progress and prospects for heavy flavour physics on the lattice

Carlos Pena

High-Precision QCD at Low Energy, Benasque, 2-22 August 2015

why we care

theory-driven discovery of new physics through loops has an impressive track record from the 70s, 80s, 90s

- no $K_{\rm L} \to \mu\mu \quad \Rightarrow \quad$ charm [Glashow, Iliopoulos, Maiani 1970]
- $\epsilon_K \quad \Rightarrow \quad$ 3rd generation [Kobayashi, Maskawa 1973]
- $\Delta m_K \quad \Rightarrow \quad m_c$ [Gaillard, Lee 1974; Vainshtein, Khriplovich 1973]
- $\Delta m_B \quad \Rightarrow \quad m_t$ large (with some hindsight...)
- ...

crucial to build and consolidate the SM!

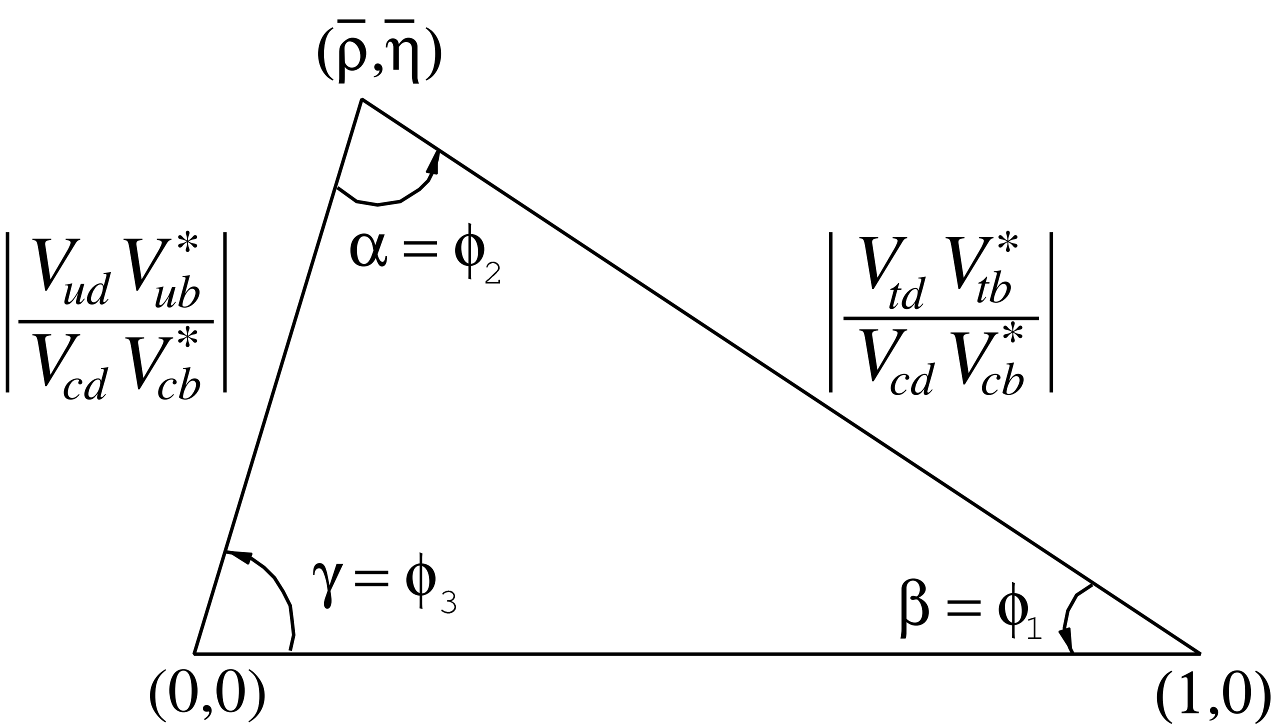
why we care

SM quark flavour dynamics neatly encoded in CKM matrix

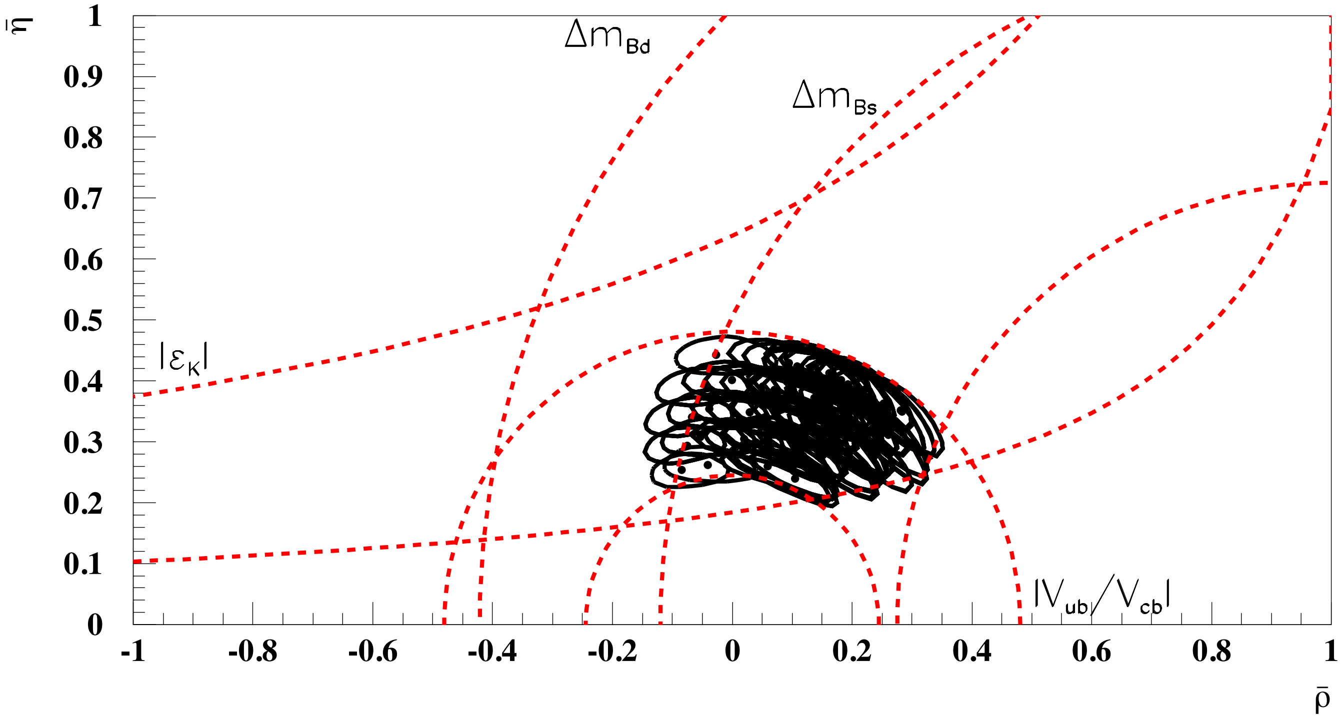
$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

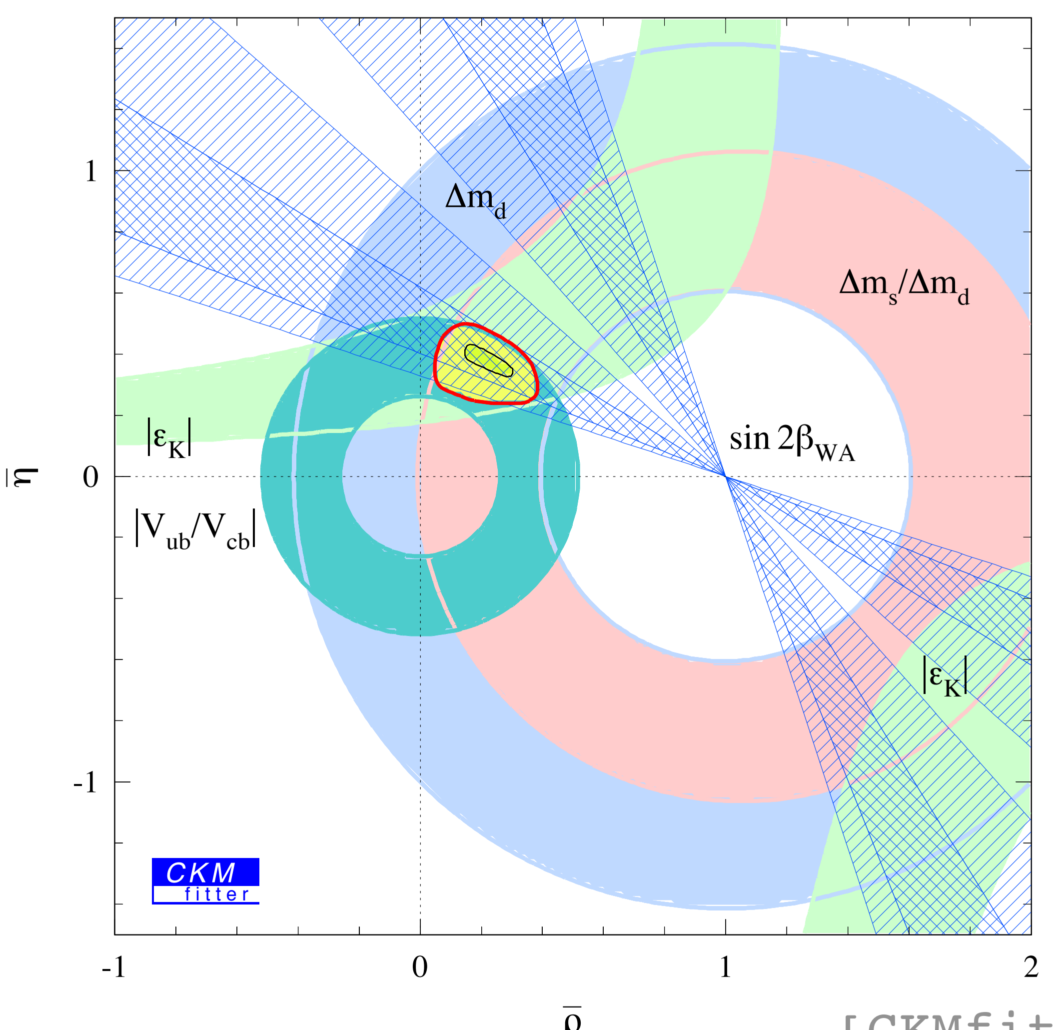
$$V_{\rm CKM}^\dagger V_{\rm CKM} = \mathbf{1} \quad \Rightarrow$$

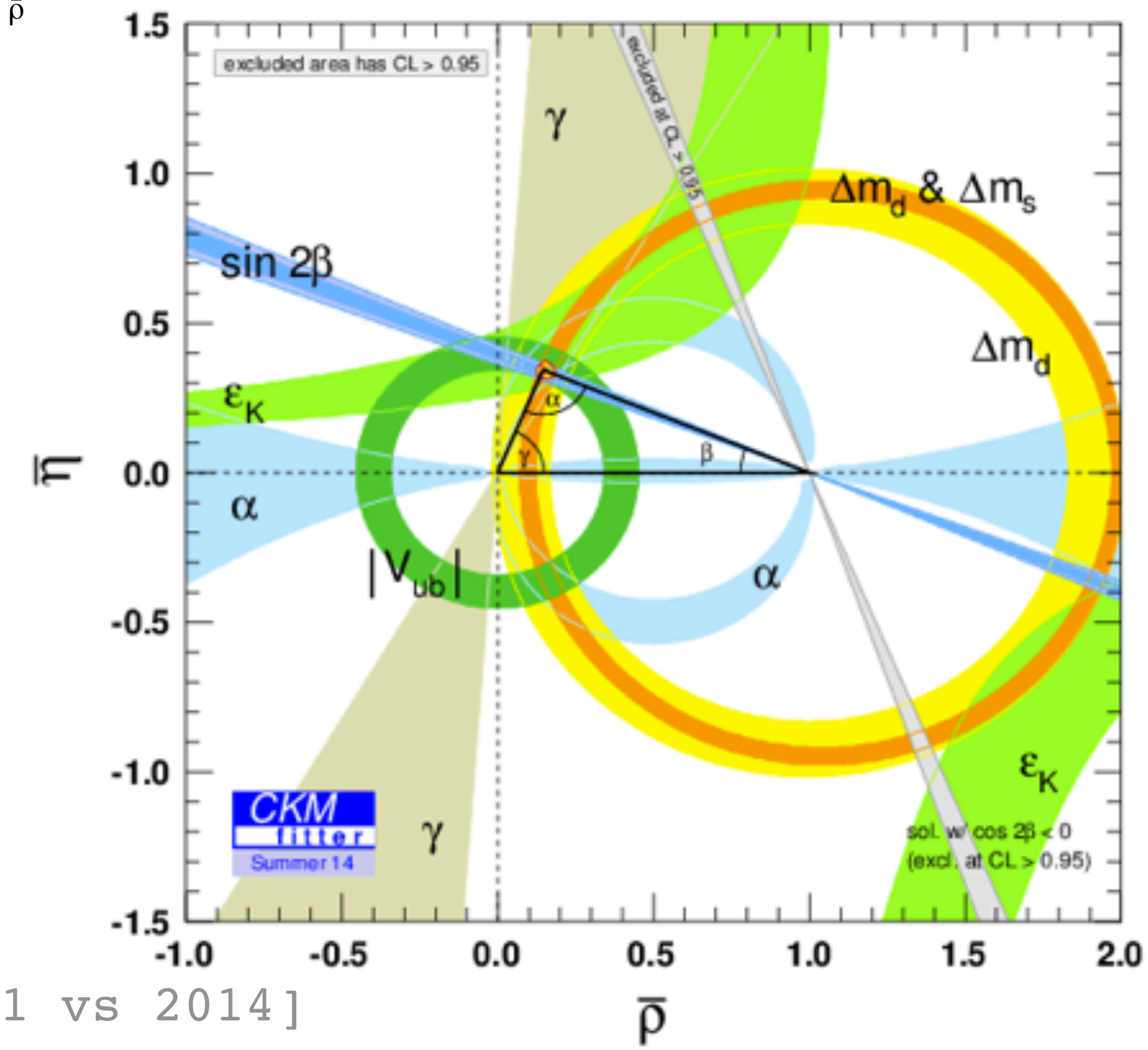


why we care



[BaBar Physics Book, 1999]





[CKMfitter 2001 vs 2014]

why we still care

- tensions/puzzles: exclusive vs inclusive $|V_{ub}|$ and $|V_{cb}|$, $b \to s$, lepton universality in $R(D)$, non-leptonic decays, D-mixing, ...

- FCNC (relatively) poorly constrained in several processes

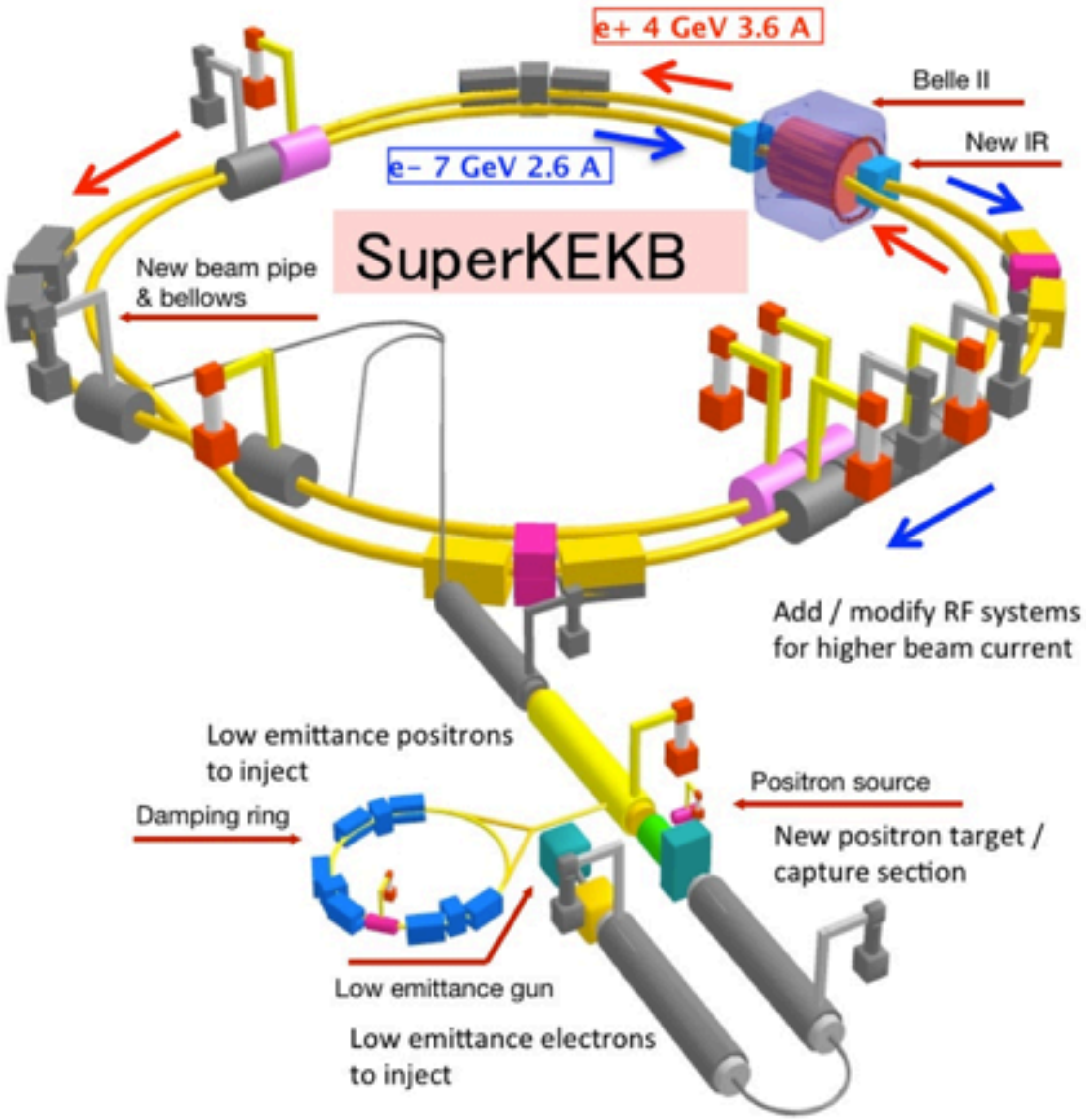
- some complementary precision tests are expected to improve significantly (EDM by 10^2-10^3, CLFV by at least 10^2, ...)

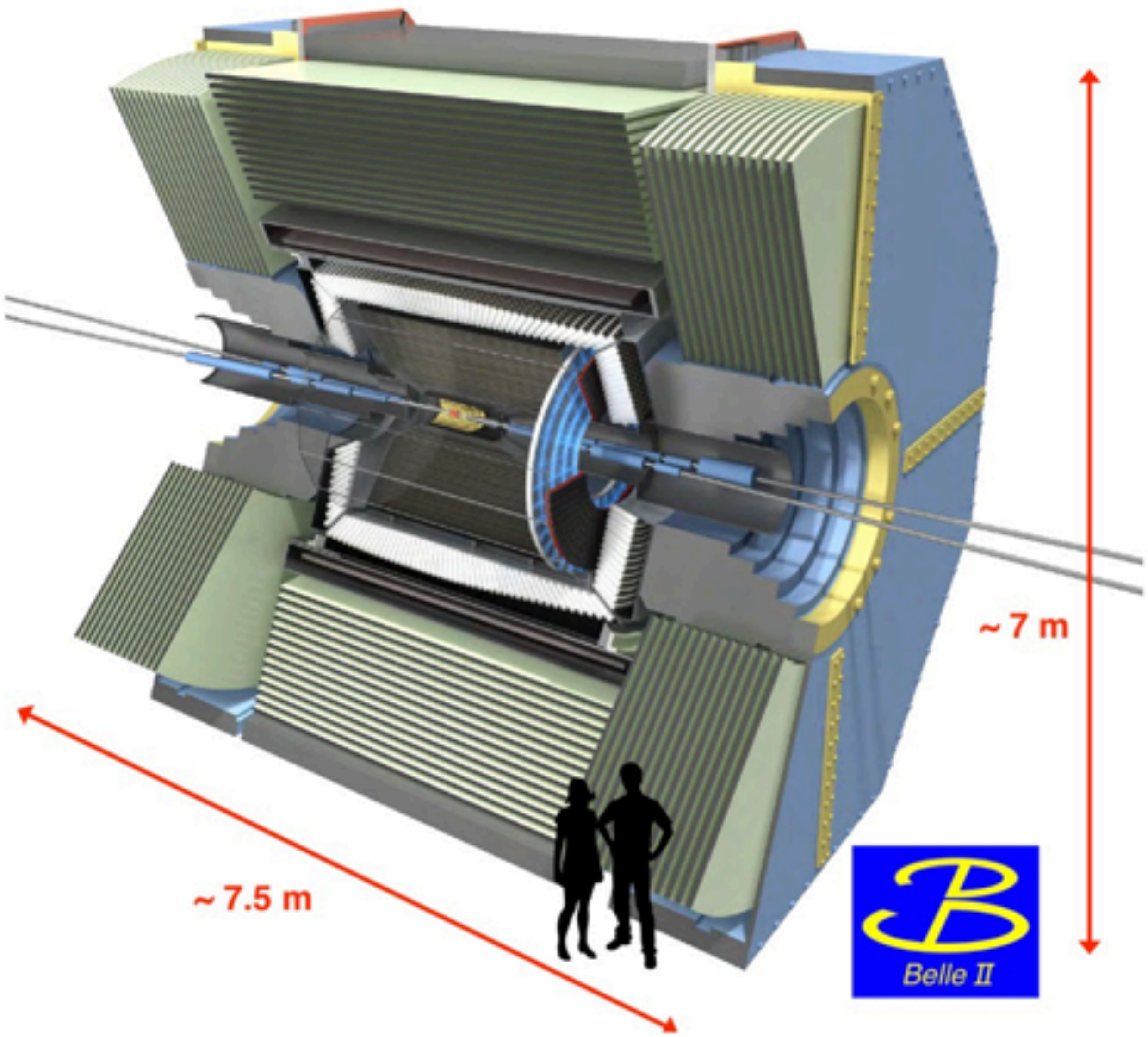
- upcoming new generation of experimental results

$$\frac{\text{LHCb upgrade}}{\text{LHCb 1/fb}} \sim \frac{\text{Belle II}}{\text{Belle}} \sim \frac{\text{BaBar 2009}}{\text{CLEO 1999}} \sim 50$$

[quoted from Z Ligeti's TASI Lectures on Flavor Physics, arXiv:1502.01372]

Belle II projections





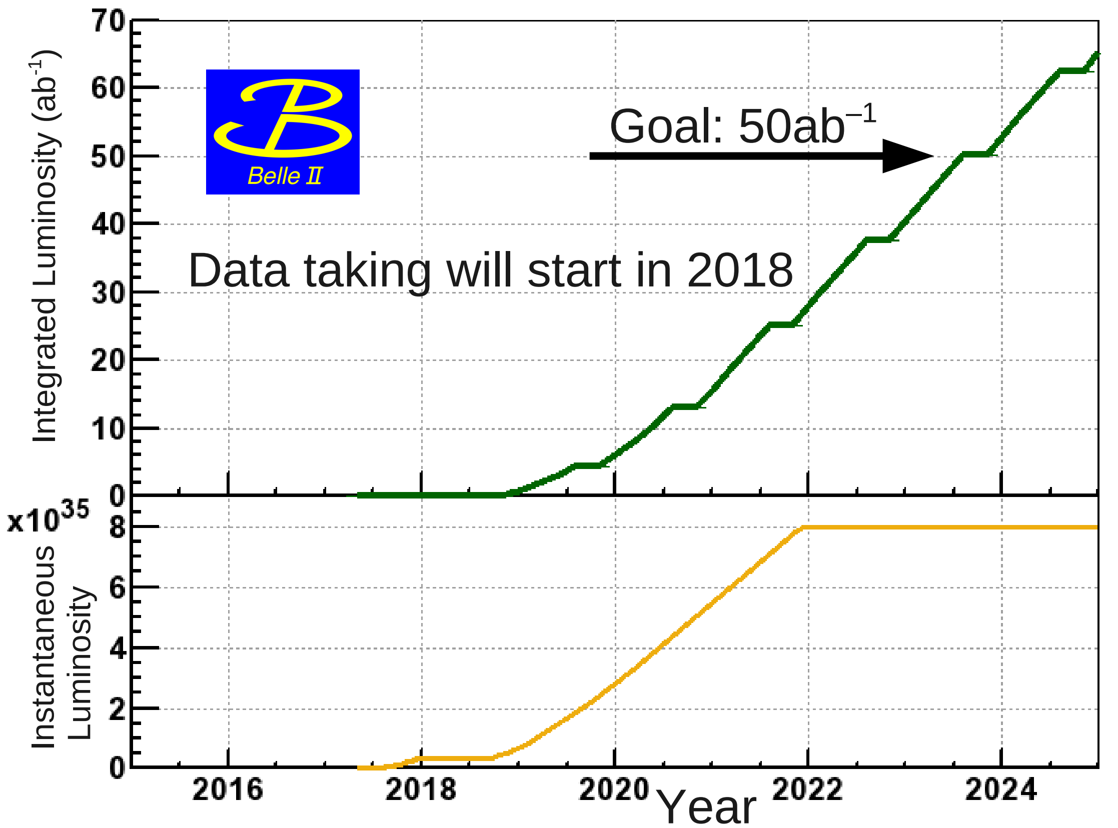
Belle II projections

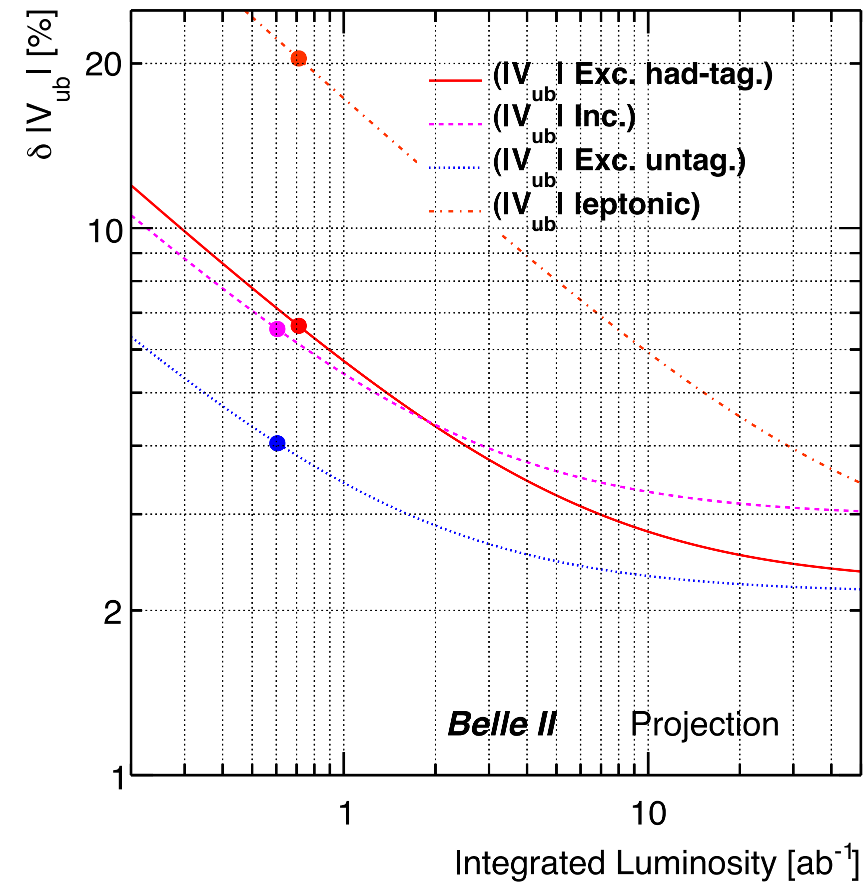
Observables	Belle (2014)	Belle II 5 ab^{-1}	50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$	± 0.012	± 0.008	6
α		$\pm 2^\circ$	$\pm 1^\circ$	
γ	$\pm 14^\circ$	$\pm 6^\circ$	$\pm 1.5^\circ$	
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	± 0.053	± 0.018	>50
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	± 0.028	± 0.011	>50
$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$	± 0.100	± 0.033	44
$\lvert V_{cb} \rvert$ incl.	$\pm 2.4\%$	$\pm 1.0\%$		< 1
$\lvert V_{cb} \rvert$ excl.	$\pm 3.6\%$	$\pm 1.8\%$	$\pm 1.4\%$	< 1
$\lvert V_{ub} \rvert$ incl.	$\pm 6.5\%$	$\pm 3.4\%$	$\pm 3.0\%$	2
$\lvert V_{ub} \rvert$ excl. (had. tag.)	$\pm 10.8\%$	$\pm 4.7\%$	$\pm 2.4\%$	20
$\lvert V_{ub} \rvert$ excl. (untag.)	$\pm 9.4\%$	$\pm 4.2\%$	$\pm 2.2\%$	3
$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	96 ± 26	$\pm 10\%$	$\pm 5\%$	46
$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7	5σ	$>> 5\sigma$	>50
$R(B \to D\tau\nu)$	$\pm 16.5\%$	$\pm 5.6\%$	$\pm 3.4\%$	4
$R(B \to D^*\tau\nu)$	$\pm 9.0\%$	$\pm 3.2\%$	$\pm 2.1\%$	3
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ [10^{-6}]	< 40		$\pm 30\%$	>50
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ [10^{-6}]	< 55		$\pm 30\%$	>50
$\mathcal{B}(B \to X_s\gamma)$ [10^{-6}]	$\pm 13\%$	$\pm 7\%$	$\pm 6\%$	< 1
$A_{CP}(B \to X_s\gamma)$		± 0.01	± 0.005	8
$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$	± 0.11	± 0.035	> 50
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	± 0.23	± 0.07	> 50
C_7/C_9 $(B \to X_s \ell\ell)$	$\sim 20\%$	10%	5%	
$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7	± 0.3		
$\mathcal{B}(B_s \to \tau^+\tau^-)$ [10^{-3}]		< 2		

Observables	Belle (2014)	Belle II 5 ab^{-1}	50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \times 10^{-3}(1 \pm 0.053 \pm 0.038)$	$\pm 2.9\%$	$\pm(0.9\%\text{-}1.3\%)$	> 50
$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \times 10^{-3}(1 \pm 0.037 \pm 0.054)$	$\pm(3.5\%\text{-}4.3\%)$	$\pm(2.3\%\text{-}3.6\%)$	3-5
y_{CP} [10^{-2}]	$1.11 \pm 0.22 \pm 0.11$	$\pm(0.11\text{-}0.13)$	$\pm(0.05\text{-}0.08)$	5-8
A_Γ [10^{-2}]	$-0.03 \pm 0.20 \pm 0.08$	± 0.10	$\pm(0.03\text{-}0.05)$	7 - 9
$A_{CP}^{K^+K^-}$ [10^{-2}]	$-0.32 \pm 0.21 \pm 0.09$	± 0.11	± 0.06	15
$A_{CP}^{\pi^+\pi^-}$ [10^{-2}]	$0.55 \pm 0.36 \pm 0.09$	± 0.17	$\pm$ 0.06	> 50
$A_{CP}^{\phi\gamma}$ [10^{-2}]	$\pm$ 5.6	± 2.5	± 0.8	> 50
$x^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	± 0.14	± 0.11	3
$y^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	± 0.08	± 0.05	15
$\lvert q/p \rvert^{K_S\pi^+\pi^-}$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	± 0.10	± 0.07	5-6
$\phi^{K_S\pi^+\pi^-}$ [$^\circ$]	$-6 \pm 11 \pm {}^{4}_{5}$	± 6	± 4	10
$A_{CP}^{\pi^0\pi^0}$ [10^{-2}]	$-0.03 \pm 0.64 \pm 0.10$	± 0.29	± 0.09	> 50
$A_{CP}^{K^0_S\pi^0}$ [10^{-2}]	$-0.10 \pm 0.16 \pm 0.09$	± 0.08	± 0.03	> 50
$Br(D^0 \to \gamma\gamma)$ [10^{-6}]	< 1.5	$\pm 30\%$	$\pm 25\%$	2
	$\tau \to \mu\gamma$ [10^{-9}]	< 45	< 14.7	< 4.7
	$\tau \to e\gamma$ [10^{-9}]	< 120	< 39	< 12
	$\tau \to \mu\mu\mu$ [10^{-9}]	< 21.0	< 3.0	< 0.3

[BELLE2-NOTE-PH-2015-002, retrieved from B2TiP]

Belle II projections

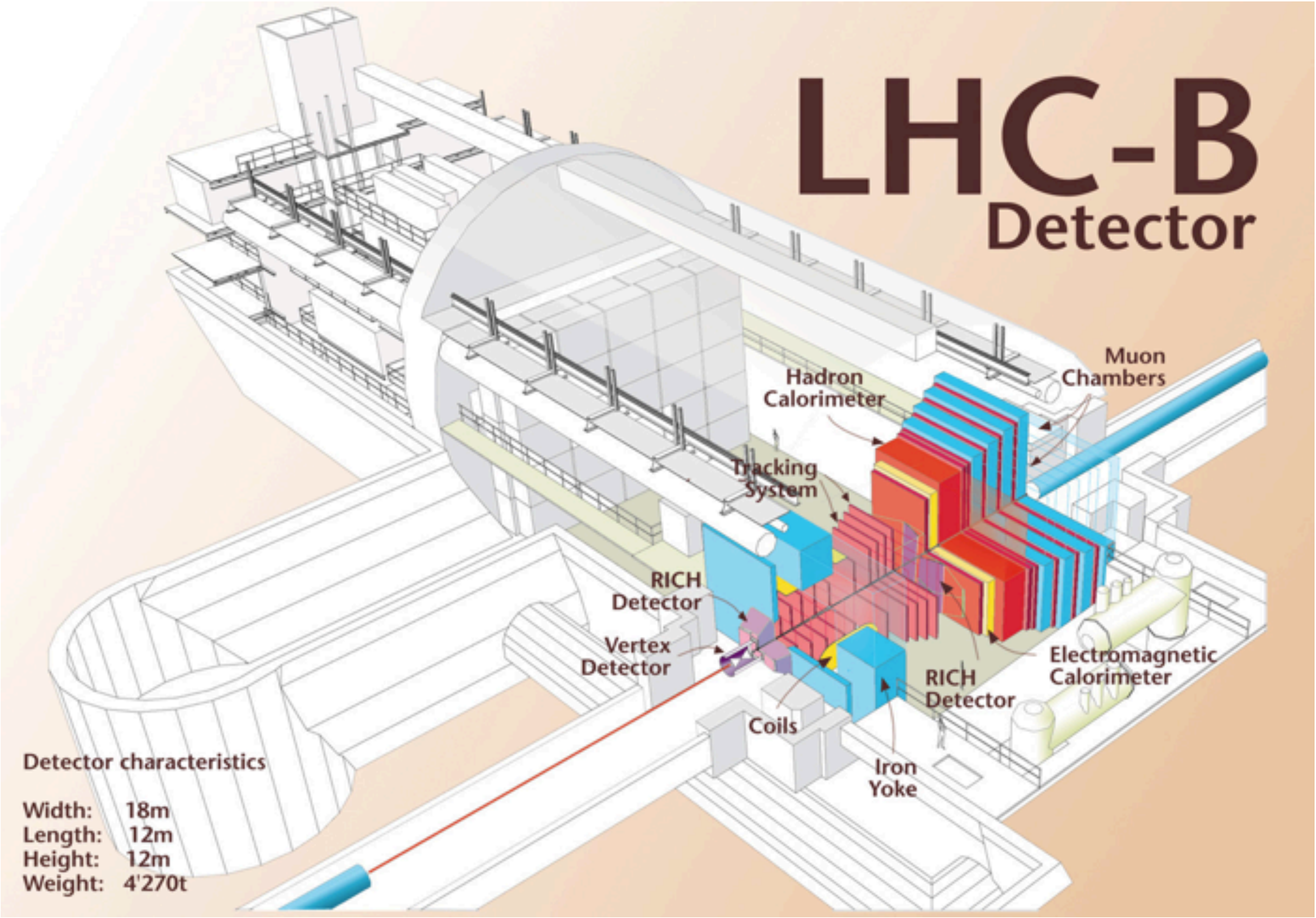




Lattice Quantity	CKM element	WA Expt. Error	Lattice error 2013 (Present)	2014	2018
$F(1)$ $(B \to D^* \ell \nu)$	$\lvert V_{cb}\rvert$	1.3	1.8	1.5	<1
$G(1)$ $(B \to D \ell \nu)$	$\lvert V_{cb}\rvert$	1.3	1.8	1.5	<1
$G_s(1)$ $(B_s \to D_s^* \ell \nu)$	$\lvert V_{cb}\rvert$	–	4.6	–	–
$\zeta(B \to \pi \ell \nu)$	$\lvert V_{ub}\rvert$	4.1	8.7	4	2
f_B $(B \to \tau\nu, \mu\nu)$	$\lvert V_{ub}\rvert$	9.0	2.5	1.5	<1
$R(D)(B \to D \tau \nu)$	–	13	4.3	4	< 2
Mixing $\zeta(\Delta m_d/\Delta m_s)$	$\lvert V_{td}\rvert/\lvert V_{ts}\rvert$	0.4	4.0	–	< 1

[BELLE2-NOTE-PH-2015-002, retrieved from B2TiP]

LHCb Run 2 and upgrade projections



n.b.: LHCb outdoing expectations (e.g. baryon semileptonic decay)

LHCb Run 2 and upgrade projections

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_{\rm S}^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\ K_{\rm S}^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

[LHCb-PUB-2014-040]

n.b.: LHCb outdoing expectations (e.g. baryon semileptonic decay)

why we still care

- B-physics: much better precision + new channels (e.g. much more information on rare decays)

- + contributions from ATLAS/CMS

- + dedicated charm physics (BESIII running from 2011, large charm production cross section at Belle II, ...)

- theory has to meet the challenge

plan

- starting point:
  - thorough reviews on HQ decays/mixing (C Bouchard) and quark masses (F Sanfilippo) at Lattice 2014 [Bouchard arXiv:1501.03204] [Sanfilippo arXiv:1505.02794]
  - contributions to the Lattice 2015 Conference
  - detailed coverage of results up to end 2013 in FLAG-2 [FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

(unfortunately, no preliminary updates of FLAG averages for HQ quantities yet)

plan

- starting point:
  - thorough reviews on HQ decays/mixing (C Bouchard) and quark masses (F Sanfilippo) at Lattice 2014
    [Bouchard arXiv:1501.03204]
    [Sanfilippo arXiv:1505.02794]
  - contributions to the Lattice 2015 Conference
  - detailed coverage of results up to end 2013 in FLAG-2
    [FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

- guidelines:
  - CKM tests focus
  - status overview for decay constants, B-mixing
  - **strong progress + expt synergy in semileptonic decays**
  - not covered: HQ masses, BSM/rare decays (exc.), processes involving resonances (exc.), D-mixing, spectroscopy, ...

plan

- methods: where we stand (brief!)
  - ensembles used in HQ physics, reach
  - HQ approaches

- brief overview of
  - leptonic charm and B decay
  - B mixing

- charm and B semileptonic decays (+ CKM 2nd and 3rd rows)

- the % precision target

- conclusions and outlook

plan

- methods: where we stand (brief!)
  - ensembles used in HQ physics, reach
  - HQ approaches

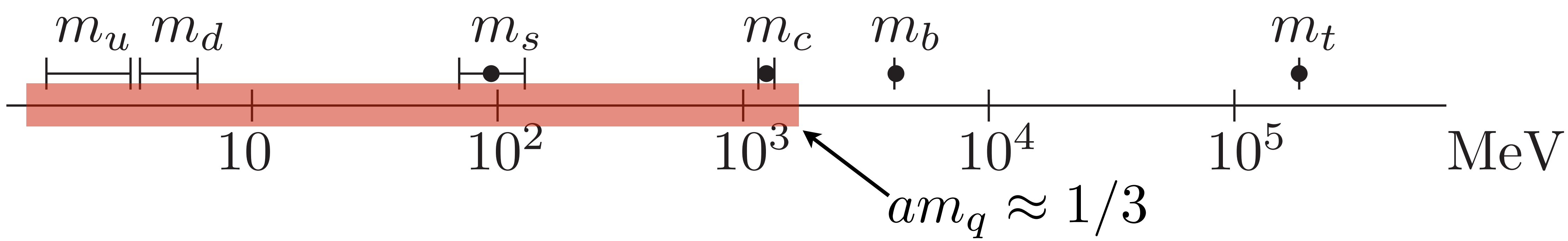
- brief overview of
  - leptonic charm and B decay
  - B mixing

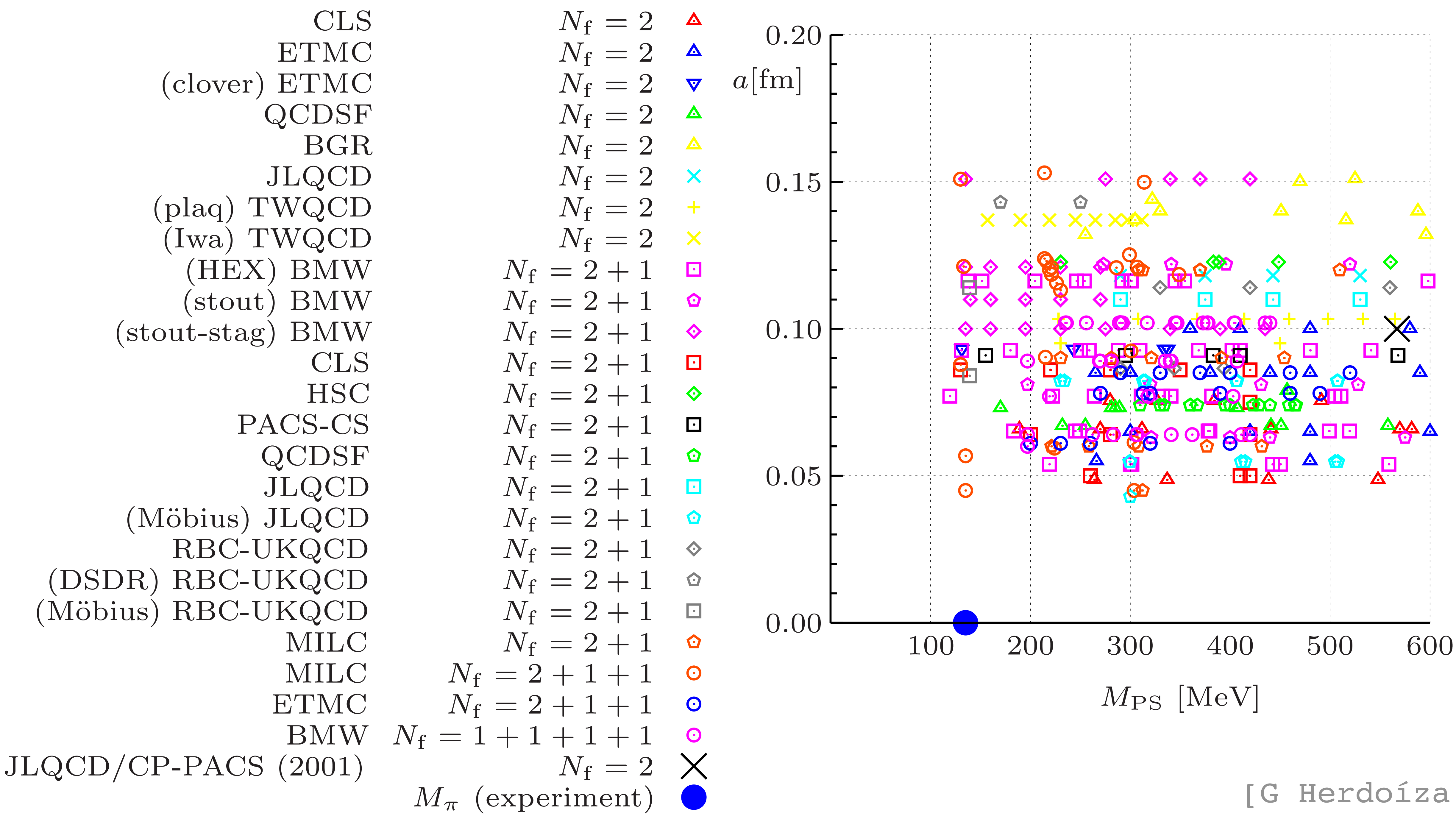
- charm and B semileptonic decays (+ CKM 2nd and 3rd rows)

- the % precision target

- conclusions and outlook

ensembles/physics reach

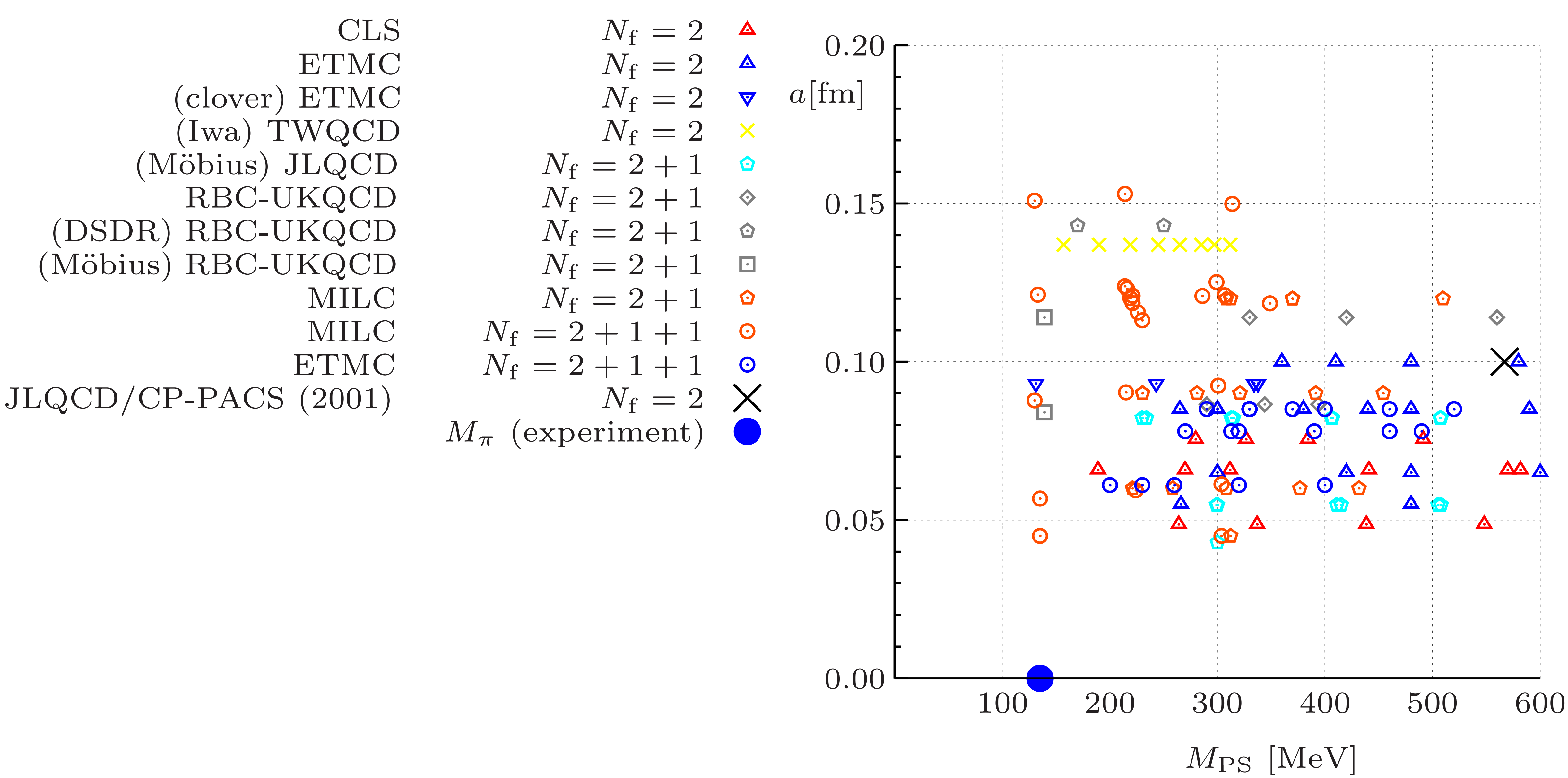




[G Herdoíza]

ensembles/physics reach

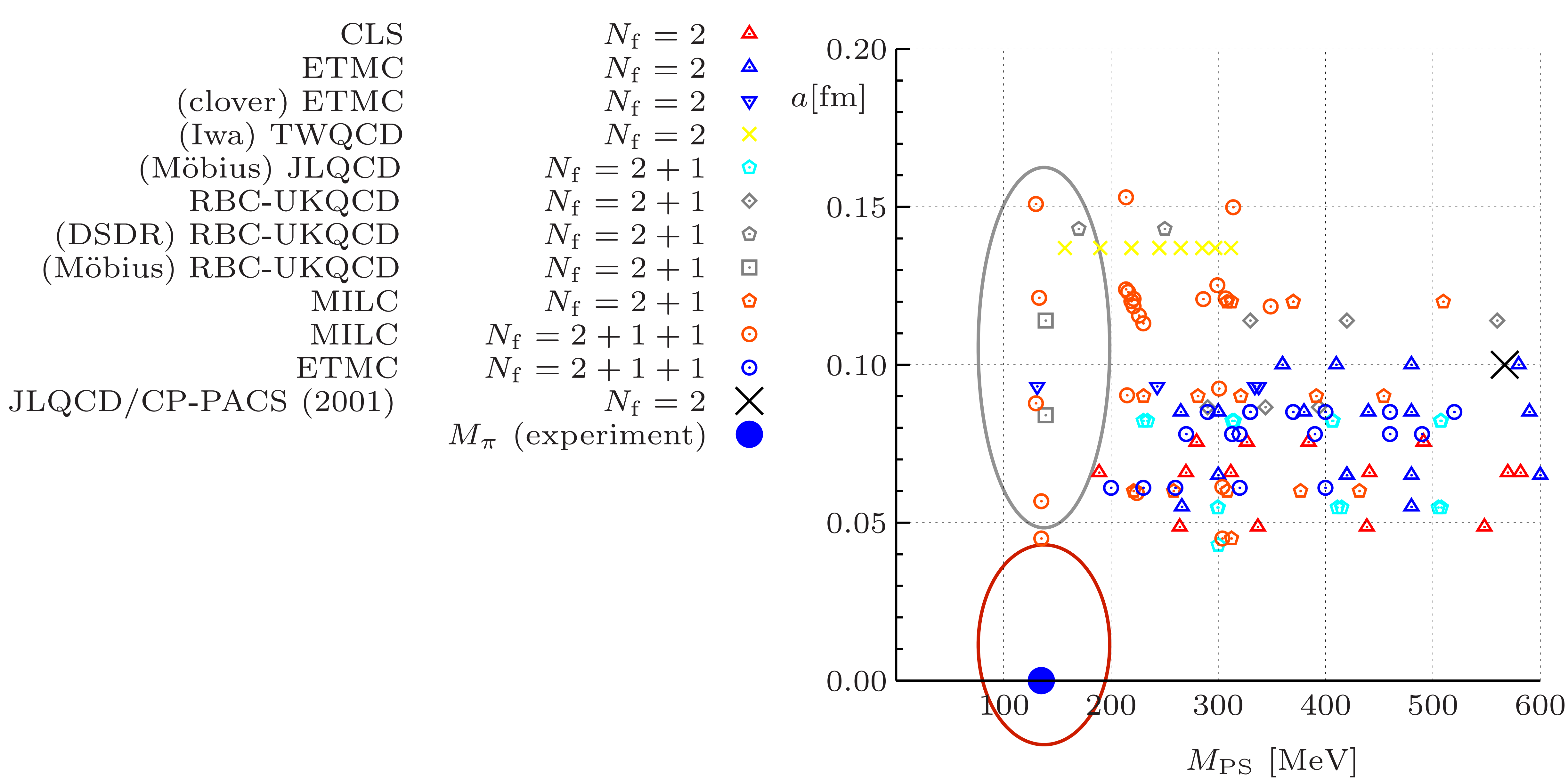
- charm physics directly accessible for some time now
- fraction of available ensembles used for HQ physics still limited



[G Herdoíza]

ensembles/physics reach

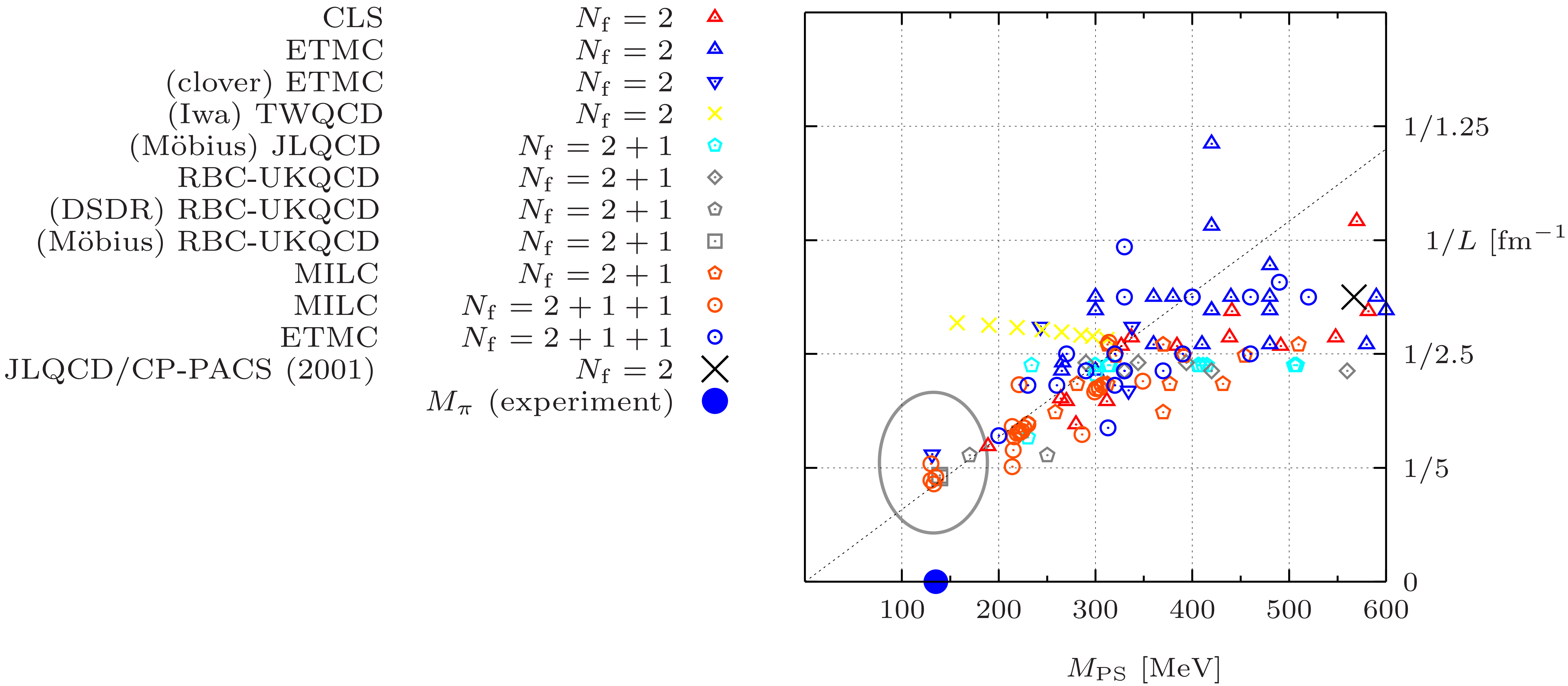
- charm physics directly accessible for some time now
- fraction of available ensembles used for HQ physics still limited



[G Herdoíza]

ensembles/physics reach

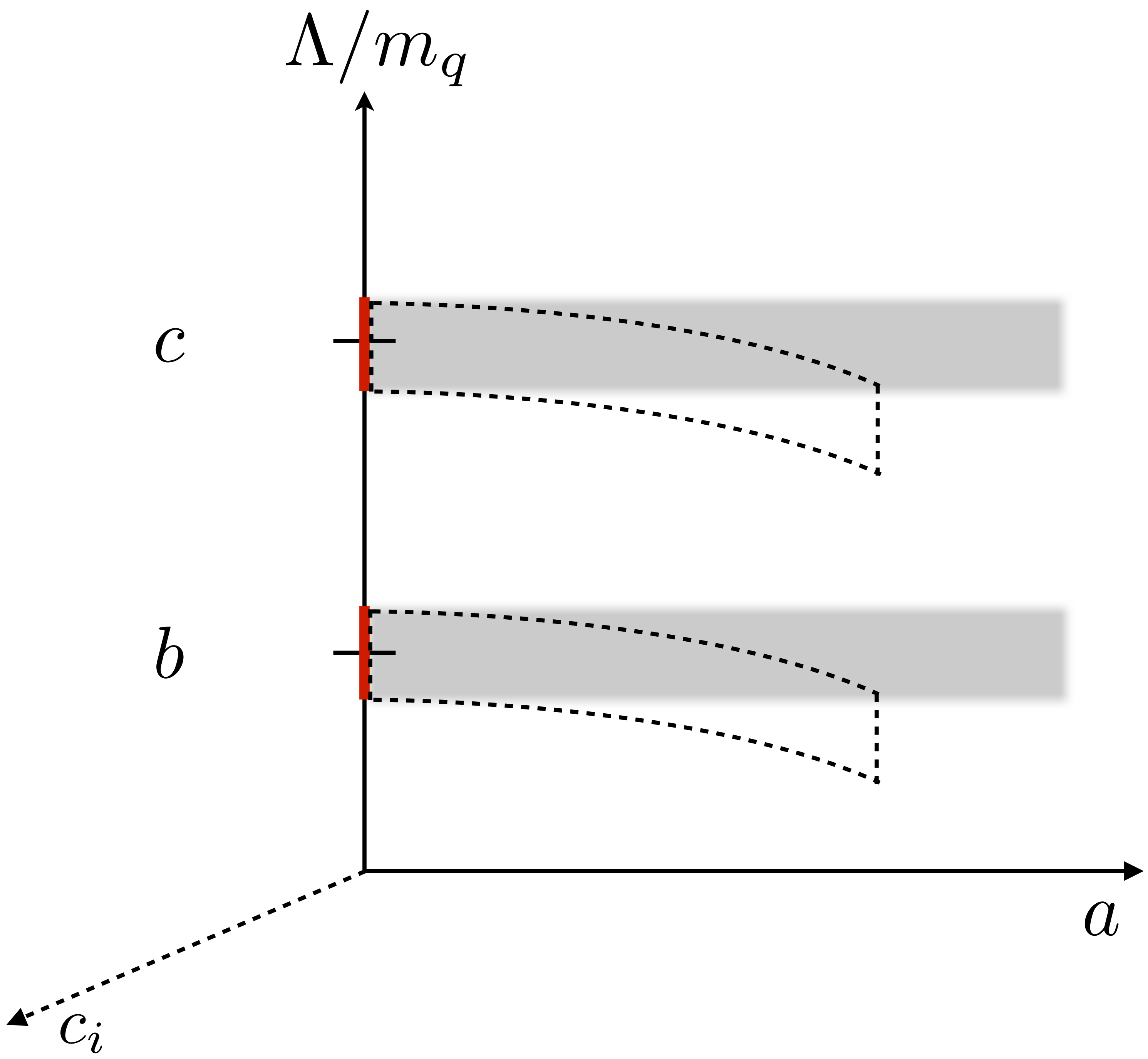
- charm physics directly accessible for some time now
- fraction of available ensembles used for HQ physics still limited



[G Herdoíza]

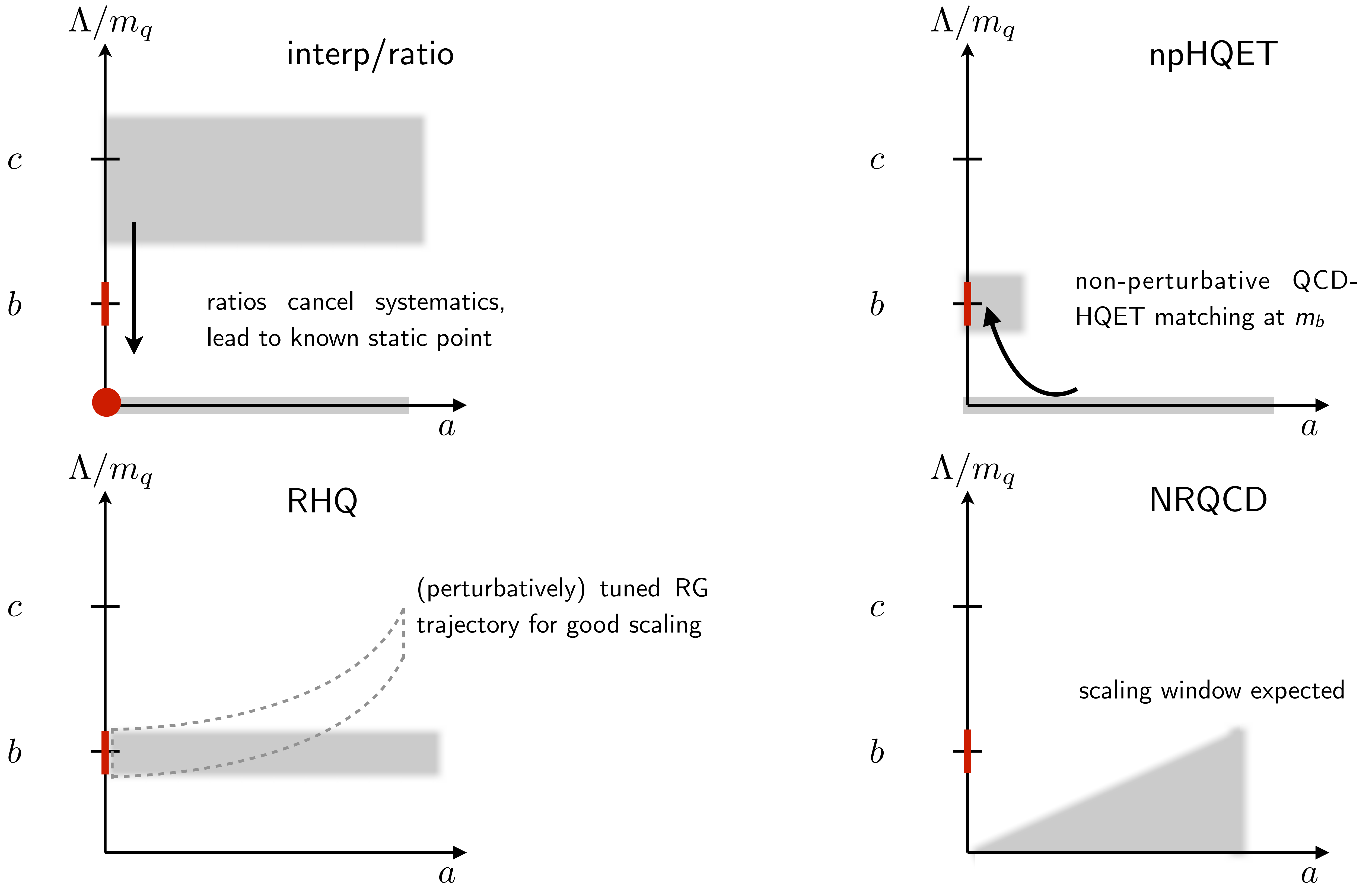
approaches to B physics

what one would like to do



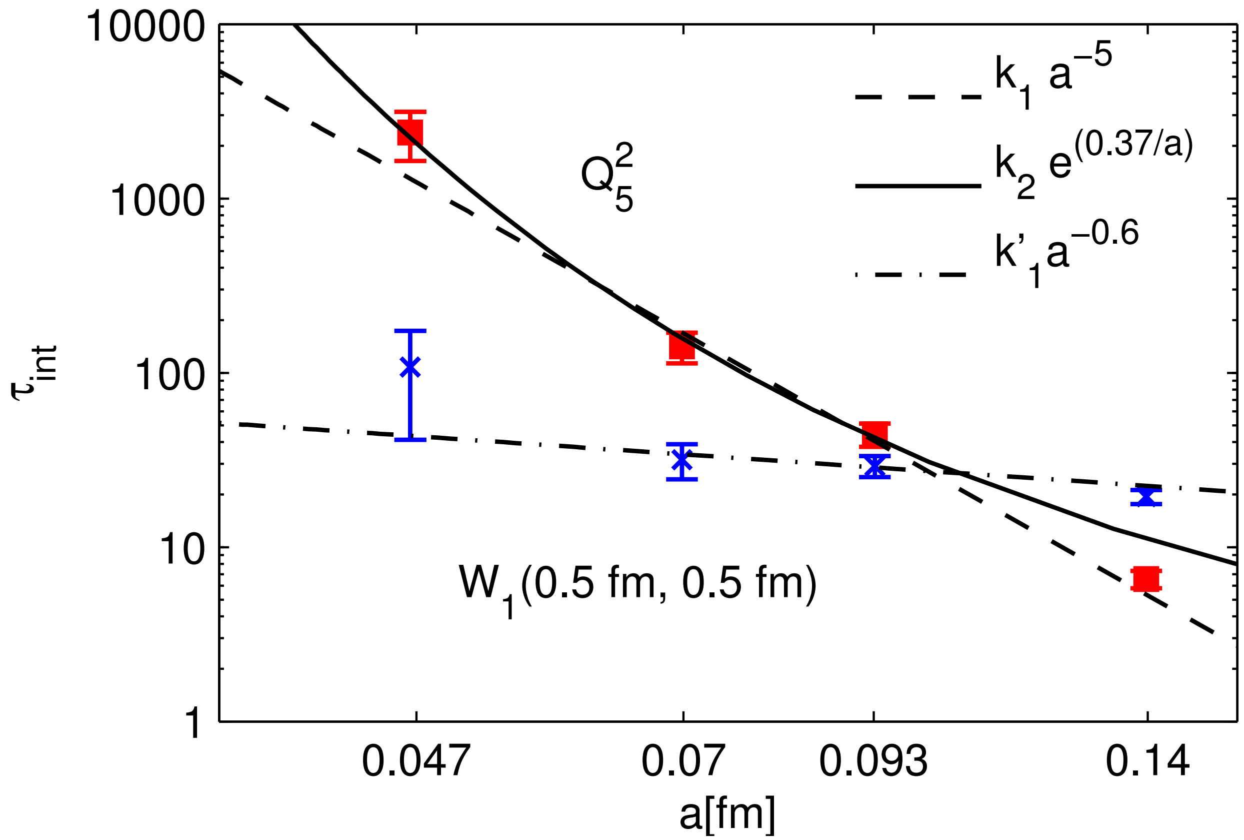
approaches to B physics

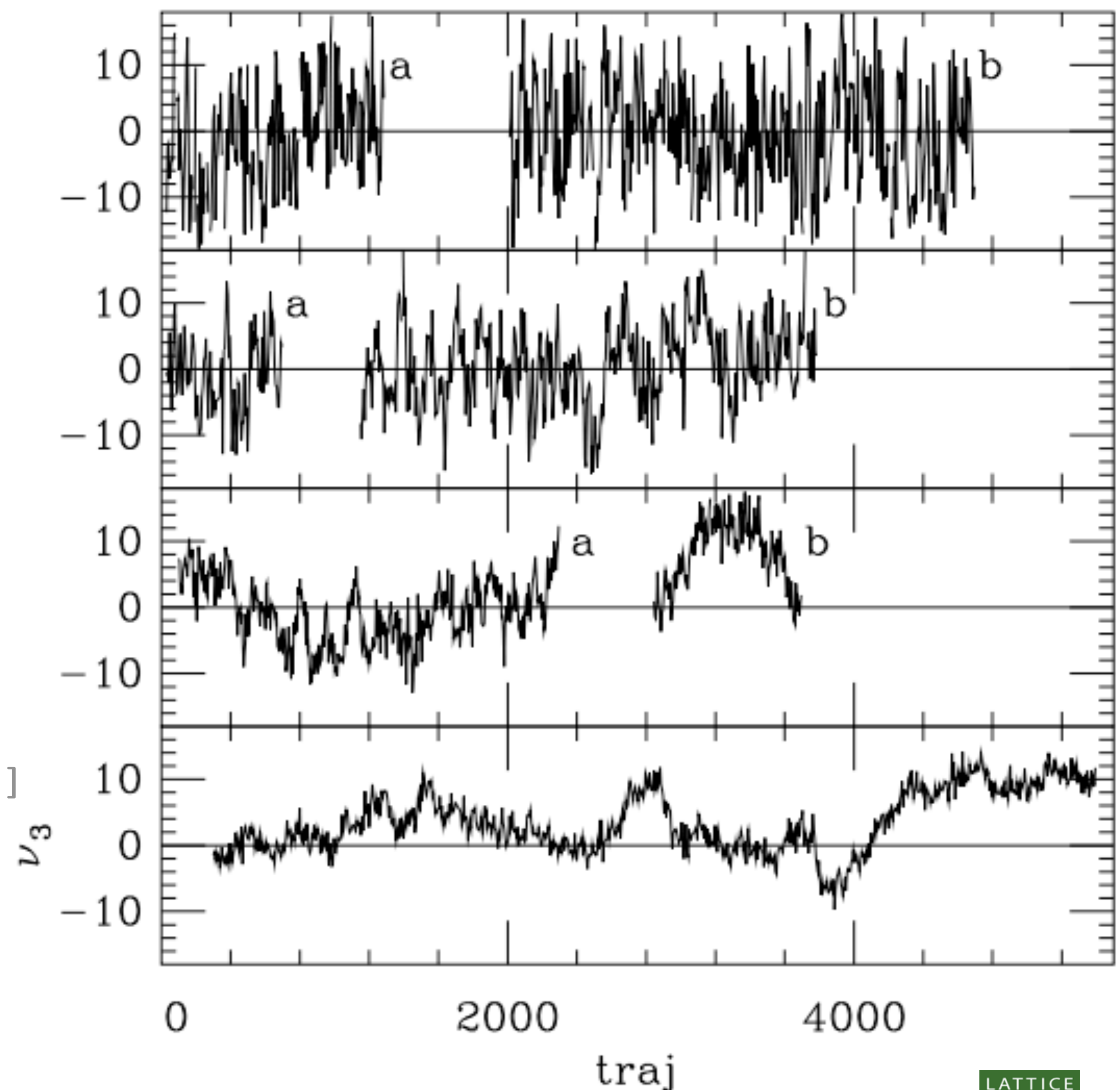
effective theory used differently, different pros/cons balance: crosschecks crucial



towards a fully relativistic b

crucial issue: strong lattice space dependence of autocorrelations





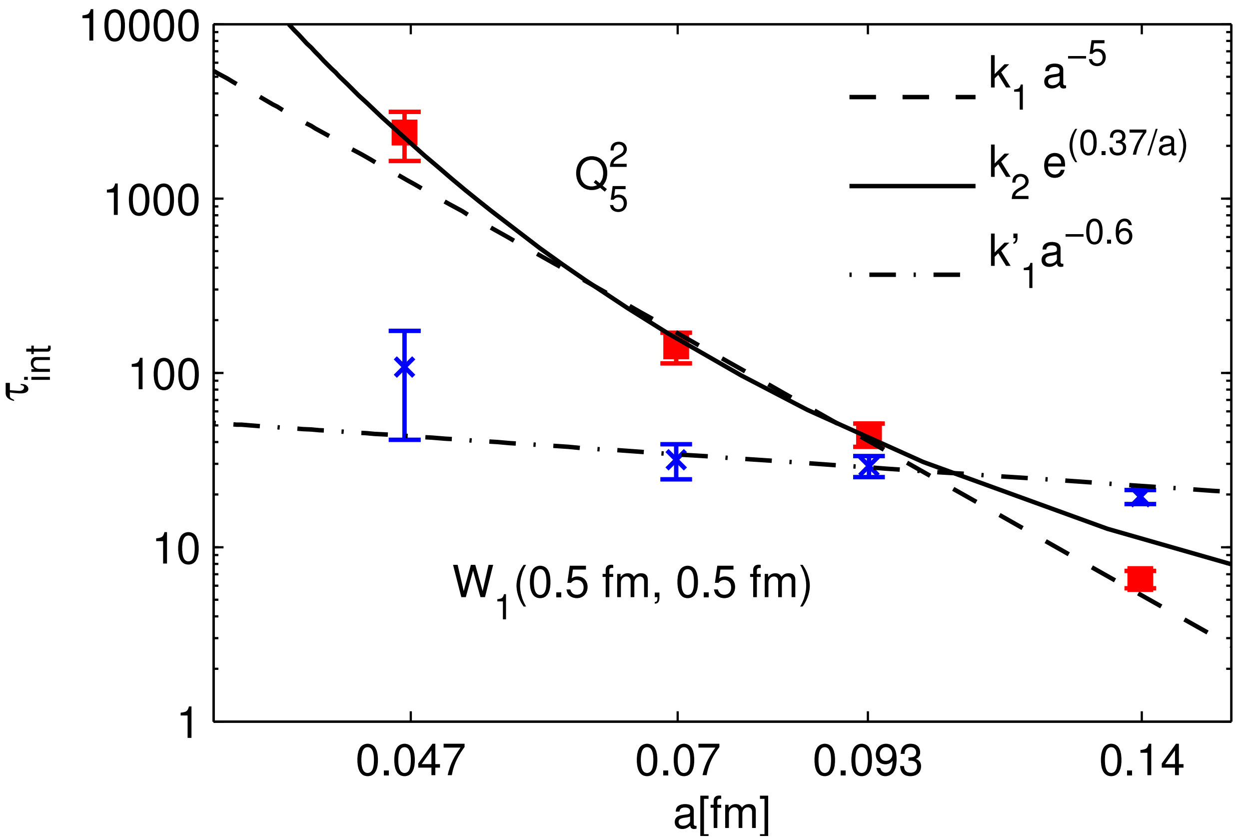
[Del Debbio, Panagopoulos, Vicari 2002]
[Schaefer, Sommer, Virotta 2010]
[Lüscher, Schaefer 2011]
[CLS N_f=2+1 obc programme]

