The future of Flavor Physics at CERN

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We leave in a wonderful word!...

…but which world?

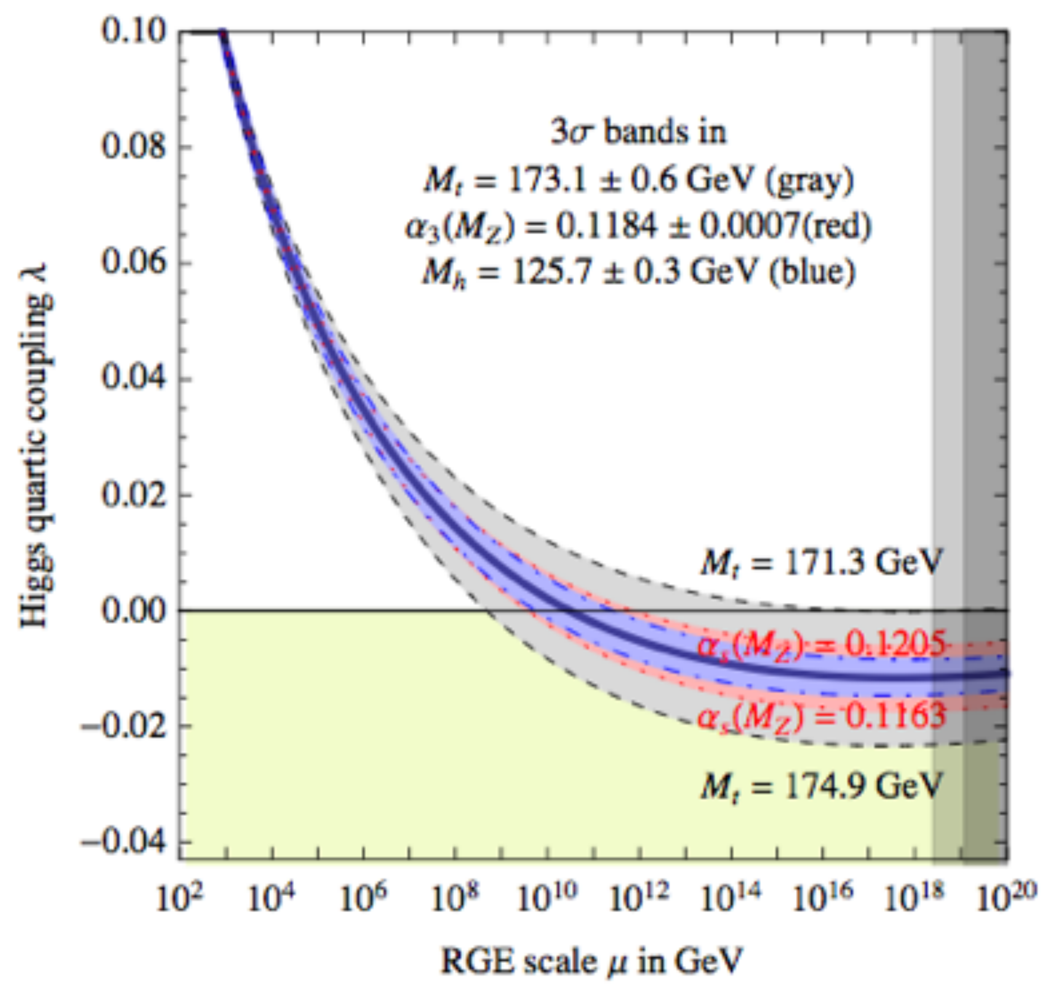
…and how can Flavor Physics/intensity frontier help answering this deep question?

Shaking hands…

SM was recently fully confirmed by the Higgs-boson discovery! (with the exception of the anti-ν_τ, whose detection is one of the goals of SHIP)

Vacuum stability

RG evolution of the scalar field quartic coupling indicate smooth behavior up to the Plank scale —> Universe metastable



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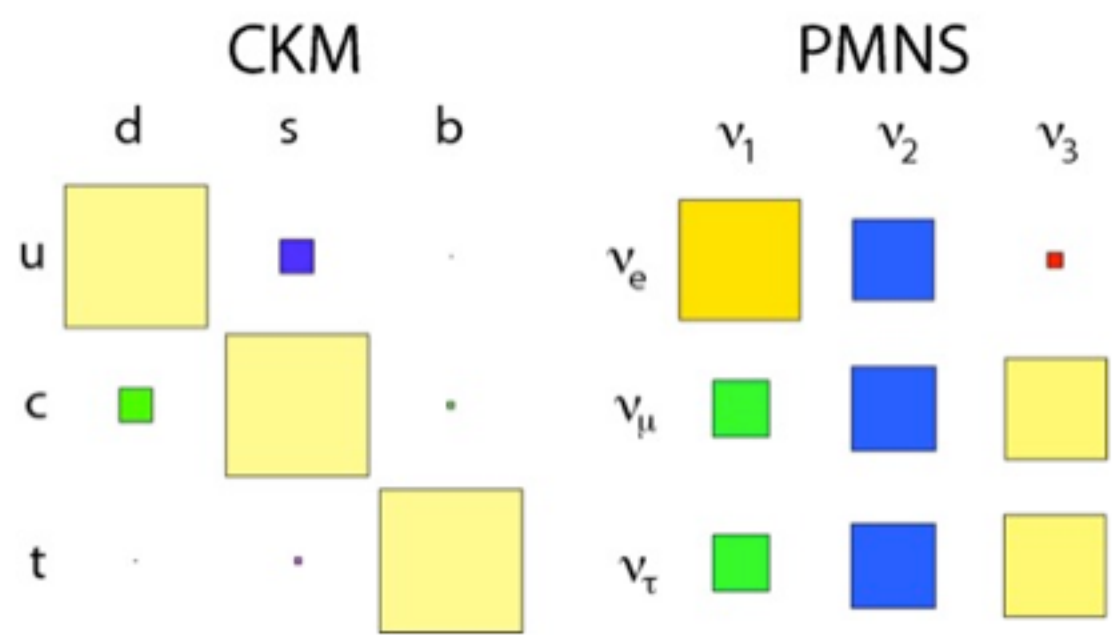
The SM incompleteness

However, we already know that the SM cannot be a complete theory due to several reasons:

one coming from particle physics experiments:

neutrinos do oscillate and therefore have mass —> 3x3 matrix PMNS (with CPV phase to be determined!); still we don't know the masses (but they are likely in the range $40meV<\sum m<230meV$), the mass hierarchy and if ν is Dirac or Majorana



Very different from CKM!

