The Belle II Experiment

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Outline

- B factories
- SuperKEKB collider and Belle II detector
- Belle II physics program
- Status and schedule

Belle II @ SuperKEKB

Belle II experiment at SuperKEKB collider – new facility for search of physics beyond the Standard Model (New Physics) in B, charm and τ decays

SuperKEKB – major upgrade of the KEKB B factory at KEK (Tsukuba, Japan)

$e^+e^- \to \Upsilon(4S) \to \bar{B}B$

$L_{design} = 8 \times 10^{35}\ cm^{-2}s^{-1}$

$E(e^+) = 4$ GeV, $E(e^-) = 7$ GeV

Belle II – upgraded Belle detector

overall Integrated luminosity ~ 50 ab^{-1}

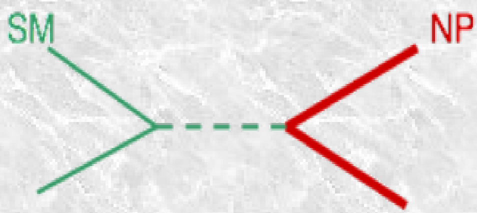
55 billion $B\bar{B}$ pairs, 47 billion $\tau^+ \tau^-$ pairs,
65 billion $c\bar{c}$ (from $e^+e^- \to c\bar{c}$)

~ 50 x Belle data

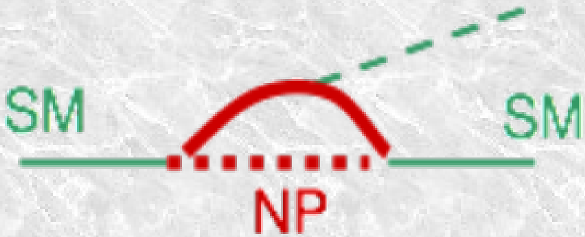
Searching for New Physics (NP)

Two approaches:

1. **Energy frontier:**
direct production of the new particles
(limited by the beam energy)
LHC (Atlas, CMS)



2. **Flavour frontier:**
indirectly reveal NP virtual particles
in loops – can probe the energies > 10 TeV
(„B factories", LHCb)



Complementarity:

If NP is found in direct searches, it is reasonable to expect NP effects in B, D and τ decays.

- Flavour structure of New Physics?
- CP violation in New Physics?

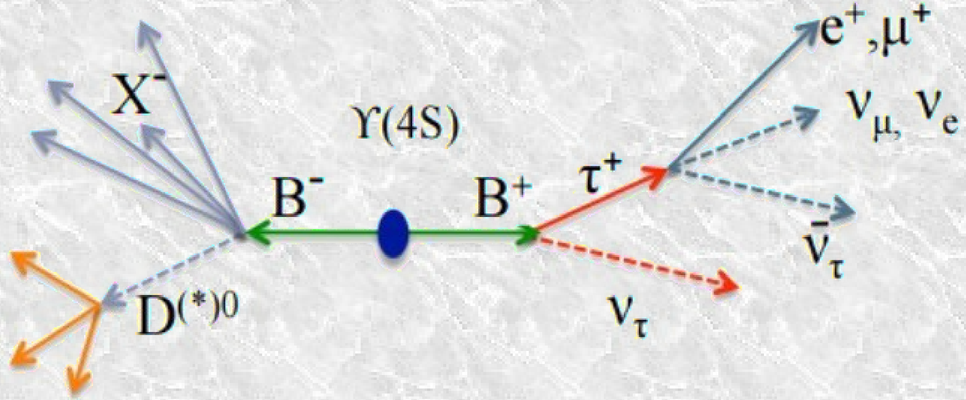
Unique features of B factory

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

Two B mesons without additional particles are produced via ϒ(4S) resonance

ADVANTAGES:

reconstruction of one B meson (B_{tag}) constrains the 4-momentum and flavour of the other (B_{sig})



hadronic tagging: B_{tag} is fully reconstructed in numerous hadronic decays
semileptonic tagging: B_{tag} is partially reconstructed in semileptonic decays

Useful in:

1. inclusive measurements
2. reconstruction of missing energy channels ex: $B \to D^{(*)}\tau\nu$, $B \to \tau\nu$

Unique features of B factory

Clear experimental environment – low background and thus easier reconstruction of decays with γ, π^0, ρ, η, η'.

low track multiplicities and detector occupancy give:

- high B, D, τ and quarkonia reconstruction efficiency
- low trigger bias.

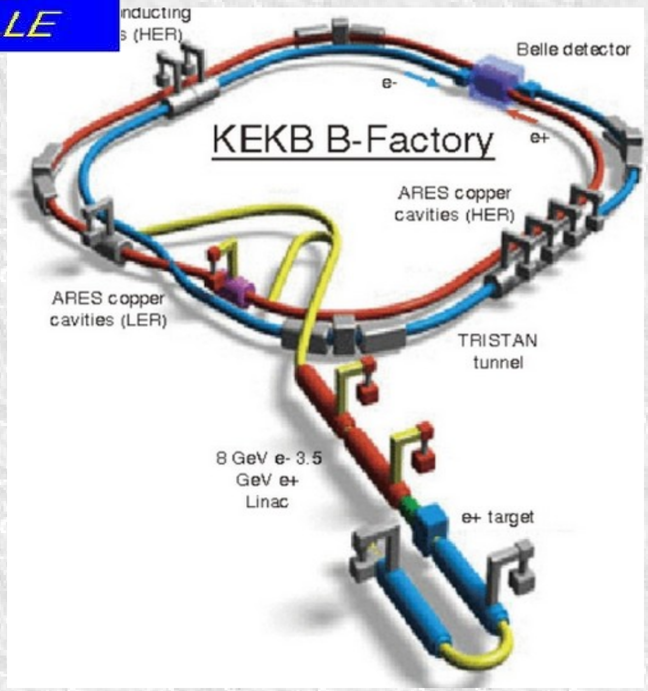
↳ corrections and systematic uncertainties are substantially reduced in many types of measurements, e.g. Dalitz plot analyses, dark sector searches...

beam energy can be adjusted for several resonances
$\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(5S)$, $\Upsilon(6S)$

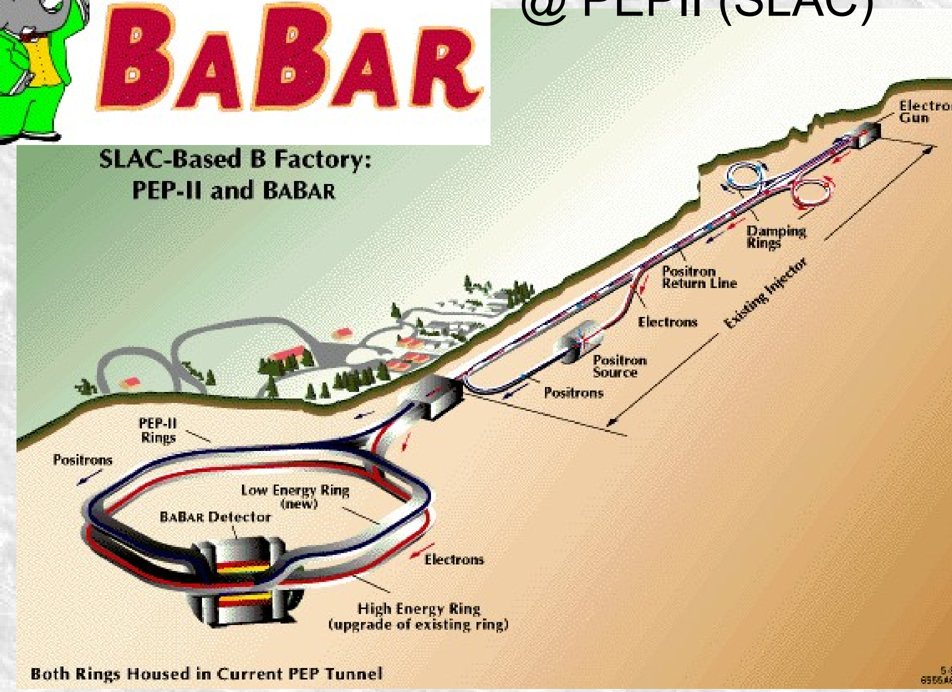
→ B_s physics

B Factories achievements

@ KEKB (KEK)

