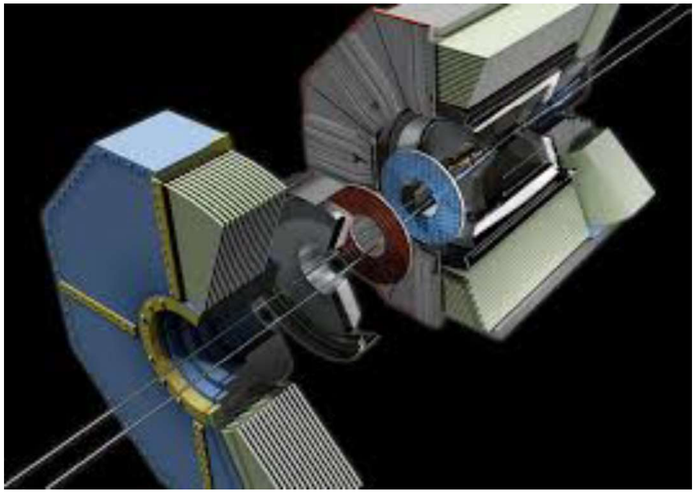


Physics Prospects of Future Asymmetric B Factories (Belle II)

Alan Schwartz

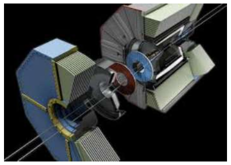
University of Cincinnati, USA

Gordon Research Conference:

New Tools for the Next Generation of Particle Physics and Cosmology

Hong Kong University of Science and Technology
4 July 2019

- *overview*
- *measurement of angles*
- *measurement of sides ($|V_{ub}|$)*
- *searches for new physics [$R(D^{(*)})$...]*
- *schedule and status*



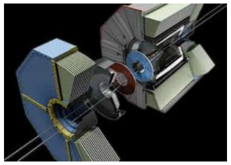
Motivation

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?

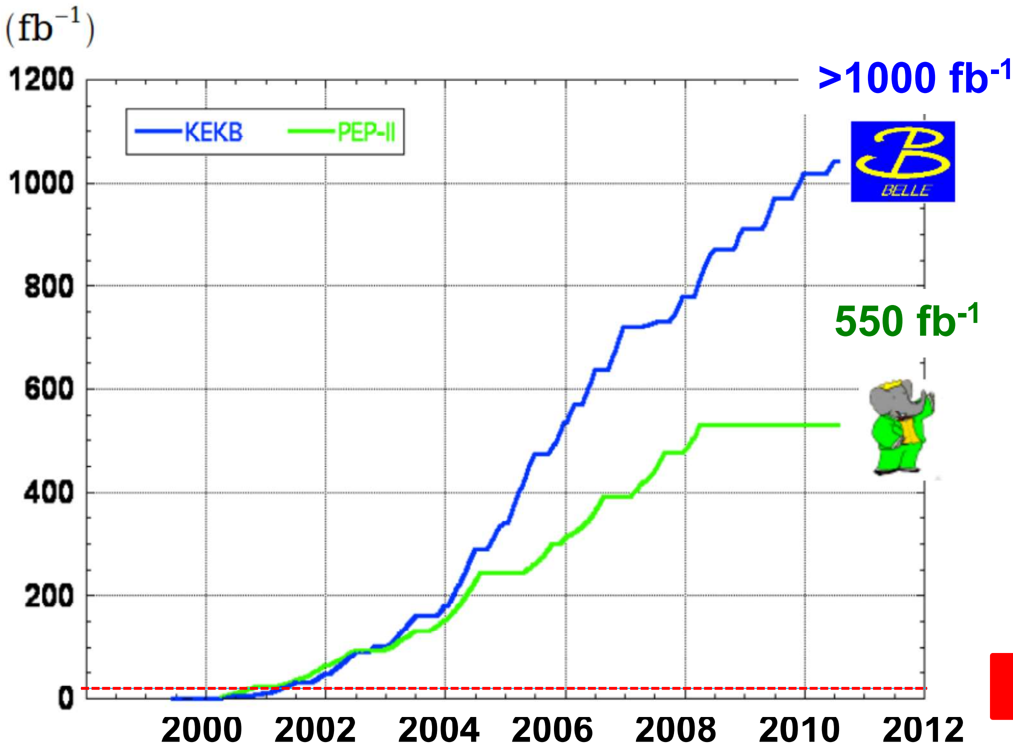
- *Low backgrounds, high trigger efficiency, excellent γ and π^0 recontruction (and thus η, η', ρ+, etc. reconstruction), high flavor-tagging efficiency with low dilution, many control samples to study systematics*
- *Due to low backgrounds, negligible trigger bias, and good kinematic resolutions, Dalitz 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:

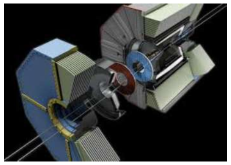
*The "B Factory" experiments Belle and BaBar ran for ~10 years (2000-2010) and were huge successes: **1108 papers** published to date, many discoveries (CPV in $B^0 \to J/\psi\, K^0$, direct CPV in $B^0 \to \pi^+\pi^-$, D^0-D^0bar mixing, X(3872), D_{sJ}(2317), etc.), **a Nobel Prize** (Kobayashi and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



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*



Physics potential

https://arxiv.org/abs/1808.10567

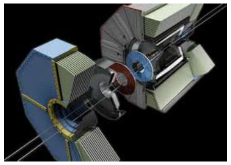
Outcome of the B2TIP (Belle II Theory Interface) Workshops
Emphasis is on New Physics (NP) reach.

Good participation from theory community,
lattice QCD community and Belle II experimenters.
689 pages, published by Oxford University Press

KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047
UWThPh 2018-26

The Belle II Physics Book

E. Kou[74,¶,†], P. Urquijo[143,§,†], W. Altmannshofer[133,¶], F. Beaujean[78,¶], G. Bell[120,¶], M. Beneke[112,¶], I. I. Bigi[146,¶], F. Bishara[148,16,¶], M. Blanke[49,50,¶], C. Bobeth[111,112,¶], M. Bona[150,¶], N. Brambilla[112,¶], V. M. Braun[43,¶], J. Brod[110,133,¶], A. J. Buras[113,¶], H. Y. Cheng[44,¶], C. W. Chiang[91,¶], M. Ciuchini[58,¶], G. Colangelo[126,¶], H. Czyz[154,29,¶], A. Datta[144,¶], F. De Fazio[52,¶], T. Deppisch[50,¶], M. J. Dolan[143,¶], J. Evans[133,¶], S. Fajfer[107,139,¶], T. Feldmann[120,¶], S. Godfrey[7,¶], M. Gronau[61,¶], Y. Grossman[15,¶], F. K. Guo[41,132,¶], U. Haisch[148,11,¶], C. Hanhart[21,¶], S. Hashimoto[30,26,¶], S. Hirose[88,¶], J. Hisano[88,89,¶], L. Hofer[125,¶], M. Hoferichter[166,¶], W. S. Hou[91,¶], T. Huber[120,¶], S. Jaeger[157,¶], S. Jahn[82,¶], M. Jamin[124,¶], J. Jones[102,¶], M. Jung[111,¶], A. L. Kagan[133,¶], F. Kahlhoefer[1,¶], J. F. Kamenik[107,139,¶], T. Kaneko[30,26,¶], Y. Kiyo[63,¶], A. Kokulu[112,138,¶], N. Kosnik[107,139,¶], A. S. Kronfeld[20,¶], Z. Ligeti[19,¶], H. Logan[7,¶], C. D. Lu[41,¶], V. Lubicz[151,¶], F. Mahmoudi[140,¶], K. Maltman[171,¶], S. Mishima[30,¶], M. Misiak[164,¶],



Belle II “golden modes”

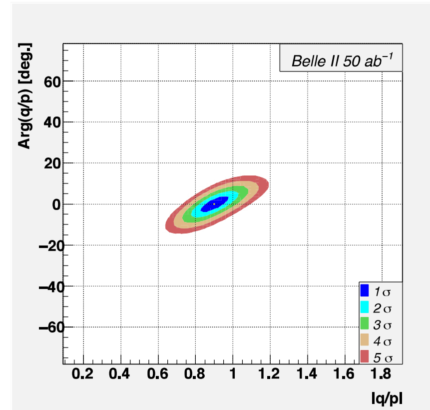
The Belle II Physics Book, arXiv:1808.10567, to appear in Prog. Theor. Exp. Physics

B physics:

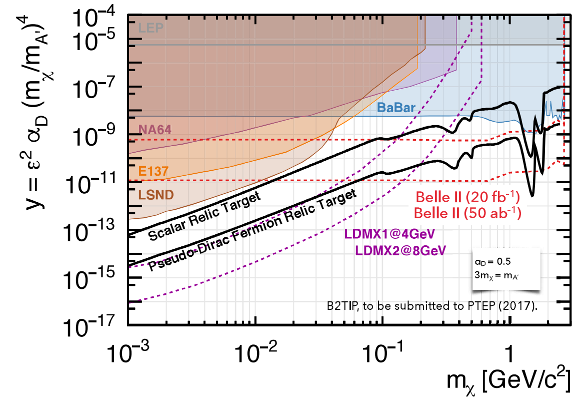
(● covered here)

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
$\lvert V_{cb}\rvert$ incl.	1%	Belle II
$\lvert V_{cb}\rvert$ excl.	1.5%	Belle II
$\lvert V_{ub}\rvert$ incl.	3%	Belle II
● $\lvert V_{ub}\rvert$ 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:

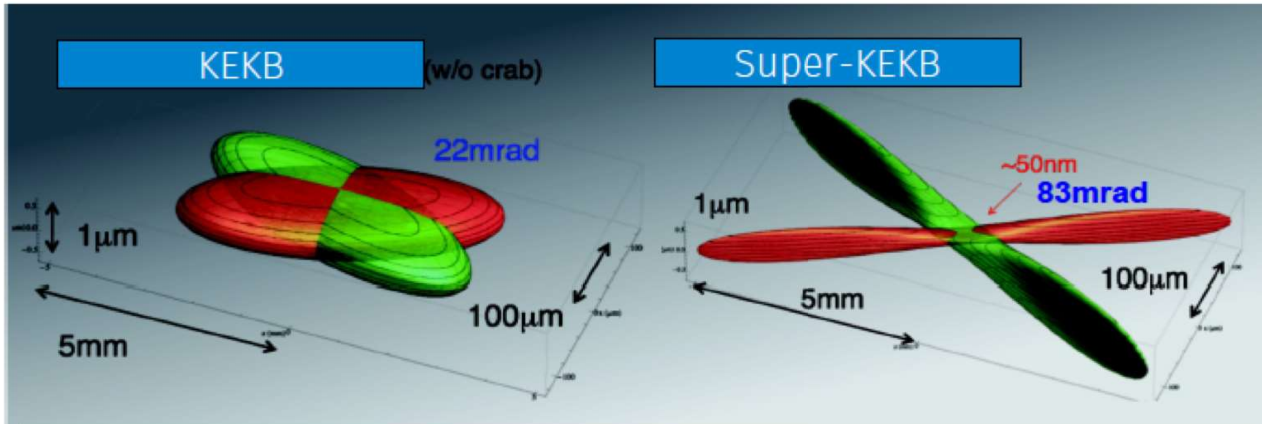


Dark Photon/Sector:



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

How to get 40x instantaneous luminosity?



