北京航空航天大學
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Status of the Belle II experiment and prospects for *B* and τ Physics

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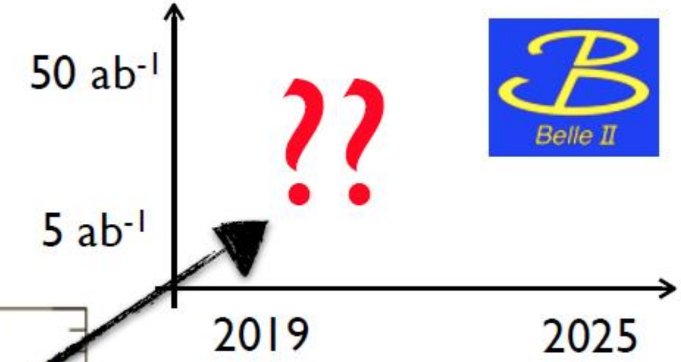
MASS2018: Origin of Mass at the High Energy and Intensity Frontier, May 28 - June 1, 2018, Denmark

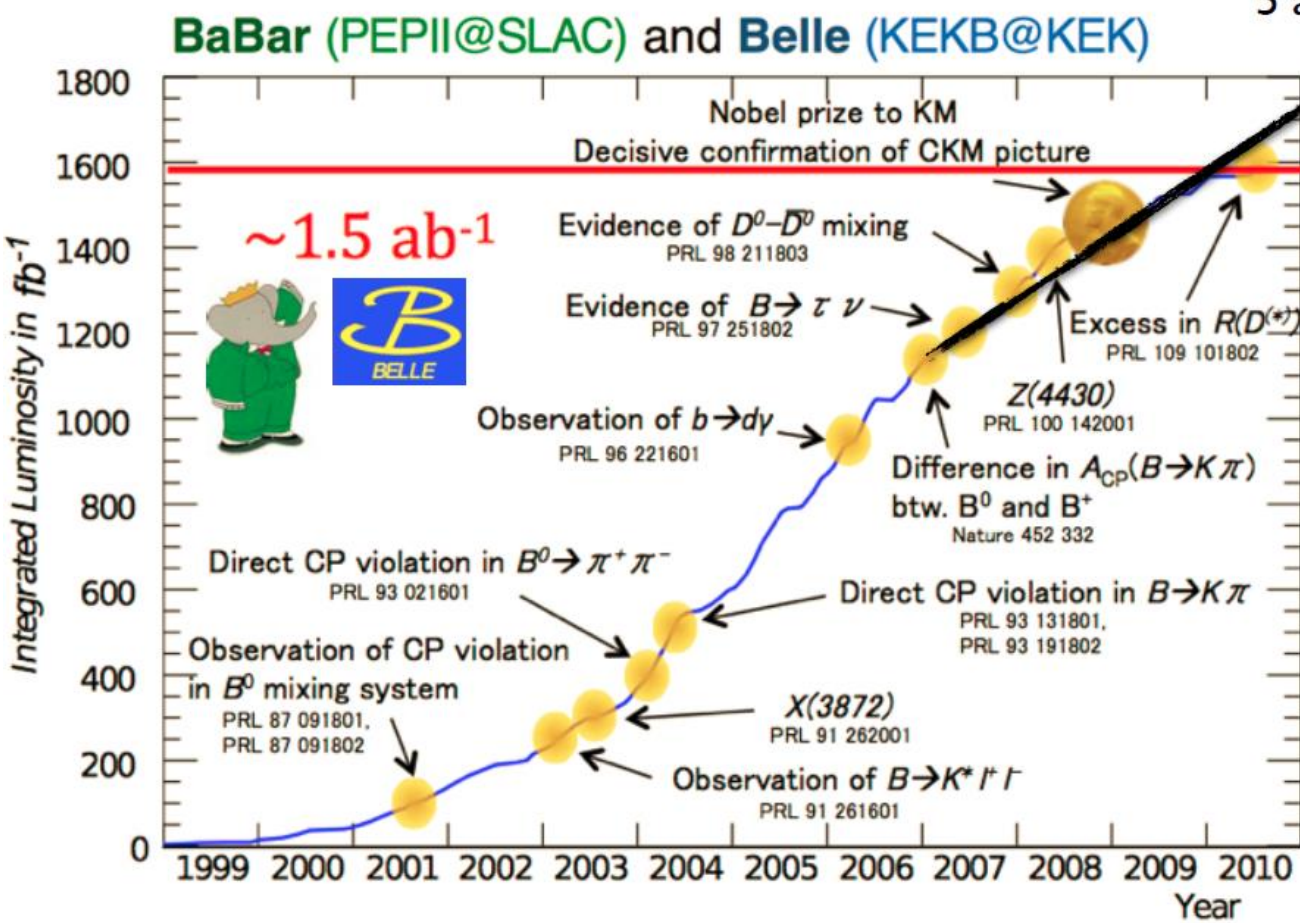
Outline

- Achievements of *B* factories
- Belle II experiment
- Belle II schedule and status
- Prospects of τ decays at Belle II
- Prospects of *B* decays at Belle II
- Summary

Due to limited time, I will only give highlights on some topics which will be studied at Belle II. Apologies if I neglect your favorite topics.

B-physics in the last decade





- Belle and BaBar have produced a large number of important results, since the beginning of their data taking
- Competition between the two experiments has helped in pulling out the best from the two datasets

The Physics of B factories
EPJC 74, 3026 (2018)

Belle II will provide a significantly larger data sample (x50 Belle) that will allow to continue the investigation with a much more powerful instrument

τ–physics in the last decade

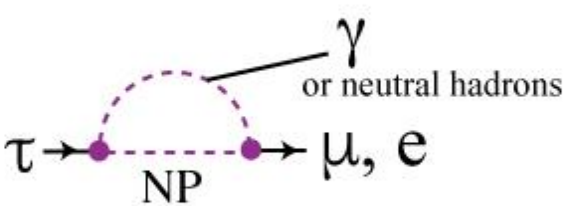
(~0.9 x 10^9 $\tau^+\tau^-$ pairs per ab^{-1})

NP hunting: SM suppressed decay searches have reached limits down to $10^{-7} \sim 10^{-8}$.

SM: (Phys. Rev. D16 (1977) 1444)

$$\mathcal{B}(\tau \to l\gamma) = \frac{3\alpha}{32\pi}\Big|\sum_i U^*_{\tau i} U_{\mu i} \frac{\triangle^2_{3i}}{m^2_W}\Big|^2 \leq 10^{-53} \sim 10^{-49}$$

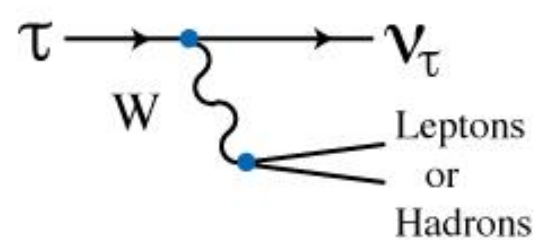
NP:



Calibbi et al., PRD 74, 116002 (2006)

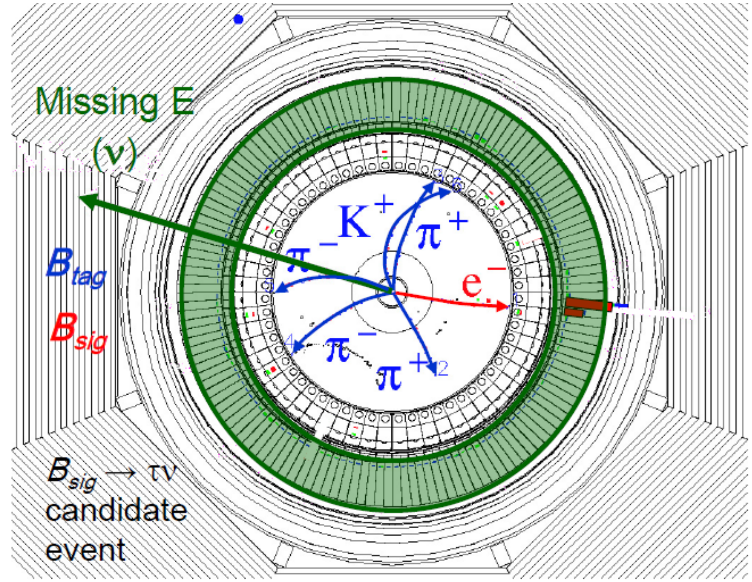
$$\mathcal{B}(\tau \to \mu\gamma) \simeq (4.5 \times 10^{-6})|(\delta_{LL})_{32}|^2 \left(\frac{500\ \mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^4 \left(\frac{\tan\beta}{10}\right)^2$$

Hadronic decays of τ offer unique tools for the precise study of low energy QCD, CP violation is also searched for

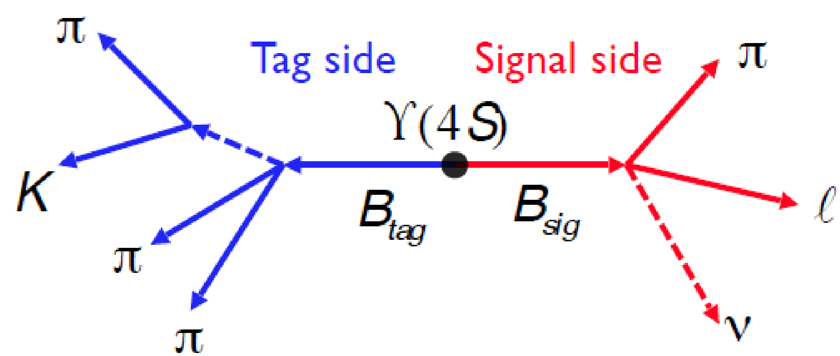


Complementarity to LHCb

- Clean environment
  - Efficient detection of neutrals (γ, π^0, η, …)
- Quantum correlated $B^0\bar{B}^0$ pairs
  - High effective flavor tagging efficiency :
    ~34%(Belle II) ⟷ ~3% (LHCb)
- Large sample of τ leptons
  - Search for LFV τ decays at $O(10^{-9})$



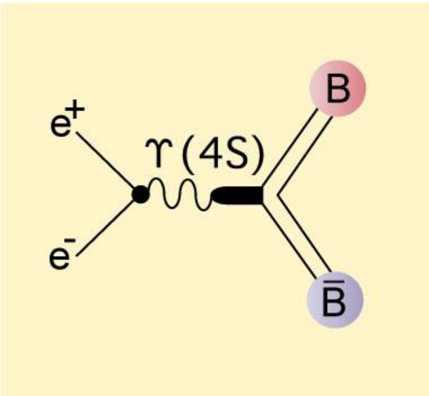
- Full reconstruction tagging possible
  - A powerful tool to measure;
    - b→u semileptonic decays (CKM)
    - decays with large missing energy
    - etc.

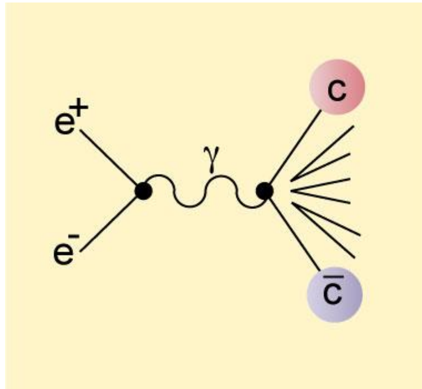


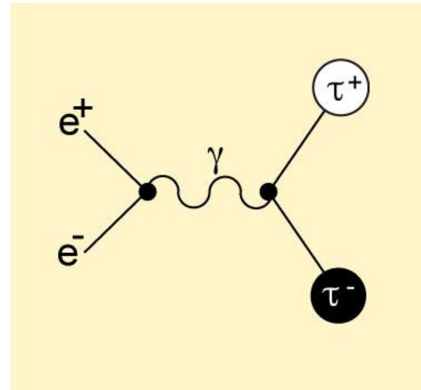
$B \to \pi\, l\, \nu$
$B \to \tau\, \nu,\ D\, \tau\, \nu$
$B \to K\, \nu\, \nu$

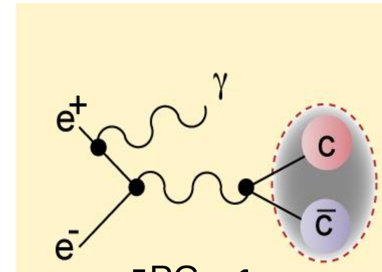
- Systematics different from LHCb
  - Two experiments are required to establish NP
  - Large cross section and decays to all charged particles

The Physics Program





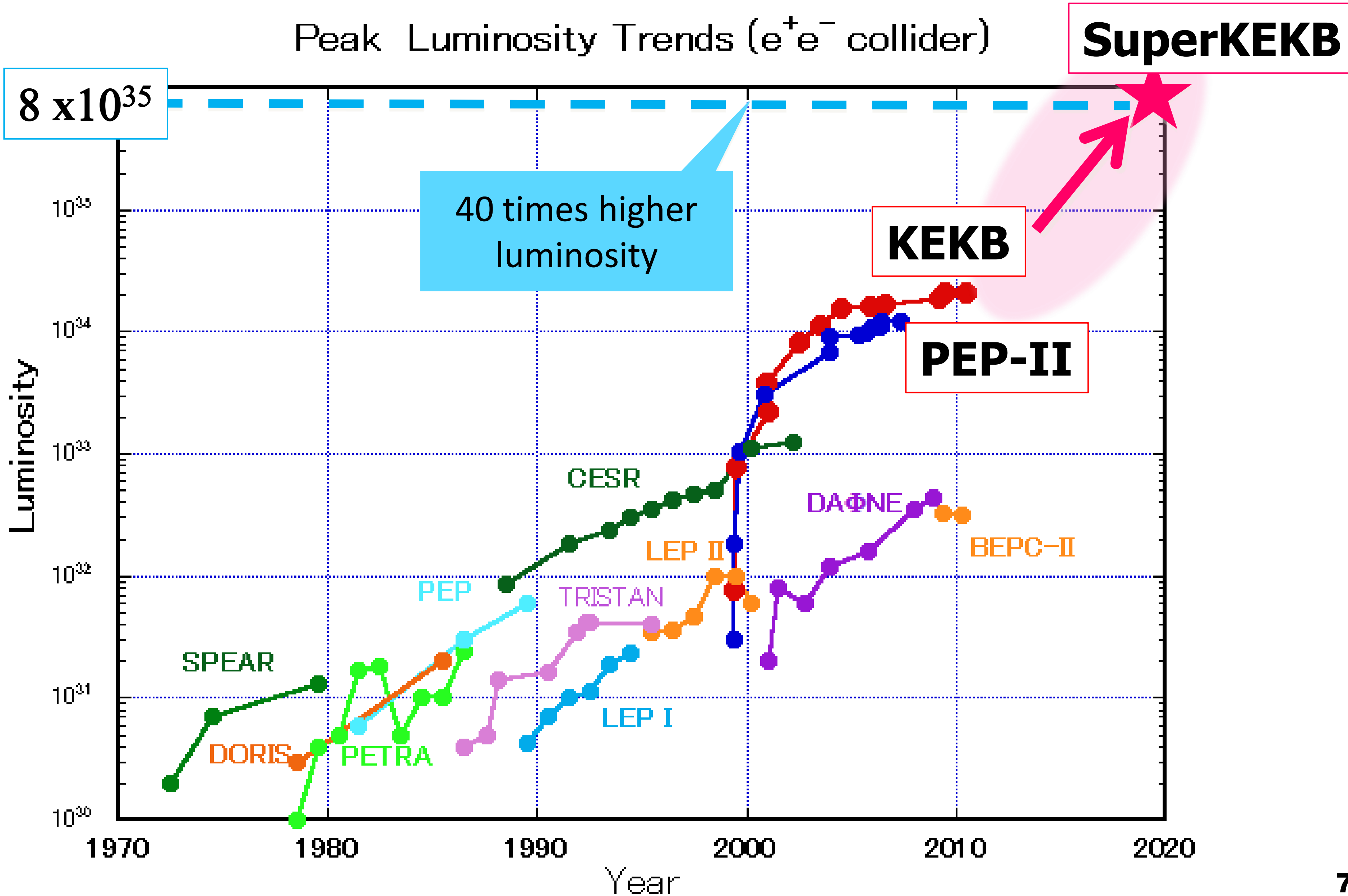




$J^{PC}=1^{--}$.
Initial state radiation

- a (Super) B-factory (~1.1 x 10^9 $B\bar{B}$ pairs per ab^{-1});
- a (Super) charm factory (~1.3 x 10^9 $c\bar{c}$ pairs per ab^{-1});
- a (Super) τ factory (~0.9 x 10^9 $\tau^+\tau^-$ pairs per ab^{-1});
- thanks to the Initial State Radiation, we can effectively scan the range [0.5 – 10] GeV and measure the $e^+e^- \rightarrow$ light hadrons cross-section very precisely;

Need O(100x) more data →Next generation B-factories



High-Luminosity Asymmetric B Factory

- ➡ Target luminosity is $\mathscr{L}$ = 8x10^{35} cm^{-2}s^{-1} (x40 w.r.t. BELLE)
- ➡ Achievable in the *nano-beam scheme* (P. Raimondi for SuperB)
  - double beam currents
  - squeeze beams @ IP by 1/20

Lorentz factor

beam current

beam-beam parameter

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

geometrical reduction factors

beam aspect ratio at the IP

vertical beta-function at the IP

parameters		KEKB LER	KEKB HER	SuperKEKB LER	SuperKEKB HER	units
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	0.129	0.09	0.0881	0.0807	
beam size at IP	σ_x^*/σ_y^*	100/2		10/0.059		μm
Luminosity	$\mathscr{L}$	2.1x10		8x10^{35}		cm^{-2}s^{-1}

High-Luminosity Asymmetric B Factory

- Target luminosity is $\mathscr{L}$ = 8x10^{35} cm^{-2}s^{-1} (x40 w.r.t. BELLE)
- Achievable in the *nano-beam scheme* (P. Raimondi for SuperB)
  - double beam currents
  - squeeze beams @

