Searching for New Physics in the Flavour Sector

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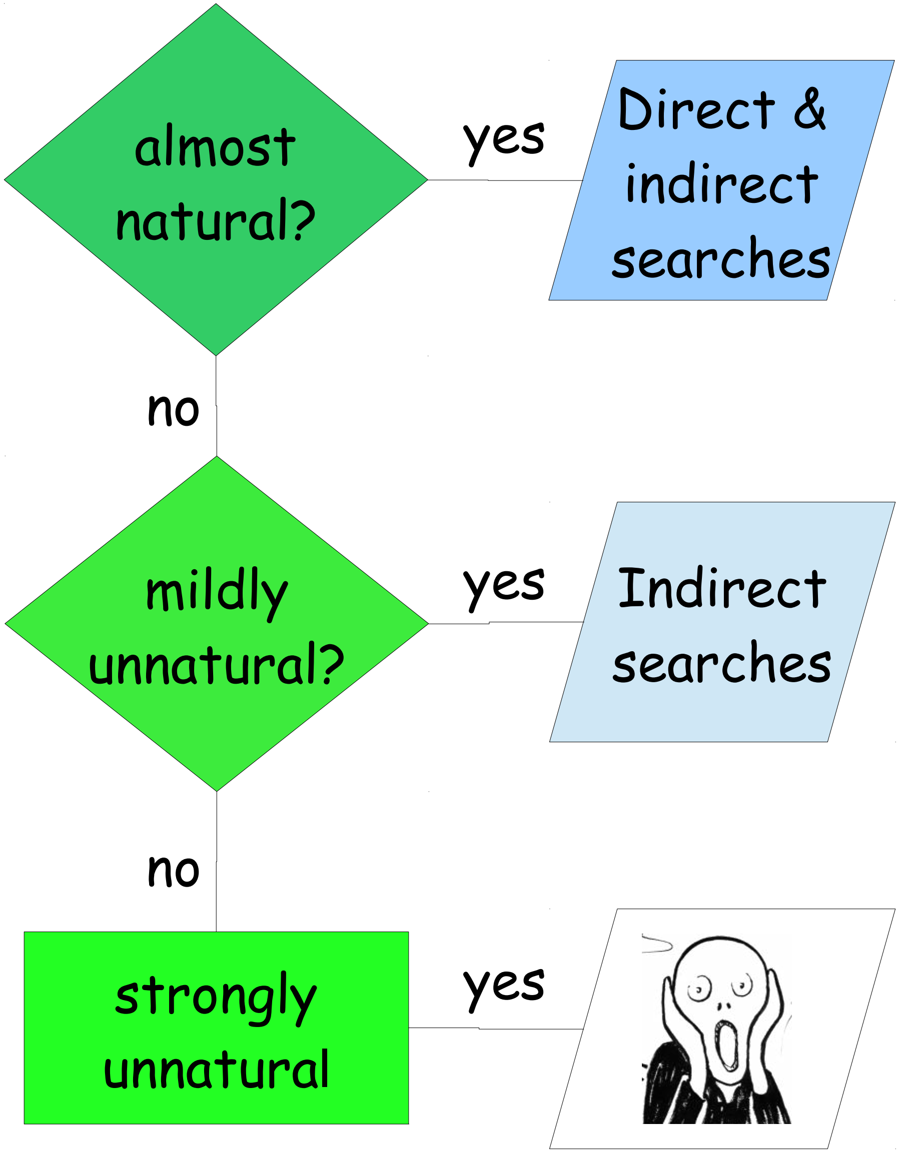
- Introduction
- Bounds on NP from Flavour
- Impact of BelleII
- Conclusions

How much “natural” is Nature?



almost natural?

yes

Direct & indirect searches

no

mildly unnatural?

yes

Indirect searches

no

strongly unnatural

yes

illustration by G. Villadoro

Courtesy of Marco Ciuchini

WHY FLAVOUR?

- No tree-level flavour changing neutral currents in the SM
- GIM suppression of FCNC @ the loop level
- Tiny CP violation in K and D mesons due to small CKM angles
- Unobservable LFV

⇒ Flavour & CP violation ideal places to get indirect evidence of NP

ROLE OF FLAVOUR

- In the framework of future experimental developments, Flavour physics should:
- Guarantee that the flavour structure of any directly discovered NP can be efficiently probed, and/or
- Push the NP scale that can be indirectly probed up by (at least) one order of magnitude

- A generic FCNC amplitude has the form

$$A_{SM}+A_{NP}=K_{SM}\frac{\alpha_W}{4\pi}\frac{F_{CKM}}{M_W^2}+K_{NP}L\frac{F_{NP}}{\Lambda^2}$$

where L is a possible loop factor, F_{NP} denotes the NP flavour coupling and $K_{SM,NP}$ O(1) #'s.

