Physics Prospects at Belle II

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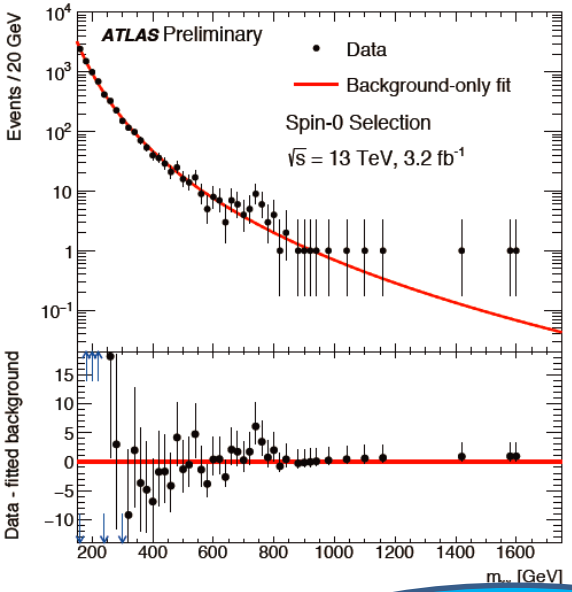
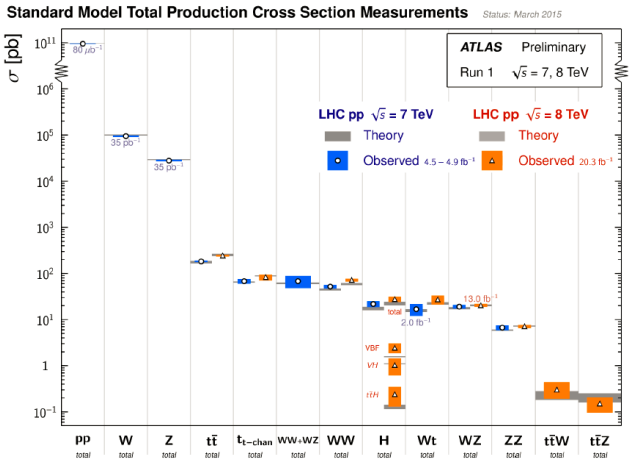
PASCOS 2016: 22nd International Symposium on Particles, Strings and Cosmology at Quy Nhon, Vietnam

Flavor Physics

Diphoton excess at LHC?



SM cross sections consistent with theory

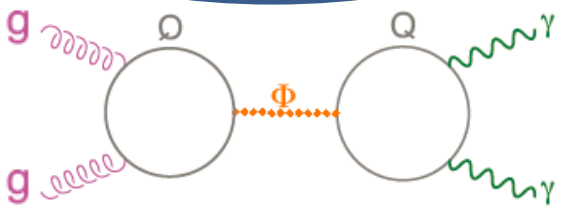


LHC finds new physics(NP)?

Yes

No

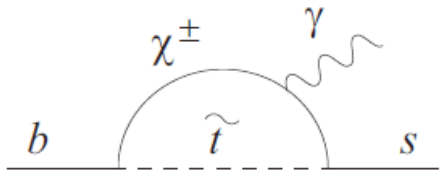
Determination of flavor structure in NP



Scalar Particle and Multiple Vector Like Quarks which mix with SM quarks?

Constraint from B(Z→bb)?

Search for NP with precise measurements and forbidden processes

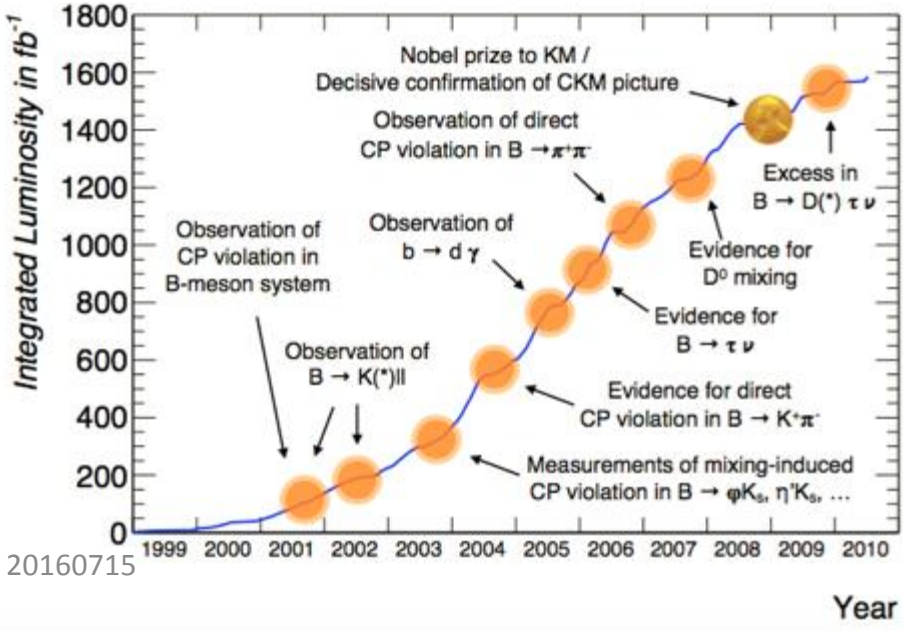


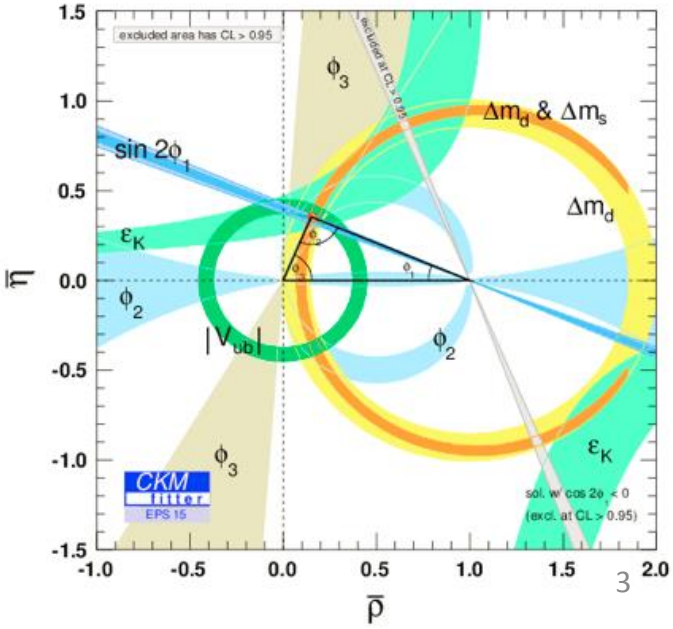
New particles in the loop or tree.

Either cases, flavor physics is crucial for NP.

Success of B factories

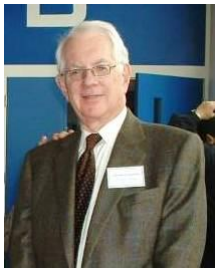
- Belle@KEKB and Babar@PEPII
  - Integrated luminosity : >1ab^{-1} by Belle and ~550fb^{-1} by Babar
- Observation of CPV in B meson system and confirmation of CKM picture.
  - But still room for NP





Anomalies in B Decays

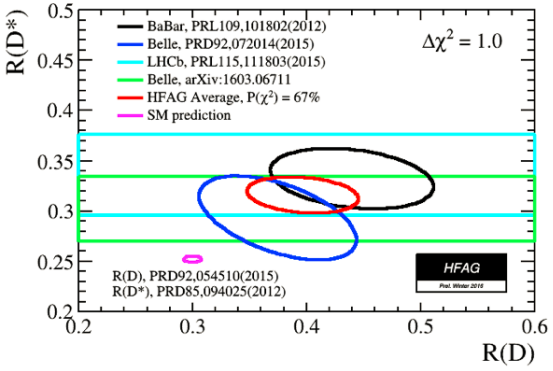
- ~3σ anomalies at Belle/Babar/LHCb
  - Ratio of $B \to D^{(*)}\tau\nu$ to $B \to D^{(*)}l\nu$
  - R_K : Ratio of $B \to K\mu\mu$ to $B \to Kee$
  - Angular distribution of $B \to K^*ll$: P5'
  - $|V_{ub}|$ from inclusive and exclusive decays
  - Etc.
- The hints should be tested at new experiments



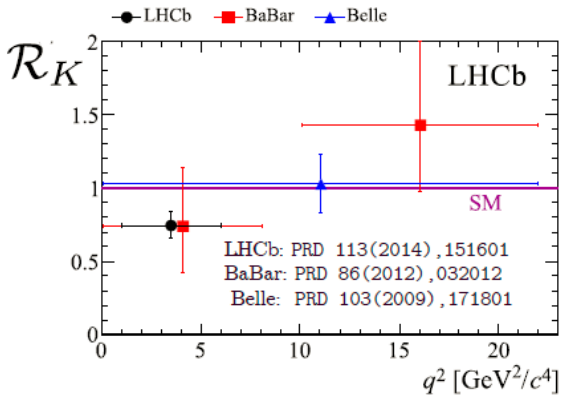
Lepton Flavor Violation in B decays?

S. L. Glashow et al. PRL 114 091801 (2015)

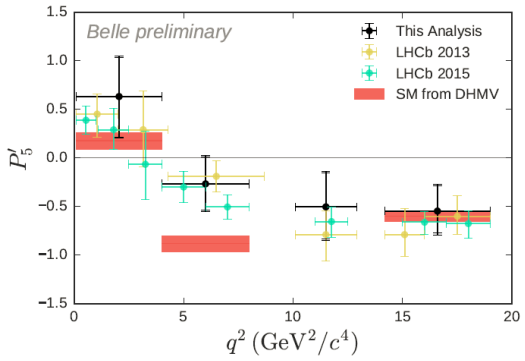
$B \to D^{(*)}\tau\nu$



$B \to K\mu\mu / B \to Kee$



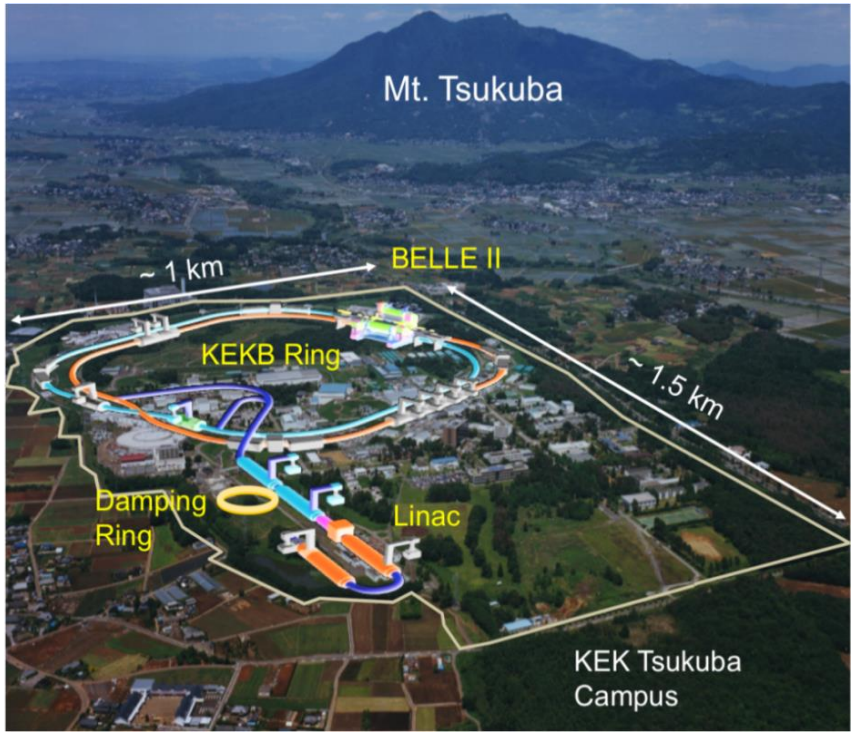
Angular analysis of $B \to K^*ll$



SuperKEKB and Belle II

Search for new physics with 100 billion B, charm and τ decays

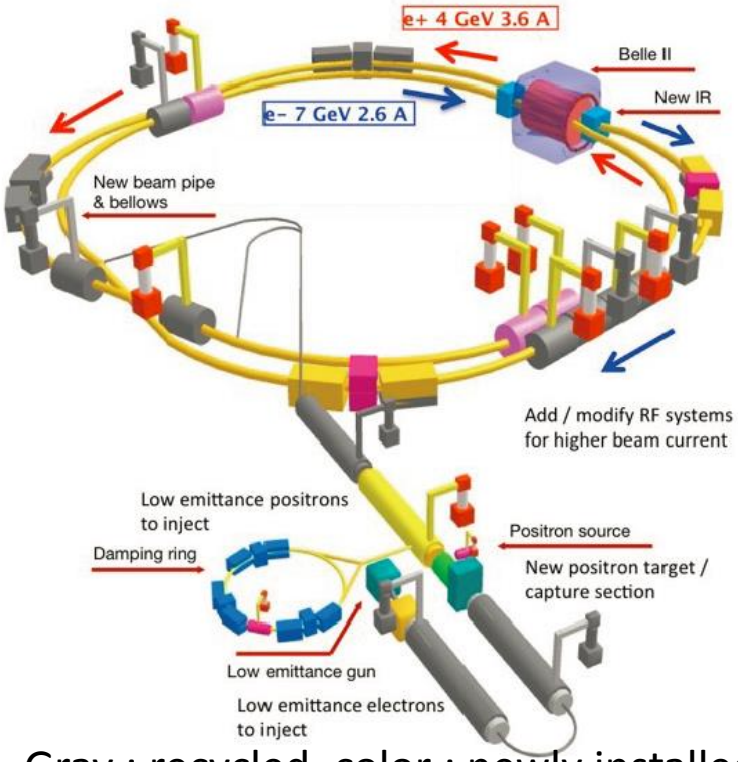
Super flavor factory !



