Studies of leptonic and semileptonic B decays at Belle and Belle II

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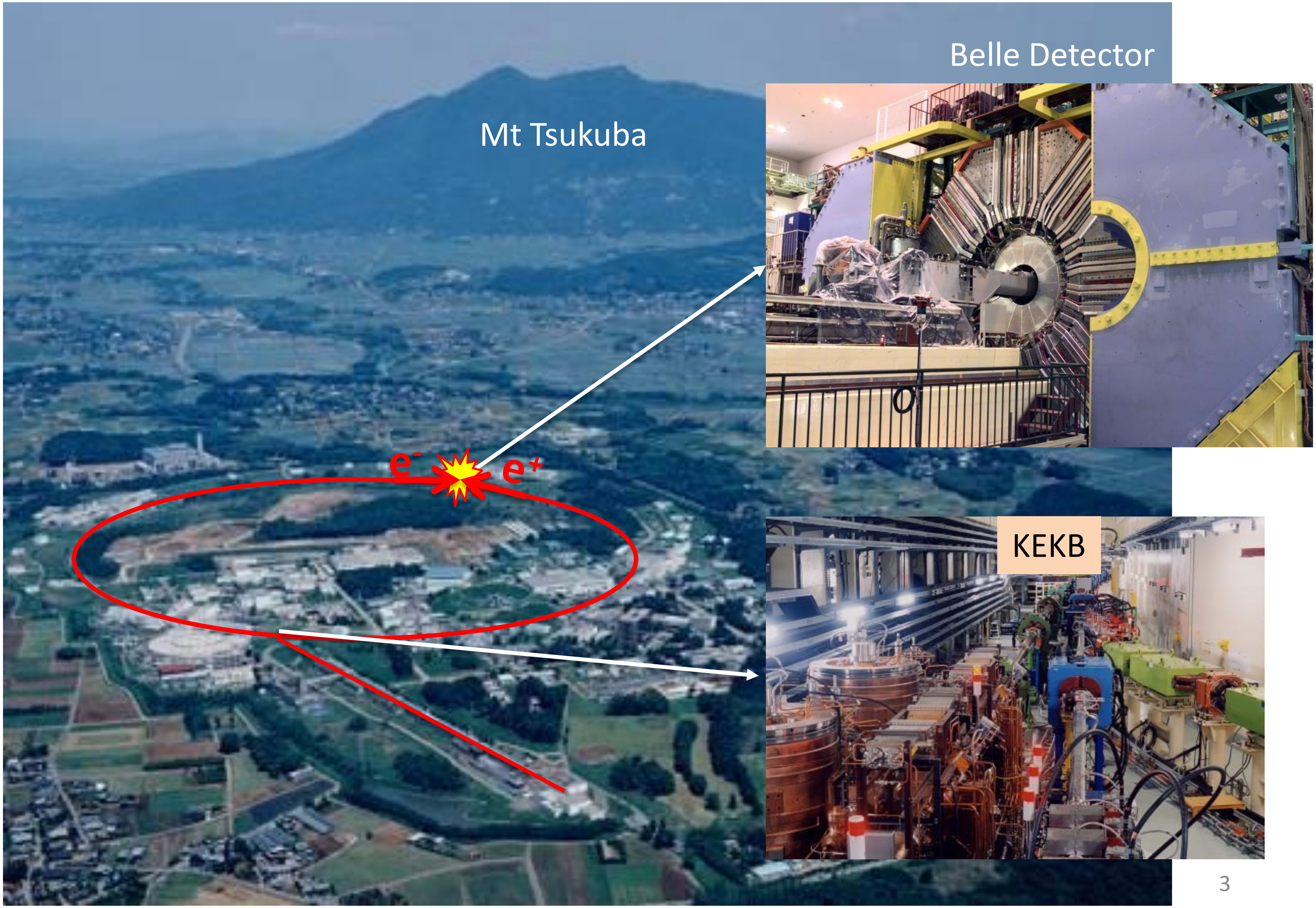
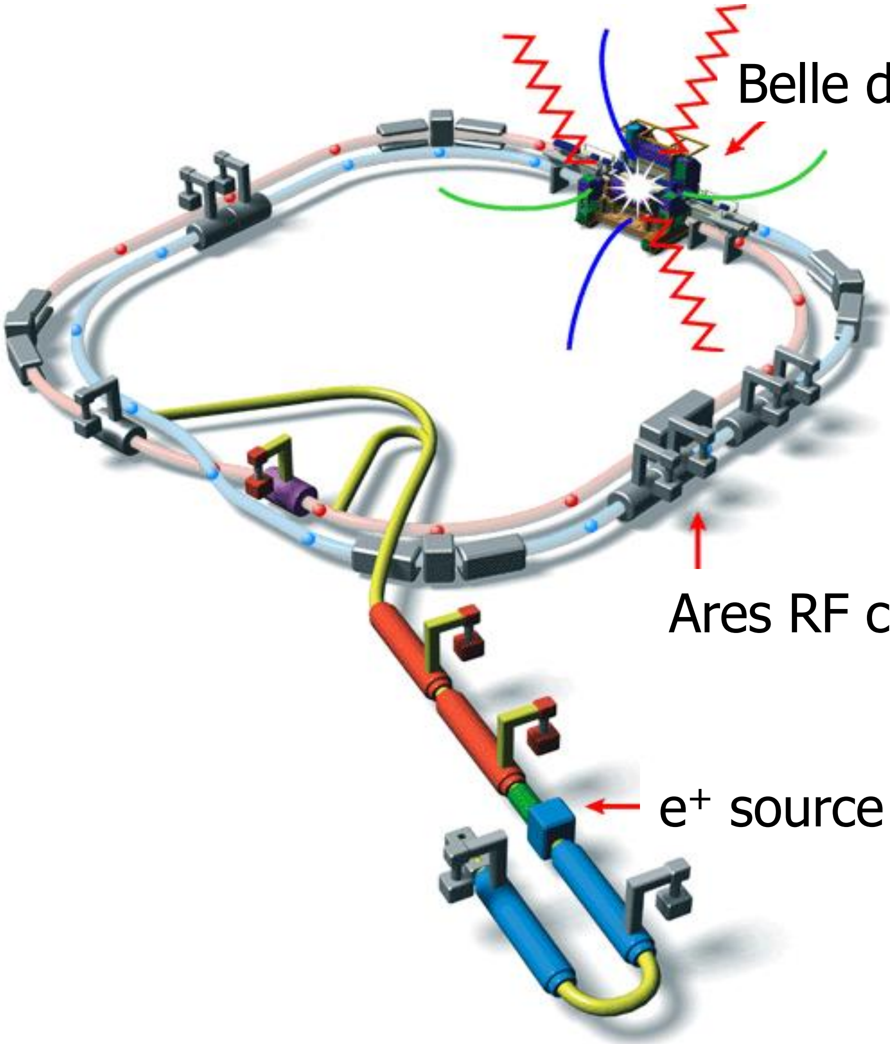
Outline

- KEKB and Belle
- Identification of $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- Measurements of $|V_{cb}|$, $|V_{ub}|$
- $R(D^{(*)})$ and $\mathcal{P}_\tau(D^*)$
- $\mathcal{B}(B^+ \to \tau^+ \nu)$ measurement

KEK Laboratory, Tsukuba Japan



The KEKB Collider



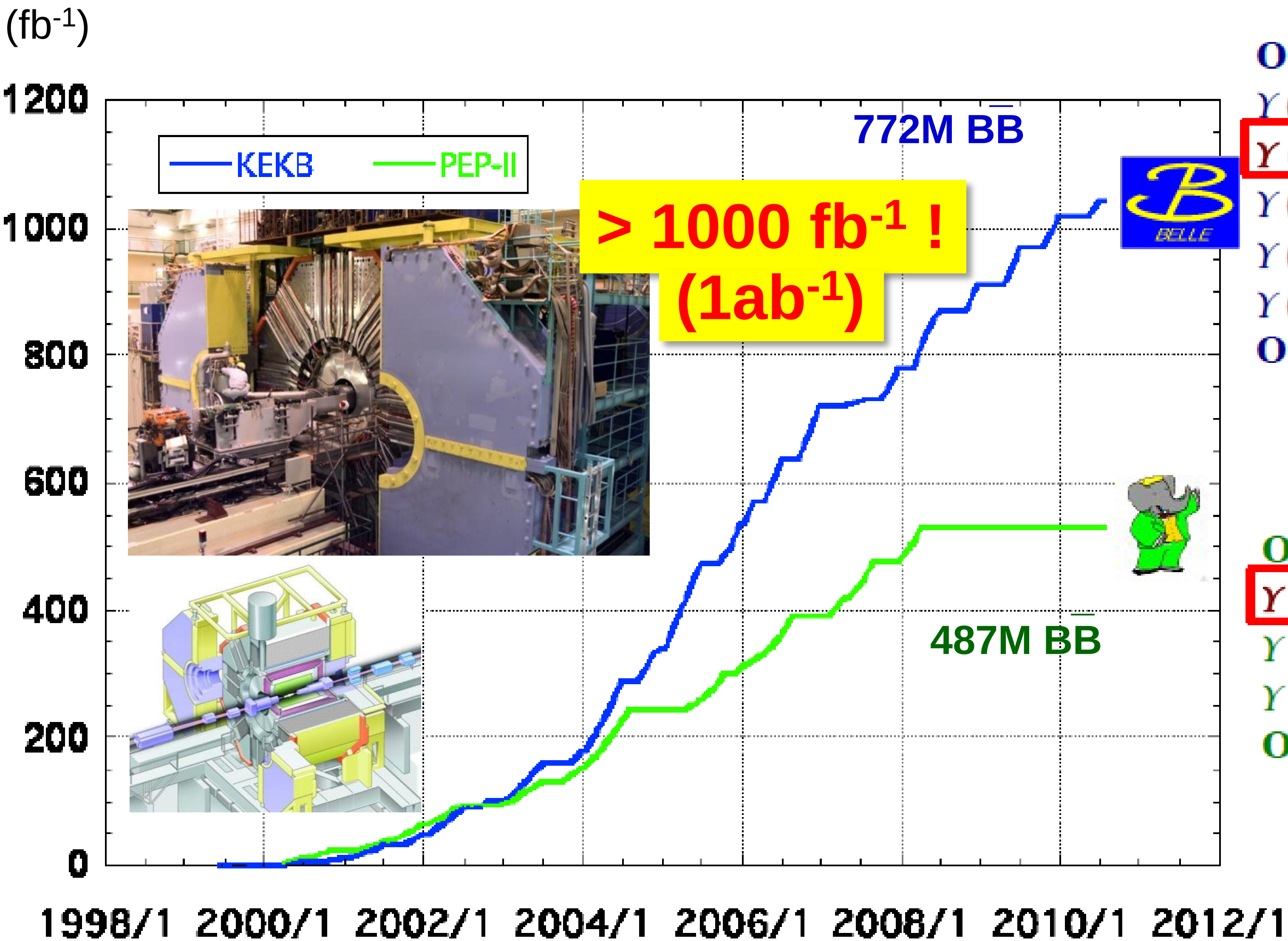
- Asymmetric energy collider (8 GeV e^- x 3.5 GeV e^+)
  - $\sqrt{s} \approx m_{\Upsilon(4S)}$ **(Υ(nS), n=1,2,3,5)**
  - Lorentz boost: $\beta\gamma = 0.425$
- Finite angle beam crossing (22mrad)

Peak luminosity (WR!) :
2. 1 x 10^{34} $cm^{-2}s^{-1}$
=2x design value

First physics run on June 2, **1999**
Last physics run on June 30, **2010**
$L_{peak} = 2.1 \times 10^{34}/cm^2/s$

$\int \mathcal{L}\, dt = 1.04\ ab^{-1}$

Data at KEKB/Belle



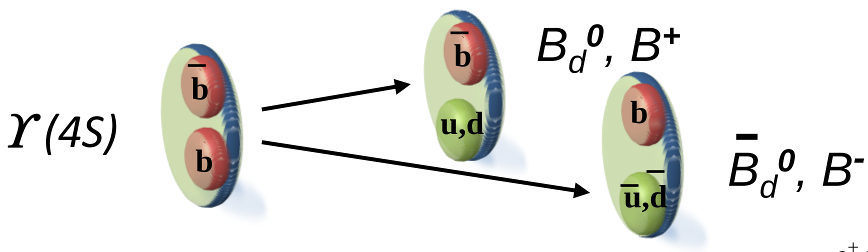
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 24 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

Physics at B factory

Accelerator

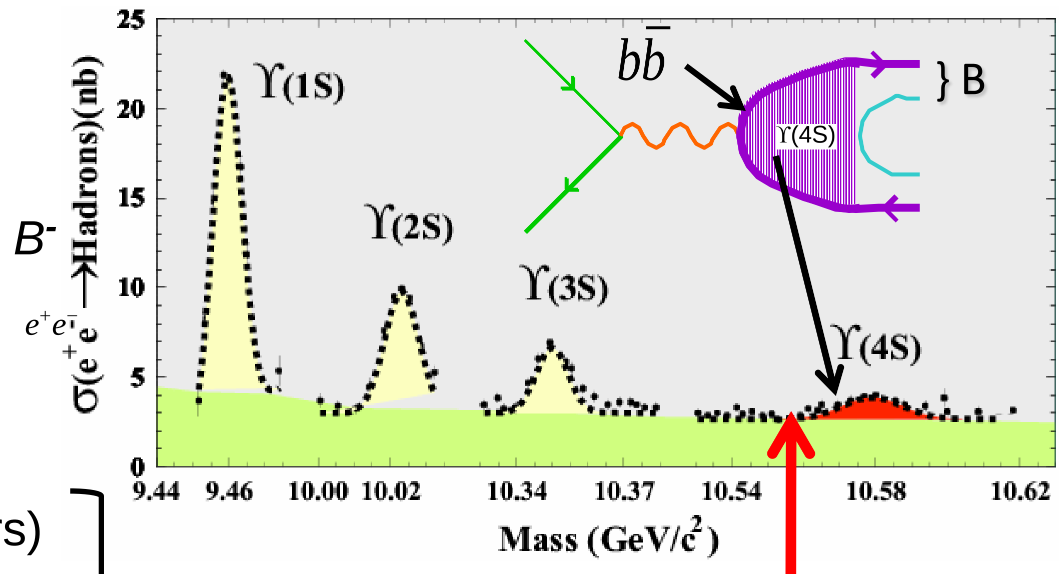
“B-Factory”, KEKB @, KEK



“on resonance” production

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_d^0\bar{B}_d^0,\ B^+B^-$

Belle $\int \mathcal{L}dt \approx 1020\ \mathrm{fb}^{-1}$



$B\bar{B}$ threshould

$\sigma(e^+e^- \rightarrow B\bar{B}) \approx 1.1$ nb (~10^9 $B\bar{B}$ pairs)

”continuum” production

$\sigma(e^+e^- \rightarrow c\bar{c}) \approx 1.3$ nb (~1.3×10^9 $X_c\bar{Y}_c$ pairs)

$\tau^+\tau^-$ production

$\sigma(e^+e^- \rightarrow \tau^+\tau^-) \approx 0.9$ nb (~0.9×10^9 $\tau^+\tau^-$ pairs)

Running at $\Upsilon(nS)$, e.g. $\Upsilon(5S) \rightarrow (B_s\bar{B}_s)$

Variety of Physics

Primary goal: search for and study of CP violation in weak decays of B meson

DONE !

