Impact of Future Experimental Scenarios on Flavour Physics

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- Introduction
- What can we learn from the "ballistic" program
- First ideas on the impact of extreme flavour
- Conclusions and Outlook

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INTRODUCTION

- Most of the discoveries of the past 45 years anticipated by arguments or indirect evidence:
  - Ioffe&Shabalin, GIM: NP (charm) @ GeV
  - Unitarization of Fermi theory: NP at 10^2 GeV
  - KM: 3rd generation
  - Flavour, EW fit: m_t~170 GeV
  - EW fit: m_H=100±30 GeV

INTRODUCTION II

- Now we are left with arguments only:
  - Hierarchy problem: NP close to EW scale
  - WIMP miracle: NP close to EW scale
  - gauge coupling unification: NP (SUSY) close to EW scale
- In parallel with increasing the energy probed by direct search, seek for indirect evidence!

How much "natural" is Nature?

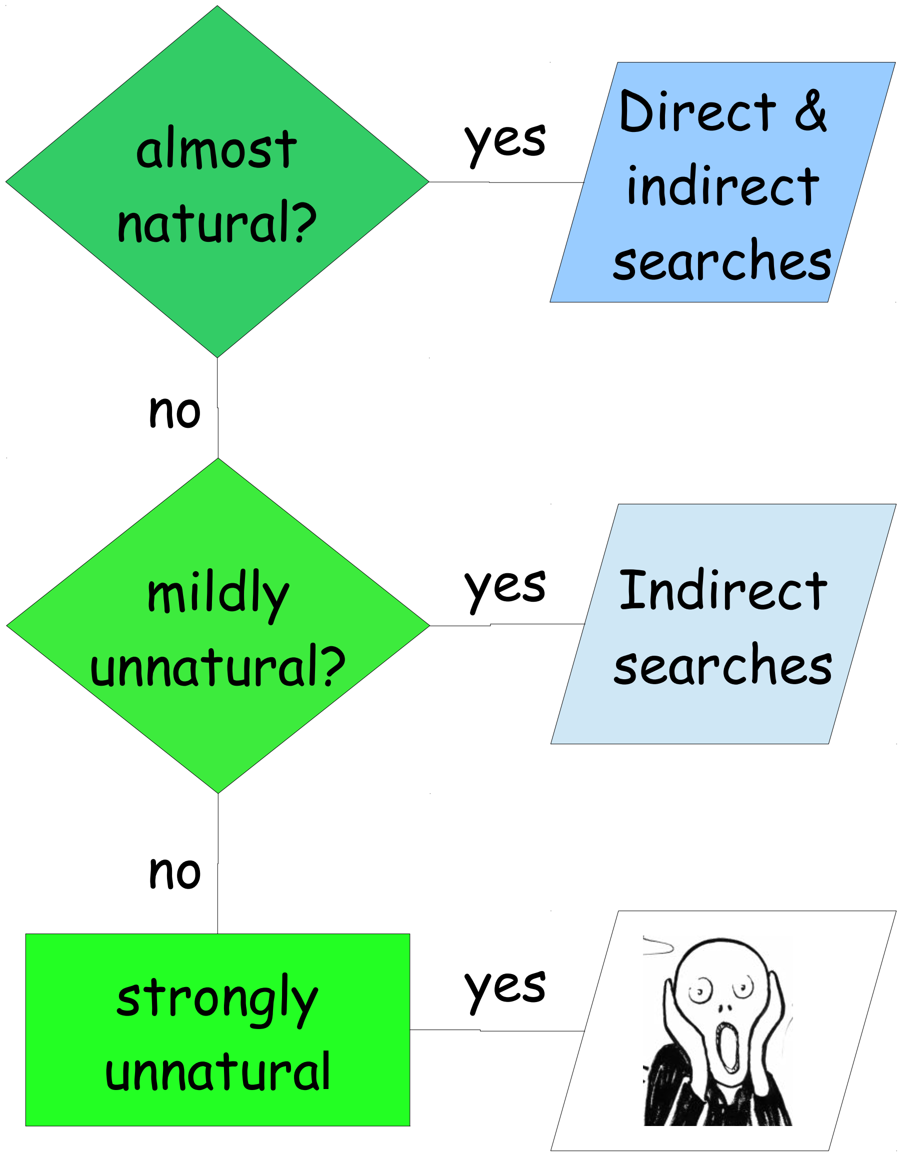


illustration by G. Villadoro

Courtesy of Marco Ciuchini

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

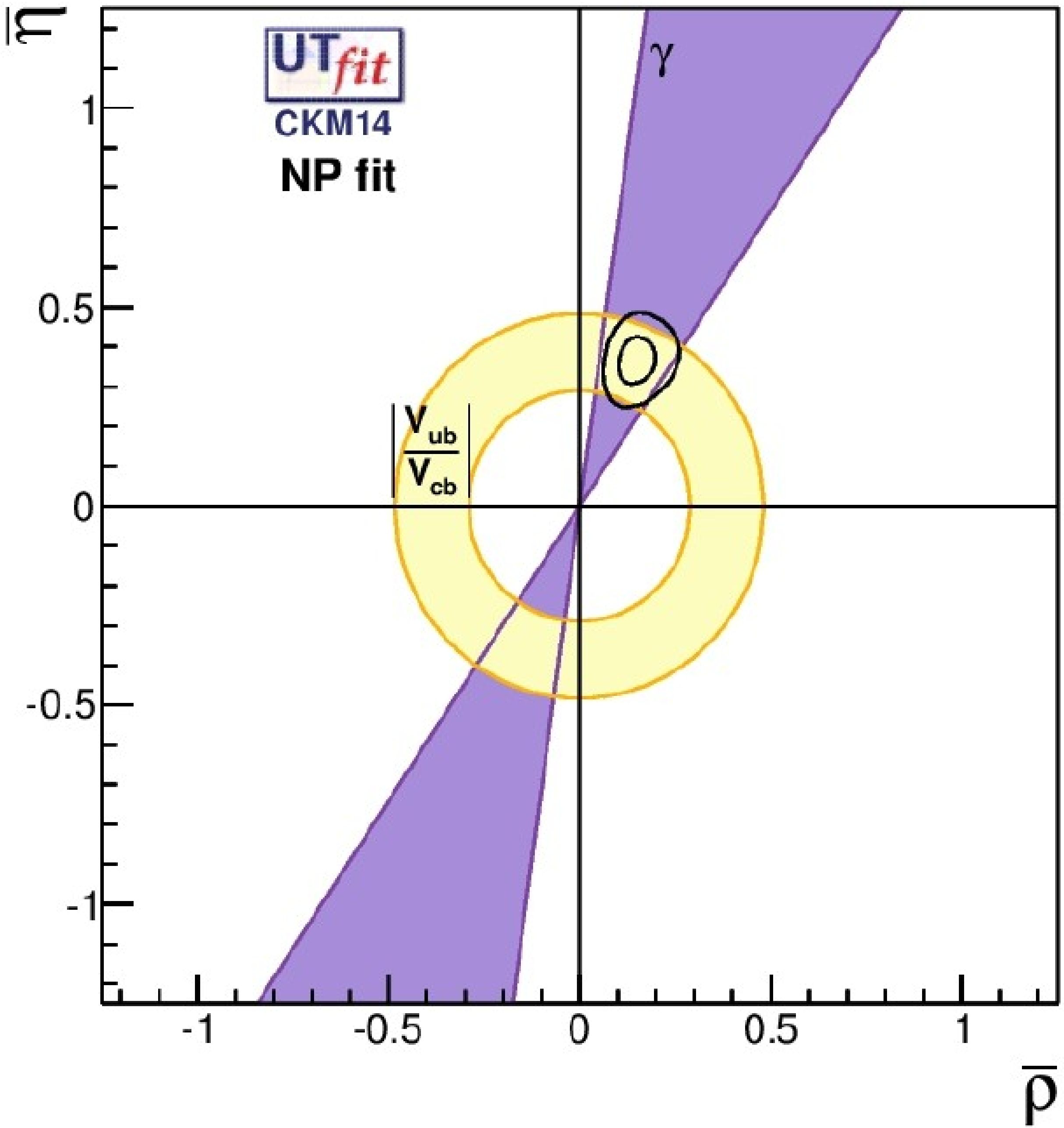
- A generic FCNC amplitude has the form

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

  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)

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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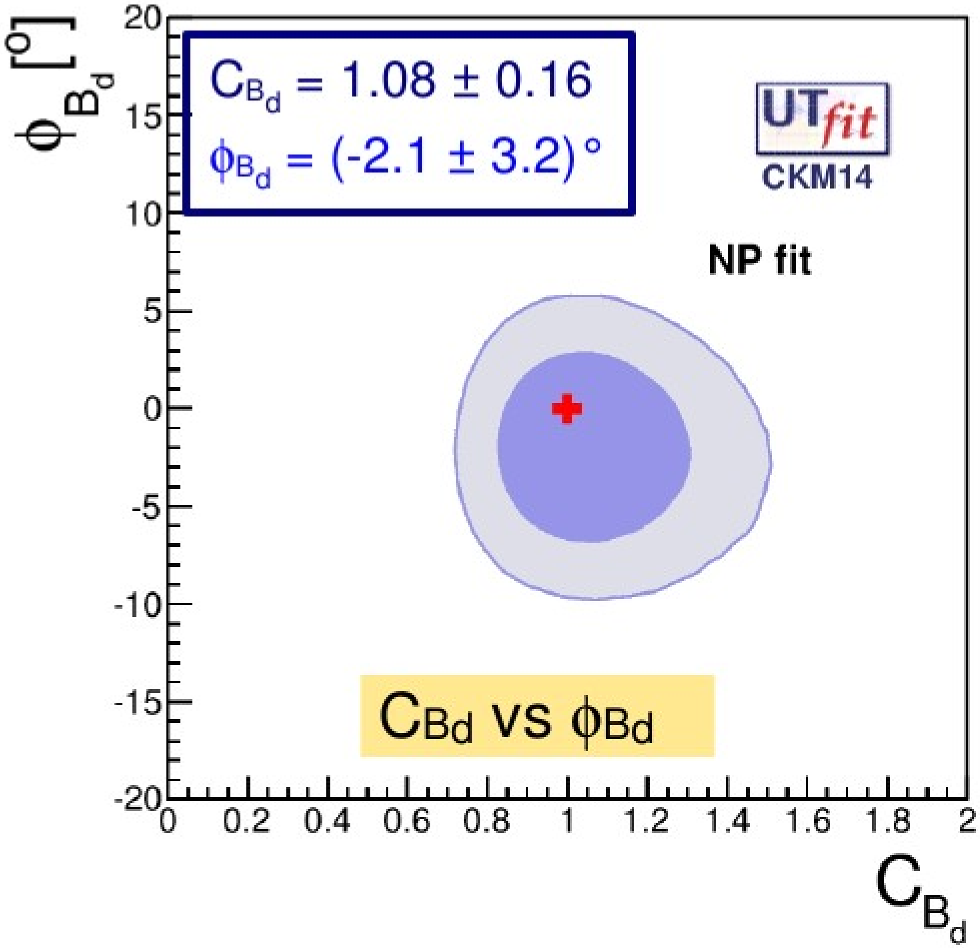
NP parameter results

