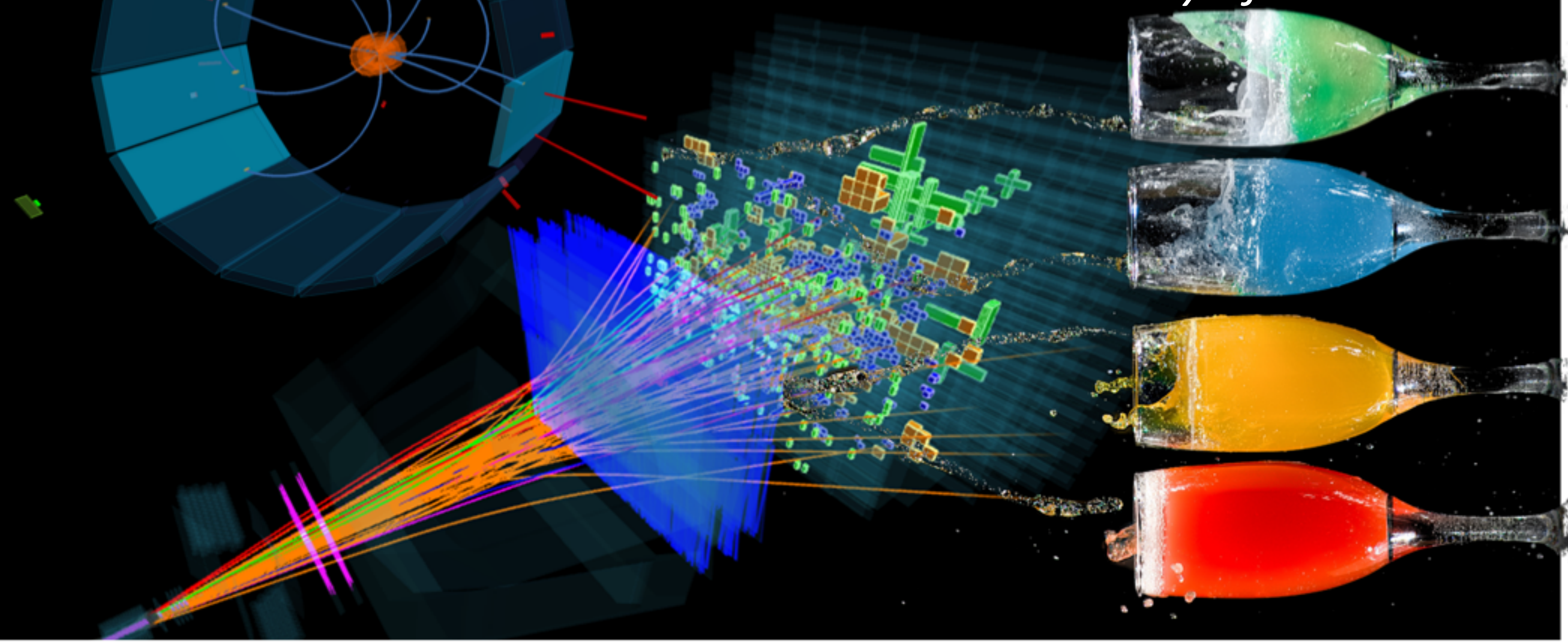
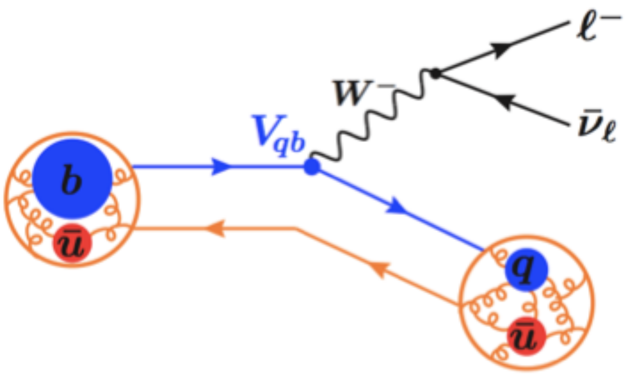
# $|V_{cb}|$ at Belle/Belle II

Christoph Schwanda
*Institute of High Energy Physics*
*Austrian Academy of Sciences*



Flavor 2019: New Physics in Flavor from LHC to Belle II
Munich Institute for Astro- and Particle Physics, May 20-22, 2019

# $|V_{cb}|$ from semileptonic B decays




$$d\Gamma \propto G_F^2 |V_{qb}|^2 \left| L_\mu \langle X | \bar{q}\gamma_\mu P_L b | B \rangle \right|^2$$

| | **Experiment** | **Theory** |
|---|---|---|
| **Exclusive $\|V_{cb}\|$** | $B \to D l \nu$, $D^* l \nu$ (low backgrounds) | Lattice QCD, light cone sum rules |
| **Inclusive $\|V_{cb}\|$** | $B \to X l \nu$ (higher background) | Operator product expansion |

HFLAV 2016:

$|V_{cb}|$ excl ($D^* l \nu$): $(39.05 +/- 0.75) \times 10^{-3}$

$|V_{cb}|$ incl: $(42.19 +/- 0.78) \times 10^{-3}$

# Let's look at $B \to D^{(*)} l\nu$

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

$B \to D^* l\nu$

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

$B \to D l\nu$

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

# Form factor parameterizations

- Caprini, Lellouch, Neubert [Nucl.Phys. B530, 153(1998)]

$B \to D^* l\nu$

$$\begin{aligned} h_{A_1}(w) &= h_{A_1}(1)\big[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 \\ &\qquad - (231\rho^2 - 91)z^3\big] , \\ R_1(w) &= R_1(1) - 0.12(w-1) + 0.05(w-1)^2, \\ R_2(w) &= R_2(1) + 0.11(w-1) - 0.06(w-1)^2, \end{aligned}$$

$B \to D l\nu$

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

Parameters: $F(1)$, $\rho^2$, $R_1(1)$, $R_2(1)$
$G(1)$, $\rho^2$

- Boyd, Grinstein, Lebed [Phys. Rev. Lett. 74, 4603 (1995)]

$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{N} a_{i,n} z^n, \qquad z(w) = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

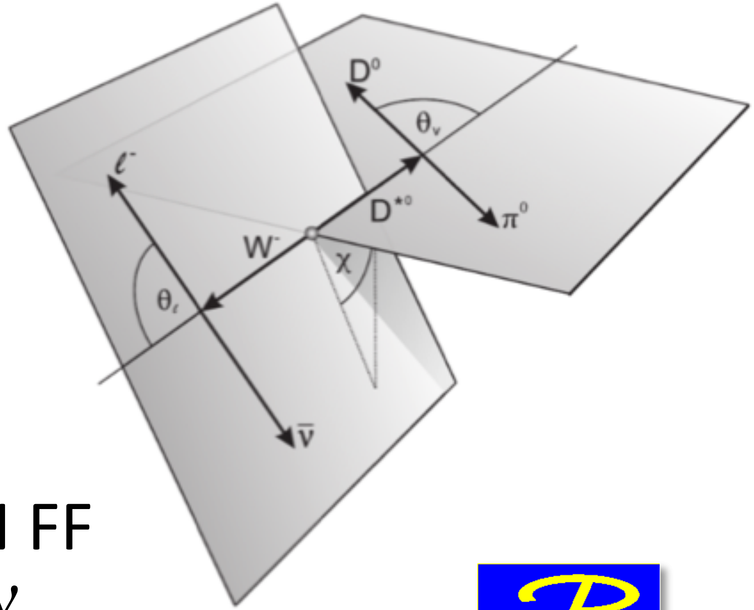
Parameters: coefficients $a_{i,n}$
Order N of the expansion a priori not defined by theory

# Belle B → D*lν hadronic tag [arXiv:1702.01521]

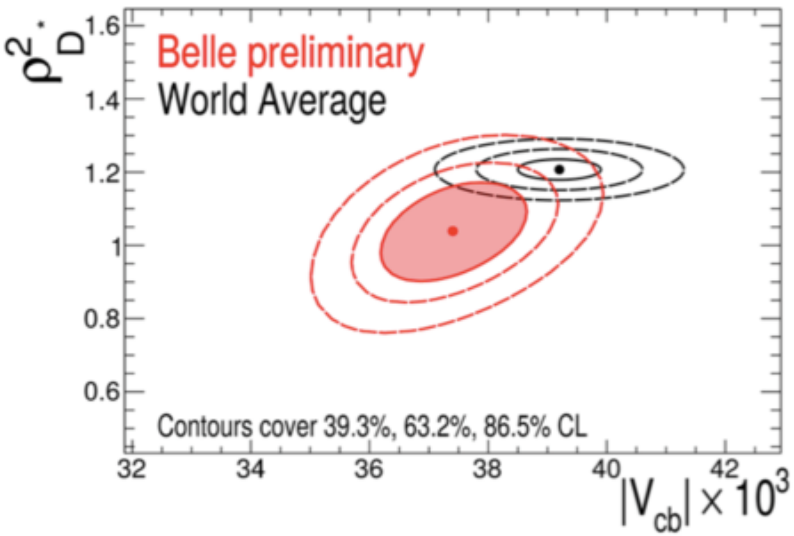
- CLN FF parameterization
  [NPB 530, 153 (1998)]

$$\frac{d^4\Gamma(B \to D^*\ell\nu)}{dw\,d\cos\theta_v\,d\cos\theta_\ell\,d\chi} = f(|V_{cb}|^2, \underbrace{\rho^2_{D^*}, R_1, R_2}_{\text{form factor parameters}})$$

$$w = \frac{m_B^2 - m_{D^*}^2 - q^2}{m_B m_{D^*}}$$




- Belle measured $|V_{cb}|$ and the CLN FF parameters in the decay B → D*lν




| Parameter | Measurement | World average |
|---|---|---|
| $\|V_{cb}\| \cdot 10^3$ | $37.4 \pm 1.2$ | $39.2 \pm 0.7$ |
| $\rho^2_{D^*}$ | $1.04 \pm 0.13$ | $1.20 \pm 0.03$ |
| $R_1$ | $1.38 \pm 0.07$ | $1.40 \pm 0.03$ |
| $R_2$ | $0.86 \pm 0.10$ | $0.85 \pm 0.02$ |

CLN parametrisation

# Parameterization dependence?

- D.Bigi, P. Gambino, S.Schacht, Phys.Lett. B769 (2017) 441

| BGL Fit: | Data + lattice | Data + lattice + LCSR |
|---|---|---|
| $\chi^2/\mathrm{dof}$ | 27.9/32 | 31.4/35 |
| $\lvert V_{cb}\rvert$ | $0.0417\,(^{+20}_{-21})$ | $0.0404\,(^{+16}_{-17})$ |
| $a_0^f$ | 0.01223(18) | 0.01224(18) |
| $a_1^f$ | $-0.054\,(^{+58}_{-43})$ | $-0.052\,(^{+27}_{-15})$ |
| $a_2^f$ | $0.2\,(^{+7}_{-12})$ | $1.0\,(^{+0}_{-5})$ |
| $a_1^{\mathcal{F}_1}$ | $-0.0100\,(^{+61}_{-56})$ | $-0.0070\,(^{+54}_{-52})$ |
| $a_2^{\mathcal{F}_1}$ | 0.12 (10) | $0.089\,(^{+96}_{-100})$ |
| $a_0^g$ | $0.012\,(^{+11}_{-8})$ | $0.0289\,(^{+57}_{-37})$ |
| $a_1^g$ | $0.7\,(^{+3}_{-4})$ | $0.08\,(^{+8}_{-22})$ |
| $a_2^g$ | $0.8\,(^{+2}_{-17})$ | $-1.0\,(^{+20}_{-0})$ |

| CLN Fit: | Data + lattice | Data + lattice + LCSR |
|---|---|---|
| $\chi^2/\mathrm{dof}$ | 34.3/36 | 34.8/39 |
| $\lvert V_{cb}\rvert$ | 0.0382 (15) | 0.0382 (14) |
| $\rho^2_{D^*}$ | $1.17\,(^{+15}_{-16})$ | 1.16 (14) |
| $R_1(1)$ | $1.391\,(^{+92}_{-88})$ | 1.372 (36) |
| $R_2(1)$ | $0.913\,(^{+73}_{-80})$ | $0.916\,(^{+65}_{-70})$ |
| $h_{A_1}(1)$ | 0.906 (13) | 0.906 (13) |