New accelerator after LHC

SuperKEKB

- Upgraded from KEKB
  - Which is the world highest luminosity machine.
- Design Luminosity : 8×10^{35} $cm^{-2}s^{-1}$
  - 40 times larger than KEKB
    - 20 times smaller beam size
    - 2 times larger beam current
- Asymmetric energy : 7GeV(e^-) x 4GeV(e^+)
  - Boost factor smaller to reduce beam background

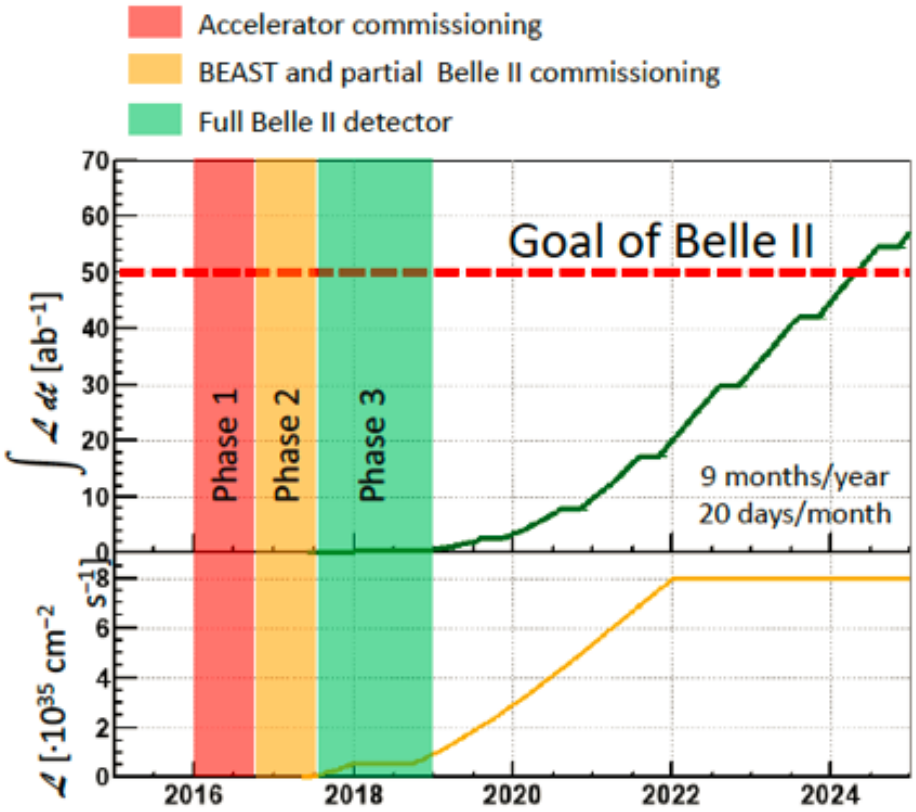


Gray : recycled, color : newly installed

Parameter		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
beam energy	E_b	3.5	8	4	7	GeV
CM boost	β_y	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	129	90	0.881	0.0807	
beam size at IP	σ_x^*/σ_y^*	100/2		10/0.059		μm
Luminosity	$\mathcal{L}$	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

Schedule of SuperKEKB

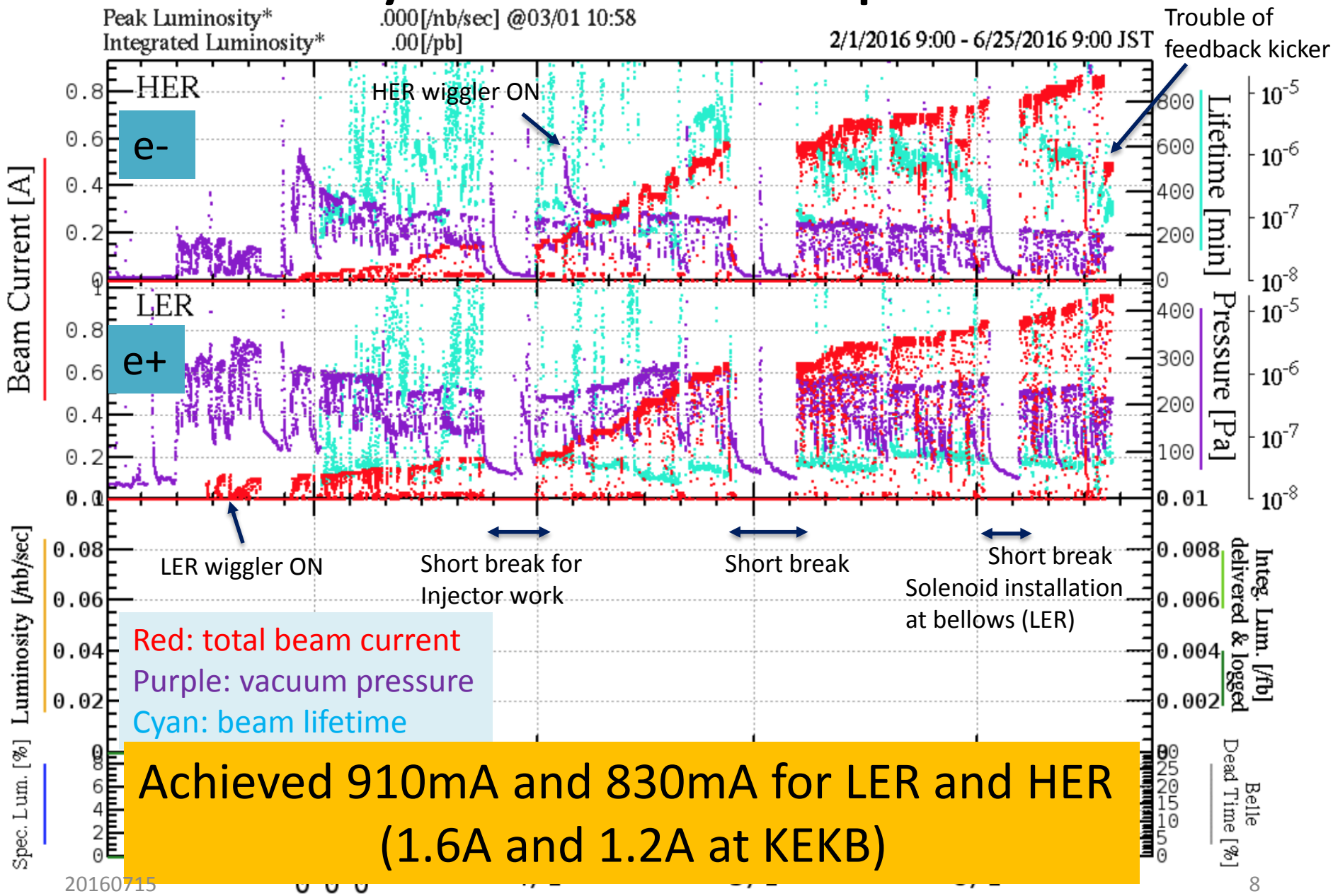
- Phase 1 : beam commissioning
  - Successfully finished on 28th Jun 2016
- Phase 2 : beam commissioning and physics run with Belle II w/o VTX
  - On Y(4S) and Y(6S)
- Phase 3 : Luminosity tuning and physics run with full Belle II detector



Accumulate 50ab^{-1} by 2024

Y. Funakoshi from SuperKEKB

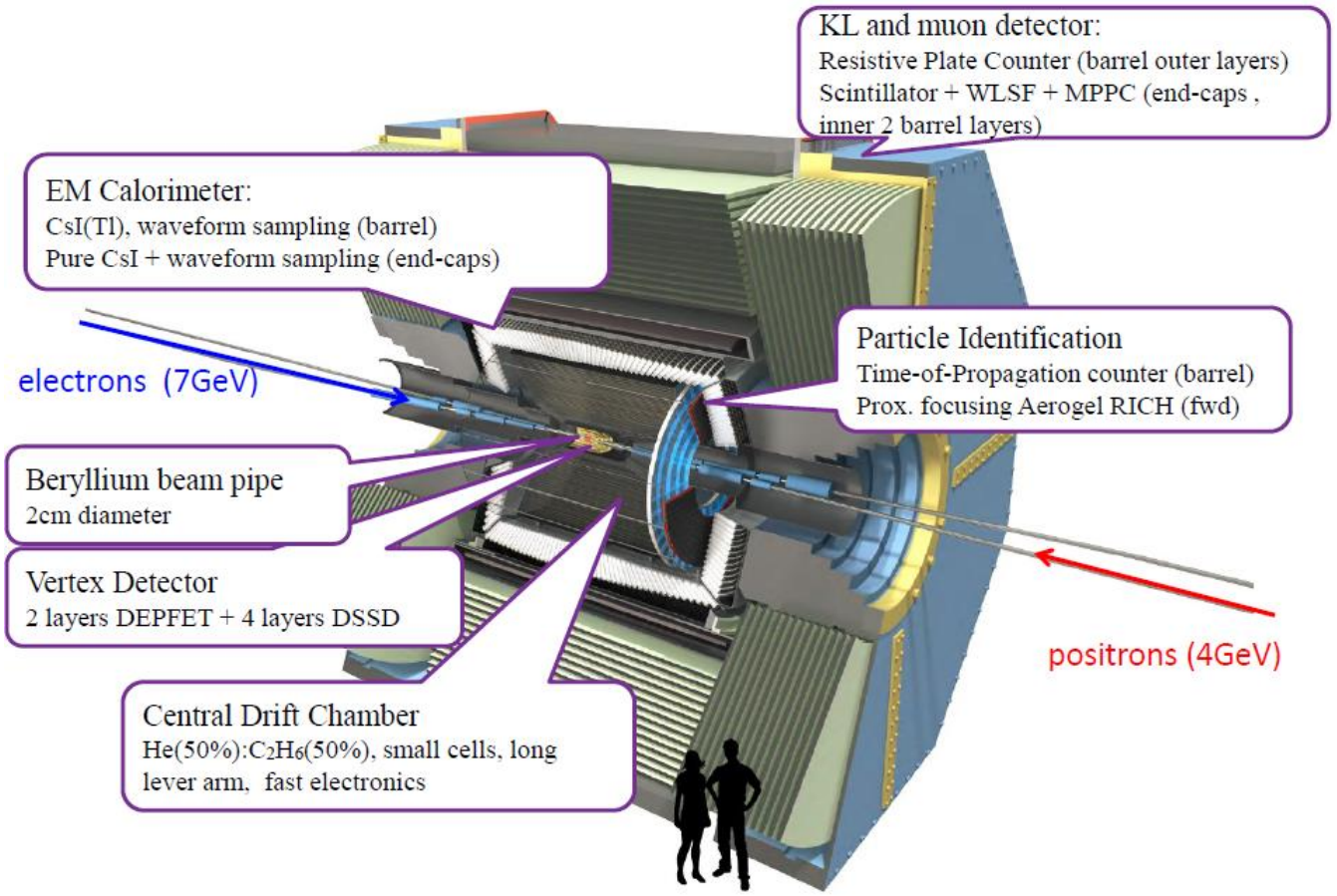
History of Phase 1 Operation



Achieved 910mA and 830mA for LER and HER (1.6A and 1.2A at KEKB)

