What's Next in Flavor Physics

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- Introduction
- What we learned so far
- Future prospects
- What's next...

Introduction

There are still very good reasons to think the SM theory is incomplete

[*hierarchy problem, charge quantization, dark matter, matter-antimatter asymmetry...*]

↓

We need to search for New Physics

[*with a broad spectrum perspective given the lack of NP signal so far...*]

↓

Twofold role of Flavor Physics

[= *study of flavor-changing and CPV phenomena, of both quarks and leptons*]

- Identify symmetries and symmetry-breaking patterns beyond those present in the SM
- Probe physics at energy scales not directly accessible at accelerators

Introduction

Twofold role of Flavor Physics

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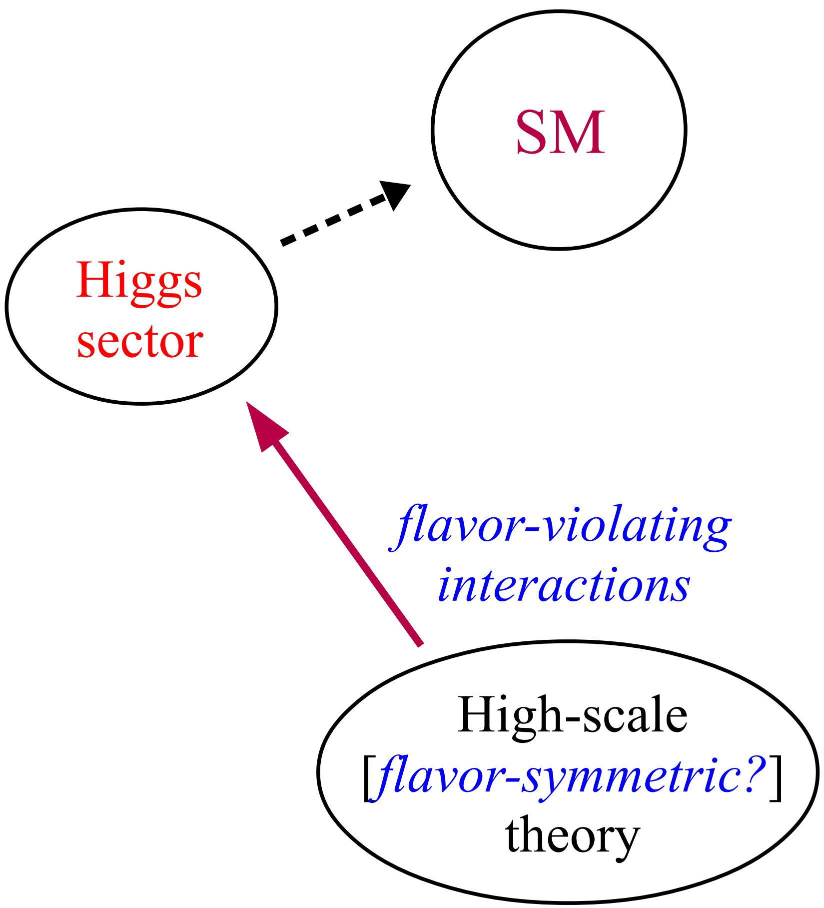

Two key open questions:

- *What determines the observed pattern of quark & lepton mass matrices*
- *Are there other sources of flavor symmetry breaking?*

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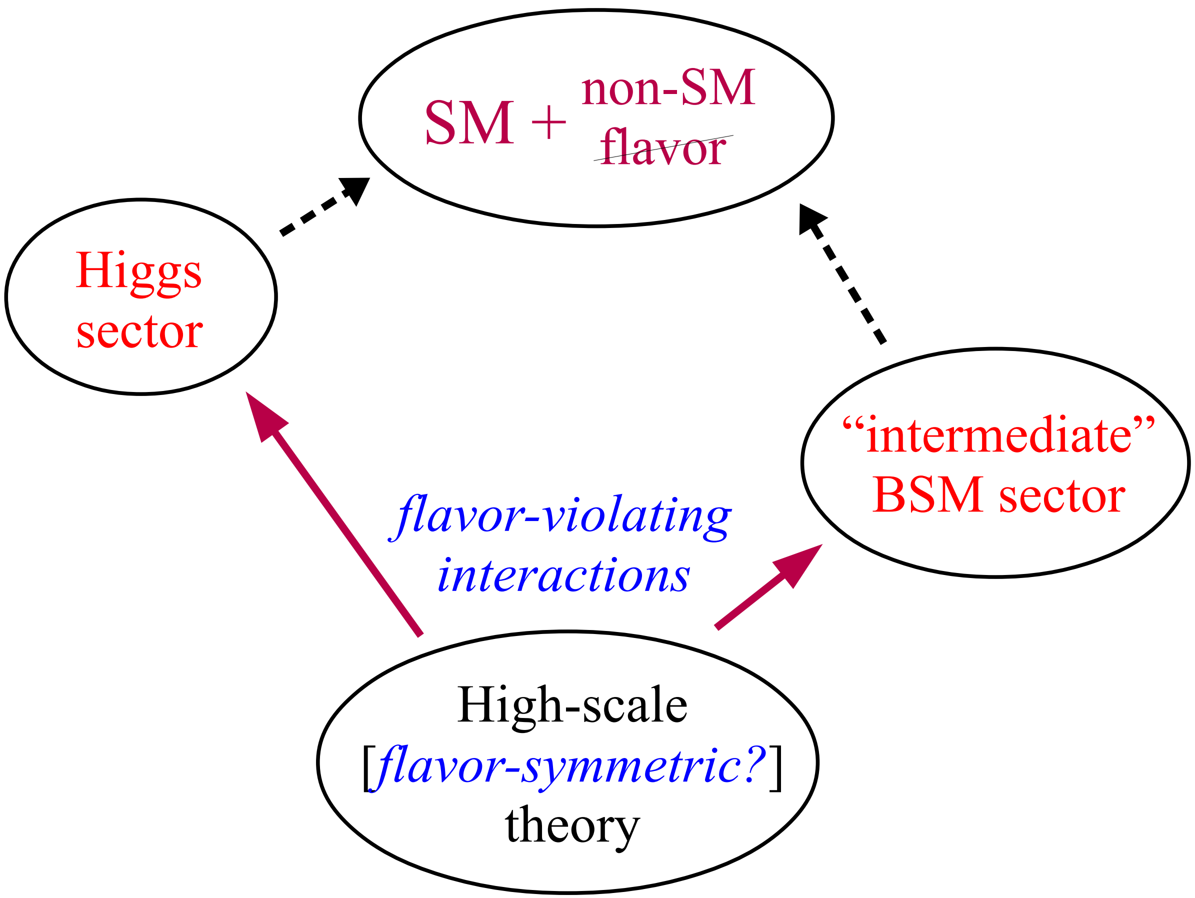

Two key open questions:

- *What determines the observed pattern of quark & lepton mass matrices*
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What we learned so far

