Physics Prospects at Belle II

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on behalf of the Belle II Collaboration

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- KEK is a laboratory in Tsukuba, Japan, with a 30-year history of building and operating electron-positron colliders and detectors for HEP.
- SuperKEKB and Belle II will extend this tradition by 10 to 15 years.
- Why? The principal justification is to seek clear evidence for processes that deviate from the Standard Model (new physics) at CM energies favorable for production of $b\,\bar{b}$.
- Belle and BaBar have taught us that this pursuit requires luminosity and detector sophistication well beyond what has been achieved to date at B factories.

The *B* factories, BaBar and Belle, have explored tens of physics topics and hundreds of channels. All can benefit from the enhancements that SuperKEKB and Belle II will bring, but

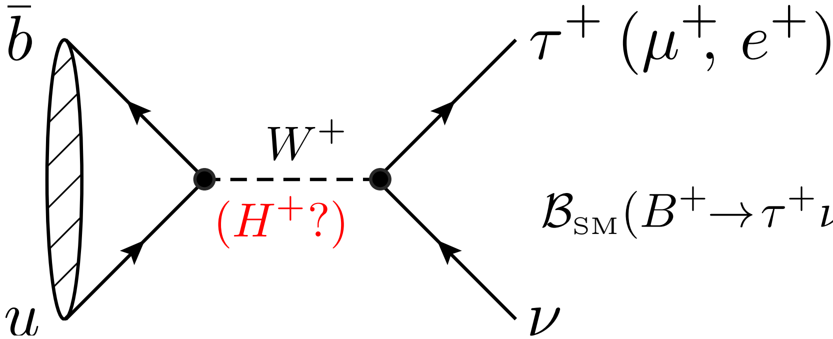
a) in 15min we can discuss only a few examples, and

b) the primary Belle II mission is to reveal New Physics (NP).

$B \to \tau\nu$	Sensitive to charged Higgs.
$B \to D^* \tau\nu$ $B \to D\ \tau\nu$	Also sensitive to charged Higgs.
$B \to X_s \ell^+ \ell^-$	An FCNC process with many observables exposed to NP

The "bible" of Belle II physics projections is BELLE2-NOTE-PH-2015-002, B. Golub, K. Trabelsi, and P. Urquijo. (Restricted access.)

$\mathcal{B}(B \to \tau\nu)$



Sensitive to existence of a charged Higgs

Measurable via other modes*

Phase space

Lattice QCD*

$$\mathcal{B}_{\rm SM}(B^+ \to \tau^+\nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \overbrace{\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2}^{\text{Phase space}} f_B^2 \overbrace{|V_{ub}|^2 \tau_B}^{\text{Measurable via other modes*}}$$

$$= 0.75^{+0.10}_{-0.05} \times 10^{-4}$$

Helicity suppression

Makes $\tau\nu \gg \mu\nu \gg e\nu$ but with precisely determined ratios

In the type II 2-Higgs doublet model (2HDM) (W.S. Hou, PRD 48, 2342 (1993)),

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

If $\tan^2\beta \dfrac{m_B^2}{m_{H^\pm}^2} \begin{array}{l} < 2, \quad r_H < 1, \\ \gg 2, \quad r_H \gg 1. \end{array}$

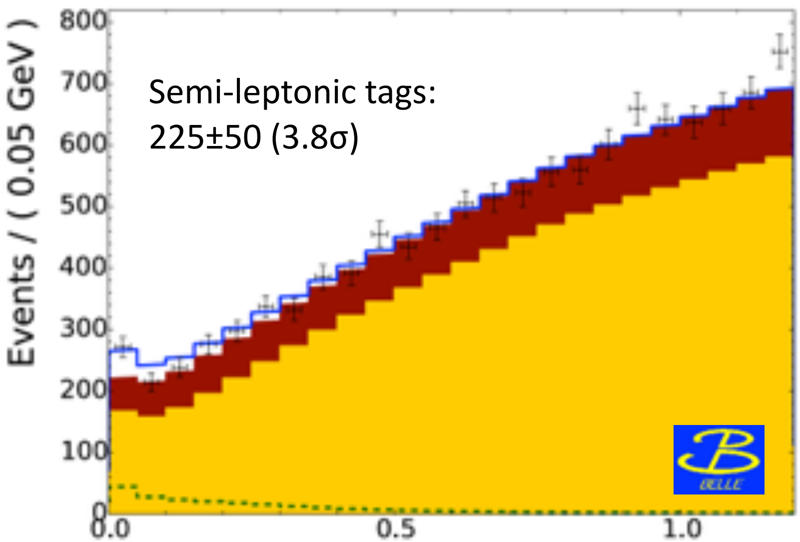
$\tan\beta$ is the ratio of the VEVs of the two doublets.

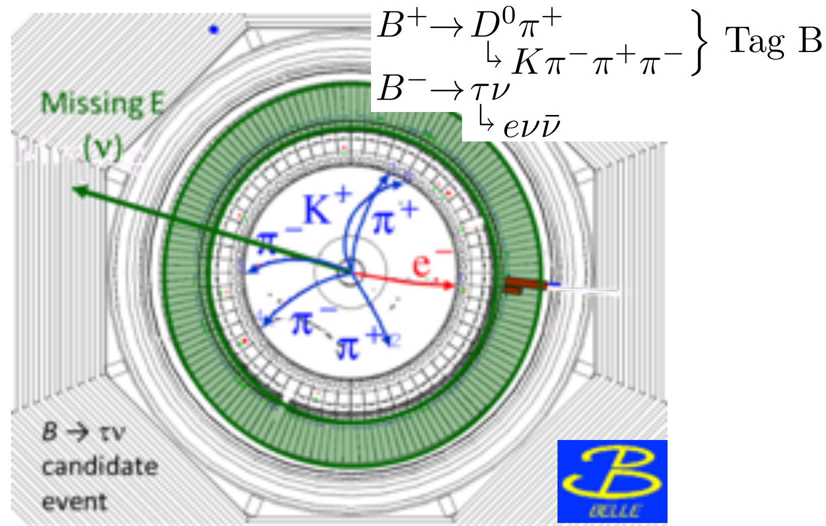
A charged Higgs breaks lepton universality.

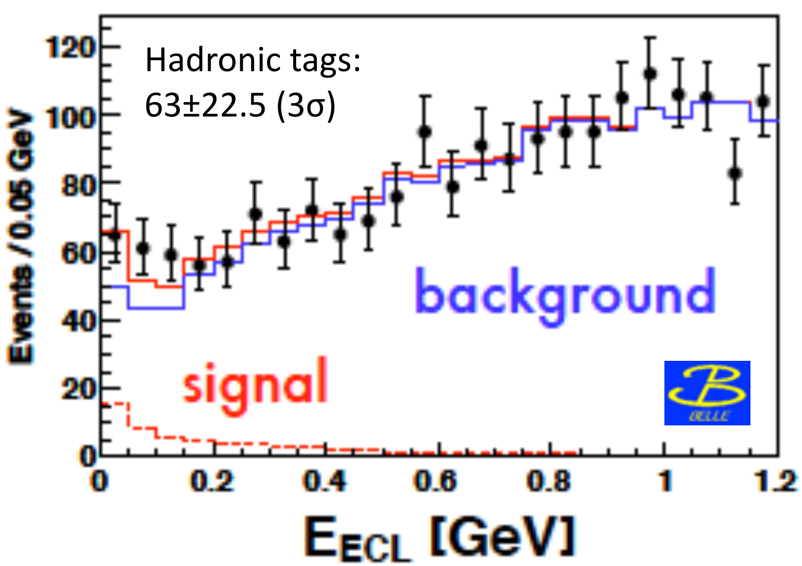
Although type II 2HDM is now in a bit of trouble (see below), other NP could force departure from SM.