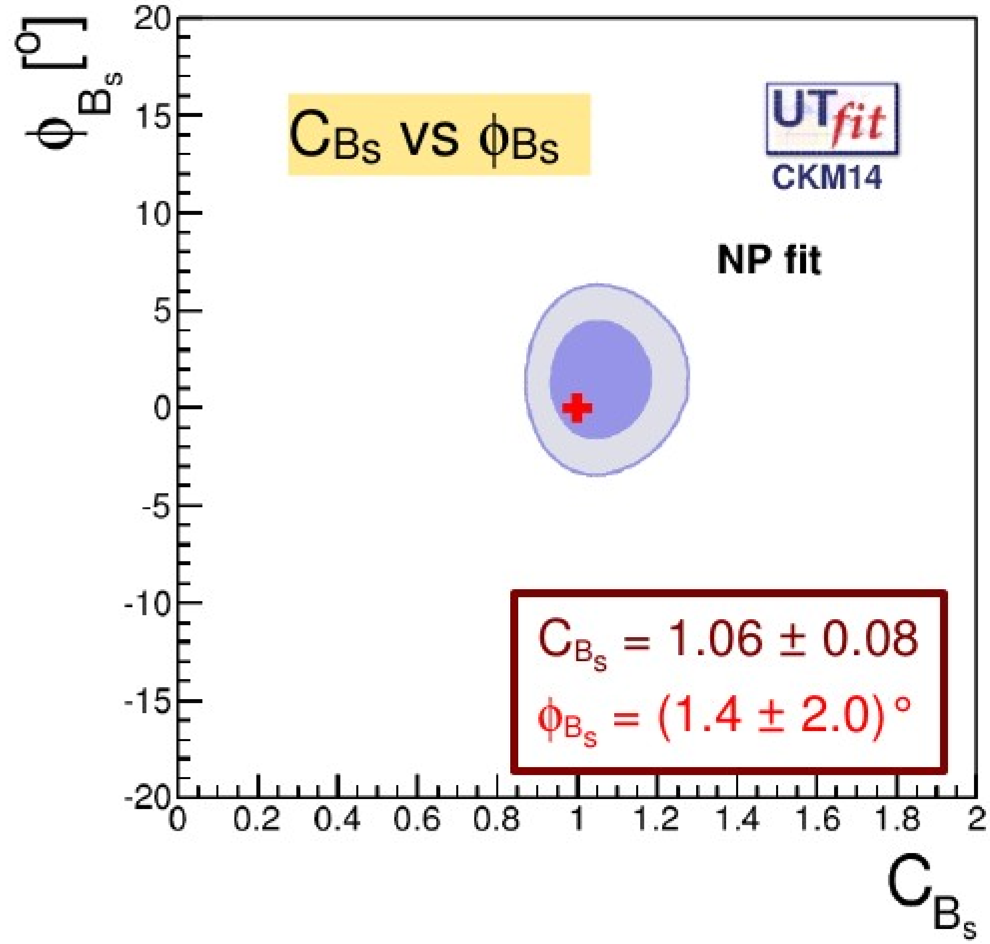
K system

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

dark: 68%
light: 95%
SM: red cross

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





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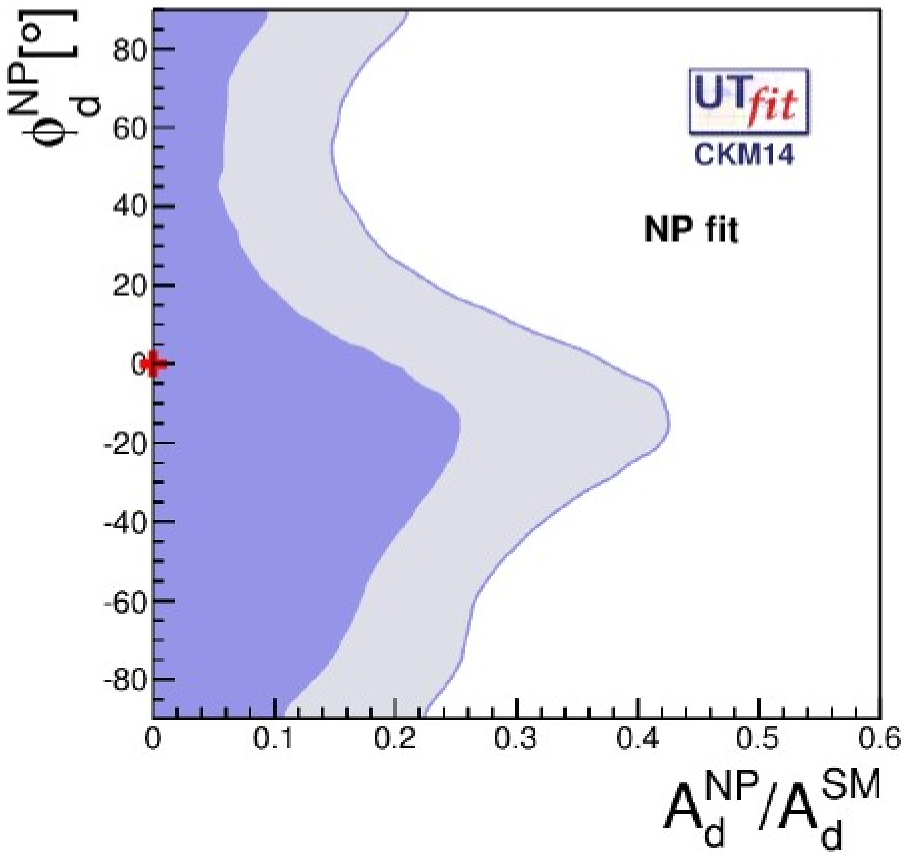
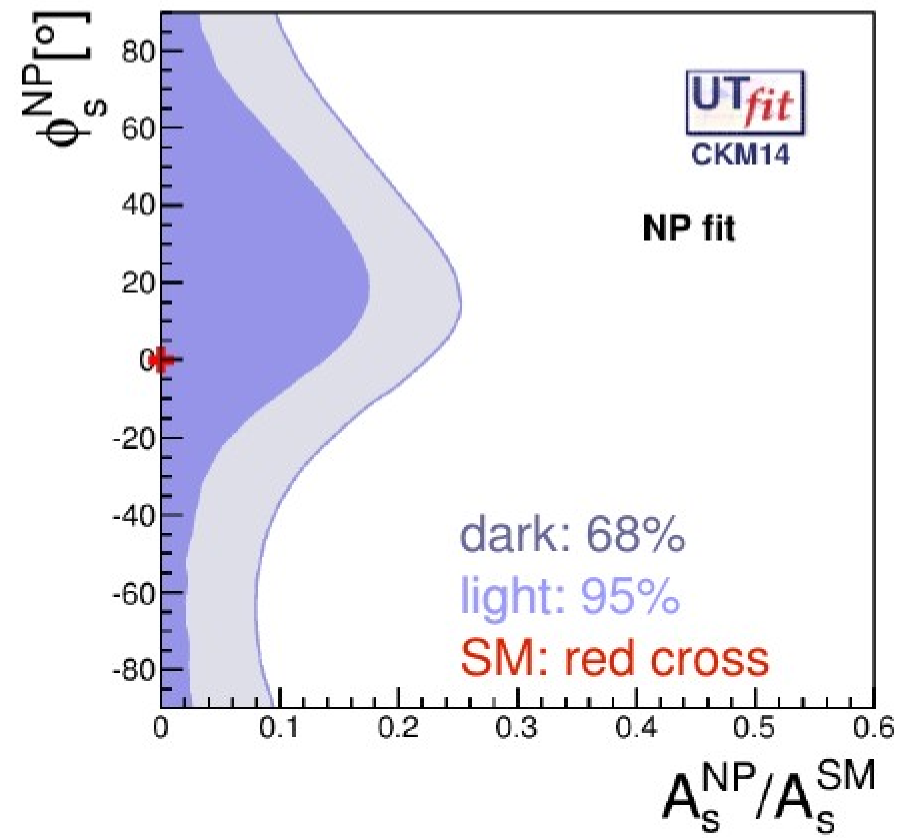
NP parameter results

