Esperimenti futuri alla frontiera della precisione/intensità

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Auditorium Antonianum, 6–7 Settembre 2018
Fisica delle Particelle, verso la nuova Strategia Europea

Summary

- Panoramica del futuro, balistico e non
  - sapore leptonico (carico)
  - g–2
  - τ
  - CKM e sapore adronico
    - b
    - K
    - intensità
  - EDMs
  - n

Eu Strategy 2013 statements

- In 2012 there was the discovery of the Higgs boson and the measurement that ϑ_{13} was large. There is no analogy for our period.

- (c) The discovery of the Higgs boson is the start of a major program of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this program. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade program will also provide further exciting opportunities for the study of flavor physics and the quark-gluon plasma.*

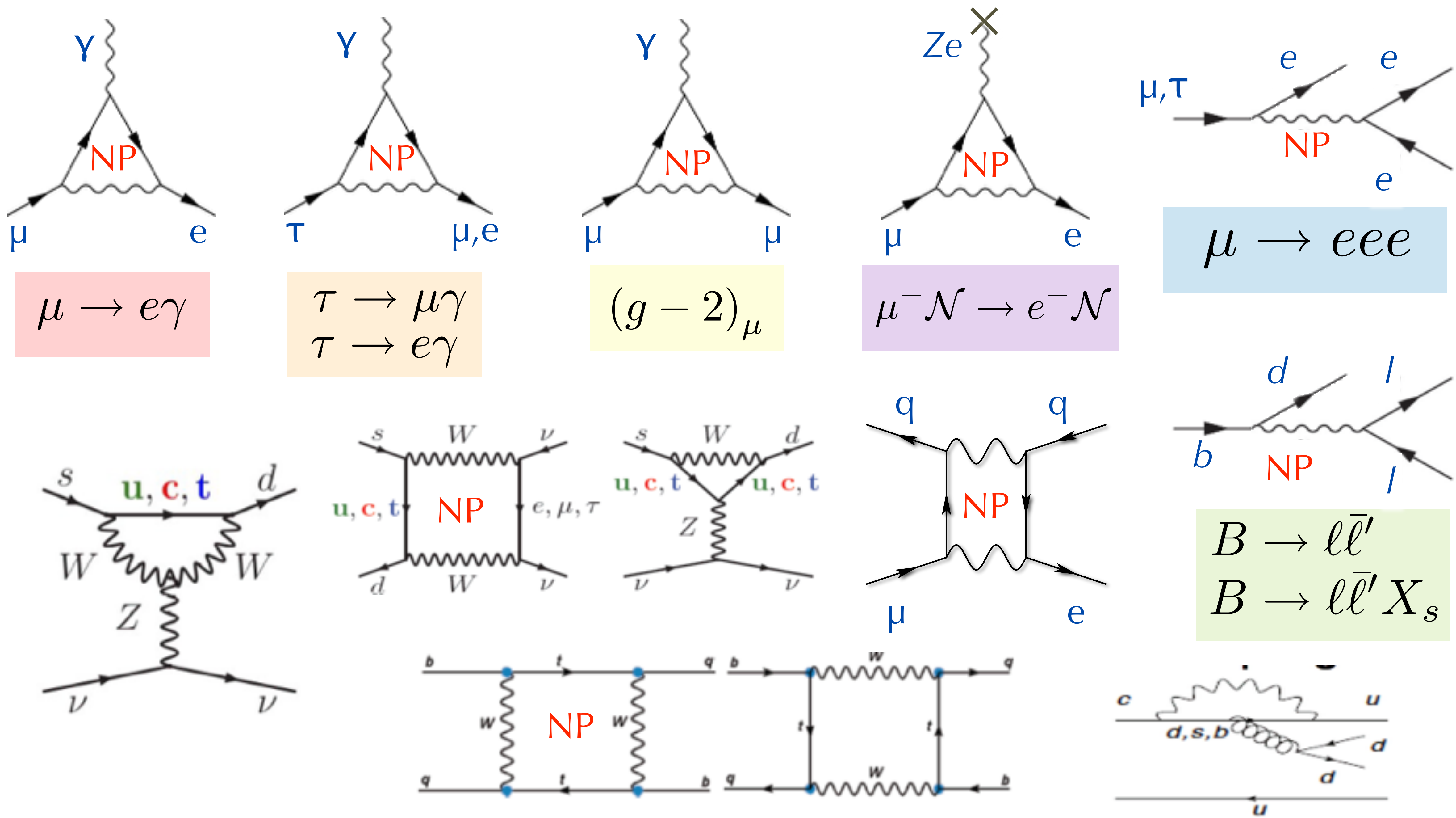
- (h) Experiments studying quark flavor physics, investigating dipole moments, searching for charged-lepton flavor violation and performing other precision measurements at lower energies, such as those with neutrons, muons and antiprotons, may give access to higher energy scales than direct particle production or put fundamental symmetries to the test. They can be based in national laboratories, with a moderate cost and smaller collaborations. *Experiments in Europe with unique reach should be supported, as well as participation in experiments in other regions of the world.*

- *Some of the most prominent anomalies come from the flavour sector*

Diverse processes

- New physics (NP) hidden in loop operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \ldots .$$



…for a wide class of processes

	Dedicated experiment	Multi-purpose experiment

…for a wide class of processes

	Dedicated experiment	Multi-purpose experiment
Exotic Searches New Physics if seen Experiment limited		
BSM physics NP if deviations from SM Theory limited		

…for a wide class of processes

	Dedicated experiment	Multi-purpose experiment
Exotic Searches New Physics if seen Experiment limited	$\mu \to e\gamma$ $\mu \to eee$ $\mu^- N \to e^- N$	$\tau \to \mu\gamma$ $\tau \to e\gamma$ $K_L^0 \to \mu e$ $\tau \to 3\ell$ $Z' \to e\mu$
BSM physics NP if deviations from SM Theory limited	e, μ, n edm $(g-2)_\mu$ $(g-2)_e$ $\frac{\pi^+(K^+) \to e^+\nu}{\pi^+(K^+) \to \mu^+\nu}$ $K_L^0 \to \pi^0\nu\nu$	$B \to \mu\mu$ $b \to s\gamma$ $\frac{\tau \to e\nu\nu}{\tau \to \mu\nu\nu}$ $K^+ \to \pi^+\nu\nu$ $K^+ \to \mu^+\mu^+\pi^-$

…for a wide class of processes

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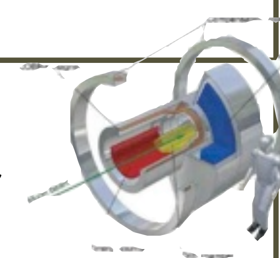
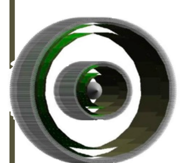
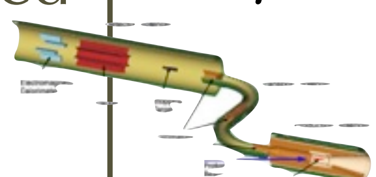
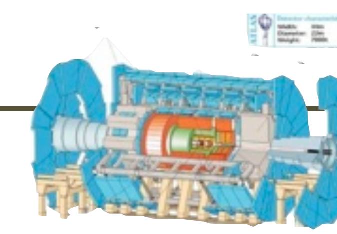
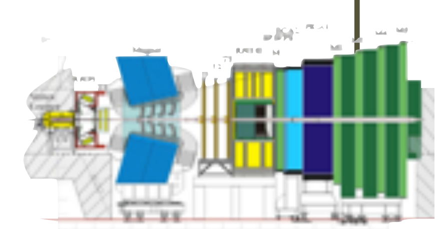
Exotic Searches New Physics if seen Experiment limited	$\mu \to e\gamma$ $\mu \to eee$ $\mu^- N \to e^- N$ 	$\tau \to \mu\gamma$ $\tau \to e\gamma$ $K_L^0 \to \mu e$ $\tau \to 3\ell$ $Z' \to e\mu$ 
BSM physics NP if deviations from SM Theory limited	e, μ, n edm $(g-2)_\mu$ $(g-2)_e$ $\frac{\pi^+(K^+) \to e^+\nu}{\pi^+(K^+) \to \mu^+\nu}$ $K_L^0 \to \pi^0\nu\nu$ 	$B \to \mu\mu$ $b \to s\gamma$ $\frac{\tau \to e\nu\nu}{\tau \to \mu\nu\nu}$ $K^+ \to \pi^+\nu\nu$ $K^+ \to \mu^+\mu^+\pi^-$ 

…for a wide class of processes

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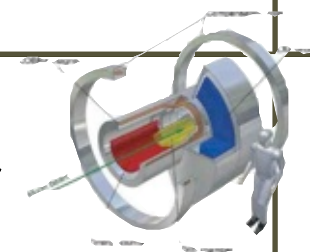
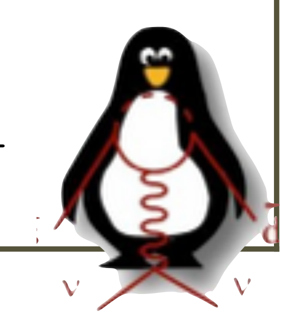
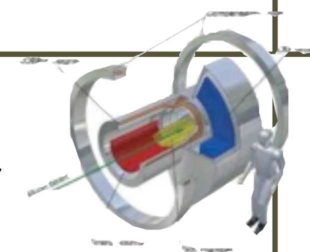
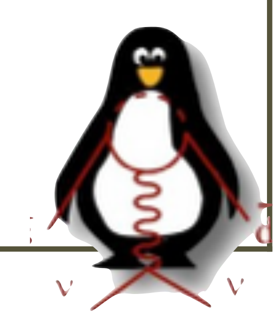




Fast timescale,
Turnaround of few years
~Few millions

Slower timescale,
Turnaround of tens of year
~multimillion

…for a wide class of processes

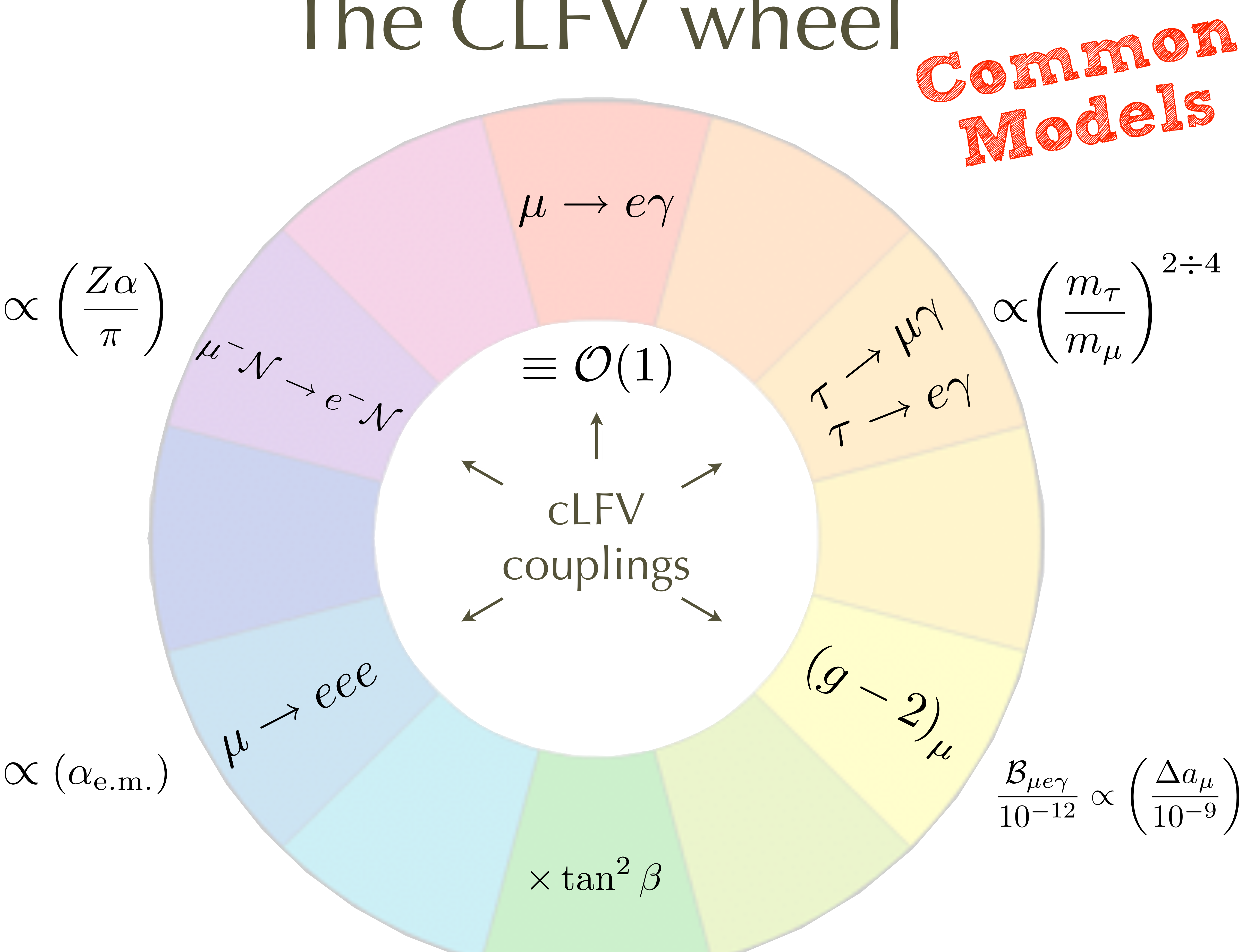
	Dedicated experiment	Multi-purpose experiment
Exotic Searches New Physi Experimen	$\mu \to e\gamma$  	$\tau \to \mu\gamma$ $\tau \to e\gamma$ $K_L^0 \to \mu e$ $\tau \to 3\ell$ 
BSM physics NP if deviations from SM Theory limited	(g (g $\frac{\pi^+(K^+) \to e^+\nu}{\pi^+(K^+) \to \mu^+\nu}$ $K_L^0 \to \pi^0\nu\nu$	$\tau \to \mu\nu\nu$ $K^+ \to \pi^+\nu\nu$ $K^+ \to \mu^+\mu^+\pi^-$ 

Fast timescale,
Turnaround of few years
~Few mill

timescale,
und of tens of year
illion

Complementarity
Need multi-measurement to disentangle the underlying new physics

The CLFV wheel



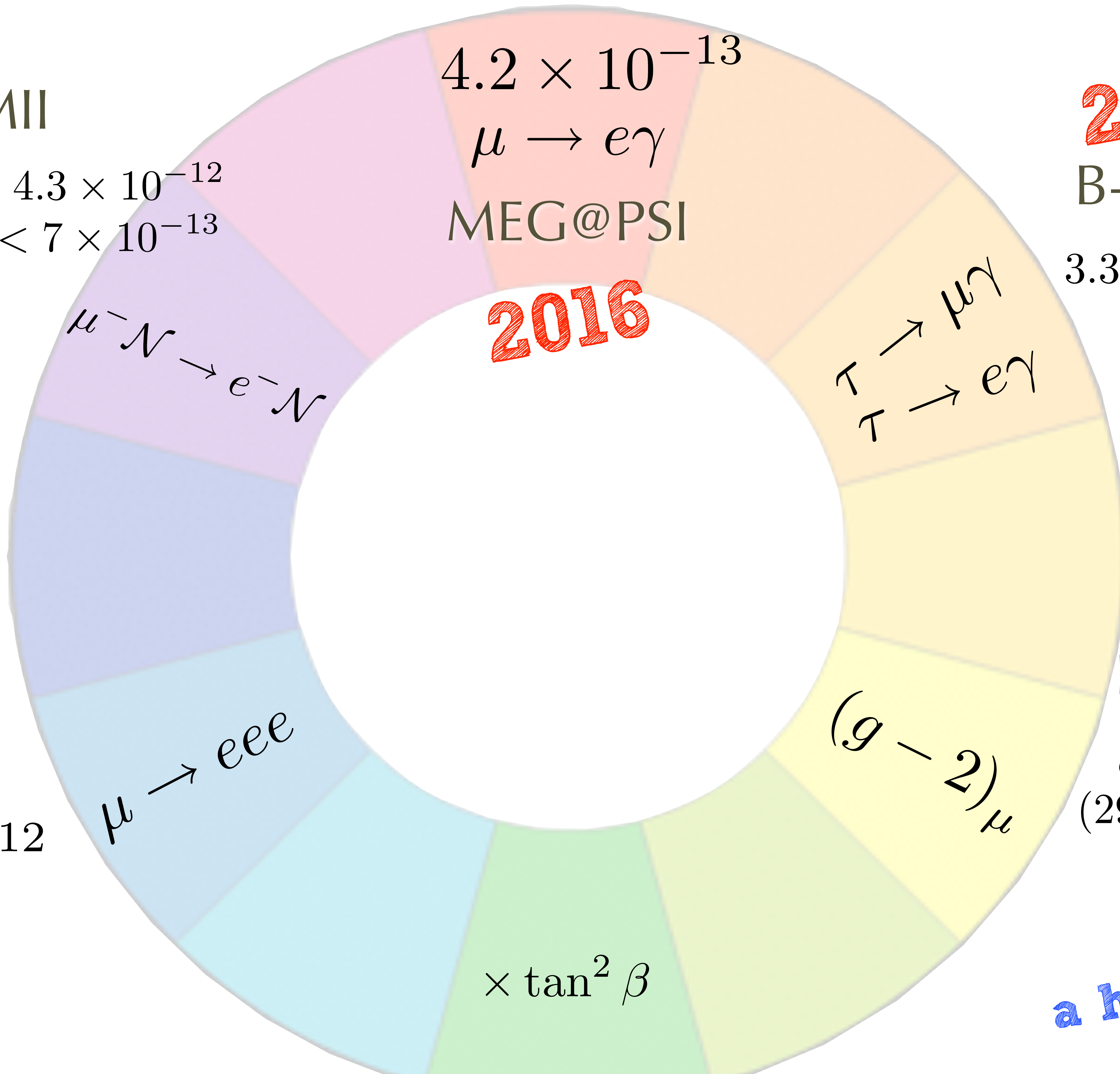
Present limits

SINDRUMII

$\mathcal{B}(\mu\text{Ti} \rightarrow e\text{Ti}) < 4.3 \times 10^{-12}$

$\mathcal{B}(\mu\text{Au} \rightarrow e\text{Au}) < 7 \times 10^{-13}$

2006



2014

B-factories

$3.3 \div 4.5 \times 10^{-8}$

BNL E821

$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (296 \pm 81) \times 10^{-11}$

2004

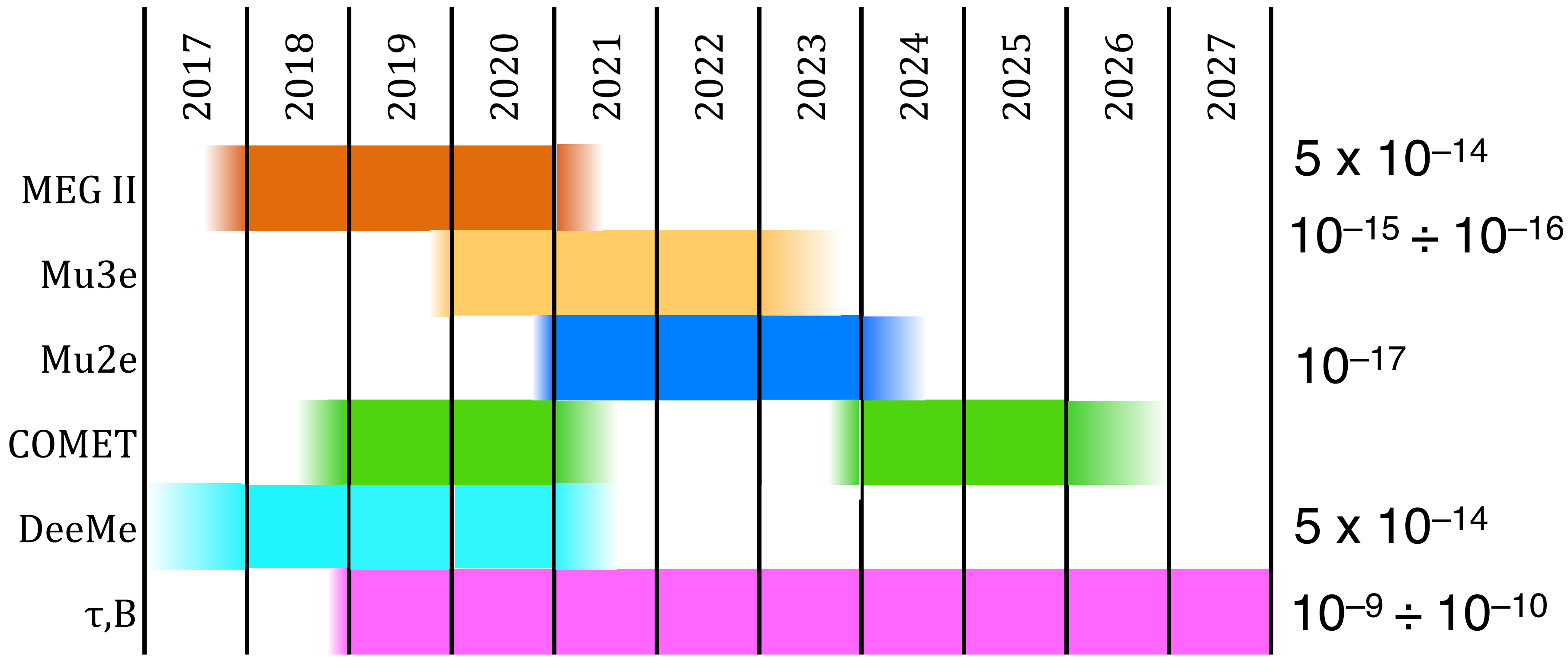
a hint for NP?