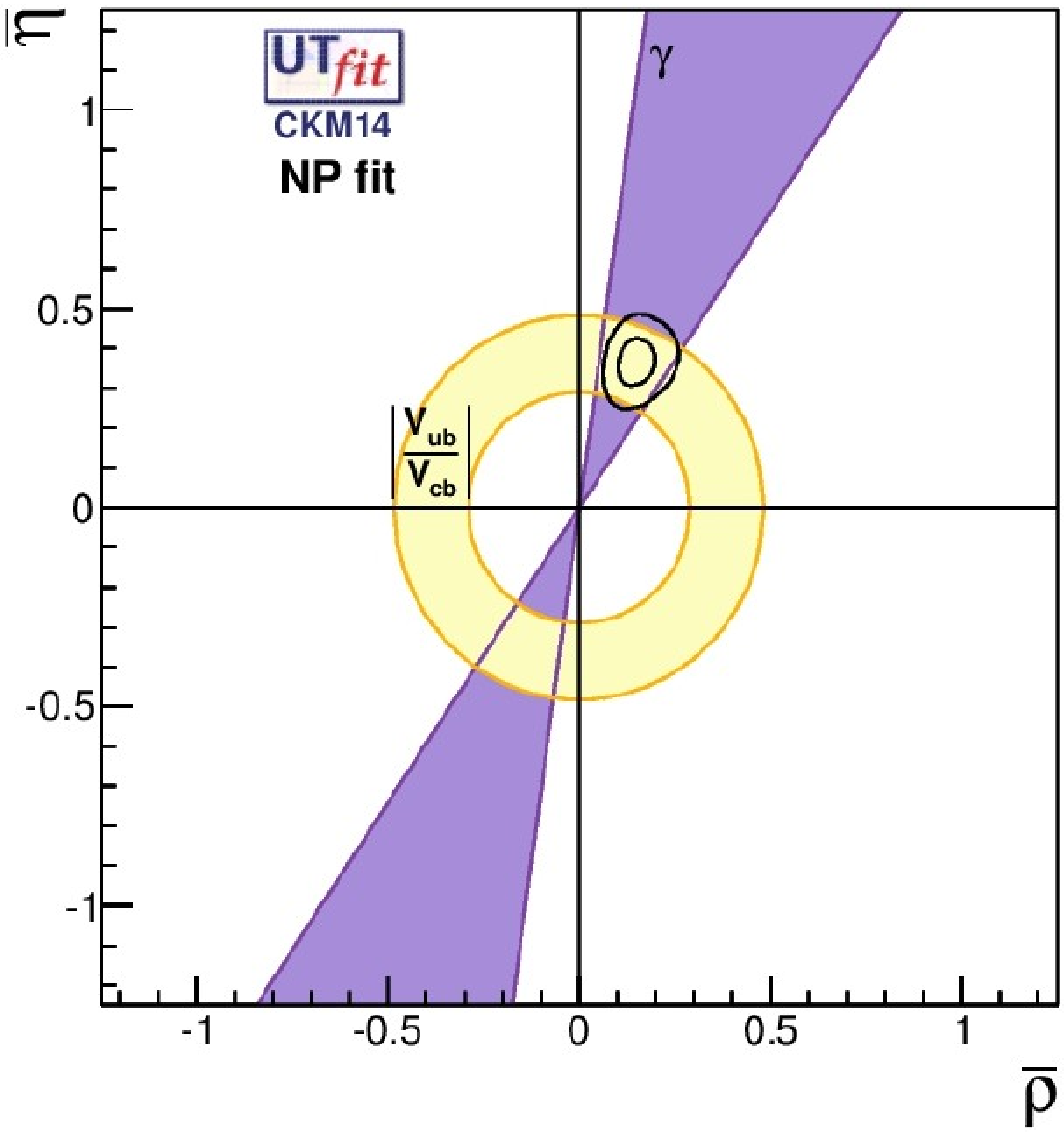
- For any directly observed NP, we know Λ and L and can extract F_{NP}
- Assuming a value for $L\geq\alpha_W/4\pi$ and $F_{NP}\geq F_{SM}$, we can extract the NP scale Λ
- Need to improve A_{exp} & A_{SM} (where present)

LEPTONIC SECTOR

- LFV decays are theoretically very clean but scale as $1/\Lambda^4$; present MEG bound $5.7\ 10^{-13}$ corresponds to O(100 TeV).
- Complementing $\mu \to e\gamma$ with other processes:
  - $\mu \to eee$ and $\mu \to e$ conversion
  - $\tau \to \mu(e)\gamma$ and $\tau \to \mu(e)ll$