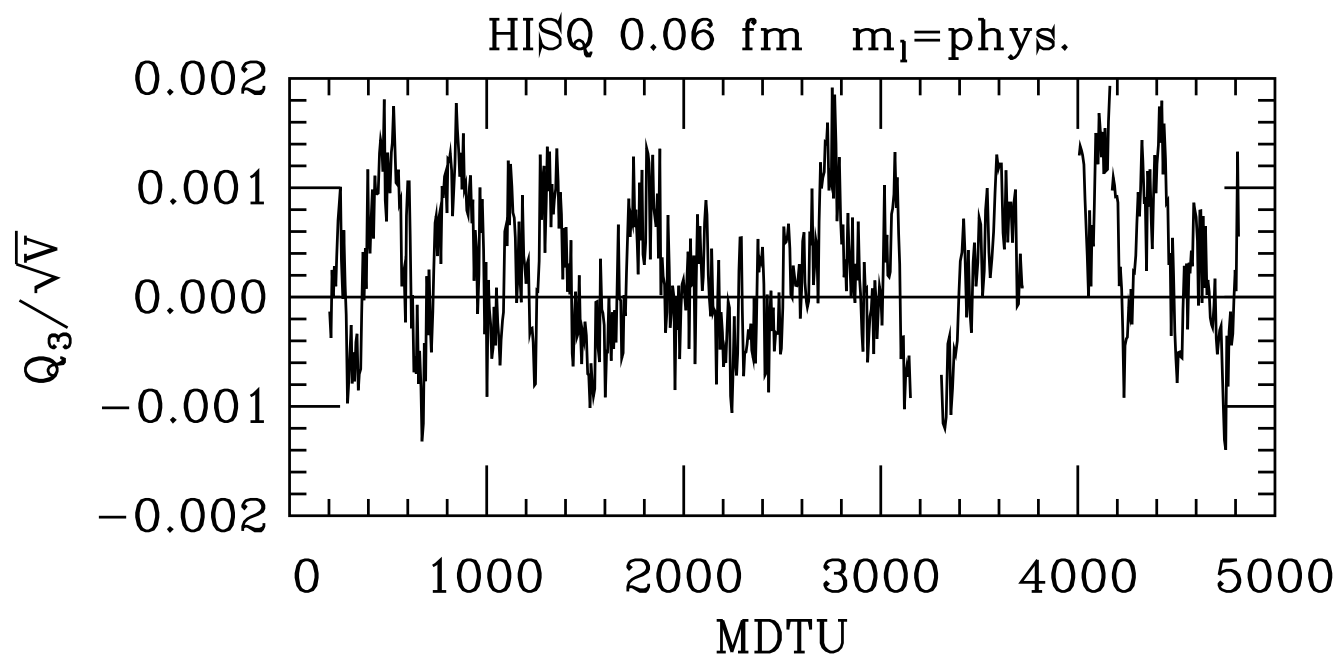
[S Gottlieb, Tue 18:10]

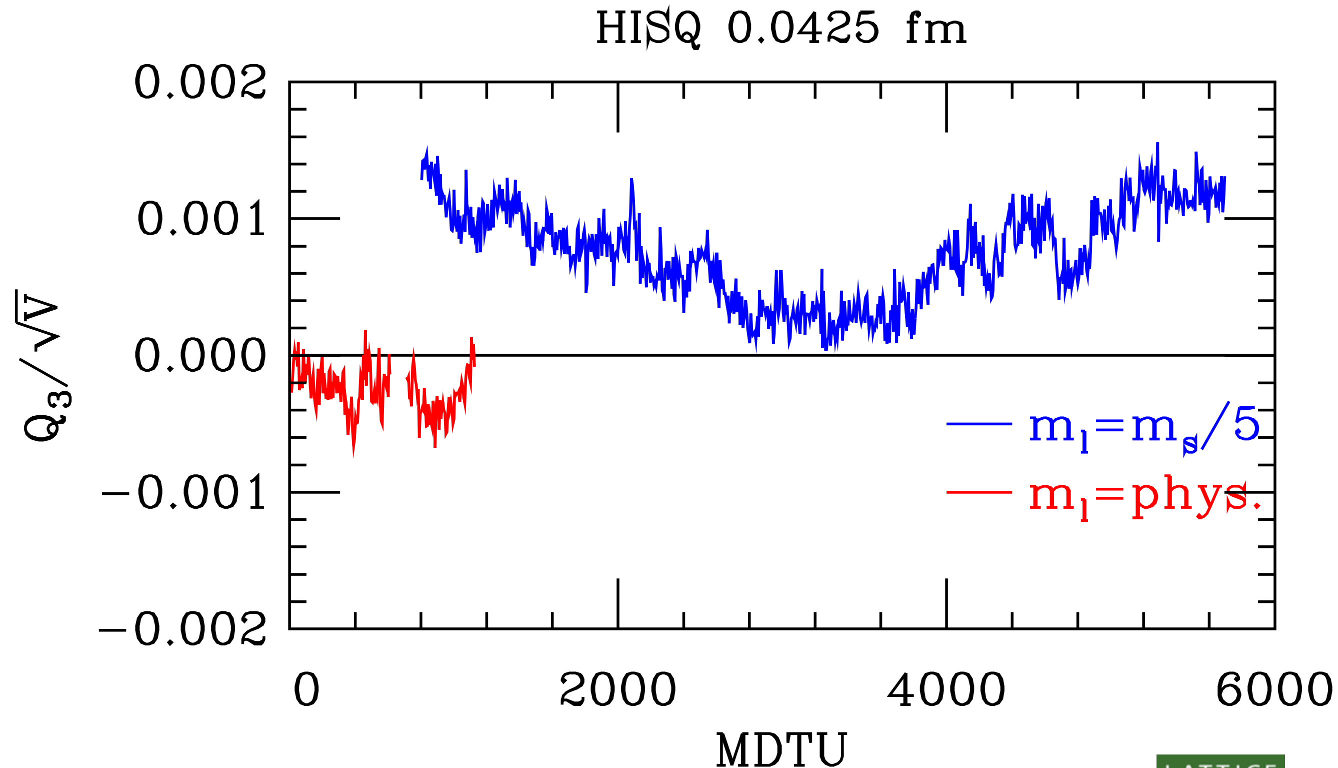
LATTICE 2015 KOBE

towards a fully relativistic b

crucial issue: strong lattice space dependence of autocorrelations







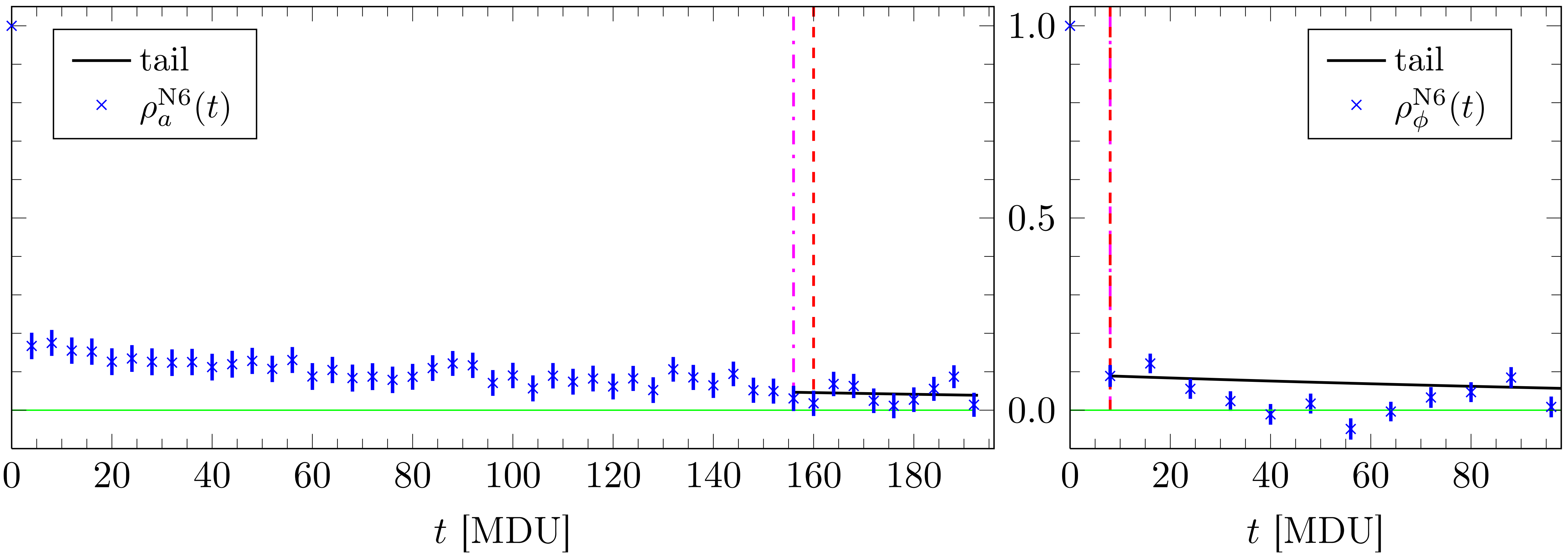
[Del Debbio, Panagopoulos, Vicari 2002]
[Schaefer, Sommer, Virotta 2010]
[Lüscher, Schaefer 2011]
[CLS N_f=2+1 obc programme]

[C DeTar, Thu 8:50]

towards a fully relativistic b

crucial issue: strong lattice space dependence of autocorrelations

$a = 0.048$ fm , $m_\pi = 340$ MeV

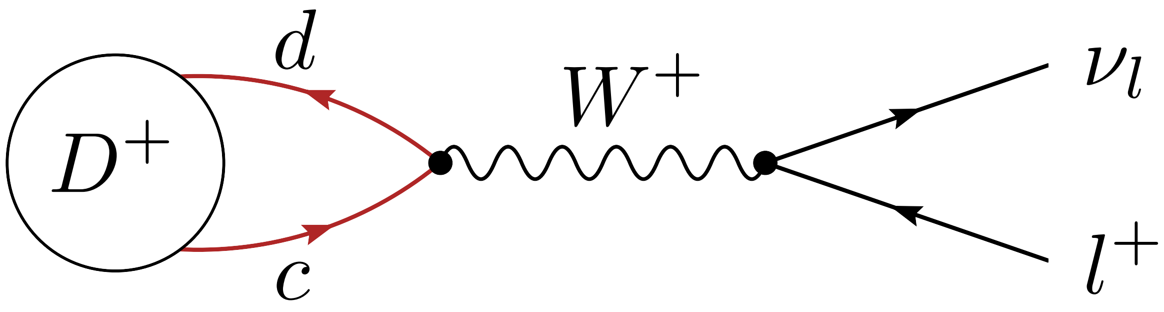


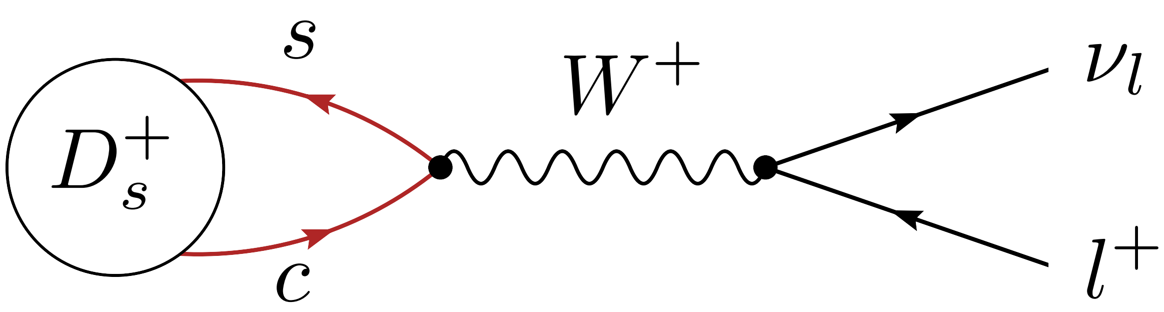
[ALPHA f_B, arXiv:1404.3590]

plan

- methods: where we stand (brief!)
  - ensembles used in HQ physics, reach
  - HQ approaches
- brief overview of
  - leptonic charm and B decay
  - B mixing
- charm and B semileptonic decays (+ CKM 2nd and 3rd rows)
- the % precision target
- conclusions and outlook

charm leptonic decay

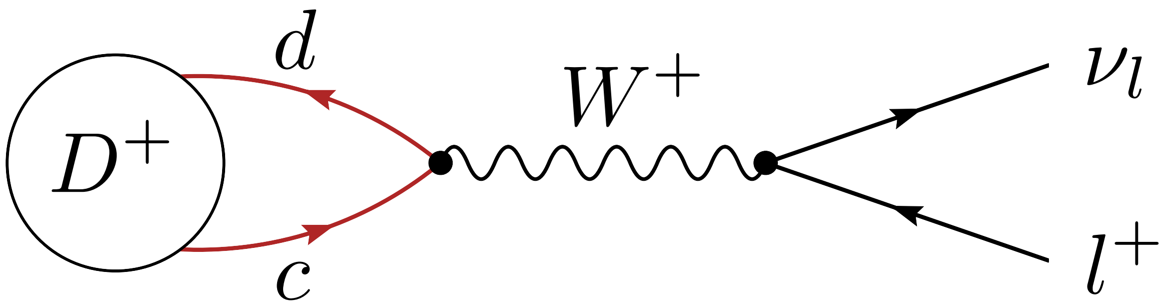


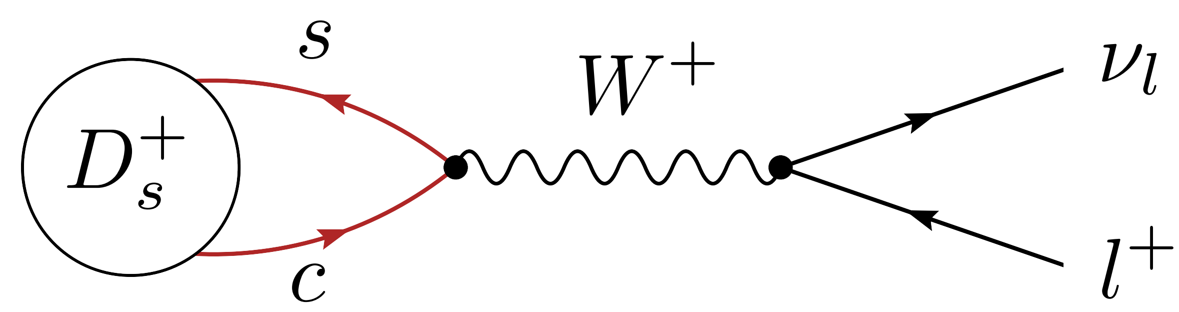


$$\frac{\mathcal{B}(D_{(s)} \to l\nu_l)}{\tau_{D_{(s)}}} = \frac{G_F^2}{8\pi} m_{D_{(s)}} m_l^2 \left(1 - \frac{m_l^2}{m_{D_{(s)}}^2}\right)^2 |V_{cq}|^2 \, f_{D_{(s)}}^2 \quad \text{[+ h.o. OPE]}$$

$$\langle 0|\bar{c}\gamma^\mu\gamma^5 q|D_q(p)\rangle = f_{D_q}\, p^\mu$$

charm leptonic decay





$$\frac{\mathcal{B}(D_{(s)} \to l\nu_l)}{\tau_{D_{(s)}}} = \frac{G_F^2}{8\pi} m_{D_{(s)}} m_l^2 \left(1 - \frac{m_l^2}{m_{D_{(s)}}^2}\right)^2 |V_{cq}|^2 f_{D_{(s)}}^2$$ [+ h.o. OPE]

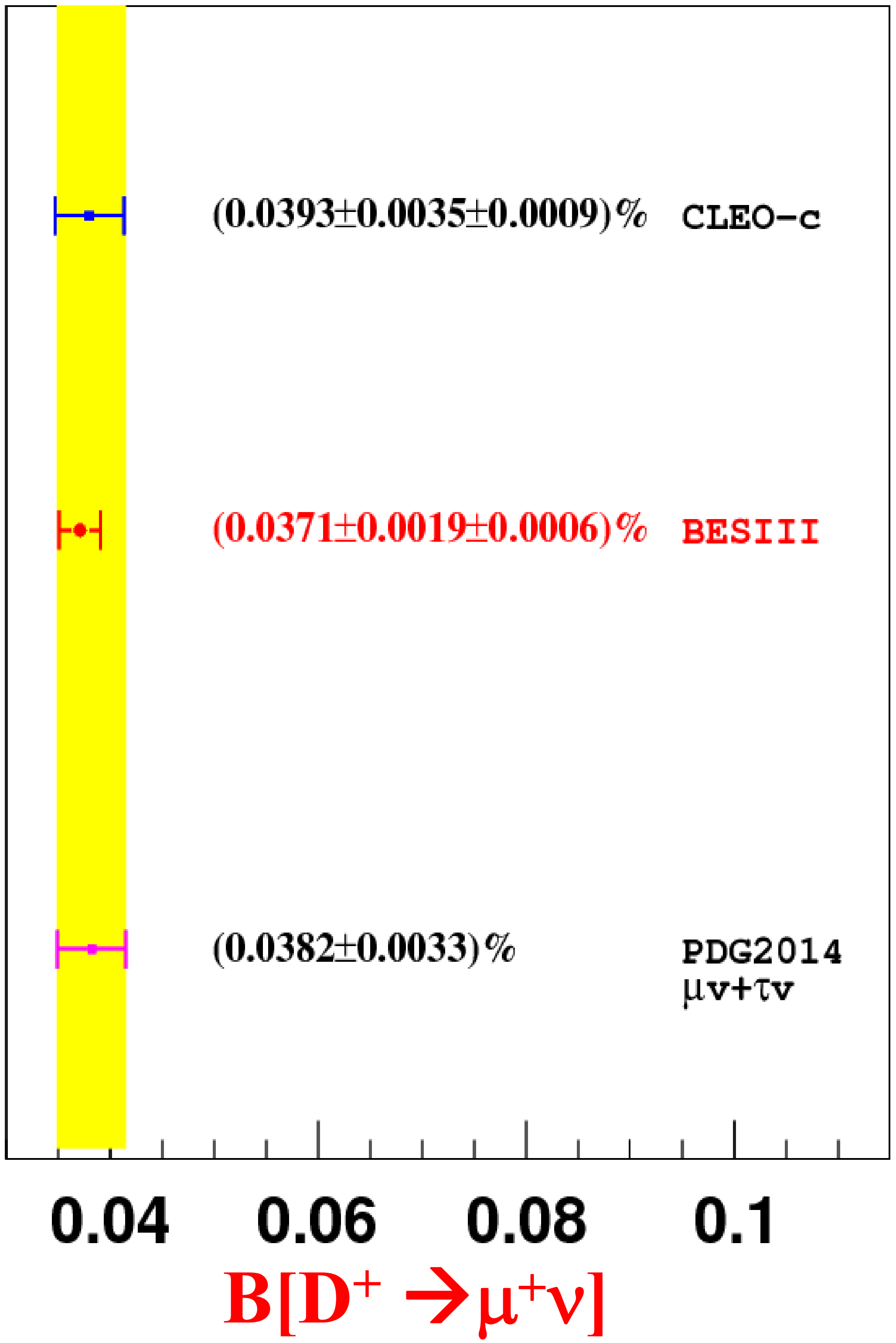
$$\Delta \sim 10^{-3} \ (m_{D_{(s)}})$$

$$\Delta = 0.7\% \ (D), \ 1.4\% \ (D_s)$$

(+ e.m. corrections!)

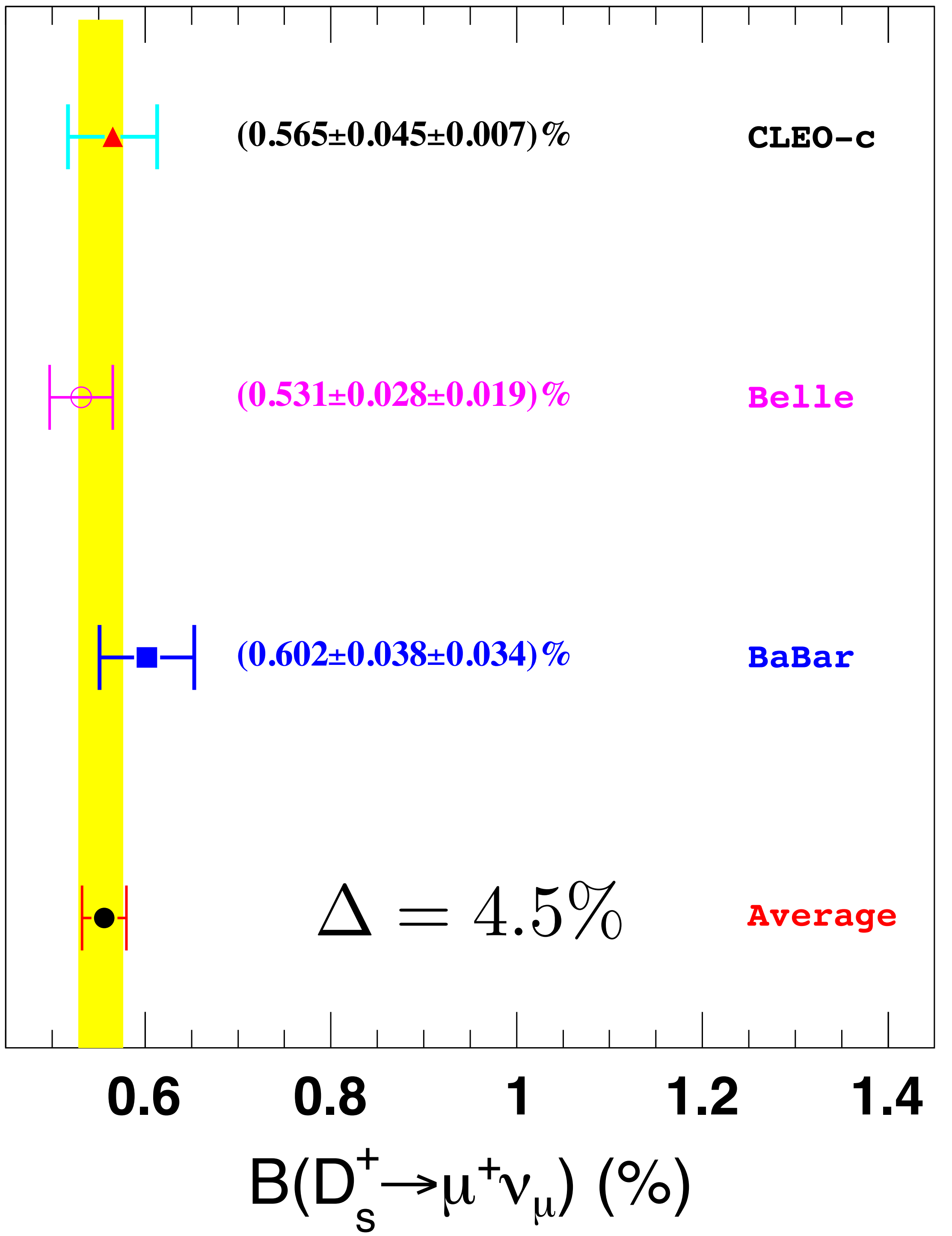
$$\Delta \sim \mathcal{O}\left(\frac{m_{D_{(s)}}^2}{M_W^2}\right) \sim 10^{-4}$$

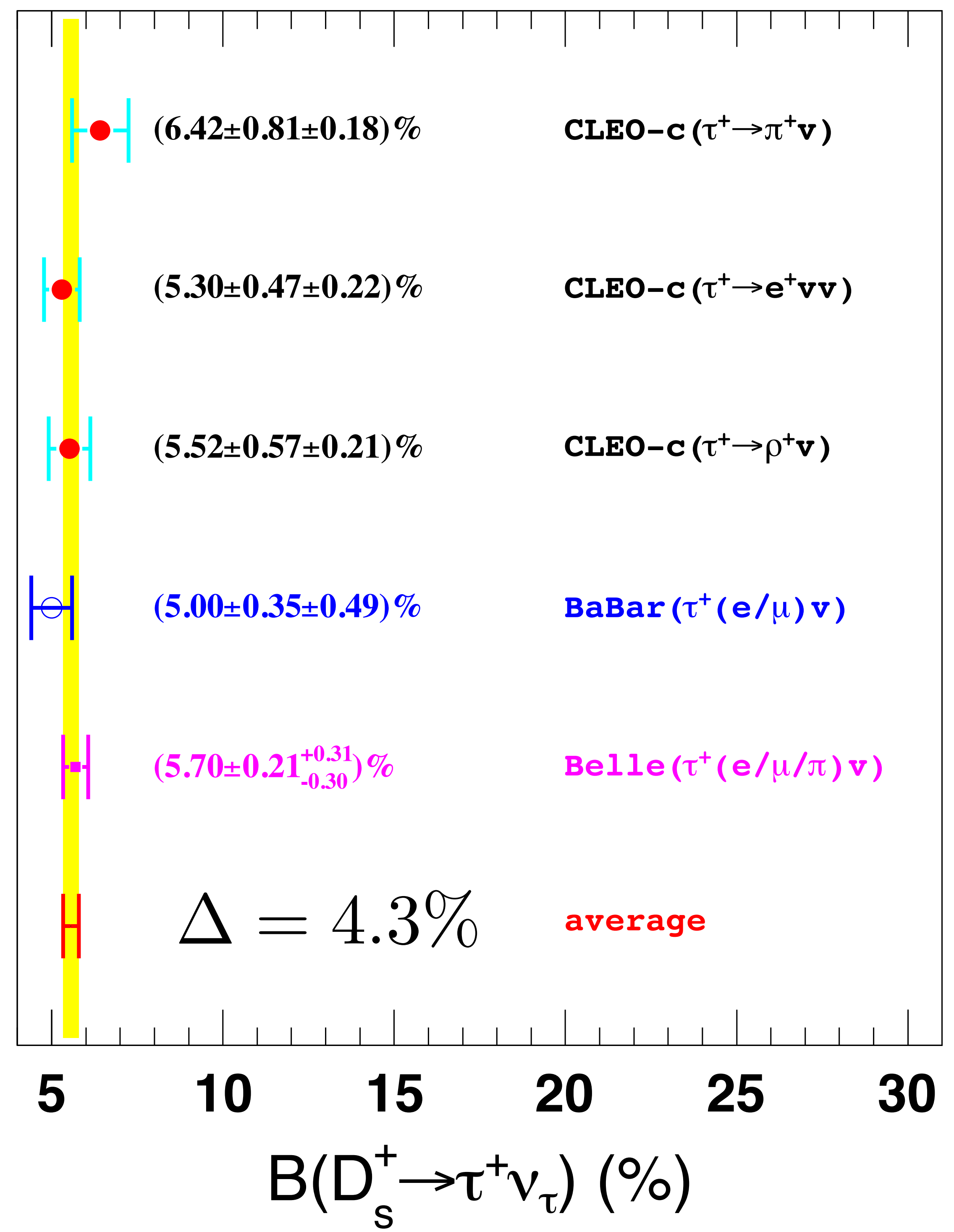
charm leptonic decay



[from H Ma's talk on behalf of BESIII at CHARM 2015]

charm leptonic decay





[from S Eidelman's talk on behalf of Belle at CHARM 2015]

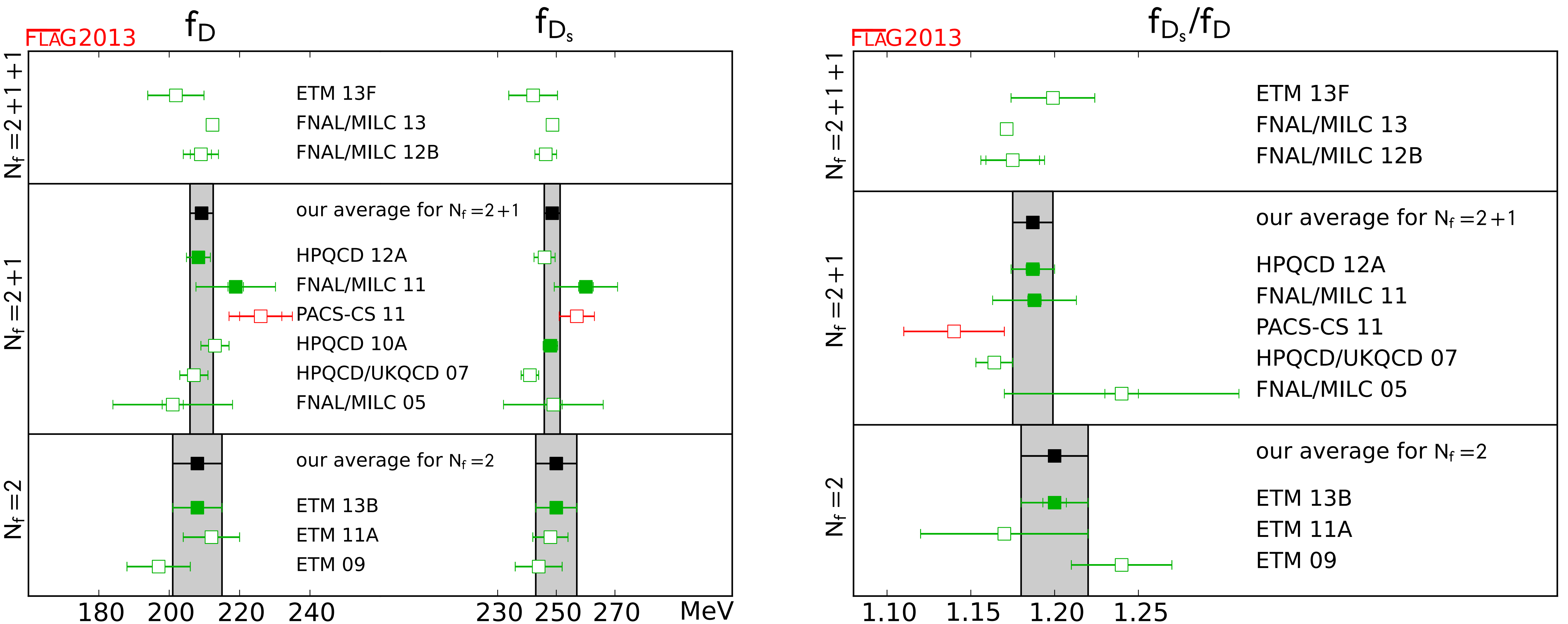
Belle II projections

Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$	± 0.012	± 0.008	6
α		$\pm 2°$	$\pm 1°$	
γ	$\pm 14°$	$\pm 6°$	$\pm 1.5°$	
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	± 0.053	± 0.018	>50
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	± 0.028	± 0.011	>50
$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$	± 0.100	± 0.033	44
$\|V_{cb}\|$ incl.	$\pm 2.4\%$	$\pm 1.0\%$		< 1
$\|V_{cb}\|$ excl.	$\pm 3.6\%$	$\pm 1.8\%$	$\pm 1.4\%$	< 1
$\|V_{ub}\|$ incl.	$\pm 6.5\%$	$\pm 3.4\%$	$\pm 3.0\%$	2
$\|V_{ub}\|$ excl. (had. tag.)	$\pm 10.8\%$	$\pm 4.7\%$	$\pm 2.4\%$	20
$\|V_{ub}\|$ excl. (untag.)	$\pm 9.4\%$	$\pm 4.2\%$	$\pm 2.2\%$	3
$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	96 ± 26	$\pm 10\%$	$\pm 5\%$	46
$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7	5σ	$>> 5\sigma$	>50
$R(B \to D\tau\nu)$	$\pm 16.5\%$	$\pm 5.6\%$	$\pm 3.4\%$	4
$R(B \to D^*\tau\nu)$	$\pm 9.0\%$	$\pm 3.2\%$	$\pm 2.1\%$	3
$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})$ [10^{-6}]	< 40		$\pm 30\%$	>50
$\mathcal{B}(B \to K^{+}\nu\bar{\nu})$ [10^{-6}]	< 55		$\pm 30\%$	>50
$\mathcal{B}(B \to X_s\gamma)$ [10^{-6}]	$\pm 13\%$	$\pm 7\%$	$\pm 6\%$	< 1
$A_{CP}(B \to X_s\gamma)$		± 0.01	± 0.005	8
$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$	± 0.11	± 0.035	> 50
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	± 0.23	± 0.07	> 50
C_7/C_9 ($B \to X_s \ell\ell$)	$\sim 20\%$	10%	5%	
$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7	± 0.3		
$\mathcal{B}(B_s \to \tau^+\tau^-)$ [10^{-3}]		< 2		

Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \times 10^{-3}(1 \pm 0.053 \pm 0.038)$	$\pm 2.9\%$	$\pm$(0.9%-1.3%)	> 50
$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \times 10^{-3}(1 \pm 0.037 \pm 0.054)$	$\pm$(3.5%-4.3%)	$\pm$(2.3%-3.6%)	3-5
y_{CP} [10^{-2}]	$1.11 \pm 0.22 \pm 0.11$	$\pm$(0.11-0.13)	$\pm$(0.05-0.08)	5-8
A_Γ [10^{-2}]	$-0.03 \pm 0.20 \pm 0.08$	± 0.10	$\pm$(0.03-0.05)	7 - 9
$A_{CP}^{K^+K^-}$ [10^{-2}]	$-0.32 \pm 0.21 \pm 0.09$	± 0.11	± 0.06	15
$A_{CP}^{\pi^+\pi^-}$ [10^{-2}]	$0.55 \pm 0.36 \pm 0.09$	± 0.17	$\pm$ 0.06	> 50
$A_{CP}^{\phi\gamma}$ [10^{-2}]	$\pm$ 5.6	± 2.5	± 0.8	> 50
$x^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	± 0.14	± 0.11	3
$y^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	± 0.08	± 0.05	15
$\|q/p\|^{K_S\pi^+\pi^-}$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	± 0.10	± 0.07	5-6
$\phi^{K_S\pi^+\pi^-}$ [°]	$-6 \pm 11 \pm {}^{4}_{5}$	± 6	± 4	10
$A_{CP}^{\pi^0\pi^0}$ [10^{-2}]	$-0.03 \pm 0.64 \pm 0.10$	± 0.29	± 0.09	> 50
$A_{CP}^{K^0_S\pi^0}$ [10^{-2}]	$-0.10 \pm 0.16 \pm 0.09$	± 0.08	± 0.03	> 50
$Br(D^0 \to \gamma\gamma)$ [10^{-6}]	< 1.5	$\pm 30\%$	$\pm 25\%$	2
	$\tau \to \mu\gamma$ [10^{-9}]	< 45	< 14.7	< 4.7
	$\tau \to e\gamma$ [10^{-9}]	< 120	< 39	< 12
	$\tau \to \mu\mu\mu$ [10^{-9}]	< 21.0	< 3.0	< 0.3

[BELLE2-NOTE-PH-2015-002, retrieved from B2TiP]

FLAG-2 on charm decay constants

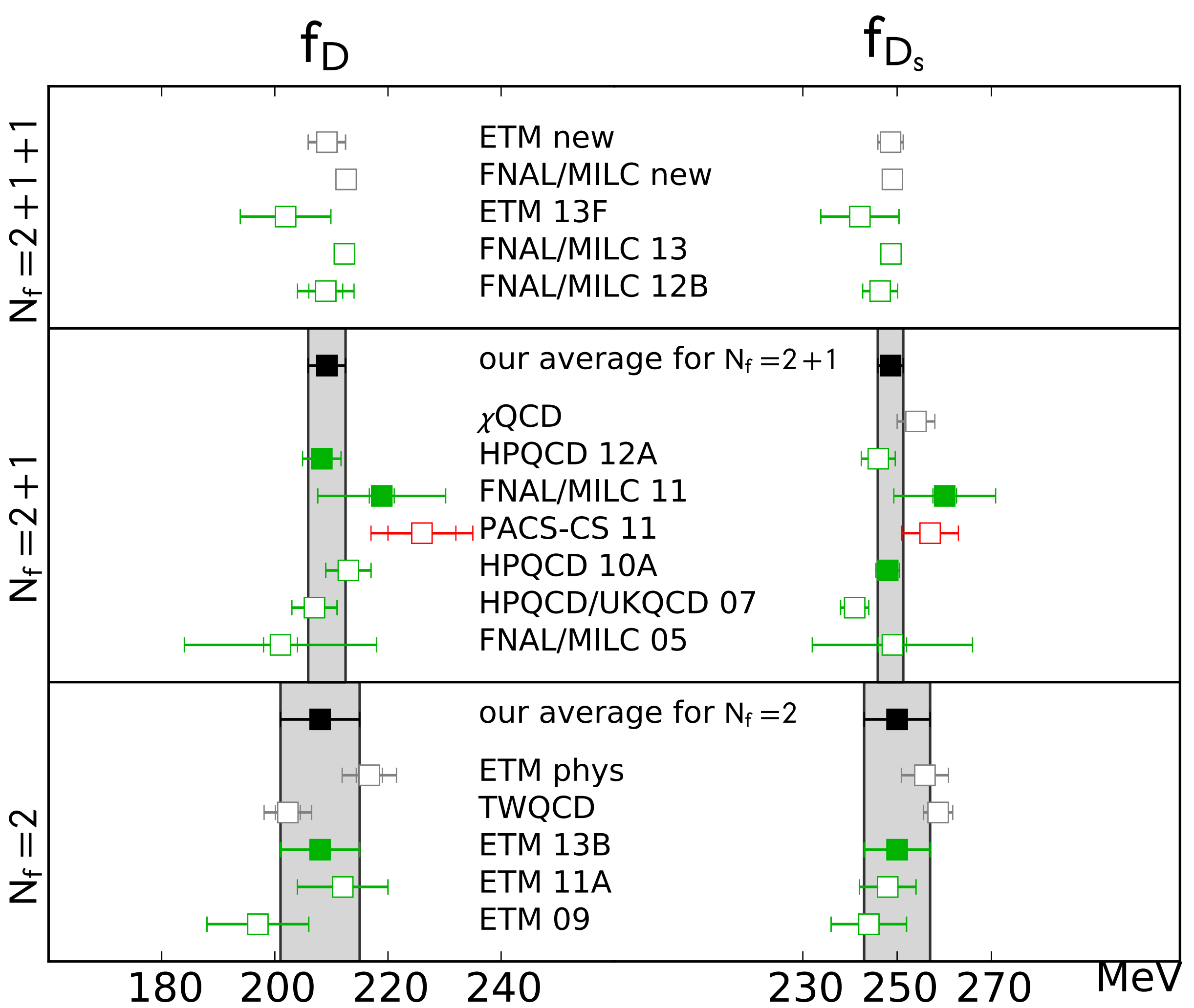


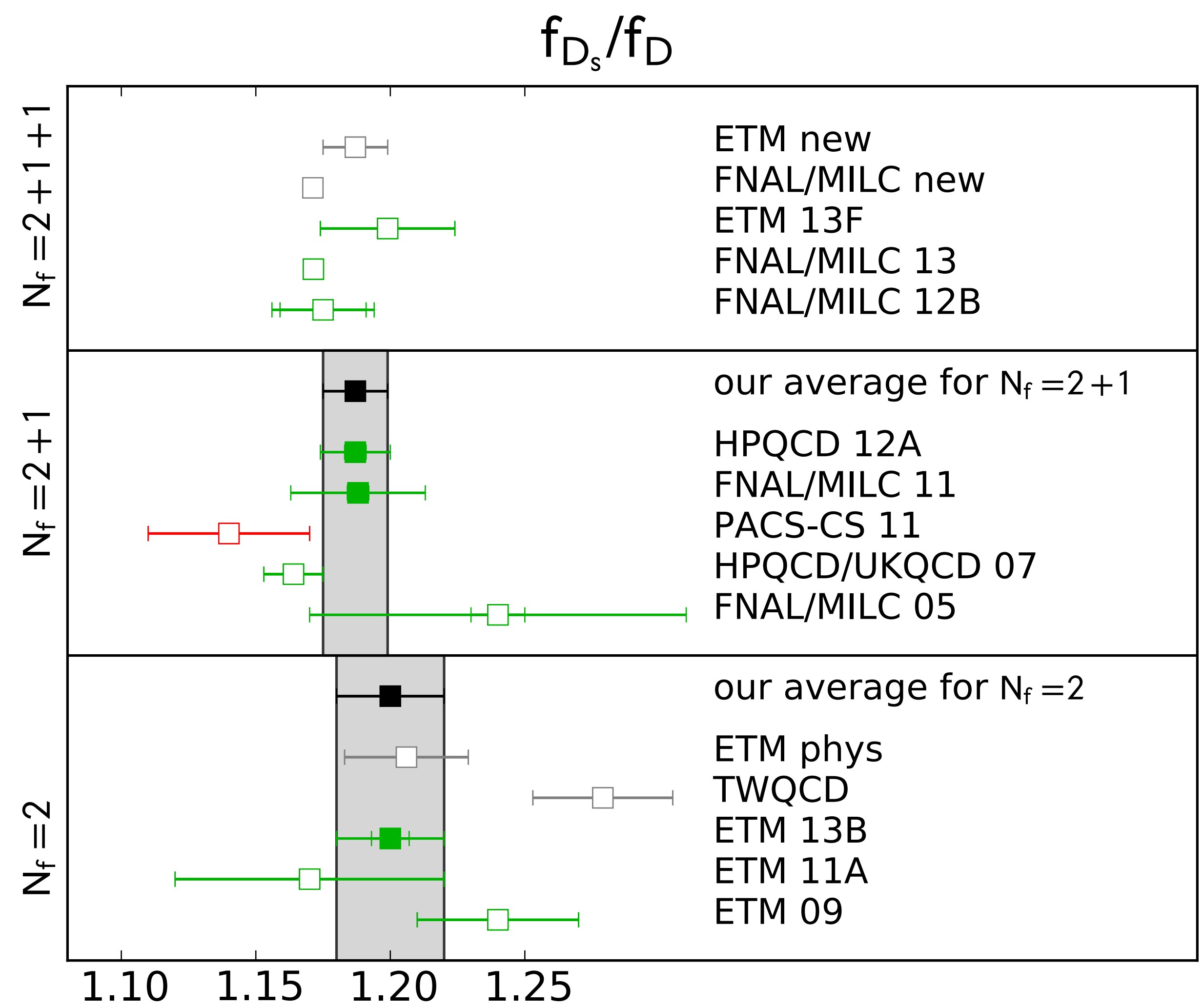
N_f	f_D [MeV]	f_{D_s} [MeV]	f_{D_s}/f_D
2	208(7)	250(7)	1.20(2)
2+1	209.2(3.3)	248.6(2.7)	1.187(12)

[FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

new results for $f_{D_{(s)}}$

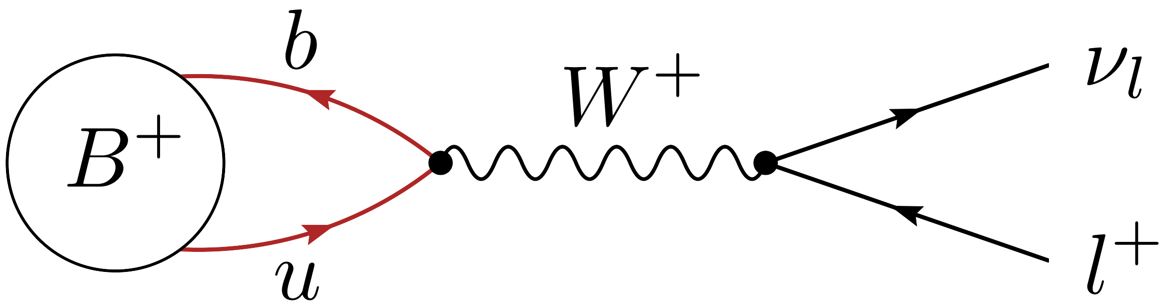
new results superimposed on FLAG-2 summary plots:

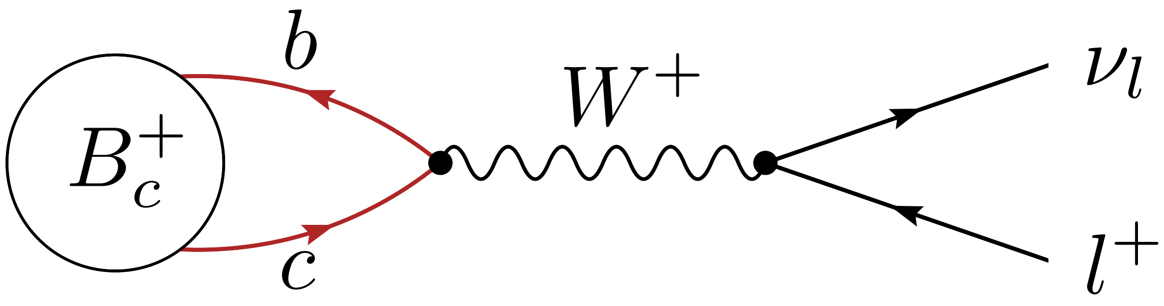




- close to 1% accuracy: “raw” potential of lattice methods
- already at the level where e.g. electromagnetic effects are relevant

B leptonic decay

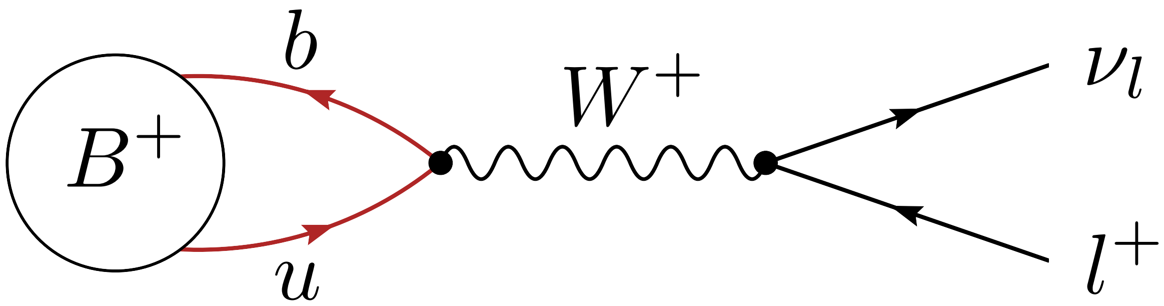


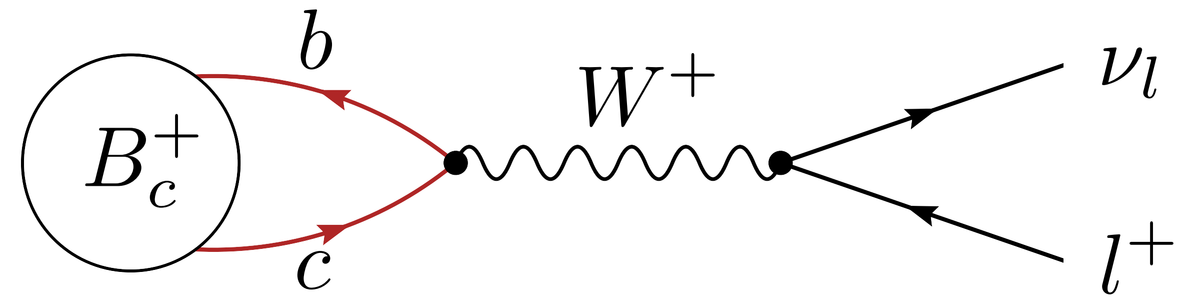


$$\frac{\mathcal{B}(B_{(c)} \to l\nu_l)}{\tau_{B_{(c)}}} = \frac{G_F^2}{8\pi} m_l^2 m_{B_{(c)}} \left(1 - \frac{m_l^2}{m_{B_{(c)}}^2}\right)^2 |V_{qb}|^2 f_{B_{(c)}}^2 \text{ [+ h.o. OPE]}$$

$$\langle 0|\bar{b}\gamma^\mu\gamma^5 q|B_q(p)\rangle = f_{B_q}\, p^\mu$$

B leptonic decay





$$\frac{\mathcal{B}(B \to l\nu_l)}{\tau_B} = \frac{G_F^2}{8\pi} m_l^2 m_B \left(1 - \frac{m_l^2}{m_B^2}\right)^2 |V_{ub}|^2 f_B^2 \quad \text{[+ h.o. OPE]}$$

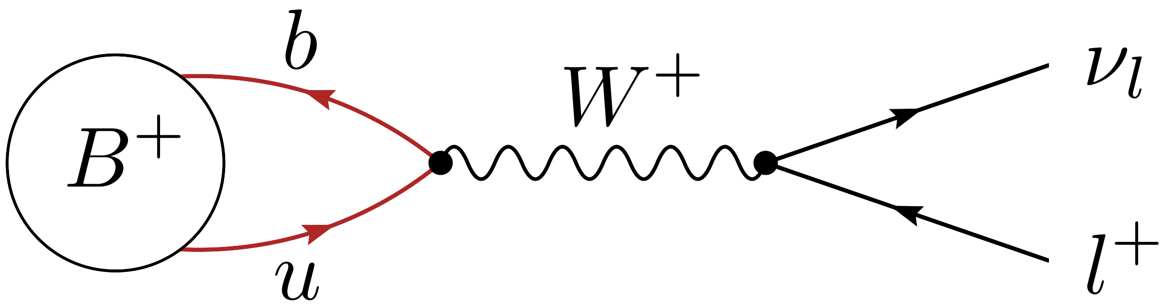
$\Delta = 0.2\%$

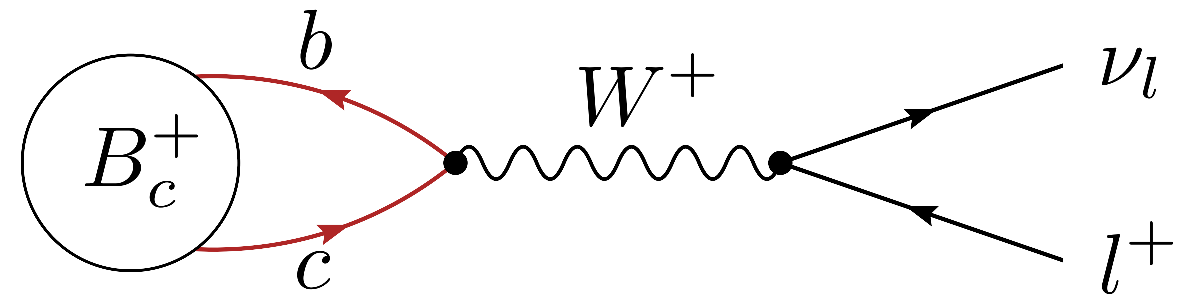
(negligible)

$$\Delta \sim \mathcal{O}\left(\frac{m_B^2}{M_W^2}\right) \sim 0.4\%$$

(+ e.m. corrections!)

B leptonic decay





$$\frac{\mathcal{B}(B_c \to l\nu_l)}{\tau_{B_c}} = \frac{G_F^2}{8\pi} m_l^2 m_{B_c} \left(1 - \frac{m_l^2}{m_{B_c^2}}\right)^2 |V_{qb}|^2 f_{B_c}^2 \quad \text{[+ h.o. OPE]}$$

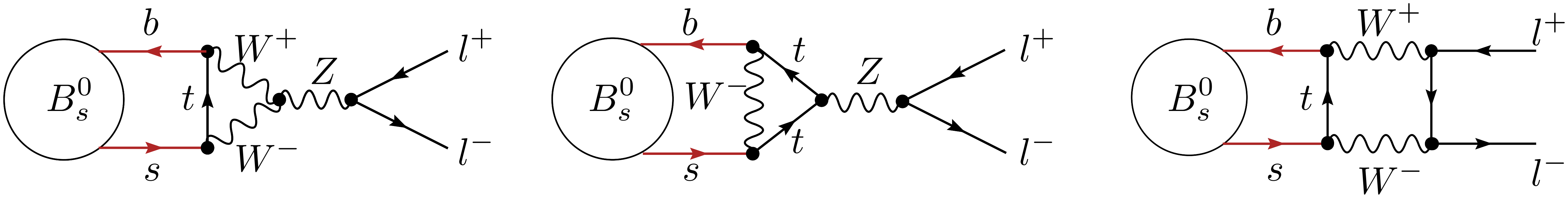
(negligible)

$$\Delta = 7.3\%$$

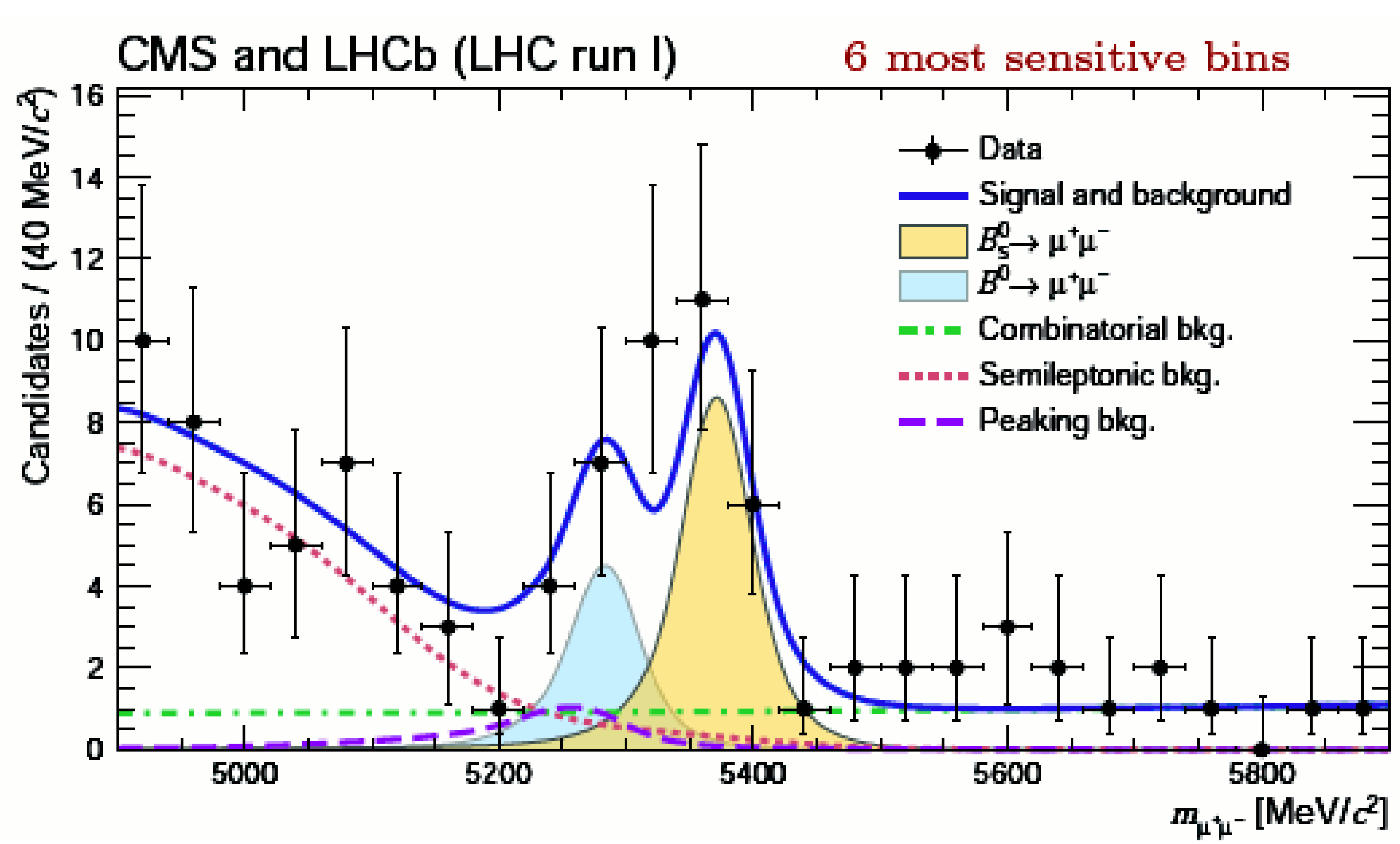
$$\Delta \sim \mathcal{O}\left(\frac{m_{B_c}^2}{M_W^2}\right) \sim 0.6\%$$

(+ e.m. corrections!)