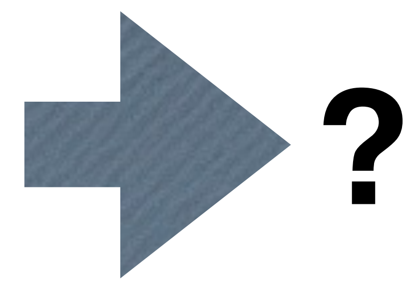
SINDRUM

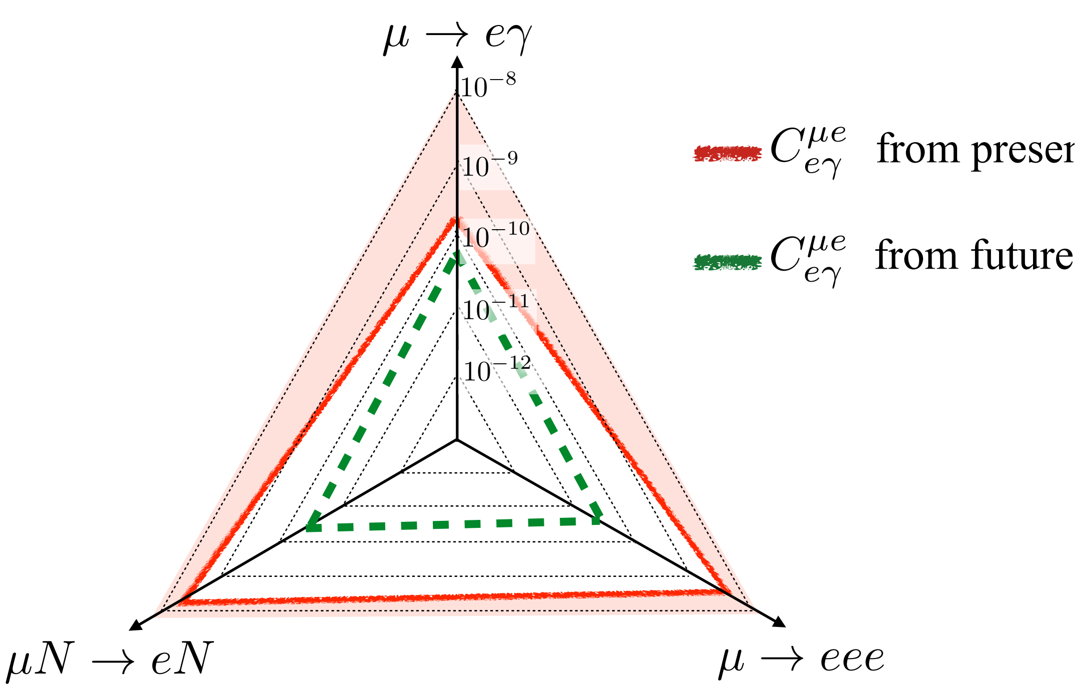
1×10^{-12}

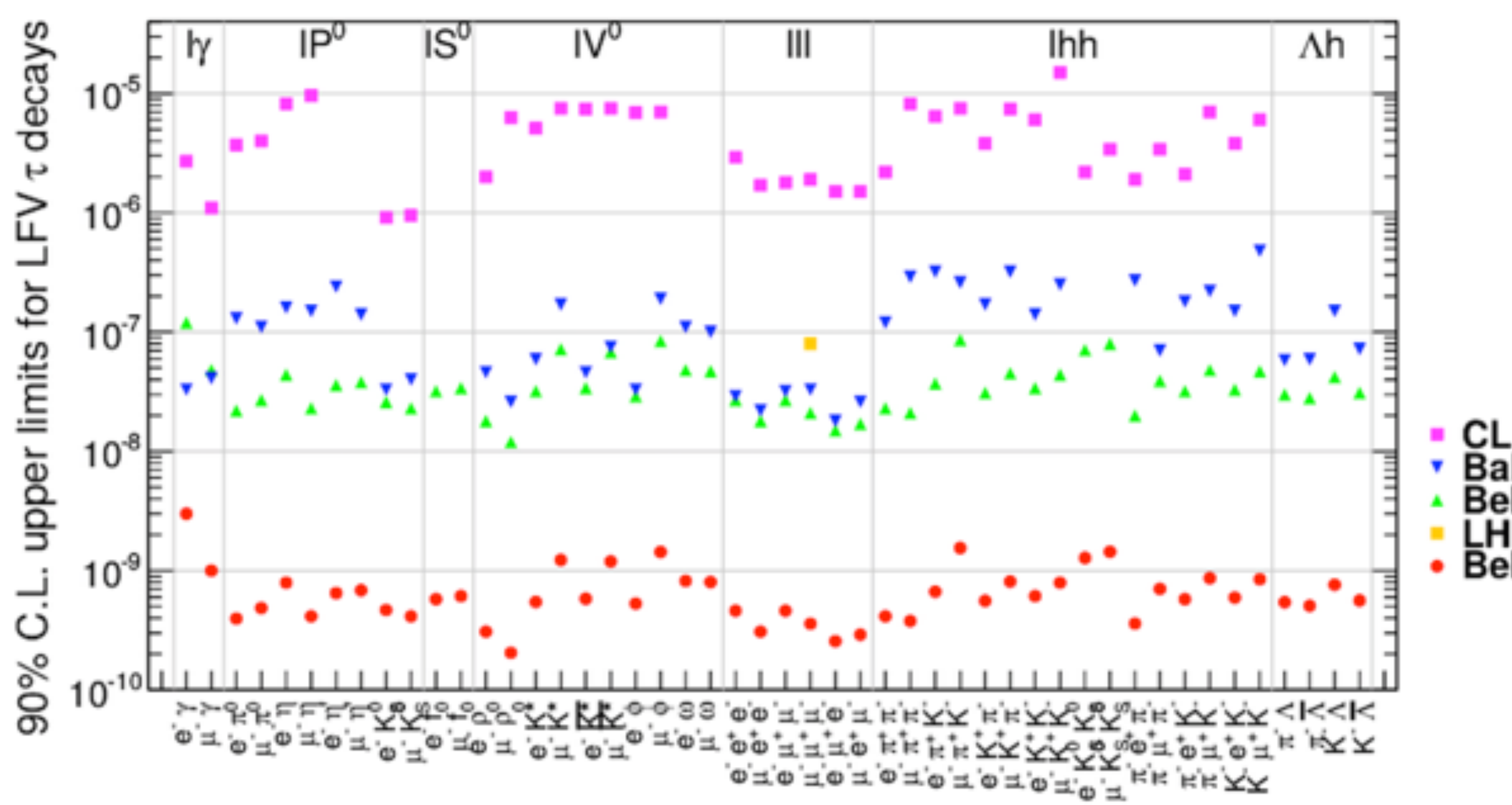
1988

Situation in 2025







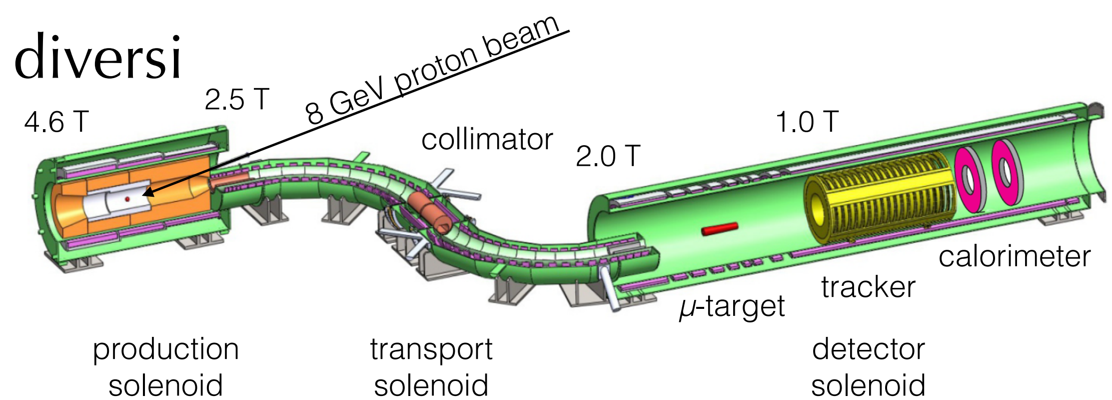


L. Calibbi & GS, Riv. Nuovo Cim. 41 (2018) 71

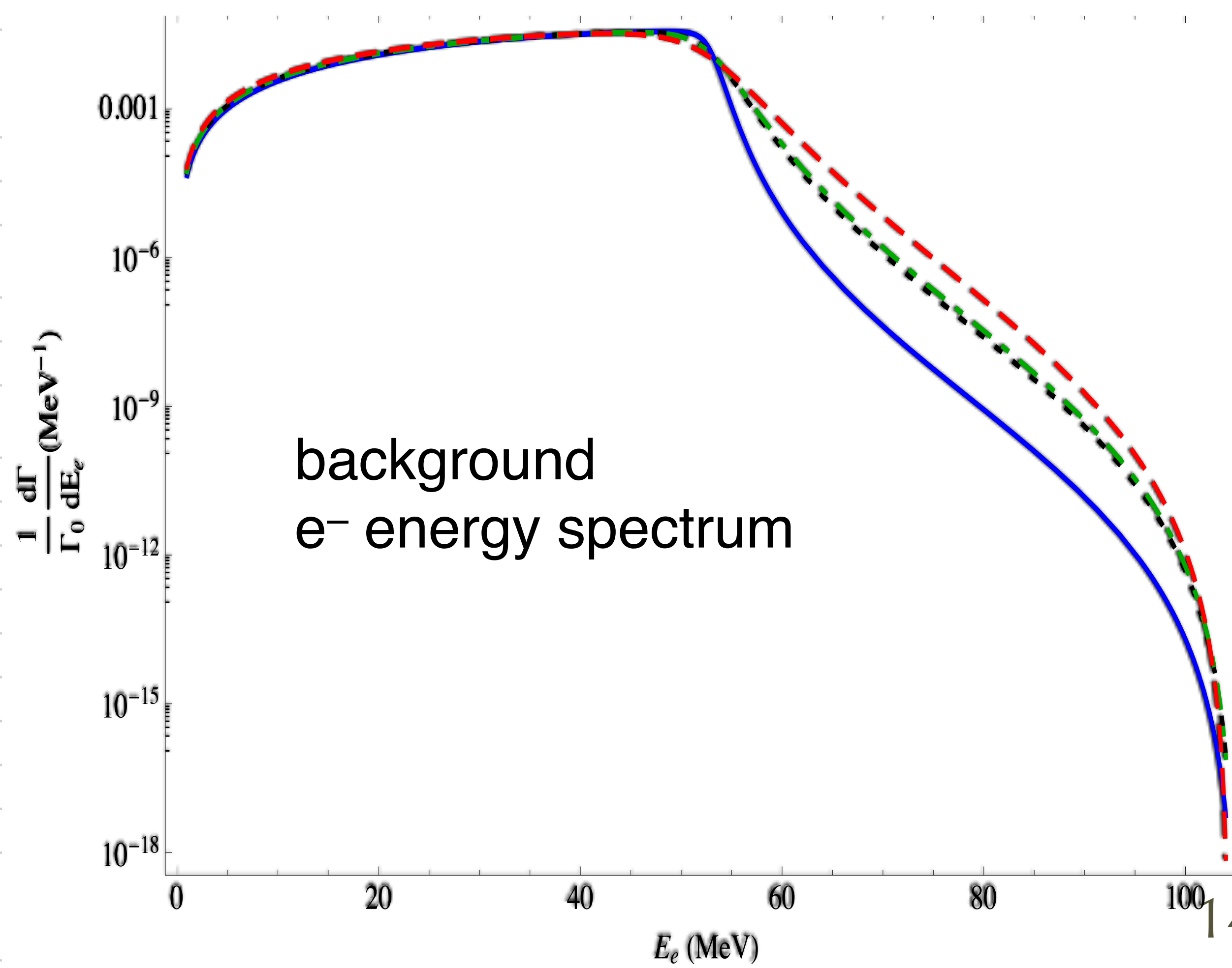
E. Kou *et al.,* The Belle II physics book, arXiv:1808.10576 [hep-ex]

Mu2e-II

- L'unica proposta (al momento) non balistica è mu2e-II (PRISM/PRIME)
  - (mu2e Coll, arXiv:1802.02599 [hep-ex], Feb 2018)
    - si vede un segnale → possibile studio con bersagli diversi
    - non si vede un segnale → x10 improvement
- Un ulteriore ordine di grandezza (10^{-18}) > 2028
    - utilizzo della maggiore intensità di PIP-II upgrade
    - miglioramento della detector technology
    - Epsression of interest, workshops (l'ultimo ad agosto 2018)

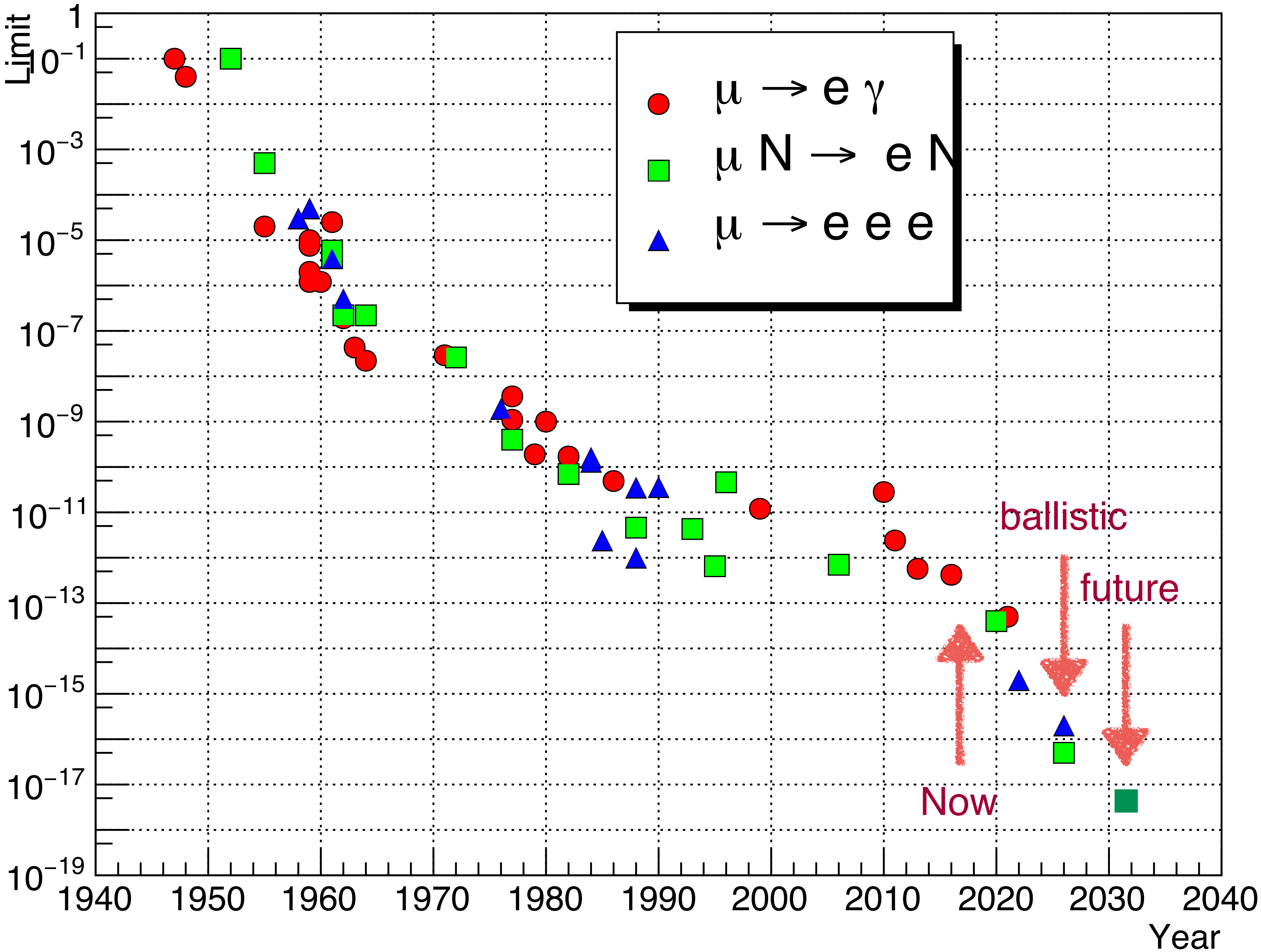


	Mu2e	Mu2e-II	Comments
source	Slow extracted from Delivery Ring	H- direct from PIP-II Linac	Mu2e-II will need to strip H- ions upstream of production target
beam energy (MeV)	8000	800	optimal beam energy 1-3 GeV
p pulse full width (ns)	250	<= 100	from PIP-II could range 40-100 ns for ~100 kW
p pulse spacing (ns)	1695	1699	assumes an Al. target; shorter spacing better for Ti or Au targets
p pulse full width (ns)	250	<= 100	from PIP-II could range 40-100 ns for ~100 kW
protons per pulse	4.00E+07	1.20E+09	
experimental duty factor	25%	>90%	important for keeping instantaneous rates under control
peak pulse rate	590 kHz	589 kHz	
avg. pulse rate	145 kHz	530 kHz	
protons per second	5.80E+12	6.36E+14	
stopped μ per second	1.16E+10	1.17E+11	
run time (sec/yr)	2.0E+07	2.0E+07	
run duration (yr)	3.0E+00	3.0E+00	
Total POT (3+1)y	4.7E+20	4.40E+22	approximate, depends on stopped-muon yield
Total stop-μ 3y	6.96E+17	7.00E+18	
extinction	1.0E-10	1.0E-11	ratio of (out-of-time / in-time) protons
average beam power (kW)	8	80	80kW is approximate; will depend on production target design and transport, which will affect mu-stop yield



Situazione> 2025

- Se esiste uno esistono anche gli altri
- Discriminazione dei modelli?



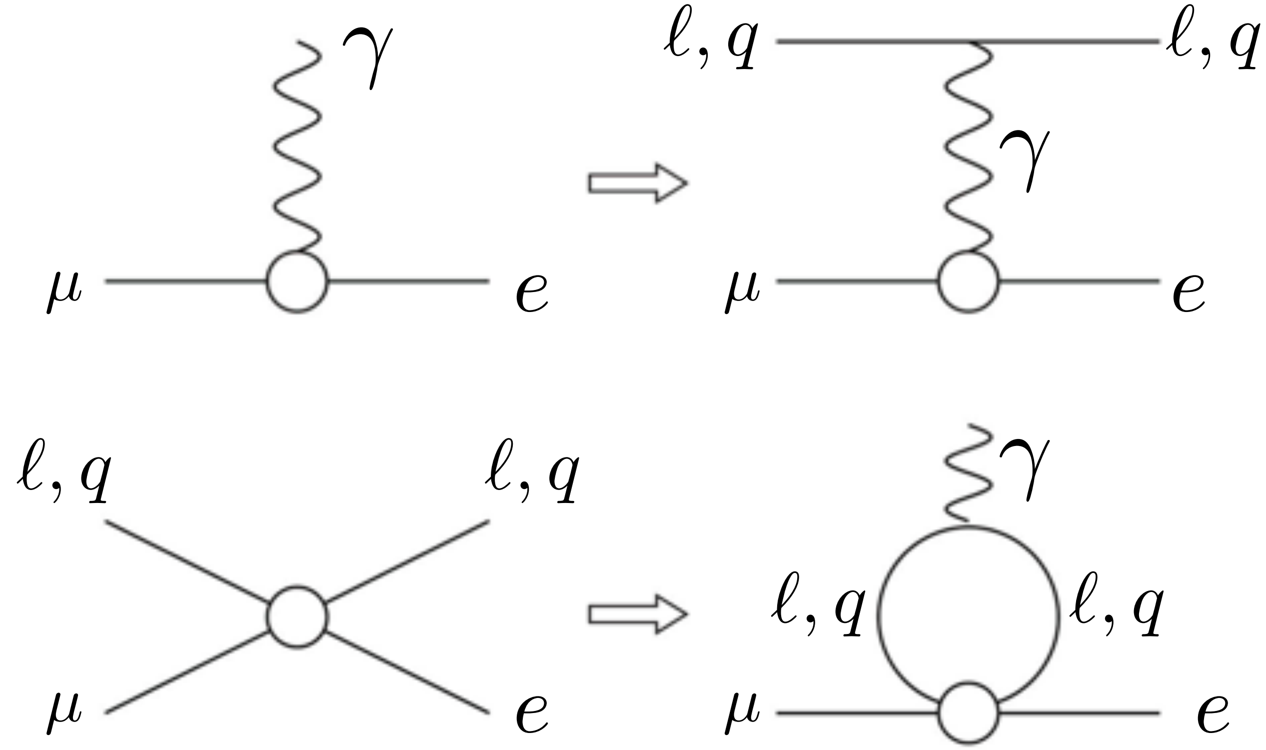


TABLE VII. – *Pattern of the relative predictions for the $\mu \to e$ processes as predicted in several models (see the text for details). Whether the dominant contributions to $\mu \to eee$ and $\mu \to e$ conversion are at the tree or at the loop level is indicated; Loop* indicates that there are contributions that dominate over the dipole one, typically giving an enhancement compared to eqs.* (40), (41).

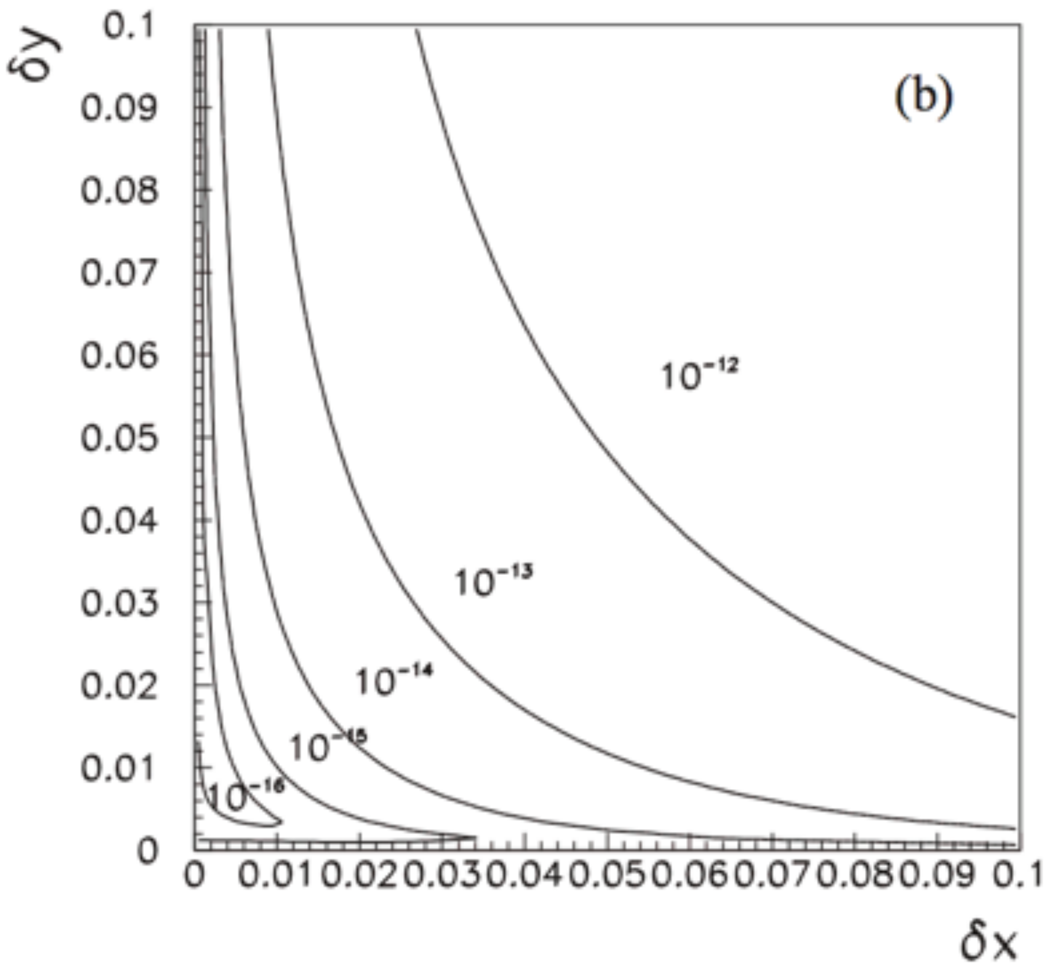
Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu \to eee)}{\mathrm{BR}(\mu \to e\gamma)}$	$\frac{\mathrm{CR}(\mu N \to eN)}{\mathrm{BR}(\mu \to e\gamma)}$
MSSM	Loop	Loop	$\approx 6 \times 10^{-3}$	10^{-3}–10^{-2}
Type-I seesaw	Loop*	Loop*	3×10^{-3}–0.3	0.1–10
Type-II seesaw	Tree	Loop	$(0.1$–$3) \times 10^{3}$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^{3}$	$\mathcal{O}(10^{3})$
LFV Higgs	Loop(a)	Loop*(a)	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	0.05–0.5	2–20

(a) A tree-level contribution to this process exists but it is subdominant.