The SM incompleteness (2)

other ones coming from astrophysical observation/ considerations, i.e. how do we explain

dark matter

baryogenesis —> the SM cannot account for this

Indeed one of the most popular explanation for neutrino masses is the see-saw model, i.e. assuming there are right-handed massive neutrinos (so far unseen) that couple e.g. through mixing with the light ones

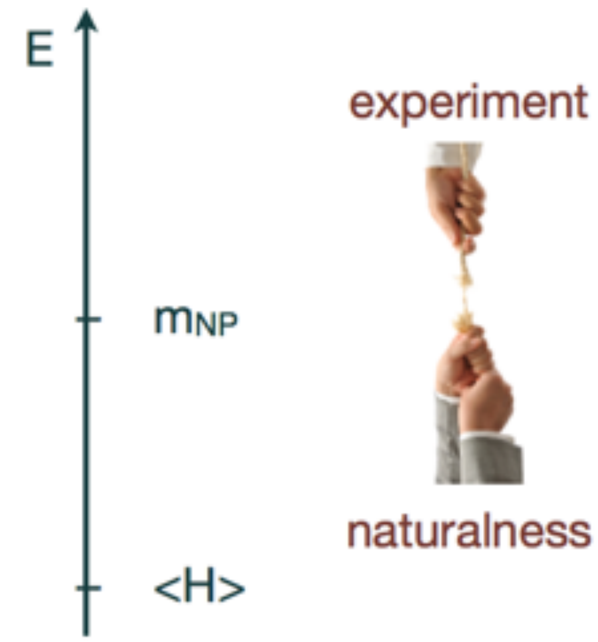
Should we stop calling it Standard Model ??? —> Current Model ?

The hierarchy problem

One other outstanding issue with the SM comes from so called Naturalness arguments (or Hierarchy problem):

if there exists a new scalar particle of mass M between EW scale and Planck scale, then the Higgs mass is not protected against radiative corrections and is brought towards high values —>fine tuning is then needed to explain why m_H=125GeV

(I neglect here for simplicity other issues such as how to solve the strong CP problem, who is the inflaton, what is dark energy,…)



How to build a consistent model?(i)

1) Address the Hierarchy problem, assuming that dynamics or symmetries or space-time modifications can cure it

a)SUSY —>

this also provides a DM candidate (LSP WIMP)

it may explain Baryogenesis

also gives a GUT scale (but not really "needed")

b) Composite Higgs is another possibility

—> many tests of these theories with Flavor Physics are possible, i.e. rare or forbidden meson decays and CPV in meson mixing and decay

(it should also be said that Natural SUSY, due to lack of observation of super partners, is in turn already "fine-tuned" to about 10% and will be more with 13TeV run if nothing is found—>a lot of debate on this in the community, 1-2 papers/day on the arXiv!)

How to build a consistent model?(ii)

2) Accept that fine tuning exists as a fact of Nature —>multiverse, anthropic selection?

physics at 100GeV depends on specific choices of parameters made at 10^{16} GeV!

but who knows… we have other unsolved fine tunings (cosmological constant, strong CP)

3) Assume there is no other scalar heavier of the Higgs up to the Planck mass

—> still one is left with the need of explaining DM, Baryogenesis

—> νMSM and its variants

some issues with the Planck scale but again, who knows…

Meson decay to search for NP

NP can be observed in loop-mediated decays of heavy flavors

e.g. FCNC are only allowed in the SM at loop level and are GIM suppressed: in K and D decays one expects a very tiny CPV and "small" in B decays

NP can also be observed in tree level decays

e.g. charged Higgs contributions to B—>(D*)lν

in semi-leptonic decays if the ν mixes with a massive on-shell state, which can be detected:

either as a kink in a kinematic distribution —>NA62, B factories

with a direct decay to SM particles (with another mixing) —>NA62, SHIP, FCC-ee

NP can be searched in tree level interactions of e.g. $\nu\tau$'s

Present bounds

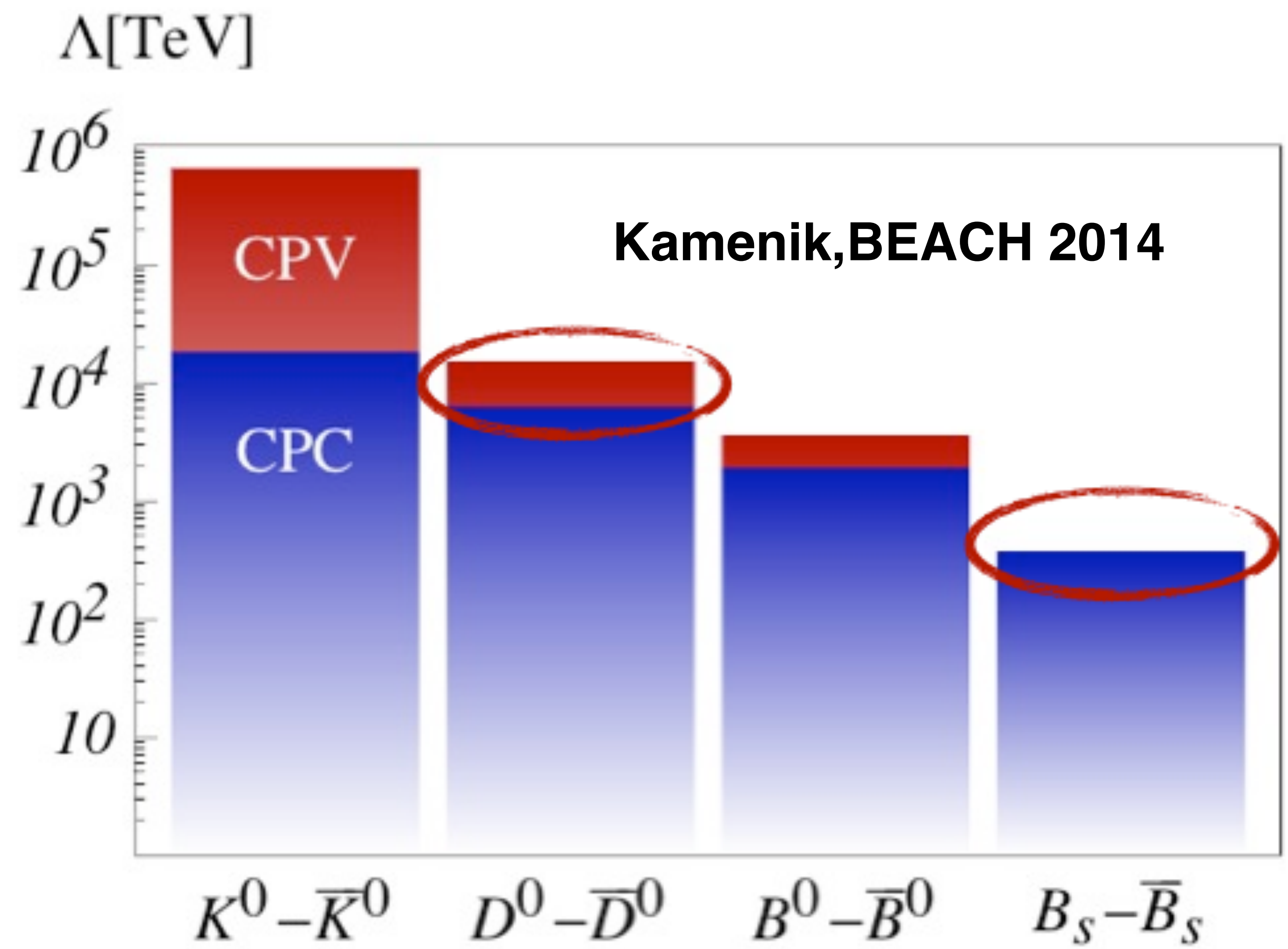
If the SM model is considered as an effective theory then,