Complete Test of KM & SM

Measurements of CKM

Determination of UT

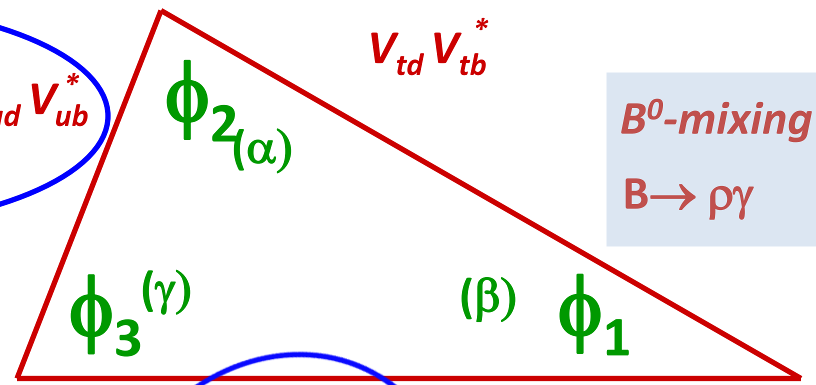
LQCD: important roles

$B \to \pi\pi, \rho\pi, \rho\rho$

$b \to u \ell^- \nu$

$B \to X_u \ell \nu$

→ $V_{ud} V_{ub}^*$



B^0-mixing (Δm_d)

$B \to \rho\gamma$

$B^- \to D_{com} K^-$

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

$V_{cd} V_{cb}^*$

$b \to c \ell^- \nu$

$B \to X_c \ell \nu$

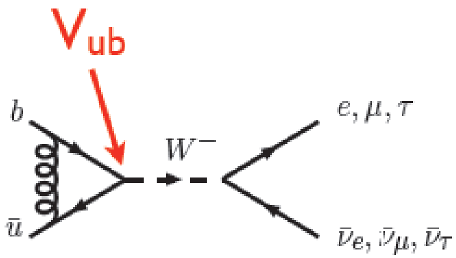
$B^0 \to (cc) K^{(*)0}$

$B^0 \to D^{*+} D^{(*)-} (K)$

***B* experiments can provide all measurements !**

Measurements of $|V_{ub}|$ and $|V_{cb}|$

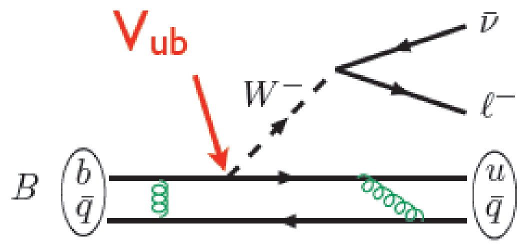
Leptonic



Helicity suppressed

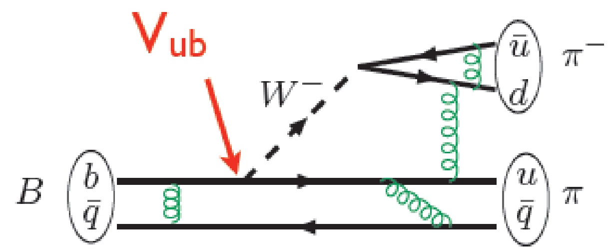
Experimentally difficult

Semileptonic



Leptonic and hadronic currents factorize

Hadronic

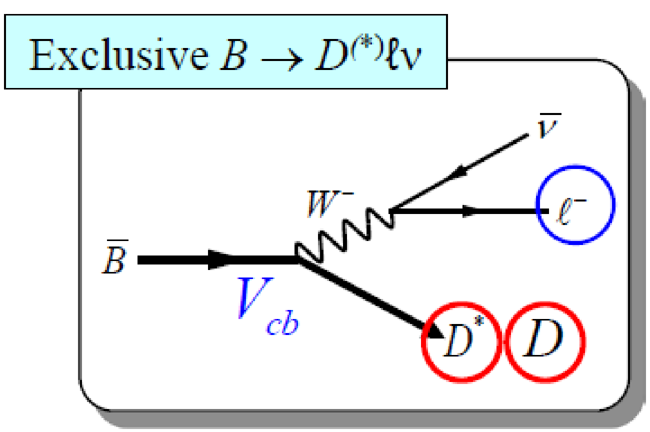


Complex QCD interactions

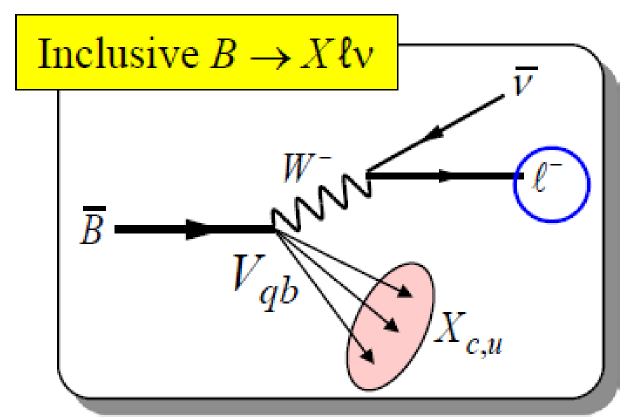
Theoretically challenging

Semileptonic *B*-decays provide a clean environment

B -> D^(*)ℓν
B -> πℓν



B -> X_cℓν
B -> X_uℓν



General strategy for $|V_{ub}|$, $|V_{cb}|$ measurements

- Measure branching fraction of channel(s) involving the associated transition (semileptonic decays used in most cases).
- Extract matrix element using theory input

Example for $|V_{ub}|$:

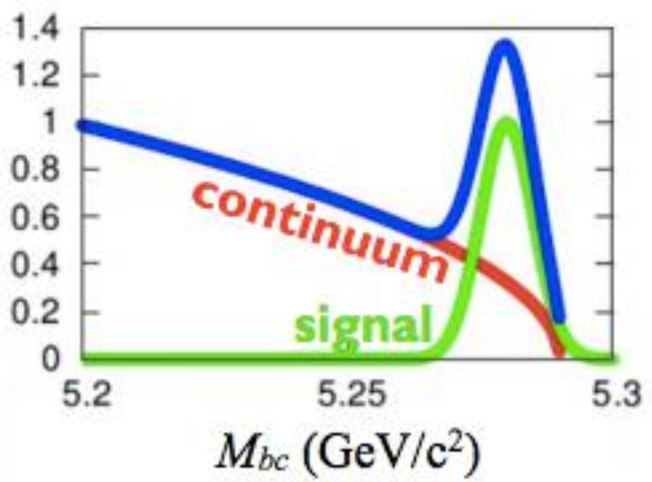
$$\frac{d\mathcal{B}(B \to \pi l \nu)}{dq^2} = \frac{G_F^2 \tau_B}{24\pi^3} p_\pi^3 |V_{ub}|^2 |f_+^{B\pi}(q^2)|^2$$

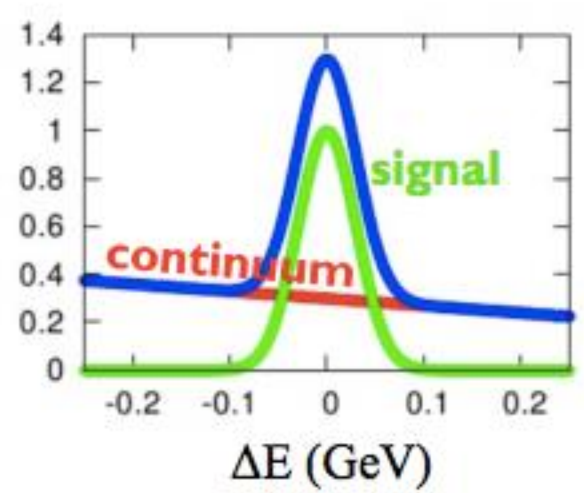
Measure differential $\mathcal{B}$ and form factors to extract $|V_{ub}|$.

Differentiate between exclusive and inclusive measurements, both differ in sample composition and type of theoretical input.

Identification of $e^+e^- \to \Upsilon(4S) \to B\bar{B}$

Kinematic variables are used to identify B decays:





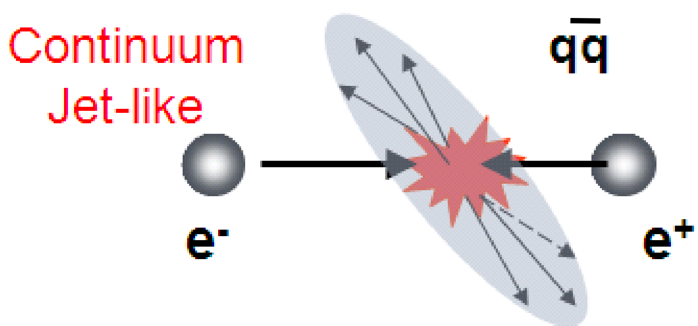
$$M_{bc} = \sqrt{(E^*_{beam})^2 - (p^*_B)^2}$$

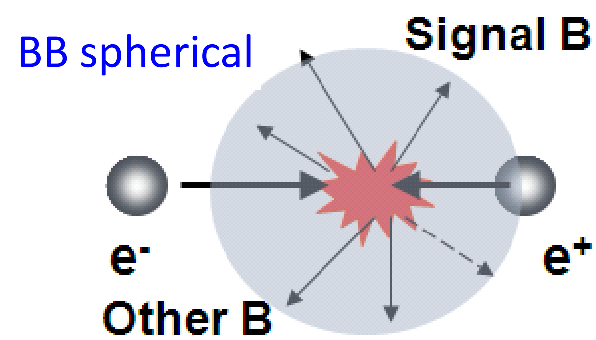
$$\Delta E = E^*_B - E^*_{beam}$$

E^*_B, p^*_B - energy, momentum of a reconstructed *B*-meson in the CM frame

Background suppression

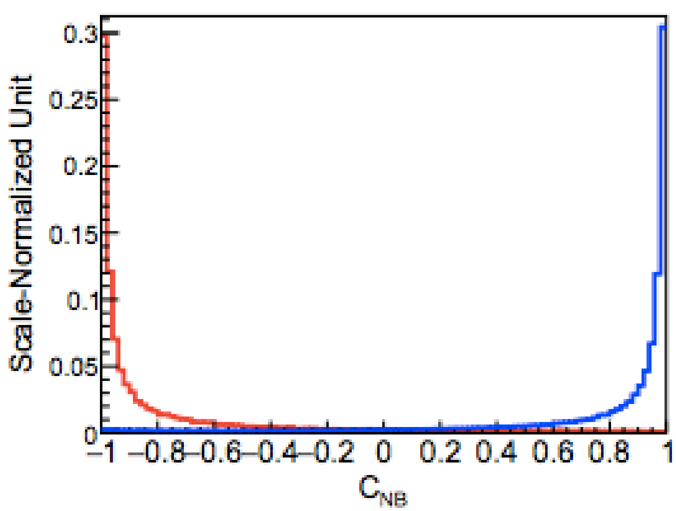
The dominant source of background $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$



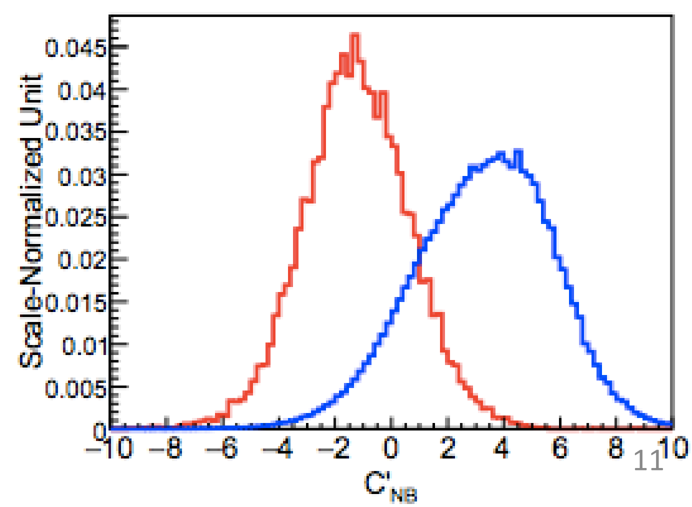


Continuum suppression: a multivariate analyzer based on

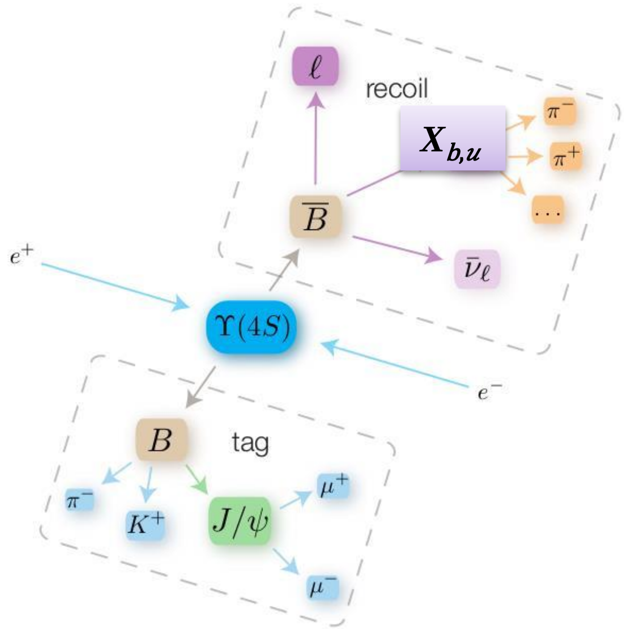
neural network



Fisher discriminant



Tagging techniques for $\Upsilon(4S)$ events



- Tagging provides:
  - Background suppression
  - Information on B_{sig} 4-momentum

$$p(B_{sig}) = p_{e^+e^-} - p(B_{tag})$$

PURITY →

← EFFICIENCY

Untagged
- No requirement on B_{tag}
- High efficiency, low purity

$$p_\nu^2 = m_{miss}^2 = 0 \longrightarrow \cos\theta_{B-D^{(*)}\ell} = \frac{2E^*_{beam}E^*_{D^{(*)}\ell} - m_B^2 - M^2_{D^{(*)}\ell}}{2|\vec{p}^{\,*}_B|\cdot|\vec{p}^{\,*}_{D^{(*)}\ell}|}$$

Semileptonic tag
- $B_{\text{tag}} \rightarrow D^{(*)}\ell\nu$
- Efficiency $\sim \mathcal{O}(0.2\%)$

Hadronic tag
- $B_{\text{tag}} \rightarrow$ hadrons
- Efficiency $\sim \mathcal{O}(0.1\%)$

NeuroBayes NN package
Efficiency $\sim \mathcal{O}(0.2\text{-}0.3\%)$

$$B \rightarrow D^{*} \ell \nu$$

$|V_{cb}|$:Exclusive decays

$B^0 \to D^{*-}\ell^+\nu$ with hadronic tag

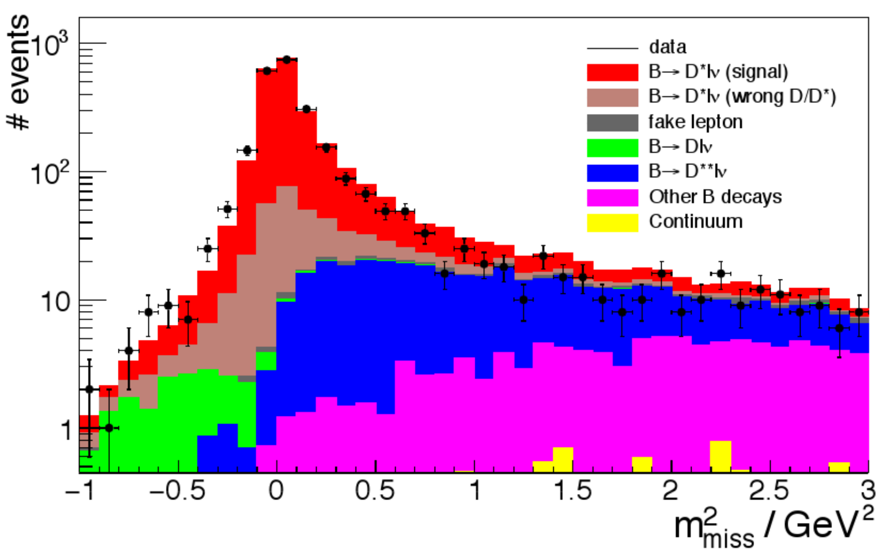
Belle, [arXiv:1702.01521]

Event reconstruction

- *Tag side*: B_{tag} reconstructed in over 1100 hadronic decay chaines, 0.2% efficiency for neutral B mesons
- *Signal side*: B_{sig} assembled from an identified charged lepton (electron or muon) and a D^{*+} candidate
  - $D^{*+} \to D^0\pi^+, D^+\pi^0$ (98.4%)
  - $D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+$ (26.3%), $D^+ \to K^-\pi^+\pi^+$ (9.4)%

Signal is extracted from the missing mass distribution by an unbinned maximum likelihood fit

$$p_{miss} = p_\nu = p_{e^+e^-} - p_{tag} - p_{D^*} - p_\ell \qquad m^2_{miss} = p^2_{miss} = p^2_\nu$$



ℓ	ν^{sig}
$e+\mu$	2374 ± 53
e	1306 ± 40
μ	1066 ± 34

$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu) = (4.95 \pm 0.11 \pm 0.22) \times 10^{-2}$

Largest syst: tag calibration (~ 0.18×10^{-2})

$|V_{cb}|$ determination from exclusive $B \to D^* \ell \nu$

Differential decay ratio with respect to the variable *w*
in the limit of small lepton masses :

$$\frac{d\Gamma}{dw} = \frac{G_F^2 m_{D^*}^3}{48\pi^3}(m_B - m_{D^*})^2 \sqrt{w^2-1}\,\chi(w)\mathcal{F}^2(w)|V_{cb}|^2$$

w: the Lorentz boost of *D** meson in the *B* rest frame

$$w = \frac{P_B \cdot P_{D^{(*)}}}{m_B m_{D^{(*)}}} = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$$

$(q = p_B - p_{D^*} = p_\ell + p_\nu)$

- Parameterization of the form factors in the framework of Heavy Quark Effective Theory.