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





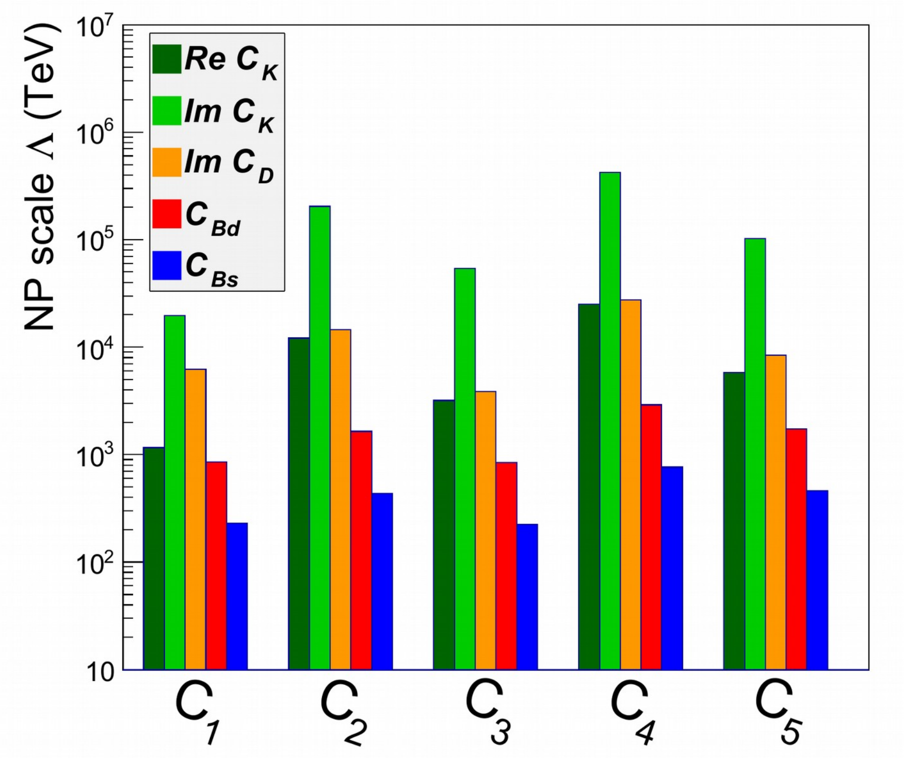
The ratio of NP/SM amplitudes is:

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

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

PRESENT BOUNDS ON NP

Bounds from $\Delta F=2$ processes



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

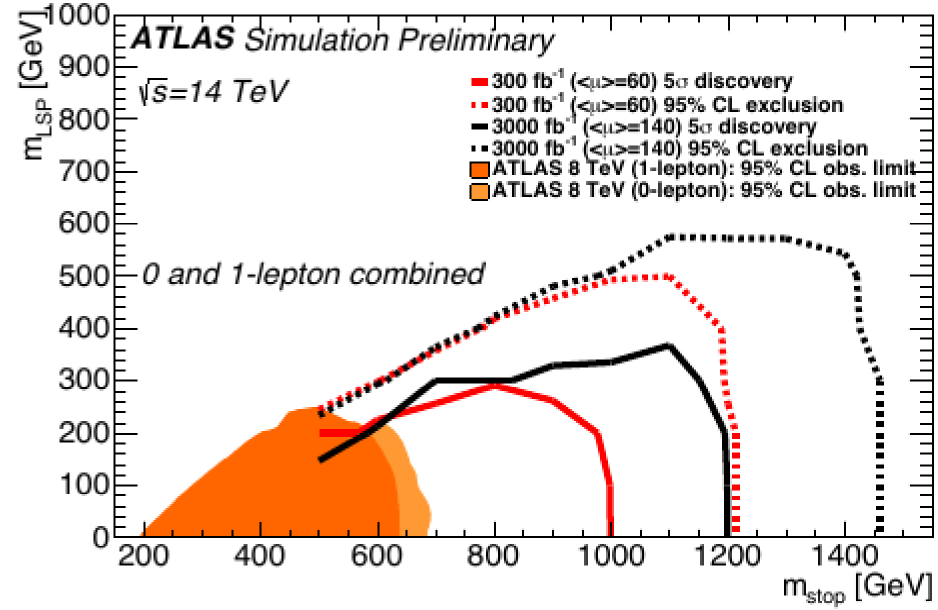
- Best bound from ε_K, dominated by CKM error
- CPV in charm mixing follows, exp error dominant
- Best CP conserving from Δm_K, dominated by long distance
- B_d and B_s behind, error from both CKM and B-params

INTERPRETING THE BOUNDS

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

COMPLEMENTARITY WITH DIRECT SEARCHES

- The weakly-interacting MFV case provides a lower bound on NP contribution to flavour observables (worst-case scenario)
- This often corresponds to worst-case scenarios for direct searches as well
- Keep the two reaches in sync so that we can see flavour effects of any directly visible NP



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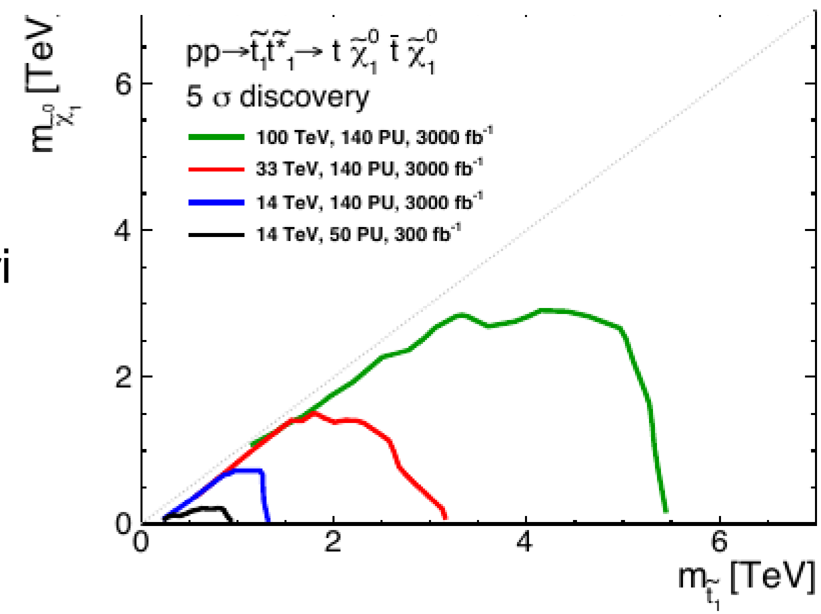

BALLISTIC FUTURE

- Belle II and LHCb upgrade will improve present precision/sensitivity in B, D and τ physics by a factor of 3-10 De Nardo, Lanfranchi
- NA62 will provide a 10% measurement of BR($K^+ \to \pi^+ \nu\nu$), KOTO should observe $K_L \to \pi^0 \nu\nu$ Ceccucci
- MEG-II and Mu2e will improve the sensitivity on $\mu \to e\gamma$ to 6 10^{-14} and on $\mu \to e$ conversion to 6-7 10^{-17} Signorelli

Flavour Golden Modes

Experiment: No Result | Moderately precise | Precise | Very precise
Theory: | Moderately clean | Clean, needs Lattice | Clean

