Status of B-physics on the lattice

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outline

- lattice QCD in the precision era
  - cost scaling: reach of lattice QCD computations.
  - lattice techniques for B-physics.

- overview of results (CKM, UT) (simulations with light dynamical quarks only!)
  - B-meson decay constants, mixing amplitudes, semileptonic form factors.
  - summaries of lattice results: FLAG.

- a word on issues involving perturbation theory

hadronic effects in flavour physics

We are in an era of *precision* flavour physics. Hadronic effects can be ...

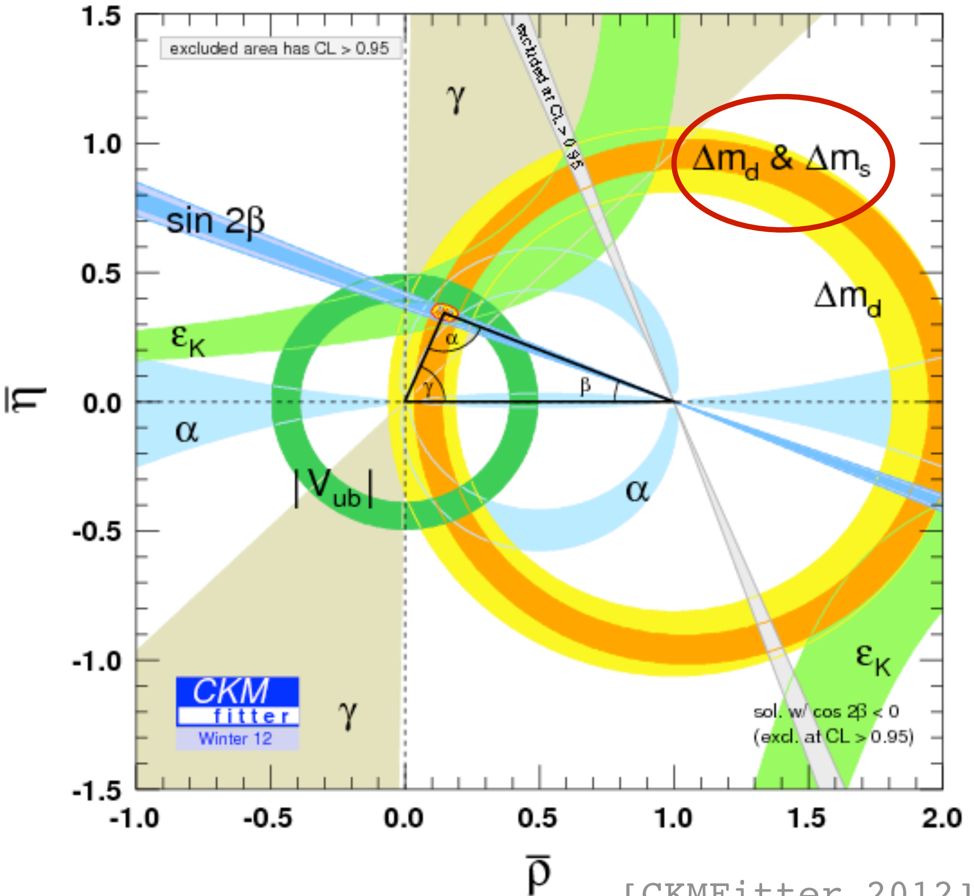
- mostly irrelevant: $\mu \to e\gamma,\ \mathbf{d}_{\mathrm{n}}$
- under good theoretical control: $K \to \pi\nu\bar{\nu}$
- relevant, difficult, but measured indirectly: $(g-2)_\mu$
- relevant and difficult to compute: $V_{xy},\ K \to \pi\pi,\ \Delta m_{d,s},\ \ldots$

Use first-principles technique to deal with low-energy hadronic physics: lattice QCD.

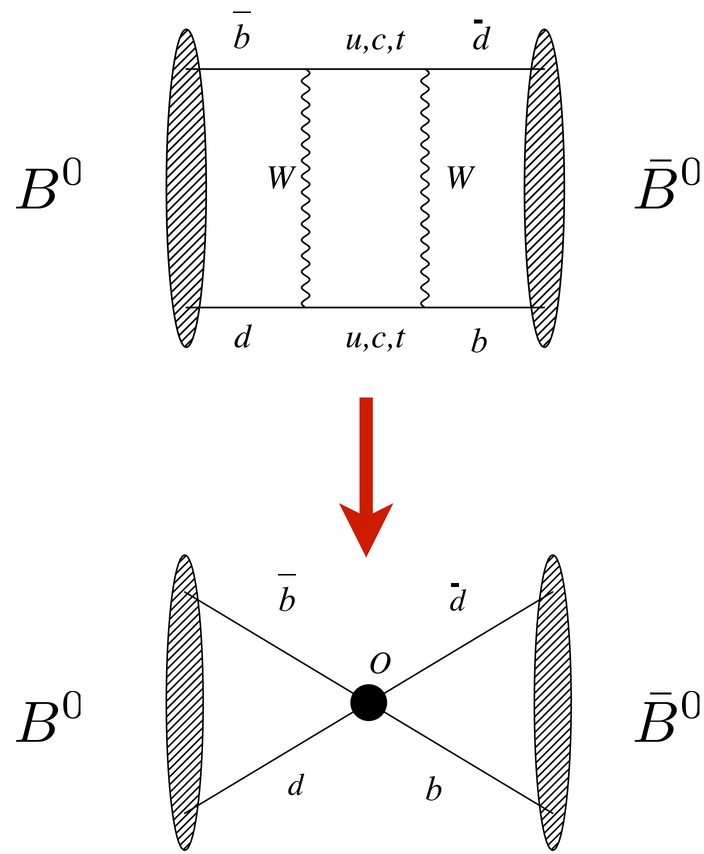
(Complement with other first-principles/systematic approaches: dispersion relations, effective theories.)

hadronic effects in flavour physics

Your typical weak hadronic matrix element:



[CKMFitter 2012]



$$\mathcal{H}_{\rm w}^{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}} \sum_k f_k(V_{\rm CKM})\, C_k(M_W)\, \mathcal{O}_k$$

$$\mathcal{A}(B^0 \to \bar{B}^0) \approx \langle \bar{B}^0 | \mathcal{H}_{\rm w}^{\rm eff} | B^0 \rangle$$

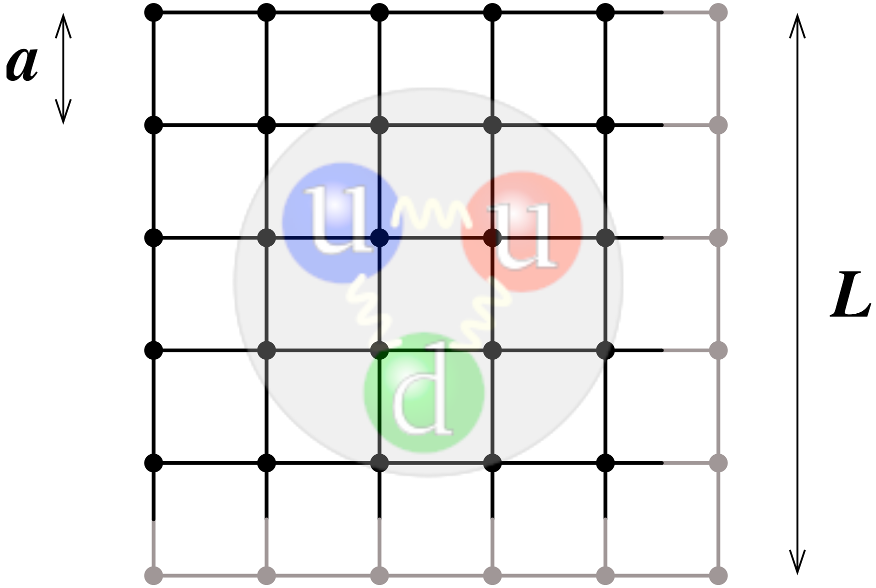
$$\bar{\eta}^2 - (\bar{\rho} - 1)^2 \approx c\, f_B^2 \hat{B}_B$$

$$f_B^2 \hat{B}_B \propto \langle \bar{B}^0 | (\bar{b}\gamma_\mu^{\rm L} d)(\bar{b}\gamma_\mu^{\rm L} d) | B^0 \rangle$$

lattice field theories

First-principles approach to strongly coupled quantum field theories.

[Wilson 1974]



lattice field theories

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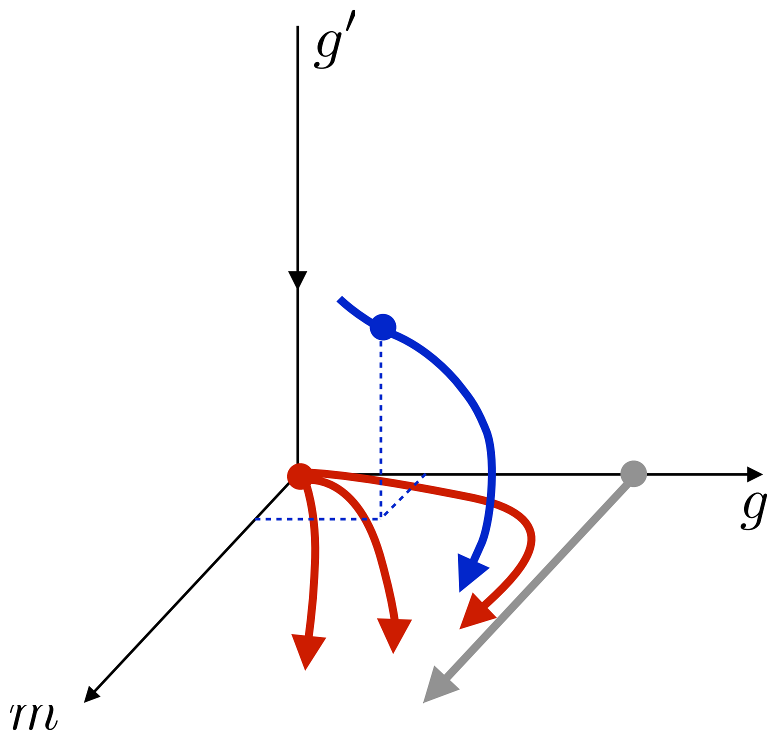

- Take continuum, infinite volume limits.
- Tune irrelevant couplings to preserve symmetries, improve scaling to CL ...

$$S_{\mathrm{lat}} = S_0 + aS_1 + a^2 S_2 + \ldots$$
$$\mathcal{O}_{\mathrm{lat}} = \mathcal{O}_0 + a\mathcal{O}_1 + a^2 \mathcal{O}_2 + \ldots$$

several different lattice actions: universality

fermion actions: (improved) Wilson, (improved) staggered, domain-wall, perfect actions, Neuberger fermions, twisted-mass QCD, ...

lattice field theories

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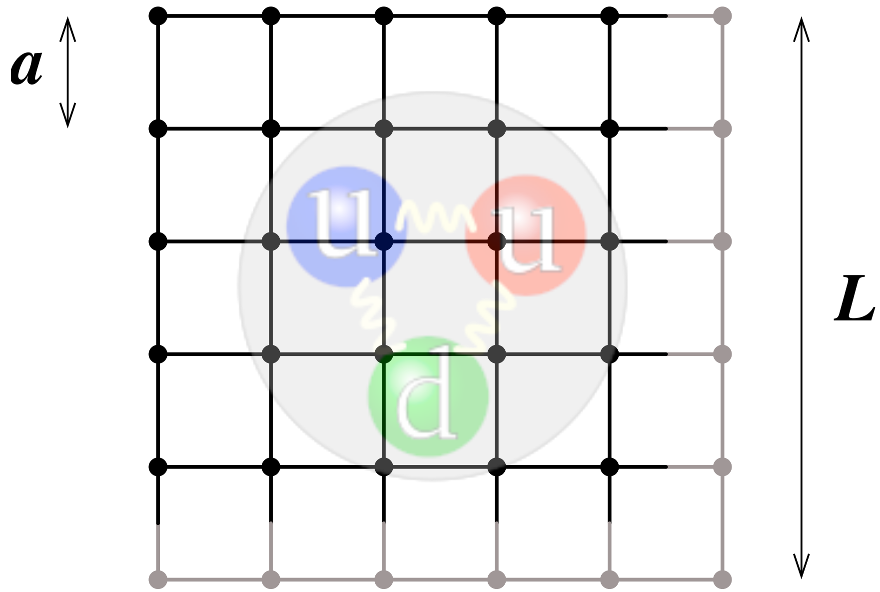

Many tools developed along the last 20+ years:

- Control scaling (Symanzik improvement).
- Non-perturbative renormalisation and matching (e.g. to effective theories).
- Lattice regularisations with exact chiral symmetry.
- ...

lattice field theories

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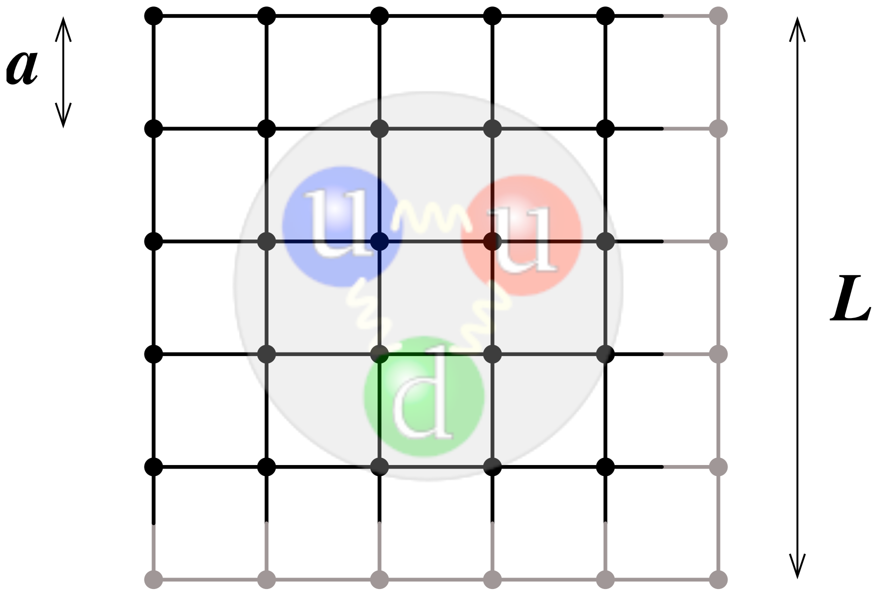
[Wilson 1974]

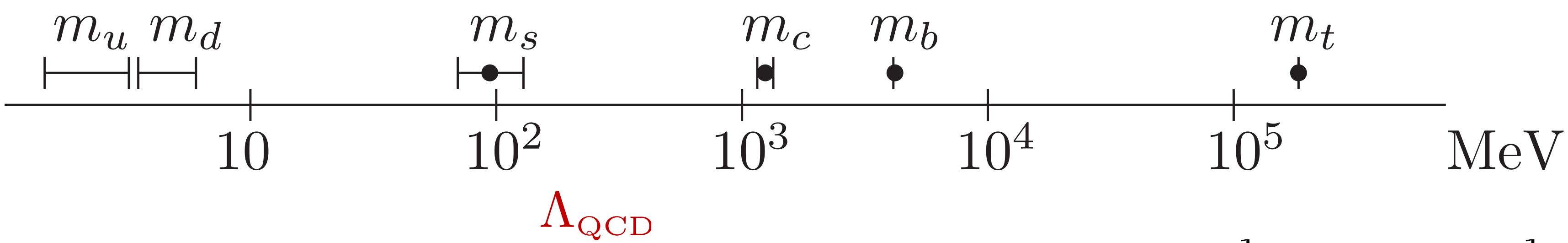


Crucial: control systematic uncertainties.

- Get rid of cutoffs ($a \to 0,\ L \to \infty$).
- Compute in / extrapolate to physical SSB regime (light quarks, isospin breaking).
- Keep all relevant scales far from cutoffs.

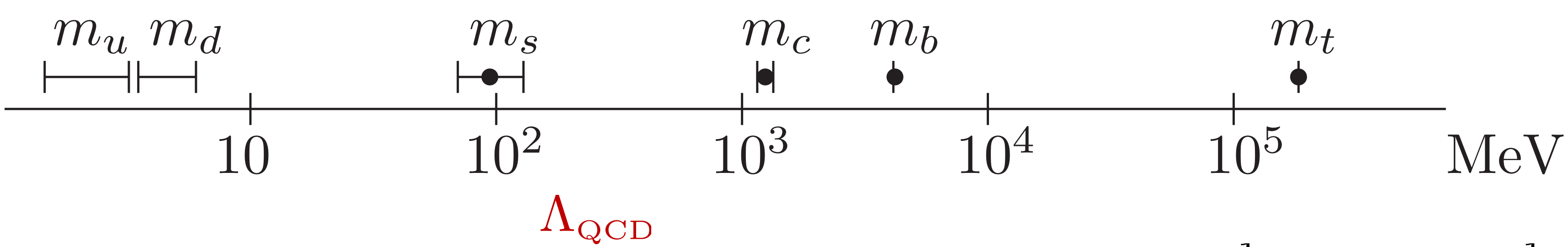
What is the current physics reach of LQCD?

lattice QCD reach: scales and cost



$$L^{-1} \ll \mu \ll a^{-1}$$

lattice QCD reach: scales and cost



$$L^{-1} \ll \mu \ll a^{-1}$$

Main cost factor: reiterated inversion of lattice Dirac operator on fixed gauge field.

