Semileptonic (and leptonic) B decays

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SuperKEKB collaboration

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Semileptonic/leptonic decays

precision measurements of $|V_{cb}|$ and $|V_{ub}|$

①

rare decays, search for new phenomena

②

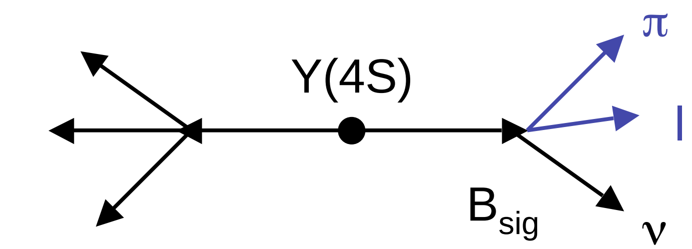
① Current precision

Specific final states

	$\|V_{cb}\|$	$\|V_{ub}\|$
exclusive	~3%	~16%
inclusive	~2%	~7%

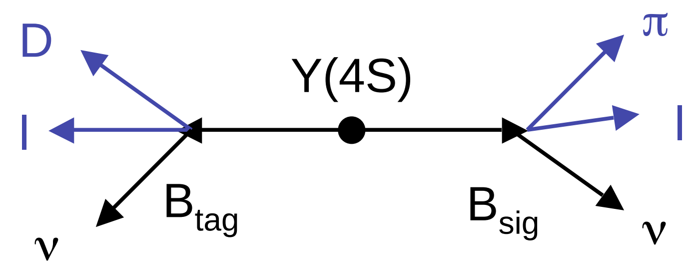
All final states within a given region of phase space

Tagging



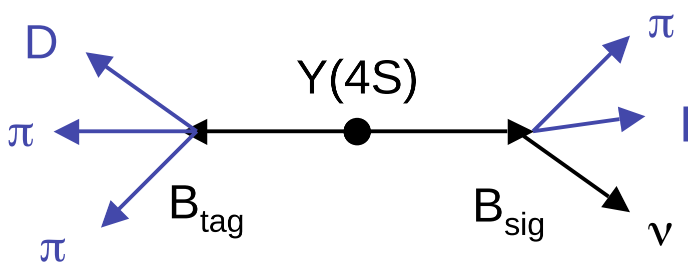
Untagged

- Only signal reconstructed
- High efficiency



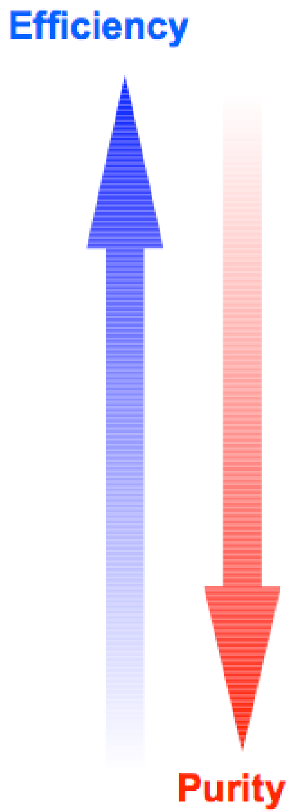
Semileptonic tag

- Good statistics, clean events
- Kinematics not fully reconstructed



Fullrecon tag

- Kinematics fully known
- Low statistics



$|V_{cb}|$ from $B^0 \to D^{(*)-} l^+ \nu$

- Decay width

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

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

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

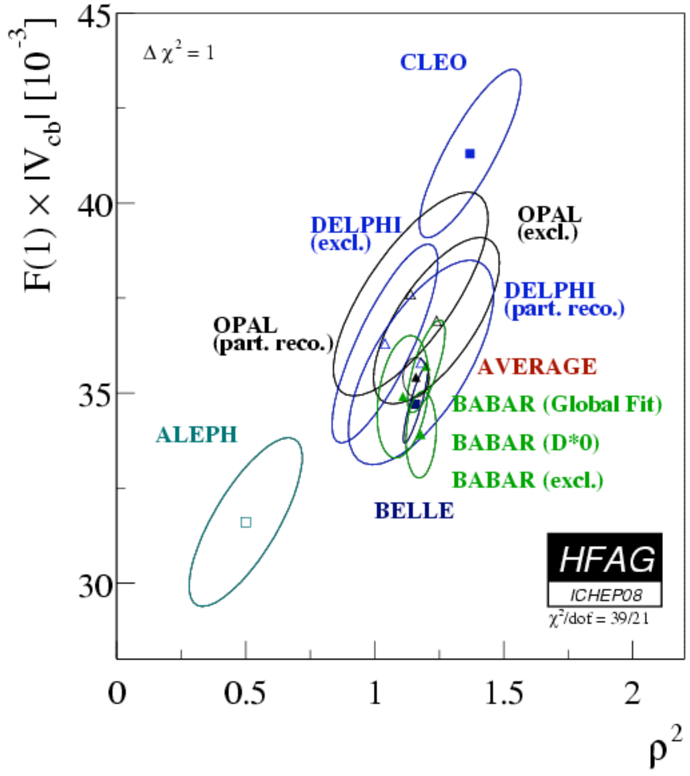
form factor

$$w \equiv v \cdot v'$$

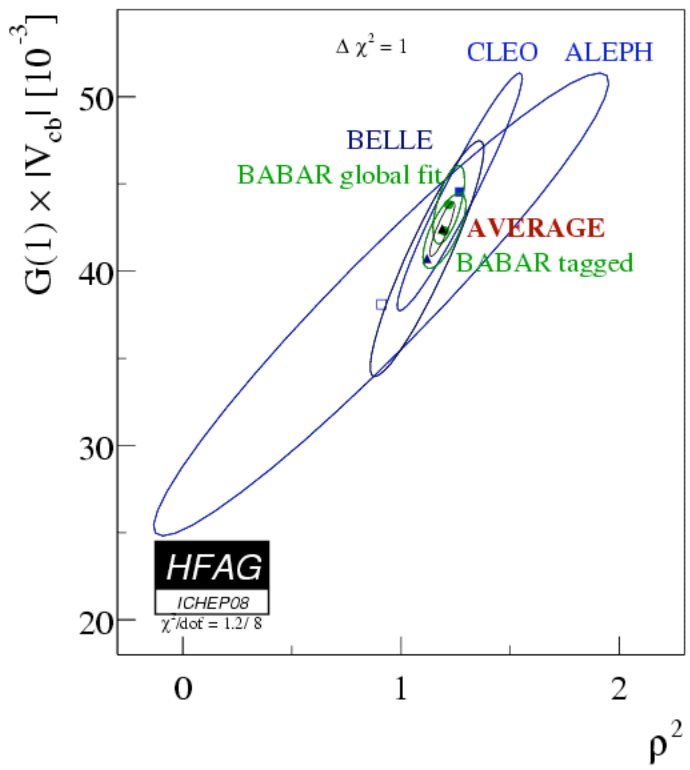
- Experiments fit $F(1)|V_{cb}|$ and $G(1)|V_{cb}|$ using a form factor parameterization based on HQET and dispersion relations [Caprini et al., Nucl. Phys. B530, 153 (1998)]
- Form factor normalizations from lattice QCD

F(1) = 0.921 +/- 0.013 +/- 0.020	J.Laiho et al. [arXiv:0808.2519]
G(1) = 1.074 +/- 0.018 +/- 0.016	M.Okamoto et al. [Nucl.Phys.Proc.Suppl. 140, 461 (2005)]

D*



D



1.6% 2.4%

$|V_{cb}| = (38.1 \pm 0.6(\text{exp}) \pm 0.9(\text{th})) \times 10^{-3}$ (D*)

$|V_{cb}| = (39.7 \pm 1.4(\text{exp}) \pm 0.9(\text{th})) \times 10^{-3}$ (D)

