University of Zurich[UZH]

Kaon Physics: the next step

(*a theoretical perspective*)

Gino Isidori

[*University of Zürich*]

DISCLAIMER:
despite this the last session of the conference, this is not a summary talk !

University of Zurich[UZH]

Kaon Physics: the next step

(*a ~~theoretical~~ perspective*)
personal

Gino Isidori
[*University of Zürich*]

- Introduction
- Three interesting open frontiers:
  - *SUSY & CPV in the $K \to \pi\pi$ system*
  - *Lepton Flavor Universality*
  - *SM, BSM, & "non-standard BSM" in $K \to \pi\nu\nu$*
- The next step...

Introduction

Why we are still interested in Kaon physics...

▶ *Introduction* (Where do we stand in the search for NP?)

We entered into a new era in particle physics, that is interesting and somehow "scaring" at the same time...

This era is characterized by the (unexpected) success of the Standard Model: a *successful theory* of microscopic phenomena with *no intrinsic energy limitation*.

The key results obtained at the LHC so far (run I + beginning of run II) can indeed be summarized as follows:

- The Higgs boson (= last missing ingredient of the SM) has been found
- The Higgs boson is "light" ($m_h \sim 125$ GeV → not the heaviest SM particle)
- There is a "mass-gap" above the SM spectrum (i.e. no unambiguous sign of NP up to ~ 1 TeV)

Introduction (Where do we stand in the search for NP?)

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This era is characterized by the (unexpected) success of the Standard Model: a *successful theory* of microscopic phenomena with *no intrinsic energy limitation*.

The key results obtained at the LHC so far (run I + beginning of run II) can indeed be summarized as follows:

- The Higgs boson has been found
- The Higgs boson is "light"
- There is a "mass-gap" above the SM spectrum

Was this really unexpected?

Not really... This is perfectly consistent with the (pre-LHC) indications coming from indirect NP searches (EWPO + flavor physcs → light Higgs + mass gap above SM spectrum).

… no reason to be too surprised (or disappointed)

Introduction (Where do we stand in the search for NP?)

Despite all its phenomenological successes, the SM has some deep unsolved problems (hierarchy problem, flavor pattern, dark-matter, U(1) charges,…)

The motivation for NP are still there (*somehow even stronger than before*) and the SM should be regarded as an *effective theory*, i.e. the limit *–in the accessible range of energies and effective couplings*– of a more fundamental theory, with new degrees of freedom

⬇

We need to search for New Physics with a broad spectrum perspective given the lack of clear indications on the SM-EFT boundaries (*both in terms of energies and effective couplings*)

⬇

key (unique) role of
Kaon Physics

Introduction (On the key role of Kaon Physics in NP searches)

Unique probe of the flavor mixing among 1st-2nd generations of quarks

Highly suppressed phenomenon within the SM, in neutral currents [$A(s\to d)_{SM} \sim \lambda^5$] and/or helicity-suppressed charged curr. [$R_{e/\mu}(K)$]

→ indirect probe of flavor-violating NP occurring at energies not directly accessible at accelerators

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Unique probe of possible light, weakly coupled, new dynamics

(*dark photon, massive neutrinos*,...)

Unique probe of some of the fundamental SM parameters

→ unique access to the light quark Yukawa couplings (m_s, m_d/m_s, V_{us}, ...)

Ideal set-up for the "R&D" of theory tools about non pert. dynamics

(Lattice, CHPT,... → key ingredients to improve our understanding of the SM and possibly uncover NP).

Introduction (On the key role of Kaon Physics in NP searches)

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Unique probe of possible light, weakly coupled, new dynamics

Unique probe of some of the fundamental SM parameters

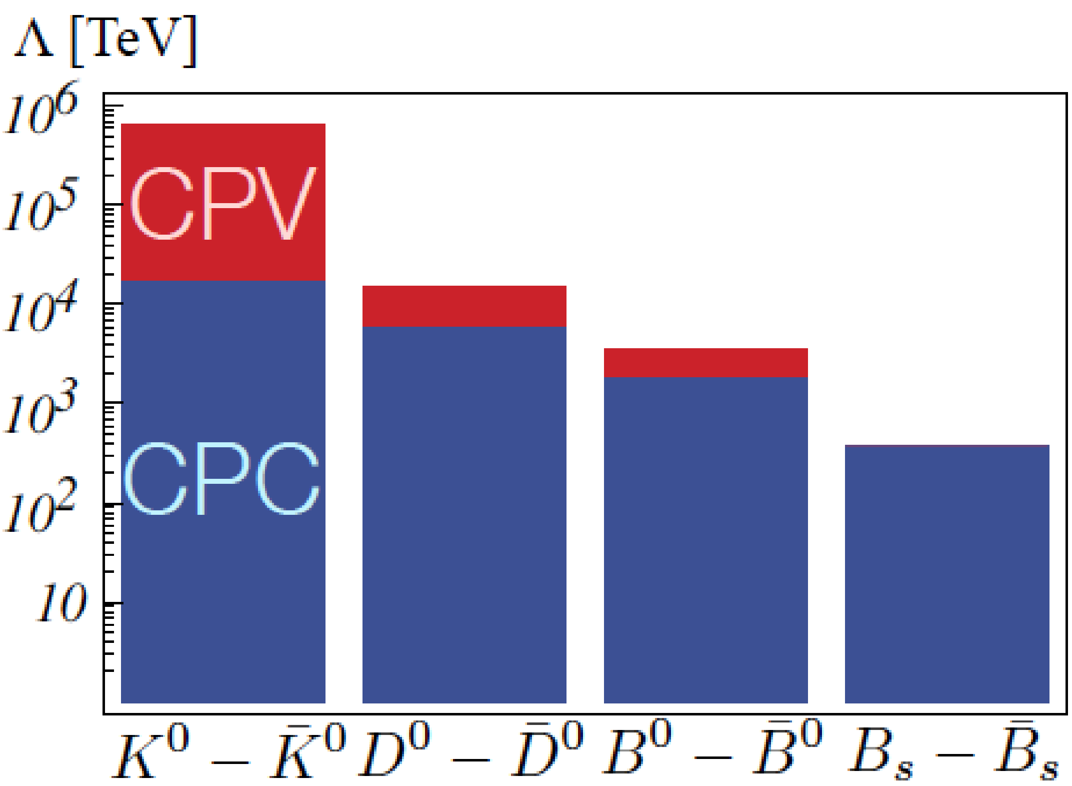
Not covered in this talk, despite <u>very interesting</u> talks/results presented at this conference

Ideal set-up for the "R&D" of theory tools about non pert. dynamics

▶ *Introduction* (On the key role of Kaon Physics in NP searches)

As a quick reminder of the key role played by kaon physic in indirect NP searches, we can simply look at the NP bounds on generic four-fermion operators:

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2} \text{O}_{\Delta F=2}$$



Introduction (What's next?)

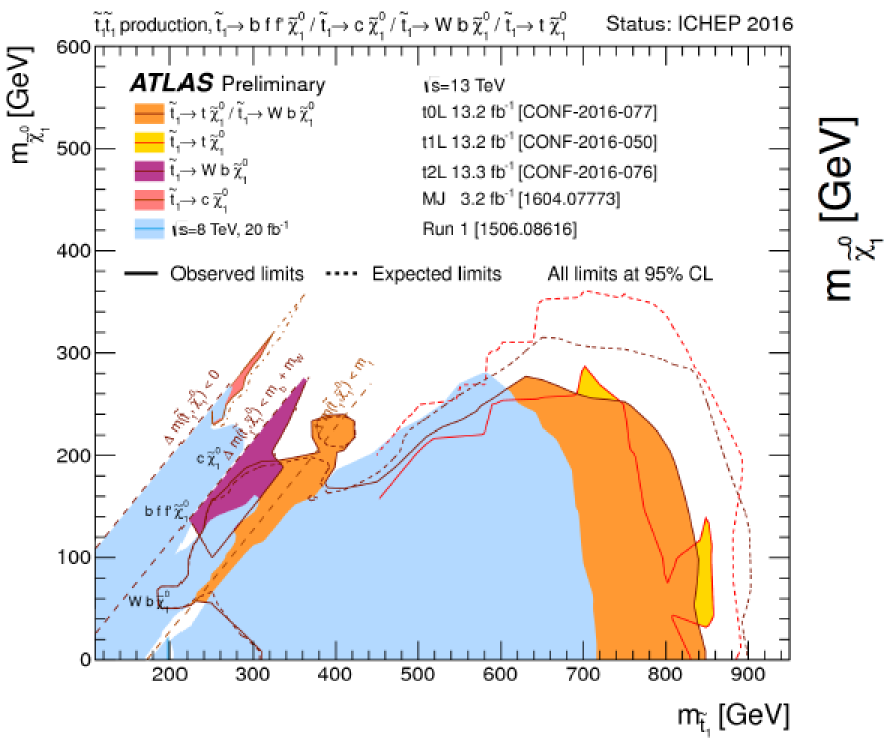
Is there a realistic hope to see a NP signal in Kaon Physics in the near future?

Of course I have not a clear answer to this question....

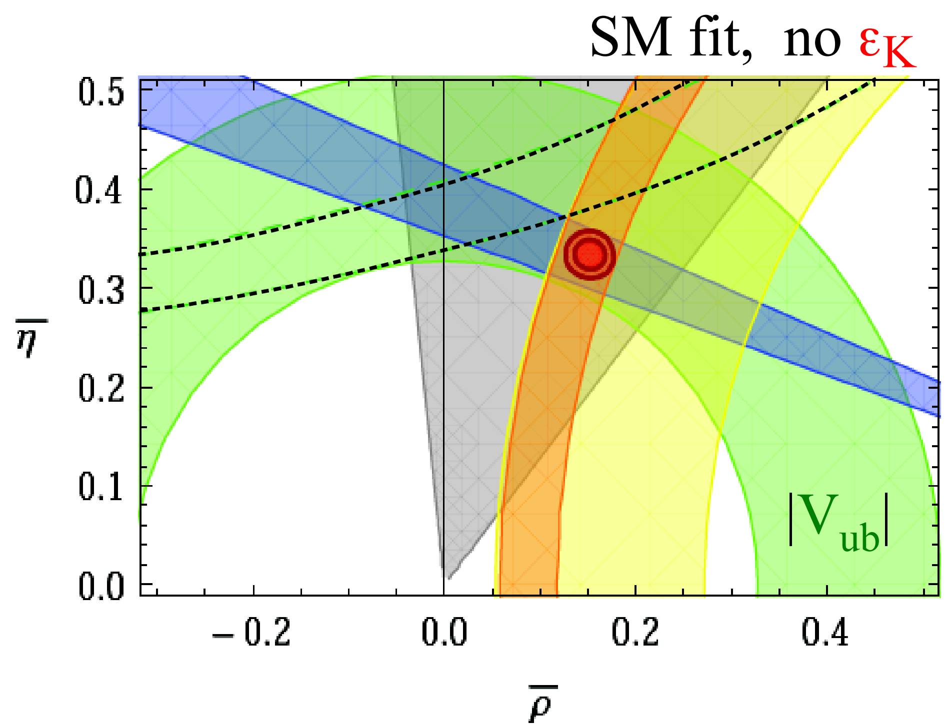
What I'll try to argue in the rest of the talk, with a few selected examples, is that

- This possibility is not unrealistic in well motivated cases
- Kaon physics has still potential “unexplored frontiers”, that would deserve future exp. & th. efforts.