L. Calibbi & GS, Riv. Nuovo Cim. 41 (2018) 71

Futuro μ→eγ

- μ→e conversion non limitata dalle coincidenze accidentali
- Un MEG futuro?
  - attualmente limitato dalle coincidenze accidentali
- Per μ→eγ esiste un limite "fisico" che è il decadimento radiativo μ→eγνν ($>10^{-16}$)
  - con un miglioramento della risoluzione ed eventualmente un convertitore si potrebbe pensare ad un ulteriore ordine di grandezza
  - Non esiste ad oggi la dimostrazione sperimentale che un tale tracciatore esista.



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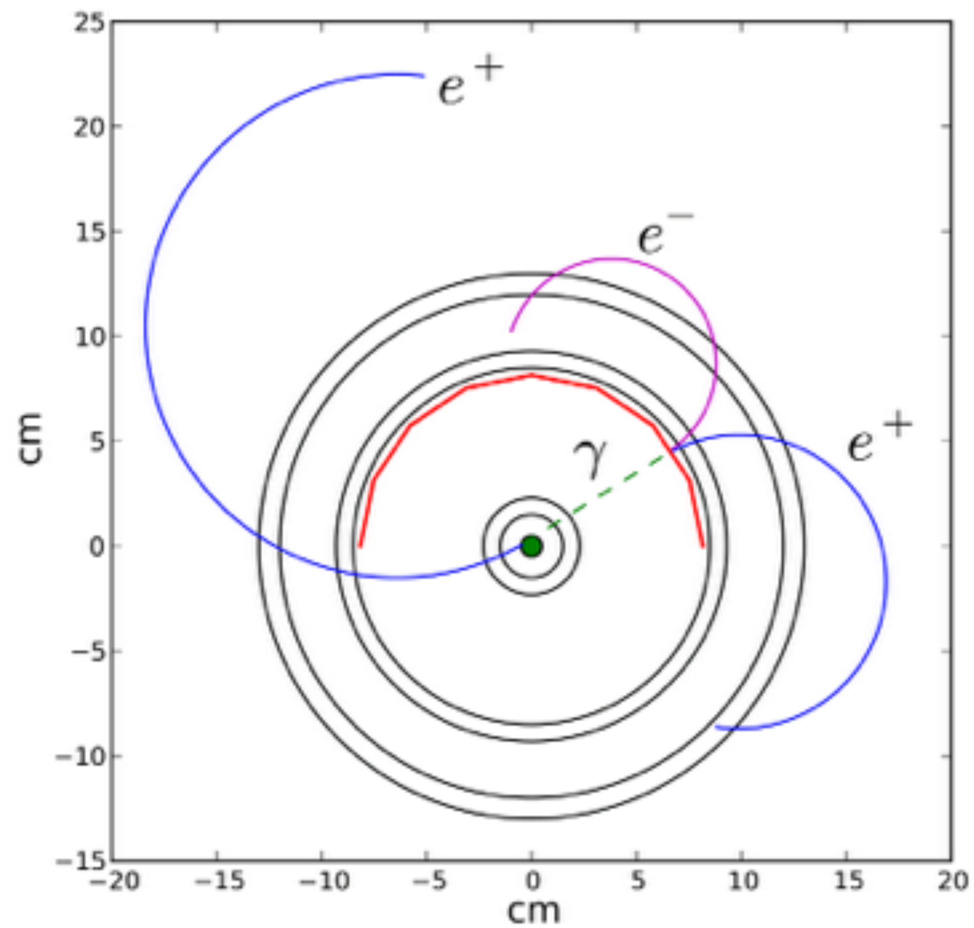
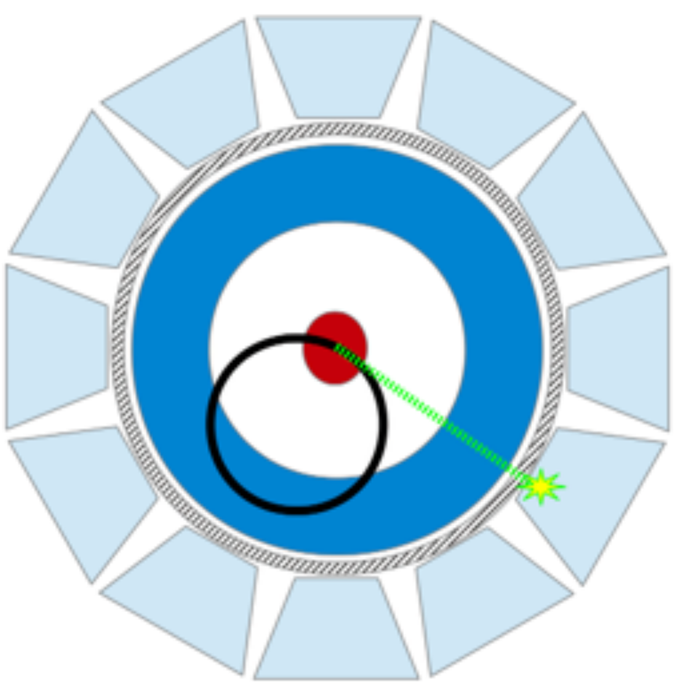
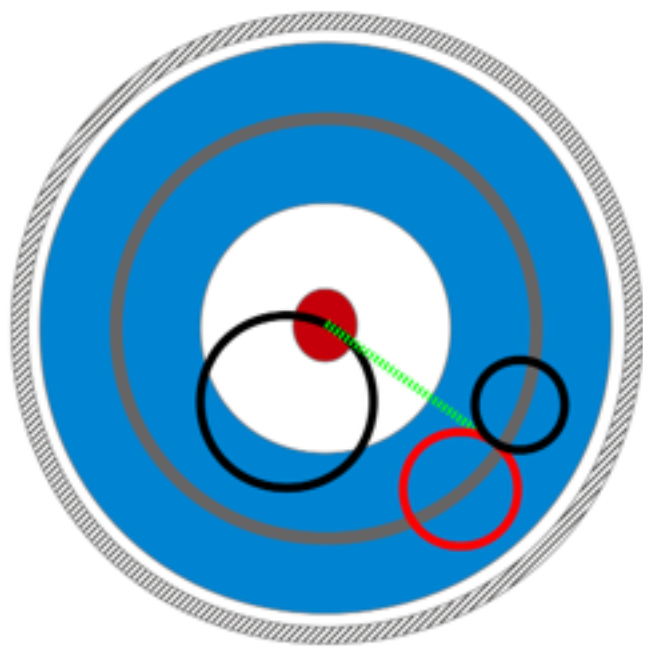


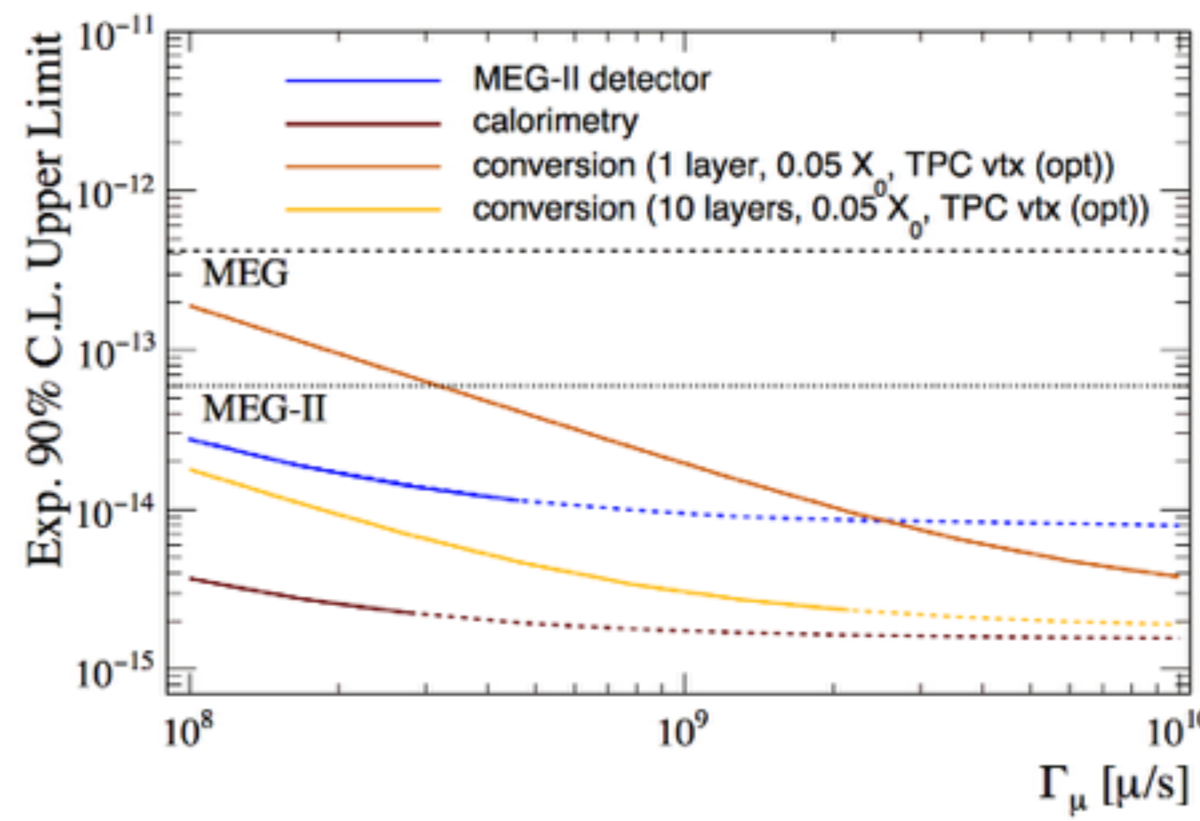
M. D. Cooper, Nucl. Phys. B 59 (1997) 209
C. Cheng et al. arXiv: 1309.7679v1 [physics.ins-det]
A. Andreazza et al. What Next white paper
G. Cavoto et al, Eur. Phys. J. C (2018) 78:37

Futuro μ→eγ

- Vogliamo farlo? Serve un R&D
  - convertitore/tracciatore con risoluzione angolare ed energetica sufficiente
  - calorimetro con risoluzione ~1%, 50ps, granularità
  - bersaglio attivo o rivelatore per il vertice (TPC)
- Sarebbe d'uopo in quanto necessario per il disentangling dei vari modelli
- In ogni caso spingere l'R&D sui fasci di muoni intensi e.g. PSI HIMB expected $10^{9}\div10^{10}$ μ^{+}





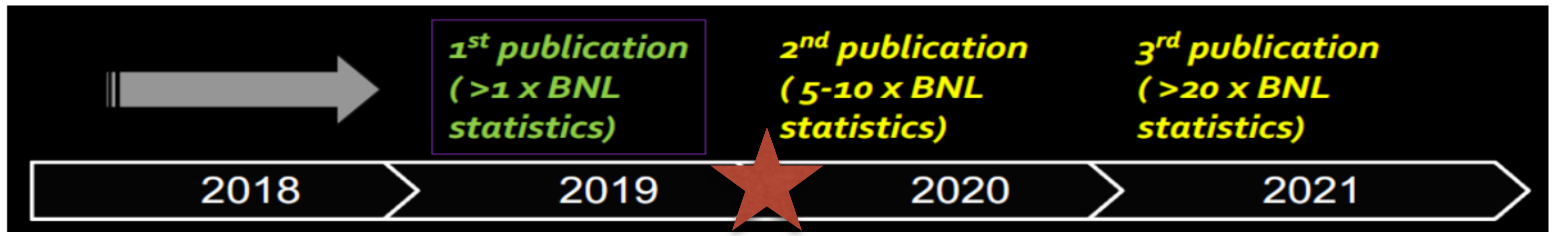


Performance	
Acceptance	70%
Efficiency	60%
Photon energy resolution	800 keV
Photon angle resolution	4.5/2.7 mrad ($\theta_\gamma/\phi_\gamma$)
Photon time	30 ps

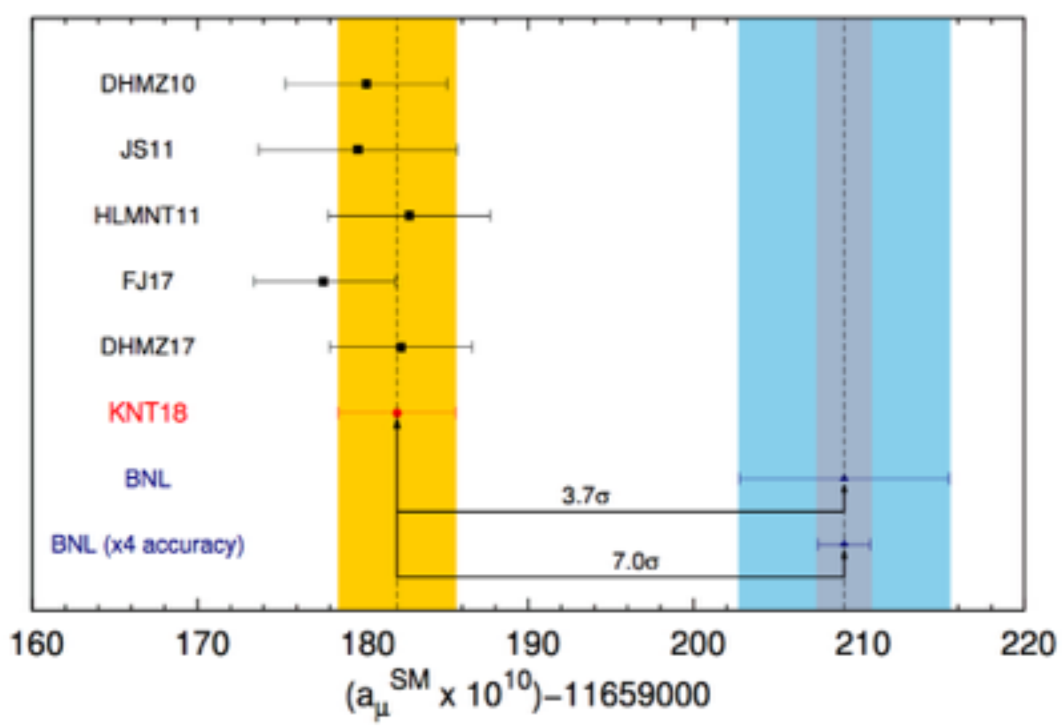
Performance	
Acceptance	70%
Conversion efficiency	2.2%
E_{e^+}, E_{e^-} > 5 MeV selection efficiency	80%
Photon energy resolution	250 keV ⊕ 200 keV
Photon angle resolution	4.5/2.7 mrad ($\theta_\gamma/\phi_\gamma$)
Photon time	50 ps

The muon g–2 at Fermilab

- E989 (Muon g-2) running a Fermilab con una sensibilità aspettata di BNL/4 (0.14ppm)
- Atteso risultato con ~BNL ppm per fine 2019



- What if the central value stays while the error shrinks?



- Le prospettive in questo senso sono molteplici per attaccare il problema da varie direzioni
  - (A) esperimento completamente diverso → E34 a J-PARC
  - (B) Riduzione dell'incertezza teorica nella computazione dei contributi (dominanti l'errore) adronici (HVP, HLbL)

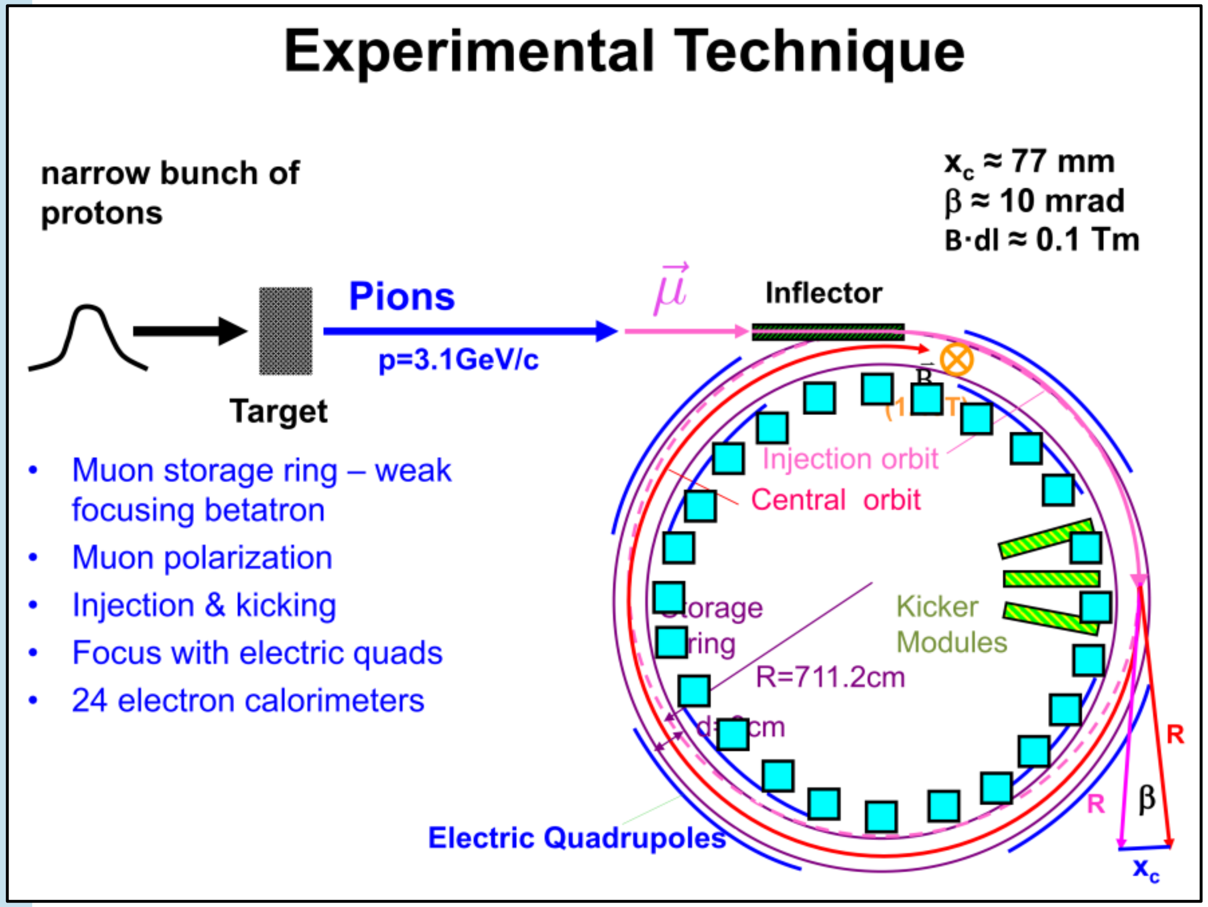
J-PARC E34 g–2/EDM experiment

- Fascio di muoni ultralenti riaccelerati da un linac ed inseriti in un piccolo magnete tipo NMR
  - local field uniformity ~1ppm vs 50ppm
  - 0.66m vs 14m
  - tracking vs calorimetry
- Sistematiche "completamente" diverse

