The physics of SuperB

from a theorist's point of view

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outline of the talk:

i) overview of the physics case

* basic concepts and selected topics

ii) theoretical uncertainties

* classification of the observables
* projections to 2015 (mainly lattice)

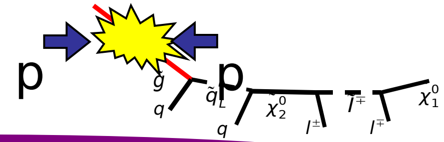
iii) comparison with (S-)LHCb

* overlap and complementarity
* the S-LHCb option

thanks to:
T. Gershon
V. Lubicz
A. Stocchi

the physics case

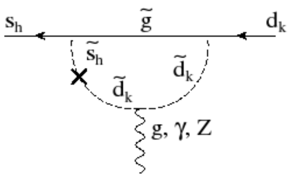
"The relativistic path"



Standard Model

New Physics

"The quantum path"



Why flavour physics?

SM flavour-changing neutral currents (FCNC) and CP-violating processes occur at the loop level and thus potentially receive O(1) NP corrections

SM quark FV and CPV are governed by the weak interactions and suppressed by the mixing angles, SM lepton FV is strongly suppressed by $(\delta m_\nu/M_W)^2$

NP not necessarily shares this pattern of suppressions and can give very large contributions

Flavour Observables Sensitive to New Physics

$\Delta m_K \quad \epsilon_K \quad \epsilon'/\epsilon_K \quad B(K_L \to \pi^0 \nu \bar{\nu}) \quad B(K^+ \to \pi^+ \nu \bar{\nu}) \quad B(K^+ \to l^+ \nu)$

$\Delta m_d \quad A_{SL}(B_d) \quad S(B_d \to J/\psi K_S) \quad S(B_d \to \phi K_S)$

$\alpha(B \to \pi\pi, \rho\pi, \rho\rho) \quad \gamma(B \to DK) \quad CKM \ fits$

$\Delta m_s \quad A_{SL}(B_s) \quad S(B_s \to J/\psi \phi) \quad S(B_s \to \phi\phi)$

$B(b \to s\gamma) \quad A_{CP}(b \to s\gamma) \quad S(B^0 \to K_S \pi^0 \gamma) \quad S(B_s \to \phi\gamma)$

$B(b \to d\gamma) \quad A_{CP}(b \to d\gamma) \quad A_{CP}(b \to (d+s)\gamma) \quad S(B^0 \to \rho^0 \gamma)$

$B(b \to s l^+ l^-) \quad B(b \to d l^+ l^-) \quad A_{FB}(b \to s l^+ l^-) \quad B(b \to s \nu \bar{\nu})$

$B(B_s \to l^+ l^-) \quad B(B_d \to l^+ l^-) \quad B(B^+ \to l^+ \nu)$

$B(\mu \to e\gamma) \quad B(\mu \to e^+ e^- e^+) \quad (g-2)_\mu \quad \mu \ EDM$

$B(\tau \to \mu\gamma) \quad B(\tau \to e\gamma) \quad B(\tau^+ \to l^+ l^- l^+) \quad \tau \ CPV \quad \tau \ EDM$

$B(D^+_{(s)} \to l^+ \nu) \quad x_D \ \ y_D \quad charm \ CPV$

Will be Studied at SuperB

Δm_K ϵ_K ϵ'/ϵ_K $B(K_L \to \pi^0 \nu \bar{\nu})$ $B(K^+ \to \pi^+ \nu \bar{\nu})$ $B(K^+ \to l^+ \nu)$

Δm_d $A_{SL}(B_d)$ $S(B_d \to J/\psi K_S)$ $S(B_d \to \phi K_S)$

$\alpha(B \to \pi\pi, \rho\pi, \rho\rho)$ $\gamma(B \to DK)$ CKM fits

Δm_s $A_{SL}(B_s)$ $S(B_s \to J/\psi \phi)$ $S(B_s \to \phi\phi)$

$B(b \to s\gamma)$ $A_{CP}(b \to s\gamma)$ $S(B^0 \to K_S \pi^0 \gamma)$ $S(B_s \to \phi\gamma)$

$B(b \to d\gamma)$ $A_{CP}(b \to d\gamma)$ $A_{CP}(b \to (d+s)\gamma)$ $S(B^0 \to \rho^0 \gamma)$

$B(b \to s l^+ l^-)$ $B(b \to d l^+ l^-)$ $A_{FB}(b \to s l^+ l^-)$ $B(b \to s \nu \bar{\nu})$

$B(B_s \to l^+ l^-)$ $B(B_d \to l^+ l^-)$ $B(B^+ \to l^+ \nu)$

$B(\mu \to e\gamma)$ $B(\mu \to e^+ e^- e^+)$ $(g-2)_\mu$ μ EDM

$B(\tau \to \mu\gamma)$ $B(\tau \to e\gamma)$ $B(\tau^+ \to l^+ l^- l^+)$ τ CPV τ EDM

$B(D^+_{(s)} \to l^+ \nu)$ x_D y_D charm CPV

SuperB physics in tables

Observable	B factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$\sin(2\beta)$ $(J/\psi\, K^0)$	0.018	0.005 (†)
$\cos(2\beta)$ $(J/\psi\, K^{*0})$	0.30	0.05
$\sin(2\beta)$ (Dh^0)	0.10	0.02
$\cos(2\beta)$ (Dh^0)	0.20	0.04
$S(J/\psi\, \pi^0)$	0.10	0.02
$S(D^+D^-)$	0.20	0.03
$S(\phi K^0)$	0.13	0.02 (∗)
$S(\eta' K^0)$	0.05	0.01 (∗)
$S(K^0_S K^0_S K^0_S)$	0.15	0.02 (∗)
$S(K^0_S \pi^0)$	0.15	0.02 (∗)
$S(\omega K^0_S)$	0.17	0.03 (∗)
$S(f_0 K^0_S)$	0.12	0.02 (∗)
γ $(B \to DK,\, D \to CP$ eigenstates$)$	$\sim 15^\circ$	2.5°
γ $(B \to DK,\, D \to$ suppressed states$)$	$\sim 12^\circ$	2.0°
γ $(B \to DK,\, D \to$ multibody states$)$	$\sim 9^\circ$	1.5°
γ $(B \to DK$, combined$)$	$\sim 6^\circ$	1–2°
α $(B \to \pi\pi)$	$\sim 16^\circ$	3°
α $(B \to \rho\rho)$	$\sim 7^\circ$	1–2° (∗)
α $(B \to \rho\pi)$	$\sim 12^\circ$	2°
α (combined)	$\sim 6^\circ$	1–2° (∗)
$2\beta + \gamma$ $(D^{(*)\pm}\pi^\mp,\, D^\pm K^0_S \pi^\mp)$	20°	5°
$\lvert V_{cb}\rvert$ (exclusive)	4% (∗)	1.0% (∗)
$\lvert V_{cb}\rvert$ (inclusive)	1% (∗)	0.5% (∗)
$\lvert V_{ub}\rvert$ (exclusive)	8% (∗)	3.0% (∗)
$\lvert V_{ub}\rvert$ (inclusive)	8% (∗)	2.0% (∗)
$BR(B \to \tau\nu)$	20%	4% (†)
$BR(B \to \mu\nu)$	visible	5%
$BR(B \to D\tau\nu)$	10%	2%
$BR(B \to \rho\gamma)$	15%	3% (†)
$BR(B \to \omega\gamma)$	30%	5%
$A_{CP}(B \to K^*\gamma)$	0.007 (†)	0.004 († ∗)
$A_{CP}(B \to \rho\gamma)$	~ 0.20	0.05
$A_{CP}(b \to s\gamma)$	0.012 (†)	0.004 (†)
$A_{CP}(b \to (s+d)\gamma)$	0.03	0.006 (†)
$S(K^0_S \pi^0 \gamma)$	0.15	0.02 (∗)
$S(\rho^0\gamma)$	possible	0.10
$A_{CP}(B \to K^*\ell\ell)$	7%	1%
$A^{FB}(B \to K^*\ell\ell)s_0$	25%	9%
$A^{FB}(B \to X_s\ell\ell)s_0$	35%	5%
$BR(B \to K\nu\overline{\nu})$	visible	20%
$BR(B \to \pi\nu\bar{\nu})$	–	possible

Mode	Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$D^0 \to K^+K^-$	y_{CP}	2–3×10^{-3}	5×10^{-4}
$D^0 \to K^+\pi^-$	y'_D	2–3×10^{-3}	7×10^{-4}
	x'^2_D	1–2×10^{-4}	3×10^{-5}
$D^0 \to K^0_S\pi^+\pi^-$	y_D	2–3×10^{-3}	5×10^{-4}
	x_D	2–3×10^{-3}	5×10^{-4}
Average	y_D	1–2×10^{-3}	3×10^{-4}
	x_D	2–3×10^{-3}	5×10^{-4}

	Sensitivity
$D^0 \to e^+e^-$, $D^0 \to \mu^+\mu^-$	1×10^{-8}
$D^0 \to \pi^0 e^+e^-$, $D^0 \to \pi^0\mu^+\mu^-$	2×10^{-8}
$D^0 \to \eta e^+e^-$, $D^0 \to \eta\mu^+\mu^-$	3×10^{-8}
$D^0 \to K^0_S e^+e^-$, $D^0 \to K^0_S\mu^+\mu^-$	3×10^{-8}
$D^+ \to \pi^+ e^+e^-$, $D^+ \to \pi^+\mu^+\mu^-$	1×10^{-8}
$D^0 \to e^\pm\mu^\mp$	1×10^{-8}
$D^+ \to \pi^+ e^\pm\mu^\mp$	1×10^{-8}
$D^0 \to \pi^0 e^\pm\mu^\mp$	2×10^{-8}
$D^0 \to \eta e^\pm\mu^\mp$	3×10^{-8}
$D^0 \to K^0_S e^\pm\mu^\mp$	3×10^{-8}
$D^+ \to \pi^- e^+e^+$, $D^+ \to K^- e^+e^+$	1×10^{-8}
$D^+ \to \pi^-\mu^+\mu^+$, $D^+ \to K^-\mu^+\mu^+$	1×10^{-8}
$D^+ \to \pi^- e^\pm\mu^\mp$, $D^+ \to K^- e^\pm\mu^\mp$	1×10^{-8}

5-10x improvement

Process	Sensitivity
$\mathcal{B}(\tau \to \mu\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\,\mu\,\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}
$\mathcal{B}(\tau \to \mu\eta)$	4×10^{-10}
$\mathcal{B}(\tau \to e\eta)$	6×10^{-10}
$\mathcal{B}(\tau \to \ell K^0_S)$	2×10^{-10}

+ τ FC physics (CPV, …)

Super Flavour Factory

a "treasure chest" of new physics-sensitive observables

Observable	Error with 1 ab^{-1}
$\Delta\Gamma$	0.16 ps^{-1}
Γ	0.07 ps^{-1}
β_s from angular analysis	20°
A^s_{SL}	0.006
A_{CH}	0.004
$\mathcal{B}(B_s \to \mu^+\mu^-)$	-
$\lvert V_{td}/V_{ts}\rvert$	0.08
$\mathcal{B}(B_s \to \gamma\gamma)$	38%
β_s from $J/\psi\phi$	10°

does SuperB probe interesting physics?