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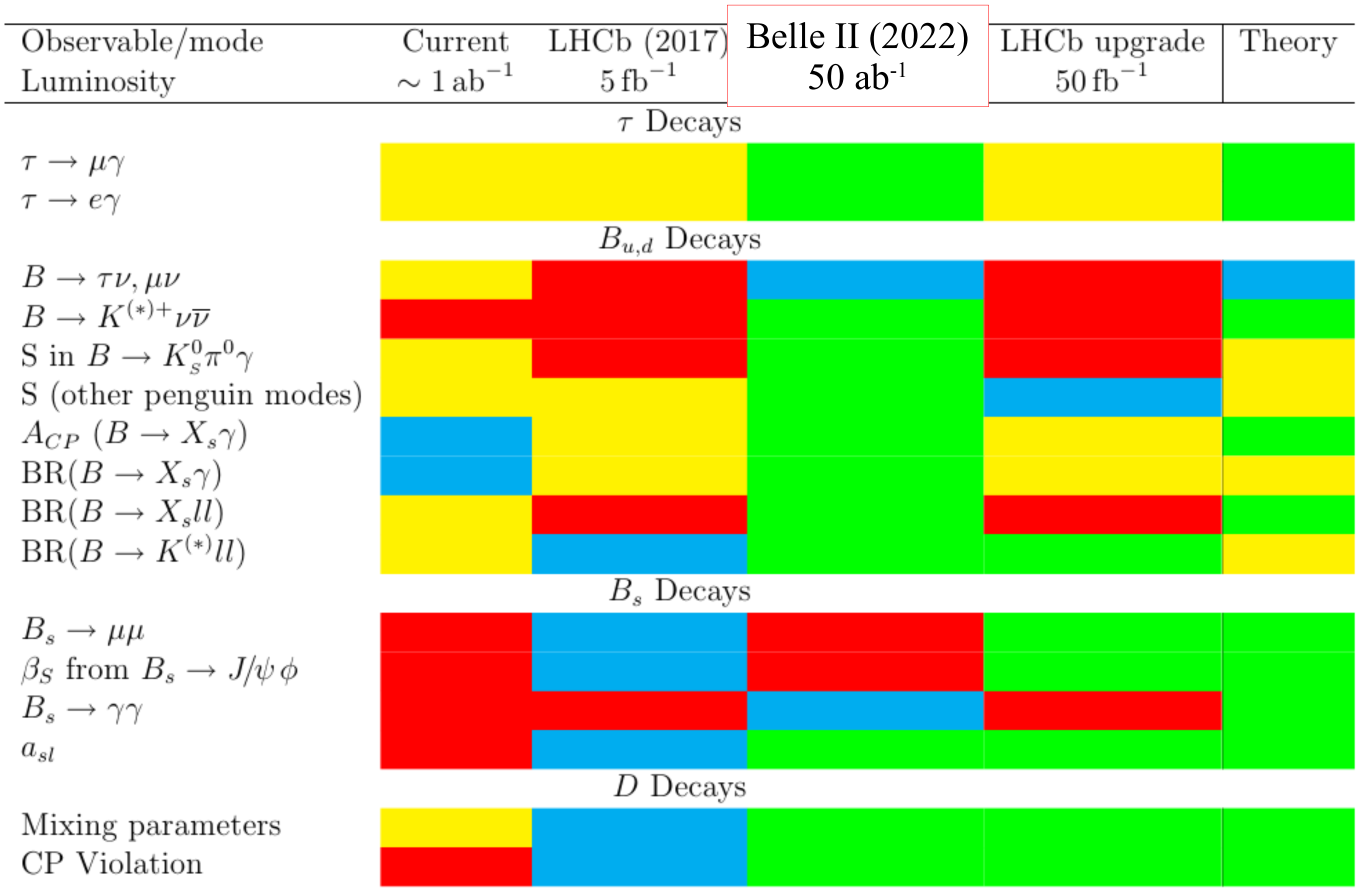
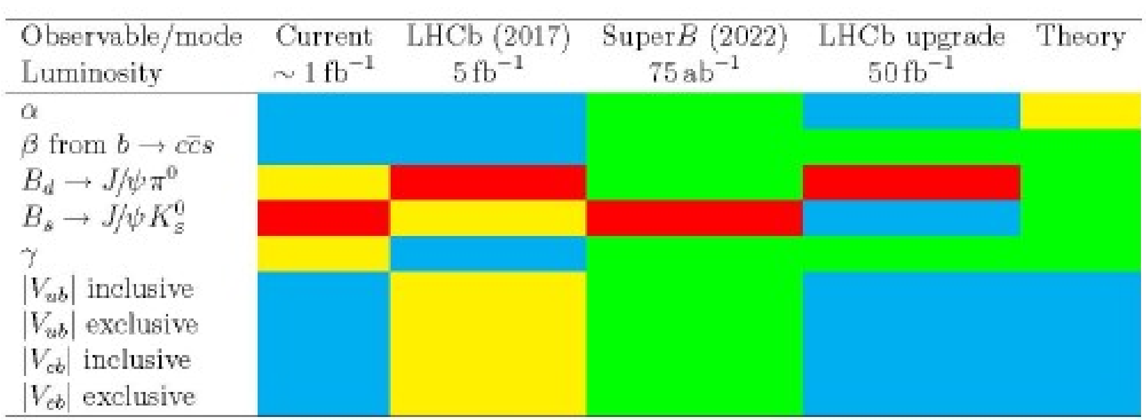
based on arXiv:1109.5028



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)



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

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%]	[≳1%]

