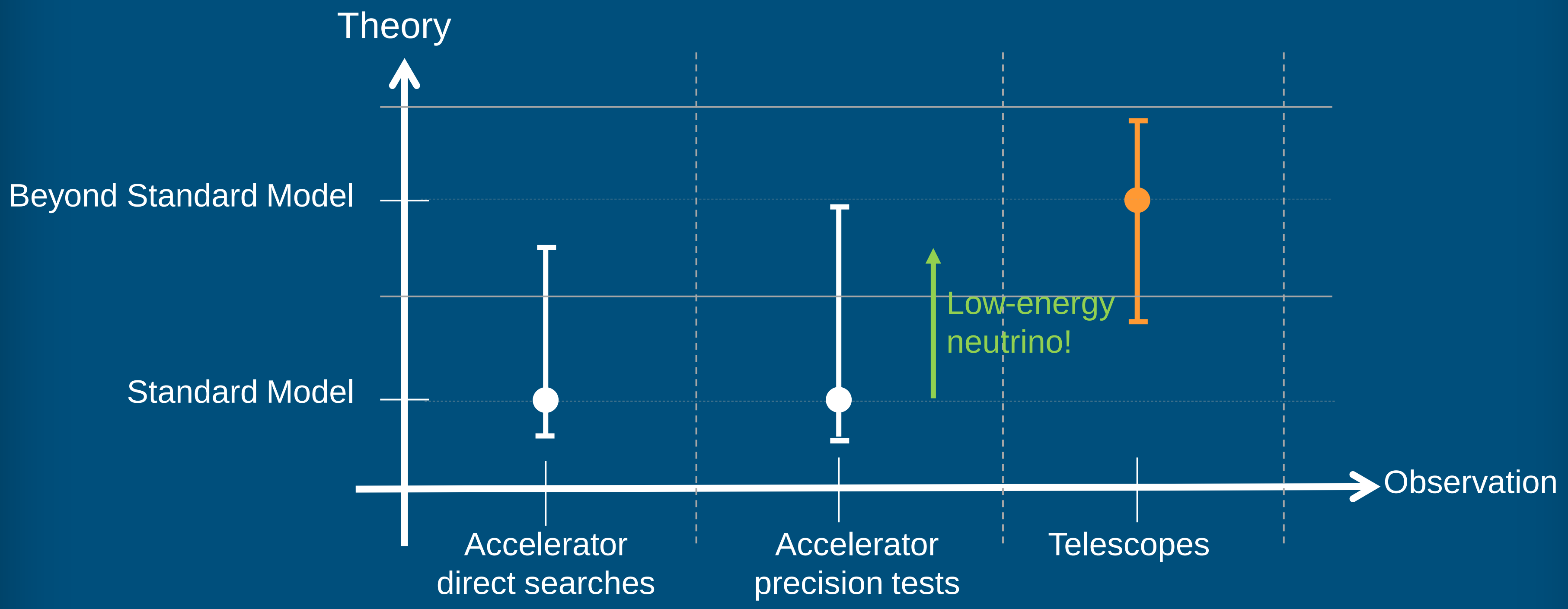
An Experiment to Search for Hidden Particles at the SPS

Richard Jacobsson

on behalf of the SHIP Collaboration

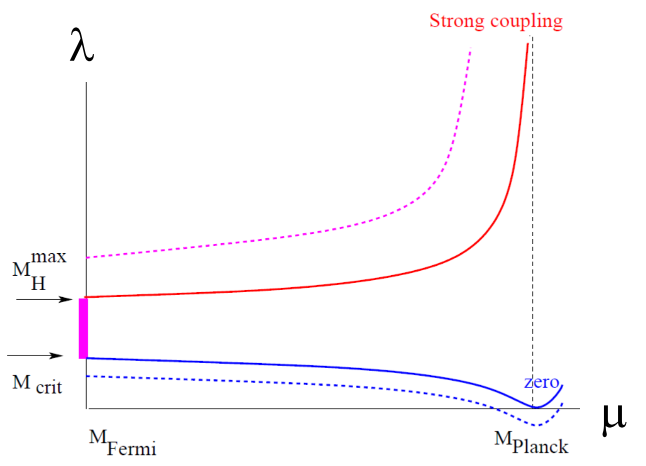
Physics Situation after LHC Run 1

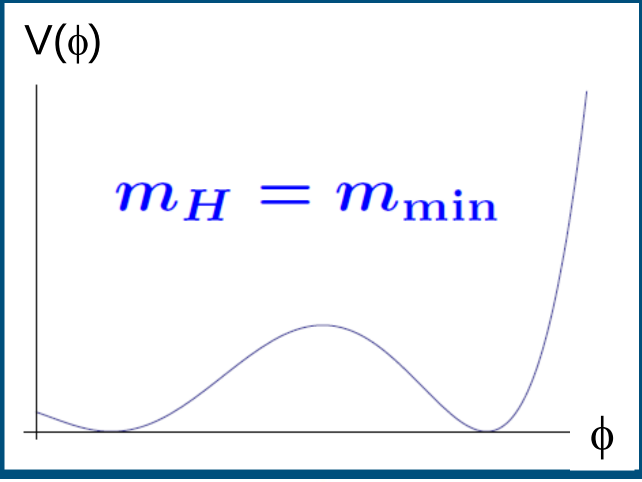


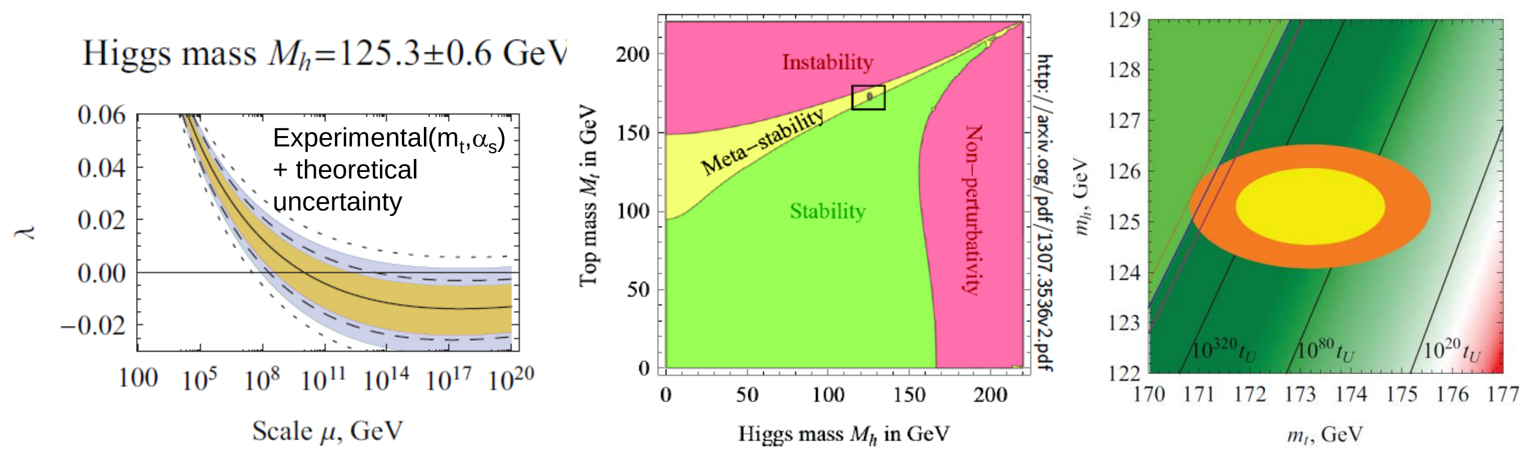
➔ Standard Model success: Higgs!

SM Validity

- Requirement that the E.W. vacuum be the minimum of the potential up to a scale Λ, implies that $\lambda(\mu) > 0$ for any $\mu < \Lambda$.
- $M_H = 125.5 \pm 0.2_{stat}{}^{+0.5}_{-0.6}{}_{syst} GeV$ (ATLAS) / $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{syst}\ GeV$ (CMS)
  - $m_H < 175\ GeV$: Landau pole in the self-interaction is above the quantum gravity scale $M_{Pl} \sim 10^{19}$ GeV
  - $m_H > 111\ GeV$: Electroweak vacuum is sufficiently stable with a lifetime >> $\tau_{Universe}$



