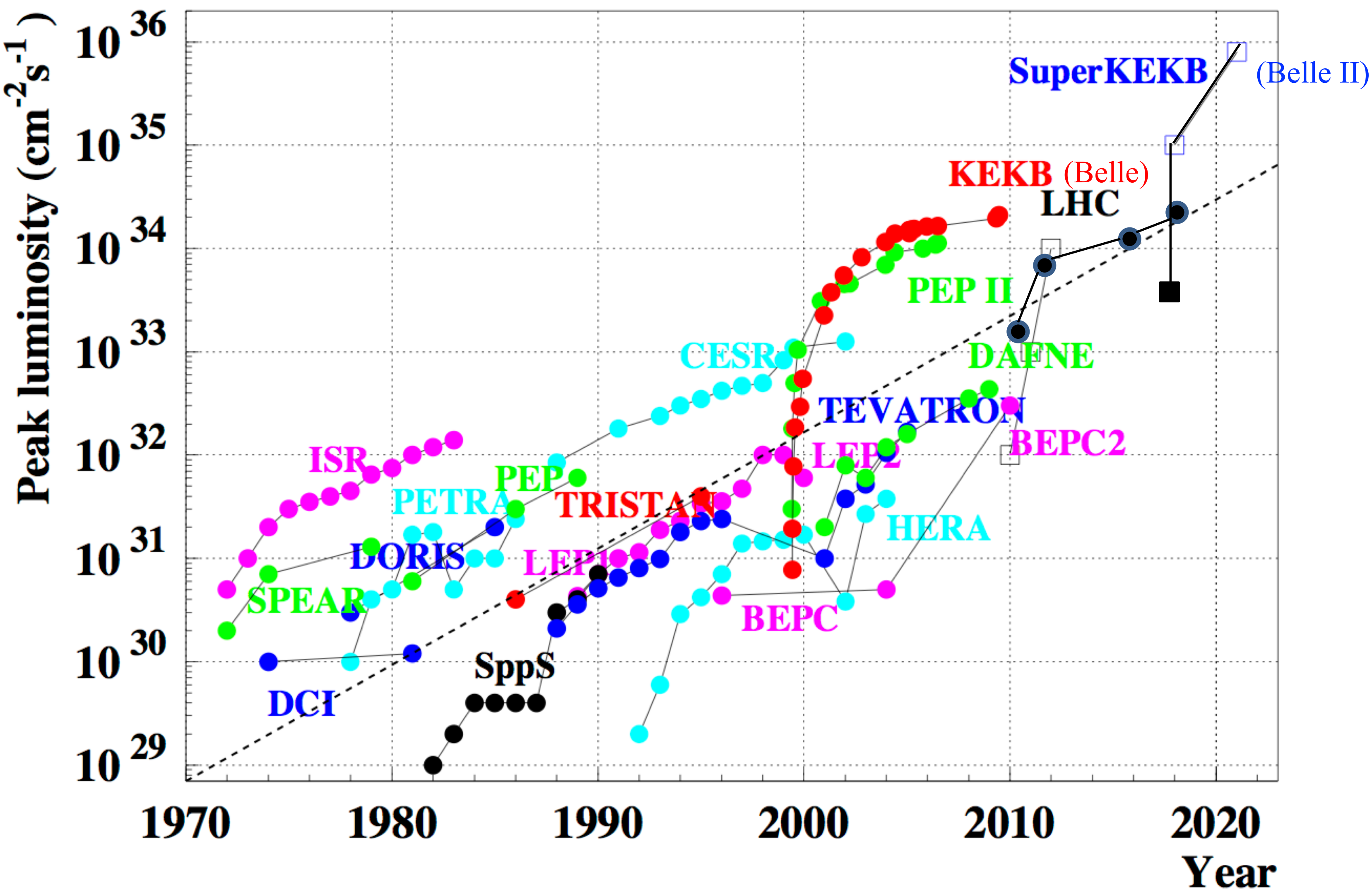
Property	LHCb	Belle II
$\sigma_{b\bar{b}}$ (nb)	~150,000	~1
$\int L\,dt$ (fb^{-1}) by ~2027	~25	~50,000
Background level	High	Low
Typical efficiency	Low	High
π^0, K_S efficiency	Low	High
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Good
Collision spot size	Large	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	Partly B_s
τ physics capability	Limited	Excellent
B-flavor tagging efficiency	3.5 - 6%	36%

The Belle II Collaboration



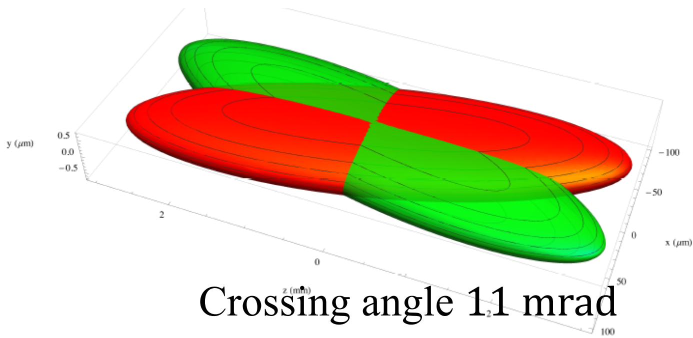
- 26 countries, 113 institutions, close to 1000 collaborators

"Moore's law" of collider luminosity



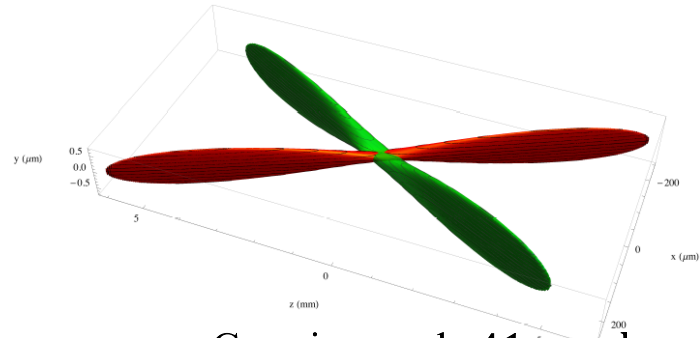
SuperKEKB: ×40 increase in luminosity wrt. KEKB

Beams at KEKB

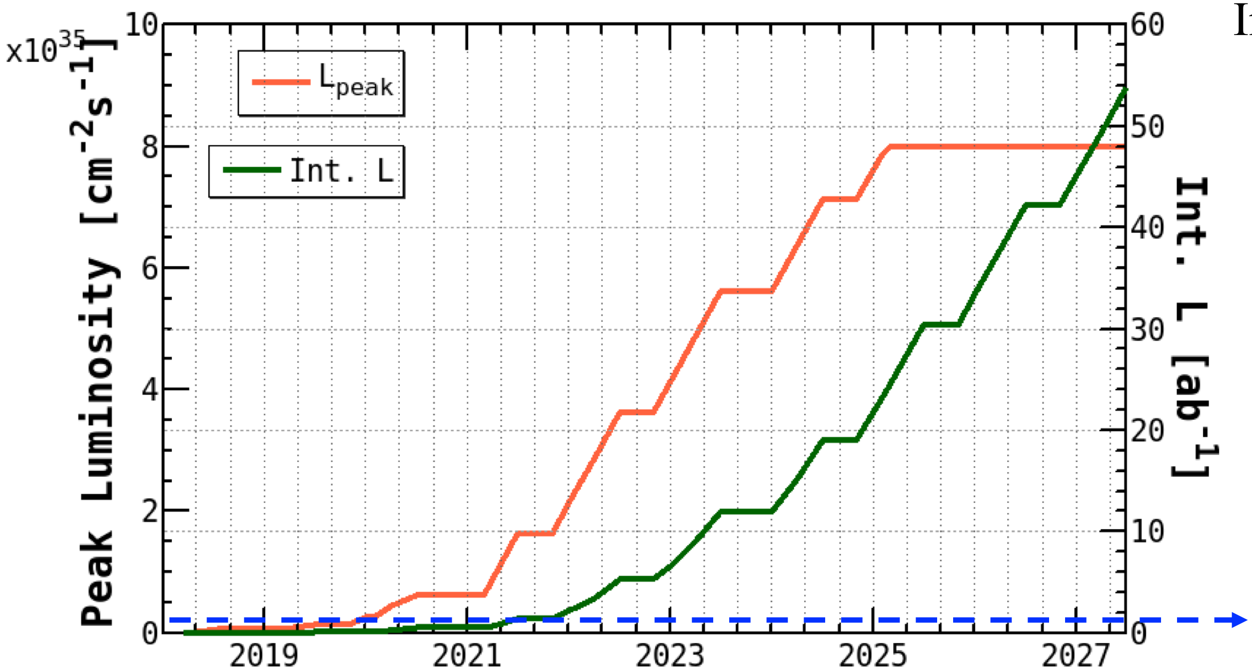


Crossing angle 11 mrad

"Nanobeams" at SuperKEKB



Crossing angle 41 mrad



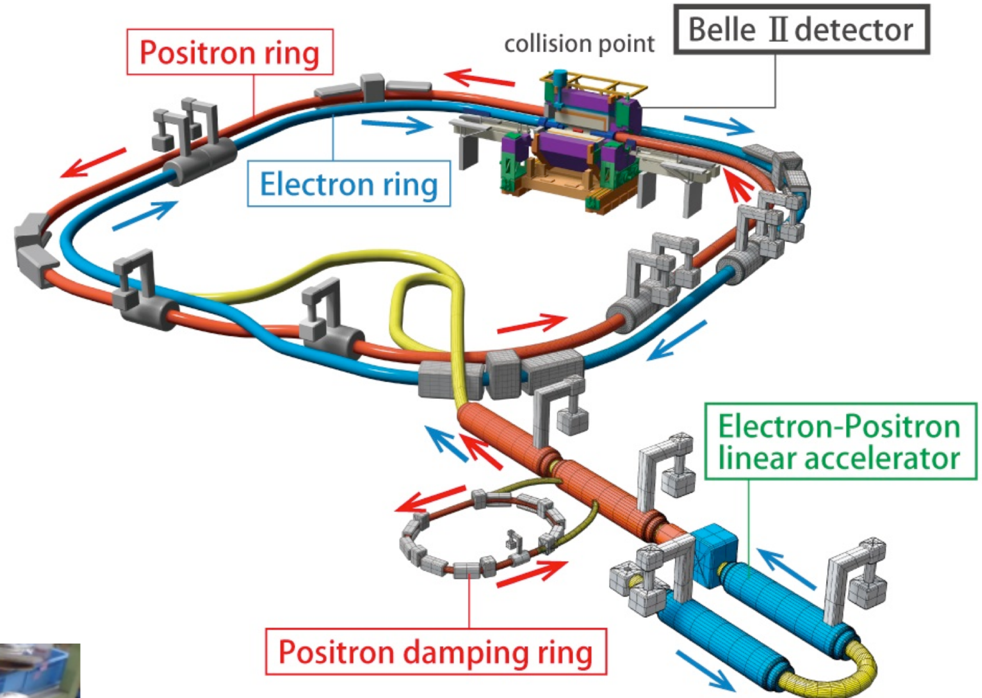
Int. L of Belle

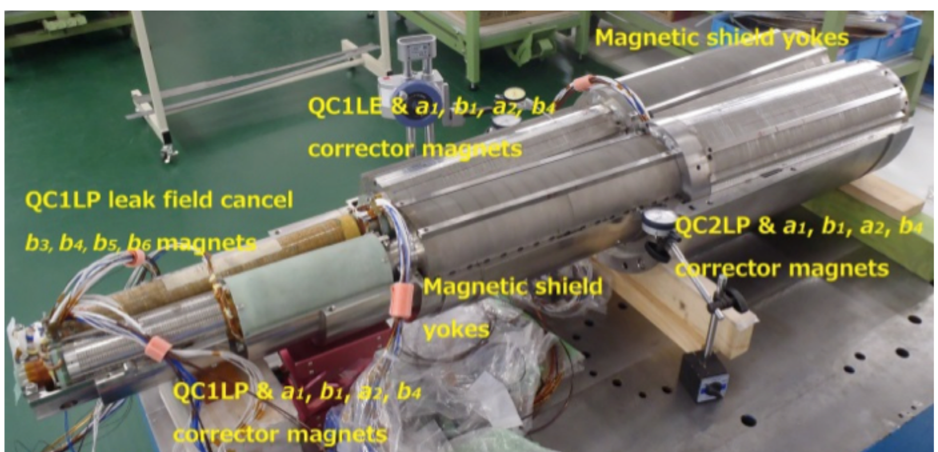
Interaction-point size:

$\sigma_x \times \sigma_y \times \sigma_z =$

$6 \times 0.06 \times 150\ (\mu\text{m})^3$

SuperKEKB collider

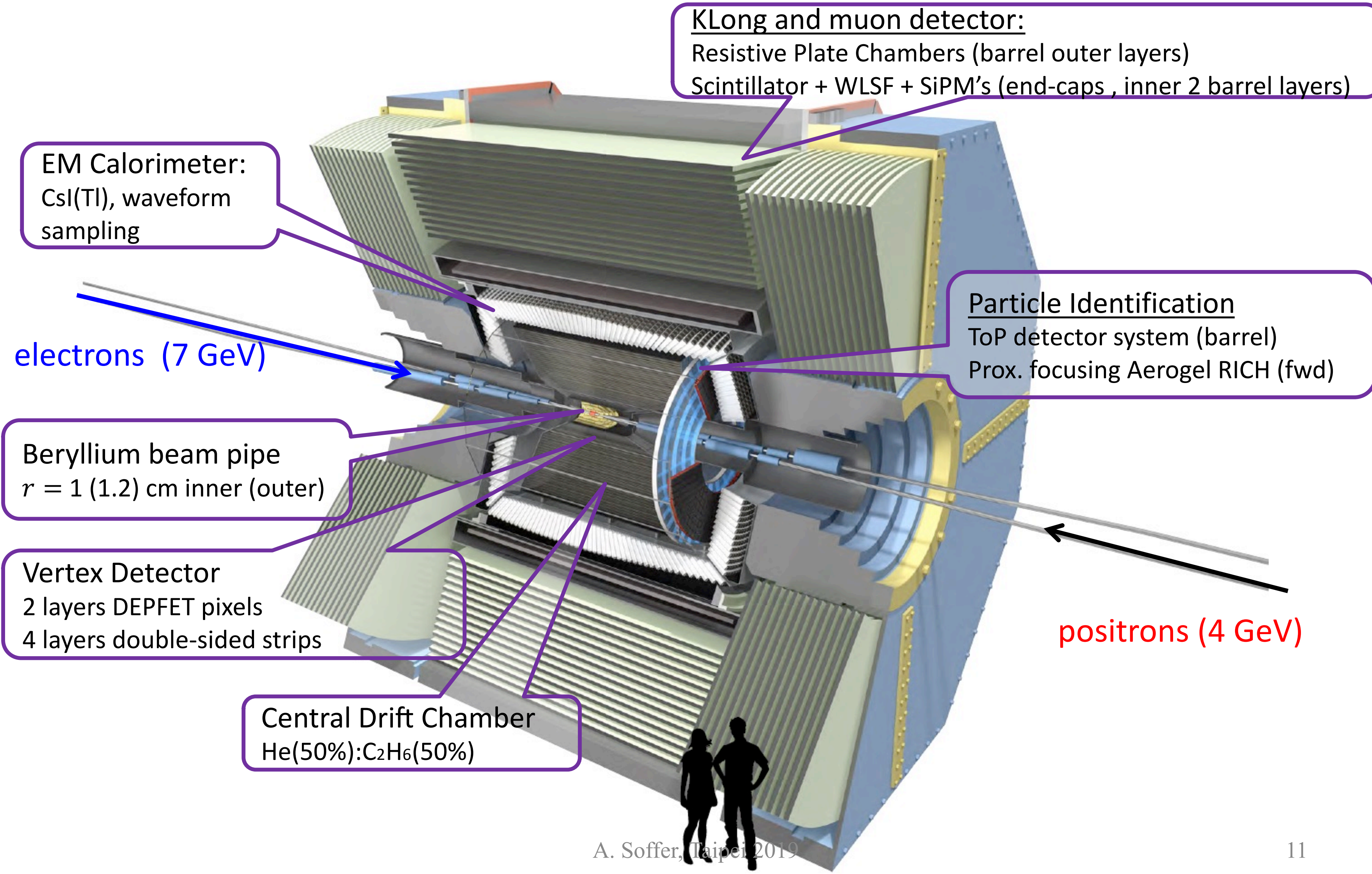




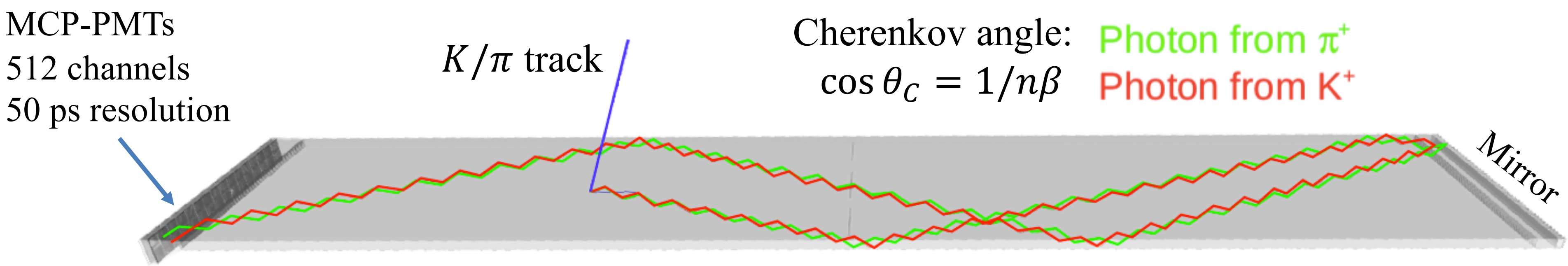
New:
- 3-km-long positron main ring.
- Positron damping ring.
- Complex superconducting final focusing.

http://ipac2018.vrws.de/papers/tuzgbe2.pdf

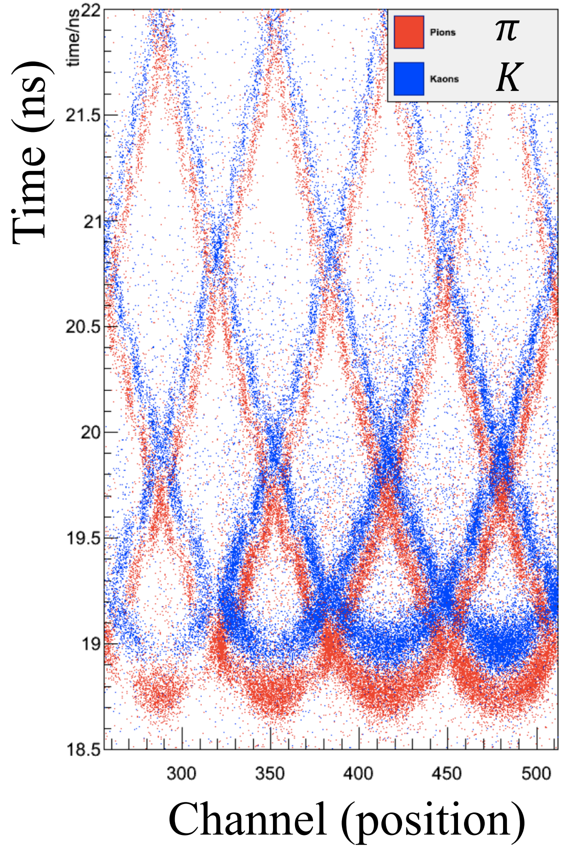
Belle II detector



Barrel hadron ID: Time of Propagation (ToP)



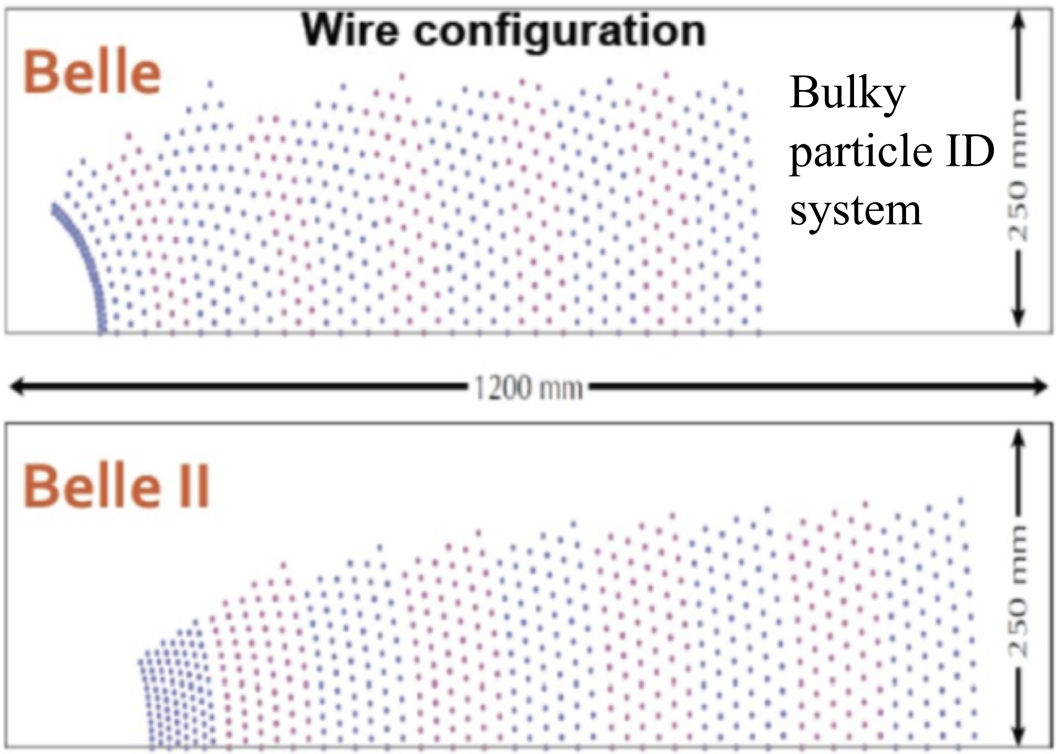
Bar length = 2600 mm, width = 450 mm, thickness = 20 mm



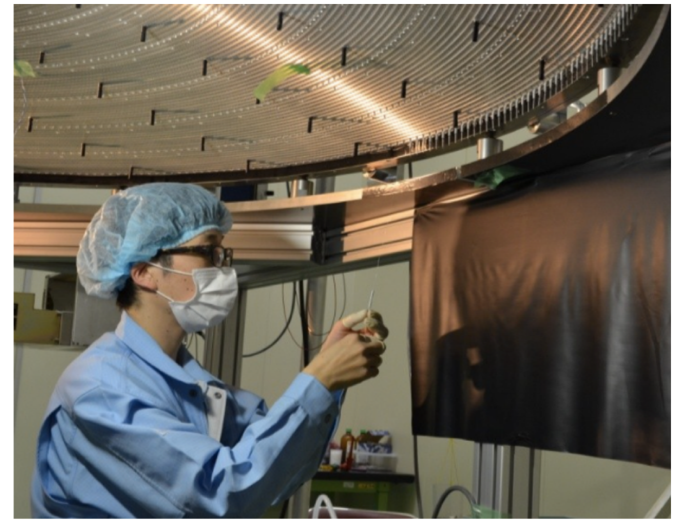
16 quartz-bar modules:

Quartz Property	Requirement
Flatness	<6.3μm
Perpendicularity	<20 arcsec
Parallelism	<4 arcsec
Roughness	< 0.5nm (RMS)
Bulk transmittance	> 98%/m
Surface reflectance	>99.9%/reflection

Detector highlights: drift chamber



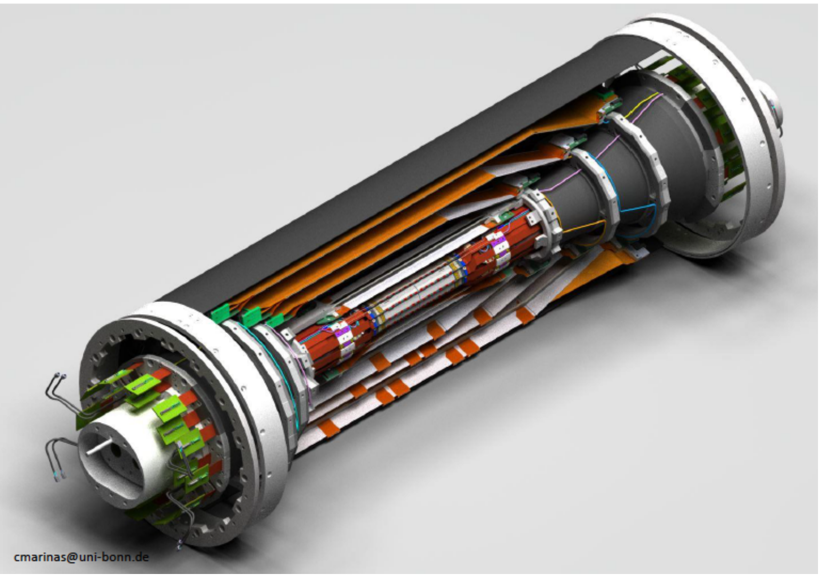
Outer radius almost ~20% larger than at BABAR/Belle: Improved momentum resolution



Stringing 51456 wires

	Belle	Belle II
Innermost sense wire	r=88mm	r=168mm
Outermost sense wire	r=863mm	r=1111.4mm
Number of layers	50	56
Total sense wires	8400	14336
Gas	He:C_2H_6	He:C_2H_6
Sense wire	W(Φ30μm)	W(Φ30μm)
Field wire	Al(Φ120μm)	Al(Φ120μm)