is crucial to pin down NP flavour couplings

NP analysis results



$\bar{\rho} = 0.154 \pm 0.040$
$\bar{\eta} = 0.367 \pm 0.048$

SM is

$\bar{\rho} = 0.137 \pm 0.022$
$\bar{\eta} = 0.349 \pm 0.014$

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NP parameter results

K system

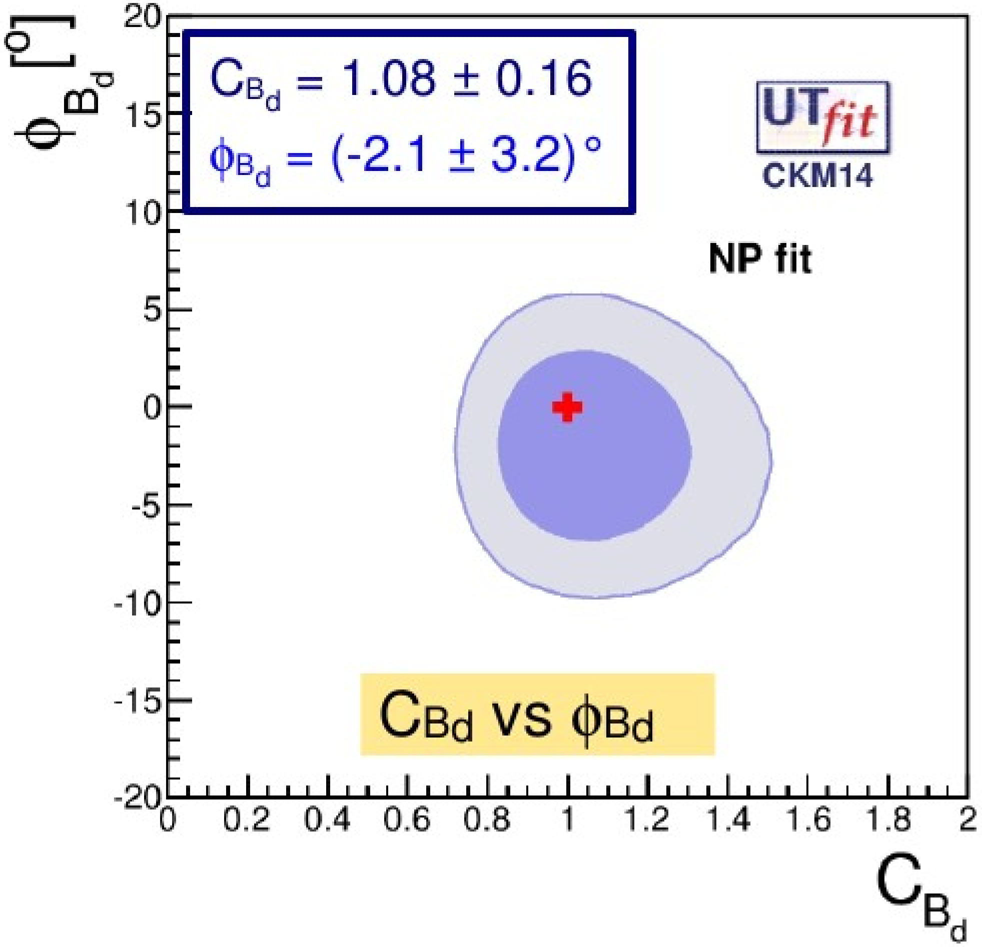
$C_{\varepsilon_K} = 1.07 \pm 0.16$

dark: 68%

light: 95%

SM: red cross

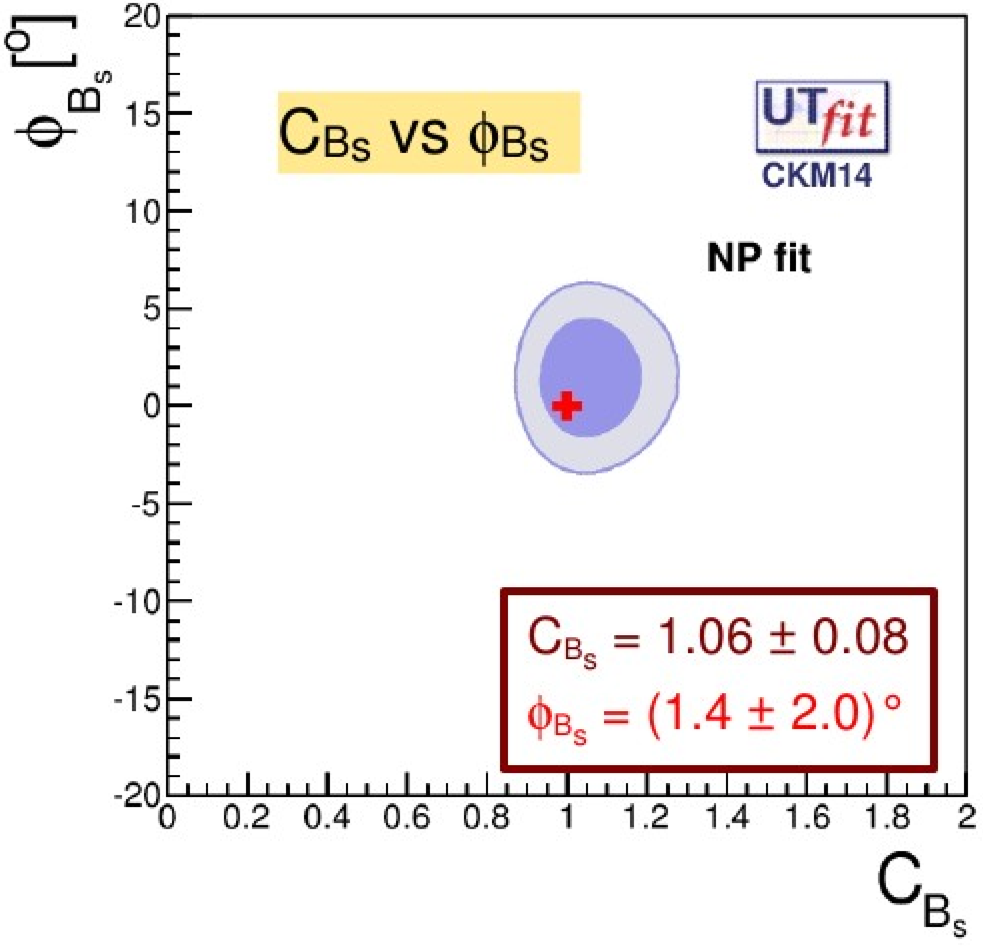
$$A_q = C_{B_q} e^{2i\varphi_{B_q}} A_q^{SM} e^{2i\varphi_q^{SM}}$$



$C_{B_d} = 1.08 \pm 0.16$

$\phi_{B_d} = (-2.1 \pm 3.2)°$

CBd vs ϕBd



CBs vs ϕBs

$C_{B_s} = 1.06 \pm 0.08$

$\phi_{B_s} = (1.4 \pm 2.0)°$

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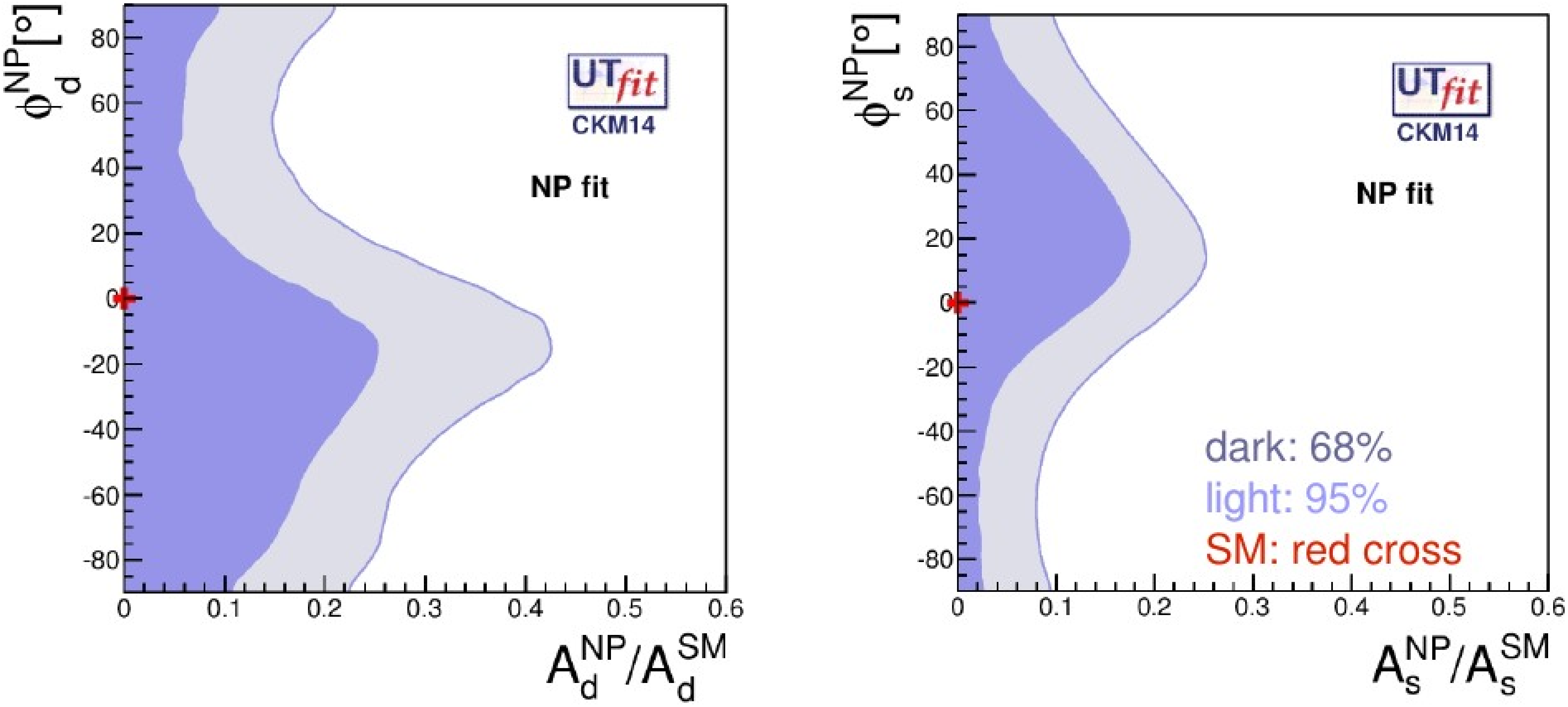
NP parameter results