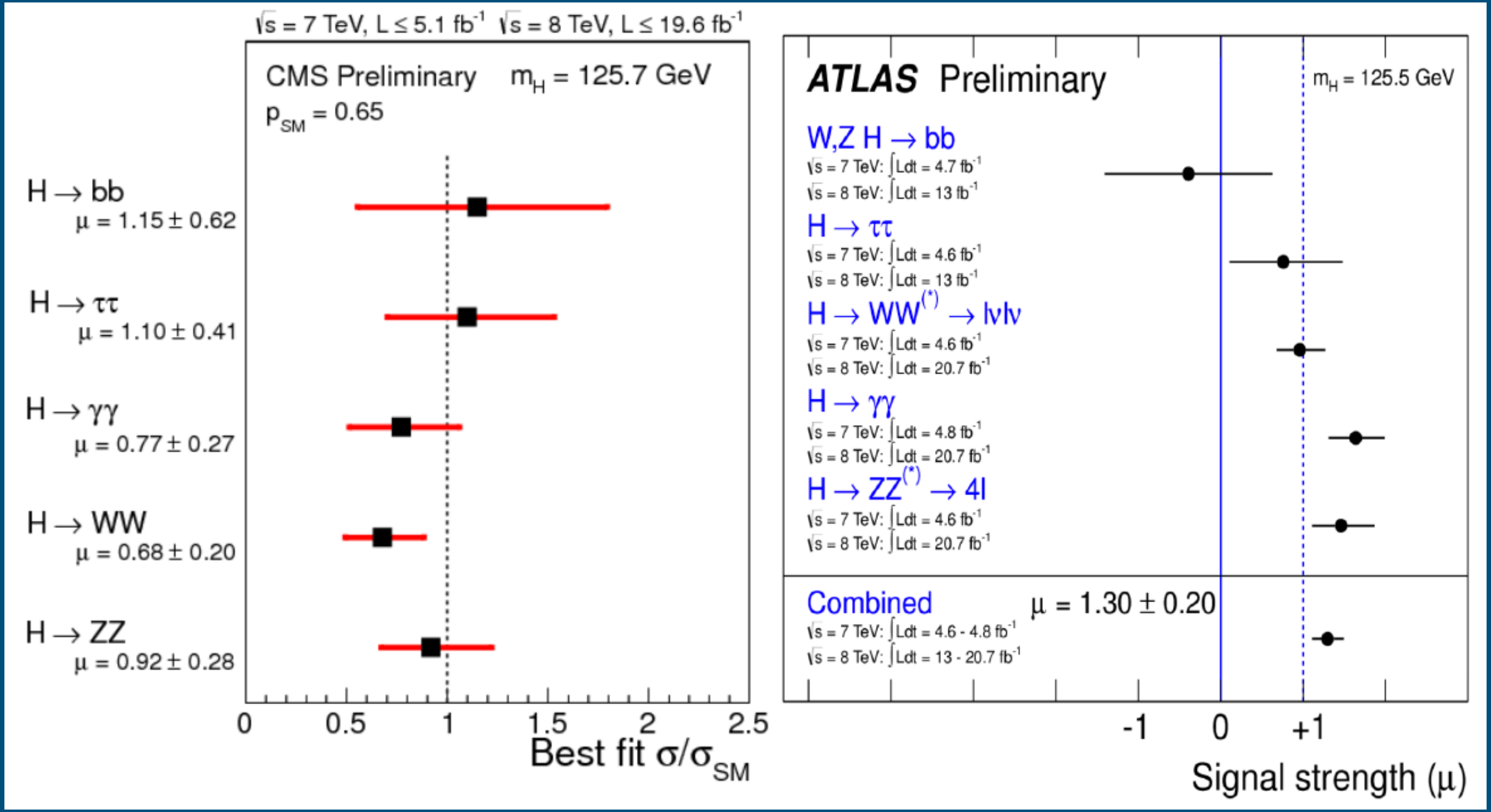




arXiv:0906.0954

Higgs Discovery

- It looks very much like THE Higgs boson:



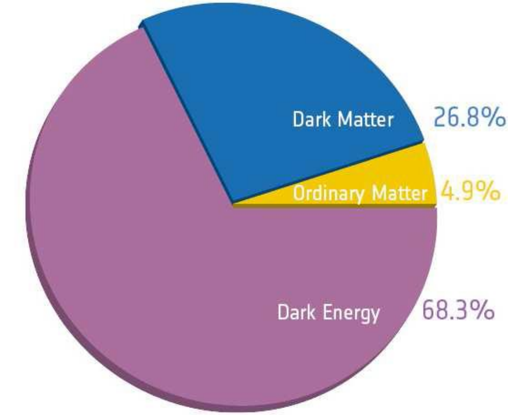
- To be done
  - Measure more precisely fermion couplings
  - Measure triple and quartic gauge couplings to reconstruct vacuum potential

Physics Situation after LHC Run 1

- *With a mass of the Higgs boson of 125 − 126 GeV, the Standard Model may be a self-consistent weakly coupled effective field theory up to very high scales (possibly up to the Planck scale) without adding new particles*
  - ➔ No *need* for new particles *up to* Planck scale!?

Experimental evidence for New Physics

1. Neutrino oscillations: *tiny* masses and flavour mixing
   - → Requires new degrees of freedom in comparison to SM
2. Baryon asymmetry of the Universe
   - → Measurements from BBN and CMB $\eta = \left\langle \frac{n_B}{n_\gamma} \right\rangle_{T=3K} \sim \left\langle \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \right\rangle_{T \gtrsim 1\ GeV} \sim 6 \times 10^{-10}$
   - → Current measured CP violation in quark sector ➔ $\eta \sim 10^{-20}$!!
3. Dark Matter from indirect gravitational observations
   - → Non-baryonic, neutral and stable or long-lived
4. Dark Energy and Inflation

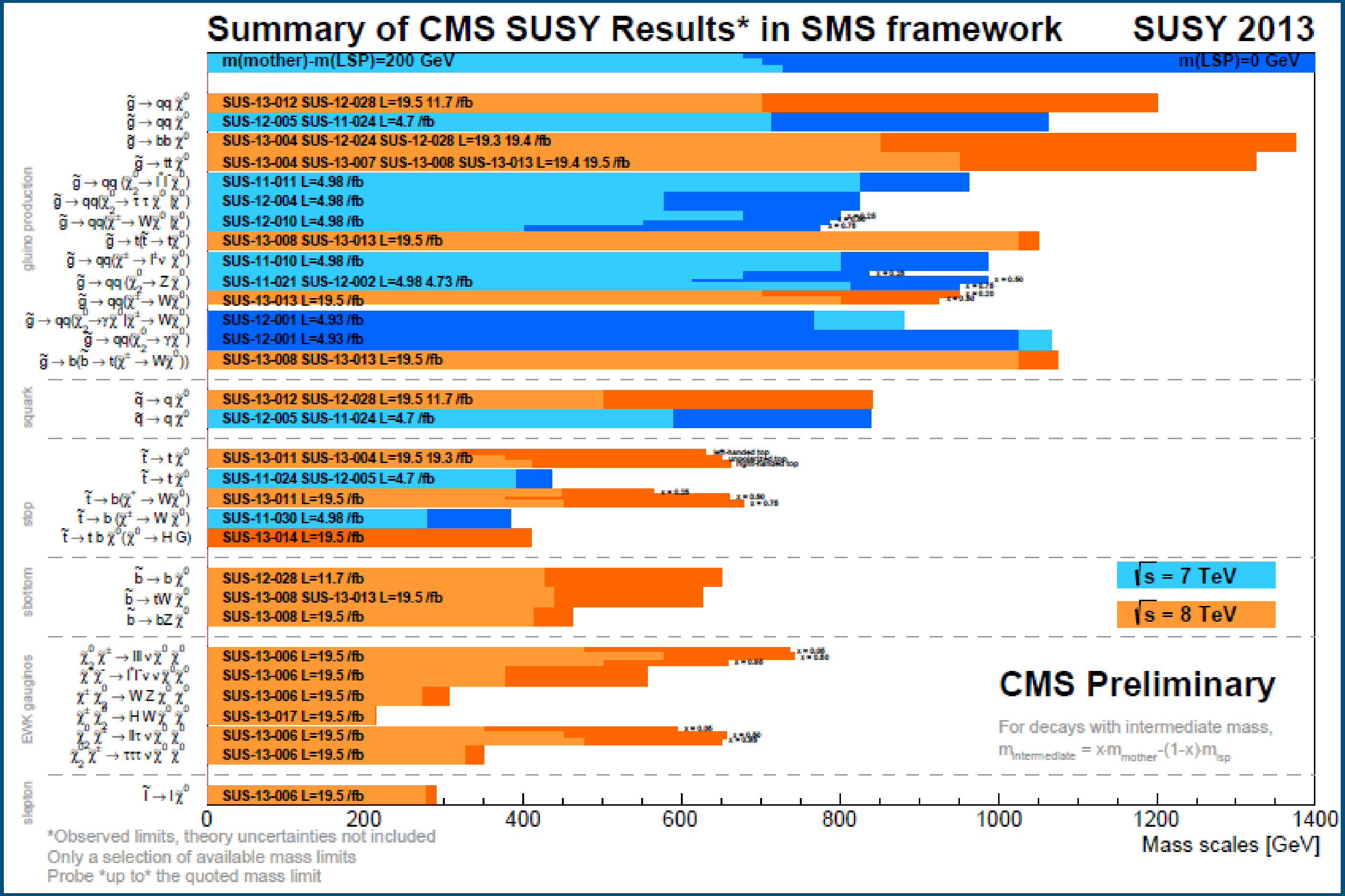


Theoretical "evidence" for New Physics

1. Hierarchy problem and stability of Higgs mass
2. SM flavour structure
3. Strong CP problem
4. Gravity
5. ….

➔ *While we had unitarity bounds for the Higgs, no such indication on the next scale….*

What did we not find....