Lorentz factor

beam

beam-beam

$L = \frac{\gamma}{2e_e} \ldots$

beam aspect … at the IP

vertical beta-function at the IP

reduced CM boost

- reduced vertex separation, Δt resolution
- increased detector hermeticity

squeezed beams @ IP

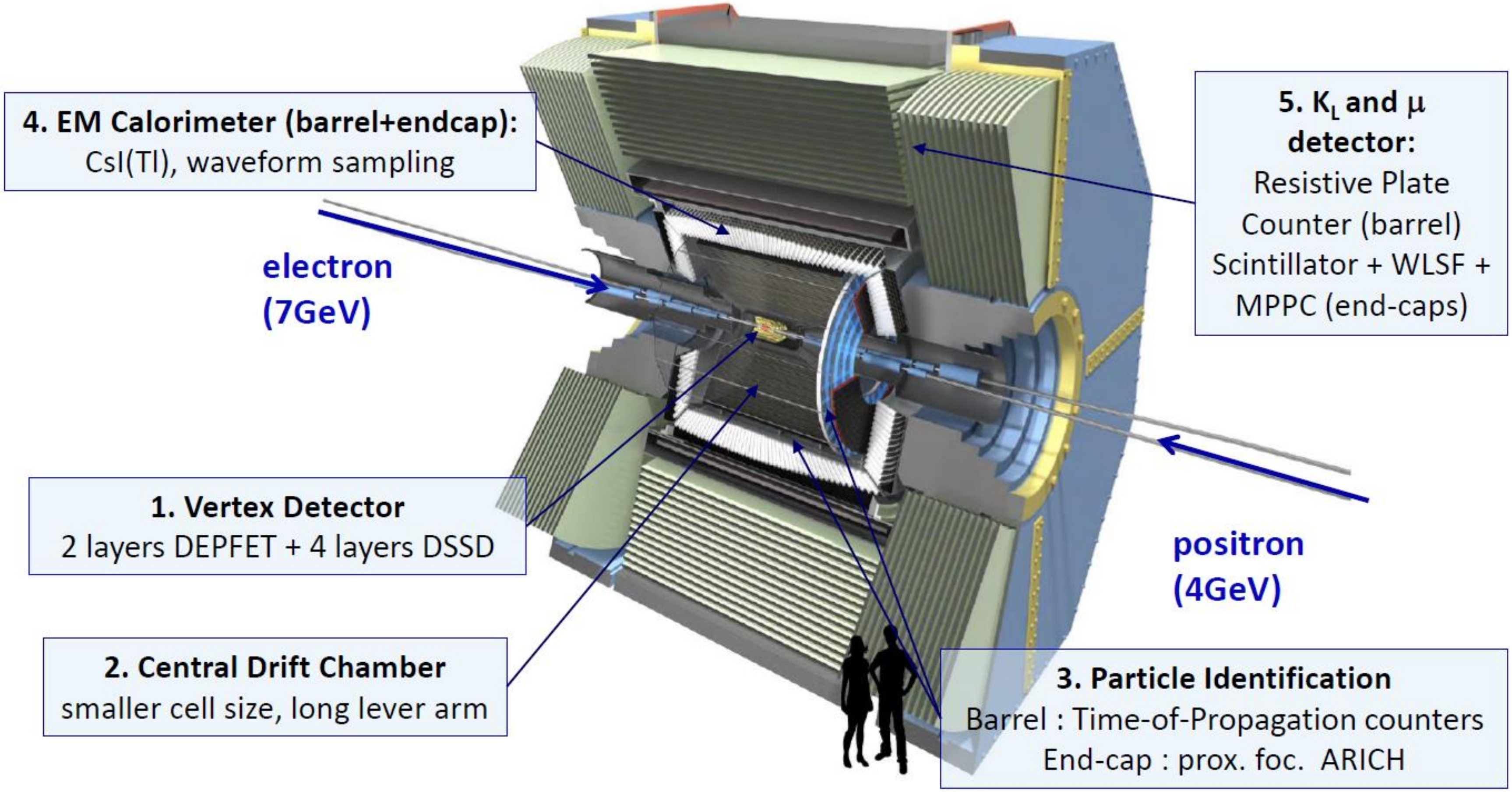
- greatly improved constraint for decay chain vertex fitting

parameters		LER	HER	SuperKEKB LER	SuperKEKB HER	units
beam energy	E_b	3.5	8	4	7	GeV
CM boost	$\beta\gamma$	0.425		0.28		
h[illegible]				41.5		mrad
ho[illegible]			24	3.2	4.6	nm
			0.66	[illegible]37	0.40	%
b[illegible]			5.9	32/0.27	25/0.30	mm
			1.19	3.6	2.6	A
bea[illegible]			90	0.0881	0.0807	
			2	10/0.059		μm
			0	8x10^{35}		cm^{-2}s^{-1}

x40 luminosity

- higher background rates (~10-20x)
  - detectors occupancy, radiation damage, fake hits, pile-up noise in the calorimeter
- higher event rate
  - higher trigger rate, DAQ, computing
- x40 produced signal events

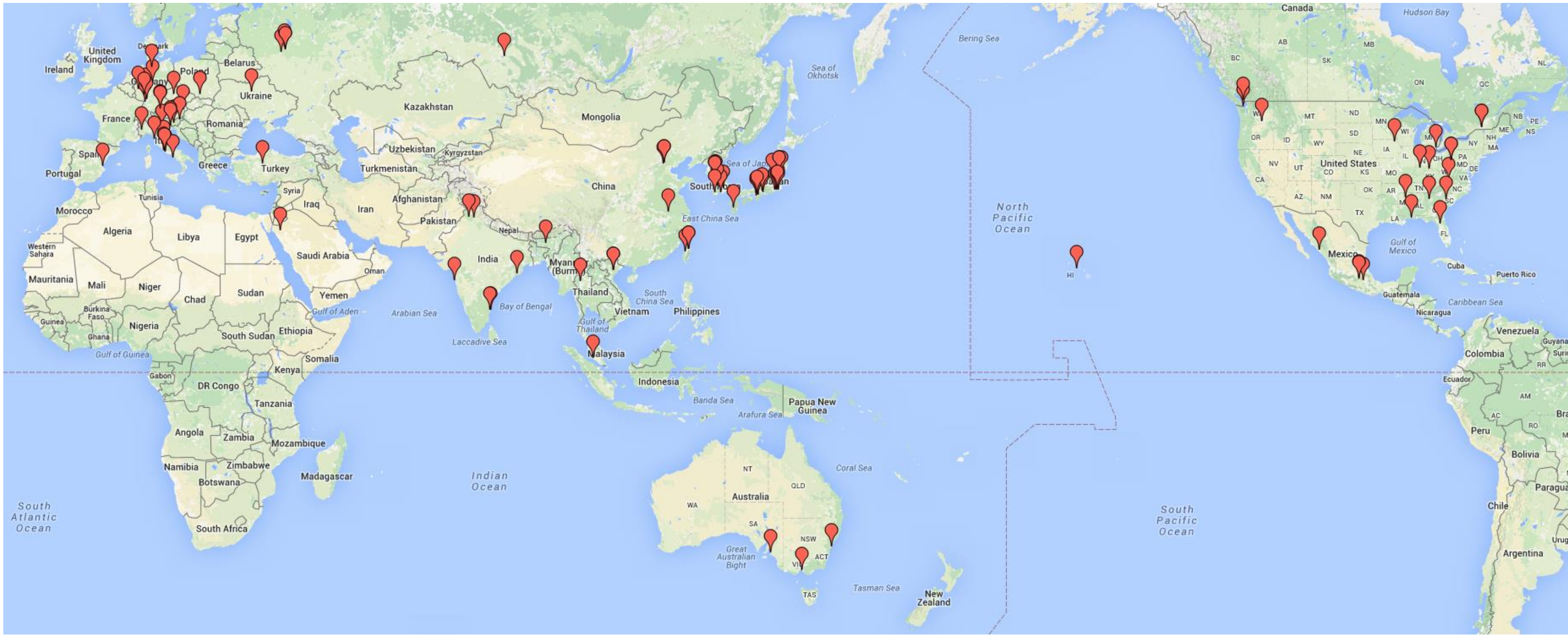
Belle II Detector



- All sub-detectors are upgraded from Belle II:
  - Except for ECL crystals and a part of Barrel KLM

- Improved IP and secondary vertex resolution
- Better K/π separation and flavor tagging
- Higher Ks, π^0 and slow pion reconstruction efficiency

Belle II Collaboration



800+ colleagues, 25 countries/regions

nature

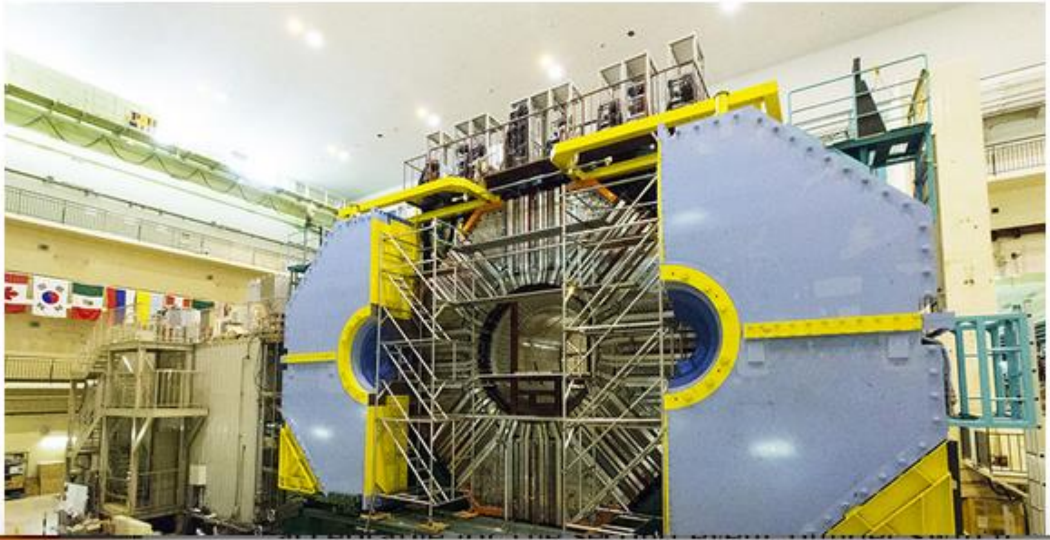
The world is waiting for us

NEWS · 12 JANUARY 2018

Revamped collider hunts for cracks in the fundamental theory of physics

Experiment smashes electrons into positrons to search for unseen particles and problems with overarching physics framework.

Elizabeth Gibney



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Transitions to Operations

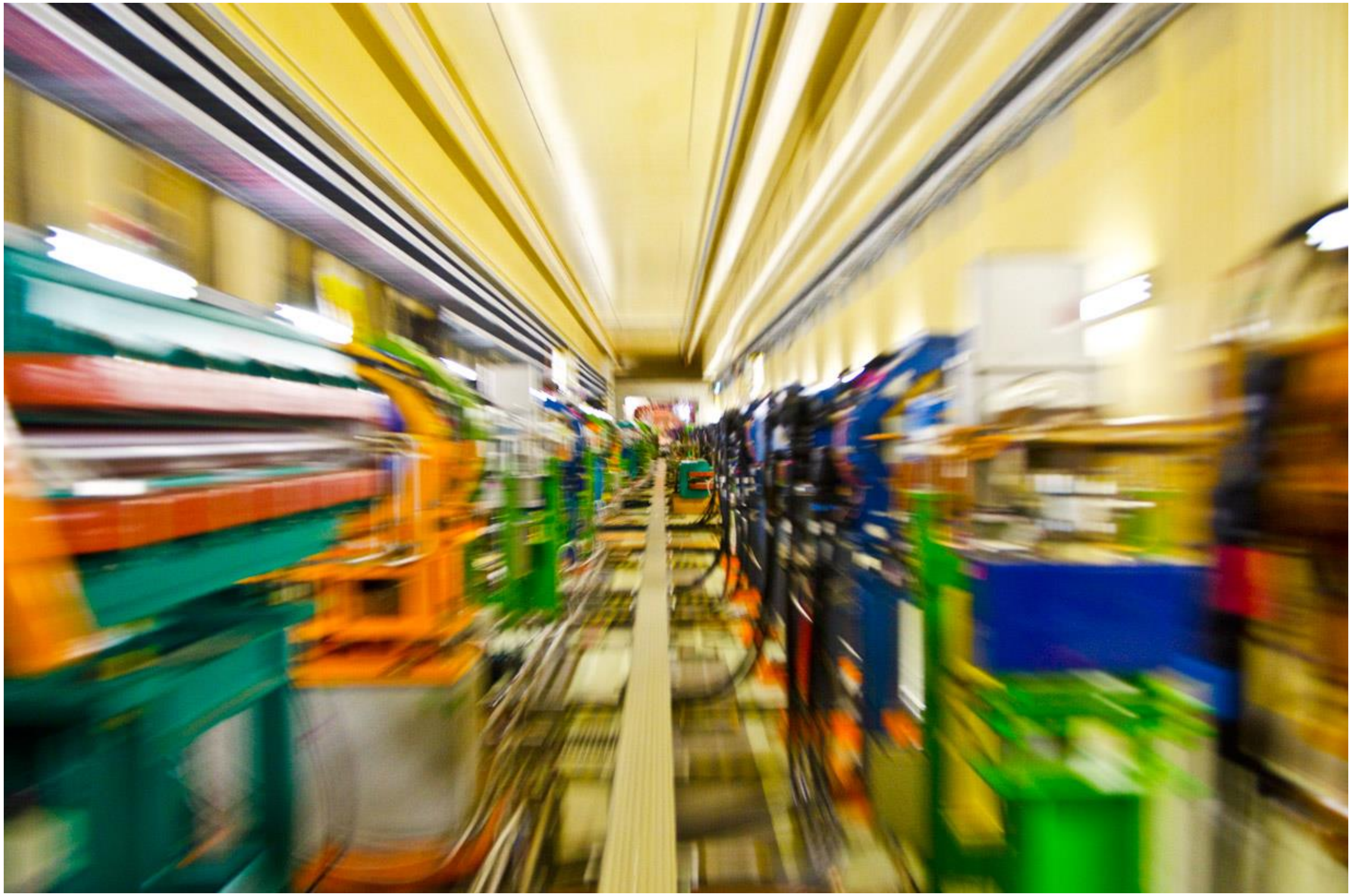
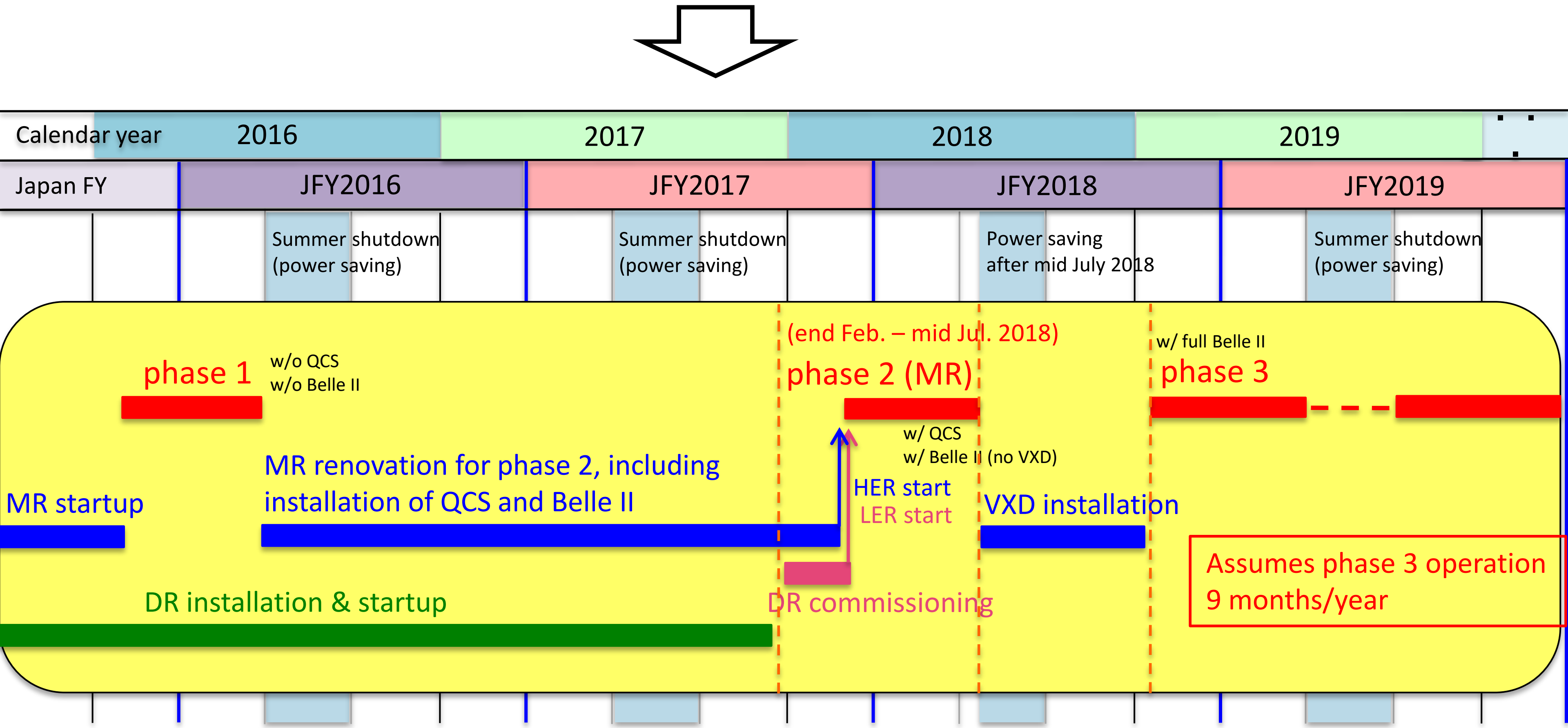


Photo credit: M. Friedl

SuperKEKB/Belle II schedule

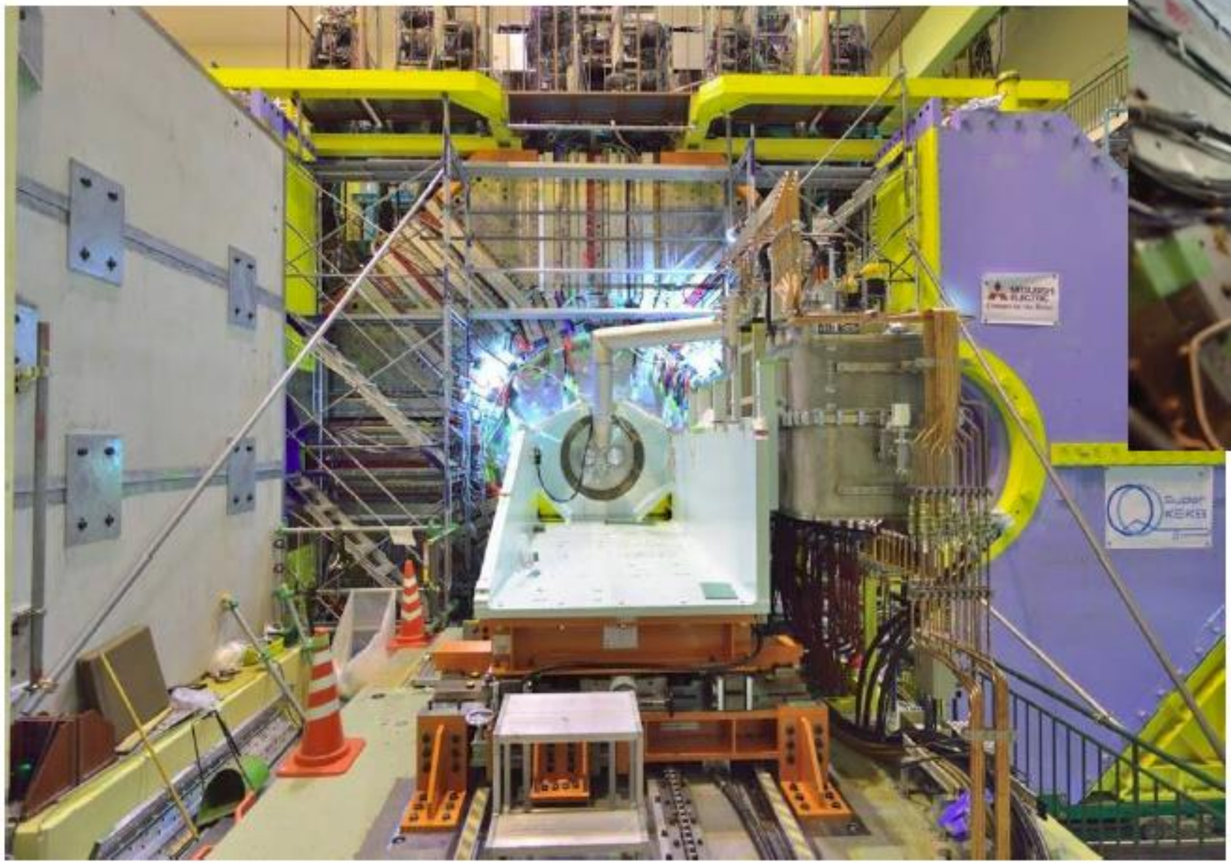
Oct. 2017

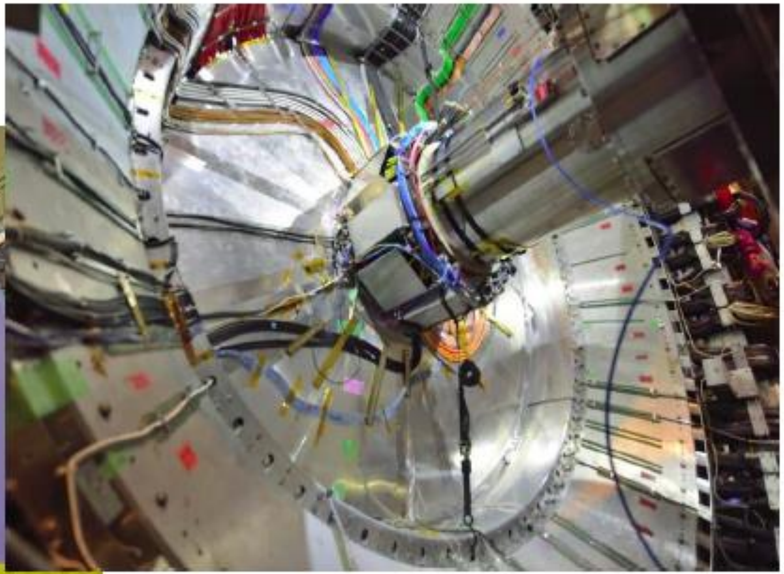


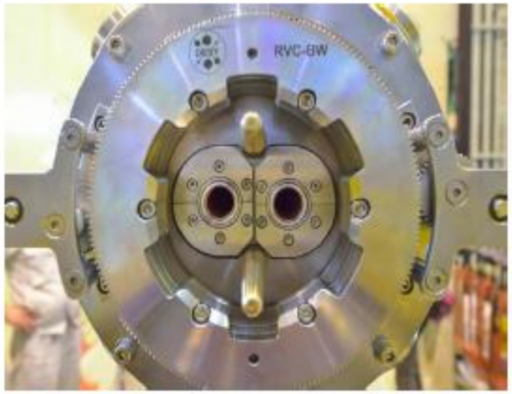
- Phase I: commissioning of the main ring; installation of outer detectors; vacuum scrubbing and beam bkg. studies
- Phase 2: start of the collisions, detector commissioning without vertex detector; first physics runs on Υ(4S) and Υ(6S) (~20±20 fb^{-1}) [now- July 2018]
- Phase 3: full detector operation in the end of 2018

15.01.2018: MILESTONE!