$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\varphi_q^{NP} - \varphi_q^{SM})}\right) A_q^{SM} e^{2i\varphi_q^{SM}}$$



The ratio of NP/SM amplitudes is:

$< 25\%$ @68% prob. (42% @95%) in B_d mixing

$< 17\%$ @68% prob. (25% @95%) in B_s mixing

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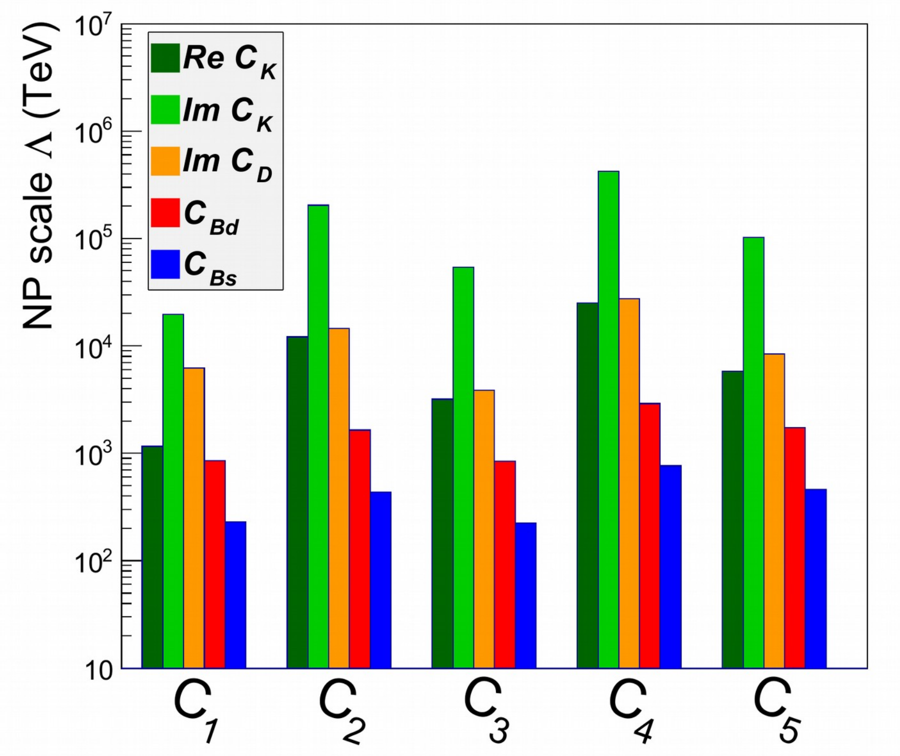
PRESENT BOUNDS ON NP

Bounds from $\Delta F=2$ processes



$\Delta F=2$ processes scale as $1/\Lambda^2$

- Best bound from ε_K, dominated by CKM error
- CPV in charm mixing follows, exp error dominant
- Best CP conserving from Δm_K, dominated by long distance
- B_d and B_s behind, error from both CKM and B-params

INTERPRETING THE BOUNDS

- generic case (no loop, no flavour suppression, all chiral structures): Λ>4.2 10^5 TeV
- Extra-Dim case (no loop suppression, CKM suppression, all chiral structures): Λ>96 TeV
- MFV case (no loop suppression, CKM suppression, only left-handed): Λ>9 TeV
- weakly-interacting MFV case (EW loop & CKM suppression, left-handed): Λ>300 GeV

IMPACT OF BELLE II

- Belle II and LHCb upgrade will drastically improve exp data on B, D and τ physics
  - Direct impact on NP bounds in the B, D and τ sectors
  - Indirect impact on NP bounds in the K sector via CKM determination

Flavour Golden Modes

	🟥	🟨	🟦	🟩
Experiment:	No Result	Moderately precise	Precise	Very precise
Theory:		Moderately clean	Clean, needs Lattice	Clean