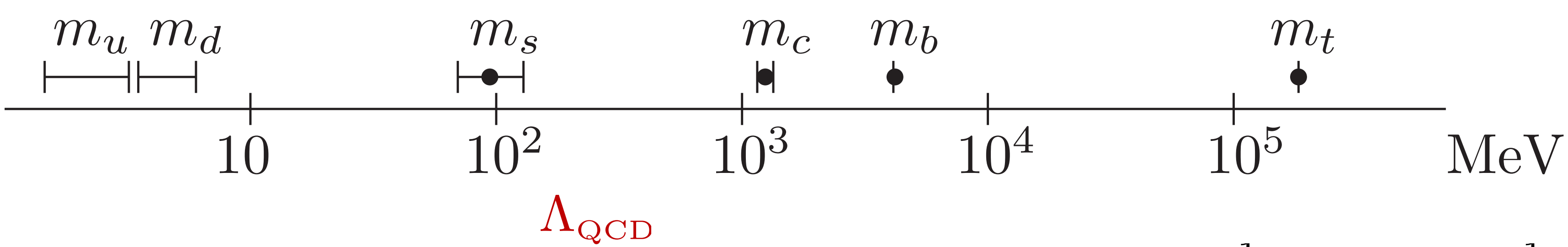
$$\text{cost} \;=\; N \left(\frac{20\ \text{MeV}}{m}\right)^{\alpha} \left(\frac{L}{3\ \text{fm}}\right)^{\beta} \left(\frac{0.1\ \text{fm}}{a}\right)^{\gamma}$$

overall cost (⇒ cpu power)

physics reach

For a long time: serious difficulties in reaching light dynamical quark masses.

lattice QCD reach: scales and cost



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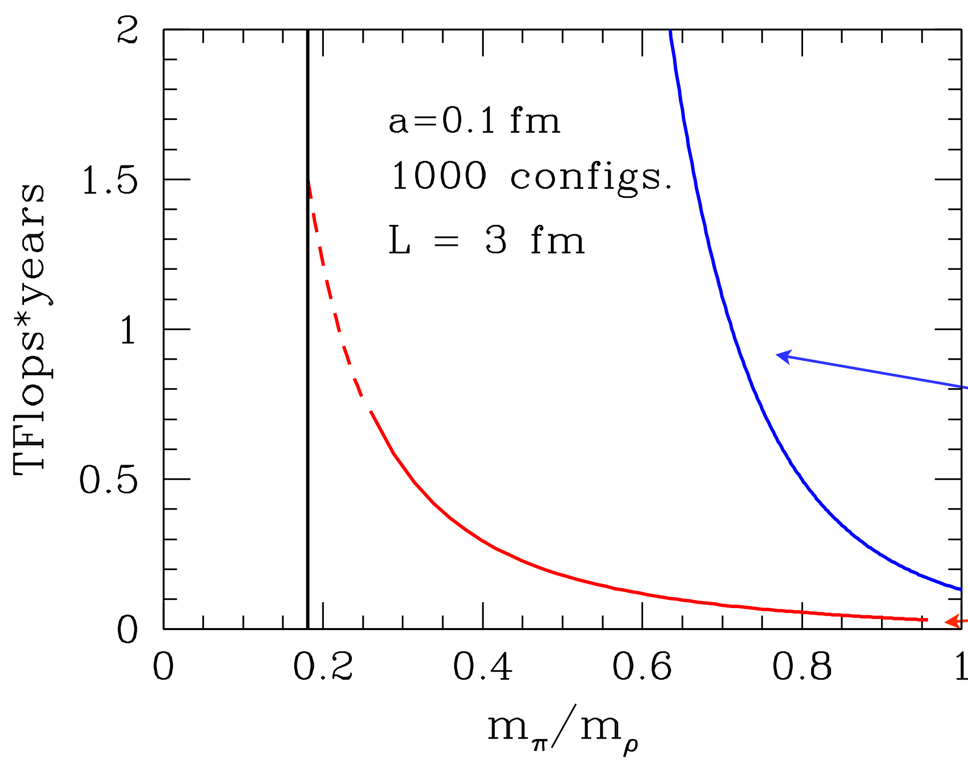
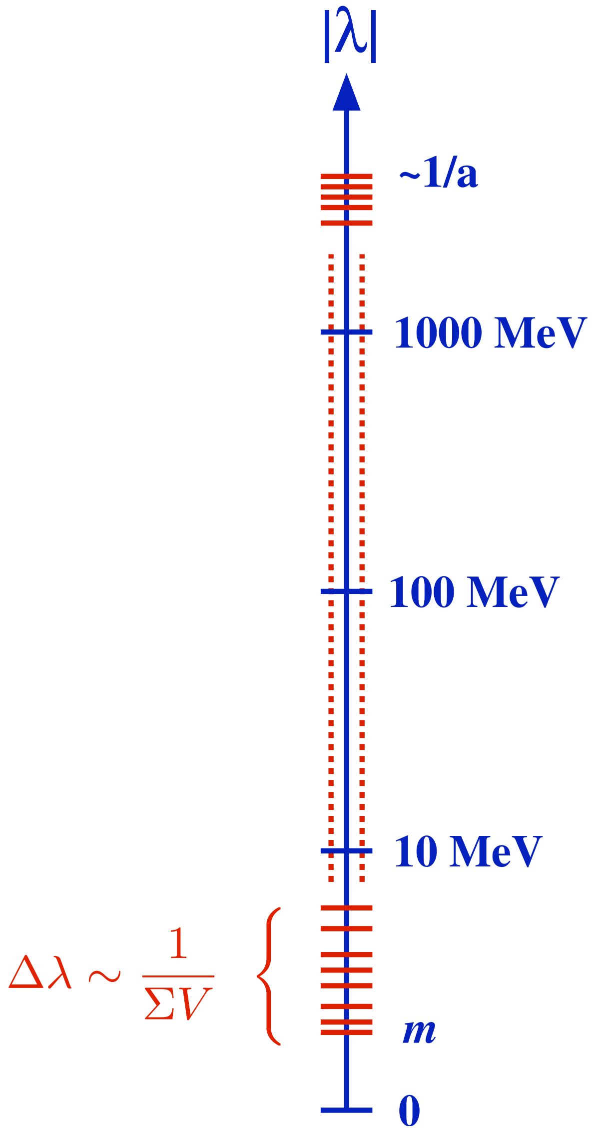


$$5\left[\frac{20\ \mathrm{MeV}}{m}\right]^{3}\left[\frac{L}{3\ \mathrm{fm}}\right]^{5}\left[\frac{0.1\ \mathrm{fm}}{a}\right]^{7}$$ [Ukawa 2001]

$$0.05\left[\frac{20\ \mathrm{MeV}}{m}\right]^{1}\left[\frac{L}{3\ \mathrm{fm}}\right]^{5}\left[\frac{0.1\ \mathrm{fm}}{a}\right]^{6}$$ [Giusti 2006]

lattice QCD reach: scales and cost

Reaching physical quarks masses difficult because of spontaneous chiral symmetry breaking.



Hierarchy of scales ↔ SSB: $m \ll M_\pi \ll 4\pi F_\pi$

[Leutwyler, Smilga 1992]

- Condition number $\lambda_{\max}/\lambda_{\min}$ large.
- Computation of $D^{-1}\phi$ expensive.

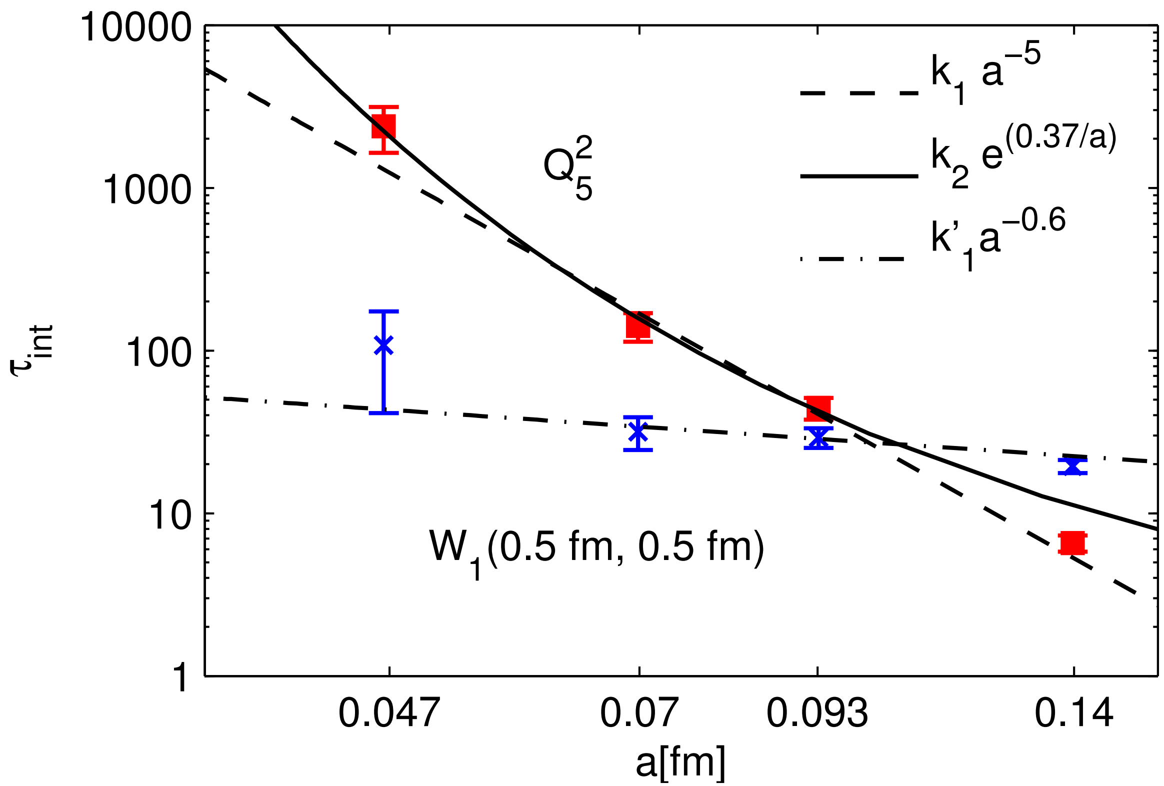
Teach the physics to the algorithms!

[Sexton-Weingarten 1990s; Hasenbusch, Lüscher 2000s]

Mass preconditioning/domain decomposition, deflation ⇒ mild mass dependence.

lattice QCD reach: scales and cost

Algorithm efficiency degrades rapidly below lattice spacings ∼0.05 fm ("topology freezing"). [Del Debbio, Panagopoulos, Vicari 2002; Schaefer, Sommer, Virotta 2010]

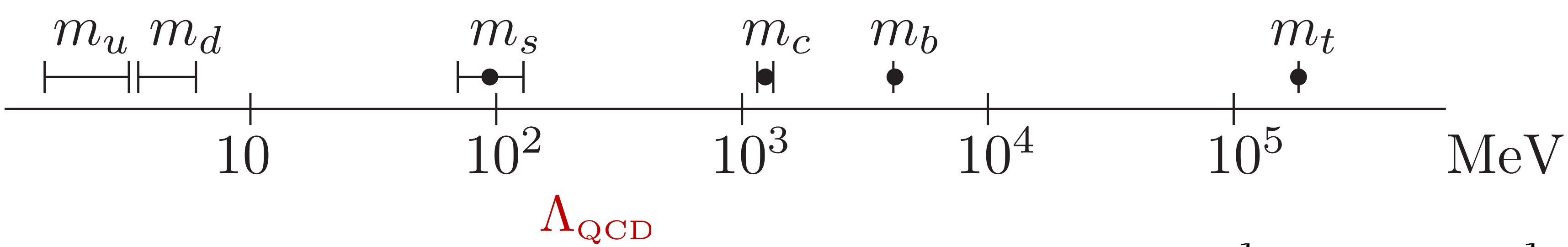


Work with open boundary conditions?

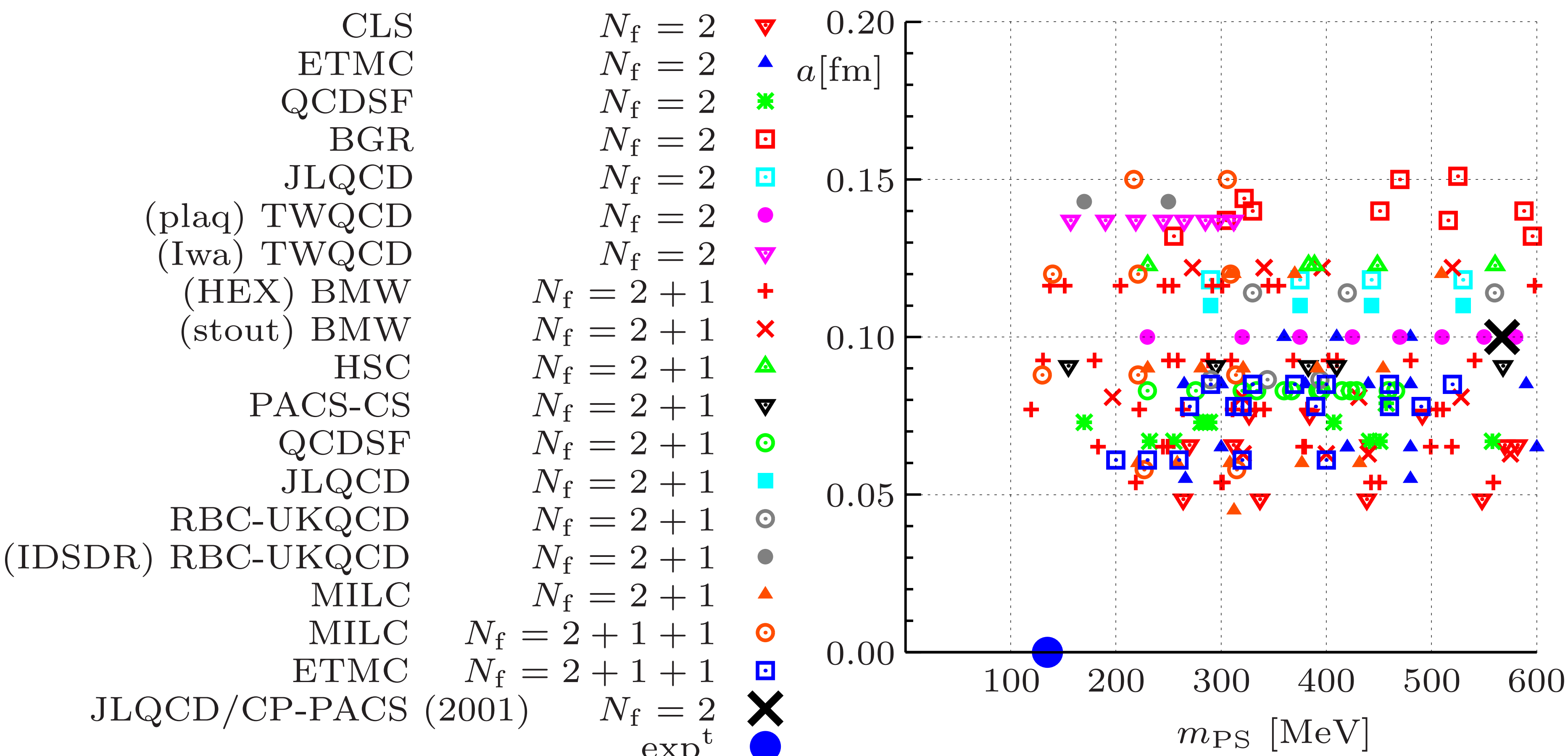
[Lüscher, Schaefer 2011]

n.b.: $0.05\ \mathrm{fm}\ \times\ 4\ \mathrm{GeV} \approx 1$

lattice QCD reach: simulation landscape



$L^{-1} \ll \mu \ll a^{-1}$



[plot courtesy of G. Herdoíza]

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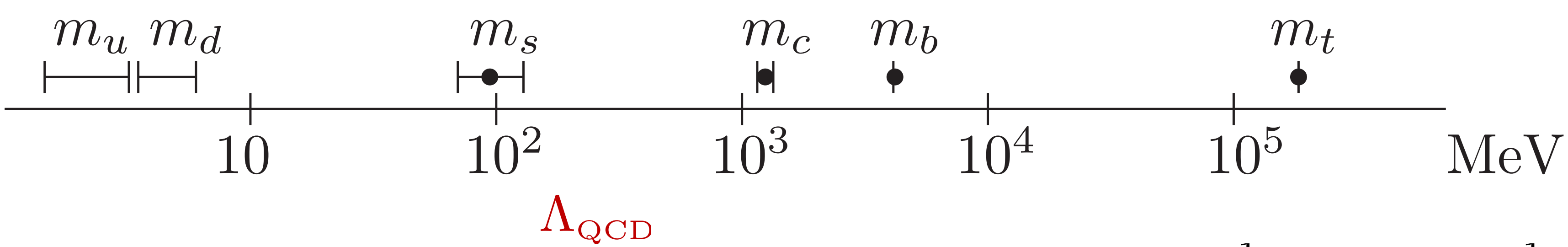