$$\Delta\mathcal{L}_{d>4} = \sum_{d>4}\sum_{n=1}^{N_d}\frac{c_n^{(d)}}{\Lambda^{d-4}}\mathcal{O}_n^{(d)}(\text{SM fields}).$$

assuming a natural coupling of order one —>

—>NP with a generic flavor structure at the TeV scale is already ruled out (the same holds for LFV)

Luminosity dependence: roughly 3x in Λ —>10x in exp & th —>100x in L)

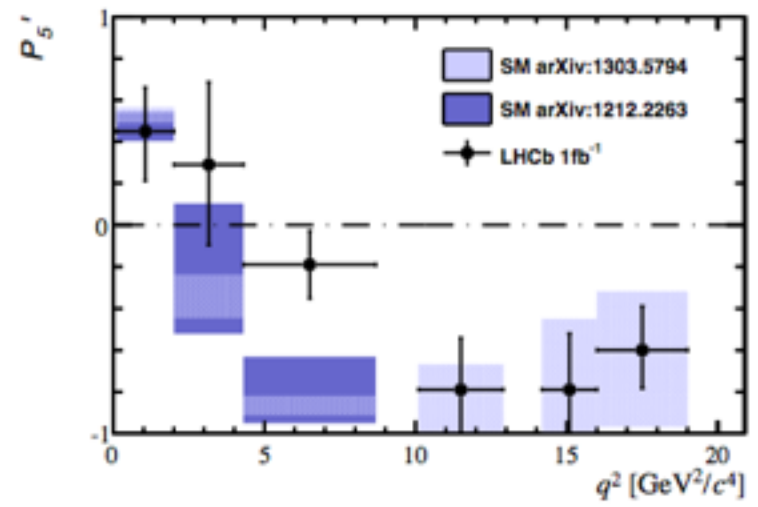


theory/CKM limited: K and B^0

experimentally limited: D^0 and B_S

Any hint of NP in decays?

In B_d—>$K^*\mu\mu$ —>P5' some 3σ from SM—>explained by non perturbative hadronic effects?



R_K(B_d—>$K\mu\mu$/ee) —>2.6 σ from SM

R(B_d—>D(*)lν) at B factories —>3.4σ from SM

A(CP) (τ—>$\pi K^0_S \nu_\tau$) —>2.8σ from SM

For the last two a study of ν_τ interaction with good statistics may help shedding light (see SHIP EOI and A.Datta, PRD 87 (2013)013002)