Detector highlights: vertex detector

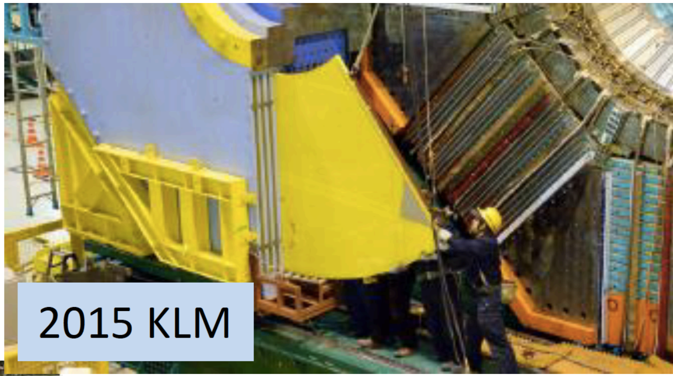


			(@ Belle)
Beampipe		r= 10 mm	(14 mm)
DEPFET pixels			
	Layer 1	r=14 mm	
	Layer 2	r= 22 mm	
DSSD (double sided silicon detectors)			
	Layer 3	r=38 mm	(20 mm)
	Layer 4	r=80 mm	
	Layer 5	r=115 mm	
	Layer 6	r=140 mm	

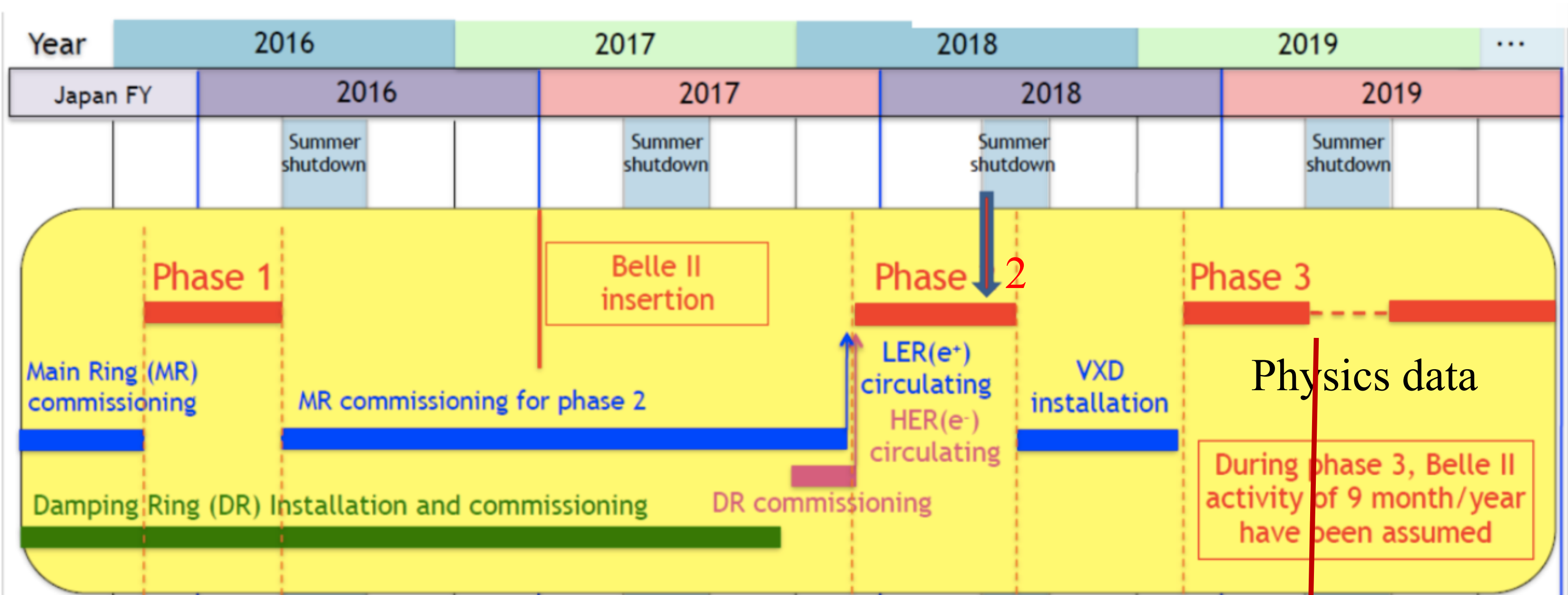
Improvement relative to Belle:

- ~×2 better resolution
  - Enables reduction of collider boost
  - Improves charm & tau detection
- Tolerance of ~×20 background rate

Sub-detector installation



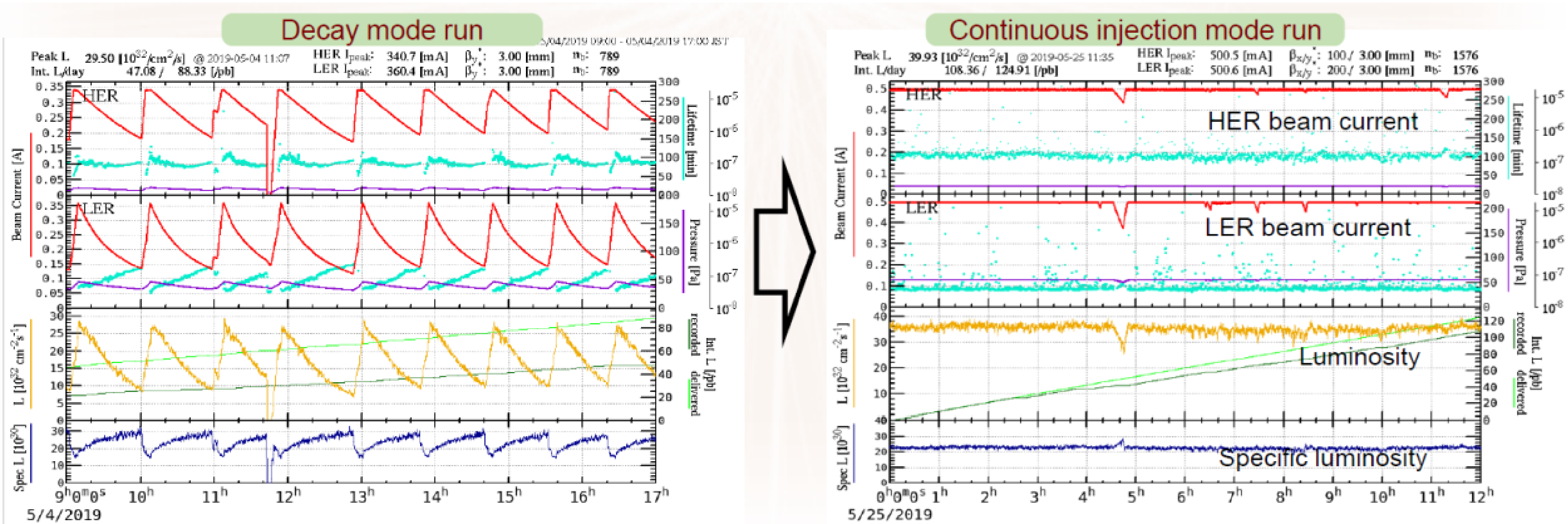
Start-up schedule



First collisions, 26 April, 2018

- Collected ~ 5 fb^{-1}
  - 0.5% of Belle
- Mostly at L ~ $0.5\times10^{34}\ \mathrm{cm}^2\mathrm{s}^{-1}$
  - 25% of KEKB
- Reached L ~ $1.2\times10^{34}\ \mathrm{cm}^2\mathrm{s}^{-1}$
  - With high background
  - Ongoing work on background

Milestone: continuous injection



4 May, 2019 25 May, 2019

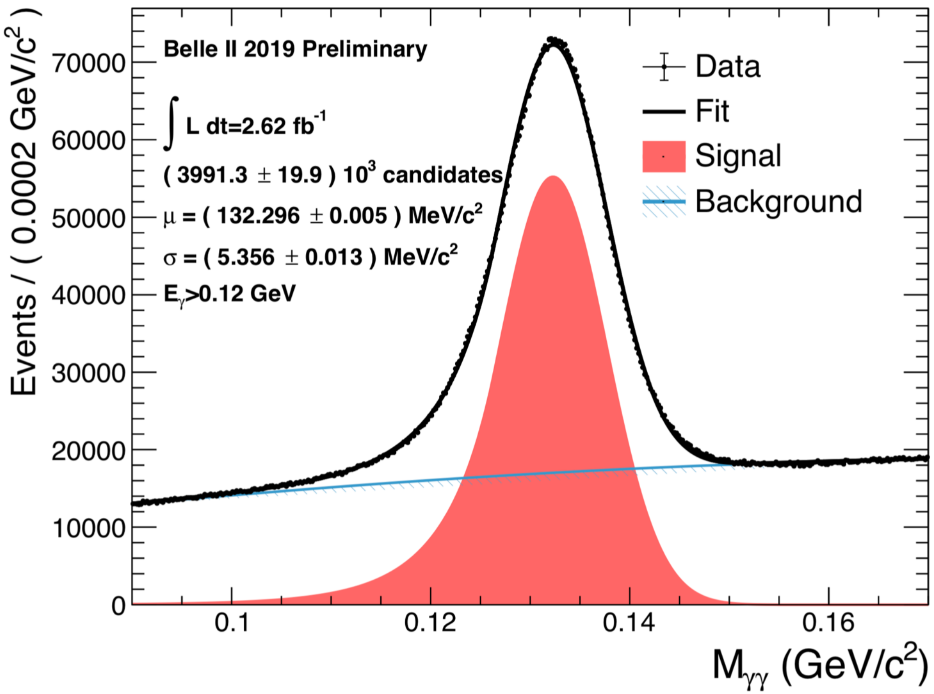
- Employed at PEP-II and KEKB to increase integrated luminosity
- Challenges: high injection background while detector HV is on
- A necessity at SuperKEKB, where beam lifetime is minutes, due to collisions

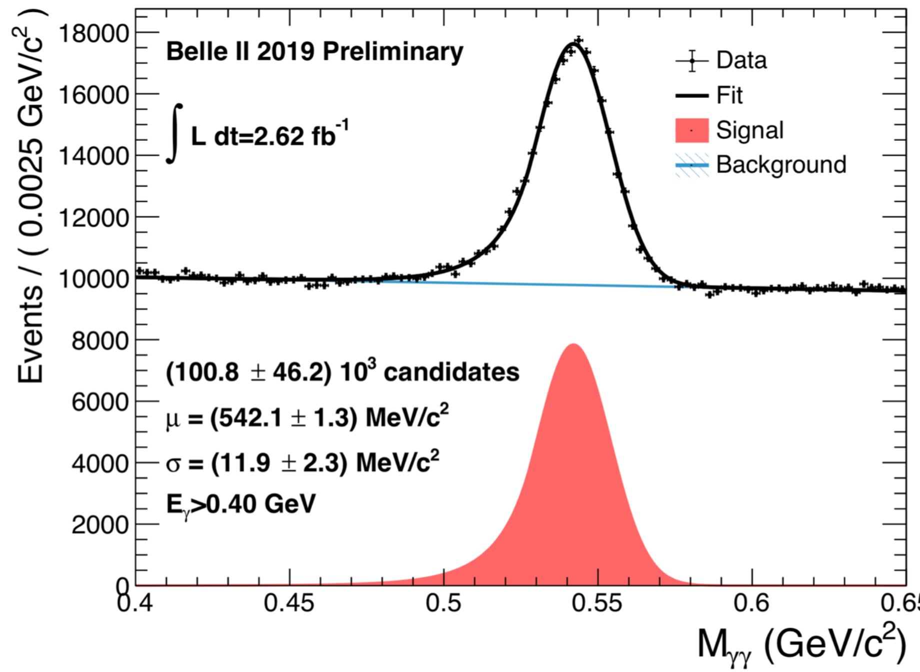
Detector performance and “rediscovery” of known physics

- Current integrated luminosity similar to that of CLEO in mid-90’s
- Used mostly for validating detector performance and commissioning
- A mix of 2018 and 2019 results shown below
- See additional results in talks by A. Gaz and A. Ishikawa

