Future Belle II experiment at the KEK laboratory

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Rencontres de Moriond

QCD and High Energy Interactions

Outline

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

Belle II @ SuperKEKB

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

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

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

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

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

Belle II – upgraded Belle detector

overall Integrated luminosity ~ 50 ab^{-1}

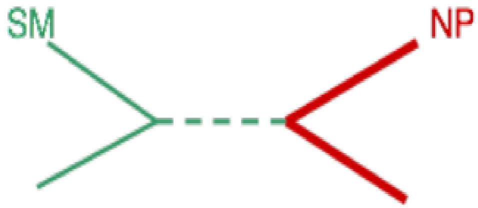
55 billion $B\bar{B}$ pairs, 47 billion $\tau^+\tau^-$ pairs, 65 billion $c\bar{c}$ (from $e^+e^- \to c\bar{c}$)

~ 50 x Belle data

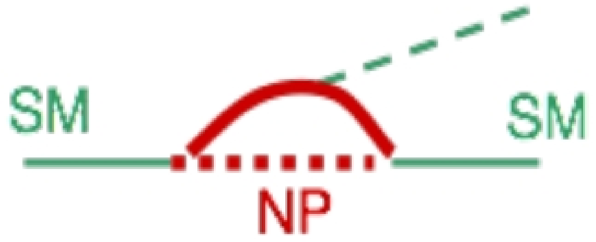
Searching for New Physics (NP)

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 – probe the energy above 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?

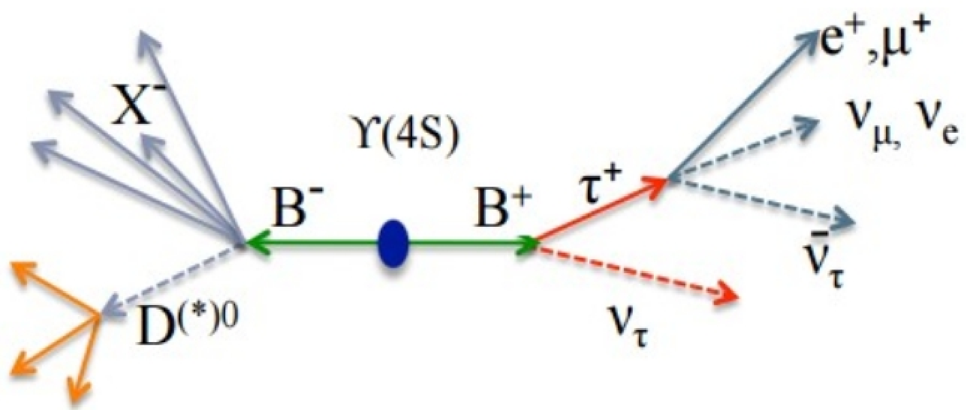
Unique features of B factory

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

Two B mesons without additional particles are produced via $\Upsilon(4S)$ resonance

ADVANTAGES:

1. 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: $B \rightarrow D^{(*)}\tau\nu$, $B \rightarrow \tau\nu$

Unique features of B factory

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

3. low track multiplicities and detector occupancy give:

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

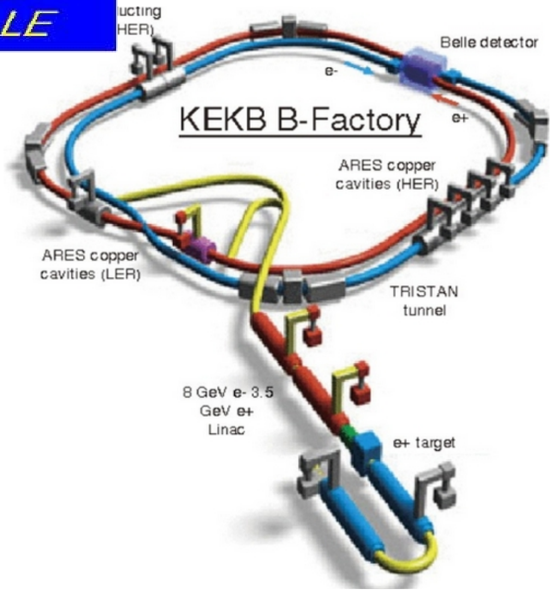
↳ corrections and systematic uncertainties are substantially reduced in many types of measurements, e.g. Dalitz plot analyses, dark sector searches...