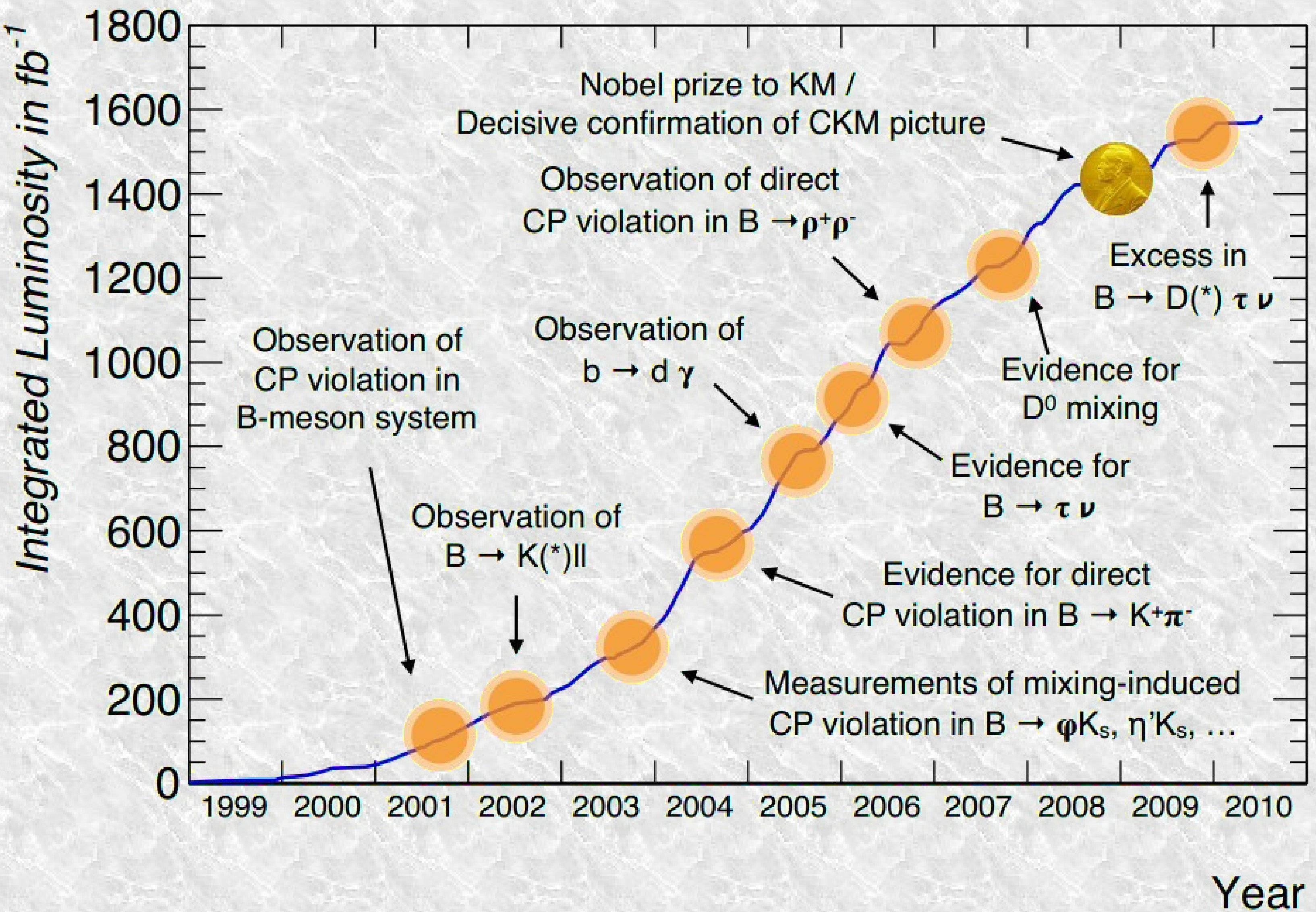


@ PEPII (SLAC)

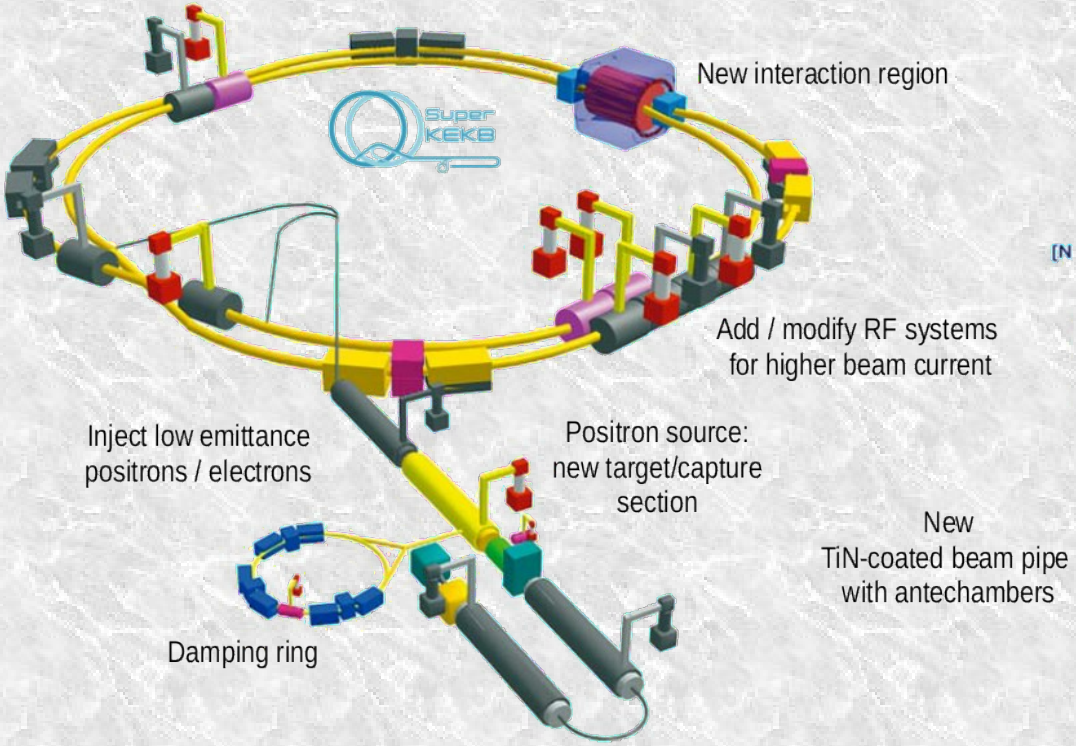


B Factories achievements

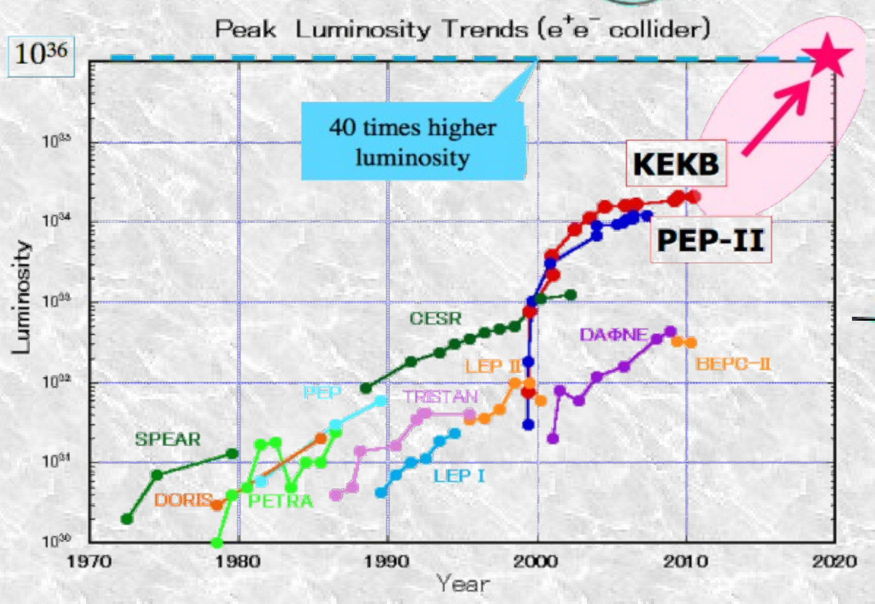
The previous generation of B factories achieved a great success in B (charm, τ) physics studies and explored possible new physics



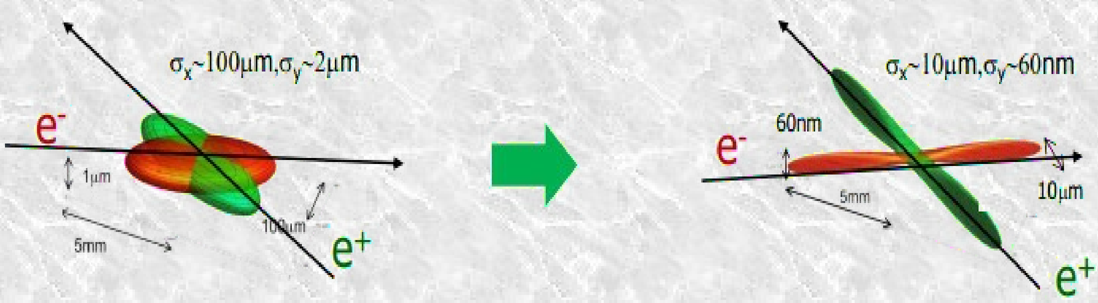
SuperKEKB $e^+ e^-$ collider



- instantaneous luminosity: $L = 8 \times 10^{35}\ cm^{-2}\ s^{-2}$
- goal int. luminosity $50 ab^{-1}$ by 2025
- New technologies: nano beam scheme



