SHiP:

Search for Hidden Particles

A new experiment proposal at CERN

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on behalf of the SHIP collaboration (235 authors, 45 institutions from 14 countries)

The TP: submitted 14 April to CERN/SPS-C

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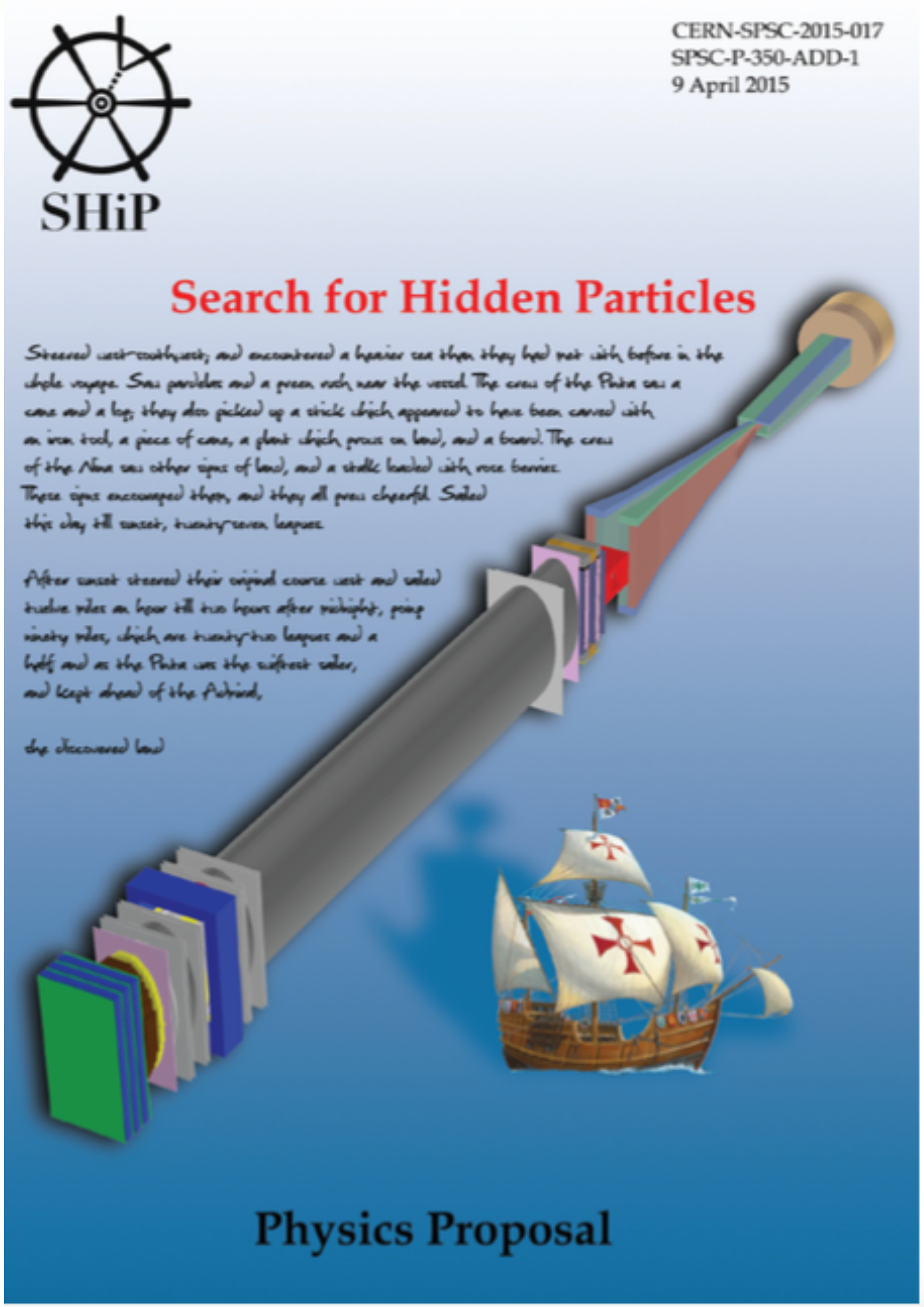
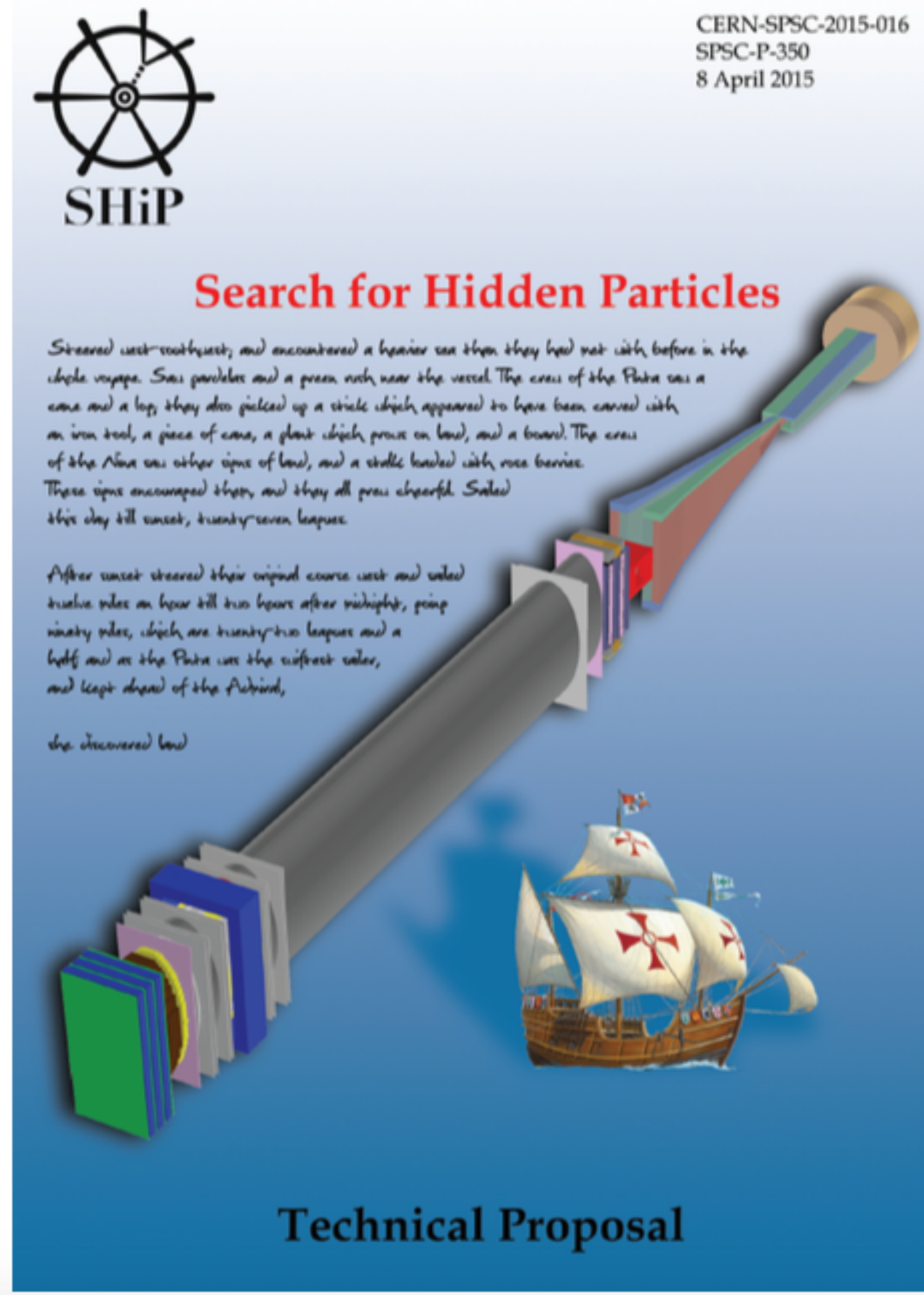
Under review

A large (15% in total number of physicists) INFN participation (BA,BO,LNF,CA,NA,FE,RM1) with many leadership roles since the EOI !!

INFN



CERN-SPSC-2015-017
SPSC-P-350-ADD-1
9 April 2015
SHiP
Search for Hidden Particles
Physics Proposal



CERN-SPSC-2015-016
SPSC-P-350
8 April 2015
SHiP
Search for Hidden Particles
Technical Proposal

Addendum to the TP

We are submitting this also this week to SPSc

What is SHIP

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

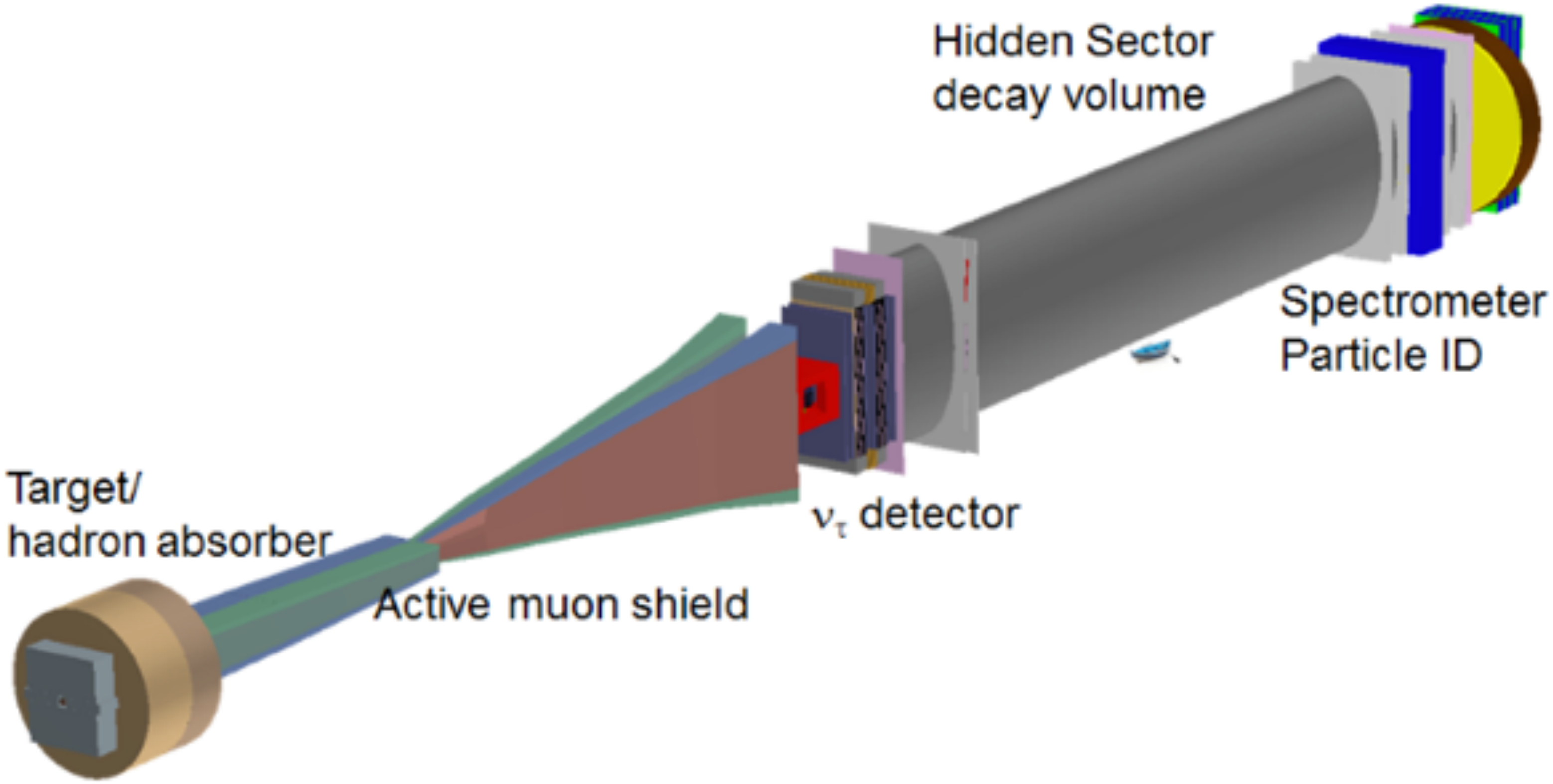
Main goals (so far…):

1) **detection of long lived particles, very weakly interacting or sterile:** statistical sensitivity with respect to previous experiments of similar type (for HNL) x**10000**

—> 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 x**600**

How?



The high E proton beam of CERN (400GeV)…

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

signature: a >= two track decay vertex in the decay tunnel

Shaking hands…

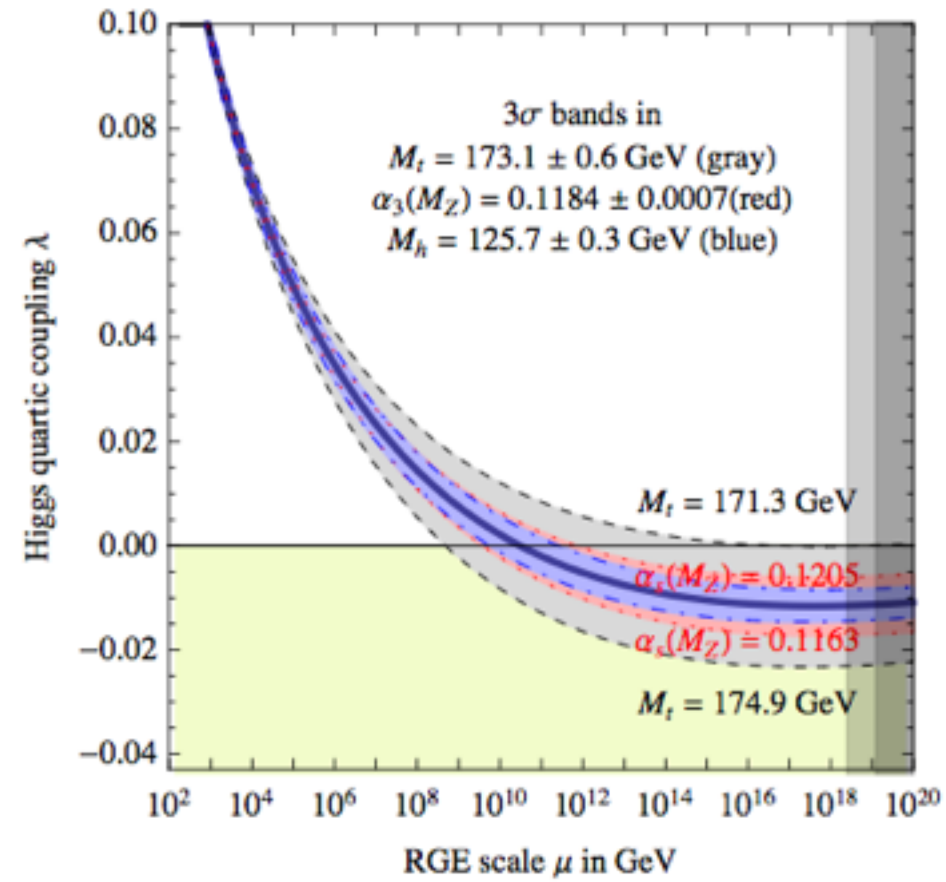
SM was recently fully confirmed by the Higgs-boson discovery!

However…

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

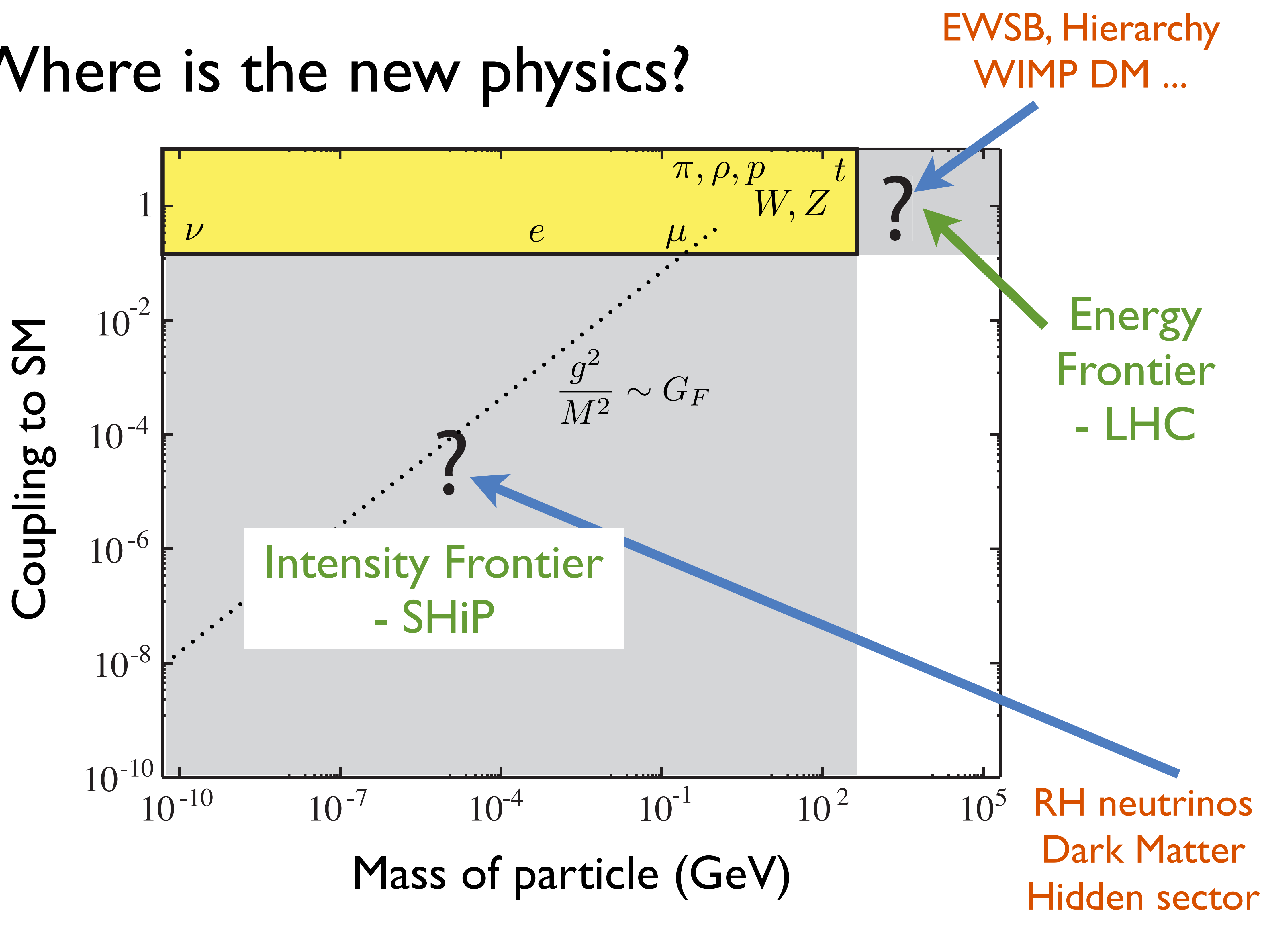
The peculiar Higgs mass suggest that, even in absence of NP, the Universe is metastable.

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?