3.5% 2.3%

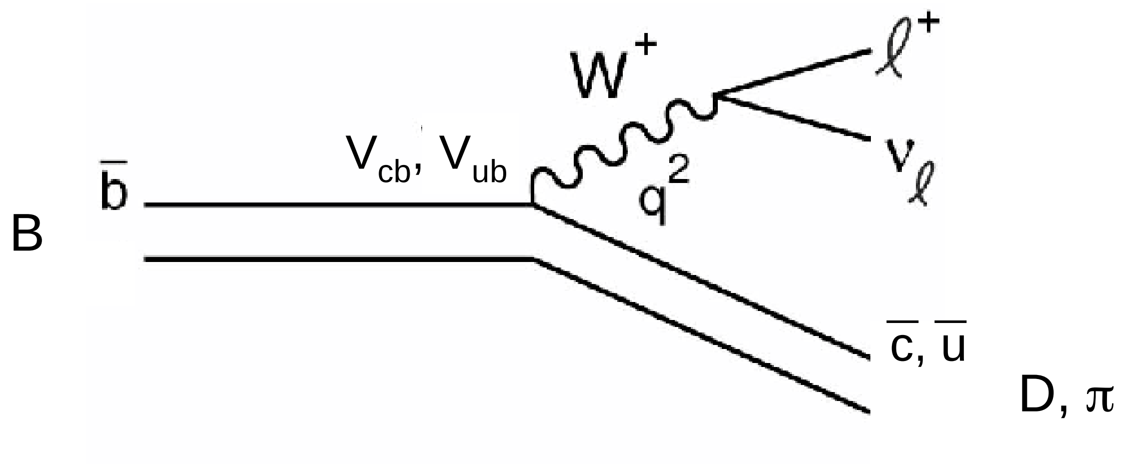
Belle $B^0 \to D^{*-} l^+ \nu$ untagged

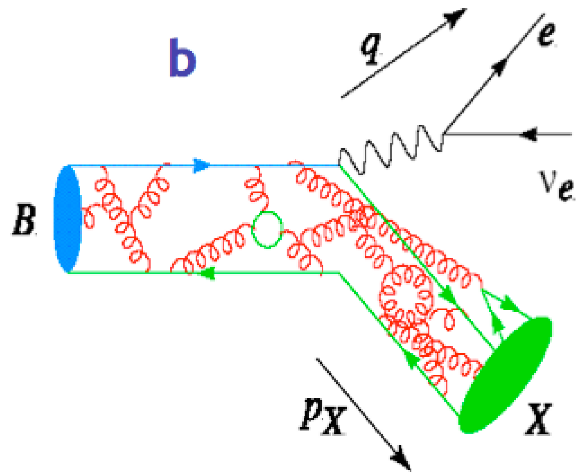
Breakdown of the systematic error components

	ρ^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 ℓ	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_{00}	0.003	0.011	0.005	0.001	0.04
Syst. error	0.029	0.062	0.019	0.251	1.04

[arXiv:0810.1657]

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





- $\Gamma(B \to X_c l \nu)$ can be systematically calculated with the operator production expansion (OPE)

$$\Gamma_{sl}(b\to c) = \frac{G_F^2\, m_b^5(\mu)}{192\,\pi^3} |V_{cb}|^2 (1+A_{ew})\, A^{pert}(r,\mu) \left[z_0(r)\left(1 - \frac{\mu_\pi^2(\mu) - \mu_G^2(\mu) + \frac{\rho_D^3(\mu)+\rho_{LS}^3(\mu)}{m_b(\mu)}}{2m_b^2(\mu)}\right) - 2(1-r)^4 \frac{\mu_G^2(\mu) - \frac{\rho_D^3(\mu)+\rho_{LS}^3(\mu)}{m_b(\mu)}}{m_b^2(\mu)} + d(r)\frac{\rho_D^3(\mu)}{m_b^3(\mu)} + \ldots \right]$$

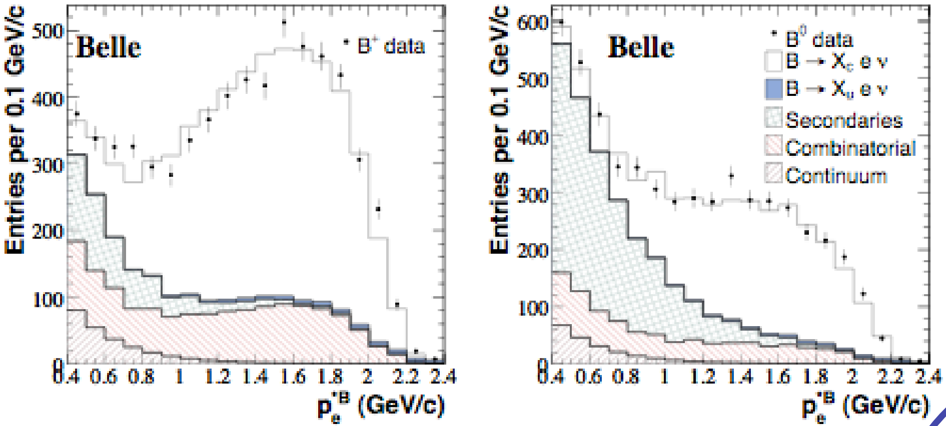
$$r = m_c^2(\mu)/m_b^2(\mu)$$

HQ parameters (non-calculable; contain soft QCD physics)

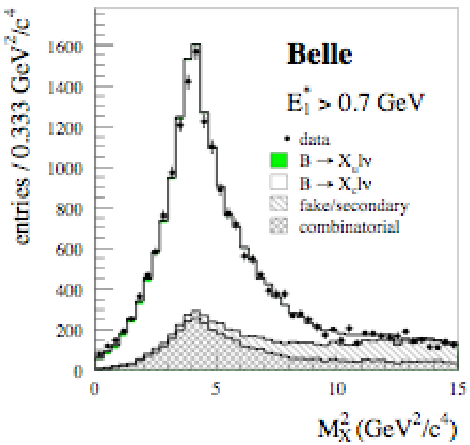
from [Benson et al., Nucl. Phys. B665, 367 (2003)]

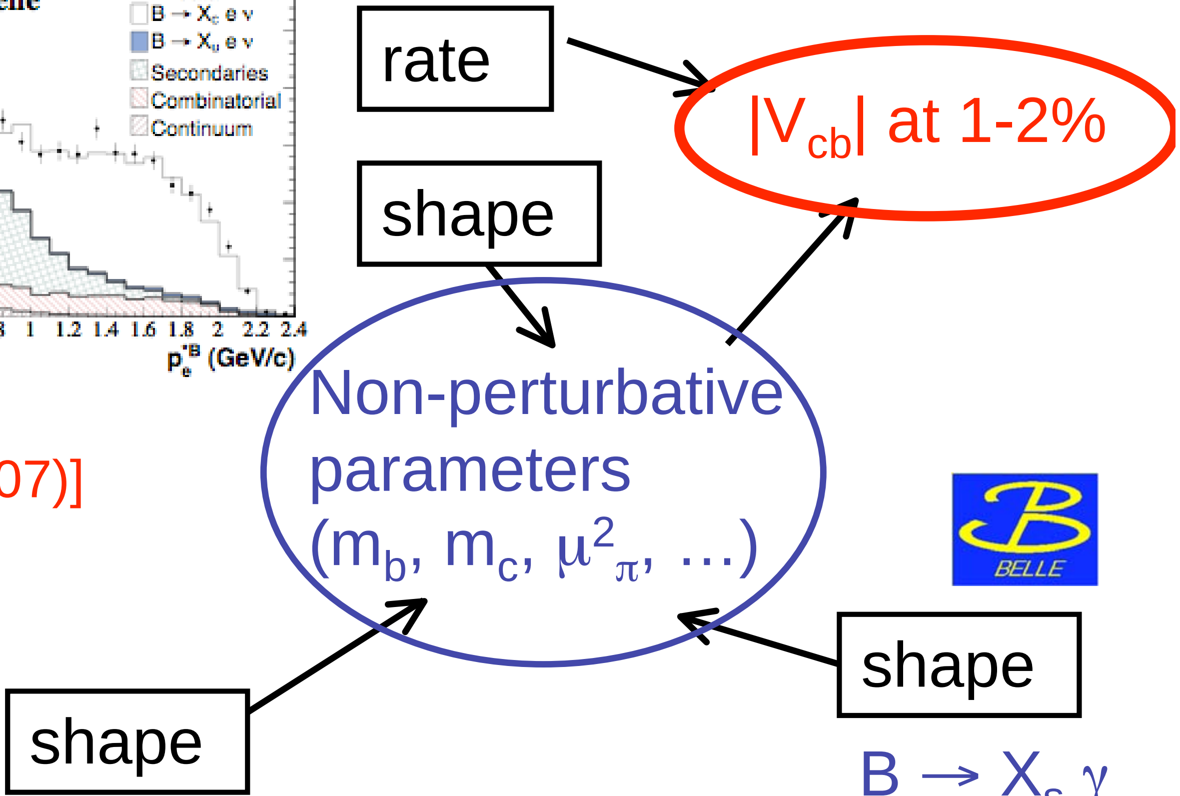
- Non-perturbative parameters can be measured from inclusive observables in B decays