  Model **CLN** (Caprini, Lellouch, Neubert, [Nucl.Phys. B530, 153(1998)])

  $\mathcal{F}$(w) : $\mathcal{F}(1)$, ρ^2, $R_1(1)$, $R_2(1)$

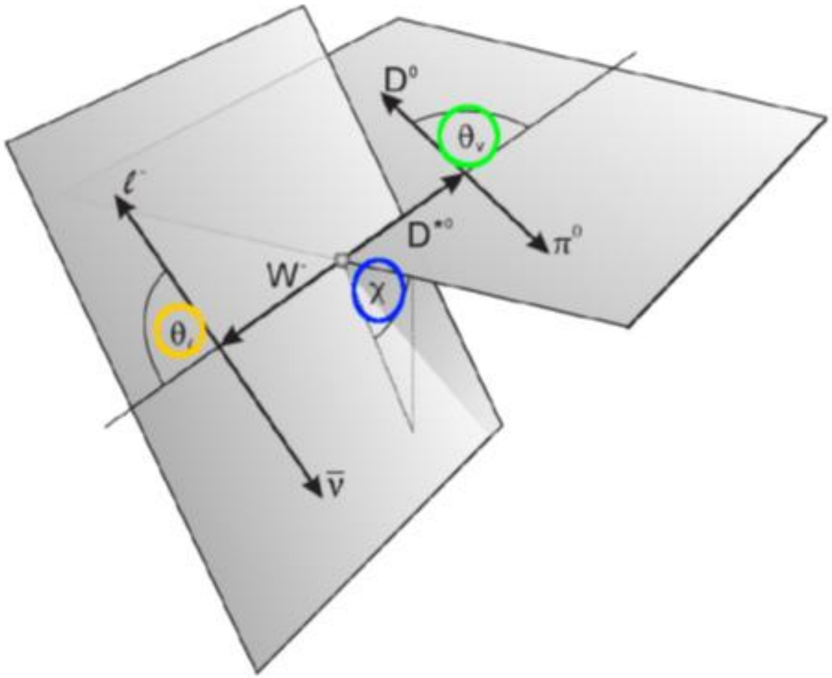
- The form factor normalization at *w* = 1 (zero-recoil) computed by Lattice QCD

  $\mathcal{F}(1) = 0.906 \pm 0.013$ [PRD 89, 114504(2014)]

Differential decay ratio is parametrized by 4 parameters: $|V_{cb}|$, ρ^2, $R_1(1)$, $R_2(1)$

HQFT

Differential fit result

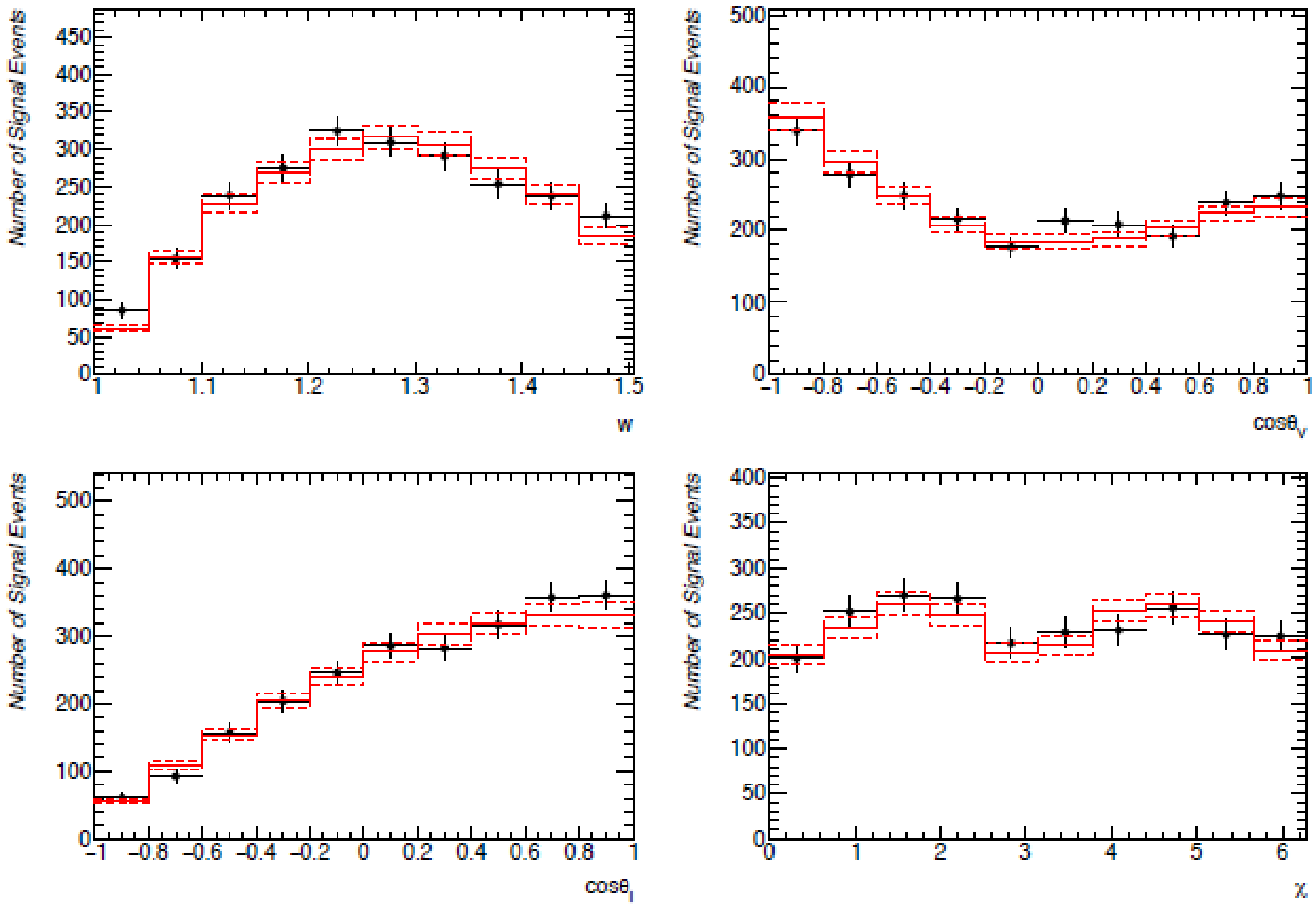


- Kinematics of the decay is characterized by four variables w, θ_ℓ, θ_v, χ
- In the experiment yield is extracted in 4x10 bins of w, $\cos\theta_\ell$, $\cos\theta_v$, χ
- Fit to w, $\cos(\theta_\ell)$, $\cos(\theta_v)$, χ

Variable	Bin	$\Delta\Gamma/\Delta x$ [10^{-15}GeV]
w	1	1.32 ± 0.11
	2	2.08 ± 0.15
	3	2.39 ± 0.15
	4	2.57 ± 0.16
	5	2.63 ± 0.15
	6	2.46 ± 0.14
	7	2.25 ± 0.14
	8	2.08 ± 0.13
	9	1.99 ± 0.12
	10	1.83 ± 0.13
$\cos\theta_v$	1	2.80 ± 0.19
	2	2.30 ± 0.14
	3	1.95 ± 0.13
	4	1.70 ± 0.11
	5	1.58 ± 0.11
	6	1.65 ± 0.11
	7	1.77 ± 0.12
	8	2.00 ± 0.14
	9	2.50 ± 0.16
	10	3.19 ± 0.25
$\cos\theta_\ell$	1	0.73 ± 0.07
	2	1.18 ± 0.09
	3	1.64 ± 0.11
	4	2.04 ± 0.13
	5	2.34 ± 0.14
	6	2.50 ± 0.15
	7	2.54 ± 0.15
	8	2.68 ± 0.16
	9	2.83 ± 0.20
	10	2.82 ± 0.24
χ	1	1.86 ± 0.16
	2	2.31 ± 0.15
	3	2.59 ± 0.16
	4	2.37 ± 0.15
	5	1.95 ± 0.13
	6	1.87 ± 0.15
	7	2.11 ± 0.15
	8	2.33 ± 0.15
	9	2.15 ± 0.15
	10	1.89 ± 0.16

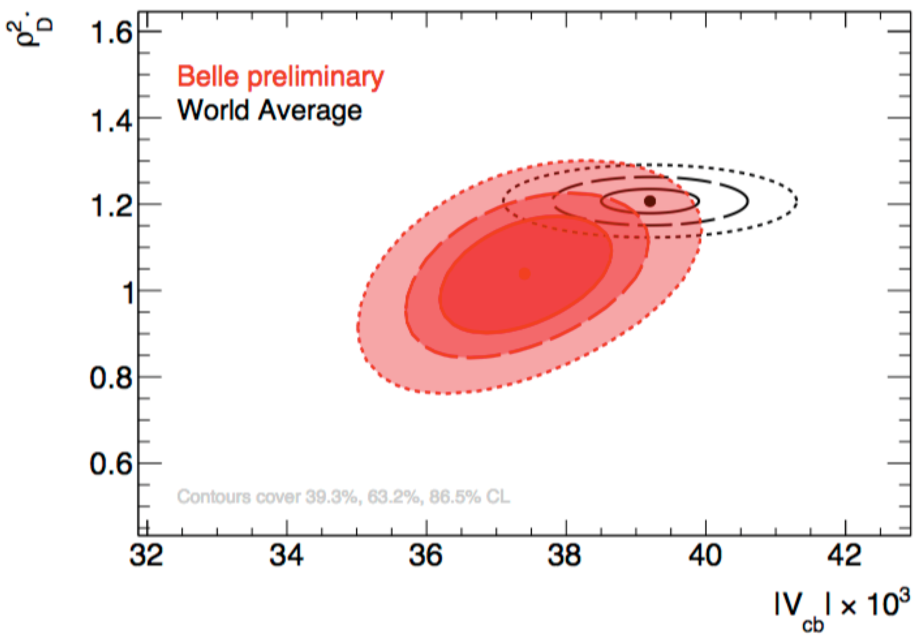
CLN fit to the differential widths

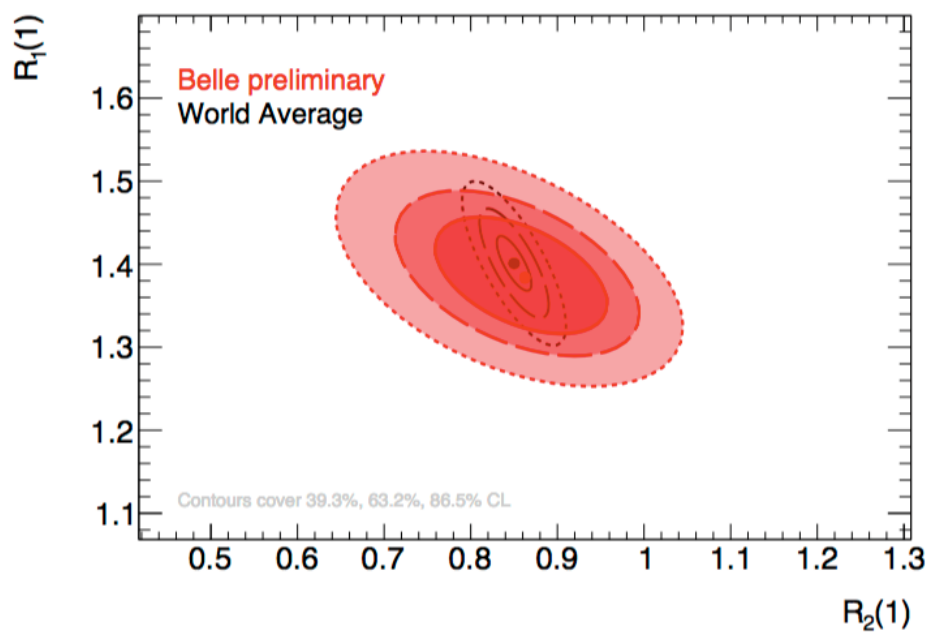
$$\chi^2 = \left(\boldsymbol{\nu}_{\rm sig} - \boldsymbol{\nu}^{\rm pred}_{\rm sig}\right) C^{-1} \left(\boldsymbol{\nu}_{\rm sig} - \boldsymbol{\nu}^{\rm pred}_{\rm sig}\right) + \left(h_{A1}(1) - h^{\rm la}_{A1}(1)\right)^2 / \left(\sigma^{\rm la}_{h_{A1}(1)}\right)^2$$



Points with error bars: Belle data,
red histogram: fit result, dashed histogram: $\Delta\chi^2$=1 contour

CLN fit to the differential widths (2)





Parameter	This result	World Average
$\|V_{cb}\| \times 10^3$	37.4 ± 1.3	39.2 ± 0.7
$\rho^2_{D^*}$	1.03 ± 0.13	1.21 ± 0.03
$R_1(1)$	1.38 ± 0.07	1.40 ± 0.03
$R_2(1)$	0.87 ± 0.10	0.85 ± 0.02

$$C = \begin{pmatrix} 1 & 0.41 & -0.20 & -0.14 \\ 0.41 & 1 & 0.19 & -0.86 \\ -0.20 & 0.19 & 1 & -0.46 \\ -0.14 & -0.86 & -0.46 & 1 \end{pmatrix}$$

Preliminary!

$$B \to D\ell\nu$$

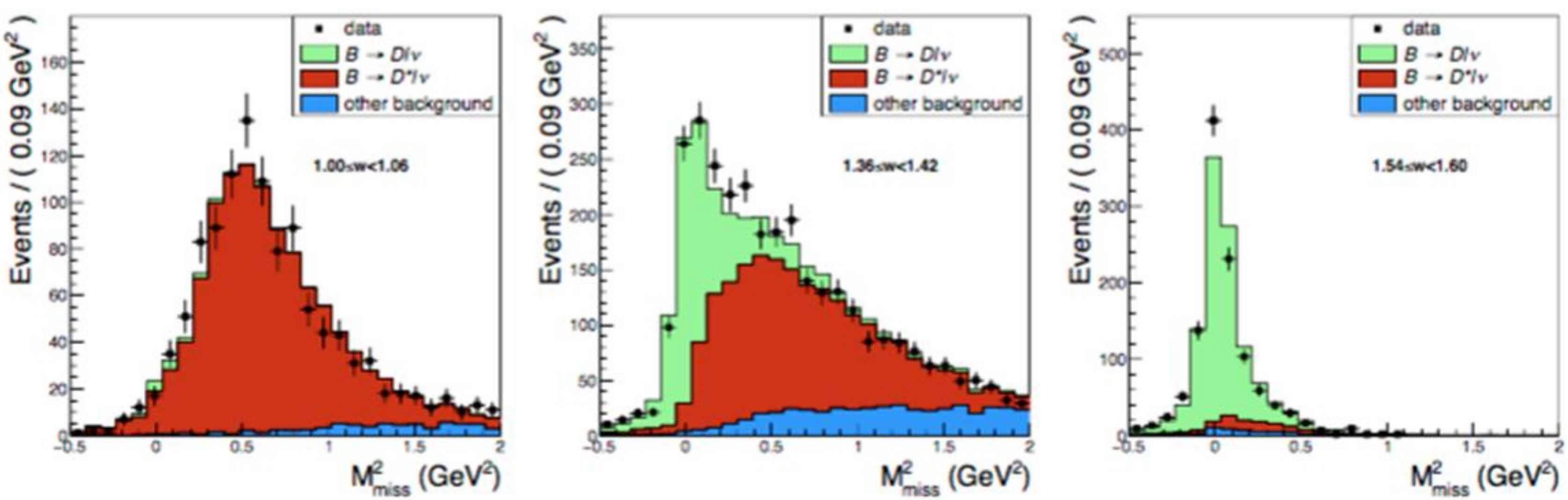
Exclusive $B \to D\,\ell\,\nu$ with hadronic tag