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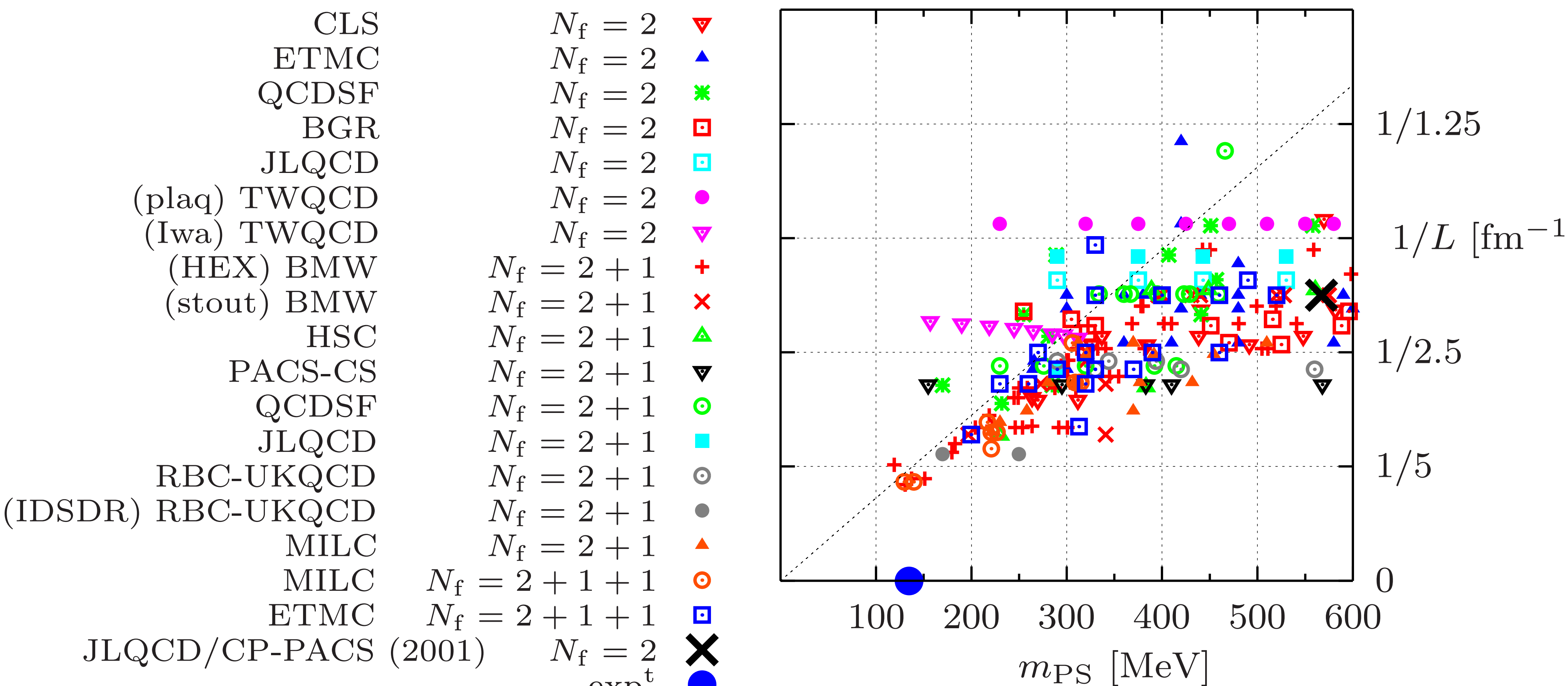

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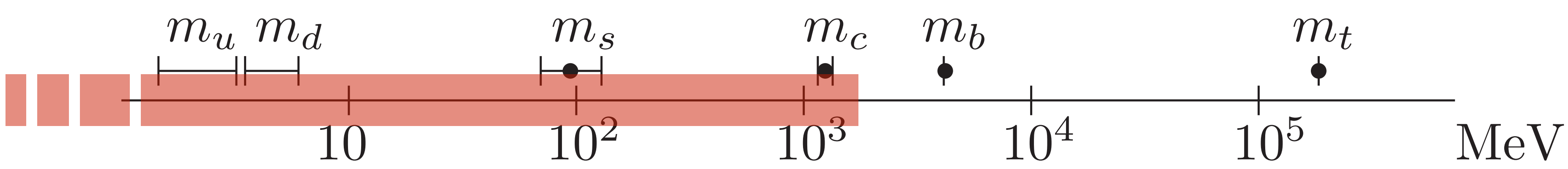
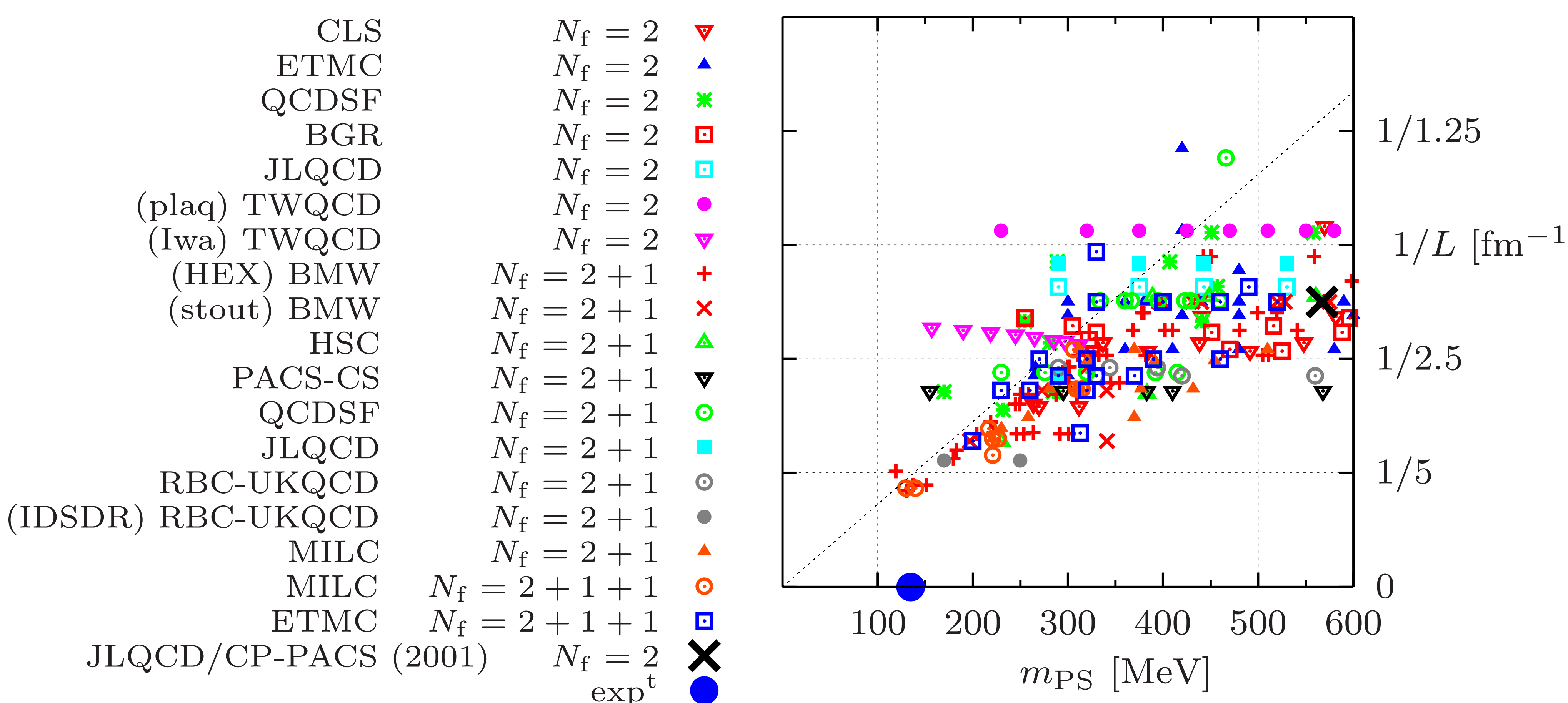


scales covered in large volumes

Λ_{QCD}

$L^{-1} \ll \mu \ll a^{-1}$



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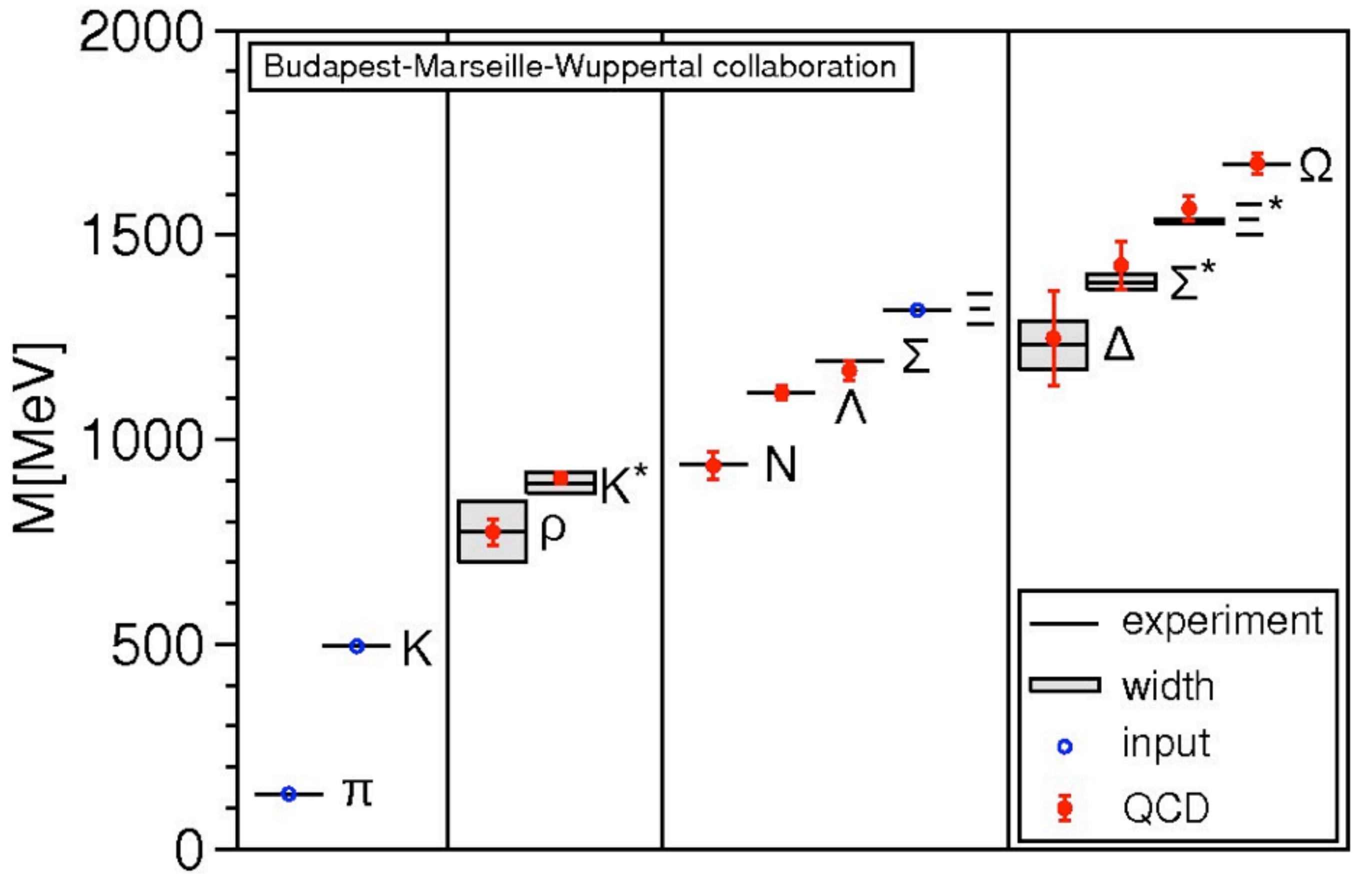
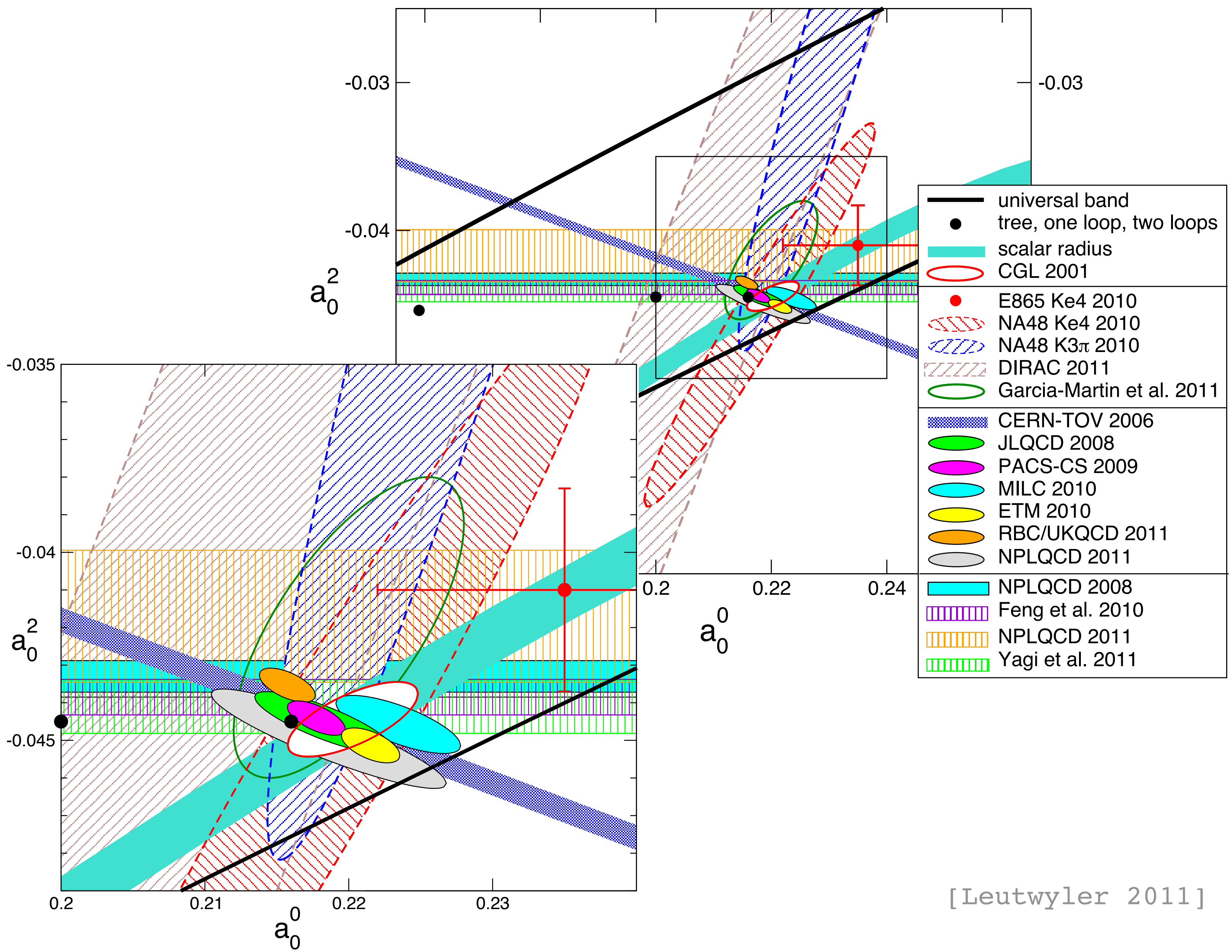
lattice QCD reach: a precision era



[BMW Collaboration 2008]

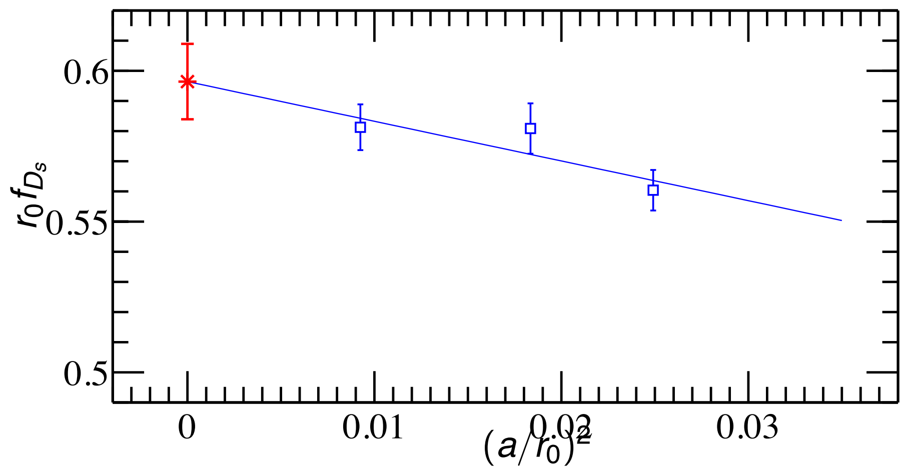
lattice QCD reach: a precision era

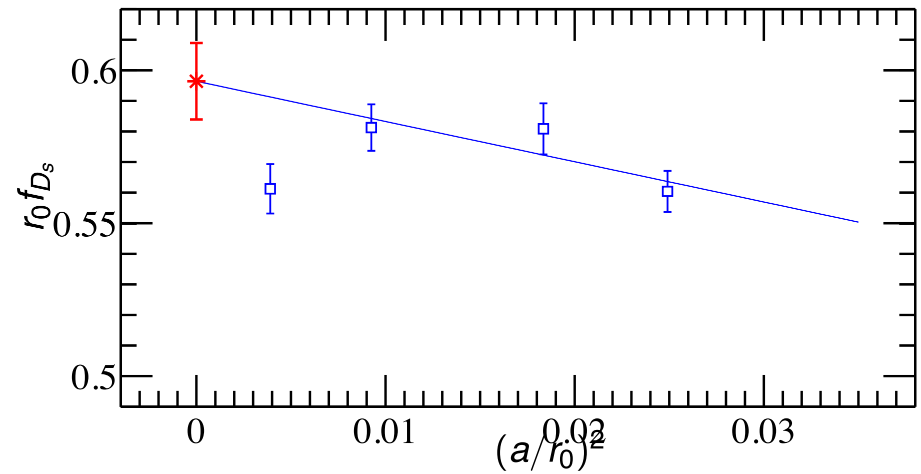


[Leutwyler 2011]

B-physics on the lattice: not quite there yet

b quark scale (naively) not accessible without introducing large am_b cutoff effects.





