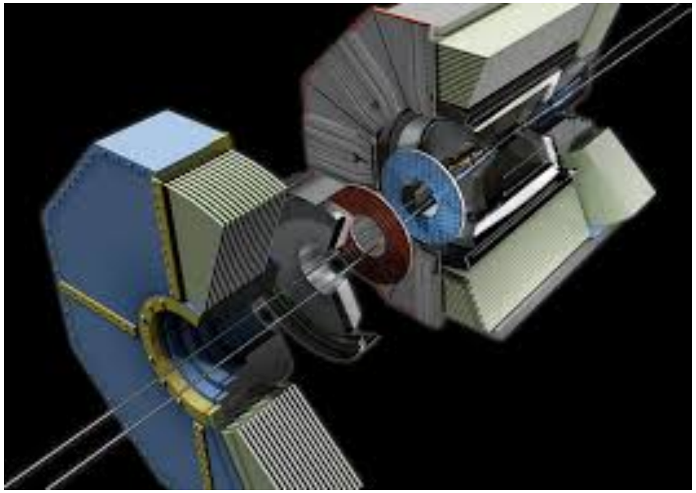


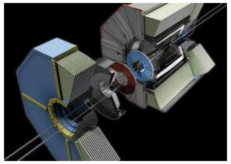
B and K Physics: Prospects for Belle II + KOTO

Alan Schwartz
University of Cincinnati, USA

40th Anniversary Symposium
US-Japan Science and Technology Cooperation Program in High Energy Physics

East-West Center
University of Hawaii
Honolulu, Hawaii
16 April 2019

- *overview*
- *measurement of angles*
- *measurement of sides ($|V_{ub}|$)*
- *searches for new physics [$R(D^{(*)})$...]*
- *charm, τ, and $(g\text{-}2)_\mu$ physics*
- *KOTO prospects*



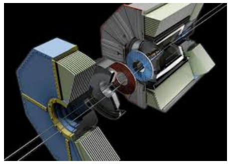
Motivation

Why a flavor factory?

A flavor factory searches for NP by measuring phases, CP asymmetries, inclusive decay processes, rare leptonic decays, absolute branching fractions. There is a wide range of observables with which to confront theory.

Why an e^+e^- Machine?

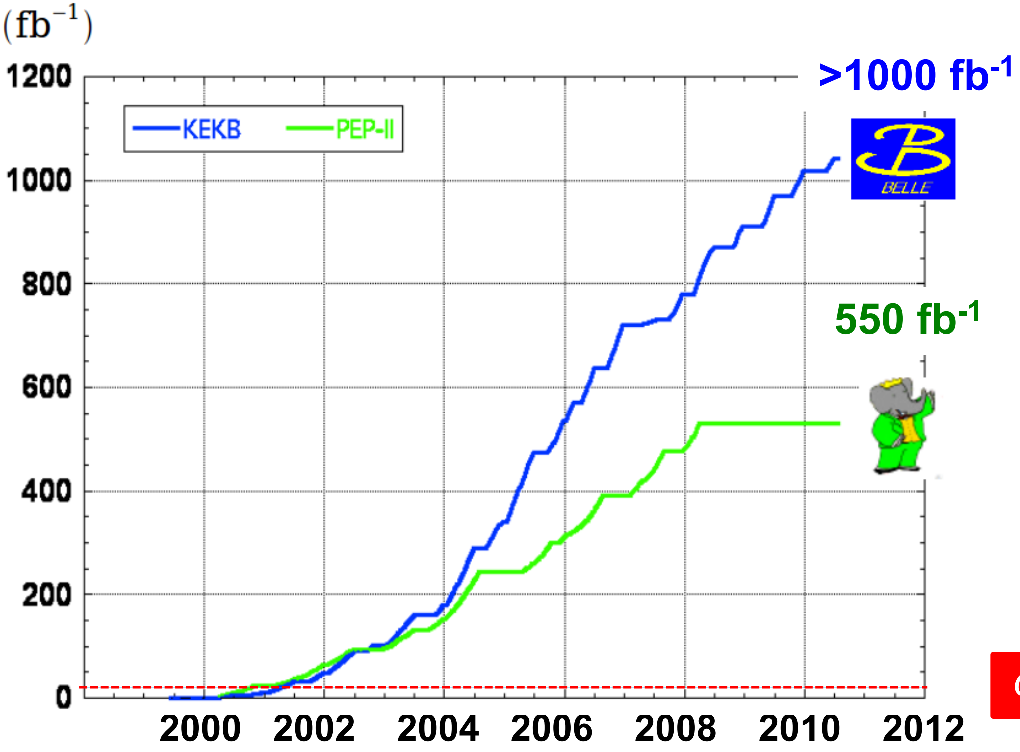
- *Low backgrounds, high trigger efficiency, excellent γ and π^0 recontruction (and thus η, η', ρ+, etc. reconstruction), high flavor-tagging efficiency with low dilution, many control samples to study systematics*
- *Due to low backgrounds, negligible trigger bias, and good kinematic resolutions, Dalitz plots analyses are straightforward. Absolute branching fractions can be measured. Missing energy and missing mass analyses are straightforward.*
- *Systematics quite different from those at LHCb. If true NP is seen by one of the experiments, confirmation by the other would be important.*



History

The Belle + BaBar Era:

*The "B Factory" experiments Belle and BaBar ran for ~10 years (2000-2010) and were huge successes: **1108 papers** published to date, many discoveries (CPV in $B^0 \rightarrow J/\psi K^0$, direct CPV in $B^0 \rightarrow \pi^+\pi^-$, D^0-D^0bar mixing, X(3872), D_{sJ}(2317), etc.), **a Nobel Prize** (Kobayashi and Maskawa, 2008)*



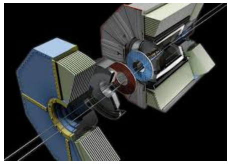
>1000 fb^{-1}

550 fb^{-1}

CLEO 11 fb^{-1}

Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$	7.7×10^8	4.8×10^8	1.1×10^{10}
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8		1.8×10^{11}
$\Upsilon(2S)$	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}

***Belle II** is a significant upgrade of Belle: new accelerator, new detector, new electronics, new DAQ, new trigger. **Goal:** 50 ab^{-1} of data*



Belle II physics: “golden modes”

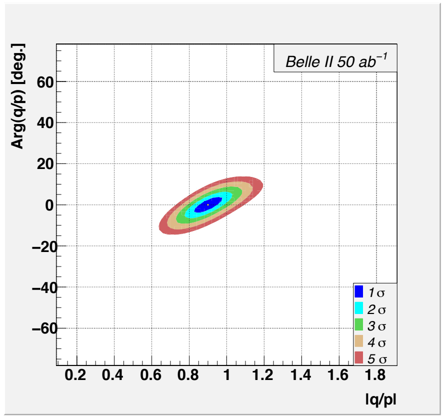
The Belle II Physics Book, arXiv:1808.10567, to appear in Prog. Theor. Exp. Physics

B physics:

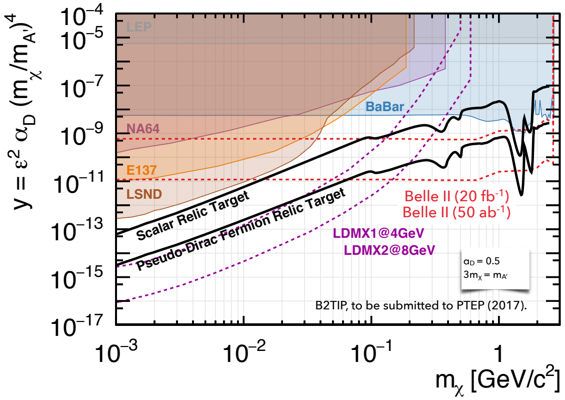
(● covered here)

Observables	Expected exp. uncertainty	Facility (2025)
UT angles & sides		
● ϕ_1 [°]	0.4	Belle II
ϕ_2 [°]	1.0	Belle II
ϕ_3 [°]	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	1%	Belle II
$\|V_{cb}\|$ excl.	1.5%	Belle II
$\|V_{ub}\|$ incl.	3%	Belle II
● $\|V_{ub}\|$ excl.	2%	Belle II/LHCb
CPV		
$S(B \to \phi K^0)$	0.02	Belle II
$S(B \to \eta' K^0)$	0.01	Belle II
● $\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	0.20	LHCb/Belle II
(Semi-)leptonic		
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	7%	Belle II
● $R(B \to D\tau\nu)$	3%	Belle II
● $R(B \to D^*\tau\nu)$	2%	Belle II/LHCb
● **Radiative & EW Penguins**		
$\mathcal{B}(B \to X_s\gamma)$	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	0.03	Belle II
$S(B \to \rho\gamma)$	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	15%	Belle II
$\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$	20%	Belle II
$R(B \to K^*\ell\ell)$	0.03	Belle II/LHCb

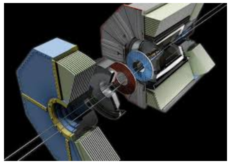
- **Charm physics:**



Dark Photon/Sector:



- **Tau physics**
  Quarkonium-like
  B_s physics at Υ(5S)



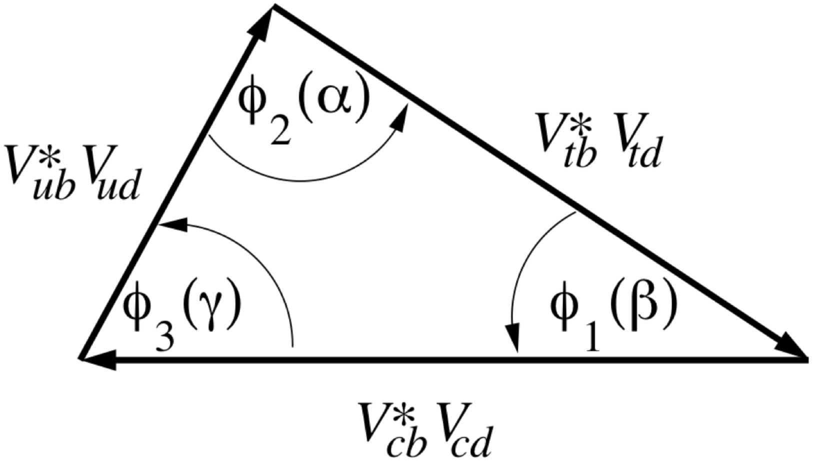
Unitarity triangle – determining the angles

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

The internal angles of this triangle are phase differences that can be measured via various strategies:

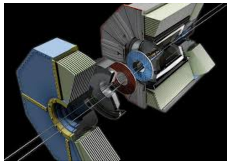
Belle/BaBar **LHCb**

$B \to \pi^+\pi^- / \pi^+\pi^0 / \pi^0\pi^0$
$B \to \rho^+\rho^- / \rho^+\rho^0 / \rho^0\rho^0$
$B^0 \to \rho\,\pi$
$B^0 \to a_1(\rho\pi)^+\,\pi^-$



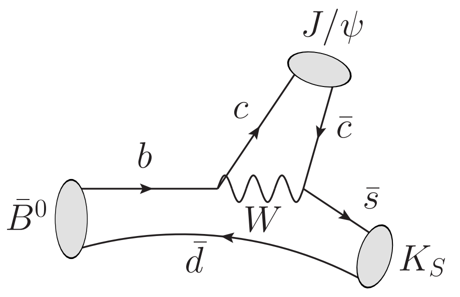
$B^0 \to J/\psi\,K_S$
$B^0 \to J/\psi\,K_L$
$B^0 \to \psi'\,K_S$
$B^0 \to \chi_c\,K_S$
$B^0 \to \eta_c\,K_S$
$B^0 \to D^{(*)}{}_{CP}\,h^0$
$B^0 \to (\phi/\eta'/\pi^0/f^0)K^0$
$B^0 \to (K_S K_S/\rho^0/\omega)K_S$

$B^- \to D^{(*)}{}_{CP}\,K^{(*)-}$
$B^0 \to D_{CP}\,K^{*0}$
$B^- \to D^{(*)}(K^+\pi^-)\,K^{(*)-}$
$B^- \to D^{(*)0}\,\pi^-$
$B^- \to D^{(*)}(K_S\,\pi^+\pi^-)\,K^{(*)-}$
$B^- \to D(\pi^0\pi^+\pi^-)\,K^-$
$B^- \to D(K_S\,K^+\pi^-)\,K^-$



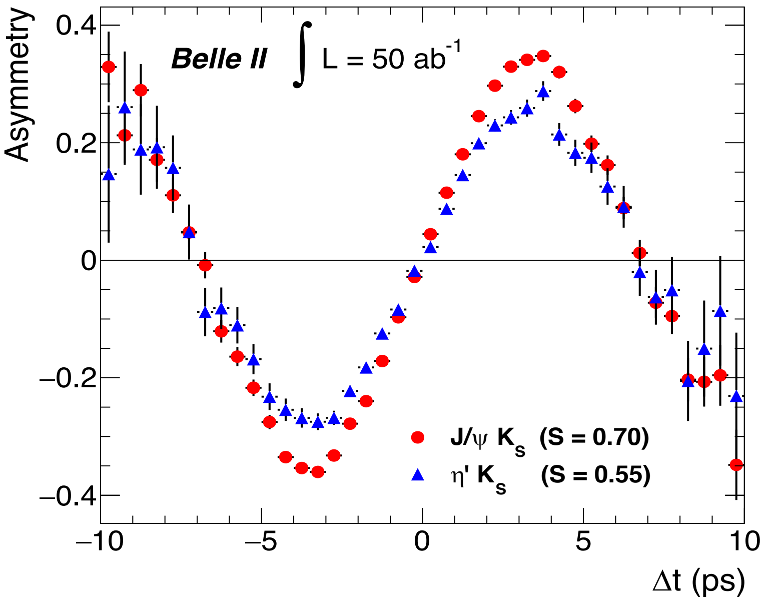
Determining ϕ_1 (β)

