# *Measurements of $|V_{cb}|$*

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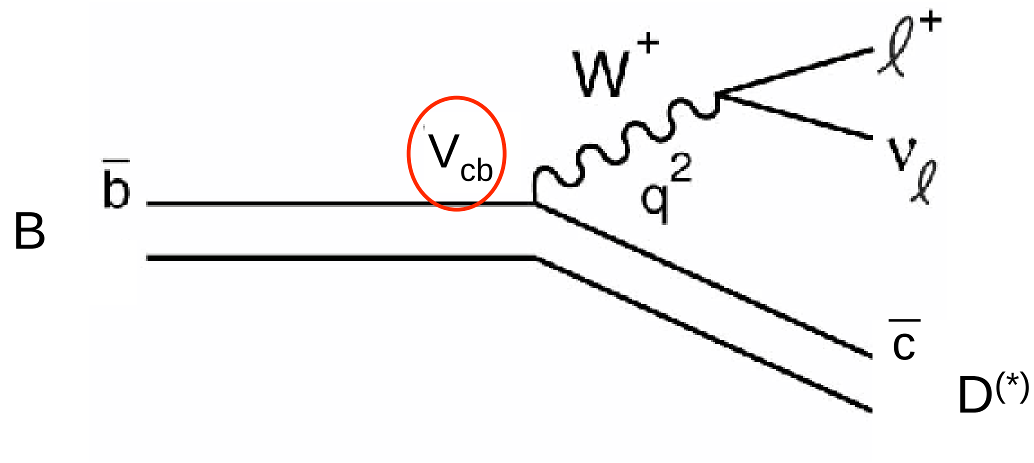
# $|V_{cb}|$ from inclusive decays

# Semileptonic width




- $\Gamma(B \to X_c l\nu)$ can be expanded in powers of $1/m_b$ (Operator Product Expansion)
- At each order in $1/m_b$: perturbative Wilson coefficient multiplied by expectation value of local operator which encodes soft QCD physics
- Lowest order: decay of free b-quark, linear order absent, non-perturbative corrections are $O(1/m_b^2)$

from [Benson et al., Nucl. Phys. B665, 367 (2003)]

$$\Gamma_{\rm sl}(b\to c) = \frac{G_F^2\, m_b^5(\mu)}{192\,\pi^3}\,|V_{cb}|^2\,(1+A_{\rm ew})\,A^{\rm pert}(r,\mu)$$

$$\left[ z_0(r)\left(1-\frac{\mu_\pi^2(\mu)-\mu_G^2(\mu)+\frac{\rho_D^3(\mu)+\rho_{LS}^3(\mu)}{m_b(\mu)}}{2m_b^2(\mu)}\right) - 2(1-r)^4\frac{\mu_G^2(\mu)-\frac{\rho_D^3(\mu)+\rho_{LS}^3(\mu)}{m_b(\mu)}}{m_b^2(\mu)} + d(r)\frac{\rho_D^3(\mu)}{m_b^3(\mu)} + \ldots \right]$$

$$r = m_c^2(\mu)/m_b^2(\mu)$$

$$\mu_\pi^2(\mu) \equiv \frac{1}{2M_B}\langle B|\bar{b}(i\vec{D})^2 b|B\rangle_\mu\,, \qquad \mu_G^2(\mu) \equiv \frac{1}{2M_B}\langle B|\bar{b}\frac{i}{2}\sigma_{jk}G^{jk}b|B\rangle_\mu$$

$$\rho_D^3(\mu) \equiv \frac{1}{2M_B}\langle B|\bar{b}(-\frac{1}{2}\vec{D}\cdot\vec{E})b|B\rangle_\mu\,, \qquad \rho_{LS}^3(\mu) \equiv \frac{1}{2M_B}\langle B|\bar{b}(\vec{\sigma}\cdot\vec{E}\times i\vec{D})b|B\rangle_\mu$$

(result in kinetic scheme)

# Other observables in B decays

- Moments of the lepton energy spectrum in $B \to X_c l\nu$

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

- Moments of the hadronic mass spectrum in $B \to X_c l\nu$

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

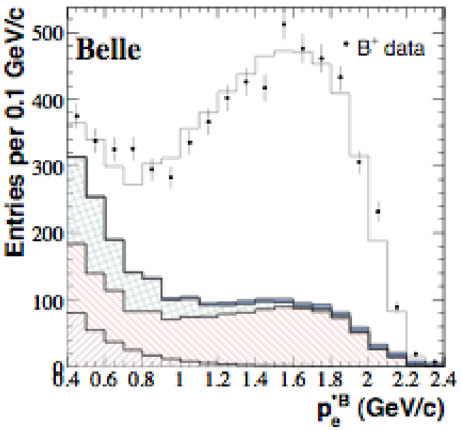
- Moments of the photon energy spectrum in $B \to X_s \gamma$

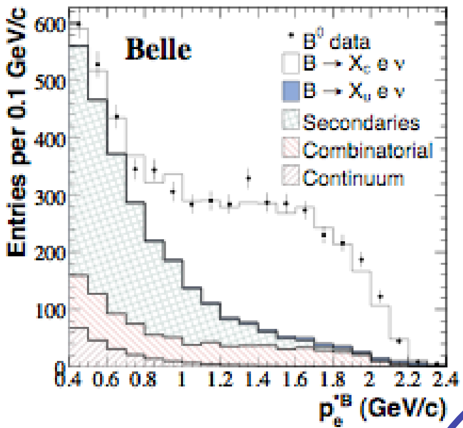
$$\langle E_\gamma^n \rangle_{E_{\rm cut}} = \frac{\displaystyle\int_{E_{\rm cut}} E_\gamma^n \, \frac{{\rm d}\Gamma}{{\rm d}E_\gamma}\, {\rm d}E_\gamma}{\displaystyle\int_{E_{\rm cut}} \frac{{\rm d}\Gamma}{{\rm d}E_\gamma}\, {\rm d}E_\gamma}$$

The OPEs of these inclusive observables contain the same HQ parameters

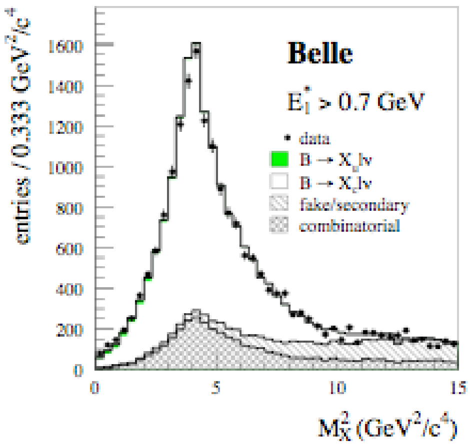
- Non-perturbative parameters can be measured from inclusive observables in B decays

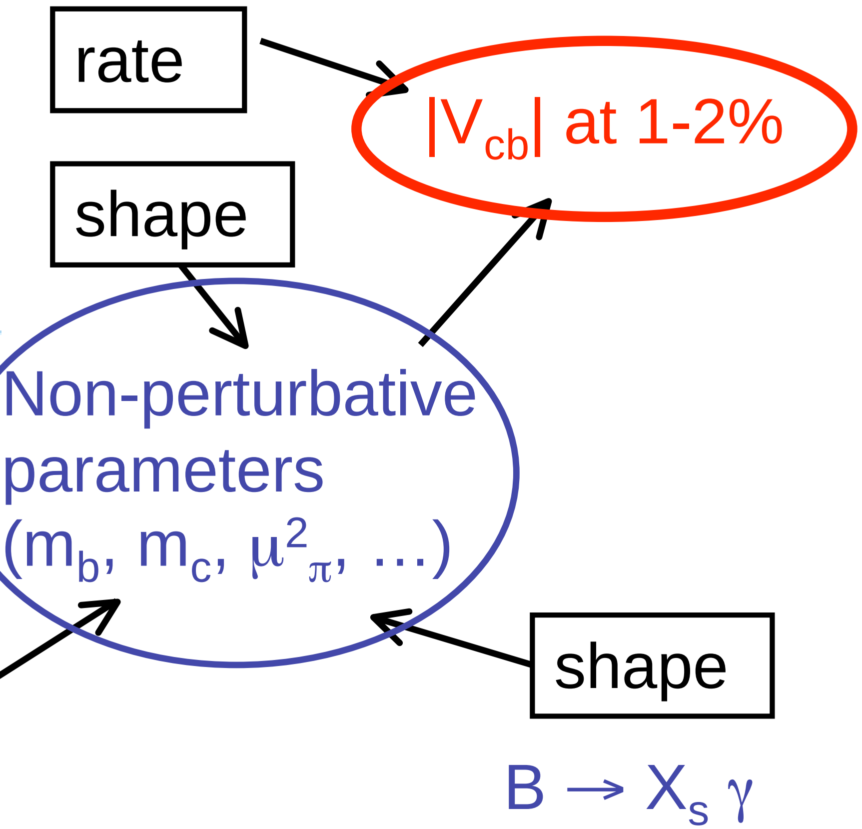
Inclusive $E_l$ spectrum




Inclusive $M^2_X$ spectrum



# Available calculations

- Kinetic running mass
  - [P.Gambino, N.Uraltsev, Eur.Phys.J. C34, 181 (2004)]
  - [D.Beson, I.Bigi, N.Uraltsev, Nucl.Phys. B710, 371 (2005)]