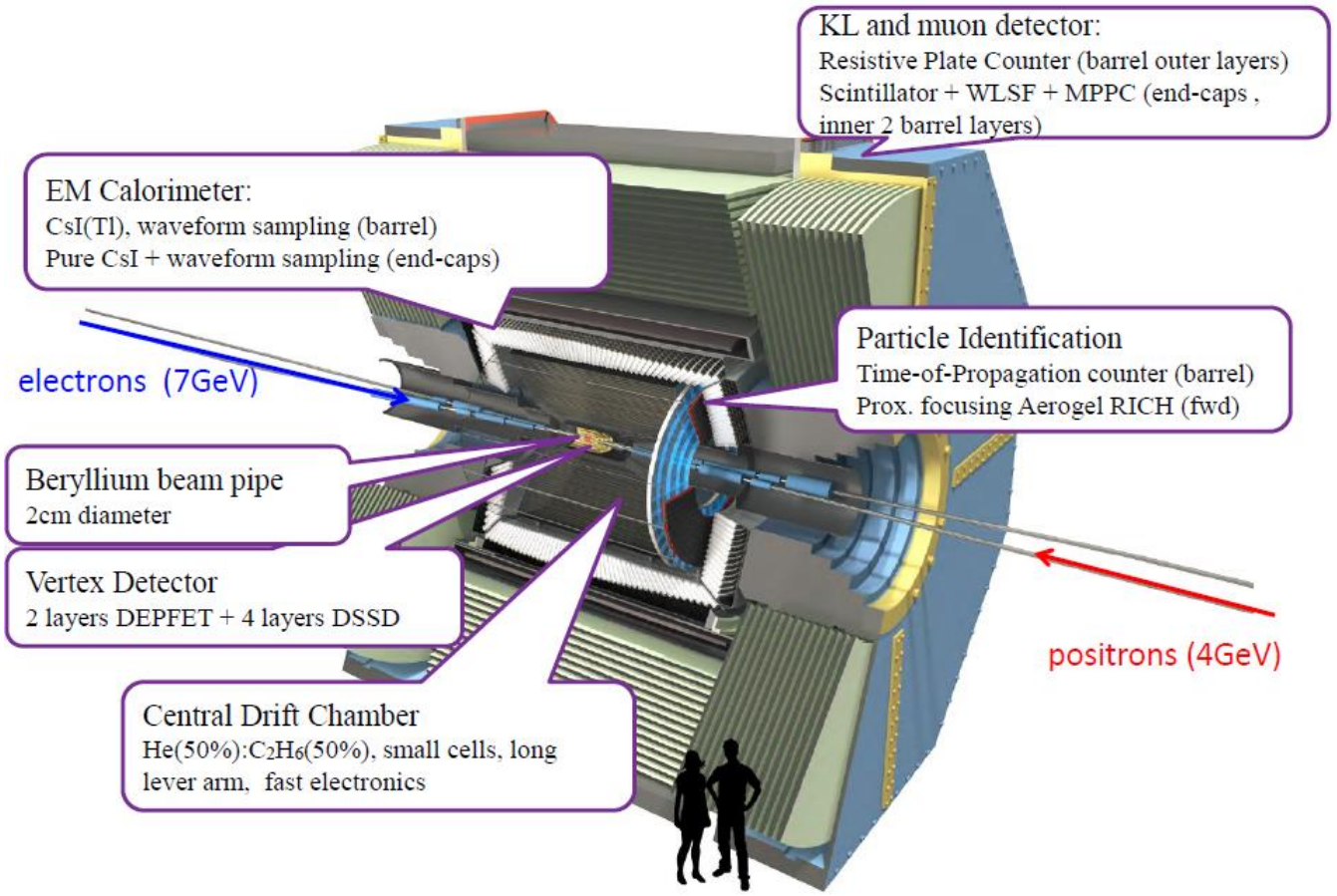
Belle II

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



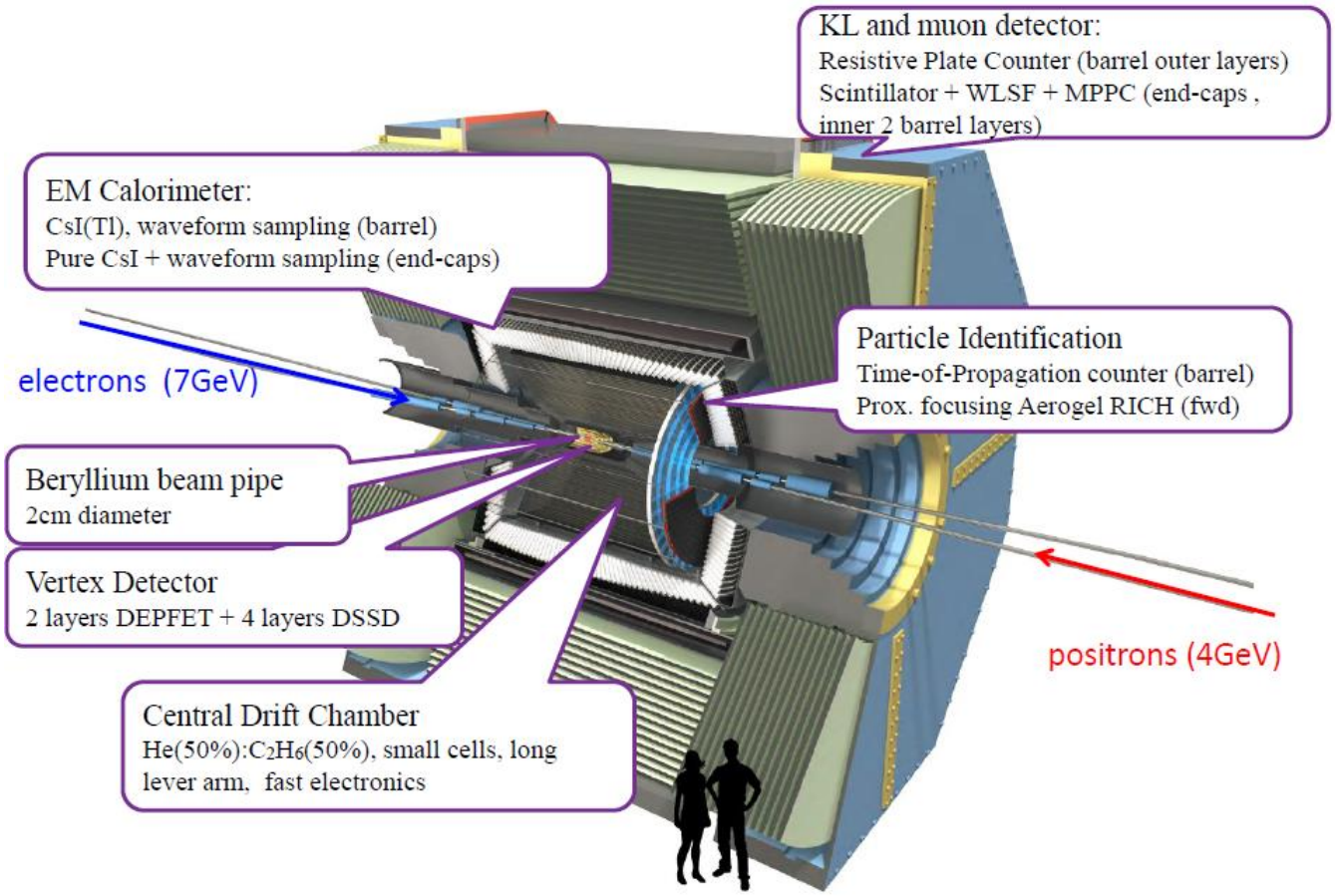
Belle II

- Similar or better performance than Belle even under 20 times higher backgrounds
  - Larger VTX detector → Better Ks efficiency for TDCPV in B→Ks$\pi^0\gamma$
  - TOP and ARICH provide better K/π separation : B→$\pi\pi$, B→DK, B→$\rho^0\gamma$



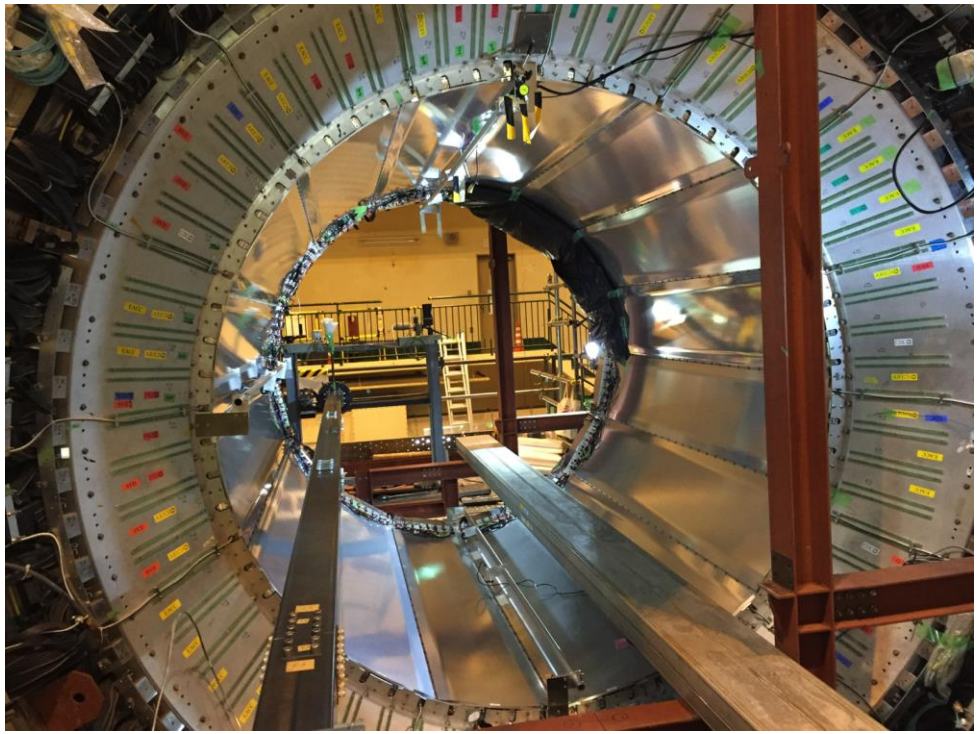
Belle II

- Almost all B decay events are saved to tape
  - Even invisible B can be searched.

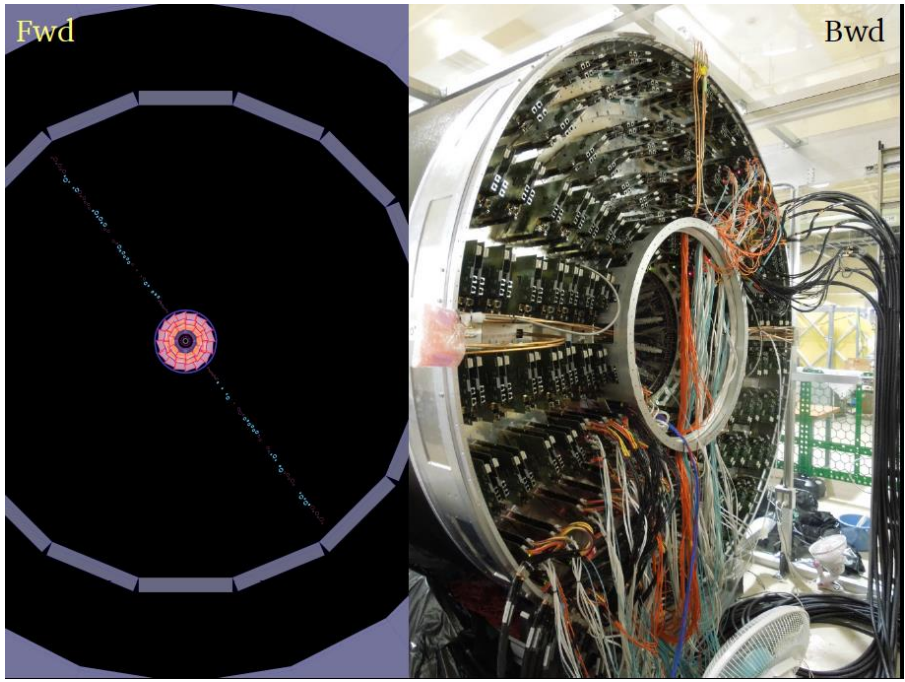


Status of Belle II Detector

- 20 May 2016 : TOP detector installed
- Now : mapping of magnetic field on-going
- Aug 2016 : CDC installation → ready for Phase2



TOP Modules now form a self-supporting "Roman Arch"