Event reconstruction

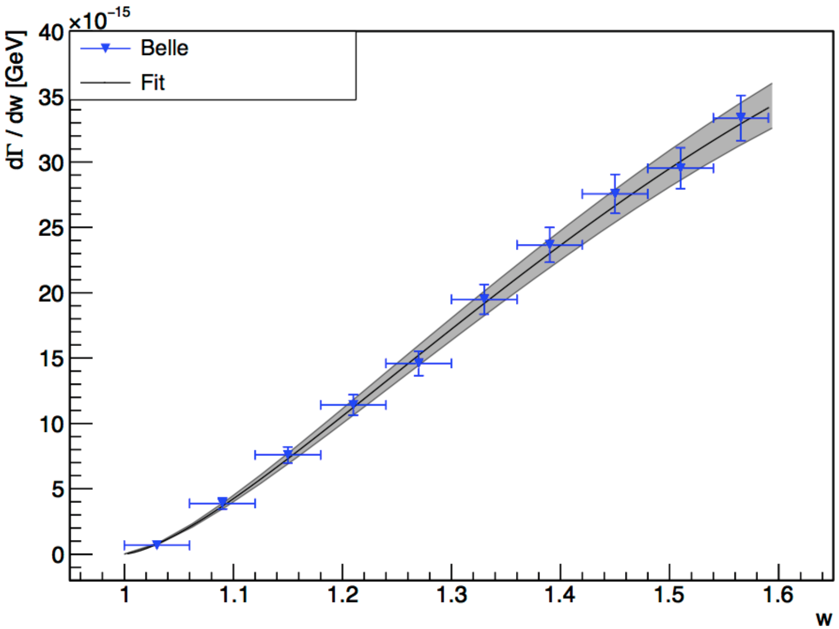
Belle, [Phys.Rev. D93, 032006 (2016)]

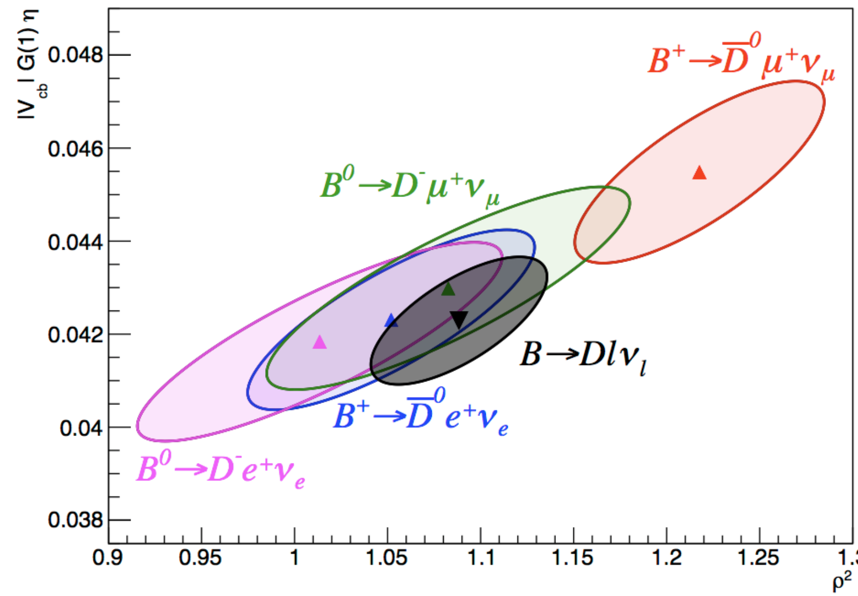
- Identical event reconstruction method
- *Signal side*: 15 D^- and 17 D^0 modes are used
- Signal extraction from M^2_{miss} in 10 bins of w
- $16\,992 \pm 192$ signal events
  ($5\,150 \pm 95$ B^0 events,
  $11\,843 \pm 167$ B^+ events)

Sample	Signal yield	$\mathcal{B}$ [%]
$B^0 \to D^- e^+ \nu_e$	$2848 \pm 72 \pm 17$	$2.44 \pm 0.06 \pm 0.12$
$B^0 \to D^- \mu^+ \nu_\mu$	$2302 \pm 63 \pm 13$	$2.39 \pm 0.06 \pm 0.11$
$B^+ \to \bar{D}^0 e^+ \nu_e$	$6456 \pm 126 \pm 66$	$2.57 \pm 0.05 \pm 0.13$
$B^+ \to \bar{D}^0 \mu^+ \nu_\mu$	$5386 \pm 110 \pm 51$	$2.58 \pm 0.05 \pm 0.13$
$B^0 \to D^- \ell^+ \nu_\ell$	$5150 \pm 95 \pm 29$	$2.39 \pm 0.04 \pm 0.11$
$B^+ \to \bar{D}^0 \ell^+ \nu_\ell$	$11843 \pm 167 \pm 120$	$2.54 \pm 0.04 \pm 0.13$
$B \to D \ell \nu_\ell$	$16992 \pm 192 \pm 142$	$2.31 \pm 0.03 \pm 0.11$



CLN fit to the differential widths





	$B^+ \to \bar{D}^0 e^+ \nu_e$	$B^+ \to \bar{D}^0 \mu^+ \nu_\mu$	$B^0 \to D^- e^+ \nu_e$	$B^0 \to D^- \mu^+ \nu_\mu$	$B \to D \ell \nu_\ell$
$\eta_{\rm EW} \mathcal{G}(1) \lvert V_{cb} \rvert [10^{-3}]$	42.31 ± 1.94	45.48 ± 1.96	41.84 ± 2.14	42.99 ± 2.18	42.29 ± 1.37
ρ^2	1.05 ± 0.08	1.22 ± 0.07	1.01 ± 0.10	1.08 ± 0.10	1.09 ± 0.05
Correlation	0.81	0.77	0.85	0.84	0.69
$\eta_{\rm EW} \lvert V_{cb} \rvert [10^{-3}]$	40.14 ± 1.86	43.15 ± 1.89	39.69 ± 2.05	40.78 ± 2.09	40.12 ± 1.34
$\chi^2 / n_{\rm df}$	2.19/8	2.71/8	9.65/8	4.36/8	4.57/8
Prob.	0.97	0.95	0.29	0.82	0.80

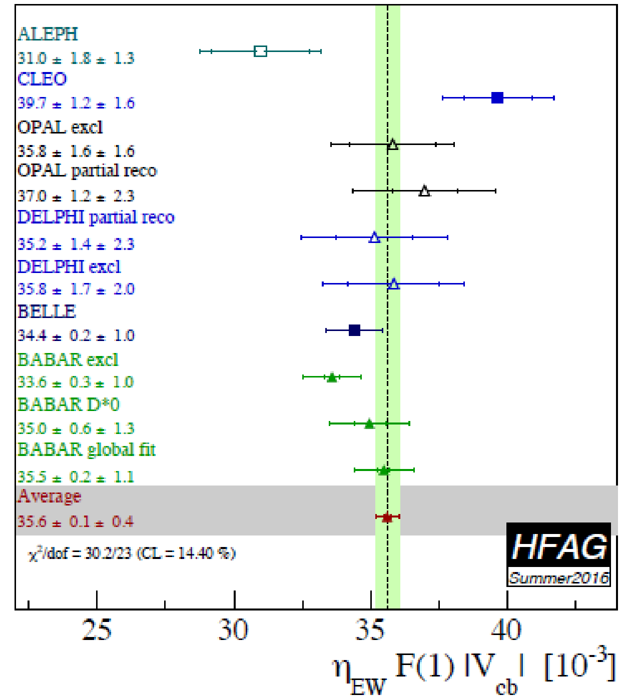
Exclusive Average

$B \to D^* \ell \nu$

HFAG summer 2016

$|V_{cb}| = (38.71 \pm 0.47_{\,exp} \pm 0.59_{\,th}) \times 10^{-3}$

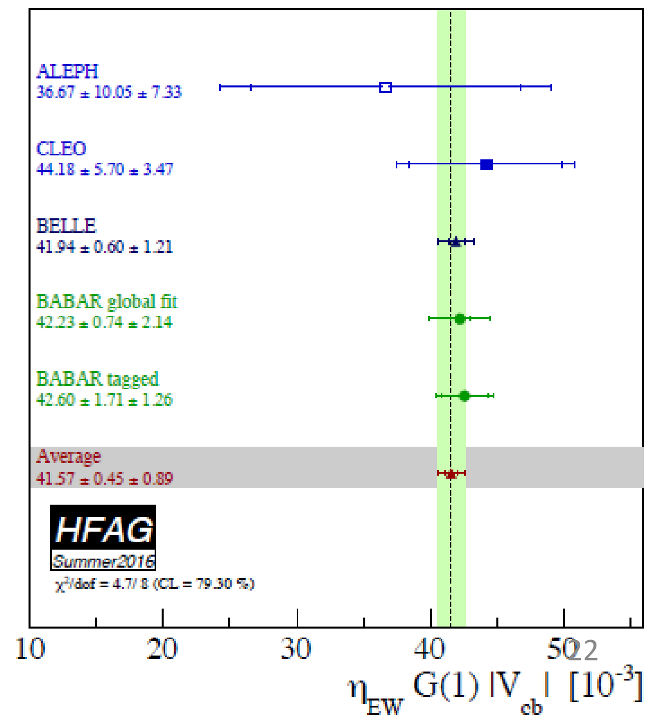
- HFAG 2016: $\eta_{EW} \cdot \mathcal{F}(1) \cdot |Vcb| = (35.61 \pm 0.11_{\,stat} \pm 0.41_{\,syst}) \times 10^{-3}$
- LQCD: $\mathcal{F}(1) = 0.920 \pm 0.014$
- Leading EW correction: $\eta_{ew} = 1.015 \pm 0.005$



$B \to D \ell \nu$

$|V_{cb}| = (39.18 \pm 0.94_{\,exp} \pm 0.31_{\,th}) \times 10^{-3}$

- HFAG 2016: $\eta_{EW} \cdot \mathcal{G}(1) \cdot |Vcb| = (41.57 \pm 0.45_{\,stat} \pm 0.89_{\,syst}) \times 10^{-3}$
- LQCD: $\mathcal{G}(1) = 1.0541 \pm 0.0083$
- Leading EW correction: $\eta_{ew} = 1.0066 \pm 0.0016$



PDG 2017: average of the results from $B \to D \ell \nu$ and $B \to D^* \ell \nu$

$|V_{cb}| = (39.2 \pm 0.7) \times 10^{-3}$ (exclusive)

$|V_{cb}|$ inclusive measurements

$|V_{cb}|$ inclusive measurements

$B \to X_c e\nu$

At parton level, the decay rate for $b \to c\,\ell\,\nu \sim |V_{cb}|^2$ *and can be calculated*

- To relate measurements of semileptonic *B*-meson decays to $|V_{cb}|^2$ the parton-level expressions have to be corrected for the effects of non-perturbative effects.

- Operator Product Expansions (OPE)/Heavy-Quark-Expansions (HQE) successful tool to incorporate perturbative and nonperturbative QCD corrections.

The OPE/HQE parameters and $|V_{cb}|^2$ can be extracted from

the moments of the lepton spectrum ($\langle E_\ell^n \rangle$)

$$\left\langle E_l^n \right\rangle = \frac{1}{\Gamma_{E_l > E_{cut}}} \int_{E_l > E_{cut}} E_l^n \frac{d\Gamma}{dE_l} dE_l$$

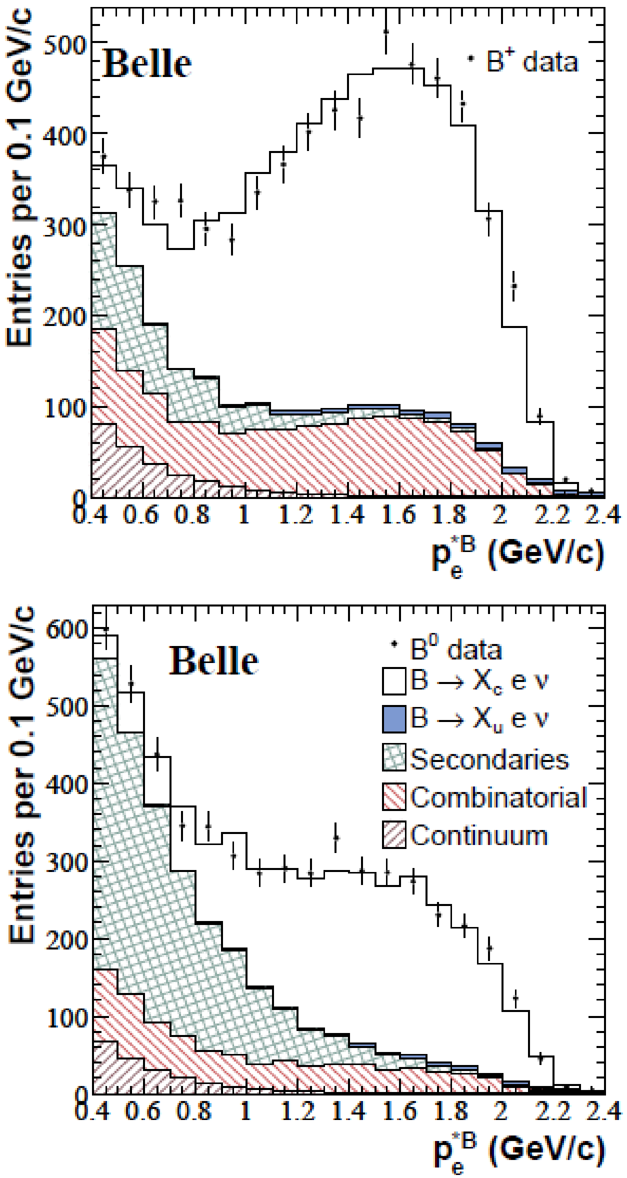
or the moments of the X_c invariant mass squared spectrum ($\langle m_x^{2n} \rangle$)

$$\left\langle m_X^{2n} \right\rangle = \frac{1}{\Gamma_{E_l > E_{cut}}} \int_{E_l > E_{cut}} m_X^{2n} \frac{d\Gamma}{dm_X^2} dm_X^2$$

Moments are measured with incremental cuts on the lepton momentum

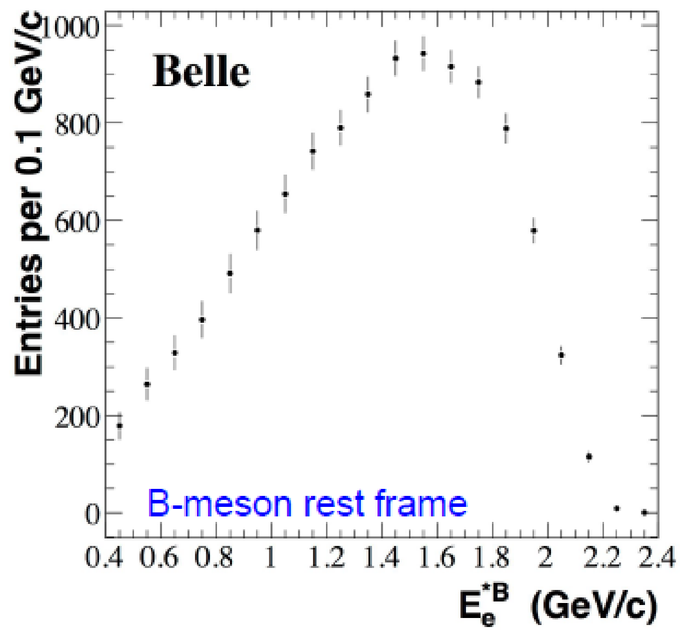
Lepton spectrum measurements

Inclusive semileptonic decays $B \to X_c e \nu$ (+ hadronic tag)