nano-beams



Belle II detector

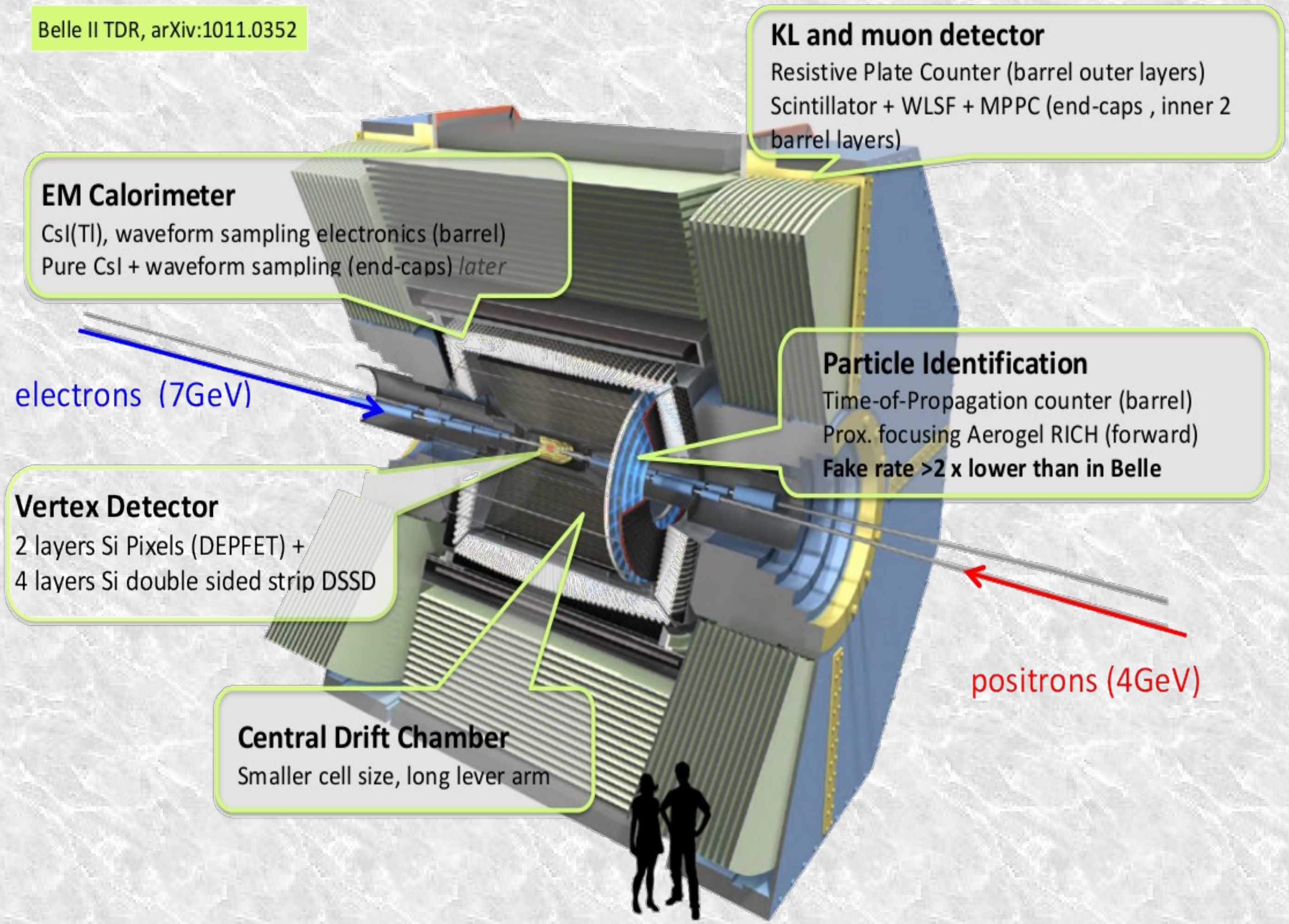
Better hermeticity by adding K/π ID to the endcaps

Increase K_s efficiency (by ~30%)

Improve IP and secondary vertex resolution (~factor of 2)

Better K/π separation (π fake rate decreases by ~2.5)

Improve π^0 reconstruction



Must be capable of handling higher beam-related background

Tests with beams and cosmics are ongoing

Belle II is complementary to the LHC indirect searches :

Well defined initial state

- neutral final states: $\pi^0\pi^0$, $K_S\pi^0(\gamma)$, $K_SK_SK_S$
- final states with missing energy: $\tau\nu$, $D^{(*)}\tau\nu$
- inclusive modes, e.g. $B \to X_S\,\gamma$, $B \to X_s l^+l^-$

Large B and charm statistics:

Specializes in (very) rare decays to clean final states: $B\to K^*\mu\mu$, $B\to\mu\mu$ and hadronic B decays into charged states

not only complementary but also... competitive

Observables	Belle (2015)	Belle II 50 ab^{-1} 70%@$\Upsilon(4S)$, improved K_S	50 ab^{-1}@$\Upsilon(4S)$	LHCb Run-1	22 fb^{-1}
	$(\sigma_{stat}, \sigma_{sys})$	$(\sigma_{stat}, \sigma_{sys})$	$(\sigma_{stat}, \sigma_{sys})$	$(\sigma_{stat}, \sigma_{sys})$	$(\sigma_{stat}, \sigma_{sys})$
$\sin(2\phi_1)$ in $B \to J/\psi K_S$	(0.023, 0.011)	(0.003, 0.007)	(0.007)	(0.035, 0.020)	(0.012, 0.007#)
$\sin(2\phi_1)$ in $B \to \phi K_S$	(0.14)	(0.018)	(0.015)	(0.30)#	(0.06)
$\sin(2\phi_1)$ in $B \to \eta' K_S$	(0.07, 0.03)	(0.008, 0.008)	(0.009)	–	–

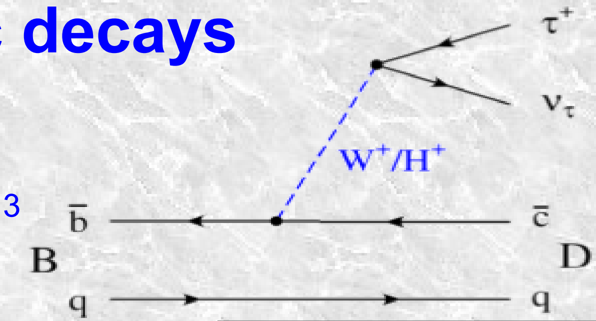
Physics at Belle II

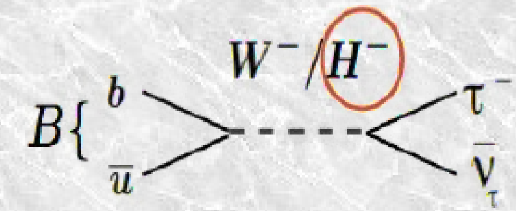
Leptonic and semileptonic decays

$B \to D^{(*)}\tau\nu$, $B \to \tau\nu$

arXiv:1507.03233 arXiv:hep-ex/1503.05613

Phys. Rev. Lett.99(2007) 191807.
Phys. Rev. D82(2010) 072005.





- sensitive to charged scalars
(ex. charged Higgs)
→ BF modification

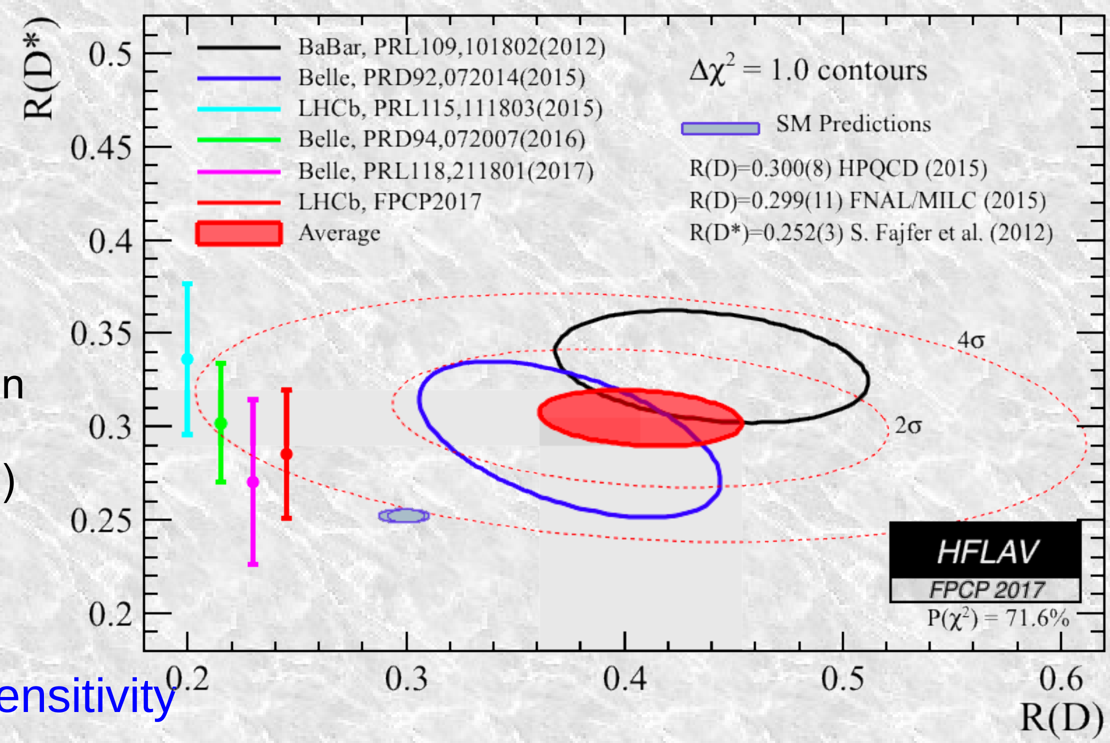
Sensitivity:

	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$R(B \to D\tau\nu)$	$0.440(1 \pm 16.5\%)$	5.6%	3.4%
$R(B \to D^*\tau\nu)$	$0.332(1 \pm 9.0\%)$	3.2%	2.1%
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$96(1 \pm 27\%)$	10%	5%

$B \to D^{(*)}\tau\nu$ is sensitive to the tensor operator

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau\nu)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell\nu)}$$

- lepton universality test
- the world average value gives 4σ deviation from SM at the moment
- Belle II can reach 3% sensitivity for $R(D^{(*)})$ at 50 at^{-1}



+ Belle II allows for the measurements of τ and D* polarization with good sensitivity

Physics at Belle II

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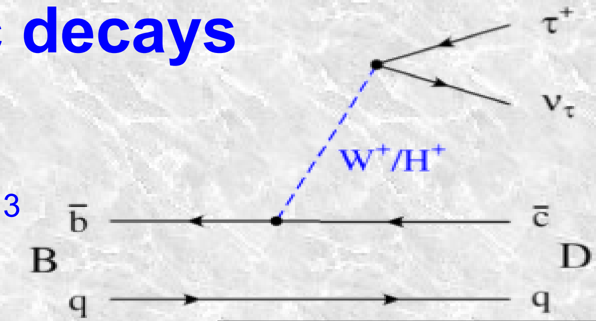

