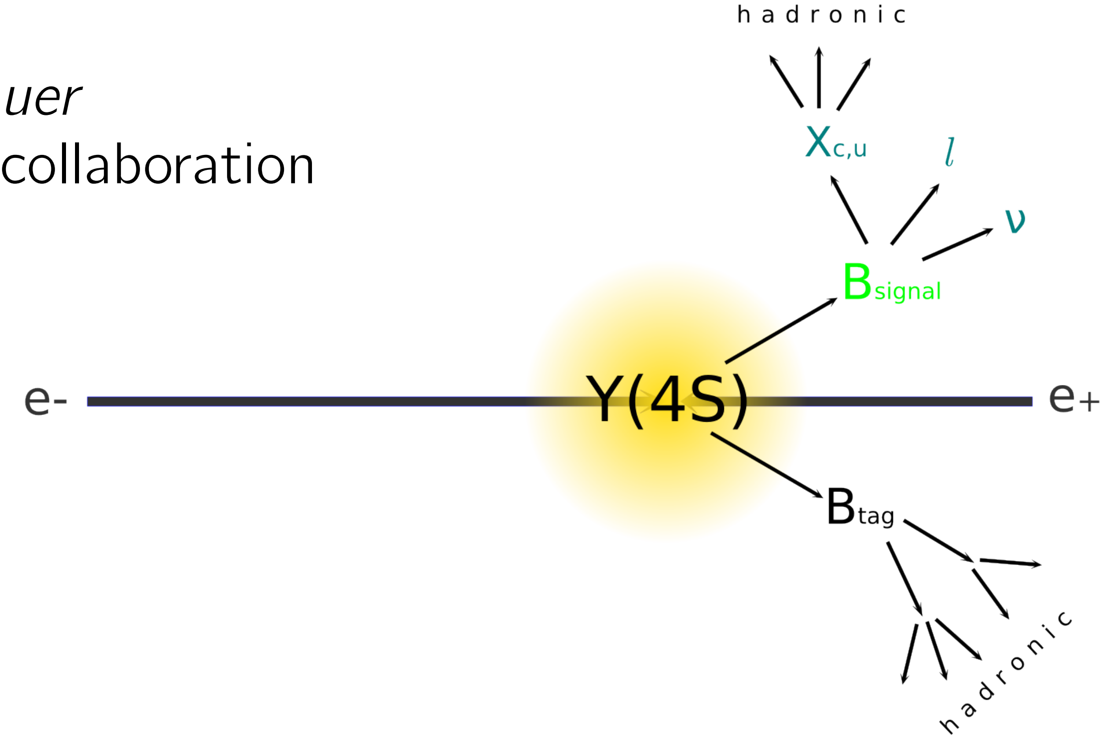
Semileptonic B decays and CKM elements V_{ub} and V_{cb} from Belle

Robin Glattauer
on behalf of the Belle collaboration



Funded by the Austrian Science Fund (FWF): P22742-N16

The Cabibbo-Kobayashi-Maskawa matrix

- Quarks: Weak eigenstates mixture of flavour eigenstates

$$-\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}}\, \overline{u_{Li}}\, \gamma^\mu\, (V_{\mathrm{CKM}})_{ij}\, d_{Lj}\, W_\mu^+ + \mathrm{h.c.}$$

- Allows for quark mixing
- Contains CP-violating phase

$$\mathrm{V}_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & \enclose{circle}{V_{ub}} \\ V_{cd} & V_{cs} & \enclose{circle}{V_{cb}} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

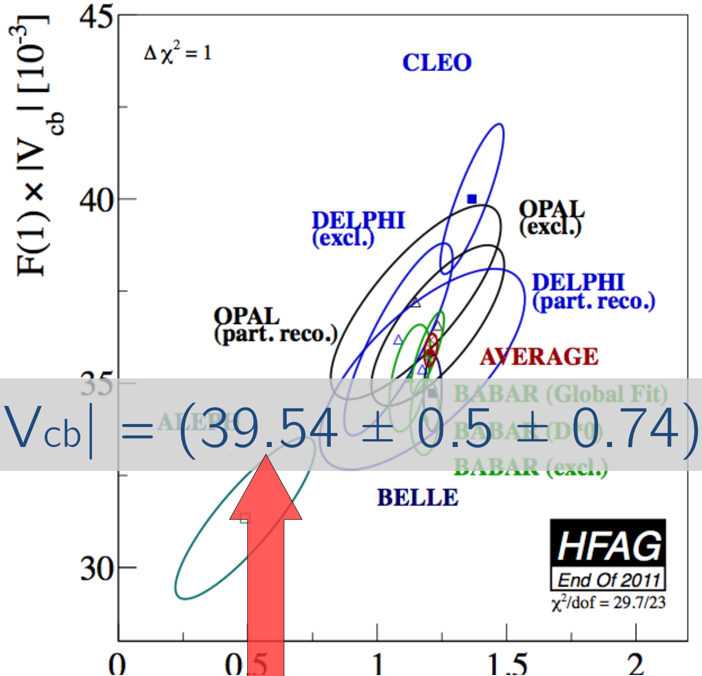
What we want to measure

Why still measure Vcb and Vub?