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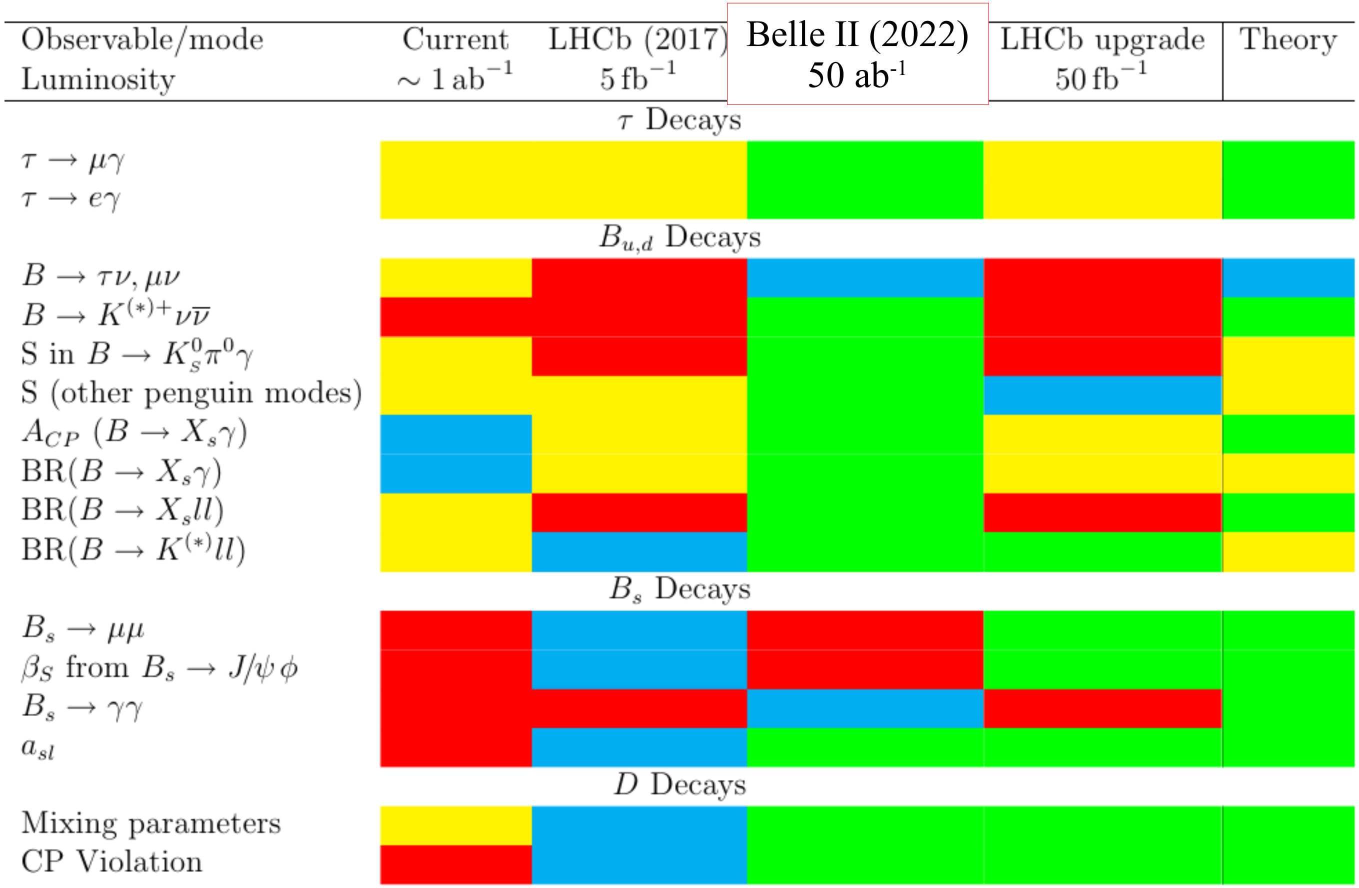


Observable/mode Luminosity	Current $\sim 1\,\mathrm{ab}^{-1}$	LHCb (2017) $5\,\mathrm{fb}^{-1}$	Belle II (2022) 50 ab^{-1}	LHCb upgrade $50\,\mathrm{fb}^{-1}$	Theory
τ Decays					
$\tau \to \mu\gamma$	🟨	🟨	🟩	🟨	🟩
$\tau \to e\gamma$	🟨	🟨	🟩	🟨	🟩
$B_{u,d}$ Decays					
$B \to \tau\nu, \mu\nu$	🟨	🟥	🟦	🟥	🟦
$B \to K^{(*)+}\nu\overline{\nu}$	🟥	🟥	🟩	🟥	🟩
S in $B \to K_S^0\pi^0\gamma$	🟨	🟥	🟩	🟥	🟨
S (other penguin modes)	🟨	🟨	🟩	🟦	🟨
A_{CP} $(B \to X_s\gamma)$	🟦	🟨	🟩	🟨	🟩
$\mathrm{BR}(B \to X_s\gamma)$	🟦	🟨	🟩	🟨	🟨
$\mathrm{BR}(B \to X_s ll)$	🟨	🟥	🟩	🟥	🟩
$\mathrm{BR}(B \to K^{(*)}ll)$	🟨	🟦	🟩	🟩	🟨
B_s Decays					
$B_s \to \mu\mu$	🟥	🟦	🟥	🟩	🟩
β_S from $B_s \to J/\psi\,\phi$	🟥	🟦	🟥	🟩	🟩
$B_s \to \gamma\gamma$	🟥	🟥	🟦	🟥	🟩
a_{sl}	🟥	🟦	🟩	🟩	🟩
D Decays					
Mixing parameters	🟨	🟦	🟩	🟩	🟩
CP Violation	🟥	🟦	🟩	🟩	🟩

based on arXiv:1109.5028

very precise with improved detector

statistically limited

right handed currents

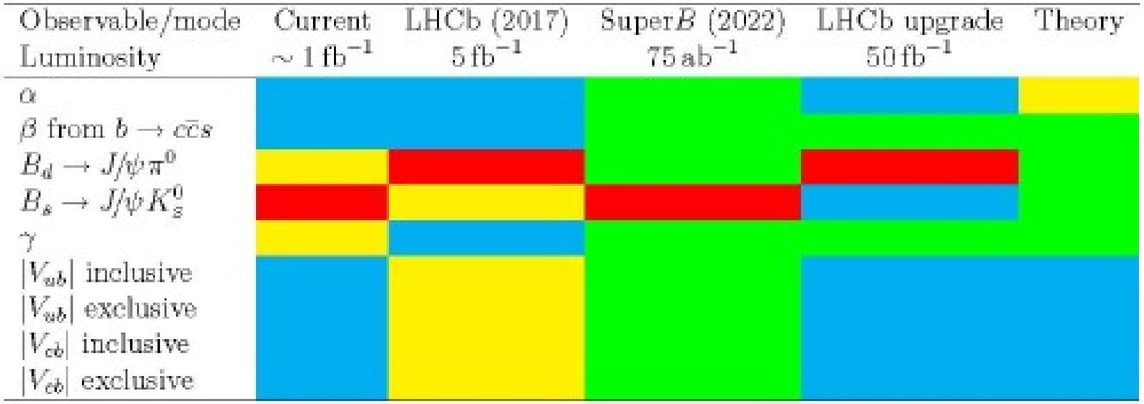
Belle II measures many more modes

systematic error is main challenge

control systematic error with data

Belle II measures e mode well, LHCb does μ

Comparison of present and future flavour experiments on "golden modes" (an incomplete list)