SUSY & CPV in the K → ππ system



ATLAS summary



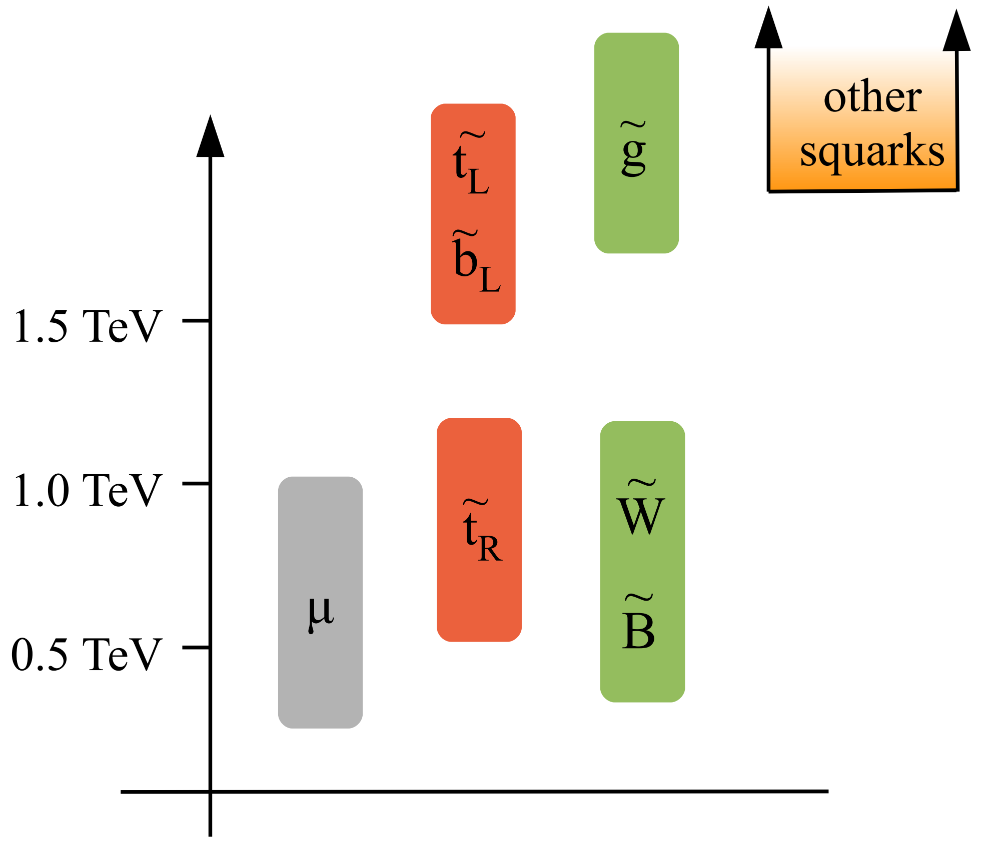
SUSY and CPV in the $K \to \pi\pi$ system

Despite the absence of signals, SUSY remains one of the best candidate for a UV completion of the SM:

- Weakly coupled theory + light Higgs (*125 is well the SUSY region...*) + dark-matter & unification
- Some tuning in m_h is unavoidable: *do we really care if the fine-tuning is ~1% ?*

Most of the low-scale SUSY virtues are maintained if we assume a flavor non-trivial spectrum →

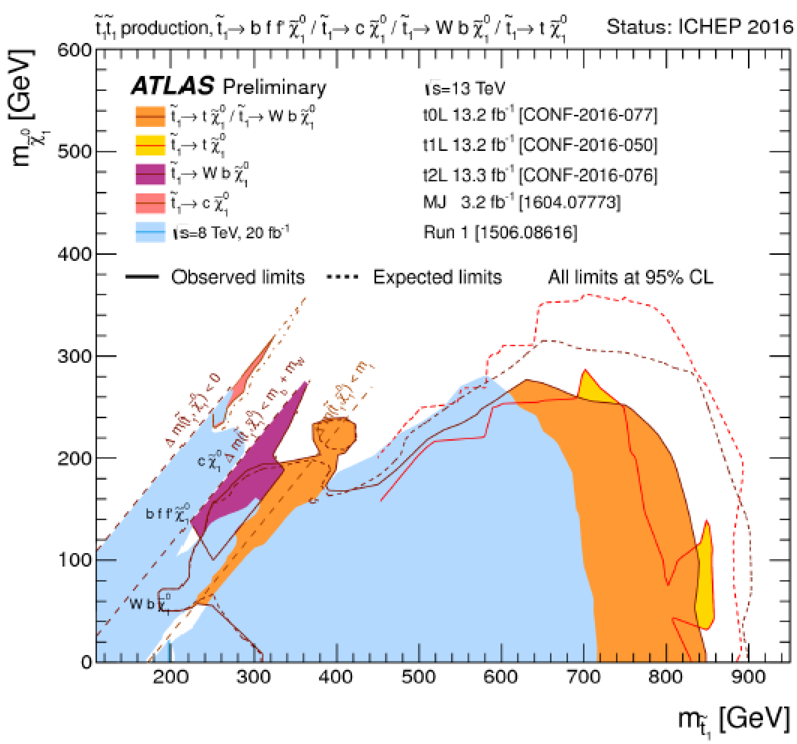
Dimopulos, Giudice, '95
Cohen, Kaplan, Nelson '96
+ many others...



- 3^{rd} gen. squarks + Higgsinos key ingredients in the m_h tuning
- splitting the 3^{rd} family can easily be motivated in flavor models

▶ *SUSY and CPV in the $K \to \pi\pi$ system*

- LHC experiments are setting stringent constraints on this scenario, but a stop below ~ 1 TeV is still allowed.



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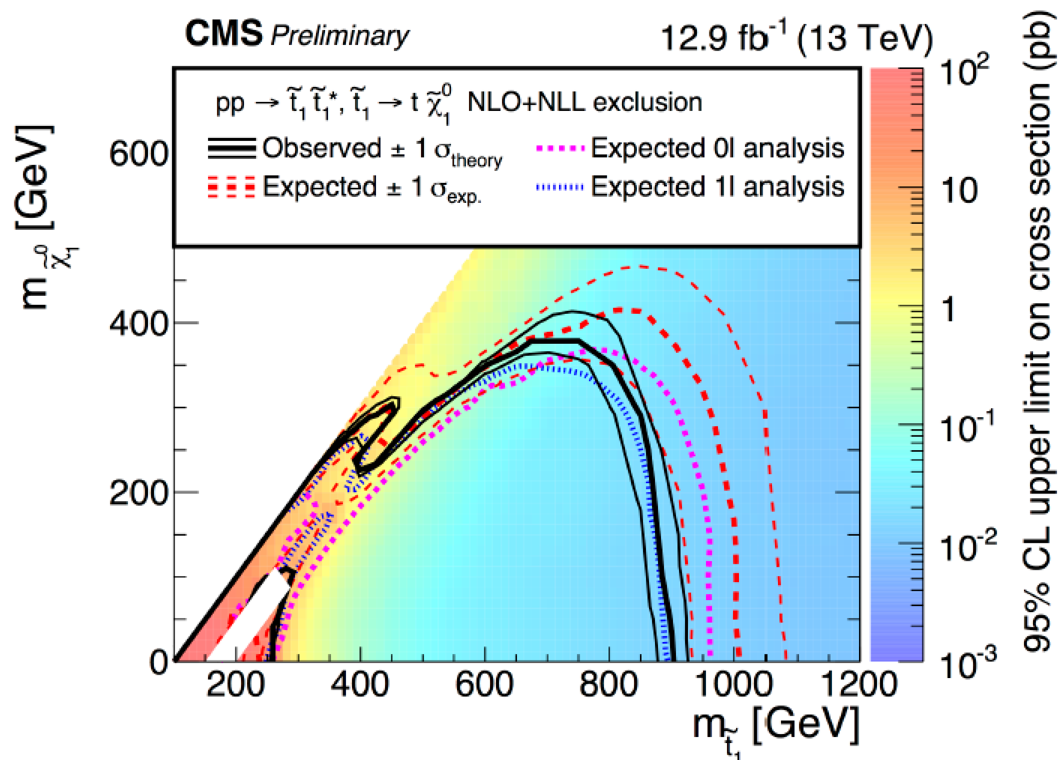
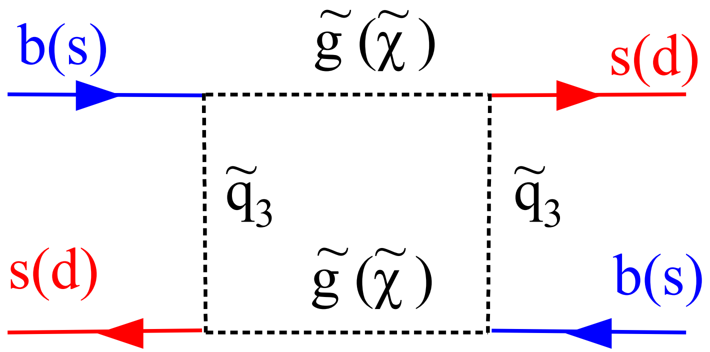


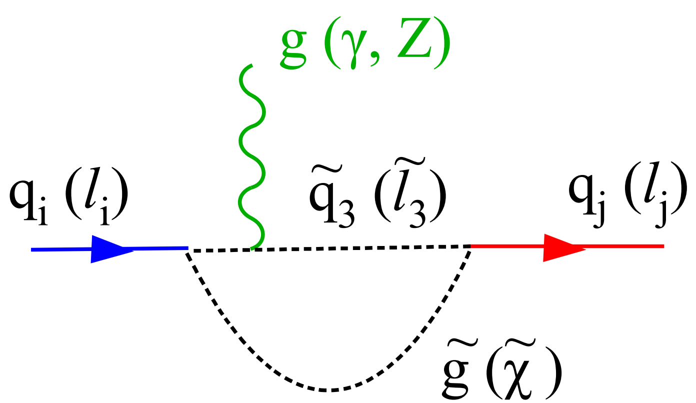
CMS 0l+1l combination for 2-/3-body decay

SUSY and CPV in the $K \to \pi\pi$ system

- LHC experiments are setting stringent constraints on this scenario, but a stop below ~ 1 TeV is still allowed.
- In this context, flavor physics plays a key role [non-trivial flavor structure] → BSM effects mediated by 3rd gen. squarks & leptons:



Possible "sizable" [~ 5-20%] effects in
- CPV in K mixing (ε_K)
- $B_{s,d}$ mixing ($\Delta M_{s,d}$)



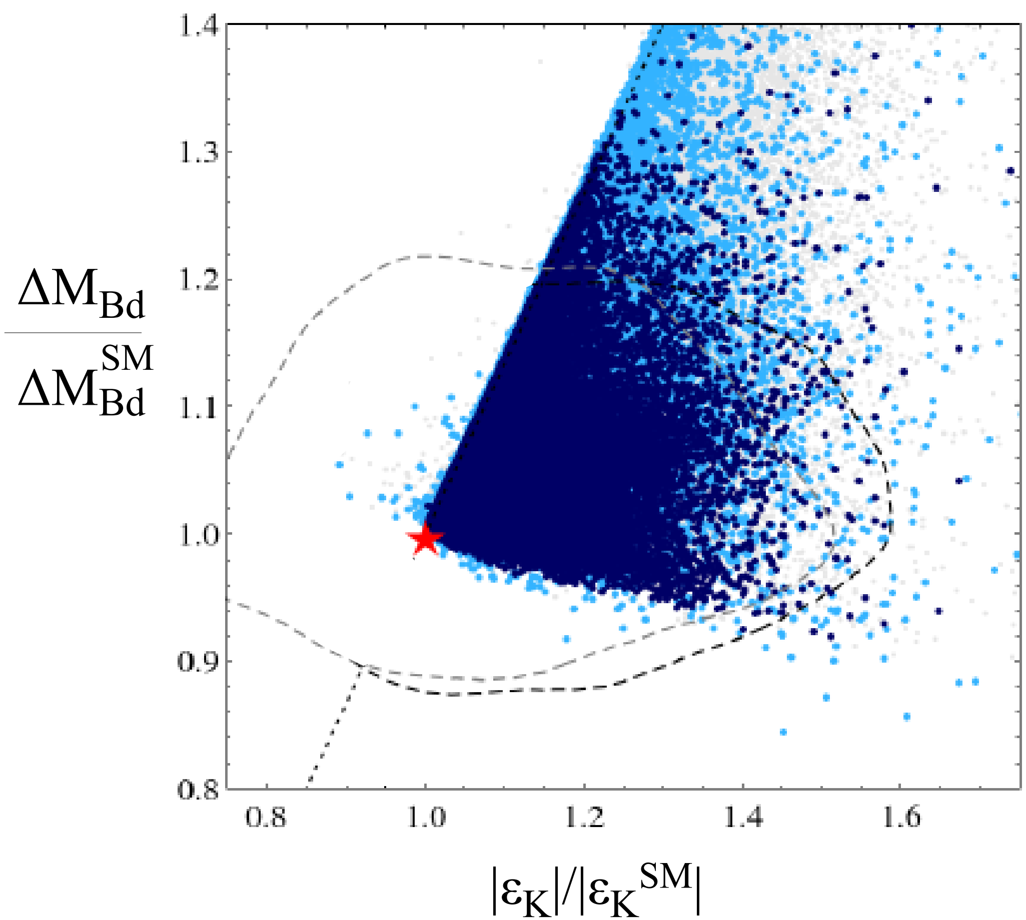
Possible "sizable" [~ 5-100%] effects in
- Rare B & K decays
- direct CPV in $K \to \pi\pi$ (ε'/ε)

Barbieri *et al.* '12-'14; Delgado *et al.* '13
Althmanshofer, Harnik, Zupan, '13
Katz, Reece, Sajjad '14 + ...