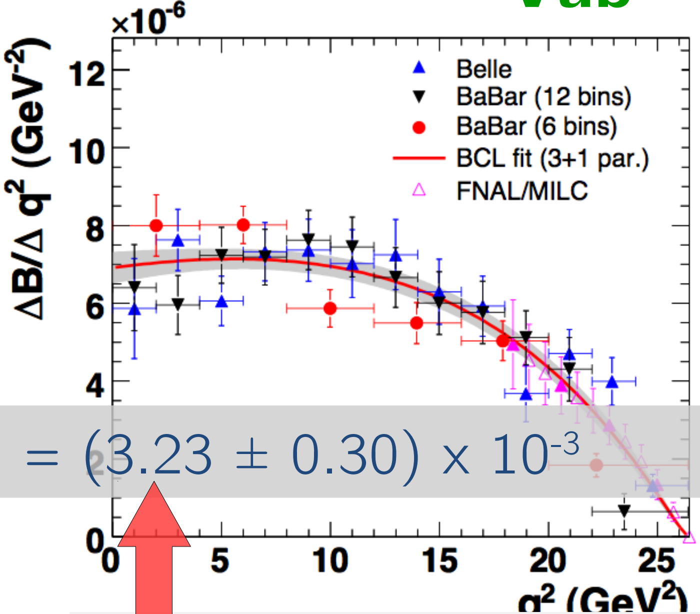
Vcb

Vub

exclusive

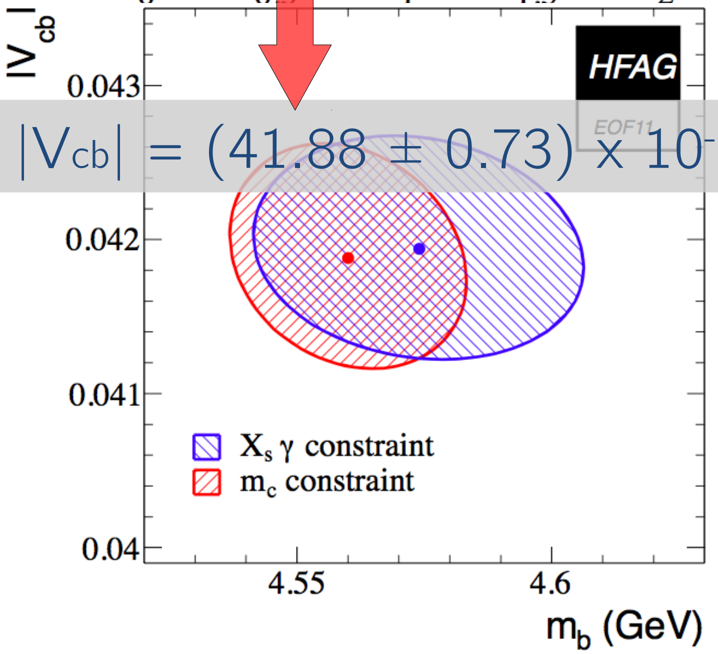


$|V_{cb}| = (39.54 \pm 0.5 \pm 0.74) \times 10^{-3}$

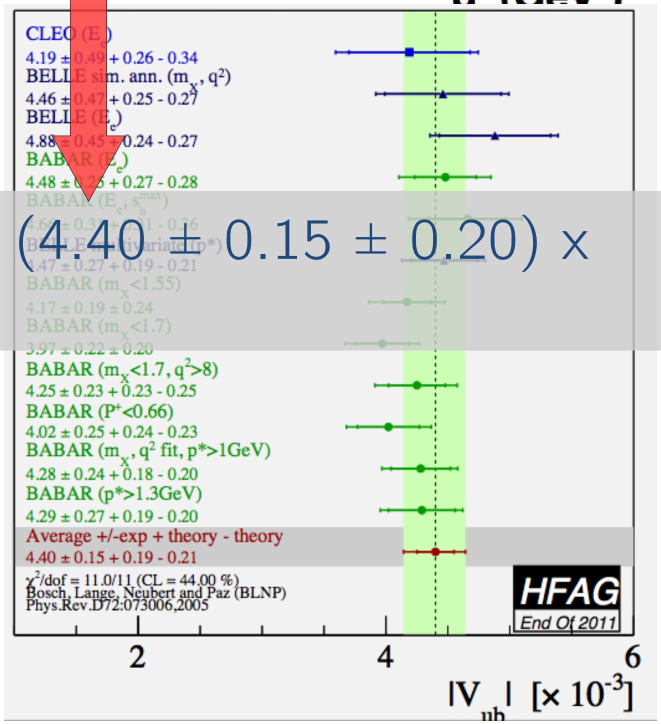


$|V_{ub}| = (3.23 \pm 0.30) \times 10^{-3}$

inclusive



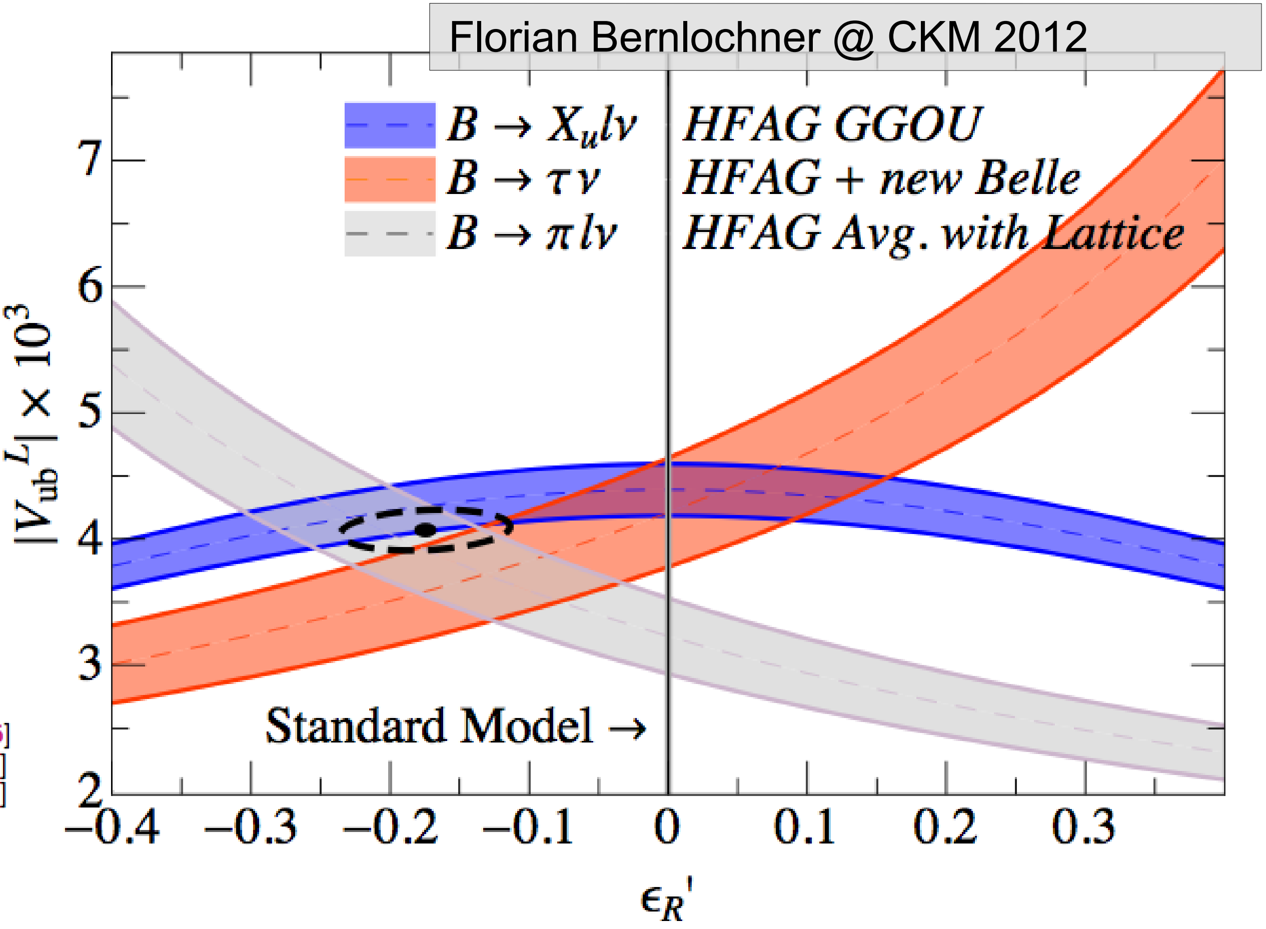
$|V_{cb}| = (41.88 \pm 0.73) \times 10^{-3}$



$|V_{ub}| = (4.40 \pm 0.15 \pm 0.20) \times 10^{-3}$

Reason for discrepancy?

- Experimental?
- Theory?
- New Physics?
    - e.g. right handed couplings


Florian Bernlochner @ CKM 2012

Proposed by
[hep-ph/0505166]
[arXiv:0907.2461]
[arXiv:1007.1993]

V_{cb} exclusive

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

- Accessing V_{cb} via differential decay rate:

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

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

$B \to D \ell \nu$

$$\frac{d\Gamma}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2 (w^2-1)^{3/2}\mathcal{G}^2(w)|\underline{V_{cb}}|^2$$

- w: 4-velocity product:

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

$$1.0 \leq w \lessapprox 1.6$$

zero recoil mass dependent limit

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

z-expansion

$$z = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

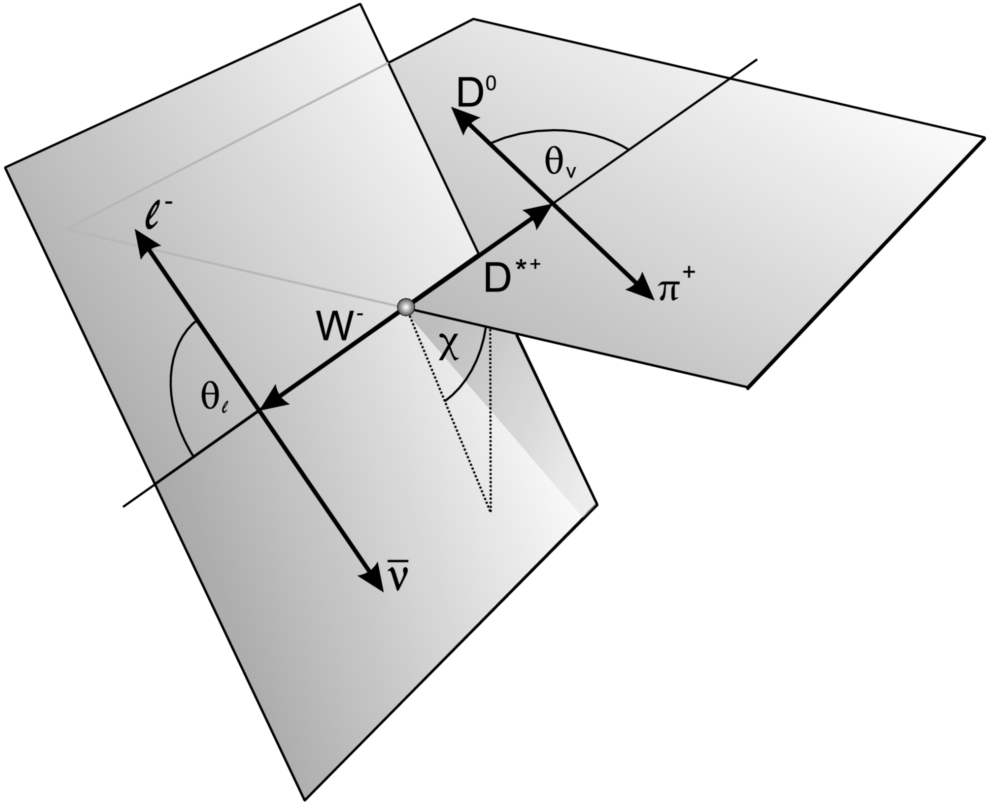
$$\mathcal{G}(w) = \underbrace{\mathcal{G}(1)}_{\text{from theory: LQCD / LCSR}}(1 - 8\rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3)$$

- Differential decay rate depends on
  - $V_{cb}\mathcal{G}(1)$
  - ρ
  - w
- For D* two parameters more are needed