$B^0 \to J/\psi K_S$ (the "Golden" mode):



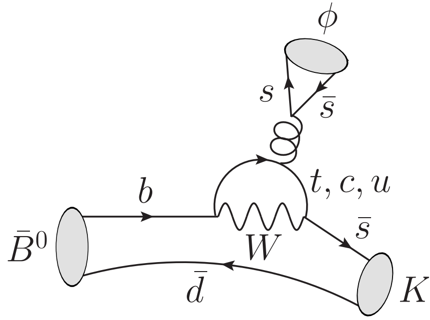
$$\mathcal{A}_{c\bar{c}s} = V_{cb}^* V_{cs} T + V_{ub}^* V_{us} P$$

expected 50 ab^{-1} uncertainty: $\delta\phi_1$ = 0.4°
(this is less than the current theory error of 1-2°)



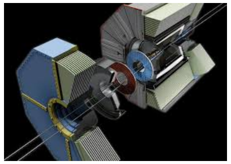
$$A_{CP} = A\cos(\Delta M \Delta t) + S\sin(\Delta M \Delta t)$$

$B^0 \to \phi K_S, \eta' K_S, \omega K_S, \pi^0 K_S$ ("penguin" modes):



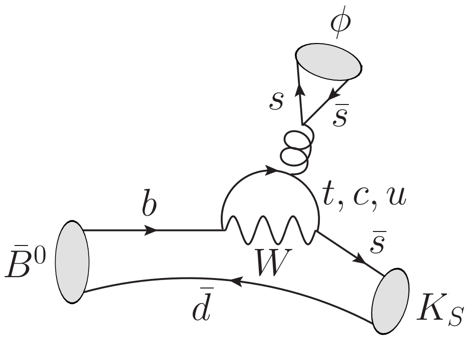
$$\mathcal{A}_{q\bar{q}s} = V_{cb}^* V_{cs} P + V_{ub}^* V_{us} T'$$

	WA (2017)		5 ab^{-1}		50 ab^{-1}	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$J/\psi K^0$	0.022	0.021	0.012	0.011	0.0052	0.0090
ϕK^0	0.12	0.14	0.048	0.035	0.020	0.011
$\eta' K^0$	0.06	0.04	0.032	0.020	0.015	0.008
ωK_S^0	0.21	0.14	0.08	0.06	0.024	0.020
$K_S^0 \pi^0 \gamma$	0.20	0.12	0.10	0.07	0.031	0.021
$K_S^0 \pi^0$	0.17	0.10	0.09	0.06	0.028	0.018



Searching for NP via $B^0 \to \pi^0 K_S$

The Belle II Physics Book, arXiv:1808.10567

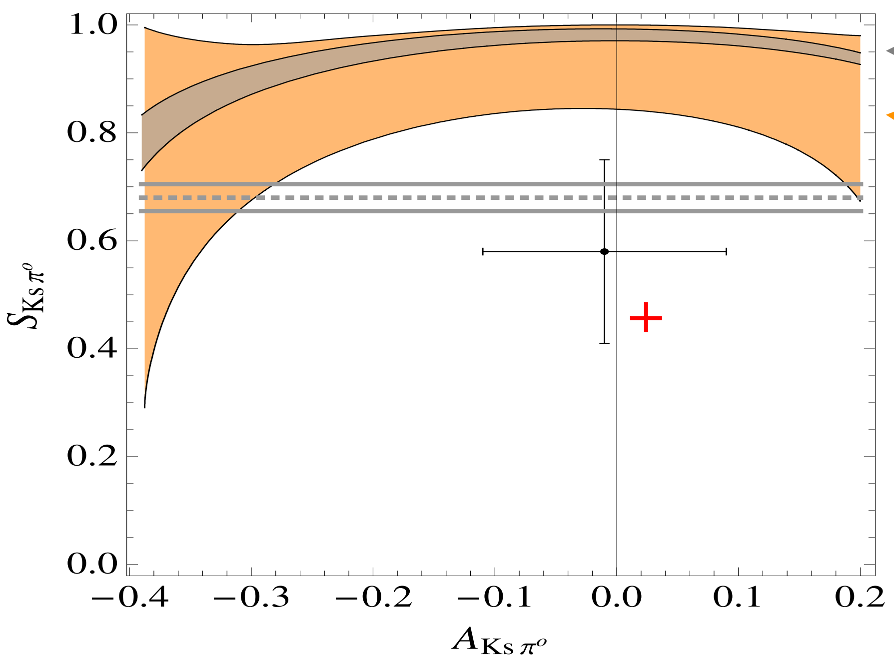


$$A_{CP} = A\cos(\Delta M \Delta t) + S\sin(\Delta M \Delta t)$$

	WA (2017)		5 ab^{-1}		50 ab^{-1}	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$K_S^0\pi^0$	0.17	0.10	0.09	0.06	0.028	0.018

Isospin symmetry:

$\mathcal{B}(B^0 \to \pi^0 K_S)$, $\mathcal{B}(B^0 \to \pi^+ K^-)$, $\mathcal{B}(B^+ \to \pi^0 K^+)$, $\mathcal{B}(B^+ \to \pi^+ K_S)$ *constrain* A_{CP} *of* $B^0 \to \pi^0 K_S$



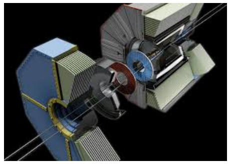
Belle II 50 ab^{-1}

Preferred region based on current branching fractions

Current WA

Belle II 50 ab^{-1}

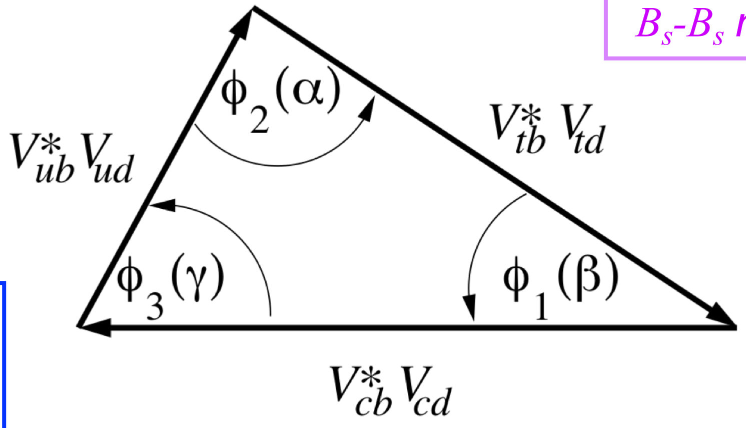
Also: Fleischer et al., arXiv:1806.08783



Determining sides of the Unitarity Triangle

Belle
LHCb

$B^0 \to \rho^0 \gamma$
B_s-B_s mixing



Jubb et al., Nucl. Phys. B 915, 431 (2017)
Artuso et al., RMP 88, 045002 (2016)
Lenz, Nierste, arXiv:1102.4274 (2011)
FNAL/MILC, PRD 93, 113016 (2016)
FLAG, EPJC 77, 112 (2017)

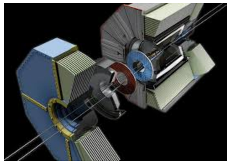
$B^0 \to \pi \ell^+ \nu$
$B^0 \to X_u \ell \nu$
$B^+ \to \tau^+ \nu$
$\Lambda_b \to p \ell^+ \nu$

Bourrely et al., PRD 79, 013008 (2009)
FLAG, arXiv:1607.00299 (2016)
Bharucha, JHEP 05, 092 (2012)
Detmold et al., PRD 92, 034503 (2015)
Faustov and Galkin, PRD 94, 073008 (2016)

Lange et al. (BLNP), PRD 72, 073006 (2005)
Andersen, Gardi (DGE), JHEP 601, 97 (2006)
Gambino et al. (GGOU), JHEP 10, 058 (2007)
Aglietti et al. (ADFR), EPJ C59 (2009)
Bauer et al. (BLL), PRD 64, 113004 (2001)

$B^0 \to D^{(*)} \ell \nu$
$B^0 \to X_c \ell \nu$ (ℓ energy, hadron mass moments)
$B^0 \to X_s \gamma$ (γ energy moments)

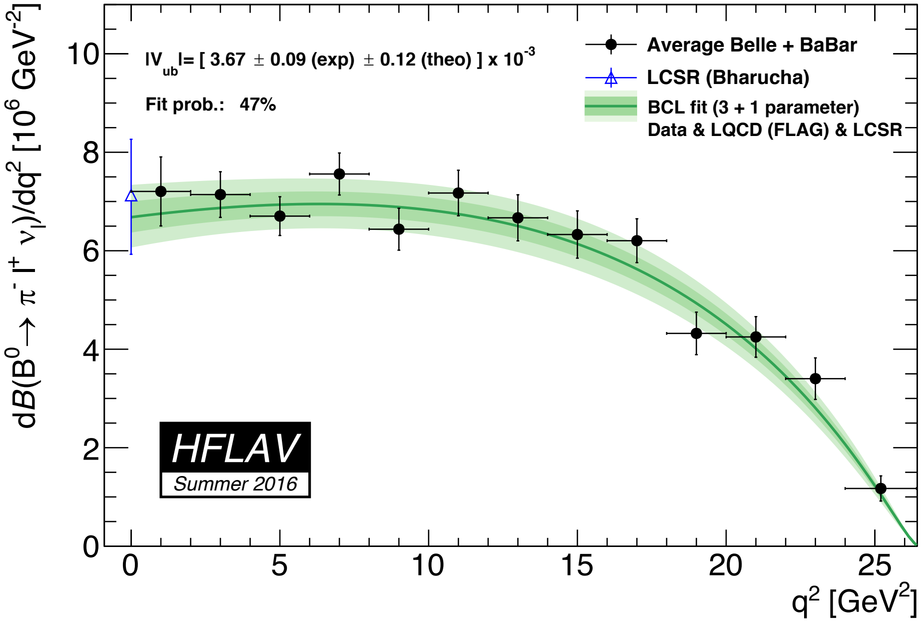
Caprini et al., Nucl. Phys. B530, 153 (1998)
FNAL/MILC, PRD 89, 114504 (2014)
FNAL/MILC, PRD 92, 034506 (2015)
Benson et al., Nucl. Phys. B665, 367 (2003)
Gambino, Uraltsev, EPJ C34, 181 (2004)
Gambino, JHEP 09, 055 (2011)
Alberti et al., PRL 114, 061802 (2015)
Bauer, Ligeti, et al., PRD 70, 094017 (2004)
Gambino and Schwanda, PRD 89, 014002 (2014)



$|V_{ub}|$ via exclusive $B\to \pi l \nu$

$$\frac{d\Gamma(B\to P\ell^+\nu)}{dq^2} = \frac{G_F^2}{24\pi^3}|f^+(q^2)|^2|V_{ub}|^2 p^{*3}$$

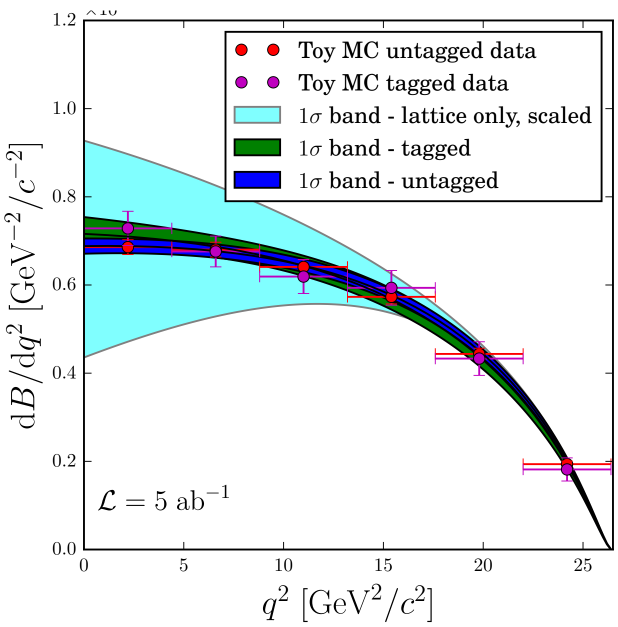
Use BCL parametrization of form factor, fit q^2 spectrum for BCL parameters and $|V_{ub}|$