B leptonic decay



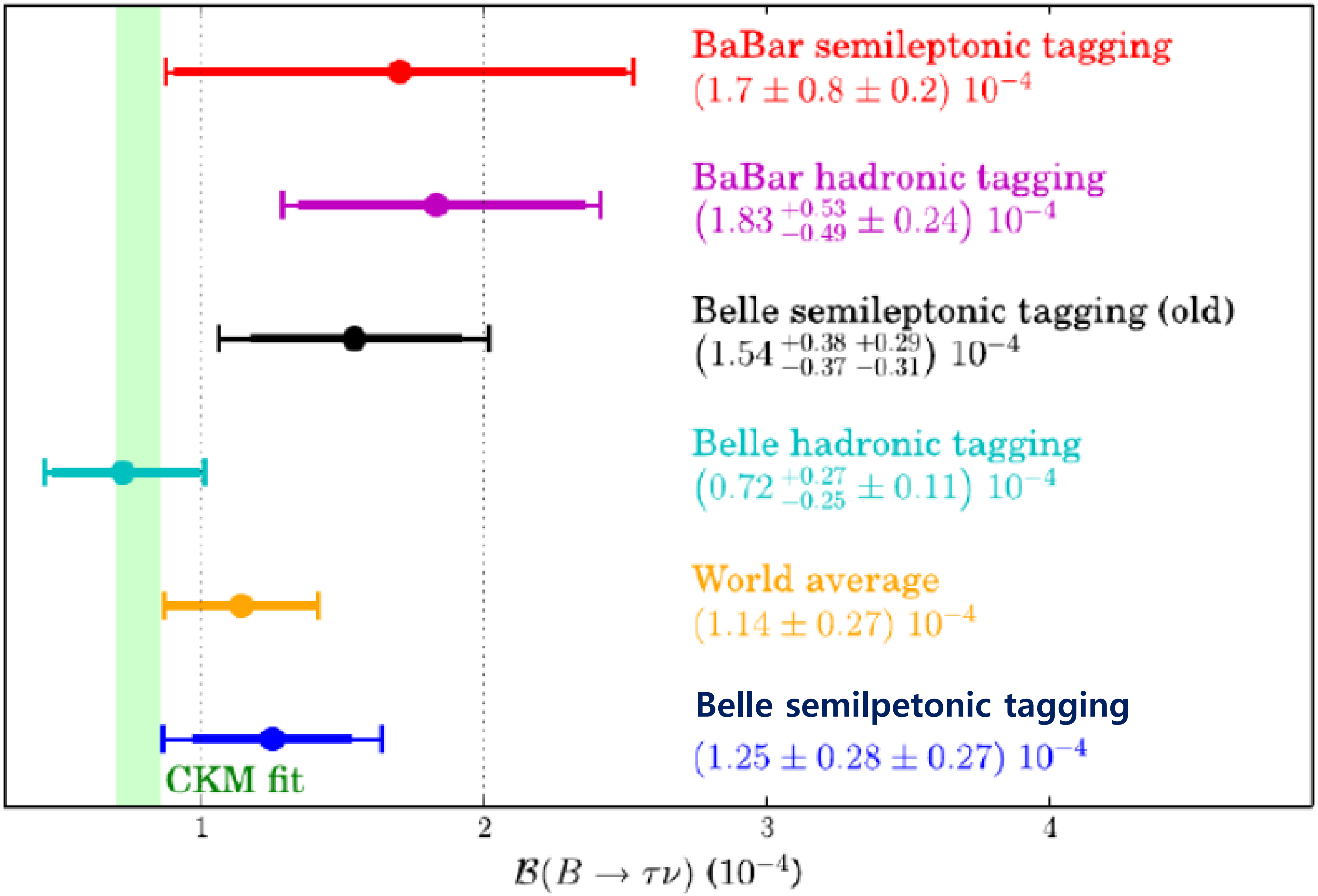
$$\frac{\mathcal{B}(B_q \to l^+ l^-)}{\tau_{B_q}} = \frac{G_F^2}{\pi} Y \left(\frac{\alpha}{4\pi \sin^2 \theta_W} \right)^2 m_{B_q} m_l^2 \sqrt{1 - 4\frac{m_l^2}{m_{B_q}^2}} \, |V_{tb}^* V_{tq}|^2 \, f_{B_q}^2$$



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

[arXiv:1411.4413]

B leptonic decay



[from C Park's talk at FPCP 2015]

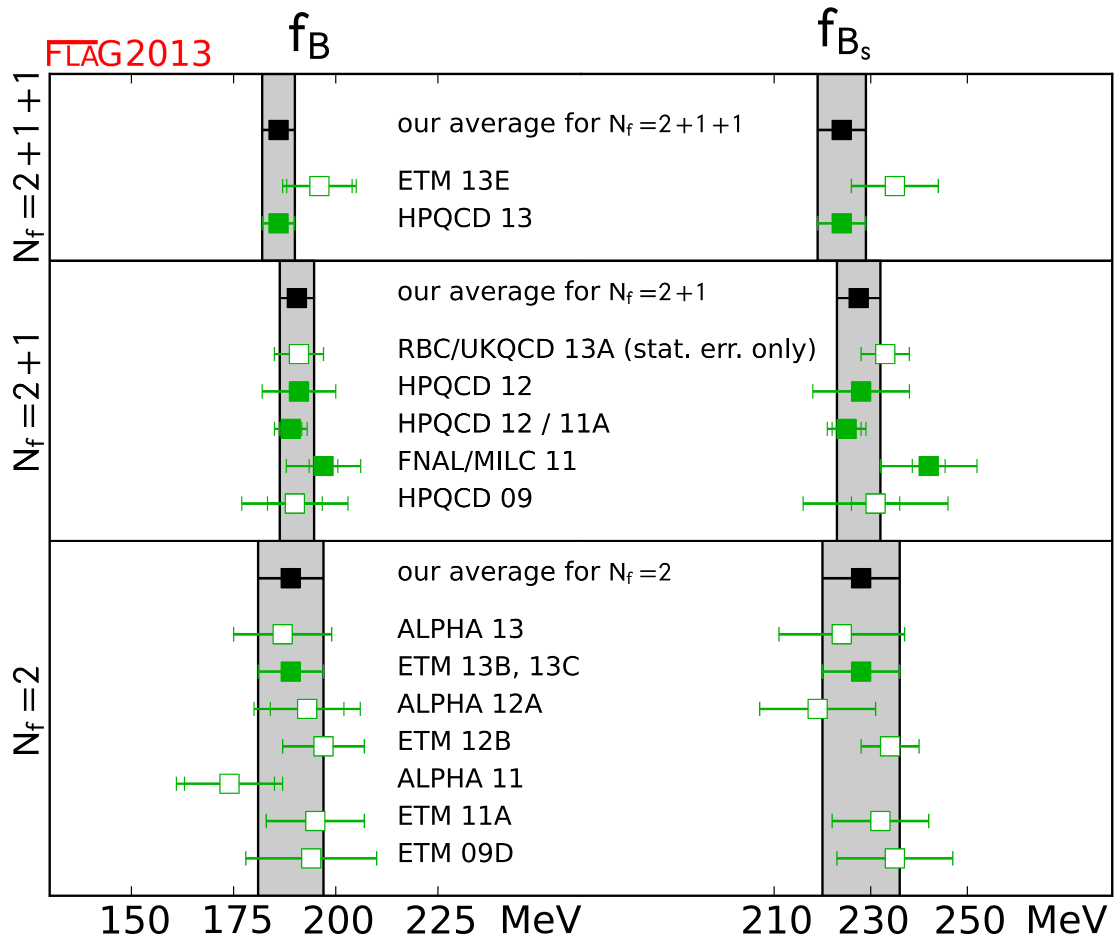
Belle II projections

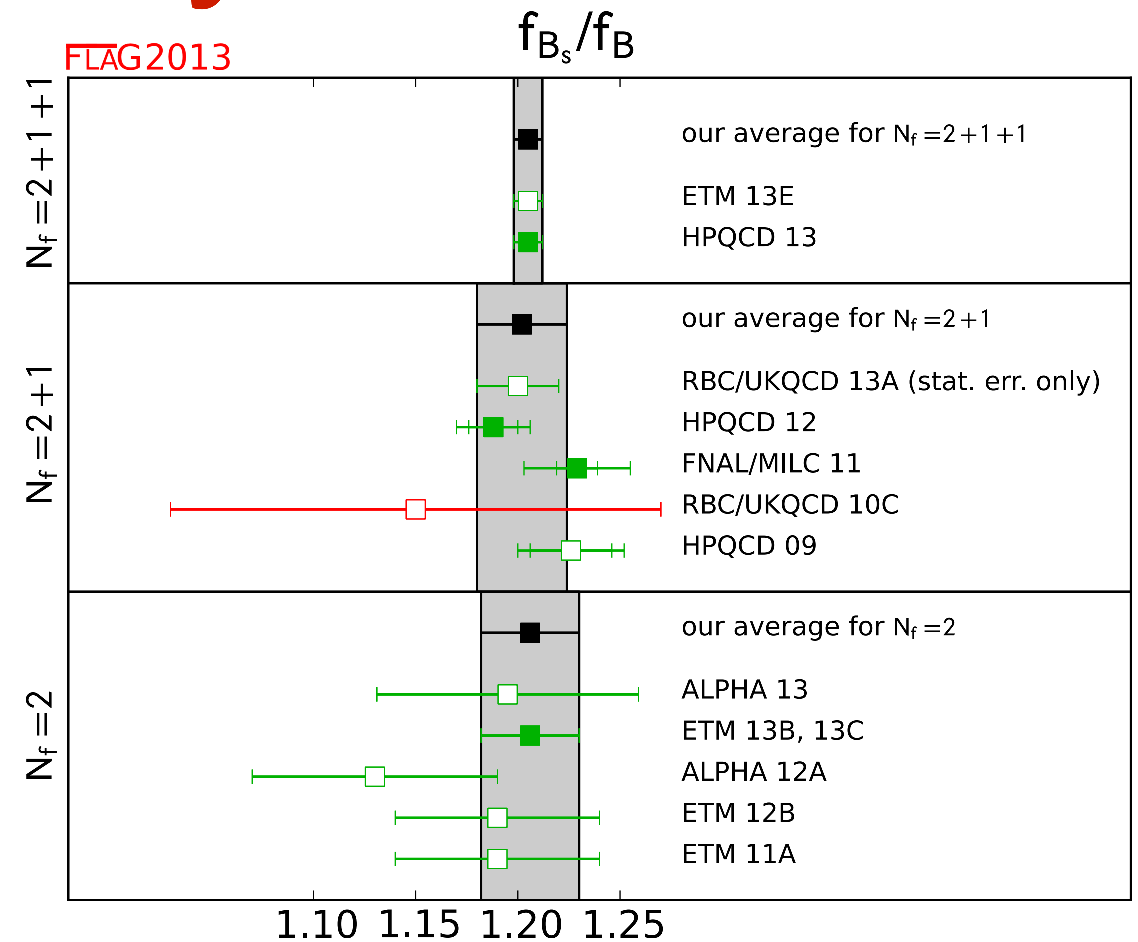
Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$	± 0.012	± 0.008	6
α		$\pm 2^\circ$	$\pm 1^\circ$	
γ	$\pm 14^\circ$	$\pm 6^\circ$	$\pm 1.5^\circ$	
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	± 0.053	± 0.018	>50
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	± 0.028	± 0.011	>50
$S(B \to K_S^0 K_S^0 K_S^0)$	$0.30 \pm 0.32 \pm 0.08$	± 0.100	± 0.033	44
$\lvert V_{cb} \rvert$ incl.	$\pm 2.4\%$	$\pm 1.0\%$		< 1
$\lvert V_{cb} \rvert$ excl.	$\pm 3.6\%$	$\pm 1.8\%$	$\pm 1.4\%$	< 1
$\lvert V_{ub} \rvert$ incl.	$\pm 6.5\%$	$\pm 3.4\%$	$\pm 3.0\%$	2
$\lvert V_{ub} \rvert$ excl. (had. tag.)	$\pm 10.8\%$	$\pm 4.7\%$	$\pm 2.4\%$	20
$\lvert V_{ub} \rvert$ excl. (untag.)	$\pm 9.4\%$	$\pm 4.2\%$	$\pm 2.2\%$	3
$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	96 ± 26	$\pm 10\%$	$\pm 5\%$	46
$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7	5σ	$>> 5\sigma$	>50
$R(B \to D\tau\nu)$	$\pm 16.5\%$	$\pm 5.6\%$	$\pm 3.4\%$	4
$R(B \to D^*\tau\nu)$	$\pm 9.0\%$	$\pm 3.2\%$	$\pm 2.1\%$	3
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ [10^{-6}]	< 40		$\pm 30\%$	>50
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ [10^{-6}]	< 55		$\pm 30\%$	>50
$\mathcal{B}(B \to X_s\gamma)$ [10^{-6}]	$\pm 13\%$	$\pm 7\%$	$\pm 6\%$	< 1
$A_{CP}(B \to X_s\gamma)$		± 0.01	± 0.005	8
$S(B \to K_S^0\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$	± 0.11	± 0.035	> 50
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	± 0.23	± 0.07	> 50
C_7/C_9 ($B \to X_s\ell\ell$)	$\sim 20\%$	10%	5%	
$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7	± 0.3		
$\mathcal{B}(B_s \to \tau^+\tau^-)$ [10^{-3}]		< 2		

Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \times 10^{-3}(1 \pm 0.053 \pm 0.038)$	$\pm 2.9\%$	$\pm(0.9\%\text{-}1.3\%)$	> 50
$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \times 10^{-3}(1 \pm 0.037 \pm 0.054)$	$\pm(3.5\%\text{-}4.3\%)$	$\pm(2.3\%\text{-}3.6\%)$	3-5
y_{CP} [10^{-2}]	$1.11 \pm 0.22 \pm 0.11$	$\pm(0.11\text{-}0.13)$	$\pm(0.05\text{-}0.08)$	5-8
A_Γ [10^{-2}]	$-0.03 \pm 0.20 \pm 0.08$	± 0.10	$\pm(0.03\text{-}0.05)$	7 - 9
$A_{CP}^{K^+K^-}$ [10^{-2}]	$-0.32 \pm 0.21 \pm 0.09$	± 0.11	± 0.06	15
$A_{CP}^{\pi^+\pi^-}$ [10^{-2}]	$0.55 \pm 0.36 \pm 0.09$	± 0.17	$\pm$ 0.06	> 50
$A_{CP}^{\phi\gamma}$ [10^{-2}]	$\pm$ 5.6	± 2.5	± 0.8	> 50
$x^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	± 0.14	± 0.11	3
$y^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	± 0.08	± 0.05	15
$\lvert q/p \rvert^{K_S\pi^+\pi^-}$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	± 0.10	± 0.07	5-6
$\phi^{K_S\pi^+\pi^-}$ [$^\circ$]	$-6 \pm 11 \pm {}^{4}_{5}$	± 6	± 4	10
$A_{CP}^{\pi^0\pi^0}$ [10^{-2}]	$-0.03 \pm 0.64 \pm 0.10$	± 0.29	± 0.09	> 50
$A_{CP}^{K_S^0\pi^0}$ [10^{-2}]	$-0.10 \pm 0.16 \pm 0.09$	± 0.08	± 0.03	> 50
$Br(D^0 \to \gamma\gamma)$ [10^{-6}]	< 1.5	$\pm 30\%$	$\pm 25\%$	2
	$\tau \to \mu\gamma$ [10^{-9}]	< 45	< 14.7	< 4.7
	$\tau \to e\gamma$ [10^{-9}]	< 120	< 39	< 12
	$\tau \to \mu\mu\mu$ [10^{-9}]	< 21.0	< 3.0	< 0.3

[BELLE2-NOTE-PH-2015-002, retrieved from B2TiP]

FLAG-2 on B decay constants





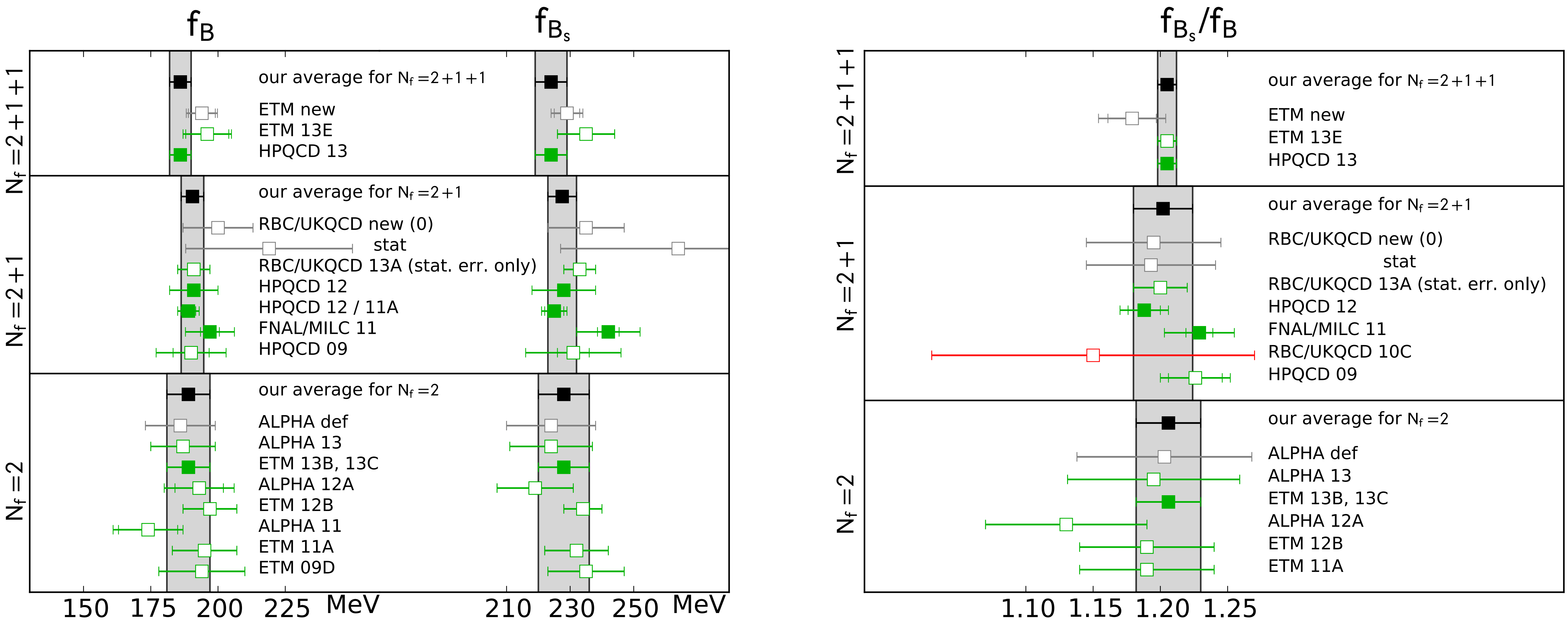
N_{f}	f_B [MeV]	f_{B_s} [MeV]	f_{B_s}/f_B
2	189(8)	228(8)	1.206(24)
2+1	190.5(4.2)	227.7(4.5)	1.202(22)
2+1+1	186(4)	224(5)	1.205(7)

[FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

(+ HPQCD results for f_{B_c}, not covered by FLAG) [PRD 86 (2012) 074503]

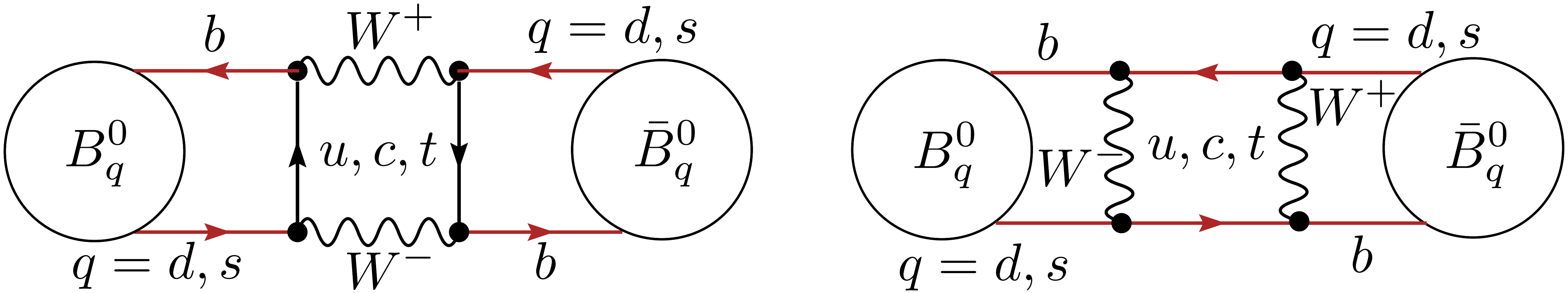
new results for f_{B_q}

new results superimposed on FLAG-2 summary plots:



- still significantly larger error than for charm decay
- few values enter averages, strong need of more results involving different HQ treatments

CP violation: B-mixing



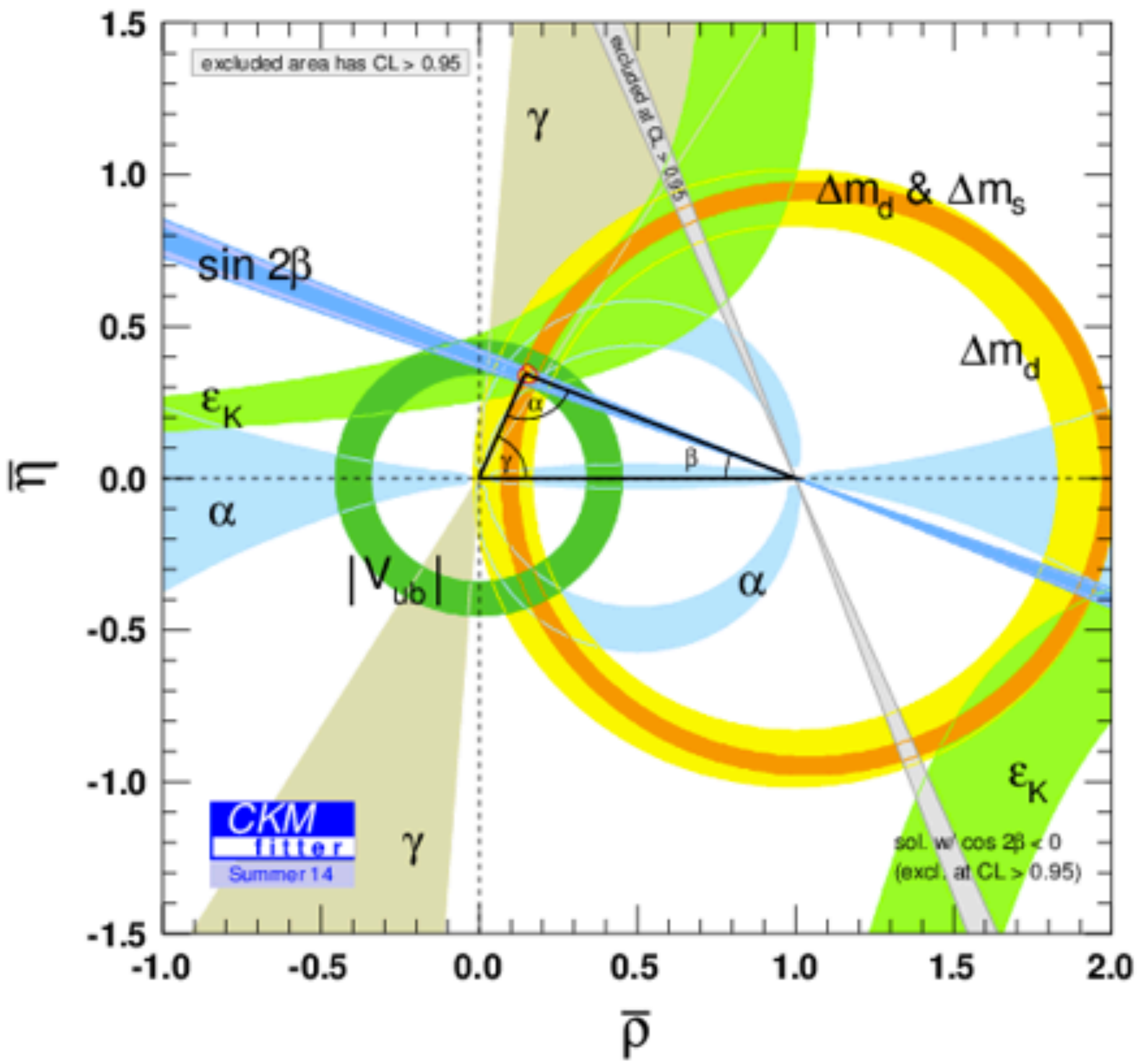
$$H_{\rm eff}^{\Delta B=2} = \frac{G_{\rm F}^2 M_W^2}{16\pi^2} \left(\mathcal{F}_d^0 Q_1^d + \mathcal{F}_s^0 Q_1^s\right)$$

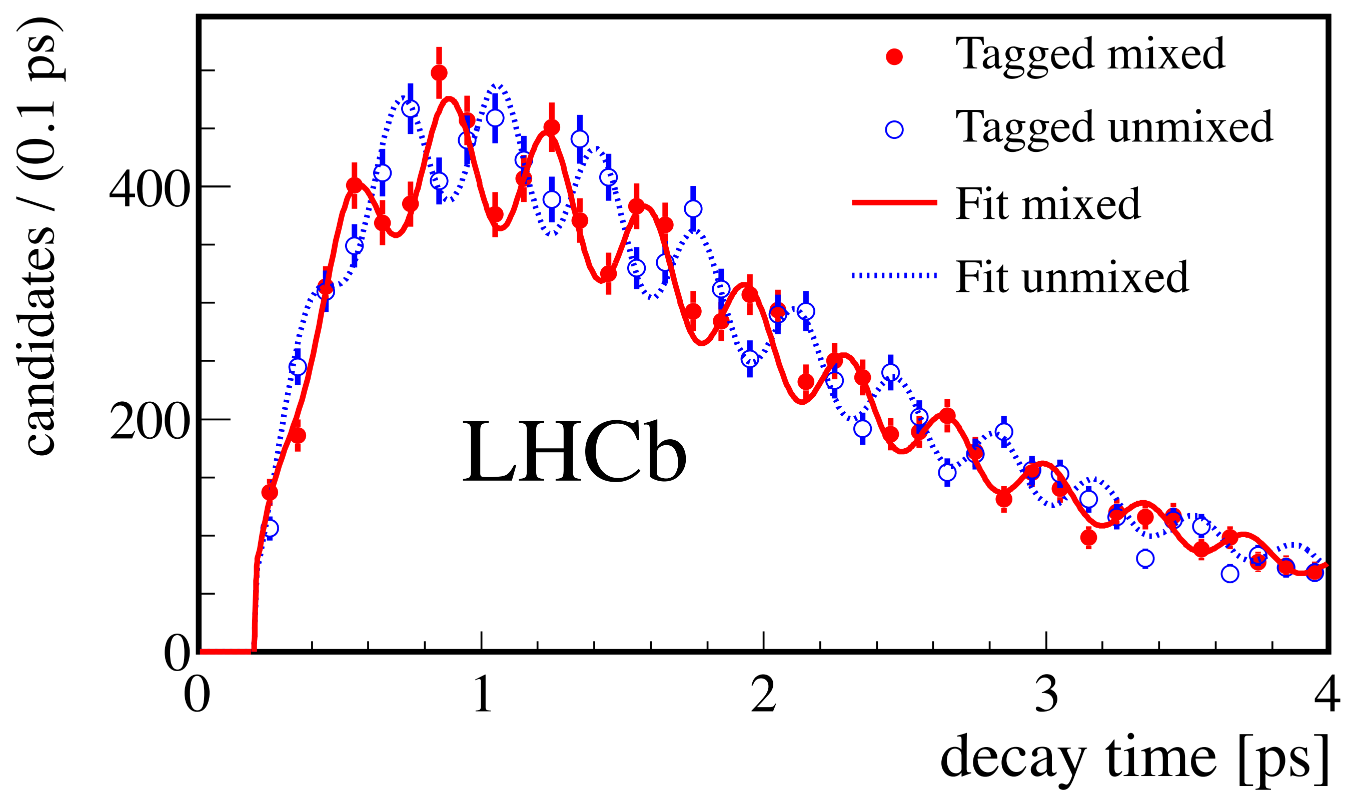
$$Q_1^q = (\bar{b}\gamma_\mu^{\rm L} q)(\bar{b}\gamma_\mu^{\rm L} q) \qquad \mathcal{F}_q^0 = \lambda_{tq}^2 S_0(m_t^2/M_W^2)\,, \qquad \lambda_{tq} = V_{tq}^* V_{tb}$$

$$\langle B_q^0 | H_{\rm eff}^{\Delta B=2} | B_q^0 \rangle = \frac{G_{\rm F}^2 M_W^2}{16\pi^2} S_0(x_t)\eta_{2B}\, \lambda_{tq}^2\, \langle B_q^0 | Q_{\rm RGI}^q | B_q^0 \rangle$$ [+ h.o. OPE]

$$B_{B_q} = \frac{\langle B_q^0 | Q_{\rm RGI}^q | B_q^0 \rangle}{\frac{8}{3} f_{B_q}^2 m_{B_q}^2}$$

CP violation: B-mixing

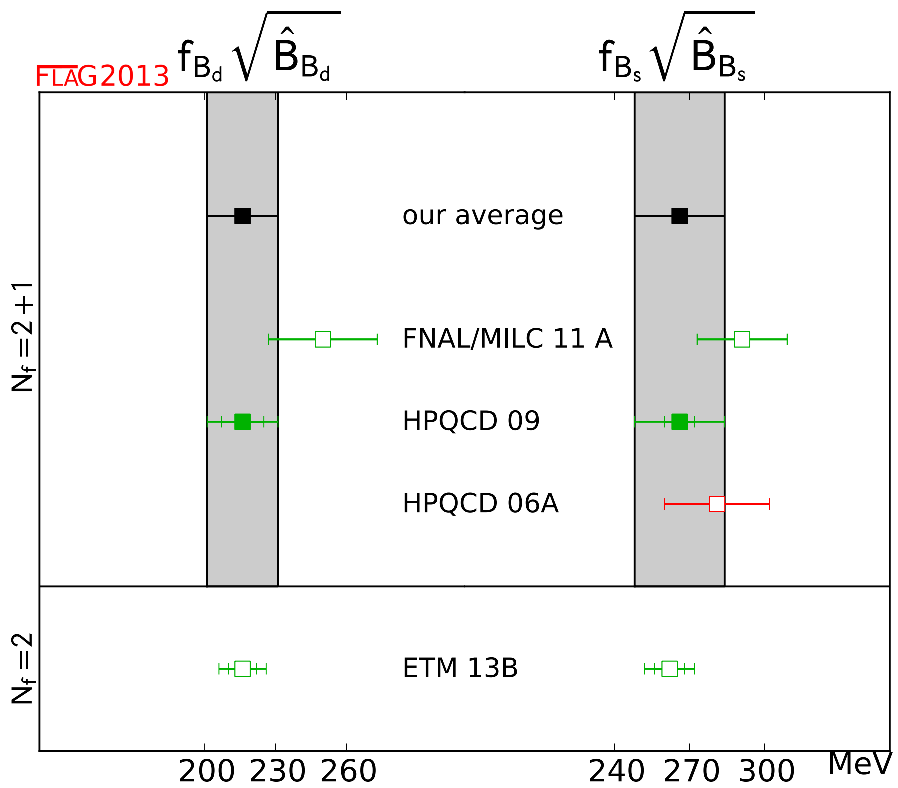


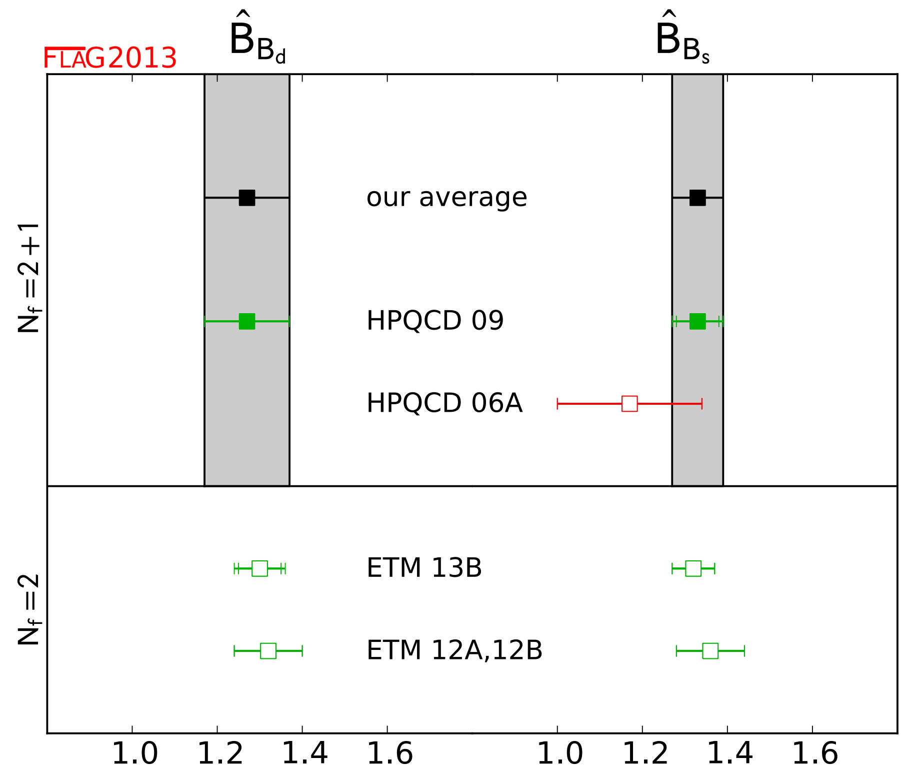


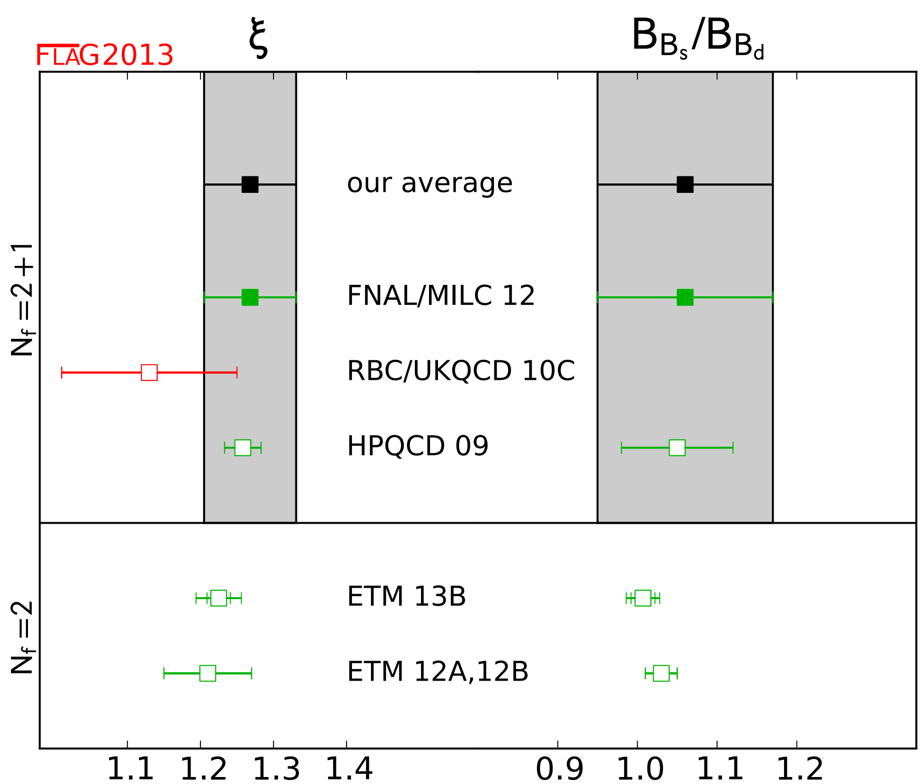
$$\langle B_q^0 | H_{\rm eff}^{\Delta B=2} | B_q^0 \rangle = \frac{G_{\rm F}^2 M_W^2}{16\pi^2} S_0(x_t) \eta_{2B}\, \lambda_{tq}^2\, \langle B_q^0 | Q_{\rm RGI}^q | B_q^0 \rangle \quad \text{[+ h.o. OPE]}$$

n.b.: in this case one is interested in constraining the apex position, so a priori knowledge of CKM's is needed $[\,\Delta(\lambda_{tq}^2) \approx 7\text{–}8\%\,]$

FLAG-2 on B-mixing

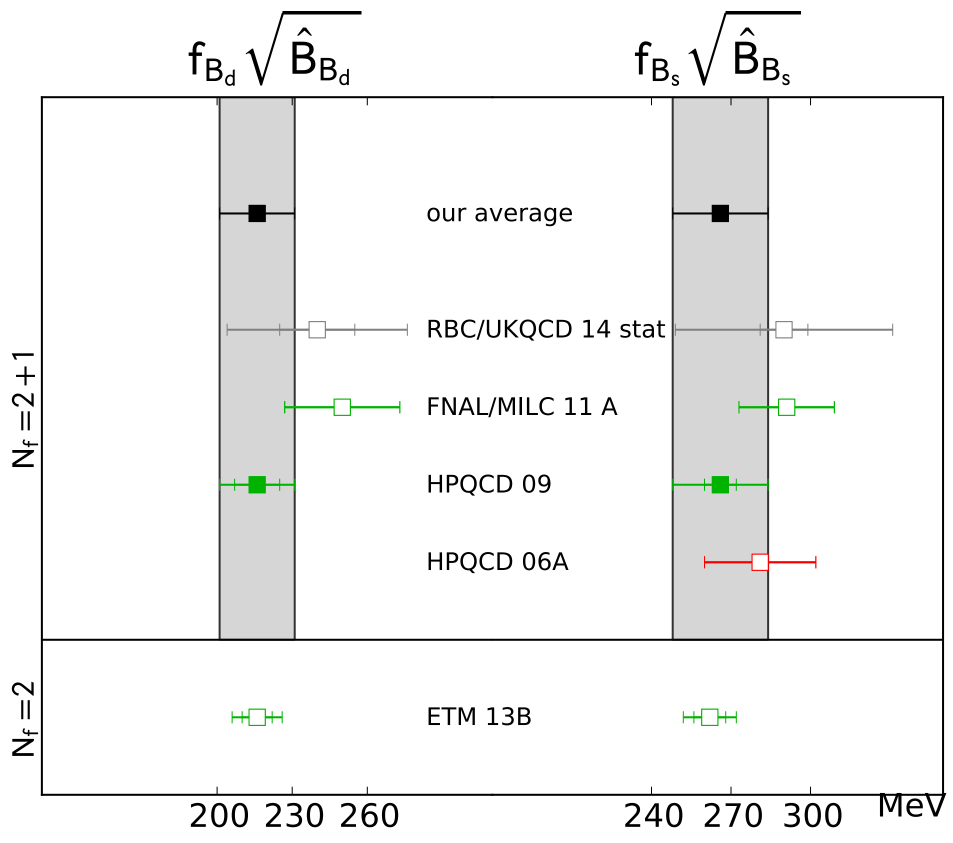


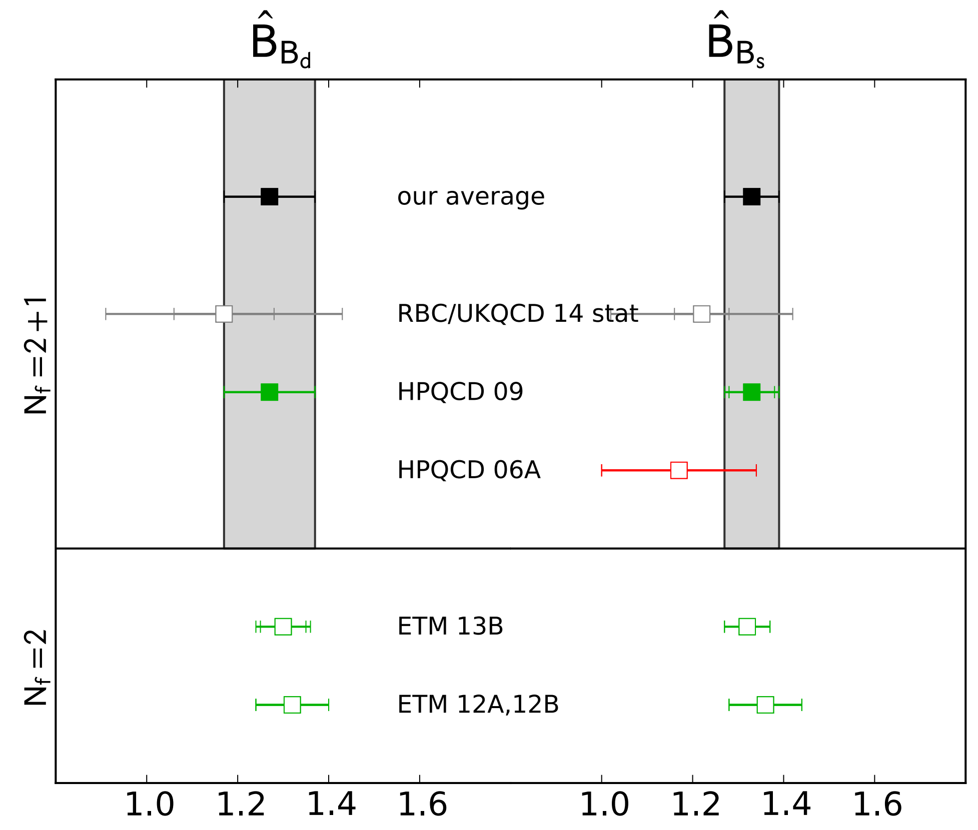


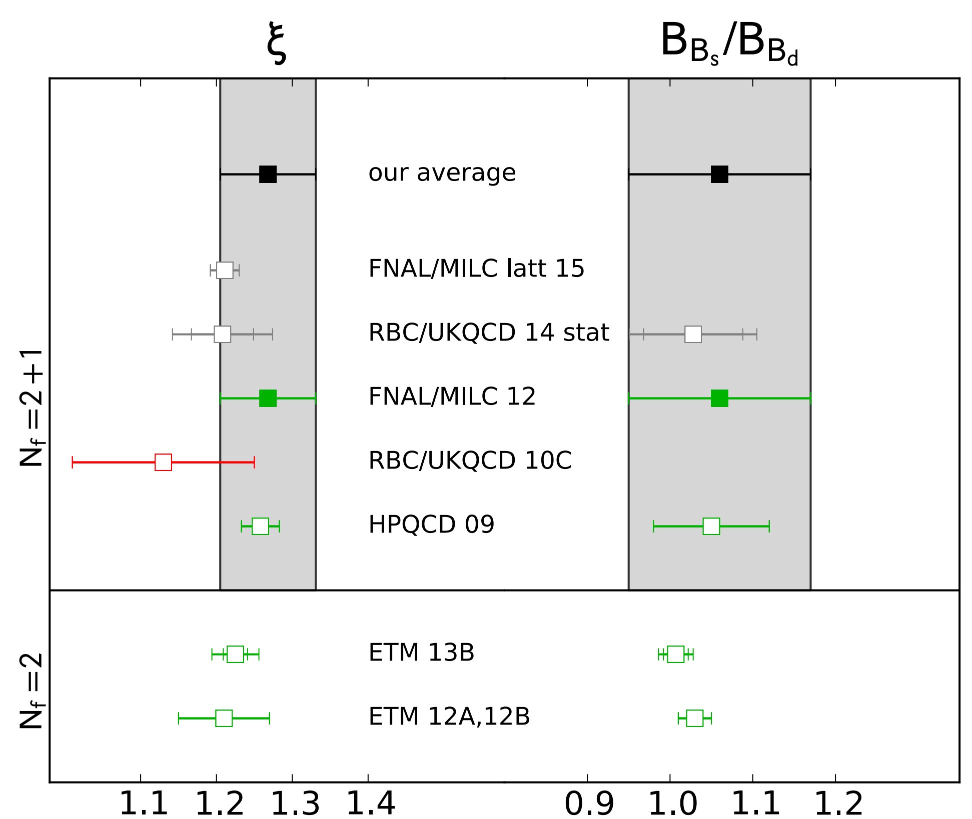


new results for B-mixing

new results superimposed on FLAG-2 summary plots:



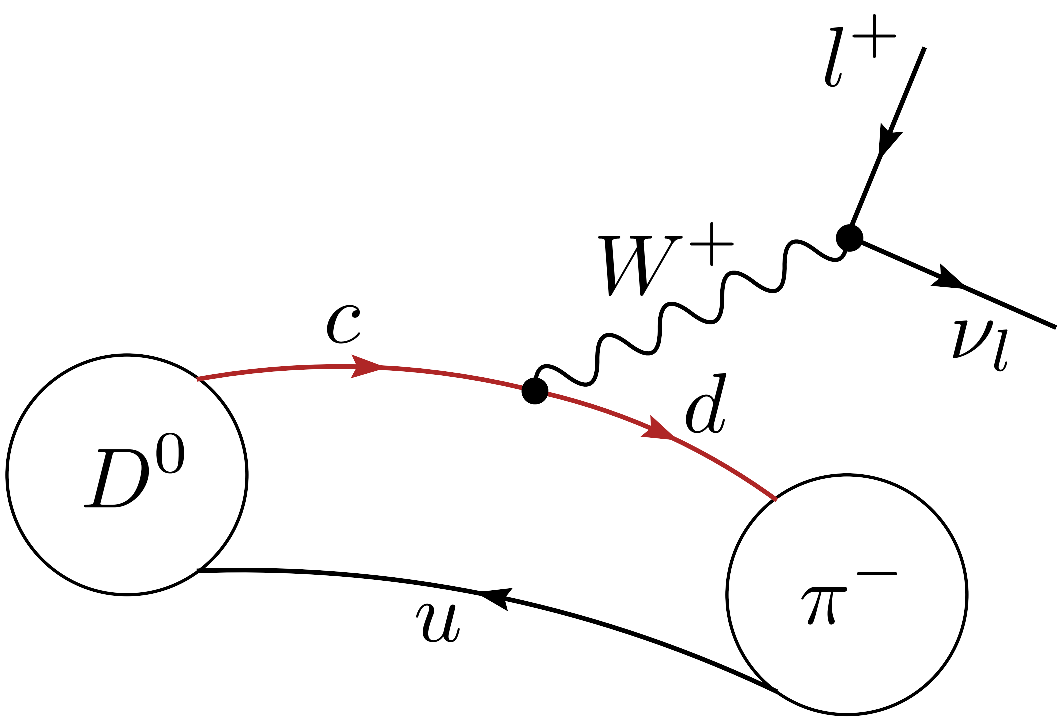


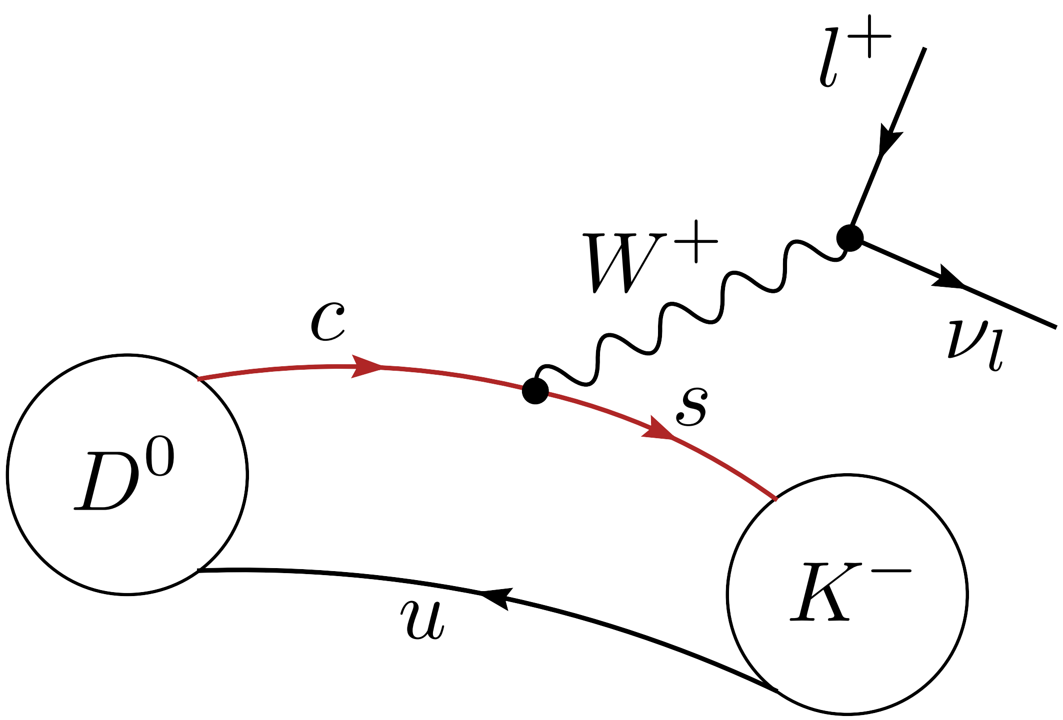


plan

- methods: where we stand (brief!)
  - ensembles used in HQ physics, reach
  - HQ approaches
- brief overview of
  - leptonic charm and B decay
  - B mixing
- charm and B semileptonic decays (+ CKM 2nd and 3rd rows)
- the % precision target
- conclusions and outlook

charm semileptonic decay

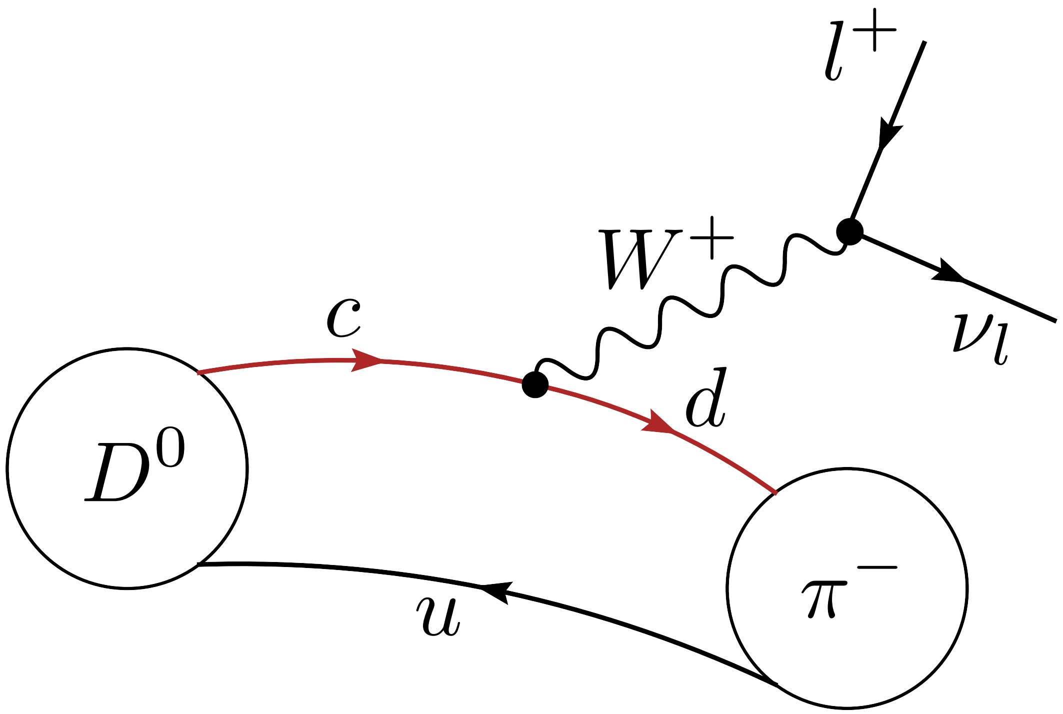


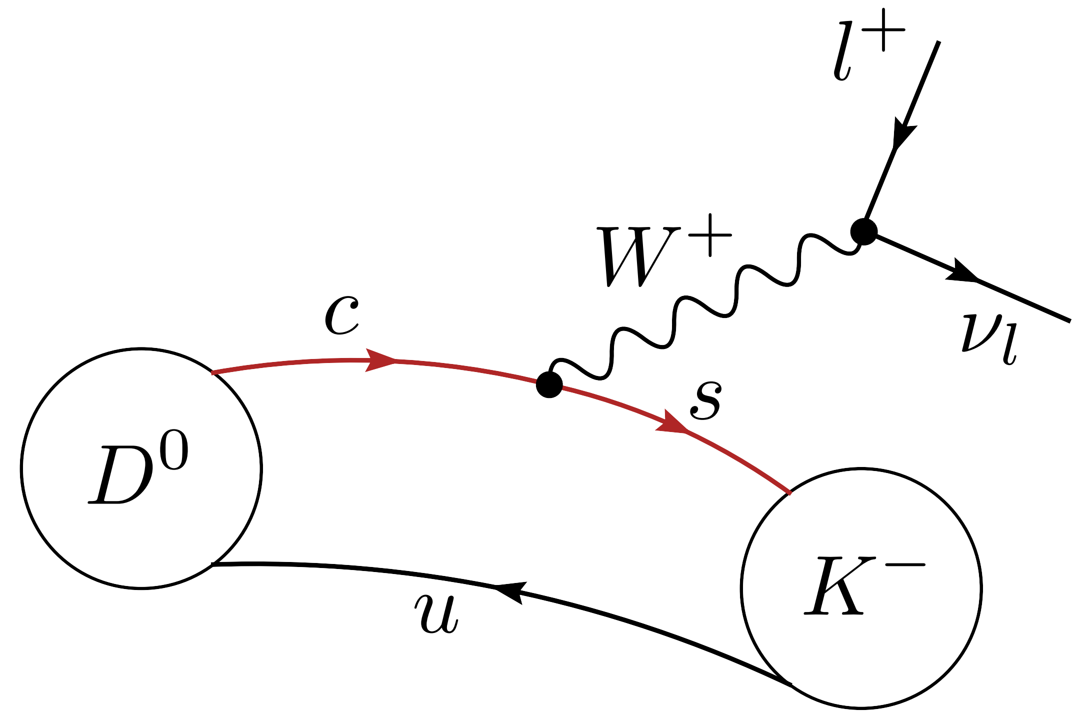


$$\frac{\mathrm{d}\Gamma(D\to Pl\nu)}{\mathrm{d}q^2} = \frac{G_{\mathrm{F}}^2|V_{cq}|^2}{24\pi^3}\frac{(q^2-m_l^2)^2\sqrt{E_P^2-m_P^2}}{q^4m_D^2}\left[\left(1+\frac{m_l^2}{2q^2}\right)m_D^2(E_P^2-m_P^2)|f_+(q^2)|^2 + \frac{3m_l^2}{8q^2}(m_D^2-m_P^2)^2|f_0(q^2)|^2\right]$$

$$\langle P(p')|\bar{c}\gamma_\mu q|D_q(p)\rangle = f_+(q^2)\left(p_\mu+p'_\mu-\frac{m_{D_q}^2-m_P^2}{q^2}\,q_\mu\right) + f_0(q^2)\,\frac{m_{D_q}^2-m_P^2}{q^2}\,q_\mu\,, \qquad q=p-p'$$

charm semileptonic decay



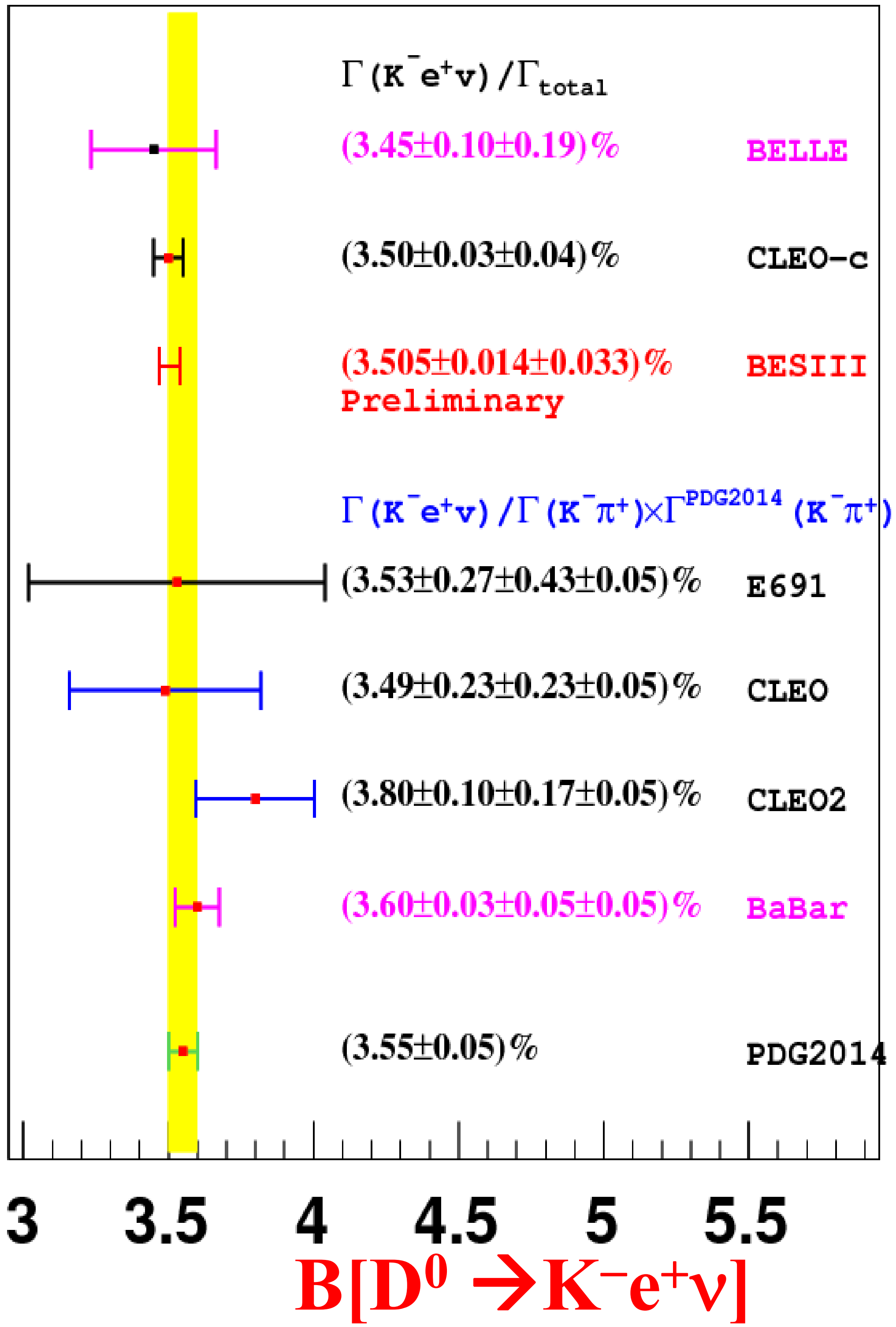


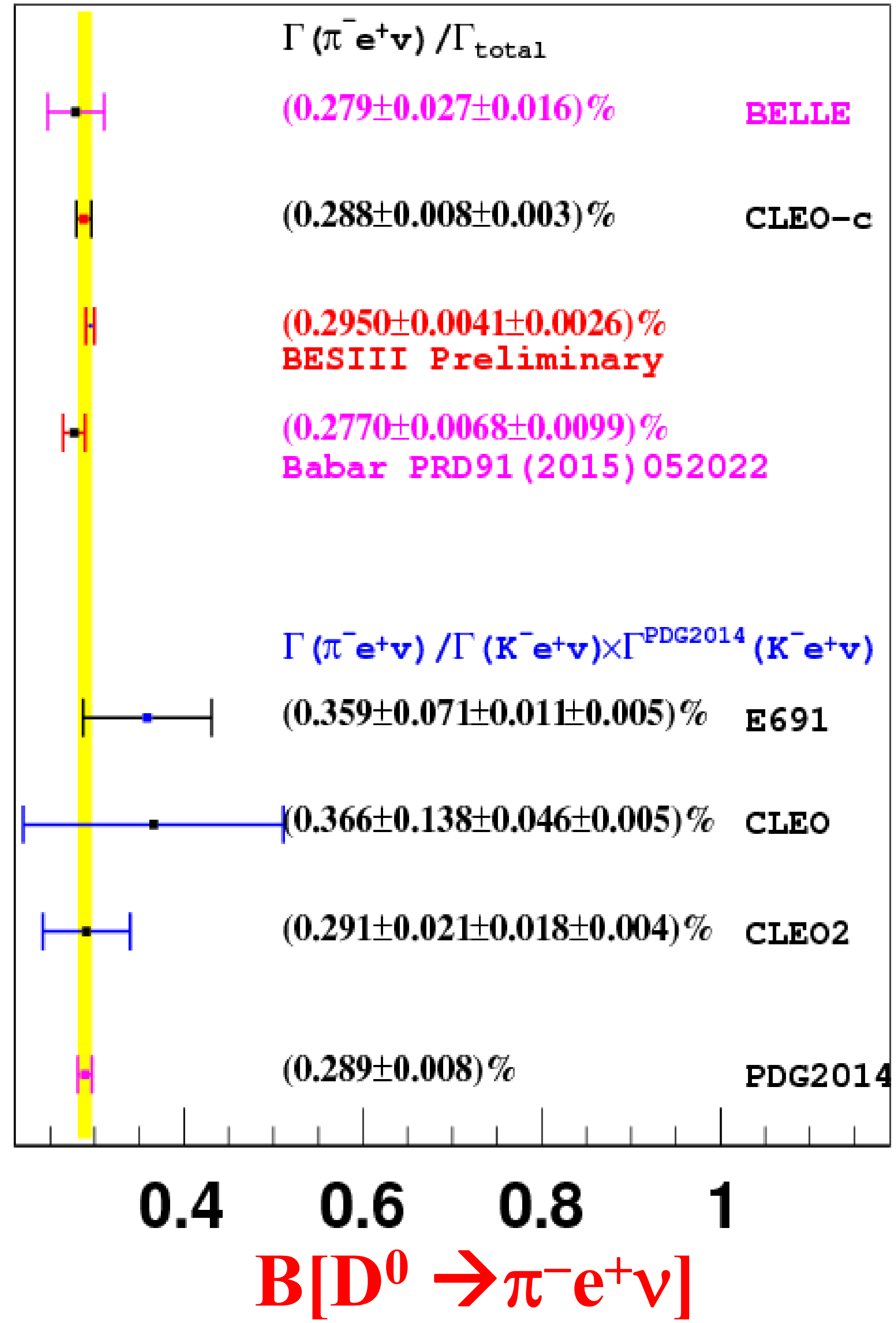
$$\frac{\mathrm{d}\Gamma(D \to P l \nu)}{\mathrm{d}q^2} = \frac{G_\mathrm{F}^2 |V_{cq}|^2}{24\pi^3} \frac{(q^2 - m_l^2)^2 \sqrt{E_P^2 - m_P^2}}{q^4 m_D^2} \left[\left(1 + \frac{m_l^2}{2q^2}\right) m_D^2 (E_P^2 - m_P^2) |f_+(q^2)|^2 + \frac{3m_l^2}{8q^2} (m_D^2 - m_P^2)^2 |f_0(q^2)|^2 \right]$$

e,μ suppressed

uncertainties from kinematical factors / neglected h.o. OPE at the permille level

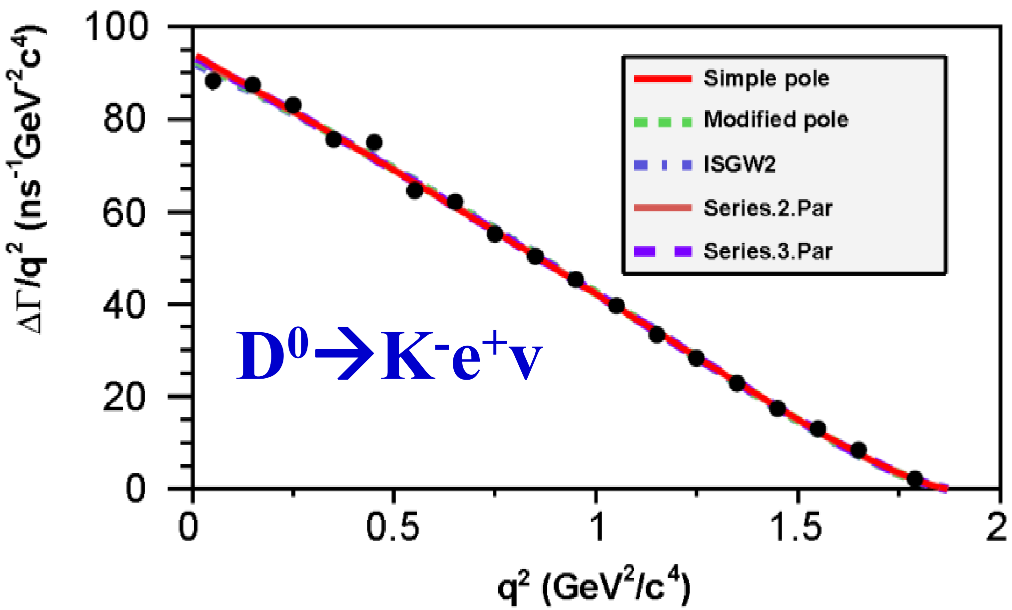
charm semileptonic decay

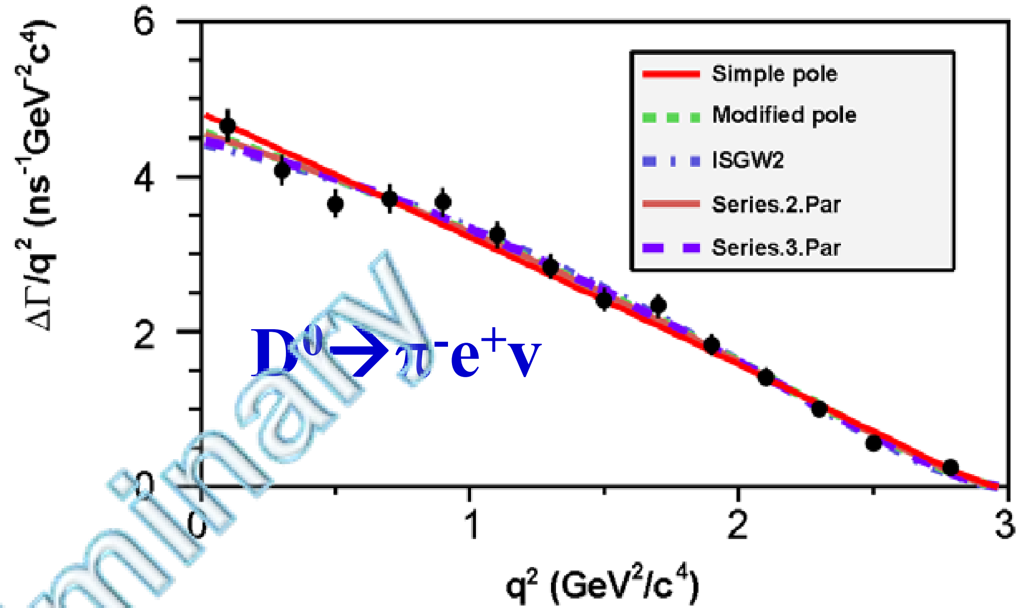




[from H Ma's talk on behalf of BESIII at CHARM 2015]

charm semileptonic decay



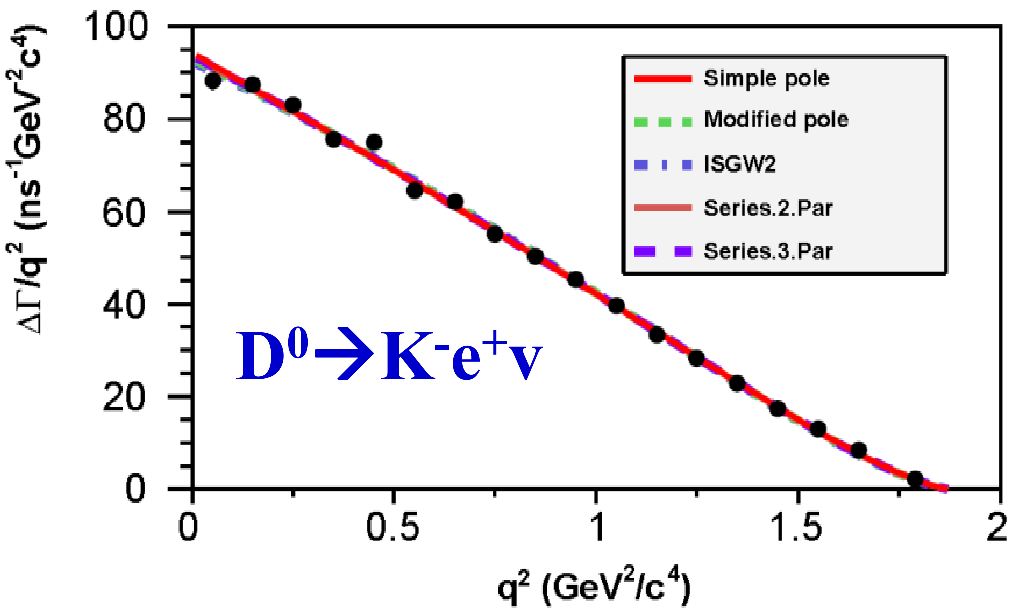


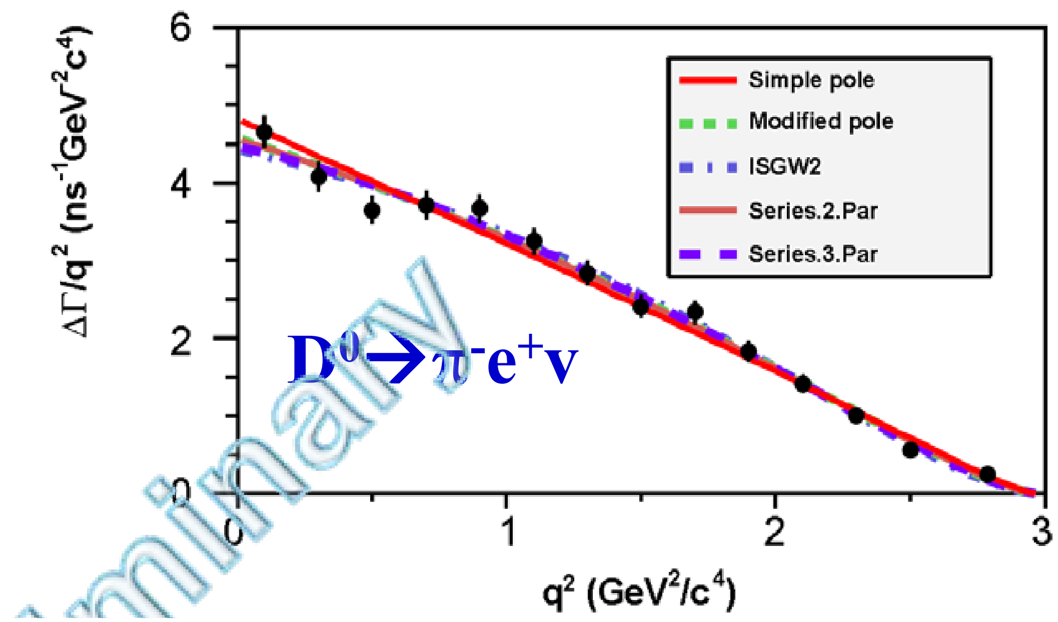
BESIII Preliminary

		$D^0 \rightarrow K^- e^+ \nu$		$D^0 \rightarrow \pi^- e^+ \nu$
Simple Pole	$f_K^+(0)\|V_{cs}\|$	0.7209±0.0022±0.0033	$f_\pi^+(0)\|V_{cd}\|$	0.1475±0.0014±0.0005
	M_{pole}	1.9207±0.0103±0.0069	M_{pole}	1.9114±0.0118±0.0038
Mod. Pole	$f_K^+(0)\|V_{cs}\|$	0.7163±0.0024±0.0034	$f_\pi^+(0)\|V_{cd}\|$	0.1437±0.0017±0.0008
	α	0.3088±0.0195±0.0129	α	0.2794±0.0345±0.0113
ISGW2	$f_K^+(0)\|V_{cs}\|$	0.7139±0.0023±0.0034	$f_\pi^+(0)\|V_{cd}\|$	0.1415±0.0016±0.0006
	r_{ISGW2}	1.6000±0.0141±0.0091	r_{ISGW2}	2.0688±0.0394±0.0124
Series.2.Par	$f_K^+(0)\|V_{cs}\|$	0.7172±0.0025±0.0035	$f_\pi^+(0)\|V_{cd}\|$	0.1435±0.0018±0.0009
	r_1	-2.2278±0.0864±0.0575	r_1	-2.0365±0.0807±0.0260
Series.3.Par	$f_K^+(0)\|V_{cs}\|$	0.7196±0.0035±0.0041	$f_\pi^+(0)\|V_{cd}\|$	0.1420±0.0024±0.0010
	r_1	-2.3331±0.1587±0.0804	r_1	-1.8434±0.2212±0.0690
	r_2	3.4223±3.9090±2.4092	r_2	-1.3871±1.4615±0.4677

[from H Ma's talk on behalf of BESIII at CHARM 2015]

charm semileptonic decay

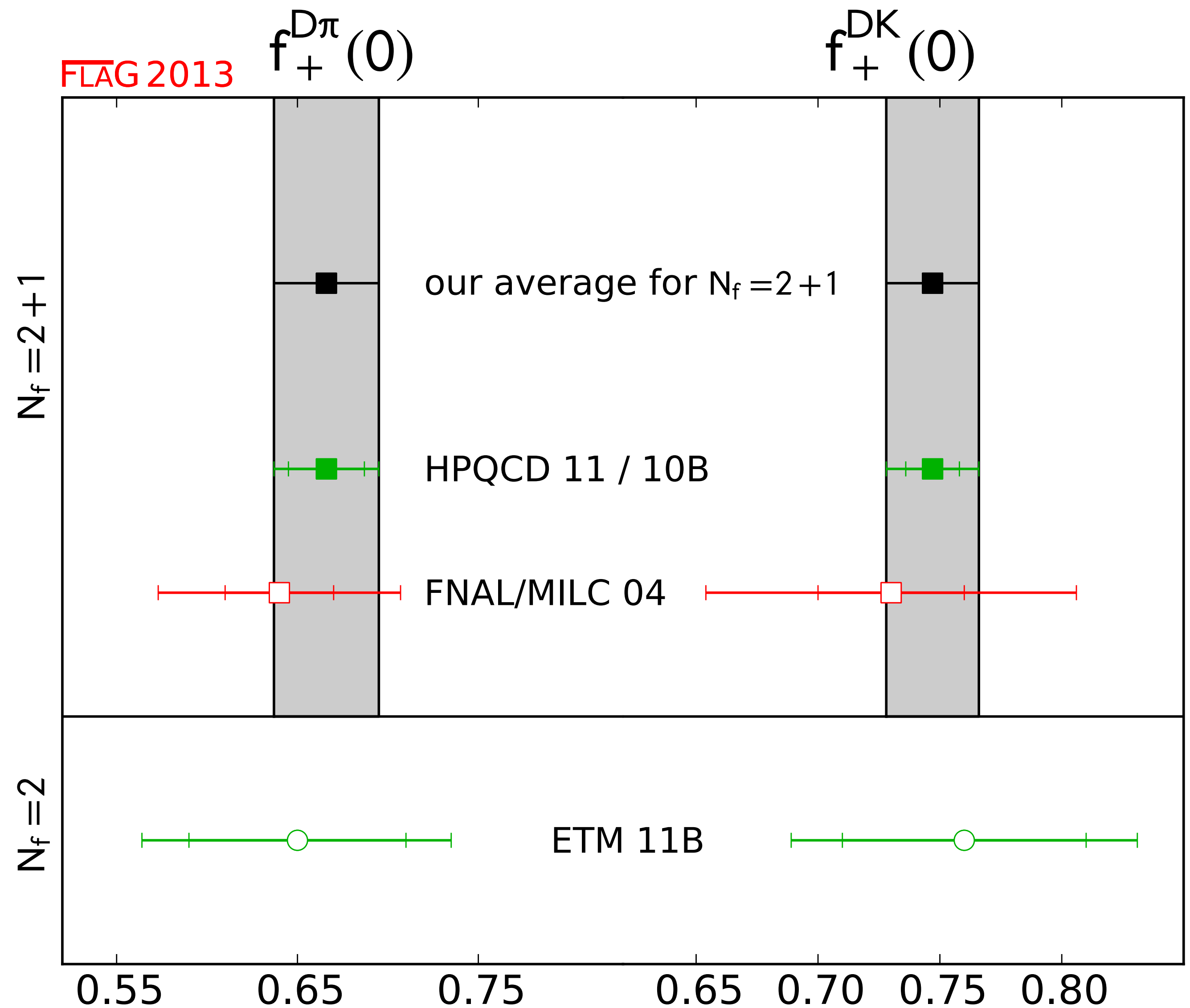




low q^2 region accessible to lattice computations $\Rightarrow$ CKM can be determined by computing form factors at zero momentum

experimental precision increasing, parametrisation dependence of experimental result for q^2=0 relevant: need to start worrying about q^2 dependence (which provides a stronger SM test anyway!)