both calculations up to $O(1/m^3_b)$

- 1S mass
  - [C.Bauer, Z.Ligeti, M.Luke, A.Manohar, M.Trott, Phys.Rev. D70, 094017 (2004)]

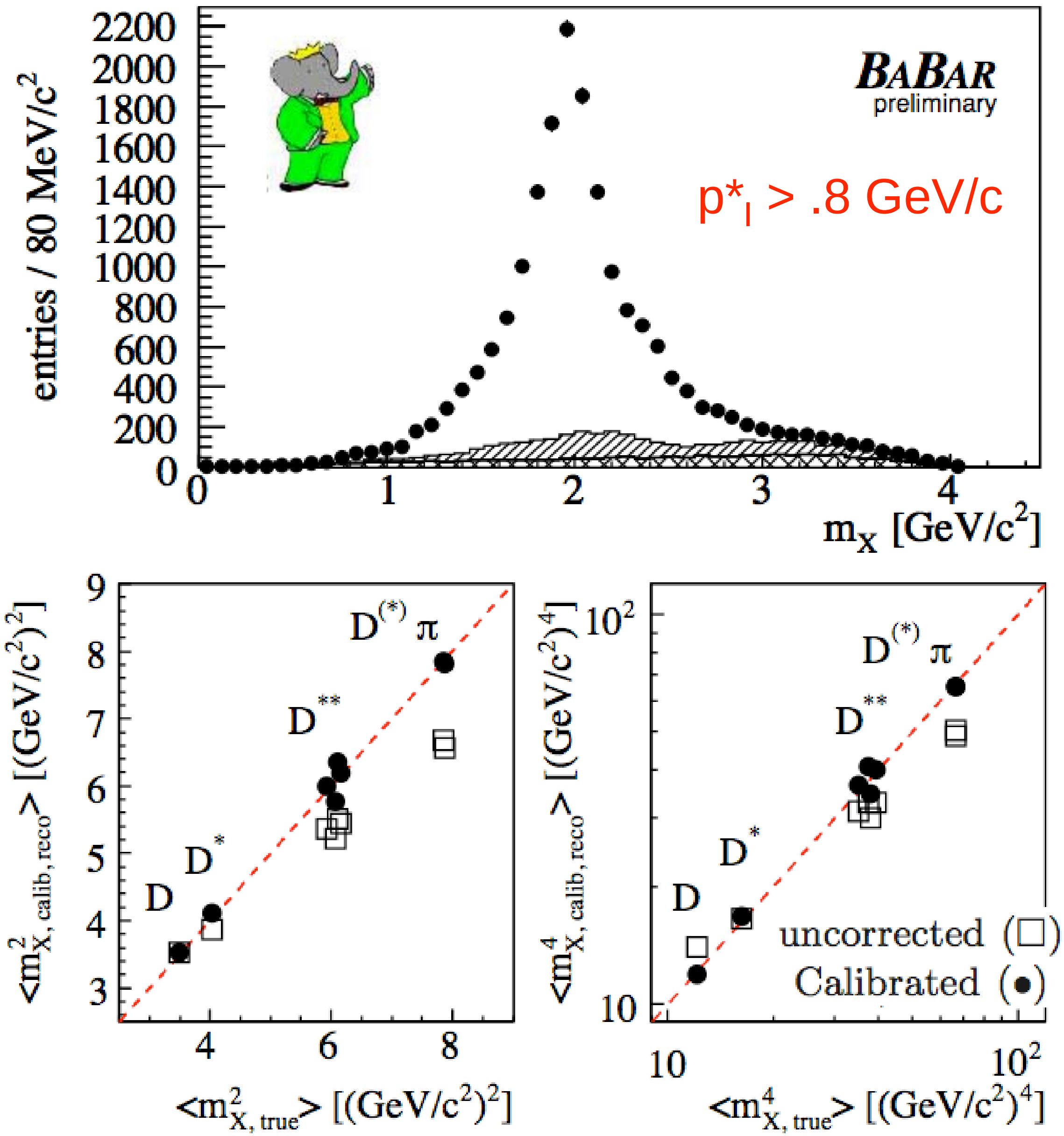
- Non-perturbative parameters in the $1/m_b$ expansion

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

# BaBar $M^2_X$ moments

[arXiv:0707.2670] preliminary

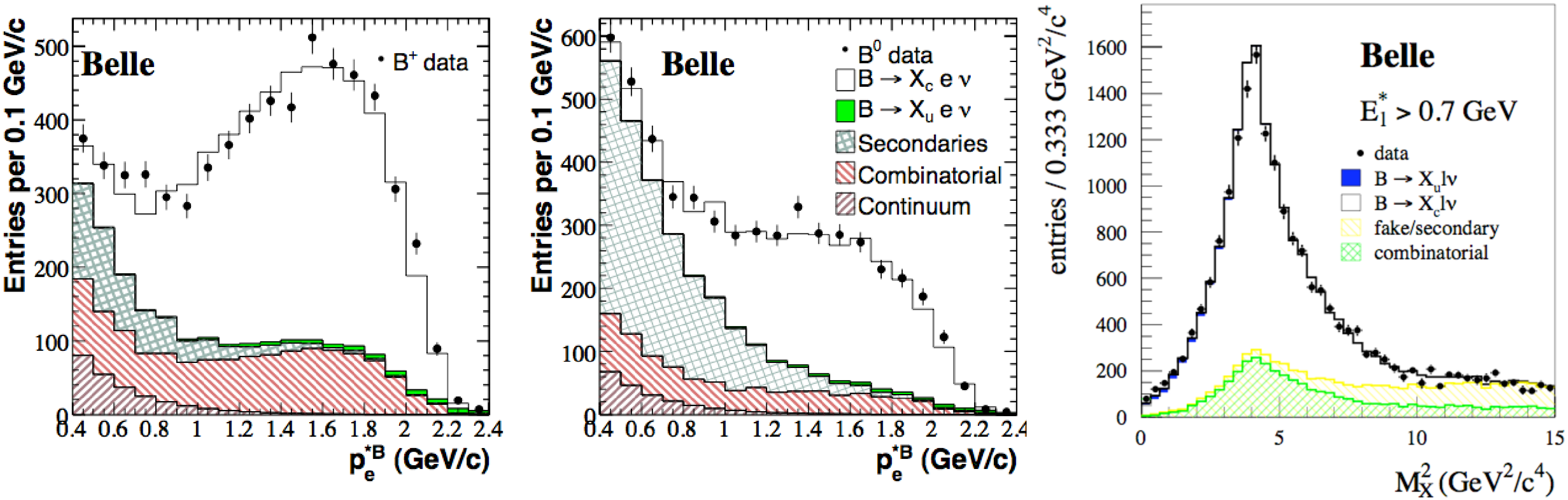
- 210/fb of Y(4S) data
- Hadronic decay of one B meson fully reconstructed
- Semileptonic decay of other B selected by requiring identified lepton (e/μ)
- Reconstructed moments corrected event-by-event for detector effects
- $\langle M^k_X \rangle$ measured for k=1,…,6 and $p^*_{cut}$ from 0.8 to 1.9 GeV/c