$\Delta a_\mu / a_\mu$	$\rightarrow 0.1$ ppm
ΔEDM_μ	1.4×10^{-21} e · cm

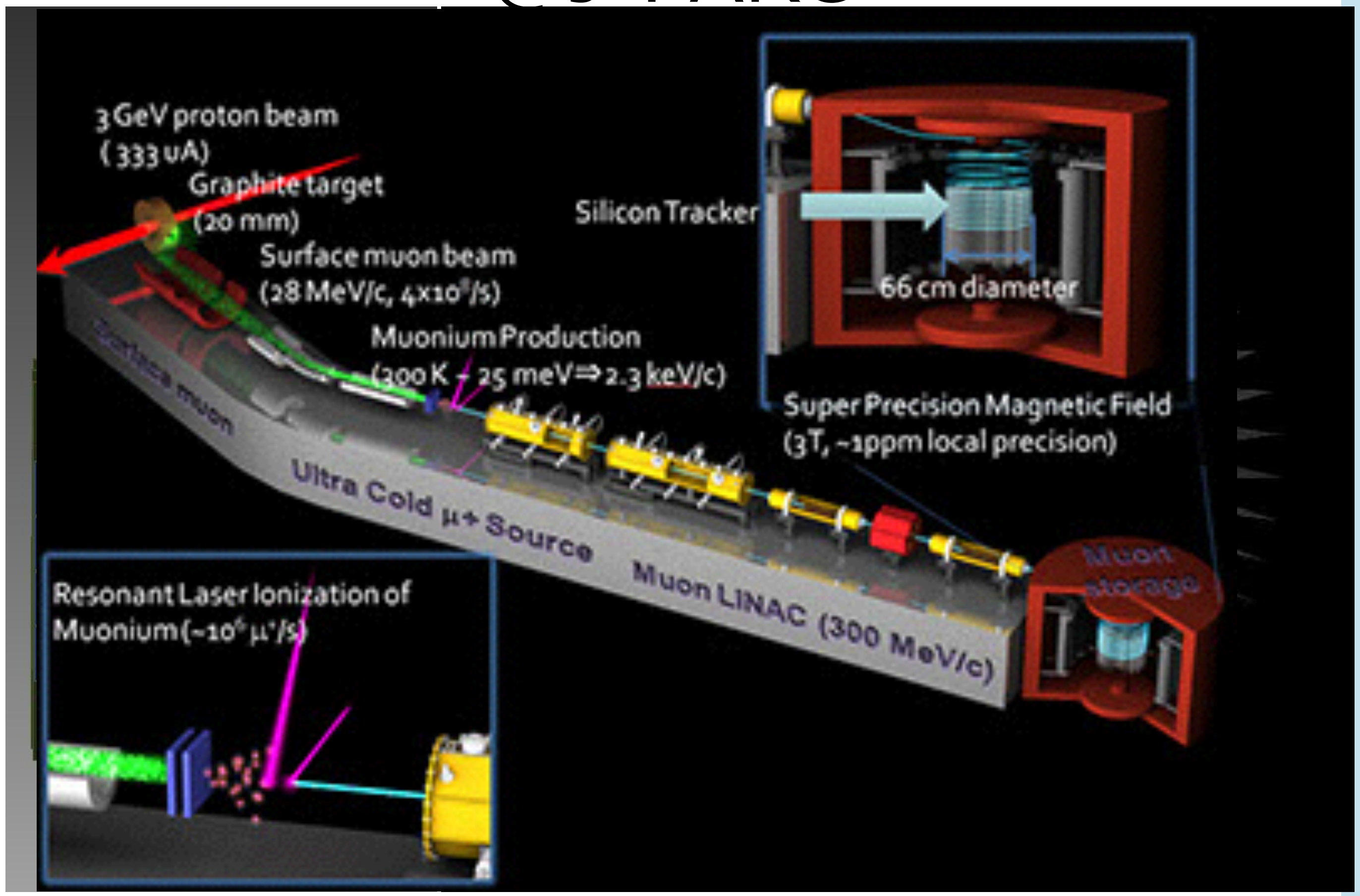
> 2021

Calorimeters @BNL, FNAL



Acceptance ~ 65%

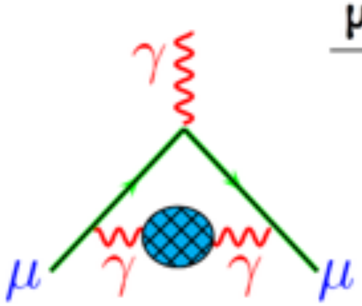
tracking @J-PARC

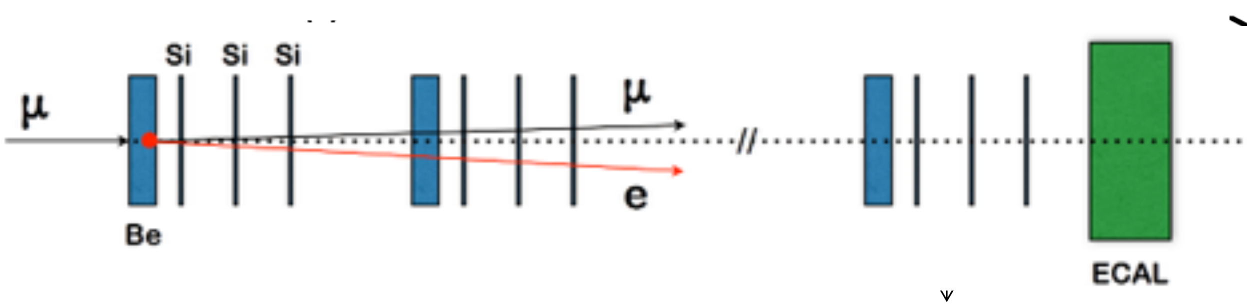


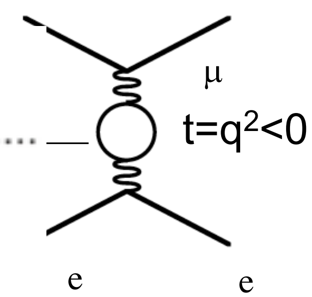
Acceptance ~ 100 %

MuonE

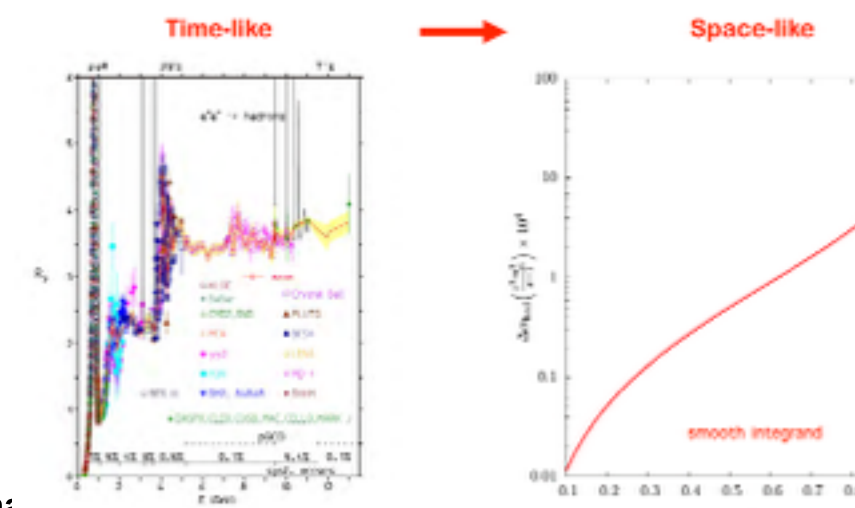
- Contributo adronico al g–2 generalmente ricavato utilizzando i dati dello scattering
  - $e^+e^- \rightarrow$ had (time-like data – KLOE…)
  - L'integrale a bassa energia dà contributo dominante all'incertezza
- Si può calcolare indipendentemente il contributo adronico LO utilizzando dati space-like (scattering elastico $\mu e \rightarrow \mu e$)
  - fascio di muoni da 150 GeV su bersaglio di Be al CERN
    - primo test beam 2017, secondo test beam in corso al CERN
    - run 2021-2024 con costruzione nel 2020-2021 (LoI expected in 2019)
    - possibile raggiungere un'incertezza di 0.3% (stat, syst. comp.)
  - rimuovere la componente QED ⇒ sforzo teorico in corso (full NNLO MC per μe scattering)
  - rivelatori utilizzano tecnologia attuale (no R&D). 60 tracking stations + Calo = ~50m
  - M2 beam line @North Area







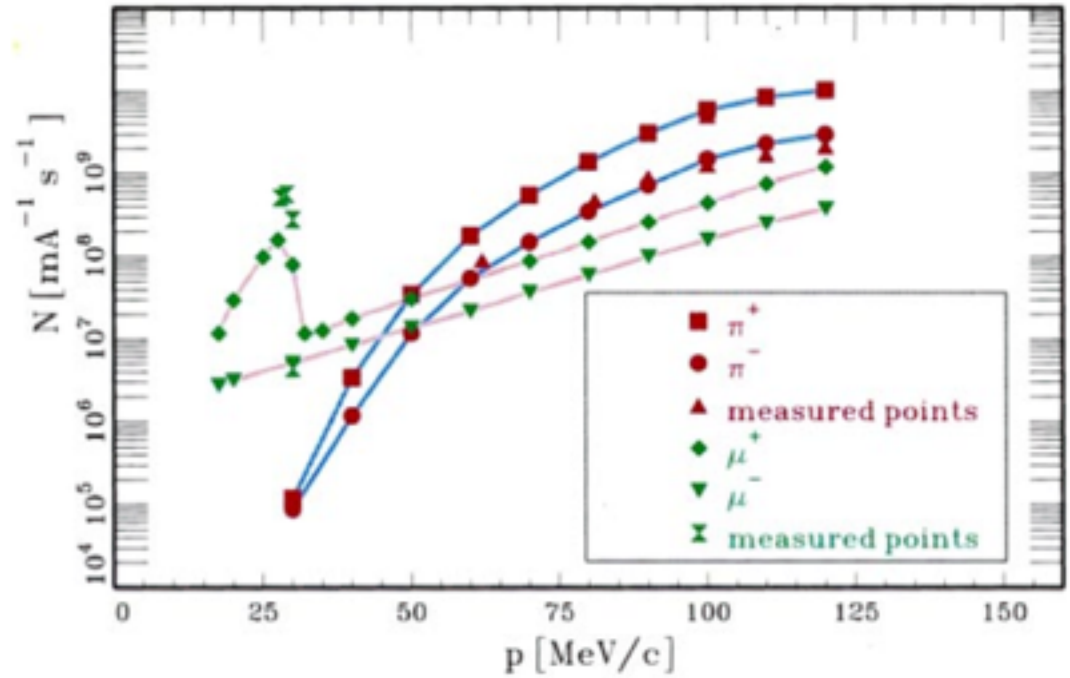
$$\left|\frac{\alpha(t)}{\alpha_0}\right|^2 = \left|\frac{1}{1-\Delta\alpha(t)}\right|^2 \qquad \Delta\alpha=\Delta\alpha_{lep}+\Delta\alpha_{ha}$$

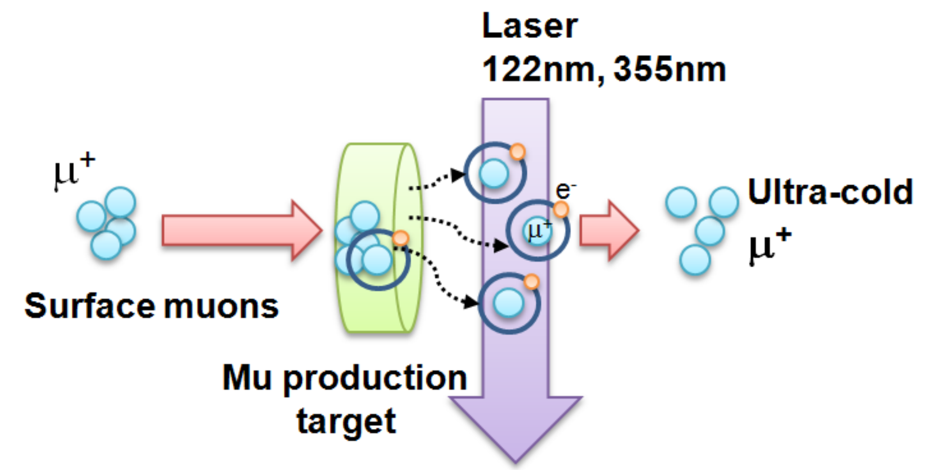


Calame, Passera, Trentadue, Venanzoni, PLB 746 2015
Abbiendi et al, EPJC 77 2017.

Fasci di muoni

- Complementarietà fra CERN ed altri laboratori (PSI, J-PARC, FNAL, TRIUMF…)
  - Fasci pulsati (RCS, LINACS)
  - Fasci continui DC (ciclotroni)
  - Cloud muons
    - da decadimenti di π in volo (50 MeV/c → 200GeV/c)
  - Surface muons
    - prodotti da decadimenti del π a riposo
    - p_μ = 29 MeV/c con 4.2 MeV energia cinetica
    - prodotti sulla buccia del bersaglio
  - Sub-surface muons
    - da decadimenti del π all'interno del bersaglio
    - p_μ < 29 MeV/c ⇒ range < 1 mm CH2
  - Ultra-slow muons
    - surface muons → muonio → laser → riaccelerazione
  - HiMB at PSI
    - $O(10^{10})$ > 2018 necessaria per il futuro di mu3e, mu2e etc…)





The High intensity Muon Beam (HiMB) project at PSI

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Slanted E target test ("towards the new M-target"): planned for **next year**
- Time schedule: **O(2025)**

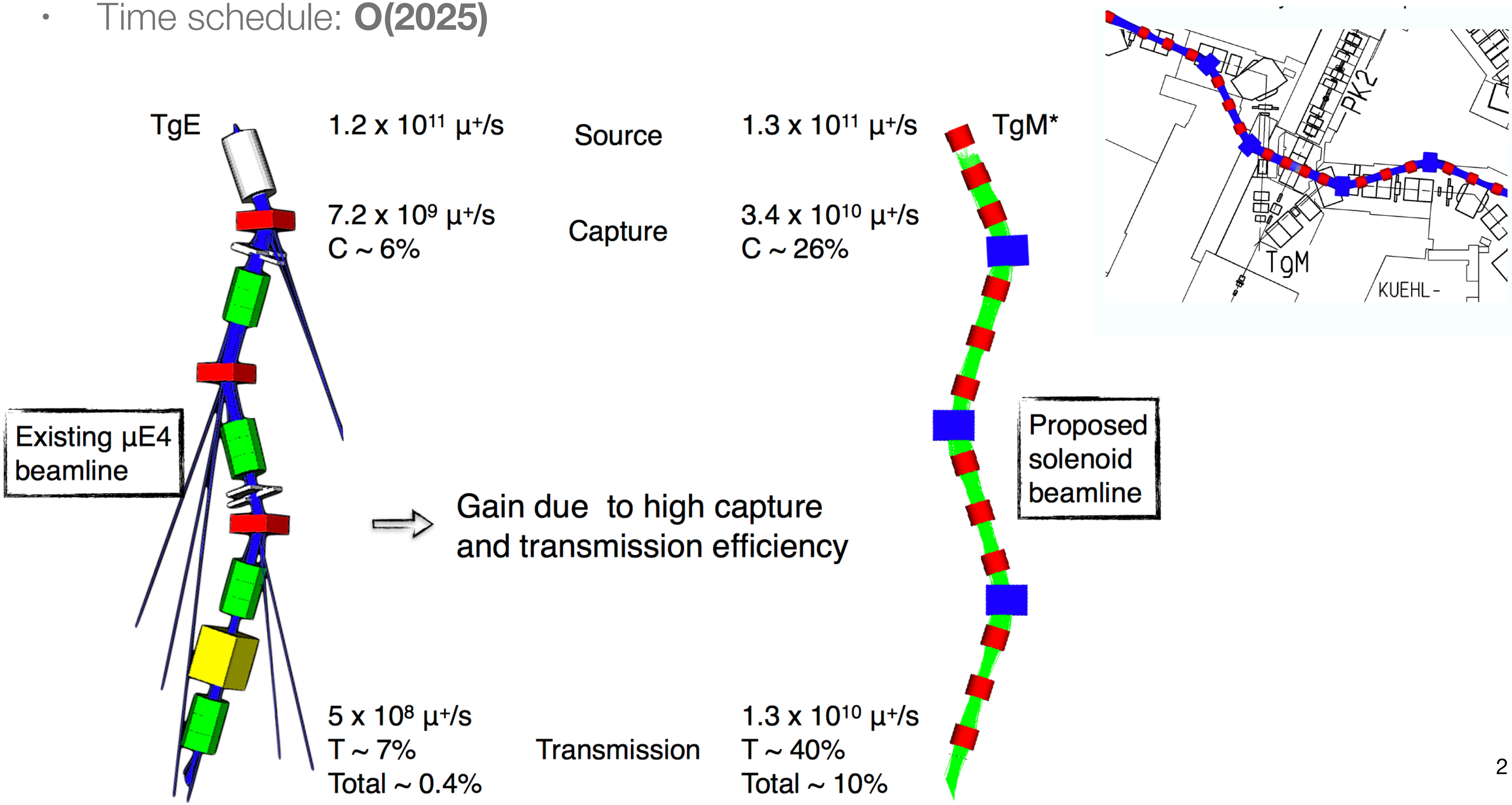


TABLE VIII. – *Intensities of present and near future muon beams of positive and negative charge, continuous and pulsed. Note that for surface muon beams, increasing the proton beam energy does not necessarily increases the rate, since at higher proton energies most pions escape the target rather than come to rest and decay* [298]. *Table compilation based on* [42, 284-287].

Laboratory	Beam line	DC rate (μ/sec)	Pulsed rate (μ/sec)
PSI (CH)	$\mu E4$, $\pi E5$	2–4 $\times 10^8$ (μ^+)	
(590 MeV, 1.3 MW)	HiMB at EH	$\mathcal{O}(10^{10})$ (μ^+) ($>$ 2018)	
J-PARC (Japan)	MUSE D-Line		$3 \times 10^7 (\mu^+)$
(3 GeV, 210 kW)	MUSE U-Line		$6.4 \times 10^7 (\mu^+)$
(8 GeV, 56 kW)	COMET		$1 \times 10^{11} (\mu^-)$(2020)
FNAL (USA)			
(8 GeV, 25 kW)	Mu2e		$5 \times 10^{10} (\mu^-)$(2020)
TRIUMF (Canada)			
(500 MeV, 75 kW)	M13, M15, M20	1.8–2 $\times 10^6 (\mu^+)$	
RAL-ISIS (UK)	EC/RIKEN-RAL		$7 \times 10^4 (\mu^-)$
(800 MeV, 160 kW)			$6 \times 10^5 (\mu^+)$
KEK (Tsukuba, Japan)			
(500 MeV, 25 kW)	Dai Omega		$4 \times 10^5 (\mu^+)$(2020)
RCNP (Osaka, Japan)	MuSIC	$10^4 (\mu^-)$–$10^5 (\mu^+)$	
(400 MeV, 400 W)		$10^7 (\mu^-)$–$10^8 (\mu^+)$ ($>$ 2018)	
JINR (Dubna, Russia)	Phasotron		
(660 MeV, 1.6 kW)		$10^5 (\mu^+)$	
RISP (Korea)	RAON		
(600 MeV, 0.6 MW)		$2 \times 10^8 (\mu^+)$ ($>$ 2020)	
CSNS (China)	HEPEA		
(1.6 6 eV, 4 kW)		$1 \times 10^8 (\mu^+)$ ($>$ 2020)	

Complementarietà

L. Calibbi & GS, Riv. Nuovo Cim. 41 (2018) 71

TABLE XII. – *Present and future limits for selected CLFV processes.*

Reaction	Present limit	Expected limit	Reference	Experiment
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	5×10^{-14}	[313]	MEG II
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	10^{-16}	[46]	Mu3e
$\mu^-\mathrm{Al} \to e^-\mathrm{Al}$ (a)	$< 6.1 \times 10^{-13}$	10^{-17}	[318, 321]	Mu2e, COMET
$\mu^-\mathrm{Si/C} \to e^-\mathrm{Si/C}$ (a)	–	5×10^{-14}	[280]	DeeMe
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	5×10^{-9}	[336]	Belle II
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	10^{-9}	[336]	”
$\tau \to eee$	$< 2.7 \times 10^{-8}$	5×10^{-10}	[336]	”
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	5×10^{-10}	[336]	”
$\tau \to e$ had	$< 1.8 \times 10^{-8}$ (b)	3×10^{-10}	[336]	”
$\tau \to \mu$ had	$< 1.2 \times 10^{-8}$ (b)	3×10^{-10}	[336]	”
had $\to \mu e$	$< 4.7 \times 10^{-12}$ (c)	10^{-12}	[337]	NA62
$h \to e\mu$	$< 3.5 \times 10^{-4}$	3×10^{-5} (d)	[338]	HL-LHC
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	3×10^{-4} (d)	[338]	”
$h \to \tau e$	$< 6.1 \times 10^{-3}$	3×10^{-4} (d)	[338]	”

(a) Rate normalised to the muon capture rate by the nucleus, see eq. (99).
(b) Best limits from $\tau \to e\rho^0$ and $\tau \to \mu\rho^0$ respectively.
(c) Best limit from K^0_L decay.
(d) Reference [338] quotes the branching ratio for which one can make a 2σ or 5σ observation; we use the number of expected signal and background events in there to infer 95% C.L. sensitivities on the three channels, which turn out to be compatible with the scaling for the square root of the relative luminosity: 3000 fb^{-1} assumed in [338] *vs.* 20 [74] or 36 [75] fb^{-1}.

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$\tau \to e$ had	$< 1.8 \times 10^{-8}$ (b)	3×10^{-10}	[336]	"
$\tau \to \mu$ had	$< 1.2 \times 10^{-8}$ (b)	3×10^{-10}	[336]	"
had $\to \mu e$	$< 4.7 \times 10^{-12}$ (c)	10^{-12}	[337]	NA62
$h \to e\mu$	$< 3.5 \times 10^{-4}$	3×10^{-5} (d)	[338]	HL-LHC
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	3×10^{-4} (d)	[338]	"
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(a) Rate normalised to the muon capture rate by the nucleus, see eq. (99).
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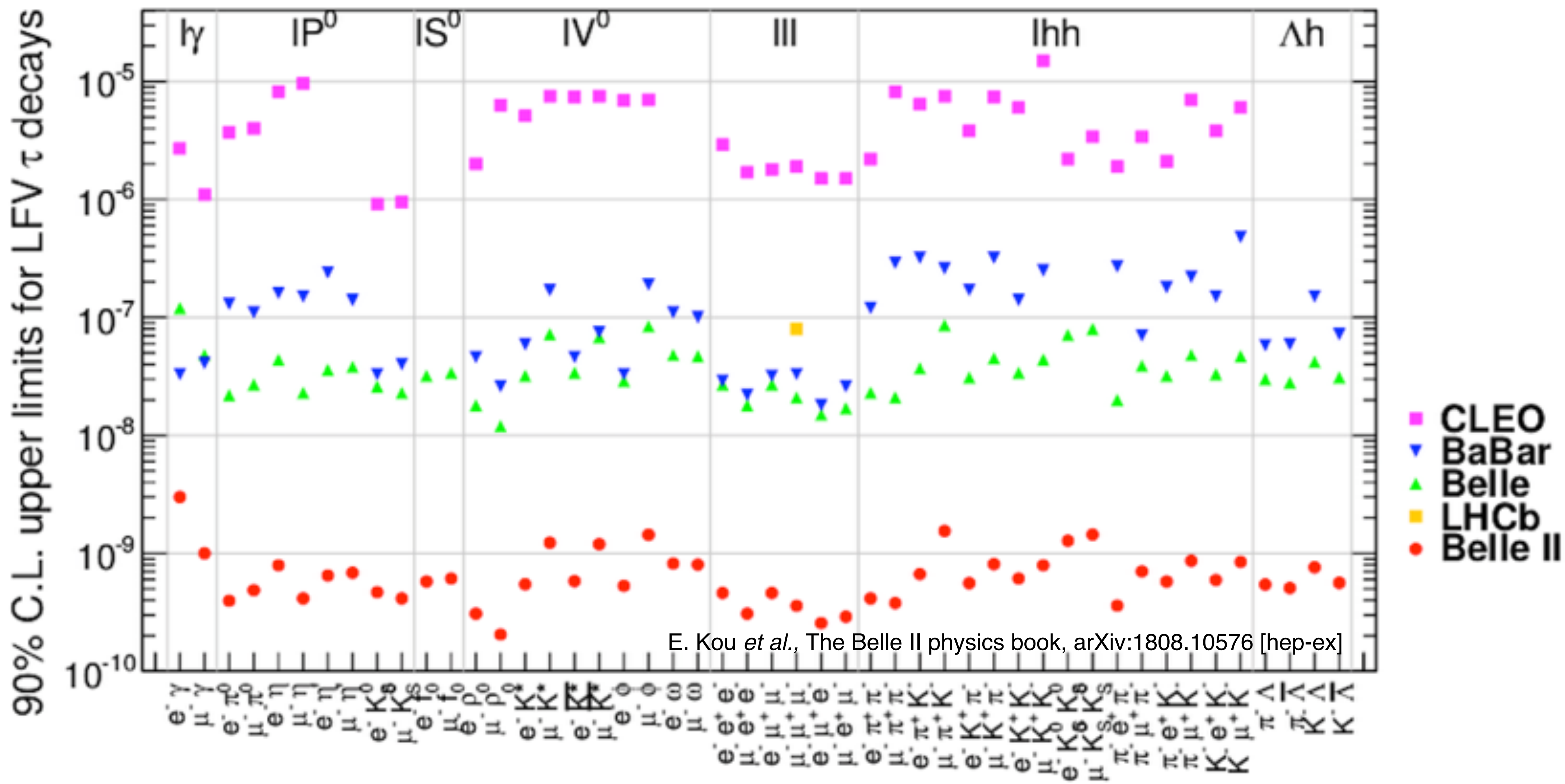
(d) Reference [338] quotes the branching ratio for which one can make a 2σ or 5σ observation; we use the number of expected signal and background events in there to infer 95% C.L. sensitivities on the three channels, which turn out to be compatible with the scaling for the square root of the relative luminosity: $3000\,\text{fb}^{-1}$ assumed in [338] *vs.* 20 [74] or 36 [75] fb^{-1}.

