Status and prospects of Belle II at SuperKEKB

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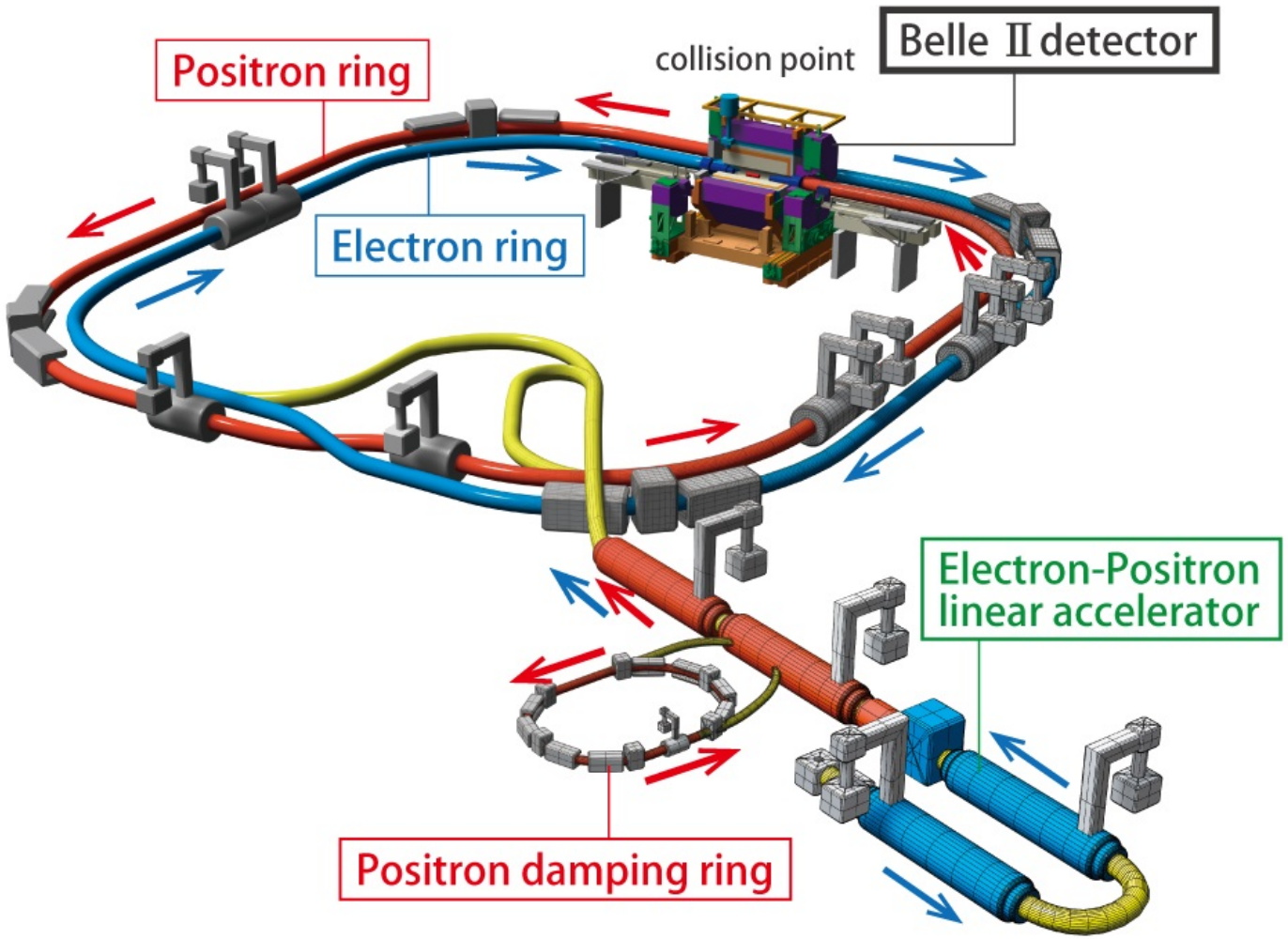
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

SuperKEKB

Status and improvements since KEKB

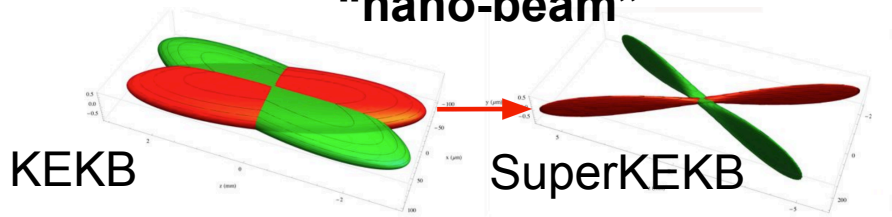


e^+e^- accelerator located in Tsukuba, Japan

Built in tunnels of KEKB, but is almost entirely new machine:

- x20 smaller beam focus at interaction region

“nano-beam”