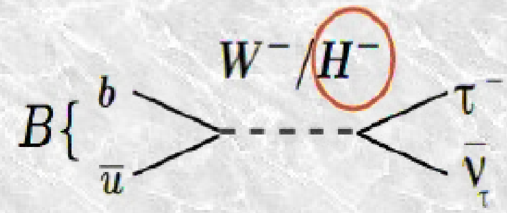

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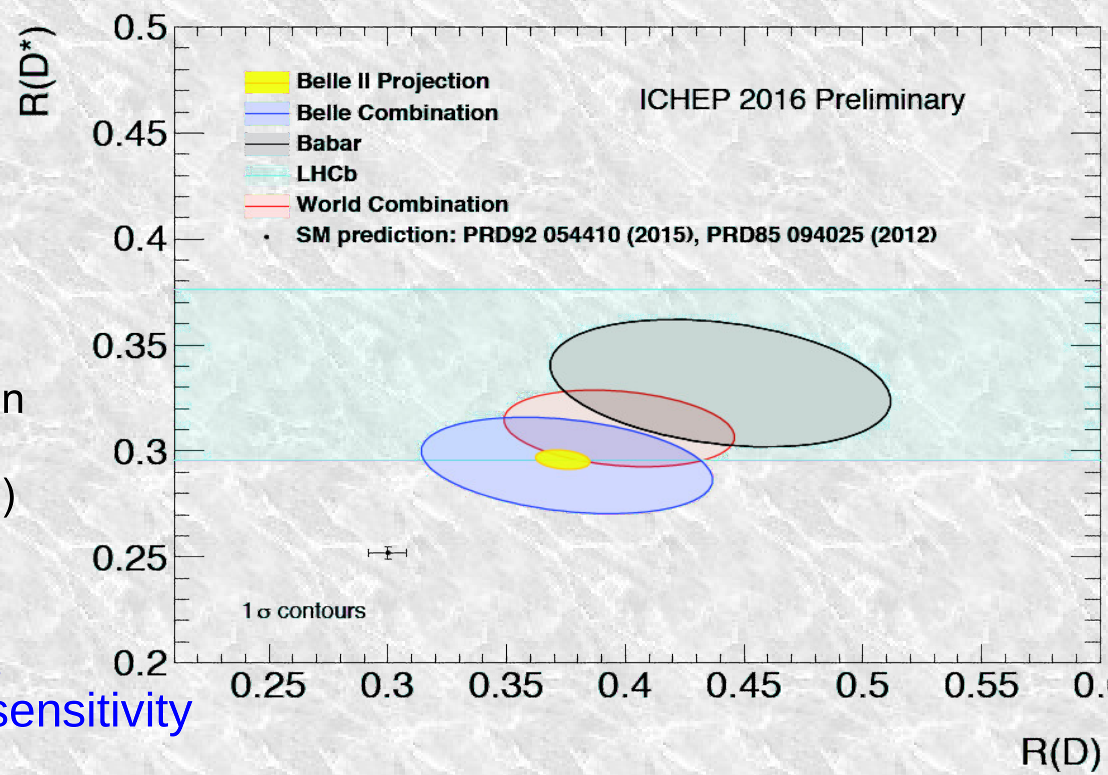

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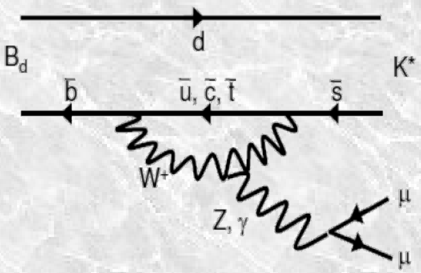
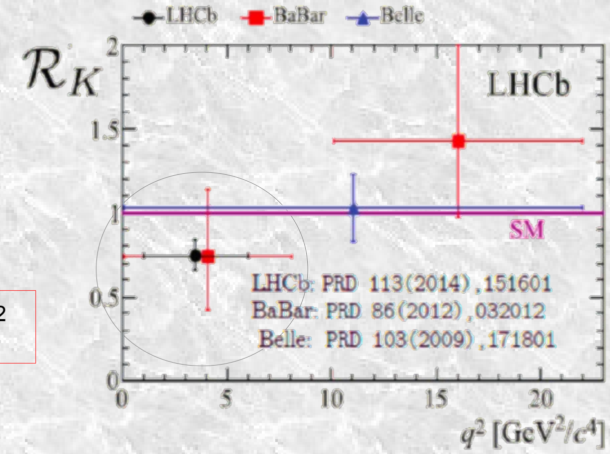
Physics at Belle II



FCNC semileptonic $b \to s\,ll$ decays

Discrepancies in observables versus the invariant dilepton mass squared (q^2)



1. LHCb tension for $\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} =$

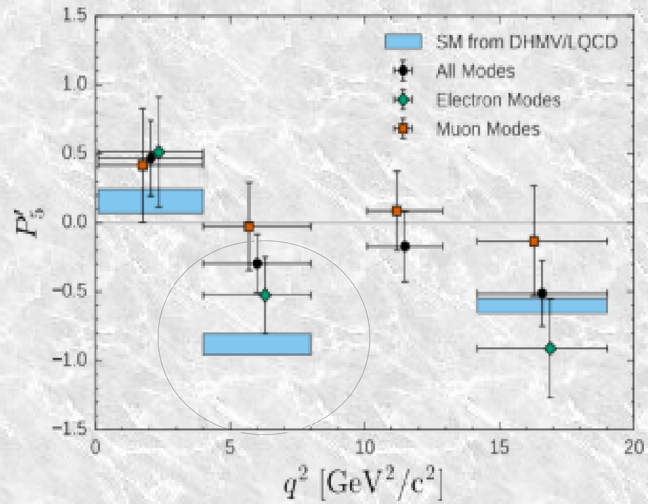
$0.745^{+0.090}_{-0.074} \pm 0.036$ (2.6σ)

1 < q^2 < 6 GeV^4/c^2

---> Belle II can handle electron and muon modes with comparable efficiencies, for wide q^2 region

2. for the known P'_5 tension (LHCb), **Belle** observes 2.6σ deviation for μ channel in the lepton-flavor-dependent angular analysis

4 < q^2 < 8 GeV^4/c^2



---> Belle II can do:

- isospin comparison of K^{*+} and K^{*0} (or the ground K states)
- inclusive $b \to X_s ll$ studies (less theoretical uncertainties)

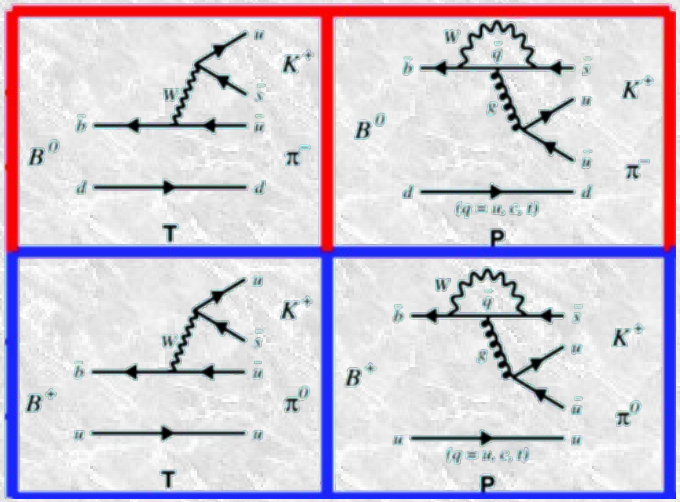
competitive to LHCb !

Physics at Belle II

Direct CP violation in B→Kπ decay:

puzzling tension between SM prediction and measurement:

$$\Delta A \equiv A_{CP}^{B^0\to K^+\pi^-} - A_{CP}^{B^+\to K^+\pi^0} =$$
$$= -0.122 \pm 0.022$$ (HFAG 2013) (4σ)

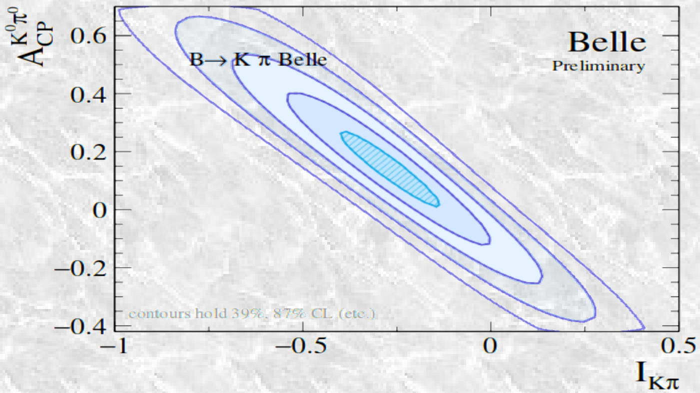


ΔA ≈ 0 in Standard Model, but may be changed:
- due to neglected diagrams
- NP effects

Model independent sume rule to test SM

$$A_{CP}^{K^+\pi^-} + A_{CP}^{K^0\pi^+}\frac{\mathcal{B}(B^+\to K^0\pi^+)\tau_{B^0}}{\mathcal{B}(B^0\to K^+\pi^-)\tau_{B^+}} = A_{CP}^{K^+\pi^0}\frac{2\,\mathcal{B}(B^+\to K^+\pi^0)\tau_{B^0}}{\mathcal{B}(B^0\to K^+\pi^-)\tau_{B^+}} + A_{CP}^{K^0\pi^0}\frac{2\,\mathcal{B}(B^0\to K^0\pi^0)}{\mathcal{B}(B^0\to K^+\pi^-)}$$

M. Gronau, PLB 627 (2005) 82, D. Atwood, A. Soni, PRD 58 (1998) 036005



Neutral final states are crucial !!!