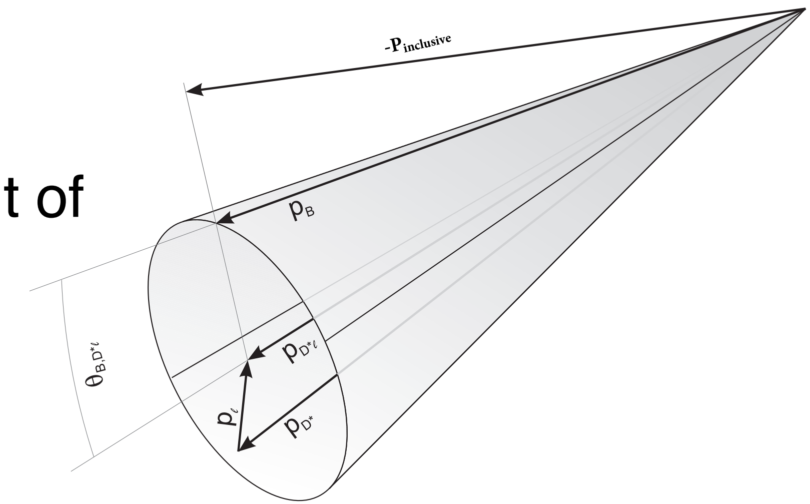
- B.Grinstein, A.Kobach, Phys.Lett. B771 (2017) 359

$$|V_{cb}| = (37.4 \pm 1.3) \times 10^{-3} \qquad \text{(CLN)}$$

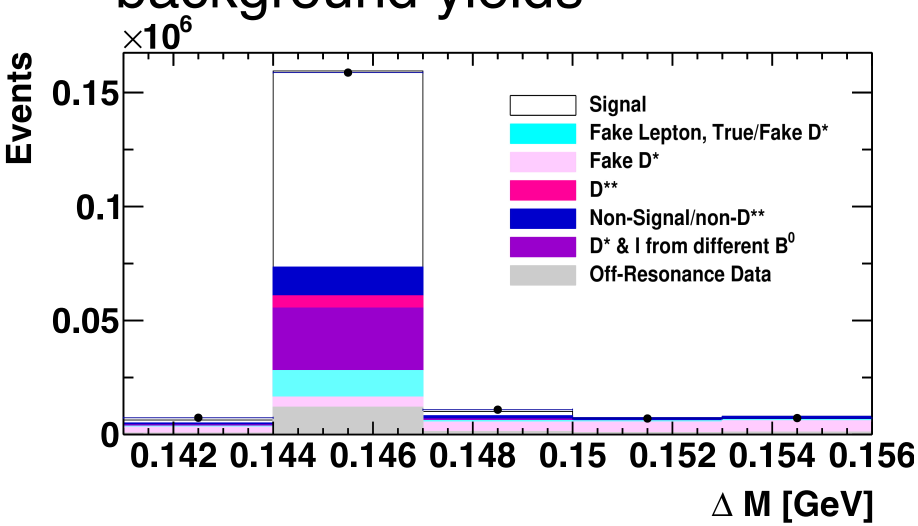
$$|V_{cb}| = (41.9\ ^{+2.0}_{-1.9}) \times 10^{-3} \qquad \text{(BGL)}$$

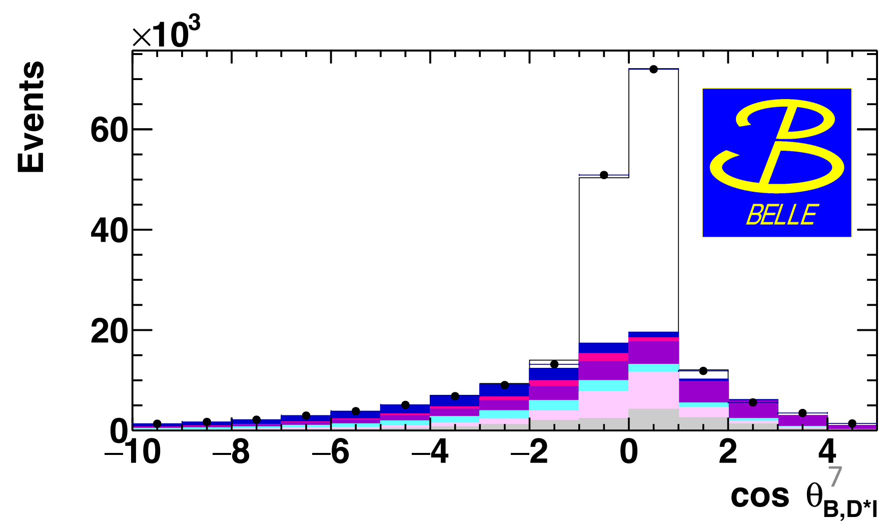
# Belle $B^0 \to D^{*-} l^+ \nu$ untagged [arXiv:1809.03290] subm.to PRD

- Measure $|V_{cb}|$ using **Belle** 711fb$^{-1}$.
- Signal Selection using
  - 3D - Binned Maximum Likelihood fit of
  - ($\cos\theta_{B,D^*l}$)
  - $\Delta M$ = mass ($D^*$-$D^0$)
  - lepton momentum



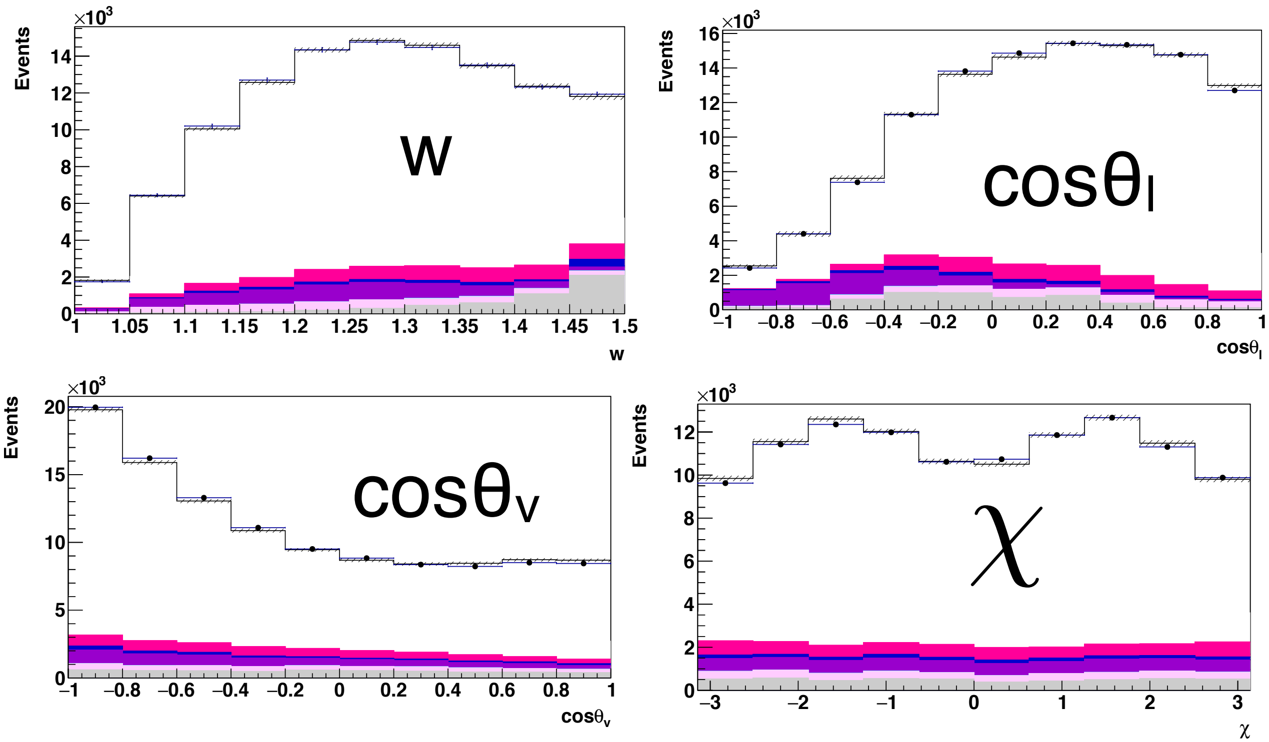

- Float Signal & Backgrounds components from MC to extract background yields

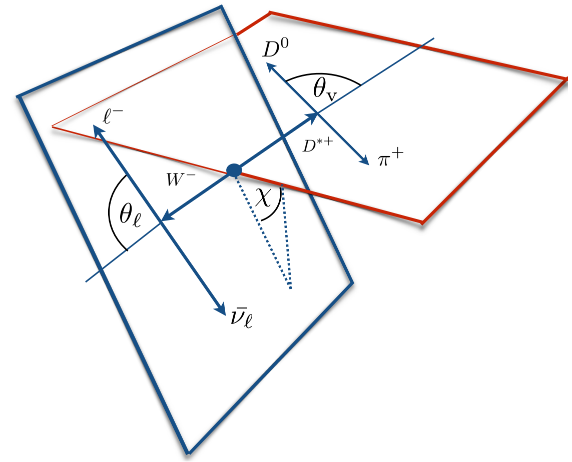


# CLN: FF parameters and $|V_{cb}|$

Simultaneous fit of 1D projections of w, $\cos\theta_l$, $\cos\theta_v$, X to extract $\rho^2$, $R_1(1)$, $R_2(1)$ and $F(1)|V_{cb}|$




- Signal
- Fake Lepton, True/Fake D*
- Fake D*
- D**
- Non-Signal/non-D**
- D* & l from different $B^0$
- Off-Resonance Data

$$\rho^2 = 1.106 \pm 0.031 \pm 0.007$$
$$R_1(1) = 1.229 \pm 0.028 \pm 0.009$$
$$R_2(1) = 0.852 \pm 0.021 \pm 0.006$$