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

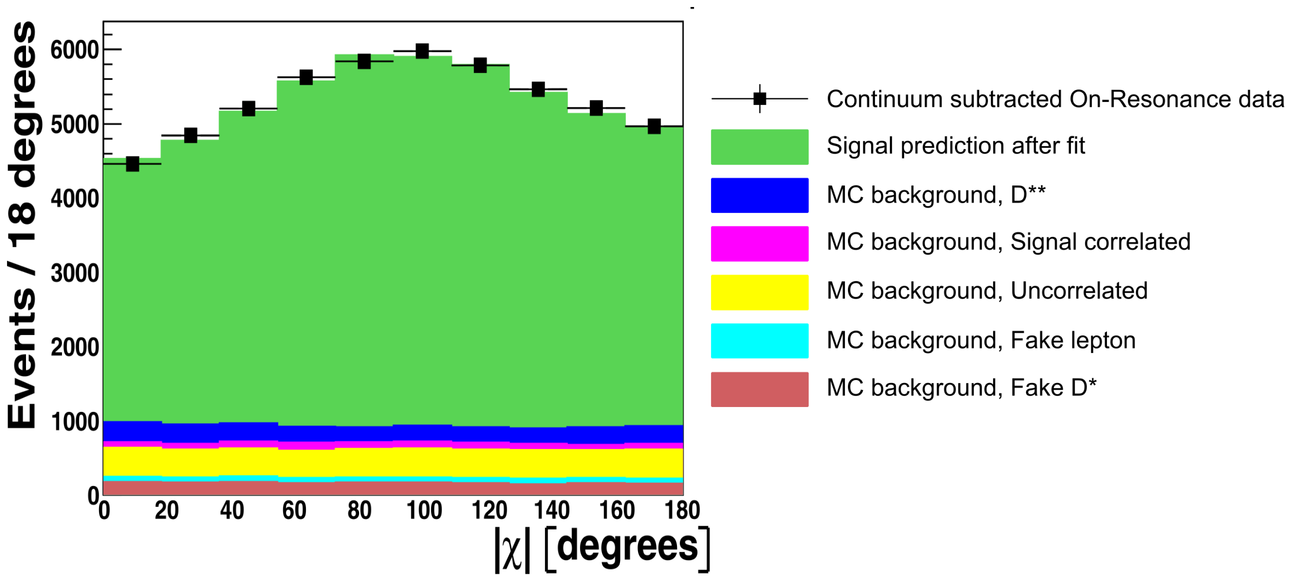
PRD 82.112007
(arXiv:1011.4397)

- Untagged analysis on full Belle data (772 10^6 $B\bar{B}$ pairs)
- Study: $D^{*-} \to \bar{D}^0 \pi^-$
  $\bar{D}^0 \to K^+ \pi^-$



- Simultaneous fits to
  - w
  - $cos(\theta_\nu)$
  - $cos(\theta_\ell)$
  - χ
- 4 parameters: fit projections

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



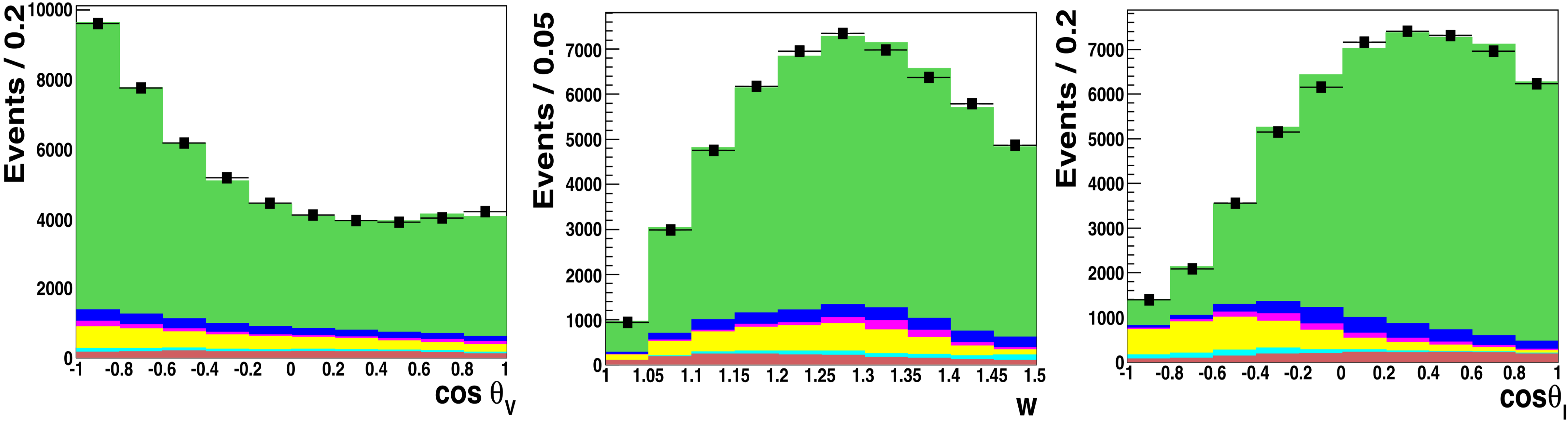
$$\mathcal{F}(1)|V_{cb}| = (34.6 \pm 0.2 \pm 1.0) \times 10^{-3}$$

$$\rho^2 = 1.214 \pm 0.034 \pm 0.009,$$

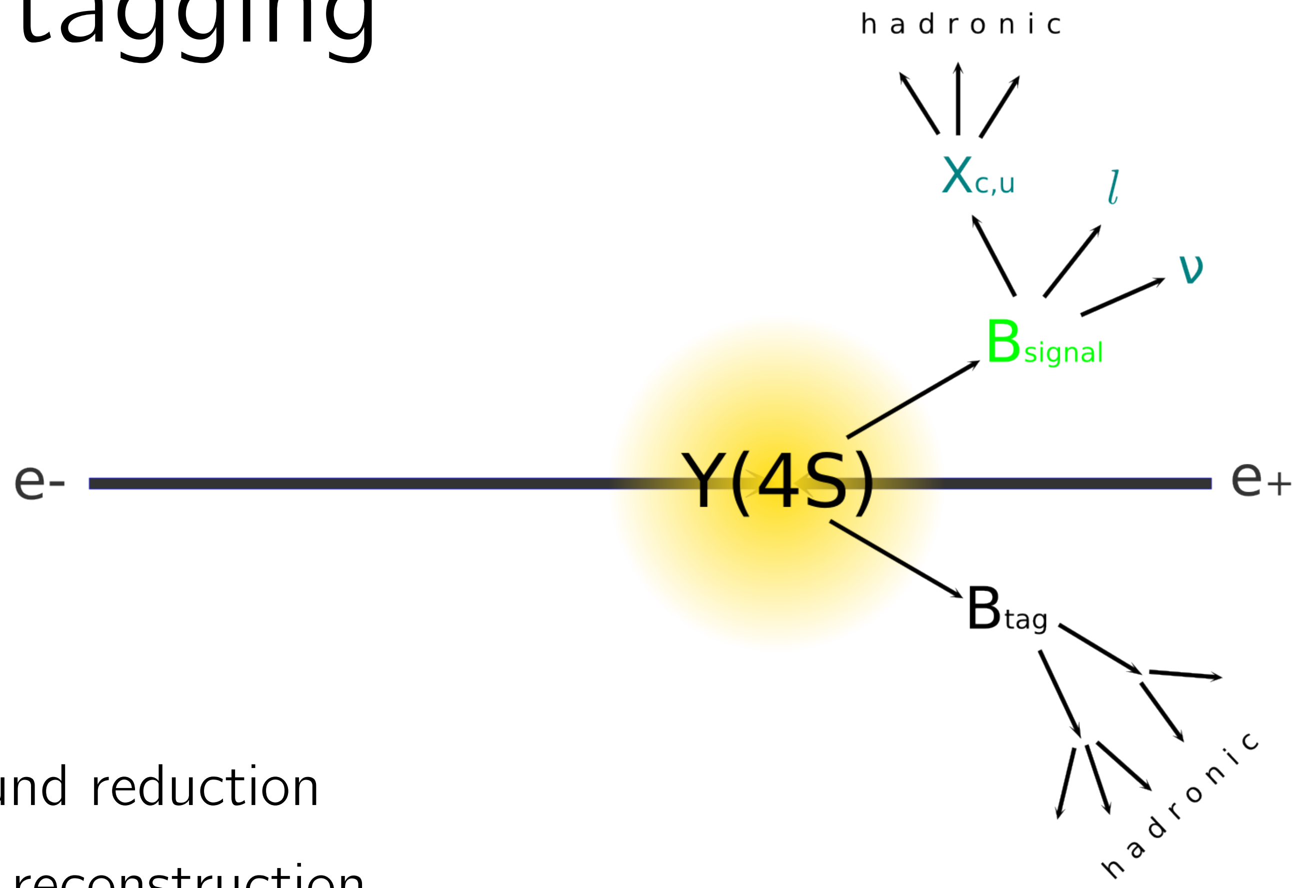
$$R_1(1) = 1.401 \pm 0.034 \pm 0.018,$$

$$R_2(1) = 0.864 \pm 0.024 \pm 0.008,$$

$$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (4.58 \pm 0.03 \pm 0.26)\%.$$