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

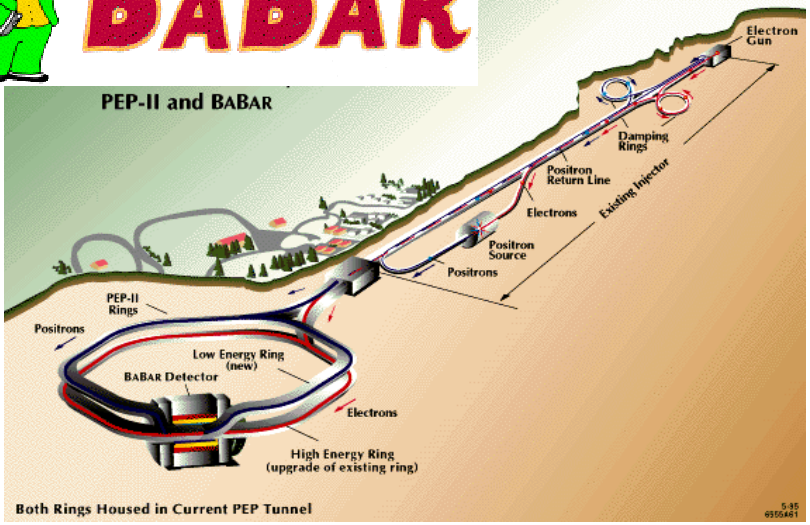
→ B_s physics

B Factory achievements

@ KEKB (KEK)

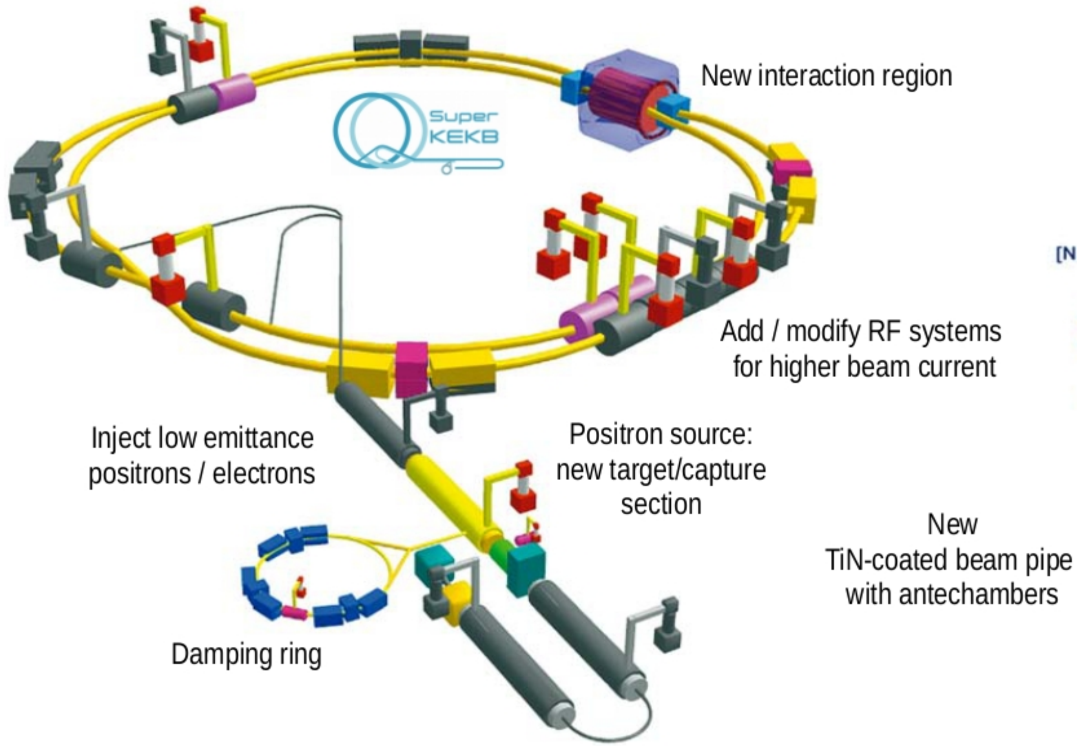


@ PEPII (SLAC)

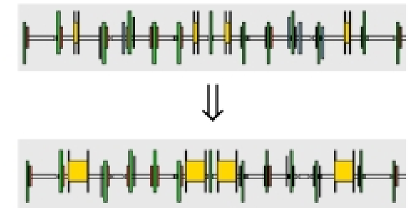


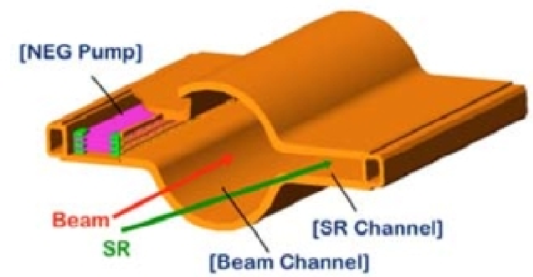
- *CP Violation in B decays*
- *Determination of Unitary Triangle parameters (sides, angles)*
- *Studies on rare B decays*
- *Measurements of* $B \to \tau\nu$ *and* $B \to D^{(*)}\tau\nu$ *decays*
- *Found mixing in charm*
- *Discovery of many new states ex. quarkonium(+like), X(3872),* $Z(4430)^{+}$

