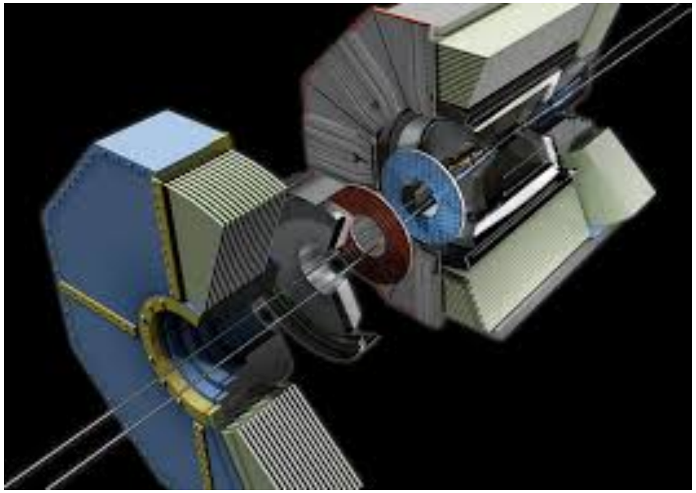


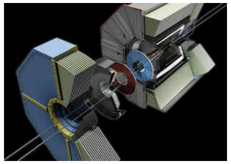
The Belle II experiment: a powerful lens for New Physics

Alan Schwartz
University of Cincinnati, USA

Workshop on Physics of a High Luminosity LHC

Fermilab
4 April 2018

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



Motivation:

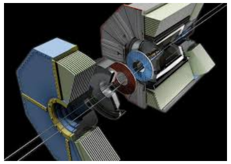
Why a flavor factory in the LHC Era?

- A flavor factory studies processes that occur at 1-loop in the SM but may be O(1) in NP: FCNC, neutral meson mixing, CP violation. These loops probe energy scales that cannot be accessed directly - even at the LHC.
- If supersymmetry is found at the LHC, it will be important to resolve how it is broken. By studying flavor couplings, a flavor factory can address this.

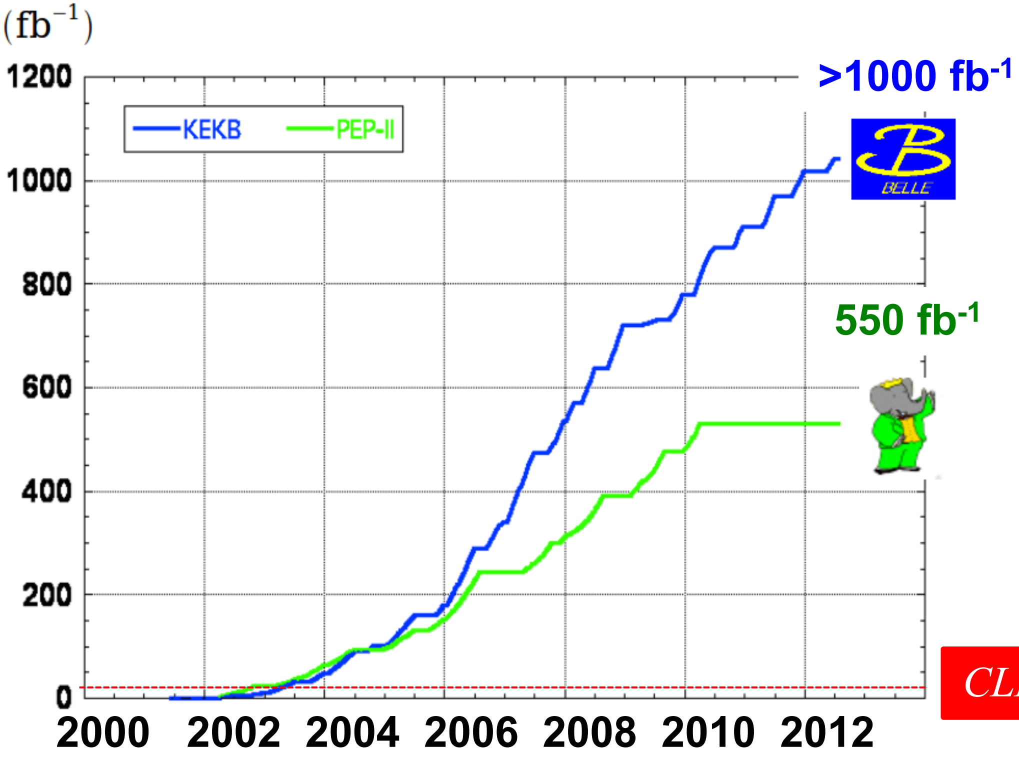
A flavor factory searches for NP by measuring phases, CP asymmetries, inclusive decay processes, rare leptonic decays, absolute branching fractions. There is a wide range of observables with which to confront theory.

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.



The Belle + BaBar Era



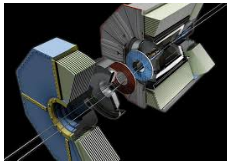
>1000 fb^{-1}

550 fb^{-1}

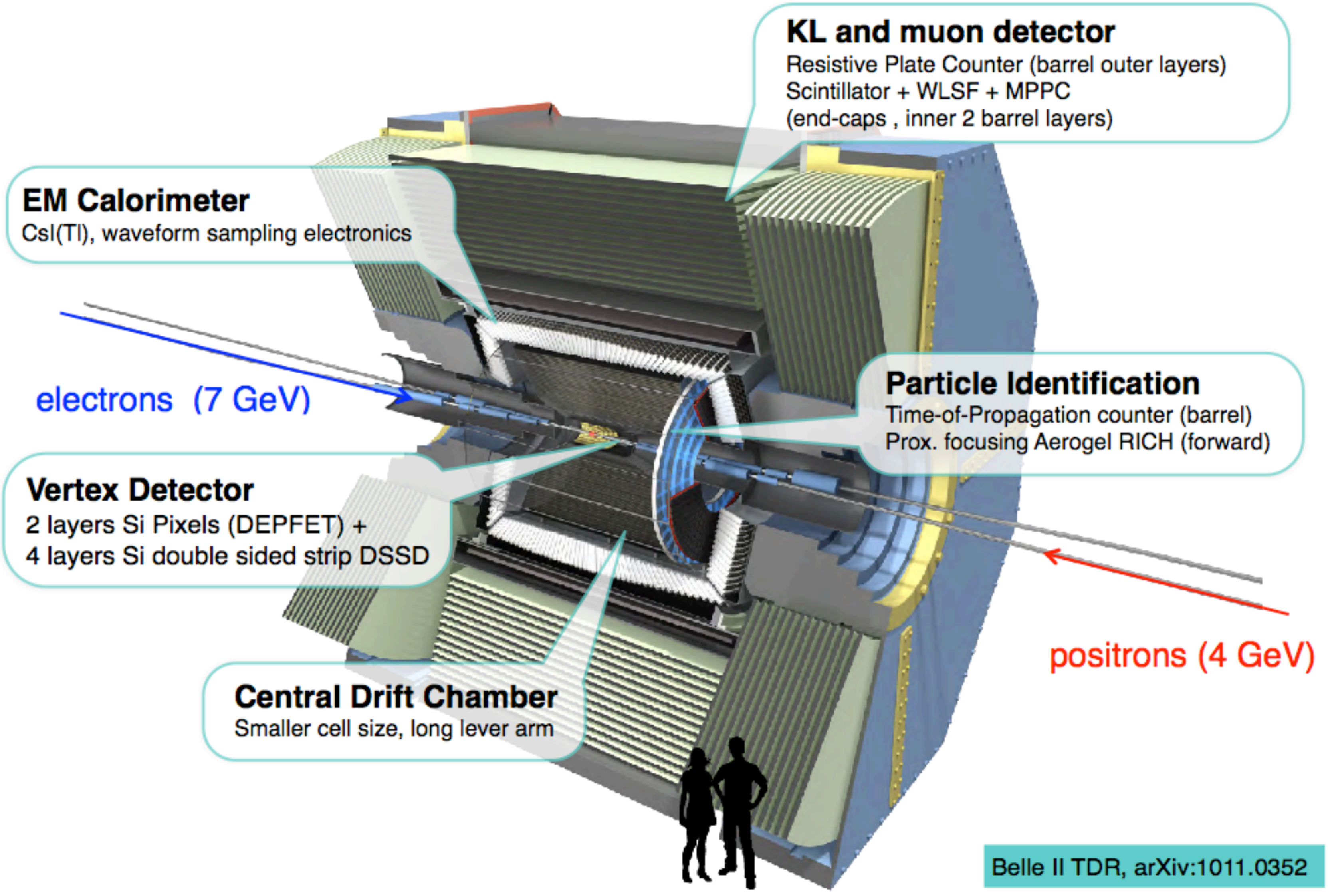
CLEO 11 fb^{-1}

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 Goal: *50 x present = 40 x 10^9 BB pairs*



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)

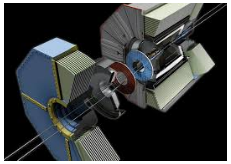
Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

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

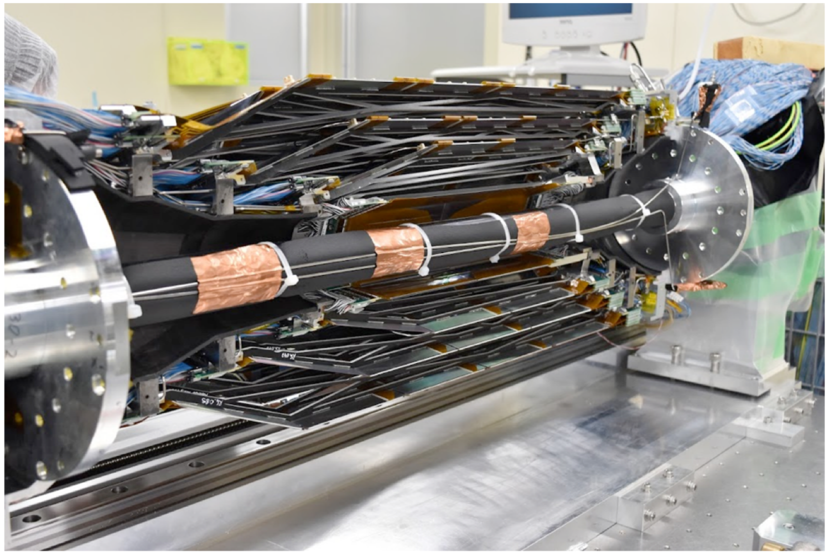
positrons (4 GeV)

