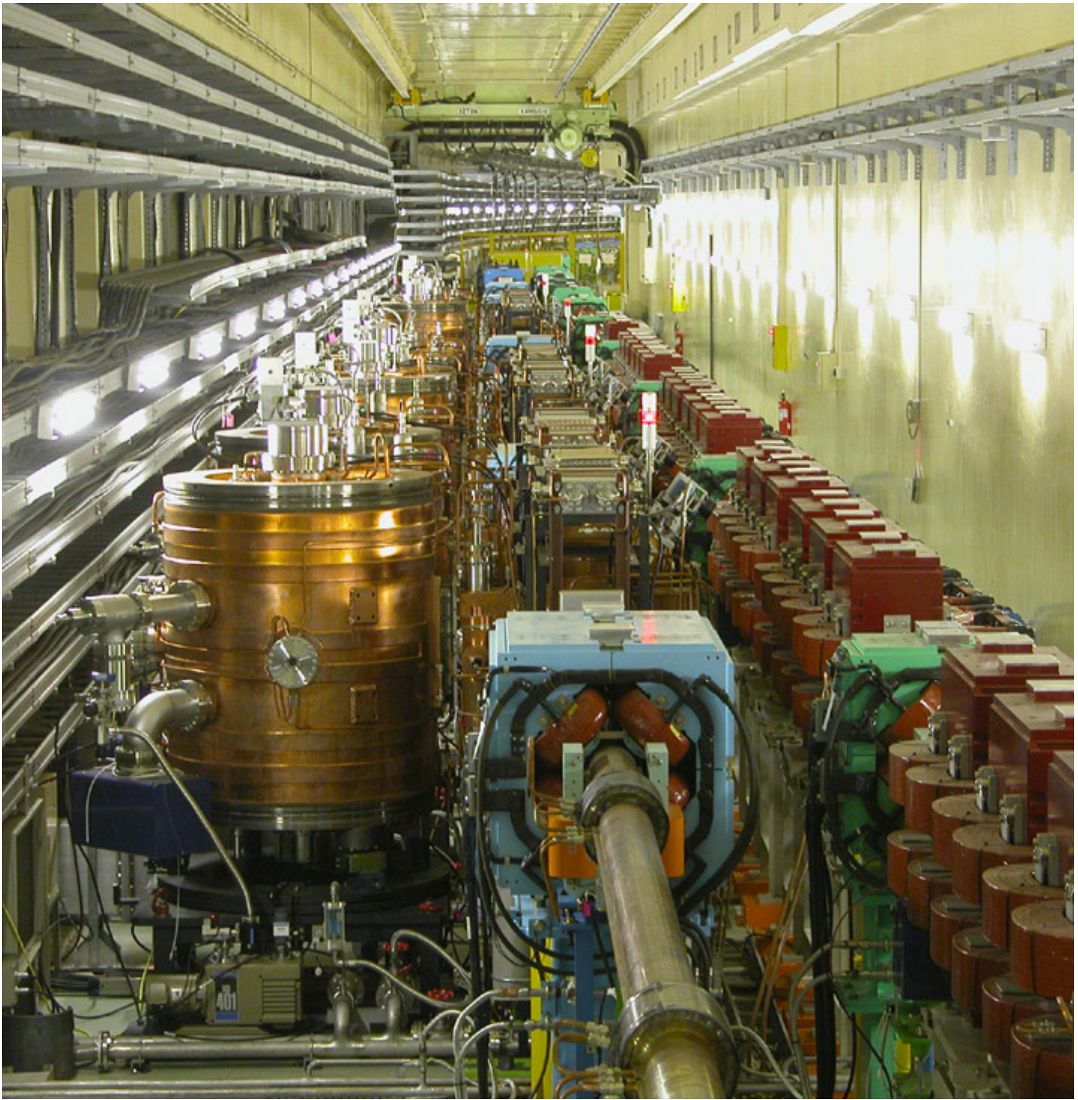
Belle Results and Belle II Prospects: the Impact of the Lattice



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Lattice Gauge Theory for the LHC and Beyond
Kavli Institute for Theoretical Physics
8 September 2015

- *motivation*
- $|V_{cb}|$ *and* $|V_{ub}|$
- $B \rightarrow D^{(*)}\tau\nu$
- *Belle II prospects*

Motivation:

Why a flavor factory in the LHC Era?

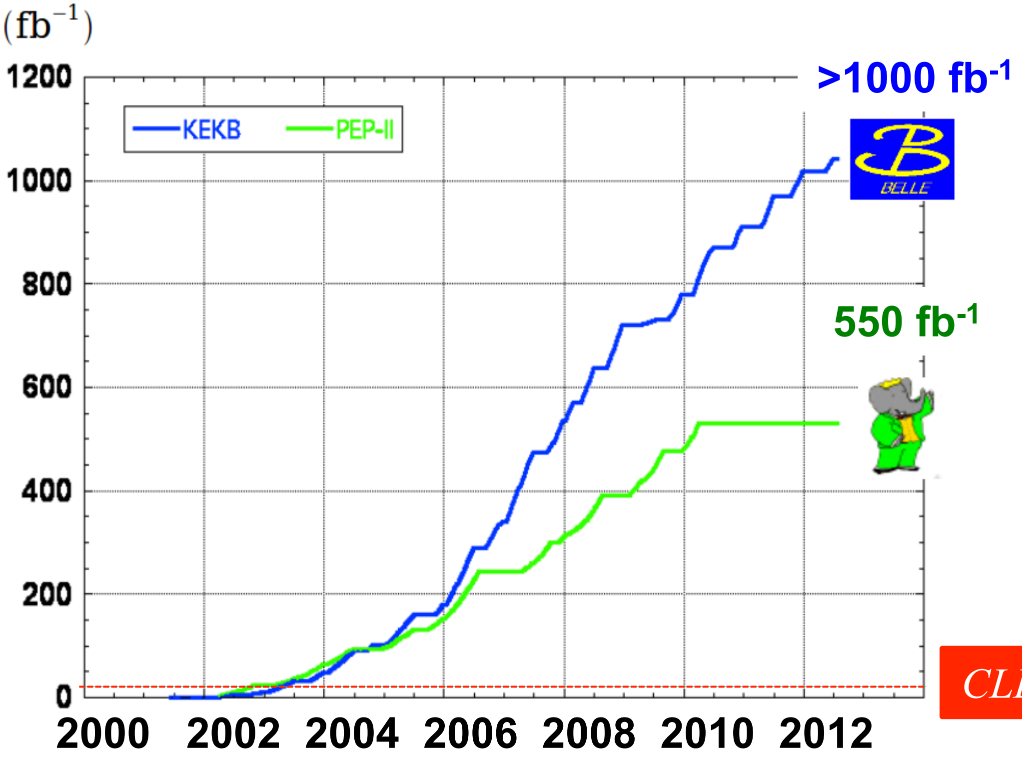
- *A flavor factory studies processes that occur at 1-loop in the SM but may be O(1) in NP: FCNC, neutral meson mixing, CP violation. These loops probe energy scales that cannot be accessed directly - even at the LHC.*
- *If supersymmetry is found at the LHC, it will be important to resolve how it is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

A (super) 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', $\rho+$, 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



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:** 40 x present = 4 x 10^{10} BB pairs*

Unitarity triangle – determining the angles

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

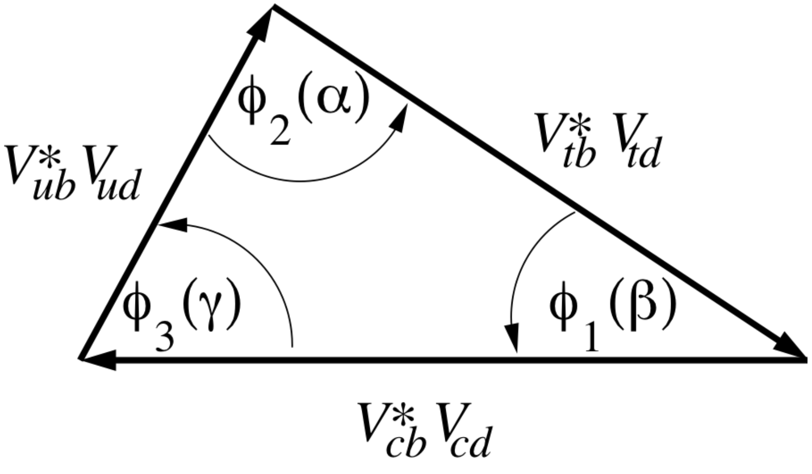
The internal angles of this triangle are phase differences that can be measured via various strategies:

Belle/BaBar
** = recent update*

LHCb
** = update to 3 fb^{-1}*

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

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

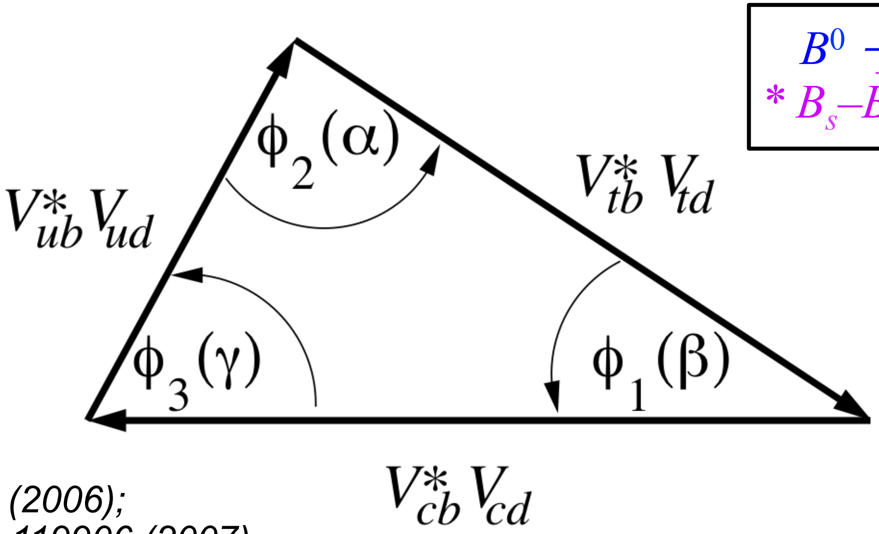


$*\ B^0 \to J/\psi\,K_S$
$B^0 \to J/\psi\,K_L$
$B^0 \to \psi'\,K_S$
$B^0 \to \chi_c\,K_S$
$B^0 \to \eta_c\,K_S$
$B^0 \to D^{(*)}{}_{CP}\,h^0$
$*\ B^0 \to (\phi/\eta'/\pi^0/f^0)K^0$
$*\ B^0 \to (K_SK_S/\rho^0/\omega)K_S$

Unitarity triangle – determining the sides

Belle
LHCb

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



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

Ali et al., arXiv:hep-ph/0610149;
PLB 595, 323 (2004)
Ball et al., JHEP 04, 046 (2006);
PRD 75, 054004 (2007)
Bosch et al., JHEP 0501, 035 (2005)

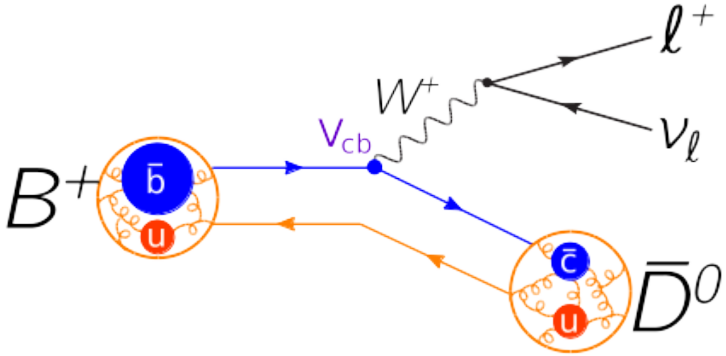
HPQCD, PRD 73, 074502 (2006);
PRD75, 119906 (2007)
FNAL/MILC, Nucl. Phys. Proc.
Suppl. 140, 461 (2005)

Lange et al. (BLNP), PRD 72, 073006 (2005)
Andersen, Gardi (DGE), JHEP 601, 97 (2006)
Gambino et al. (GGOU), JHEP 710, 58 (2007)
Aglietti et al. (ADFR), EPJ C59 (2009);
Nucl. Phy. B768, 85 (2007)
Bauer et al. (BLL), PRD64, 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, Lellouch, Neubert,
Nucl. Phys. B530, 153 (1998)
Neubert, Phys. Rep. 245, 259 (1994)
Isgur, Wise, PLB 237, 527 (1990);
PLB 232, 113 (1989)
Gambino, Uraltsev, EPJ C34, 181 (2004)
Benson, Bigi, Uraltsev, Nucl. Phys. B710, 371 (2005)
Benson et al., Nucl. Phys. B665, 367 (2003)
Boyd, Grinstein, Lebed, PRL 74, 4603 (1995)

$|V_{cb}|$ from $B\to D^{(*)}l\nu$



HFAG 2015

exclusive:

$B\to D^*\ell\nu$: $(38.94 \pm 0.76) \times 10^{-3}$

$B\to D\ell\nu$: $(39.45 \pm 1.67) \times 10^{-3}$

inclusive:

$B\to X_c\ell\nu$: $(42.46 \pm 0.88) \times 10^{-3}$ (kinetic sch.)

For exclusive decays, $|V_{cb}|$ determined via differential decay rate:

$$\frac{d\Gamma}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B+m_D)^2(w^2-1)^{3/2}\eta_{\mathrm{EW}}^2\,|V_{\mathrm{cb}}|^2\,\underbrace{\mathcal{G}(w)^2}_{\text{form factor}}$$

Kinematics:

$$w \equiv v_B\cdot v_D = \frac{M_B^2+M_D^2-q^2}{2M_BM_D}$$

$q^2 = (P_B - P_D)^2 = (P_l + P_\nu)^2$
$q^2 = 0 \to w_{max} = 1.6$
$w = 1 \to q^2_{max}$

Caprini, Lelouch, Neubert:

$$\mathcal{G}(w) = \mathcal{G}(1)(1-8\rho^2 z + (51\rho^2-10)z^2 - (252\rho^2-84)z^3), \qquad z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}$$

Boyd, Grinstein, Lebed:

$$\mathcal{G}(w) = \frac{\sqrt{4M_D/M_B}}{1+M_D/M_B}\;\frac{1}{P_i(z)\phi_i(z)}\sum_{n=0}^{N} a_{i,n}z^n$$

Bailey et al., arXiv:1503.07237

$$P_+(z) = 1$$

$$\phi_+(z) = \frac{1.1213\,(1+z)^2\sqrt{1-z}}{[(1+M_D/M_B)(1-z)+2\sqrt{M_D/M_B}(1+z)]^5}$$

$|V_{cb}|$ from $B\to Dl\nu$

703 fb^{-1}

Glattauer, presented at EPS-HEP 2015 (new)

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

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

charged tags (17 modes)

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

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

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

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

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

neutral tags (15 modes)

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

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

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

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

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

charged signals (10 modes)

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

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

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

neutral signals (13 modes)

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

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

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

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

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

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

703 fb^{-1}

Glattauer, presented
at EPS-HEP 2015

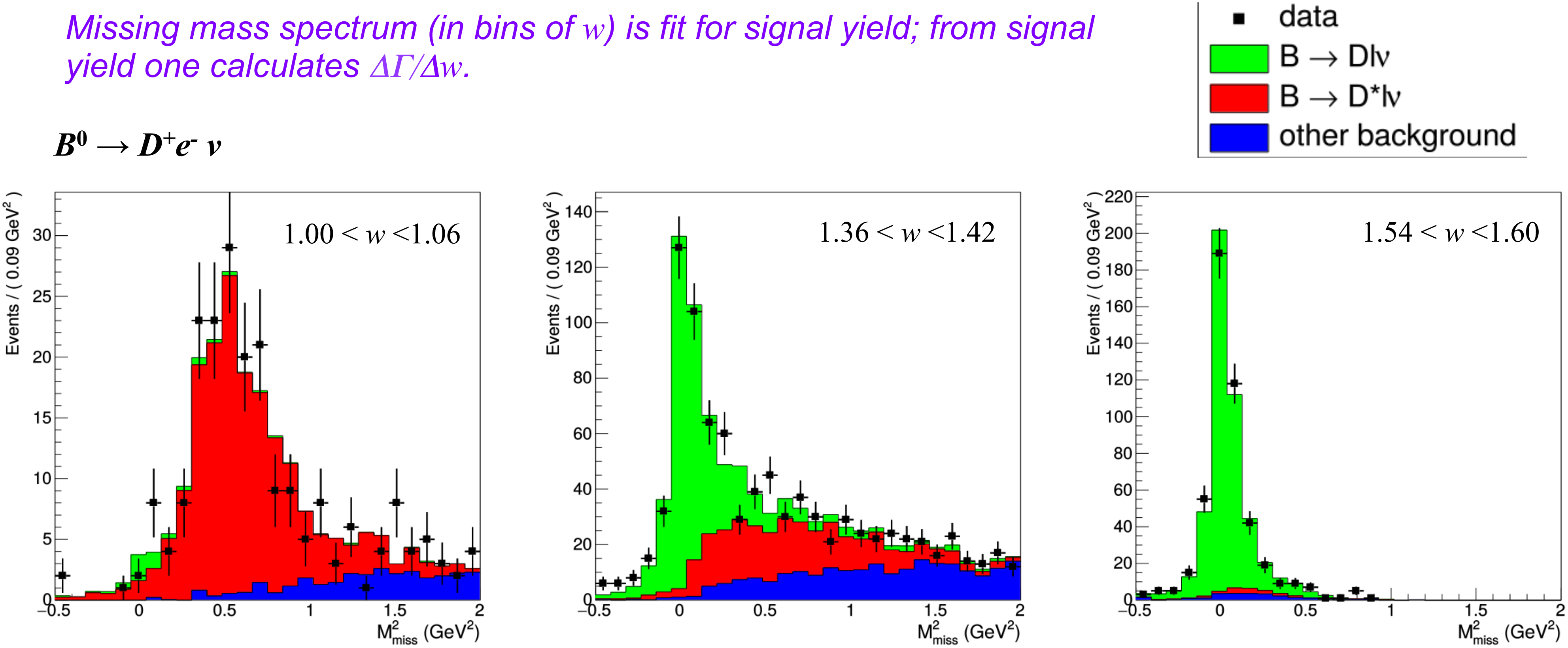
$B \to D\ell\nu$ Reconstruction:

After tag side reconstructed, tracks are “removed” and signal side D reconstructed. After D reconstructed, e or μ is added to decay and missing mass calculated:

$$M^2_{\rm miss} = \left(P_{\rm beam} - P_D - P_\ell\right)^2$$

Missing mass spectrum (in bins of w) is fit for signal yield; from signal yield one calculates $\Delta\Gamma/\Delta w$.