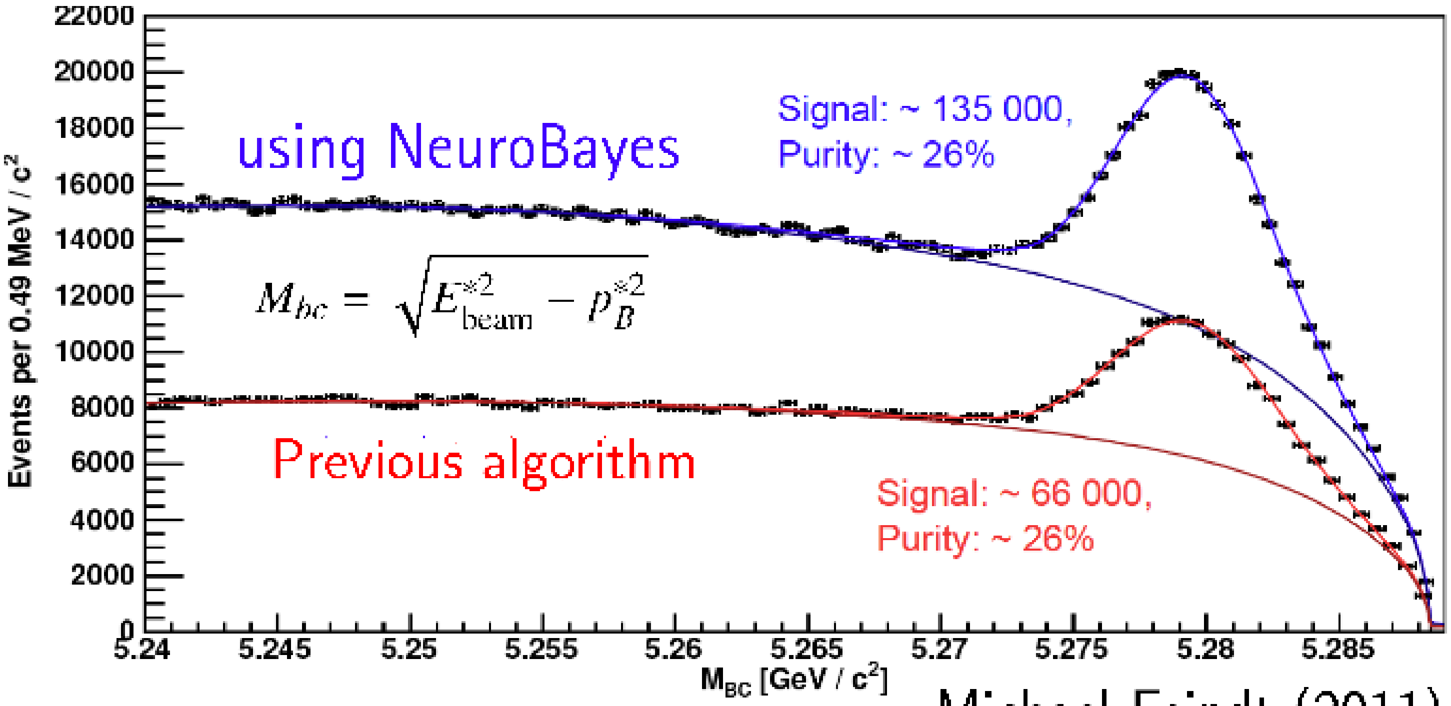
Hadronic tagging



- Benefits:
  - high background reduction
  - full kinematic reconstruction
  - $M^2_{\text{miss}} = [p(\text{Beam}) - (p(B_{\text{tag}}) + p(\text{visible}))]^2$
  - relevance for semileptonics: neutrino

New Belle hadronic tag

- Based on neural network
- >1100 exclusive hadronic decay channels
- 2x signal compared to previous cut based algorithm



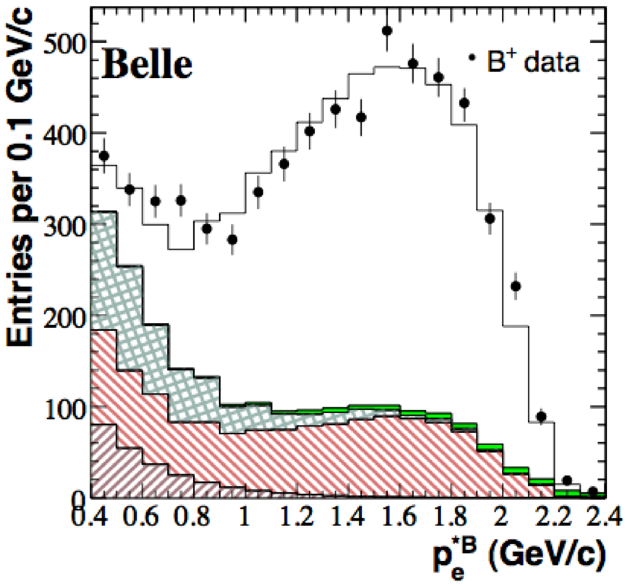
Michael Feindt (2011)

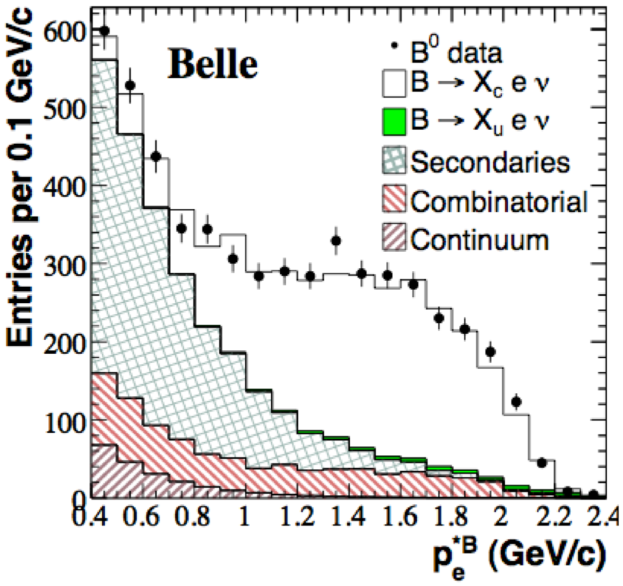
V_{cb} inclusive: Moments of E_l and M_X^2

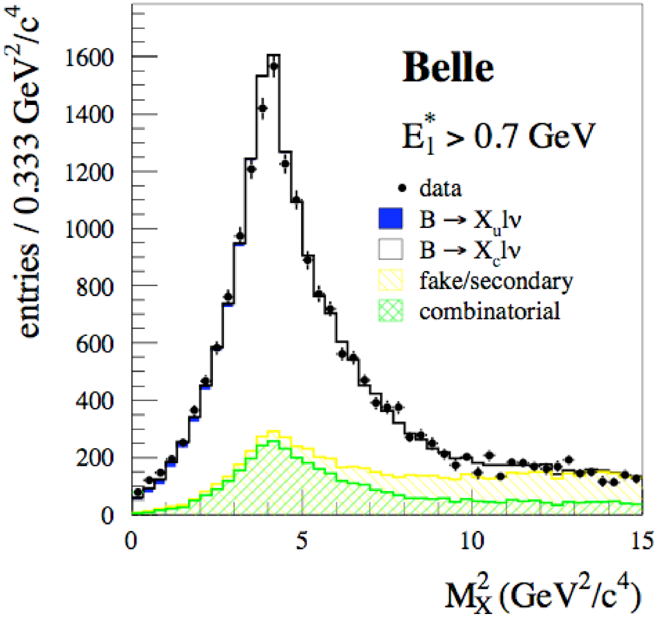
PRD 75, 032001 (arXiv:hep-ex/0610012)

PRD 75, 032005 (arXiv:hep-ex/0611044)

- $B \to X_c \ell \nu$
- $140\,\text{fb}^{-1}$ of Y(4S) data; use hadronic tagging
- Measured:
  - $\langle E_e \rangle, \langle (E_e - \langle E_e \rangle)^n \rangle; n = 2, 3, 4$ $\quad E_{\min} = 0.4 - 2.0\,\text{GeV}$
  - $\langle M_X^2 \rangle, \langle (M_X^2 - \langle M_X^2 \rangle)^2 \rangle, \langle M_X^4 \rangle$ $\quad E_{\min} = 0.7 - 1.9\,\text{GeV}$
  - Decay rates







V_{cb} inclusive: fit

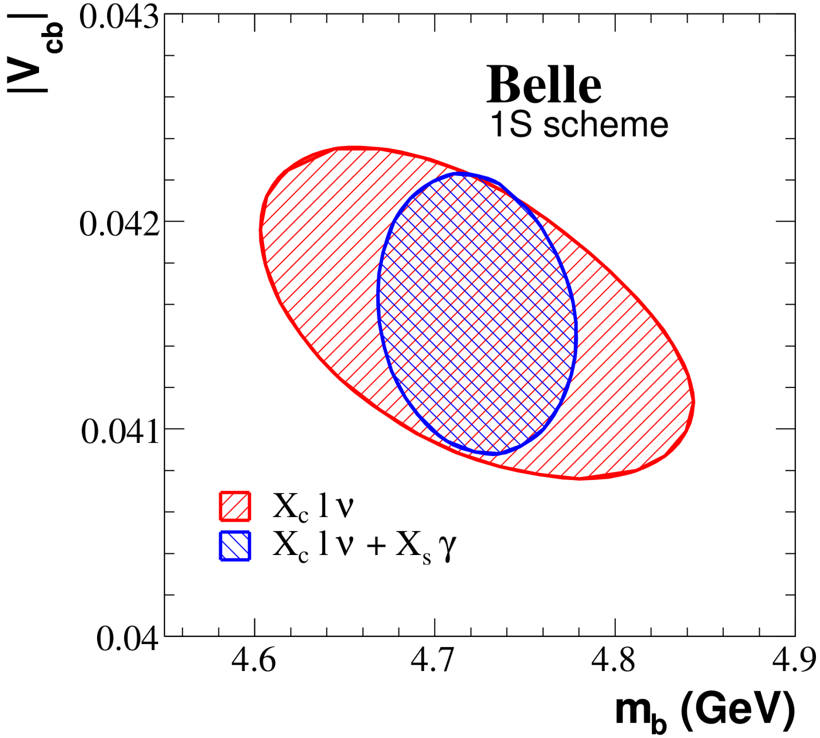
PRD 78, 032016
(arxiv: 0803.2158)

