Physics opportunities using CERN injectors: *Theoretical considerations*

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- Introduction
- LFV in charged leptons
- Precision measurements of FCNCs
- Exotic light states
- Conclusions

Introduction

Despite all its successes, the SM 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*?]
- No natural inclusion of neutrino masses [*hint of unification*?]
- Non coherent inclusion of gravity at the quantum level

...

- No good candidates to explain dark matter, inflaton, and dark-energy

⬇

The SM is likely to be an *effective theory*,
i.e. the limit of a more fundamental theory, with new degrees of freedom

Introduction

The SM is likely to be an *effective theory*

↓

We need to search for New Physics
[*with a broad spectrum perspective given the lack of NP signal so far...*]

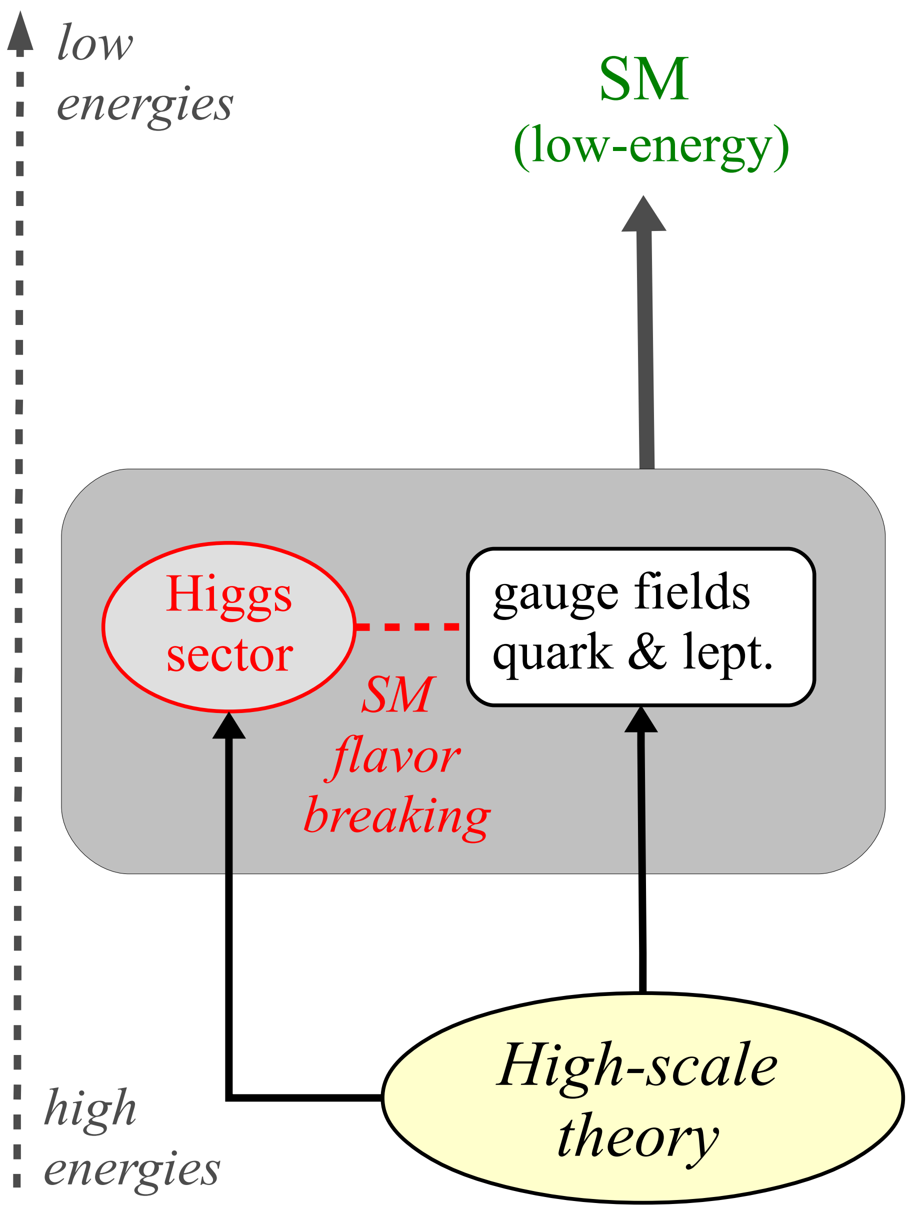
i.e. we need to search for new degrees of freedom
beyond the range of *energies* and *effective couplings* explored so far

↓

High-precision low-energy physics
[= *search for forbidden/rare phenomena occurring at low-energies*]

- Indirect sensitivity to physics ay high-energy scales, not directly accessible at colliders
- Direct sensitivity to weakly-coupled exotic light-states, not seen so far because of limited statistics

Introduction



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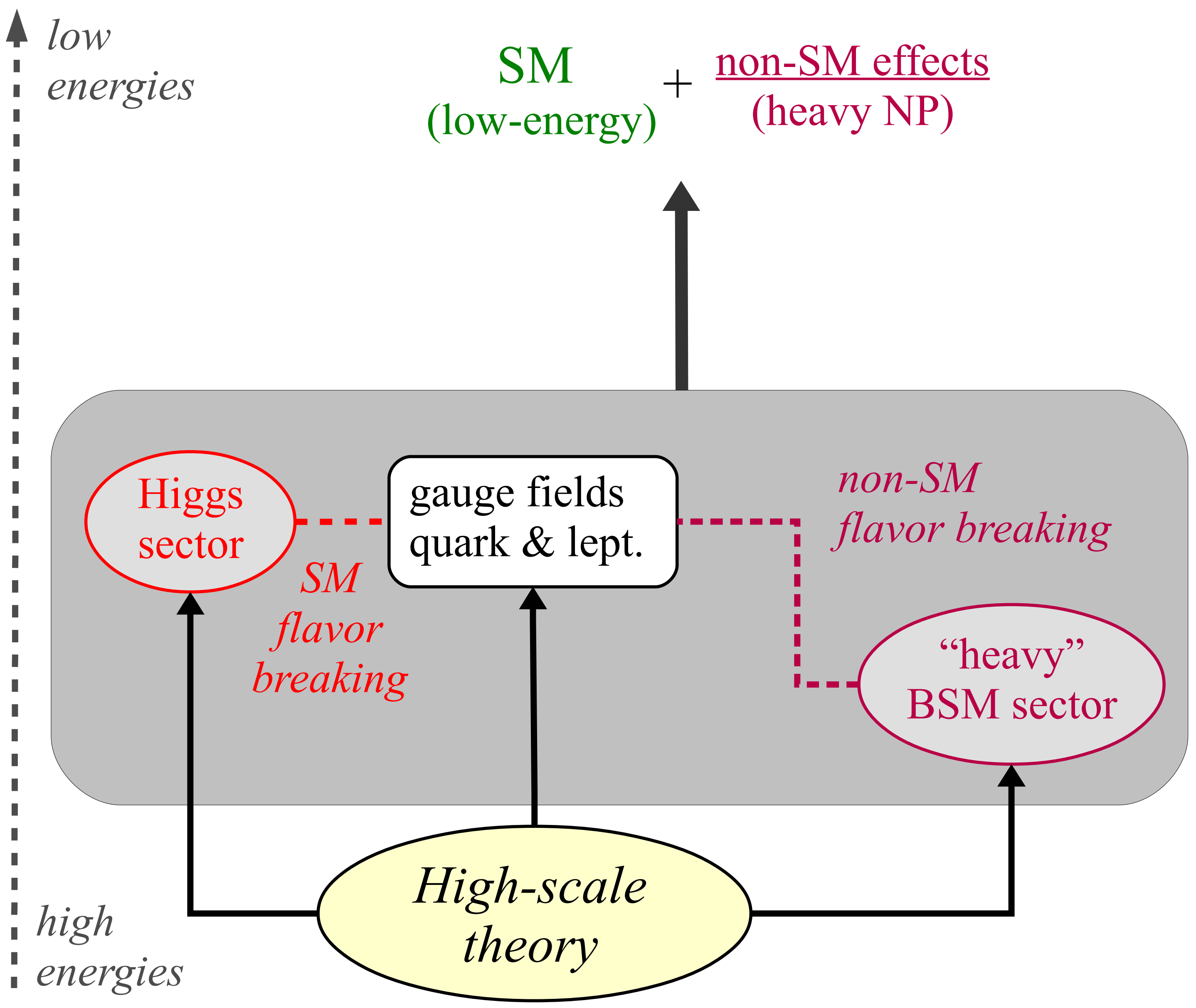