- Doubled beam currents

This yields **x40 higher peak luminosity (8×10^{34} $cm^{-2}s^{-1}$)**

First beams in 2016
First collisions: next month

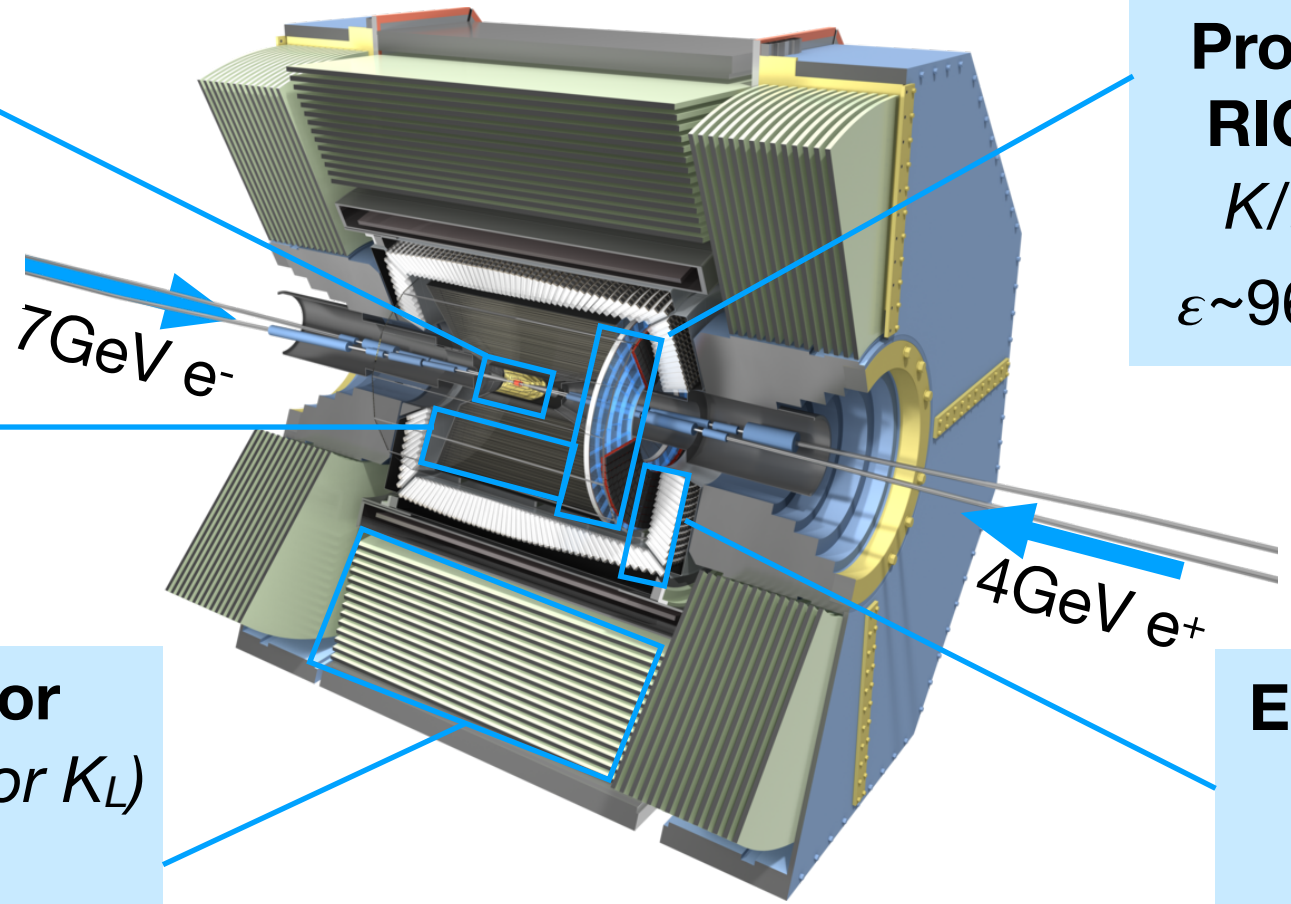
The Belle II detector

Design and key performance numbers

Vertex detector
Tracking
$\sigma_{z0} \sim 15\ \mu m$
(2x better than Belle)

Drift chamber
Tracking
$\sigma_{r\phi} \sim 100\ \mu m$
$\sigma_{dE/dx} \sim 5\%$

K_L and Muon detector
$\Delta\phi = \Delta\theta \sim$ 10-20 *mrad (for K_L)*
μ/π separation:
ε~90% @ 1.5% fake



Time of Propagation and RICH detectors
K/π separation:
ε~96% @ 1% fake

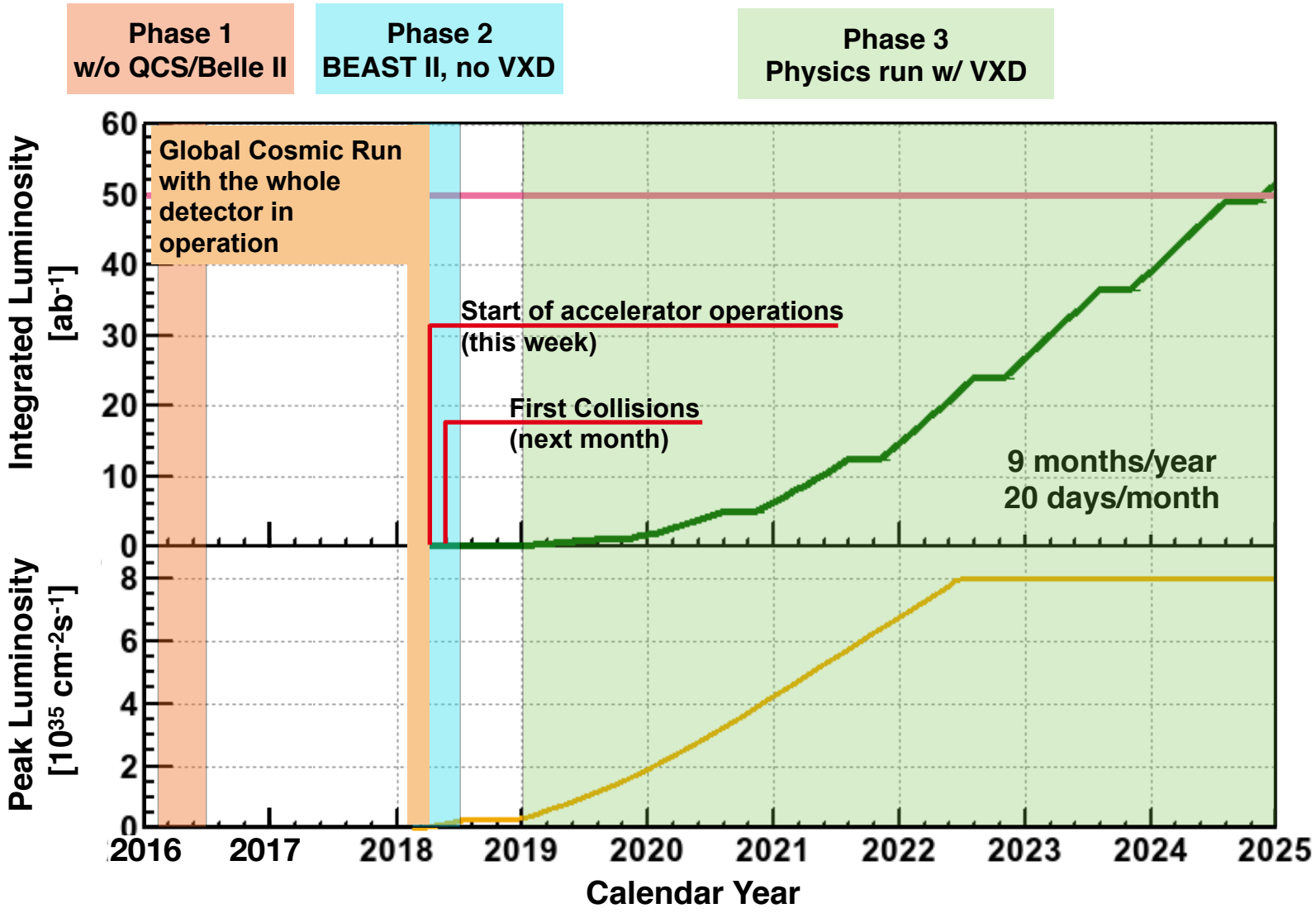
EM Calorimeter
$\sigma_E/E = 2\%$
(for E=1GeV)

Belle II schedule

Phase 1: first beams
Goal: Main ring commissioning

Phase 2: first collisions
Goal: Establish nano-beam scheme and reach KEKB luminosity
Goal: Understand backgrounds