CDC cosmic ray test

Physics at Belle II

- There are so wide physics program at Belle II
  - Flavor physics
    - Including hadronic vacuum polarization for muon g-2
  - Direct searches of NP
    - Dark Photon/Higgs etc.
  - Electroweak measurements
  - Exotic hadron and hadron spectroscopy

- In this talk, focusing on NP search with flavor observables
  - $\Delta B=2$ loop process : B^0-$\overline{B}^0$ mixing
  - $\Delta B=1$ loop processes : Penguin B decays
  - B decays involving τ
  - Charm and τ decays

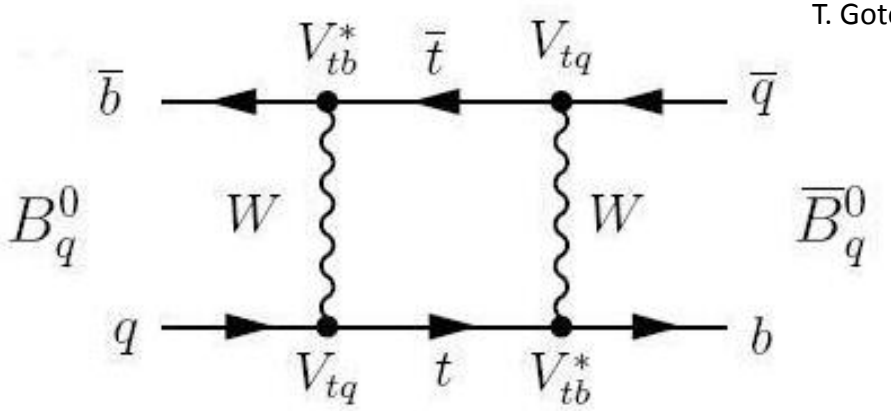
$\Delta B=2$ loop process : B^0-$\overline{B}^0$ mixing

B^0-$\overline{B}^0$ Mixing

- B^0-$\overline{B}^0$ mixing is allowed at loop diagram in the SM.
  - Loop is dominated by top quark and W
- New particles, such as SUSY particles or charged Higgs, can enter in the loop
- Two approaches to search for NP with B^0-B^0 mixing (assuming no NP in other tree level processes)
  - Unitarity Triangle
  - NP amplitude and phase (h and σ)

$$M_{12}^{d,s} = (M_{12}^{d,s})_{\mathrm{SM}} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

T. Goto et al, Phys.Rev. D53 (1996) 6662-6665

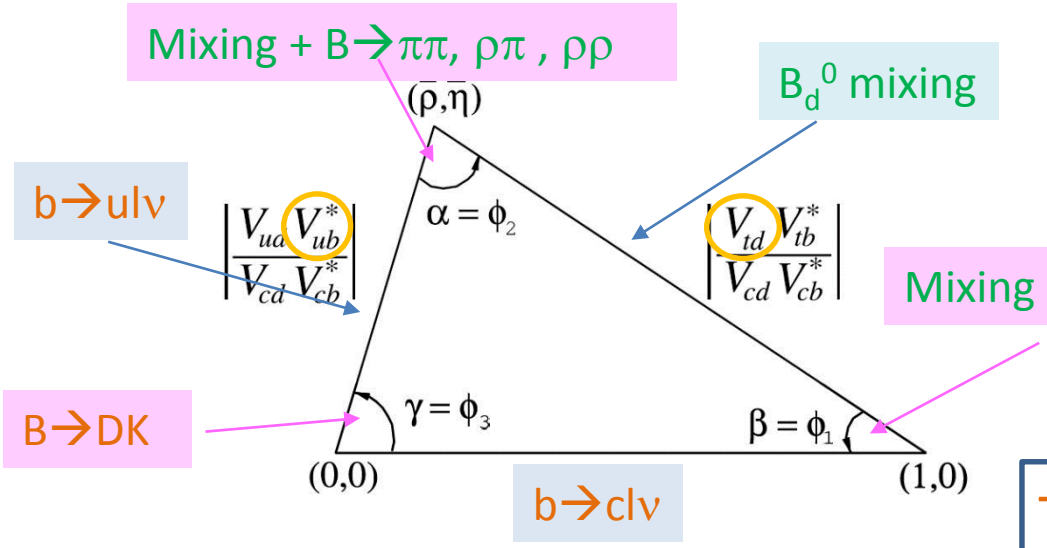


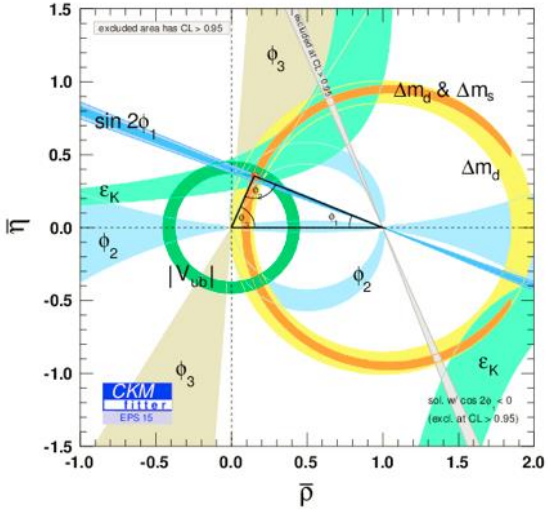
Unitarity Triangle

- To search for the NP in mixing, we use so called Unitarity Triangle (UT)
- From the Unitarity of CKM matrix, triangle can be drawn onto complex plain.

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- If UT drawn with tree measurements is not consistent with the one with mixing loop measurements, observation of NP in the mixing
  - All the angles and sides can be measured at Belle II





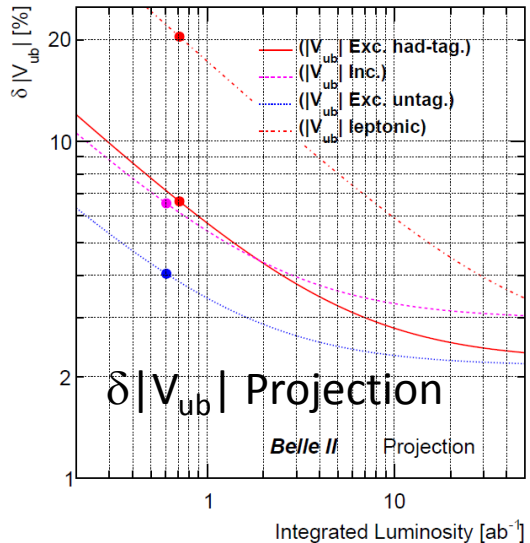
Tree Loop side angle phase

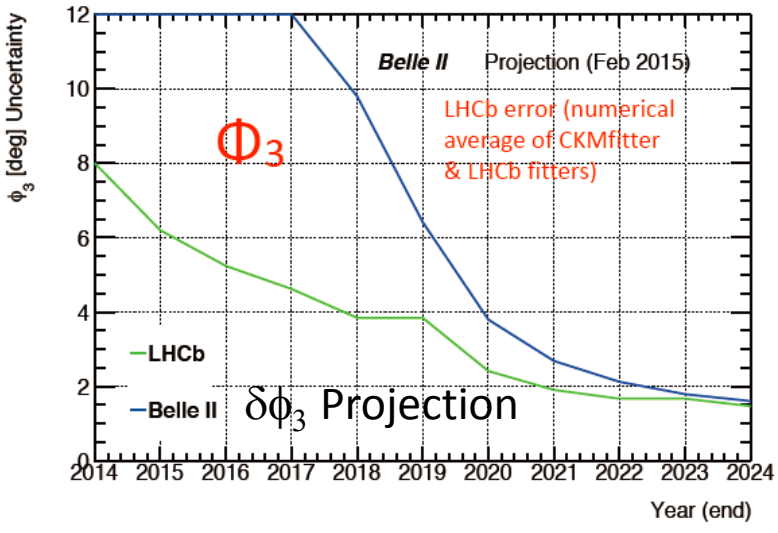
$$\bar{\rho} = \rho(1-\lambda^2/2), \quad \bar{\eta} = \eta(1-\lambda^2/2)$$

Sensitivities of UT Observables

- Loop processes (ϕ_1, ϕ_2) are better precision than tree
  - |Vtd| from Δm_d is not shown since this is already dominated by Lattice QCD uncertainty
- Improvement of tree processes (ϕ_3, $|V_{ub}|$) are crucial at Belle II

		Observables	Belle (2014,	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
UT angles	$\beta = \phi_1$	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012 (1.4°)$	0.7°	0.4°
	$\alpha = \phi_2$	α [°]	85 ± 4 (Belle+BaBar)	2	1
	$\gamma = \phi_3$	γ [°] ($B \to D^{(*)}K^{(*)}$)	68 ± 14	6	1.5
UT sides		$\lvert V_{cb}\rvert$ incl.	$41.6 \cdot 10^{-3}(1 \pm 2.4\%)$	1.2%	
		$\lvert V_{cb}\rvert$ excl.	$37.5 \cdot 10^{-3}(1 \pm 3.0\%_{\text{ex.}} \pm 2.7\%_{\text{th.}})$	1.8%	1.4%
		$\lvert V_{ub}\rvert$ incl.	$4.47 \cdot 10^{-3}(1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$	3.4%	3.0%
		$\lvert V_{ub}\rvert$ excl. (had. tag.)	$3.52 \cdot 10^{-3}(1 \pm 10.8\%)$	4.7%	2.4%

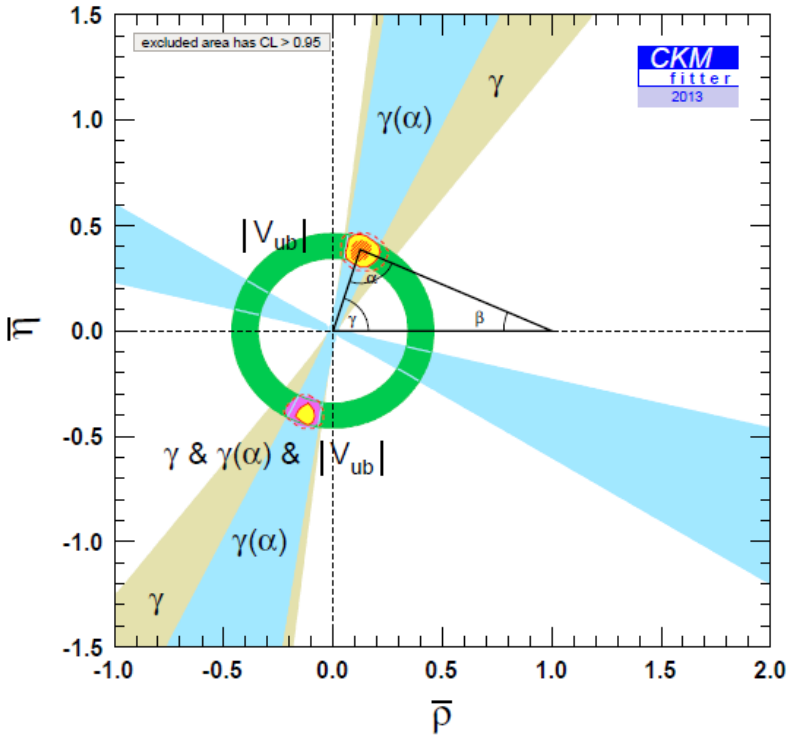




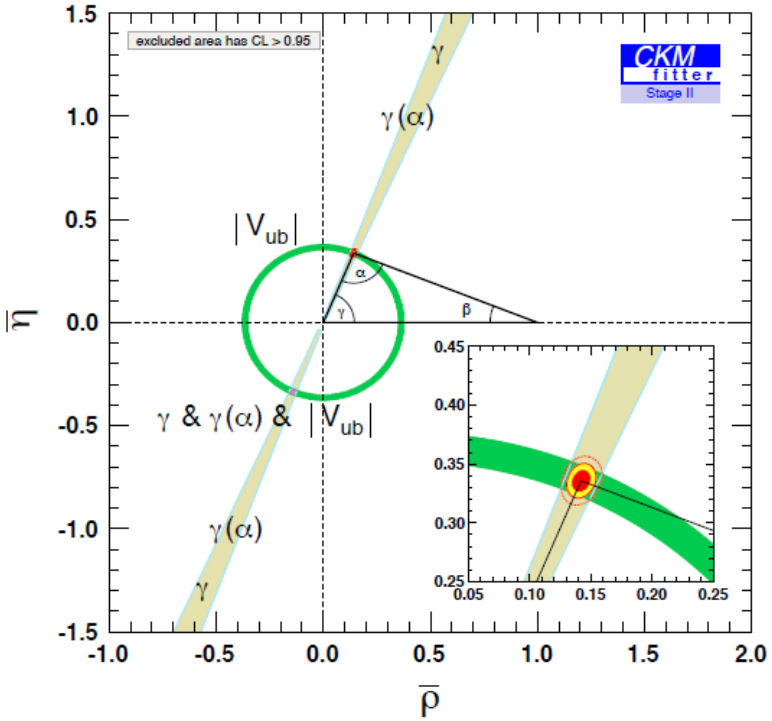
UT (ϕ_3 and |Vub| only)

- $|V_{ub}|$ and ϕ_3 can be improved by factors of 3 and 8, respectively.

