

The Flavour of New Physics

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- Introduction
- Indirect searches for NP
- Determining the NP Lagrangian
- Conclusions

INTRODUCTION

- In the past 45 years, we (almost) always found what we expected, where we expected
- Discoveries anticipated by arguments or indirect evidence:
 - GIM: charm @ GeV
 - Unitarization of Fermi theory: NP at 10^2 GeV
 - KM: 3rd generation

INTRODUCTION II

- Flavour, EW fit: $m_{\dagger} \sim 170 \text{ GeV}$
- EW fit: $m_H = 100 \pm 30 \text{ GeV}$
- 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

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

INDIRECT SEARCHES FOR NP

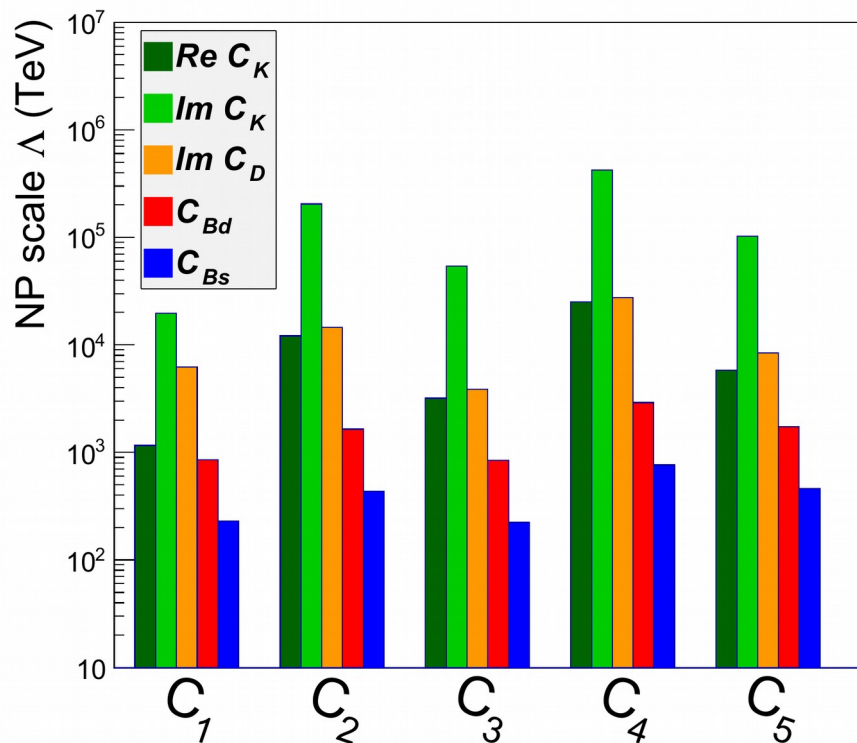
- Search for virtual contributions of new particles: sensitive to $g_{\text{NP}}^2/\Lambda^2$
- Use observables where SM contributions are either absent (BNV, LNV, LFV) or loop-suppressed (EWPO, FCNC).
- Advantage of flavour over EWPO: hierarchical structure of CKM provides very strong suppression of FCNC & CPV

INDIRECT SEARCHES FOR NP II

- For models with new sources of flavour and CP violation, flavour sensitivity orders of magnitude larger than EWPO
- For models with Minimal Flavour and CP Violation, flavour sensitivity comparable to EWPO
- Flavour physics plays a key role in indirect searches for NP

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

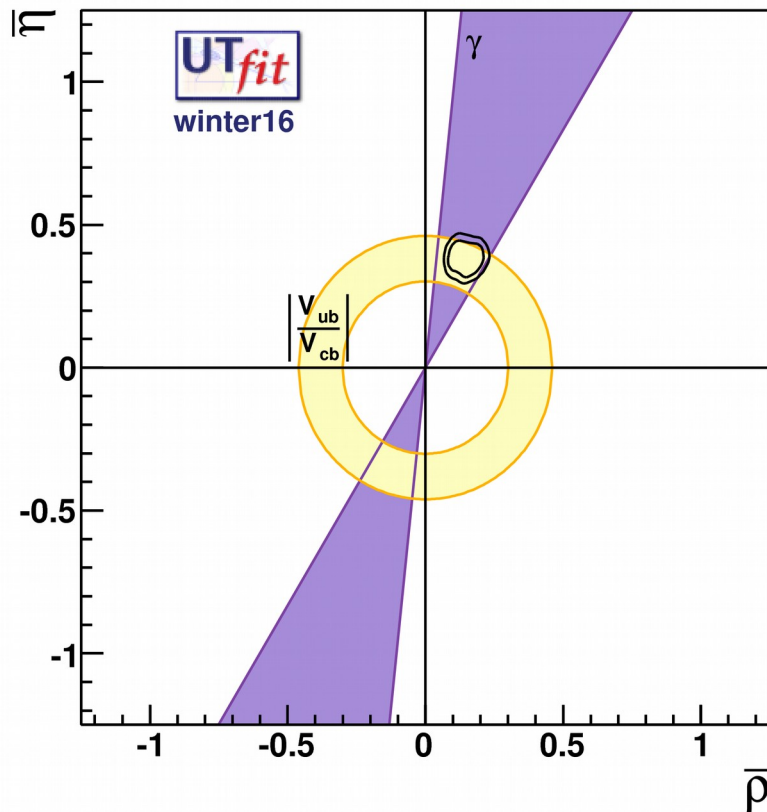
INTERPRETING THE BOUNDS

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

INGREDIENTS TO OBTAIN/ IMPROVE THE BOUNDS

- A NP-independent determination of the CKM matrix
- An estimate of SM amplitudes (value and uncertainty)
- An estimate of the NP contribution
- Interplay between different observables (generally model-dependent)

NP-INDEPENDENT CKM



SM fit:

$$\rho = 0.142 \pm 0.018$$

$$\eta = 0.348 \pm 0.012$$

Perugia, 1/3/2016

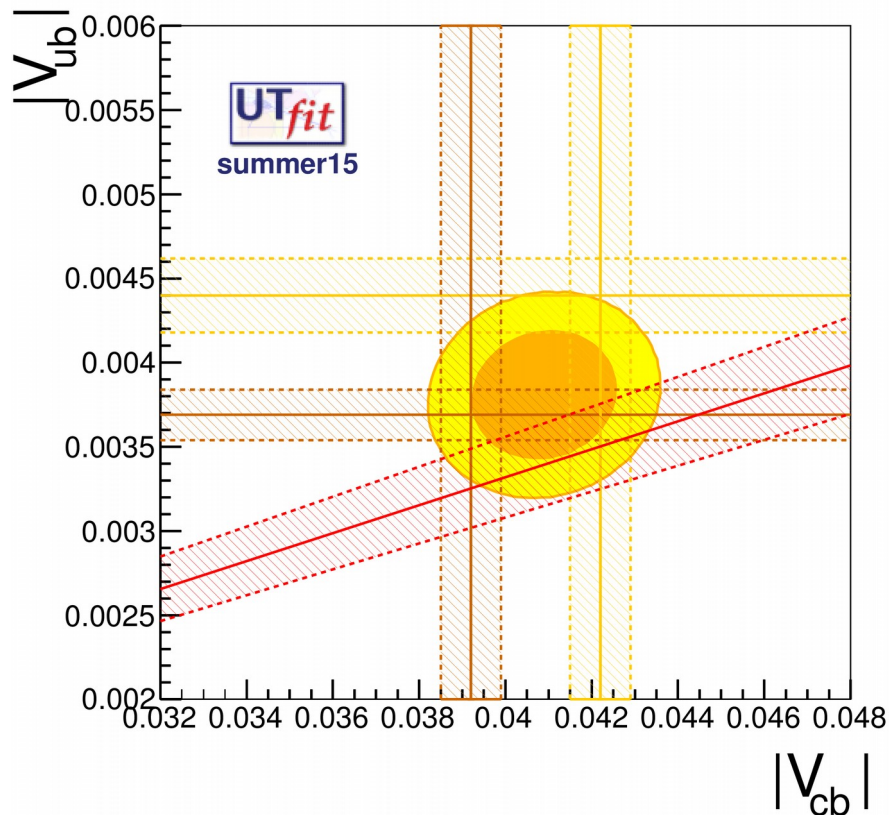
NP fit:

