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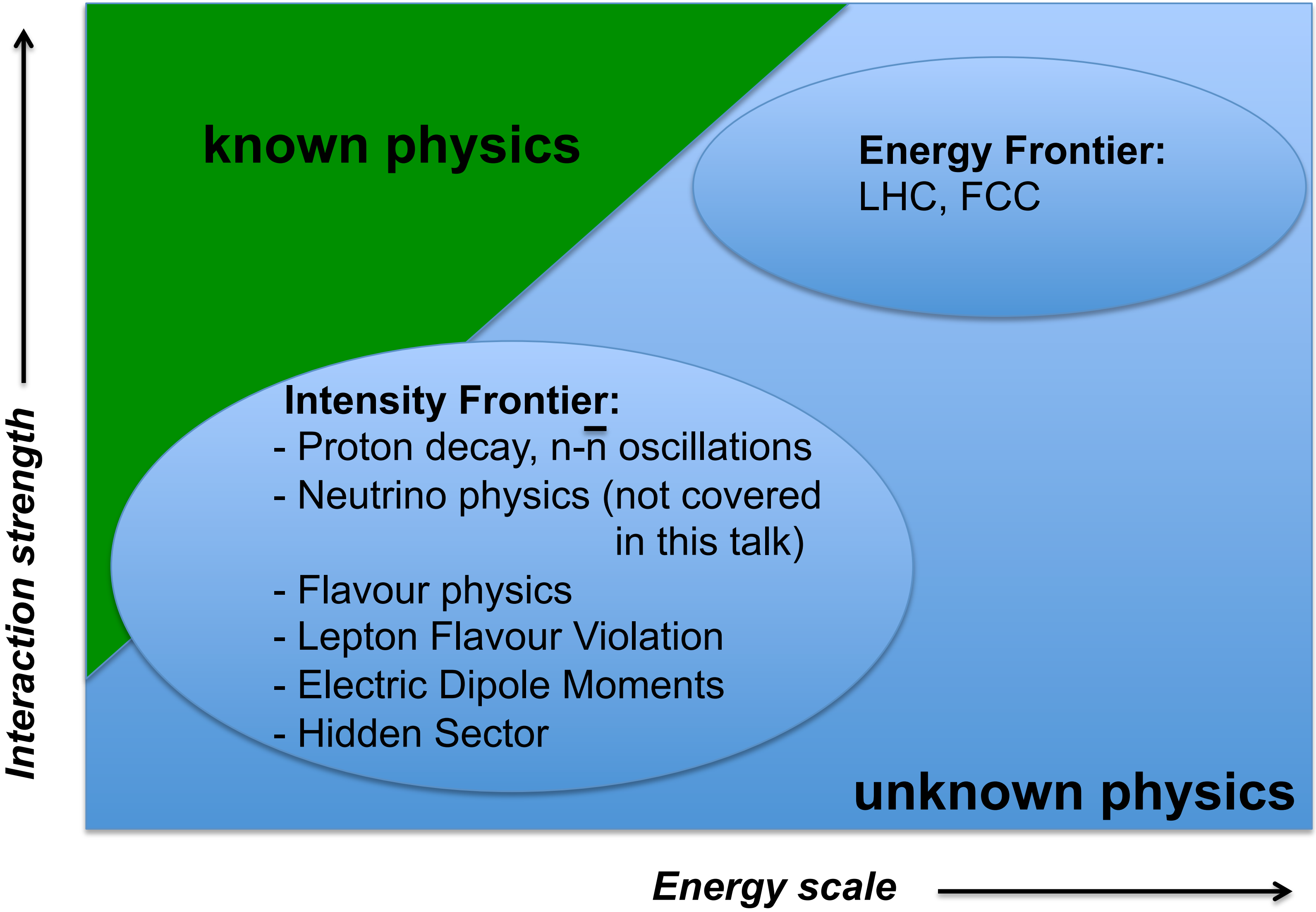
CERN

High Intensity Frontier



known physics

Energy Frontier:
LHC, FCC

Intensity Frontier:
- Proton decay, n-$\bar{n}$ oscillations
- Neutrino physics (not covered in this talk)
- Flavour physics
- Lepton Flavour Violation
- Electric Dipole Moments
- Hidden Sector

unknown physics

Physics motivation: Standard Model is great but it is not a complete theory

Experimental facts of BSM physics

- *Neutrino masses & oscillations*
- *The nature of non-baryonic Dark Matter*
- *Excess of matter over antimatter in the Universe*
- *Inflation of the Universe*

Theoretical shortcomings

Gap between Fermi and Planck scales, Dark Energy, connection to gravity, resolution of the strong CP problem, the naturalness of the Higgs mass, the pattern of masses and mixings in the quark and lepton sectors, …

No clear guidance at the scale of New Physics and on its coupling strength to the SM particles !

Scale of NP: See-saw generation of neutrino masses

Most elegant way to incorporate non-zero neutrino mass to the SM Lagrangian is given by the see-saw formula:

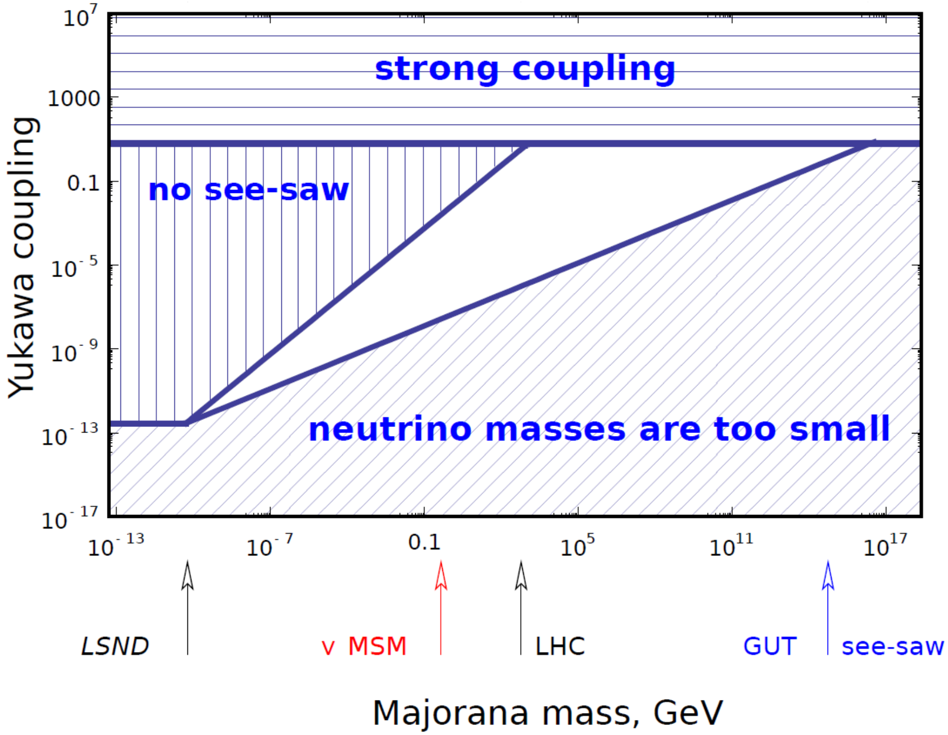
$$m_\nu = \frac{m_D^2}{M}$$

where $m_D \sim Y_{I\alpha} < \phi >$ *- typical value of the Dirac mass term*

Example:

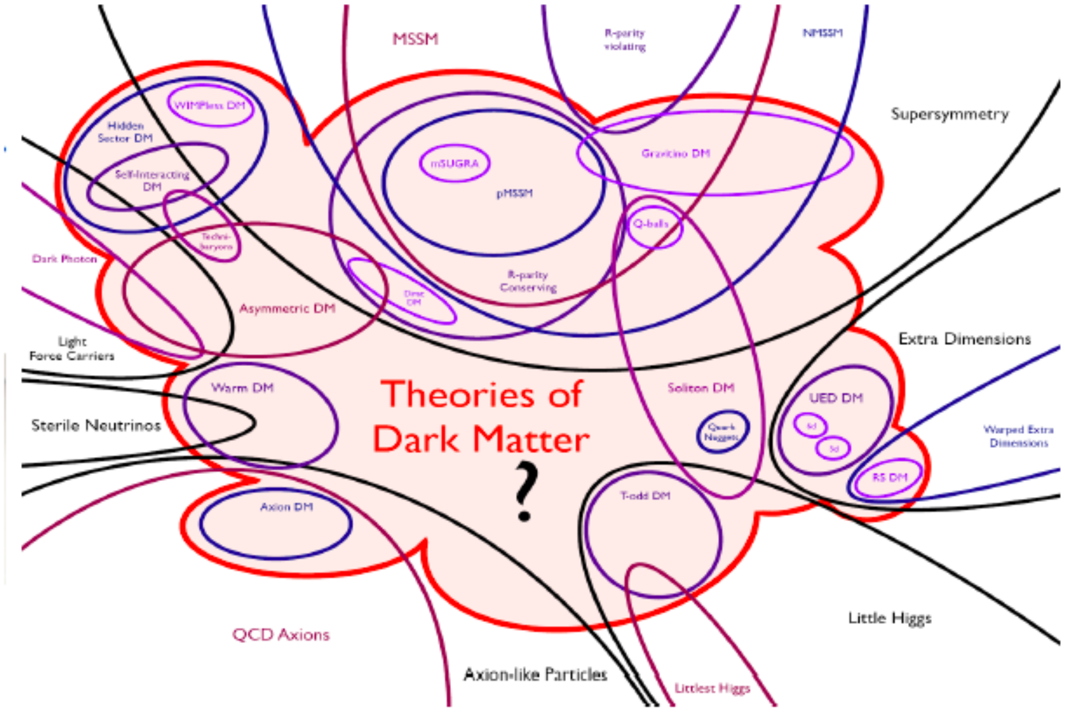
For M ~ 1 GeV and m_ν *~ 0.05 eV it results in* m_D *~ 10 keV and Yukawa coupling ~* 10^{-7}

Smallness of the neutrino mass hints either on very large M or very small $Y_{I\alpha}$



Scale of NP: Dark Matter

The energy scale(s) of new physics



T. Tait, DM@LHC '14

The prediction for the mass scale of Dark Matter spans from 10^{-22} eV (ALPs) to 10^{20} GeV (Wimpzillas, Q-balls)

BSM theories with a new energy scale

(which may also contain "light" particles)

GUT → *(SM particles)* ~ 10^{16} GeV

SUSY → *(sgoldstinos from SUSY breaking, with couplings ~1/F)* ?

Composite Higgs → *(Higgs)* ?