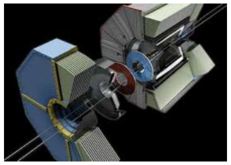
	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

factor 20   factor 2-3

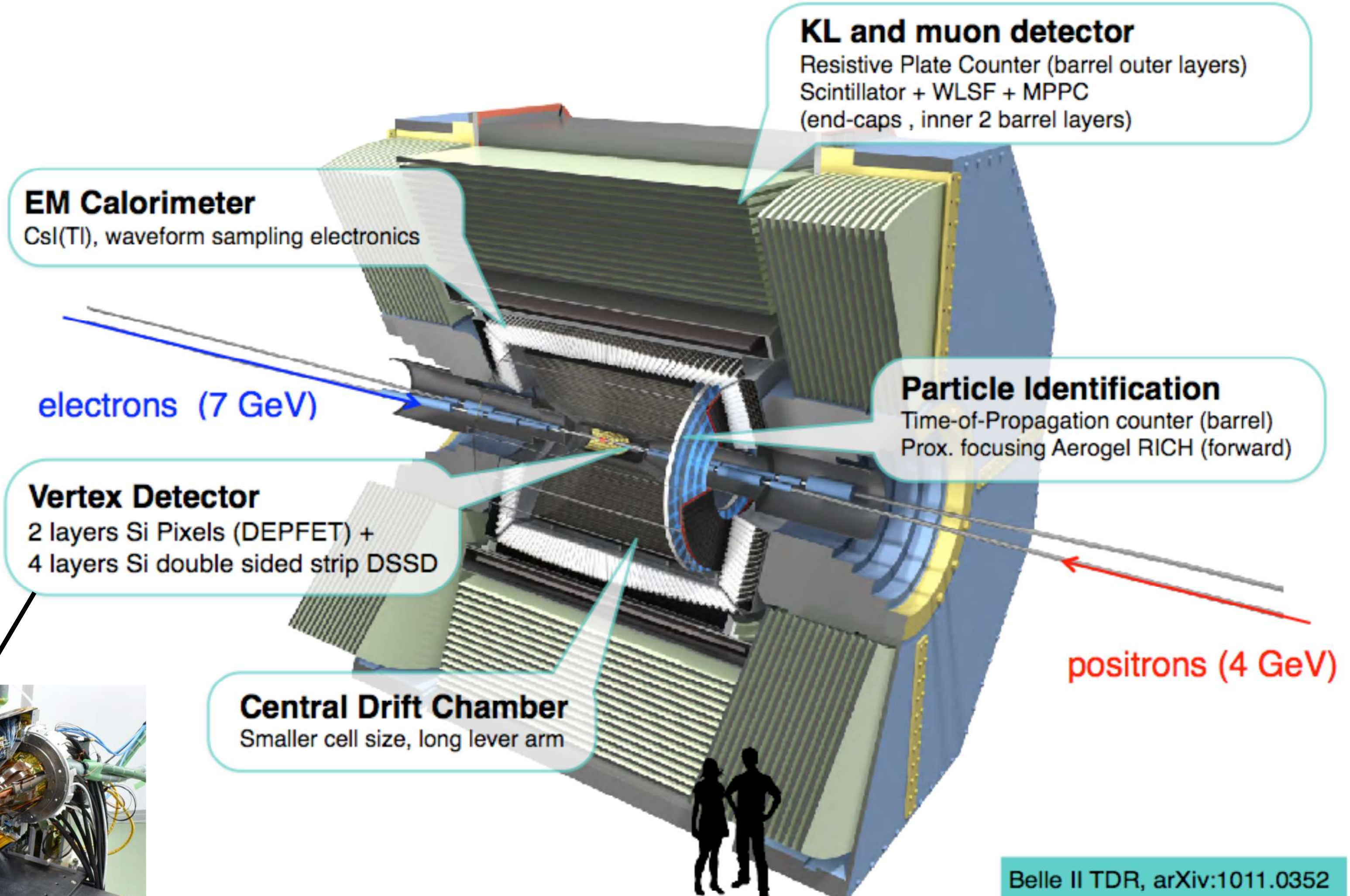
beam size:
100 μm(H) x 2 μm(V)
→ 10 μm(H) x 59 nm(V)

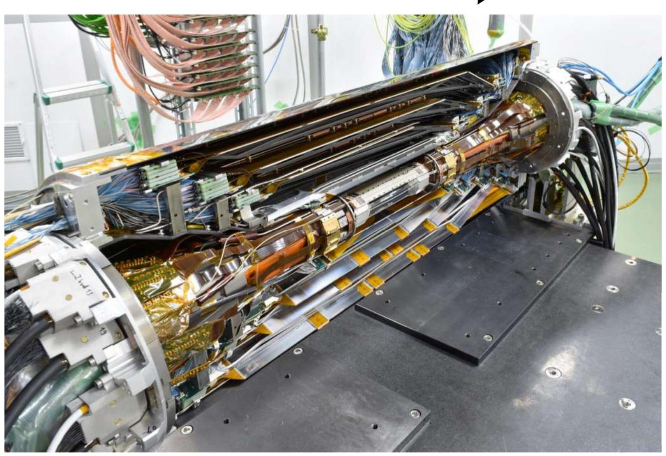
Belle-II Goal:
40 x Belle = 8 x 10^{35}

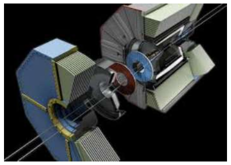
Final focus quadrupole being inserted:



The Belle II Detector







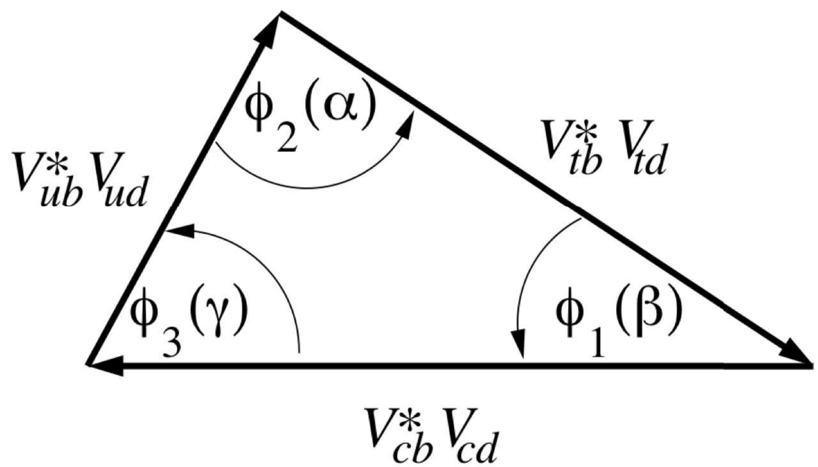
Unitarity triangle – determining the angles

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

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

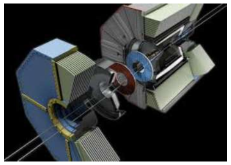
Belle/BaBar **LHCb**

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



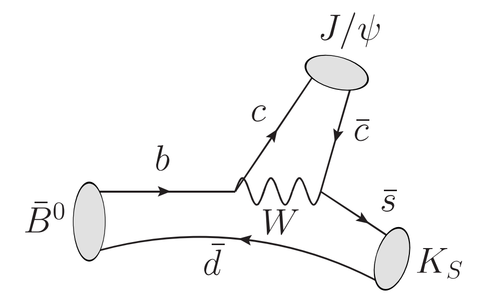
$B^- \to D^{(*)}_{CP}\, K^{(*)-}$
$B^0 \to D_{CP}\, K^{*0}$
$B^- \to D^{(*)}(K^+\pi^-)\, K^{(*)-}$
$B^- \to D^{(*)0}\,\pi^-$
$B^- \to D^{(*)}(K_S\,\pi^+\pi^-)\, K^{(*)-}$
$B^- \to D(\pi^0\pi^+\pi^-)\, K^-$
$B^- \to D(K_S\,K^+\pi^-)\, K^-$

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



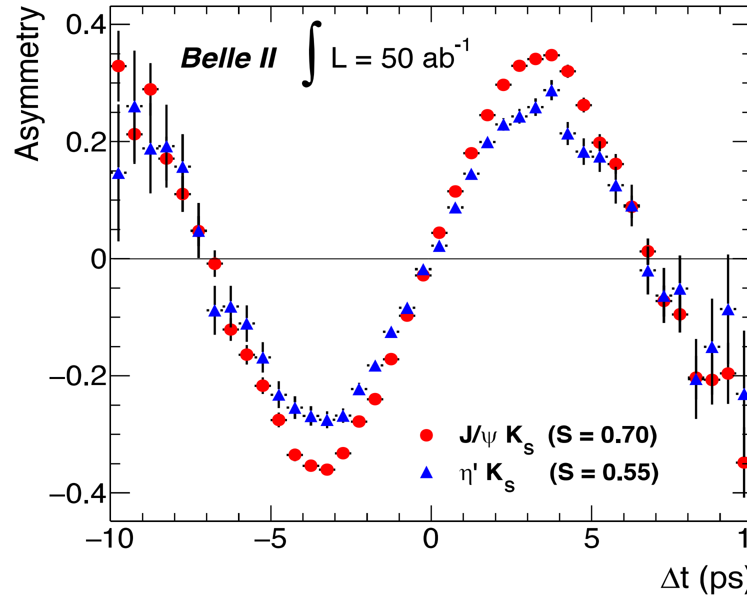
Determining ϕ_1 (β)

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



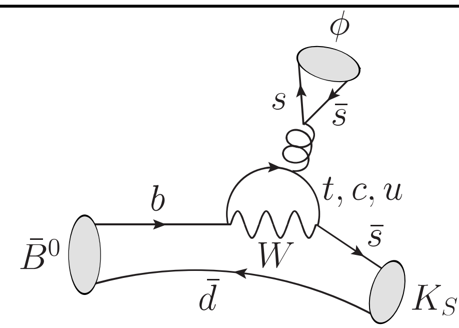
$$\mathcal{A}_{c\bar{c}s} \;=\; V_{cb}^{*}V_{cs}T + V_{ub}^{*}V_{us}P$$

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



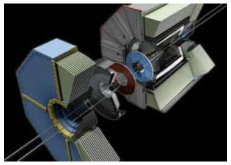
$$A_{CP} \;=\; A\cos(\Delta M\Delta t) + S\sin(\Delta M\Delta t)$$

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



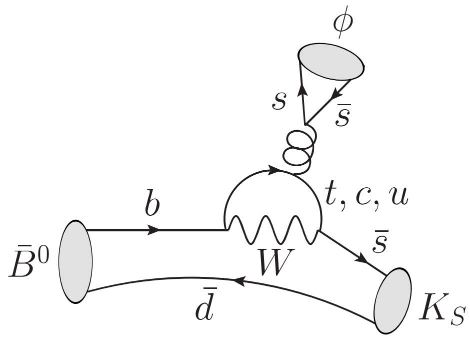
$$\mathcal{A}_{q\bar{q}s} \;=\; V_{cb}^{*}V_{cs}P + V_{ub}^{*}V_{us}T'$$