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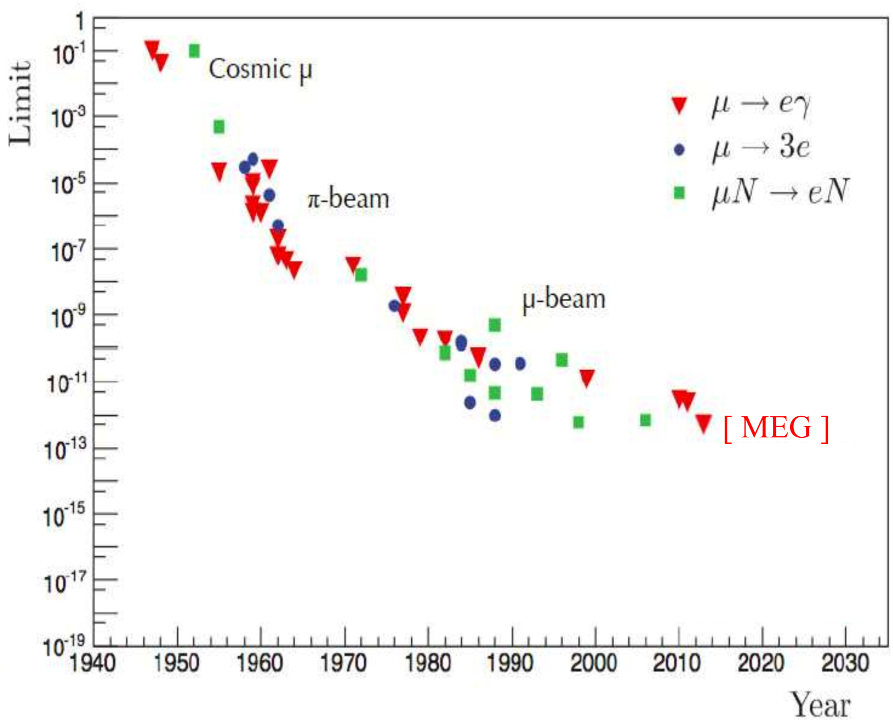
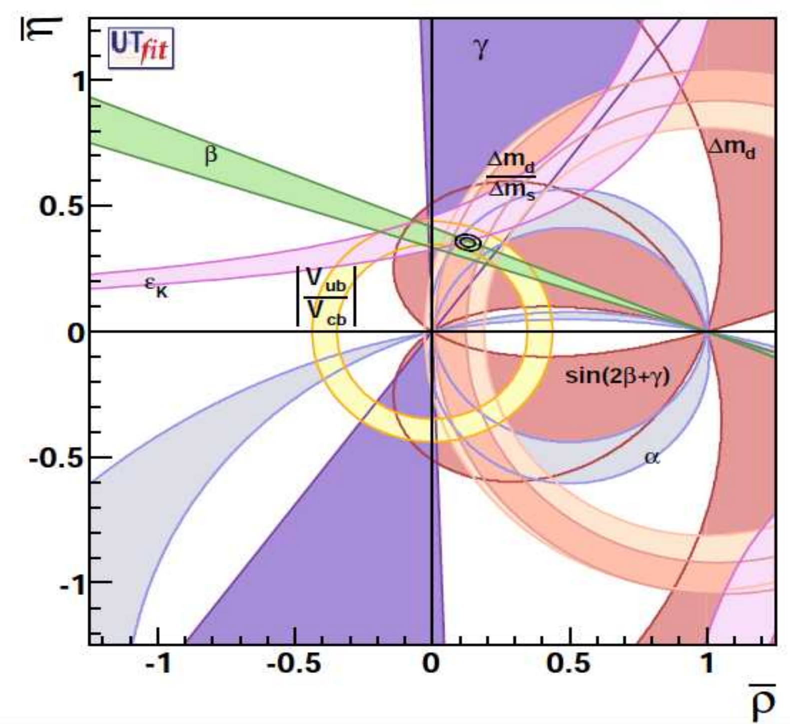
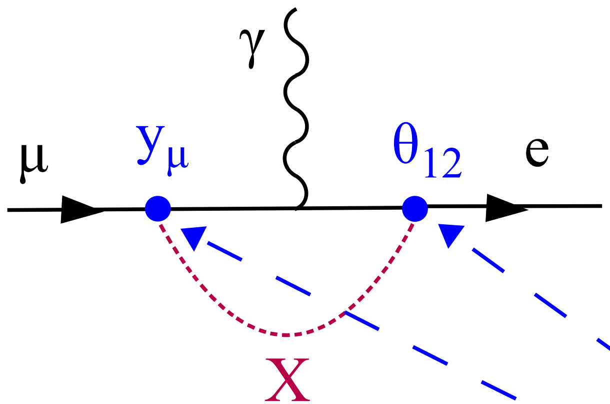




That's the question addressed by precision measurements (& searches) of flavor-changing processes of quarks & charged-leptons → So far everything seems to fit well with the SM...→ Strong limits on several NP modes

What we learned so far

E.g.:



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

MEG '13

$M_X \gtrsim 200$ TeV

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

Long list of (qualitatively) similar bounds from flavor-violating observables in the quark sector...

Future prospects

General decomposition of flavor-violating observables:

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

decomposition that holds for both forbidden processes
(e.g.: $\tau \to \mu\gamma$, where $c_{SM} \approx 0$)
and precision measurements
(e.g.: $B_\sigma \to \mu\mu$, where $c_{SM} \neq 0$)

↓

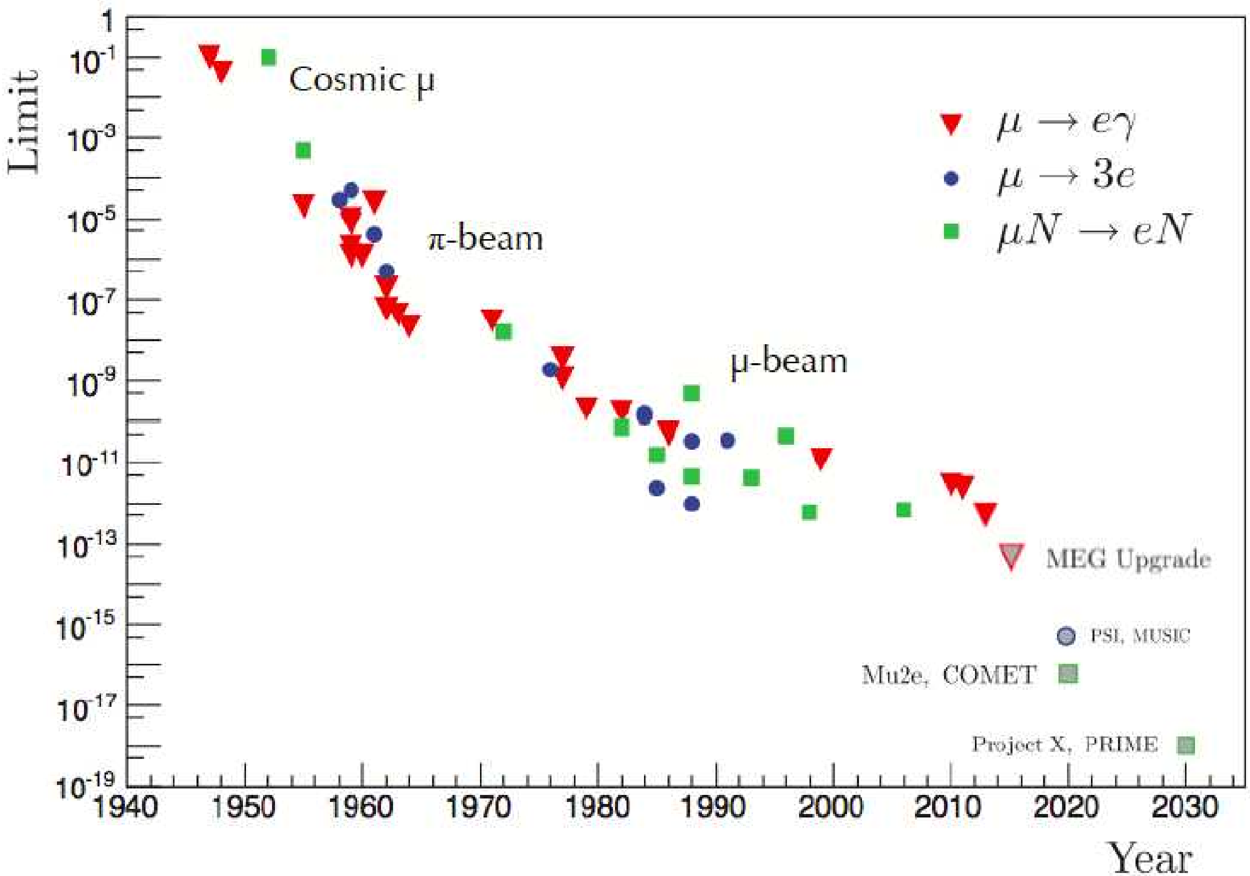
- For statistically limited measurements, the sensitivity to the energy scale grows as $\sigma(\Lambda) \sim 1/N^{1/4}$ → plan "ambitious" improvements

- If the SM contribution is non-zero, the theory error on c_{SM} may "obscure" the NP effect → concentrate on th. clean processes, but is also worth to consider processes where the theory error can be improved with auxiliary data (parametric error)

Future prospects [LFV and EDMs]

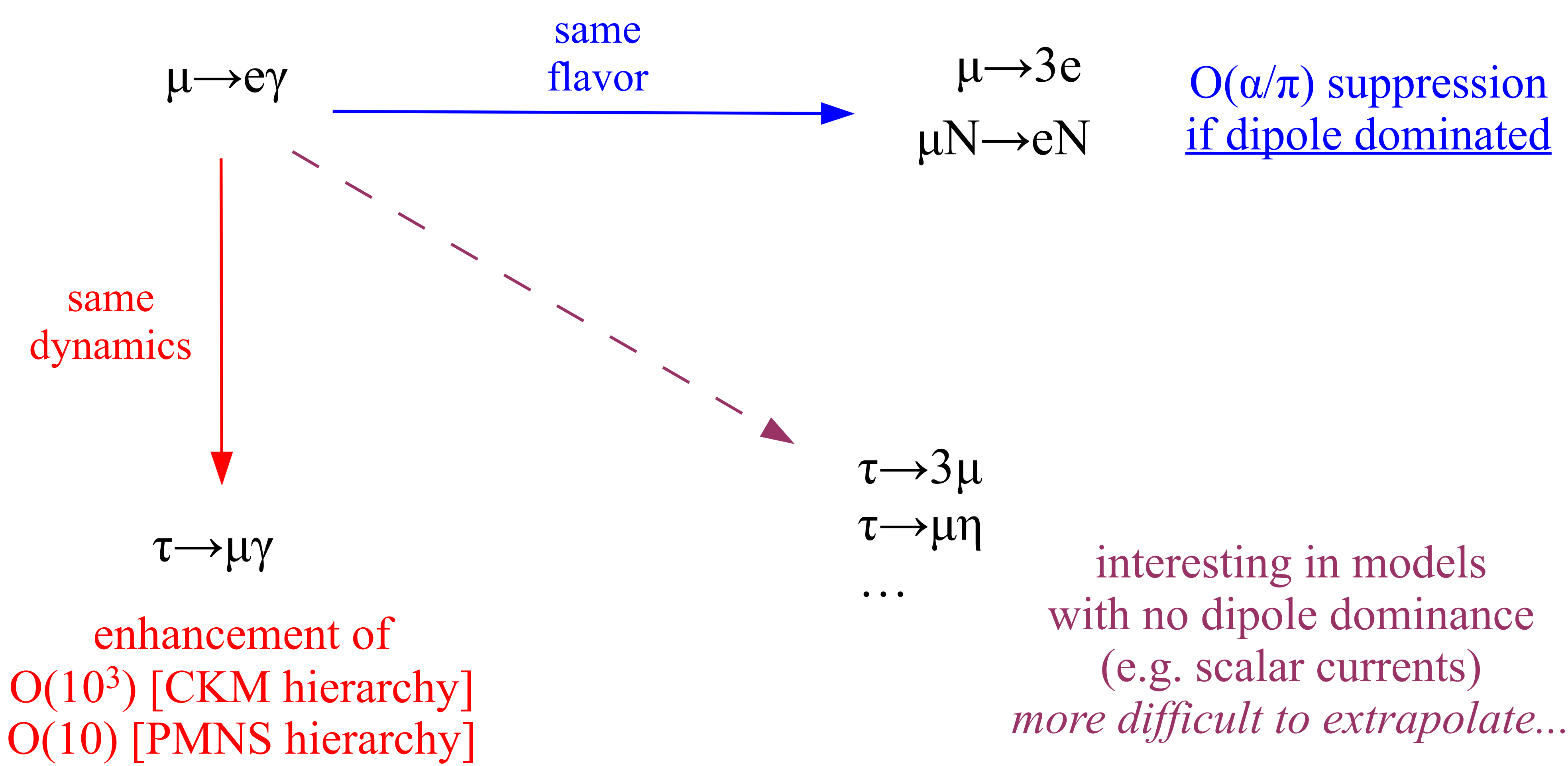
After what we learned from neutrino physics, LFV in charged leptons is probably the most interesting (*and potentially rewarding*) search in the flavor sector.