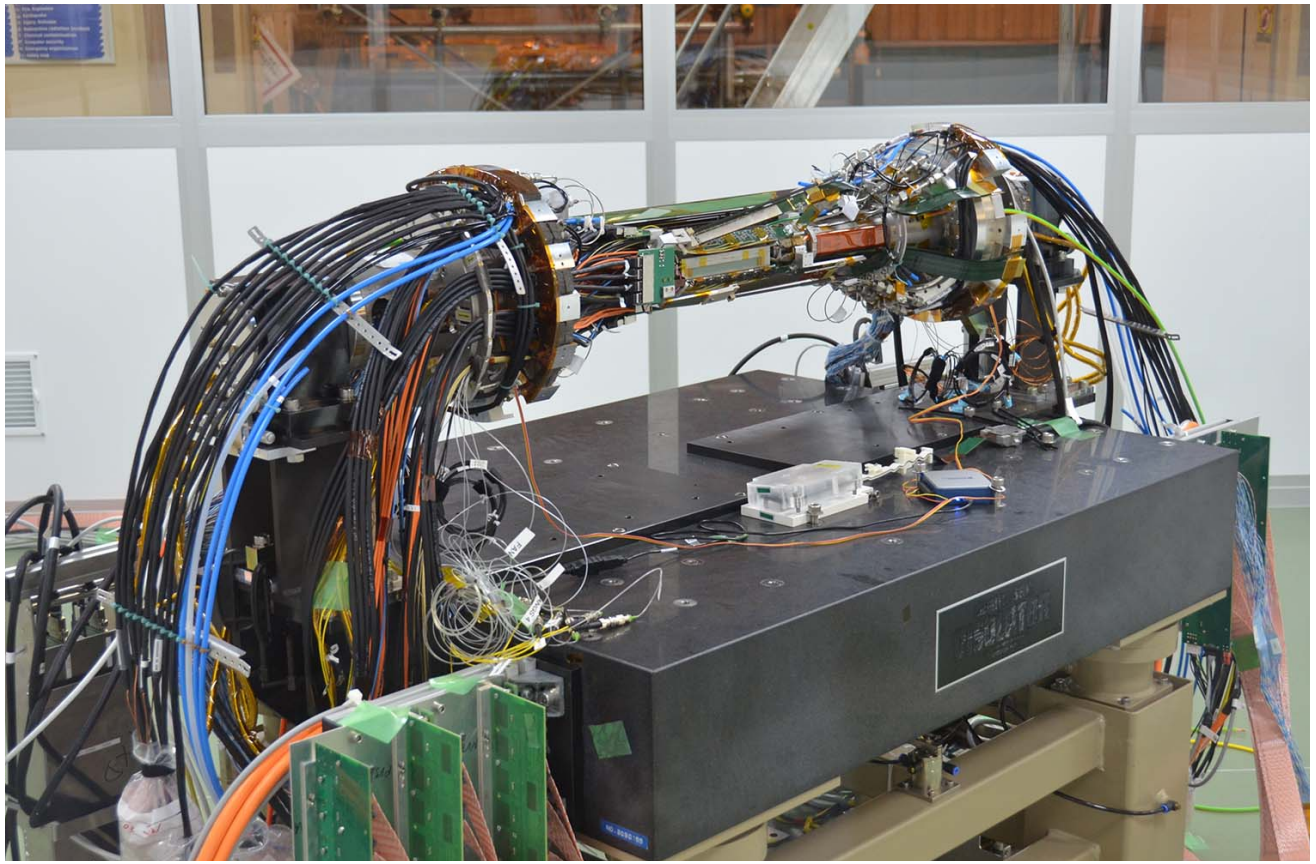
Phase 3 luminosity milestones:
1ab^{-1} after one year of data taking
5ab^{-1} mid 2020
50ab^{-1} by 2025



Belle II at Phase 2

Special conditions and unique opportunities

- Belle II and SuperKEKB will soon start collecting data of the first collisions during the Phase 2 of commissioning.
- We aim to get 20-40 fb^{-1} of data in e^+e^- collisions
- Phase II special conditions:
  - Dedicated detector that includes VXD sector and radiation monitors (BEAST II) is installed to measure radiation and backgrounds levels. Will be replaced by VXD in Phase 3.
  - To demonstrate the nano-beam scheme, we will reach $1x10^{34}cm^{-2}s^{-1}$ instantaneous luminosity, 1.25% of the SuperKEKB design.
  - Low initial luminosity allows to open up triggers for low-multiplicity events



BEAST II detector after assembly on the central beam pipe

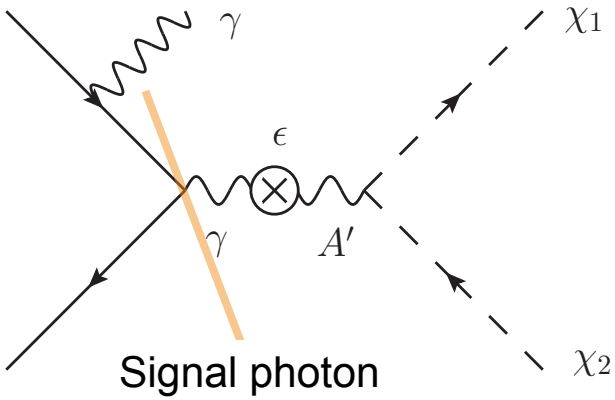
Time for physics searches going hand in hand with detector studies!

An example of Physics at Phase II

Dark photon search

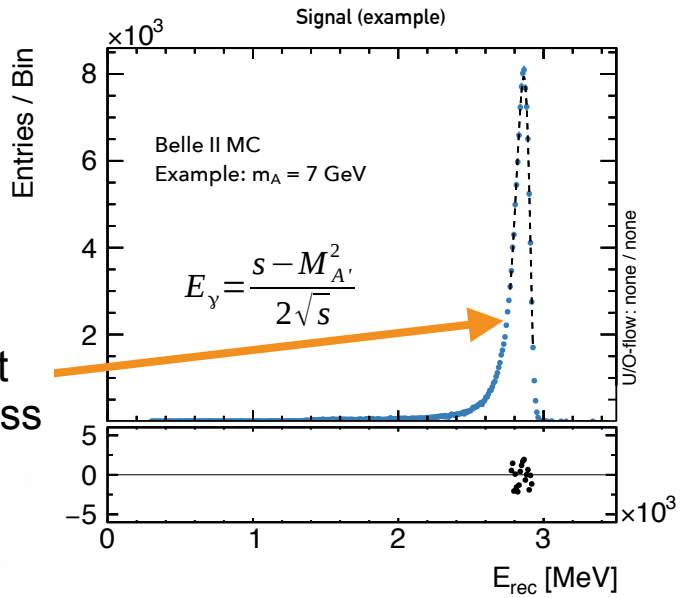
Dark matter manifests itself in numerous cosmological and astrophysical observations, but yet is **not discovered in laboratory environment**.

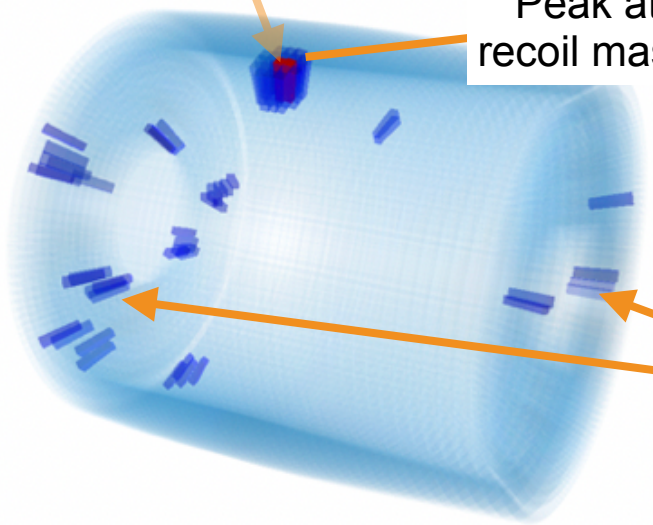
- Dark sector can be connected to the SM through the Dark Photon A': it has kinetic mixing with γ of strength ε.
- One of experimental signatures for this signal is a single photon in the detector with the recoil mass peaking at the mass of A'.
- Biggest challenge: **performance study of the photon detection**.
- Improvement of BaBar results already at 20 fb^{-1}!