$^*V_{ub} = (3.70 \pm 0.12 \pm 0.26) \times 10^{-3}$
$f_{B_s} = (225.6 \pm 1.1 \pm 5.4)$ MeV
$f_{B_s}/f_{B_d} = 1.205 \pm 0.004 \pm 0.007$
from <http://ckmfitter.in2p3.fr> in early 2014.

$\mathcal{B}(B\to\tau\nu)$

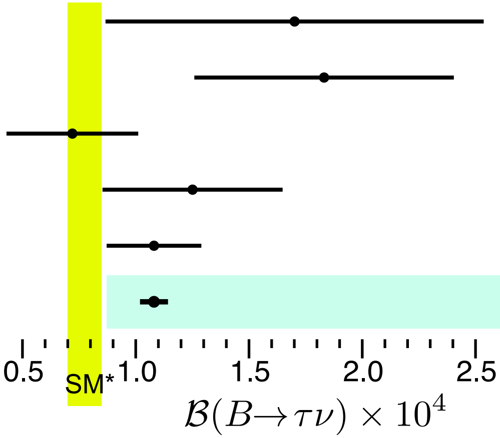






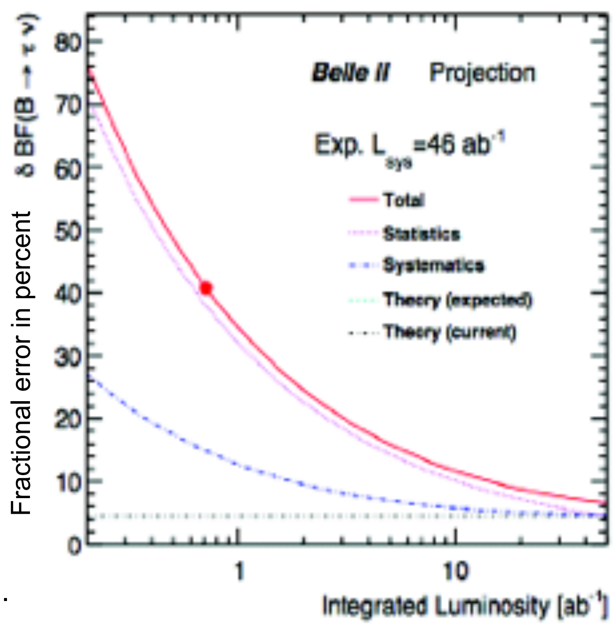
E_{ECL} is calorimeter energy not associated with the daughters of the Υ(4S).
Ultimately the signal is the small excess above projected background at low E_{ECL}.
Challenging for the instrumentation at the B factories.
(Much more challenging at LHCb.)

$\mathcal{B}(B \to \tau\nu)$

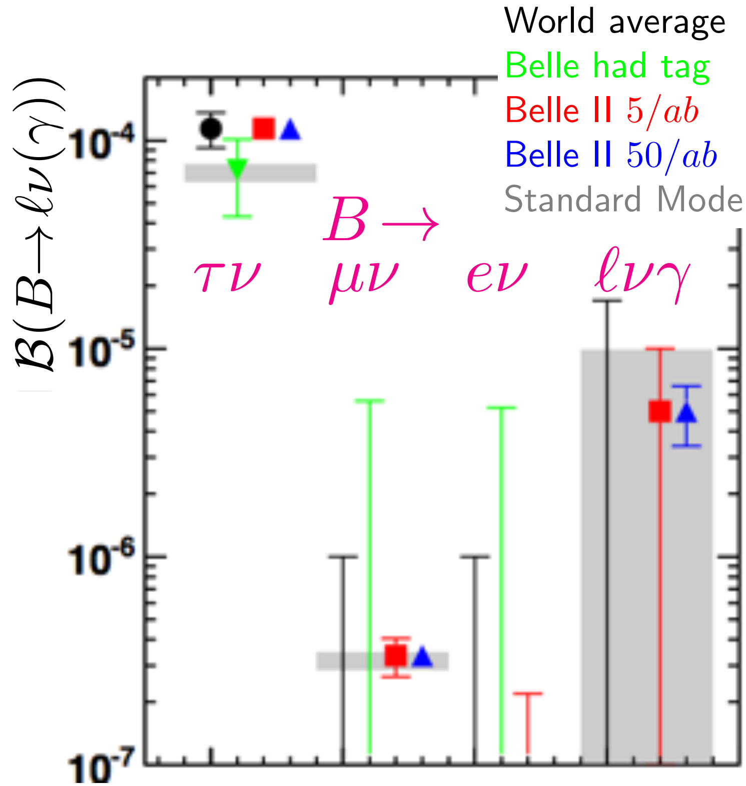


BaBar	$X\ell\nu$ tag	PRD81, 051101 (2010)
BaBar	hadronic tag	PRD88, 031102 (2013)
Belle	hadronic	PRL110, 131801 (2013)
Belle	$X\ell\nu$	PRD92, 051102 (2015)
Average		CKM 2015, http://ckmfitter.in2p3.fr/
Belle II @ $5ab^{-1}$		