[Heitger, Jüttner 2009]

various approaches:

- Effective theories for HQ sector (NRQCD, non-perturbative HQET).
- Relativistic quarks in charm region + static limit ⇒ HQET-inspired interpolations to b region.
- Use heavily improved actions and/or mass-dependent matching conditions to try and push relativistic quarks into b mass regime.

B-physics on the lattice: not quite there yet

- NRQCD: combined expansion in $v^2,\ \Lambda/m_b,\ a$, perturbative matching to QCD.
  - \+ easy to carry out to high orders, allows to work at large lattice spacing.
  - − only works in scaling window $a\Lambda \ll 1,\ m_{\rm h}a \gtrsim 1$, no continuum limit.

[HPQCD]

- npHQET: expansion in $m_{\rm h}^{-1}$, matched non-perturbatively to QCD (using small V).
  - \+ continuum limit exists at any order in the expansion, systematic tool.
  - − difficult to go beyond $1/m_{\rm h}$ order (⇒ percent systematic uncertainties).

[ALPHA]

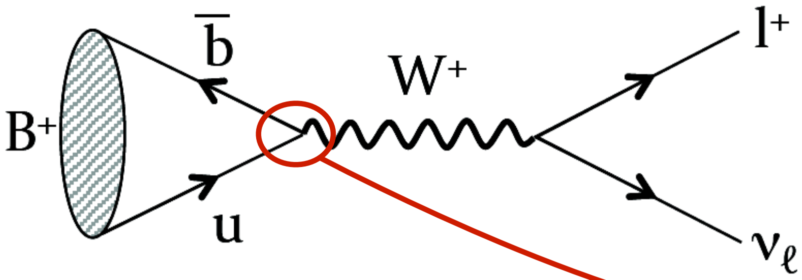
- combined: (smartly) interpolate between charm region and static limit.
  - \+ well-controlled systematics in either end.
  - − systematics associated to true mass dependence hard to control.

[ETMC, ALPHA]

- relativistic b-quark: (HQET-inspired) tuning of counterterms to improve scaling.
  - \+ easy to carry out to high orders in the O(a) improvement philosophy.
  - − systematics difficult to test (perturbative matching, "true" mass dependence).

[Fermilab/MILC, HPQCD]

results: $f_{B_{(s)}}$



$$\langle 0|\bar{b}\gamma_\mu\gamma_5 q|B\rangle = f_{B_{(s)}} p_\mu$$

$$\mathrm{BR}(B \to \ell\nu) = \frac{G_\mathrm{F}^2 m_B}{8\pi}\, m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B$$

$$\underset{\mathrm{exp}}{=} 1.68 \pm 0.31$$

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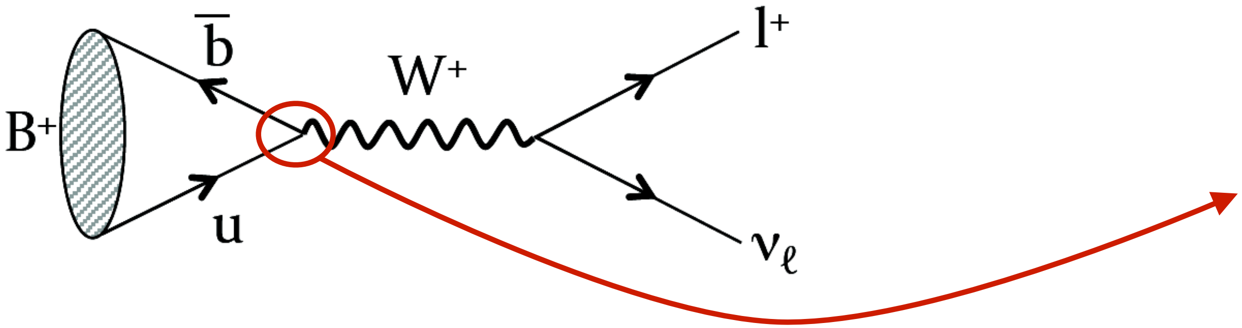

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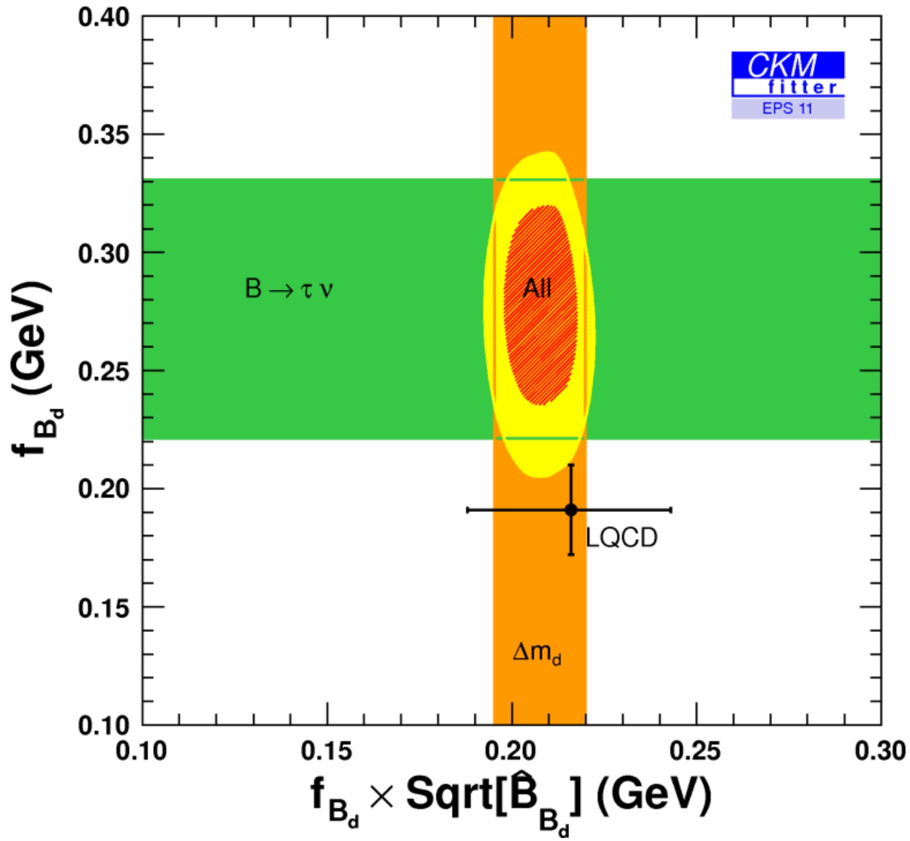
collaboration	N_f	f_B (MeV)	f_{B_s} (MeV)	method
HPQCD 11-12	2+1	191(9)	227(10)	HISQ+rSTAG
FNAL/MILC 11	2+1	197(9)	242(10)	FNAL+rSTAG
HPQCD 09	2+1	197(13)	240(16)	NRQCD+rSTAG
ALPHA 11	2	174(11)(2)	—	npHQET+iW
ETMC 11	2	195(12)	232(10)	interp+tmQCD

results: $f_{B_{(s)}}$



[CKMfitter 2011]

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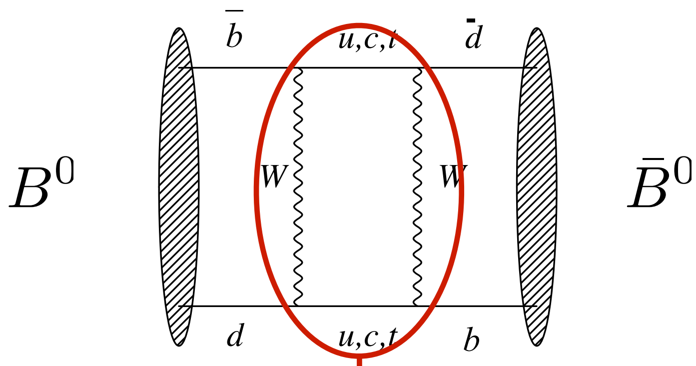
$\delta \lesssim 5\%$

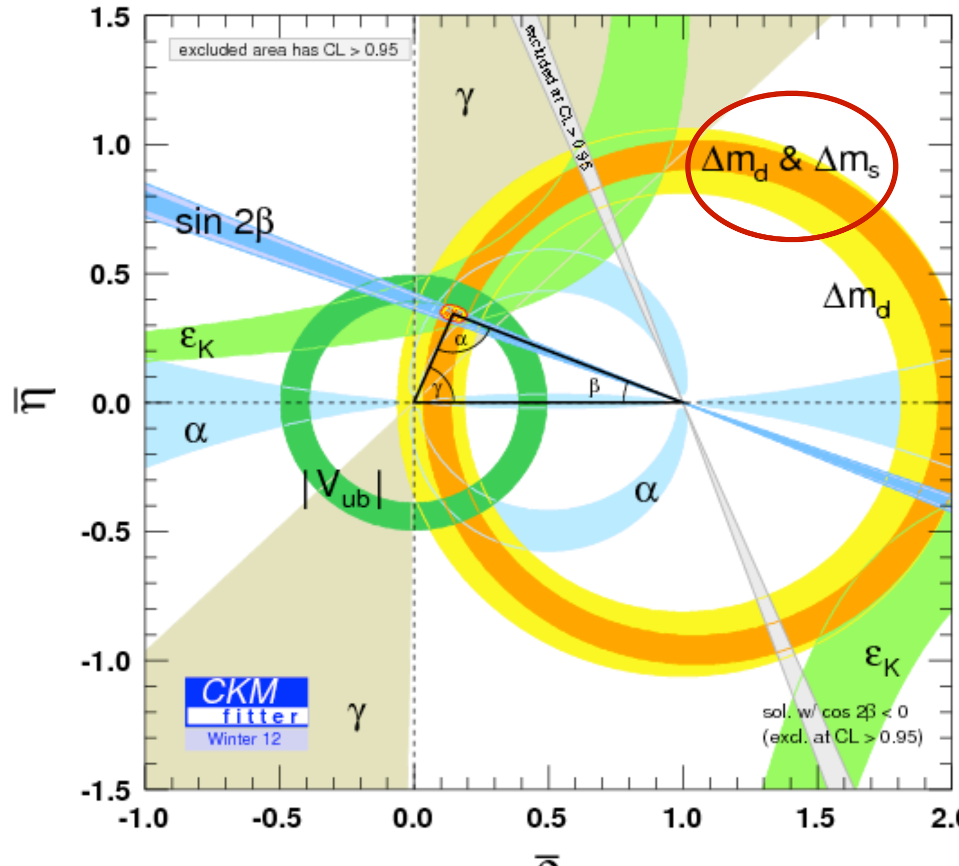
are we fully controlling all systematic uncertainties?

results: $f^2_{B_{(s)}} B_{B_{(s)}}$ and ξ



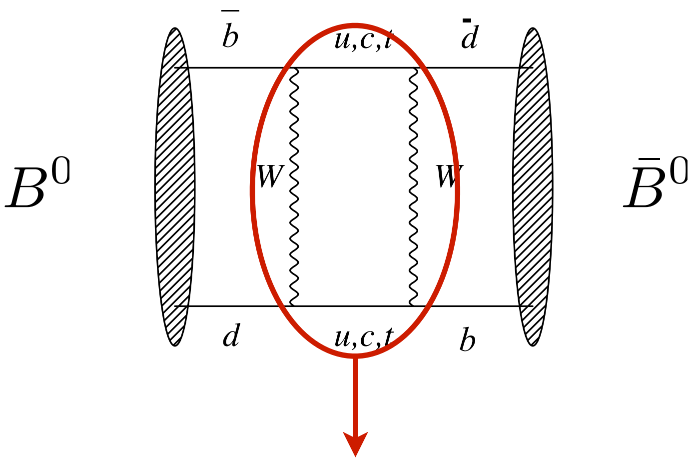
$$\langle \bar{B}^0 | (\bar{b}\gamma^{\mathrm{L}}_\mu d)(\bar{b}\gamma^{\mathrm{L}}_\mu d) | B^0 \rangle_{\mathrm{RGI}} = \tfrac{8}{3}\, m_B^2\, f_B^2\, \hat{B}_B$$

$$\xi = \frac{f_{B_s}\sqrt{\hat{B}_{B_s}}}{f_B\sqrt{\hat{B}_B}} \qquad \propto \frac{\Delta M_{B_s}}{\Delta M_B}$$



[CKMFitter 2012]

results: $f^2_{B_{(s)}} B_{B_{(s)}}$ and ξ



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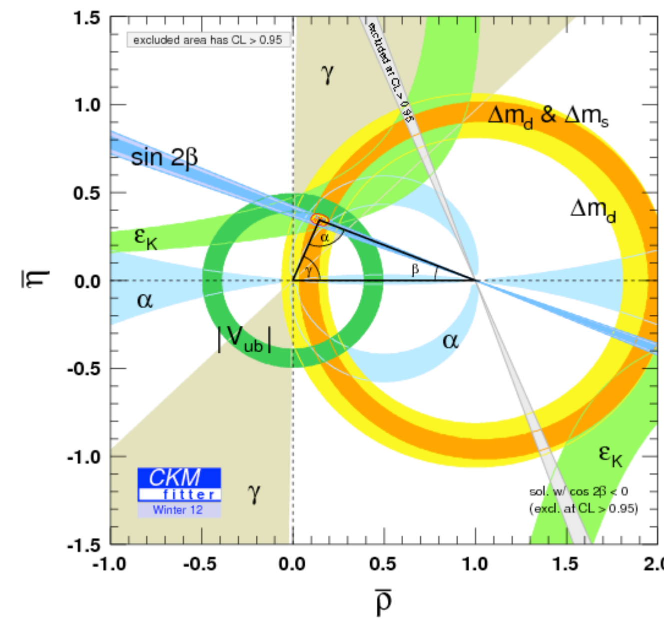
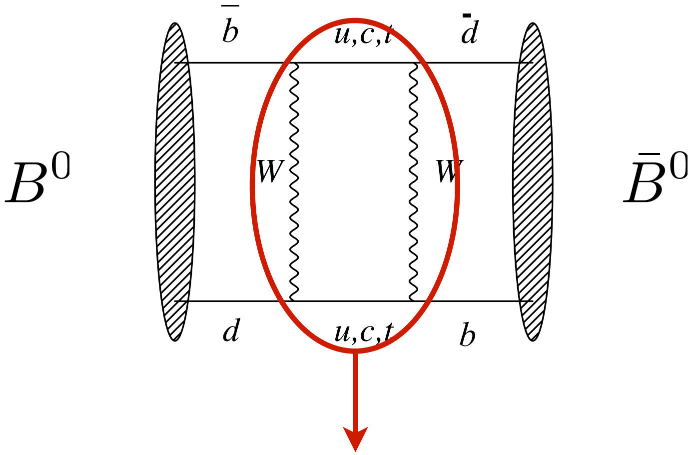


non-lattice: $B_{B_s} = 1.220^{+0.103}_{-0.044}$

[CKMFitter 2012]

collaboration	$f_B\sqrt{\hat{B}_B}$	$f_{B_s}\sqrt{\hat{B}_{B_s}}$	$\hat{B}_B$	$\hat{B}_{B_s}$	method
FNAL/MILC 11	252(23)	239(18)	—	—	FNAL+rSTAG
HPQCD 09	216(9)(12)	266(6)(17)	1.27(10)	1.33(5)(3)	NRQCD+rSTAG
HPQCD 06	—	281(21)	—	1.17(17)	NRQCD+rSTAG

results: $f^2_{B_{(s)}} B_{B_{(s)}}$ and ξ



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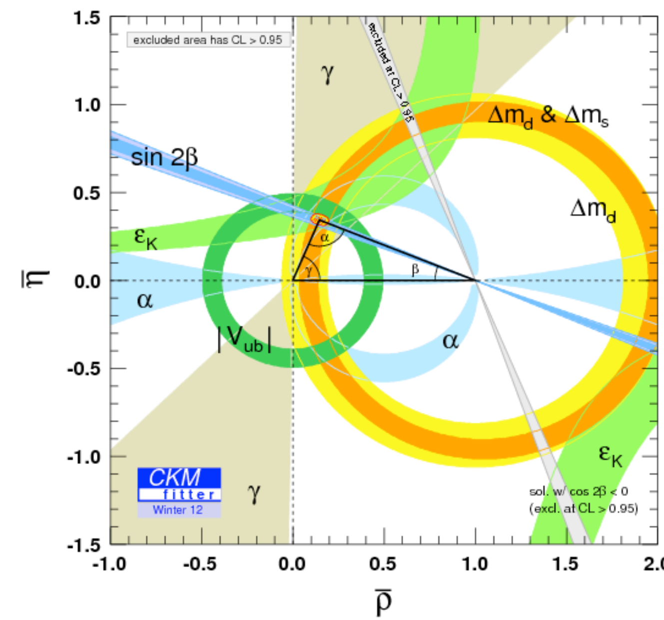

non-lattice: $B_{B_s}/B_B = 1.134^{+0.074}_{-0.093}$

[CKMFitter 2012]

collaboration	ξ	$\hat{B}_{B_s}/\hat{B}_B$	method
RBC/UKQCD 10	1.13(12)	—	static+DWF
HPQCD 09	1.258(25)(21)	1.05(7)	NRQCD+rSTAG
FNAL/MILC 09	1.205(37)(34)	—	FNAL+rSTAG

results: $f^2_{B_{(s)}} B_{B_{(s)}}$ and ξ

Errors not far from 5% ballpark, even if cutting-edge lattice (lightest dynamical masses, finest lattice spacings) not included.

