Theoretical Uncertainties of CKM Parameters

Patricia Ball

IPPP, Durham

Heavy Flavour Forum, Cosener's House, Solstice 2007

University of Durham

Outline

Status of and prospects for

- $|V_{us}|$
- $|V_{cb}|$
- $|V_{ub}|$
- γ

Don't include:

- $\alpha \rightarrow$ talk on global fits
- $|V_{td}|$, $|V_{ts}|$: potentially contaminated by new physics
- $|V_{cd}|$, $|V_{cs}|$ from charm decays & lattice
- DCS penguin pollution of β

$$|V_{us}|$$

How to determine $|V_{us}|$?

- $K_{\ell 3}$ decays (i.e. $K \to \pi \ell \nu$)
- ratio f_K/f_π and leptonic decays $\Gamma(K \to \ell\nu)/\Gamma(\pi \to \ell\nu)$
- hadronic τ decays
- hyperon decays

News from $K \to \pi\ell\nu$

$$\Gamma(K \to \pi\ell\nu) \propto |V_{us}|^2 \int dt \lambda^{3/2}(t) f_+^2(t)$$

Determine shape of form factor from data on spectrum, extract $|V_{us} f_+(0)|$ from data: (recent new results from E865, KTeV, NA48, KLOE)

$\|V_{us} f_+(0)\|_{\rm exp}$	$=$	$0.2169(9)$	(PDG 06)
$\|V_{us} f_+(0)\|_{\rm exp}$	$=$	$0.21673(46)$	(FLAVIAnet K WG 06)

New result for $f_+(0)$ from lattice (UKQCD/RBC): (CKM06, hep-lat/0702026)

$f_+(0) = 0.9609(51)$, i.e. error is 0.5% $(\Delta(1 - f_+(0)) = 13\%)$

NB: $f_+(0) = 1 - O((m_s - m_q)^2)$ (Ademollo-Gatto theorem)

Gives

$\|V_{us}\|$	$=$	$0.2257(9)_{\rm exp}(12)_{\rm th}$	(PDG 06)
$\|V_{us}\|$	$=$	$0.2255(5)_{\rm exp}(12)_{\rm th}$	(FLAVIAnet K WG 06)

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Funnily enough, this new result coincides with the rather old one from Leutwyler/Roos (1984) (χPT + quark model):

$$f_+(0) = 0.961(8).$$

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Theory error still larger than experimental one. . .

UKQCD/RBC result is preliminary and has been obtained using domain wall quarks with 2+1 dynamical flavours. Finalisation & further improvements under way.

Expected accuracy?

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A question for Chris & Jonathan. . .

News from $\Gamma(K \to \ell\nu)/\Gamma(\pi \to \ell\nu)$

From $\Gamma(K \to \ell\nu)/\Gamma(\pi \to \ell\nu)$, get $\dfrac{|V_{us}|}{|V_{ud}|}\dfrac{f_K}{f_\pi} = 0.27618(48)\,.$

Nuclear β decay: $|V_{ud}| = 0.97377(27)$.

New lattice result (HPQCD/UKQCD, arXiv:0706.1726):

$f_K/f_\pi = 1.189(7)$, i.e. error is 0.6%.

gives

$$|V_{us}| = 0.2262(4)_{\rm exp}(13)_{\rm th}$$

Theory error larger than experimental one.

That's a new state-of-the-art result, so probably too much to ask for improvement soon.

$|V_{us}|$ from hadronic τ decays and hyperons

τ decays: $R_\tau = \Gamma(\tau \to \text{ hadrons })/\Gamma(\tau \to e\nu_e\nu_\tau) = 3.6410(10)$.

Related to QCD correlation functions, calculable from operator product expansion (Braaten/Narison/Pich 92).

Most recent result: (Gamiz et al., hep-ph/0612154, updated by Jamin, Moriond EW 07)

$$|V_{us}| = 0.2214(33)_{\text{exp}}(10)_{\text{th}}$$

Hyperon decays: $\Lambda \to pe\nu$, $\Sigma \to ne\nu$, $\Xi \to \Sigma e\nu$, $\Xi \to \Lambda e\nu$:

$$|V_{us}| = 0.226(5)$$ (Mateu/Pich 05)

- no longer competitive with other determinations
- main disadvantage: in contrast to $K \to \pi e\nu$, contribution from AV form factors, not protected by Ademollo-Gatto

Final Result for $|V_{us}|$

$$|V_{us}|(K_{\ell 3}) = 0.2257(15) \qquad |V_{us}|(f_K/f_\pi) = 0.2262(14)$$

$$|V_{us}|(\tau) = 0.2225(34) \qquad |V_{us}|(\text{hyp}) = 0.226(5)$$

Average: $|V_{us}| = 0.2257(10)$, i.e. 0.4% error

Up from Jamin's average 0.2240(11) (Moriond EW 07) because of larger $|V_{us}|(K_{\ell 3})$ and $|V_{us}|(f_K/f_\pi)$.

Check unitarity relation: $|V_{ud}| + |V_{us}|^2 + |V_{ub}|^2 = 1 - \delta$

$\delta = (0.8 \pm 0.7) \cdot 10^{-3}$: no significant discrepancy

$|V_{cb}|$

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

Based on application of **heavy quark symmetry (HQS)** :

$$\frac{d\Gamma(B \to D^*\ell\nu)}{dw} \propto |V_{cb}|^2(\mathcal{F}(w))^2\,, \quad w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}\,.$$