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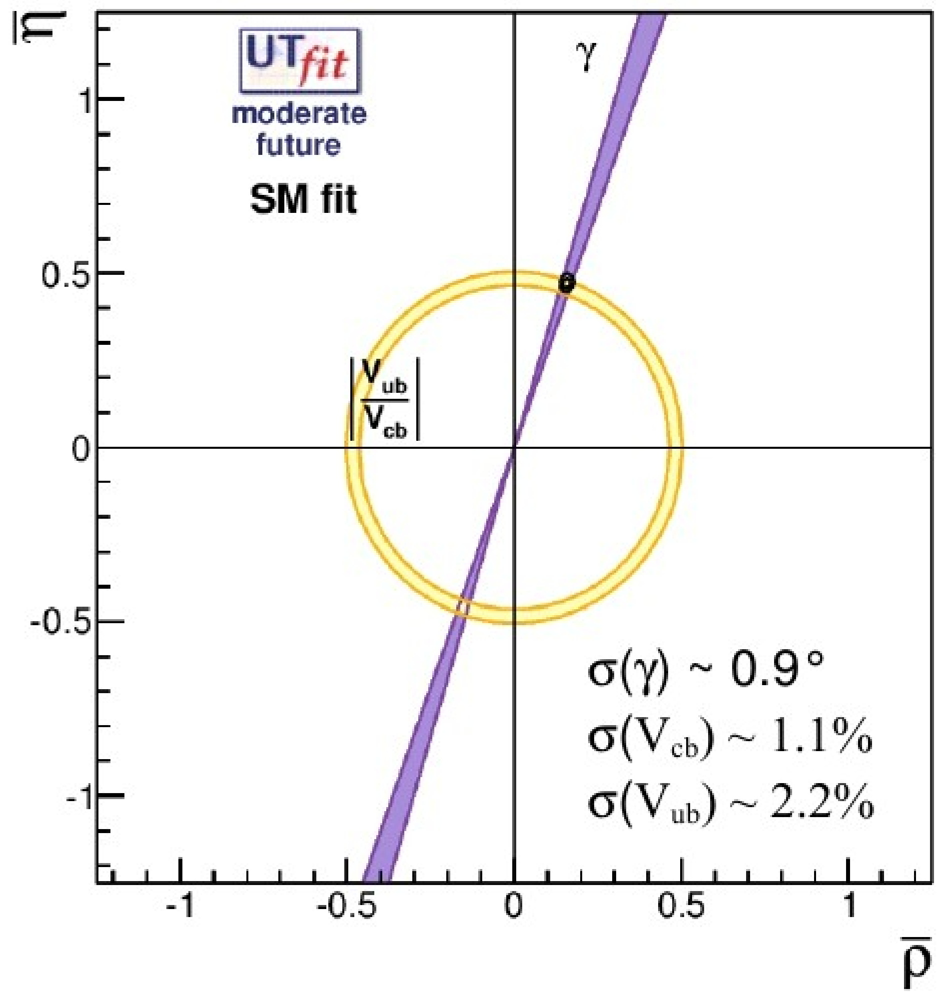
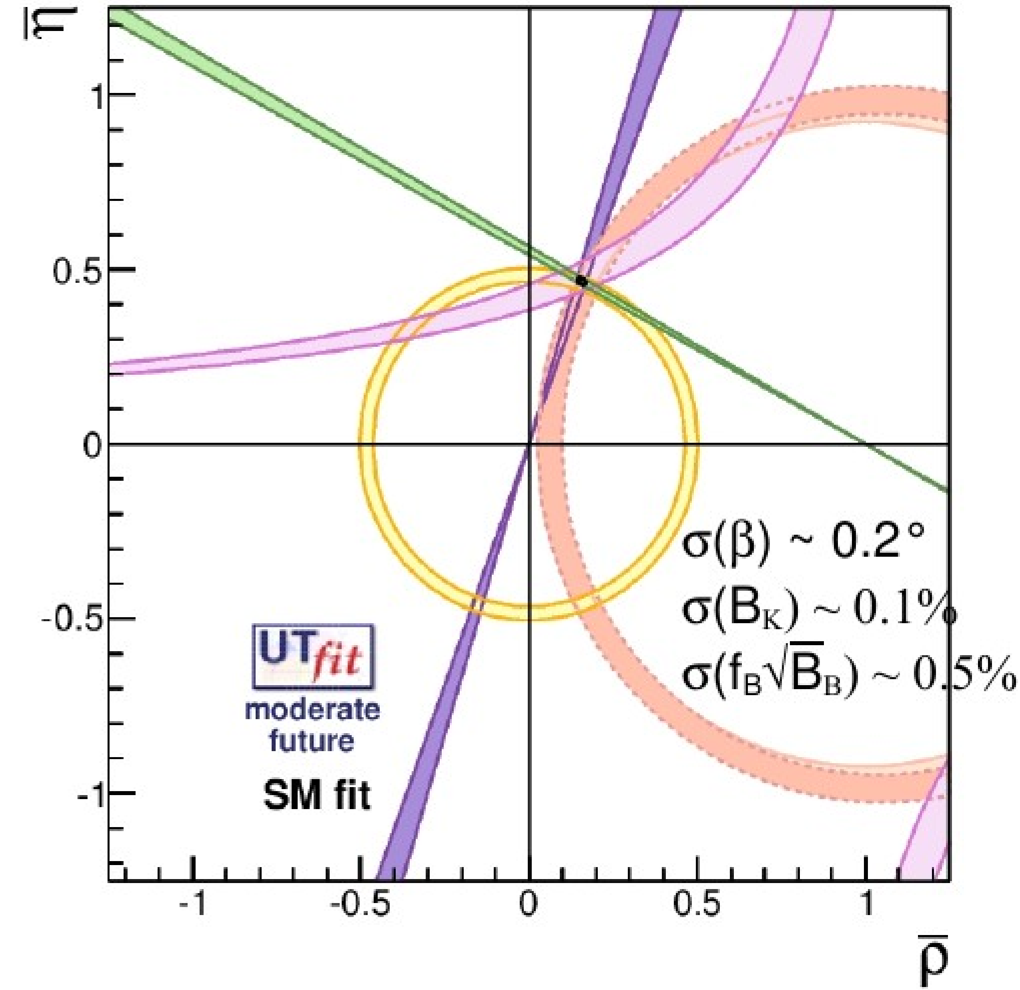
More unpredictable but more surprising progresses can occur for the observables that today are very difficult (or infeasible): $K \to \pi \nu \bar{\nu}$, $K \to \pi l^+ l^-$, $K \to \pi \pi$, Δm_K





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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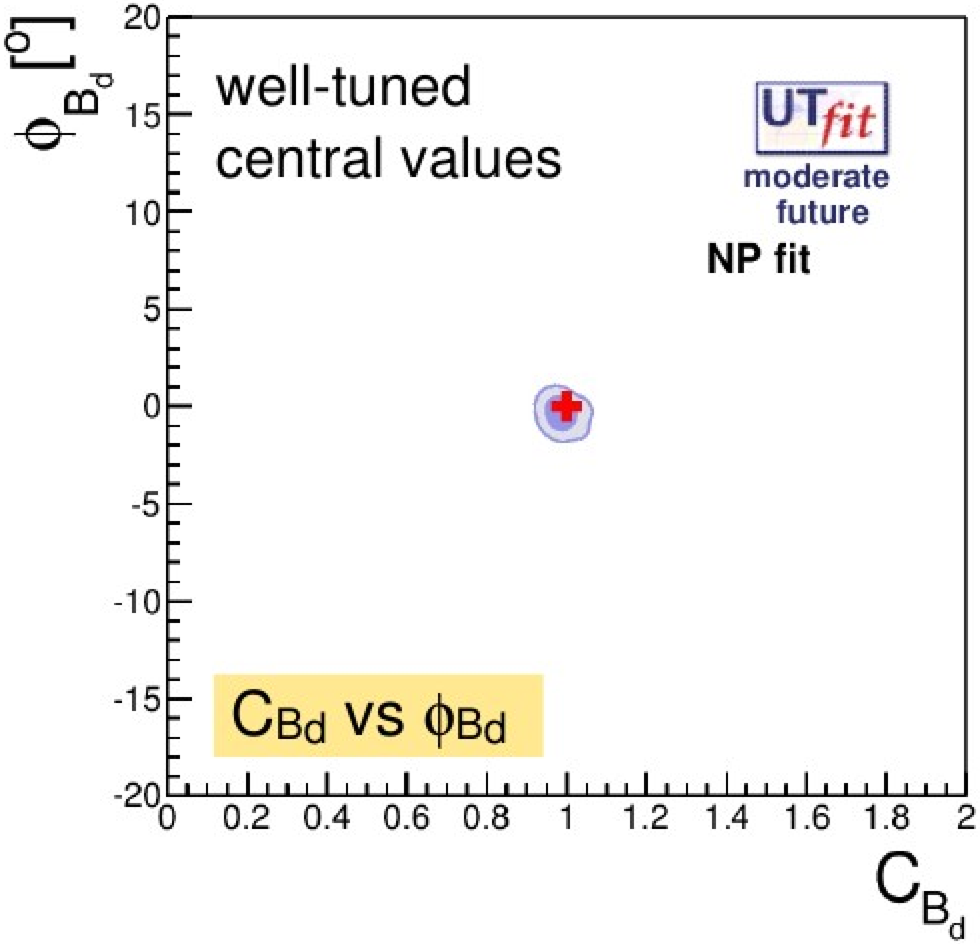