The Hidden Sector

Leading SM coupling to Neutral Hidden Sector

Portals

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

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)

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

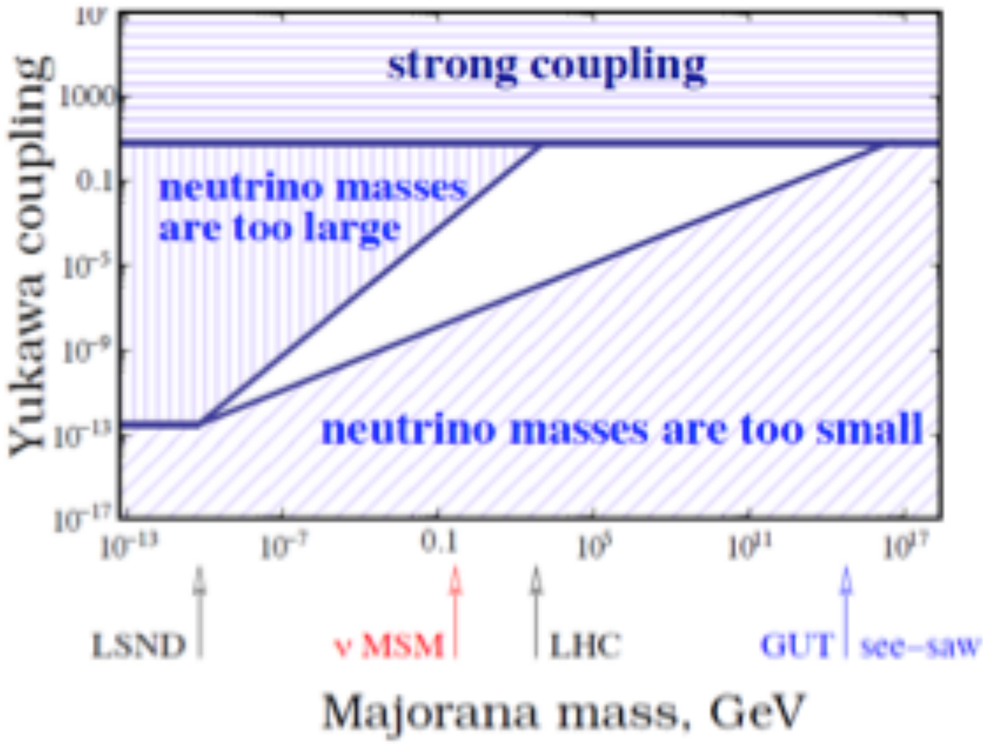
The scale of the active neutrino mass is given by the see-saw formula: $m_\nu \sim \frac{m_D^2}{M}$

where $m_D \sim Y_{I\alpha} v$ - typical value of the Dirac mass term

$v \sim 246$ GeV

Example:

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



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The νMSM and its variants

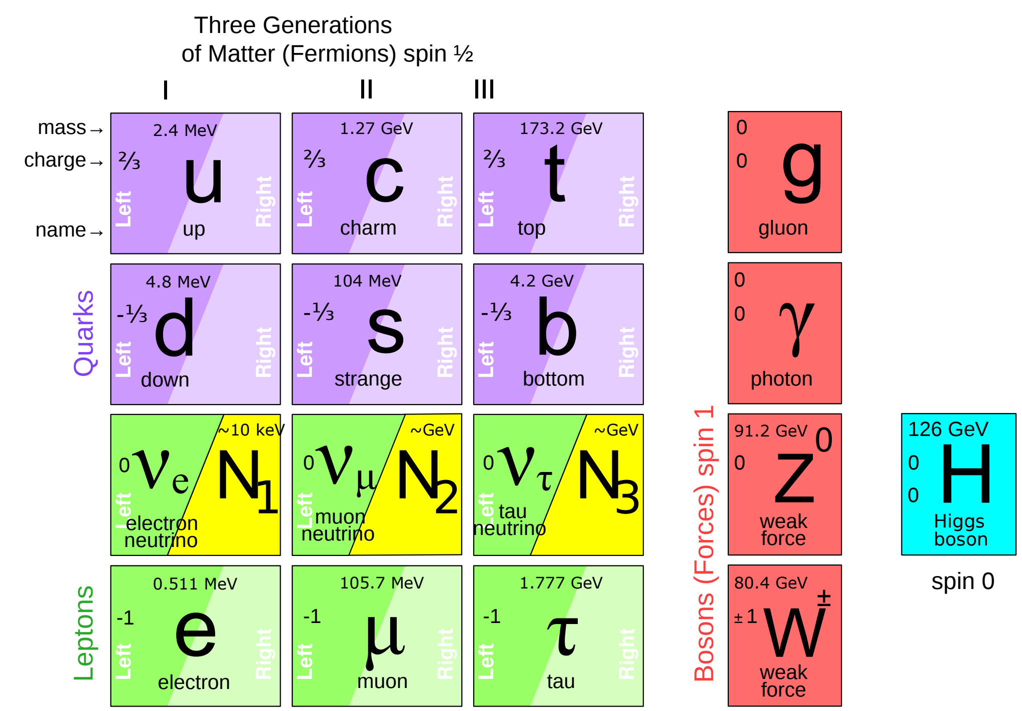
3 Majorana (HNL) partners of ordinary ν, with $M_N<M_W$

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

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

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



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

$N_{2,3}$ production

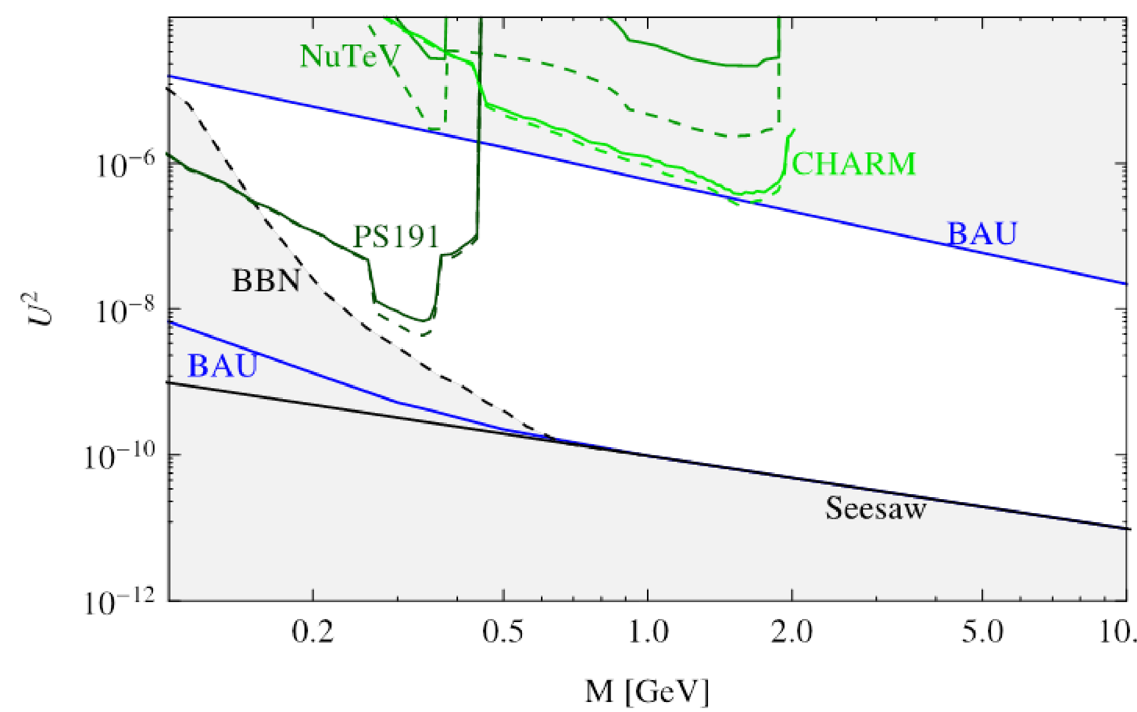
inverted mass hyerarchy

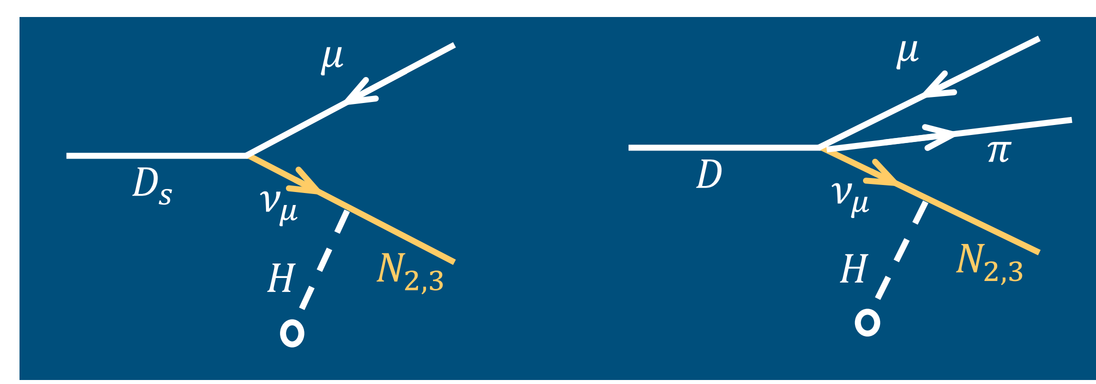
Interaction with the Higgs v.e.v. —>mixing with active neutrinos with U^2

in the vMSM 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)