FLAG-2 on charm semileptonic decay



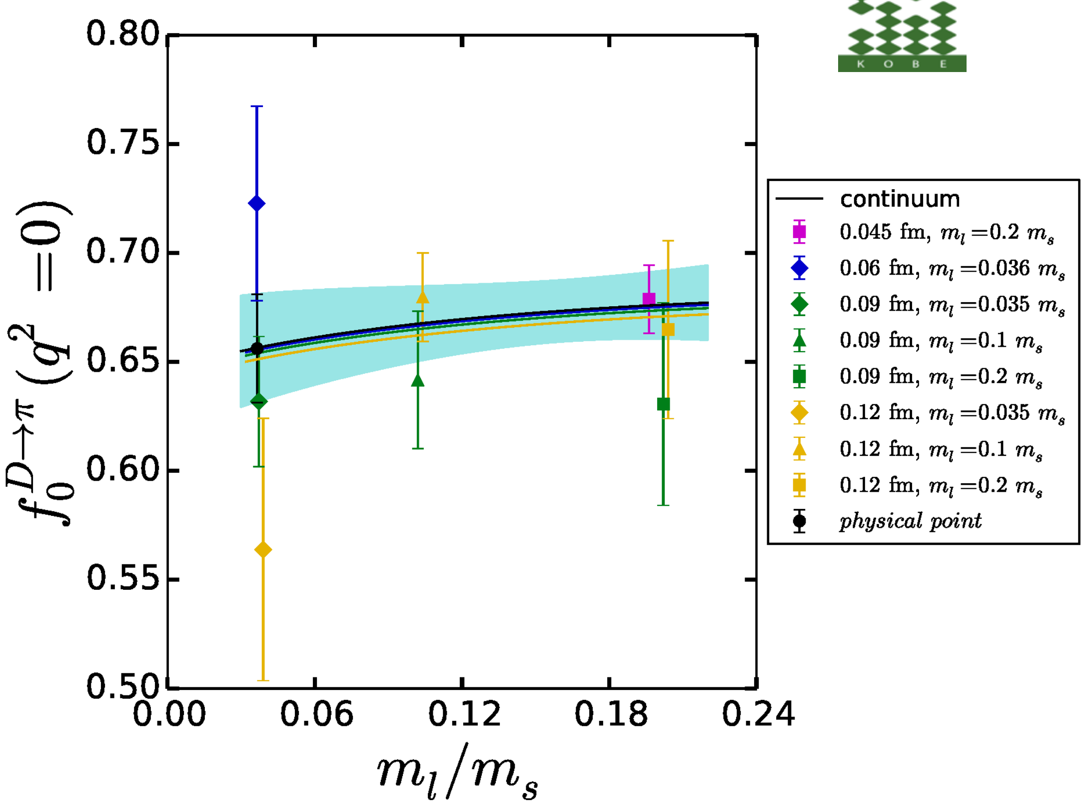
	$f_+^{D\pi}(0)$	$f_+^{DK}(0)$
2+1	0.666(29)	0.747(19)

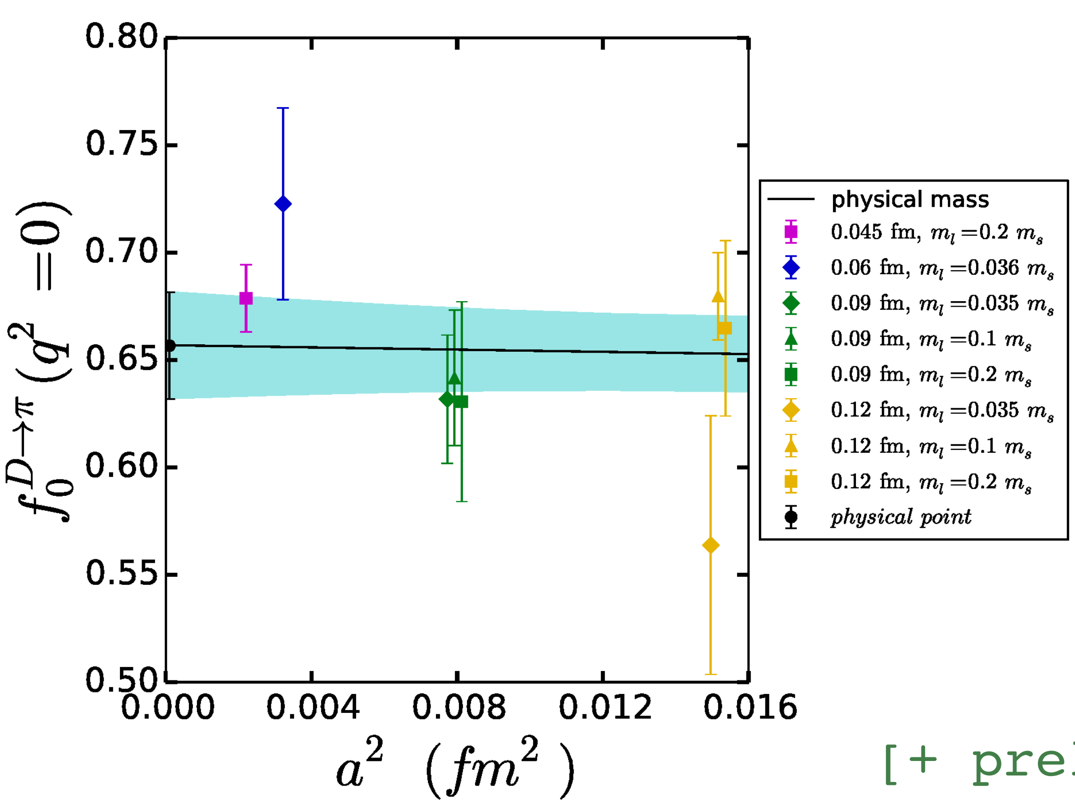
[FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

new results for charm SL form factors

[FNAL/MILC arXiv:1411.1651]

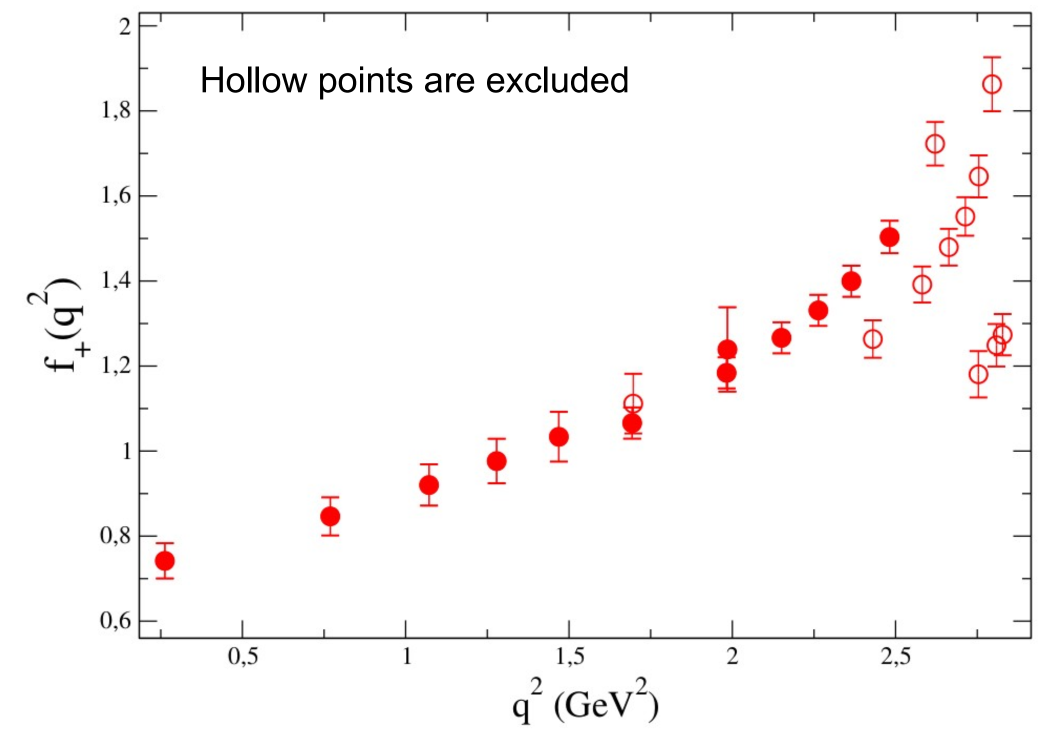
[T Primer, Thu 11:40]

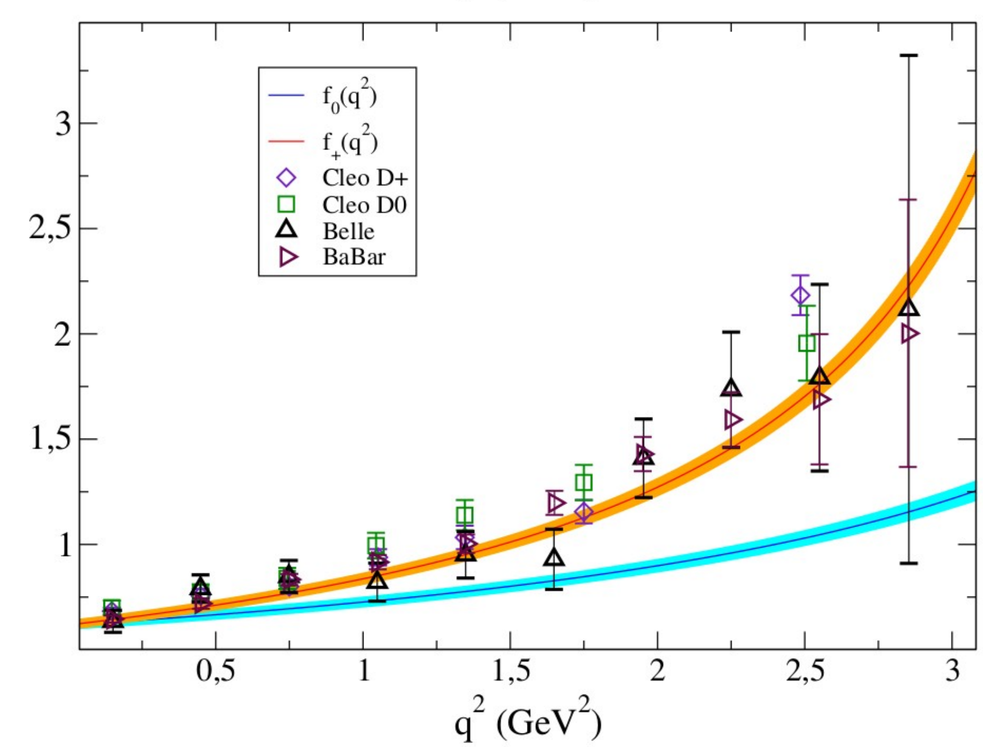




[P Lami, Wed 14:20]

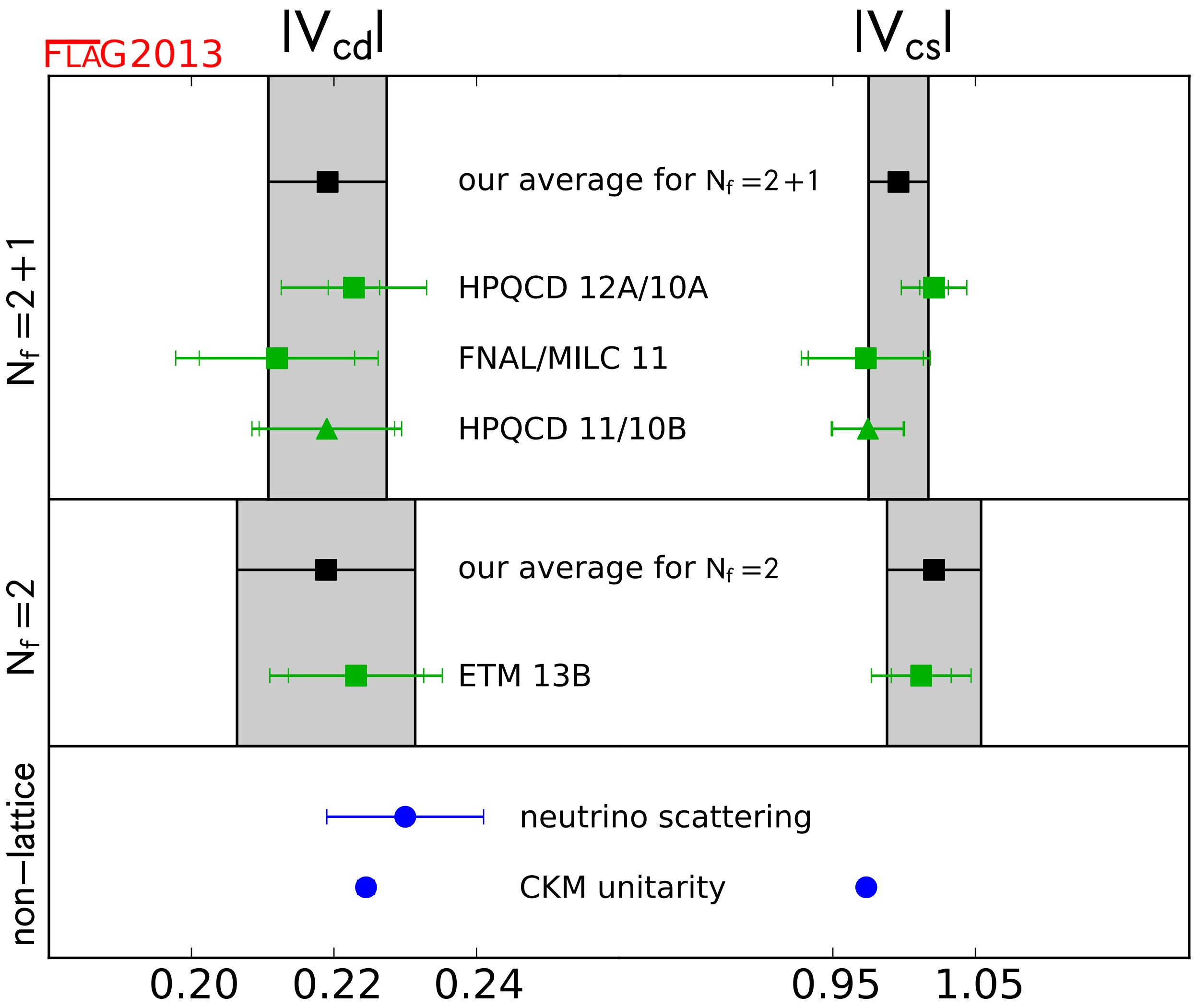
β =1.90 L=24 μ =0.0060





[+ preliminary work by JLQCD, cf. T Suzuki's talk]

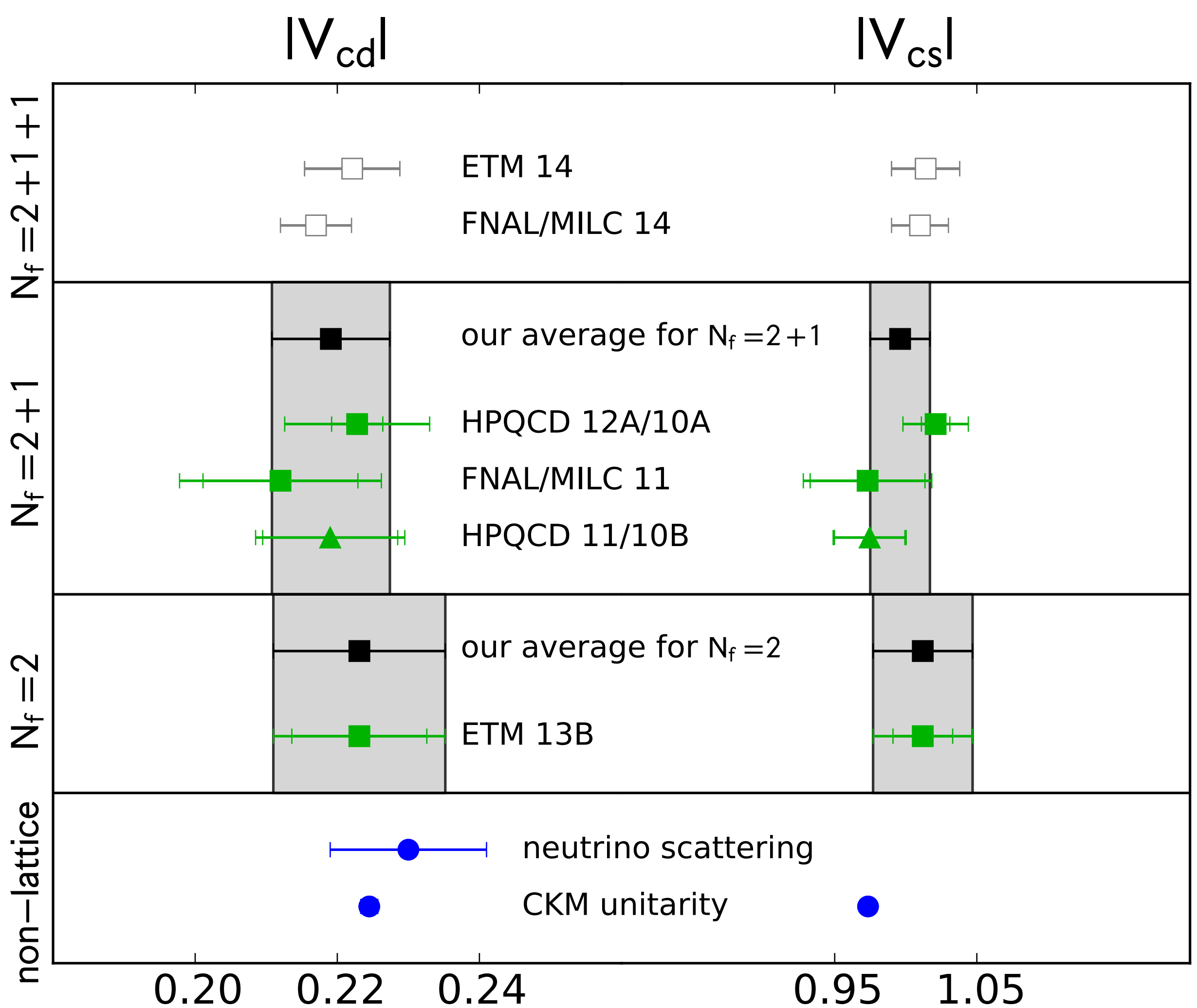
$|V_{cd}|$, $|V_{cs}|$, 2nd row CKM unitarity



$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 - 1 = 0.04(6)$$

averaged leptonic (more precise) and semileptonic determinations

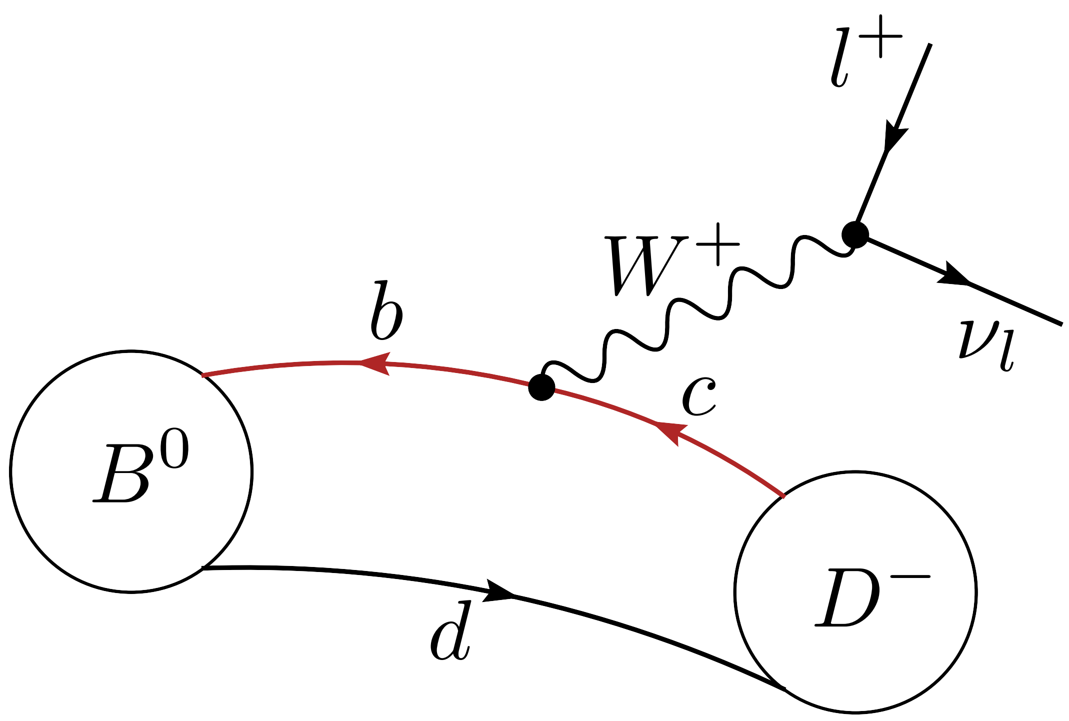
$|V_{cd}|$, $|V_{cs}|$, 2nd row CKM unitarity

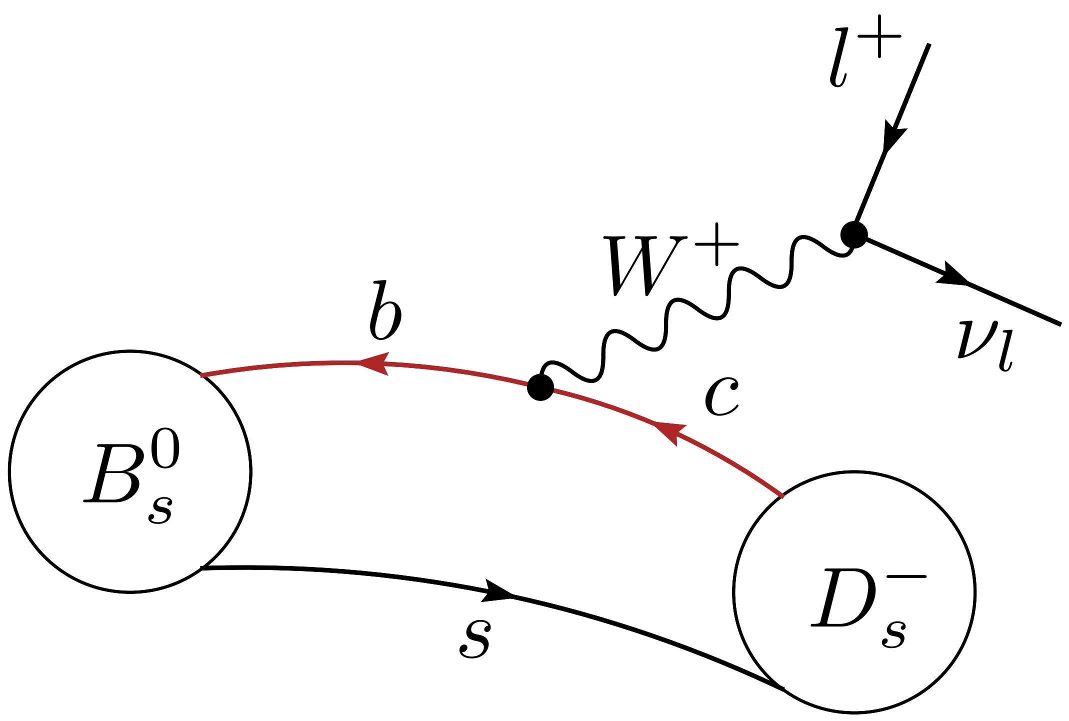


$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 - 1 = 0.04(6)$$

precise semileptonic determination will be interesting, sensitivity to $|V_{\mathrm{cb}}|$ around the corner

B semileptonic decay: $|V_{cb}|$

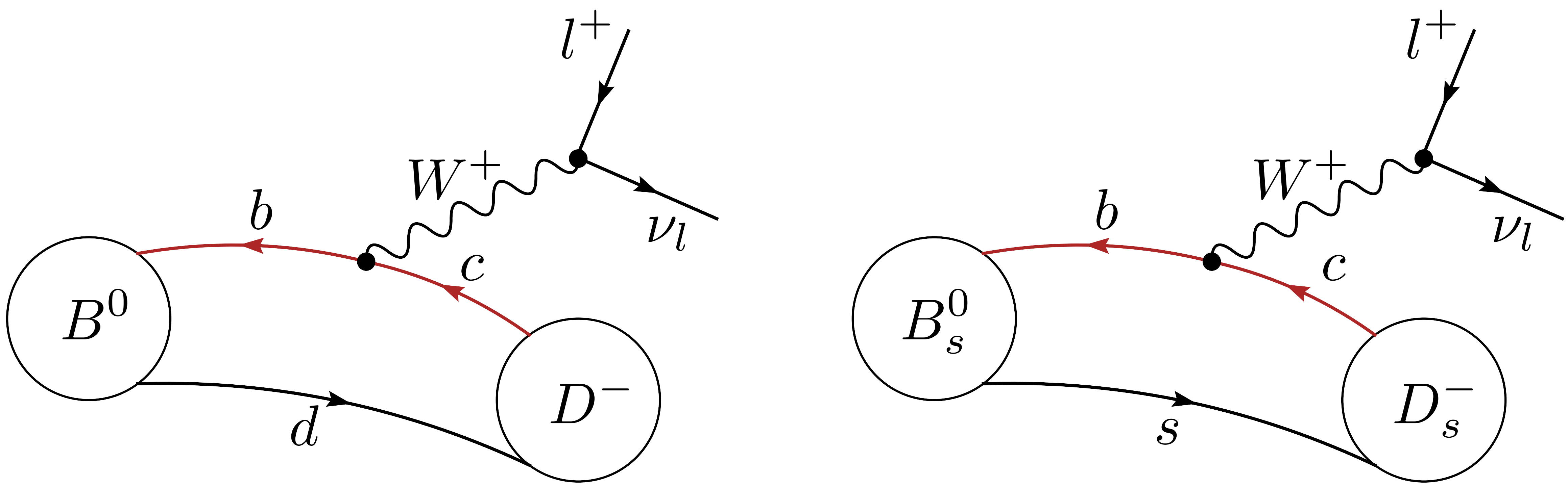




$$\frac{\mathrm{d}\Gamma(B_{(s)} \to Pl\nu)}{\mathrm{d}q^2} = \frac{G_F^2\,|V_{cb}|^2}{24\pi^3}\,\frac{(q^2-m_l^2)^2\sqrt{E_P^2-m_P^2}}{q^4 m_{B_{(s)}}^2}\left[\left(1+\frac{m_l^2}{2q^2}\right)m_{B_{(s)}}^2(E_P^2-m_P^2)|f_+(q^2)|^2 + \frac{3m_l^2}{8q^2}(m_{B_{(s)}}^2-m_P^2)^2|f_0(q^2)|^2\right]$$

$$\langle P(p')|\bar{b}\gamma_\mu q|B_q(p)\rangle = f_+(q^2)\left(p_\mu + p'_\mu - \frac{m_{B_q}^2-m_P^2}{q^2}\,q_\mu\right) + f_0(q^2)\,\frac{m_{B_q}^2-m_P^2}{q^2}\,q_\mu\,, \qquad q = p - p'$$

B semileptonic decay: $|V_{cb}|$

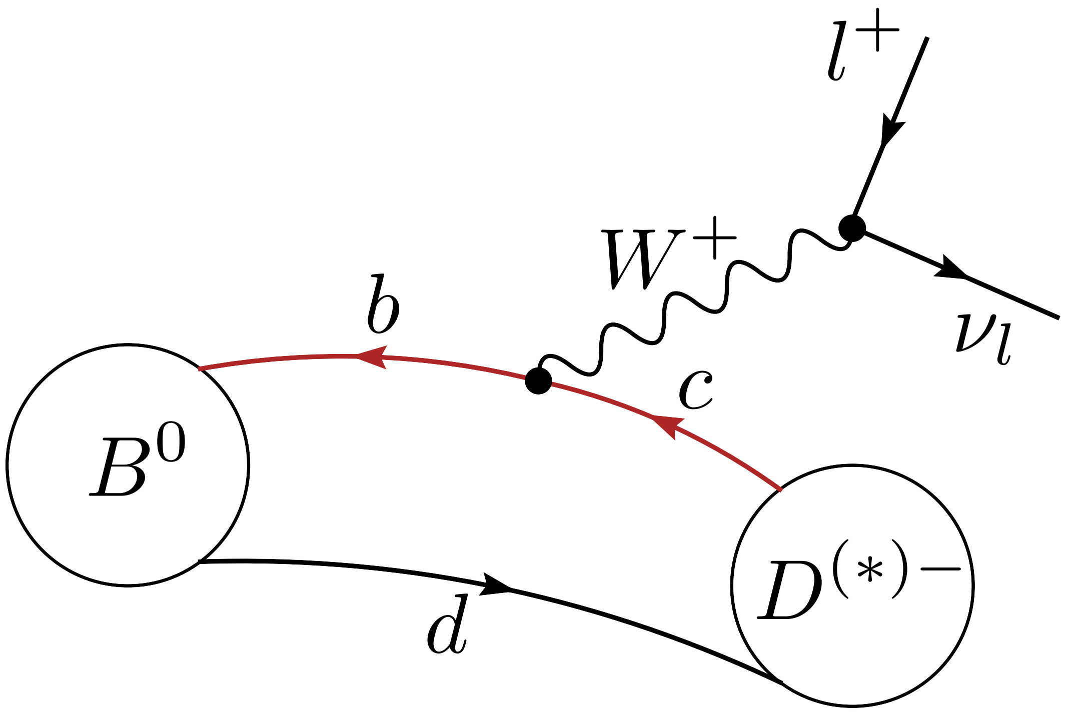


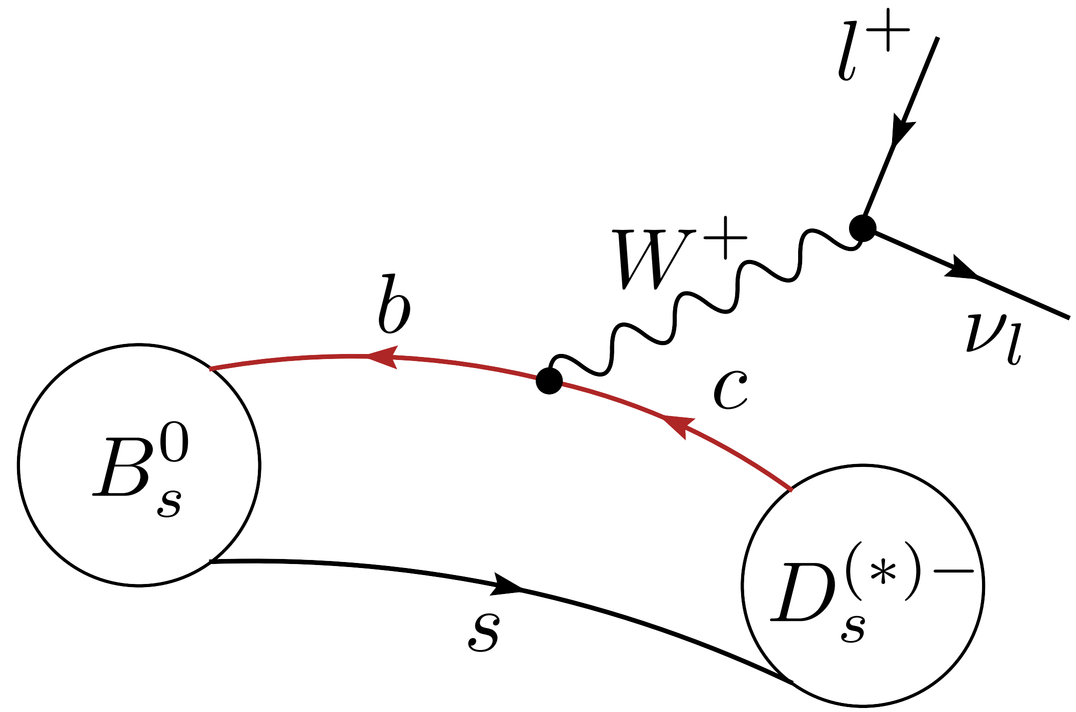
$$\frac{\mathrm{d}\Gamma(B_{(s)} \to P l \nu)}{\mathrm{d}q^2} = \frac{G_F^2 |V_{cb}|^2}{24\pi^3} \frac{(q^2 - m_l^2)^2 \sqrt{E_P^2 - m_P^2}}{q^4 m_{B_{(s)}}^2} \Bigg[\left(1 + \frac{m_l^2}{2q^2}\right) m_{B_{(s)}}^2 (E_P^2 - m_P^2) |f_+(q^2)|^2 + \frac{3m_l^2}{8q^2} (m_{B_{(s)}}^2 - m_P^2)^2 |f_0(q^2)|^2 \Bigg]$$

e,μ suppressed

uncertainties from kinematical factors / neglected h.o. OPE at the permille level

B semileptonic decay: $|V_{cb}|$



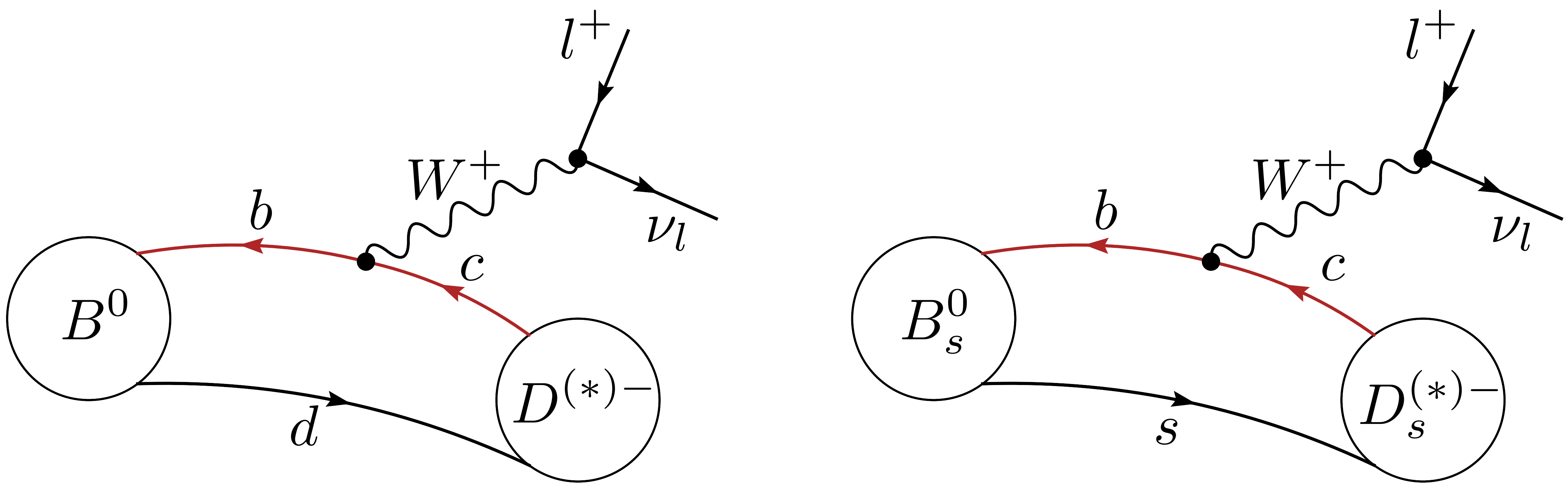


$$\frac{\mathrm{d}\Gamma(B \to D l \nu_l)}{\mathrm{d}w} = \frac{G_F^2}{48\pi^3}(m_B + m_D)^2(w^2-1)^{3/2}|\eta_{\mathrm{EW}}|^2\,|V_{cb}|^2\,|\mathcal{G}(w)|^2 \;+\; \mathcal{O}\left(\frac{m_l^2}{q^2}\right)$$

$$\frac{\mathrm{d}\Gamma(B \to D^* l \nu_l)}{\mathrm{d}w} = \frac{G_F^2}{4\pi^3}(m_B - m_{D^*})^2(w^2-1)^{1/2}|\eta_{\mathrm{EW}}|^2\chi(w)\,|V_{cb}|^2\,|\mathcal{F}(w)|^2 \;+\; \mathcal{O}\left(\frac{m_l^2}{q^2}\right)$$

$$w = \frac{p_B \cdot p_{D^{(*)}}}{m_B m_{D^{(*)}}} \qquad \mathcal{G}(w) = \frac{4\,\frac{m_D}{m_B}}{1+\frac{m_D}{m_B}}\,f_+(q^2) \qquad \text{etc}$$

B semileptonic decay: $|V_{cb}|$



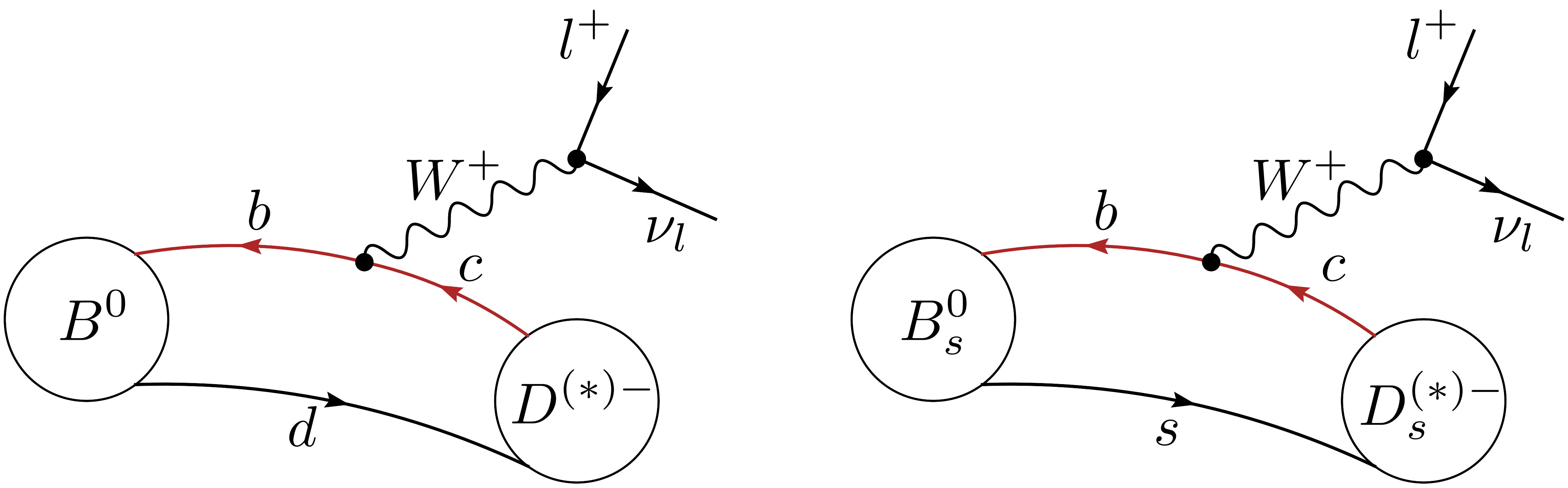
$$\frac{\mathrm{d}\Gamma(B \to D l \nu_l)}{\mathrm{d}w} = \frac{G_F^2}{48\pi^3}(m_B + m_D)^2 (w^2-1)^{3/2} |\eta_{\mathrm{EW}}|^2 \, |V_{cb}|^2 \, |\mathcal{G}(w)|^2 \; + \; \mathcal{O}\left(\frac{m_l^2}{q^2}\right)$$

$$\frac{\mathrm{d}\Gamma(B \to D^* l \nu_l)}{\mathrm{d}w} = \frac{G_F^2}{4\pi^3}(m_B - m_{D^*})^2 (w^2-1)^{1/2} |\eta_{\mathrm{EW}}|^2 \chi(w) \, |V_{cb}|^2 \, |\mathcal{F}(w)|^2 \; + \; \mathcal{O}\left(\frac{m_l^2}{q^2}\right)$$

low recoil region accessible to lattice computations ⇒ CKM can be determined by computing form factors at w=1

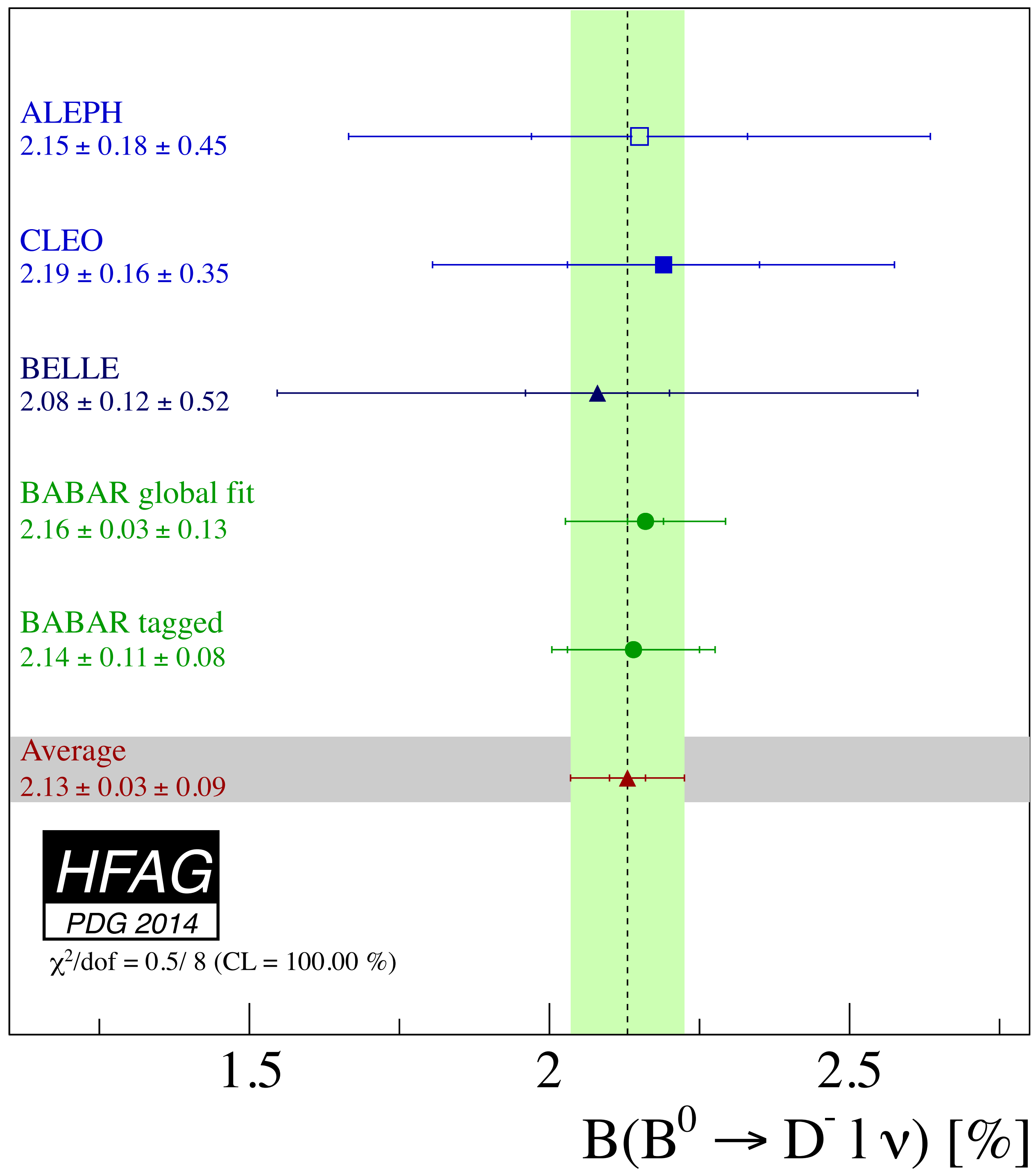
shape information relevant as precision increases

B semileptonic decay: $|V_{cb}|$

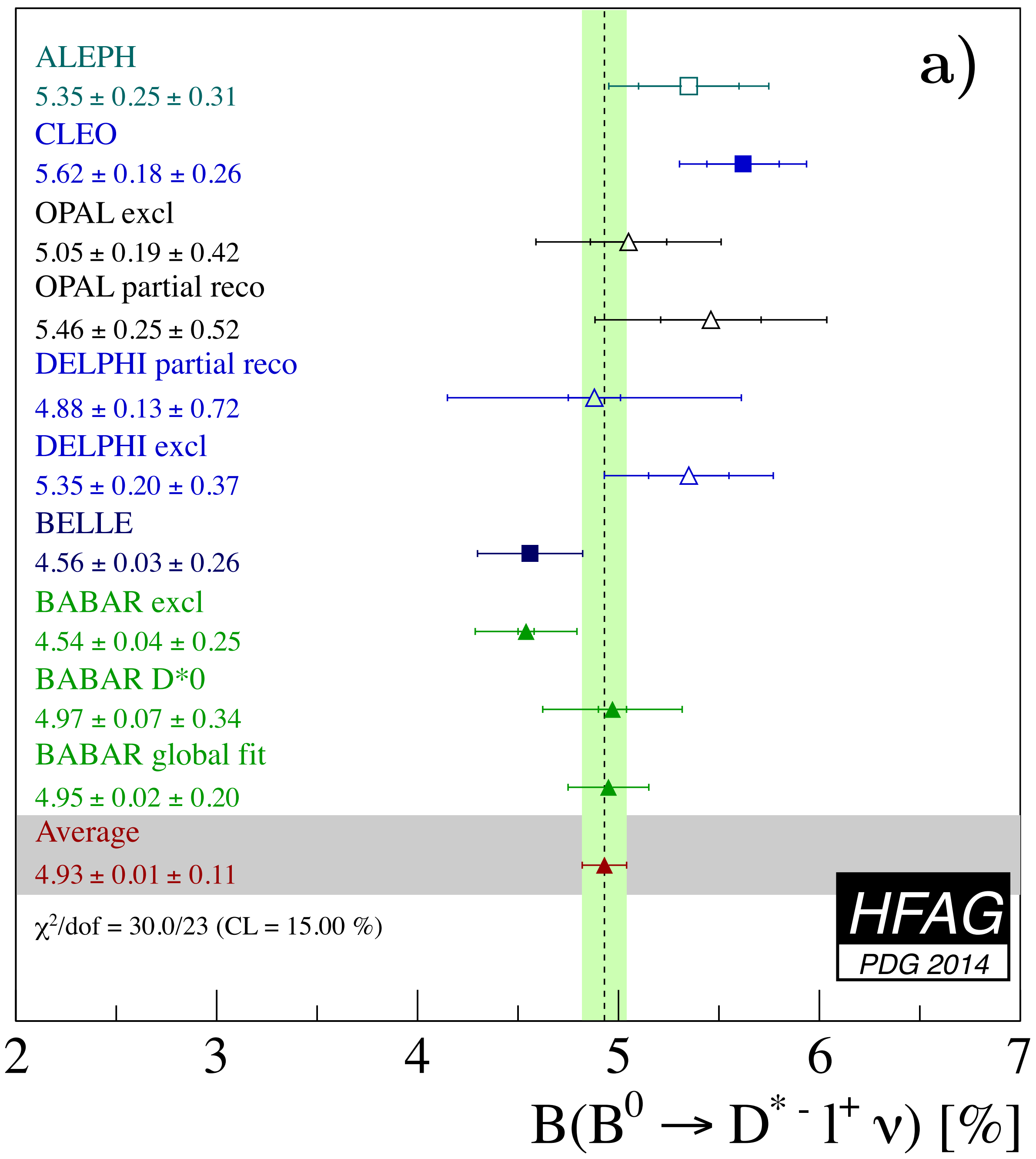


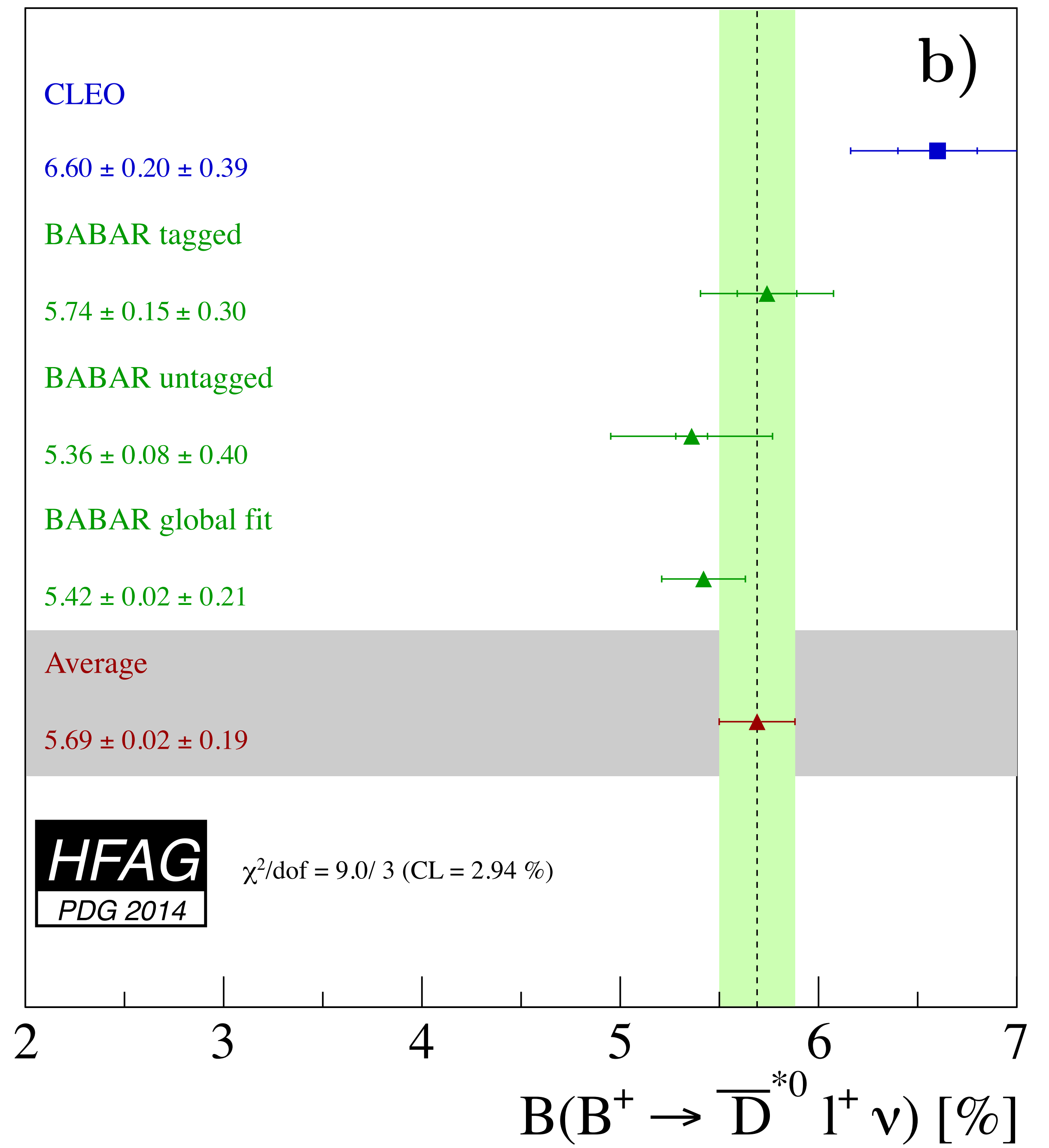
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)} \quad [\longrightarrow f_0(q^2)]$$

B semileptonic decay: $|V_{cb}|$

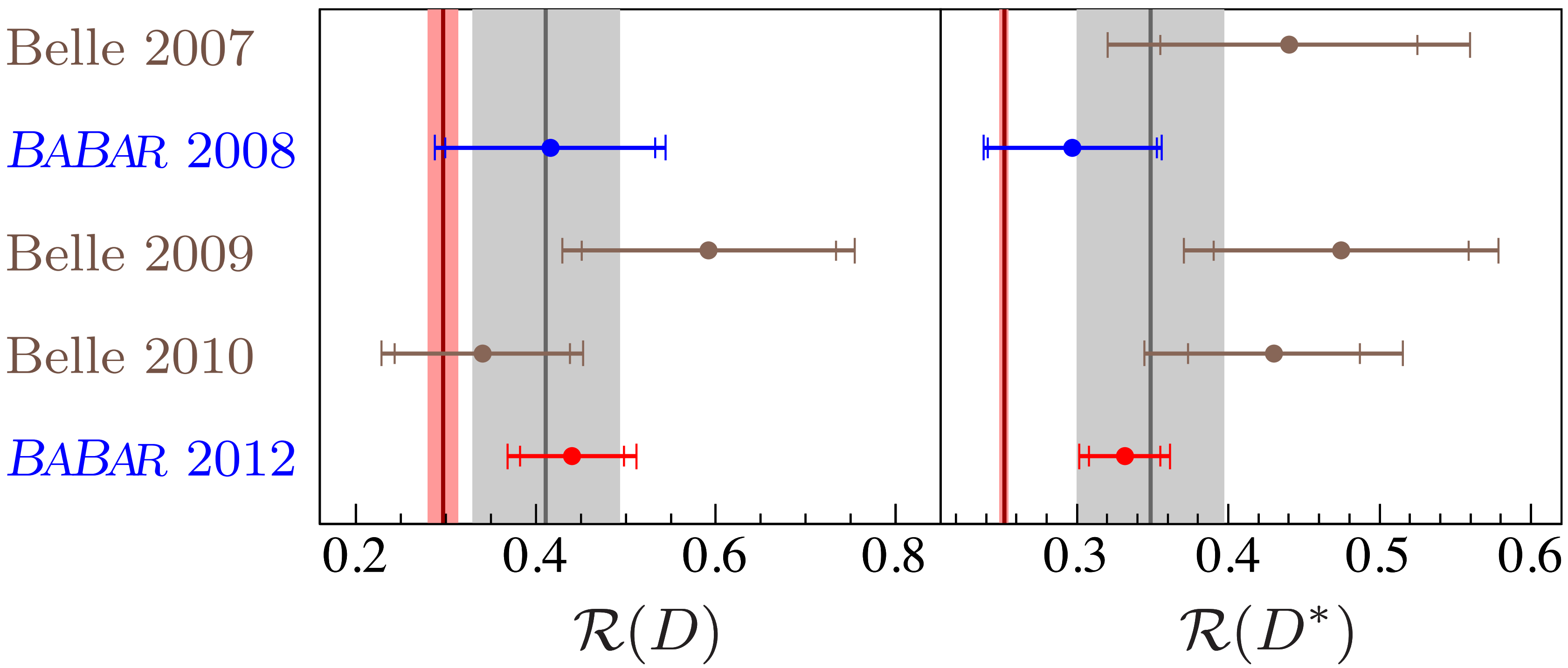


B semileptonic decay: $|V_{cb}|$

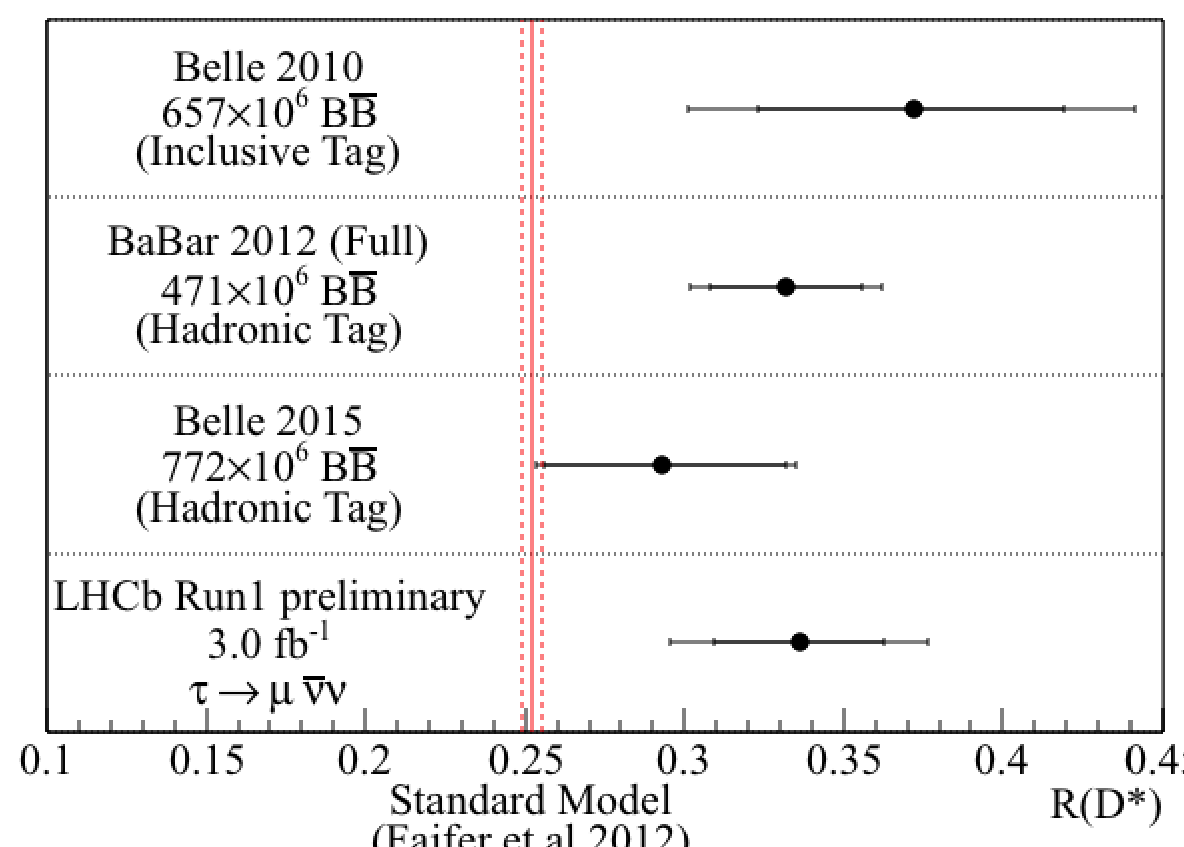




$R(D^{(*)})$, new measurements of $B \to D^* \tau \nu$



[pre-2015, arXiv:1303.0571]



[Ciezarek/Kuhr, FPCP 2015]
[LHCb, arXiv:1506.08614]
[Belle, arXiv:1507.03233]

Belle II projections

Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$	± 0.012	± 0.008	6
α		$\pm 2^\circ$	$\pm 1^\circ$	
γ	$\pm 14^\circ$	$\pm 6^\circ$	$\pm 1.5^\circ$	
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	± 0.053	± 0.018	>50
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	± 0.028	± 0.011	>50
$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$	± 0.100	± 0.033	44
$\lvert V_{cb} \rvert$ incl.	$\pm 2.4\%$	$\pm 1.0\%$		< 1
$\lvert V_{cb} \rvert$ excl.	$\pm 3.6\%$	$\pm 1.8\%$	$\pm 1.4\%$	< 1
$\lvert V_{ub} \rvert$ incl.	$\pm 6.5\%$	$\pm 3.4\%$	$\pm 3.0\%$	2
$\lvert V_{ub} \rvert$ excl. (had. tag.)	$\pm 10.8\%$	$\pm 4.7\%$	$\pm 2.4\%$	20
$\lvert V_{ub} \rvert$ excl. (untag.)	$\pm 9.4\%$	$\pm 4.2\%$	$\pm 2.2\%$	3
$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	96 ± 26	$\pm 10\%$	$\pm 5\%$	46
$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7	5σ	$>> 5\sigma$	>50
$R(B \to D\tau\nu)$	$\pm 16.5\%$	$\pm 5.6\%$	$\pm 3.4\%$	4
$R(B \to D^*\tau\nu)$	$\pm 9.0\%$	$\pm 3.2\%$	$\pm 2.1\%$	3
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ [10^{-6}]	< 40		$\pm 30\%$	>50
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ [10^{-6}]	< 55		$\pm 30\%$	>50
$\mathcal{B}(B \to X_s\gamma)$ [10^{-6}]	$\pm 13\%$	$\pm 7\%$	$\pm 6\%$	< 1
$A_{CP}(B \to X_s\gamma)$		± 0.01	± 0.005	8
$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$	± 0.11	± 0.035	> 50
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	± 0.23	± 0.07	> 50
C_7/C_9 $(B \to X_s \ell\ell)$	$\sim$20%	10%	5%	
$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7	± 0.3		
$\mathcal{B}(B_s \to \tau^+\tau^-)$ [10^{-3}]		< 2		

Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \times 10^{-3}(1 \pm 0.053 \pm 0.038)$	$\pm 2.9\%$	$\pm(0.9\%$-$1.3\%)$	> 50
$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \times 10^{-3}(1 \pm 0.037 \pm 0.054)$	$\pm(3.5\%$-$4.3\%)$	$\pm(2.3\%$-$3.6\%)$	3-5
y_{CP} [10^{-2}]	$1.11 \pm 0.22 \pm 0.11$	$\pm$(0.11-0.13)	$\pm$(0.05-0.08)	5-8
A_Γ [10^{-2}]	$-0.03 \pm 0.20 \pm 0.08$	± 0.10	$\pm$(0.03-0.05)	7 - 9
$A_{CP}^{K^+K^-}$ [10^{-2}]	$-0.32 \pm 0.21 \pm 0.09$	± 0.11	± 0.06	15
$A_{CP}^{\pi^+\pi^-}$ [10^{-2}]	$0.55 \pm 0.36 \pm 0.09$	± 0.17	$\pm$ 0.06	> 50
$A_{CP}^{\phi\gamma}$ [10^{-2}]	$\pm$ 5.6	± 2.5	± 0.8	> 50
$x^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	± 0.14	± 0.11	3
$y^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	± 0.08	± 0.05	15
$\lvert q/p \rvert^{K_S\pi^+\pi^-}$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	± 0.10	± 0.07	5-6
$\phi^{K_S\pi^+\pi^-}$ [$^\circ$]	$-6 \pm 11 \pm {}^{4}_{5}$	± 6	± 4	10
$A_{CP}^{\pi^0\pi^0}$ [10^{-2}]	$-0.03 \pm 0.64 \pm 0.10$	± 0.29	± 0.09	> 50
$A_{CP}^{K^0_S\pi^0}$ [10^{-2}]	$-0.10 \pm 0.16 \pm 0.09$	± 0.08	± 0.03	> 50
$Br(D^0 \to \gamma\gamma)$ [10^{-6}]	< 1.5	$\pm 30\%$	$\pm 25\%$	2
	$\tau \to \mu\gamma$ [10^{-9}]	< 45	< 14.7	< 4.7
	$\tau \to e\gamma$ [10^{-9}]	< 120	< 39	< 12
	$\tau \to \mu\mu\mu$ [10^{-9}]	< 21.0	< 3.0	< 0.3

[BELLE2-NOTE-PH-2015-002, retrieved from B2TiP]

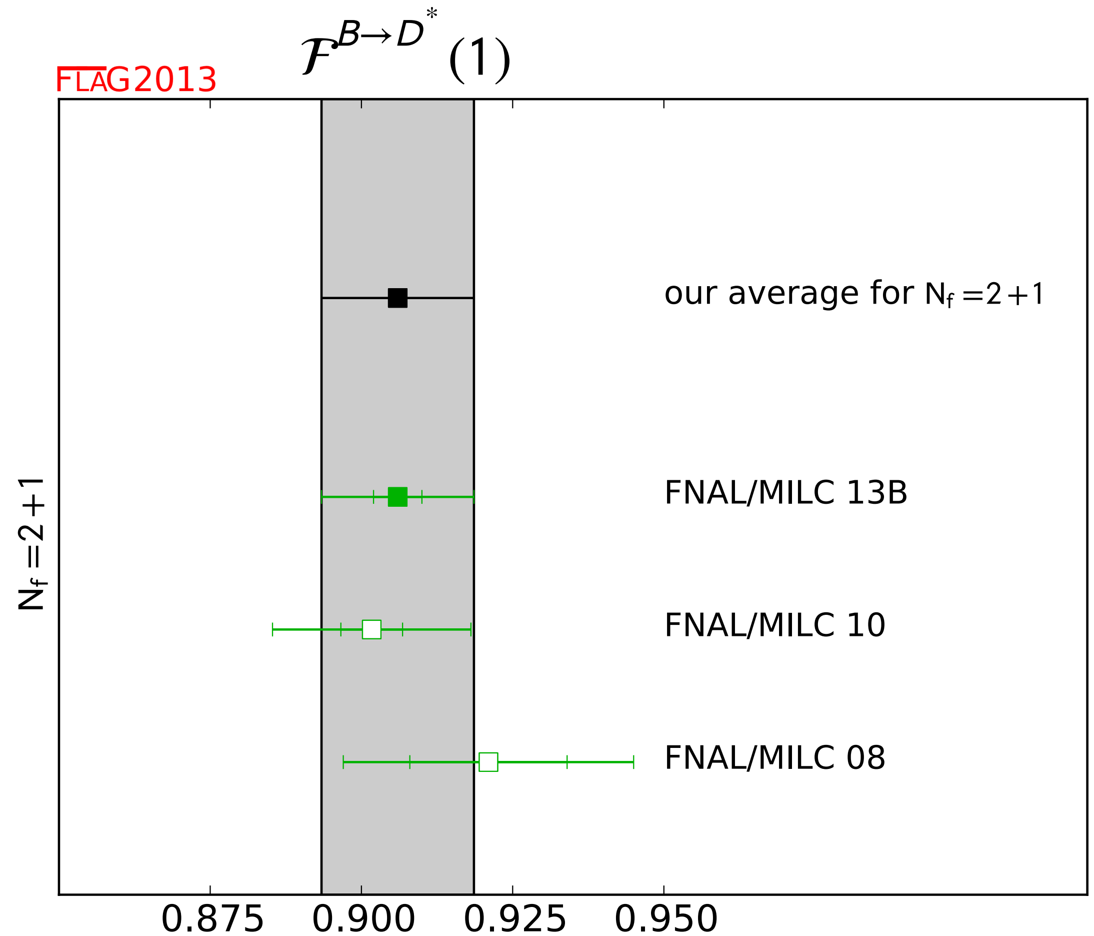
FLAG-2 on $B \to D^{(*)} l\nu$

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization	heavy-quark treatment	form factor		
FNAL/MILC 13B	[446]	2+1	C$^{\nabla}$	★	○	★	○	✓	$\mathcal{F}^{B\to D^*}(1)$	0.906(4)(12)	$w = 1$
FNAL/MILC 10	[443]	2+1	C§	★	○	★	○	✓	$\mathcal{F}^{B\to D^*}(1)$	0.9017(51)(87)(83)(89)(30)(33) ‡	$w = 1$
FNAL/MILC 08	[444]	2+1	A	★	○	★	○	✓	$\mathcal{F}^{B\to D^*}(1)$	0.921(13)(8)(8)(14)(6)(3)(4)	$w = 1$
FNAL/MILC 13B	[446]	2+1	C	★	○	★	○	✓	$\mathcal{G}^{B\to D}(1)$	1.081(25)	$w = 1$
FNAL/MILC 04A	[445]	2+1	C	■	■	○*	○†	✓	$\mathcal{G}^{B\to D}(1)$	1.074(18)(16)	$w = 1$
FNAL/MILC 12A	[452]	2+1	A	○	○	★	○	✓	$R(D)$	0.316(12)(7)	$w = 1$
Atoui 13	[448]	2	P	★	★	★	—	✓	$\mathcal{G}^{B\to D}(1)$	1.033(95)	$w \geq 1$
Atoui 13	[448]	2	P	★	★	★	—	✓	$\mathcal{G}^{B_s\to D_s}(1)$	1.052(46)	$w \geq 1$

$^{\nabla}$ Update of FNAL/MILC 08 for Lattice 2013.
§ Update of FNAL/MILC 08 for CKM 2010.
‡ Value of $\mathcal{F}(1)$ presented in Ref. [443] includes 0.7% correction η_{EW}. This correction is unrelated to the lattice calculation and has been removed here.
* No explicit estimate of FV error, but expected to be small.
† No explicit estimate of perturbative truncation error in vector current renormalization factor, but expected to be small because of mostly-nonperturbative approach.

[FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

FLAG-2 on $B \to D^{(*)} l\nu$

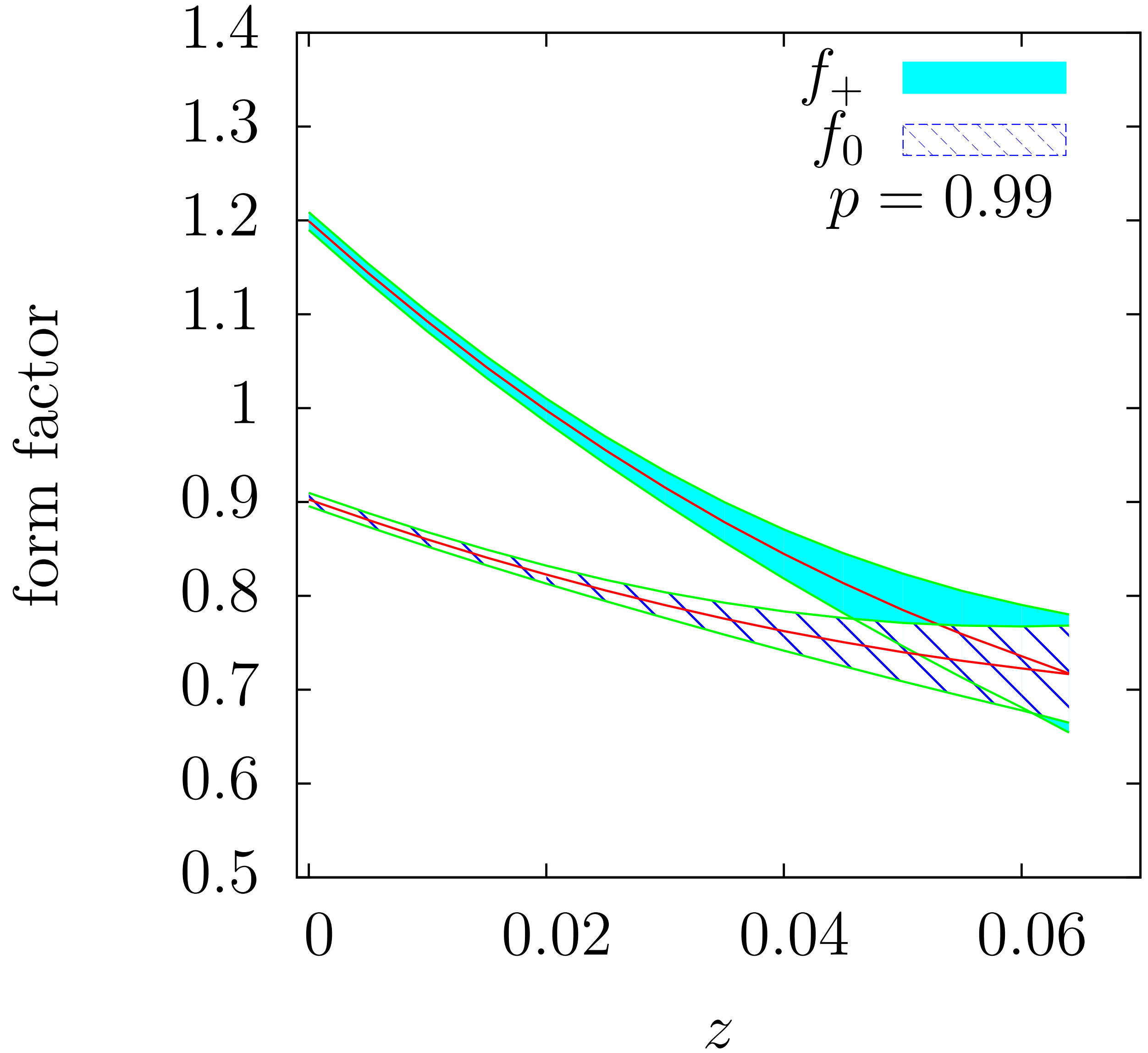


N_f	$\mathcal{G}^{B\to D}(1)$	$\mathcal{G}^{B_s\to D_s}(1)$	$\mathcal{F}^{B\to D^*}(1)$	$R(D)$
2	1.033(95)	1.052(46)	—	—
2+1	1.081(25)	—	0.906(4)(12)	0.316(12)(7)

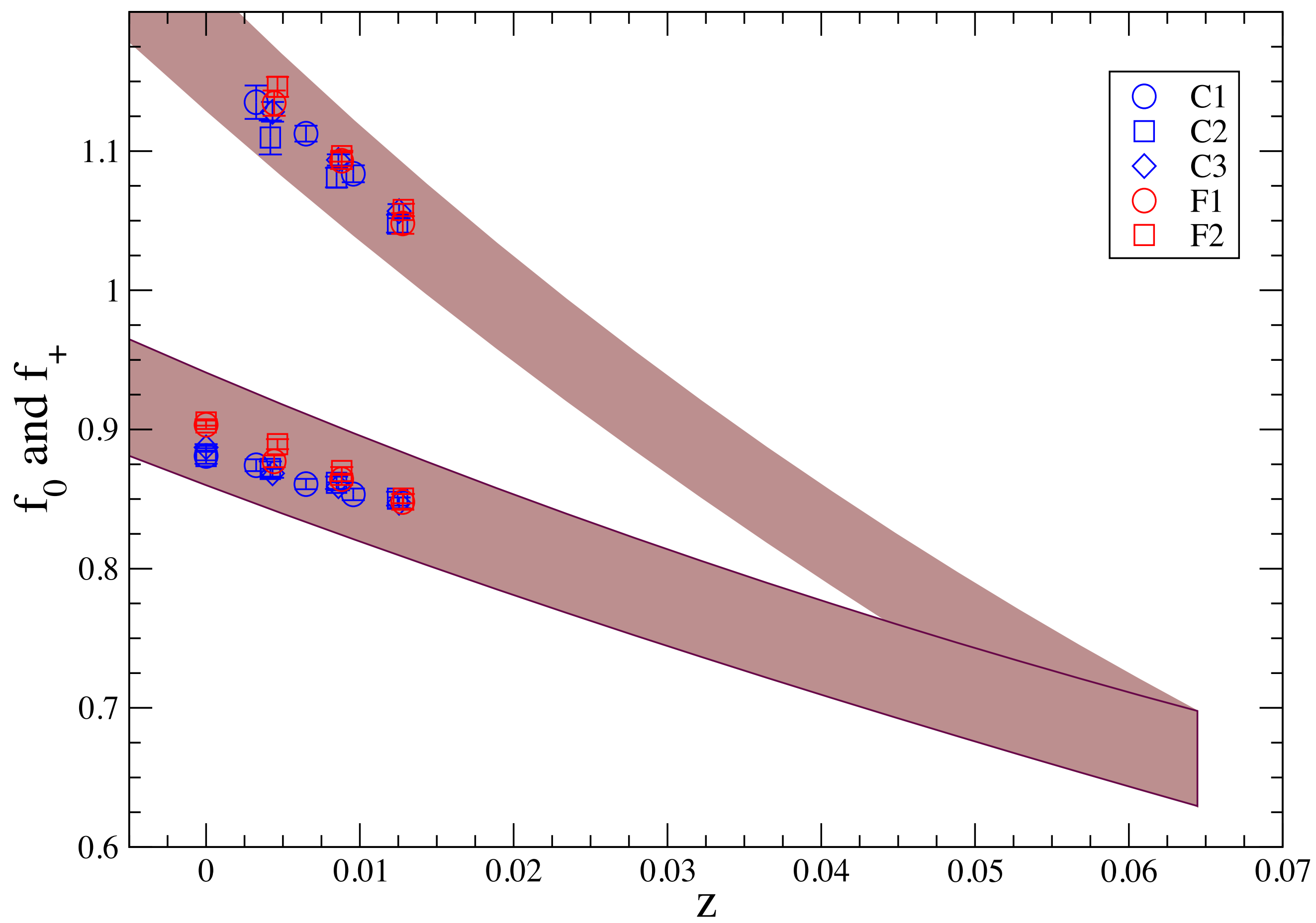
[FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

new results for $B \to Dl\nu$

[FNAL/MILC]



[HPQCD]



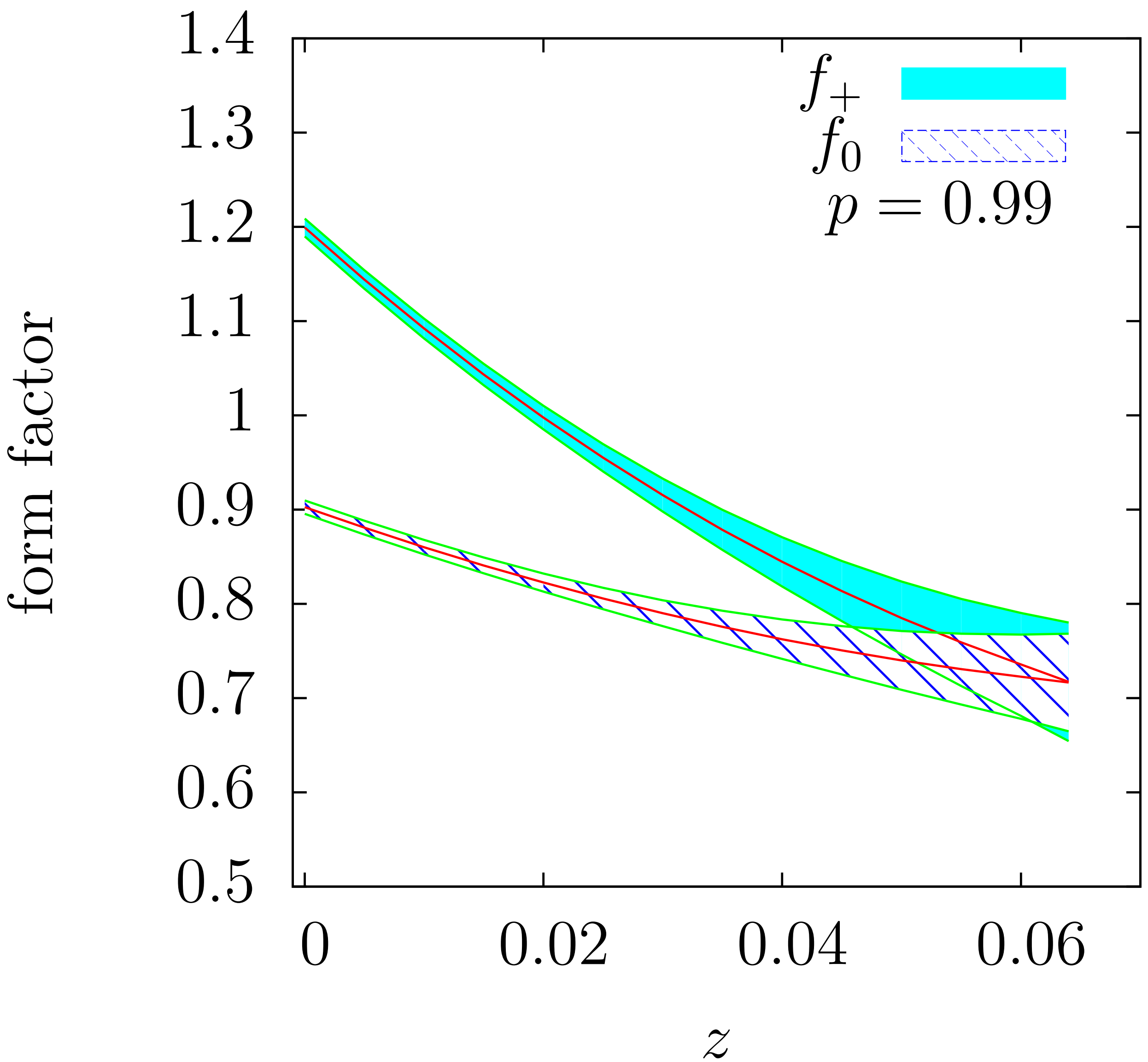
$$z(w) = \frac{\sqrt{1+w} - \sqrt{2}}{\sqrt{1+w} + \sqrt{2}}$$

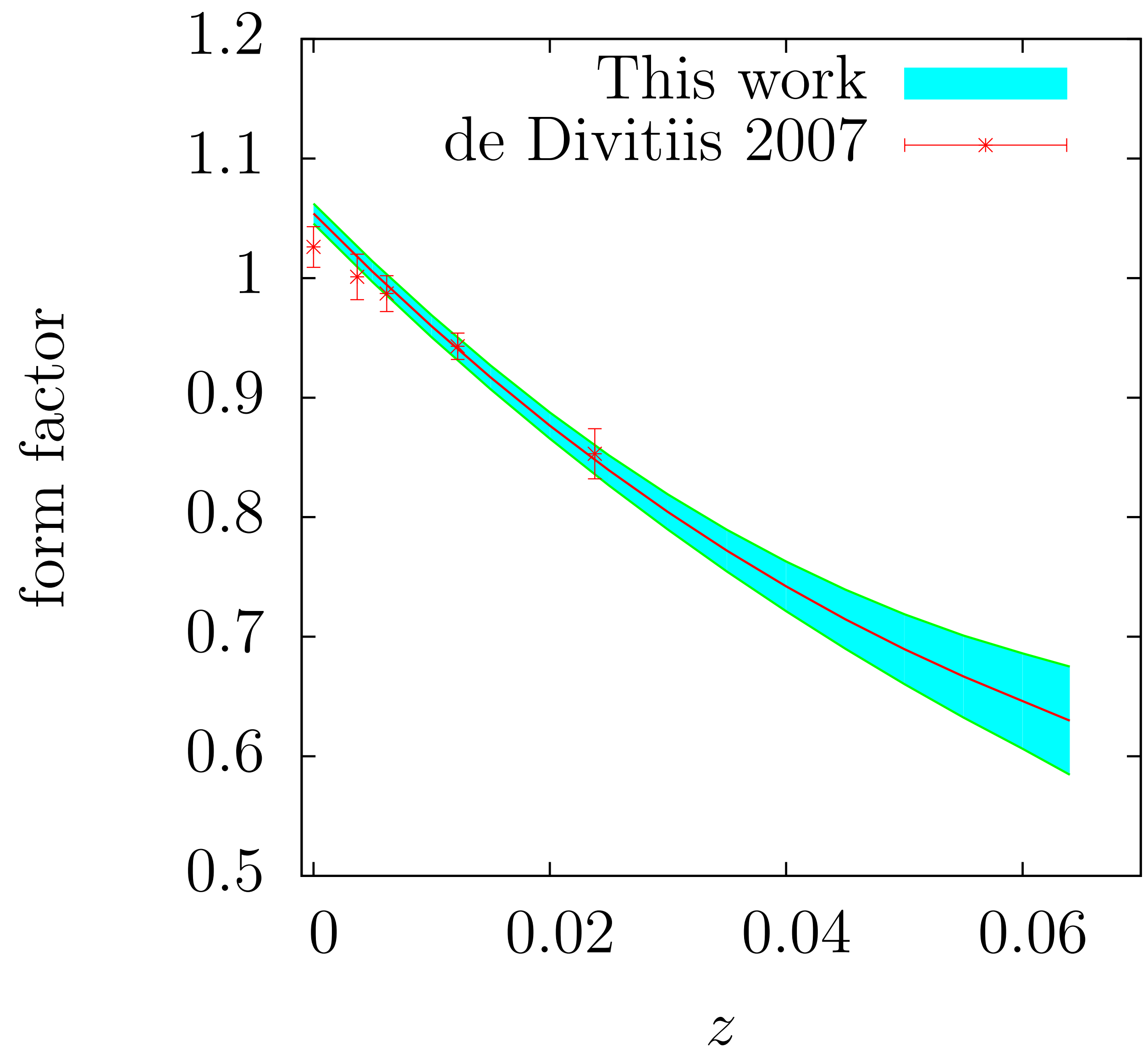
$w_{\rm latt} \in [1.00, 1.16]$ $w_{\rm exp} \in [1.00, 1.58]$

$z_{\rm latt} \in [0.00, 0.02]$ $z_{\rm exp} \in [0.00, 0.06]$

new results for $B \to Dl\nu$

[FNAL/MILC]





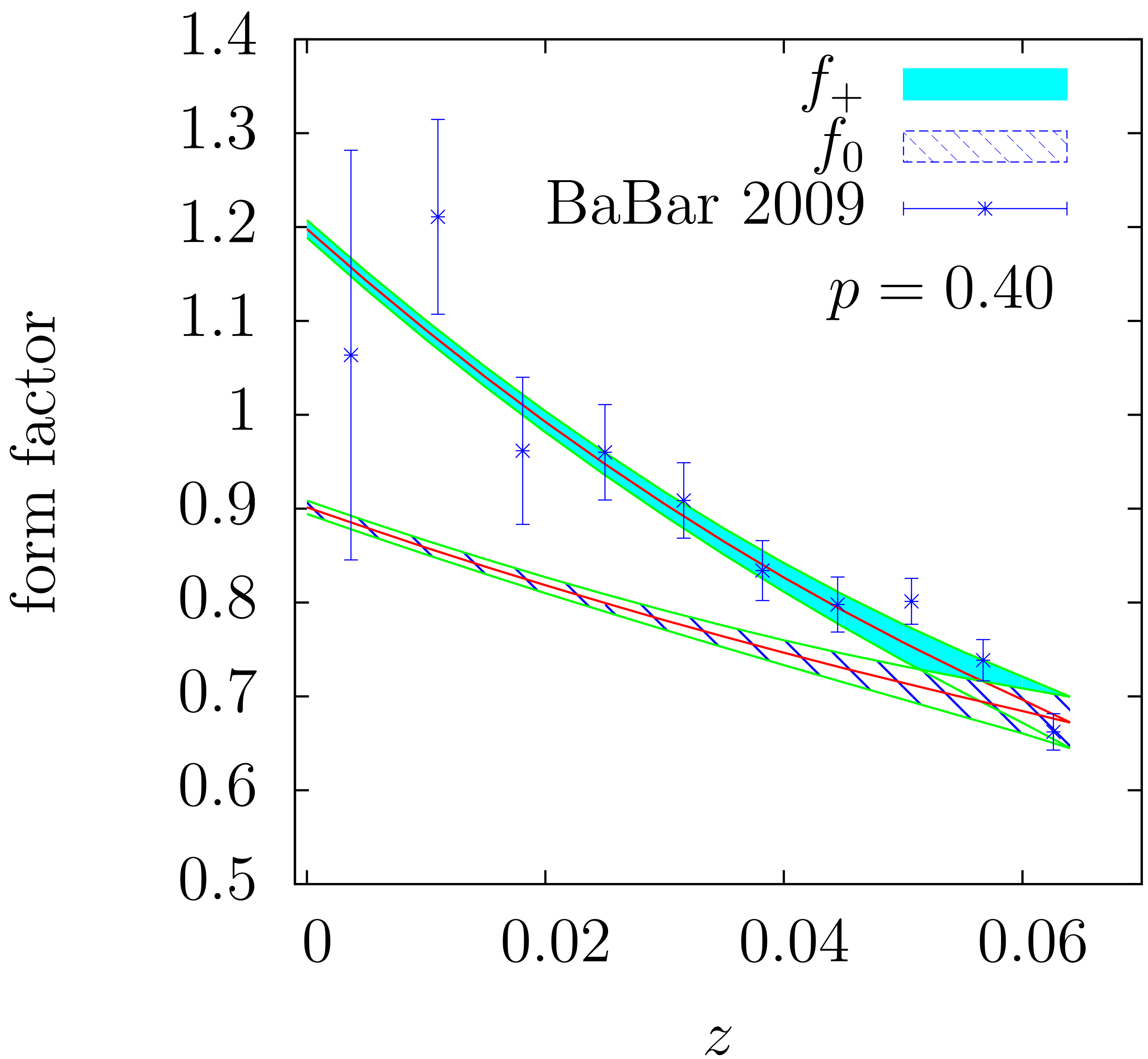
comparison with quenched results

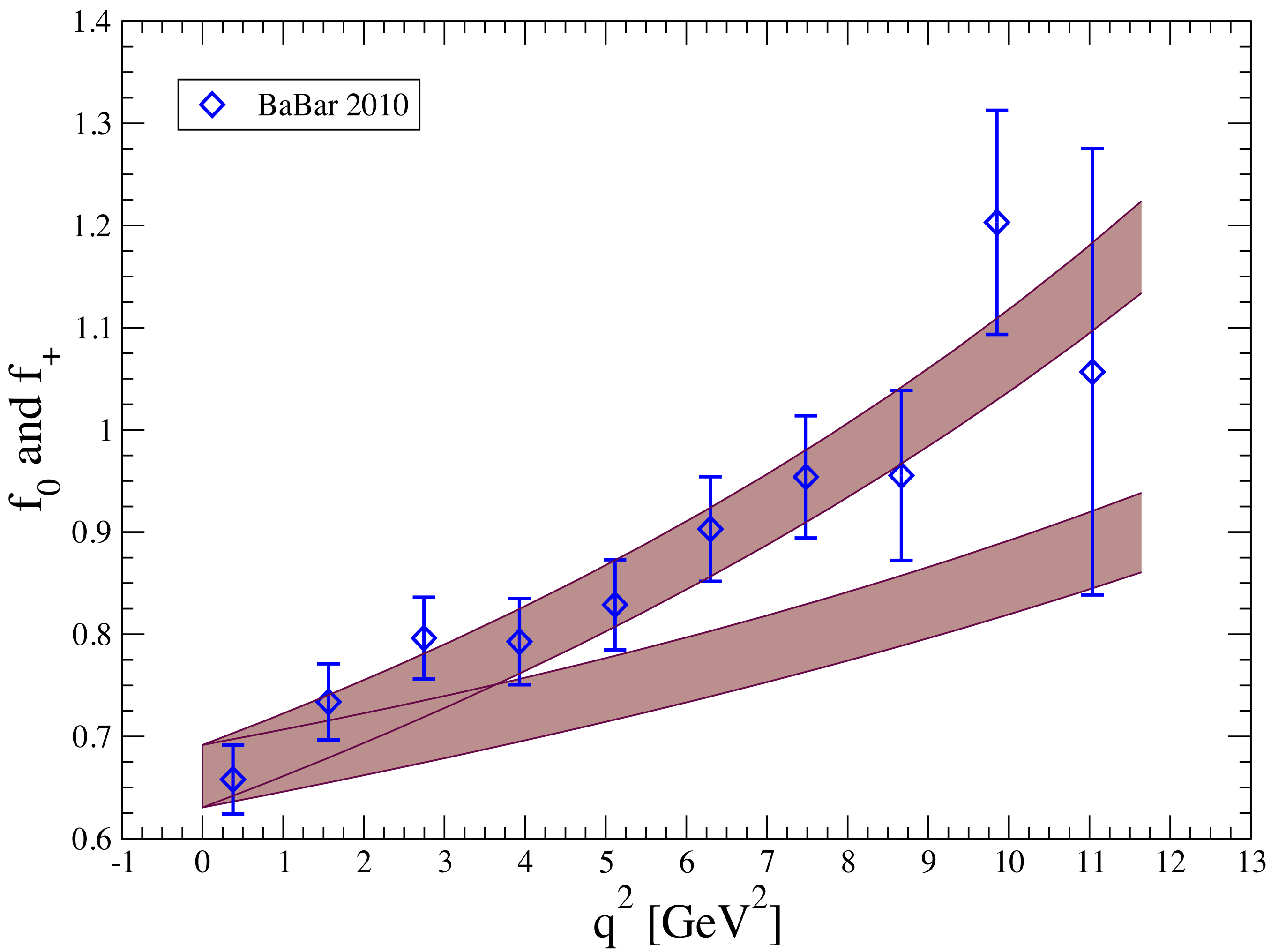
[De Divitiis, Molinaro, Petronzio, Tantalo PLB 655 (2007) 45]

new results for $B \to Dl\nu$

[FNAL/MILC]

[HPQCD]





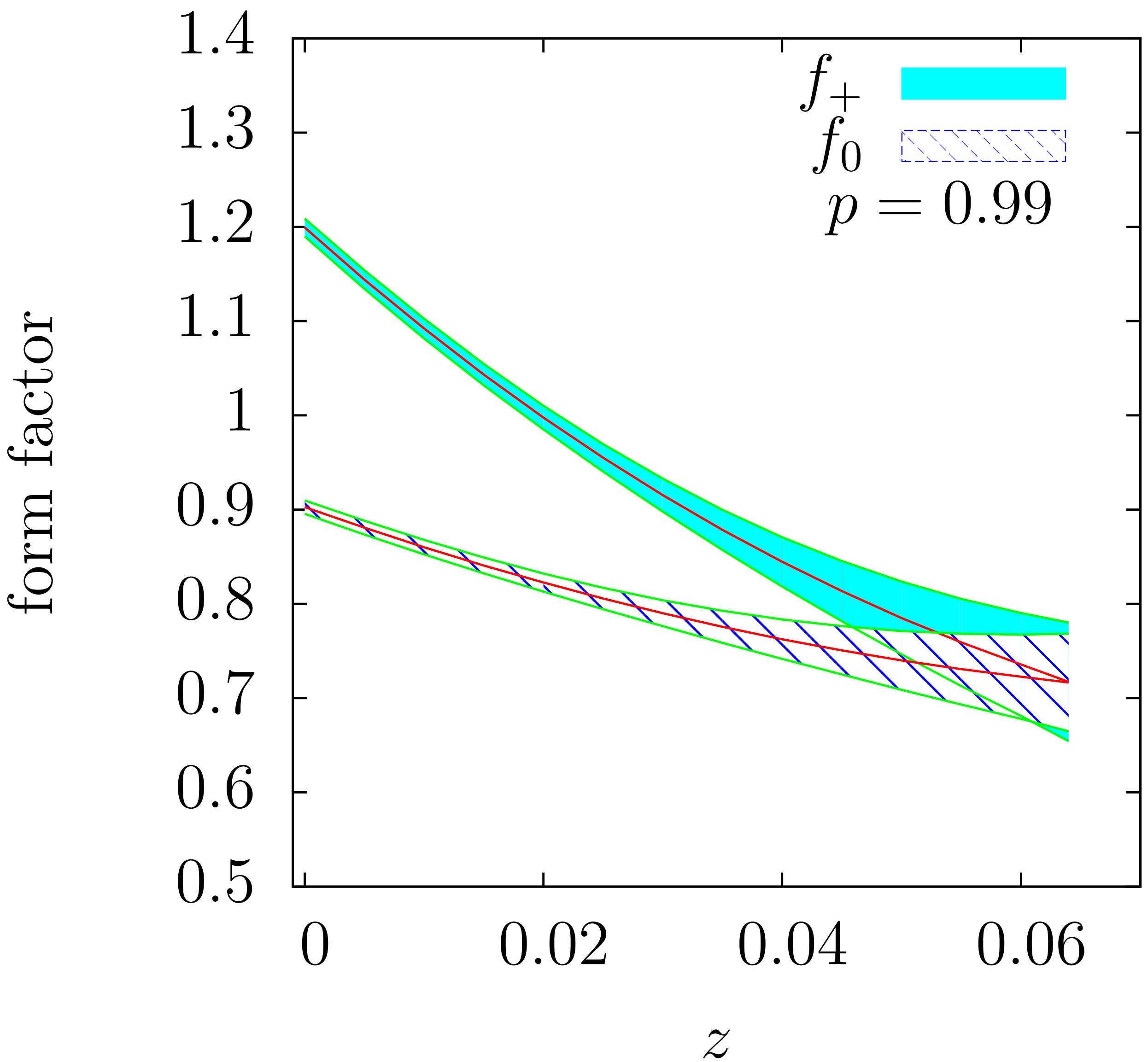
$$|V_{cb}| = 39.6(1.7)_{\rm QCD+exp}(0.2)_{\rm QED} \times 10^{-3}$$

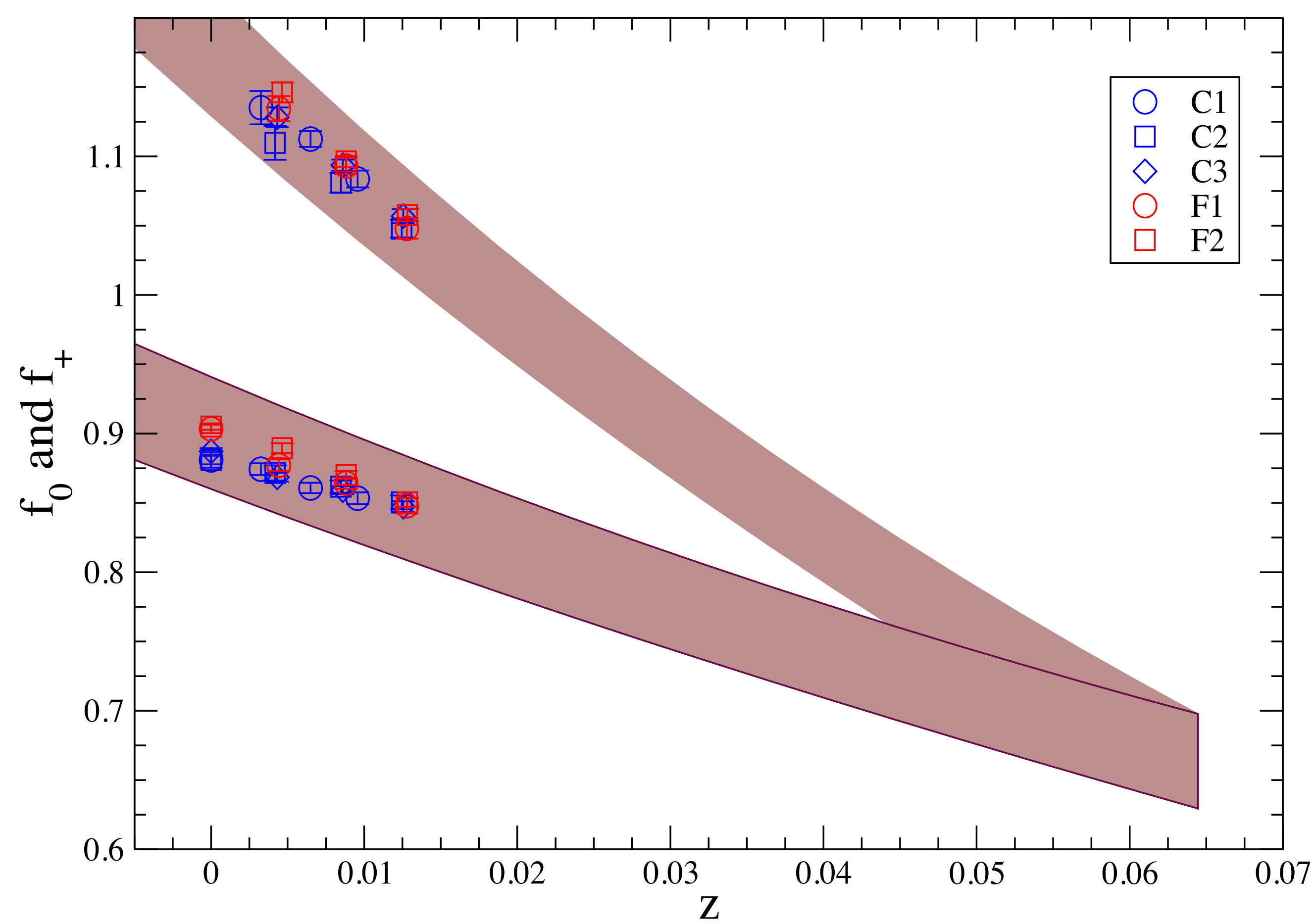
$$|V_{cb}| = 40.2(17)(13) \times 10^{-3}$$

new results for $B \to Dl\nu$

[FNAL/MILC]

[HPQCD]

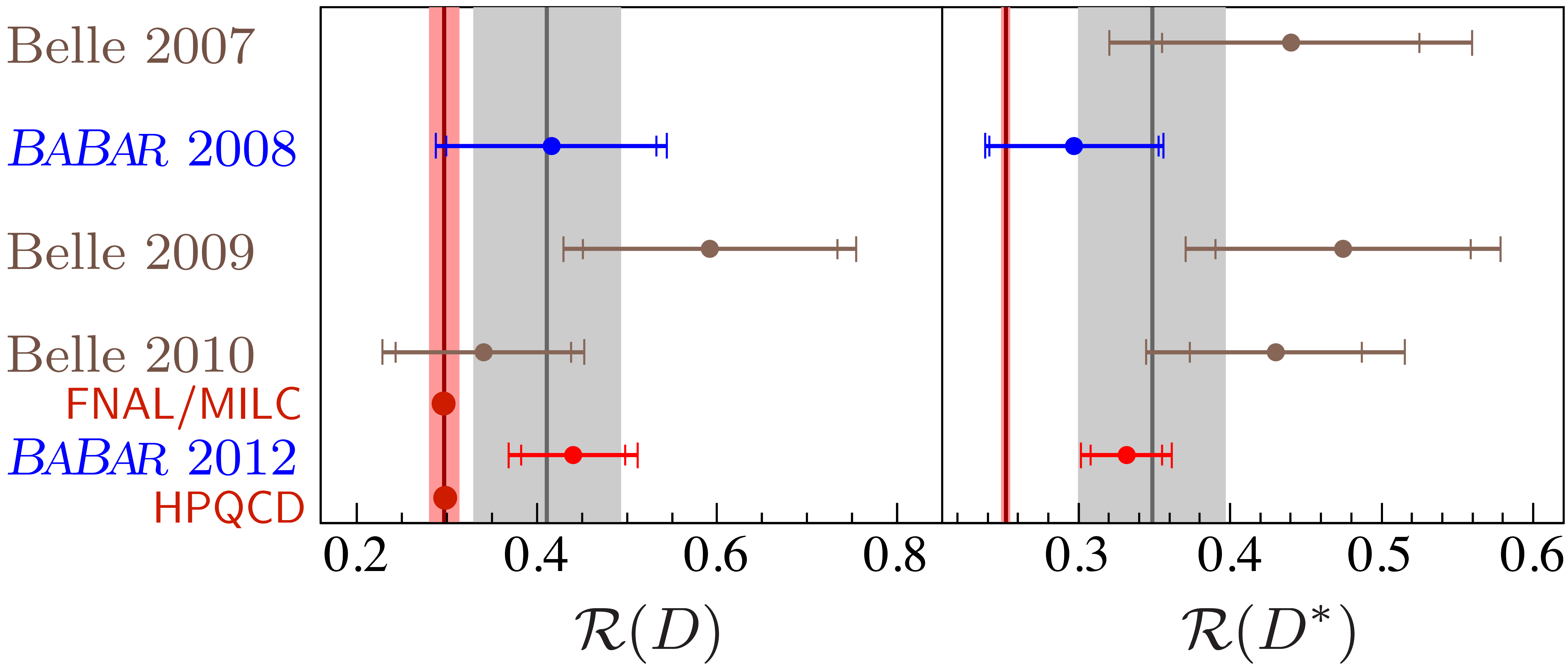




$$R(D) = \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)} = 0.299(11)$$

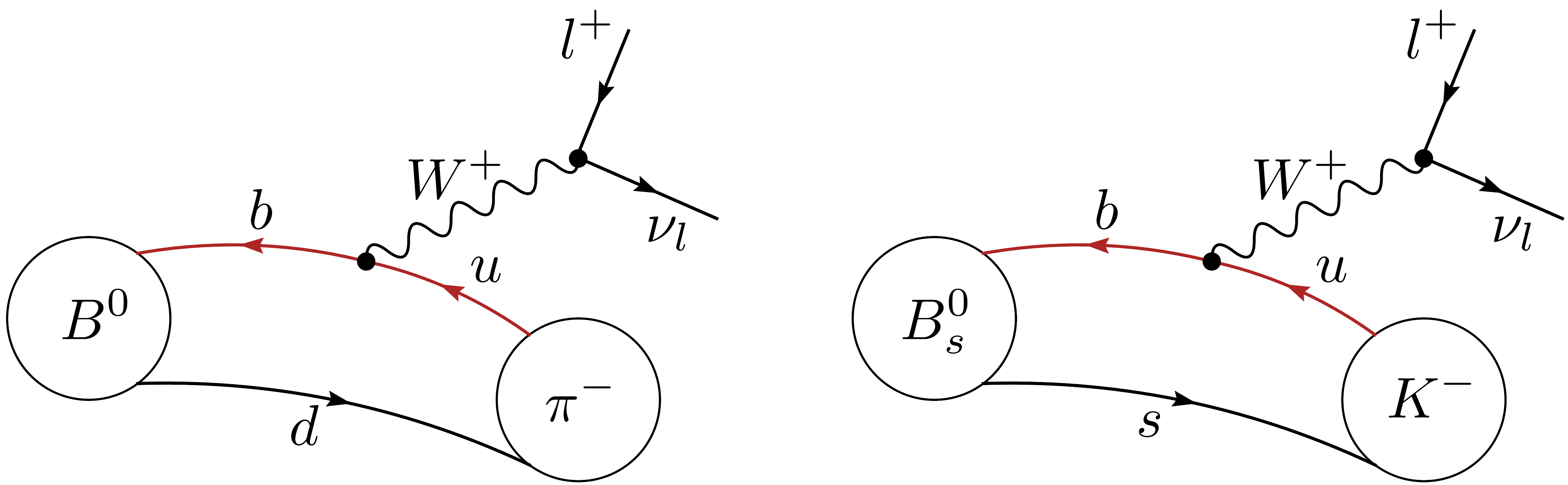
$0.300(8)$

status of $R(D)$



n.b.: Belle II expected to decrease error by factor of 3 at 5/ab, and a factor 5 at 50/ab

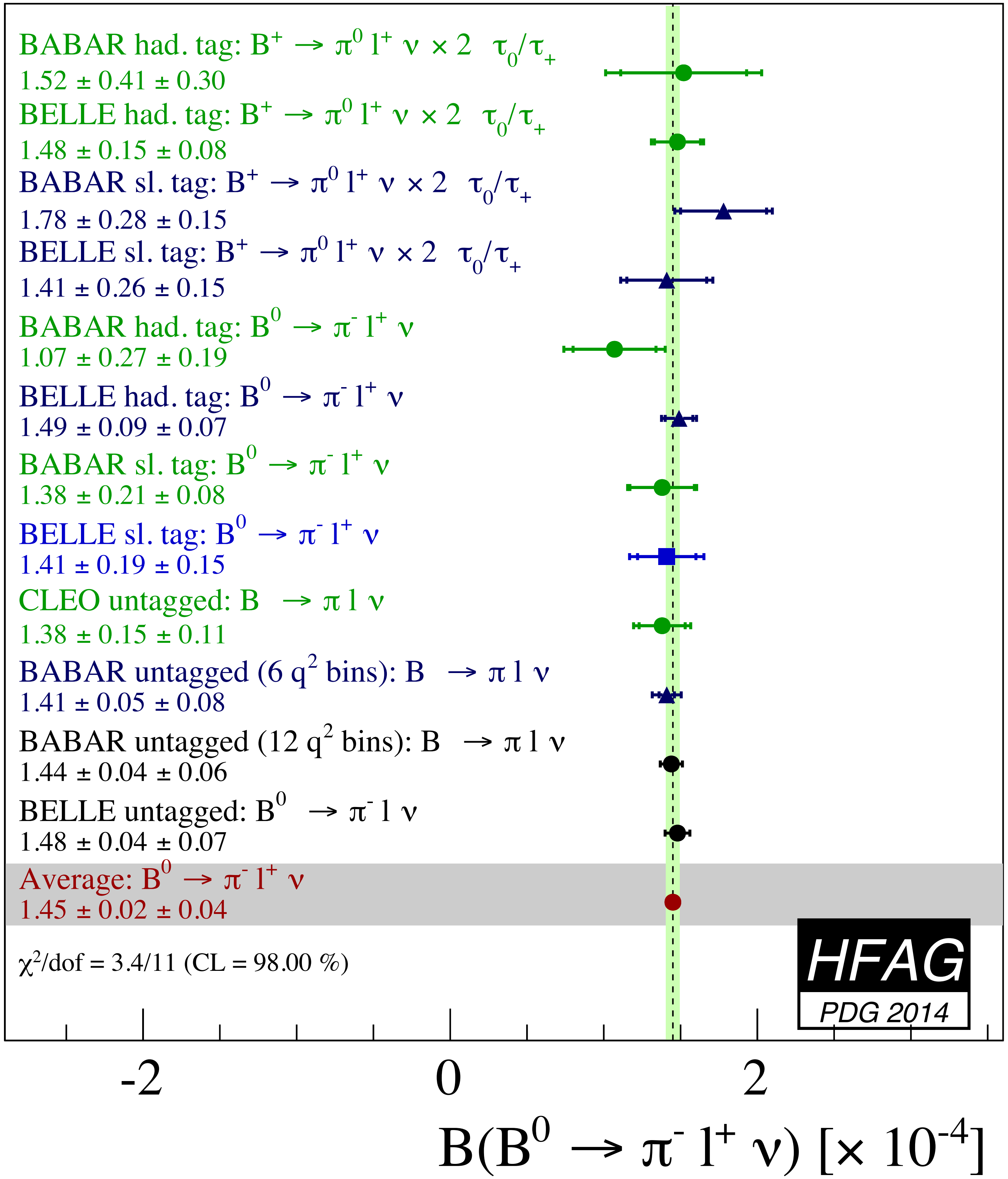
B semileptonic decay: $|V_{ub}|$



$$\frac{\mathrm{d}\Gamma(B_{(s)}\to Pl\nu)}{\mathrm{d}q^2} = \frac{G_F^2|V_{ub}|^2}{24\pi^3}\,\frac{(q^2-m_l^2)^2\sqrt{E_P^2-m_P^2}}{q^4 m_{B_{(s)}}^2}\left[\left(1+\frac{m_l^2}{2q^2}\right)m_{B_{(s)}}^2(E_P^2-m_P^2)|f_+(q^2)|^2 + \frac{3m_l^2}{8q^2}(m_{B_{(s)}}^2-m_P^2)^2|f_0(q^2)|^2\right]$$

$$\langle P(p')|\bar{b}\gamma_\mu q|B_q(p)\rangle = f_+(q^2)\left(p_\mu + p'_\mu - \frac{m_{B_q}^2-m_P^2}{q^2}\,q_\mu\right) + f_0(q^2)\,\frac{m_{B_q}^2-m_P^2}{q^2}\,q_\mu\,, \qquad q = p - p'$$

B semileptonic decay: $|V_{ub}|$



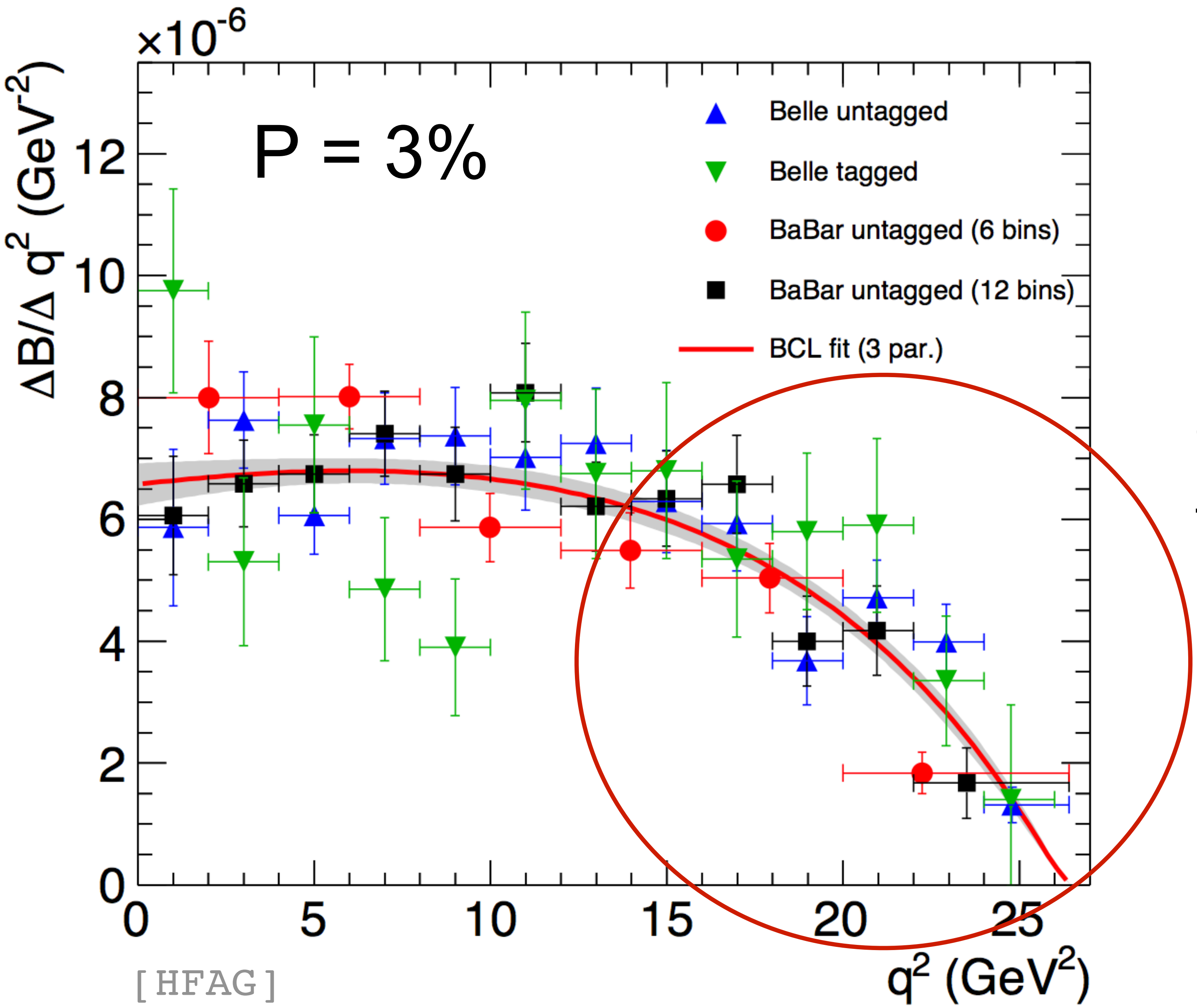
Belle II projections

Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$	±0.012	±0.008	6
α		$\pm2^\circ$	$\pm1^\circ$	
γ	$\pm14^\circ$	$\pm6^\circ$	$\pm1.5^\circ$	
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	±0.053	±0.018	>50
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	±0.028	±0.011	>50
$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$	±0.100	±0.033	44
$\|V_{cb}\|$ incl.	$\pm2.4\%$	$\pm1.0\%$		< 1
$\|V_{cb}\|$ excl.	$\pm3.6\%$	$\pm1.8\%$	$\pm1.4\%$	< 1
$\|V_{ub}\|$ incl.	$\pm6.5\%$	$\pm3.4\%$	$\pm3.0\%$	2
$\|V_{ub}\|$ excl. (had. tag.)	$\pm10.8\%$	$\pm4.7\%$	$\pm2.4\%$	20
$\|V_{ub}\|$ excl. (untag.)	$\pm9.4\%$	$\pm4.2\%$	$\pm2.2\%$	3
$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	96 ± 26	$\pm10\%$	$\pm5\%$	46
$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7	5σ	$>> 5\sigma$	>50
$R(B \to D\tau\nu)$	$\pm16.5\%$	$\pm5.6\%$	$\pm3.4\%$	4
$R(B \to D^*\tau\nu)$	$\pm9.0\%$	$\pm3.2\%$	$\pm2.1\%$	3
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ [10^{-6}]	< 40		$\pm30\%$	>50
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ [10^{-6}]	< 55		$\pm30\%$	>50
$\mathcal{B}(B \to X_s\gamma)$ [10^{-6}]	$\pm13\%$	$\pm7\%$	$\pm6\%$	< 1
$A_{CP}(B \to X_s\gamma)$		±0.01	±0.005	8
$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$	±0.11	±0.035	> 50
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	±0.23	±0.07	> 50
C_7/C_9 $(B \to X_s \ell\ell)$	$\sim$20%	10%	5%	
$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7	±0.3		
$\mathcal{B}(B_s \to \tau^+\tau^-)$ [10^{-3}]		< 2		

Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \times 10^{-3}(1 \pm 0.053 \pm 0.038)$	$\pm2.9\%$	$\pm$(0.9%-1.3%)	> 50
$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \times 10^{-3}(1 \pm 0.037 \pm 0.054)$	$\pm$(3.5%-4.3%)	$\pm$(2.3%-3.6%)	3-5
y_{CP} [10^{-2}]	$1.11 \pm 0.22 \pm 0.11$	$\pm$(0.11-0.13)	$\pm$(0.05-0.08)	5-8
A_Γ [10^{-2}]	$-0.03 \pm 0.20 \pm 0.08$	±0.10	$\pm$(0.03-0.05)	7 - 9
$A_{CP}^{K^+K^-}$ [10^{-2}]	$-0.32 \pm 0.21 \pm 0.09$	±0.11	±0.06	15
$A_{CP}^{\pi^+\pi^-}$ [10^{-2}]	$0.55 \pm 0.36 \pm 0.09$	±0.17	$\pm$ 0.06	> 50
$A_{CP}^{\phi\gamma}$ [10^{-2}]	$\pm$ 5.6	±2.5	±0.8	> 50
$x^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	±0.14	±0.11	3
$y^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	±0.08	±0.05	15
$\|q/p\|^{K_S\pi^+\pi^-}$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	±0.10	±0.07	5-6
$\phi^{K_S\pi^+\pi^-}$ [$^\circ$]	$-6 \pm 11 \pm {}^{4}_{5}$	±6	±4	10
$A_{CP}^{\pi^0\pi^0}$ [10^{-2}]	$-0.03 \pm 0.64 \pm 0.10$	±0.29	±0.09	> 50
$A_{CP}^{K^0_S\pi^0}$ [10^{-2}]	$-0.10 \pm 0.16 \pm 0.09$	±0.08	±0.03	> 50
$Br(D^0 \to \gamma\gamma)$ [10^{-6}]	< 1.5	$\pm30\%$	$\pm25\%$	2
	$\tau \to \mu\gamma$ [10^{-9}]	< 45	< 14.7	< 4.7
	$\tau \to e\gamma$ [10^{-9}]	< 120	< 39	< 12
	$\tau \to \mu\mu\mu$ [10^{-9}]	< 21.0	< 3.0	< 0.3

[BELLE2-NOTE-PH-2015-002, retrieved from B2TiP]

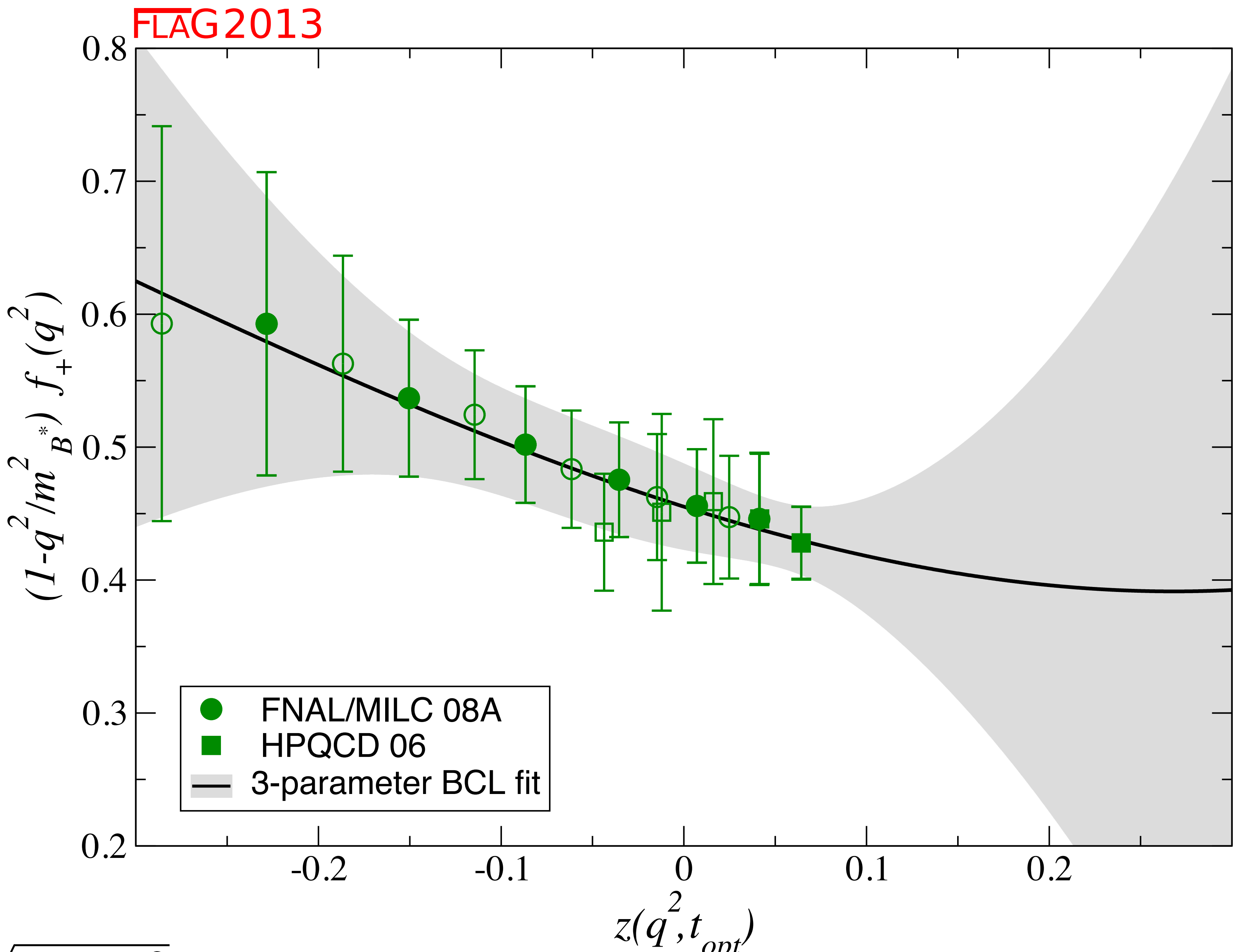
B semileptonic decay: $|V_{ub}|$



easily accessible kinematics on the lattice (not-too-fast pions)

large phase space ⇒ accurate description of q^2 dependence over a significant region crucial for a precise CKM determination

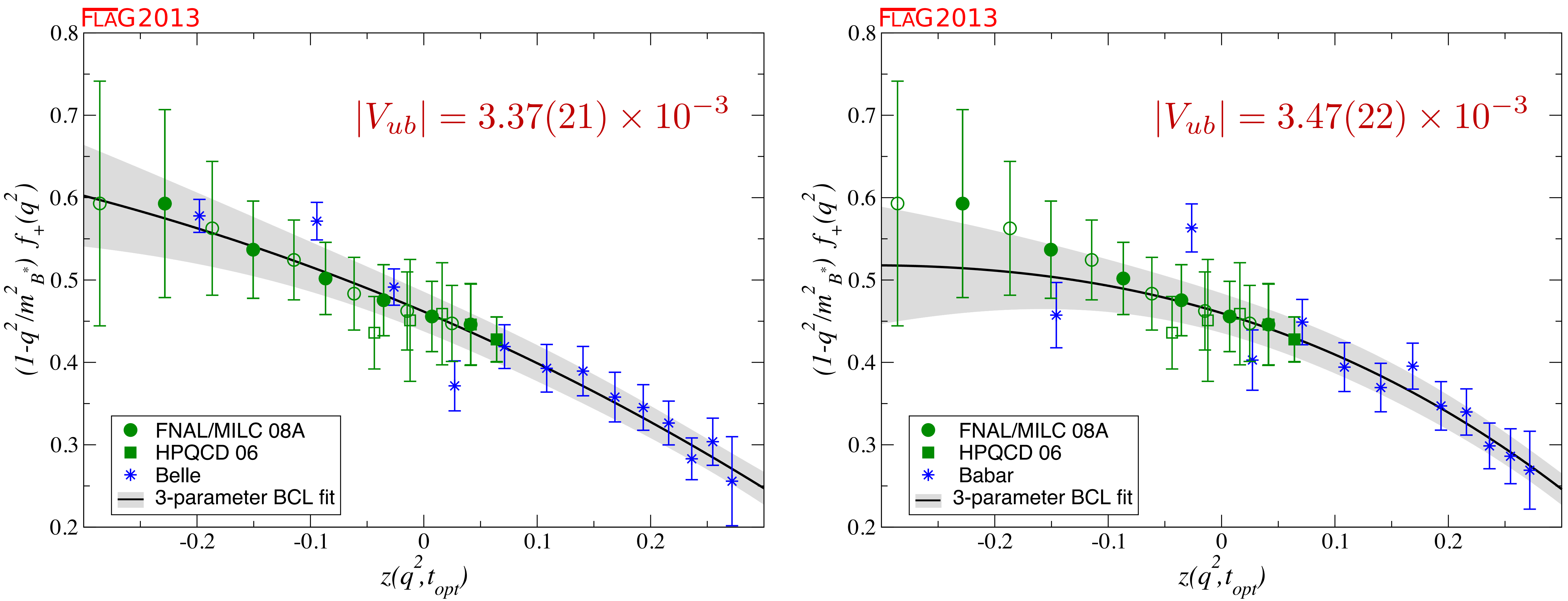
FLAG-2 on $B \to \pi l \nu$



$$z = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}} \qquad t_+ = (m_B + m_\pi)^2\,, \qquad t_0 < t_+$$

[FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

FLAG-2 on $B \to \pi l \nu$

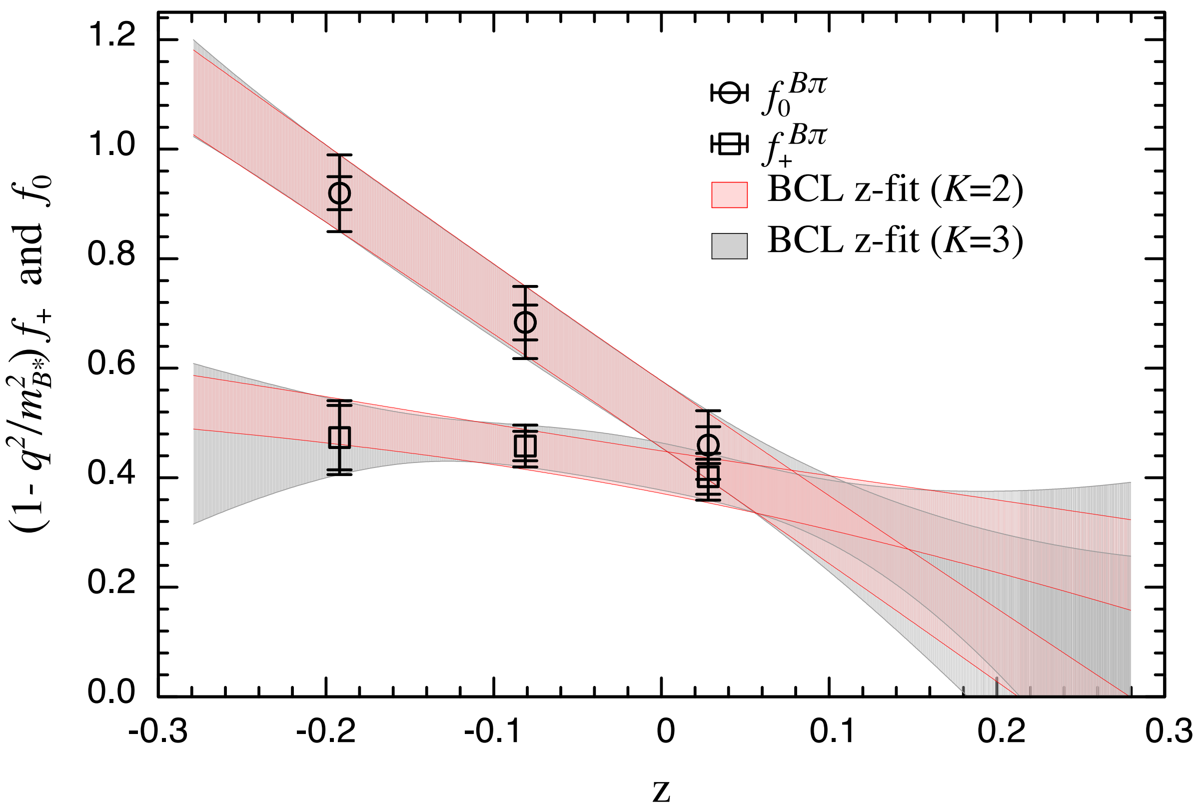


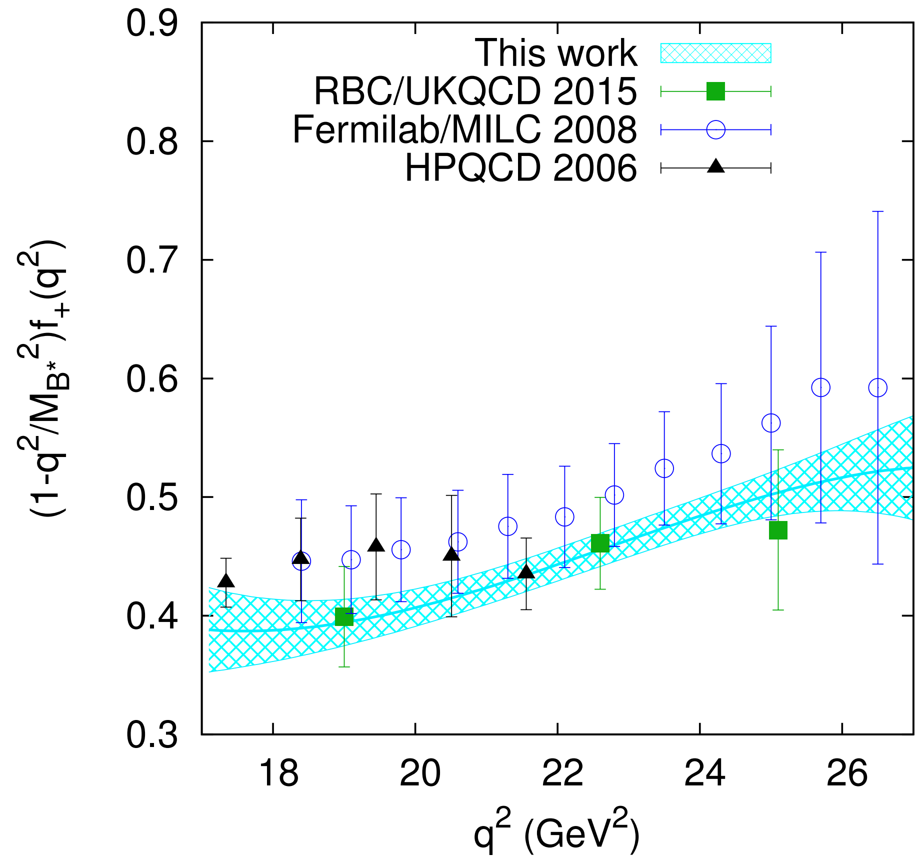
[FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

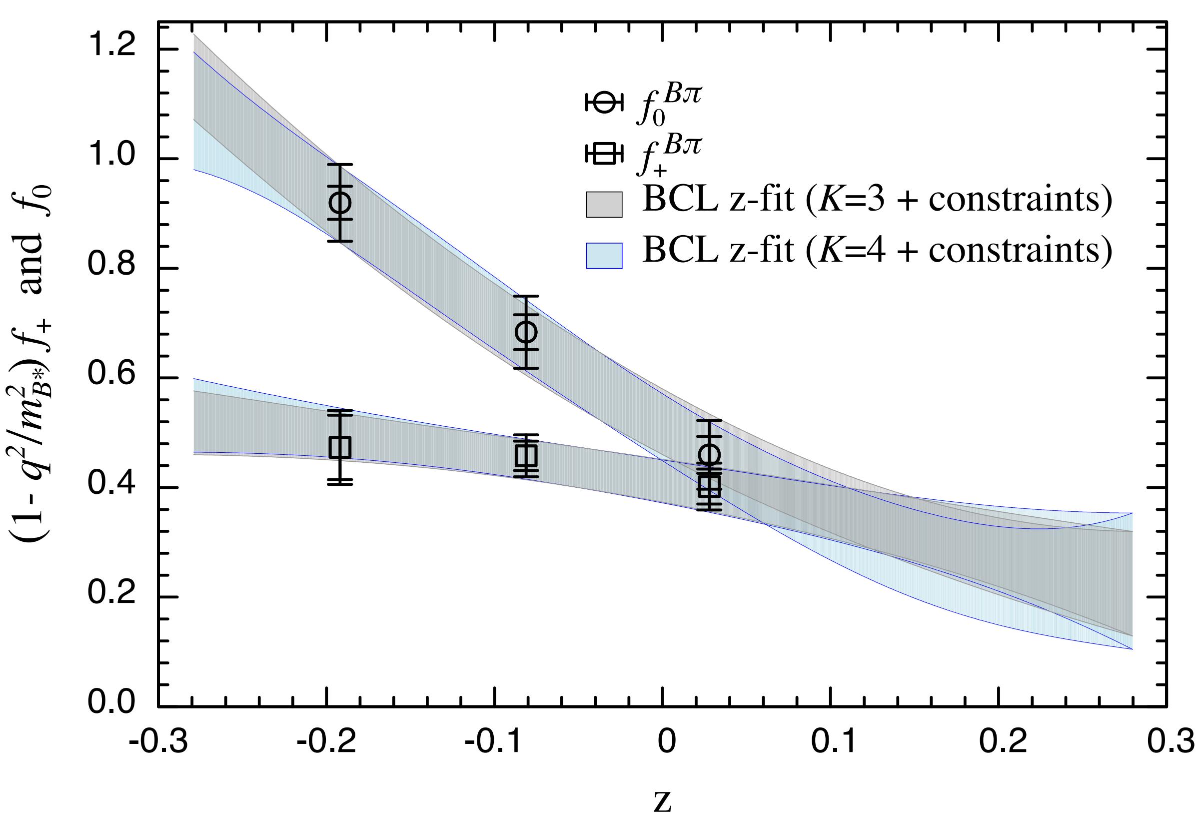
new results for $B \to \pi l \nu$

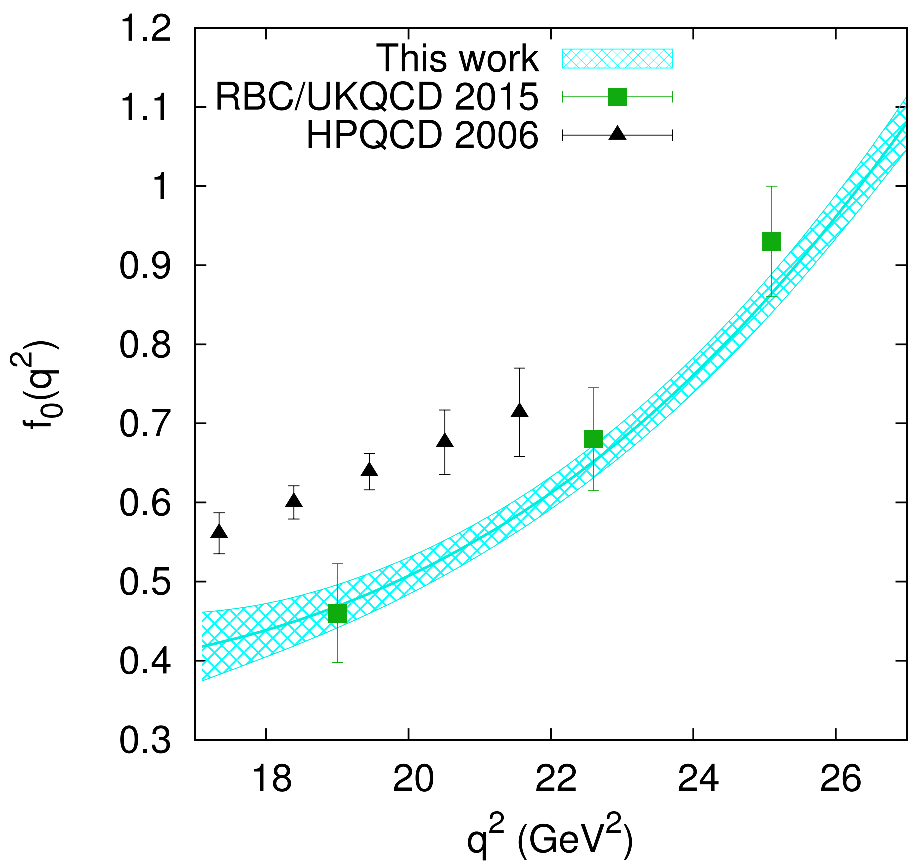
[RBC/UKQCD]