Careful, global assessment of involved systematics crucial.

results: $f^2_{B_{(s)}} B_{B_{(s)}}$ and ξ

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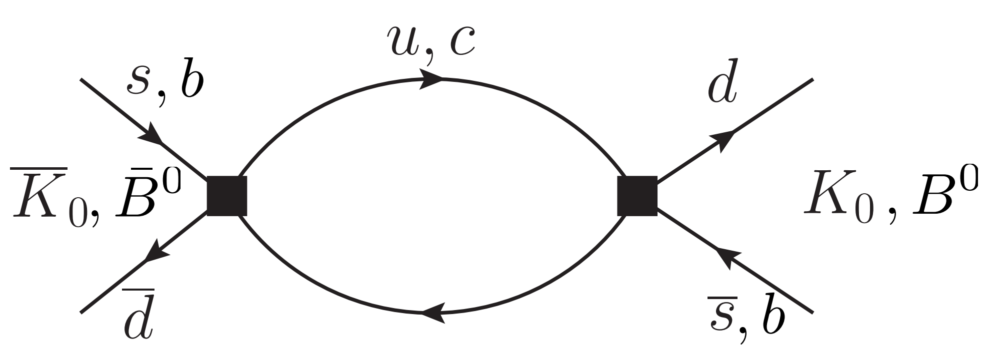
what about Γ_{12}?



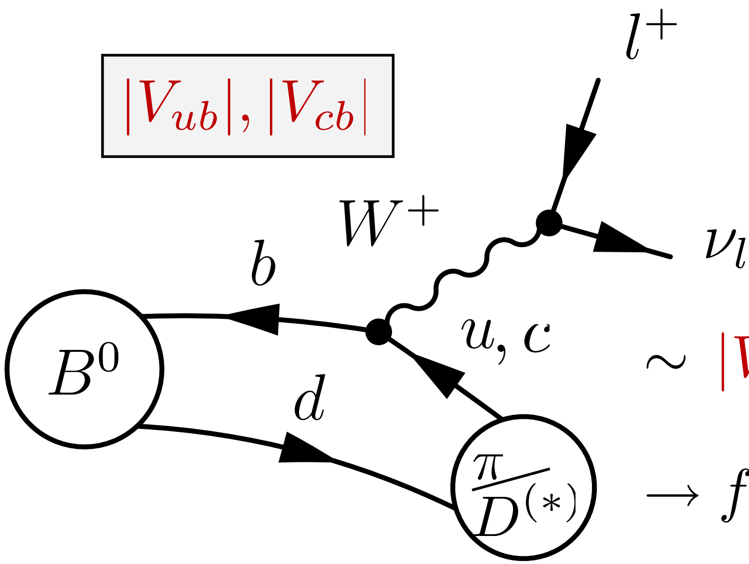
charm kicking back: keeping it as an active d.o.f. starts to be relevant for B_K.

[cf. Buras, Guadagnoli, Isidori 10]

bonus: if properly tackled, would allow to study *D* mixing.

results: semileptonic B decays

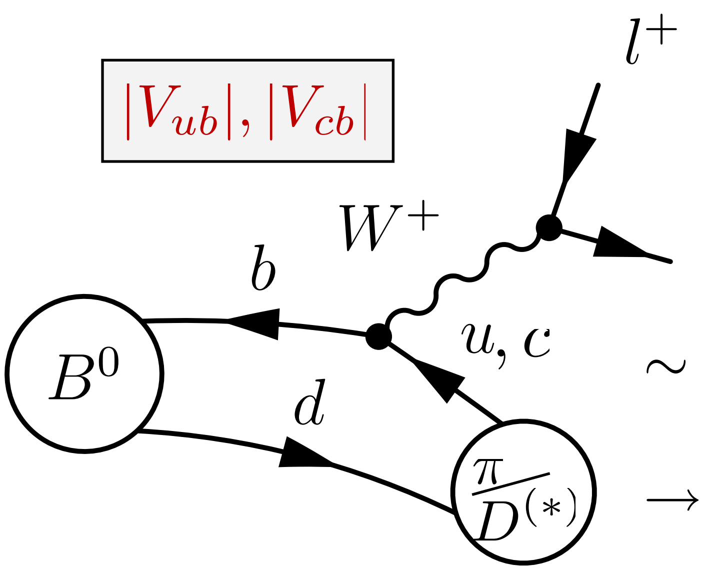
$\boxed{|V_{ub}|, |V_{cb}|}$



$\sim |V_{qb}| \langle X | \bar{b} \gamma_\mu q | B^0 \rangle$

$\to f_+(q^2), \; f_0(q^2)$

results: semileptonic B decays



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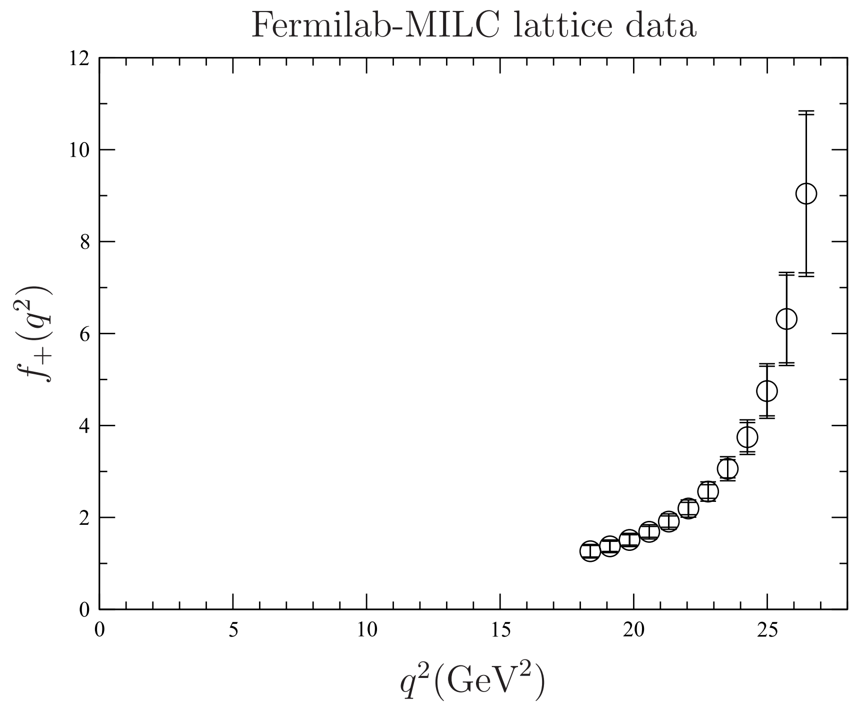
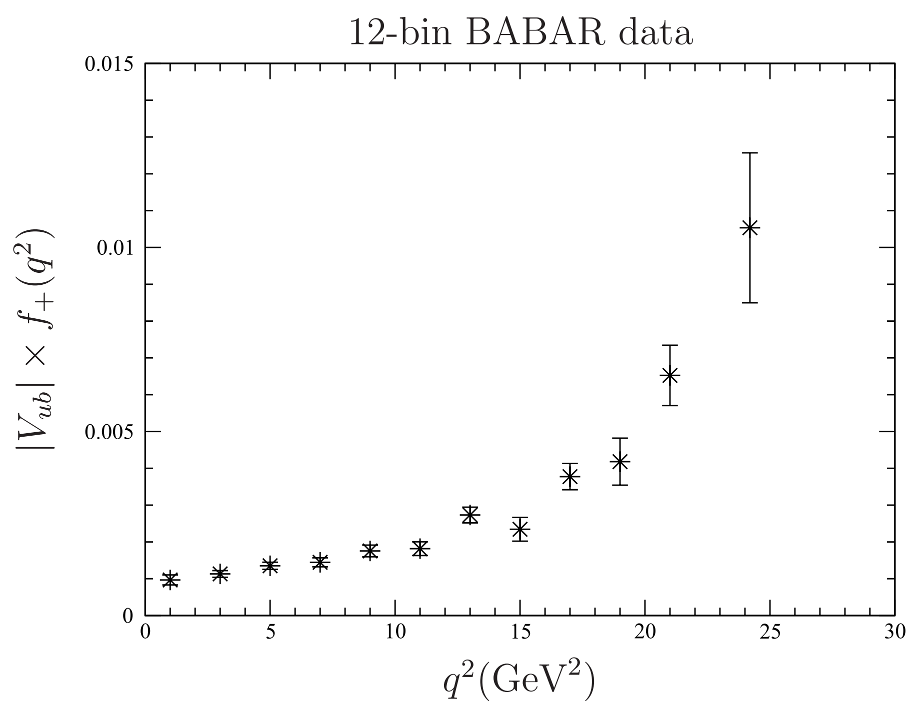


issue #1

decay into π: lattice QCD limited by discretisation effects to $q^2 \gtrsim 15\ \mathrm{GeV}^2$

experiment most precise in low q^2 region



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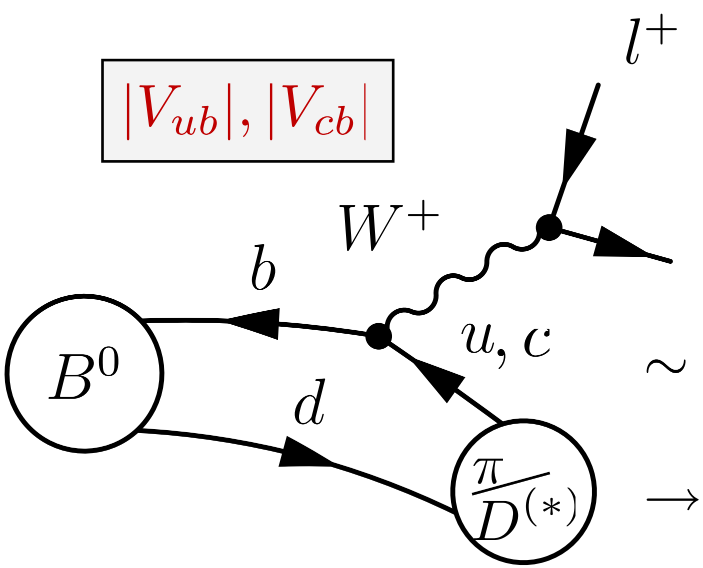

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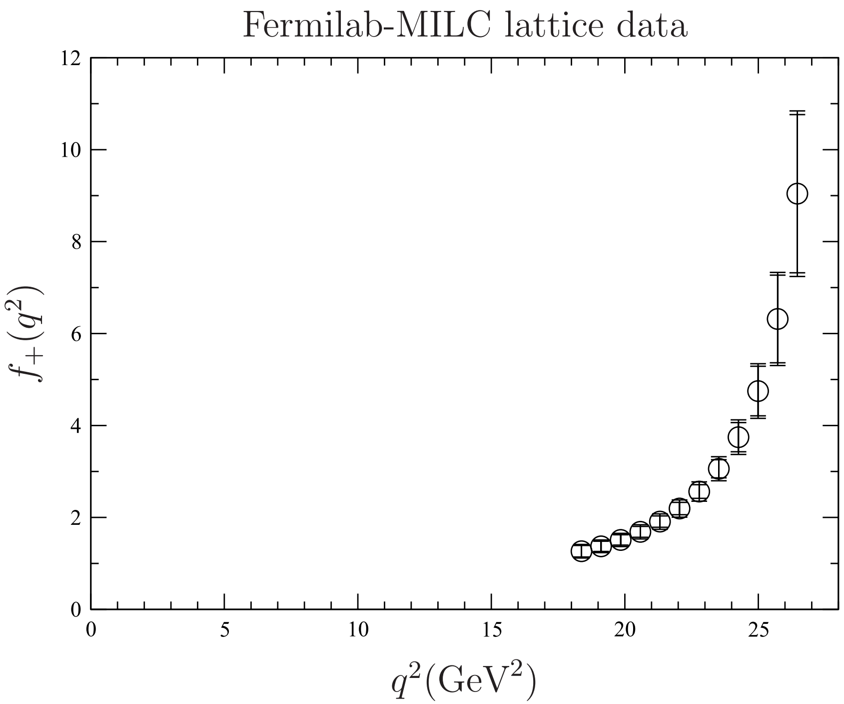

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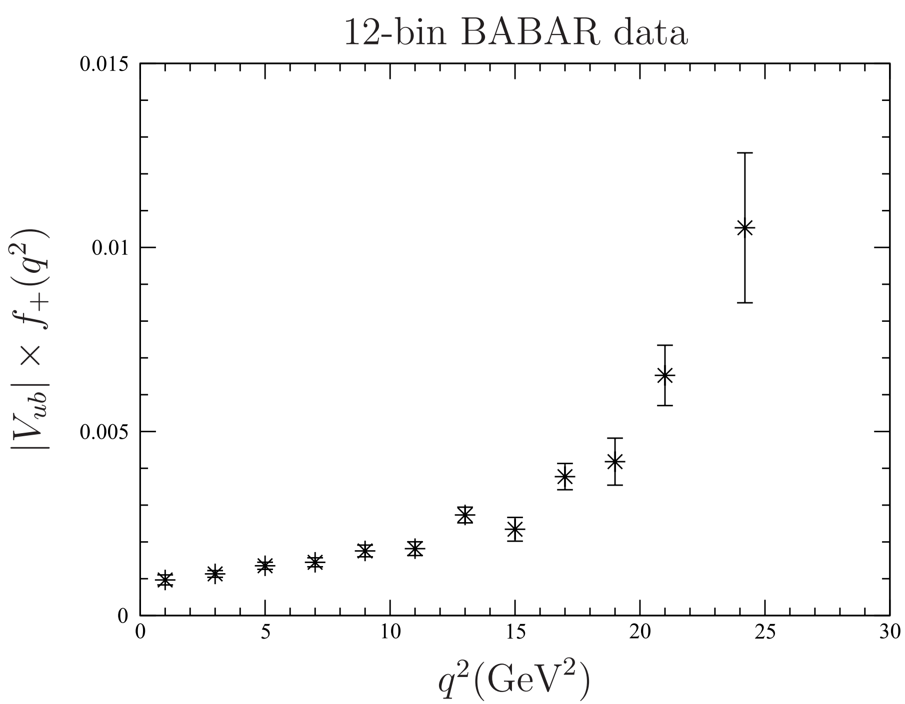


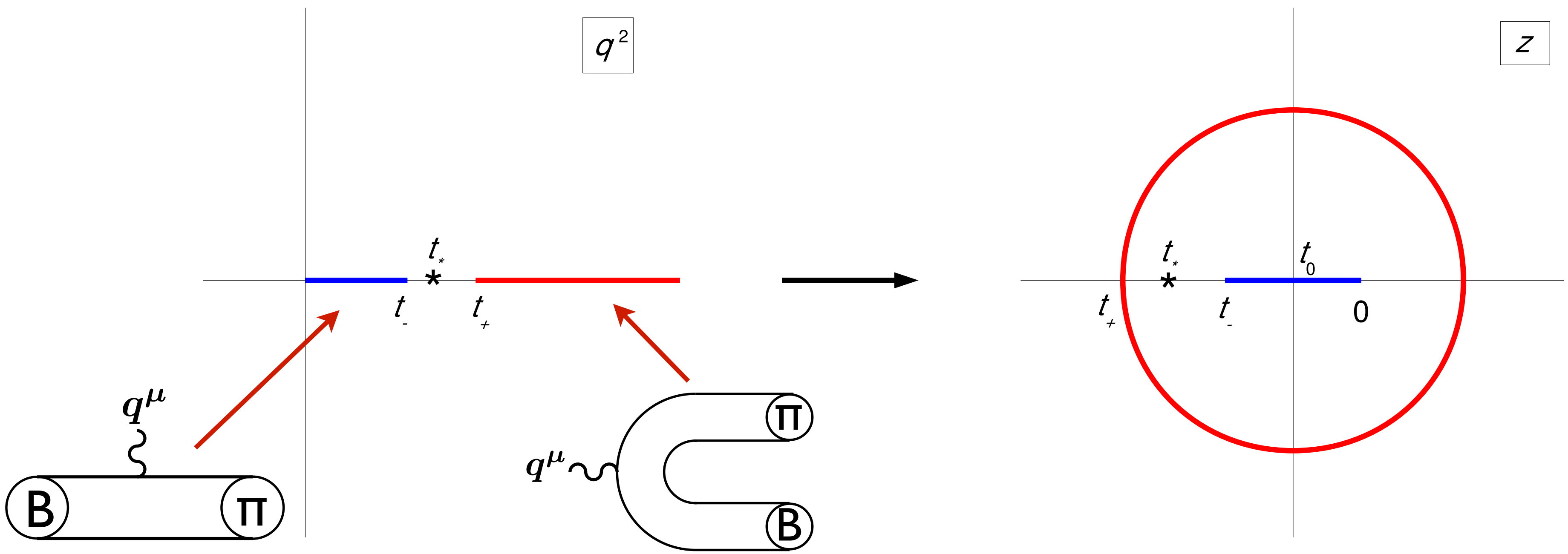
issue #2

lack of fully first-principles ansatz for momentum dependence

results: semileptonic B decays

Simultaneous solution: use dispersion relations, analyticity, unitarity to find well-behaved parametrisation.