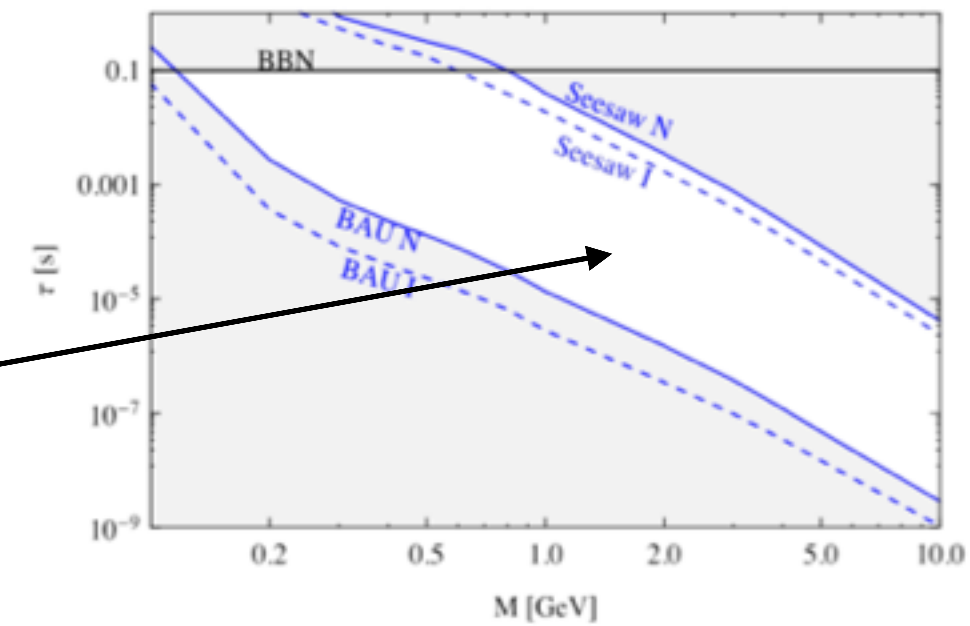




$N_{2,3}$ decays

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

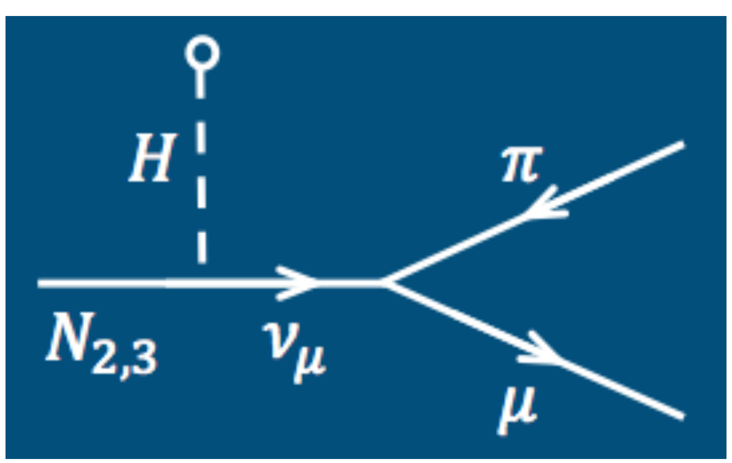


Various decay modes : the BR's depend on flavor mixing

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 %

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

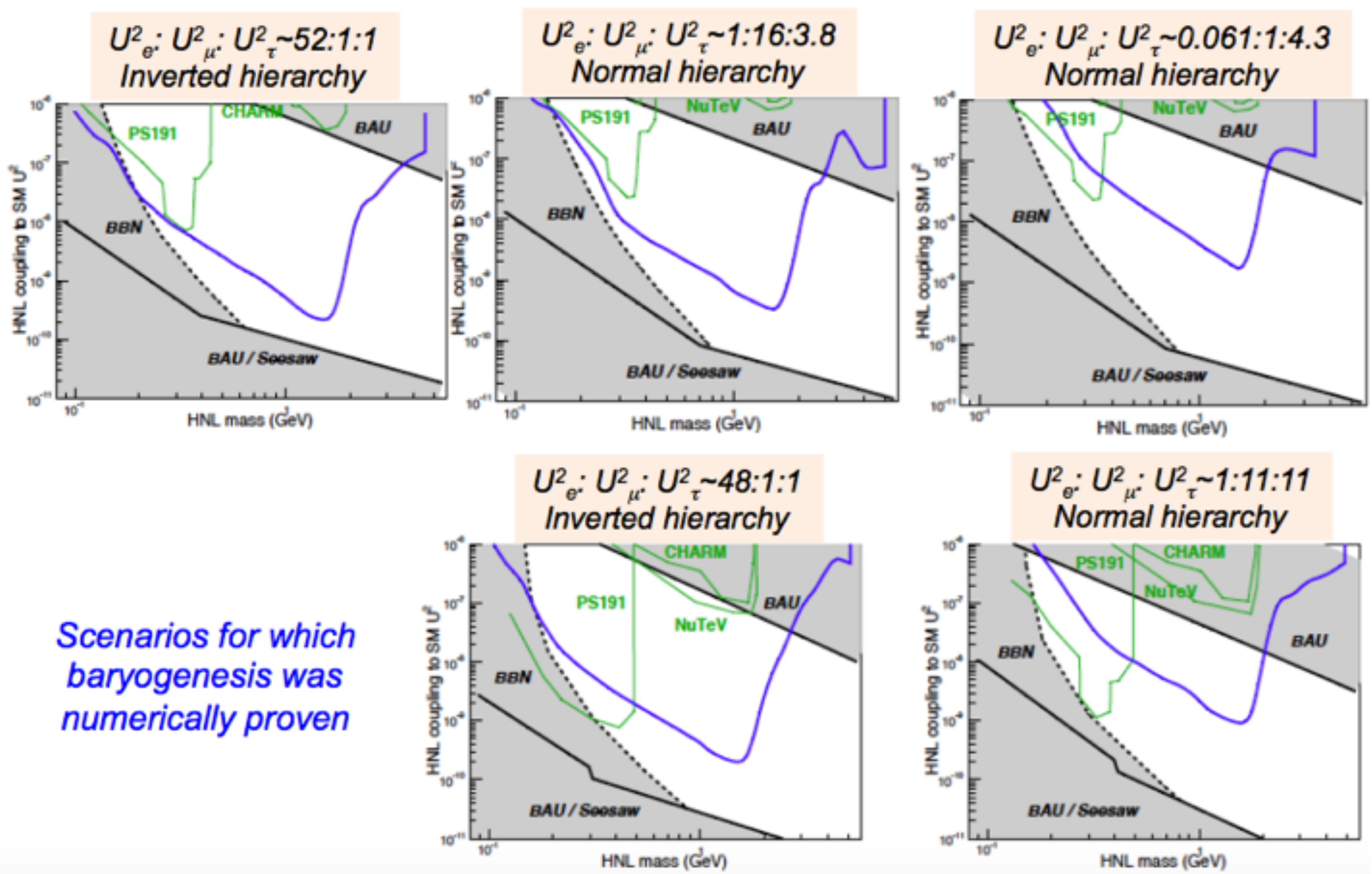
—> number of events $\propto U_\mu^4$

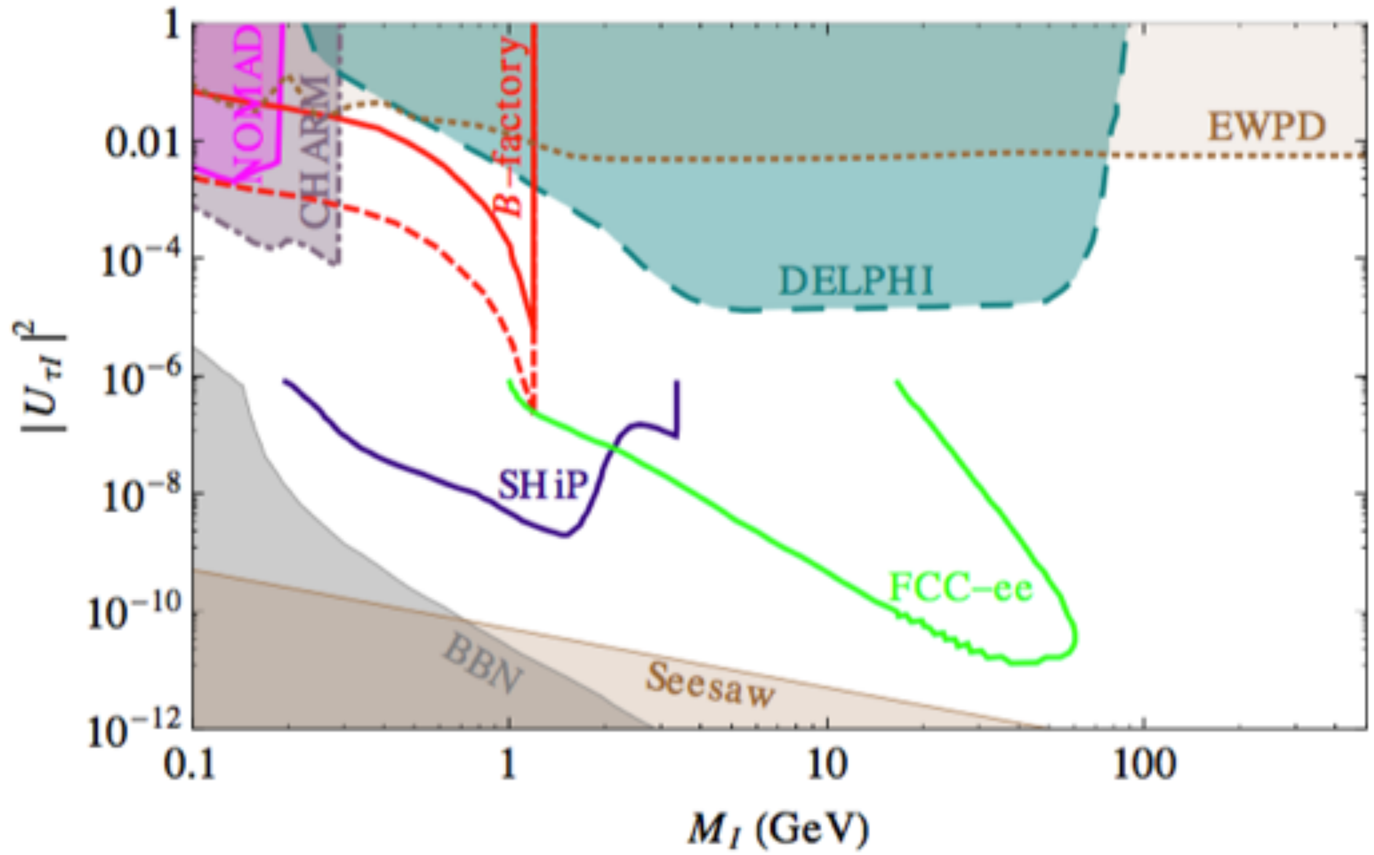


SHIP sensitivity to HNL

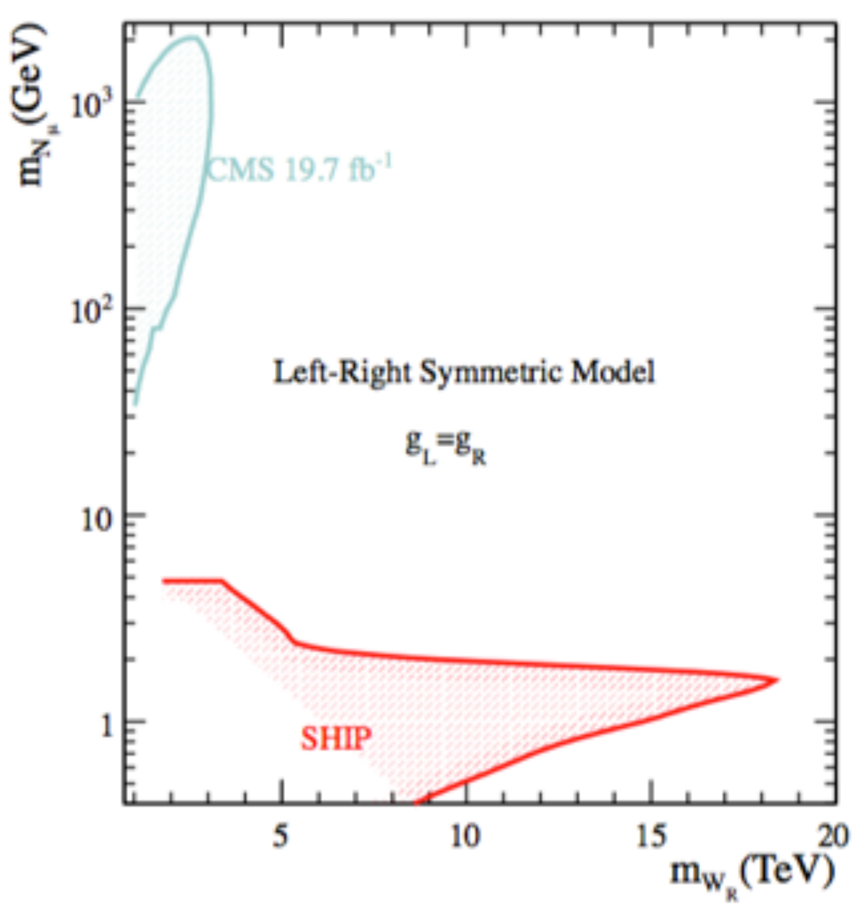
SHIP will scan most of the cosmologically allowed region below the charm mass

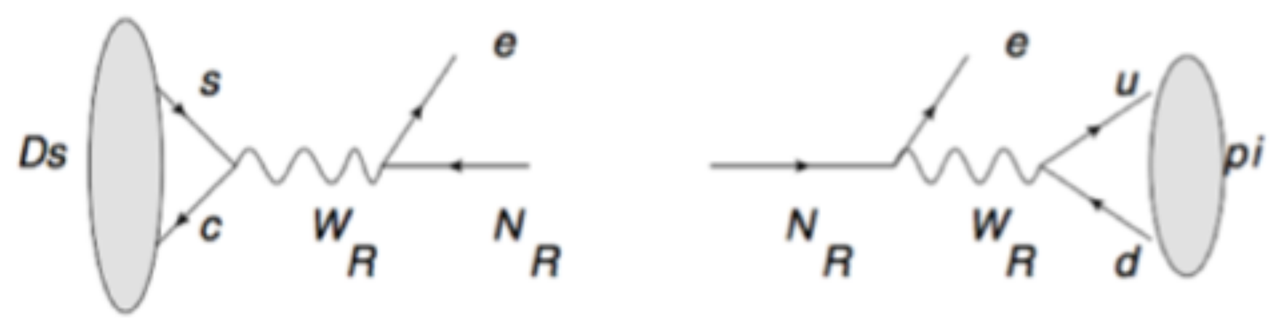
Reaching the see-saw limit would require increase of the SPS intensity by an order of magnitude (does not currently seem realistic)





Comparison with others



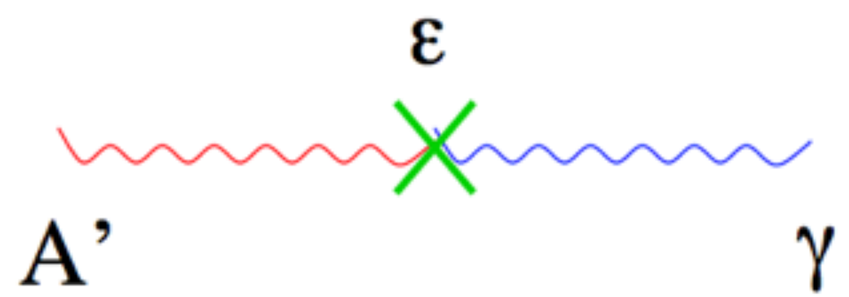


Interpretation in context of Left-Right symmetric model

Portals to Hidden Physics

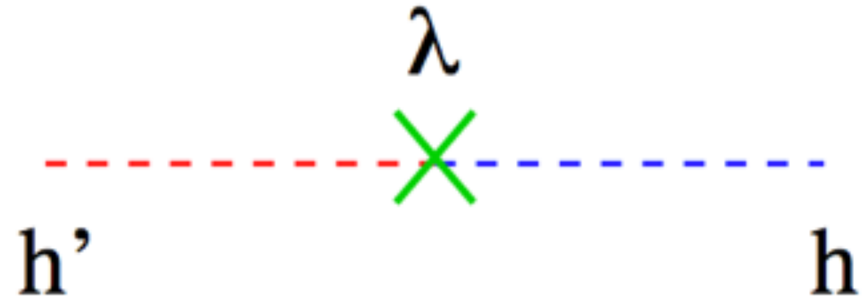
- Two nice ways for new hidden physics to couple:
  - Vector Portal:
    (A’ = “hidden photon”)

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



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

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



(+A |H’| |H|²)

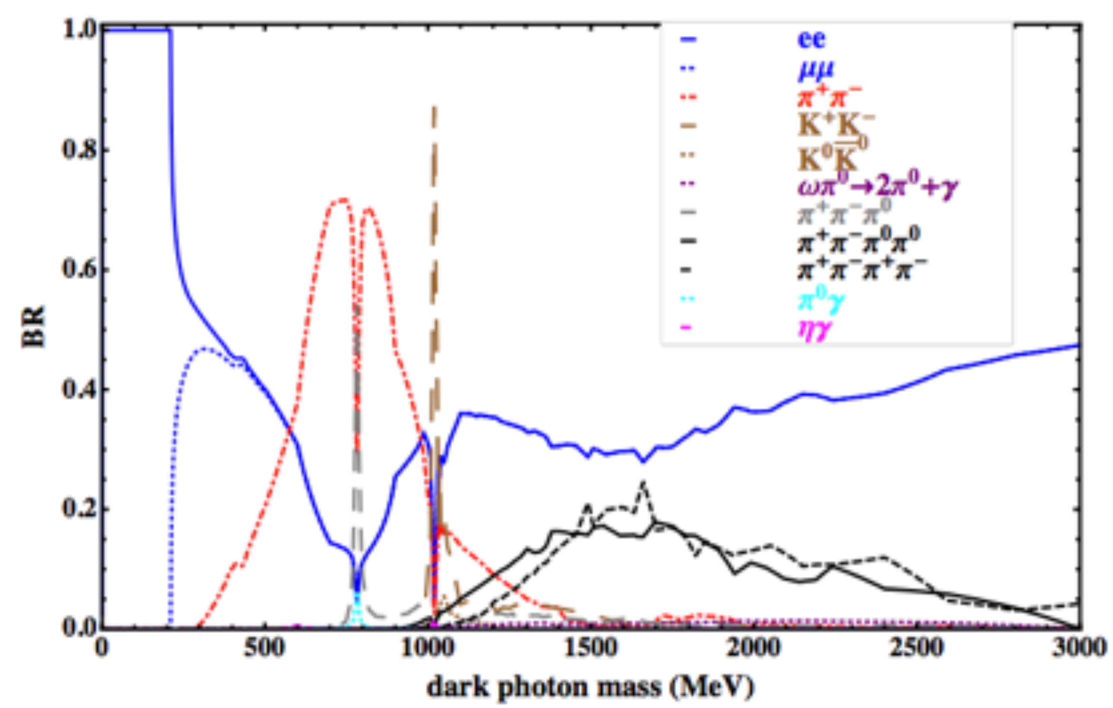
Minimal vector portal

Three photon production modes considered:

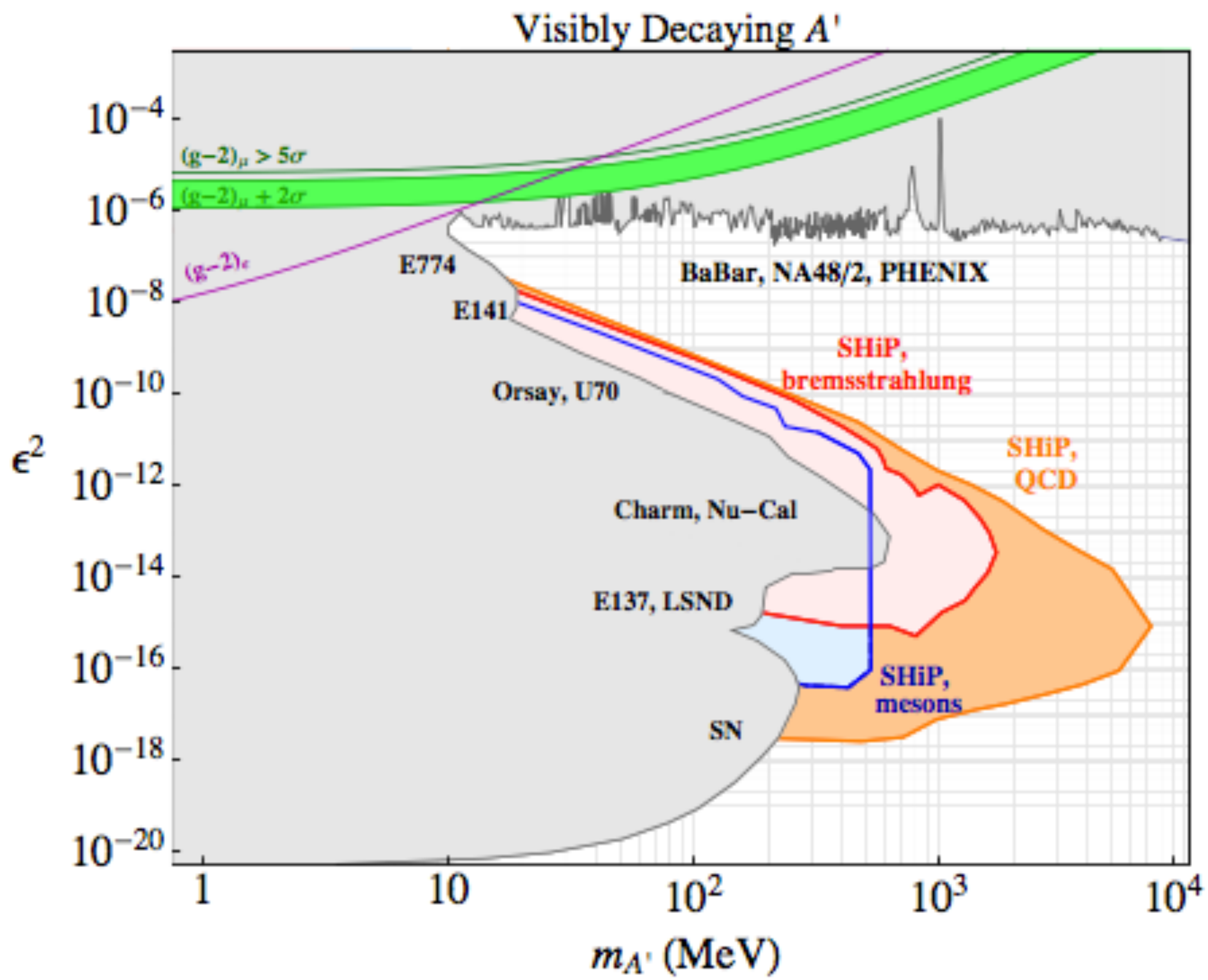
1) in pseudo-scalar decays
2) in proton brehmsstrahlung **Physics Letters B 731 (2014) 320–326**
3) QCD production (Batell et al. 2015)

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

decay to SM particles

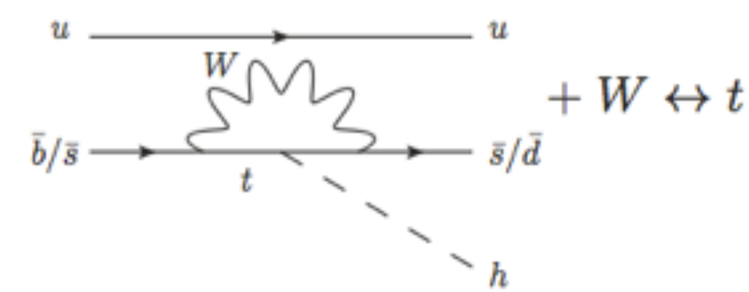


Dark photons



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

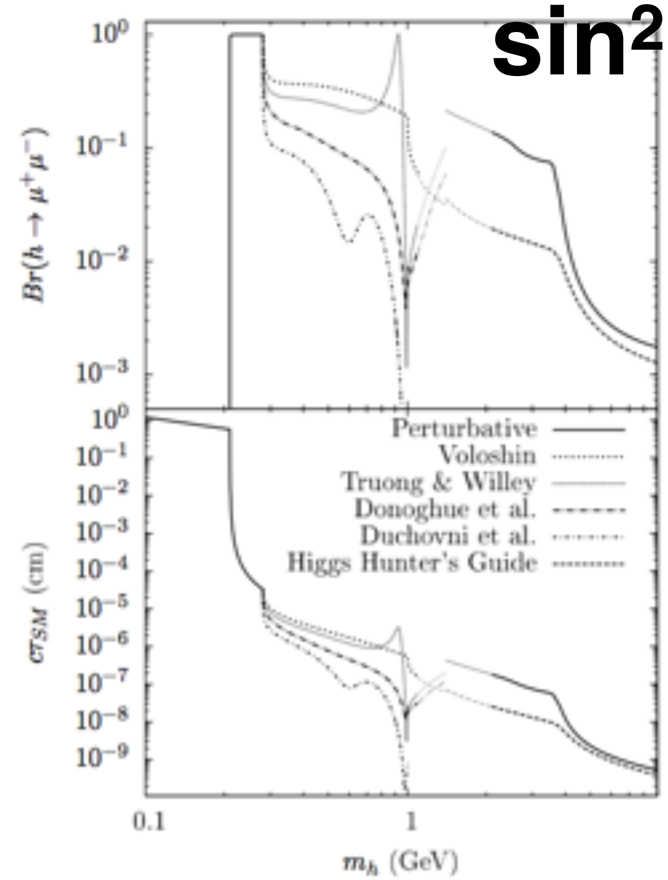
Scalar (Higgs) portal: production/decay

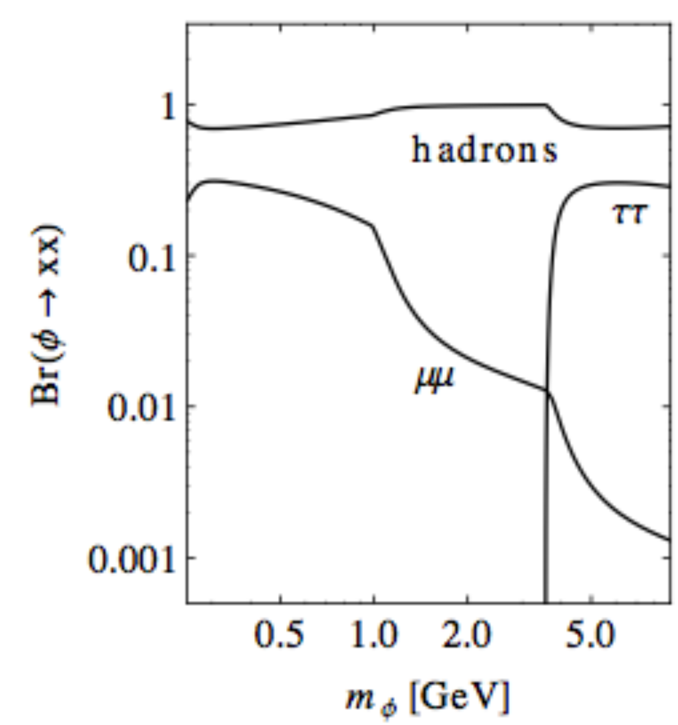


Production via meson decay, D CKM suppressed wrt B ($5x10^{-10}$) and D cross section only 20k times larger than B cross section at 27GeV

