$|V_{ub}|$ and $|V_{cb}|$ determination

via hadronic form factors

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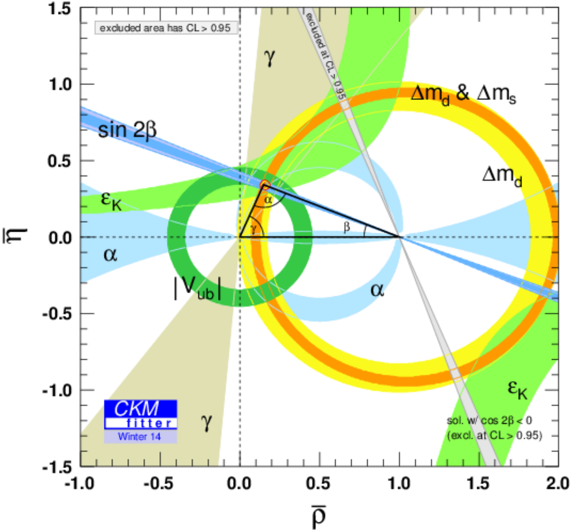
An overview of the progress in the last two years

Outline

- Introduction
- V_{ub}
  - $B \to \pi$ from LCSR
  - $B \to \pi$ from Lattice
  - Progress in $\Lambda_b \to p$
- V_{cb}
  - $B \to D^*$ Lattice updates
  - Resolving the puzzle in $B \to D^{(*)}(\pi)$ decays
  - Ongoing lattice projects in $B_{(s)} \to D_{(s)}$
- Summary

Isn't the CKM triangle known up to a few percent?



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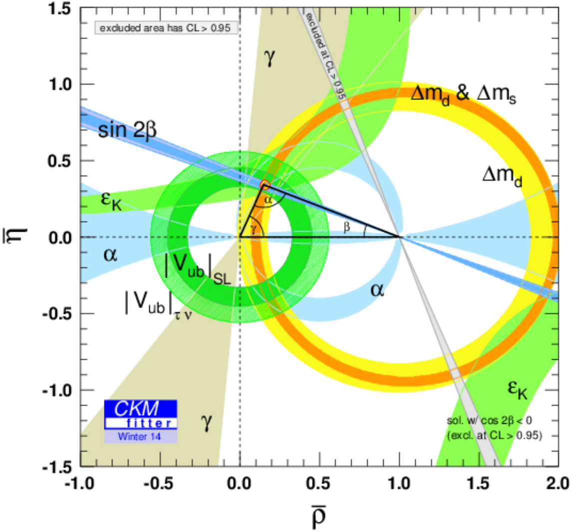
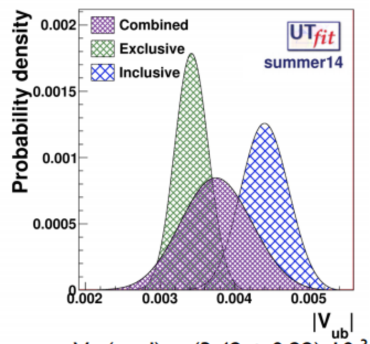
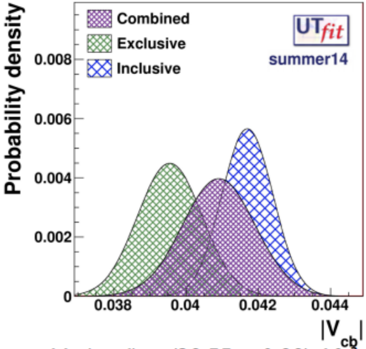


It seems that tensions abound





$V_{ub}(\mathrm{excl}) = (3.42 \pm 0.22)\ 10^{-3}$

$V_{ub}(\mathrm{incl}) = (4.40 \pm 0.31)\ 10^{-3}$

$V_{ub} = (3.75 \pm 0.46)\ 10^{-3}$

$\sim 1.9\,\sigma$ discrepancy

$V_{cb}(\mathrm{excl}) = (39.55 \pm 0.88)\ 10^{-3}$

$V_{cb}(\mathrm{incl}) = (41.7 \pm 0.7)\ 10^{-3}$

$V_{cb} = (40.9 \pm 1.0)\ 10^{-3}$

$\sim 2.5\,\sigma$ discrepancy

D. Derkach UTFIT@ICHEP2014

It seems that tensions abound

	Measurement	Prediction (remove parameter from the fit)	Pull
α, °	(90.8±7.5)	(87.2±3.9)	<1
$\sin(2\beta)$	(0.680±0.023)	(0.756±0.042)	-1.5
γ, °	(68.4±7.5)	(69.5±3.9)	~0
$\|V_{ub}\|$, 10^{-3}	(3.75±0.46)	(3.62±0.13)	+0.3
$\|V_{cb}\|$, 10^{-3}	(40.9±1.0)	(42.1±0.7)	-1.0
ε_K, 10^{-3}	(2.228±0.011)	(2.04±0.19)	+1.0
Δm_s, ps^{-1}	(17.768±0.024)	(17.5±1.1)	-0.3
$B(B_u \to \tau\nu)$, 10^{-4}	(1.14±0.22)	(0.805±0.07)	-1.4
$\overline{B}(B_s \to \mu\mu)$, 10^{-9}	(2.9±0.7)	(3.90±0.16)	1.3
$B(B_d \to \mu\mu)$, 10^{-9}	(0.37±0.15)	(0.114±0.007)	-1.7
β_s, rad (not in the SM fit)	(0.005±0.035)	(0.01867±0.0008)	<1

Note uncertainty on $|V_{ub}|^{\text{incl}} \sim 10\%$ ($< 2\%$ on $|V_{cb}|^{\text{incl}}$) due to large $b \to c l \nu$ background

How does one obtain V_{xb} exclusively

via the hadronic form factors?

By measuring the differential branching fraction

Schematically ($_{\text{ignoring kinematics}}$): $\frac{d\mathcal{B}}{dq^2} \propto |V_{xb}|^2 |f(q^2)|^2$

One can then extract $|V_{xb}|$ by considering either:

- the integrated spectrum over range in q^2: for V_{ub}, $\Delta\zeta(0, q^2_{\max}) = \frac{1}{|V_{xb}|^2} \int_0^{q^2_{\max}} dq^2 \frac{d\Gamma}{dq^2}$
- the kinematical endpoint where form factors simplify: e.g. $|V_{ub}|^2 |f_+^{B\to\pi}(0)|^2$ or $|V_{cb}|^2 |\mathcal{F}^{B\to D^*}(q_{\max})|^2$
- the entire spectrum using an extrapolation technique.....

Extrapolation in q^2

between Lattice and LCSR results

- Simple pole-type BK/BZ: e.g. $f(q^2) = \frac{r_1}{1-q^2/m_1^2} + \frac{r_2}{1-q^2/m_{\rm fit}^2}$
- Low-lying resonances via simple pole $P(t) = 1 - t/m_R^2$

- Series Expansion (BGL[1]): $f(t) = \frac{1}{B(t)\,\phi_f(t)} \sum_k \alpha_k\, z^k(t)$

$$z(t) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}, \qquad t_0 = t_+\left(1 - \sqrt{1 - \frac{t_-}{t_+}}\right),$$

$$B(t) = z(t, m_{\rm R}^2) \quad \text{and} \qquad t_\pm = \sqrt{m_B^2 \pm m_\pi^2}$$

- Simplified SE (BCL[2]): $f(t) = \frac{1}{P(t)} \sum_k \tilde{\alpha}_k\, z^k(t, t_0)$.