Central Drift Chamber
Smaller cell size, long lever arm

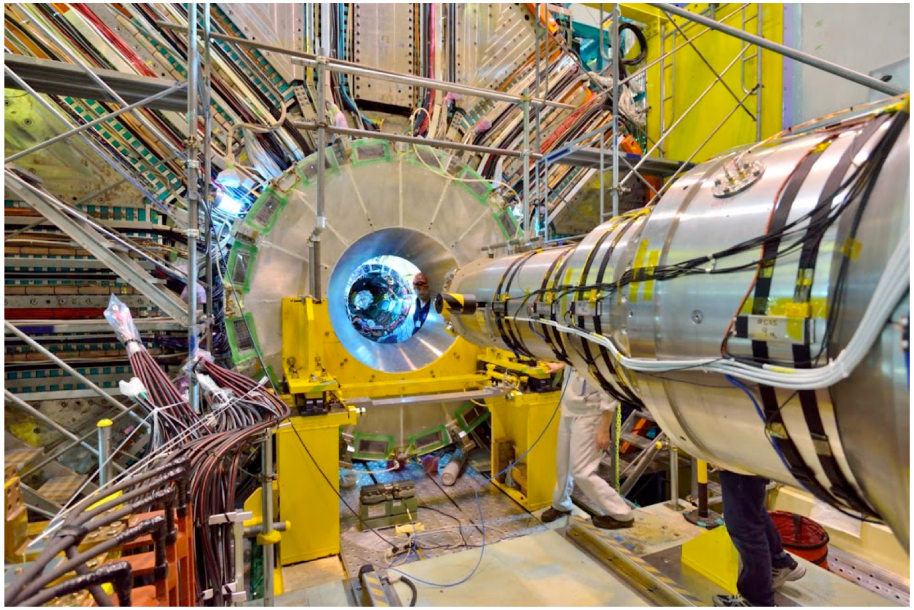
Belle II TDR, arXiv:1011.0352



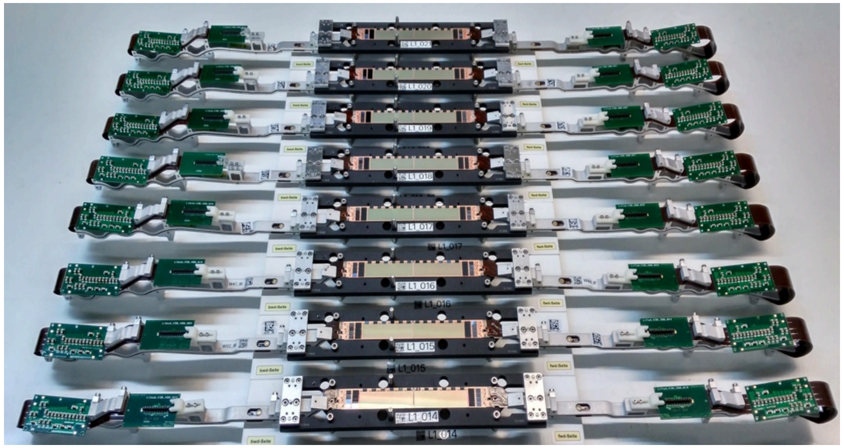
Great progress:



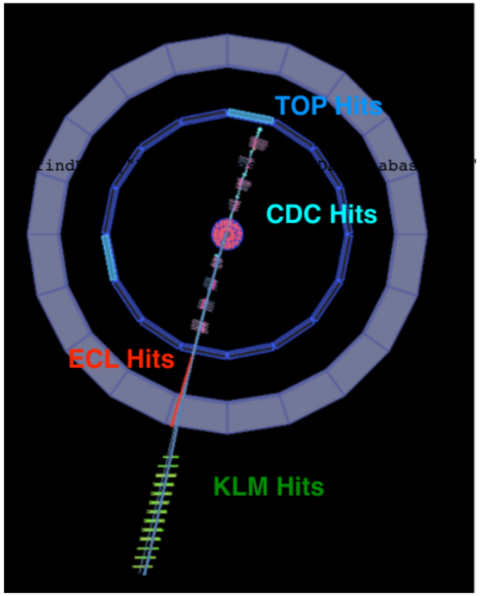
Completion of the first SVD clam-shell in Jan 2018.



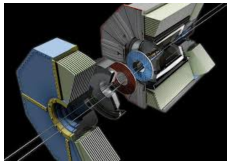
Superconducting final focus QCSL being prepared for final integration, January 2018



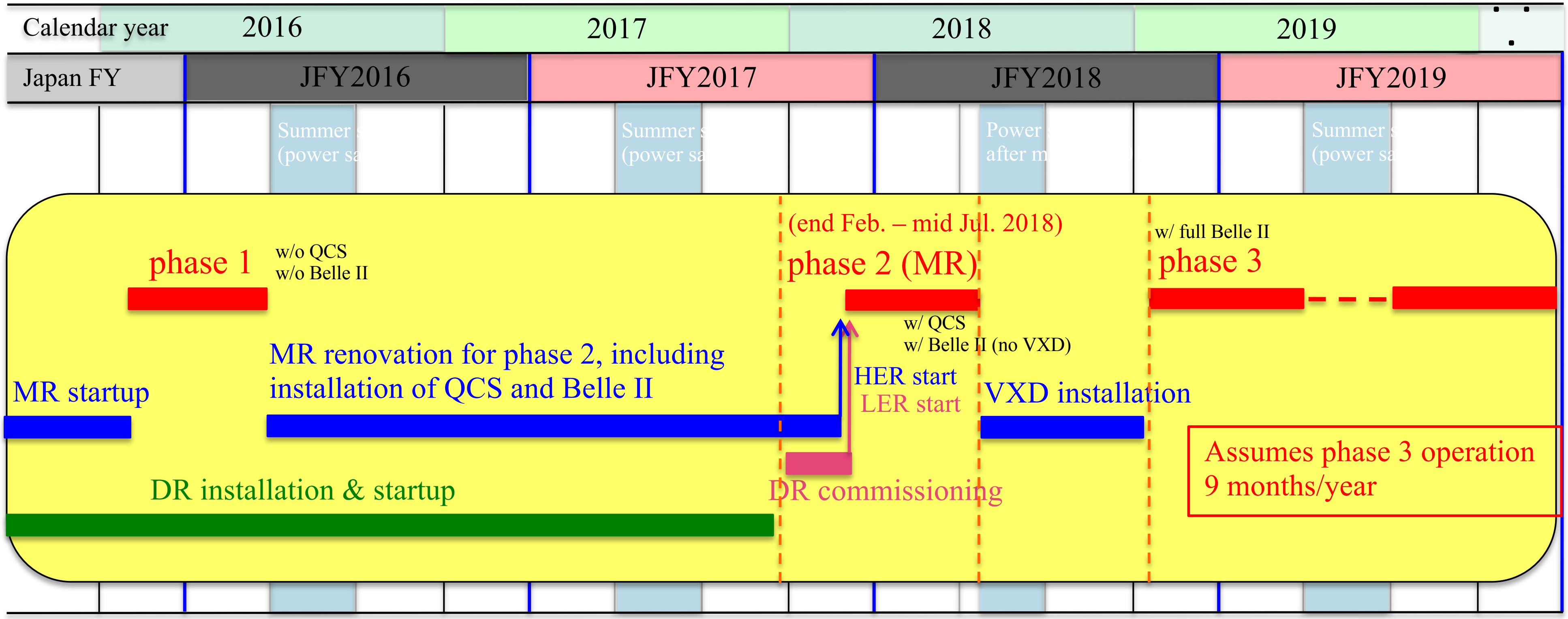
PXD L1 ladders ready for half-shell assembly



Event display, global cosmic ray run



Schedule:



Calendar year 2016 2017 2018 2019

Japan FY JFY2016 JFY2017 JFY2018 JFY2019

Summer s (power sa

Summer s (power sa

Power after m

Summer s (power sa

phase 1
w/o QCS
w/o Belle II

(end Feb. – mid Jul. 2018)
phase 2 (MR)
w/ QCS
w/ Belle II (no VXD)

w/ full Belle II
phase 3

MR startup

MR renovation for phase 2, including installation of QCS and Belle II

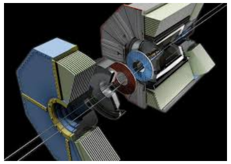
HER start
LER start

VXD installation

DR installation & startup

DR commissioning

Assumes phase 3 operation
9 months/year



B physics in Belle II

Initial physics program description:

arXiv:1002.5012 (Belle II)

arXiv:1008.1541 (SuperB)

Belle II Theory Interface Platform Workshop series, 2015-2018:

WG1
Semileptonic & Leptonic B decays

WG2
Radiative & Electroweak Penguins

WG3
$\alpha = \phi_1 \, , \beta = \phi_2$

WG4
$\gamma = \phi_3$

WG5
Charmless Hadronic B Decay

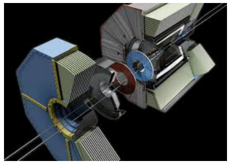
WG6
Charm

WG7
Quarkonium(like)

WG8
Tau, low multiplicity

WG9
New Physics

To be submitted to PTEP, 2018



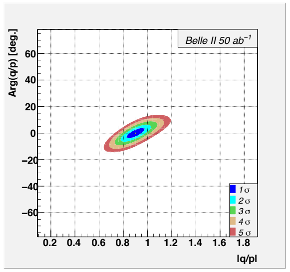
Belle II physics: “golden modes”

B physics:

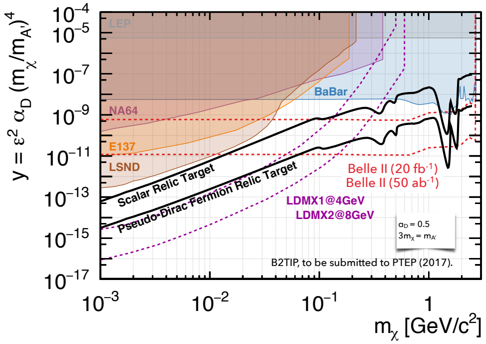
Observables	Expected exp. uncertainty	Facility (2025)
UT angles & sides		
ϕ_1 [°]	0.4	Belle II
ϕ_2 [°]	1.0	Belle II
ϕ_3 [°]	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	1%	Belle II
$\|V_{cb}\|$ excl.	1.5%	Belle II
$\|V_{ub}\|$ incl.	3%	Belle II
$\|V_{ub}\|$ excl.	2%	Belle II/LHCb
CPV		
$S(B \to \phi K^0)$	0.02	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

Other physics:

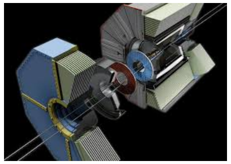
Charm



Dark Photon/Sector



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



Unitarity triangle – determining the angles

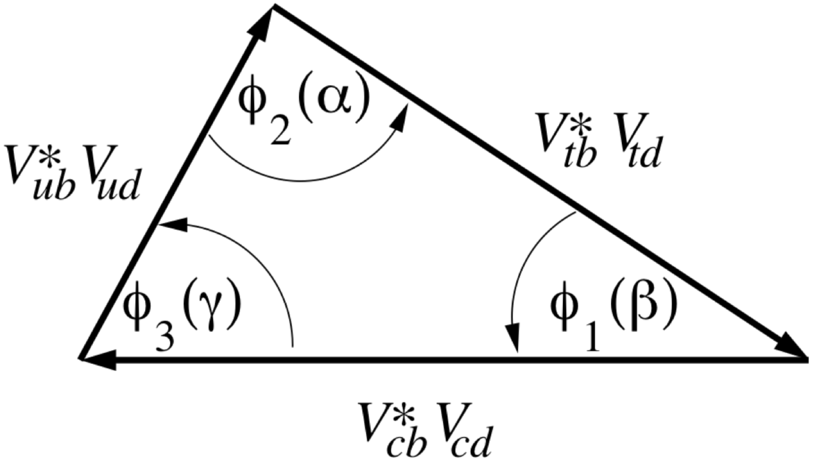
$$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$$

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

Belle/BaBar
** = recent update*

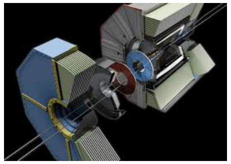
LHCb
** = 3 fb^{-1} result*

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



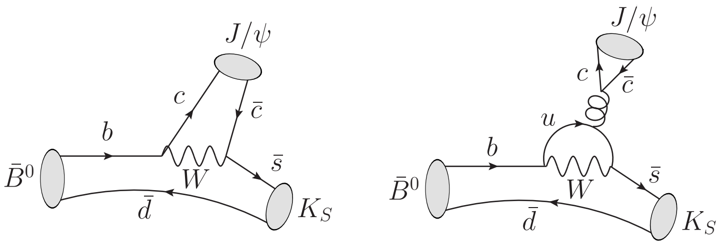
$B^- \to D^{(*)}{}_{CP}\,K^{(*)-}$
** $B^0 \to D_{CP}\,K^{*0}$
$B^- \to D^{(*)}(K^+\pi^-)\,K^{(*)-}$
$B^- \to D^{(*)0}\,\pi^-$
* $B^- \to D^{(*)}(K_S\,\pi^+\pi^-)\,K^{(*)-}$
$B^- \to D(\pi^0\pi^+\pi^-)\,K^-$
* $B^- \to D(K_S\,K^+\pi^-)\,K^-$