$F(1)|V_{cb}|\eta_{EW} \times 10^3 = 35.1 \pm 0.2 \pm 0.6$

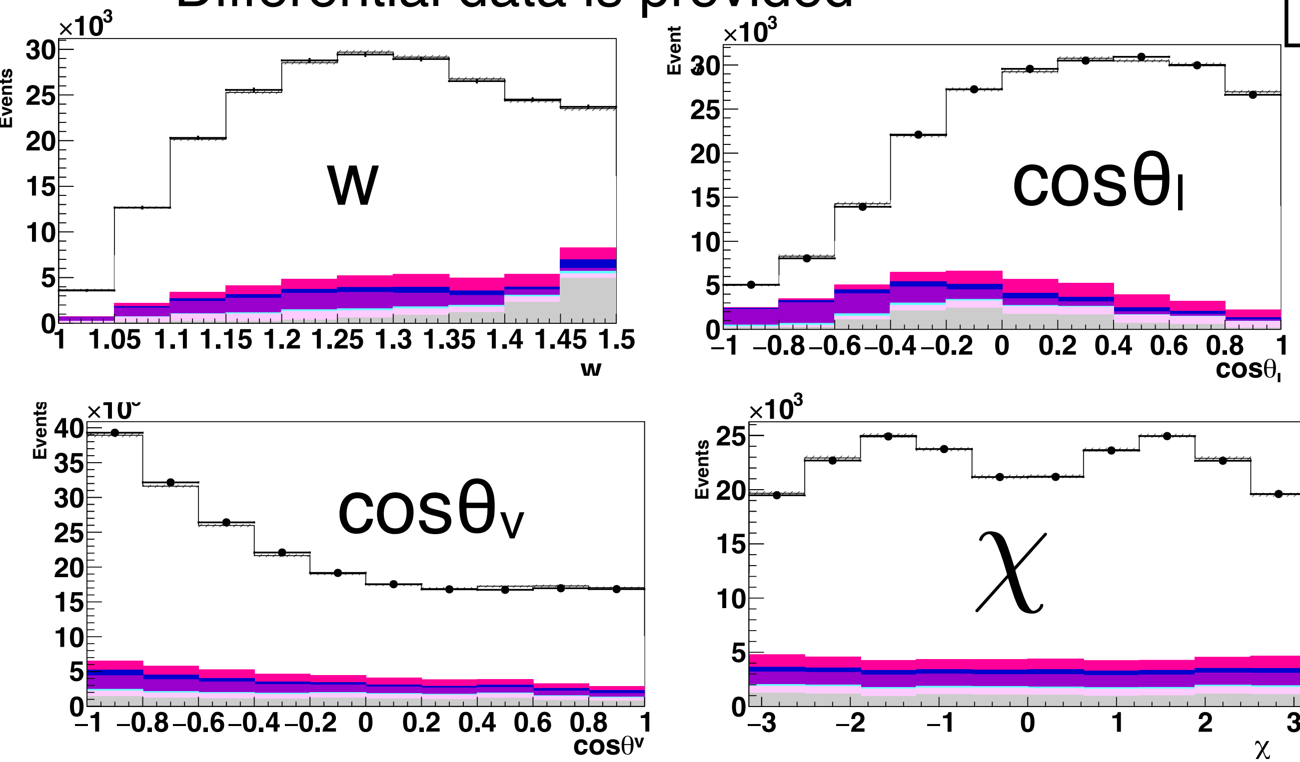
# BGL: FF parameters and $|V_{cb}|$

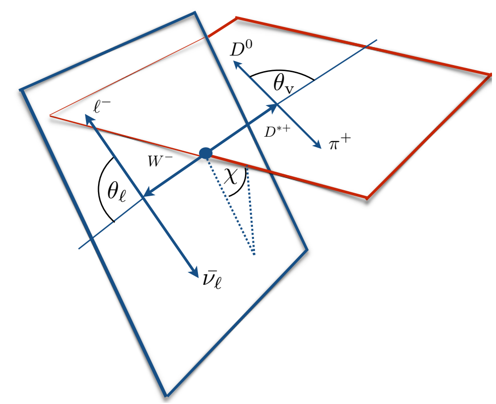
Simultaneous fit of 1D projections of w, $\cos\theta_l$, $\cos\theta_v$, X to extract the coefficients of the BGL expansion (up to 3rd order) and $F(1)|V_{cb}|$

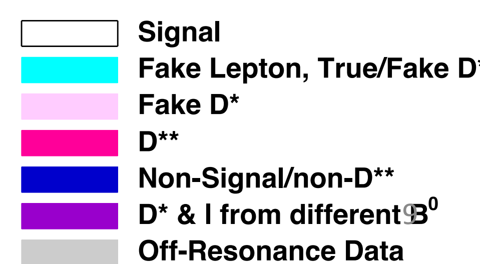
$$F(1)|V_{cb}|\eta_{EW} \times 10^3 = 34.9 \pm 0.2 \pm 0.6$$

- Consistent with CLN
- Differential data is provided

$$\begin{aligned}
\tilde{a}_0^f \times 10^3 &= -0.506 \pm 0.004 \pm 0.008, \\
\tilde{a}_1^f \times 10^3 &= -0.65 \pm 0.17 \pm 0.09, \\
\tilde{a}_1^{F_1} \times 10^3 &= -0.270 \pm 0.064 \pm 0.023, \\
\tilde{a}_2^{F_1} \times 10^3 &= +3.27 \pm 1.25 \pm 0.45, \\
\tilde{a}_0^g \times 10^3 &= -0.929 \pm 0.018 \pm 0.013,
\end{aligned}$$



# Summary $B \to D^* l \nu$

## CLN

| | $\lvert V_{cb} \rvert \times 10^3$ | |
|---|---|---|
| Belle tagged 2018 | 37.4 +/- 1.2 | arXiv:1702.01521 |
| Belle untagged 2018 | 38.4 +/- 0.6 | arXiv:1809.03290, subm. to PRD |
| HFLAV 2016 | 39.1 +/- 0.7 | Eur.Phys.J. C77 (2017) 895 |

## BGL

| | $\lvert V_{cb} \rvert \times 10^3$ | |
|---|---|---|
| Belle tagged 2018 | 41.7 +/- 2.0 | arXiv:1702.01521, PLB769 (2017) 441 |
| Belle untagged 2018 | 38.3 +/- 0.8 | arXiv:1809.03290, subm. to PRD |
| BaBar tagged 2019 | 38.4 +/- 0.9 | arXiv:1903.10002, subm. to PRL |

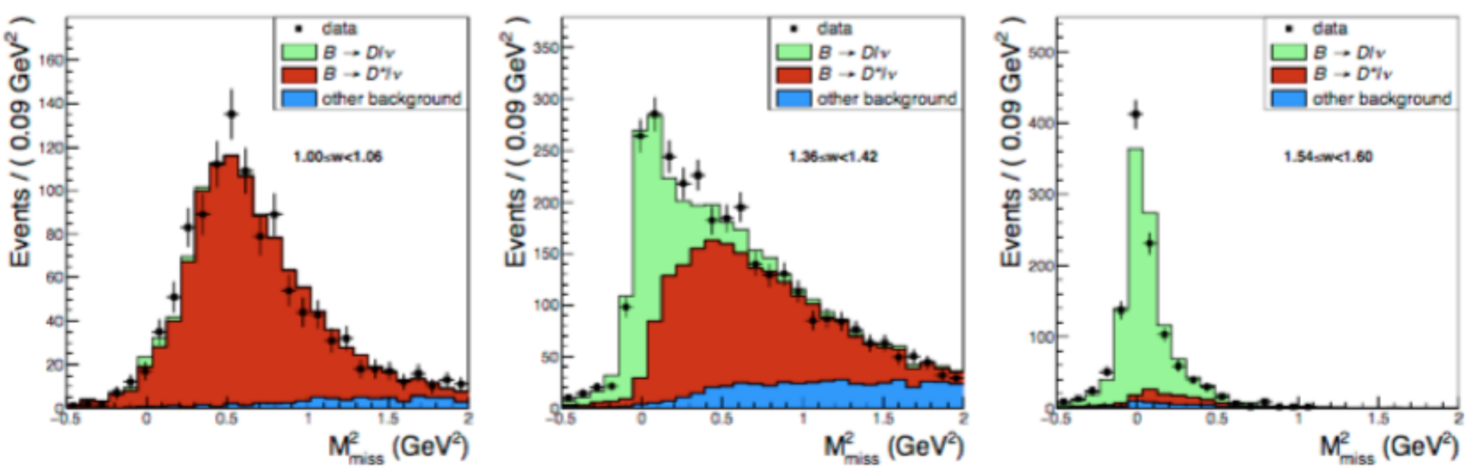
← Talk by Biplab Dey yesterday

Recent data does not support the FF parameterization dependence of |Vcb| excl!!

# $B \to D l \nu$ at Belle

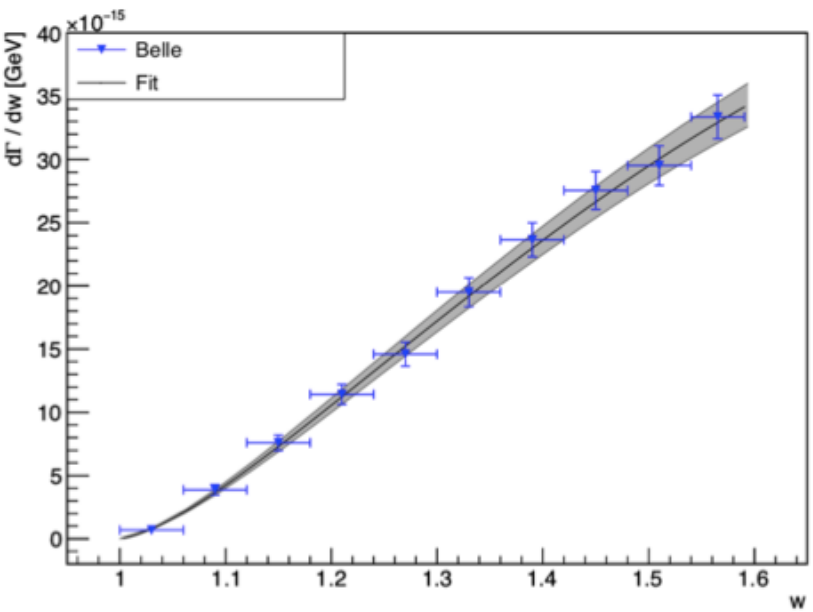
[R. Glattauer, CS, Phys. Rev. D93, 032006 (2016)]

- 711/fb of Belle Υ(4S) data
- Full reconstruction of one B (hadronic tag)
- 10 $D^+$ and 13 $D^0$ modes are used on the signal side, covering 28.9% and 40.1% of the width
- Signal extraction from $M^2_{miss}$ in 10 bins of w
- 16,992 +/- 192 signal events
  (5150 +/- 95 neutral, 11,843 +/- 167 charged B events)



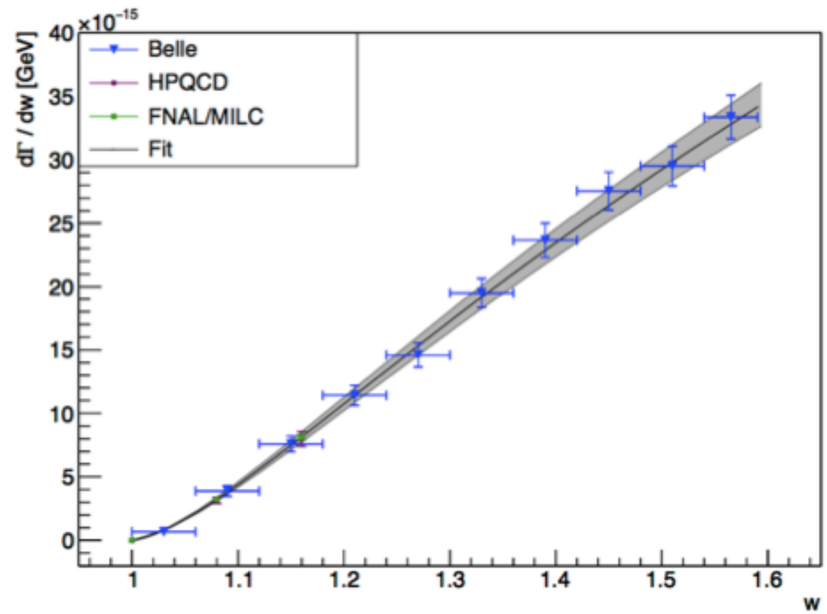
# Belle 2016: CLN vs. BGL fit with lattice data

CLN




Vs.