Superconductive magnet systems installed

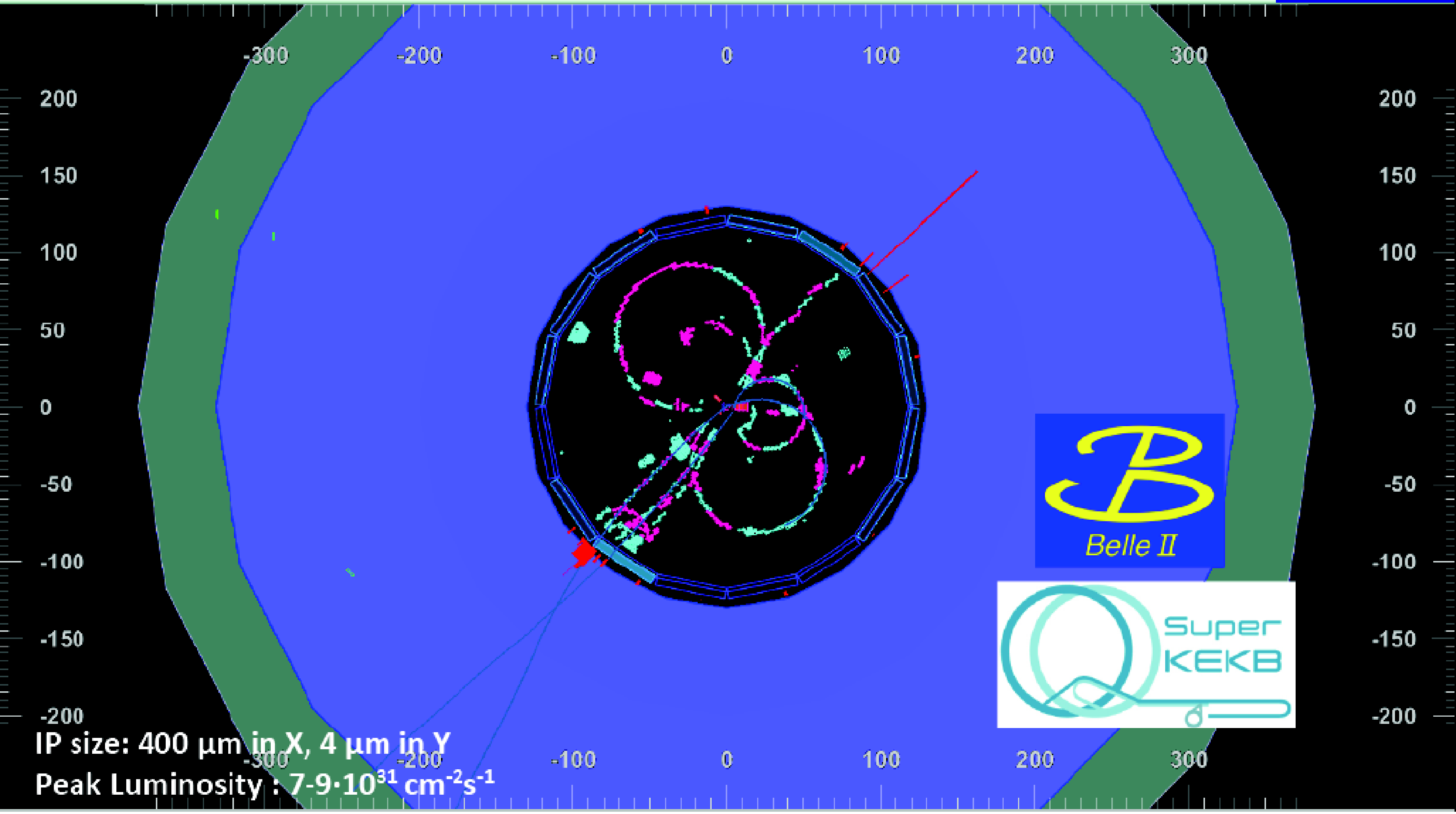


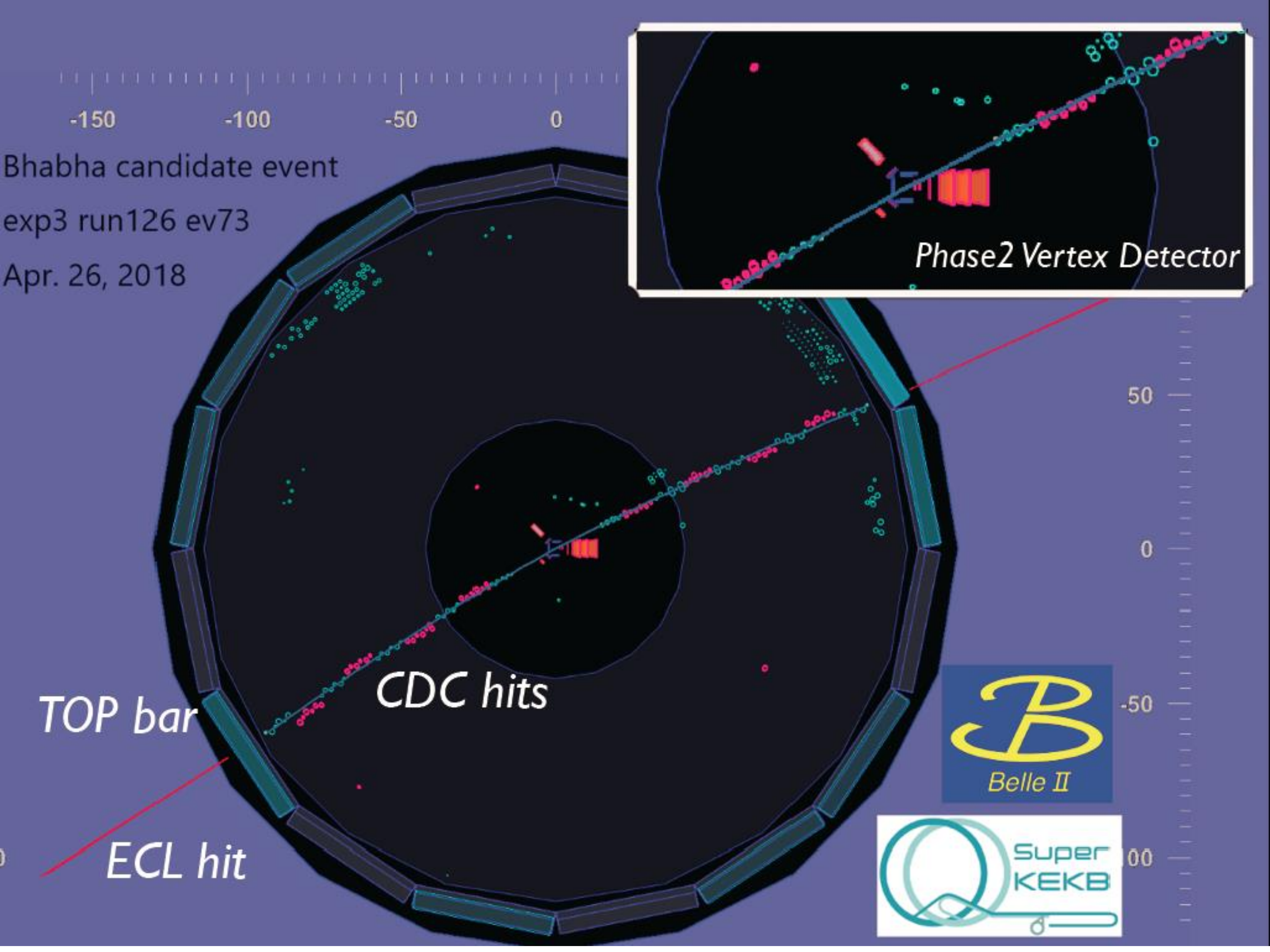




14.02.2018: Phase-II Has Started

A hadronic event recorded at h. 00:38, **26.04.2018** –
first collision confirmation

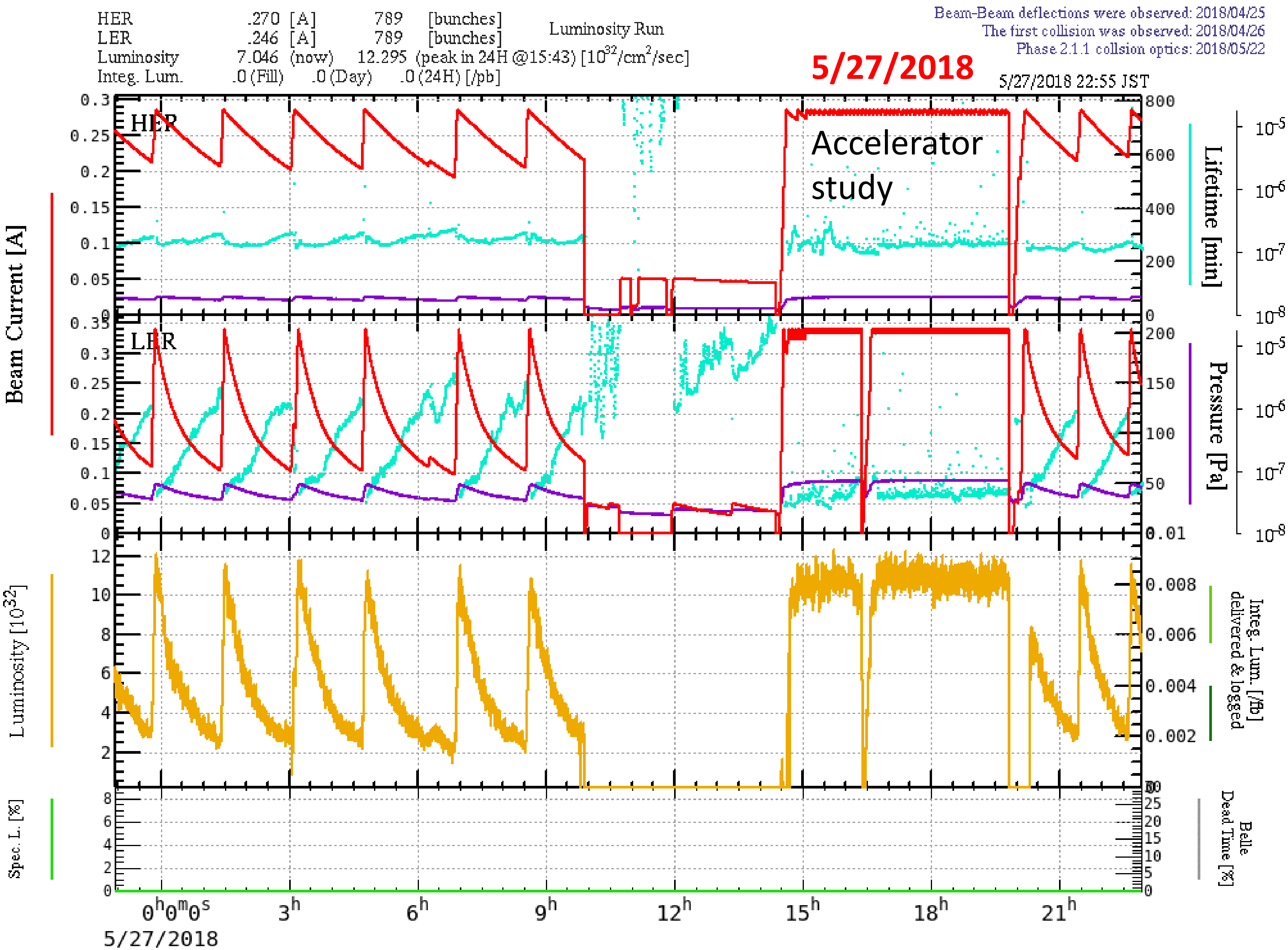




-150
-100
-50
0
Bhabha candidate event
exp3 run126 ev73
Apr. 26, 2018
Phase2 Vertex Detector
50
0
-50
CDC hits
TOP bar
ECL hit
Belle II
Super
KEKB

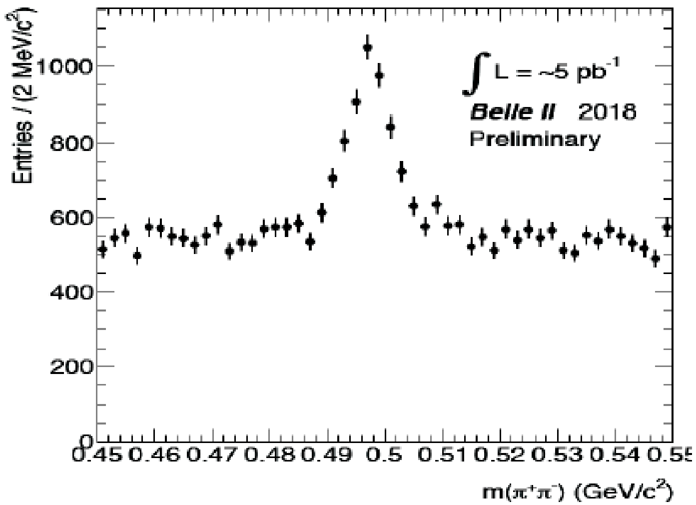
Belle II

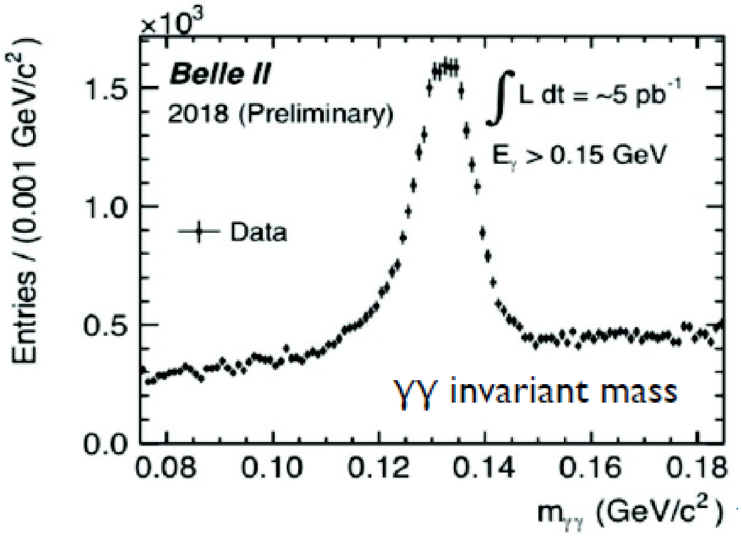
SuperKEKB operation status



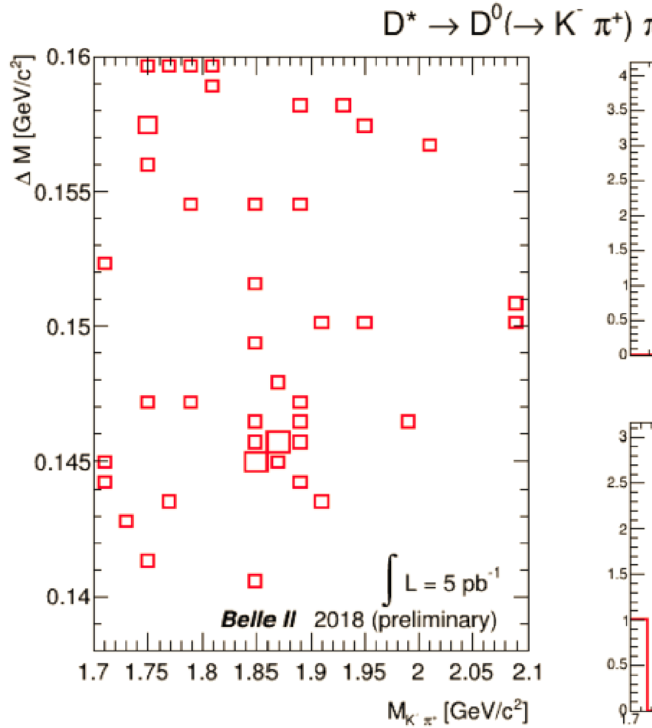
First Preliminary Study with Data (5 pb^{-1})

ππ invariant mass

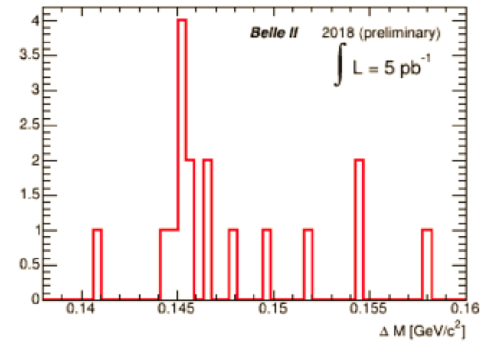


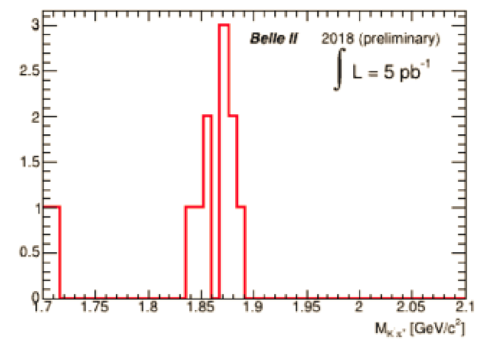


first bumps observed!