π^0 and $\eta \to \gamma\gamma$

BELLE2-NOTE-PL-2019-019

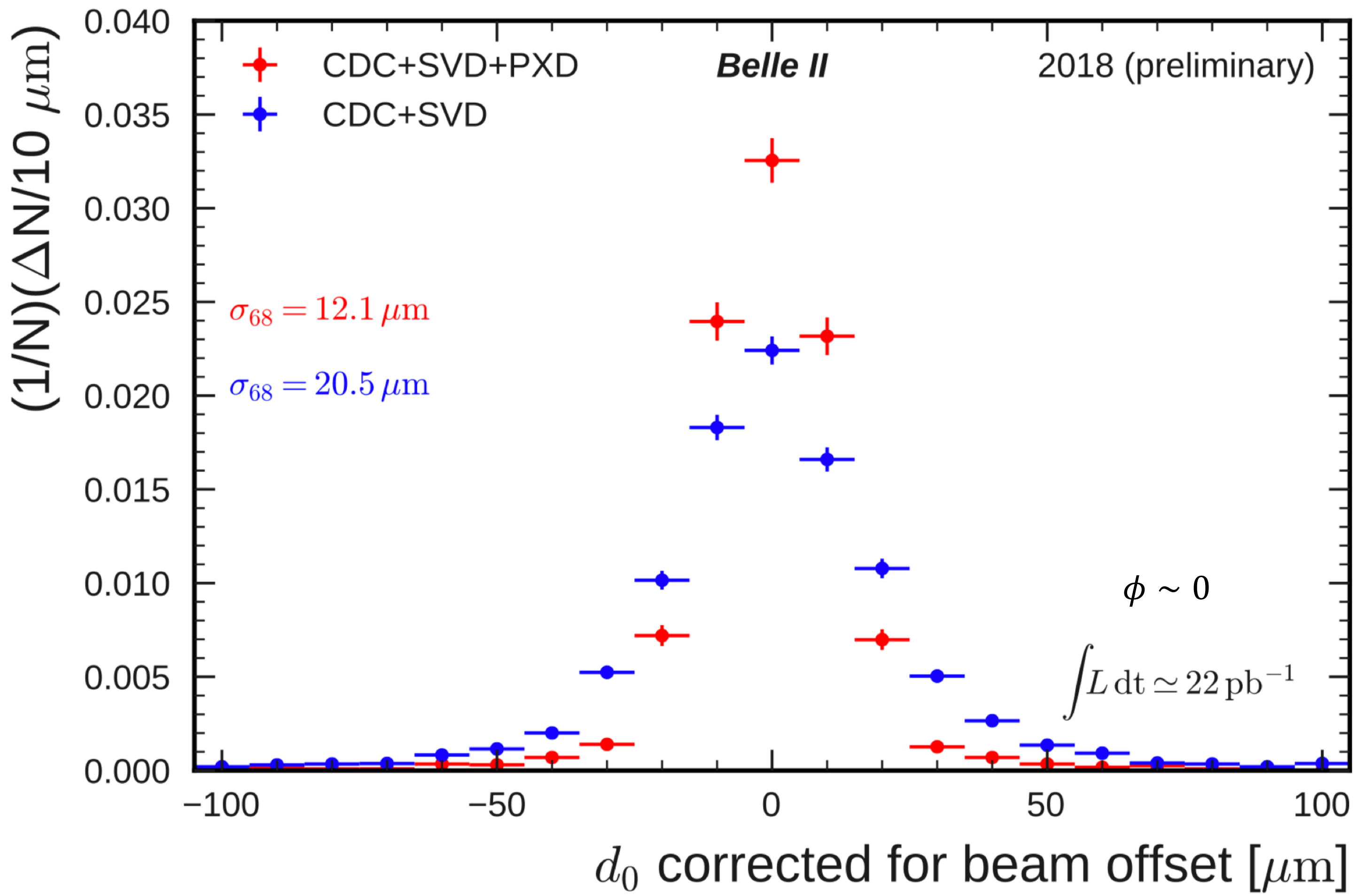




- Photon selection:
  E_9/E_{21} (energy in 9 crystals / energy in 21 crystals) > 0.9

Tracking resolution

BELLE2-NOTE-PL-2018-037



= Impact parameter of track wrt. the beam.

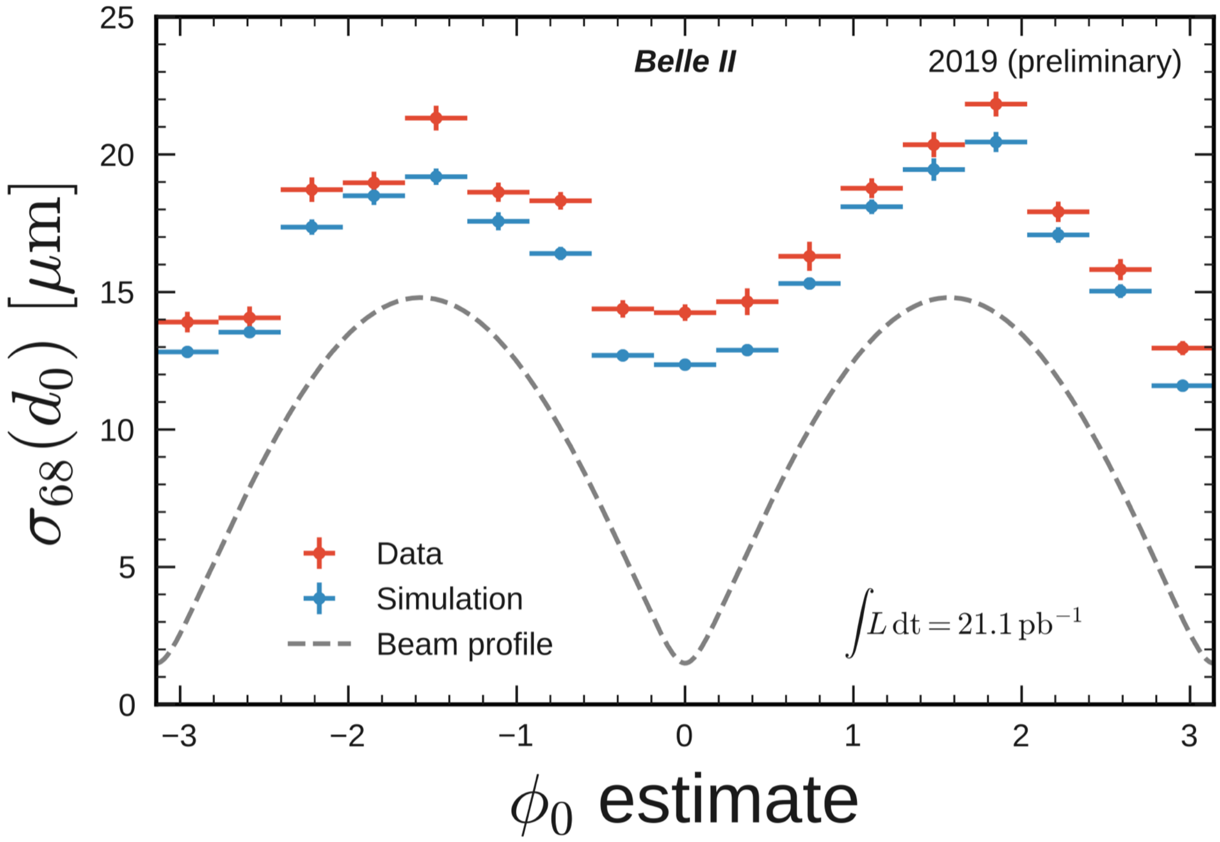
Sign(d_0) = sign of track "angular momentum" in $\hat{z}$