	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

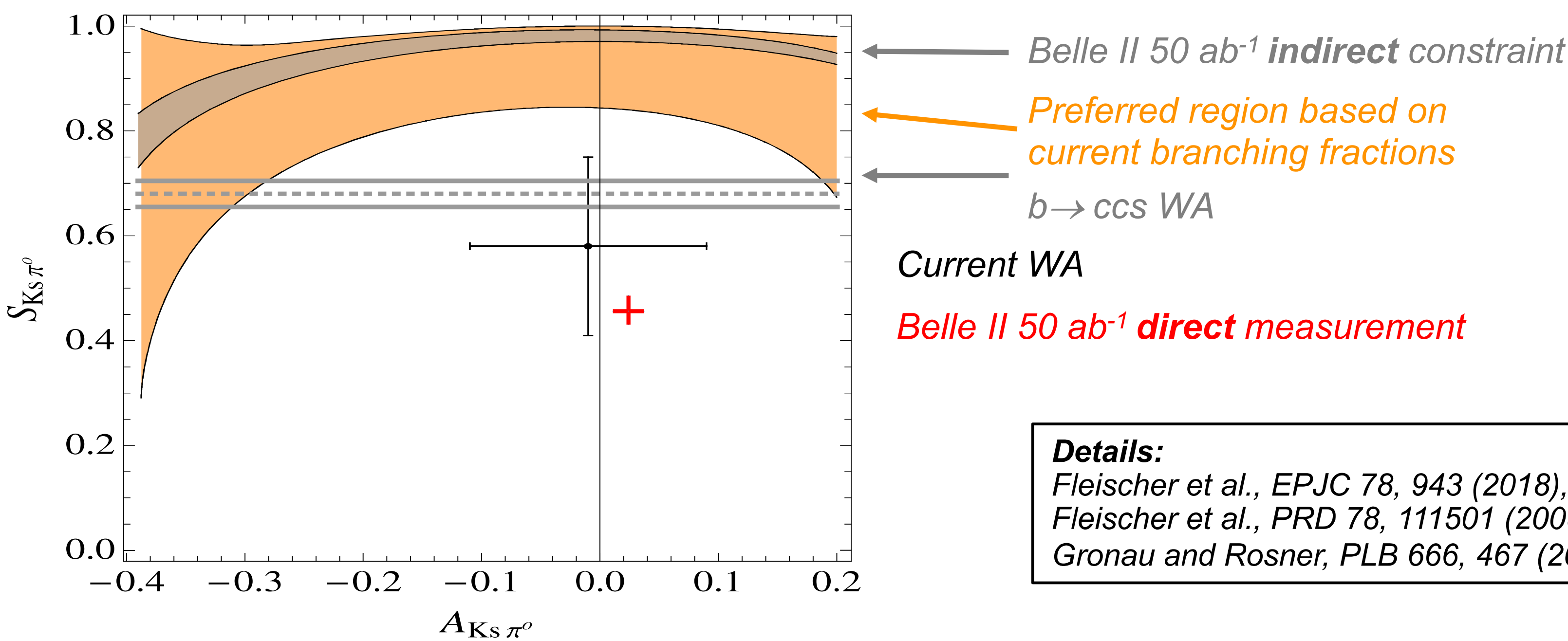


$$A_{CP} = A\cos(\Delta M \Delta t) + S\sin(\Delta M \Delta t)$$

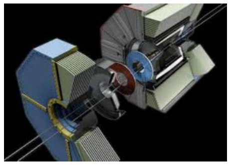
	WA (2017)		5 ab^{-1}		50 ab^{-1}	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$K^0_S\pi^0$	0.17	0.10	0.09	0.06	0.028	0.018

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 $B^0 \to \pi^0 K_S$



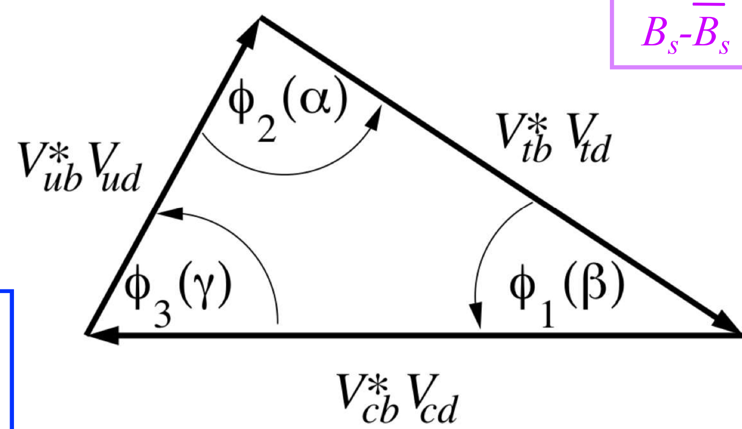
Details:
Fleischer et al., EPJC 78, 943 (2018), arXiv:1806.08783;
Fleischer et al., PRD 78, 111501 (2008), arXiv:0806.2900;
Gronau and Rosner, PLB 666, 467 (2008), arXiv:0807.3080.



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)

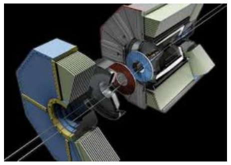
$B^0 \to \pi \ell^+ \nu$
$B^0 \to X_u \ell \nu$
$B^+ \to \tau^+ \nu$
$\Lambda_b \to p \ell^+ \nu$

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)

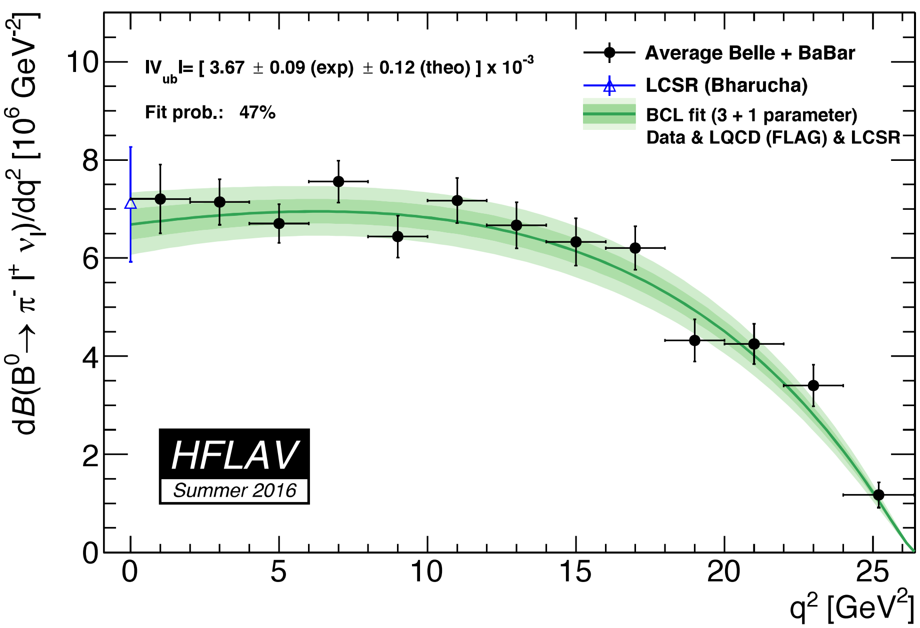
Caprini et al., Nucl. Phys. B530, 153 (1998)
FNAL/MILC, PRD 89, 114504 (2014)
FNAL/MILC, PRD 92, 034506 (2015)
Benson et al., Nucl. Phys. B665, 367 (2003)
Gambino, Uraltsev, EPJ C34, 181 (2004)
Gambino, JHEP 09, 055 (2011)
Alberti et al., PRL 114, 061802 (2015)
Bauer, Ligeti, et al., PRD 70, 094017 (2004)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



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

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

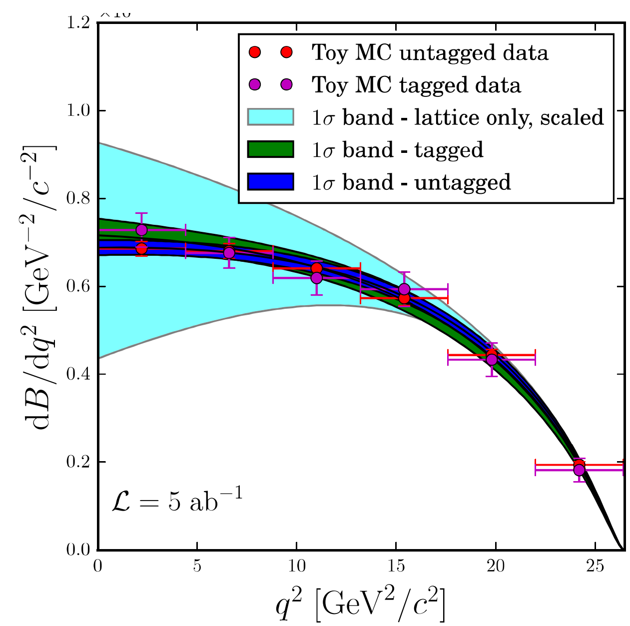
Use BCL parametrization of form factor, fit q^2 spectrum for BCL parameters and $|V_{ub}|$

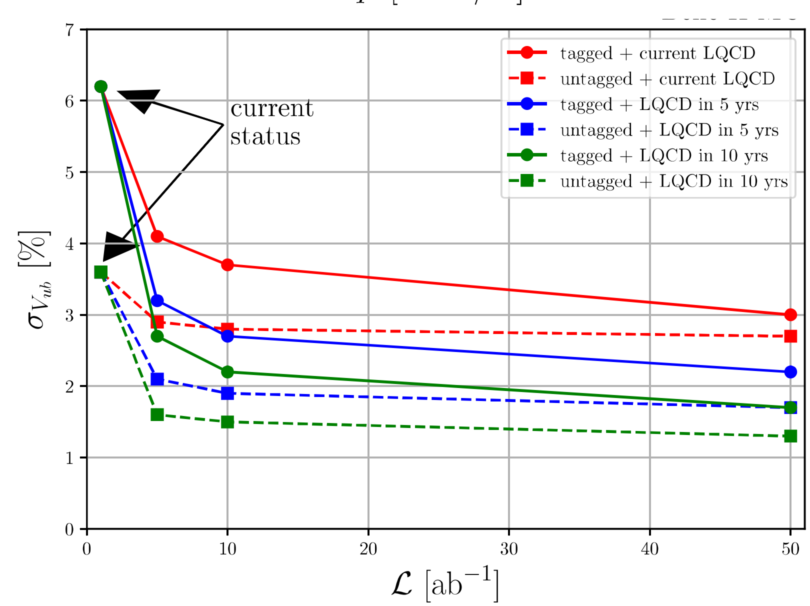


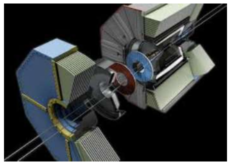
$|V_{ub}| = (3.67 \pm 0.09_{exp} \pm 0.12_{th}) \times 10^{-3}$