$$\rho = 0.146 \pm 0.043$$

$$\eta = 0.384 \pm 0.043$$

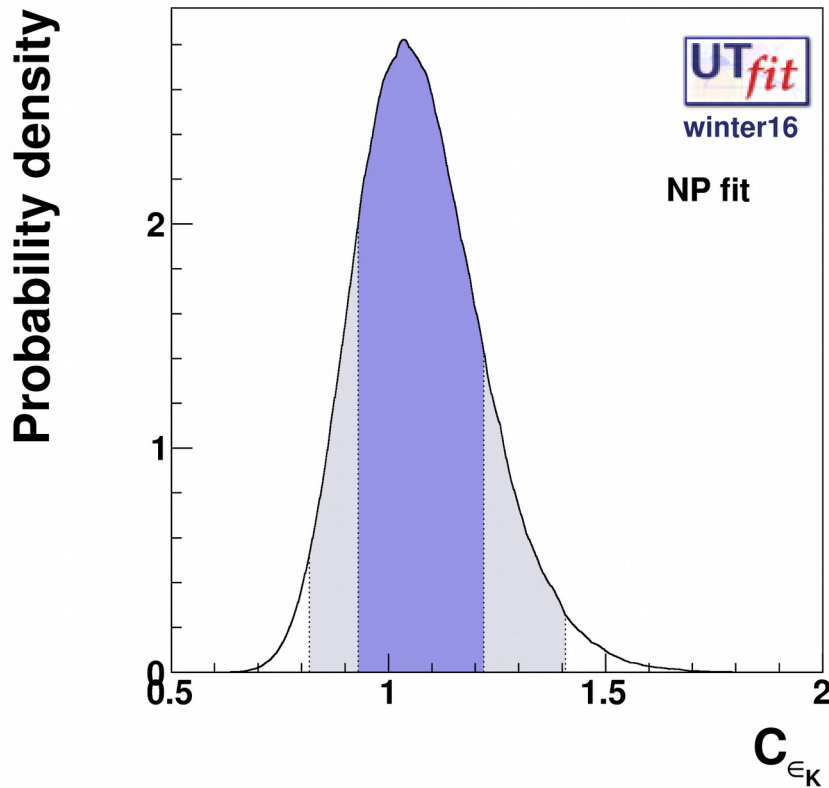
- $|V_{ub}|$ and $|V_{cb}|$ from semileptonic B dec.
- γ from tree-level decays
- A_{sl}^d to exclude 2nd solution model-independently

NP-INDEPENDENT CKM



- Disagreement between inclusive and exclusive
- Use inflated error à la PDG
- Need to be clarified: LHCb doing very well, but Belle-II plays a crucial role

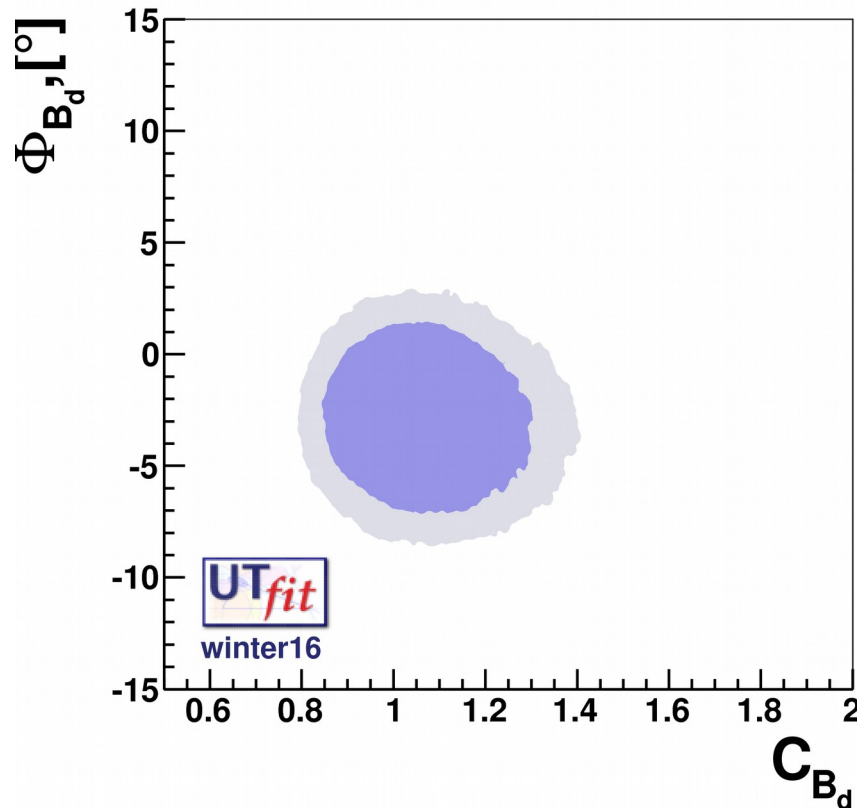
NP FIT RESULTS



- $C_{\epsilon_K} = \epsilon_K / \epsilon_K^{SM} = 1.07 \pm 0.14$
([0.80, 1.38] @ 95% probability)
- Main source of error: **CKM**, then B_K (1.3%), LD (~%)

Preliminary!

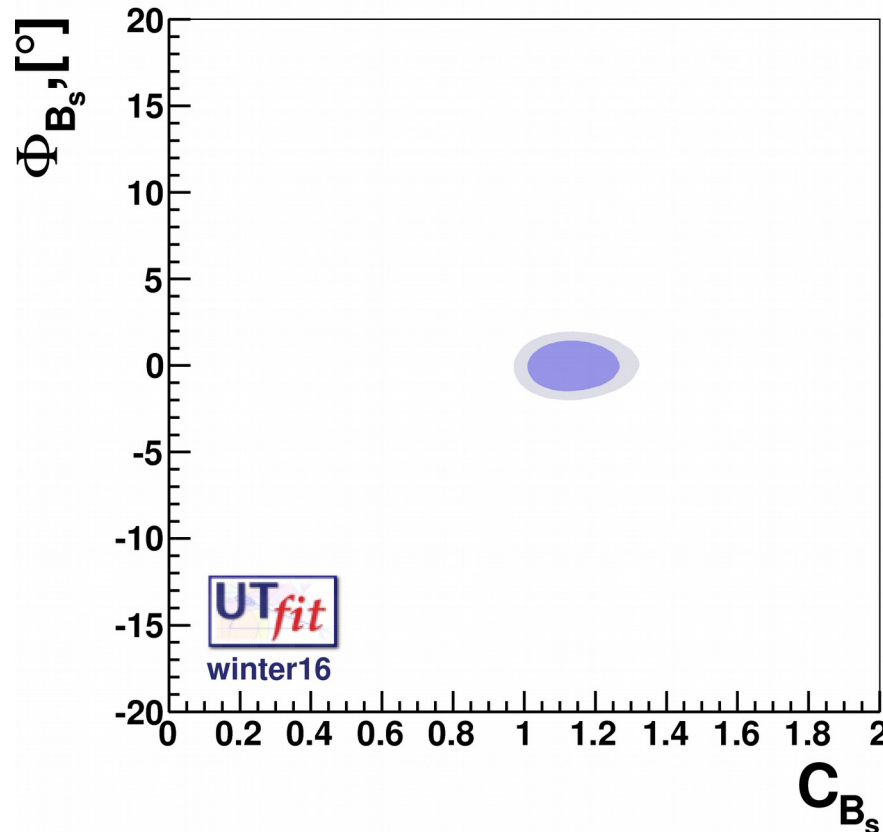
NP IN B_d MIXING



- $C_{B_d} = 1.08 \pm 0.15$
([0.79, 1.40] @ 95%)
- $\phi_{B_d} = (-2.8 \pm 2.8)^\circ$
([-8.5, 2.7]° @ 95%)
- Sources of error:
CKM ~ M.E. ~ 10%

Preliminary!