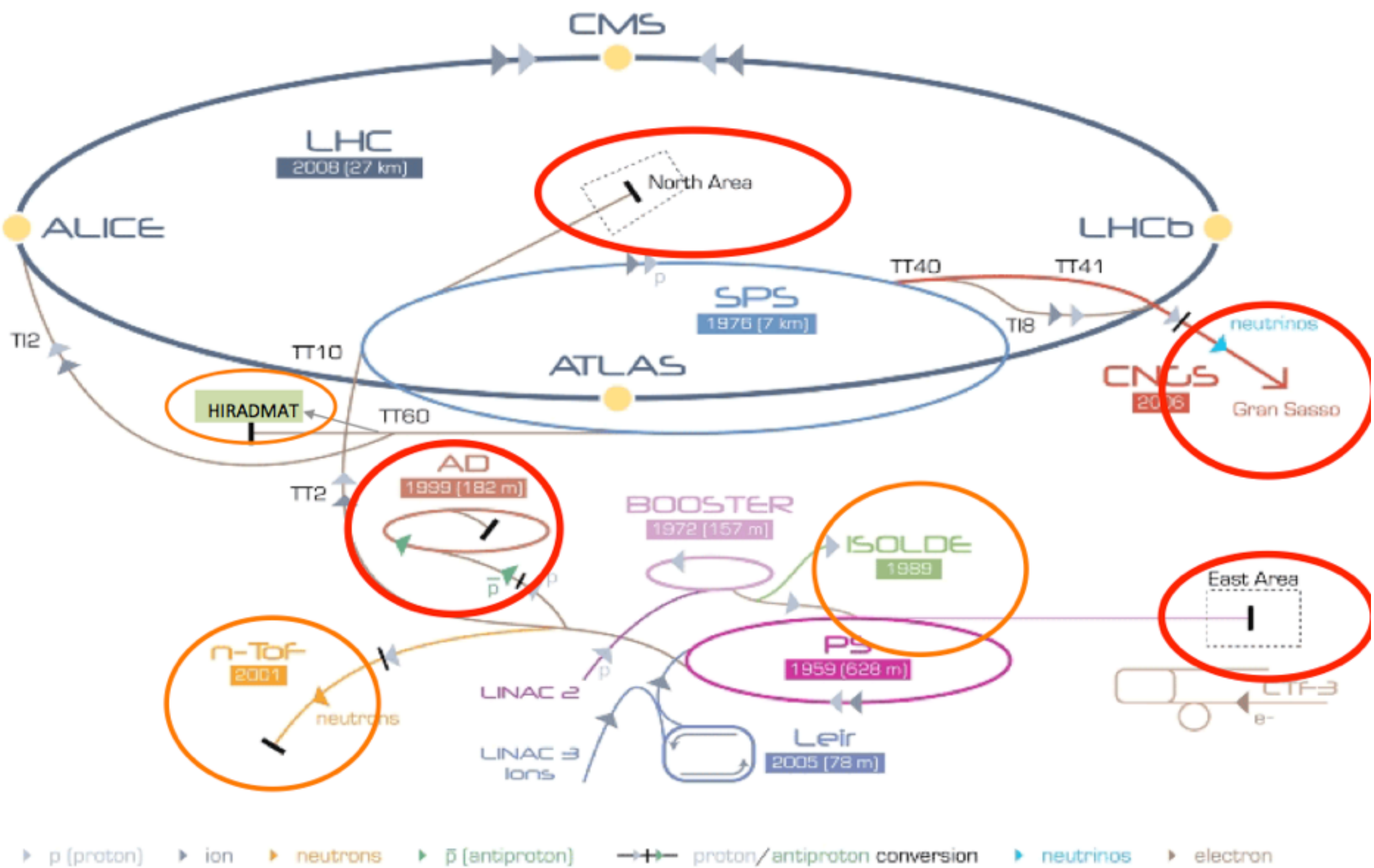
Future projects of CERN

Of course I would be in better position to tell you what is the future of Flavor Physics at CERN if I were the DG or the Director of Research or their successor(s)

Here I can only tell you what are the options for the Future or what they should be in my opinion and I take full responsibility for what I am going to say!

I will discuss the near future (approved), the mid-term future (in discussion in committees), the might-be very long term (just some ideas), assuming all can be done at CERN (and I hope not, for the healthiness of our field)!

THE CERN ACCELERATOR COMPLEX WITH ITS EXPERIMENTAL AREAS



Future flavor projects approved at CERN

	LHC era			HL-LHC era	
	Run 1 (2010–12)	Run 2 (2015–17)	Run 3 (2019–21)	Run 4 (2024–26)	Run 5+ (2028–30+)
ATLAS & CMS	$25\,\text{fb}^{-1}$	$100\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$	$\longrightarrow$	$3000\,\text{fb}^{-1}$
LHCb	$3\,\text{fb}^{-1}$	$8\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$46\,\text{fb}^{-1}$	$100\,\text{fb}^{-1}$

LONG LIFE TO CERN!

LHCb Run 2 —>Run I LHCb with double b and c cross section AND more output bandwidth (4x)

LHCb Upgrade —> Run at 4x Luminosity and remove L0 trigger pT cuts (mostly) on hadrons —>gain factor 8-10 on hadronic channels

ATLAS and CMS Run2, Run3 and HL (it is not a flavor project but can do a lot, in particular top physics which I don't have time to cover but it is VERY important for Flavor)

NA62—> starts taking data this year

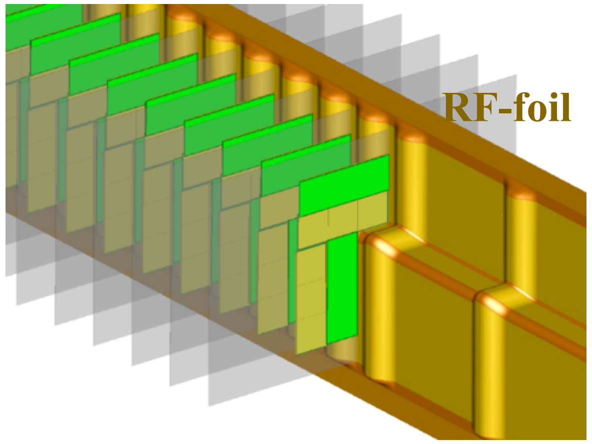
The core of the LHCb upgrade

Trigger upgrade

Remove L0 hardware —>full software trigger at 40MHz

Tracker upgrade

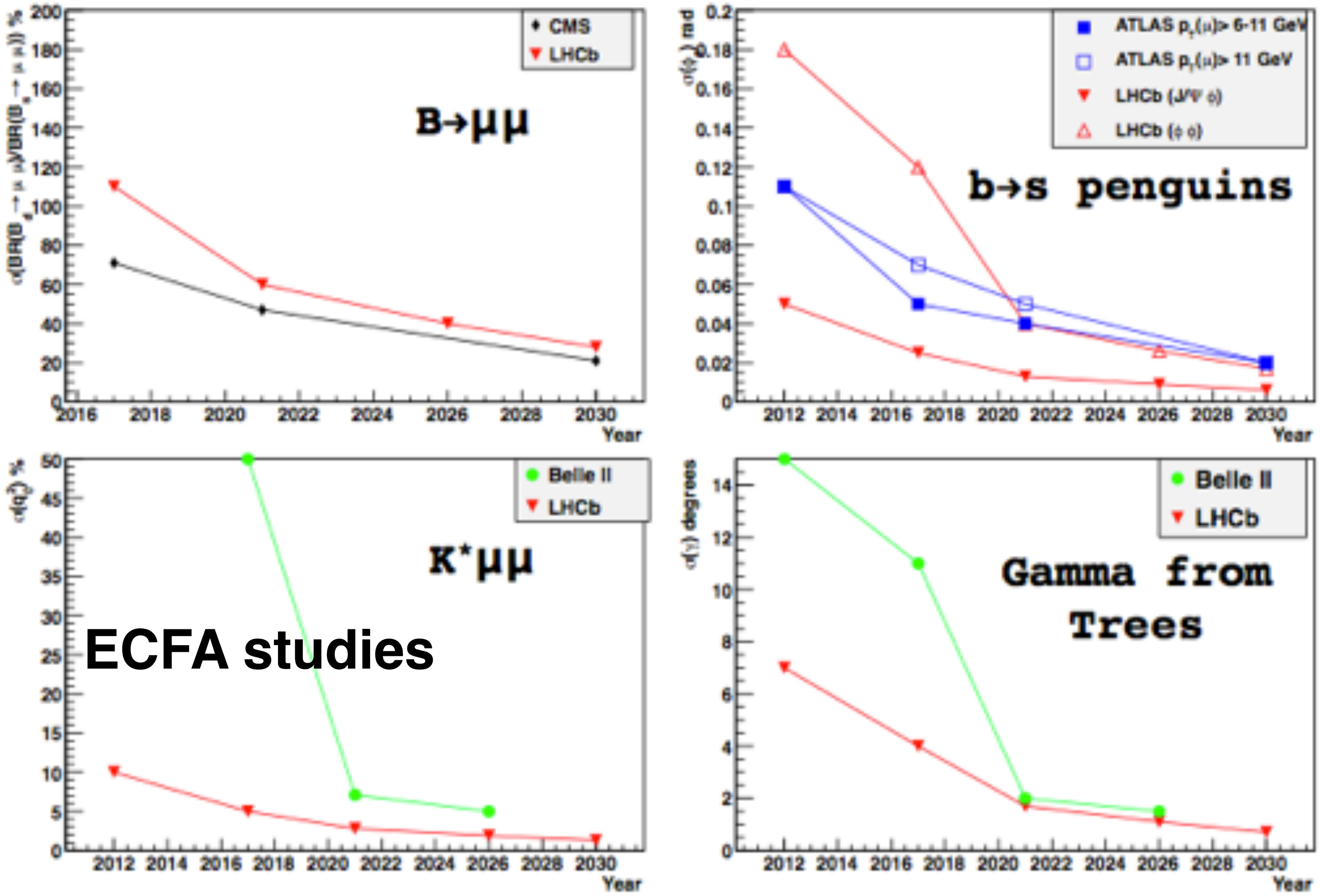
New VELO pixel detector (55μx55μm with μ-channel cooling), inner aperture 3.5mm from the beam