$1.845 < M(K\pi) < 1.885$ (GeV/c^2)





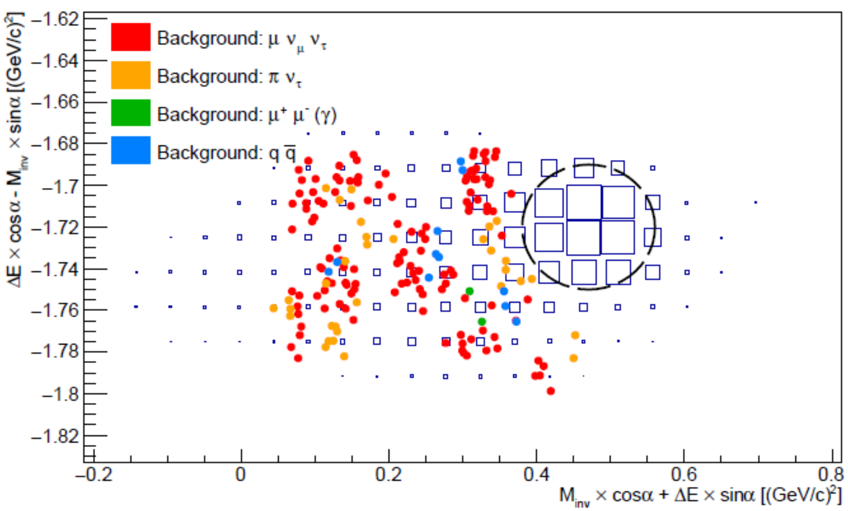
$0.144 < \Delta M < 0.146$ (GeV/c^2)

calibrations at a very early stage,

no PID cuts applied

Status of Belle II Physics Book

- Belle II physics book (>630 pages), to be printed by PTEP very soon
  https://confluence.desy.de/display/BI/B2TiP+ReportStatus
- The contents include Belle II detector, simulation, reconstruction. analysis software, B decays, CKM angles, charm, quarkonium(-like), τ, new physics, ….
- Some golden channels are given with Belle II MC simulations, theoretical discussions, sensitivity and systematic estimates



MC signal and background estimates for $\tau \to \gamma\mu$

1 ab^{-1}

Mode	Eff.(%)	N_{BG}^{exp}	UL (10^{-8})
$\mu\eta(\to\gamma\gamma)$	8.2	0.63 ± 0.37	3.6
$e\eta(\to\gamma\gamma)$	7.0	0.66 ± 0.38	8.2
$\mu\eta(\to\pi\pi\pi^0)$	6.9	0.23 ± 0.23	8.6
$e\eta(\to\pi\pi\pi^0)$	6.3	0.69 ± 0.40	8.1
$\mu\eta$(comb.)			2.3
$e\eta$(comb.)			4.4
$\mu\eta'(\to\pi\pi\eta)$	8.1	$0.00^{+0.16}_{-0.00}$	10.0
$e\eta'(\to\pi\pi\eta)$	7.3	0.63 ± 0.45	9.4
$\mu\eta'(\to\gamma\rho^0)$	6.2	0.59 ± 0.41	6.6
$e\eta'(\to\gamma\rho^0)$	7.5	0.29 ± 0.29	6.8
$\mu\eta'$(comb.)			3.8
$e\eta'$(comb.)			3.6
$\mu\pi^0$	4.2	0.64 ± 0.32	2.7
$e\pi^0$	4.7	0.89 ± 0.40	2.2

Prospects of τ decays at Belle II

Precise studies of τ at B factories

- **Michel parameters in $\tau \to \ell\nu\nu$ (ρ, η, ξ, δ) at Belle**: arXiv:1409.4969
- **Study of the radiative leptonic decays $\tau \to \ell\nu\nu\gamma$:**

  BABAR: Measurement of $\mathcal{B}(\tau \to \ell\nu\nu\gamma)$; PRD 91, 051103(R) (2015)

  Belle(prelim.): $\bar{\eta} = -1.3 \pm 1.5 \pm 0.8$, $\xi\kappa = 0.5 \pm 0.4 \pm 0.2$; arXiv:1609.08280
- **Lepton universality with $\tau \to \ell\nu\nu$ and $\tau \to h\nu$ (h=π,K) at *BABAR*:**

  $\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0036 \pm 0.0020$, $\left(\frac{g_\tau}{g_\mu}\right)_{\rm h} = 0.9850 \pm 0.0054$; PRL 105, 051602 (2010)
- **Tau lifetime:**

  Belle: $\tau_\tau = (290.17 \pm 0.53(\mathrm{stat}) \pm 0.33(\mathrm{syst}))$ fs; PRL 112, 031801 (2014)

  BABAR(prelim.): $\tau_\tau = (289.40 \pm 0.91(\mathrm{stat}) \pm 0.90(\mathrm{syst}))$ fs; Nucl. Phys. B 144, 105 (2005)
- Tau mass:

  Belle: $m_\tau = (1776.61 \pm 0.13(\mathrm{stat}) \pm 0.35(\mathrm{syst}))$ MeV/c^2; PRL 99, 011801 (2007)

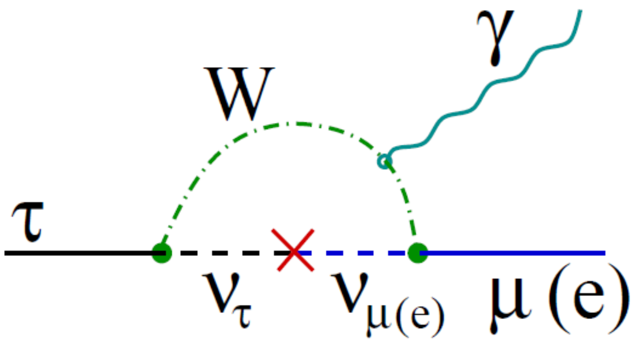
  BABAR: $m_\tau = (1776.68 \pm 0.12(\mathrm{stat}) \pm 0.41(\mathrm{syst}))$ MeV/c^2; PRD 80, 092005 (2009)

  Accuracy comparable with the most precision measurements done by **BES** and **KEDR** at the $\tau^+\tau^-$ production threshold.
- Tau electric dipole moment (EDM):

  Belle: $\mathrm{Re}(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$ $e\cdot$cm, $\mathrm{Im}(d_\tau) = (-0.83 \pm 0.86) \times 10^{-17}$ $e\cdot$cm; PLB 551, 16 (2003) ($\int Ldt = 29.5$ fb^{-1}) We are working on EDM with full Belle statistics
- Hadronic contribution to a_μ ($\tau^- \to \pi^-\pi^0\nu_\tau$):

  Belle: $a_\mu^{\pi\pi} = (523.5 \pm 1.1(\mathrm{stat}) \pm 3.7(\mathrm{syst})) \times 10^{-10}$; PRD 78, 072006 (2008)

Lepton-flavor-violating (LFV) decays of τ



Model	Reference	τ→μγ	τ→μμμ
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-14}
SM+ heavy Maj ν_R	PRD 66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66 (2002) 115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}

- Probabililty of LFV decays of charged leptons is extremely small in the Standard Model, $\mathcal{B}(\tau \to l\gamma) = \frac{3\alpha}{32\pi}|\sum_i U^*_{\tau i} U_{\mu i} \frac{\triangle^2_{3i}}{m^2_W}|^2 \leq 10^{-53} \sim 10^{-49}$
- Many models beyond the SM predict LFV decays with the branching fractions up to $\lesssim 10^{-8}$. As a result observation of LFV is a clear signature of New Physics (NP).
- τ lepton is an excellent laboratory to search for the LFV decays due to the enhanced couplings to the new particles as well as large number of LFV decay modes
- Study of the different τ LFV decay modes allows us to test various NP models.

τ LFV in NP beyond SM

Ratios of τ LFV decay's BF's allow one to discriminate between new physics models

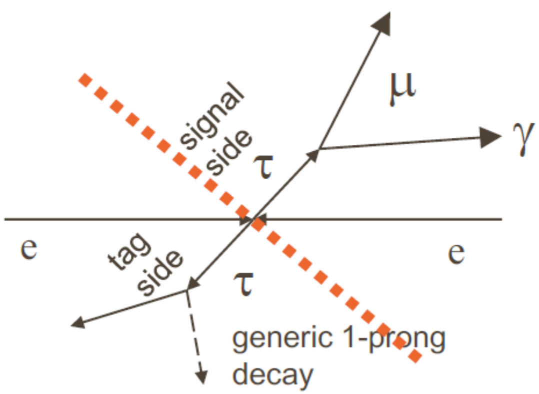
	SUSY+GUT (SUSY+Seesaw)	Higgs mediated	Little Higgs	non-universal Z'
$\frac{\mathcal{B}(\tau \to \mu\mu\mu)}{\mathcal{B}(\tau \to \mu\gamma)}$	~2 x 10^{-3}	0.06 - 0.1	0.4 - 2.3	~16
$\frac{\mathcal{B}(\tau \to \mu ee)}{\mathcal{B}(\tau \to \mu\gamma)}$	~1 x 10^{-2}	~1 x 10^{-2}	0.3 - 1.6	~16
$\mathcal{B}(\tau \to \mu\gamma)_{\mathrm{max}}$	< 10^{-7}	< 10^{-10}	< 10^{-10}	< 10^{-9}

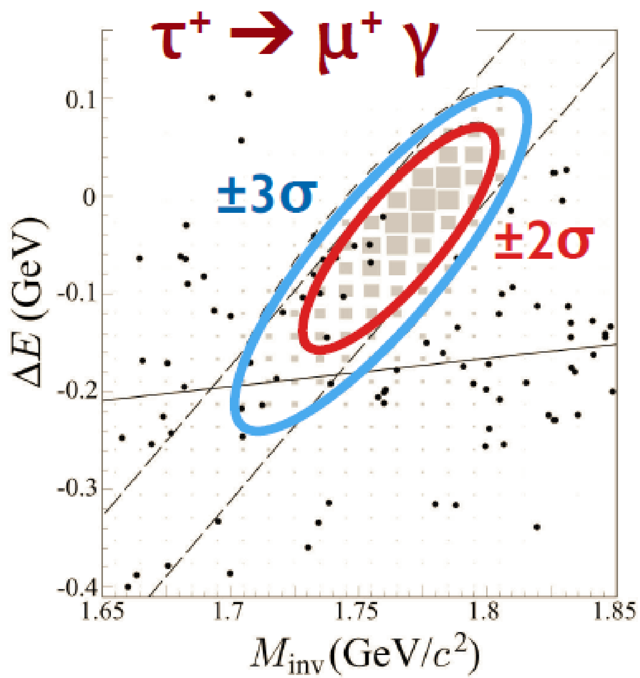
JHEP 0705, 013 (2007); PLB 547, 252 (2002)

∴ Good to measure LFV in as many modes as possible!

Past searches for $\tau \rightarrow \gamma\mu$ at Belle

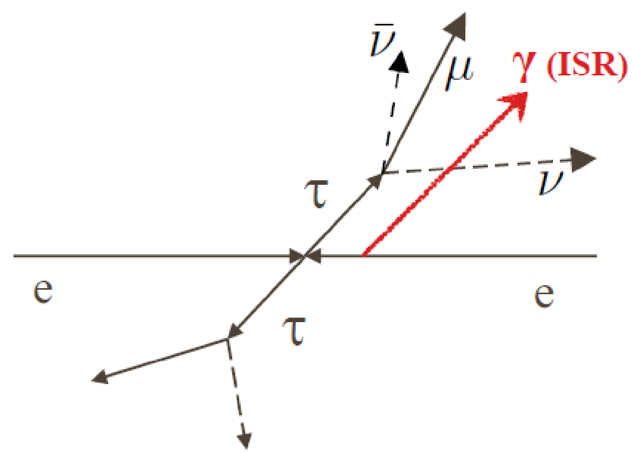
- Blinding box approach with BG evaluated outside the signal region
- Observables space: — $\mathbf{\Delta E} = E_{CM}^{(\mu+\gamma)} - E_{beam}/2$ (expected $\Delta E = 0$)
  — Signal-side $\mathbf{m_{inv}}$ (expected $m_{inv} = m_\tau = 1.777$ GeV/c^2)
- Signal regions after BG rejection cuts — data (points) and signal MC (shaded):





Irreducible background

- $\tau \rightarrow \ell\nu\nu$ with ISR



- $B(\tau^- \to \mu^-\gamma) < 4.5 \times 10^{-8}$
- $B(\tau^- \to e^-\gamma) < 12.0 \times 10^{-8}$ @ 90%CL
- $B(\tau^- \to \mu^-\gamma) < 4.4 \times 10^{-8}$
- $B(\tau^- \to e^-\gamma) < 3.3 \times 10^{-8}$

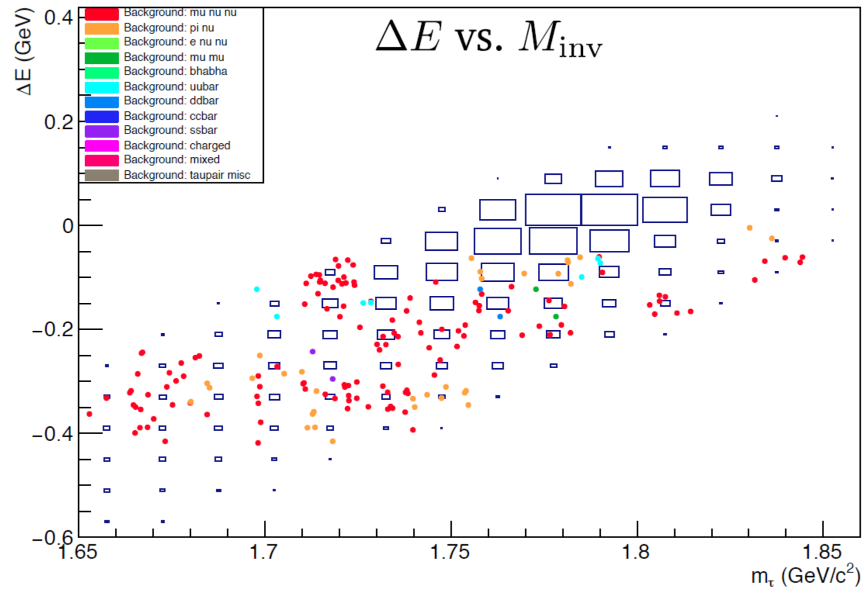
Belle: PLB 666,16(2008)

best limits, BaBar: PRL 104,021802(2010)

$\tau \to \gamma\mu$ at Belle II

sensitivity study using Belle II MC incl. beam background simulation

- for sensitivity comparison with Belle (with $\int \mathcal{L} dt = 1\ \mathrm{ab}^{-1}$)

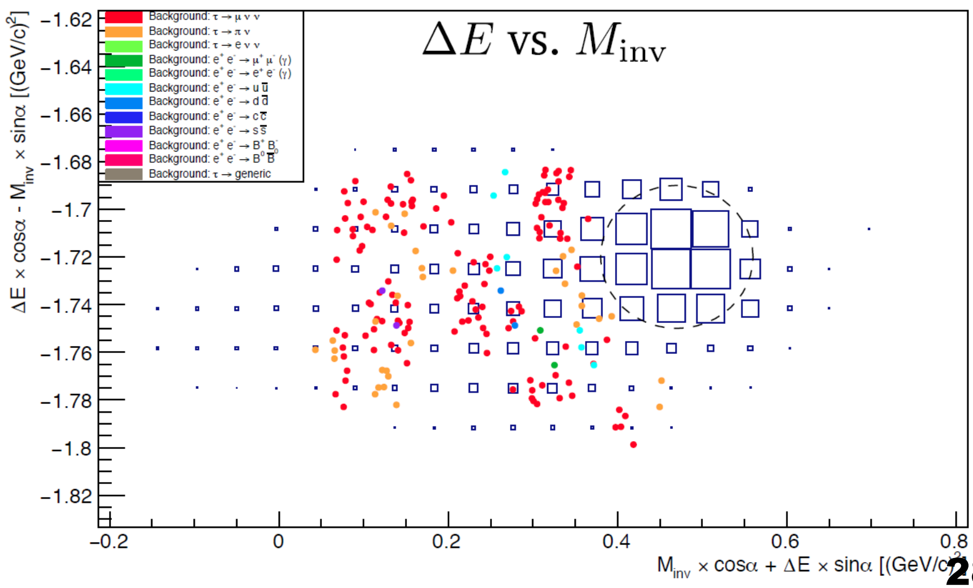


Background:

— $\tau \to \mu\nu\nu$
— $\tau \to e\nu\nu$ $\Big\}$ + γ
— $\tau \to \pi\nu$

— ee → ee/μμ (γ)
— ee → hadronic

- rotating $(M_{\rm inv}, \Delta E)$ to minimize correlation



Background rejection by

- event shape variables — thrust, Fox-Wolfram moments, momentum flow distributions ("CLEO cones"), etc.

Signal extraction by $(\Delta E, M_{\rm inv})$

$\tau \to \gamma\mu$ sensitivity at Belle II

	Belle (535 fb^{-1})	Belle II (1 ab^{-1})
$\mathcal{L}$ (cm^2/s)	2.11×10^{34}	80×10^{34}
ε_{signal}	5.09%	4.59%
n_{BG}	10	-
$B_{90}(\tau \to \mu\gamma)$	**4.5×10^{-8}**	**2.7×10^{-8}**

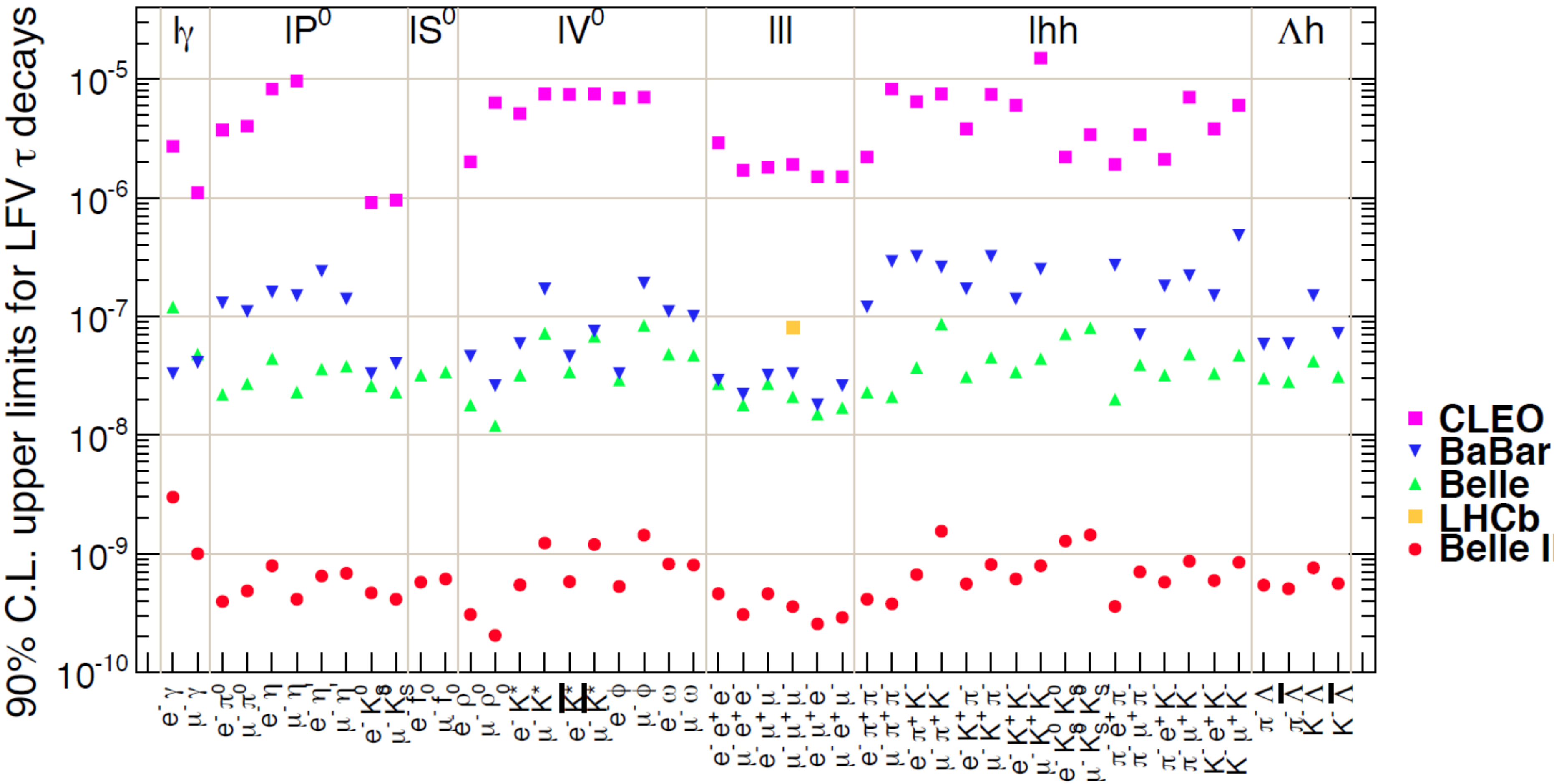
→

Belle II (50 ab^{-1})
5.5×10^{-10}

a naive extrapolation by luminosity

- First τ LFV sensitivity study at Belle II
  - even with much higher beam background, the sensitivity is comparable to that of Belle (scaled by luminosity)
  - signal region is background-free

τ LFV summary & prospects



HFAG summary plot for **τ** LFV decays,
overlaid with Belle II extrapolation to 50 ab^{-1} assuming zero background

CPV in hadronic τ decays

- CPV has never been observed in lepton decays; SM ($A^{CP} \leq 10^{-12}$)

- Observation of large CPV would be clear signal of NP, for examples, MSSM[IHEP12,021;RMP80,577], multi-Higgs-doublet-models [PRL37,657;NPB426,355]

- $\tau \to 2\pi\nu$ [PRD50,4544], $K\pi\nu$ [PLB398,407], $3\pi\nu$ [PRD52,1614], $K\pi\pi\nu, KK\pi\nu$ [Z. Phys.G62,413; PRD78, 113008; PRD91, 073006] have been suggested to do CPV measurements.