30% precision at Belle → <5% precision at Belle II

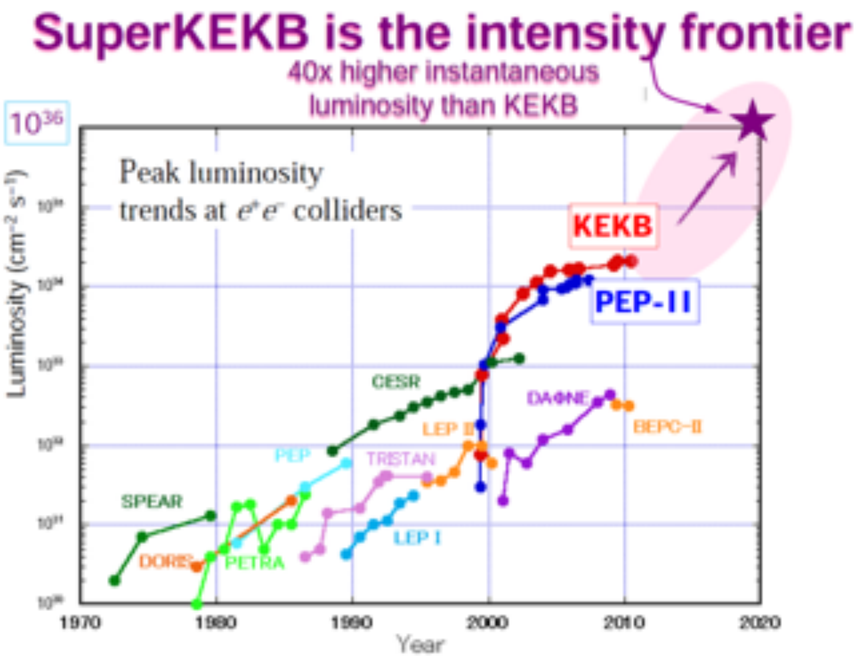


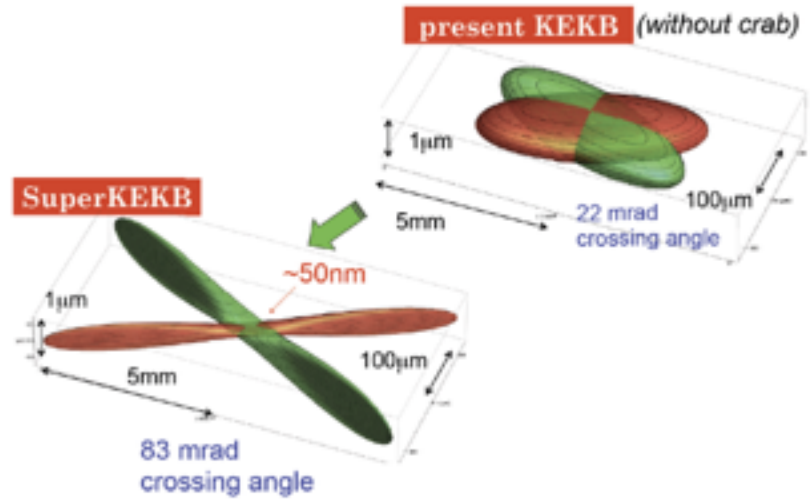
*See slide 4.



Belle, B→ μ ν , e ν (Had) PRD91, 052016 (2015)
Belle, B→ l ν gamma Preliminary (2014 B2TiP)