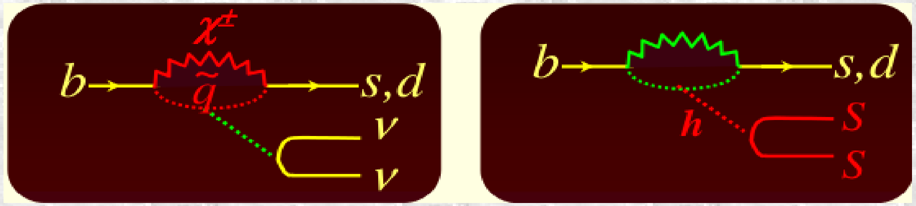
Belle II can measure A(B→K^0pi^0) from time-dep. analyses with uncertainty ~ 4%

Physics at Belle II

Electroweak decays with neutrinos b→d(s)νν

Missing energy modes: B → $h^{(*)}\nu\nu$

- possible window to light dark matter, not accessible in direct searches



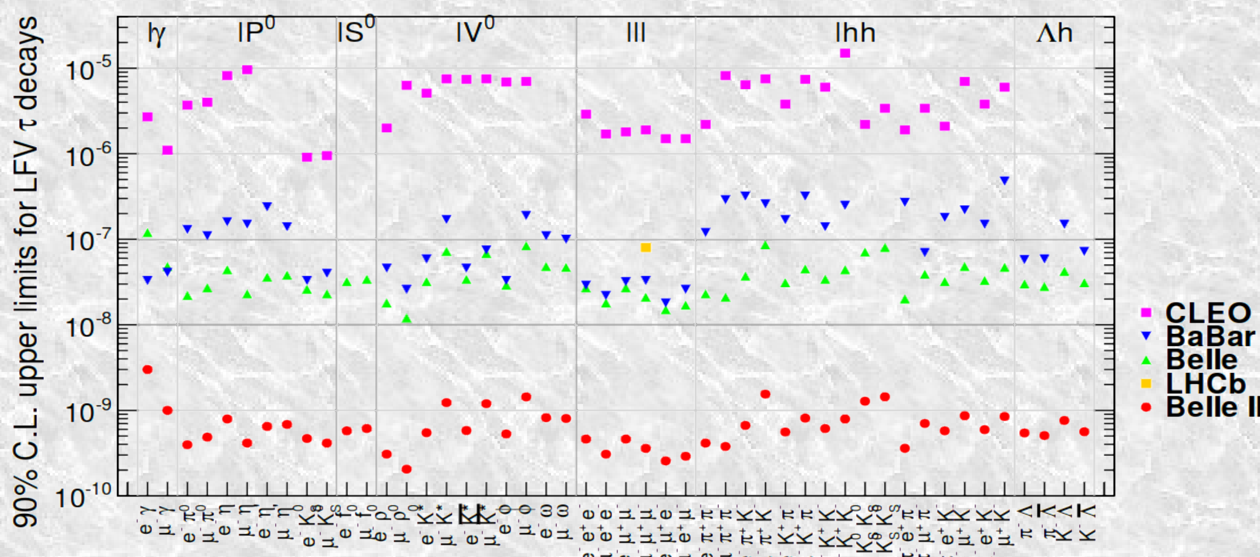
Also a window for SUSY !!!

Mode	$\mathcal{B}$ $[10^{-6}]$	Efficiency Belle $[10^{-4}]$	$N_{\text{Backg.}}$ 711 fb^{-1} Belle	$N_{\text{Sig-exp.}}$ 711 fb^{-1} Belle	$N_{\text{Backg.}}$ 50 ab^{-1} Belle II	$N_{\text{Sig-exp.}}$ 50 ab^{-1} Belle II	Statistical error 50 ab^{-1}	Total Error
$B^+ \to K^+\nu\bar{\nu}$	3.98	5.68	21	3.5	2960	245	23%	24%
$B^0 \to K^0_S\nu\bar{\nu}$	1.85	0.84	4	0.24	560	22	110%	110%
$B^+ \to K^{*+}\nu\bar{\nu}$	9.91	1.47	7	2.2	985	158	21%	22%
$B^0 \to K^{*0}\nu\bar{\nu}$	9.19	1.44	5	2.0	704	143	20%	22%
$B \to K^*\nu\bar{\nu}$ combined							15%	17%

Sources of LFV beyond the SM?

$\tau \to \mu\gamma$ $\tau \to eee$

Highly suppressed in SM, but in some NP scenarios BF may be expanded to 10^{-10} - 10^{-7}



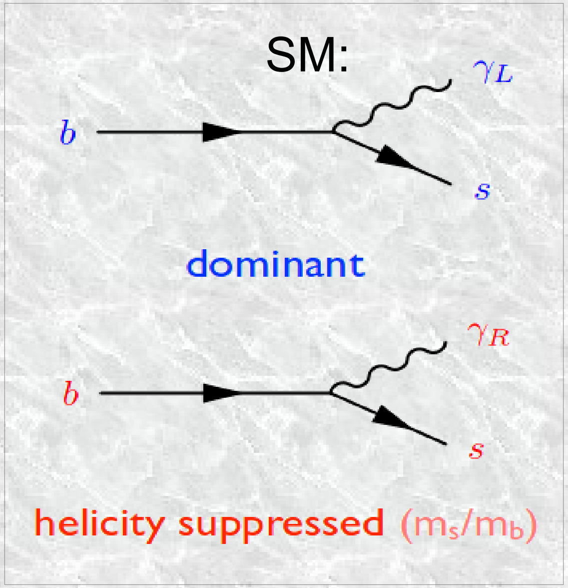
Physics at Belle II

Are there right-handed currents from NP?

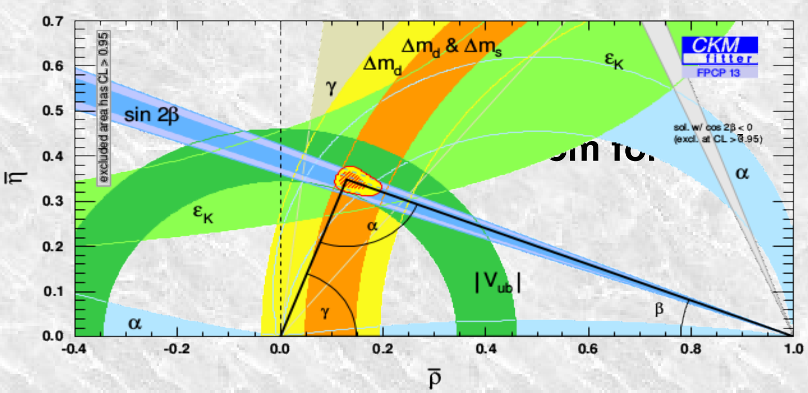
- Time-dependent CP Violation in $B \to K^{*0}\gamma$ $\to K^0_S\,\pi^0$

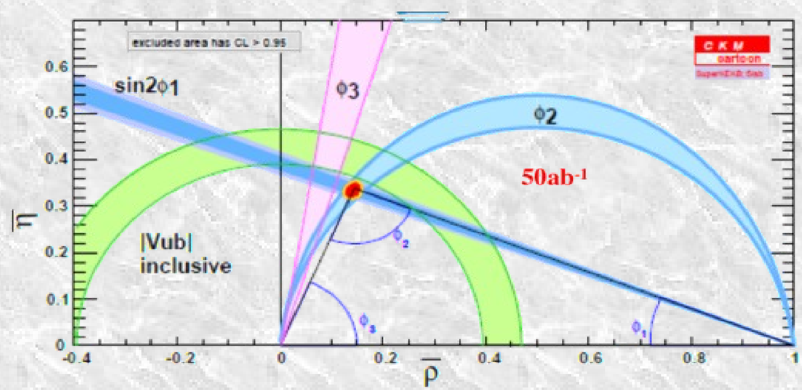
Phys. Rev. Lett.79, 185
Phys. Rev. D71, 076003

no charged tracks from B decay to reconstruct the vertex !!!



Enhanced precision of UT parameters (sides, angles)