CLFV τ decays

- Belle-II
  - ultimate ballistic experiment to improve the limits on τ CLFV decays



  - dopo Belle-II non c'è essenzialmente miglioramento sui decadimenti rari del τ
    - τ-charm factory
    - TauFV "concept"
  - insieme a LHCb et al. continua l'esplorazione degli elementi della matrice CKM

Misura degli elementi di CKM

- Gli elementi di CKM, come parametri fondamentali, devono essere misurati il più precisamente possibile
- Sovracostringere le grandezze e le fasi di ogni possibile contributo di nuova fisica

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

nxn real parameter
2n-1 unphysical pahses
n(n-1)/2 rotation angles
(n-1)(n-2)/2 complex phases

For n>2 CP Violation is automatically possible!

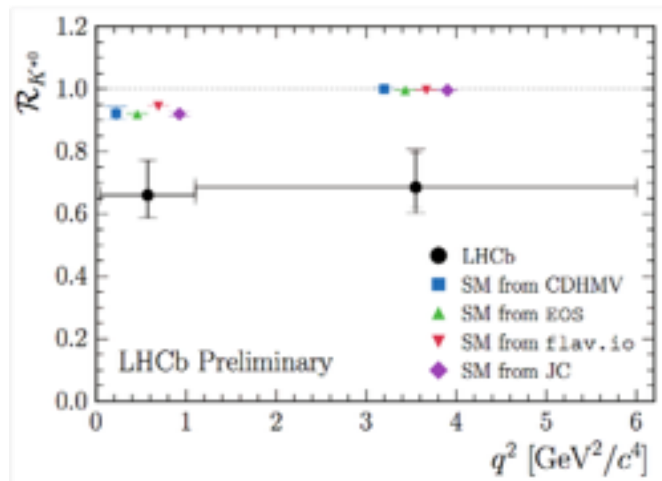
PDG 2018

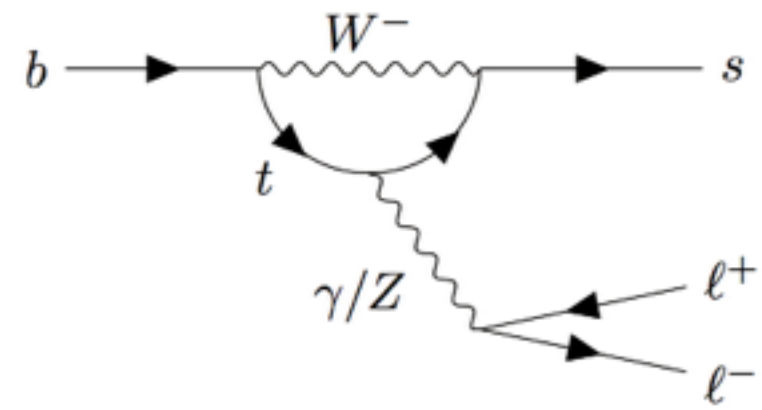
$\lvert V_{ud}\rvert = 0.97420 \pm 0.00021$	$0^+ \rightarrow 0^+$ super-allowed nuclear β decays
$\lvert V_{us}\rvert = 0.2243 \pm 0.0005$	Kaon semi-leptonic and leptonic decays
$\lvert V_{cd}\rvert = 0.218 \pm 0.004$	semi-leptonic D decays and neutrino/antineutrino
$\lvert V_{cs}\rvert = 0.997 \pm 0.017$	Average of semi-leptonic D and leptonic D_s decays
$\lvert V_{cb}\rvert = (42.2 \pm 0.8) \times 10^{-3}$	Combination of exclusive and inclusive B decays
$\lvert V_{ub}\rvert = (3.94 \pm 0.36) \times 10^{-3}$	Comb. of exclusive and inclusive charmless B decays
$\lvert V_{tb}\rvert = 1.019 \pm 0.025$	Single top-quark production cross-section

V_{td} & V_{ts} accessible from FCNC processes (loops)

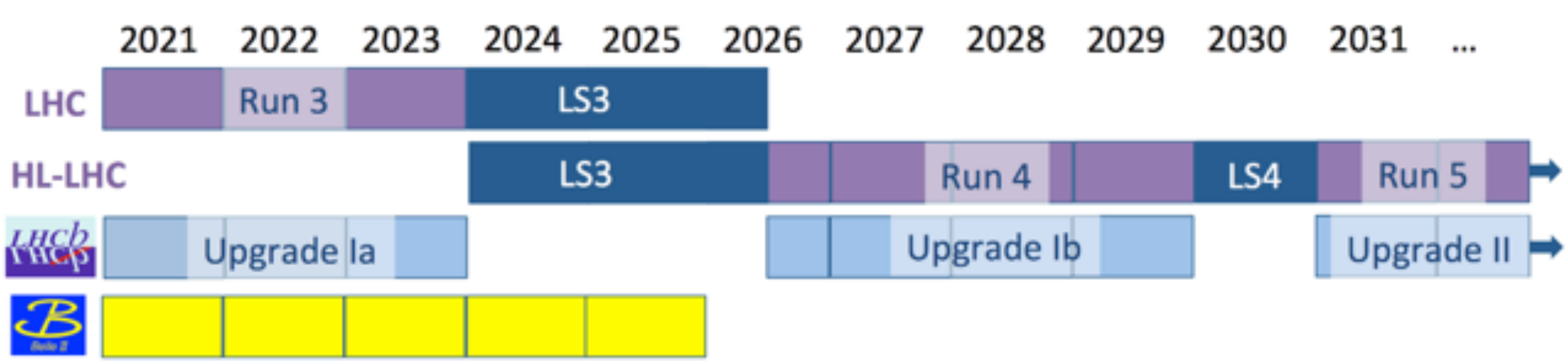
Upgrade nel flavour

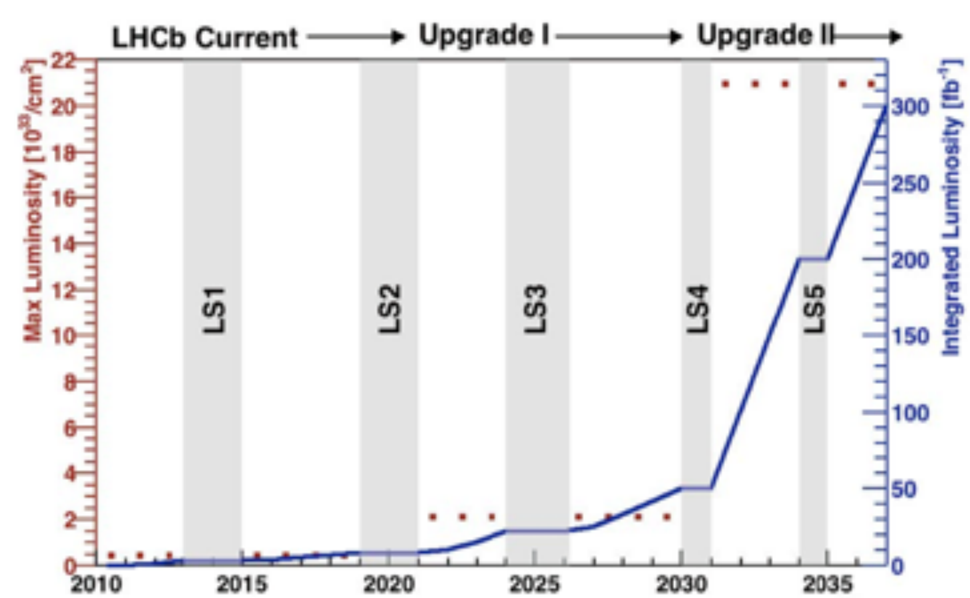
- È vero inoltre che allo stato attuale è nella fisica del flavour che si vedono hints di nuova fisica
  - semileptonic B decays con un τ
  - FCNC B decays in μ ed elettroni





- LHCb ha in cantiere un Upgrade-2 (vedi arXiv:1808.08865[hep-ex]) da effettuare dopo il LS4 (>2030)
  - Luminosità UP-2 ~ 10x
  - New detector components
  - CP phases, FCNC, Minimal Flavour Violation, CP nel charm…





LHCb Upgrade-2

- Integrated luminosity 300 fb^{-1}

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [605].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [606]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [607]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	150 mrad [94]	60 mrad	–	17 mrad	Under study [608]
$a_{\rm sl}^s$	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [610]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

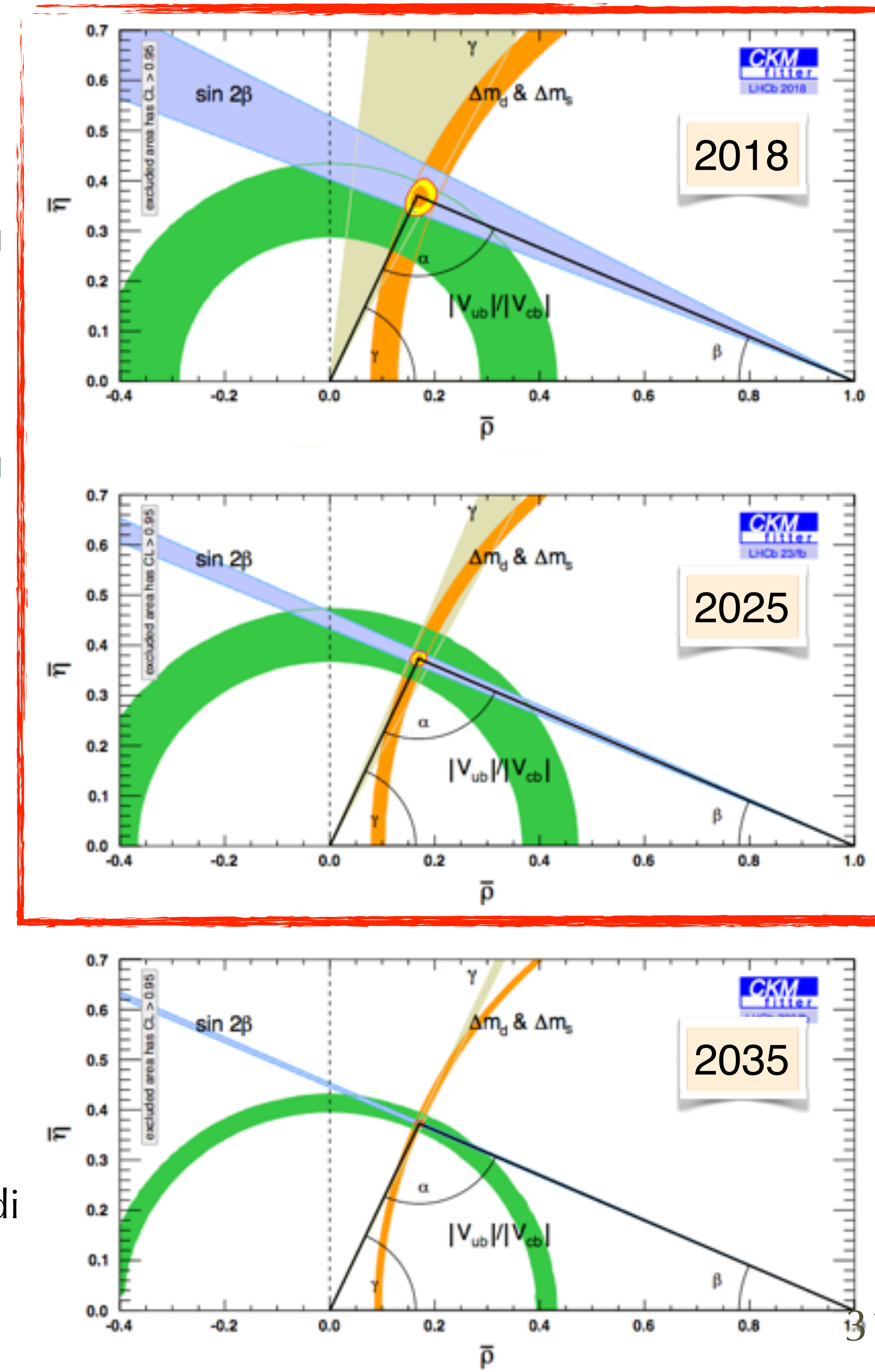
$\div 4$ $\approx$ $\div 4$

LHCb Upgrade-2

- Integrated luminosity 300 fb^{-1}
- R&D sui rivelatori
  - Calorimetro ad alta granularità
  - Miglioramento al sistema di tracking
  - PID migliorato (p/K sotto 10 GeV, K/π nel RICH)
  - Rimozione del materiale davanti al VELO
  - Migliore capacità di selezionare gli eventi e ricostruire le tracce online
- Questioni tecniche relative alla zona di interazione
  - esiste un aspetto infrastrutturale

- Essenzialmente nessun competitor di LHCb dopo il 2025
  - Belle-II avrà raggiunto i 50 ab^{-1}
    - al momento non ci sono programmi specifici di upgrade
    - si sta pensando contemporaneo miglioramento
      - macchina
      - detector
    - È ovvio che qui c'è da tenere d'occhio l'evoluzione di ILC

LHCb Coll. arXiv:1808.08865 [hep-ex]

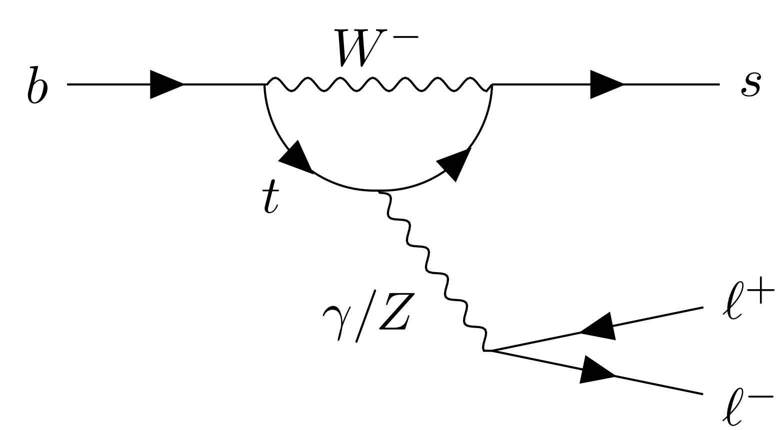


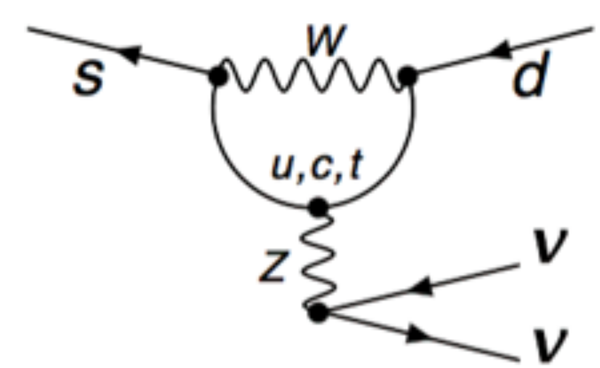
Tornando ai grafici di Feynman

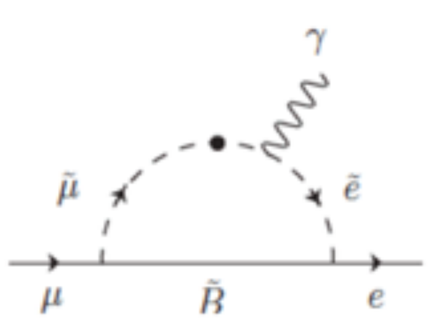
"Minimalistic" list of the key (low-energy) quark flavor-violating observables:

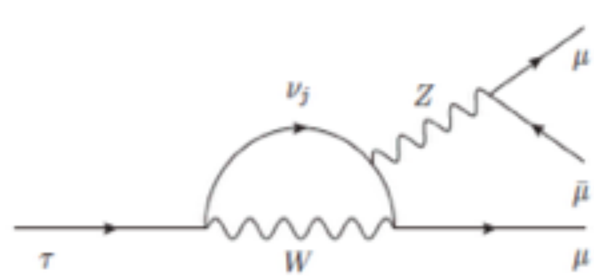
from Gino Isidori

- γ from tree ($B \to DK$, ...) — S-LHCb
- $|V_{ub}|$ from exclusive semi-leptonic B decays — S-Bfactory [SuperKEKB & SuperB]
- $B_{s,d} \to l^+ l^-$ — S-LHCb + ATLAS & CMS
- CPV in B_s mix. [ϕ_s] — S-LHCb + ATLAS & CMS
- $B \to K^{(*)} l^+ l^-$, $\nu\nu$ — S-LHCb / S-Bfactory
- $B \to \tau\nu$, $\mu\nu$ (+D) — S-Bfactory
- $K \to \pi\nu\nu$ — Kaon beams [NA62, KOTO, ORKA]
- CPV in charm — S-LHCb / S-Bfactory







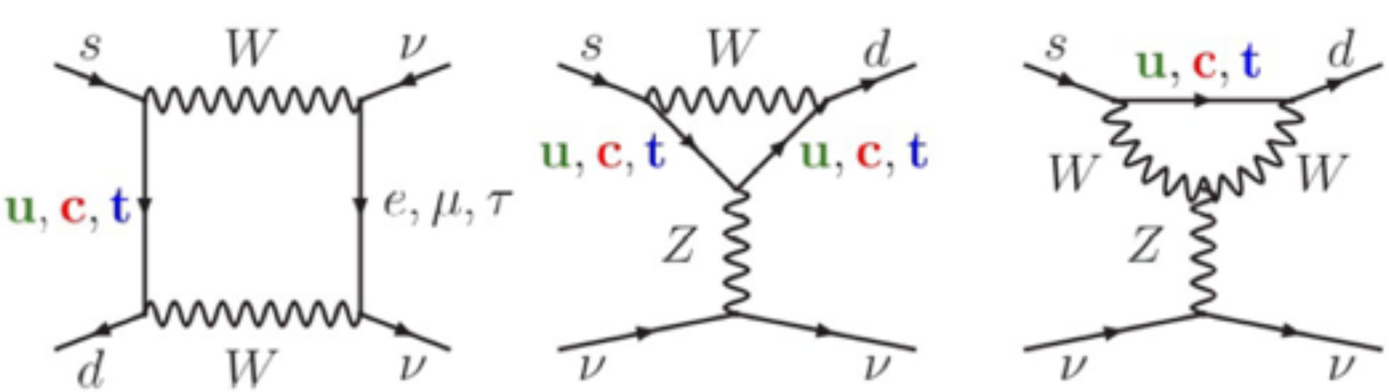


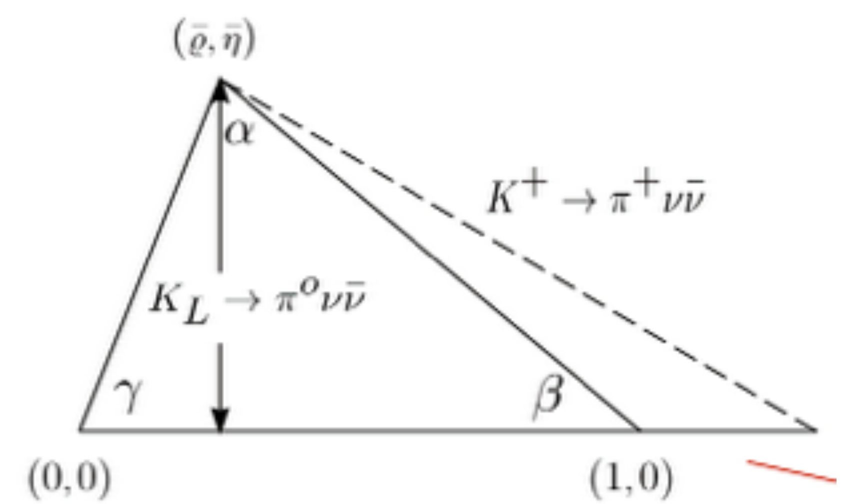
Kaons

- Non serve stare qui a ricordare i contributi alla comprensione della fisica: violazione di parità, mixing dei quark, oscillazione mesone-antimesone, violazione di CP, soppressione delle FCNC, meccanismo GIM e predizione del quark c….
- Golden Rare Kaon Decays
  - processi $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$
  - BR(SM) ~10^{-10}
  - Theoretical uncertainty on $K^o \to \pi^o \nu\nu$ < $K^+ \to \pi^+ \nu\nu$