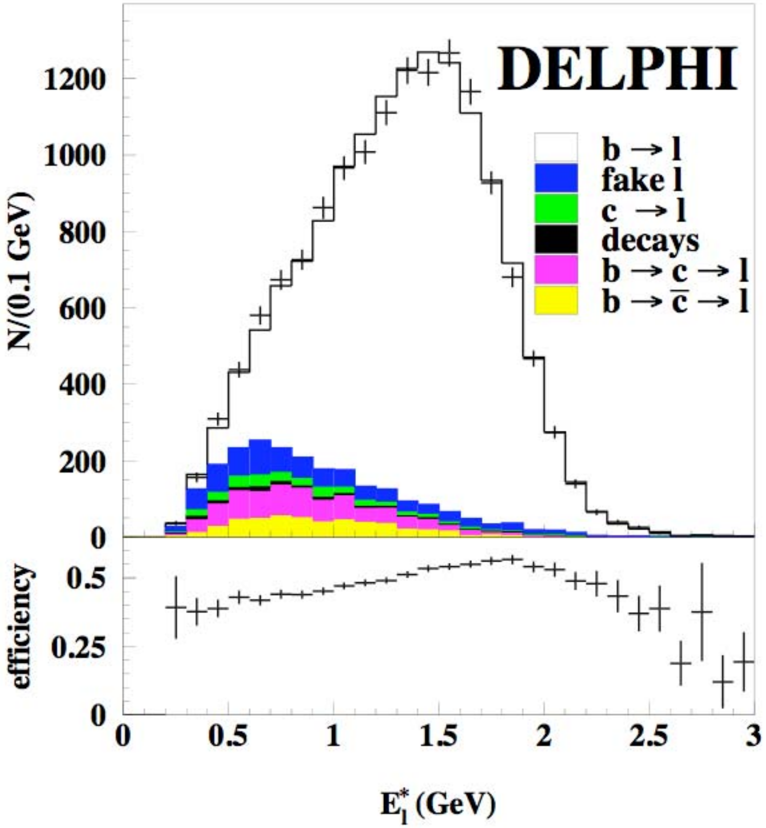
# Belle $E_l$ and $M^2_X$ moments

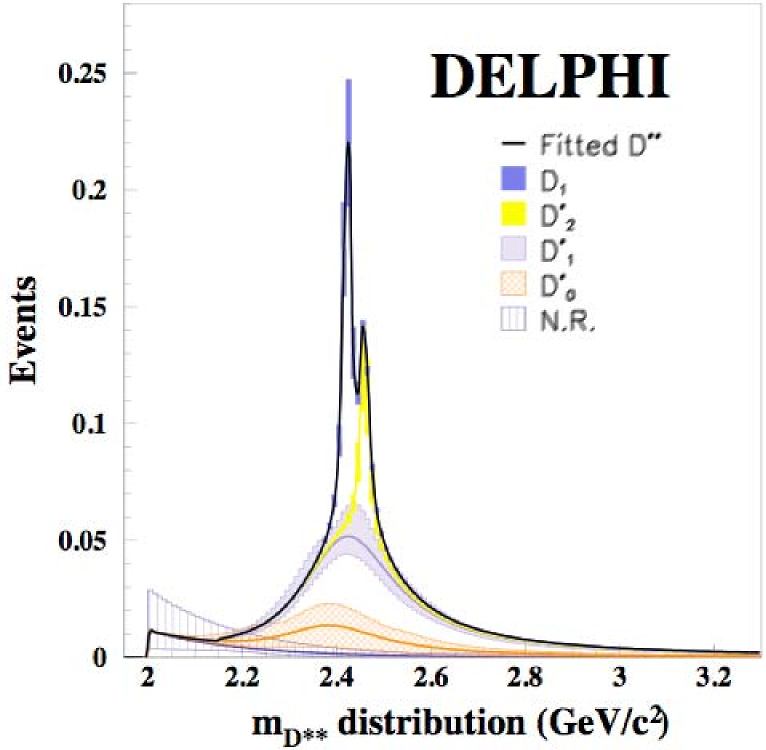
[PRD 75, 032001 (2007)]
[PRD 75, 032005 (2007)]

- 140/fb of Y(4S) data
- Measurement also done with fully reconstructed events
- The finite detector resolution is unfolded with SVD algorithm [NIM A372, 469 (1996)]
- $\langle E^n_e \rangle$ measured for n=0,…,4 and $E_{cut}$=0.4-2.0 GeV
- $\langle M^{2n}_X \rangle$ measured for n=1,2 and $E_{cut}$=0.7-1.9 GeV



# DELPHI $E_l$ and $M^2_X$ moments [EPJ C45, 35 (2006)]



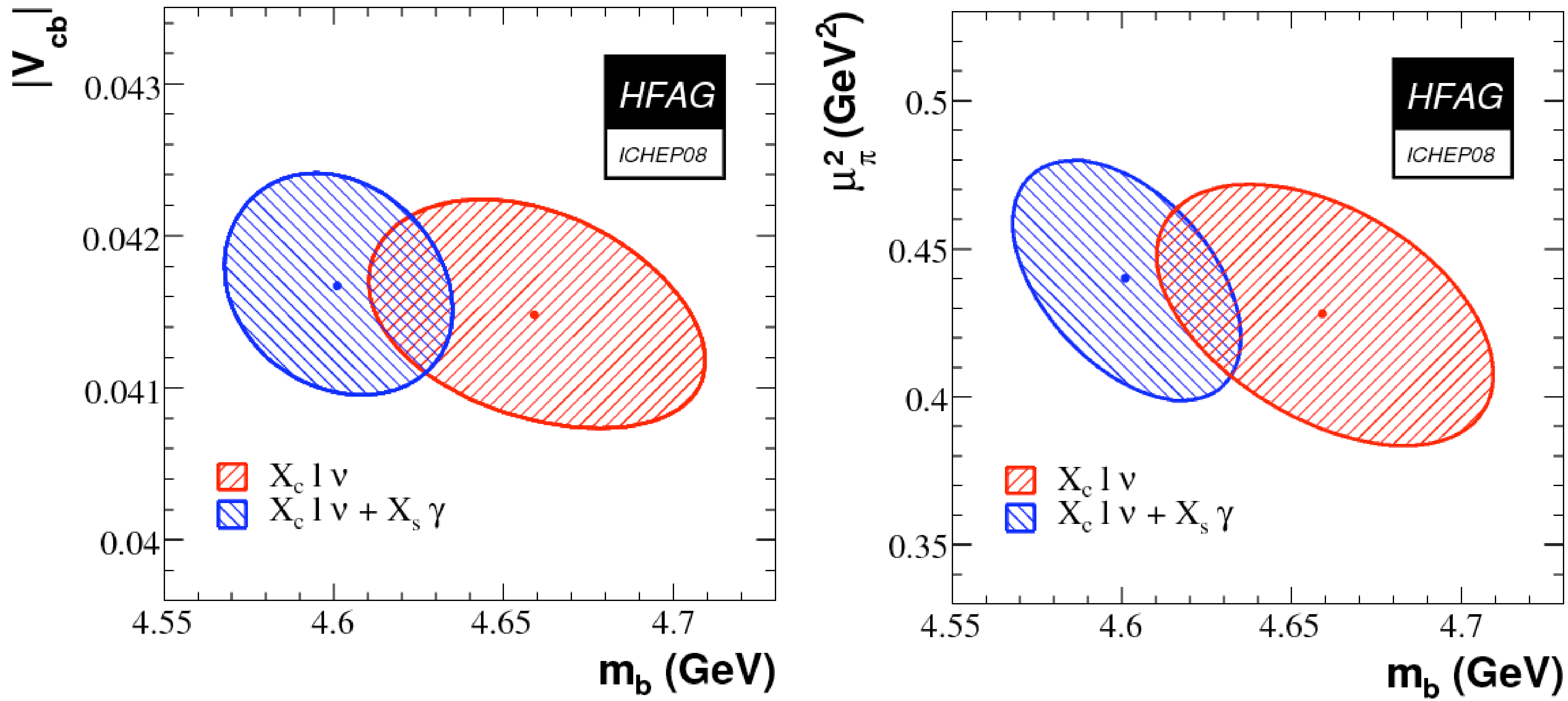




- $\langle E^n_l \rangle$, n=1,…,3 and $\langle M^{2n}_X \rangle$, n=1,…,5 measured at $E_{cut} = 0$ as in Z events the b-quark is produced with a boost
- The hadronic moments are derived from the fitted D** mass spectrum; assumptions on the D** decay are made