Inclusive E_l spectrum
[Phys.Rev. D75, 032001 (2007)]



Inclusive M^2_X spectrum
[Phys.Rev. D75, 032005 (2007)]





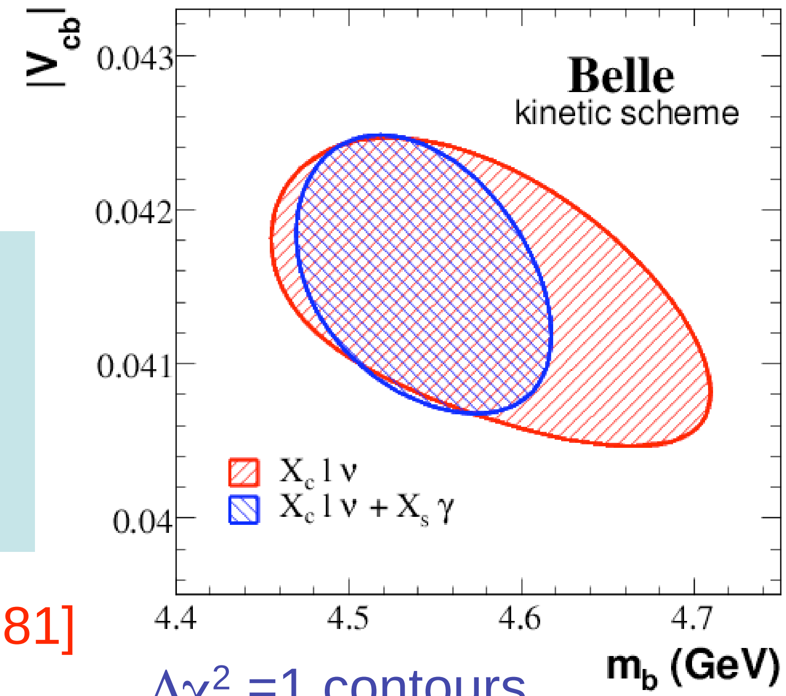
$B \to X_s \gamma$
[Phys.Rev. D78, 032016 (2008)]

[Phys.Rev. D78, 032016 (2008)]

Kinetic scheme ($X_c l\nu + X_s\gamma$ data)

$|V_{cb}| = (41.58 \pm 0.69_{fit} \pm 0.08_{\tau B} \pm 0.58_{th}) \times 10^{-3}$
$m_b^{kin} = 4.543 \pm 0.075$ GeV
$m_c^{kin} = 1.055 \pm 0.118$ GeV

[P.Gambino, N.Uraltsev, Eur.Phys.J. C34, 181]



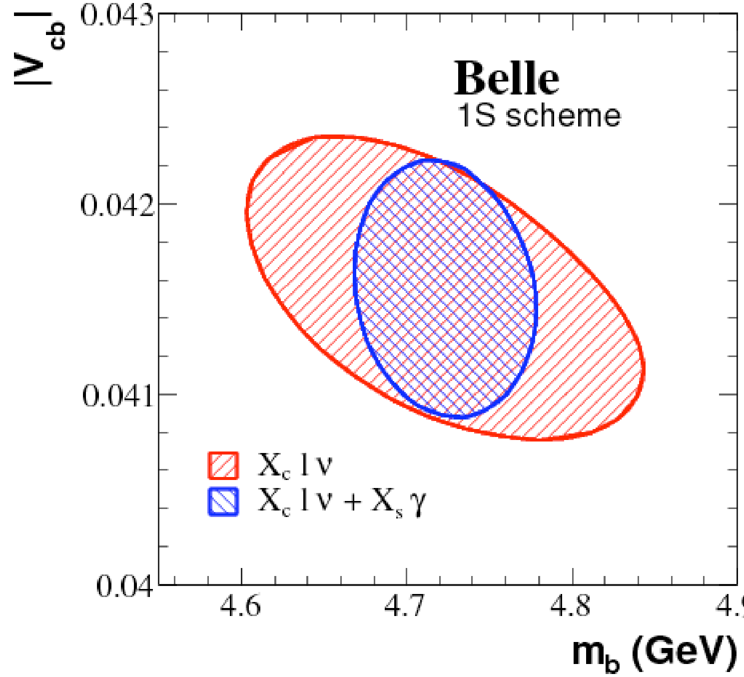
$\Delta\chi^2 = 1$ contours

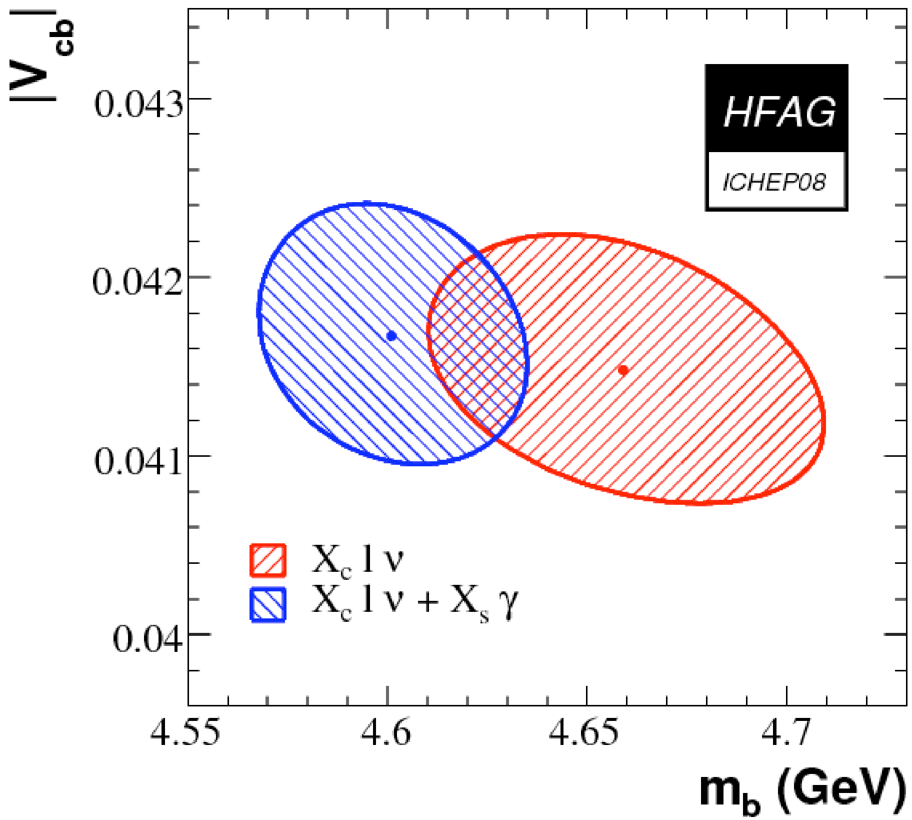
Results for m_b compatible after scheme translation

