SHIP:

Search for HIdden Particles

A new experiment proposal at CERN

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http://ship.web.cern.ch/ship/

What is SHIP

SHIP is a proposal for a beam dump experiment at CERN/SPS (400GeV p)

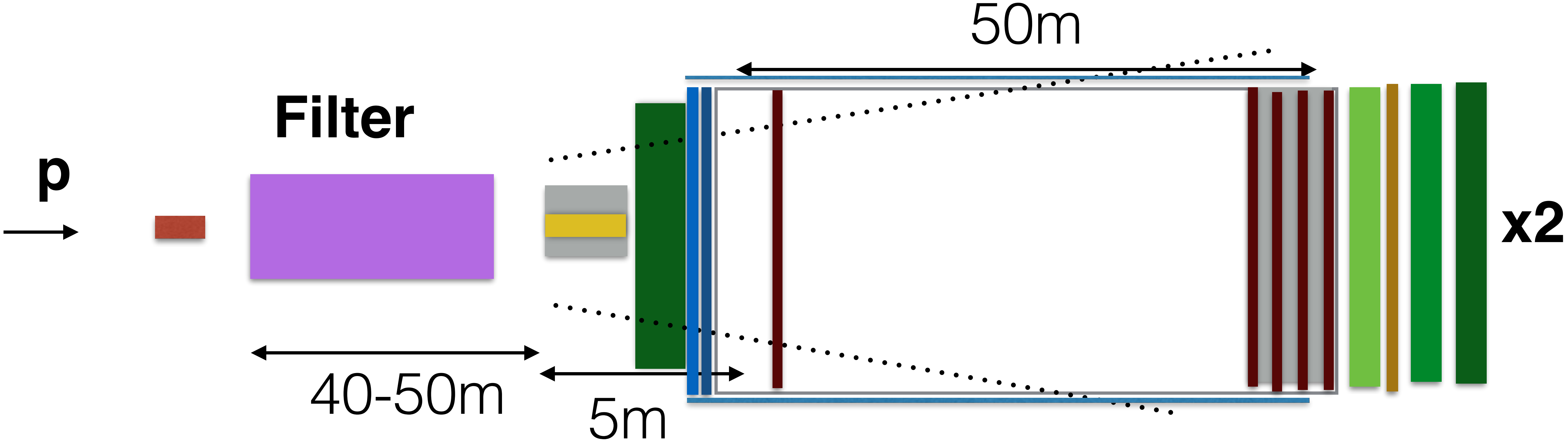
Main goals (so far…):

1) detection of long lived particles, very weakly interacting or sterile: statistical sensitivity with respect to previous experiments of similar type x10000 (this is the first dedicated experiment ever!)

—> this allows to explore NEW TERRITORIES previously unexplored. Many theories and models on the market (models of DM, SUSY, theories providing explanation for ν masses and baryogenesis,…) have some sensitivity region to be explored with SHIP!

2) textbook measurements of ν_τ interactions with statistical sensitivity with respect to previous experiments of similar type x200

How?



The highest E/I proton beam of the world…

…dumped and followed by the closest, longest and widest possible and technically feasible decay tunnel

Physics

What survives the dump?

D and B mesons, π^0's, a tiny fraction of π^+,K decay before absorption

—> $\nu(e,\mu,\tau)$ +

all sterile particles (NP) that mix with $\nu(e,\mu,\tau)$, π^0 and γ or that are produced in B decay or by the proton-proton interaction

Final states in the decay tunnel:

vertexes with or without missing energy :

e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, $\pi^+\mu^-$, π^+e^-, $\rho^+\mu^-$, ρ^+e^-

All we observe in the decay tunnel is signal

What physics are we looking for? What are the models that we can probe?

What is their relevance for HEP?

Shaking hands…

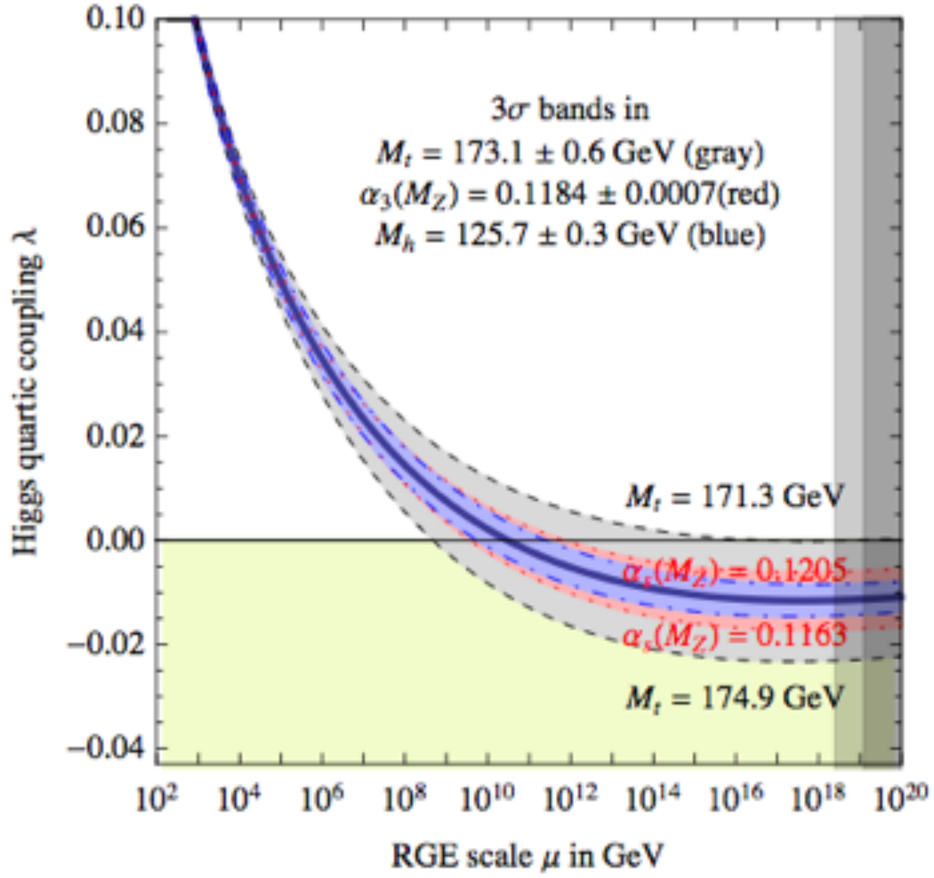
SM was recently fully confirmed by the Higgs-boson discovery!

However…

However: no NP anywhere! Also, naturalness is now severely challenged.

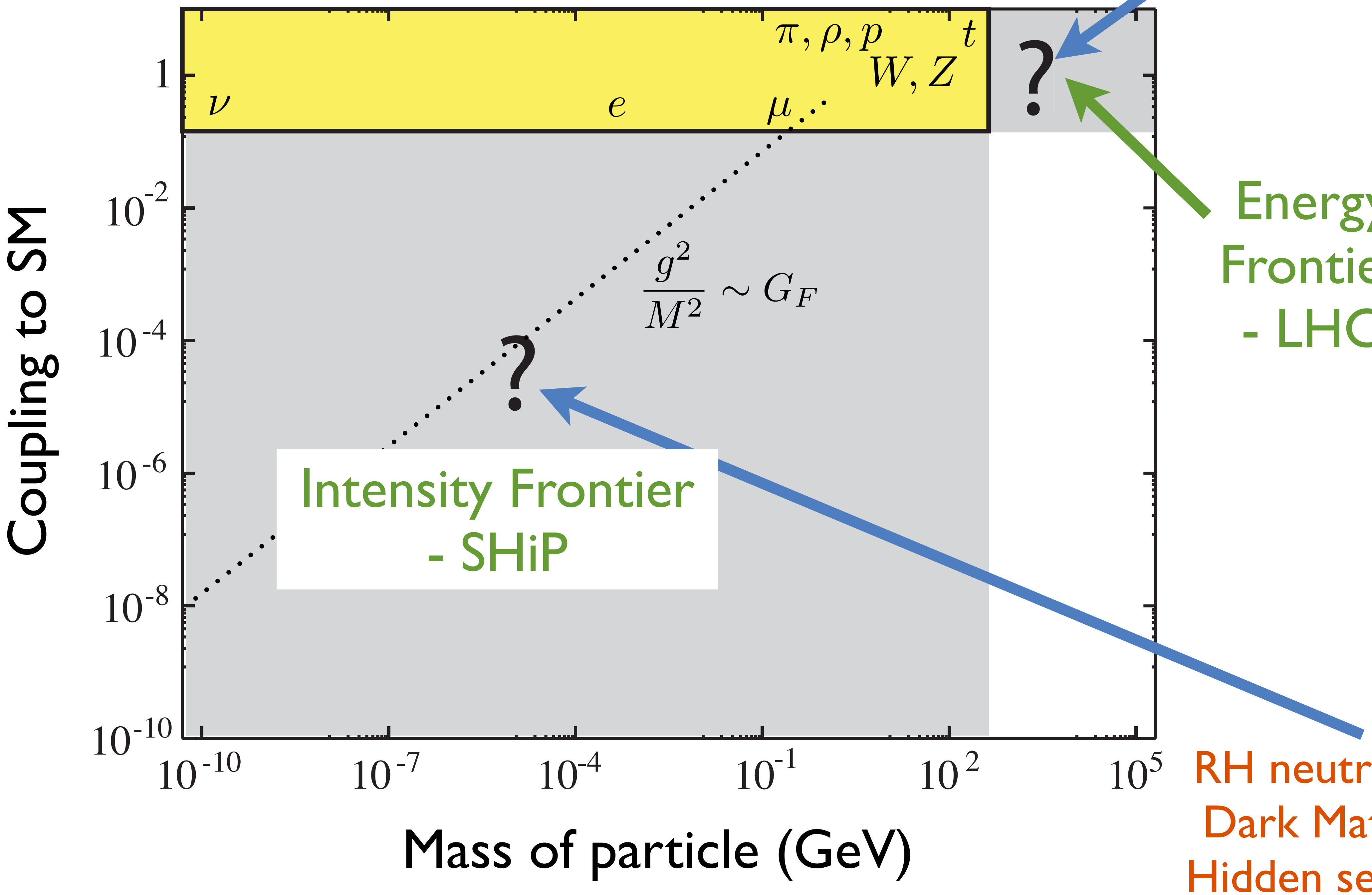
The peculiar Higgs mass suggest that, even in absence of NP, the Universe is metastable.

SM could well be valid up to Planck scale but we have to explain some facts: neutrino oscillations, bariogenesis, dark matter (+inflation, dark energy…)



JHEP 1312 (2013) 089

Where is the new physics?



Intensity Frontier
- SHiP

EWSB, Hierarchy
WIMP DM ...

Energy
Frontier
- LHC

RH neutrinos
Dark Matter
Hidden sector
...

The Hidden Sector

Leading SM coupling to Neutral Hidden Sector

Portals

Scalar	Right-Handed neutrino	U(1)
$\mathcal{O}_s H^\dagger H$	LHN_R	$B_{\mu\nu}V^{\mu\nu}$

renormalizable couplings, i.e. NOT suppressed!

+other of higher dimensions (e.g. axion-like portal)

(stolen from A.Fradette, New Physics at the Intensity Frontier - Victoria, BC,Sept 2014)

Why the Hidden Sector

DM —> possible link with the hidden sector

recent revival since HS may explain some astrophysical anomalies (e.g. e+/e- increase with energy, 511keV line from galactic centre), interpreted in the context of DM; the suggested mass range, from few MeV to few GeV, with τ<1sec and τ>100ns, is peculiar for fixed-target experiments

also a generic feature of many BSM models —> in this context the widest parameter space explored, the better!

even in the SM some of the matter fields are un-charged under one of more of the color and ew gauge group —> another sector would not be particularly exotic from this point of view (PhysRevD80.095024)

A different way to search for NP!

Flavour Physics: shake the Box, listen

Virtual Particles

LHC: Open the box

Real Particles

© R. Cahn

HS is yet another different way!

NB: a very popular subject among theorists, indeed every day on the arXiv there is at least one new paper on HS posted!

Neutrino portal

See-saw generation of neutrino masses

Most general renormalisable Lagrangian of SM particles (+3 singlets wrt SM gauge group):

$$L_{singlet} = i\bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\alpha} \bar{N}_I^c \tilde{H} L_\alpha - M_I \bar{N}_I^c N_I + h.c$$

Yukawa term: mixing of N_I with active neutrinos to explain oscillations

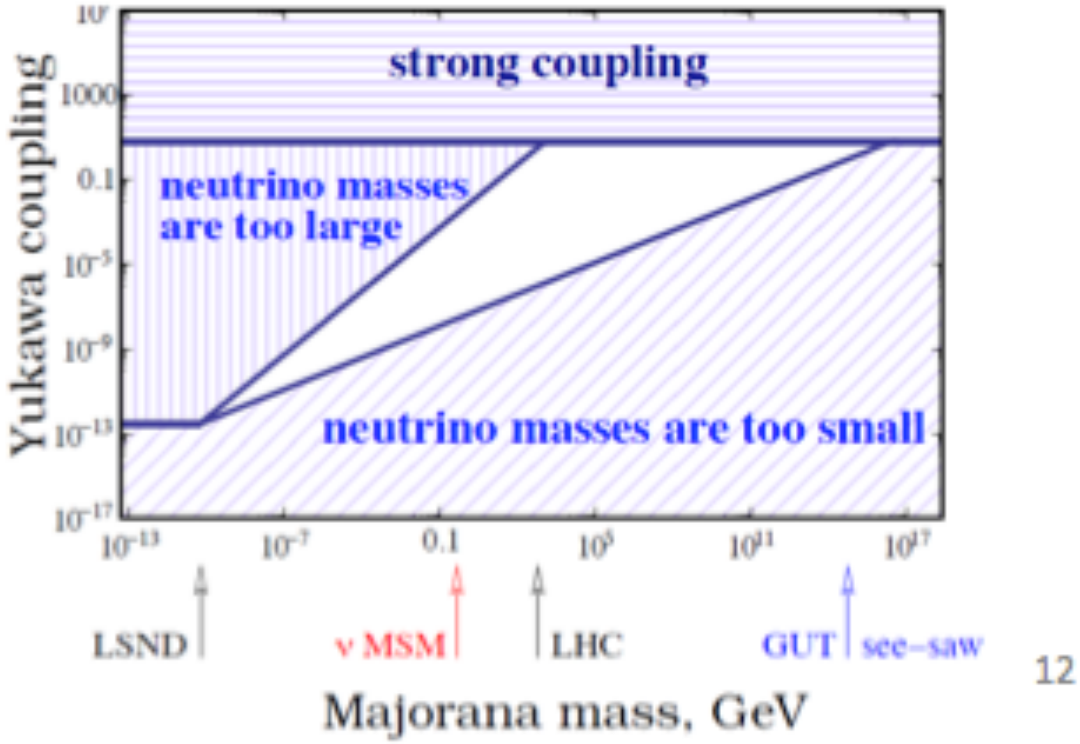
Majorana term which carries no gauge charge

The scale of the active neutrino mass is given by the see-saw formula: $m_\nu \sim \frac{m_D^2}{M}$
where $m_D \sim Y_{I\alpha} v$ *- typical value of the Dirac mass term*

$v \sim 246\ \mathrm{GeV}$

Example:

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

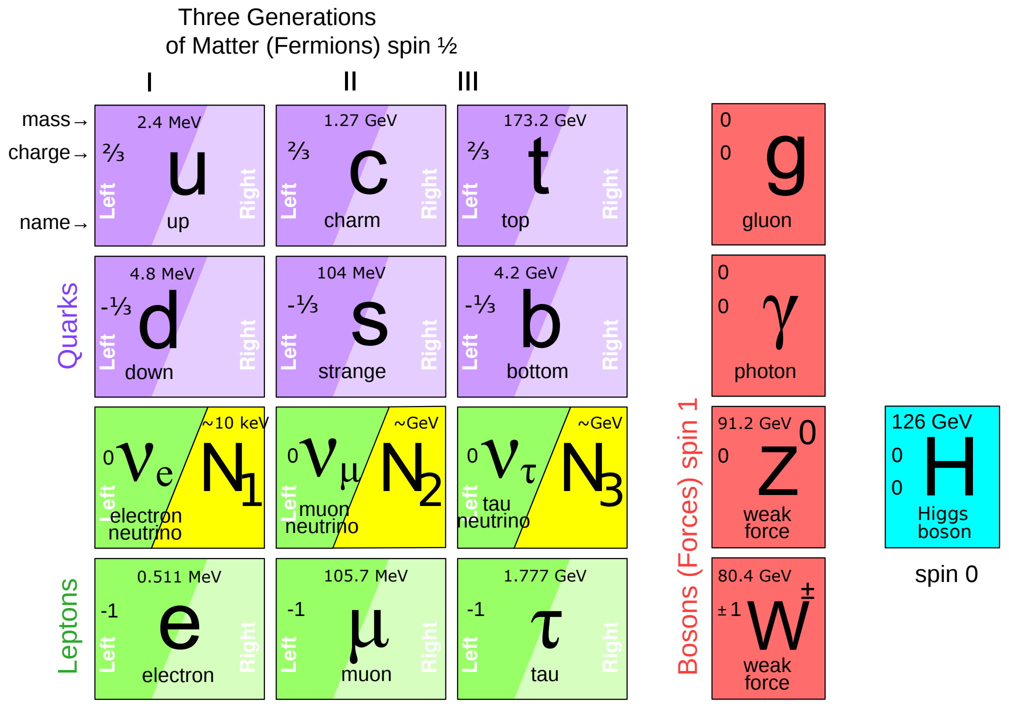


The **ν**MSM and its variants

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)! (but most probably DM has to be generated outside the νMSM, by e.g. the decay of an inflaton—>see Higgs portal)



No hierarchy problem (if also the inflaton or the NP yielding N1 has mass below EW scale)