Observable/mode Luminosity	Current $\sim 1\,\mathrm{fb}^{-1}$	LHCb (2017) $5\,\mathrm{fb}^{-1}$	Super$B$ (2022) $75\,\mathrm{ab}^{-1}$	LHCb upgrade $50\,\mathrm{fb}^{-1}$	Theory
α	🟦	🟦	🟩	🟦	🟨
β from $b \to c\bar{c}s$	🟦	🟦	🟩	🟩	🟩
$B_d \to J/\psi\,\pi^0$	🟨	🟥	🟩	🟥	🟩
$B_s \to J/\psi\,K_S^0$	🟥	🟨	🟥	🟦	🟩
γ	🟨	🟦	🟩	🟩	🟩
$\lvert V_{ub}\rvert$ inclusive	🟦	🟨	🟩	🟦	🟦
$\lvert V_{ub}\rvert$ exclusive	🟦	🟨	🟩	🟦	🟦
$\lvert V_{cb}\rvert$ inclusive	🟦	🟨	🟩	🟦	🟦
$\lvert V_{cb}\rvert$ exclusive	🟦	🟨	🟩	🟦	🟦

LHCb can only use ρπ

β theory error Bd
β theory error Bs

need an e+e− environment to do a precision measurement using semi-leptonic B decays.

Courtesy of M. Ciuchini

Precision flavour physics & theory uncertainties

no theory improvements needed	$\beta(J/\psi\ K)$, $\gamma(DK)$, $\alpha(\pi\pi)$*, lepton FV and UV, CPV in $B\to X_{s+d}\gamma$, 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
improved OPE+HQE	$B\to X_{u,c}l\nu$, $(B\to X_s\gamma)$	target error: ~1-2% Possibly feasible with large samples. Detailed studies required
improved QCDF/SCET or flavour symmetries	S from TD A_{CP} in $b\to s$ transitions	target error: ~2-3% large and hard to improve uncertainties on small corrections. FS+data can bound the th. error

Courtesy of M. Ciuchini

Therefore, my tentative (INACCURATE!) estimates are:

Hadronic parameter	L.Lellouch ICHEP 2002 [hep-ph/0211359]	FLAG 2013 [1310.8555]	2025 [What Next]
$f_+^{K\pi}(0)$	- First Lattice result in 2004 [0.9%]	[0.4%]	[0.1%]
$\hat{B}_K$	[17%]	[1.3%]	[0.1-0.5%]
f_{Bs}	[13%]	[2%]	[0.5%]
f_{Bs}/f_B	[6%]	[1.8%]	[0.5%]
$\hat{B}_{Bs}$	[9%]	[5%]	[0.5-1%]
B_{Bs}/B_B	[3%]	[10%]	[0.5-1%]
$F_{D^*}(1)$	[3%]	[1.8%]	[0.5%]
$B \to \pi$	[20%]	[10%]	[$\gtrsim$1%]