d_0 resolution ~ 12.1 μm in data,
10 μm in simulation

Tracking resolution

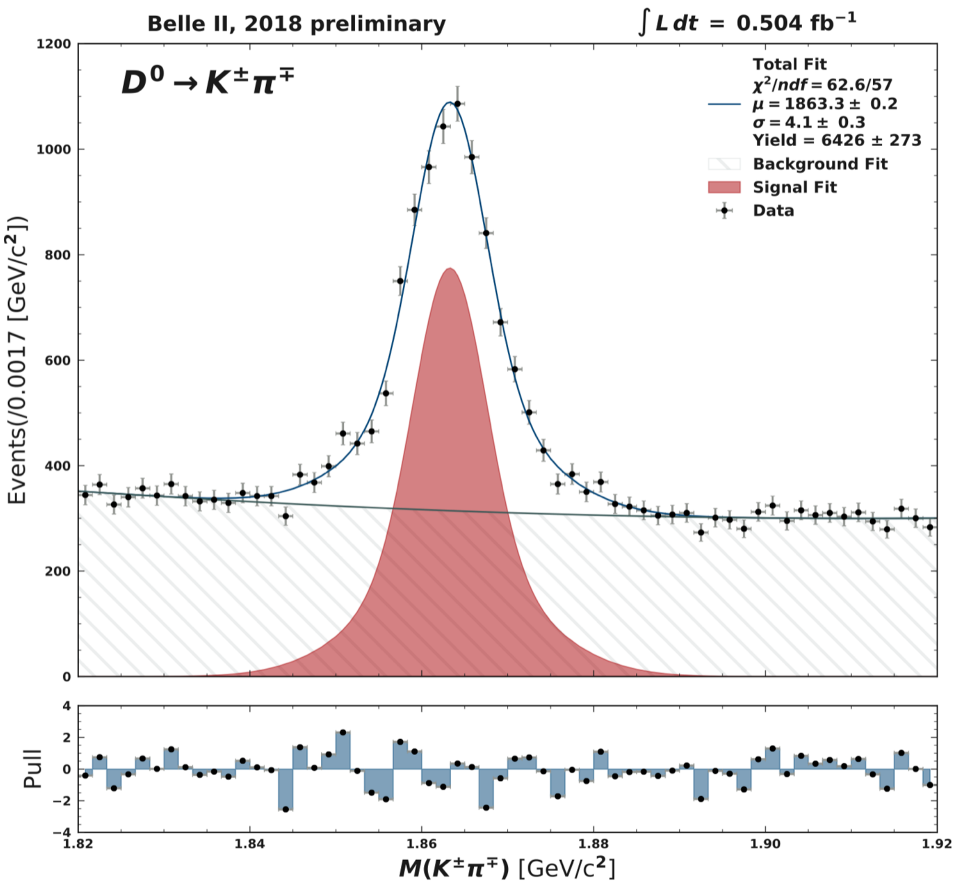
BELLE2-NOTE-PL-2019-011

Difference wrt. expected beam profile gives the ϕ-dependent detector resolution



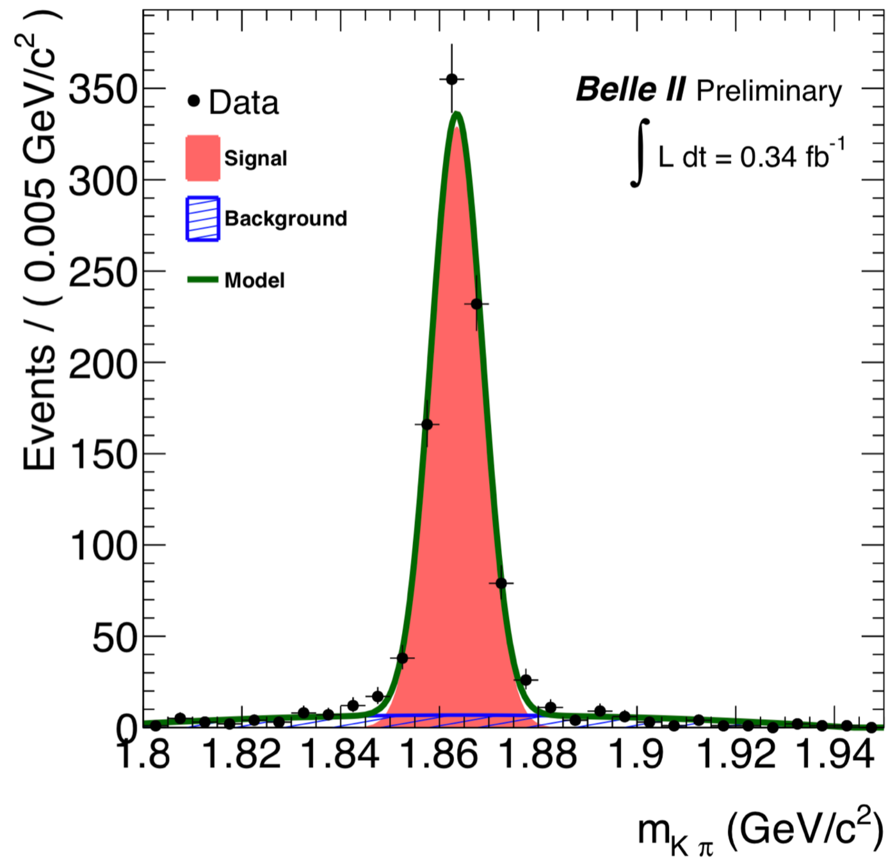
D^0 decays

BELLE2-NOTE-PL-2019-024



Inclusive reconstruction of $D^0 \rightarrow K^-\pi^+$

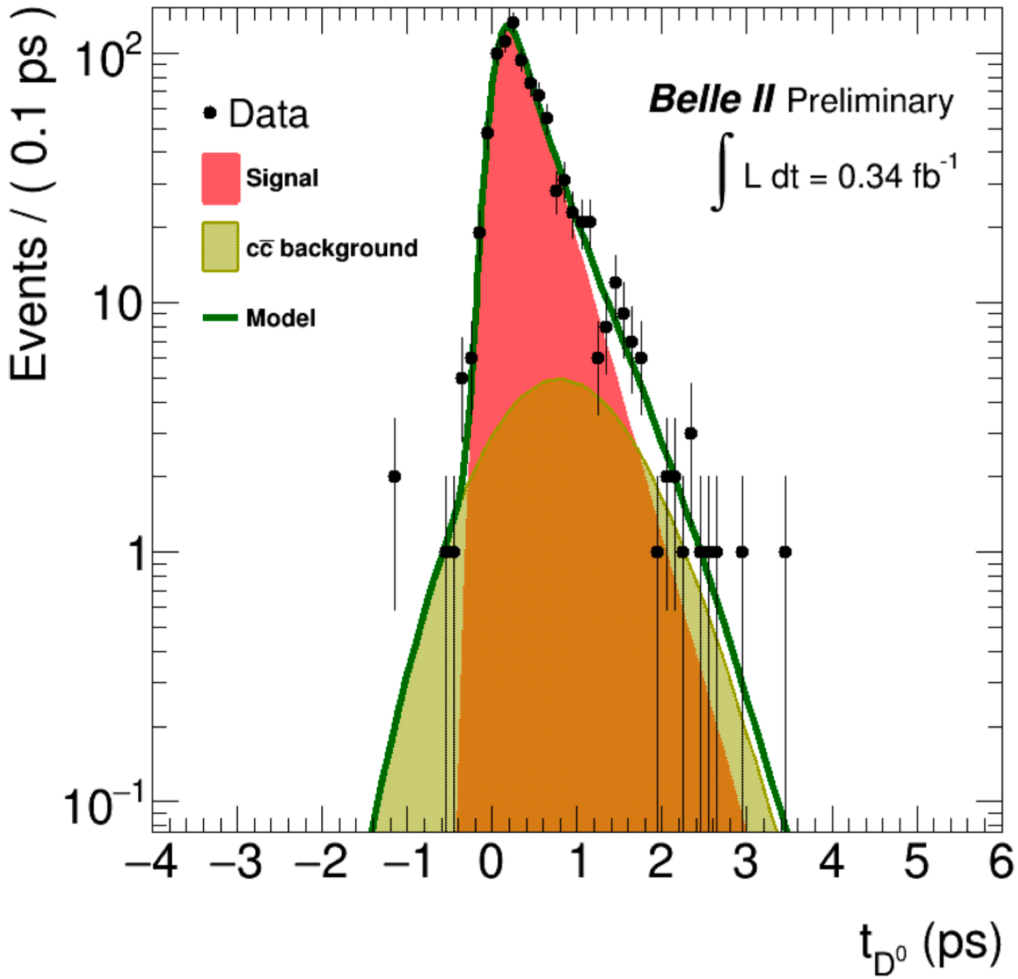
BELLE2-NOTE-PL-2019-003



With D^0 produced in $D^{*+} \rightarrow D^0\pi^+$

D^0 lifetime

BELLE2-NOTE-PL-2019-003



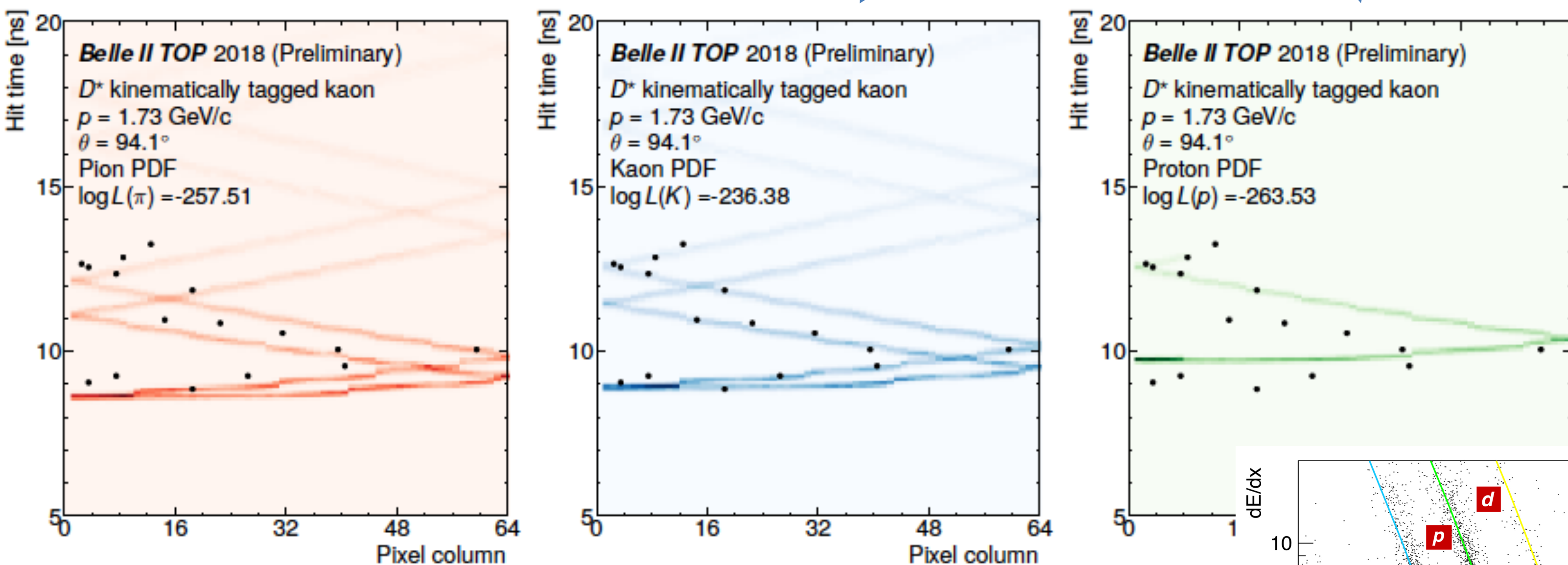
parameter	extracted value
N^1_{sig}	$(81 \pm 6) \cdot 10$
μ_1 (fs)	31 ± 16
σ_1 (fs)	127 ± 15
N^2_{sig}	$(10 \pm 5) \cdot 10$
μ_2 (ps)	(0.48 ± 0.17)
σ_2 (ps)	(0.73 ± 0.13)
τ (fs)	(370 ± 40)

PDG: 410.1 ± 1.5 fs

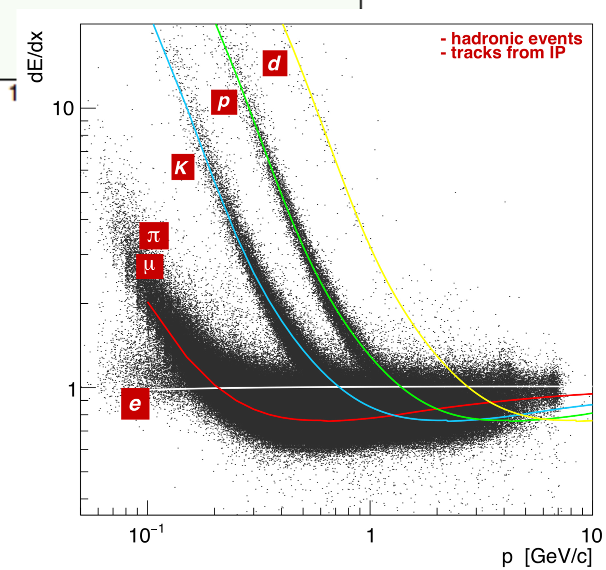
$$T_{PDF}(t) = N^1_{sig} \times Gauss(t|\mu_1, \sigma_1) * Exp(t|\tau) + N^2_{sig} \times Gauss(t|\mu_2, \sigma_2) * Exp(t|\tau)$$

Hadron-ID performance

ToP signature of kaon identified kinematically via $D^{*+} \to \pi^+ D^0 (\to K^- \pi^+)$ is visibly more consistent with being a kaon than a pion or proton



dE/dx in the drift chamber:

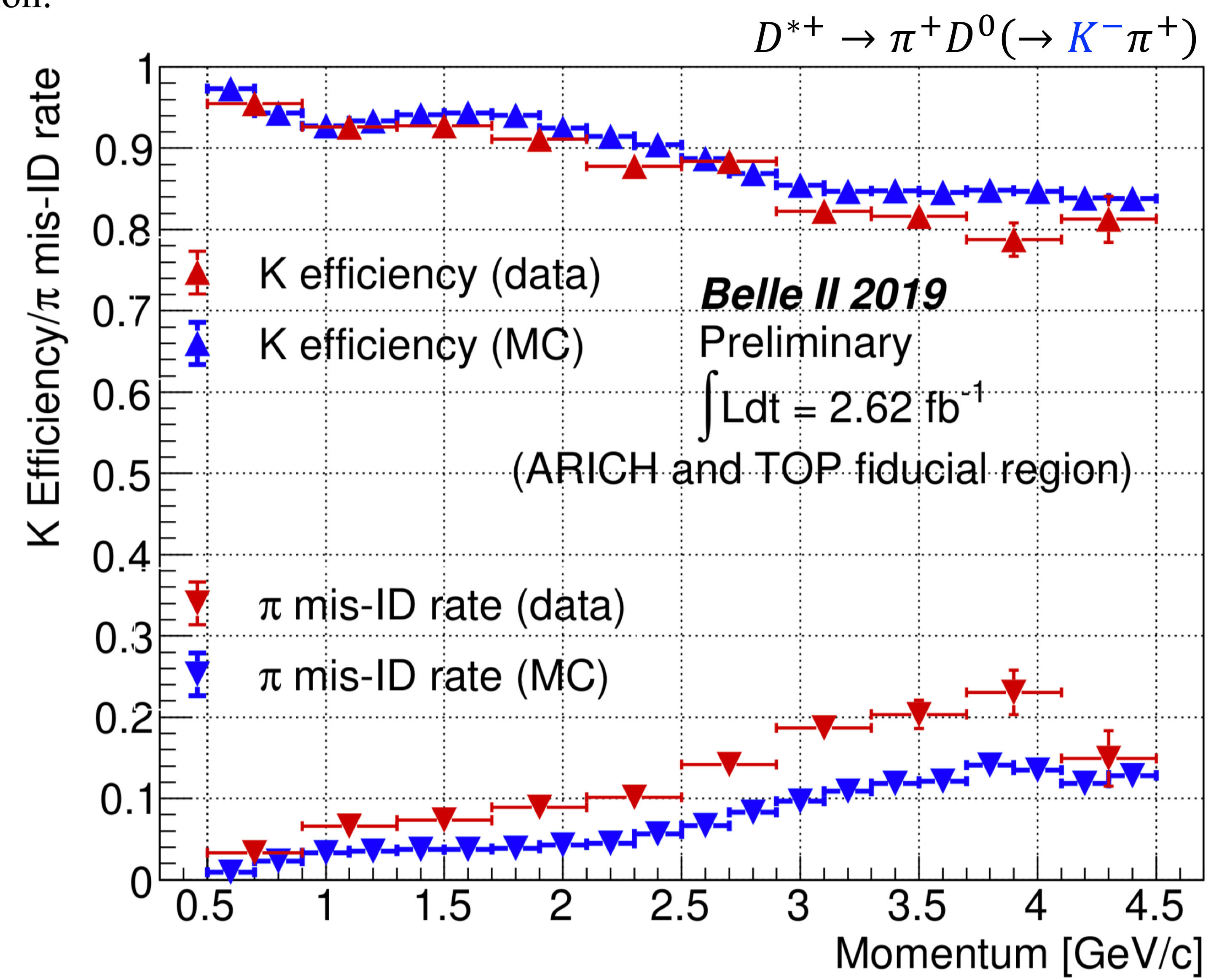


Hadron-ID performance

BELLE2-NOTE-PL-2019-022

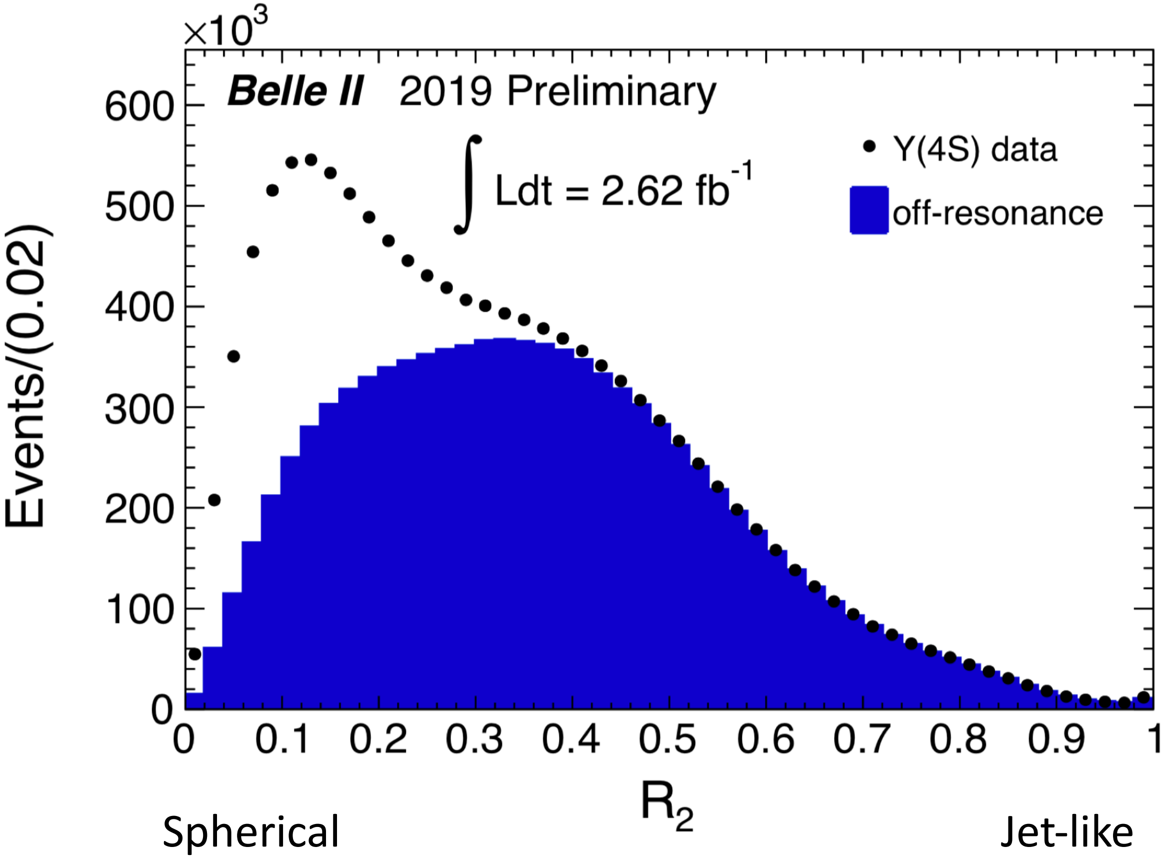
Kaon candidate selection:

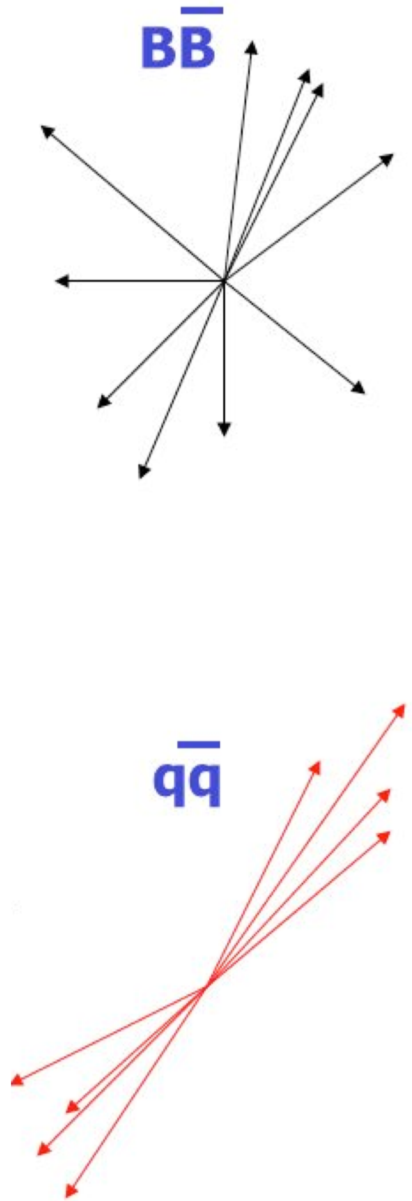
$$\frac{L_K}{L_K + L_\pi} > 0.5$$



Event Topology tells us we are producing B's

BELLE2-NOTE-PL-2019-017

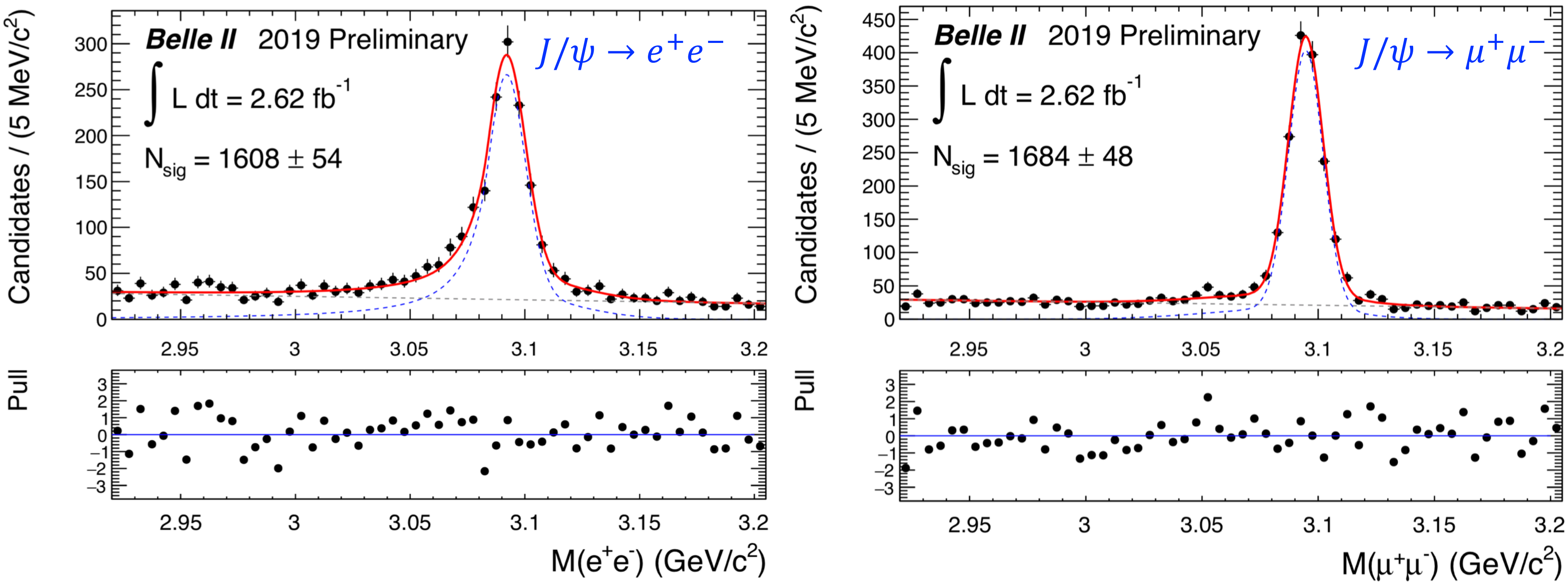




→We are running on the $\Upsilon(4S)$ resonance

$J/\psi \to \ell^+\ell^-$ reconstruction

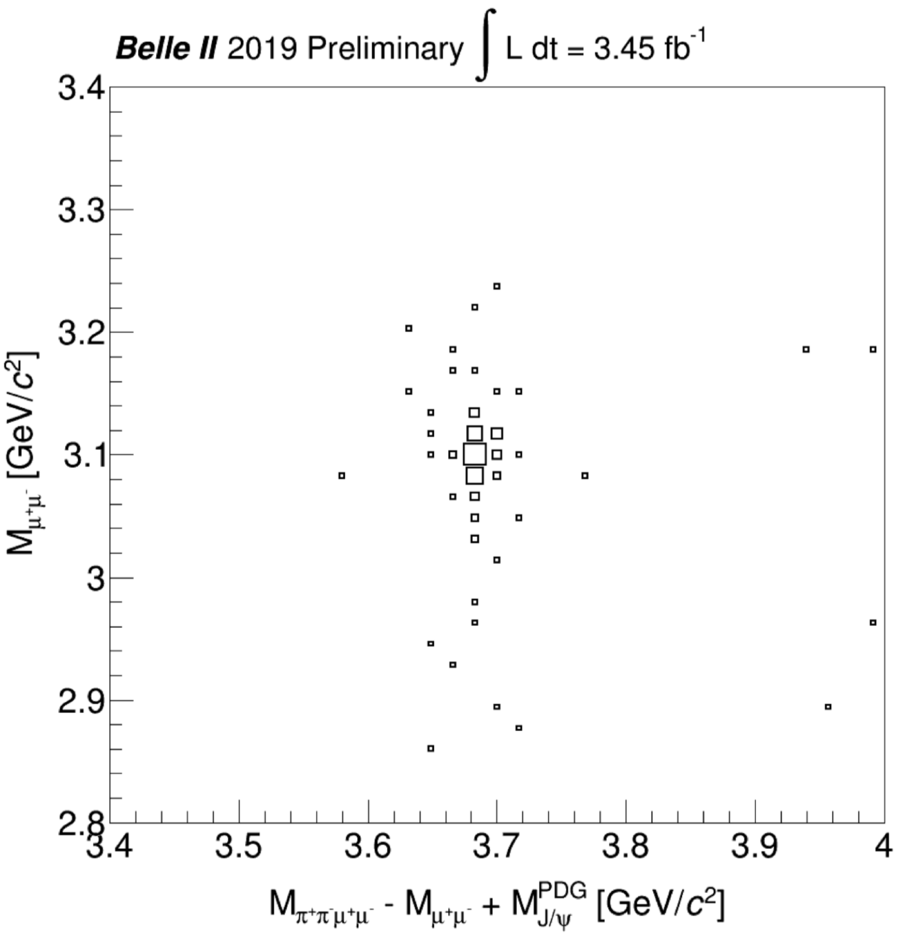
BELLE2-NOTE-PL-2019-027



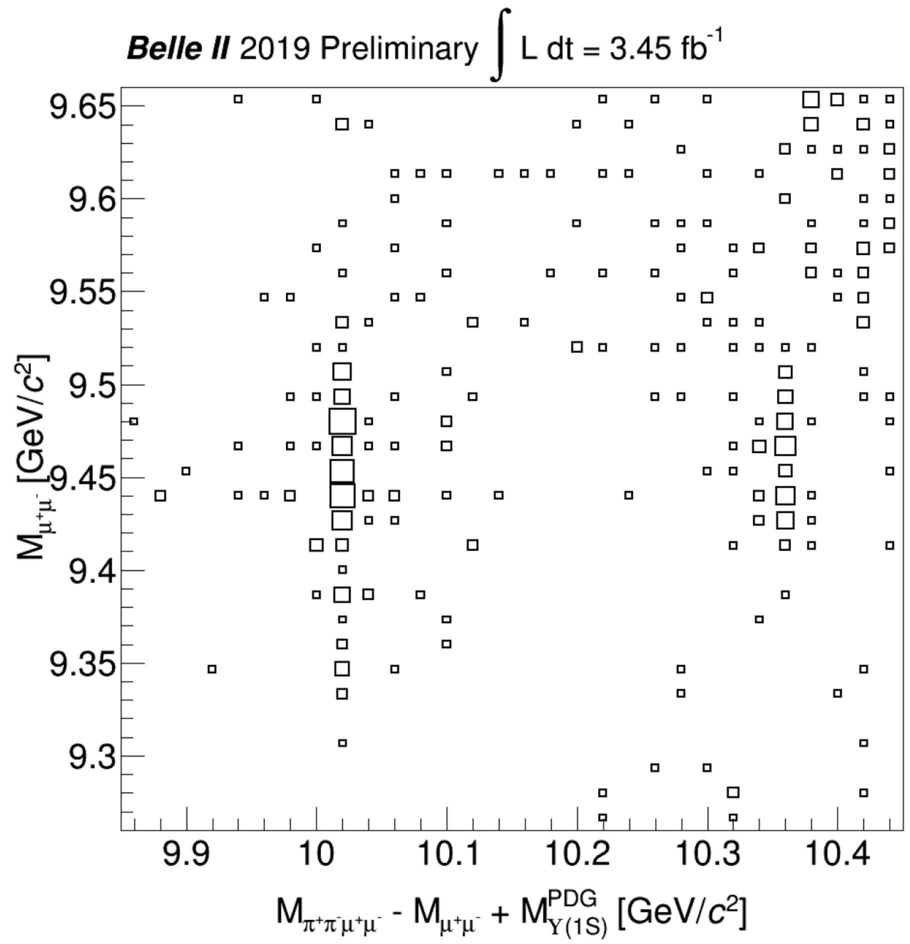
- With electron and muon ID requirements.
- $R_2 < 0.4$ & $p^*_{J/\psi} < 2$ GeV to enhance $B\bar{B}$ events & reduce background
- In e^+e^- channel: adding p4 of $E < 1$ GeV clusters within 5° cone of electron (“bremsstrahhlung recovery”)