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} $B\to \pi l \nu$



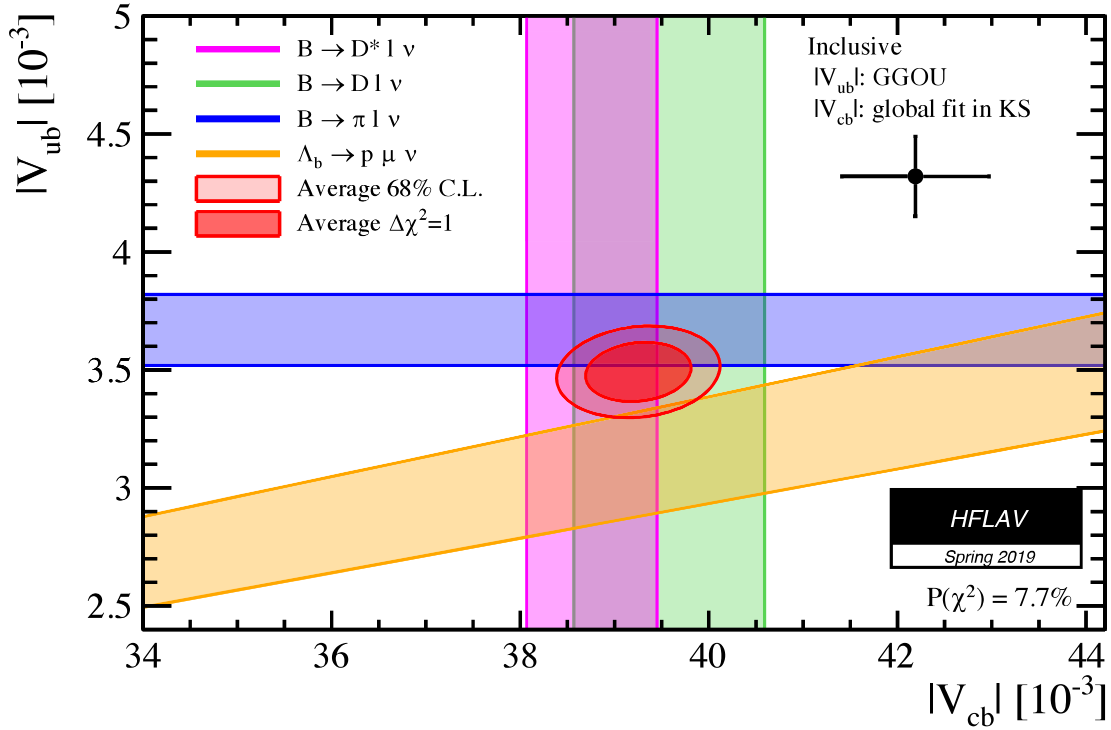




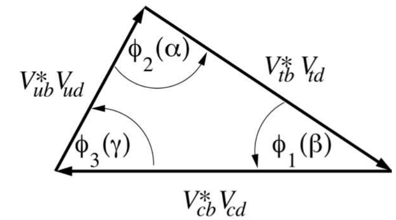
$|V_{ub}|$ via exclusive $B \to \pi l \nu$

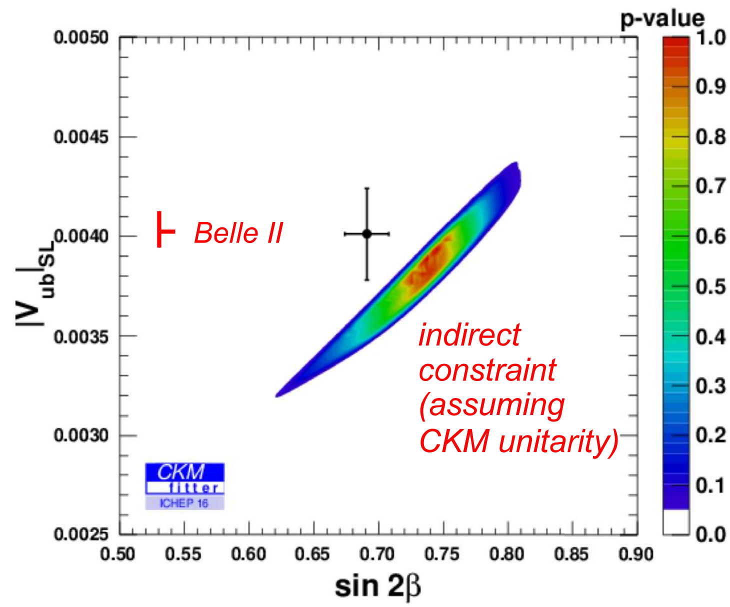
Should help resolve 2 "tensions" (discrepancies):

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



Consistency with ϕ_1 (β)



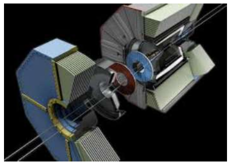


Exclusive: $|V_{ub}| = (0.349 \pm 0.013)\%$

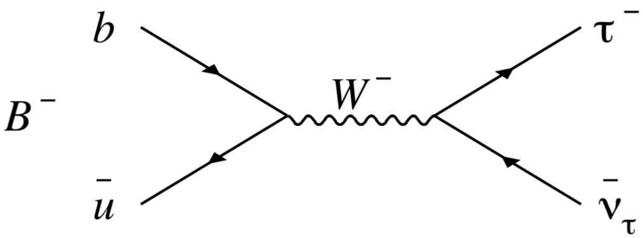
Inclusive: $|V_{ub}| = (0.430 \pm 0.020)\%$ [GGOU]

$|V_{cb}| = (3.925 \pm 0.056)\%$

$|V_{cb}| = (4.219 \pm 0.078)\%$ [spectral moments in $B \to X \ell \nu$]



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

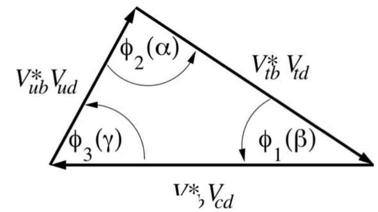


World average: $\mathcal{B}(B^+ \to \tau^+ \nu) = (1.06 \pm 0.19) \times 10^{-4}$

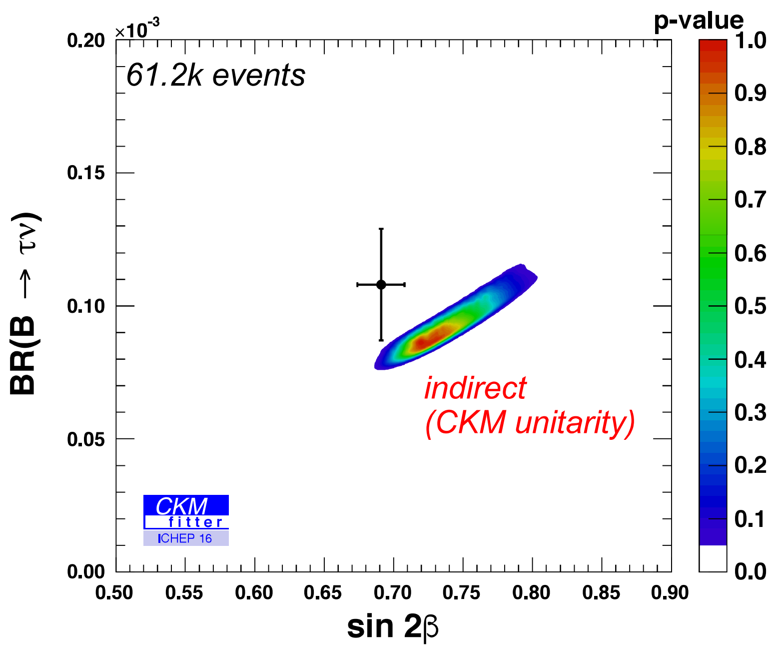
$\Rightarrow$ $|V_{ub}| = (3.55 \pm 0.12) \times 10^{-3}$

using $f_B = (185 \pm 3)$ MeV (FLAG 2017)

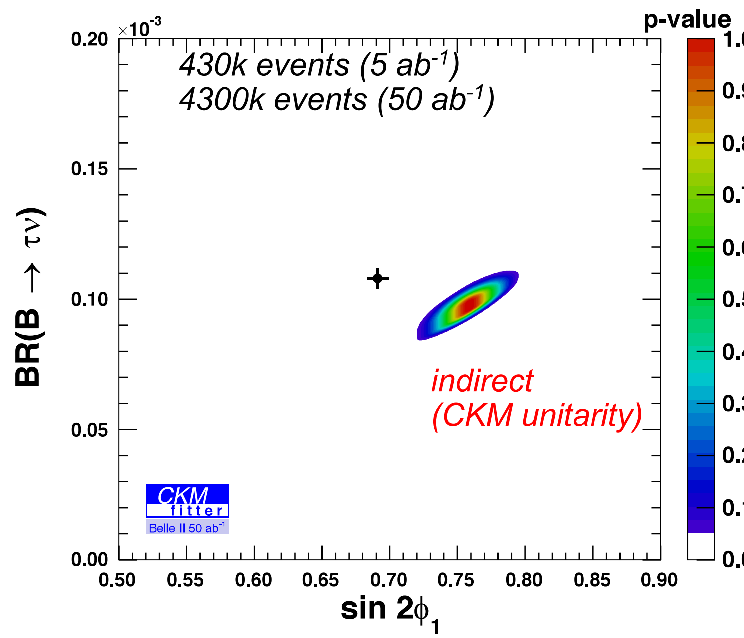
There is tension coming from $|V_{td}|$ *measured in* $\mathcal{B}(B^+ \to \tau^+ \nu)$ *and* ϕ_1 (β) *and* ϕ_2 (α):

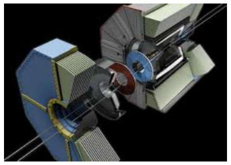


Today:

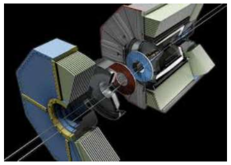


Belle II 50 ab^{-1}:

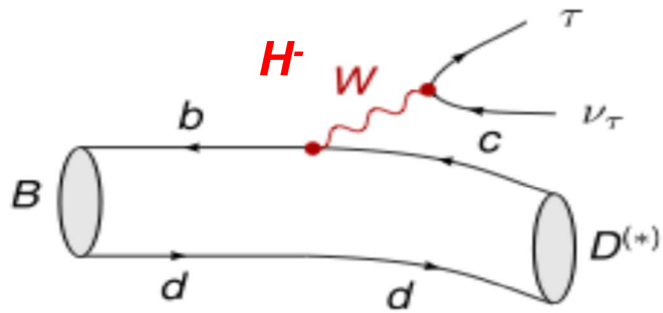




Searches for New Physics



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

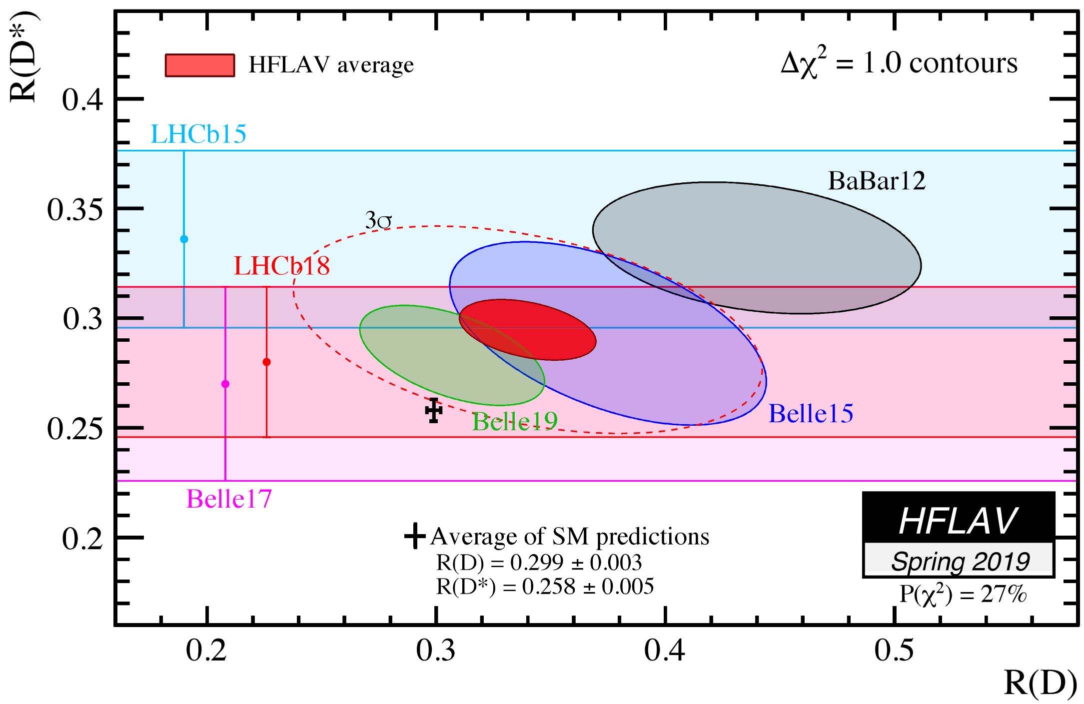


$B \to D^{(*)} \tau \nu$ can also receive contribution from a charged Higgs, changing the rate, q^2 distribution, etc.

Define ratios:

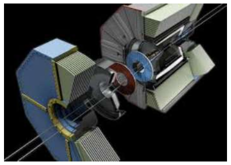
$$\mathcal{R}_{D^*} \equiv \frac{\mathcal{B}(B \to D^* \tau \nu)}{\mathcal{B}(B \to D^* \ell \nu)} \qquad \mathcal{R}_D \equiv \frac{\mathcal{B}(B \to D \tau \nu)}{\mathcal{B}(B \to D \ell \nu)}$$

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 1.4σ and 2.5σ respectively. As R(D)-R(D*) correlation = -0.38, two-dimensional χ^2 =12.3*

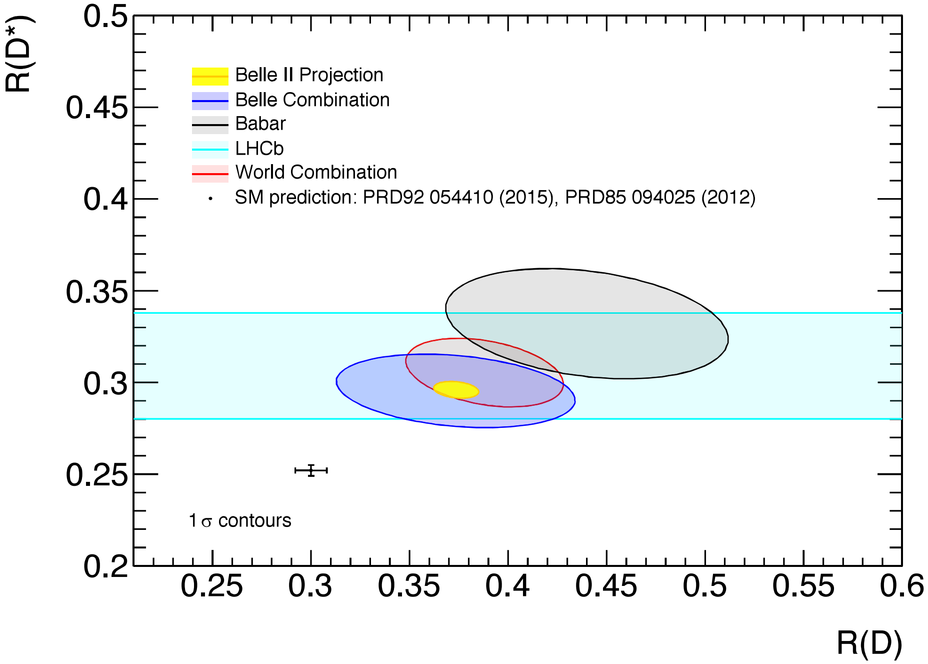
⇒ for 2 deg. of freedom, p-value = 2.1×10^{-3} (3.1σ)



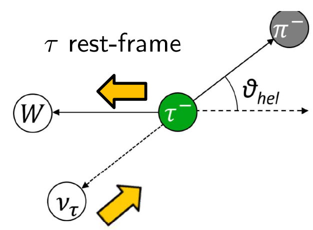
$B \to D^{(*)} \tau \nu$ @ Belle II

The Belle II Physics Book, arXiv:1808.10567

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



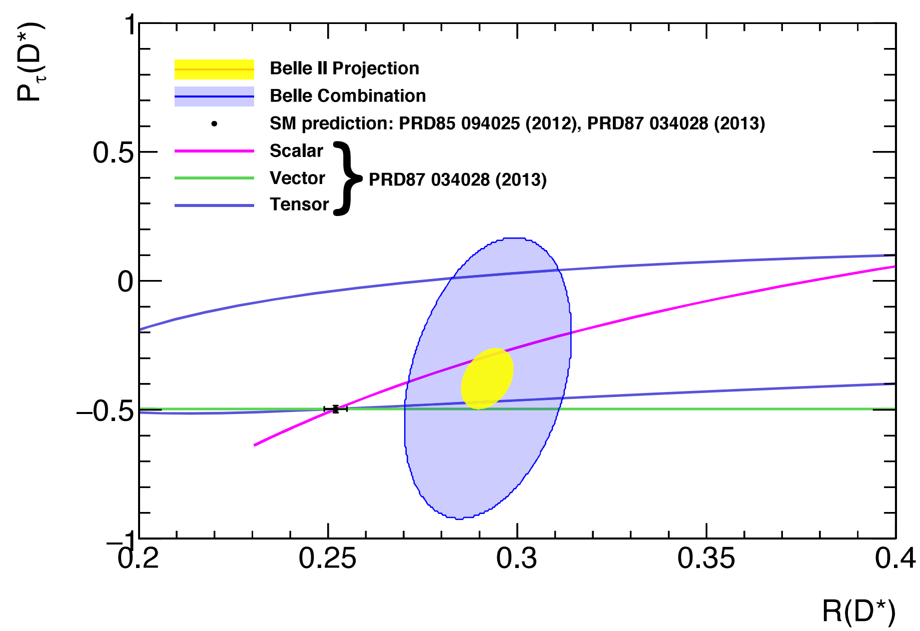
Belle II can measure $\tau^- \to \pi^- \nu$, allowing a measurement of τ polarization:



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

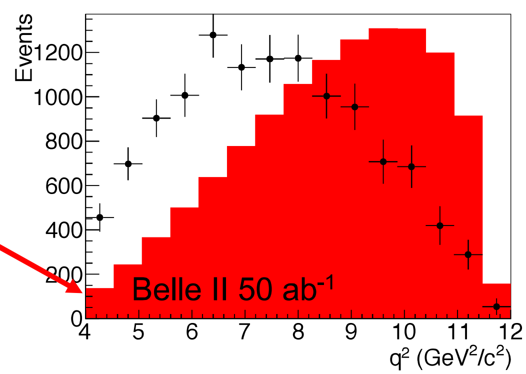
$$\frac{d\Gamma}{d\cos\theta_h} \propto 1 + \alpha P_\tau \cos\theta_h$$

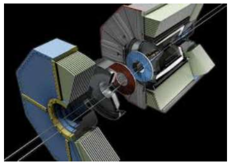
$$\left(\begin{array}{l} \tau \to \pi\nu: \;\; \alpha = 1 \\ \tau \to \rho\nu: \;\; \alpha = 0.45 \end{array} \right)$$



New physics from q^2 spectrum:

Type II 2HDM
$\tan\beta/M_H = 0.5$





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:

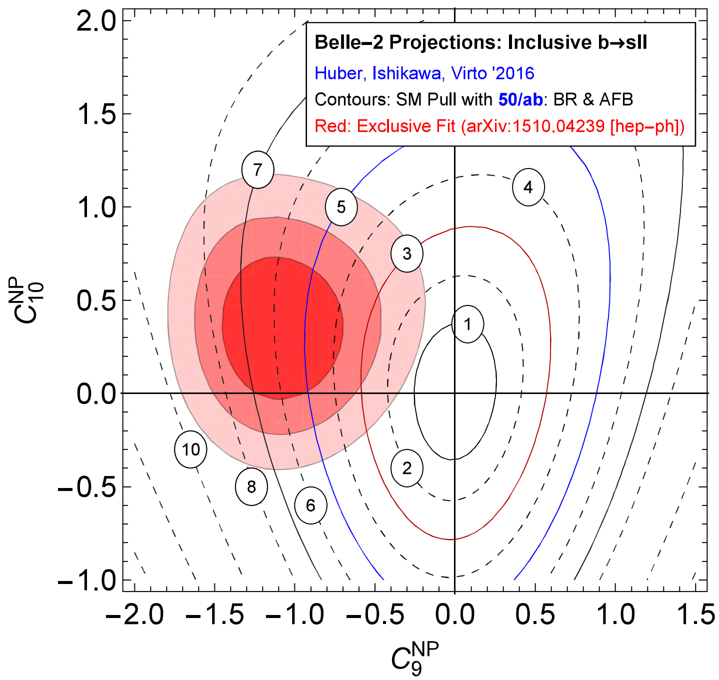
- *3 K modes can be included;*
- *more π^+ can possibly be included;*
- *another π^0 can possibly be included;*
- *improved full reconstruction on tagging side (with neural network) should make true inclusive analysis feasible (under study)*

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%

$[\Delta_{CP}(A_{FB}) = A_{FB}(B\text{-}bar) - A_{FB}(B)]$

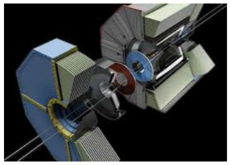
Note: *A_{FB} provides stringent constraint on C_9, C_{10}*