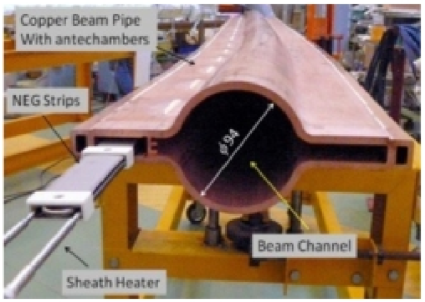
SuperKEKB e^+ e^- collider

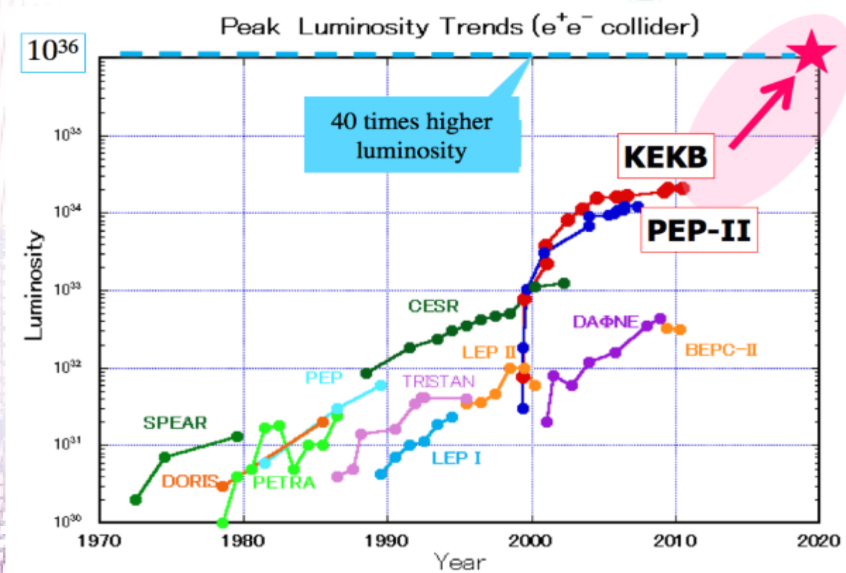


Replace short dipoles with longer ones (LER)