SUSY and CPV in the $K \to \pi\pi$ system

Example: $\Delta F=2$ *observables in "Split-family" SUSY with* $U(2)^3$ *flavor symmetry*

Barbieri, Buttazzo, Sala, Straub, '14



Points allowed by 2015 CMS/ATLAS data

SUSY and CPV in the $K \to \pi\pi$ system

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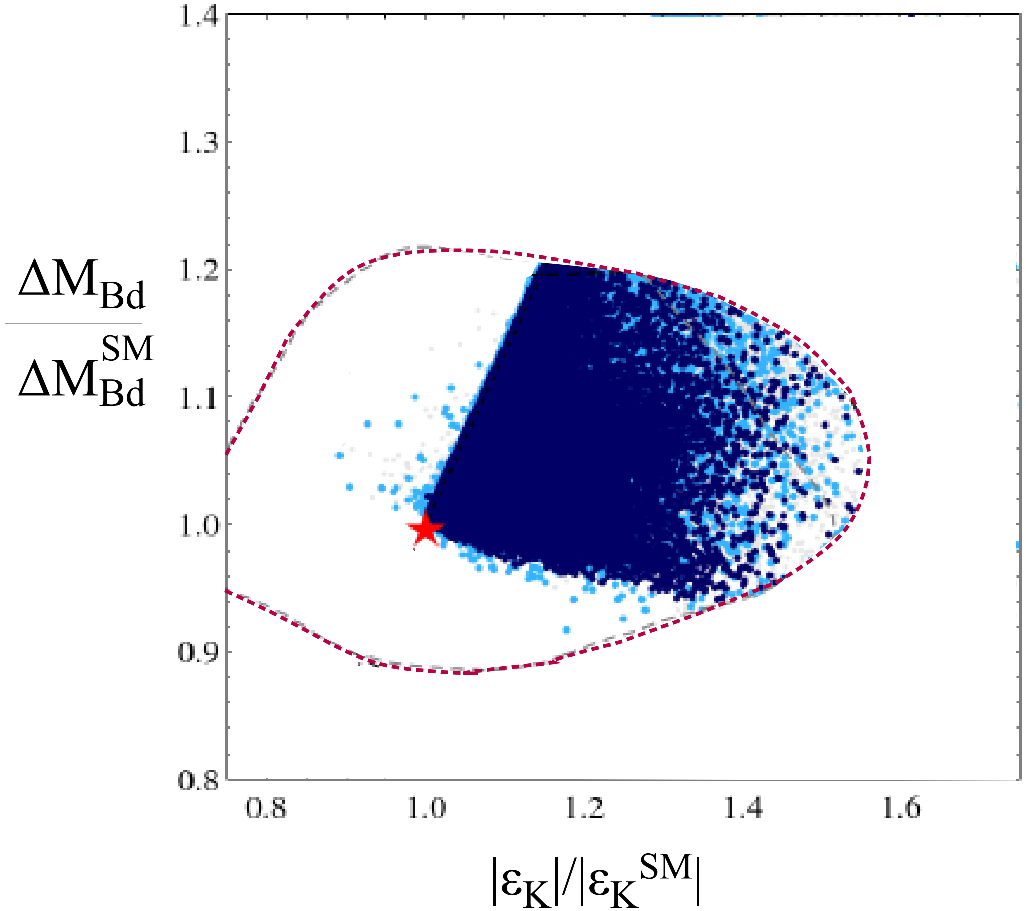
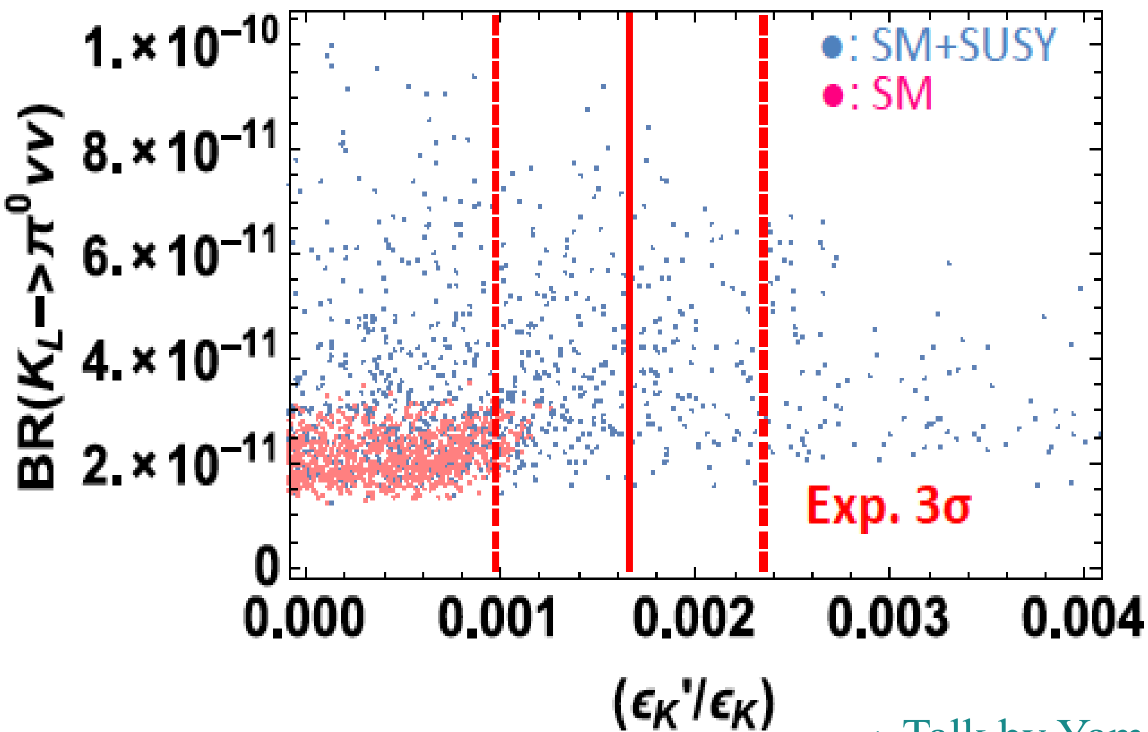


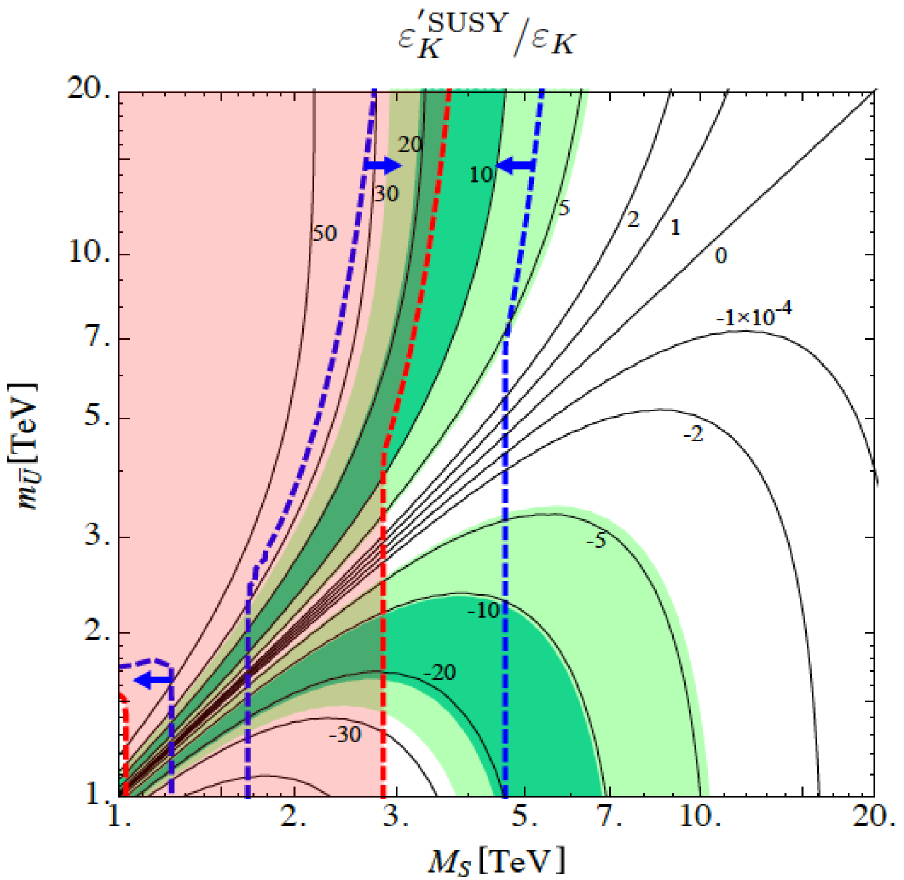
Points allowed by 2015 CMS/ATLAS data + flavor constraints

▶ SUSY and CPV in the $K \to \pi\pi$ system

The effects are potentially even larger in ε'/ε, compared to SM, in the absence of "*protective flavor symmetries*" (such as $U(2)^3$)

→ explicit examples of sensitivity to models not directly accessible in high-pT experiments:





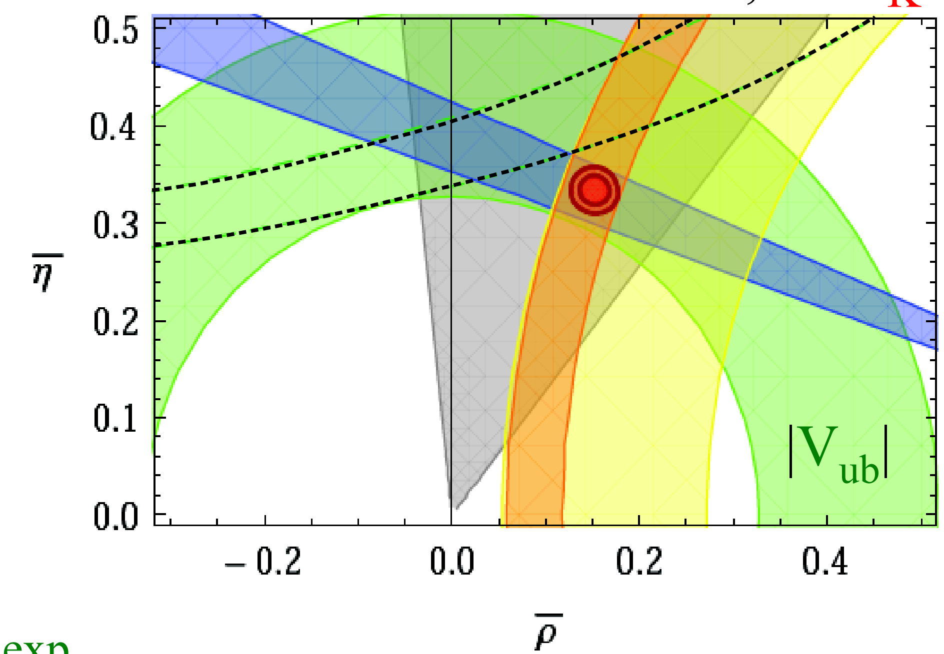
→ Talk by Yamamoto

→ Talk by Kitahara

SUSY and CPV in the $K \to \pi\pi$ system

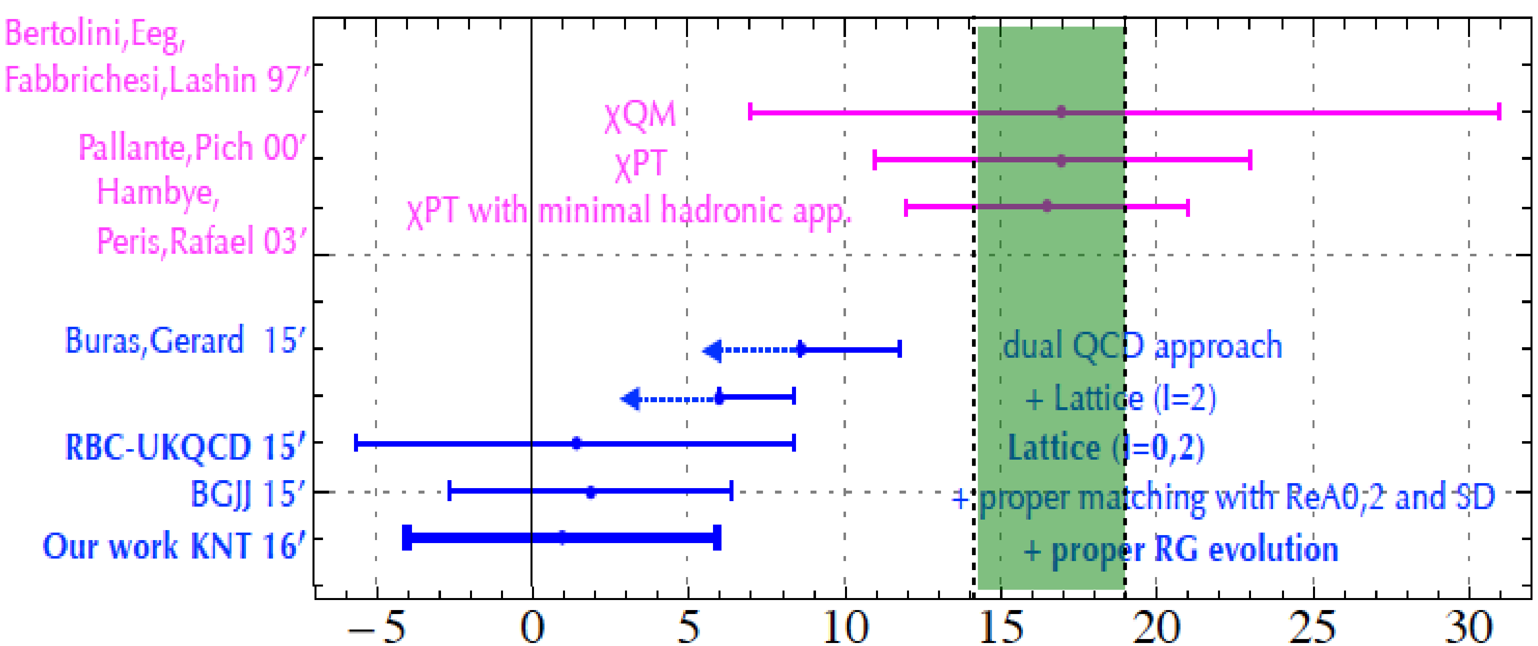
All these NP effects are particularly interesting in view of the present $(\mathrm{TH})_{SM}$ vs. EXP status of both ε_K & ε'/ε

SM fit, no ε_K



Th. predictions of $(\varepsilon'/\varepsilon)_{SM}$

$(\varepsilon/\varepsilon)_{exp}$



→ Talks by Buras & Kitahara

▶ *SUSY and CPV in the $K \to \pi\pi$ system*

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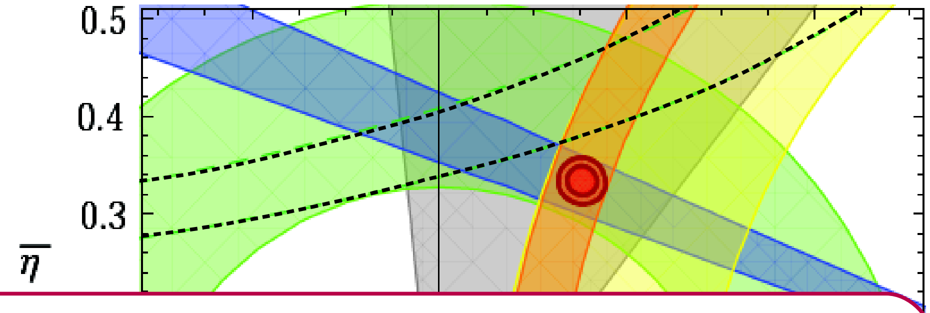
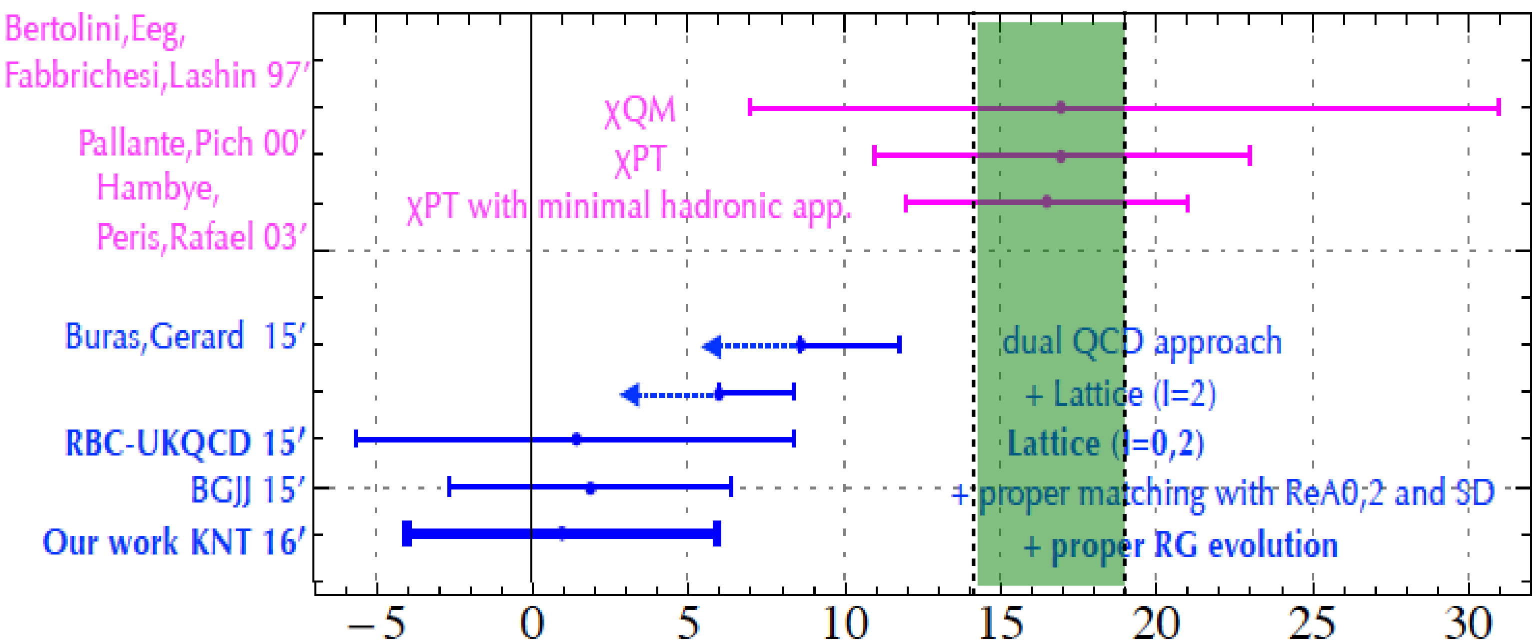


I believe we are still far from a definite conclusion (TH errors still large), but the *future is very promising* given the recent remarkable progress from Lattice QCD [→ Sachrajda, Garron, Feng, Martinelli, Lee]

$(\varepsilon/\varepsilon)_{exp}$



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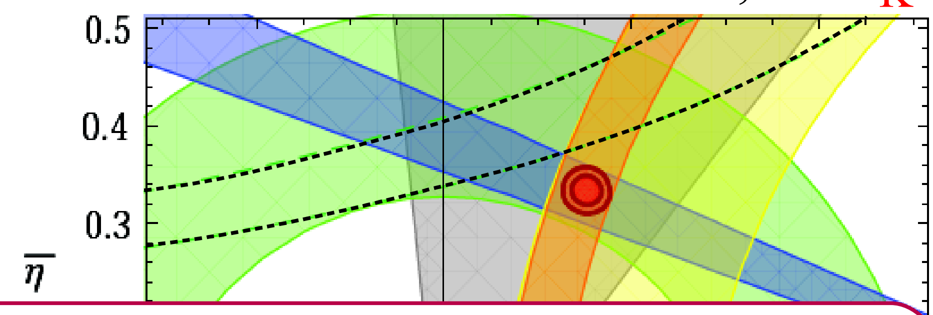

