

THEORY INTRODUCTION

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- Introduction & motivations
- Future prospects in the leptonic sector
- Future prospects in the hadronic sector
- 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: $m_t \sim 170 \text{ GeV}$
- 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
- In parallel with increasing the energy probed by direct search, seek for indirect evidence!

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 & EDM's
- ⇒ 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 (ϵ_k now at $5 \cdot 10^5$ 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 $K_{NP} \geq K_{SM}$.

- 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)



multi-purpose
flavor expts @
hadron colliders

An “Extreme Flavor”
experiment @ LHC?

K/ π beams

Can we hope to
measure $K_L \rightarrow \pi \nu \nu$?

LFV [$\mu \rightarrow e$]

What's the ultimate sensitivity on $\mu \rightarrow e \gamma$?

Future progress on
Lattice QCD
(& SM-TH in general)

Ultimate Lattice precision
on HF form factors?

EDMs (& g-2)

An electron-EDM
storage ring [@ LNF]?

LEPTONIC SECTOR

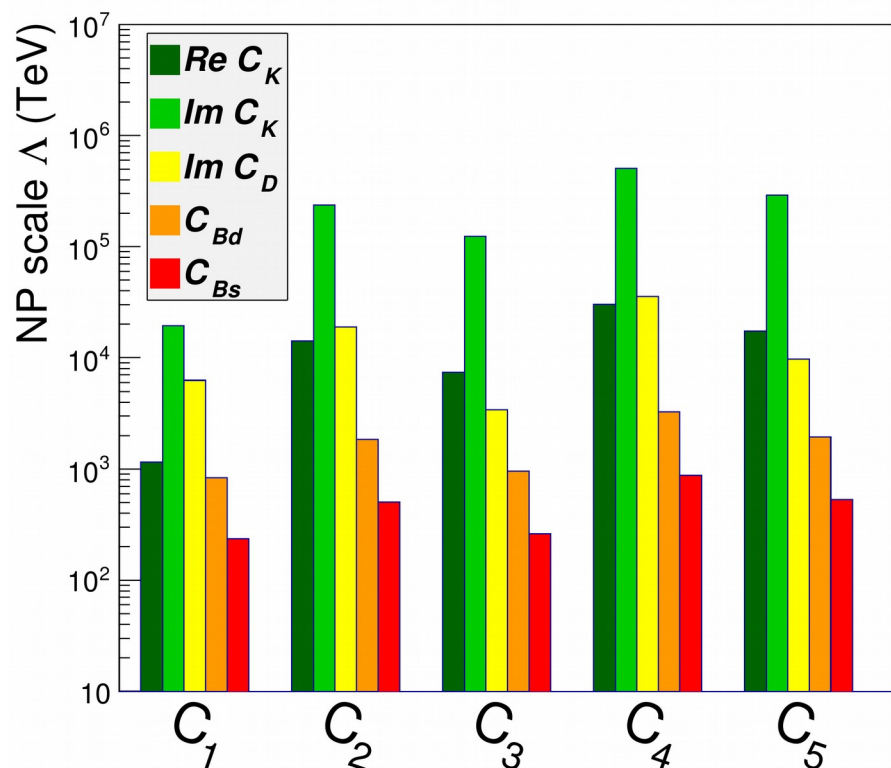
- LFV decays are theoretically very clean but scale as $1/\Lambda^4$; present MEG bound $5.7 \cdot 10^{-13}$ corresponds to $O(100 \text{ TeV})$.
 - Complementing $\mu \rightarrow e \gamma$ with other processes:
 - $\mu \rightarrow e e e$ and $\mu \rightarrow e$ conversion
 - $\tau \rightarrow \mu(e) \gamma$ and $\tau \rightarrow \mu(e) \ell \ell$
- is crucial to pin down NP flavour couplings

LEPTONIC SECTOR II

- Electron EDM also **very clean** above 10^{-33} ecm, scales as $1/\Lambda^2$; present bound 10^{-27} ecm corresponds to $O(100 \text{ TeV})$.
- Muon $g-2$ affected by theoretical uncertainties, scales as $1/\Lambda^2$; present result, if confirmed, requires light NP (below TeV).

HADRONIC SECTOR: PRESENT

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

HADRONIC SECTOR: FUTURE

- Belle II/LHCb upgrade scenario has been studied in detail, for example for the UT analysis in the NP scenario one has an order-of-magnitude improvement, leading to a factor of three in the NP scale

Parameter	New Physics fit today	New Physics fit at SuperB
$\bar{\rho}$	0.187 ± 0.056	± 0.005
$\bar{\eta}$	0.370 ± 0.036	± 0.005
α ($^{\circ}$)	92 ± 9	± 0.85
β ($^{\circ}$)	24.4 ± 1.8	± 0.4
γ ($^{\circ}$)	63 ± 8	± 0.7

PROSPECTS FOR HI-LUM

- 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

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%]	[$\gtrsim 1\%$]

C. Tarantino
parallel
talk

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

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 / τ -c factory:
 - $\delta\phi_{M12} = \pm 1^\circ$ and $\delta\phi_{\Gamma12} = \pm 2^\circ$ @ 95% prob.
 - $\Lambda > 10^5 \text{ TeV}$

CHARM CPV EXTRAPOLATED

- **HI-LUM** (very preliminary and very naïve: just scaled LHCb upgrade estimates for $K_S\pi\pi$ and γ_{CP}, A_Γ):
 - $\delta\phi_{M12} = \pm 0.1^\circ$ and $\delta\phi_{\Gamma12} = \pm 0.2^\circ$ @ 95% prob.
 - $\Lambda > 3 \cdot 10^5$ TeV, close to the bound from ε_K

$$B_{d,s} \rightarrow \mu^+ \mu^-$$

- One could reach an uncertainty on $\frac{\text{BR}(B_d \rightarrow \mu\mu)}{\text{BR}(B_s \rightarrow \mu\mu)}$ at the level of few percent, allowing for a very stringent test of NP and of its flavour structure, without hitting the th error wall
- A time-dependent analysis of the B_s channel also very interesting with very high accuracy
- Very clean probe of NP