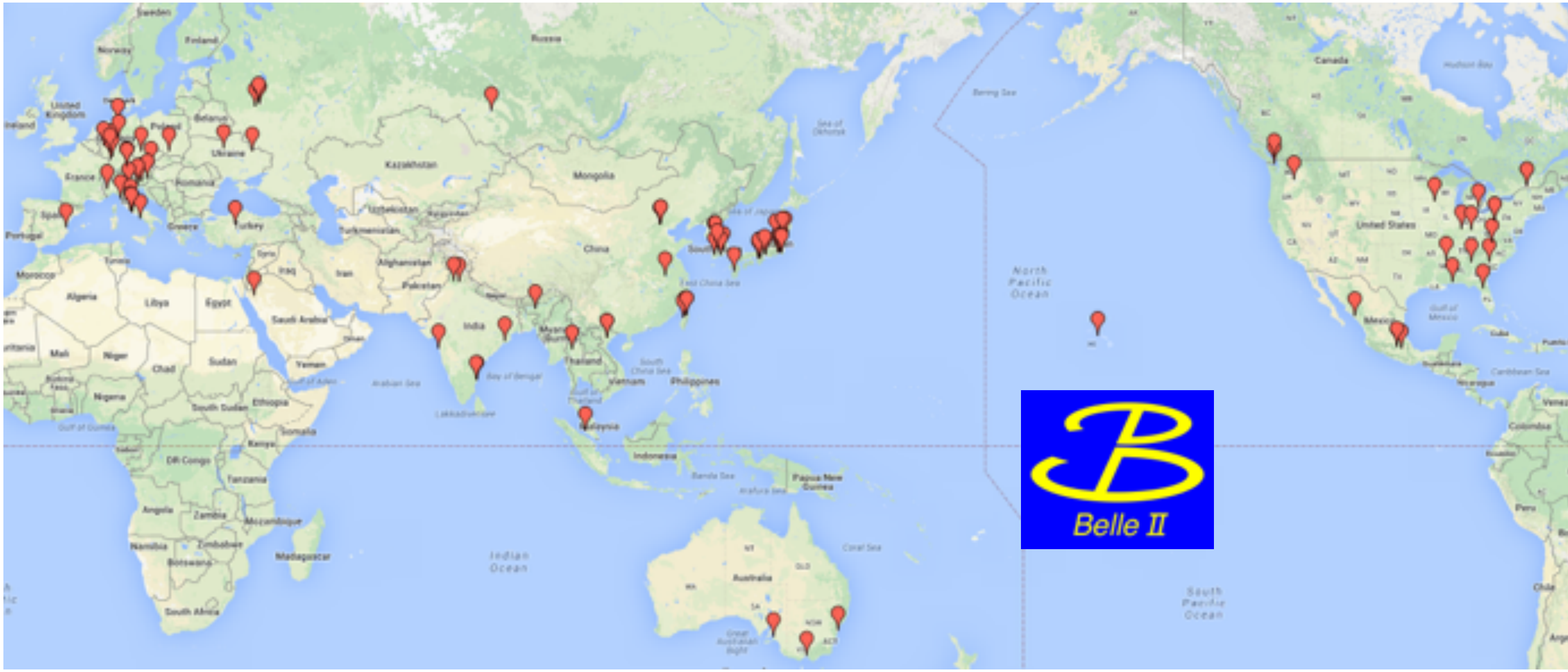
SuperKEKB





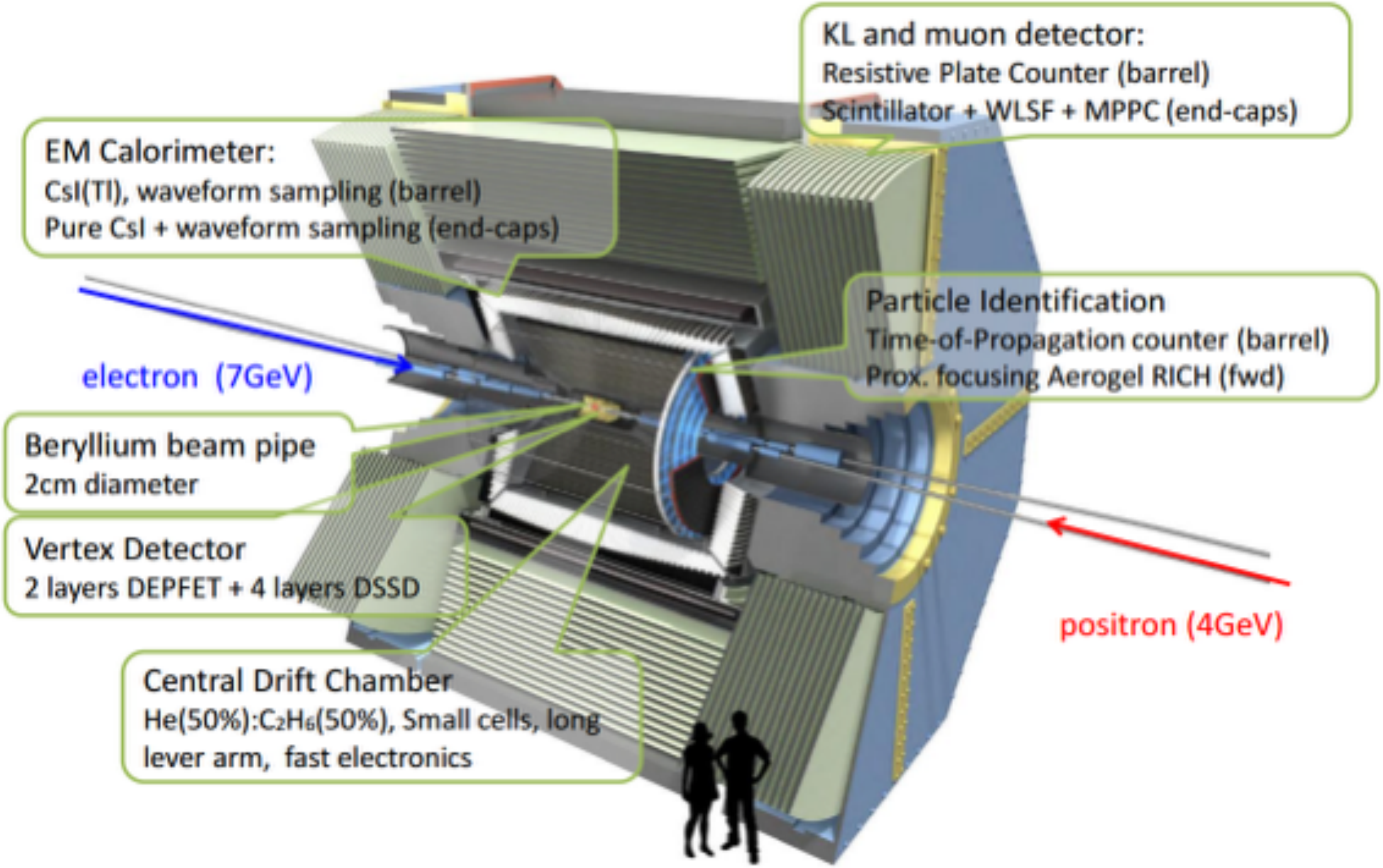
- Compared with KEKB, the design luminosity of SuperKEKB is higher by a factor of 40.
- Increase in beam current contributes a factor of ~2.
- Reduction in spot size at the interaction point contributes a factor of ~20.
- Beam commissioning is scheduled to begin in January 2016 and to continue, with interruptions, for two years.

Belle II Collaboration



- 23 countries,
- 99 institutions,
- ~600 collaborators as of May 2015.

Belle II Detector



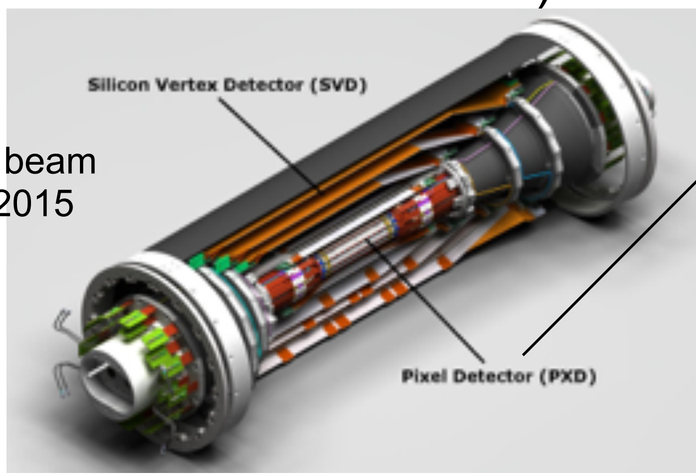
- All Belle sub-detectors to be upgraded or replaced in part to cope better with higher particle fluxes associated with higher beam currents.

Vertex Detectors

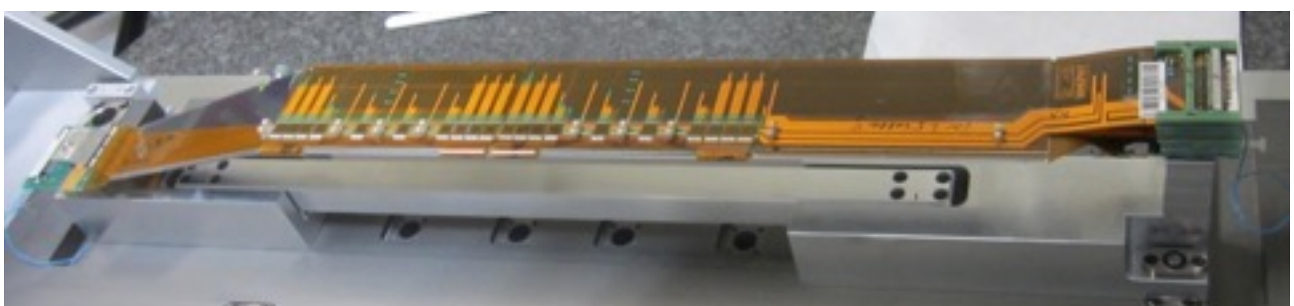
Beam pipe radius reduced from 2cm-1.5cm for Belle to 1cm for Belle II.

New vertex detectors: 2 layers of DEPFETs (Depleted P- Channel Field Effect Transistor) and 4 layers of DSSD (Double Sided Silicon Detector).

Into test beam in June 2015



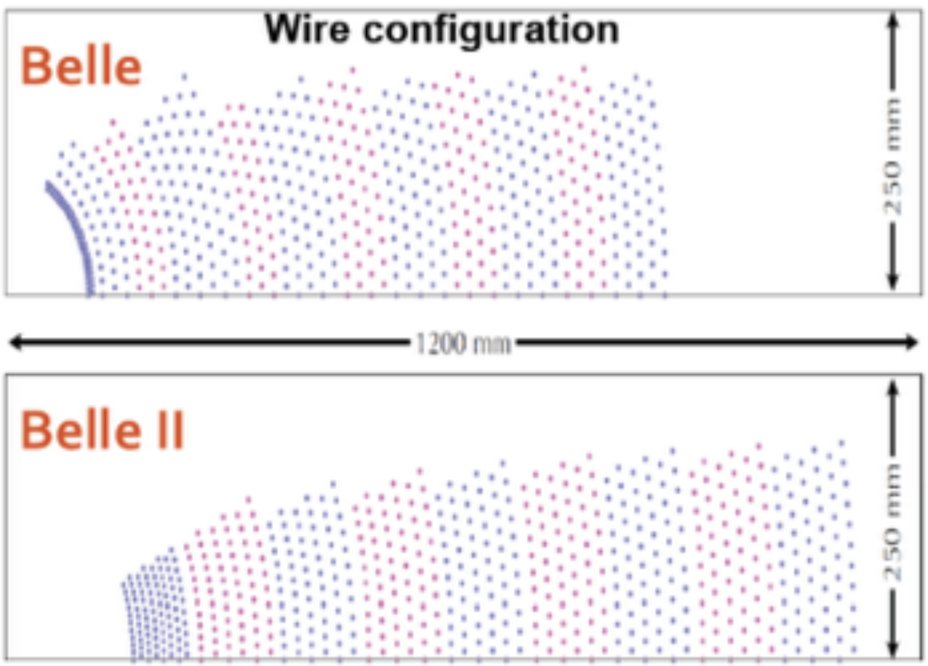
Beam Pipe		r = 10mm
DEPFET		
	Layer 1	r = 14mm
	Layer 2	r = 22mm
DSSD		
	Layer 3	r = 38mm
	Layer 4	r = 80mm
	Layer 5	r = 115mm
	Layer 6	r = 140mm