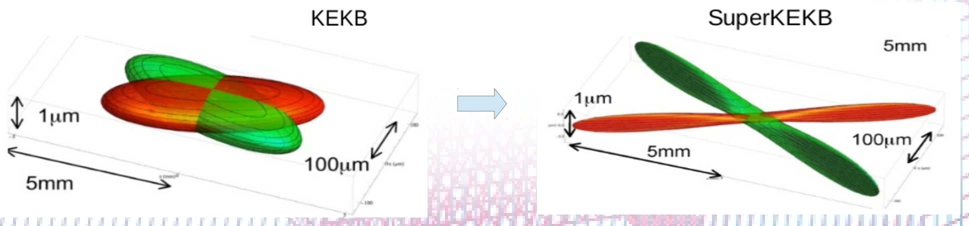








nano-beams



Belle II detector

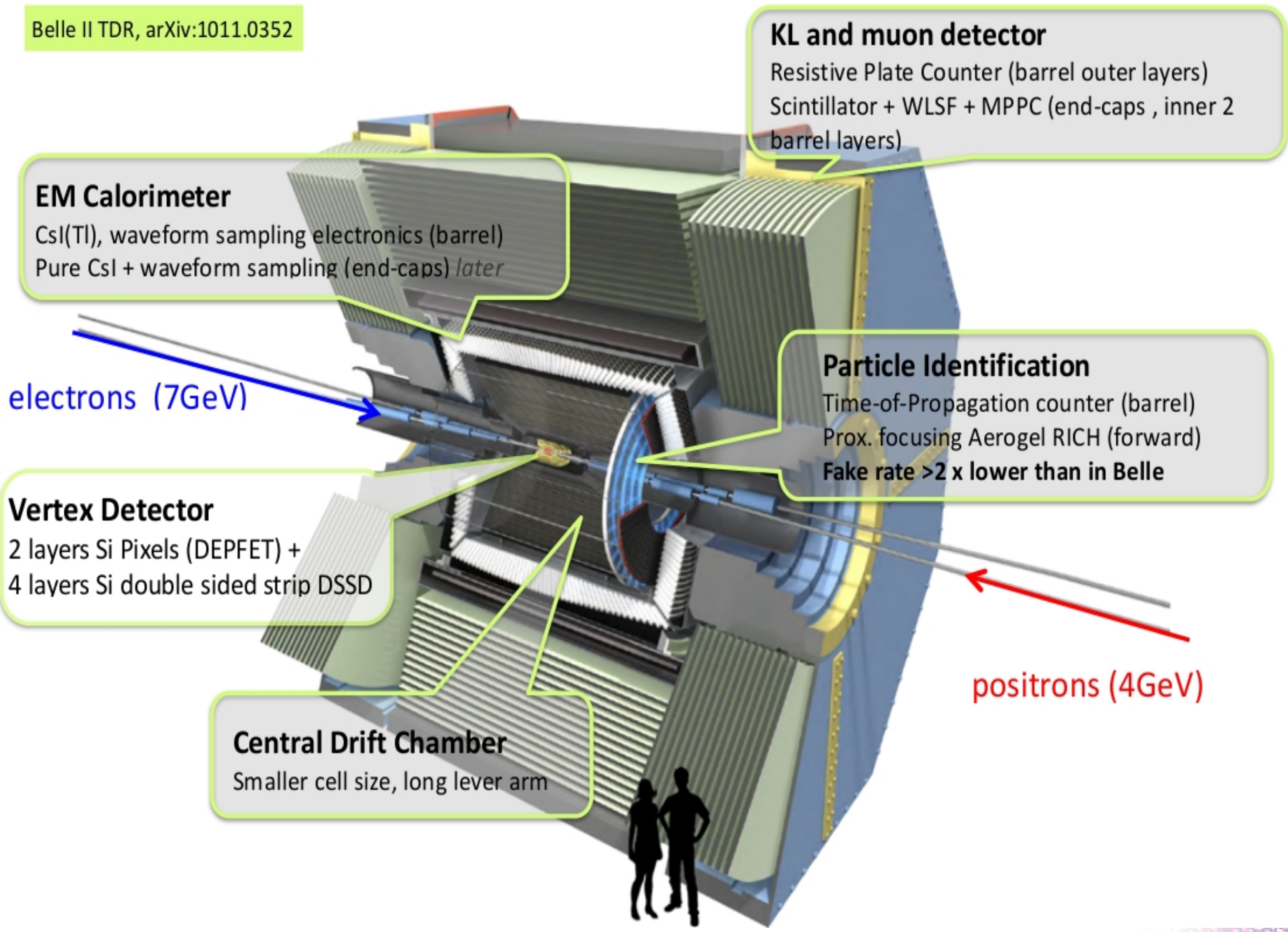
Better hermeticity by adding K/π ID and μID to the endcaps

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 LHCb on *indirect* searches:

Well defined initial state → we can handle:

- 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: $B \to K^*\mu\mu$, $B \to \mu\mu$

not only complemetary but also... competitive

Observables	Belle (2015)	Belle II 50 ab^{-1} 70%@$\Upsilon(4S)$, improved K_S	Belle II 50 ab^{-1}@$\Upsilon(4S)$	LHCb Run-1	LHCb 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)	–	–