$B^0 \to D^+ e^- \nu$



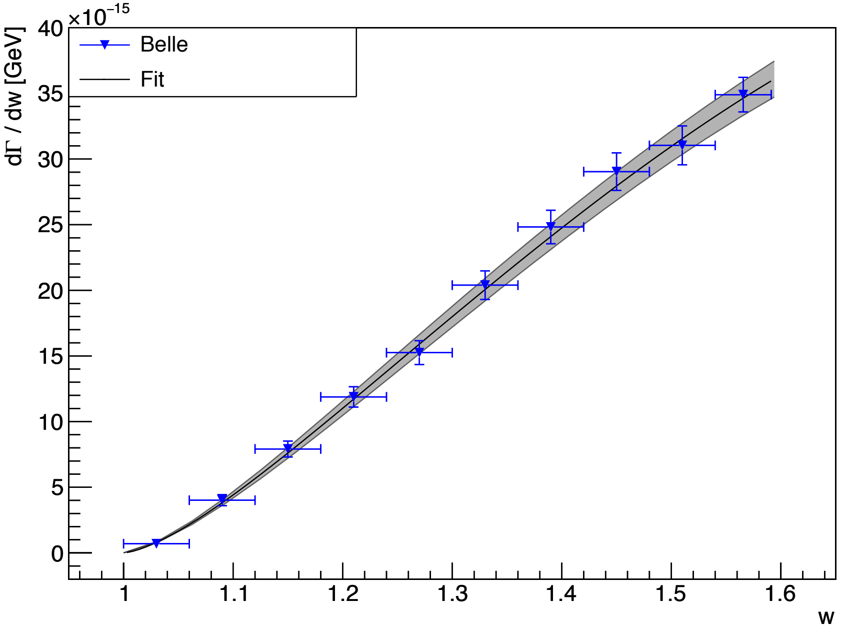
$|V_{cb}|$ from $B \rightarrow D \, l \nu$

703 fb^{-1}

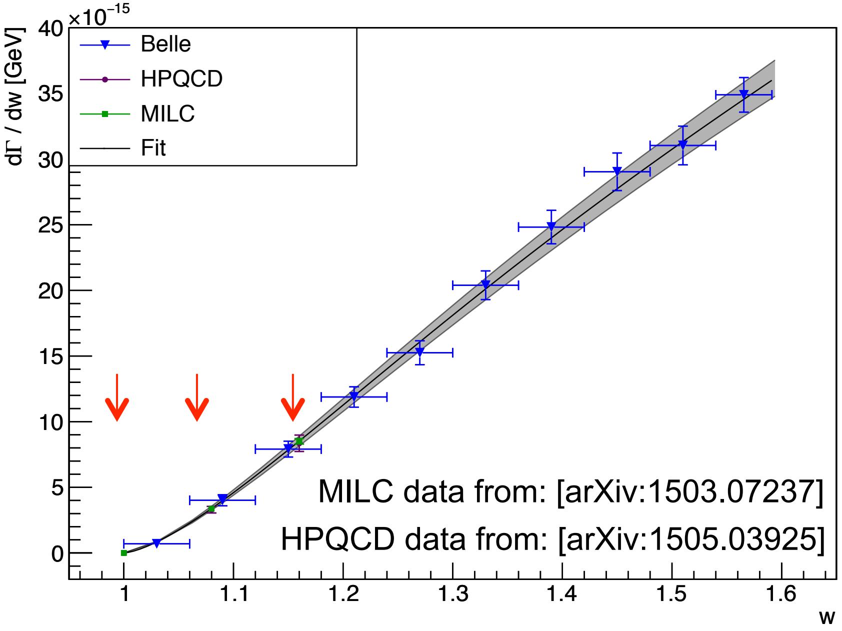
Glattauer, presented at EPS-HEP 2015

Results:

CLN (2 params, heavy quark symmetry)



BGL (more params, less constraints) We also include lattice "data" in the fit:



MILC data from: [arXiv:1503.07237]

HPQCD data from: [arXiv:1505.03925]

$$|V_{\rm cb}|\eta_{\rm EW} = (40.93 \pm 1.33) \times 10^{-3}$$

Belle preliminary

$$|V_{\rm cb}|\eta_{\rm EW} = (42.09 \pm 1.07) \times 10^{-3}$$

Using G(1) = 1.0541 ± 0.0083 from MILC [arXiv:1503.07237]

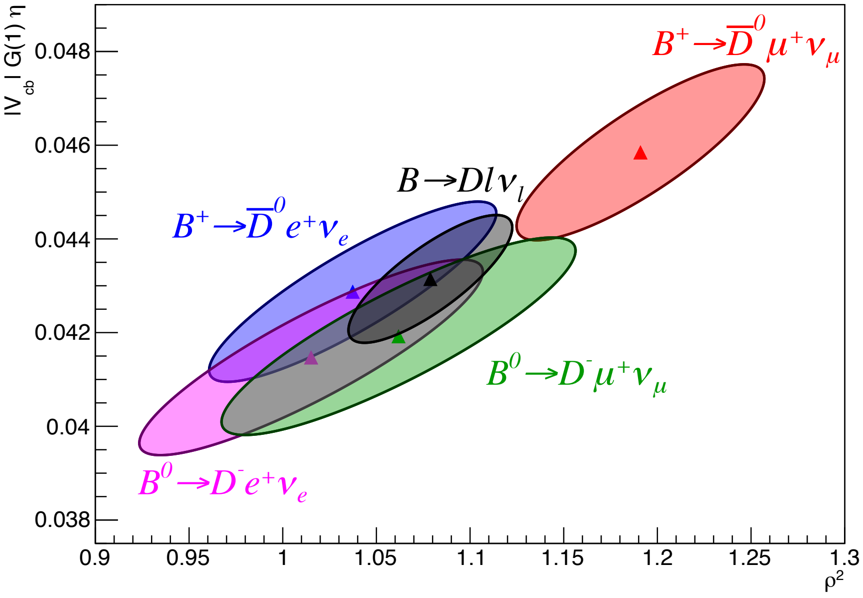
Note: *η_{EW} = 1.0066 (leading order,) Sirlin, Nucl. Phys. B196, 83 (1982)*

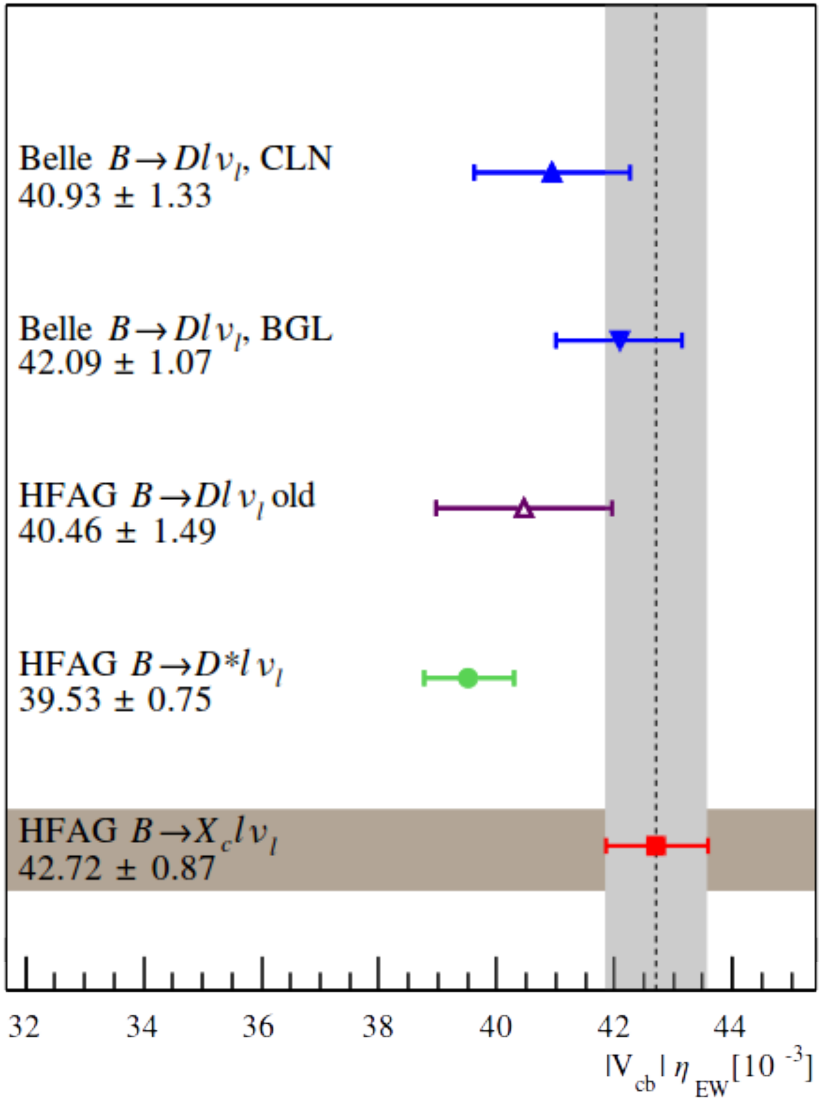
$|V_{cb}|$ from $B\to D\,l\nu$

Belle $703\ \mathrm{fb}^{-1}$

Glattauer, presented at EPS-HEP 2015

Results:





$$\mathcal{B}(B^0 \to D^-\ell^+\nu_\ell) = (2.35 \pm 0.04 \pm 0.11)\%$$
$$\mathcal{B}(\mathrm{B}^+ \to \bar{D}^0\ell^+\nu_\ell) = (2.67 \pm 0.04 \pm {}^{0}.12)\%$$
$$\mathcal{B}(B \to D\ell\nu_\ell) = (2.43 \pm 0.03 \pm 0.10)\%$$

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

$703\ \text{fb}^{-1}$

Glattauer, presented
at EPS-HEP 2015

$B\to D\ell\nu$: Comparison of different BGL set-ups

■ = default

Using different lattice data:

[14] = arXiv:1503.07237
[30] = arXiv:1505.03925

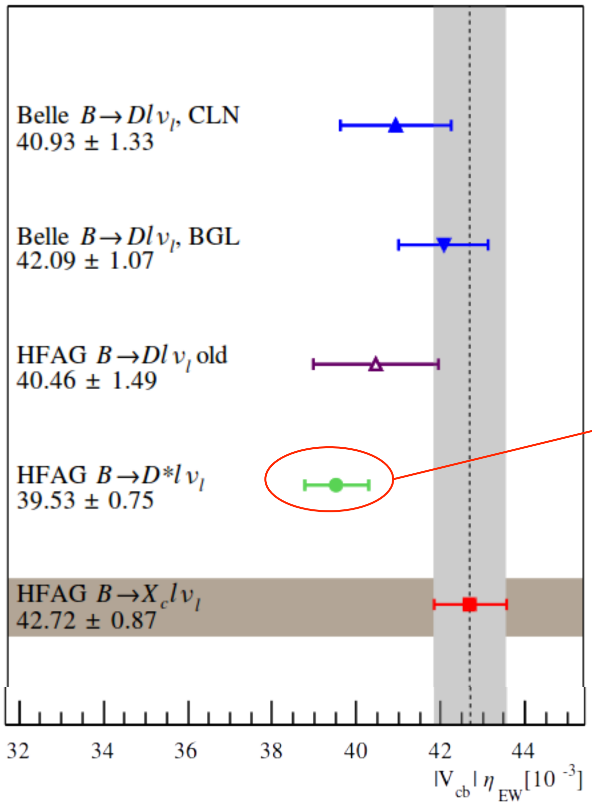
m.

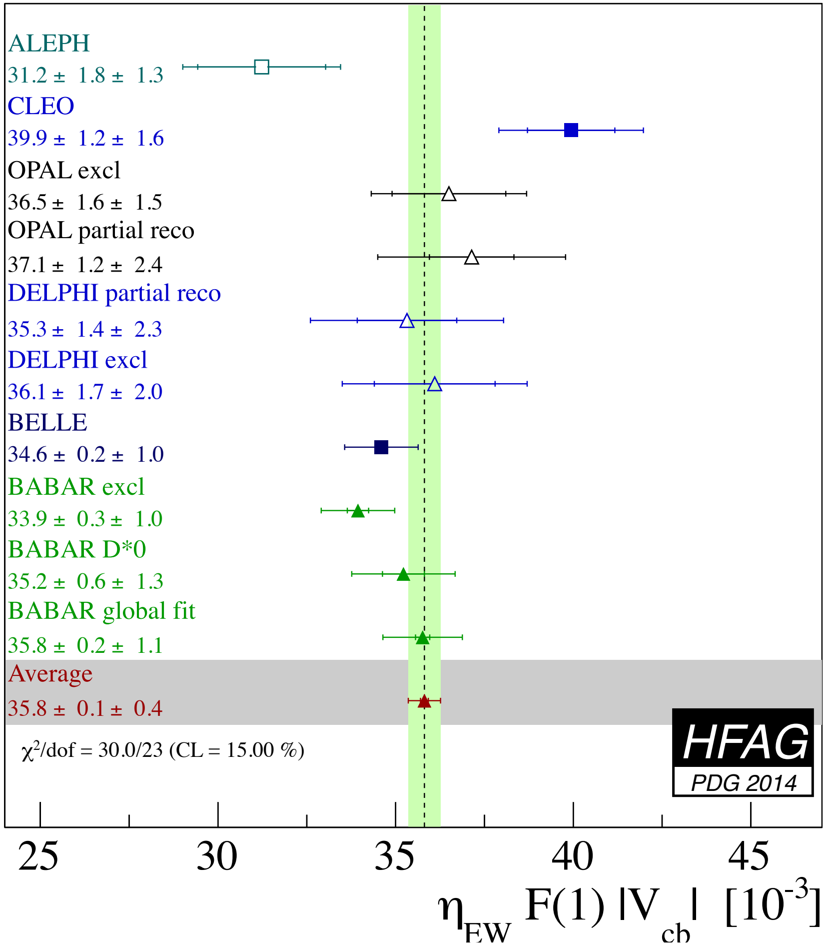
Lattice data	$\eta_{\rm EW}\|V_{cb}\|[10^{-3}]$	$\chi^2/n_{\rm df}$	Prob.
MILC [14]	41.84 ± 1.31	$7.41/10$	0.69
HPQCD [30]	41.97 ± 1.96	$5.83/10$	0.83
MILC & HPQCD [14, 30]	41.91 ± 1.23	$12.40/16$	0.72

Using different series truncations (N):