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



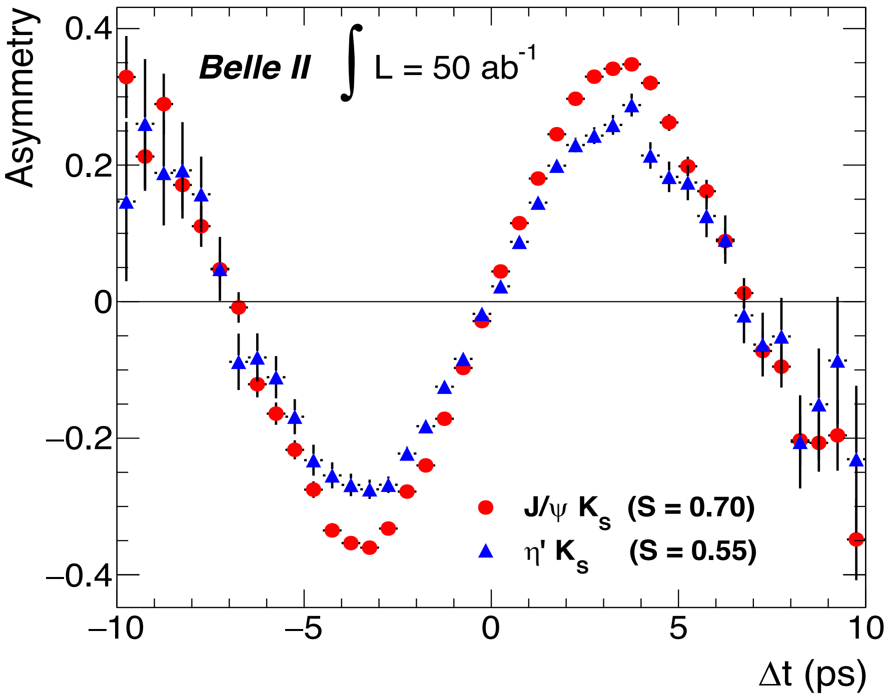
Determining ϕ_1 (β)

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



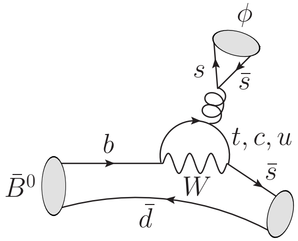
$$\mathcal{A}_{c\bar{c}s} \;=\; V_{cb}^{*}V_{cs}T + V_{ub}^{*}V_{us}P$$

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



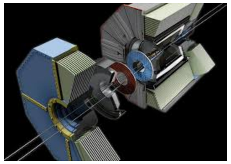
$$A_{CP} \;=\; A\cos(\Delta M\Delta t) + S\sin(\Delta M\Delta t)$$

$B^0 \to \phi\, K_S, \eta' K_S, \omega K_S, \pi^0 K_S$ *("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 $B^0 \to \pi^0 K_S$

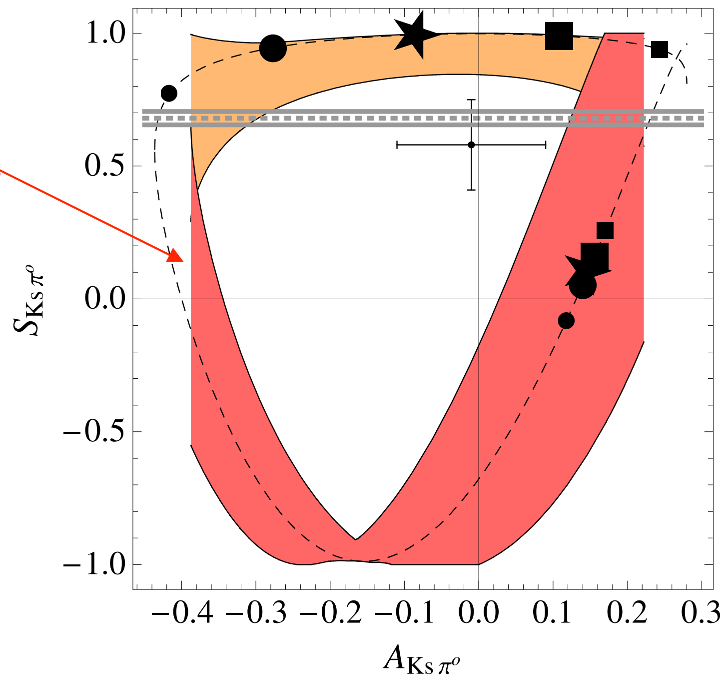
	WA (2017)		5 ab^{-1}		50 ab^{-1}	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$K^0_S\pi^0$	0.17	0.10	0.09	0.06	0.028	0.018

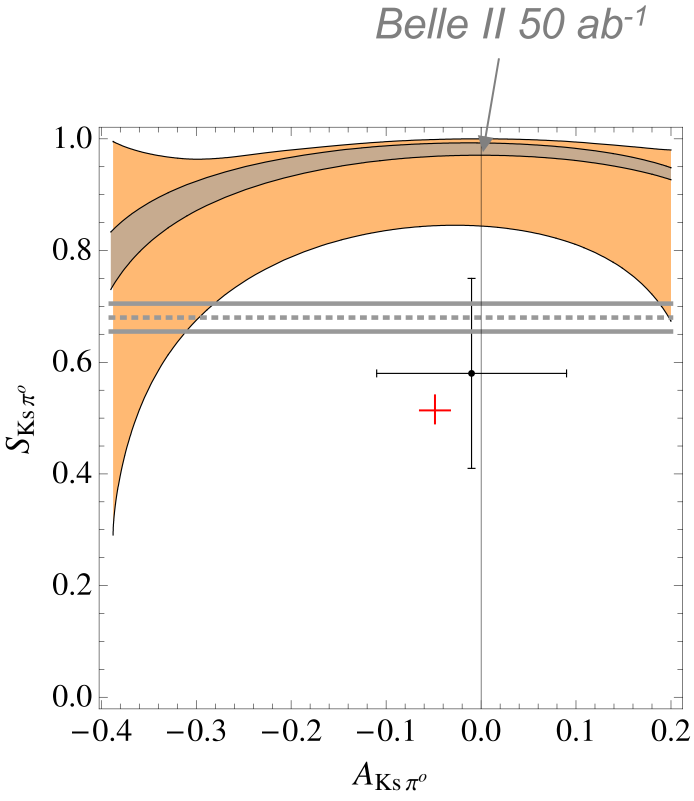
Branching fractions of $B^0 \to \pi^0 K_S$, $B^0 \to \pi^+ K^-$, $B^+ \to \pi^0 K^+$, $B^+ \to \pi^+ K_S$

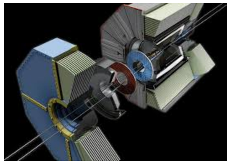
constrain CP asymmetry of $B^0 \to \pi^0 K_S$ *(via isospin):*

Colored bands are allowed regions based on current measurements

(orange preferred; red is inconsistent with SU(3) applied to $B \to \pi\pi$ measurements)

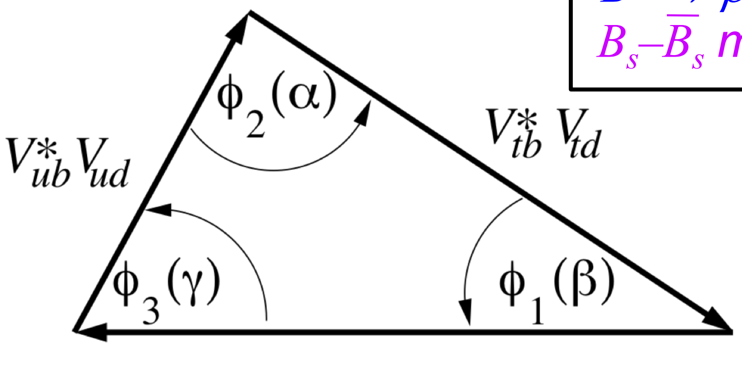






Determining sides of the Unitarity Triangle

Belle
LHCb



$B^0 \to \rho^0 \gamma$
B_s–$\bar{B}_s$ 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)

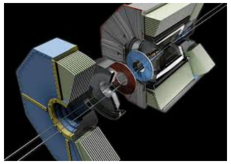
$B^0 \to \pi \ell^+ \nu$
$B^0 \to X_u \ell \nu$
$B^+ \to \tau^+ \nu$
$\Lambda_b \to p \ell^+ \nu$

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)

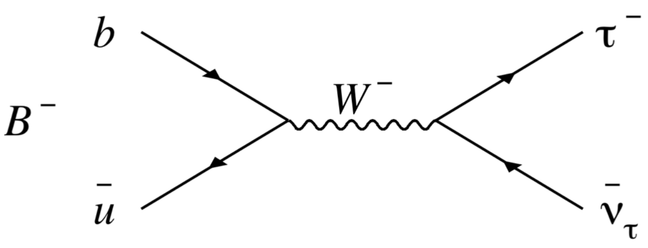
Lange et al. (BLNP), PRD 72, 073006 (2005)
Andersen, Gardi (DGE), JHEP 601, 97 (2006)
Gambino et al. (GGOU), JHEP 10, 058 (2007)
Aglietti et al. (ADFR), EPJ C59 (2009)
Bauer et al. (BLL), PRD 64, 113004 (2001)

$B^0 \to D^{(*)} \ell \nu$
$B^0 \to X_c \ell \nu$ (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 $B^+ \to \tau^+\nu$



Aubert et al., PRD 81, 051101 (2010) 418 fb^{-1} $D^0\ell$tag
Lees et al., PRD 88, 031102 (2013) 426 fb^{-1} hadr.tag

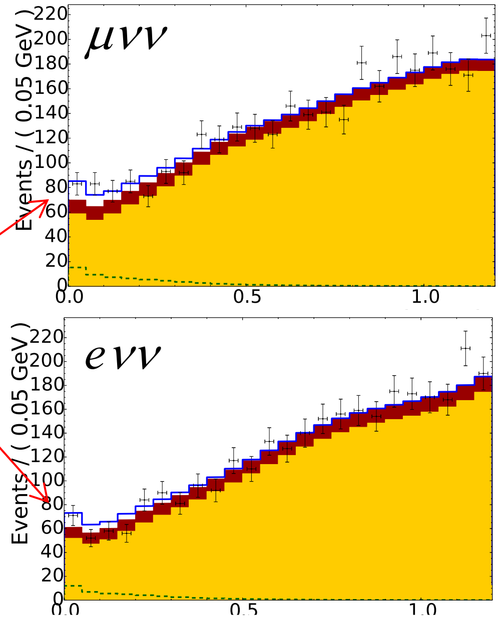
Hara et al., PRD 82, 071101 (2010) 605 fb^{-1} semi.tag
Hara et al., PRL 110, 131801 (2013) 711 fb^{-1} had.tag
Kronenbitter et al., PRD 92, 051102 (2015) 711 fb^{-1} semi.tag

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

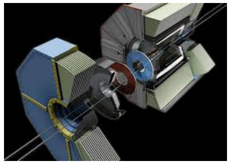
PRD 92, 051102 (2015):

- $B^+ \to D^{(*)0}\ell^+\nu$, $D^{*0} \to D^0\gamma$, $D^0\pi^0$; $D^0 \to K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$...
- $\tau^- \to \mu^-\nu\nu$, $e^-\nu\nu$, $\pi^-\nu$, $\rho\nu$ *(1 charged track)*
- *large backgrounds from* $b \to c$ (BB) *and continuum*
- *signal is obtained by fitting the ECL (electromagnetic calorimeter energy) distribution: peak new zero indicates* $\tau \to \ell\nu\nu$, $\pi\nu$ *decay.*
- *ECL simulation is validated with identically tagged* $B^+ \to D^{(*)0}\ell^+\nu$ *control sample*