NP IN B_s MIXING



- $C_{B_s} = 1.141 \pm 0.087$
([0.97, 1.32] @ 95%)
- $\phi_{B_s} = (0 \pm 1)^\circ$
([-2, 2]° @ 95%)
- sources of error:
CKM ~ M.E. ~ 5%

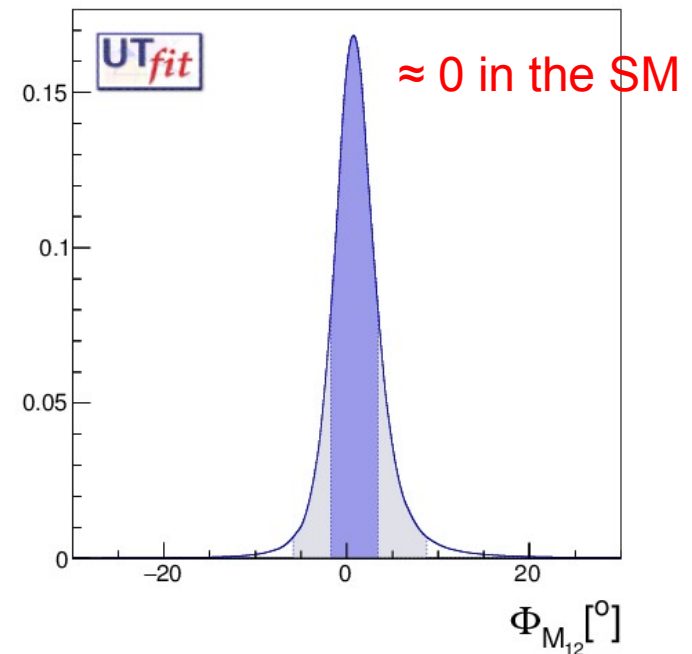
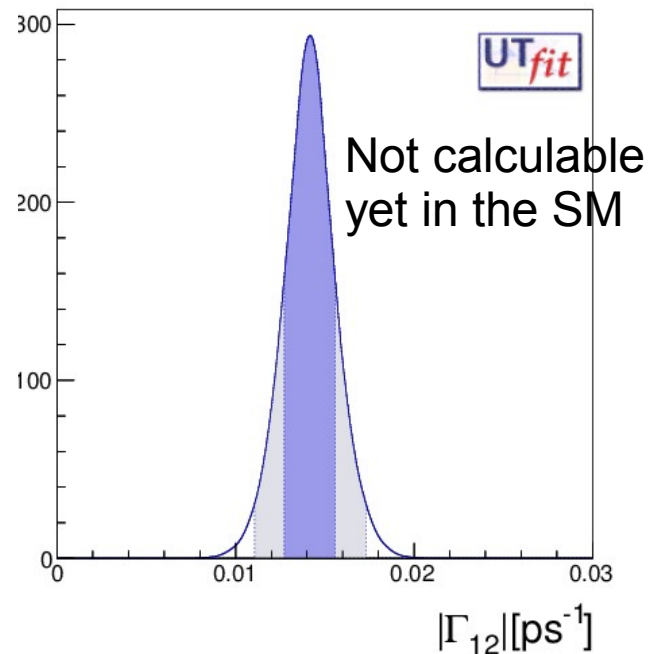
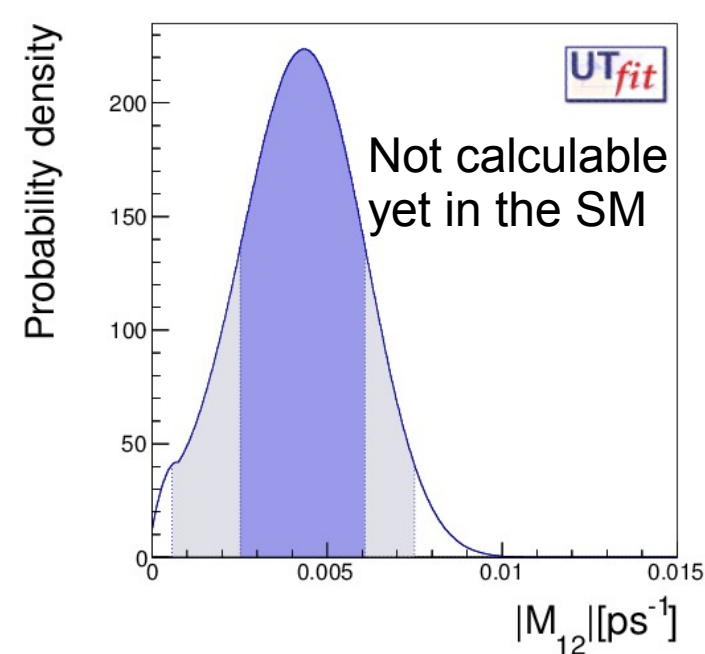
NP contributions at the level of 30-40% of the SM still allowed in all sectors!

CPV IN CHARM MIXING

- From a global analysis of D mixing data we extract the mixing parameters:

$$|M_{12}| = (4 \pm 2)/fs, |\Gamma_{12}| = (14 \pm 1)/fs$$

and $\Phi_{12} = (0 \pm 3)^\circ$ ($[-6, 9]^\circ$ @ 95% prob.)

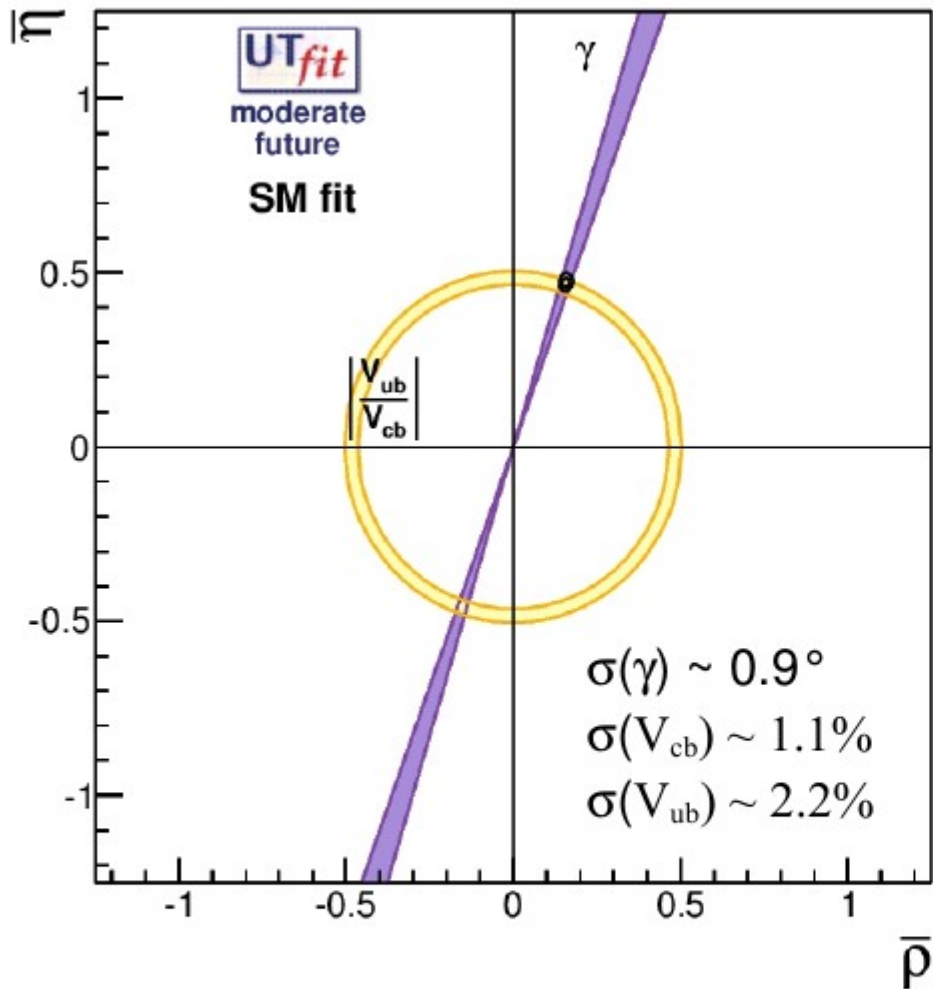


FROM A_{NP} TO Λ

- Having derived the NP amplitudes from the fit, the extraction of the NP scale Λ requires:
 - computing the hadronic matrix elements of NP-induced operators: currently all M.E. computed on the lattice, not a limitation
 - choosing a NP coupling and flavour structure