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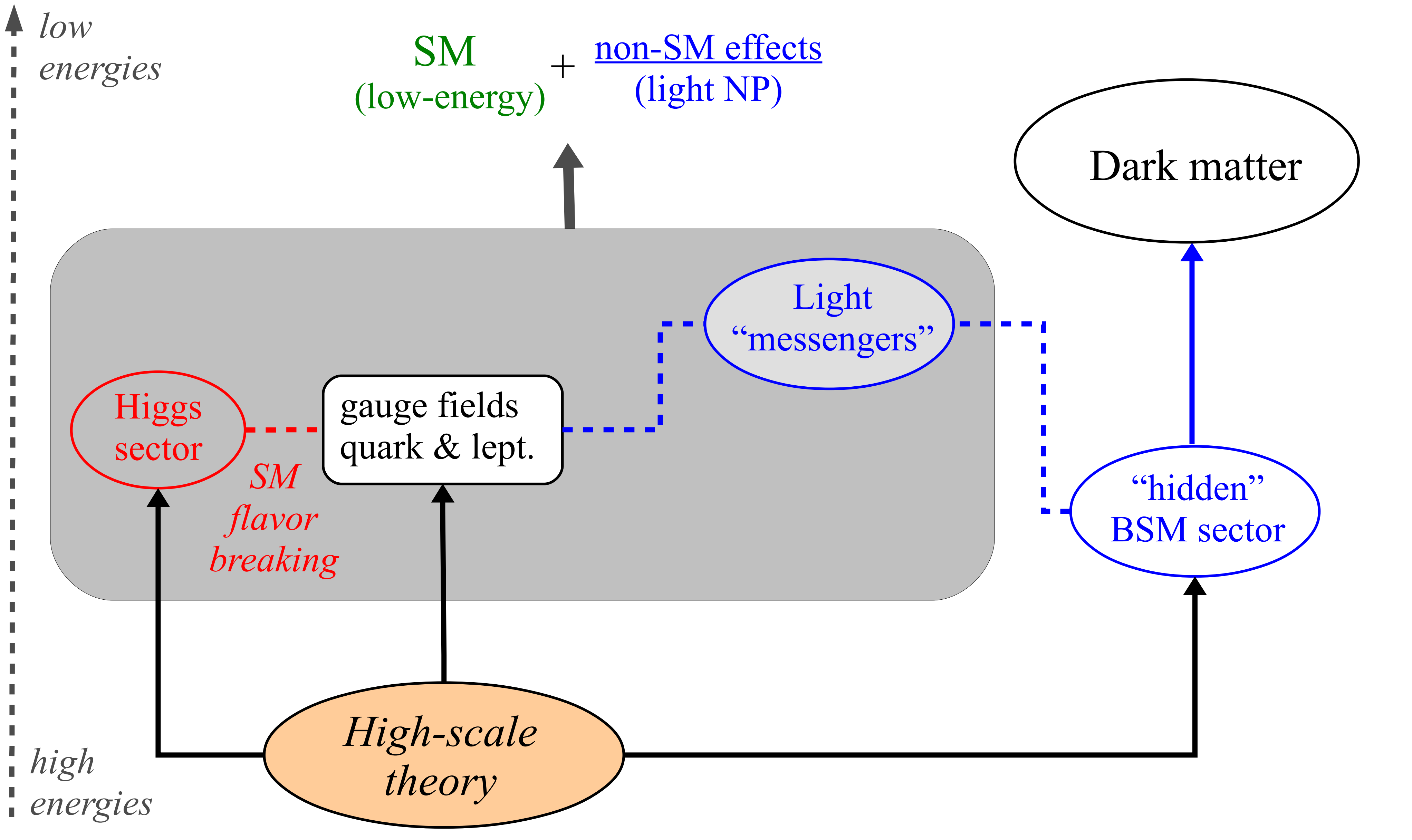


What have we learned so far?

A long series of high-precision measurements (& searches) of flavor-changing processes at low energies has already been performed, both in the quark and in the lepton sector → So far everything seems to fit well with the SM...

→ Strong limits on several NP modes

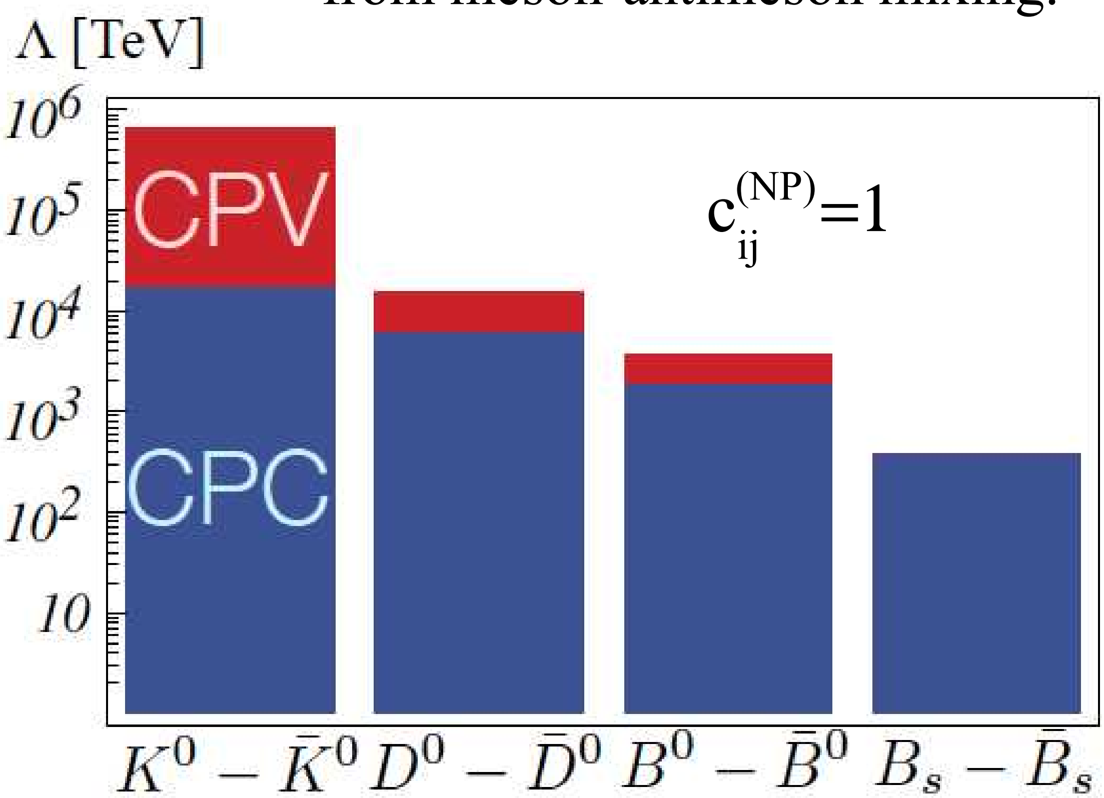
$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{c_{ij}^{(NP)}}{\Lambda^2} O_{ij}^{(6)}$$

Either NP is very heavy...

or

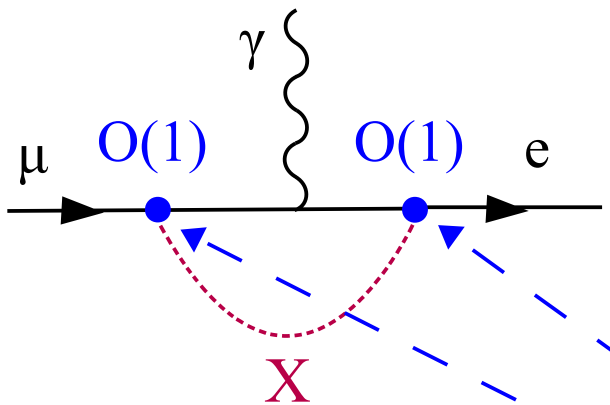
it has a non-trivial flavor-breaking pattern...

E.g.: bounds on the NP scale from meson-antimeson mixing.



What have we learned so far?

A closer look to a specific observable:



$BR(\mu \to e\gamma)^{exp} < 5.7\times10^{-13}$

MEG '13

$M_X \gtrsim 15000$ TeV

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At first sight the bound on the scale is quite impressive...

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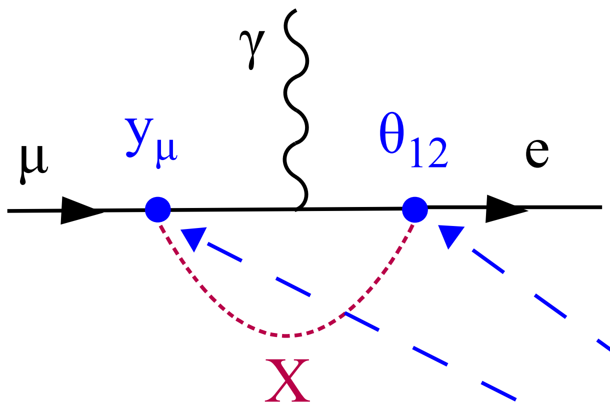

$BR(\mu\to e\gamma)^{exp} < 5.7\times10^{-13}$

MEG '13

$M_X \gtrsim 200$ TeV

Either NP is very heavy... or it has a non-trivial flavor-breaking pattern...

At first sight the bound on the scale is quite impressive...

...but we should not get too depressed!

What have we learned so far?

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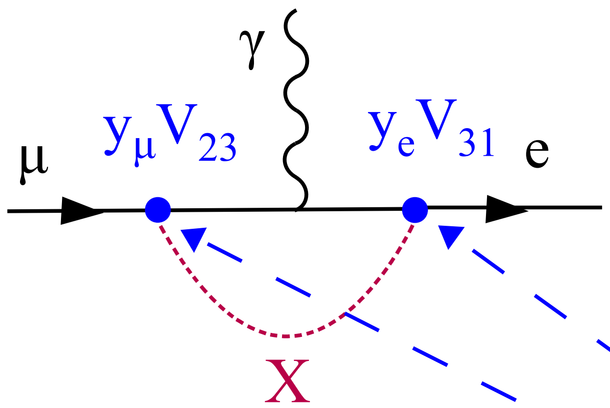

$BR(\mu \to e\gamma)^{exp} < 5.7\times10^{-13}$

MEG '13

$M_X \gtrsim 10$ GeV

Either NP is <u>very heavy</u>... or it has a non-trivial flavor-breaking pattern...

At first sight the bound on the scale is quite impressive...
...but we should not get too depressed!
...and should not forget that a wide region of exotic models is still open!