	$N = 2$	$N = 3$	$N = 4$
$a_{+,0}$	0.0127 ± 0.0001	0.0126 ± 0.0001	0.0126 ± 0.0001
$a_{+,1}$	-0.091 ± 0.002	-0.094 ± 0.003	-0.094 ± 0.003
$a_{+,2}$	0.34 ± 0.03	0.34 ± 0.04	0.34 ± 0.04
$a_{+,3}$	–	-0.2 ± 0.6	-0.2 ± 0.6
$a_{+,4}$	–	–	0.0 ± 1.0
$a_{0,0}$	0.0115 ± 0.0001	0.0114 ± 0.0001	0.0114 ± 0.0001
$a_{0,1}$	-0.058 ± 0.002	-0.057 ± 0.002	-0.057 ± 0.002
$a_{0,2}$	0.23 ± 0.02	0.12 ± 0.04	0.12 ± 0.04
$a_{0,3}$	–	0.3 ± 0.7	0.3 ± 0.7
$a_{0,4}$	–	–	0.0 ± 1.0
$\eta_{\rm EW}\|V_{cb}\|$	40.61 ± 1.18	41.91 ± 1.23	41.91 ± 1.23
$\chi^2/n_{\rm df}$	$31.0/16$	$12.4/16$	$12.4/16$
Prob.	0.014	0.716	0.716

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





Using:

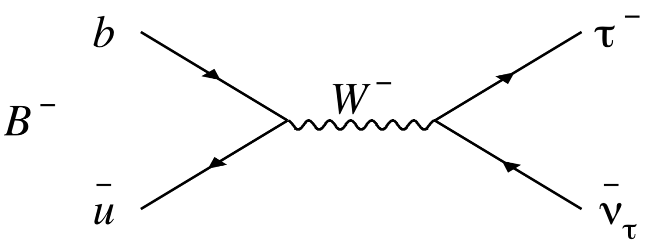
$$\eta_{EW}\mathcal{F}(1) \;=\; 0.920 \pm 0.014$$

⇒

$$|V_{cb}| \;=\; (38.94 \pm 0.49_{\rm exp} \pm 0.58_{\rm theor}) \times 10^{-3}$$

A. Bailey et al. [FNAL/MILC], PRD 89, 114504 (2014)

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



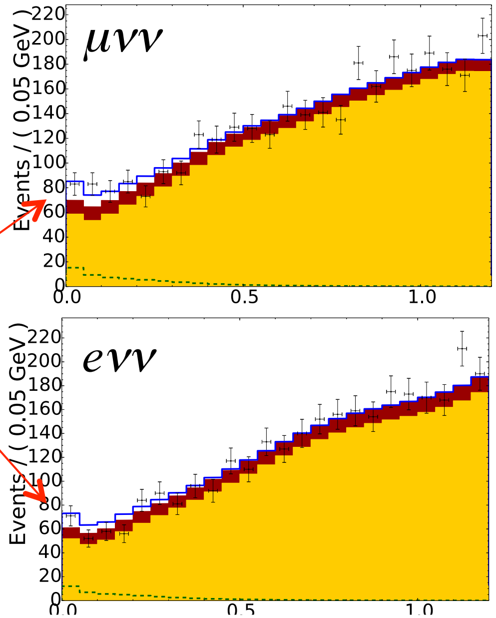
Aubert et al., PRD 81, 051101 (2010) 418 fb^{-1} $D^0\ell$ tag
Lees et al., PRD 88, 031102 (2013) 426 fb^{-1} hadr.tag

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., arXiv:1503.0561 (2015) 711 fb^{-1} semi.tag

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

arXiv:1503.0561 (to appear in PRD):

- $B^+ \to D^{(*)0}\ell^+\nu$, $D^{*0} \to D^0\gamma$, $D^0\pi^0$; $D^0 \to K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$...
- $\tau \to \mu\nu\nu$, $e\nu\nu$, $\pi\nu$, $\rho\nu$ (1 charged track)
- large backgrounds from $b \to c$ ($B\bar{B}$) 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 $B^+ \to \tau^+\nu$

Kronenbitter et al., arXiv:1503.05613 (2015)

$\mathcal{B}(B^+ \to \tau^+\nu) = (1.25 \pm 0.28 \pm 0.27) \times 10^{-4}$

World average:

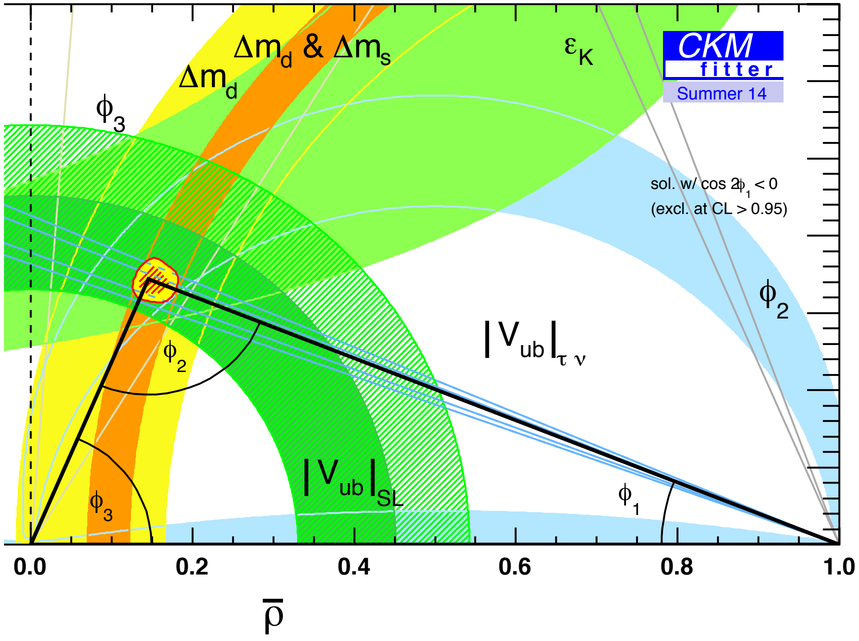
$\mathcal{B}(B^+ \to \tau^+\nu) = (1.14 \pm 0.27) \times 10^{-4}$

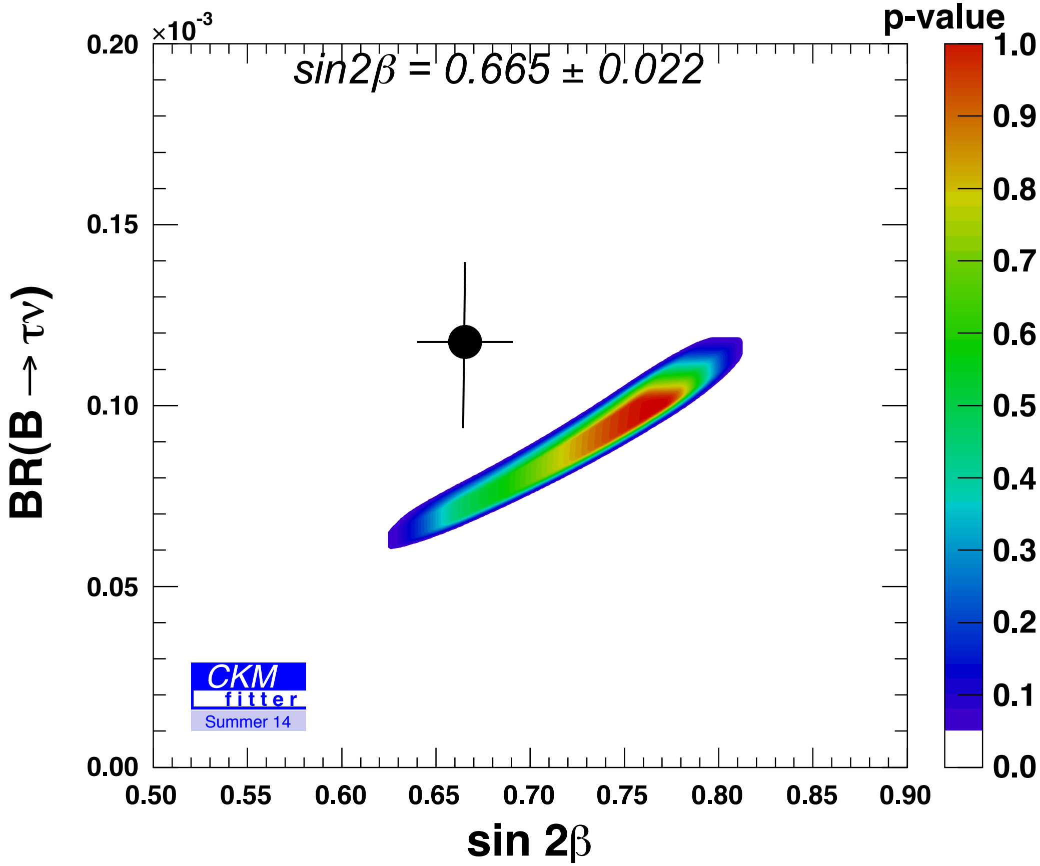
Combining: $\mathcal{B}(B^+ \to \tau^+\nu) = (1.176 \pm 0.222) \times 10^{-4}$

$\Rightarrow \left|V_{ub}\right| = (4.28\,^{+0.39}_{-0.43}) \times 10^{-3}$

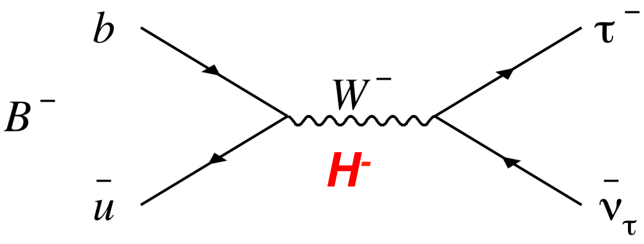
Using f_B = (190.5 ± 4.2) MeV (PDG14)

There is tension is coming from $|V_{td}|$ measured in B^0-$\bar{B}^0$ mixing, ϕ_1 (β) and ϕ_2 (α):





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



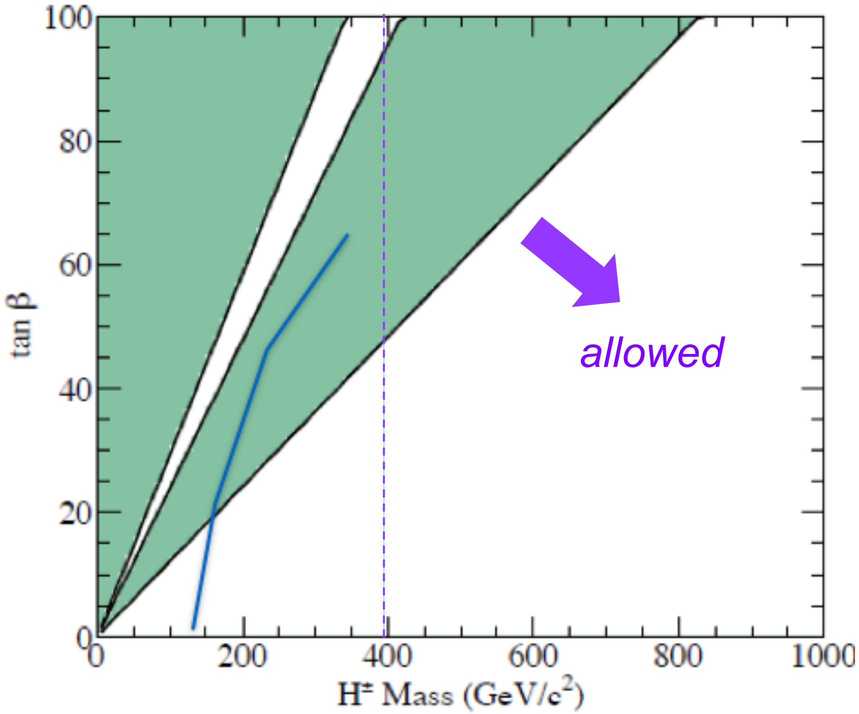
2-Higgs doublet model:

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

Taking f_B = (190.5 ± 4.2) MeV and $|V_{ub}|$ = $(4.13 \pm 0.49) \times 10^{-3}$ (PDG14) gives

$\mathcal{B}_{SM} = (1.09\,^{+0.27}_{-0.24}) \times 10^{-4}$

⇒ measurement $\mathcal{B} = (1.176 \pm 0.222) \times 10^{-4}$ gives a constraint in the $\tan\beta$-m_H plane:

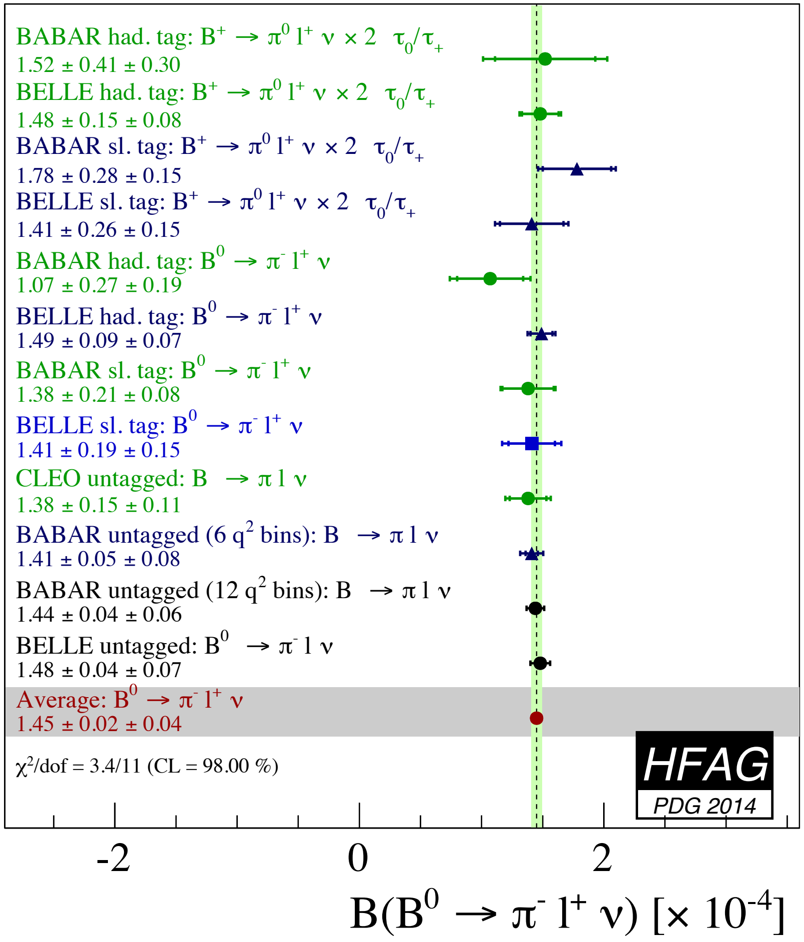


Note: current measured value of $\mathcal{B}$ ($b \to s\gamma$) excludes m_H<400 GeV/c^2 for all $\tan\beta$.