The problem of today particle physics:

where is the NP scale Λ? 0.5, 1, 10, 10^{13}, 10^{16} TeV??

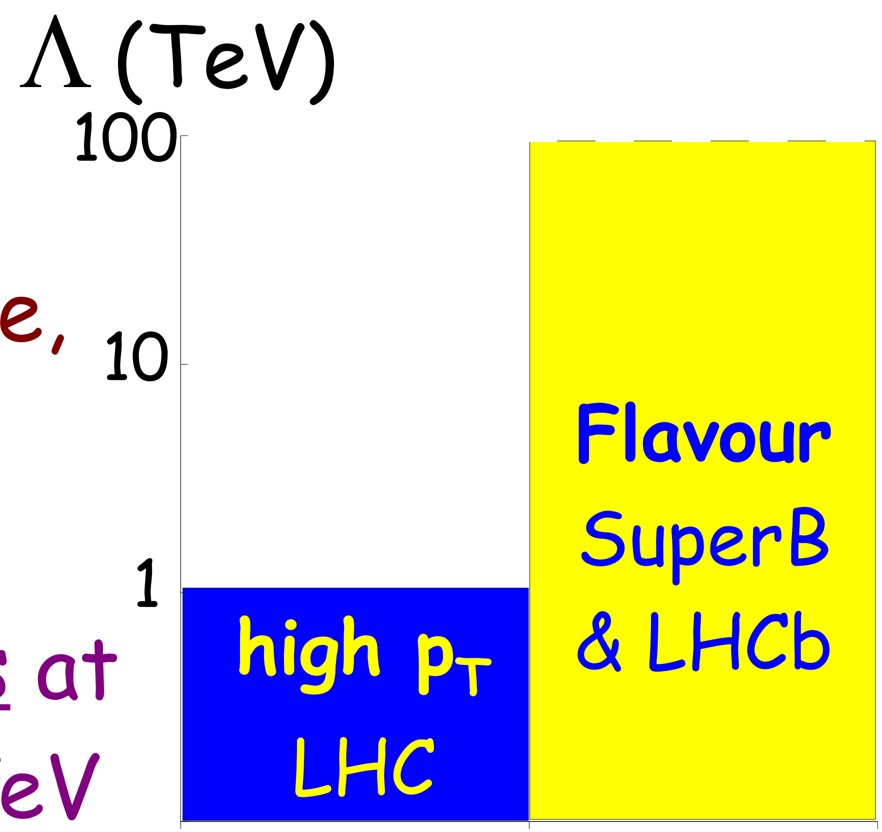
The quantum stabilization of the weak scale suggests ≲ 1 TeV

LHC searches in this range

What if the scale is just above, in the 10-100 TeV range?

naturalness is not at loss yet

CDR: <u>precision flavour physics</u> at SuperB explores up to ~100 TeV



New Flavour Physics & EFT: a problem of scale and couplings

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{k=1} \left(\sum_i C_i^k \, Q_i^{(k+4)} \right) / \Lambda^k$$

NP flavour effects are governed by two players:

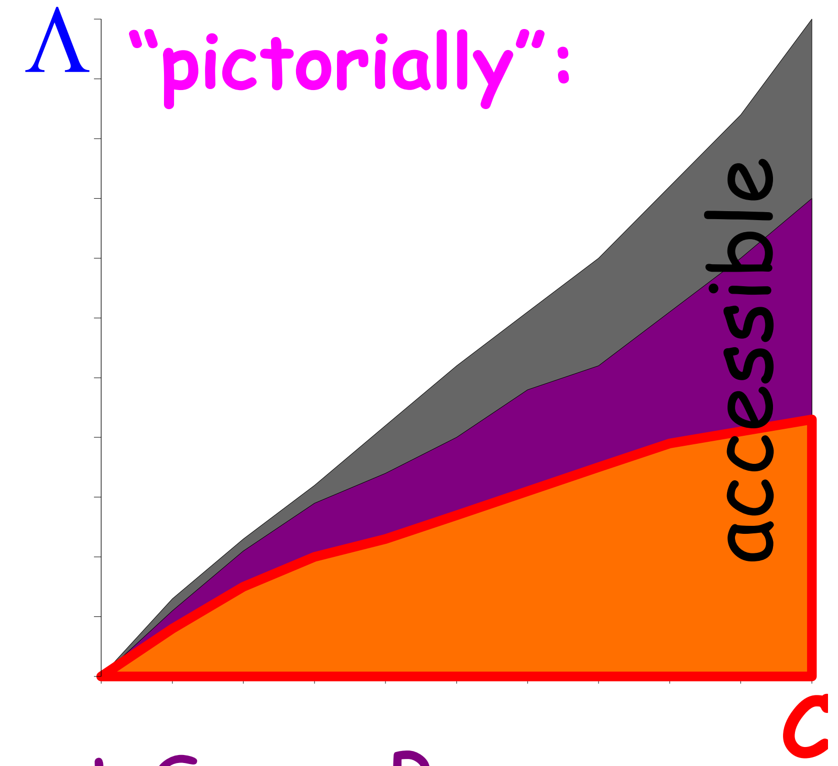
i) the value of the new physics scale Λ

ii) the effective flavour-violating couplings **C's**

+ couplings can follow a given pattern (e.g. dictated by symmetries)

+ couplings can have different strength (e.g. generated by different interactions)

- exp. constraints give a bound on Λ for any given *c* and vice-versa
- different curves correspond to different flavour models



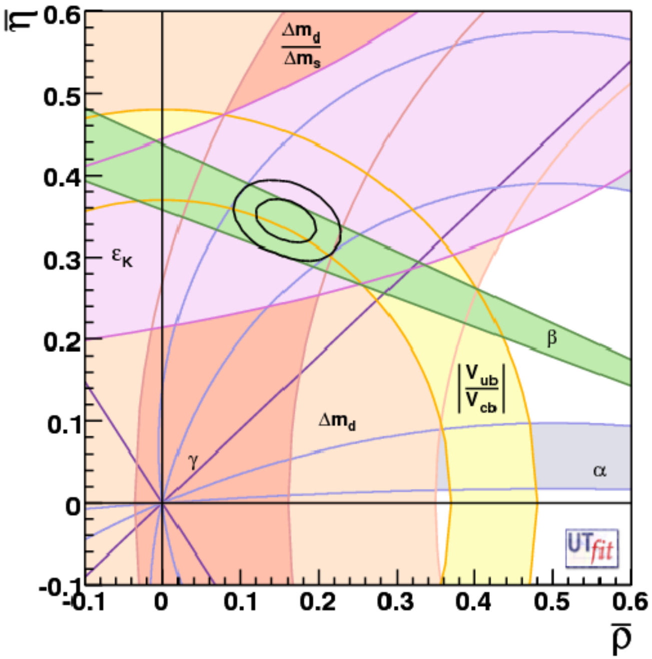
What do these plots teach us?

A branch point for NP searches at SuperB:

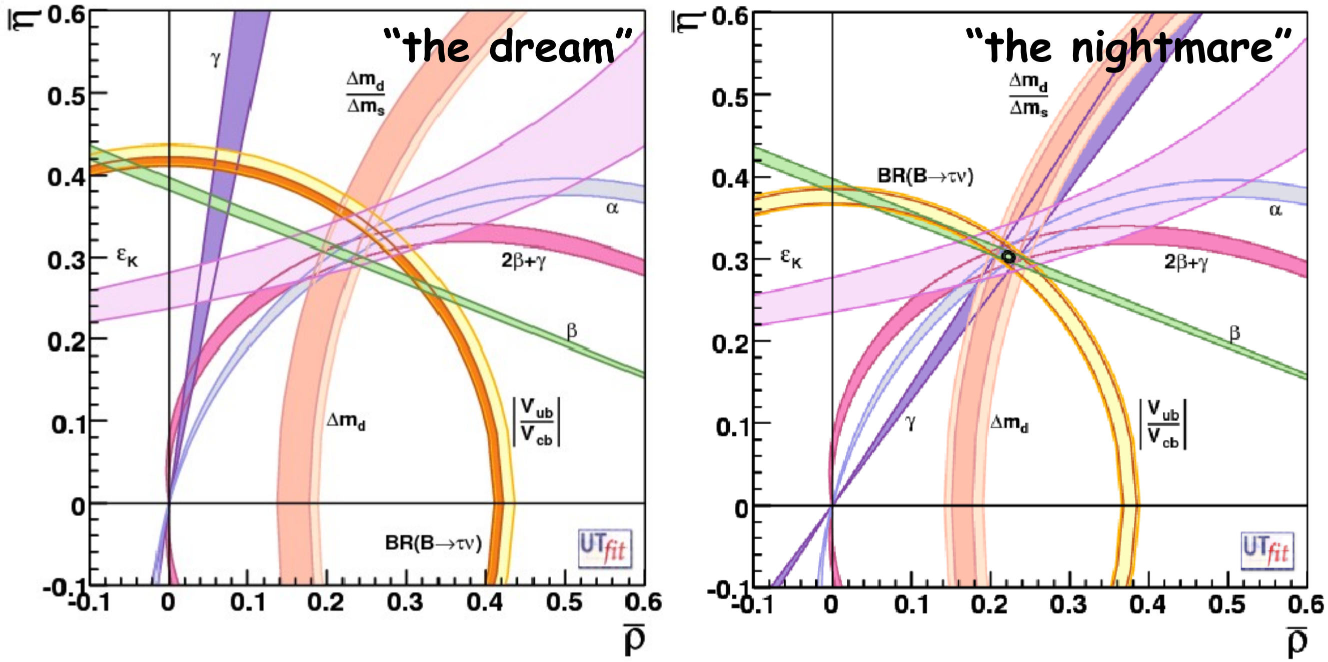
NP(Λ) found at LHC	NP(Λ) not found at LHC
* determine the NP FV and CPV couplings * look for heavier states * study the flavour structure of NP	* look for indirect NP signals * understand where they come from * exclude regions in the parameter space

UT fits: test of the CKM paradigm at 1%

Today



With a SuperB in 2015



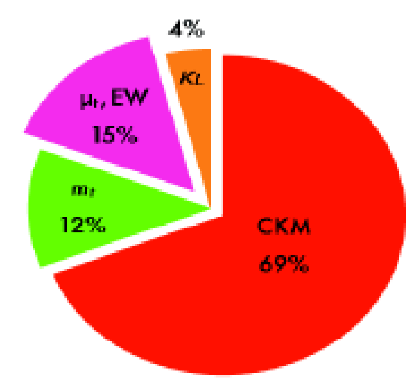
Generalized UT fits:
CKM at 1% in the presence of NP!

	today	SuperB
$\bar{\rho}$	0.187±0.056	±0.005
$\bar{\eta}$	0.370±0.036	±0.005

- crucial for many NP searches with flavour (not only for B decays!)