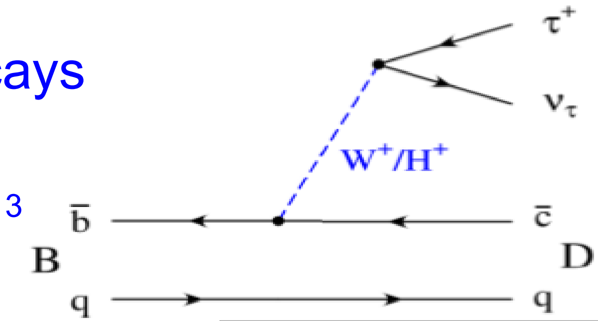
Physics case for Belle II

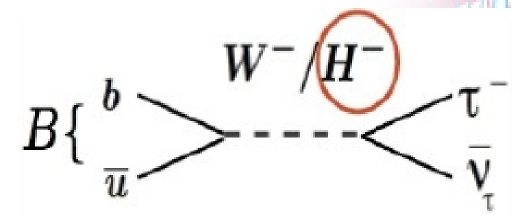
1. Leptonic and semileptonic decays

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

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

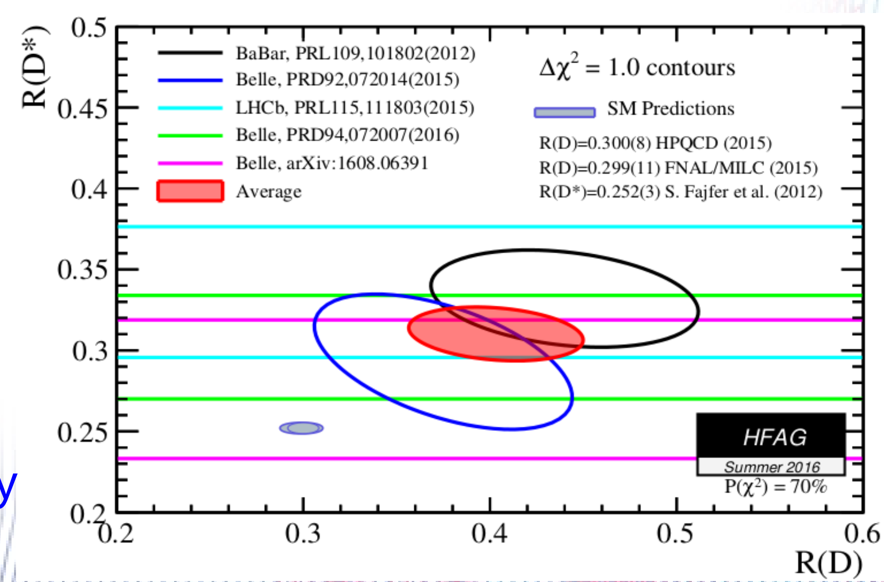
Sensitivity:	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$R(B \to D\tau\nu)$	$0.440(1 \pm 16.5\%)$	5.6%	3.4%
$R(B \to D^*\tau\nu)$	$0.332(1 \pm 9.0\%)$	3.2%	2.1%
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$96(1 \pm 27\%)$	10%	5%

$B \to D^{(*)}\tau\nu$ is sensitive to the tensor operator
→ good scope for testing **leptoquarks** models (ex. R_2-type LQ model)

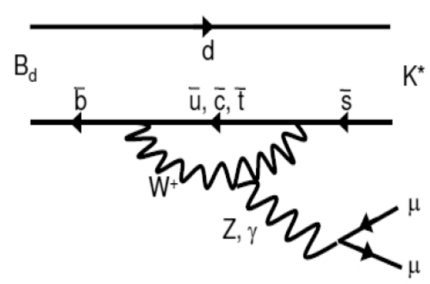
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau\nu)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell\nu)}$$

- 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

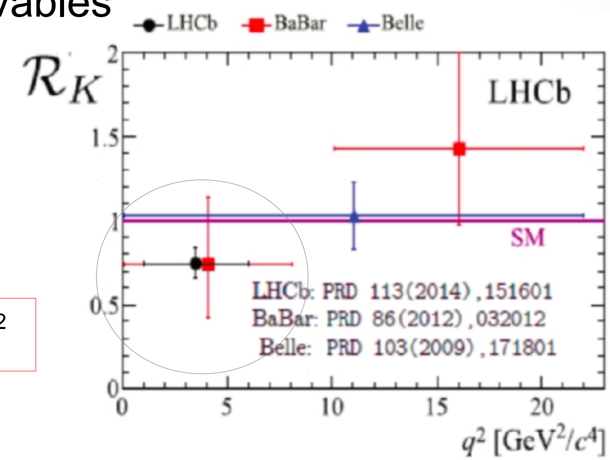


Physics case for Belle II



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

Some discrepancies from SM in observables measured along the squared invariant mass of dilepton (q^2)



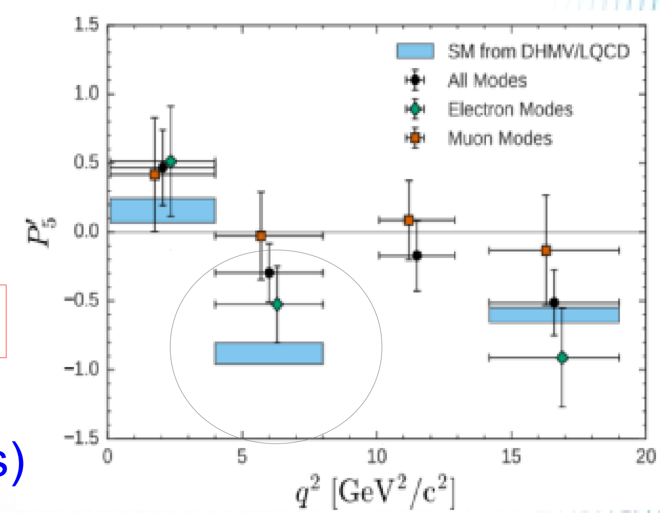
1. LHCb tension for $\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} =$ $0.745^{+0.090}_{-0.074} \pm 0.036$ (2.6σ)

$1 < q^2 < 6$ GeV⁴/c²

---> Belle II can handle electrons and muons mode 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

