Non-lattice QCD calculations for semileptonic *B* and *D* decays

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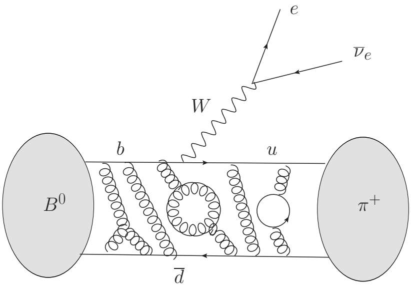
$B \to \pi l \nu_l$ and $|V_{ub}|$

$$\langle \pi(p) | \bar{u}\gamma_\mu b | B(p+q) \rangle$$

$$\Downarrow$$

$$\{ f^+_{B\pi}(q^2),\ f^0_{B\pi}(q^2) \}$$



$$\frac{d\Gamma(\bar{B}^0 \to \pi^+ l^- \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} p_\pi^3 |f^+_{B\pi}(q^2)|^2 + O(m_l^2)$$

- partial width and shape: precision improving,

$BR(\bar{B}^0 \to \pi^+ l \bar{\nu}) = (1.36 \pm 0.05) \times 10^{-4}$ *[HFAG average '09]*

- shape constrained by analyticity (z-series-parameterization)
- need normalization from QCD calculation, e.g., $f^+_{B\pi}(0)$

Non-lattice method: QCD light-cone sum rules

Correlator of quark currents = *hadronic sum (disp.relation)*

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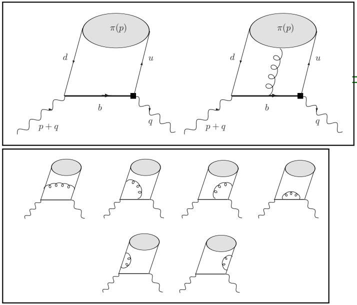
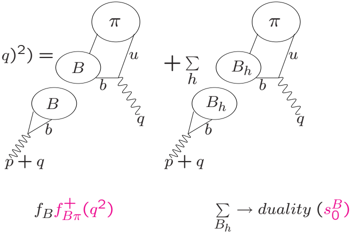


$\Longrightarrow F(q^2,(p+q)^2) =$



{light-cone OPE, pion DA's}

{quark-hadron duality}

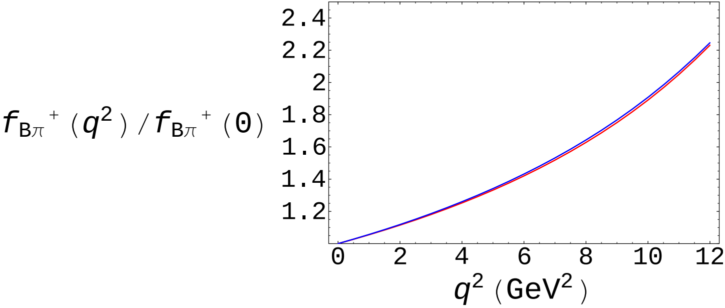
Status of LCSR calculation

- last update: $f^+_{B\pi}(q^2)$ at $0 \leq q^2 \leq 12$ GeV^2 ,

  [G.Duplancic, A.K., B.Melic, Th.Mannel, N.Offen JHEP, 0804, 014 (2008)]

  - with f_B from two-point QCD sum rules (exp. f_B still with a larger error)
  - fitting the shape to the *BABAR* data to constrain LCSR input (twist-2 DA)
  - in this region fitted to BK parameterization with $\alpha_{BK} = 0.53 \pm 0.06$

  (equally well to Boyd-Grinstein-Lebed series-parameterization)

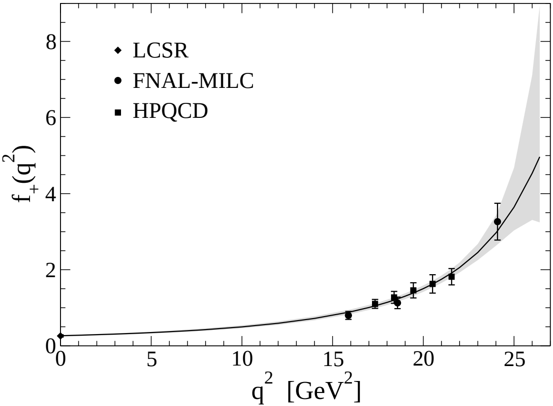


- the result: $f^+_{B\pi}(0) = 0.26^{+0.04}_{-0.03}$

Combining LCSR⊕BaBar shape ⊕ lattice QCD

[Bourrely, Caprini, Lellouch, 0807.222 hep-ph]