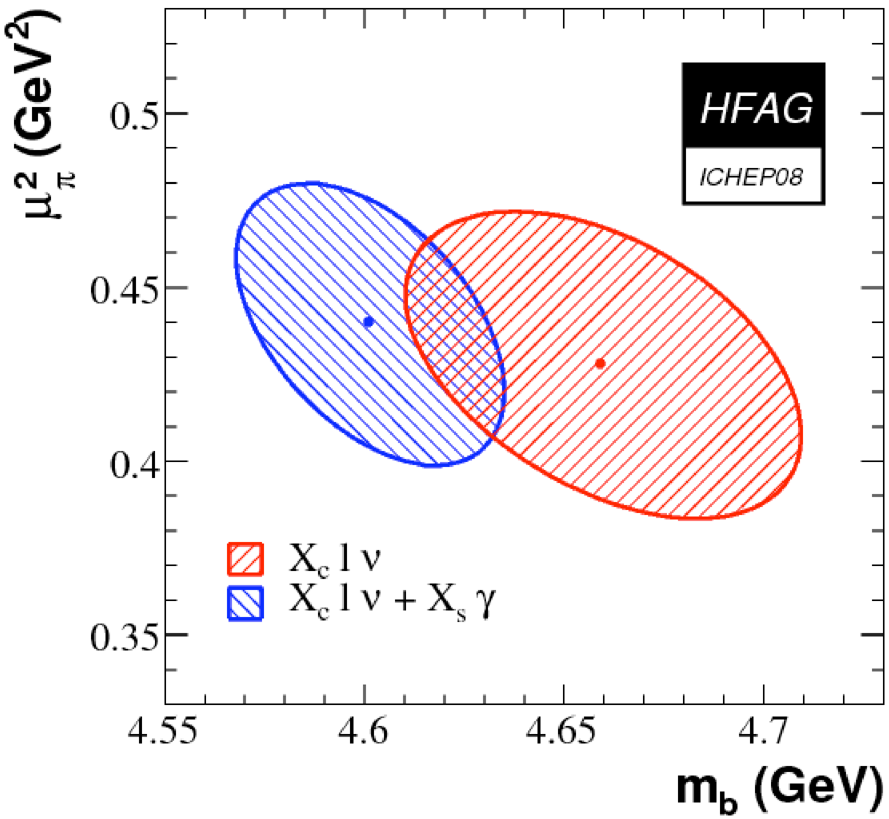
1S scheme ($X_c l\nu + X_s\gamma$ data)

$|V_{cb}| = (41.56 \pm 0.68_{fit} \pm 0.08_{\tau B}) \times 10^{-3}$
$m_b^{1S} = 4.723 \pm 0.055$ GeV

[C.Bauer, Z.Ligeti, M.Luke, A.Manohar, Phys.Rev. D70, 094017]







Input	$\lvert V_{cb}\rvert$ (10^{-3})	m_b (GeV)	μ^2_π (GeV^2)	χ^2/ndf	
All moments	41.67+/-0.43(fit)+/-0.08(τ_B)+/-0.58(th)	4.601+/-0.034	0.440+/-0.040	29.7/57	1.7%
$X_c l\nu$ only	41.48+/-0.47(fit)+/-0.08(τ_B)+/-0.58(th)	4.659+/-0.049	0.428+/-0.044	24.1/46	1.8%

Prospects for $|V_{cb}|$

How can we improve the measurement of $|V_{cb}|$?

- Exclusive
  - Move to tagged measurements to reduce background systematics
  - Test assumptions of the measurement (form factor parametrization)
  - Progress in lattice QCD needed

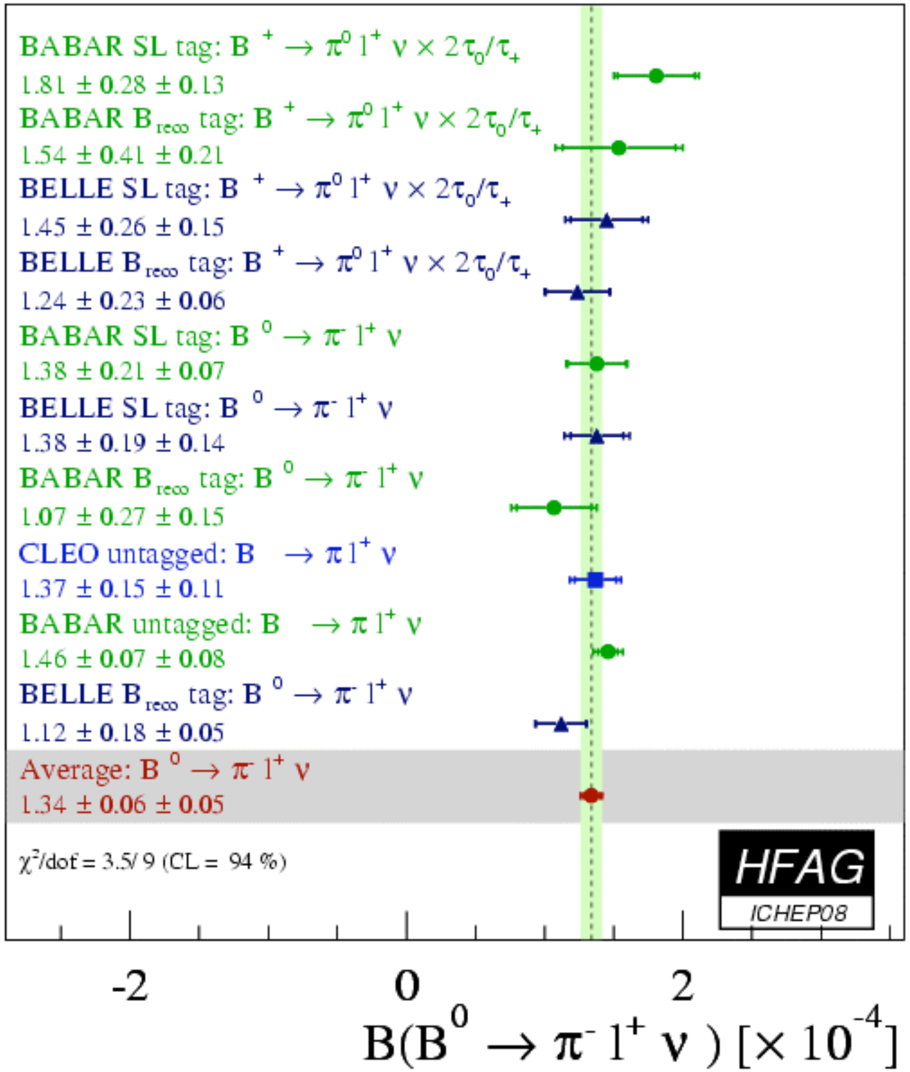
- Inclusive
  - Current uncertainty mainly theoretical
  - Different observables might better constraint HQ parameters
  - Remove the $B \to X_s\gamma$ data from the analysis?