$4 < q^2 < 8$ GeV⁴/c²



---> 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)

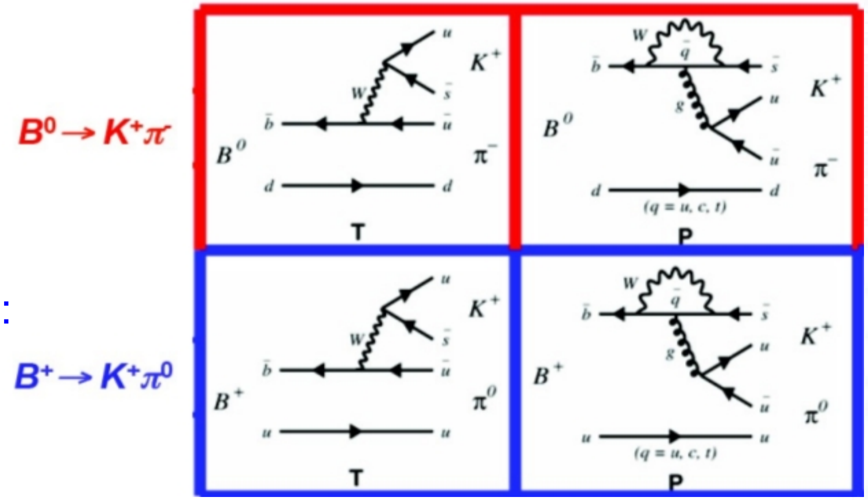
competitive to LHCb !

Physics case for Belle II

3. 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)

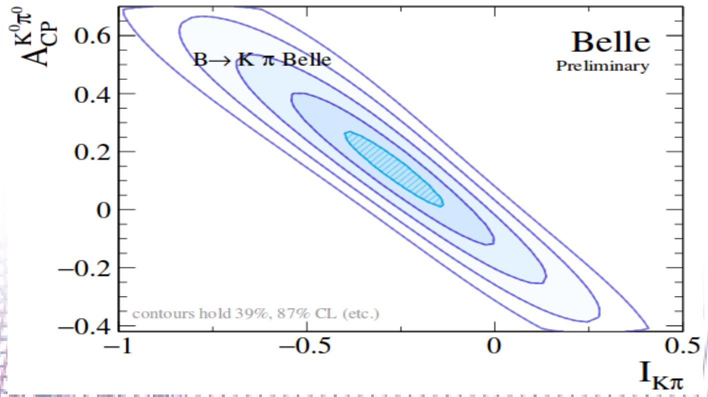


ΔA ≈ 0 in Standard Model, but may be changed:
- due to neglected diagrams
- NP effects

Model independent sum 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 !!!

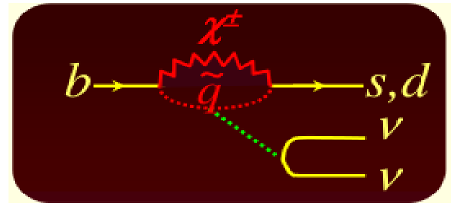
Belle II can measure A(B→K⁰pi⁰) from time-dep. analyses with uncertainty ~ 4%