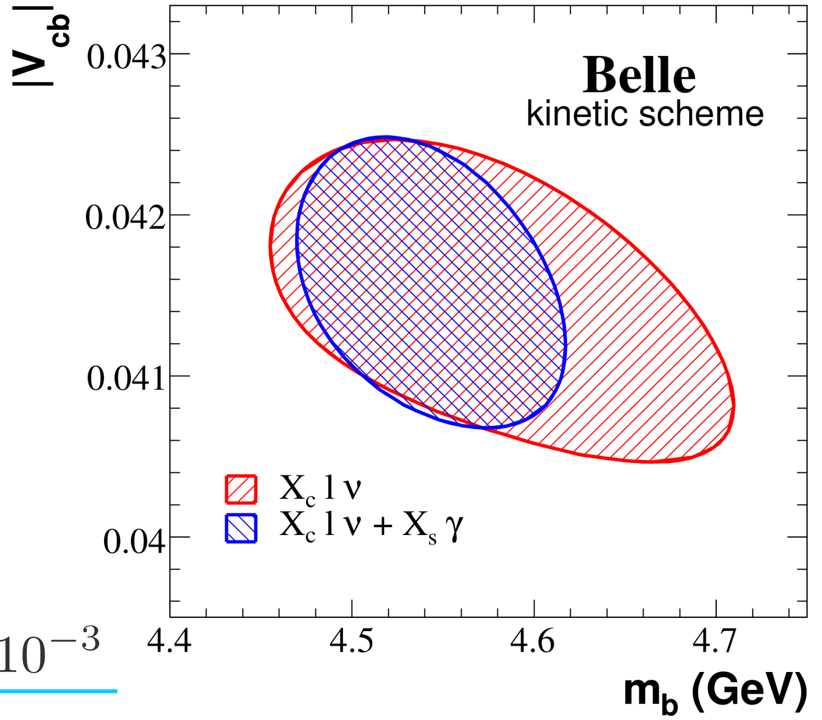
- Theory:
  - Operator Product Expansion (OPE)
  - Heavy Quark Effective Theory (HQET)
  - Predicts: decay rates and spectral momenta
- Use: $B \to X_c \ell \nu$ and $B \to X_s \gamma$
- b-mass:
  - 1S mass scheme (relating to Υ(1S) mass), or
  - kinetic mass scheme (relating to E_{kin})
- Result:
  - 1S:

$$|V_{cb}| = (41.56 \pm 0.68(\text{fit}) \pm 0.08(\tau_B)) \times 10^{-3}$$

  - kinetic:

$$|V_{cb}| = (41.58 \pm 0.69(\text{fit}) \pm 0.08(\tau_B) \pm 0.58(\text{th})) \times 10^{-3}$$





Institute of High Energy Physics

V_{cb} inclusive fit: more experiments, updated theory

Gambino and Schwanda
Submitted to PRD
(arXiv:1307.4551)

- Input from: Belle, BaBar, CDF, CLEO, DELPHI
- Use updated theoretical predictions:
  - Reassess theoretical uncertainties
  - Use additional constraints (e.g. m_c values)
  - Include NNLO perturbative corrections
- Result: $|V_{cb}| = (42.42 \pm 0.86) \times 10^{-3}$

V_{ub} exclusive

PRD 88, 032005
(arxiv: 1306.2781)

- Use full Belle data sample (772 x10^6B$\overline{\text{B}}$ pairs)
- Use hadronic tagging
- Study the channels:

$$\left.\begin{array}{l} \left.\begin{array}{l} B^- \to \pi^0 \ell^- \bar{\nu}_\ell \\ \bar{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell \end{array}\right\} |V_{ub}| \\ B^- \to \rho^0 \ell^- \bar{\nu}_\ell \\ \bar{B}^0 \to \rho^+ \ell^- \bar{\nu}_\ell \\ B^- \to \omega \ell^- \bar{\nu}_\ell \end{array}\right\} \text{branching fractions}$$

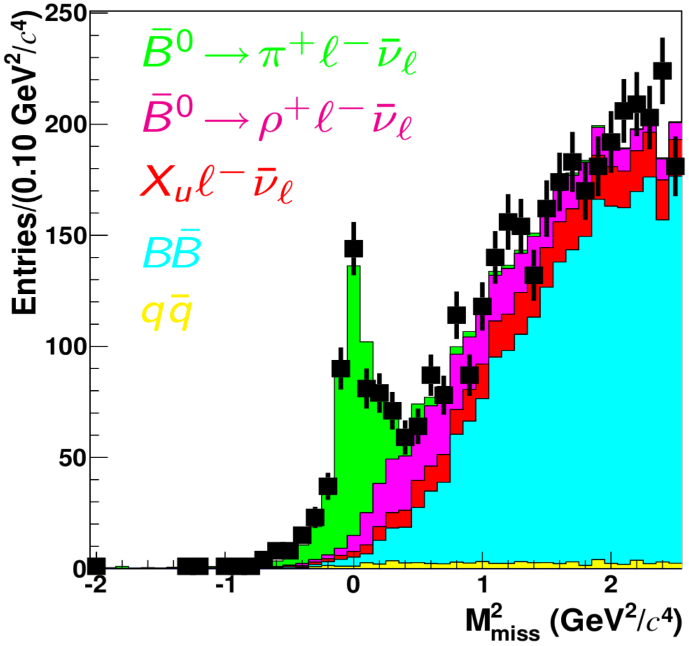
- Accessing V_{ub} via differential decay rate

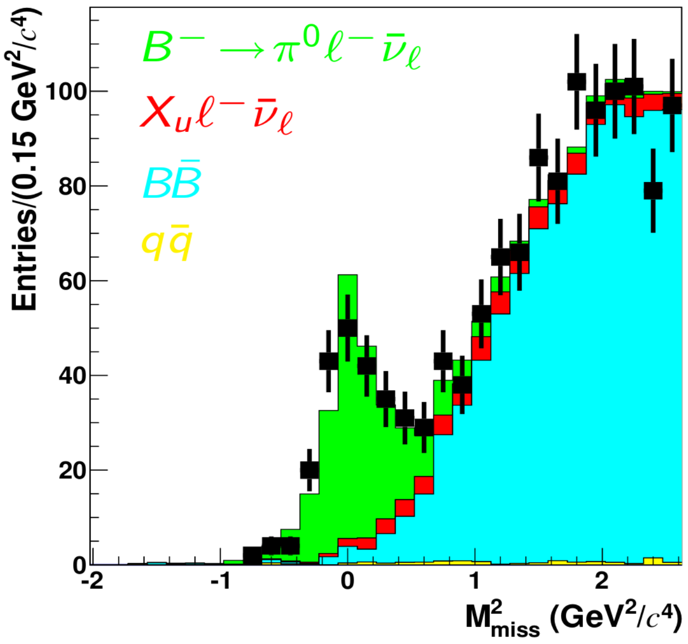
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} = \frac{G_F^2}{24\pi^3}|V_{ub}|^2 \left|f_+(q^2)\right|^2 |\vec{p}_\pi|^3 .$$

$$f_+(q^2,\vec{b}) = \frac{1}{1-q^2/m_{B^*}^2}\sum_{k=0}^{K} b_k(t_0)\, z(q^2)^k$$

(see Bourrely, Lellouch and Caprini PRD 79, 013008)

$B \to \pi \ell \bar{\nu}_\ell$





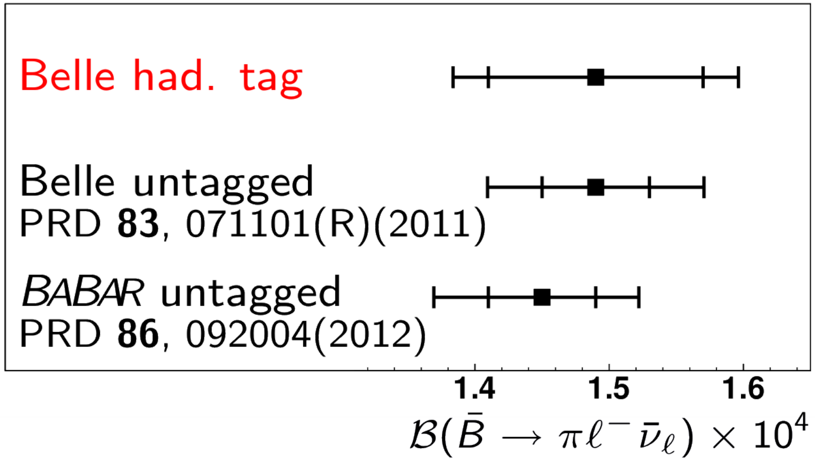
X_u	Yield	$\mathcal{B} \times 10^4$
π^+	462.6±27.7	$1.49 \pm 0.09 \pm 0.07$
π^0	232.2±22.6	$0.80 \pm 0.08 \pm 0.04$