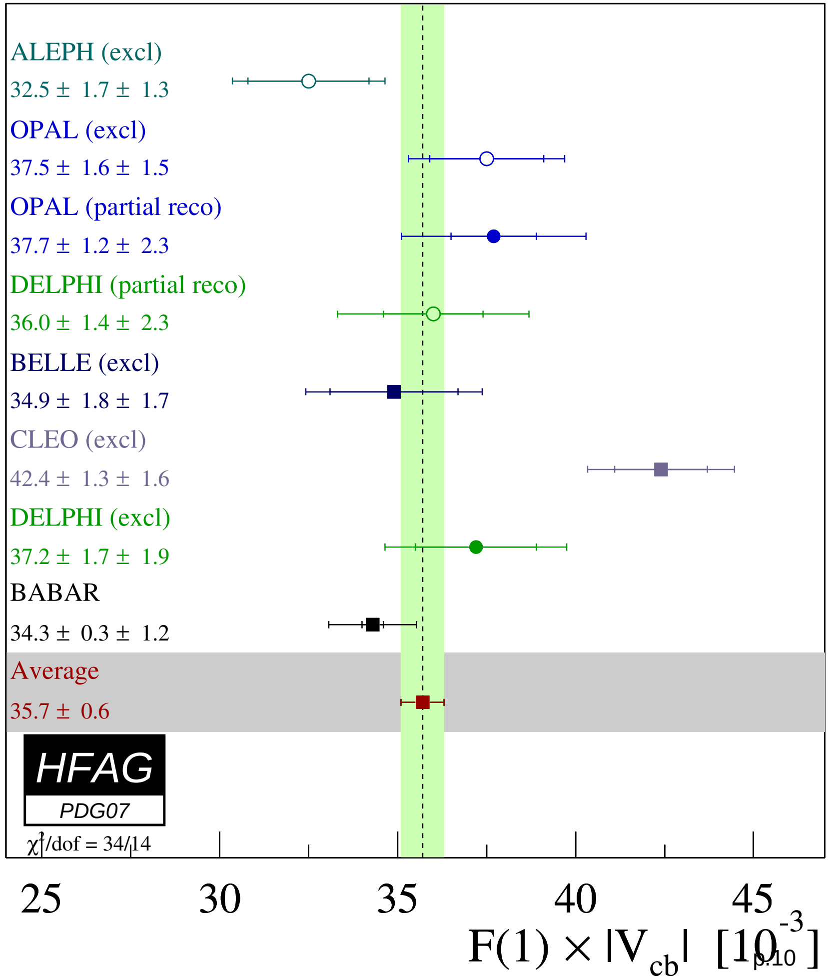
Form factor $\mathcal{F}(1) = 1$ in HQL (Isgur-Wise function), corrections only 2nd order in $1/m_{b,c}$ (Luke's theorem). Parametrise

$$\mathcal{F}(w) = \eta_{\rm QED}\eta_{\rm QCD}\left[1 + \delta_{1/m^2} + \ldots\right] - (w-1)\rho^2 + O((w-1)^2)\,.$$

Exp: $\mathcal{F}(1)|V_{cb}| = 35.7(6)\cdot 10^{-3}$ (2% error).

Th: $\mathcal{F}(1) = 0.9130^{+0.029}_{-0.035}$ (4% error).

$$|V_{cb}|_{\rm ex} = 39.1(7)_{\rm exp}(^{+15}_{-12})_{\rm th}\cdot 10^{-3}$$ (4% error)



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

- current theoretical $\mathcal{F}(1)$ from quenched lattice calculations (Hashimoto et al. 2002)
- method does not rely on explicit $1/m_b$ expansion, also include $1/m_b^3$ terms
- unquenching under way: 2+1 staggered fermions, Fermilab method for heavy quarks (Laiho et al.)
- first results may be available for this year's lattice conference (Laiho, priv. comm.)
  - one complication: $D^* \to D\pi$ threshold to be crossed when extrapolating input light quark to physical quark masses (Laiho/van de Water 05)

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

$$\frac{d\Gamma(B \to D\ell\nu)}{dw} \propto |V_{cb}|^2 (\mathcal{G}(w))^2 , \quad w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D} .$$

Still form factor $\mathcal{G}(1) = 1$ in HQL, but now corrections are 1st order in $1/m_{b,c} \to$ HQS not that useful any more. Parametrise

$$\mathcal{G}(w) = \mathcal{G}(1) \left[1 - (w-1)\rho^2 + O((w-1)^2)\right] .$$

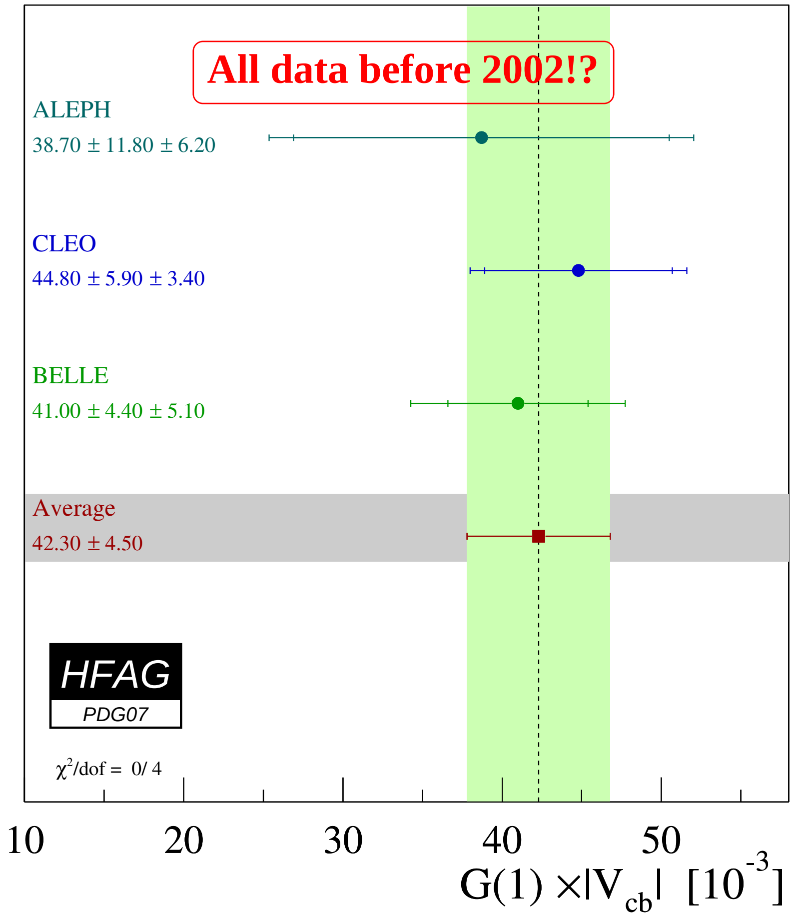
Exp: $\mathcal{G}(1)|V_{cb}| = 42.3(45) \cdot 10^{-3}$ (11% error).