FUTURE OF $\Delta F=2$

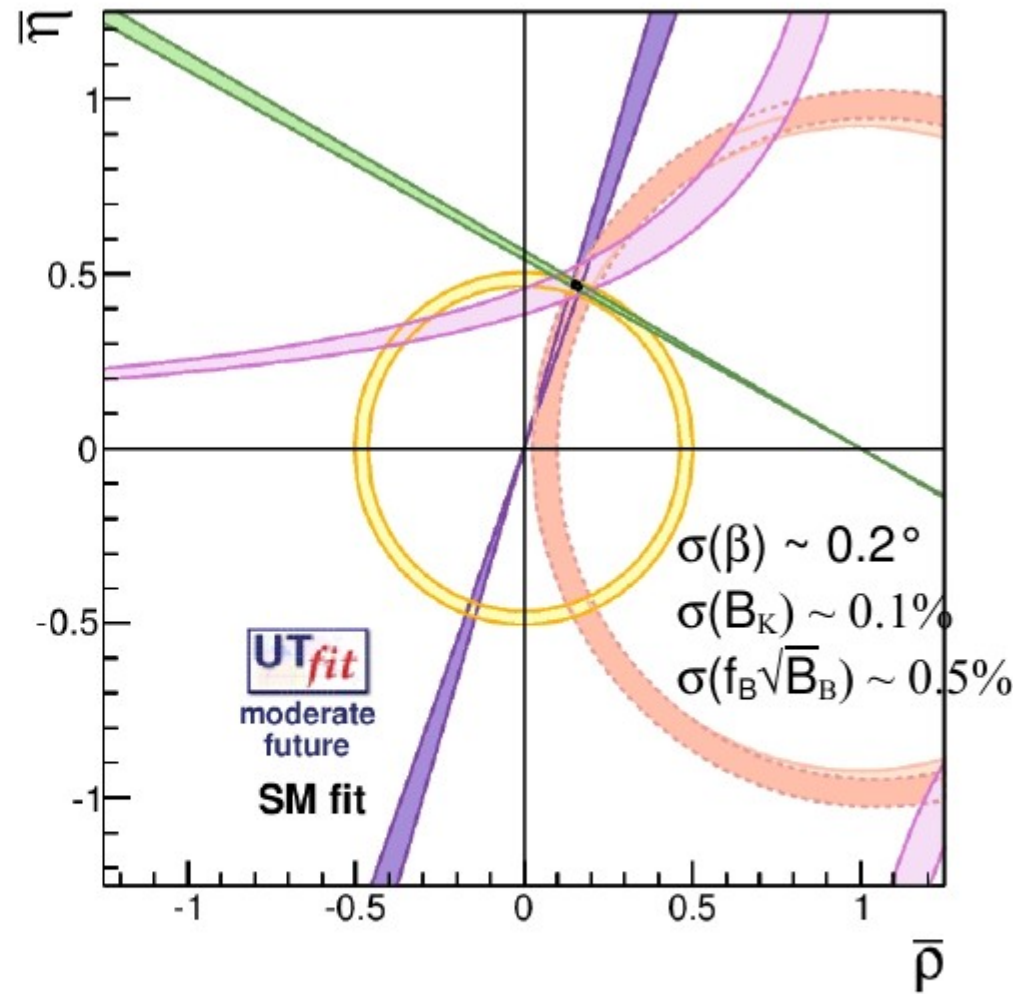
- In the next decade, Belle-II and LHCb upgrade will push down the exp. error on $\sin 2\beta_{(s)}$ to less than 0.01
- Th. error can be kept below 0.01 using control channels as $S(B \rightarrow J/\psi\pi)$ (Belle-II)
- B-parameters will go below the % level, new ideas to attack long-distance in K and D
- Improving γ , α , $|V_{cb}|$ & $|V_{ub}|$ crucial!



errors from tree-only fit on ρ and η :

$\sigma(\rho) = 0.008$ [currently 0.051]

$\sigma(\eta) = 0.010$ [currently 0.050]

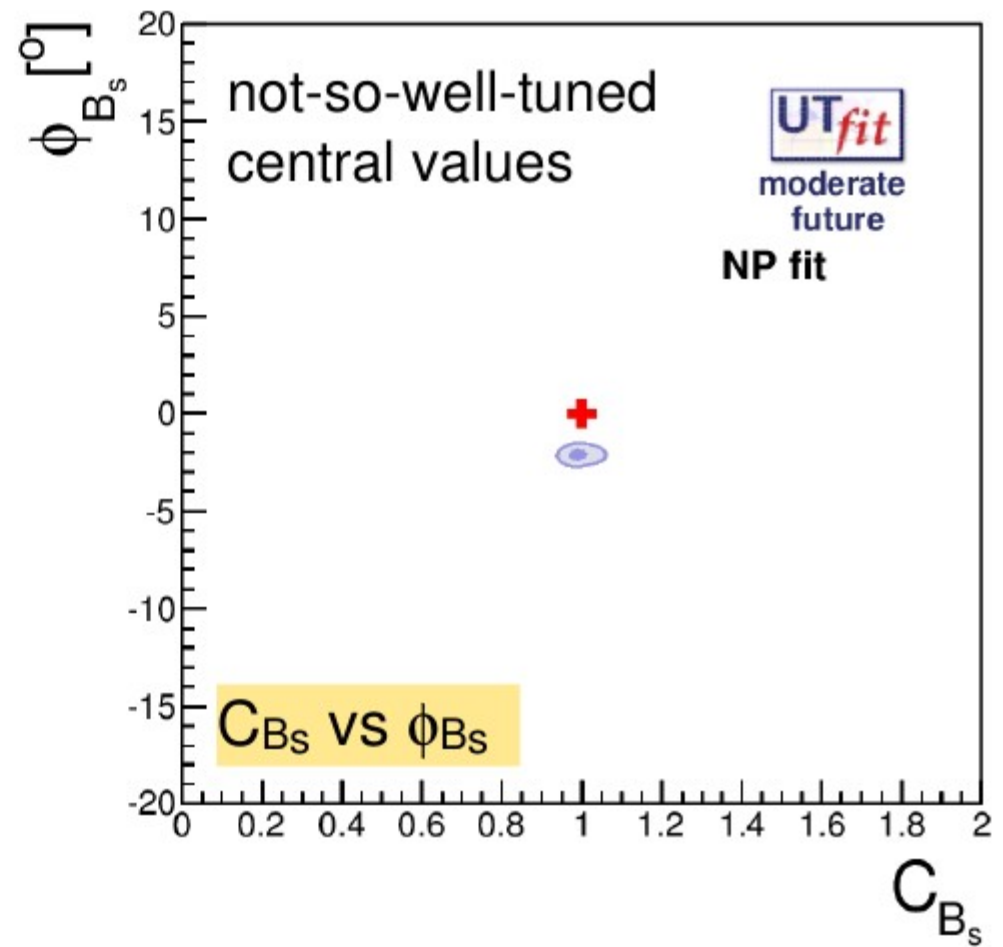
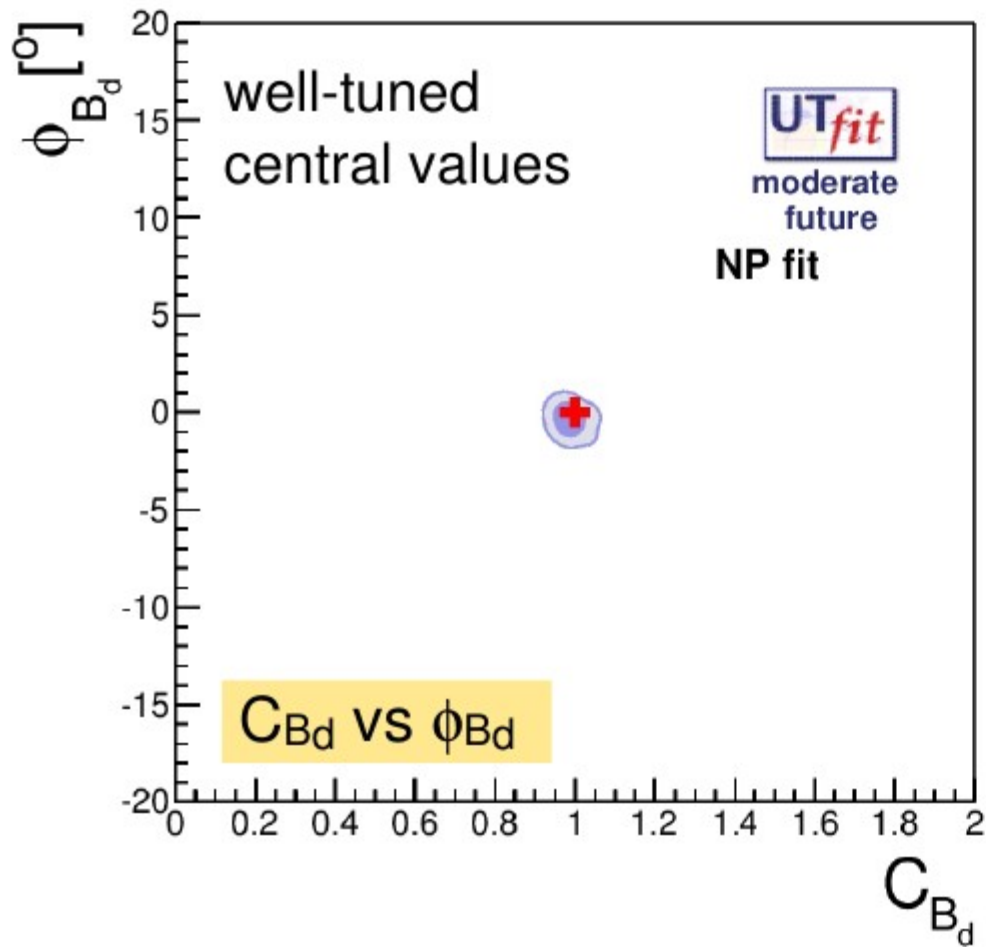