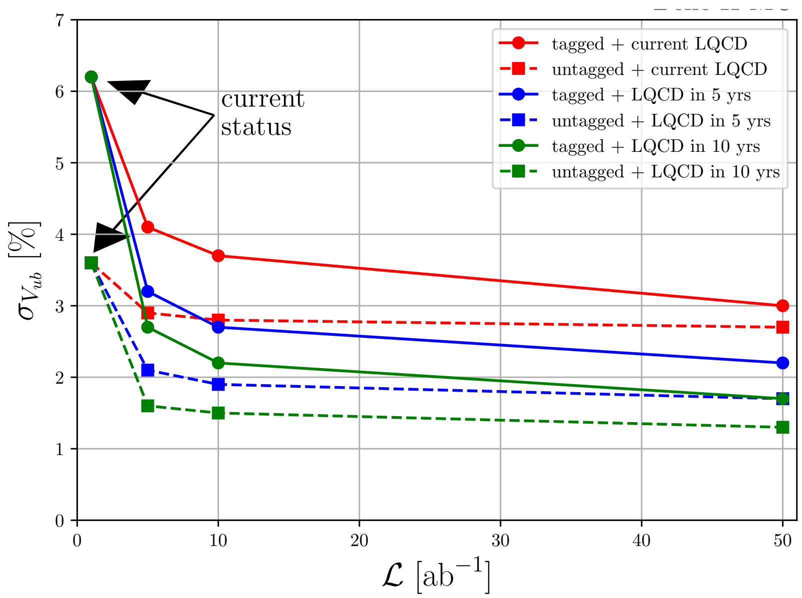


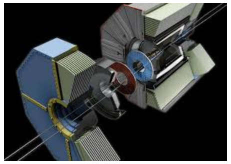
$|V_{ub}| = (3.67 \pm 0.09_{exp} \pm 0.12_{th}) \times 10^{-3}$

BCL: *Bourrely, Caprini, Lellouch, PRD 79, 013008 (2009)*
Lattice: *Aoki et al., (FLAG), EPJC 77, 112, (2017)*
LCSR: *Bharucha, JHEP 05, 092, (2012)*
HFLAV: *EPJC 77 (2017) 895 [arXiv:1612.07233]*

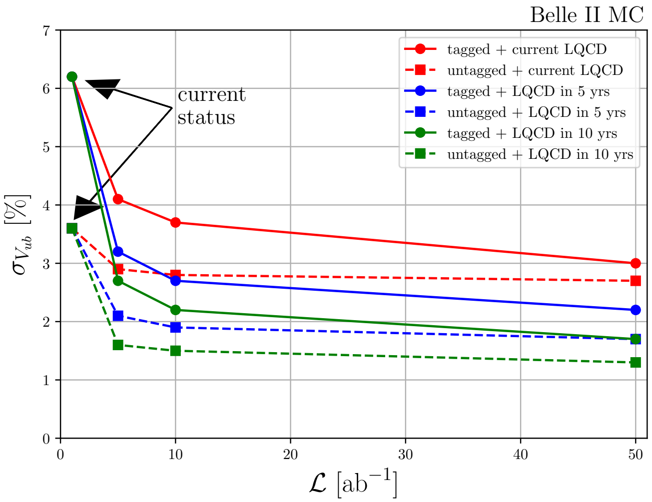
Belle II 5 ab^{-1} $B\to \pi l \nu$

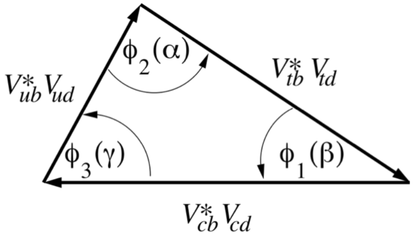






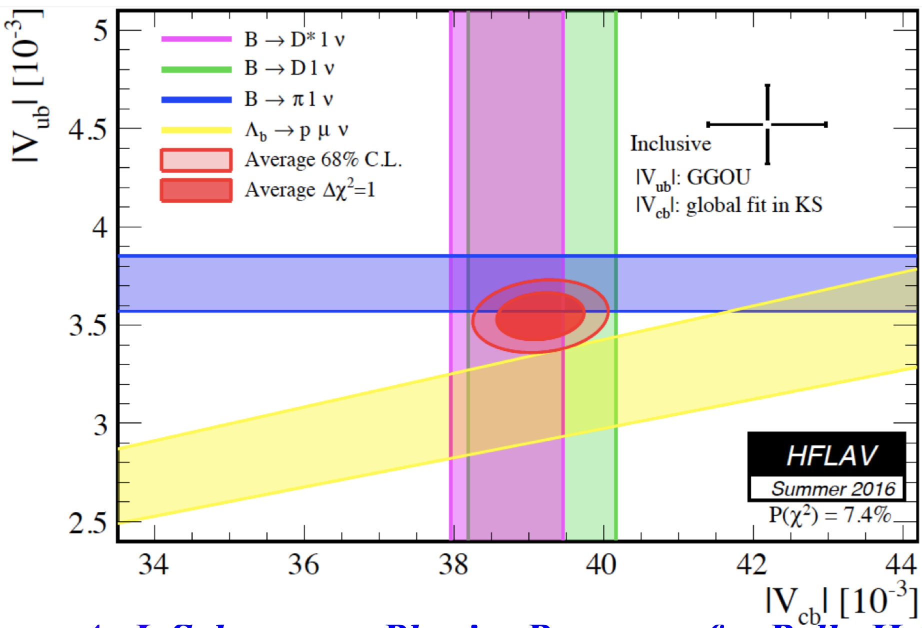
$|V_{ub}|$ via exclusive $B \to \pi l \nu$



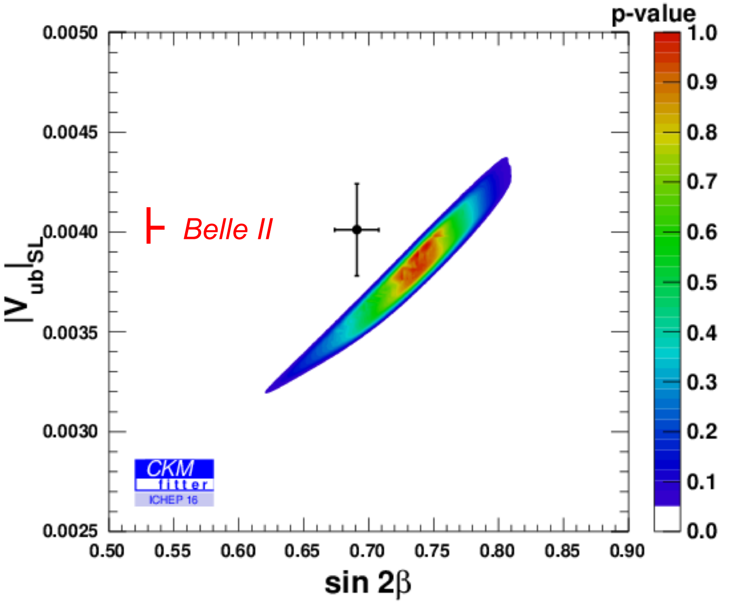


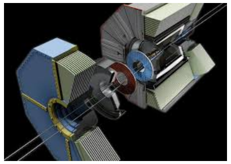
Should help resolve 2 "tensions" (discrepancies):

Exclusive $|V_{ub}|$ vs. inclusive $|V_{ub}|$

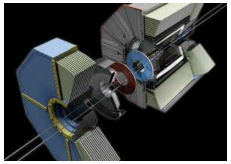


Consistency with ϕ_1 (β)

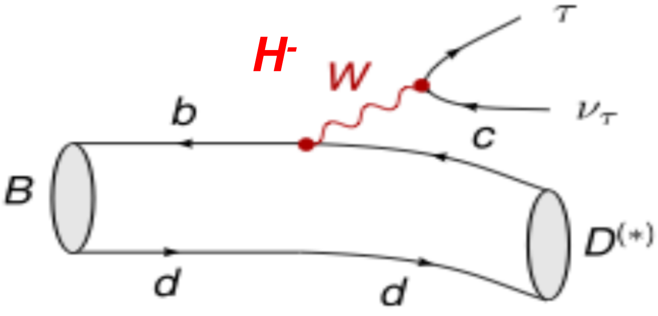




Searches for New Physics



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

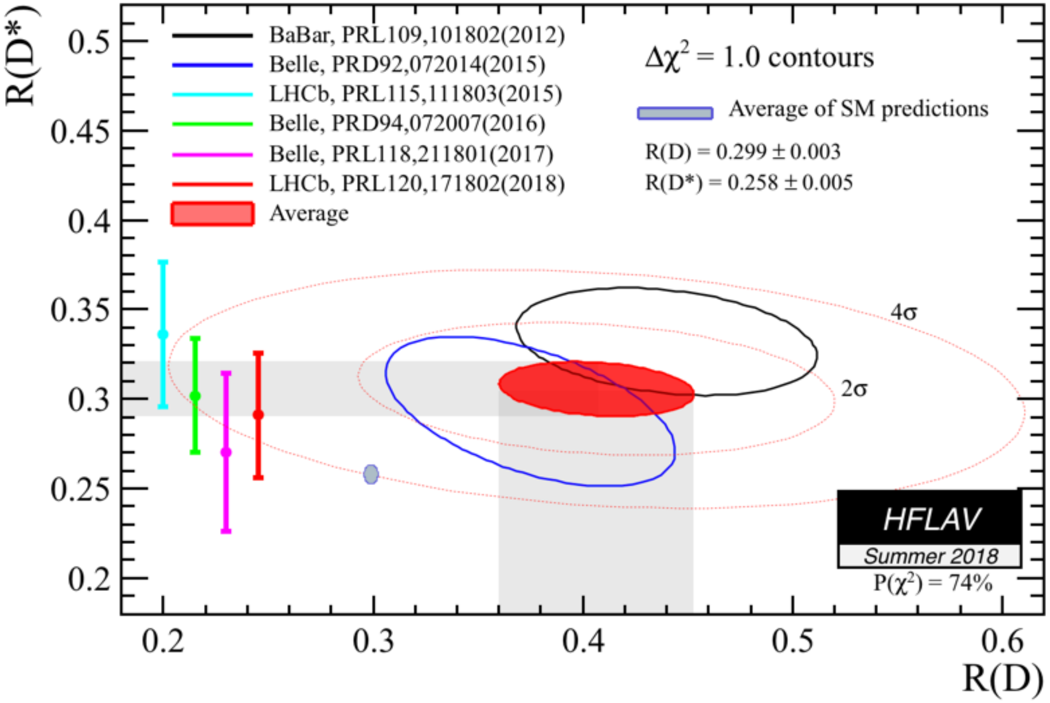


$B \to D^{(*)}\tau\nu$ can also receive contribution from a charged Higgs, changing the rate, q^2 distribution, etc.

Define ratios:

$$\mathcal{R}_{D^*} \equiv \frac{\mathcal{B}(B \to D^*\tau\nu)}{\mathcal{B}(B \to D^*\ell\nu)} \qquad \mathcal{R}_D \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$$

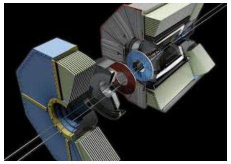
Uncertainties from form factors and V_{cb} drop out ⇒ ratios test lepton universality. Measured values are above SM prediction:



R(D) and R(D) exceed SM predictions by 2.3σ and 3.0σ respectively. As R(D)-R(D*) correlation = -0.203, two-dimensional χ^2 =17.55*

⇒ for 2 deg. of freedom,
p-value = 1.57 x 10^{-4} (3.8σ)

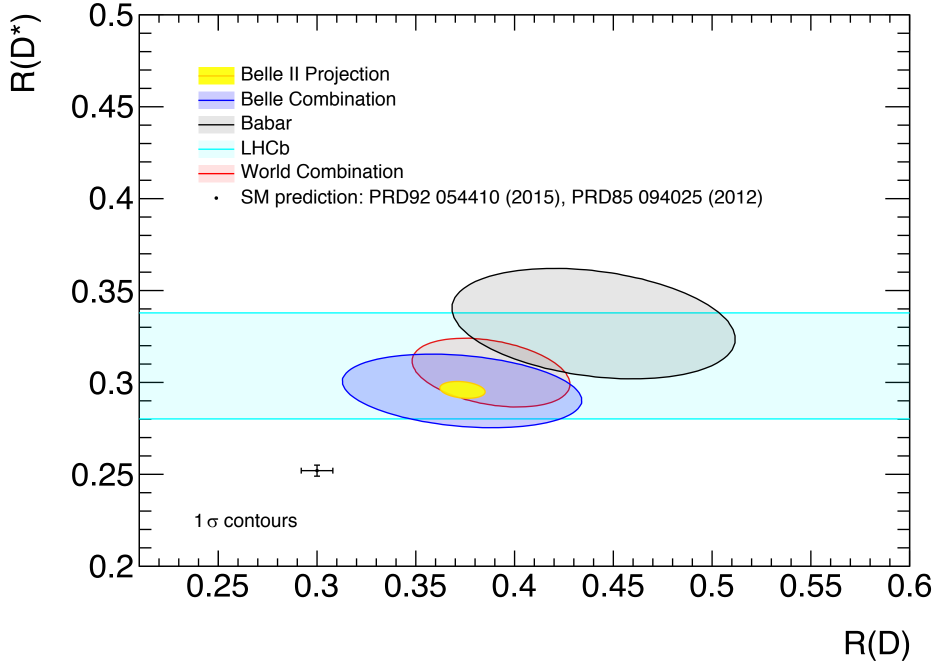
[Moriond 2019: 3.1σ]



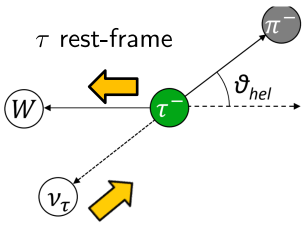
$B\to D^{(*)}\tau\nu$ @ Belle II

The Belle II Physics Book, arXiv:1808.10567

Scaling from Belle → Belle II (50 ab^{-1}):