- Modified series-parameterization used :



$q^2 = 0$: LCSR *[DKMMO]* , $q^2 >$15 GeV^2: lattice QCD *[FNAL-MILC, HPQCD]*

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

a sample of most recent results

[Ref.]	$f^+_{B\pi}(q^2)$ calculation	$f^+_{B\pi}(q^2)$ input	$\|V_{ub}\| \times 10^3$
FNAL-MILC '08	lattice	-	3.38±0.35
HPQCD '07	lattice	-	3.55±0.25±0.50
Ball, Zwicky '04	LCSR	-	$3.5 \pm 0.4 \pm 0.1$
Flynn, Nieves '07	-	lattice $\oplus$ LCSR	$3.47 \pm 0.29 \pm 0.03$
DKMMO '07	LCSR	-	$3.5 \pm 0.4 \pm 0.2 \pm 0.1$
Bourrely, Caprini, Lellouch '08	-	lattice$\oplus$ LCSR	3.54 ± 0.24

$D \to \pi$ and $D \to K$, a test of LCSR

A. K., Ch. Klein, Th. Mannel and N. Offen, arXiv:0907.2842[hep-ph].

- replacing $b \to c$ in the (updated) LCSR $\to$ $D \to \pi, K$
- Comparison with lattice QCD and previous LCSR results:

Method	[Ref.]	$f^+_{D\pi}(0)$	$f^+_{DK}(0)$
Lattice QCD	[APE(2001)]	$0.57 \pm 0.06 \pm 0.02$	$0.66 \pm 0.04 \pm 0.01$
	[Aubin et al (2005)]	$0.64 \pm 0.03 \pm 0.06$	$0.73 \pm 0.03 \pm 0.07$
	[QCDSF(2009)]	$0.74 \pm 0.06 \pm 0.04$	$0.78 \pm 0.05 \pm 0.04$
LCSR	[A.K. et al. (2000)]	0.65 ± 0.11	$0.78^{+0.2}_{-0.15}$
	[P. Ball (2006)]	0.63 ± 0.11	0.75 ± 0.12
	this work	$0.67^{+0.10}_{-0.07}$	$0.75^{+0.11}_{-0.08}$

Determination of $|V_{cd}|$

- LCSR predicts the product, $[f_D f_{D\pi}(0)]_{LCSR} = 137^{+19}_{-14}$ MeV
- CLEO data :

$$\frac{dBR}{dq^2}(D \to \pi l \nu_l) \oplus \{\text{fit of the } q^2\text{-bins}\}$$

$$\Rightarrow f_{D\pi}(0)|V_{cd}| = 0.150 \pm 0.004 \pm 0.001\,,$$

$$BR(D \to l\nu_l) \Rightarrow f_D|V_{cd}| = 46.5 \pm 2.0 \text{ MeV}$$

(CLEO quotes f_D assuming $|V_{cd}| = |V_{us}|$)

- multiply two exp. numbers and divide by LCSR prediction:

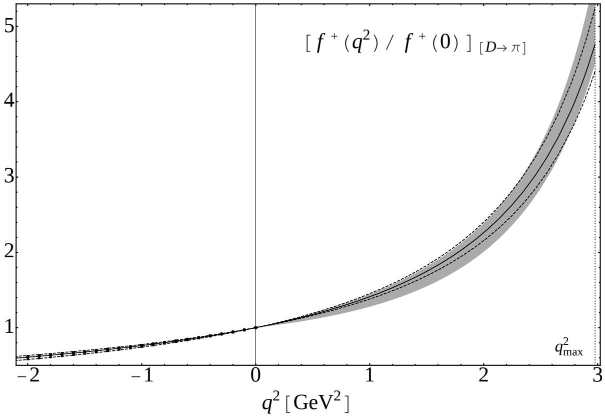
$$|V_{cd}| = 0.225 \pm [0.005]_{exp1} \pm [0.003]_{exp2}{}^{+0.016}_{-0.012}\,,$$

theory (LCSR) error is effectively halved !