2013



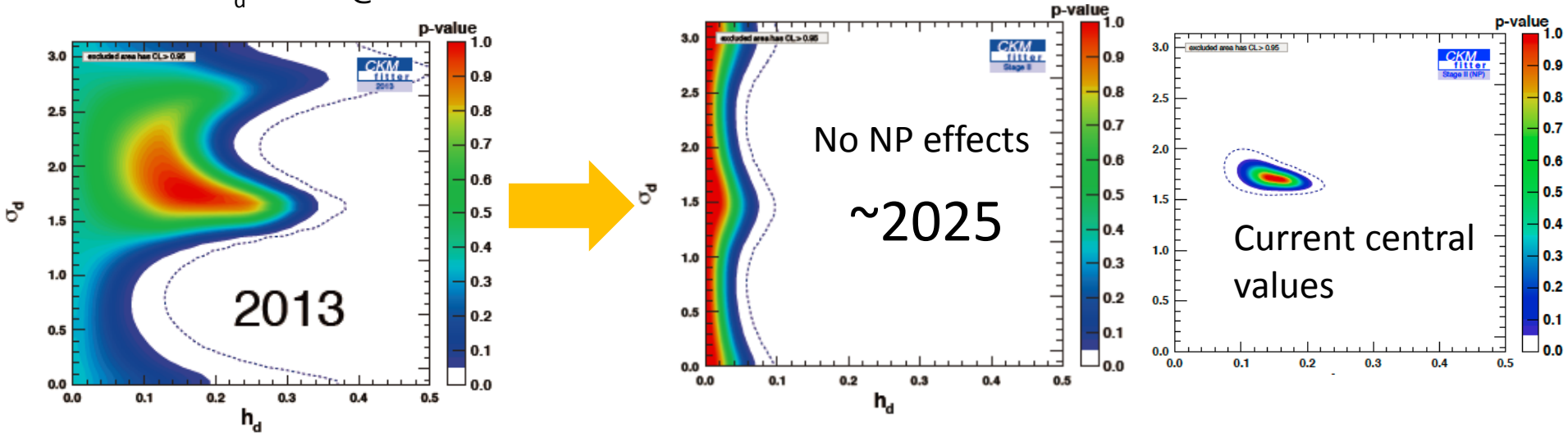
~2025 No NP effects



CKM fitter PRD 89, 033016 (2014)

NP Amplitude in B^0-$\overline{B}^0$ Mixing

- ϕ_1, ϕ_2, Δm_d, a^{SL}_d ➡ $M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$
- Assuming no NP in Tree
- O(0.1) NP can be excluded or observed by Belle II
  - $h_d < 0.07$ @95%CL



$$\frac{C_{ij}^2}{\Lambda^2}\left(\bar{q}_{i,L}\gamma^\mu q_{j,L}\right)^2$$

$$h \simeq 1.5\,\frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2}\,\frac{(4\pi)^2}{G_F\Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2}\left(\frac{4.5\,\text{TeV}}{\Lambda}\right)^2$$

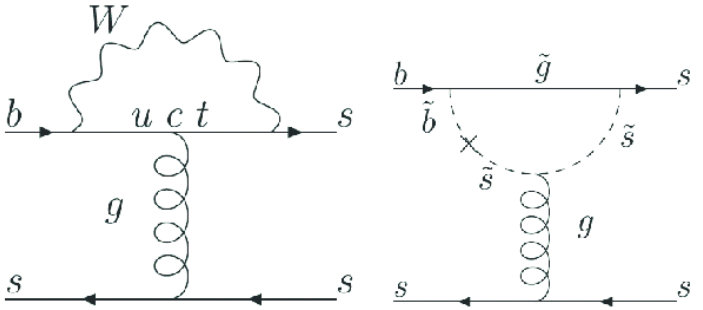
$$\sigma = \arg\left(C_{ij}\,\lambda_{ij}^{t*}\right),$$

C_{ij} > 20TeV (2PeV) for tree level NP
C_{ij} > 2 TeV (0.2PeV) for loop level NP
assuming λ_{ij} is CKM like (unity)

ΔB=1 loop processes : Penguin Decays

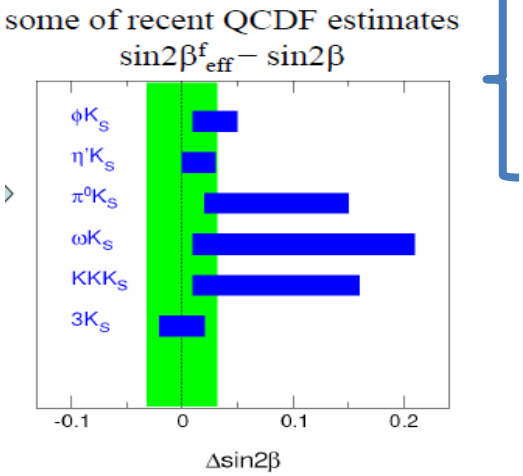
Time dependent CPV in b→sq$\bar{q}$ decays

- b→s QCD penguin
  - In the SM, the CPV parameter $\sin2\phi_1^{eff}$ should be consistent with $\sin2\phi_1$ with B→J/ψK^0
  - New source of CPV phases if new particles enter in the loop
  - If deviated from $\sin2\phi_1$, observation of NP

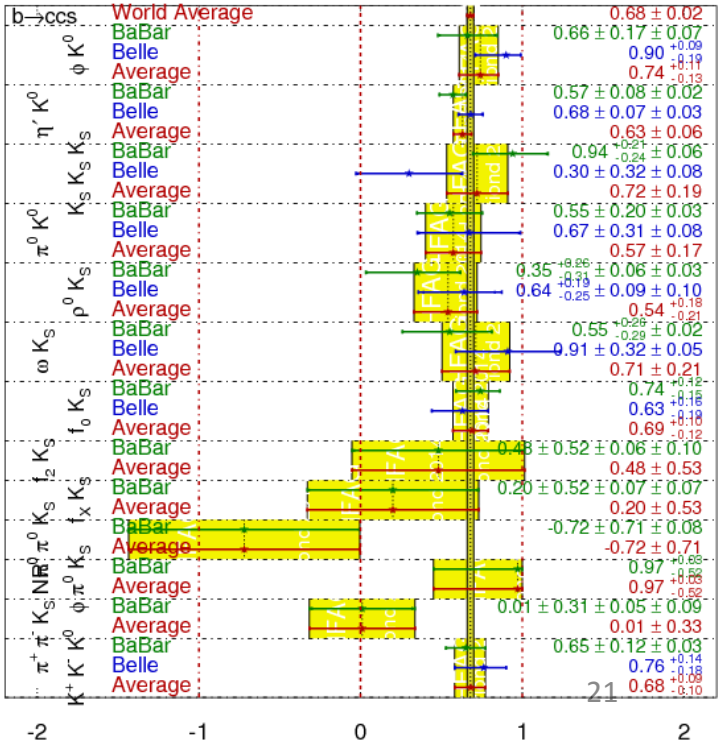


$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$ HFAG Moriond 2014 PRELIMINARY

- Decay modes
  - B→φKs
  - B→η'Ks
  - B→KsKsKs
  - ~2% theoretical error



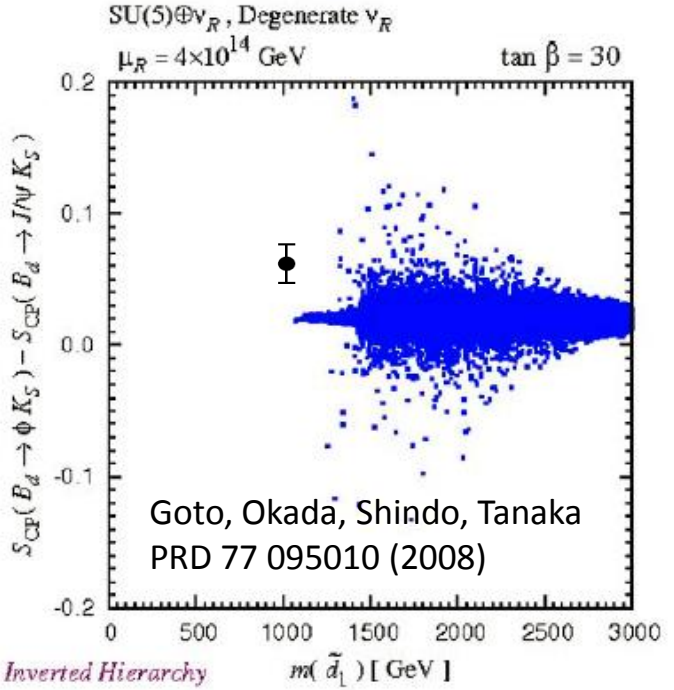
- Current measurements are consistent with B→J/ψK^0 with large errors



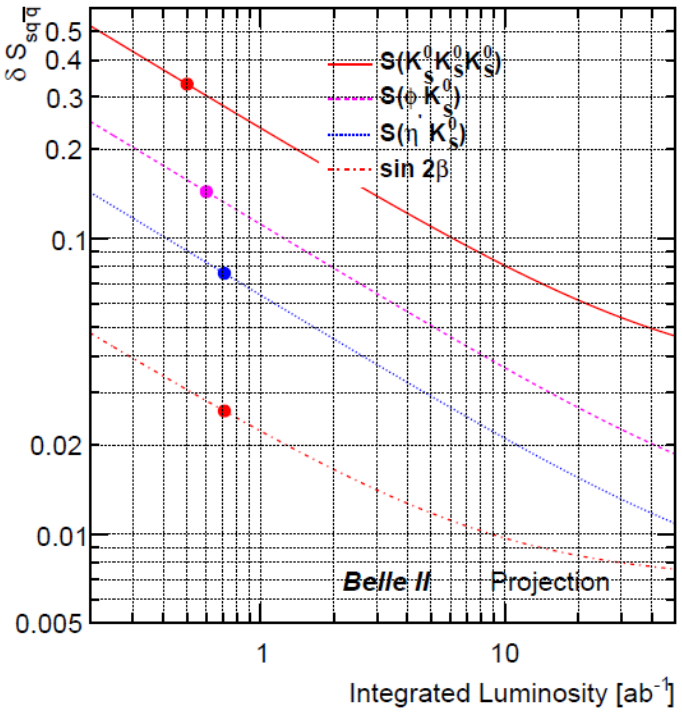
TDCPV in b→sq$\bar{q}$

- The error is close to theoretical uncertainty of 0.02

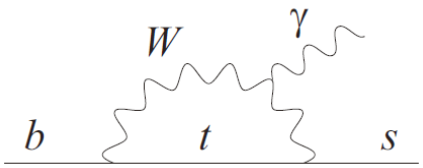
Mode	5 ab^{-1}		50 ab^{-1}	
	$\sigma(\mathcal{S})$	$\sigma(\mathcal{A})$	$\sigma(\mathcal{S})$	$\sigma(\mathcal{A})$
$\eta' K^0$	0.028	0.020	0.011	0.009
ϕK^0_S	0.053	0.070	0.018	0.023
$K_S K_S K_S$	0.101	0.064	0.033	0.021



- Strong constraints to NP models
  - SU(5) SUSY GUT + degenerate ν_R with inverted hierarchy



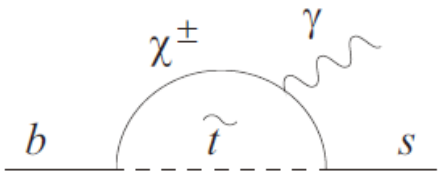
TDCPV in $B^0 \rightarrow K_s \pi^0 \gamma$