Four main type of searches relevant to this workshop:

High-scale physics

I. SM forbidden modes [mainly LFV]

E.g.: $\tau \to 3\mu$, $\tau \to \mu\gamma$

But also $K/D \to \mu e$, $K/D \to \pi^+\mu^-\mu^-$, ...

II. Precise measurements of rare FCNCs predicted with high TH accuracy

Not many, but worth dedicated expts.

E.g.: $K \to \pi\nu\nu$, $\Gamma(B_d \to \mu\mu)/\Gamma(B_s \to \mu\mu)$

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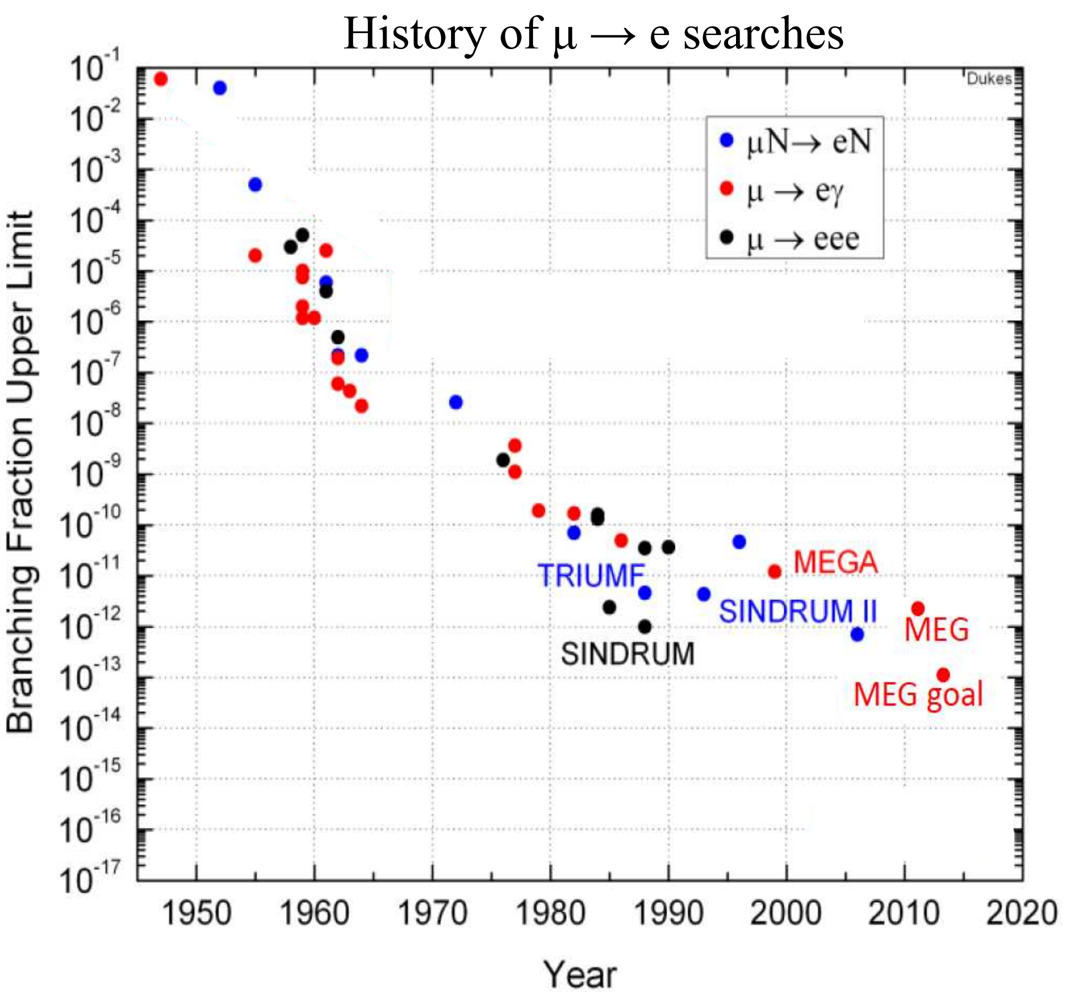
Weakly-coupled exotic light-states

III. Search for short-lived new states
(typically produced in B, D, K
decays & decaying into l^+l^- pairs)
$\to$ high-precision l^+l^- spectra

IV. Search for long-lived new states
$\to$ (largely) displaced vertices
["beam-dump" set-up]

LFV in charged leptons
[*the role of tau decays*]

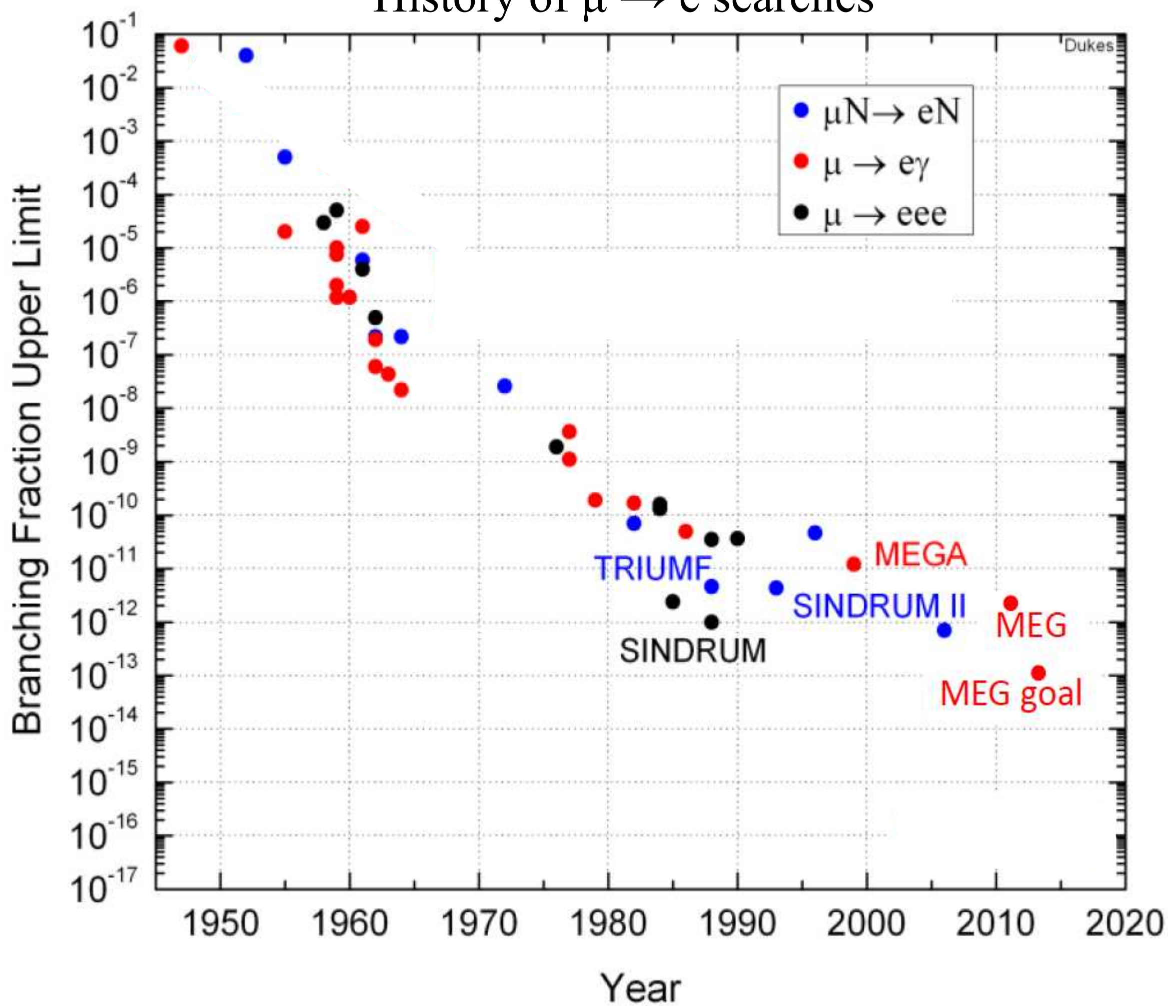


LFV in charged leptons

After what we learned from neutrino physics, LFV in charged leptons is probably the most interesting (*and potentially rewarding*) search in the flavor sector.