*νMSM: T.Asaka, M.Shaposhnikov PL **B620** (2005) 17*
M.Shaposhnikov Nucl. Phys. B763 (2007) 49

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

$N_{2,3}$ production

Interaction with the Higgs v.e.v. —>mixing with active neutrinos with U^2

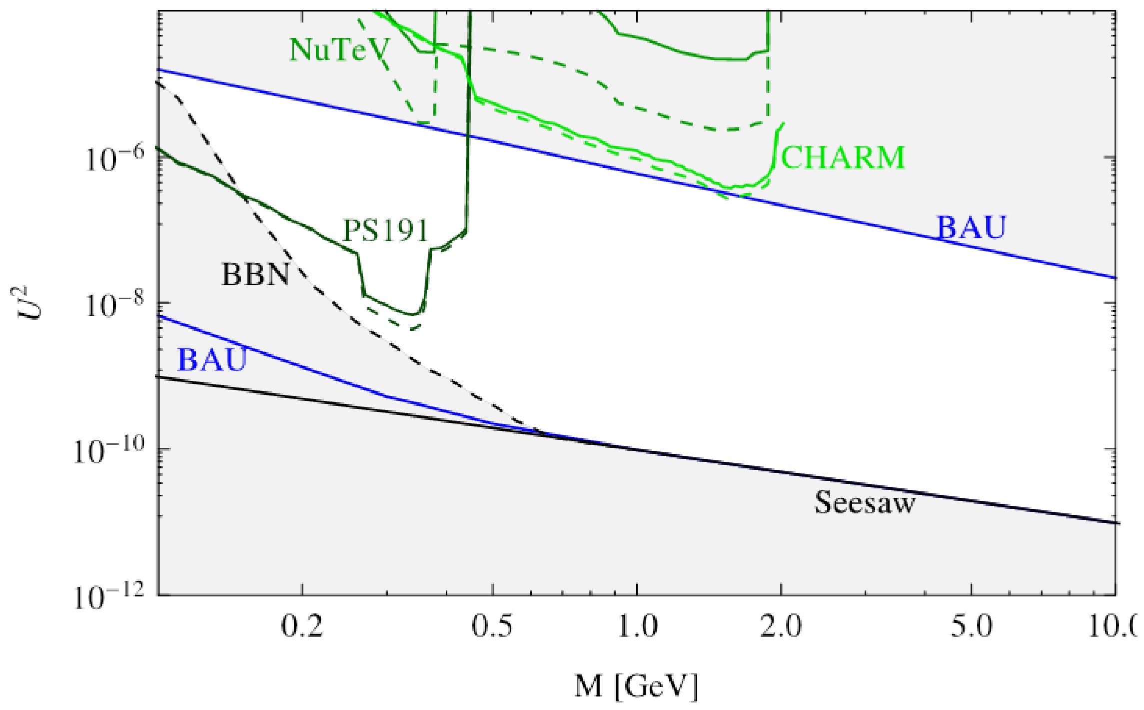
in the νMSM strong limitations in the parameter space (U^2,m)

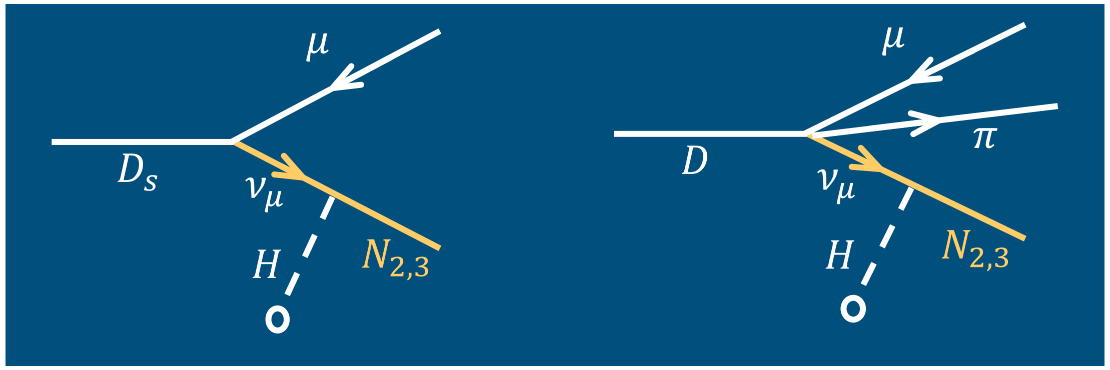
a lot of HNL searches in the past but, for $m > m_K$, with a sensitivity not of cosmological interest (e.g. LHCb with B decays obtained $U^2 \approx 10^{-4}$, arXiv:1401.5361)

this proposal: search in D meson decays (produced with high statistics in fixed target p collisions at 400 GeV)

Taking into account the existing beams and those possibly existing in the near future, this is the best experiment to problem the cosmologically interesting region

inverted mass hyerarchy





$N_{2,3}$ decays

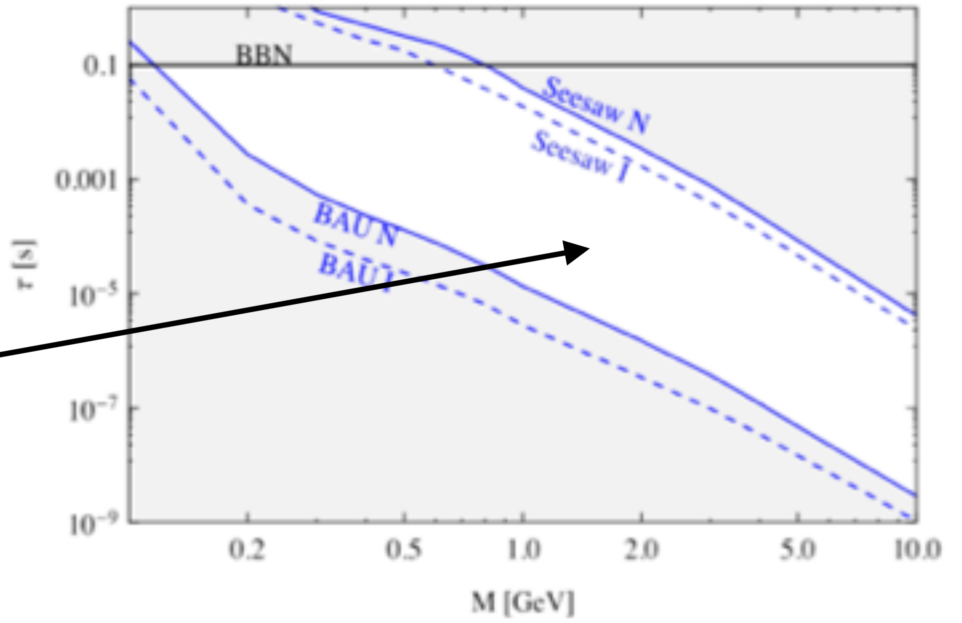
Very weak HNL-active ν —>$N_{2,3}$ have very long life-time

decay paths of O(km)!: for $U^2_\mu=10^{-7}$, $\tau_N=1.8\times10^{-5}$ s

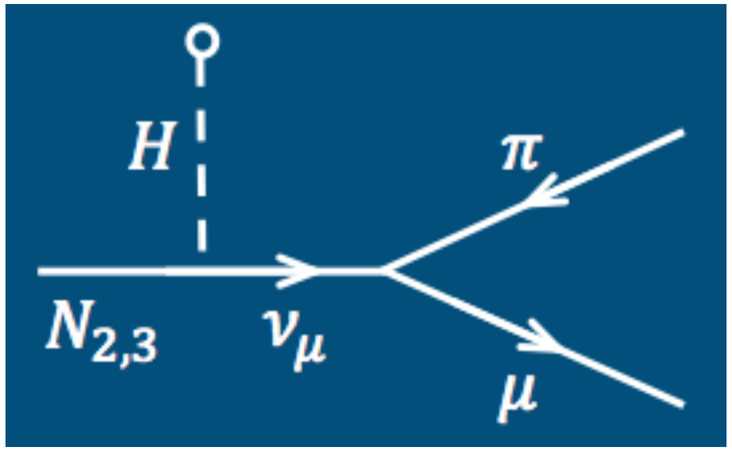
Various decay modes : the BR's depend on flavor mixing

The probability that $N_{2,3}$ decays within the fiducial volume of the experiment $\propto U_\mu^2$

—> number of events $\propto U_\mu^4$



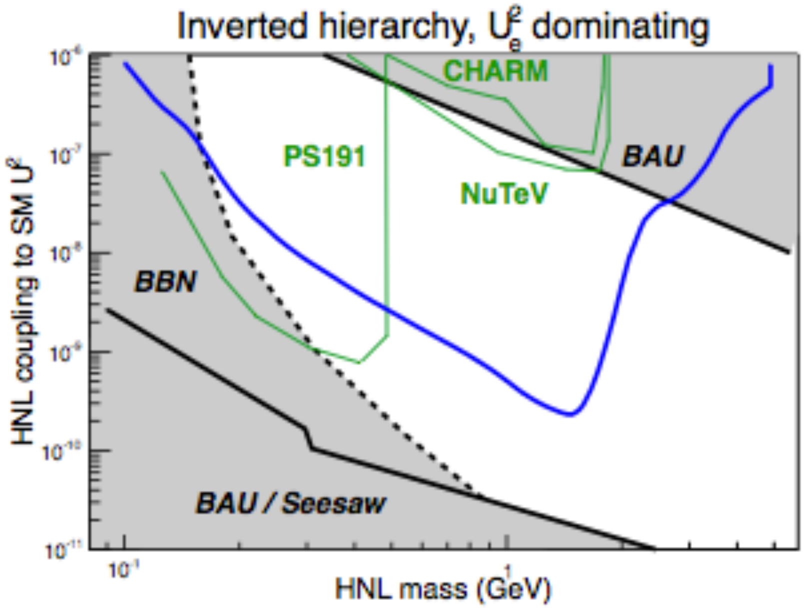
Decay mode	Branching ratio
$N_{2,3} \rightarrow \mu/e + \pi$	0.1 - 50 %
$N_{2,3} \rightarrow \mu^-/e^- + \rho^+$	0.5 - 20 %
$N_{2,3} \rightarrow \nu + \mu + e$	1 - 10 %

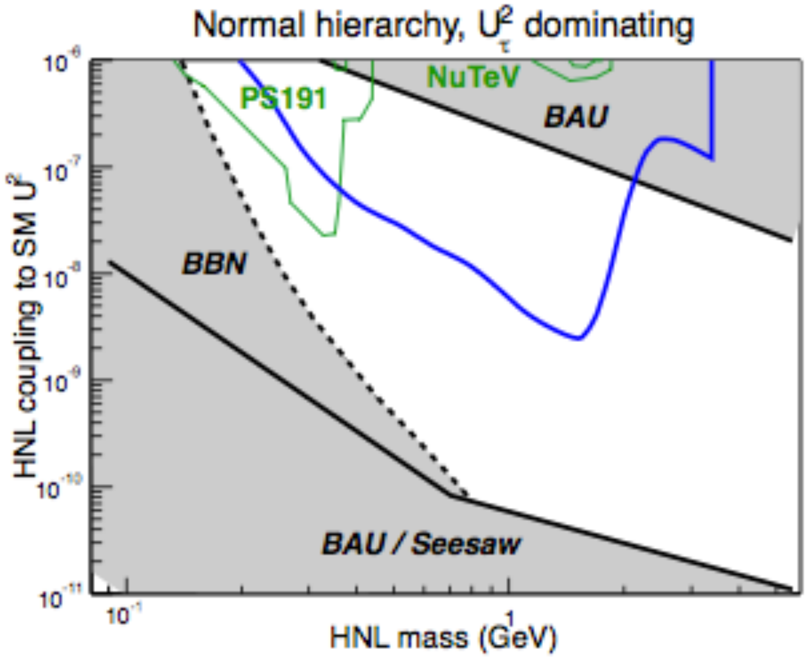


SHIP sensitivity to HNL

SHIP will scan most of the cosmologically allowed region below the charm mass

Reaching the see-saw limit would require increase of the SPS intensity by an order of magnitude (does not currently seem realistic)



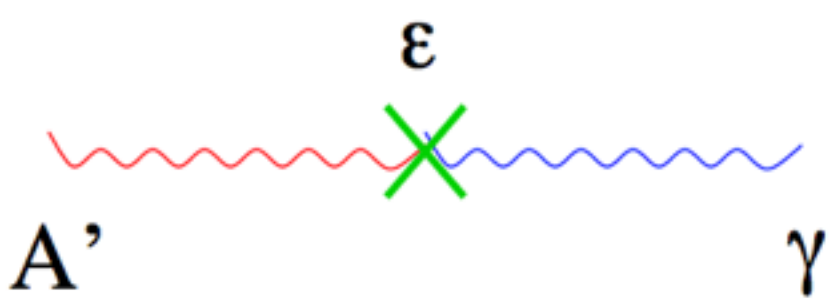


Vector and scalar portal

Portals to Hidden Physics

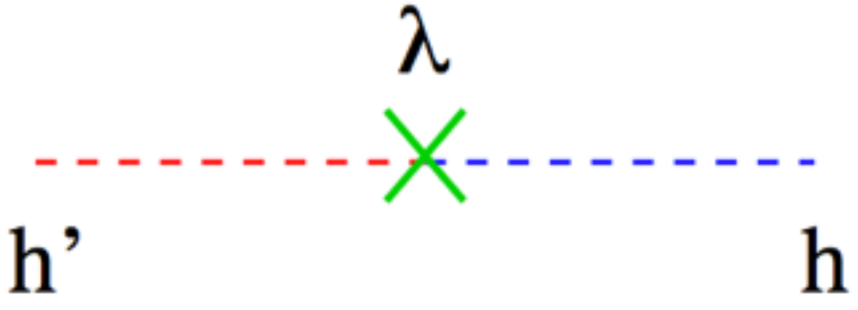
- Two nice ways for new hidden physics to couple:
  - Vector Portal:
    (A’ = “hidden photon”)

$$\epsilon F'_{\mu\nu} F^{\mu\nu}$$



  - Higgs Portal:
    (H’ = “hidden Higgs”)

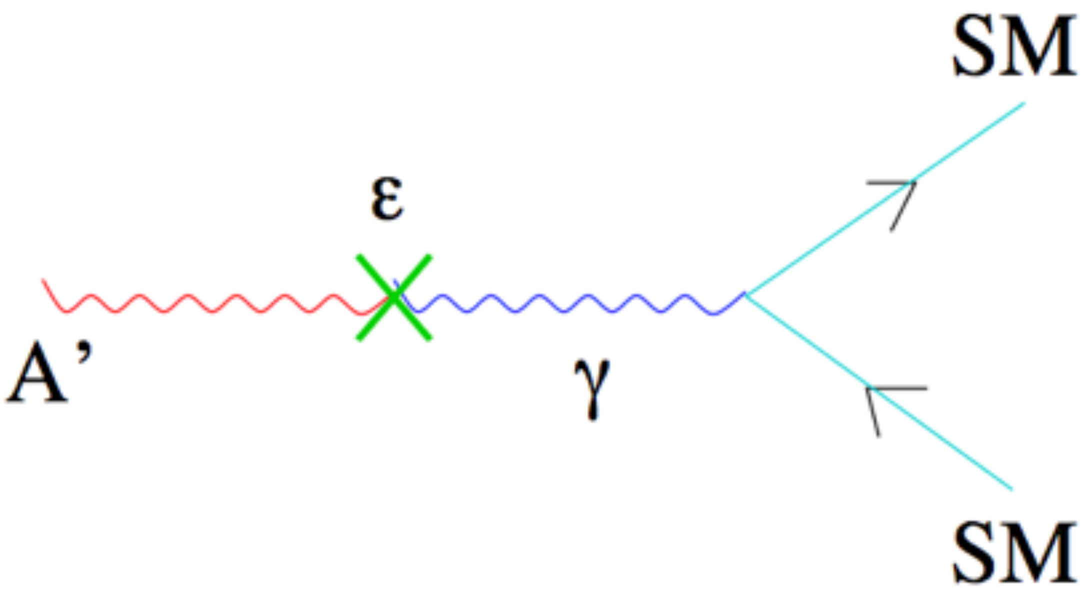
$$\lambda |H'|^2 |H|^2$$

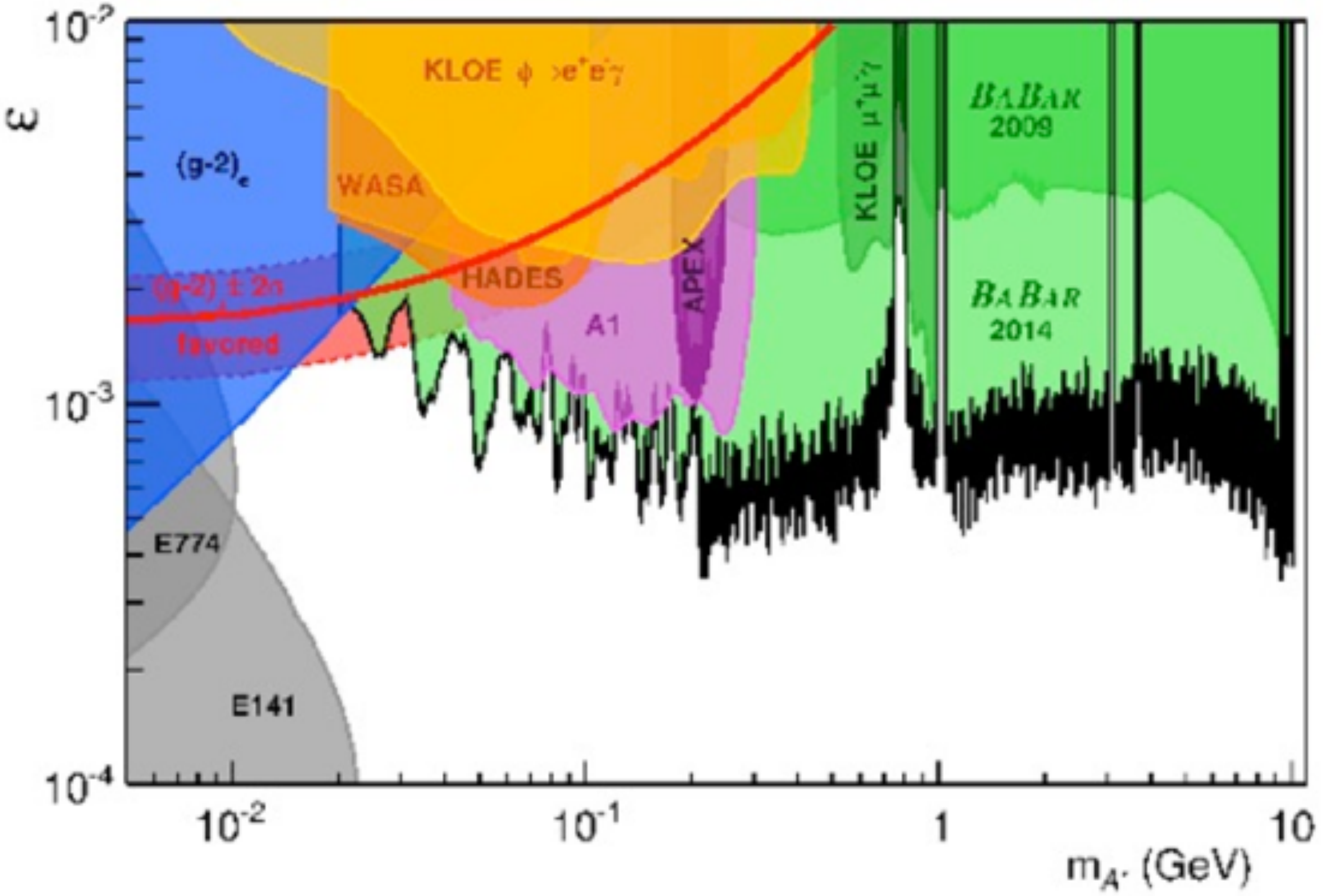


(+A IH’I IHI^2)