Signal photon

Peak at recoil mass





Beam background

An example of Physics at Phase II

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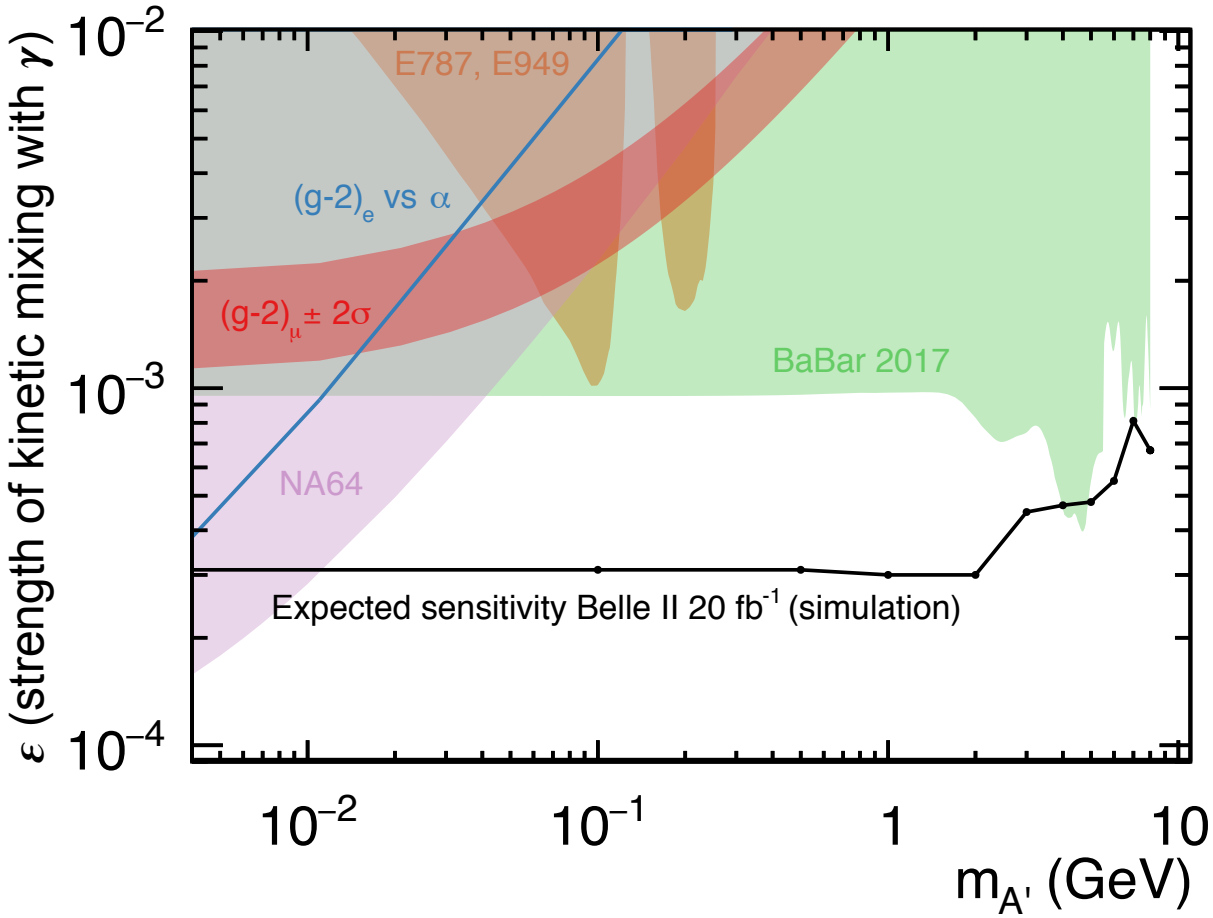


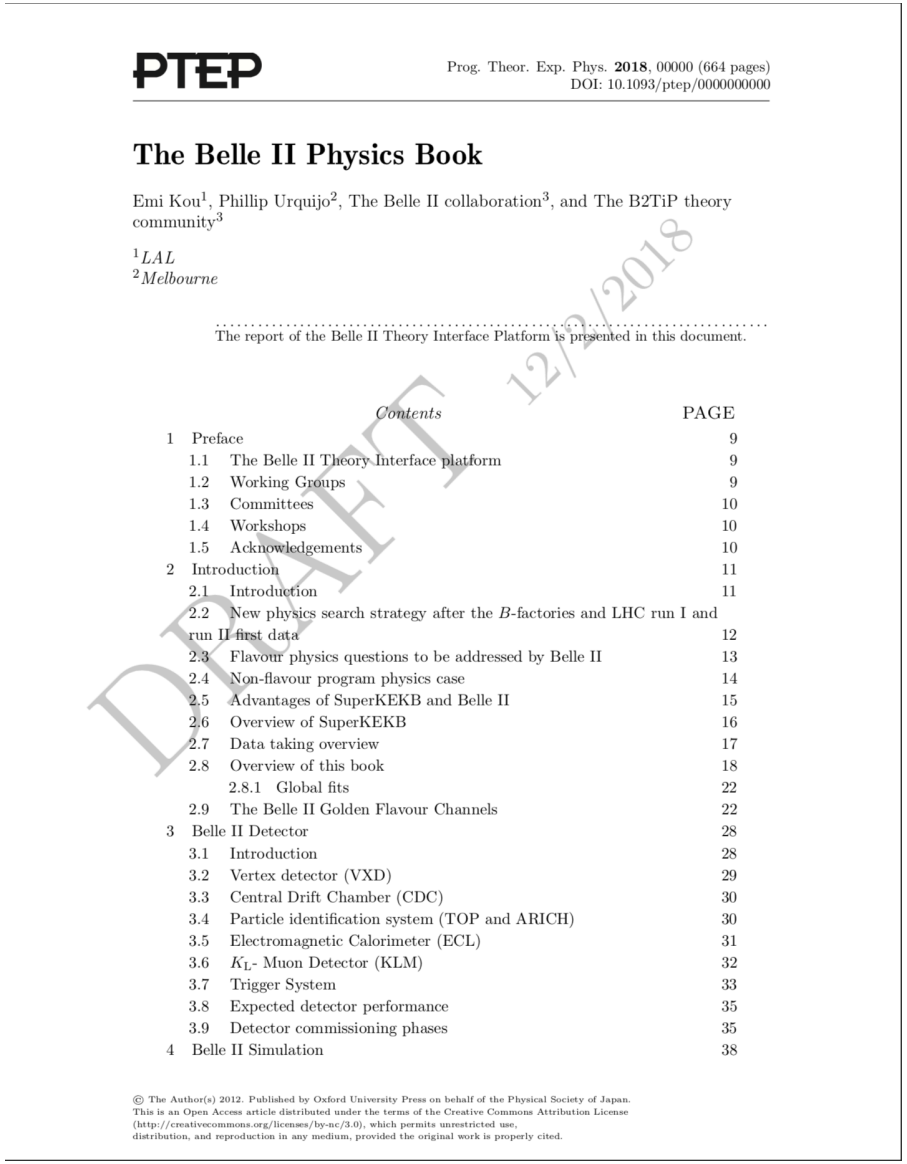
Belle II physics programme

Link to the current status

Belle II has a rich physics programme that is being summarised in a single document (664 pages now):

- Leptonic and semileptonic B decays
- Radiative and EWP B decays
- Precise measurements of CKM parameters
- Charm physics
- Quarkonium physics
- Tau physics
- BSM searches

Impossible to cover everything in short talk, but lets discuss some planned measurements showing key features of Belle II.



PTEP

Prog. Theor. Exp. Phys. **2018**, 00000 (664 pages)
DOI: 10.1093/ptep/0000000000

The Belle II Physics Book

Emi Kou[1], Phillip Urquijo[2], The Belle II collaboration[3], and The B2TiP theory community[3]

[1]*LAL*
[2]*Melbourne*

The report of the Belle II Theory Interface Platform is presented in this document.

Contents PAGE

Belle II Key techniques

Full event interpretation

At Belle II, B-mesons are produced in pairs during decay of the $\Upsilon(4S)$.

This is just above the $b\bar{b}$ threshold, i.e. only the two B-mesons are produced in the collision.