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



▶ *Future prospects* [LFV and EDMs]

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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$\mu\to e\gamma$

$< 5.7\times10^{-13}$

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]

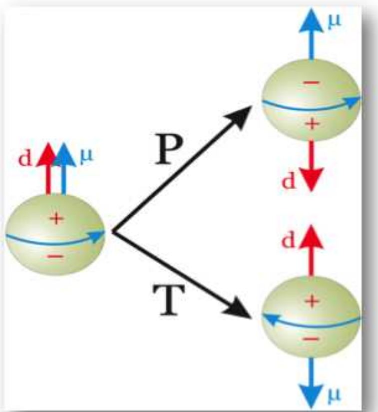
Key observables & planned exp. Limits:

- $\mu\to e\gamma$ — 5×10^{-14} [PSI/MEG-II]
- $\mu\to 3e$ — 10^{-16} [PSI/μ3e]
- $\mu N\to eN$ — $10^{-15}\to10^{-18}$ [JPARC/COMET]; $10^{-15}\to10^{-18}$ [FNAL/Mu2e]
- $\tau\to\mu\gamma$ — 2×10^{-9} [Belle-II]
- $\tau\to3\mu$ — 10^{-9}-10^{-10} [Belle-II, S-LHCb]

▶ *Future prospects* [LFV and EDMs]

The search for Electric Dipole Moments of fundamental particles (n, e, μ, …) share the three main virtues of LFV searches:

- We know CP is not an exact symmetry of nature → non-vanishing EDMs



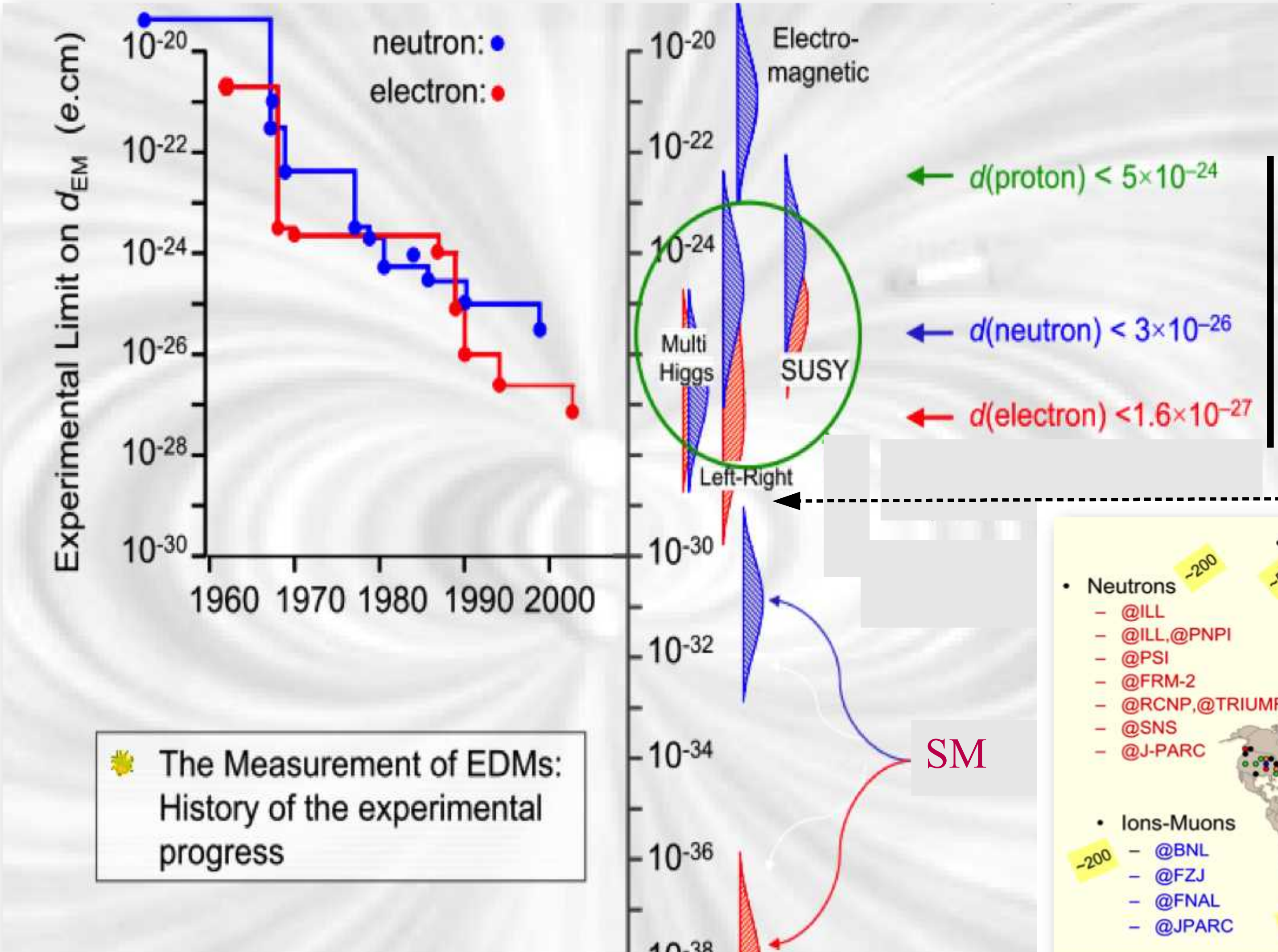
$$H = -\mu\vec{\sigma}\cdot\vec{B} - d\vec{\sigma}\cdot\vec{E}$$
$$\mathcal{T}:\ H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$
$$\mathcal{P}:\ H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

EDMs of elementary particles violate P & T (hence CP assuming CPT)

- Virtually no problems of SM backgrounds "accidental" SM suppression ($d_n^{SM} \lesssim 10^{-32}$ *e* cm, $d_e^{SM} \lesssim 10^{-38}$ *e* cm)

- EDMs close to the present bounds in several realistic models (e.g. SUSY) with new CPV phases around the TeV scale

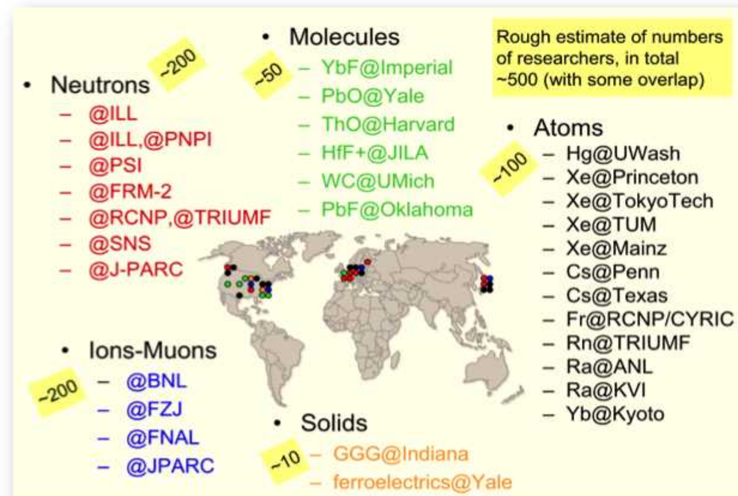
Future prospects [LFV and EDMs]