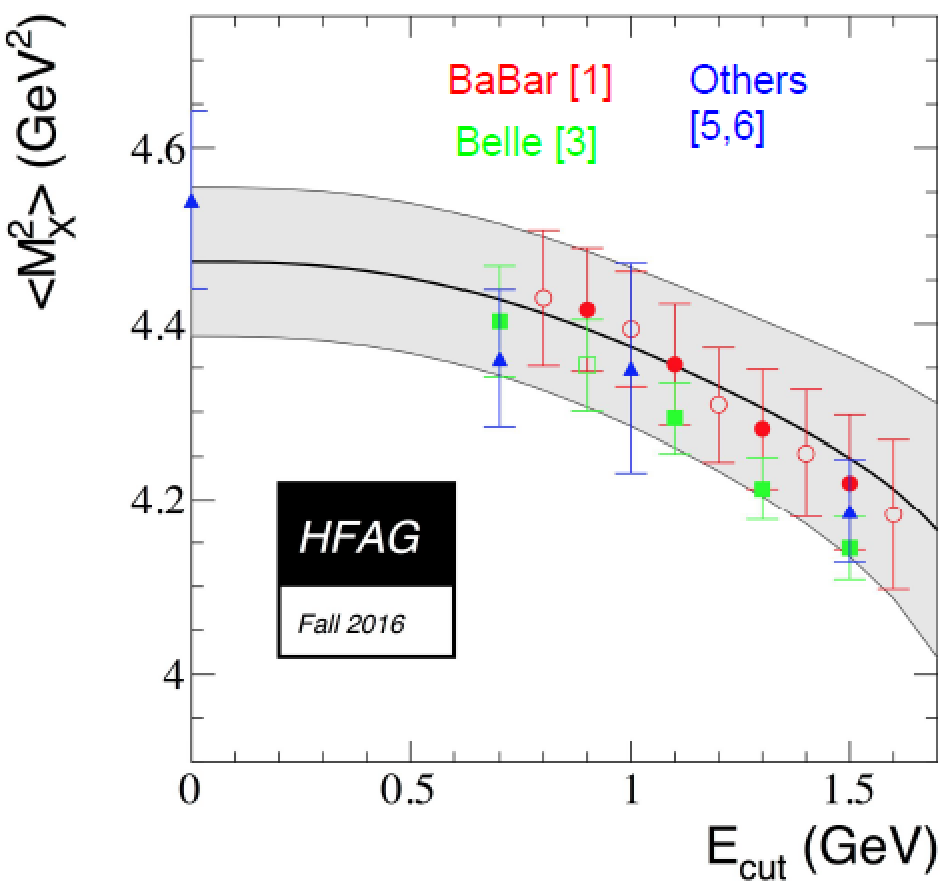
Belle, [Phys.Rev. D75, 032001 (2007)]

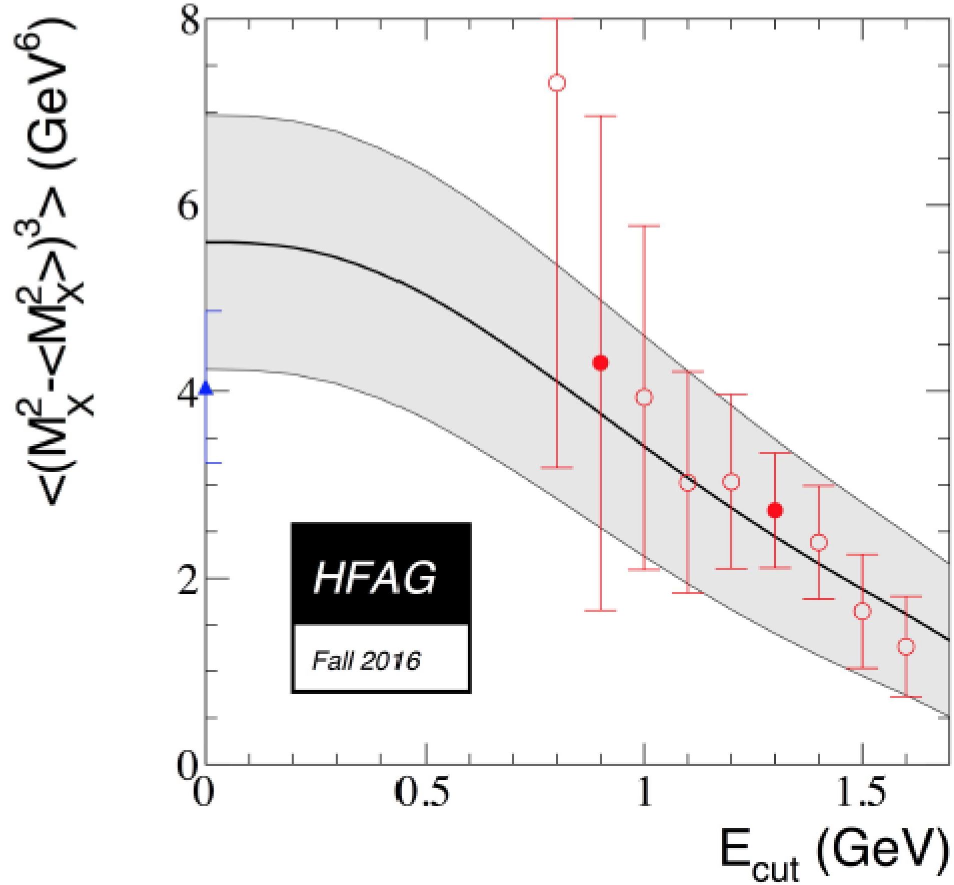
No new experimental results since 2010



Example of the X_c invariant mass moments

grey band: fit error (including theory errors)





$\mathcal{B}(B \to X_c \ell \nu)$ = (10.65 ± 0.16) %

$|V_{cb}|$ = (42.19 ± 0.78) × 10^{-3}

PDG 2017 $|V_{cb}|$ = (42.2 ± 0.8)×10^{-3} (inclusive)

$|V_{ub}|$

Measuring $|V_{ub}|$

Exclusive measurement

- Charmless hadronic final states
- $B \to \pi \ell \nu$ most precise, but only 7% of all $B \to X_u \ell \nu$
- Others include $X_u = \rho, \omega, \eta$, multi-particle states, …
- Needs LQCD or Light Cone Sum Rules (LCSR) as theory input

Pseudoscalar

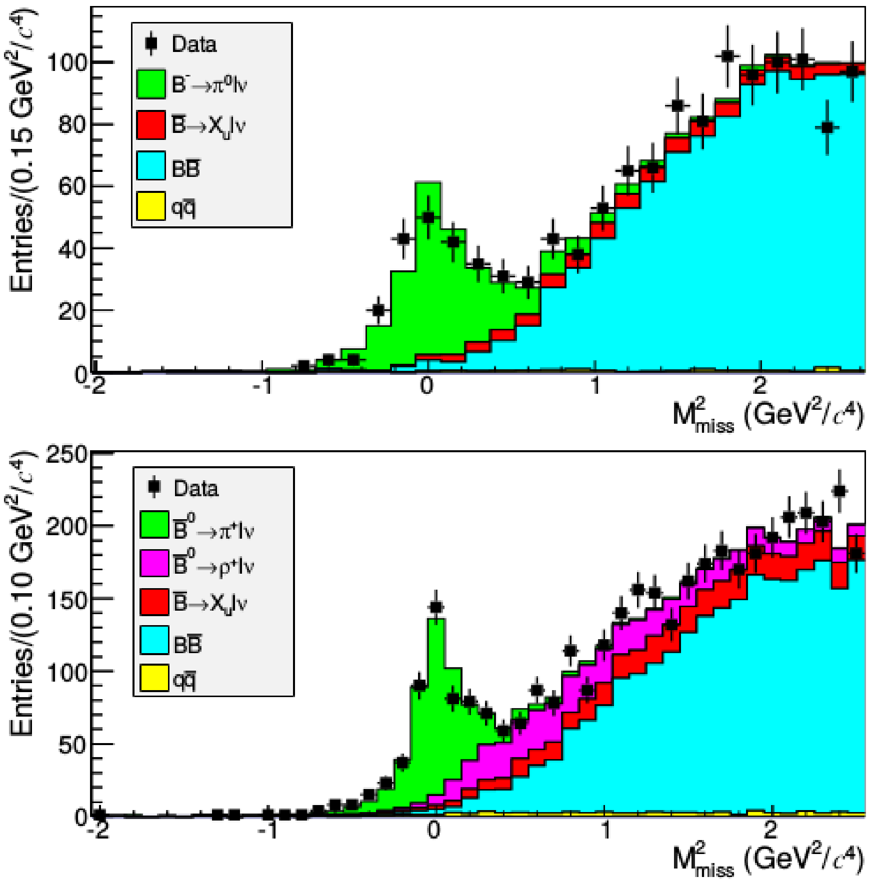
$$\frac{d\mathcal{B}(B \to \pi l \nu)}{dq^2} = \frac{G_F^2 \tau_B}{24\pi^3} p_\pi^3 |V_{ub}|^2 | f_+^{B\pi}(q^2)|^2$$

Vector (helicity basis)

$$\frac{d\mathcal{B}(B \to V l \nu)}{dq^2} = \frac{G_F^2 p_V q^2 \tau_B}{96\pi^3 m_B^2} |V_{ub}|^2 \left[|H_0(q^2)|^2 + |H_+(q^2)|^2 + |H_-(q^2)|^2 \right]$$

Experimental measurement of the branching fraction and theoretical input on form factors needed to determine $|V_{ub}|$

$B \to \pi \ell^+ \nu$ tagged at Belle



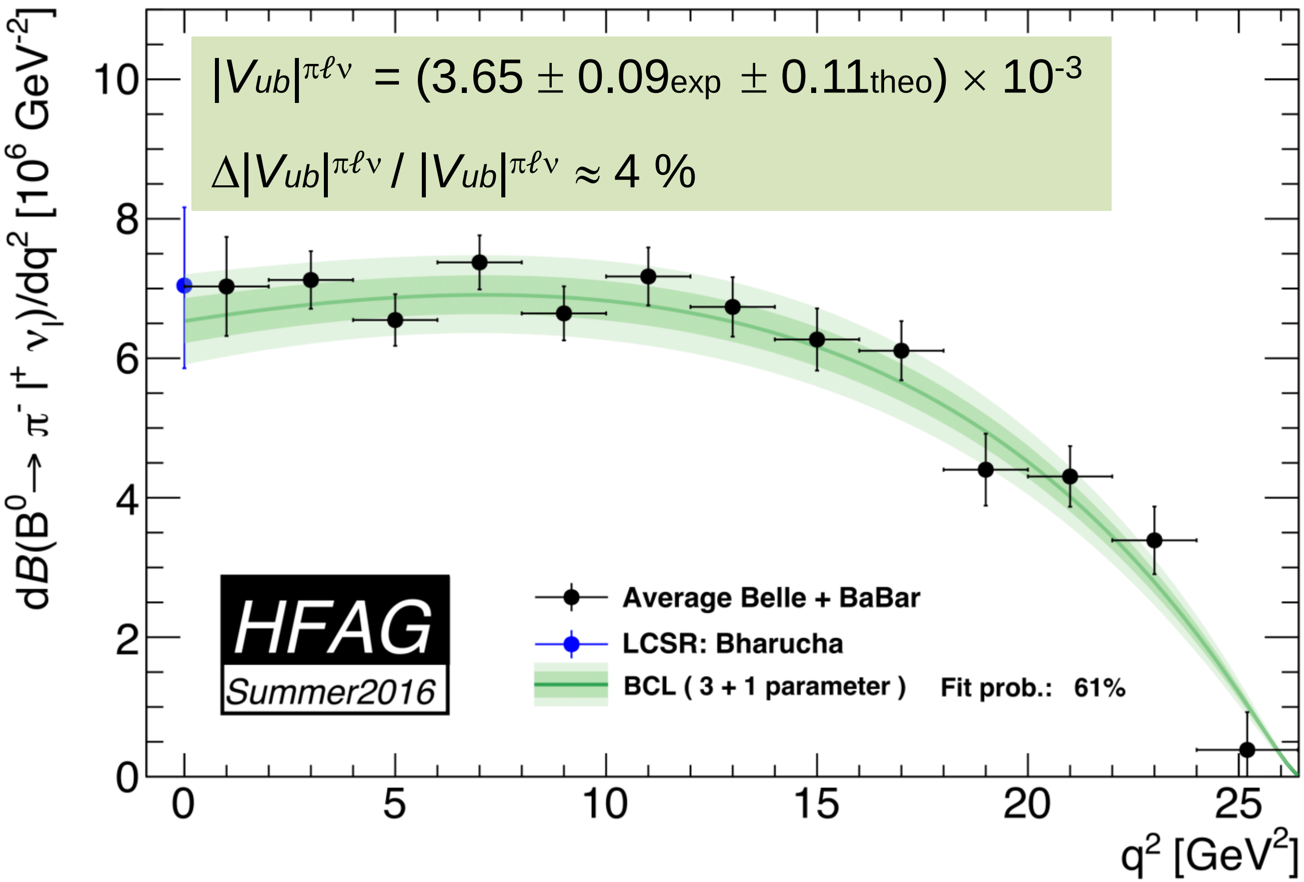
Belle, [Phys.Rev. D88, 032005 (2013)]

- Data sample: 711 fb^{-1}
- Signal candidates
  $N_{B0} \approx 500 \pm 30$
  $N_{B+} \approx 200 \pm 20$
- $d\mathcal{B}/dq^2$ spectrum in
  13 (7) bins for π^- (π^0)

B^+, B^0 combined result:

$\mathcal{B}(B \to \pi \ell^+ \nu) = (1.49 \pm 0.08_{stat} \pm 0.07_{sys}) \times 10^{-4}$

$B \to \pi \ell \nu$



Fit, data averaging: [F. Bernlochner, S. Duell, J. Dingfelder]
LQCD averaging: [FLAG-3 review (arXiv:1607.00299)]
LQCD: [Fermilab/MILC, Phys.Rev. D92 (2015) no.1, 014024]
LQCD: [RBC/UKQCD, Phys.Rev. D91 (2015) no.7, 074510]
LCSR: [A. Bharucha, JHEP 1205 (2012) 092]

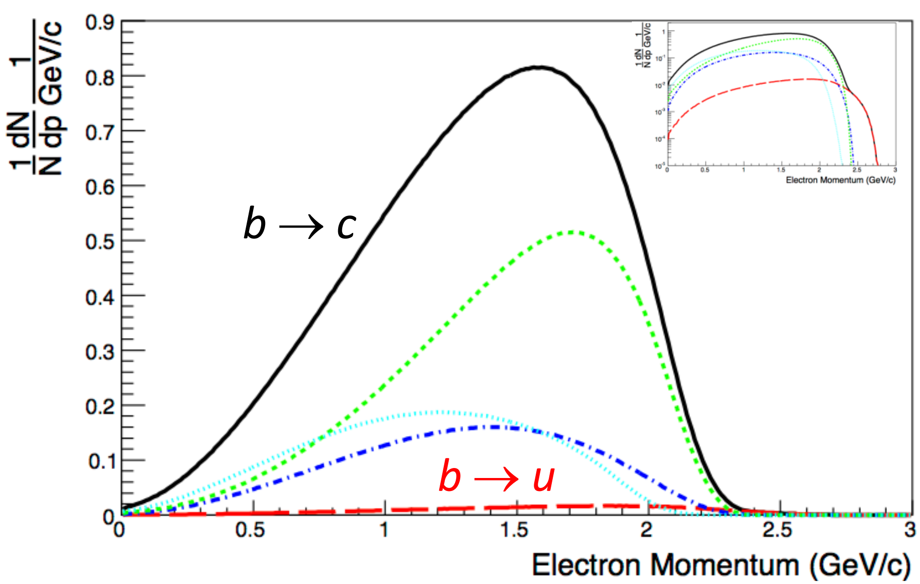
Optimal $|V_{ub}|$ extraction with simultaneous fit to: averaged data (full q^2) + averaged lattice + LCSR with model independent FF parametrization