222 ± 50
(all chan.)
3.8σ



Excess calorimeter energy (GeV)

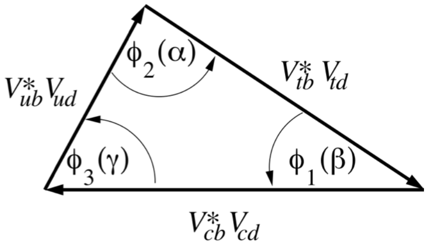


$|V_{ub}|$ via $B^+ \rightarrow \tau^+ \nu$

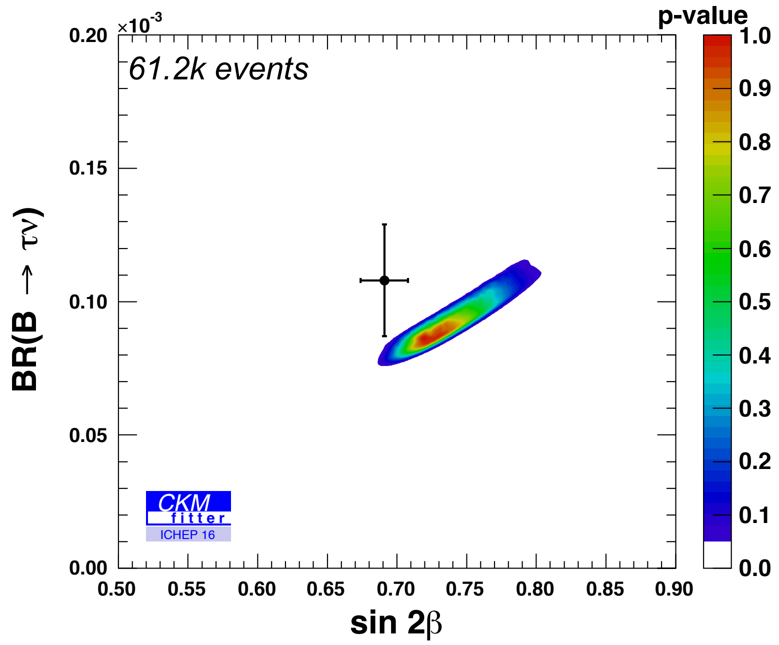
World average: $\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = (1.06 \pm 0.19) \times 10^{-4}$

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

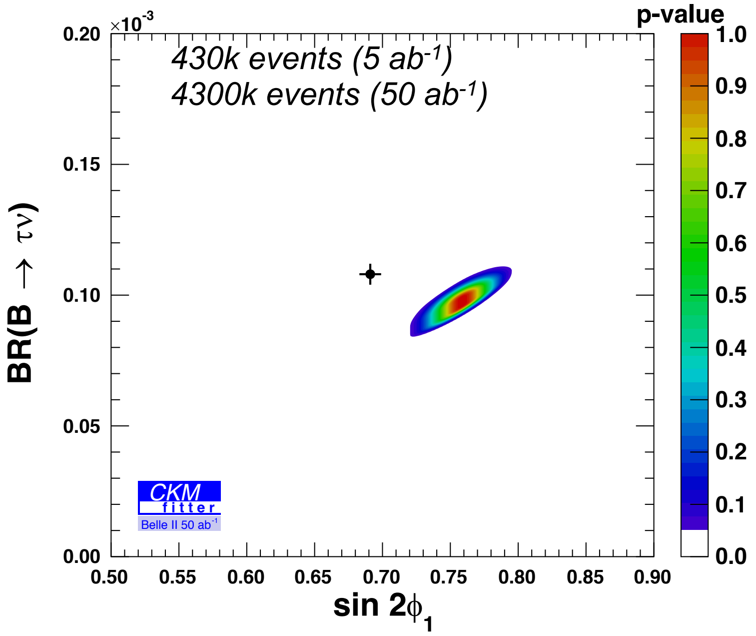
There is tension coming from $|V_{td}|$ measured in $\mathcal{B}(B^+ \rightarrow \tau^+ \nu)$ and ϕ_1 (β) and ϕ_2 (α):

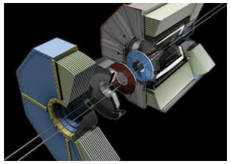


Today:



Belle II 50 ab^{-1}:

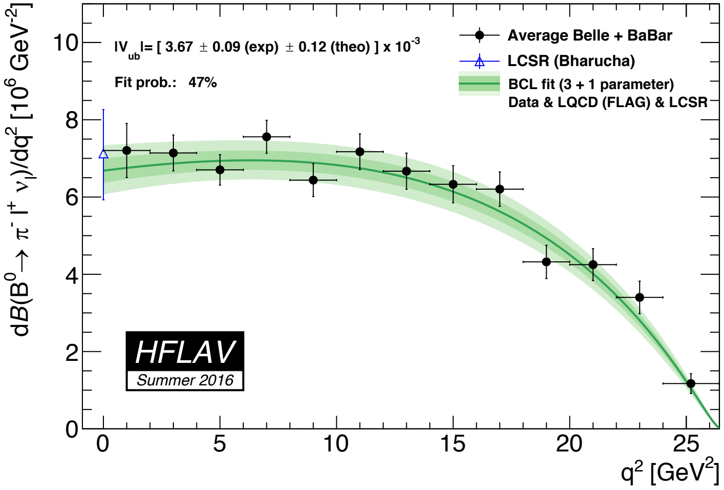




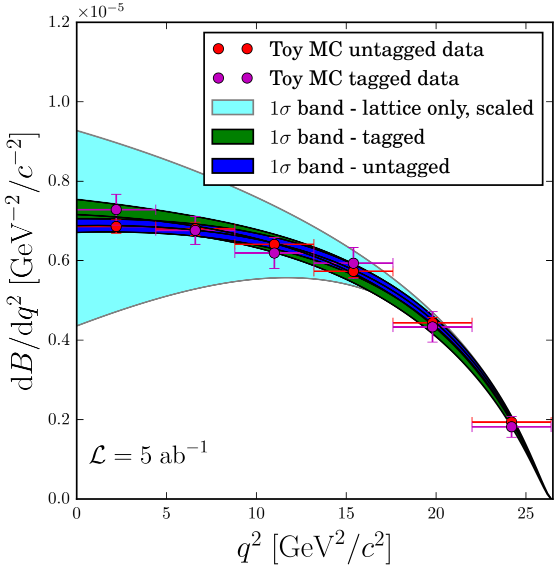
$|V_{ub}|$ via exclusive $B \rightarrow \pi l \nu$

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

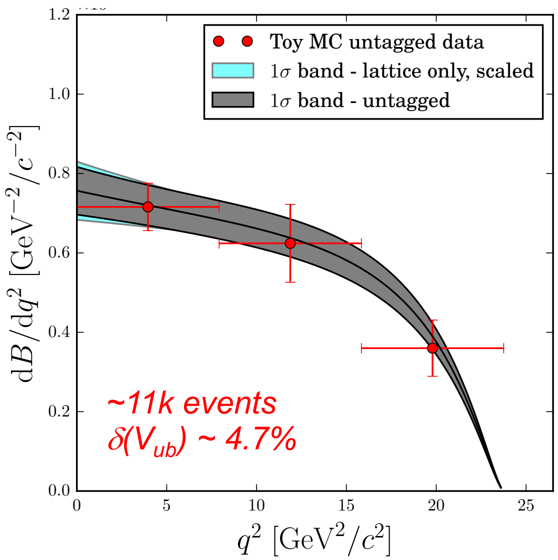
Use BCL parametrization of form factor, fit q^2 spectrum for BCL parameters and $|V_{ub}|$



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



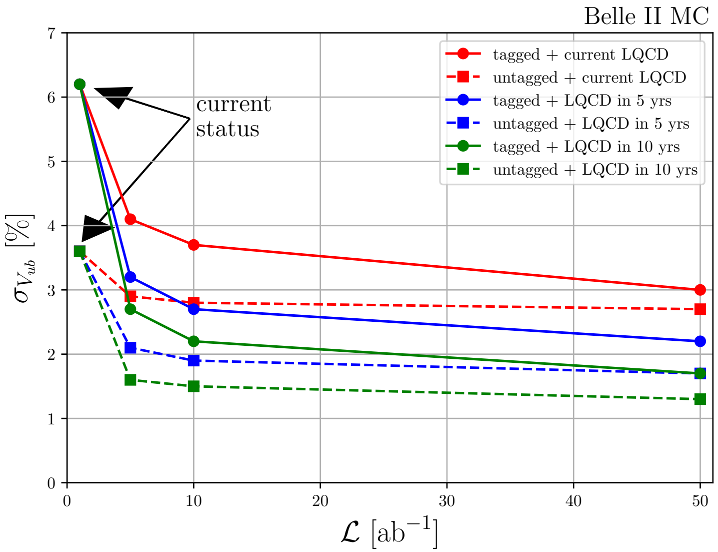
Belle II 5 ab^{-1} $\Upsilon(5S)$: $B_s \rightarrow K l \nu$



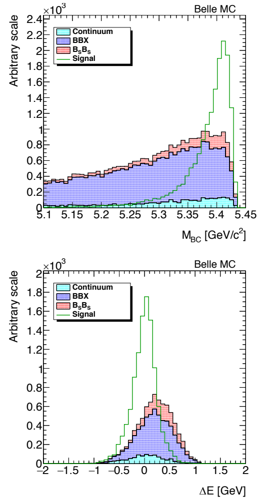
~11k events

$\delta(V_{ub})$ ~ 4.7%

$$\chi^2 = \left(\vec{\mathcal{B}} - \Delta\vec{\Gamma}\,\tau\right)^T C^{-1}\left(\vec{\mathcal{B}} - \Delta\vec{\Gamma}\,\tau\right) + \chi^2_{\mathrm{LQCD}}$$

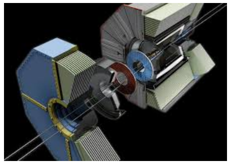


$\Upsilon(5S)$: $B_s \rightarrow K l \nu$



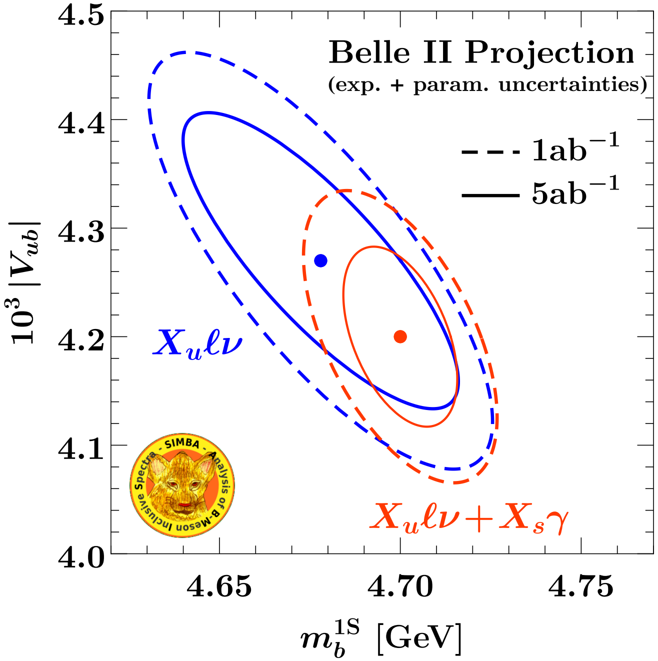
BCL: *Bourrely, Caprini, Lellouch, PRD 79, 013008 (2009)*
Lattice: *Aoki et al., (FLAG), EPJC 77, 112, (2017)*
LCSR: *Bharucha, JHEP 05, 092, (2012)*
HFLAV: *EPJC 77 (2017) 895, arXiv:1612.07233*