$K^+ \to \pi^+ \nu\bar{\nu}$ — NA62 @ CERN

$K_L \to \pi^0 \nu\bar{\nu}$ — KOTO @ J-PARC

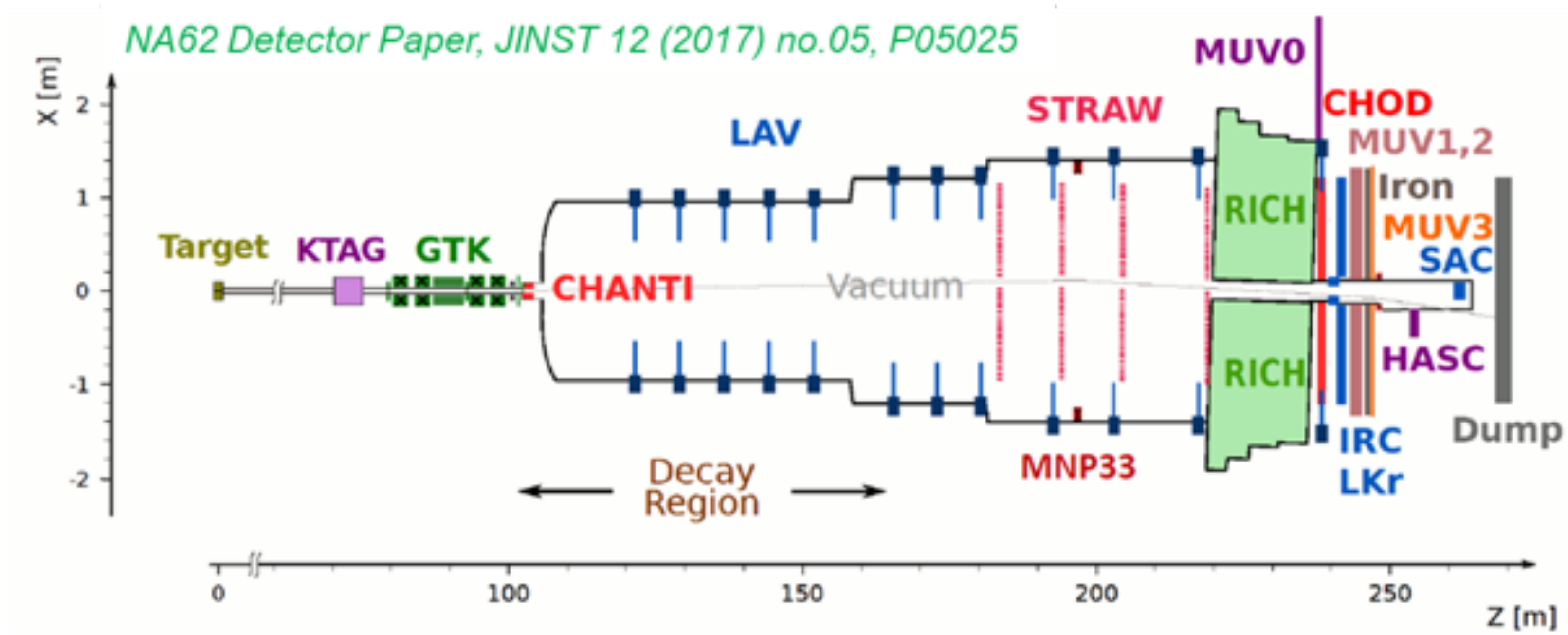




$$BR(K^o \to \pi^o \nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

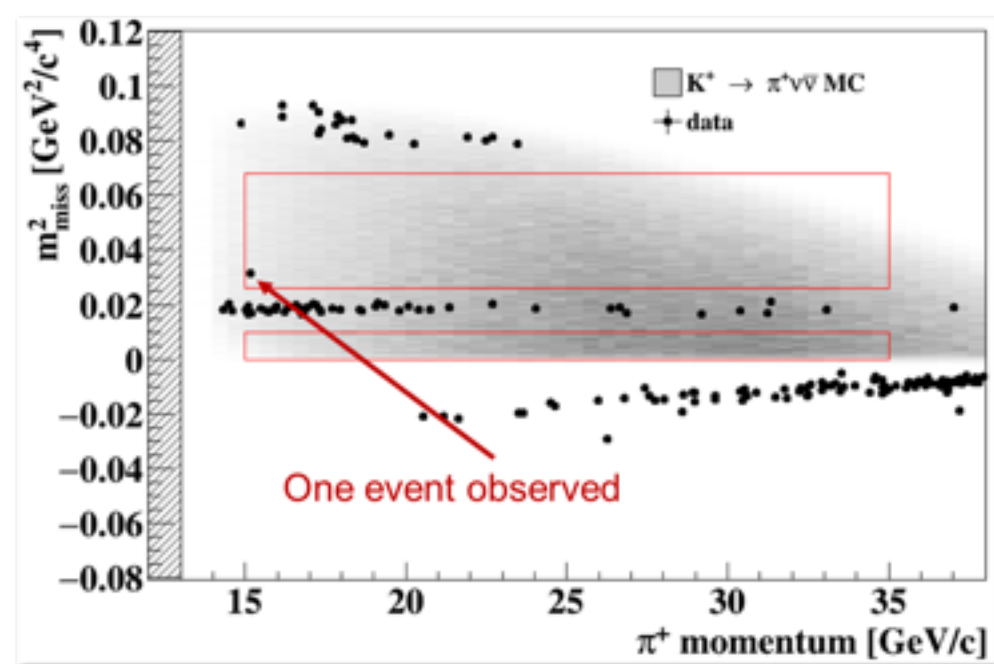
Decadimenti rari del K

- NA62 sta prendendo dati con l'obiettivo di dare un BR($K^+ \rightarrow \pi^+ \nu\nu$) al 10%
  - 20 SM events attesi < LS2 (2020)
  - possible run after LS2 under discussion



- Present result E787/E949
  - «Kaon decay-at-rest» technique
  - LESBIII beamline @ AGS(BNL): 800 MeV/c Kaons (~71% purity)
  - K+ decays: $\sim 3.5 \cdot 10^{12}$
  - Single Event Sensitivity: $\sim 0.8 \cdot 10^{-10}$

<2015: Technical and pilot runs
2015: commissioning run
2016: commissioning+physics run
2017: physics run
2018: physics run



- One event observed in region 2
- The result is compatible with the standard model
- Upper limit on the BR (still preliminary)

$$SES_{2016} = (3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$$

$$BR_{2016}(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 14 \times 10^{-10} \ @ \ 95\% \ CL$$

Decadimenti rari del K

- NA62 sta prendendo dati con l'obiettivo di dare un BR($K^+ \rightarrow \pi^+ \nu\nu$) al 10%
  - 20 SM events attesi < LS2 (2020)
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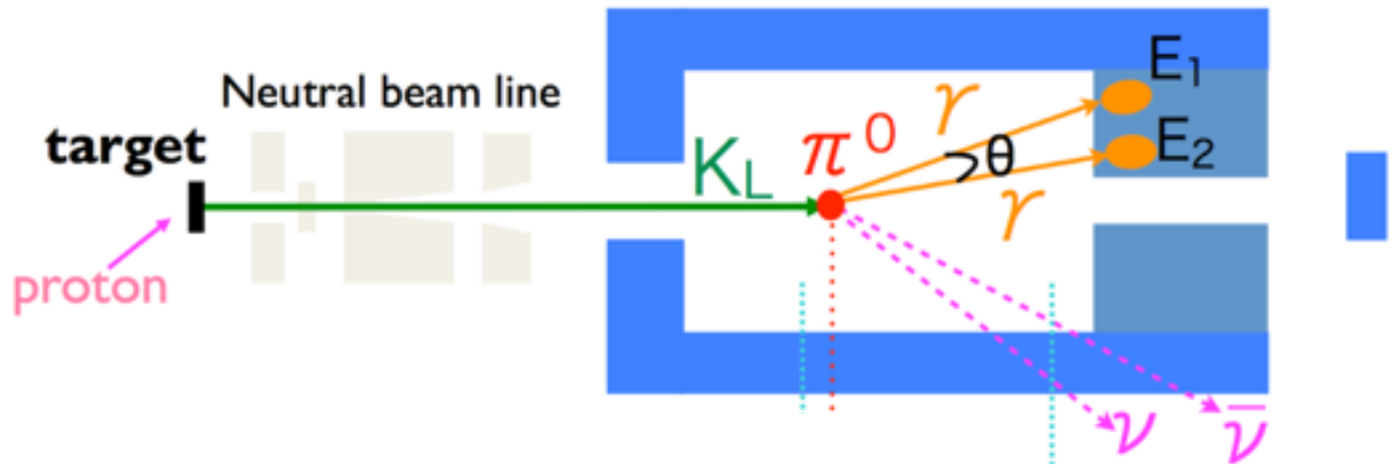
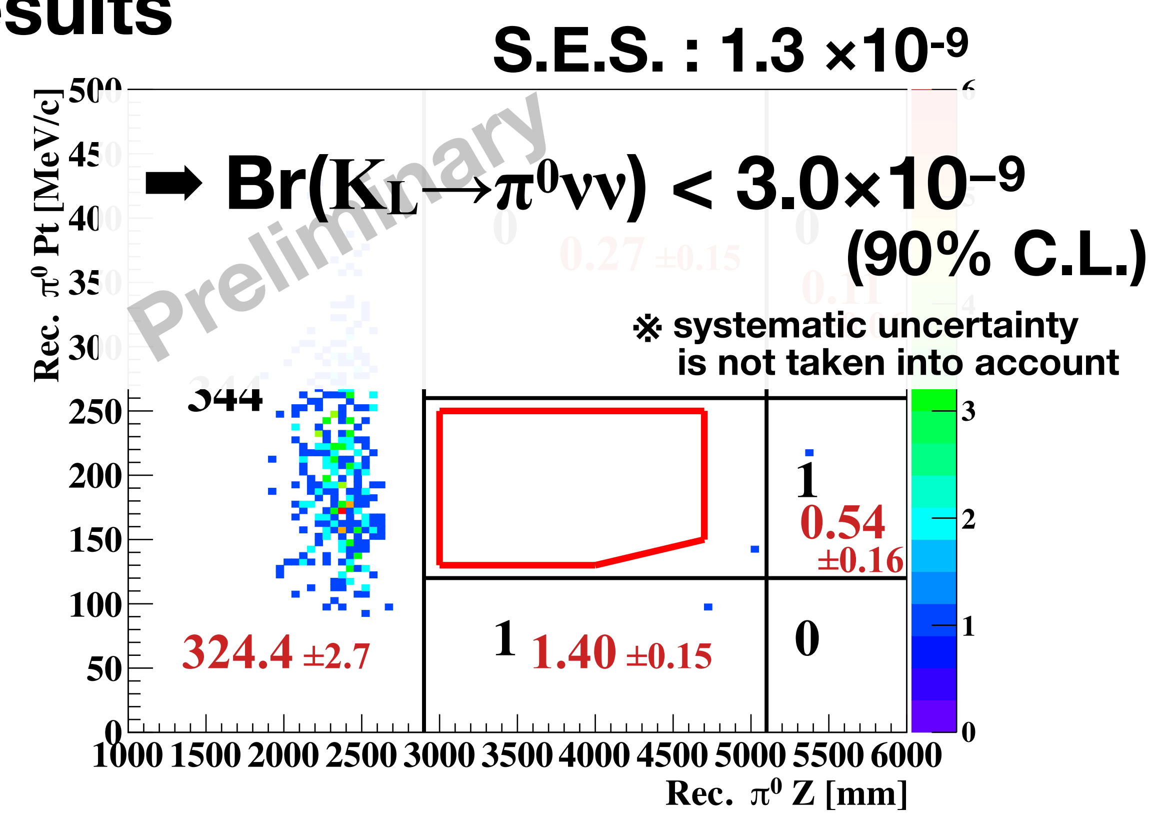
- KOTO dovrebbe migliorare il limite sul canale neutro BR($K^o \rightarrow \pi^o \nu\nu$)
  - SM sensitivity by 2022

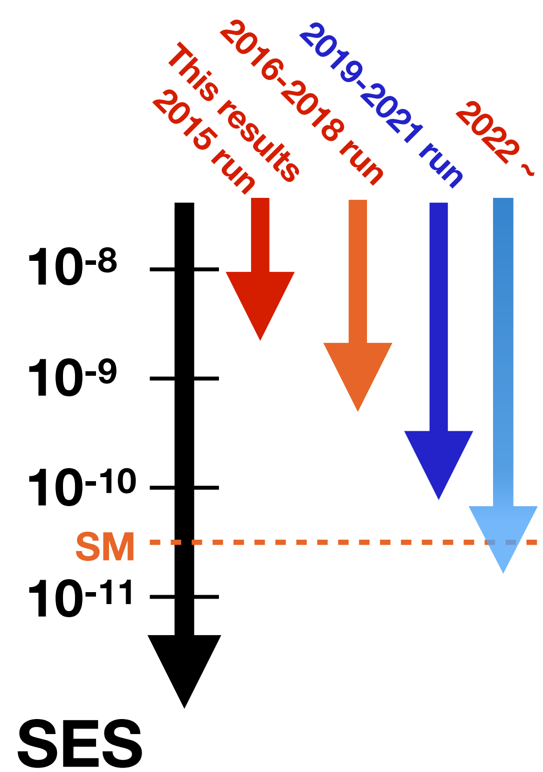


Results



No candidate event observed

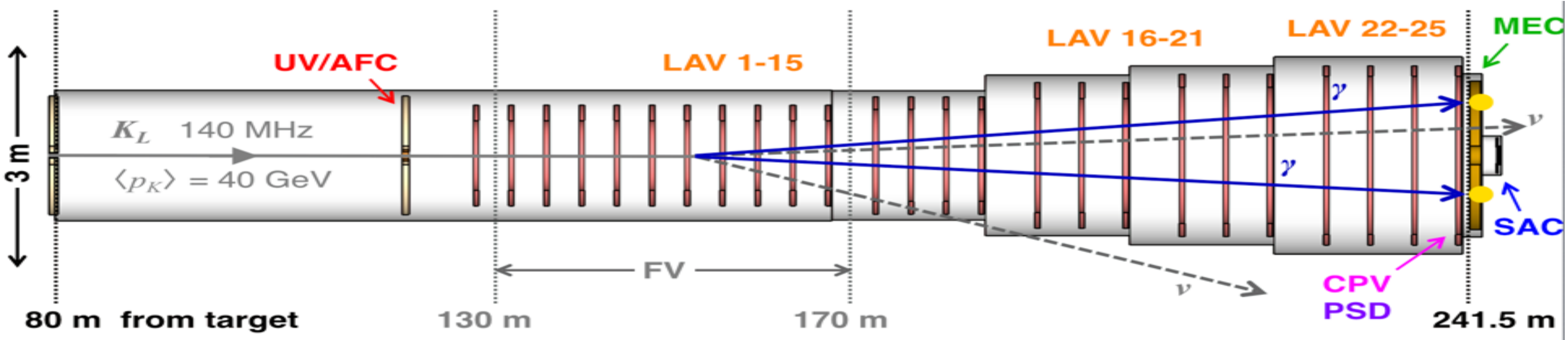
31



- expect O(10^{-11}) SES with the next 3-year data
  - beam power 50→90kW and more
- aim to SM sensitivity
  - better beam condition by the power supply upgrade of the accelerator

Decadimenti rari del K

- NA62 sta prendendo dati con l'obiettivo di dare un BR($K^+ \to \pi^+ \nu\nu$) al 10%
  - 20 SM events attesi < LS2 (2020)
  - possible run after LS2 under discussion
- KOTO dovrebbe migliorare il limite sul canale neutro BR($K^o \to \pi^o \nu\nu$)
  - SM sensitivity by 2022
- KLever si propone di misurarlo con 400-GeV SPS → 60 SM events by 2030



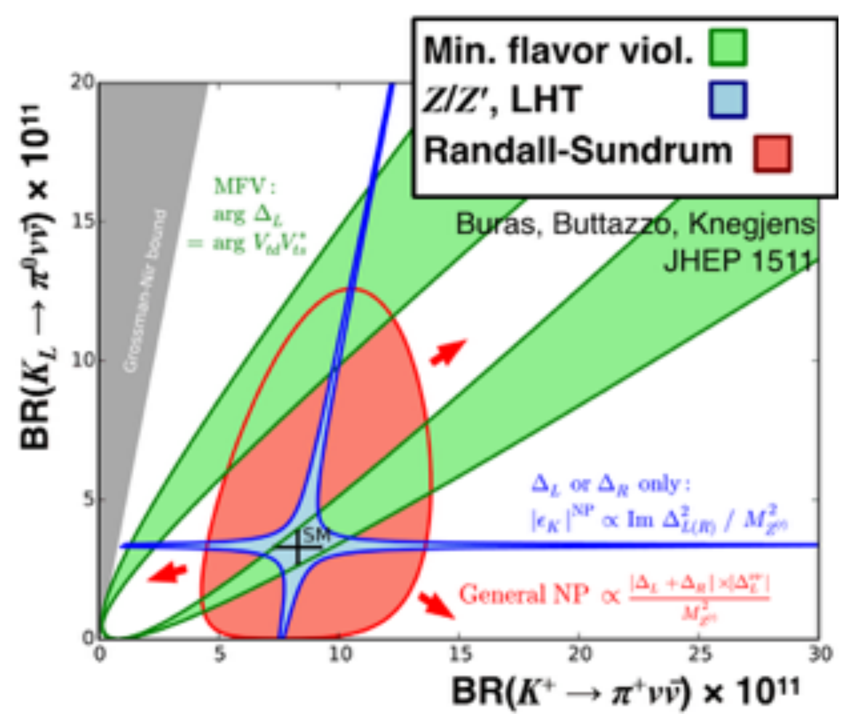
KLEVER target sensitivity

5 years starting Run 4 (2026)
(assuming the start of construction at the completion of the NA62 program)

60 SM $K_L \to \pi^0 \nu\bar{\nu}$ events

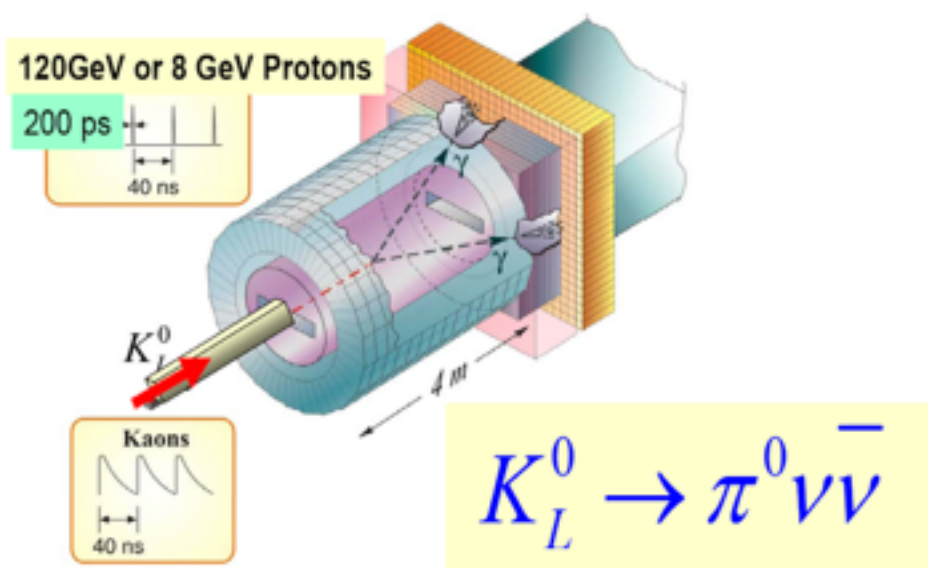
$S/B \sim 1$

δBR($K_L \to \pi^0 \nu\bar{\nu}$) ~ 20%

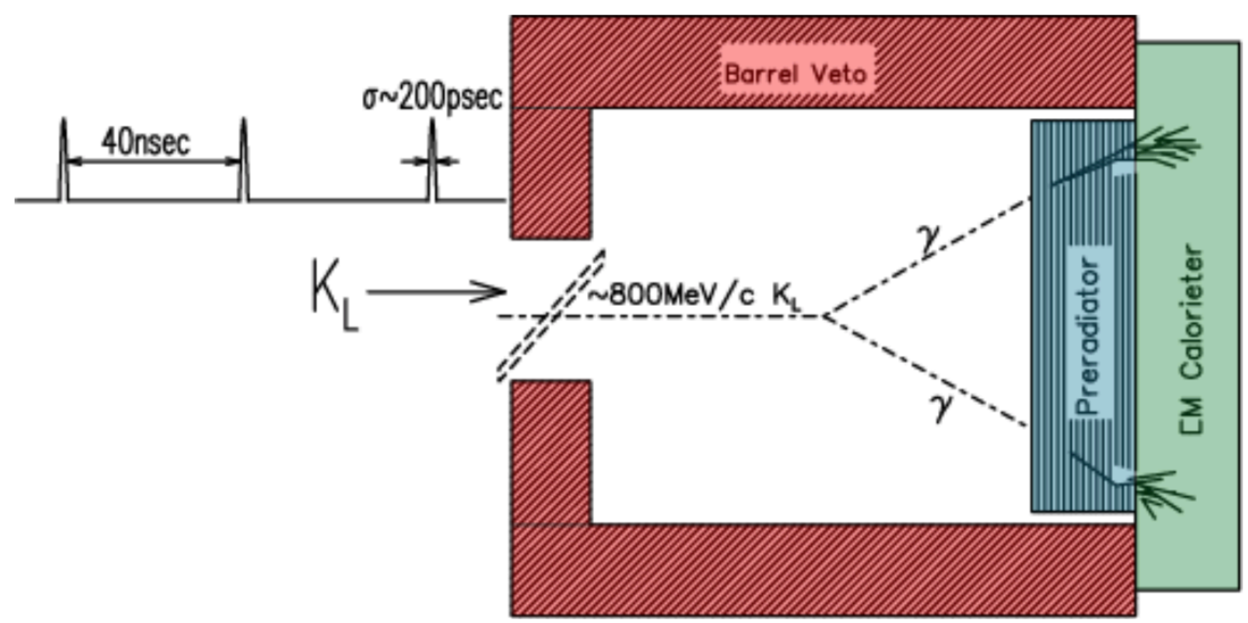


Decadimenti rari del K

- NA62 sta prendendo dati con l'obiettivo di dare un BR($K^+ \rightarrow \pi^+ vv$) al 10%
  - 20 SM events attesi < LS2 (2020)
  - possible run after LS2 under discussion
- KOTO dovrebbe migliorare il limite sul canale neutro BR($K^o \rightarrow \pi^o vv$)
  - SM sensitivity by 2022
- KLever si propone di misurarlo all'SPS
- Per ora nessuna evoluzione per un esperimento à la KOPIO o KLOE (kinem. constr.)
  - beam