- Neutrino oscillations => Lepton Flavor Violation
- No problems of SM (and SM + ν) backgrounds
- LFV in charged leptons at "visible rates" if there are new particles carrying lepton flavor not too far from the TeV scale (*as in most realistic NP models*)

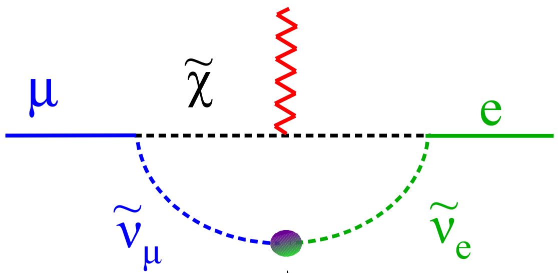
History of μ → e searches



LFV in charged leptons

LFV in charged leptons at "visible rates" if there are new particles carrying lepton flavor not too far from the TeV scale:

E.g.: SUSY



$$(\delta_{LL})_{12} \sim \begin{cases} y_t^2 \; V_{13}V_{23}^* \; [\textit{GUT}] \\ y_{\nu_3}^2 \; U_{13}U_{23}^* \; [\textit{see-saw}] \end{cases}$$

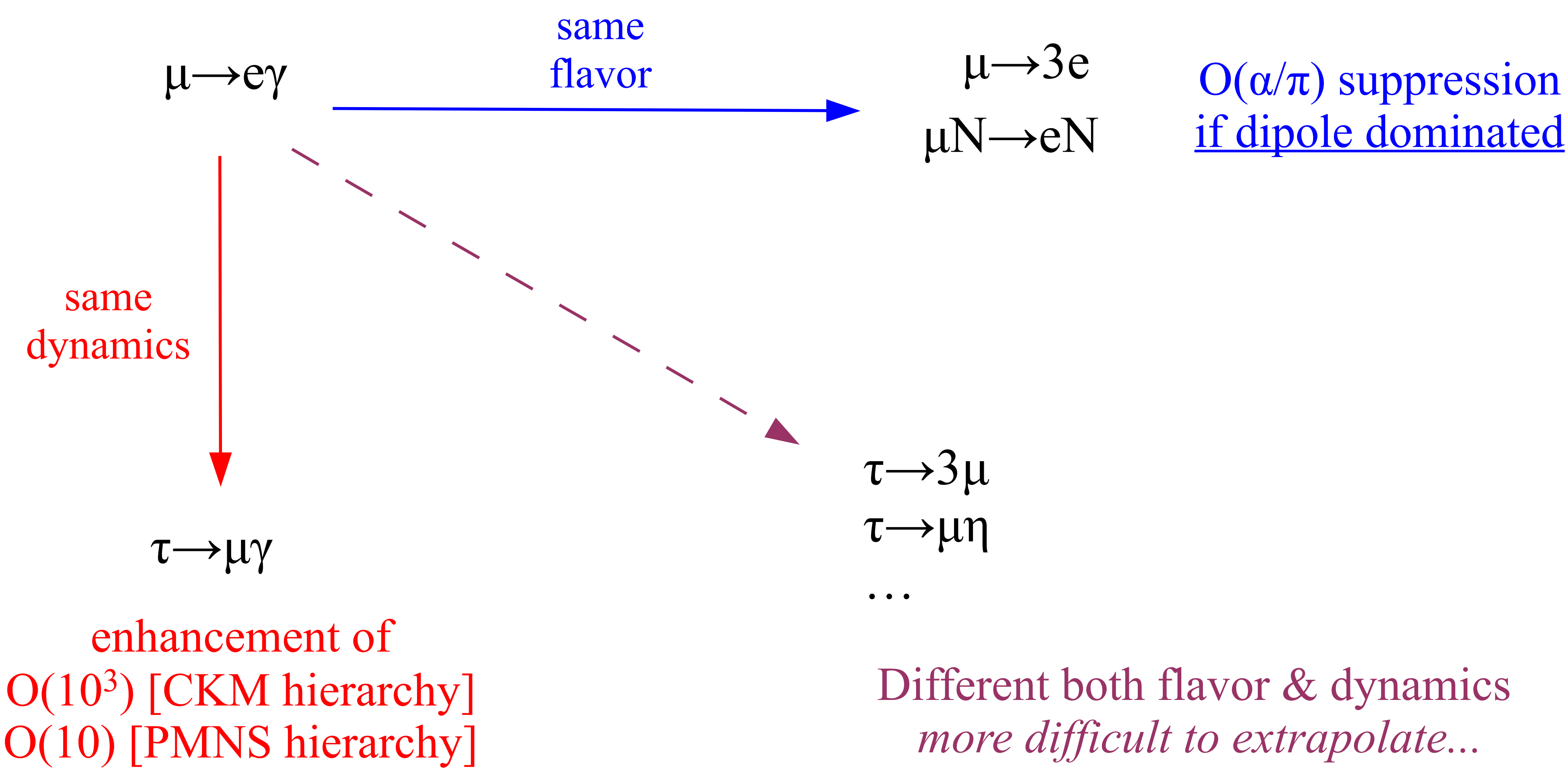
$$B(\mu \to e\gamma) \sim 10^{-13} \left[\frac{\tan\beta}{10}\right]^2 \left[\frac{0.5\ \text{TeV}}{\tilde{m}}\right]^4 \left[\frac{(\delta_{LL})_{12}}{10^{-4}}\right]^2$$

…and similar expressions holds in many other models:

=> MEG has realistic chances to see $\mu \to e\gamma$ (*but remember that* $\Gamma \sim \Lambda^{-4}$)

LFV in charged leptons: future prospects

The recent MEG bound, $BR(\mu\to e\gamma) < 5.7\times10^{-13}$, can be taken as reference values to estimate potentially interesting levels for future LFV searches in different channels:



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→ same flavor →

$\mu\to 3e$

$\mu N\to eN$

$O(\alpha/\pi)$ suppression if dipole dominated

$\lesssim 5\times10^{-15}$

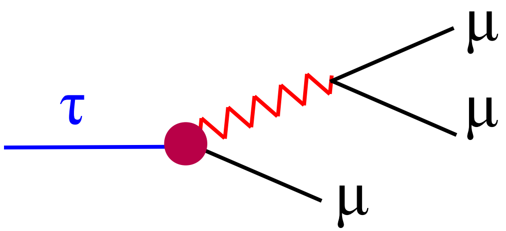
↓ same dynamics ↓

$\tau\to\mu\gamma$ $\lesssim 1\times10^{-9}$

enhancement of
$O(10^3)$ [CKM hierarchy]
O(10) [PMNS hierarchy]

Assuming dipole dominance:

$\tau\to 3\mu$ $\lesssim 1\times10^{-11}$



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N.B.: *if the LFV transitions are "dipole-dominated" no constraints/competition from h(Z) → τμ*

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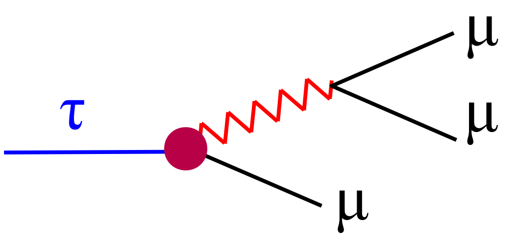

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same dynamics

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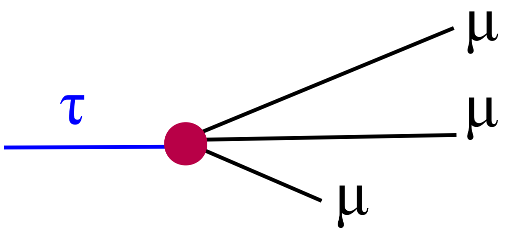
enhancement of
$O(10^3)$ [CKM hierarchy]
$O(10)$ [PMNS hierarchy]

$\mu N\to eN$ $< 7\times10^{-13}$

Sindrum-II

N.B.: *if the LFV transitions are* *not* *"dipole-dominated" (more exotic NP), weaker constraints & possible competition from* $h\to\tau\mu$

$\tau\to3\mu$ $\lesssim 1\times10^{-9}$



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same flavor →

$\mu\to 3e$
$\mu N\to eN$

O(α/π) suppression
if dipole dominated

$\lesssim 5\times10^{-15}$

COMET & Mu2e → $[10^{-15}$–$10^{-18}]$
Mu3e → 10^{-16}

same dynamics ↓

$\tau\to\mu\gamma$ $\lesssim 1\times10^{-9}$

enhancement of
$O(10^3)$ [CKM hierarchy]
O(10) [PMNS hierarchy]

Belle-II → 2×10^{-9}

Assuming dipole dominance:

$\tau\to 3\mu$ $\lesssim 1\times10^{-11}$

LHCb → $\sim10^{-10}$ (?)

LFV in charged leptons: future prospects

The recent MEG bound, $BR(\mu\to e\gamma) < 5.7\times10^{-13}$, can be taken as reference values to estimate potentially interesting levels for future LFV searches in different channels:

$B(\mu\to e\gamma) < 5.0\times10^{-14}$

Final goal of MEG-II

same flavor →

$\mu\to 3e$

$\mu N\to eN$

O(α/π) suppression if dipole dominated

$\lesssim 5\times10^{-16}$

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Assuming dipole dominance:

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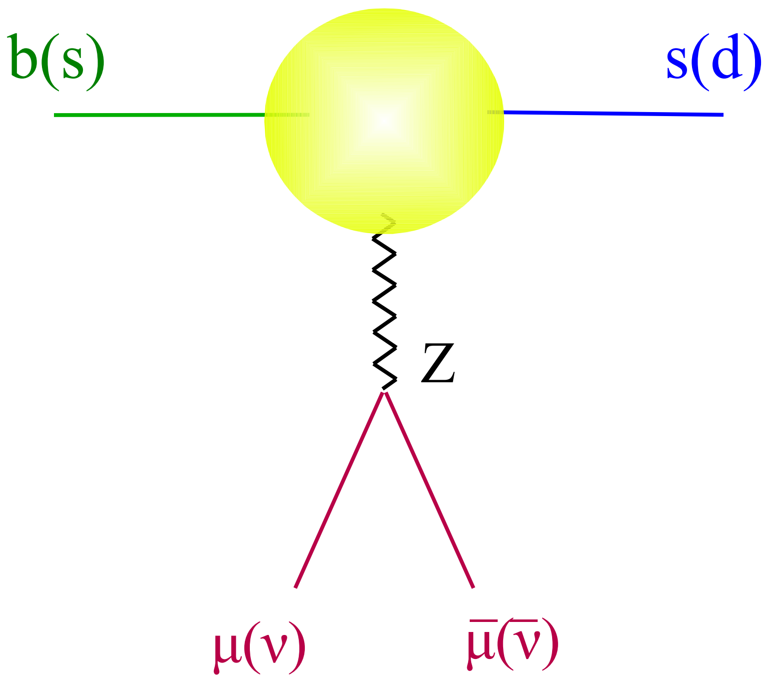
In the tau sector we would definitely need some dedicated experiments !