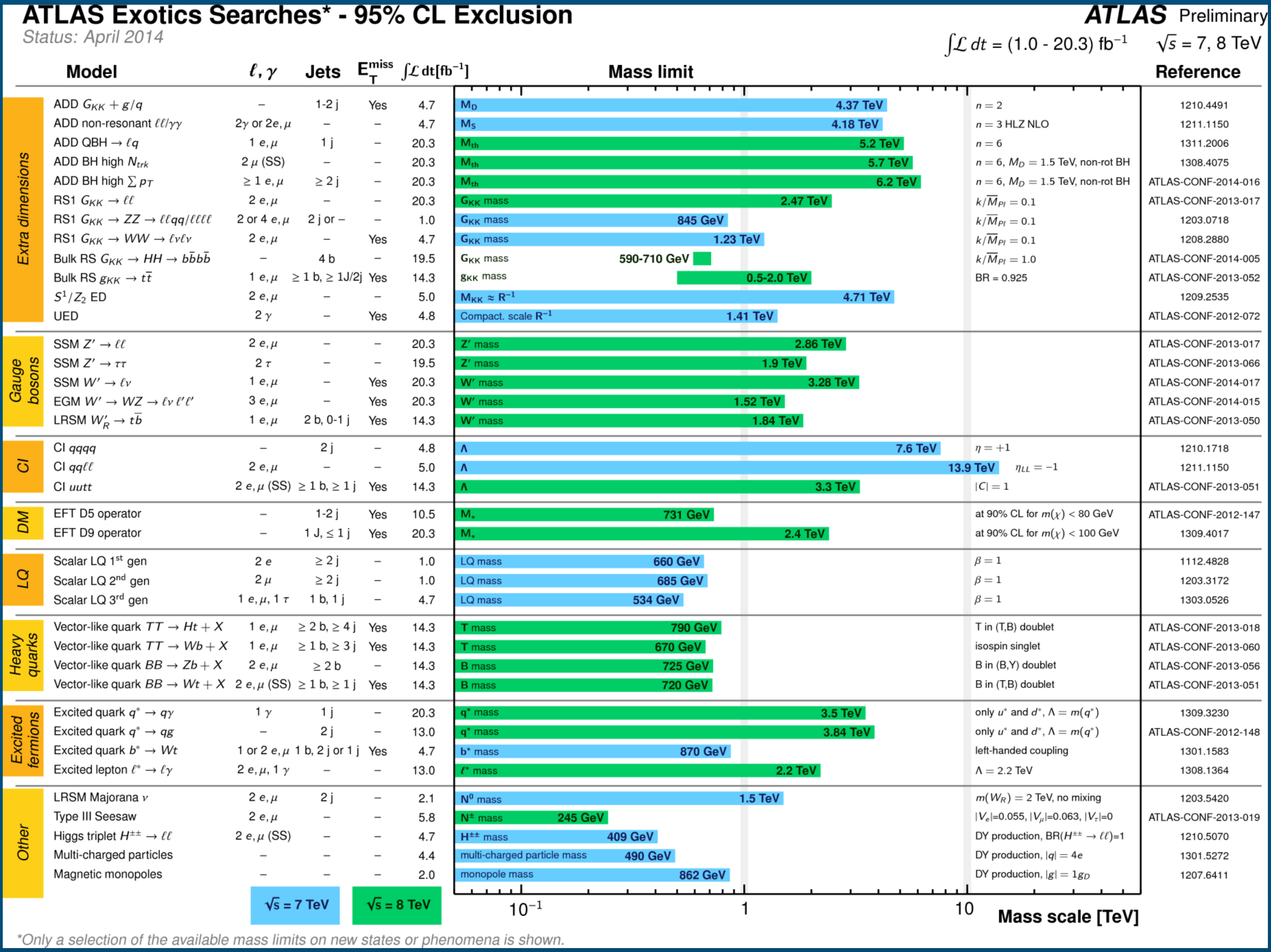


Very intriguing situation! Multitude of “solutions” to these questions

➔ Search for Beyond Standard Model physics at the LHC, FHC (Energy Frontier):

- Continued direct searches for new particles
- Higgs and top (EW) precision physics
- Flavour precision physics

What did we not find…



ATLAS Exotics Searches* - 95% CL Exclusion

Status: April 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	🟦 M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell/\gamma\gamma$	2γ or $2e, \mu$	–	–	4.7	🟦 M_S 4.18 TeV	$n = 3$ HLZ NLO	1211.1150
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	🟩 M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	🟩 M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	🟩 M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	ATLAS-CONF-2014-016
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	🟩 G_{KK} mass 2.47 TeV	$k/\overline{M}_{Pl} = 0.1$	ATLAS-CONF-2013-017
	RS1 $G_{KK} \to ZZ \to \ell\ell qq/\ell\ell\ell\ell$	2 or 4 e, μ	2 j or –	–	1.0	🟦 G_{KK} mass 845 GeV	$k/\overline{M}_{Pl} = 0.1$	1203.0718
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\ e, \mu$	–	Yes	4.7	🟦 G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	🟩 G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	🟩 g_{KK} mass 0.5-2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e, \mu$	–	–	5.0	🟦 $M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	🟦 Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	20.3	🟩 Z' mass 2.86 TeV		ATLAS-CONF-2013-017
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	🟩 Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	20.3	🟩 W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\, \ell'\ell'$	$3\ e, \mu$	–	Yes	20.3	🟩 W' mass 1.52 TeV		ATLAS-CONF-2014-015
	LRSM $W'_R \to t\bar{b}$	$1\ e, \mu$	2 b, 0-1 j	Yes	14.3	🟩 W' mass 1.84 TeV		ATLAS-CONF-2013-050
CI	CI $qqqq$	–	2 j	–	4.8	🟦 Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\ e, \mu$	–	–	5.0	🟦 Λ 13.9 TeV	$\eta_{LL} = -1$	1211.1150
	CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	🟩 Λ 3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator	–	1-2 j	Yes	10.5	🟩 M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator	–	1 J, ≤ 1 j	Yes	20.3	🟩 M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	1.0	🟦 LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	1.0	🟦 LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	$1\ e, \mu, 1\ \tau$	1 b, 1 j	–	4.7	🟦 LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	$1\ e, \mu$	≥ 2 b, ≥ 4 j	Yes	14.3	🟩 T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	14.3	🟩 T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $BB \to Zb + X$	$2\ e, \mu$	≥ 2 b	–	14.3	🟩 B mass 725 GeV	B in (B,Y) doublet	ATLAS-CONF-2013-056
	Vector-like quark $BB \to Wt + X$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	🟩 B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	20.3	🟩 q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	13.0	🟩 q^* mass 3.84 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2012-148
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	🟦 b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\ e, \mu, 1\ \gamma$	–	–	13.0	🟩 ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LRSM Majorana ν	$2\ e, \mu$	2 j	–	2.1	🟦 N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\ e, \mu$	–	–	5.8	🟩 $N^\pm$ mass 245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e, \mu$ (SS)	–	–	4.7	🟦 $H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	🟦 multi-charged particle mass 490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	🟦 monopole mass 862 GeV	DY production, $\lvert g \rvert = 1 g_D$	1207.6411

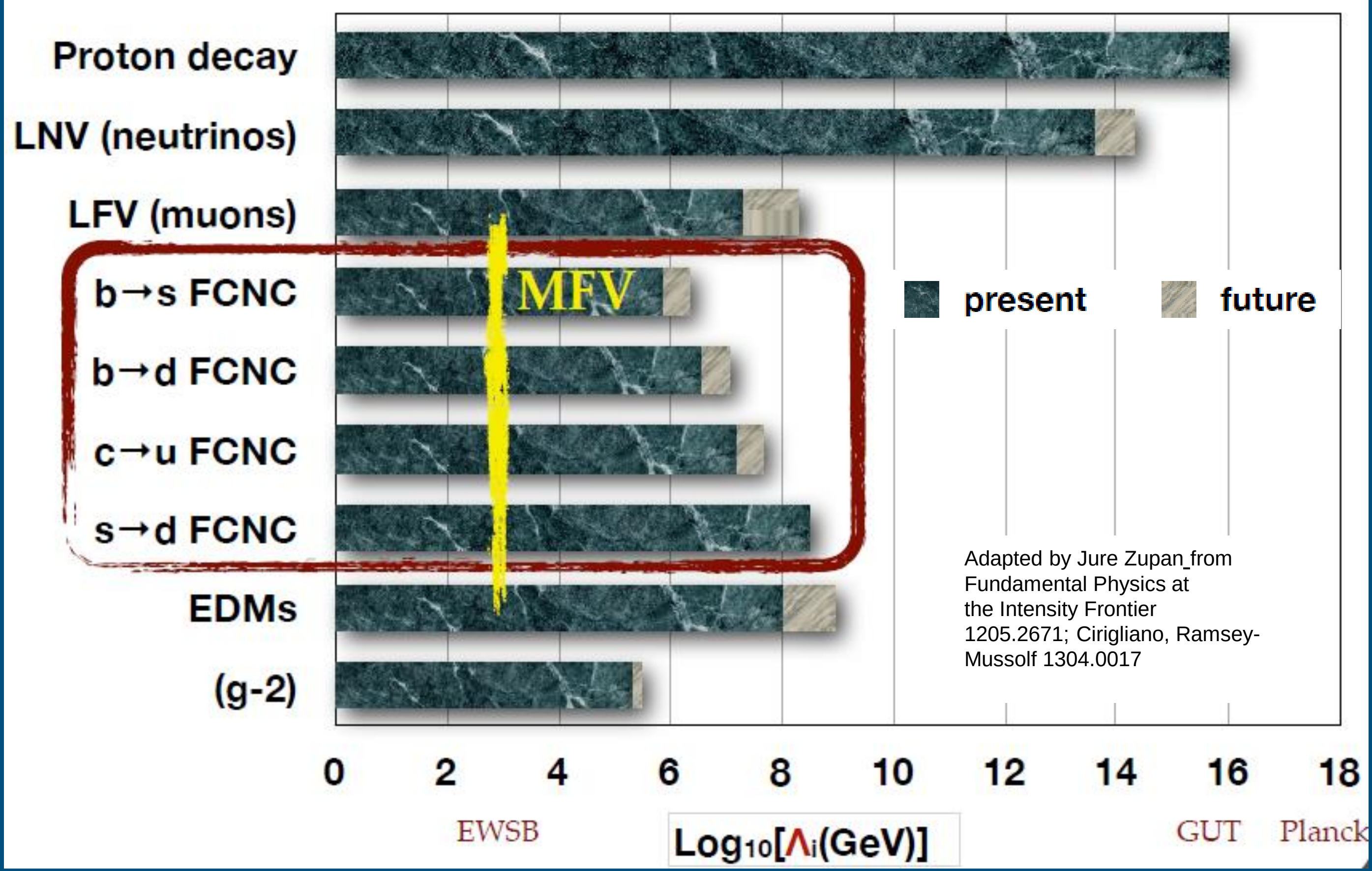
🟦 $\sqrt{s}$ = 7 TeV 🟩 $\sqrt{s}$ = 8 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

Precision Flavour Physics

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \delta C\left[\frac{\epsilon^{NP}}{\Lambda^2_{NP}}\right] \qquad \sigma_{stat+sys+th} < \delta C\left[\frac{\epsilon^{NP}}{\Lambda^2_{NP}}\right]$$

- Low-energy probes exceed the reach of the direct searches at the high-energy frontier