$K_L \to \pi^0 \nu\bar{\nu}$

error budget



U. Haisch, Kaon '07

MSSM

$M^2_{\tilde{d}} =$

SuperB

$$\begin{pmatrix} m^2_{\tilde{d}_L} & m_d(A_d-\mu\tan\beta) & (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{LR} & (\Delta^d_{13})_{LL} & (\Delta^d_{13})_{LR} \\ & m^2_{\tilde{d}_R} & (\Delta^d_{12})_{RL} & (\Delta^d_{12})_{RR} & (\Delta^d_{13})_{RL} & (\Delta^d_{13})_{RR} \\ & & m^2_{\tilde{s}_L} & m_s(A_s-\mu\tan\beta) & (\Delta^d_{23})_{LL} & (\Delta^d_{23})_{LR} \\ & & & m^2_{\tilde{s}_R} & (\Delta^d_{23})_{RL} & (\Delta^d_{23})_{RR} \\ & & & & m^2_{\tilde{b}_L} & m_b(A_b-\mu\tan\beta) \\ & & & & & m^2_{\tilde{b}_R} \end{pmatrix}$$

LHC, ILC - HE frontier

Mass Insertions

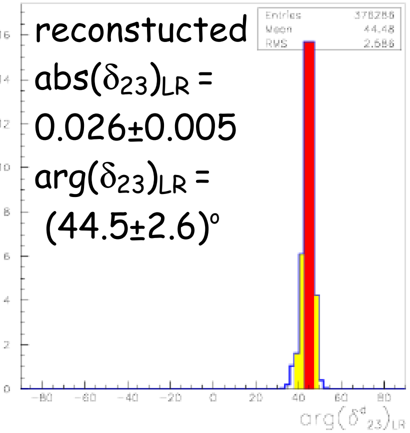
$(\delta^d_{ij})_{AB} = (\Delta^d_{ij})_{AB}/m_{\tilde{q}}^2$

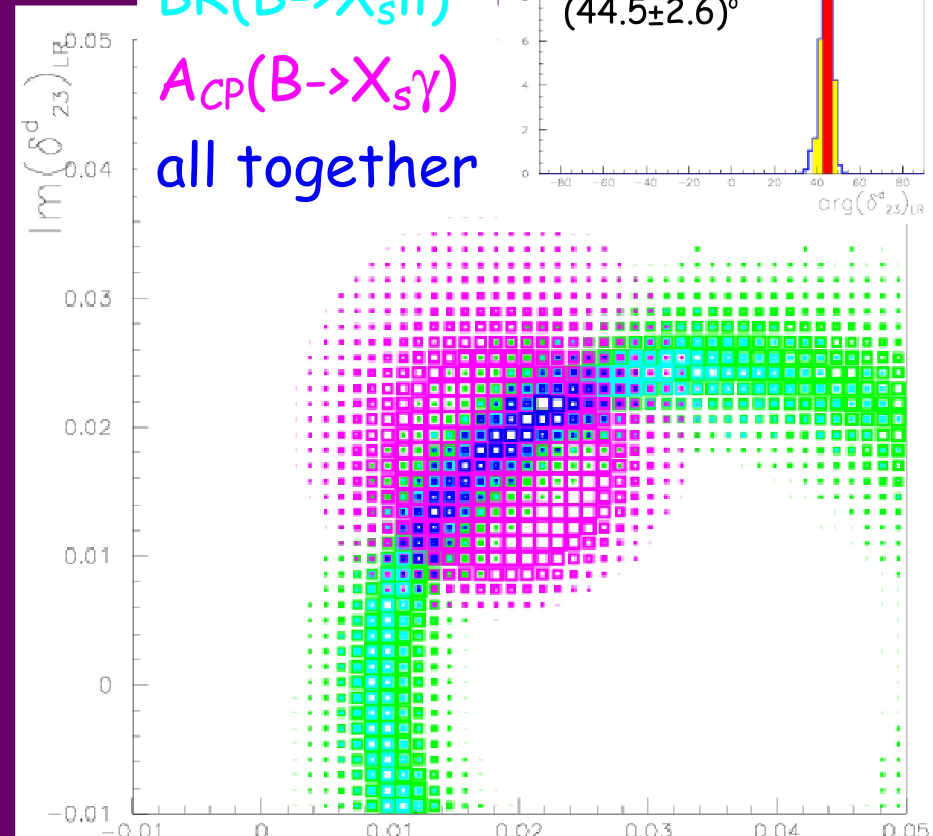
BR(B->$X_s\gamma$)

BR(B->$X_s ll$)

A_{CP}(B->$X_s\gamma$)

all together



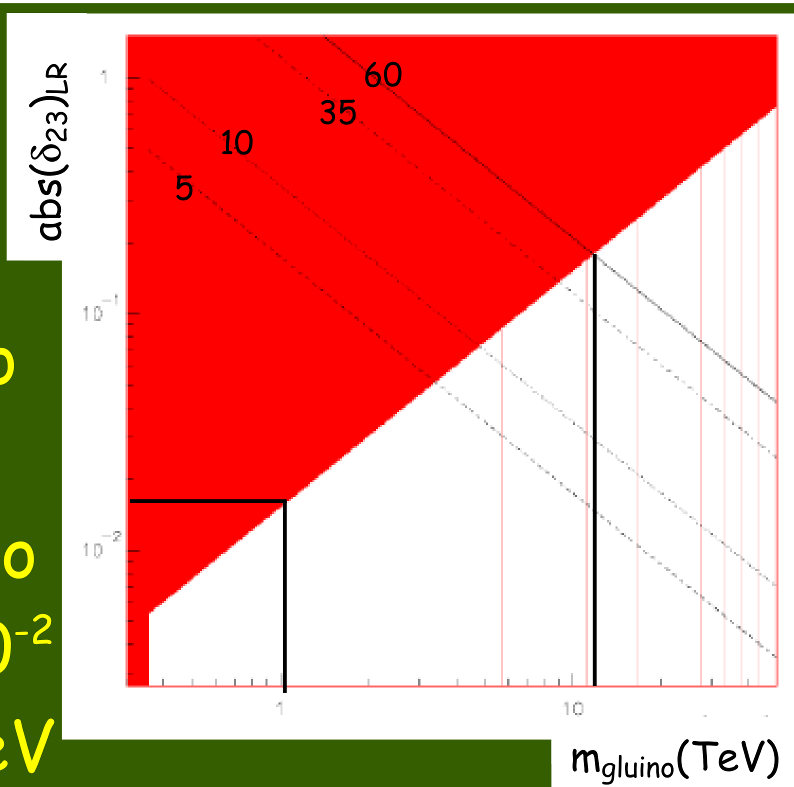


Im(δ^d_{23})$_{LR}$ vs Re(δ^d_{23})$_{LR}$

3σ from 0 sensitivity plot

i) sensit. to Λ<20 TeV

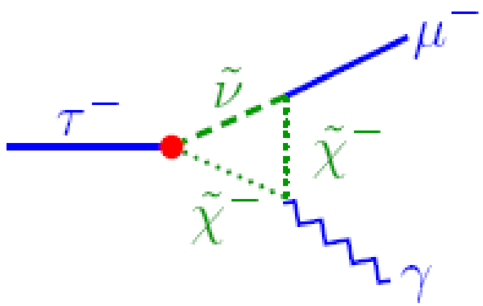
ii) sensit. to $|(\delta^d_{23})_{LR}|>10^{-2}$ for Λ<1 TeV



Reconstruction of $(\delta^d_{23})_{LR}=0.028\ e^{i\pi/4}$ for $\Lambda = m_{\tilde{g}} = m_{\tilde{q}} = 1$ TeV

τ flavour violation

Process	Sensitivity
$\mathcal{B}(\tau \to \mu\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\,\mu\,\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}
$\mathcal{B}(\tau \to \mu\eta)$	4×10^{-10}
$\mathcal{B}(\tau \to e\eta)$	6×10^{-10}
$\mathcal{B}(\tau \to \ell K_s^0)$	2×10^{-10}



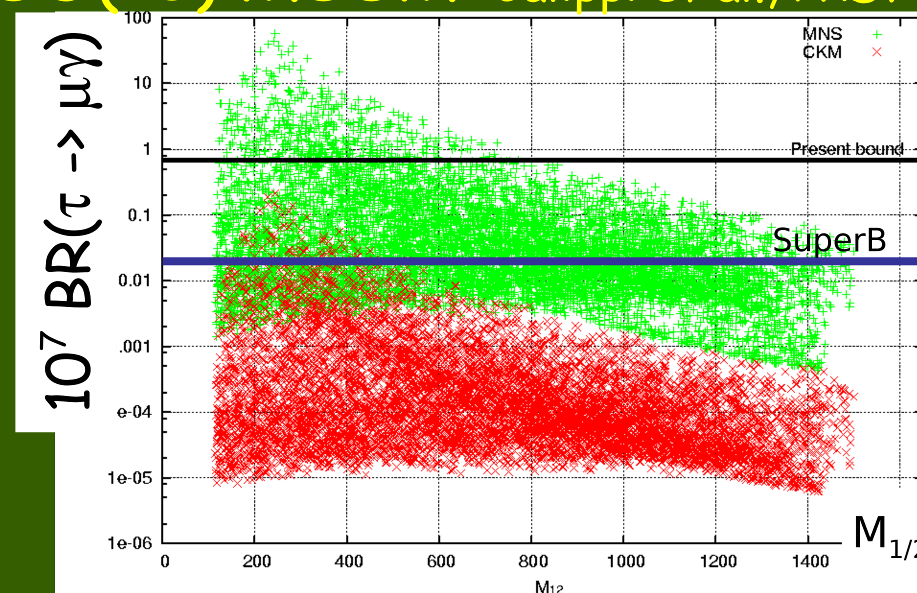
not just yet-another order of magnitude: start probing the interesting region

- help disentangle SUSY and LHT models see Hitlin's talk
- in Grand-Unified models:

* can identify the origin of LFV (CKM or PMNS);

* is complementary to the MEG sensitivity to BR(μ->eγ) ~10^{-13}

SO(10) MSSM Calippi et al., PRD74



Lepton MFV GUT models

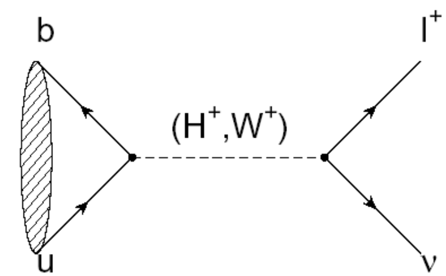
Isidori, 4th SuperB workshop

$B(\tau\to\mu\gamma):B(\tau\to e\gamma):B(\mu\to e\gamma) \sim \lambda^{-6}:\lambda^{-4}:1 \sim 10^4:500:1$ ← **LFV from CKM**