Th1: $\mathcal{G}(1)_{\mathrm{latt}} = 1.074(24)$ (2% error) (Okamoto et al. 04, unquenched, preliminary)

Th2: $\mathcal{G}(1)_{\mathrm{BPS}} = 1.04(1)$ (1% error) (Uraltsev 03)

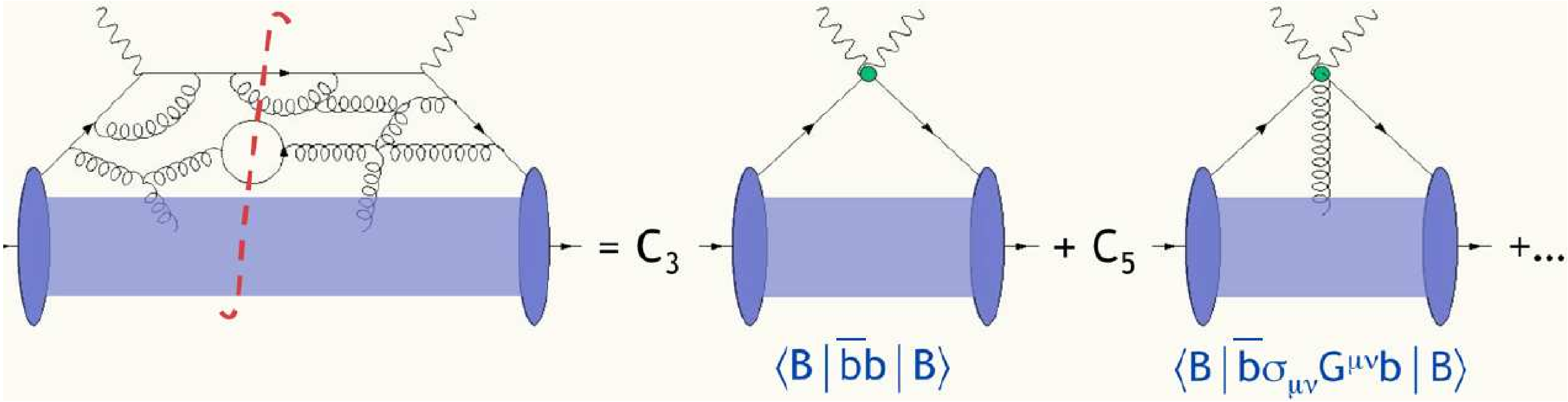
$$|V_{cb}|_{\mathrm{Th1}} = 39.4(42)_{\mathrm{exp}}(9)_{\mathrm{th}} \cdot 10^{-3}$$ (11% error)

$$|V_{cb}|_{\mathrm{Th2}} = 40.7(43)_{\mathrm{exp}}(4)_{\mathrm{th}} \cdot 10^{-3}$$ (11% error)



$|V_{cb}|$ inclusive

Theoretical tool: operator product expansion (OPE)



- hadronic physics encoded in a few parameters (m_b, μ_π^2 etc.)
- basic theoretical assumption: validity of quark-hadron duality
  - deviations would manifest themselves as badly converging $1/m_b$ expansion: no sign for that

$|V_{cb}|$ inclusive

Status of theory:

- $\Gamma(B \to X_c \ell \nu)$ at $O(\alpha_s^2 \beta_0)$, but not $O(\alpha_s^2)$
- power corrections at tree level
- technology for two-loop calculation of spectra available (Anastasiou/Melnikov/Petriello 2005)
- work in progress! (Neubert et al.)

Result:

$|V_{cb}| = 41.78(36)_{\rm fit}(08)_{\tau_B} \cdot 10^{-3}$, i.e. theory error 0.9% (HFAG 2007, prelim.)

$|V_{ub}|$ inclusive – Error Estimates

Neubert, talk at FPCP07:

- perturbative error on $|V_{cb}|$
  - $O(\alpha_s^2)$ to total rate not known, BLM approximation $O(\alpha_s^2\beta)$ need not be very good (see $\Gamma(\tau \to X\nu)$)
  - estimate this uncertainty by averaging the non-BLM $O(\alpha_s^2)$ terms in $\Gamma(\tau \to X\nu)$ and $\Gamma(B \to X_u e\nu)$
  - gives $\delta|V_{cb}|_{\text{pert}} = \pm 0.72 \cdot 10^{-3}$, i.e. 1.7%: twice the theory error quoted by HFAG 2007

Conclusion: need to complete $O(\alpha_s^2)$ corrections!

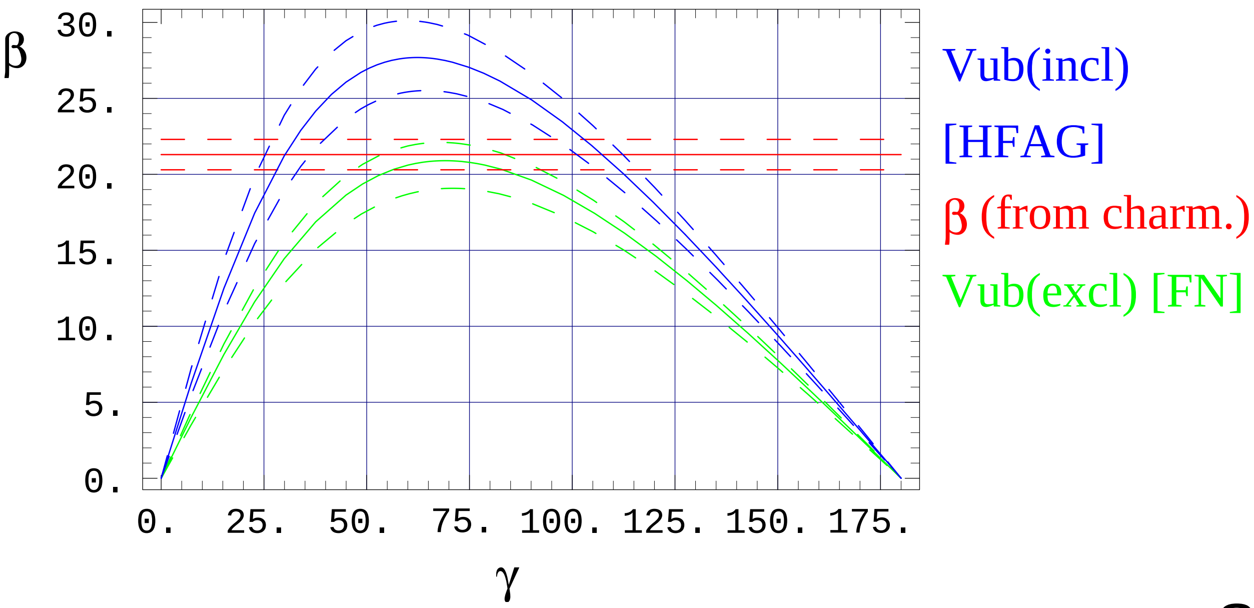
$$|V_{ub}|$$

A rising “tension”…

β known in terms of $|V_{ub}/V_{cb}|$, γ and $\lambda \equiv |V_{us}|$:

$$\sin\beta = \frac{R_b \sin\gamma}{\sqrt{1 + R_b^2 - 2R_b\cos\gamma}}, \quad \cos\beta = \frac{1 - R_b\cos\gamma}{\sqrt{1 + R_b^2 - 2R_b\cos\gamma}}$$

with $R_b = \left(1 - \frac{\lambda^2}{2}\right)\frac{1}{\lambda}\frac{|V_{ub}|}{|V_{cb}|}$.