New Belle 711 fb^{-1} measurement: Saito et. al., PRD 91, 052004 (2015)

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

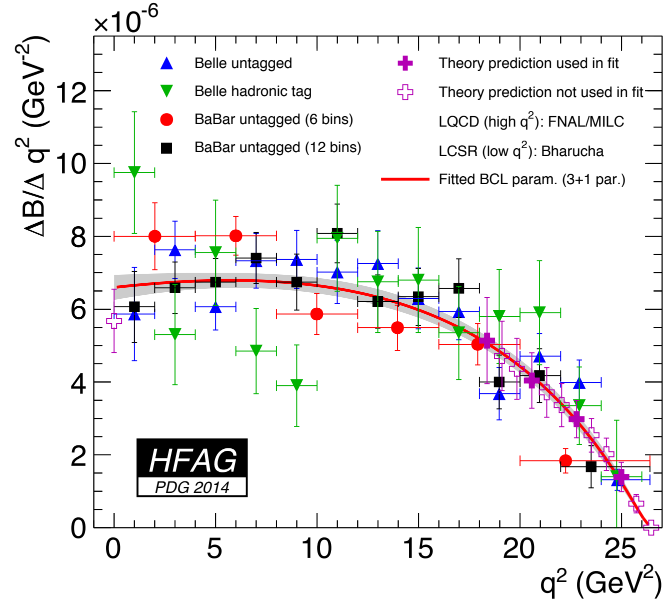
$|V_{ub}|$ via exclusive $B \rightarrow \pi l \nu$



Method	q^2 range [GeV$^2/c^2$]	$\lvert V_{ub}\rvert[10^{-3}]$
Khodjamirian et al. (LCSR) [468]	0 – 12	$3.41 \pm 0.06^{+0.37}_{-0.32}$
Ball & Zwicky (LCSR) [469]	0 – 16	$3.58 \pm 0.06^{+0.59}_{-0.40}$
HPQCD (LQCD) [470]	16 – 26.4	$3.52 \pm 0.08^{+0.61}_{-0.40}$
FNAL/MILC (LQCD) [471]	16 – 26.4	$3.36 \pm 0.08^{+0.37}_{-0.31}$

Dalgic et al. [HPQCD], PRD 73, 074502 (2006)
Bailey et al. [FNAL/MILC], PRD 79, 054507 (2009)

Using BCL form factor parametrization:



Bourrely, Caprini, Lellouch, PRD 79, 013008 (2009)

Bailey et al. [FNAL/ MILC], PRD 79, 054507 (2009)

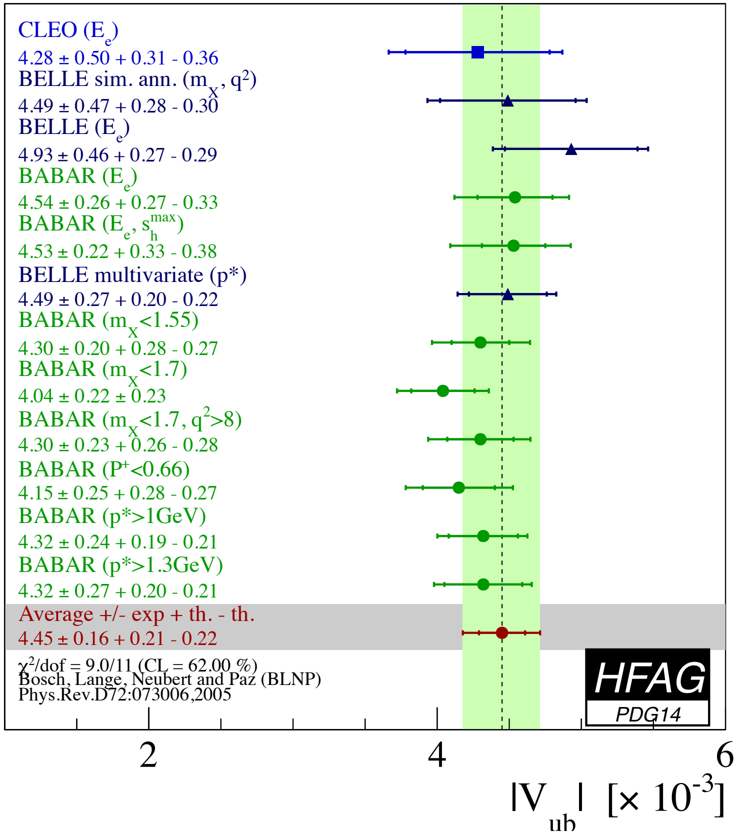
⇒ $\boxed{|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}}$

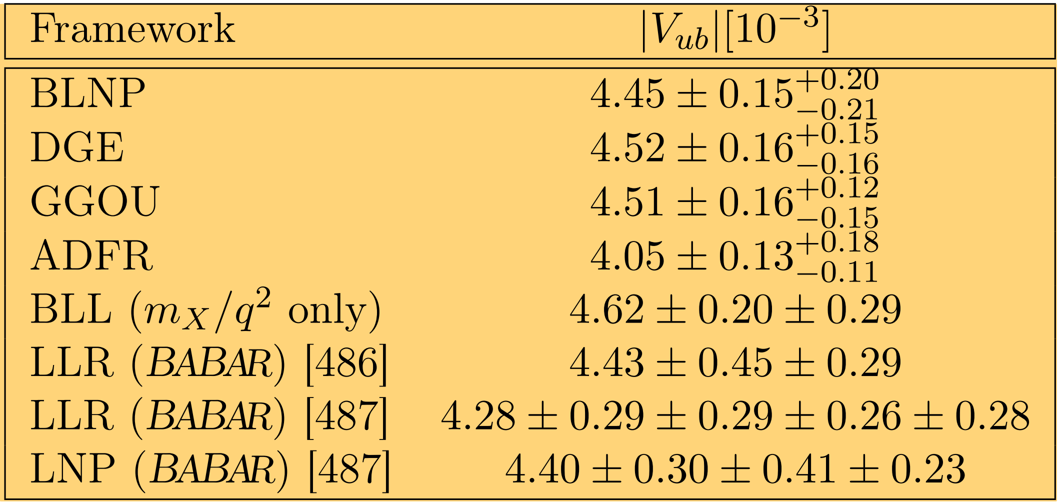
$|V_{ub}|$ via inclusive $B \to X_u l\nu$

To reduce large backgrounds from $B \to X_c l\nu$, one must make cuts that severly restrict the acceptance. To calculate partial rates for such restricted regions requires complicated theoretical machinery. Five theory models are used.

BLNP: *Lange, Neubert, Paz, PRD 72:073006 (2005)*
DGE: *Andersen, Gardi, JHEP 0601:097 (2006); arXiv:0806.4524*
GGOU: *Gambino, Giordano, Ossola, Uraltsev, JHEP 0710:058, 2007*
ADFR: *Aglietti, Di Lodovico, Ferrera , Ricciardi, EPJC, Vol. 59 (2009); Aglietti, Ferrera, Ricciardi, Nucl. Phys. B768, 85 (2007)*
BLL: *Bauer, Ligeti Luke, PRD 64:113004 (2001)*

BLNP:





Framework	$\lvert V_{ub}\rvert [10^{-3}]$
BLNP	$4.45 \pm 0.15^{+0.20}_{-0.21}$
DGE	$4.52 \pm 0.16^{+0.15}_{-0.16}$
GGOU	$4.51 \pm 0.16^{+0.12}_{-0.15}$
ADFR	$4.05 \pm 0.13^{+0.18}_{-0.11}$
BLL (m_X/q^2 only)	$4.62 \pm 0.20 \pm 0.29$
LLR (*BABAR*) [486]	$4.43 \pm 0.45 \pm 0.29$
LLR (*BABAR*) [487]	$4.28 \pm 0.29 \pm 0.29 \pm 0.26 \pm 0.28$
LNP (*BABAR*) [487]	$4.40 \pm 0.30 \pm 0.41 \pm 0.23$

LHCb: $|V_{ub}|$ from $\Lambda_b \to p\ell\nu$ decays

LHCB-PAPER-2015-013

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\bar{\nu})_{q^2>15\ \mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu^-\bar{\nu})_{q^2>7\ \mathrm{GeV}^2}} = \frac{N_{p\mu^-\bar{\nu}}}{N_{\Lambda_c\mu^-\bar{\nu}}}\left(\frac{\varepsilon_{\Lambda_c\mu^-\bar{\nu}}}{\varepsilon_{p\mu^-\bar{\nu}}}\right) = \frac{|V_{ub}|^2}{|V_{cb}|^2}\, R_{\mathrm{lattice}}$$

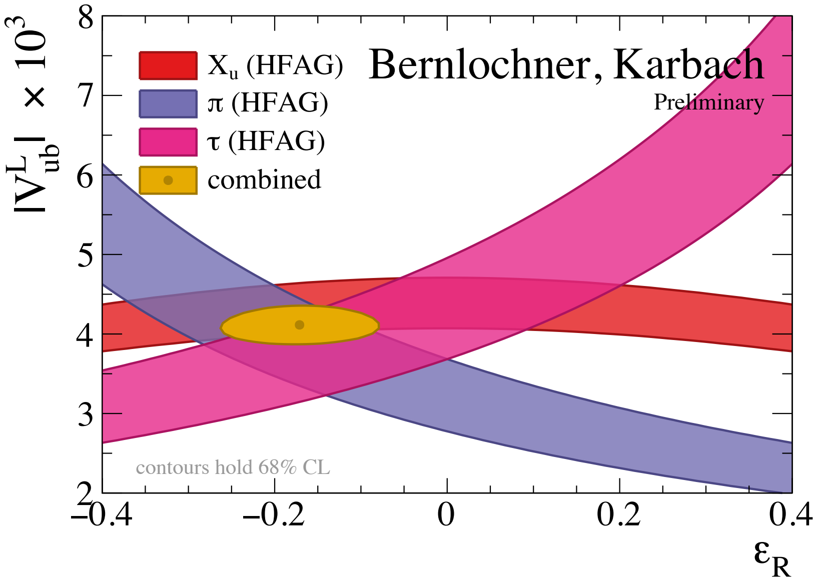
$$\Rightarrow \quad (1.00 \pm 0.04 \pm 0.08) \times 10^{-2} = \frac{|V_{ub}|^2}{|V_{cb}|^2}\,(1.470 \pm 0.115 \pm 0.104)$$

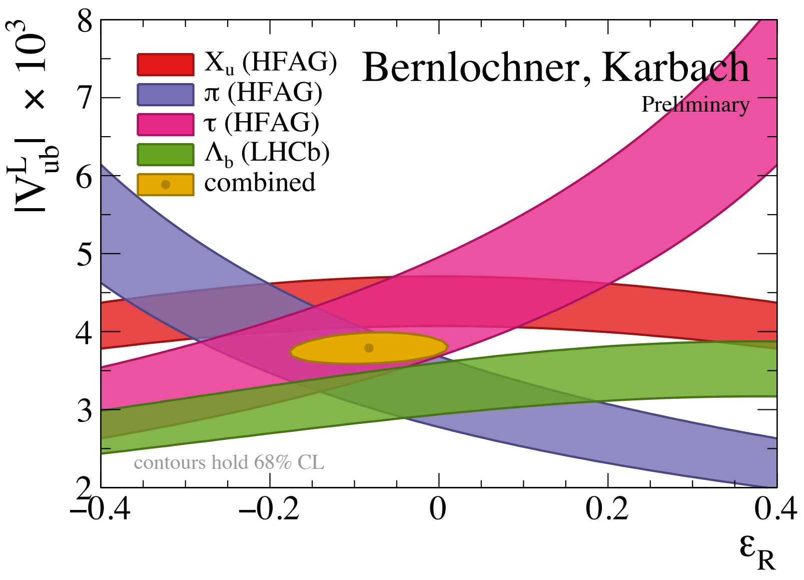
[Detmold, Lehner, & Meinel, arXiv:1503.01421]

$$\Rightarrow \quad |V_{ub}| = (3.27 \pm 0.15_{\mathrm{exp}} \pm 0.17_{\mathrm{theory}} \pm 0.06_{V_{cb}}) \times 10^{-3}$$

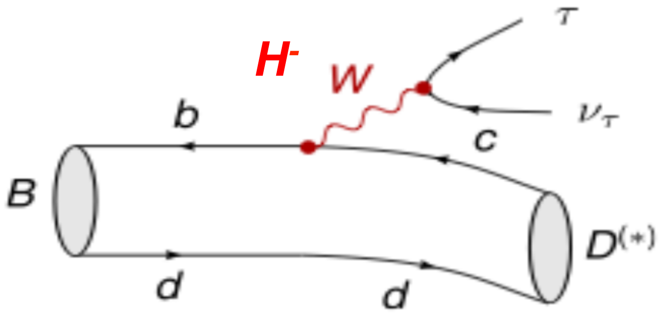
Update to Bernlochner, Ligeti, & Turczyk, PRD 90, 094003 (2014) [Sutcliffe talk, Moriond Electroweak 2015]:

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{ub}^L(\bar{u}\gamma_\mu P_L b + \epsilon_R \bar{u}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu P_L l) + h.c.$$





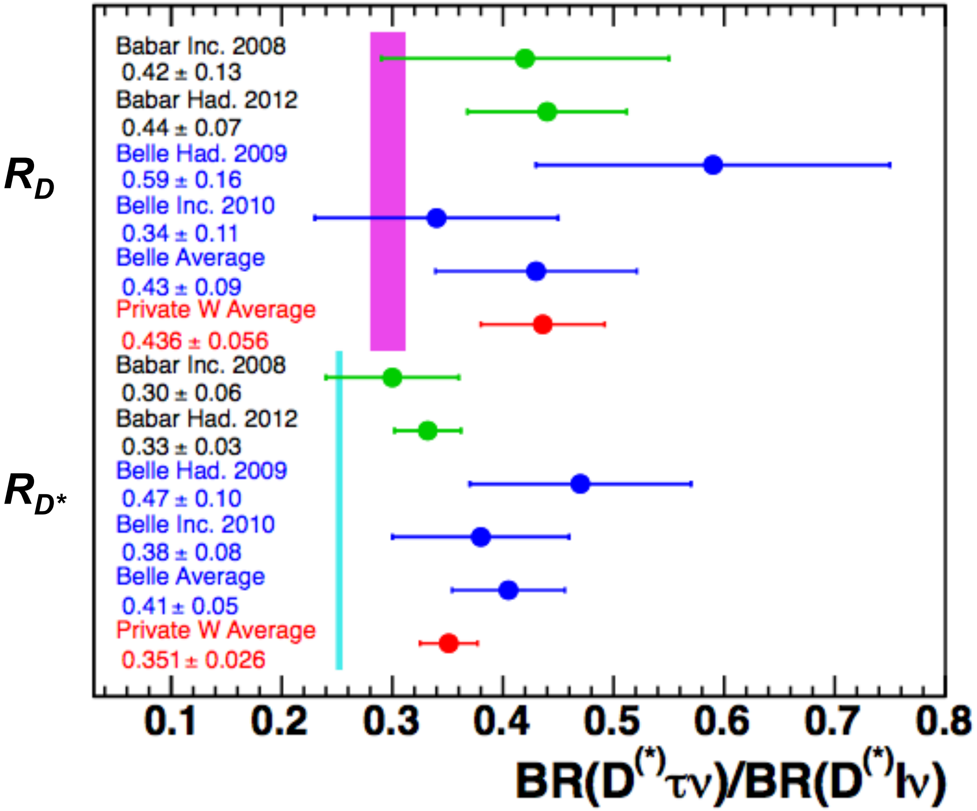
Constraint on Type II charged Higgs: $B \to D^{(*)}\tau\nu$



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

Define ratios:

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



Measured values of these ratios have traditionally been above SM (SM) predition. Current averages are ~ 4σ high. Belle II should resolve this.

These values in turn can be used to constrain a charged Higgs
[Lees et al., PRD 88, 072012 (2013); PRL 109, 101802 (2012)]

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

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

2-Higgs doublet model:

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

	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

703 fb^{-1} Huschle, arXiv:1507.03233, submitted to PRD (new)

- Use hadronically tagged events (as done for $B \to D\ell\nu$ analysis).
- On signal side consider only $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$ (to minimize systematic uncertainty): select $D^{(*)}\mu$ and $D^{(*)}e$ on signal side
- calculate missing mass squared:

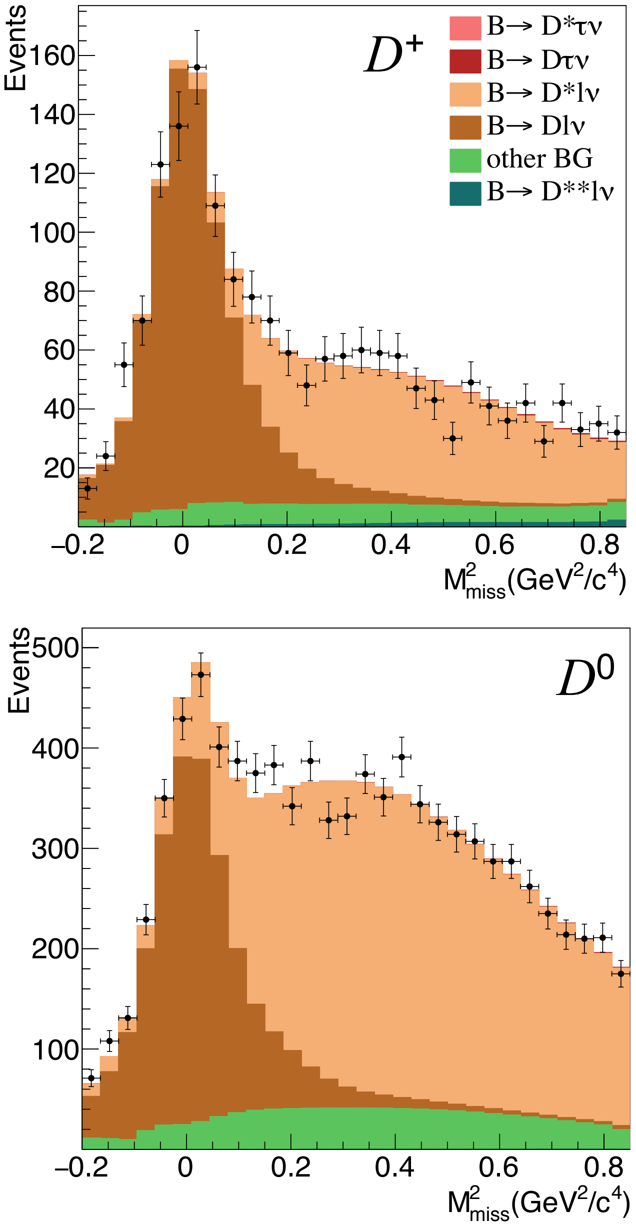
$$M^2_{\rm miss} = \left(P_{\rm beam} - P_D - P_\ell\right)^2$$