[1] C. G. Boyd, B. Grinstein and R. F. Lebed, Phys. Rev. Lett. **74**, 4603 (1995) [arXiv:hep-ph/9412324] and I. Caprini, L. Lellouch and M. Neubert, Nucl. Phys. B **530**, 153 (1998) [arXiv:hep-ph/9712417]

[2] C. Bourrely, I. Caprini and L. Lellouch, Phys. Rev. D **79**, 013008 (2009) [arXiv:0807.2722 [hep-ph]]

Status of V_{ub} theory

Decay	Calculation	Collaboration	arXiv
$B \to \pi$	LCSR (PS)	Ball and Zwicky	hep-ph/0406232
	LCSR ($\overline{\text{MS}}$)	Khodjamirian et al	1103.2655 [hep-ph]
	LCSR ($@q^2 = 0$)	AB	1203.1359 [hep-ph]
	LQCD	FNAL/MILC	1311.6552 [hep-lat]
	LQCD	RBC/UKQCD	1311.1143 [hep-lat]
	LQCD	HPQCD	1310.3207 [hep-lat]
$B \to \rho$	LCSR (PS)	Ball and Zwicky	hep-ph/0406232
	LCSR (corr. errors)	AB Zwicky Straub	1409.xxxx [hep-ph]
$B_s \to K^{(*)}$	LCSR (PS)	Ball and Zwicky	hep-ph/0406232
	LCSR (corr. errors)	AB Zwicky Straub	1409.xxxx [hep-ph]
	LQCD	FNAL/MILC	1312.3197 [hep-lat]
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$\Lambda_b \to p$	LCSR	Khodjamirian et al	1108.2971 [hep-ph]
	LQCD	Meinel	1401.2685 [hep-lat]

Golden channel for $|V_{ub}|^{\textbf{excl}}$ is $B \to \pi l \nu$, depends on $f_+(q^2)$ from Lattice QCD ($q^2 \gtrsim 15\,\text{GeV}^2$) or Light cone sum rules (LCSR) ($q^2 \lesssim 6 - 7\,\text{GeV}^2$)

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Other B channels e.g. $B \to \rho$ provide possibilties for comparison at B factories or even at LHCb via B_s or Λ_b decays.

State of $f_+(q^2)$ in LCSR < 2012

17 years since twist-2 NLO corrections calculated

The form factors describing the $B \to \pi l \nu$ decay are:

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

The decay rate is then given by:

$$\frac{d\Gamma}{dq^2}(\bar{B}^0 \to \pi^+ l^- \bar{\nu}_\ell) = \frac{G_F^2 |V_{ub}|^2}{192\pi^3 m_B^3} \lambda^{3/2}(q^2)|f_+(q^2)|^2,$$

where $\lambda(q^2) = (m_B^2 + m_\pi^2 - q^2)^2 - 4m_B^2 m_\pi^2$

State of $f_+(q^2)$ in LCSR < 2012

17 years since twist-2 NLO corrections calculated

Sum rule for $f_+(q^2)$

$$f_+(q^2) = \frac{1}{f_B m_B^2} \int_{m_b^2}^{s_0} ds\, \rho_{\rm LC}\, e^{-(s-m_B^2)/M^2},$$

- 1997: NLO twist-2 corrections were calculated[3]
- 2000: LO corrections up to twist-4 were calculated[4]
- 2004: NLO twist-3 corrections[5]
- 2008: $\overline{\rm MS}$ m_b is used in place of the pole mass [6]
- 2011: Updated analysis, a_2, a_4 from F_π, LCSR+new JLab [7]

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[3] A. Khodjamirian et al, Phys. Lett. B **410** (1997) 275 [arXiv:hep-ph/9706303]; E. Bagan, P. Ball and V. M. Braun, Phys. Lett. B **417** (1998) 154 [arXiv:hep-ph/9709243]

[4] A. Khodjamirian et al, Phys. Rev. D **62** (2000) 114002 [arXiv:hep-ph/0001297]

[5] P. Ball and R. Zwicky, Phys. Rev. D **71** (2005) 014015 [arXiv:hep-ph/0406232]

[6] G. Duplancic et al, J. Phys. Conf. Ser. **110** (2008) 052026

[7] A. Khodjamirian, T. .Mannel, N. Offen, Y. -M. Wang, Phys. Rev. **D83** (2011) 094031, 1103.2655 [hep-ph]

Why two-loop corrections in LCSR?

A. Bharucha, JHEP **1205** (2012) 092 [arXiv:1203.1359 [hep-ph]].

- Improved determination of $|V_{ub}|$!
- Test argument that radiative corrections to $f_+ f_B$ and f_B should cancel when both calculated in sum rules, in view of the sizeable two-loop contribution to f_B in QCDSR

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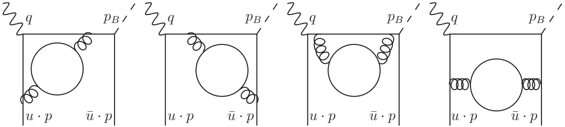
$\Rightarrow$ Calculate subset of two-loop radiative corrections for twist-2 contribution to $f_+(0)$ proportional to β_0 (good approximation to the complete next-to-next-to-leading order (NNLO) result.)

NLO twist two diagrams + fermion loop insertion

$$\Pi^{(2)}_\mu = \mathcal{N} \int_0^1 du\, \phi(u,\mu^2) \int \frac{d^D k}{(2\pi)^D} \frac{\Gamma(\epsilon)\Gamma(2-\epsilon)^2}{\Gamma(4-2\epsilon)} \left(\frac{-k^2}{4\pi\mu^2}\right)^{-\epsilon} \frac{1}{k^2} \left(g^{\alpha\beta} - \frac{k^\alpha k^\beta}{k^2}\right) F^{\mathrm{T}}_\mu ,$$



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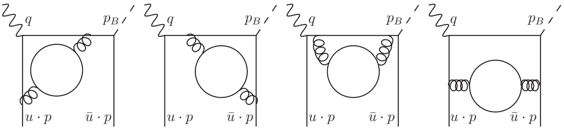


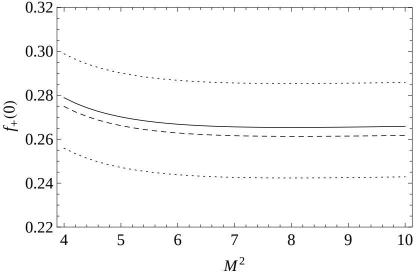
Propagator changes

$$-i\frac{g^{\alpha\beta}}{k^2}\to -i\frac{1}{k^2}\left(g^{\alpha\beta}-\frac{k^\alpha k^\beta}{k^2}\right)$$