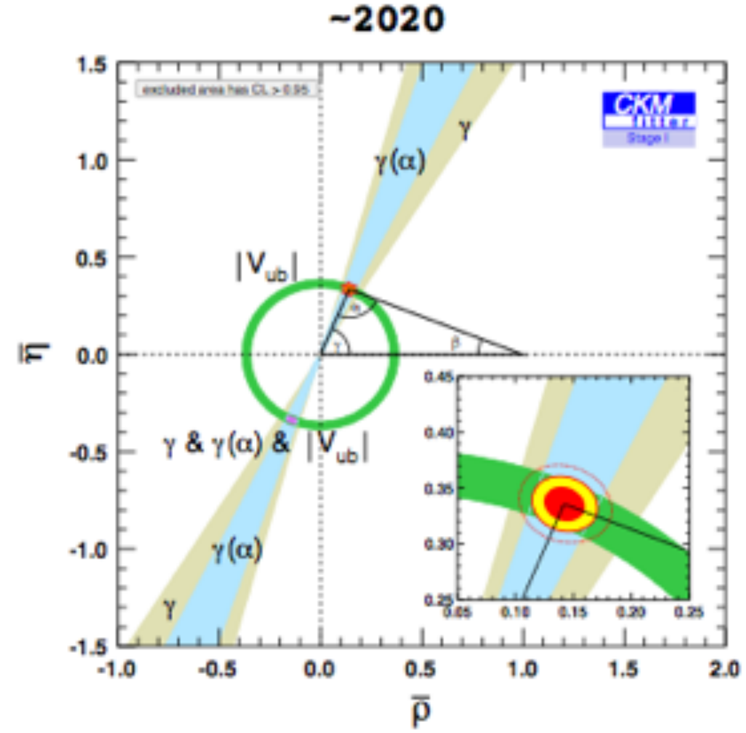


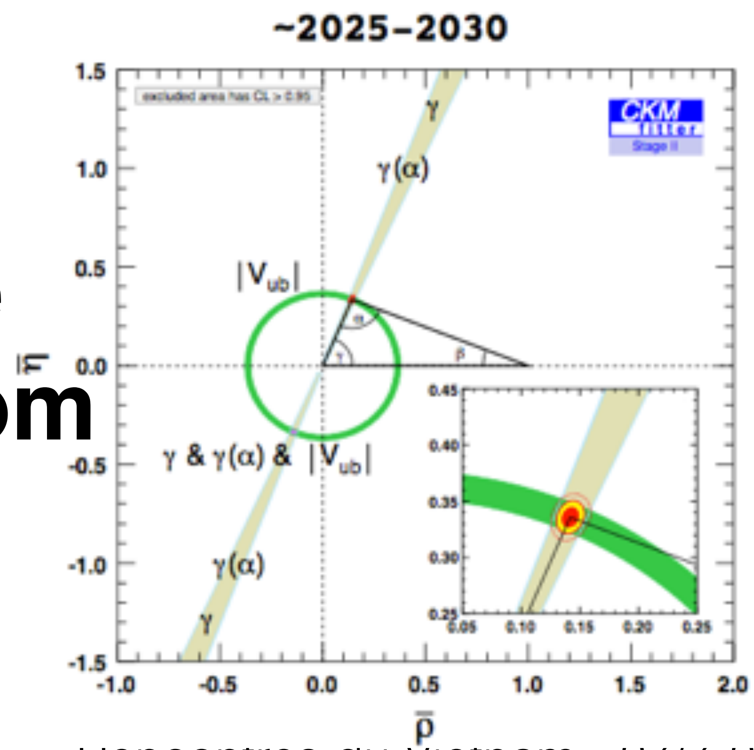
New trackers (main news is fiber 250μm tracker after magnet readout by SiPM instead of straw tubes+silicon strips)