Precision measurements of FCNC decays
[*the usual suspects...*]



Precision measurements of FCNC decays

Under very general assumptions (gauge symmetry + absence of new light states) flavor and e.w. observables used for indirect NP searches can be decomposed as follows:

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

trivial kinematical factors (A_0)

(adimensional) effective couplings (c_{SM}, c_{NP})

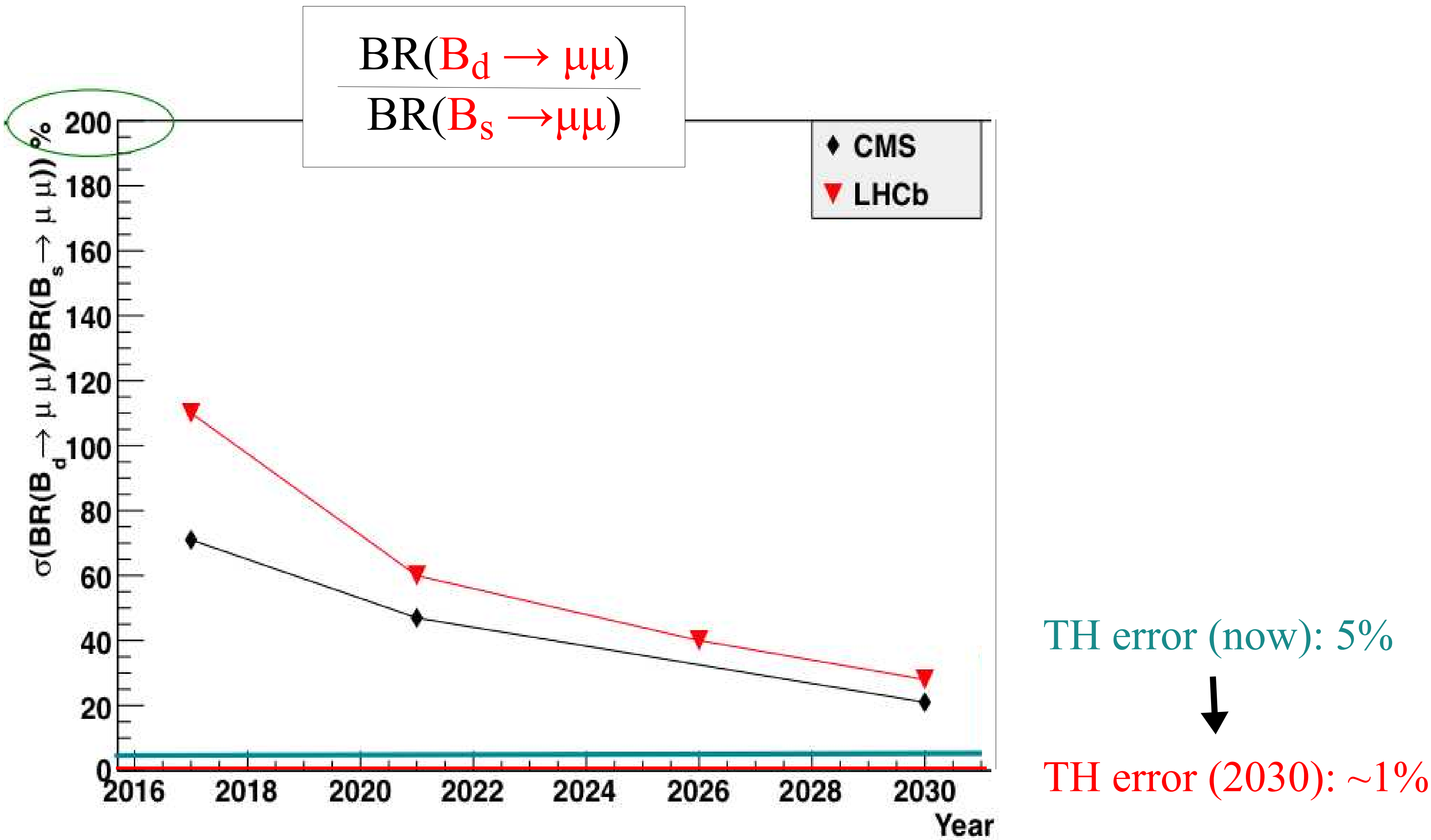
<u>This decomposition is very general:</u> it holds <u>both</u> for forbidden processes (e.g.: $\tau \to \mu\gamma$) and precision measurements (e.g.: $B_s \to \mu\mu$)

The key problem of precision measurements is to find observables where the TH error on does not “obscure” the sensitivity to NP → <u>few cases in a long-term perspective, but each of them is worth a dedicated experiment.</u>

Most notable examples: $K_L \to \pi^0 \nu\nu$ [→ talk by Moulson] & $\Gamma(B_d \to \mu\mu)/\Gamma(B_s \to \mu\mu)$

Precision measurements of FCNC decays

Example of B-physics observable that will NOT be dominated by the TH error for a while (*up to 2030…!*)



Precision measurements of FCNC decays

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$$\frac{BR(B_d \to \mu\mu)}{BR(B_s \to \mu\mu)}$$

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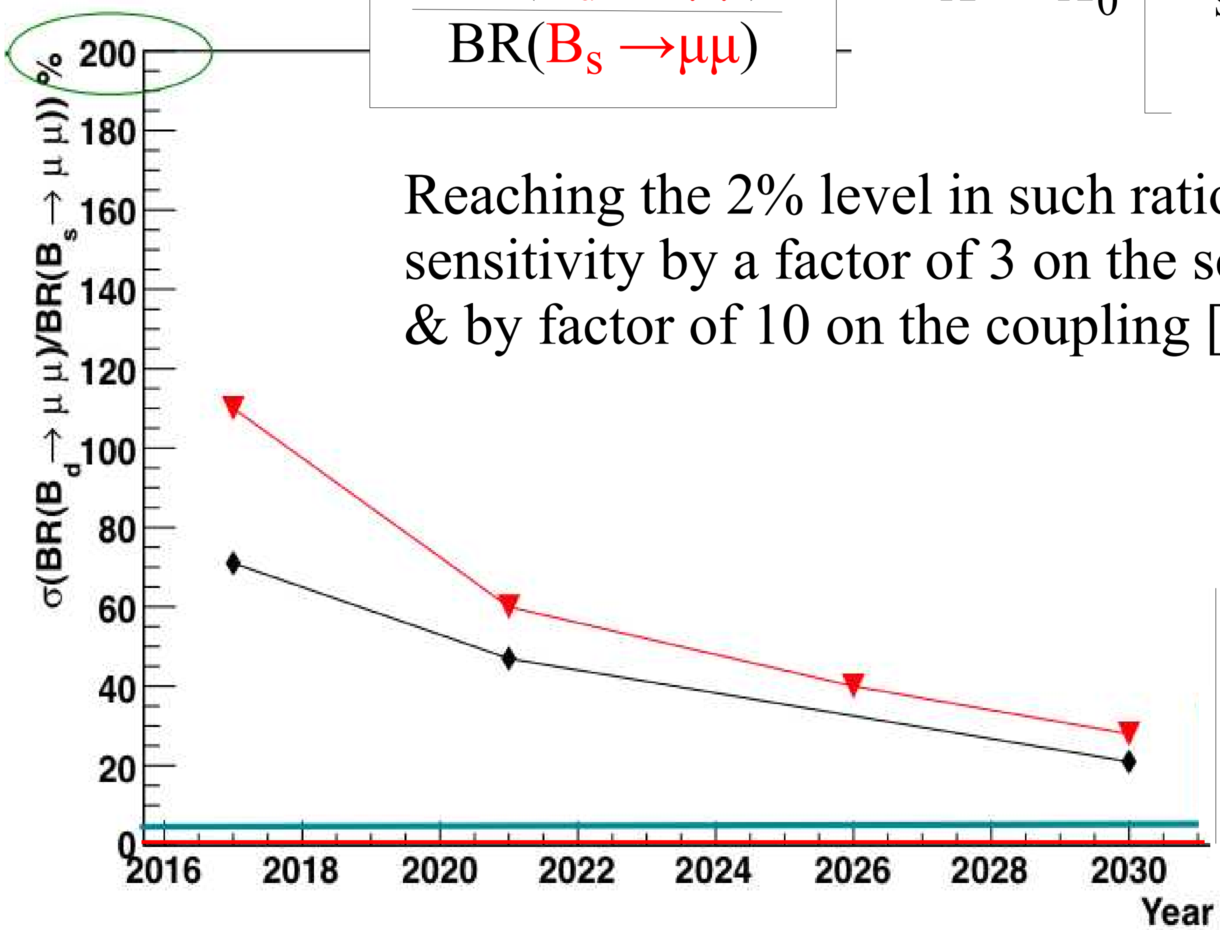

Reaching the 2% level in such ratio will increase the NP sensitivity by a factor of 3 on the scale [$\Lambda \to 3\Lambda$]
& by factor of 10 on the coupling [$\sigma(c_{NP}) \to 0.1\sigma(c_{NP})$]