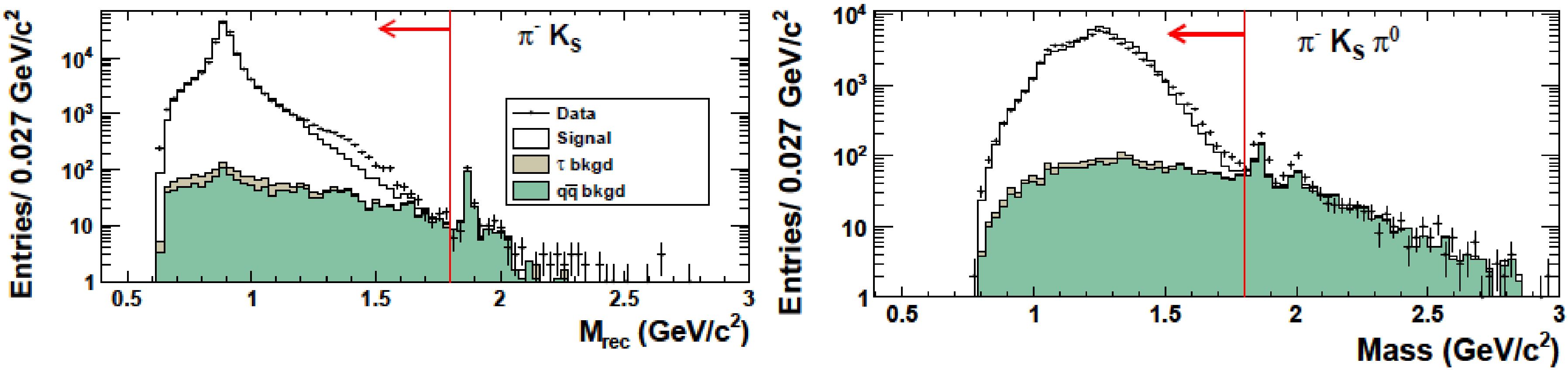
CPV in hadronic τ decays

Two ways to measure CPV in hadronic τ decays

I: Direct measure positive and negatively charged tau lepton decays

$\tau^- \to \pi^- K_s(\geq 0\pi^0)\nu_\tau$: **BaBar (PRD85, 031102(2012); 476 fb^{-1})**

Signal region



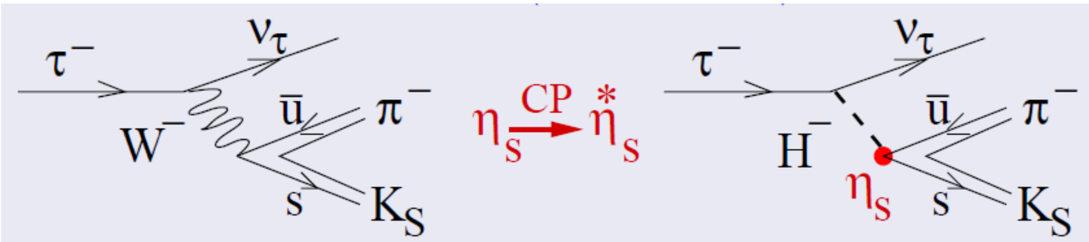
$$A_{cp} = \frac{\Gamma(\tau^+ \to \pi^+ K_s(\geq 0\pi^0)\bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_s(\geq 0\pi^0)\bar{\nu}_\tau)}{\Gamma(\tau^+ \to \pi^+ K_s(\geq 0\pi^0)\bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_s(\geq 0\pi^0)\bar{\nu}_\tau)} = (-0.36 \pm 0.23 \pm 0.11)\%$$

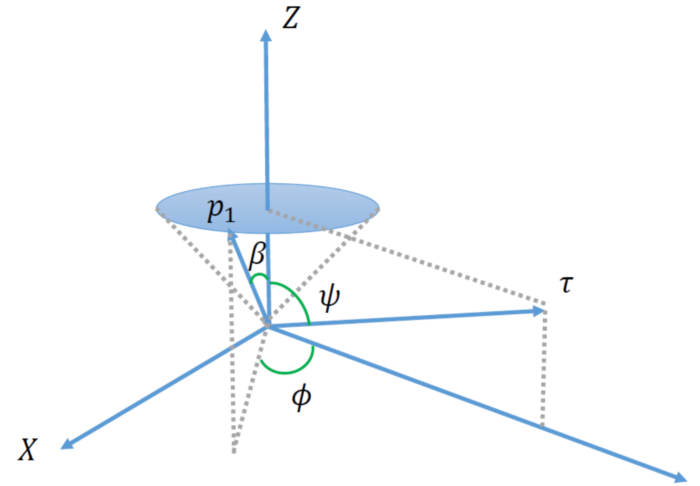
2.8σ deviation from the SM expectation: $A_{CP(SM)} = (+0.36 \pm 0.01)\%$

CPV in hadronic τ decays

II: CPV in $\tau^- \to \pi^- K_s \nu_\tau$ at Belle (PRL107, 131801(2011); 699 fb^{-1})

Angular distributions were analyzed, $A_{CP}(W = M_{Ks\pi})$ was measured

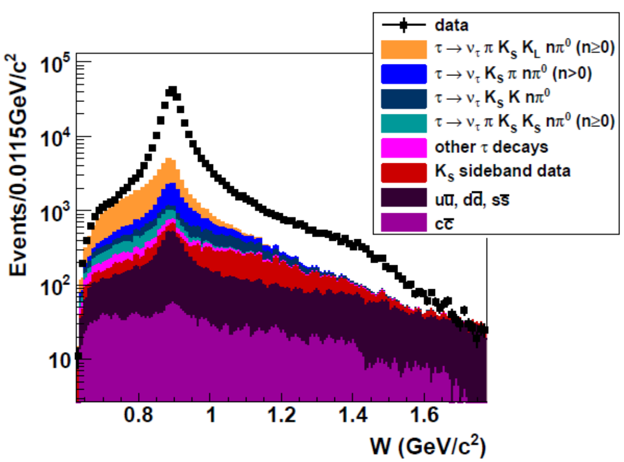


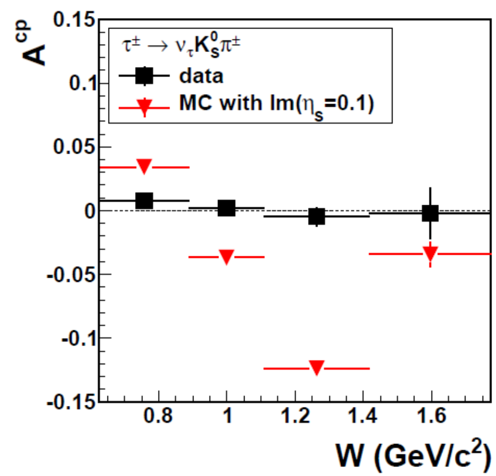


η_s is the dimensionless complex coupling constant

$$A_i^{CP} = \frac{\iint_{Q^2_{1,i}}^{Q^2_{2,i}} \cos\beta\cos\psi \left(\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega}{\frac{1}{2}\iint_{Q^2_{1,i}}^{Q^2_{2,i}} \left(\frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega}$$

$$\simeq \langle\cos\beta\cos\psi\rangle^i_{\tau^-} - \langle\cos\beta\cos\psi\rangle^i_{\tau^+}, \quad d\omega = dQ^2 d\cos\theta d\cos\beta$$



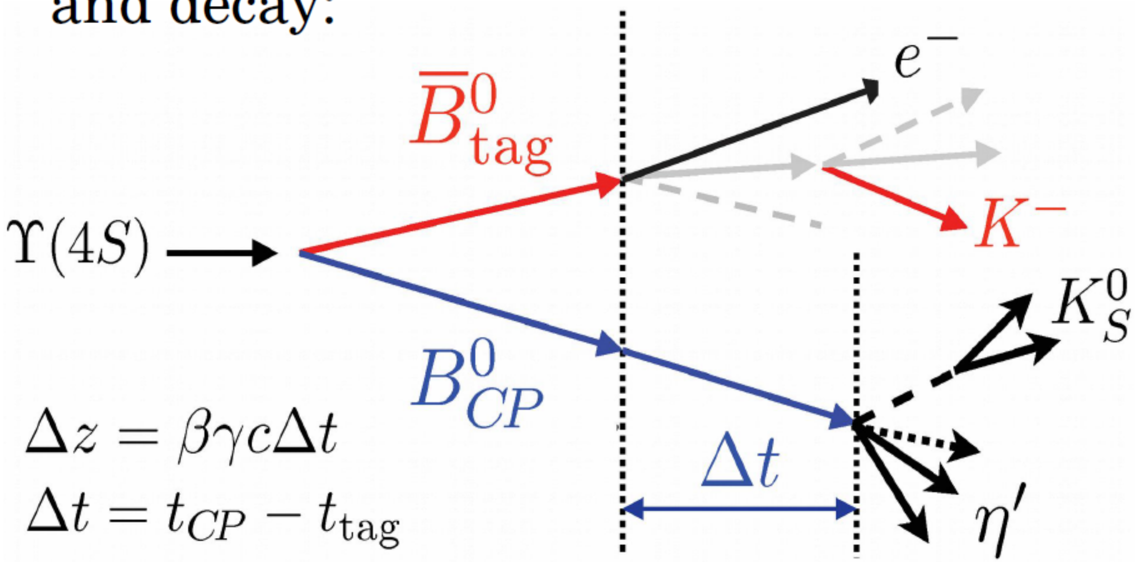


With 50 ab-1 data at Belle II, we expect 70 times improvement, i.e., $|A^{CP}| < (0.5 - 3.8) \times 10^{-4}$, at 90% C.L. *assuming the central value* $A^{CP} = 0$

Prospects of B decays at Belle II

Time Dependent CP Violation

- Flagship measurements of the B-factories: access the weak phase of the CKM Matrix by exploiting the interference between mixing and decay:



All aspects of the experiment crucially important:

- tracking efficiency;
- neutrals reconstruction;
- vertexing;
- PID;
- B Flavor Tagging;
- background rejection;
- …

- Significant improvements over the previous generation of experiments:
  - ➔ Δt resolution ~0.77 ps (30% to a factor 2 better compared to Belle);
  - ➔ effective flavor tagging efficiency ~35.8% (was 30.1% at Belle).

Time Dependent CP Violation

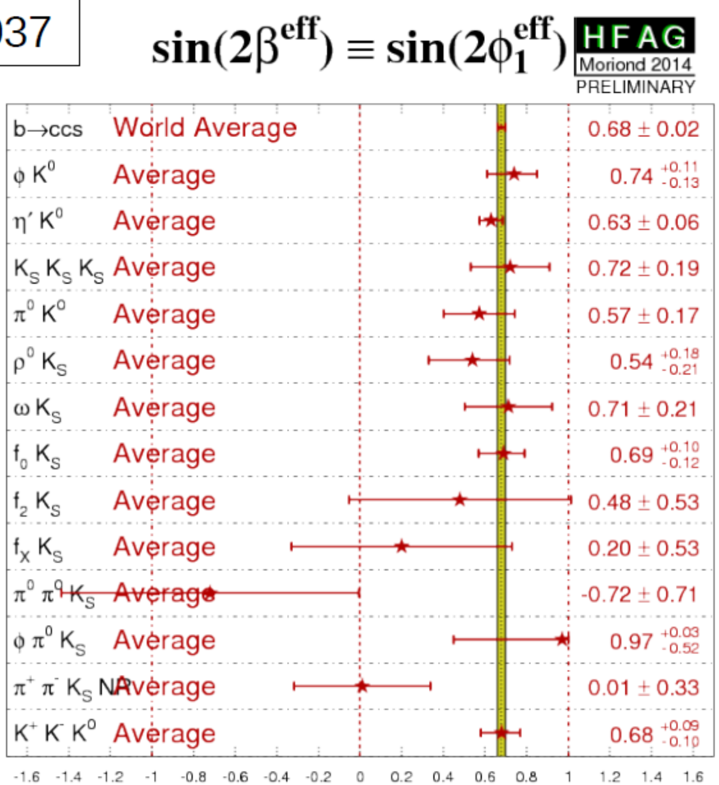
- The measurement of $\sin 2\phi_1$ from $B \to c\bar{c}\, K^0$ with the full dataset will be dominated by systematic uncertainties:

	Belle	Belle II (50 ab^{-1})
S	0.667 ± 0.023 ± 0.012	x.xxxx ± 0.0027 ± 0.0044
A	0.006 ± 0.016 ± 0.012	x.xxxx ± 0.0033 ± 0.0037

(PRL 108 (2012), 171802)

- Most gluonic penguin dominated modes will be limited by statistical uncertainties.

Mode	50 ab^{-1} $\sigma(\mathcal{S})$	$\sigma(\mathcal{A})$
$\eta' K^0$	0.011	0.009
ϕK^0_S	0.018	0.023
$K_S K_S K_S$	0.033	0.021



These modes are theoretically clean, and can be used for precise tests for non-SM contributions.

Belle's legacy on EWP

- First observation of $B \to K\ell^+\ell^-$ PRL 88, 021801 (2002)
- First observation of $B \to K^*\ell^+\ell^-$ PRL 91, 261601 (2003)
- First observation of $B \to X_s\ell^+\ell^-$ PRL 90, 021801 (2003)
- First measurement of A_{FB} of $B \to K^*\ell^+\ell^-$ PRL 96, 251801 (2006)
- First observations of several radiative modes, $\phi K\gamma$, $K_1\gamma$, etc.
- First observation of $B \to (\rho, \omega)\gamma$ PRL 96, 221601 (2006)
- Most precise measurement of $B \to X_s\gamma$ covering the widest E_γ range PRL 103, 241801 (2009)
- *and many more published results*

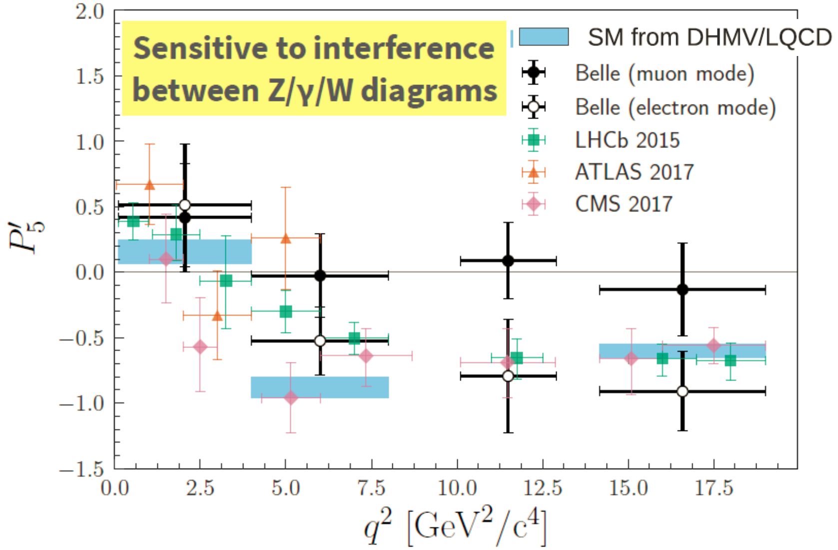
Electroweak Penguins

- Several tensions at the 2-3σ level

Projection of uncertainties at Belle II for P_5'

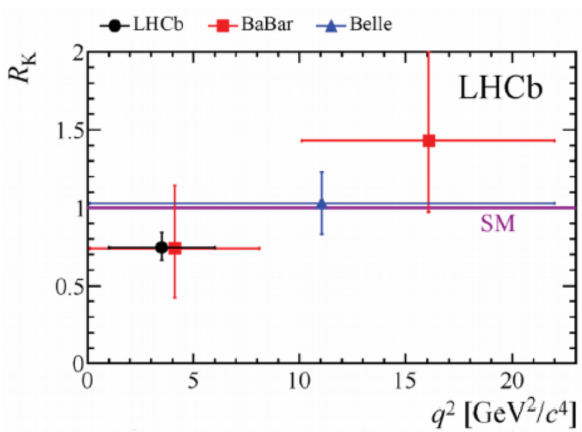
q^2 (GeV^2c^{-4})	Belle	Belle II
0.1 – 4	0.416	0.059
4 – 8	0.277	0.040
10.09 – 12	0.344	0.049
14.18 – 19	0.248	0.033

$B \to K^* \ell^+ \ell^-$



- Lepton Flavor Universality violation in $B^+ \to K^+ l^+ l^-$?

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2} \approx 1$$

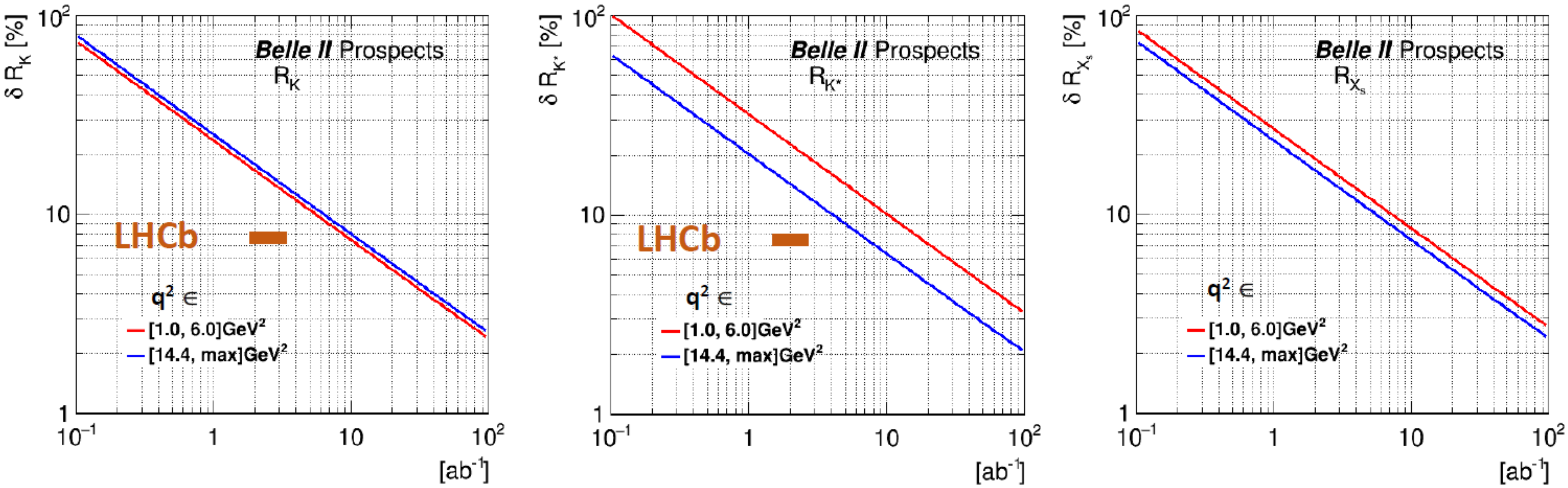


2.6σ tension from latest LHCb measurement

- LHCb will have the edge on many of these decays, but confirmation from Belle II will be crucial.

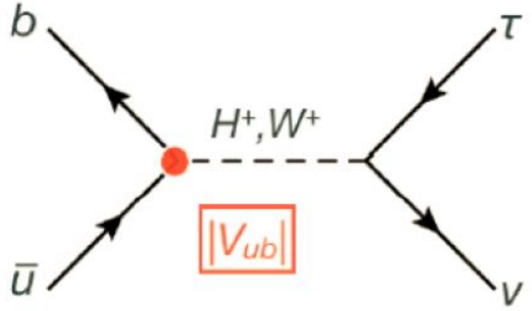
R(K), R(K*), R(Xs) at Belle II

- The errors reach to 0.04 for all K, K* and Xs modes in Belle II.
- Errors are still statistically limited (systematic error ~ 0.4%)



- Belle II should be able to claim the $R(K^{(*)})$ anomaly with a significance of 5σ, if it is indeed due to new physics.
- However electron mode is challenging at LHCb, especially for high q^2.