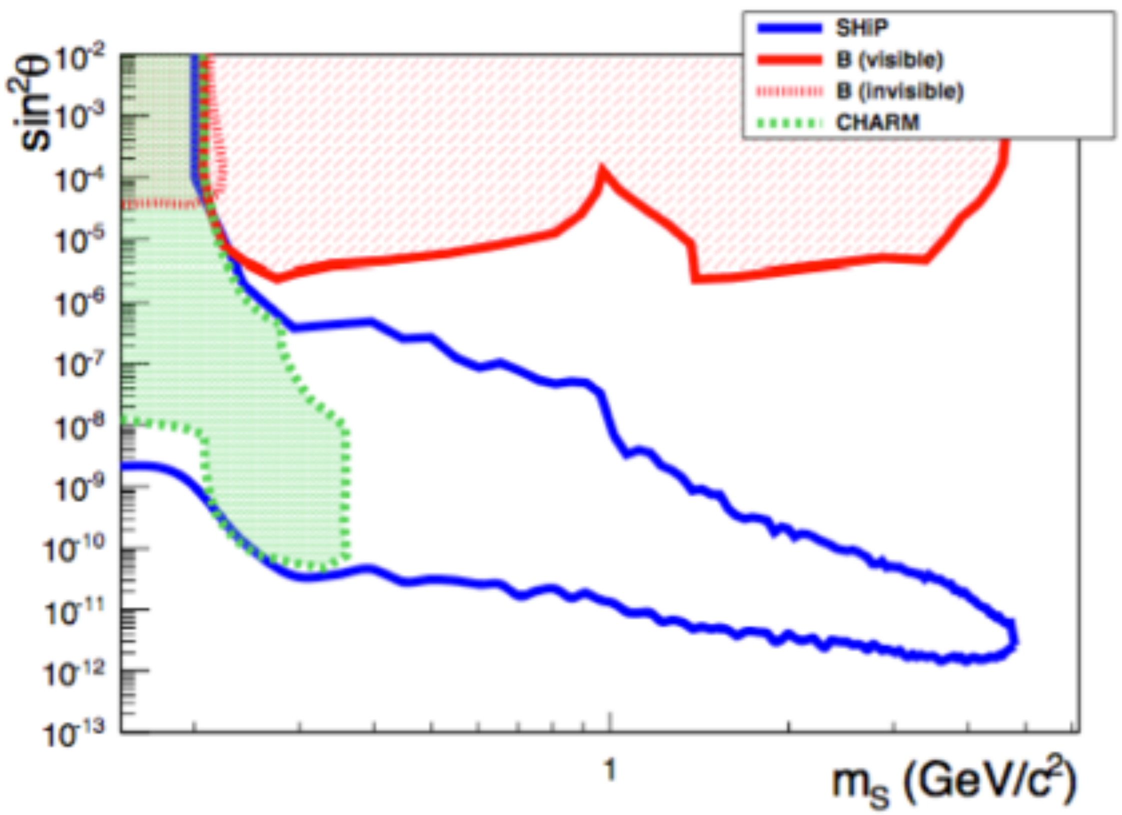
Some uncertainty in the calculation of BR's

$\sin^2\rho=1$

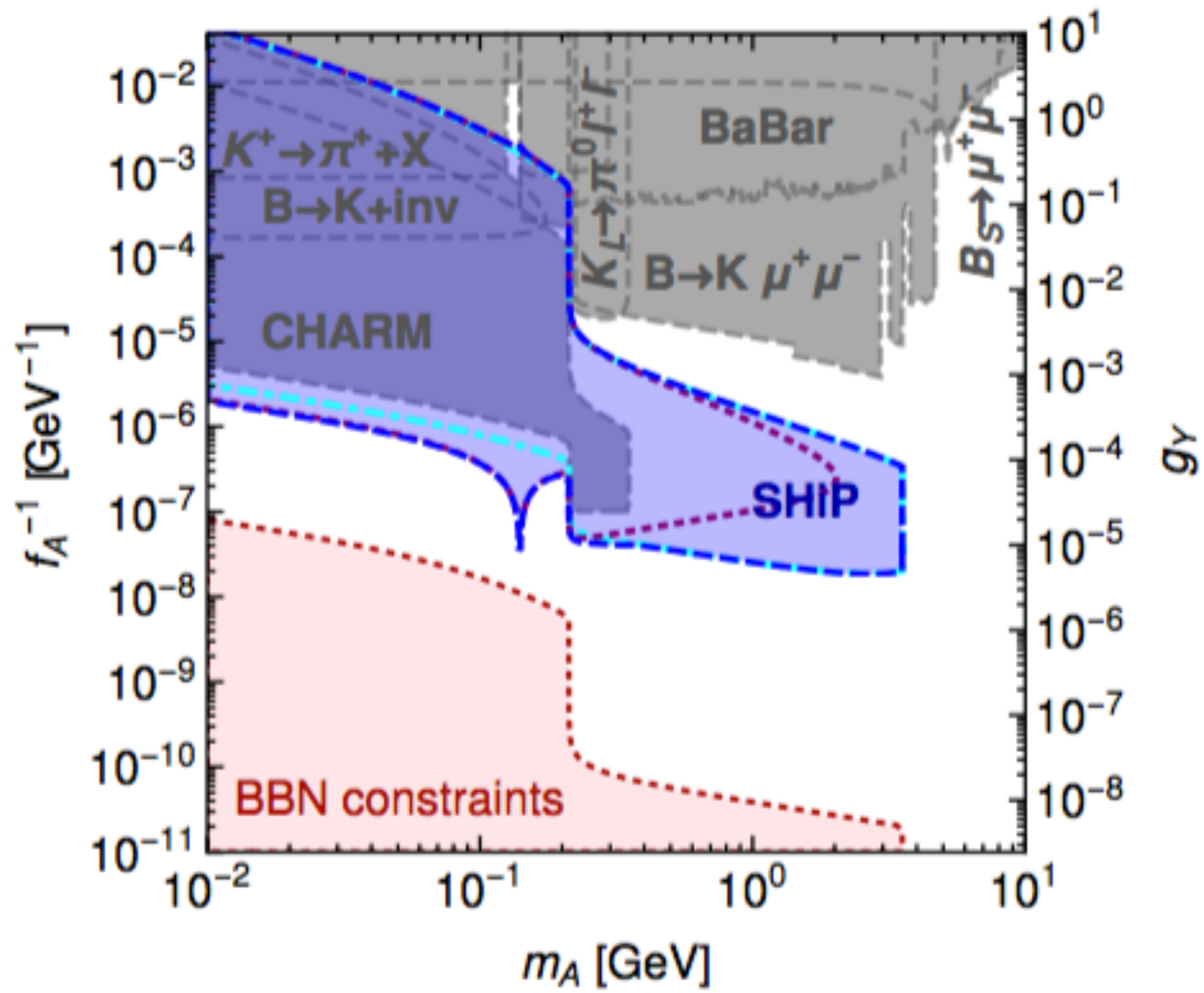




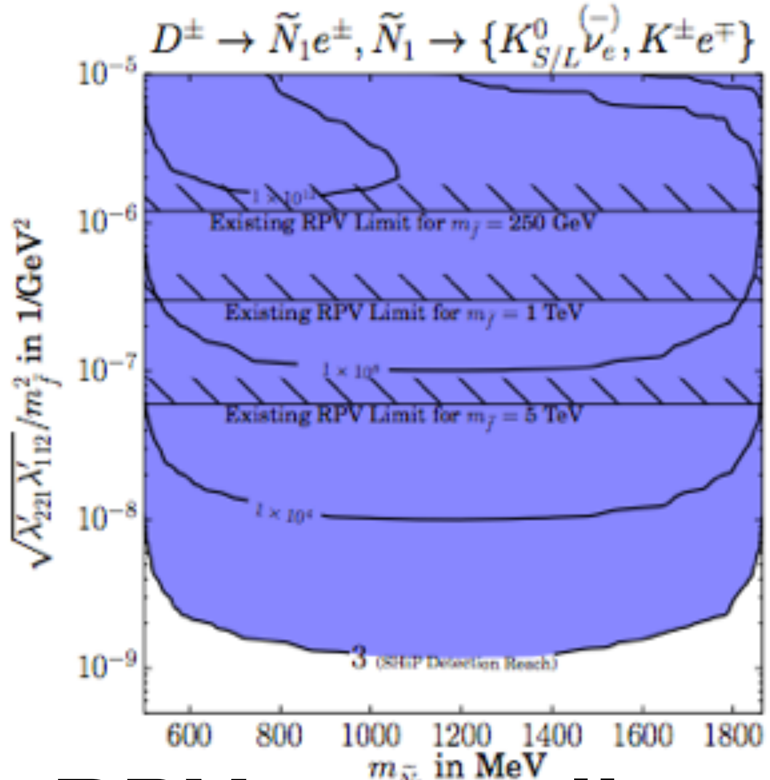
Scalar and pseudo-scalar portal



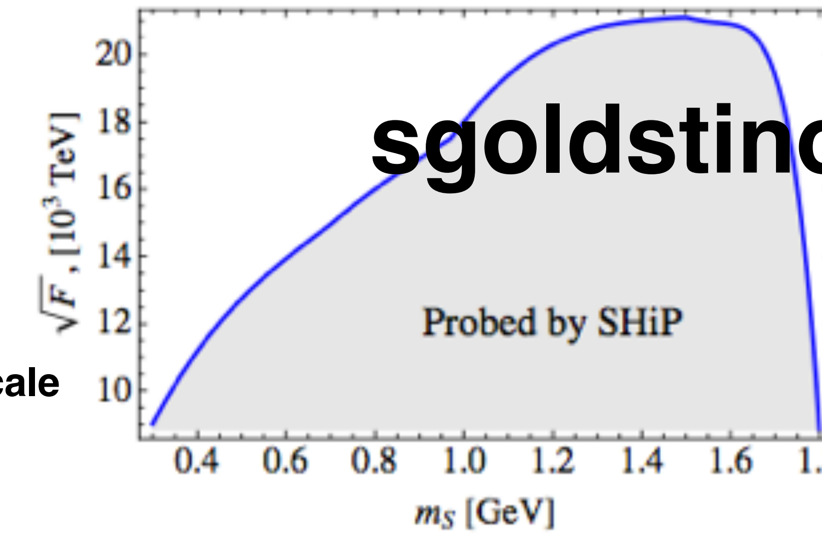
PNGBs or generic axions with couplings of order m_X/F to SM matter X