First working SVD ladder readout at Vienna in April

Central Drift Chamber

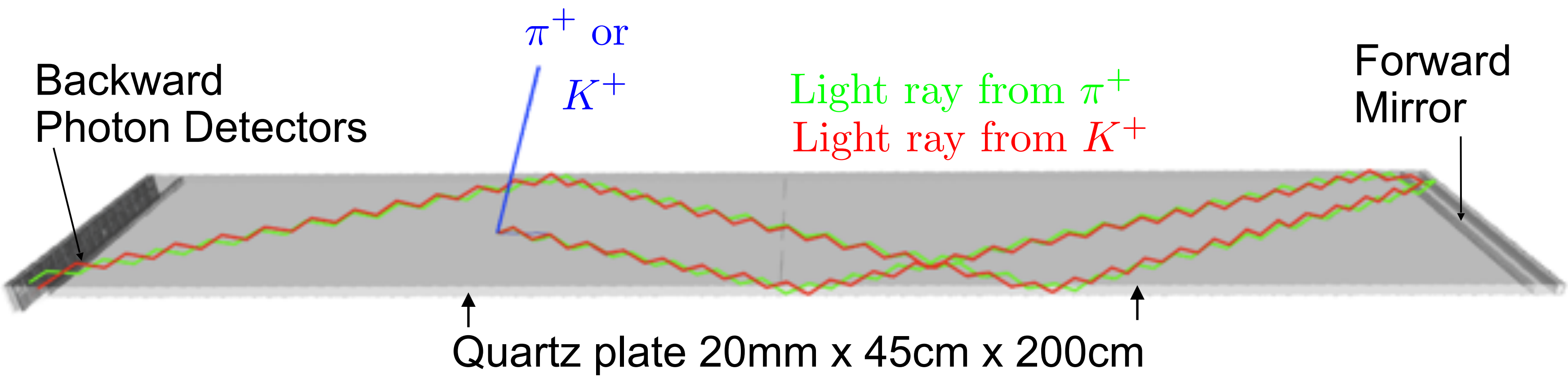
- Outer radius of Belle II CDC is 28% bigger than the Belle CDC.
- Stringing of 51456 wires was completed in January 2014.
- Commissioning with cosmic rays is ongoing.



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

iTOP Detector

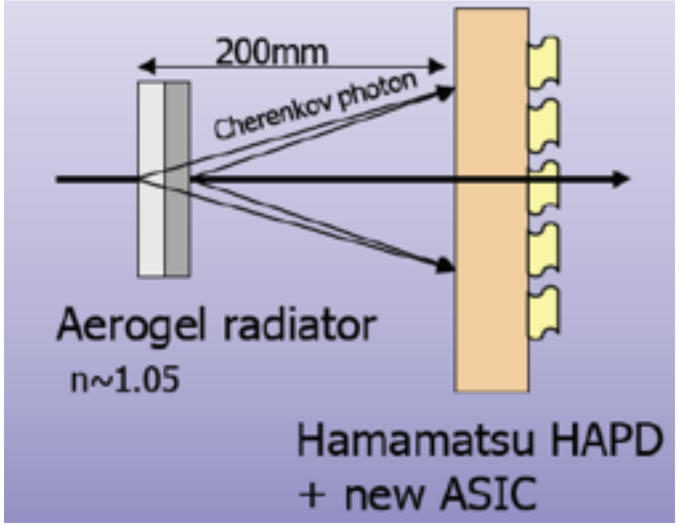
- The Imaging Time of Propagation (iTOP) detector does particle ID from a perch between the CDC and EM calorimeter, a gap of ~10cm.
- It operates both as a time-of-flight detector and a ring imaging Cherenkov counter.



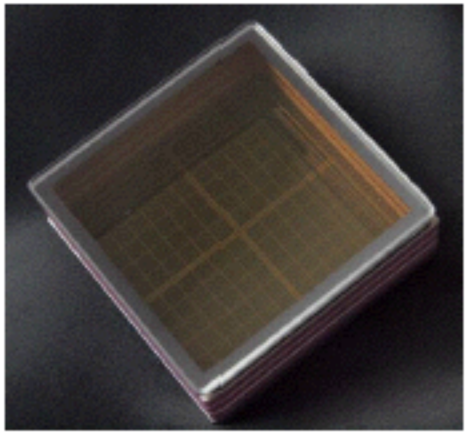
- The light rays never have the opportunity to form a ring image in space only. The “image” is in space-time and thus requires superb time measurement to resolve.
- The point of impact and the angle of the trajectory are determined from CDC data.

Aerogel RICH

- The ARICH does particle ID in the forward endcap.
- In contrast with the iTOP it detects Cherenkov light as rings in space only.

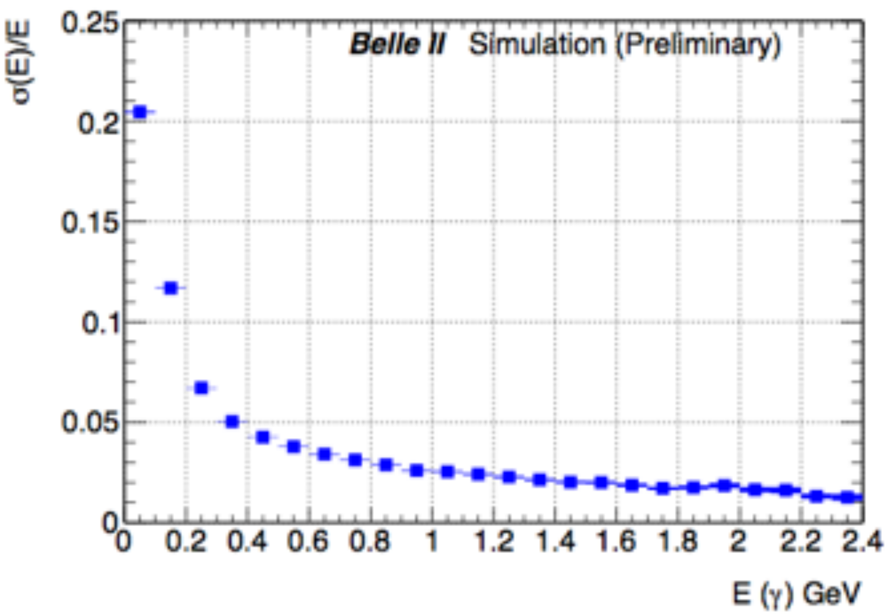


HAPD



- ARICH incorporates 420 Hybrid Avalanche Photo Detectors (HAPD), each with 144 channels.