$B(\tau\to\mu\gamma):B(\tau\to e\gamma):B(\mu\to e\gamma) \sim [500-10]:1:1$ ← **LFV from PMNS**

Higgs-mediated NP in MFV at large tanβ

$$\mathrm{BR}(B^+ \to l^+ \nu) = \mathrm{BR}_{SM}(B^+ \to l^+ \nu)\left(1 - \frac{m_B^2}{M_H^2}\tan^2\beta\right)^2$$



formula and plot for 2HDM

similar results for MSSM

sensitivity:

B factories (2/ab)

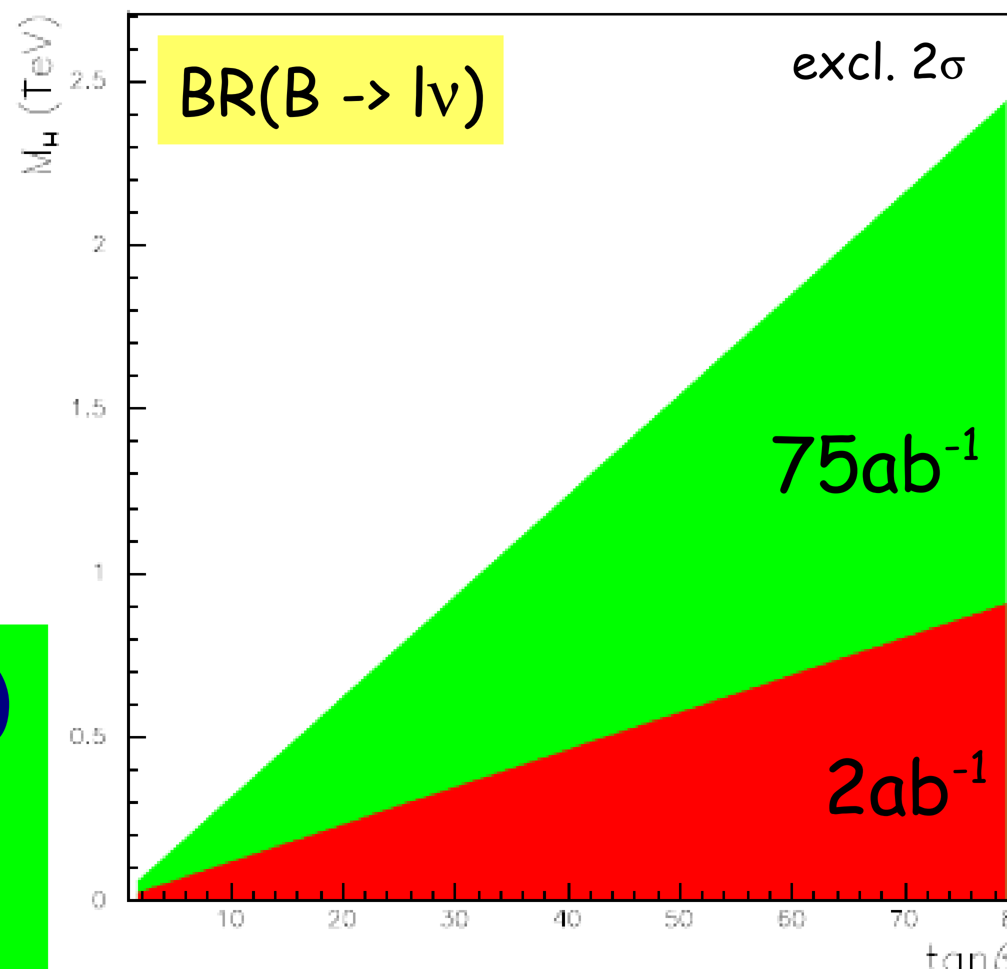
$M_H \sim 0.4$ TeV

for tanβ ~ 50

SuperB (75/ab)

$M_H \sim 1.5$ TeV

for tanβ ~ 50



theoretical uncertainties

Issues on theoretical errors

* how much does the SuperB physics program count on improvements of the theory?
* what are the theoretical tools needed for doing precision flavour physics? Are they available?
* could theoretical uncertainties hinder NP contributions irrespective of the achieved experimental precision?
* are the projections of the theoretical errors presented in the CDR realistic?

no theory improvements needed	$\beta(J/\psi K)$, $\gamma(DK)$, $\alpha(\pi\pi)^*$, lepton FV and UV, $S(\rho^0\gamma)$ CPV in $B\to X\gamma$, D and τ decays zero of FB asymmetry $B\to X_s l^+l^-$	NP insensitive or null tests of the SM or SM already known with the required accuracy
improved lattice QCD	meson mixing , $B\to D(^*)l\nu$, $B\to\pi(\rho)l\nu$, $B\to K^*\gamma$, $B\to\rho\gamma$, $B\to l\nu$, $B_s\to\mu\mu$	target error: ~1-2% Feasible (see below)
improved OPE+HQE	$B\to X_{u,c}l\nu$, $B\to X\gamma$	target error: ~1-2% Possibly feasible with SuperB data getting rid of the shape function. Detailed studies required
improved QCDF or SCET or flavour symmetries	S's from TD A_{CP} in $b \to s$ transitions	target error: ~2-3% large and hard to improve uncertainties on small corrections. In addition, FS+data can bound the theoretical error

Estimates of Lattice QCD uncertainties in the SuperB factory era:

WARNING

- Uncertainties in Lattice QCD calculations are dominated by systematic errors. The accuracy does not improve according to simple scaling laws

Predictions on the 10 years scale are not easy. Estimates are approximate

- I have tried to be conservative...
  - I neglect the impact of algorithmic improvements and of the development of new theoretical techniques. **Very conservative**
  - I assume that non hadronic uncertainties, e.g. N^2LO calculations, will be reduced at a level $< 1\%$ **Realistic**

CDR: Estimates of error for 2015

Hadronic matrix element	Current lattice error	6 TFlop Year	60 TFlop Year [2011 LHCb]	1-10 PFlop Year [2015 SuperB]
$f_+^{K\pi}(0)$	0.9% (22% on $1-f_+$)	0.7% (17% on $1-f_+$)	0.4% (10% on $1-f_+$)	< 0.1% (2.4% on $1-f_+$)
$\hat{B}_K$	11%	5%	3%	1%
f_B	14%	3.5 - 4.5%	2.5 - 4.0%	1 – 1.5%
$f_{B_s} B_{B_s}^{1/2}$	13%	4 - 5%	3 - 4%	1 – 1.5%
ξ	5% (26% on ξ-1)	3% (18% on ξ-1)	1.5 - 2 % (9-12% on ξ-1)	0.5 – 0.8 % (3-4% on ξ-1)
$\mathcal{F}_{B \to D/D^* l\nu}$	4% (40% on $1-\mathcal{F}$)	2% (21% on $1-\mathcal{F}$)	1.2% (13% on $1-\mathcal{F}$)	0.5% (5% on $1-\mathcal{F}$)
$f_+^{B\pi}, \ldots$	11%	5.5 - 6.5%	4 - 5%	2 – 3%
$T_1^{B \to K^*/\rho}$	13%	----	----	3 – 4%

S.Sharpe @ Lattice QCD: Present and Future, Orsay, 2004
and report of the U.S. Lattice QCD Executive Committee

Strategy:

1. Determine the parameters of a "target" lattice simulation (i.e. lattice spacing, lattice size, quark masses...) aiming at the 1% accuracy on the physical predictions

2. Evaluate the computational cost of the target simulation

3. Compare this cost with the computational power presumably available to lattice QCD collaborations in 2015

—— SuperB-driven requirement

Sources of errors in lattice calculations

- Statistical

  - $O(100)$ independent configurations are typically required to keep these errors at the percent level

- Discretization errors and continuum extrapolation: $a \to 0$ [Now $a \lesssim 0.1$ fm]

- Chiral extrapolation: $\hat{m}_q \to m_{u,d}^{phys.}$ [Now $m_{u,d} \gtrsim m_s/6$]

- Heavy quarks extrapolation: $m_H \to m_b, \ldots$ [Now $m_H \simeq m_c$]

- Finite volume [Now $L \simeq 2\text{-}2.5$ fm]

- Renormalization constants: $O_{cont}(\mu) = Z(a\mu, g)\, O_{latt}(a)$

  - In most of the cases Z can be calculated non-perturbatively: accuracy can be better than 1%

Cost of the target simulations:

Light quarks phys.

Nconf = 120

a = 0.05 fm
[$1/a$ = 3.9 GeV]

$\hat{m}/m_s$ = 1/12

[m_π = 200 MeV]

L_s = 4.5 fm
[$V = 90^3 \times 180$]

0.07 PFlop-years Wilson
1-2 PFlop-years GW

Heavy quarks phys

Nconf = 120

a = 0.033 fm
[$1/a$ = 6.0 GeV]

$\hat{m}/m_s$ = 1/12

[m_π = 200 MeV]

L_s = 4.5 fm
[$V = 136^3 \times 270$]

0.9 PFlop-years Wilson

Overhead for Nf=2+1 and lattices at larger a and m is about 3

Affordable with 1-10 PFlops !!

Empirical formulae for CPU cost

For Nf=2 Wilson fermions:

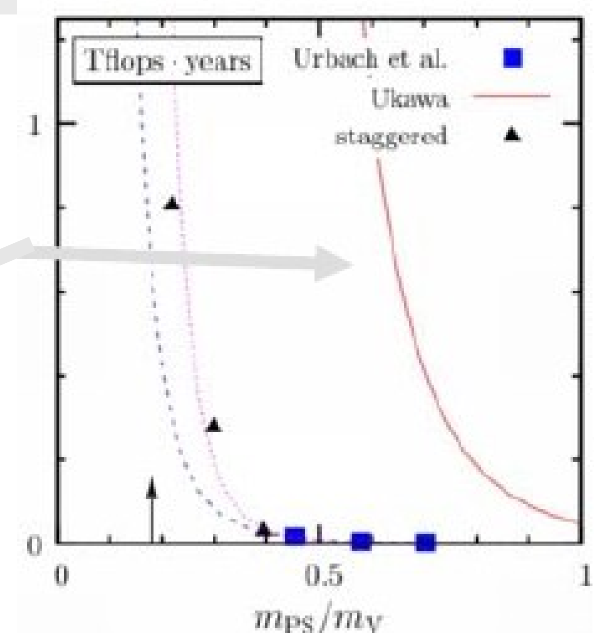
[Del Debbio et al. 06]

$$\text{TFlops-years} \simeq 0.03 \left(\frac{N_{conf}}{100}\right) \left(\frac{L_s}{3\ \text{fm}}\right)^5 \left(\frac{L_t}{2L_s}\right) \left(\frac{0.2}{\hat{m}/m_s}\right) \left(\frac{0.1\ \text{fm}}{a}\right)^6$$

0.05 for improved Wilson

×10-30 for GW

- Comparison with Ukawa 2001 (the Berlin wall):