$q^2=0$, but still 3 scales

Use HypExp, FeynCalc and Polylog Identities

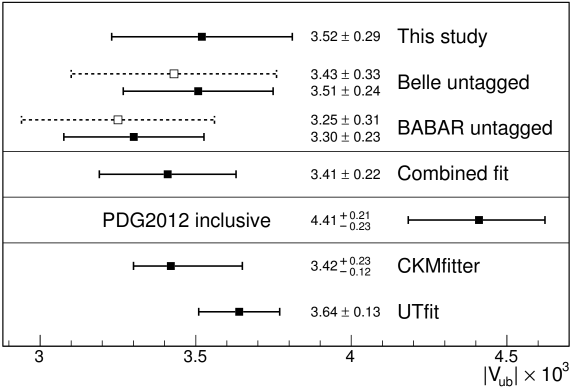
Results



- $f_+(0)$ ($0.262^{+0.020}_{-0.023}$) at $\mathcal{O}(\alpha_s^2\beta_0)$ (solid) with uncertainties$\lesssim$ 9% (dotted), compared to $\mathcal{O}(\alpha_s)$ result (dashed), as a function of Borel parameter M^2
- Despite $\sim$ 9% $\mathcal{O}(\alpha_s^2\beta_0)$ corrections to f_B, change in $f_+(0)$, only $\sim$ 2%

This enforces the stability of LCSR w.r.t. higher order corrections, confirmation f_B from sum rules not Lattice QCD

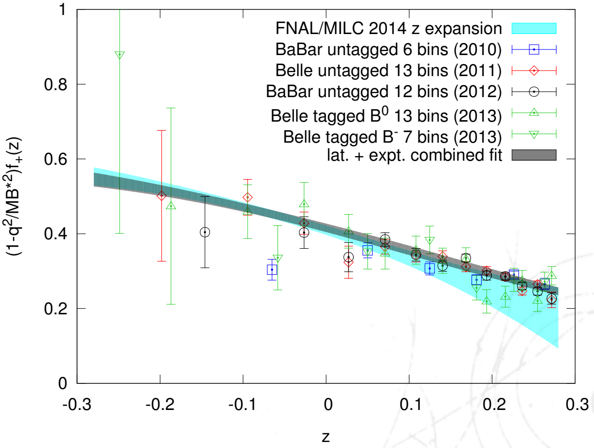
BABAR and BELLE Results 2013



Comparison of $|V_{ub}|$ using BCL with $K = 3$, using LCSR and LQCD inputs for tagged, untagged Belle and BABAR data as well as a combined fit with those three data sets. The value of inclusive $|V_{ub}|$ is taken from a recent PDG review. The CKMfitter/UTfit estimates of $|V_{ub}|$ are from global fits where $|V_{ub}|$ related inputs are excluded. The dashed lines represent $|V_{ub}|$ values quoted in the original papers

Recent Lattice updates

Talk by Daping Du (FNAL/MILC) at Lattice 2014



Recent Lattice updates

Talk by Daping Du (FNAL/MILC) at Lattice 2014

- We use a new functional method to implement the z-expansion.
- We combine the lattice result (**normalization blinded**) for the form factors with experimental measurements to determine $|V_{ub}|$.

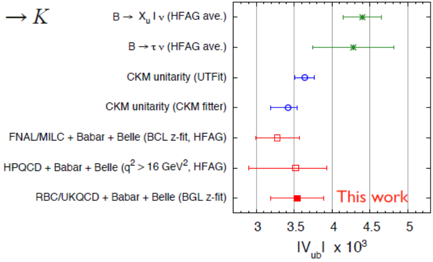
Fit	χ^2[dof]	p-value	b_0	b_1	b_2	b_3	$\lvert V_{ub}\rvert$ error
Lattice only	0.62 [3]	0.6	0.410(12)	-0.69(12)	-0.54(94)	0.33(150)	-
Exp. only(BaBar 10,12+Belle 11,13)	1.1[51]	0.32	0.397(12)	-0.42(14)	-0.72(52)	-	-
All (exp. + lattice)	1.1[53]	0.27	0.417(11)	-0.580(53)	-0.30(12)	0.58(29)	4.1%

- The error for $|V_{ub}|$ is **4.1%**, compared to the result of using FNAL/MILC 2008 analysis: $|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$ (8.8%).
- We are also working on the $B_s \to K\ell\nu$ semileptonic form factors (**Y. Liu, 1312.3197**) which provides an another exclusive determination of $|V_{ub}|$. The work is in progress.

Recent Lattice updates

Talk by Taichi Kawanai (RBC/UKQCD) at Lattice 2014

- We have calculated the $B \to \pi$ and $B_s \to K$ form factors using 2+1 flavor dynamical domain-wall fermion gauge field configurations with relativistic heavy quark action.
- Provide important independent check on existing calculations using staggered light quarks.
- Will present final results for $B \to \pi$ and $B_s \to K$ lattice form factors as coefficients of the z-expansion and their correlations.
- $|V_{ub}|$ is determined by combined z-fit with experimental data from Babar and Belle to about 10% precision.



$|V_{ub}|$: Other possibilities

Form factors fo $\Lambda_b \to p$ decays

- Heavy-light baryon interpolating current, $\eta = \epsilon^{ijk}(u_i C\Gamma_b d_j)\tilde{\Gamma}_b c_k$, choice of Γ_b and $\tilde{\Gamma}_b$ debated since 80s
- Λ_b^* with $J^P = 1/2^-$, mass (measured at LHCb 2012) 5.91 GeV, $m_{\Lambda_b} = 5.62$ GeV.
- 3 point sum rules+HQET[8]. Large continuum dependence, treatment of -ve parity baryons not clear, large 4 quark resonance contribution
- LCSR+HQET, Λ_b DA[9] (Use CZ current for p, couples to Δ), and in full QCD with the p DA[10], using a mixing parameter β in Γ_b and $\tilde{\Gamma}_b$ (introduces new systematic error), and including the Λ_b^* in continuum
- Recently, Λ_b^* contribution separated in SR [11], results less dependent on current, use both $\Gamma_b = \gamma_5(\gamma_5\gamma_\lambda)$ and $\tilde{\Gamma}_b = 1(\gamma_\lambda)$.

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[8] e.g. R. S. Marques de Carvalho, F. S. Navarra, M. Nielsen, E. Ferreira and H. G. Dosch, Phys. Rev. D **60** (1999) 034009 [hep-ph/9903326]

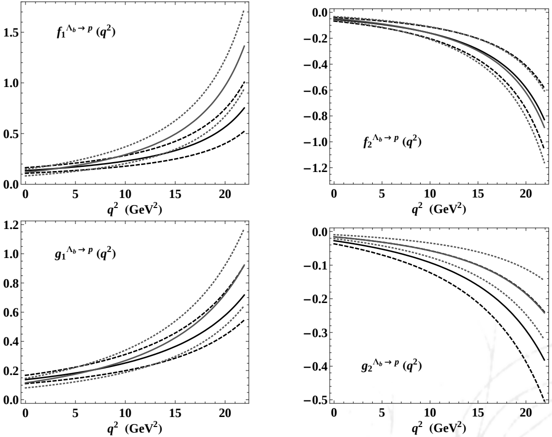
[9] e.g. Y. -M. Wang, Y. -L. Shen and C. -D. Lu, Phys. Rev. D **80** (2009) 074012 [arXiv:0907.4008 [hep-ph]]

[10] K. Azizi, M. Bayar, Y. Sarac and H. Sundu, Phys. Rev. D **80** (2009) 096007. [arXiv:0908.1758 [hep-ph]]

[11] A. Khodjamirian, C. .Klein, T. .Mannel and Y. -M. Wang, JHEP **1109** (2011) 106 [arXiv:1108.2971 [hep-ph]].