[Okubo et al. 71; Bourrely et al. 81]
[several works 2005-...]



$$z(q^2,t_0)=\frac{\sqrt{t_+-q^2}-\sqrt{t_+-t_0}}{\sqrt{t_+-q^2}+\sqrt{t_+-t_0}}\;\rightarrow\; f_+(q^2)=\frac{1}{B(q^2)\phi(q^2,t_0)}\sum_{n\geq 0}a_n(t_0)\,z(q^2,t_0)^n$$

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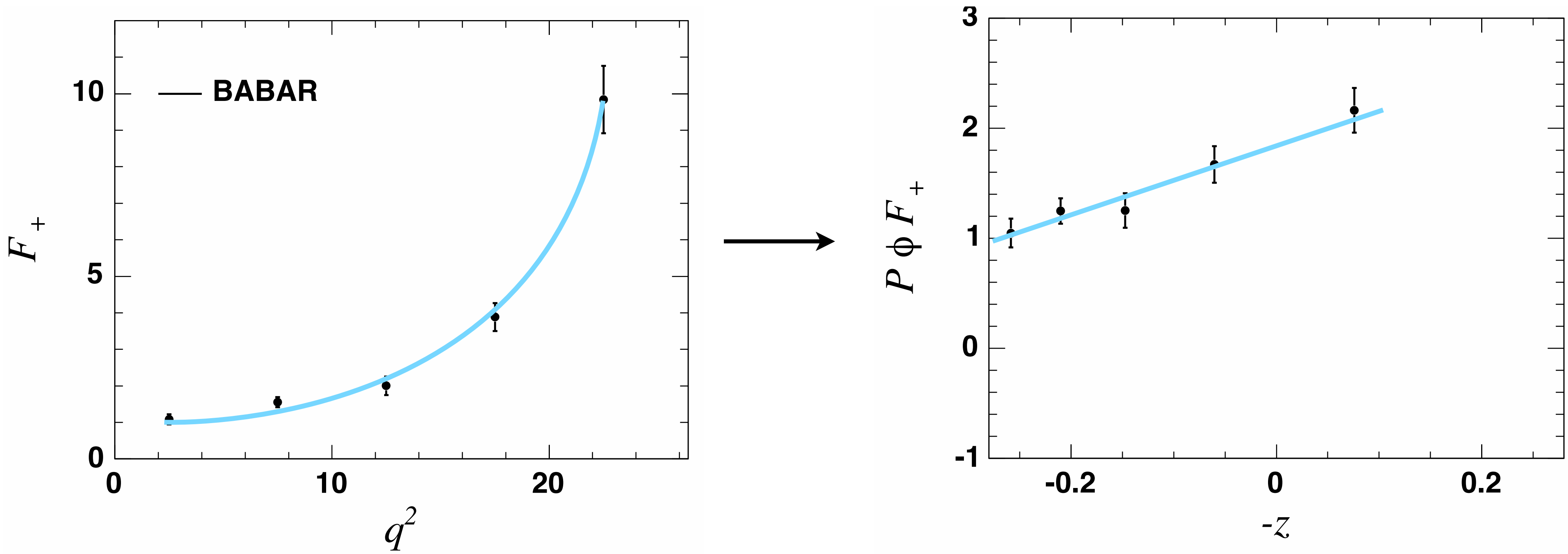

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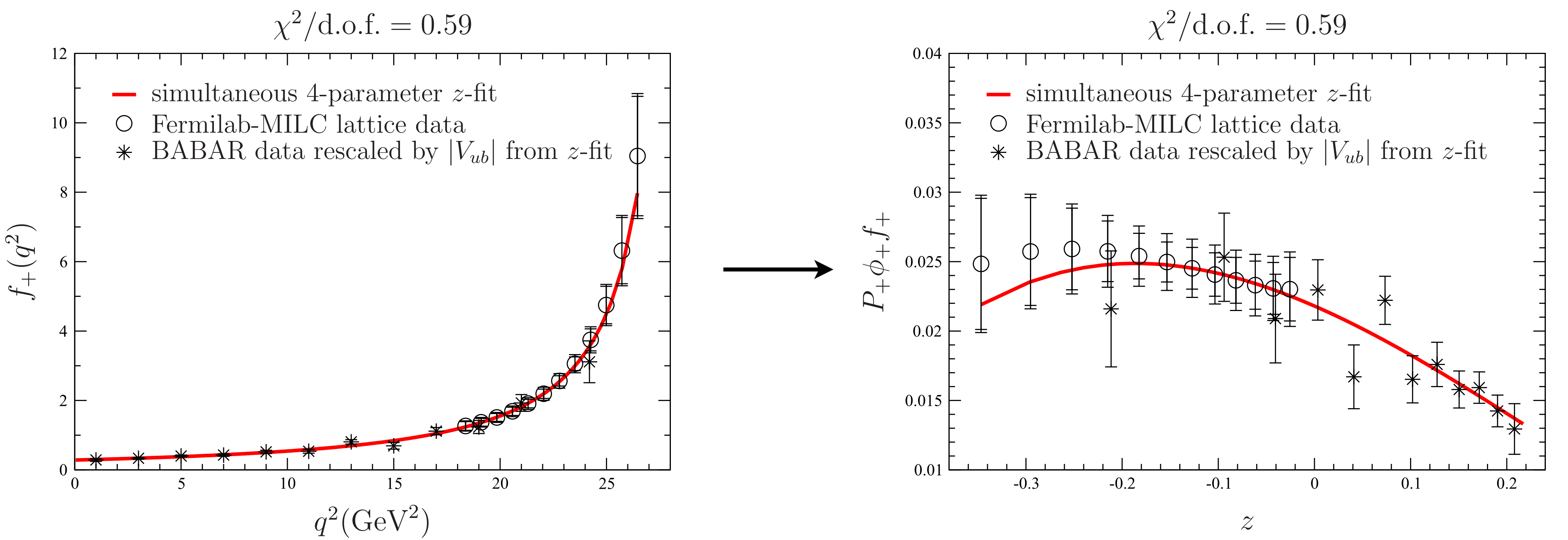

$$z(q^2,t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}} \quad \rightarrow \quad f_+(q^2) = \frac{1}{B(q^2)\phi(q^2,t_0)} \boxed{\sum_{n\geq 0} a_n(t_0)\, z(q^2,t_0)^n}$$

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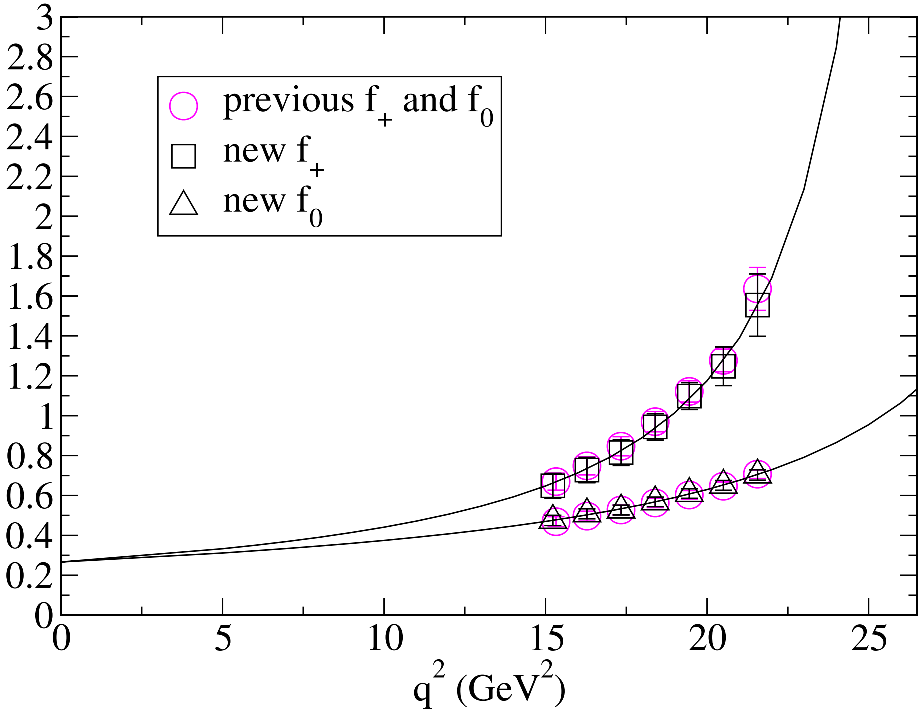
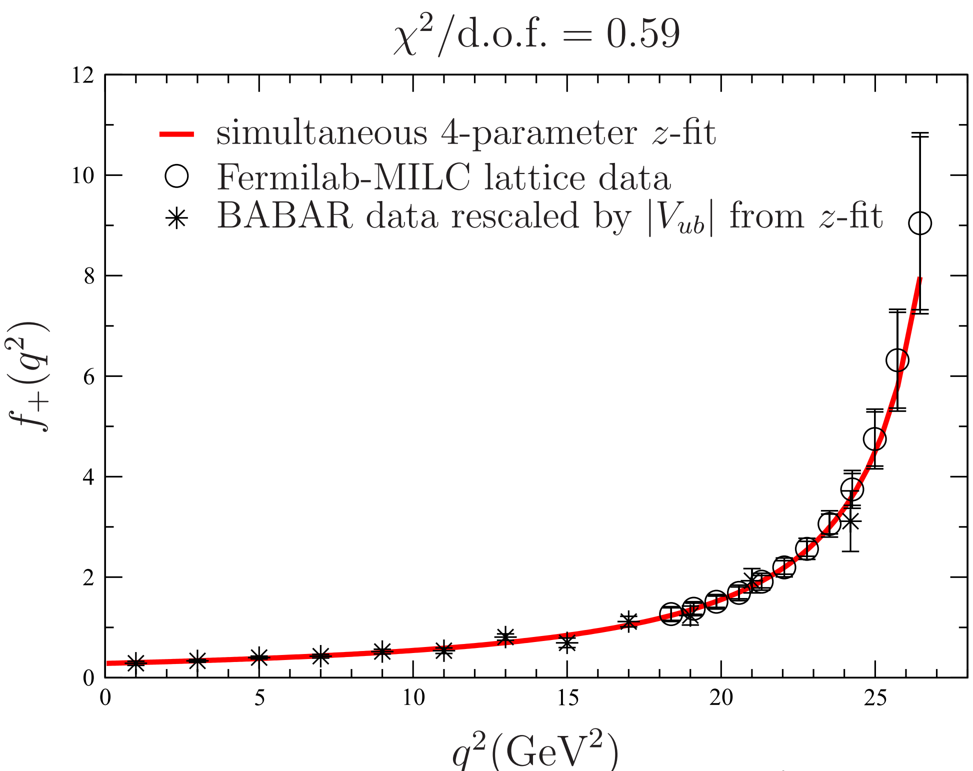


[HPQCD 06]



[FNAL/MILC 08]

B-factories and HFAG (and FLAG) already adopting this technique to describe results.

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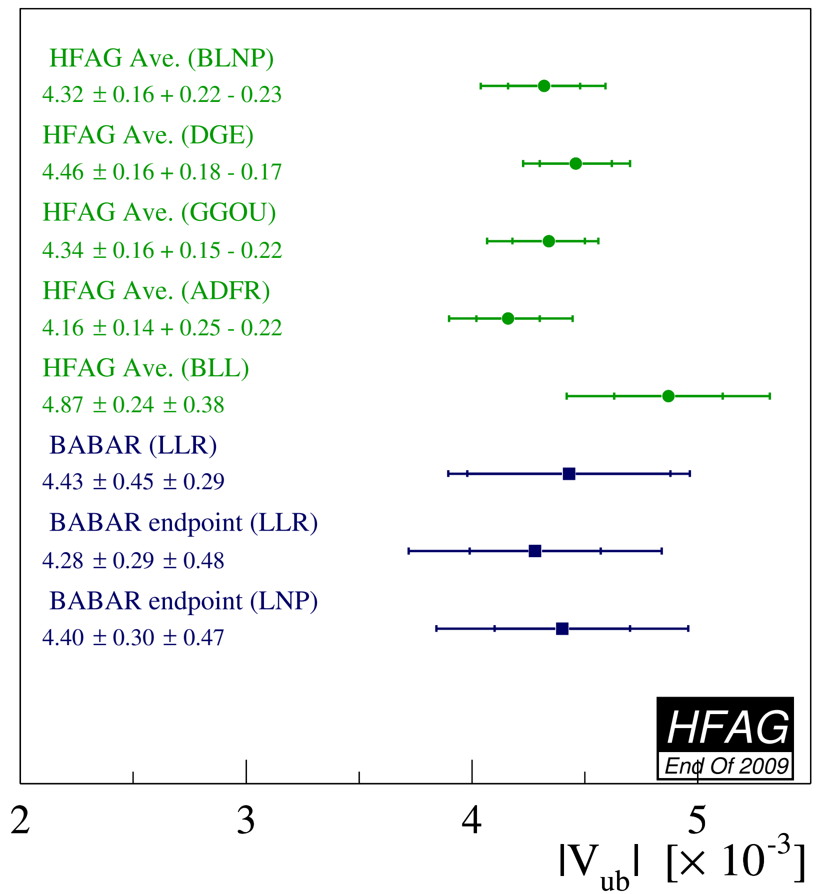

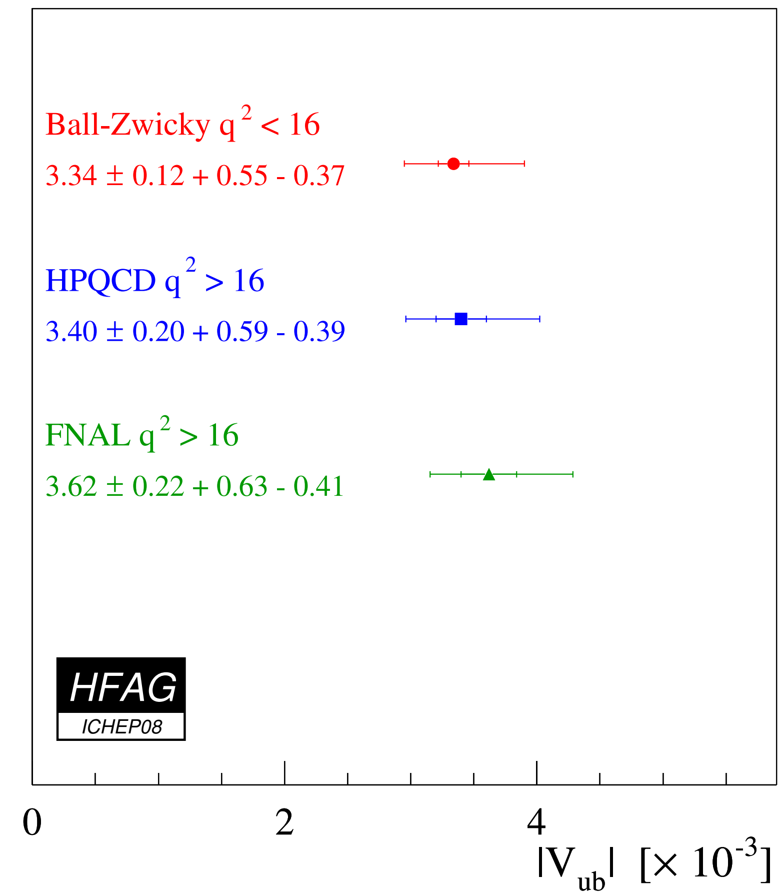

Lots of room for improvement by incorporating existing finer lattices with lighter dynamical quarks into the analysis.

results: semileptonic B decays

$B \to D^{(*)}$: less kinematical trouble, can extract $|V_{cb}|$ from one single combination of form factors at zero recoil.

$$\frac{d\Gamma(\bar{B} \to D l \bar{\nu})}{dw} = \frac{G_F^2}{48\pi^3} m_D^3 (M_B + M_D)^2 (w^2 - 1)^{3/2} |V_{cb}|^2 |\mathscr{G}(w)|^2,$$

$$\frac{d\Gamma(\bar{B} \to D^* l \bar{\nu})}{dw} = \frac{G_F^2}{4\pi^3} m_{D^*}^3 (M_B - M_{D^*})^2 (w^2 - 1)^{1/2} |V_{cb}|^2 \chi(w) |\mathscr{F}(w)|^2$$

$$q^2 = M_B^2 + M_{D^{(*)}}^2 - 2w M_B M_{D^{(*)}}$$

collaboration	$\mathcal{F}(1)$	$\mathcal{G}(1)$	method
FNAL/MILC 08-10	0.908(17)	—	FNAL+rSTAG
FNAL/MILC 04	—	1.074(24)	FNAL+rSTAG