Direct SUSY particles detection

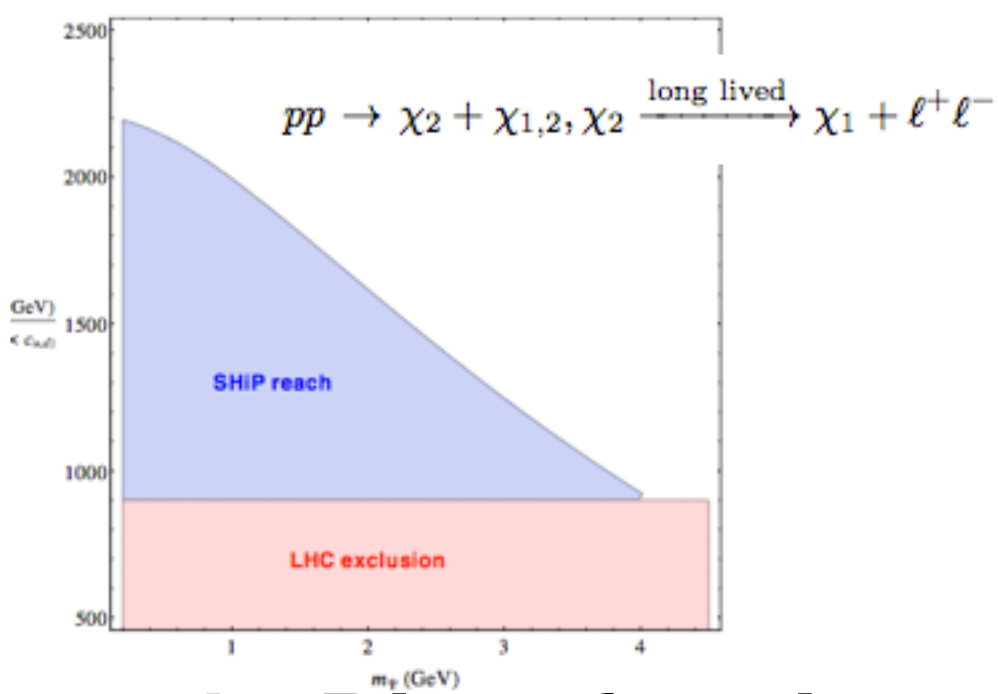


RPV neutralinos

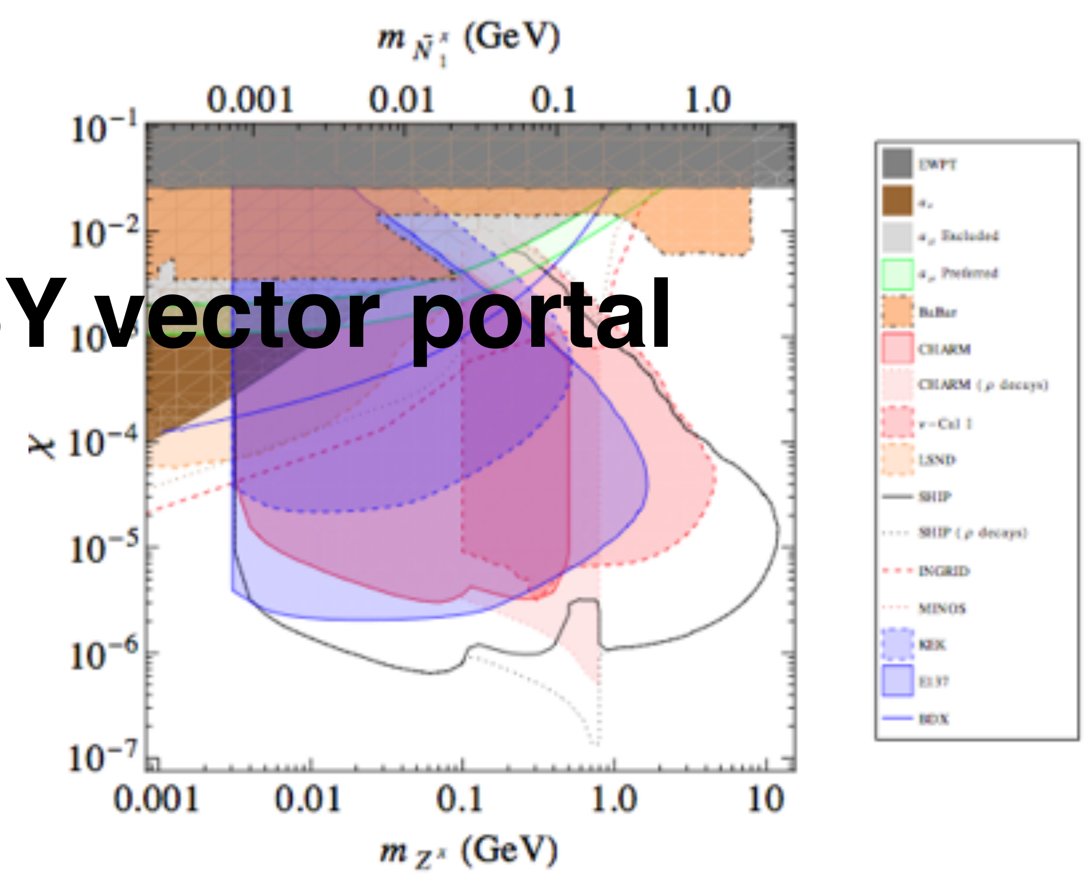


sgoldstinos

SUSY breaking scale



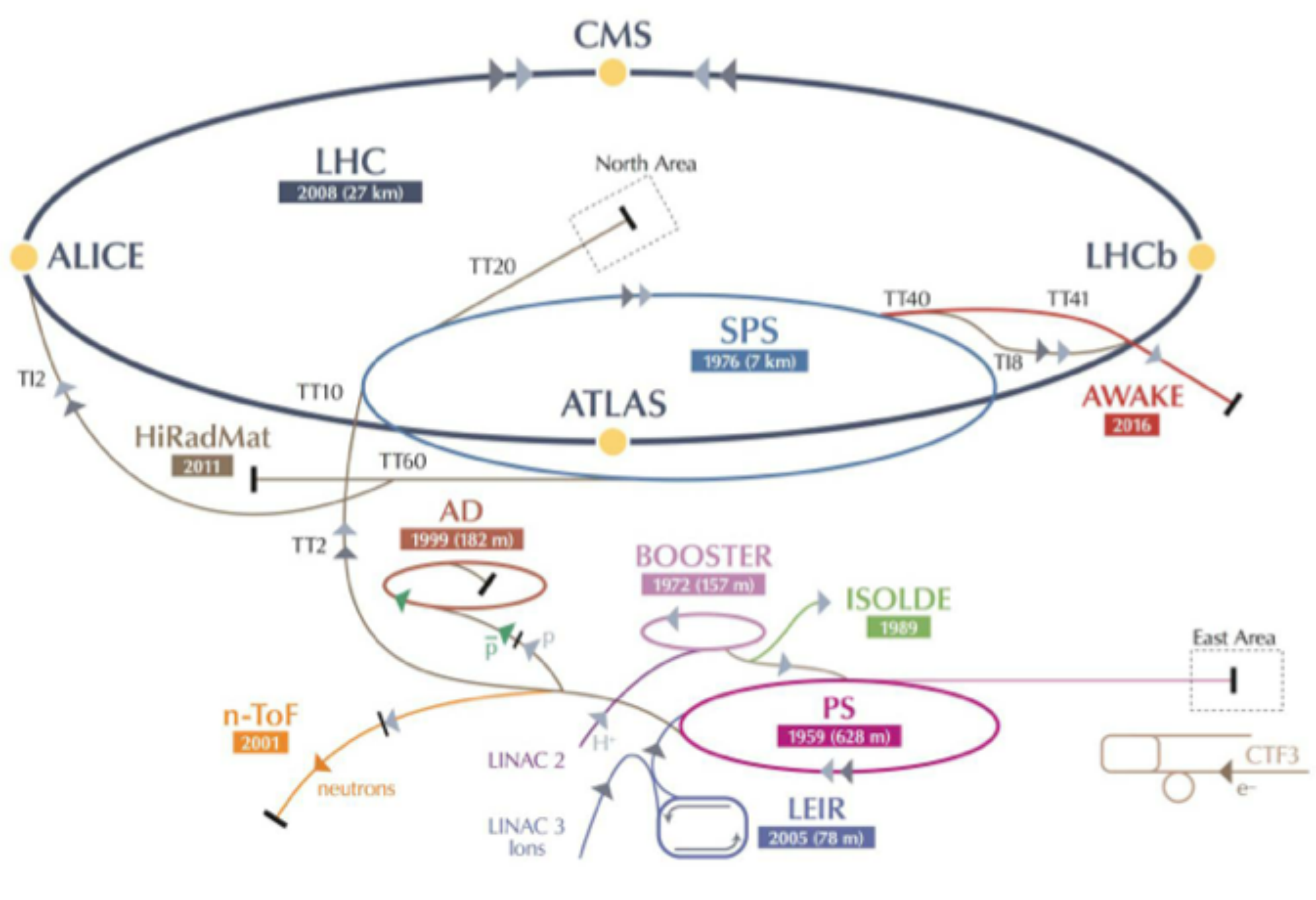
pseudo-Dirac fermions



SUSY vector portal

The experiment

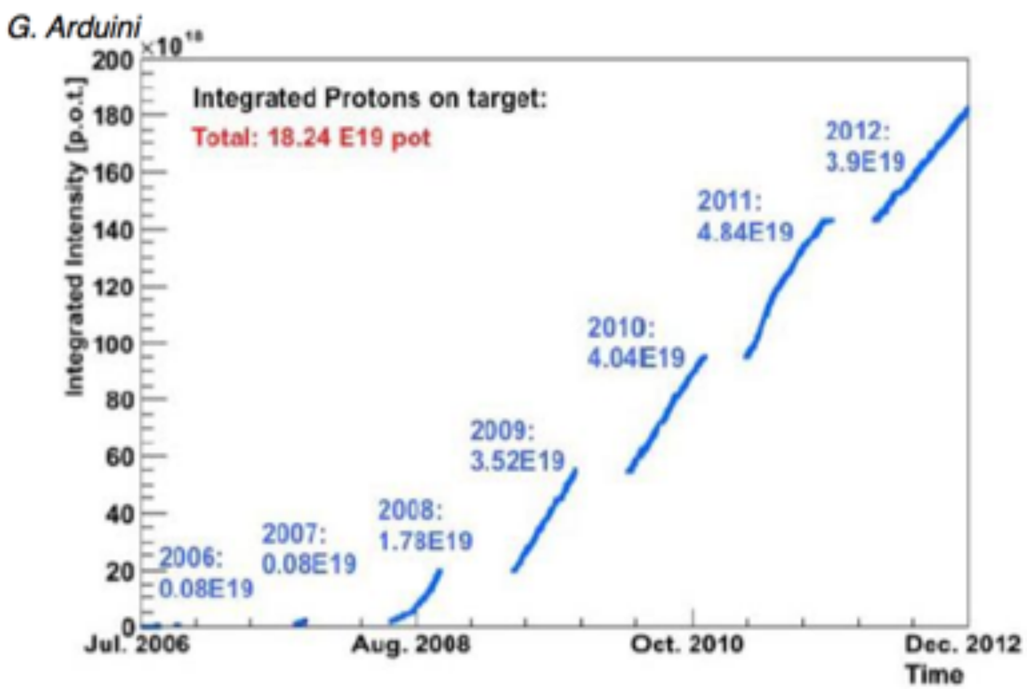
CERN accelerator complex

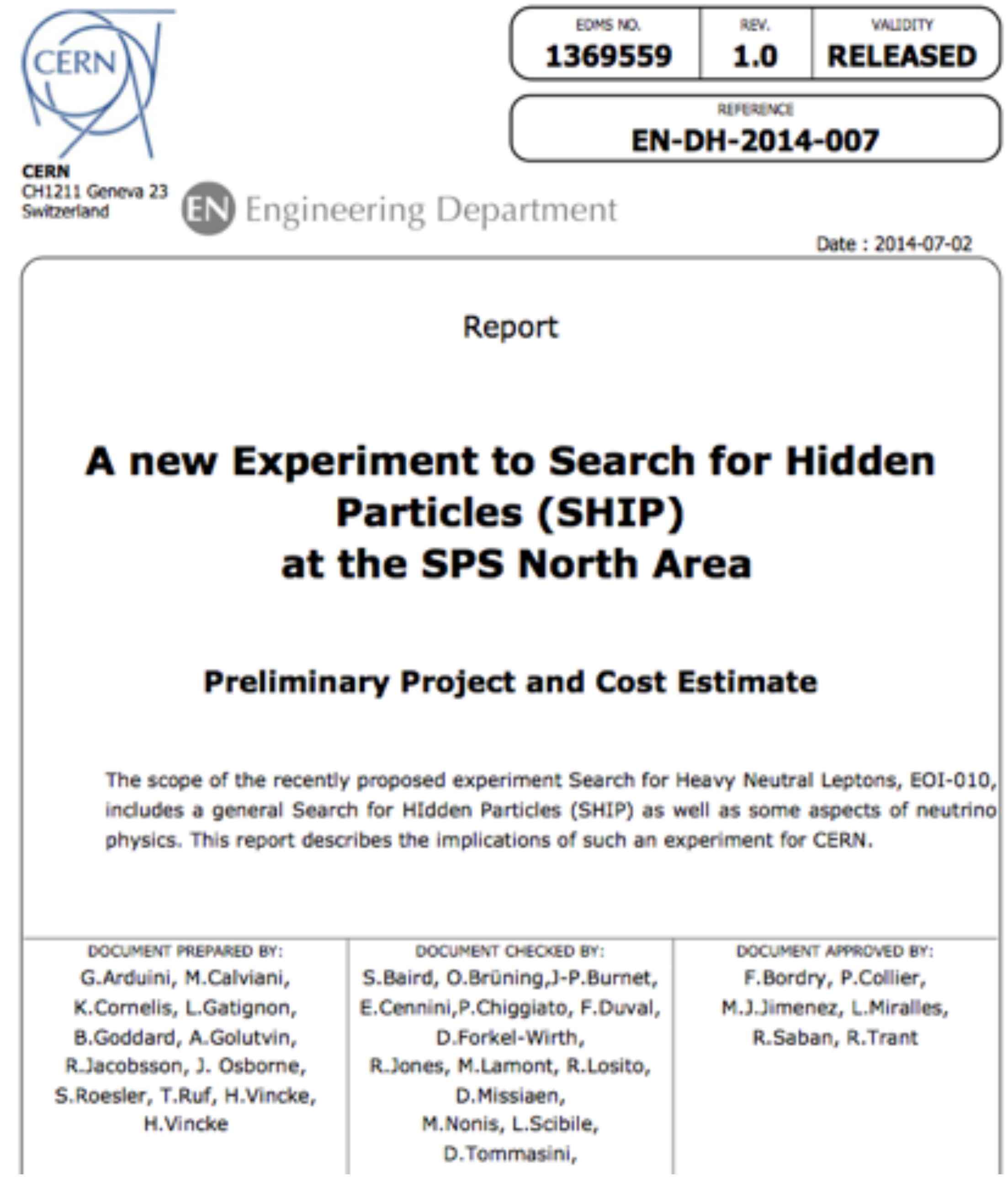


The beam

Extracted SPS beam 400GeV;

like CNGS 4.5×10^{19} pot/year





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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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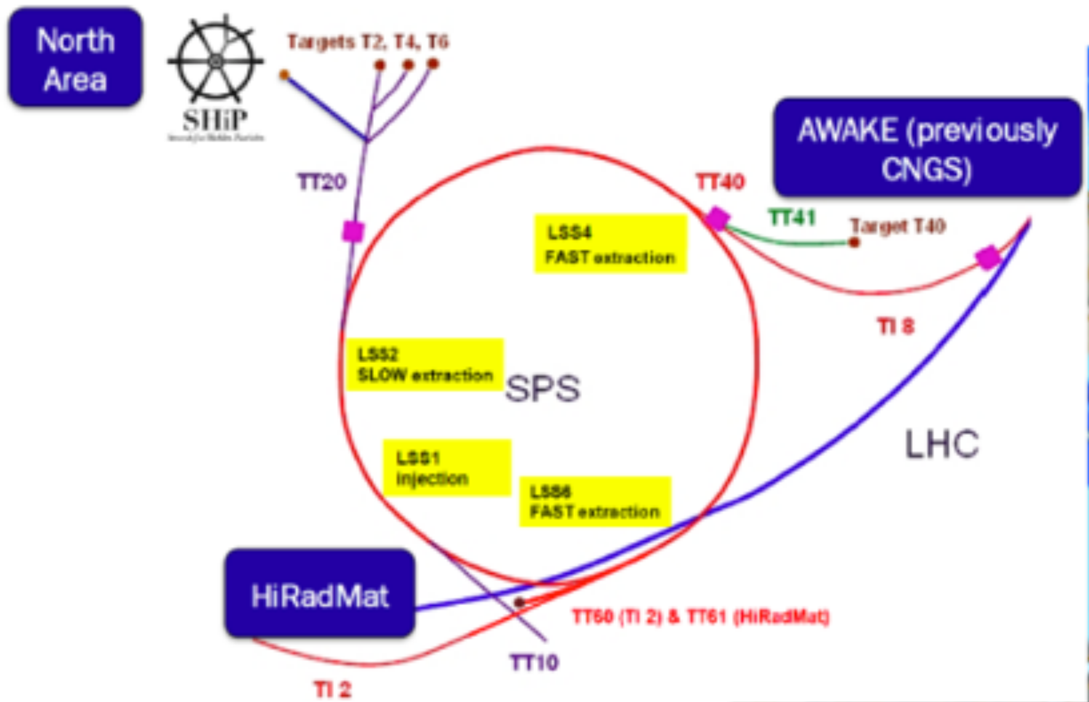
design figures for the SHIP beam:

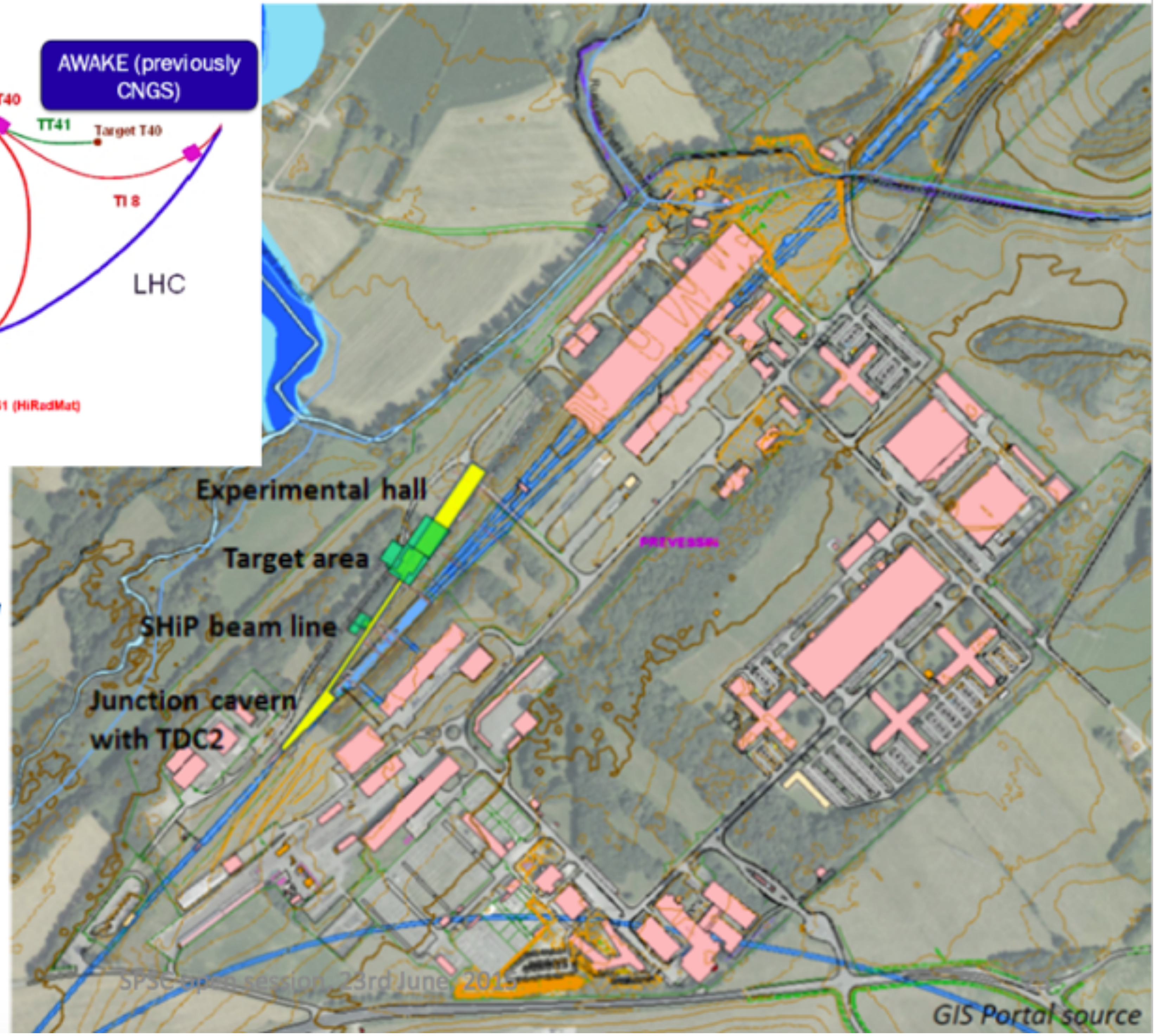
slow extraction (1s)

4e13 ppp

4e19pot/year

fully compatible with NA operation

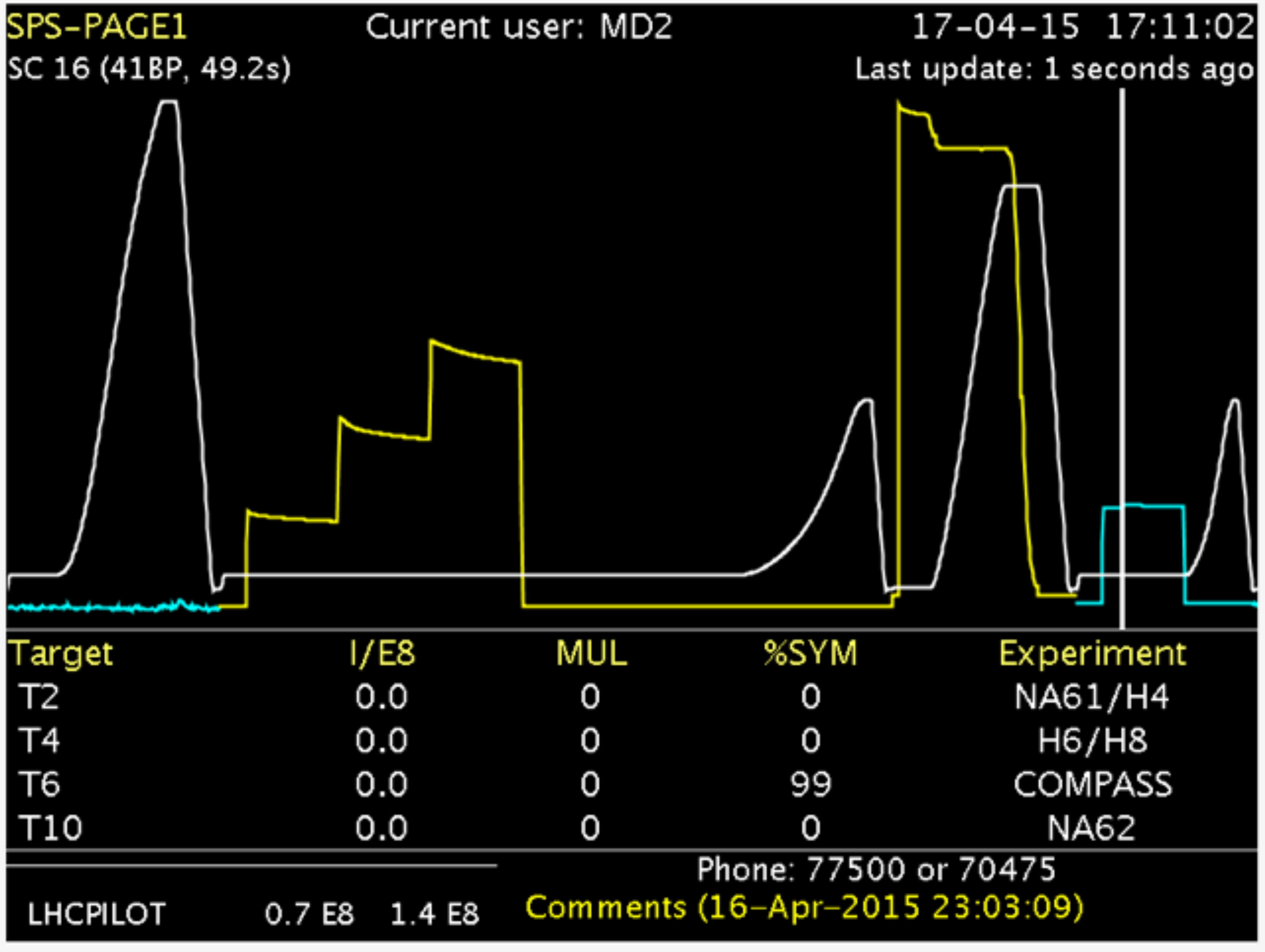




The SHiP facility is located on the North Area, and shares the TT20 transfer line and slow extraction mode with the fixed target programmes

Extraction test SHIP

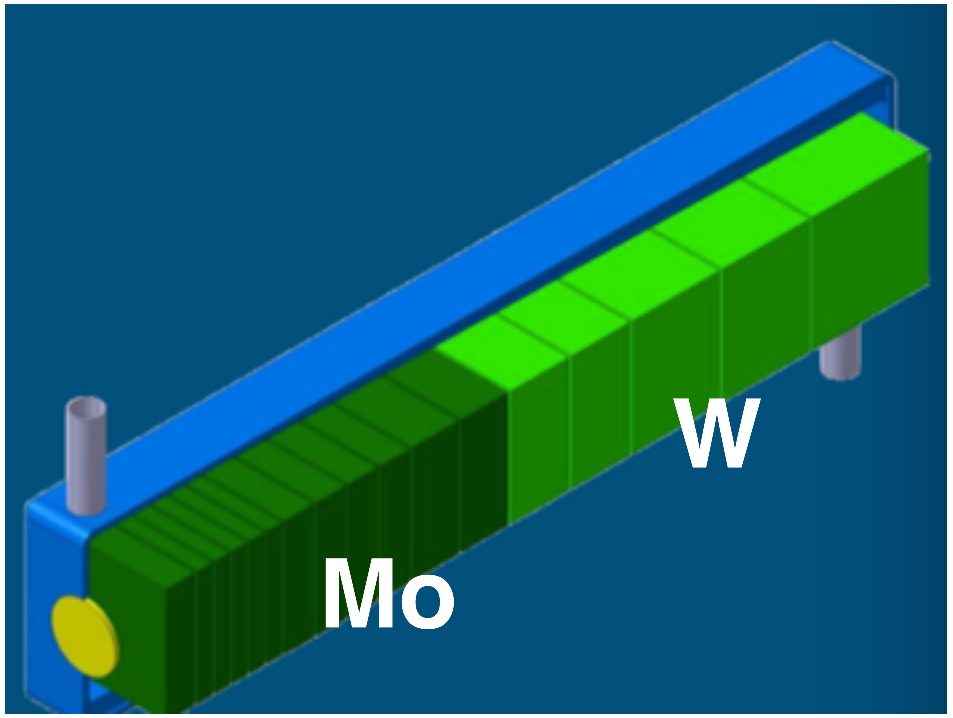
the current 49.2s SPS super-cycle with one single SHiP cycle starting at about 35s (under the text "last update") with a single injection of protons from PS to SPS (beam intensity in yellow), the acceleration to 400 GeV (energy illustrated in white), and the extraction during the flat top of 1s into the TT20 transfer line to the North Area as seen by the smooth drop of intensity with almost all beam extracted! The beam was sent to a beam stopper in the TT20 line. Few times 10^12 per spill every 49.2s for a couple of hours!