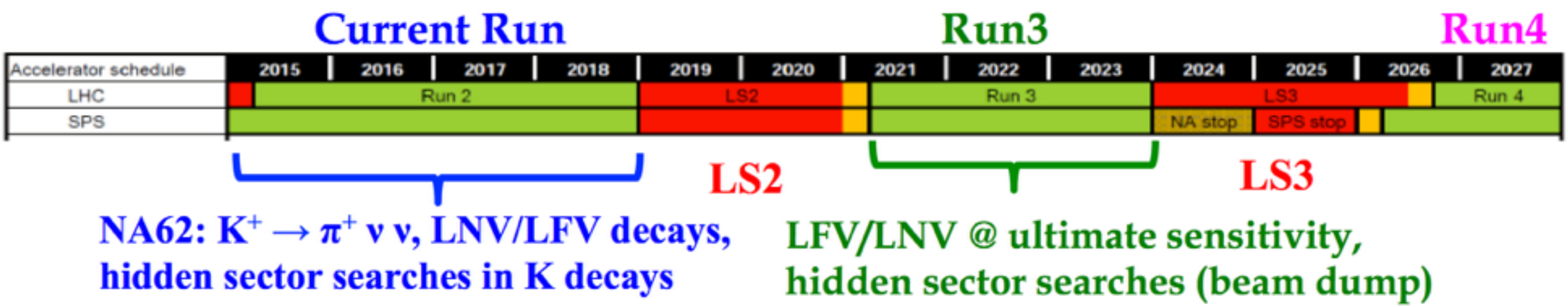
KOPIO Concept



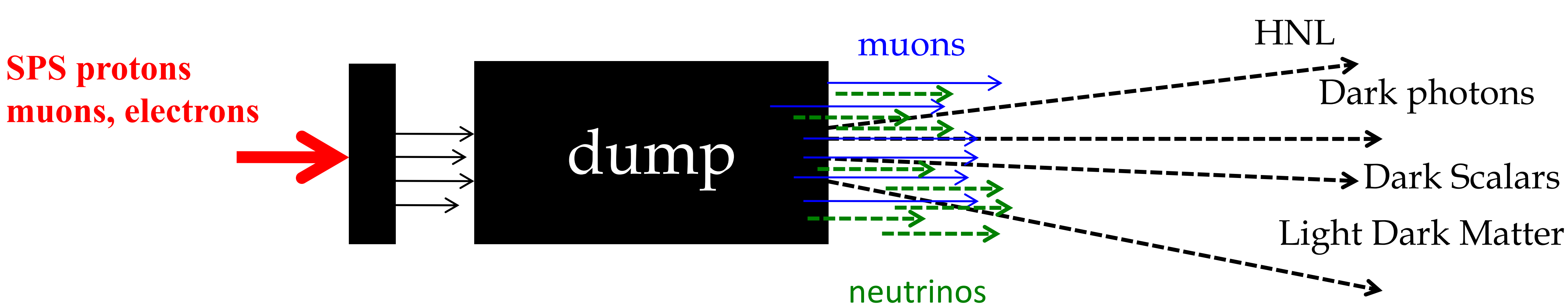
- KOPIO-like: TOF to determine Kaon Energy
- Knowledge of E_K allows rejection of two body decays
- Pointing Calorimeter
- 4 π veto for neutral and charged particles
- Small Beam instead of flat beam

NA62 in beam dump mode

- NA62 può operare in beam dump mode usando dei collimatori in rame/ferro di circa 22 λ_I
  - 75 GeV/c K+ beam, → futuro NA62++ 10^{18} pot/year dopo LS2
  - Ricerca di Dark Photons, Axion-like particles, heavy neutral leptons
  - Range di massa dal MeV al GeV (non accessibile da esperimenti di scattering diretto)



High-resolution tracking, PID, vetoing: high sensitivity to closed signatures



Technique used by NA62^{++}, SHiP, NA64^{++}

NA62 in beam dump mode

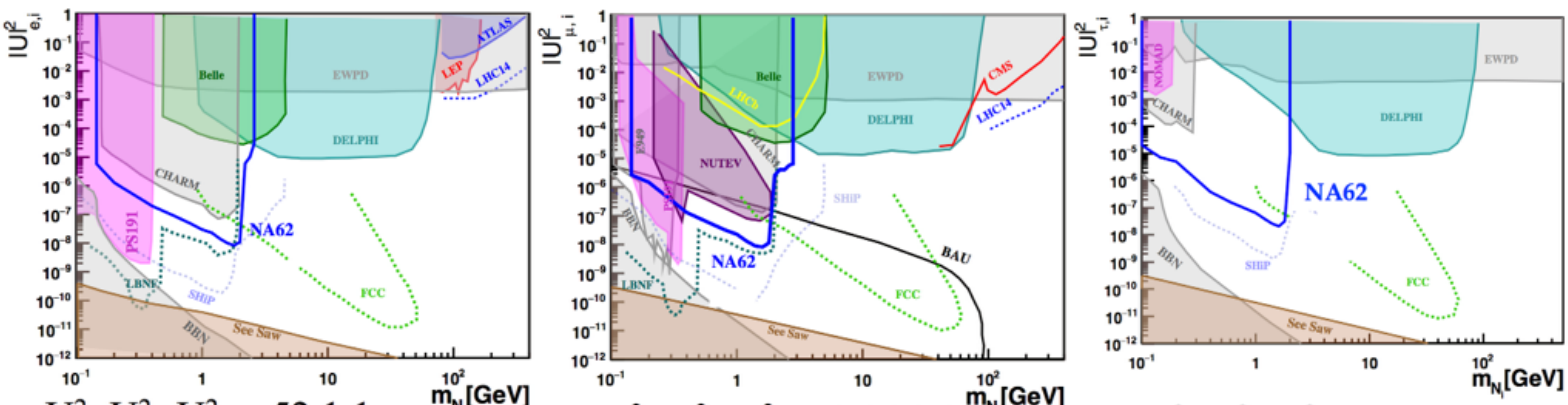
- NA62 può operare in beam dump mode usando dei collimatori in rame/ferro di circa 22 λ_I
  - 75 GeV/c K+ beam, → futuro NA62++ 10^{18} pot/year dopo LS2
  - Ricerca di Dark Photons, Axion-like particles, heavy neutral leptons
  - Range di massa dal MeV al GeV (non accessibile da esperimenti di scattering diretto)

Assume 10^{18} 400-GeV POT:

search for two-track final states originating **at the TAX**

sensitivity includes open channels, assume 0 background

separately address 3 extreme coupling scenarios



$U^2_e:U^2_\mu:U^2_\tau = 52:1:1$
Normal hierarchy of active **ν** masses

$U^2_e:U^2_\mu:U^2_\tau = 1:16:3.8$
Normal hierarchy of active **ν** masses

$U^2_e:U^2_\mu:U^2_\tau = 0.061:1:4.3$
Normal hierarchy of active **ν** masses

Technique used by NA62^{++}, SHiP, NA64^{++}

Projects considered at CERN in the Physics Beyond Colliders framework

Dark sector in the MeV-GeV range:

Proposal	physics case	beam line	beam type	beam yield
sub-eV range:				
IAXO	axions/ALPs (photon coupling)	–	axions from sun	–
ALPS-III	axions/ALPs (photon coupling)	laboratory	LSW	–
CPEDM	p, d EDM,	EDM ring	p, d	–
	axions/ALPs (gluon coupling)		p, d	–
LHC-FT	charmed hadrons MDMs, EDMs	LHCb IP	7 TeV p	–
MeV-GeV range:				
SHiP	ALPs, Dark Photons,	BDF	400 GeV p	$2 \cdot 10^{20}$/5 years
	Dark Scalars, LDM, HNLs			
NA62^{++}	ALPs (photon, fermion coupling)	K12	400 GeV p	up to $3 \cdot 10^{18}$/year
	Dark Photons, Dark Scalars, HNLs			
NA64^{++}	ALPs (which couplings?)	H4	100 GeV e^-	$5 \cdot 10^{12}$ eot/year
	Dark Photons, Dark Scalars, LDM			
	$+ L_\mu - L_\tau$	M2	160 GeV μ	$10^{12} - 10^{13}$ mot/year
	+ CP, CPT, leptophobic DM	H2-H8, T9	~ 40 GeV π, K, p	$5 \cdot 10^{12}$/year
LDMX	Dark Photon, LDM, ALPs,...	eSPS	8 (SLAC) -16 (eSPS) GeV e^-	$10^{16} - 10^{18}$ eot/year
RedTop	Dark Photon, Dark scalar	CERN PS	1.8 or 3.5 GeV	10^{17} pot
MATHUSLA	Dark Scalar, Dark Photon, HNLs,...	ATLAS or CMS IP	14 TeV p	3000 fb^{-1}
FASER	Dark Photon, Dark Scalar, ALPs	ATLAS IP	14 TeV p	3000 fb^{-1}
MilliQan	milli charge	CMS IP	14 TeV p	300-3000 fb^{-1}
Codex-b	Dark Scalar, Dark Photons, ...	LHCb IP	14 TeV p	300 fb^{-1}
> TeV range:				
KLEVER	$K_L \to \pi^0 \nu \bar{\nu}$	P42	400 GeV p	$5 \cdot 10^{19}$ pot /5 years
TauFV	LFV τ decays	BDF	400 GeV p	5% of the SHiP yield

@ SPS

@ PS

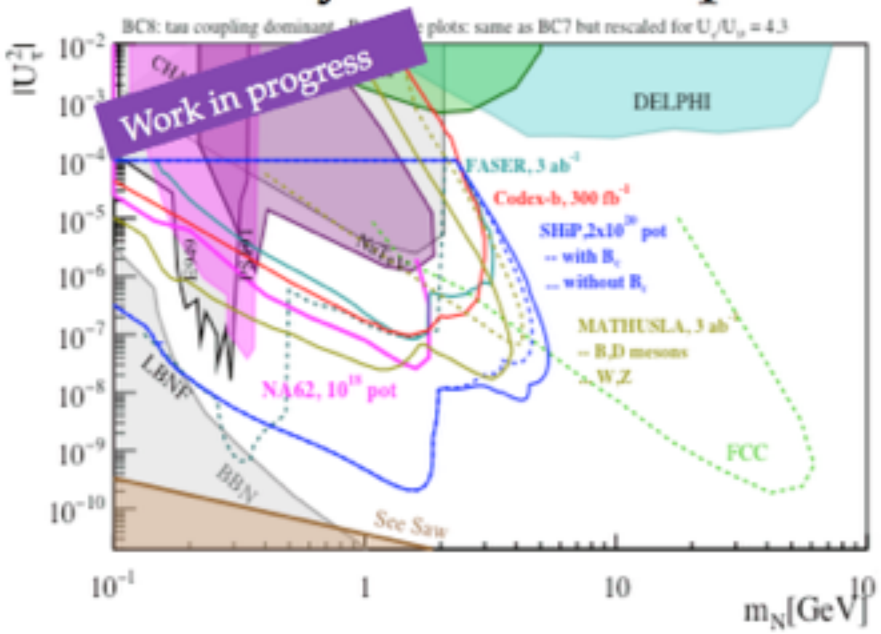
@ LHC

from CERN PBC

SHIP @ CERN beam dump facility

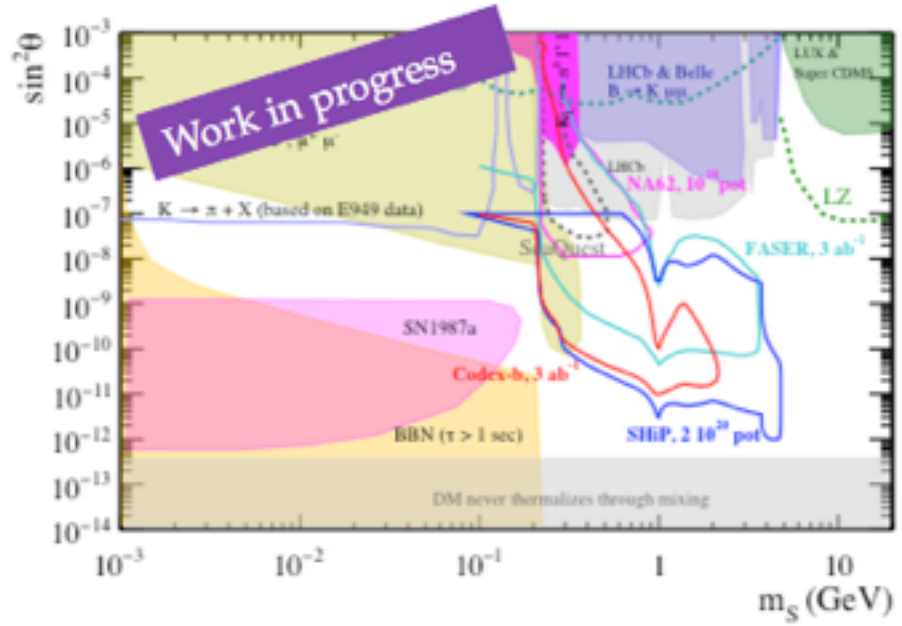
- Completato lo studio preparatorio
  - 400 GeV p beam, 2 x 10^{20} p/5 years (un fattore ~200 rispetto a NA62++) starting in 2026

Heavy Neutral Leptons

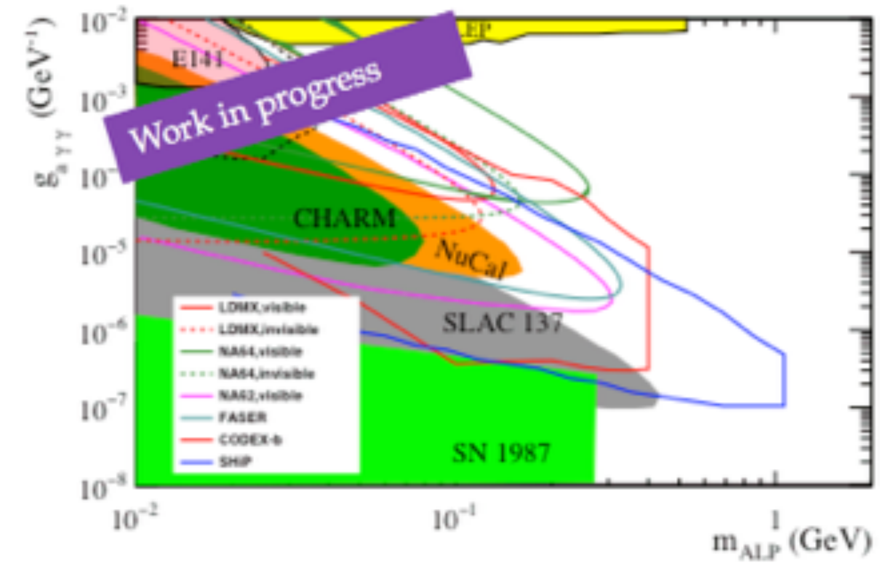


U_τ^2 enhanced

Dark Scalar

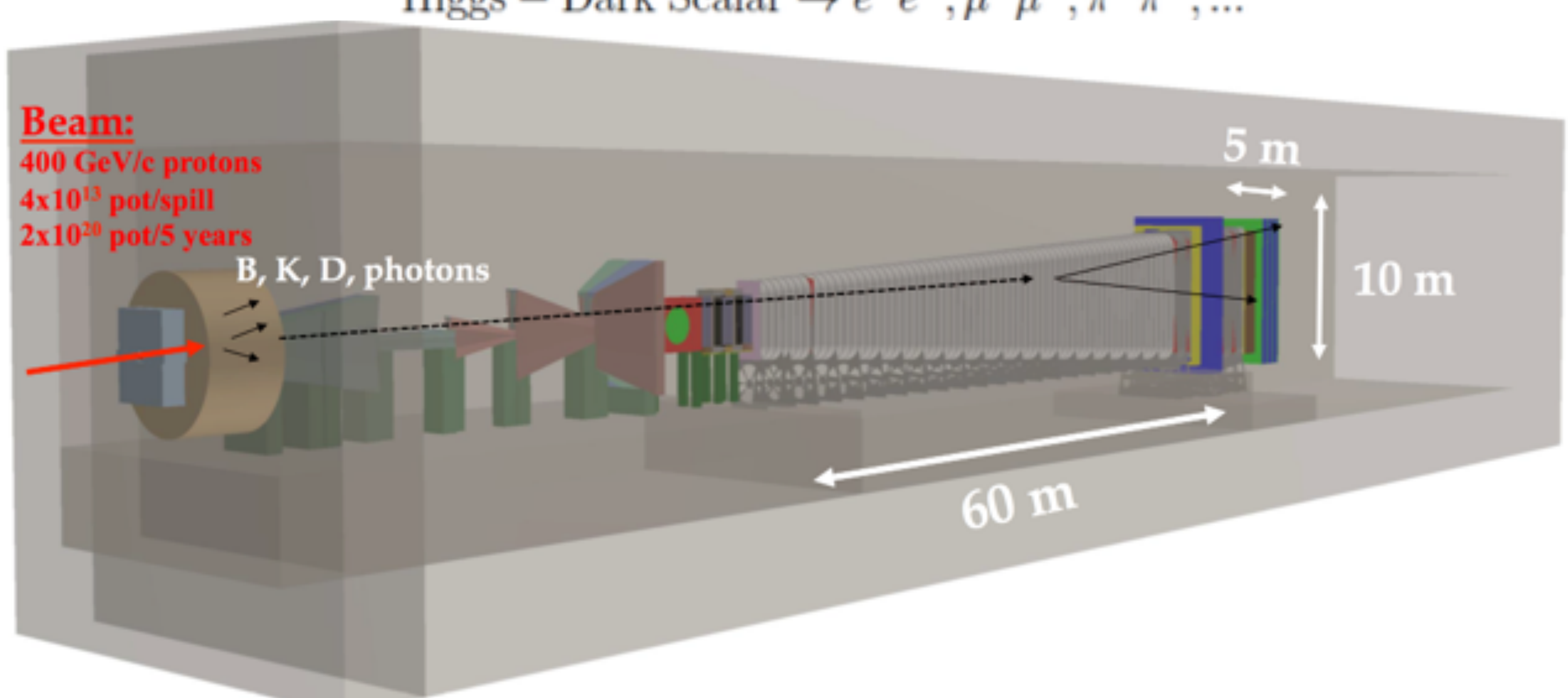


ALP →γγ



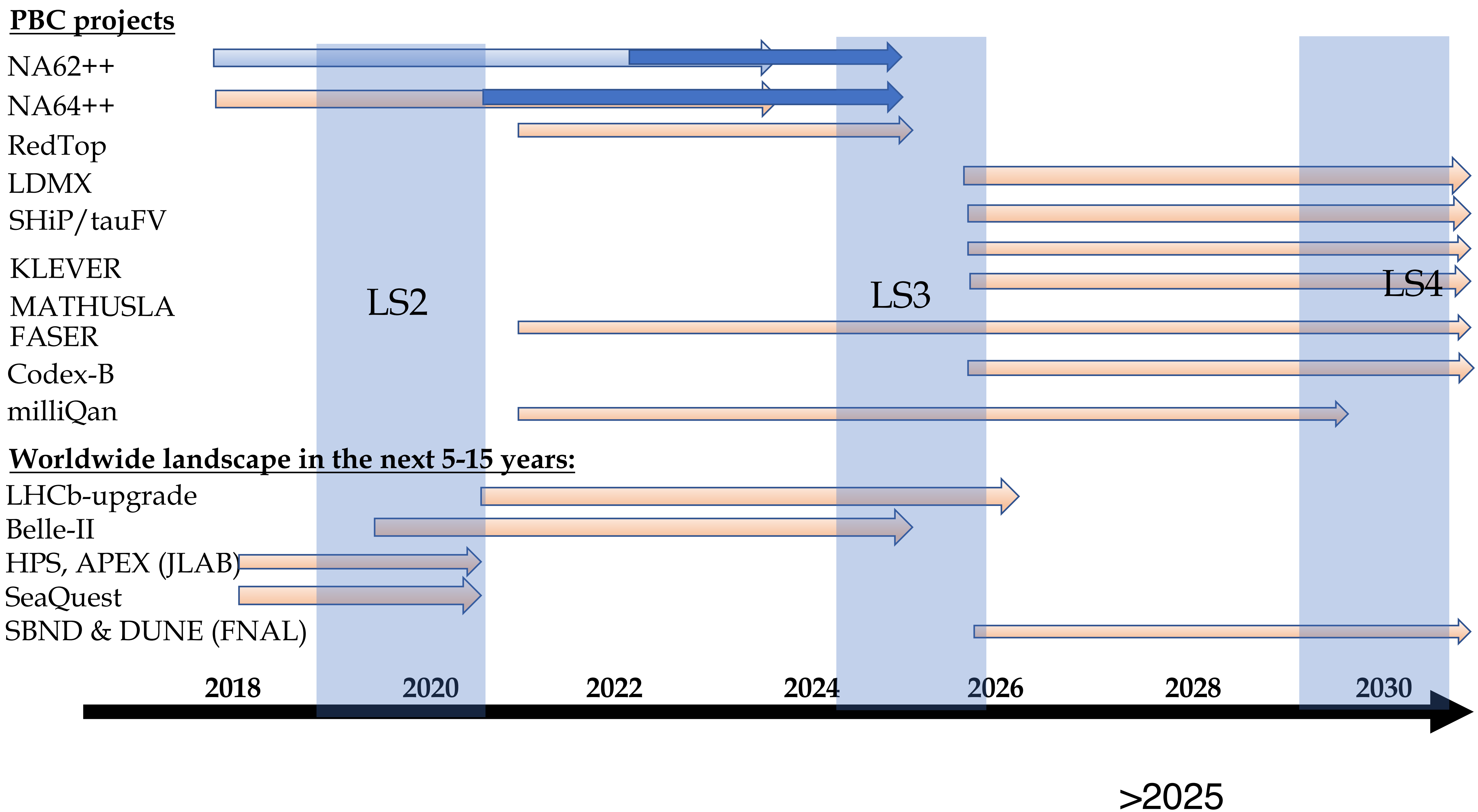
$ALP \to \gamma\gamma$, invisible

Higgs – Dark Scalar $\to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \ldots$