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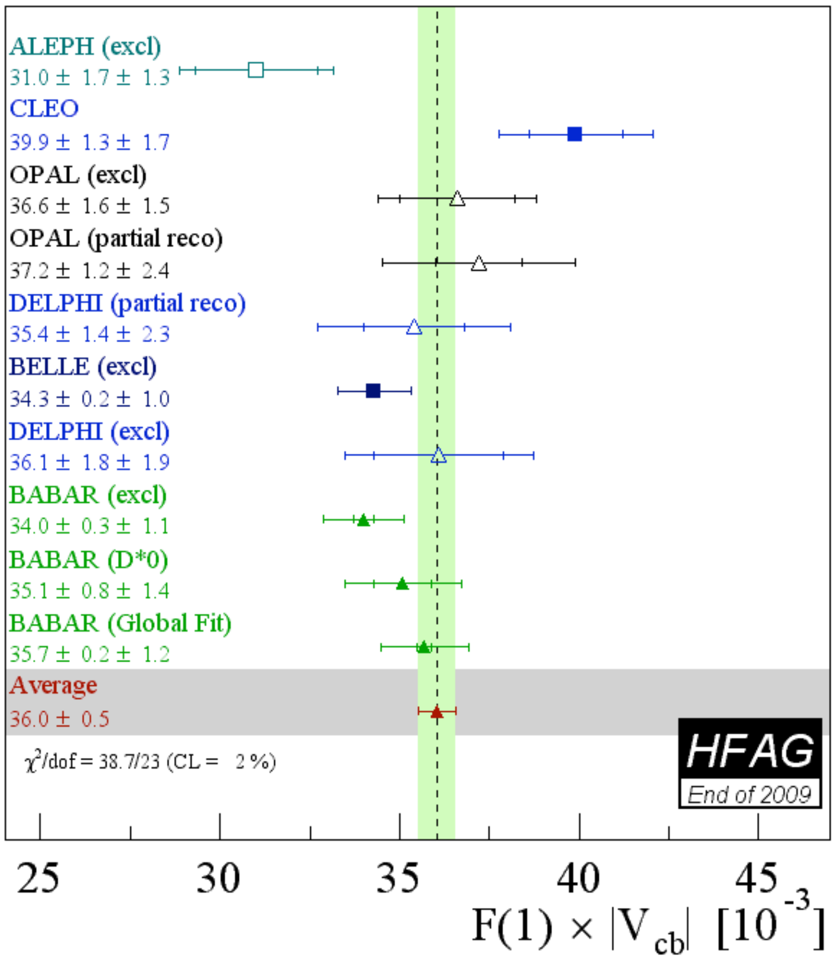

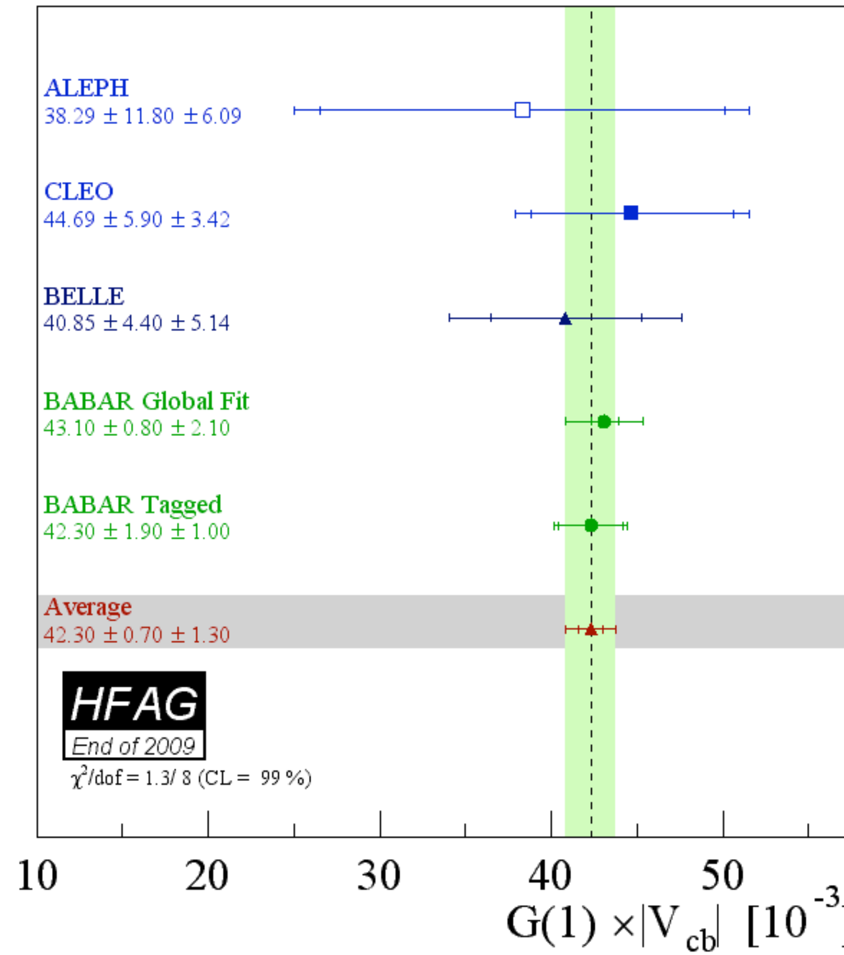

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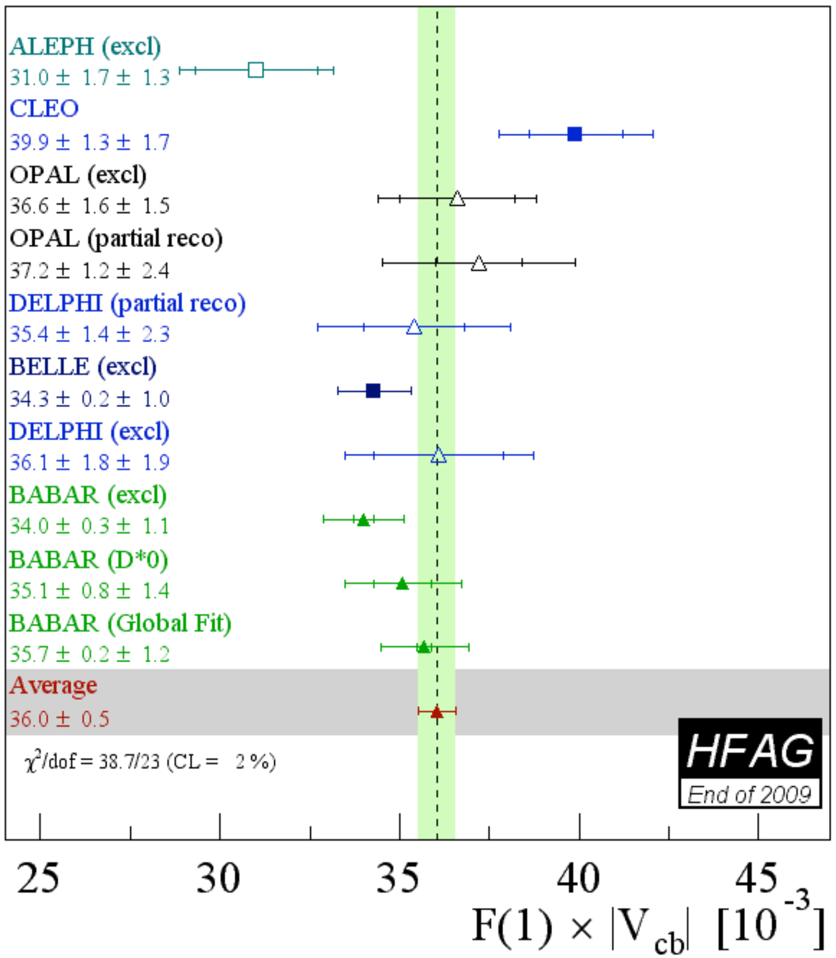

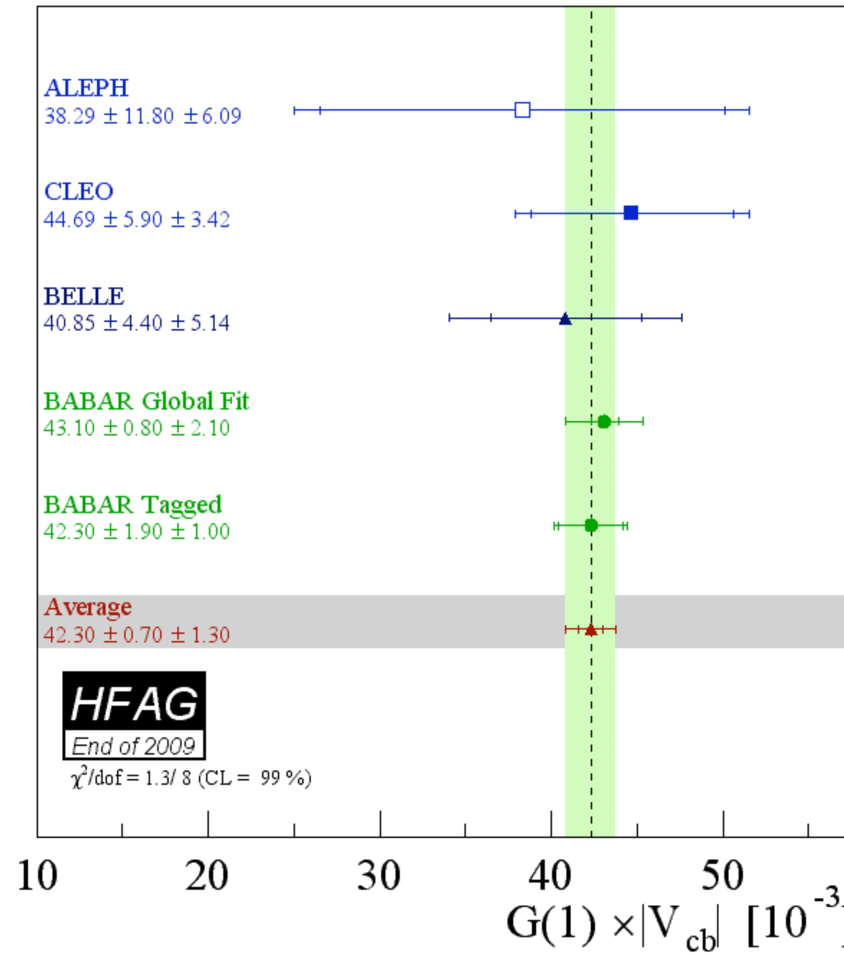

[BaBar,arXiv:1205.5442]

Update by various collaborations due soon. Progress most welcome in view of recently reported BaBar excess.

(Requires good control of τ decay channel $\longrightarrow$ scalar form factor.)

FLAG

Users of lattice results should be (made) aware of potential systematic effects. Lattice groups should provide qualified global averages of lattice results.

$\Rightarrow$ FLAG

FLAG-1

Users of lattice results should be (made) aware of potential systematic effects. Lattice groups should provide qualified global averages of lattice results.

FLAG = FLAVIAnet Lattice Averaging Group

FLAG-1 members:

- G Colangelo (BERN)
- S Dürr (Jülich, BMW)
- A Jüttner (CERN, RBC/UKQCD)
- L Lellouch (Marseille, BMW)
- H Leutwyler (Bern)
- V Lubicz (Rome 3, ETM)
- S Necco (CERN, Alpha-CLS)
- C Sachrajda (Southampton, RBC/UKQCD)
- S Simula (Rome 3, ETM)
- A Vladikas (Rome 2, Alpha and ETM)
- U Wenger (Bern, ETM)
- H Wittig (Mainz, Alpha-CLS)

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FLAG = FLAVIAnet Lattice Averaging Group

First review appeared on Nov 2010, updated May 2011 (EPJC).

regularly updated web: http://itpwiki.unibe.ch/flag

what does FLAG offer?

FLAG-1: concentrate on light hadron physics.

- light quark masses
- LECs
- decay constants
- pion and kaon form factors
- kaon bag parameter

For each quantity provide:

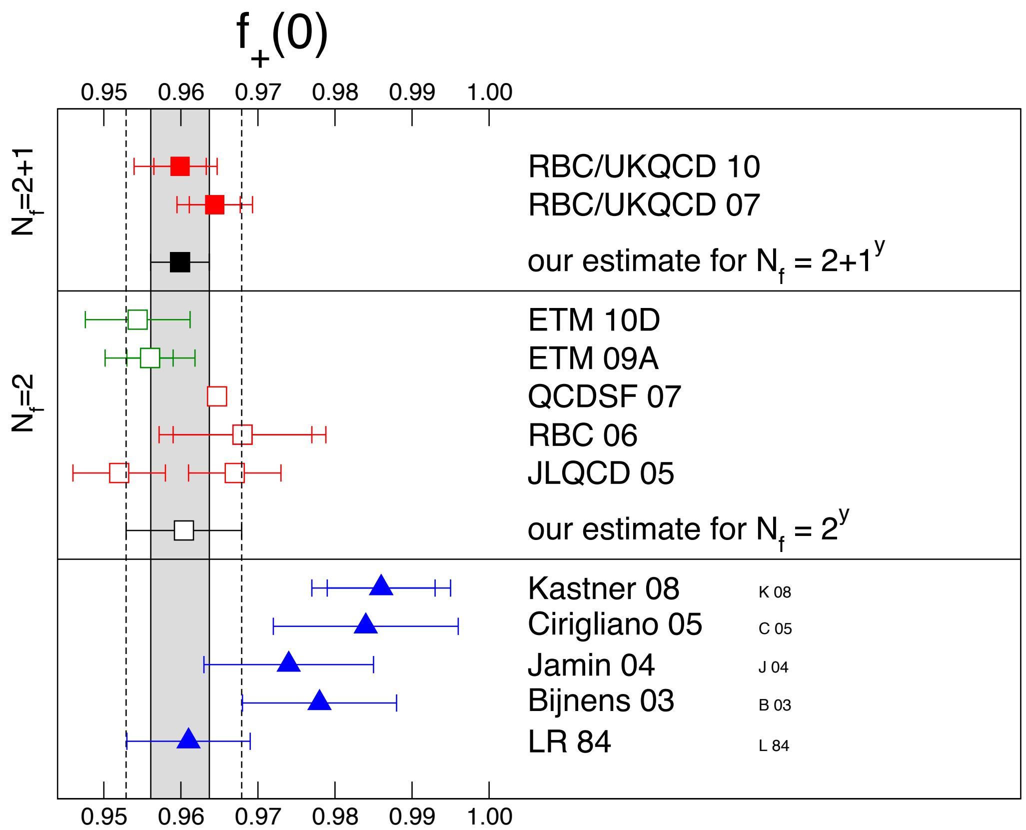
- complete list of references, summary of formulae/notations, ...
- summary of essential aspects of each computation
- averages (if sensible)
- “lattice dictionary” for non-experts

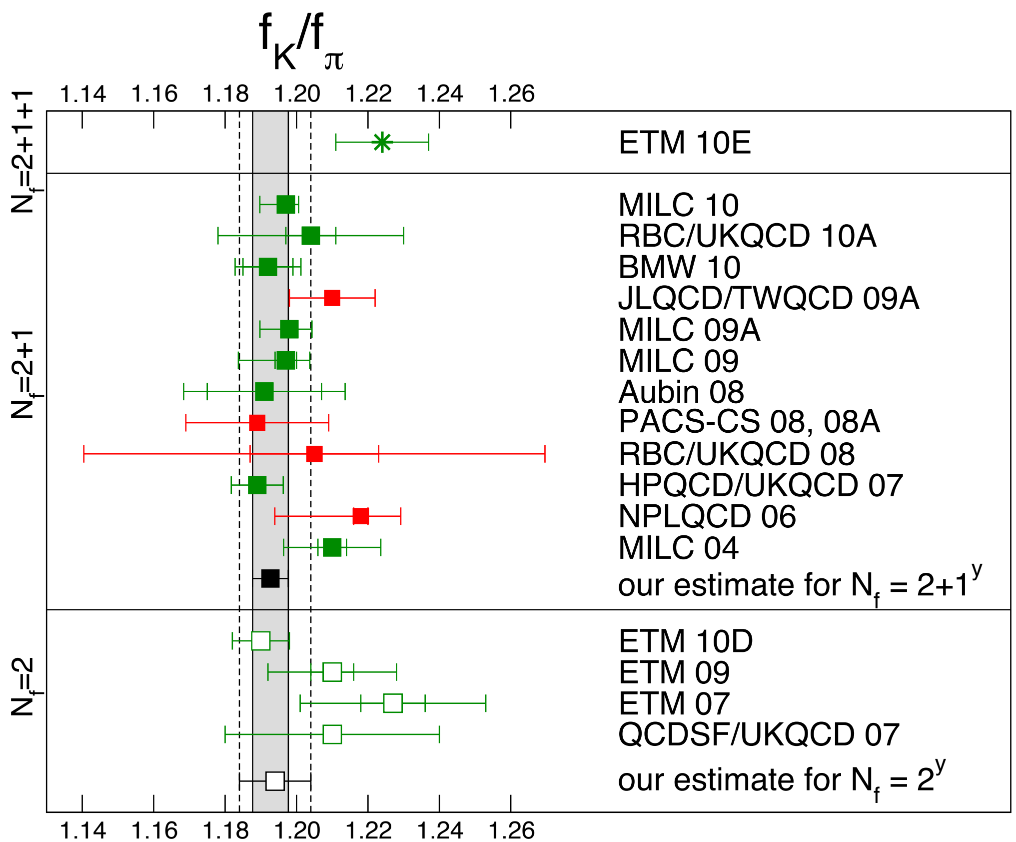
what does FLAG offer?