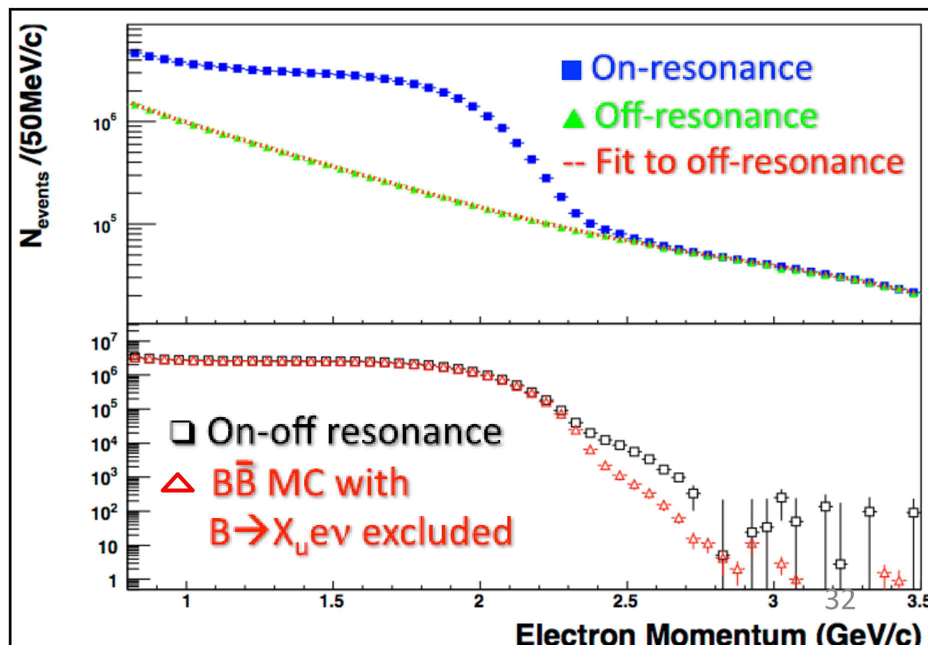
$|V_{ub}|$ - inclusive measurements

Electron spectrum from B decays at $\Upsilon(4S)$

- $B \to X_c e\nu$ decays dominate ($\Gamma(B \to X_c e\nu) \approx 50\,\Gamma(B \to X_u e\nu)$);
  $B \to X_u e\nu$ contribute a sizeable fraction only above the $b \to c$ kinematic endpoint, $E_e > 2.3$ GeV
- Large contribution from $e^+e^- \to c\,c \to eX$ decays; dedicated sample of data collected below BB threshold (off---resonance) needed
- Additional contributions at lower energy from secondary processes $b \to c \to e$ and misidentified hadrons

- Statistical uncertainties on BB spectrum dominated by continuum subtraction
- Region above 2.3 GeV shows clear contribution from $B \to X_u e\nu$ decays





Theoretical models and results

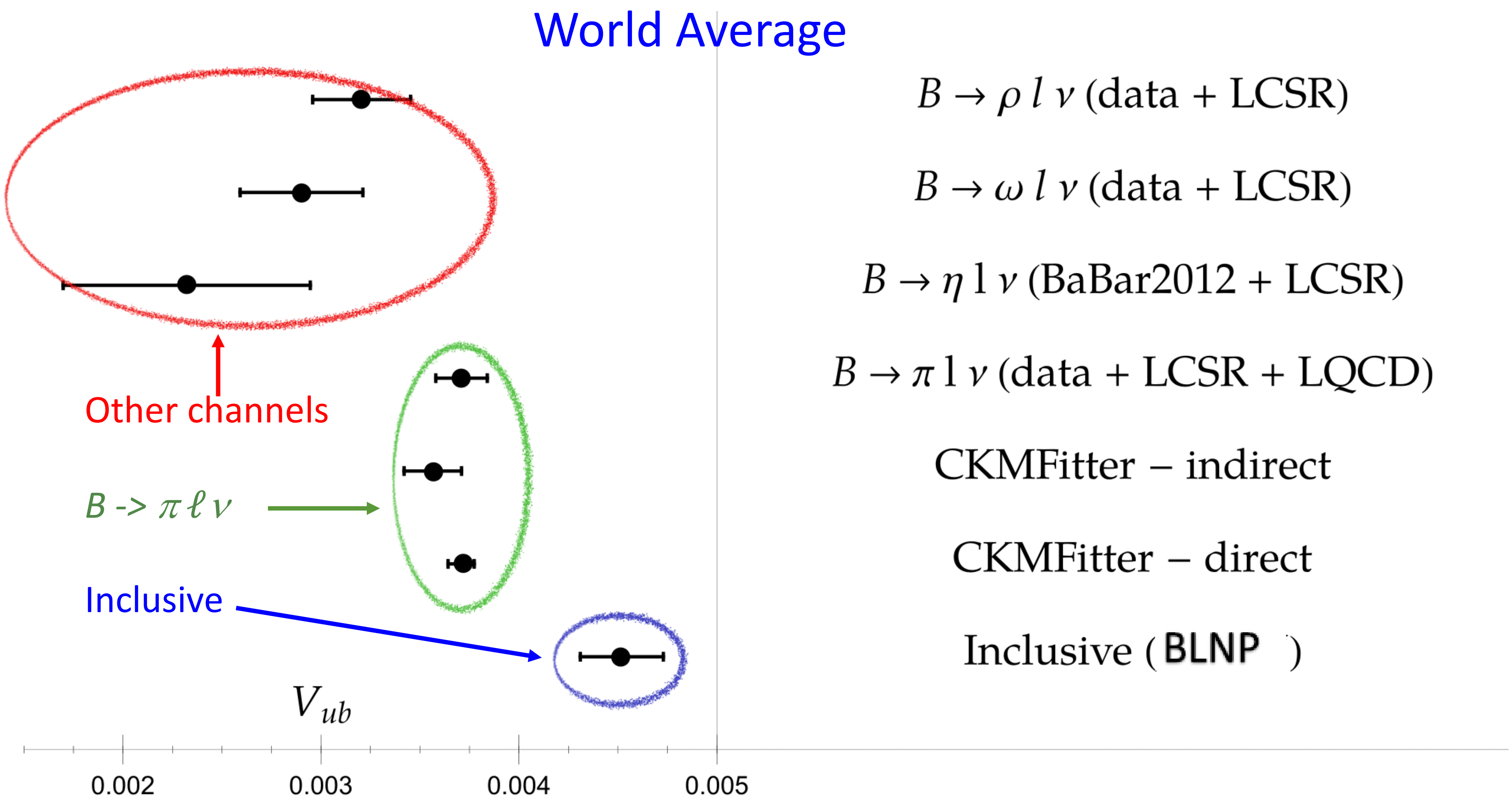
- The OPE calculation is only valid for partial rates that include large portions of the available phase space
  - near the endpoint non-perturbative shape functions (SF) are needed
  - different prescriptions different "models"

- **DN** DeFazio, and Neubert, JHEP 9906, 017 (1999)
- **BLNP** Bosh, Lange, Neubert, Paz, Nucl. Phys. B 699, 335 (2004)
- **GGOU** Gambino, Giordano, Ossola, Uraltsev, JHEP 908 10, 058 (2007)
- **DGE** Andersen, Gardi, JHEP 0601, 097 (2006)

PDG 2017 $|Vub|$ (in units of 10^{-3}) from inclusive $B \rightarrow X_u \ell \nu$ measurements

	BLNP	GGOU	DGE
HFAG average	$4.45 \pm 0.16^{+21}_{-22}$	$4.51 \pm 0.16^{+12}_{-15}$	$4.52 \pm 0.16^{+15}_{-16}$

Overview of various $|V_{ub}|$ values



PDG 2017 (average results)

$|V_{ub}| = (3.72 \pm 0.16)\times 10^{-3}$

exclusive

$|V_{ub}| = (4.49 \pm 0.23)\times 10^{-3}$

inclusive

$|V_{cb}|$, $|V_{ub}|$ measurements summary

- $|V_{cb}|$ and $|V_{ub}|$ are measured with different methods

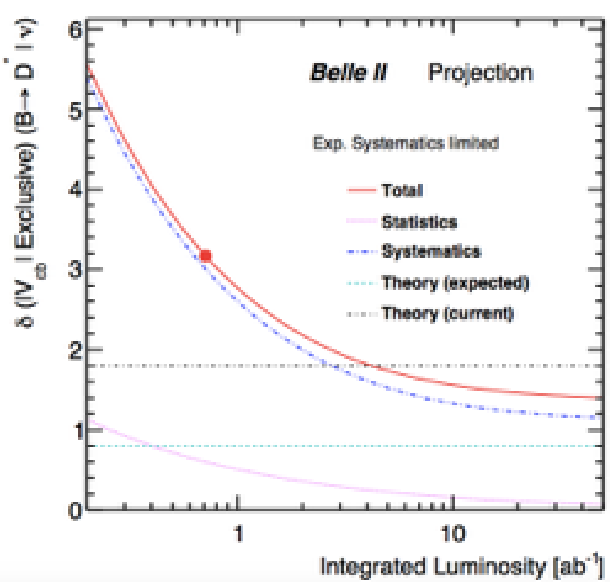
✓ Inclusive $B \to X_c \ell \nu$, $B \to X_u \ell \nu$, Hadronic tag, Semileptonic tag, Untagged

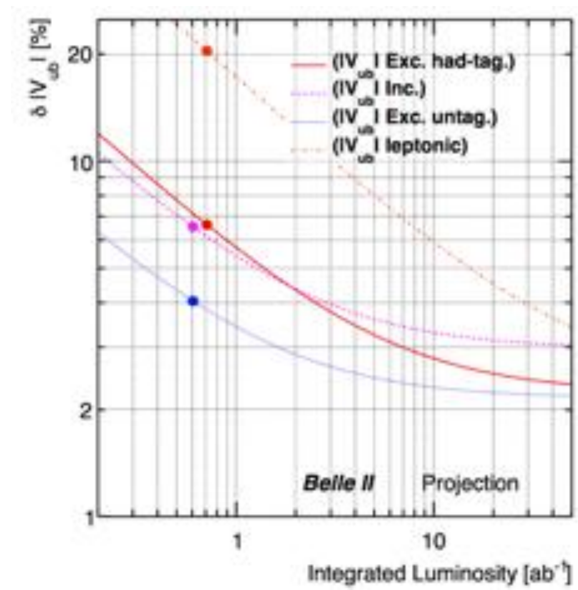
✓ Exclusive $B \to D^{(*)} \ell \nu$, $B \to \pi \ell \nu$

- Inclusive-Exclusive tension in both $|V_{cb}|$ and $|V_{ub}|$ still exist

		Measurements (10^{-3})	δV/V
2.8σ	**$|V_{ub}|$ Inc.**	4.49 ± 0.23	5%
	$|V_{ub}|$ Exc.	3.72 ± 0.16	4%
2.9σ	**$|V_{cb}|$ Inc.**	42.2 ± 0.8	2%
	$|V_{cb}|$ Exc.	39.2 ± 0.7	2%

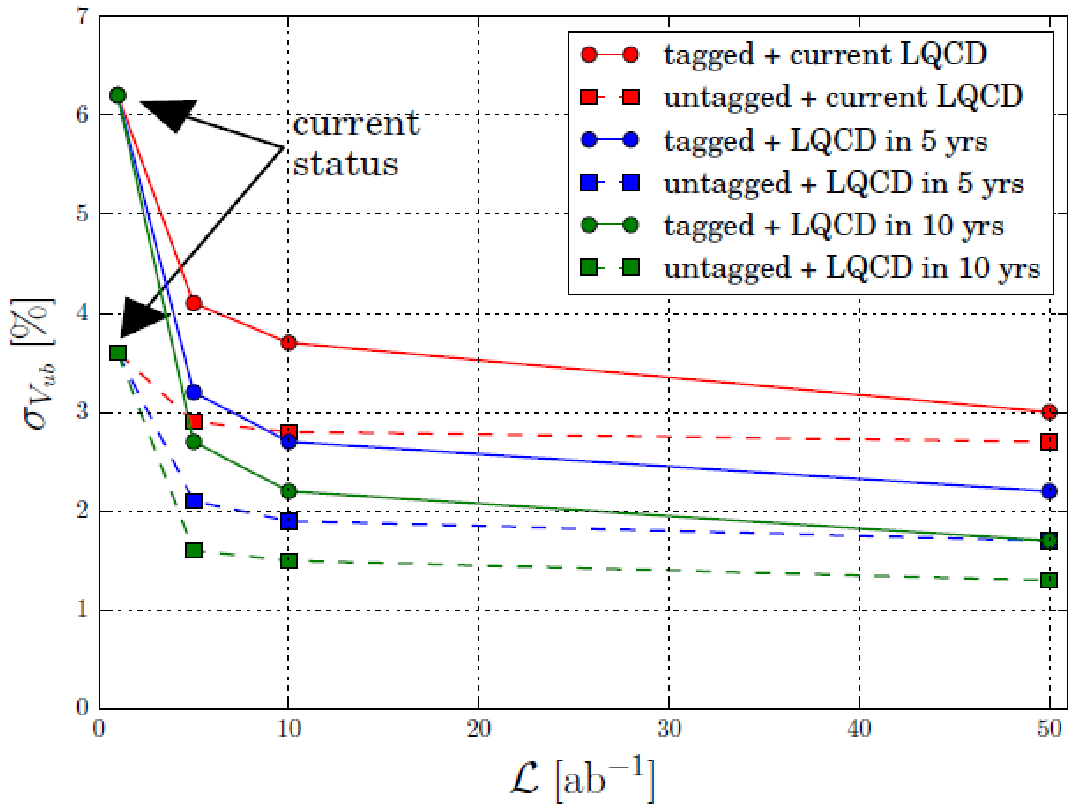
- Belle II will provide more precise measurements (B2TiP)





Belle II: $|V_{ub}|$ from $B \to \pi \ell \nu$

B2TiP Toy MC studies based on Belle II MC, LQCD forecasts estimated for 5, 10 and 50 ab^{-1}

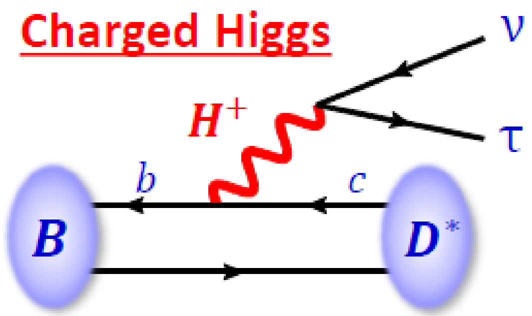


$\delta\|V_{ub}\|$ estimates for	5,	10,	50 ab^{-1}
Tagged:	3.2,	2.7,	1.7 %
Untagged:	2.1,	1.9,	1.3 %

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

New physics searches in $B \to D^{(*)}\tau\nu$ decay

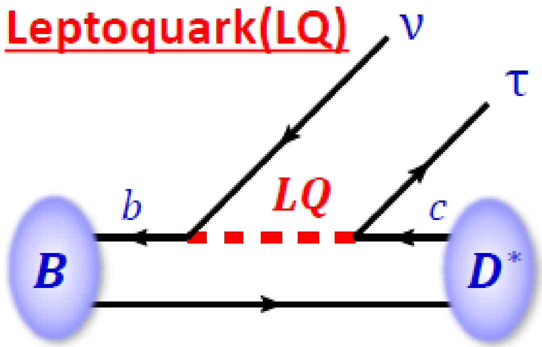
SM extensions - **enhanced coupling to the third generation**



New physics could change $\mathcal{B}$ and **τ polarization ($\mathcal{P}_\tau$)**

$$R(D^{(*)}) = \frac{\mathcal{B}\left(B \to D^{(*)}\tau\nu\right)}{\mathcal{B}\left(B \to D^{(*)}\ell\nu\right)} \qquad (\ell = e, \mu)$$

Uncertainties are largely cancelled:
V_{cb}, form factors, efficiency etc.



SM:

- $R(D)$ = 0.300 ± 0.008
  Fermilab Lattice and MILC Collaborations, Phys. Rev. D 92, 034506 (2015)
- $R(D^*)$ = 0.252 ± 0.003
  S. Fajfer, et al., Phys. Rev. D 85, 094025 (2012)
  - Belle, BaBar, and LHCb measured
- $\mathcal{P}_\tau(D^*)$ = −0.497 ± 0.013
  M. Tanaka, R. Watanabe, PRD 87, 034028 (2013)
  - Belle measured

Belle: *Phys. Rev. D 92, 072014 (**2015**)*

hadronic tag, leptonic τ decay : $\tau \to \ell\nu\nu$

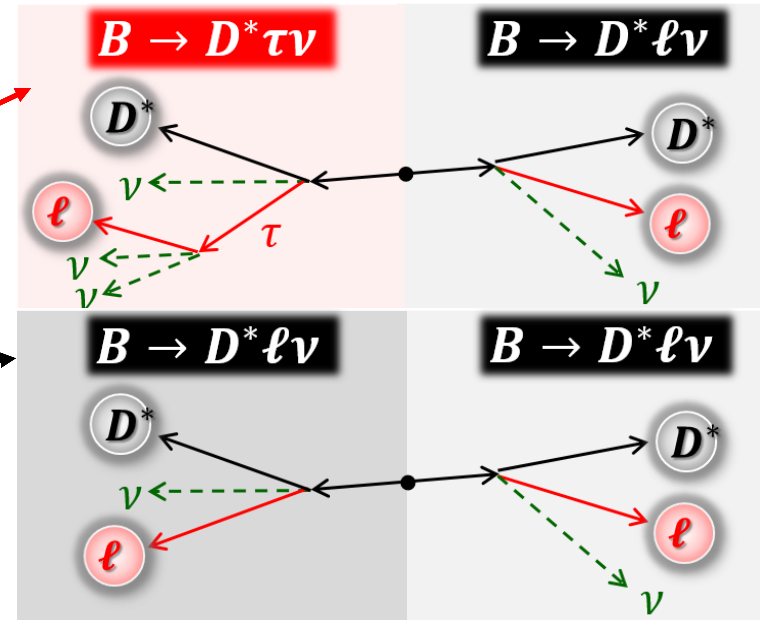
- $R(D)$ = 0.375 ± 0.064(stat.) ± 0.026(syst.)
- $R(D^*)$ = 0.293 ± 0.038(stat.) ± 0.015(syst.)