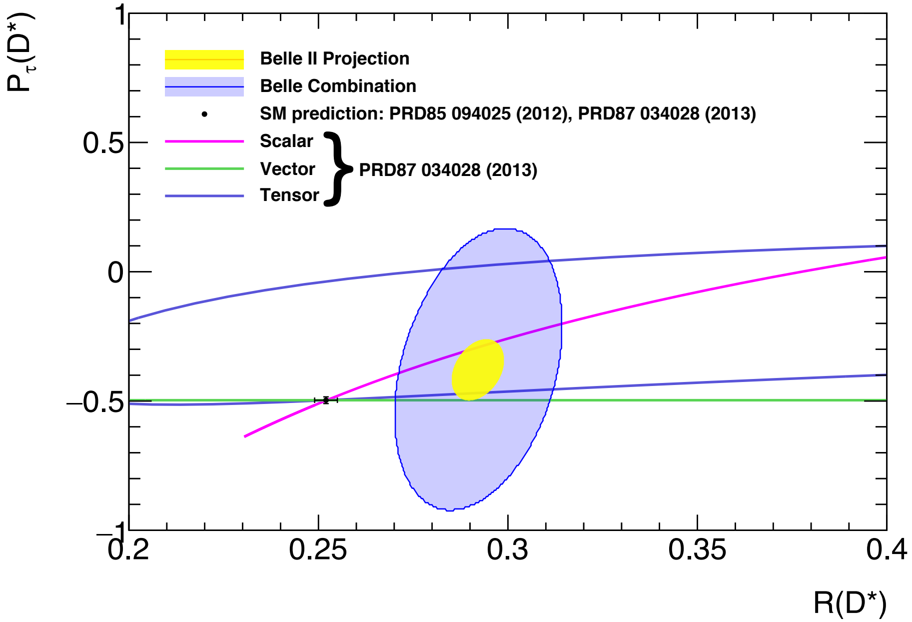
Belle II can measure the τ polarization:

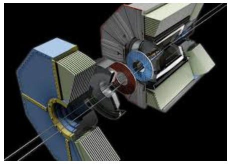


$$P_\tau \equiv \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

$$\frac{d\Gamma}{d\cos\theta_h} \propto 1 + \alpha P_\tau \cos\theta_h$$

$$\left(\begin{array}{l} \tau\to\pi\nu:\ \alpha = 1 \\ \tau\to\rho\nu:\ \alpha = 0.45 \end{array}\right)$$





Inclusive $B \to X_{(s,d)}\ell^+\ell^-$ decays

The Belle II Physics Book, arXiv:1808.10567

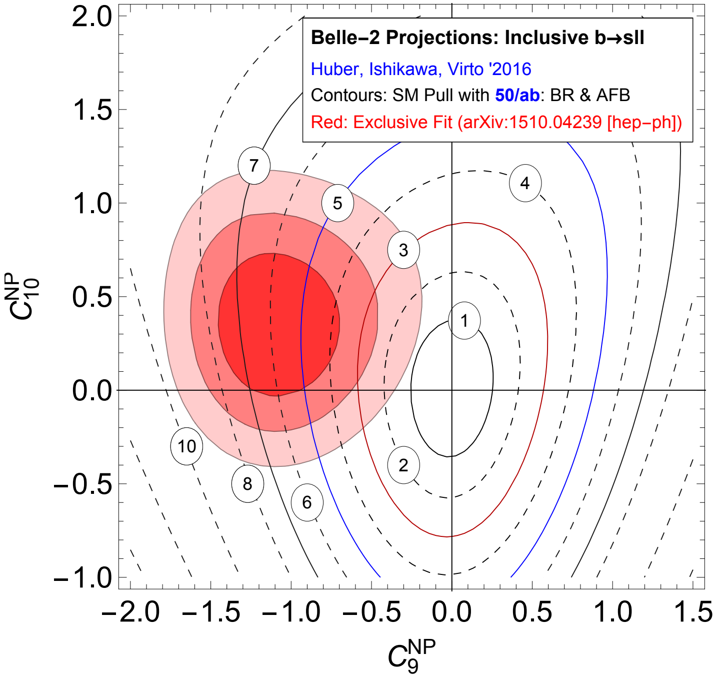
Inclusive decays were measured at Belle/BaBar using a sum-of-exclusives method: e.g., $X_s = Kn(\pi)$ with n<5 and max 1 π^0. This can be improved at Belle II in several ways:

- *3 K modes can be included;*
- *more π^+ can possibly be included;*
- *another π^0 can possibly be included;*
- *improved full reconstruction on tagging side (with neural network)*

  may make true inclusive analysis feasible (under study)

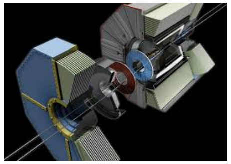
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$B(B \to X_s\ell^+\ell^-)$ $(1.0 < q^2 < 3.5\ \mathrm{GeV}^2)$	29%	13%	6.6%
$B(B \to X_s\ell^+\ell^-)$ $(3.5 < q^2 < 6.0\ \mathrm{GeV}^2)$	24%	11%	6.4%
$B(B \to X_s\ell^+\ell^-)$ $(q^2 > 14.4\ \mathrm{GeV}^2)$	23%	10%	4.7%
$A_{CP}(B \to X_s\ell^+\ell^-)$ $(1.0 < q^2 < 3.5\ \mathrm{GeV}^2)$	26%	9.7 %	3.1 %
$A_{CP}(B \to X_s\ell^+\ell^-)$ $(3.5 < q^2 < 6.0\ \mathrm{GeV}^2)$	21%	7.9 %	2.6 %
$A_{CP}(B \to X_s\ell^+\ell^-)$ $(q^2 > 14.4\ \mathrm{GeV}^2)$	21%	8.1 %	2.6 %
$A_{FB}(B \to X_s\ell^+\ell^-)$ $(1.0 < q^2 < 3.5\ \mathrm{GeV}^2)$	26%	9.7%	3.1%
$A_{FB}(B \to X_s\ell^+\ell^-)$ $(3.5 < q^2 < 6.0\ \mathrm{GeV}^2)$	21%	7.9%	2.6%
$A_{FB}(B \to X_s\ell^+\ell^-)$ $(q^2 > 14.4\ \mathrm{GeV}^2)$	19%	7.3%	2.4%
$\Delta_{CP}(A_{FB})$ $(1.0 < q^2 < 3.5\ \mathrm{GeV}^2)$	52%	19%	6.1%
$\Delta_{CP}(A_{FB})$ $(3.5 < q^2 < 6.0\ \mathrm{GeV}^2)$	42%	16%	5.2%
$\Delta_{CP}(A_{FB})$ $(q^2 > 14.4\ \mathrm{GeV}^2)$	38%	15%	4.8%

Belle II 50 ab^{-1} exclusion contours (BR and A_{FB} of inclusive $b \to sll$) :

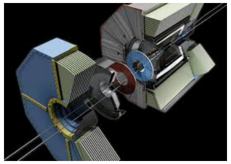


(n) σ pull to SM fit if true values

Exclusive decays fit: JHEP 06 (2016)092

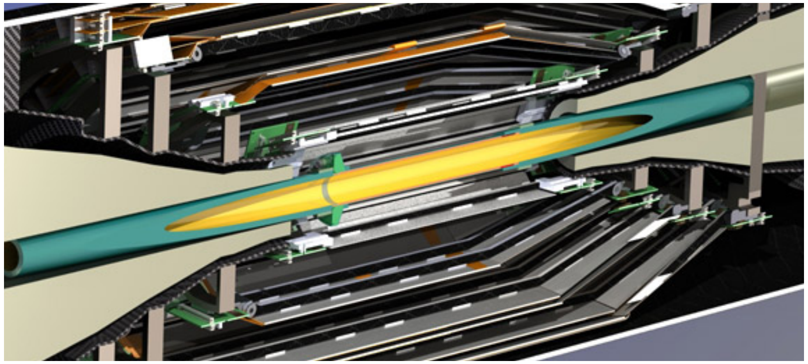


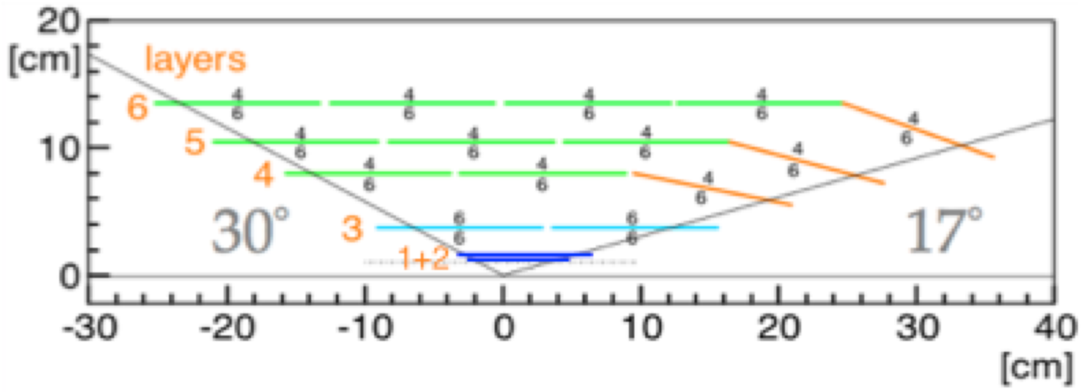
Charm Physics



The Belle II Vertex Detector

Two detectors for vertexing:
- *2 layers of DEPFET pixels*
- *4 layer of silicon strips*



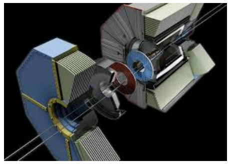


Pixel detector:

	Inner layer (L1)	Outer layer (L2)
# modules	2 x 8	2 x 12
distance from IP (cm)	1.4	2.2
thickness (µm)	75	75
total # pixels	3.072 x 10^{6}	4.608 x 10^{6}
pixel size (µm^2)	55, 60 x 50	70, 85 x 50
sensitive area (mm^2)	44.8 x 12.5	61.44 x 12.5

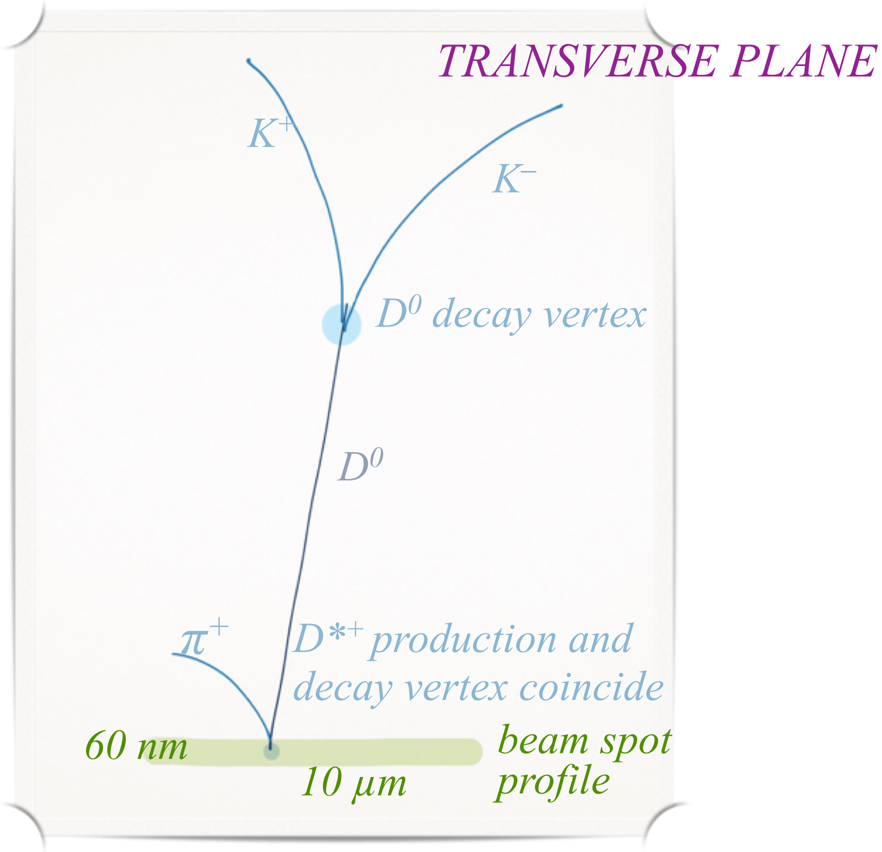
Silicon strip detector:

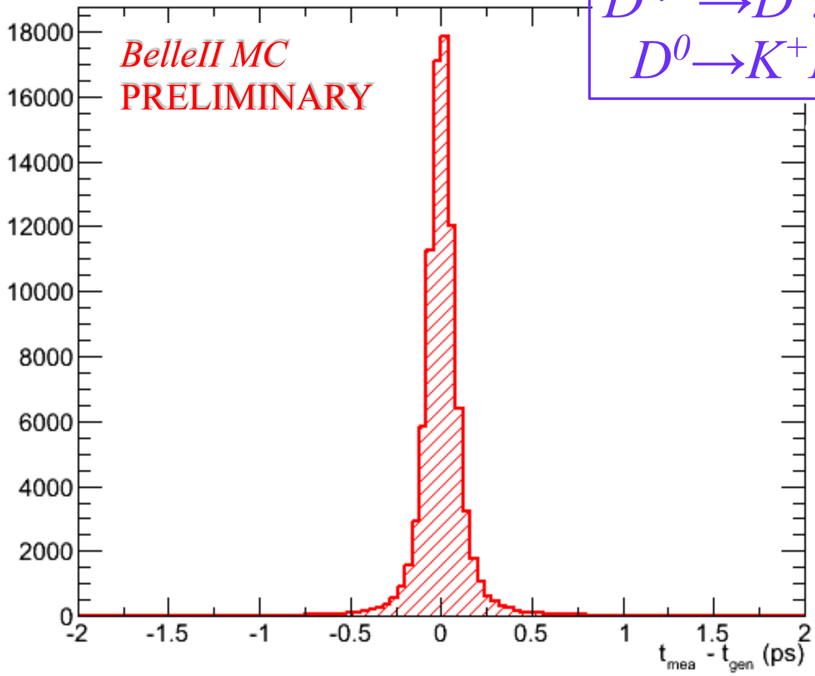
layer	type	readout strip(p/r-ϕ)	readout strip(n/z)	strip pitch (p/r-ϕ)	strip pitch (n/z)
4,5,6	Large	768	512	75 µm	240 µm
4,5,6 forward	Trapezoidal	768	512	50-75 µm	240 µm
3	Small	768	768	50 µm	160 µm