errors from 5-constraint fit on ρ and η :

$\sigma(\rho) = 0.005$ [currently 0.034]

$\sigma(\eta) = 0.004$ [currently 0.015]

M. Bona @ CKM2014



errors on general NP parameters:

$$\sigma(C_{B_d}) = 0.03 \text{ [currently } 0.16\text{]}$$

$$\sigma(\phi_{B_d}) = 0.7 \text{ [currently } 3.2\text{]}$$

$$\sigma(C_{B_s}) = 0.03 \text{ [currently } 0.08\text{]}$$

$$\sigma(\phi_{B_s}) = 0.6 \text{ [currently } 2.0\text{]}$$

M. Bona @ CKM2014

RARE DECAYS

- Rare and CP -violating decays are an excellent probe of NP
- Main (only) showstoppers are long-distance / infrared contributions to matrix elements
- $K \rightarrow \pi\nu\nu$ and $B_{d,s} \rightarrow \mu^+\mu^-$ extremely clean: dominated by parametric error, well below current and future exp error

$K \rightarrow \pi \nu \bar{\nu}$ ERROR BUDGET

Rare K - (vs.) B -decays

Ulrich Haisch

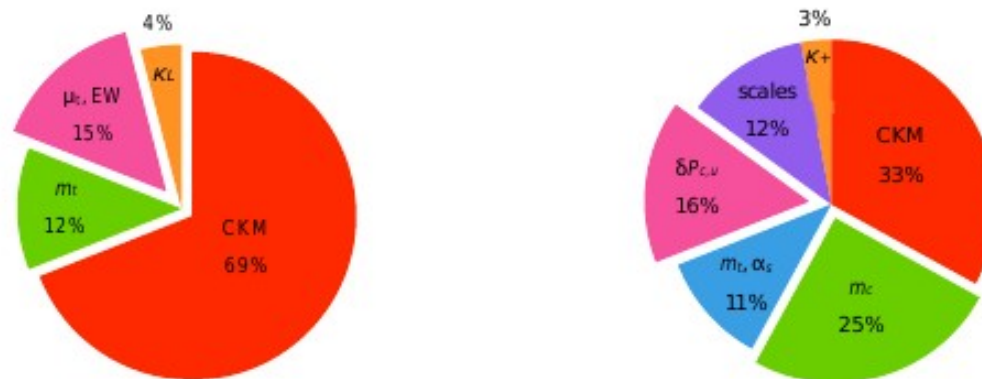
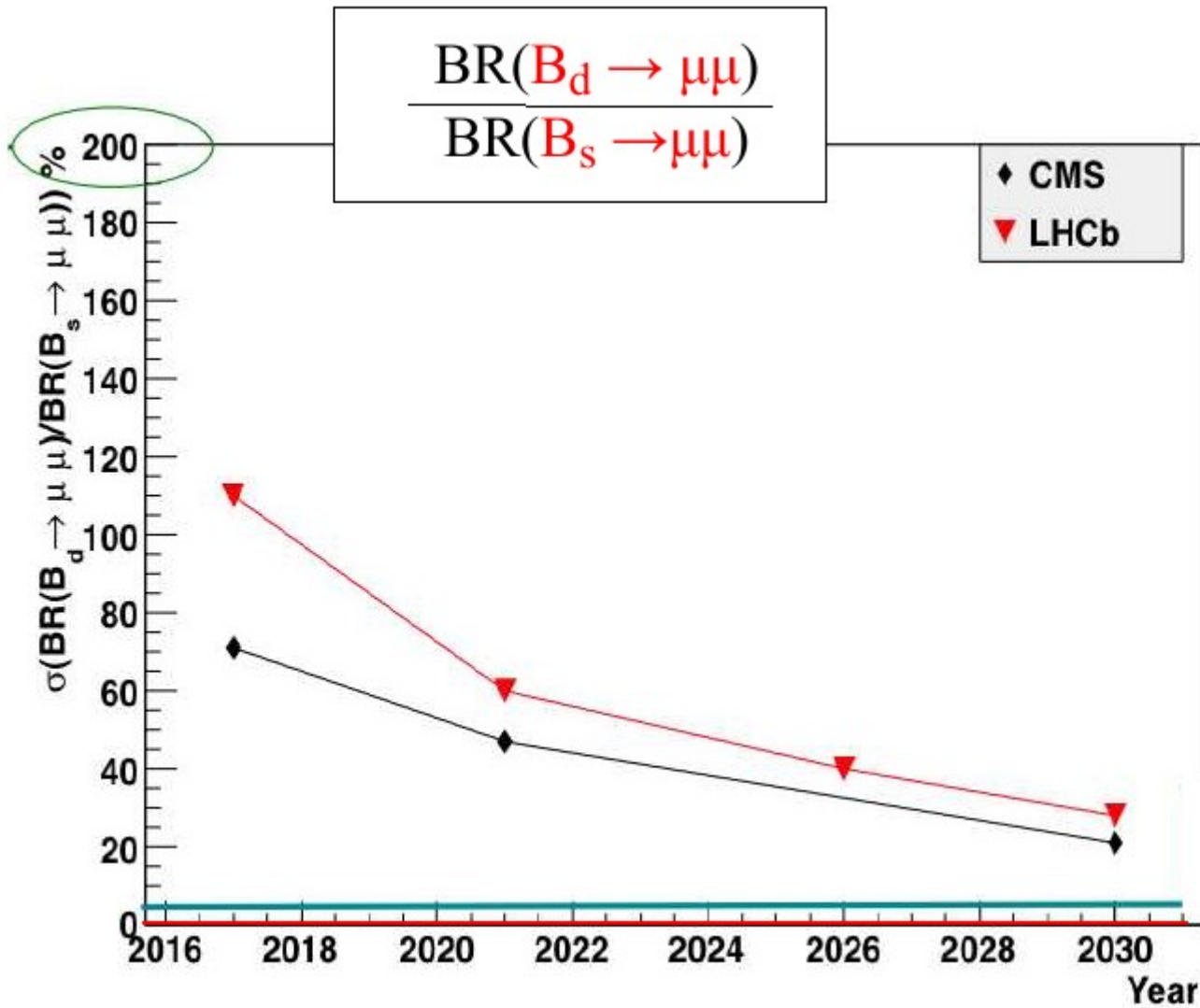


Figure 3: Error budget of the SM prediction of $BR(K_L \rightarrow \pi^0 \nu \bar{\nu})$ (left) and $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}(\gamma))$ (right). See text for details.