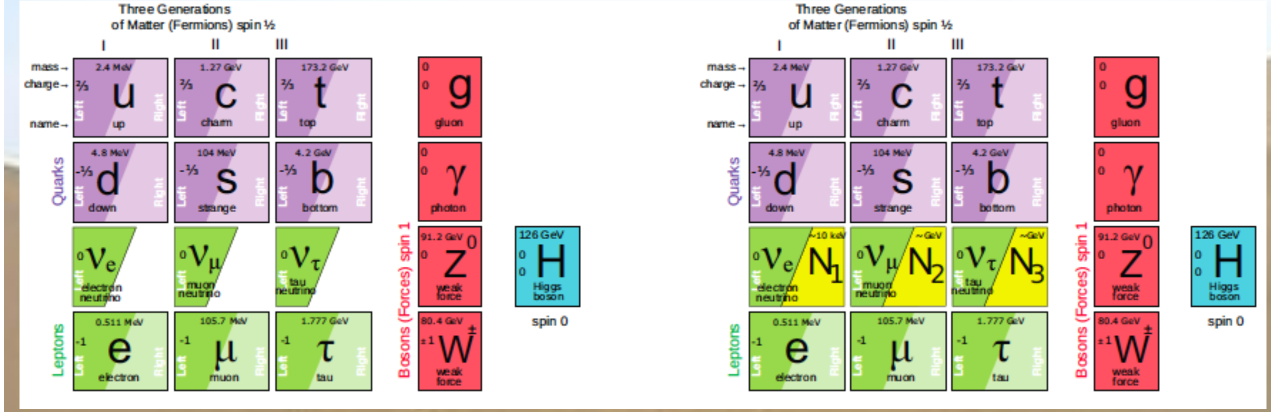
Large extra dimensions → *(Branons)* ?

Peccei-Quinn symmetry → *(Axions)* 10^9-10^{12} GeV

Models with Hidden Sector → *(Various messengers: dark photons, scalars, ALPs)* ?

So, there is always a good reason to increase the energy (even $\sqrt{s} > 14$ TeV) and intensity, even if the scale of NP happens to be inaccessible directly. LHC is also one of the best machines at the Intensity Frontier !

BSM theories with no NP between Fermi and Planck scales



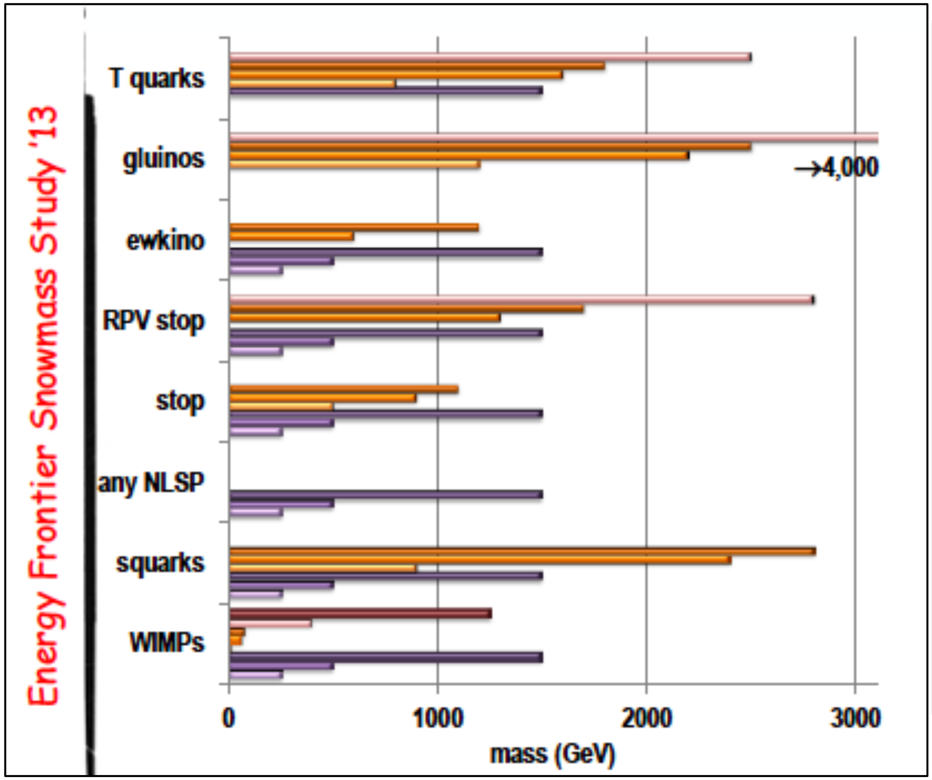
N_1 → Dark Matter

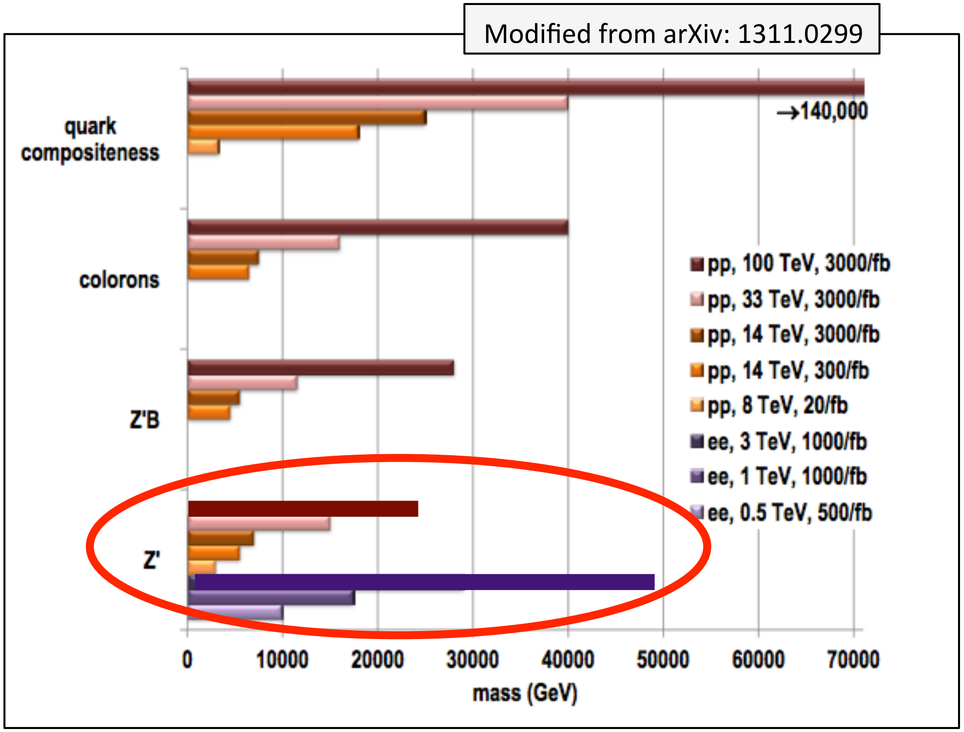
$N_{2,3}$ → Neutrino masses and BAU

νMSM (T.Asaka, M.Shaposhnikov PL B620 (2005) 17) explains all experimental evidences of the BSM physics at once by adding 3 Heavy Neutral Leptons (HNL): N_1, N_2 and N_3

Reach at the Energy Frontier

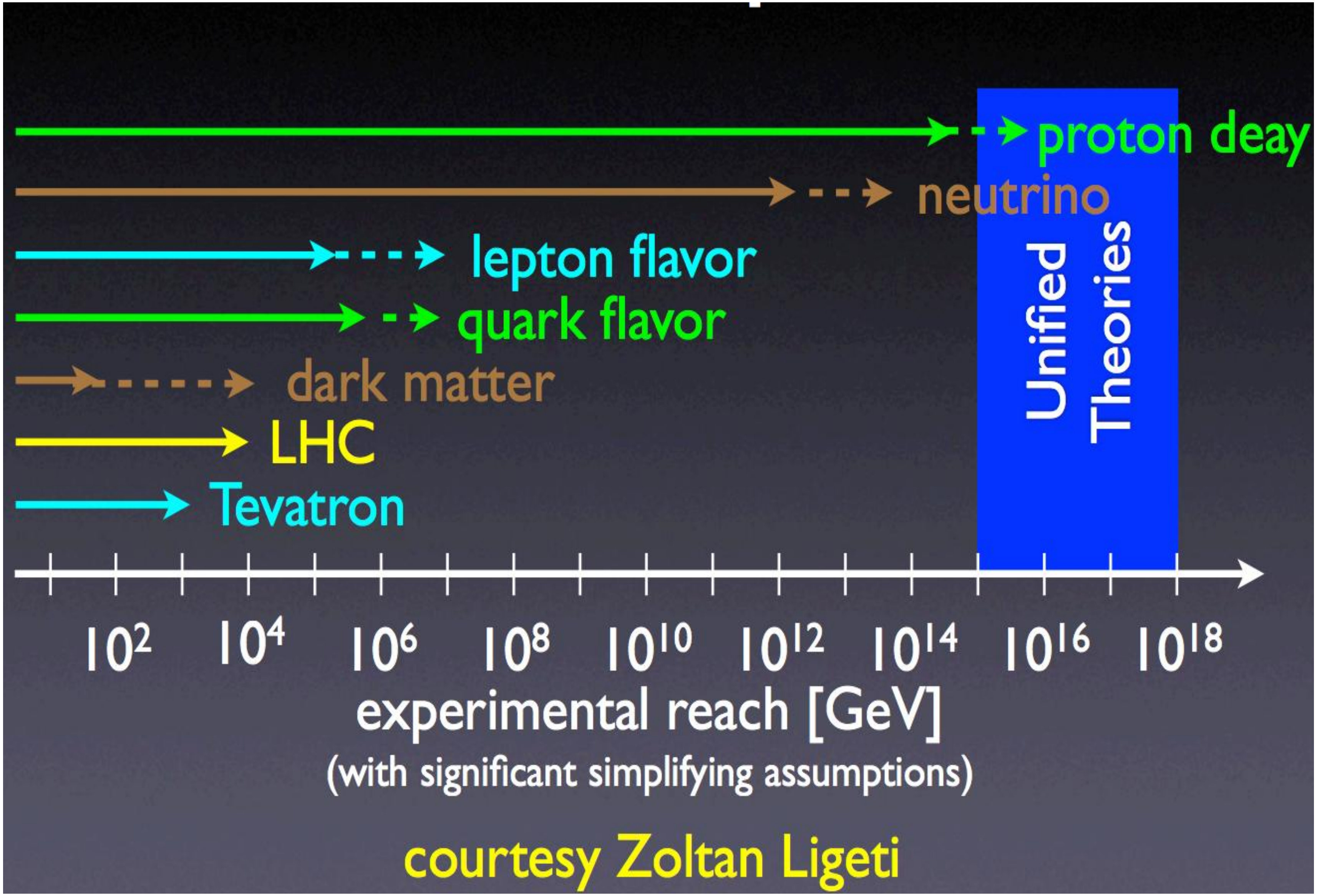
No sign of New Physics yet




Modified from arXiv: 1311.0299

Wait for new LHC data at √s = 13 TeV

Exploration power of the Intensity Frontier



courtesy Zoltan Ligeti

Intensity Frontier: bounds on the NP scale

(Requires assumption on the NP coupling: strong or weak)