- comparison: CLEO $\oplus$ lattice:
  $|V_{cd}| = 0.234 \pm 0.007 \pm 0.002 \pm 0.025$

The shapes of $D \to \pi$ and $D \to K$ form factors

- LCSR for $q^2 \leq 0$ $\Rightarrow$ (BCL) series-parameterization
  $\Rightarrow$ { access q^2 in SL region }

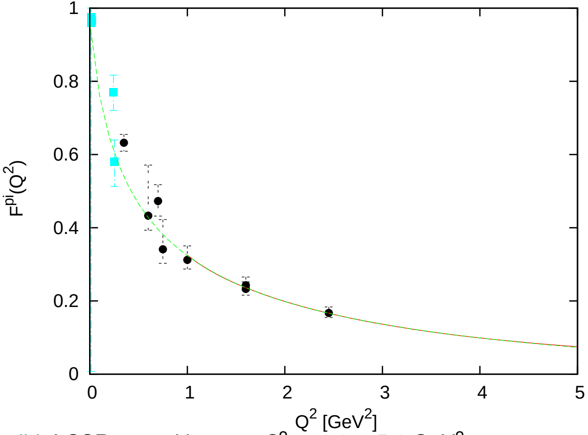


shaded region: CLEO fit to the shape

Another test of LCSR

- the pion e.m. form factor (spacelike): *[A.K. 0909.2154 [hep-ph]]*

  input: pion DA's used for $B \to \pi$, $D \to \pi$



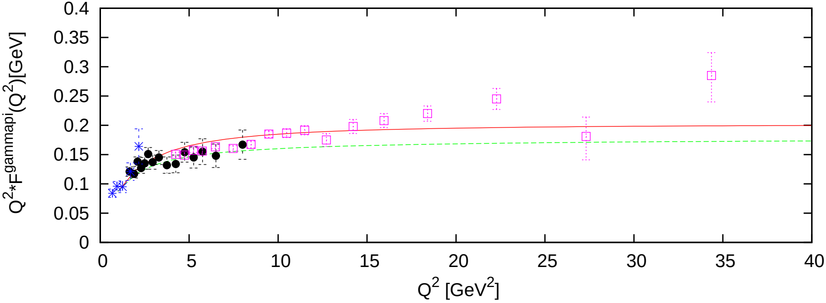
solid: LCSR central input at $Q^2 = 1.0 - 5.0$ GeV^2 ,

dashed fit to series-param. $\to Q^2 < 1.0$ GeV^2

data: Jlab [2008] (points), FNAL (points) [Amendolia et al (1986)]

$\gamma^*\gamma \to \pi^0$ form factor

$Q^2 F^{\gamma\pi}(Q^2)$ from LCSR *[A.K. 0909.2154 [hep-ph]]*



"default" $\varphi_\pi(u)$ (solid), asymptotic (dashed)

data: CELLO (crosses), CLEO (points), BABAR '09 (squares)

- can Belle remeasure this form factor ?

$D^* D\pi$ -coupling, LCSR vs experiment

very old issue: A.K., hep/ph 0108205

- the total width of D^* meson was measured only once
  CLEO (2001)→ PDG :
  $\Gamma_{tot}(D^*) = 96 \pm 4 \pm 22$ keV $\Rightarrow g_{D^* D\pi} = 17.9 \pm 0.3 \pm 1.9$
- old LCSR prediction (for finite m_c !)
  V.Belyaev, V.Braun, A.K., R.Rückl PRD (1995)
  A.K. R.Rückl, S.Weinzierl, O.Yakovlev PL B(1999)
  $g_{D^* D\pi} = 10 \pm 3.5$, also $g_{B* B\pi} = 22 \pm 7$
- quark-hadron duality for double dispersion relation is less certain, influence of radial D', D*' excitations on LCSR?
  [D.Becirevic et al 2002]
- plan to reanalyze/update this calculation including NLO twist-3 effects
- remeasuring D^* total width is difficult but extremely important

Can the LCSR accuracy be improved ?

- twist (power) expansion in LCSR up to twist 4
  twist-5,6 effects should (and can) be studied
- quark masses used in LCSR, all taken from QCD SR:

  $\bar{m}_b(\bar{m}_b) = (4.164 \pm 0.025(0.05))\,\mathrm{GeV}$
  $\bar{m}_c(\bar{m}_c) = (1.29 \pm 0.03)\,\mathrm{GeV}$
  $m_s(\mu = 2\,\mathrm{GeV}) = (98 \pm 16)\,\mathrm{MeV}$,

- $O(\alpha_s^2)$ effects in LCSR beyond reach, but expected very small
  diags with at least 2-loops and several momentum/mass scales
- π, K DA's : need more data on pion and kaon e.m. form factors ;
  more precision in the shape measurements of $B \to \pi$, $D \to \pi, K$
- quark-hadron duality approximation:
  data on radial excitations of D and B
  can help to get a better duality ansatz

Other non-lattice approaches

- heavy-light form factors in effective theories (SCET): factorization, $1/m_Q$ hierarchy, useful relations

  [C.Bauer et al.(2002-...)], [B.Lange,M.Neubert(2003),..], a recent overview in B. Grinstein, arXiv:0910.2422 [hep-ph]

- QCD sum rules and LCSR in SCET to assess "soft" components of the form factors

  [Th. Feldmann, F.de Fazio, T.Hurth (2006)]

- LCSR with B meson DA's (HQET)

  [A.K. T. Mannel, N.Offen (2006)]

B decay constant, a tension with QCD?