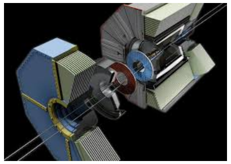
$|V_{ub}|$ = $(3.67 \pm 0.09_{\mathrm{exp}} \pm 0.12_{\mathrm{th}}) \times 10^{-3}$



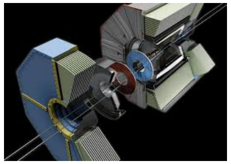
$|V_{ub}|$ via all

	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\lvert V_{ub}\rvert$ exclusive (had. tagged)					
711 fb^{-1}	3.0	(2.3, 1.0)	3.8	7.0	8.0
5 ab^{-1}	1.1	(0.9, 1.0)	1.8	1.7	3.2
50 ab^{-1}	0.4	(0.3, 1.0)	1.2	0.9	1.7
$\lvert V_{ub}\rvert$ exclusive (untagged)					
605 fb^{-1}	1.4	(2.1, 0.8)	2.7	7.0	7.5
5 ab^{-1}	1.0	(0.8, 0.8)	1.2	1.7	2.1
50 ab^{-1}	0.3	(0.3, 0.8)	0.9	0.9	1.3
$\lvert V_{ub}\rvert$ inclusive					
605 fb^{-1} (old B tag)	4.5	(3.7, 1.6)	6.0	2.5−4.5	6.5−7.5
5 ab^{-1}	1.1	(1.3, 1.6)	2.3	2.5−4.5	3.4−5.1
50 ab^{-1}	0.4	(0.4, 1.6)	1.7	2.5−4.5	3.0−4.8
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (had. tagged)					
711 fb^{-1}	18.0	(7.1, 2.2)	19.5	2.5	19.6
5 ab^{-1}	6.5	(2.7, 2.2)	7.3	1.5	7.5
50 ab^{-1}	2.1	(0.8, 2.2)	3.1	1.0	3.2
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (SL tagged)					
711 fb^{-1}	11.3	(10.4, 1.9)	15.4	2.5	15.6
5 ab^{-1}	4.2	(4.4, 1.9)	6.1	1.5	6.3
50 ab^{-1}	1.3	(2.3, 1.9)	2.6	1.0	2.8

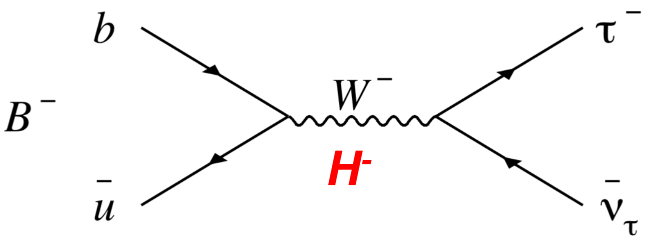




Searches for New Physics



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

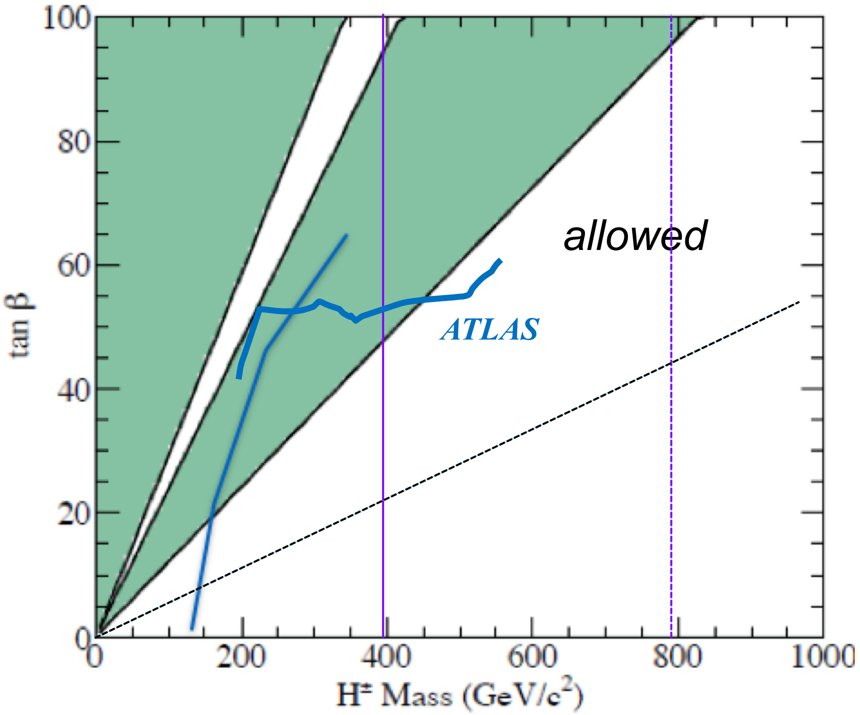


2-Higgs doublet model:

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

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

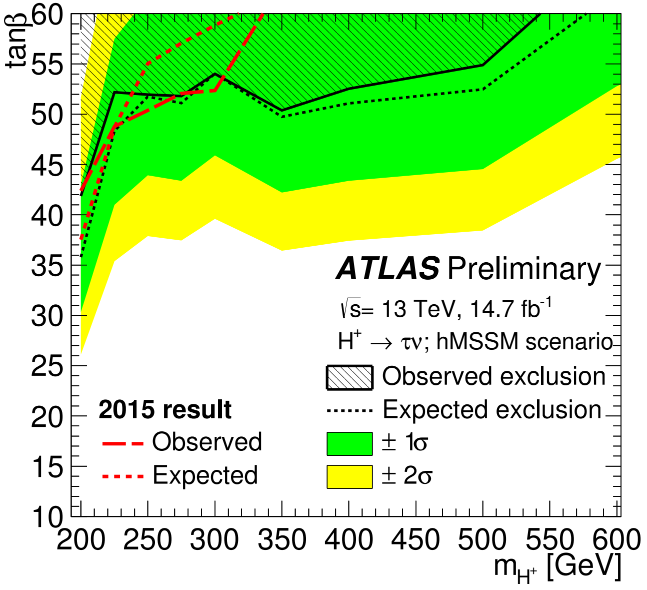
⇒ *WA $\mathcal{B} = (1.06 \pm 0.19) \times 10^{-4}$ gives a constraint in the $\tan\beta$-m_H plane:*

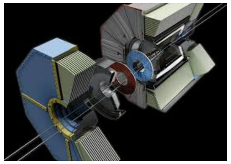


current measured value of $\mathcal{B}(b\to s\gamma)$ excludes m_H<400 GeV/c² for all $\tan\beta$.

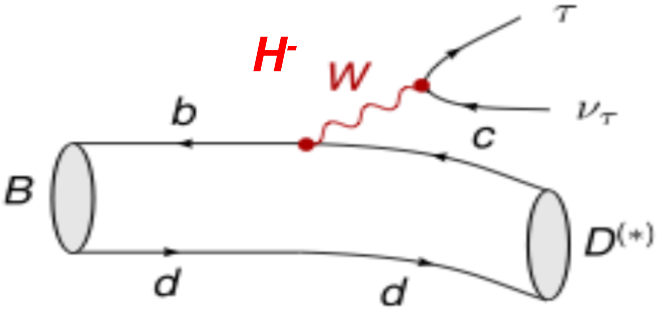
Theory: Hermann, Misiak, & Steinhauser, JHEP 1211 (2012) 036; Misiak et al., PRL 98, 022002 (2007)

Compare to direct search at LHC (ATLAS-CONF-2016-088):





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

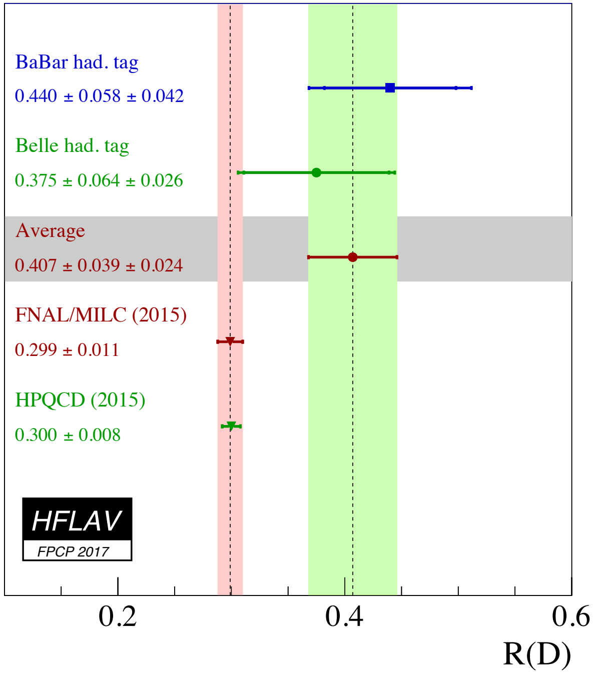


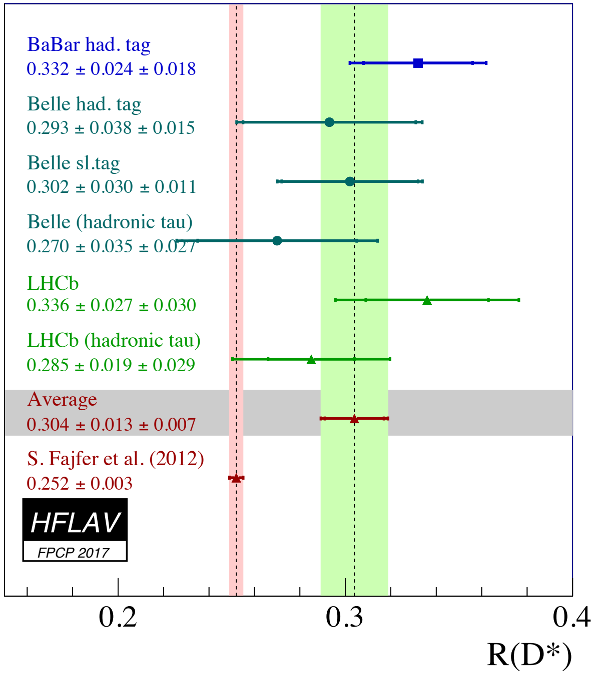
$B\to D^{(*)}\tau\nu$ *can also receive contribution from a charged Higgs, changing the rate, q^2 distribution, etc.*

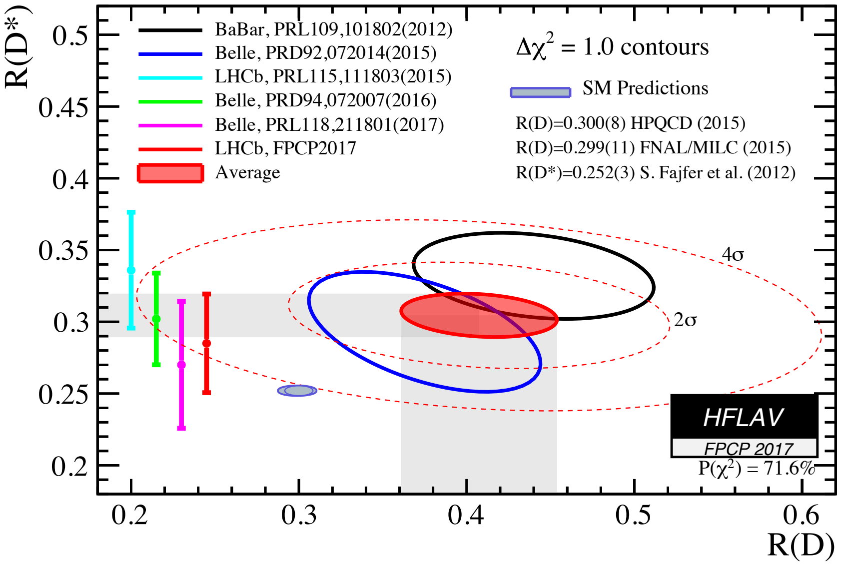
Define ratios:

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

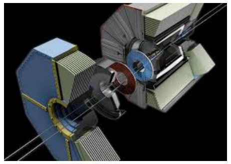
Uncertainties from form factors and V_{cb} drop out ⇒ ratios test lepton universality. Measured values are above SM prediction:







3.9σ discrepancy, p-value = 8.3×10^{-5}

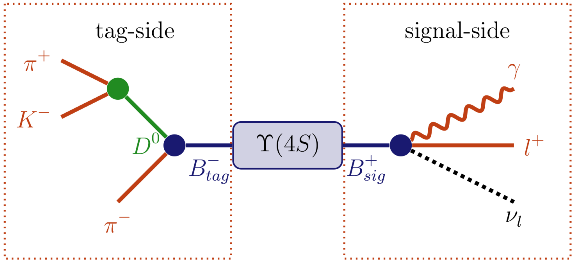


$B\rightarrow D^{(*)}\tau\nu$: results confirmed by Belle

711 fb^{-1} *Huschle, PRD 92, 072014 (2015)*

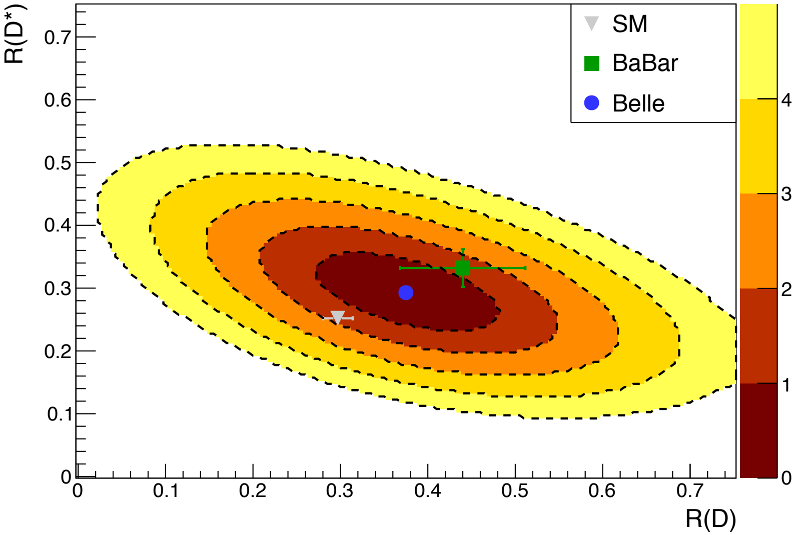
$$\mathcal{R}_{D^*} \equiv \frac{\mathcal{B}(B\rightarrow D^*\tau\nu)}{\mathcal{B}(B\rightarrow D^*\ell\nu)} \qquad \mathcal{R}_{D} \equiv \frac{\mathcal{B}(B\rightarrow D\tau\nu)}{\mathcal{B}(B\rightarrow D\ell\nu)}$$

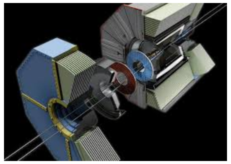
- *Use hadronically tagged events (as done for $B\rightarrow D\ell\nu$ analysis, 1149 possible states)*
- *On signal side consider only $\tau\rightarrow e\nu\nu$, $\tau\rightarrow\mu\nu\nu$, select $D^{(*)}\mu$ and $D^{(*)}e$*
- *calculate missing mass squared:* $M^2_{\rm miss} = \left(P_{\rm beam} - P_D - P_\ell\right)^2$
- *for M^2_{miss} < 0.85 ($B\rightarrow D^{(*)}\ell\nu$ dominated), fit M^2_{miss} spectrum for $B\rightarrow D\ell\nu$ yield*
- *for M^2_{miss} > 0.85 ($B\rightarrow D^{(*)}\tau\nu$ dominated), fit a NN spectrum to obtain $B\rightarrow D^{(*)}\tau\nu$ yield, because M^2_{miss} cannot discriminate between $D^{(*)}\tau\nu$ signal and $D^{**}\ell\nu$ background.*



$$\begin{aligned}\mathcal{R}_{D^*} &= 0.293 \pm 0.038 \pm 0.015\\ \mathcal{R}_{D} &= 0.375 \pm 0.064 \pm 0.026\end{aligned}$$

Higher than SM:
$$\begin{aligned}\mathcal{R}^{SM}_{D^*} &= 0.252 \pm 0.003\\ \mathcal{R}^{SM}_{D} &= 0.297 \pm 0.017\end{aligned}$$

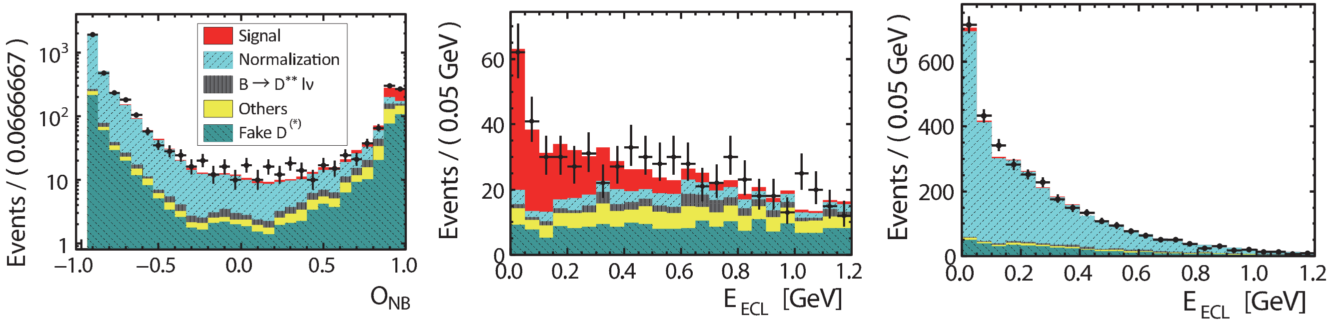




$B \to D^{(*)} \tau^+ \nu$: two more Belle analyses

$711\ \text{fb}^{-1}$ Sato et al., PRD 94, 072007 (2016)

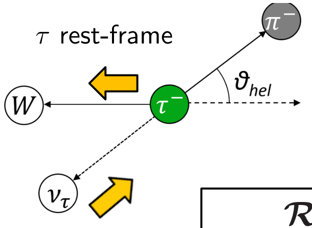
- *Use semileptonically tagged events: $B_{\text{tag}} \to D^{*+}\ell^- \nu$*
- *On signal side consider only $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$, select $D^{(*)}\mu$ and $D^{(*)} e$ on signal side*
- *most discrimination power comes from E_{ECL} (unassociated energy in calorimeter)*



$$\boxed{\mathcal{R}_{D^*} = 0.302 \pm 0.030 \pm 0.011}$$

$711\ \text{fb}^{-1}$ Hirose et al., PRL 118, 211801 (2017); arXiv:1709.00129

- *Use hadronically tagged events (1104 possible states); On signal side: $\tau^- \to \pi^- \nu$, $\tau^- \to \rho^- \nu$*
- *Measure τ polarization via helicity angle:* $P_\tau \equiv \dfrac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$

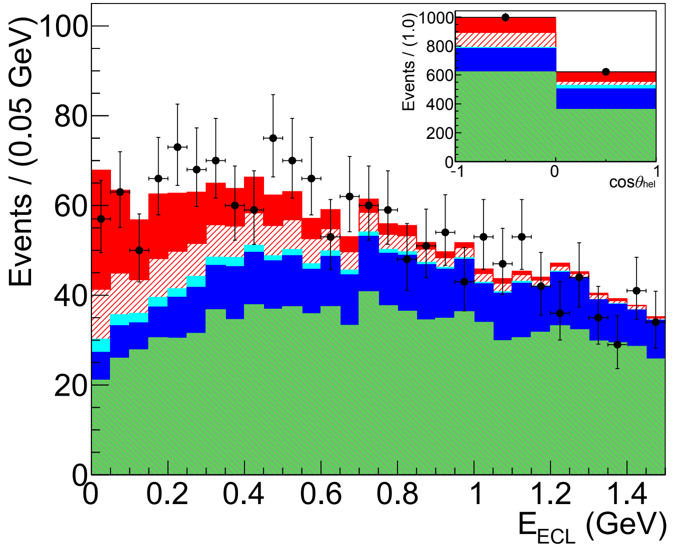


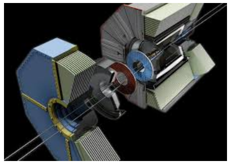
$$\frac{d\Gamma}{d\cos\theta_h} \propto 1 + \alpha P_\tau \cos\theta_h$$

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

$$\begin{aligned} \mathcal{R}_{D^*} &= 0.270 \pm 0.035\,^{+0.028}_{-0.025} \\ P_\tau(D^*) &= -0.38 \pm 0.51\,^{+0.21}_{-0.16} \end{aligned}$$