BGL




$|V_{cb}|$ = ( 39.9 +/- 1.3 ) x $10^{-3}$

$|V_{cb}|$ = ( 40.8 +/- 1.1 ) x $10^{-3}$

# $|V_{cb}|$ from inclusive decays

$B \to X l \nu$

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2\left(1 + \frac{c_5(\mu)\,\langle O_5\rangle(\mu)}{m_b^2} + \frac{c_6(\mu)\,\langle O_6\rangle(\mu)}{m_b^3} + \mathcal{O}\left(\frac{1}{m_b^4}\right)\right)$$

- Based on the Operator Product Expansion (OPE)
- $\langle O_i \rangle$: hadronic matrix elements (non-perturbative)
  $c_i$: coefficients (perturbative)
- Parton-hadron duality $\to$ the hadronic ME depend only on the initial state

| | Kinetic [JHEP 1109 (2011) 055] | 1S [PRD70, 094017 (2004)] |
|---|---|---|
| O(1) | $m_b$, $m_c$ | $m_b$ |
| $O(1/m^2_b)$ | $\mu^2_\pi$, $\mu^2_G$ | $\lambda_1$, $\lambda_2$ |
| $O(1/m^3_b)$ | $\rho^3_D$, $\rho^3_{LS}$ | $\rho_1$, $\tau_{1\text{-}3}$ |

# Moments of the $E_l$ and $M^2_X$ spectrum

Also other observables in B → Xlν can be expanded into an OPE with the same heavy quark parameters, e.g.,

- The n[th] moment of the (truncated) lepton energy spectrum

$$R_n(E_{\rm cut},\mu) = \int_{E_{\rm cut}} (E_\ell - \mu)^n \, \frac{{\rm d}\Gamma}{{\rm d}E_\ell} \, {\rm d}E_\ell \,, \quad \langle E_\ell^n \rangle_{E_{\rm cut}} = \frac{R_n(E_{\rm cut},0)}{R_0(E_{\rm cut},0)}$$

- The n[th] moment of the (truncated) $M^2_X$ spectrum

$$\langle m_X^{2n} \rangle_{E_{\rm cut}} = \frac{\displaystyle\int_{E_{\rm cut}} (m_X^2)^n \, \frac{{\rm d}\Gamma}{{\rm d}m_X^2} \, {\rm d}m_X^2}{\displaystyle\int_{E_{\rm cut}} \frac{{\rm d}\Gamma}{{\rm d}m_X^2} \, {\rm d}m_X^2}$$

**Master plan:**

- Measure the quark masses and heavy quark parameters using moments
- Substitute them in the formula of the semileptonic width
- Determine $|V_{cb}|$ from the semileptonic branching fraction

# Two sets of theoretical calculations

- "Kinetic running mass"
  - P. Gambino, N. Uraltsev, Eur. Phys. J. C34, 181 (2004)
  - P. Gambino, JHEP 1109 (2011) 055
  - A. Alberti, P. Gambino, K.J. Healey, S. Nandi, Phys. Rev. Lett. 114, 061802 (2015)
- "1S mass"
  - C. Bauer, Z. Ligeti, M. Luke, A. Manohar, M. Trott, Phys. Rev. D70, 094017 (2004)
- Non-perturbative parameters in the $1/m_b$ expansion

| | Kinetic | 1S |
|---|---|---|
| O(1) | $m_b$, $m_c$ | $m_b$ |
| $O(1/m^2_b)$ | $\mu^2_\pi$, $\mu^2_G$ | $\lambda_1$, $\lambda_2$ |
| $O(1/m^3_b)$ | $\rho^3_D$, $\rho^3_{LS}$ | $\rho_1$, $\tau_{1\text{-}3}$ |

# Data used in $b \to c$ inclusive analyses

| | |
|---|---|
| BaBar | $\langle E^n_l \rangle$: n=0,1,2,3 [PRD 69, 111104 (2004), PRD 81, 032003 (2010)]<br>$\langle M^{2n}_X \rangle$: n=1,2, 3 [PRD 81, 032003 (2010)] |
| Belle | $\langle E^n_l \rangle$: n=0,1,2,3 [PRD 75, 032001 (2007)]<br>$\langle M^{2n}_X \rangle$: n=1,2 [PRD 75, 032005 (2007)] |
| CDF | $\langle M^{2n}_X \rangle$: n=1,2 [PRD 71, 051103 (2005)] |
| CLEO | $\langle M^{2n}_X \rangle$: n=1,2 [PRD 70, 032002 (2004)]<br>$\langle E^n_\gamma \rangle$: n=1 [PRL 87, 251807 (2001)] |
| DELPHI | $\langle E^n_l \rangle$: n=1,2,3<br>$\langle M^{2n}_X \rangle$: n=1,2 [EPJ C45, 35 (2006)] |

- 23 measurements from BaBar, 15 measurements from Belle, 12 from other experiments
- Newest measurement is from the year 2010!