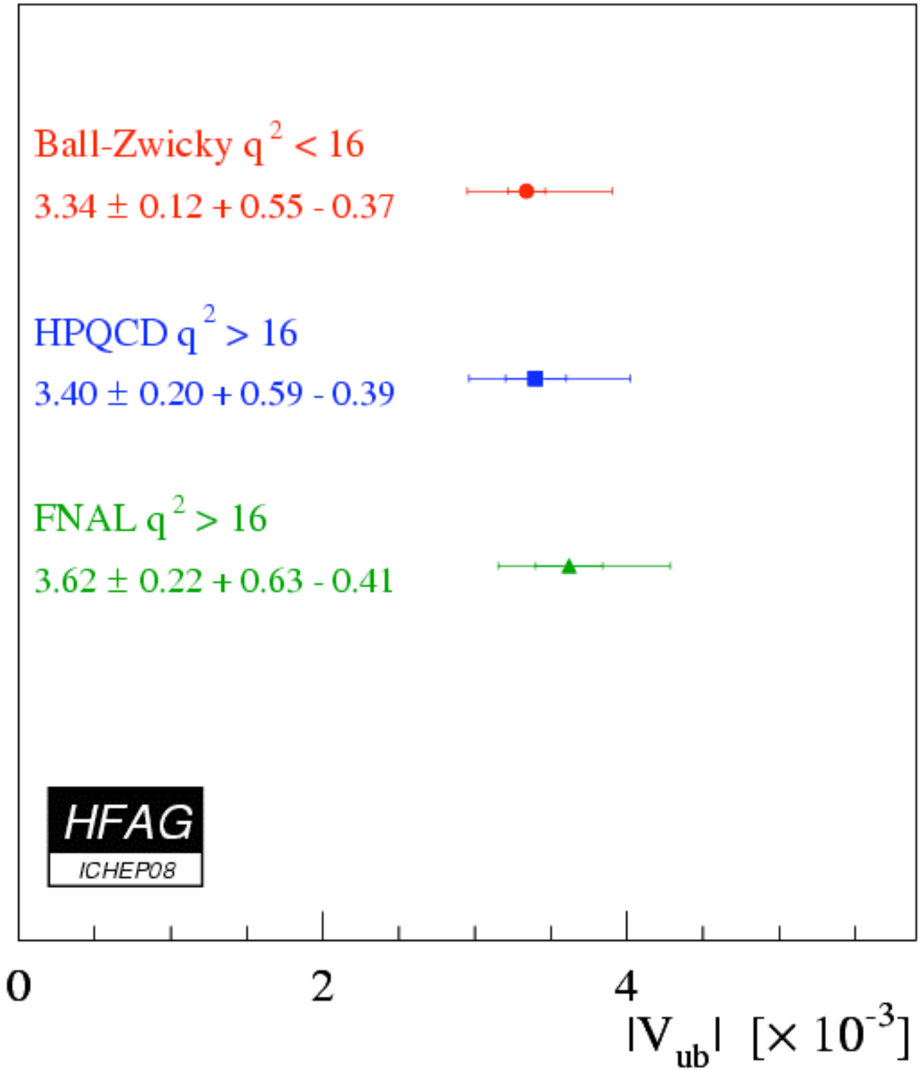
$|V_{ub}|$ from $B \to \pi l \nu$

- Decay width

$$\frac{d\Gamma(B \to \pi \ell \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{192\pi^3 m_b^3} \lambda(q^2)^{3/2} |f_+(q^2)|^2 \,, \quad q^2 = (p_\ell + p_\nu)^2$$

- Need form factor shape and normalization for $|V_{ub}|$
- Available form factor calculations
  - Relativistic quark models
    - ISGW2 [Phys. Rev. D52, 2783 (1995)]
  - Light cone sum rules (LCSR) in the region $q^2 < 14$ GeV^2
    - Ball-Zwicky [Phys. Rev. D71, 014015 (2005)]
  - Lattice QCD in the region $q^2 > 16$ GeV^2
    - HPQCD [Phys. Rev. D73, 074502 (2006)]
    - FNAL [Nucl. Phys. Proc. Suppl. 140, 461 (2005)]



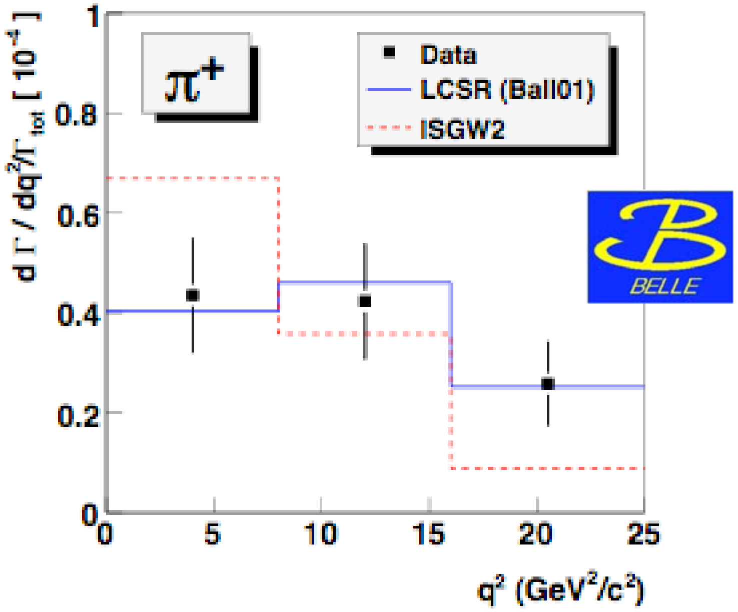


Experimental uncertainty ~ 4-6%

F.F. normalization uncertainty ~ 13-15%

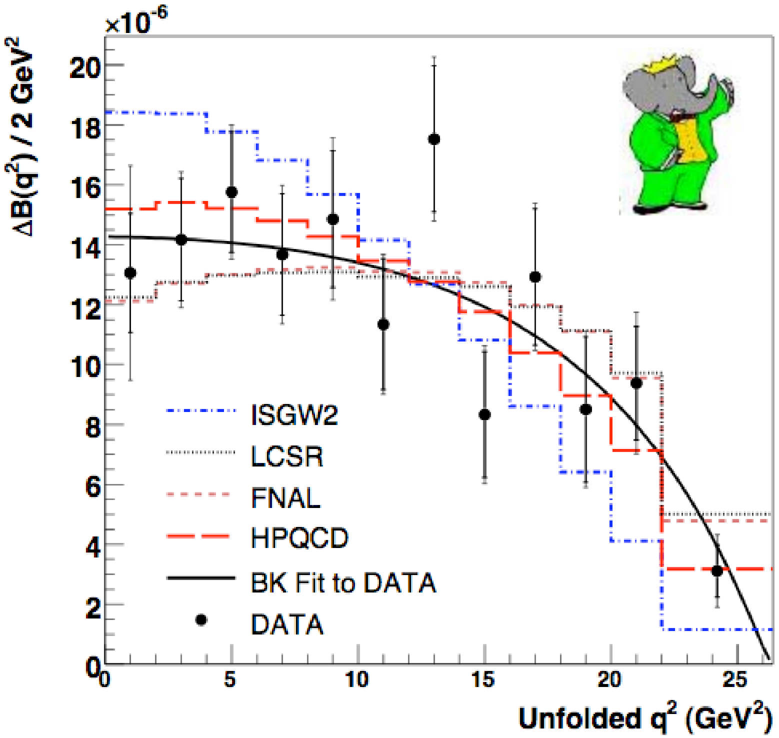
$B^0 \to \pi^- l^+ \nu$ q^2 spectrum

Belle fullrecon (605/fb)



[arXiv:0812.1414]

BaBar untagged (206/fb)