# HFAG kinetic scheme fit

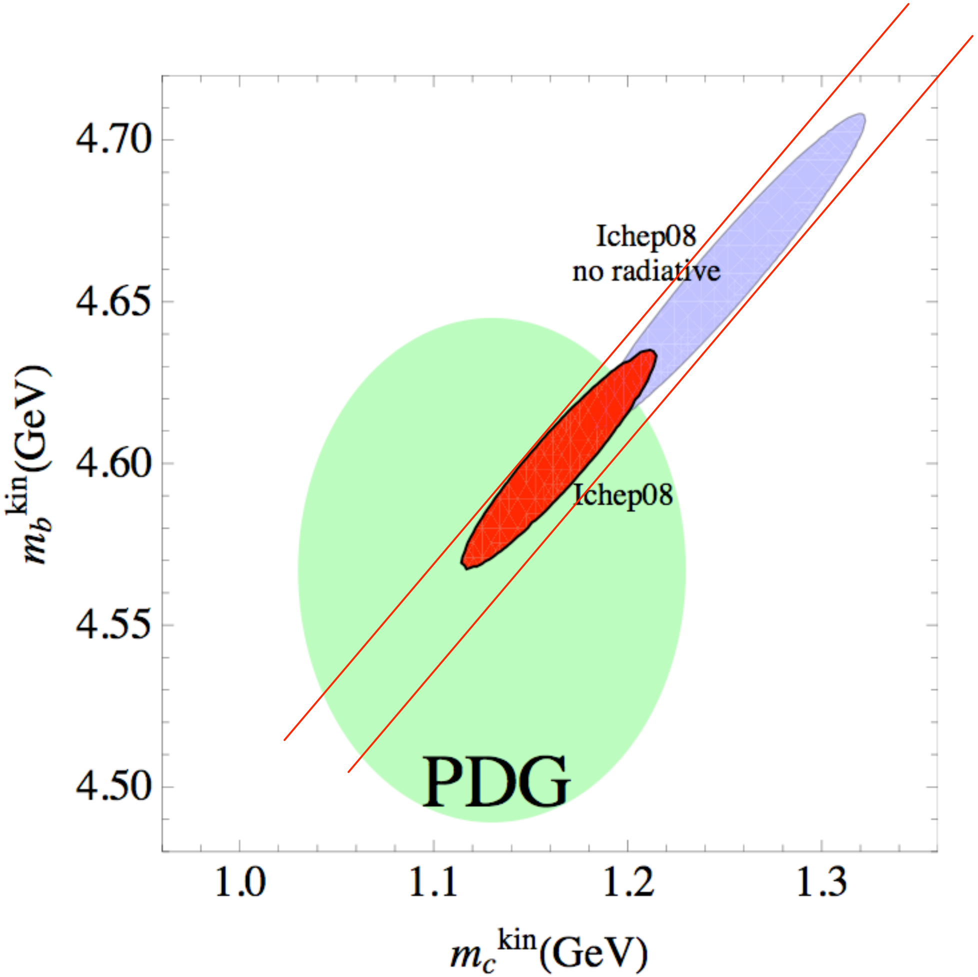
| | |
|---|---|
| BaBar | $\langle E^n_l \rangle$: n=0,1,2,3 [PRD 69, 111104 (2004)]<br>$\langle M^{2n}_X \rangle$: n=1,2 [arXiv:0707.2670] preliminary<br>$\langle E^n_\gamma \rangle$: n=1,2 [PRL 97, 171803 (2006)] and [PRD 72, 052004 (2005)] |
| Belle | $\langle E^n_l \rangle$: n=0,1,2,3 [PRD 75, 032001 (2007)]<br>$\langle M^{2n}_X \rangle$: n=1,2 [PRD 75, 032005 (2007)]<br>$\langle E^n\gamma \rangle$: n=1,2 [arXiv:0804.1580] preliminary |
| 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)] |

- 27 moments from BaBar, 25 moments from Belle and 12 moments from other experiments




| Input | $\lvert V_{cb}\rvert$ ($10^{-3}$) | $m_b$ (GeV) | $\mu^2_\pi$ ($GeV^2$) | $\chi^2$/ndf |
|---|---|---|---|---|
| All moments | 41.67+/-0.43(fit)+/-0.08($\tau_B$)+/-0.58(th) | 4.601+/-0.034 | 0.440+/-0.040 | 29.7/57 |
| $X_c l\nu$ only | 41.48+/-0.47(fit)+/-0.08($\tau_B$)+/-0.58(th) | 4.659+/-0.049 | 0.428+/-0.044 | 24.1/46 |

- $B \to X_c l \nu$ moments only determine a band in the ($m_b$, $m_c$)-plane
- $B \to X_s \gamma$ needed to fix b-quark mass $m_b$
- $m_b$ from global fit (with $B \to X_s \gamma$) consistent with PDG estimate




Paolo Gambino

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

# $B^0 \rightarrow D^{(*)-} l^+ \nu$ width

$$\frac{d\Gamma}{dw}(\overline{B} \rightarrow D^* \ell \overline{\nu}_\ell) = \frac{G_F^2}{48\pi^3}|V_{cb}|^2 m_{D^*}^3 (w^2 - 1)^{1/2} P(w) (\mathcal{F}(w))^2$$

$$\frac{d\Gamma}{dw}(\overline{B} \rightarrow D \ell \overline{\nu}_\ell) =$$

form factor

$$\frac{G_F^2}{48\pi^3}|V_{cb}|^2 (m_B + m_D)^2 m_D^3 (w^2 - 1)^{3/2} (\mathcal{G}(w))^2 \qquad w \equiv v \cdot v'$$

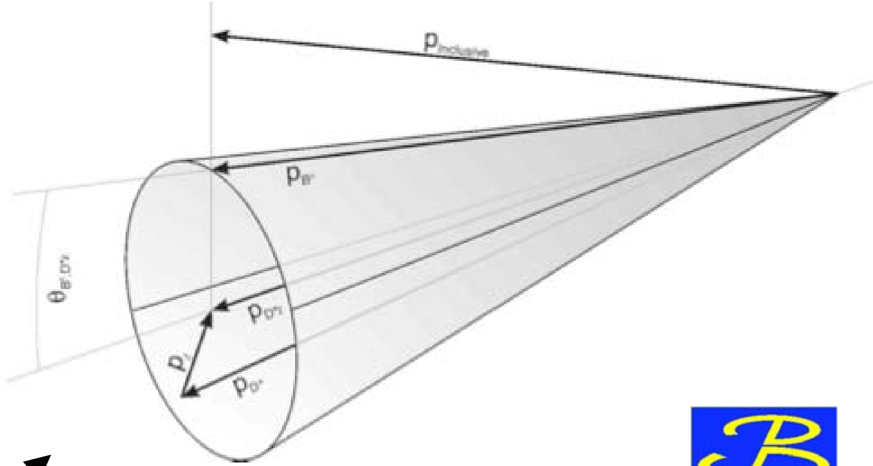
- Experiments fit $F(1)|V_{cb}|$ and $G(1)|V_{cb}|$ using a form factor parameterization based on HQET and dispersion relations [Caprini et al., Nucl. Phys. B530, 153 (1998)]
- Form factor parameters are $\rho^2$, $R_1$, $R_2$ ($\rho^2$) for $D^*l\nu$ ($Dl\nu$)
- Form factor normalizations from lattice QCD