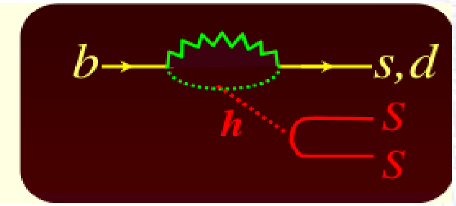
Physics case for Belle II

4. Electroweak decays with neutrinos $b \to d(s)\nu\nu$

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

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





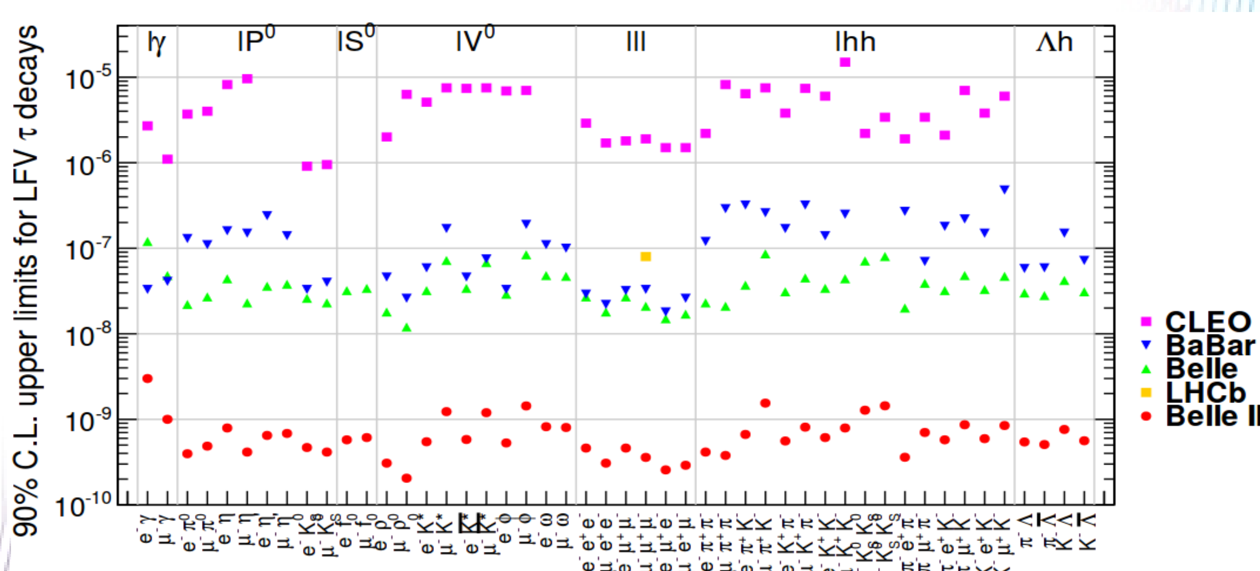
Also a window for SUSY !!!

Mode	$\mathcal{B}$ $[10^{-6}]$	Efficiency Belle $[10^{-4}]$	$N_{\rm Backg.}$ 711 $\rm fb^{-1}$ Belle	$N_{\rm Sig-exp.}$ 711 $\rm fb^{-1}$ Belle	$N_{\rm Backg.}$ 50 $\rm ab^{-1}$ Belle II	$N_{\rm Sig-exp.}$ 50 $\rm ab^{-1}$ Belle II	Statistical error 50 $\rm ab^{-1}$	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%

5. Sources of LFV beyond the SM?

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

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



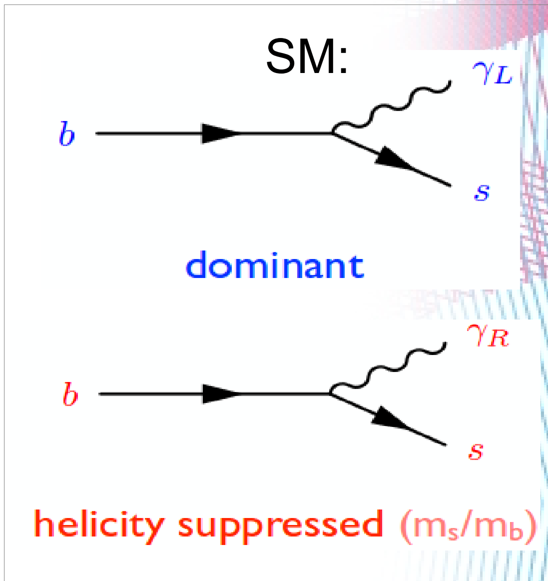
Physics case for Belle II

6. Are there right-handed currents from NP?

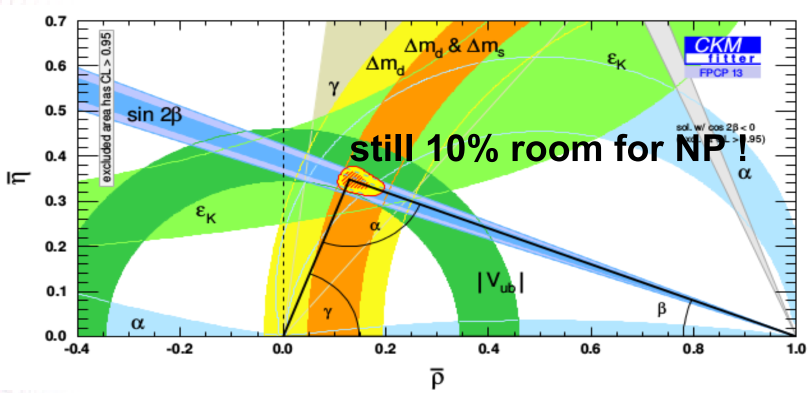
- Time-dependent CP Violation in $B \to K^{*0}\,\gamma$ → $K^0_S\,\pi^0$