- for $M^2_{miss} < 0.85$ ($B \to D^{(*)}\ell\nu$ dominated), fit M^2_{miss} spectrum directly for $B \to D\ell\nu$ yield
- for $M^2_{miss} > 0.85$ ($B \to D^{(*)}\tau\nu$ dominated), fit a NN spectrum to obain $B \to D^{(*)}\tau\nu$ yield, because M^2_{miss} cannot discriminate between $D^{(*)}\tau\nu$ signal and $D^{**}\ell\nu$ background. NN has 8 inputs, but most discrimination power comes from E_{ECL} (unassociated energy in calorimeter) and p_ℓ^* (lepton momentum in CM frame)

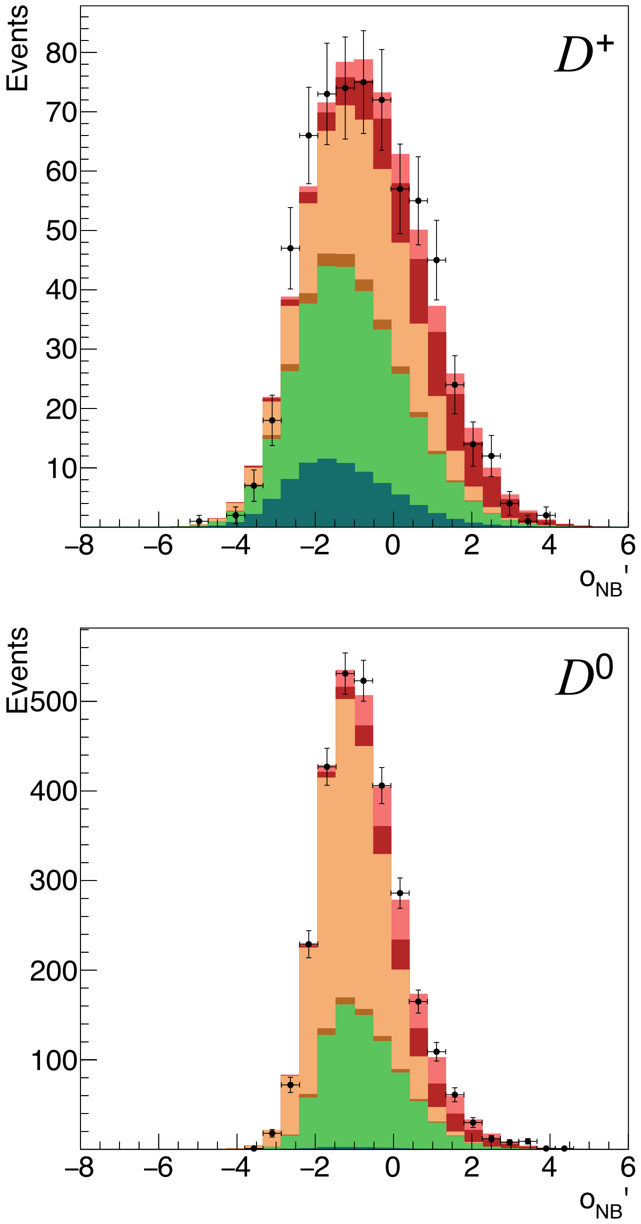
$B \to D^{(*)}\tau\nu$ (cont'd)

$703\ \mathrm{fb}^{-1}$ Huschle, arXiv:1507.03233,
submitted to PRD

M^2_{miss}



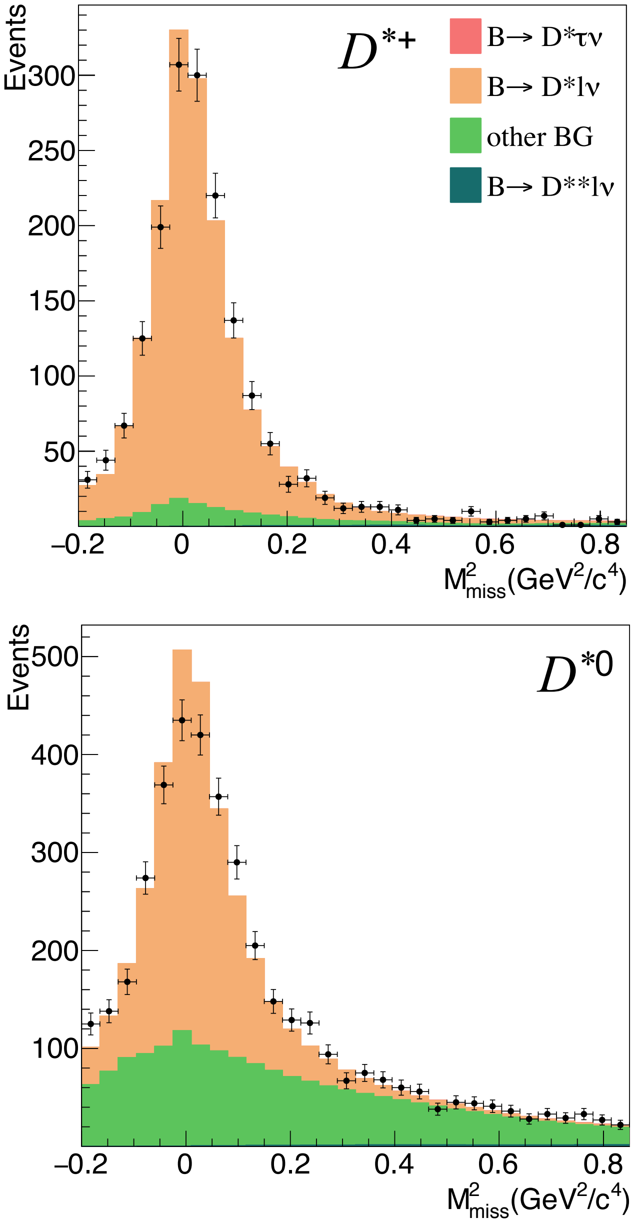
NN
($M^2_{miss} > 0.85$)



$B \rightarrow D^{(*)}\tau\nu$ (cont'd)

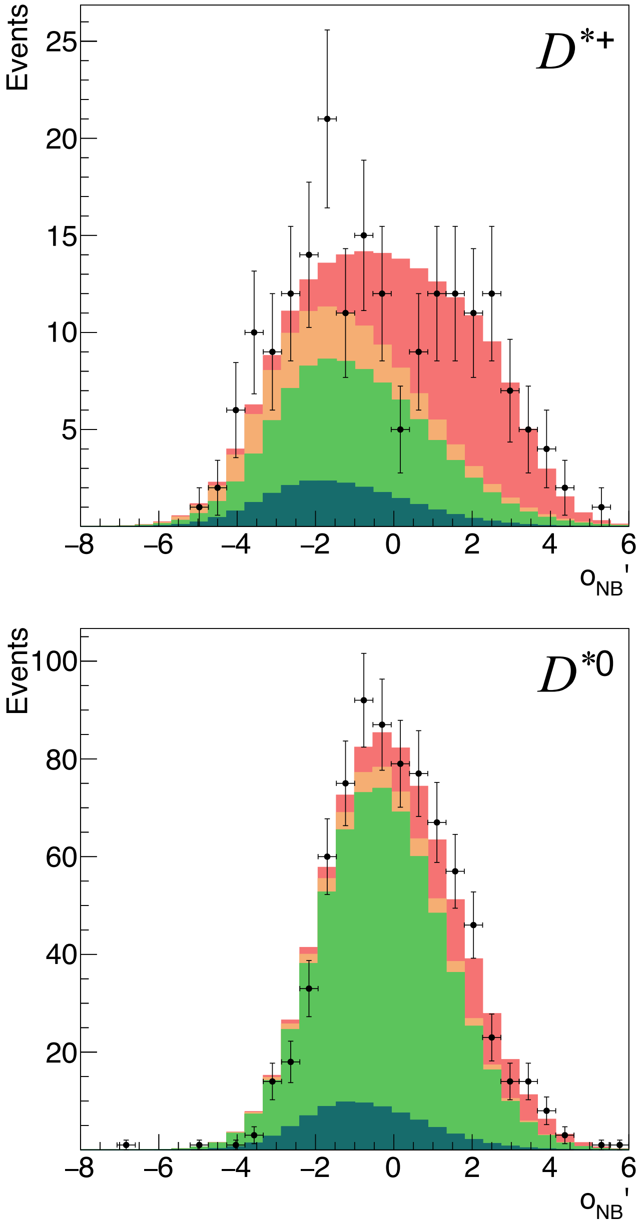
703 fb^{-1} Huschle, arXiv:1507.03233, submitted to PRD

M^2_{miss}



NN

(M^2_{miss} > 0.85)



$B \rightarrow D^{(*)}\tau\nu$ (cont'd)

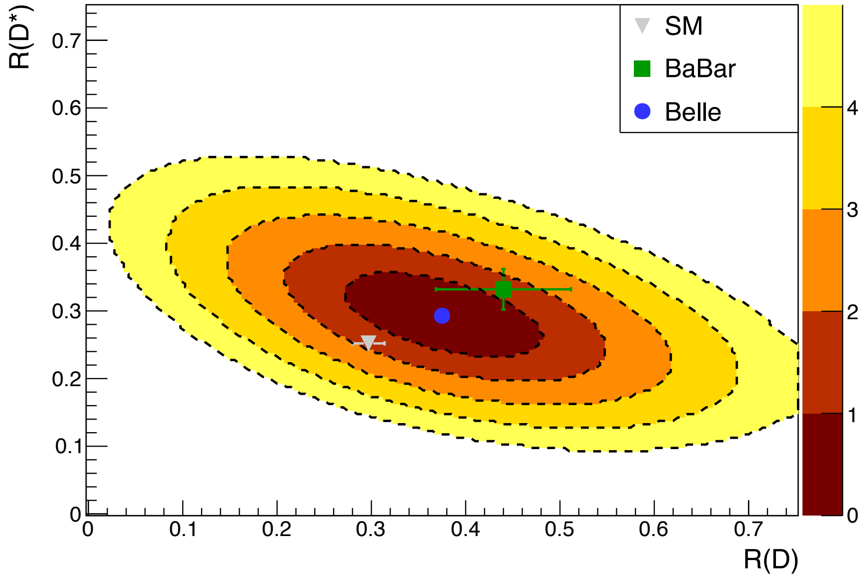
$703\ \mathrm{fb}^{-1}$ *Huschle, arXiv:1507.03233,*
submitted to PRD

Results

$B \rightarrow D^{(*)}\ell\nu$ (normalization) yields:

Sample	Component	Yield	Expected yield
$D^+\ell^-$	ℓ normalization	844 ± 34	870
$D^+\ell^-$	ℓ CF	924 ± 47	970
$D^+\ell^-$	D^{**} BG	108 ± 38	133
$D^0\ell^-$	ℓ normalization	2303 ± 64	2290
$D^0\ell^-$	ℓ CF	7324 ± 122	7440
$D^0\ell^-$	D^{**} BG	131 ± 81	210
$D^{*+}\ell^-$	ℓ normalization	1609 ± 43	1680
$D^{*+}\ell^-$	D^{**} BG	36 ± 18	76
$D^{*0}\ell^-$	ℓ normalization	2188 ± 60	2280
$D^{*0}\ell^-$	D^{**} BG	117 ± 39	40

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



$B \rightarrow D^{(*)}\tau\nu$ signal yields:

$N(D\tau\nu) = 320$
$N(D^*\tau\nu) = 503$

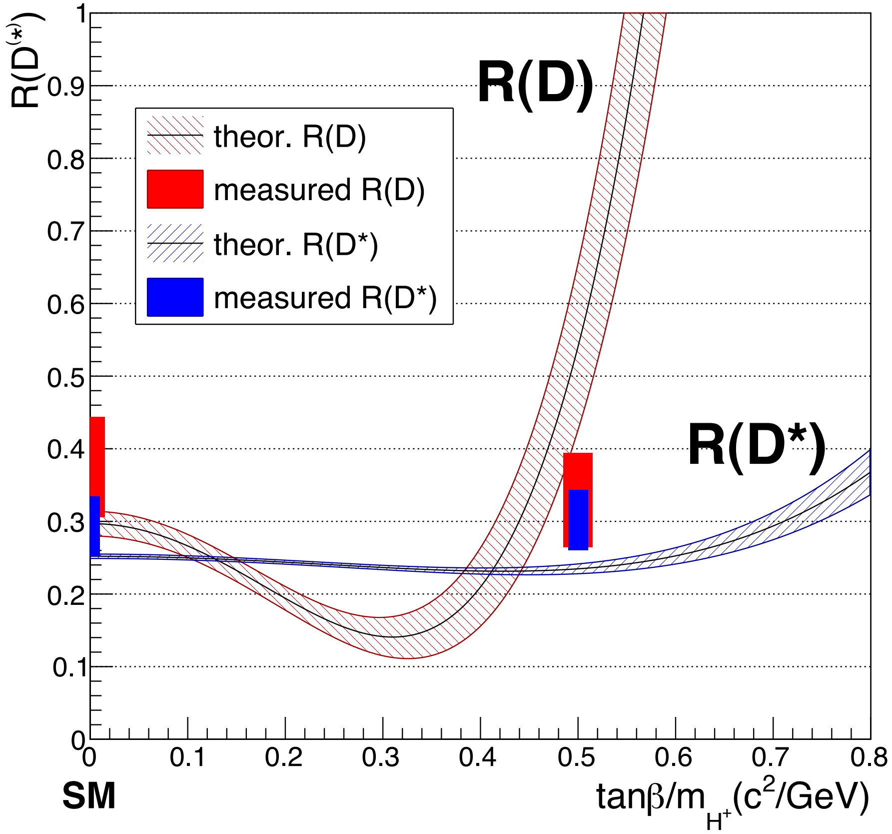
$B \rightarrow D^{(*)}\tau\nu$ (cont'd)

703 fb^{-1} Huschle, arXiv:1507.03233, submitted to PRD

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 $\tan\beta/M_H$.

Result for 2HDM on $\tan\beta/M_H = 0.5$:

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

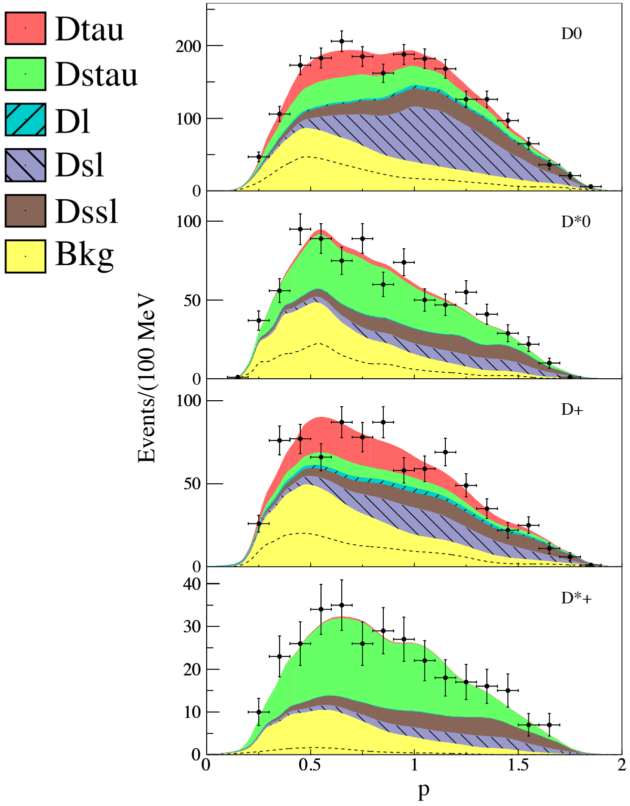


⇒ *results compatible with 2HDM*

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

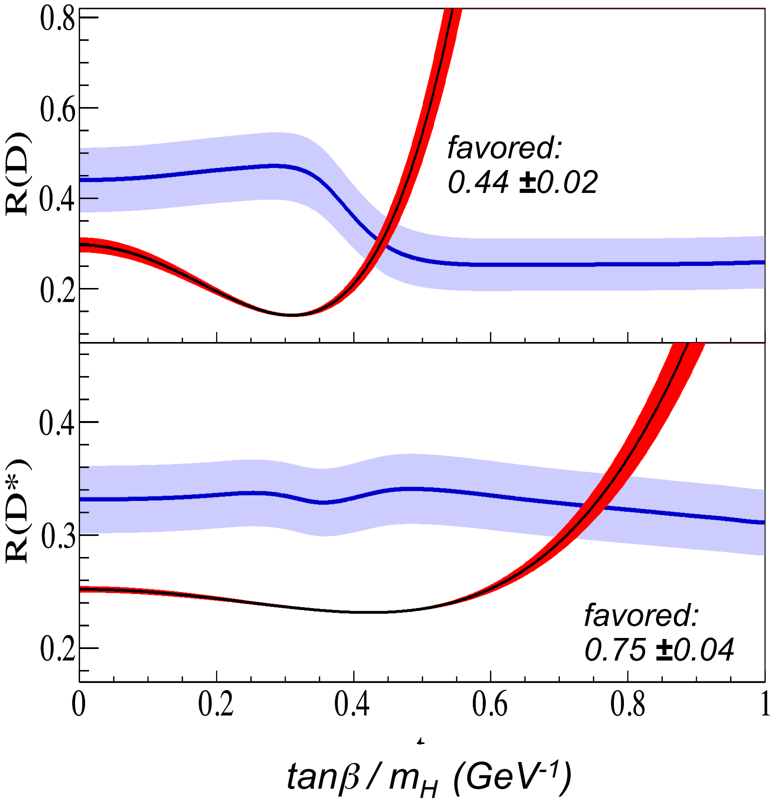
Lees et al., PRD 88, 072012 (2013); PRL 109, 101802 (2012)