TH error (now): 5%

↓

TH error (2030): ~1%

Precision measurements of FCNC decays

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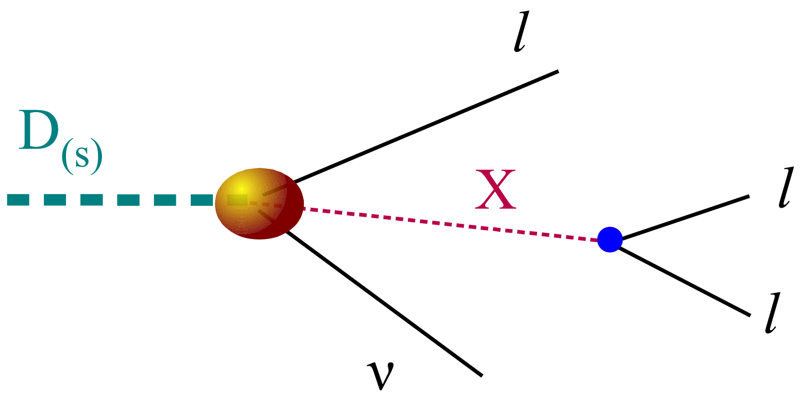
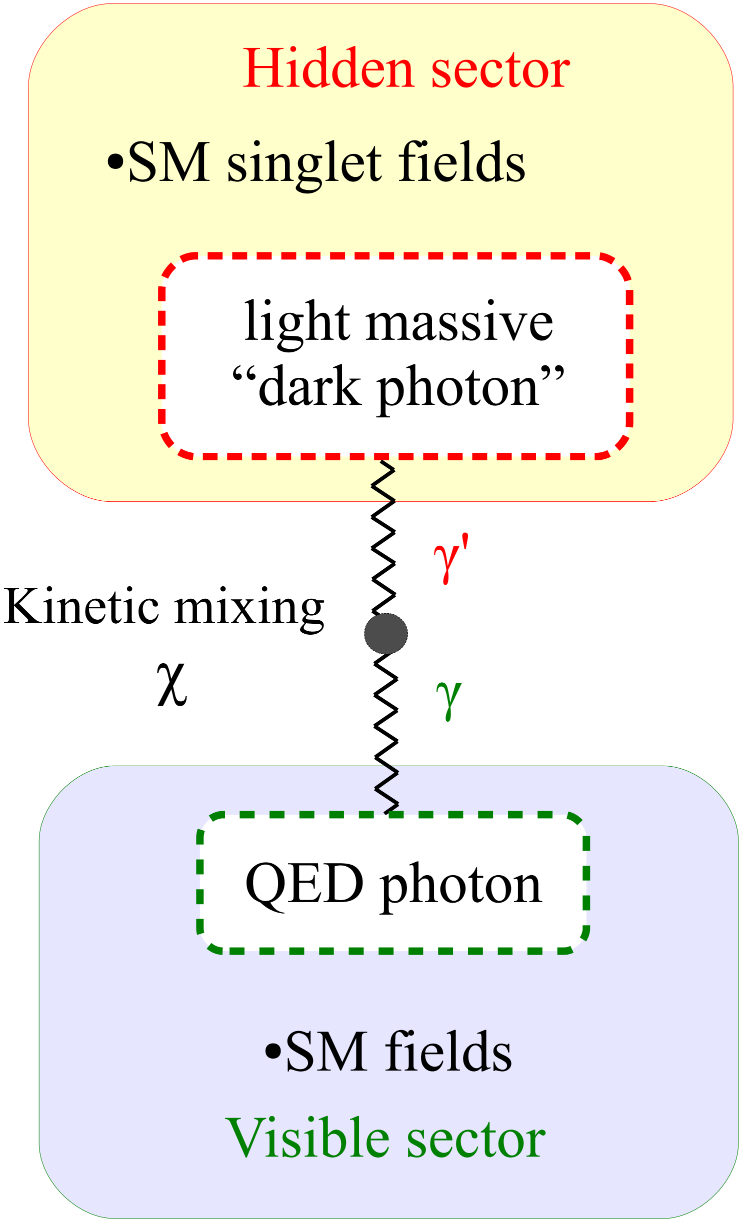
Very similar considerations on the NP reach holds for the theoretically clean $K_L \to \pi^0 \nu\nu$ & $K^+ \to \pi^+ \nu\nu$ decays that, however, are sensitive to a different class of NP models (↔ full complementarity)

Exotic light states



Exotic light states [*the "hidden-sector" & "dark-photon" paradigm*]

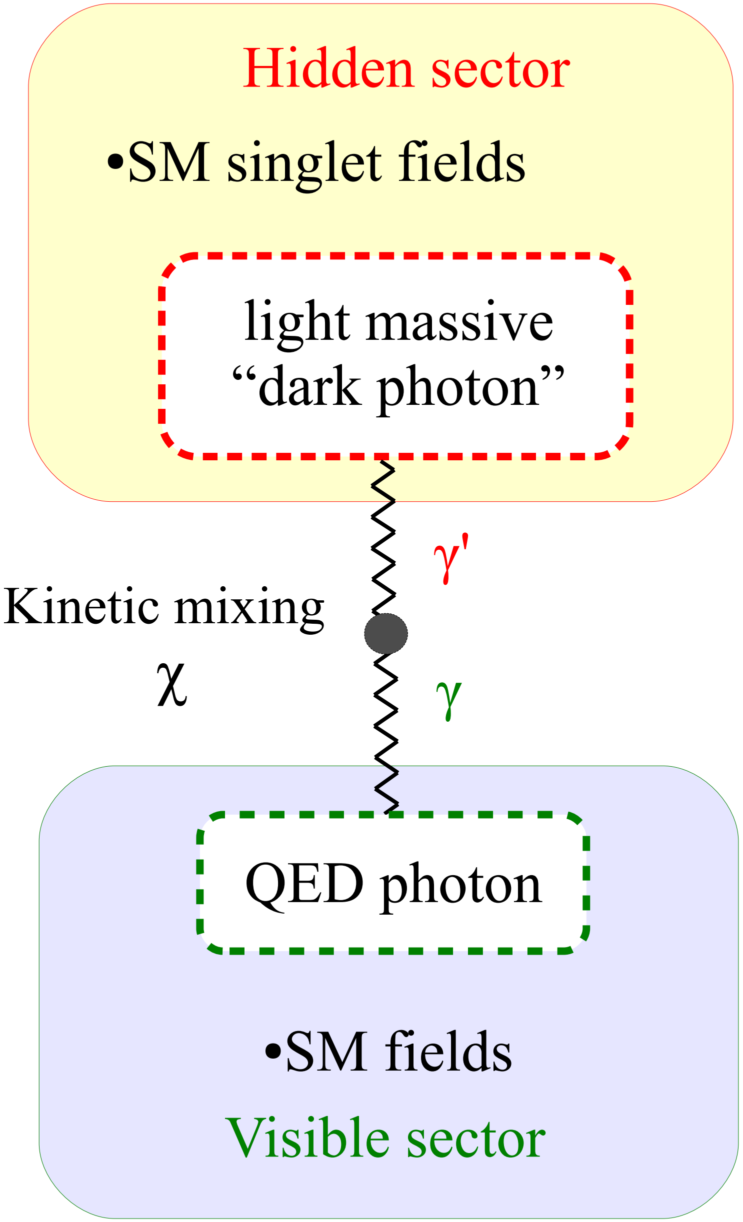


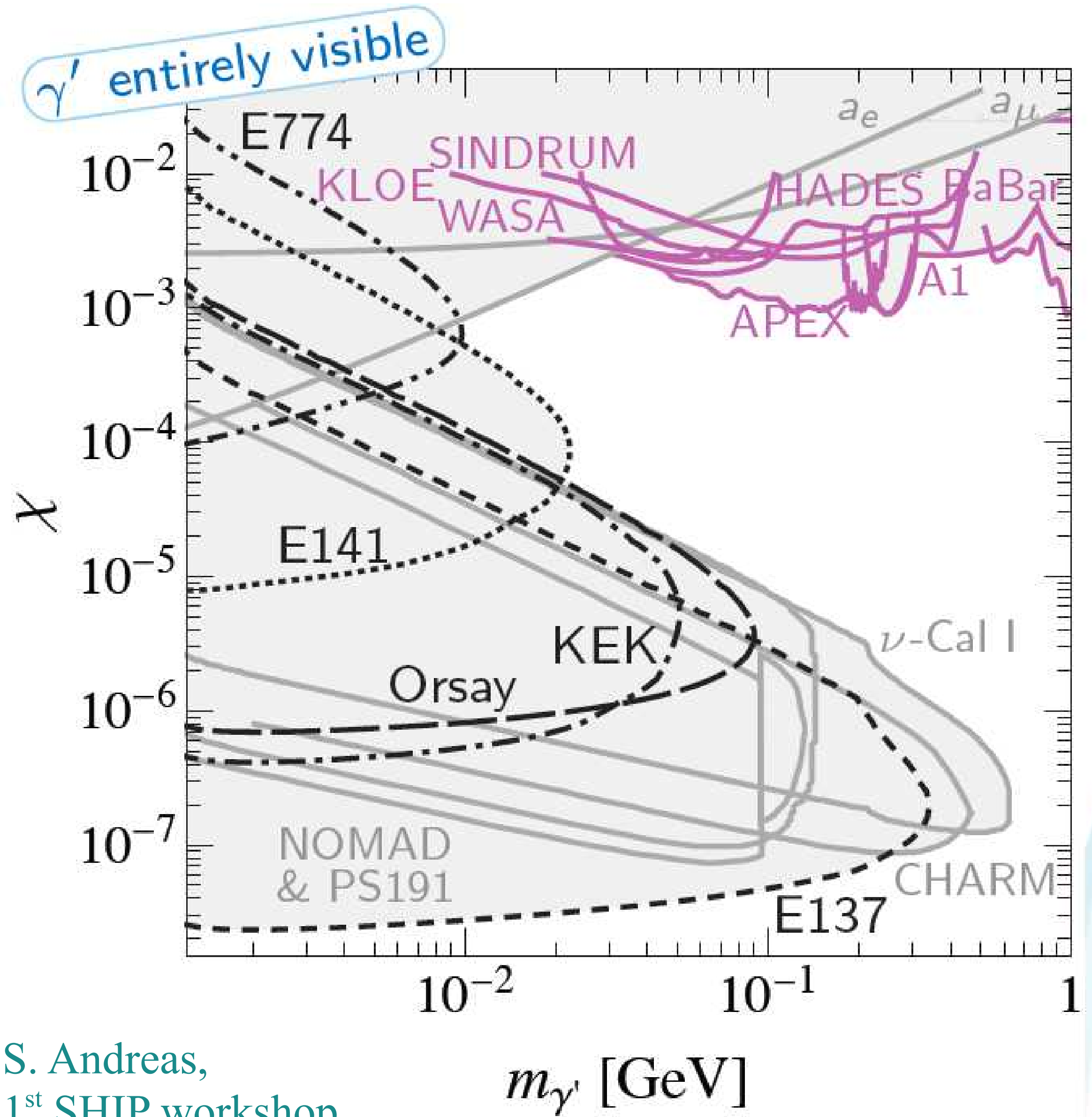
Dark-matter, g-2 anomaly, … provide a good phenomenological motivation to search for new light (*up to few GeV*) neutral states weakly coupled to e, μ, or τ.