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

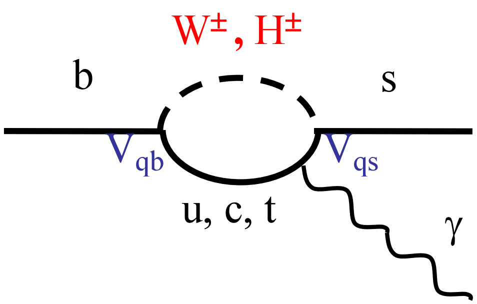


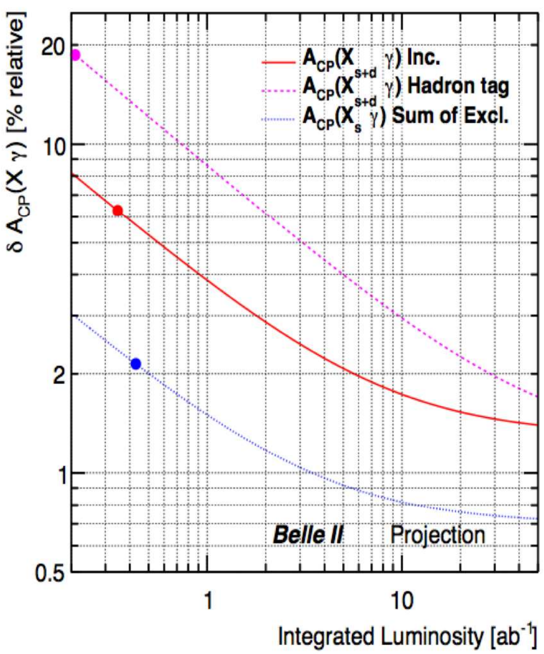
(n) σ pull to SM fit if true values

Exclusive decays fit:
Descotes-Genon et al., JHEP 06 (2016)092
Aebischer et al., arXiv:1903.10434



Inclusive $B \to X_{(s,d)}\gamma$ radiative decays



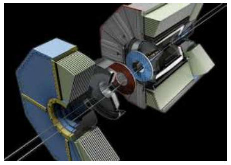


Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B \to X_s\gamma)^{\text{lep-tag}}_{\text{inc}}$	5.3%	3.9%	3.2%
$\mathrm{Br}(B \to X_s\gamma)^{\text{had-tag}}_{\text{inc}}$	13%	7.0%	4.2%
$\mathrm{Br}(B \to X_s\gamma)_{\text{sum-of-ex}}$	10.5%	7.3%	5.7%
$\Delta_{0+}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.1%	0.81%	0.63%
$\Delta_{0+}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	9.0%	2.6%	0.85%
$A_{\text{CP}}(B \to X_s\gamma)_{\text{sum-of-ex}}$	1.3%	0.52%	0.19%
$A_{\text{CP}}(B^0 \to X_s^0\gamma)_{\text{sum-of-ex}}$	1.8%	0.72%	0.26%
$A_{\text{CP}}(B^+ \to X_s^+\gamma)_{\text{sum-of-ex}}$	1.8%	0.69%	0.25%
$A_{\text{CP}}(B \to X_{s+d}\gamma)^{\text{lep-tag}}_{\text{inc}}$	4.0%	1.5%	0.48%
$A_{\text{CP}}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	8.0%	2.2%	0.70%
$\Delta A_{\text{CP}}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.5%	0.98%	0.30%
$\Delta A_{\text{CP}}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	16%	4.3%	1.3%
$\mathrm{Br}(B \to X_d\gamma)_{\text{sum-of-ex}}$	30%	20%	14%
$\Delta_{0+}(B \to X_d\gamma)_{\text{sum-of-ex}}$	30%	11%	3.6%
$A_{\text{CP}}(B^+ \to X^+_{u\bar{d}}\gamma)_{\text{sum-of-ex}}$	42%	16%	5.1%
$A_{\text{CP}}(B^0 \to X^0_{d\bar{d}}\gamma)_{\text{sum-of-ex}}$	84%	32%	10%
$A_{\text{CP}}(B \to X_d\gamma)_{\text{sum-of-ex}}$	38%	14%	4.6%
$\Delta A_{\text{CP}}(B \to X_d\gamma)_{\text{sum-of-ex}}$	93%	36%	11%

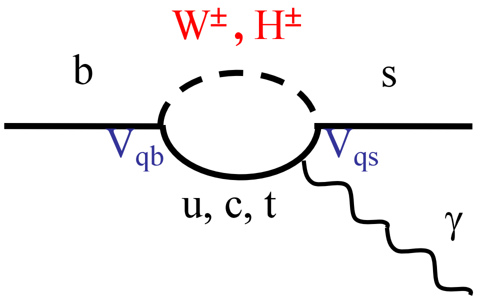
un-measured (Belle values for the last six rows)

[$\Delta A_{\text{CP}} = A_{\text{CP}}(B^+) - A_{\text{CP}}(B^0) \propto \mathrm{Im}(C_8/C_7)$]

Note: *experimental error from background subtraction grows as E_γ is lower; theoretical errors grow as E_γ is higher. Both A_{CP} (residual photon contribution) and isospin asymmetry Δ_{0+} (S_{78}) reduce theoretical uncertainties in the inclusive BF*



Exclusive $B \to V\gamma$ radiative decays



Theory:

$\Delta_{0+}(K^*\gamma)$ = (4.9 ± 2.6)%
$A_{CP}(K^*\gamma)$ = (0.3 ± 0.1)%
[constrains Im(C_7)]

$\Delta_{0+}(\rho\gamma)$ = (5.2 ± 2.8)%

Lyon and Zwicky, PRD D88, 094004 (2013)

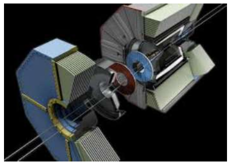
Paul and Straub, JHEP 04, 027 (2017)

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\Delta_{0+}(B \to K^*\gamma)$	2.0%	0.70%	0.53%
$A_{CP}(B^0 \to K^{*0}\gamma)$	1.7%	0.58%	0.21%
$A_{CP}(B^+ \to K^{*+}\gamma)$	2.4%	0.81%	0.29%
$\Delta A_{CP}(B \to K^*\gamma)$	2.9%	0.98%	0.36%
$S_{K^{*0}\gamma}$	0.29	0.090	0.030
$\mathrm{Br}(B^0 \to \rho^0\gamma)$	24%	7.6%	4.5%
$\mathrm{Br}(B^+ \to \rho^+\gamma)$	30%	9.6%	5.0%
$\mathrm{Br}(B^0 \to \omega\gamma)$	50%	14%	5.8%
$\Delta_{0+}(B \to \rho\gamma)$	18%	5.4%	1.9%
$A_{CP}(B^0 \to \rho^0\gamma)$	44%	12%	3.8%
$A_{CP}(B^+ \to \rho^+\gamma)$	30%	9.6%	3.0%
$A_{CP}(B^0 \to \omega\gamma)$	91%	23%	7.7%
$\Delta A_{CP}(B \to \rho\gamma)$	53%	16%	4.8%
$S_{\rho^0\gamma}$	0.63	0.19	0.064
$\lvert V_{td}/V_{ts}\rvert_{\rho/K^*}$	12%	8.2%	7.6%
$\mathrm{Br}(B_s^0 \to \phi\gamma)$	23%	6.5%	–
$\mathrm{Br}(B^0 \to K^{*0}\gamma)/\mathrm{Br}(B_s^0 \to \phi\gamma)$	23%	6.7%	–
$\mathrm{Br}(B_s^0 \to K^{*0}\gamma)$	–	15%	–
$A_{CP}(B_s^0 \to K^{*0}\gamma)$	–	15%	–
$\mathrm{Br}(B_s^0 \to K^{*0}\gamma)/\mathrm{Br}(B_s^0 \to \phi\gamma)$	–	15%	–
$\mathrm{Br}(B^0 \to K^{*0}\gamma)/\mathrm{Br}(B_s^0 \to K^{*0}\gamma)$	–	15%	–

systematics limited: f_{+-}/f_{00}

statistics limited

statistics limited

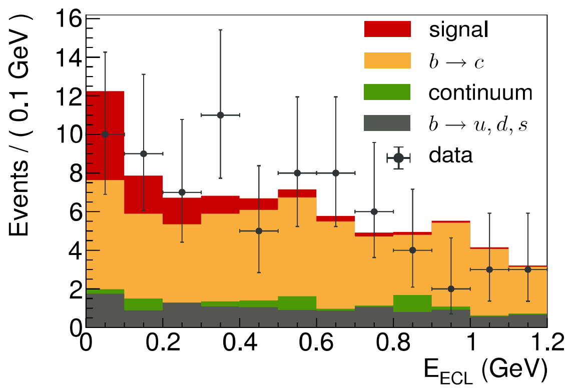


$B \to h \nu \nu$ ($h = \pi^+, \pi^0, \rho^+, \rho^0, K^+, K_S, K^{*0}, K^{*+}$)

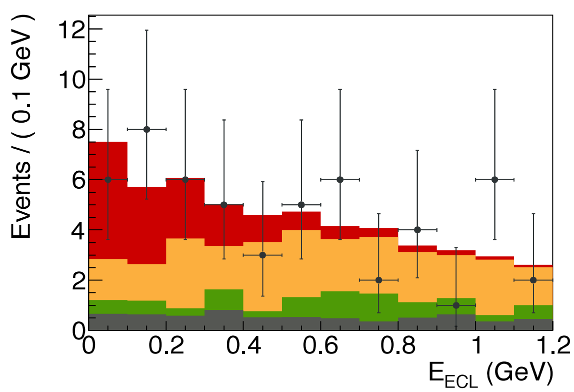
711 fb^{-1} Grygier et al. (Belle), PRD 96, 091101 (2017)

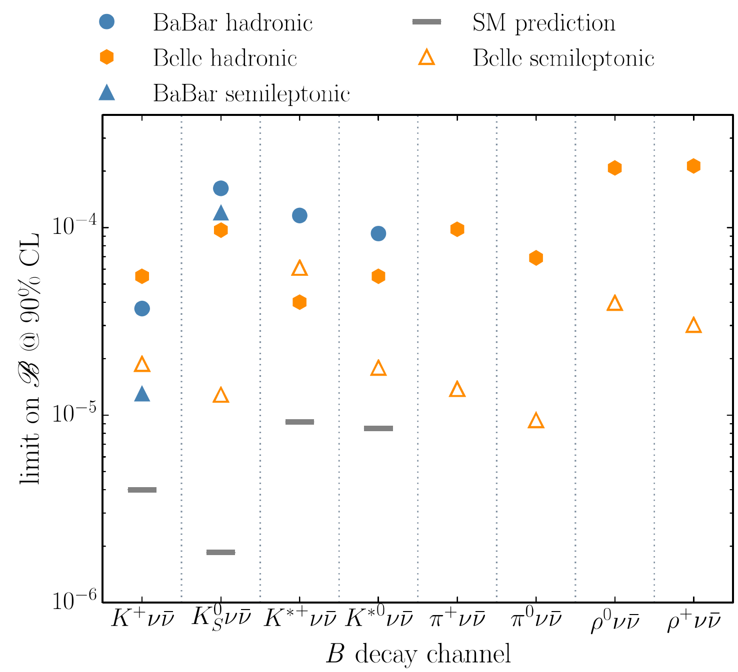
- ***Semileptonic tag**: use Neural Network (NN) to identify $B \to D^{(*)} l \nu$ decay on tagging side. Including D^0 and D^+ modes, there are 108 different decay channels considered.*
- *Require only relevant tracks on signal side: no extra tracks, extra π^0's, or K_L's.*
- *Suppress continuum background (uu, dd, ss, cc) with a second NN based on Fox-Wolfram moments, event topology*
- *Reject backgrounds with a third NN based on 17-31 kinematic variables*
- *Fit E_{ECL} (unassociated energy in the calorimeter) distribution for signal*