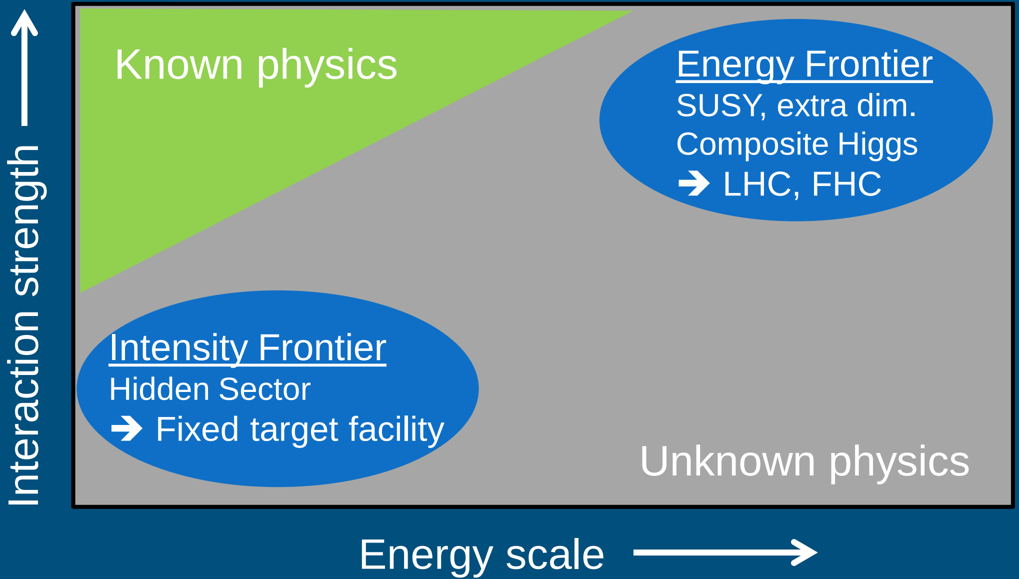


Adapted by Jure Zupan from Fundamental Physics at the Intensity Frontier 1205.2671; Cirigliano, Ramsey-Mussolf 1304.0017

- Most stringent general bounds on the scale of New Physics from mixing

What if...?

What about solutions to (some) these questions *below* Fermi scale?



Known physics

Energy Frontier
SUSY, extra dim.
Composite Higgs
➔ LHC, FHC

Intensity Frontier
Hidden Sector
➔ Fixed target facility

Unknown physics

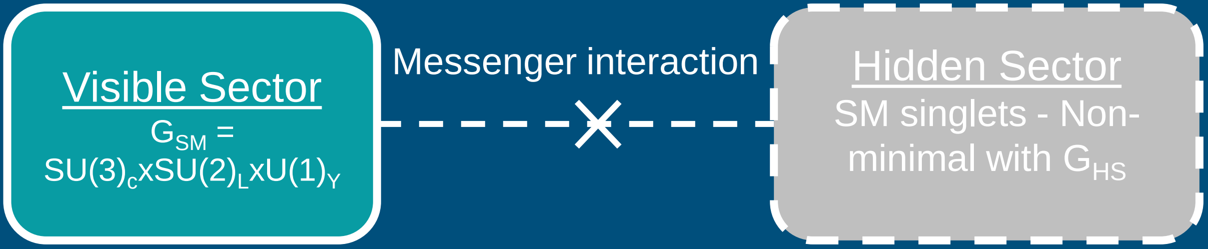
Interaction strength ⟶

Energy scale ⟶

➔Must have very weak couplings ➔ Hidden Sector (Not the first time! Cmp. neutrino)

Hidden Sector Exploration

$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$



Visible Sector

$G_{SM} = SU(3)_c xSU(2)_L xU(1)_Y$

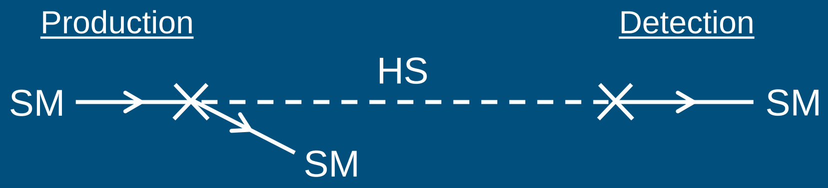
Messenger interaction

Hidden Sector

SM singlets - Non-minimal with G_{HS}

- New light hidden particles are singlet under the SM gauge group
- Composite operators (hoping there is not just gravity…) $\mathcal{L}_{mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{HS}^{(k)}\mathcal{O}_{SM}^{(l)}}{\Lambda^n}$
- Lowest dimension SM operator makes up "portals" to the Hidden Sector

1. "Indirect detection" through portals in (missing mass)
2. "Direct detection" through both portals in and out



Many different possibilities for Hidden Sector

- Standard Model portals:
  - D = 2: Vector portal
    - Kinetic mixing with massive dark/secluded/paraphoton V : $\frac{1}{2}\varepsilon F_{\mu\nu}^{SM} F_{HS}^{\mu\nu}$

    ➔ Interaction with 'mirror world' constituting dark matter

  - D = 2: Higgs portal
    - Mixing with dark scalar χ : $(\mu\chi + \lambda\chi^2)H^\dagger H$

    ➔ Mass to Higgs boson and right-handed neutrino, and function as inflaton in accordance with Planck and BICEP measurements

  - D = 5/2: Neutrino portal, e.g. νMSM
    - Mixing with right-handed neutrino N (Heavy Neutral Lepton): $YH^\dagger\bar{N}L$

    ➔ Neutrino oscillation, baryon asymmetry, dark matter

  - D = 4: Axion portal
    - Mixing with axion like particles, pseudo-scalars, axial vectors : $\frac{a}{F}G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi$, etc

    ➔ Solve strong CP problem

  - And possiby higher dimensional operator portals and super-symmetric portals (light neutralino, light sgoldstino,…)

    ➔ SUSY parameter space explored by LHC

    ➔ Some of SUSY low-energy parameter space open to complementary searches

HS Common experimental features

- Cosmologically interesting and experimentally accessible $m_{HS} \sim \mathcal{O}(MeV\ - GeV)$
  - ➔ Production through meson decays (π, K, D, B), proton bremsstrahlung,…
  - ➔ Decay to $l^+l^-,\ \pi^+\pi^-, l\pi,\ l\rho,\ \gamma\gamma$, etc (and modes including neutrino)
  - ➔ Full reconstruction and particle ID aim at maximizing the model independence

- Production and decay rates are very suppressed relative to SM
  - Production branching ratios $\mathcal{O}(10^{-10})$
  - Long-lived objects
  - Travel unperturbed through *ordinary* matter
  - ➔ Challenge is background suppression

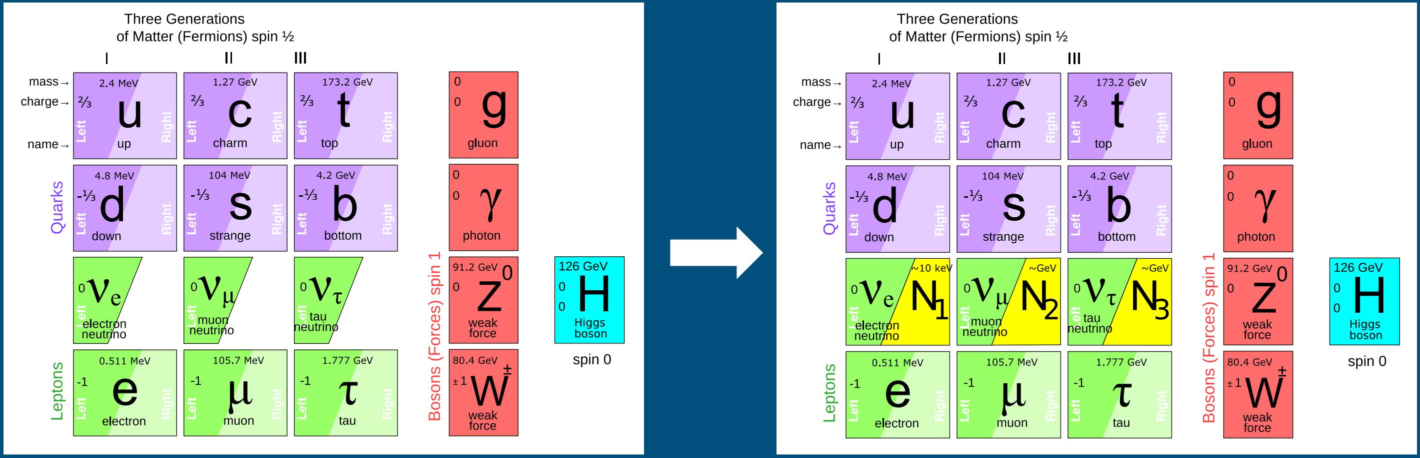
➔ Fixed-target (“beam-dump”) experiment

- ➔ Large number of protons on target and large decay volume!

➔ Complementary physics program to searches for new physics by LHC!

For development of experimental facility and detector concept, and sensitivity studies neutrino portal and the vector portal

“Neutral Fermion” Portal - Ockham’s Razor



- Introduce three neutral fermion singlets – right-handed Majorana leptons N_I with Majorana mass m_I^R ≡ ”Heavy Neutral Leptons (HNL)”
  - Make the leptonic sector similar to the quark sector
  - No electric, strong or weak charges ➔ “sterile”

Minkowski 1977
Yanagida 1979
Gell-Mann, Ramond, Slansky 1979
Glashow 1979

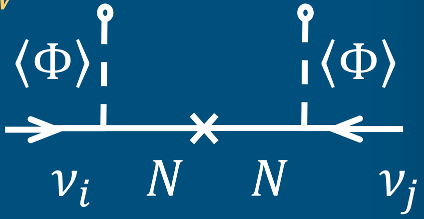
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{\substack{I=1,2,3;\\ \ell=1,2,3(e,\mu,\tau)}} i\bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\ell} H^\dagger \bar{N}_I L_\ell - m_I^R \bar{N}_I^c N_I + h.c$$

where L_ℓ are the lepton doublets, Φ is the Higgs doublet, and $Y_{I\ell}$ are the corresponding new Yukawa couplings

- Discovery of Higgs vital for the see-saw model! ➔ Responsible for the Yukawa couplings!