Use hadronically tagged events with a $D\mu$ or De on signal side. Perform 2-d fit to lepton momentum spectrum and missing mass, simultaneously for 8 subsamples (neutral/charged/μ/e)



Final results:

$$\begin{aligned} \mathcal{R}_{D^*} &= 0.332 \pm 0.024 \pm 0.018 \\ \mathcal{R}_{D} &= 0.440 \pm 0.058 \pm 0.042 \end{aligned}$$

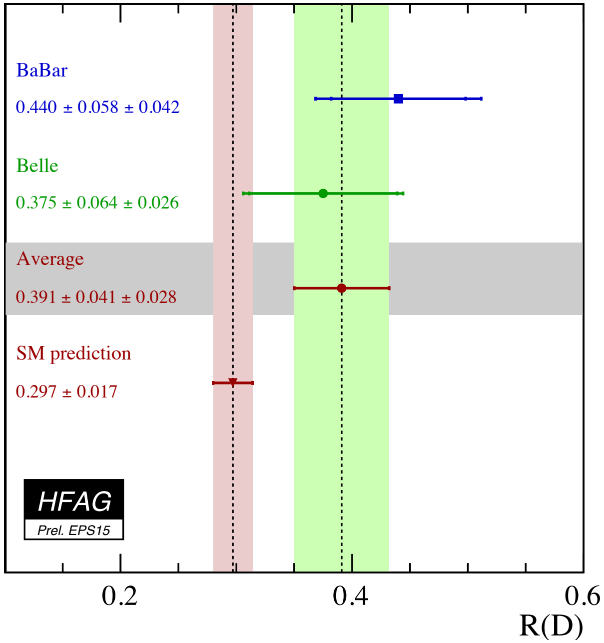


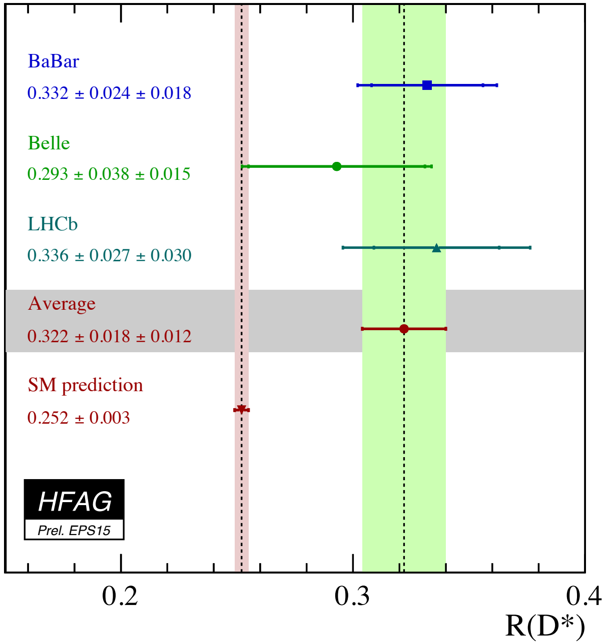
favored:
0.44 ±0.02

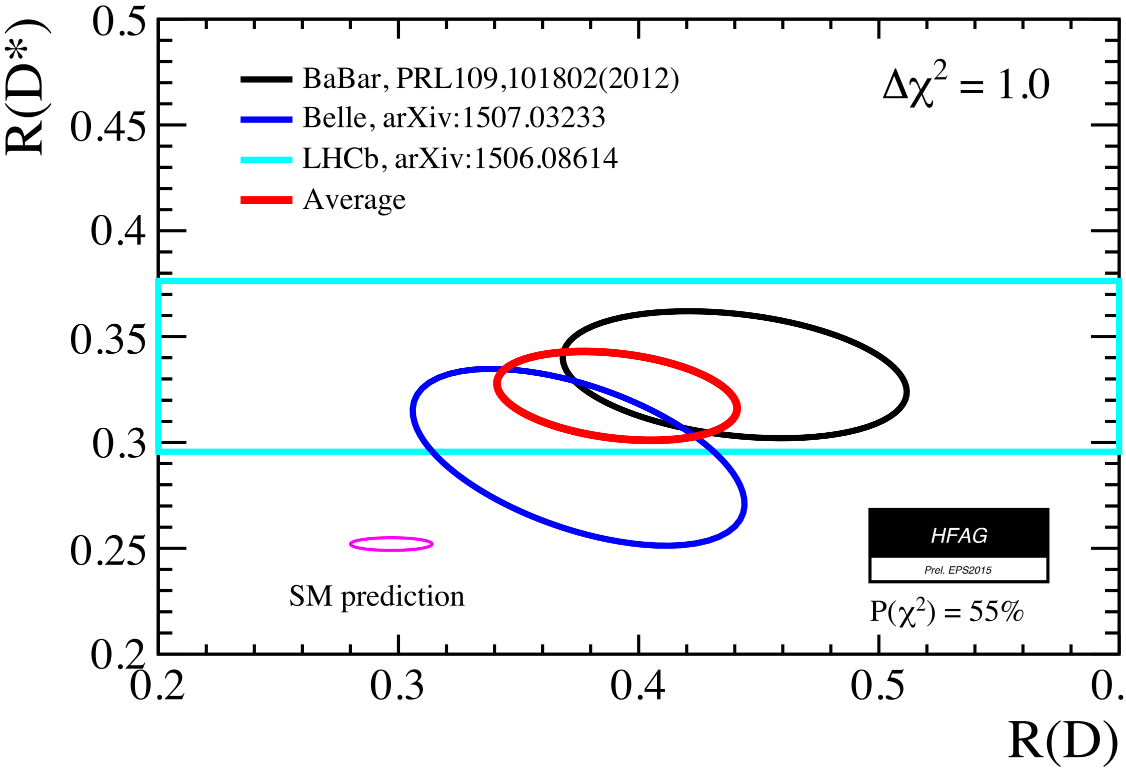
favored:
0.75 ±0.04

As before, results higher than SM. But 2HDM cannot explain it, inconsistent at 3.1σ level

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







SM Predictions:

R(D) =0.297 +- 0.017 [Kamenik & Mescia, PRD 78, 014003 (2008)]

R(D)=0.252 +- 0.003 [Fajfer et al., PRD 85, 094025 (2012)]*

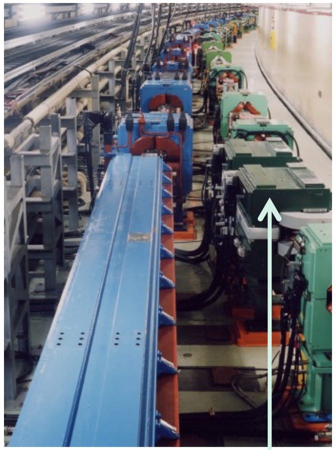
More Recent SM Predictions (Lattice):

R(D) =0.299 +- 0.011 [Bailey et al. (FNAL/MILC), arXiv:1503.07237]

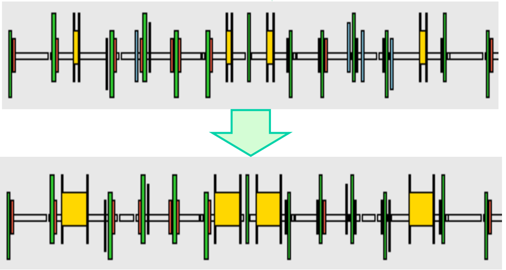
R(D) =0.300 +- 0.008 [Na et al. (HPQCD), arXiv:1505.03925]

In both cases discrepancy between SM and data is 3.9σ

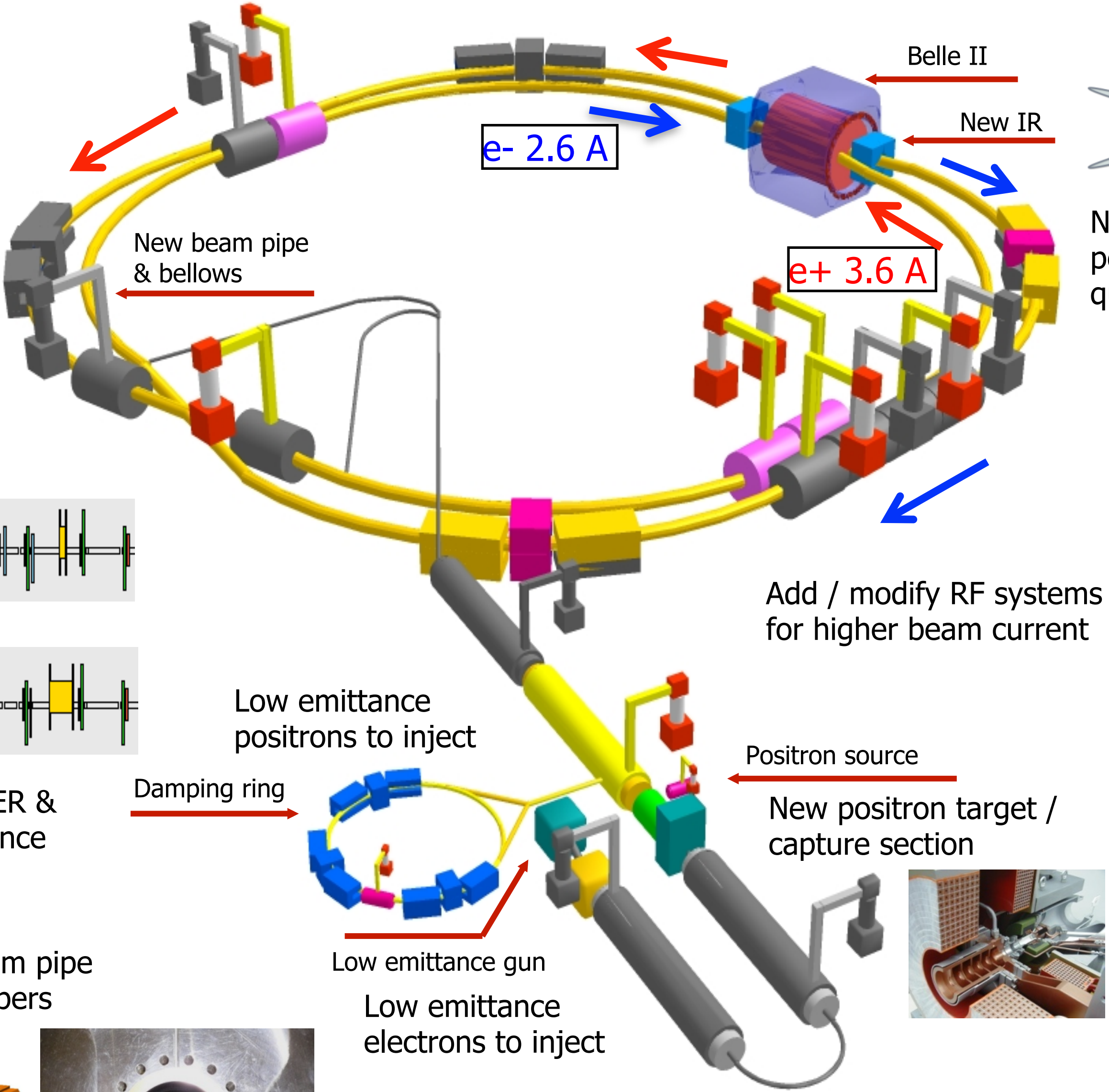
KEKB → SuperKEKB (nano-beam)



Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance



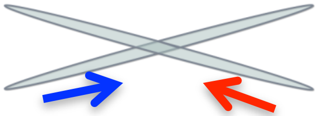
Low emittance positrons to inject

Low emittance electrons to inject

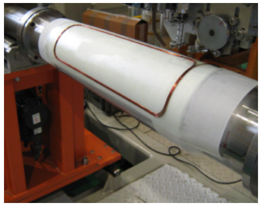
Add / modify RF systems for higher beam current

New positron target / capture section

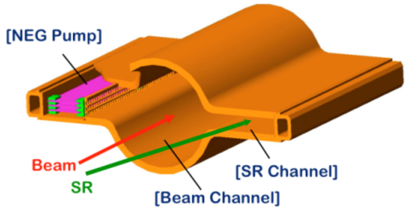
Colliding bunches

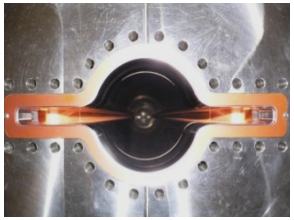


New superconducting / permanent final focusing quads near the IP



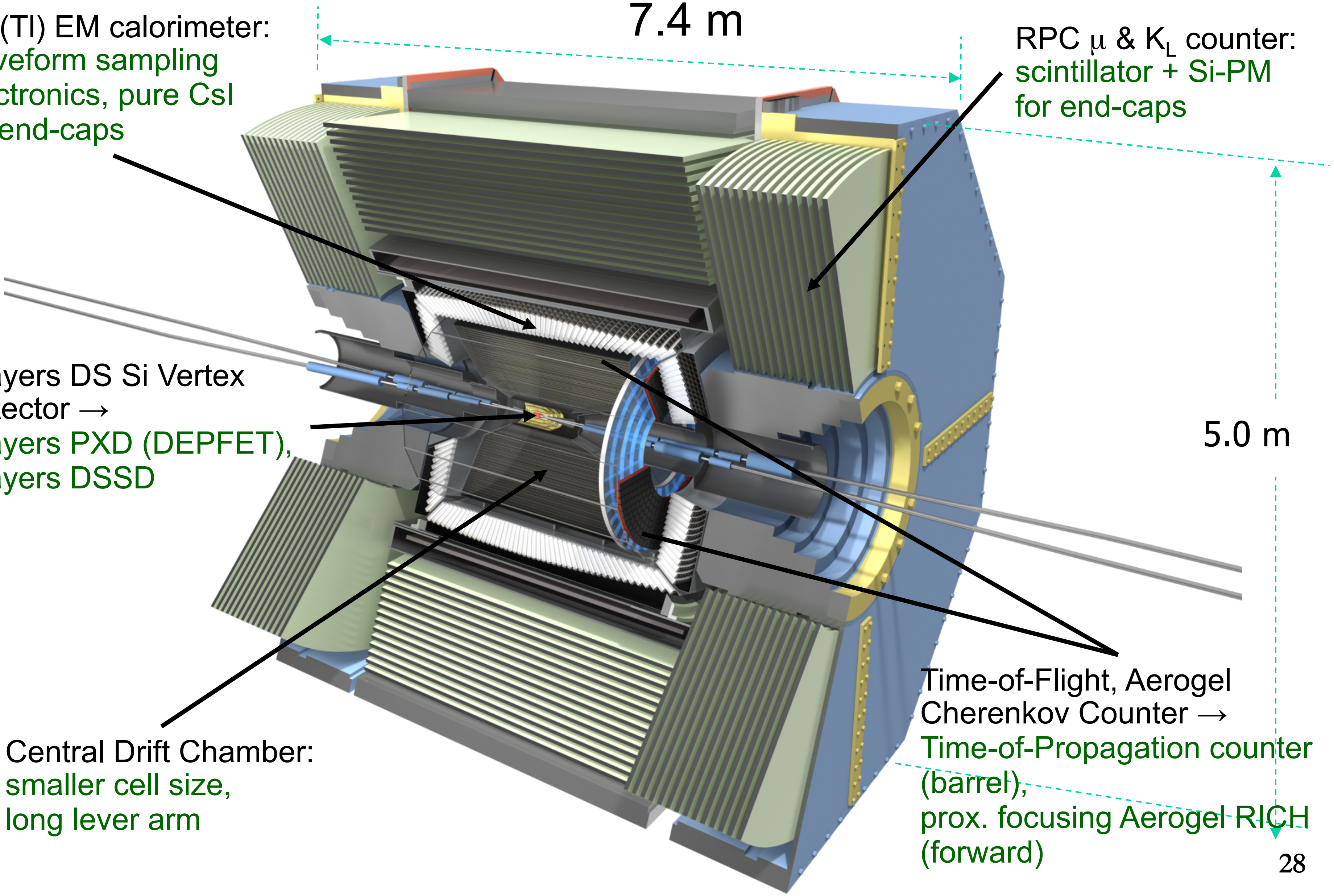
TiN-coated beam pipe with antechambers





To get 40x higher luminosity

The Belle II Detector



CsI(TI) EM calorimeter:
waveform sampling electronics, pure CsI for end-caps

RPC μ & K_L counter:
scintillator + Si-PM for end-caps

4 layers DS Si Vertex Detector →
2 layers PXD (DEPFET),
4 layers DSSD

Time-of-Flight, Aerogel Cherenkov Counter →
Time-of-Propagation counter (barrel),
prox. focusing Aerogel RICH (forward)

Central Drift Chamber:
smaller cell size,
long lever arm

Belle II Physics Program I

arXiv:1002.5012 (Belle II)
see also: arXiv:1008.1541 (SuperB)

errors.