Search for NP in $B^+ \to \tau^+ \nu_\tau$



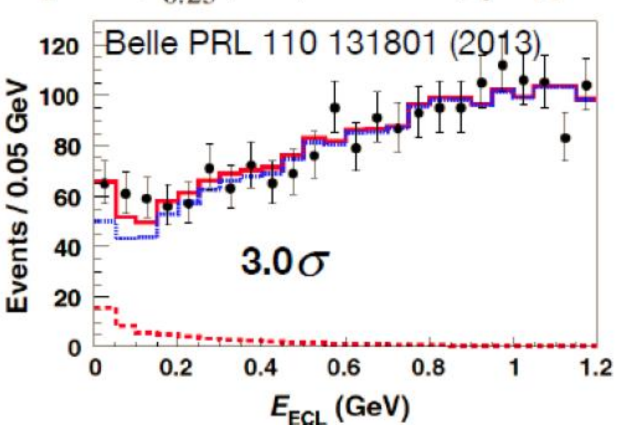
- Branching ratio depends strongly on the mass of the lepton due to helicity suppression. Thus $B^+ \to \tau^+ \nu_\tau$ is expected to have the largest leptonic branching fraction.
- NP could significantly suppress or enhance the branching ratio i.e. via exchange a charged Higgs boson from supersymmetry or from two-Higgs doublet models (2HDM).
- In the absence of NP, this channel provides a direct determination of the B decay constant f_B and the CKM matrix $|V_{ub}|$.

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau)_{\rm SM} = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

$$\mathcal{B}_{(B\to\tau\nu)} = \mathcal{B}_{SM} \times \left(1 - \tan^2\beta \frac{m_{B^\pm}^2}{m_{H^\pm}^2}\right)$$

- Hadronic tagging
- dominate backgrounds: $B^- \to D^{(*)0} \ell^- \bar{\nu}_\ell$

$[0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$



tau decays:

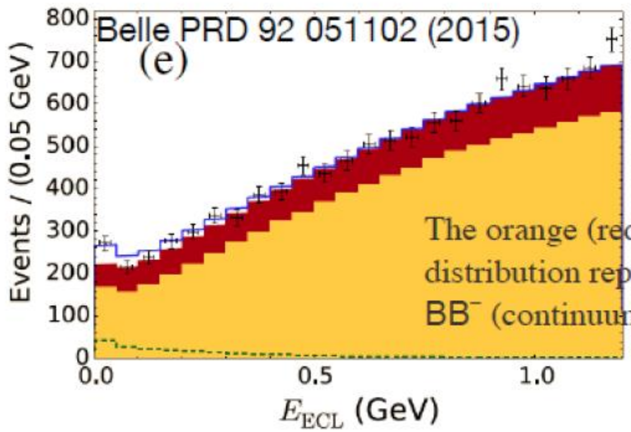
$\tau^- \to l^- \bar{\nu}_l \nu_\tau$

$\tau^- \to \pi^- \nu_\tau$

$\tau^- \to \rho^- \nu_\tau$

- Semi-leptonic tagging (agree with Had. tag and SM)

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = [1.25 \pm 0.28(\text{stat.}) \pm 0.27(\text{syst.})] \times 10^{-4}$$



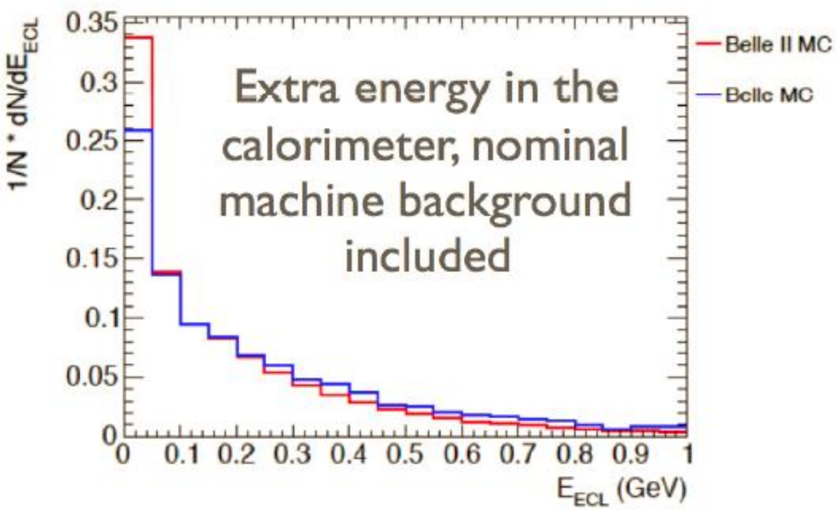
The orange (red) filled distribution represents the BB⁻ (continuum) background.

$B^+ \to \tau^+ \nu_\tau$ prospect at Belle II

- **Analysis on Belle II full simulation using hadronic B reconstruction.**
- **Signal yields extracted from fit to extra neutral energy.**
- **The extra energy resolution at Belle II is better than Belle despite the increased beam background.**

- **Comparison with Belle hadronic tag. 1 ab^{-1} equivalent statistics**

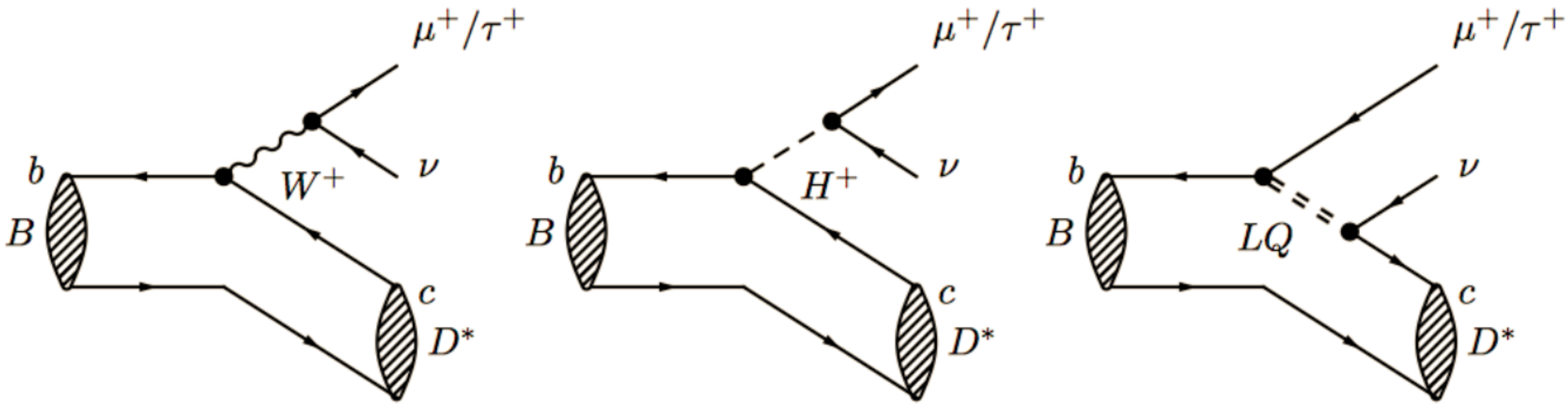
E_{ECL}		$< 0.25\,\mathrm{GeV}$
Belle II	# background events	1348
	# signal events	136
	signal efficiency (‰)	1.6
Belle	# background events	365
	# signal events	60
	signal efficiency (‰)	0.7



- **Extrapolation at full Belle II statistics**

	Integrated Luminosity (ab^{-1})	50
hadronic tag	statistical uncertainty (%)	4.1
	systematic uncertainty (%)	4.6
	total uncertainty (%)	6.2
semileptonic tag	statistical uncertainty (%)	2.7
	systematic uncertainty (%)	4.5
	total uncertainty (%)	5.3

Search NP in $B \to D^{(*)}\tau^{+}\nu_{\tau}$



- In the Standard Model (SM), the only difference between $B \to D^{(*)}\tau^{+}\nu_{\tau}$ and $B \to D^{(*)}\mu^{+}\nu_{\mu}$ is the mass of the lepton
- The ratio of them is sensitive to additional amplitudes, i.e. involving an intermediate charged Higgs boson.
- NP: type-II-2HDM (charged Higgs boson appears), Leptoquarks(LQ) model…
- NP could affect this decay topology in two ways:
  - Branching fraction
  - τ polarization

R(D$^{(*)}$) in $B \to D^{(*)}\tau^+\nu_\tau$

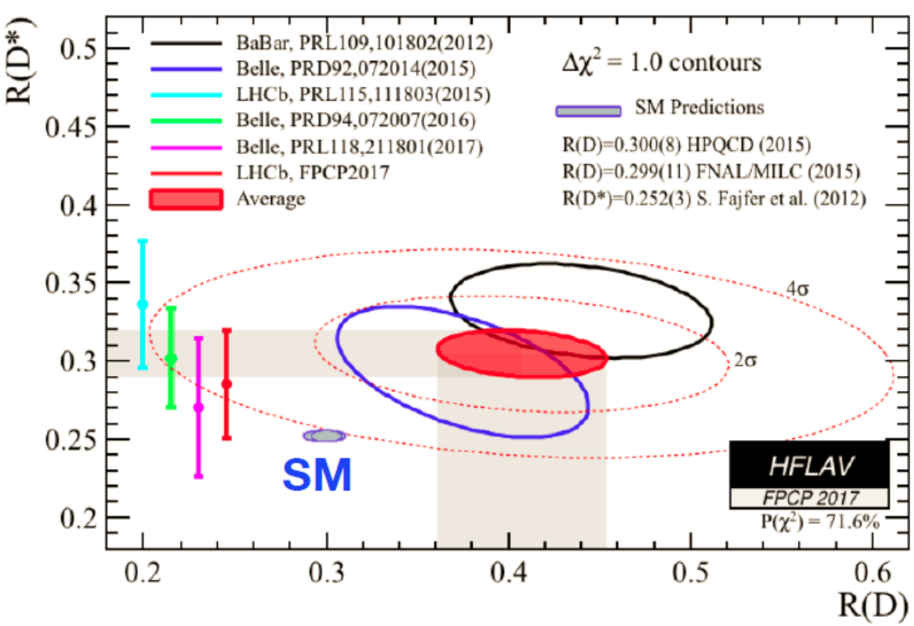
Test for lepton universality using the ratio typically:

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)} \quad (\ell = e, \mu).$$

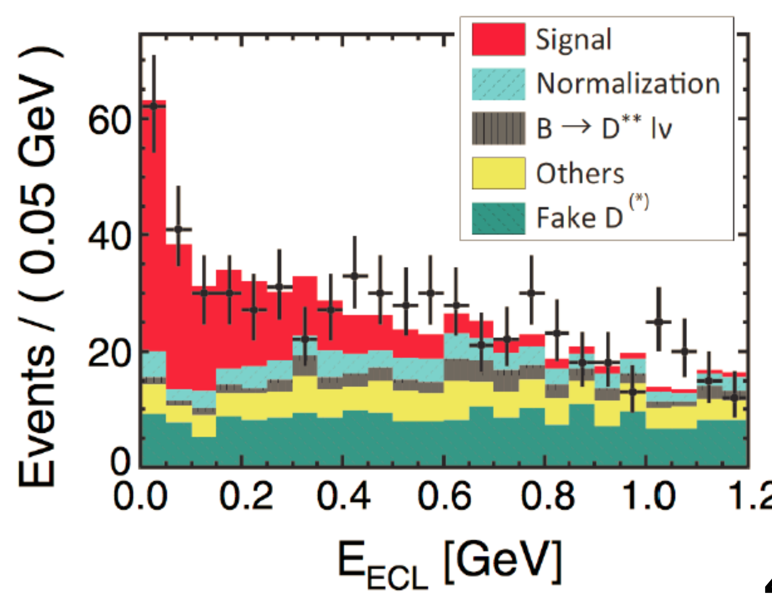
SM: R(D) = 0.300 +- 0.008 Phys. Rev. D 92, 034506 (2015)
R(D*) = 0.252 +- 0.003 Phys. Rev. D 85, 094025 (2012)

BaBar PRL 109 101802 (2012)
PRD 88 072012 (2013)
Belle PRD 92 072014 (2015)
PRD 94, 072007 (2016)
PRL 118, 211801 (2017)
arxiv1603.06711
LHCb PRL 115 111803 (2015)

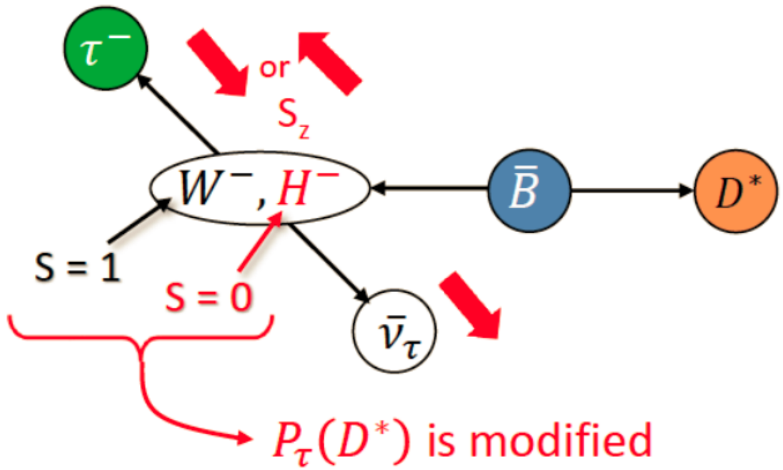
- Current world average for R(D$^{(*)}$) is in ~4.1σ tension with SM!



PRD 94 072007 (2016) SL tag



τ Polarization in $B \to D^{(*)}\tau^+\nu_\tau$



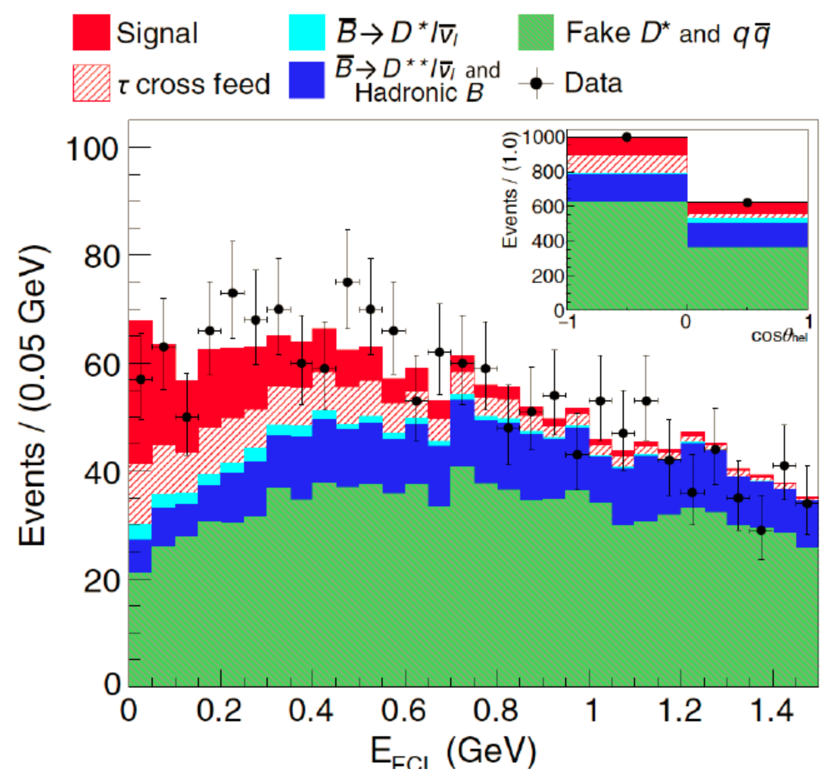
First measurement of the tau polarization in this decay.
First use tau had. decays in $B \to D^{(*)}\tau^+\nu_\tau$

$\tau^- \to \pi^-\nu_\tau$ $\tau^- \to \rho^-\nu_\tau$

Belle PRL 118, 211801 (2017) had. tag

$$P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

$\Gamma^{+(-)}$ for right-(left-)handed τ



$R(D^*) = 0.270 \pm 0.035(\text{stat.})\,^{+0.028}_{-0.025}\,(\text{syst.})$

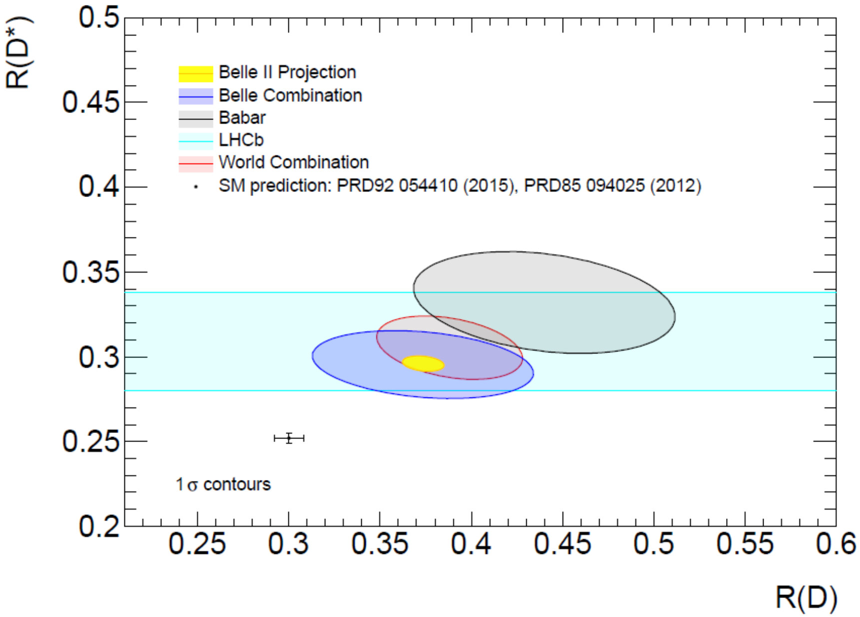
$\mathcal{P}_\tau(D^*) = -0.38 \pm 0.51(\text{stat.})\,^{+0.21}_{-0.16}\,(\text{syst.})$

Signal significance of about 7σ

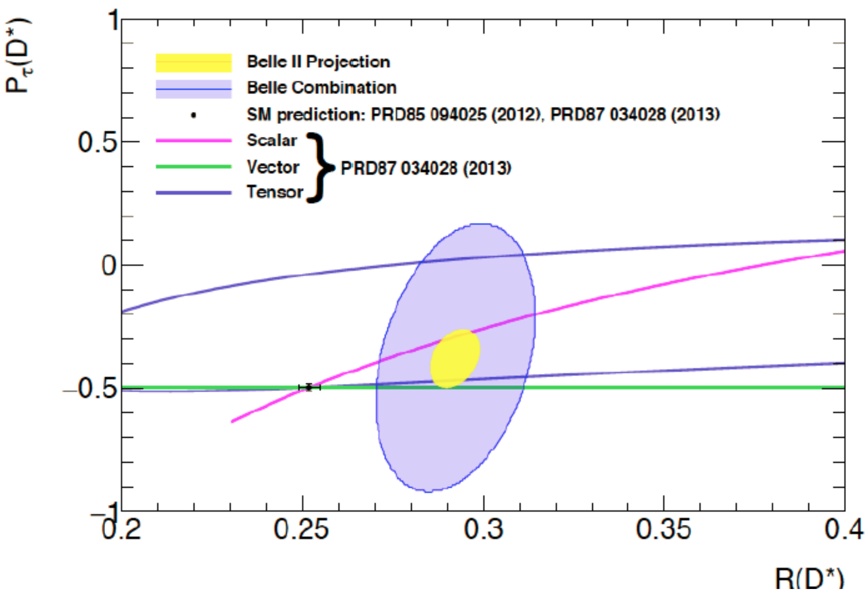
Compatibility with the SM.

$P_\tau(D^*)_{\rm SM} = -0.497 \pm 0.013$ Phys. Rev. D 87, 034028 (2013)

$B \to D^{(*)}\tau^+\nu_\tau$ prospect at Belle II



- Current measurements are statistically limited, dominant systematic uncertainties from
  - limited signal MC samples → larger at Belle II
  - limited knowledge of dominant bkg (involving soft pions) → dedicated measurement with large data samples feasible at Belle II
- With higher statistics, study polarization and q^2 distributions, essential to distinguish NP.



Uncertainties at Belle II

	$5\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

the first and the second values are the expected statistical and systematic errors.