If we fully reconstruct one B-meson decay than we can study final states with missing energy because the initial state is well known.

Useful variable here is missed 4-momentum:

$$p_{\text{miss}} = (p_{\text{beam}} - p_{\text{Btag}} - p_{\text{Signal}})$$

Fully interpreted event at Belle II

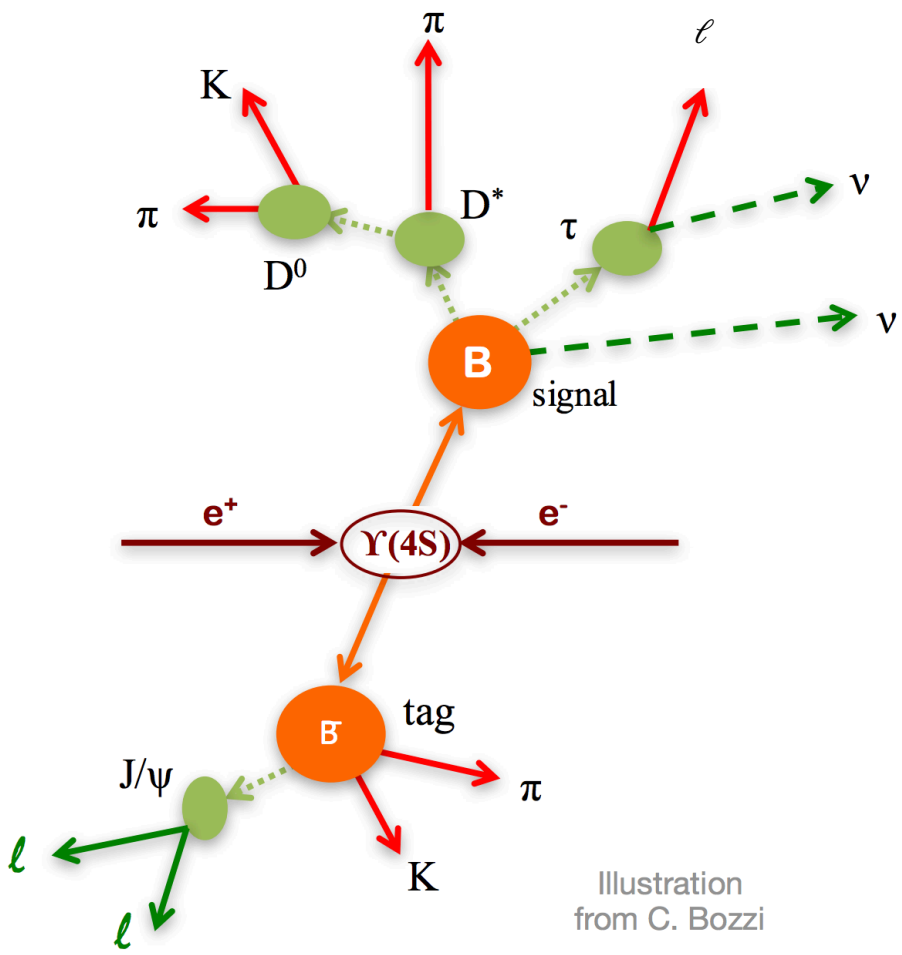


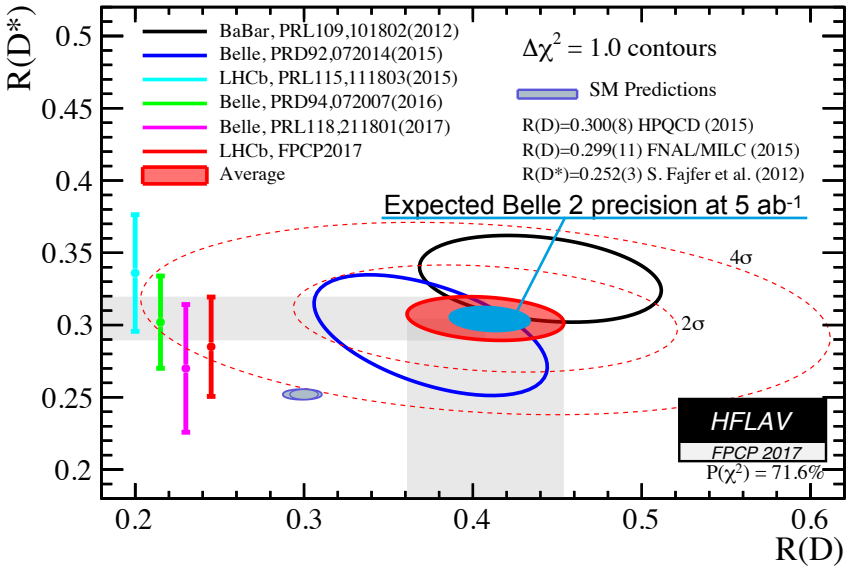
Illustration from C. Bozzi

Some of the Phase III key measurements

R(D) and R(D*) measurement

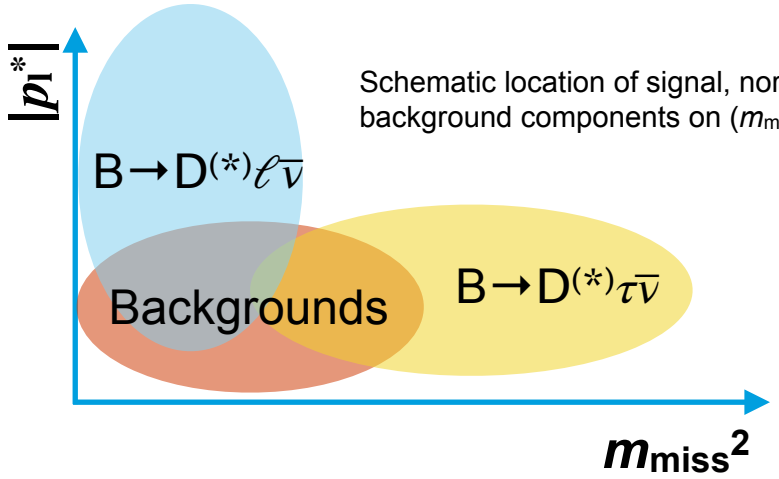
Combined R(D)/R(D*) measurement is 4σ away from the SM prediction

$$\mathscr{R}\left(D^{(*)}\right) = \frac{\mathscr{B}\left(B \to D^{(*)}\tau\bar{\nu}_\tau\right)}{\mathscr{B}\left(B \to D^{(*)}l\bar{\nu}_l\right)}$$



Belle II R(D) measurement strategy:

- Using the **Full Event Interpretation (FEI)** algorithm: reconstruct both B-mesons to missed momentum of signal candidate.
- Discriminate signal ($B \to D^{(*)}\tau\bar{\nu}$), normalisation ($B \to D^{(*)}\ell\bar{\nu}$, $\ell = \mu, e$) and backgrounds events in 2D fit to (m_{miss}^2; $|p_l|$) plane



Schematic location of signal, normalisation and background components on (m_{miss}^2; $|p_l^*|$) plane

Current World Average precision for R(D(*)) is 12%(6%). **With only 5ab^{-1} Belle II will measure both values twice more precise** according to simulations study