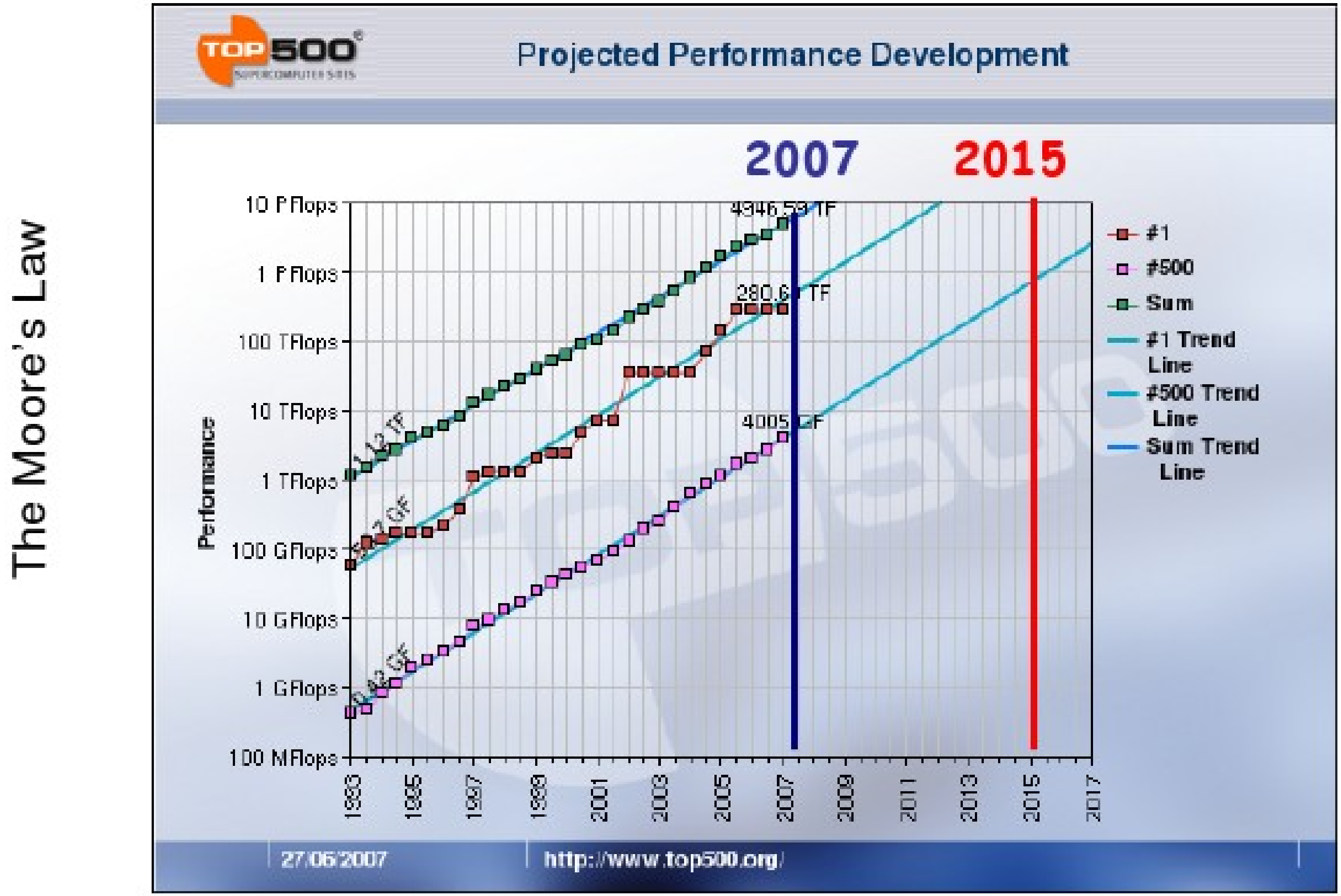
[Ukawa, Latt'01]

Berlin plot

- Tremendous progress of the algorithms in the last years.

$$\text{TFlops-years} \simeq 3.1 \left(\frac{N_{conf}}{100}\right) \left(\frac{L_s}{3\ \text{fm}}\right)^5 \left(\frac{L_t}{2L_s}\right) \left(\frac{0.2}{\hat{m}/m_s}\right)^3 \left(\frac{0.1\ \text{fm}}{a}\right)^7$$

Estimate of computational power



For Lattice QCD:

Today ~ 1 - 10 TFlops

2015 ~ 1 - 10 PFlops

comparison with (S-)LHCb

"Who will be the true superhero of 2015 flavour physics ?"

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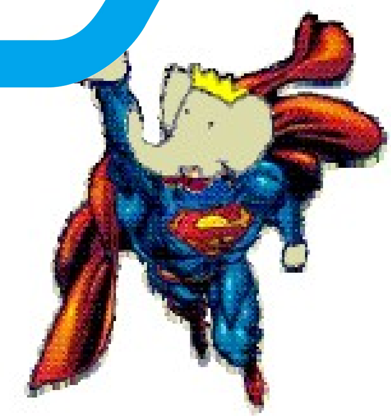


The LHCb legacy for SuperB

LHCb reach from O. Schneider,
1st LHCb Collaboration Upgrade Workshop

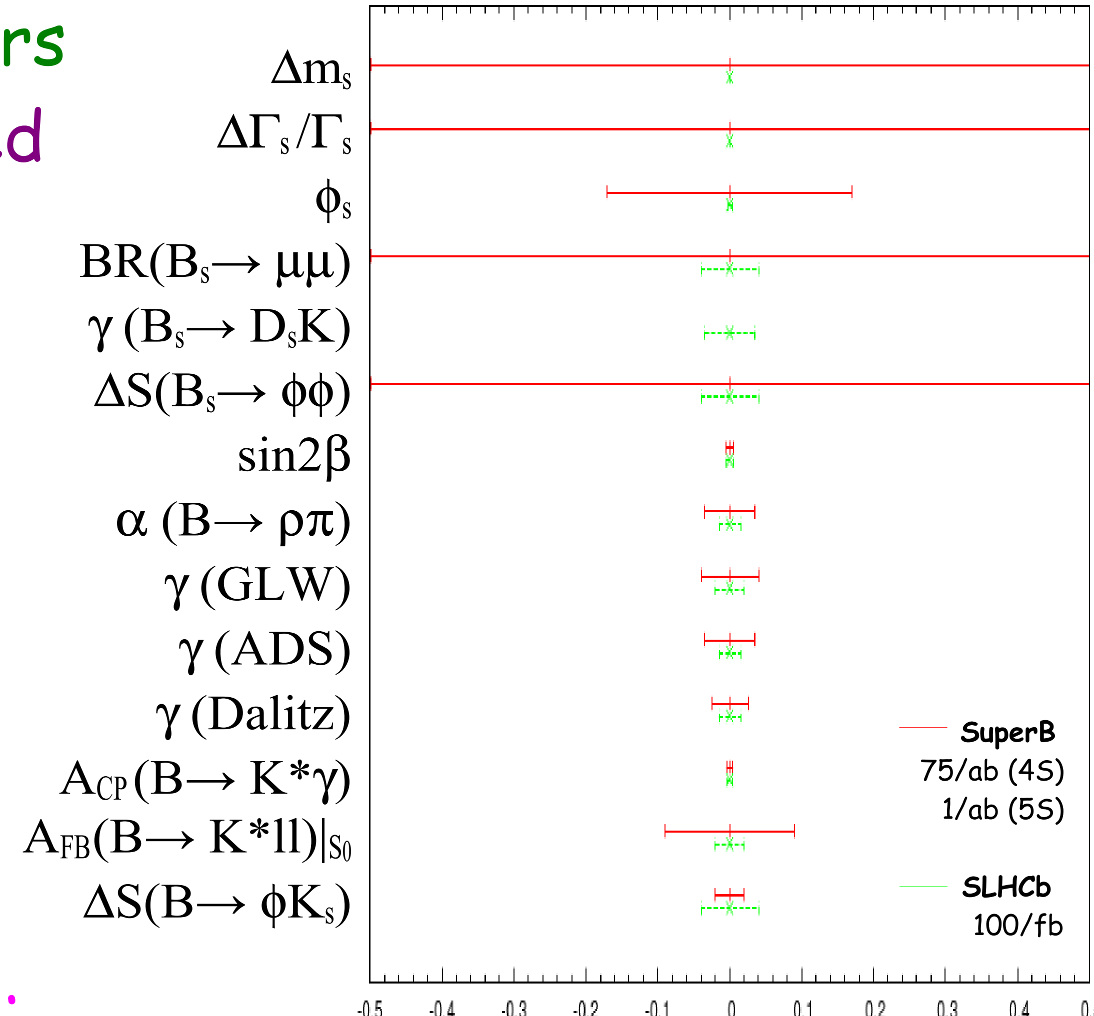
	LHCb - 2015	SuperB
	10/fb (5 years)	1/ab (1 month at $\Upsilon(5S)$)
Δm_s	0.07%(+0.5%)	no
$B_s \to \mu\,\mu$	5σ observation of SM BR	no
$\phi_s(J/\psi\,\phi)$	0.01+syst	0.14
$S(B_s \to \phi\,\phi)$	0.042+syst	possible
	10/fb (5 years)	75/ab (5 years at $\Upsilon(4S)$)
$\sin 2\beta\ (J/\psi\,K_s)$	0.010	0.005
$S(\phi\,K_s)$	0.14+syst	0.02
$A_{FB}(K^*\mu\mu)_0$	$\pm$ 0.28 GeV^2+syst	$\pm$ 0.3 GeV^2
$A_{CP}(K^*\gamma)$	< 0.01	0.004
γ (all methods)	2.4°	1-2°
$\alpha\ (\rho\pi)$	4.5°	1-2°

* LHCb main results on B_s where SuperB potential is limited (but not vanishing: A_{SL}!!) - complementarity
* SuperB provides significant improvements (x2-8 better) over LHCb on the overlapping observables

S-LHCb: a SuperB competitor in 2015?