Electromagnetic Calorimeter (ECL)

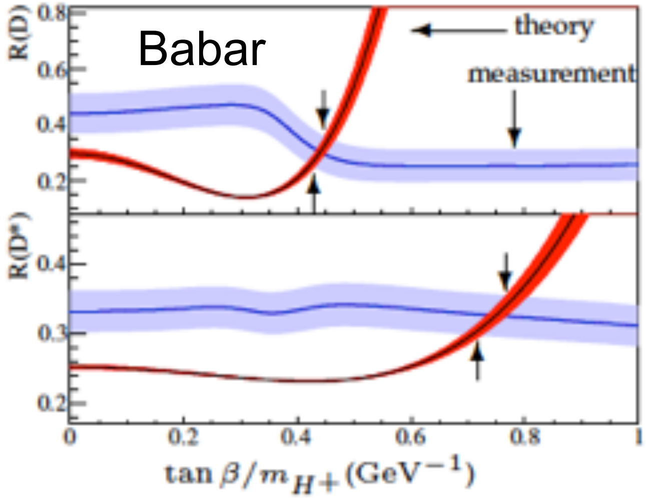


- Higher rates in Belle II (Bhabha's, Touschek scattering) require ECL upgrades to combat "pile-up."
- New electronics for the entire ECL will provide waveform sampling. All barrel counters are already communicating with the DAQ.

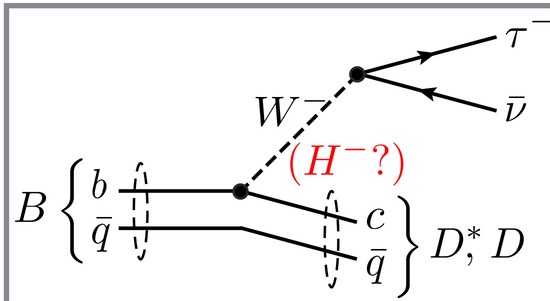
K_L and Muon Detector (KLM)

- The Belle KLM used resistive plate chambers interleaved with steel sheets.
- In some places the RPCs cannot handle the higher rates of Belle II. In those places scintillator will replace the RPCs.
- The KLM also gets new electronics.

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



BaBar: Neither R* nor R is a good match to the SM (tan $\boldsymbol{\beta}$/M$_H$ = 0) calculation.
Both can match the type II 2HDM but not at a consistent value of tan $\boldsymbol{\beta}$/M$_H$.



In common with $\mathcal{B}(B \to \tau\nu)$ this process has good sensitivity to existence of a charged Higgs.

$$R(D^*) \equiv \frac{\mathcal{B}\left(\bar{B} \to D^*\tau\bar{\nu}\right)}{\mathcal{B}\left(\bar{B} \to D^*\ell\bar{\nu}\right)} \qquad \ell = e$$

or

$$R(D) \equiv \frac{\mathcal{B}\left(\bar{B} \to D\tau\bar{\nu}\right)}{\mathcal{B}\left(\bar{B} \to D\ell\bar{\nu}\right)} \qquad \ell = \mu$$

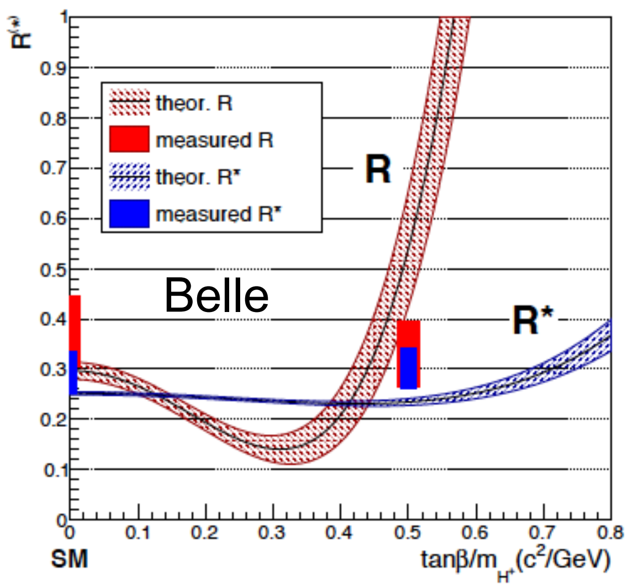


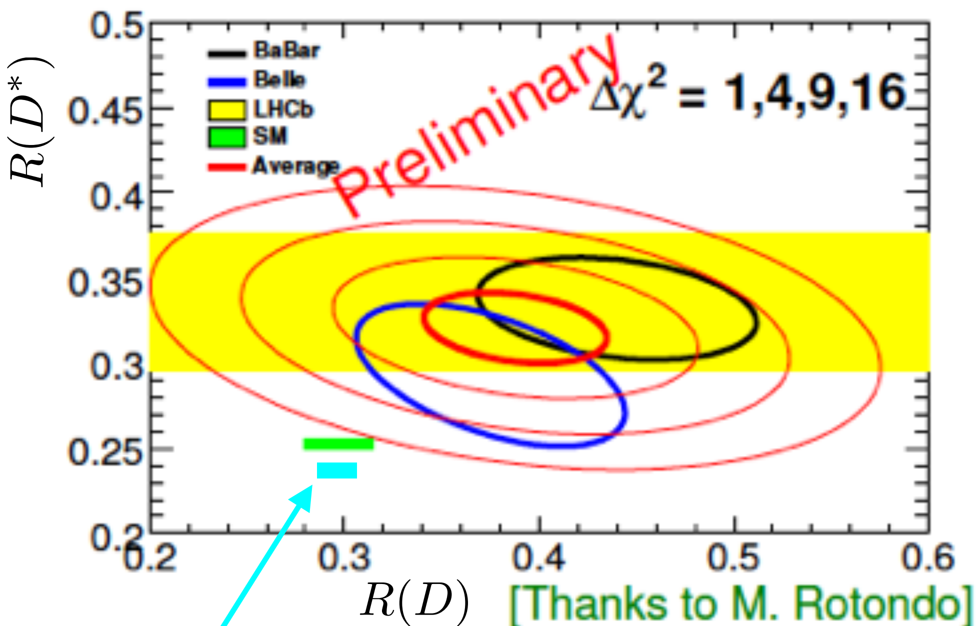
FIG. 8. Theoretical predictions with $1\,\sigma$ error ranges for R (red) and R^* (blue) for different values of tan β/m_{H^+} in the 2HDM of type II. This analysis' fit results for tan $\beta/m_{H^+} = 0.5\,c^2/\text{GeV}$ and SM are shown with their $1\,\sigma$ ranges as red and blue bars with arbitrary width for better visibility.