R(D)* with semileptonic tag

*Belle, Phys. Rev. D 94, 072007 (**2016**)*

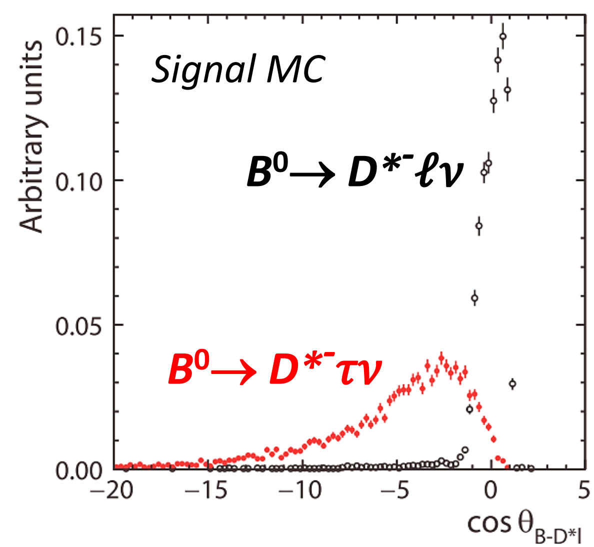
- "Clean" channels are only used to get high purity
  - leptonic τ decay : $\tau \to \ell \bar{\nu} \nu$
  - $B^0 \overline{B}^0 \to (D^{*-} \ell^+)\ (D^{*+} \ell^-)$ channel

- $R(D^*) = \dfrac{\textbf{signal}}{\textbf{normalization}}$



- Signal and normalization are tagged by double semileptonic tag.

- Signal/normalization separation based on smaller $\cos\theta_{B-D^*\ell}$



Signal extraction

*Belle, Phys. Rev. D 94, 072007 (**2016**)*

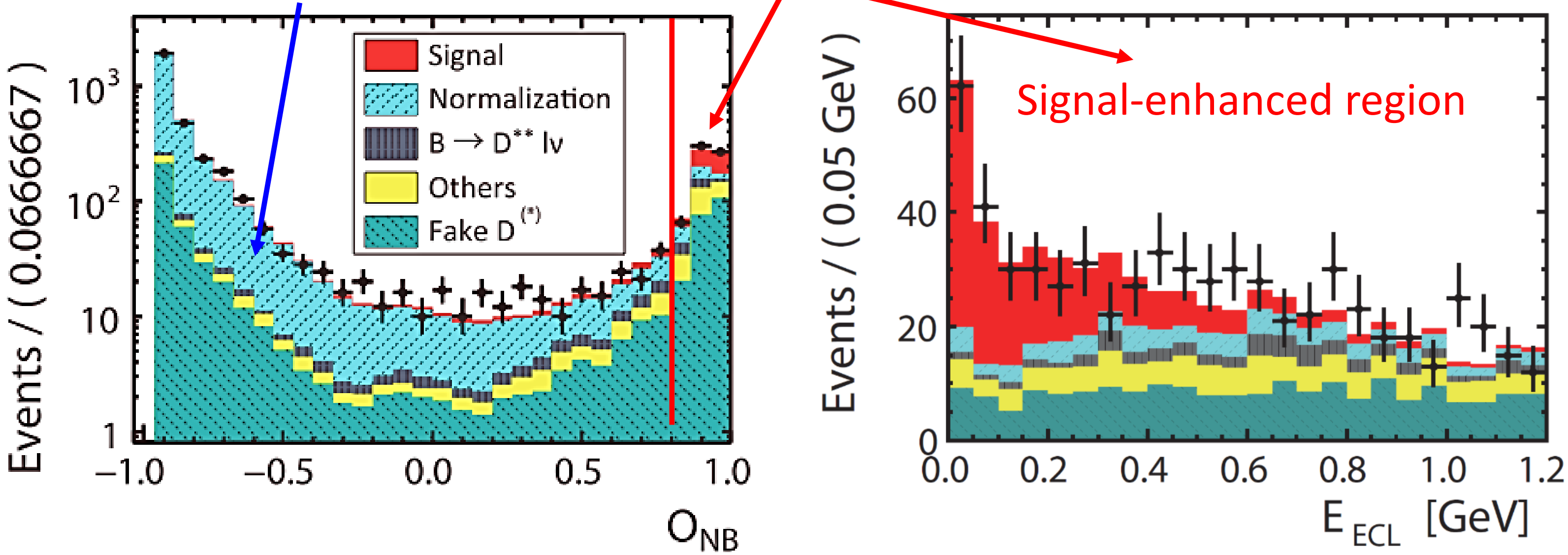
Two-dimensional fit to neural network output (O_{NB}) and E_{ECL}

- $\cos\theta_{B-D*\ell}$
- $M_{miss}{}^2$
- Total energy of $B_{tag}+B_{sig}$

Summed energy, not used for the event reconstruction

$\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$

$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$



$R(D^*) = 0.302 \pm 0.030(\text{stat.}) \pm 0.011(\text{syst.})$

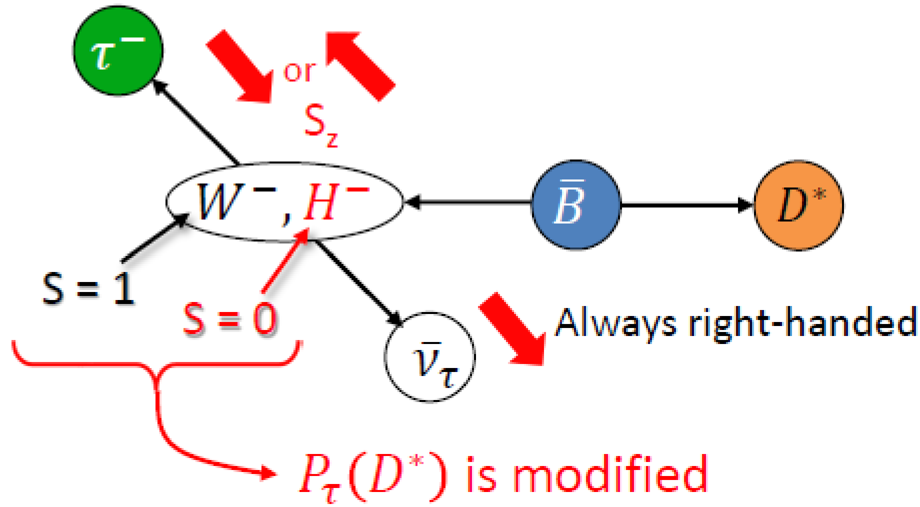
- ✓ 13.8 σ significance including syst. error.
- ✓ Compatibility with the SM is 1.6σ
- ✓ Consistent with other measurements

$R(D^*)$ and $\mathcal{P}_\tau(D^*)$ with hadronic τ decays

*Belle, Phys. Rev. Lett. 118, 211801 (**2017**)*

$$\mathcal{P}_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

$\Gamma^{+(-)}$ for right-(left-) handed τ



$\mathcal{P}_\tau(D^*)_{SM} = -0.497 \pm 0.013$
M. Tanaka and R. Watanabe,
Phys. Rev. D 87, 034028 (2013)

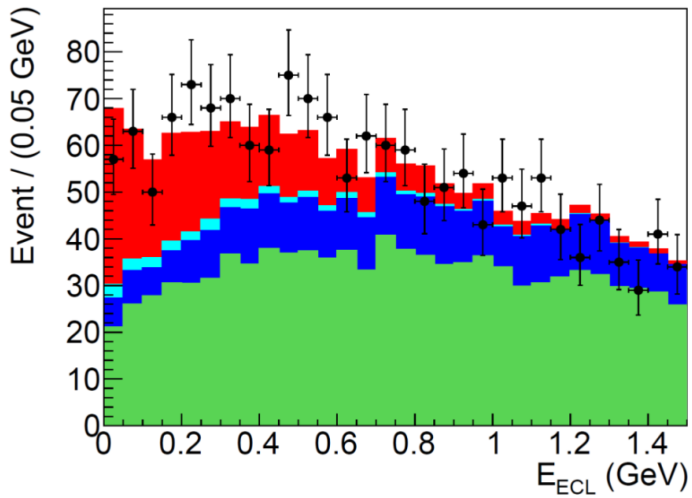
- τ polarization is a variable sensitive to NP
  - It can be measured using two-body decays of τ

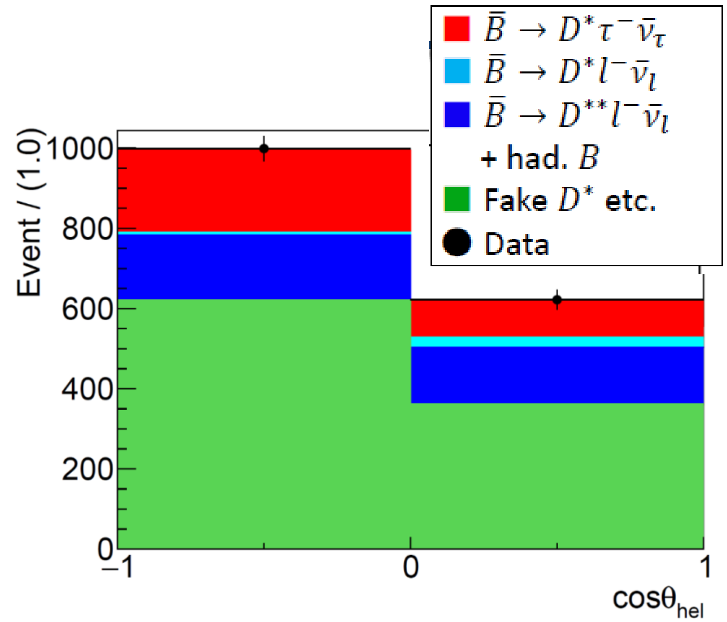
Target of this analysis

- First measurement of $\mathcal{P}_\tau(D^*)$ using $\tau^- \to \pi^- \nu_\tau$, $\rho^- \nu_\tau$
- New measurement of $R(D^*)$
  - Independent study of previous measurements using $\tau^- \to \ell^- \bar{\nu} \nu$

Different final state - different background

Results





Signal significance of about 7σ

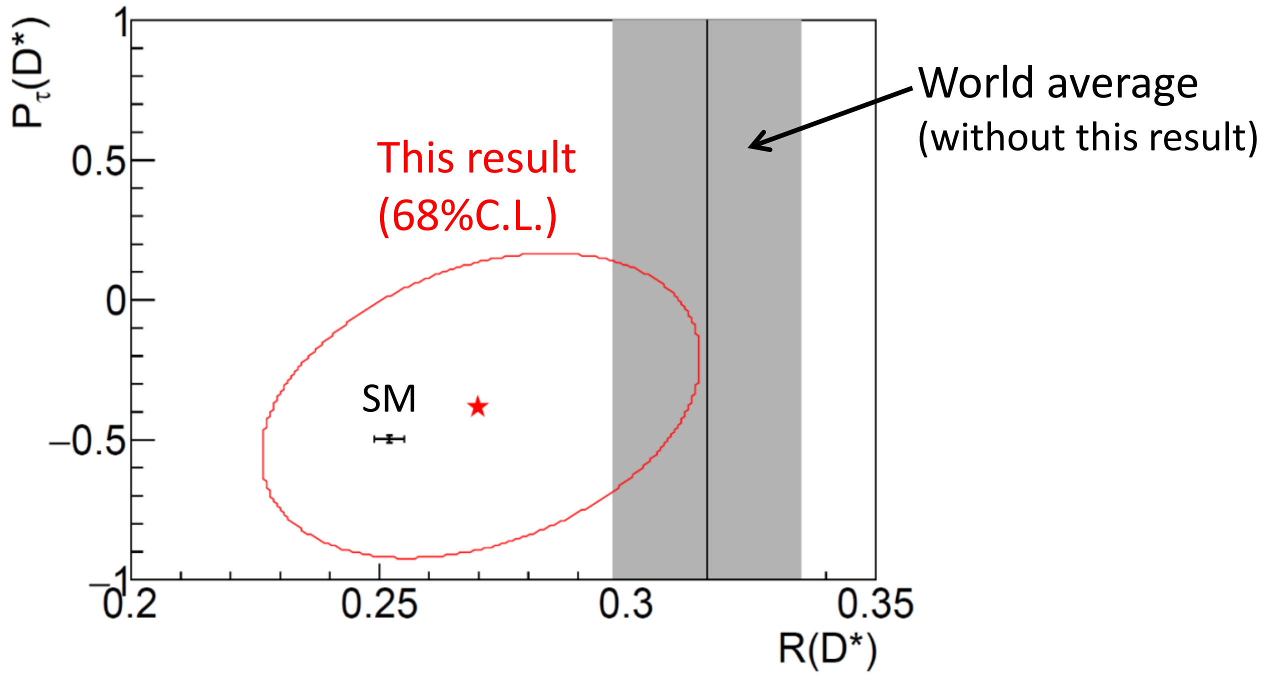
- First observation of the $B \to D^{*}\tau\nu$ signal using only hadronic τ decays

$$R(D^{*}) = 0.270 \pm 0.035(\text{stat.}) \,{}^{+0.028}_{-0.025}\,(\text{syst.})$$

$$\mathcal{P}_{\tau}(D^{*}) = -0.38 \pm 0.51(\text{stat.}) \,{}^{+0.21}_{-0.16}\,(\text{syst.})$$