Search for processes highly suppressed in SM by certain symmetries

- *LFV in muon and tau decays*
- *FCNC in B/D decays like B→μμ, D→μμ, …*
- *CPV effects in EDM*
- *Proton decay*

Search for departures from the SM predictions in well understood processes

- *(g-2)*
- *CPV phases in flavour decays*
- *Lepton universality in flavour decays*

★★★ large effects

★★ visible but small effects

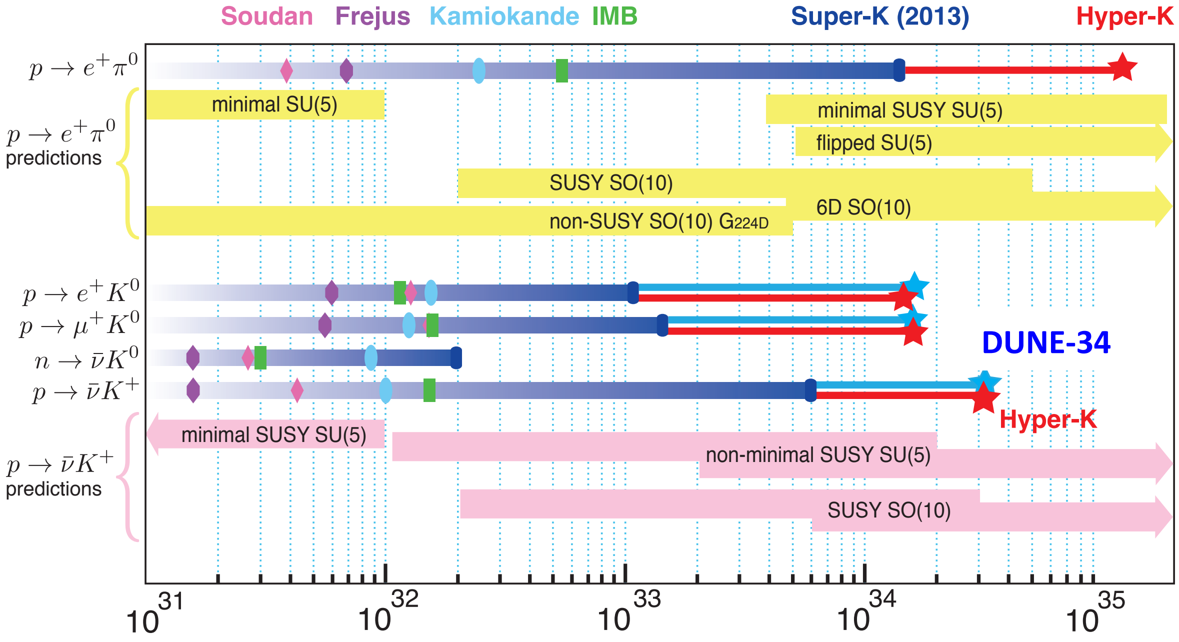
★ unobservable effects

GLOSSARY	
AC [10]	RH currents & U(1) flavor symmetry
RVV2 [11]	SU(3)-flavored MSSM
AKM [12]	RH currents & SU(3) family symmetry
δLL [13]	CKM-like currents
FBMSSM [14]	Flavor-blind MSSSM
LHT [15]	Little Higgs with T Parity
RS [16]	Warped Extra Dimensions

W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi and D.M. Straub

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\mathrm{CP}}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Proton decay(ΔB=1) and n-$\bar{n}$(ΔB=2) oscillations experiments



arXiv 1401.6077v1

Sensitivities of future experiments (560 kT Hyper-K, 34 kT DUNE LArTPC) are at the level predicted for SUSY GUT models

Good tracking capabilities of LArTPC technology
→ less background in final states with kaons

Neutron-antineutron lifetime low limits (90% CL)

Experiment	10^{32} n-yr	$\tau_m(10^{32}$ yr)	$R(10^{23}/\mathrm{s})$	$\tau_{n-\bar{n}}(10^8$ s)
ILL (free-n) [56]	n/a	n/a	n/a	0.86
IMB (^{16}O) [88]	3.0	0.24	1.0	0.88
Kamiokande (^{16}O) [89]	3.0	0.43	1.0	1.2
Frejus (^{56}Fe) [90]	5.0	0.65	1.4	1.2
Soudan-2 (^{56}Fe) [84]	21.9	0.72	1.4	1.3
SNO (^{2}H) [86]	0.54	0.30	0.25	1.96
Super-K (^{16}O) [85]	245	1.89	1.0	2.44^a

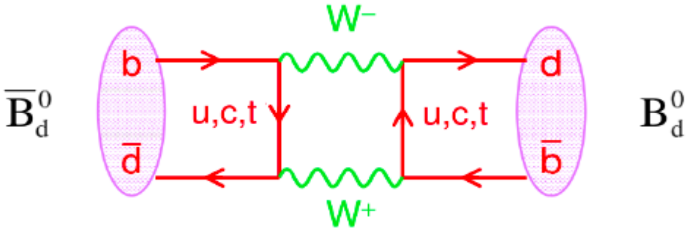
Sensitivity of large underground detectors is limited by significant backgrounds. Study of LArTPC sensitivity ongoing

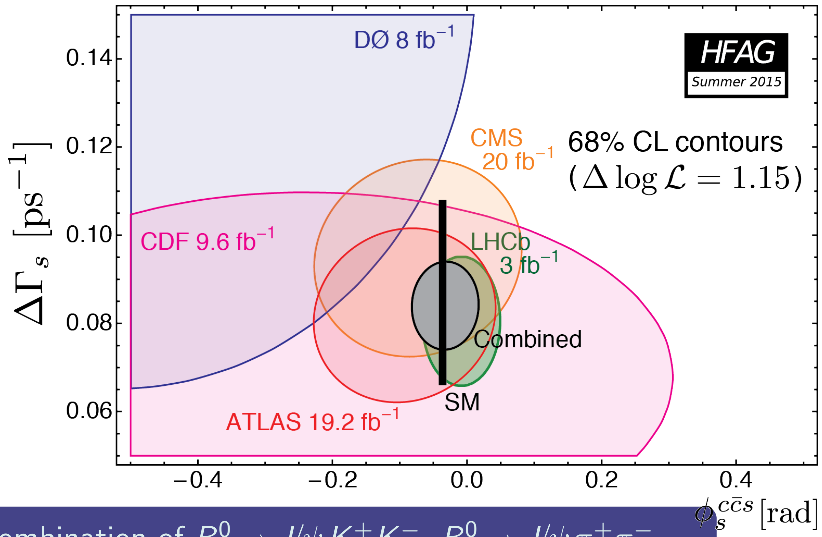
New free neutron decay experiment is being discussed to improve current sensitivity by 2 orders ($\tau_{n\text{-}n}$ ~ 10^{10} s)

arXiv 1410.1100v1

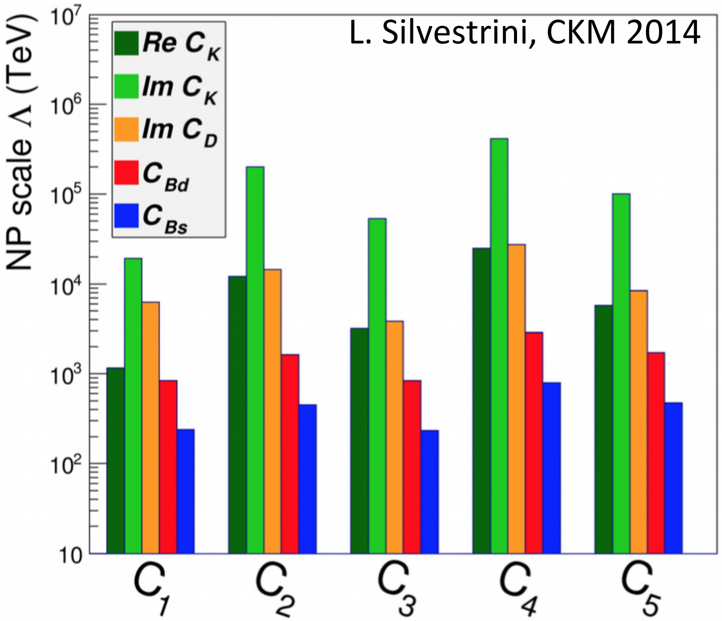
Indirect bounds from Flavour Physics

Most stringent limits come from observables in mixing of neutral mesons





Combination of $B^0_s \to J/\psi K^+K^-$, $B^0_s \to J/\psi \pi^+\pi^-$ and $B^0_s \to D^+_s D^-_s$: $\varphi_s = -0.034 \pm 0.033\,\mathrm{rad}$



$C_i = F_i L_i / \Lambda^2$
F_i – NP flavour coupling
L_i – loop factor
Λ – NP scale

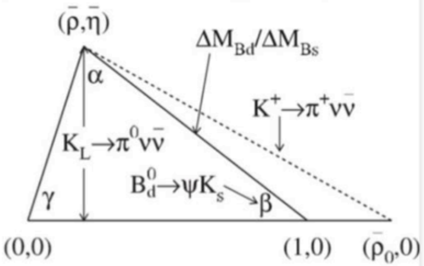
Λ > 10^3 – 10^5 TeV for strongly coupled NP ($F_i\, L_i$ ~ 1)
The best sensitivity in kaon mixing

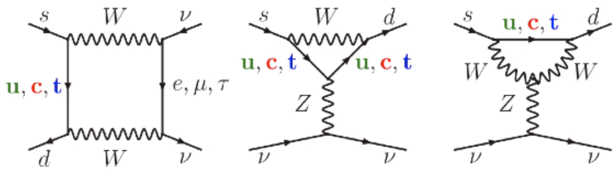
Prospects in kaon physics

Progress is limited by theoretical uncertainties in hadronic channels

Very clean case in $K^+ \rightarrow \pi^+\nu\nu$ and $K^0 \rightarrow \pi^0\nu\nu$ decays:

- *High sensitivity to NP*
- *No hadronic uncertainties*





In SM:

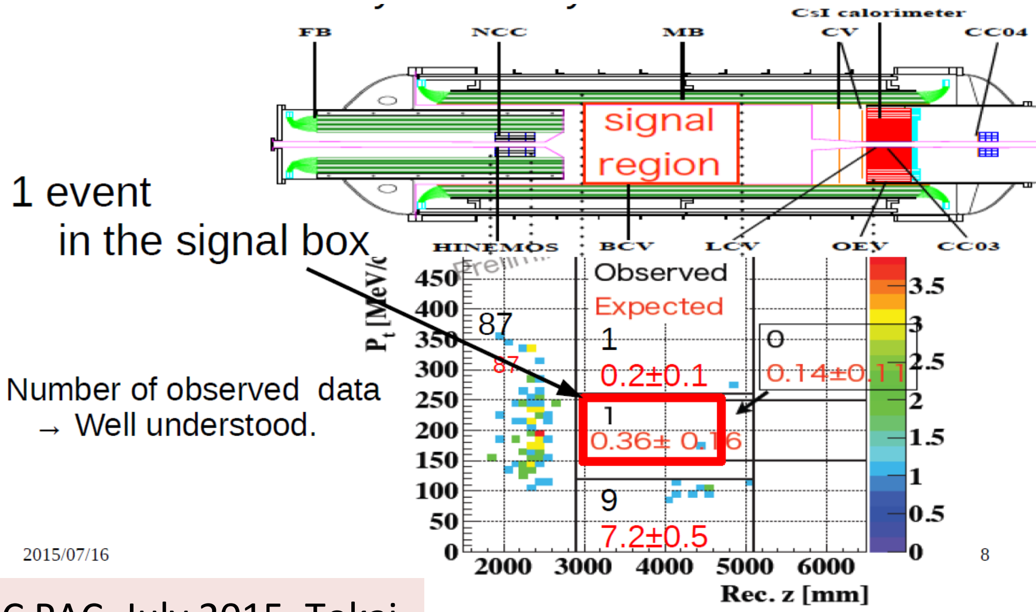
$$BR(K_L \rightarrow \pi^0\nu\nu) = (3.00 \pm 0.30)\times 10^{-11}$$

$$BR(K \rightarrow \pi^+\nu\nu) = (9.11 \pm 0.72)\times 10^{-11}$$

[A.J. Buras, D. Buttazzo, J. Girrbach-Noe and R.Knegjens, arXiv:1503.02693]

KOTO (J-PARC) *(successor of E391a)*

- *E391a sensitivity: 1.29×10^{-8}*
- *1st Physics Run in May 2013*
- *Upgrade to reduce background*
- *Resumed data taking in June 2015, sensitivity approaches GN limit (10^{-9}) Goal to reach SM (10^{-11})*



1 event
in the signal box

Number of observed data
→ Well understood.

2015/07/16

8

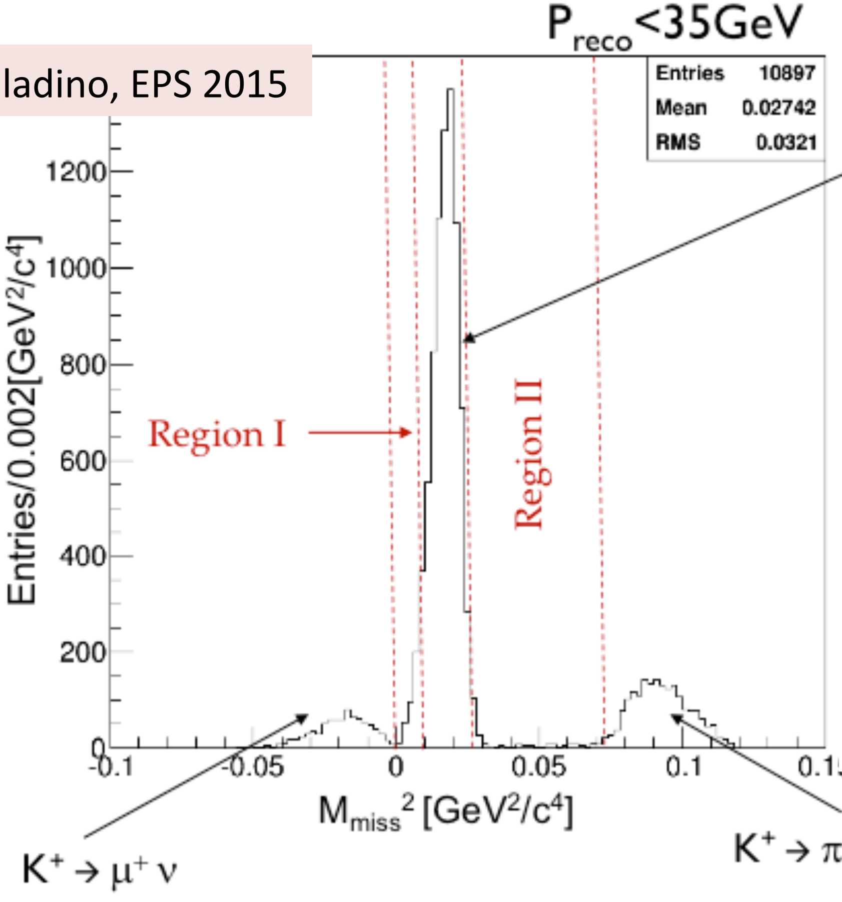
Nanjo-san, J-PARC PAC, July 2015, Tokai

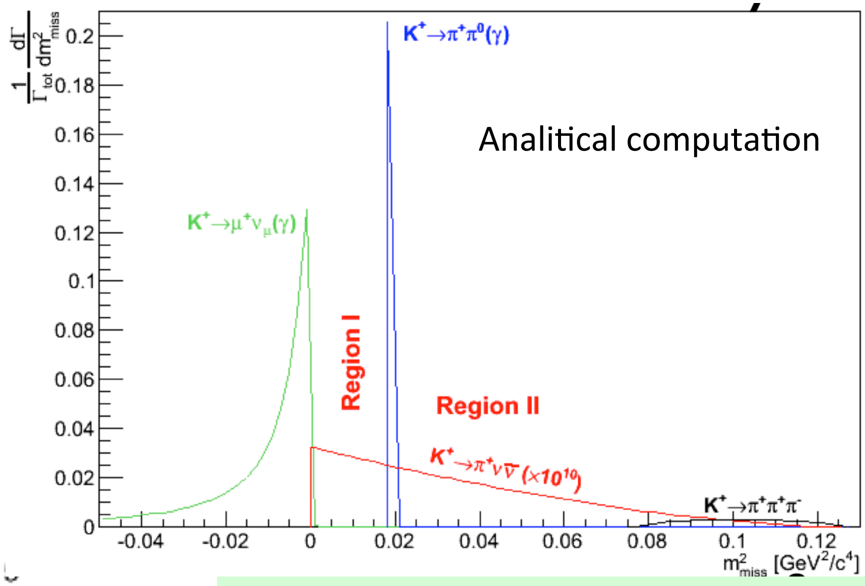
Prospects in kaon physics

First Physics Run started

- *Events with a single track in the spectrometer reconstructed (40 ns)*
- *10^2 muon rejection at trigger level*

V. Palladino, EPS 2015



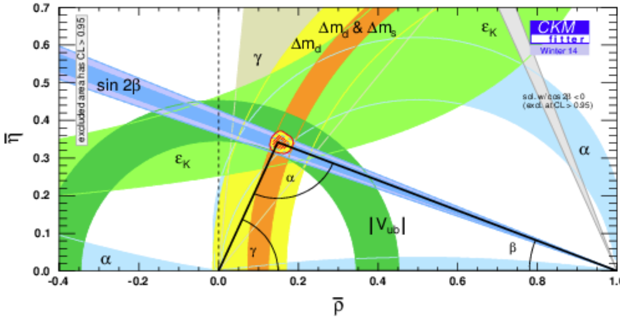


Goal to collect 100 SM events in ~2 years

Selected prospects in Charm & Beauty

✓ **Clarify current hints for BSM physics (LFU in $R_{K,}$ $R_{D^*,}$ P'_5 in $B \to K^*\mu\mu$, …)**

See talk by Диего Мартинес Сантос)



✓ **CP Violation in $B_s \to \phi\phi$**
LHCb upgrade will improve accuracy to 0.02
(theory uncertainty ~ 0.003)

✓ **Unitarity Triangle sides and angles**
Currently largest uncertainties in $|V_{ub}/V_{cb}|$ and the angle γ
V_{ub} will be possible at a few % with Belle II (and LHCb upgrade)
(requires progress in theory !)
The stat. reach in γ is expected at 1°(LHCb upgrade) to 2°(Belle II)

✓ ***$Br(B^0 \to \mu\mu)/Br(B_s \to \mu\mu)$** should be possible at 25% with the CMS (and LHCb) upgrades*
Theory uncertainty is 5%
- ***Dedicated flavour experiment at HL LHC to improve experimental accuracy***
Also useful for many other observables in flavour physics

✓ *Belle II will measure **$Br(B \to K^{*+}/K^+$** $\nu\nu$) at 0.2×10^{-6}*

✓ **Charm CPV & mixing**
LHCb upgrade will measure ΔA_{CP} at 0.12×10^{-3} and A_Γ at 0.5×10^{-4}

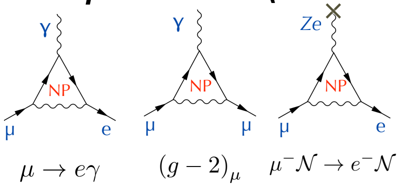
Well secured and healthy future extending into the HL LHC era !

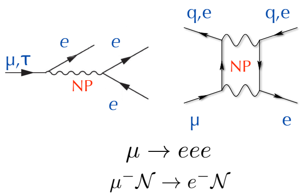
Charged Lepton Flavour Violation (CLFV)

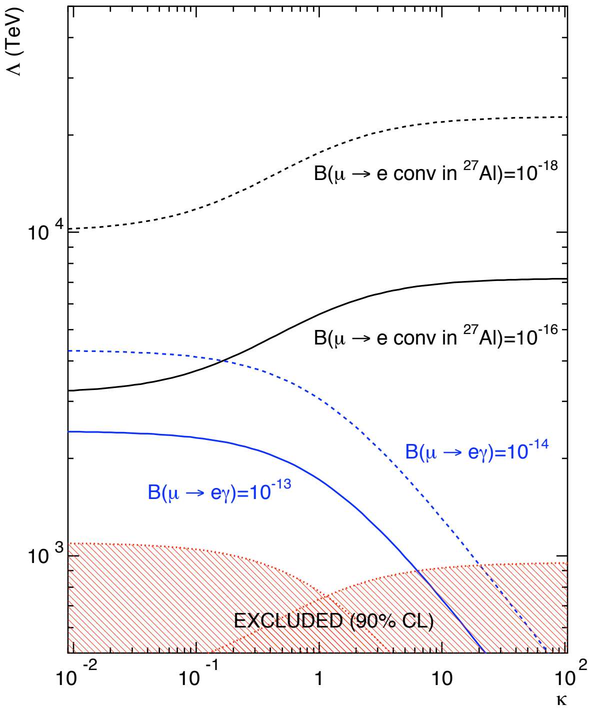
(muon decays & conversion)