Test of isospin symmetry:

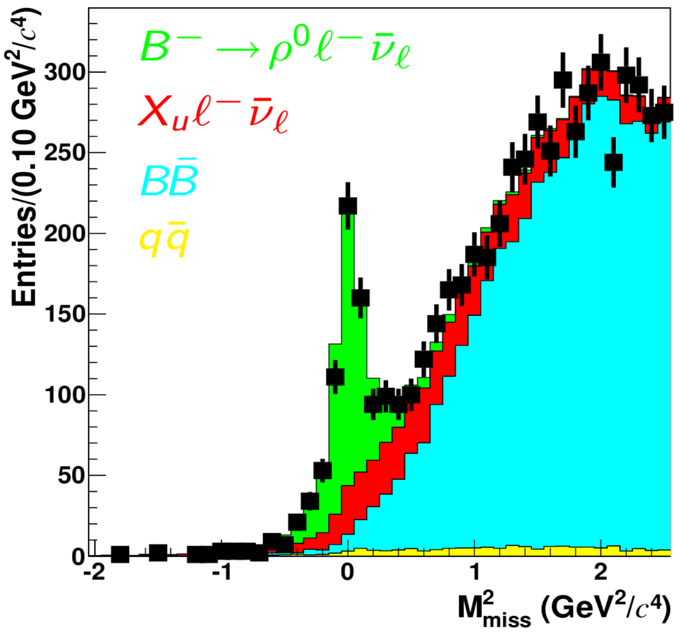
$$2 \times \frac{\mathcal{B}(B^- \to \pi^0 \ell^- \bar{\nu}_\ell)}{\mathcal{B}(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell)} \frac{\tau_{B^0}}{\tau_{B^+}} = 1.00 \pm 0.13$$

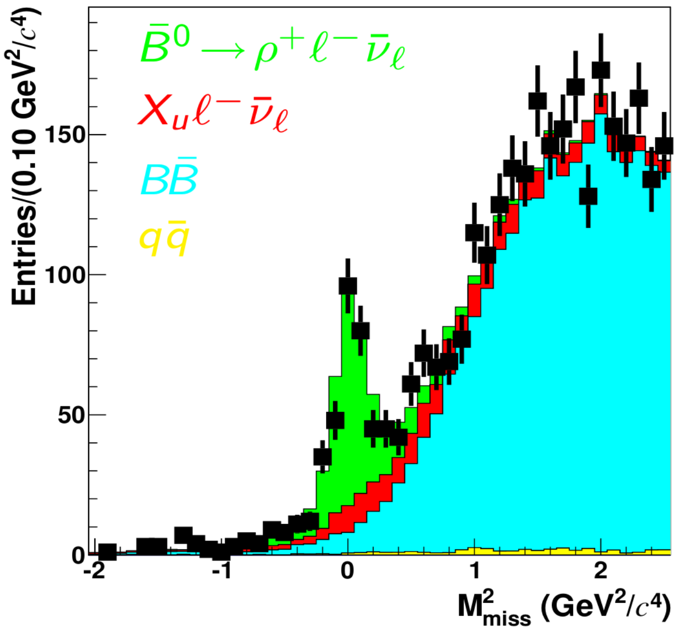
Combined branching fraction:

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



$B \to \rho \ell \bar{\nu}_\ell$





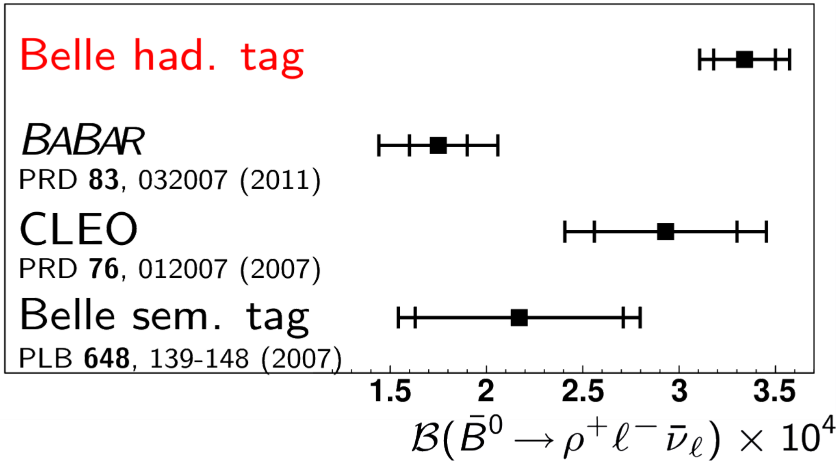
X_u	Yield	$\mathcal{B} \times 10^4$
ρ^+	343.3±28.3	$3.22 \pm 0.27 \pm 0.24$
ρ^0	621.7±35.0	$1.83 \pm 0.10 \pm 0.10$

Test of isospin symmetry:

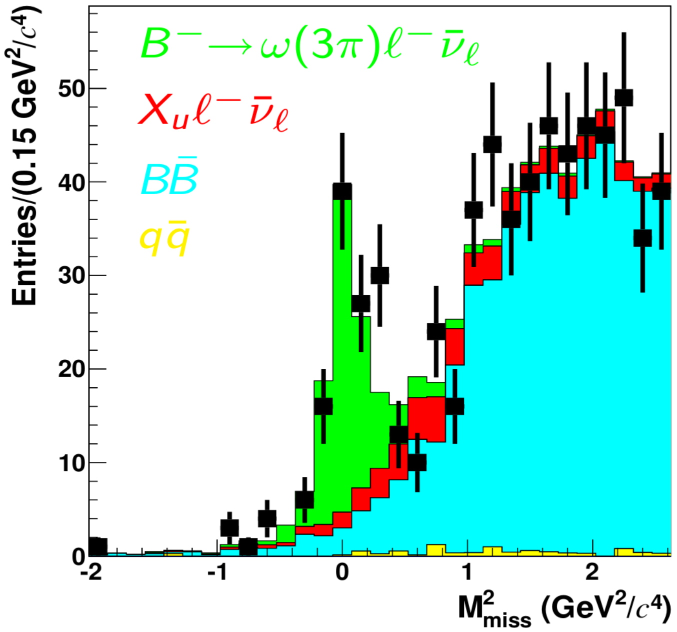
$$2 \times \frac{\mathcal{B}(B^- \to \rho^0 \ell^- \bar{\nu}_\ell)}{\mathcal{B}(\bar{B}^0 \to \rho^+ \ell^- \bar{\nu}_\ell)} \frac{\tau_{B^0}}{\tau_{B^+}} = 1.06 \pm 0.13$$

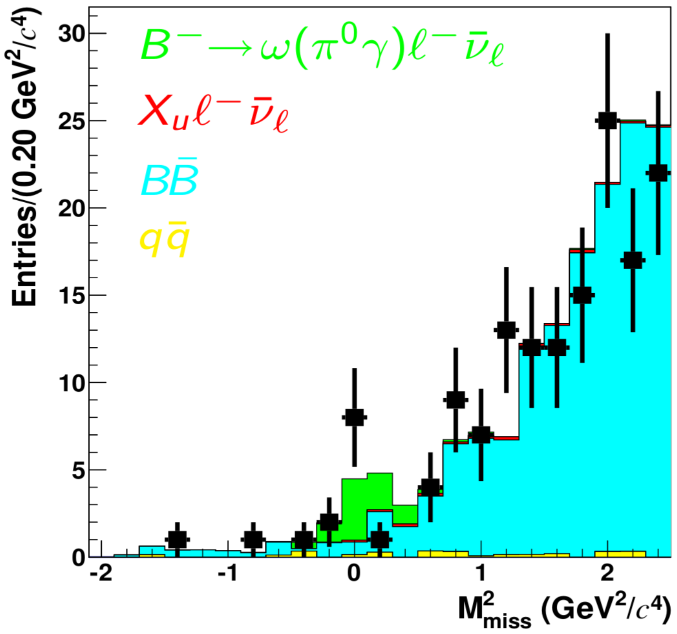
Combined branching fraction:

$$\mathcal{B}(\bar{B} \to \rho \ell^- \bar{\nu}_\ell) = (3.34 \pm 0.16_{\mathrm{stat}} \pm 0.17_{\mathrm{syst}}) \times 10^{-4}$$