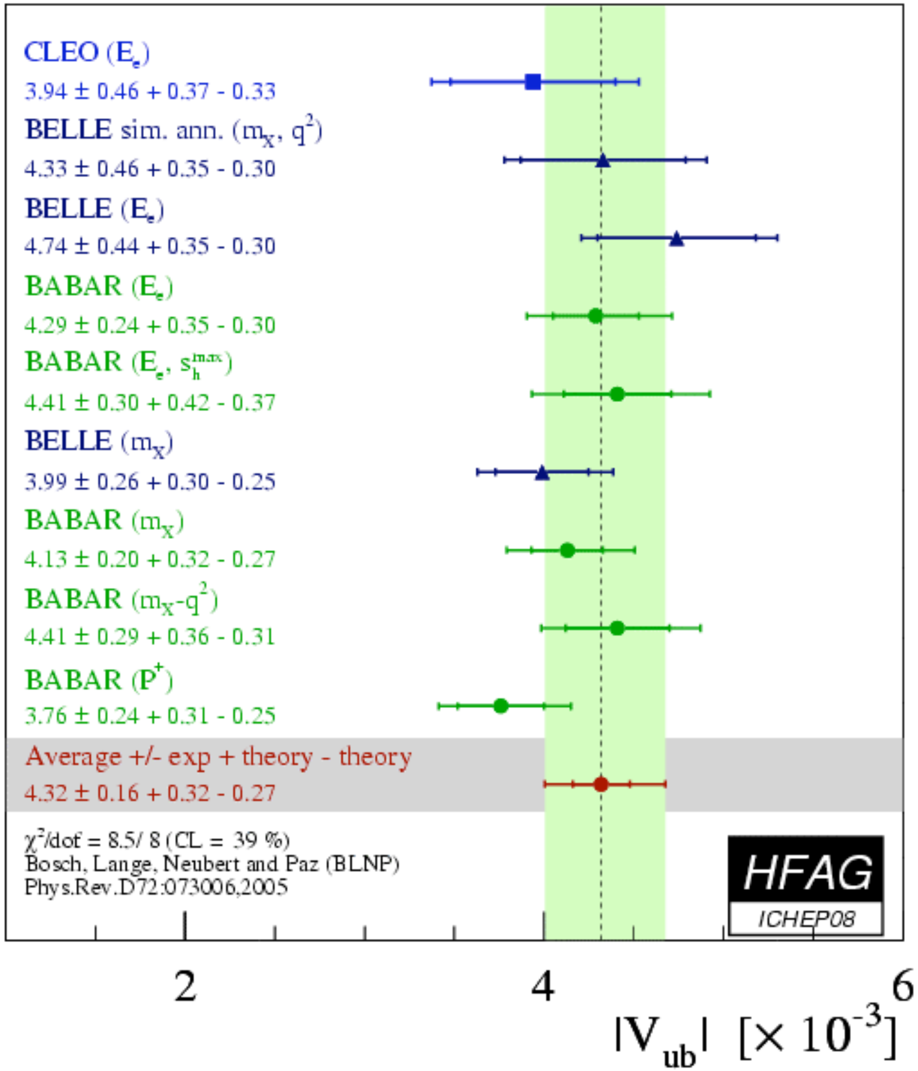


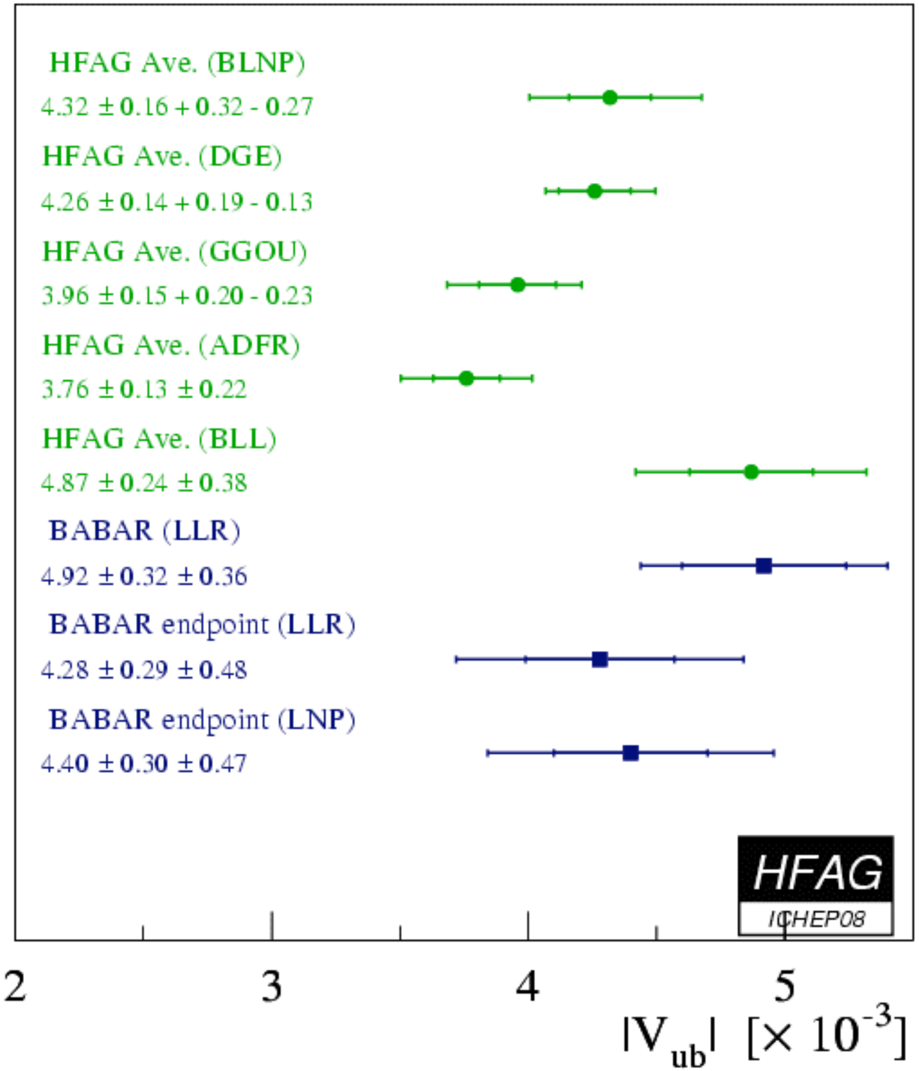
[PRL 98, 091801 (2007)]

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

- Also based on the OPE, as for $B \to X_c \, l \, \nu$ decays
- However, experimental cuts to suppress $X_c l \nu$ background compromise the convergence of the OPE
- Different theoretical approaches to model the non-perturbative component
  - Bosch, Lange, Neubert, Paz (BLNP) [Phys.Rev. D72, 073006 (2005)]
  - Anderson, Gardi (DGE) [JHEP 0601:097 (2006)]
  - Gambino, Giordano, Ossola, Uraltsev (GGOU) [JHEP 0710:058 (2007)]
  - Aglietti, Di Lodovico, Ferrera, Ricciardi (AC) [arXiv:0711.0860]
  - Bauer, Ligeti, Luke (BLL) [Phys.Rev. D64, 113004 (2001)]

BLNP framework

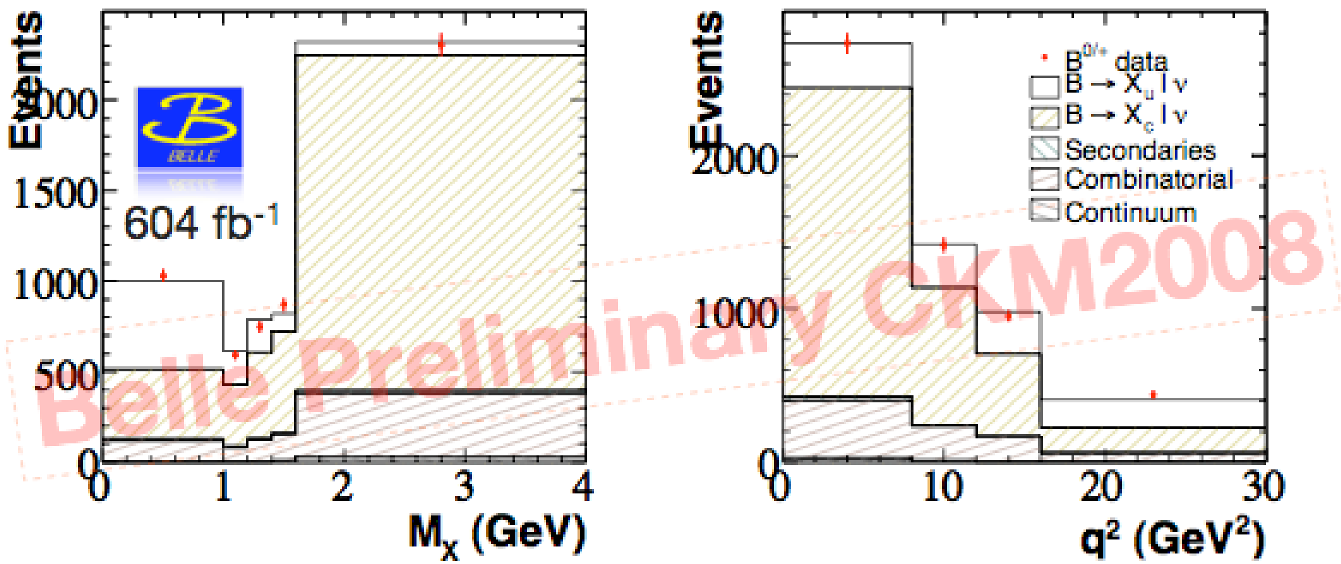




How predictive is the theory?