Target and muon filter

Longitudinally segmented hybrid target: Mo(58cm)/W(58cm)

the beam is spread on the target to avoid melting



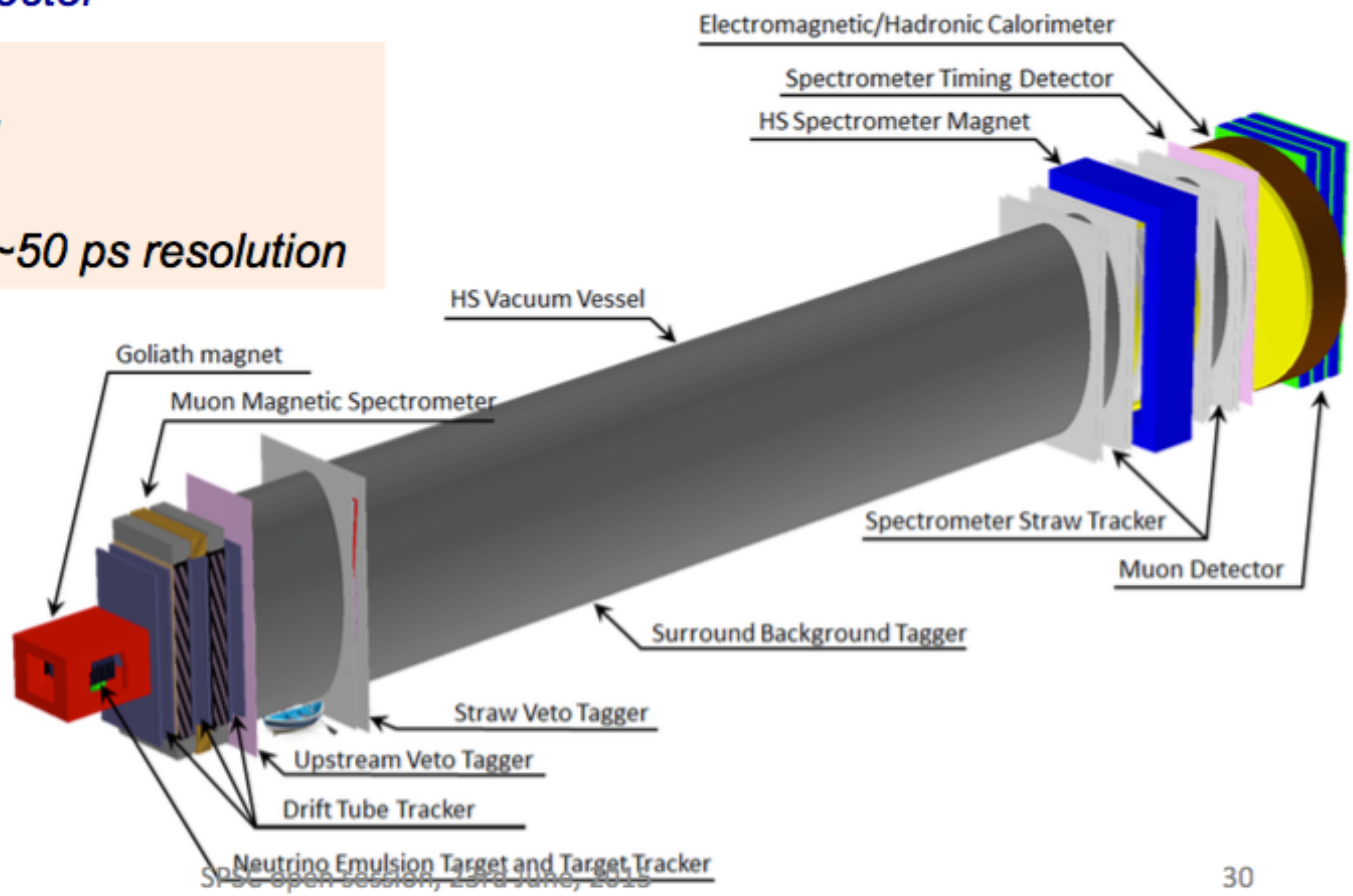
It is followed by a muon filter.

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

The detector

✓ *Reconstruction of HS decays in all possible final states*
Long decay volume protected by various Veto Taggers, Magnetic Spectrometer followed by the Timing Detector, and Calorimeters and Muon systems.
All heavy infrastructure is at distance to reduce neutrino / muon interactions in proximity of the detector

Challenges:
- *Large vacuum vessel*
- *5 m long straw tubes*
- *Timing detector with ~50 ps resolution*

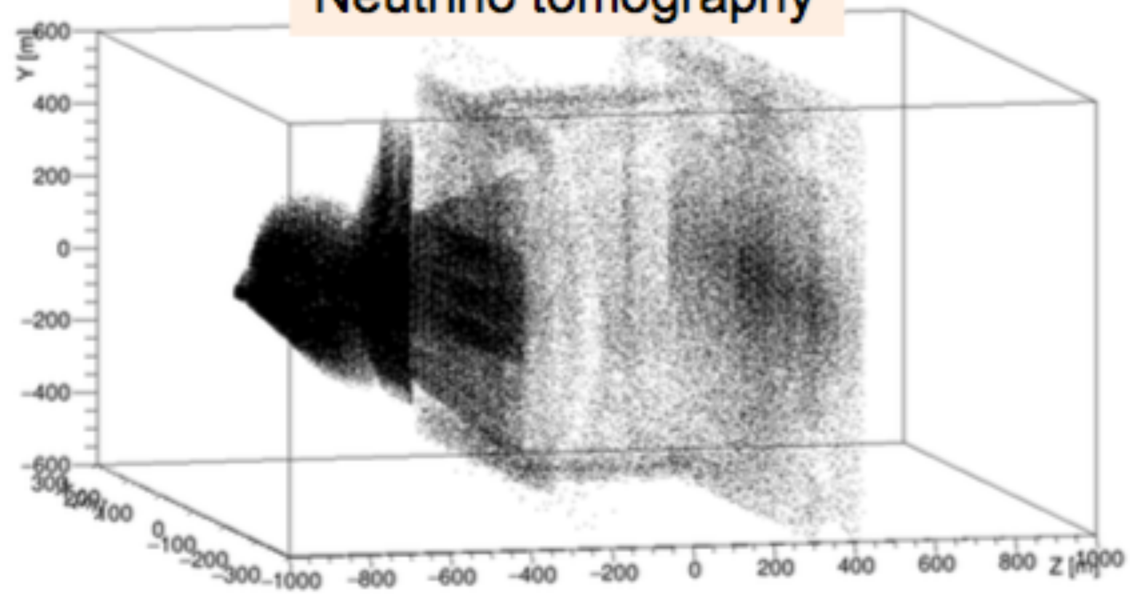


Backgrounds

Main sources of background

✓ ***Neutrino DIS interactions with material in the vicinity of the HS decay*** ***volume*** *(interactions of ν with air in the decay volume are negligible at 10^{-3} mbar)*

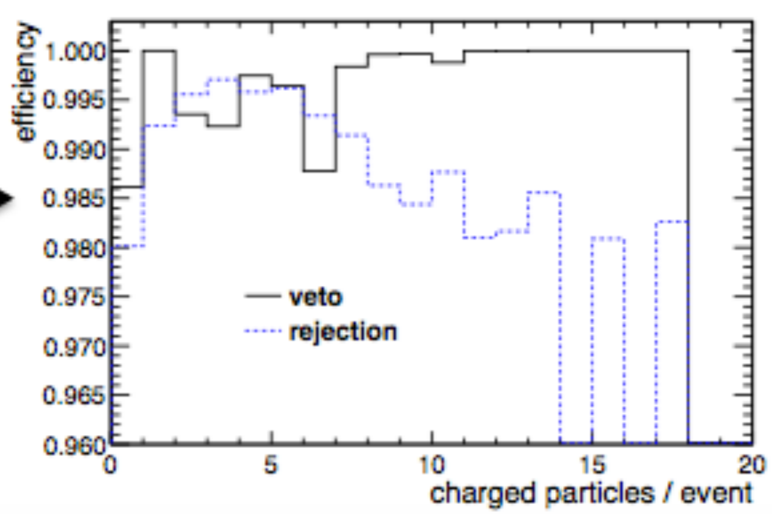
Neutrino tomography

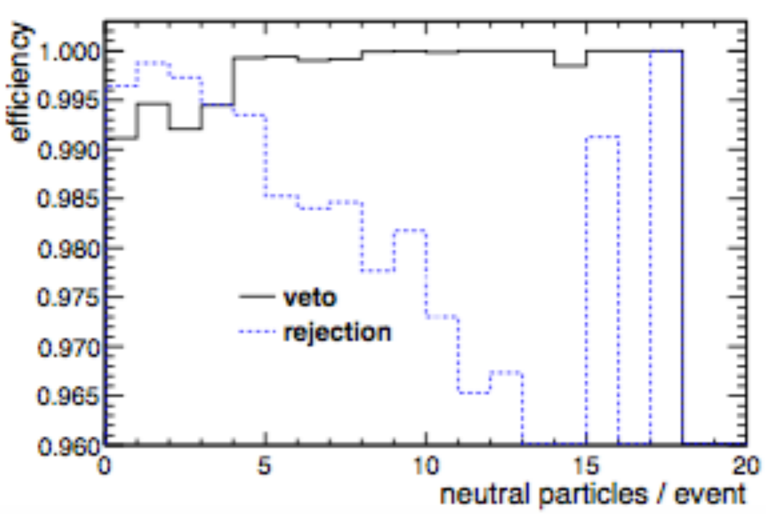


Origin of neutrino interactions
- *Walls of the decay volume (>80%)*
- *Tau neutrino detector*
- *HS tracking system*

Combination of veto and selection cuts reduces the ν-induced background to zero

Veto efficiency increases with event multiplicity →





Background

✓ ***Muon combinatorial background***

Simulation predicts O(10^{12}) muon pairs in the decay volume in 5 years of data taking

Suppressed by:

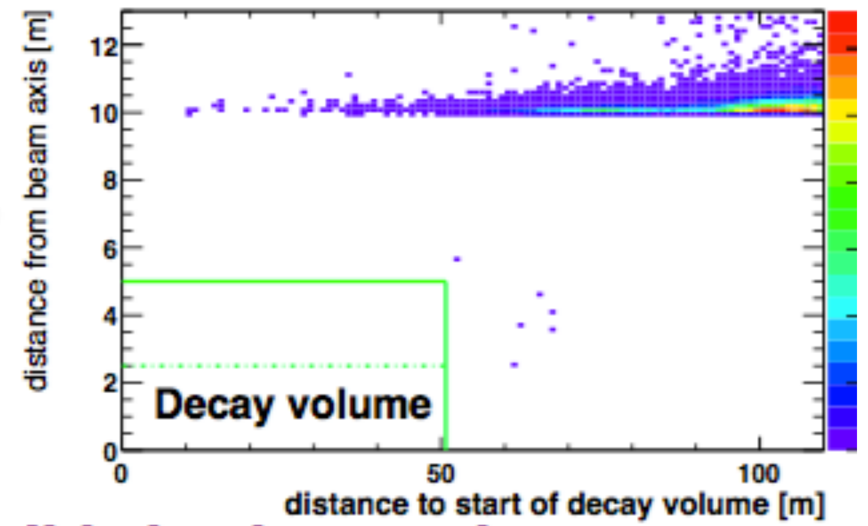
- *Basic kinematic and topological cuts ~10^4*
- *Timing veto detectors ~10^7*
- *Upstream veto and surrounding veto taggers ~10^4*

Cut	Value
Track P	> 1.5 GeV/c
Track χ^2/ndof	< 25
dimuon DOCA	< 1 cm
dimuon vertex	fiducial
dimuon mass	> 0.2 GeV/c^2
IP w.r.t target	< 2.5 m
Efficiency	10^{-4}

✓ ***Muon DIS interactions***

- *V^0s produced in the walls of the cavern*
- *DIS close to the entry of the decay volume* ⟶

  → smaller than neutrino induced background



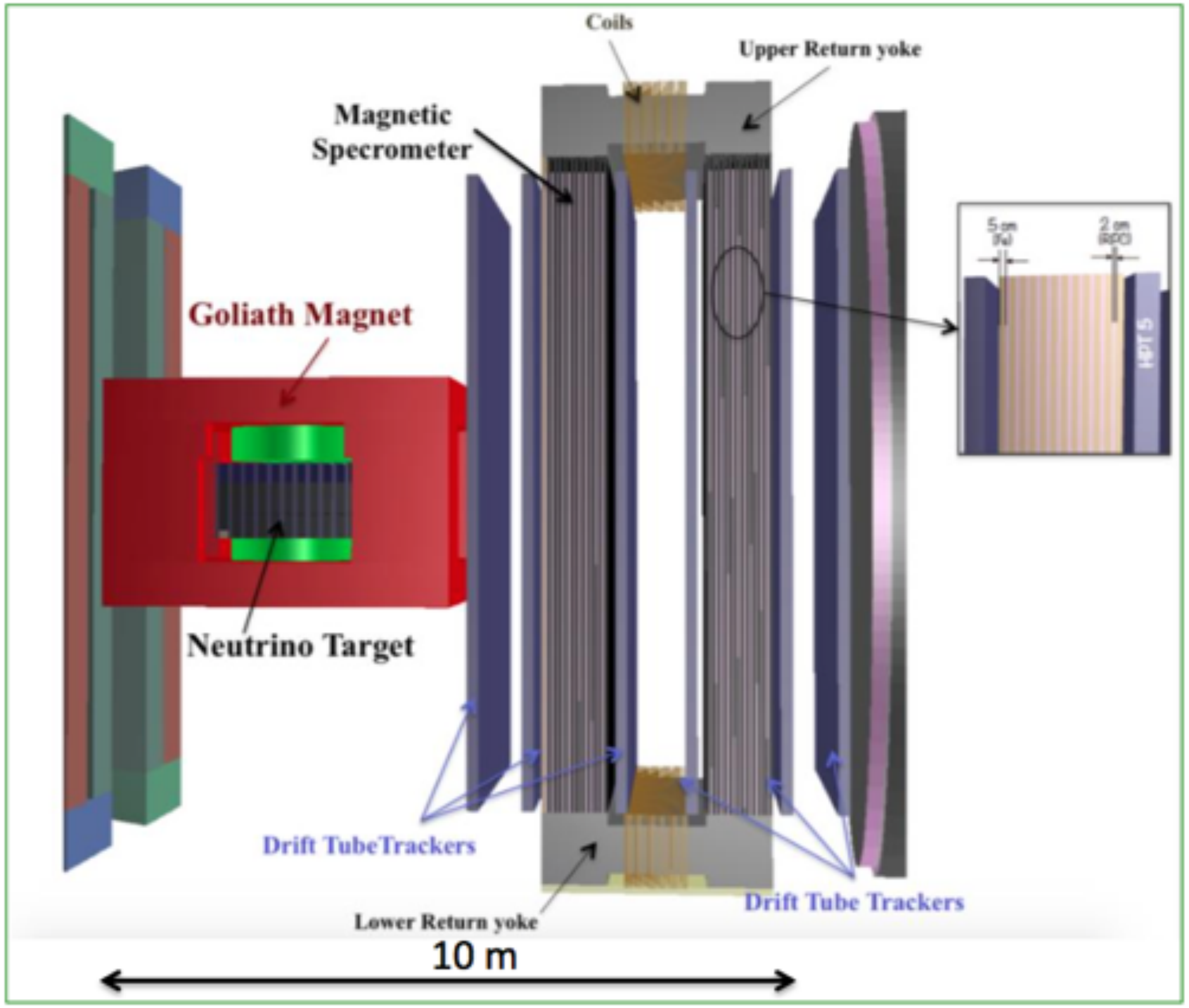
✓ ***Cosmics***

✓ ***Background summary: no evidence for any irreducible background***

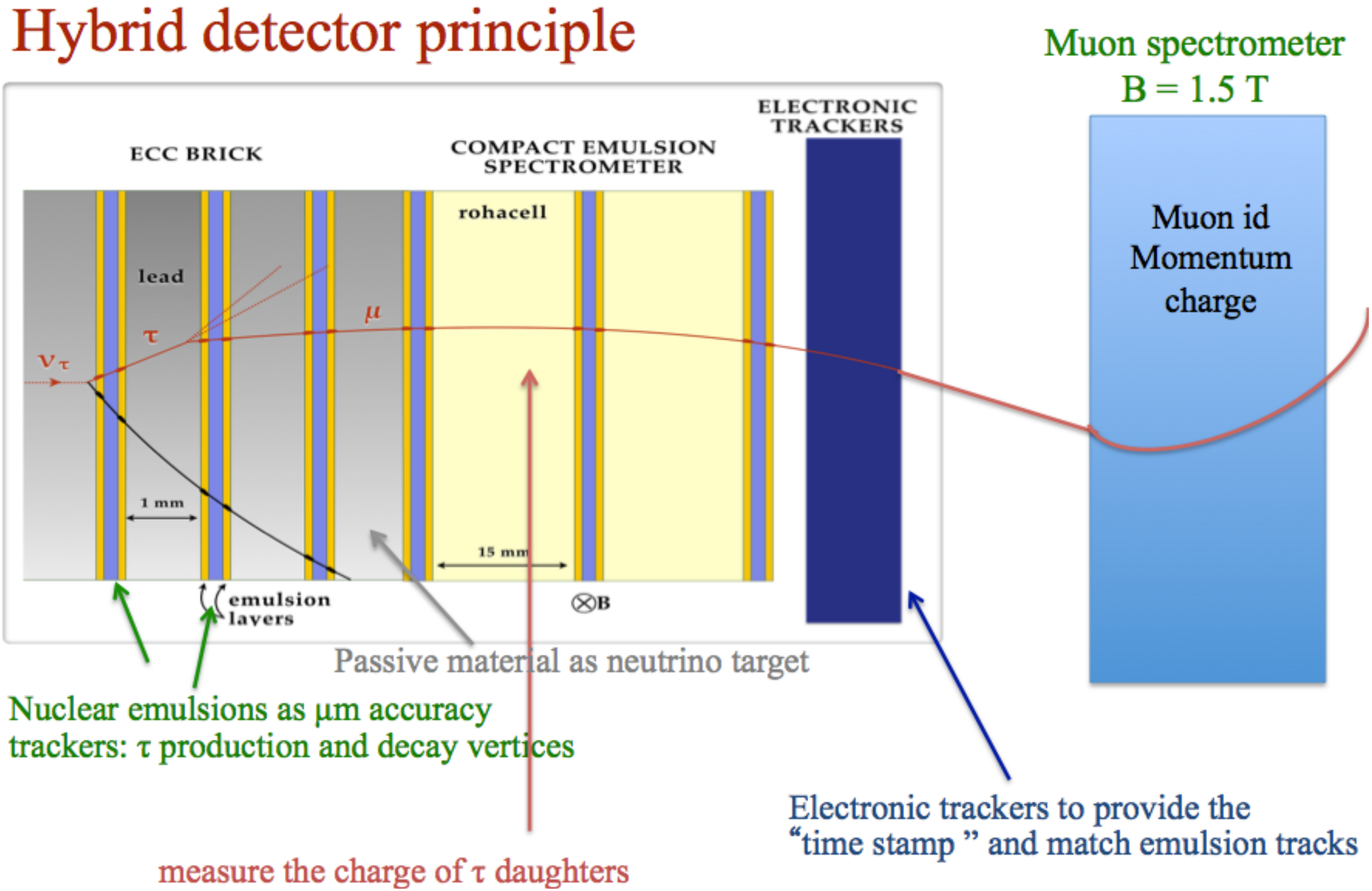
Studies with larger simulated samples of backgrounds are ongoing

Light ν'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)