For $\gamma \in [50°, 80°]$

- β from $|V_{ub}|_{\rm excl}$ from $B \to \pi e\nu$ agrees perfectly well with β from $B \to (c\bar{c})K$ (Flynn/Nieves, arXiv:0705.3553)
- β from $|V_{ub}|_{\rm incl}$ from inclusive $B \to X_u e\nu$ as averaged by HFAG is on the large side.

Significance? See global fits…

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

Theory input needed: form factors:

$$\langle \pi(p)|\bar{u}\gamma_\mu(1-\gamma_5)b|B(p+q)\rangle$$
$$= \quad (q+2p)_\mu\, f_+(q^2) + \frac{m_B^2 - m_\pi^2}{q^2}\, q_\mu \left(f_0(q^2) - f_+(q^2)\right)$$

$$0 \le q^2 \le (m_B - m_\pi)^2 \qquad \longleftrightarrow \qquad m_\pi \le E_\pi \le \frac{1}{2m_B}\left(m_B^2 - m_\pi^2\right)$$
$$0 \le q^2 \le 26.4\,\mathrm{GeV}^2 \qquad \longleftrightarrow \qquad 0.14\,\mathrm{GeV} \le E_\pi \le 2.6\,\mathrm{GeV}$$

Theoretical methods:

- lattice: HPQCD (Dalgic et al. 06) & Fermilab (Arnesen et al. 05): unquenched, 2+1 staggered fermions
- SCET/dispersive constraints (Arnesen et al. 05, Williamson/Zupan 06)
- QCD sum rules on the light-cone (Ball/Zwicky 04)

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

Experimental data:

$$\mathcal{B}(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell) = 1.37(6)_{\rm stat}(6)_{\rm syst} \cdot 10^{-4}$$

(HFAG), i.e. 6% error.

q^2-spectrum measured by BaBar, Belle and CLEO in various bins in q^2.
Allows model-independent extraction of $|V_{ub} f_+(0)|$ based on five different parametrisations of the shape of f_+ in q^2 (Ball 06, only BaBar spectrum):

$$|V_{ub} f_+(0)|_{\rm exp} = 9.1(7) \cdot 10^{-4}$$

$f_+(0)$ from QCD sum rules one the light-cone: $f_+(0)|_{\rm LCSR} = 0.258(31)$.

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Lattice calculations only available for $q^2 > 16\,\text{GeV}^2$. Combine experimental partial branching fractions with HPQCD/Fermilab and LCSR results, parametrise $f_+(q^2)$ based on Omnès representation: (Flynn/Nieves hep-ph/0703284)

$$|V_{ub}| = 3.90(32)_{\text{exp+th}}(18)_{\text{syst}} \cdot 10^{-3}$$

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$$3.90(32)(18) \cdot 10^{-3} \to |V_{ub}| = 3.47(29)_{\rm exp+th}(03)_{\rm syst} \cdot 10^{-3}$$

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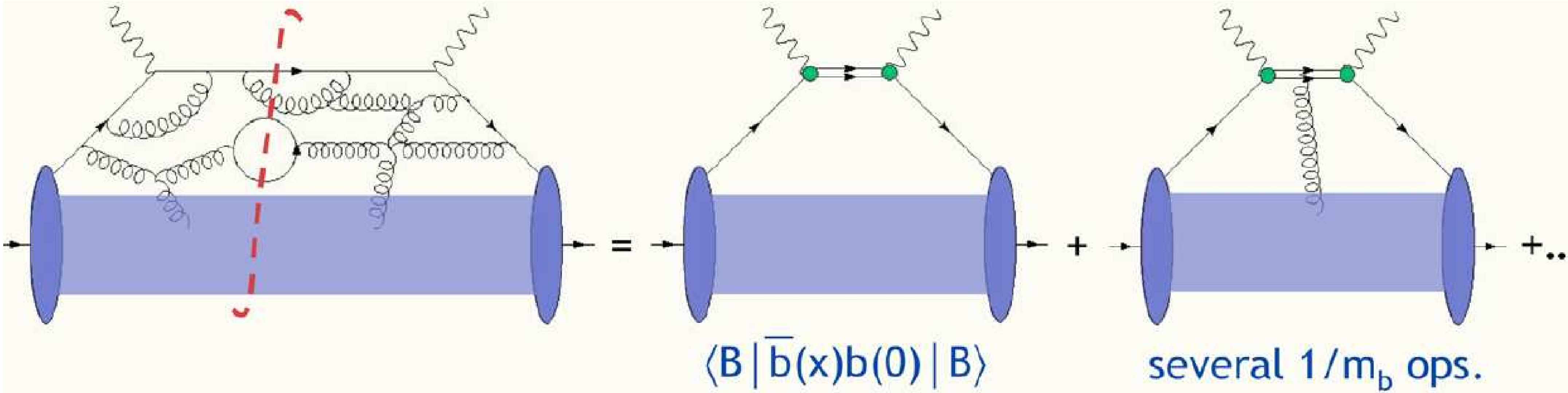
Why? Original HPQCD result incorrect – correct result ca. 15% smaller.
hep-lat/0601021v4

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

Experimental problem: reduce/eliminate dominant $B \to X_c e\nu$ background

Theoretical tool: light-cone expansion (LCE) (Neubert 93, Bigi et al. 93)



In LCE, $d\Gamma(B \to X_u e\nu) = HJ \otimes S$:

- H, J: hard and jet functions, calculate in perturbation theory
- S: shape function, non-perturbative & process-independent

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

Strategy (BLNP): (Bosch et al. 04,05)

- extract shape function from $B \to X_s\gamma$ spectrum in photon energy, use this to predict $B \to X_u e\nu$ spectra
- functional form of shape function restricted from moment relations

Other approaches: dressed gluon exponentiation (DGE): (Gardi 04)

- renormalon-inspired model for the leading shape function
- sub-leading shape functions not related to renormalon in m_b not included
- predictive functional form of shape function
- numerical results very close to BNLP