The "*dark photon*" paradigm is only a simple (and quite general) example, but many more options are possible.

Arkani-Hamed, Finkbeiner, Slatyer Weiner, '09

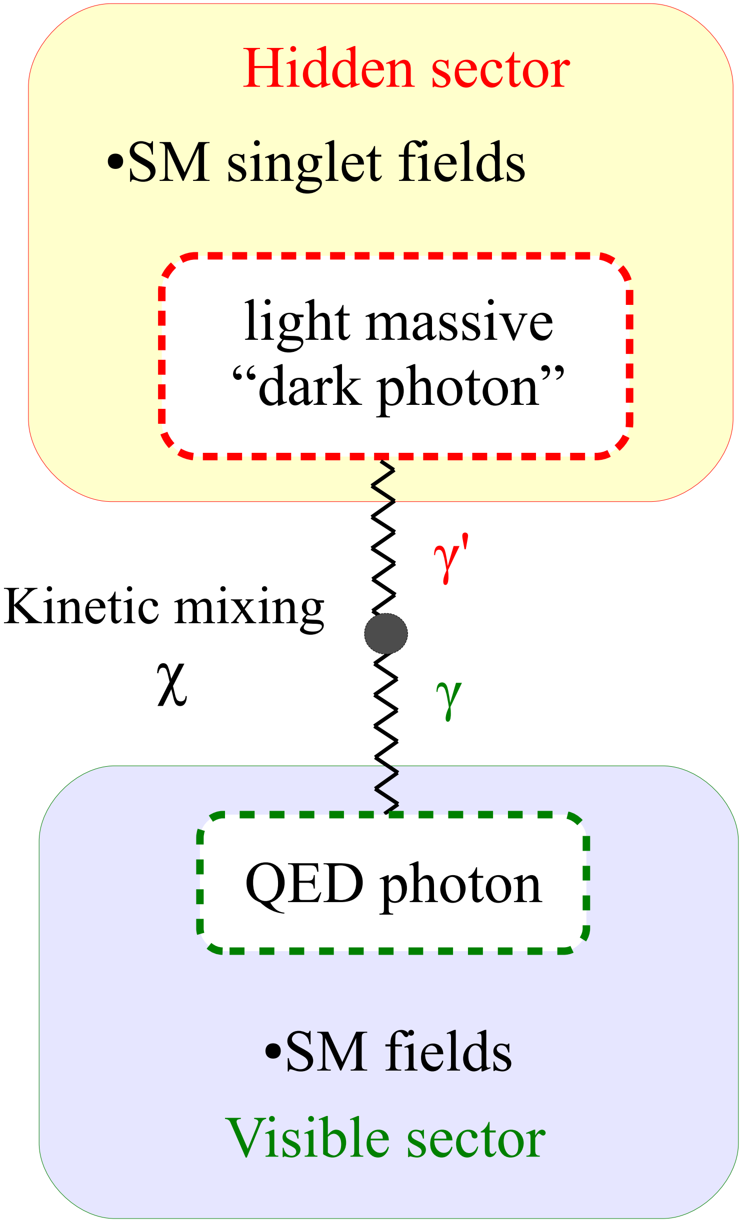
Exotic light states [*the "hidden-sector" & "dark-photon" paradigm*]

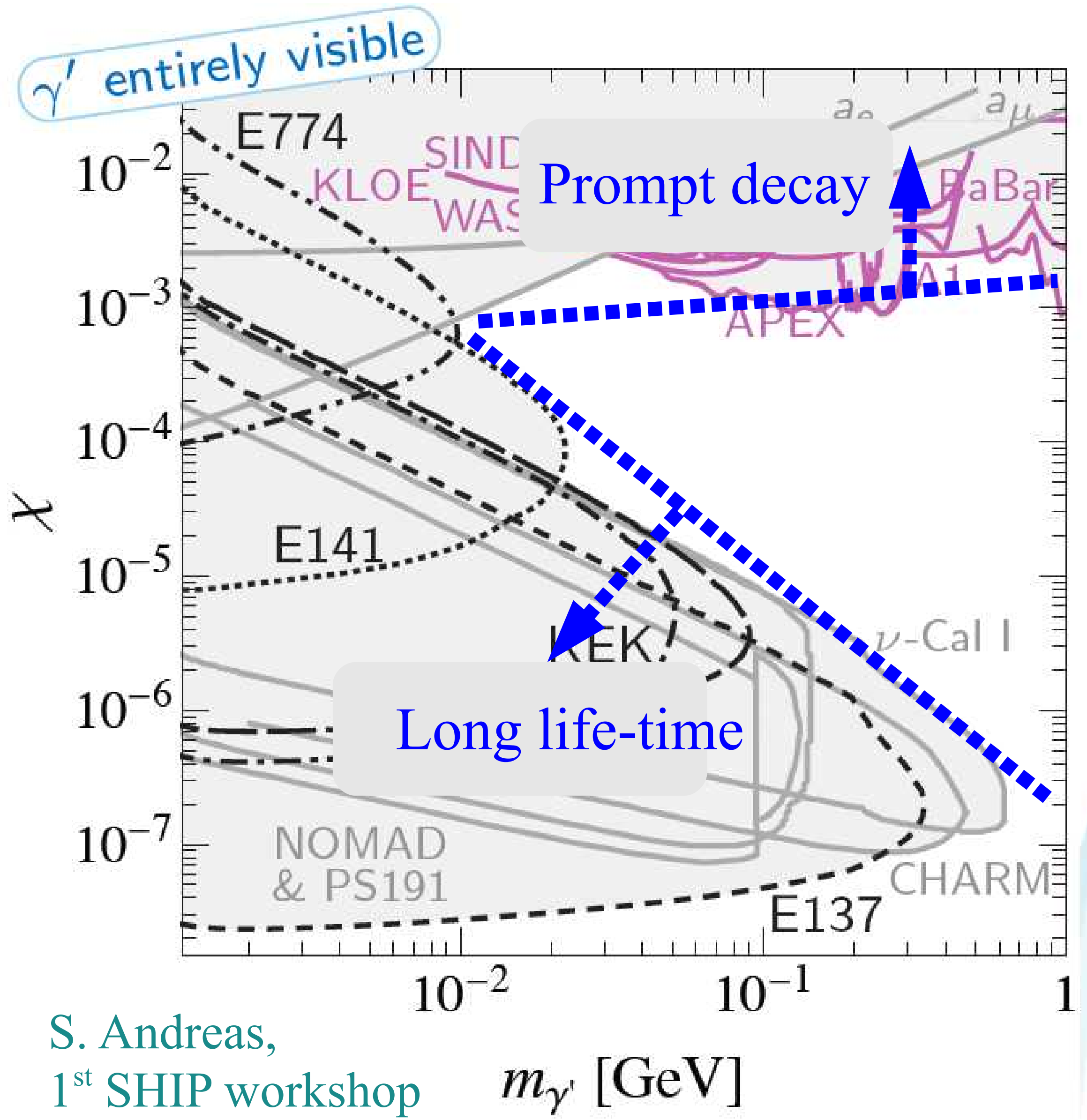




S. Andreas, 1st SHIP workshop

Exotic light states [*the "hidden-sector" & "dark-photon" paradigm*]



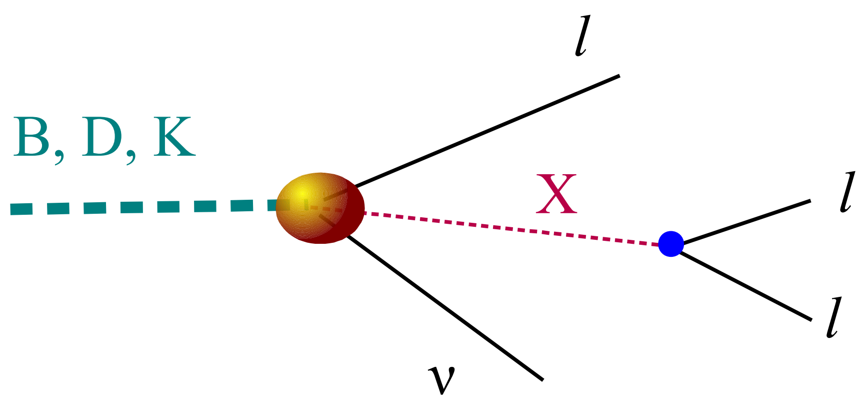


S. Andreas, 1st SHIP workshop

▶ Exotic light states [*a simple toy-model*]

The "*dark photon*" paradigm is only a simple (and quite general) example, but many more options are viable.