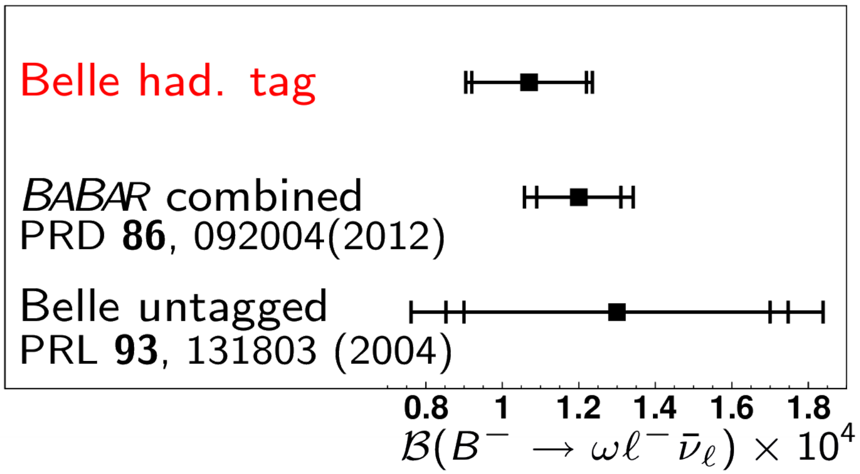


$B \to \omega \ell \bar{\nu}_\ell$



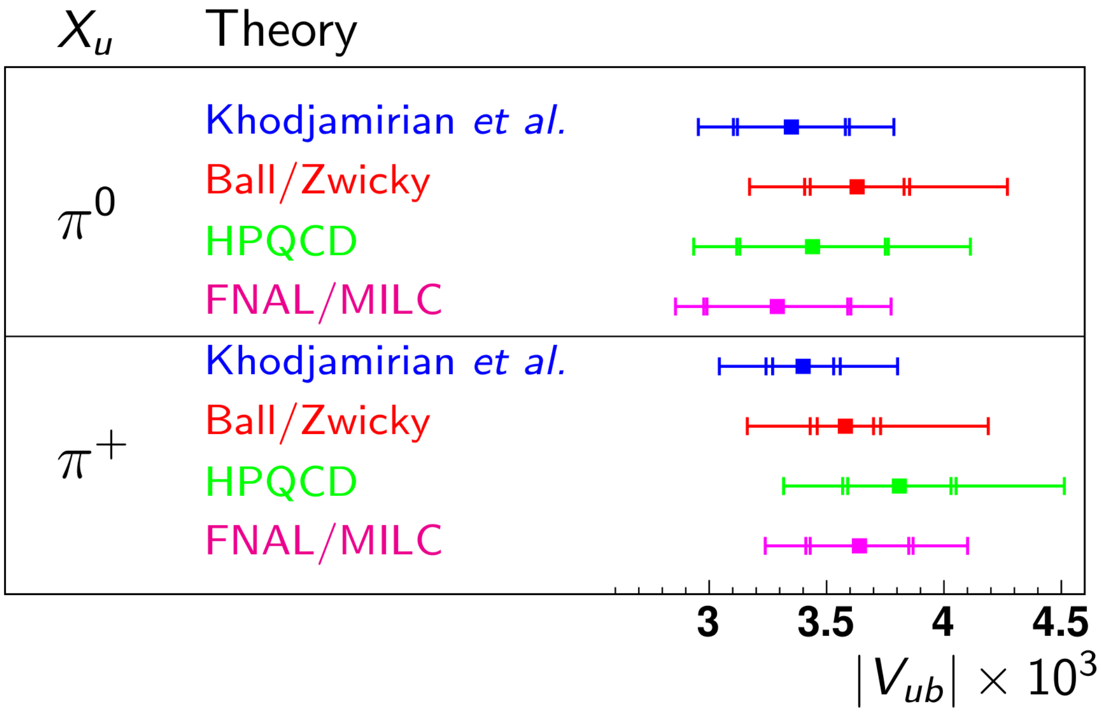


X_u	Yield	$\mathcal{B} \times 10^4$
$\omega(3\pi)$	96.7±14.5	$1.07 \pm 0.16 \pm 0.07$
$\omega(\pi\gamma)$	9.0±4.0	$1.06 \pm 0.47 \pm 0.07$



Vub from $B \to \pi\ell\bar{\nu}_\ell$

- $|V_{ub}| = \sqrt{\dfrac{C_v \Delta\mathcal{B}}{\tau_B \Delta\zeta}}$
  partial branching fraction
  normalized decay width($\Delta\zeta = \int \mathrm{d}\Gamma/|V_{ub}|^2$)
- Different q² regions for LQCD (high q²) and LCSR (low q²)



Khodjamirian *et al.*
PRD **83**, 094031 (2011)

Ball/Zwicky
PRD **71**, 014015 (2005)
PRD **71**, 014029 (2005)

HPQCD
PRD **73**, 074502 (2006)

FNAL/MILC
PRD **79**, 054507 (2009)

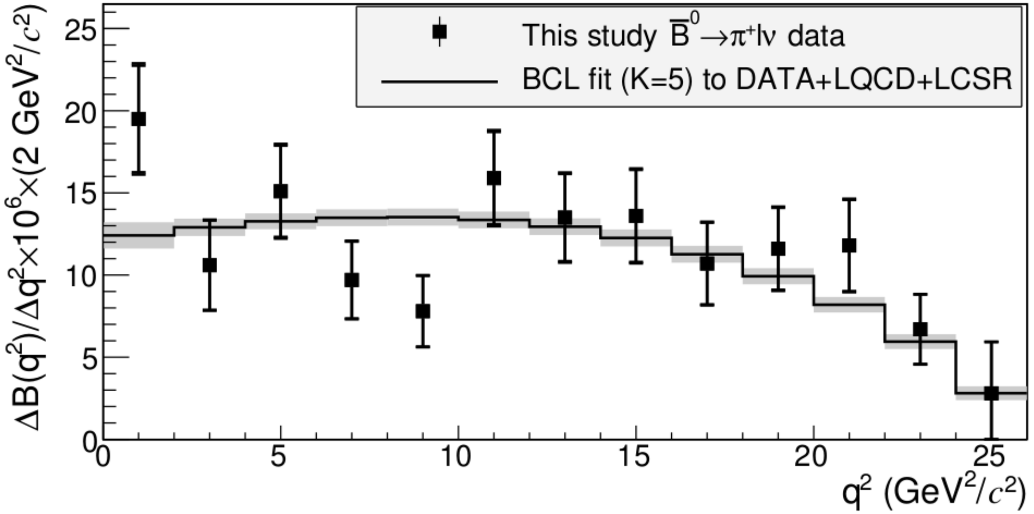
Vub from $B \to \pi \ell \bar{\nu}_\ell$ model independent

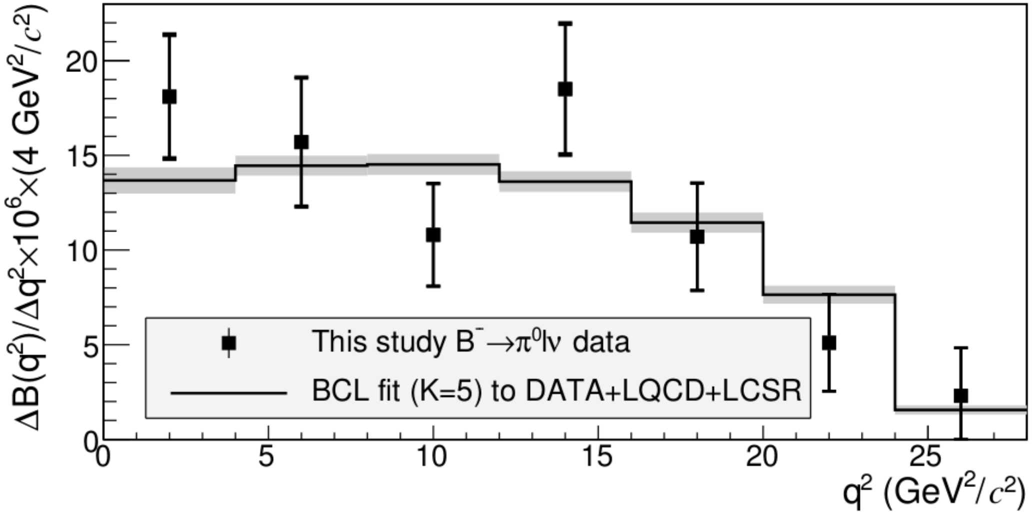
- Fit prediction and signal yield simultaneously

$$\chi^2 = \chi^2_{\bar{B}\to\pi\ell^-\bar{\nu}_\ell} + \chi^2_{\mathrm{LCSR}} + \chi^2_{\mathrm{LQCD}}.$$

$$\chi^2_{\bar{B}\to\pi\ell^-\bar{\nu}_\ell} = \sum_{i,j} \delta\mathcal{B}_i (C^{\mathrm{EXP}})^{-1}_{ij} \delta\mathcal{B}_j,$$

$$\chi^2_{\mathrm{LCSR}} = \left(\frac{f_+^{\mathrm{LCSR}}(0) - f_+(0,\vec{b})}{\delta f_+^{\mathrm{LCSR}}(0)} \right)^2$$





$$|V_{ub}| = (3.52 \pm 0.29) \times 10^{-3}$$

Summary

- Belle V_{cb} exclusive:
  - $B \to D^* \ell \nu$, PRD 82.112007 (arXiv:1011.4397)
    $\mathcal{F}(1)|V_{cb}| = (34.6 \pm 0.2 \pm 1.0) \times 10^{-3}$
    $\longrightarrow |V_{cb}| = (37.5 \pm 0.2 \pm 1.1 \pm 1.0_{theo}) \times 10^{-3}$
- V_{cb} inclusive:
  - Belle Lepton moments, PRD 75.032001 (arXiv:hep-ex/0610012)
  - Belle Hadron moments, PRD 75, 032001 (arXiv:hep-ex/0611044)
  - Fit Belle + BaBar, Gambino and Schwanda: arXiv:1307.4551
    $|V_{cb}| = (42.42 \pm 0.86) \times 10^{-3}$
- Belle V_{ub} exclusive:
  - PRD 88, 032005 (arxiv: 1306.2781)
    $|V_{ub}| = (3.52 \pm 0.29) \times 10^{-3}$

For both V_{cb} and V_{ub}: inclusive vs. exclusive problem remains!