# Kinetic scheme analysis

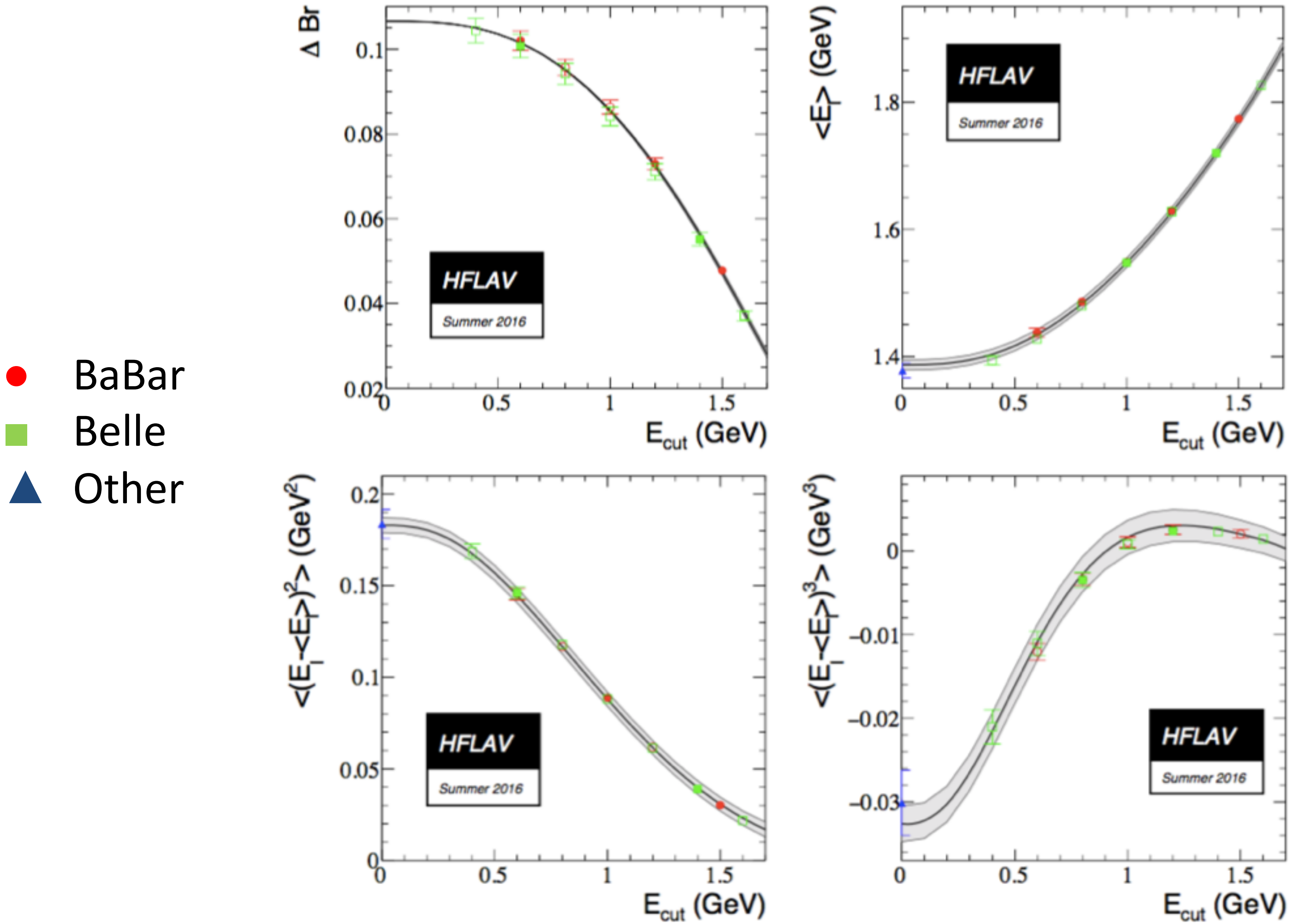
HFLAV
Summer 2016

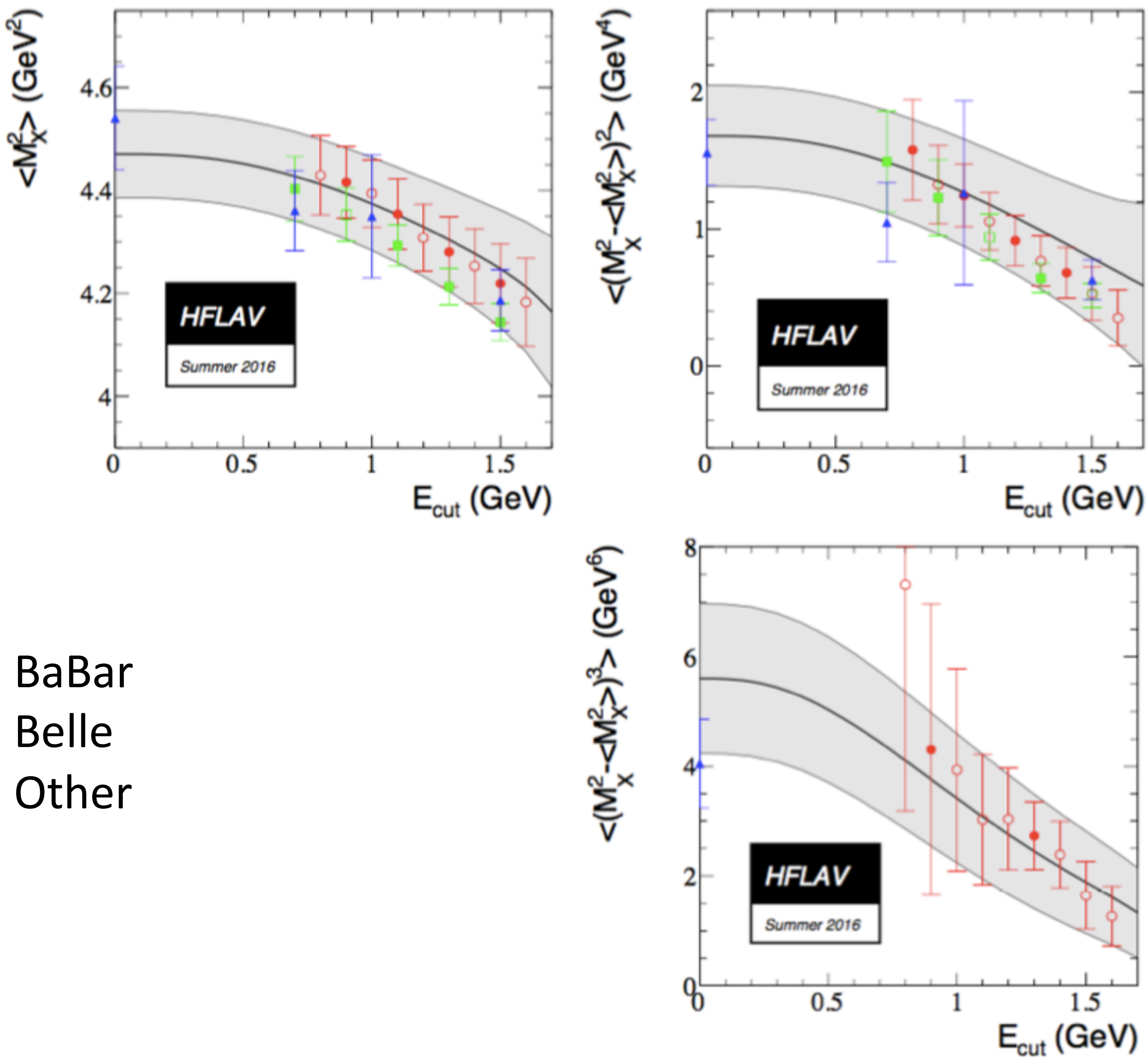
| | $\lvert V_{cb}\rvert$ $[10^{-3}]$ | $m_b^{\rm kin}$ [GeV] | $m_c^{\overline{\rm MS}}$ [GeV] | $\mu_\pi^2$ [GeV$^2$] | $\rho_D^3$ [GeV$^3$] | $\mu_G^2$ [GeV$^2$] | $\rho_{LS}^3$ [GeV$^3$] |
|---|---|---|---|---|---|---|---|
| value | 42.19 | 4.554 | 0.987 | 0.464 | 0.169 | 0.333 | −0.153 |
| error | 0.78 | 0.018 | 0.015 | 0.076 | 0.043 | 0.053 | 0.096 |
| $\lvert V_{cb}\rvert$ | 1.000 | −0.257 | −0.078 | 0.354 | 0.289 | −0.080 | −0.051 |
| $m_b^{\rm kin}$ | | 1.000 | 0.769 | −0.054 | 0.097 | 0.360 | −0.087 |
| $m_c^{\overline{\rm MS}}$ | | | 1.000 | −0.021 | 0.027 | 0.059 | −0.013 |
| $\mu_\pi^2$ | | | | 1.000 | 0.732 | 0.012 | 0.020 |
| $\rho_D^3$ | | | | | 1.000 | −0.173 | −0.123 |
| $\mu_G^2$ | | | | | | 1.000 | 0.066 |
| $\rho_{LS}^3$ | | | | | | | 1.000 |

$$\mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu}_\ell) = (10.65 \pm 0.16)\%$$

$\chi^2$ of 15.6 for 43 degrees of freedom.

- c quark mass constraints $m_c^{\overline{\rm MS}}(3\ {\rm GeV}) = 0.986 \pm 0.013\ {\rm GeV}$
- Average B lifetime: ( 1.579 +/- 0.004 ) ps


BaBar
Belle
Other
HFLAV
Summer 2016
Δ Br
0.1
0.08
0.06
0.04
0.02
0
0.5
1
1.5
E_cut (GeV)
<E_γ> (GeV)
1.8
1.6
1.4
<(E_γ-<E_γ>)^2> (GeV^2)
0.2
0.15
0.1
0.05
<(E_γ-<E_γ>)^3> (GeV^3)
0
-0.01
-0.02
-0.03

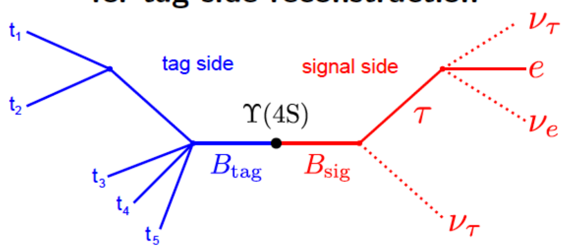



● BaBar
■ Belle
▲ Other

# Outlook to Belle II – improved tagging

1807.08680

**New Full Event Interpretation (FEI) algorithm for tag-side reconstruction**

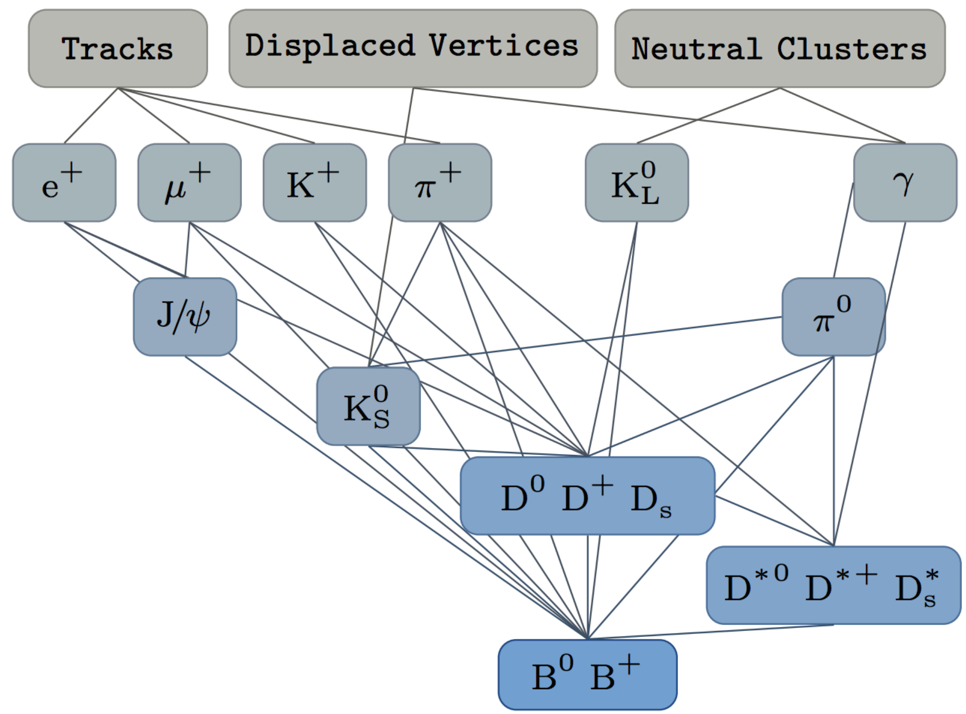



- > 5000 B decays modes reconstructed
- O(200) particle decay channels for training
- Output is candidate-wise **signal probability**

Tagging $\varepsilon$ on MC

| Tag | FR[1] | FEI Belle | FEI Belle II |
|---|---|---|---|
| Hadronic $B^+$ | 0.28% | 0.76% | 0.66% |
| SL $B^+$ | 0.67% | 1.80% | 1.45% |
| Hadronic $B^0$ | 0.18% | 0.46% | 0.38% |
| SL $B^0$ | 0.63% | 2.04% | 1.94% |

[1]Belle Full Reconstruction algorithm.



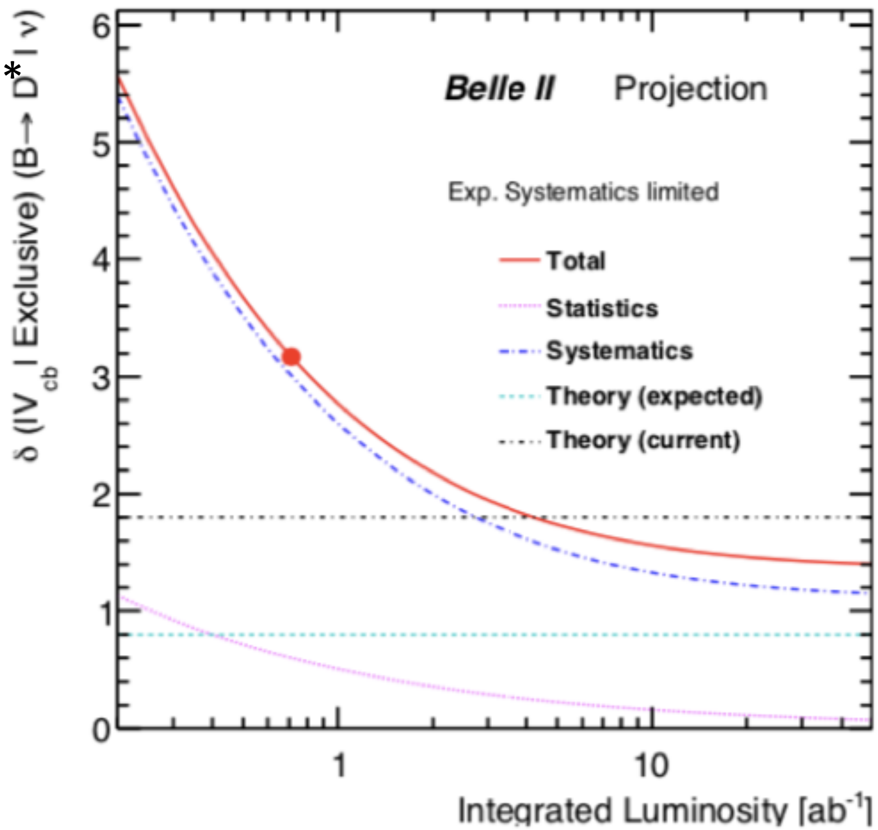

Talk by Lu Cao yesterday

# Outlook to Belle II (2)

- $|V_{cb}|$ exclusive

| | $ab^{-1}$ | Stat. | Syst (Red.,Irred.) | $\sum$Exp | Theory | $\sum$ |
|---|---|---|---|---|---|---|
| $D^*\ell^-\bar{\nu}_\ell$ | 0.7 | 0.6% | (2.8, 1.1)% | 3.1% | 1.8% | 3.6% |
| | 5 | 0.2% | (1.1, 1.1)% | 1.5% | 1.0% | 1.8% |
| | 50 | 0.1% | (0.3, 1.1)% | 1.2% | 0.8%* | 1.4% |
| $D\ell^-\bar{\nu}_\ell$ | 0.4 | 4.5% | (3.1, 1.2)% | 5.6% | 2.2% | 6.0% |
| | 5 | 1.3% | (0.9, 1.2)% | 2.0% | 1.5%* | 2.7% |
| | 50 | 0.6% | (0.4, 1.2)% | 1.4% | 1.0%* | 1.7% |