+ Some other changes…

As an example: b sector



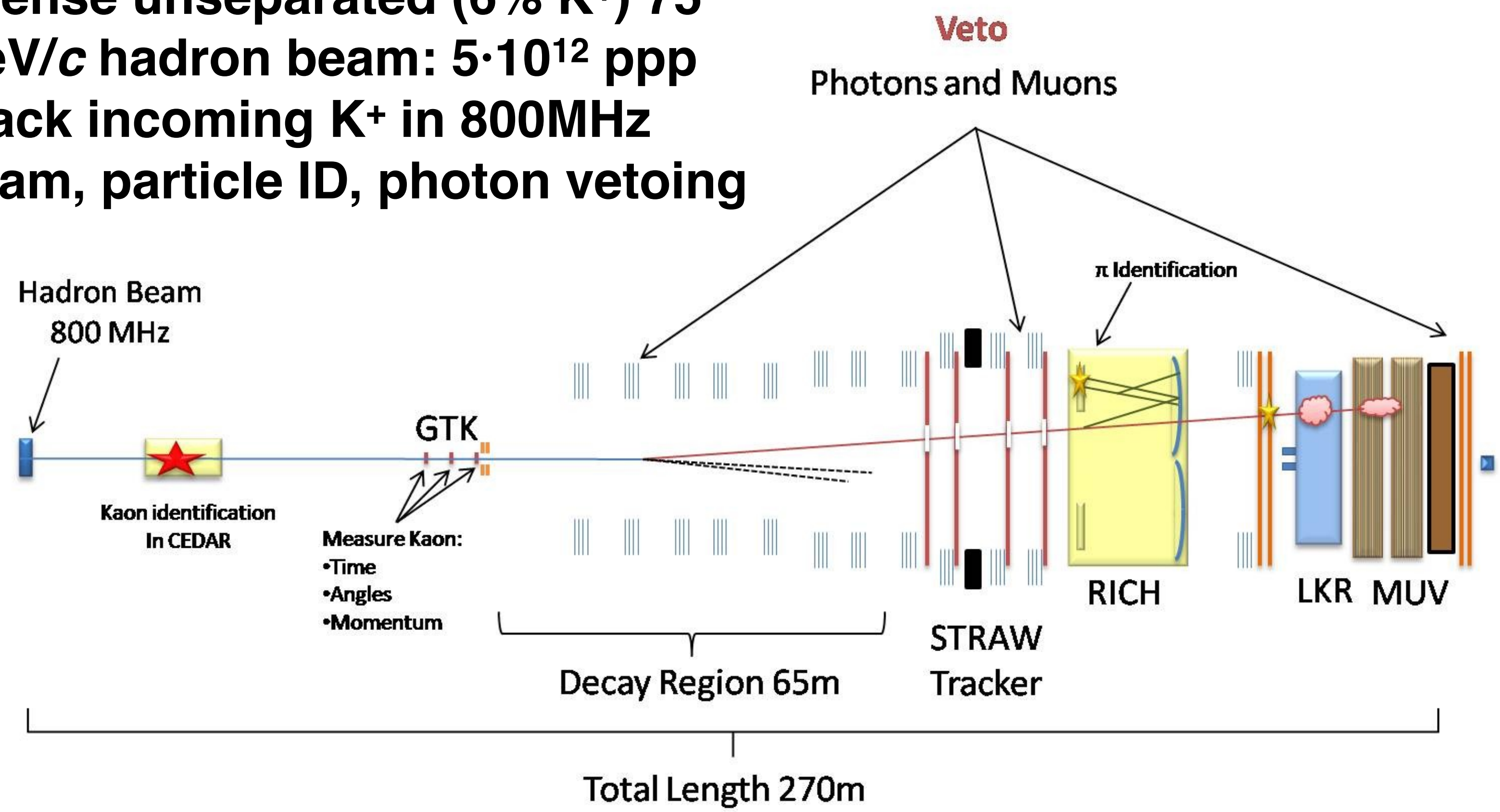


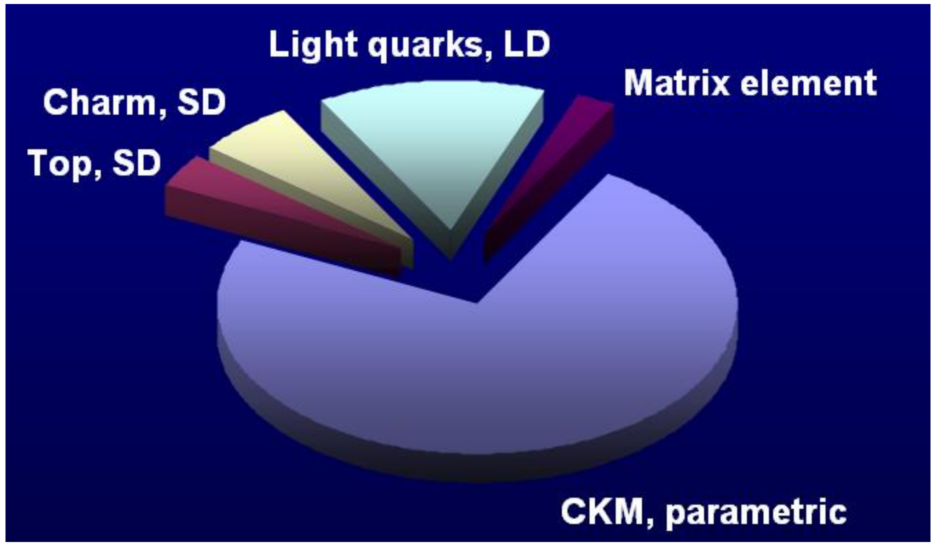


We should also not forget that the full picture in b physics comes from the combination with Bellell measurements!

NA62

Measurement of $K^+ \to \pi^+\nu\nu$ with new decay in-flight technique
Intense unseparated (6% K^+) 75 GeV/*c* hadron beam: $5 \cdot 10^{12}$ ppp
Track incoming K^+ in 800MHz beam, particle ID, photon vetoing