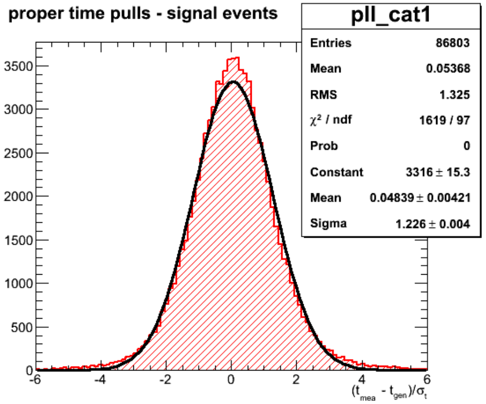
$D^0 \to K^+K^-$ Decay Time Resolution (D^* tag)

$$t = \frac{\ell}{\beta\gamma c} = \frac{\ell}{c}\frac{m_D}{|\vec{p}|}$$





$D^{*+} \to D^0\pi^+$,
$D^0 \to K^+K^-$

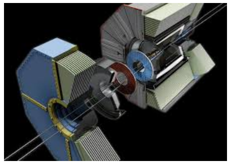


⇒

resolution = 0.14 ps
(2x better than Belle/BaBar (0.27 ps)

pulls distribution ok

$K\pi$, $\pi\pi$ results similar



D^0-$\bar{D}^0$ mixing and CPV

The Belle II Physics Book,
arXiv:1808.10567

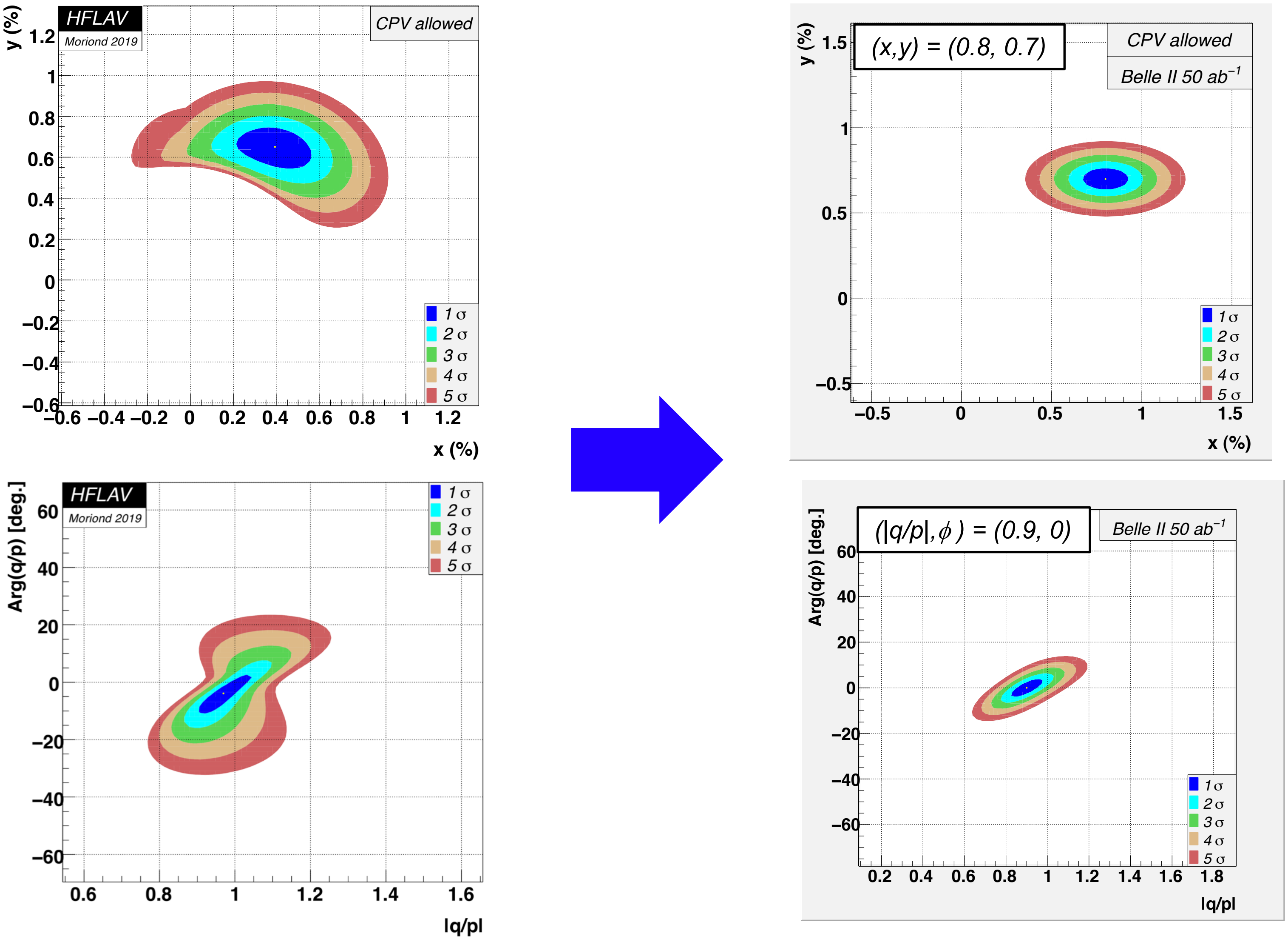
Analysis	Observable	Uncertainty (%)	
		Now (~ 1.0 fb^{-1})	$\mathcal{L} = 50$ fb^{-1}
$K^0_S\pi^+\pi^-$	x	0.21	0.11
	y	0.17	0.05
	$\|q/p\|$	0.21	0.074
	ϕ	14°	4.2°
$\pi^+\pi^-$, K^+K^-	y_{CP}	0.11	0.05
	A_Γ	0.026	0.026
$K^+\pi^-$	x'^2	0.022	0.007
	y'	0.34	0.097
	$\|q/p\|$		0.043
	ϕ		5.4°

***NOTE:** does not include factor of ~2 improvement in decay time resolution*

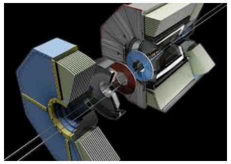
Note: *statistical error and some systematics scale by luminosity, but other systematics do not.*

Mixing Constraints in the D^0-$\overline{D}^0$ system

Inserting these errors for y_{CP}, A_Γ, x'^2, y', and $K_S\pi^+\pi^-$ observables into the HFAG global fit:



Current measurements of x, y give many constraints on NP models [Golowich et al., PRD76, 095009 (2007)]



Direct CP Asymmetries

The Belle II Physics Book,
arXiv:1808.10567

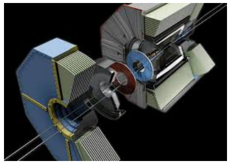
$$\sigma_{\text{Belle II}} = \sqrt{(\sigma^2_{\text{stat}} + \sigma^2_{\text{syst}}) \cdot \frac{\mathcal{L}_{\text{Belle}}}{50\ \text{ab}^{-1}} + \sigma^2_{\text{irred}}}$$

mainly due to K^0-K^0bar interaction asymmetry

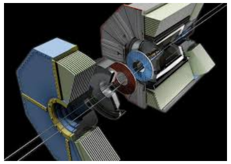
Mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II 50 ab^{-1}
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	±0.03
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	±0.05
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	±0.09
$D^0 \to K^0_S\,\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	±0.02
$D^0 \to K^0_S\,K^0_S$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	±0.23
$D^0 \to K^0_S\,\eta$	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
$D^+ \to \pi^+\pi^0$	921	$+2.31 \pm 1.24 \pm 0.23$	±0.17
$D^+ \to \eta\pi^+$	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	$-0.36 \pm 0.09 \pm 0.07$	±0.02
$D^+ \to K^0_S\,K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	±0.04
$D^+_s \to K^0_S\,\pi^+$	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

singly Cabibbo-suppressed

doubly Cabibbo-suppressed



τ Physics

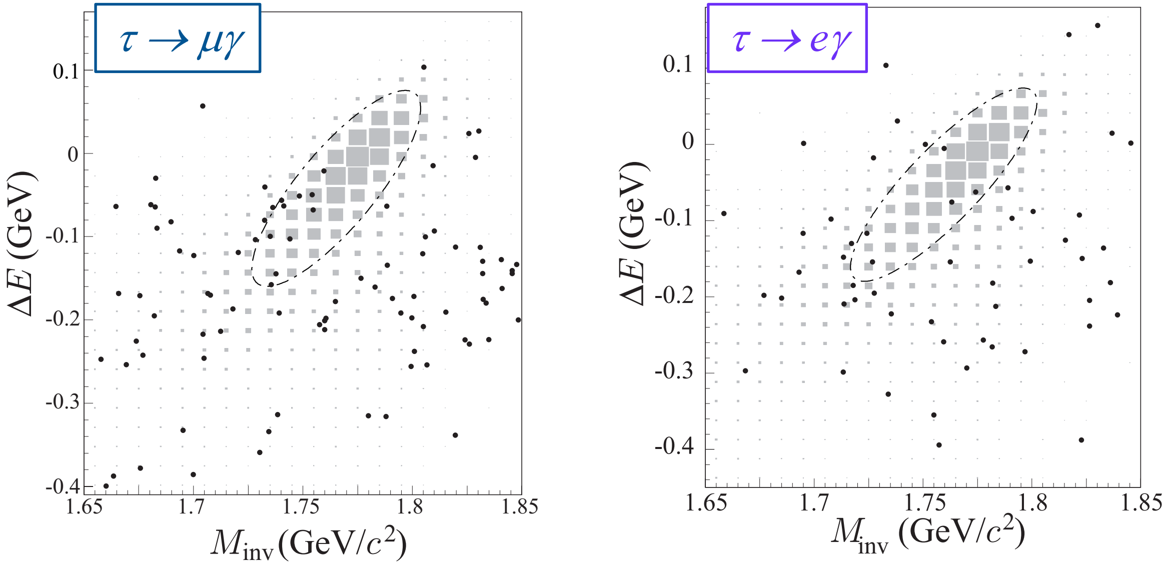


Lepton-flavor-violating (LFV) decays

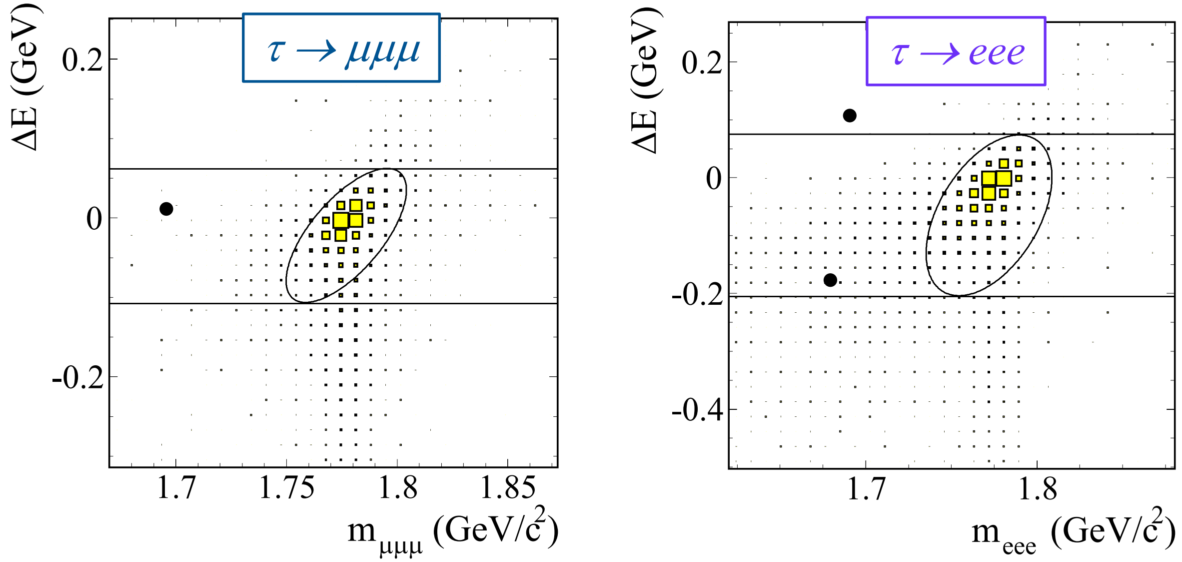
Belle II is ideally suited for searching for LFV decays:

$$M_{\mu\gamma} = \sqrt{E^2_{\mu\gamma} - p^2_{\mu\gamma}}$$

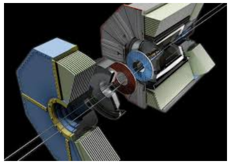
$$\Delta E = E^{CM}_{\mu\gamma} - E^{CM}_{\rm beam}$$