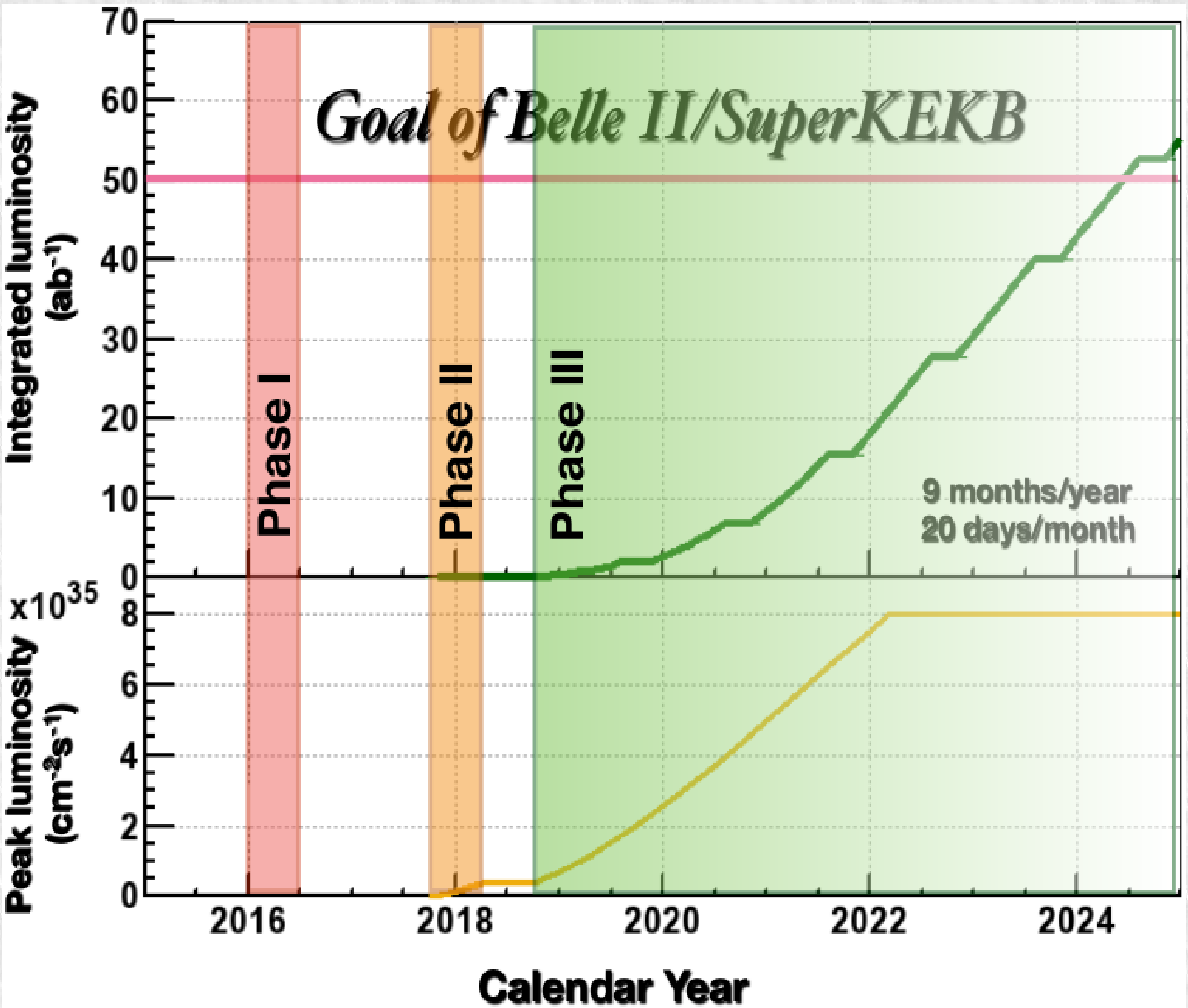


Expected precision for 50 ab^{-1}: α, β, γ angles: 1°, 0.3°, 1.5°

Inconsistency between angles or/and sides → NP

SuperKEKB luminosity /Belle II status & schedule

- Commissioning/operation of Belle II phases:



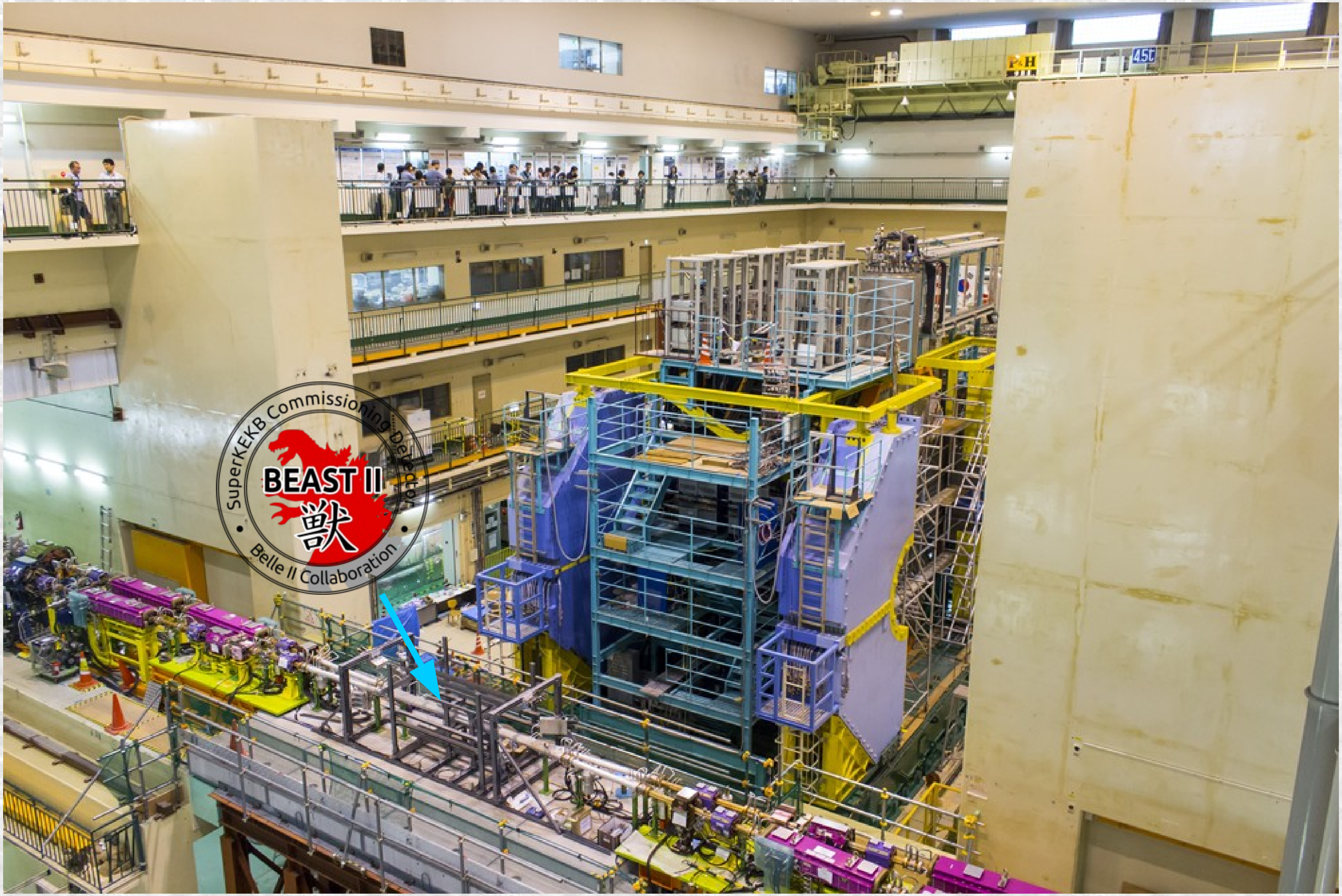
Phase 1 –
- commisioning of the main ring
- Installation of outer detectors
- Vacuum scrubbing & beam background studies with BEASTII

Phase 2 – Start of the collisions, detector commissioning (Nov 2017 – spring 2018) **without vertex detector. First physics runs on Y(4S) and Y(6S)! ~20±20 fb -1**

Phase 3 - full detector operation by the end 2018

- Full data sample (50 ab^{-1}) to be collected by 2025

Beast II


SuperKEKB Commissioning Detector
BEAST II
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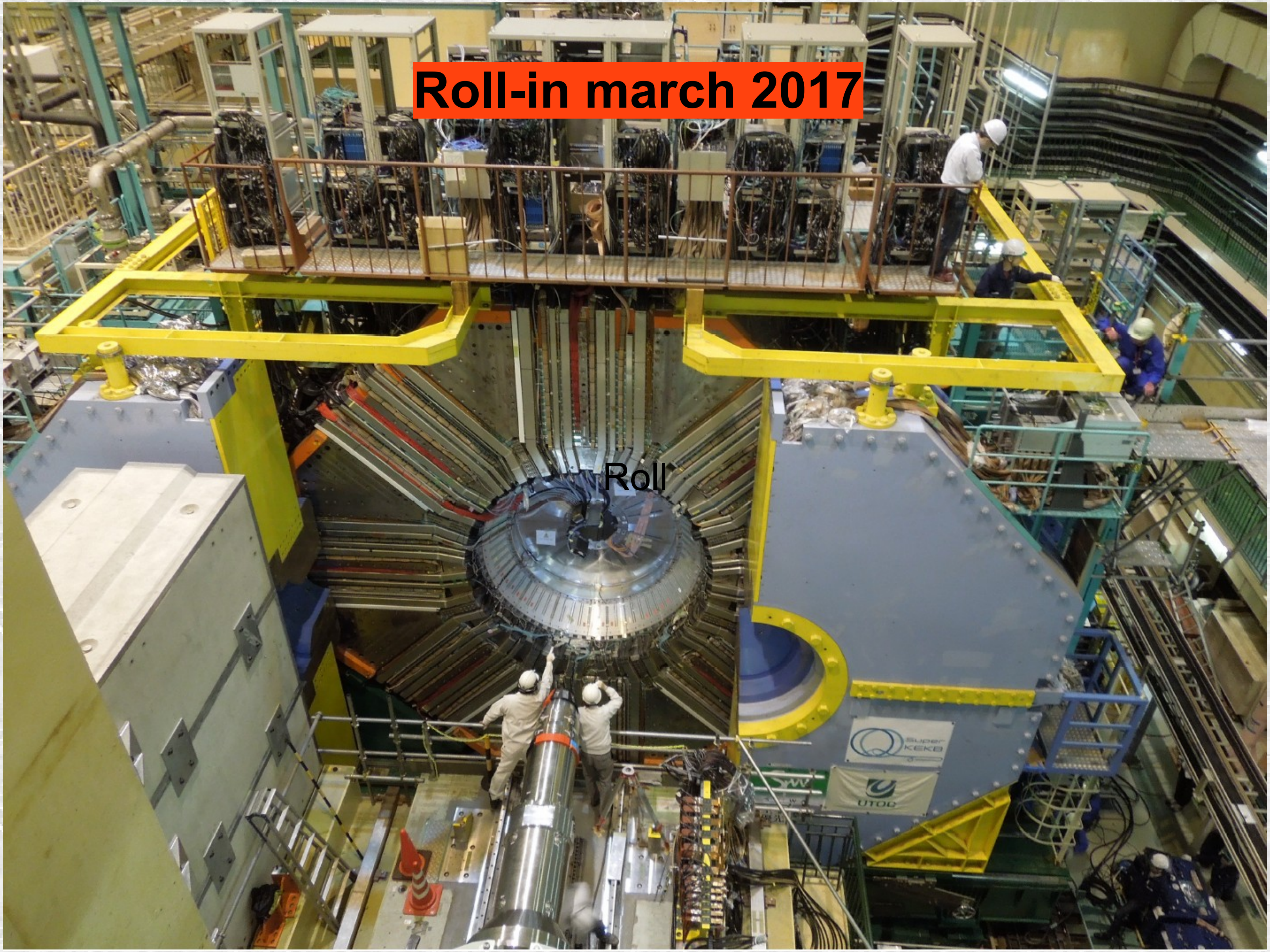
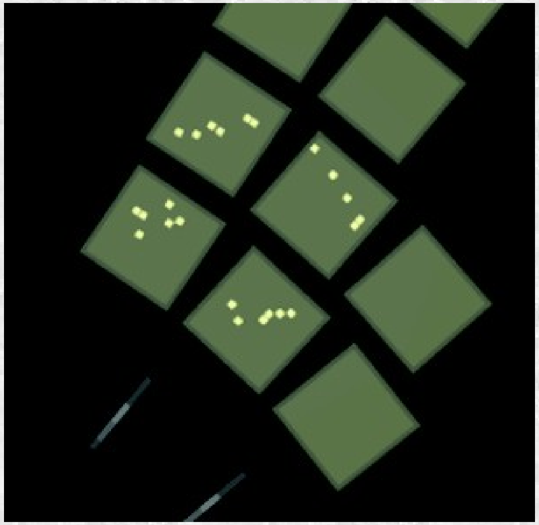
Belle II Collaboration