Minimal Vector Portal

- Hidden photon A' with mass $m_{A'}$, A' → SM+SM:





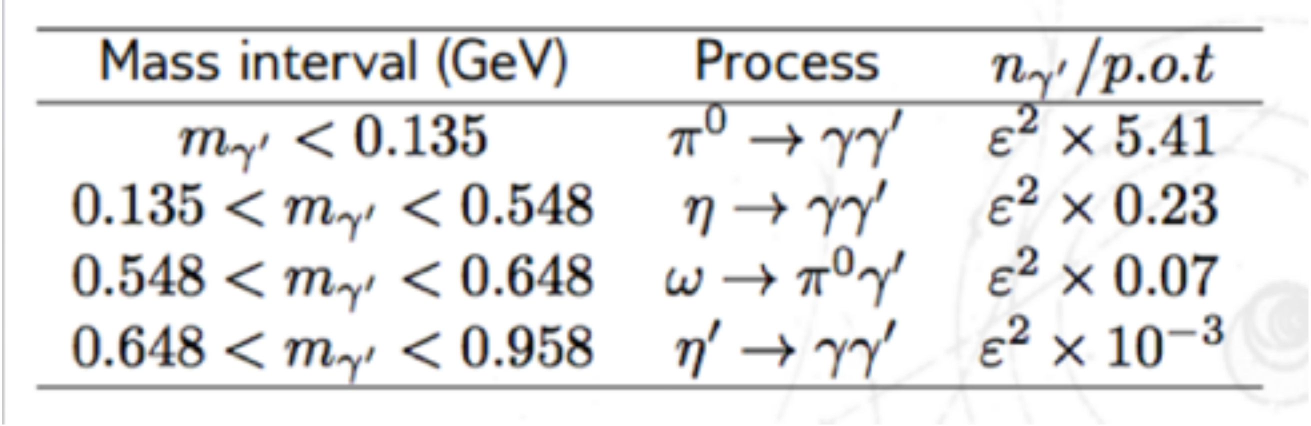
[Bjorken, Essig, Schuster, Toro 2009; ...; BaBar 2014]

Minimal vector portal

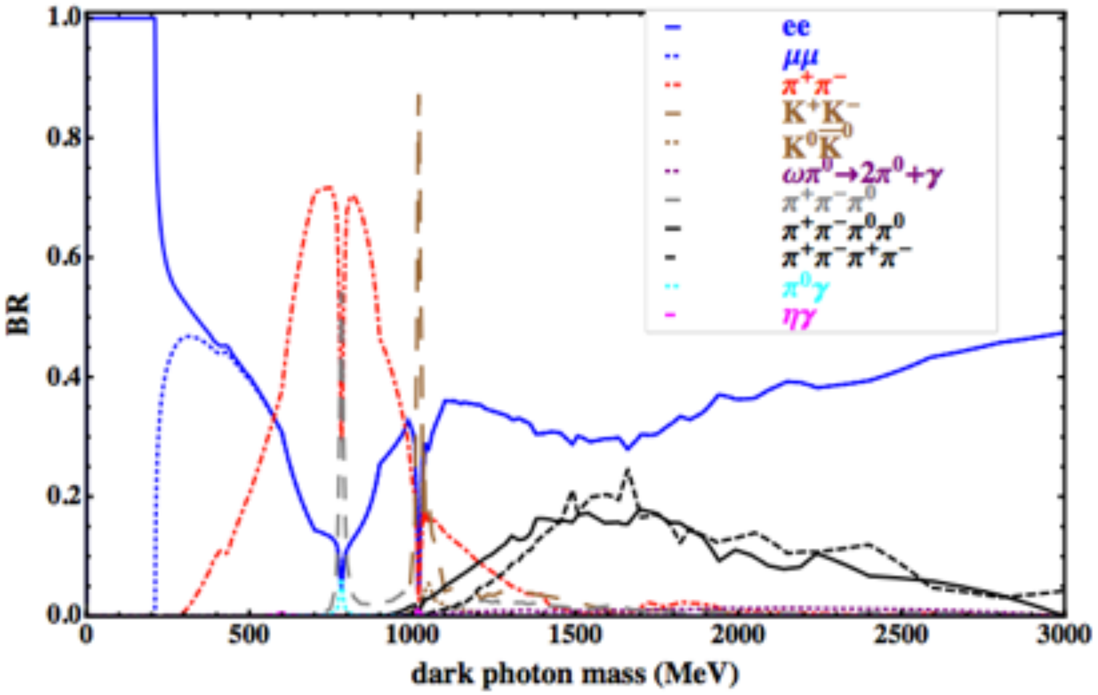
Two photon production modes considered:

1) in pseudo-scalar decays
2) in proton brehmsstrahlung

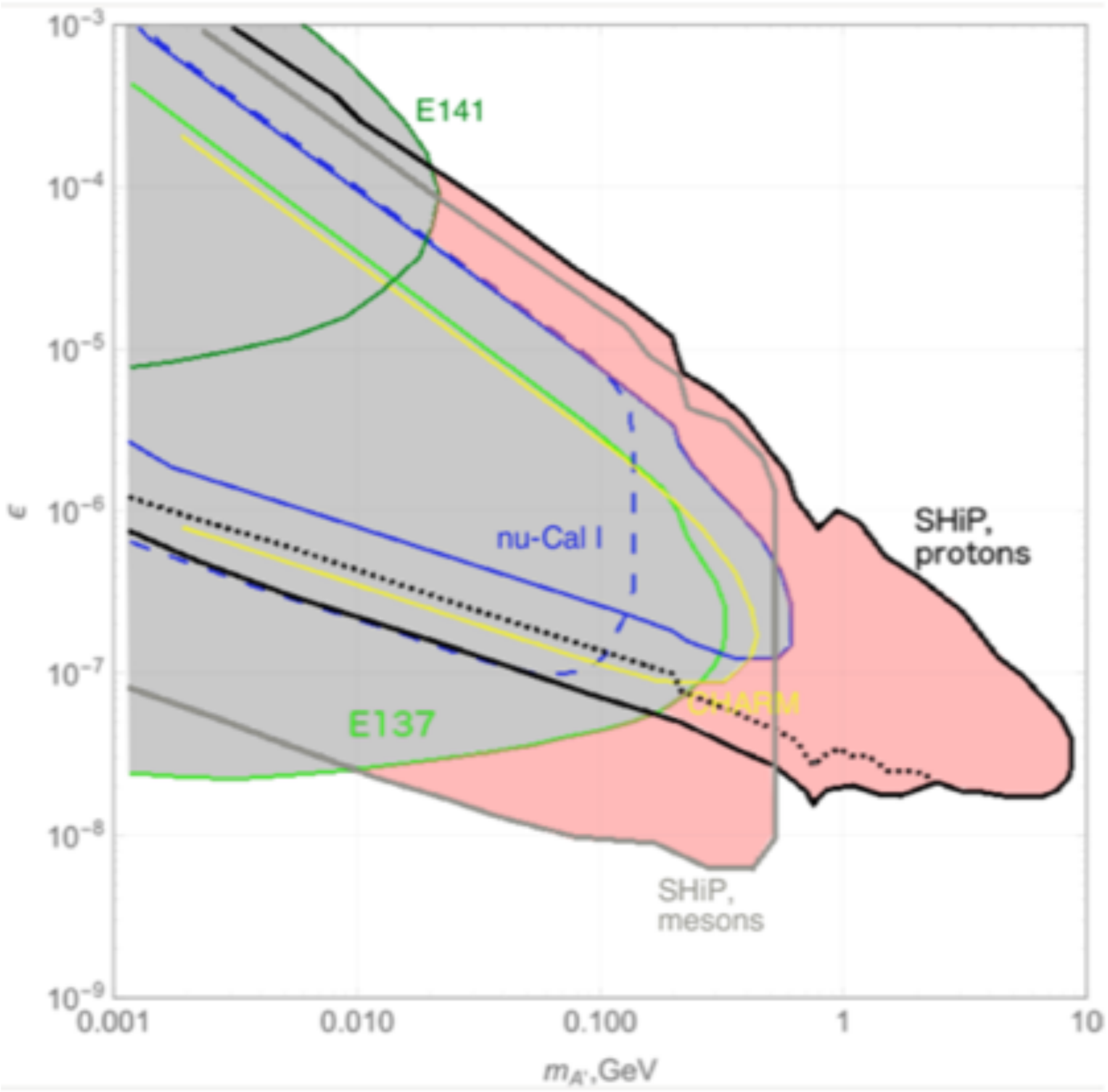
Physics Letters B 731 (2014) 320–326



Mass interval (GeV)	Process	$n_{\gamma'}/p.o.t$
$m_{\gamma'} < 0.135$	$\pi^0 \to \gamma\gamma'$	$\varepsilon^2 \times 5.41$
$0.135 < m_{\gamma'} < 0.548$	$\eta \to \gamma\gamma'$	$\varepsilon^2 \times 0.23$
$0.548 < m_{\gamma'} < 0.648$	$\omega \to \pi^0\gamma'$	$\varepsilon^2 \times 0.07$
$0.648 < m_{\gamma'} < 0.958$	$\eta' \to \gamma\gamma'$	$\varepsilon^2 \times 10^{-3}$



Dark photons



hadronic fixed target experiments overcome the kinematic limitation of e- fixed target allowing for m>1GeV!

http://arxiv.org/abs/1411.4007

only e^+e^- and $\mu^+\mu^-$ decays:

Higgs portal

M. Winkler et al., arXiv:1310.6752

J. Clarke et al., arXiv:1310.80.

A real singlet scalar:

SM: complex scalar doublet → four degrees of freedom, three are eaten by the W±/Z bosons, one becomes the SM Higgs;

SM+ real singlet scalar (ϕ or h): one extra degree of freedom and one extra physical scalar:

could have mass $m_h < 5$ GeV;

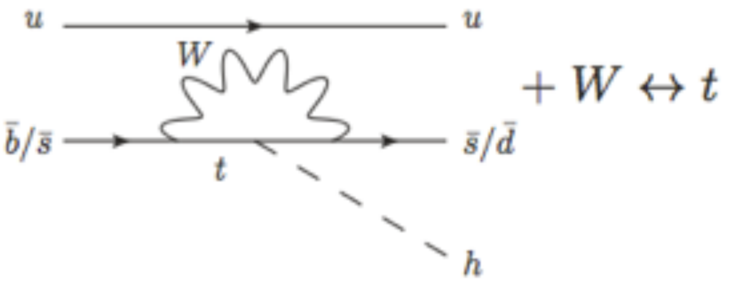
could “mass mix” with the SM Higgs with mixing angle ρ:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\rho & -\sin\rho \\ \sin\rho & \cos\rho \end{pmatrix} \begin{pmatrix} \phi_0' \\ S' \end{pmatrix}$$

Motivated in many models BSM including SUSY, Coleman-Weinberg

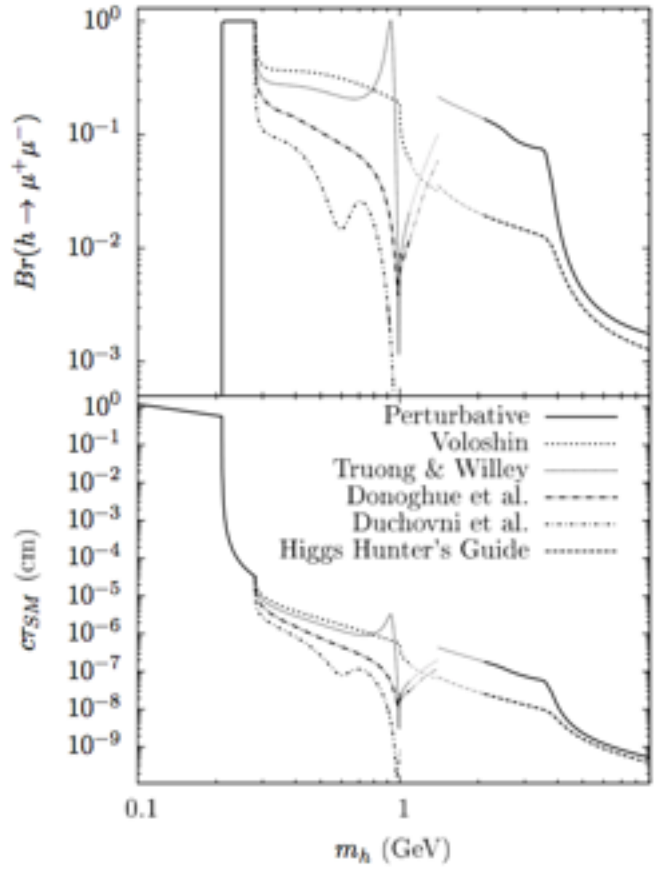
Interpretation as inflaton also possible (Bezrukov et al, JHEP05(2010)010 and arXiv:1403.4638v1)

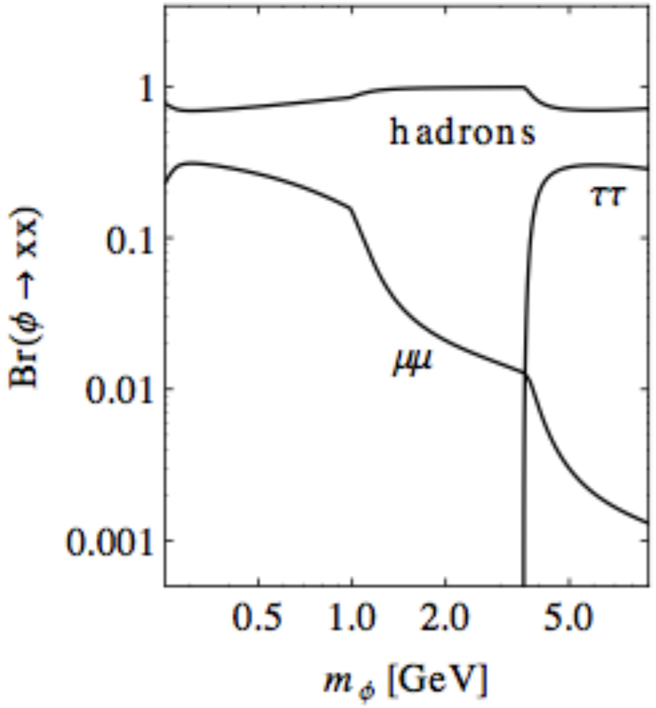
Scalar production/decay



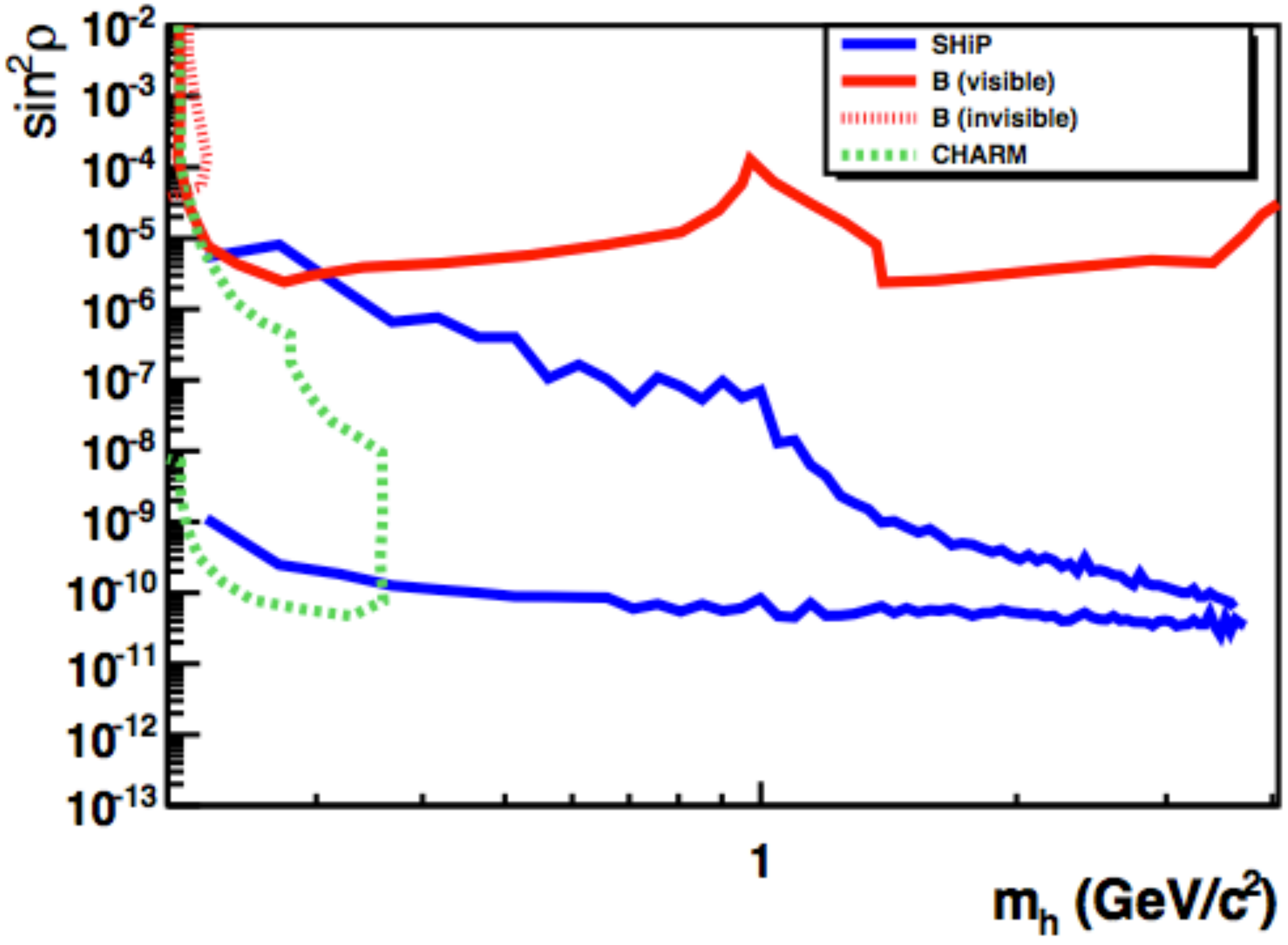
Production via meson decay, D CKM suppressed wrt B (5×10^{-10}) and D cross section only 20k times larger than B cross section at 27GeV