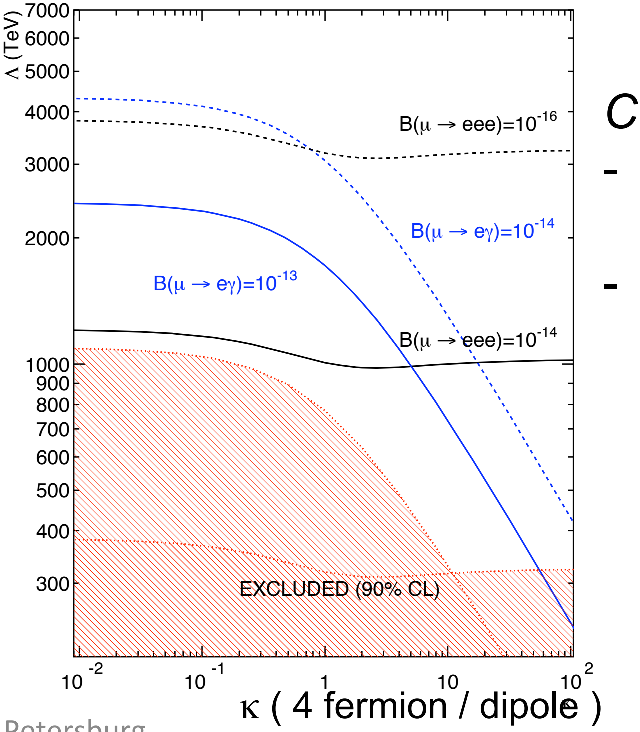
- ✓ Expect big step forward in the next few years (MEG and MEG-II @ PSI, proposed Mu3e search @ PSI, new searches for μ – e conversion with Mu2e @ Fermilab and COMET @ J-PARC)
- ✓ SM contribution is negligible (@ 10^{-52} level for $\mu \rightarrow e\gamma$)
- ✓ Described by dipole amplitudes (dim. 5) operators and four-fermion (dim. 6) operators

from Gouvea and Vogel, arXiv:1303.4097









Constraints dominated the

- Dipole type operators for k << 1
- Four-fermion operators for k >> 1

Different searches are needed to explore the whole parameter space

Comparison of muon LFV experiments and prospects

μ → eγ	**μ → eee**	**μ – e conversion**
Background: *accidentals, radiative decays* **Continuous beam**	**Background:** *accidentals and radiative decays with internal conversion* **Continuous beam**	**Background:** *cosmics, beam related π, muon decays in orbit, low energy (n,p) noise* **Pulsed beam**

✓ *Currently best limits*

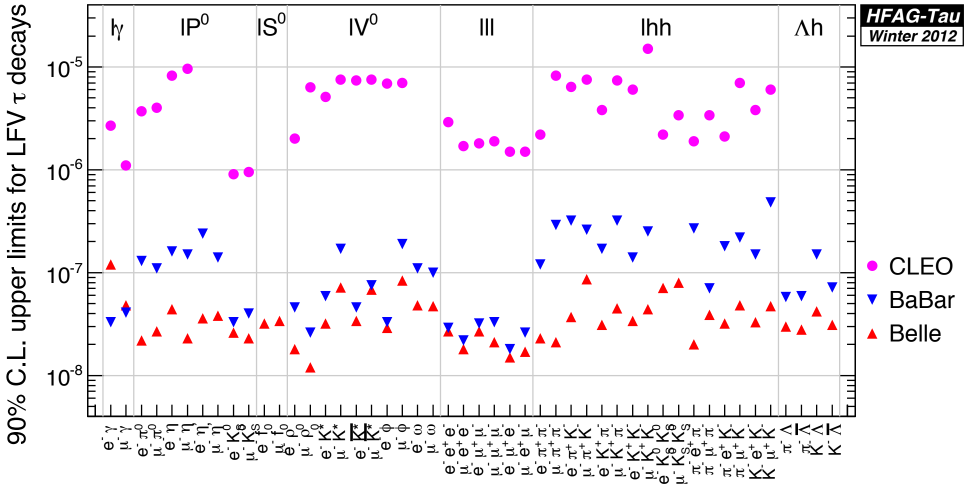
μ → eγ	**μ → eee**	**μ – e conversion**
5.7×10^{-13} MEG 2013	1×10^{-12} SINDRUM I 1988	7×10^{-13} SINDRUM II 2006

✓ *Future prospects of next generation experiments*

μ → eγ	**μ → eee**	**μ – e conversion**
O(10^{-14}) MEG ~2017	O(10^{-15}) Mu3e ~2017 O(10^{-16}) Mu3e >2017	O(10^{-17}) COMET ~2020 O(10^{-17}) Mu2e ~2020 O(10^{-18}) PRISM > 2020

Future LFV experiments will probe NP at Λ ~ O(10^4 TeV)

CLFV in τ decays



✓ *So far the best limits achieved at B-factories (with ~10^9 τ leptons):*
$Br(\tau \rightarrow \mu\gamma) < 1.4\times10^{-8}$ @ 90%C.L.
$Br(\tau \rightarrow \mu\mu\mu) < 2.1\times10^{-8}$ @ 90% C.L.
Nearly background free analyses !

✓ ***Will be improved down to few×10^{-9} – 10^{-10} @ Belle II***

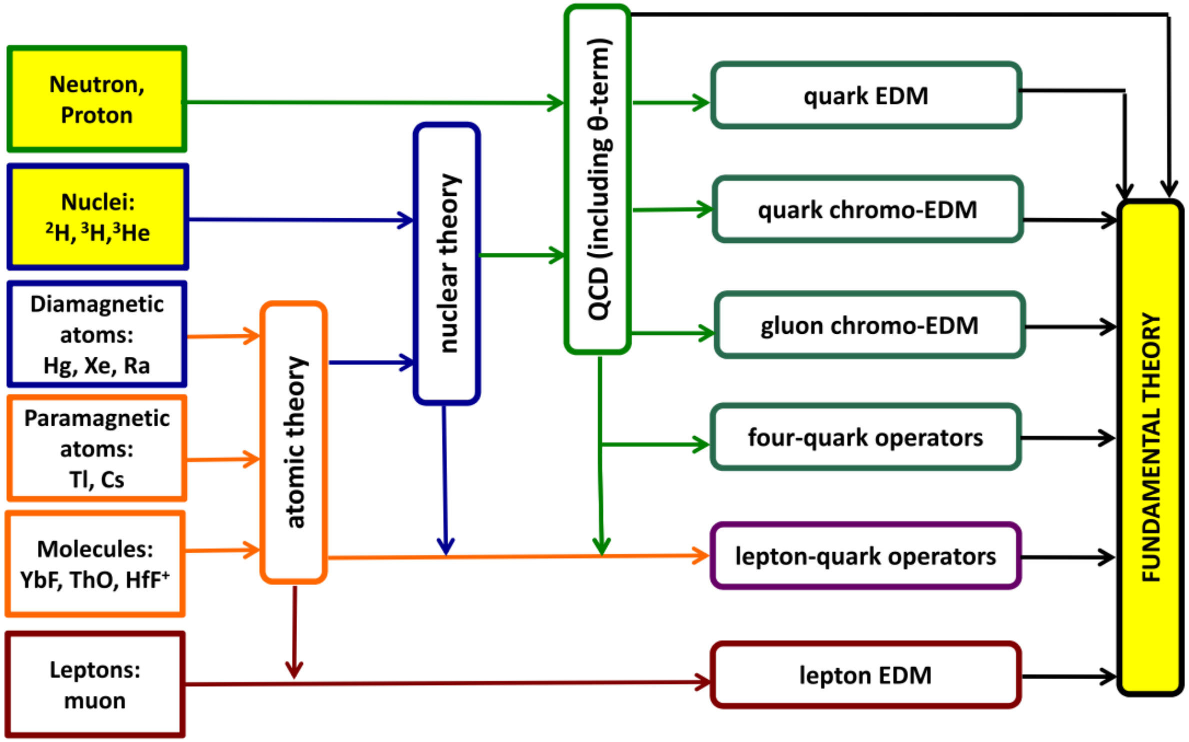
✓ *τ leptons are copiously produced in HE pp-collisions, mainly in $D_s \rightarrow \tau\nu_\tau$ decays LHCb reached similar sensitivity for $Br(\tau \rightarrow \mu\mu\mu)$ with 3fb^{-1} (~10^{11} τ leptons) in presence of non zero backgrounds, in particular from $D_s \rightarrow \eta\mu\nu$ with $\eta \rightarrow \mu\mu$*
LHCb: $Br(\tau \rightarrow \mu\mu\mu) < 4.6\times10^{-8}$ @ 90% C.L.

✓ ***Good possibilities for improvement at LHCb upgrade (50 fb^{-1}) and even better at dedicated flavour experiment running at HL LHC (~10^6 τ per sec.) Expect $Br(\tau \rightarrow \mu\mu\mu) < 10^{-10}$, or even 10^{-11} depending on how background scales.***

✓ *Very interesting sensitivity, ~10^{-10}, can also be reached at the fixed target facility (SHiP) being discussed at the SPS at CERN*

Electric Dipole Moments (EDM)

EDM introduces new CP-odd sources
*(required for new CPV physics, strong CP problem)**:***



Neutron, Proton

Nuclei: ^2H, ^3H, ^3He

Diamagnetic atoms: Hg, Xe, Ra

Paramagnetic atoms: Tl, Cs

Molecules: YbF, ThO, HfF$^+$

Leptons: muon

atomic theory

nuclear theory

QCD (including θ-term)

quark EDM

quark chromo-EDM

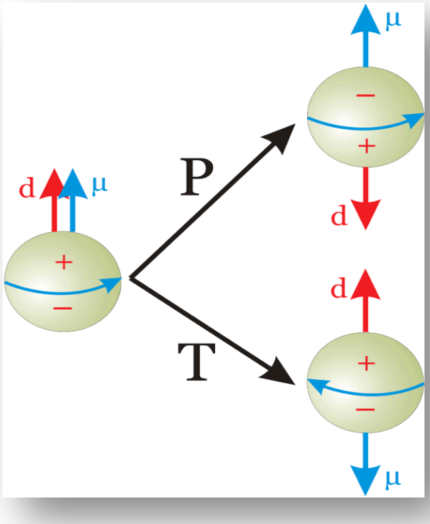
gluon chromo-EDM

four-quark operators

lepton-quark operators

lepton EDM

FUNDAMENTAL THEORY



Jordy de Vries, 2012

- *SM contribution to quark, lepton EDM is tiny*
- *Long distance effects dominate in atoms and molecules, but still few orders of magnitude below experimental sensitivity*

EDM is very sensitive probe of CP Violation. Any EDM observed in currently running or planned experiments → BSM physics or CPV in strong interaction

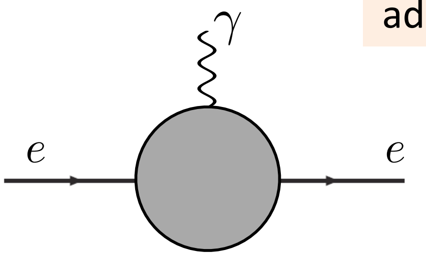
Electric Dipole Moments

So far, most sensitive EDM searches on electron, nuclei and neutron

Best limits for nucleons (n, p), leptons (e, μ), diamagnetic atom (^{199}Hg), paramagnetic atom (^{205}Tl) and molecules (YbF, ThO) (Hans Stroher, EPS HEP 2015):