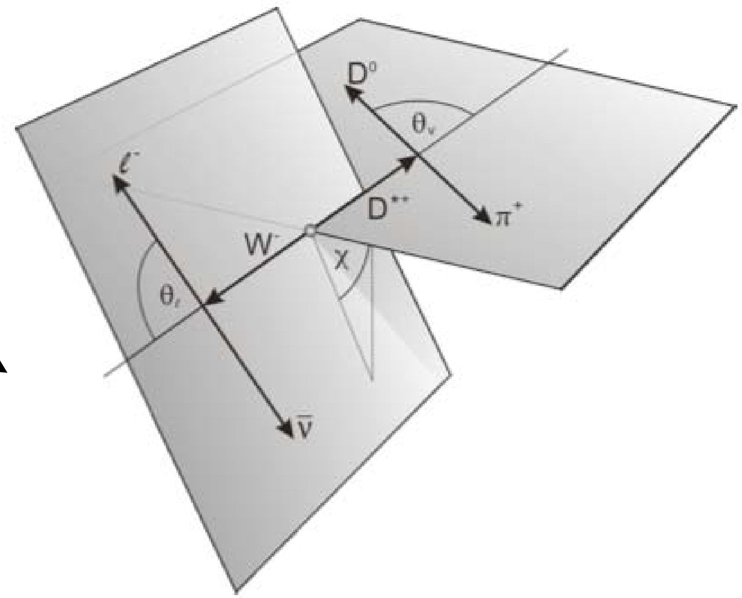
| | |
|---|---|
| F(1) = 0.921 +/- 0.013 +/- 0.020 | C.Bernard et al. [Phys.Rev.D79, 014506 (2009)] New ! |
| G(1) = 1.074 +/- 0.018 +/- 0.016 | M.Okamoto et al. [Nucl.Phys.Proc.Suppl. 140, 461 (2005)] |

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

[arXiv:0810.1657] preliminary

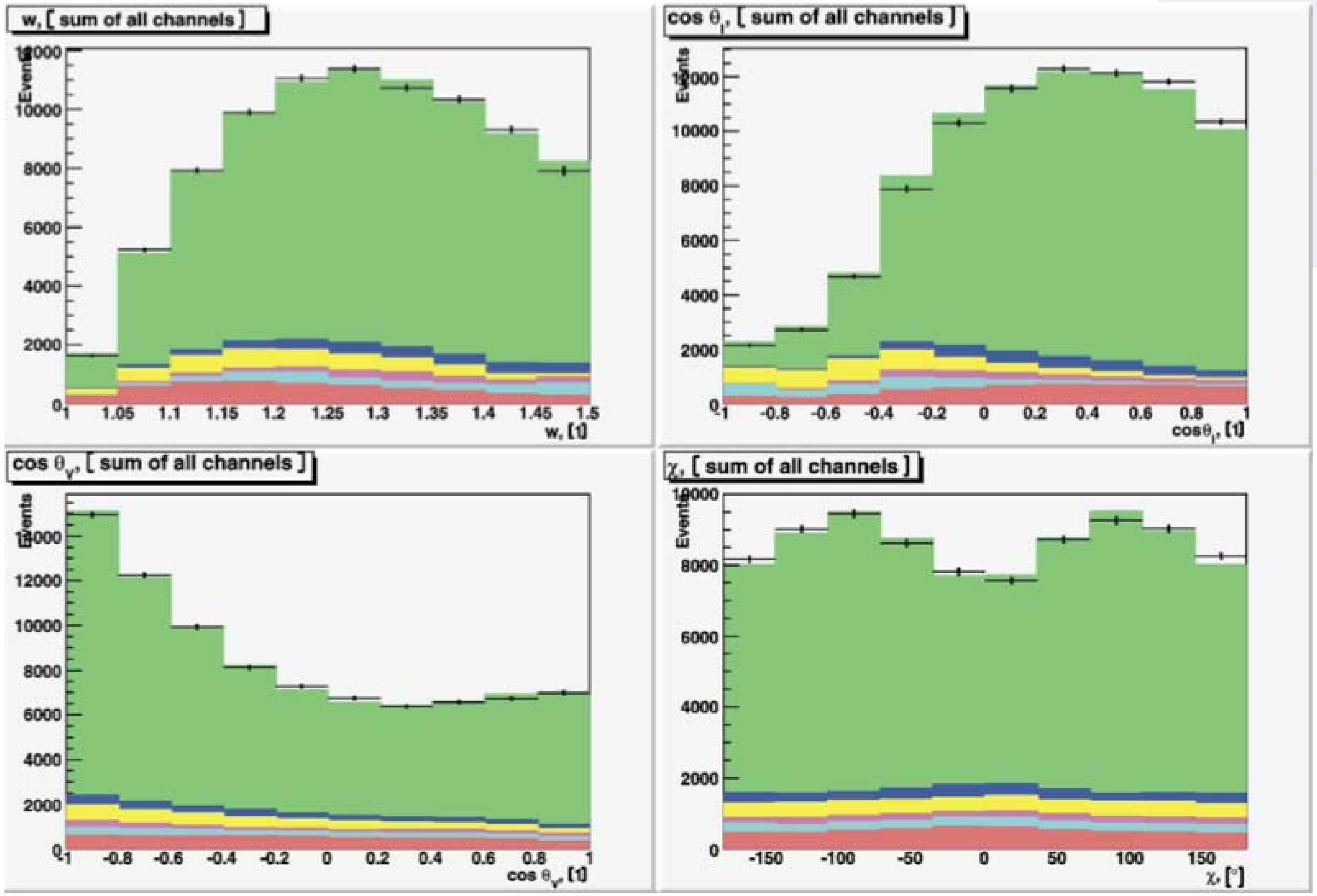
- Reconstruct the decay in 140/fb of Y(4S) data
  - $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$,
    - $D^{*+} \to D^0\pi^+$
      - $D^0 \to K^-\pi^+$
      - $D^0 \to K^-\pi^+\pi^-\pi^+$
- Reconstruct the neutrino momentum using kinematics and the remaining particles in the event, to estimate B direction
- Reconstruct w and three angles that describe the decay
  - $w = \frac{p_B^\mu \cdot p_{D^*,\mu}}{m_B\, m_{D^*}}$
  - $\cos\theta_\ell$, $\cos\theta_V$, $\chi$





- Fit the 4 observables to the HQET parameterization of the quadruple differential cross section (binned least squares fit to the marginal distributions)

$$
\begin{aligned}
&\frac{\mathrm{d}^4\Gamma(B^0 \to D^{*-}\ell^+\nu_\ell)}{\mathrm{d}w\,\mathrm{d}(\cos\theta_\ell)\mathrm{d}(\cos\theta_V)\mathrm{d}\chi} = \\
&\quad = \frac{6 m_B m_{D*}^2}{8(4\pi)^4}\sqrt{w^2-1}(1-2wr+r^2)G_F^2|V_{cb}|^2 \\
&\quad \times \{(1-\cos\theta_\ell)^2\sin^2\theta_V H_+^2(w) \\
&\qquad + (1+\cos\theta_\ell)^2\sin^2\theta_V H_-^2(w) \\
&\qquad + 4\sin^2\theta_\ell\cos^2\theta_V H_0^2(w) \\
&\qquad - 2\sin^2\theta_\ell\sin^2\theta_V\cos 2\chi H_+(w)H_-(w) \\
&\qquad - 4\sin\theta_\ell(1-\cos\theta_\ell) \\
&\qquad\qquad \sin\theta_V\cos\theta_V\cos\chi H_+(w)H_0(w) \\
&\qquad + 4\sin\theta_\ell(1+\cos\theta_\ell) \\
&\qquad\qquad \sin\theta_V\cos\theta_V\cos\chi H_-(w)H_0(w)\}
\end{aligned}
$$