Some uncertainty in the calculation of BR's





Light scalar



SHIP sensitivity: only muon final states

Axion-like portal

PNGB

PNGBs or generic axions with couplings of order m_{χ}/F to SM matter X

can arise as pseudo GB in many extensions of the SM

- **they are naturally light if there is an approximate shift symmetry**

- **their interaction is proportional to the inverse of some SB scale F**

the coupling to a fermion field is

$$L \supset \frac{m_{\chi}}{F} a \chi \chi,$$

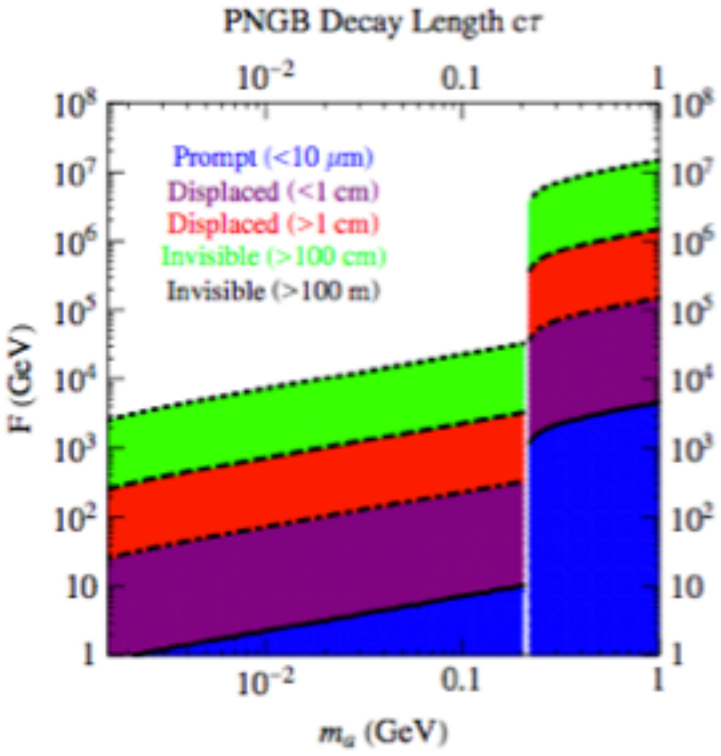
lifetime

and induces a partial width

$$\Gamma_\ell = \frac{m_a}{8\pi}\left(\frac{m_\ell}{F}\right)^2\sqrt{1-(4m_\ell^2/m_a^2)},$$

for m_a<400MeV the total width is approximated by $\Gamma ee+\Gamma\mu\mu$ (we use the same approximation up to 1GeV)

PRD 82,113008 (2010)



Production in beam dump

If the PNGB couples to quarks, with c of O(1)

$$\frac{m_q}{F} a\bar{q}q \Rightarrow c\frac{m_\pi^2 F_\pi}{F} a\pi^0;$$

Production from mixing with neutral pion

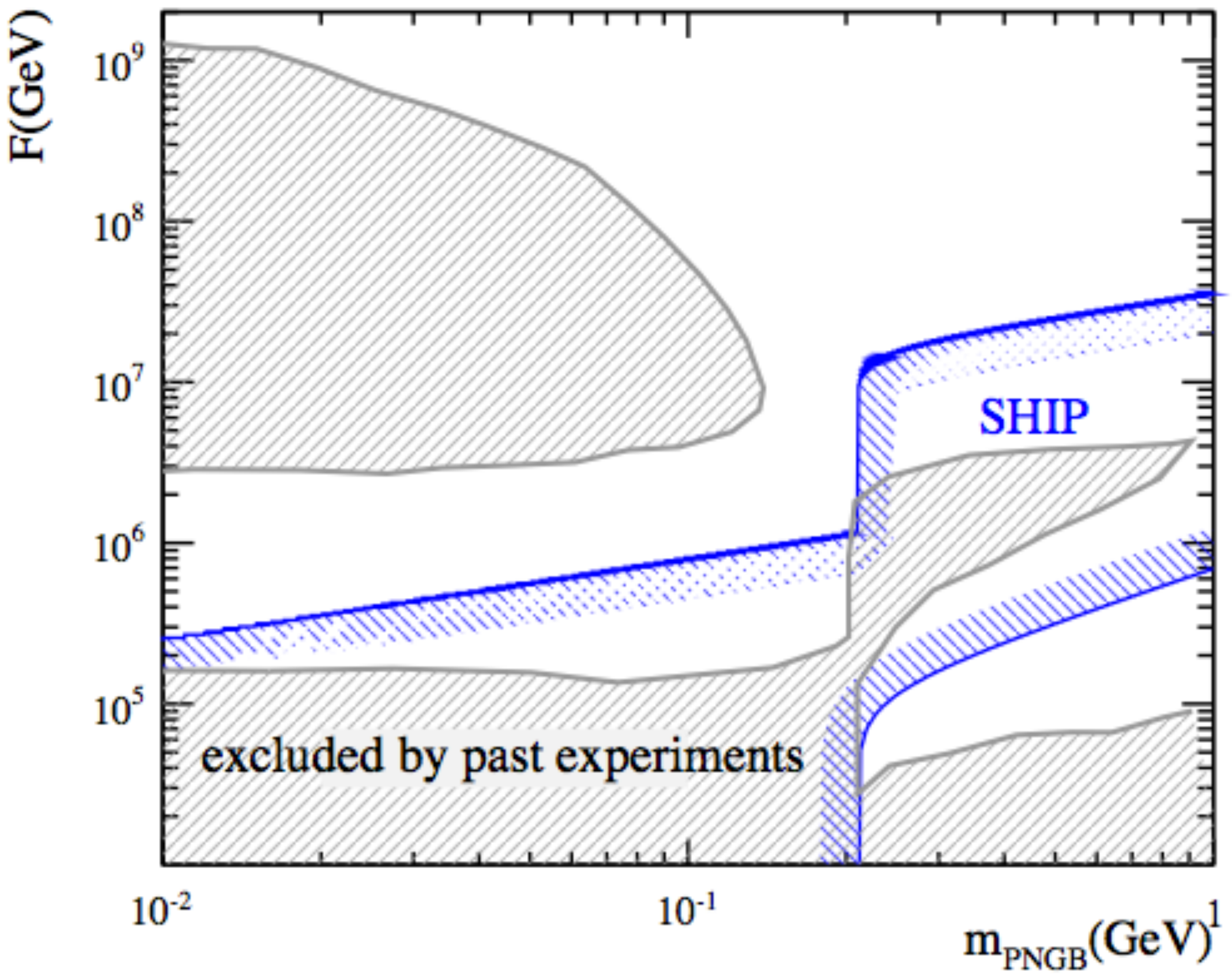
$$N_a = \left(\frac{F_\pi}{F}\right)^2 n_{\pi^0} N_p \epsilon_{\text{geo}}.$$

times the probability of decaying into the detector

$$N_e = N_a(e^{-(X_t/\gamma c\tau)} - e^{-(X_d/\gamma c\tau)})$$

so sensitivity goes like F^{-4}

PNGB sensitivity



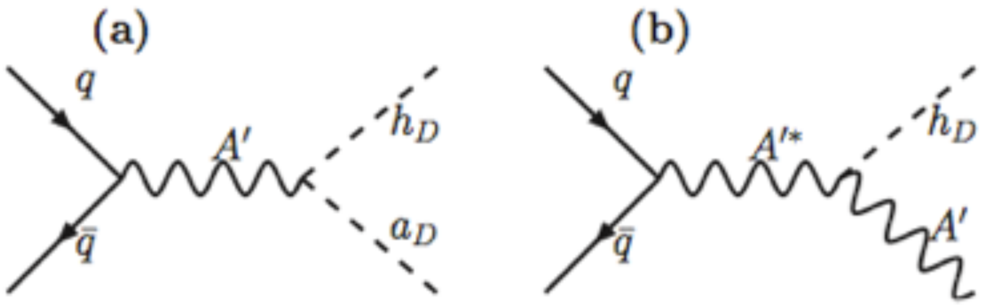
only e^+e^- and $\mu^+\mu^-$ decays: beyond 1GeV things are more complicated due to dominance of hadronic decays

what happens a m>1GeV to be understood

Other models under study

Beyond minimal vector portal

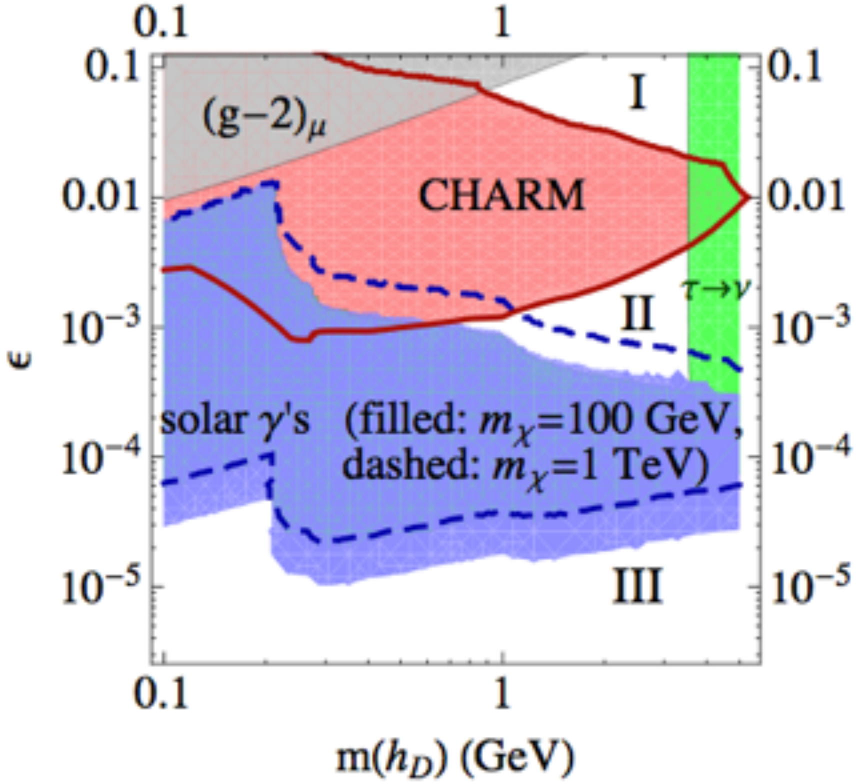
In some models A’ can be coupled to dark sector particles and decay into them without the ε suppression, rather than fermion pairs (e.g. Higgs-like scalar considered in arXiv:0910.1602v2)



production modes

FIG. 2: Feynman diagrams for (a) A' decay into a
higgs and (b) higgs$'$-strahlung process.

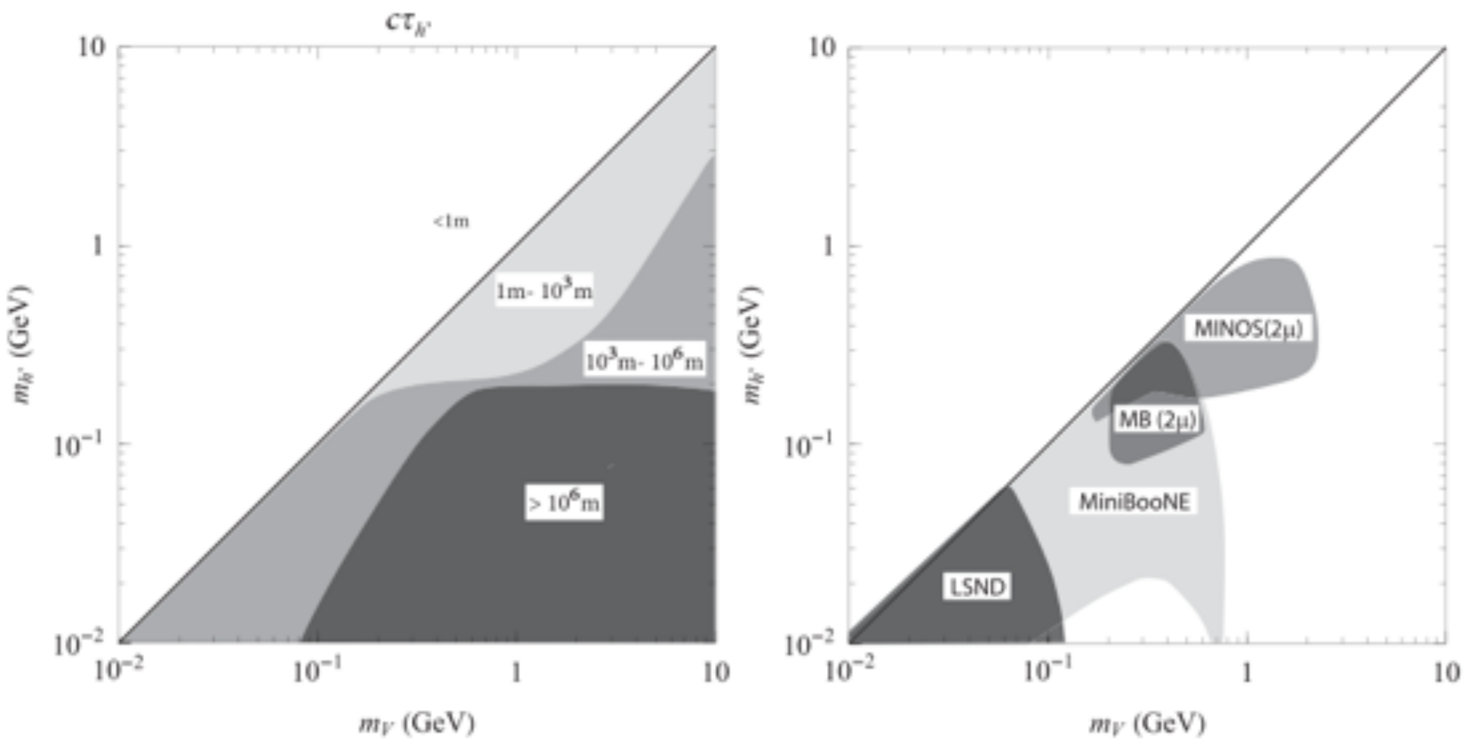
decays though loops with a rate controlled by ε



Secluded Higgs sector

Secluded sector Higgs (giving mass to the dark photon) and vectors, see arXiv:0903.0363,PhysRevD.80.095024 after SSB in secluded sector:

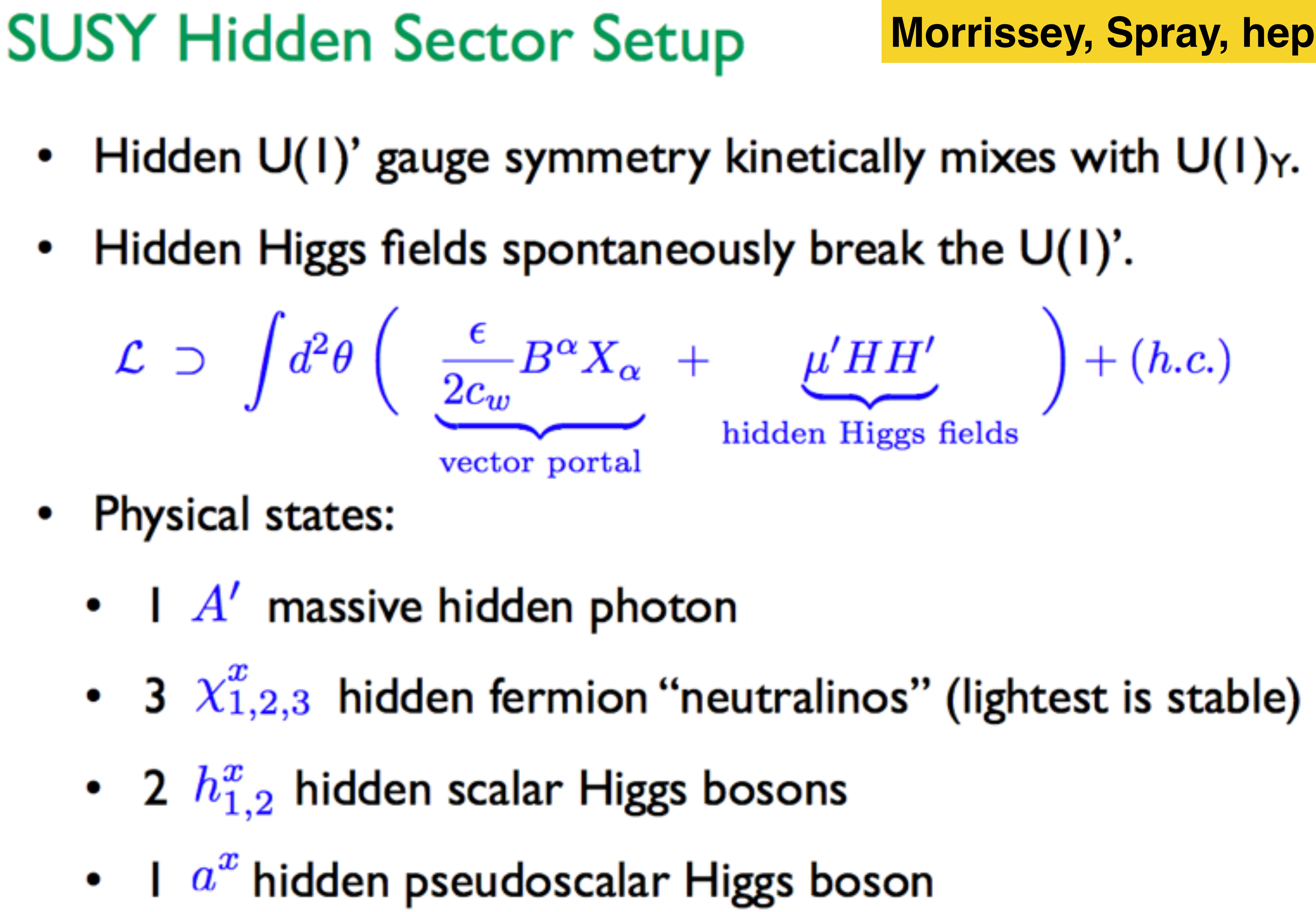
qq—>h'V' , π^0—>γVh', ρ—>Vh'



$$\mathcal{L}_{\rm int} = \kappa V_\mu J_\mu^{\rm EM} + \frac{m_V^2}{v'} h' V_\mu^2 + \cdots .$$

SUSY HS

Morrissey, Spray, hep-ph1402.4817v2



SUSY Hidden Sector Setup

- Hidden U(1)' gauge symmetry kinetically mixes with U(1)$_Y$.
- Hidden Higgs fields spontaneously break the U(1)'.

$$\mathcal{L} \supset \int d^2\theta \left(\underbrace{\frac{\epsilon}{2c_w} B^\alpha X_\alpha}_{\text{vector portal}} + \underbrace{\mu' H H'}_{\text{hidden Higgs fields}} \right) + (h.c.)$$

- Physical states:
  - 1 A' massive hidden photon
  - 3 $\chi^x_{1,2,3}$ hidden fermion "neutralinos" (lightest is stable)
  - 2 $h^x_{1,2}$ hidden scalar Higgs bosons
  - 1 a^x hidden pseudoscalar Higgs boson

Experimental Signals of the Theory

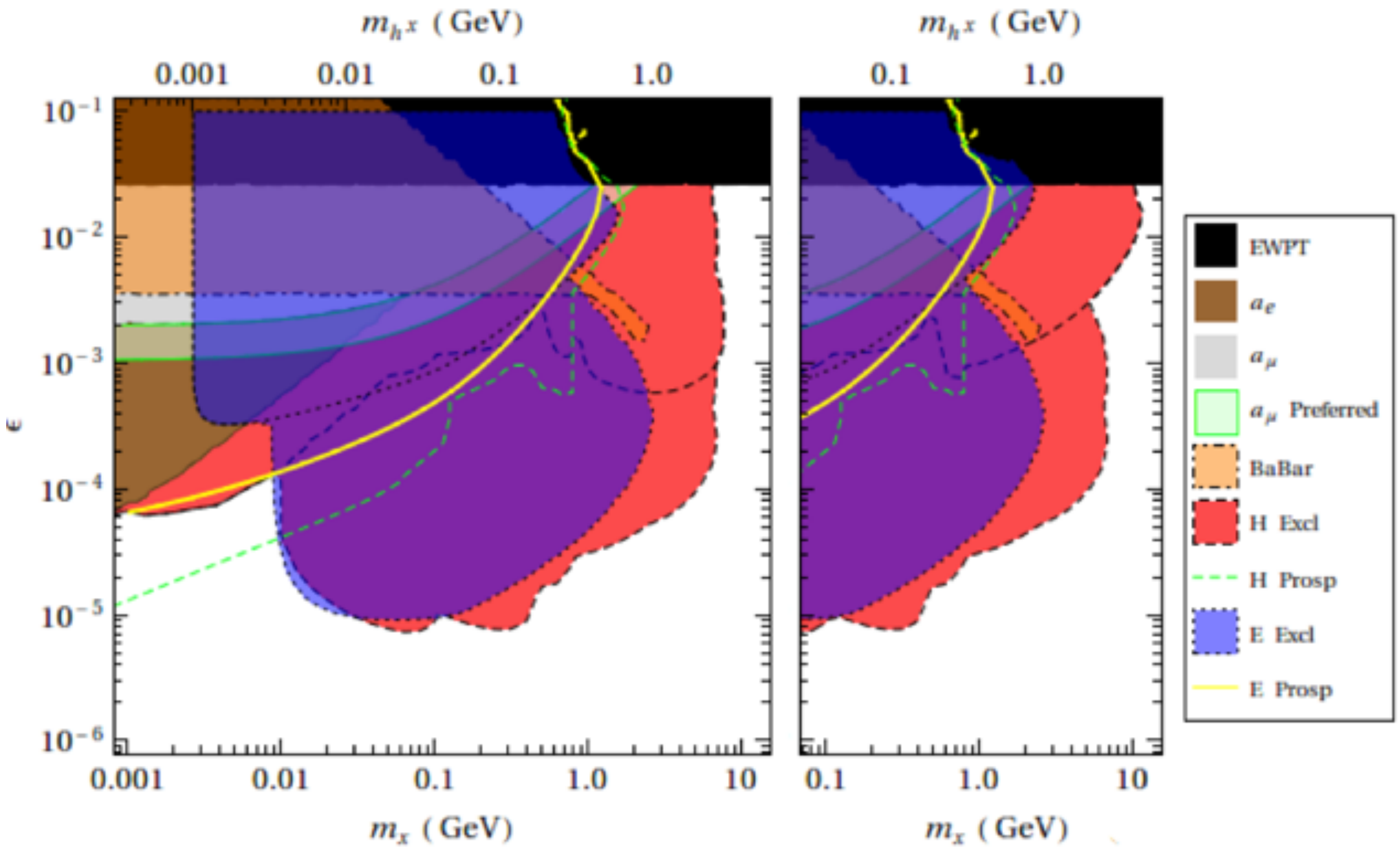
- Depend mainly on how the hidden photon decays. This is determined mostly by the mass spectrum.
- Four main cases:
  - A: $A' \to SM + SM$, similar to minimal vector portal
  - B: $A' \to \chi_1^x + \chi_1^x$, similar to dark vector portal
  - C: $A' \to h_1^x + a^x$, not much attention [Schuster, Toro, Yavin 2009]
  - D: $A' \to \chi_1^x + \chi_2^x$, new!

SUSY HIDDEN SECTOR

$$A' \to h_1^x + a^x$$

h1—>ffbar

ax—>h1+SM+SM



new phenomenology!

Summary of signals

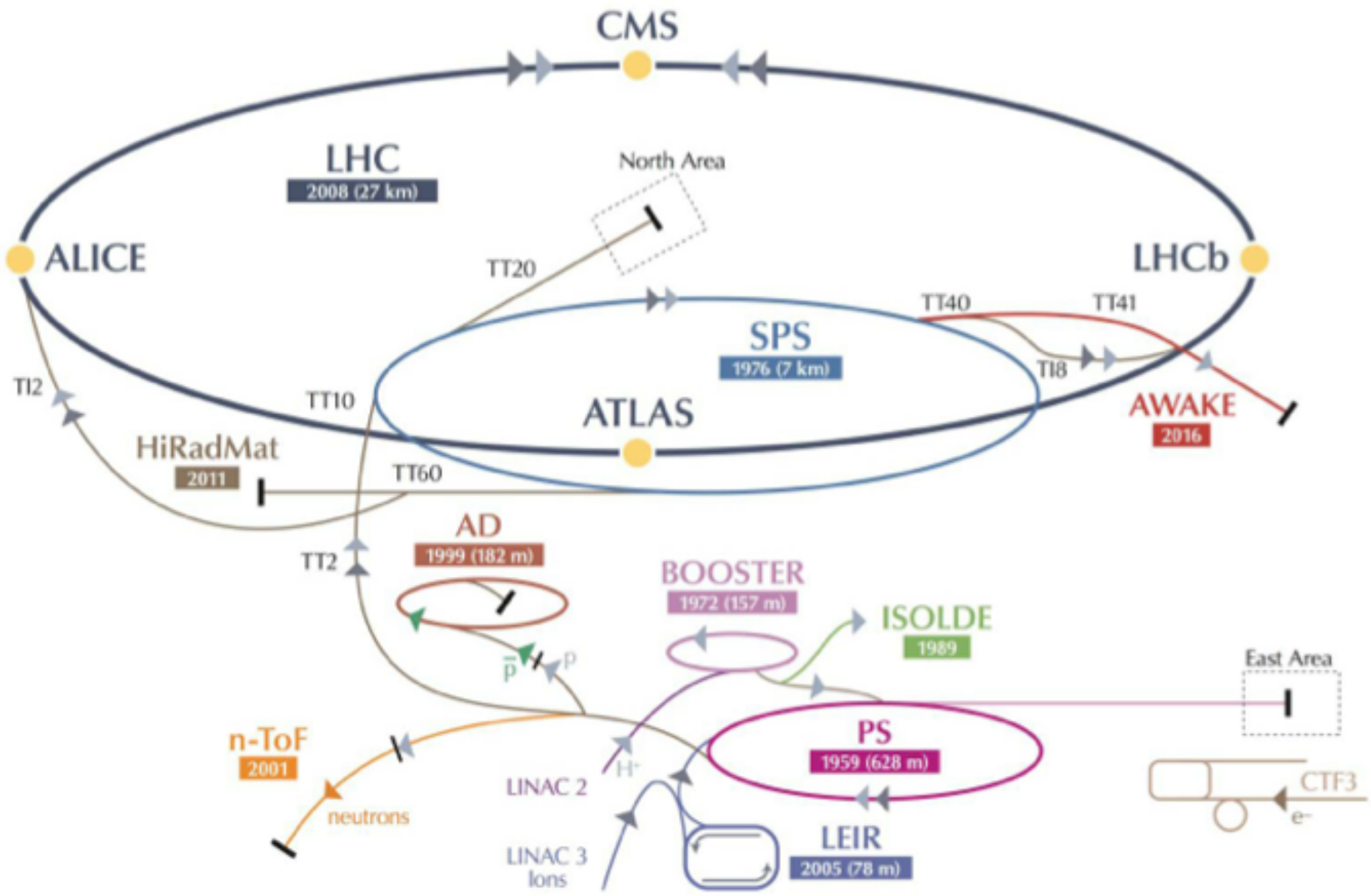
Leptonic, Leptonic-hadronic AND purely hadronic (also with kaons!)

Some decays with missing energy (active neutrinos)

Also with neutrals —> need for energy resolution and separation photon - neutral pion!

The experiment

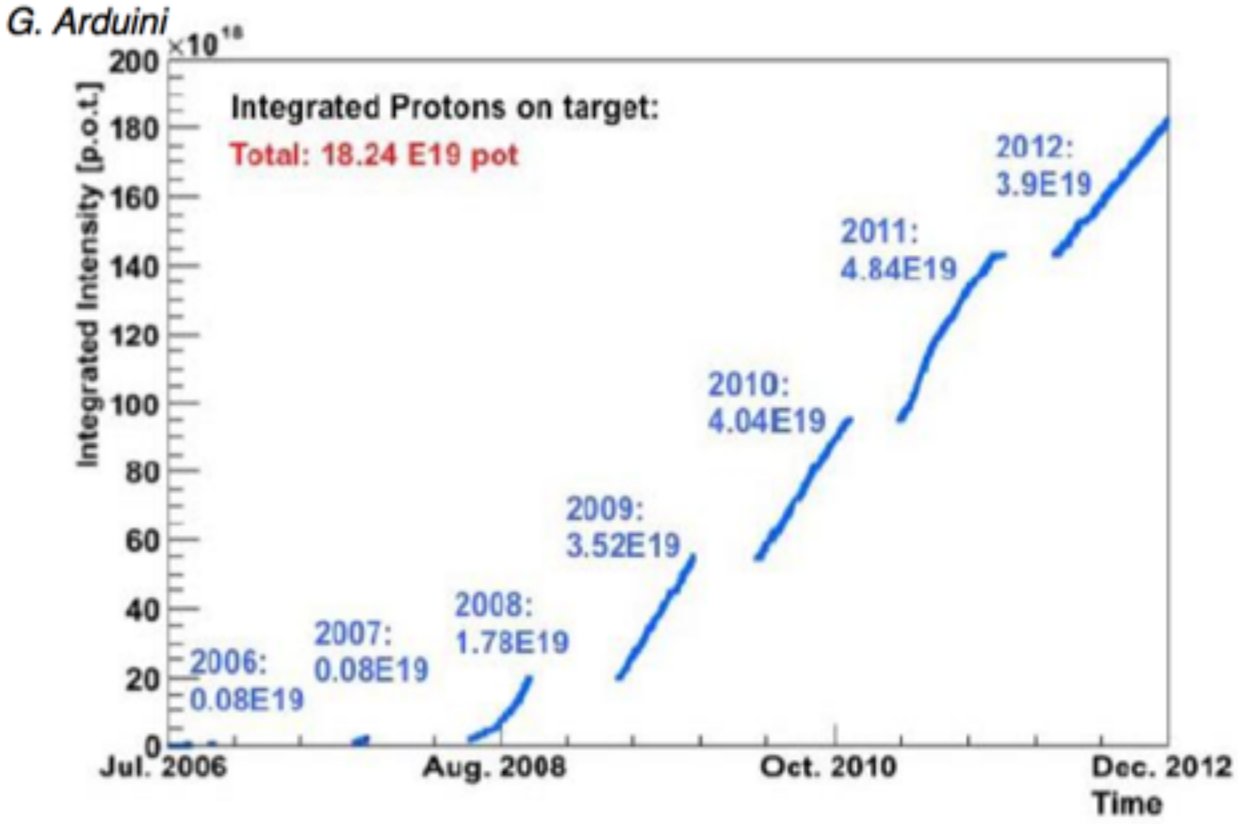
CERN accelerator complex

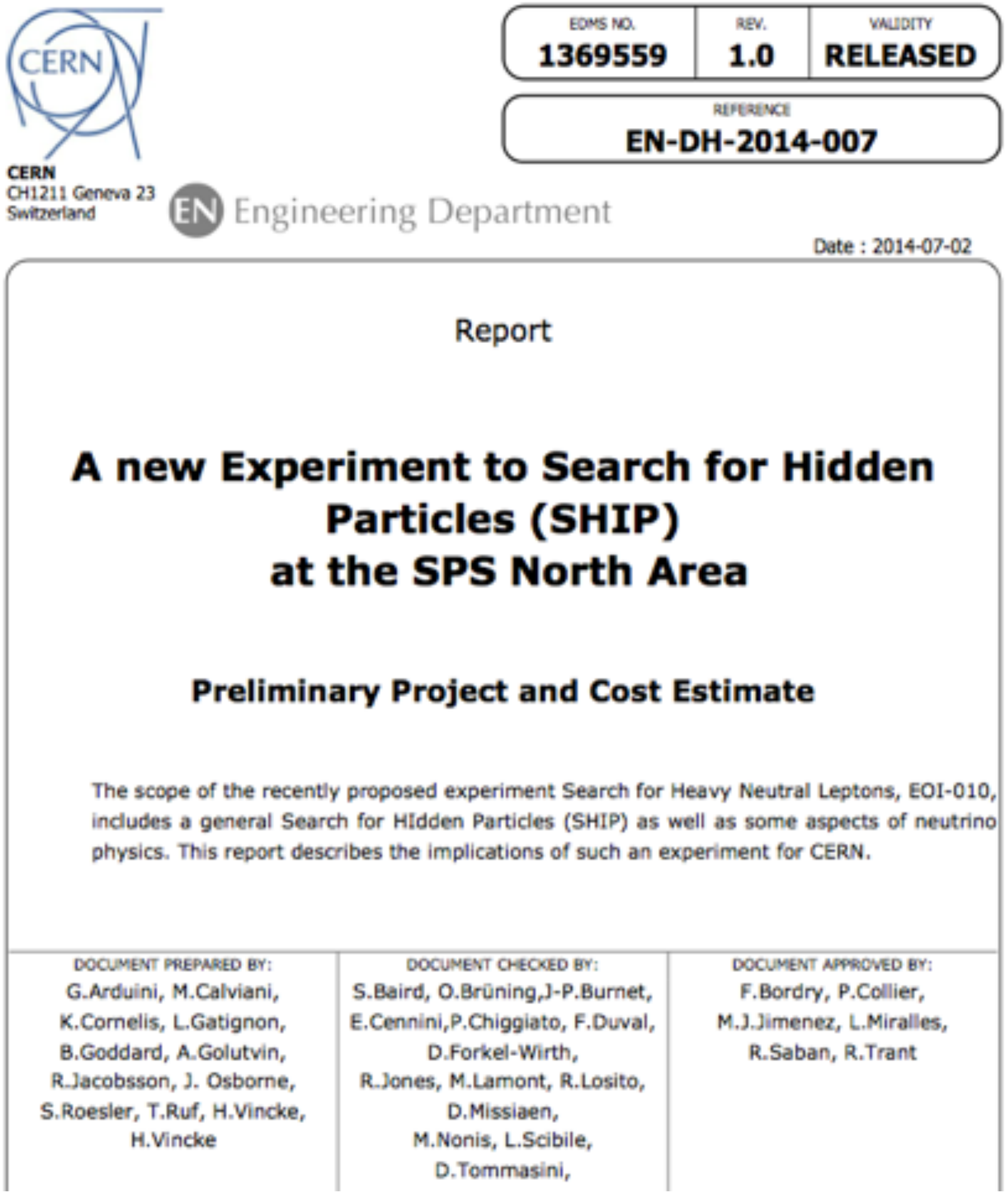


The beam

Extracted SPS beam 400GeV;

like CNGS 4.5×10^{19} pot/year
—> in 5 years it will be 2×10^{20}pot





EDMS NO.	REV.	VALIDITY
1369559	1.0	RELEASED

REFERENCE
EN-DH-2014-007

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EN Engineering Department

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.