Summary

- *B*-factories have provided unprecedented information on the flavor dynamics in SM: CPV in *B*/*D* decays, evidence in $D\bar{D}$ mixing, XYZ states, (semi-)leptonic *B* decays, …
- *B*-factory is also a τ-factory experiment. With ~1 billion $\tau^+\tau^-$ sample, many precise measurements and most stringent upper limits in τ LFV/LNV/BNV are obtained.
- Belle II will start full physics run in the end of 2018, reach 50 ab^{-1} by 2023-2024, which will provide greater sensitivity and complimentary approach to LHC in flavor physics area: CKM angles, CPV in *B* and charm decays, NP searches at the loop level, …
- With ~50 billion $\tau^+\tau^-$ events expected at Belle II, most searches and measurements in τ decays will be greatly improved.
- Belle II physics book (to be published in PTEP):
  https://confluence.desy.de/display/BI/B2TiP+ReportStatus

Michel parameters

In the SM charged weak interaction is described by the exchange of $W^{\pm}$ with a pure vector coupling to only left-handed fermions ("V-A" Lorentz structure). Deviations from "V-A" indicate New Physics. $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$ ($\ell = e, \mu$) decays provide clean laboratory to probe electroweak couplings.
The most general, Lorentz invariant four-lepton interaction matrix element:

$$\mathcal{M} = \frac{4G}{\sqrt{2}} \sum_{\substack{N=S,V,T \\ i,j=L,R}} g_{ij}^N \left[\bar{u}_i(l^-)\Gamma^N v_n(\bar{\nu}_l)\right] \left[\bar{u}_m(\nu_\tau)\Gamma_N u_j(\tau^-)\right],$$

$$\Gamma^S = 1,\ \Gamma^V = \gamma^\mu,\ \Gamma^T = \frac{i}{2\sqrt{2}}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$$

Ten couplings g_{ij}^N, in the SM the only non-zero constant is $g_{LL}^V = 1$

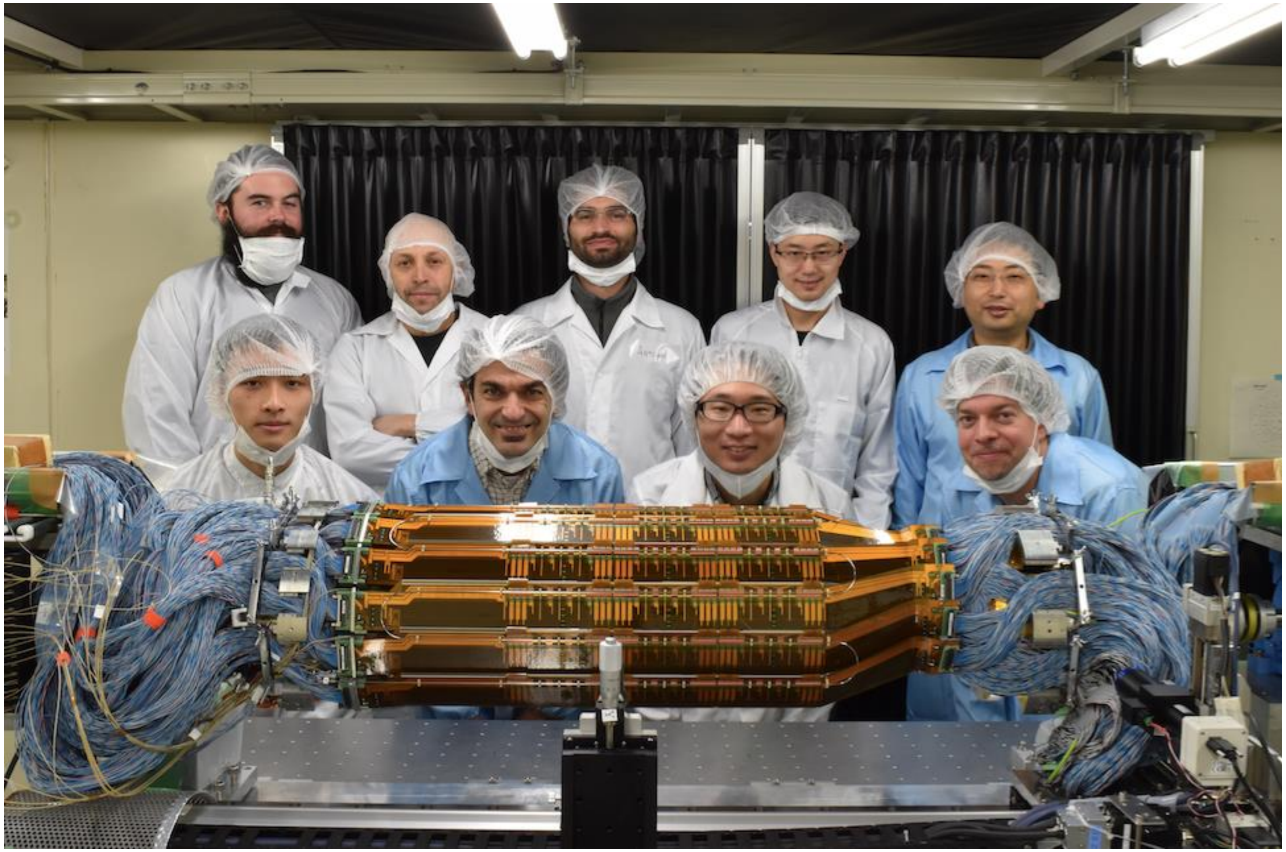
Four bilinear combinations of g_{ij}^N, which are called as Michel parameters (MP): ρ, η, ξ and δ appear in the energy spectrum of the outgoing lepton:

$$\frac{d\Gamma(\tau^{\mp})}{d\Omega dx} = \frac{4G_F^2 M_\tau E_{\max}^4}{(2\pi)^4}\sqrt{x^2 - x_0^2}\left(x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)\right.$$

$$\left. \mp\frac{1}{3}P_\tau \cos\theta_\ell \xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left(4x - 4 + \sqrt{1 - x_0^2}\right)\right]\right),\ x = \frac{E_\ell}{E_{\max}},\ x_0 = \frac{m_\ell}{E_{\max}}$$

In the SM: $\rho = \frac{3}{4}$, $\eta = 0$, $\xi = 1$, $\delta = \frac{3}{4}$

SVD ladder mount



- Jan 2018: Mount of the +X half shell was successfully completed

Beam Background Group

- *First Measurements of Beam Backgrounds at SuperKEKB*, submitted to NIMA, 101 pages
- Final experiment/simulation

$$LER\ beam\text{-}gas:\ 2.8^{+3.4}_{-2.3}$$

$$LER\ Touschek:\ 1.4^{+1.8}_{-1.1}$$

$$HER\ beam\text{-}gas:\ 108^{+180}_{-64}$$

$$HER\ Touschek:\ 4.8^{+8.2}_{-2.8}$$

- Phase 2 dedicated beam background detectors installed
  - VXD Volume: FANGS,CLAWS,PLUME
  - VXD dock space: TPCs, He-3 tubes
  - On QCS: PIN diodes, scintillators
- Next challenge: Phase 2 integration of DAQ and simulation

S. Vahsen, H. Nakayama et al

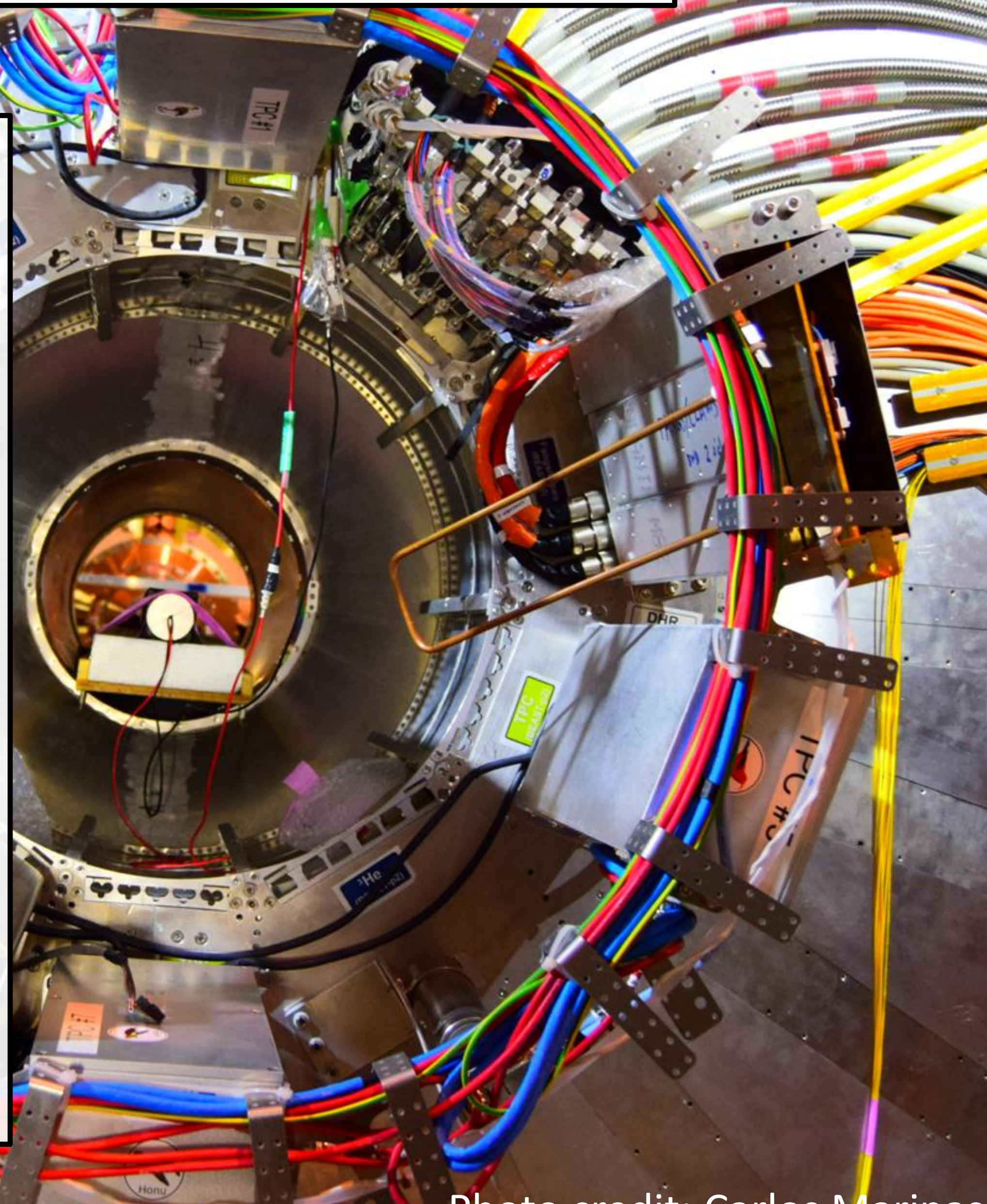


Photo credit: Carlos Marinas

Phase III:

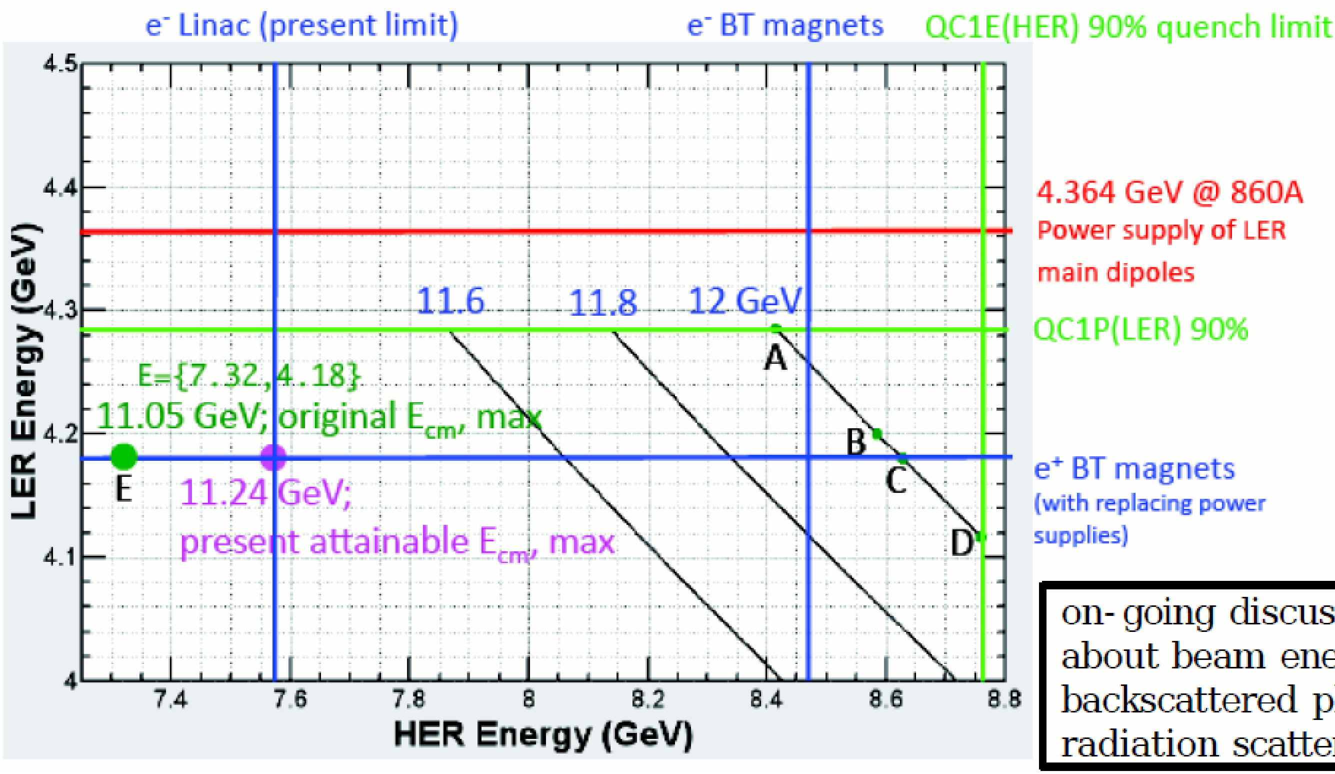
Milestone: Completion of +X clam-shell of the SVD on Jan 18, 2018

Higher energy run

from K. Akai, BPAC Feb 2012

- Design: original design maximum energy is 11.05 GeV at $\Upsilon(6S)$
- Possible higher energy run (11.5 GeV – 12 GeV) ?
  - If any, higher energy run will be after several years running at $\Upsilon(4S) \sim \Upsilon(6S)$
  - **present max E_{cm} is 11.24 GeV**, limited by e^- Linac and e^+ BT magnets
  - In order to inject the electron beam to HER at the required energy for 12 GeV operation, there must be huge reinforcement of Linac (replacement of S-band with C-band, 7.571 → 8.6 GeV

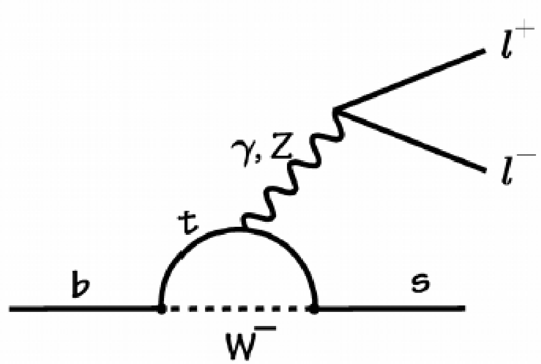
11.24 GeV region: $\Lambda_b\bar{\Lambda}_b$ threshold

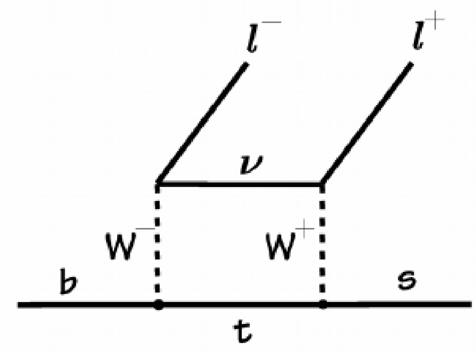


e.g. [arXiv:1211.0103]

on-going discussion with SuperKEKB people about beam energy measurement using backscattered photons produced by laser radiation scattered head-on the beams

Electroweak Penguins





Sensitive to the:

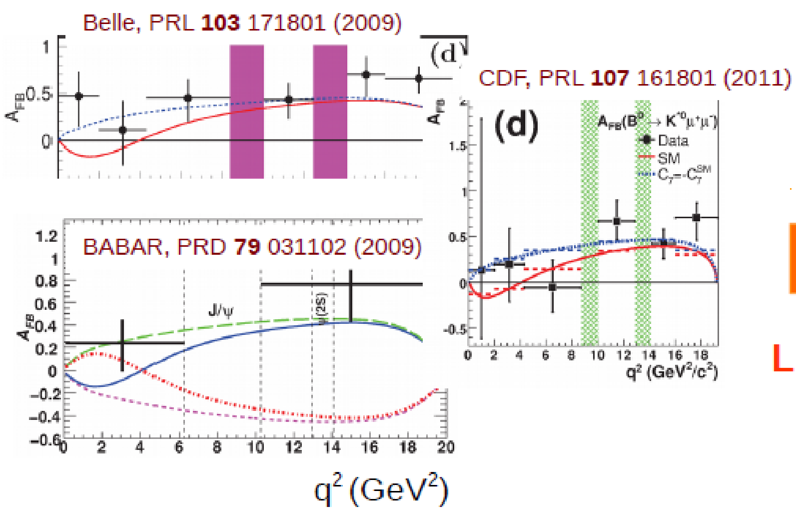
C_7: elctromagnetic penguin

C_9: vector electroweak

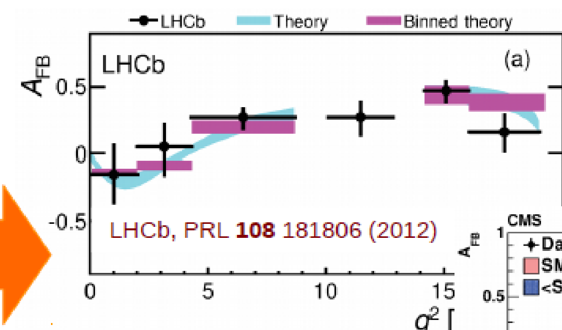
C_{10}: axial-vector electroweak

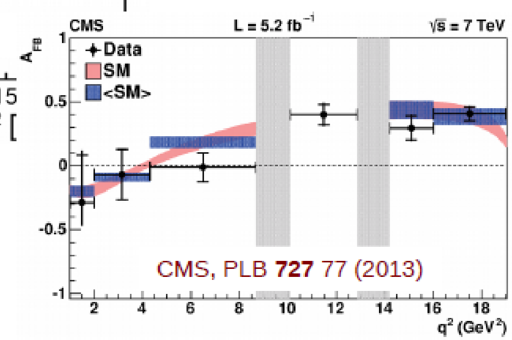
Wilson Coefficients

- Very suppressed in the SM (BF ~ 10^{-6});
- Many observables and often very precise predictions from theory;



LHC turn-on

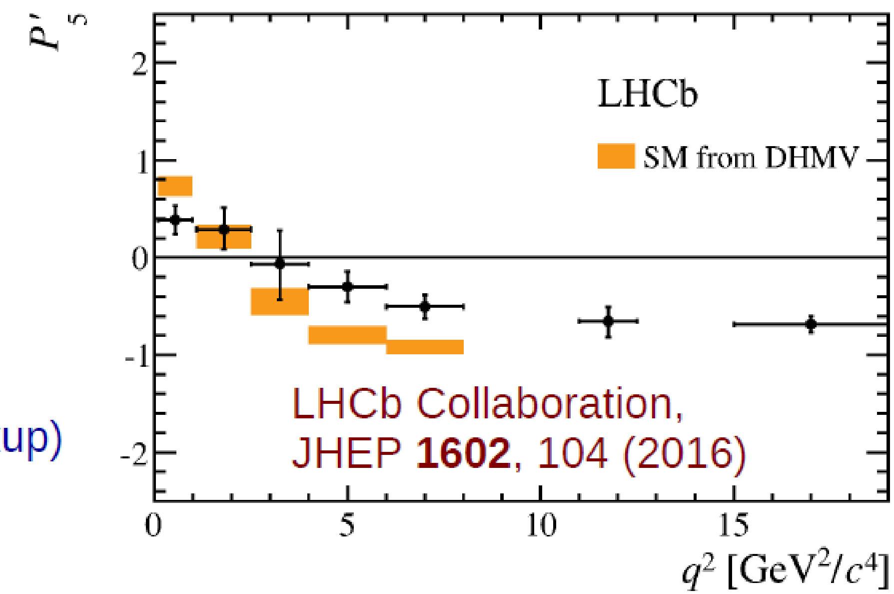




Electroweak Penguins: P'_5

- Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$;
- Many observables investigated, can cancel the leading uncertainty on hadronic form factor by defining "optimised" observables:
- Interesting discrepancy is observed in P'_5;

(full definitions of observables in backup)



DHMV:
JHEP **1412**,
125 (2014)

- Global fit to complete set of observables gives a 3.4σ tension with SM: New Physics or hadronic effects larger than expected?
- While the experiments improve the precision, input from theory is essential.