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

Results for various cuts: (HFAG 2007)

	accepted region	f_u	$\|V_{ub}\|[10^{-3}]$
CLEO [313]	$E_e > 2.1\,\mathrm{GeV}$	0.13	$4.09 \pm 0.48 \pm 0.37$
BELLE [316]	$E_e > 1.9\,\mathrm{GeV}$	0.24	$4.82 \pm 0.45 \pm 0.30$
BABAR [315]	$E_e > 2.0\,\mathrm{GeV}$	0.19	$4.39 \pm 0.25 \pm 0.32$
BABAR [314]	$E_e > 2.0\,\mathrm{GeV},\ s_{\mathrm{h}}^{\max} < 3.5\,\mathrm{GeV}^2$	0.13	$4.57 \pm 0.31 \pm 0.42$
BELLE [309]	$M_X < 1.7\,\mathrm{GeV}/c^2$	0.47	$4.06 \pm 0.27 \pm 0.24$
BELLE [318]	$M_X < 1.7\,\mathrm{GeV}/c^2, q^2 > 8\,\mathrm{GeV}^2/c^2$	0.24	$4.37 \pm 0.46 \pm 0.29$
BABAR [317]	$M_X < 1.7\,\mathrm{GeV}/c^2, q^2 > 8\,\mathrm{GeV}^2/c^2$	0.24	$4.75 \pm 0.35 \pm 0.31$
Average	$\boldsymbol{\chi^2 = 6/6}$, **CL= 0.41**		$\mathbf{4.52 \pm 0.19 \pm 0.27}$

Neubert FPCP07:

select “best” determinations (highest effi ciency, best theoretical control):

$$|V_{ub}| = 4.10(30)_{\mathrm{exp}}(?)(29)_{\mathrm{th}} \cdot 10^{-3}$$

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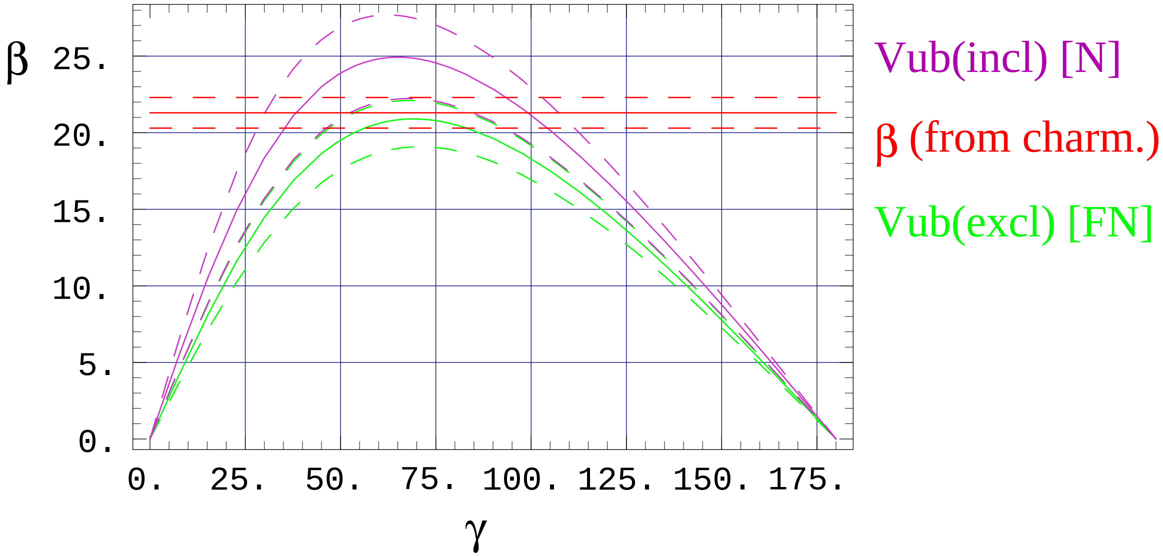
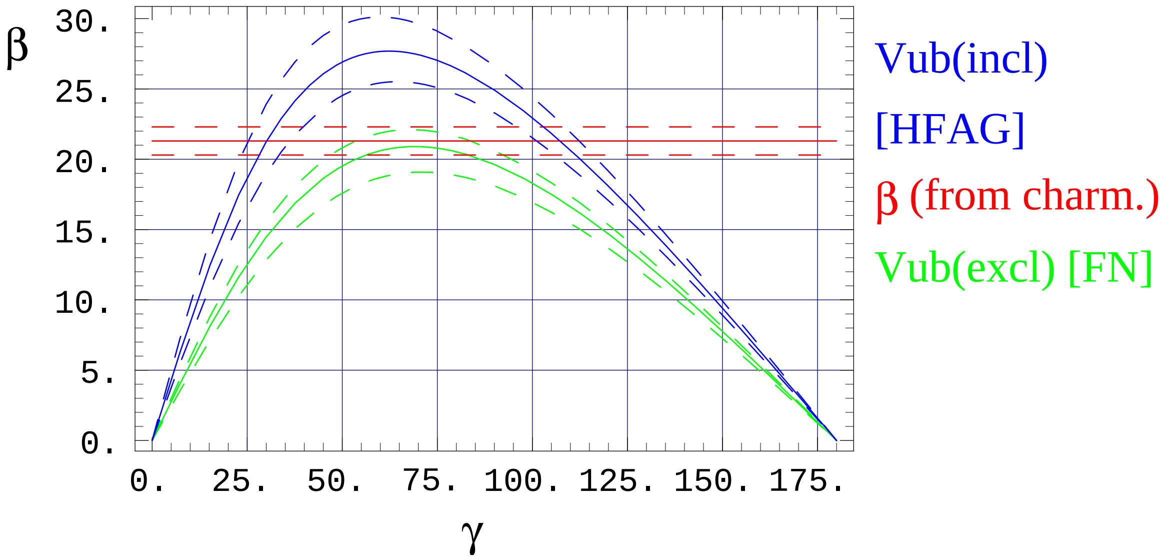
Again – caveat emptor: shape function uncertainty in exp. error – what impact would a more conservative analysis have?

Tension? What tension?





If Neubert's estimate of $|V_{ub}|_{\rm incl}$ stands after a more thorough analysis, $|V_{ub}|_{\rm incl}$ will still be on the large side, but not significantly so.