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Figure 20: Schematic layout of the civil engineering complex.

The key features of this layout are:

- 85m long Junction Cavern in the TDC2 line
- 170m long machine Extraction Tunnel (4m wide by 4m high similar to TDC2)
- 15m long by 15m wide Access building including a shaft to reach the Extraction Tunnel line

Target and muon filter

W target of 50cm : the beam is spread on the target to avoid melting

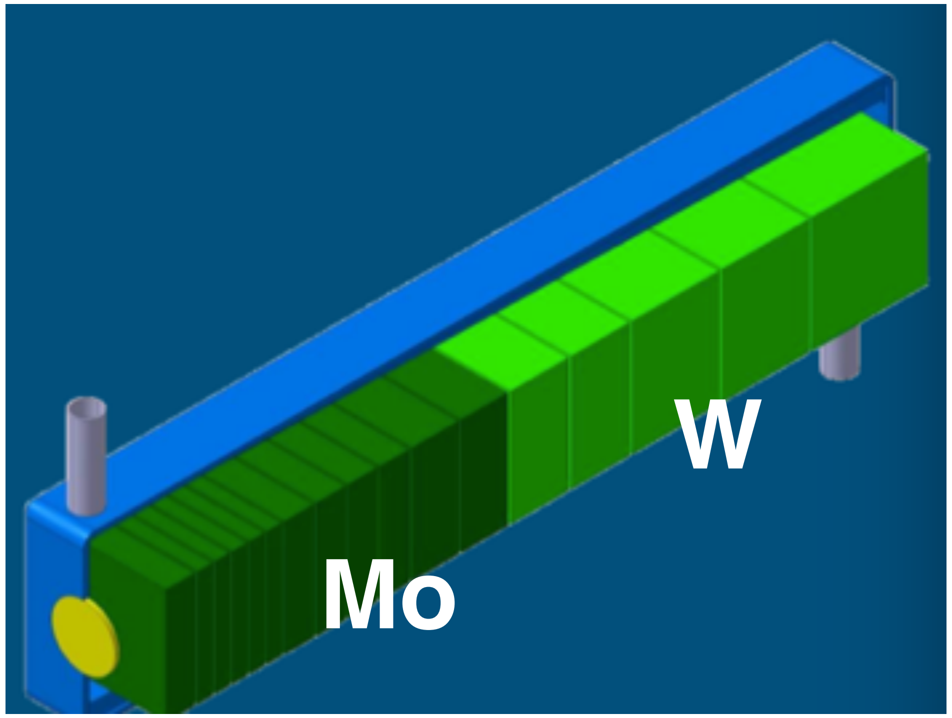
It is followed by a muon filter. Now the preferred option is an active filter with sweeping magnets.

The issue is not trivial since the muon flux is enormous: 10^{11}/SPS-spill(5×10^{13} pot)

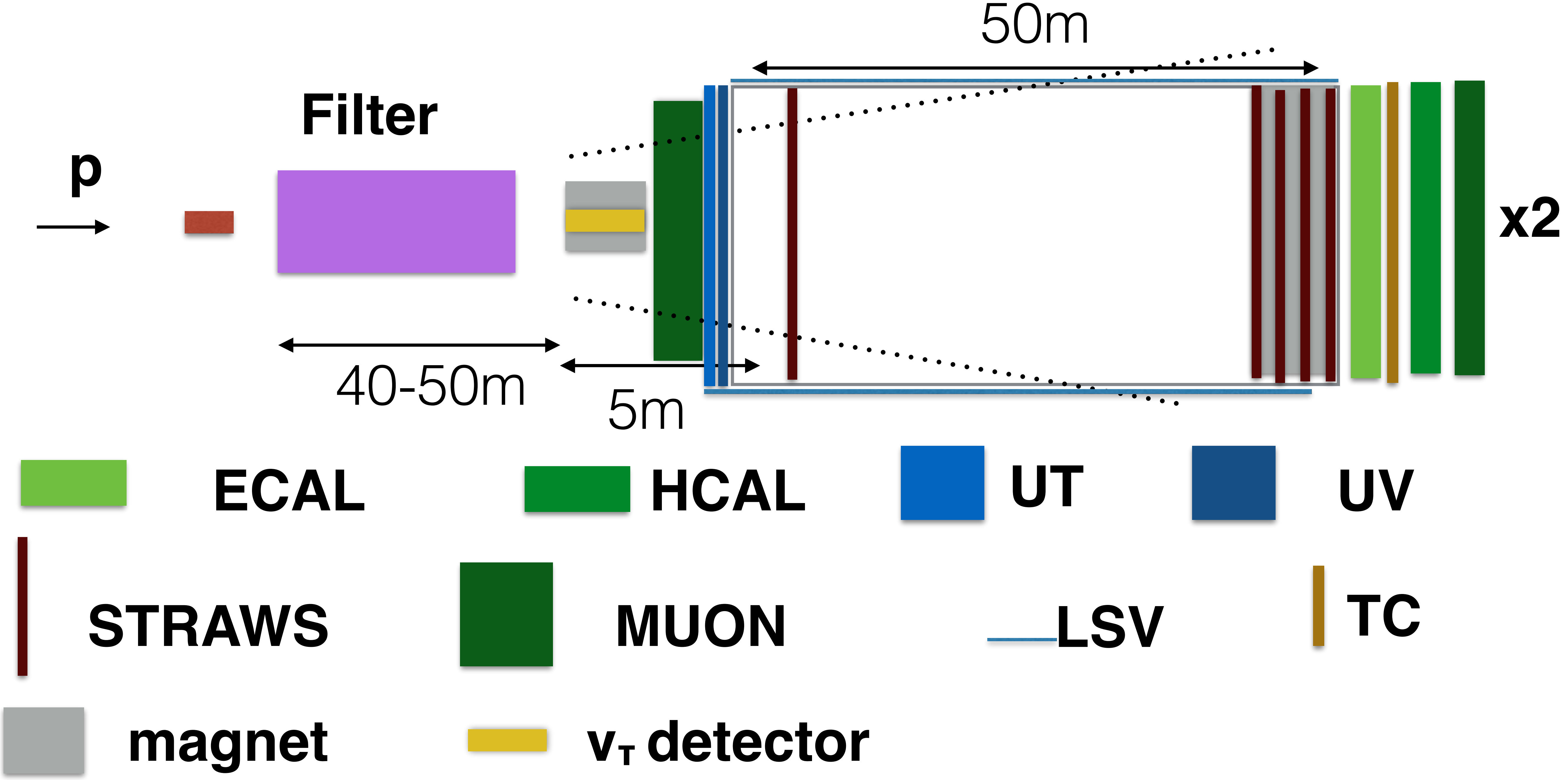
1 sec extraction, continuous

—> this is good for detector operation but does not allow any timing with the beam pulse (e.g. for detecting dark matter particles)

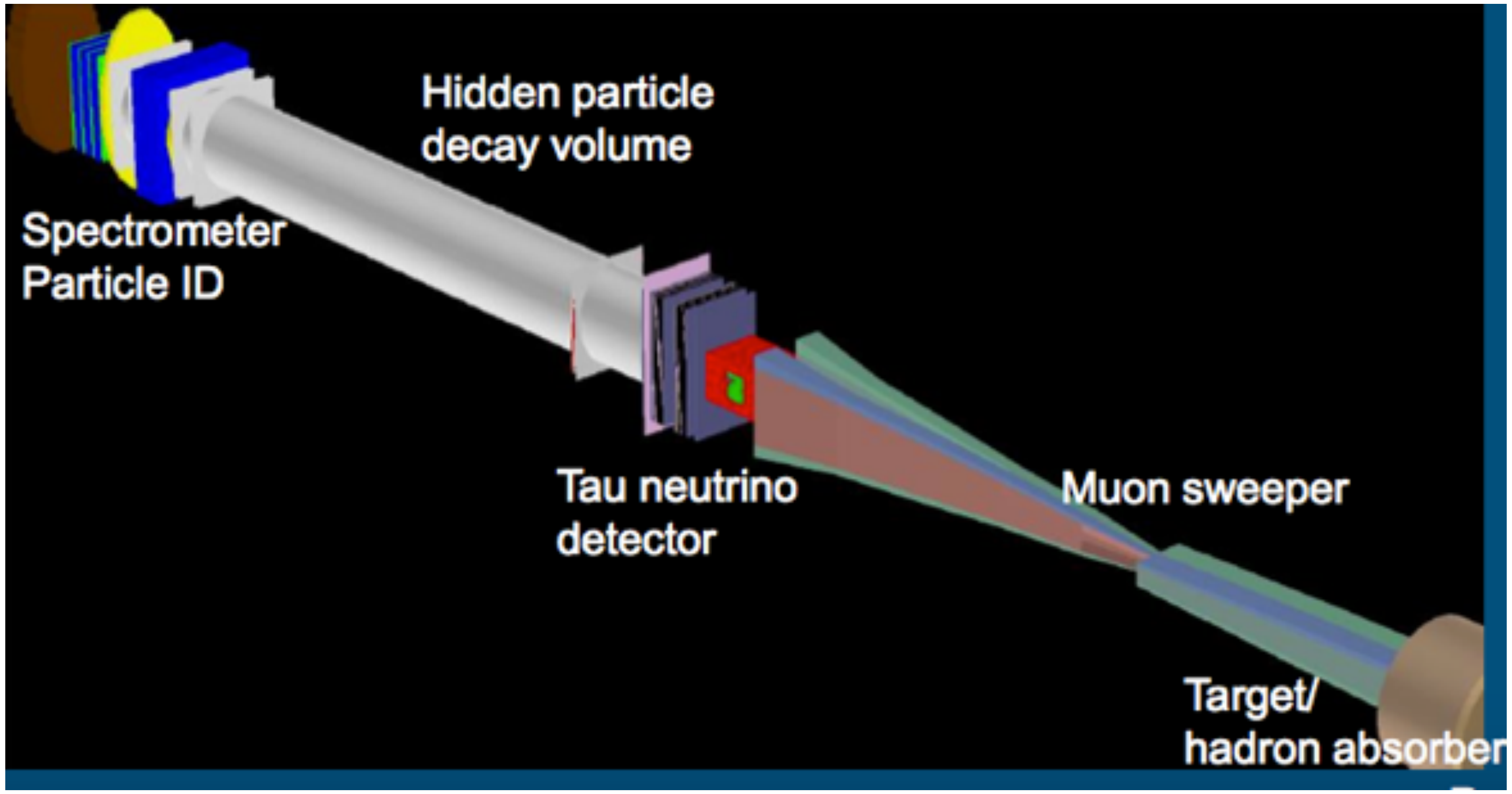
—> under study also the possibility to run with bunched beam

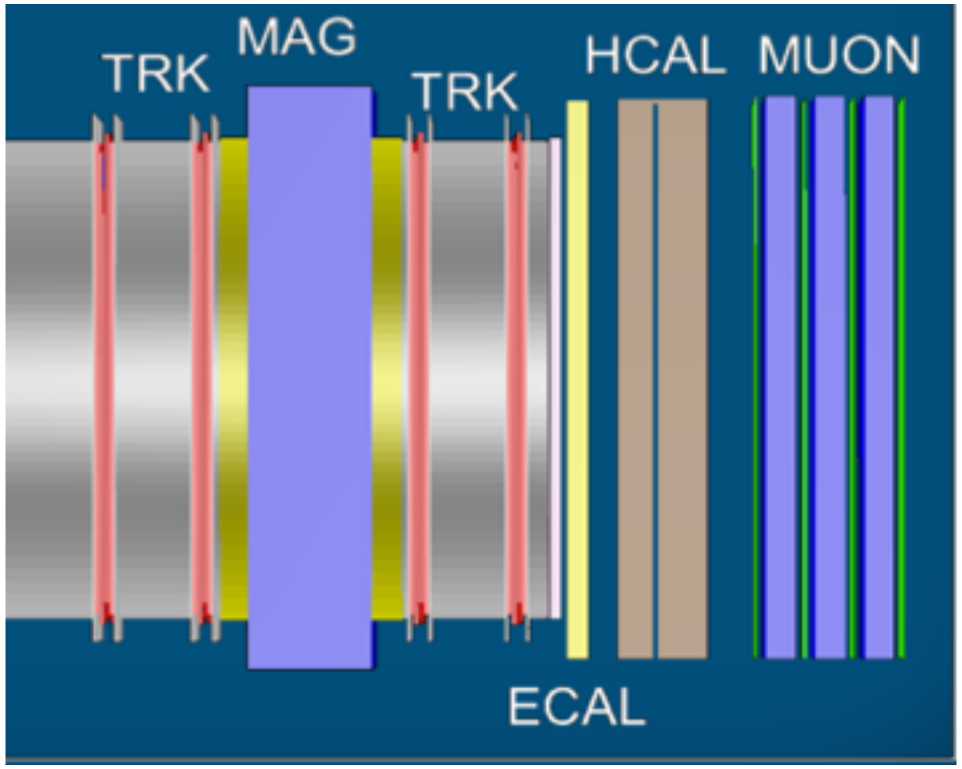


The detectors



In the simulation…





Vacuum 10^{-5}atm (NB: NA62 10^{-8}atm!)

Detectors and DAQ

Almost no R&D to do, we can make it with detectors already built in the past, optimizing the parameters

Muon detector, baseline now is extruded scintillator bars read out by SiPM —> experience from SuperB, but also RPC are considered.