Type I See-saw

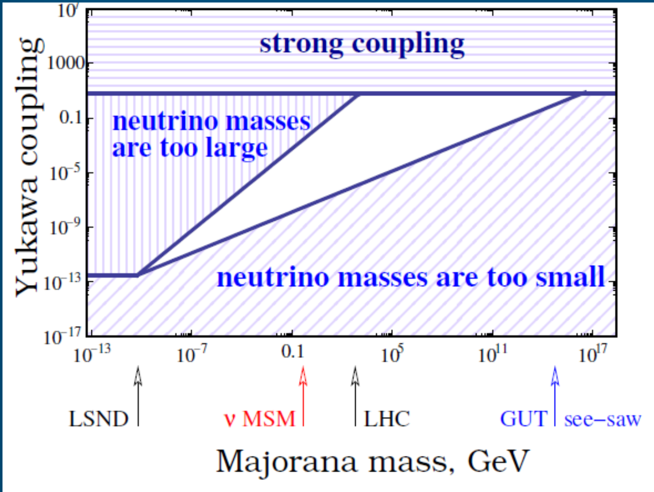
- $Y_{I\ell}H^{\dagger}\overline{N}_I L_\ell$ lepton flavour violating term results in mixing between N_I and SM active neutrinos when the Higgs SSB develops the $< VEV > = v \sim 246\ GeV$
  - ➔ Oscillations in the mass-basis and CP violation



- Type I See-saw with $m^R >> m_D(= Y_{I\ell}v)$ ➔ superposition of chiral states give
  - ➔ Active neutrino $(\nu = U_\nu(\nu_L + \theta\nu_R^c))$ mass in mass basis $\tilde{m}_1 \sim \frac{m_D^2}{m^R} \sim m_\nu$
  - ➔ Heavy singlet fermion mass in mass basis $\tilde{m}_2 \sim m^R\left(1 + \frac{m_D^2}{{m^R}^2}\right) \sim m^R \sim M_N$

- Four “popular” N mass ranges:

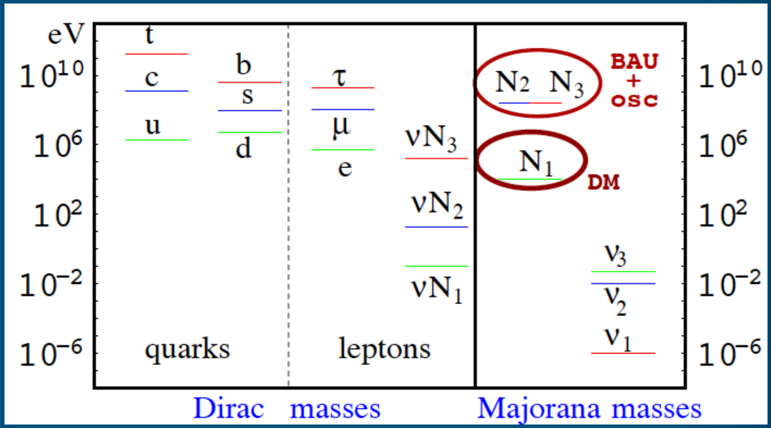
arXiv:1204.5379



	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a’la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a’la LSND

νMSM (Asaka, Shaposhnikov: hep-ph/0505013)

- Assumption that N_I are $\mathcal{O}(m_q/m_{l^{\pm}})$
  - ➔ Consequence: Yukuawa couplings are very small
    - $Y_{I\ell} = \mathcal{O}\left(\frac{\sqrt{m_{atm} m_I^R}}{v}\right) \sim 10^{-8} \quad (m^R = 1\ GeV, m_\nu = 0.05\ eV)$
    - $\mathcal{U}^2 \sim 10^{-11}$



➔ Experimental challenge ➔ Intensity Frontier

Role of N_1 with a mass of $\mathcal{O}$(keV)
➔ Dark Matter

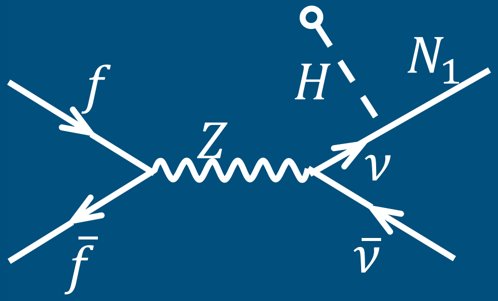
Role of N_2 and N_3 with a mass of $\mathcal{O}(m_q/m_{l^{\pm}})$ (100 MeV – GeV):
➔ Neutrino oscillations and mass, and BAU

➔ No new energy scale!

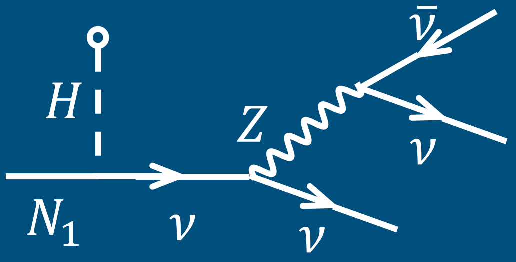
νMSM N_1 = Dark Matter

- Assume lightest singlet fermion N_1 has a very weak mixing with the other leptons
  - Mass $M_1 \backsim \mathcal{O}(keV)$ and very small coupling
    - ➔ Sufficiently stable to act as Dark Matter candidate
    - ➔ Give the right abundance
    - ➔ Decouples from the primordial plasma very early
  - Produced relativistically out of equilibrium in the radiation dominant epoque ➔ erase density fluctuations below free-streaming horizon ➔ sterile neutrinos are redshifted to be non-relativistic before end of radiation dominance (Warm Dark Matter → CDM)
    - ➔ Decaying Dark Matter