Can even attempt to average $|V_{ub}|_{\rm excl,FN}$ and $|V_{ub}|_{\rm incl,N}$:

$$|V_{ub}|_{\rm HFforum} = 3.68(24) \cdot 10^{-3}$$

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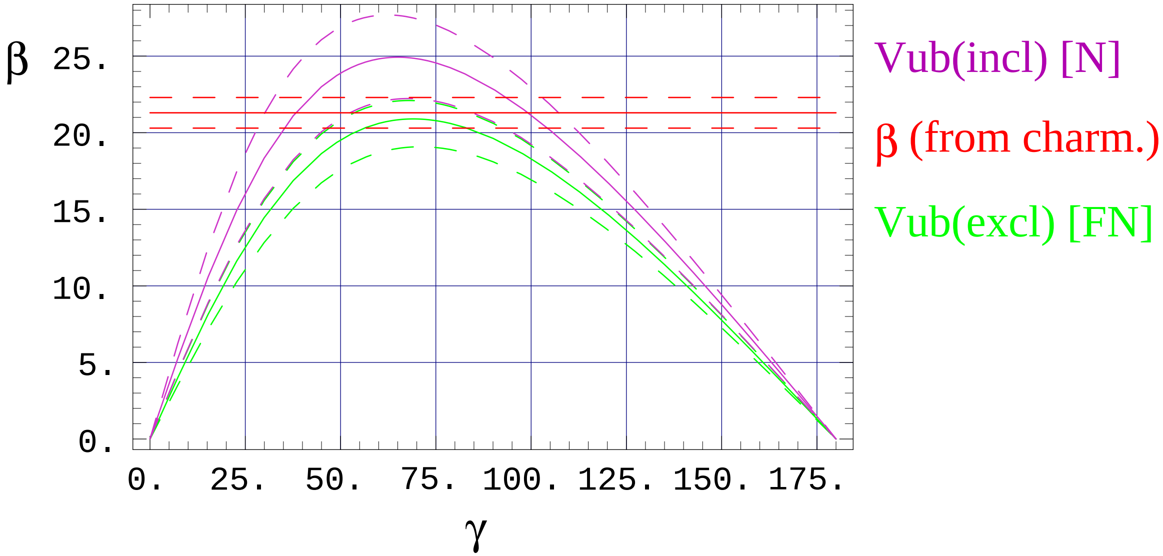

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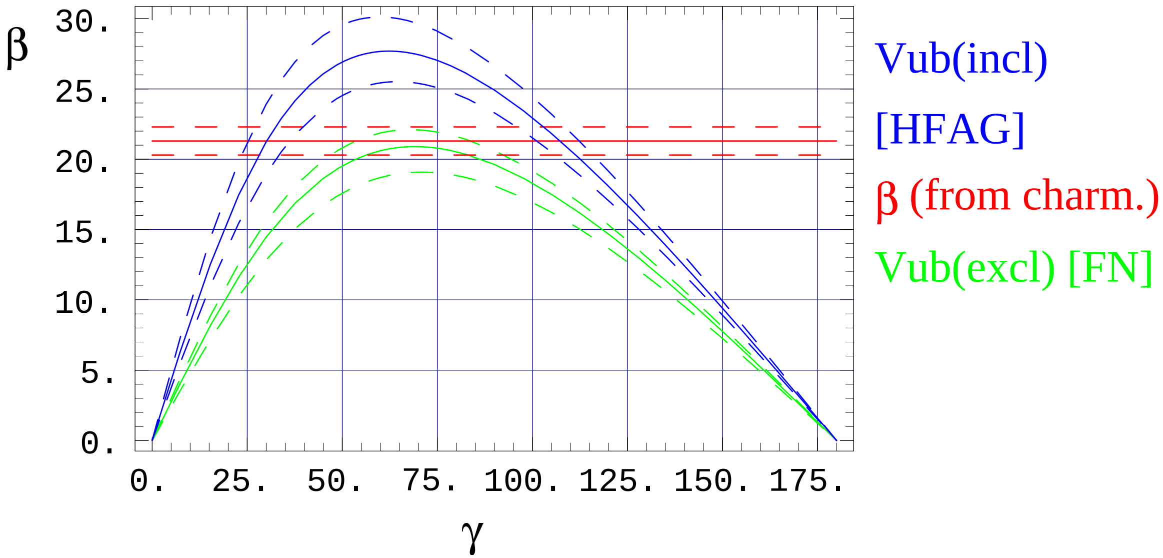

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Is this reasonable? Caveat emptor!

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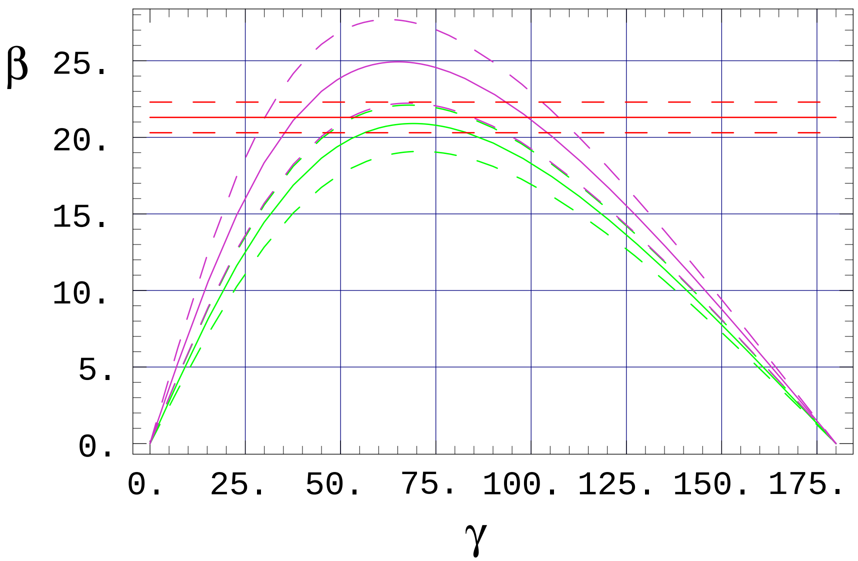

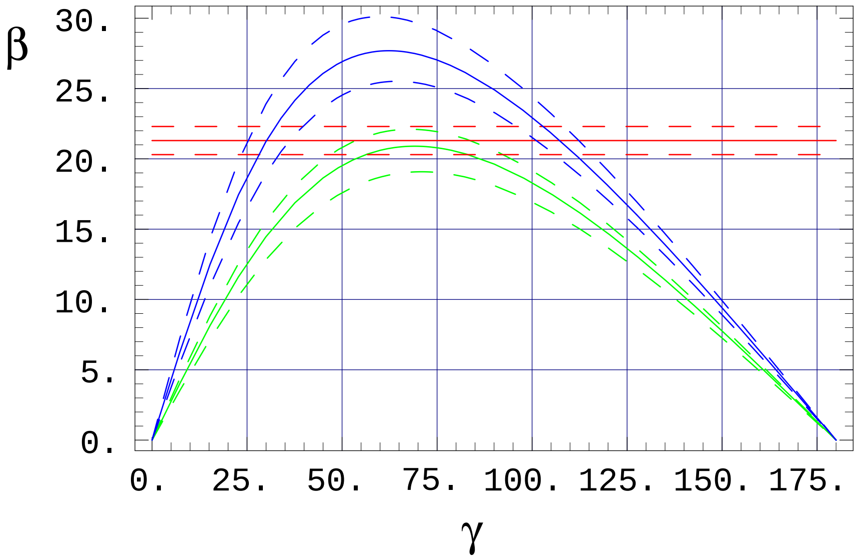

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BTW: can determine $|V_{ub}|$ from UT angles only:

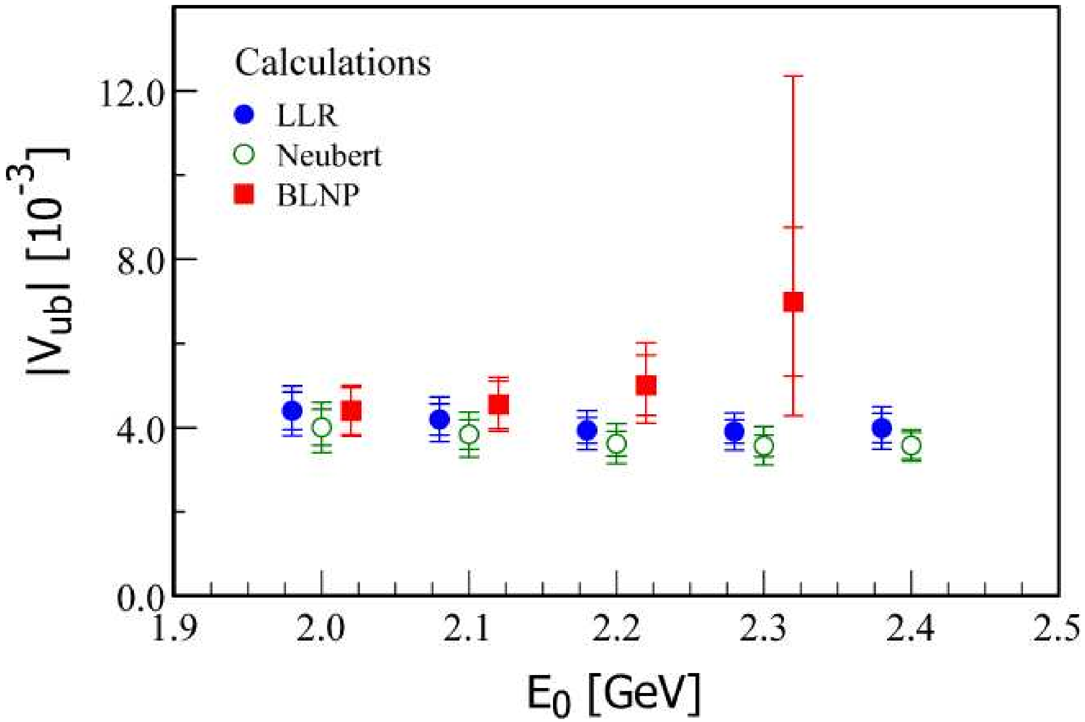
$$|V_{ub}|^{\rm UTfit,CKMfitter}_{\rm UTangles} = 3.50(18)\cdot 10^{-3}$$

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

Reduce dependence on shape-function by constructing SF-free relations between weighted spectra, for instance (Neubert 93):

$$\left|\frac{V_{ub}}{V_{tb}V_{ts}^*}\right|^2 = \frac{3\alpha}{\pi}\,|C_7(m_b)|^2 \eta_{\mathrm{QCD}}\,\frac{\hat{\Gamma}_u(E_0)}{\hat{\Gamma}_s(E_0)} + O(1/m_b)$$

with a lower cut-off E_0 on the spectra.



- power-corrections (sub-leading shape functions) must blow up for $E_0 \to m_B/2$
- nicely verified by Golubev/ Skovpen/Lüth 07 (see plot)
- LLR and Neubert 01 don't include power-corrections and produce deceivingly small errors for large E_0

Prospects for $|V_{ub}|$

Evidently, theorists have some homework to do:

- Fermilab calculation of $f_+^{B\to\pi}$ still preliminary: expect results soon?
- breaking through the low-q^2 barrier: moving NRQCD? (HPQCD)
- lattice form factor calculations not based on staggered fermions? (e.g. domain wall light + fully relativistic heavy quarks at fi nite volume + step scaling [Sommer + Alpha coll.])
- anything about sub-leading shape functions

Also, some words of caution (see Neubert, FPCP07):