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

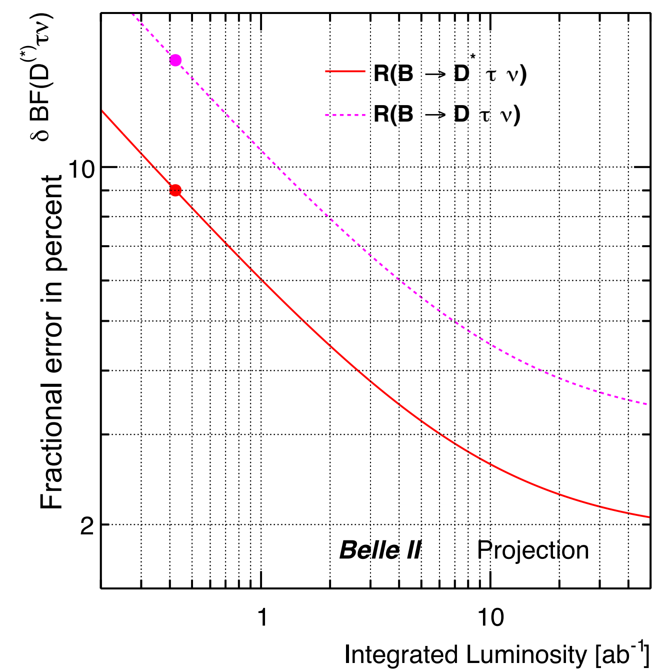
	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375^{+0.064}_{-0.063} \pm 0.026$	$0.293^{+0.039}_{-0.037} \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Average	0.388 ± 0.047	0.321 ± 0.021
SM expectation	$0.300 \pm \cancel{0.010} \rightarrow 0.016$	$0.252 \pm \cancel{0.005} \rightarrow 0.003$
Belle II, 50/ab	± 0.010	± 0.005

TABLE XX: Extrapolation of the Babar $B \to D^* \tau\nu$ result with a SM hypothesis. Errors are given in percent.

	Statistical	Systematic (reducible, irreducible)	Total Exp
$R(D)$			
423 fb^{-1}	13.1	(9.1, 3.1)	16.2
5 ab^{-1}	3.8	(2.6, 3.1)	5.6
50 ab^{-1}	1.2	(0.8, 3.1)	3.4
$R(D^*)$			
423 fb^{-1}	7.1	(5.2, 1.9)	9.0
5 ab^{-1}	2.1	(1.5, 1.9)	3.2
50 ab^{-1}	0.7	(0.5, 1.9)	2.1



The ultimate Belle II error bars will look like

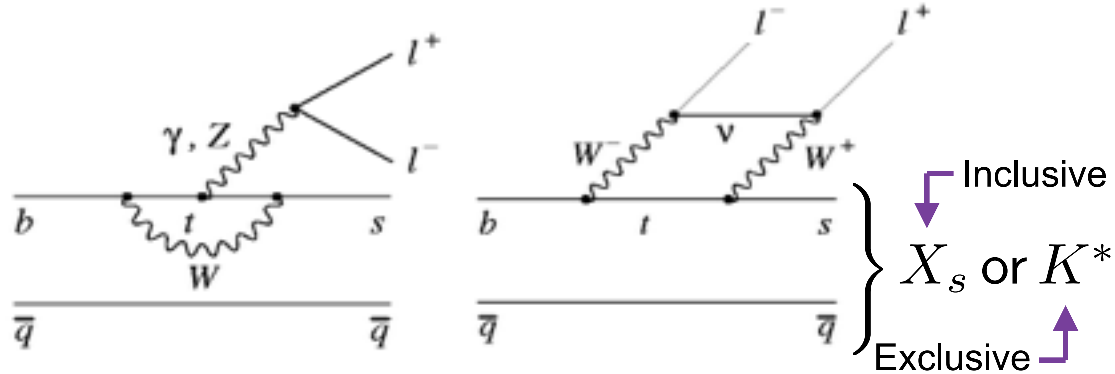


$B \to X_s \ell^+ \ell^-$

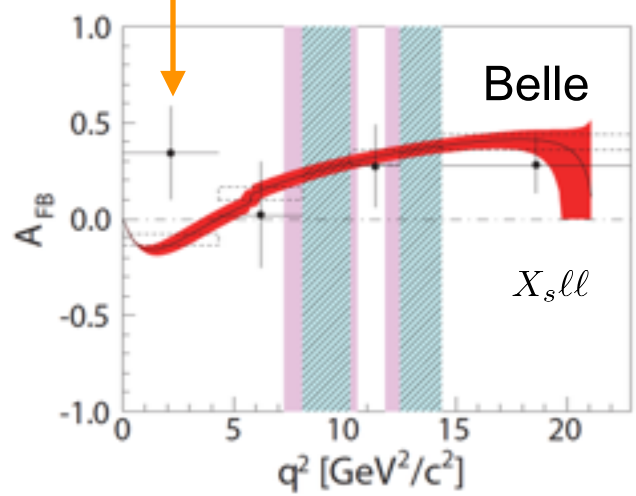
For $B \to K^* \ell^+ \ell^-$ one considers a veritable zoo of observables, for $B \to X_s \ell^+ \ell^-$ not so many.

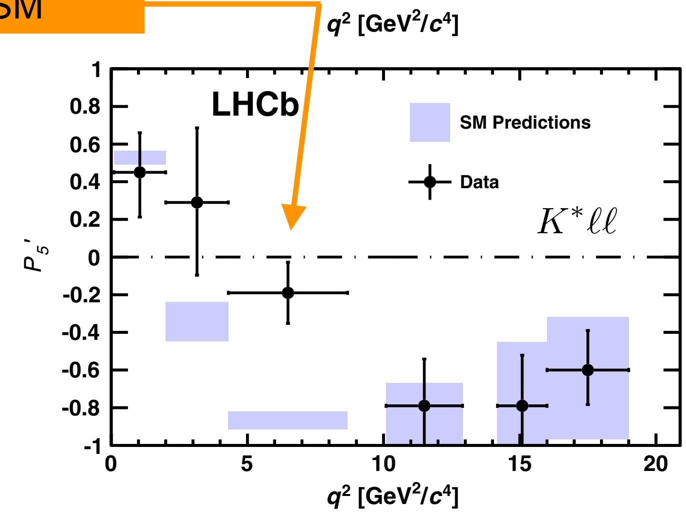
Observable	LHCb $K^*\ell\ell$	BaBar $X_s\ell\ell$	Belle $X_s\ell\ell$	Belle II projection $X_s\ell\ell$
$d\Gamma/dq^2$	✓	✓		✓
A_{FB}	✓	✓	✓	✓
q_0^2	✓			✓
F_{L}	✓	✓		
S_3	✓			
S_3	✓			
$S_4,\ P_4'$	✓			
$S_5,\ P_5'$	✓			
P_6'	✓			
S_7	✓			
$S_8,\ P_8'$	✓			
S_9	✓			
A_9	✓			
A_{T}^2	✓			
$A_{\mathrm{T}}^{\mathrm{Re}}$	✓			
A_{CP}		✓		