- BABAR $\oplus$ Belle: $BR(B \to \tau\nu_\tau) = [1.73 \pm 0.35] \times 10^{-4}$
  [T. Iijima , talk at Lepton-Photon '09, Hamburg]
- with $|V_{ub}| = \left(3.5^{+0.15}_{-0.14}\right) \times 10^{-3}$ *[CKMfitter , Moriond '09]*
  ($B \to \pi l \nu_l \Rightarrow |V_{ub}|$ in the same ballpark)

method	f_B [MeV]	ref.
lattice [a]	190 ± 13	HPQCD '09
	195 ± 11	FNAL/MILC '08
	203 ± 17	ETMC '09
QCD SR	210 ± 19	Jamin-Lange '01
	206 ± 20	Penin-Steinhauser'01
exp. $\oplus$ CKM	$(280 \pm 30 \pm 25_{V_{ub}}) \times \frac{3.5\times10^{-3}}{|V_{ub}|}$	BABAR$\oplus$ Belle

[a] C. Aubin, review talk at Lattice '09, Beijing

- OPE upper bound for f_{D_s}: *[A.K., PRD 79, 031503(R) (2009)]*

recalculated $c \to b$: $f_B < 270$ MeV (preliminary)

$B \to \pi\tau\nu_\tau$

- if there is new physics in $B \to \tau\nu_\tau$ it should be visible in $B \to \pi\tau\nu_\tau$ in the $O(m_\tau^2|f^0_{B\pi}(q^2)|^2)$ part of the width
- new observable at $q^2 > 3$ GeV^2:
  (V_{ub} and normalization independent !)

$$R_{\tau\mu} \equiv \frac{d\Gamma(B \to \pi\tau\nu_\tau)/dq^2}{d\Gamma(B \to \pi\mu\nu_\mu)/dq^2} = \frac{(q^2 - m_\tau^2)^2}{(q^2)^2}\left(1 + \frac{m_\tau^2}{2q^2}\right) \times \left\{1 + \frac{3m_\tau^2(m_B^2 - m_\pi^2)^2}{4(m_\tau^2 + 2q^2)m_B^2 p_\pi^2} \frac{|f^0_{B\pi}(q^2)|^2}{|f^+_{B\pi}(q^2)|^2}\right\}$$

- LCSR predict $f^0_{B\pi}(q^2)$ and the ratio of form factors has a smaller uncertainty (preliminary estimate) $\sim (5-8)\%$
- lattice QCD can (optimistically) provide $O(2-3\%)$ accuracy in the ratio

B, D semileptonic decay measurements, a wish list

- $B \to \pi l \nu_l$, $D \to \pi, K \nu_l$ shapes with a better accuracy
  in a fitted-to-z-parameterization form
  the lepton energy spectrum in $B \to \pi l \nu$

  $$\frac{d\Gamma}{dE_l}\Big|_{m_l, m_\pi \simeq 0} = \frac{G_F^2 |V_{ub}|^2}{16\pi^3 m_B}(m_B - 2E_l) \int_0^{2m_B E_l} dq^2 (2E_l m_B - q^2) |f_{B\pi}^+(q^2)|^2$$

  a cross-check of the fitted q^2 shape
- find radial excitations of B and D
  a resonance $D' \to D * \pi, D\pi\pi$, $J^P = 0^-$,
  $m_{D'} - m_D \sim 500 - 600$MeV,
  in B-decays and/or in $e^+e^- \to \bar{c}c$,
  B' a task for CDF and LHCb
- remeasure D^* total width
- remeasure $\gamma\gamma^* \to \pi$ at Belle
- $B \to \pi \tau \nu_\tau$ looks like an interesting enterprise

Concluding remarks

- results of LCSR on heavy-light form factors are in a good agreement with lattice QCD
- provide analytical formulae for a given form factor and not only a number
- the accuracy is intrinsically limited, some mainly phenomenological resources of improvement still remain