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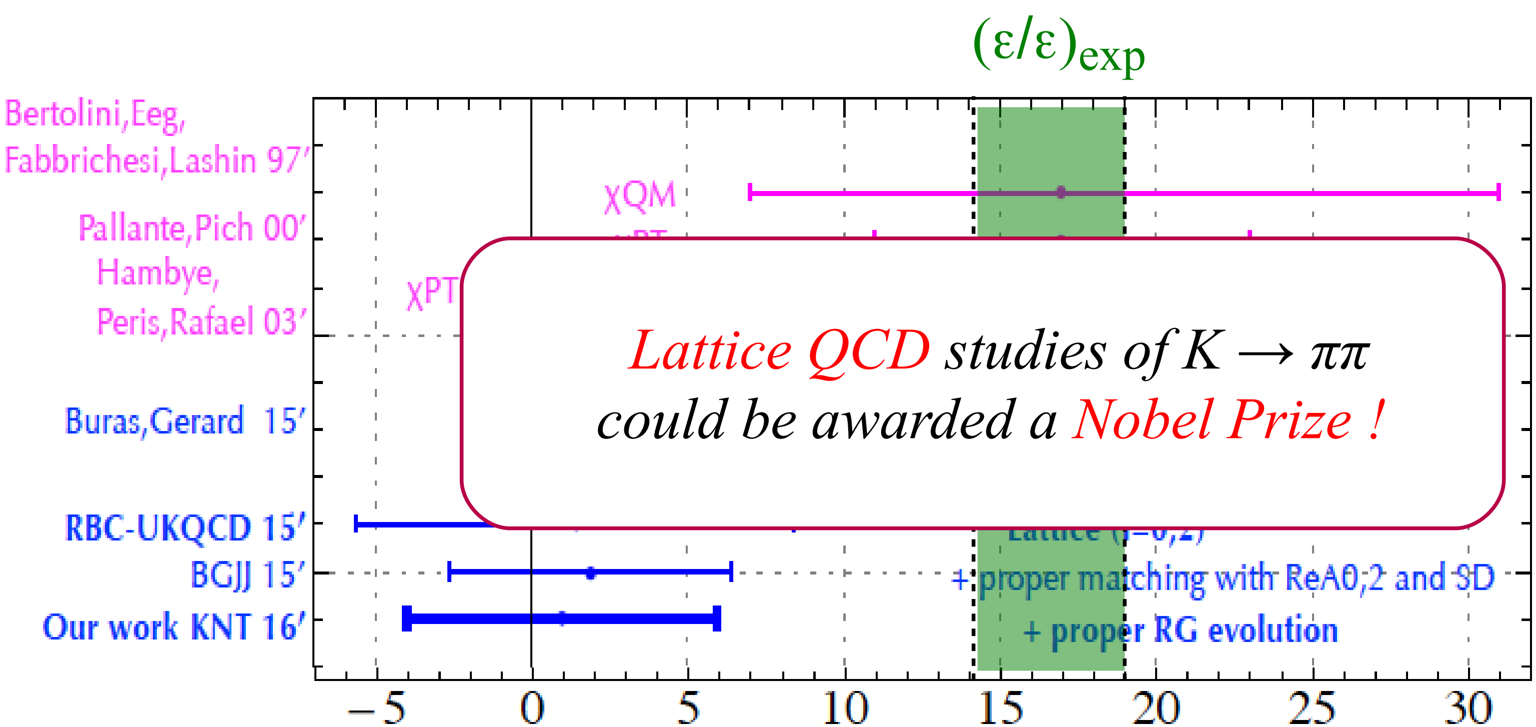
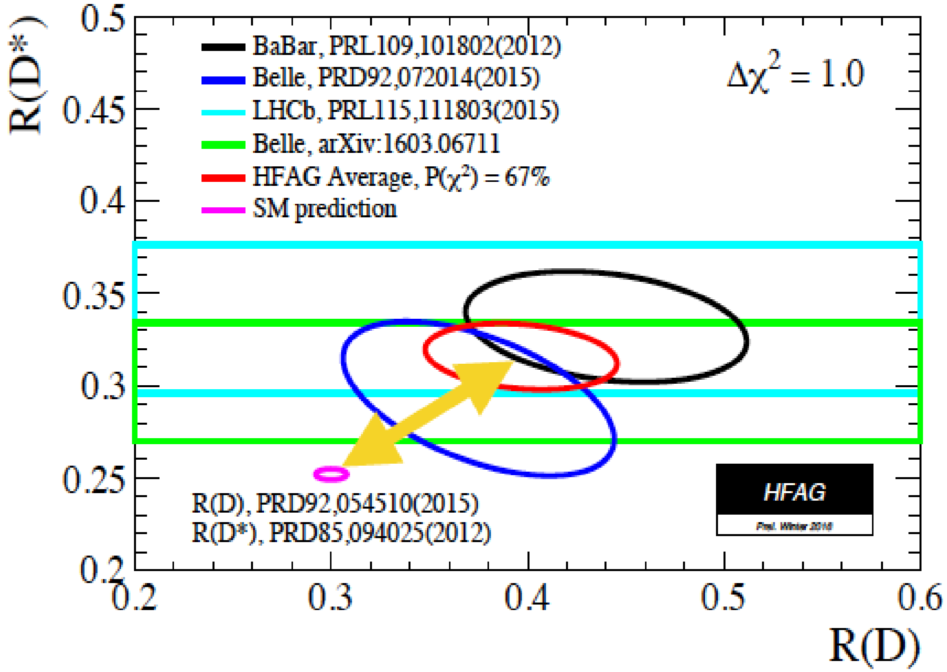
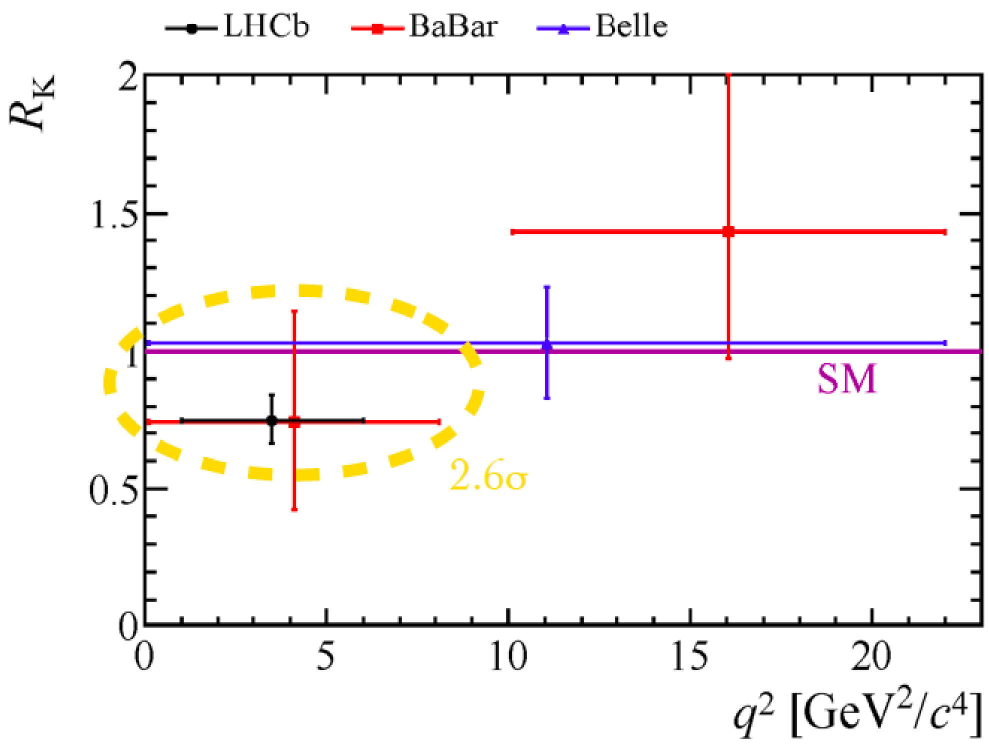


Lattice QCD studies of $K \to \pi\pi$ could be awarded a Nobel Prize !

→ Talks by Buras & Kitahara

Lepton Flavor Universality



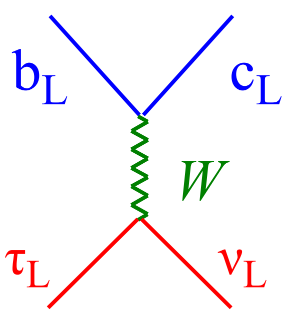


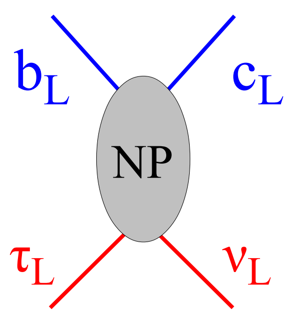
Lepton Flavor Universality

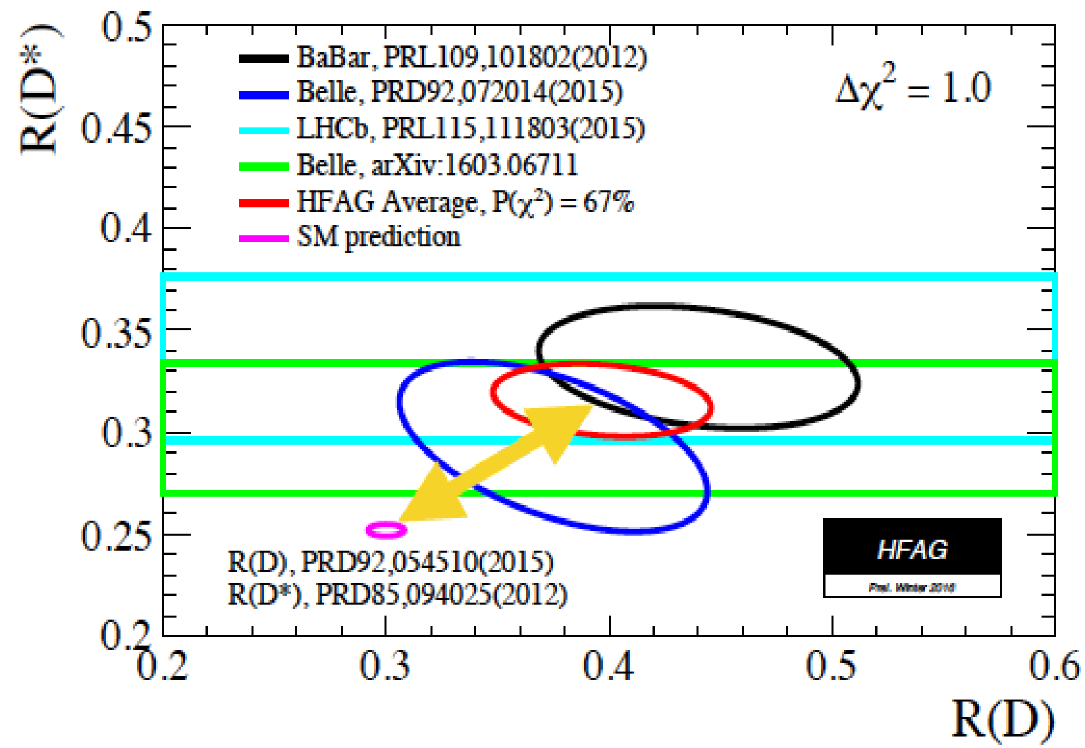
A renewed interest in possible violations of LFU has been triggered by two very different sets of observations in B physics:

I) LFU test in $b \to c$ charged currents: τ vs. light leptons (μ, e)

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$







- SM prediction quite solid: f.f. uncertainty cancel (*to a good extent...*) in the ratio
- Consistent results by 3 different exps. → 4σ excess over SM (*combining D and D**)
- D & D* channels are well consistent with a universal enhancement (~15%) of the SM $b_L \to c_L\ \tau_L\ \nu_L$ amplitude (*RH or scalar amplitudes disfavored*)

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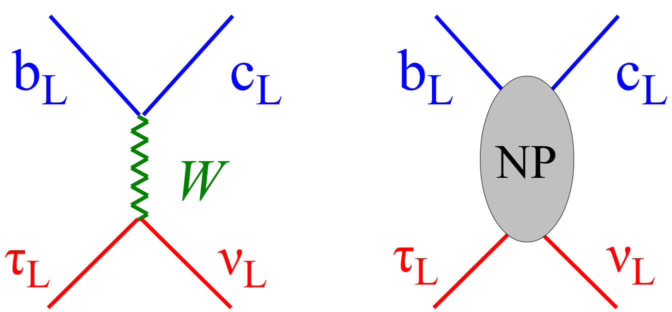