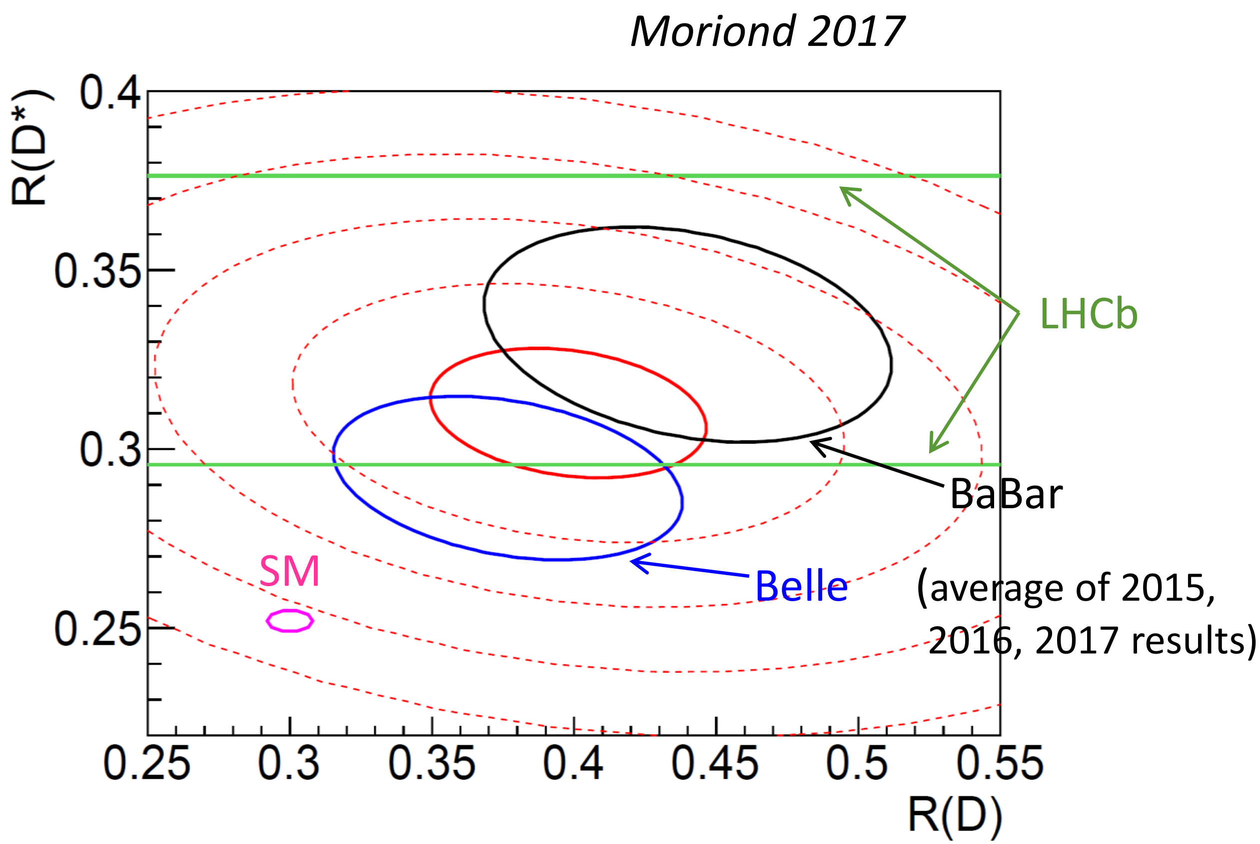
Compatibility with the SM within 0.4σ

Results *cont*



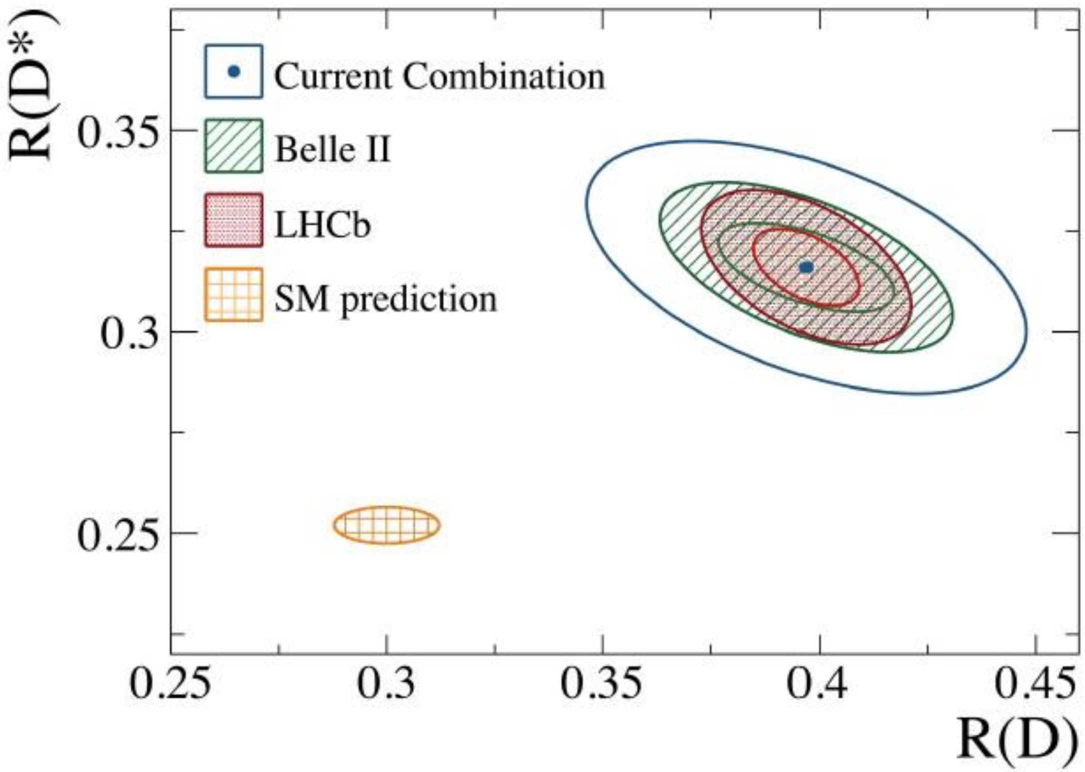
- Result is consistent with the SM within 0.4σ
- Excludes $\mathcal{P}_\tau(D^*) > +0.5$ at 90% C.L. $\longrightarrow$ *First measurement of $\mathcal{P}_\tau(D^*)$*
- First $R(D^*)$ measurement only with hadronic τ decays
  - Precision of 16%; comparable to the previous measurements (9-14%)

Status of $R(D^{(*)})$



- ~4σ discrepancy from the SM remains
  - All the experiments show the larger $R(D^{(*)})$ than the SM
- More precise measurements at Belle II and LHCb are essential

Future

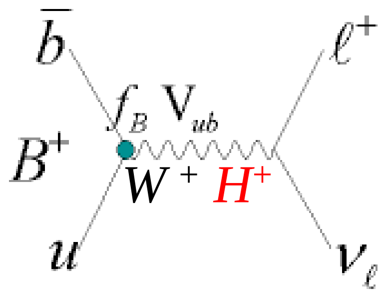


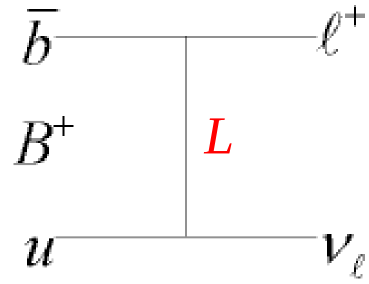
	Belle ~1/ab	Belle II 5/ab	Belle II 50/ab
$R(D)$	~15.8 %	5.6 %	3.2 %
$R(D^*)$	~6.9 %	3.9 %	2.2 %

$$B^+ \to \tau^+ \nu_\tau$$

$B^+ \to \tau^+ \nu_\tau$

(Decays with Large Missing Energy)





Sensitivity to NP

SM:

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

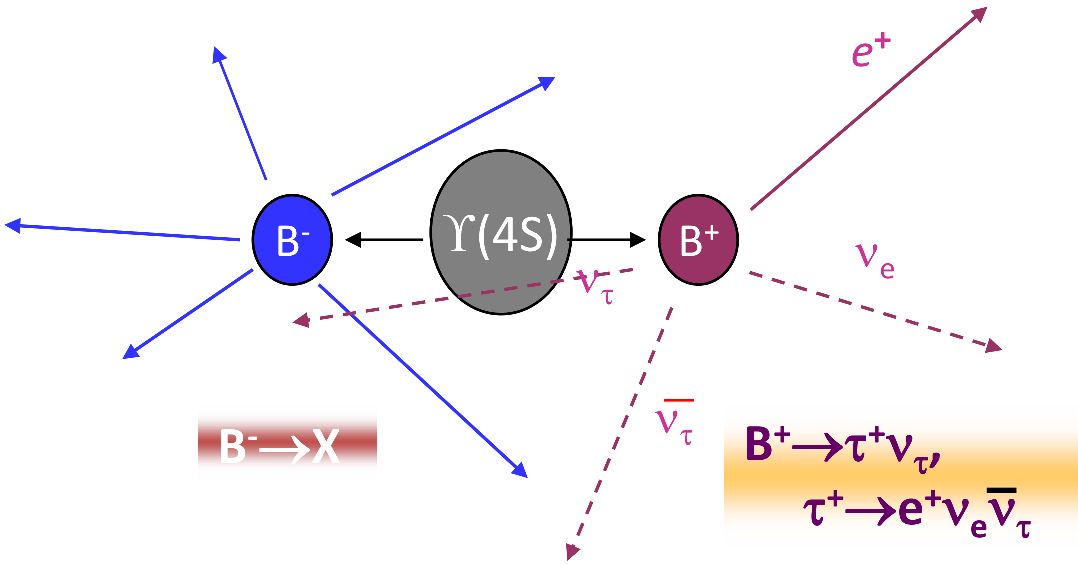
NP effects (2-Higgs doublet model (type II))

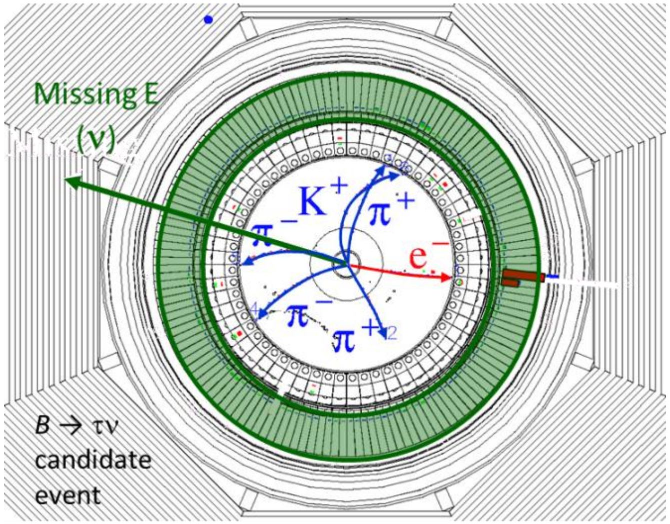
$$\mathcal{B}(B^+ \to \tau^+ \nu) = \mathcal{B}_{SM}(B^+ \to \tau^+ \nu) \times r_H$$

$$r_H = [1 - (m_B^2 / m_H^2) \cdot \tan^2\beta]^2$$

- very clean place to measure $f_B \cdot |V_{ub}|$ and/or search for new physics (e.g. H^+, LQ)
- helicity-suppressed: $\mathcal{B} \propto m_\ell^2$
  $\mathcal{B}(B^+ \to e^+ \nu) \ll \mathcal{B}(B^+ \to \mu^+ \nu) \ll \mathcal{B}(B^+ \to \tau^+ \nu)$
  ~ 10^{-11} ~ 10^{-6} ~ 10^{-4}
- experimental features $B^+ \to \tau^+ \nu_\tau$
  large BF, but multiple ν

$B \to \tau\nu$: Experimental Challenge



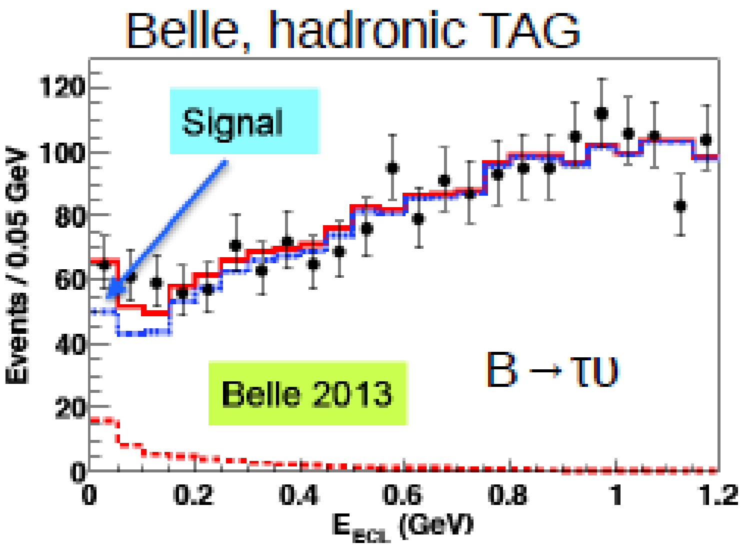


Always ≥ 2 neutrinos appear in B → τ ν decay

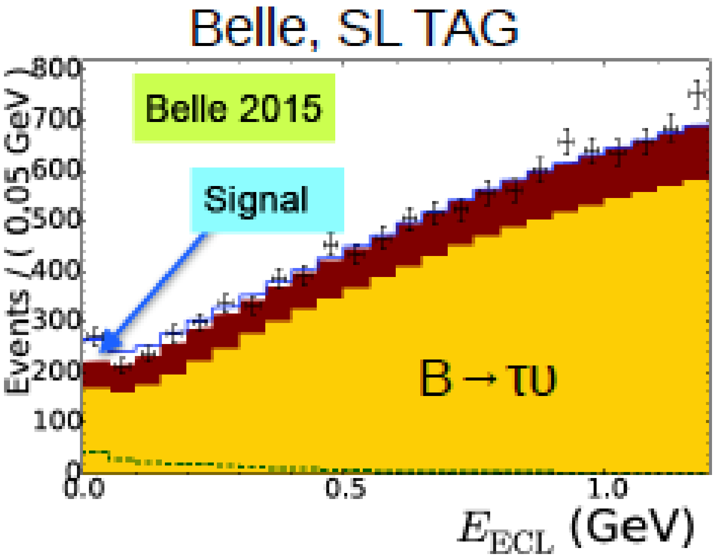
Signature : 1 track +invisible

Experimental Challenge !

Belle experimental results



Phys. Rev. Lett. 110, 131801 (2013)



Phys. Rev. D92, 051102 (R) (2015)

N_{sig} = $62^{+23}_{-22} \pm 6$ events

N_{sig} = 222 ± 50 events

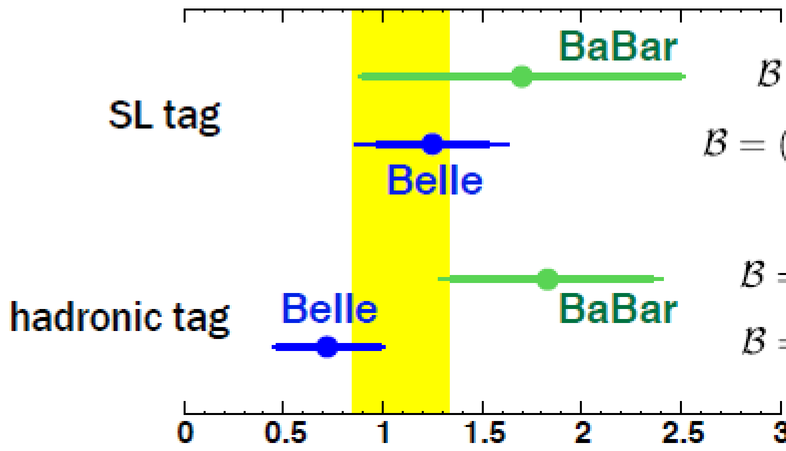
$\mathcal{B}(B^{+} \rightarrow \tau^{+} \nu) = (0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$

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

3σ significance

4.6σ significance

$B^+ \to \tau^+ \nu$ summary



Belle combined: $\mathcal{B}(B^+ \to \tau^+ \nu) = (0.91 \pm 0.22) \times 10^{-4}$

BaBar combined: $\mathcal{B}(B^+ \to \tau^+ \nu) = (1.79 \pm 0.48) \times 10^{-4}$

World average: $\mathcal{B}(B^+ \to \tau^+ \nu) = (1.09 \pm 0.24) \times 10^{-4}$

- Belle vs. BaBar – consistent within $\sim 1.7\sigma$
- The average is consistent with SM ($\mathcal{B}(B^+ \to \tau^+ \nu)_{SM} = (0.83 \pm 0.08) \times 10^{-4}$)

Prospect at Belle II

B2TiP

Semileptonic / Leptonic decays with τ final states:

Observable	Belle / LHCb Measurements	SM Prediction	Belle II 5/ab	Belle II 50/ab	LHCb 10/fb	LHCb 22/fb
R(D)	0.397 +/- 0.040 +/- 0.028	0.300 +/- 0.008	5.6%	3.2%	4%	2%
$R(D^*)$	0.316 +/- 0.016 +/- 0.010	0.252 +- 0.003	3.9%	2.2%	4%	2%
$R(\pi)$	1.05 +/- 0.51	0.641 +/- 0.016	19%	8%	-	-
$BF(B \to \tau \nu)$	(1.06+/- 0.19) x 10^{-4}	(0.83 +/- 0.08) x 10^{-4}	9%	4%	-	-

Summary

- $|V_{cb}|$ and $|V_{ub}|$ are measured at Belle with different methods

✓ Inclusive $B \to X_c \ell \nu$, $B \to X_u \ell \nu$, Hadronic tag, Semileptonic tag, Untagged

✓ Exclusive $B \to D^{(*)} \ell \nu$, $B \to \pi \ell \nu$

- Inclusive-Exclusive tension in both $|V_{cb}|$ and $|V_{ub}|$ still exist ($\sim 3\sigma$)

- $\sim 4\sigma$ discrepancy from the SM remains for the world average of $R(D^{(*)})$

✓ All the experiments show the larger $R(D^{(*)})$ than the SM

- The world average of $\mathcal{B}(B^+ \to \tau^+ \nu)$ is consistent with the SM

- The precision of these measurements will be improved by the Belle II experiment (factor ~2-3) (NP ?...)