Comparable, unprecedented, *tiny* theoretical errors

$5 \cdot 10^{12}$ K^+ decays/year

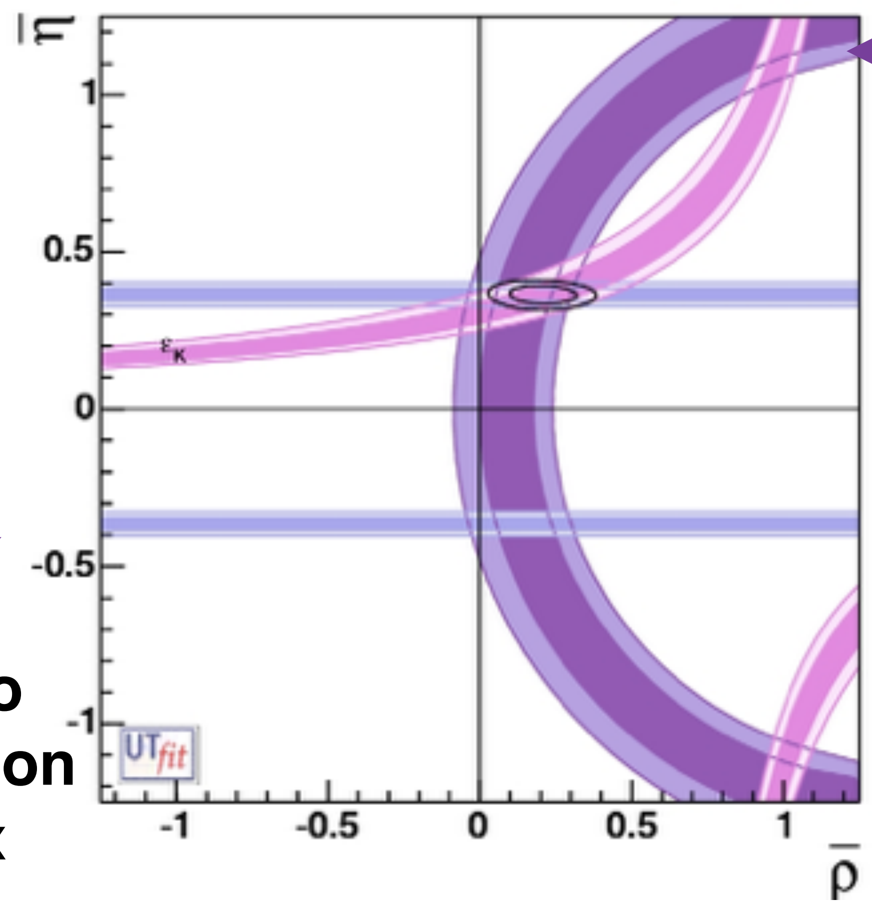
O(100) SM events in 2 years, S/B ≈ 5

★★★ large effects
★★ visible but small effects
★ unobservable effects

Buras et al.

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★

In the CKM language…



NA62 with only 2years of running

KOTO-II 10% precision (>2025?)

KOTO-I is not able to contribute to a precision location of the apex

impact of Kaon physics to the UTfit, assuming agreement between rare kaon decays and the SM

courtesy M.Bona, very preliminary

SHIP

SHIP is a proposal for a beam dump experiment at CERN/SPS (400GeV p) —> run could start in 2022

Main goals (so far…):

A. **detection of long lived particles, weakly interacting or sterile: statistical sensitivity with respect to previous experiments of similar type x10000**

   A. **HNL's**
   B. **massive photons** → **CONNECTION WITH DARK MATTER**
   C. **PNGB(Pseudo Nambu Goldstone bosons)**

B. **study of ν_τ interactions with statistical sensitivity with respect to previous experiments of similar type x200**

News from CERN

CERN
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EN Engineering Department

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1369559	1.0	RELEASED

REFERENCE
EN-DH-2014-007

Date : 2014-07-02

Report

A new Experiment to Search for Hidden Particles (SHIP) at the SPS North Area

Preliminary Project and Cost Estimate

The scope of the recently proposed experiment Search for Heavy Neutral Leptons, EOI-010, includes a general Search for HIdden Particles (SHIP) as well as some aspects of neutrino physics. This report describes the implications of such an experiment for CERN.

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
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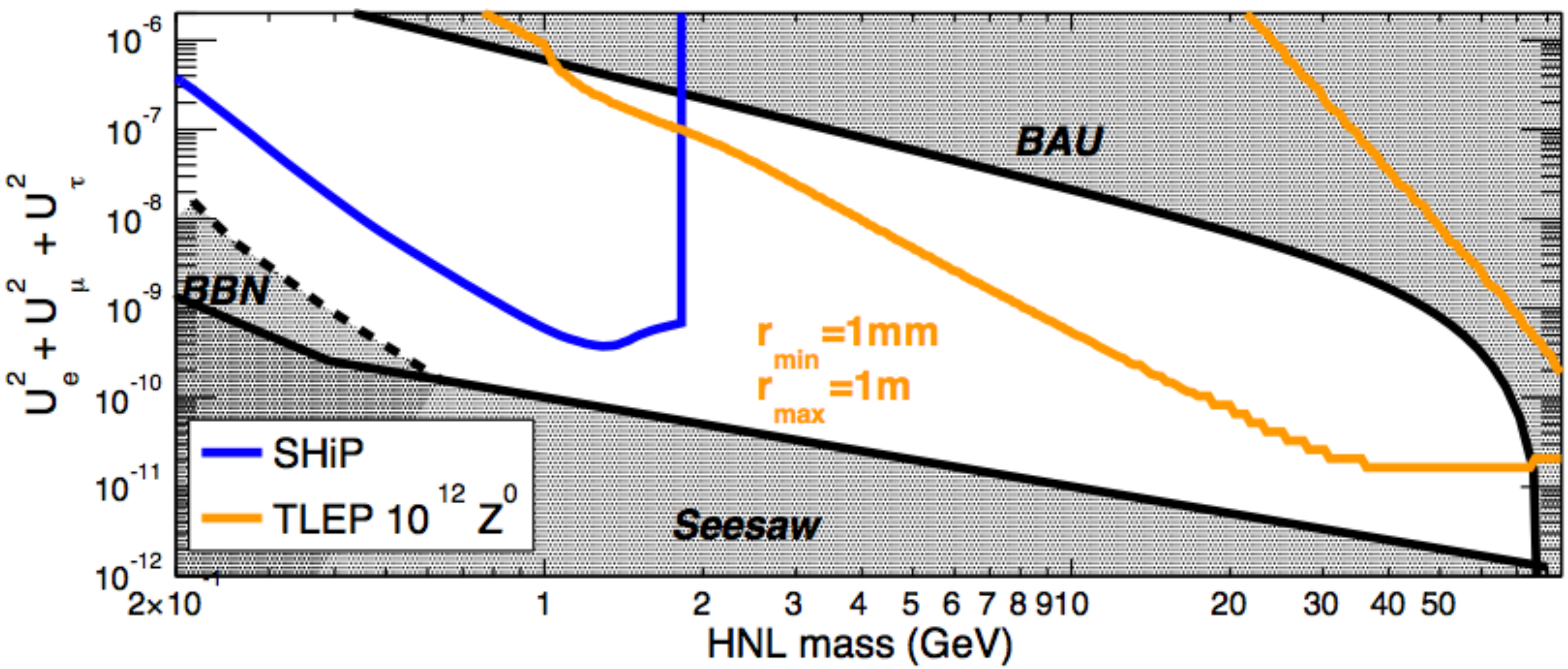
Only CERN has “the” right beam (but not yet the beamline! >x10 intensity of NA62 beam line)

HNL sensitivity



FCC-ee becomes competitive at large masses due to lifetime dependence

While the SHIP assumption of 0 background appears to be well justified, that of FCC-ee needs to be proven (e.g. Z—>bbar is huge)

NA62 also can say its words below kaon mass.