LAST BUT NOT LEAST: $K_L \rightarrow \pi^0 \nu \nu$

- A theorist's dream: clean and very sensitive to NP
- Very exciting to think of measuring it at a K_L experiment @ SPS
- Would greatly contribute to our understanding of NP flavour structure

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

- From the theory side, LFV & electron EDM very clean, progress is needed for $g-2$;
- A global assessment of the physics potential of a very HI-LUM flavour experiment requires extensive studies, including, on the theory side:
 - extrapolation of lattice errors;
 - evaluation of uncertainties in the UTA;
 - projection of NP sensitivities in all sectors

BACKUP SLIDES

EXP INPUT FOR CHARM MIXING

- LHCb upgrade:
 - $\delta x = 1.5 \cdot 10^{-4}$, $\delta y = 10^{-4}$, $\delta |q/p| = 10^{-2}$, $\delta \phi = 3^\circ$ (from $K_s \pi \pi$); $\delta y_{CP} = \delta A_\Gamma = 4 \cdot 10^{-5}$ (from $K^+ K^-$)
- τ -c factory:
 - $\delta x = 3 \cdot 10^{-4}$, $\delta y = 3 \cdot 10^{-4}$, $\delta |q/p| = 9 \cdot 10^{-3}$, $\delta \phi = .8^\circ$ (from $K_s \pi \pi$);
- HI-Lumi (LHCb upgrade lumi x 100):
 - $\delta x = 1.5 \cdot 10^{-5}$, $\delta y = 10^{-5}$, $\delta |q/p| = 10^{-3}$, $\delta \phi = .3^\circ$ (from $K_s \pi \pi$); $\delta y_{CP} = \delta A_\Gamma = 4 \cdot 10^{-6}$ (from $K^+ K^-$)

Parameter	95% allowed range (GeV ⁻²)	Lower limit on Λ (TeV) for arbitrary NP	Lower limit on Λ (TeV) for NMFV
$\text{Re}C_K^1$	$[-6.8, 7.5] \cdot 10^{-13}$	$1.2 \cdot 10^3$	0.4
$\text{Re}C_K^2$	$[-5.0, 4.6] \cdot 10^{-15}$	$14.2 \cdot 10^3$	3.9
$\text{Re}C_K^3$	$[-1.7, 1.8] \cdot 10^{-14}$	$7.4 \cdot 10^3$	2.0
$\text{Re}C_K^4$	$[-1.0, 1.1] \cdot 10^{-15}$	$30.3 \cdot 10^3$	7.3
$\text{Re}C_K^5$	$[-3.1, 3.3] \cdot 10^{-15}$	$17.4 \cdot 10^3$	4.1
$\text{Im}C_K^1$	$[-1.9, 2.6] \cdot 10^{-15}$	$19.5 \cdot 10^3$	6.4
$\text{Im}C_K^2$	$[-1.8, 1.3] \cdot 10^{-17}$	$237.0 \cdot 10^3$	60.5
$\text{Im}C_K^3$	$[-4.8, 6.6] \cdot 10^{-17}$	$123.5 \cdot 10^3$	31.7
$\text{Im}C_K^4$	$[-2.9, 3.9] \cdot 10^{-18}$	$506.1 \cdot 10^3$	113.2
$\text{Im}C_K^5$	$[-8.8, 11.8] \cdot 10^{-18}$	$291.2 \cdot 10^3$	64.5
$\text{Im}C_D^1$	$[-8.7, 25.2] \cdot 10^{-15}$	$6.3 \cdot 10^3$	2.0
$\text{Im}C_D^2$	$[28.2, 9.7] \cdot 10^{-16}$	$18.8 \cdot 10^3$	4.6
$\text{Im}C_D^3$	$[-3.0, 8.6] \cdot 10^{-14}$	$3.4 \cdot 10^3$	1.1
$\text{Im}C_D^4$	$[-2.7, 8.0] \cdot 10^{-16}$	$35.4 \cdot 10^3$	8.5
$\text{Im}C_D^5$	$[-3.6, 10.6] \cdot 10^{-15}$	$9.7 \cdot 10^3$	2.7
$ C_{B_d}^1 $	$< 1.4 \cdot 10^{-12}$	833.3	7.1
$ C_{B_d}^2 $	$< 2.9 \cdot 10^{-13}$	$1.8 \cdot 10^3$	13.0
$ C_{B_d}^3 $	$< 1.1 \cdot 10^{-12}$	954.8	6.7
$ C_{B_d}^4 $	$< 9.3 \cdot 10^{-14}$	$3.3 \cdot 10^3$	20.9
$ C_{B_d}^5 $	$< 2.6 \cdot 10^{-13}$	$2.0 \cdot 10^3$	12.8
$ C_{B_s}^1 $	$< 1.8 \cdot 10^{-11}$	235.8	9.5
$ C_{B_s}^2 $	$< 3.9 \cdot 10^{-12}$	506.4	17.1
$ C_{B_s}^3 $	$< 1.4 \cdot 10^{-11}$	262.6	8.9
$ C_{B_s}^4 $	$< 1.3 \cdot 10^{-12}$	877.1	27.0
$ C_{B_s}^5 $	$< 3.6 \cdot 10^{-12}$	529.3	16.8