Belle II Key techniques

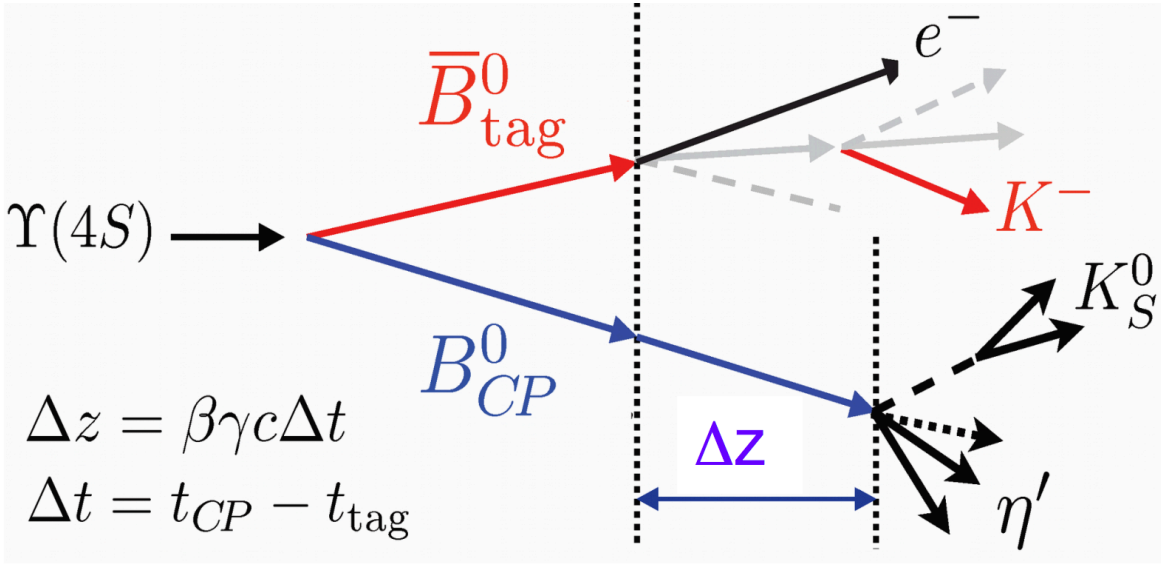
Time-dependent CP violation

As with the FEI technique, measurement of the TD CPV requires reconstruction of the both mesons.

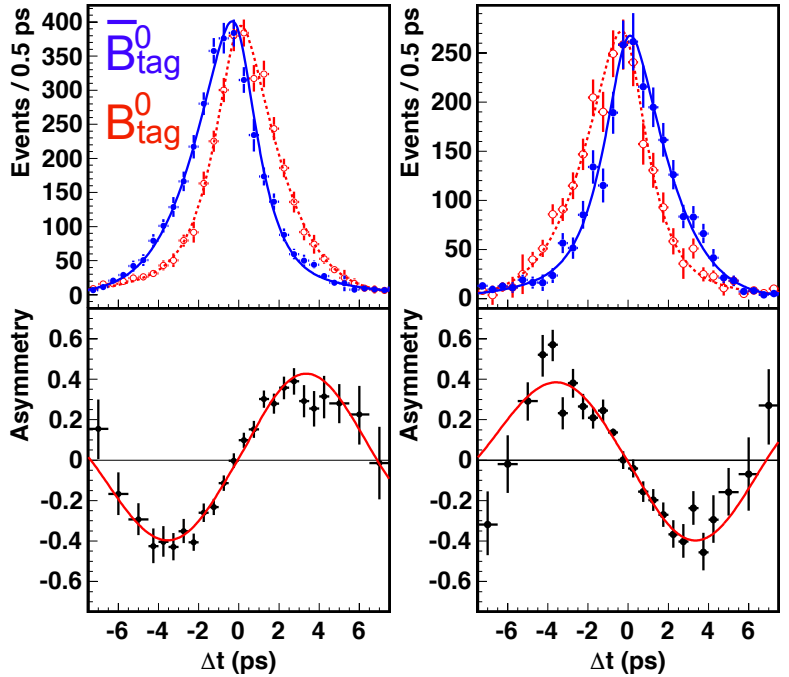
Unlike FEI, we don't need to fully reconstruct the tag B: we only need to find its decay vertex and flavour.

$$a_f(\Delta t) \equiv \frac{\Gamma_{\bar{B}^0 \to f}(\Delta t) - \Gamma_{B^0 \to f}(\Delta t)}{\Gamma_{\bar{B}^0 \to f}(\Delta t) + \Gamma_{B^0 \to f}(\Delta t)} =$$

$$= \mathcal{S}_f \sin(\Delta m \Delta t) + \mathcal{A}_f \cos(\Delta m \Delta t)$$



<Δz> ~ 130 μm at Belle II



Δt and A_{cp} distributions for CP-odd (left) and CP-even (right) $B \to (cc)K^0$ modes
[Phys. Rev. Lett. 108 171802]

Some of the Phase III key measurements

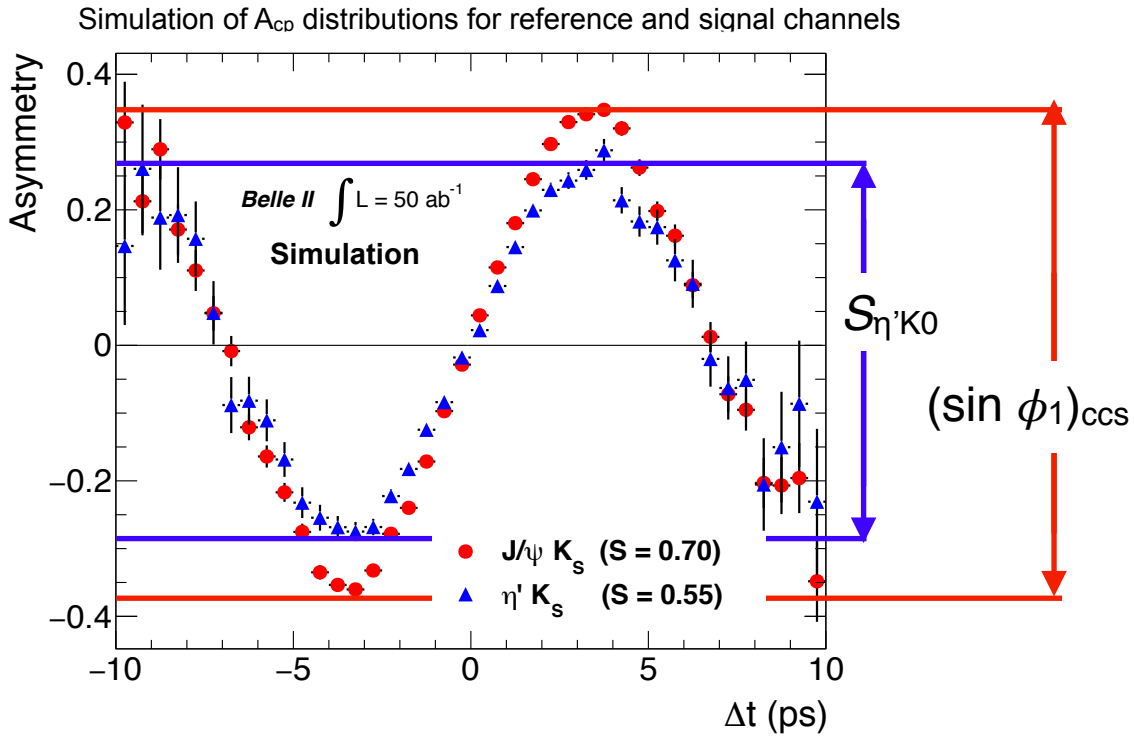
Time-dependent CP violation in penguin-dominated decays

Theory gives clean constraints on $\Delta S_f = S_f - (\sin \phi_1)_{ccs}$ for penguin-dominated b→qqs (q = u, d, s) processes, while the experiment is behind in precision.