INFN

Timescale of the PBC BSM projects accelerator-based

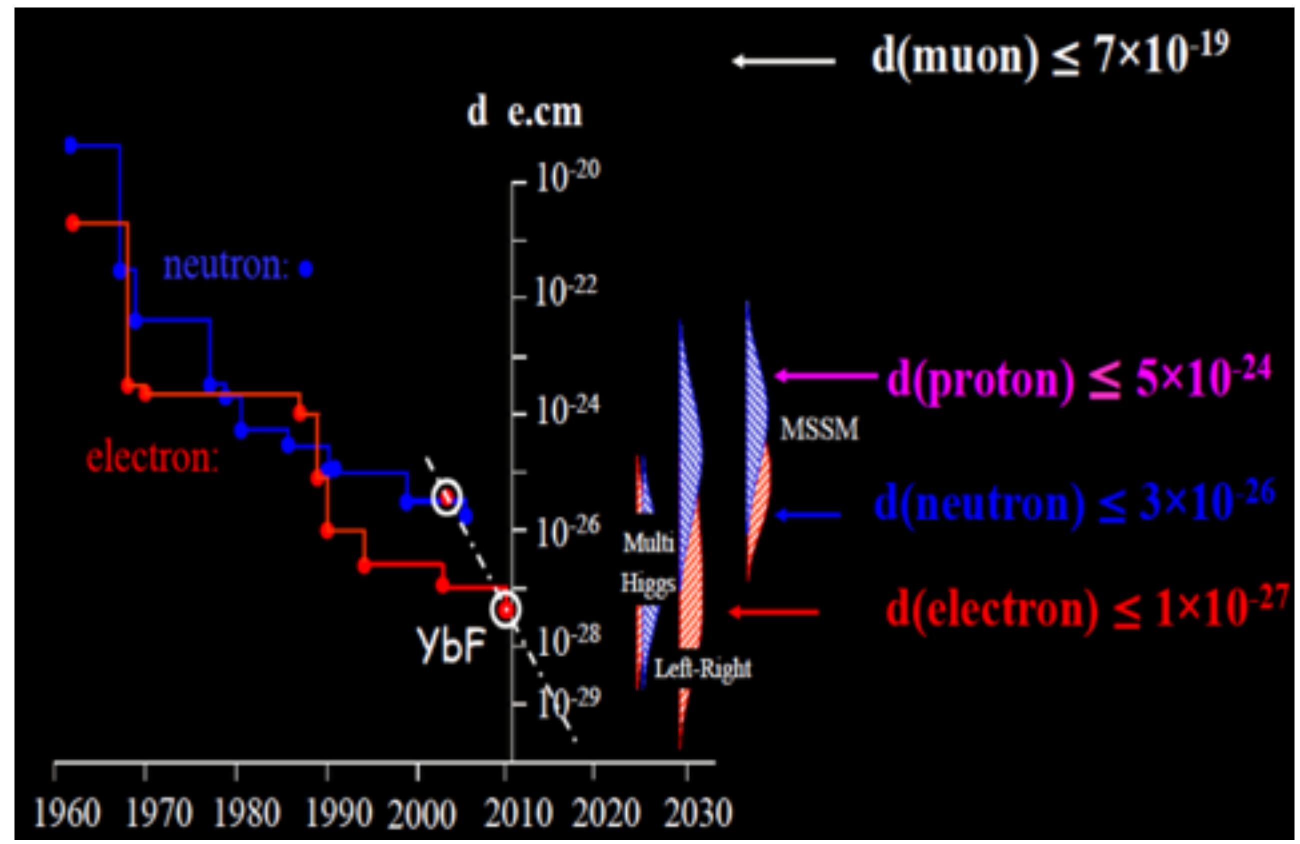


EDMs

- The search for Electric Dipole Moments of fundamental particles (n, e, μ, nuclei, atoms)
  - We know that CP is not an exact symmetry nor sufficient → non vanishing EDMs
  - No SM background
  - EDMs close to present bounds are predicted in several models

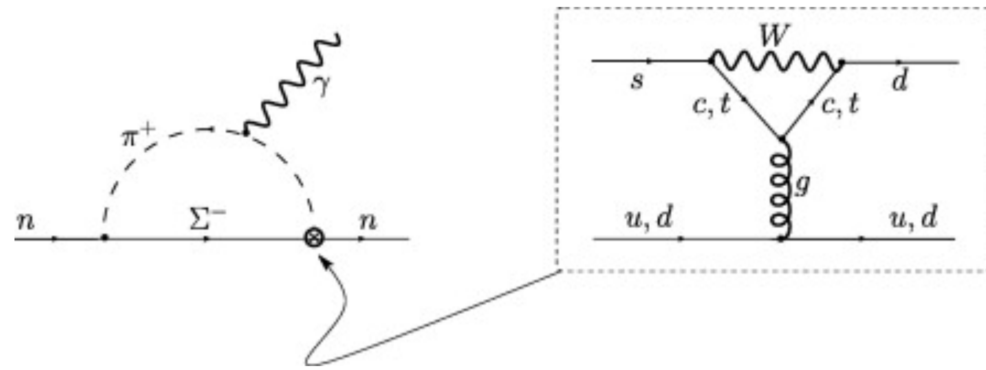
Observable	Exp. Current
$\lvert d_{Tl}\rvert$ [e cm]	$< 9.0 \times 10^{-25}$
$\lvert d_{Hg}\rvert$ [e cm]	$< 3.1 \times 10^{-29}$
$\lvert d_{n}\rvert$ [e cm]	$< 2.9 \times 10^{-26}$

Leptons		
Electron	ThO	8.9×10^{-29}
Muon	–	1.9×10^{-19}
Tau	$e^+e^- \to \tau^+\tau^-$	1.0×10^{-16}



- Muon EDM ⇒ byproduct of g–2

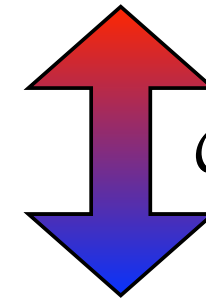
- Other EDM measurements are extremely sensitive to BSM physics
  - electron EDM (14.5 MeV, 2.5 m radius storage ring)
  - n EDM
- Small experiments, maybe do not need a “strategy” but need an endorsement and a community



ref.: M. Pospelov and A. Ritz, Annals of Physics 318 (2005) 119

Current Upper Limit

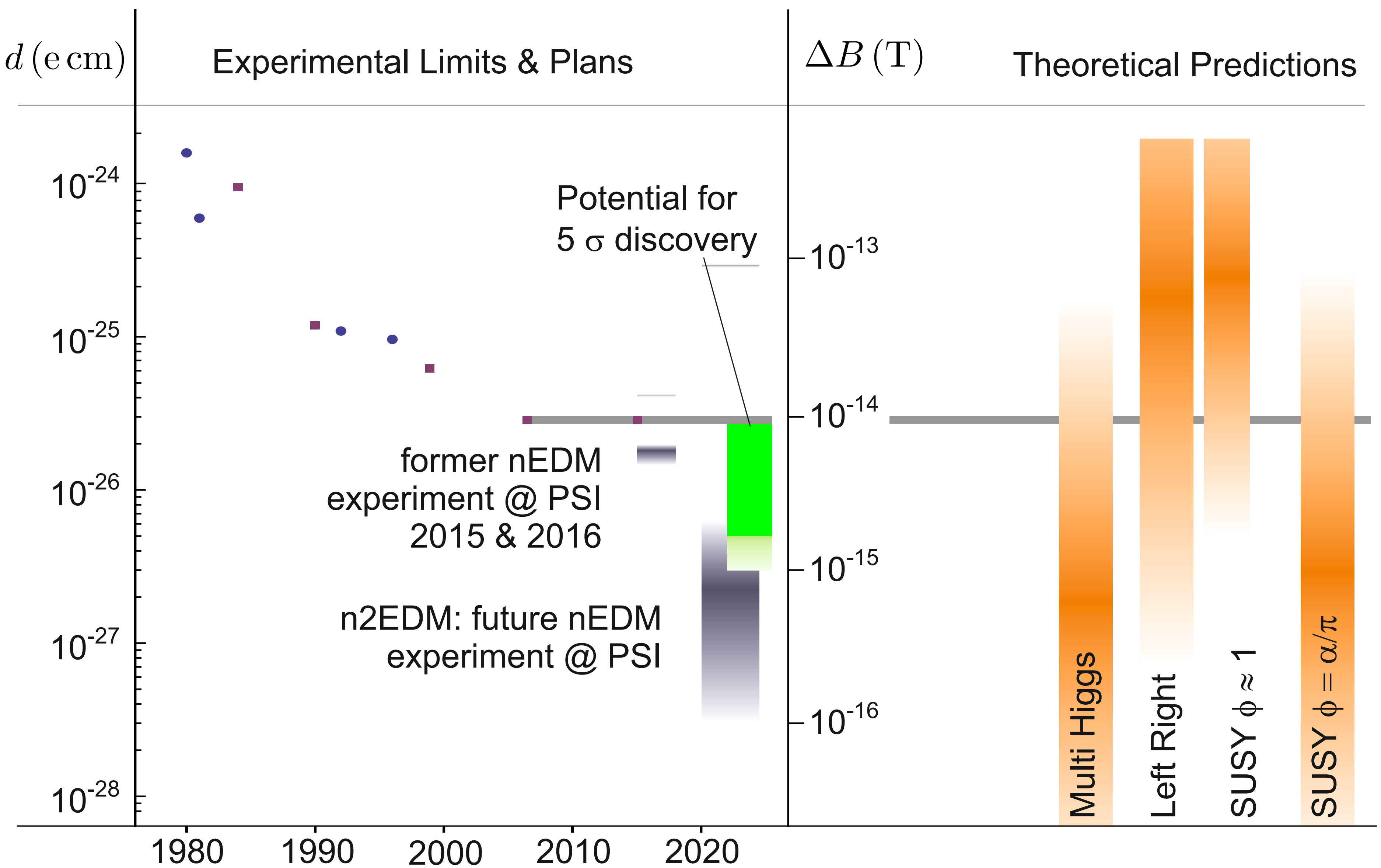
$d_n < 3 \times 10^{-26}\ e\ cm$



$\mathcal{O}(10^{5-6})$

SM predictions

$d_n \approx 10^{-32} - 10^{-31}\ e\ cm$

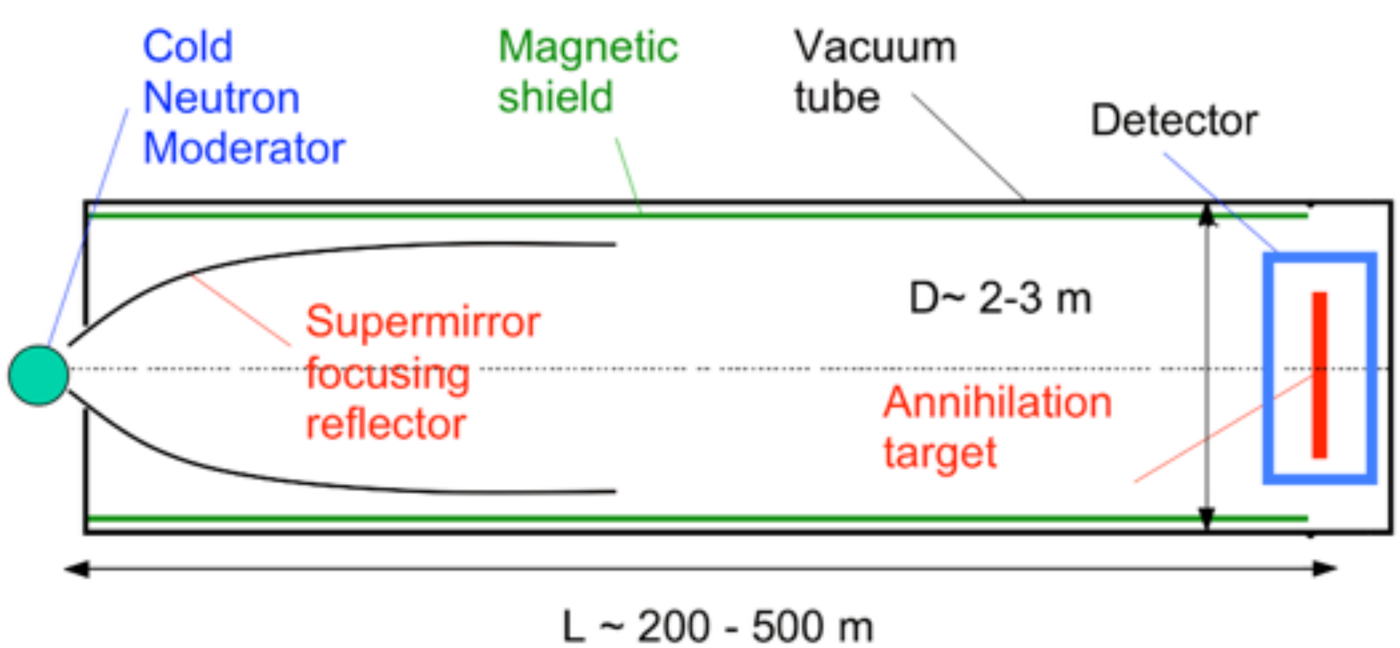


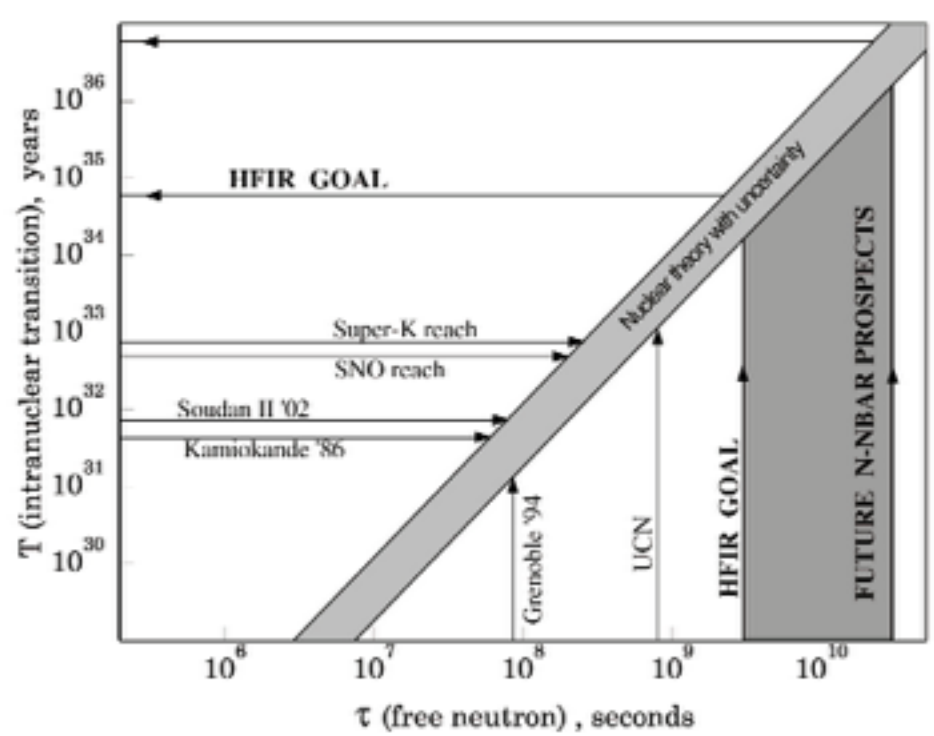
▪ Sussex RAL ILL • LNPI/PNPI

Theoretical data from «Particle electric dipole moments»
J.M. Pendlebury & E.A. Hinds, NIM A 440 (2000) 471

n nbar oscillation

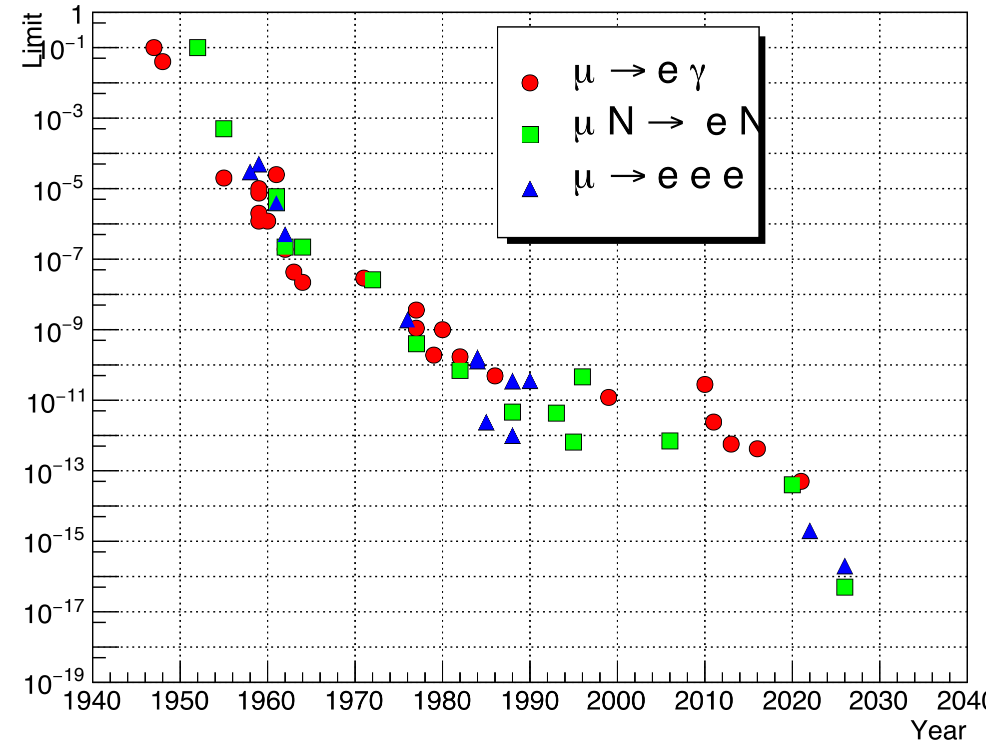
- In questo contesto l'ultima cosa da considerare è un esperimento per la rivelazione delle oscillazioni neutrone-antineutrone
- Costo elevato a causa dell'infrastruttura (screening, neutron reflectors) ~100M€
- beam of neutron + far detector where the nbar annihilates
- limit ILL in Grenoble $\tau > 8.6 \times 10^7$ sec.
- Spallation target to improve the limit by 2 orders of magnitude ⇒ optics technology developed for material science experiments
- n-nbar exp at ESS (European Spallation Source, Lund, Sweden) Y. Kamishkov et al.
- use the know-how of the 1991 exp + implementing a new idea of cold neutron focussing from the large aperture source. Improvement by a factor of 100 by using mirrors from swiss neutronics

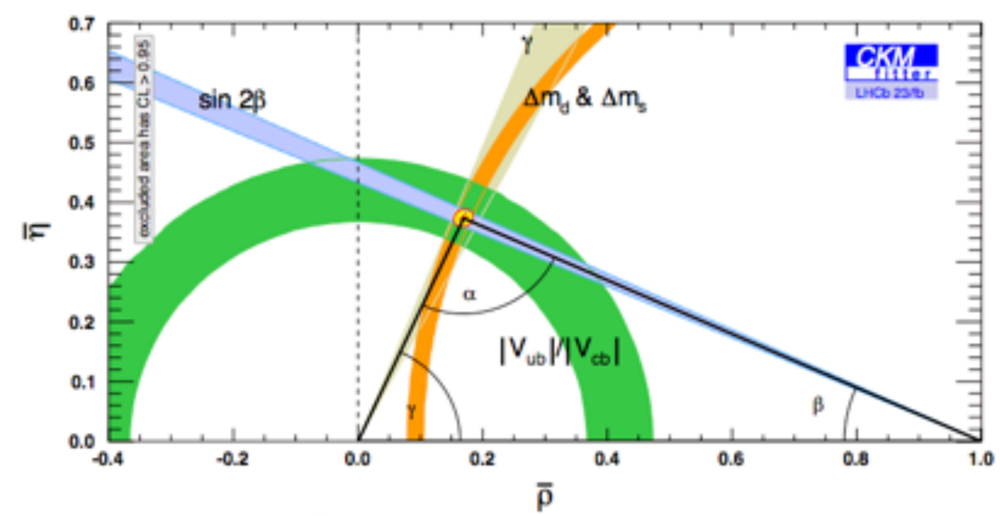


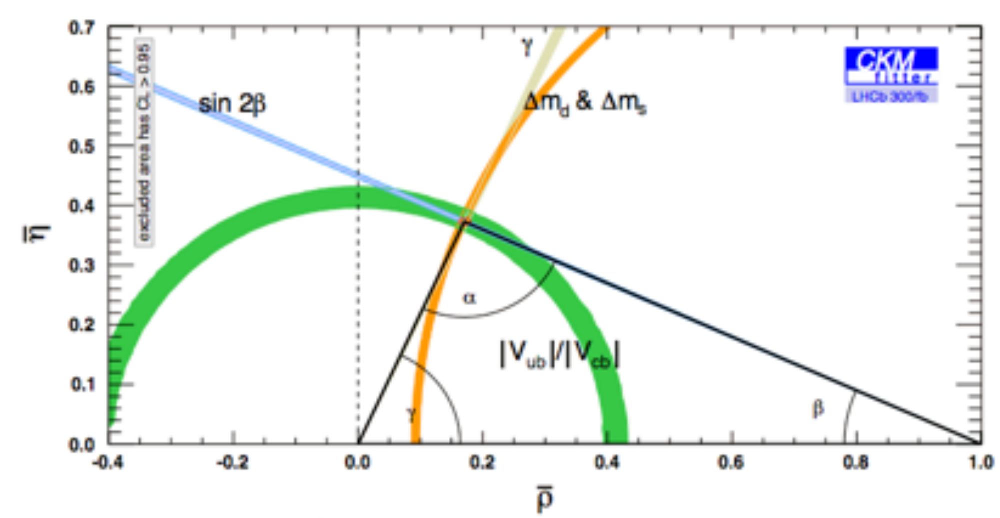


Riassumendo

- Flavour leptonico e adronico nel 2030
- CLFV
  - mu2e-II
  - MEG/mu3e? → R&D sul tracker
- muon g–2 va assediato
- Gli elementi di CKM
  - LHCb-Up2
  - Novella flavour factory??
  - K-physics
  - sfruttare l'intensità
    - invisibles?
    - τ-decays?
- new CP
- EDMs
- neutroni







Spunti per la discussione

- La high intensity/precision frontier ha in generale a che fare con
  - piccoli esperimenti (<100M€)
  - laboratori diversi
- Attualmente fra i pochi segnali di fisica oltre il MS
  - lepton flavor universality anomaly
  - muon g–2 anomaly
- Today this indirect search for new physics signature takes place almost in complete darkness.
- It is likely that signals from NP will come from the flavour sector.
- The investigation requres massive and/or fine tuned detectors
  - Gli esperimenti sono tipicamente al limite della tecnologia
    - piccoli → rivelatori
    - grandi → DAQ and readout challenge

- Panoramica non comprensiva delle linee che possono essere perseguite
  - (A) bisogna sviluppare la tecnologia dei rivelatori (costo = R&D)
  - (B) bisogna sviluppare il fascio (costo = beam)
  - (C) As is se si hanno i soldi e c'è la comunità che lo vuole fare

- There is overlap of instrumentation needs between kaon and muon experiments. Most of these require detection of particles in the 10 MeV to 1 GeV range.

- Calibration of large detectors has a number of challenges and R&D towards calibration systems for these large detectors should be supported.

- Maintaining the diversity while setting priorities since the available resources are limited.

- Competitive small and medium size projects are seen important to keep the diversity of our field, because a breakthrough or hints to physics beyond the standard model may emerge in unexpected areas

Possible R&Ds

- R&D towards cost effective calorimeters with good photon pointing and Time of Flight (TOF) (goal is <20mrad, 10's of psec).
- R&D towards cost effective, high efficiency photon detection for kaon experiments (with inefficiencies of 10^{-4} per photon)
- R&D to develop very fast, very high resolution photon/electron calorimetry for muon experiments (goal is 100ps, sub-percent energy resolution)
- Development of very low mass, high resolution, high-speed tracking for muon and kaon experiments (0.001 X_0 per space point, 100ps per track)
- Development of high fidelity simulation of low energy particle interactions. Development of strategies to effectively simulate $>10^{12}$ particle decays & interactions should also be a priority.
- A concerted effort to develop high throughput, fault tolerant streaming data acquisition systems (goal of TB/second throughput to PB/year data storage) + digitization

Adapted from Snowmass "Intensity Frontier Instrumentation"

End of Slides