Preliminary results

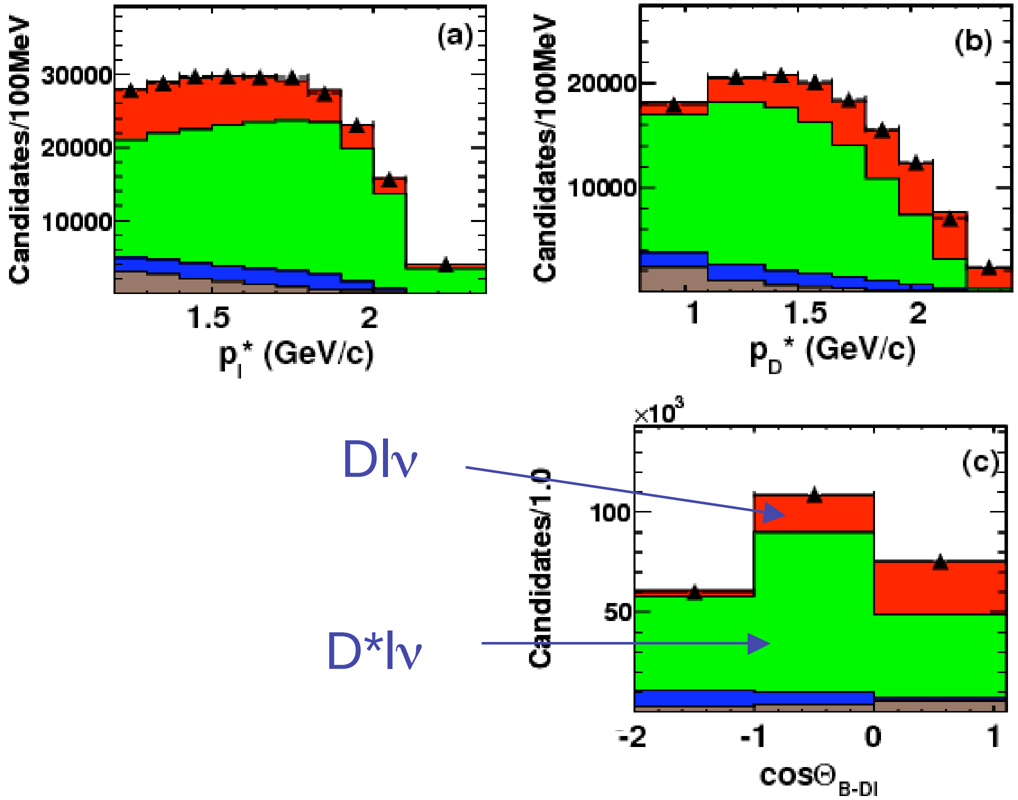
| | |
|---|---|
| $\rho^2$ | $1.293 \pm 0.045 \pm 0.029$ |
| $R_1(1)$ | $1.495 \pm 0.050 \pm 0.062$ |
| $R_2(1)$ | $0.844 \pm 0.034 \pm 0.019$ |
| $R_{K3\pi/K\pi}$ | $2.153 \pm 0.011$ |
| $\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell)$ | $(4.42 \pm 0.03 \pm 0.25)\%$ |
| $\mathcal{F}(1)\,\lvert V_{cb}\rvert \times 10^3$ | $34.4 \pm 0.2 \pm 1.0$ |
| $\chi^2/\text{n.d.f.}$ | $138.8/155$ |
| $P_{\chi^2}$ | $82.0\%$ |

| | $\rho^2$ | $R_1(1)$ | $R_2(1)$ | $\mathcal{B}(B^0)$ | $\mathcal{F}(1)\,\lvert V_{cb}\rvert$ |
|---|---|---|---|---|---|
| Stat. error | 0.050 | 0.060 | 0.043 | 0.030 | 0.22 |
| $D^{**}$ | 0.015 | 0.038 | 0.011 | 0.051 | 0.25 |
| Uncorr. | 0.009 | 0.028 | 0.002 | 0.003 | 0.04 |
| Sig.corr. | 0.003 | 0.003 | 0.007 | 0.028 | 0.14 |
| Fake $\ell$ | 0.020 | 0.037 | 0.009 | 0.002 | 0.04 |
| Fake $D^*$ | 0.012 | 0.011 | 0.009 | 0.034 | 0.33 |
| Continuum | 0.003 | 0.008 | 0.000 | 0.001 | 0.02 |
| Trk., det.eff. | - | - | - | 0.221 | 0.86 |
| $\mathcal{B}(D^0)$ | - | - | - | 0.081 | 0.31 |
| $\mathcal{B}(D^*)$ | - | - | - | 0.033 | 0.13 |
| $B^0$ life time | - | - | - | 0.026 | 0.10 |
| $N_{B\bar{B}}$ | - | - | - | 0.036 | 0.14 |
| $f_{+-}/f_{0\bar{0}}$ | 0.003 | 0.011 | 0.005 | 0.001 | 0.04 |
| Syst. error | 0.029 | 0.062 | 0.019 | 0.251 | 1.04 |

Systematic uncertainty

# BaBar B → DXlν global fit [PRD 79, 012002 (2009)]

- Reconstruct $D^0l$ and $D^+l$ ($l$=e,μ) combinations in 207/fb of Υ(4S) data
- Fit $F(1)|V_{cb}|$, $G(1)|V_{cb}|$, $\rho^2_{D^*}$ and $\rho^2_D$ using the kinematic variables $p^*_l$, $p^*_D$ and $\cos\theta_{B\text{-}Dl}$
- No slow pion systematics for D*lν