[FNAL/MILC]





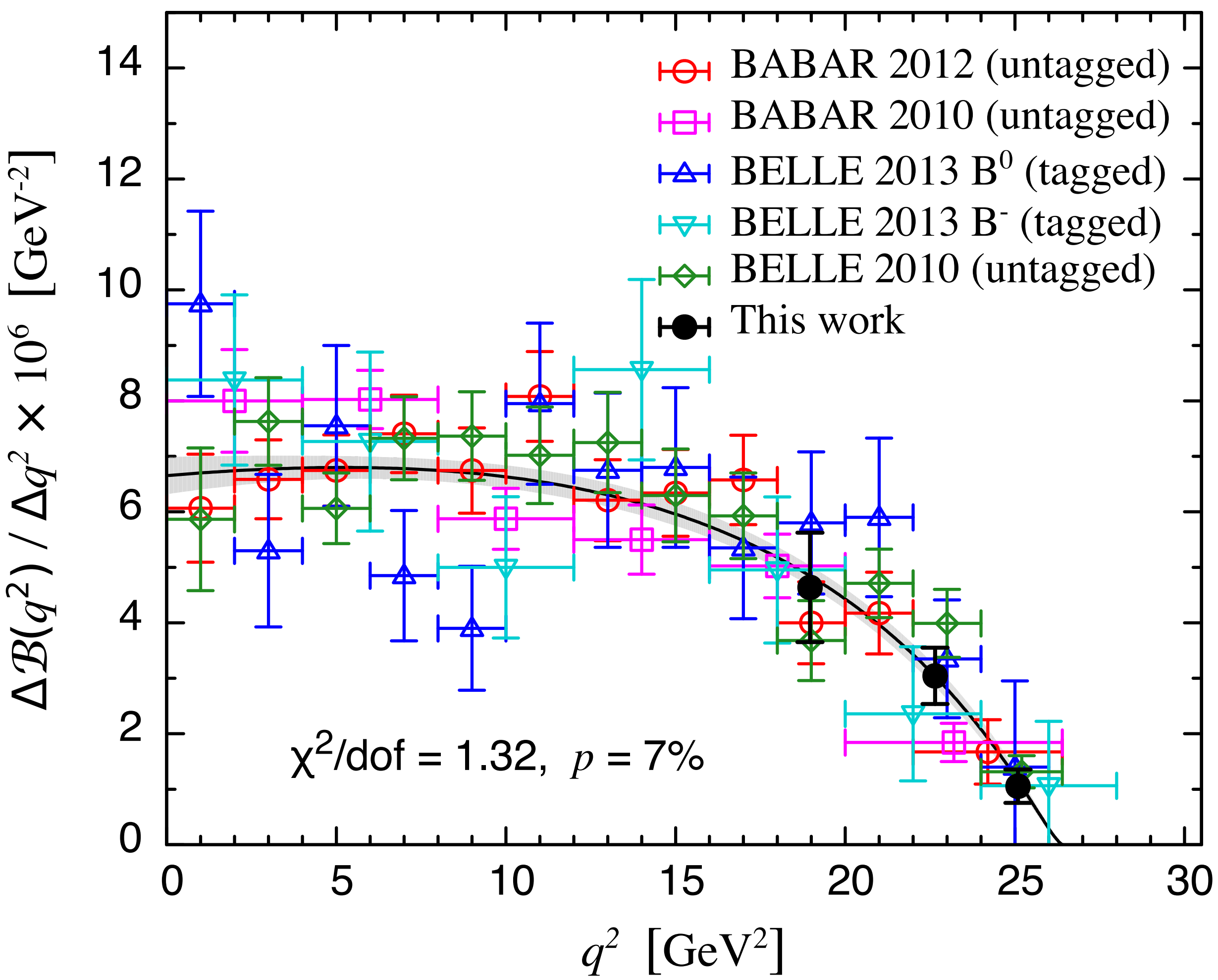


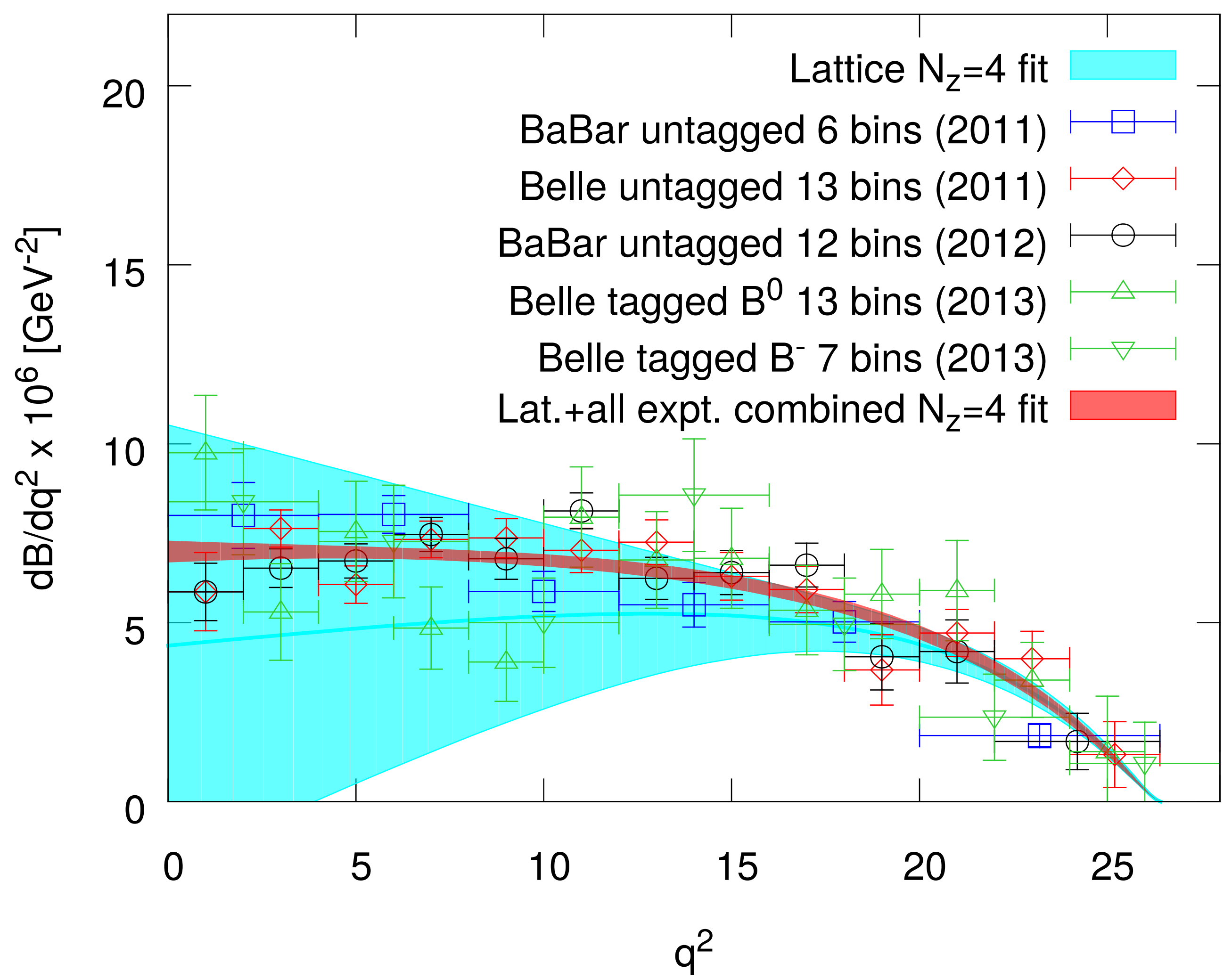


new results for $B \to \pi l \nu$

[RBC/UKQCD]

[FNAL/MILC]



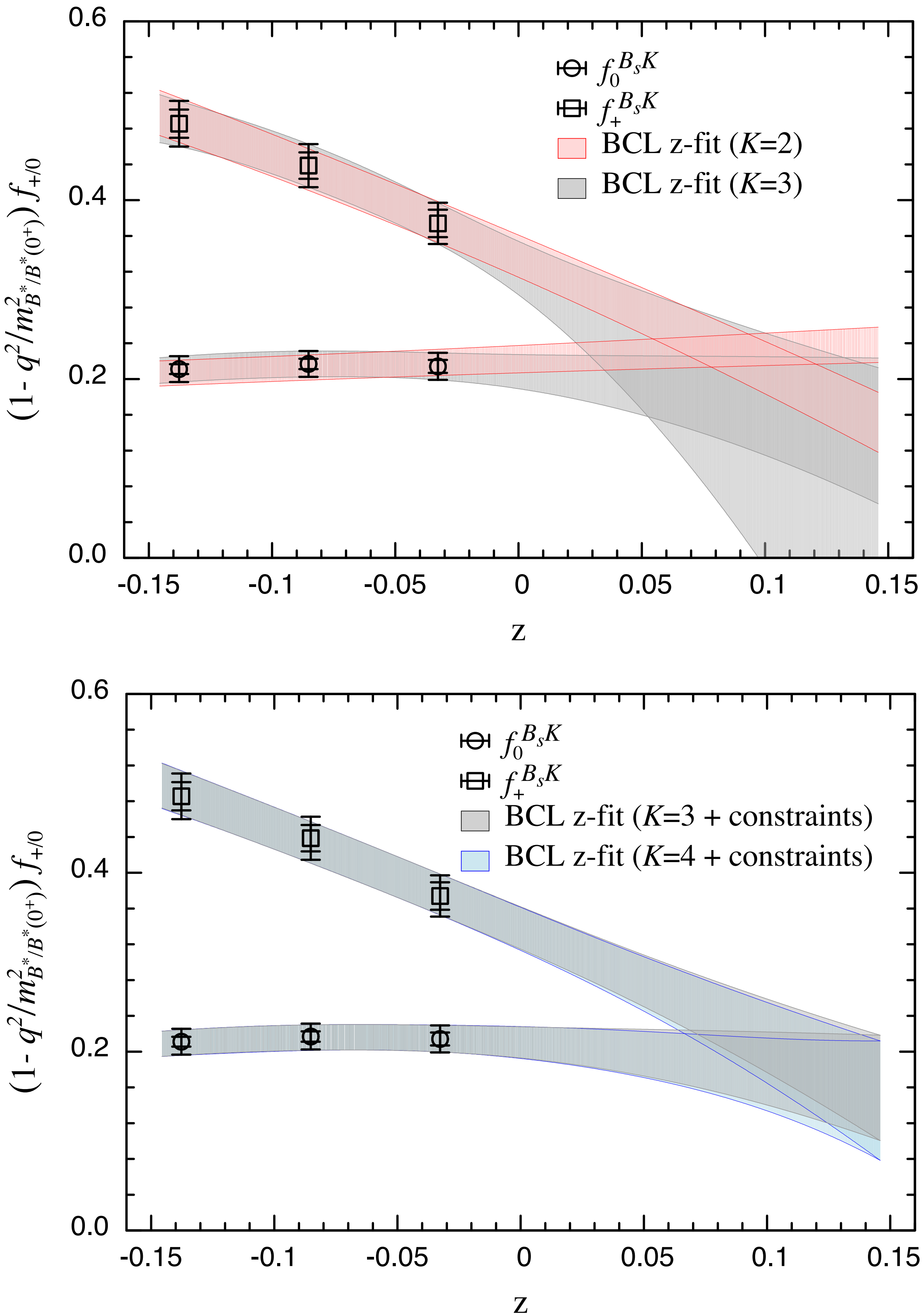


$|V_{ub}| = 3.61(32) \times 10^{-3}$

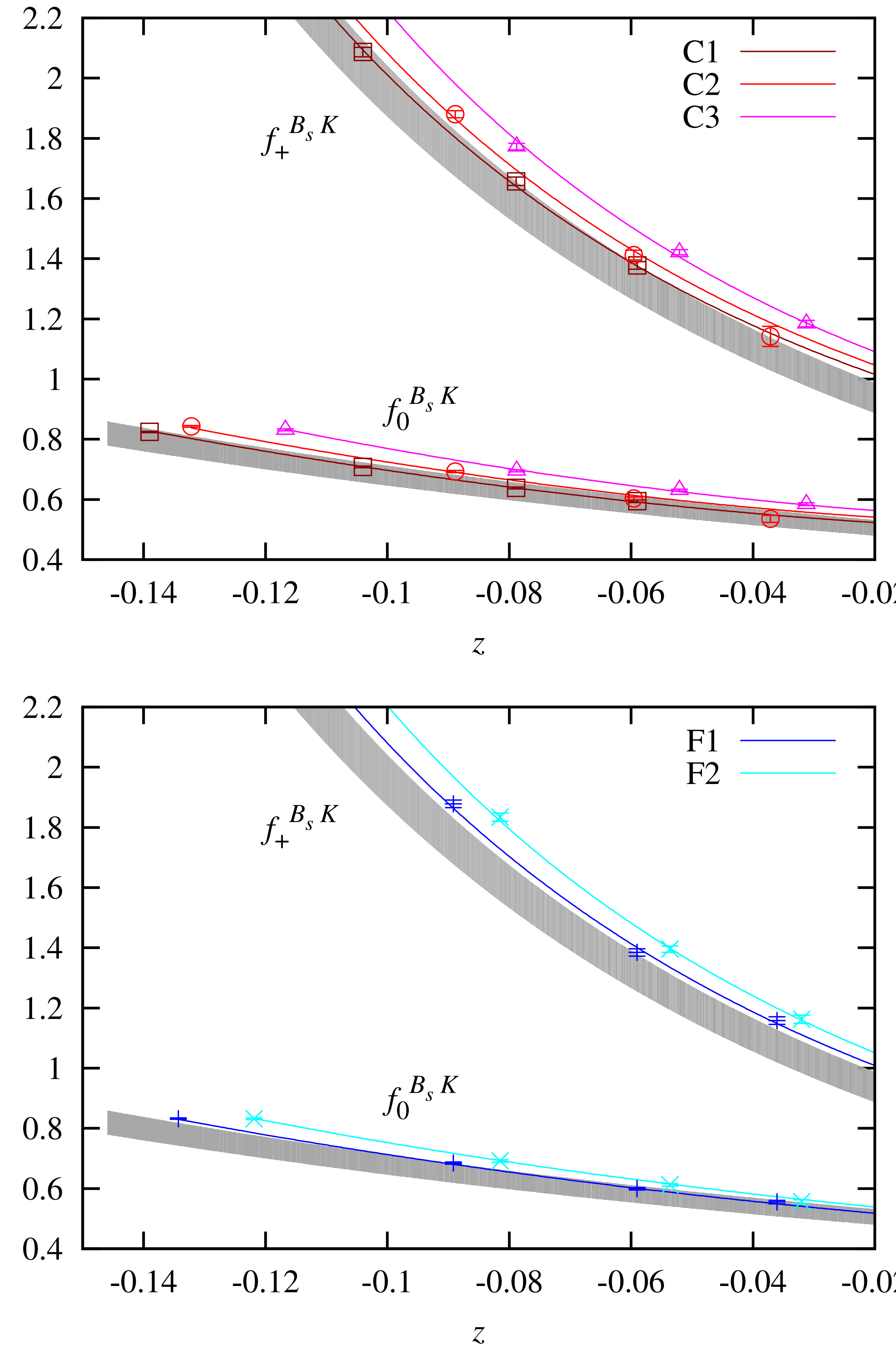
$|V_{ub}| = 3.72(16) \times 10^{-3}$

$B_s \to K l \nu$

[RBC/UKQCD]

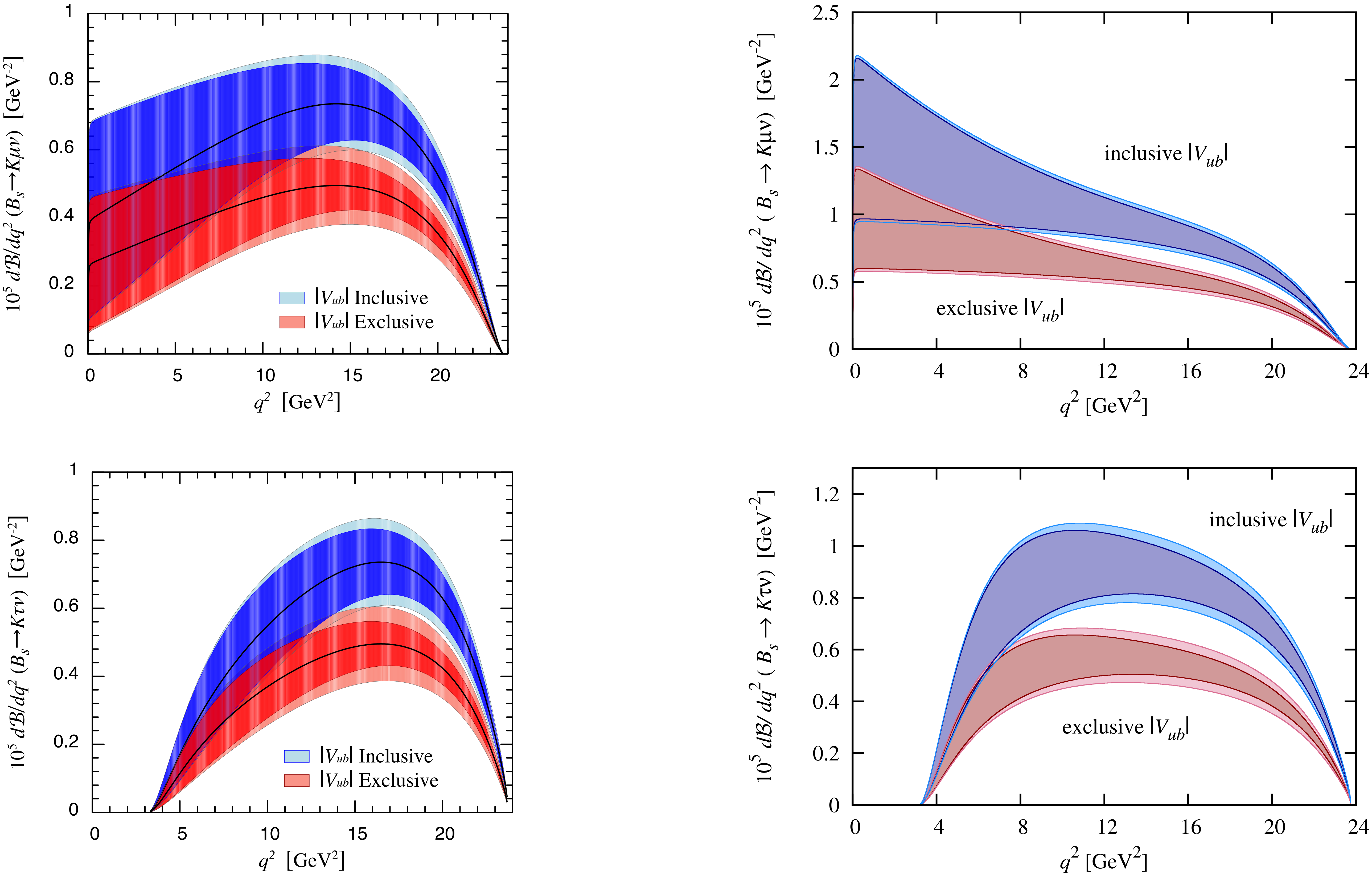


[HPQCD]

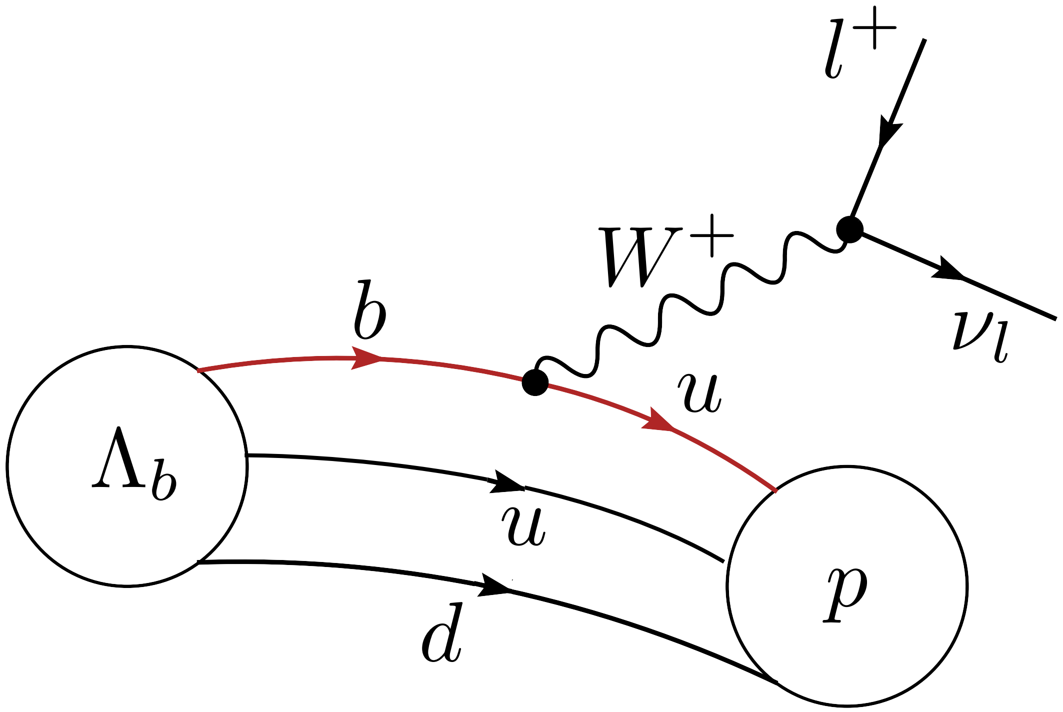


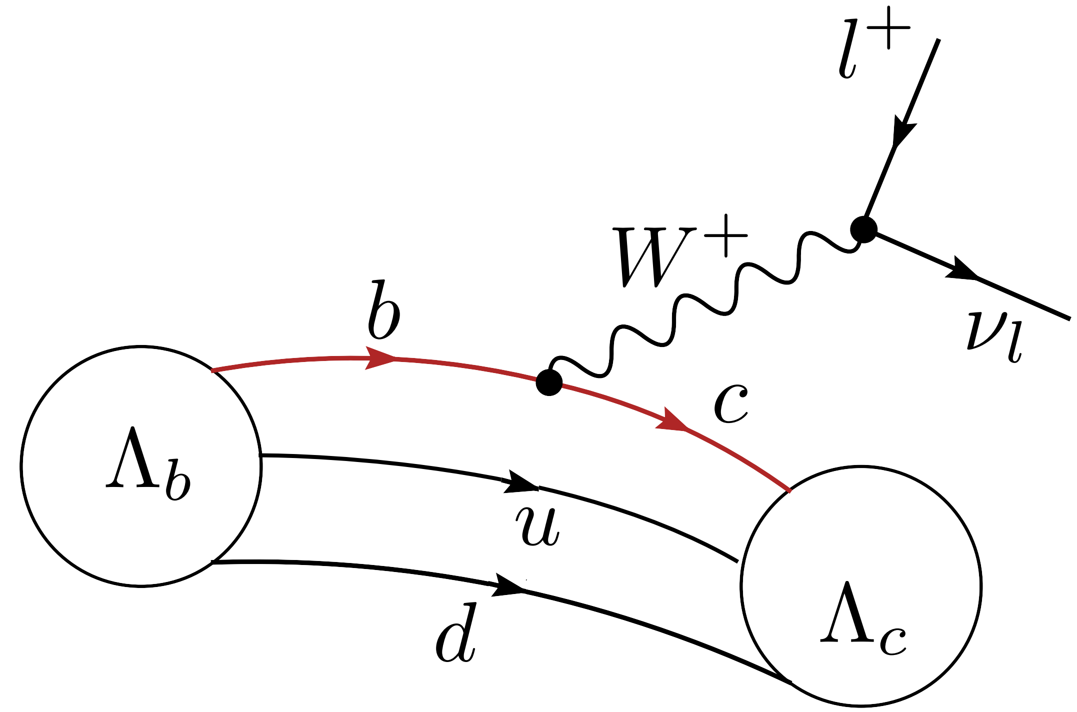
$B_s \to K l \nu$

[RBC/UKQCD] [HPQCD]



$|V_{ub}|$ and $|V_{cb}|$ from SL baryon decay



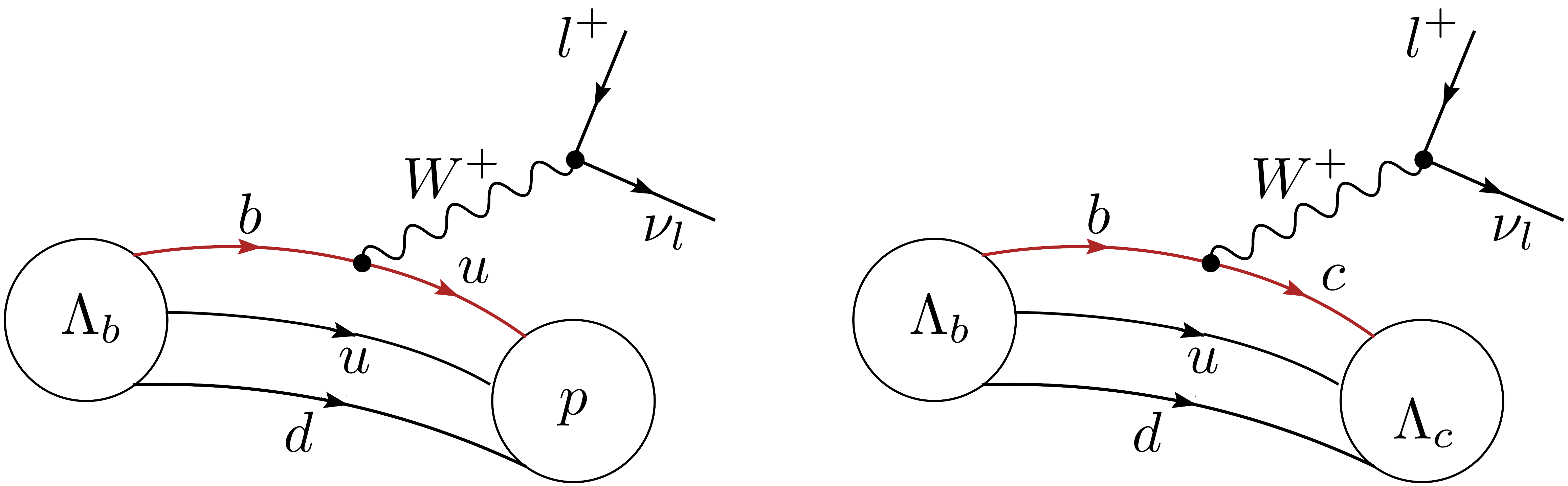


new exclusive determination of $|V_{cb}|/|V_{ub}|$ from LHCb measurement + LQCD computation of form factors

Kenneth G. Wilson Award for Excellence in Lattice Field Theory 2015: **S Meinel**

LATTICE 2015 KOBE

$|V_{ub}|$ and $|V_{cb}|$ from SL baryon decay



helicity-based parametrisation: [Feldmann, Yip PRD 85 (2012) 014035]

$$\begin{aligned}
\langle X(p',s')|\bar{q}\,\gamma^\mu\, b|\Lambda_b(p,s)\rangle = \bar{u}_X(p',s')\Big[& f_0(q^2)\,(m_{\Lambda_b}-m_X)\frac{q^\mu}{q^2} \\
& + f_+(q^2)\frac{m_{\Lambda_b}+m_X}{s_+}\left(p^\mu + p'^\mu - (m^2_{\Lambda_b}-m^2_X)\frac{q^\mu}{q^2}\right) \\
& + f_\perp(q^2)\left(\gamma^\mu - \frac{2m_X}{s_+}p^\mu - \frac{2m_{\Lambda_b}}{s_+}p'^\mu\right)\Big]u_{\Lambda_b}(p,s),
\end{aligned}$$

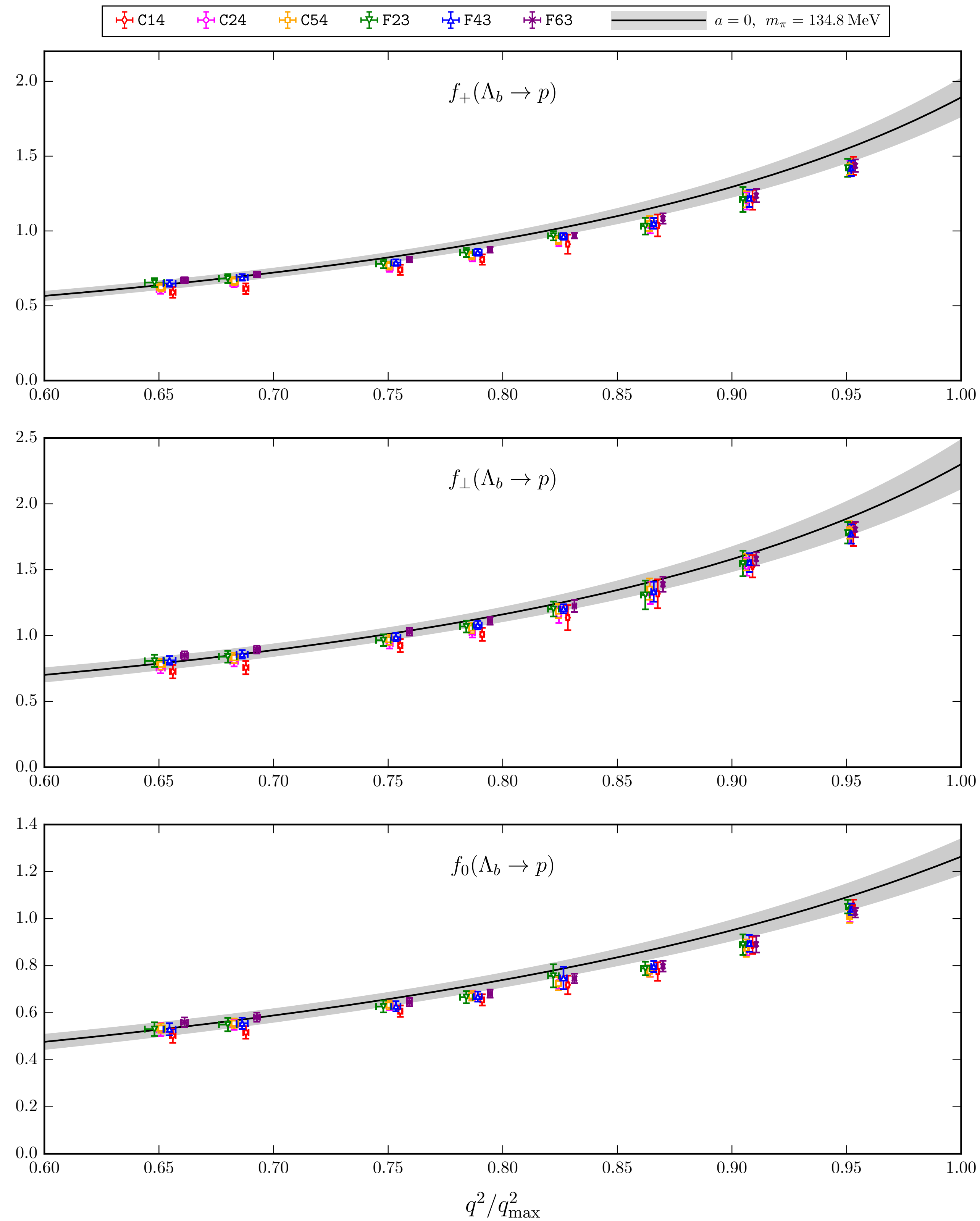
$$\begin{aligned}
\langle X(p',s')|\bar{q}\,\gamma^\mu\gamma_5\, b|\Lambda_b(p,s)\rangle = -\bar{u}_X(p',s')\,\gamma_5\Big[& g_0(q^2)\,(m_{\Lambda_b}+m_X)\frac{q^\mu}{q^2} \\
& + g_+(q^2)\frac{m_{\Lambda_b}-m_X}{s_-}\left(p^\mu + p'^\mu - (m^2_{\Lambda_b}-m^2_X)\frac{q^\mu}{q^2}\right) \\
& + g_\perp(q^2)\left(\gamma^\mu + \frac{2m_X}{s_-}p^\mu - \frac{2m_{\Lambda_b}}{s_-}p'^\mu\right)\Big]u_{\Lambda_b}(p,s).
\end{aligned}$$

$|V_{ub}|$ and $|V_{cb}|$ from SL baryon decay

[Detmold, Lehner, Meitnel arXiv:1503.01421]

[cf. Detmold, Lin, Meitnel, Wingate PRD 88 (2013) 014512]

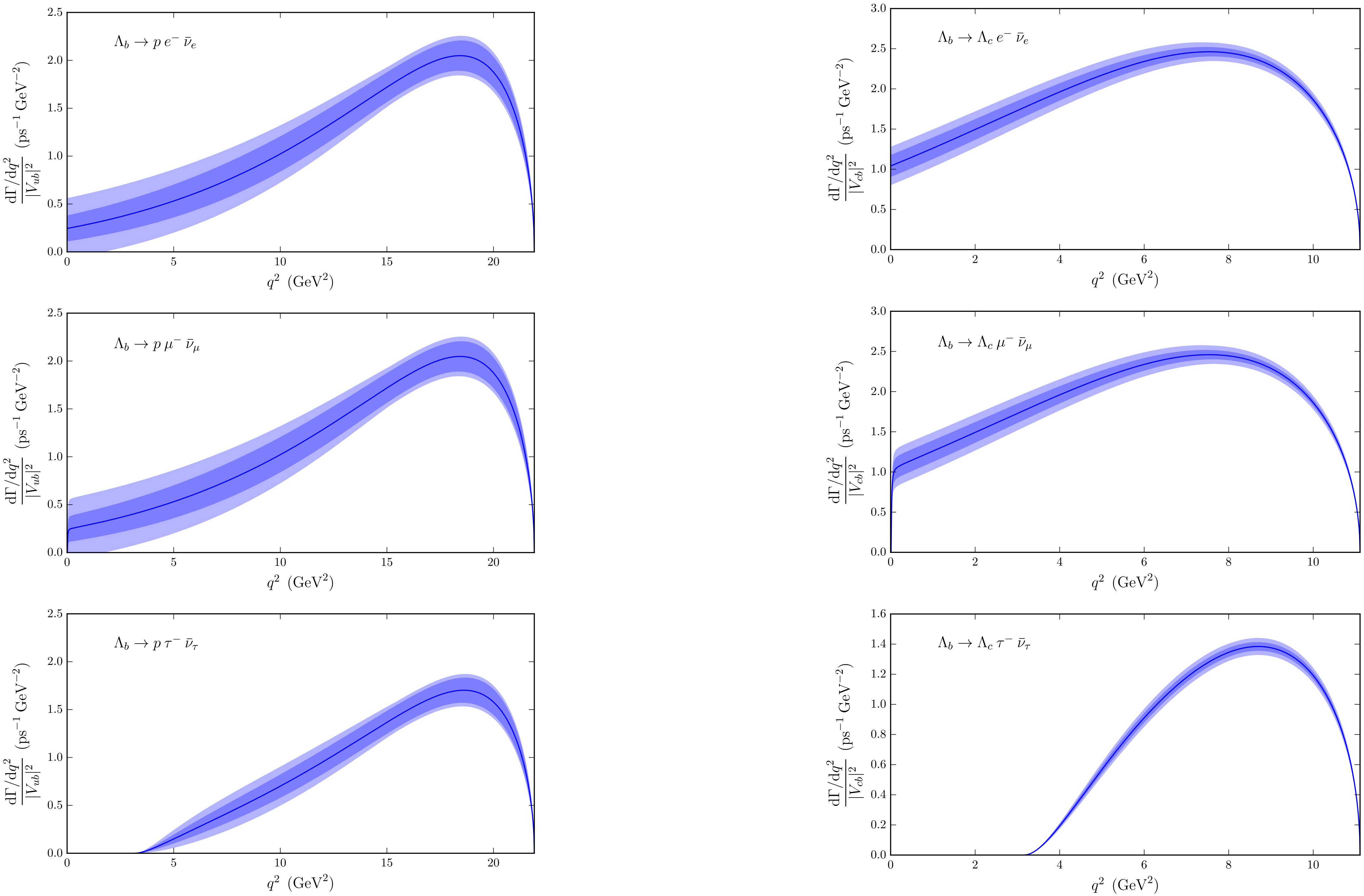
ensembles	RBC/UKQCD
N_f	2+1
a (fm)	2/0.085, 0.111
$M_\pi^{\min}$ [MeV]	320 (sea) / 230 (val)
$M_\pi^{\min} L$	4.3 (sea) / 3.1 (val)
l quarks	DWF
b quark	RHQ



$|V_{ub}|$ and $|V_{cb}|$ from SL baryon decay

[Detmold, Lehner, Meitnel arXiv:1503.01421]

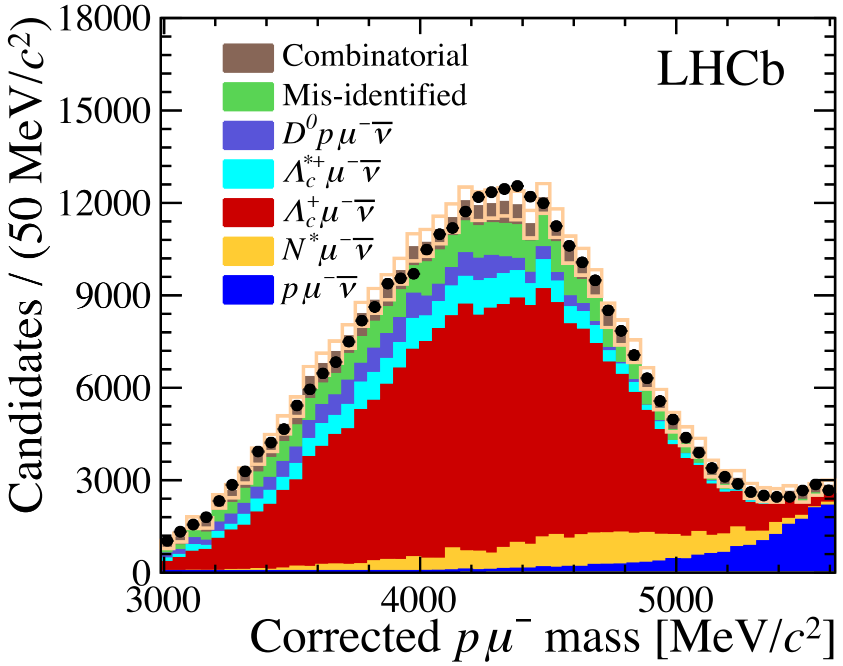
[cf. Detmold, Lin, Meitnel, Wingate PRD 88 (2013) 014512]

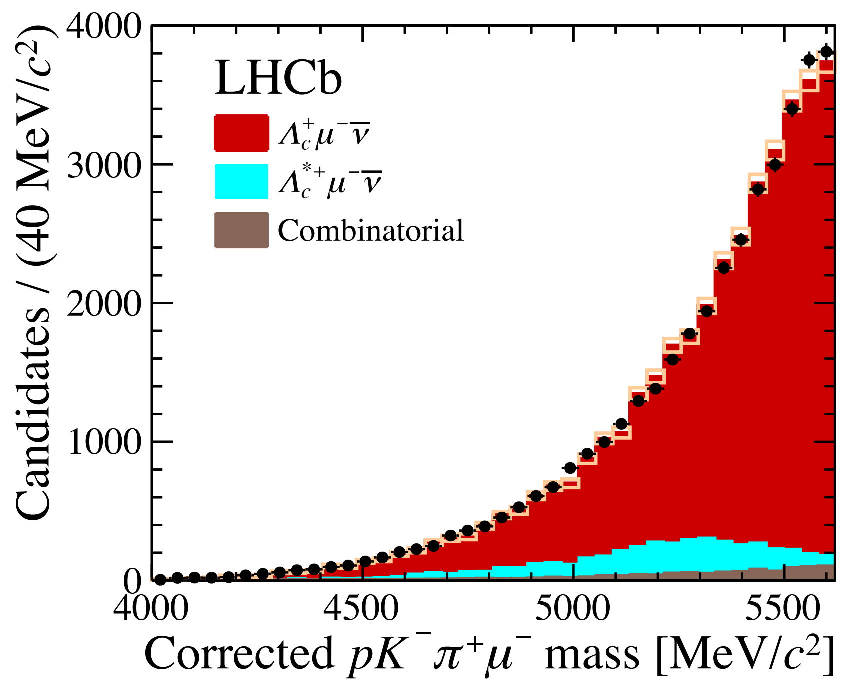


$|V_{ub}|$ and $|V_{cb}|$ from SL baryon decay

[LHCb arXiv:1504.01568]

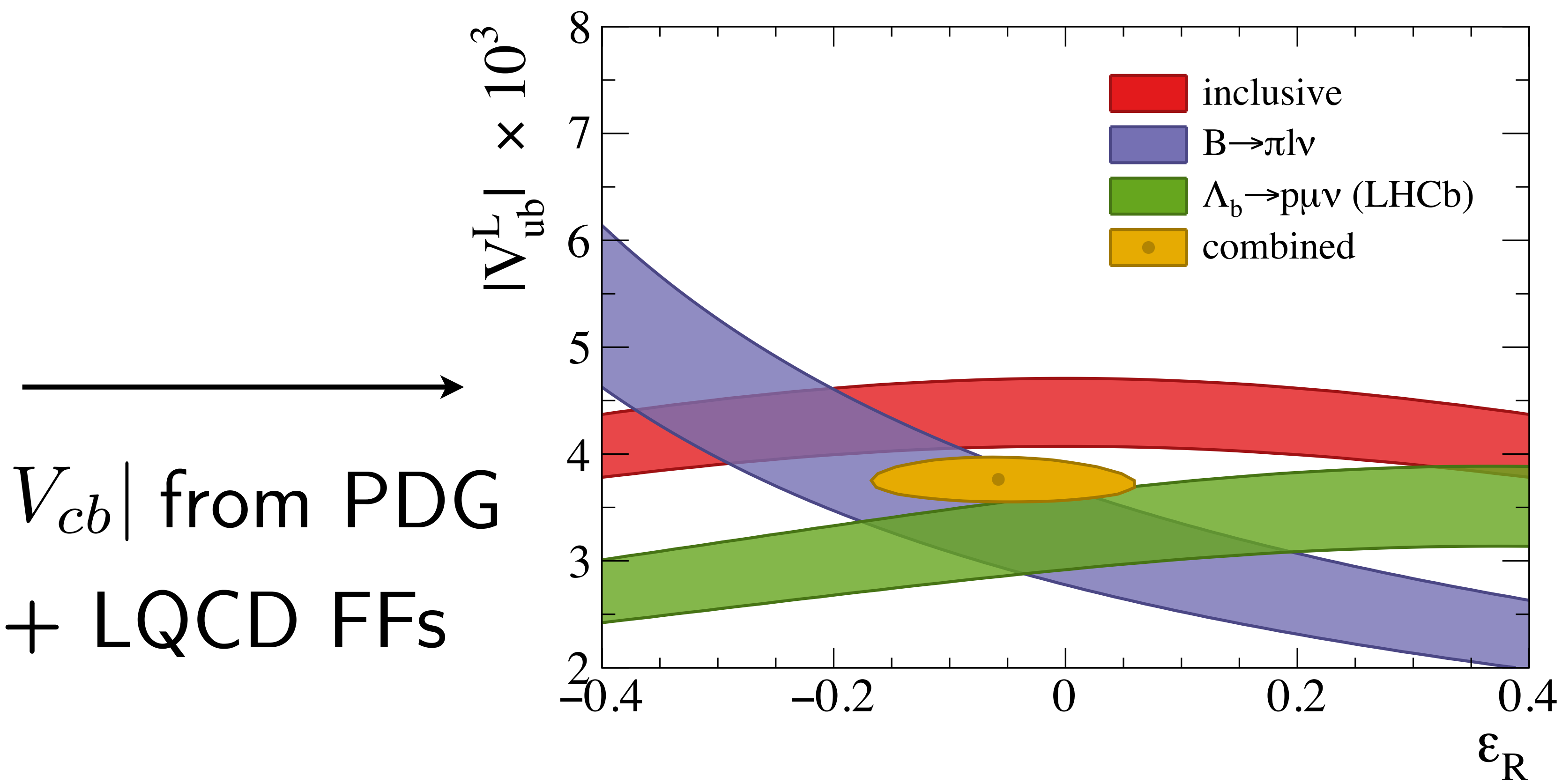
LHCb measurement of $\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)} = 1.00(4)(8) \times 10^{-2}$



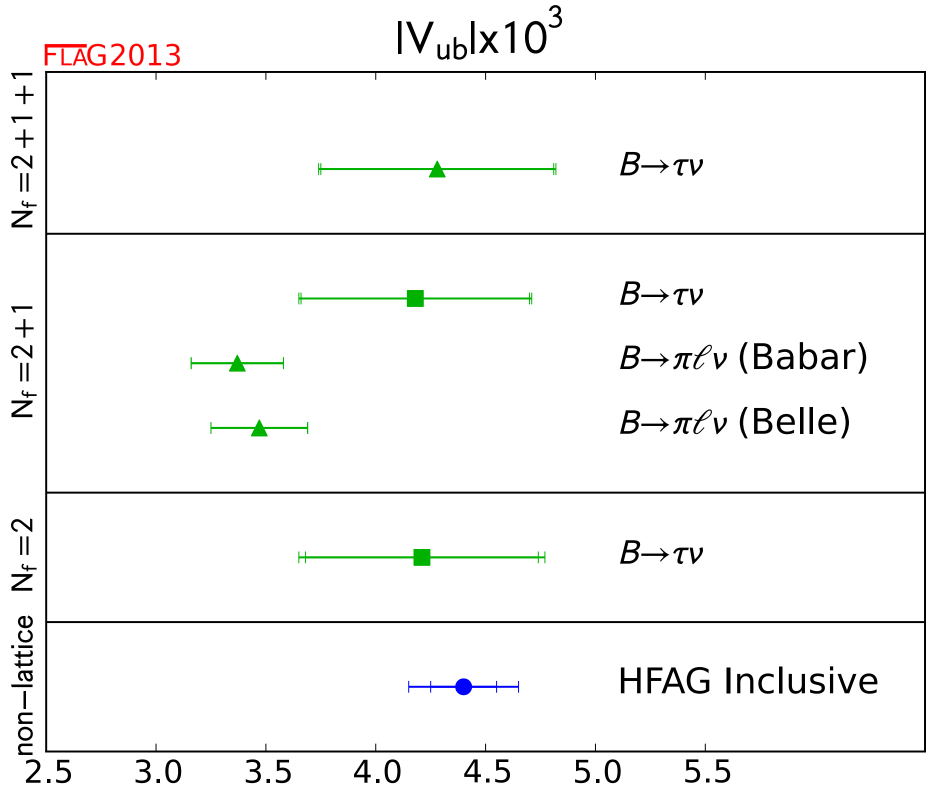


$|V_{cb}|$ from PDG

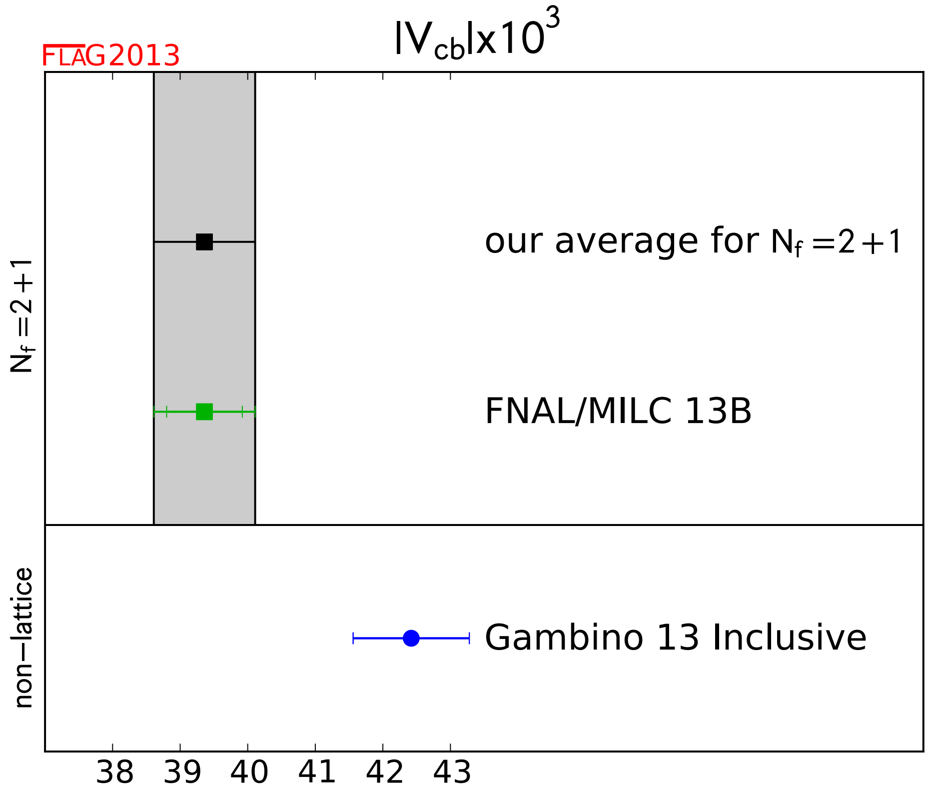
+ LQCD FFs



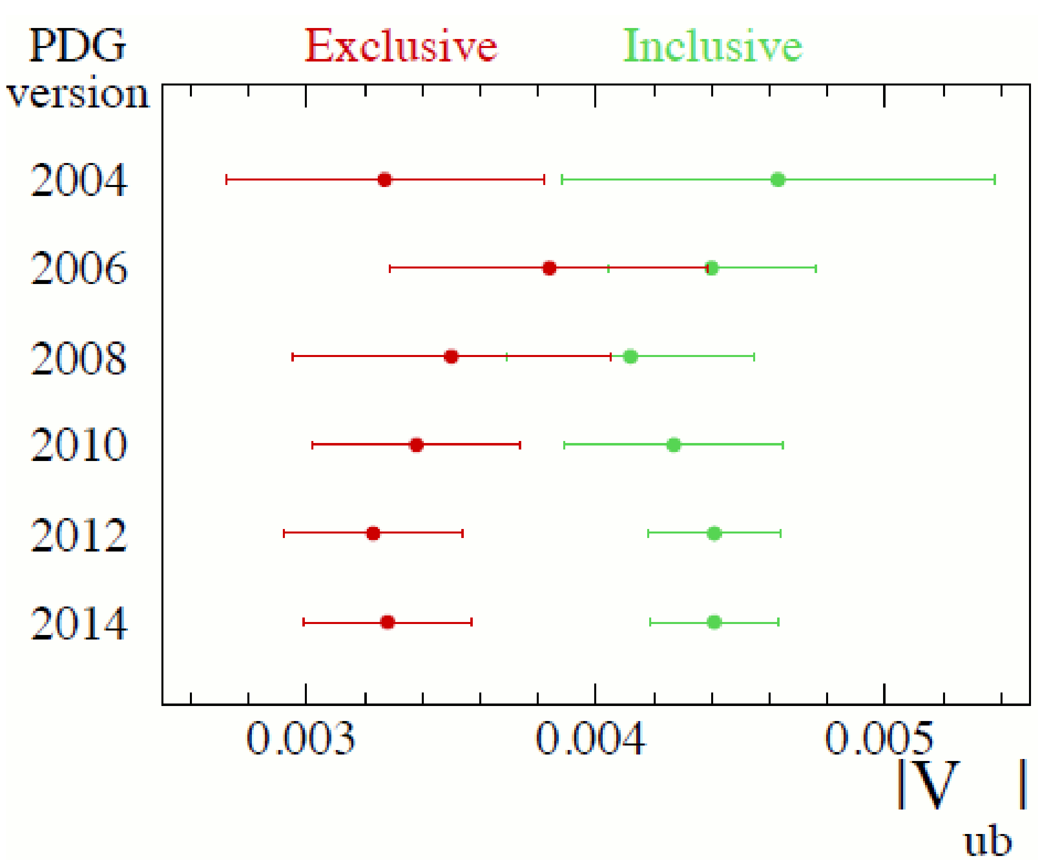
$|V_{ub}|$, $|V_{cb}|$



FLAG2013
|Vub|x10³
Nf=2+1+1
Nf=2+1
Nf=2
non−lattice
B→τν
B→τν
B→πℓν (Babar)
B→πℓν (Belle)
B→τν
HFAG Inclusive
2.5
3.0
3.5
4.0
4.5
5.0
5.5

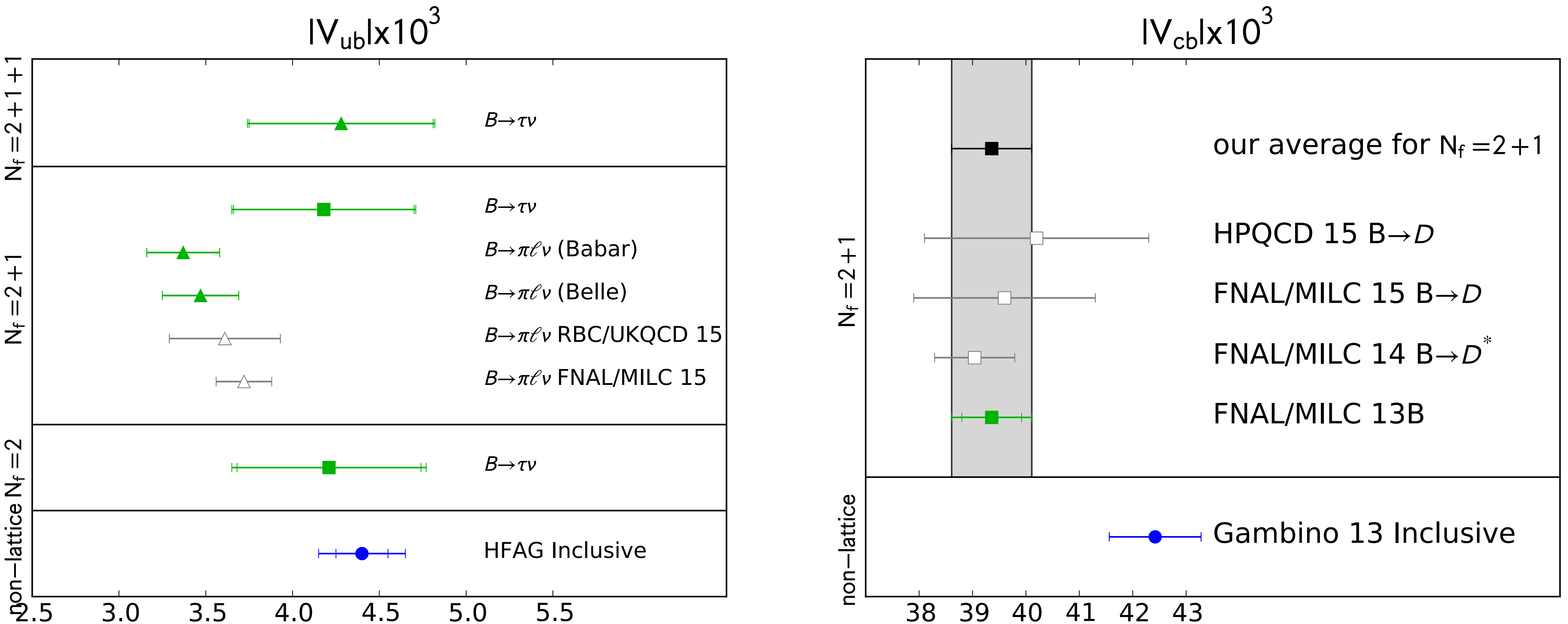


FLAG2013
|Vcb|x10³
Nf=2+1
non−lattice
our average for Nf=2+1
FNAL/MILC 13B
Gambino 13 Inclusive
38
39
40
41
42
43



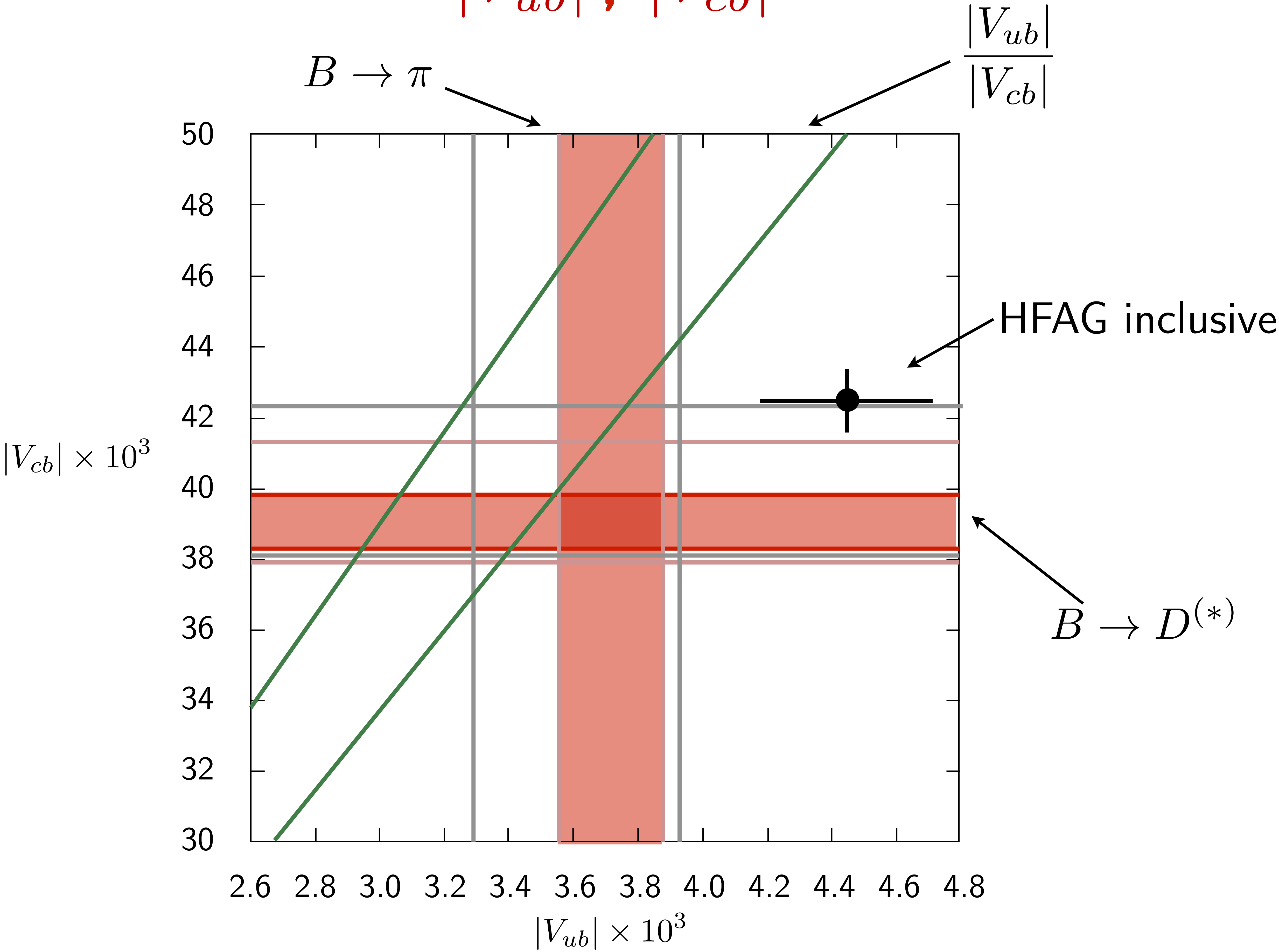
PDG version
Exclusive
Inclusive
2004
2006
2008
2010
2012
2014
0.003
0.004
0.005
|Vub|

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



|Vub|x10^3
Nf =2+1+1
Nf =2+1
non−lattice Nf =2
B→τν
B→τν
B→πℓν (Babar)
B→πℓν (Belle)
B→πℓν RBC/UKQCD 15
B→πℓν FNAL/MILC 15
B→τν
HFAG Inclusive
2.5 3.0 3.5 4.0 4.5 5.0 5.5
|Vcb|x10^3
Nf =2+1
non−lattice
our average for Nf =2+1
HPQCD 15 B→D
FNAL/MILC 15 B→D
FNAL/MILC 14 B→D*
FNAL/MILC 13B
Gambino 13 Inclusive
38 39 40 41 42 43

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



$B \to \pi$
$\frac{|V_{ub}|}{|V_{cb}|}$
HFAG inclusive
$B \to D^{(*)}$
$|V_{cb}| \times 10^3$
30
32
34
36
38
40
42
44
46
48
50
2.6 2.8 3.0 3.2 3.4 3.6 3.8 4.0 4.2 4.4 4.6 4.8
$|V_{ub}| \times 10^3$

plan

- methods: where we stand (brief!)
  - ensembles used in HQ physics, reach
  - HQ approaches

- brief overview of
  - leptonic charm and B decay
  - B mixing

- charm and B semileptonic decays (+ CKM 2nd and 3rd rows)

- the % precision target

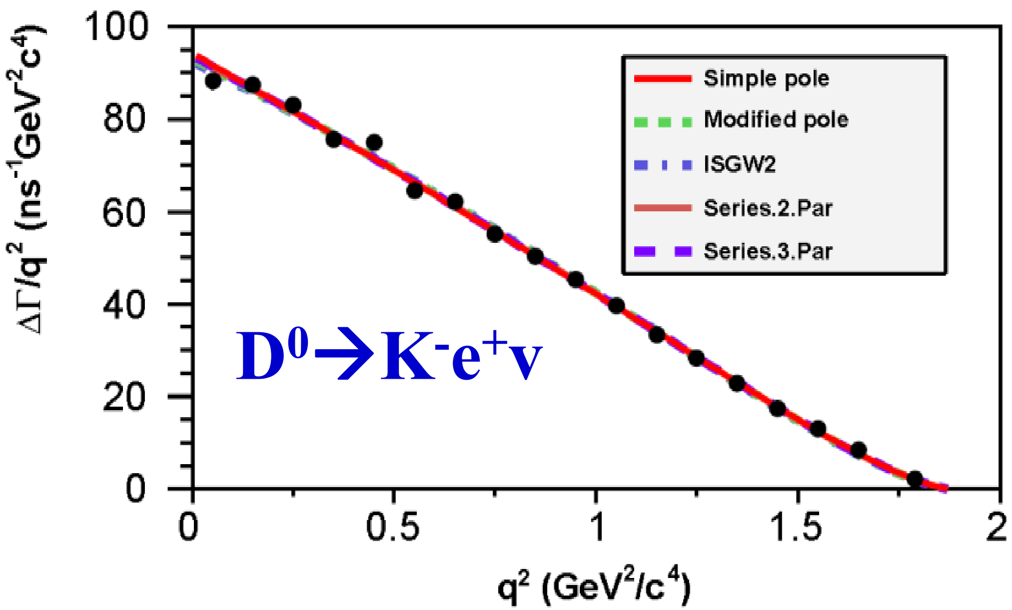
- conclusions and outlook

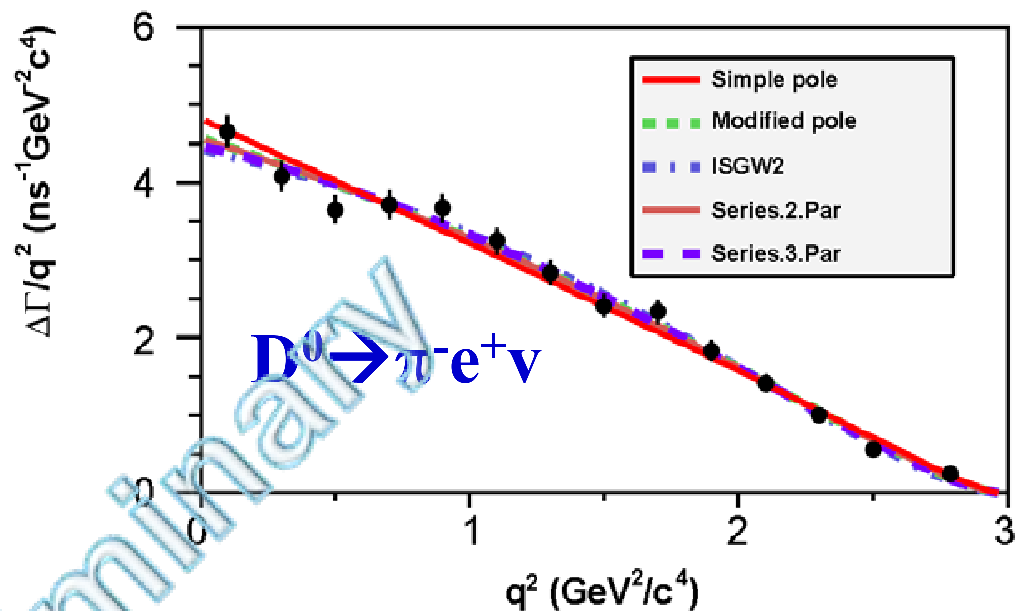
the % semileptonic precision target

- in order to achieve few % precision there are common issues with other quantities ...
  - limitations of HQ approaches
  - (related:) reliance on perturbation theory
  - mixed-action aspects
  - correct treatment of resonances
  - QED (also inclusive determinations), isospin, OPE corrections

- ... and some specific questions
  - contamination from excited states
  - matching of currents / four-quark operators
  - chiPT for form factors
  - **momentum dependence of form factors**

q^2 dependence of form factors





BESIII Preliminary

		$D^0 \to K^- e^+ v$		$D^0 \to \pi^- e^+ v$
Simple Pole	$f_K^+(0)\|V_{cs}\|$	0.7209±0.0022±0.0033	$f_\pi^+(0)\|V_{cd}\|$	0.1475±0.0014±0.0005
	M_{pole}	1.9207±0.0103±0.0069	M_{pole}	1.9114±0.0118±0.0038
Mod. Pole	$f_K^+(0)\|V_{cs}\|$	0.7163±0.0024±0.0034	$f_\pi^+(0)\|V_{cd}\|$	0.1437±0.0017±0.0008
	α	0.3088±0.0195±0.0129	α	0.2794±0.0345±0.0113
ISGW2	$f_K^+(0)\|V_{cs}\|$	0.7139±0.0023±0.0034	$f_\pi^+(0)\|V_{cd}\|$	0.1415±0.0016±0.0006
	r_{ISGW2}	1.6000±0.0141±0.0091	r_{ISGW2}	2.0688±0.0394±0.0124
Series.2.Par	$f_K^+(0)\|V_{cs}\|$	0.7172±0.0025±0.0035	$f_\pi^+(0)\|V_{cd}\|$	0.1435±0.0018±0.0009
	r_1	-2.2278±0.0864±0.0575	r_1	-2.0365±0.0807±0.0260
Series.3.Par	$f_K^+(0)\|V_{cs}\|$	0.7196±0.0035±0.0041	$f_\pi^+(0)\|V_{cd}\|$	0.1420±0.0024±0.0010
	r_1	-2.3331±0.1587±0.0804	r_1	-1.8434±0.2212±0.0690
	r_2	3.4223±3.9090±2.4092	r_2	-1.3871±1.4615±0.4677

[from H Ma's talk on behalf of BESIII at CHARM 2015]

a benchmark case: $f_+(B \to \pi l \nu)$

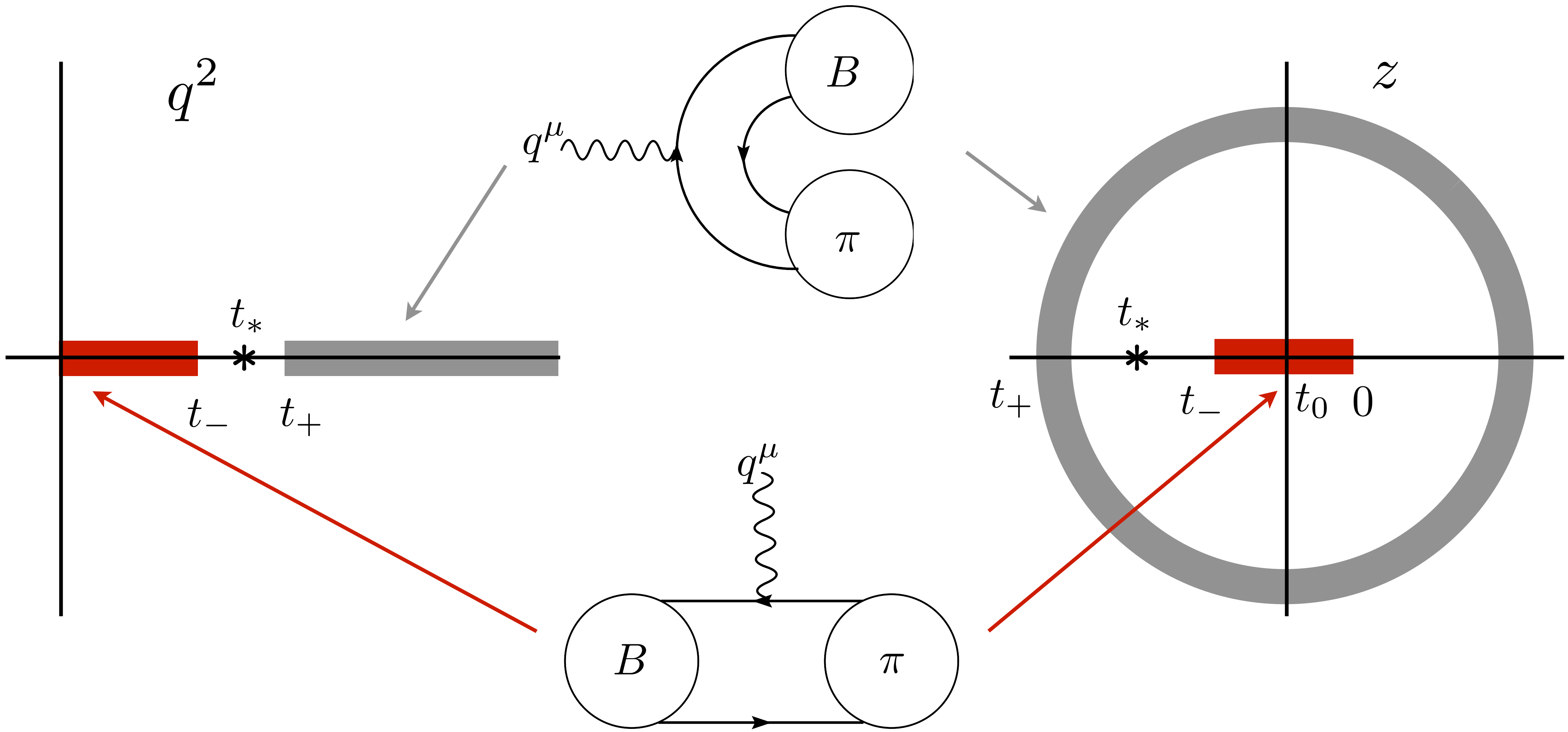
various parametrisations based on pole dominance: Bećirević-Kaidalov, Ball-Zwicky, Hill, ... difficult to systematically improve precision

[Bećirević, Kaidalov PLB 478 (2000) 417]
[Ball, Zwicky PRD 71 (2005) 014015]
[Hill PRD 73 (2006) 014012]

z-parametrisations proposed to solve this issue (almost) rigourously by exploiting unitarity and crossing symmetry

[Okubo PRD 3 (1971) 2807, 4 (1971) 725]
[Bourrely, Machet, de Rafael NPB 189 (1981) 157]
[Boyd, Grinstein, Lebed PRL 74 (1995) 4603]
[Lellouch NPB 479 (1996) 353]
[Bourrely, Caprini, Micu EJPC 27 (2003) 439]
[Arnesen, Grinstein, Rothstein, Stewart PRL 95 (2005) 071802]
[Becher, Hill PLB 633 (2006) 61]
[Flynn, Nieves PRD 75 (2007) 013008]
[Bourrely, Caprini, Lellouch PRD 79 (2009) 013008]

a benchmark case: $f_+(B \to \pi l\nu)$



$$z = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

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

$$t_+ = (m_B + m_\pi)^2\,, \qquad t_0 < t_+$$

unitarity bound: $\sum_{m,n} B_{mn}^{(\phi)} a_m a_n \leq 1$

a benchmark case: $f_+(B \to \pi l \nu)$

$$f_+(q^2) = \frac{1}{B(q^2)\phi(q^2,t_0)} \sum_{n\geq 0} a_n z(q^2,t_0)^n \qquad B(q^2) = z(q^2, m_{B^*}^2)$$

BGL: complicated outer function $\phi \longrightarrow \sum_{n\geq 0} |a_n|^2 \lesssim 1$

[Boyd, Grinstein, Lebed PRL 74 (1995) 4603]

BCL: $f_+(q^2) = \frac{1}{1 - q^2/m_{B^*}^2} \sum_{n\geq 0} a_n z^n \longrightarrow \sum_{m,n\geq 0} B_{mn} a_m a_n \lesssim 1$

(recommended by FLAG)

[Bourrely, Caprini, Lellouch PRD 79 (2009) 013008]

crucial for optimal use:

- *all* sub-threshold poles included in Blaschke factor
- fixed kinematics (coefficients implicitly depend on quark masses)

does the unitarity bound apply?