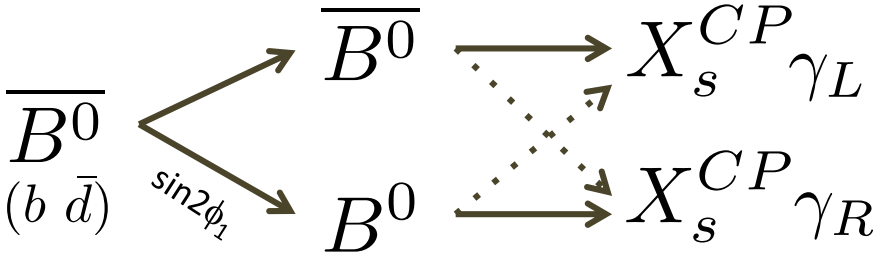


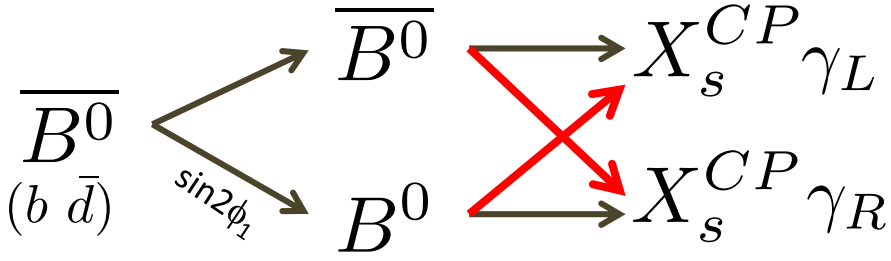
- Sensitive to Right handed current
- In the SM, photon is predominantly left handed
  - Almost No TDCPV

$$|S_{CP}| \approx \frac{2m_s}{m_b} \sin 2\phi_1 \quad \sim \text{a few \%}$$

- New physics with right handed current increases the fraction of right handed photon
  - Interfere with the SM occurs and large TDCPV possible







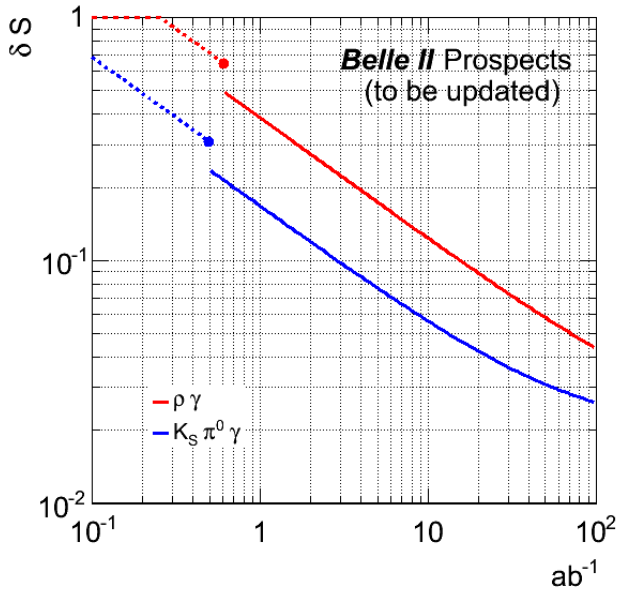
dotted : helicity flip

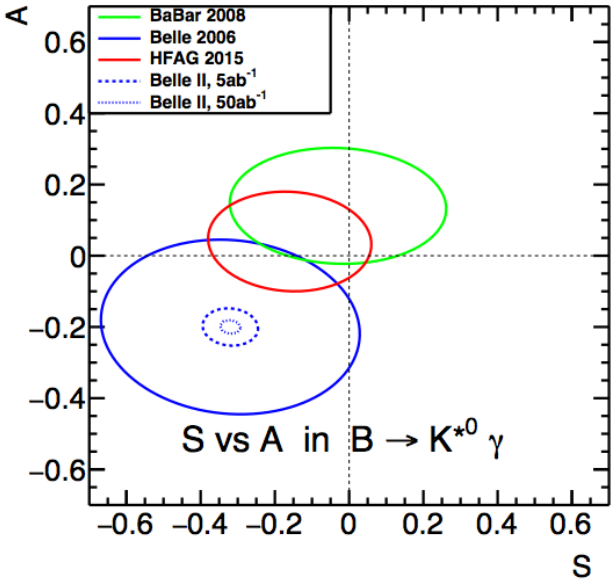
red : helicity flip + NP

TCPV in $B^0 \rightarrow K_s \pi^0 \gamma$ at Belle II

- Almost same error as theory one ~0.03
- Strong constraint on NP
  - SU(5) SUSY GUT + degenerate ν_R with inverted hierychy

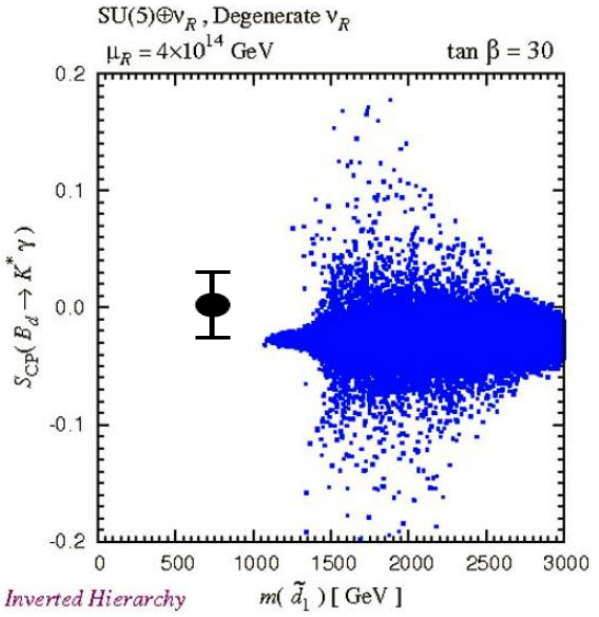
Mode	5 ab^{-1}	50 ab^{-1}
$K_S\pi^0\gamma$	0.11	0.03
$\rho^0\gamma$	0.23	0.06





16σ deviation with 50ab^{-1}

Theoretical uncertainty in progress



Goto, Okada, Shindo, Tanaka
PRD 77 095010 (2008)

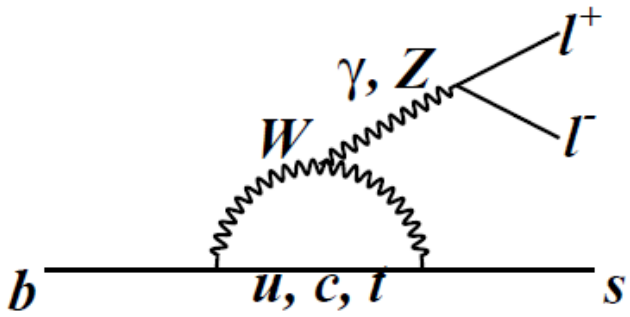
Ratio of B→Kμμ and Kee

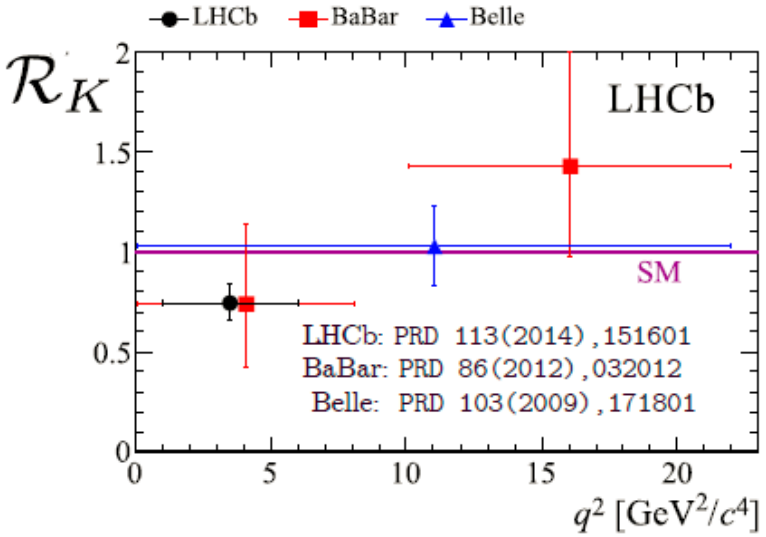
- B→Kll proceeds via one loop diagram.
  - Lepton flavor universality holds in the SM.
- LHCb reported 2.6s deviation of ratio of BFs from unity.

$$R_K = \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to Kee)}$$

$$\mathcal{R}_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

  - However electron mode is not so easy at LHCb, especially for high q^2
- Belle II
  - Electron and muon modes are same efficiency
  - Both Low and high q^2 possible
  - All K, K* and Xs modes possible





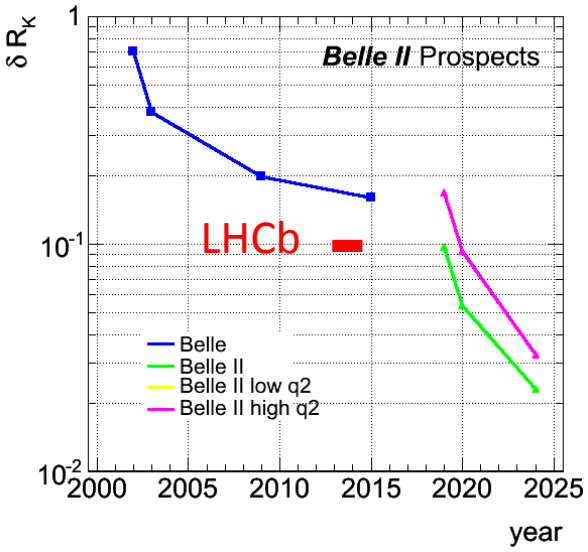
Phys. Rev. Lett. 113, 151601 (2014)

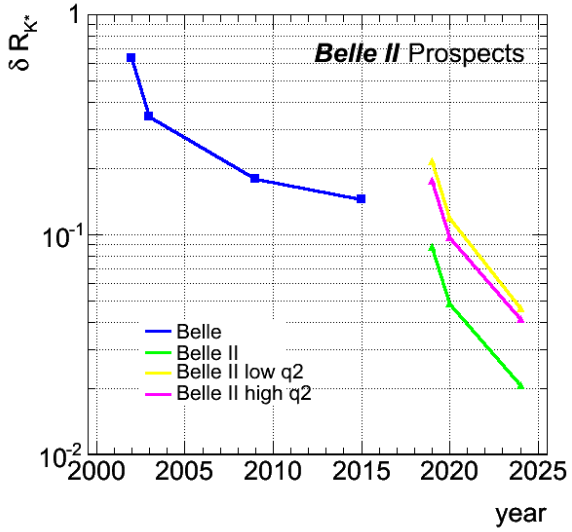
R_K, R_{K^*} and R_{Xs}

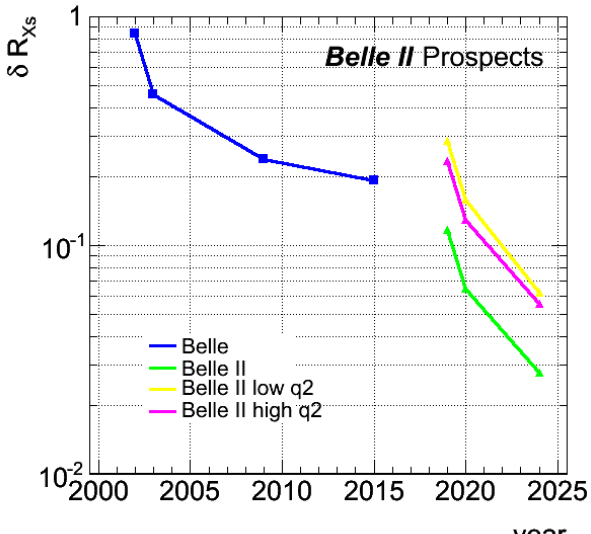
- LHCb 2014

$$\mathcal{R}_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

- Belle II
  - The errors reach to 0.02 for all K, K* and Xs modes
  - Still dominated by statistical error
- Test of LFV in one loop B decays

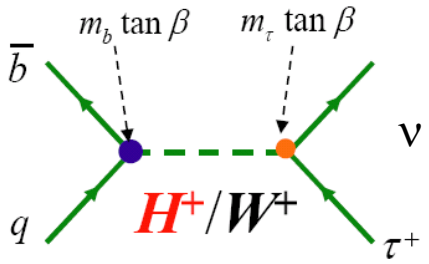






B decays involving τ

B→τν and B→D(*)τν



- B→τν
  - SM : helicity suppression with m_τ

$$\mathcal{B}(B \to \ell\nu) = \frac{G_F^2 m_B}{8\pi} m_\ell^2 (1 - \frac{m_\ell^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$

