Future prospects in kaon physics: some remarks

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- Introduction
- The special role of kaons
- Selected rare decays (in the LHCb perspective)
- Probing more exotic scenarios
- Conclusions

Introduction

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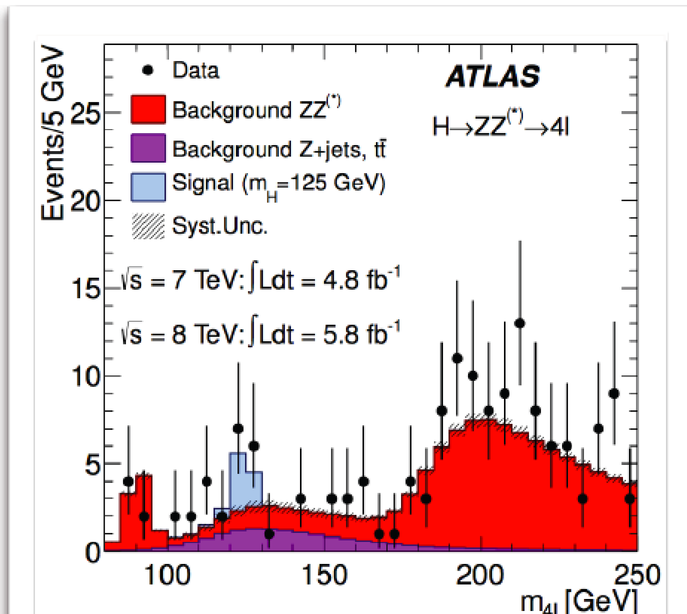
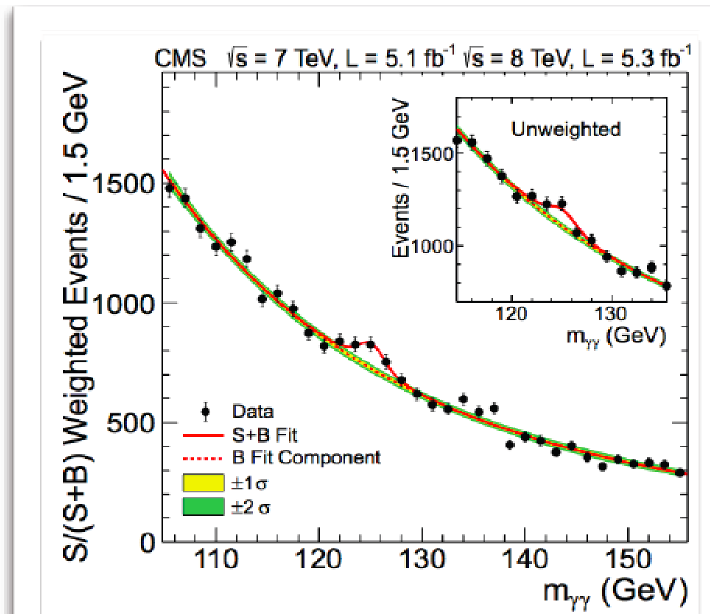
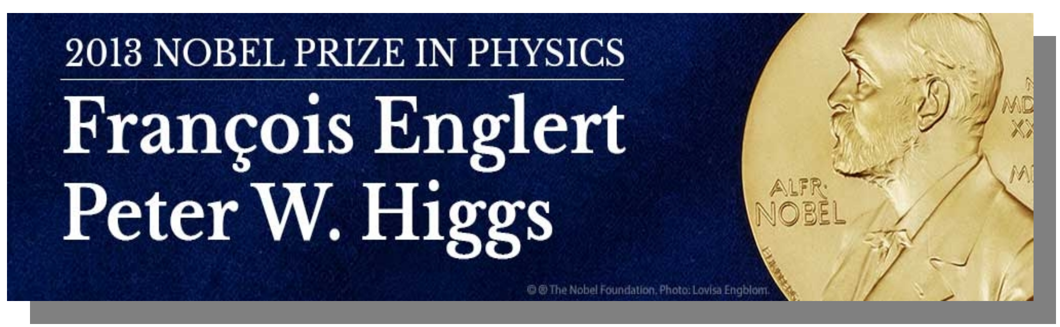


arXiv:1207.7214v1 [hep-ex]



arXiv:1207.7235v1 [hep-ex]



Introduction

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Still, this theory suffers of a series of theoretical & cosmological problems:

- Fine-tuning/UV sensitivity of the Higgs-mass term ["*hierarchy problem*"]
- Unexplained hierarchical structure of the Yukawa couplings ["*flavor puzzle*"]
- No explanation for the quantization of the U(1) charges [*hint of unification*?]
- Non coherent inclusion of gravity at the quantum level
- No good candidate for dark matter

⬇

The SM is likely to be an *effective theory*, or the low-energy limit of a more fundamental theory, with new degrees of freedom around or above the electroweak scale (i.e. around or above 1 TeV).