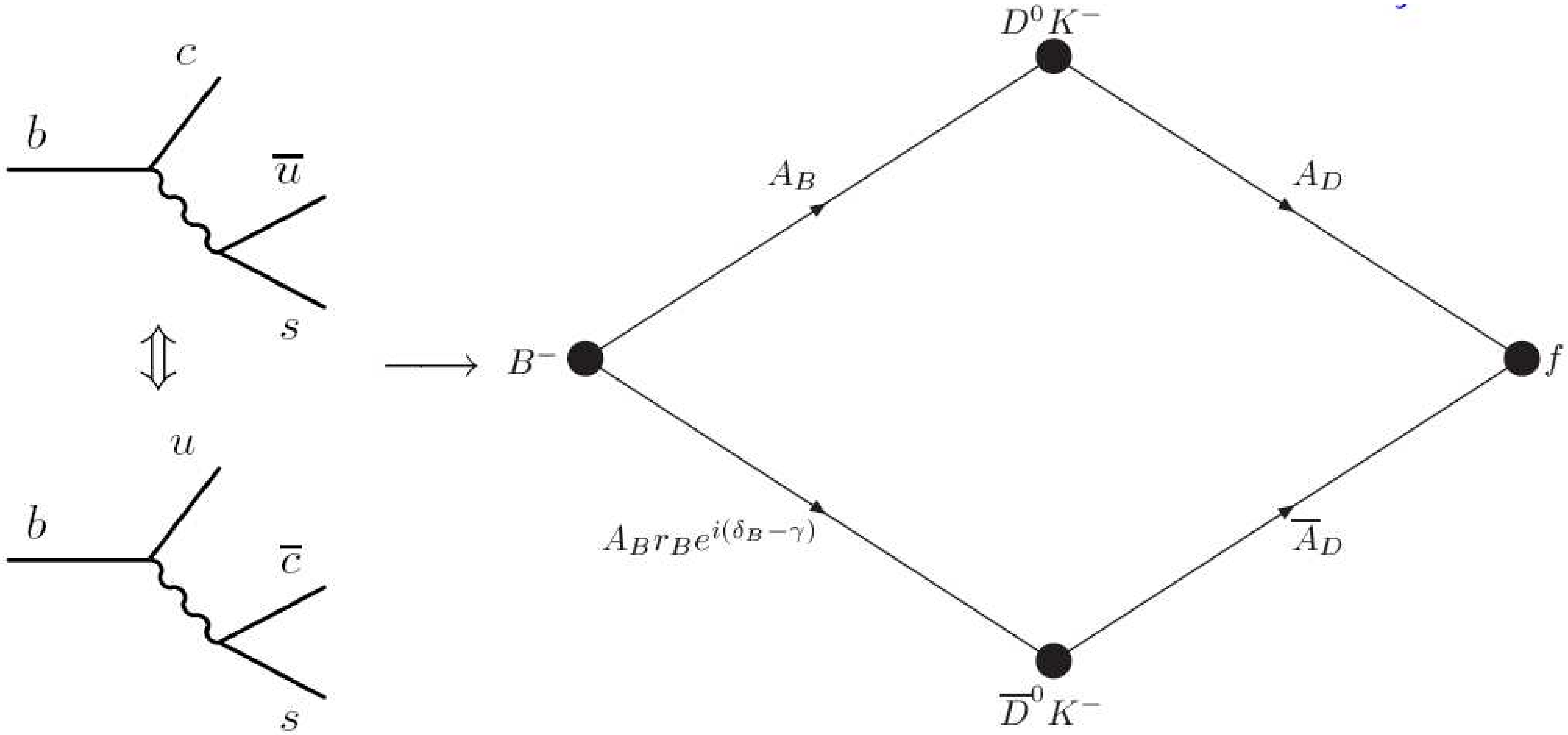
- don't average theory approaches using different approximations (e.g. LO vs. NLO)
- don't quote small theory errors from approaches without a serious error-analysis
- don't be fooled by the notion of "model-independent" approaches: that doesn't imply errors are 0 or small!! Always look out for estimates of neglected corrections!

γ from $B \to DK$

Many ways lead to γ…

…but not all of them are theoretically clean or feasable presently.
Focus on method suggested by Gronau/Wyler 1991:

- interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$



- no penguin contributions

$B \to (K_S\pi^+\pi^-)_D K$

Inteference between amplitudes Cabibbo-suppressed $\to$ extraction of γ from low-statistics data.

Only method with significant results so far: $B \to (K_S\pi^+\pi^-)_D K$:(Giri et al. 03)

$$\gamma = (92 \pm 41 \pm 11 \pm 12)^\circ \text{ (BaBar)}, \quad \gamma = (53^{+15}_{-18} \pm 3 \pm 9)^\circ \text{ (Belle)}$$

Right now error limited by statistics – at what level do we have to worry about theory errors?

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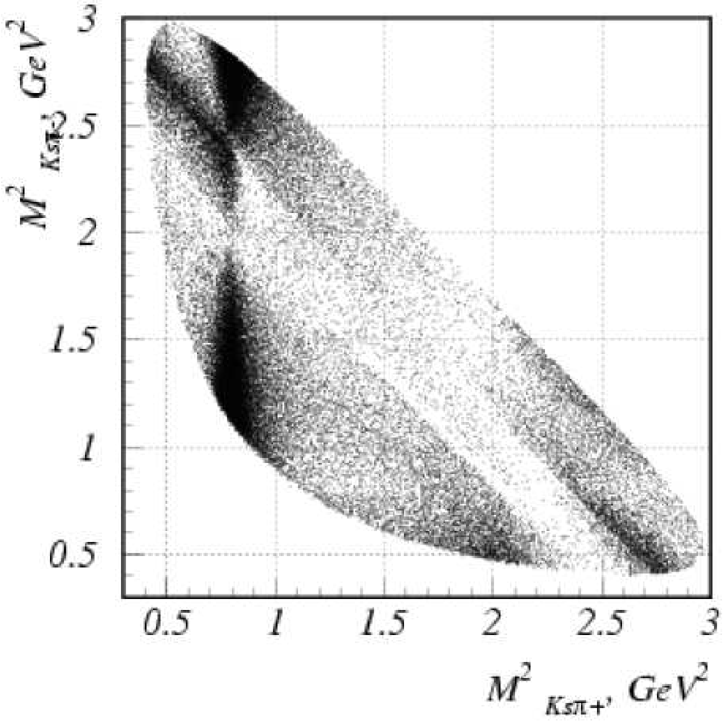
Sources of theory errors:

- treatment of Dalitz plot of $D \to K_S \pi^+ \pi^-$
- neglect of D mixing (Grossman/Soffer/Zupan 05)
- neglect of B lifetime difference in $B^0 \to D K_S$ (Gronau et al. 07)

Dalitz-Plot Analysis

Main source of uncercainty: ansatz for A_D



- standard: fit A_D as a sum of Breit-Wigners plus a constant non-resonant term
  - best for describing isolated, non-overlapping resonances far from threshold of additional decay channels
  - expect induced error of γ to be $\sim 10^\circ$ (Zupan CKM06)
- alternative I: K matrix formalism : recently implemented by FOCUS for $D^+ \to K^-\pi^+\pi^-$ (Focus 07, see also Descotes-Genon CKM06)
- alternative II: model-independent description: partition Dalitz plot in bins (Giri et al. 03)
  - implemented & studied by Belle (Poluektov CKM06), needs input from CLEO

Summary

- determinations of $|V_{us}|$ in a very mature state
  - small error reduction possible from even better lattice calculation of $f_+(0)$
- determinations of $|V_{cb}|$ in mature state
  - small discrepancy $\sim 1.6\,\sigma$ between exclusive and inclusive determination – could be resolved by unquenched form factor calculation and calculation of full $O(\alpha_s^2)$ corrections to $\Gamma(B \to X_c e\nu)$
- determinations of $|V_{ub}|$ in a slightly puzzling state
  - correction of HPQCD form factor has increased “tension” between exclusive and inclusive (HFAG) $|V_{ub}|$
- determination of γ from $B \to DK$ still limited by statistics
  - some theory questions to ponder about: model-independent Dalitz plot analysis including finite lifetime $\Delta\Gamma_d$ and D mixing