Hayasaka et al. (Belle), PLB 666, 16 (2008)

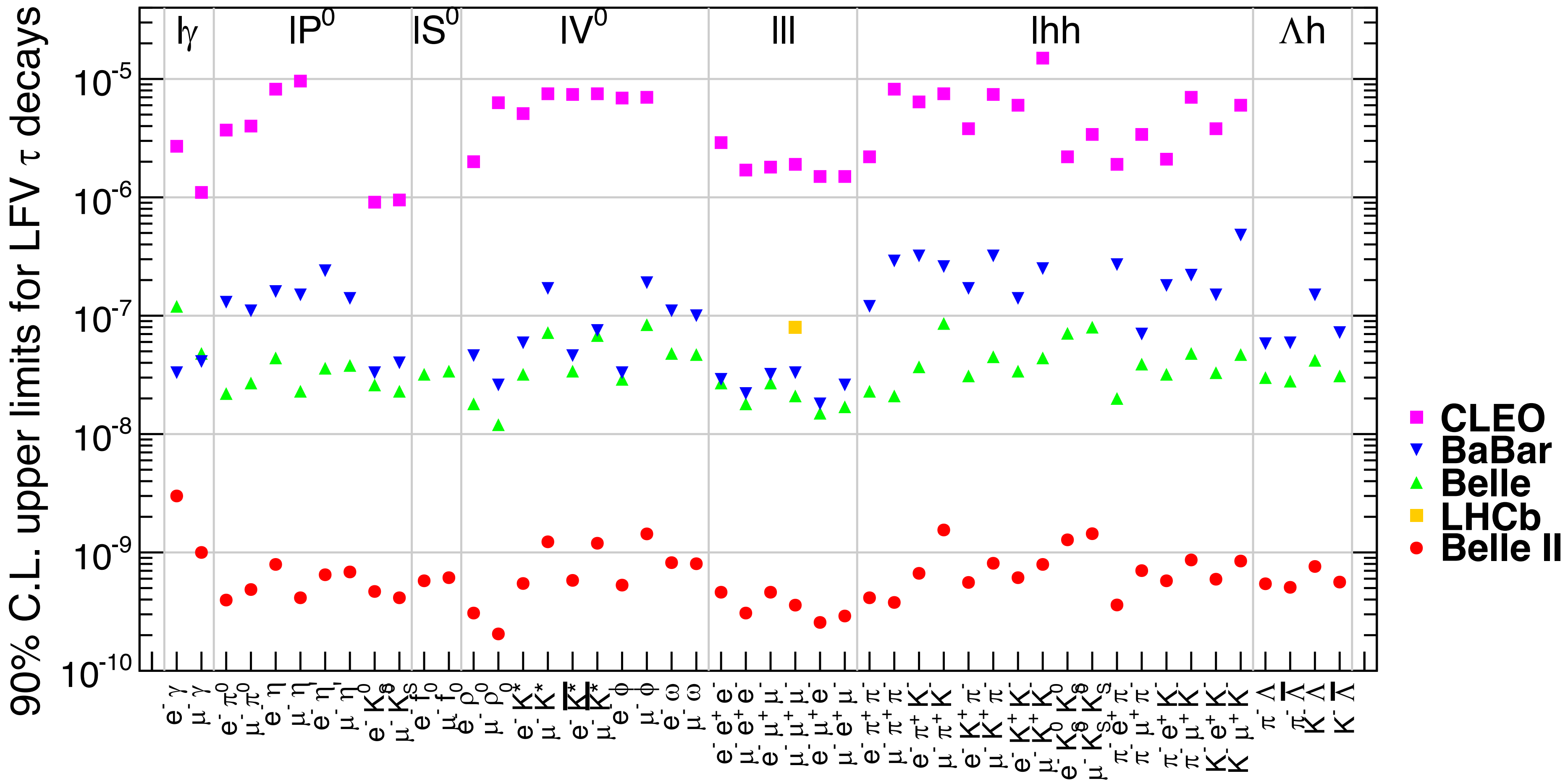


Hayasaka et al. (Belle), PLB 687, 139 (2010)



Lepton-flavor-violating (LFV) decays

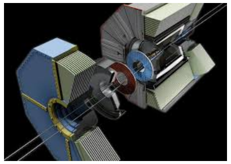
The Belle II Physics Book, arXiv:1808.10567



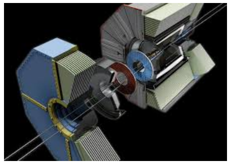
Theory predictions:

SUSY extension to SM: $\mathcal{B}(\tau \to \mu\gamma) \sim [10^{-4} - 10^{-9}]$

SUSY Seesaw model: $\mathcal{B}(\tau \to \mu\gamma) \sim [10^{-9} - 10^{-13}]$



Belle II contribution to $a_\mu = (g\text{-}2)/2$



$a_\mu = (g-2)/2$

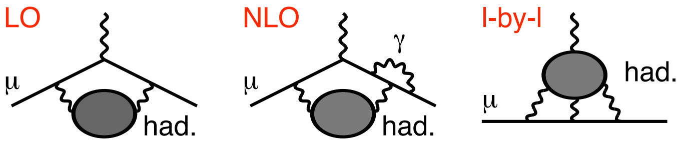
Discrepancy:
a_μ *[Experiment – Theory]* = $(260 \pm 72) \times 10^{-11}$

Experimental uncertainty:
$\delta a_\mu = 63 \times 10^{-11} \rightarrow \sim 16 \times 10^{-11}$
E-989

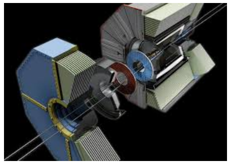
Theoretical uncertainty: *[T. Blum, talk at Moriond Electroweak 2019]*

Contribution	Magnitude (10^{-11})	Uncertainty (10^{-11})
QED	116584718.951	0.080
electroweak	153.6	1.0
NLO hadronic	-98.2	0.4
NNLO hadronic	12.4	0.1
light-by-light hadronic	105	26
LO hadronic	6931 6932.6 6925	34 24.6 27

Hadronic contributions:

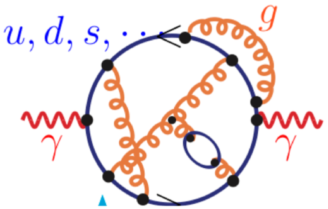


errors from lattice. But LO hadronic can be determined more precisely using data

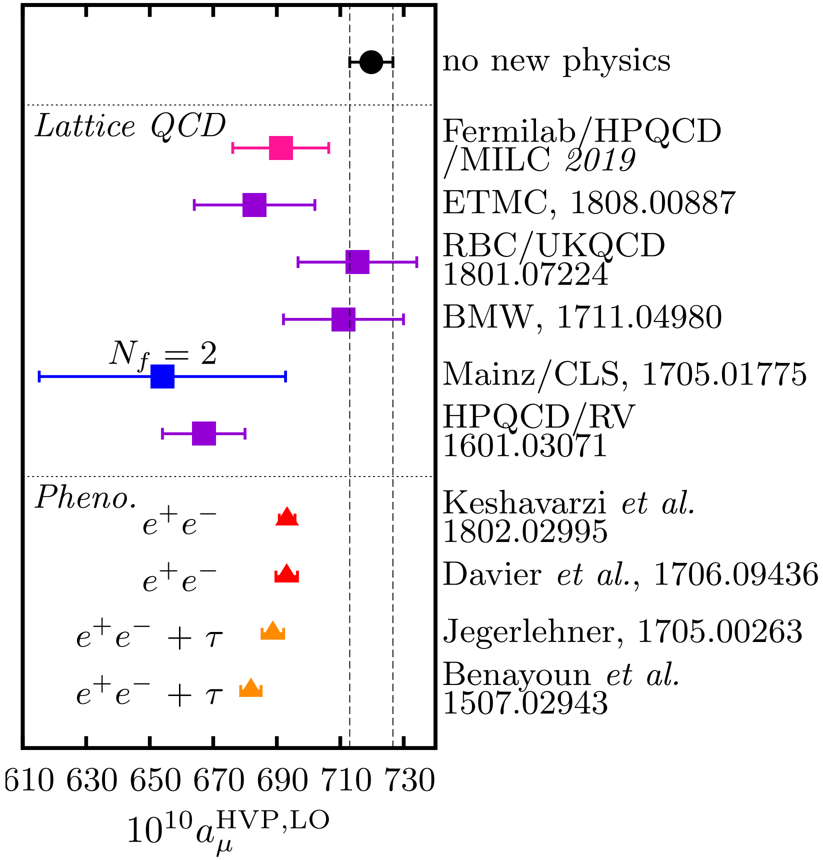


$a_\mu = (g-2)/2$

Leading order hadronic (Vacuum Polarization):

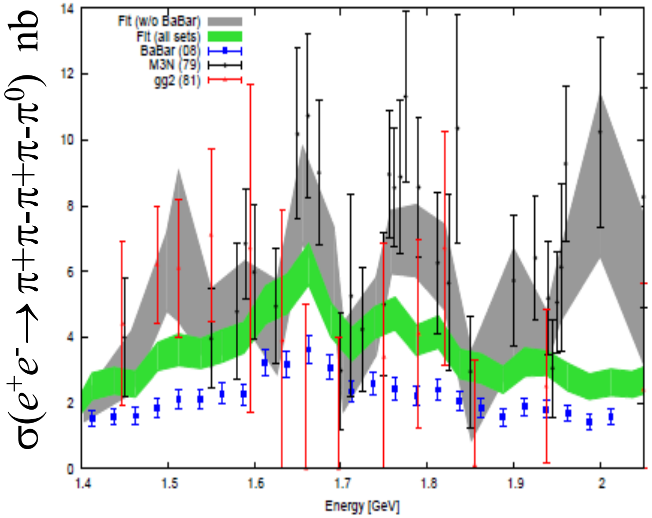


Davies et al.,1902.04223:



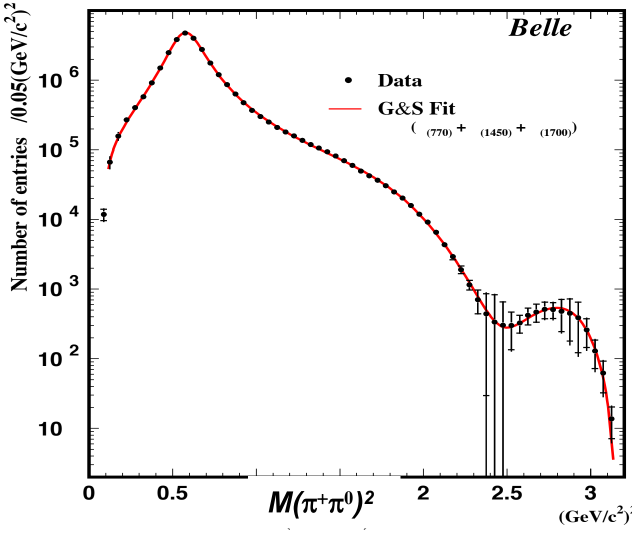
Method 1: $e^+e^- \rightarrow$ _hadrons, 1-2 GeV region_

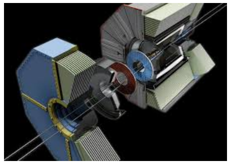
[BaBar, PRL 103, 231801 (2009)]



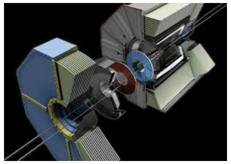
Method 2: $\tau^+ \rightarrow \pi^+\pi^0\nu$ _spectral function_

[Belle, PRD 78, 072006 (2008)]





KOTO Physics

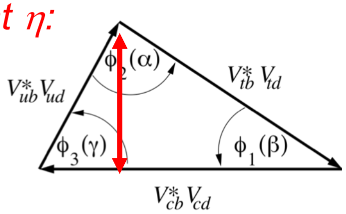


$K_L \rightarrow \pi^0 \nu\nu$: the original ‘golden channel’

June 1989, Littenberg: *indirect and direct CPV contributions to $K_L \rightarrow \pi^0 \nu\nu$ can be estimated from real and imaginary parts of $\mathcal{A}(K^+ \rightarrow \pi^+ \nu\nu)$. The direct CPV piece is much larger. Estimated $\mathcal{B}$: ~10^{-11} . This seems ~impossible to measure.*