* Major upgrade of LHCb aiming at collecting 100/fb in 5 years
* LHCb physics program pushed to extremely high precision
* few new modes become accessible: S(φ/η'K)

sLHCb reach from G. Wilkinson,
1st LHCb Collaboration Upgrade Workshop



SuperB and S-LHCb are:

- still largely complementary
- competitive with each other on the common modes (up to systematics to be studied),

but SuperB can measure more:

* multiple approaches to the same physics (e.g. S(b->s), α, LFV)
* theoretically cleaner channels (e.g. inclusive b -> sγ, b -> s ll)

overlap with sLHCb in red

Observable	B factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$\sin(2\beta)$ $(J/\psi\, K^0)$	0.018	0.005 (†)
$\cos(2\beta)$ $(J/\psi\, K^{*0})$	0.30	0.05
$\sin(2\beta)$ (Dh^0)	0.10	0.02
$\cos(2\beta)$ (Dh^0)	0.20	0.04
$S(J/\psi\, \pi^0)$	0.10	0.02
$S(D^+D^-)$	0.20	0.03
$S(\phi K^0)$	0.13	0.02 (∗)
$S(\eta' K^0)$	0.05	0.01 (∗)
$S(K^0_S K^0_S K^0_S)$	0.15	0.02 (∗)
$S(K^0_S \pi^0)$	0.15	0.02 (∗)
$S(\omega K^0_S)$	0.17	0.03 (∗)
$S(f_0 K^0_S)$	0.12	0.02 (∗)
γ $(B \to DK,\, D \to CP$ eigenstates)	$\sim 15^\circ$	2.5°
γ $(B \to DK,\, D \to$ suppressed states)	$\sim 12^\circ$	2.0°
γ $(B \to DK,\, D \to$ multibody states)	$\sim 9^\circ$	1.5°
γ $(B \to DK$, combined)	$\sim 6^\circ$	1–2°
α $(B \to \pi\pi)$	$\sim 16^\circ$	3°
α $(B \to \rho\rho)$	$\sim 7^\circ$	1–2° (∗)
α $(B \to \rho\pi)$	$\sim 12^\circ$	2°
α (combined)	$\sim 6^\circ$	1–2° (∗)
$2\beta + \gamma$ $(D^{(*)\pm}\pi^\mp,\, D^\pm K^0_S \pi^\mp)$	20°	5°
$\lvert V_{cb}\rvert$ (exclusive)	4% (∗)	1.0% (∗)
$\lvert V_{cb}\rvert$ (inclusive)	1% (∗)	0.5% (∗)
$\lvert V_{ub}\rvert$ (exclusive)	8% (∗)	3.0% (∗)
$\lvert V_{ub}\rvert$ (inclusive)	8% (∗)	2.0% (∗)
$BR(B \to \tau\nu)$	20%	4% (†)
$BR(B \to \mu\nu)$	visible	5%
$BR(B \to D\tau\nu)$	10%	2%
$BR(B \to \rho\gamma)$	15%	3% (†)
$BR(B \to \omega\gamma)$	30%	5%
$A_{CP}(B \to K^*\gamma)$	0.007 (†)	0.004 († ∗)
$A_{CP}(B \to \rho\gamma)$	~ 0.20	0.05
$A_{CP}(b \to s\gamma)$	0.012 (†)	0.004 (†)
$A_{CP}(b \to (s+d)\gamma)$	0.03	0.006 (†)
$S(K^0_S \pi^0 \gamma)$	0.15	0.02 (∗)
$S(\rho^0\gamma)$	possible	0.10
$A_{CP}(B \to K^*\ell\ell)$	7%	1%
$A^{FB}(B \to K^*\ell\ell)s_0$	25%	9%
$A^{FB}(B \to X_s\ell\ell)s_0$	35%	5%
$BR(B \to K\nu\overline{\nu})$	visible	20%
$BR(B \to \pi\nu\bar{\nu})$	–	possible

Mode	Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$D^0 \to K^+K^-$	y_{CP}	$2\text{–}3 \times 10^{-3}$	5×10^{-4}
$D^0 \to K^+\pi^-$	y'_D	$2\text{–}3 \times 10^{-3}$	7×10^{-4}
	x'^2_D	$1\text{–}2 \times 10^{-4}$	3×10^{-5}
$D^0 \to K^0_S\pi^+\pi^-$	y_D	$2\text{–}3 \times 10^{-3}$	5×10^{-4}
	x_D	$2\text{–}3 \times 10^{-3}$	5×10^{-4}
Average	y_D	$1\text{–}2 \times 10^{-3}$	3×10^{-4}
	x_D	$2\text{–}3 \times 10^{-3}$	5×10^{-4}

SuperB only
* D studies at threshold
* semilept. D decays

	Sensitivity
$D^0 \to e^+e^-$, $D^0 \to \mu^+\mu^-$	1×10^{-8}
$D^0 \to \pi^0 e^+e^-$, $D^0 \to \pi^0\mu^+\mu^-$	2×10^{-8}
$D^0 \to \eta e^+e^-$, $D^0 \to \eta\mu^+\mu^-$	[illegible]
$D^0 \to K^0_s e^+e^-$, $D^0 \to K^0_s\mu^+\mu^-$	3 × [illegible]
$D^+ \to \pi^+e^+e^-$, $D^+ \to \pi^+\mu^+\mu^-$	1×10^{-8}
$D^0 \to e^\pm\mu^\mp$	
$D^+ \to \pi^+e^\pm\mu^\mp$	
$D^0 \to \pi^0 e^\pm\mu^\mp$	
$D^0 \to \eta e^\pm\mu^\mp$	
$D^0 \to K^0_s e^\pm\mu^\mp$	
$D^+ \to \pi^-e^+e^+$, $D^+ \to K^-e^+e^+$	1×10^{-8}
$D^+ \to \pi^-\mu^+\mu^+$, $D^+ \to K^-\mu^+\mu^+$	1×10^{-8}
$D^+ \to \pi^-e^\pm\mu^\mp$, $D^+ \to K^-e^\pm\mu^\mp$	1×10^{-8}

?

likely competitive in all charged track final states

+ τ physics (CPV, ...) incl. polarization

see next talk

Process	Sensitivity
$\mathcal{B}(\tau \to \mu\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\,\mu\,\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}
$\mathcal{B}(\tau \to \mu\eta)$	4×10^{-10}
$\mathcal{B}(\tau \to e\eta)$	6×10^{-10}
$\mathcal{B}(\tau \to \ell K^0_S)$	2×10^{-10}

Super Flavour Factory

a "treasure chest" of new physics-sensitive observables

Observable	Error with 1 ab^{-1}
$\Delta\Gamma$	0.16 ps^{-1}
Γ	0.07 ps^{-1}
β_s from angular analysis	20°
$A^s_{\rm SL}$	0.006
$A_{\rm CH}$	0.004
$\mathcal{B}(B_s \to \mu^+\mu^-)$	-
$\lvert V_{td}/V_{ts}\rvert$	0.08
$\mathcal{B}(B_s \to \gamma\gamma)$	38%
β_s from $J/\psi\phi$	10°

Conclusions (i)

Many NP studies exploiting precision flavour physics can be carried out at SuperB

The SuperB physics program complements and extends the NP searches with high p_T at LHC:

(i) LHC tells us where NP is: SuperB (only) can measure systematically the new FV&CPV couplings, i.e. the flavour structure of NP

(ii) NP at scales beyond the LHC reach could give measurable effects at SuperB: unique opportunity to explore the 5-100 TeV range

Conclusions (ii)

Only part of the SuperB physics program relies on theory upgrades. For this part, theoretical errors of O(1-2%) are needed: feasible for LQCD; challenging but possibly reachable in inclusive measurements; factorization needs checking on channel basis

SuperB and S-LHCb physics programs are largely complementary. As for the part in common, they are competitive but SuperB can measure more and th. cleaner channels

Spare Slides

Minimum lattice spacing

[From S.Sharpe @ Lattice QCD: Present and Future, Orsay, 2004]

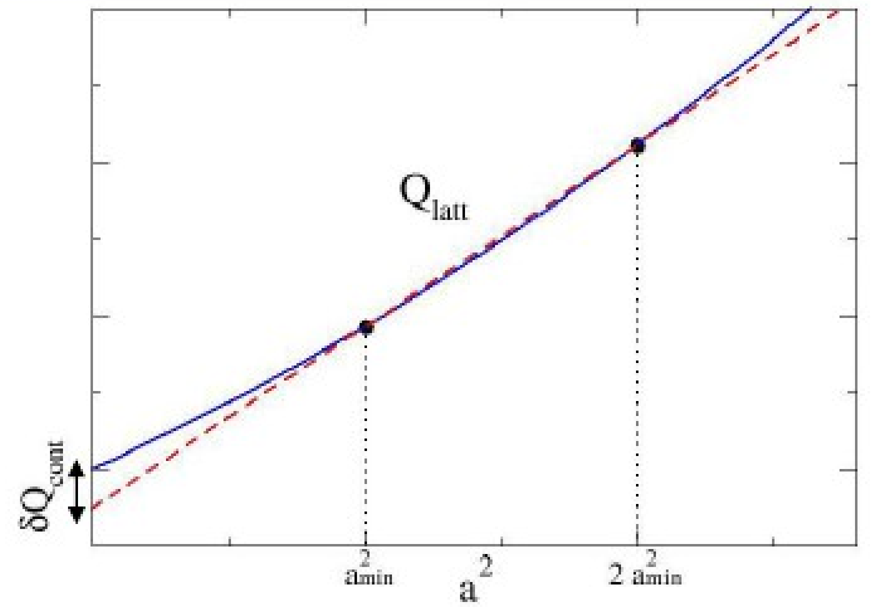
Rough estimate: • Assume O(a) improved action:

$$Q_{latt} = Q_{cont}\left[1 + (a\Lambda_2)^2 + (a\Lambda_n)^n + \dots\right]$$

- Improved Wilson: n=3. Staggered, maximally twisted, GW: n=4
- For light quarks: $\Lambda_2 \sim \Lambda_n \sim \Lambda_{QCD}$. For heavy quarks: $\Lambda_2 \sim \Lambda_n \sim m_H$

Assume simulations at a_{min} and $\sqrt{2}a_{min}$, and linearly extrapolate in a^2. The resulting error is:

$$\varepsilon = \delta Q_{cont} / Q_{cont} \approx (2^{n/2} - 2)\,(a_{min}\Lambda_n)^n$$



Minimum lattice spacing (cont.)

We require: $\varepsilon = \delta Q_{cont} / Q_{cont} \approx (2^{n/2} - 2)(a_{min} \Lambda_n)^n$ $\underline{= \; 0.01}$

Simulations with <u>light quarks</u> only:

$\Lambda_n \approx m_{Had} \approx 0.8$ GeV

$$\begin{cases} a_{min} \approx 0.056 \text{ fm}, & n=3 \\ a_{min} \approx 0.065 \text{ fm}, & n=4 \end{cases}$$

Simulations with <u>heavy quarks</u>:

$\Lambda_n \approx m_c \approx 1.5$ GeV

$$\begin{cases} a_{min} \approx 0.030 \text{ fm}, & n=3 \\ a_{min} \approx 0.035 \text{ fm}, & n=4 \end{cases}$$

Today: a ~ 0.06 - 0.10 fm (cost ~ a^{-6})

Minimum quark mass

- Chiral perturbation theory (schematic):

$$Q_{latt} = Q_{phys}\left[1 + c_1(m_\pi/m_\rho)^2 + c_2(m_\pi/m_\rho)^4 + \dots\right]$$

  - $c_1 \sim c_2 \sim O(1)$

- Assume simulations at two values of m_π/m_ρ. The resulting error is

$$\varepsilon = \delta Q_{phys}/\,Q_{phys} \approx 2\,c_2\left(m_\pi/m_\rho\right)^4_{min}$$