New ideas (i)

The Ultimate B, D flavor experiment at LHC (G.Punzi, FCC Workshop 2014)

go beyond luminosity leveling in LHCb at $2x10^{33}$,in principle aiming at 10^{35}

NB: LHCb was conceived in ≈ 1995 —>by 2025 we may benefit from many years of technological developments!

just some possible resolutions:

UT angles 0.1^{o}, charm CPV—> 10^{-5} (Λ>$3x10^{5}$TeV, close to the K bound), BR(Bd/Bs—>$\mu\mu$)≈3%, τ—>$\mu\mu\mu$ ≈10^{-10}

if MFV is the flavor structure of BSM, the testing BR(Bd/Bs—>$\mu\mu$) to few % may be the only way to say it!

New ideas (i+)

need to process the full data from each crossing —>strong requirements on the DAQ system

real time calibration and processing at 40MHz

New ideas with pattern recognition: hardware tracking ! (very different from LHCb upgrade at hit level!)

Double-layer detectors (a la CMS) → Local measurement of track angle

Time-tagged silicon detectors —>vertexing from single layers>σ(t)<20ps

Parallel, low latency tracking with retina-like algorithms on processors

Ideas (ii):NA62+

Under study the feasibility of some detector improvements

Also a detector adaptation (e.g. new photon vetoes) for measuring $K^0_L \to \pi^0 \nu\nu$

—>Possibly for run3 or even run4

—>would require higher beam intensity to be competitive with KOTO

(see M.Moulson, LTS1 – Isola d'Elba, 22 May 2014)

Also $K^0_L \to \pi^0 ll$ very interesting; may allow to distinguish between physics models but larger theory uncertainties;

both channels would require substantial modifications of the present apparatus

Not really flavor experiments but a lot of flavor…

FCC-ee 10^{12}Z

- **$3x10^{10}$ τ pairs**
- **$2x10^{11}$ b and c —>e.g. 20k B^0_S—>$\tau^+\tau^-$**
- **$4x10^{11}$ ν's —> complements SHIP on Majorana ν search**

FCC-pp $10ab^{-1}$ at 100TeV

- **10^{12} t—>Wb (i.e. with tagging)**
- **10^{11} t—>W—>τ**
- **few 10^{11} t—>W—>c**

Synergies!

Within the IF community there are similarities and complementarities

Notice that NA62 is a similar apparatus to SHIP but

with lower beam intensity, smaller detector and no muon filter

—> SHIP can learn a lot from the NA62 run (that can perform with lower sensitivity some of the measurements) and the new high intensity beam line could be used for Kaon or other types of experiments later on

Another example, SHIP and LHCb can test similar models in different parameter space values

e.g. dark photons or PNGB's

Financial considerations

As you saw in this talk Intensity frontier physics at CERN is done in a parasitic way!

High energy beams are built for other (noble) purposes and as Flavor Physicists we contribute to exploit them as much as we can

Indeed e.g for the SPS after the closure of the Gran Sasso beam most of the protons are unused

the SHIP experiment aims at using these protons to do frontier research

Also the LHCb upgrade and the recently discussed “extreme flavor” idea follow the same reasoning

Financial considerations(ii)

When considering additional costs for beam lines, and detectors we often forget that this has to be compared with the cost of

building, upgrading, maintaining the accelerators —> e.g. LHC 10BCHF

electricity bill, salaries ecc. —> quite high…

and the waste of money of not fully exploiting the beams for physics!

Take home message!

We know for sure that there is NP

Yet, we don’t know which one among the NP theories is the right one.

Maybe none of them is right!

We should keep an open mind

Pursuing a diversity of experimental approaches is very important to maximize our likelihoods of finding NP

and even if we don't find NP…

…we anyway leave in a wonderful world!

Backup

Time evolution

			LHC era		HL-LHC era	
		Run 1	Run 2	Run 3	Run 4	Run 5+
$\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s^0\to\mu^+\mu^-)}$	CMS	> 100%	71%	47%	...	21%
	LHCb	220%	110%	60%	40%	28%
$\phi_s(B_s^0 \to J/\psi\phi)$	ATLAS	0.11	0.05–0.07	0.04–0.05	...	0.020
	LHCb	0.05	0.025	0.013	0.009	0.006
$\phi_s(B_s^0 \to \phi\phi)$	LHCb	0.18	0.12	0.04	0.026	0.017
γ	LHCb	7°	4°	1.7°	1.1°	0.7°
	Belle II	—	11°	2°	1.5°	—
$A_\Gamma(D^0 \to K^+K^-)$	LHCb	3.4×10^{-4}	2.2×10^{-4}	0.9×10^{-4}	0.5×10^{-4}	0.3×10^{-4}
	Belle II	—	18×10^{-4}	$4–6 \times 10^{-4}$	$3–5 \times 10^{-4}$	—
$q_0^2\ A_{\rm FB}(K^{*0}\mu^+\mu^-)$	LHCb	10%	5%	2.8%	1.9%	1.3%
	Belle II	—	50%	7%	5%	—
$t \to qZ$	ATLAS	...	...	23×10^{-5}	...	$4.1–7.2 \times 10^{-5}$
	CMS	100×10^{-5}	...	27×10^{-5}	...	10×10^{-5}
$t \to q\gamma$	ATLAS	...	...	7.8×10^{-5}	...	$1.3–2.5 \times 10^{-5}$

The νMSM and its variants

3 Majorana (HNL) partners of ordinary ν, with $M_N<M_W$

In a peculiar parameter space (N_2 and N_3 almost degenerate in mass and with m=O(GeV) and N_1 decoupled with m=O(keV)), νMSM explains:

neutrino masses (see-saw), baryogenesis (via lepto-genesis) and DM (N_1)!

No hierarchy problem

Naturalness of the above parameter space comes from a U(1) lepton symmetry, broken at 10^{-4} level.

Forgetting about DM, it is also possible to build a model without the above degeneracies with larger allowed parameter space