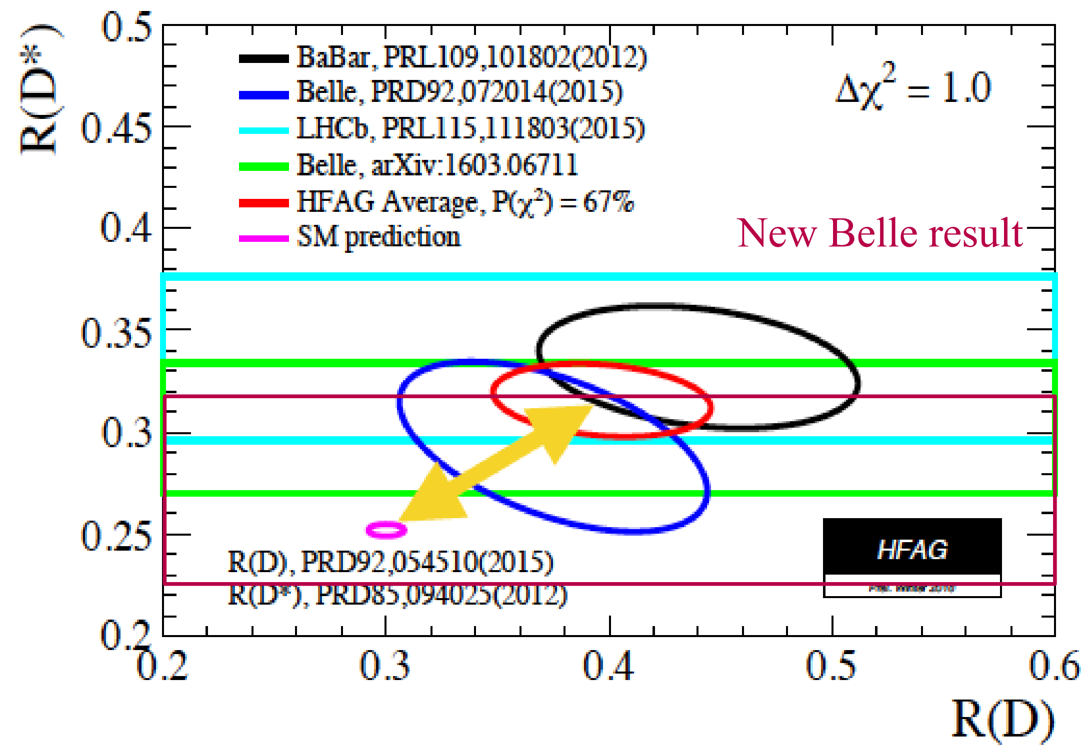

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I) LFU test in $b \to c$ charged currents: τ vs. light leptons (μ, e)

II) LFU test in $b \to s$ neutral currents: μ vs. e

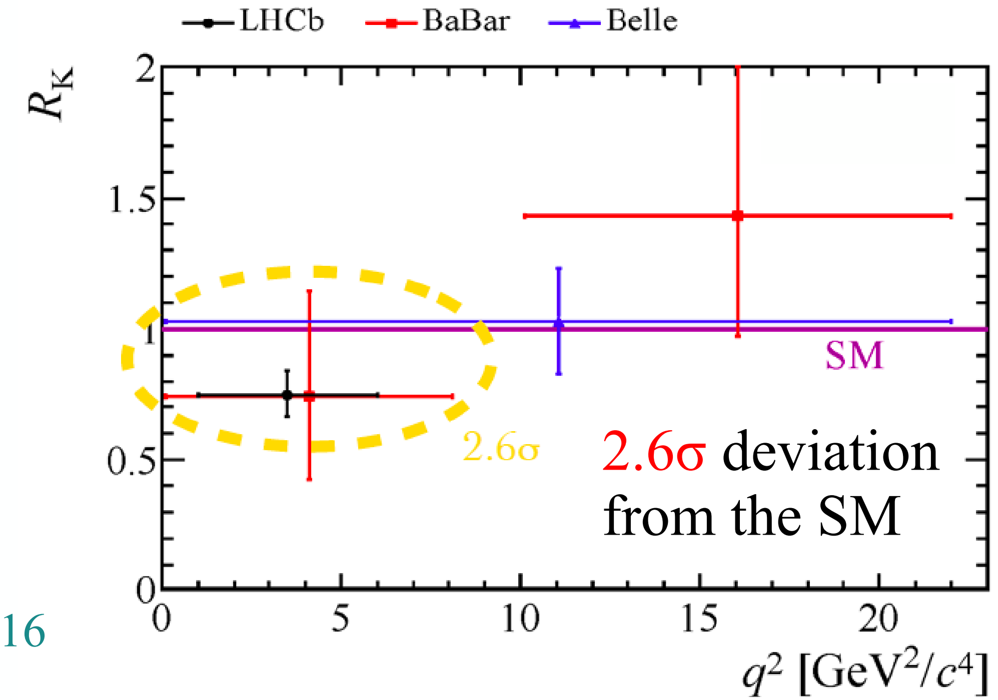
$$R_K = \frac{\int d\Gamma(B^+ \to K^+ \mu\mu)}{\int d\Gamma(B^+ \to K^+ ee)}$$

[1-6] GeV^2

- Negligible th. error → clean test of LFU (in neutral currents)

$$(R_K)_{SM} = 1.00 \pm 0.01$$

Bordone, G.I., Pattori, '16



- The statistical significance of R_K alone is small, but it increases significantly when combined with the P5'($B \to K^*\mu\mu$) anomaly → consistency of the two effects assuming ~~LFU~~ NP that affects only (mainly) $b \to s\mu\mu$ [*and not* $b \to see$]

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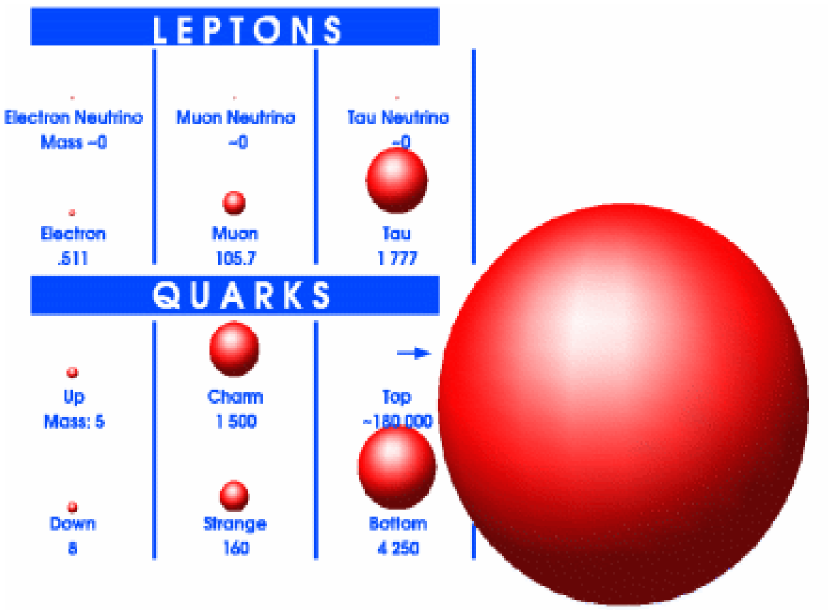
This is probably the largest "coherent" set of NP effects in present data... … and indeed it has triggered a lot of discussion

A few general messages:

- LFU is not a fundamental symmetry of the SM Lagrangian (*global symmetry of the gauge sector only, broken by Yukawas*)
- LFU tests at the Z peak are not too stringent ($\to$ gauge sector)
- Most stringent tests of LFU involve only 1st-2nd gen. quarks & leptons



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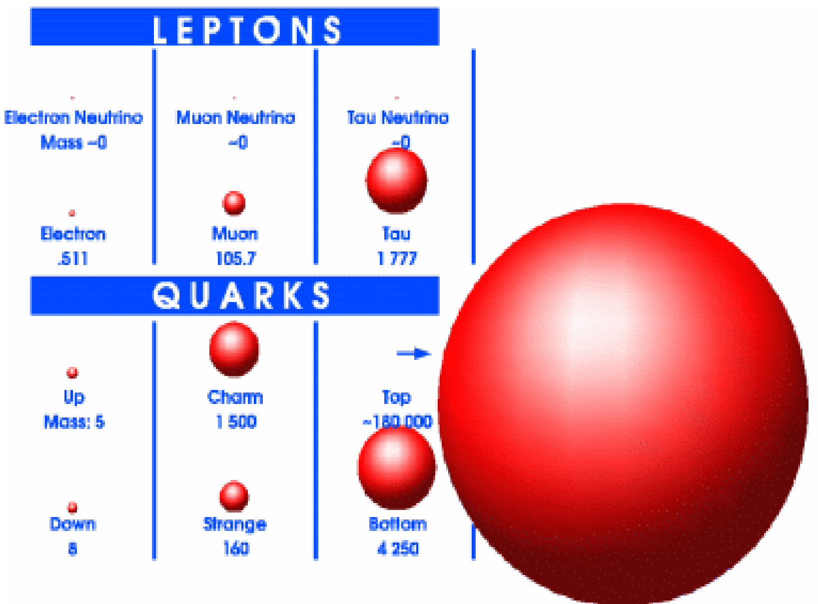

Natural to conceive NP models where LFU is violated more in processes involving 3rd gen. quarks & leptons (↔ *hierarchy in Yukawa coupl.*)

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↓

Natural to conceive NP models where LFU is violated more in processes involving 3rd gen. quarks & leptons (↔ *hierarchy in Yukawa coupl.*)

… but some smaller effects should be expected also in the 2nd generation → Kaon Physics

↓

Strong renewed interest in all possible LFU tests in Kaon Physics, both in charged & in neutral currents

Important shift of paradigm in our view of NP tests in flavor physics

▶ *Lepton Flavor Universality*

EFT considerations connect LFU violations in B physics ("hints") & K physics:

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- RR and scalar currents disfavored → LL current-current operators
- Necessity of at least one $SU(2)_L$-triplet effective operator (*as in the Fermi theory*):

$$\frac{g_q g_\ell}{\Lambda^2}\lambda^q_{ij}\lambda^\ell_{kl}(\bar{Q}^i_L T^a \gamma_\mu Q^j_L)(\bar{L}^k_L T^a \gamma^\mu L^l_L)$$

Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15

- Large coupling (competing with SM tree-level) in bc ($=33_{CKM}$) → $l_3\, \nu_3$
- Small non-vanishing coupling (competing with SM FCNC) in bs → $l_2\, l_2$

$$\lambda^{q,\ell}_{ij} = \delta_{i3}\delta_{3j}$$ + small corrections for 2nd (& 1st) generations

→ fits well with the idea of approximate $U(2)^n$ flavor symmetry
(possible links with models explaining the "origin" of flavor)

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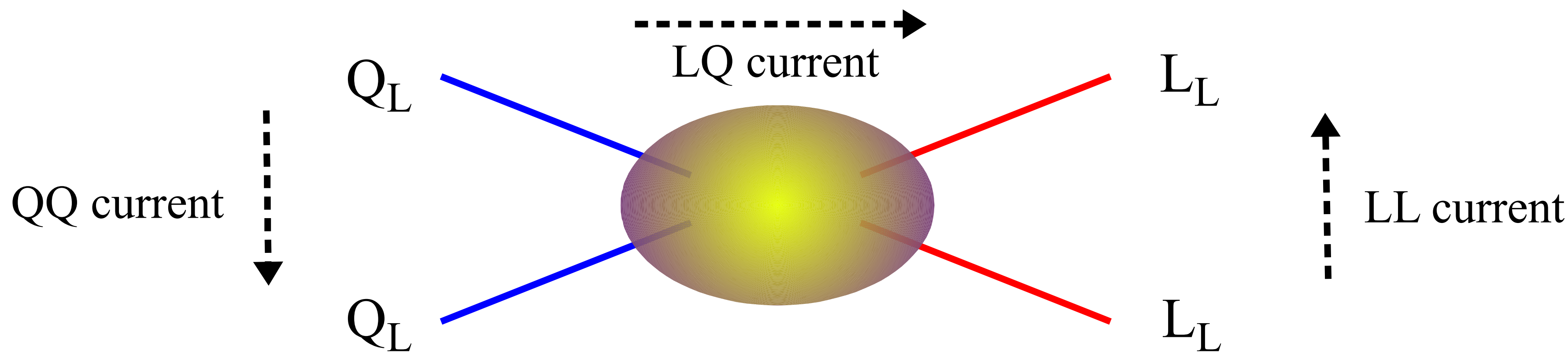