Present bounds

planned future sensitivity:

SM



A wide-spread effort where INFN is almost absent

[N.B.: d_μ is a natural extension of the new $(g\text{-}2)_\mu$ expt. @ FNAL & JPARC]

Future prospects [The quark sector]

- Several "*SM null tests*" possible also in the quark sector ($B \to \mu e$, $K^+ \to \pi^- \mu^+ \mu^+$, …): same virtues as $\mu \to e$ (*but less motivated in most "natural" models*)
- In many CPV and FCNC measurements the main limitation is provided by TH errors. However, there are notable exceptions.
- Still significant room for improvements in all purely-leptonic or semi-leptonic modes (↔ key role of Lattice)

Hadronic parameter	L.Lellouch ICHEP 2002 [hep-ph/0211359]		FLAG 2013 (The flavor lattice averaging group) [1310.8555]	
$\hat{B}_K$	0.86(15)	[17%]	0.77(1)	[1.3%]
f_{Bs}	238(31) MeV	[13%]	228(5) MeV	[2%]
f_{Bs}/f_B	1.24(7)	[6%]	1.20(2)	[1.7%]
$\hat{B}_{Bs}$	1.34(12)	[9%]	1.33(10)	[7%]

C. Tarantino

2030

→ *The 0.1% level does not seem to be impossible*

▶ *Future prospects* [The quark sector]

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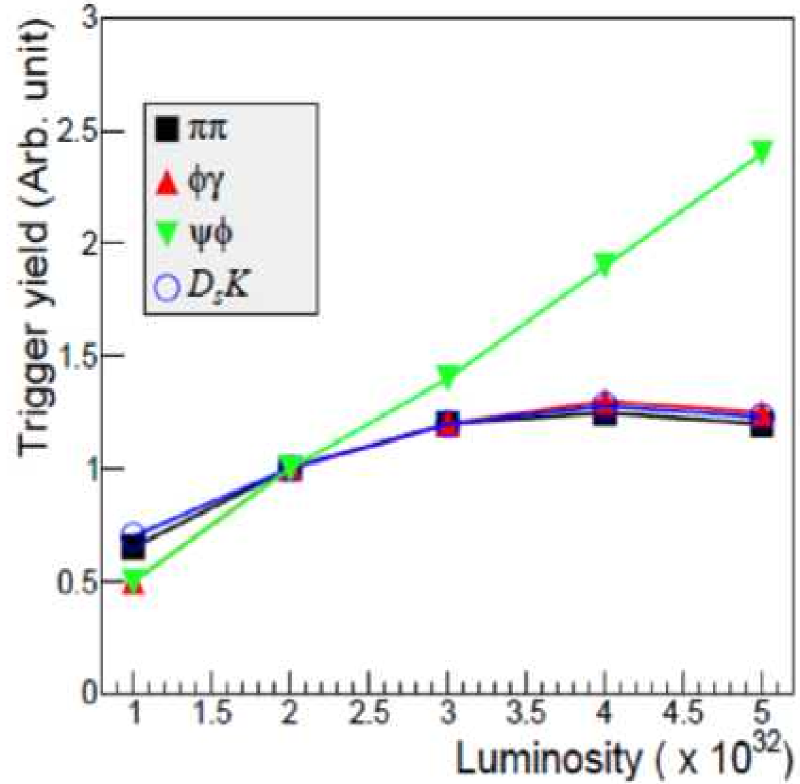
"Minimalistic" list of the key (low-energy) CPV and FCNC observables that still need to be improved & are not yet TH-error dominated:

- γ [from tree: $B \to DK$, ...]
- $|V_{ub}|$ & $|V_{cb}|$
- $B_{s,d} \to l^+ l^-$
- ϕ_s [CPV in B_s mixing]
- $B \to K^{(*)}\, l^+ l^-$, $\nu\nu$
- $B \to \tau\nu$, $\mu\nu$ (+D)
- K_L & $K^+ \to \pi\nu\nu$
- CPV in selected charm modes

→ Goal of the intense "ballistic" program (LHCb + Belle-II + Rare K)

Future prospects [The quark sector]

LHCb upgrade:



- In 2012 luminosity levelled @ 4×10^{32} cm^{-2}s^{-1} (*mean n. of coll./cross.* ~1.6) → 3fb^{-1} on tape
- By 2017 expect to collect ~ 7fb^{-1} in total

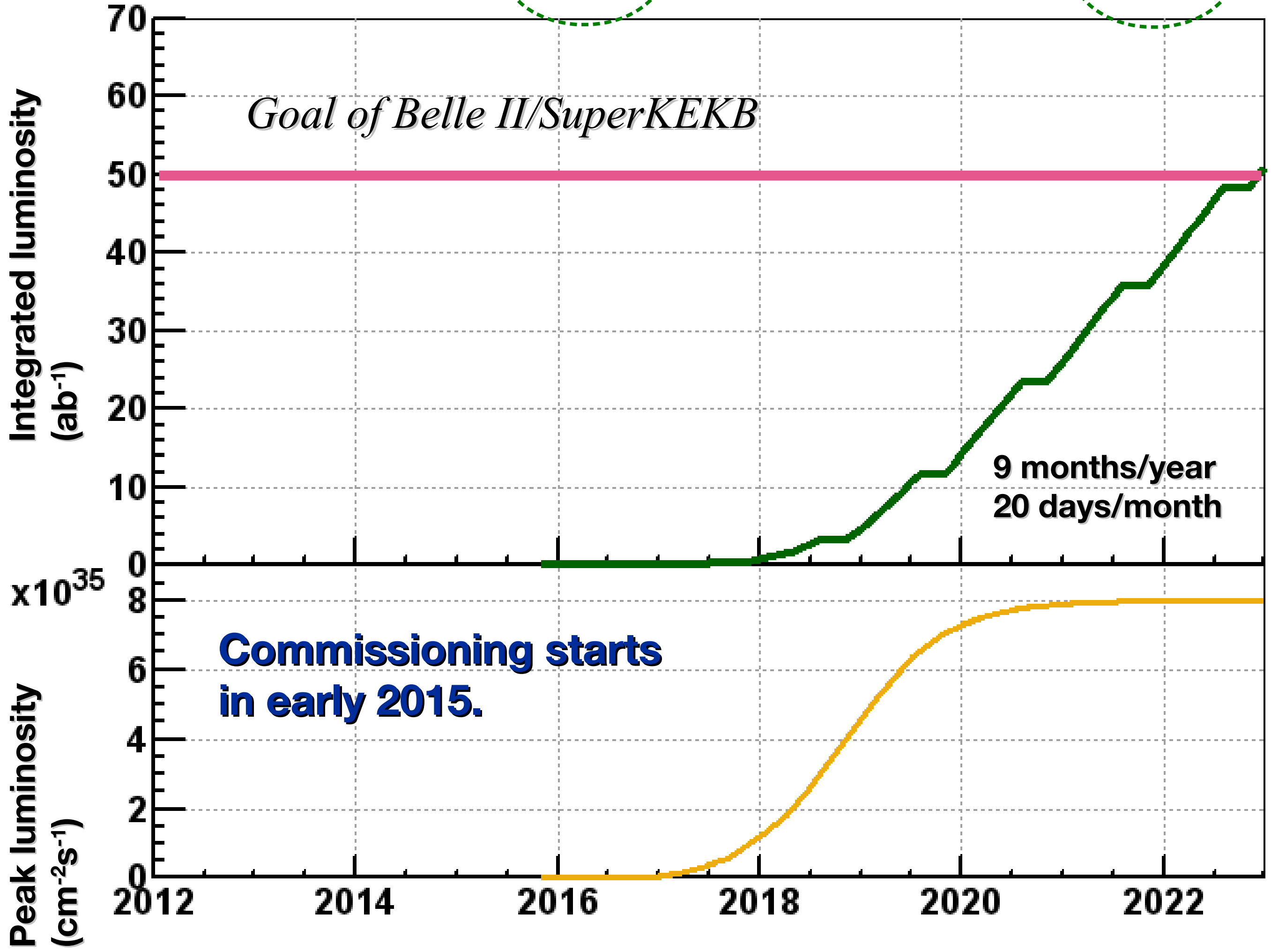
  Most important limitation ofcurrent LHCb is the requirement to limit full detector readout to 1MHz (*currently achieved by L0 trigger*)

- Upgrade in 2018:
  - Readout entire detector at 40MHz + software trigger
  - High level trigger (HLT) reduce rate to 10-20 kHz to tape
  - Replace R/O, tracking detectors and RICH photosensors
- 2019 onwards:
  - Level luminosity at 1-2x10^{33} cm^{-2}s^{-1} (→ 2-4)
  - Collect ~ 5fb^{-1}/year for a total of ~ 50fb^{-1}

▶ *Future prospects* [The quark sector]