ρ^0



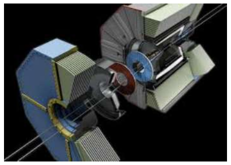
K^{*+}



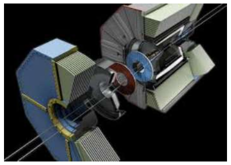


- *no signals observed. most limits are the world's best*
- *limits are a factor of 2.7 (K^*) – 3.9 (K) above SM prediction*

⇒ *Belle II should get to SM level*



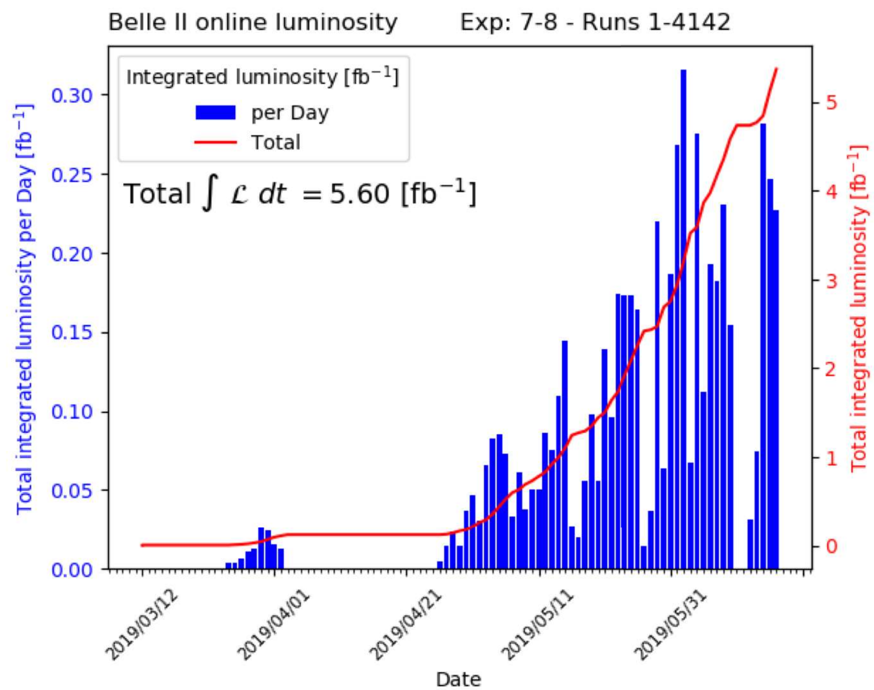
Status of the Experiment



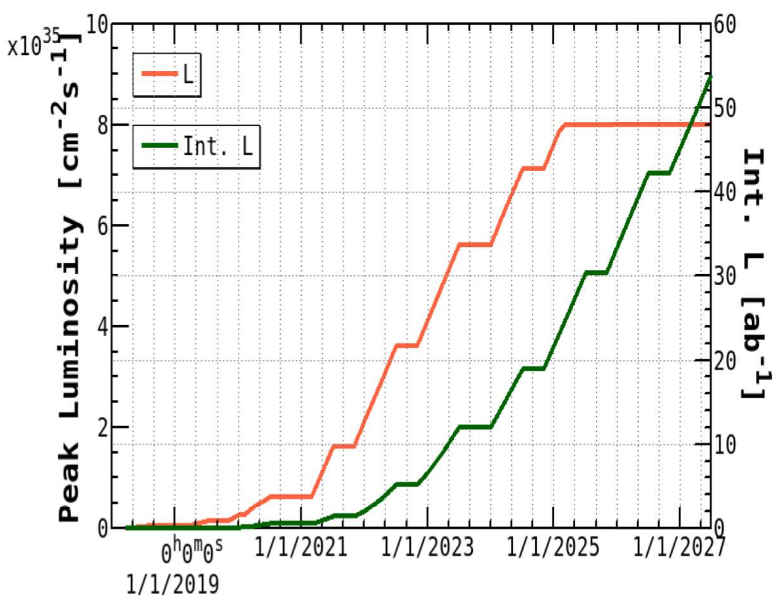
Integrated luminosity

- *Run began at the beginning of April*
- *Backgrounds are high: after addition/adjustment of collimators, now dominated by beam gas*
- *Specific luminosity is low; accelerator group actively tuning optics*
- *Lost 3 weeks of running due to a fire at a test station near end of LINAC*
- ***Achieved:***

I_{beam} (max)	*= 660 mA*	*(target: 2.6/3.6 A)*
β_y^*	*= 2 mm*	*(target: 0.3 mm)*
# bunches	*= 1576 [6 ns]*	*(target: 2364 [4 ns])*
L_{peak}	*= 6.1 x 10^{33}*	*(Belle: 1 x 10^{34}*
	[1.0 x 10^{34}]	*target: 8 x 10^{35})*

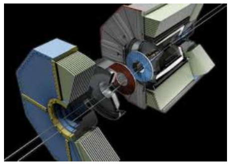


Long term:

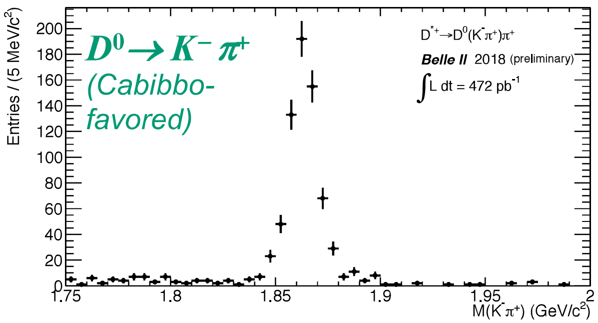


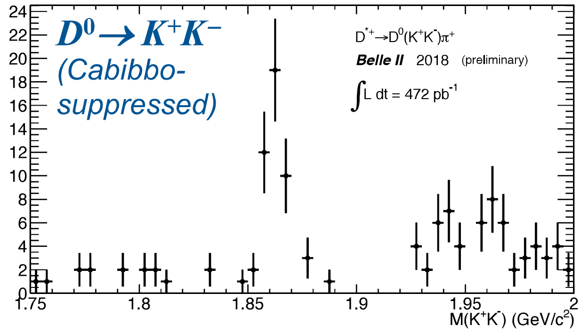
Assumptions:

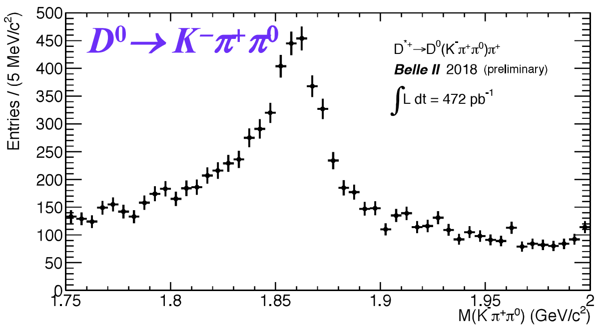
- *8x10^{35} will be achieved after 4 years*
- *Efficiency of luminosity integration is 70% (includes maintenance days, etc.)*
- *~8 months operation per year*
- *8 months shutdown in 2020 for PXD and 6 months in 2023 for RF upgrade.*

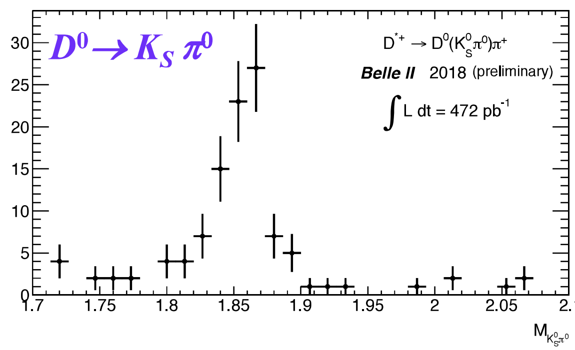


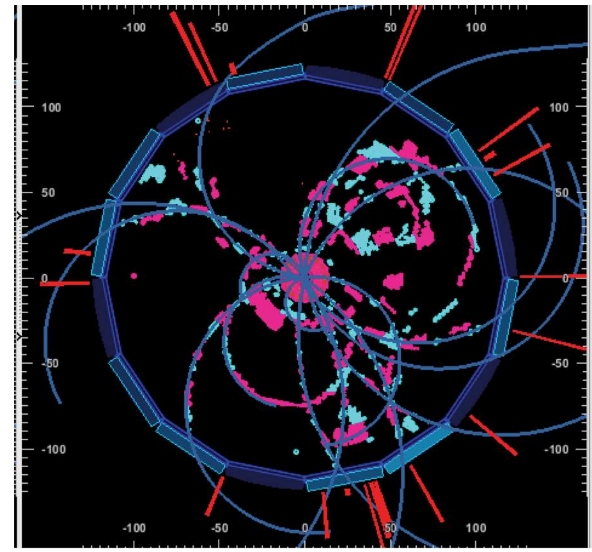
Detector is working (!)







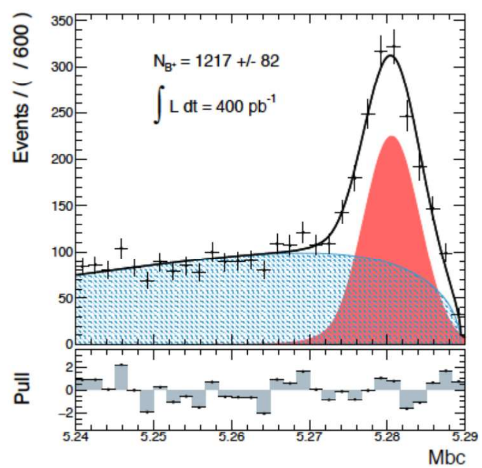


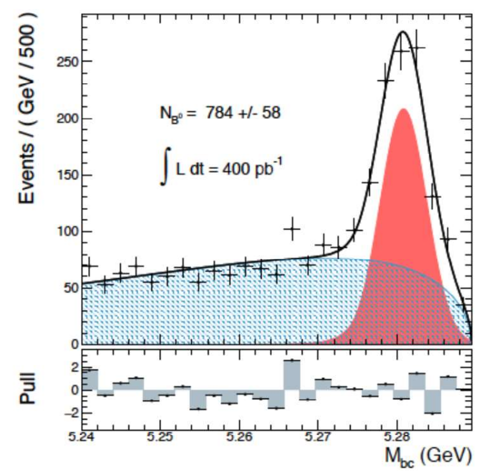


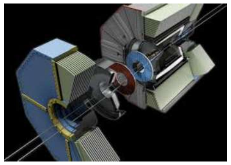
B decays:

$$M_{\rm bc} = \sqrt{E_{\rm beam} - p_B^2}$$

$B^+ \to D^0 \pi^+$
$B^+ \to D^0 \rho^+$
$B^+ \to D^{*0} \pi^+$
$B^0 \to D^{*+} \pi^-$
$B^0 \to D^{*+} \rho^-$
$B^0 \to D^+ \pi^-$
$B^0 \to D^+ \rho^-$
$B^0 \to J/\psi\, K_S$