- Two natural classes of mediators, giving rise to different correlations among quark×lepton ("hints") and quark×quark + lepton×lepton (bounds)

Lepton Flavor Universality

Example-I: *charged currents*

The key observable for LFU tests is

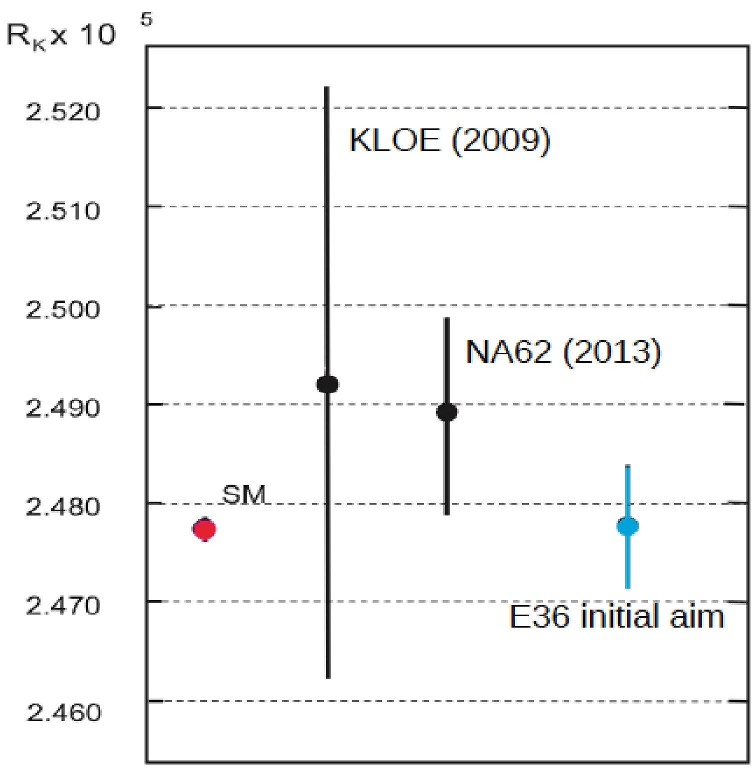
$R_K = \Gamma(K^+ \to e^+\nu) / \Gamma(K^+ \to \mu^+\nu)$

From R(D*) & R(D):
$[\Gamma(b \to c\tau\nu)/\Gamma(b \to c\mu\nu)] \sim 20\%$

→ $\Gamma(b \to c\mu\nu)/\Gamma(b \to ce\nu) \sim 2\,\%$

↓

$\Gamma(s \to u\mu\nu)/\Gamma(s \to ue\nu) \sim 0.2\,\%$



- **Highly Precise SM value**

  R_K = (2.477 ± 0.001) x 10^{-5}

  [V. Cirigliano, I. Rosell, Phys. Rev. Lett. 99, 231801

- **World Average (2013)**

  R_K = (2.488 ± 0.01) x 10^{-5} $\Delta R_K/R_K \approx 0.4\%$

Maybe not impossible to reach this natural NP "benchmark"...

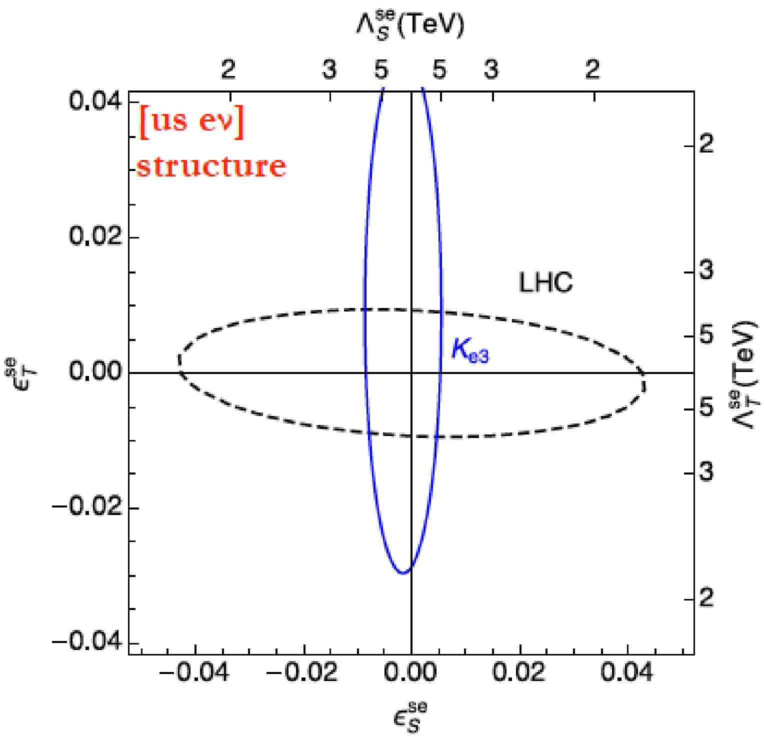
Lepton Flavor Universality

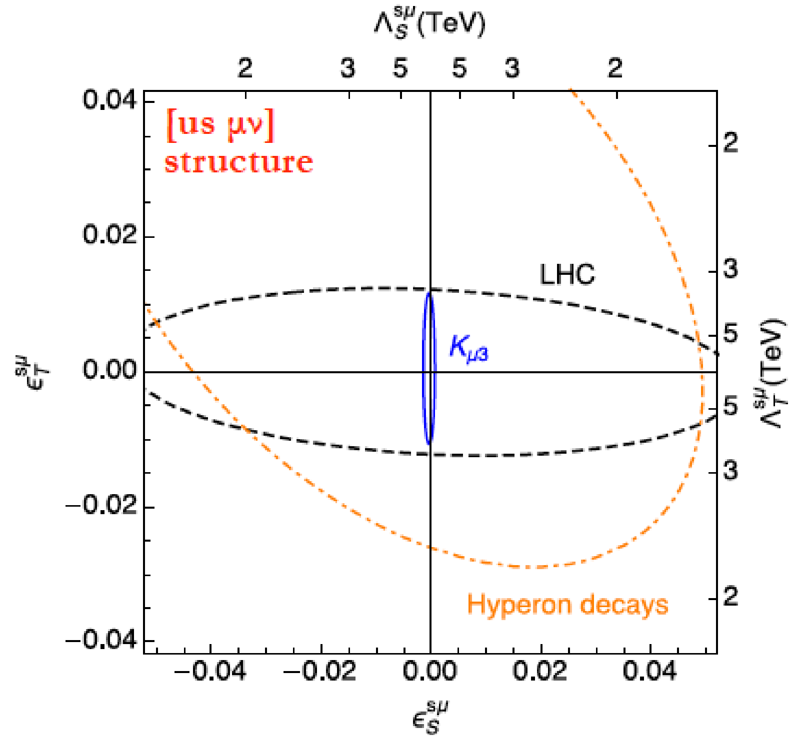
Example-I: *charged currents*

The key observable for LFU tests is

$$R_K = \Gamma(K^+ \to e^+\nu) \, / \, \Gamma(K^+ \to \mu^+\nu)$$

More generally, precise tests of c.c. are definitely worth to be improved (*combined effort of* Exp + Lattice + EFT) → very powerful constraints on NP:

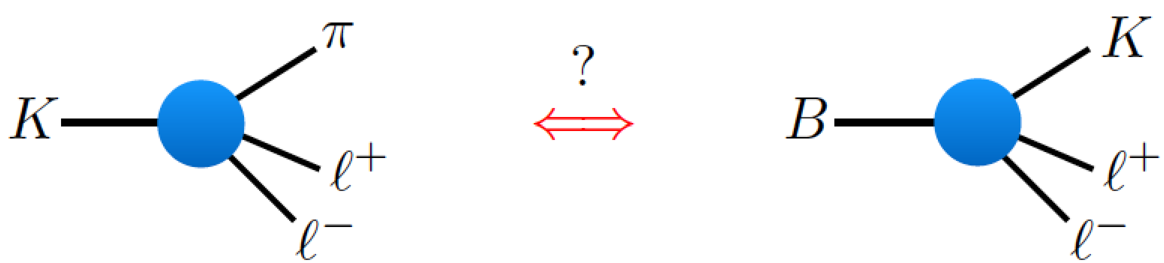




→ Talk by Gonzales-Alonso

Lepton Flavor Universality

Example-II: *neutral currents, $\mu^+\mu^-$ vs. e^+e^-*



→ Talk by Tunstall

$$V_+(z) = a_+ + b_+ z + V_+^{\pi\pi}(z)$$

Channel	a_+	b_+	Reference
ee	-0.587 ± 0.010	-0.655 ± 0.044	E865 [78]
ee	-0.578 ± 0.016	-0.779 ± 0.066	NA48/2 [79]
$\mu\mu$	-0.575 ± 0.039	-0.813 ± 0.145	NA48/2 [80]

→ Talk by Portoles

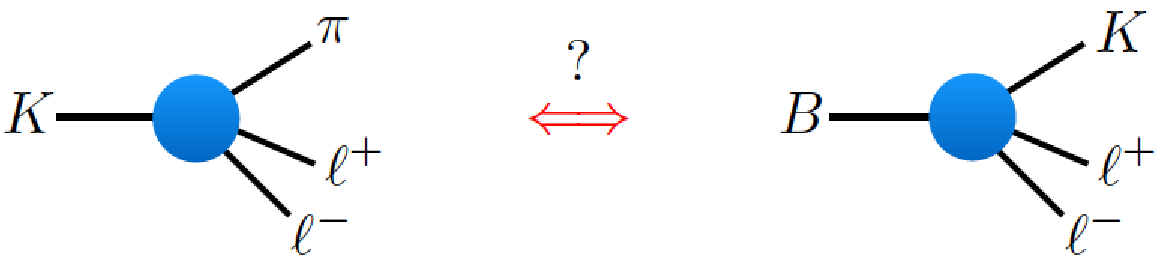
From $\Delta R_K(B) \sim 20\%$
[*assuming* MFV *or* $U(2)^3$]

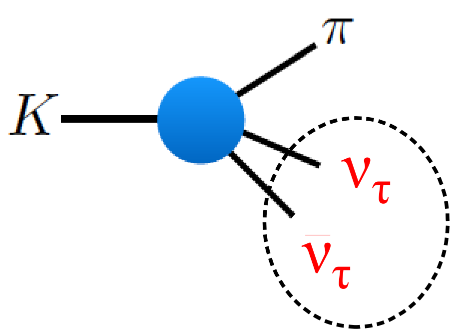
$$\left| a_+^{\mu\mu} - a_+^{ee} \right| \lesssim 0.5 \times 10^{-3}$$

Not easy (impossible?) to reach this "benchmark", but still worth trying to improve...

Lepton Flavor Universality

Example-II: *neutral currents, $\mu^+\mu^-$ vs. e^+e^-*





Access to 3rd gen. leptons as in R(D) & R(D*)

...but a potential more promising effect could appear in our beloved $K \to \pi\nu\nu$ decays....

SM, BSM, & "non-standard BSM" in K → πνν

The "holy grail" of kaon physics...