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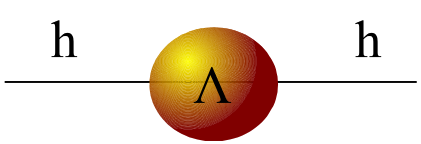
→ The only (qualitative) indication of NP <u>around</u> 1 TeV:



$$\Delta m_h^2 \sim \Lambda^2$$

The (relatively) small value of m_h + compatibility of the h couplings with SM + absence of NP signals so far

↓

NP is likely to be *weakly coupled* with a *non-negligible mass gap* (*hopefully not too large..*) between NP and SM degrees of freedom

CAUTION *personal bias...*

↓

Flavor physics is even more interesting that in the pre LHC8-era:

- we don't know the magnitude of this mass-gap
- we are not anymore forced to assume a MFV structure to accommodate low-scale NP → we can (hope) to probe high scales via flavor physics

Mass scale of New Physics (*new colored & flavored particles*)

Simplifying a complicated multi-dim. problem...	< 1 TeV	few TeV	> few TeV
	Direct New Physics searches @ high pT:		
	NP within direct reach @ 8 TeV	NP within reach @ 14 TeV	NP beyond direct searches @ LHC
Flavor Structure	*NP effects in Quark Flavor Physics:*		
Anarchic	huge [> O(1)]	sizable [O(1)]	sizable/small [< O(1)]
Small misalignment (*e.g. partial compositeness*)	sizable [O(1)]	small [O(10%)]	small/tiny [O(1-10%)]
Aligned to SM (*MFV*)	small [O(10%)]	tiny [O(1%)]	not visible [< 1%]

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There is still a wide range of "NP parameter space" that can and need to be explored (*without strong theoretical prejudices*) in quark & lepton flavor physics

The special role of kaons

Some of the main virtues:

- Weak decays (↔ *natural probes of the electroweak scale*) with high theoretical cleanness (*similar to B mesons in this respect*)

- Short-distance FCNCs with the strongest CKM suppression:

$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

$\sim V_{ts} V_{td} \sim 10^{-4}$ for (short-distance) $s \to d$ transitions

- Limited number of possible final states which allow clean studies of light weakly-coupled new particles.

The special role of kaons

- Short-distance FCNCs with the strongest CKM suppression:

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}+\nu} + \frac{c_{\text{NP}}}{\Lambda^2} O_{ij}^{(6)}$$

G.I., Perez, Nir '10 (2013 update)

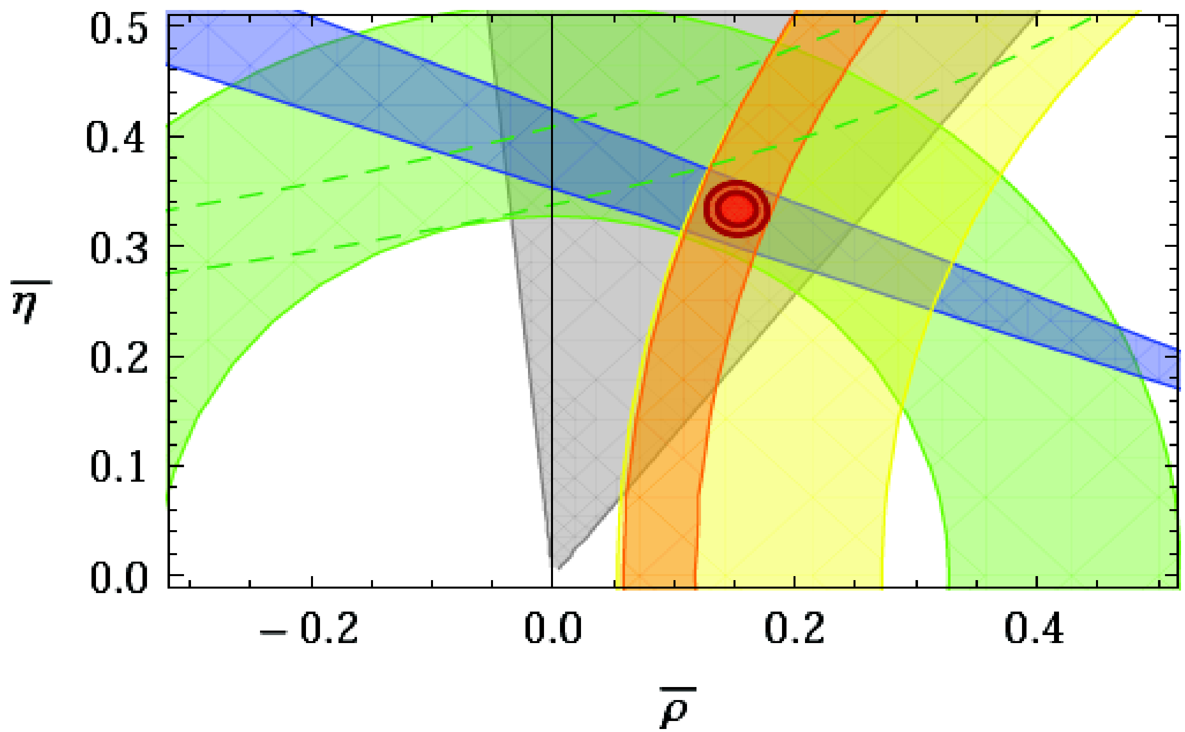
Operator	Bounds on Λ in TeV ($c_{\text{NP}}=1$) Re	Im	Bounds on c_{NP} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\,d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\,u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\,d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\ S_{\psi\phi}$
$(\bar{b}_R\,s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