Trigger and DAQ: a simplified version of the HLT of LHCb upgrade (i.e. no L0)

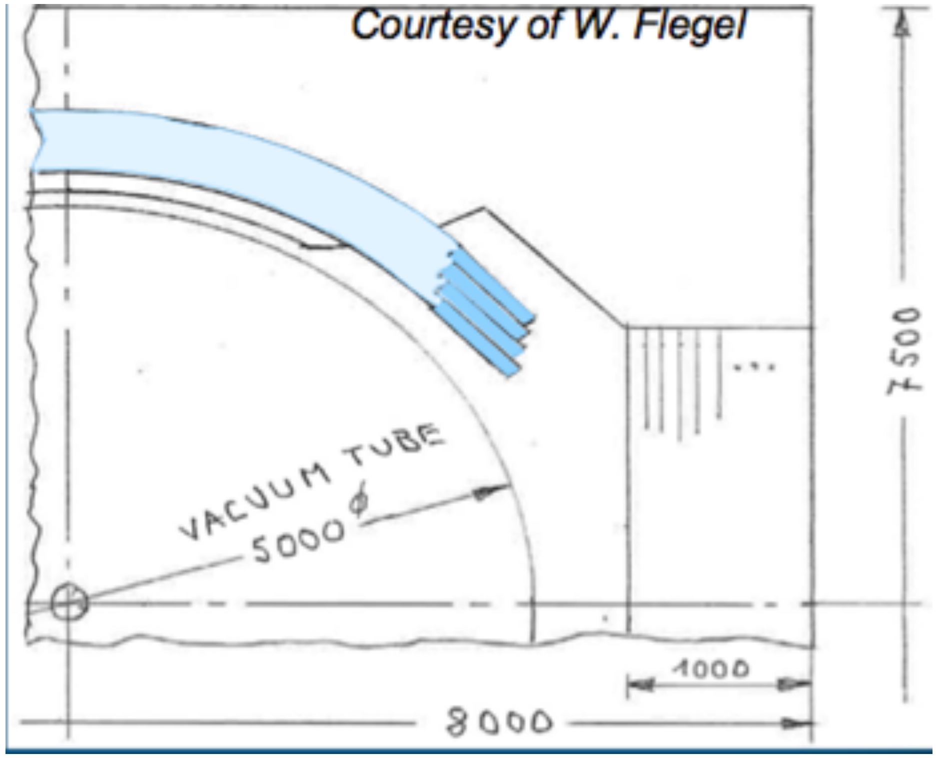
The spectrometer magnet

A dipole magnet very similar to the LHCb one but with 40% less iron and three times less power

LHCb: 4Tm and aperture ~ 16 m^2

This design:

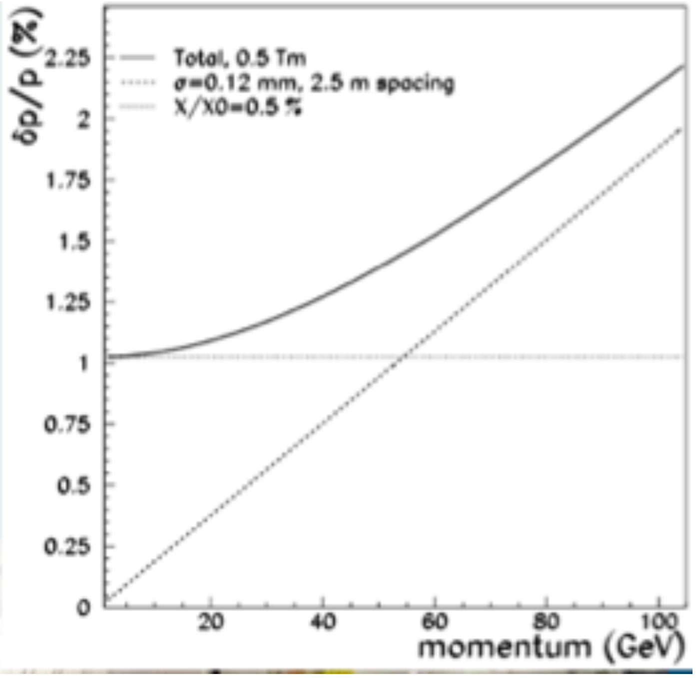
- aperture 20 m^2
- Two coils Al-99.7
- peak B field ~ 0.2 T
- field integral ~ 0.5 Tm su 5 m



Courtesy of W. Flegel

Tracking and VETO

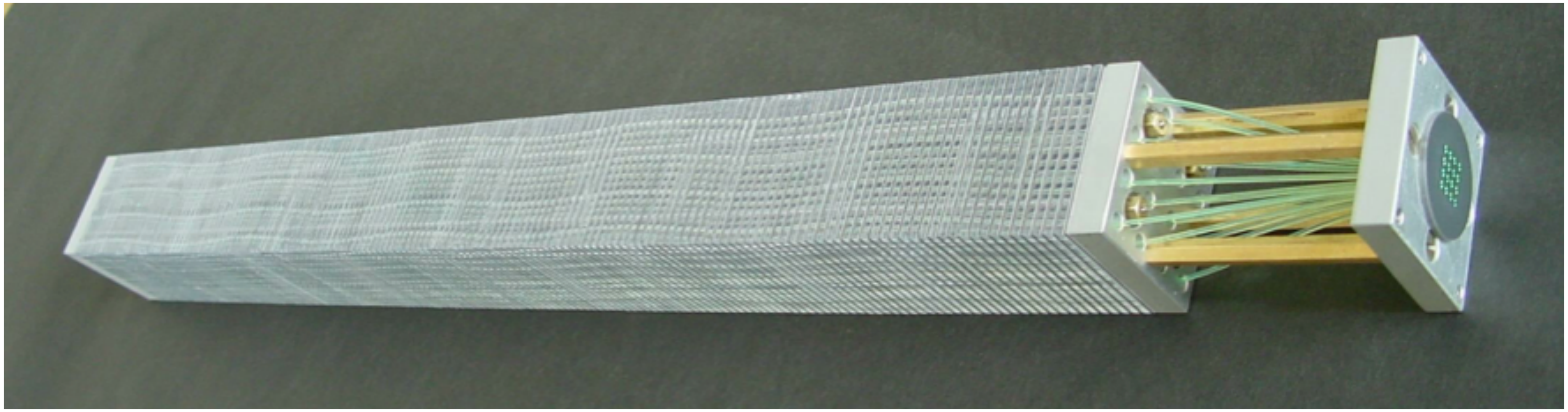
Straw tubes similar to NA62 with 120 μm space resolution, 0.5% X_0/X.



Main difference to NA62:

A. 5m lenght
B. vacuum 10^{-2} mbar
C. 2kHz/straw of 1cm diam

A possibile calorimeter



The spiral Shashlik ECAL

Uniformity few %, time resolution σ~1ns and σ(E)/E=6.5%/√E⊕1%

Backgrounds

We aim at 0 background —>we should have estimates of << 0.1 events in $2x10^{20}$pot

A. **Charged background —> from random combinations of muons from pion decays, (a few 10's in $2x10^{20}$ pot) primarily a background for μμ final states (dark photons, PNGBs and HNL) —>very much dependent on the type of the muon filter**

B. **Neutral background —>background for HNL (K^0_L) and more (n): produced by $\nu\mu$ interactions in the last interaction lengths of the muon filter (about 200 reconstructed $\mu\pi$ pairs in $2x10^{20}$ pot)**

C. **K^0_S—>$\pi\pi$ —> Muon detector and CALO**

Background

A. **Charged background —> detector with timing <100ps (multi-gap RPC like ALICE or MCP and quarz) and UV (a very high efficiency veto) with scintillators upstream of the decay tunnel**

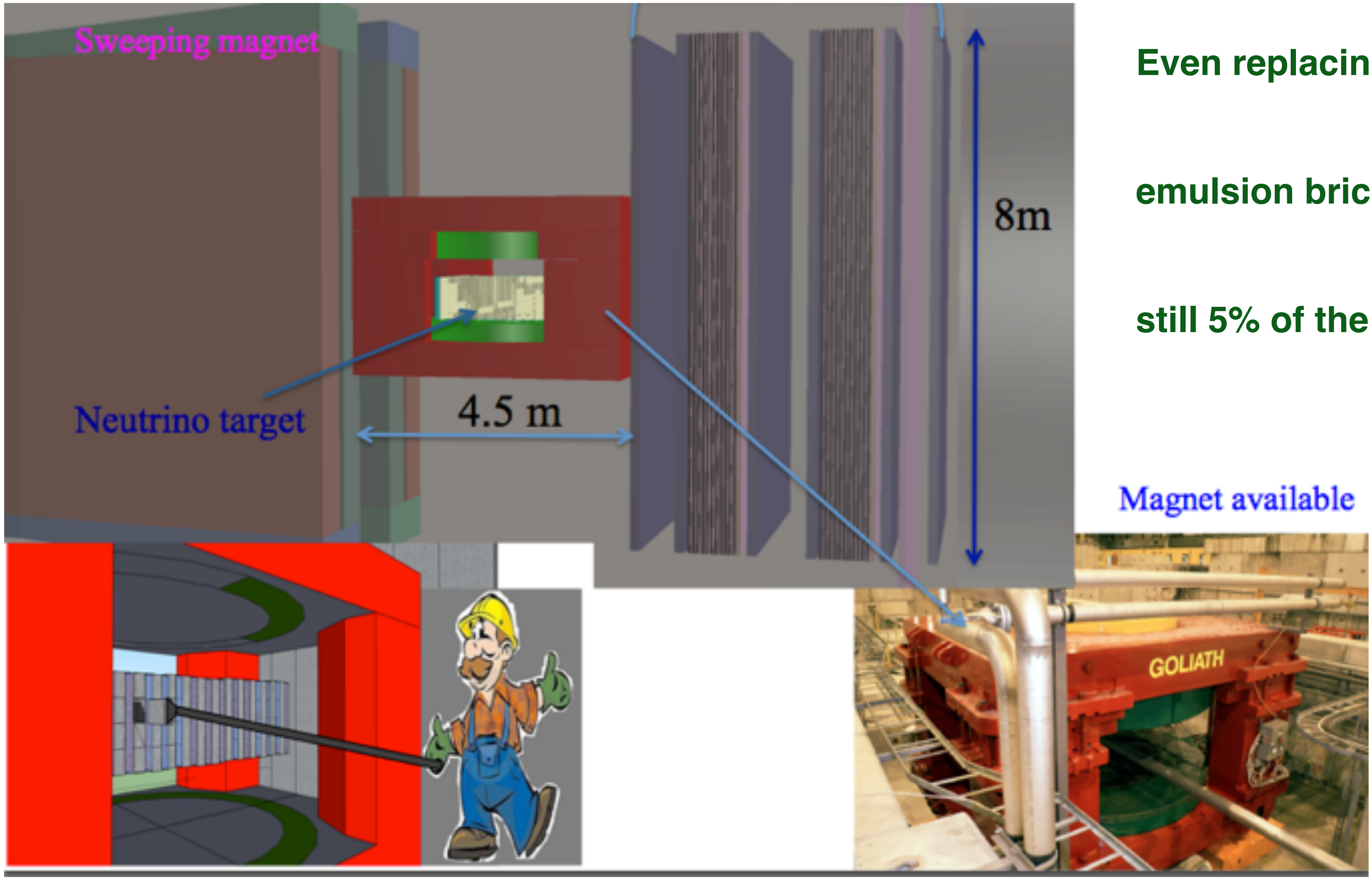
B. **Neutral background —>**

   A. **K^0_L —> kinematic selection (IP,P_T) and equipping the last part of the muon filter with an upstream tagger (UT) to tag the neutrino interactions and PID**

   B. **n —> under study**

Light $\boldsymbol{\nu}$’s detector

Emulsion based detector with the LNGS OPERA brick technolgy, but with a much smaller mass (750 bricks) very compact (2m), upstream of the HNL decay tunnel —> with B field and followed by a muon detector (to suppress charm background)



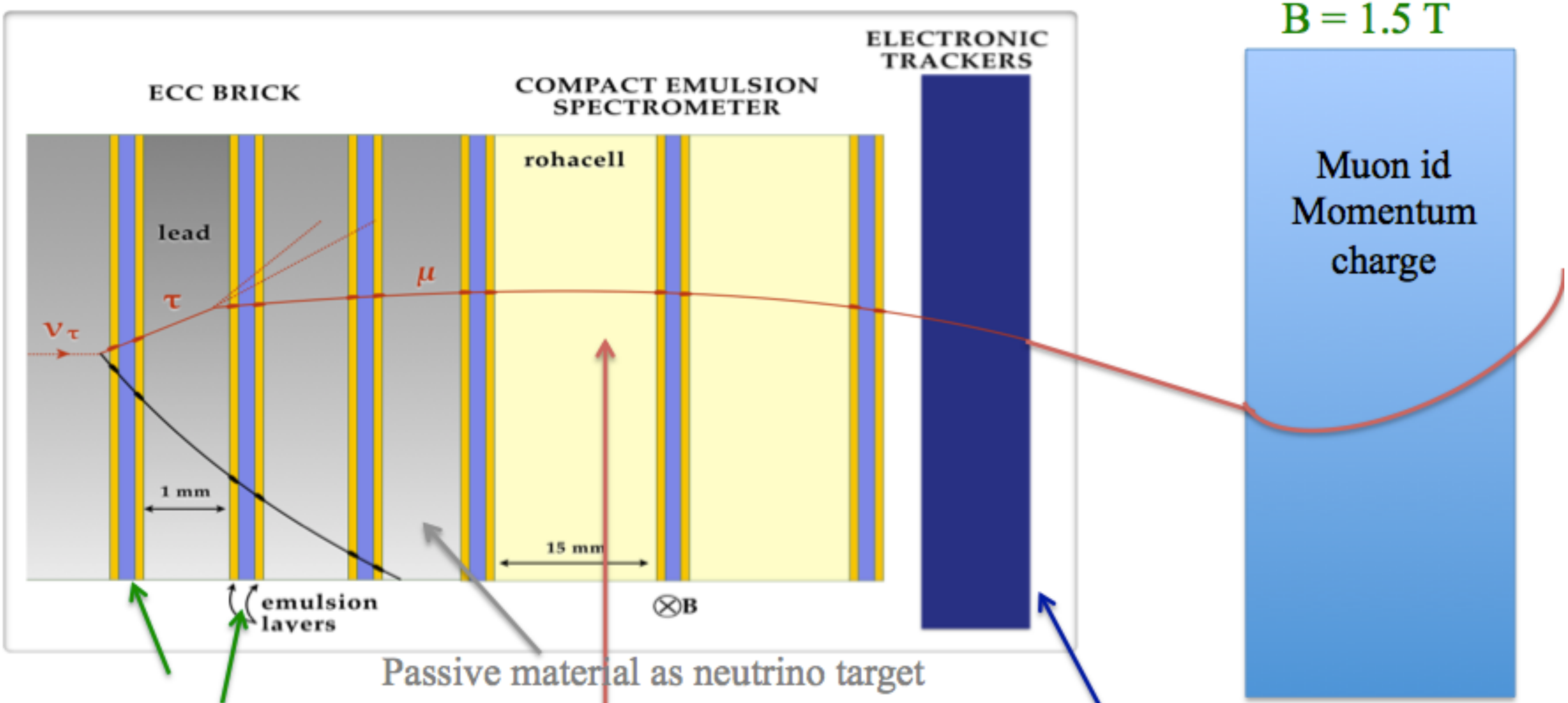
Even replacing 10 times the

emulsion bricks during the run—>

still 5% of the OPERA

Hybrid detector principle

Muon spectrometer
B = 1.5 T



Passive material as neutrino target

Nuclear emulsions as μm accuracy trackers: τ production and decay vertices

Electronic trackers to provide the "time stamp" and match emulsion tracks

measure the charge of τ daughters when magnetized

Active neutrino physics: ν_τ e ν_μ

It is possible to achieve a statistics of reconstructed and selected ν_τ interactions >200x the present one:

DONUT observed 9 events (from charm) with a background of 1.5

OPERA observed 4 events (from oscillations)

In general NP in the third generation (i.e. τ) is experimentally less constrained than the other two families

In particular, two important experimental "anomalies" in the charged flavor sector involve the τ lepton:

- **A. R(D), R(D*) from B factories —>3.4σ from the SM**
- **B. A(CP) (τ—>$\pi K^0_S \nu_\tau$) —>2.8σ from the SM**

Active neutrino physics: $\boldsymbol{\nu_\tau}$ e $\boldsymbol{\nu}_\mu$

A. Integrated and differential ν_τ cross section measurements in CC interaction

—>measurement of form factors F_4 and F_5 in DIS never measured before

B. anti-ν_τ observation (the only SM particle never observed)

C. ν_τ anomalous magnetic moment

D. charm production in ν_μ interactions (large statistical increase, >100x, compared to CHORUS and in particular for the anti-ν_μ, : indeed, in a beam dump anti-ν_μ/ν_μ 60%)

—>sensitivity to the strangeness content of the nucleon

EOI and TP

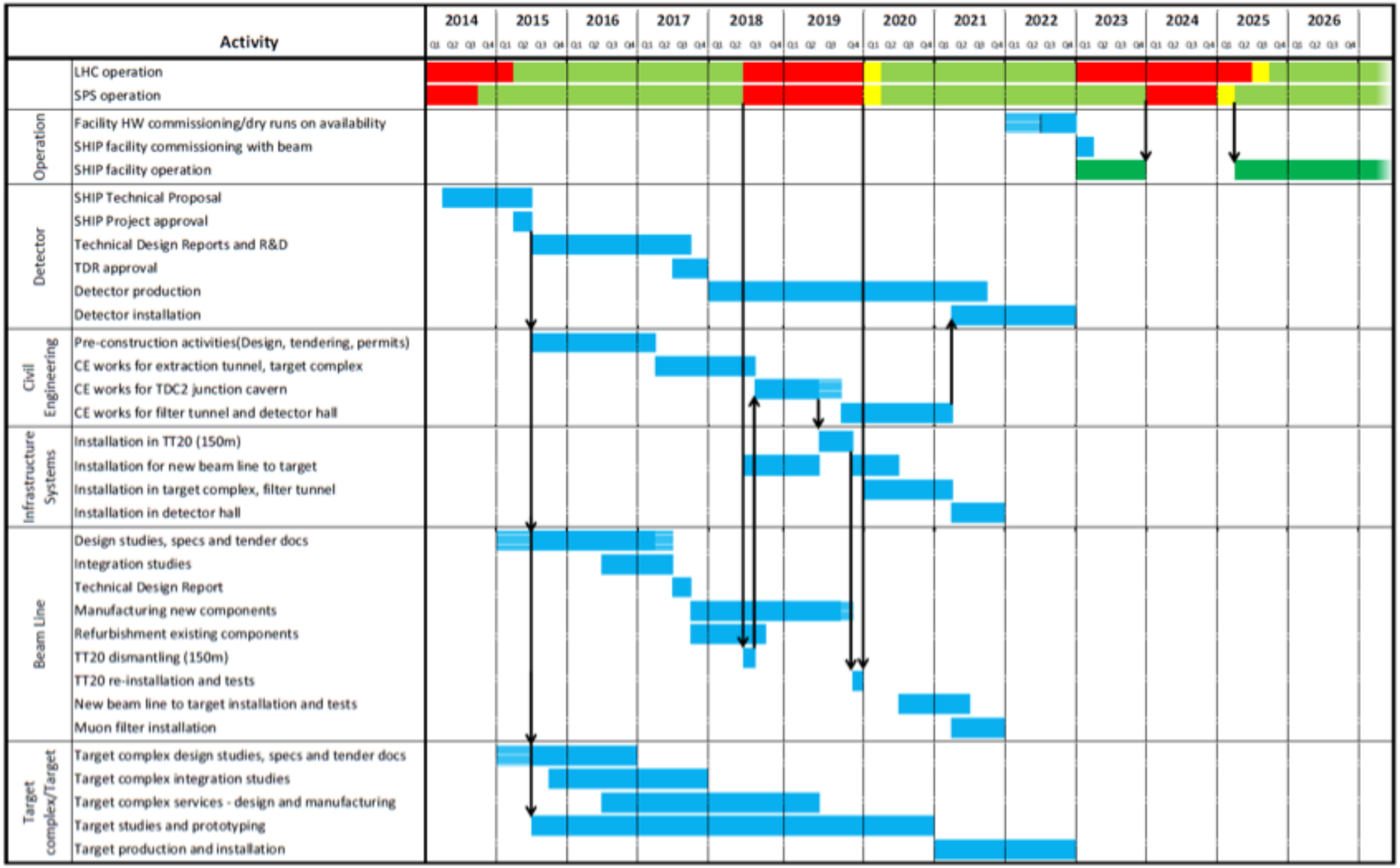
SPC EOI-2013-010 + addendum submitted October 2013

SPSc recommendation:

The Committee **received with interest** the response of the proponents to the questions raised in its review of EOI010.
The SPSC **recognises** the interesting physics potential of searching for heavy neutral leptons and investigating the properties of neutrinos.
Considering the large cost and complexity of the required beam infrastructure as well as the significant associated beam intensity, such a project should be designed as a general purpose beam dump facility with the broadest possible physics programme, including maximum reach in the investigation of the hidden sector.
To further review the project the Committee **would need** an extended proposal with further developed physics goals, a more detailed technical design and a stronger collaboration.