K. Lieret @ CKM 2018




- $|V_{cb}|$ inclusive
  - Experimental correlations between input measurements (only partially accounted for in the current analysis)

# Summary and outlook

- After the excitement in 2017/2018, recent data for $B \rightarrow D^* l\nu$ seem to indicate that there is no significant form FF parameterization dependence in the determination of $|V_{cb}|$ exclusive
  - $|V_{cb}|$ exclusive fit values reported by Belle [arXiv:1809.03290] and BaBar [arXiv:1903.10002] are consistent with the previous HFLAV 2016 average
  - The 2-3$\sigma$-ish discrepancy with $|V_{cb}|$ inclusive remains
- Experimental $D(^*) l\nu$ data does not constrain the FF slope around zero recoil well [arXiv:1905.08209] $\rightarrow$ lattice input for $D^* l\nu$ at non-zero recoil needed
- New experimental input to the $|V_{cb}|$ inclusive analysis might also provide insights

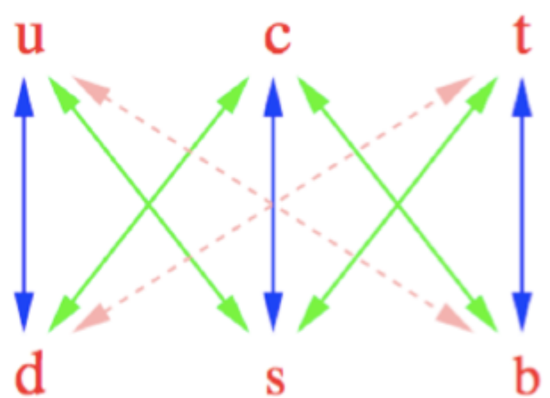
# Backup

# Cabibbo-Kobayashi-Maskawa quark mixing

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathbf{V} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\mathbf{V}\,\mathbf{V}^\dagger = \mathbf{V}^\dagger\,\mathbf{V} = 1$$




- The unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix transforms the flavour eigenstates into the physical quark states
- The CKM element magnitudes determine the possible quark flavour transitions in charged current processes

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

# CP violation

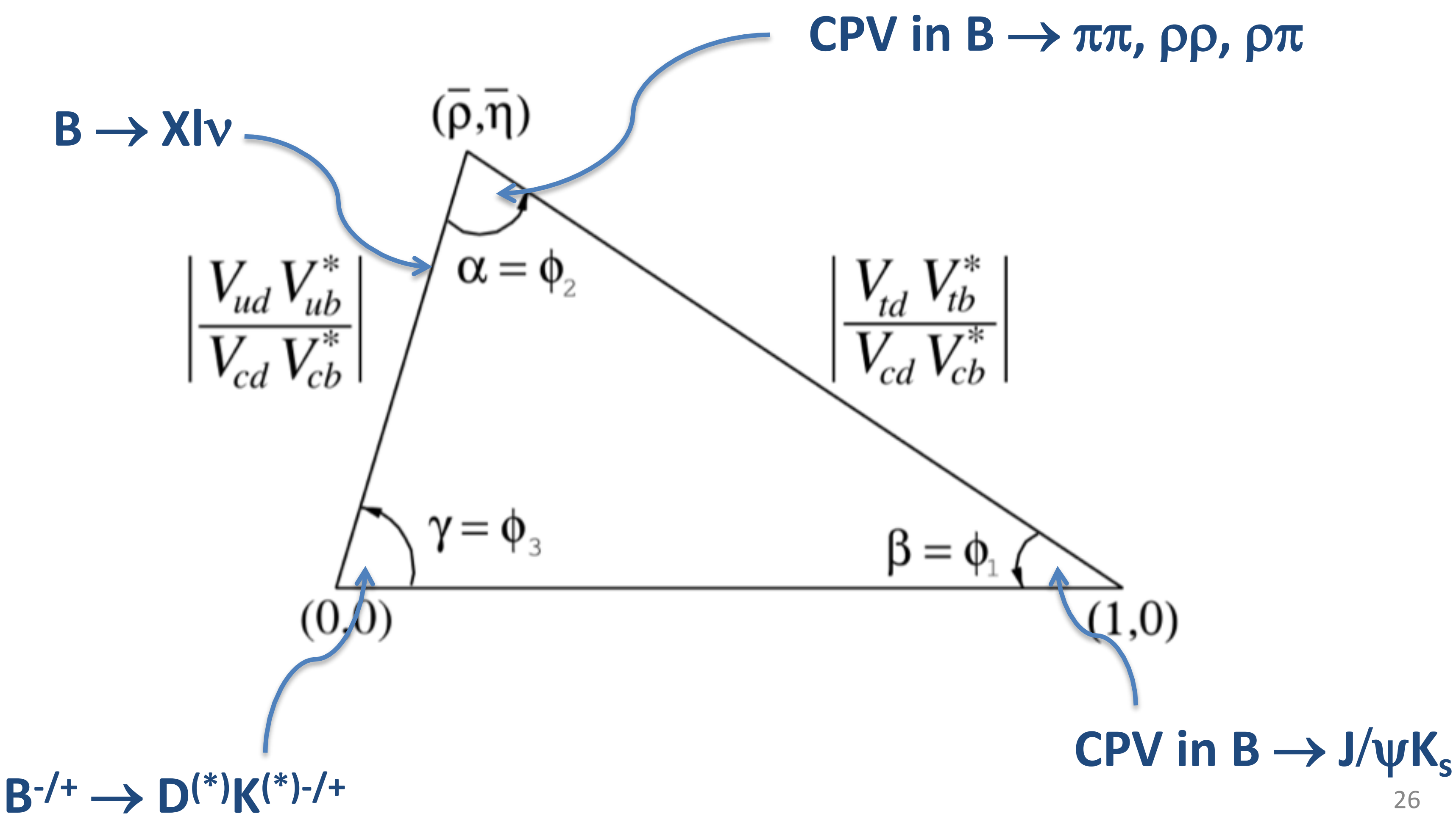
Wolfenstein parametrization of $V_{CKM}$

$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

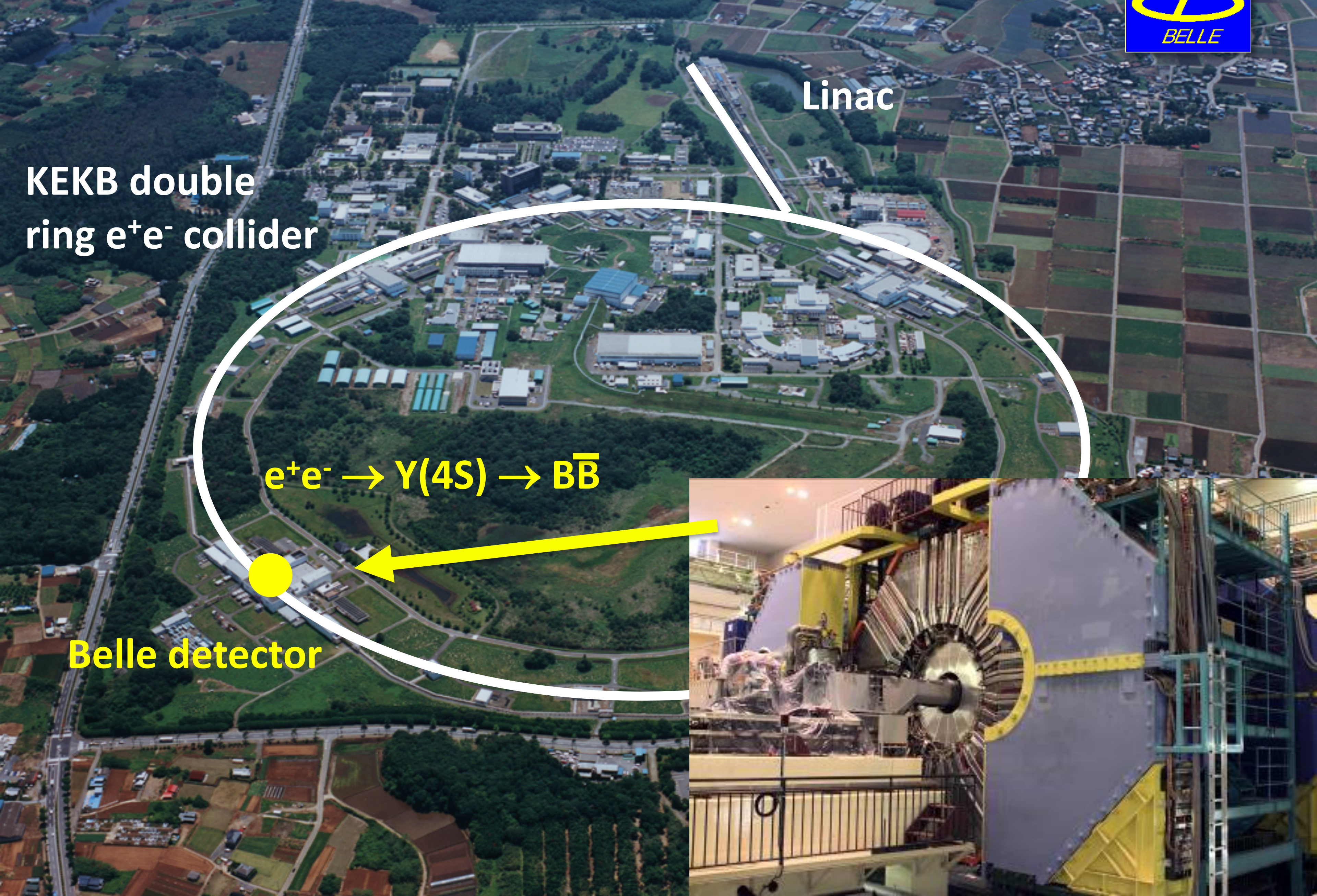
- However, $V_{CKM}$ also contains a complex phase, responsible for all CP-violating phenomena in the SM
- CPV established ( $>5\sigma$ ) in 17 observables ( in K and B physics ) $\rightarrow$ extremely constrained system
- New physics would typically disturb the SM pattern of CPV