	Observables	Belle (2014)	Belle II 5 ab^{-1}	 50 ab^{-1}
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$ [64]	0.012	0.008
	α [°]	85 ± 4 (Belle+BaBar) [24]	2	1
	γ [°]	68 ± 14 [13]	6	1.5
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$ [19]	0.053	0.018
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$ [65]	0.028	0.011
	$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$ [17]	0.100	0.033
	$\mathcal{A}(B \to K^0 \pi^0)$	$-0.05 \pm 0.14 \pm 0.05$ [66]	0.07	0.04
UT sides	$\lvert V_{cb}\rvert$ incl.	$41.6 \cdot 10^{-3}(1 \pm 1.8\%)$ [8]	1.2%	
	$\lvert V_{cb}\rvert$ excl.	$37.5 \cdot 10^{-3}(1 \pm 3.0\%_{\text{ex.}} \pm 2.7\%_{\text{th.}})$ [10]	1.8%	1.4%
	$\lvert V_{ub}\rvert$ incl.	$4.47 \cdot 10^{-3}(1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$ [5]	3.4%	3.0%
	$\lvert V_{ub}\rvert$ excl. (had. tag.)	$3.52 \cdot 10^{-3}(1 \pm 8.2\%)$ [7]	4.7%	2.4%
Missing E decays	$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$96(1 \pm 27\%)$ [26]	10%	3%
	$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7 [67]	20%	7%
	$R(B \to D\tau\nu)$	$0.440(1 \pm 16.5\%)$ $[29]^\dagger$	5.2%	2.5%
	$R(B \to D^*\tau\nu)^\dagger$	$0.332(1 \pm 9.0\%)$ $[29]^\dagger$	2.9%	1.6%
	$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ $[10^{-6}]$	< 40 [30]	< 15	30%
	$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ $[10^{-6}]$	< 55 [30]	< 21	30%
Rad. & EW penguins	$\mathcal{B}(B \to X_s\gamma)$	$3.45 \cdot 10^{-4}(1 \pm 4.3\% \pm 11.6\%)$	7%	6%
	$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$ [68]	1	0.5
	$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$ [20]	0.11	0.035
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$ [21]	0.23	0.07
	C_7/C_9 $(B \to X_s\ell\ell)$	$\sim$20% [36]	10%	5%
	$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	< 8.7 [42]	0.3	–
	$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	–	< 2 [44]‡	–

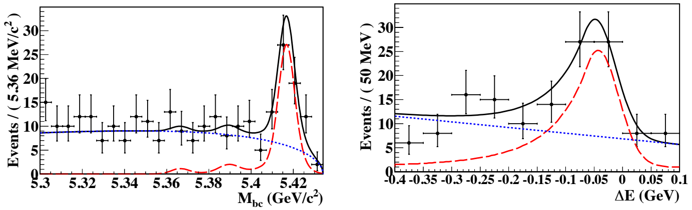
Belle II Physics Program II

arXiv:1002.5012 (Belle II)

	Observables	Belle	Belle II	
		(2014)	5 ab^{-1}	50 ab^{-1}
Charm Rare	$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \cdot 10^{-3}(1 \pm 5.3\% \pm 3.8\%)$ [46]	2.9%	0.9%
	$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \cdot 10^{-3}(1 \pm 3.7\% \pm 5.4\%)$ [46]	3.5%	3.6%
	$\mathcal{B}(D^0 \to \gamma\gamma)$ $[10^{-6}]$	< 1.5 [49]	30%	25%
Charm CP	$A_{CP}(D^0 \to K^+K^-)$ $[10^{-2}]$	$-0.32 \pm 0.21 \pm 0.09$ [69]	0.11	0.06
	$A_{CP}(D^0 \to \pi^0\pi^0)$ $[10^{-2}]$	$-0.03 \pm 0.64 \pm 0.10$ [70]	0.29	0.09
	$A_{CP}(D^0 \to K^0_S\pi^0)$ $[10^{-2}]$	$-0.21 \pm 0.16 \pm 0.09$ [70]	0.08	0.03
Charm Mixing	$x(D^0 \to K^0_S\pi^+\pi^-)$ $[10^{-2}]$	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$ [52]	0.14	0.11
	$y(D^0 \to K^0_S\pi^+\pi^-)$ $[10^{-2}]$	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$ [52]	0.08	0.05
	$\lvert q/p \rvert(D^0 \to K^0_S\pi^+\pi^-)$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$ [52]	0.10	0.07
	$\phi(D^0 \to K^0_S\pi^+\pi^-)$ $[^\circ]$	$-6 \pm 11 \pm {}^{4}_{5}$ [52]	6	4
Tau	$\tau \to \mu\gamma$ $[10^{-9}]$	< 45 [71]	< 4.6	< 0.5
	$\tau \to e\gamma$ $[10^{-9}]$	< 120 [71]	< 12	< 1.2
	$\tau \to \mu\mu\mu$ $[10^{-9}]$	< 21.0 [72]	< 4.5	< 0.5

+ rare B decays, D_{sJ}/X/Y/Z studies, B_s physics at Υ(5S), etc.

$B_s \to \phi\gamma$:



$\mathcal{B} = (3.6 \pm 0.5 \pm 0.6) \times 10^{-5}$

[Dutta et al., PRD91, 011101 (2015)]

Measuring a charged Higgs: $B^+ \to \tau^+\nu$

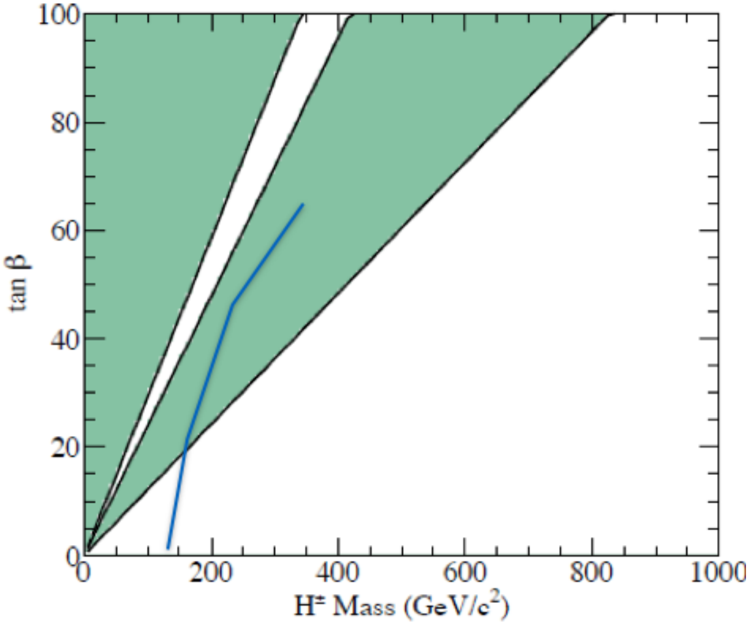
Using f_B = (191 ± 9) MeV (HPQCD, PDG12), |Vub| = (4.15 ± 0.49) x 10^{-3} (PDG12)
one obtains $\mathcal{B}_{SM}$ = (1.11 ± 0.28) x 10^{-4}

2-Higgs doublet model:

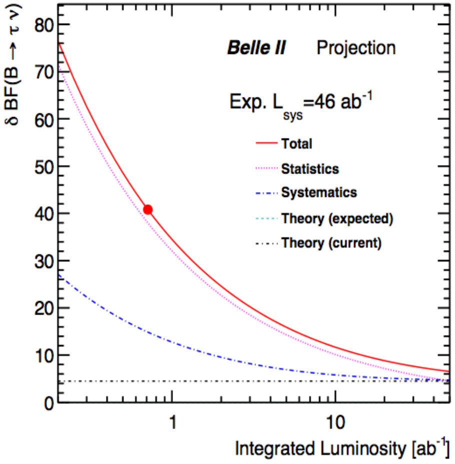
$$\mathcal{B}(B^+ \to \tau^+\nu) = \mathcal{B}_{SM} \cdot \left(1 - m_B^2 \frac{\tan^2\beta}{m_H^2}\right)$$

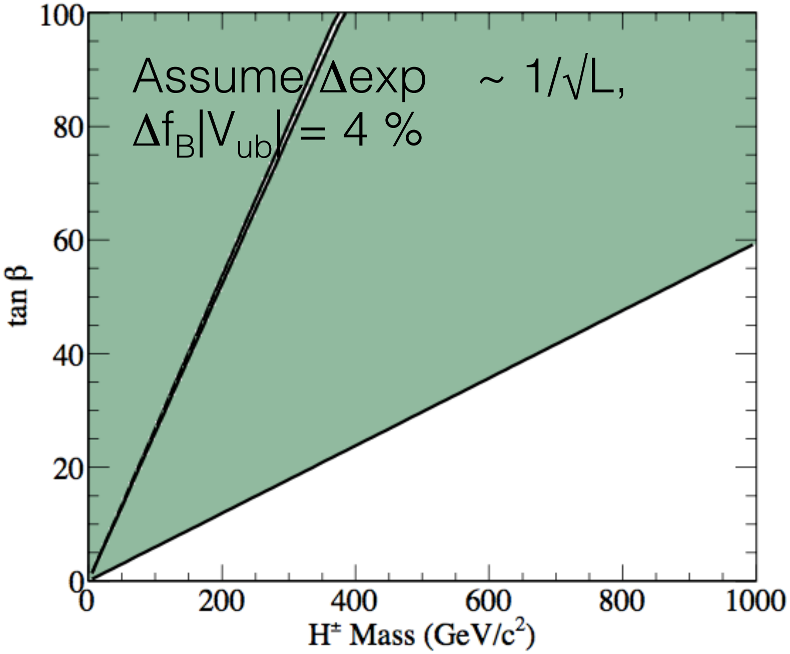
⇒ *lack of a signal constrains tanβ and m_H*

will notably improve in 50 ab^{-1}:



B-factories exclusion plot



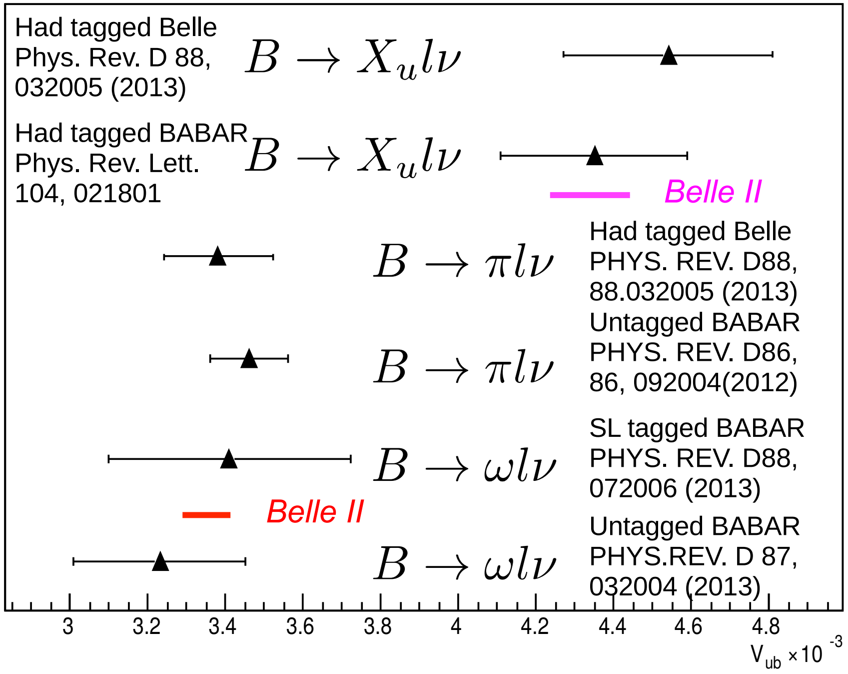


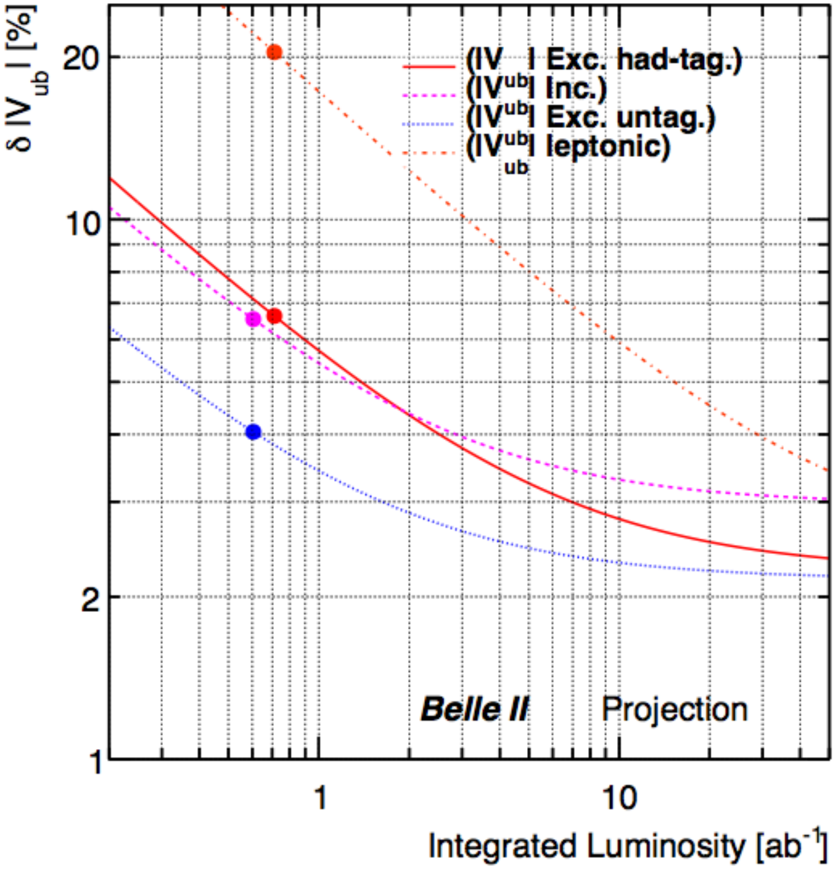
Assume Δexp ~ 1/√L,
$\Delta f_B|V_{ub}|$ = 4 %

Measuring $|V_{cb}|$ and $|V_{ub}|$

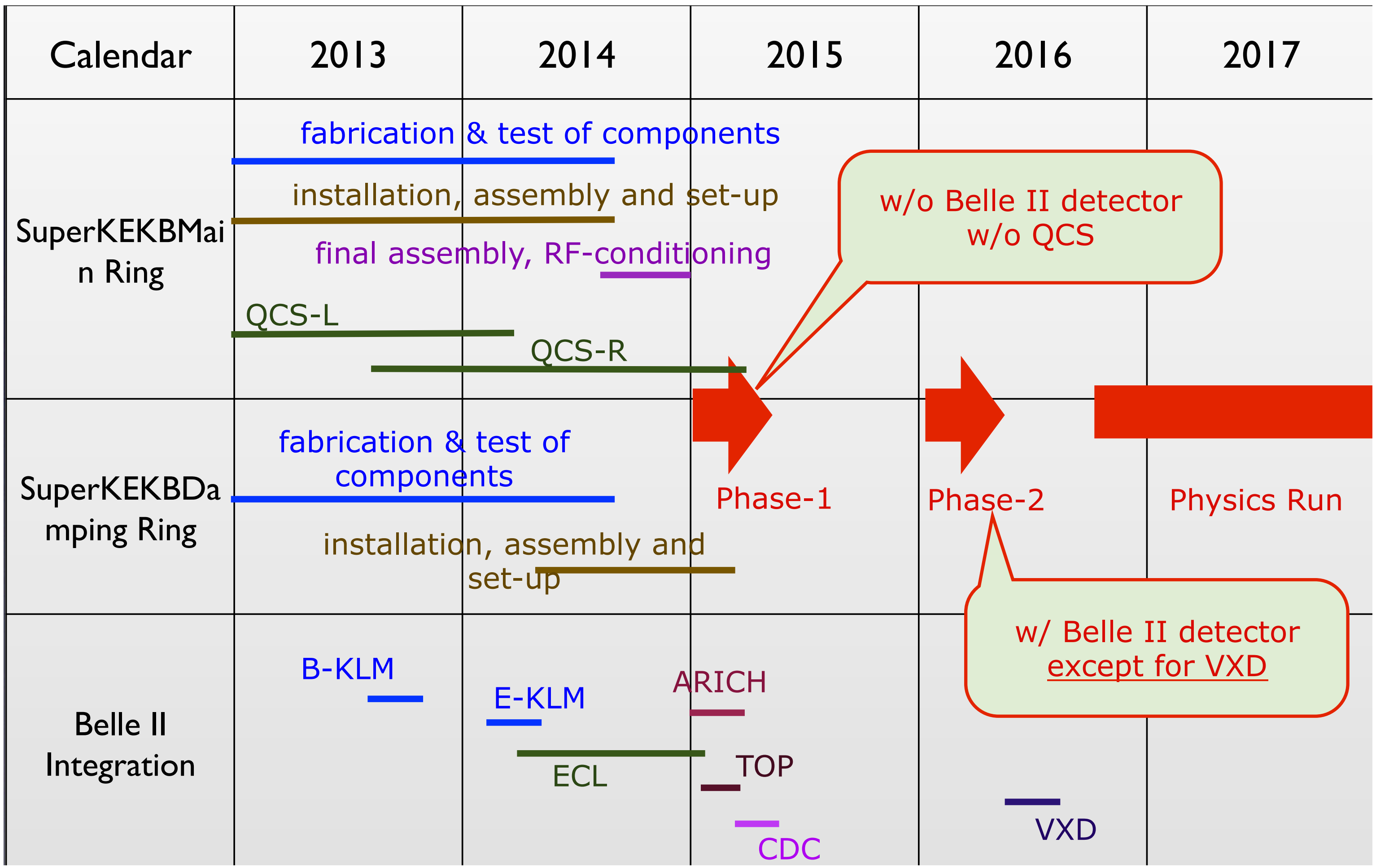
3σ discrepancy between exclusive and inclusive measurements for $|V_{ub}|$.