	Upper Limit	*Comment*
n	*2.9×10^{-26} 90% CL*	
μ	*1.9×10^{-19} 95% CL*	
Atoms: *Dia – ^{199}Hg* *Para– ^{205}Tl*	*3.1×10^{-29} 95% CL* *9×10^{-25} 90% CL*	***$d_p < 8\times10^{-25}$*** *(indirect)* *$d_e < 1.6\times10^{-27}$ (indirect)*
Molecules: *YbF* *ThO (ACME)*	*1.1×10^{-22} 90% CL*	*$d_e < 1.05\times10^{-27}$ (indirect)* ***$d_e<8.7\times10^{-29}$ 90% CL*** *(indirect)* *Factor 10 improvement in next 10 years*

Electron EDM



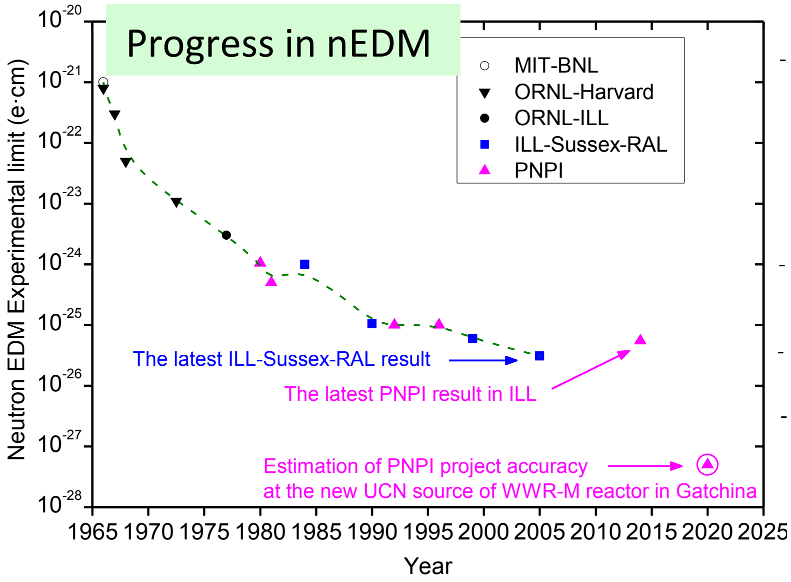
adopted from B.Batell, FCC working group

$$d_e = c_W \times \sin\phi \times vev / \Lambda^2$$

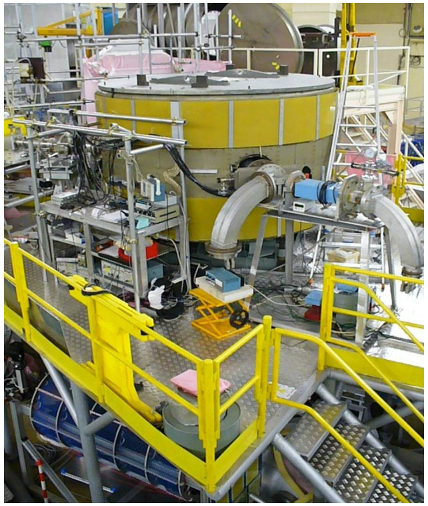
$$\sim \underbrace{8.7\times10^{-29}\,\mathrm{e\,cm}}_{\text{ACME limit}} \times \sin\phi \left(\underbrace{\frac{4\times10^{5}\,\mathrm{TeV}}{\Lambda}}_{\text{New physics scale}}\right)^{2}$$

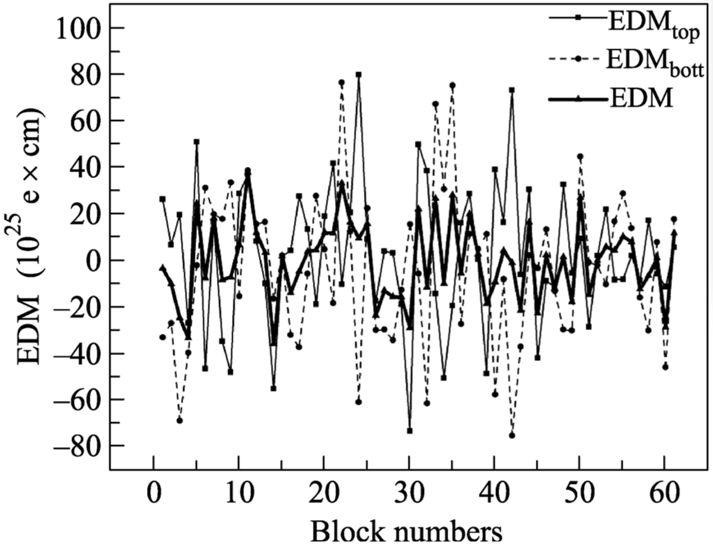
Neutron EDM

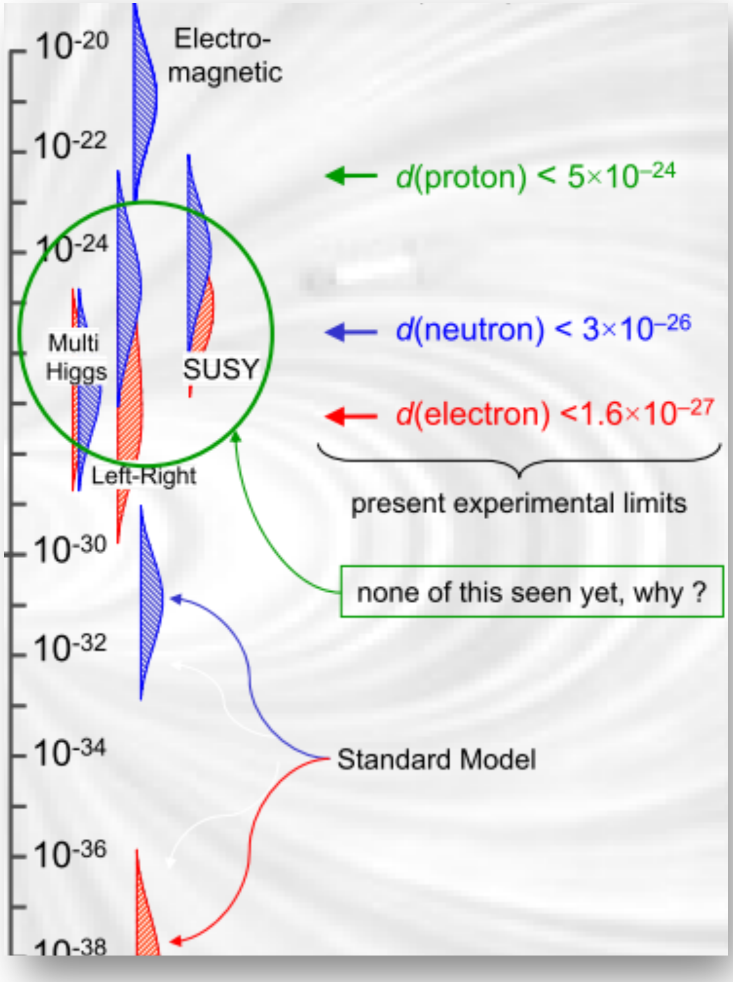
Serebrov et al., arXiv 1408.6430



PNPI double-chamber EDM spectrometer at ILL







SUSY is not natural any longer

Electric Dipole Moments

(future prospects)

- ✓ *Ongoing and future experiments on **nEDM** use Ultra Cold Neutrons (UCN)*
- ✓ *Future goal to reach sensitivity few×10^{-28} e cm (experiments at reactors & spallation sources)*
- ✓ *New ideas to measure EDM of proton, and deuteron, at the storage ring experiments. Sensitive to combination of CPV parameters that differ from nEDM.*

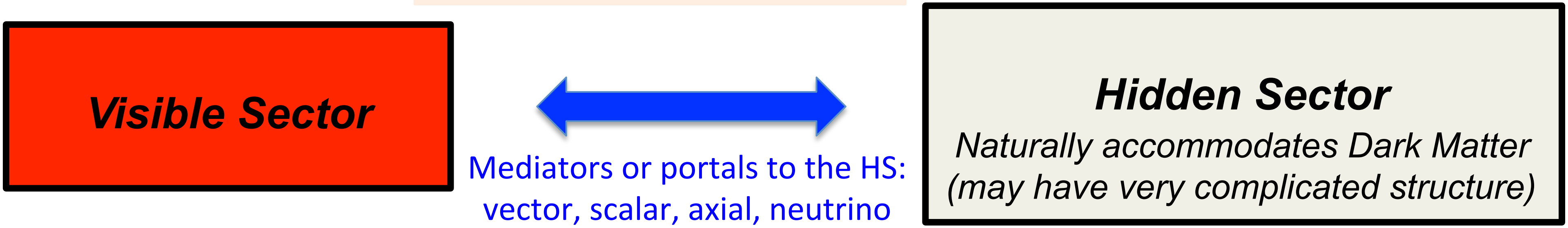
  - *Stat. reach 10^{-29} e cm*
  - *Control of systematics (long spin coherence time, efficient polarimetry, large electric fields, …) to be proven !*

COSY FZJ, Julich provides very good starting point (JEDI collaboration)

Cooler Synchrotron COSY

Search for Hidden Sector (HS)

$$L = L_{SM} + L_{mediator} + L_{HS}$$



Visible Sector

Mediators or portals to the HS:
vector, scalar, axial, neutrino

Hidden Sector

Naturally accommodates Dark Matter
(may have very complicated structure)

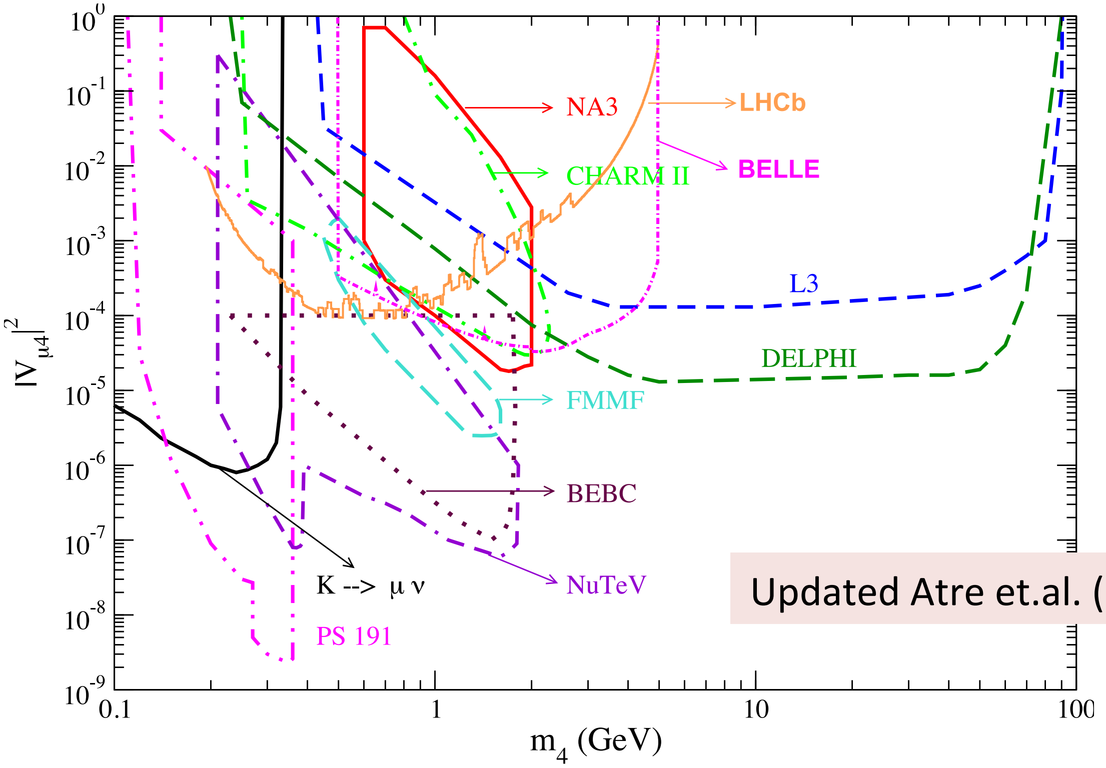
- ✓ *HS production and decay rates are strongly suppressed relative to SM*
  - *Production branching ratios O(10^{-10})*
  - *Long-lived objects*
  - *Travel unperturbed through ordinary matter*