High-precision measurements of l^+l^- spectra (l=e, μ) in B, D, K decays provide a very useful probe of such scenarios

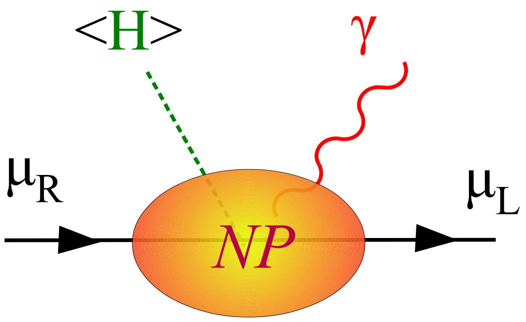


What I will explore in the next few slides is a simple toy-model for "short-lived" searches, based on

- one single new light neutral scalar coupled (*at least*) to muons,
- built to "solve" the $(g-2)_\mu$ anomaly.

Exotic light states [*a simple toy-model*]

Solving the $(g-2)_\mu$ anomaly in terms of NP, requires the introduction of some new (*light or heavy...*) states coupled to muons:



$m_{NP} > m_h$

Tiny (model-independent) effect in

$h \to \mu\mu\gamma$

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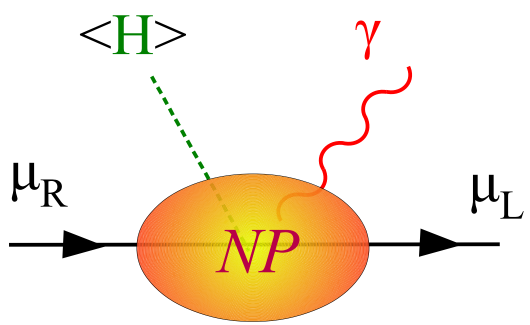
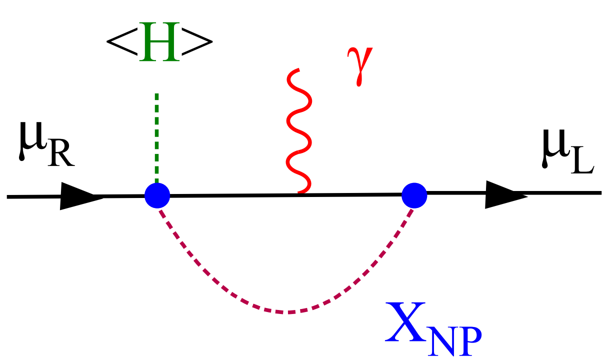


$m_{NP} > m_h$ → Tiny (model-independent) effect in

$h \to \mu\mu\gamma$

$2m_\mu < m_{NP} \ll m_h$ → Possible clean non-standard peak in various $m_{\mu\mu}$ distributions.



in particular:

$h \to \mu\mu + (\mu\mu)$ [Gonzales-Alonso & GI, '14]

but also (depending on m_{NP}*):*

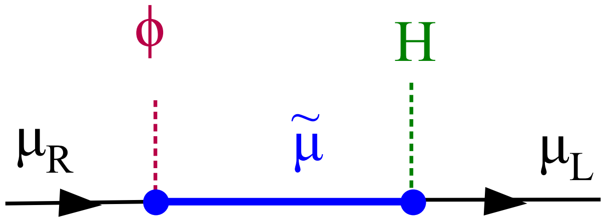
$D_s \to \mu\nu + (\mu\mu)$ $B_u \to \mu\nu + (\mu\mu)$, ...

Exotic light states [*a simple toy-model*]

- One light $SU(2)_L$-singlet scalar field, ϕ
- One effective coupling $c_\mu/\Lambda \rightarrow$ Two parameter model (c_μ/Λ and m_ϕ):

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm kin}(\phi) + \left(\frac{c_\mu}{\Lambda} \, \bar{\mu}_L \, \mu_R \, H \, \phi + \text{h.c.} \right)$$

This $\mathscr{L}_{eff}$ can be generated, for instance, introducing an heavy vector-like partner of the muon



- The ratio of the two free parameters is the fixed by $(g\text{-}2)_\mu$ anomaly:

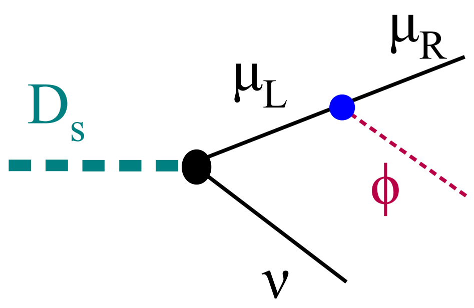
$$\Delta a_\mu = \frac{|c_\mu|^2}{96\pi^2} \frac{v^2}{\Lambda^2} \frac{m_\mu^2}{m_\phi^2} \approx 6.4 \times 10^{-9} \left| \frac{c_\mu/\Lambda}{(10~\text{TeV})^{-1}} \right|^2 \left| \frac{1~\text{GeV}}{m_\phi} \right|^2$$

Exotic light states [*a simple toy-model*]

For 0.3 GeV $\lesssim m_\phi \lesssim$ 1.5 GeV, a promising possibility to test/constrain this model is

BR ($D_s \to \phi\mu\nu$) = $\sim 10^{-7}$ $\leftrightarrow$ $\sim 10^{-6}$

[0.5 GeV] [1.0 GeV]



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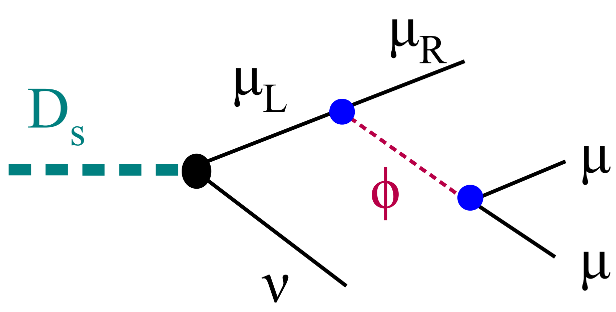


⬇

$\mathrm{BR}\,(D_s \to (\mu\mu)_\phi\mu\nu) = \mathrm{BR}\,(D_s \to \phi\mu\nu) \times \mathrm{BR}\,(\phi \to \mu\mu)$

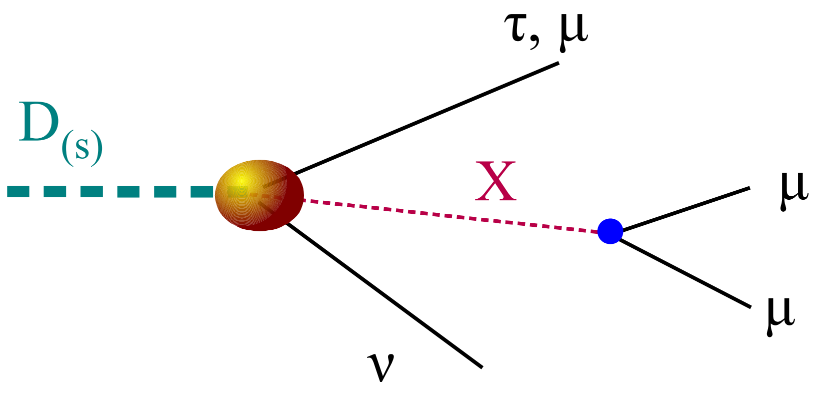
- The ϕ is certainly <u>short-lived</u> [$\leftrightarrow$ $(g-2)_\mu$ constraint]
- BR ($\phi \to \mu\mu$) can be << 1 if there are additional (invisible) decay modes (ν's, DM states, etc...). Actually BR <<1 is welcome to avoid existing constraints

⬇

The $D_s \to (\mu\mu)_\phi\mu\nu$ decay could could be searched for at LHCb, but in principle a new dedicated experiment could cover a much wider range.

Exotic light states

What I just illustrated is only one example of the class of models that could be tested in an experiment reconstructing the muons produced from weak charm decays



Possible variations:

- X could be a scalar or a vector
- X could couple also/only to tau's
- X could couple to the weak current
- ….

Conclusions

- Despite we have not seen any clear NP signal yet, we still have strong arguments to believe that the SM is not a complete theory
- Low-energy high-precision physics offer a unique discovery potential
- Four main directions:

I. SM forbidden modes

II. Precise measurements of rare FCNCs

III. Search for short-lived new states

IV. Search for long-lived new states

Conclusions

- Despite we have not seen any clear NP signal yet, we still have strong arguments to believe that the SM is not a complete theory
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- Four main directions:

D(τ)-"beam"

I. SM forbidden modes

III. Search for short-lived new states

K-"beam"

B-"beam"

II. Precise measurements of rare FCNCs

"far detectors"

IV. Search for long-lived new states