Excited quarkonia

BELLE2-NOTE-PL-2019-015



$\psi(2S) \rightarrow J/\psi\pi^+\pi^-$

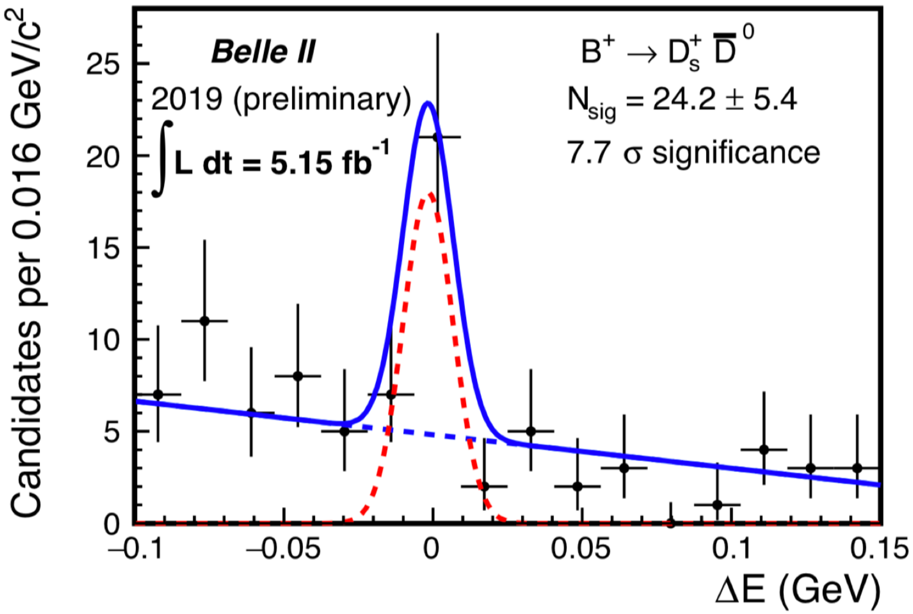


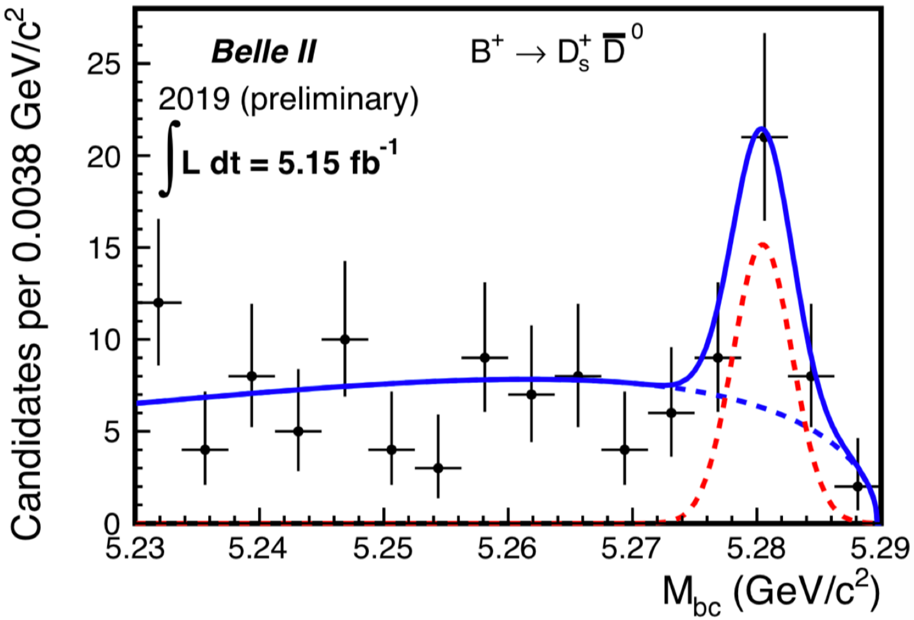
$\Upsilon(3S, 2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$

B-meson decays

BELLE2-NOTE-PL-2019-026

- $B^+ \to \overline{D}^0 D_s^+$
  (See additional B decays in talks by A. Gaz and A. Ishikawa)





$$\Delta E \equiv E_B^* - \sqrt{s}/2$$

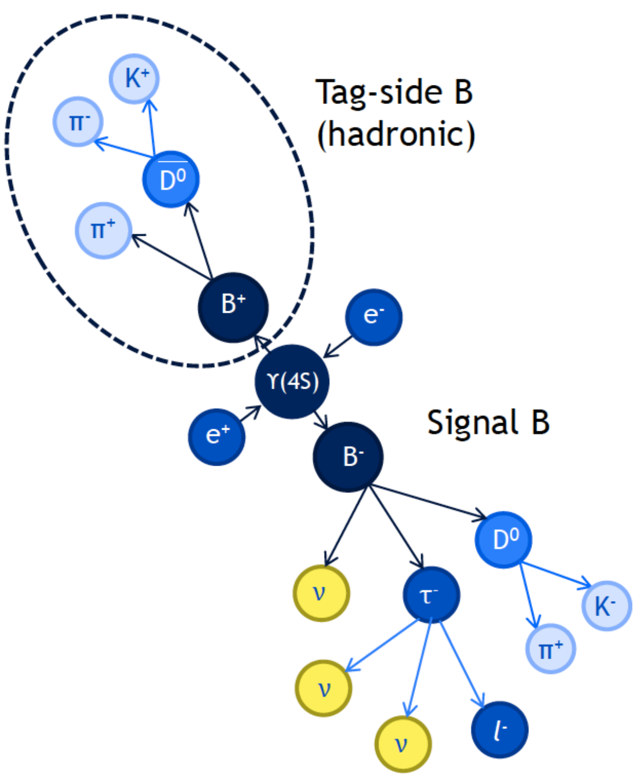
$$M_{bc} \equiv \sqrt{\frac{s}{4} - p_B^{*\,2}}$$

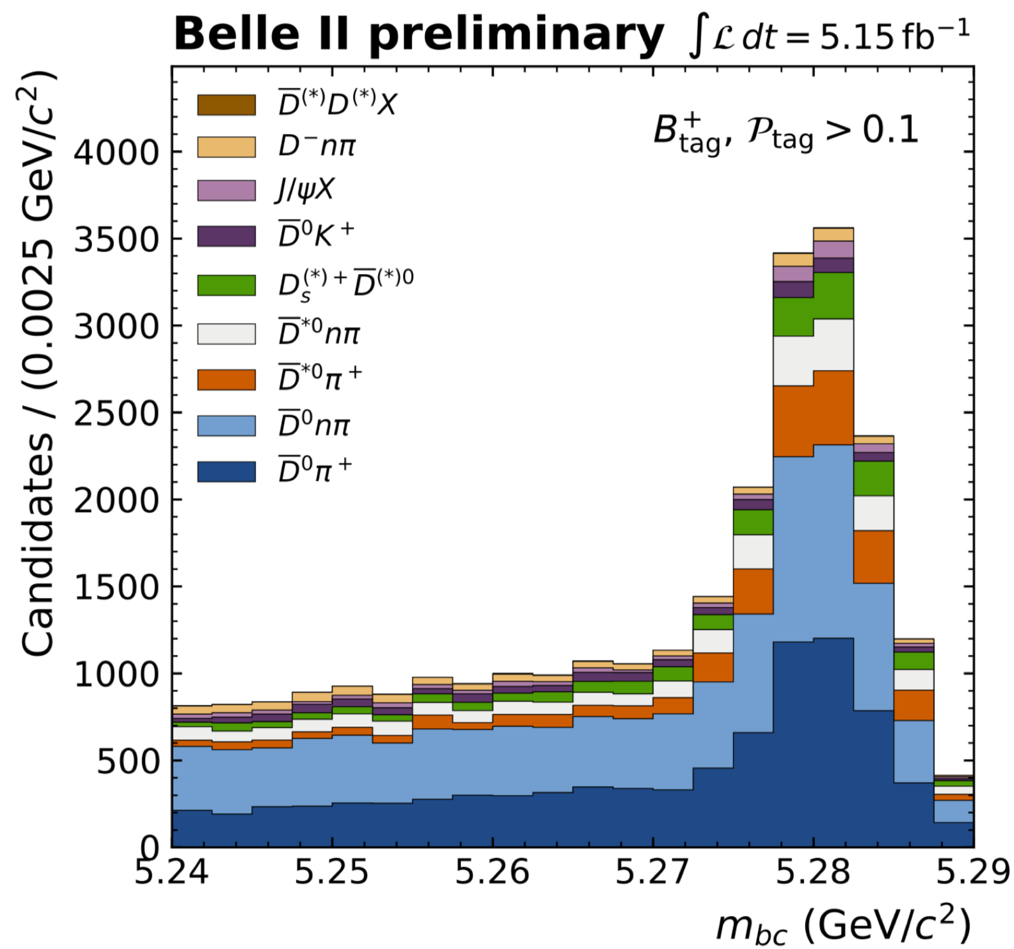
$e^+e^- \to B\bar{B}$ full-event interpretation (FEI)

BELLE2-NOTE-PL-2019-030

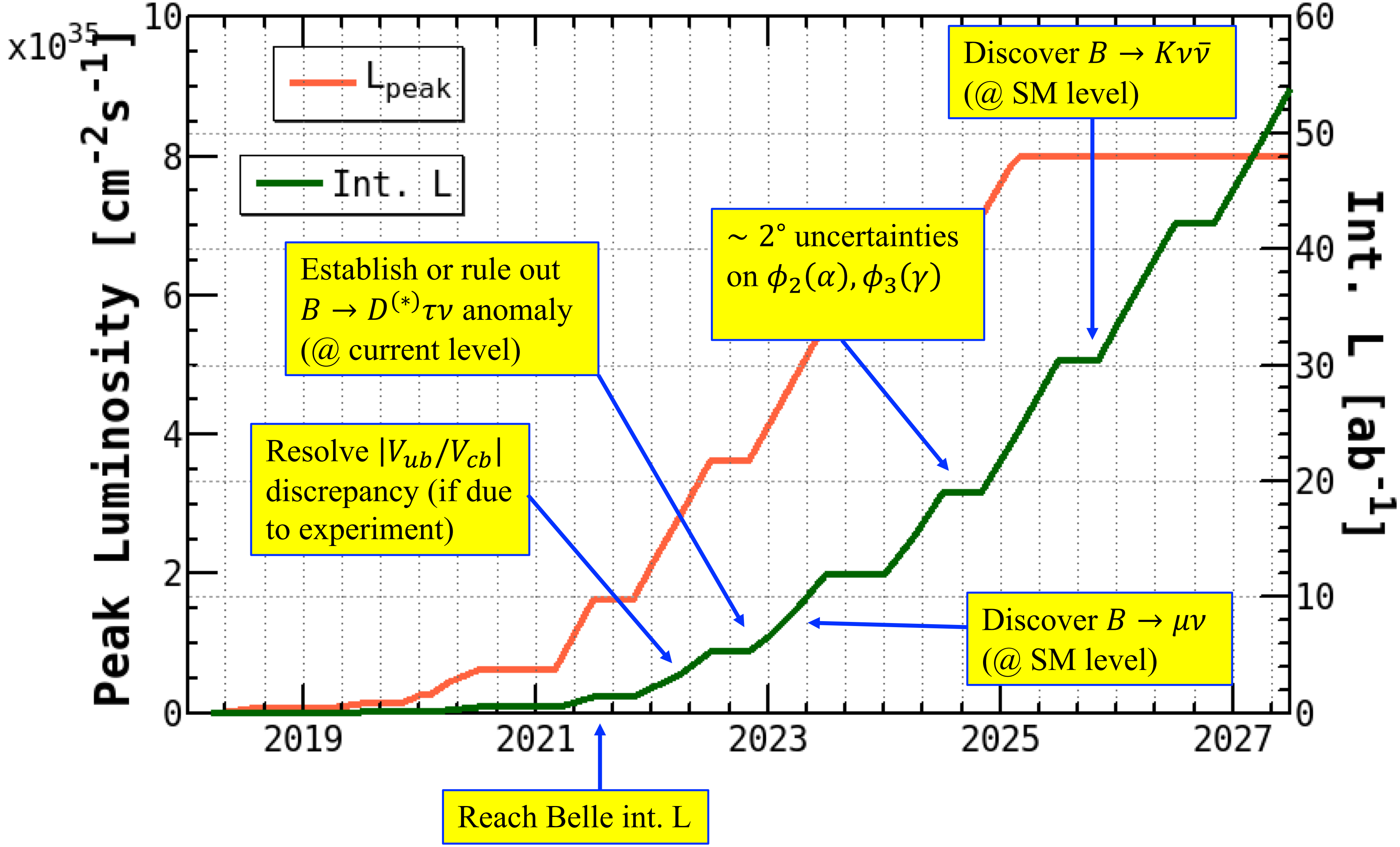
Important B-factory technique:

- Reconstruct one the "tag" B meson to detect the "signal" B in multiple-neutrino modes ($B \to \tau\nu$, $D\tau\nu$, $D^*\tau\nu$, $\tau\tau$, $K\nu\bar{\nu}$, $K\tau\tau$…) or inclusive studies ($KX_{c\bar{c}}$, $X_u\ell\bar{\nu}$…)