- using a z-parametrisation as part of a global fit including a, m_q, ... (modified z-expansion) tricky
  - poles can cross threshold as quark masses change
  - complicated entanglement of (m_q,a) dependence (complete form factor vs. z-parametrisation coefficient)

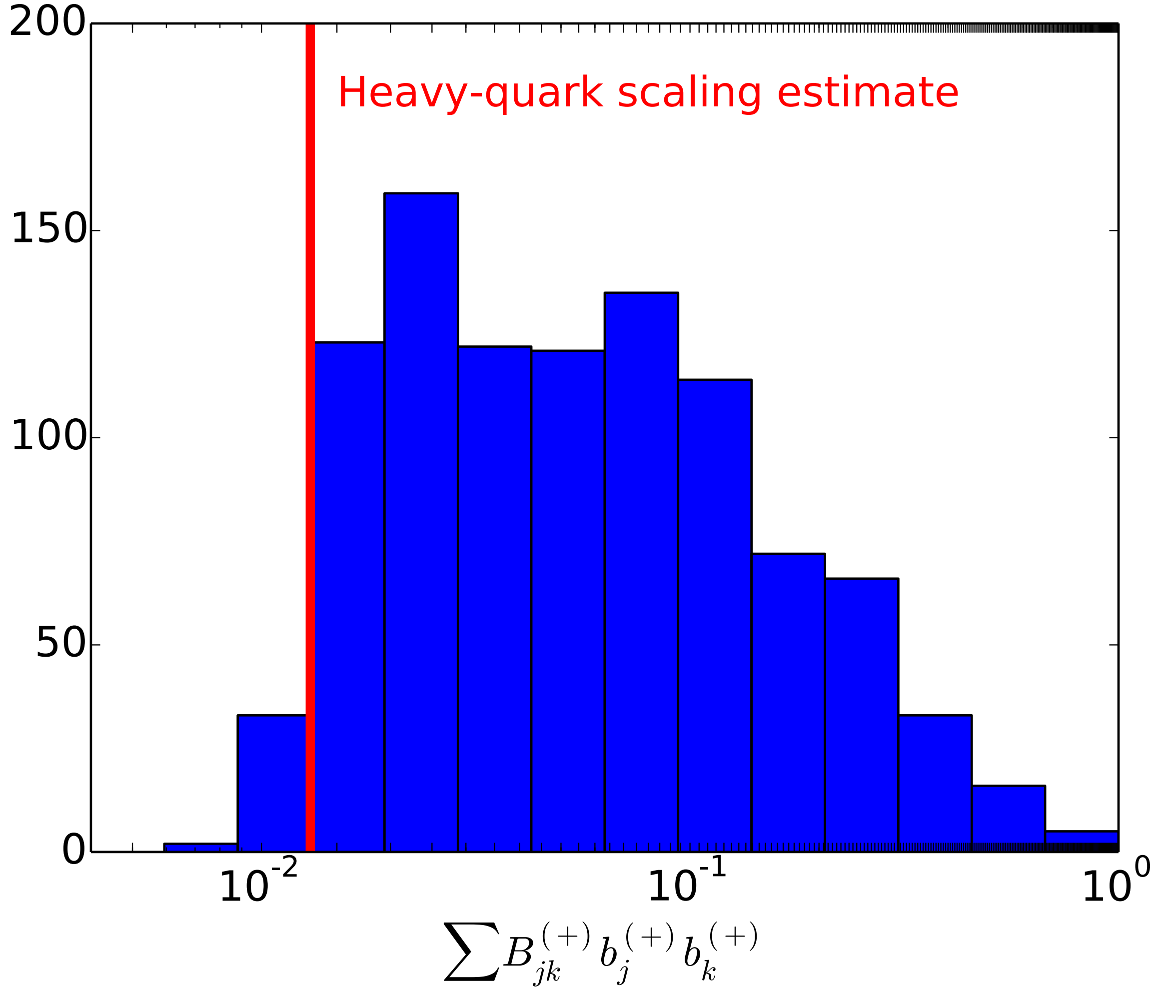
- pole structure not always well-known (scalar channels, D decay), or complicated (Λ_b decay)

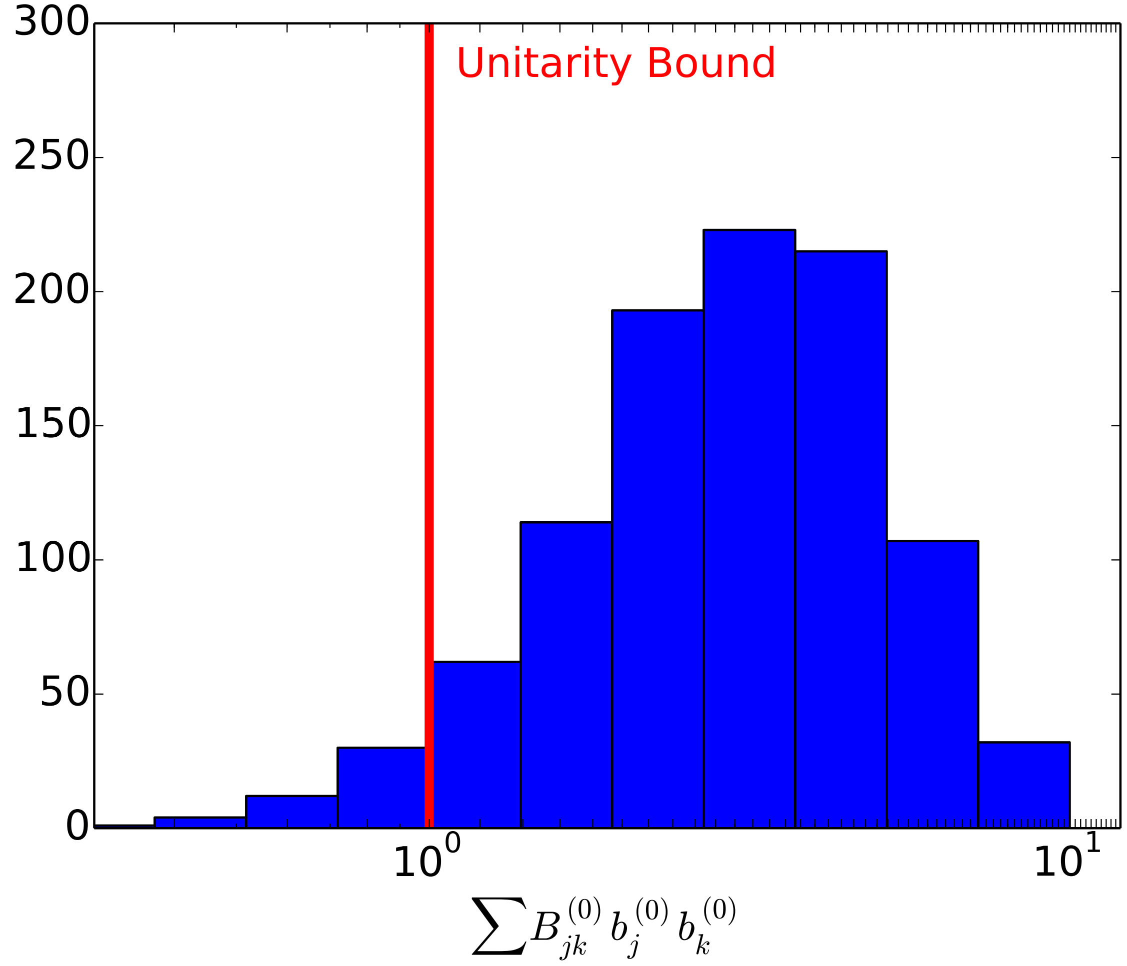
- missing sub-threshold poles may imply convergence breakdown (proton charge radius analysis by Hill, Paz et al, D semileptonic decay data by Bećirević et al)

[Hill, Paz PRD 82 (2010) 113005]
[Bhattacharya, Hill, Paz PRD 84 (2011) 073006]
[Epstein, Paz, Roy PRD 90 (2014) 074027]
[cf talk by J Zanotti]
[Bećirević et al arXiv:1407.1019]

is your z-parametrisation well-behaved?

convergence properties can actually be tested

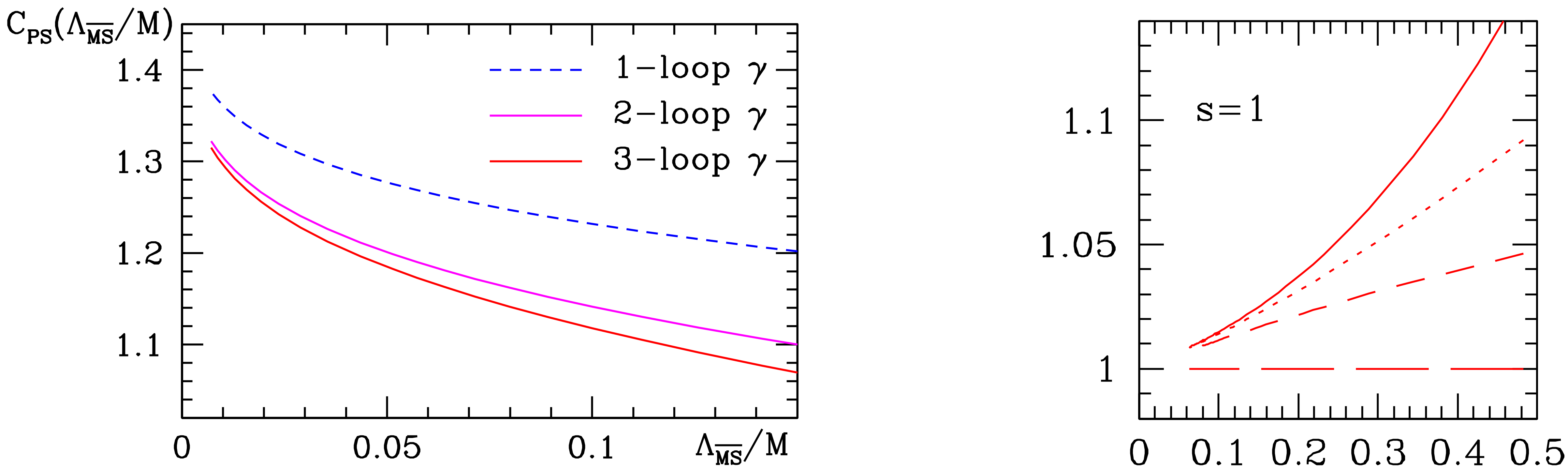




[FNAL/MILC arXiv:1503.07839]

matching/renormalisation

perturbative convergence known to be poor at b scale



[R Sommer, Les Houches Lectures arXiv:1008.0710]

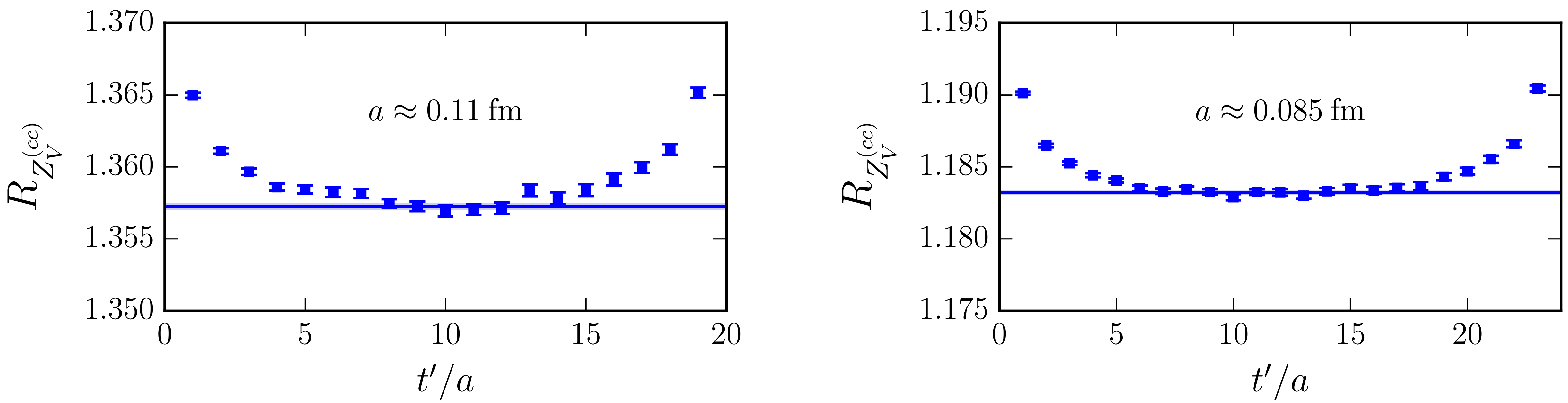
e.g. systematics due to using perturbative running in HQET may well be O(4%) for B decay constant

[cf. P Fritzsch's talk]

extensive one-loop input for matchings/renormalisation needed in RHQ actions and operators (even tree-level, e.g. $B \to D$ transition amplitudes at non-zero recoil)

matching/renormalisation

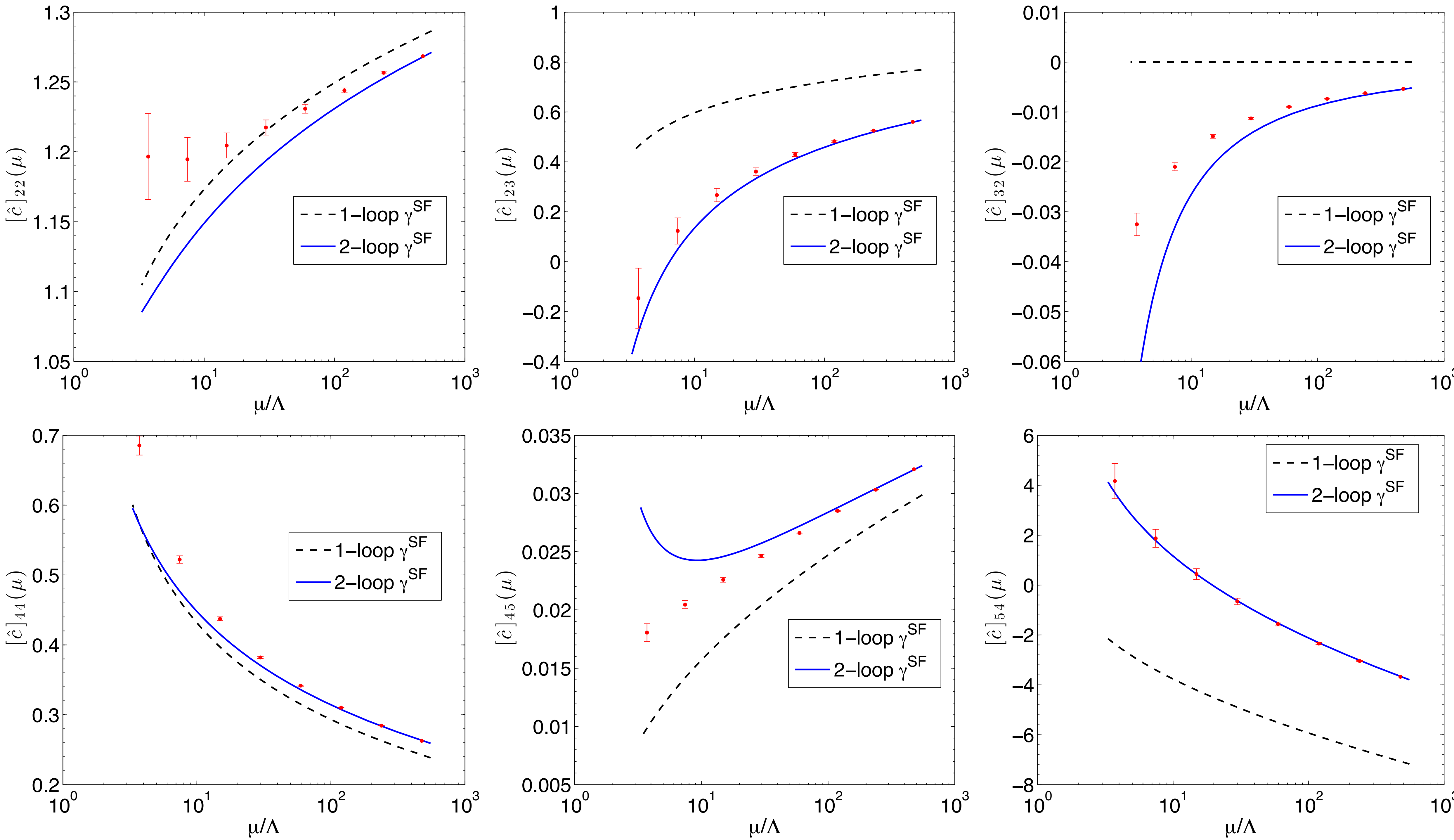
non-perturbative current normalisations for RHQ actions significantly large, huge cutoff dependence; expected effect of RG trajectory tuning?



Parameter	coarse	fine
$Z_V^{(bb)}$	10.037(34)	5.270(13)
$Z_V^{(cc)}$	1.35725(23)	1.18321(14)
$Z_V^{(uu)}$	0.71651(46)	0.74475(12)

[Detmold, Lehner, Meinel arXiv:1503.01421]

matching/renormalisation



[Papinutto, CP, Preti arXiv:1412.1742]

chiPT for SL form factors

- issues in fitting FF light quark mass dependence:
  - how reliable HQchiPT is?
  - uncertainties from g_{H^*HP}
  - explored range in momentum transfer goes well beyond slow pion kinematics

- extension of chiPT to hard pions being rapidly incorporated into analyses

  [Bijnens, Jemos NPB 840 (2010) 54, 844(2011) 182]

- recent efforts aimed at improving precision on g_{H^*HP}

  [RBC/UKQCD arXiv:1311.1251]
  [ALPHA PLB 740 (2015) 278]
  [A Gérardin, Fri 17:30]

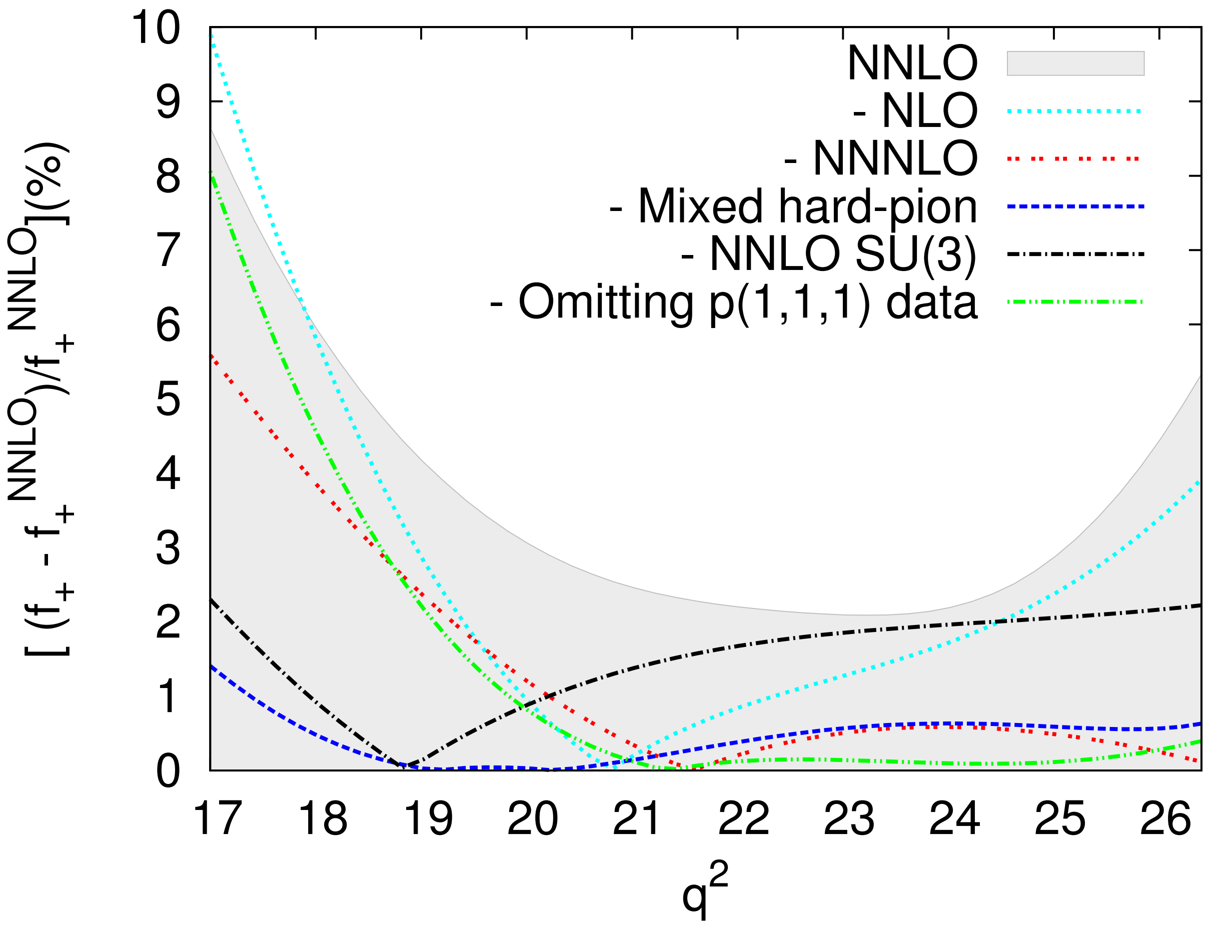
- (HQchiPT systematic dependence should become less relevant as physical pion points enter analyses — H Leutwyler allowing)

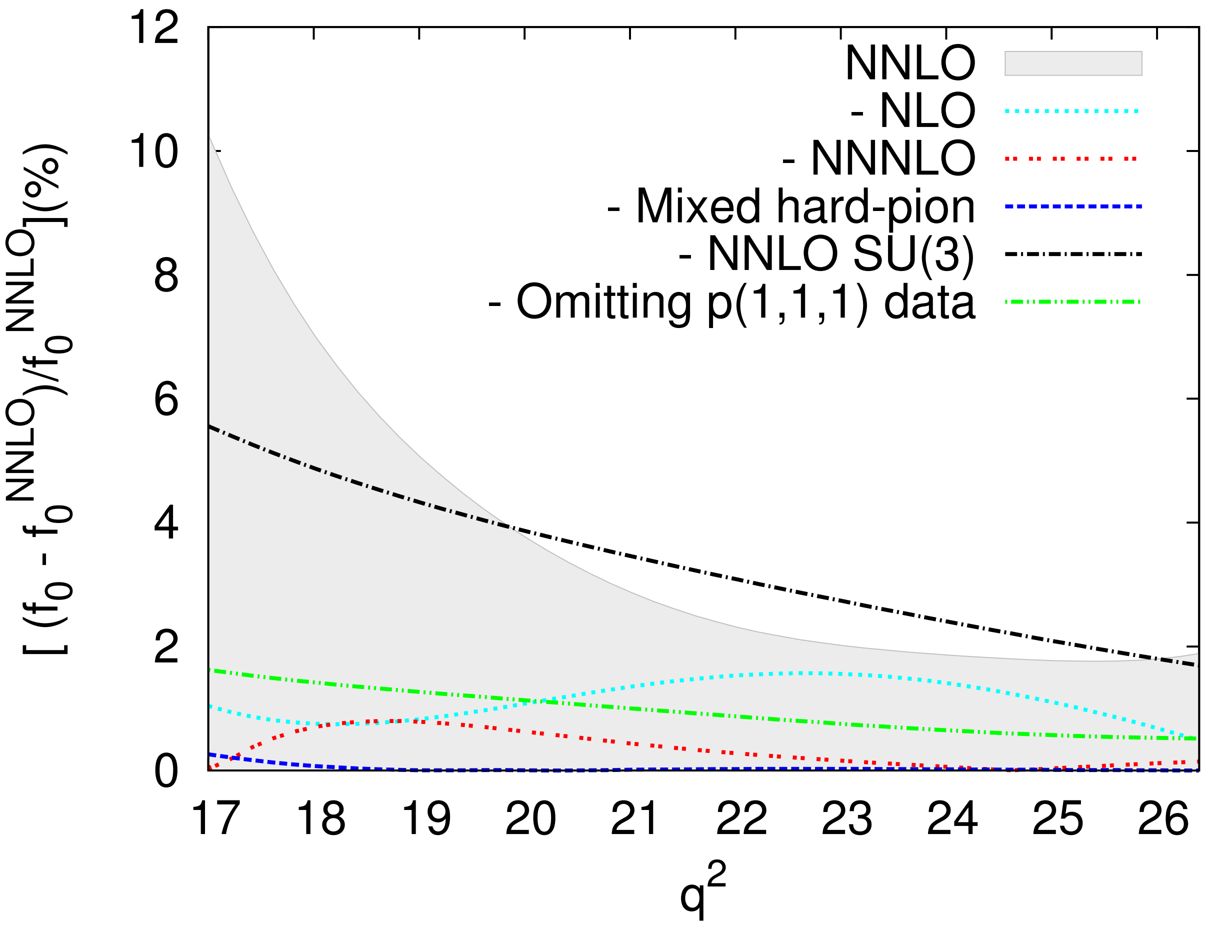
  [cf. A Jüttner's talk]

chiPT for SL form factors

FNAL/MILC analysis of hard-pion chiPT impact in $B \to \pi$

[arXiv:1503.07839]





conclusions and outlook

- HQ physics making great progress, remarkably in semileptonics

- still much way to go to meet the new era precision requirements
  - crosscheck HQ approaches as much as possible
  - full incorporation of available ensembles to HQ physics
  - many systematics to be improved: use of perturbation theory, momentum dependence of FFs, incorporation of QED effects, resonances ...

- decrease the lattice spacing and get direct access to the b region

- FLAG-3 review foreseen for early 2016: keep tuned

backup

Flavour Lattice Averaging Group

advisory board: S Aoki, C Bernard, C Sachrajda

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
$\alpha_{\rm s}$	R Horsley, T Onogi, R Sommer
f_{D_q} , f_{B_q} , B_{B_q}	Y Aoki, M Della Morte, A El-Khadra
SL, rare	E Lunghi, CP, R Van de Water

FLAG-2 review published in 2014, includes results up to $\lesssim$ end 2013

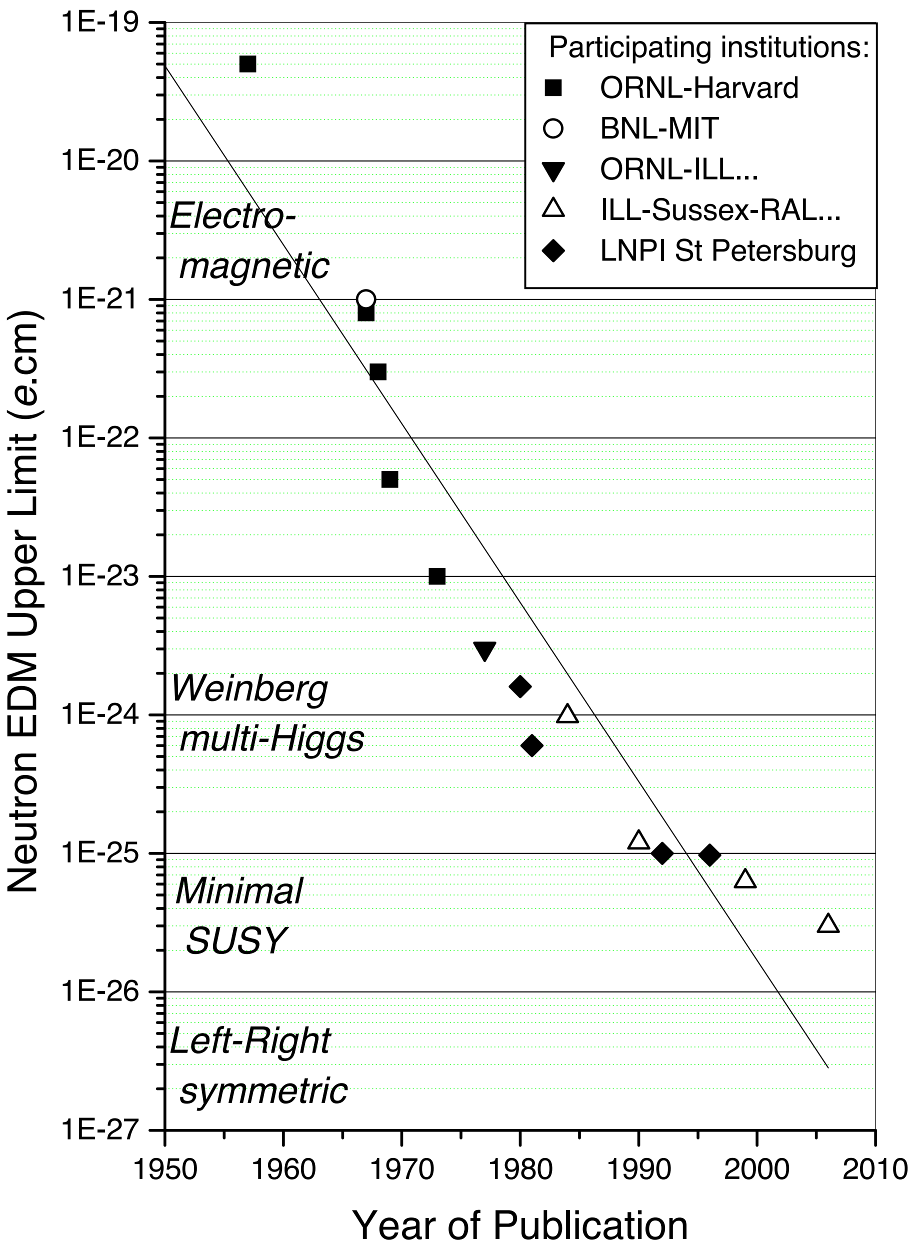
[FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

FLAG-3

AB: S Aoki, C Bernard, H Leutwyler, C Sachrajda	
EB: G Colangelo, S Hashimoto, A Jüttner, S Sharpe, A Vladikas, U Wenger	
WGs:	
quark masses (+HQ)	T Blum, L Lellouch, V Lubicz
V_{ud} , V_{us}	P Boyle, T Kaneko, S Simula
LECs	S Dürr, H Fukaya, U Heller
B_K (+BSM)	P Dimopoulos, R Mawhinney, H Wittig
$\alpha_{\rm s}$	R Horsley, T Onogi, R Sommer
f_{D_q} , f_{B_q} , B_{B_q}	Y Aoki, D Lin, M Della Morte
SL, rare	D Bećirević, S Gottlieb, E Lunghi, CP

expected publication early 2016, **no preliminary averages yet :-(**

bounds on neutron EDM



[P Harris, arXiv:0709.3100]

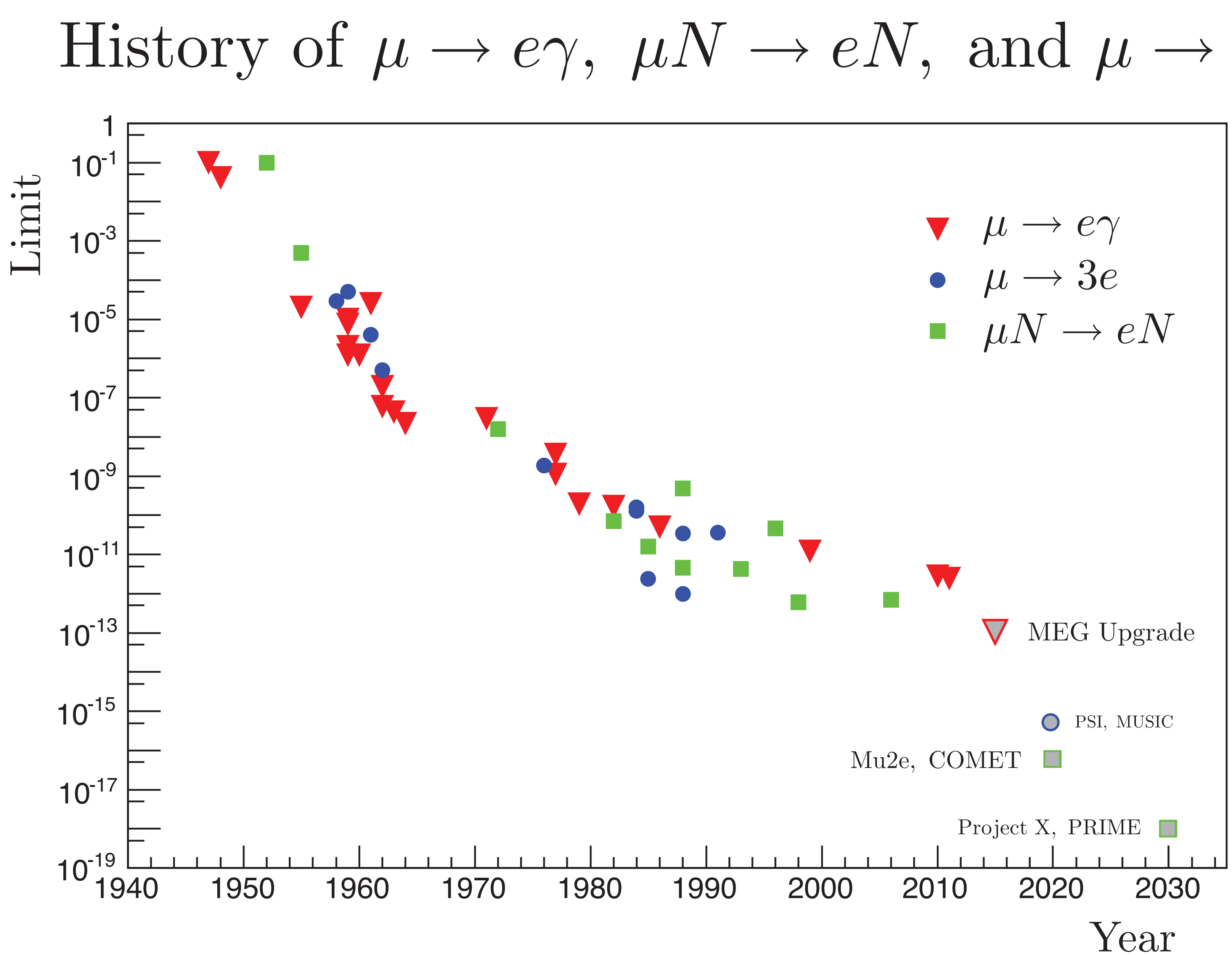
confined ultracold atoms $\Rightarrow |d_n| \sim 10^{-27}$—$10^{-28}\ e \cdot cm$

(slow neutron sources at Oak Ridge, J-PARC, PSI, TRIUMF, Lund)

[H Shimizu, FPCP15]

bounds on charged lepton flavour violation

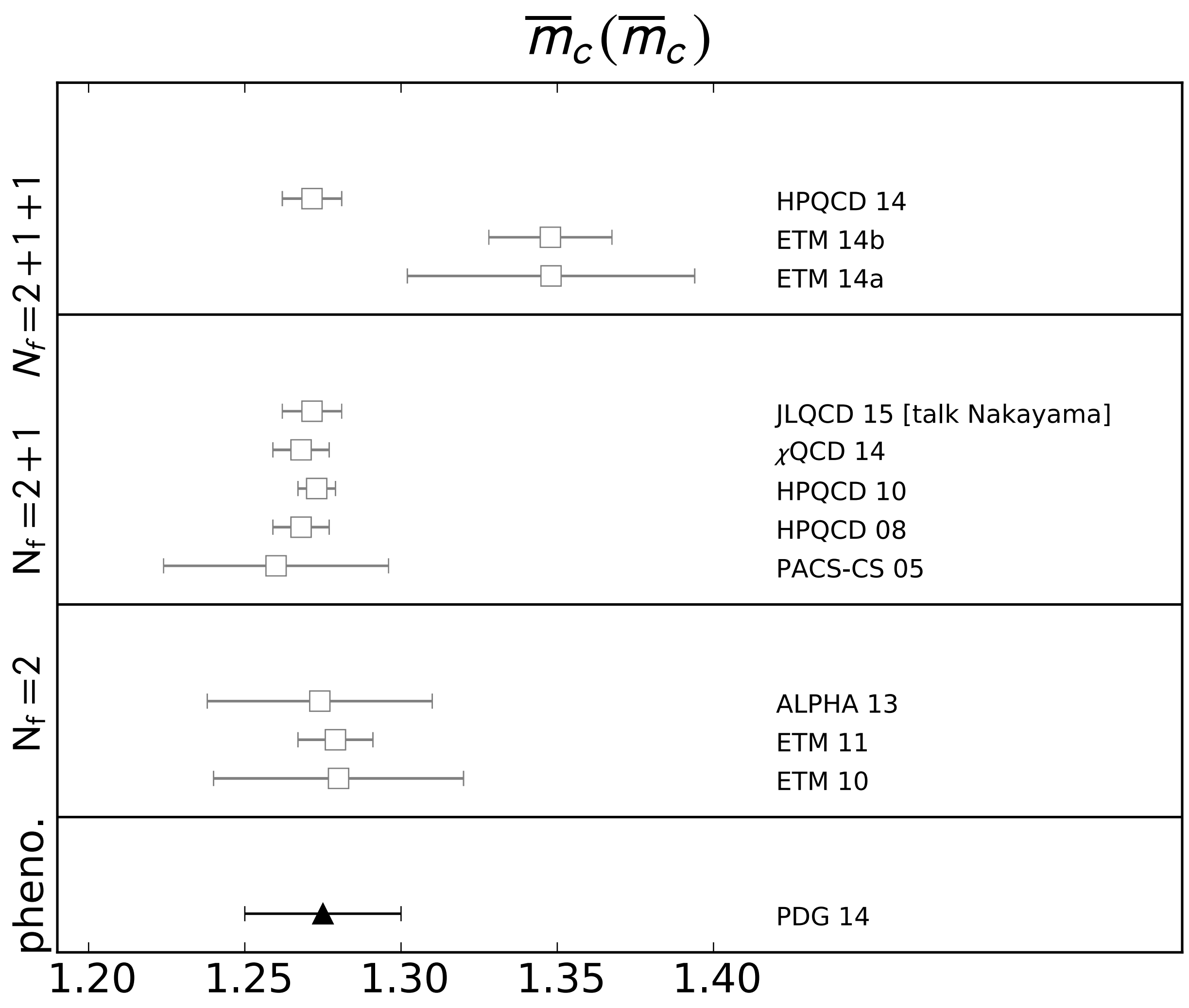
LFV not present in the SM for $m_\nu \neq 0$, no reason to impose it

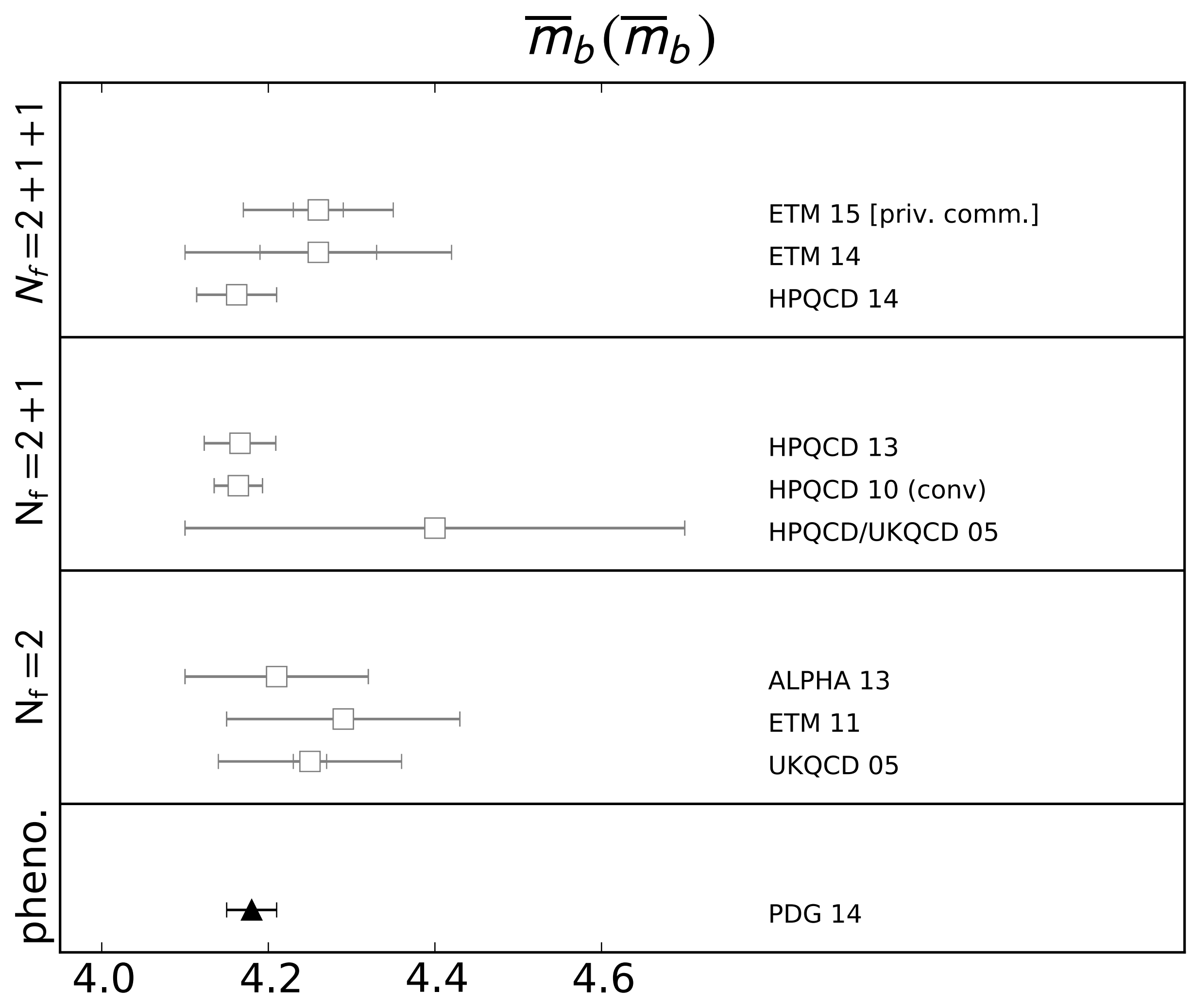


[plot from Z Ligeti's review talk at FPCP 2015]

c and *b* quark masses

almost no new results after F Sanfilippo's review at Lattice 2014





see also talk on JLQCD results from moments method

[K Nakayama, Wed 16:50]

FLAG-2 on charm decay constants

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization/matching	heavy quark treatment	f_D	f_{D_s}	f_{D_s}/f_D
ETM 13F	[154]	2+1+1	C	○	○	○	★	✓	202(8)	242(8)	1.199(25)
FNAL/MILC 13$^{\triangledown}$	[328]	2+1+1	C	★	★	★	★	✓	212.3(0.3)(1.0)	248.7(0.2)(1.0)	1.1714(10)(25)
FNAL/MILC 12B	[329]	2+1+1	C	★	★	★	★	✓	209.2(3.0)(3.6)	246.4(0.5)(3.6)	1.175(16)(11)
HPQCD 12A	[330]	2+1	A	○	○	★	★	✓	208.3(1.0)(3.3)	246.0(0.7)(3.5)	1.187(4)(12)
FNAL/MILC 11	[331]	2+1	A	○	○	★	○	✓	218.9(11.3)	260.1(10.8)	1.188(25)
PACS-CS 11	[332]	2+1	A	■	★	■	○	✓	226(6)(1)(5)	257(2)(1)(5)	1.14(3)
HPQCD 10A	[94]	2+1	A	★	○	★	★	✓	213(4)*	248.0(2.5)	
HPQCD/UKQCD 07	[164]	2+1	A	★	○	★	★	✓	207(4)	241 (3)	1.164(11)
FNAL/MILC 05	[333]	2+1	A	○	○	★	○	✓	201(3)(17)	249(3)(16)	1.24(1)(7)
ETM 13B$^{\square}$	[334]	2	P	★	○	★	★	✓	208(7)	250(7)	1.20(2)
ETM 11A	[335]	2	A	★	○	★	★	✓	212(8)	248(6)	1.17(5)
ETM 09	[168]	2	A	○	○	★	★	✓	197(9)	244(8)	1.24(3)

$^{\triangledown}$ Update of FNAL/MILC 12B.
* This result is obtained by using the central value for f_{D_s}/f_D from HPQCD/UKQCD 07 and increasing the error to account for the effects from the change in the physical value of r_1.
$^{\square}$ Update of ETM 11A and ETM 09.

[FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

new results for $f_{D_{(s)}}$

	TWQCD	ETMC phys	χQCD	FNAL/MILC	ETMC
f_D [MeV]	202.3(2.2)(2.6)	216.7(2.3)(4.2)	—	212.6(0.4)$(^{+1.2}_{-1.0})$	209.2(3.3)
f_{D_s} [MeV]	258.7(1.1)(2.9)	255.9(0.5)(5.0)	254(2)(4)	249.0(0.3)$(^{+1.1}_{-1.5})$	248.6(2.7)
f_{D_s}/f_D	1.279(26)	1.206(23)	—	1.1712(10)$(^{+29}_{-32})$	1.187(12)
ensembles	TWQCD	ETMC	RBC/UKQCD	MILC	ETMC
N_f	2	2	2+1	2+1+1	2+1+1
a (fm)	1/0.06	1/0.09	2/0.085, 0.111	4/0.06 – 0.15	3/0.062 – 0.089
$M_\pi^{\min}$ [MeV]	259	132	320	130	210
$M_\pi^{\min} L$	2	3.0	4.3	3.2	3.1
sea	DW	tmQCD	DW	HISQ	tmQCD
valence	DW	tmQCD/OS	overlap	HISQ	tmQCD/OS
reference	[1404.3648]	[priv. comm.]	[1410.3343]	[1407.3772]	[1411.7908]

+ report of work in progress by RBC/UKQCD [T Tsang, Thu 10:40]

LATTICE 2015 KOBE

FLAG-2 on B decay constants

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization/matching	heavy quark treatment	f_{B^+}	f_{B^0}	f_B	f_{B_s}
ETM 13E	[398]	2+1+1	C	○	○	○	○	✓	–	–	196(9)	235(9)
HPQCD 13	[399]	2+1+1	A	★	★	★	○	✓	184(4)	188(4)	186(4)	224(5)
RBC/UKQCD 13A	[400]	2+1	C	○	○	★	○	✓	–	–	$191(6)^{\diamond}_{\rm stat}$	$233(5)^{\diamond}_{\rm stat}$
HPQCD 12	[401]	2+1	A	○	○	★	○	✓	–	–	191(9)	228(10)
HPQCD 12	[401]	2+1	A	○	○	★	○	✓	–	–	$189(4)^{\triangle}$	–
HPQCD 11A	[365]	2+1	A	★	○	★	★	✓	–	–	–	$225(4)^{\nabla}$
FNAL/MILC 11	[331]	2+1	A	○	○	★	○	✓	197(9)	–	–	242(10)
HPQCD 09	[402]	2+1	A	○	○	★	○	✓	–	–	$190(13)^{\bullet}$	$231(15)^{\bullet}$
ALPHA 13	[403]	2	C	★	★	★	★	✓	–	–	187(12)(2)	224(13)
ETM 13B, 13C	[334, 404]	2	$P^{\dagger}$	★	○	★	○	✓	–	–	189(8)	228(8)
ALPHA 12A	[369]	2	C	★	★	★	★	✓	–	–	193(9)(4)	219(12)
ETM 12B	[392]	2	C	★	○	★	○	✓	–	–	197(10)	234(6)
ALPHA 11	[364]	2	C	★	○	★	★	✓	–	–	174(11)(2)	–
ETM 11A	[335]	2	A	○	○	★	○	✓	–	–	195(12)	232(10)
ETM 09D	[391]	2	A	○	○	○	○	✓	–	–	194(16)	235(12)

$^{\diamond}$Statistical errors only.
$^{\triangle}$Obtained by combining f_{B_s} from HPQCD 11A with f_{B_s}/f_B calculated in this work.
$^{\nabla}$This result uses one ensemble per lattice spacing with light to strange sea-quark mass ratio $m_\ell/m_s \approx 0.2$.
$^{\bullet}$This result uses an old determination of $r_1 = 0.321(5)$ fm from Ref. [379] that has since been superseded.
†Update of ETM 11A and 12B.

[FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

new results for f_{B_q}

	ALPHA (def)	RBC/UKQCD	RBC/UKQCD$_{\text{stat}}$	ETMC
f_B [MeV]	186(13)	196(15)/200(13)*	219(31)	194(5)(3)
f_{B_s} [MeV]	224(14)	235(12)	264(37)	229(4)(3)
f_{B_s}/f_B	1.203(65)	1.223(71)/1.197(50)*	1.193(48)	1.179(18)(18)
ensembles	CLS	RBC/UKQCD	RBC/UKQCD	ETMC
N_f	2	2+1	2+1	2+1+1
a (fm)	3/0.0483 – 0.0749	2/0.085, 0.111	2/0.085, 0.111	3/0.062 – 0.089
M_π^{min} [MeV]	190	289	289	210
$M_\pi^{\mathrm{min}} L$	4.0	4.0	4.0	3.1
l quarks	NP O(*a*) improved	DW	DW	tmQCD
b quark	npHQET	RHQ (Columbia)	static	tmQCD/OS
reference	[1404.3590]	[1404.4670]	[1406.6192]	[priv. comm.]

* f_{B^+}/f_{B^0}

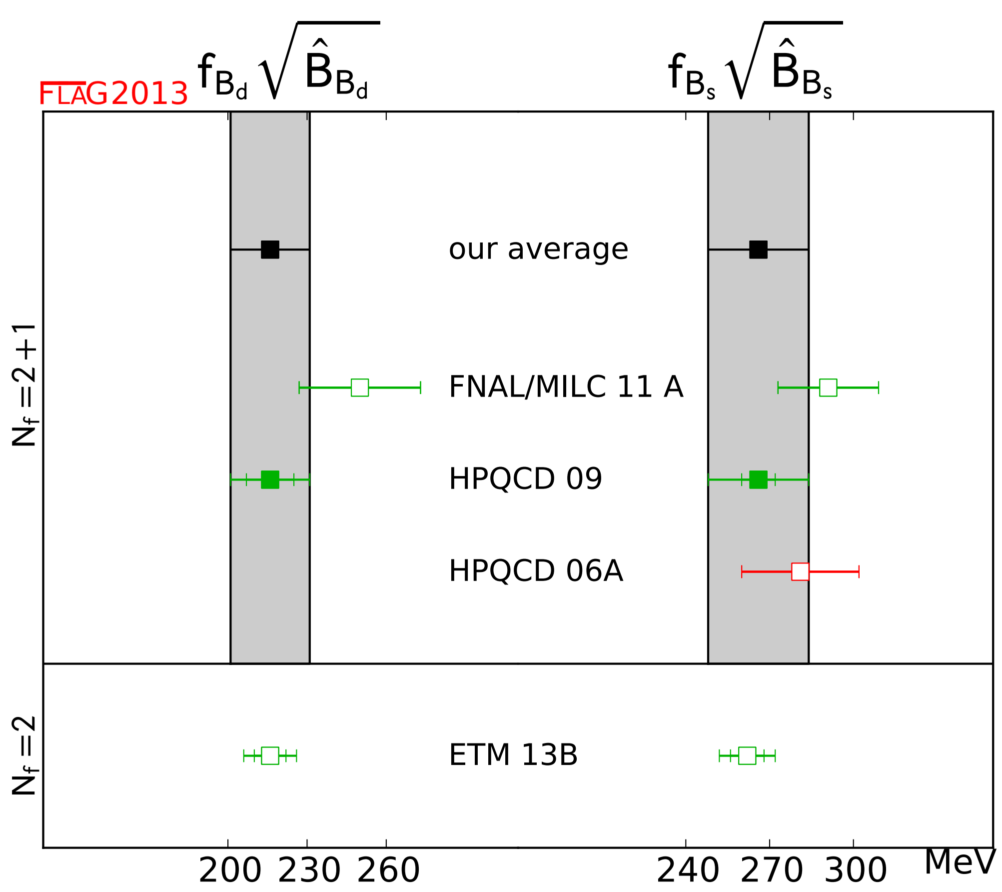
+ report of work in progress by RBC/UKQCD, FNAL/MILC [T Ishikawa, Thu 8:30] [C DeTar, Thu 8:50]

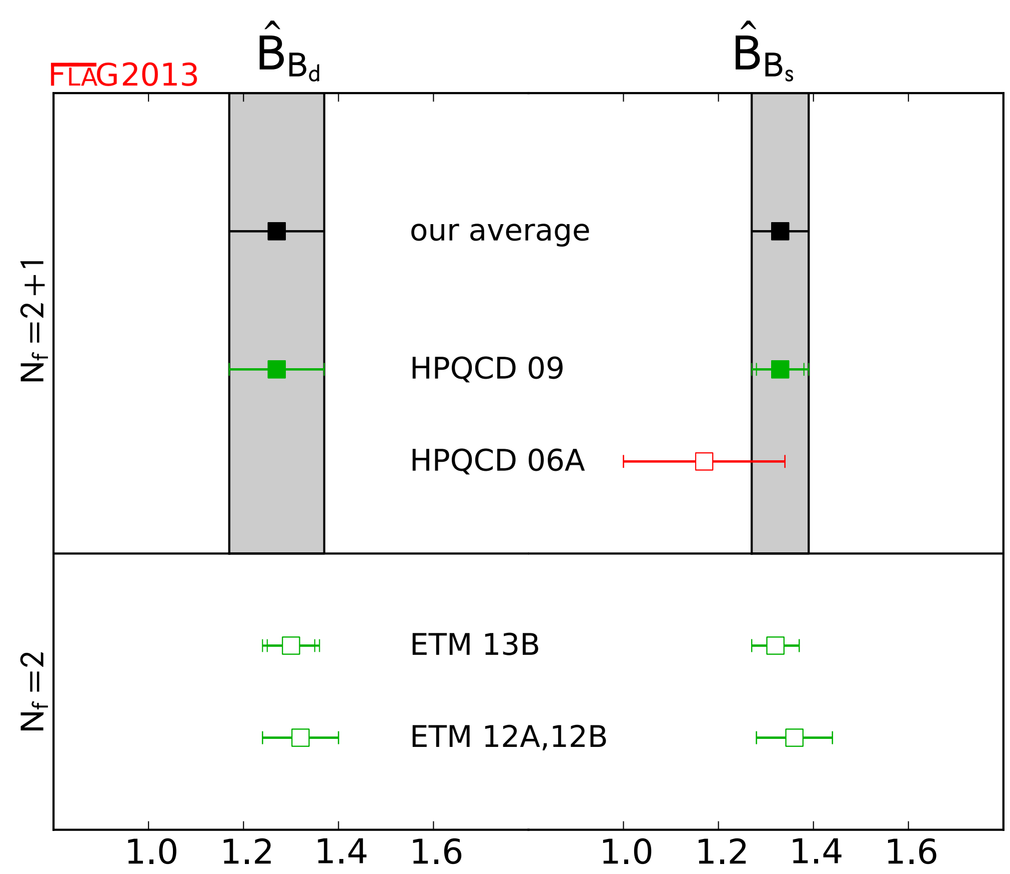
LATTICE 2015 KOBE

FLAG-2 on B-mixing

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization/matching	heavy quark treatment	$f_{B_d}\sqrt{\hat{B}_{B_d}}$	$f_{B_d}\sqrt{\hat{B}_{B_s}}$	$\hat{B}_{B_d}$	$\hat{B}_{B_s}$
FNAL/MILC 11A	[411]	2+1	C	★	○	★	○	✓	250(23)†	291(18)†	–	–
HPQCD 09	[402]	2+1	A	○	○$^\nabla$	★	○	✓	216(15)*	266(18)*	1.27(10)*	1.33(6)*
HPQCD 06A	[412]	2+1	A	■	■	★	○	✓	–	281(21)	–	1.17(17)
ETM 13B	[334]	2	P	★	○	★	★	✓	216(6)(8)	262(6)(8)	1.30(5)(3)	1.32(5)(2)
ETM 12A, 12B	[392, 413]	2	C	★	○	★	★	✓	–	–	1.32(8)$^\diamond$	1.36(8)$^\diamond$

now published (ETM 13B)

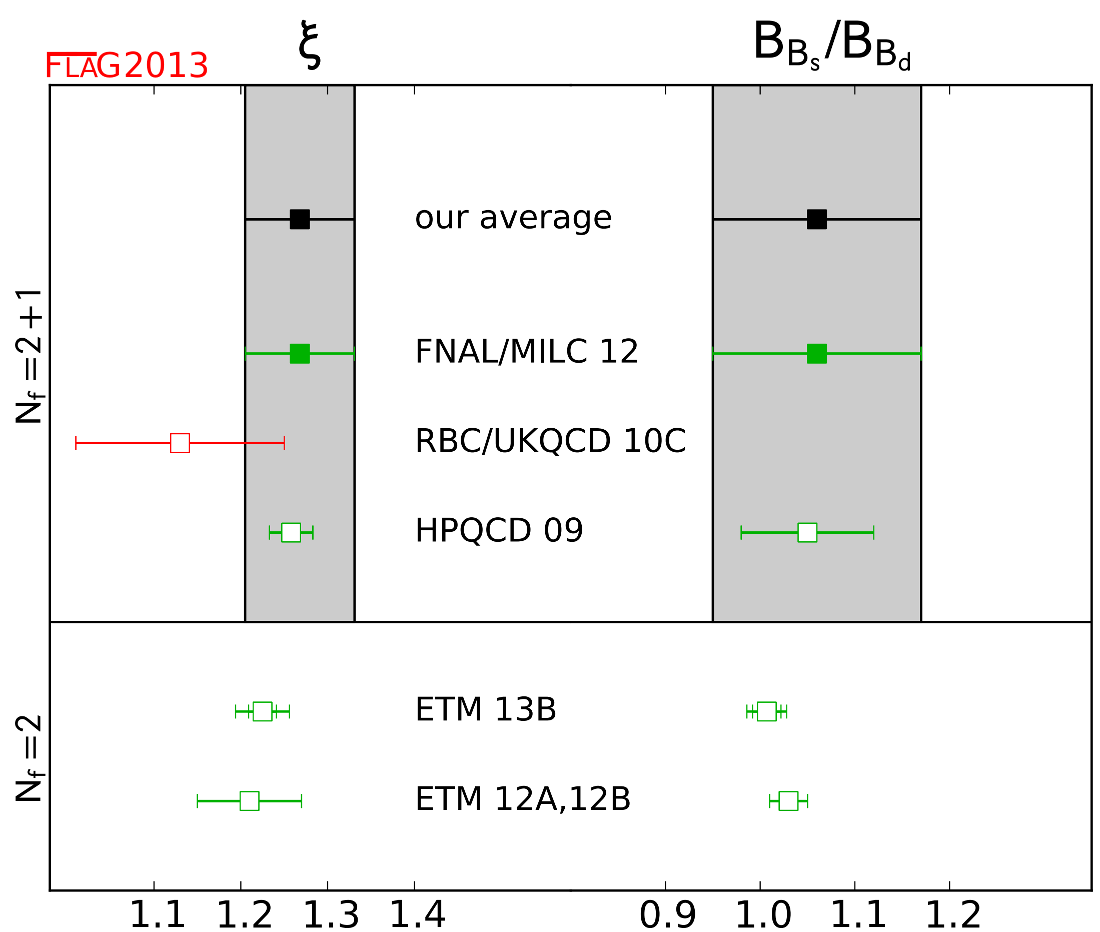




FLAG-2 on B-mixing

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization/matching	heavy quark treatment	ξ	B_{B_s}/B_{B_d}
FNAL/MILC 12	[414]	2+1	A	○	○	★	○	✓	1.268(63)	1.06(11)
RBC/UKQCD 10C	[405]	2+1	A	■	■	★	○	✓	1.13(12)	–
HPQCD 09	[402]	2+1	A	○	○$^\triangledown$	★	○	✓	1.258(33)	1.05(7)
ETM 13B	[334]	2	P	★	○	★	★	✓	1.225(16)(14)(22)	1.007(15)(14)
ETM 12A, 12B	[392, 413]	2	C	★	○	★	★	✓	1.21(6)	1.03(2)

now published (ETM 13B)



new results for B-mixing

RBC/UKQCD static limit

[Y Aoki et al, PRD 91 (2014) 114505, arXiv:1406.6192]

ensembles	RBC/UKQCD
N_f	2+1
a (fm)	2/0.085, 0.111
M_π^min [MeV]	320
$M_\pi^\mathrm{min} L$	4.3
l quarks	DWF
b quark	static

$$f_{B_d}\sqrt{\hat{B}_{B_d}} = 240(15)(33)$$

$$f_{B_s}\sqrt{\hat{B}_{B_s}} = 290(9)(40)$$

$$\hat{B}_{B_d} = 1.17(11)(24)$$

$$\hat{B}_{B_s} = 1.22(6)(19)$$

$$B_{B_s}/B_{B_d} = 1.028(60)(49)$$

$$\xi = 1.208(41)(52)$$

preliminary FNAL/MILC N_f=2+1: $\xi = 1.211(19)$

+ work in progress by FNAL/MILC, RBC/UKQCD

[J Simone, Thu 9:10]
[A Khamseh, Thu 11:00]
[T Ishikawa, Thu 8:30]
[T Kawanai, Fri 16:30]
[O Witzel, Fri 17:10]
[P Korcyl, Tue 16:30]