→ K decays are the most sensitive probes of possible non-MFV couplings

The special role of kaons

And if we want to be optimistic... at present there is even a small tension in CKM fits that could be due to NP in the (neutral) kaon system...

SM fit, no ε_K (no K-meson mix. phase)



▶ Selected rare decays (in the LHCb perspective)

I. $K_S \to ll$

Rate decomposition of neutral K decays into a lepton pair:

$$\Gamma(K_{L,S} \to \ell^+\ell^-) = \frac{m_K \beta_\ell}{8\pi} \left(|A|^2 + \beta_\ell^2 |B|^2 \right)$$

$$\beta_\ell = \left(1 - \frac{4m_\ell^2}{m_K^2}\right)^{1/2}$$

S-wave ($|A|^2$):

Long-distance (2γ)
+
Short-distance (↔ NP)

K_S=CPV K_L=CPC

P-wave ($|B|^2$):

Long-distance (2γ) dominated

K_S=CPC K_L=CPV

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S-wave (A):

~~Long-distance (2γ)~~
+
CPV Short-distance (↔ NP)

- *Sub-leading within the SM*
- *Not directly bounded by* $K_L \to \mu\mu$

Ecker, Pich, '91
G.I, Unterdorfer, '04

P-wave (B):

Long-distance (2γ) dominated

- *Calculable with good accuracy*
- *Not interfering with short-distance*
- *Leads to tiny SM rates:*

$BR(K_S \to \mu\mu)_{SM} \sim 5\times10^{-12}$

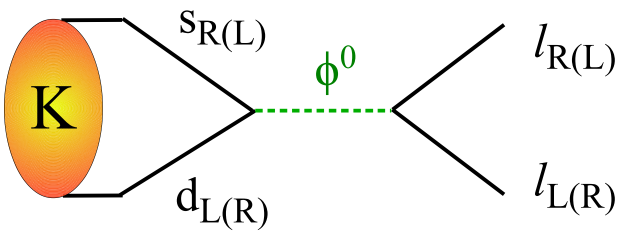
$BR(K_S \to ee)_{SM} \sim 2\times10^{-14}$

Selected rare decays (in the LHCb perspective)

I. $K_S \to ll$

$K_S \to \mu\mu$

- Clean signal of NP if BR $\geq 10^{-11}$
- BR ~ few$\times 10^{-11}$ possible without "tuning" the CPV phase of the amplitude (possible in "natural" NP models)
- BR >> 10^{-11} not directly excluded, but require a pure CPV s.d. amplitude to evade the K_L bound ("*ad hoc NP model*"...)



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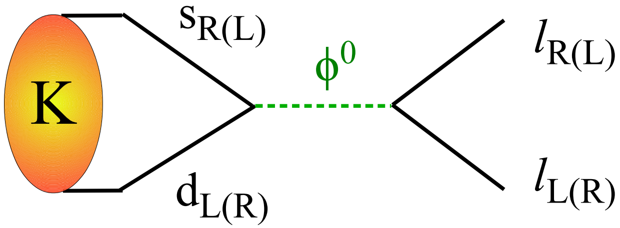

$K_S \to ee$

- Clean signal of NP if BR $\geq 5\times 10^{-14}$
- "Visible" rates not impossible, but generated only in rather exotic models (e.g. new scalar coupled to sd and ee, but not $\mu\mu$)

Selected rare decays (in the LHCb perspective)

II. $K_S \to \mu e$

Similarly to $K_S \to \mu\mu$, here the main problem is the constraint from the corresponding K_L mode (same flavor structure, but different parity of the $s \to d$ current).