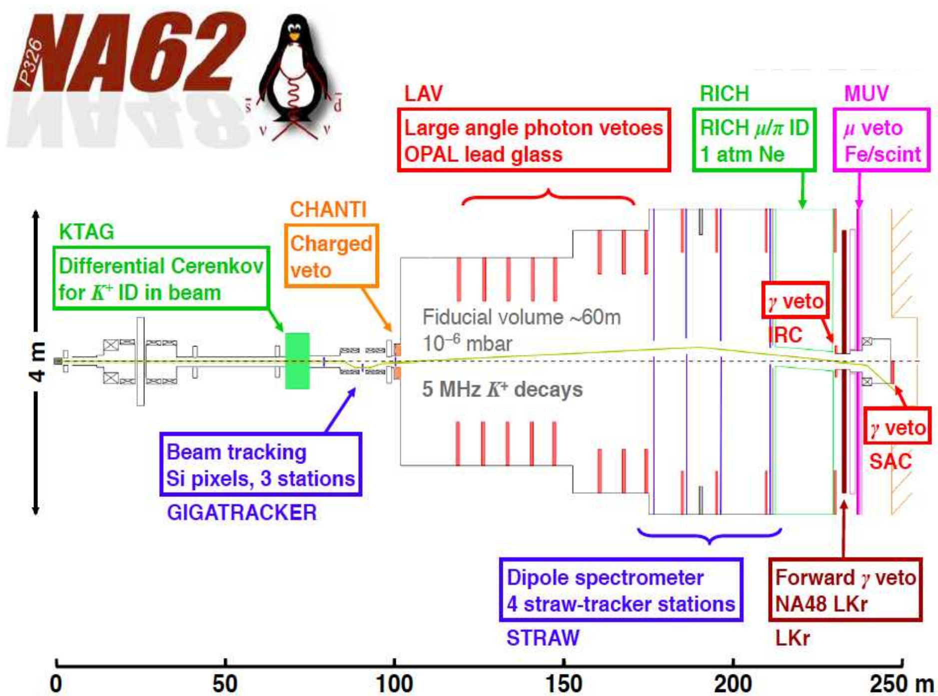
Belle-II:

Belle recorded ~ 1 ab^{-1} → Belle-II aims at 50ab^{-1}



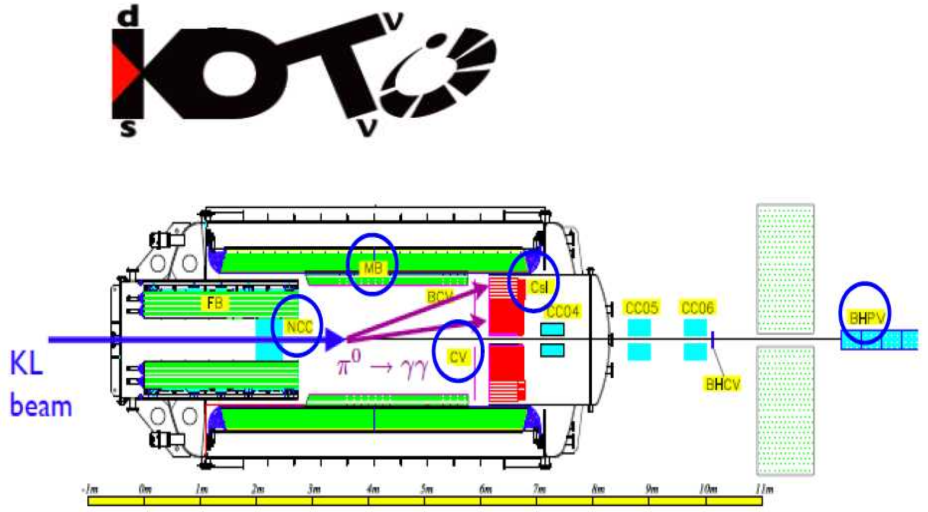
▶ *Future prospects* [The quark sector]

Rare K [@CERN & @JPARC]



Performance for $K^+ \to \pi^+ \nu\bar{\nu}$

45 signal events/yr



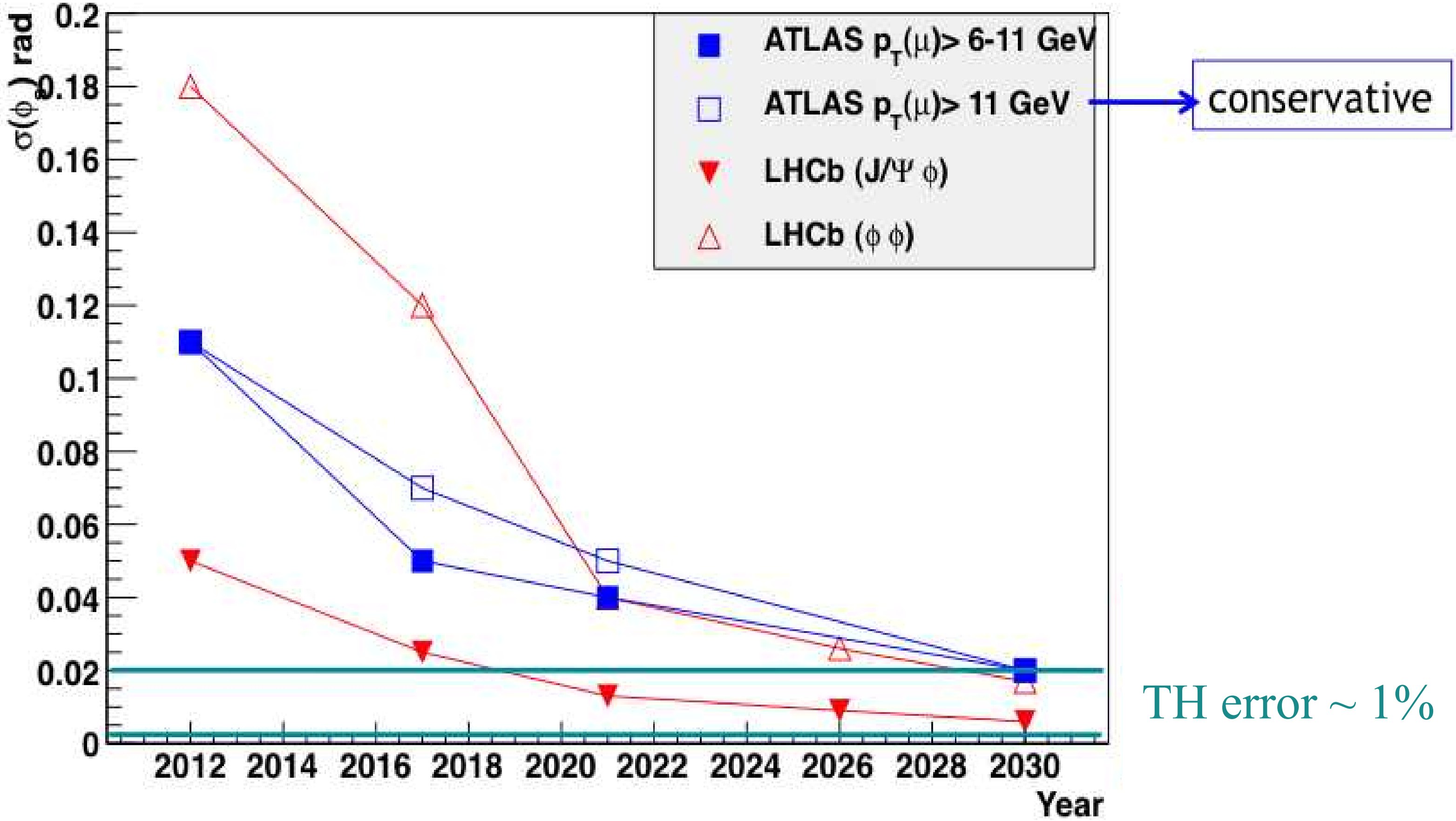
SES on $K_L \to \pi\nu\nu$ ~ BR_{SM}

Still orders of magnitudes far from the TH-error limitation !

Future prospects [The quark sector]