Going for the Technical Proposal by March 2015

Time-table



	Activity
	LHC operation
	SPS operation
Operation	Facility HW commissioning/dry runs on availability
	SHIP facility commissioning with beam
	SHIP facility operation
Detector	SHIP Technical Proposal
	SHIP Project approval
	Technical Design Reports and R&D
	TDR approval
	Detector production
	Detector installation
Civil Engineering	Pre-construction activities(Design, tendering, permits)
	CE works for extraction tunnel, target complex
	CE works for TDC2 junction cavern
	CE works for filter tunnel and detector hall
Infrastructure Systems	Installation in TT20 (150m)
	Installation for new beam line to target
	Installation in target complex, filter tunnel
	Installation in detector hall
Beam Line	Design studies, specs and tender docs
	Integration studies
	Technical Design Report
	Manufacturing new components
	Refurbishment existing components
	TT20 dismantling (150m)
	TT20 re-installation and tests
	New beam line to target installation and tests
	Muon filter installation
Target complex/Target	Target complex design studies, specs and tender docs
	Target complex integration studies
	Target complex services - design and manufacturing
	Target studies and prototyping
	Target production and installation

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

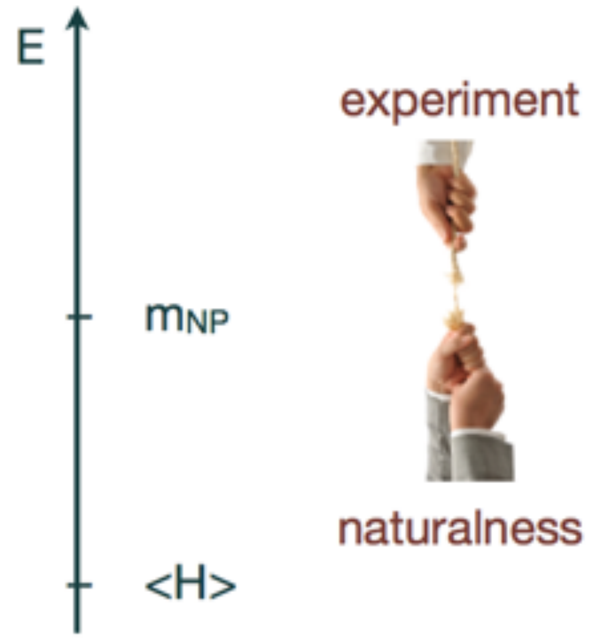
Pursuing a diversity of experimental approaches is very important to maximize our likelihoods of finding NP

The end

The hierarchy problem

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

if there exists a new scalar particle of between EW scale and Planck scale, then mass is not protected against radiative co is brought towards high values—>fine tun 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…

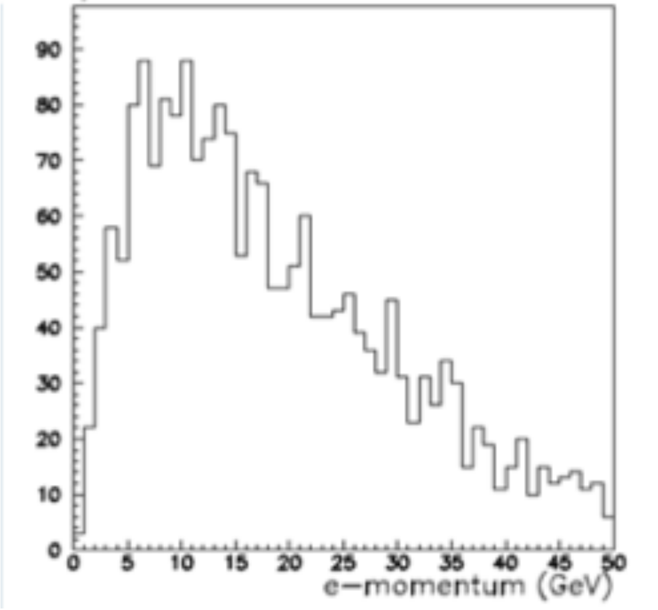
The calorimeter

An e.m. calo allows the reconstruction of additional decay modes:

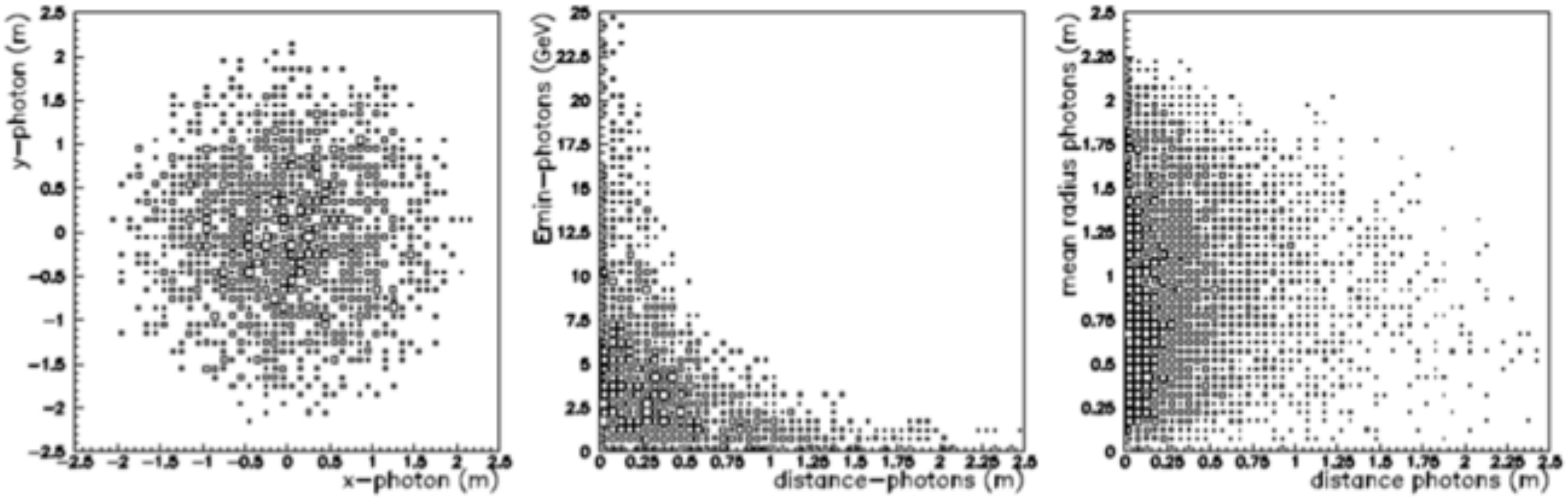
N—>$e^+\pi^-$ allowing to access the limit on Ue (since the flavor structure is not known these channels could also be favored)

N—>$\mu^+\rho^-$ with ρ^- —>$\pi^-\pi^0$ that allows to improve the limit on U_μ (about the same BR of μ+π-, for m>700Mev)

$N_{2,3} \rightarrow e\pi$: Energy of electron



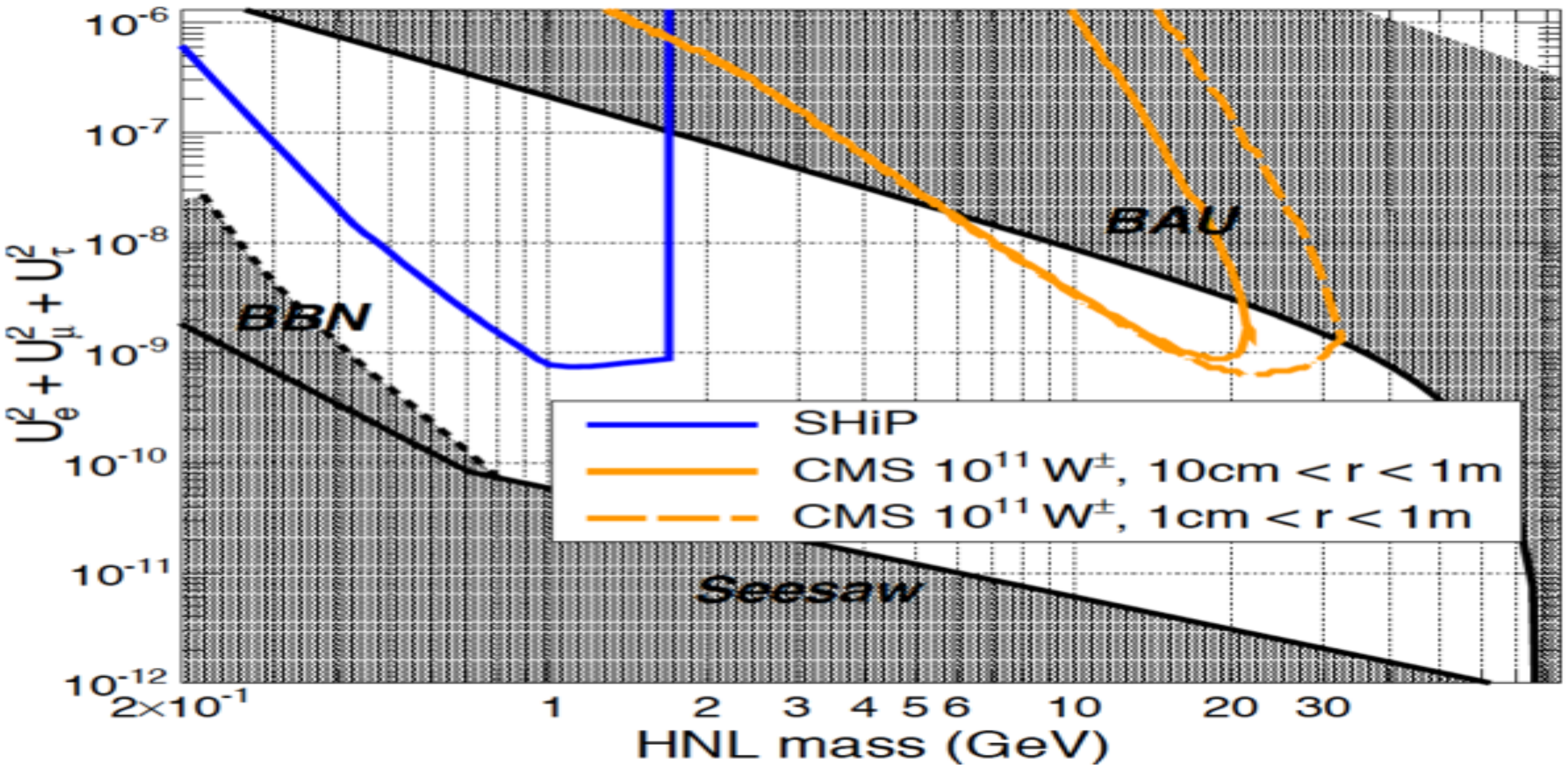
$N_{2,3} \rightarrow \mu\rho$, $\rho \rightarrow \pi\pi^0$: Position and energy of photons



Assuming 10x10cm2 cells

How to go to higher masses(ii)

CMS 10^{11} W , assuming zero background



Light scalar

Properties of the scalar: if y=sin ρ

couples to SM particles with a factor y^2 compared to the Higgs;

production cross section is proportional to y^2;

lifetime is inversely proportional to y^2 and depends on the mass (the more channels become kinematically accessible the shorter the lifetime);

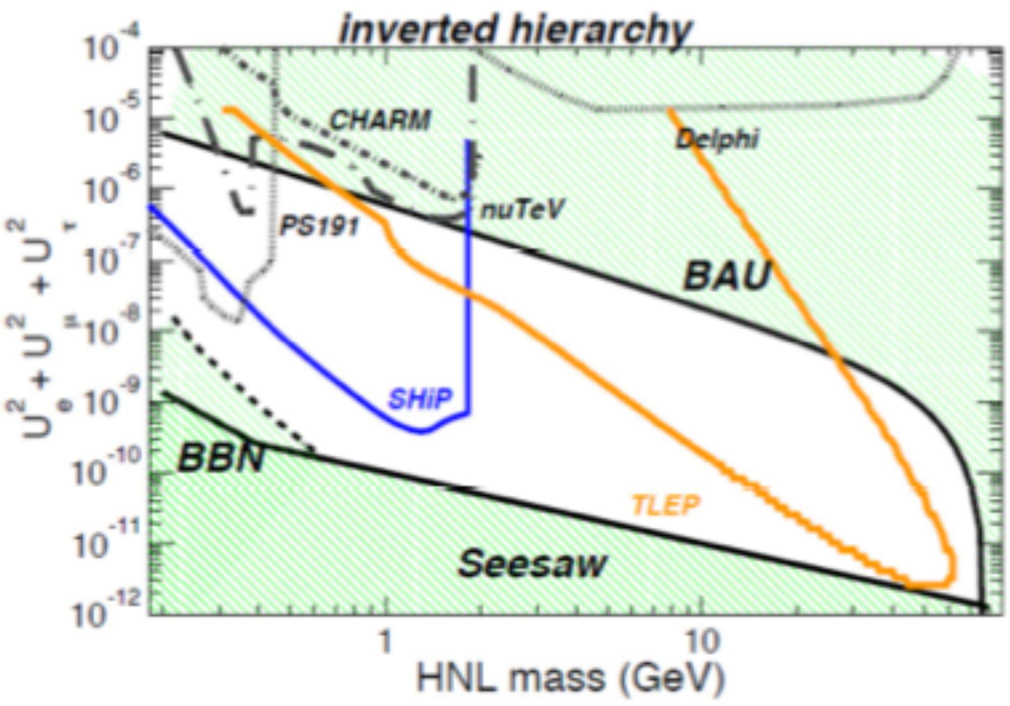
the branching fractions do not depend on y^2;

How to go to higher masses

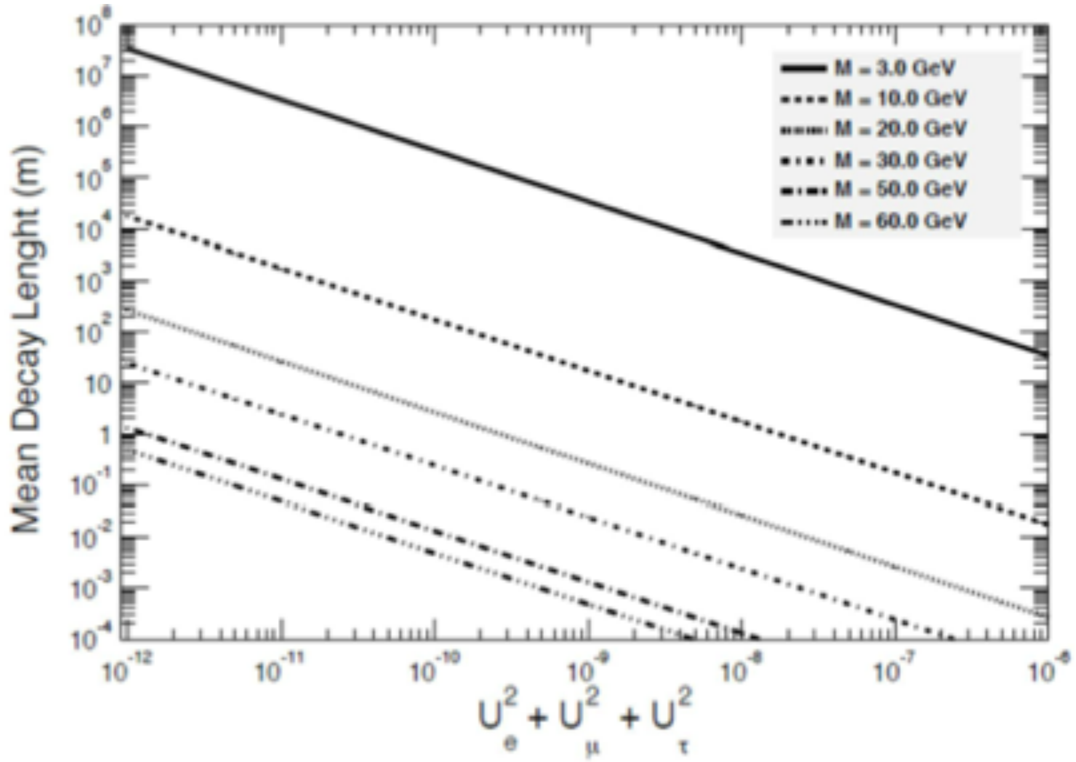
Use processes Z—>Nν with N—>lepton + 2 jets
BR(Z —>νN) ≅ BR(Z—>νν)×U², $\Gamma_N \cong G_F^2 \times M_N^5 \times U^2 \times N_{\text{decay channels}} / 192\pi^3$

Assuming data sample of 10^{12} Z decays one can reach very interesting sensitivity for $M_N > 10$ GeV

Expected sensitivity of FCCin e^+e^- mode, assuming zero background



Inverted hierarchy, decay length 10-100cm, 10^{13}Z



A.Blondel , ICHEP 2014