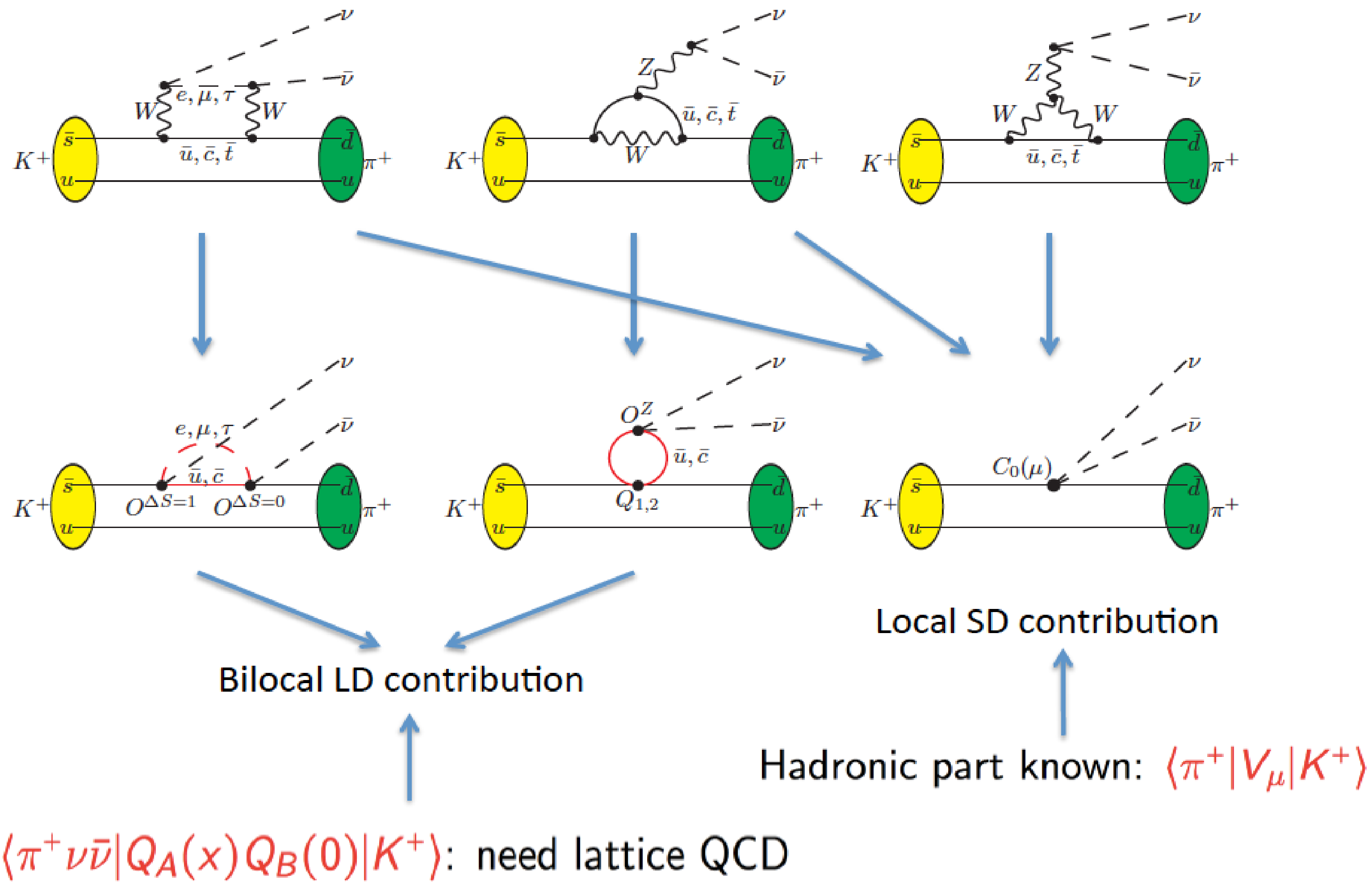
The "golden modes"...

The good ones:

$$A(s \to d\nu\bar{\nu}) \sim \frac{m_t^2}{m_W^2}\lambda_t + \frac{m_c^2}{m_W^2}\ln\frac{m_W}{m_c}\lambda_c + \frac{\Lambda_{\rm QCD}^2}{m_W^2}\lambda_u$$

SM, BSM, & "non-standard BSM" in $K \to \pi\nu\nu$

Actually "good" ≠ "trivial"... some "bad" & "ugly" features are hidden also these golden modes, but luckily their relative weight in the BR is quite small...



→ Talk by Feng

SM, BSM, & "non-standard BSM" in $K \to \pi\nu\nu$

$K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ in the SM

QCD Corrections:

NLO Buchalla, AJB; Misiak, Urban (93, 98)
NNLO AJB, Gorbahn, Haisch, Nierste (2005)

NLO EW Corrections:

Large m_t: Buchalla, AJB (1997)
Exact NLO (m_t): Brod, Gorbahn, Stamou (2010)
" " (m_c): Brod, Gorbahn (2008)

LD Effects:

+ **Isospin breaking corrections**

Isidori, Mescia, Smith (2005)
Mescia, Smith (2007)

⇒ **TH uncertainties at the level of 2% in BR**

Unique in Flavour Physics !!

A long story.... that is likely to continue thanks to the progress of Lattice QCD

SM, BSM, & "non-standard BSM" in $K \to \pi\nu\nu$

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LD Effects:

Isidori, Mescia, Smith (2005)
Mescia, Smith (2007)

\+ **Isospin breaking corrections**

After inclusion of parametric errors

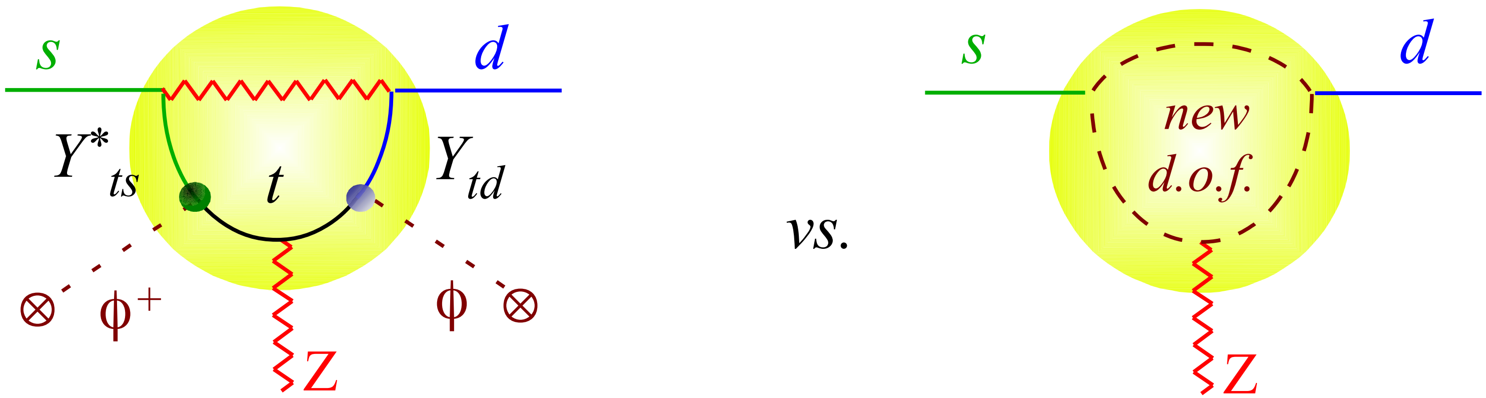
$$\mathrm{Br}\left(K^+ \to \pi^+\nu\bar{\nu}\right) = \left(8.4 \pm 1.0\right)\cdot 10^{-11}$$
$$\mathrm{Br}\left(K_L \to \pi^0\nu\bar{\nu}\right) = \left(3.4 \pm 0.6\right)\cdot 10^{-11}$$

Buras *et al.* '15

A long story.... that is likely to continue thanks to the progress of Lattice QCD

Most important: *we are finally not far from a precise comparison with data...!*

SM, BSM, & "non-standard BSM" in $K \to \pi\nu\nu$



A unique probe of possible deviations from MFV
and of the interplay between flavor and EW symmetry breaking.

O(10-20%) deviations in the Zsd effective coupling are perfectly allowed in well-motivated BSM models
[e.g. SUSY with "disoriented A terms" → Giudice, GI, Paradisi '12]

SM, BSM, & "non-standard BSM" in $K \to \pi\nu\nu$

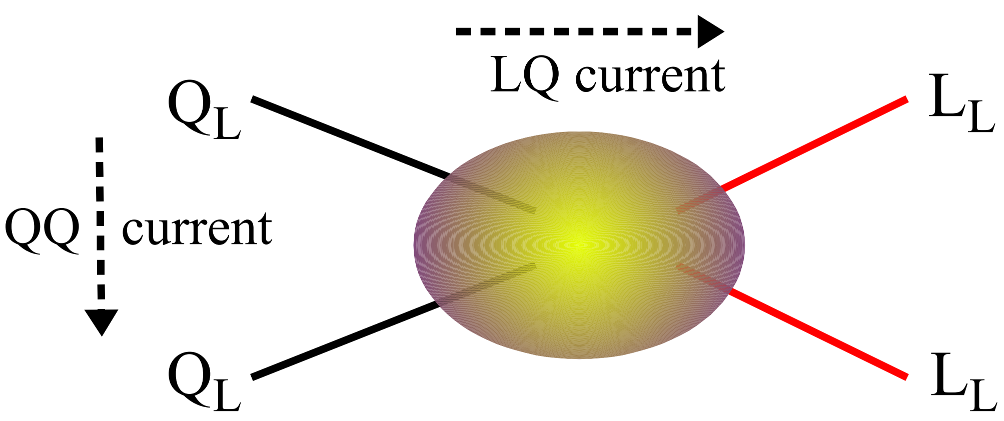
But what I find even more interesting, is the natural link with LFU effects in B-physics, thanks to the presence of 3rd generation leptons in the final state

$$\Gamma(K \to \pi\nu\nu) = \Gamma(K \to \pi\nu_e\bar{\nu}_e) + \Gamma(K \to \pi\nu_\mu\bar{\nu}_\mu) + \Gamma(K \to \pi\nu_\tau\bar{\nu}_\tau)$$

SM like

few % deviation as in $b\to s\mu\mu$

possible O(1) deviation from SM expected also in $b\to s\tau\tau$



Explicit (UV) models:

- LQ (composite) mediators
  Barbieri, GI, Pattori, Senia '16
- Z',W' (composite) mediators
  GI *et al.* - work in prog.

SM, BSM, & "non-standard BSM" in $K \to \pi\nu\nu$

But what I find even more interesting, is the natural link with LFU effects in B-physics, thanks to the presence of 3rd generation leptons in the final state

$$\Gamma(K \to \pi\nu\nu) = \Gamma(K \to \pi\nu_e\bar{\nu}_e) + \Gamma(K \to \pi\nu_\mu\bar{\nu}_\mu) + \Gamma(K \to \pi\nu_\tau\bar{\nu}_\tau)$$

SM like

few % deviation as in $b \to s\mu\mu$

possible O(1) deviation from SM expected also in $b \to s\tau\tau$

↓

The natural "benchmark" is a O(30%) deviation from SM in the measurable (neutrino inclusive) rate

↓

If such a deviation were observed, it would be extremely interesting trying to precisely measure $K_L \to \pi^0 ee/\mu\mu$, (short-distance sensitive but no 3rd gen. leptons)

What's next

The next step

- With a few examples I tried to illustrate the variety of *"BSM frontiers"* that are still open in kaon physics (*and many more I could not discuss for reasons of time: LFV, LNV, portals, ...*).

- The attempt to measure $BR(K^+ \to \pi^+ \nu\nu)$ @ 10% relative error is a milestone (*eagerly awaited...*) in this field, but future dedicated experimental efforts are absolutely justified, independently of the outcome of this crucial step.

- A few examples:
  - $BR(K^+ \to \pi^+ \nu\nu)$ @ few %
  - $BR(K_L \to \pi^0 \nu\nu)$ @ few %
  - $BR(K_L \to \pi^0 l^+ l^-)$ @ few %
  - $R(K_{l2})_{\mu/e}$ @ few 0.01%

- With the steady progress of Lattice QCD, even more ambitious targets could be set in a not too-distant future...

The next step

...is continuing playing in the Kaon Team !

THANK YOU !