B→η'K⁰ has among the strictest predictions here:

$\Delta S^{QCDF}_{\eta'K0} = 0.01 \pm 0.01$ $\Delta S^{Data}_{\eta'K0} = -0.05 \pm 0.06$

- Belle II will test several combinations for the final states:
  - $\eta' \to \eta(\gamma\gamma)\pi^+\pi^-$; $\eta' \to \eta(\pi^+\pi^-\pi^0)\pi^+\pi^-$; $\eta' \to \rho\gamma$;
  - $K_S \to \pi^+\pi^-$; $K_S \to \pi^0\pi^0$; K_L
- Key components of the measurement:
  - **Tagging**: Effective tagging efficiency is ~37%
  - **Vertexing**: signal Δt resolution is 20% better than for Belle
  - **Sensitivity to neutrals**: 23% selection efficiency for $B \to \eta'(\to \eta(\gamma\gamma)\pi^+\pi^-)K^0_S$ final state



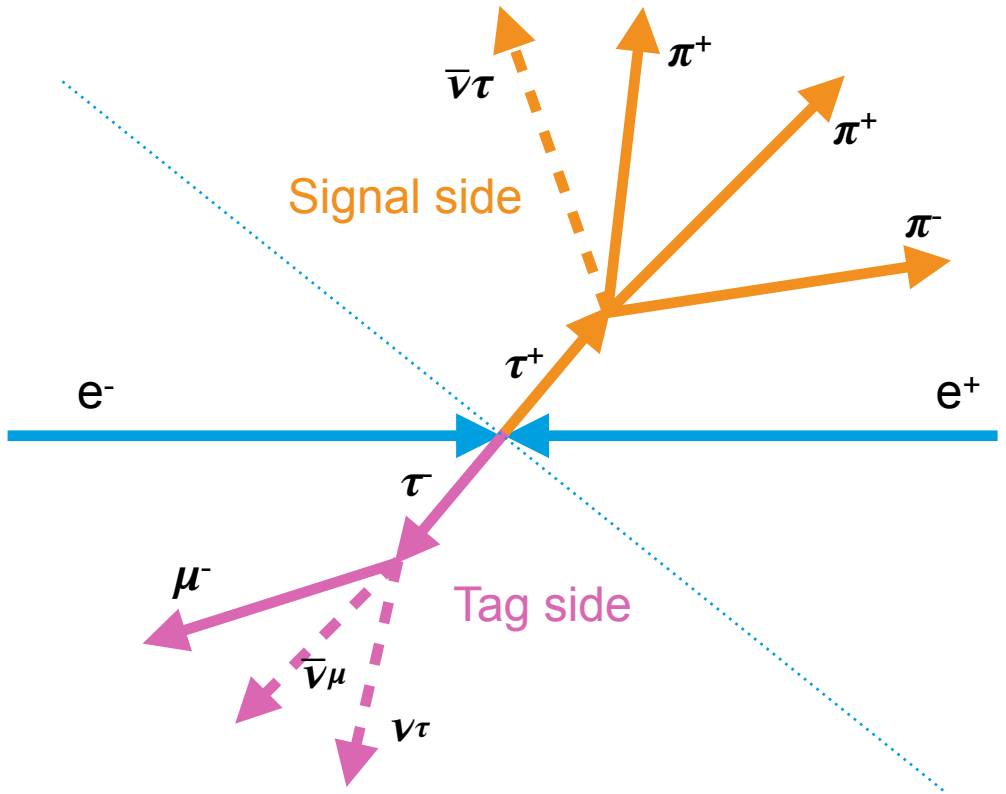
Current World Average precision for $S_{\eta'K0}$ is 10%.
With only 5ab⁻¹ Belle II will measure it twice as precise according to simulation

Belle II Key features

Belle II as a tau factory

Belle II is the best laboratory to study τ physics:

- **High rate of the tau:** 45x10^9 τ^+ τ^- pairs are expected in the full dataset.
  $\sigma(ee \to \tau\tau) \approx 0.91nb$; $\sigma(ee \to b\bar{b}) \approx 1.05nb$
- **Clean environment:** exclusive production of τ pairs in $e^+e^- \to \tau^+ \tau^-$



Belle II reconstruction procedure for τ:

- For each reconstructed τ we calculate invariant mass and $\Delta E = E_\tau^{CM} - E_{beam}^{CM}/2$
- Use event shape variables to discriminate from non-tau backgrounds ($e^+e^- \to q\bar{q}$)
- For neutrinoless τ decays (CLFV searches), the missing momentum of the tag side can also be used as a discriminating variable