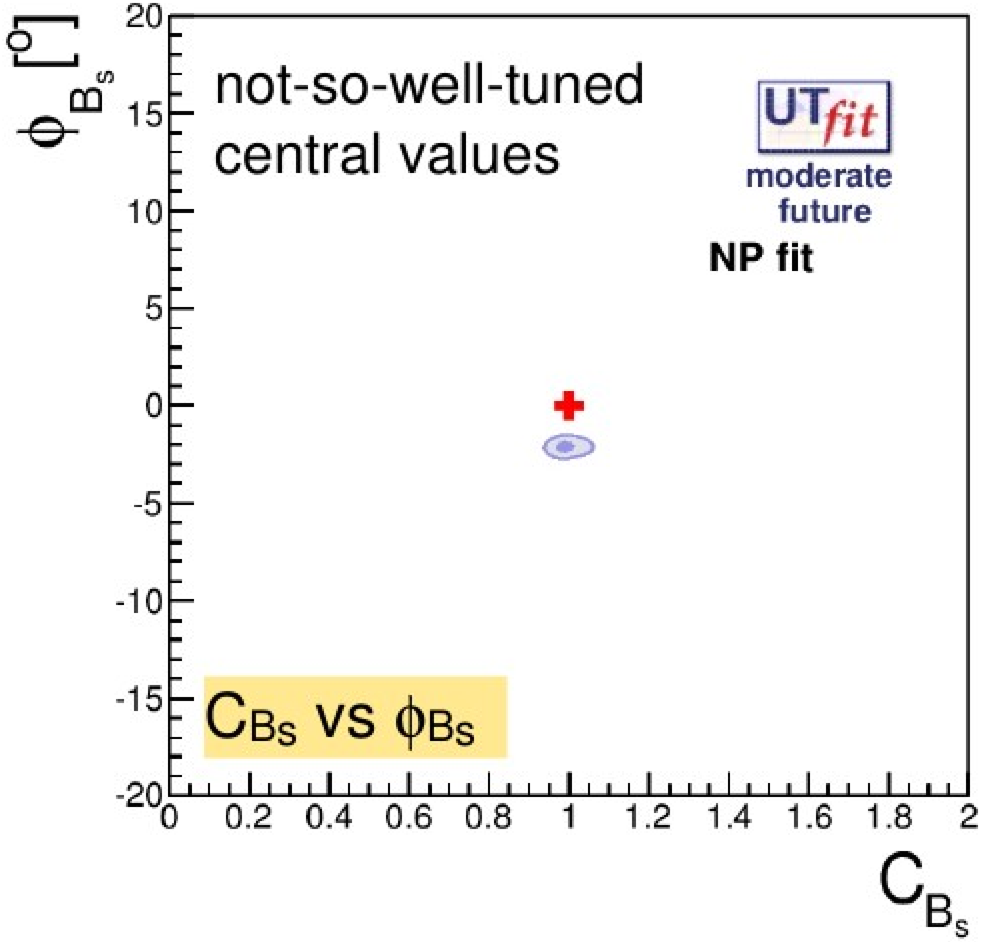

errors on general NP parameters:

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

Zupan

- Present fit:
  - $\phi_{M12} = [-4,12]°$ @ 95% prob., no reach on $\phi_{\Gamma 12}$
  - $\Lambda > 3.5\ 10^4$ TeV
- LHCb upgrade / Belle II:
  - $\delta\phi_{M12} = \pm 1°$ and $\delta\phi_{\Gamma 12} = \pm 2°$ @ 95% prob.
  - $\Lambda > 10^5$ TeV

EXTREME FLAVOUR

- A very interesting possibility has been put forward: collect 100x the LHCb upgrade luminosity
- A detailed study of the impact of such possibility should be carried out to assess its full physics potential.
- I'll just briefly flash a few items to make you interested

ASSESSING THE IMPACT OF EXTREME FLAVOUR

- Determine expected exp and th uncertainties on the widest spectrum of observables
- Extrapolate accuracy in CKM determination in the presence of NP
- Assess the NP reach in all sectors and various scenarios

EXTREME UTA INPUT

Parameter	Error	comments
$\alpha_s(M_Z)$	$2 \cdot 10^{-4}$	
m_t	250 MeV	theory limited
m_b	10 MeV	$\times 3$ better
V_{us}	$1 \cdot 10^{-4}$	$\times 10$ better
V_{cb}	1%	Belle II
V_{ub}	1%	extreme baryons + B_s
ϵ_K	0.4%	includes a 5% error on long distance + dim. 8
B_K^i		$\times 10$ better
F_{B_s}	1 MeV	
F_{B_s}/F_{B_d}	0.5%	
B_{B_s}	6%	
B_{B_s}/B_{B_d}	0.5%	
ΔM_d	0.06%	
ΔM_s	0.01%	
$\sin 2\beta$	0.06%	th. error from $B_d \to J/\psi \pi^0$
γ	0.09°	
ϕ_{B_s}	0.0004°	th. error to be investigated

EXTREME UTA (PRELIMINARY)

Parameter	SM fit error		NP fit error	
	now	extreme	now	extreme
$\bar{\rho}$	16%	0.4%	26%	1.5%
$\bar{\eta}$	4%	0.1%	13%	1.4%
$\mathrm{Im}\lambda_t$	2.8%	0.8%	13%	1.4%
$\mathrm{Re}\lambda_t$	2.9%	0.8%	7.4%	2.1%
$\|V_{td}/V_{ts}\|$	2.3%	0.09%	5%	0.15%
C_{ϵ_K}	–	–	0.16	0.034
C_{B_d}	–	–	0.16	0.029
ϕ_{B_d}	–	–	3.2°	0.41°
C_{B_s}	–	–	0.08	0.028
ϕ_{B_s}	–	–	2.0°	0.023°

EXTREME BEYOND UTA

- D mixing, scaling LHCb upgrade estimates for $K_S\pi\pi$ and y_{CP}, A_Γ:
  - $\delta\phi_{M12} = \pm\, 0.1°$ and $\delta\phi_{\Gamma 12} = \pm\, 0.2°$ @ 95% prob.
  - $\Lambda > 3\ 10^5$ TeV, close to the bound from ε_K
- $BR(B_d \to \mu^+\mu^-)/BR(B_s \to \mu^+\mu^-)$ @ ~4%, with much smaller theoretical uncertainty: very powerful probe of MFV
- …