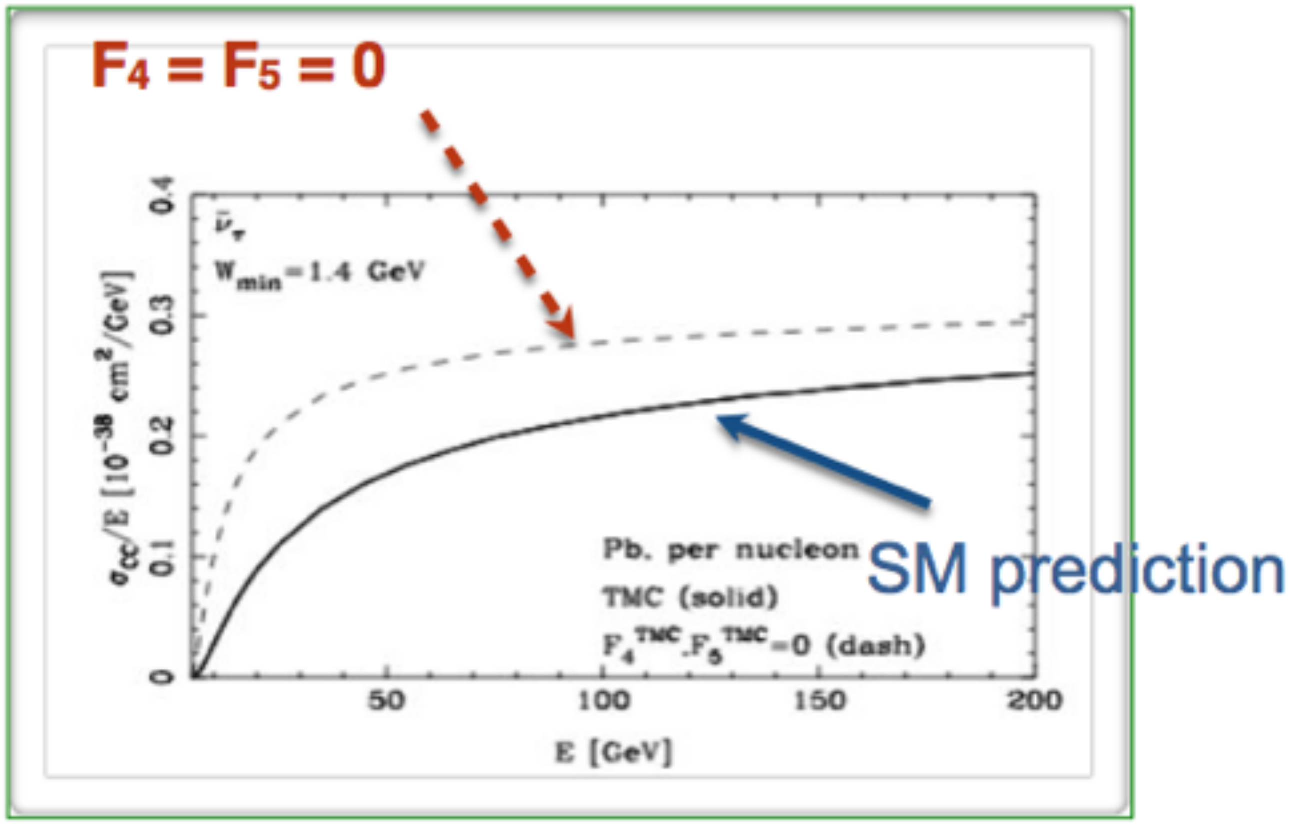
Neutrino target

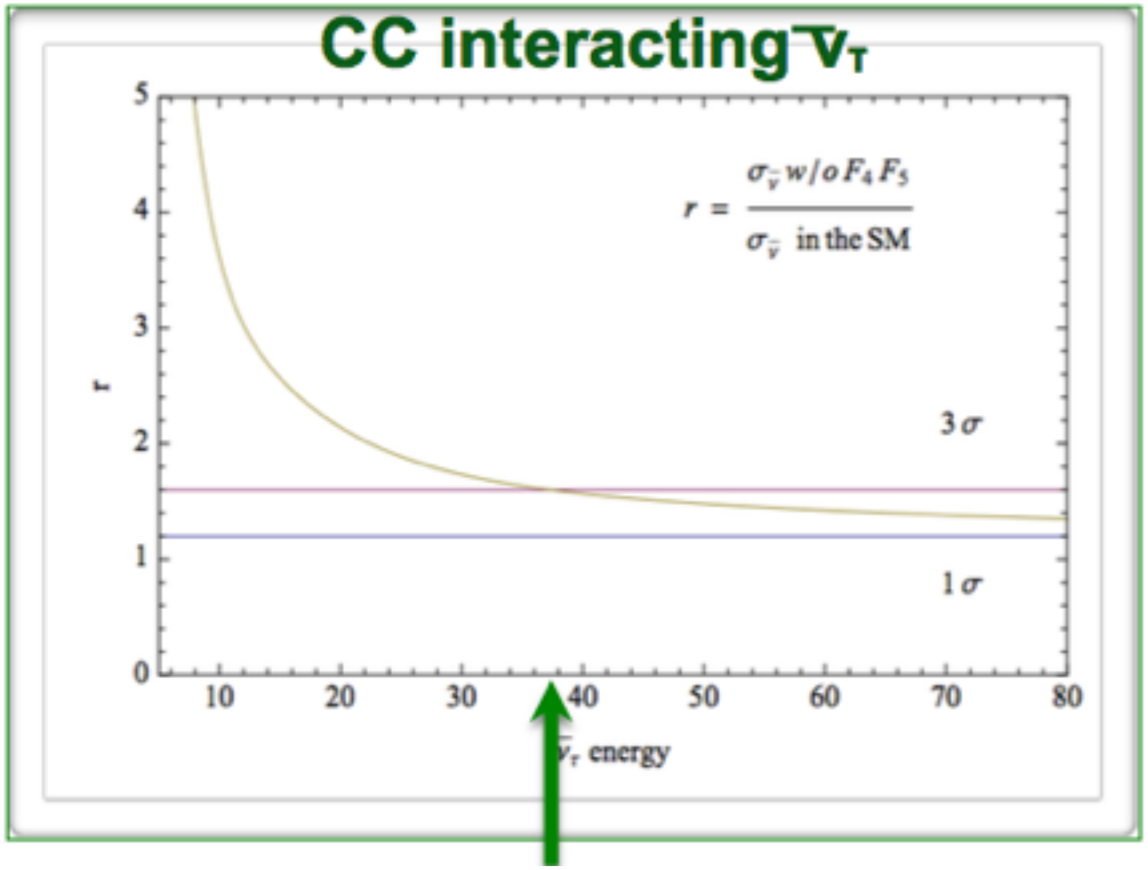


Tau neutrino physics

First evaluation of F_4 and F_5, not accessible with other neutrinos

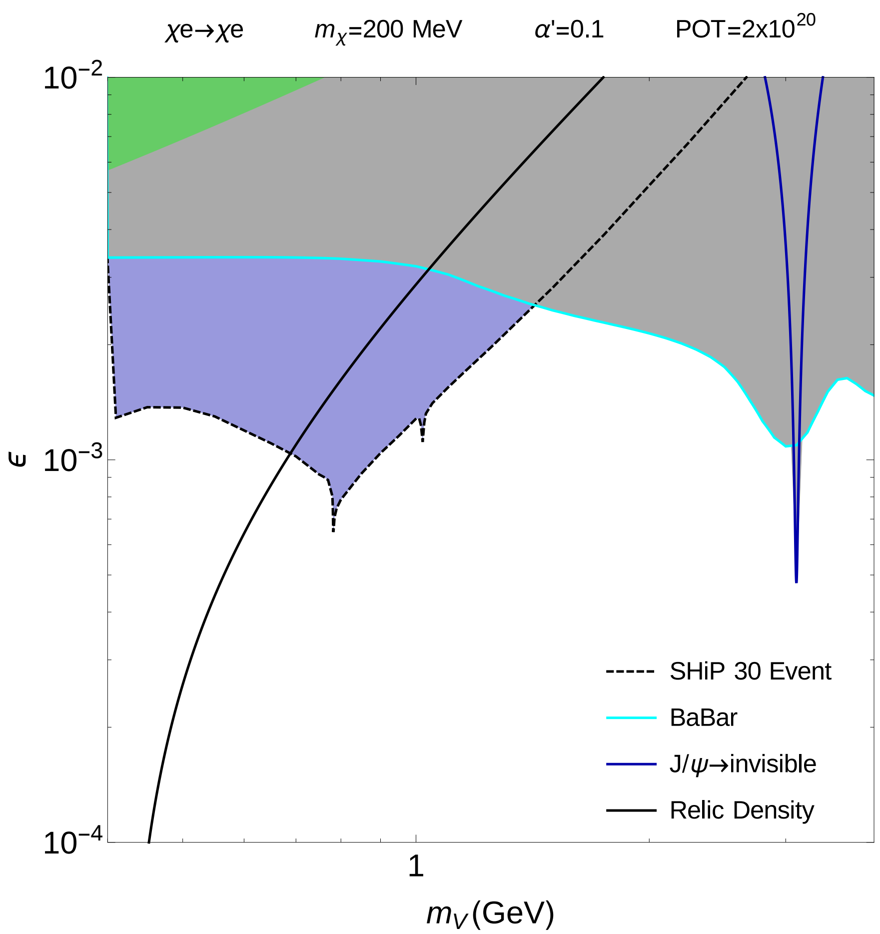
$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg(\left(y^2 x + \frac{m_\tau^2 y}{2E_\nu M}\right)F_1 + \left[\left(1-\frac{m_\tau^2}{4E_\nu^2}\right) - \left(1+\frac{Mx}{2E_\nu}\right)\right]F_2 \pm \left[xy\left(1-\frac{y}{2}\right) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\Bigg),$$





- At LO $F_4 = 0$, $2xF_5 = F_2$
- At NLO $F_4 \sim 1\%$ at 10 GeV

Dark photon to dark matter



Use neutrino detector (emulsions) and detect neutral current interaction on atomic e-

—>not a background-free search (but calculable)

after cuts (angle 10-20mrad, E<20GeV), the beam backgrounds:

	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	16	2	20	18	56
Quasi - elastic scattering	105	73			178
Resonant scattering	13	27			40
Deep inelastic scattering	3	7			10
Total	137	109	20	18	284

Time-table

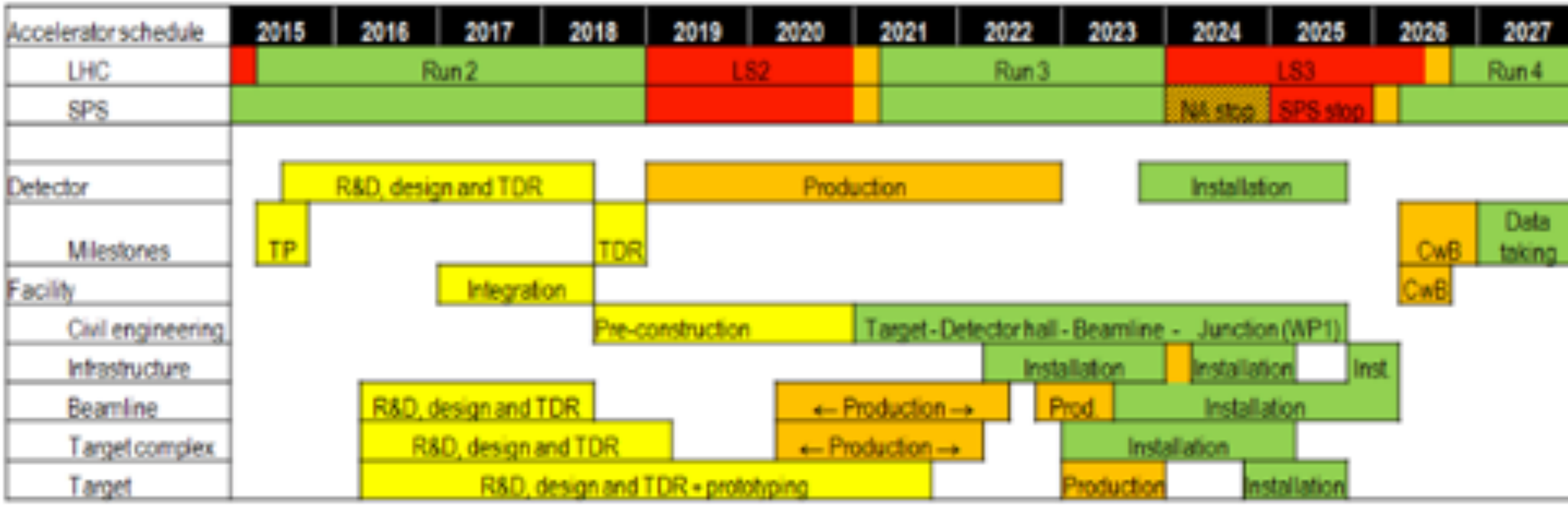


Figure 5.4: Alternative project schedule for the SHiP facility and detector with WP1 in LS3 and adapted to latest accelerator schedule MTP 2016-2020 V1.

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

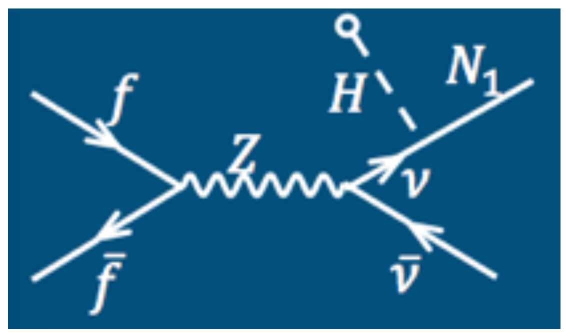
Pursuing a diversity of experimental approaches is very important to maximize our likelihoods of finding NP

Backup

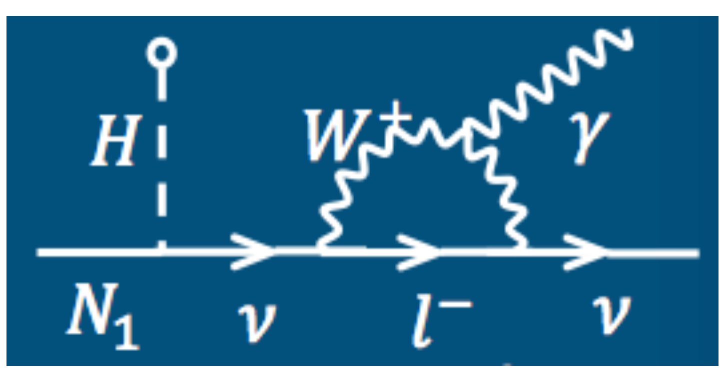
About N1

Stability —> τ>τ(universe)

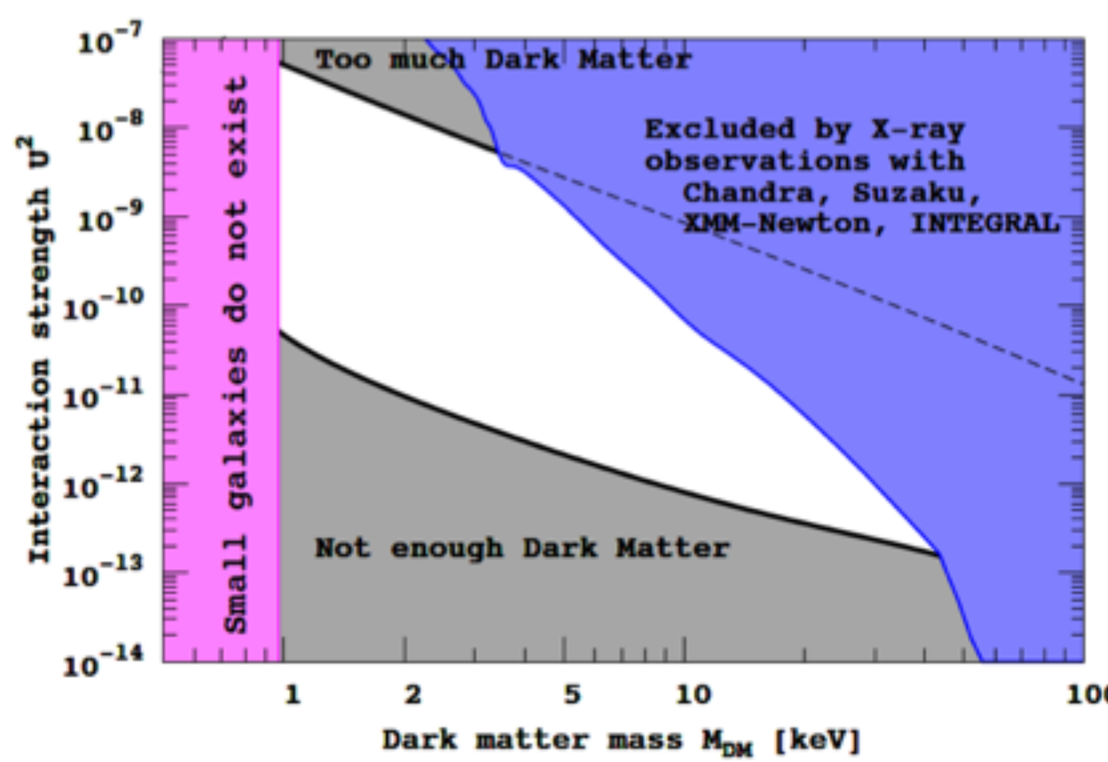
Production —> ll>νN_1 , qq—>νN_1



Decay —> the radiative decay N_1—>γν provides a line in the X spectrum at E(γ)=m1/2