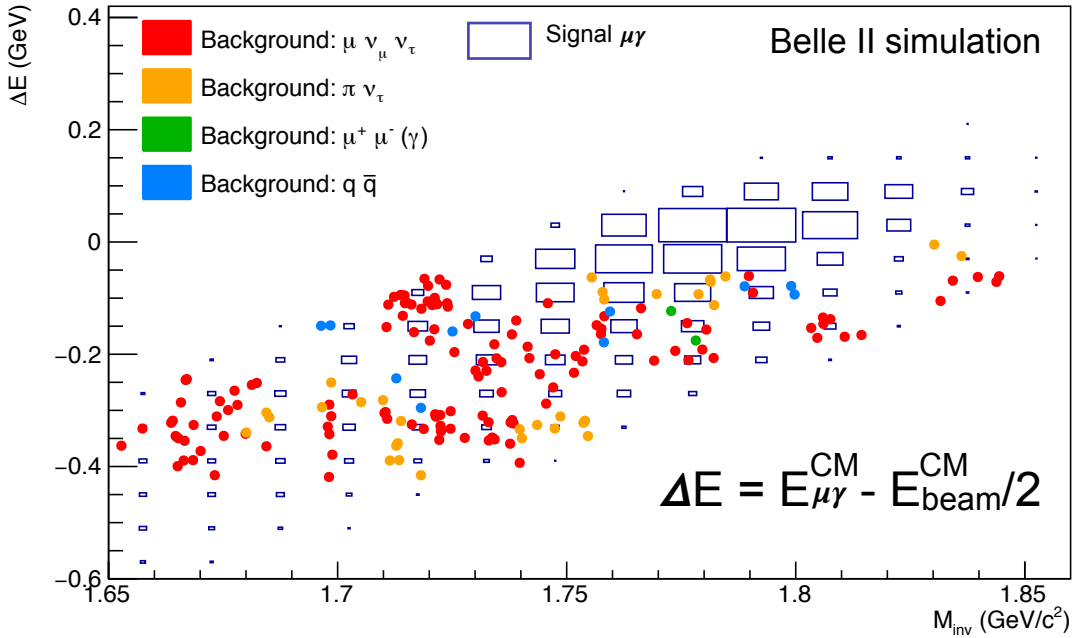
Some of the Phase III key measurements

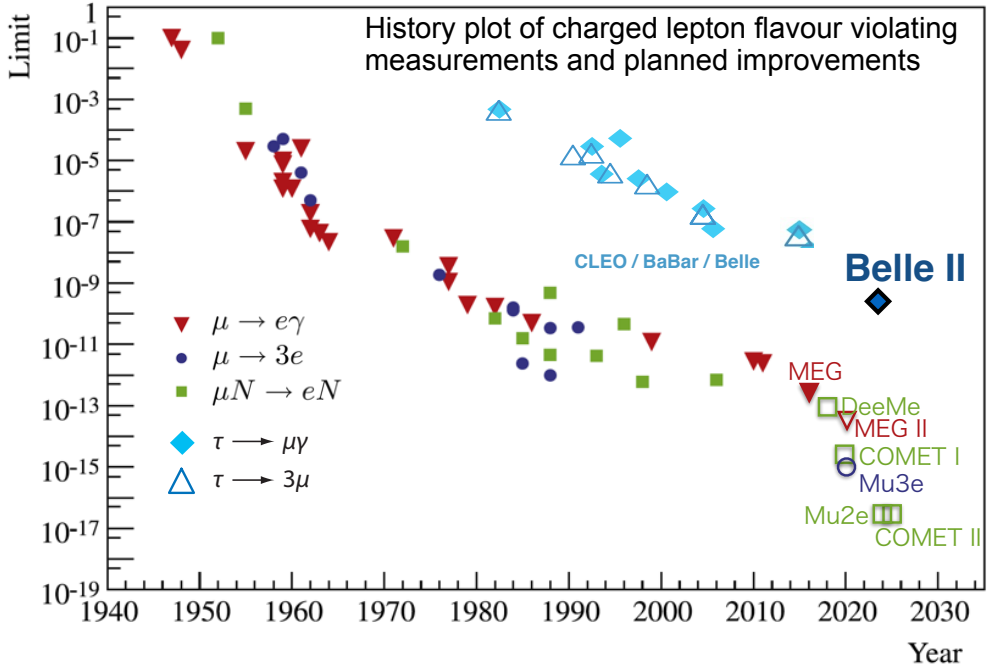
Charged Lepton Flavour Violation in τ decays

$\tau \to \mu\gamma$ decays are prohibited in SM (Br($\tau \to \mu\gamma$)~10^{-40}) and among the most sensitive to loop-generated CLFV.

Signal events peak in (ΔE; M$_{\mu\gamma}$) plane.

Signal region ($\tau \to \mu\gamma$)





Belle II expected sensitivity at 50 ab^{-1} is Br($\tau \to \mu\gamma$)<10^{-9}

Model	Br($\tau \to \mu\gamma$)	Source
SUSY+GUT	10^{-7}	PRD 66(2002)11501
SUSY SO(10)	10^{-8}	PRD 68(2003)033012
SM+ heavy ν_R	10^{-9}	PRD 66(2002)034008
Non-universal Z'	10^{-9}	PLB 547(2002)252
Little Higgs	10^{-10}	JHEP 0705, 013 (2007)
SUSY Higgs	10^{-10}	PLB 566(2003)217
SM	10^{-40}	EPJ C8 (1999) 513

Some of the Phase III key measurements

Energy scan of heavy bottomonium

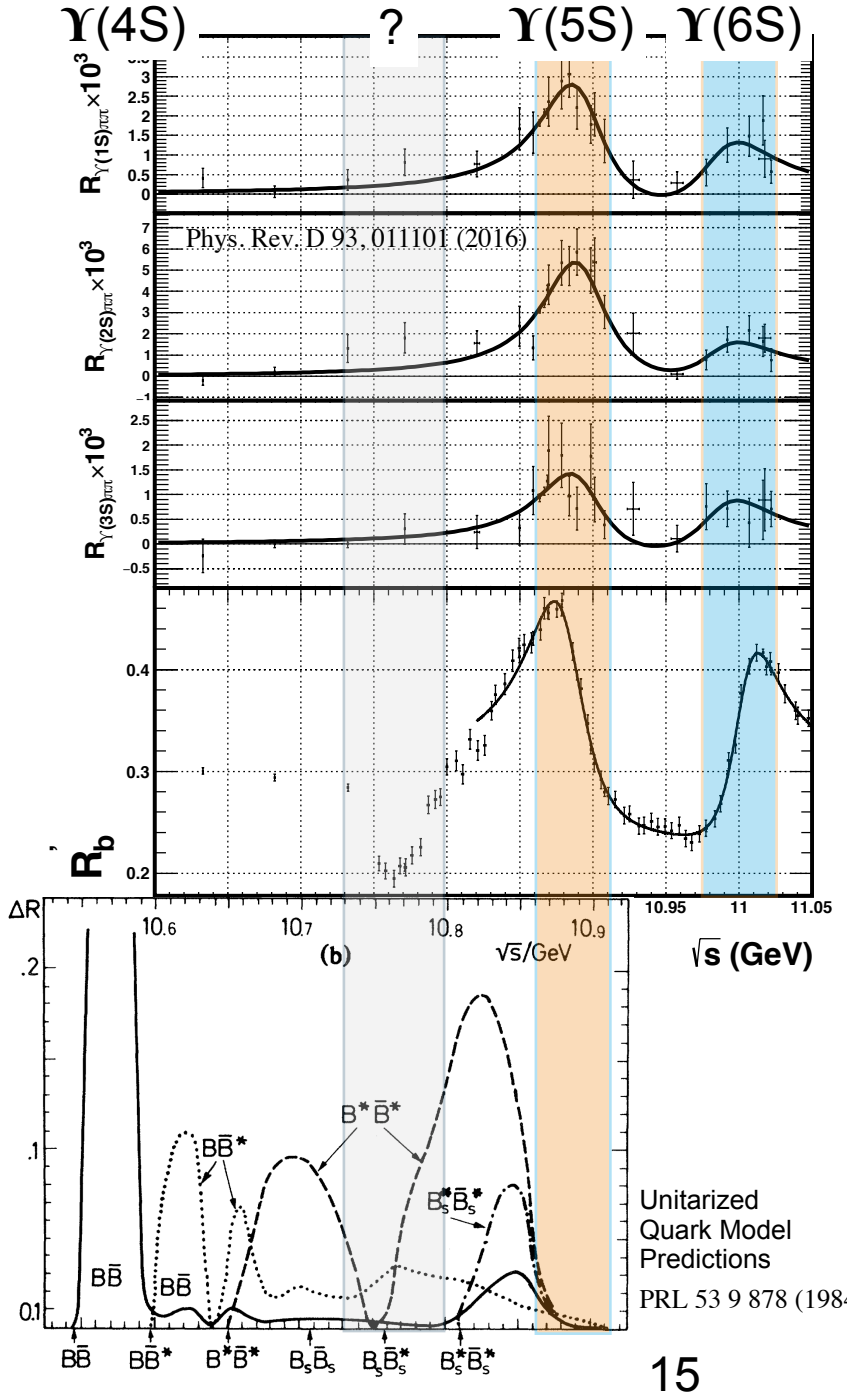
Inner structure of heavy hadrons above the open flavour limit is still unclear: are there XYZ states, analogous to charmonium case?

- Cross-sections around 10.75 have different behaviour for BB, $h_b(nP)\pi\pi$ and $\Upsilon(nS)\pi\pi$ states
- Belle II will make precise scan of the region and decompose cross-sections to different BB states, that are predicted to have rich structure
- Scans beyond $\Upsilon(6S)$ will investigate new resonances around new thresholds

No other experiment, running or planned, can address the open topics in bottomonium physics

Current samples in fb^{-1} (millions of events), and the proposal for Belle II

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%



SuperKEKB limit: 11.24 GeV

Unitarized Quark Model Predictions

PRL 53 9 878 (1984)

Summary

- Next month Belle II will start collect data from the first collisions (without the vertex detector)
- The goal for this year's data taking is to understand the machine and backgrounds, but early physics program aimed at low multiplicity physics is also planned
- By the end of the year, vertex detector will be installed and Belle II will start data taking fully operational in early 2019
- Rich physics programme with plenty of unique measurements
- **Looking forward to the first results**