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

- Impact of "ballistic" flavour program studied in detail, expected improvements will keep indirect searches in sync with direct ones
- First steps to assess the impact of an extreme flavour experiment in progress:
  - extrapolation of lattice errors (done)
  - prelim. estimate of exp. reach (in progress)
  - projection of UTA (in progress)
  - projection of NP sensitivities in all sectors

BACKUP SLIDES

I follow Vittorio Lubicz's Appendix in the SuperB CDR (2007 -> 2015)

(and Stephen Sharp's talk at *Lattice QCD: Present and Future* (Orsay, 2004))

Values of the simulation parameters (N_{conf}, a, m_l, L) to achieve a certain accuracy (1%, 0.5%, 0.1%)

↓

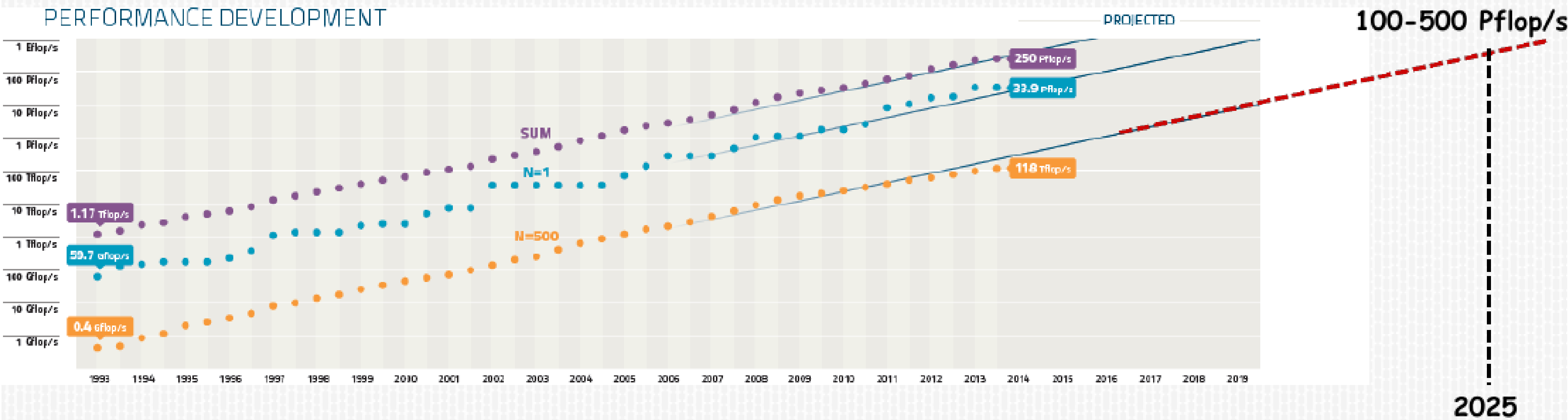
Computational cost of the corresponding simulation

↓

Comparison to the expected future computational power

History (and prediction) of the computational power
from Moore's Law (1965):
The number of transistors on integrated circuits doubles approximately every two years
(thanks to miniaturization)

→ Performance improvement of $O(10^3)$ every 10 years



Lattice collaborations typically have at hand per year
a computational power similar to the 500° most powerful computer
(0.1-0.5 Pflops-years in 2014 → 100-500 Pflops-years in 2025)

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Computational cost of a Lattice Simulation as a function of the parameter values (e.g. Wilson-like fermions, $N_f=2$)

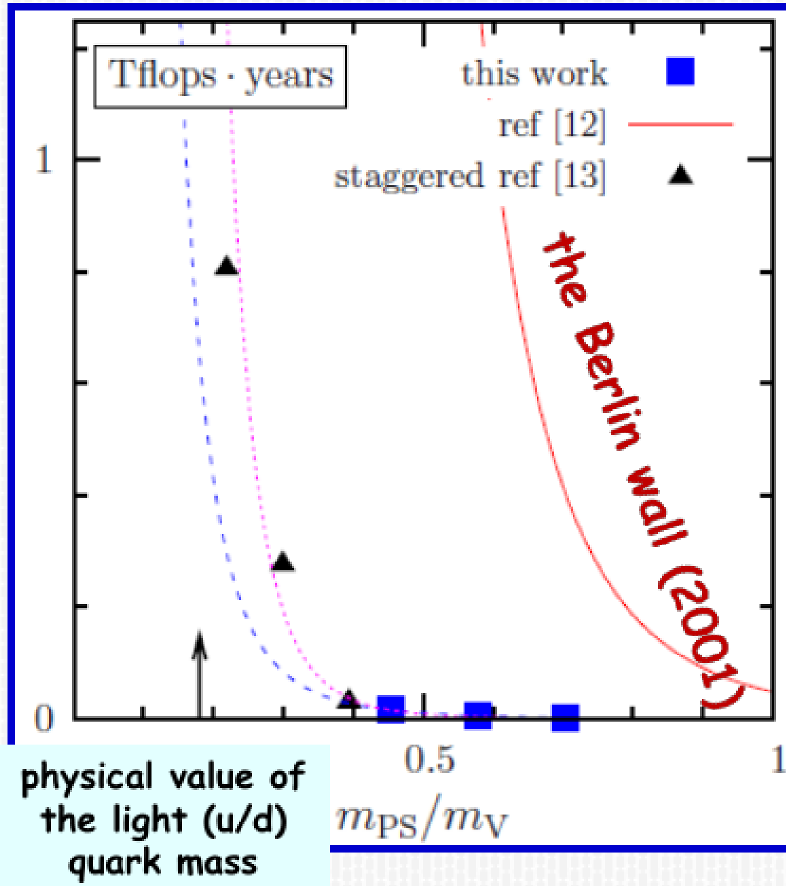
Del Debbio, Giusti, Luscher, Petronzio, Tantalo, hep-lat/0610059

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

0.03 →0.1 [$N_f=2+1$]
→0.05 [O(a)-improved]
→0.3-1.0 [Ginsparg-Wilson]

x3 of overhead (less expensive simulations to perform continuum extrapolation...)

(We will see if a more detailed study of recent simulations provides a more optimistic estimate)



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The wall fall ($1/m_l^3 \rightarrow 1/m_l$) is an important example of how unpredictable (theoretical and algorithmic) developments can have a significant impact

EXP INPUT FOR CHARM MIXING

- LHCb upgrade:
  - δx=1.5 10^{-4}, δy=10^{-4}, $\delta|q/p|$=10^{-2}, $\delta\phi$=3° (from $K_s\pi\pi$); δy_{CP}=δA_Γ=4 10^{-5} (from K^+K^-)
- extreme (LHCb upgrade lumi x 100):
  - δx=1.5 10^{-5}, δy=10^{-5}, $\delta|q/p|$=10^{-3}, $\delta\phi$=.3° (from $K_s\pi\pi$); δy_{CP}=δA_Γ=4 10^{-6} (from K^+K^-)