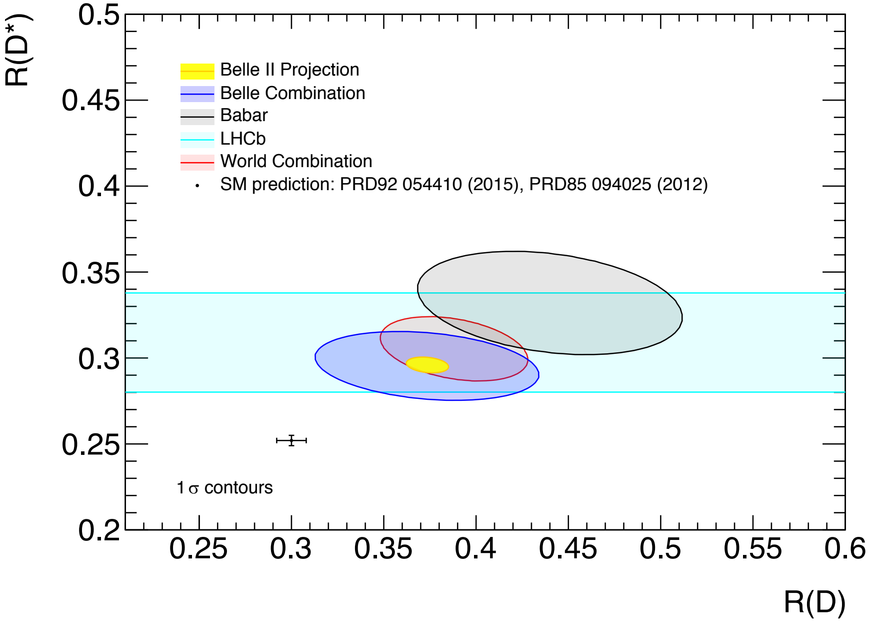
SM: -0.497

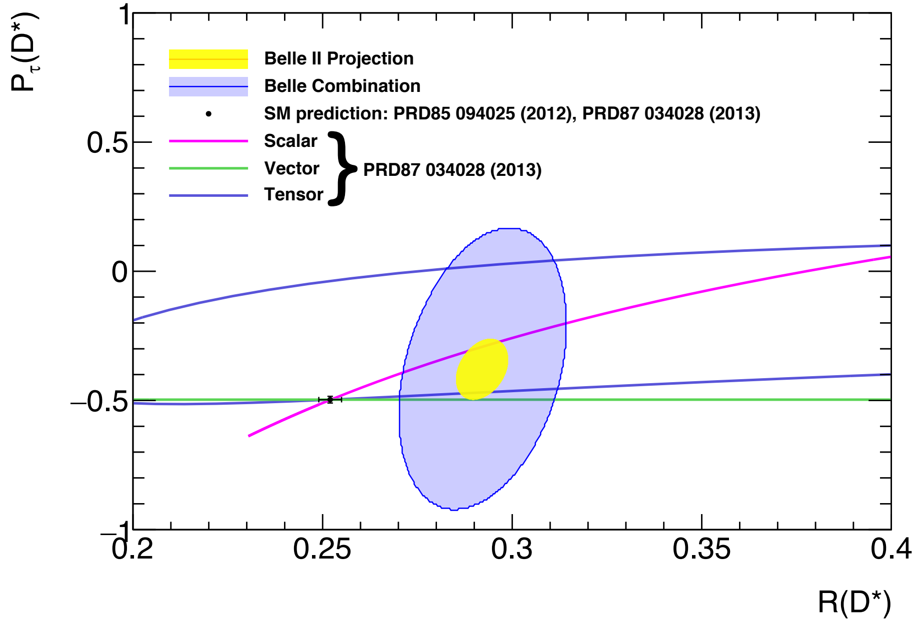




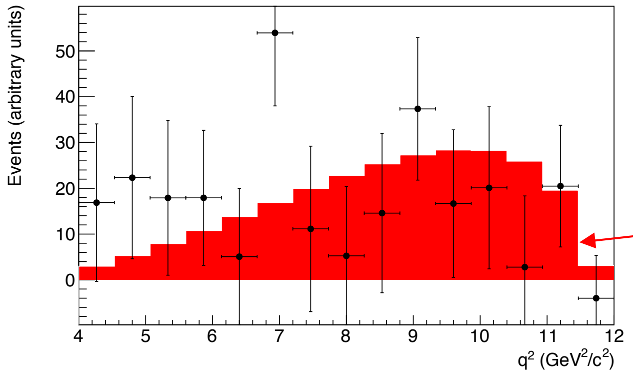
$B \to D^{(*)}\tau\nu$ @ Belle II

Careful scaling from Belle → Belle II:

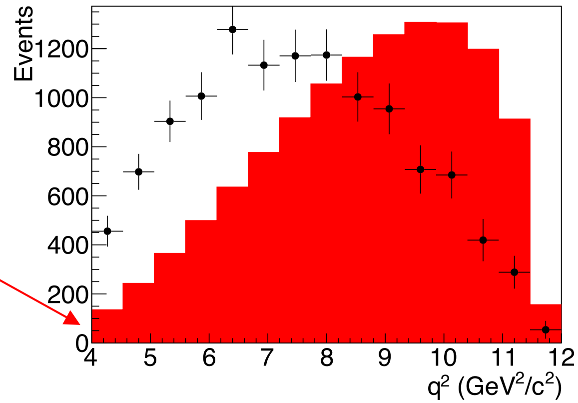




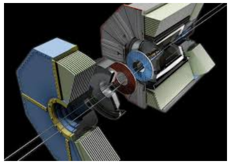
Belle 0.71 ab^{-1}:



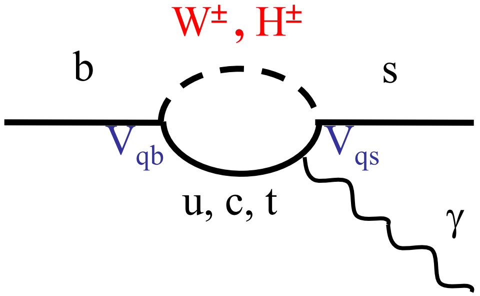
Belle II 50 ab^{-1}:

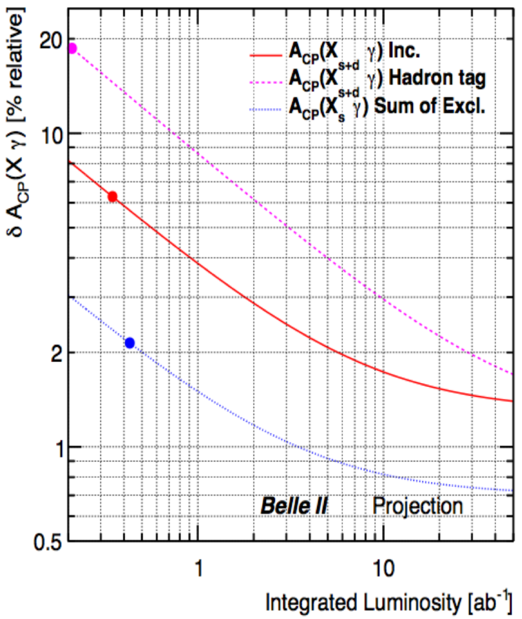


Type II 2HDM
$\tan\beta/M_H = 0.5$



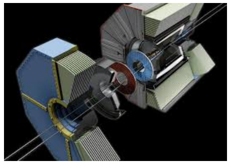
Inclusive $B\rightarrow X_{(s,d)}\gamma$ radiative decays



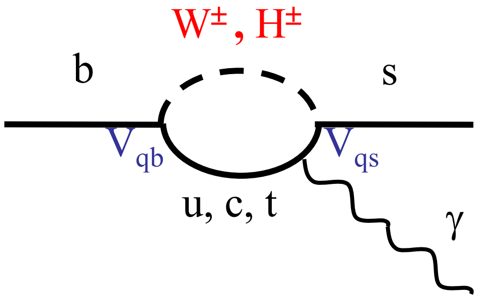


Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B\to X_s\gamma)^{\text{lep-tag}}_{\text{inc}}$	5.3%	3.9%	3.2%
$\mathrm{Br}(B\to X_s\gamma)^{\text{had-tag}}_{\text{inc}}$	13%	7.0%	4.2%
$\mathrm{Br}(B\to X_s\gamma)_{\text{sum-of-ex}}$	10.5%	7.3%	5.7%
$\Delta_{0+}(B\to X_s\gamma)_{\text{sum-of-ex}}$	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%
$A_{\text{CP}}(B^0\to X^0_s\gamma)_{\text{sum-of-ex}}$	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%

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



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%
$A_{\mathrm{CP}}(B^0 \to K^{*0}\gamma)$	1.7%	0.58%	0.21%
$A_{\mathrm{CP}}(B^+ \to K^{*+}\gamma)$	2.4%	0.81%	0.29%
$\Delta A_{\mathrm{CP}}(B \to K^*\gamma)$	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%
$A_{\mathrm{CP}}(B^0 \to \rho^0\gamma)$	44%	12%	3.8%
$A_{\mathrm{CP}}(B^+ \to \rho^+\gamma)$	30%	9.6%	3.0%
$A_{\mathrm{CP}}(B^0 \to \omega\gamma)$	91%	23%	7.7%
$\Delta A_{\mathrm{CP}}(B \to \rho\gamma)$	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%	–
$A_{\mathrm{CP}}(B_s^0 \to K^{*0}\gamma)$	–	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

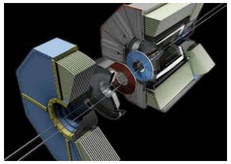
Theory:

$\Delta_{0+}(K^*\gamma) = (4.9 \pm 2.6)\%$
$A_{CP}(K^*\gamma) = (0.3 \pm 0.1)\%$

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

Lyon and Zwicky, PRD D88, 094004 (2013)

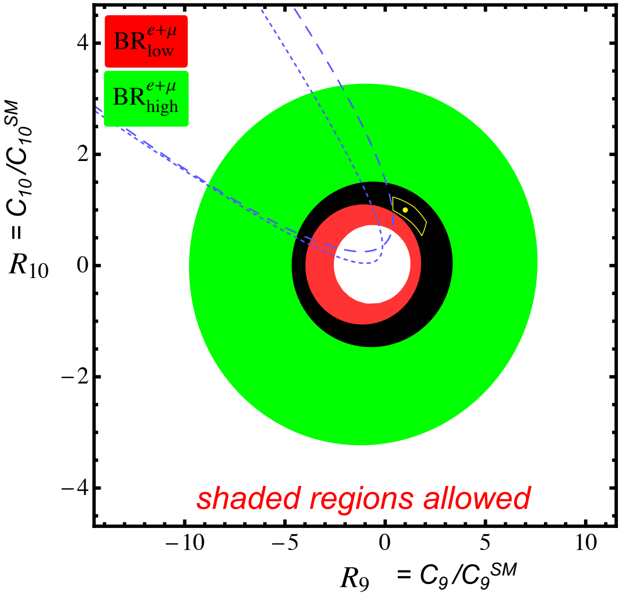
Paul and Straub, JHEP 04, 027 (2017)



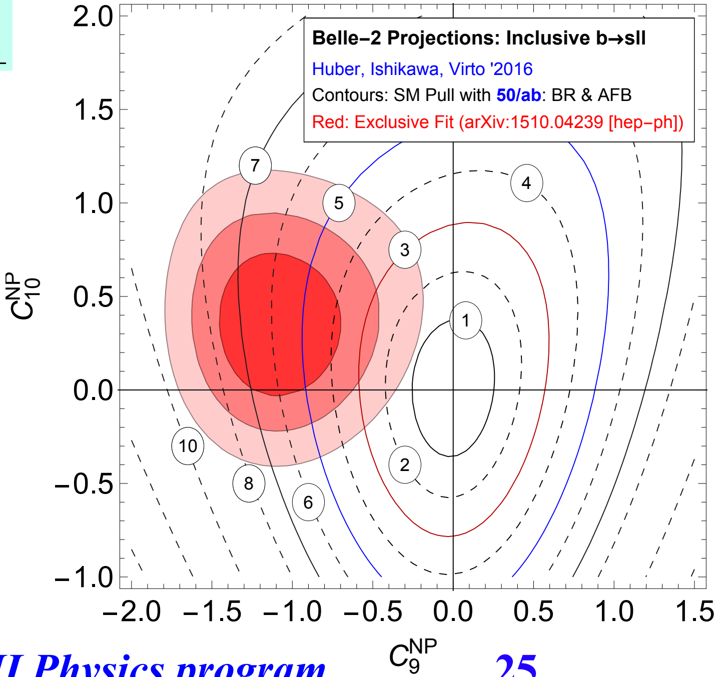
Inclusive $B\to X_{(s,d)}\ell^+\ell^-$ electroweak decays

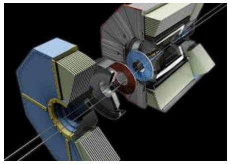
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathcal{B}(B\to X_s\ell^+\ell^-)$ $(1.0 < q^2 < 3.5\ \mathrm{GeV}^2)$	29%	13%	6.6%
$\mathcal{B}(B\to X_s\ell^+\ell^-)$ $(3.5 < q^2 < 6.0\ \mathrm{GeV}^2)$	24%	11%	6.4%
$\mathcal{B}(B\to X_s\ell^+\ell^-)$ $(q^2 > 14.4\ \mathrm{GeV}^2)$	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%

Huber, Hurth, Lunghi, JHEP 06, 176 (2015)



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



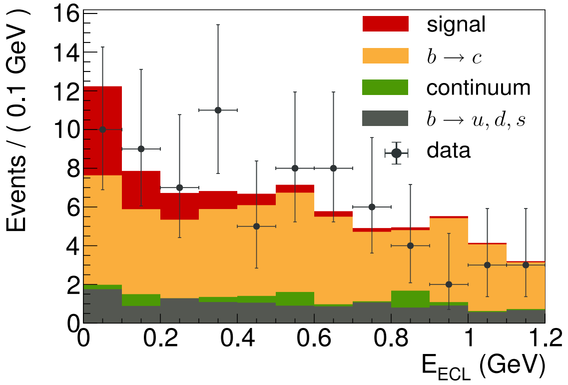


$B \to h\nu\nu$ ($h = \pi^+, \pi^0, \rho^+, \rho^0, K^+, K_S, K^{*0}, K^{*+}$)