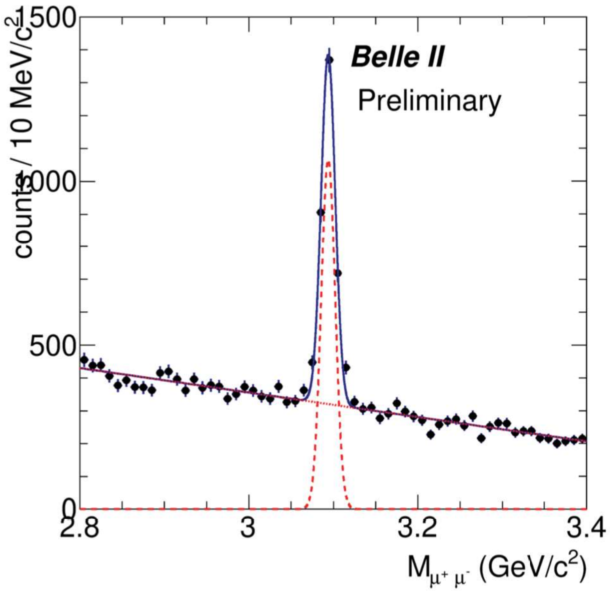




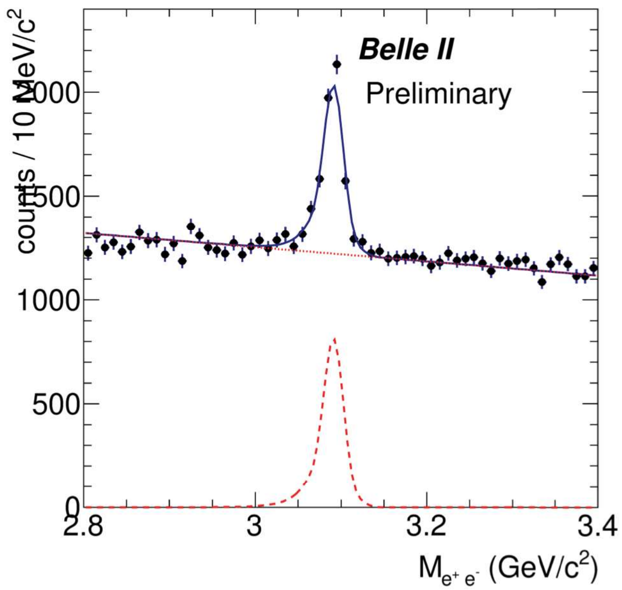


First signals of $B^0 \to J/\psi\, K_S$

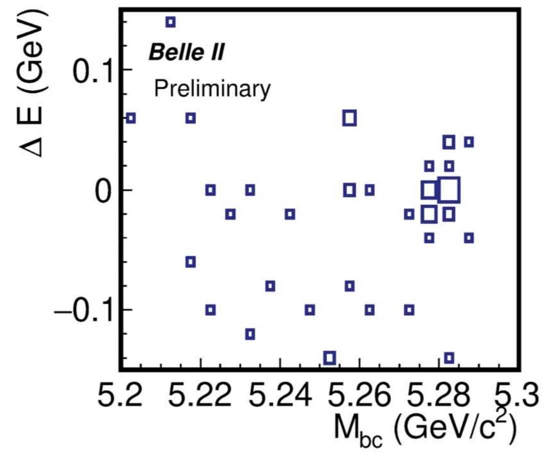
~ 3 fb^{-1}

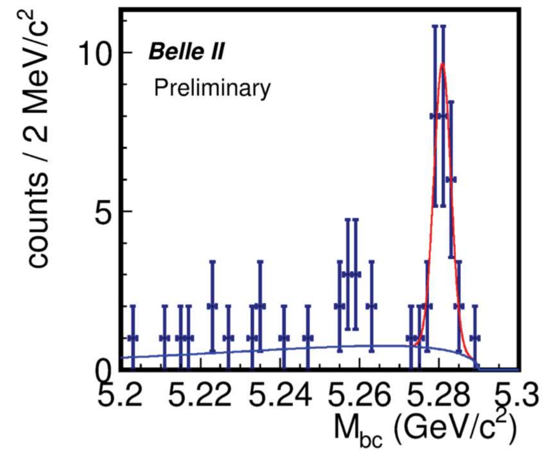


$J/\psi \to \mu^+\mu^-$



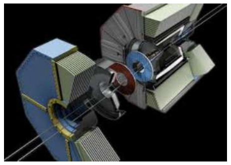
$J/\psi \to e^+e^-$





$B^0 \to J/\psi\, K_S$

$M_{bc} = \sqrt{(E_{beam}{}^2 - p_B{}^2)}$
$\Delta E = E_{beam} - E_B$



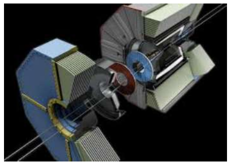
Summary

- Belle II is now ~fully constructed and installed. The only missing element is the second layer of the PXD (to be installed in 2020/2021). The experiment has finished its first "physics" run (April-July, "Phase 3"), accumulating > 6 fb^{-1} of data. This should finalize commissioning of the detector, i.e., calibrations, alignment, particle ID efficiencies, decay time resolution, tagging efficiency, trigger streams, skim streams, etc.

- Detector is working: seeing clean signals for $D \rightarrow h^+h^-$, $h^+h^-\pi^0$ decays, and reconstructing B decays. Goals for this data (6 fb^{-1}): measure B and D lifetimes, measure B-B-bar mixing with semileptonic decays, observe $B \rightarrow K^*\gamma$ penguin decays, rough time-dependent CP asymmetry of $B \rightarrow J/\psi\, K_S$ decays (demonstrating ability to make the measurement).

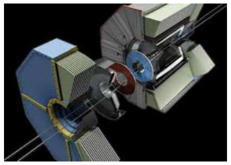
- Accelerator commissioning is proceeding, but there are challenges as expected for a new machine: background is high, dominated by beam gas. Presumably this will decrease as new LER is aged. β_y^* is slowly being reduced. Specific luminosity is lower than in Belle ⇒ much tuning of optics still needed.

- Physics potential is large: there is much better vertexing (and thus decay time resolution); better particle ID than in Belle; factor of 50x statistics; and full reconstruction on tag side is notably improved over Belle/BaBar.



Extra

Extra Slides



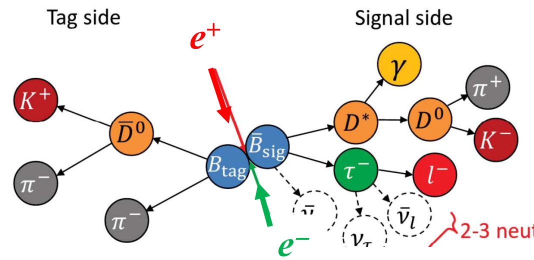
$|V_{cb}|$ from $B \to D l \nu$

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

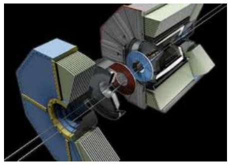
$D^0 \to K^-\pi^+$
$D^0 \to K^-\pi^+\pi^0$
$D^0 \to K^-\pi^+\pi^+\pi^-$
$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$

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

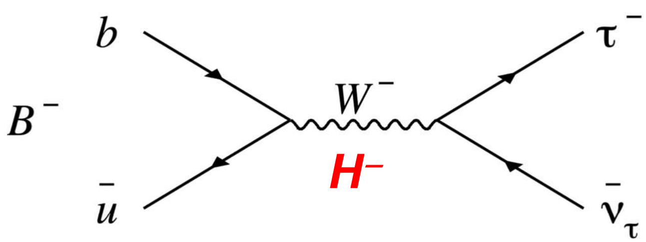
$D^0 \to K^-K^+$
$D^0 \to \pi^+\pi^-$
$D^0 \to K_S K_S$
$D^0 \to \pi^0\pi^0$
$D^0 \to K_S\pi^0\pi^0$

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

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



Constraint on Type II charged Higgs: $B^+ \to \tau^+ \nu$

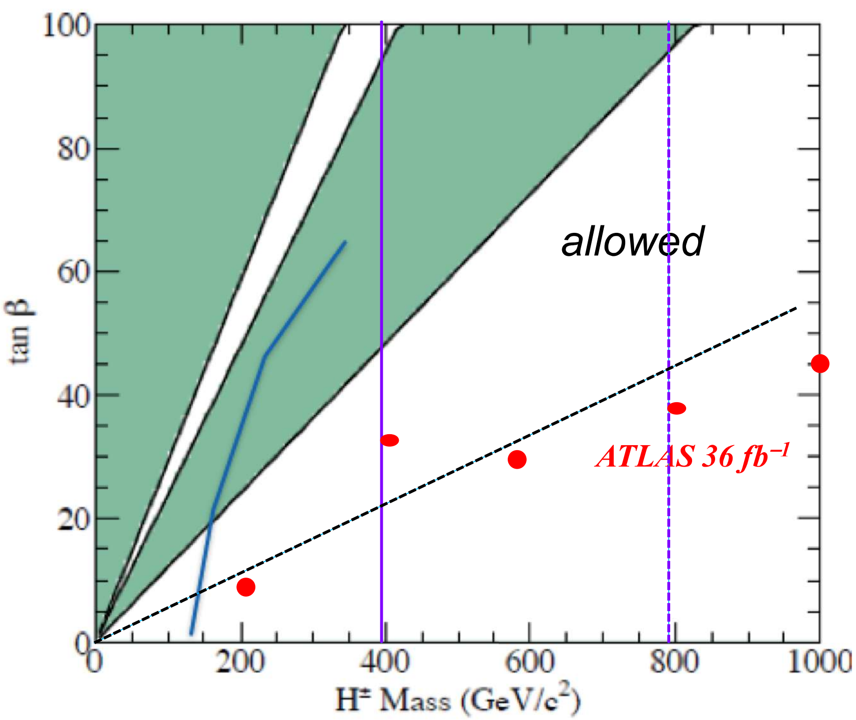


2-Higgs doublet model:

$$\mathcal{B}(B^+ \to \tau^+ \nu) \;=\; \mathcal{B}_{SM} \cdot \left(1 - m_B^2 \frac{\tan^2\beta}{m_H^2}\right)^2$$

Taking f_B = (185 ± 3) MeV and $|V_{ub}|$ = (3.60 ± 0.20) x 10^{-3} gives $\mathcal{B}_{SM}$ = (1.09 $^{+0.27}_{-0.24}$) x 10^{-4}

⇒ *WA $\mathcal{B}$ = (1.06 ± 0.19) x 10^{-4} gives a constraint in the $\tan\beta$-m_H plane:*



current measured value of $\mathcal{B}(b \to s\gamma)$ excludes m_H<400 GeV/c^2 for all $\tan\beta$.

Theory: Hermann, Misiak,& Steinhauser, JHEP 1211 (2012) 036; Misiak et al., PRL 98, 022002 (2007)

Compare to ATLAS: [JHEP 09 (2018) 139]