Models	*Final states*
HNL, SUSY neutralino	$l^+\pi^-$, l^+K^-, $l^+\rho^-$ $\rho^+\rightarrow\pi^+\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	l^+l^-
HNL, SUSY neutralino, axino	$l^+l^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

Full reconstruction and PID are essential to minimize model dependence

Experimental challenge is background suppression
→ requires O(0.01) carefully estimated

Experimental and cosmological constraints on HNLs

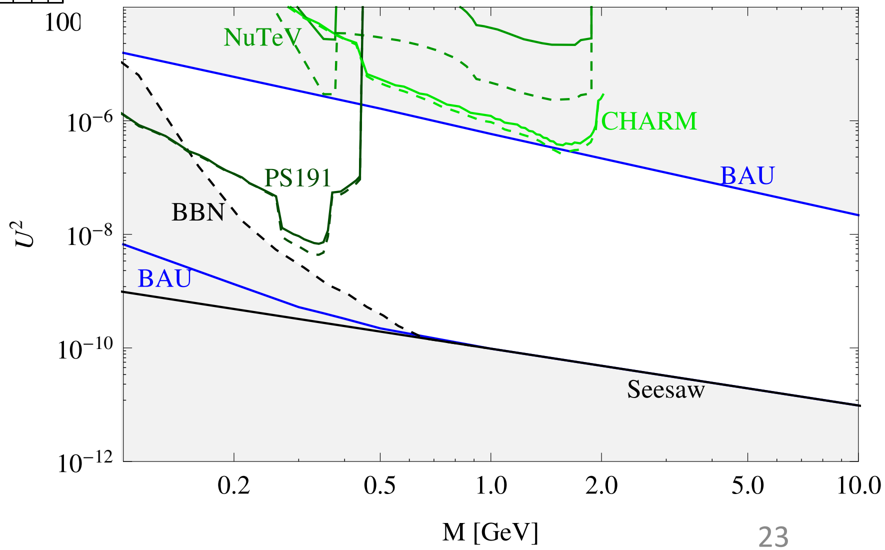


Updated Atre et.al. (0901.3589)

- ✓ *Coupling to active neutrinos*
  $U^2 = U_e^2+U_\mu^2+U_\tau^2$ ($V_{\mu 4}^2 = U_\mu^2$)
- ✓ *Stringent constraints on light HNLs below kaon mass*
- ✓ *The mass range above charm is relatively poor explored*

- ✓ ***Recent progress in cosmology***

- ✓ *The sensitivity of previous experiments did not probe the interesting region for HNL masses above the kaon mass*



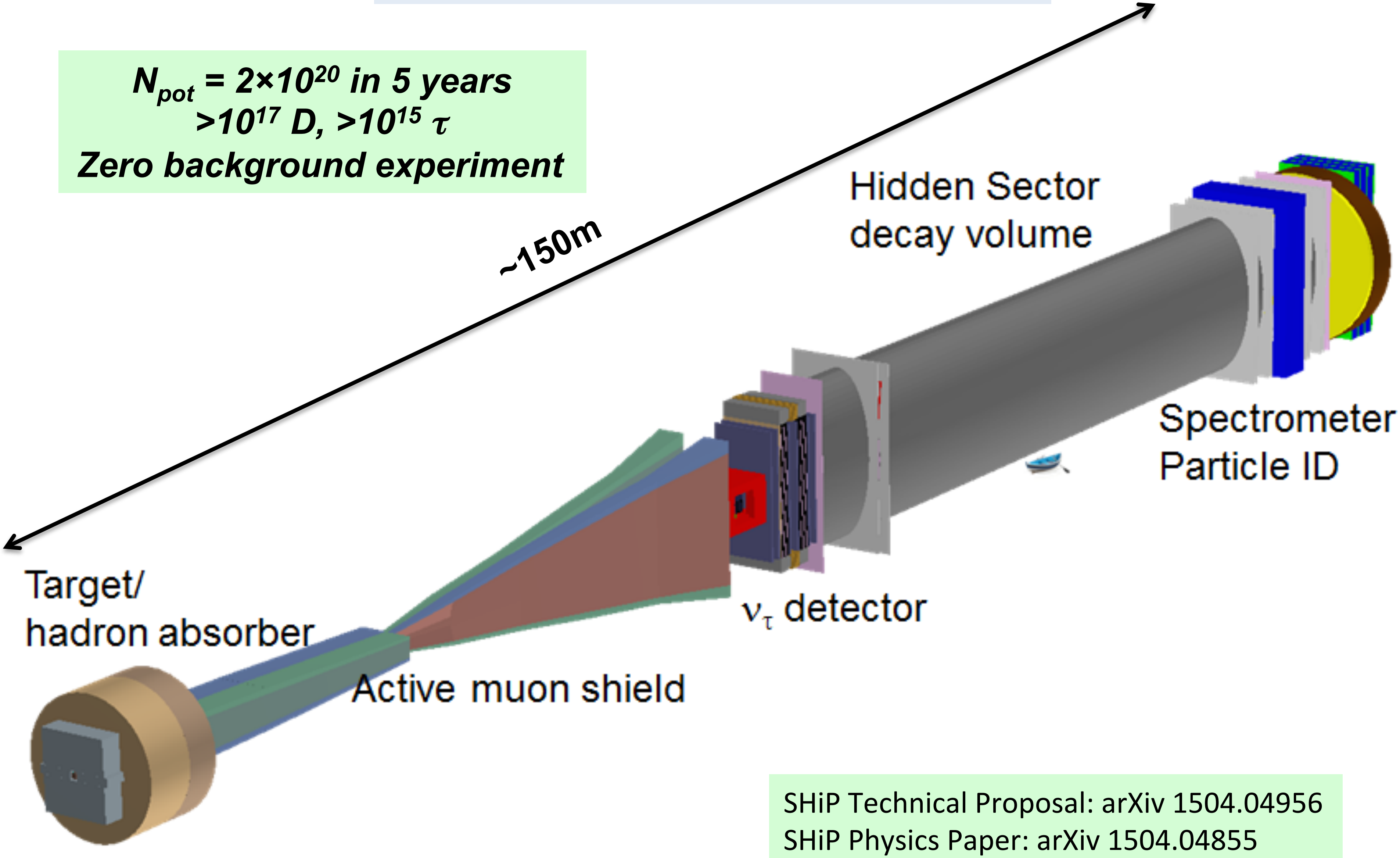
The SHiP experiment at SPS

(as implemented in Geant4)

N_{pot} = $2×10^{20}$ in 5 years

$>10^{17}$ D, $>10^{15}$ τ

Zero background experiment

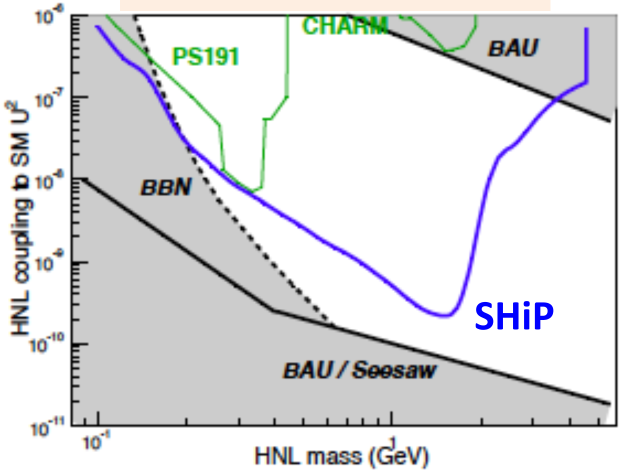


SHiP Technical Proposal: arXiv 1504.04956
SHiP Physics Paper: arXiv 1504.04855

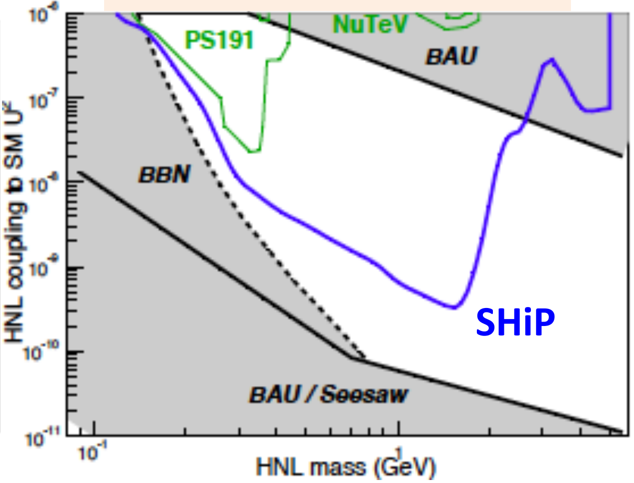
SHiP sensitivity to HNLs for representative scenarios

- ✓ *BAU constraint is model-dependent (shown below for νMSM)*
- ✓ *Seesaw limit is not*

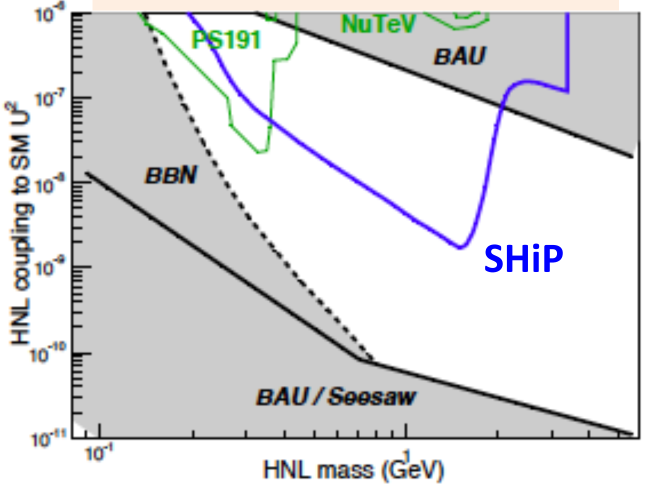
U^2_e: U^2_μ: U^2_τ~52:1:1
Inverted hierarchy