exclusion up to 2013 with single galaxies



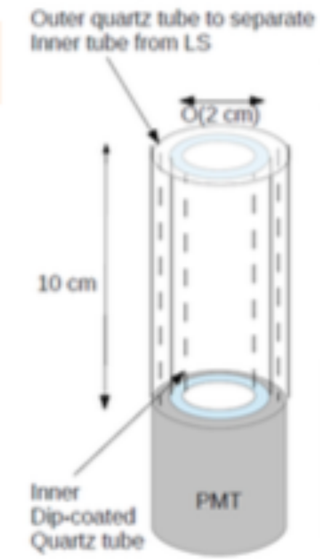
The vacuum vessel

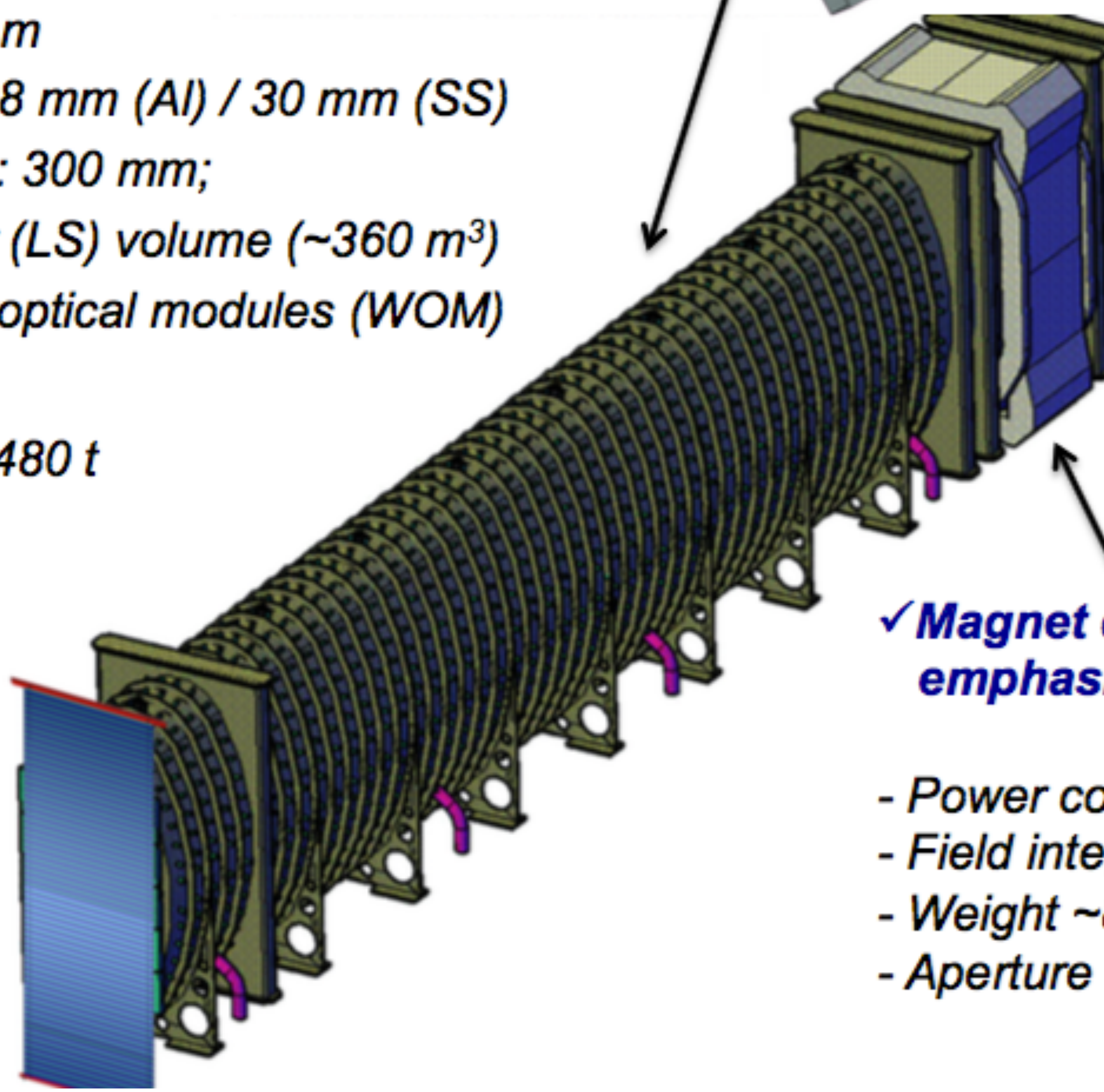
SHiP

- ✓ ***Estimated need for vacuum:***
  ~ 10^{-3} mbar

- ✓ ***Vacuum vessel***
  - *10 m x 5 m x 60 m*
  - *Walls thickness: 8 mm (Al) / 30 mm (SS)*
  - *Walls separation: 300 mm;*
  - *Liquid scintillator (LS) volume (~360 m^3) readout by WLS optical modules (WOM) and PMTs*
  - *Vessel weight ~ 480 t*

LS cell with WOMs





✓ ***Magnet designed with an emphasis on low power***

- *Power consumption < 1 MW*
- *Field integral: 0.65Tm over 5m*
- *Weight ~800 t*
- *Aperture ~50 m^2*

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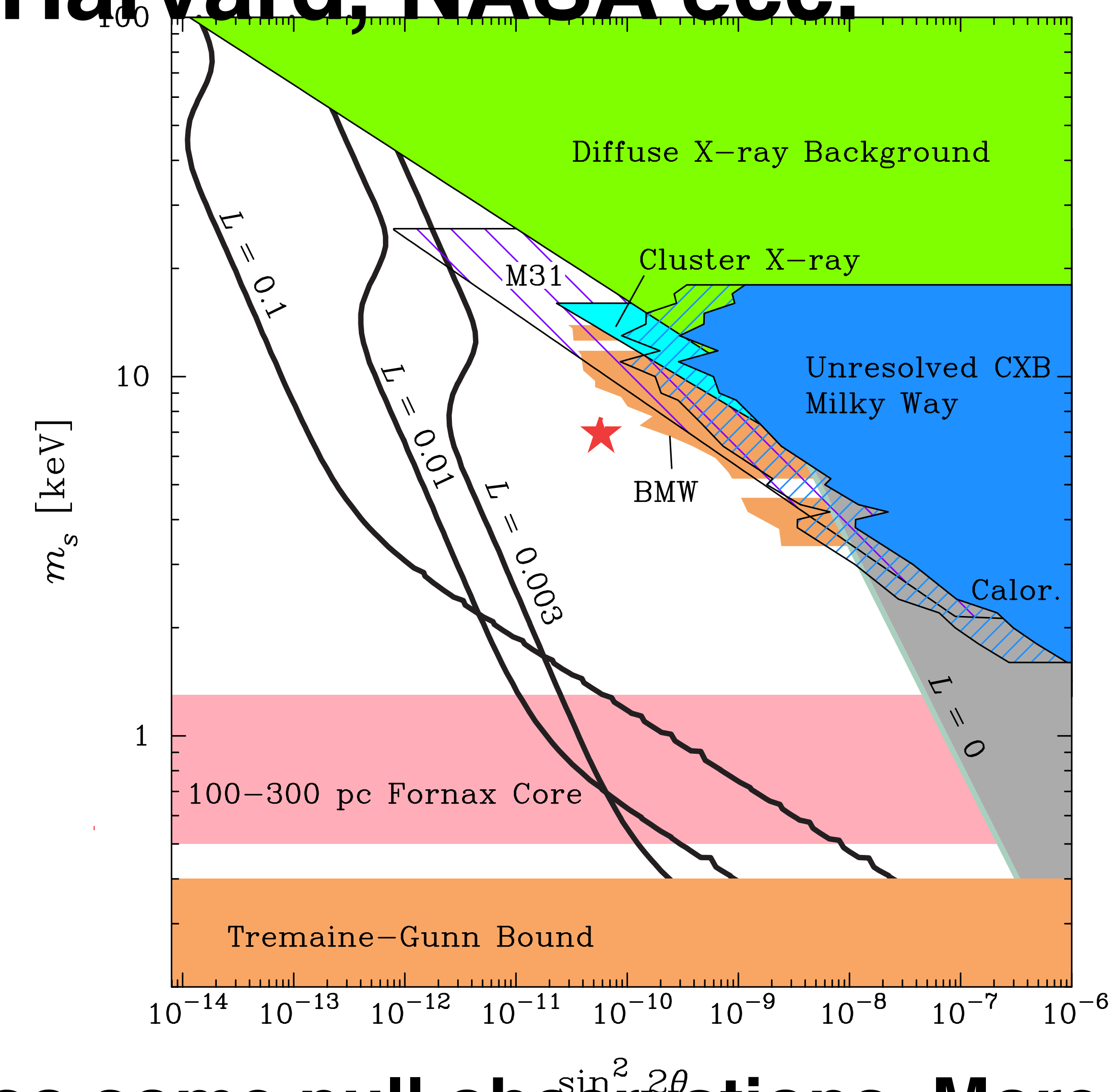
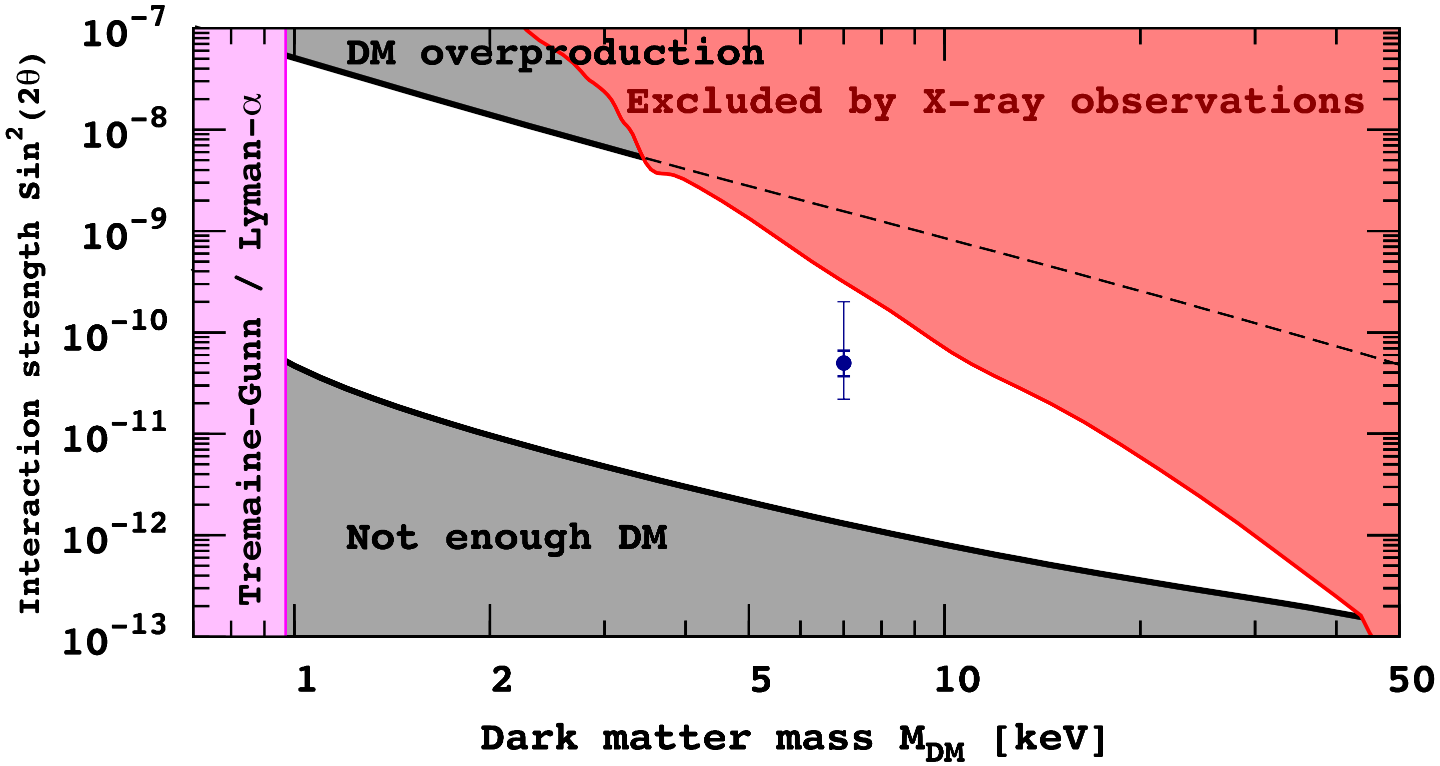
...some 3 sigma observations in 2014...
with stacked spectra of galaxies or clusters,
with XMM Newton, Chandra

Harvard, NASA ecc.



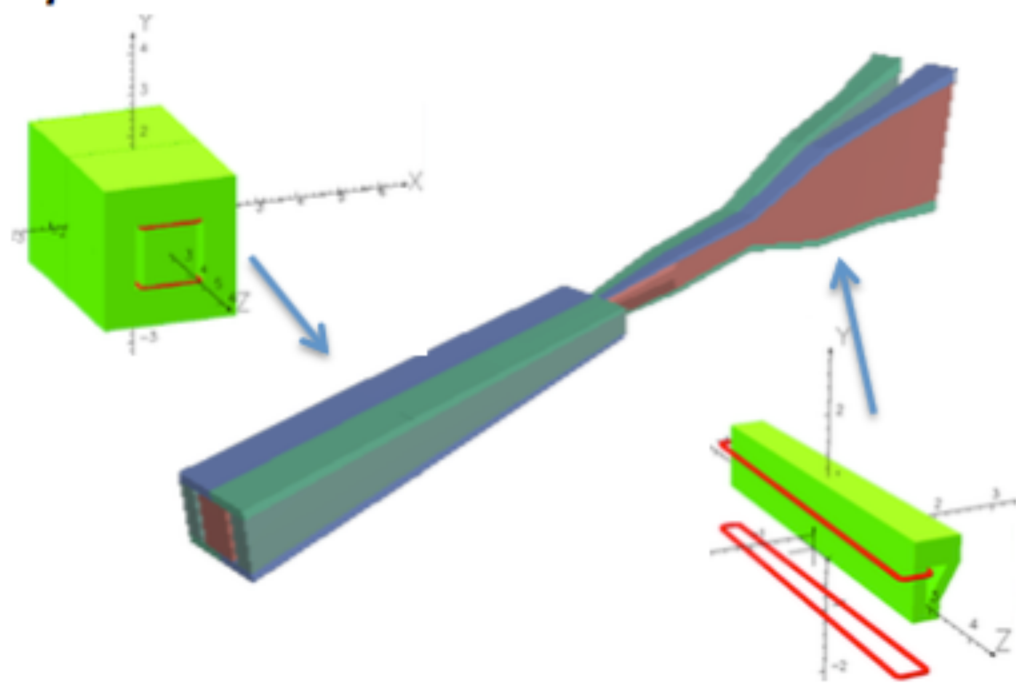


Boyarski et al.

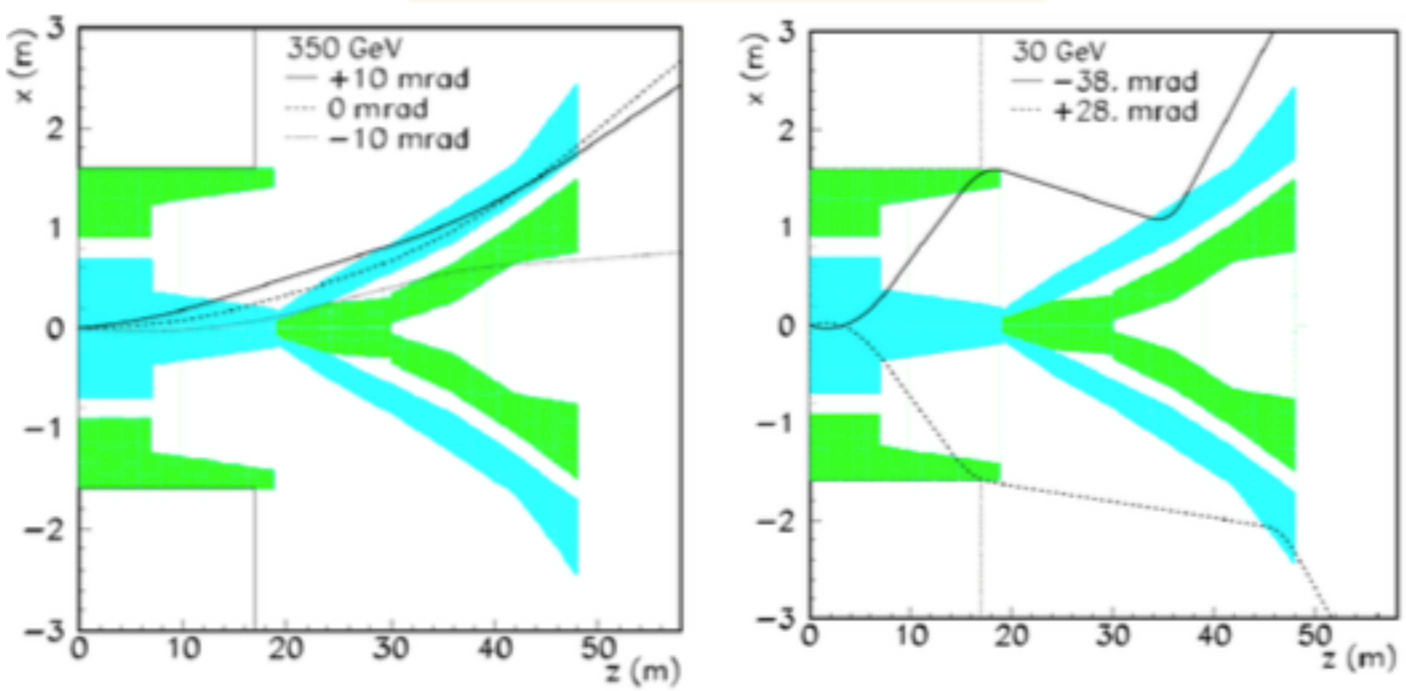
Also some null observations. More observation time for XMM-Newton on a dedicated object (1.4Msec)
—>action going on and hopefully the issue may be clarified

Muon active Filter

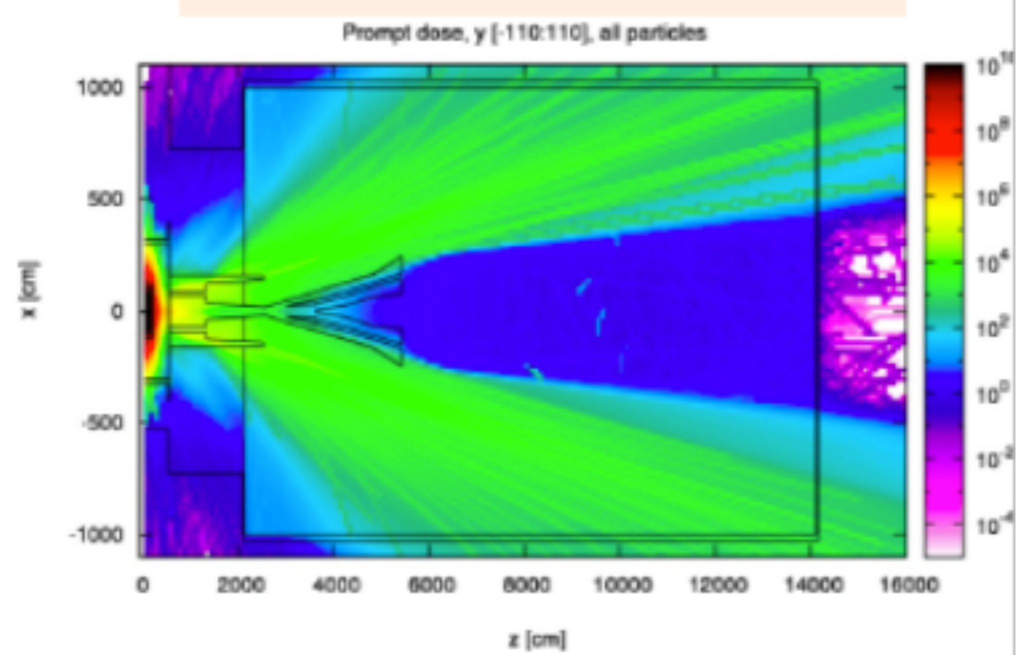
- ✓ *Muon flux limit driven by emulsion based neutrino detector and HS background*
- ✓ *Active muon shield based entirely on magnet sweeper with a total field integral B_y = 86.4 Tm*
  Realistic design of sweeper magnets in progress
  Challenges: flux leakage, constant field profile, modeling magnet shape
- ✓ *< 7k muons / spill (E_μ > 3 GeV), well below the emulsion saturation limit*
- ✓ *Negligible flux in terms of detector occupancy*



Magnetic sweeper field



Dose rate in the SHiP hall



SPSC open session, 23rd June, 2015