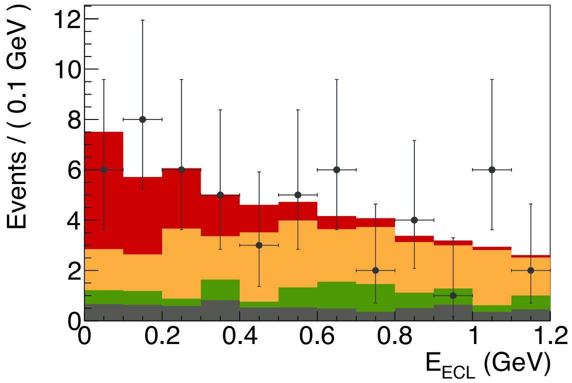
711 fb^{-1} Grygier et al. (Belle), PRD 96, 091101 (2017)

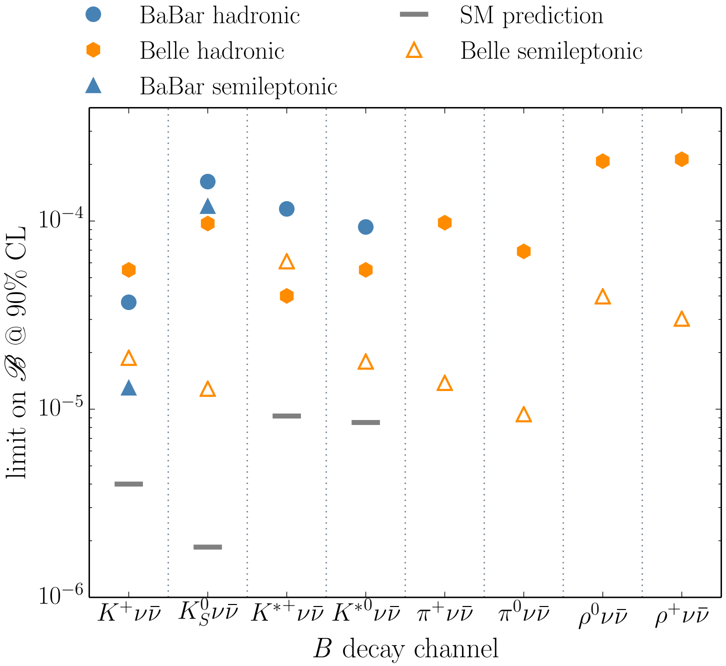
- **Semileptonic tag:** *use Neural Network (NN) to identify $B \to D^{(*)} l \nu$ decay on tagging side. Including D^0 and D^+ modes, there are 108 different decay channels considered.*
- *Require only relevant tracks on signal side: no extra tracks, extra π^0's, or K_L's.*
- *Suppress continuum background (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



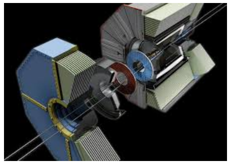
K^{*+}





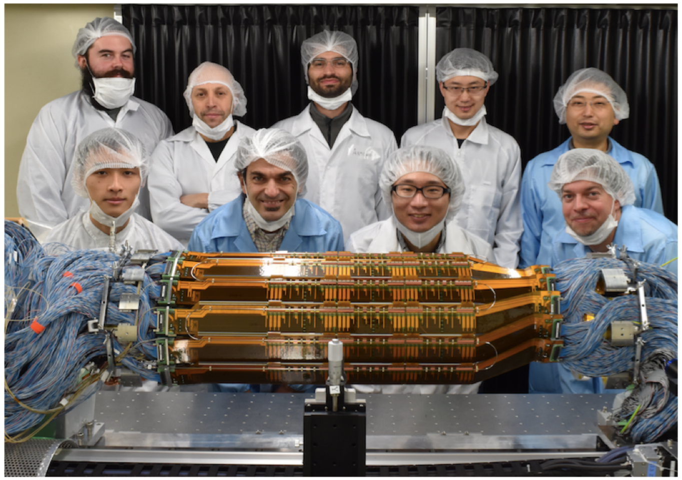
- *no signals observed. most limits are the world's best*
- *limits are a factor of 2.7 (K^*) – 3.9 (K) above SM prediction*

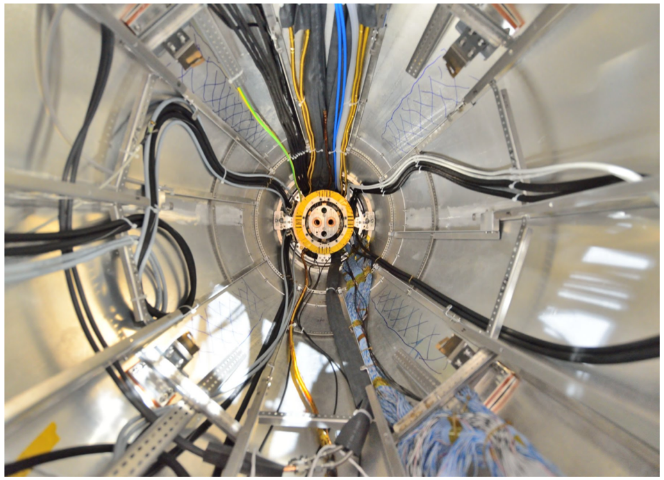
⇒ *Belle II should get to SM level*

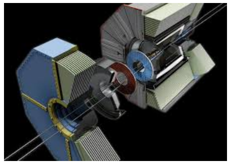


Summary

- Belle II is now (almost) fully constructed and installed. The entire detector except for the VTX is now undergoing commissioning (with cosmic rays since August, with beam in April/May)
- Belle II will take its first physics ("Phase II") run in May-June-July. This should fully commission the detector, and there will be early physics (e.g., $D^0 \to \gamma\gamma$, dark photon search, etc.)
- VTX detector (SVD + pixels) will be installed in the fall, physics run with full Belle II detector to begin in early 2019
- Physics potential is enormous: there is **much** better vertexing and particle ID than in Belle, there will be much higher statistics, and full reconstruction on the tag side is greatly improved over Belle/BaBar

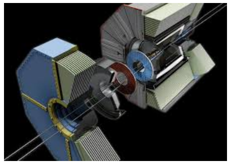






Extra

Extra Slides



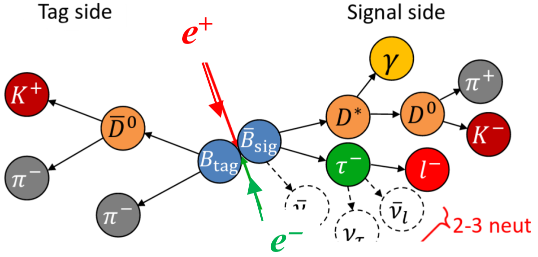
$|V_{cb}|$ from $B\to D l \nu$

$711\ \text{fb}^{-1}$

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

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

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

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

neutral signals

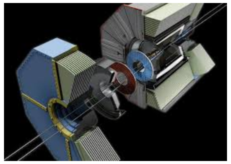
$D^0\to K^-\pi^+$
$D^0\to K^-\pi^+\pi^0$
$D^0\to K^-\pi^+\pi^+\pi^-$
$D^0\to K^-\pi^+\pi^+\pi^-\pi^0$

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

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

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

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



$B \to D^{(*)} \tau\nu$: constraint on Type II charged Higgs

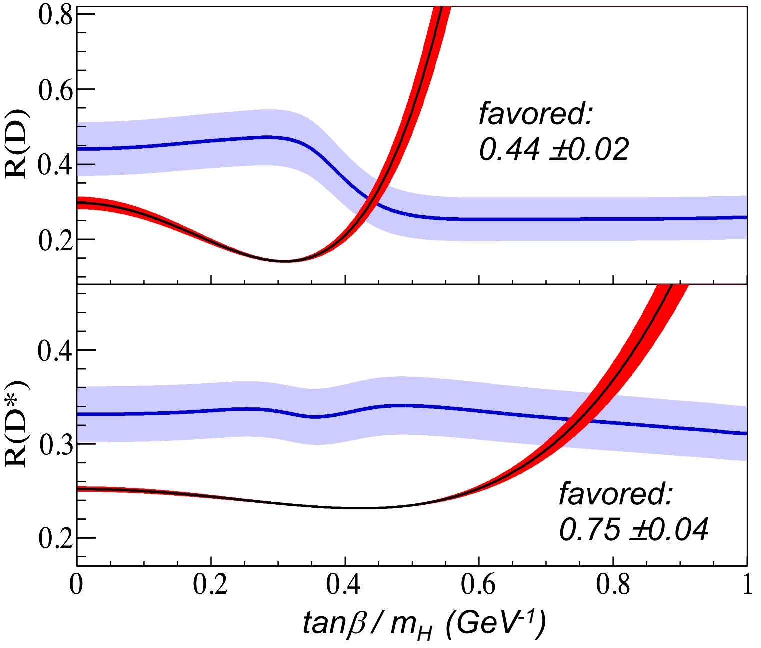
2-Higgs doublet model:

$$\boxed{\mathcal{R}^{2HDM}_{D^{(*)}} = \mathcal{R}^{SM}_{D^{(*)}} + A_{(*)} \left(\frac{\tan\beta}{m_H}\right)^2 + B_{(*)} \left(\frac{\tan\beta}{m_H}\right)^4}$$

	D^*	D
$\mathcal{R}^{SM}$	0.252 ± 0.003	0.297 ± 0.017
A	-0.230 ± 0.029	-3.25 ± 0.32
B	0.643 ± 0.085	16.9 ± 2.0

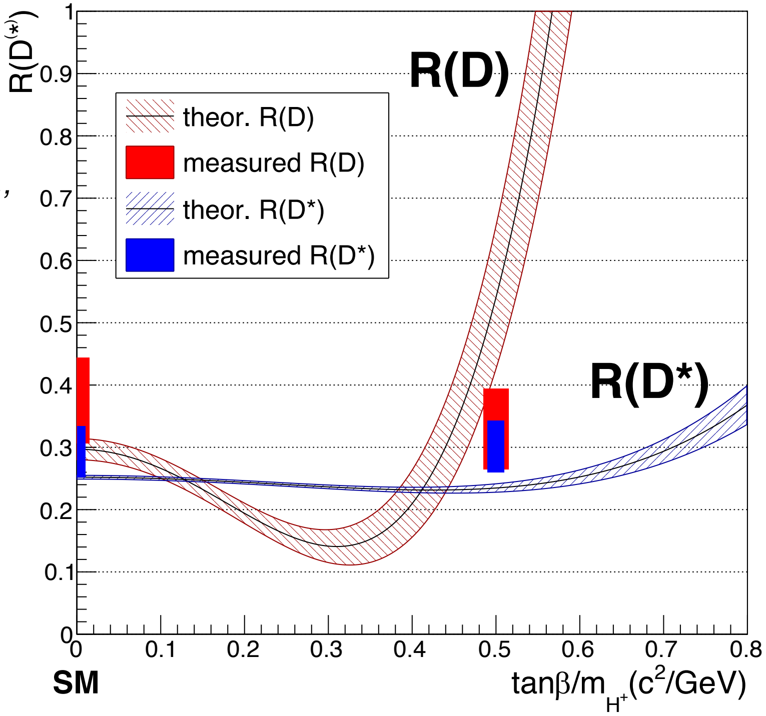
For a Type II charged Higgs doublet model (2HDM), the kinematic distribution of the $\tau\nu$ changes, and thus the PDFs used to fit the data changes → must refit ⇒ results depend on $\tan\beta/M_H$.

Lees et al., PRD 88, 072012 (2013); PRL 109, 101802 (2012)



Results inconsistent with 2HDM at 3.1σ level

Huschle et al., PRD 92, 072014 (2015)



Results consistent with 2HDM

$$\mathcal{R}^{(2HDM)}_{D^*} = 0.301 \pm 0.039 \pm 0.015$$
$$\mathcal{R}^{(2HDM)}_{D} = 0.329 \pm 0.060 \pm 0.022$$