Alexander Ermakov (FPCP14):





Belle II installation schedule



w/o Belle II detector
w/o QCS

w/ Belle II detector
<u>except for VXD</u>

2015:
KEKB commissioning

2016:
Belle detector commissioning

2017
first physics data

Summary

- New results still coming from Belle with full 711 fb^{-1} data set (and some from BaBar). Here we presented results for $B \to D\ell\nu$ $B \to \tau\nu$, and $B \to D^{(*)}\tau\nu$. Best knowledge of $|V_{cb}|$, $|V_{ub}|$, where LQCD plays a crucial.
- Belle II now under construction, will begin commissioning over next 2 years. The new experiment should reduce both statistical and theoretical errors on $|V_{cb}|$, $|V_{ub}|$, and many other SM/UT triangle parameters, greatly improving our senstivity to new physics. The physics program should be complementary to LHCb providing the best sensitivity to final states with γ, π^0, η, ρ^+, ω
- To fully exploit the data of Belle II will require parallel improvement in LQCD calculations – the symbiosis between the two has great potential to uncover NP.

$|V_{cb}|$ = 0.0425 ± 0.0009 (inclusive)
$|V_{cb}|$ = 0.0389 ± 0.0008 (exclusive)
$|V_{cb}|$ = 0.0409 ± 0.0013 ($B \to D\ell\nu$)

$|V_{ub}|$ = 0.00450 ± 0.00020 (inclusive)
$|V_{ub}|$ = 0.00328 ± 0.00030 (exclusive)
$|V_{ub}|$ = 0.00428 ± 0.00040 ($B \to \tau\nu$)
$|V_{ub}|$ = 0.00327 ± 0.00024 (Λ_b LHCb)

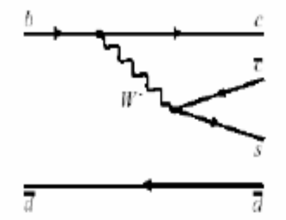
US LQCD 2013 white paper:

Quantity	CKM element	Present expt. error	2007 forecast lattice error	Present lattice error	2018 lattice error
f_K/f_π	$\vert V_{us}\vert$	0.2%	0.5%	0.5%	0.15%
$f_+^{K\pi}(0)$	$\vert V_{us}\vert$	0.2%	–	0.5%	0.2%
f_D	$\vert V_{cd}\vert$	4.3%	5%	2%	< 1%
f_{D_s}	$\vert V_{cs}\vert$	2.1%	5%	2%	< 1%
$D \to \pi\ell\nu$	$\vert V_{cd}\vert$	2.6%	–	4.4%	2%
$D \to K\ell\nu$	$\vert V_{cs}\vert$	1.1%	–	2.5%	1%
$B \to D^*\ell\nu$	$\vert V_{cb}\vert$	1.3%	–	1.8%	< 1%
$B \to \pi\ell\nu$	$\vert V_{ub}\vert$	4.1%	–	8.7%	2%
f_B	$\vert V_{ub}\vert$	9%	–	2.5%	< 1%
ξ	$\vert V_{ts}/V_{td}\vert$	0.4%	2-4%	4%	< 1%
ΔM_s	$\vert V_{ts}V_{tb}\vert^2$	0.24%	7–12%	11%	5%
B_K	$\mathrm{Im}(V_{td}^2)$	0.5%	3.5–6%	1.3%	< 1%

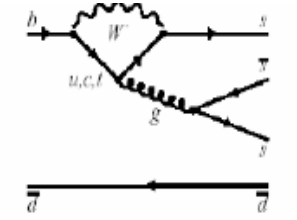
Extra

Extra Slides

Comparing Tree and Penguin ϕ_1 (β)

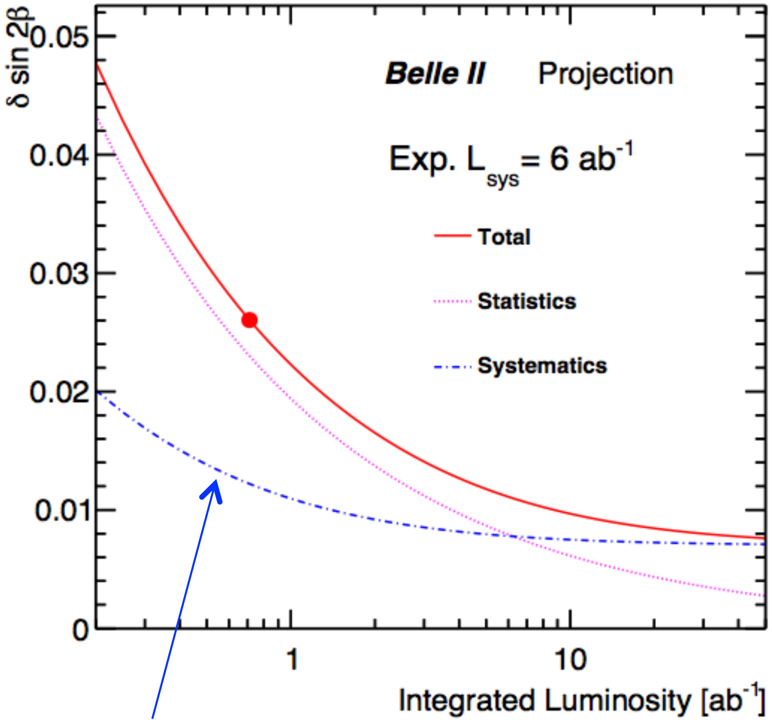


$B^0 \to J/\psi\, K^0$

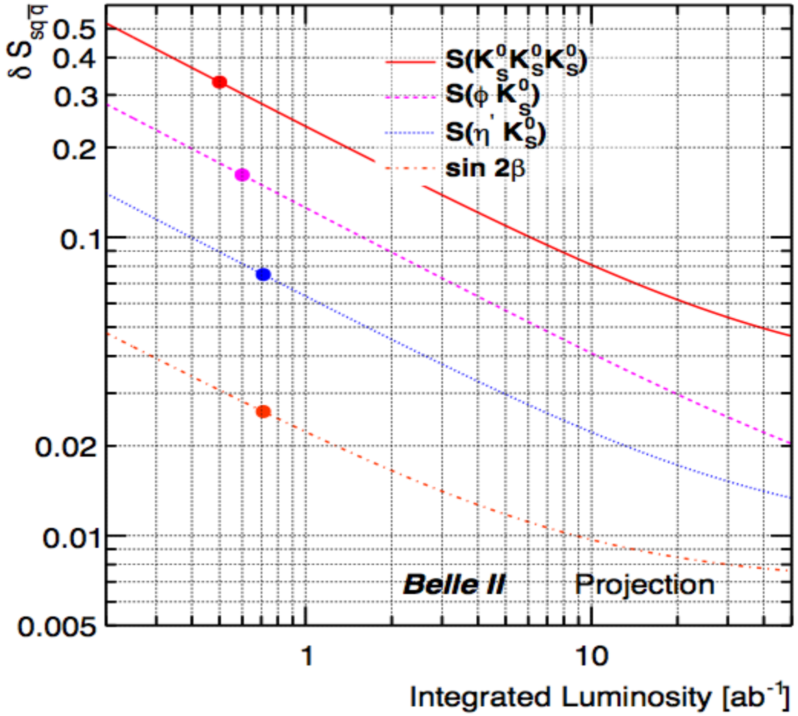


$B^0 \to \phi\, K^0$
$B^0 \to \eta'\, K^0$
$B^0 \to K^0 K^0 K^0$

$$\boxed{\frac{dN}{dt} \propto e^{-\Gamma t}\,[\,1 + q\,(A\cos\Delta m t + S\sin\Delta m t)\,]}$$



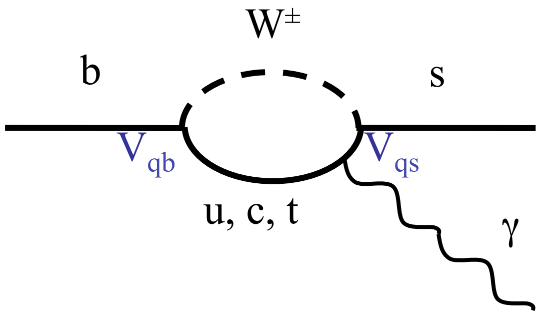
dominated by vertex resolution,
which will improve: 61 → ~18 μm

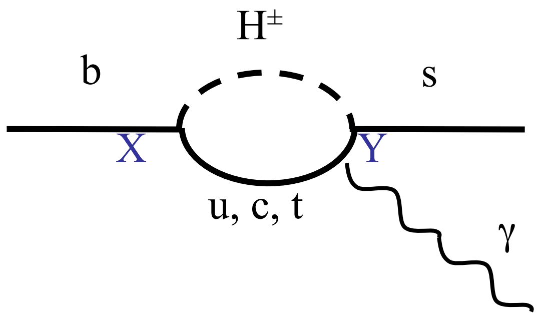


Prospect	$\delta(S_{b\to s})$ ~ 0.012 @ 50ab^{-1}

Radiative decays $b\to s\gamma$, $b\to d\gamma$ plus $b\to s l^+ l^-$

1-loop suppressed in SM ⇒ esp. sensitive to NP:



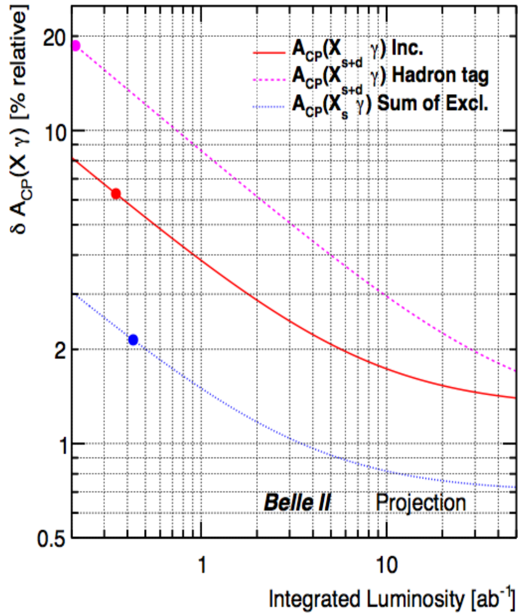


Many observables that probe new physics:

- *inclusive $B\to X_s\gamma$, $B\to X_d\gamma$, and $B\to X_s l^+ l^-$ branching fractions*
- *forward-backwards asymmetry and q^2 dependence in $B\to X_s l^+ l^-$*
- *direct CPV in $B\to X_s\gamma$*

- *exclusive $B\to K^*\gamma$ and $B\to \rho\gamma$ branching fractions*
- *forward-backwards asymmetry and q^2 dependence in $B\to K^* l^+ l^-$*
- *direct CPV in $B^+\to K^{*+}\gamma$*
- *time-dependent CPV in $B^0\to K^{*0}\gamma$, $B^0\to \rho^0\gamma$*

- *photon polarization with photon conversion*
- *lepton flavor dependence in $b\to s l^+ l^-$*



Belle II Prospects for τ

$\tau^+ \rightarrow \mu^+\gamma$

upper half of signal ellipse dominated by

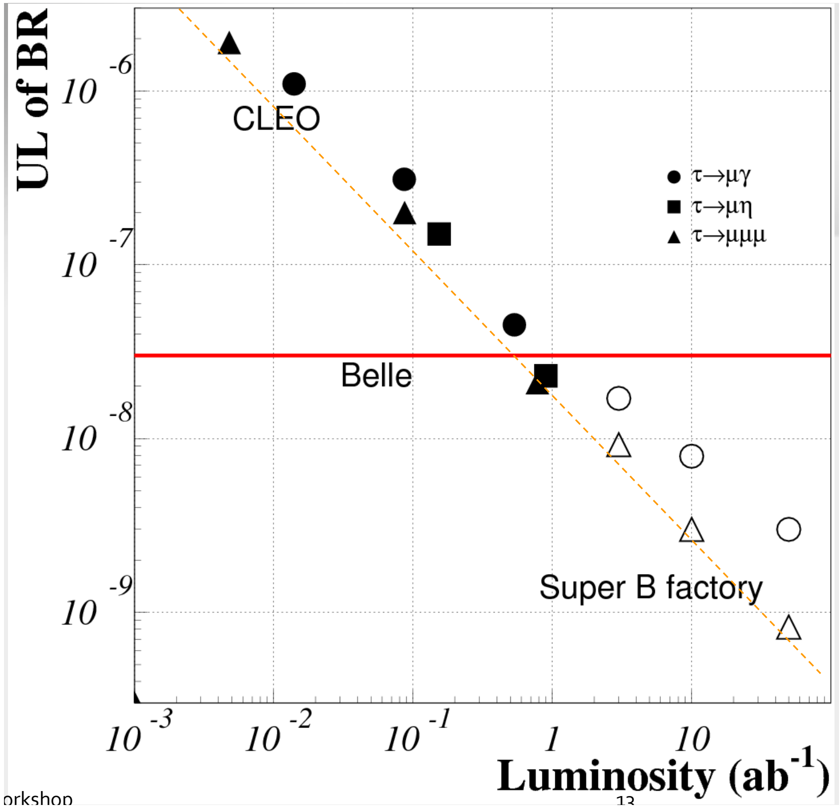
$ee \rightarrow \mu\mu\, \gamma_{ISR}$

$\Rightarrow$ possible to reduce $\Rightarrow$ sensitivity scales with $\sqrt{\mathcal{L}}$

$\tau^+ \rightarrow \mu^+\mu^+\mu^-$

very clean, essentially background-free up to 50 ab^{-1}

$\Rightarrow$ sensitivity scales linearly with $\mathcal{L}$



Upper Limits:

$\sigma(ee \rightarrow \tau\tau) = 0.92$ nb $\Rightarrow$
4.6 x 10^{10} $\tau^+\tau^-$ in 50 ab^{-1}
$\Rightarrow B(\tau^+ \rightarrow \mu^+\gamma) < \sim 10^{-9}$
$\Rightarrow B(\tau^+ \rightarrow \mu^+\mu^-\mu^+) < \sim 10^{-10}$

This probes NP models

	reference	τ→μγ	τ→μμμ
SM + heavy Maj ν_R	PRD 66(2002)034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547(2002)252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68(2003)033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66(2002)115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566(2003)217	10^{-10}	10^{-7}