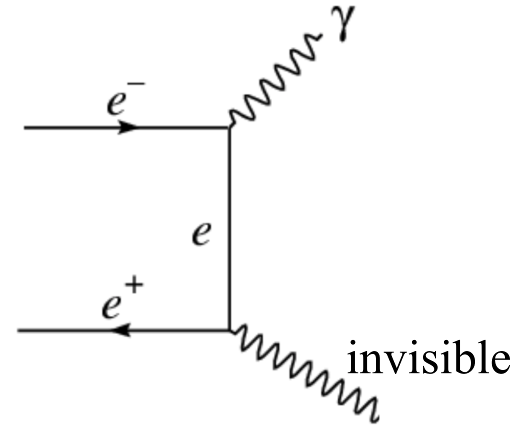


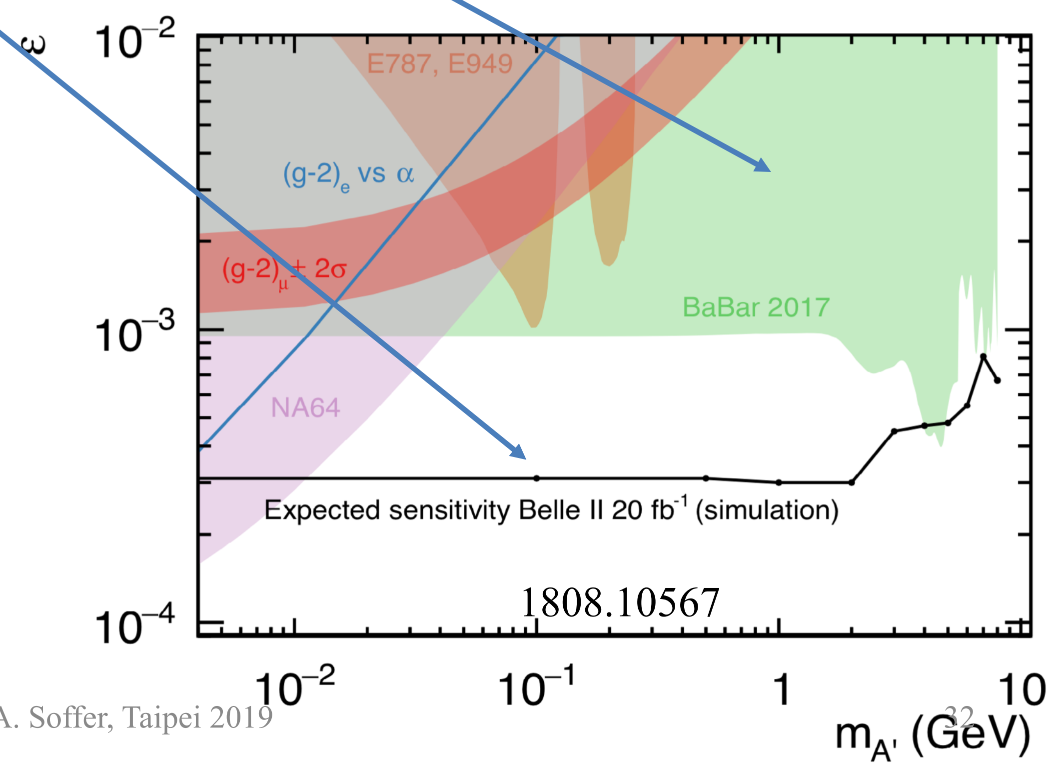
Guaranteed physics



Unique capabilities for early new physics

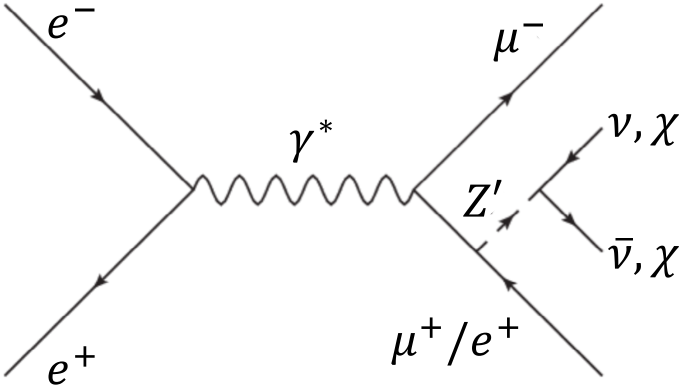
- E.g., invisible, dark photon production:
- BABAR (PRL 119 (2017) 131804) had a single-γ trigger for only 53 fb^{-1}
- Belle II has a more hermetic calorimeter (non-pointing), yielding higher sensitivity/fb^{-1}
- Belle II has a single-γ trigger for the full data set



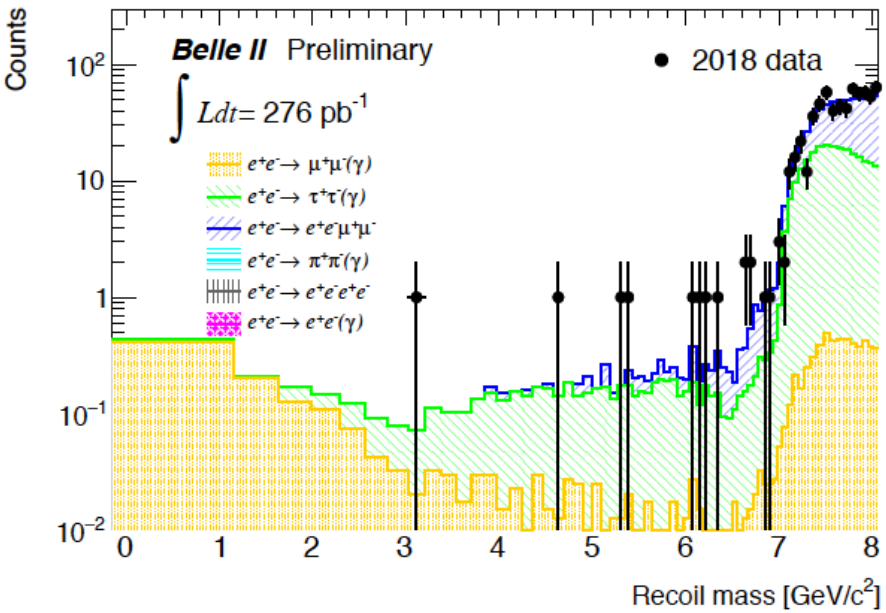


First Belle II NP search

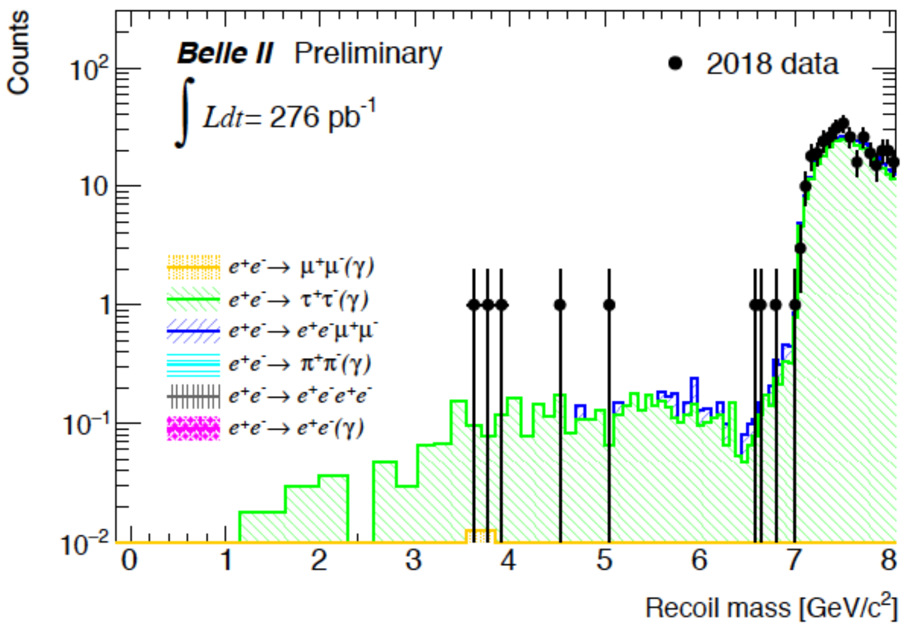
A low-mass Z' that couples to a $\mu\mu$ or μe vertex is poorly constrained in the $Z' \rightarrow$ invisible channel. Could be responsible for the $g_\mu - 2$ anomaly.



$e^+e^- \rightarrow \mu^+\mu^-$ +inv.



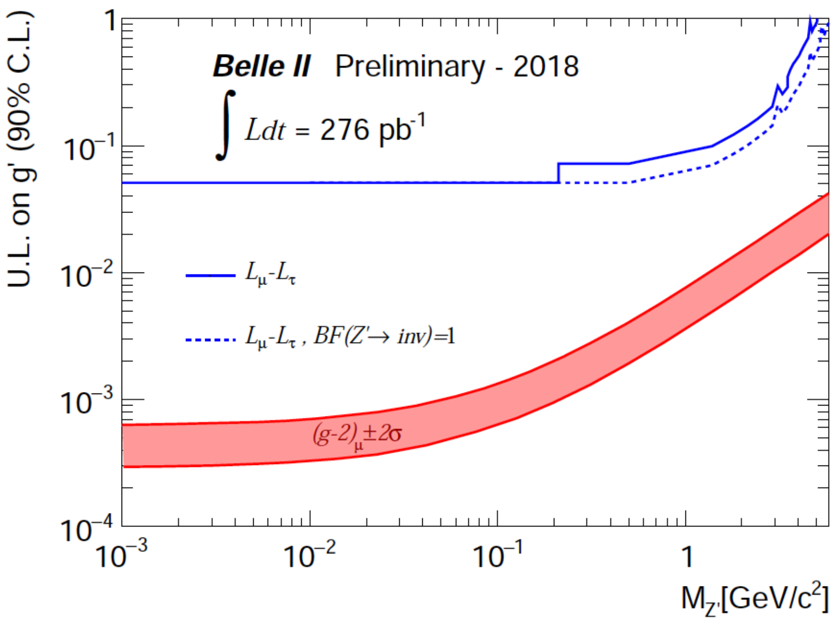
$e^+e^- \rightarrow \mu^\pm e^\mp$ +inv.



Limits on $Z' \to$ invisible

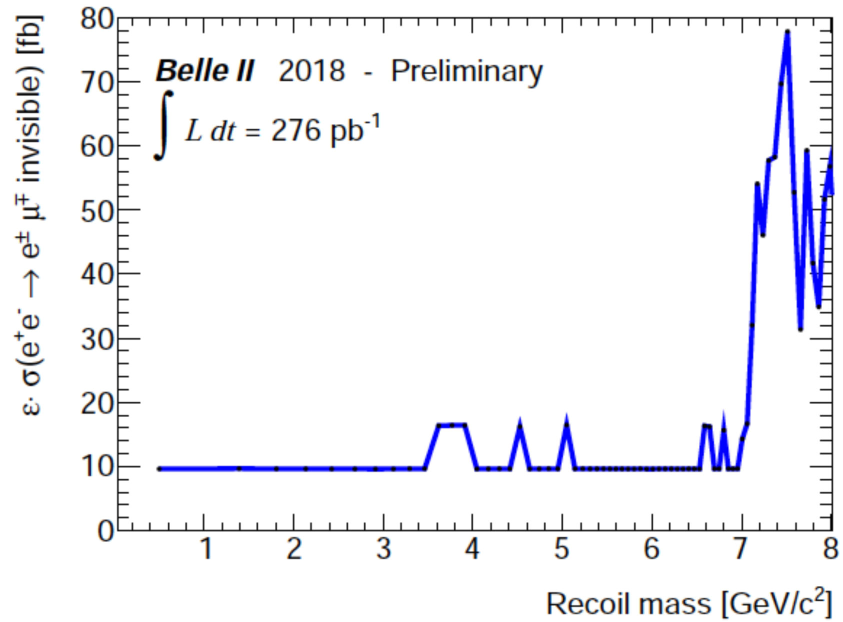
$e^+e^- \to \mu^+\mu^-$ +inv.

Limit on $Z'\mu\mu$ coupling for $Br(Z' \to \text{inv}) = 1$



$e^+e^- \to \mu^\pm e^\mp$ +inv.

Limit on efficiency times cross section



References:

- Shuve & Yavin, PRD 89 (2014) 113004
- Galon & Zupan, JHEP 2017 (2017) 83
- Galon, Kwa, Tanedo, JHEP 2017 (2017) 64
- BABAR limits in $Z' \to \mu^+\mu^-$ case: PRD 94 (2016) 011102

Some theory work on the MC needed in order to extract cross-section limits

Summary

- Belle II began taking physics data in 2019 with full detector, involving significant improvements over BABAR and Belle
- Peak luminosity already ~ 25% that of KEKB
- Integrated luminosity ~ 5 fb^{-1} used for commissioning and some unique measurements (dark bosons, magnetic monopole)
- Will reach Belle's integrated luminosity in 2021
- The experiment is on its way to groundbreaking measurements