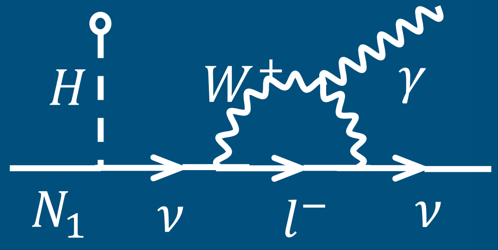
Production from υ ⟷ N oscillations



Dominant decay



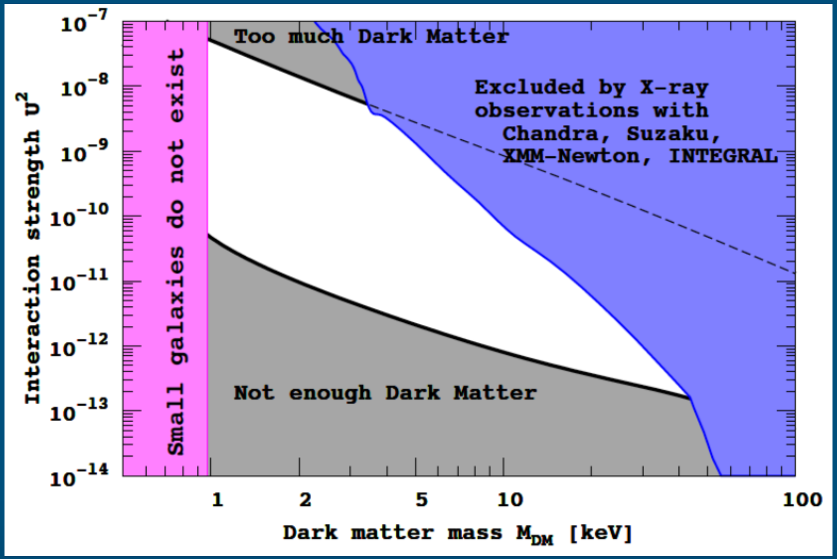
Subdominant radiative decay

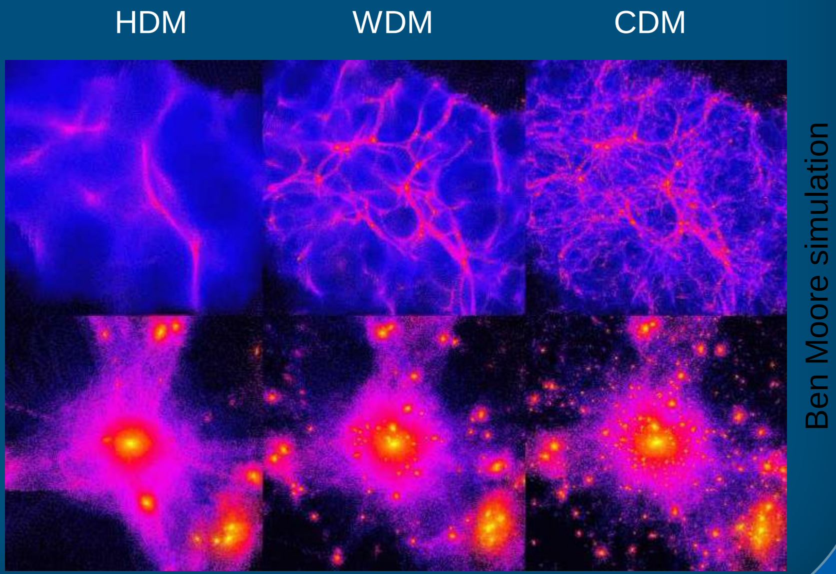


$$E_\gamma = \frac{M_{N_1} c^2}{2}$$

Dark Matter Constraint and Search

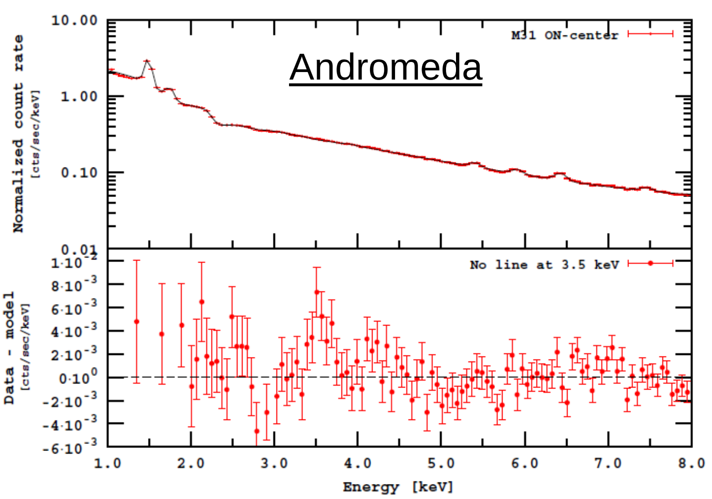
1. Tremaine-Gunn bound: average phase-space density for fermionic DM particles cannot exceed density given by Pauli exclusion principle
   - ➔ For smallest dark matter dominated objects such as dwarf spheroidal galaxies of the Milky Way
2. X-ray spectrometers to detect mono-line from radiative decay
   - Large field-of-view ~ ~ size of dwarf spheroidal galaxies ~ 1°
   - Resolution of $\frac{\Delta E}{E} \sim 10^{-3} - 10^{-4}$ coming from width of decay line due to Doppler broadening
   - ➔ Proposed/planned X-ray missions: Astro-H, LOFT, Athena+, Origin/Xenia
3. Lyman-α forest
   - Super-light sterile neutrino creates cut-off in the power spectrum of matter density fluctuations due to sub-horizon free-streaming $d_{FS} \sim 1\ \mathrm{Gpc}\ m_{eV}^{-1}$
   - Fitted from Fourier analysis of spectra from distant quasars propagating through fluctuations in the neutral hydrogen density at redshifts 2-5

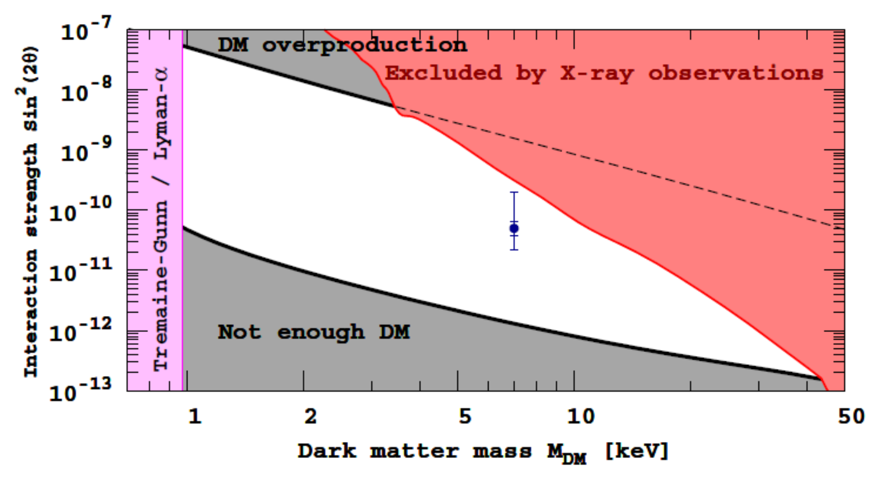


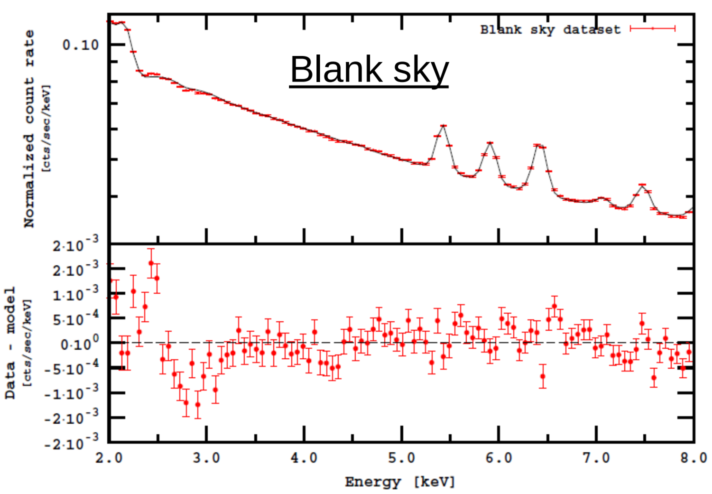


Intriguing hints from galaxy spectrum?

- Two recent publications:
  - ➔ arXiv:1402.2301 : Detection of an unidentified emission line in the stacked XMM-Newton X-ray spectra of Galaxy Clusters at $E_\gamma \sim (3.55 - 3.57) \pm 0.03 keV$
  - ➔ arXiv:1402.4119 : An unidentified line in the X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster at $E_\gamma \sim 3.5\ keV$





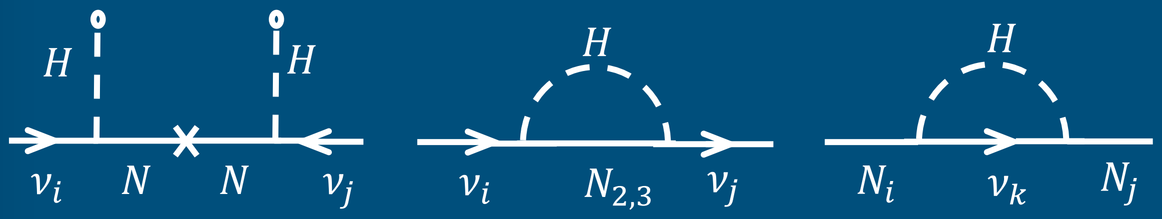


Confirmation by Astro-H with better energy resolution required

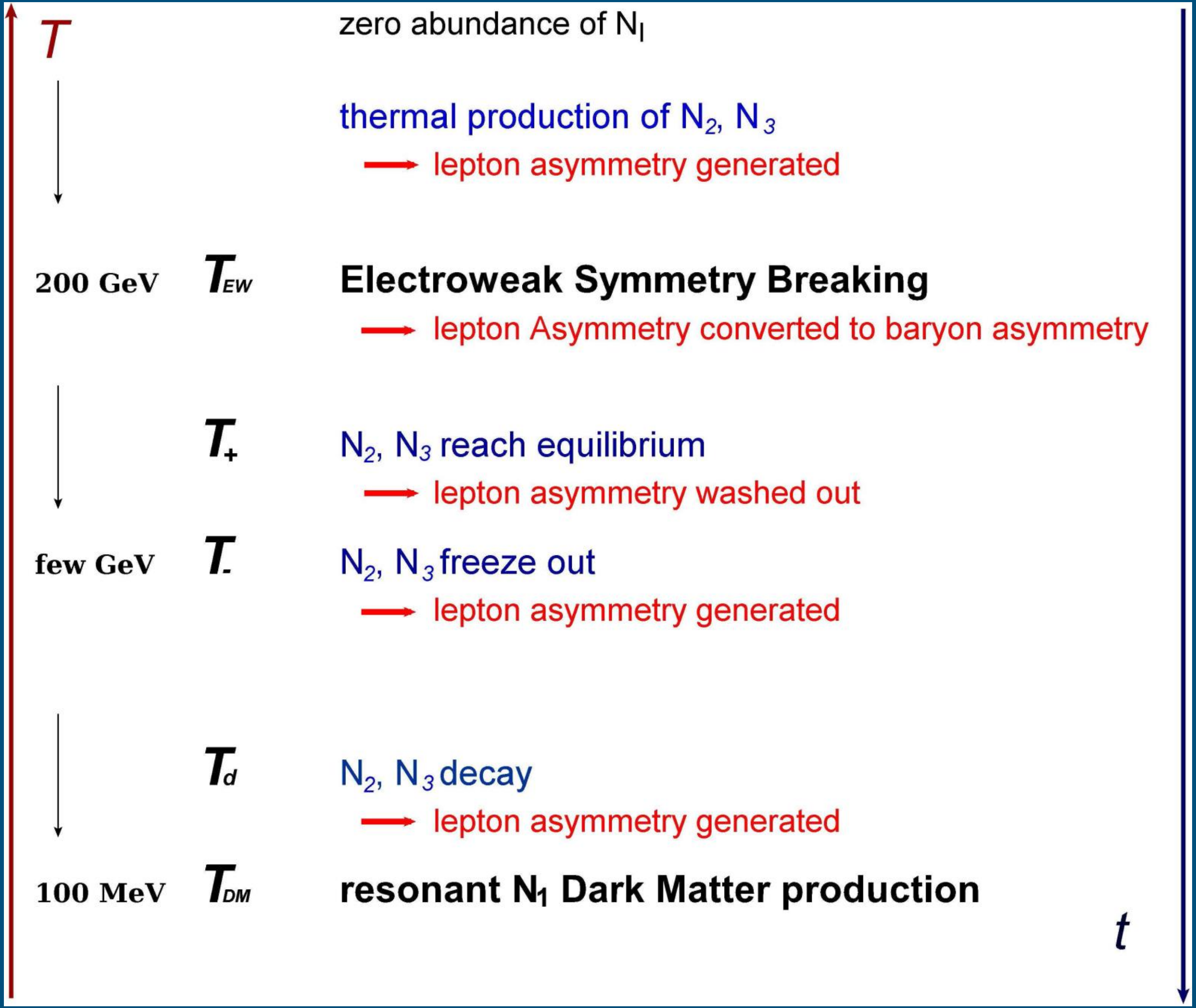
N_2 and N_3 in νMSM

- N_1 as DM ($M_{N_1} \ll M_{N_2} \approx M_{N_3}$) gives no contribution to active neutrino masses
  - ➔ Neglect for the rest
  - ➔ Reduces number of effective parameters for Lagrangian with $N_{2,3}$
    - 18 parameters ➔ 11 new parameters with 3 CP violating phases
      - ➔Two mixing angles related to active neutrinos and mass difference measured in low-energy neutrino experiment