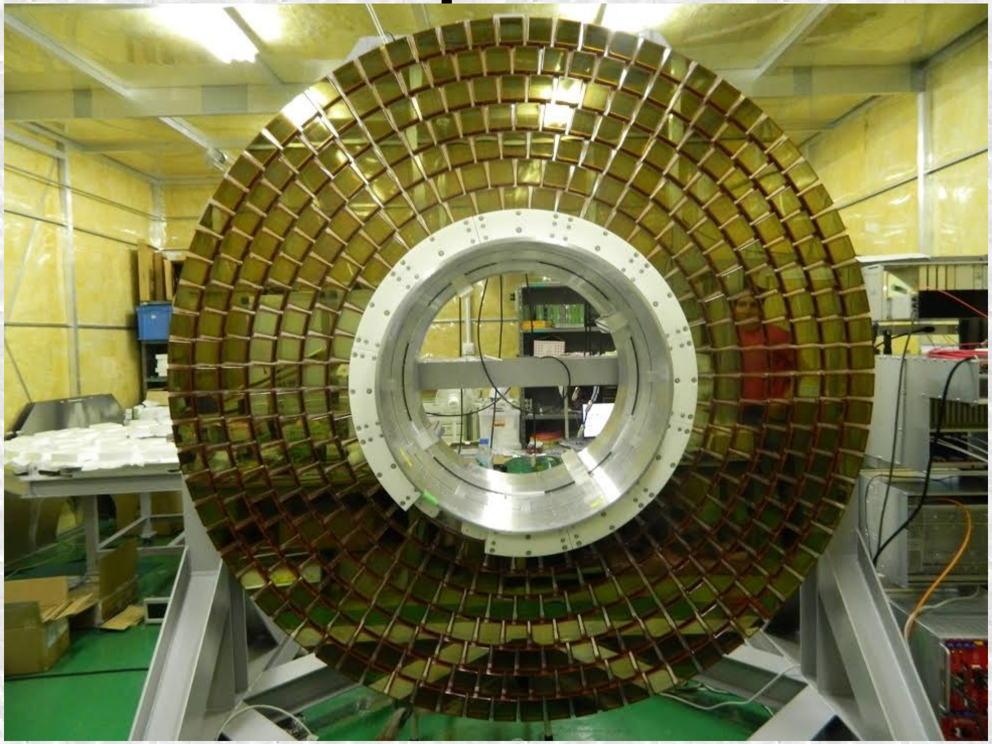
Belle II construction



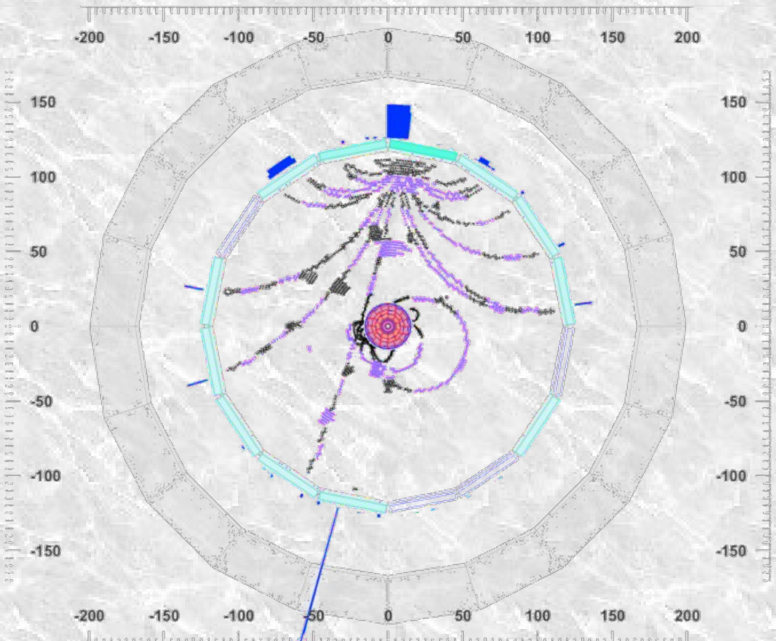
Belle II recent development

- Forward PID: Aerogel RICH installed

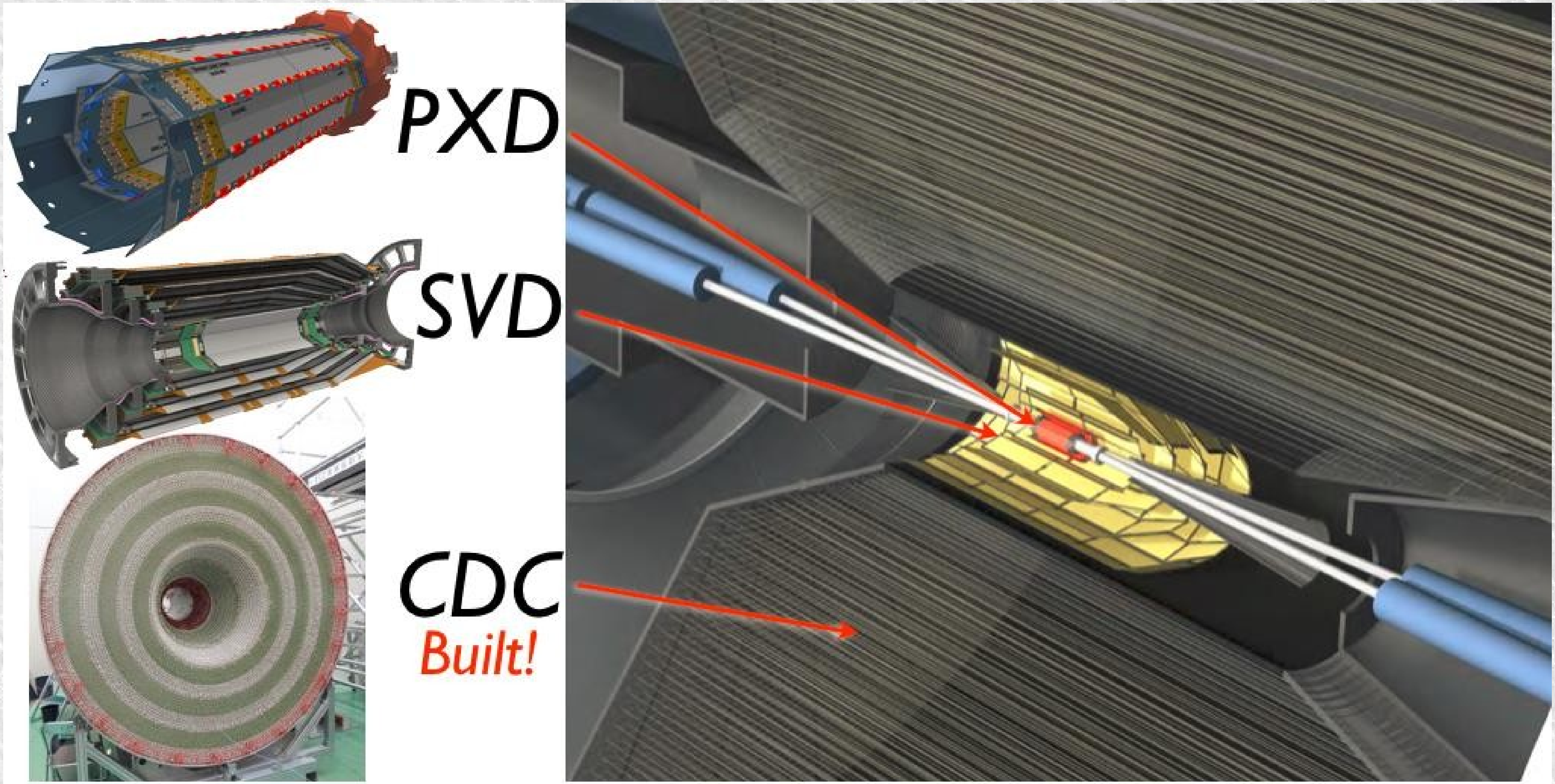




- Beautiful cosmic ray event with full detector

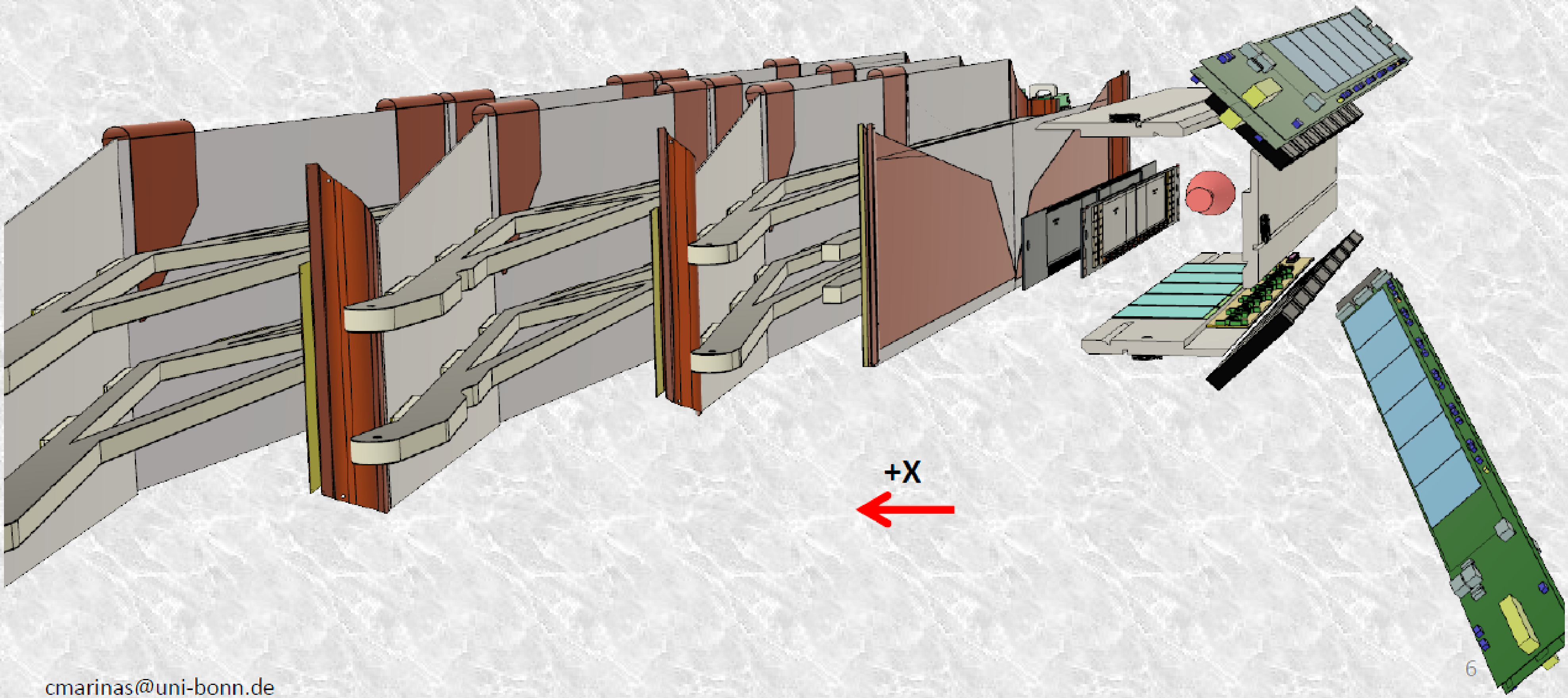


Belle II tracking system



Silicon vertex detetors (SVD +PXD_ will be installed next summer after confirmation that machine beam background is low enough

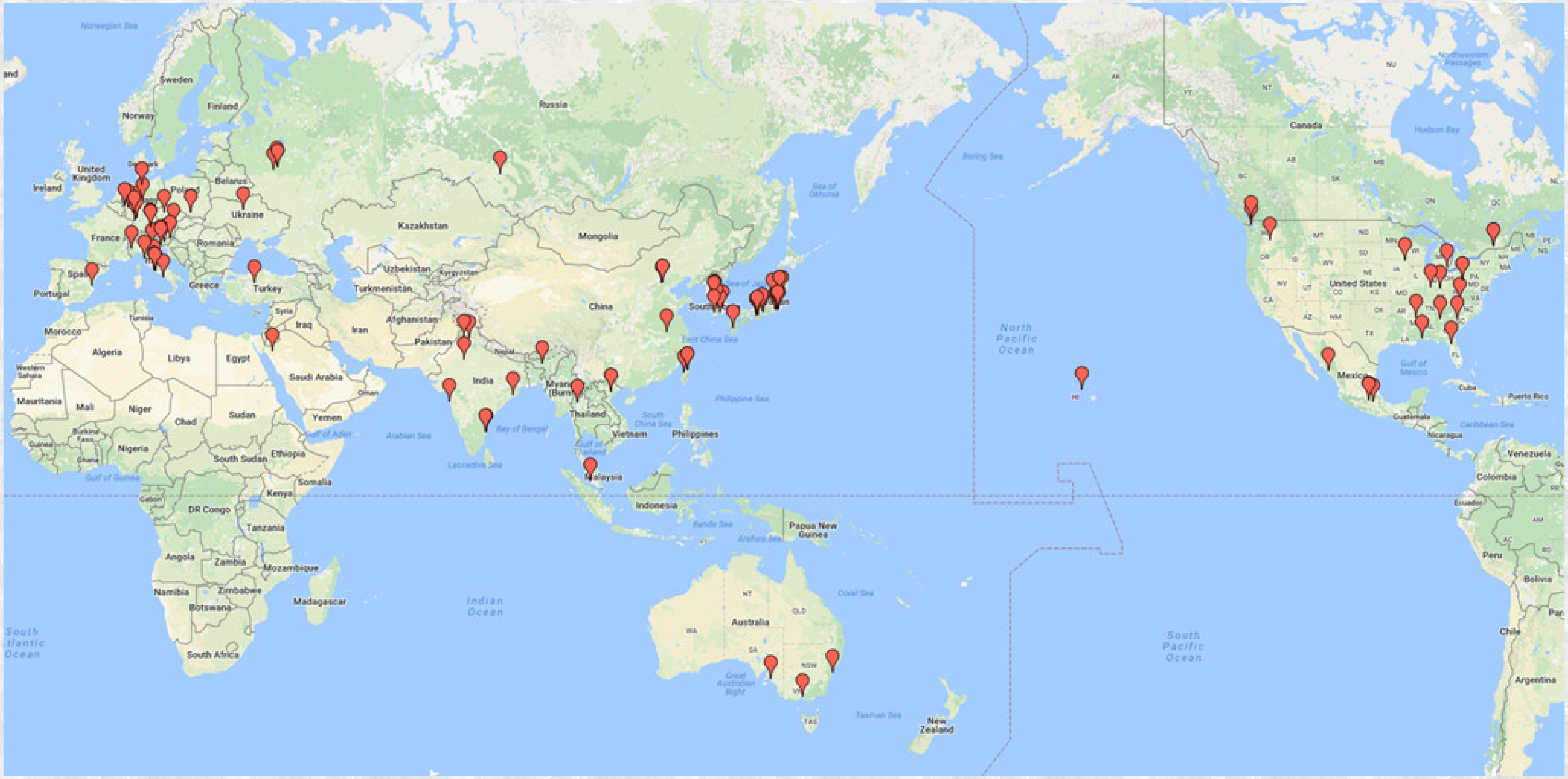
Belle II tracking system



For Beast phase II we will only one sector of pixel and DSSD detectors + some RD detectors

Summary

- *B factories have a track record of discovery in flavor physicsB, which will continue to play a fundamental role in the process of understanding Nature in the next decade*
- *Belle II detector will start taking data very soon*



24 Countries, over 700 collaborators and 104 institutions

BACKUP

	Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$ [64]	0.012	0.008
	α [°]	85 ± 4 (Belle+BaBar) [24]	2	1
	γ [°]	68 ± 14 [13]	6	1.5
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$ [19]	0.053	0.018
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$ [65]	0.028	0.011
	$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$ [17]	0.100	0.033
	$\mathcal{A}(B \to K^0 \pi^0)$	$-0.05 \pm 0.14 \pm 0.05$ [66]	0.07	0.04