$$BR(K_L \rightarrow \pi^0 \nu \bar{\nu})_{SM} = (2.54 \pm 0.35) \times 10^{-11},$$
$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}(\gamma))_{SM} = (7.96 \pm 0.86) \times 10^{-11}.$$



TH error (now): 5%



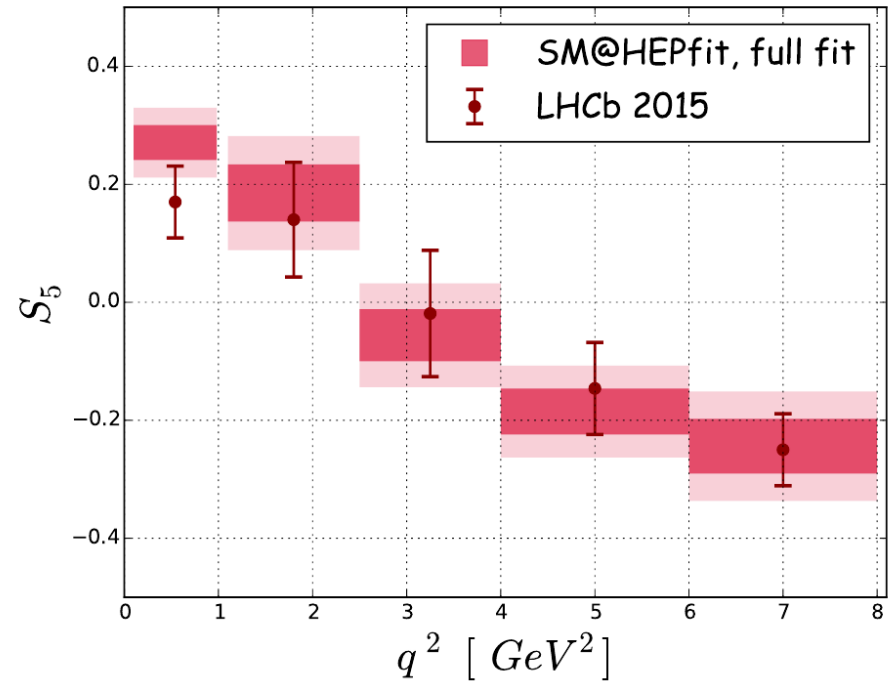
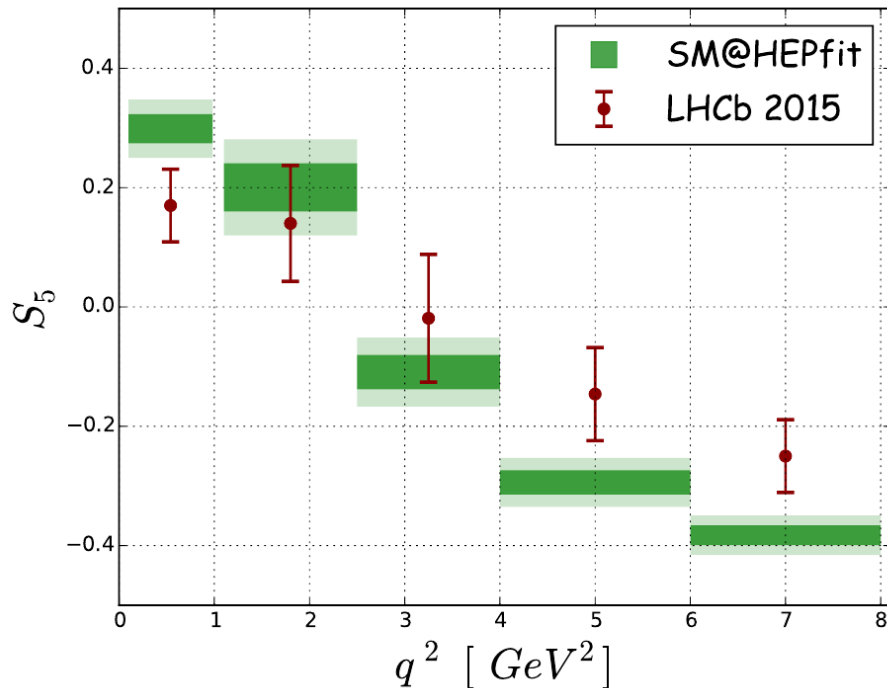
TH error (2030): ~1%

G. Isidori, What Next

BEWARE OF LD: $B \rightarrow K^* \mu^+ \mu^-$

- $B \rightarrow K^* \mu^+ \mu^-$ gets contributions from photon exchange
- Factorizes in the infinite mass limit
- Nonfactorizable contributions from charm loop induce sizable hadronic uncertainties with same quantum numbers as SM-like short-distance photon penguins (C_9)
- Cannot disentangle NP contributions to C_9

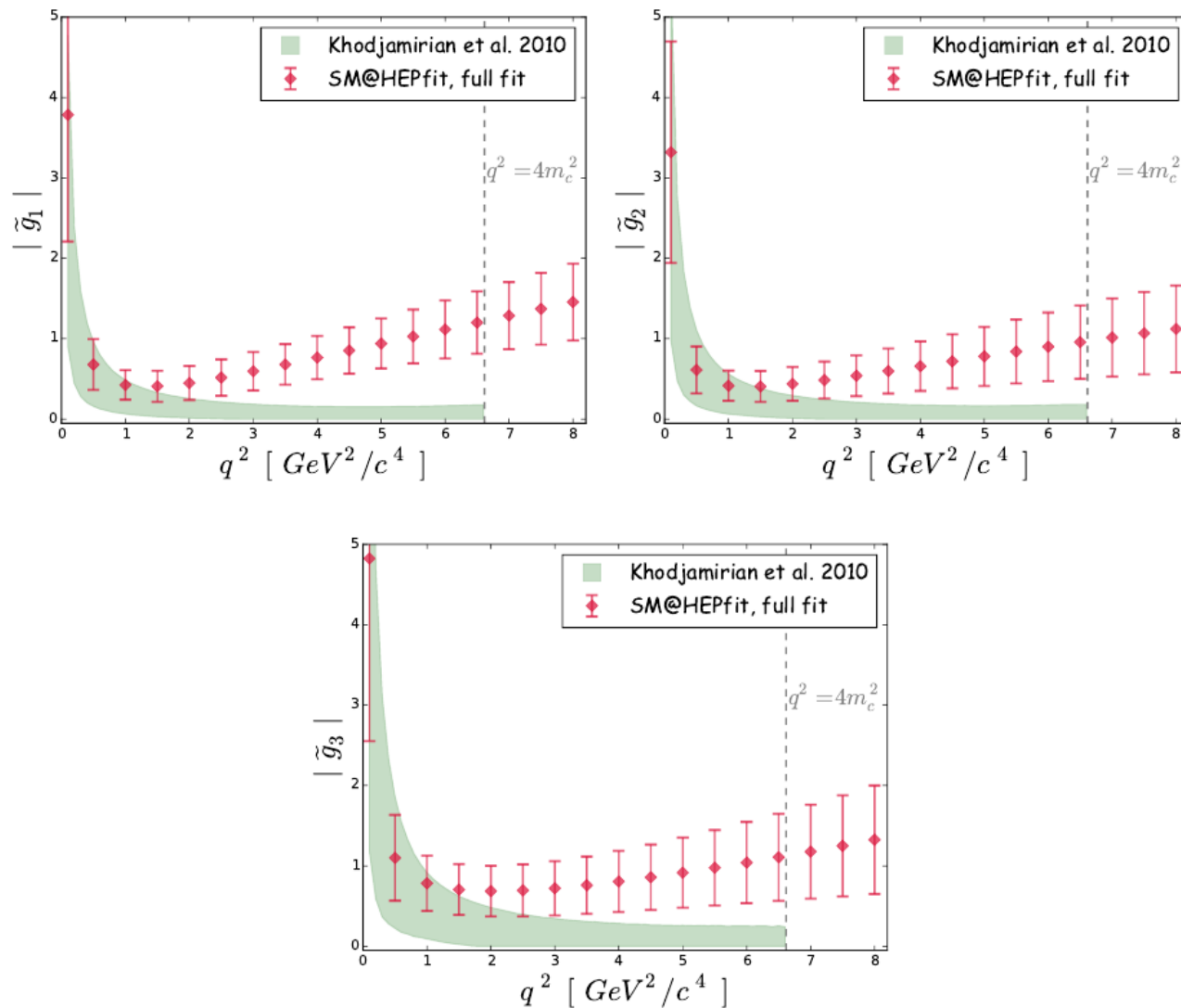
IMPACT OF CHARM LOOP



“Optimistic” evaluation
of nonfactorizable
contributions

Conservative evaluation
of nonfactorizable
contributions

SIZE OF CHARM LOOP



LESSONS FROM $B \rightarrow K^* \mu^+ \mu^-$

- Exp. data call for an extra contribution to the photonic penguin
- This contribution might come from hadronic effects or from NP
- Need additional information from other processes: inclusive modes, electron final states, etc.