# The CKM unitarity triangle

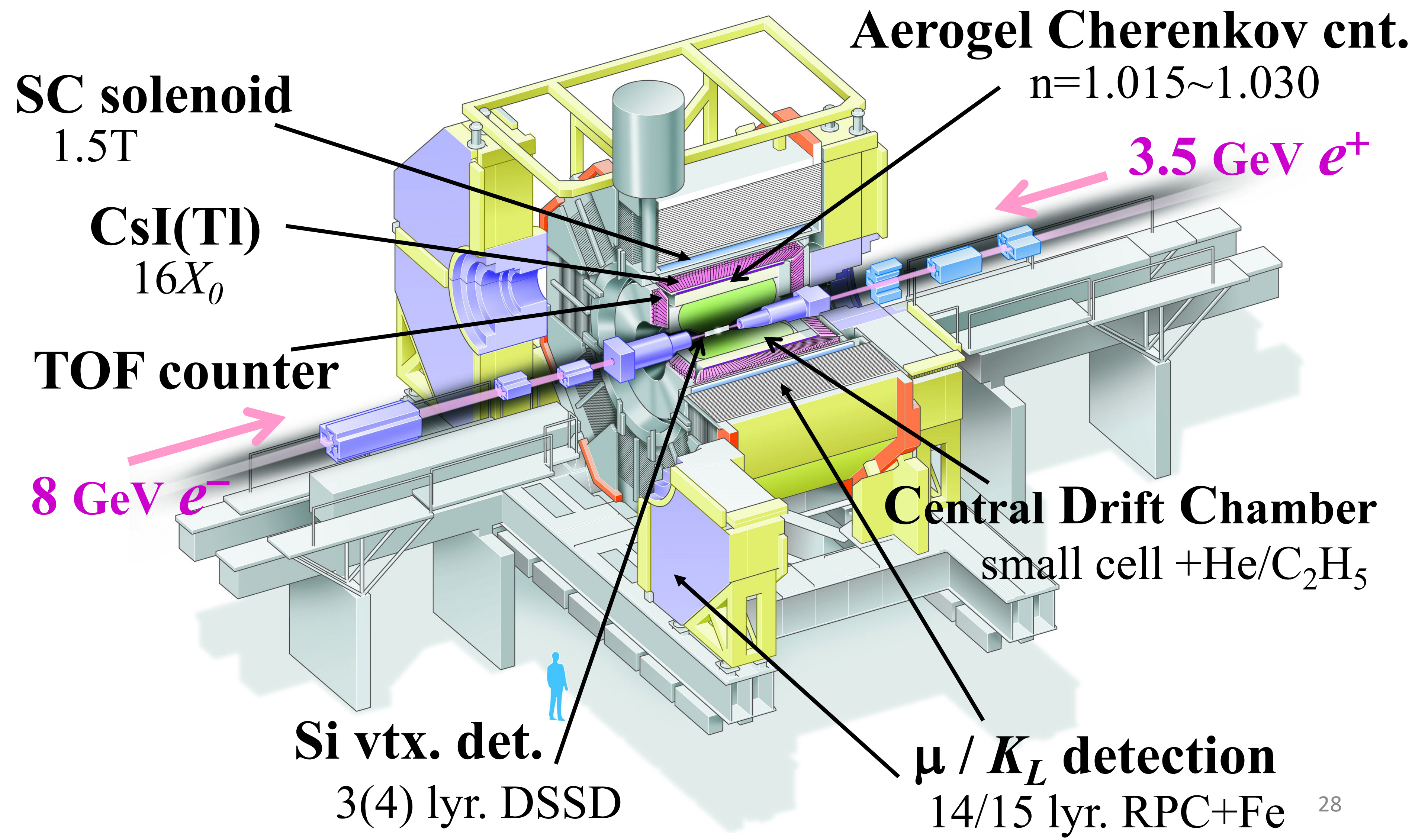
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



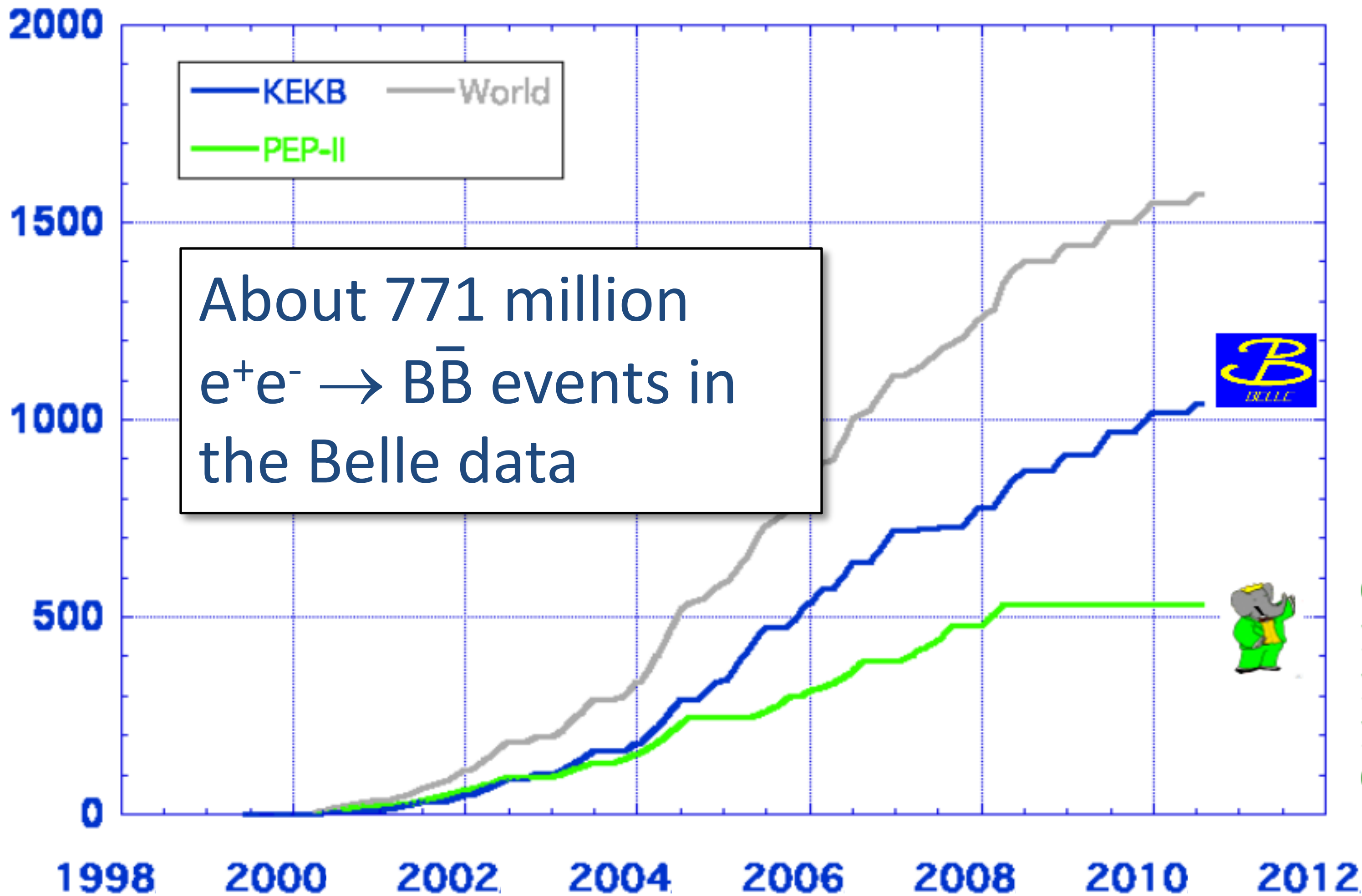
# 1999 – 2010: B factory at KEK (Japan)



# The Belle detector



# Belle and BaBar luminosity




About 771 million $e^+e^- \rightarrow B\bar{B}$ events in the Belle data

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

**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:**

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

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

**On resonance:**

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

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

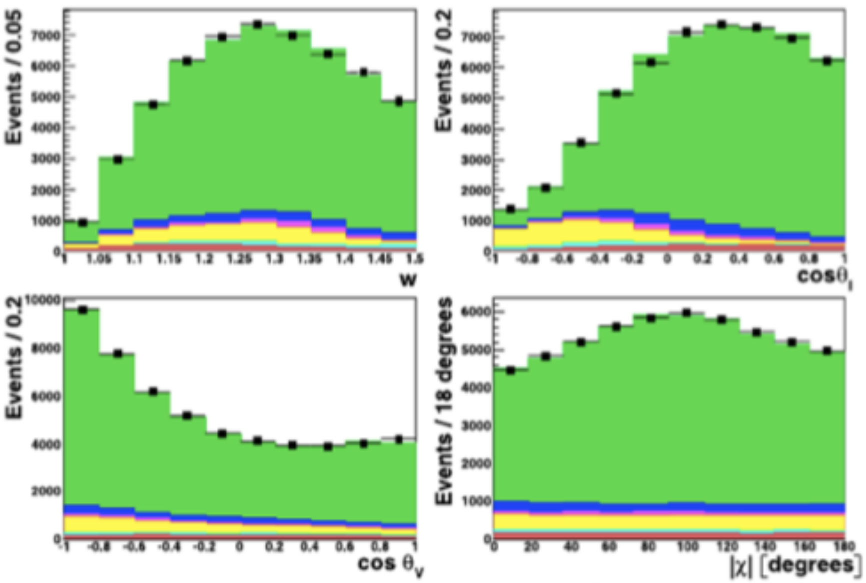
$\Upsilon(2S)$: 14 $fb^{-1}$

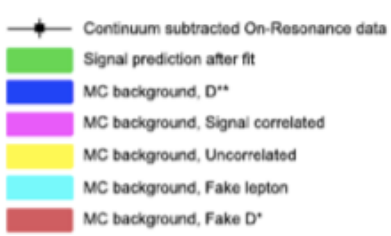
**Off resonance:**

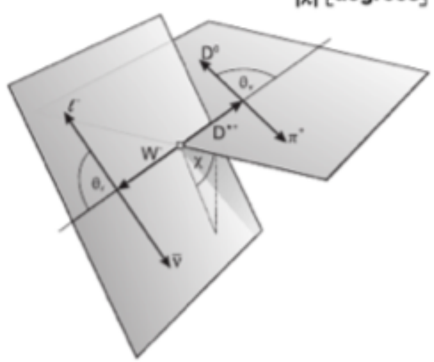
$\sim 54\ fb^{-1}$

# $B^0 \to D^{*-} l^+ \nu$ at Belle

[W. Dungel, CS, Phys. Rev. D 82, 112007 (2010)]




- 711/fb of Belle Y(4S) data
- About 120,000 reconstructed $B^0 \to D^{*-} l^+ \nu$ decays
- Fit in 40 bins of w, cos $\theta_l$, $\theta_V$ and $\chi$ to obtain CLN F.F. parameters
- Dominant experimental systematics: tracking

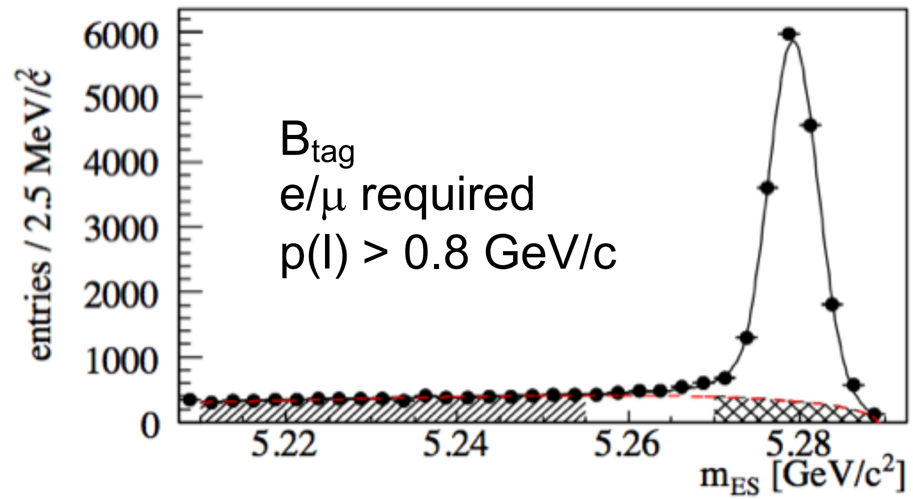
$$
\begin{aligned}
\mathcal{F}(1)|V_{cb}| &= (34.6 \pm 0.2 \pm 1.0) \times 10^{-3} \\
\rho^2 &= 1.214 \pm 0.034 \pm 0.009 \\
R_1(1) &= 1.401 \pm 0.034 \pm 0.018 \\
R_2(1) &= 0.864 \pm 0.024 \pm 0.008 \\
\chi^2/ndf &= 138.8/155
\end{aligned}
$$