UT sides	$\lvert V_{cb}\rvert$ incl.	$41.6 \cdot 10^{-3}(1 \pm 1.8\%)$ [8]	1.2%	
	$\lvert V_{cb}\rvert$ excl.	$37.5 \cdot 10^{-3}(1 \pm 3.0\%_{\text{ex.}} \pm 2.7\%_{\text{th.}})$ [10]	1.8%	1.4%
	$\lvert V_{ub}\rvert$ incl.	$4.47 \cdot 10^{-3}(1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$ [5]	3.4%	3.0%
	$\lvert V_{ub}\rvert$ excl. (had. tag.)	$3.52 \cdot 10^{-3}(1 \pm 8.2\%)$ [7]	4.7%	2.4%
Missing E decays	$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$96(1 \pm 27\%)$ [26]	10%	5%
	$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7 [67]	20%	7%
	$R(B \to D\tau\nu)$	$0.440(1 \pm 16.5\%)$ [29]†	5.6%	3.4%
	$R(B \to D^*\tau\nu)^{\dagger}$	$0.332(1 \pm 9.0\%)$ [29]†	3.2%	2.1%
	$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ $[10^{-6}]$	< 40 [30]	< 15	30%
	$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ $[10^{-6}]$	< 55 [30]	< 21	30%
Rad. & EW penguins	$\mathcal{B}(B \to X_s\gamma)$	$3.45 \cdot 10^{-4}(1 \pm 4.3\% \pm 11.6\%)$	7%	6%
	$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$ [68]	1	0.5
	$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$ [20]	0.11	0.035
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$ [21]	0.23	0.07
	C_7/C_9 $(B \to X_s \ell\ell)$	~20% [36]	10%	5%
	$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	< 8.7 [42]	0.3	–
	$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	–	< 2 [44]‡	–