FLAG-2 on charm semileptonic decay

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization	heavy-quark treatment	$f_+^{D\pi}(0)$	$f_+^{DK}(0)$
HPQCD 11	[337]	2+1	A	○	○	★	★	✓	0.666(29)	
HPQCD 10B	[341]	2+1	A	○	○	★	★	✓		0.747(19)
FNAL/MILC 04	[356]	2+1	A	■	■	★	○	✓	0.64(3)(6)	0.73(3)(7)
ETM 11B	[344]	2	C	○	○	★	★	✓	0.65(6)(6)	0.76(5)(5)

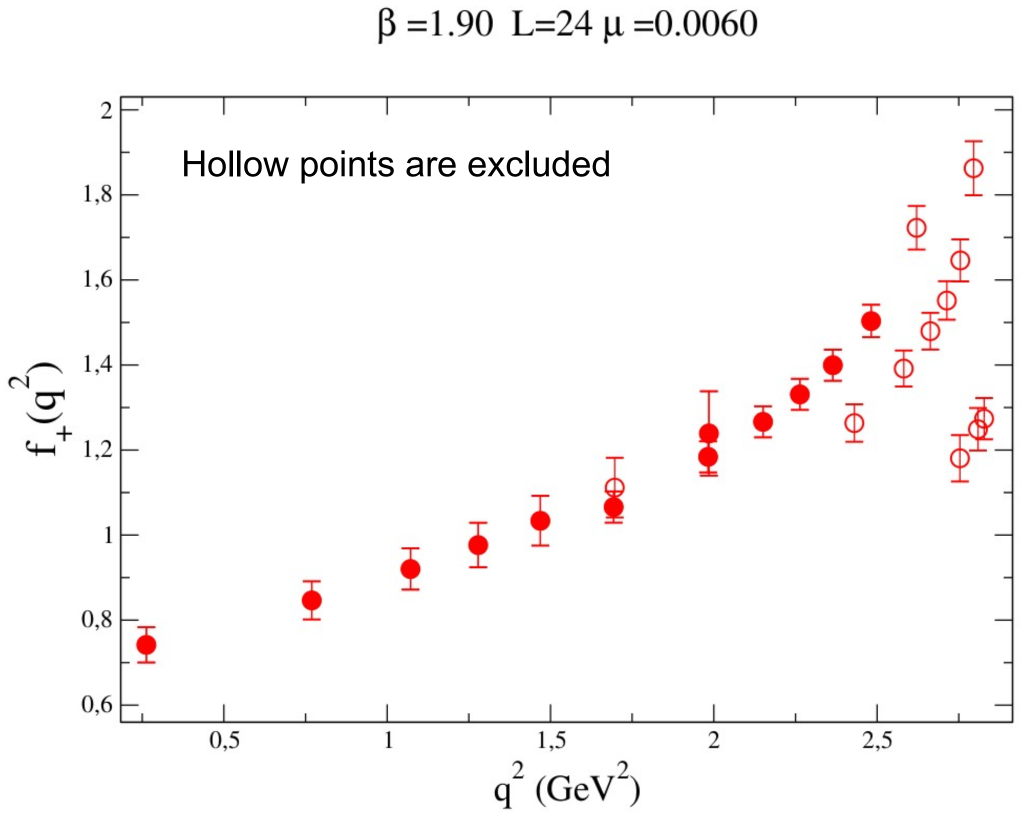
[FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

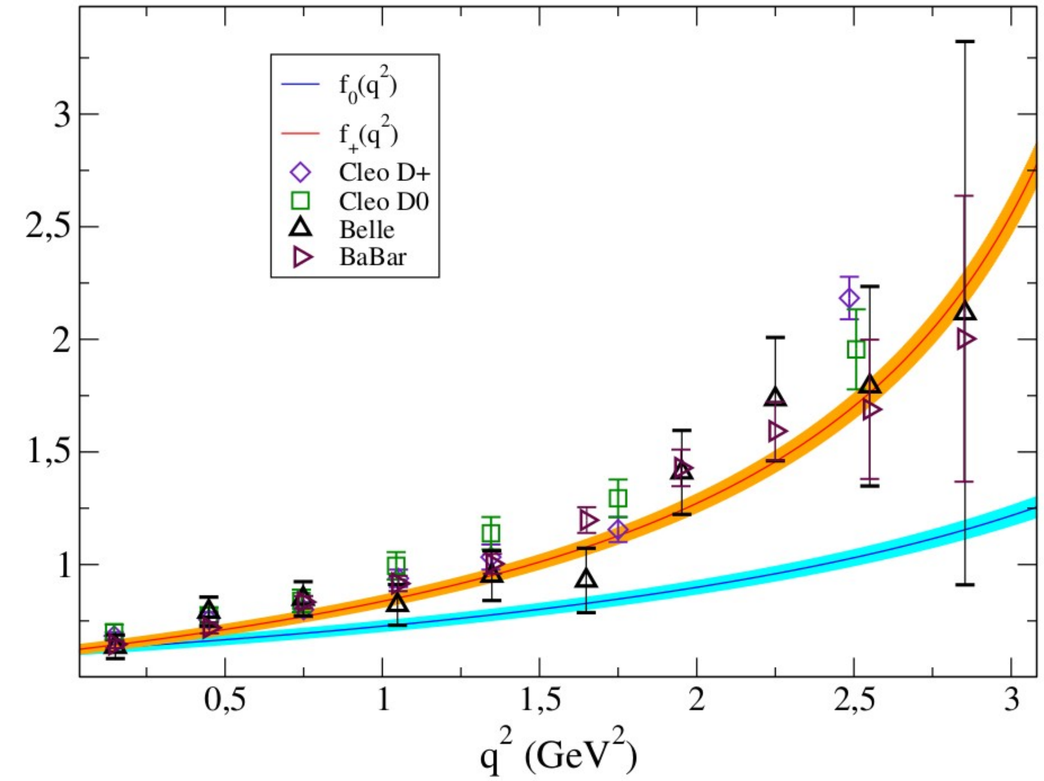
new results for charm SL form factors

[P Lami, Wed 14:20]

ensembles	ETM
N_f	2+1+1
a (fm)	3/0.062 - 0.089
$M_\pi^{\min}$ [MeV]	210
$M_\pi^{\min} L$	3.1
sea	tmQCD
valence	OS

- accurate analysis of $(aq)^2$ cutoff effects
- tbc allow for fine momentum spacing
- preliminary results with stat error only





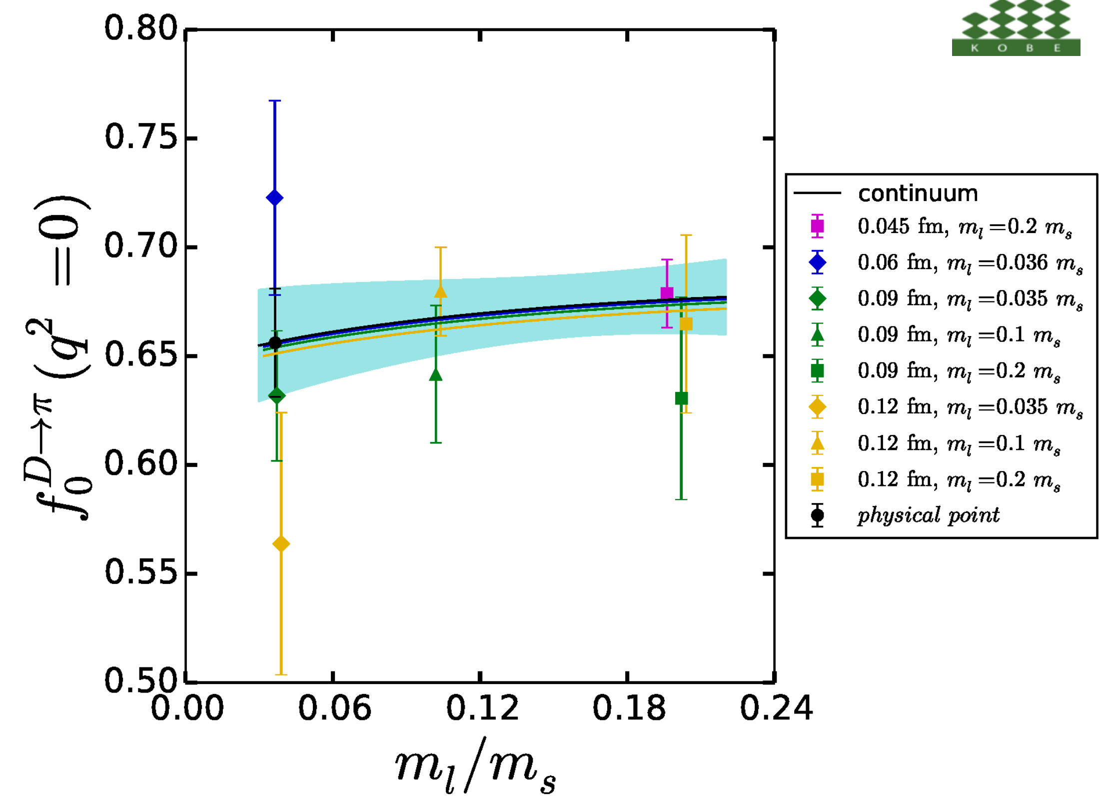
new results for charm SL form factors

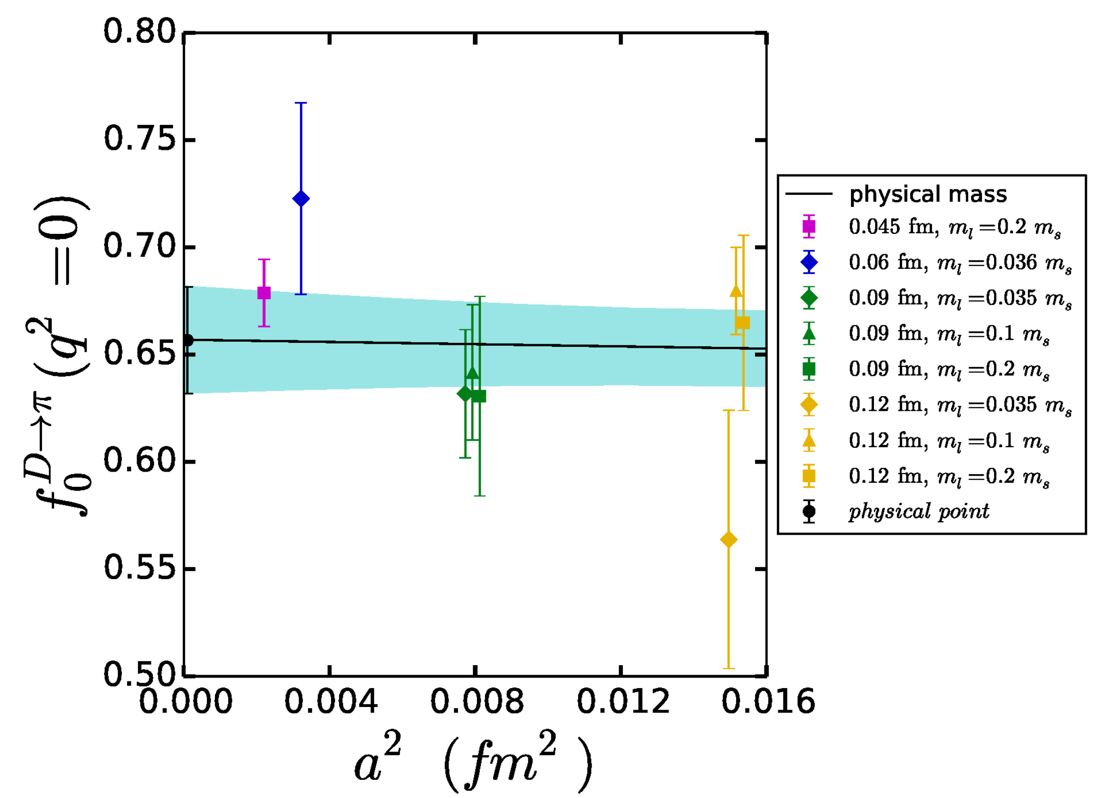
[FNAL/MILC arXiv:1411.1651]

[T Primer, Thu 11:40]

ensembles	MILC
N_{f}	2+1+1
a (fm)	4/0.042 - 0.12
$M_\pi^{\min}$ [MeV]	130
$M_\pi^{\min} L$	3.2
sea	HISQ
valence	HISQ

- tbc to get precise form factor at q^2=0
- tbc allow for fine momentum spacing
- no quotable numbers outside plots

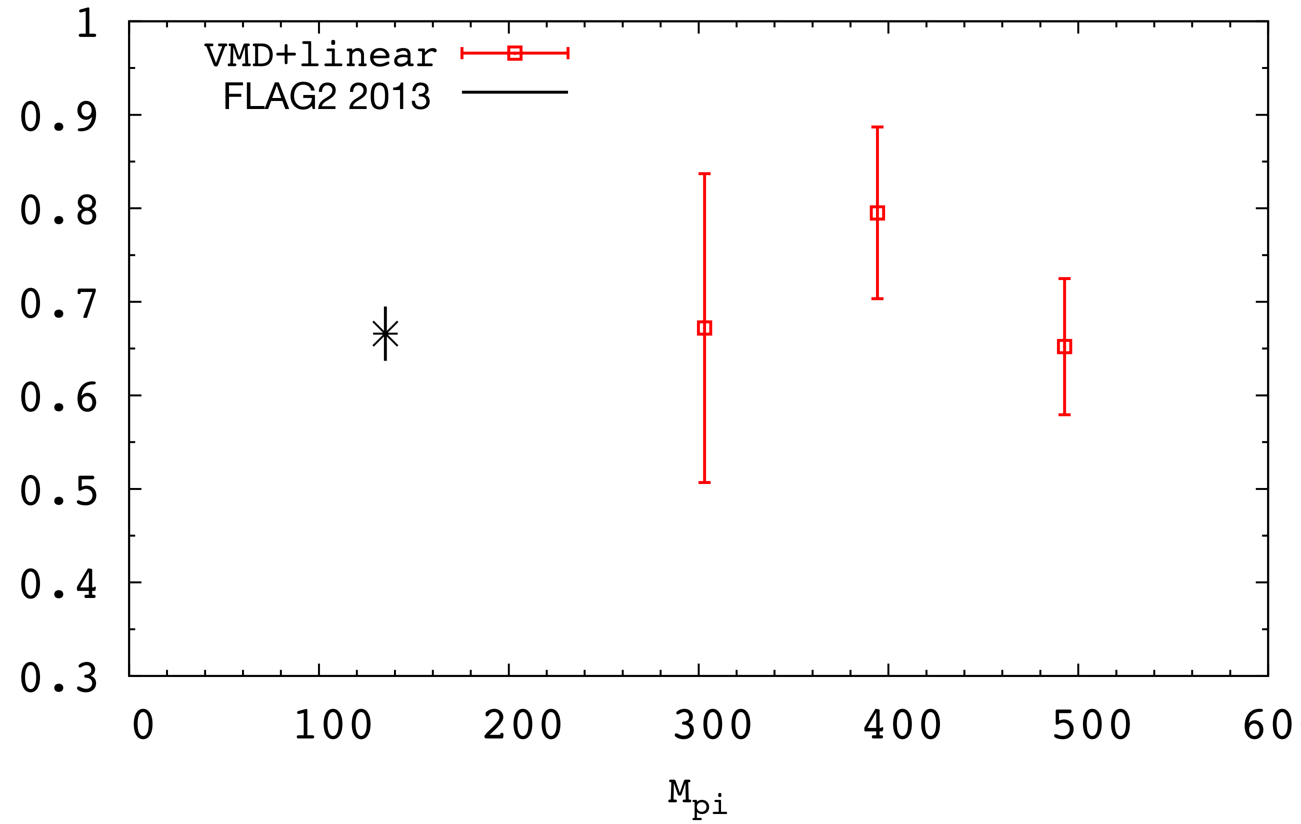




new results for charm SL form factors

[T Suzuki, Thu 11:20]

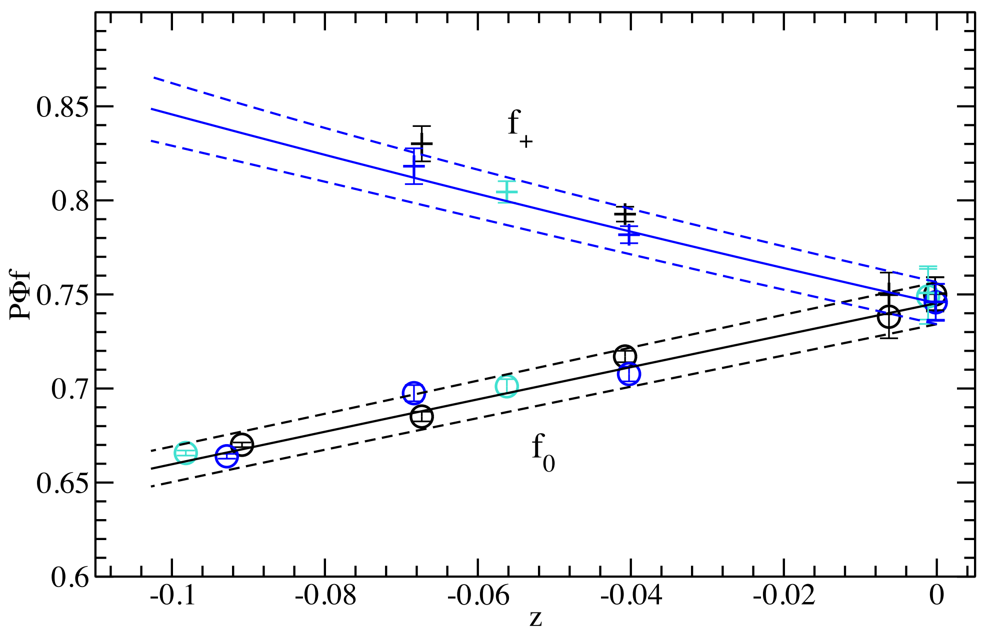
ensembles	JLQCD
N_f	2+1
a (fm)	1/0.08 fm
M_π^{min} [MeV]	300
$M_\pi^{\mathrm{min}} L$	3.9
sea	mDWF
valence	mDWF

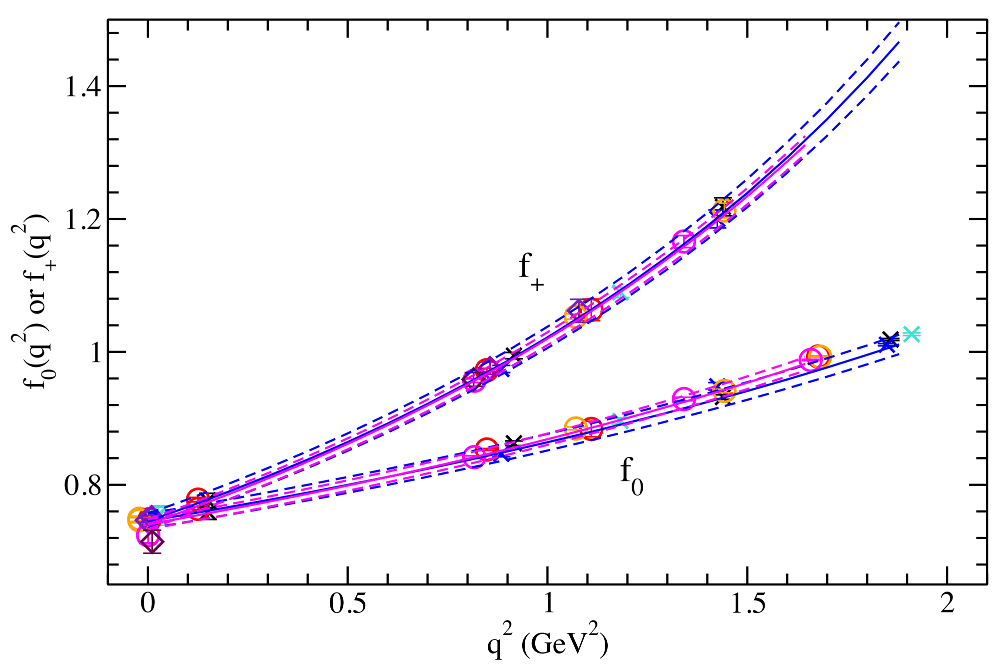


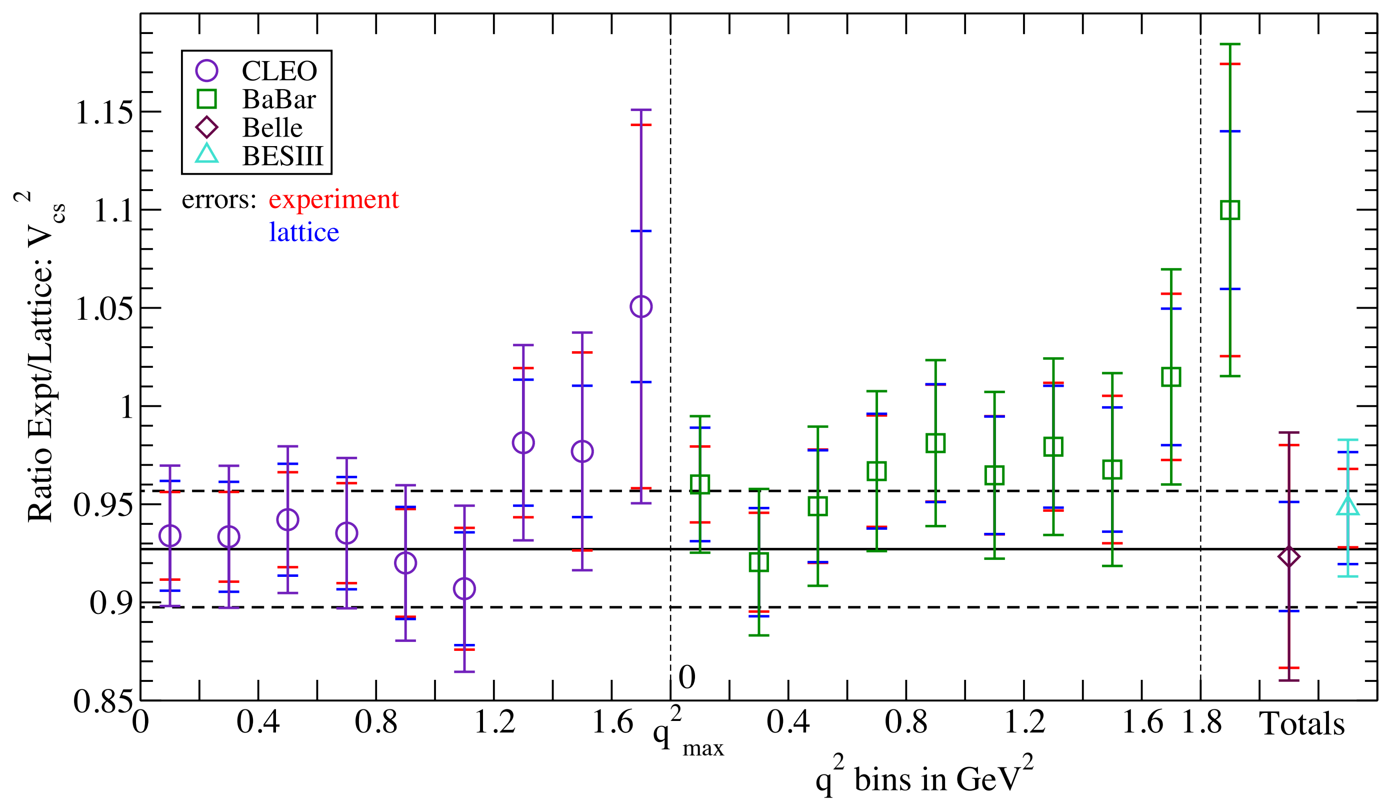
$f^{D\pi}(q^2 = 0)$

- very preliminary
- results consistent with FLAG "average" and CLEO-c shape within large errors

HPQCD arXiv:1305.1465 ($D \to K$)







discussed in FLAG-2, unable to rate/average it due to incomplete information on systematics

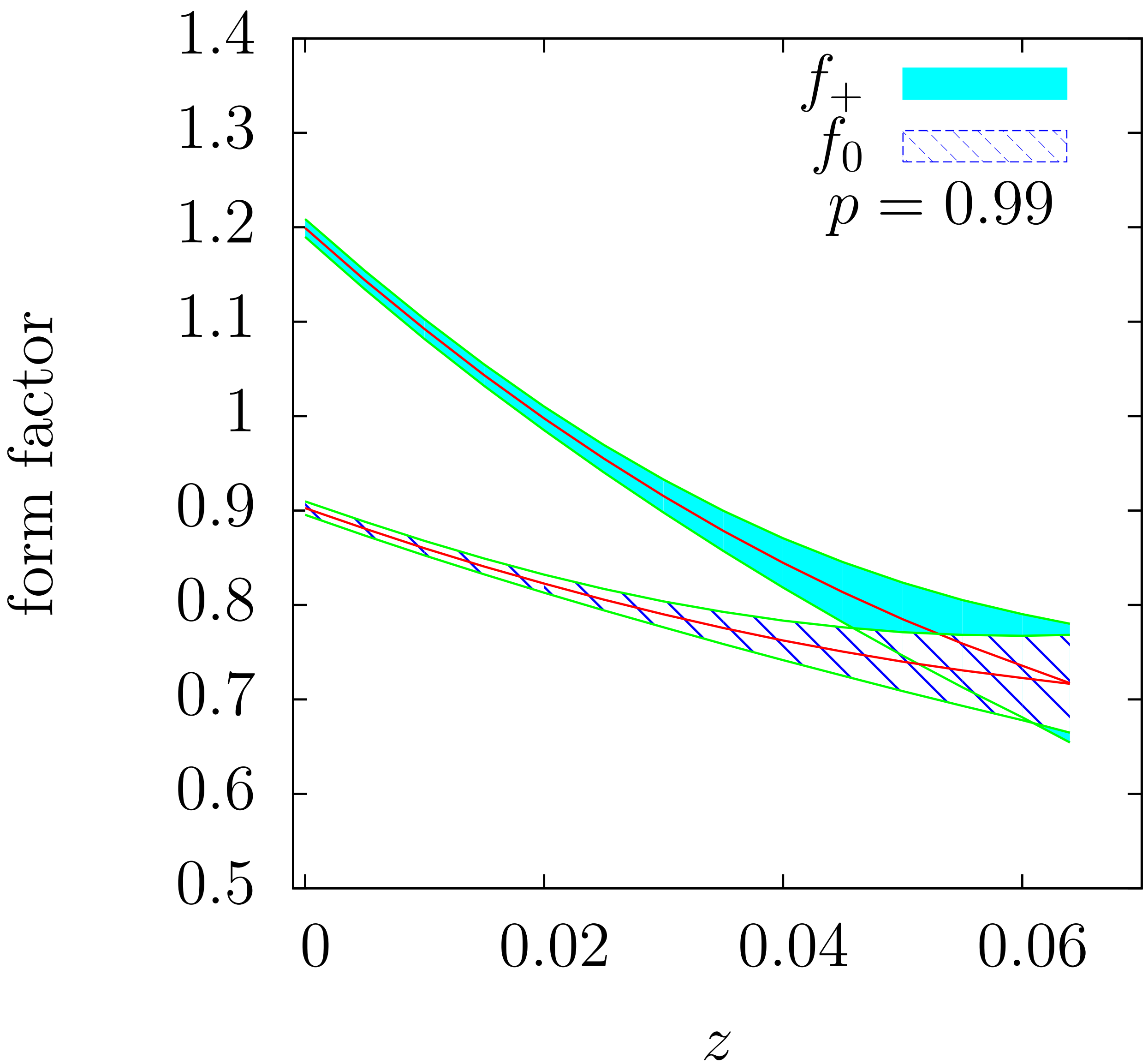
new results for $B \to D^{(*)} l\nu$

	FNAL/MILC*	FNAL/MILC	HPQCD
process	$B \to D^* \ell\nu$	$B \to Dl\nu$	$B \to Dl\nu$
kinematics	$w = 1$	$w \geq 1$	$w \geq 1$
ensembles	MILC	MILC	MILC
N_f	2+1	2+1	2+1
a (fm)	5/0.045 – 0.15	4/0.045 – 0.12	2/0.09, 0.12
$M_\pi^{\min}$ [MeV]	260	220	260
$M_\pi^{\min} L$	3.8	3.8	3.8
l quarks	asqtad	asqtad	asqtad
c quark	RHQ (Fermilab)	RHQ (Fermilab)	HISQ
b quark	RHQ (Fermilab)	RHQ (Fermilab)	NRQCD
reference	[1403.0635]	[1503.07237]	[1505.03925]

(* full publication of $B \to D^*$ results, no changes wrt proceedings value quoted in FLAG)

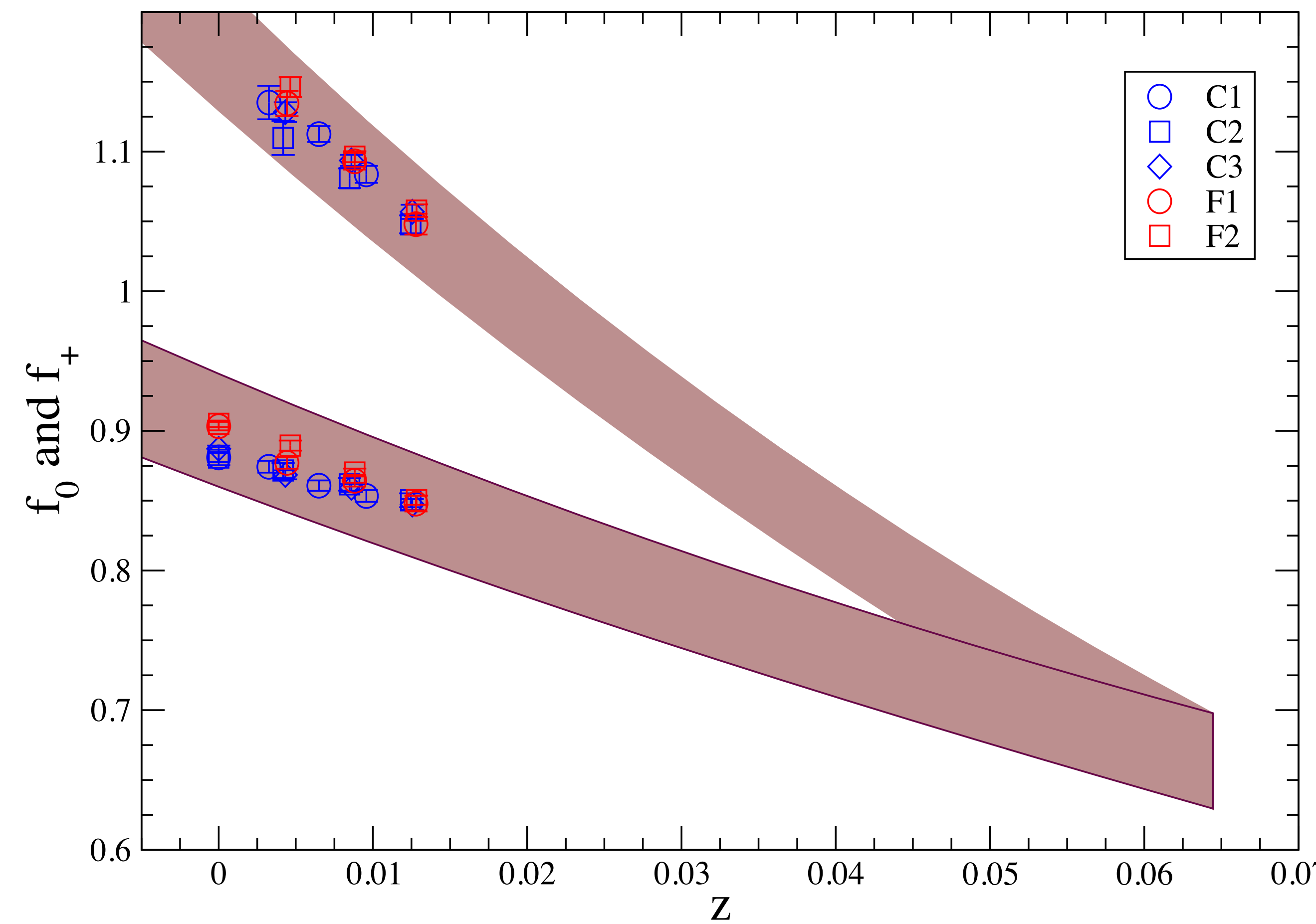
new results for $B \to Dl\nu$

[FNAL/MILC]



FFs from combination of double and single ratios of current matrix elements

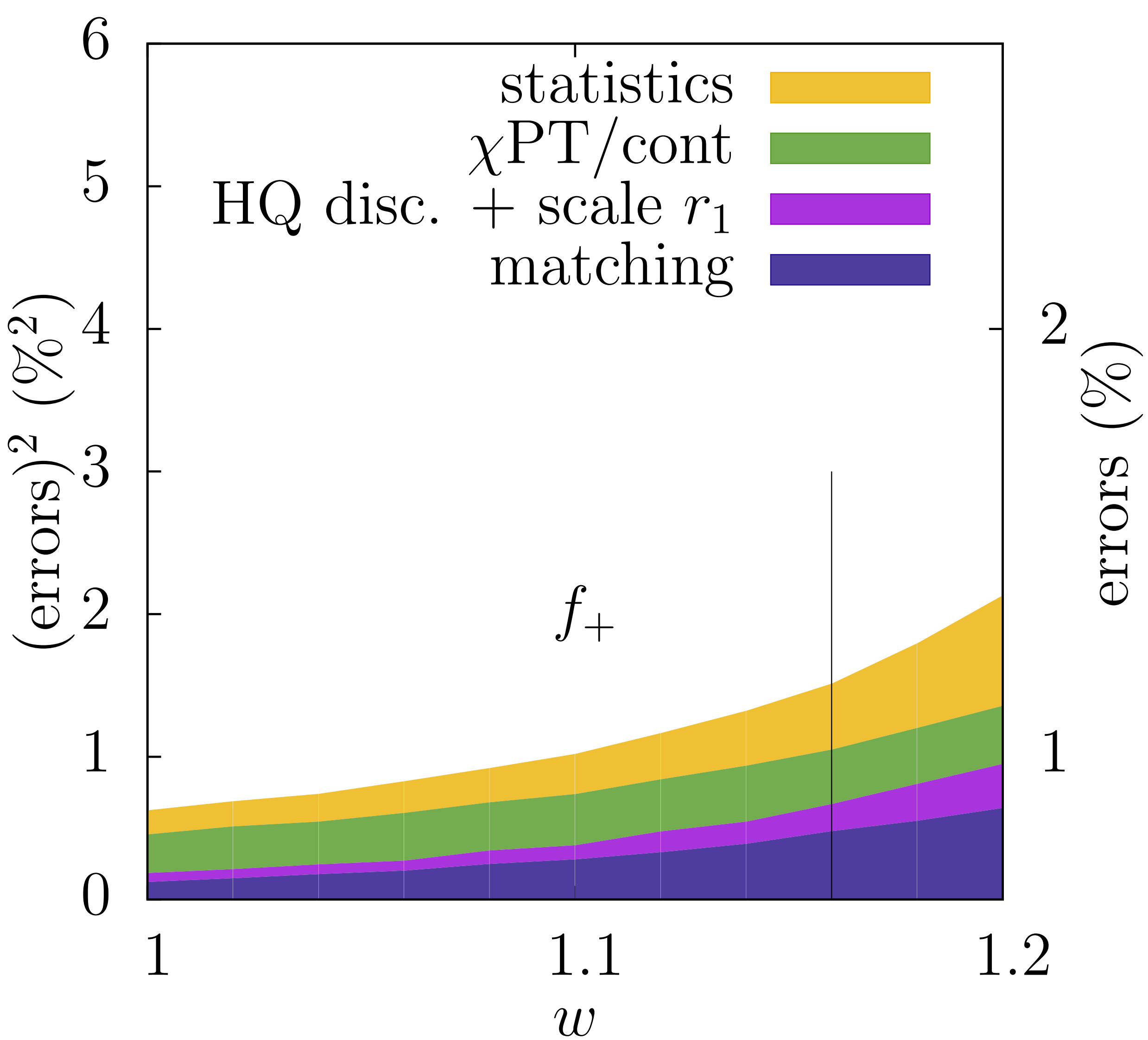
[HPQCD]



FFs from direct fit to three-point functions

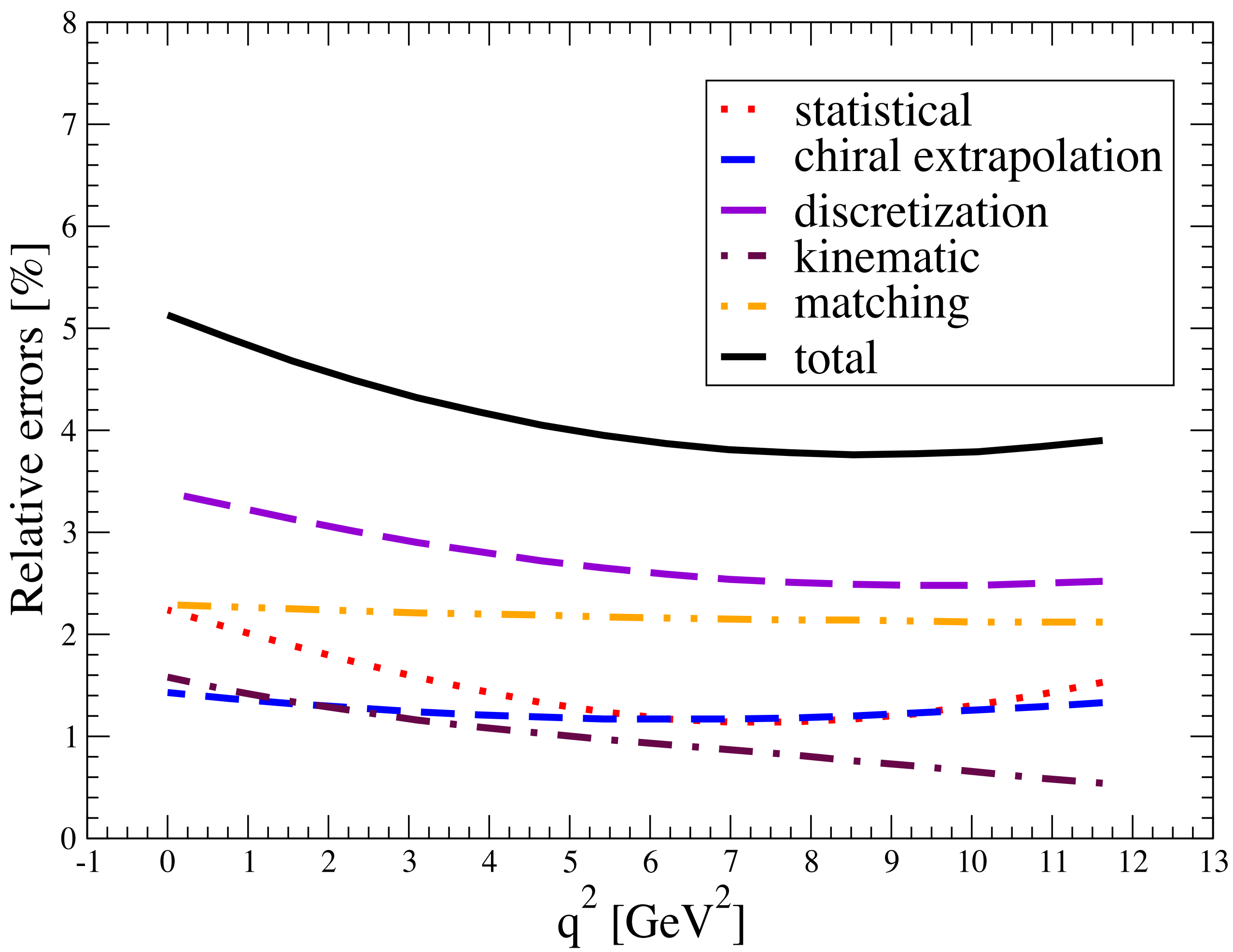
new results for $B \to Dl\nu$

[FNAL/MILC]



FFs from combination of double and single ratios of current matrix elements

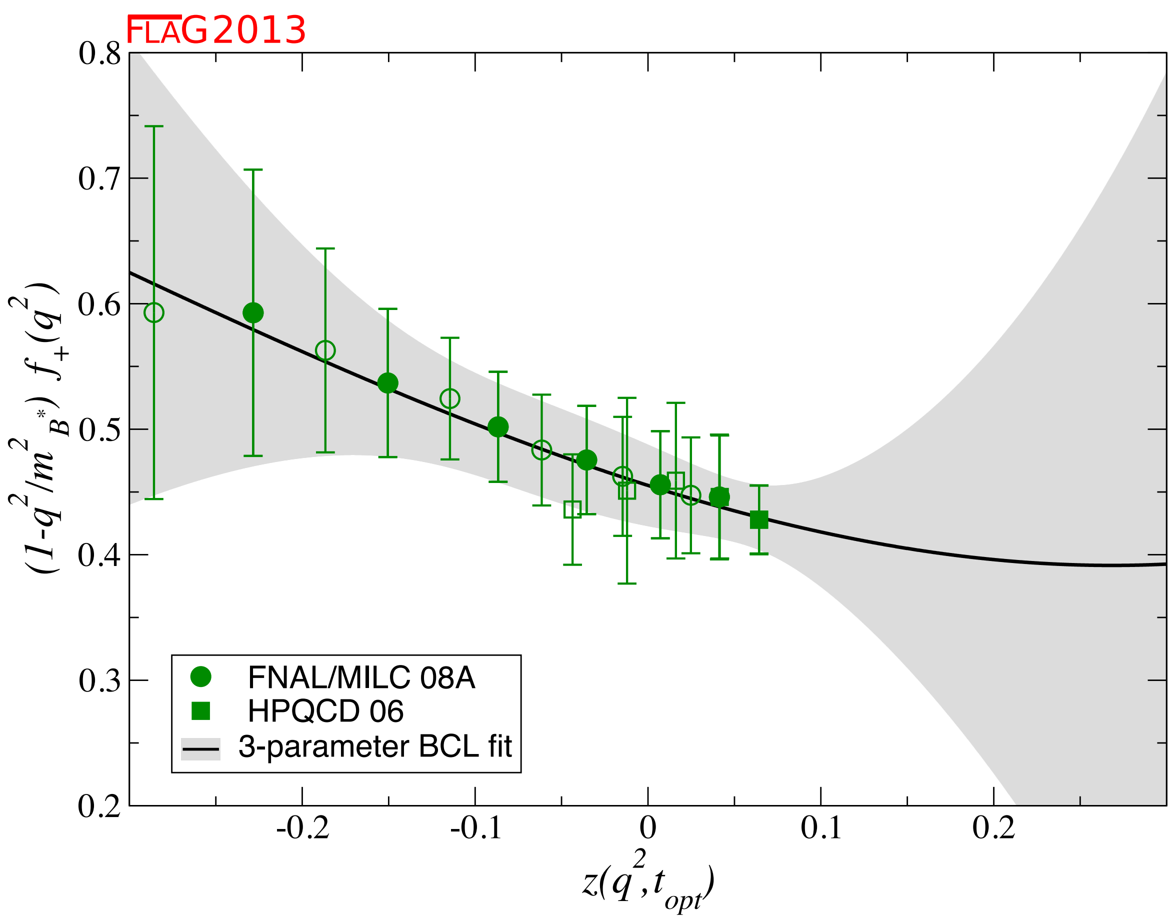
[HPQCD]



FFs from direct fit to three-point functions

FLAG-2 on $B \to \pi l \nu$

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization	heavy-quark treatment	$\Delta\zeta^{B\pi}$	z-parameterization type	z-parameterization $\{a_0, a_1, a_2\}$	cov. matrix
FNAL/MILC 08A	[350]	2+1	A	○	○	★	○	✓	$2.21^{+0.47\,\dagger}_{-0.42}$	BGL‡	$\{0.0216(27), -0.038(19), -0.113(27)\}$	yes§
HPQCD 06	[426]	2+1	A	○	○	★	○	✓	2.07(41)(39)	–	–	no



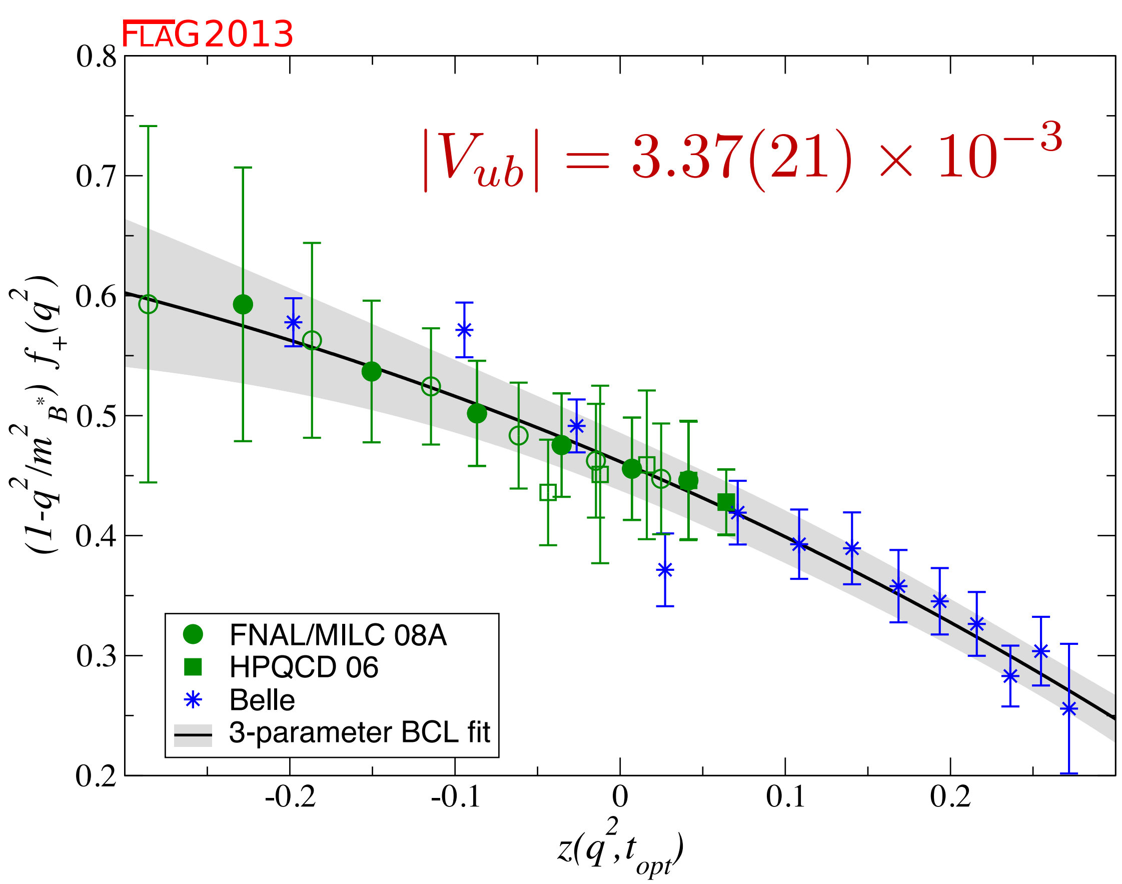
$$z = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

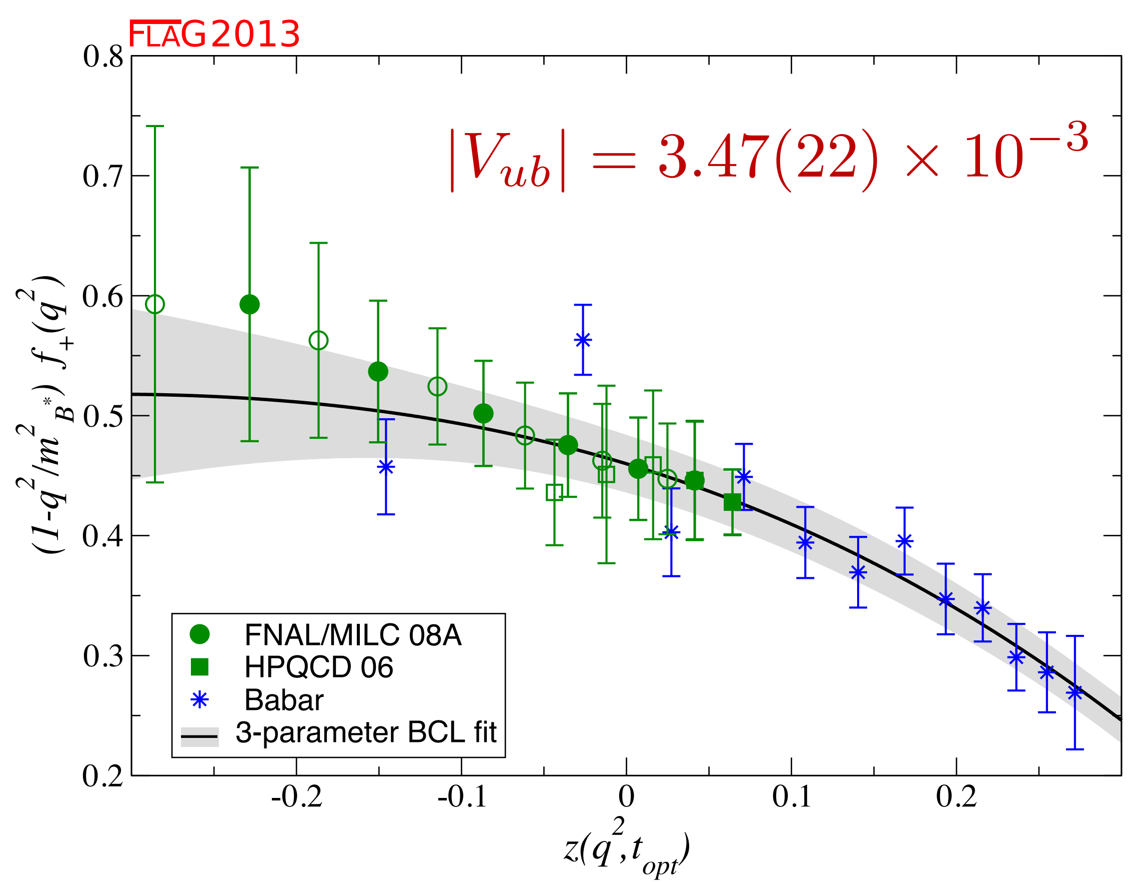
$$t_+ = (m_B + m_\pi)^2\,, \qquad t_0 < t_+$$

[FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

FLAG-2 on $B \to \pi l \nu$

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization	heavy-quark treatment	$\Delta\zeta^{B\pi}$	z-parameterization type	z-parameterization $\{a_0, a_1, a_2\}$	cov. matrix
FNAL/MILC 08A	[350]	2+1	A	○	○	★	○	✓	$2.21^{+0.47\,\dagger}_{-0.42}$	BGL‡	{0.0216(27), −0.038(19), −0.113(27)}	yes§
HPQCD 06	[426]	2+1	A	○	○	★	○	✓	2.07(41)(39)	–	–	no





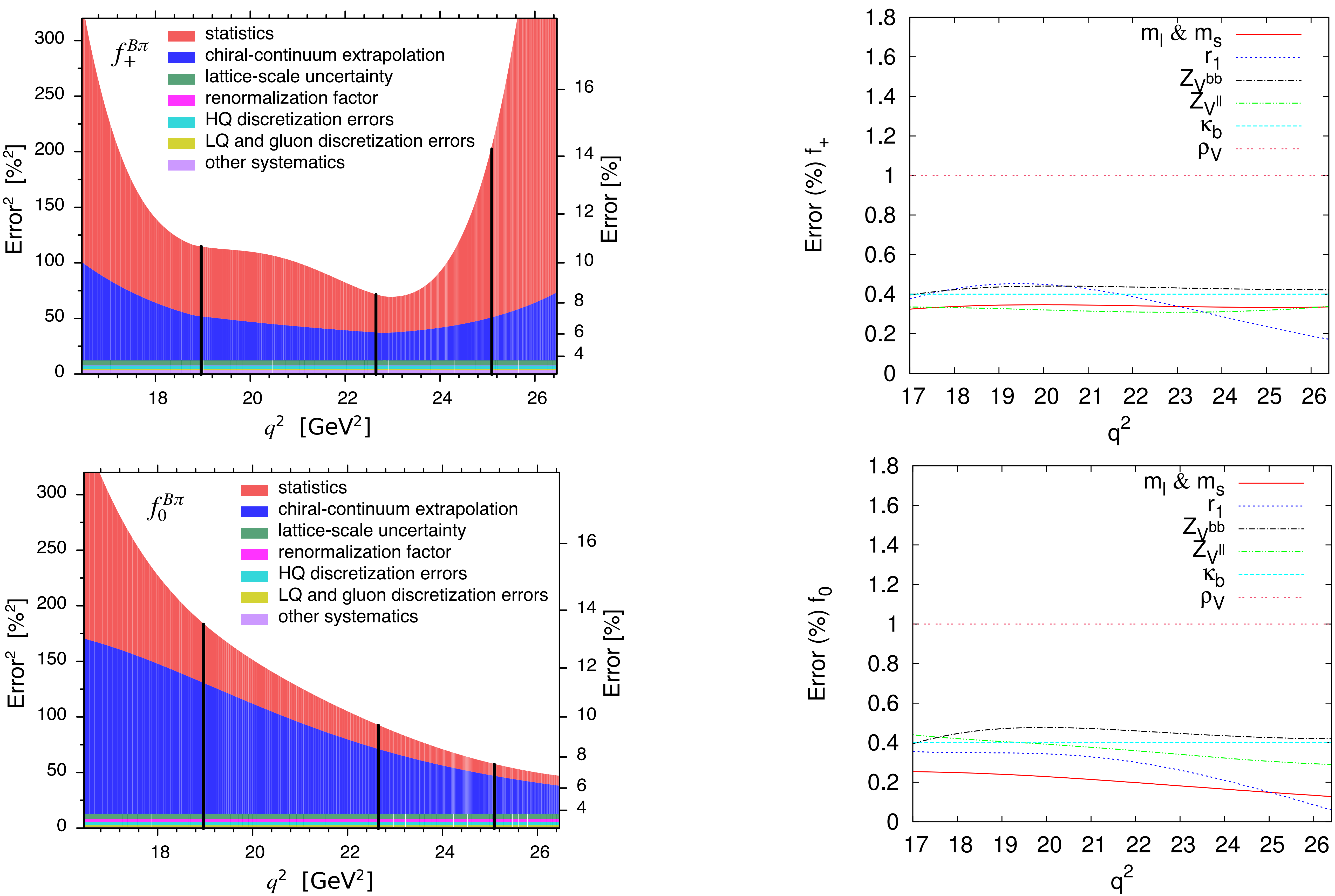
[FLAG 2013, Eur J Phys C74 (2014) 2890, arXiv:1310.8555v2]

new results for $B \to \pi l \nu$

	FNAL/MILC	RBC/UKQCD	HPQCD
ensembles	MILC	RBC/UKQCD	MILC
N_f	2+1	2+1	2+1
a (fm)	4/0.045 – 0.12	2/0.086, 0.11	2/0.09, 0.12
M_π^{min} [MeV]	220	289	260
$M_\pi^{\mathrm{min}} L$	3.8	4.0	3.8
l quarks	asqtad	DW	asqtad
b quark	RHQ (Fermilab)	RHQ (Columbia)	NRQCD
reference	[1503.07839]	[1501.05373]	[1310.3207]

new results for $B \to \pi l \nu$

[RBC/UKQCD] [FNAL/MILC]



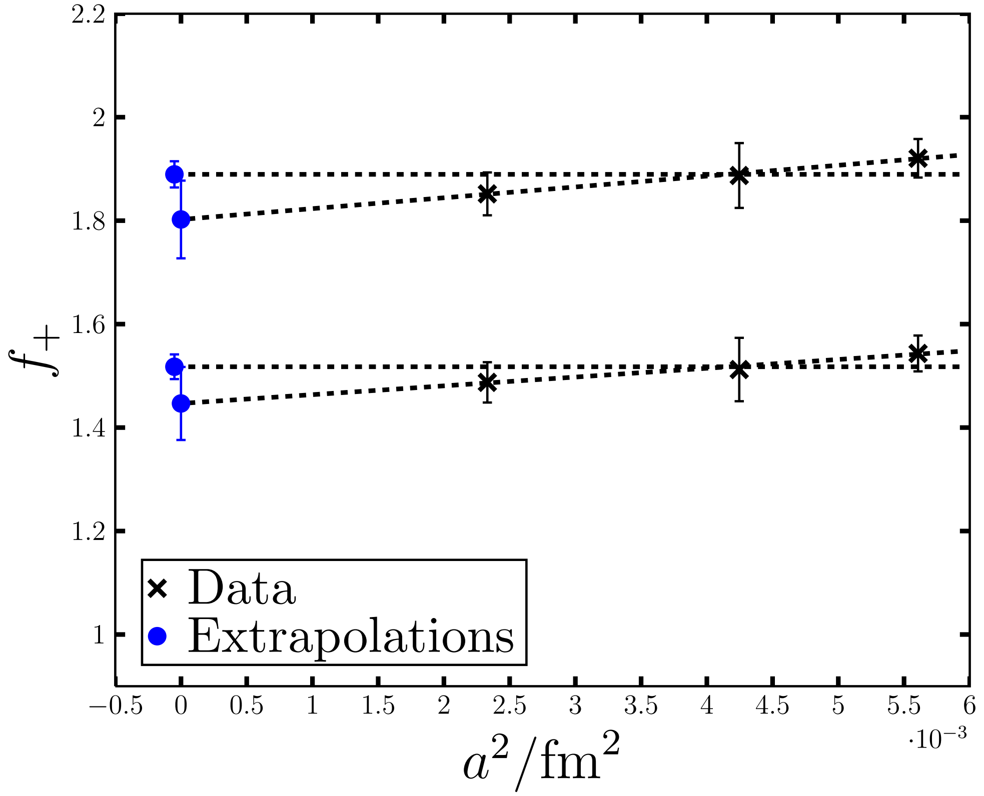
$B_s \to Kl\nu$

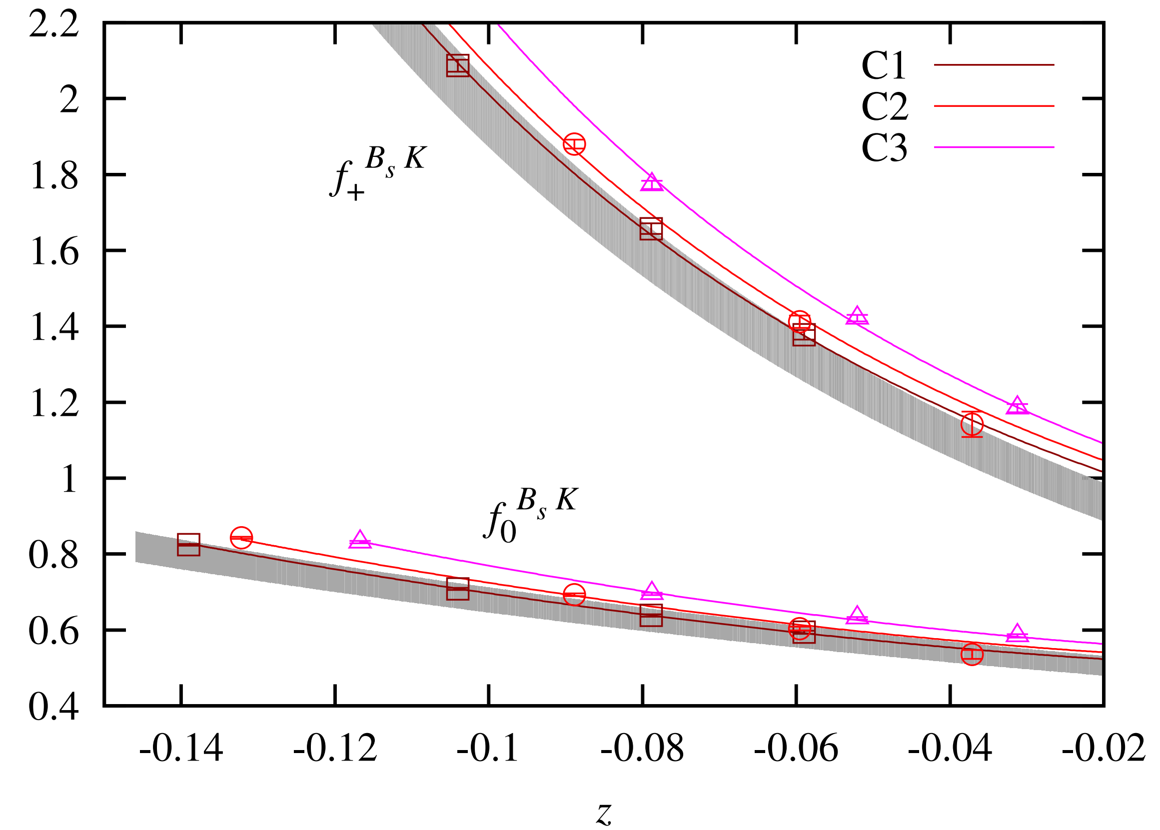
	RBC/UKQCD	HPQCD	ALPHA
ensembles	RBC/UKQCD	MILC	CLS
N_f	2+1	2+1	2
a (fm)	2/0.086, 0.11	2/0.09, 0.12	3/0.0483 – 0.0749
M_π^{min} [MeV]	289	260	310
$M_\pi^{\mathrm{min}} L$	4.0	3.8	4.0
l quarks	DW	asqtad	NP O(*a*) improved
b quark	RHQ (Columbia)	NRQCD	npHQET
reference	[1501.05373]	[1406.2279]	[1411.3916]

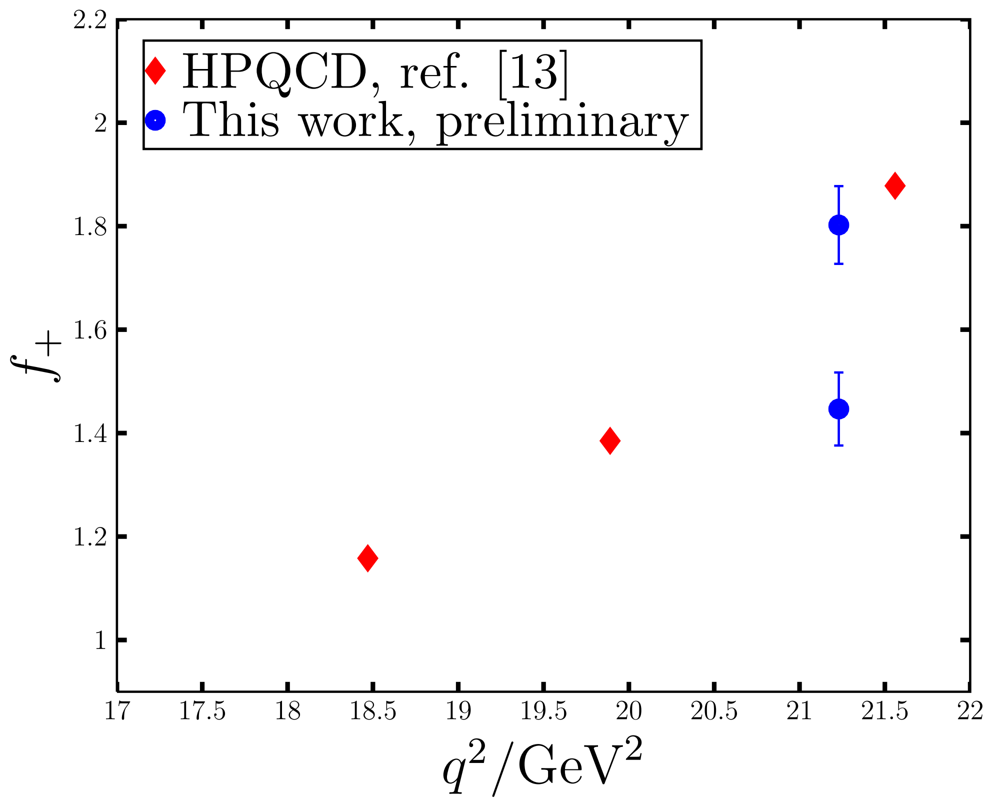
$B_s \to Kl\nu$

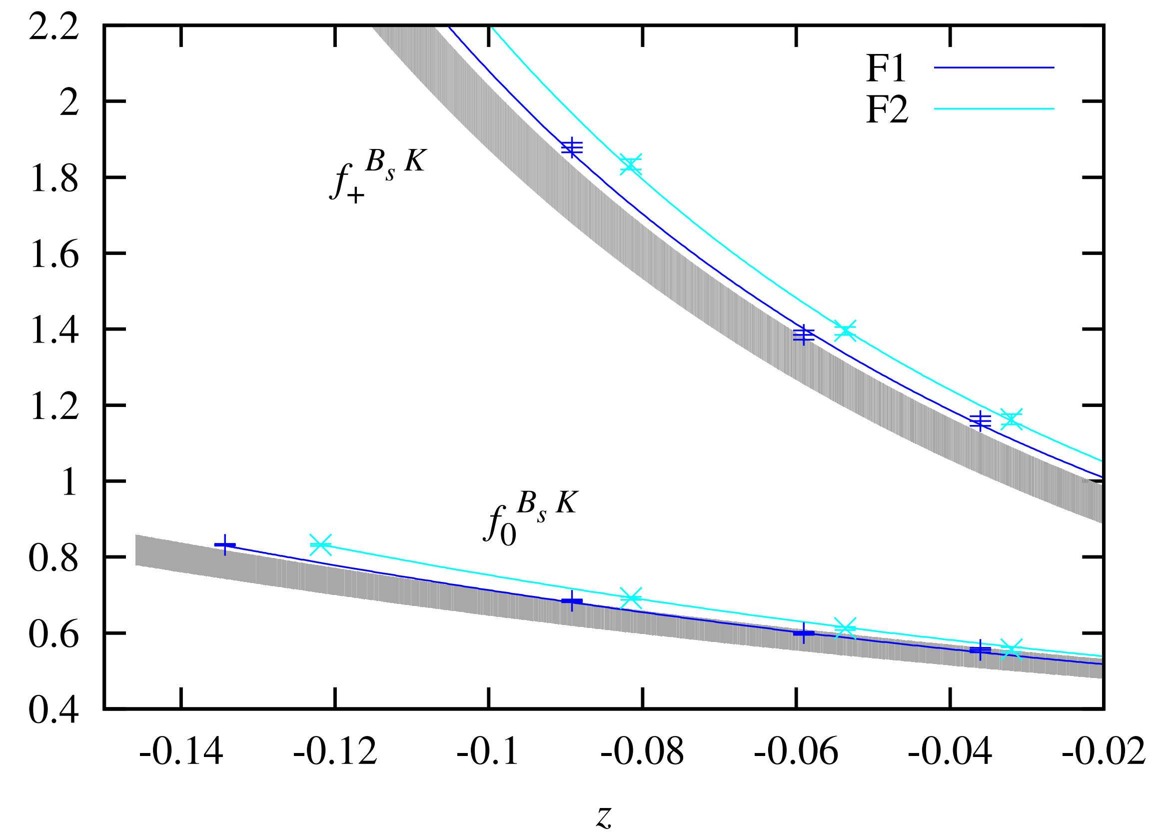
[ALPHA]

[HPQCD]









impact of fitting, systematics estimation

significant differences in estimates of fit and systematic uncertainties in otherwise very similar computations

well-known example from light-quark physics (both computations use MILC ensembles, relatively minor differences)

stat CL FV e.m.

MILC 13 $f_{K^\pm}/f_{\pi^\pm}|_{N_\mathrm{f}=2+1+1} = 1.1947(26)(33)(17)(2)$

HPQCD 13 $f_{K^\pm}/f_{\pi^\pm}|_{N_\mathrm{f}=2+1+1} = 1.1916(15)(12)(1)(10)$

stat CL FV (misc).