  - Sensitive to Charged Higgs since b and t are heavy

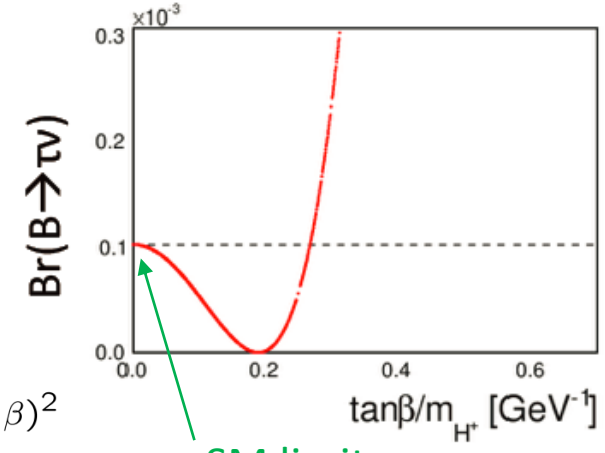
In Type -II 2HDM

$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\mathrm{SM}} \times r_H$$

  - Factor r_H independent on lepton flavor

$$r_H = (1 - \frac{m_B^2}{m_H^2} \tan^2\beta)^2$$

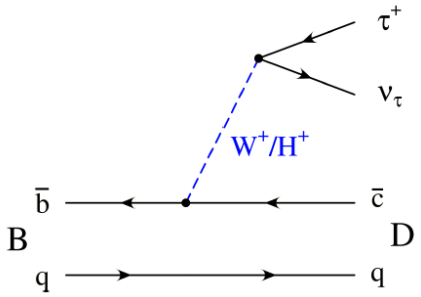
    - Charged Higgs coupling proportional to m_τ
    - B→μν also important

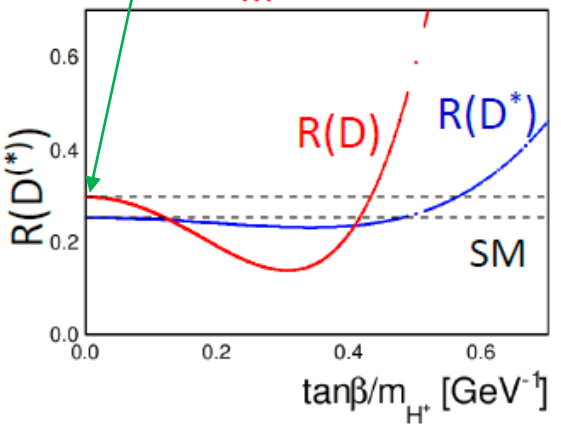


- B→D(*)τν
  - Sensitive to charged Higgs

$$R(D) = \frac{\mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_\ell)}$$

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





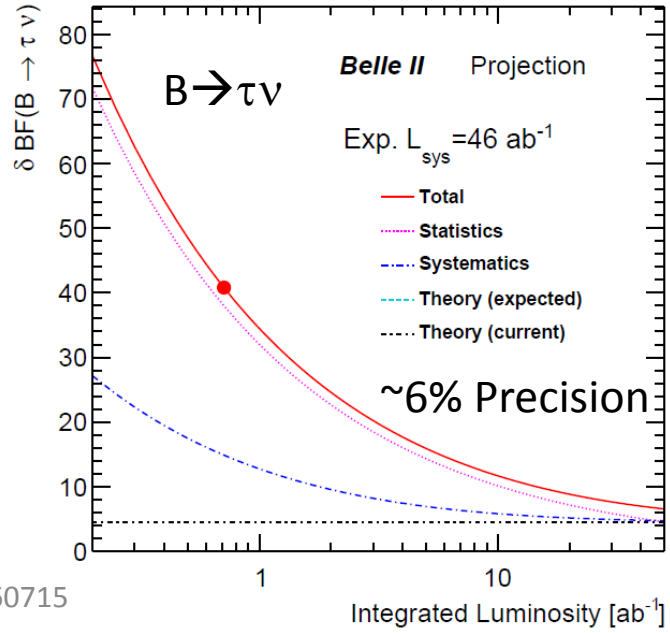
Wei-Shu Hou Phys. Rev. D48, 2342 (1993)

Projections of B→τν and B→D$^{(*)}$τν at Belle II

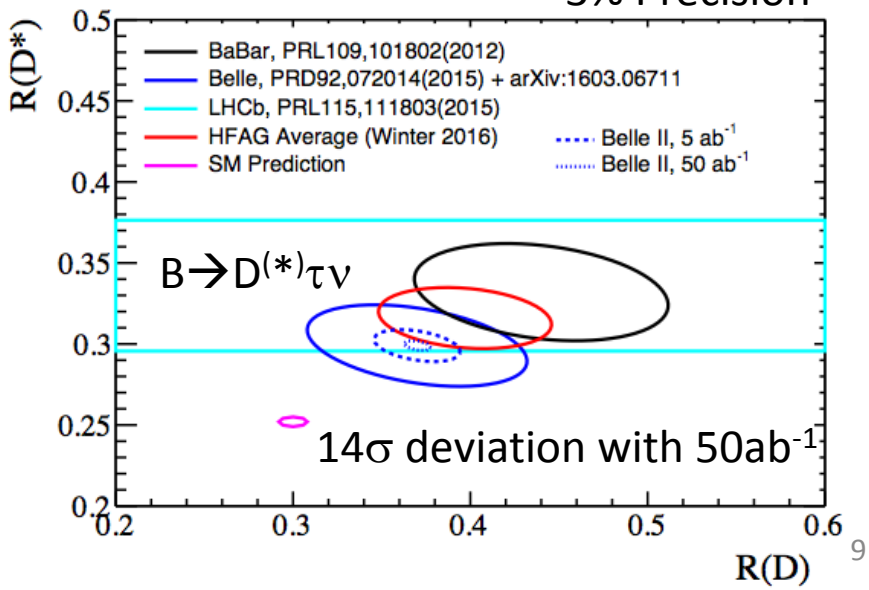
BELLE2-NOTE-PH-2015-002

	Statistical	Systematic (reducible, irreducible)	Total Exp
$\mathcal{B}(B \to \tau\nu)$ (had. tagged)			
711 fb^{-1}	38.0	(14.2, 4.4)	40.8
5 ab^{-1}	14.4	(5.4, 4.4)	15.8
50 ab^{-1}	4.6	(1.6, 4.4)	6.4
$\mathcal{B}(B \to \tau\nu)$ (semileptonic tagged)			
711 fb^{-1}	24.8	$(18, ^{+6.0}_{-9.6})$	$^{+31.2}_{-32.2}$
5 ab^{-1}	8.6	$(6.2, ^{+6.0}_{-9.6})$	$^{+12.2}_{-14.4}$
50 ab^{-1}	2.8	$(2.0, ^{+6.0}_{-9.6})$	$^{+6.8}_{-10.2}$

	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

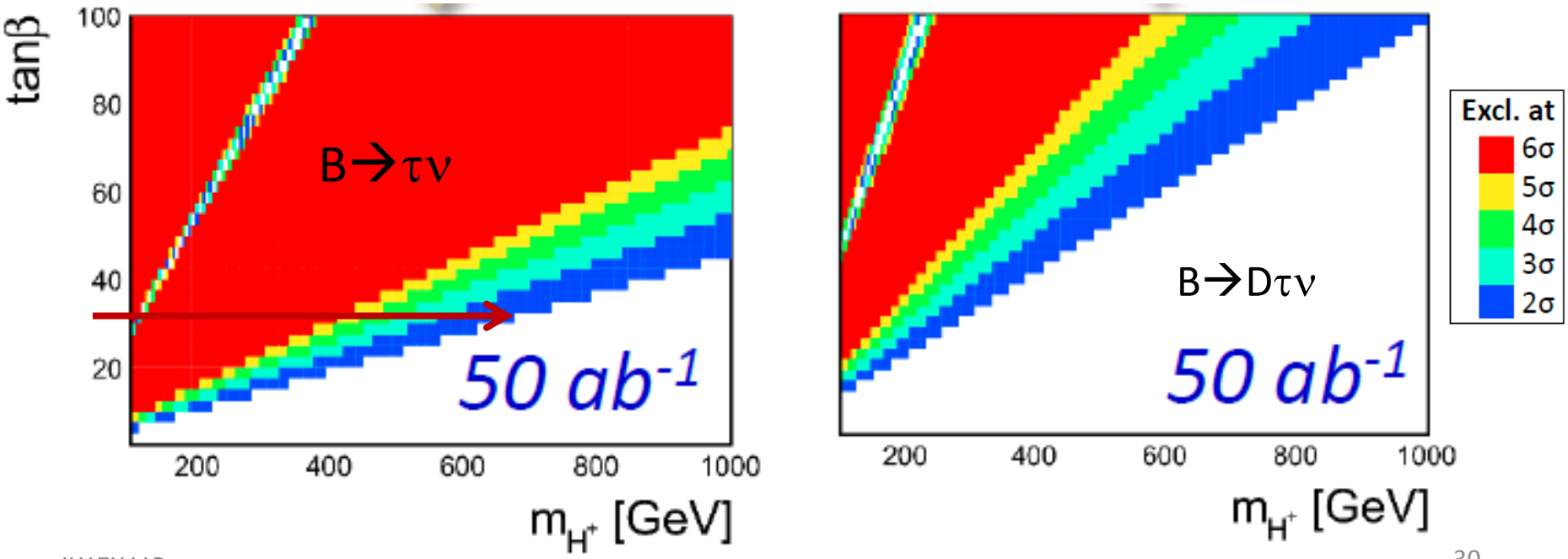


~3% Precision



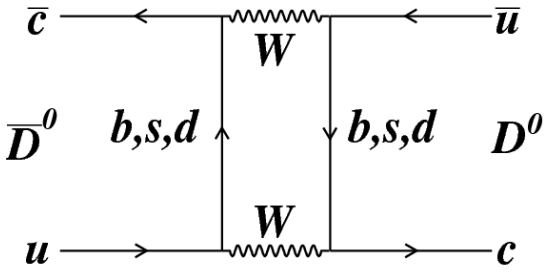
Constraint on Charged Higgs in 2HDM

- M_H ~700GeV will be excluded for tanβ=40.
  - From B(b→sγ), tanβ independent exclusion will be derived, M_H ~ 600GeV assuming 4% theoretical error (current 380GeV).



Charm and τ Decays

D^0-$\bar{D}^0$ Mixing



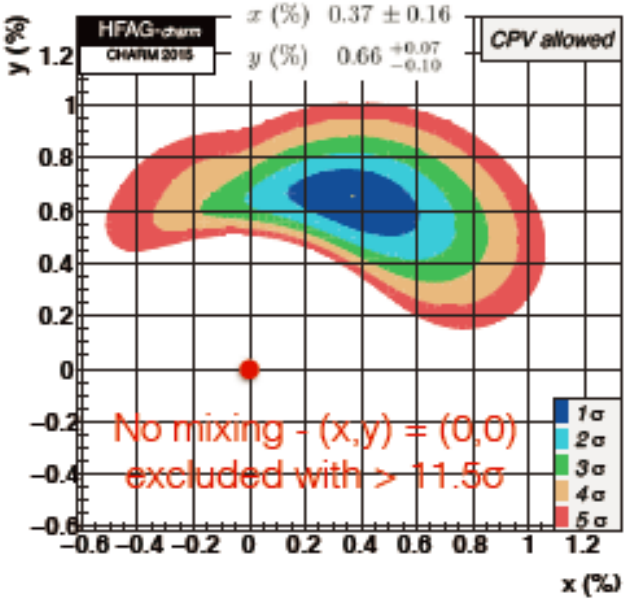
- Mass eigenstates are superposition of flavor eigenstates

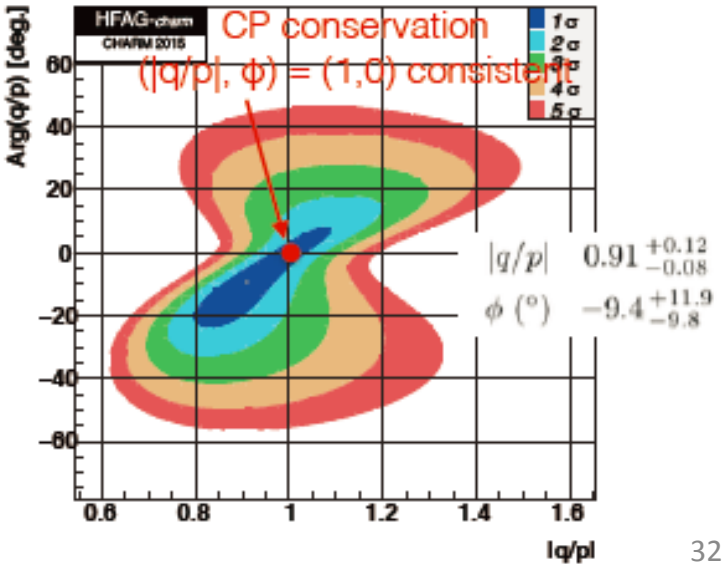
$$D_{1,2} = pD^0 \pm q\bar{D}^0$$

$$x \equiv (m_1 - m_2)/\Gamma \qquad y \equiv (\Gamma_1 - \Gamma_2)/(2\Gamma)$$

$$\Gamma \equiv (\Gamma_1 + \Gamma_2)/2 \qquad \phi = \mathrm{Arg}(q/p)$$

- Larger mixing parameter x observed by Belle/Babar/CDF/LHCb than theoretical expectation might suggest NP in the loop.
  - Smallness of x in the SM could be a good probe of NP.