Belle Multivariate analysis (NEW @ CKM2008) 2/2

Phill Urquijo



~1035 Evts

2D fit in q2 mx. (projections shown)

Kinematic Region	$\mathcal{B}(B \to X_u l\nu) \times 10^{-3}$ Δ(stat. sys.)	m_b	$\lvert V_{ub}\rvert$ (10^{-3}) % error	*Theory*
$P_{lepton} > 1.0$ GeV	1.96 x (1 ± 0.088 ± 0.076)	(kinetic) 4.613 GeV, mupi=0.440 GeV²	4.42 (± 3.1 ± 5.1)	GGOU (thanks P. Giordano)
		(MSbar) 4.243 GeV	4.47 (± 6.7)	DGE (thanks E. Gardi)

~90† % total phase space, thus theory error less correlated to other Vub determinations

Prospects for $|V_{ub}|$

How can we improve the measurement of $|V_{ub}|$?

A lot of homework for theorists but…

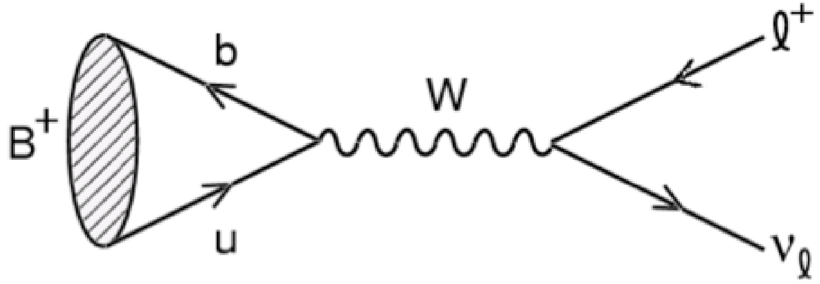
- Exclusive
  - Measure (at least) the $\pi l \nu$ q^2 spectrum
- Inclusive
  - Try to cover as much as possible of the $X_u l \nu$ phase space

② Rare decays

- Leptonic decays
  - $B^+ \rightarrow l^+\nu$ with $l = e, \mu$ or τ

- Semi-taunic decays
  - $B \rightarrow \overline{D}^{(*)}\tau\nu$

Leptonic decays



helicity suppression of light leptons

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

- SM prediction with $|V_{ub}|$ = (4.39 +/- 0.54) x 10^{-3} and f_B = 189 +/- 27 MeV

$B^+ \to e^+\nu$	$B^+ \to \mu^+\nu$	$B^+ \to \tau^+\nu$
(1.7 +/- 0.4) x 10^{-11}	(7.1 +/- 1.6) x 10^{-7}	(1.6 +/- 0.4) x 10^{-4}

- Might be enhanced due to new physics contribution (charged Higgs, …)

- Inclusive measurements

(limits are 90% C.L.)

	$B^+ \to e^+\nu$	$B^+ \to \mu^+\nu$	$B^+ \to \tau^+\nu$
Belle [PLB647, 67]	$< 9.8 \times 10^{-7}$	$< 1.7 \times 10^{-6}$	
BaBar [arXiv:0807.4187]		$< 1.3 \times 10^{-6}$	

- Semileptonic tag

	$B^+ \to e^+\nu$	$B^+ \to \mu^+\nu$	$B^+ \to \tau^+\nu$
Belle [arXiv:0809.3834]			$(1.65 \pm 0.52) \times 10^{-4}$

- Fullrecon tag

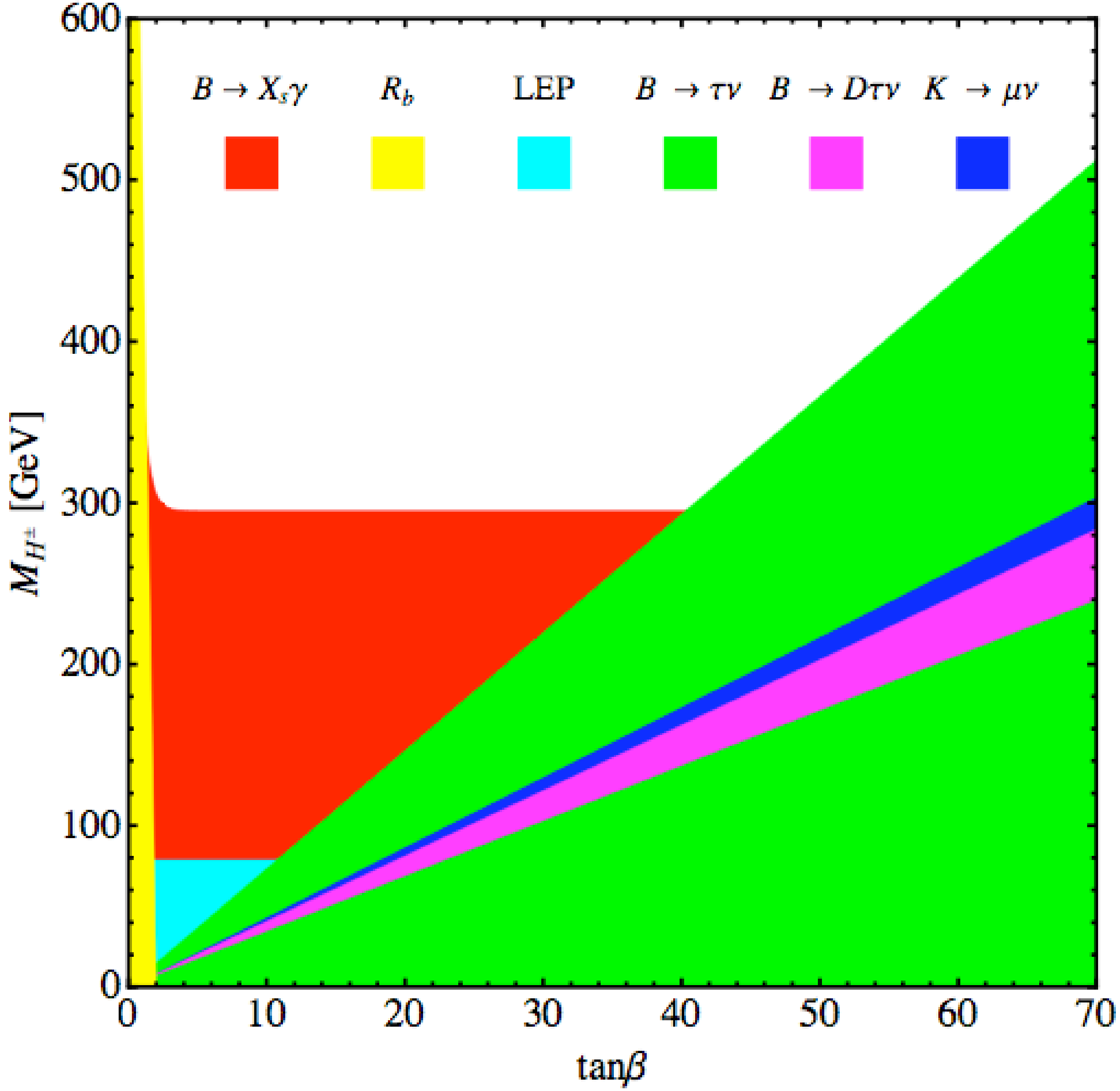
	$B^+ \to e^+\nu$	$B^+ \to \mu^+\nu$	$B^+ \to \tau^+\nu$
Belle [PRL97, 251802]			$(1.8 \pm 0.7) \times 10^{-4}$
BaBar [PRD77, 091104; PRD77, 011107]	$< 5.2 \times 10^{-6}$	$< 5.6 \times 10^{-6}$	$(1.8 \pm 1.0) \times 10^{-4}$