Flavour Golden Modes

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

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Observable/mode	Current $\sim 1 \text{ ab}^{-1}$	LHCb (2017) 5 fb^{-1}	Belle II (2022) 50 ab^{-1}	LHCb upgrade 50 fb^{-1}	Theory
τ Decays					
$\tau \rightarrow \mu\gamma$	Yellow	Yellow	Green	Yellow	Green
$\tau \rightarrow e\gamma$	Yellow	Yellow	Green	Yellow	Green
$B_{u,d}$ Decays					
$B \rightarrow \tau\nu, \mu\nu$	Yellow	Red	Cyan	Red	Cyan
$B \rightarrow K^{(*)+}\nu\bar{\nu}$	Red	Red	Green	Red	Green
S in $B \rightarrow K_s^0\pi^0\gamma$	Yellow	Red	Green	Red	Yellow
S (other penguin modes)	Yellow	Yellow	Green	Cyan	Yellow
$A_{CP} (B \rightarrow X_s\gamma)$	Cyan	Yellow	Green	Yellow	Green
$\text{BR}(B \rightarrow X_s\gamma)$	Cyan	Yellow	Green	Yellow	Yellow
$\text{BR}(B \rightarrow X_s ll)$	Yellow	Red	Green	Red	Green
$\text{BR}(B \rightarrow K^{(*)} ll)$	Yellow	Cyan	Green	Red	Yellow
B_s Decays					
$B_s \rightarrow \mu\mu$	Red	Cyan	Red	Green	Green
β_S from $B_s \rightarrow J/\psi\phi$	Red	Cyan	Red	Green	Green
$B_s \rightarrow \gamma\gamma$	Red	Red	Cyan	Red	Green
a_{sl}	Red	Cyan	Green	Green	Green
D Decays					
Mixing parameters	Yellow	Cyan	Green	Green	Green
CP Violation	Red	Cyan	Green	Green	Green

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	Current $\sim 1 \text{ fb}^{-1}$	LHCb (2017) 5 fb^{-1}	SuperB (2022) 75 ab^{-1}	LHCb upgrade 50 fb^{-1}	Theory
α	Cyan	Cyan	Green	Cyan	Yellow
β from $b \rightarrow c\bar{c}s$	Cyan	Cyan	Green	Green	Green
$B_d \rightarrow J/\psi\pi^0$	Yellow	Red	Green	Red	Green
$B_s \rightarrow J/\psi K_s^0$	Red	Yellow	Red	Cyan	Green
γ	Yellow	Cyan	Green	Green	Green
$ V_{ub} $ inclusive	Cyan	Yellow	Green	Cyan	Green
$ V_{ub} $ exclusive	Cyan	Yellow	Green	Cyan	Green
$ V_{cb} $ inclusive	Cyan	Yellow	Green	Cyan	Green
$ V_{cb} $ exclusive	Cyan	Yellow	Green	Cyan	Green

LHCb can only use $p\bar{p}$
 β theory error Bd
 β theory error Bs

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

Precision flavour physics & theory uncertainties

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

MSSM: reconstructing the Lagrangian

Parameters	MSSM	SM
gauge+Higgs	14	6
masses	30 (+ v_R 36)	9 (+ v_R 12)
mixing angles	39 (+ v_R 54)	3 (+ v_R 6)
phases	41 (+ v_R 56)	1 (+ v_R 2)
Total	124 (+ v_R 160)	19 (+ v_R 26)

SM parameter match: FC vs FV&CPV 16-8

MSSM parameter match: FC vs FV&CPV 50-110

* fast increase of the # of FV&CPV parameters

* FV&CPV are related to basic properties of the

NP Lagrangian (e.g. SUSY breaking in the MSSM)

Flavour violation in the squark sector

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

LHCb, SuperB

LHC, ILC - HE frontier

and similarly for $M^2_{\tilde{u}}$

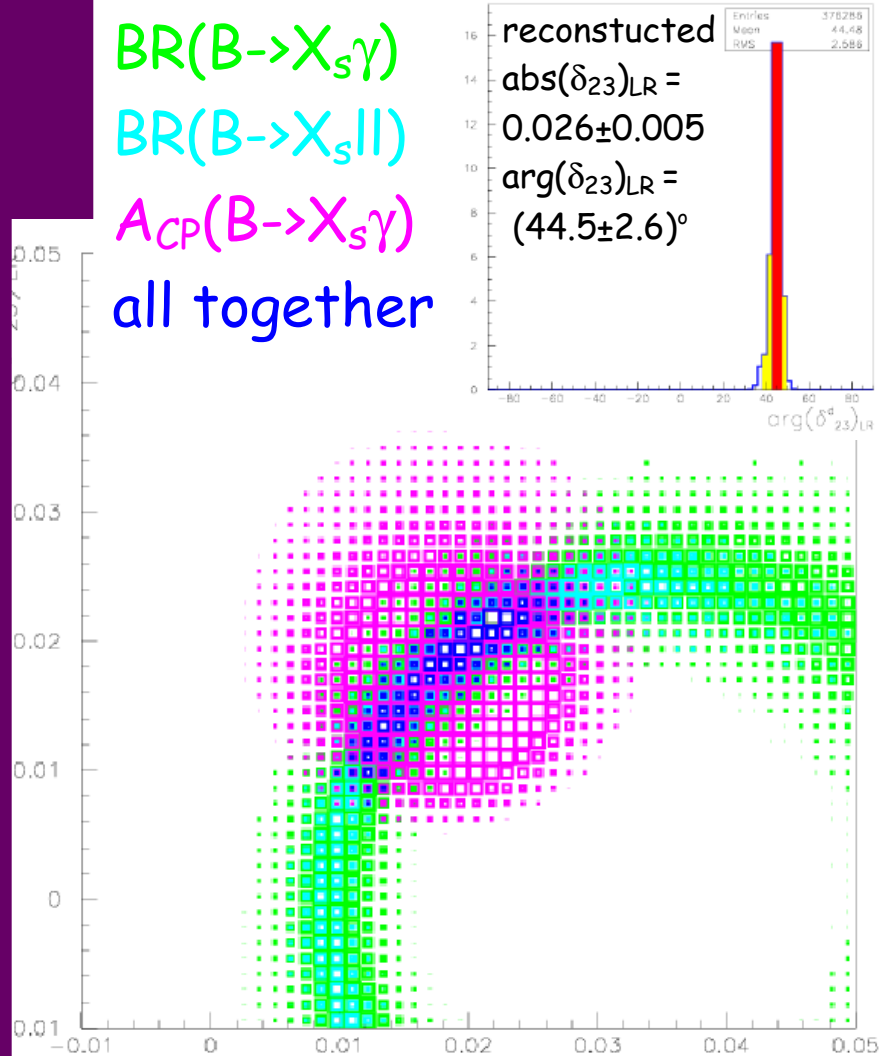
NP scale:

$$m_{\tilde{q}}$$

FV & CPV couplings:

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

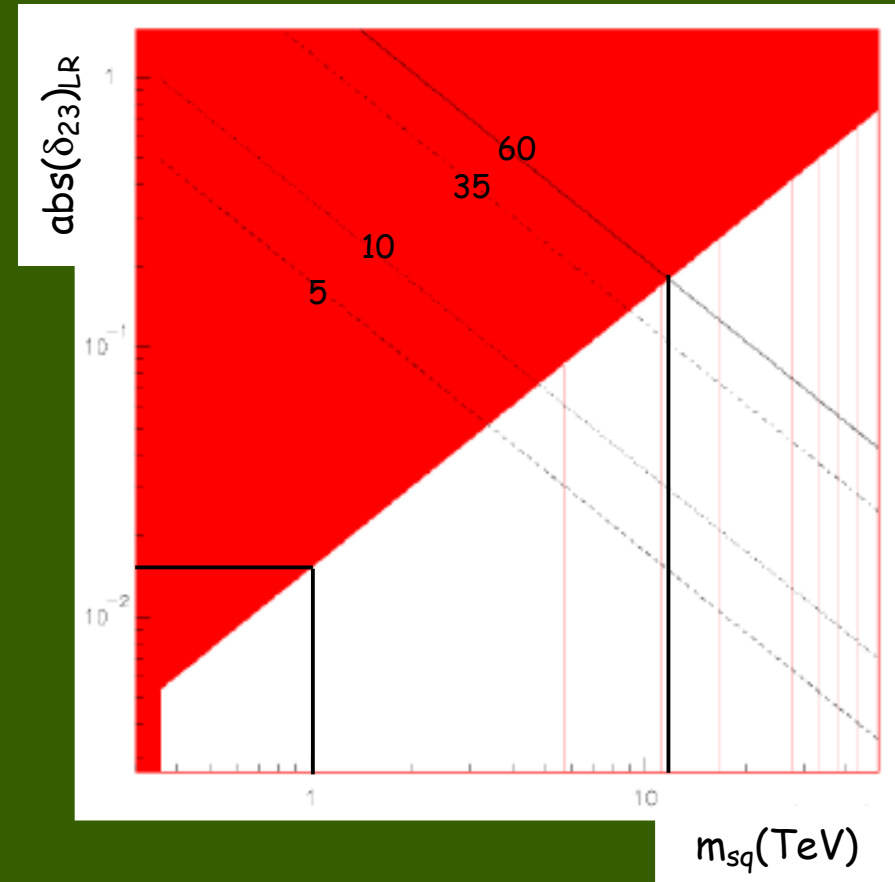
Determination of $(\delta_{23}^d)_{LR}$ using SuperB data



$\text{Im}(\delta_{23}^d)_{LR}$ vs $\text{Re}(\delta_{23}^d)_{LR}$

reconstruction of
 $(\delta_{23}^d)_{LR} = 0.028 e^{i\pi/4}$ for
 $\Lambda = m_g = m_q = 1 \text{ TeV}$

"3 σ " sensitivity plot



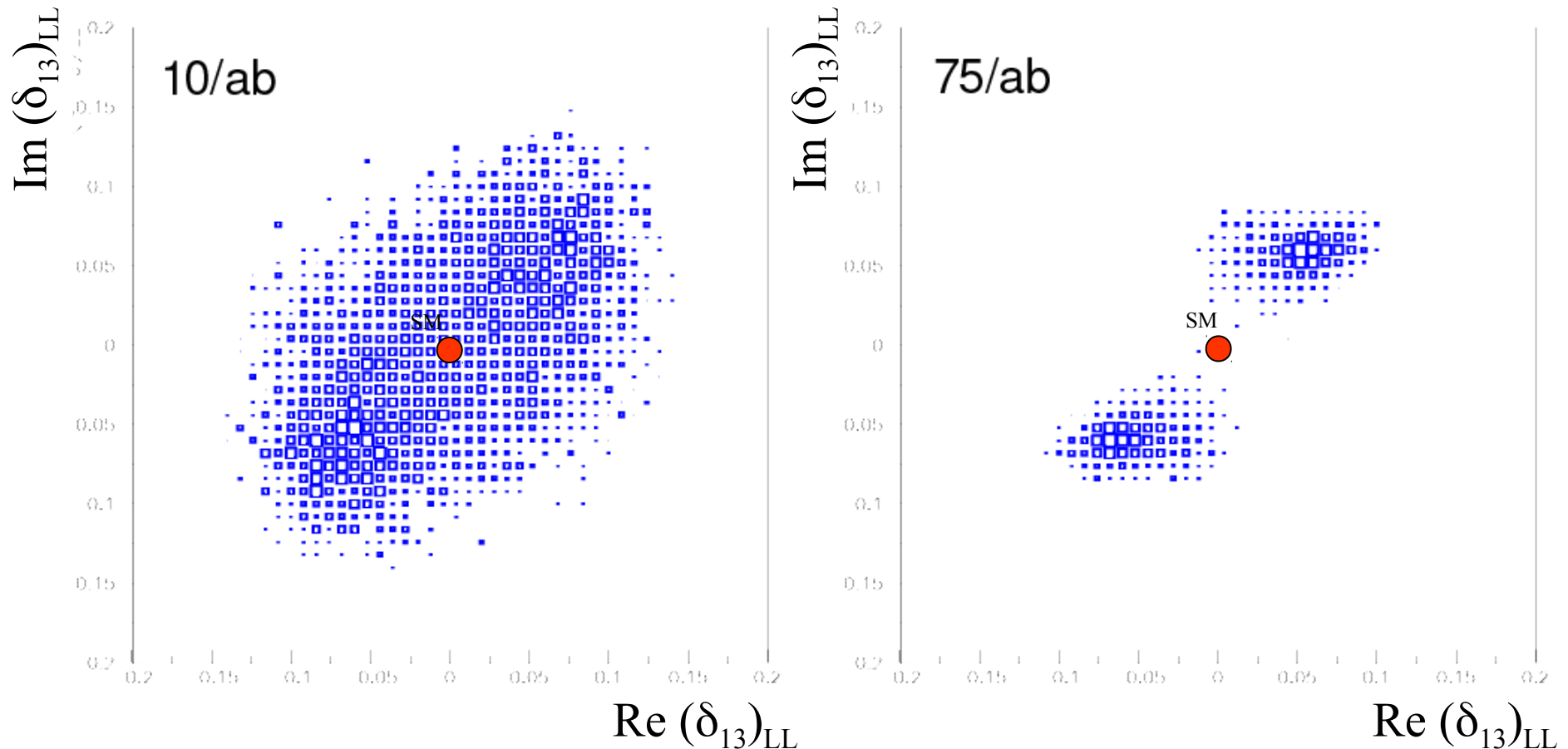
- i) sensitive to $m_{\tilde{q}} < 20 \text{ TeV}$
- ii) sensitive to $|(\delta_{23}^d)_{LR}| > 10^{-2}$ for $m_{\tilde{q}} < 1 \text{ TeV}$

Determination of $(\delta^d_{13})_{LL}$ using SuperB data

reconstruction of $(\delta^d_{13})_{LL} = 0.085 e^{i\pi/4}$

for $m_{\tilde{g}} = m_{\tilde{q}} = 1$ TeV

constraints: $\beta, A_{SL}, \Delta m_d$



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 $M_{NP} \Leftrightarrow 10x$ in exp & th $\Leftrightarrow 100x$ 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

- Emphasis often on “golden modes”, but a global experimental and theoretical effort is required to fully exploit the constraining power of flavour physics
- The complementarity of LHCb, Belle-II and dedicated K rare decays and LFV experiments is crucial

CHARM CPV EXTRAPOLATED

- SM contribution to ϕ_{M12} negligible, while one could envisage $\phi_{\Gamma12} O(1^\circ)$ due to LD penguins
- Present fit:
 - $\phi_{M12} = [-4, 12]^\circ$ @ 95% prob., no reach on $\phi_{\Gamma12}$
 - $\Lambda > 3.5 \cdot 10^4 \text{ TeV}$
- LHCb upgrade / Belle II:
 - $\delta\phi_{M12} = \pm 1^\circ$ and $\delta\phi_{\Gamma12} = \pm 2^\circ$ @ 95% prob.
 - $\Lambda > 10^5 \text{ TeV}$

- 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)

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_{B_s}	[13%]	[2%]	[0.5%]
f_{B_s}/f_B	[6%]	[1.8%]	[0.5%]
\hat{B}_{B_s}	[9%]	[5%]	[0.5-1%]
B_{B_s}/B_B	[3%]	[10%]	[0.5-1%]
$F_{D^*}(1)$	[3%]	[1.8%]	[0.5%]
$B \rightarrow \pi$	[20%]	[10%]	[>1%]

C. Tarantino
LTS1
Elba 2014

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