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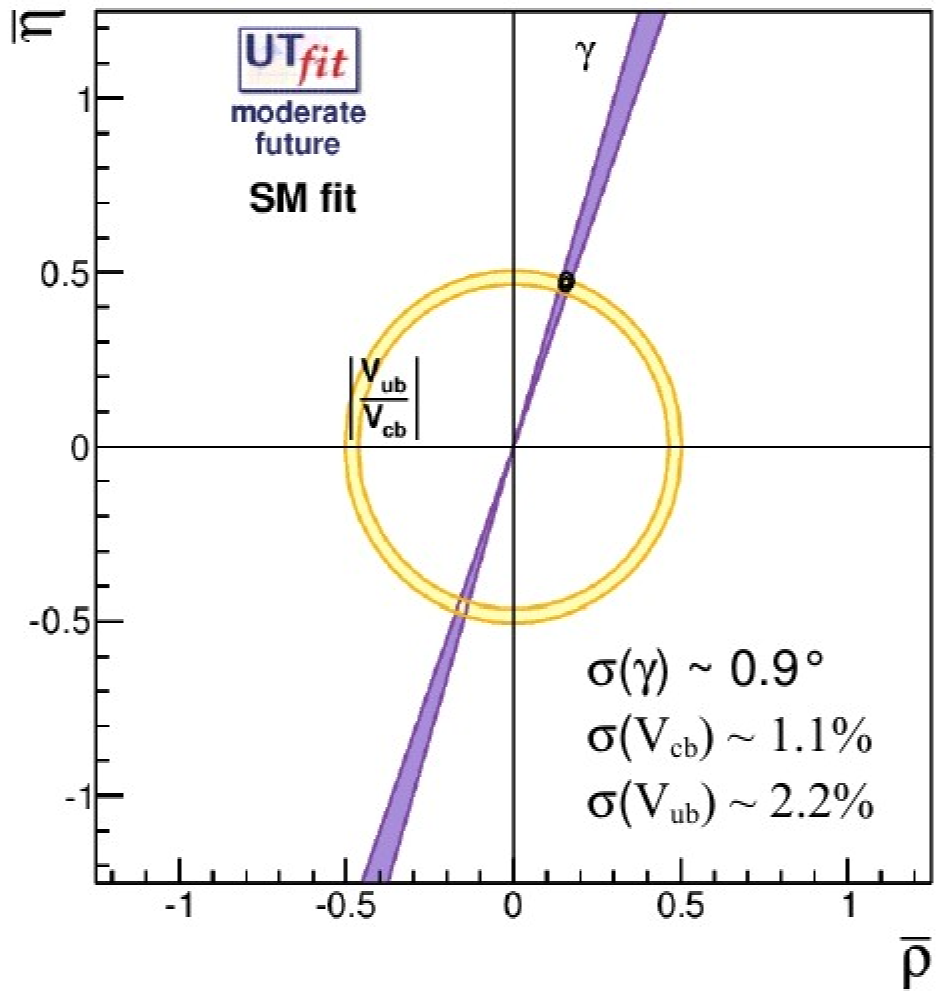
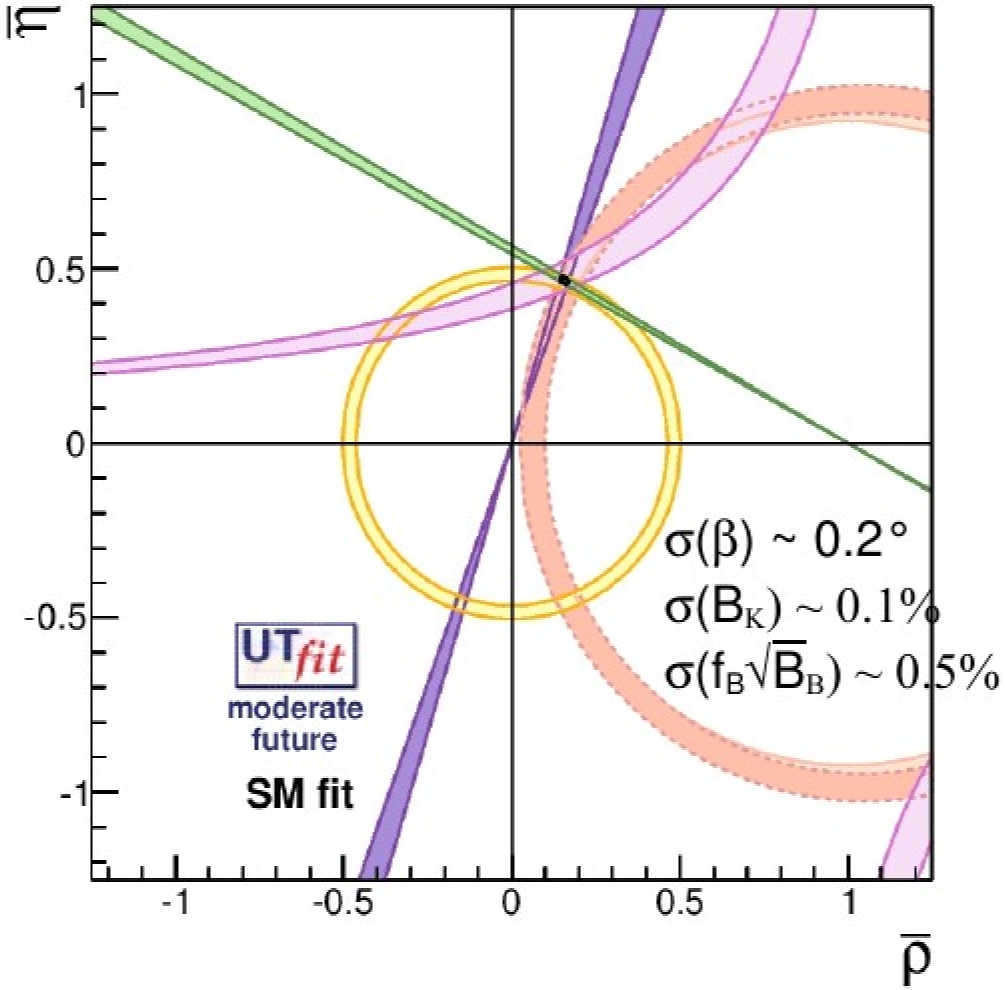
Elba 2014

More unpredictable but more surprising progresses can occur for the observables that today are very difficult (or infeasible): $K \to \pi \nu \bar{\nu}$, $K \to \pi l^+ l^-$, $K \to \pi \pi$, Δm_K



errors from tree-only fit on ρ and η:
$\sigma(\rho) = 0.008$ *[currently 0.051]*
$\sigma(\eta) = 0.010$ *[currently 0.050]*



errors from 5-constraint fit on ρ and η:
$\sigma(\rho) = 0.005$ *[currently 0.034]*
$\sigma(\eta) = 0.004$ *[currently 0.015]*

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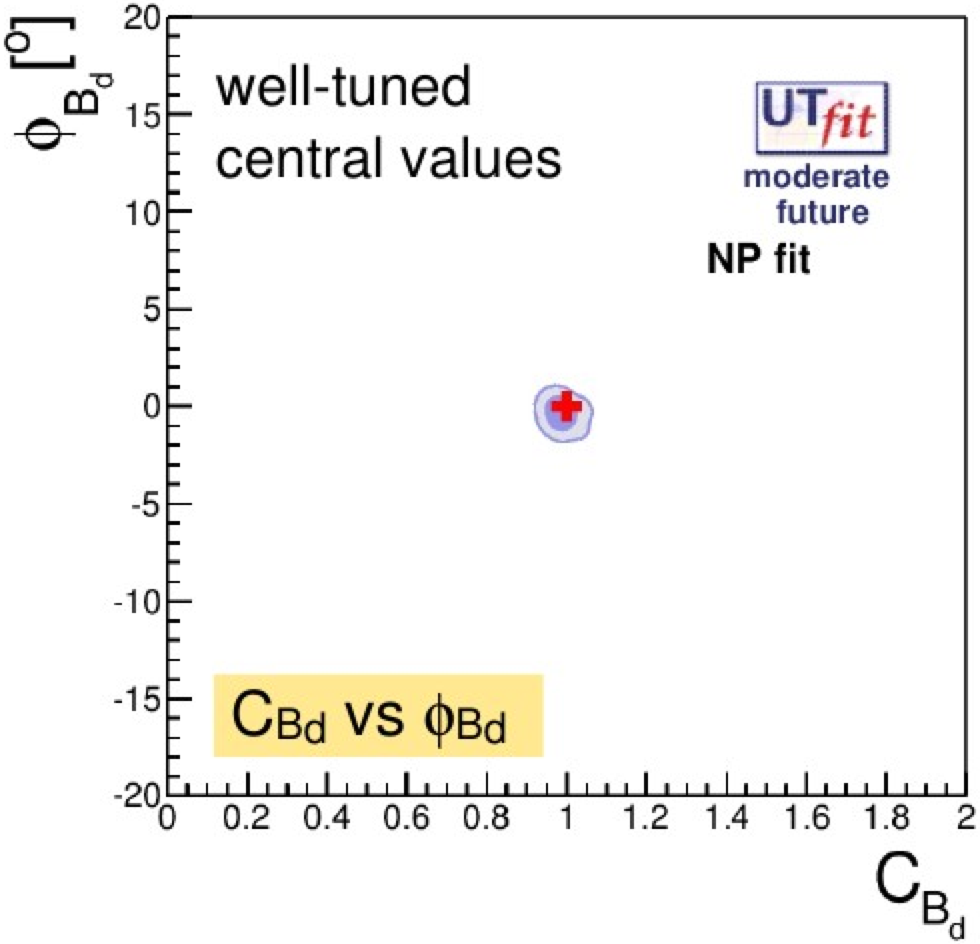