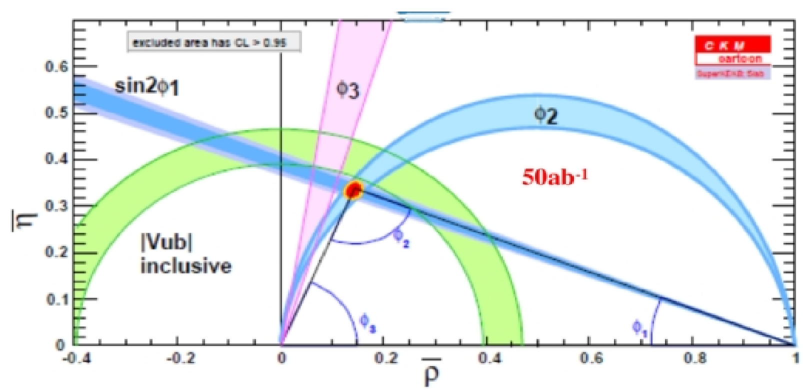
Phys. Rev. Lett.79, 185
Phys. Rev. D71, 076003

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



7. Enhanced precision of UT parameters (sides, angles)



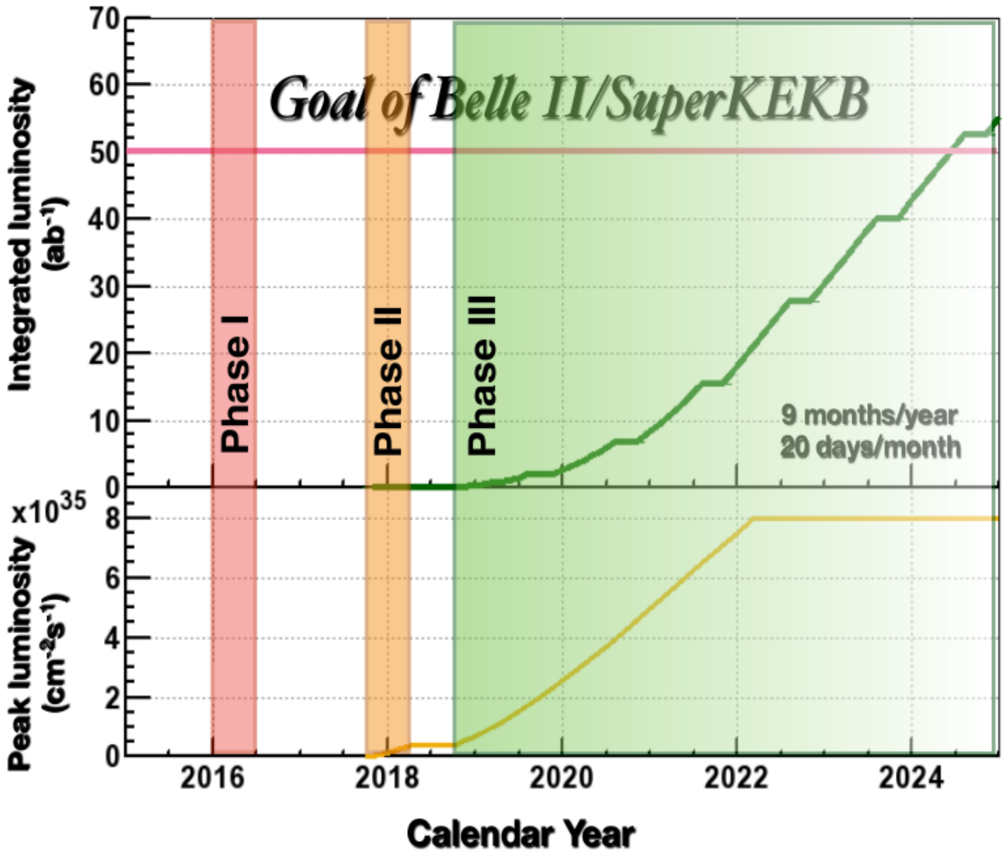


Expected precision for 50 ab^{-1}: α, β, γ angles: 1°, 0.3°, 1.5°

Inconsistency between angles or/and sides → NP

SuperKEKB/Belle II status & schedule

- There are three Phases in commissioning/operation of Belle II



Phase 1 – Succesfull commisioning of the main ring (February – June 2016)
Installation of outer detectors (finished in December 2016)
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)!**

Phase 3 - full detector operation by the end 2018

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

Summary

- *B factories proved their excellent tools for flavour physics, which will continue to play a fundamental role in the process of understanding Nature in the next decade*
- *Belle II has a rich physics program, complementary to the LHCb, to shed some light on New Physics*
- *Belle II detector construction and integration is proceeding according to the schedule*

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.	$37.5 \cdot 10^{-3}(1 \pm 3.0\%_{\rm ex.} \pm 2.7\%_{\rm th.})$ [10]	1.8%	1.4%
	$\lvert V_{ub}\rvert$ incl.	$4.47 \cdot 10^{-3}(1 \pm 6.0\%_{\rm ex.} \pm 2.5\%_{\rm th.})$ [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]‡	–