Semi-tauonic B decays

- Challenging experimentally as up to 3 neutrinos in the final state
- Fullrecon tagging is mandatory

Decay mode	BF[%]	signif.	Ref.
$B^0 \to D^{*-} \tau^+ \nu_\tau$	$2.02^{+0.40}_{-0.37}(stat) \pm 0.37(syst)$	5.2σ	
	$1.11 \pm 0.51(stat) \pm 0.04(syst) \pm 0.04(norm)$	2.7σ	
$B^- \to D^{*0} \tau^+ \nu_\tau$	$2.25 \pm 0.48(stat) \pm 0.22(syst) \pm 0.17(norm)$	5.3σ	
$B^0 \to \overline{D}^0 \tau^+ \nu_\tau$	$1.04 \pm 0.35(stat) \pm 0.15(syst) \pm 0.10(norm)$	3.3σ	
$B^- \to D^0 \tau^+ \nu_\tau$	$0.67 \pm 0.37(stat) \pm 0.11(syst) \pm 0.07(norm)$	1.8σ	

Belle [PRL 99, 191807 (2007)] BaBar [PRL 100, 021801 (2008)]



Bounds on the charged Higgs mass in the 2HDM type II model as a function of tan β. (Colored areas are excluded at 95% C.L.) [U.Haisch, arXiv:0805.2141]

Summary

- $|V_{cb}|$ and $|V_{ub}|$
  - The precision of $|V_{ub}/V_{cb}|$ can be further improved
  - Though more data alone will not suffice
- Rare (semi-)leptonic B decays
  - Sensitive probe for new physics (e.g., charged Higgs)

Backup slides

The CKM mechanism

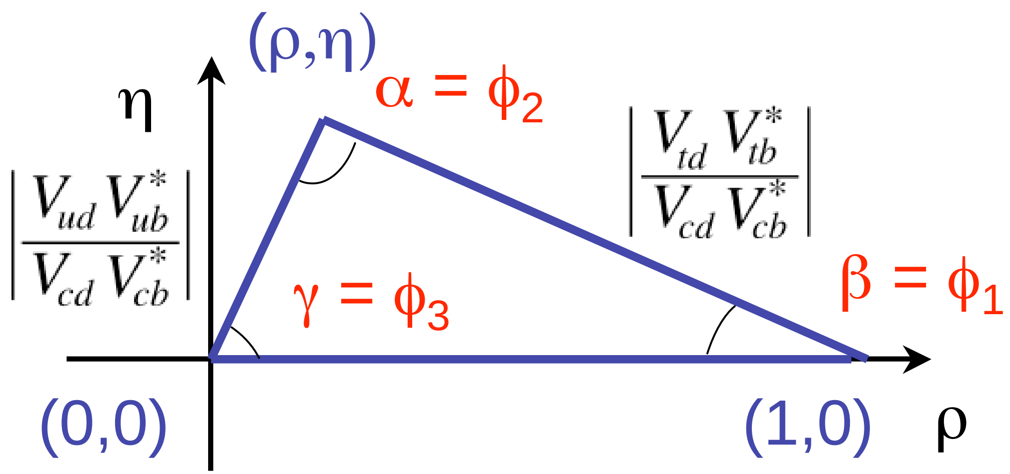
- The charged current interaction in the SM

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

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

[Kobayashi, Maskawa, Prog. Theor. Phys. 49, 652 (1973)]

- V_{CKM} is a unitary 3x3 matrix;
  it contains three real parameters and one complex phase
- Its unitarity is commonly represented by the unitarity triangle



$$\alpha \equiv \varphi_2 \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

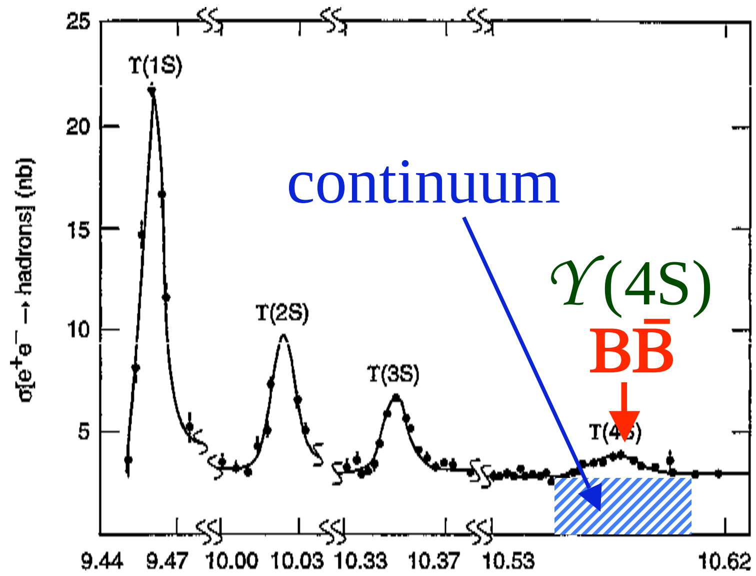
$$\beta \equiv \varphi_1 \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

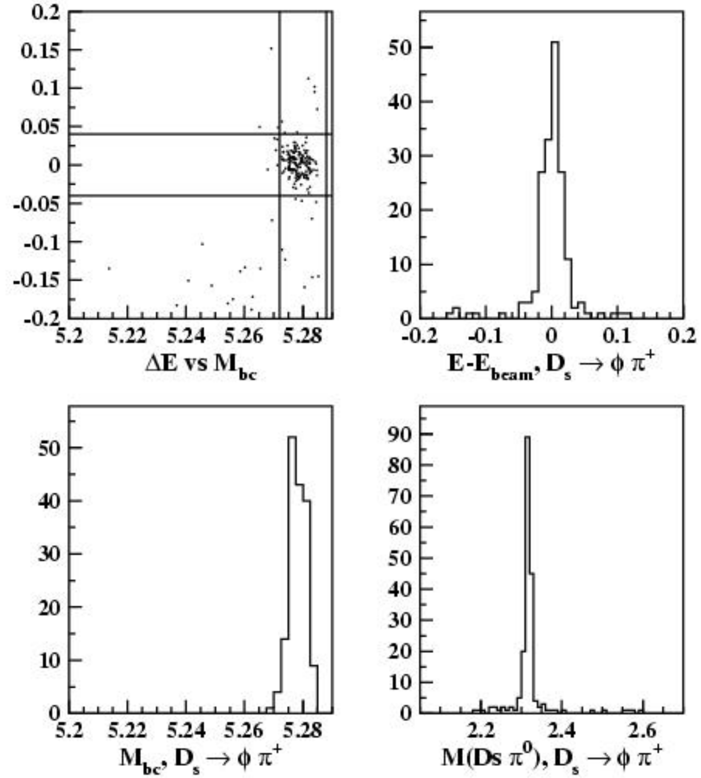
$$\gamma \equiv \varphi_3 \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- 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)