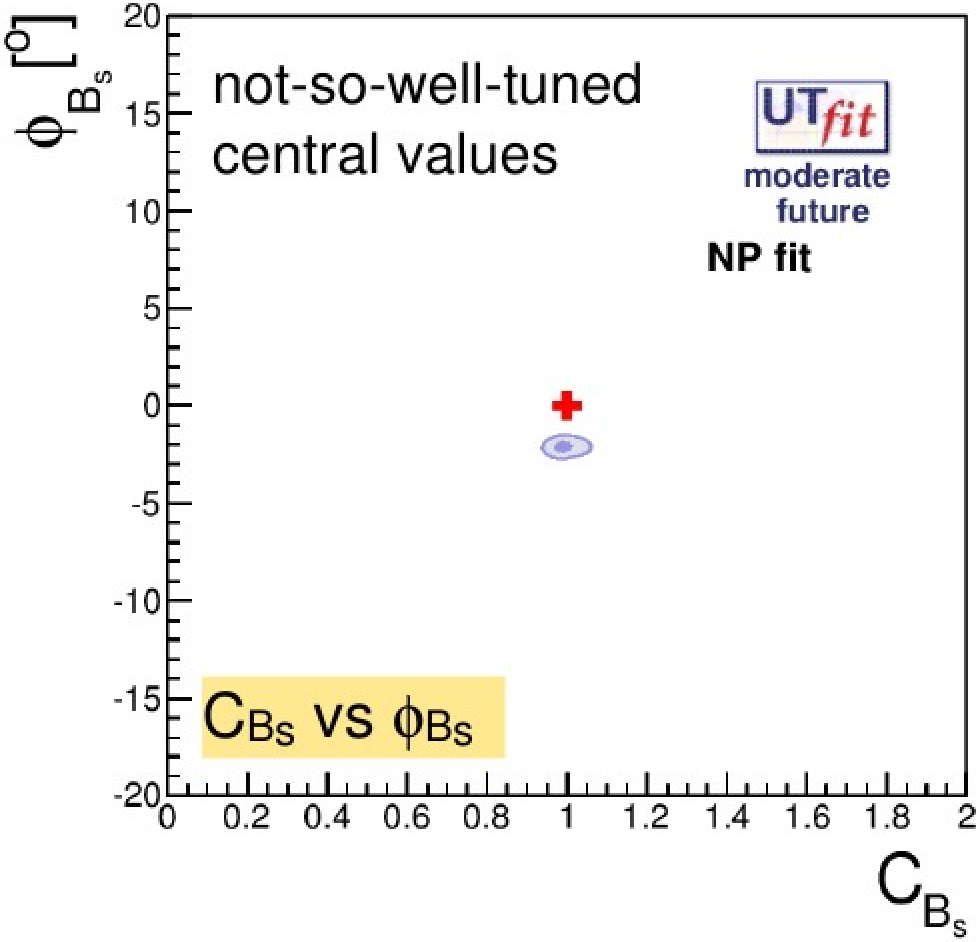

errors on general NP parameters:

$\sigma(C_{Bd}) = 0.03$ *[currently 0.16]*

$\sigma(\phi_{Bd}) = 0.7$ *[currently 3.2]*

$\sigma(C_{Bs}) = 0.03$ *[currently 0.08]*

$\sigma(\phi_{Bs}) = 0.6$ *[currently 2.0]*

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CHARM CPV EXTRAPOLATED

- SM contribution to ϕ_{M12} negligible, while one could envisage $\phi_{\Gamma 12}$ O(1°) due to LD penguins
- Present fit:
  - $\phi_{M12} = [-4,12]^\circ$ @ 95% prob., no reach on $\phi_{\Gamma 12}$
  - $\Lambda > 3.5\ 10^4$ TeV
- LHCb upgrade / Belle II:
  - $\delta\phi_{M12} = \pm 1^\circ$ and $\delta\phi_{\Gamma 12} = \pm 2^\circ$ @ 95% prob.
  - $\Lambda > 10^5$ TeV

CONCLUSIONS

- In a global strategy for NP searches, improving the accuracy on FCNC and CPV processes has a key role to ensure that:
  - we are able to determine the flavour structure of any NP directly seen, and hopefully understand its origin; roughly 3x in M_{NP} ⇔ 10x in exp & th ⇔ 100x in L
  - we increase the sensitivity of indirect searches (flavour has the lead in this field) and maybe detect an indirect NP signal

CONCLUSIONS II

- Belle II will play a key role in improving NP constraints in B, D and τ physics, with special emphasis on modes with neutrinos or neutral mesons in the final state
- Success of the NP search program requires both experimental and theoretical efforts: B2TIP excellent framework for progress on both sides