- Generation of BAU with degenerate N_2 and N_3 (Akhmedov, Rubakov, Smirnov; Asaka, Shaposhnikov)
  1. Leptogenesis from coherent resonant oscillations with interference between CP violating amplitudes
     - ➔ Two fermion singlets should be quasi-degenerate
  2. Out of equilibrium ($\Gamma_{N_{2,3}}$ < Hubble rate of expansion) at the E.W. scale above sphaleron freeze-out
  3. Lepton number of active left-handed neutrinos transferred to baryon number by sphaleron processes
     - $\mathbb{L}_\ell - \frac{\mathbb{B}}{3}$ remain conserved while $\mathbb{L}_\ell$ and $\mathbb{B}$ are violated individually



Thermal History in νMSM



zero abundance of N_I

thermal production of N_2, N_3
→ lepton asymmetry generated

200 GeV T_{EW} **Electroweak Symmetry Breaking**
→ lepton Asymmetry converted to baryon asymmetry

T_+ N_2, N_3 reach equilibrium
→ lepton asymmetry washed out

few GeV T_- N_2, N_3 freeze out
→ lepton asymmetry generated

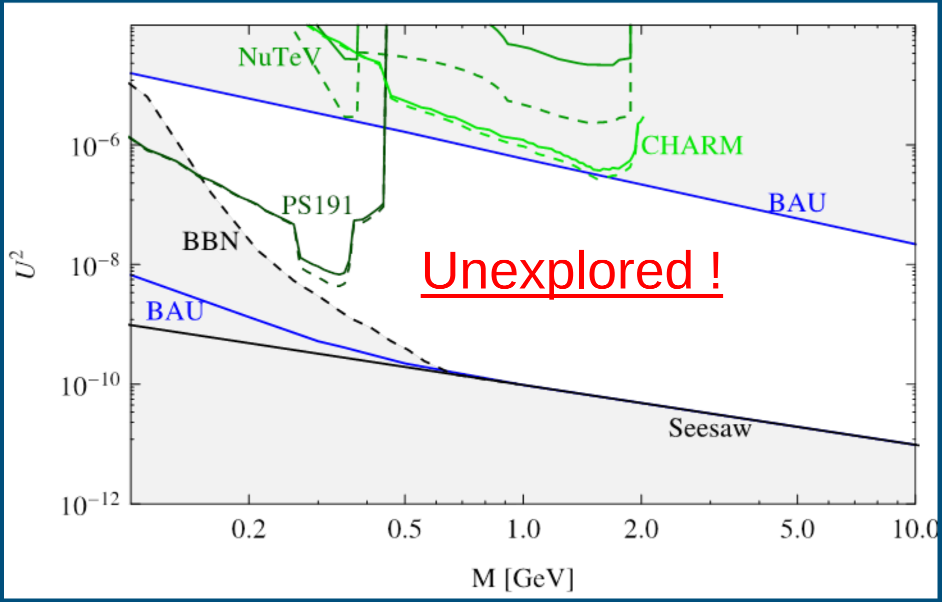
T_d N_2, N_3 decay
→ lepton asymmetry generated

100 MeV T_{DM} **resonant N_1 Dark Matter production**

(arXiv:1208.4607)

N_2 and N_3 Constraints in νMSM

1. See-saw: Lower limit on mixing with active neutrinos to produce oscillations and masses
2. BAU: Upper limit on mixing to guarantee out-of-equilibrium oscillations ($\Gamma_{N_{2,3}} < H$)
3. BBN: Decays of N_2 and N_3 must respect current abundances of light nuclei
   - ➔ Limit on lifetime $\tau_{N_{2,3}} < 0.1s \ (T > 3\ MeV)$
4. Experimental: No observation so far…
   - ➔ Constraints 1-3 now indicate that previous searches were largely outside interesting parameter space



N_2 and N_3 Constraints in νMSM

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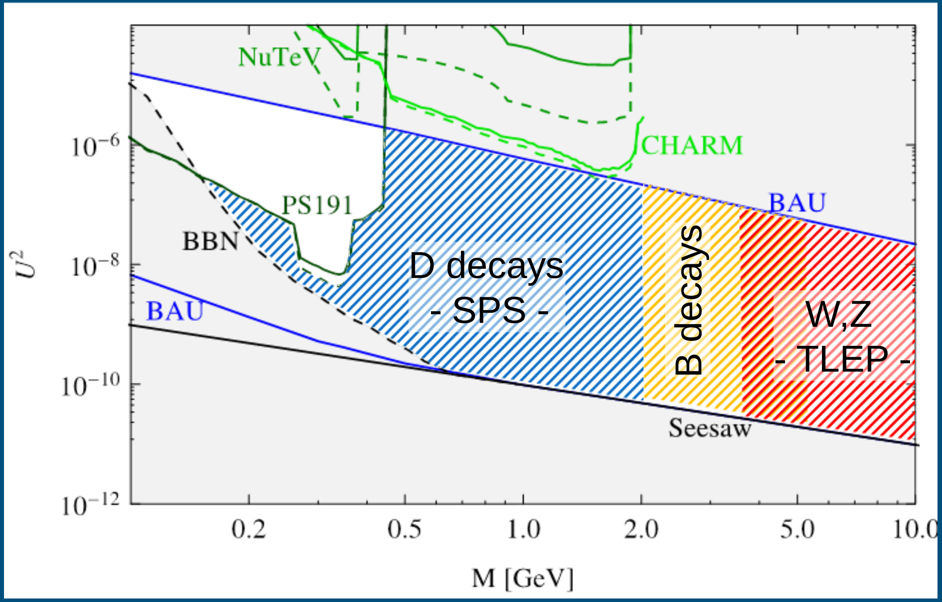
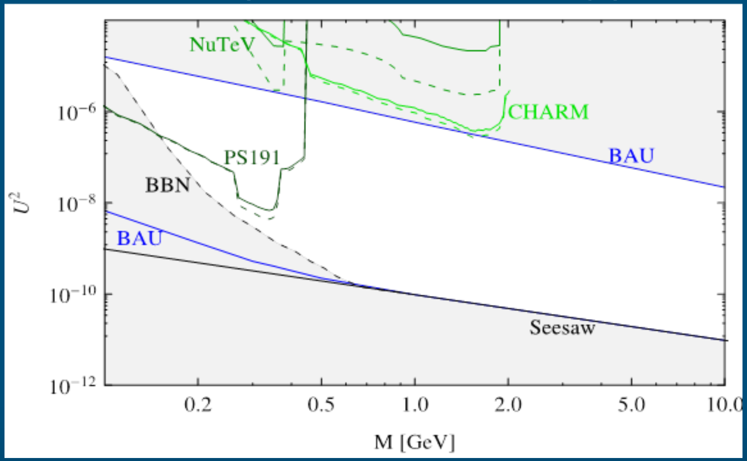


- ⊙ Large fraction of interesting parameter space can be explored in accelerator based search
  - $m_\pi < M_N <$ 2++ GeV
  - $M_N >$ 2 GeV is not reachable at any operating facility

Constraints in Variants of νMSM

1. νMSM: HNLs are required to explain neutrino masses, BAU, and DM
   - $\mathcal{U}^2$ is the most constrained
2. HNLs are required to explain neutrino masses and BAU
   - N_1 , N_2 and N_3 are available to produce neutrino oscillations/masses and BAU
3. HNLs are required to explain neutrino masses
   - Only experimental constraints remain
4. HNLs are required to explain Dark Matter
5. HNLs are helpful in cosmology and astrophysics
   - E.g. HNL may influence primordial abundance of light elements
   - E.g. HNL with masses below 250 MeV can facilitate the explosions of the supernovae

- ⊙ HNLs are not required to explain anything - just so
  - Contributions of the HNL to the rare lepton number violating processes μ → e, μ → eee



$N_{2,3}$ Production

- Production in mixing with active neutrino from leptonic/semi-leptonic weak decays of charm mesons
  - Total production depend on $\mathcal{U}^2 = \sum_{\substack{I=1,2\\ \ell=e,\mu,\tau}} |\mathcal{U}_{\ell I}|^2$
  - Relation between $\mathcal{U}_e{}^2, \mathcal{U}_\mu{}^2$ and $\mathcal{U}_\tau{}^2$ depends on exact flavour mixing

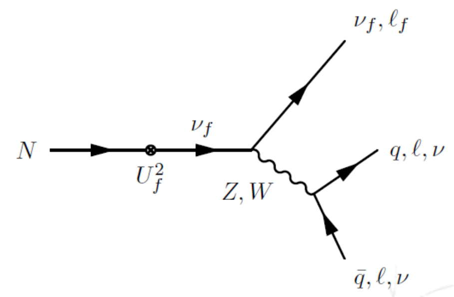
➔ For the sake of determining a search strategy, assume scenario with a predominant coupling to the muon flavour (arXiv:0605047)

- Production mechanism probes $\mathcal{U}_\mu{}^2 = \sum_{I=2,3} \frac{v^2 |Y_{\mu I}|^2}{m_I^{R\,2}}$

➔ $\mathrm{Br}(D \to NX) \sim 10^{-8} - 10^{-12}$

$N_{2,3}$ Decay

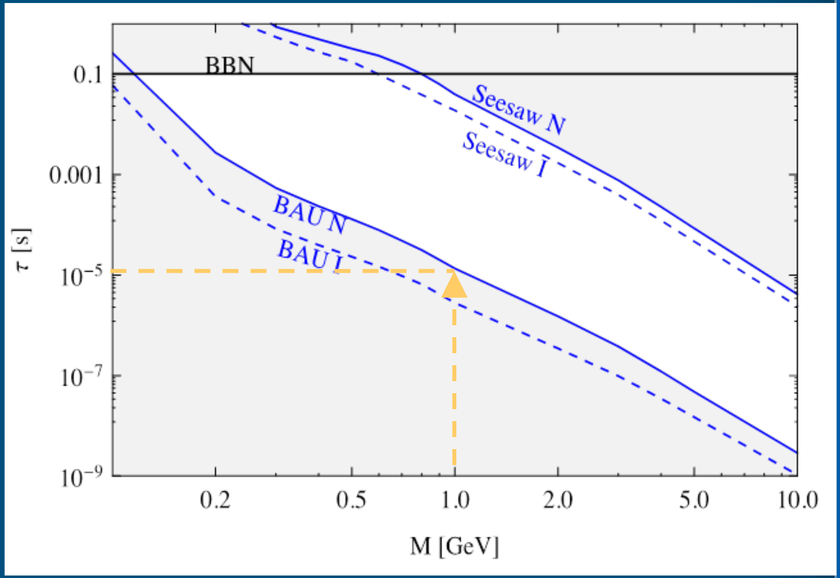
- Very weak HNL-active neutrino mixing → $N_{2,3}$ much longer lived than SM particles
  - ➔ Typical lifetimes > 10 μs for $M_{N_{2,3}} \sim 1\ GeV$ → Decay distance $\mathcal{O}(km)$



E.g.