Electroweak Penguins: LUV?

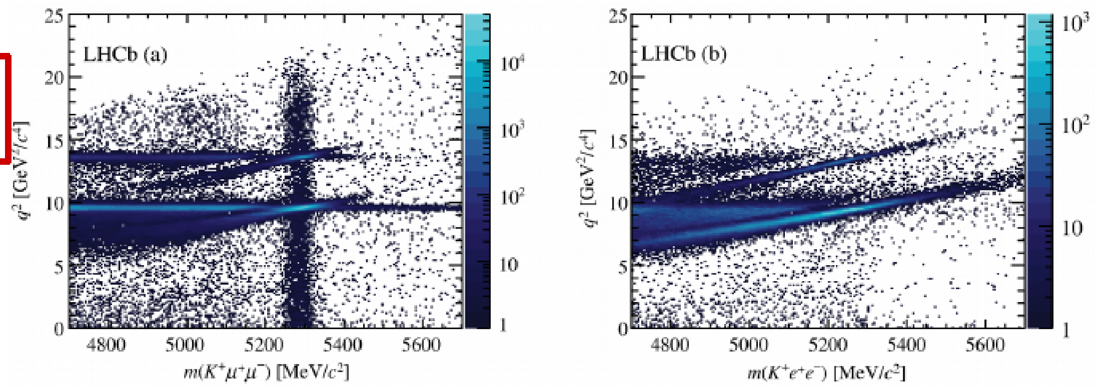
- Tests of Lepton Universality in $b \to s l^+ l^-$ decays can reveal the presence of Higgs-like particles;
- LHCb measured the ratio R_K in $B^+ \to K^+ l^+ l^-$:

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2} \approx 1 \text{ (modulo tiny corrections)}$$

- Challenging analysis, need to correct for Bremstrahlung;
- In $1 < q^2 < 6$ GeV^2:

$$\boxed{R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})}$$

- 2.6σ tension wrt expectation: this needs confirmation!



LHCb Collaboration, PRL **113**, 151601 (2014)

Electroweak Penguins: Outlook

- Quite a few channels where LHCb will improve a lot in the next couple years:
  - $B \to \pi\, l^+ l^-$;
  - $B_s \to \phi\, l^+ l^-$;
  - $\Lambda_b \to \Lambda\, l^+ l^-$;
  - …

  Keep refining precision on differential BF's, CP asymmetries, angular observables, Lepton Universality...

- … and quite a few more where we need to wait for Belle II:
  - $B \to K^{(*)} \tau^+ \tau^-$; current limit ~2 orders of magnitude above predictions
  - $B \to K^{(*)} \nu\ \nu$;
  - $B \to \gamma\gamma$;

    might see a signal with full dataset but it is crucial to control the machine backgrounds
  - (semi-)inclusive $b \to d/s\ \gamma$;
  - Time dependent CPV in $B^0 \to K_S \pi^0 \gamma$, $B^0 \to \rho^0\ \gamma$;
  - …

Electroweak Penguins

- Definitions of main observables:

$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega})$$

$$S_i = \left(I_i + \bar{I}_i\right) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$

$$A_i = \left(I_i - \bar{I}_i\right) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$

$I(q^2)$: q^2 dependent angular observables. They are expressed as a combination of 6 decay amplitudes (3 transversity states x 2 chirality states of the $\mu\mu$ system)

$$F_L = S_{1c} = \frac{|\mathcal{A}_0^L|^2 + |\mathcal{A}_0^R|^2}{|\mathcal{A}_0^L|^2 + |\mathcal{A}_0^R|^2 + |\mathcal{A}_\parallel^L|^2 + |\mathcal{A}_\parallel^R|^2 + |\mathcal{A}_\perp^L|^2 + |\mathcal{A}_\perp^R|^2}$$

$$P_1 = \frac{2\, S_3}{(1 - F_L)} = A_T^{(2)}$$

$$P_2 = \frac{2}{3}\frac{A_{FB}}{(1 - F_L)}$$

$$P_3 = \frac{-S_9}{(1 - F_L)}$$

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1 - F_L)}}$$

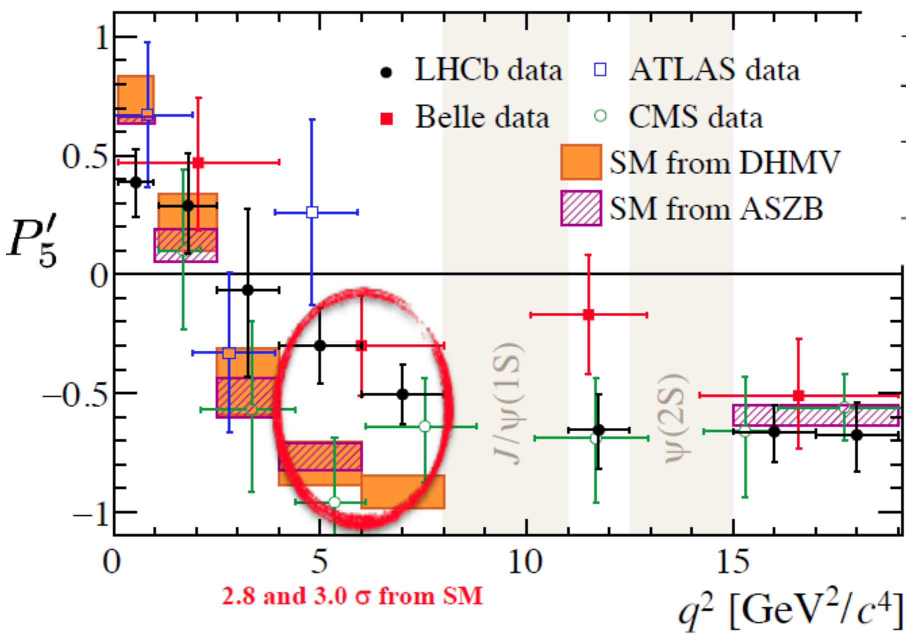
$$P'_6 = \frac{S_7}{\sqrt{F_L(1 - F_L)}}$$

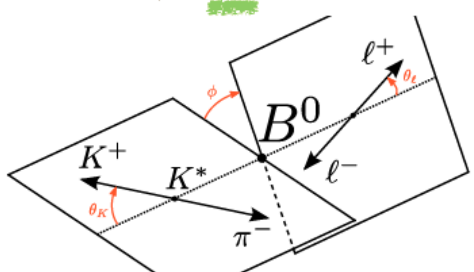
Electroweak Penguins: A_{FB}

$$\mathcal{A}_{\rm FB}(q^2_{\rm min}, q^2_{\rm max}) = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \int_{-1}^{1} d\cos\theta \, \mathrm{sgn}(\cos\theta) \frac{d^2\Gamma}{dq^2 d\cos\theta}}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \int_{-1}^{1} d\cos\theta \frac{d^2\Gamma}{dq^2 d\cos\theta}}$$

θ : angle between the l^+ (l^-)
momentum and the $\bar{B}$ (B)
momentum in the l^+l^- rest frame

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell \, \mathrm{d}\cos\theta_K \, \mathrm{d}\phi \, \mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+ \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$





$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

Belle's history of B → $D^*\tau\nu$

- **First observation** PRL 99, 191807 (2007)

$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) = (2.02^{+0.40}_{-0.37} \pm 0.37)\% \text{ with } 5.2\sigma$$

- Updated w/ full-recon hadronic B-tag PRD 92, 072014 (2015)

$$B \to D^*\tau\nu \text{ and } B \to D\tau\nu$$

- Independent measurement w/ semileptonic B-tag

$$B \to D^*\tau\nu$$

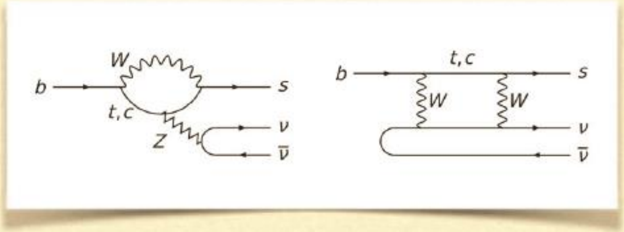
PRD 94, 072007 (2016)

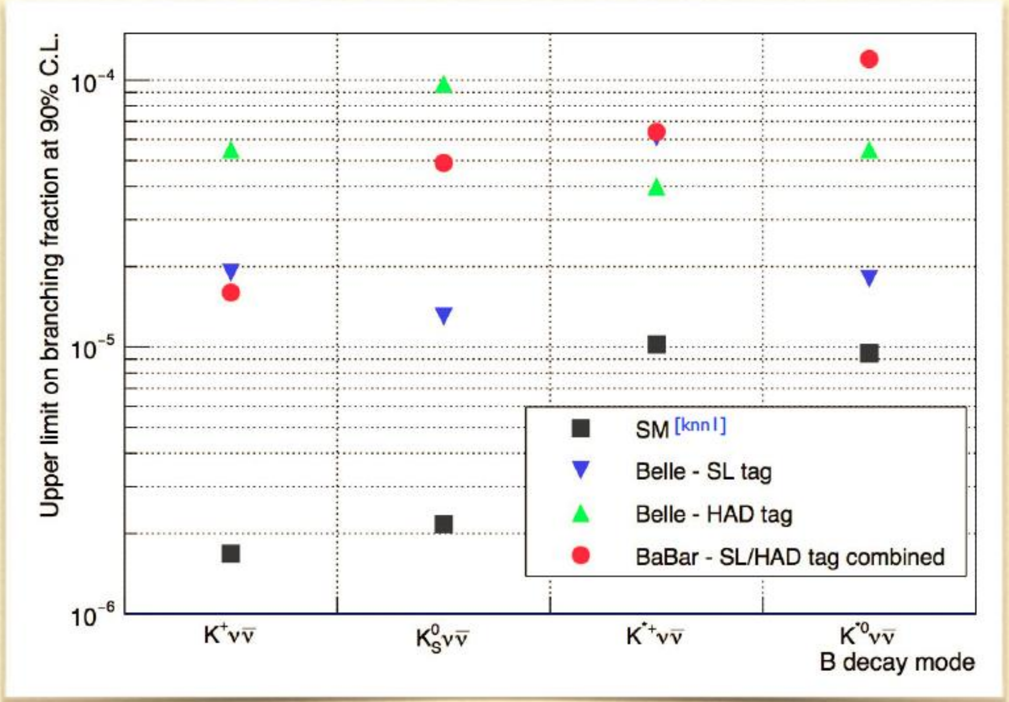
- **First measurement of τ polarization** PRL 118, 211801 (2017) PRD 97, 012004 (2018)

$$B \to D^*\tau\nu$$

$B \to K^{(*)}\nu\nu$: theoretical and experimental status

- Flavour changing neutral current, prohibited at tree level in the SM
  - NP contribution (from new mediators or sources of missing energy) may be comparable to SM ones
  - free of uncertain long-distant hadronic effects, theoretically clean
  - Experimental searches from BaBar and Belle on both HAD and SL recoil[knn2]
    - no signal evidence, UL less than 1 order of magnitude away from SM predictions for K^* channels



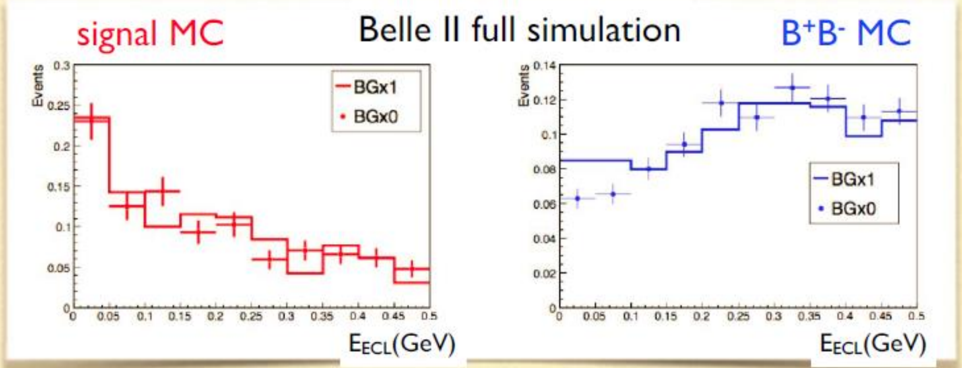


$B \to K^{(*)} \nu\nu$: robustness against machine background

- Analysis on Belle II Full simulation using hadronic B reconstruction using $K^{*+} \to K\pi^0$ to establish machine background impact
- Simple cut-and-count analysis, signal efficiency and bkg yield estimanted in extra neutral energy signal region
- nominal machine bkg (BGx1) and machine bkg-free (BGx0) simulated samples analysed
- Negligible impact of machine background both in terms of variables shape and signal significance

1 ab^{-1} equivalent statistics

	"BGx0"	"BGx1"
N_{bkg}	6415 ± 80	3678 ± 61
ε (10^{-4})	10.3 ± 0.3	5.38 ± 0.23
$N_{sig}/\sqrt{N_{bkg}}$	0.16	0.15
UL (10^{-4})	2.6	3.8



- Detector performances and reconstruction proves to be robust against machine background

$B \to K^{(*)}\nu\nu$: perspectives @ Belle II

- Extrapolation on full Belle II statistics on Belle HAD and SL analyses, assuming two times better B_{tag} reconstruction efficiency:
  - observation with about 18 ab^{-1}
  - precision on the branching fraction at 50 ab^{-1}:

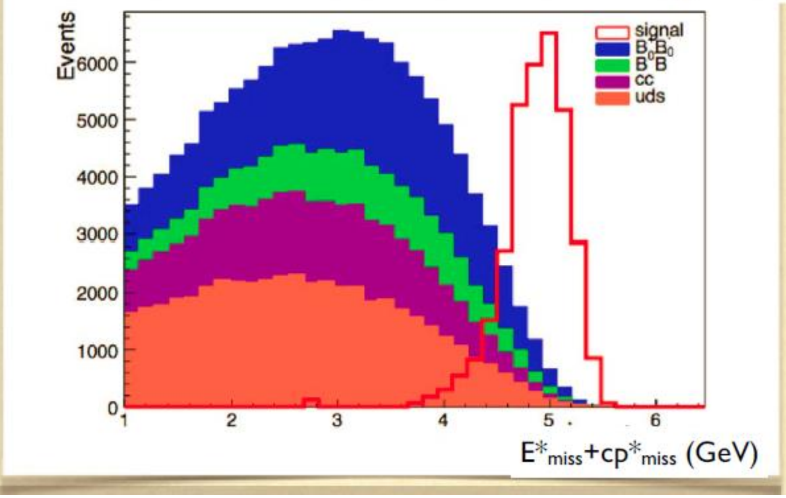
	stat only	total
$B^+ \to K^+\nu\nu$	9,5%	10,7%
$B^+ \to K^{*+}\nu\nu$	7,9%	9,3%
$B^+ \to K^{*0}\nu\nu$	8,2%	9,6%

- Fraction of longitudinally polarized K* may
- be measured, ~20% precision with full statistics

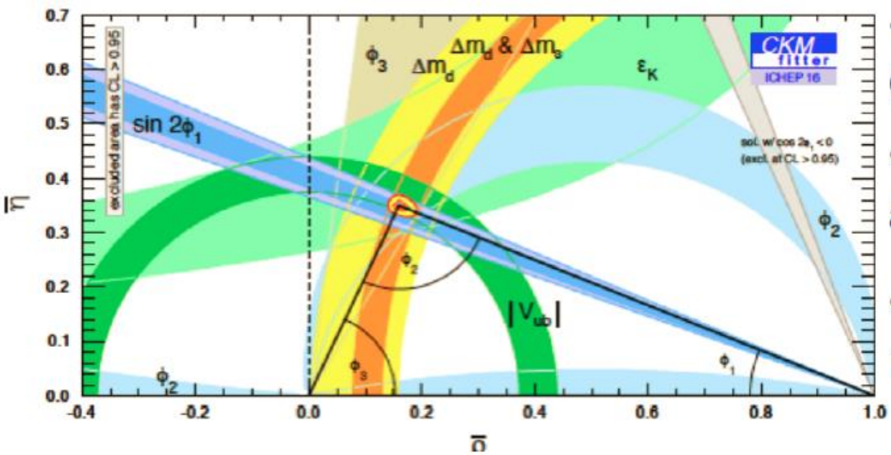
- Robustness against machine background proved,

predicted precision can be exceeded by improving analysis strategy

Belle II full simulation with machine background



Belle II Physics Prospects – CKM



- Is the unitary triangle really a triangle

Currently, $(\alpha+\beta+\gamma)=(175\pm 9)^{\circ}$

- Angle $\phi_1(\beta)$ is measured with 1° accuracy;

angles $\phi_2(\alpha)$ and $\phi_3(\gamma)\sim 5-15^{0}$ accuracy

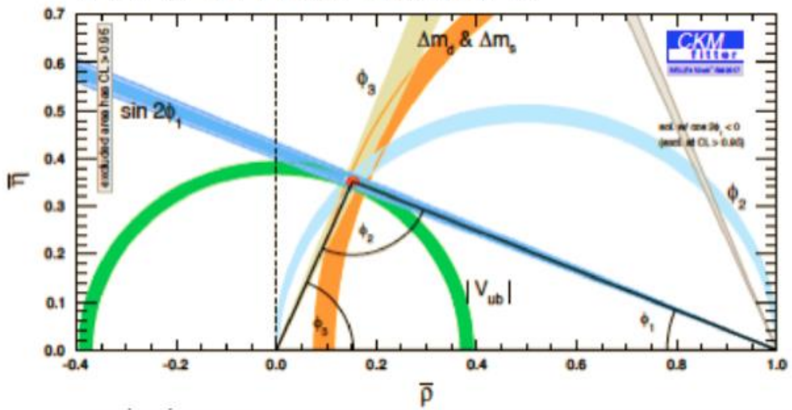
- Accuracies for $V_{cb}\sim 3\%; V_{ub}\sim 10\%;$

$V_{td}\sim 7\%; V_{ts}\sim 6\%; V_{td}/V_{ts}\sim 3\%$

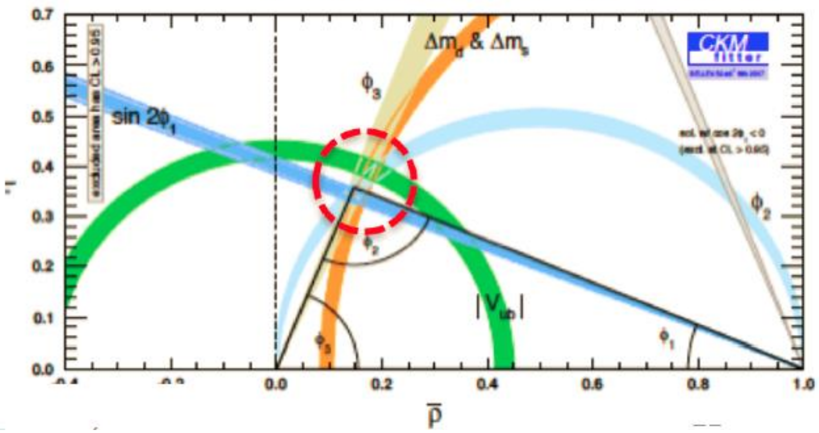
$\varphi_1(\beta)$ [deg.]	0.4
$\varphi_2(\alpha)$ [deg.]	1.0
$\varphi_3(\gamma)$ [deg.]	1.0 (w/LHCb)

$\lvert V_{cb}\rvert$ incl.	1%
$\lvert V_{cb}\rvert$ excl.	1.5%
$\lvert V_{ub}\rvert$ incl.	3%
$\lvert V_{ub}\rvert$ excl.	2% (w/LHCb)

For a SM-like scenario



If the current WAs hold



- For details, please see Belle II physics book: https://confluence.desy.de/display/BI/B2TiP+ReportStatus