$|V_{ub}|$: Other possibilities

Form factors fo $\Lambda_b \to p$ decays



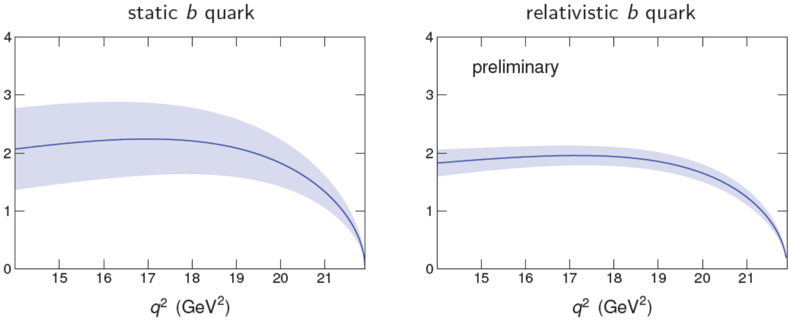
Axial vector current: $\Delta\zeta(0, 11\,\mathrm{GeV}^2) = 5.5^{+2.5}_{-2.0}\mathrm{ps}^{-1}$

Pseudoscalar current: $\Delta\zeta(0, 11\,\mathrm{GeV}^2) = 5.6^{+3.2}_{-2.9}\mathrm{ps}^{-1}$

Not yet competitive with $B \to \pi$ but offers independent determination

$|V_{ub}|$: Other possibilties

Recent Lattice results for $\Lambda_b \to p l \nu$



Comparing Detmold et al, 1306.0446 [hep-lat] (Eichten-Hill static b quarks), with Meinel, 1401.2685 [hep-lat] (RHQ b quarks), both using domain wal u,d,s quarks

Taken from Stefan Meinel's talk at FPCP 2014

Status of V_{cb} theory

Decay	Calculation	Collaboration	arXiv
$B \to D^*$	SR	Gambino et al	1206.2296 [hep-ph]
	LQCD	FNAL/MILC	1312.0155 [hep-lat]
	LQCD	HPQCD	1310.3207 [hep-lat]
$B \to D$	SR	Uraltsev et al	hep-ph/0312001
	LQCD	FNAL/MILC	1312.0155 [hep-lat]
	LQCD	HPQCD	1310.3207 [hep-lat]
$B_s \to D_s^{(*)}$	LQCD	Atoui et al	1310.5238 [hep-lat]
	LQCD	HPQCD	1310.3207 [hep-lat]

$B \to D^*$ generally preferred due to higher experimental rate and lack of nonperturbative $\mathcal{O}(1/m_b)$ corrections to the form factor

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Much progress and ongoing work from FNAL/MILC and HPQCD on above channels

$B \to D^{(*)}$: the basics

The form factors are defined via

$$\frac{d\Gamma}{d\omega}(B \to D^* \ell \bar{\nu}_\ell) = \frac{G_F^2}{48\pi^3}|V_{cb}|^2 M_{D^*}^3 (\omega^2 - 1)^{1/2} P(\omega)(\mathcal{F}(\omega))^2$$
$$\frac{d\Gamma}{d\omega}(B \to D\, \ell \bar{\nu}_\ell) = \frac{G_F^2}{48\pi^3}|V_{cb}|^2 (M_B + M_D)^2 M_D^3 (\omega^2 - 1)^{3/2}(\mathcal{G}(\omega))^2$$

$\omega = v \cdot v' = E_{D^{(*)}}/M_{D^{(*)}}$ (in the B rest frame), and where $P(\omega)$ is a known phase space factor.

In heavy quark limit: $\mathcal{F}(1) = \mathcal{G}(1) = 1$

Comparing the latest theoretical results

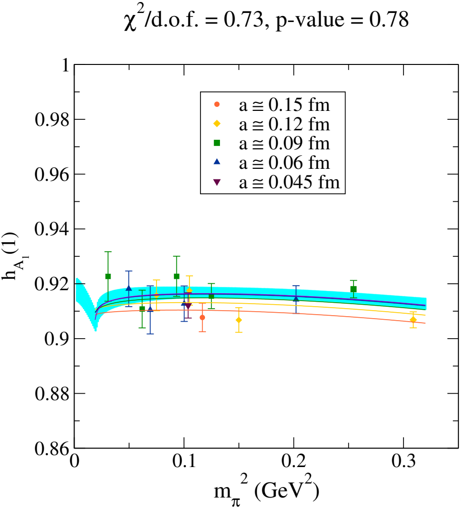
Courtesy of Giulia Ricciardi, 1403.7750 [hep-ph]

Exclusive decay	$\mathbf{|V_{cb}| \times 10^3}$
$\bar{B} \to D^* l \bar{\nu}$	
FNAL/MILC (Lattice unquenched)[17]	$39.04 \pm 0.49_{\rm exp} \pm 0.53_{\rm QCD} \pm 0.19_{\rm QED}$
HFAG (Lattice unquenched)[11,15,16]	$39.54 \pm 0.50_{\rm exp} \pm 0.74_{\rm th}$
Rome (Lattice quenched $\omega \neq 1$)[18,14]	$37.4 \pm 0.5_{\rm exp} \pm 0.8_{\rm th}$
HFAG (Sum Rules)[11,19,20]	$41.6 \pm 0.6_{\rm exp} \pm 1.9_{\rm th}$
$\bar{B} \to D l \bar{\nu}$	
FNAL/MILC (Lattice unquenched $\omega \neq 1$)[22,25]	$38.5 \pm 1.9_{\rm exp+lat} \pm 0.2_{\rm QED}$
PDG (HQE + BPS)[29,28]	$40.6 \pm 1.5_{\rm exp} \pm 0.8_{\rm th}$
Rome (Lattice quenched $\omega \neq 1$)[25,26]	$41.6 \pm 1.8_{\rm stat} \pm 1.4_{\rm syst} \pm 0.7_{\rm FF}$

Central values of $\mathcal{F}(1)$ for $B \to D^*$ from lattice unchanged:
Error decreases, tension increases

Latest news from the Lattice

Bailey et al. (FNAL/MILC) 1403.0635



MILC N_f=2+1 asqtad
FNAL b and c with asqtad
light valence
a: 0.045 to 0.15 fm
m_π: 174 to 520 MeV
$\mathcal{F}(1) = 0.906 \pm 0.004 \pm 0.01$

Compare to heavy quark sum rules result[a]:
$\mathcal{F}(1) = 0.86 \pm 0.02$

[a] P. Gambino, T. Mannel and N. Uraltsev, JHEP **1210** (2012) 169 [arXiv:1206.2296 [hep-ph]].