Thank you

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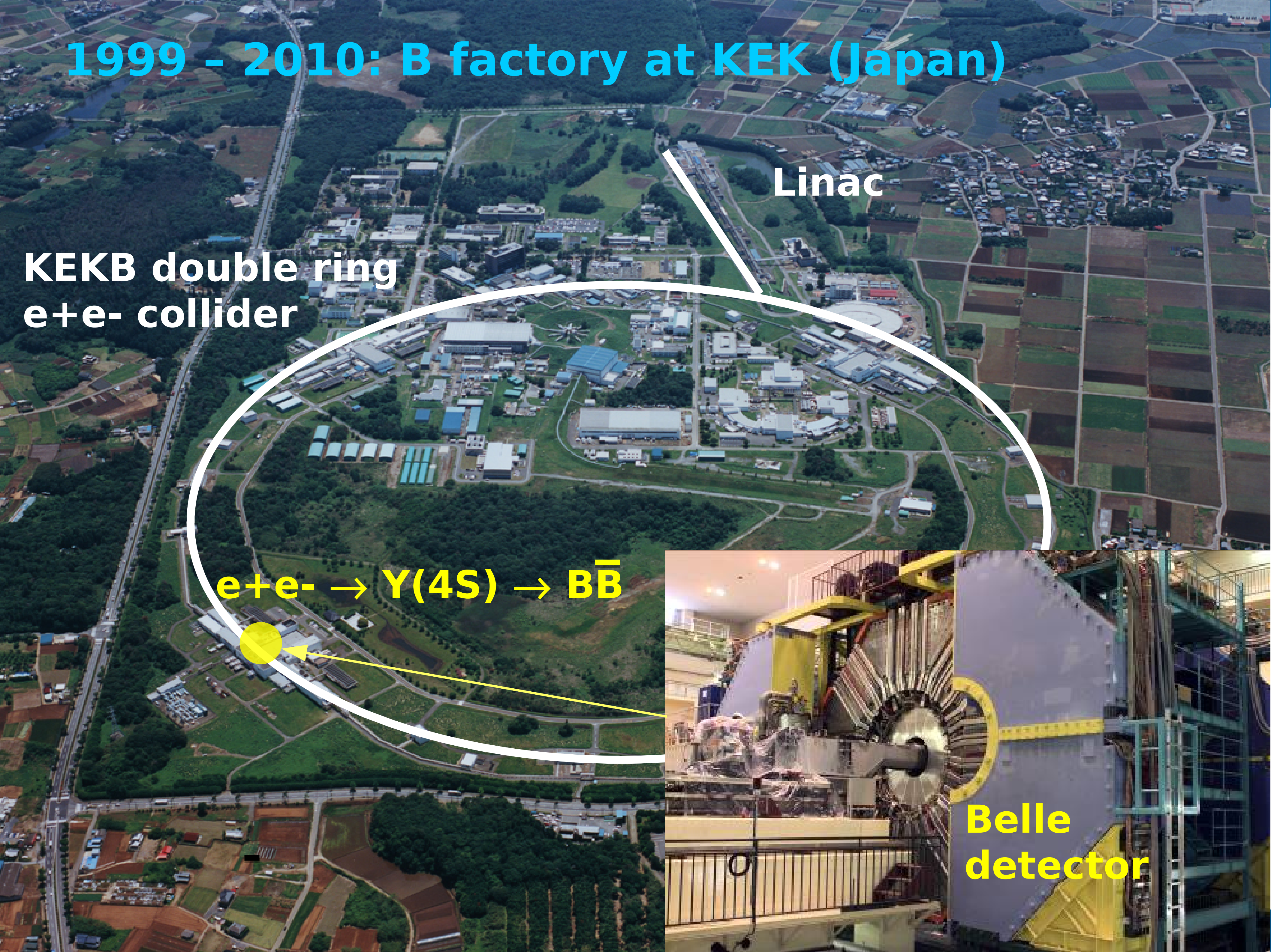
Back Up

The Belle detector

- At KEKB
  - Asymetric e^+e^- collider
  - B-Factory: working mainly at the Y(4S) resonance:
    - An excited $b\bar{b}$ state
    - Energy (10.58 GeV) just slightly above energy needed for BBbar (2x ~5.279 GeV)
    - Low remaining kinetic energy of B-mesons
    - No additional decay products

1999 – 2010: B factory at KEK (Japan)



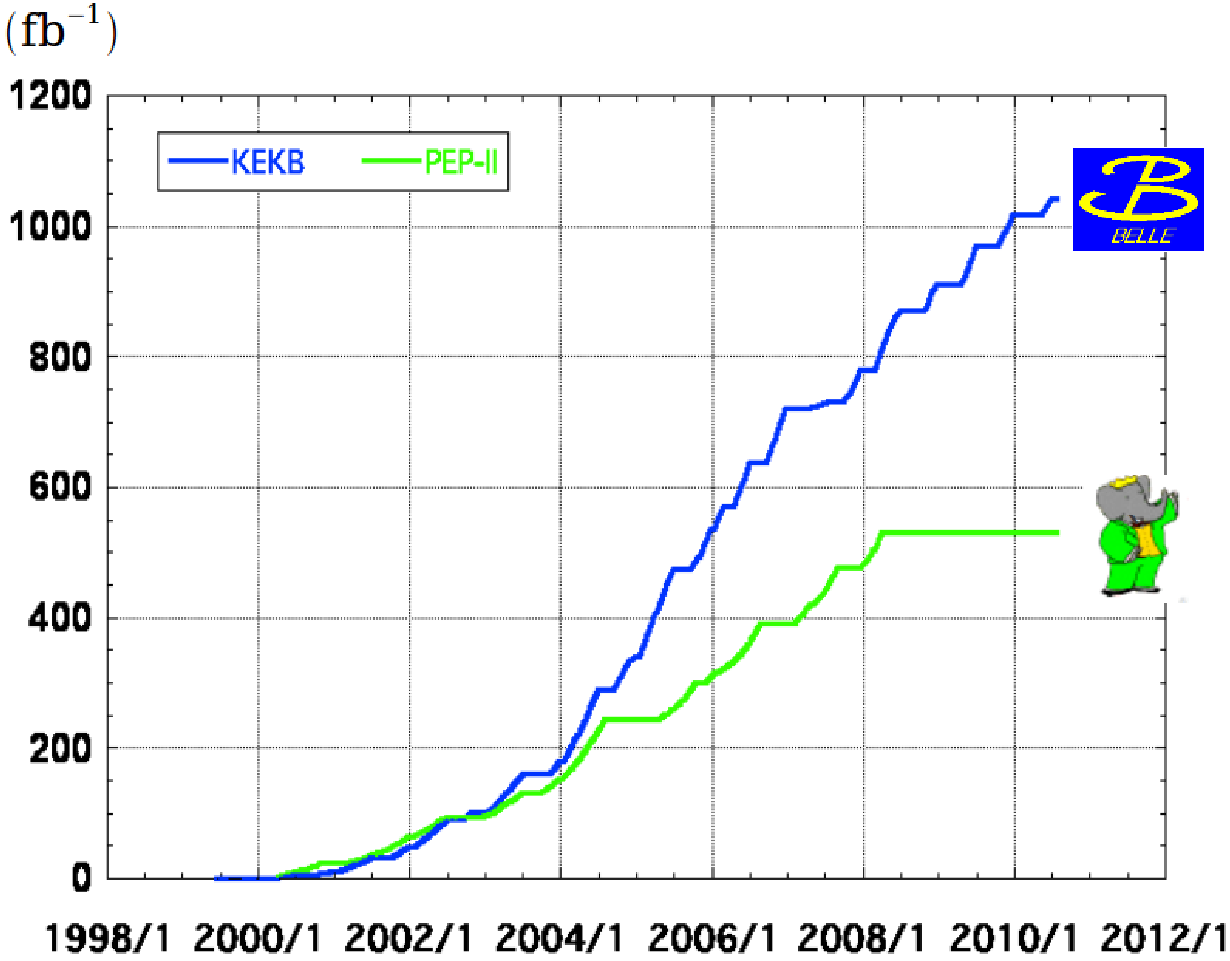
KEKB double ring
e+e- collider

Linac

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

Belle
detector

Integrated luminosity of B factories



$> 1\ \mathrm{ab}^{-1}$

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

$\sim 100\ \mathrm{fb}^{-1}$

World largest B meson sample ~771 million BB events

~400 Belle physics publications

$\sim 550\ \mathrm{fb}^{-1}$

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

$\sim 54\ \mathrm{fb}^{-1}$

Semileptonic Decays

- Mainly for Vub and Vcb
- Theory:
  cleanest for leptonic decays
- Experimental:
  cleanest for hadronic decays
- Semileptonic best approach
  - Good theoretical description
  - Good experimental accessibility