		N_f		publication status	chiral extrapol.	finite volume	continuum extrapol.	action
$f_+(0)$	$0.9599(34)(^{+31}_{-47})(14)$	2+1	RBC/UKQCD 10	A	●	★	■	DWF
	$0.9644(33)(34)(14)$	2+1	RBC/UKQCD 07	A	●	★	■	DWF
	$0.9544(68)_{stat}$	2	ETM 10D	C	●	★	●	max. tmQCD
	$0.9560(57)(62)$	2	ETM 09A	P	●	●	●	max. tmQCD
	$0.9647(15)_{stat}$	2	QCDSF 07	C	■	★	■	clover (NP)
	$0.968(9)(6)$	2	RBC 06	A	■	★	■	DWF
	$0.967(6)$	2	JLQCD 05	C	■	★	■	clover (NP)

f_K/f_π	$1.197(2)(^{+3}_{-7})$	2+1	MILC 10	C	●	★	★	$\mathrm{KS}^{\mathrm{MILC}}_{\mathrm{MILC}}$
	$1.204(7)(25)$	2+1	RBC/UKQCD 10A	P	●	●	★	DWF
	$1.192(7)(6)$	2+1	BMW 10	A	★	★	★	tlSW
	$1.210(12)_{stat}$	2+1	JLQCD/TWQCD	C	●	■	■	overlap
	$1.198(1)(^{+6}_{-8})$	2+1	MILC 09A	C	★	★	★	$\mathrm{KS}^{\mathrm{MILC}}_{\mathrm{MILC}}$
	$1.191(16)(16)$	2+1	ALVdW 08	C	★	●	●	$\mathrm{KS}_{\mathrm{MILC}}/\mathrm{DWF}$
	$1.189(20)$	2+1	PACS-CS 08	P	★	■	■	clover (NP)
	$1.18(1)(1)$	2+1	BMW 08	C	★	★	★	impr. Wilson
	$1.189(2)(7)$	2+1	HPQCD/UKQCD 08	A	★	●	★	$\mathrm{KS}^{\mathrm{HISQ}}_{\mathrm{MILC}}$
	$1.205(18)(62)$	2+1	RBC/UKQCD 07	A	●	★	■	DWF
	$1.218(2)(^{+11}_{-24})$	2+1	NPLQCD 07	A	●	■	■	$\mathrm{KS}_{\mathrm{MILC}}/\mathrm{DWF}$
	$1.210(6)(15)(9)$	2	ETM 09	A	●	●	★	max. tmQCD
	$1.21(3)$	2	QCDSF/UKQCD 07	C	●	★	●	clover (NP)

what does FLAG offer?





FLAG-2

Expand to cover most quantities, include representatives of *all* large collaborations, and distribute over Europe/US/Japan.

(n.b.: merge with parallel effort by Laiho, Lunghi, Van de Water)

advisory board: S. Aoki (J), C. Bernard (US), C. Sachrajda (EU)

editorial board: G. Colangelo, H. Leutwyler, A. Vladikas, U. Wenger

working groups:

quark masses	T. Blum, L. Lellouch, V. Lubicz
V_{ud}, V_{us}	A. Jüttner, T. Kaneko, S. Simula
LECs	S. Dürr, H. Fukaya, S. Necco
B_K	J. Laiho, S. Sharpe, H. Wittig
α_s	T. Onogi, J. Shigemitsu, R. Sommer
f_B, B_B, f_D	Y. Aoki, M. Della Morte, A. El Khadra
$B, D \to H\ell\nu$	E. Lunghi, CP, R. Van de Water

target: next review by end 2012/early 2013; new published review every 2nd year; regular web updates in between.

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Preliminary results: plenary talk by G. Colangelo at Lattice 2012 (end June).

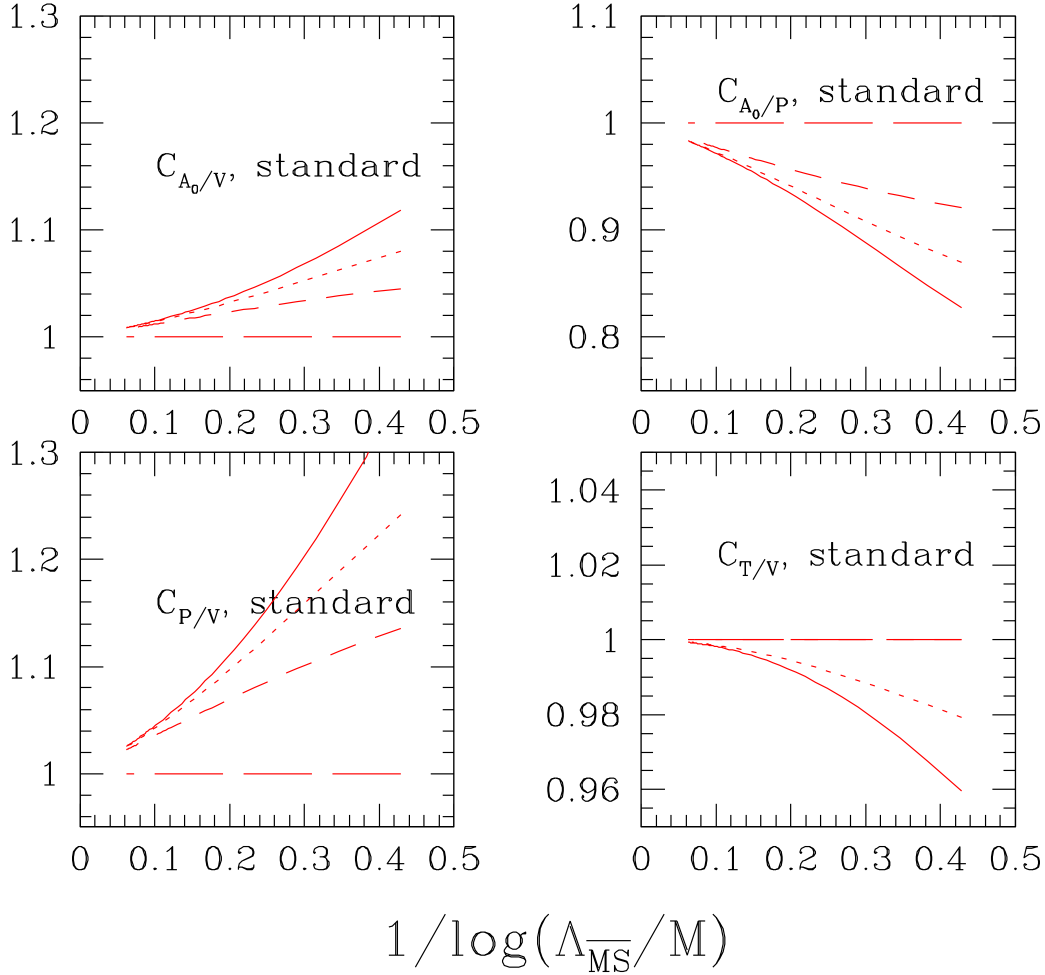
perturbation theory strikes back

Use of effective theories in lattice B-physics almost always involves some use of perturbation theory.

- matching NRQCD, HQET to QCD
- O(a) improvement (removing cutoff effects in relativistic actions)
- RG running between the QCD, b, and W scales

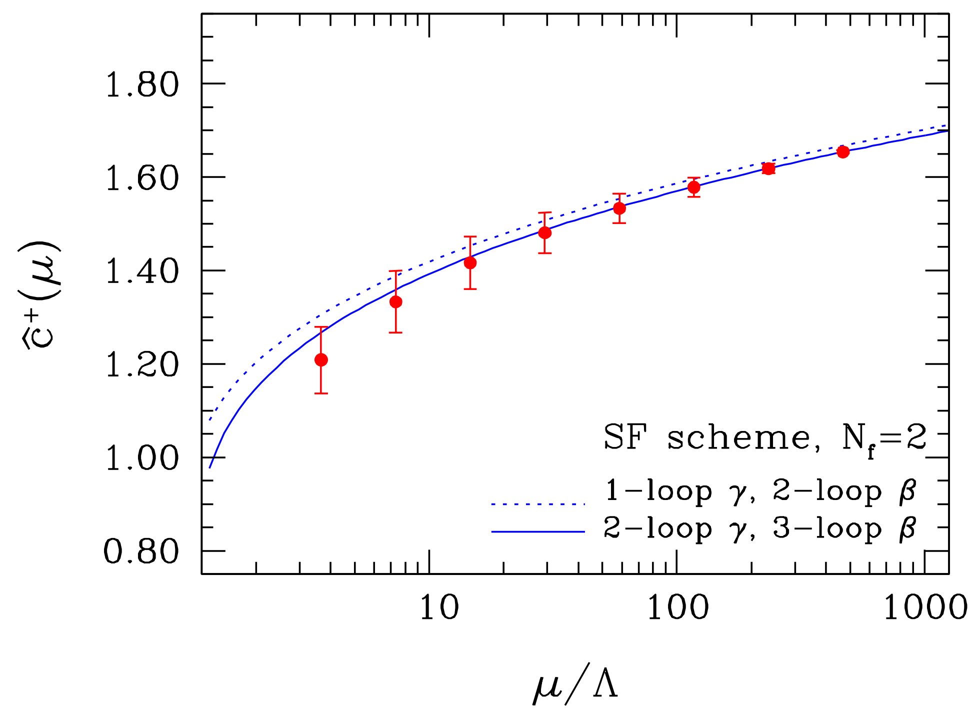
convergence of perturbation theory is sometimes poor, even at higher orders

perturbation theory strikes back



[R. Sommer's Les Houches lectures on HQET]

[CP, ALPHA 2007]



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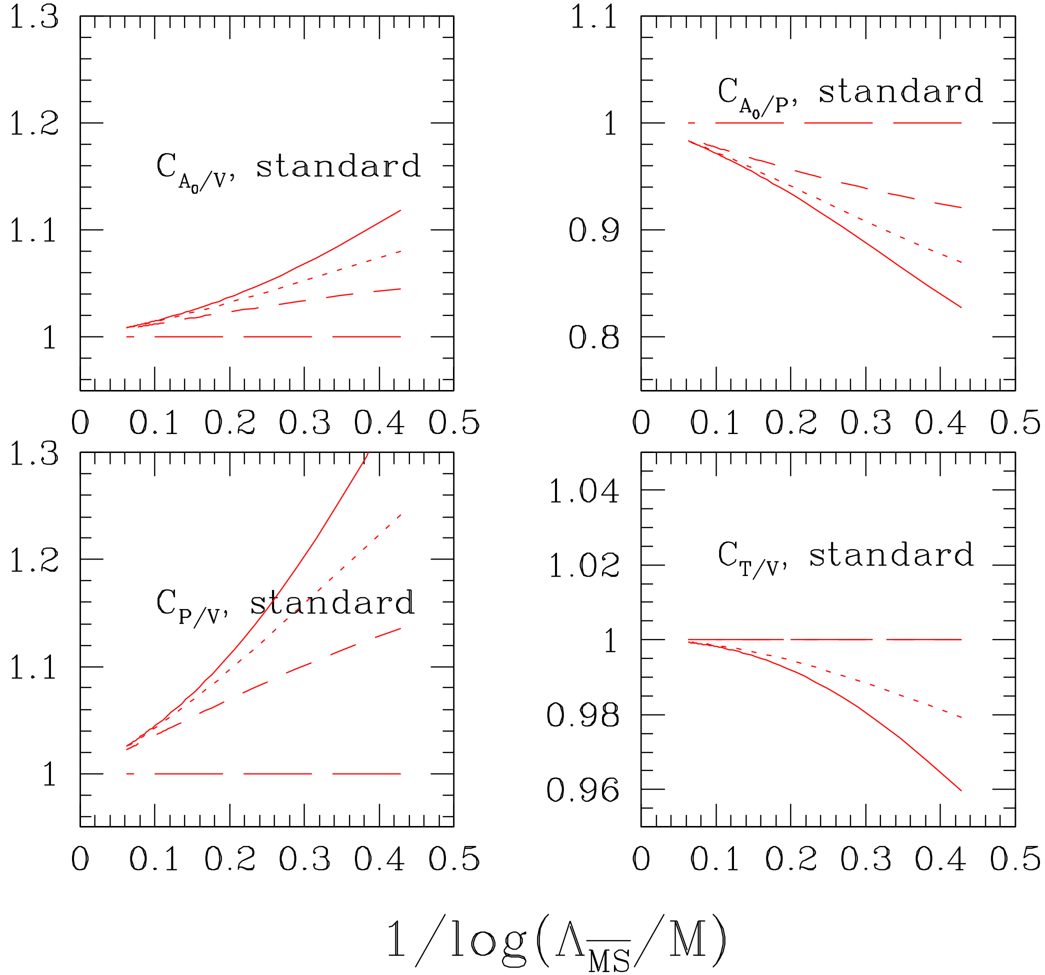

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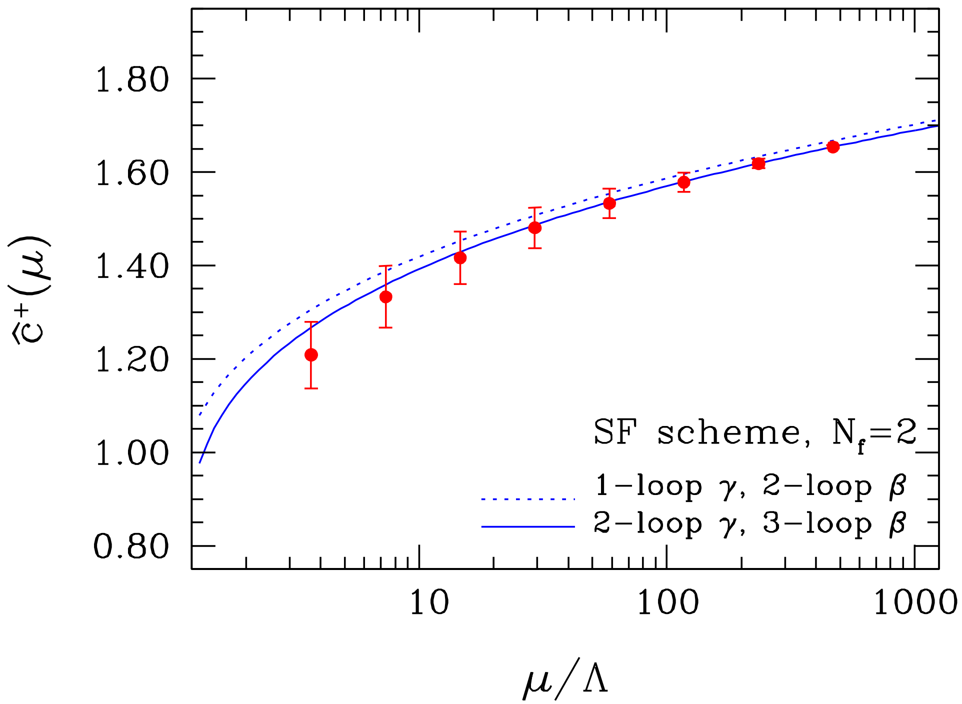


These issues *can* be brought under control within npHQET ⇒ comprehensive B-physics programme by the ALPHA Collaboration.

conclusions and outlook

- Lattice QCD has become a precision tool. B-physics still requires some crucial help from effective theories, though.

- Results for basic quantities have to be taken seriously, and have UT impact.
  - reach of effective theories, perturbative artifacts (at various levels)?
  - most collaborations do light physics first, B-physics lagging somewhat behind
  - progress will be fast in the next 2-3 years

- Effort from the lattice community to provide clean state-of-the-art input for phenomenology.
  - FLAG: next review due early 2013.

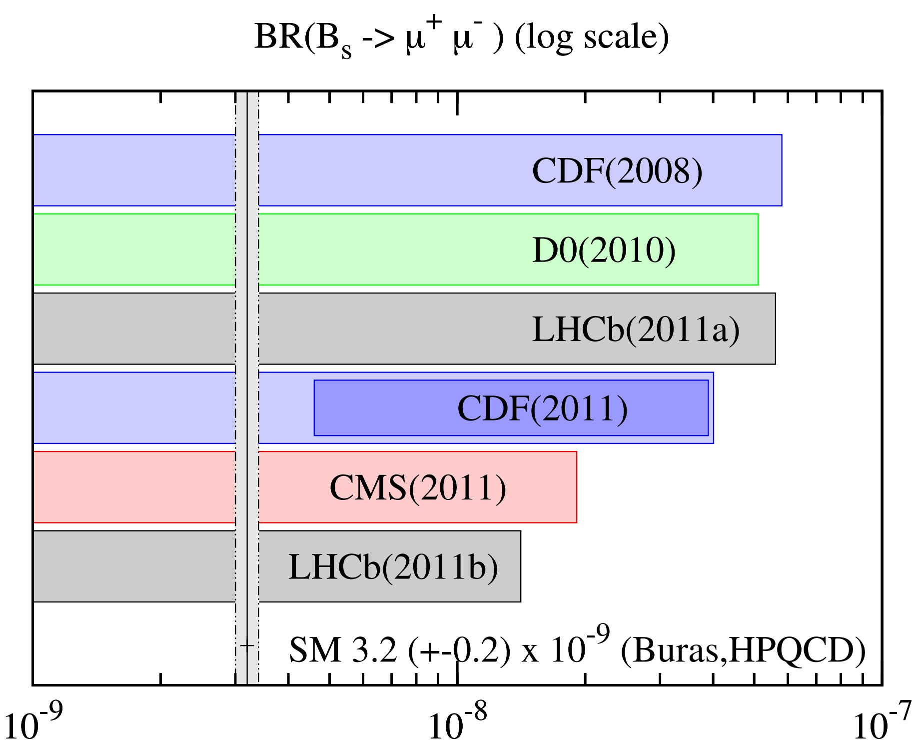
- Lots of uncharted territory (rare/non-leptonic decays? cf. K).

rare B decays?

Results start to be available for some less obvious processes, e.g. $B \to K^{(*)}$.

Example of lattice QCD keeping pace with experimental developments? FNAL-MILC update on ratios $(B_s \to D_s)/(B \to D)$ needed to normalise fragmentation fractions used in $B_s^0 \to \mu^+\mu^-$ analysis.

[FNAL-MILC, arXiv:1202.6346]



$$\frac{f_s}{f_d} = 0.286(16)_{\text{stat}}(21)_{\text{syst}}(26)_{\text{latt}}(22)_{\text{NE}}$$