$|V_{cb}|$: A possible explanation?

Babar found evidence for 2s states consistent with helicity angles [arXiv:1009.2076]

Notation	$s_l^{\pi_l}$	J^P	m (GeV)	Γ (GeV)	
D	$\frac{1}{2}^-$	0^-	1.87		} 1s
D^*	$\frac{1}{2}^-$	1^-	2.01		
D_0^*	$\frac{1}{2}^+$	0^+	2.40	0.28	} 1p "broad"
D_1^*	$\frac{1}{2}^+$	1^+	2.44	0.38	
D_1	$\frac{3}{2}^+$	1^+	2.42	0.03	} 1p "narrow"
D_2^*	$\frac{3}{2}^+$	2^+	2.46	0.04	
D'	$\frac{1}{2}^-$	0^-	2.54	0.13	} 2s
D'^*	$\frac{1}{2}^-$	1^-	2.61	0.09	

F. Bernlochner, Z. Ligeti and S. Turczyk, [Phys.Rev. D85 (2012) 094033, arXiv:1202.1834]

$|V_{cb}|$: A possible explanation?

Charm state X_c	$\mathcal{B}(B^+ \to X_c\, \ell^+\, \nu)$	
D	$(2.31 \pm 0.09)\,\%$	
D^*	$(5.63 \pm 0.18)\,\%$	
$\sum D^{(*)}$	**$(7.94 \pm 0.20)\,\%$**	
$D_0^* \to D\,\pi$	$(0.41 \pm 0.08)\,\%$	broad states $(0.86 \pm 0.12)\%$
$D_1^* \to D^*\,\pi$	$(0.45 \pm 0.09)\,\%$	
$D_1 \to D^*\,\pi$	$(0.43 \pm 0.03)\,\%$	narrow states $(0.84 \pm 0.04)\%$
$D_2^* \to D^{(*)}\,\pi$	$(0.41 \pm 0.03)\,\%$	
$\sum D^{**} \to D^*\pi$	**$(1.70 \pm 0.12)\,\%$**	
$D\,\pi$	$(0.66 \pm 0.08)\,\%$	
$D^*\,\pi$	$(0.87 \pm 0.10)\,\%$	
$\sum D^*\pi$	**$(1.53 \pm 0.13)\,\%$**	
$\sum D^{(*)} + \sum D^*\pi$	**$(9.47 \pm 0.24)\,\%$**	
$\sum D^{(*)} + \sum D^{**} \to D^{(*)}\pi$	**$(9.64 \pm 0.23)\,\%$**	
Inclusive X_c	**$(10.92 \pm 0.16)\,\%$**	

$|V_{cb}|$: A possible explanation?

1/2 vs. 3/2 puzzle

- Uraltsev sum rule prediction + quark model [Bigi et. al., arXiv:0708.1621]

$$\mathcal{B}(B^+ \to D^{**}_{1/2=\text{broad}}\,\ell^+\nu)/\mathcal{B}(B^+ \to D^{**}_{3/2=\text{narrow}}\,\ell^+\nu) \sim 0.1 - 0.2$$

- In conflict with experimental result

$D_0^* \to D\,\pi$	$(0.41 \pm 0.08)\,\%$	broad states $(0.86 \pm 0.12)\,\%$
$D_1^* \to D^*\,\pi$	$(0.45 \pm 0.09)\,\%$	
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$D_2^* \to D^{(*)}\,\pi$	$(0.41 \pm 0.03)\,\%$	

Courtesy of Florian Bernlochner

'1/2' vs '3/2' *problem*

$|V_{cb}|$ *inclusive* vs. *exclusive*

gap inclusive vs exclusive

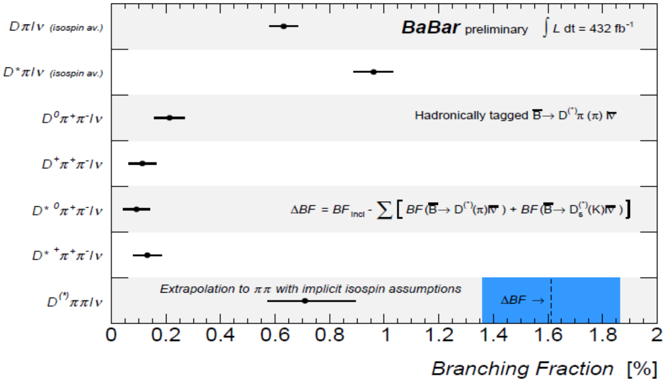
measured 1P states

Thanks to Sascha Turczyk for the tables!

$|V_{cb}|$: Experimental reaction

Preliminary BaBar results

- significance of the gap is reduced from $\approx 7\sigma$ to $\approx 3\sigma$



From Thomas Lück's talk at ICHEP14

$|V_{cb}|$: Lattice ongoing work

$B \to D\ell\bar{\nu}$

Ongoing new lattice calculations, including nonzero recoil:

	FNAL/MILC arXiv:1312.0155	HPQCD arXiv:1310.3207
u, d, s-quark action	AsqTad	HISQ/AsqTad
b-quark action	clover (Fermilab)	NRQCD
c-quark action	clover (Fermilab)	HISQ
m_π (MeV)	180 - 450	260 - 480
a (fm)	0.045 - 0.12	0.09 - 0.12

$B_s \to D_s\ell\bar{\nu}$

No experimental data yet, but measurement possible at Belle II or LHCb?
(Ongoing) lattice calculations:

- Atoui et al. [arXiv:1310.5238]
- HPQCD [Bouchard et al., arXiv:1310.3207]

Update for $B \to Dl\nu$ from BELLE presented by Robin Glattauer at ICHEP14

Summary

and Outlook[8]

Updates from LCSR and Lattice on V_{ub}:

- At $\mathcal{O}(\alpha_s^2\beta_0)$, despite $\sim 9\%$ increase in f_B from QCDSR, LCSR prediction for $f_+(0)$ increases by $\sim 2\%$ to $f_+(0) = 0.262^{+0.020}_{-0.023}$, $|V_{ub}| = (3.34 \pm 0.10 \pm 0.05 +^{0.29}_{-0.26})10^{-3}$,
- Combined fit of latest experiment and theory with BCL type analysis 3.41 ± 0.22 vs. PDG2012 inclusive $4.41^{+0.21}_{-0.23}$. CKMfitter and UTfit in agreement with exclusive result.
- Precise predictions for $B \to \pi$, reducing uncertainty by 50% since 2008, and for $\Lambda_b \to p$ form factors from LQCD

[8] Thanks to: Patricia Ball for her ideas and discussions; Stefan Meinel, Sascha Turczyk, Aida El-Khadra and Andreas Kronfeld for helpful advice and Flip Tanedo for letting me use his beamer theme

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Resolving the tension in V_{cb}:

- Progress from Lattice in $B \to D^{(*)}$ form factors, FNAL/MILC errors reduced, increasing significance of discrepancy with inclusive to 3σ
- Proposal to solve three puzzles related to $B \to D^{(*)}$ via transitions into the 'radial' and/or D-wave states being more significant than in naive quark models
- Measurement from BABAR of $\mathcal{B}(B \to D^{(*)}Xl\nu)$ supports proposal

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Things for the future:

- $|V_{ub}|$ at LHCb via $B_s \to K^{(*)}$, $\Lambda_b \to p\mu\nu$ decays
- Further measurments of radial $D^{(*)}$ mesons

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e.g. fitting to experiment to extract V_{ub}

A BCL type analysis

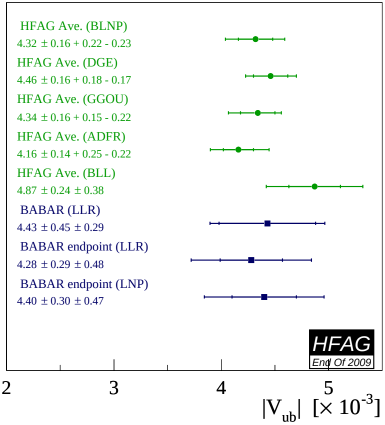
Use parameterisation: $f(t) = \frac{1}{1-t/m_R^2} \sum_k \tilde{\alpha}_k z^k(t, t_0)$

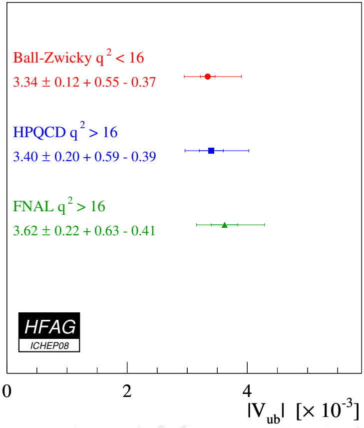
$$\chi^2_{th} = \sum_{j,k=1}^{8} [f_j^{in} - f_+(q_j^2)] C_{jk}^{-1} [f_k^{in} - f_+(q_k^2)] + (f_+(0) - f_{\rm LCSR})^2/(\delta f_{\rm LCSR})^2$$

$$\chi^2_{exp} = \sum_{j,k=1}^{22} [\mathcal{B}_j^{in} - \mathcal{B}_j(f_+)] C_{\mathcal{B}\,jk}^{-1} [\mathcal{B}_k^{in} - \mathcal{B}_k(f_+)]\,, \qquad \chi^2 = \chi^2_{th} + \chi^2_{exp}$$

- f_j^{in} is Lattice at q_j^2
- $\mathcal{B}_j^{in}$ are exp. partial branching fractions
- $\mathcal{B}_j(f_+)$ are integrated over the bins $[q_j^2, q_{j+1}^2]$, with given parametrization for $f_+(q^2)$.

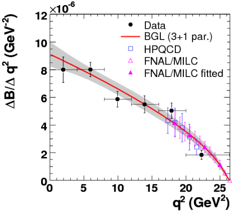
Status of V_{ub} in 2009





Experimental updates in 2010/11!

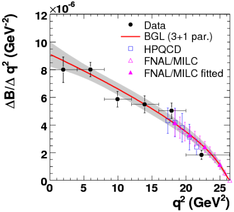
from Babar-1[9]

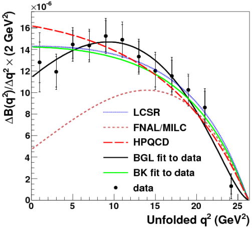


9 P. del Amo Sanchez *et al.* [BABAR Coll.], Phys. Rev. D **83** (2011) 032007, [arXiv:1005.3288 [hep-ex]].

Experimental updates in 2010/11!

from Babar-2[9]

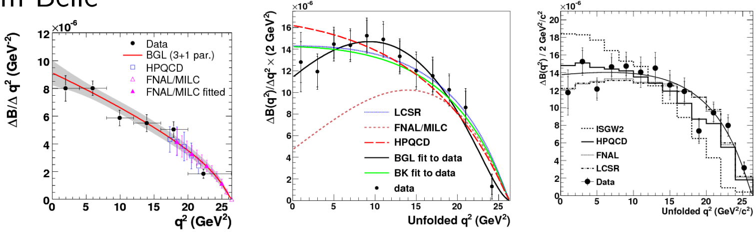




[9] P. del Amo Sanchez *et al.* [BABAR Coll.], Phys. Rev. D **83** (2011) 052011 [arXiv:1010.0987 [hep-ex]].

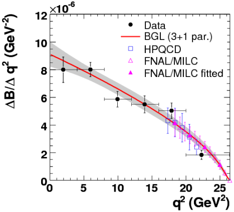
Experimental updates in 2010/11!

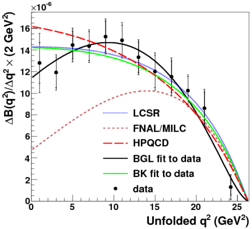
from Belle[9]

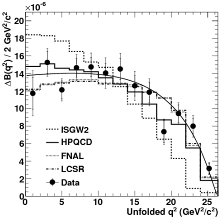


[9] H. Ha *et al.* [BELLE Coll.], Phys. Rev. D **83** (2011) 071101, [arXiv:1012.0090 [hep-ex]].

Experimental updates in 2010/11!







	BaBar (2)	BaBar (1)	BaBar Avg.	Belle
Total BF	$1.42 \pm 0.05 \pm 0.07$	$1.41 \pm 0.05 \pm 0.07$	$1.42 \pm 0.04 \pm 0.07$	$1.49 \pm 0.04 \pm 0.07$
$\lvert V_{ub}\rvert_{HPQCD} \times 10^3$	$3.28 \pm 0.13 \pm 0.15$	$3.21 \pm 0.13 \pm 0.12$	$3.23 \pm 0.09 \pm 0.13^{+0.57}_{-0.37}$	$3.64 \pm 0.06 \pm 0.09^{+0.60}$ âĹŠ0.40
$\lvert V_{ub}\rvert_{FNAL} \times 10^3$	$3.14 \pm 0.12 \pm 0.14$	$3.07 \pm 0.11 \pm 0.11$	$3.09 \pm 0.08 \pm 0.12^{+0.35}_{-0.29}$	$3.55 \pm 0.09 \pm 0.09^{+0.62}$ âĹŠ0.41
$\lvert V_{ub}\rvert_{LCSR} \times 10^3$	$3.70 \pm 0.07 \pm 0.08$	$3.78 \pm 0.08 \pm 0.10$	$3.72 \pm 0.05 \pm 0.09^{+0.54}_{-0.39}$	$3.78 \pm 0.10 \pm 0.10^{+0.63}$ âĹŠ0.43
$\lvert V_{ub} f_+(0)\rvert \times 10^4$	$8.5 \pm 0.3 \pm 0.2$	$10.8 \pm 0.5 \pm 0.3$	$9.4 \pm 0.3 \pm 0.3$	$9.24 \pm 0.18 \pm 0.21$
BGL a_1/a_0	$-0.63 \pm 0.27 \pm 0.10$	$-0.82 \pm 0.23 \pm 0.17$	$-0.79 \pm 0.14 \pm 0.14$	-
BGL a_2/a_0	$-6.9 \pm 1.3 \pm 1.1$	$-1.1 \pm 1.6 \pm 0.9$	$-4.4 \pm 0.8 \pm 0.9$	-

What is LCSR?

taking the example of f_+ for $B \to \pi$

On one hand....