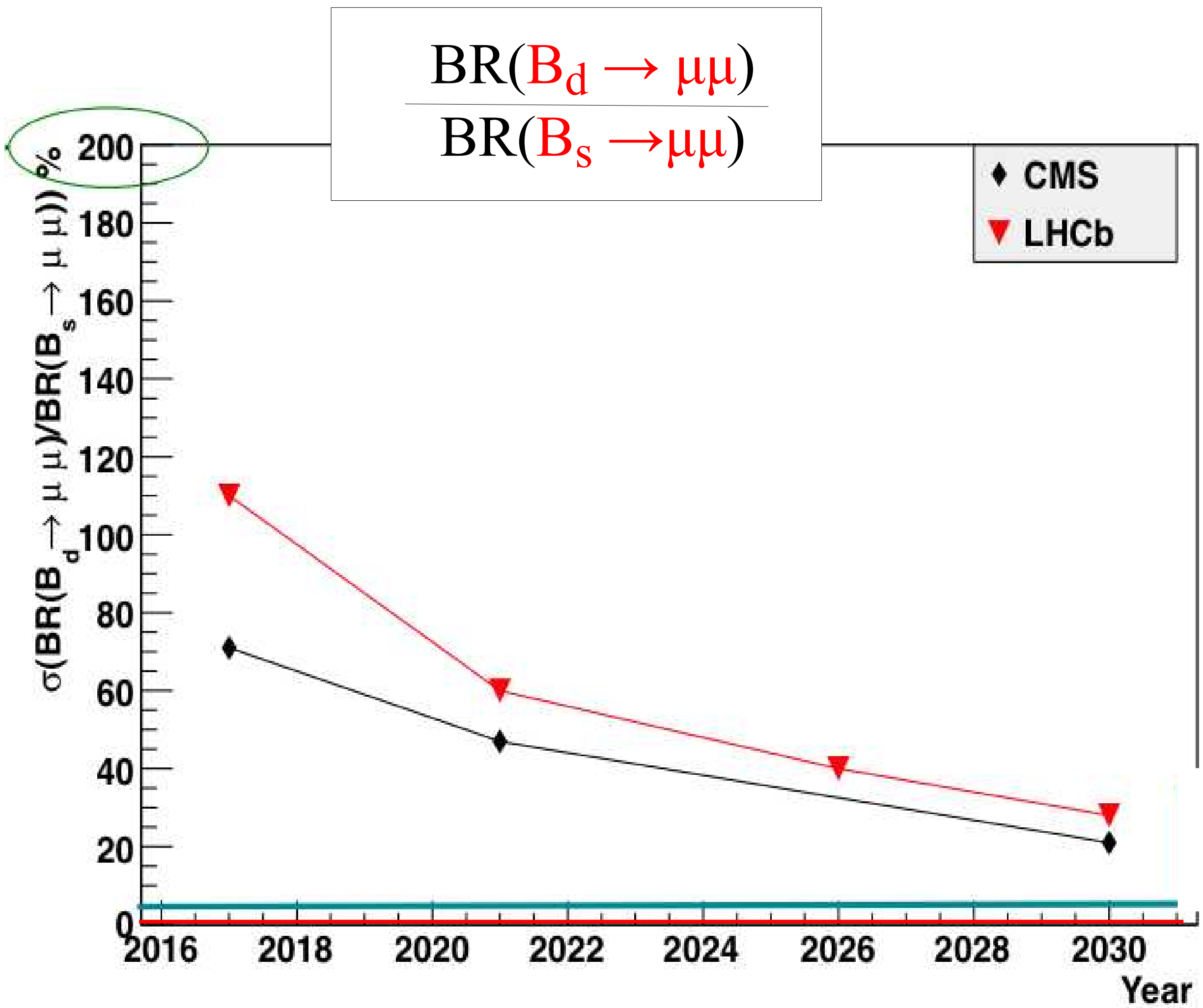
Example of B-physics observable that will be dominated by the TH error at the end of the "ballistic program", *unless significant TH improv.*:

CPV in B_s mix. [ϕ_s]



Future prospects [The quark sector]

Example of B-physics observable that will NOT be dominated by the TH error at the end of the "ballistic program":



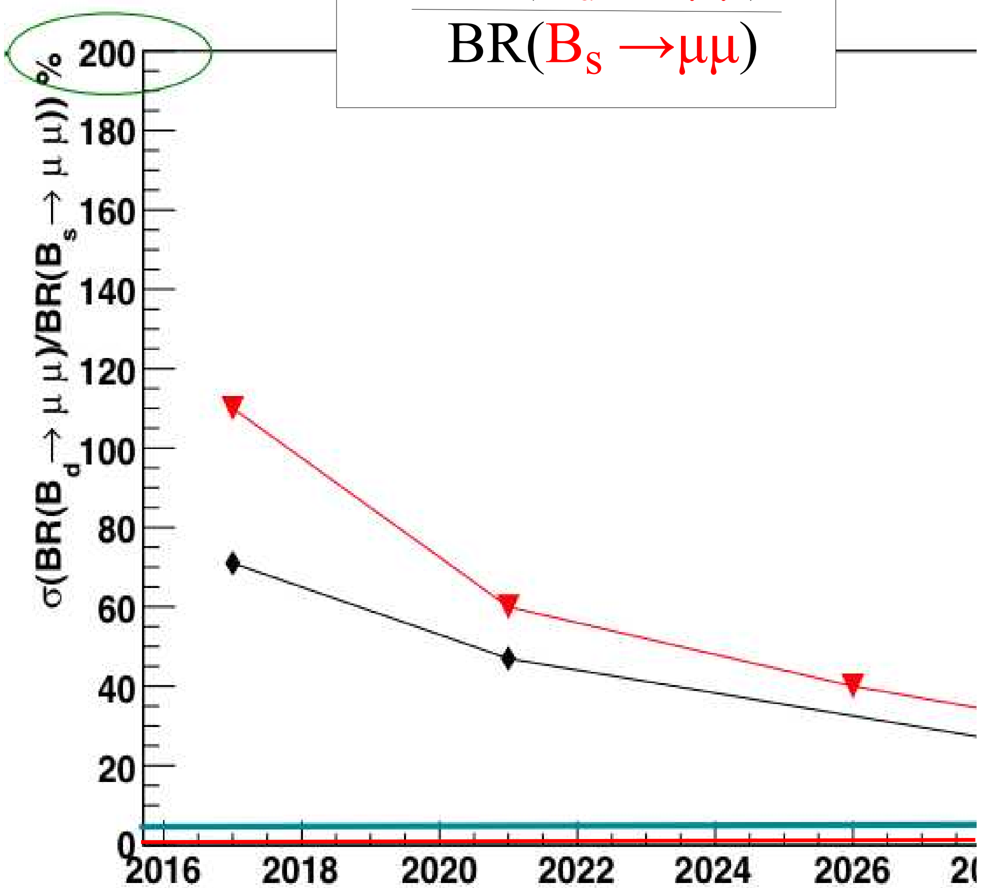
TH error (now): 5%

TH error (2030): ~1%

▶ *Future prospects* [The quark sector]

Example of B-physics observable that will NOT be dominated by the TH error at the end of the "ballistic program":

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



N.B.: there are various clean ratios of this kind

$$\frac{BR(B_u \to \tau\nu)}{BR(B_u \to \mu\nu)}$$

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

...

And future efforts in B physics could possibly address also

$\tau \to 3\mu$, $\tau \to \mu\gamma$, ...

So, What's Next?

making the right decisions at the right time

There is no unique answer, and of course a lot depends on what we'll see at the end of the planned experiments:

I. NP seen directly at ATLAS+CMS
or indirectly in Flavor
or seen in both sectors

II. NP not seen anywhere at the LHC

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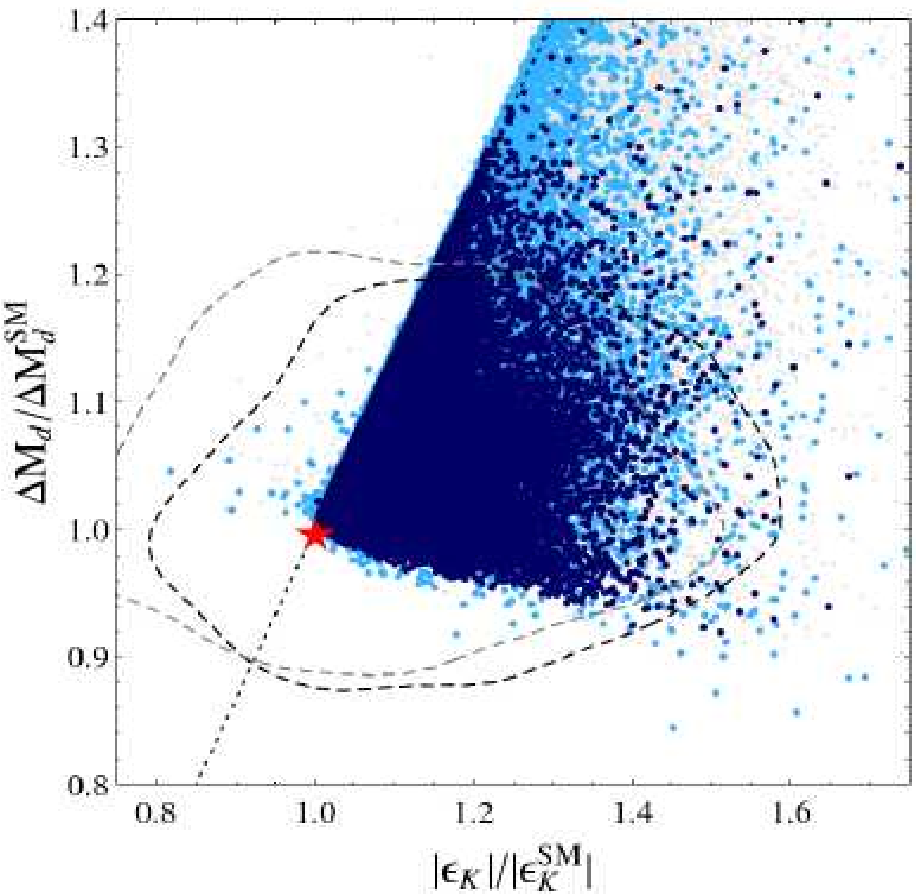
→

Data will tell us what to do...