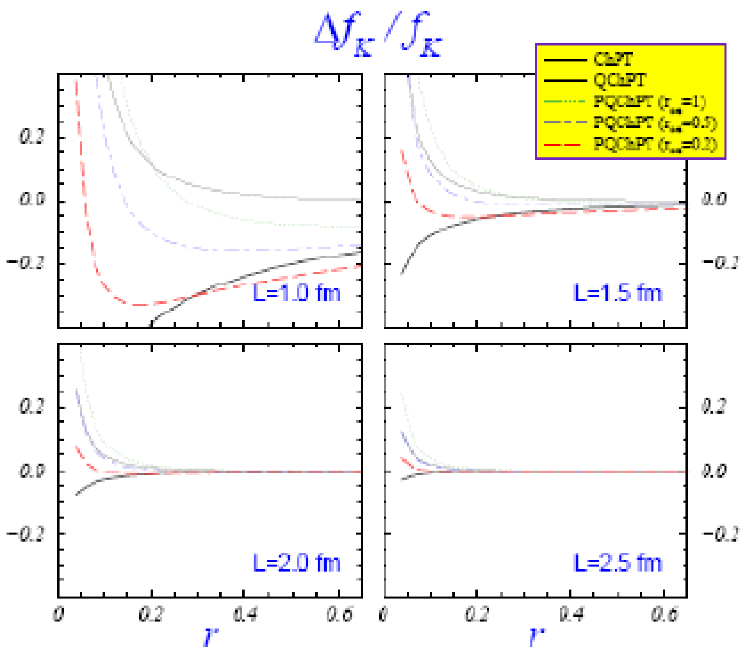
- If we require $\varepsilon = 0.01$ then (assuming c_2=1):

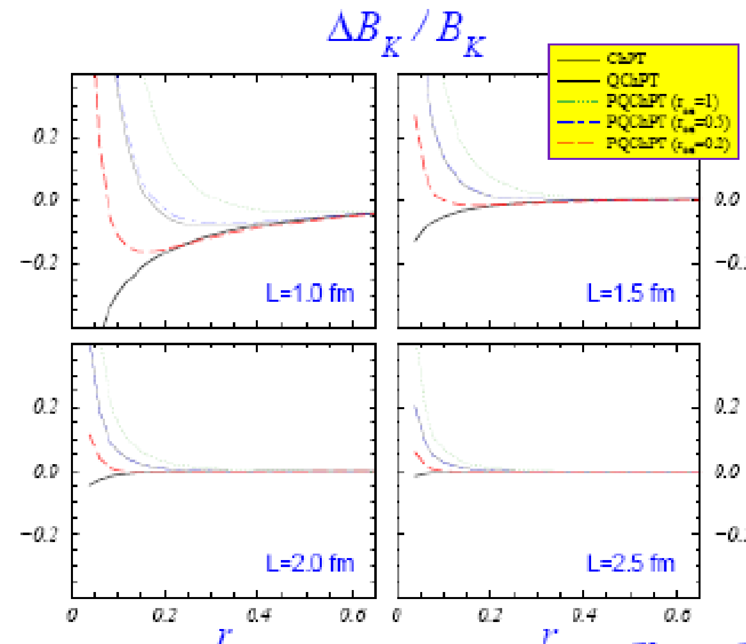
$$(m_\pi/m_\rho)_{min} \approx 0.27 \;\Rightarrow\; \left(\hat{m}_q / m_s\right)_{min} \approx 1/12$$

Today: $\left(\hat{m}_q / m_s\right)_{min} \approx 1/6$, Physical value: $\left(\hat{m}_q / m_s\right)_{phys} \approx 1/25$

Minimum box size

Finite volume effects are important when aiming for 1% precision. The dominant effects come from pion loops and can be calculated using ChPT. E.g:





$r = \hat{m} / m_s$

[Becirevic, Villadoro, hep-lat/0311028]

$$\frac{\Delta f_K}{f_K} \sim \left(\frac{m_\pi}{f}\right)^2 \frac{\exp(-m_\pi L)}{(2\pi m_\pi L)^{3/2}} \qquad \frac{\Delta B_K}{B_K} \sim \left(\frac{m_\pi}{f}\right)^2 \frac{\exp(-m_\pi L)}{(2\pi m_\pi L)^{3/2}}$$

- For matrix elements with at most one particle in the initial and final states finite volume effects are exponentially suppressed:

$$\varepsilon = \delta Q_{phys} / Q_{phys} \approx c \; \exp(-m_\pi L)$$

with $c \sim O(1)$

- If we require $\varepsilon = 0.01$ then (assuming c=1):

$$m_\pi L \approx 4.5$$

- If $\hat{m} / m_s \approx 1/12$ the pion mass is $m_\pi \simeq 200$ MeV. Thus:

$$L \approx 4.5 \text{ fm}$$

- With $a = 0.033$ fm the number of lattice sites is

$$V \approx 136^3 \times 270$$

Today the typical size is: $32^3 \times 64$
More than 300 times smaller

Heavy quark extrapolation

- A relativistic b quark cannot be simulated directly on the lattice. It would require $a\,m_b \ll 1$. Typically that means:

$$1/a \approx 20 \text{ GeV} \Longleftrightarrow a \approx 0.01 \text{ fm}$$

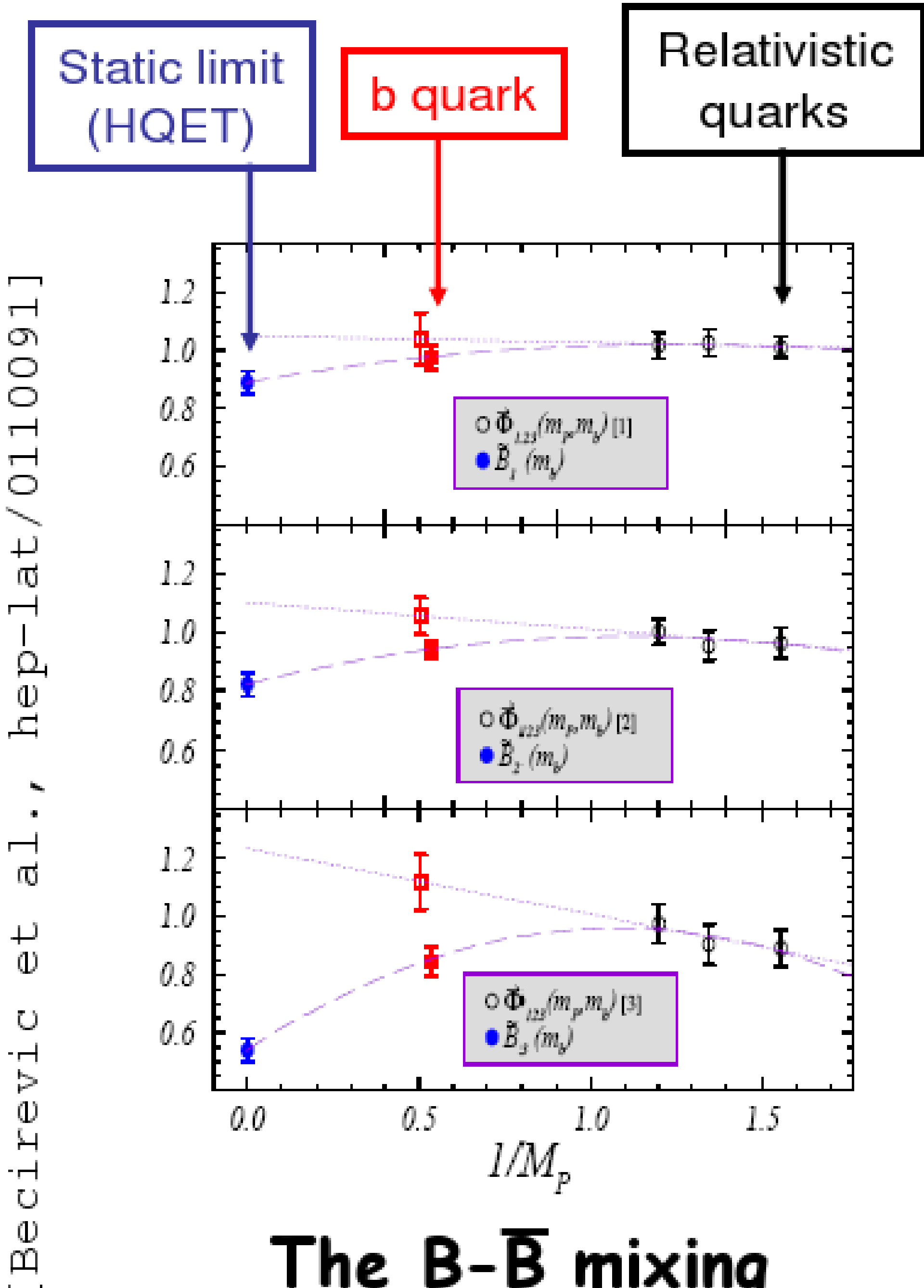
This lattice is too fine, even for PFlop computers.

- Two approaches to treat the b quark:

  1) Use an effective theory on the lattice:
  - HQET
  - NRQCD (no continuum limit)
  - "Fermilab"

  2) Simulate relativistic heavy quark in the charm mass region and extrapolate to the b quark mass

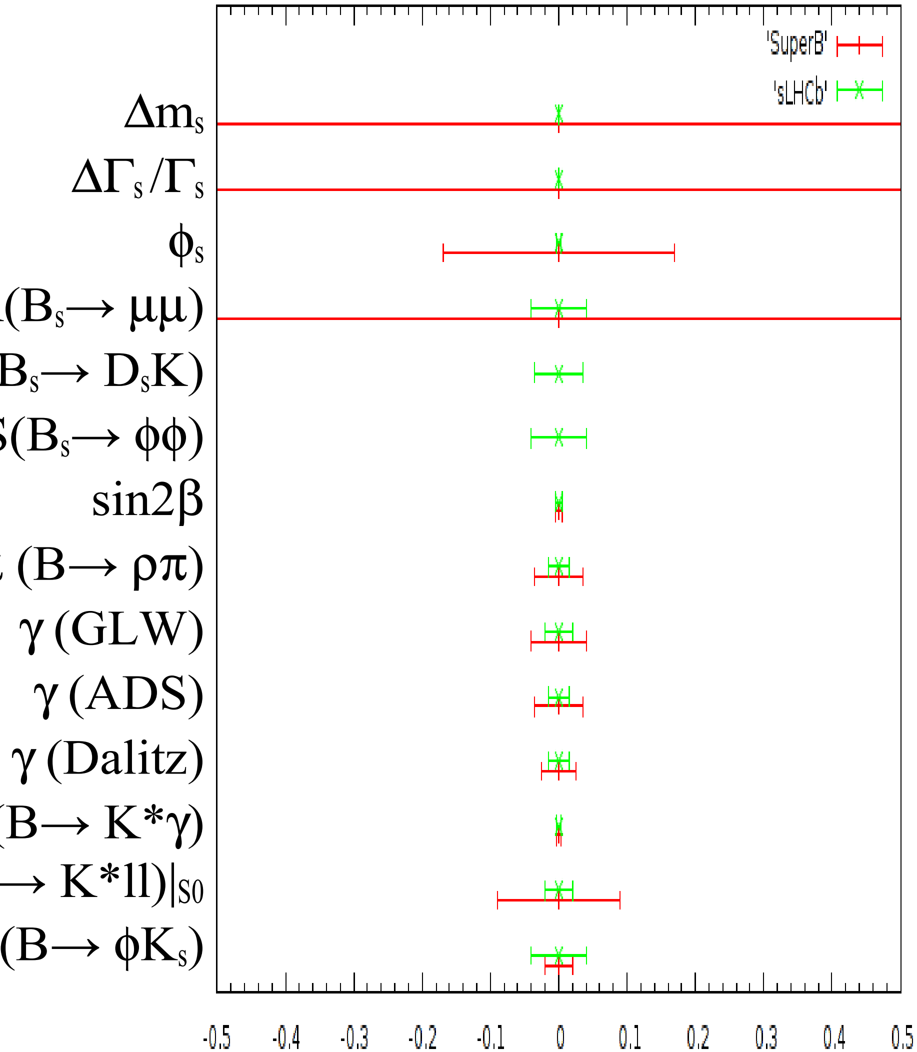
- The most accurate results can be obtained by combining the two approaches