In physical region, correlator dominated by B pole:

$$\Pi_\mu = i\, m_b \int d^D x e^{-i\, p_B \cdot x} \langle \pi(p) | T\{\bar{u}(0)\gamma_\mu b(0) \bar{b}(x) i\gamma_5 d(x)\} | 0 \rangle,$$

$$= (p_B + p)_\mu \Pi_+(p_B^2, q^2) + (p_B - p)_\mu \Pi_-(p_B^2, q^2).$$

into

$B \to \pi$ transition $(f_+(q^2))$

$$\langle \pi(p) | \bar{u}\gamma_\mu b | B(p_B) \rangle = (p_B + p)_\mu f_+(q^2) + (p_B - p)_\mu f_-(q^2)$$

B meson decay (f_B)

$$m_b \langle 0 | \bar{d} i\gamma_5 b | B \rangle = m_B^2 f_B$$

$$\Pi_+(p_B^2, q^2) = f_B m_B^2 \frac{f_+(q^2)}{m_B^2 - p_B^2} + \int_{s > m_B^2} ds \frac{\rho_{\rm had}}{s - p_B^2},$$

($\rho_{\rm had}$ is spectral density of the higher-mass hadronic states)

What is LCSR?

on the other hand..

In Euclidean region ($p_B^2 - m_B^2$ is large and negative): light-cone expand about $x^2 = 0$[9]

$$\Pi_+(p_B^2, q^2) = \sum_n \int du\, \mathcal{T}_+{}^{(n)}(u, p_B^2, q^2, \mu^2)\phi^{(n)}(u, \mu^2) = \int ds \frac{\rho_{\mathrm{LC}}}{s - p_B^2},$$

- $\mathcal{T}_+^{(n)}(u, \mu^2)$: perturbatively calculable hard kernels
- $\phi^{(n)}(u, \mu^2)$: non-perturbative LCDAs, twist n
- $\langle \pi(p)|\bar{u}(0)\gamma_\mu\gamma_5\, d(x)|0\rangle = -if_\pi p_\mu \int_0^1 du\, e^{i\bar{u}p\cdot x}\phi(u, \mu^2) + \ldots,$
- $\phi(u, \mu^2) = 6u(1-u)\sum_{n=0}^\infty a_n(\mu^2)\, C_n^{3/2}(2u-1)$

[9] Factorisation theorem not proven to all orders, verified at given order by cancellation of IR and soft divergences

What is LCSR?

....which leads to the sum rule

Above the continuum threshold s_0, a continuum of states contribute and approximation of quark-hadron duality is thought to be reasonable, such that

$$\rho_{\mathrm{had}} = \rho_{\mathrm{LC}}\,\Theta(s - s_0).$$

Subtracting from both sides, and Borel transforming (M^2=Borel parameter):

Sum rule for $f_+(q^2)$

$$f_+(q^2) = \frac{1}{f_B m_B^2} \int_{m_b^2}^{s_0} ds\, \rho_{\mathrm{LC}}\, e^{-(s-m_B^2)/M^2},$$

Which value of f_B?

Sum rule:

$$f_+(0) = \left(\int_{m_b^2}^{s_0} ds\, \rho_{\Pi_+}(s,0) e^{(m_B^2 - s)/M^2} + \mathrm{T4}_c\, e^{m_B^2/M^2} \right) / (m_B^2 f_B)$$

- Clearly requires f_B
- Use sum rules result for consistency: cancellation of radiative corrections (coulombic) and parameter dependence
- Two-loop calculation finished in 2001[10], we use result to $\mathcal{O}(\alpha_s^2 \beta_0)$
- Require mathematica package Rvs.m from authors[11] as only semi-analytical results available

---

[10] M. Jamin and B. O. Lange, Phys. Rev. D **65** (2002) 056005 [arXiv:hep-ph/0108135].

[11] K. G. Chetyrkin and M. Steinhauser, Eur. Phys. J. C **21** (2001) 319 [arXiv:hep-ph/0108017].

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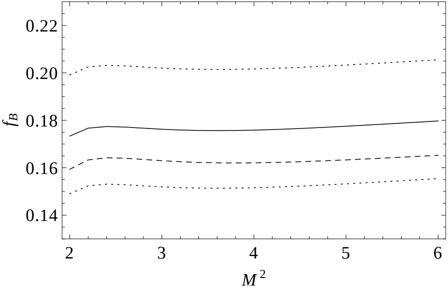
Sum rule for f_B

Careful choice of s_0 and M^2 required, to satisfy the following:



- Sum rule depends weakly on s_0 and M^2, but have a clear extremum as fn. of them
- Sum rule for m_B fulfilled to less than 0.1%
- Continuum contribution is under control
- Contributions of higher orders and twists should be suppressed

Choosing a suitable a_2

Progress from the Lattice:

- Non-perturbative LCDA require calculation of moments from sum rules or lattice
- UKQCD and RBC collaborations predict $a_2(2\,\mathrm{GeV})$, using $N_f = 2 + 1$ domain-wall fermions[12].
- Combine $a_2(\mu)$ with exp. $\gamma\gamma^*\pi$ form factor, obtain $a_4(\mu)$[13].

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[12] R. Arthur *et al.*, Phys. Rev. D **83** (2011) 074505.

[13] N. G. Stefanis, Nucl. Phys. Proc. Suppl. **181-182** (2008) 199.

[14] G. Duplancic, A. Khodjamirian, T. Mannel, B. Melic and N. Offen, J. Phys. Conf. Ser. **110** (2008) 052026.

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For consistency use LCSR result:

- $a_{2,4}(1\,\mathrm{GeV})$ from fitting F_π from LCSR to the exp. data.
- $a_2(1\,\mathrm{GeV}) = 0.17 \pm 0.08$ and $a_4(1\,\mathrm{GeV}) = 0.06 \pm 0.10$[14], consistent with existing LCSR and Lattice QCD predictions.

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[12] R. Arthur *et al.*, Phys. Rev. D **83** (2011) 074505.

[13] N. G. Stefanis, Nucl. Phys. Proc. Suppl. **181-182** (2008) 199.

[14] G. Duplancic, A. Khodjamirian, T. Mannel, B. Melic and N. Offen, J. Phys. Conf. Ser. **110** (2008) 052026.