"natural" seeing NP in both sectors
(*from which we learn different properties*)

II. NP not seen anywhere at the LHC

E.g.: "Natural" SUSY with $U(2)^3$ flavor symmetry



Points allowed by <u>present</u> CMS/ATLAS data

Barbieri, Buttazzo, Sala, Straub, arXiv:1402.6677

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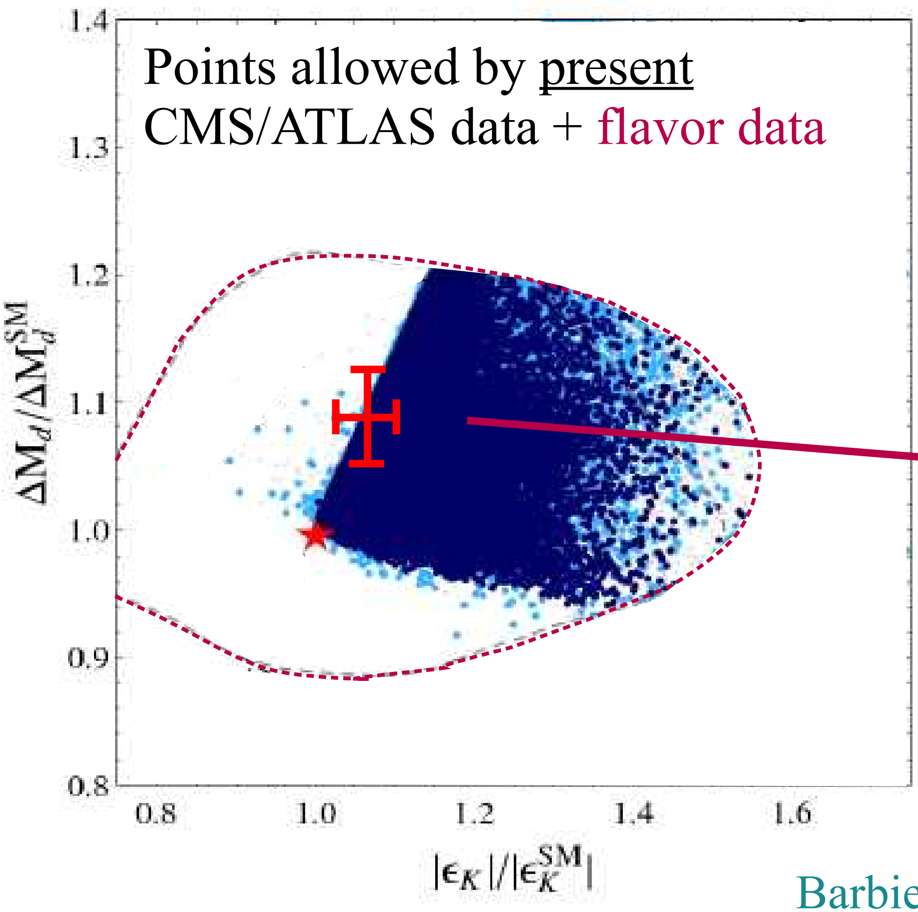
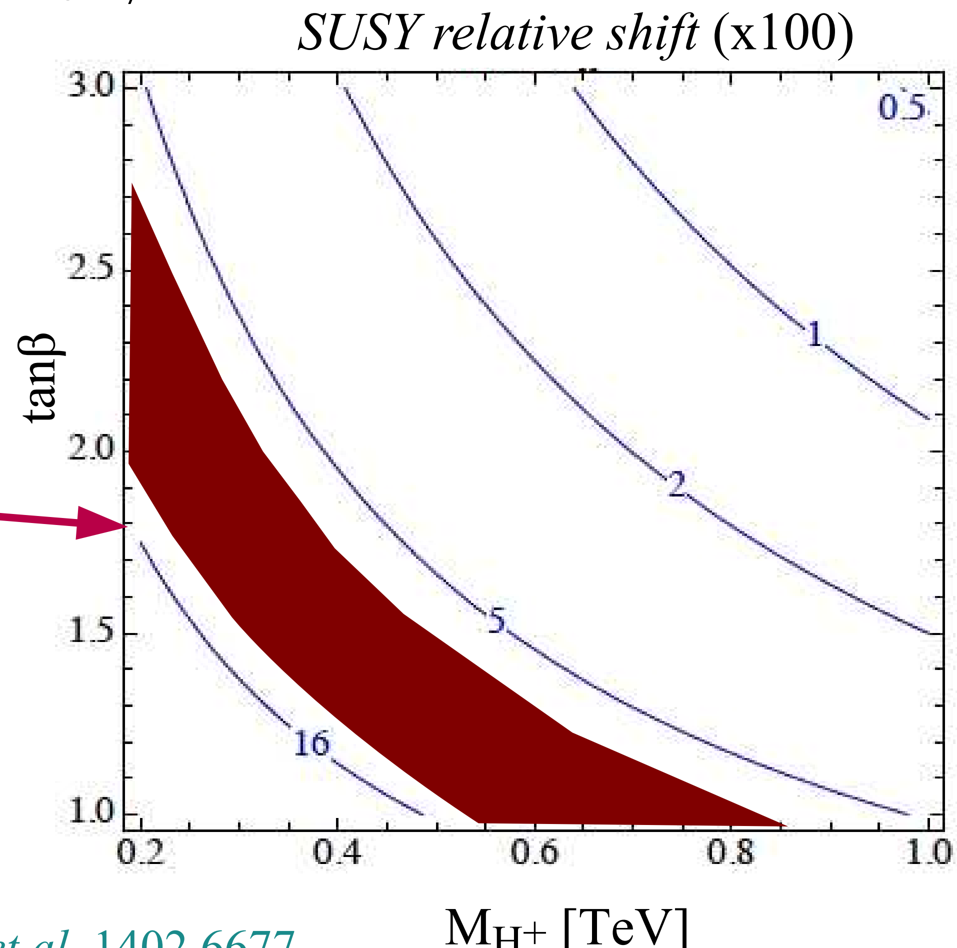




Barbieri *et al.* 1402.6677

SO, WHAT'S NEXT?

making the right decisions at the right time

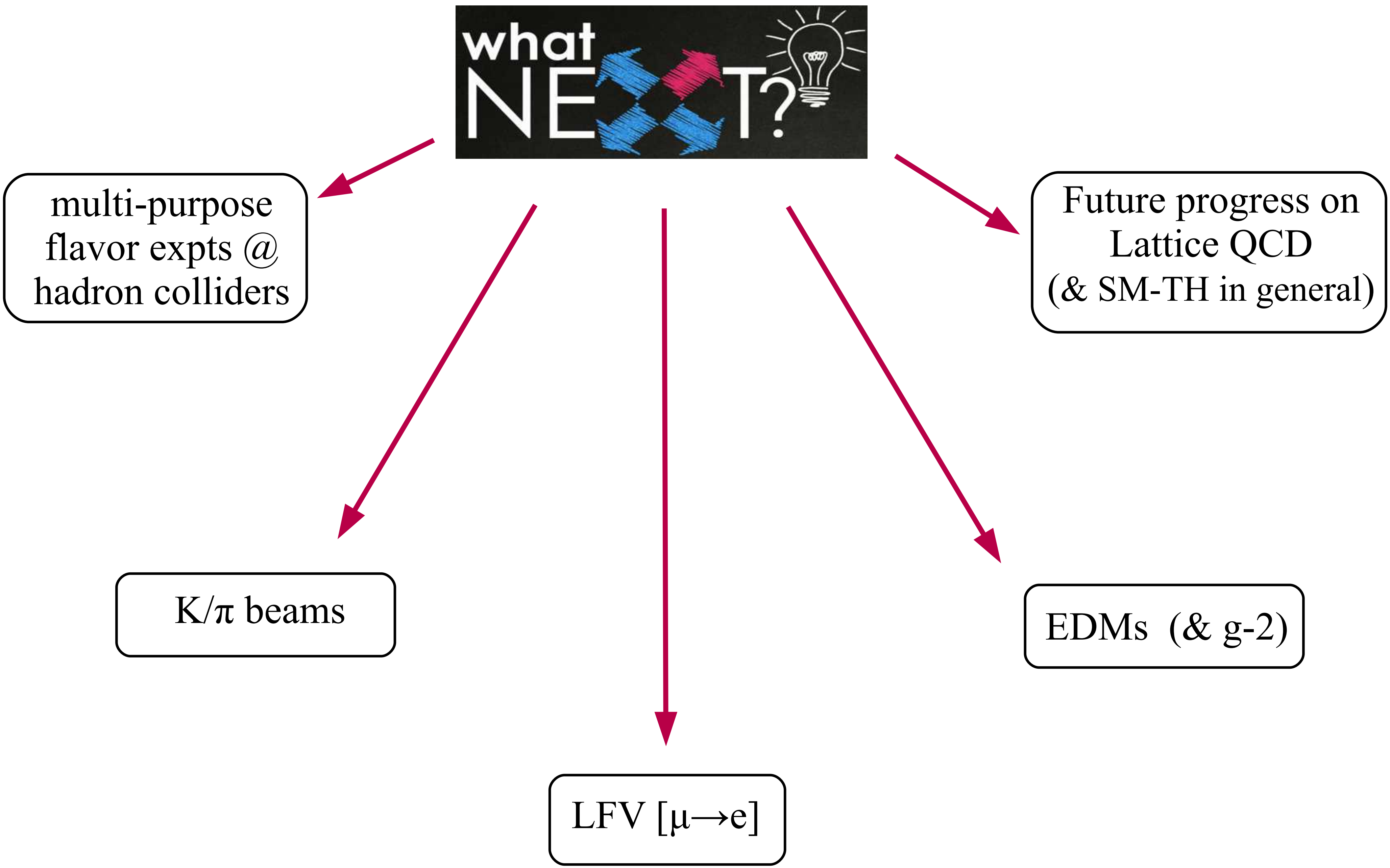
There is no unique answer, and of course a lot depends on what we'll see at the end of the planned experiments:

I. NP seen directly at ATLAS+CMS or indirectly in Flavor or seen in both sectors → *Data will tell us what to do...*

II. NP not seen anywhere at the LHC → *"Naturalness" in serious doubts*

Go for the most ambitious improvements in the experimental tests of fundamental or approximate SM symmetries

[LFV, EDMs, LFU ratios, decays to new exotic/elusive light states,...]


what NEXT?
multi-purpose flavor expts @ hadron colliders
Future progress on Lattice QCD (& SM-TH in general)
K/π beams
EDMs (& g-2)
LFV [μ→e]

what NEXT?

multi-purpose flavor expts @ hadron colliders

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

Can we plan an "Extreme Flavor" experiment @ LHC?
Foreseen experiments only exploit a small fraction of the enormous production of HF @ HL-LHC:
50fb-1 [LHCb] vs. 3000 fb-1 [ATLAS/CMS @HL]

Ingredients for an "Extreme Flavor" experiment:
- Detector with strong tracking capability at HL
- Detector readout at 40MHz
- Real-time event reconstruction at 40MHz
- Reconstruction and calibration in real-time.
- *Physics analysis* "in real time"...

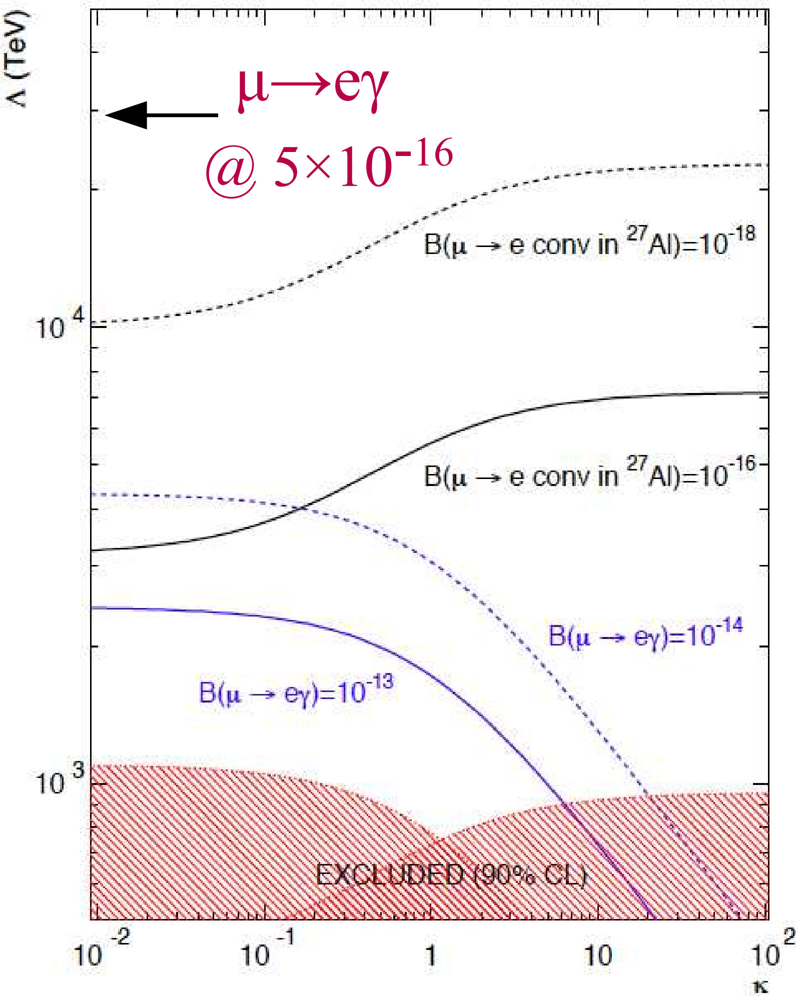
G. Punzi
F. Palla

+

Picosecond-tracking [N. Cartiglia]

What's the Ultimate Lattice precision on HF form factors?
Is the 0.1% level reachable?

Can we improve on non-leptonic channels by means of deeper studies of exotic spectroscopy, etc...



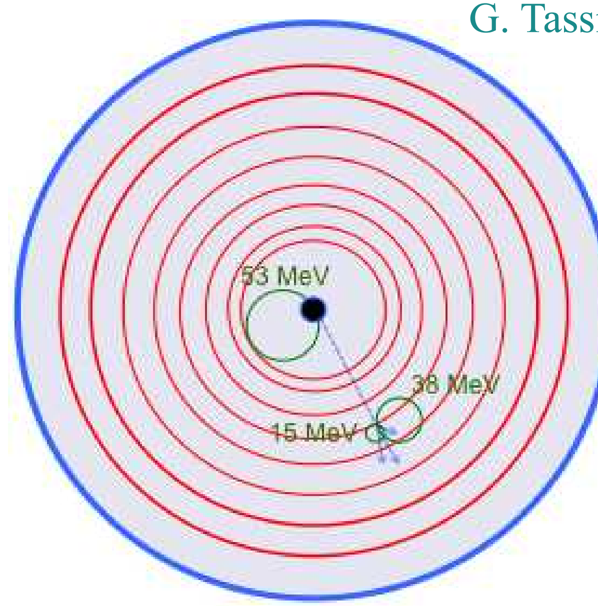
What's the ultimate sensitivity on $\mu \rightarrow e\gamma$?

A sensible improvement with respect to MEG can only be obtained by changing the approach to the γ measurement

→ γ conversion into a large (KLOE-like) drift chamber

LFV [$\mu \rightarrow e$]

F. Grancagnolo
G. Tassielli



what NEXT?

An electron-EDM storage ring (*at LNF?*) ?

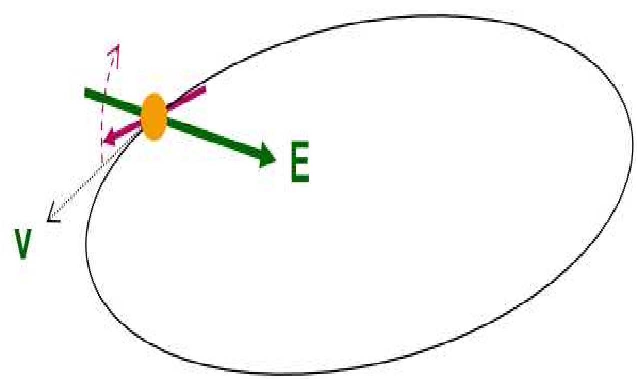
- First ever DIRECT measurement of electron EDM
- Compact (E = 2-6 MeV/m → 2πR = 50 - 20 m)
- Technical challenge, modest investment.
- Mandatory step for larger machines (p & d → 2πR > 250 m).
- *Open issue: polarimetry.*

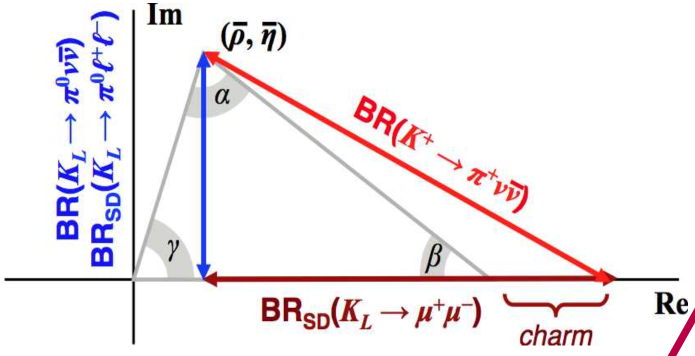
EDMs (& g-2)

P. Lenisa

The rules of the game....:

- Place particles in a storage ring
- Align spin along momentum (→ *freeze horiz. spin precession*)
- Search for time development of vertical polarization





K/π beams

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

A subset of NA62-Italy has started the feasibility study for a *KL* experiment @ SPS

Questions to answer:

- How intense a neutral beam can be obtained?
- Can an upstream photon absorber eliminate direct (beam) γ?
- Is the performance of the NA48 LKr calorimeter suitable?
- What performance will be required of the large-angle γ veto?
- How will charged particles be vetoed?
- How do we stop γ from escaping downstream in the beam pipe?
- …

F. Bucci, M. Moulson, M. Sozzi

Preliminary results: **7.8 signal events**
6.0 ± 1.7 background

Same level as or better than KOTO (JPARC)

multi-purpose flavor expts @ hadron colliders

An "Extreme Flavor" experiment @ LHC?

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

Ultimate Lattice precision on HF form factors?

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An electron-EDM storage ring [@ LNF]?