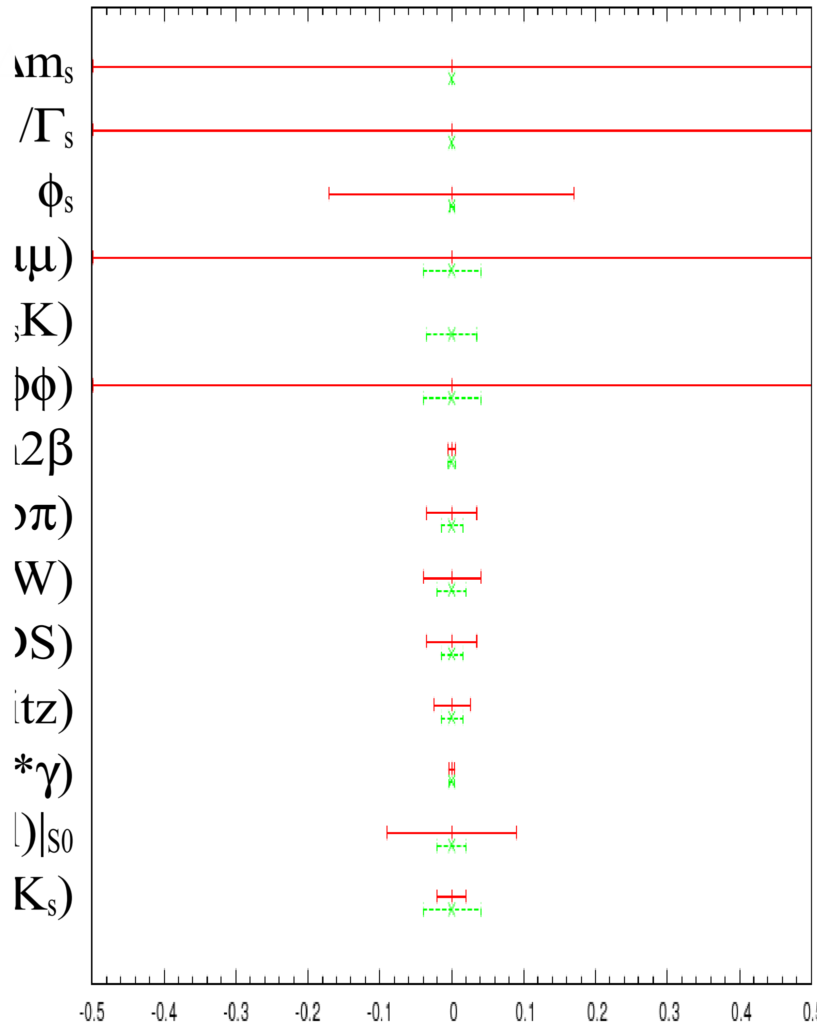


The B-$\overline{B}$ mixing B parameters

- Besides the static point, lattice HQET also allows a non-perturbative determination of $(\Lambda/M)^n$ corrections [Heitger, Sommer, hep-lat/0310035]

The point interpolated to the B meson mass has an accuracy comparable to the one obtained in the relativistic and HQET calculations


'SuperB'
'sLHCb'
Δm_s
ΔΓ_s/Γ_s
φ_s
(B_s→ μμ)
B_s→ D_sK)
S(B_s→ φφ)
sin2β
(B→ ρπ)
γ (GLW)
γ (ADS)
γ (Dalitz)
(B→ K*γ)
→ K*ll)|S0
(B→ φK_s)
-0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5


-0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5

Crucial questions for NP searches with flavour

1. can NP be flavour blind? "no",
NP couples to SM which violates flavour

2. can a "worst case" be defined? "yes",
through the class of models with

Minimal Flavour Violation

NP follows the SM pattern of flavour and CP symmetry breaking

Gabrielli, Giudice, NPB433
Buras et al, NPB500
D'Ambrosio et al., NPB645

Minimal Flavour Violation

Gabrielli, Giudice, NPB433
Buras et al., NPB500
D'Ambrosio et al., NPB645

No new sources of flavour and CP violation beyond the SM

- NP contributions governed by SM Yukawa couplings
  ex.: Constrained MSSM (MSUGRA), Universal Extra Dim.
- NP only modifies SM top contribution to FCNC & CPV
  unless other Yukawa couplings are enhanced; for example large tanβ enhances bottom contributions

1HDM/2HDM at small tanβ	2HDM at large tanβ
same operators as in H_{eff}^{SM}	new operators wrt H_{eff}^{SM}
NP in K and B correlated	NP in K and B uncorrelated

Constraints on the MFV NP scale

D'Ambrosio et al., NPB645

MFV models with 1HD or 2HD @ low/moderate tanβ:
Universal NP effect in the ΔF=2 loop function of the top

$$\mathcal{H}_{\rm eff}^{\Delta F=2} = \mathcal{H}_{\rm SM} + \mathcal{H}_{\rm NP} = \left(V_{tq}V_{tq'}^*\right)^2 \left(\frac{S_0(x_t)}{\Lambda_0^2} + \frac{a_{\rm NP}}{\Lambda^2}\right) (\bar{q}'q)_{(V-A)} (\bar{q}'q)_{(V-A)}$$

$$S_0(x_t) \to S_0(x_t) + \delta S_0, \quad |\delta S_0| = O\left(4\frac{\Lambda_0^2}{\Lambda^2}\right), \quad \Lambda_0 = \frac{\pi Y_t}{\sqrt{2} G_F M_W} \sim 2.4\,\mathrm{TeV}$$

Today:

$\Lambda_{MFV} > 2.3\Lambda_0$ @95% prob.

NP masses > 200 GeV

SuperB:

$\Lambda_{MFV} > 6\Lambda_0$ @95% prob.

NP masses > 600 GeV

NB: constraints from ΔF=1 processes not included

The ΔB=2 effective Hamiltonian beyond MFV

$$H_{eff}^{\Delta=2} = \sum_{i=1}^{5} C_i(\mu) Q_i(\mu) + \sum_{i=1}^{3} \tilde{C}_i(\mu) \tilde{Q}_i(\mu)$$

$$Q_1 = \bar{q}_L^\alpha \gamma_\mu b_L^\alpha \; \bar{q}_L^\beta \gamma^\mu b_L^\beta \qquad \text{(SM/MFV)}$$

$$Q_2 = \bar{q}_R^\alpha b_L^\alpha \; \bar{q}_R^\beta b_L^\beta \qquad Q_3 = \bar{q}_R^\alpha b_L^\beta \; \bar{q}_R^\beta b_L^\beta$$

$$Q_4 = \bar{q}_R^\alpha b_L^\alpha \; \bar{q}_L^\beta b_R^\beta \qquad Q_5 = \bar{q}_R^\alpha b_L^\beta \; \bar{q}_L^\beta b_R^\beta$$

$$\tilde{Q}_1 = \bar{q}_R^\alpha \gamma_\mu b_R^\alpha \; \bar{q}_R^\beta \gamma^\mu b_R^\beta$$

$$\tilde{Q}_2 = \bar{q}_L^\alpha b_R^\alpha \; \bar{q}_L^\beta b_R^\beta \qquad \tilde{Q}_3 = \bar{q}_L^\alpha b_R^\beta \; \bar{q}_L^\beta b_R^\beta$$

7 new operators involving quarks with different chiralities

H_{eff} can be recast in terms of the high-scale $C_i(\Lambda)$

- $C_i(\Lambda)$ can be extracted from the data (one by one)
- the associated NP scale Λ can be defined as

$$\Lambda = \sqrt{\frac{L F_i}{C_i(\Lambda)}}$$

strongly interacting NP: $L \sim 1$

weakly interacting NP: $L \sim \alpha_{W,s}^2$

MFV: $F_1 = F_{SM} \sim (V_{tq} V_{tb}^*)^2$, $F_{i \neq 1} = 0$ and $L \sim \alpha_W^2$

generic flavour structure	next-to-MFV
- $\lvert F_i \rvert \sim 1$	- $\lvert F_i \rvert \sim F_{SM}$
- arbitrary phases	- arbitrary phases

PRELIMINARY

generic FV

B_d Sector

$Re(C_d^1)$	$[-0.9,3.9]10^{-12}$	$Im(C_d^1)$	$[-1.0,3.7]10^{-12}$
$Re(C_d^2)$	$[-1.5,0.4]10^{-12}$	$Im(C_d^2)$	$[-1.5,0.4]10^{-12}$
$Re(C_d^3)$	$[-1.2,5.7]10^{-12}$	$Im(C_d^3)$	$[-1.5,5.3]10^{-12}$
$Re(C_d^4)$	$[-0.8,4.8]10^{-13}$	$Im(C_d^4)$	$[-1.2,0.4]10^{-12}$
$Re(C_d^5)$	$[-0.3,1.2]10^{-12}$	$Im(C_d^5)$	$[-0.3,1.2]10^{-12}$

Λ>1800 TeV@95% prob.

NMFV

B_d Sector

$Re(C_d^1)$	$[-0.7,2.8]10^{-8}$	$Im(C_d^1)$	$[-0.7,2.6]10^{-8}$
$Re(C_d^2)$	$[-14.4,3.6]10^{-9}$	$Im(C_d^2)$	$[-14.3,3.9]10^{-9}$
$Re(C_d^3)$	$[-1.1,5.6]10^{-8}$	$Im(C_d^3)$	$[-1.5,5.2]10^{-8}$
$Re(C_d^4)$	$[-1.1,4.8]10^{-9}$	$Im(C_d^4)$	$[-1.3,4.7]10^{-9}$
$Re(C_d^5)$	$[-0.3,1.3]10^{-8}$	$Im(C_d^5)$	$[-0.7,1.2]10^{-8}$

Λ_{NMFV}>14 TeV@95% prob.

- ΔB=2 chirality-flipping operators are RG enhanced and thus probe larger NP scales
- when scalar operators are allowed, the NP scale is easily pushed beyond the LHC reach

SuperB: typically 3 x present bounds