Numerics

and uncertainties

- The LCSR approach requires a careful choice of numerical values for the continuum limit s_0 and the Borel parameter M^2 vary s_0 by $\pm 0.5\,\mathrm{GeV}^2$ and M_2 by $\pm 1.2\,\mathrm{GeV}^2$
- we adopt $a_{2,4}(1\,\mathrm{GeV})$ from fitting the LCSR result for the pion electro-magnetic form factor to the experimental data
- Parameters describing twist-3 and 4 DA's, namely η_3, ω_3, η_4 and ω_4, calculated in QCD sum rules, error $\sim 50\%$
- Condensates varied $\langle \bar{q}q \rangle = (-0.24 \pm 0.01)^3\,\mathrm{GeV}^3$, $\langle \bar{q}\sigma g G q \rangle = (0.8 \pm 0.2)\,\langle \bar{q}q \rangle$
- Use pole mass, $m_b = 4.8 \pm 0.1$ GeV (also calculate with $\overline{\text{MS}}$ and compare
- μ typical virtuality of the b quark, $\sqrt{m_B^2 - m_b^2}$, vary in range $\mu/2$ to 2μ.

and just before

the Results..

Parameter	Value	Ref.
m_π	139.6 MeV	PDG
f_π	130.4 MeV	PDG
m_B	5.28 GeV	PDG
$\alpha_s(M_Z)$	0.118	PDG
η_3	0.015	Ball, 1998
ω_3	-3	Ball, 1998
η_4	10	Ball, 1998
ω_4	0.2	Ball, 1998
$\langle \bar{q}q \rangle$	$(-0.246^{+0.027}_{-0.019})^3\,\mathrm{GeV}^3$	Duplancic, 2008
$\langle \bar{q}\sigma gGq \rangle$	$0.8\,\langle \bar{q}q \rangle$	Ioffe, 2005

Table: Summary of values of parameters used in the numerical analysis. Note the quark condensate is given at the scale 1 GeV.

The $\overline{MS}$ scheme[15]?

- $\overline{MS}$ scheme said to be natural for the calculation of scattering amplitudes involving a virtual b quark at large space-like momentum scales $\sim m_b$
- We also calculate our result using the $\overline{MS}$ mass for the b quark
- Find $f_+(0) = 0.251^{+0.019}_{-0.030}$

[15] G. Duplancic, A. Khodjamirian, T. Mannel, B. Melic and N. Offen, J. Phys. Conf. Ser. **110** (2008) 052026, A. Khodjamirian, T. Mannel, N. Offen and Y. M. Wang, Phys. Rev. D **83** (2011) 094031 [arXiv:1103.2655 [hep-ph]].

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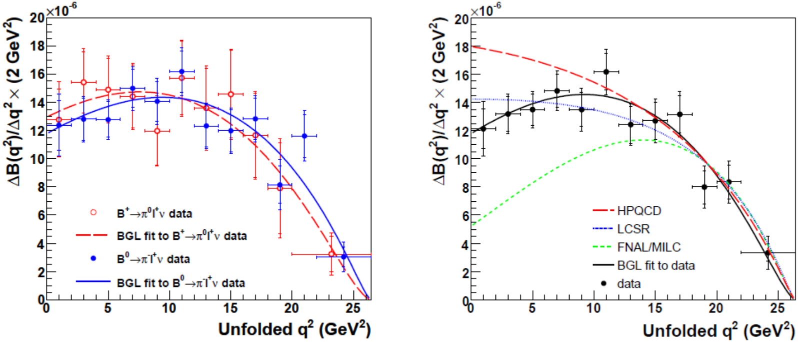
Comparison at NLO:

b-quark mass	$\overline{\textbf{MS}}$	pole
$f^+_{B\pi}(0)$	0.263	0.258
tw2 LO	50.5%	39.7%
tw2 NLO	7.4%	17.2 %
tw3 LO	46.7%	41.5 %
tw3 NLO	-4.4%	2.4 %
tw4 LO	-0.2%	-0.9%

[15] G. Duplancic, A. Khodjamirian, T. Mannel, B. Melic and N. Offen, J. Phys. Conf. Ser. **110** (2008) 052026, A. Khodjamirian, T. Mannel, N. Offen and Y. M. Wang, Phys. Rev. D **83** (2011) 094031 [arXiv:1103.2655 [hep-ph]].

Latest BaBar results

improved hybrid treatment at high q^2[16]



Fit shape to BGL: $f_+(0)|V_{ub}| = (8.7 \pm 0.3)10^{-4}$, $|V_{ub}| = (3.34 \pm 0.10 \pm 0.05 +^{+0.29}_{-0.26})10^{-3}$

16 J. P. Lees *et al.* [BABAR Collaboration], arXiv:1208.1253 [hep-ex].

Latest BaBar results

improved hybrid treatment at high q^2[16]

	q^2 (GeV^2)	$\Delta\mathcal{B}$ (10^{-4})	$\Delta\zeta$ (ps^{-1})	$\lvert V_{ub}\rvert$ (10^{-3})	χ^2/ndf	$Prob(\chi^2)$
$B \to \pi\ell^+\nu$						
HPQCD [5]	$16 - 26.4$	$0.37 \pm 0.02 \pm 0.02$	2.02 ± 0.55	$3.47 \pm 0.10 \pm 0.08^{+0.60}_{-0.39}$	2.7/4	60.1%
FNAL [6]	$16 - 26.4$	$0.37 \pm 0.02 \pm 0.02$	$2.21^{+0.47}_{-0.42}$	$3.31 \pm 0.09 \pm 0.07^{+0.37}_{-0.30}$	3.9/4	41.5%
LCSR [3]	$0 - 12$	$0.83 \pm 0.03 \pm 0.04$	$4.59^{+1.00}_{-0.85}$	$3.46 \pm 0.06 \pm 0.08^{+0.37}_{-0.32}$	8.0/6	24.0%
LCSR2 [34]	0			$3.34 \pm 0.10 \pm 0.05^{+0.29}_{-0.26}$		
$B^+ \to \omega\ell^+\nu$						
LCSR3 [18]	$0 - 20.2$	$1.19 \pm 0.16 \pm 0.09$	14.2 ± 3.3	$3.20 \pm 0.21 \pm 0.12^{+0.45}_{-0.32}$	2.24/5	81.5%

Fit shape to BGL: $f_+(0)|V_{ub}| = (8.7 \pm 0.3)10^{-4}$, $|V_{ub}| = (3.34 \pm 0.10 \pm 0.05 + ^{+0.29}_{-0.26})10^{-3}$
Simulataneous fit to Lattice gives $(3.25 \pm .31)10^{-3}$, 1σ from previous BaBar result. same analysis quotes $|V_{ub}| = (3.46 \pm 0.06 \pm 0.08^{+0.37}_{-0.32})10^{-3}$ using LCSR $\Delta\zeta(0, 12\,\mathrm{GeV}^2)$

Good agreement between different modes

[16] J. P. Lees *et al.* [BABAR Collaboration], arXiv:1208.1253 [hep-ex].

$|V_{cb}|$: Status

Is the exclusive-inclusive discrepancy caused by new physics with right-handed currents? [Chen and Nam, arXiv:0807.0896; Crivellin, arXiv:0907.2461]

Process	$\bar{c}\gamma_\mu b$	$\bar{c}\gamma_\mu\gamma_5 b$
$B \to D\ell\bar{\nu}$	✓	×
$B \to D^*\ell\bar{\nu}$ at zero recoil	×	✓
$B \to X_c\ell\bar{\nu}$	✓	✓