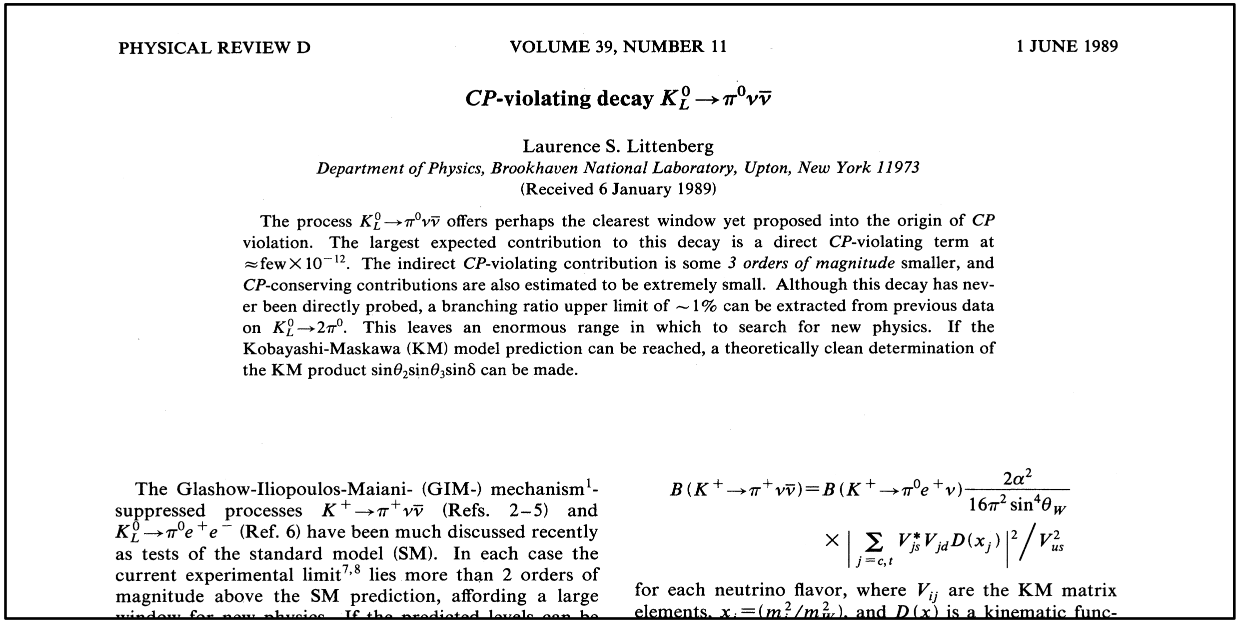
The theoretical prediction is subsequently refined by Buras and others to $\mathcal{B}(K_L \rightarrow \pi^0 \nu\nu) = (3.0 \pm 0.3) \times 10^{-11}$

Sensitive to height η:



30 years later:

15 January 2019, *KOTO publishes in PRL: $\mathcal{B}(K_L \rightarrow \pi^0 \nu\nu) < 3.0 \times 10^{-9}$ (90% CL)*



PHYSICAL REVIEW D VOLUME 39, NUMBER 11 1 JUNE 1989

CP-violating decay $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$

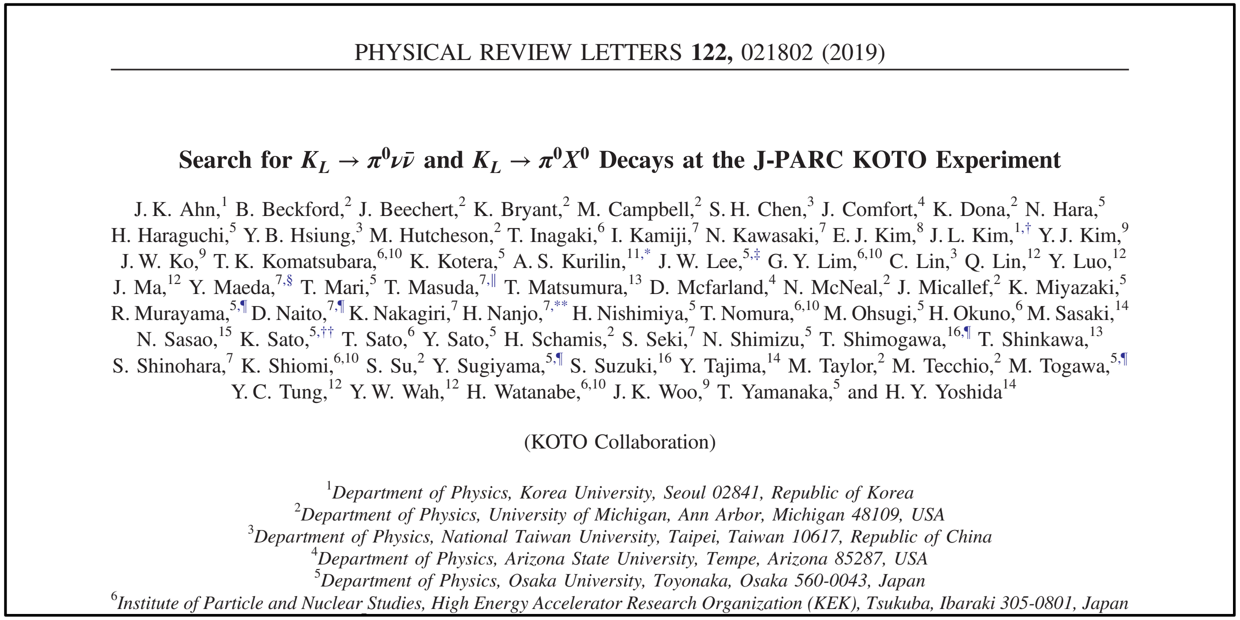
Laurence S. Littenberg
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 6 January 1989)

The process $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ offers perhaps the clearest window yet proposed into the origin of CP violation. The largest expected contribution to this decay is a direct CP-violating term at $\approx$few$\times 10^{-12}$. The indirect CP-violating contribution is some *3 orders of magnitude* smaller, and CP-conserving contributions are also estimated to be extremely small. Although this decay has never been directly probed, a branching ratio upper limit of $\sim 1\%$ can be extracted from previous data on $K_L^0 \rightarrow 2\pi^0$. This leaves an enormous range in which to search for new physics. If the Kobayashi-Maskawa (KM) model prediction can be reached, a theoretically clean determination of the KM product $\sin\theta_2 \sin\theta_3 \sin\delta$ can be made.

The Glashow-Iliopoulos-Maiani- (GIM-) mechanism[1]-suppressed processes $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (Refs. 2–5) and $K_L^0 \rightarrow \pi^0 e^+ e^-$ (Ref. 6) have been much discussed recently as tests of the standard model (SM). In each case the current experimental limit[7,8] lies more than 2 orders of magnitude above the SM prediction, affording a large

$$B(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = B(K^+ \rightarrow \pi^0 e^+ \nu) \frac{2\alpha^2}{16\pi^2 \sin^4\theta_W} \times \left| \sum_{j=c,t} V_{js}^* V_{jd} D(x_j) \right|^2 \Big/ V_{us}^2$$

for each neutrino flavor, where V_{ij} are the KM matrix



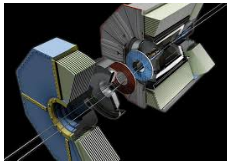
PHYSICAL REVIEW LETTERS **122,** 021802 (2019)

Search for $K_L \rightarrow \pi^0 \nu\bar{\nu}$ and $K_L \rightarrow \pi^0 X^0$ Decays at the J-PARC KOTO Experiment

J. K. Ahn,[1] B. Beckford,[2] J. Beechert,[2] K. Bryant,[2] M. Campbell,[2] S. H. Chen,[3] J. Comfort,[4] K. Dona,[2] N. Hara,[5] H. Haraguchi,[5] Y. B. Hsiung,[3] M. Hutcheson,[2] T. Inagaki,[6] I. Kamiji,[7] N. Kawasaki,[7] E. J. Kim,[8] J. L. Kim,[1,†] Y. J. Kim,[9] J. W. Ko,[9] T. K. Komatsubara,[6,10] K. Kotera,[5] A. S. Kurilin,[11,*] J. W. Lee,[5,‡] G. Y. Lim,[6,10] C. Lin,[3] Q. Lin,[12] Y. Luo,[12] J. Ma,[12] Y. Maeda,[7,§] T. Mari,[5] T. Masuda,[7,∥] T. Matsumura,[13] D. Mcfarland,[4] N. McNeal,[2] J. Micallef,[2] K. Miyazaki,[5] R. Murayama,[5,¶] D. Naito,[7,¶] K. Nakagiri,[7] H. Nanjo,[7,**] H. Nishimiya,[5] T. Nomura,[6,10] M. Ohsugi,[5] H. Okuno,[6] M. Sasaki,[14] N. Sasao,[15] K. Sato,[5,††] T. Sato,[6] Y. Sato,[5] H. Schamis,[2] S. Seki,[7] N. Shimizu,[5] T. Shimogawa,[16,¶] T. Shinkawa,[13] S. Shinohara,[7] K. Shiomi,[6,10] S. Su,[2] Y. Sugiyama,[5,¶] S. Suzuki,[16] Y. Tajima,[14] M. Taylor,[2] M. Tecchio,[2] M. Togawa,[5,¶] Y. C. Tung,[12] Y. W. Wah,[12] H. Watanabe,[6,10] J. K. Woo,[9] T. Yamanaka,[5] and H. Y. Yoshida[14]

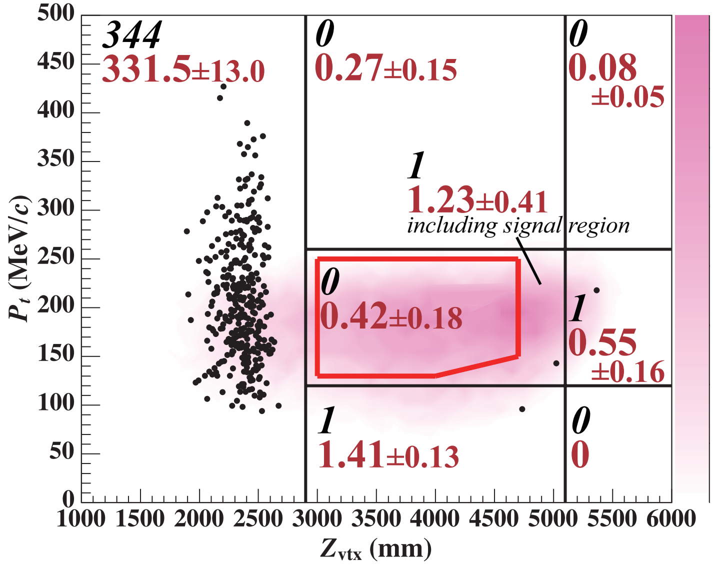
(KOTO Collaboration)

[1]*Department of Physics, Korea University, Seoul 02841, Republic of Korea*
[2]*Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA*
[3]*Department of Physics, National Taiwan University, Taipei, Taiwan 10617, Republic of China*
[4]*Department of Physics, Arizona State University, Tempe, Arizona 85287, USA*
[5]*Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[6]*Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan*



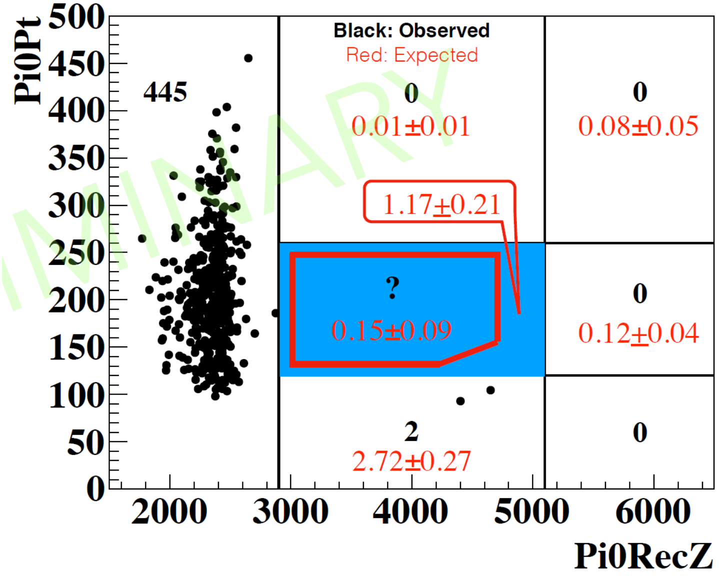
$K_L \to \pi^0 \nu\nu$: KOTO Measurement

2015 Data *[PRL 122, 021802 (2019)]:*



Signal: 0.023
Backgrnd: 0.42
S/B: 1/18

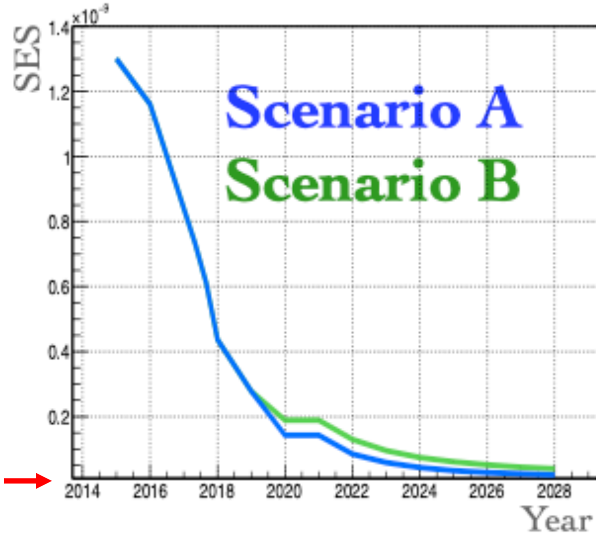
2016-2018 Data *[M. Cambell's talk]:*



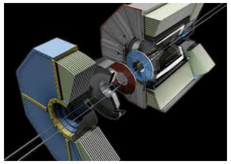
Signal: 0.037
Backgrnd: 0.15
S/B: 1/4

Future *[Y.-C. Tung, CERN EP Seminar, 26 Feb 2019]:*

Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024-
Avg. Beam Power (kW)	38	42	43	50	50	70	-	80	90	100
Run Time (month)	3.1	1	1.3	2.2						
Scenario A (month)					2	4	-	4	4	4
Scenario B (month)					2	2	-	2	2	2

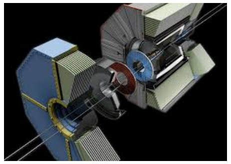


SM 0.03 →



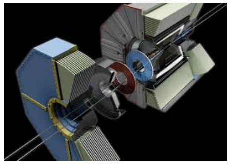
Summary

- Belle II is now (essentially) fully constructed and installed. The experiment is beginning its first physics run (“Phase III”) run (April-July). This will fully commission the detector, and there will be early physics (e.g., $D^0 \to \gamma\gamma$, dark photon search, etc.)
- Accelerator commissioning is proceeding, but there are growing pains as expected: background is high, so current is kept low. β_y is slowly being reduced.
- Physics potential is huge: there is much better vertexing, particle ID than in Belle; factor of 50x statistics; and full reconstruction on tag side is notably improved over Belle/BaBar.
- KOTO has come a long way since the first 100-hour analysis. SES is now near the Grossman-Nir bound. It looks very promising the experiment will get to 10^{-10} ; while this is still larger than the SM, it is significantly greater sensitivity to NP than previous searches.