But the problem is worse given the tighter bound from K_L:

$BR(K_L \to \mu e) < 5\times10^{-12}$ → $BR(K_S \to \mu e) \lesssim 10^{-14}$

with no "tuning" of the parity structure of the $s \to d$ *current*

Not very promising....

Selected rare decays (in the LHCb perspective)

III. The Charge asymmetry in $K^\pm \to \pi^\pm \mu^\pm \mu^\mp$

$$\frac{\Delta\Gamma}{\Gamma} = \frac{\Gamma(K^+ \to \pi^+ \mu^+ \mu^-) - \Gamma(K^- \to \pi^- \mu^+ \mu^-)}{\Gamma(K^+ \to \pi^+ \mu^+ \mu^-) + \Gamma(K^- \to \pi^- \mu^+ \mu^-)}$$

Clean probe of direct CPV

$$Q_7 \sim (\bar{s}_L \sigma_{\mu\nu} d_L) F^{\mu\nu}$$

$$Q_9 \sim (\bar{s}_L \gamma^\mu d_L)(\bar{l} \gamma_\mu l)$$

- Short-distance CP-violating phase calculable with good accuracy
- Strong re-scattering phase determined <u>unambiguously</u> from $K \to 3\pi$ data
- Non-vanishing (tiny) SM contribution: $(\Delta\Gamma/\Gamma)_{SM} \sim 10^{-4}$

D'Ambrosio, Ecker, G.I. & Portolés, '98

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With d→b we get the operator that could explain the $B \to K^*ll$ anomaly...

Small rate: BR=1×10^{-7}

Existing measurement from NA62: $(\Delta\Gamma/\Gamma)_{exp} = 0.010 \pm 0.023$

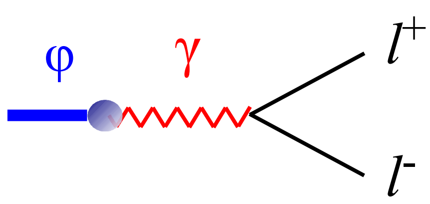
Probably difficult to do better @ LHCb, but it is worth a detailed investigation

Probing more exotic scenarios

The unique features of K decays allows a series of exotic searches (LFV, axions, heavy neutrinos...) which are absolutely worth to perform.

Particularly interesting are the searches for new light states (i.e. NP models which falls outside the general effective th. approach usually adopted). Recent revival of these models because of astrophysical puzzles

Example: new U(1) symmetry with light vector boson ($m_\varphi < 1$ GeV) weakly coupled to the photon [Arkani-Hamed et al. '08]



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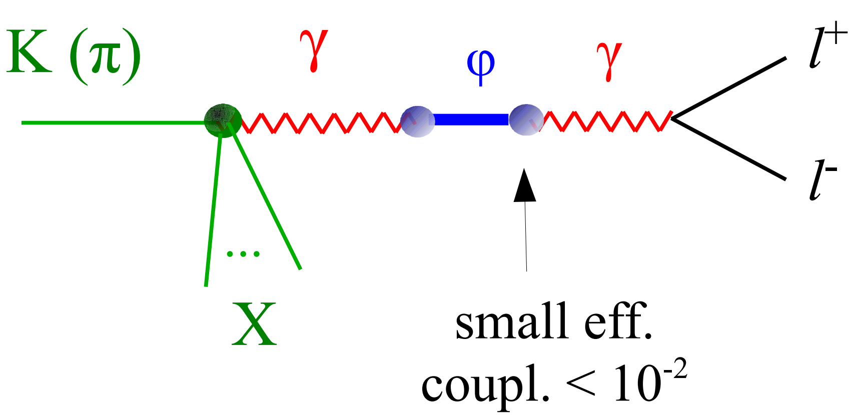

Non-trivial constraints on such particles can come from detailed analyses of K and π mesons with an ee (or μμ) pair

Tiny peaks in the m_{ee} distributions in $\pi^0 \to \gamma ee$, $K^0 \to \gamma ee$, $K_S \to \pi^+\pi^- ee$, ...

Conclusions

- Despite we have not seen any clear NP signal yet, it is still likely (and experimentally allowed) to expect some new degrees of freedom not far from the TeV scale

- On the other hand, having not seen anything so far, we can relax pessimistic assumptions about flavor mixing beyond the SM (such as MFV) → flavor physics remains an essential ingredient in the (*difficult*...) search for physics beyond the SM → worth to look in all possible channels without too strong theoretical prejudices...

- Within this context, kaon physics will continue to play an important role, due to the strong CKM suppression of s → d transitions

- Worth to extend the kaon physics program of LHCb, even if only focused on discovering/constraining exotic NP models