$q^2 \equiv M(\ell^+\ell^-)$

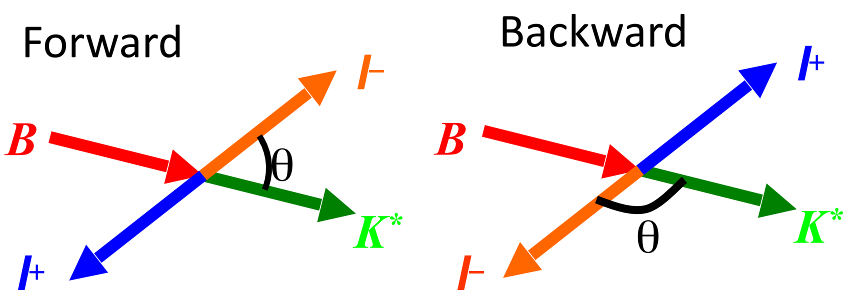


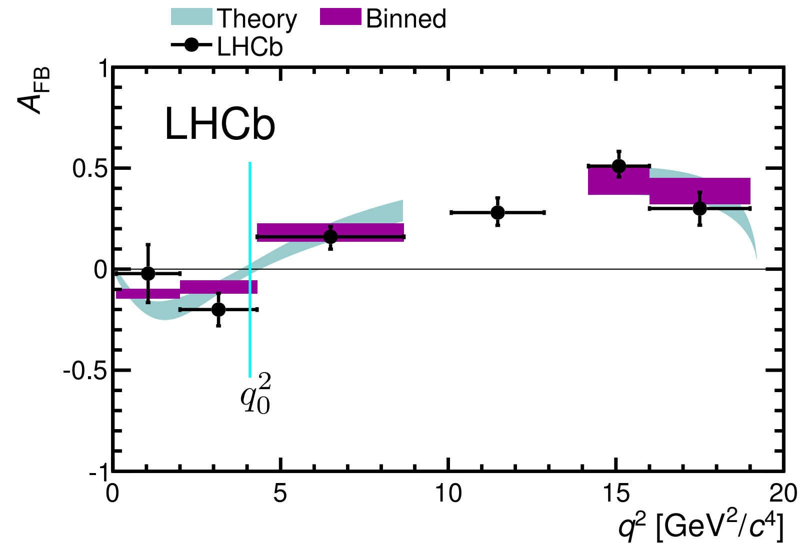
Slight tension with SM





$B \to X_s \ell^+ \ell^-$





The SM forward-backward asymmetry in $B \to s\, \ell^+ \ell^-$ arises from the **interference** between γ and Z^0 contributions.

$$A_{FB}(B \to K^* \ell^+ \ell^-) = -C_{10}\xi(q^2)\left[Re(C_9)F_1 + \frac{1}{q^2}C_7 F_2\right] \qquad q^2 \equiv M(\ell^+ \ell^-)$$

Ali, Mannel, Morozumi, PLB273, 505 (1991)

Belle II projections:

TABLE XXXIX: Expected relative uncertainties on C_7/C_9 ratio from $B \to X_s \ell^+ \ell^-$ measurement. No theoretical uncertainties are included.

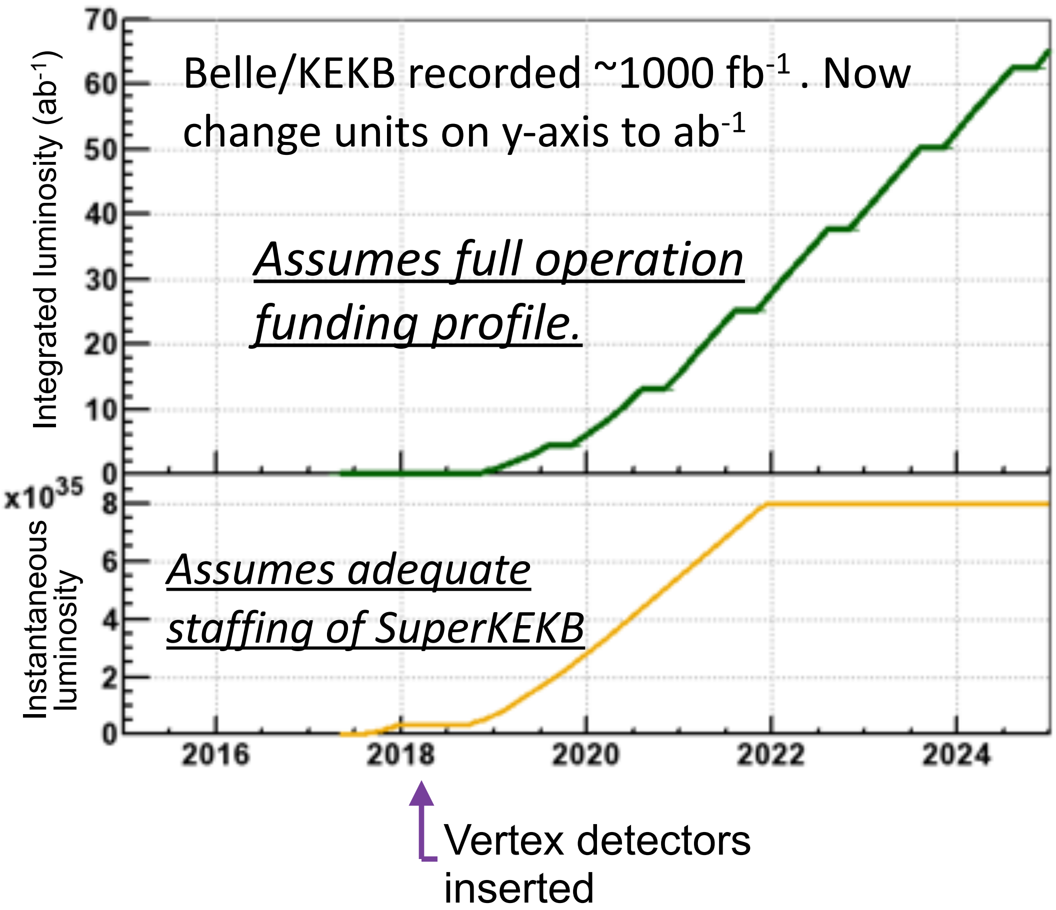
Observable	0.7 ab^{-1}	5 ab^{-1}	50 ab^{-1}
q_0^2	80%	30%	10%
$d\Gamma/dq^2$	20%	10%	9%
Combined	19%	9%	6%

N.B. The percentages apply to C_7/C_9, not to the observable.

Regrettably in this case, there is no easy opportunity for a graphical comparison of the future with the present.

Schedule

- Beam commissioning starts in Jan 2016.
- Installation of sub-detectors in Belle II will begin in earnest in spring 2016 and will be completed before the end of 2016.
- Commissioning with cosmic rays will continue to the end of 2017.
- Belle II to roll onto the beam line in spring of 2017.
- During 2016 and 2017 the Commissioning Detector will assist with beam commissioning.



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