U^2_e: U^2_μ: U^2_τ~1:16:3.8
Normal hierarchy



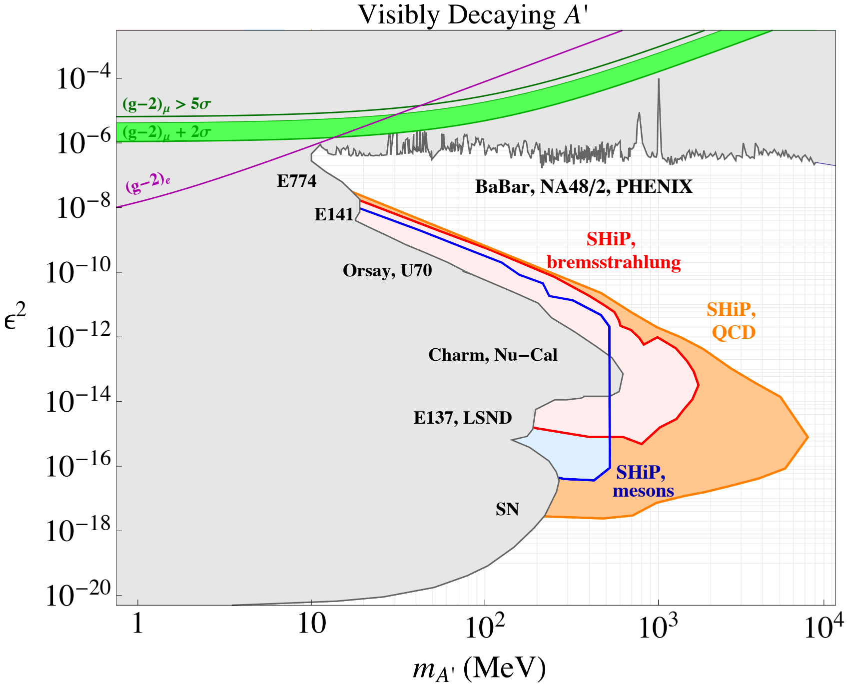
U^2_e: U^2_μ: U^2_τ~0.061:1:4.3
Normal hierarchy

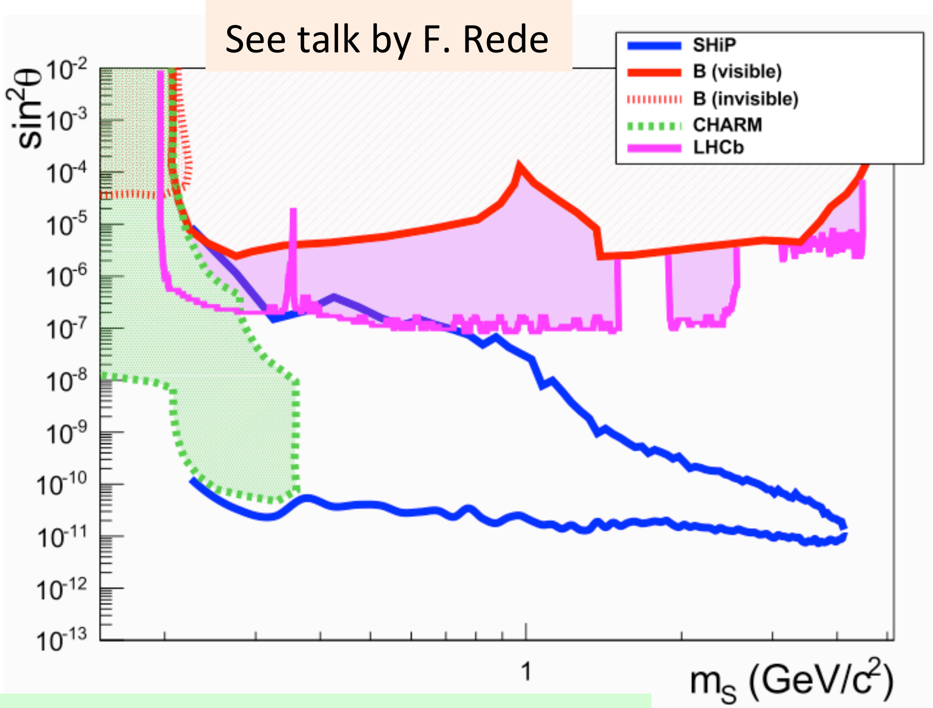


SHiP sensitivity covers large area of parameter space below the B mass
Moving down towards the ultimate see-saw limit

SHiP sensitivity to dark photons and hidden scalars

- ✓ ***Dark photons*** *→ U(1) associated particle* ***A' (γ')*** *in HS that can have non-zero mass and mix with the SM photon with ε*
  Produced in QCD processes or in decays of $\pi^0 \to \gamma'\gamma$, $\eta \to \gamma'\gamma$, $\omega \to \gamma'\pi^0$ and $\eta' \to \gamma'\gamma$
- ✓ ***Hidden scalars, S,*** *can mix with the SM Higgs with with $\sin^2\Theta$*
  Mostly produced in penguin-type decays of B and K decays
- ✓ ***Decay*** *into a pair of SM particles into e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^+$, KK, ηη, ττ, DD, …*

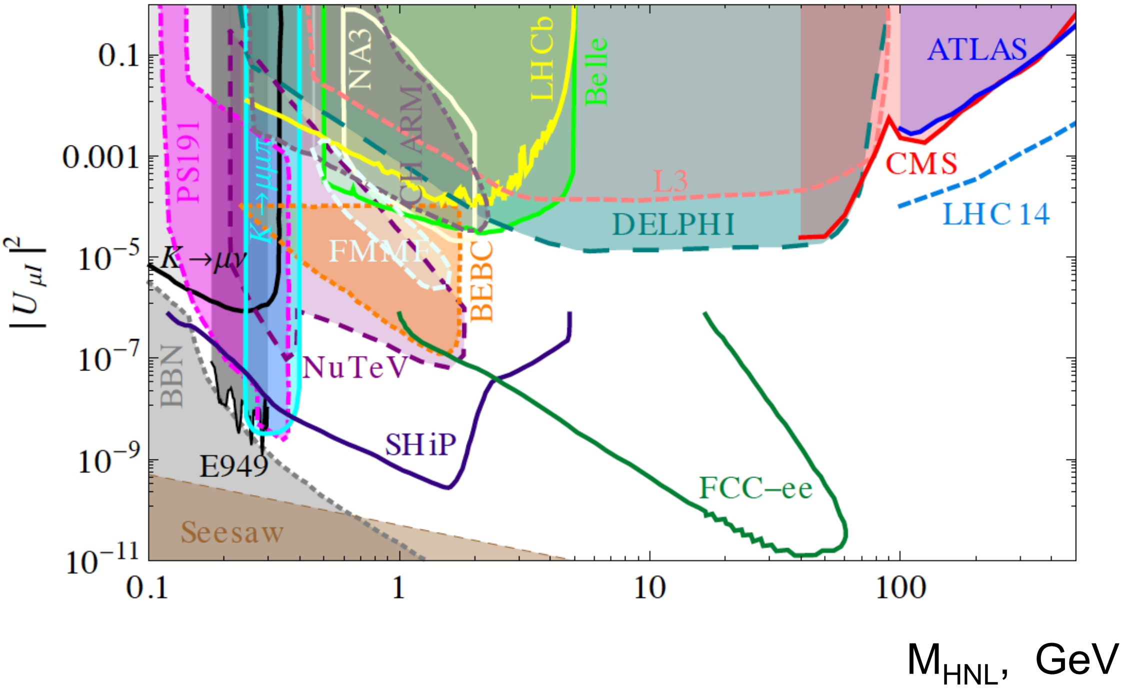



See talk by F. Rede

SHiP probes unique range of couplings and masses

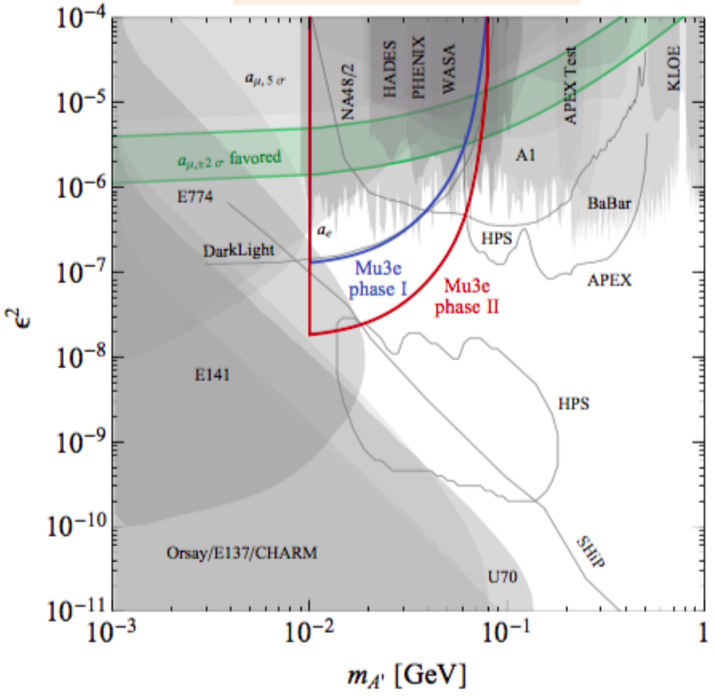
Hidden Sector experimental constraints in future

HNL



- ✓ $M_{HNL} < M_b$ LHCb, BelleII
  SHiP will have much better sensitivity
- ✓ $M_b < M_{HNL} < M_Z$ FCC in ee mode
- ✓ $M_{HNL} > M_Z$ Prerogative of ATLAS/CMS @ HL LHC

Dark photon



- ✓ SHiP will have unique sensitivity for “heavy” dark photons
- ✓ HPS is expected to cover new range of ε^2 in a couple of years

Summary

- ✓ *The message from Intensity Frontier:*
  The scale of strongly coupled NP (Λ > 10^3 TeV) is above direct reach

- ✓ *Multi-range in Intensity Frontier programme all over the world*
  Expect the major improvements and new results in:
  - *Neutrino physics*
  - *Proton decay experiments*
  - *Flavour physics*
  - *Searches for LFV in the muon and tau sectors*
  - *EDMs*

- ✓ *CERN is very well positioned to make a unique contribution, particularly in*
  - *- Flavour physics with LHCb and NA62,*
    and later with dedicated flavour experiment @ High Lumi LHC

  - *- Searches for Hidden Sector portals and HNLs*
    at the SHiP facility @ SPS and @ FCC in ee mode