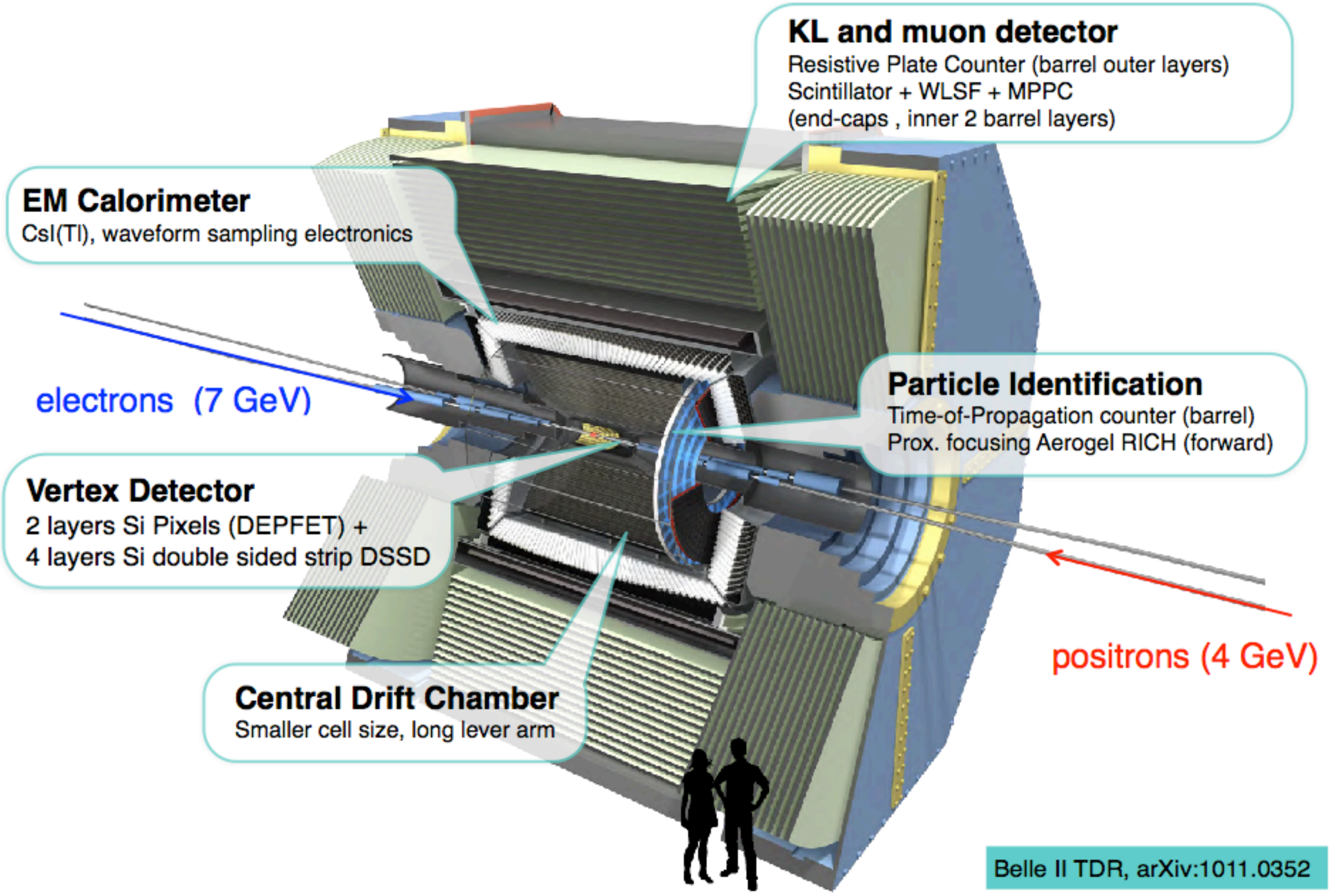


Extra

Extra Slides



The Belle II Detector



KL and muon detector
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC
(end-caps , inner 2 barrel layers)

EM Calorimeter
CsI(Tl), waveform sampling electronics

electrons (7 GeV)

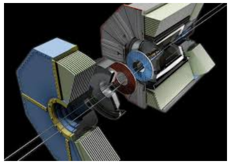
Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

Vertex Detector
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip DSSD

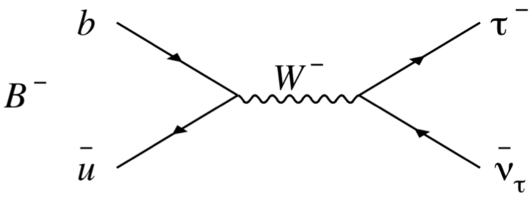
positrons (4 GeV)

Central Drift Chamber
Smaller cell size, long lever arm

Belle II TDR, arXiv:1011.0352



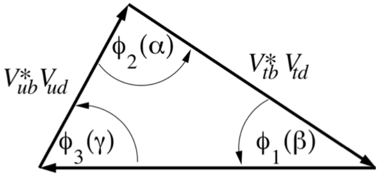
$|V_{ub}|$ via $B^+ \to \tau^+\nu$



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

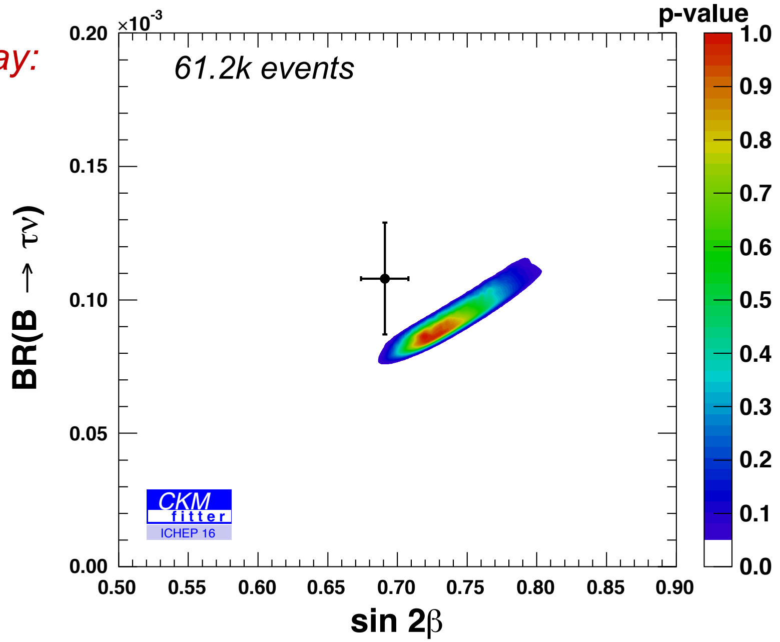
World average: $\mathcal{B}(B^+ \to \tau^+\nu) = (1.06 \pm 0.19) \times 10^{-4}$

$\Rightarrow$ $\boxed{|V_{ub}| = (3.55 \pm 0.12) \times 10^{-3}}$ *using* $f_B = (185 \pm 3)$ *MeV (FLAG 2017)*

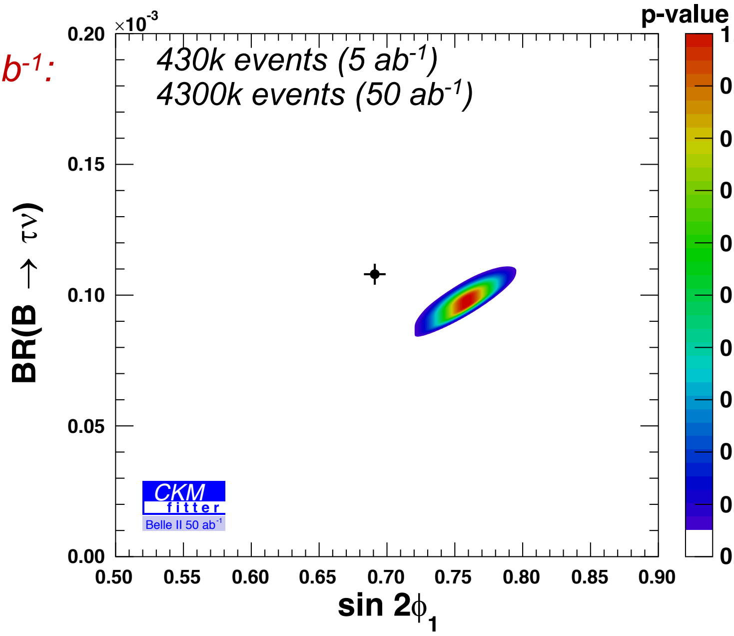


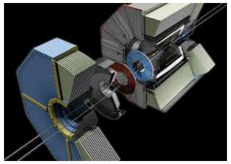
There is tension coming from $|V_{ub}|$ *measured in* $\mathcal{B}(B^+ \to \tau^+\nu)$ *and* ϕ_1 (β) *and* ϕ_2 (α):

Today:



Belle II 50 ab^{-1}:





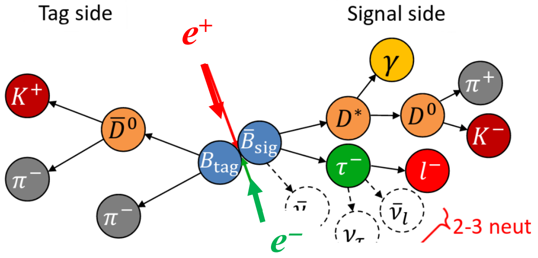
$|V_{cb}|$ from $B \to D l \nu$

711 fb^{-1}

Glattauer at al. (Belle),
PRD 93, 032006 (2016)

$B \to D \ell \nu$ Reconstruction:

Divide event into 2 hemispheres: “signal” side and “flavor tag” side. Tag side is fully reconstructed (using neural net)



charged tags

$B^- \to D^{*0}\pi^-$
$B^- \to D^{*0}\pi^-\pi^0$
$B^- \to D^{*0}\pi^-\pi^+\pi^-$
$B^- \to D^{*0}\pi^-\pi^+\pi^-\pi^0$

$B^- \to D^0\pi^-$
$B^- \to D^0\pi^-\pi^0$
$B^- \to D^0\pi^-\pi^+\pi^-$

$B^- \to D^{*0}D_s^{*-}$
$B^- \to D^{*0}D_s^-$
$B^- \to D^0D_s^{*-}$
$B^- \to D^0D_s^-$

$B^- \to J/\psi\, K^-$
$B^- \to J/\psi\, K^-\pi^+\pi^-$
$B^- \to J/\psi\, K^-\pi^0$
$B^- \to J/\psi\, K_S\pi^-$

$B^- \to D^0K^-$
$B^- \to D^+\pi^-\pi^-$

neutral tags

$B^0 \to D^{*+}\pi^-$
$B^0 \to D^{*+}\pi^-\pi^0$
$B^0 \to D^{*+}\pi^-\pi^+\pi^-$
$B^0 \to D^{*+}\pi^-\pi^+\pi^-\pi^0$

$B^0 \to D^+\pi^-$
$B^0 \to D^+\pi^-\pi^0$
$B^0 \to D^+\pi^-\pi^+\pi^-$

$B^0 \to D^{*+}D_s^{*-}$
$B^0 \to D^{*+}D_s^-$
$B^0 \to D^+D_s^{*-}$
$B^0 \to D^+D_s^-$

$B^0 \to J/\psi\, K_S$
$B^0 \to J/\psi\, K^-\pi^+$
$B^0 \to J/\psi\, K_S\pi^+\pi^-$

$B^0 \to D^0\pi^0$

charged signals

$D^+ \to K^-\pi^+\pi^+$
$D^+ \to K^-\pi^+\pi^+\pi^0$
$D^+ \to K^-\pi^+\pi^+\pi^+\pi^-$
$D^+ \to K^-K^+\pi^+$

$D^+ \to K_S\,\pi^+$
$D^+ \to K_S\,\pi^+\pi^0$
$D^+ \to K_S\,\pi^+\pi^+\pi^-$
$D^+ \to K_S\,K^+$

$D^+ \to \pi^+\pi^0$
$D^+ \to \pi^+\pi^+\pi^-$

neutral signals

$D^0 \to K^-\pi^+$
$D^0 \to K^-\pi^+\pi^0$
$D^0 \to K^-\pi^+\pi^+\pi^-$
$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$

$D^0 \to K_S\,\pi^+\pi^-$
$D^0 \to K_S\,\pi^+\pi^-\pi^0$
$D^0 \to K_S\,\pi^0$

$D^0 \to K^-K^+$
$D^0 \to \pi^+\pi^-$
$D^0 \to K_SK_S$
$D^0 \to \pi^0\pi^0$
$D^0 \to K_S\,\pi^0\pi^0$

$D^0 \to \pi^+\pi^+\pi^0$

Note: over 1000 decay topologies considered.
[This is straightforward at an e^+e^- machine]