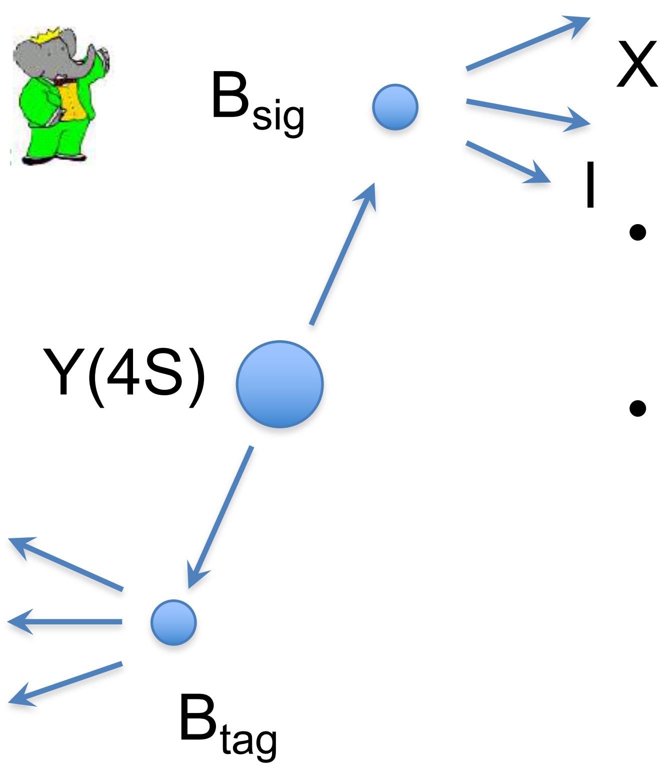
PRD 81, 032003 (2010)

# BaBar hadronic moments

232M BB

- Fully reconstruct the hadronic decay of one B in Y(4S) → BB (efficiency ~0.4%, purity ~80%)



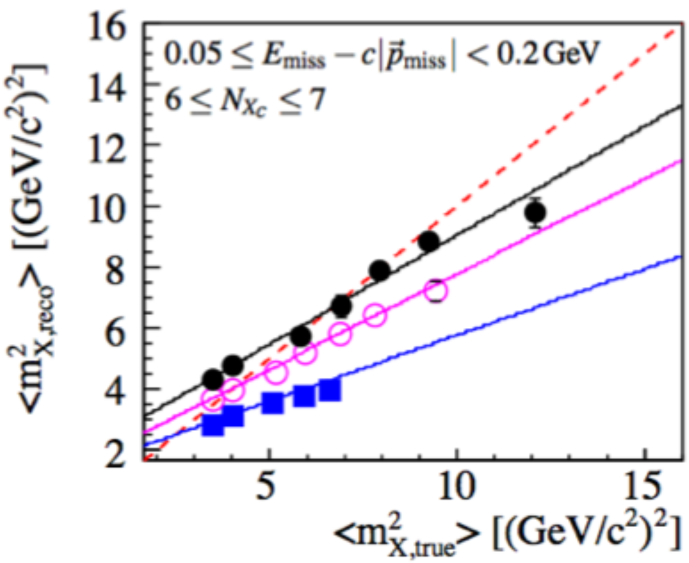

- Require one identified lepton amongst the signal-side particles (p > 0.8 GeV/c)
- Combine all remaining particles to the X system and do a kinematic fit
  - 4-momentum conservation
  - Missing mass consistent with zero mass neutrino

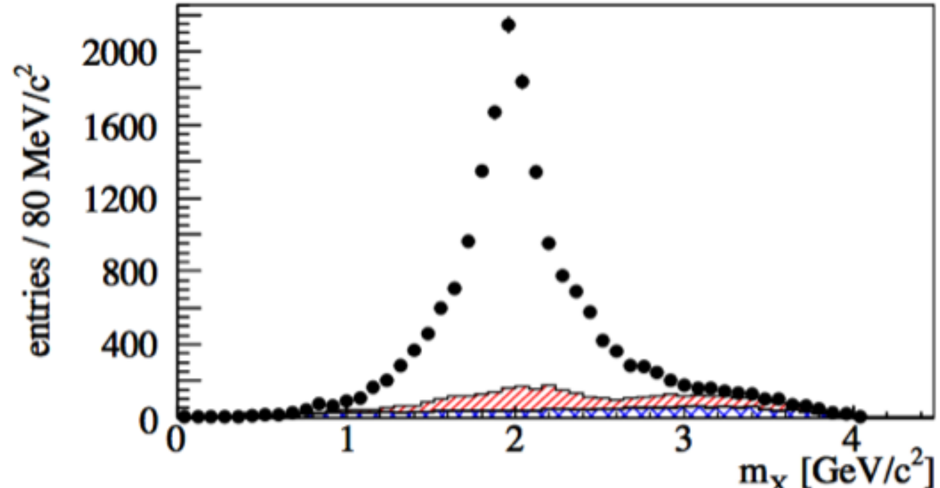
# Moment measurement

PRD 81, 032003 (2010)

232M BB

- Hadronic mass spectrum after kinematic fit




- Linear correction of the measured moments in bins of X multiplicity, $E_{miss}$-$cp_{miss}$ and lepton momentum

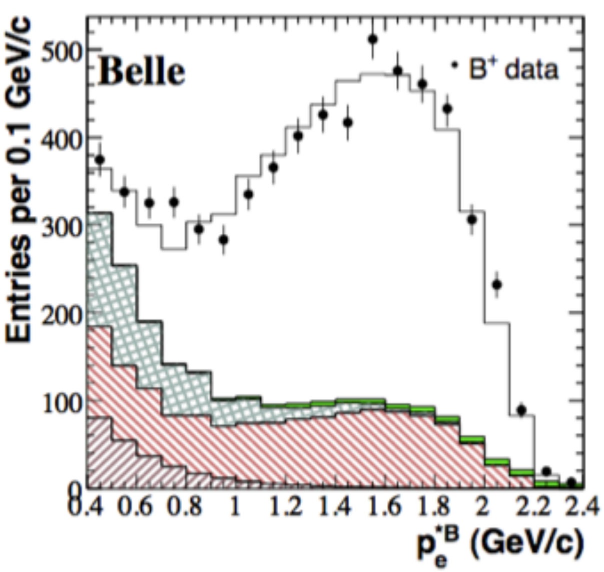
- Moments of the hadronic mass spectrum up to $M^6_X$ for $E_{cut}$ between 0.8 and 1.9 GeV are measured
- Also mixed mass-energy moments are determined and the electron energy moments from [PRD69, 111104] are re-evaluated

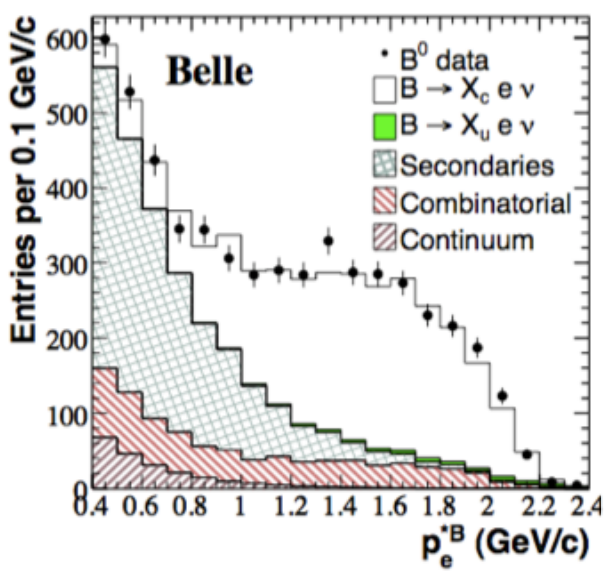
# Belle $E_l$ and $M^2_X$ moments

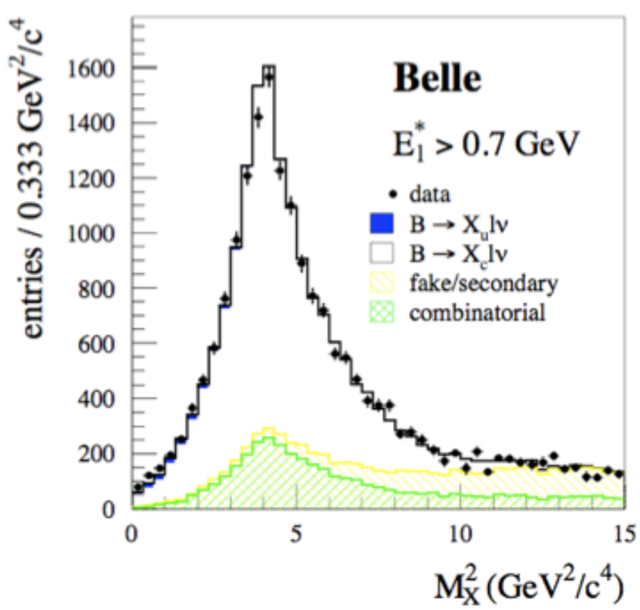
PRD 75, 032001 (2007)
PRD 75, 032005 (2007)

152M BB

- For both the $E_l$ and $M^2_X$ measurements, similar experimental method using fully reconstructed events
- The finite detector resolution is unfolded with SVD algorithm [NIM A372, 469 (1996)]
- $<E^n_e>$ measured for n=0,…,4 and $E_{cut}$=0.4-2.0 GeV
- $<M^{2n}_X>$ measured for n=1,2 and $E_{cut}$=0.7-1.9 GeV



# 1S scheme analysis

HFLAV

Summer 2016

| | $m_b^{1S}$ [GeV] | $\lambda_1$ [GeV$^2$] | $\rho_1$ [GeV$^3$] | $\tau_1$ [GeV$^3$] | $\tau_2$ [GeV$^3$] | $\tau_3$ [GeV$^3$] | $\lvert V_{cb}\rvert$ [$10^{-3}$] |
|---|---|---|---|---|---|---|---|
| value | 4.691 | −0.362 | 0.043 | 0.161 | −0.017 | 0.213 | 41.98 |
| error | 0.037 | 0.067 | 0.048 | 0.122 | 0.062 | 0.102 | 0.45 |
| $m_b^{1S}$ | 1.000 | 0.434 | 0.213 | −0.058 | −0.629 | −0.019 | −0.215 |
| $\lambda_1$ | | 1.000 | −0.467 | −0.602 | −0.239 | −0.547 | −0.403 |
| $\rho_1$ | | | 1.000 | 0.129 | −0.624 | 0.494 | 0.286 |
| $\tau_1$ | | | | 1.000 | 0.062 | −0.148 | 0.194 |
| $\tau_2$ | | | | | 1.000 | −0.009 | −0.145 |
| $\tau_3$ | | | | | | 1.000 | 0.376 |
| $\lvert V_{cb}\rvert$ | | | | | | | 1.000 |

$\chi^2$ of 23.0 for 59 degrees of freedom

- B quark mass constrained with $B \to X_s \gamma$ data
- Average B lifetime: ( 1.579 +/- 0.004 ) ps