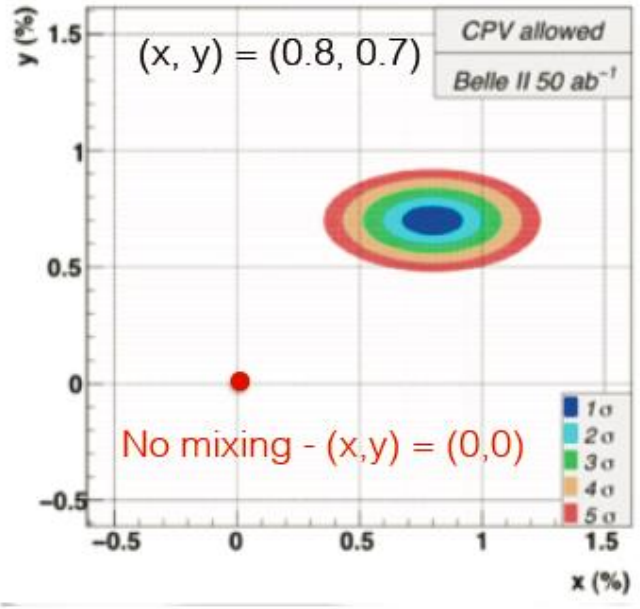


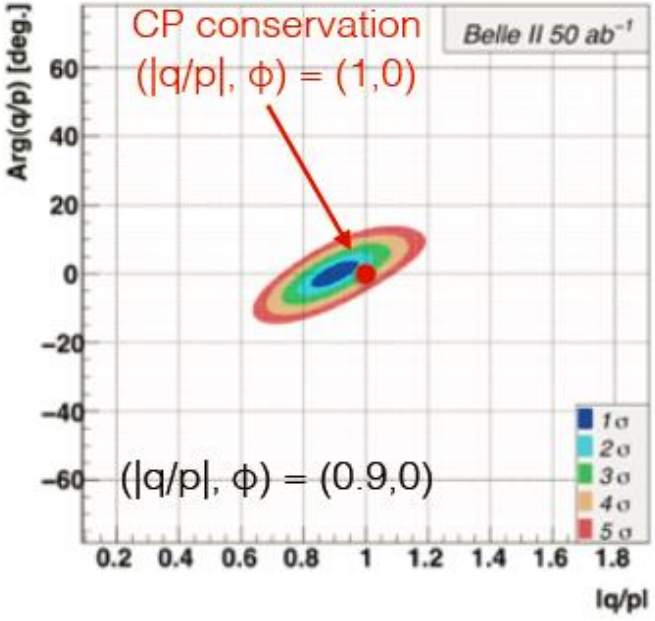
CPV in D^0-$\overline{D}^0$ Mixing

- CPV in charm is not established yet.
  - In the SM, the CPV is tiny. If found, new physics!
- Belle II can exploit CPV in mixing together with LHCb
  - Belle II : $K_S\pi^+\pi^-$, $Kl\nu$
  - LHCb : $\pi^+\pi^-$, K^+K^-, $K^+\pi^-$ (DCSD)
  - Complimentary

Expected uncertainties (M. Staric, KEK FFW14)

Analysis	Observable	Uncertainty (%)	
		Now (~ 1 ab^{-1})	$\mathcal{L} = 50$ ab^{-1}
$K^0_S\pi^+\pi^-$	x	0.21	0.08
	y	0.17	0.05
	$\lvert q/p\rvert$	18	6
	ϕ	0.21 rad	0.07 rad
$\pi^+\pi^-$, K^+K^-	y_{CP}	0.25	0.04
	A_Γ	0.22	0.03
$K^+\pi^-$	x'^2	0.025	0.003
	y'	0.45	0.04
	$\lvert q/p\rvert$	0.6	0.06
	ϕ	0.44	0.04 rad





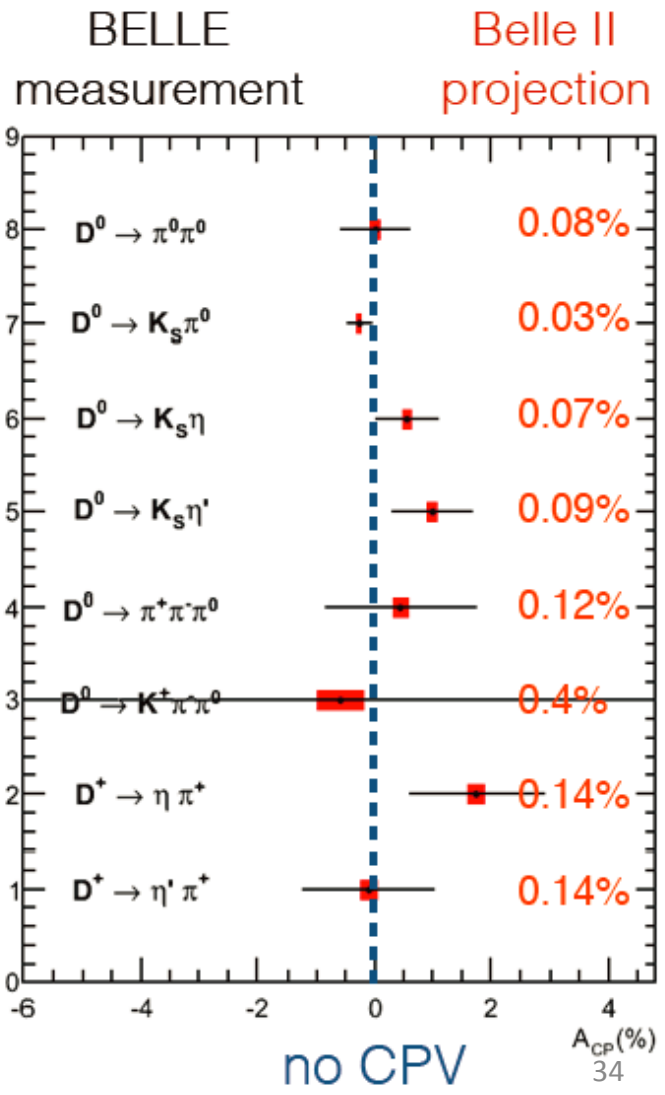
Direct CPV in Charm

- Major Belle II contribution is in channels with neutrals
  - Most measurement will be systematic dominant
  - LHCb dominates all charged final states

$$A_{CP}^{f} = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to \overline{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to \overline{f})}$$

mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II at 50 ab^{-1}
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \to \pi^0\pi^0$	976	$\sim \pm 0.60$	± 0.08
$D^0 \to K^0_S\pi^0$	791	$-0.28 \pm 0.19 \pm 0.10$	± 0.03
$D^0 \to K^0_S\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K^0_S\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \to K^0_S\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.03
$D^+ \to K^0_S K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.05
$D_s^+ \to K^0_S\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \to K^0_S K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

(table by Marko Staric)



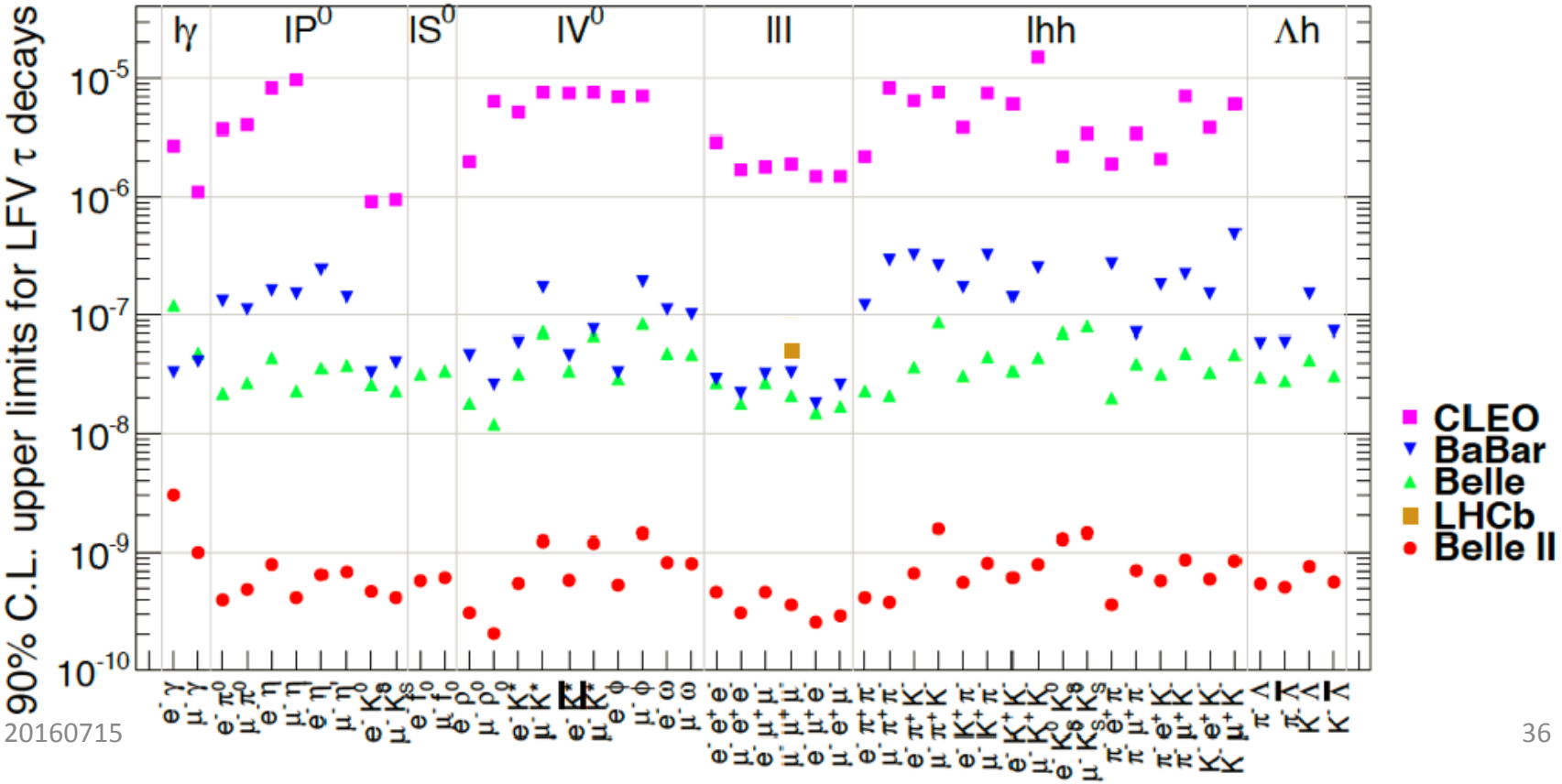
Lepton Flavor Violating τ Decays

- Highly Suppressed in the SM with neutrino mixing
  - BF($\tau \rightarrow \mu\gamma$) < 10^{-54}
- If observed, clear NP signal.
- Unique at Belle II
  - At Hadron Collider, $\tau \rightarrow 3\mu$ was only performed
    - But to reach the same sensitivity as Belle II, need to trigger low pT μ from B$\rightarrow \tau$X and Ds$\rightarrow \tau\nu$ decays, and suppress Ds$\rightarrow \phi(\mu\mu)\mu\nu$ or $\eta(\mu\mu)\mu\nu$ backgrounds

	reference	$\tau \rightarrow \mu\gamma$	$\tau \rightarrow \mu\mu\mu$
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}

Lepton Flavor Violating τ Decays at Belle II

- LFV process with mesonic and Barionic (BNV) final states also can be searched for.
- Upper limits reach below 10^{-9}



Summary

- Belle II is the super flavor factory experiment at SuperKEKB
- Rich program to search for NP with flavor observables.

- SuperKEKB commissioning is on-going.
- First physics results will come out in 2017 (phase2)
- Full detector running starts in 2018 (phase3)