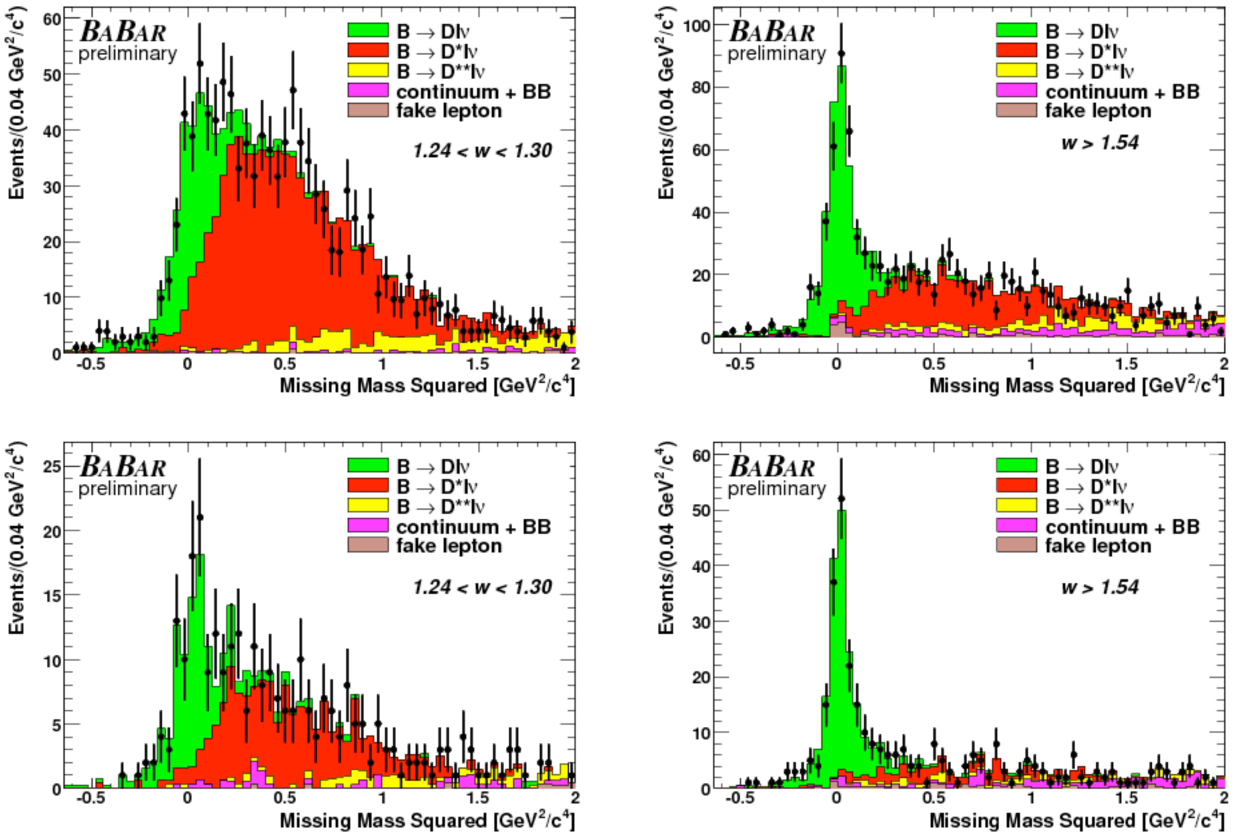



$F(1)|V_{cb}|$ = (35.9 +/- 0.2 +/- 1.2) x $10^{-3}$

$G(1)|V_{cb}|$ = (43.1 +/- 0.8 +/- 2.3) x $10^{-3}$

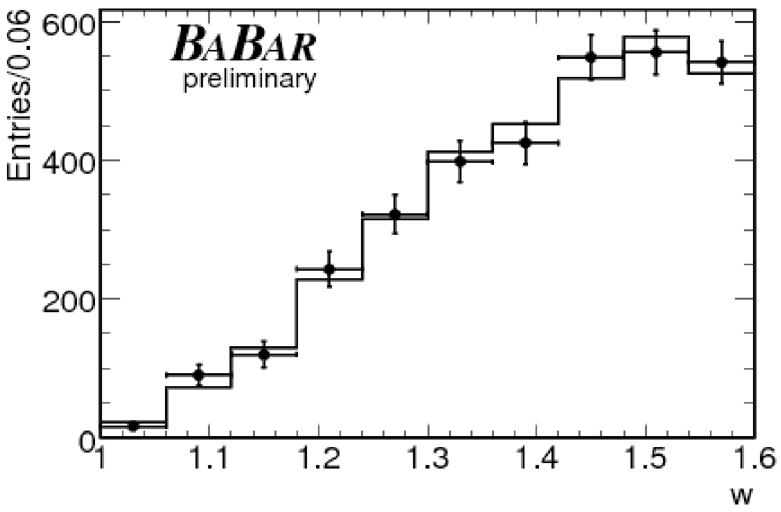
# BaBar B $\rightarrow$ Dl$\nu$ with hadronic tag

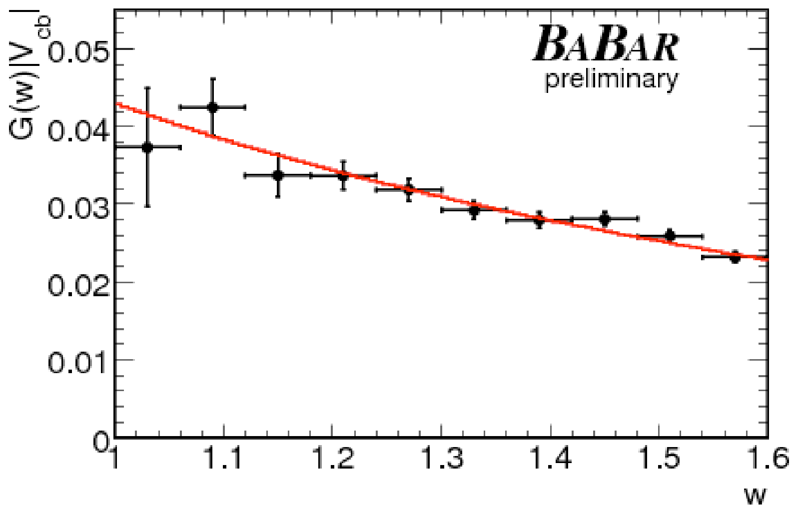
[arXiv:0807.4978] prel.




- Use 417/fb of Y(4S) data in which the hadronic decay of one B is fully reconstructed
- Reconstruct $B^0 \rightarrow D^- l^+ \nu$ and $B^+ \rightarrow D^0 l^+ \nu$ on signal side in 10 bins of w and fit $G(1)|V_{cb}|$ and $\rho^2$

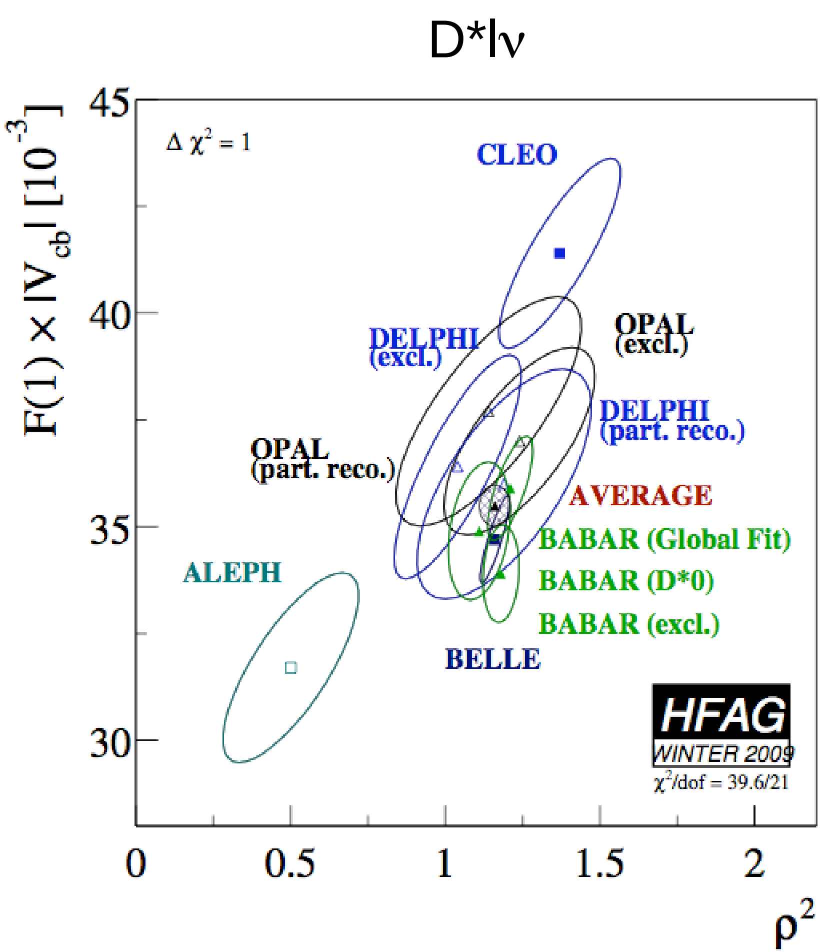
| | $B^- \to D^0 \ell^- \bar{\nu}_\ell$ | $\overline{B}^0 \to D^+ \ell^- \bar{\nu}_\ell$ | $\overline{B} \to D \ell^- \bar{\nu}_\ell$ |
|---|---|---|---|
| $\mathcal{G}(1)\lvert V_{cb}\rvert \cdot 10^3$ | $41.7 \pm 2.1$ | $45.6 \pm 3.3$ | $43.0 \pm 1.9$ |
| $\rho^2$ | $1.14 \pm 0.11$ | $1.29 \pm 0.14$ | $1.20 \pm 0.09$ |
| $\rho_{\rm corr}$ | 0.943 | 0.950 | 0.952 |
| $\chi^2/ndf$ | 3.4/8 | 5.6/8 | 9.9/18 |
| Signal Yield | $2147 \pm 69$ | $1108 \pm 45$ | - |
| Recon. efficiency | $(1.99 \pm 0.02) \cdot 10^{-4}$ | $(1.09 \pm 0.02) \cdot 10^{-4}$ | - |
| $\mathcal{B}$ | $(2.31 \pm 0.08)\%$ | $(2.23 \pm 0.11)\%$ | $(2.17 \pm 0.06)\%$ |

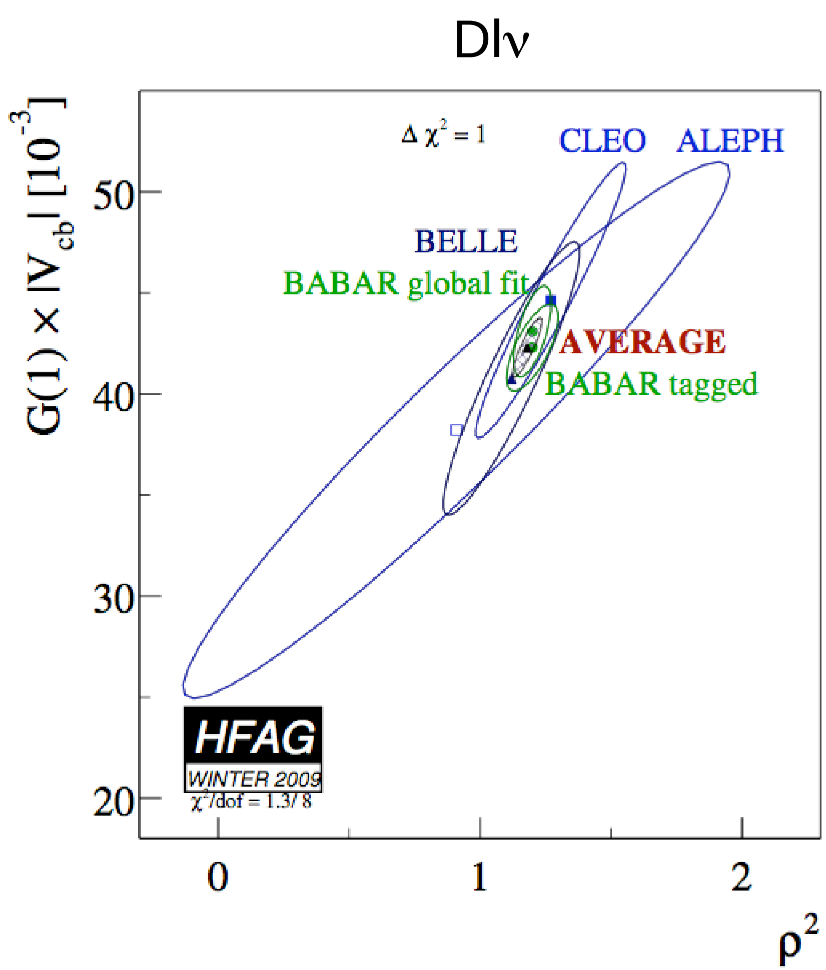



$G(1)|V_{cb}| = (43.0 +/- 1.9 +/- 1.4) \times 10^{-3}$

# HFAG winter 09 average




$$F(1)|V_{cb}| = (35.49 +/- 0.48) \times 10^{-3}$$

$$G(1)|V_{cb}| = (42.3 +/- 0.7(stat) +/- 1.3(syst)) \times 10^{-3}$$

# Summary and conclusions

- $|V_{cb}|$ inclusive

| | $\|V_{cb}\|$ ($10^{-3}$) | $m_b$ (GeV) |
|---|---|---|
| HFAG ICHEP08 | $41.67 \pm 0.43_{fit} \pm 0.08_{\tau B} \pm 0.58_{th}$ | $4.601 \pm 0.034$ |

- $|V_{cb}|$ exclusive (HFAG winter 09)

| | $\|V_{cb}\|$ ($10^{-3}$) |
|---|---|
| HFAG $D^*l\nu$ / C. Bernard et al. | $38.3 \pm 0.5_{exp} \pm 1.0_{th}$ |
| HFAG $Dl\nu$ / M. Okamoto et al. | $39.1 \pm 1.4_{exp} \pm 0.9_{th}$ |

- 2.5 sigma discrepancy between $|V_{cb}|$ inclusive and exclusive ($D^*l\nu$)

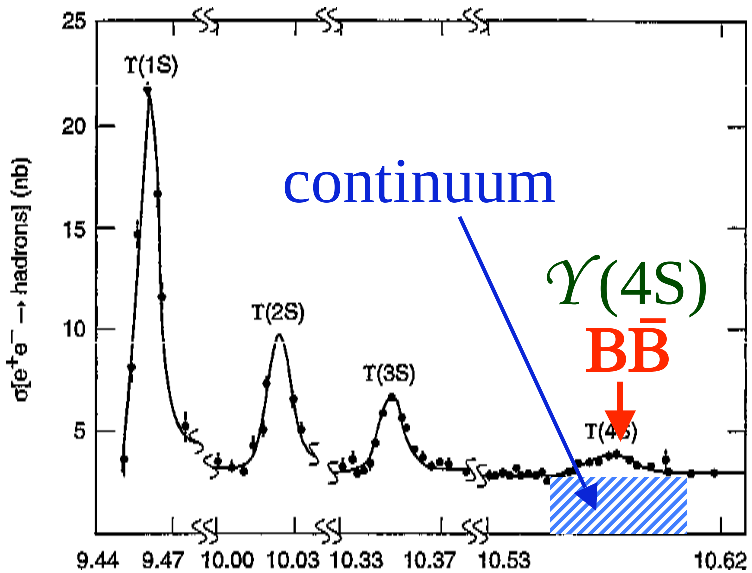
# Backup

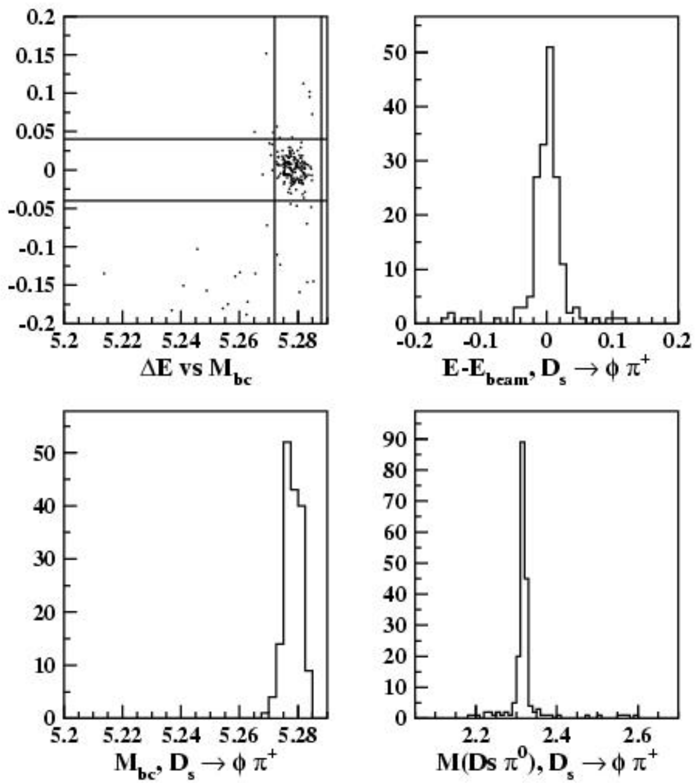
- At the Υ(4S), $B\bar{B}$ are produced at threshold
- This allows to
  - Select a B signal using two nearly independent variables

$$M_B = \sqrt{(E^*_{beam})^2 - (\Sigma P_i)^2}$$

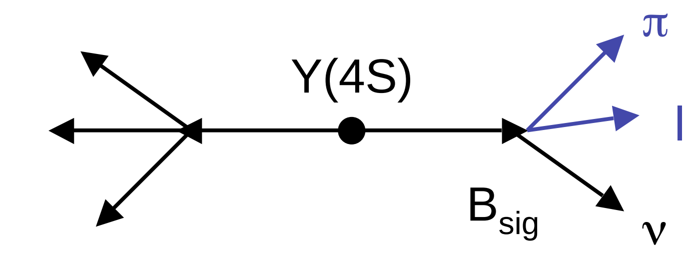
$$\Delta E = \Sigma E_i - E^*_{beam}$$

  - Determine the 4-momentum of one B by reconstructing the other
  - Distinguish $B\bar{B}$ (spherical) from continuum events (jet-like)



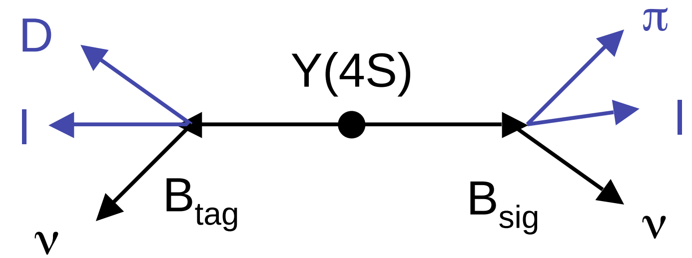
# Tagging




### Untagged

•Only signal reconstructed

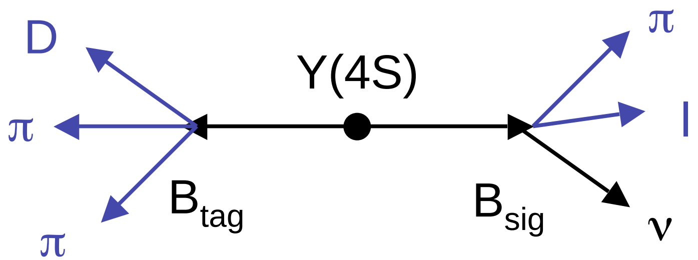
•High efficiency




### Semileptonic tag

•Good statistics, clean events

•Kinematics not fully reconstructed




### Fullrecon tag

•Kinematics fully known

•Low statistics