- Decay modes:
  - $N \rightarrow \mu e \nu, \pi^0 \nu, \pi e, \mu\mu\nu, \pi\mu, Ke, K\mu, \eta\nu, \eta'\nu, \rho\nu, \rho e, \rho\mu, \ldots$
  - Branching ratios depend on flavour mixing (again)
  - Typical:

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 %*

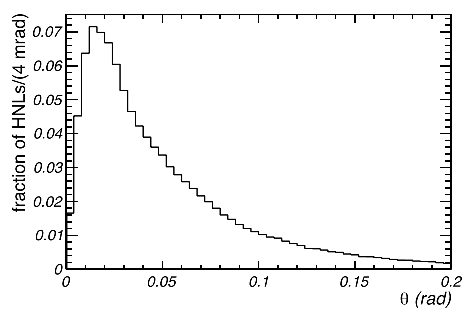


- Probability that $N_{2,3}$ decays in the fiducial volume $\propto \mathcal{U}_\mu^2$

Experimental Requirements/Challenges

Proposal: *fixed-target (beam dump like) experiment at the SPS*

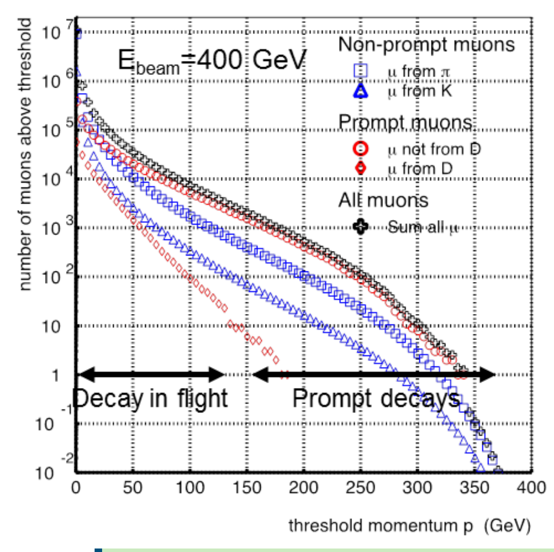
1. E.g. sensitivity to HNL $\propto \mathcal{U}^4$ → Number of protons on target (p.o.t.)
   - ➔ SPS: 4-5x10^{13} / 6-7s @ 400 GeV = 500 kW → 2x10^{20} in 5 years (similar to CNGS)
2. Preference for relatively slow beam extraction $\mathcal{O}(ms - 1s)$ to reduce detector occupancy
   - ➔ Reduce combinatorial background
3. As uniform extraction as possible for target and combinatorial background/occupancy
4. Heavy material target to stop π, K before decay to reduce flux of active neutrinos
   - ➔ Blow up beam to dilute beam energy on target
5. Long muon shield to range out flux of muons
6. Away from tunnel walls to reduce neutrino interactions in proximity of detector
7. Vacuum in detector volume to reduce neutrino interactions in detector
8. Detector acceptance compromise between lifetime and production angles
   - …and length of shield to filter out muon flux



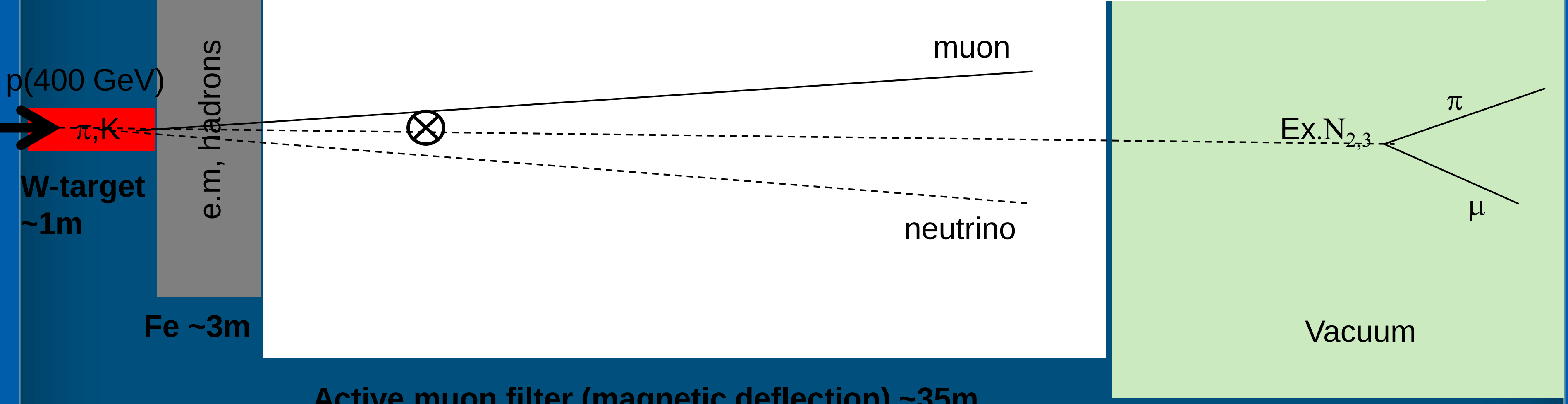
➔ Incompatible with conventional neutrino facility

Schematic Principle of Experimental Setup

- Initial reduction of beam induced background:
  - Heavy target
  - Hadron absorber
  - Muon filter (Without: Rate at detector 5×10^9 muons / 5×10^{13} p.o.t.)



Generic setup, not to scale!



Active muon filter (magnetic deflection) ~35m

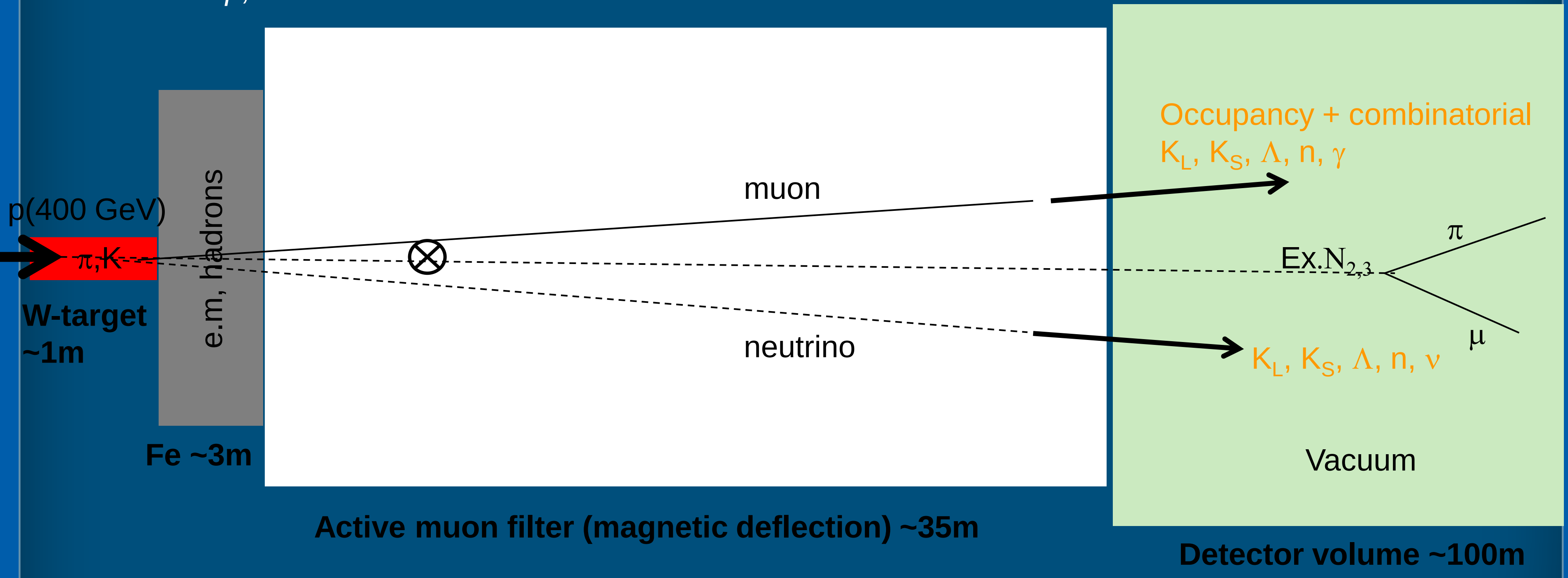
Detector volume ~100m

➔ Multi-dimensional optimization: Beam energy is compromise between σ_{charm}, beam intensity, background conditions, acceptance, detector resolution

Schematic Principle of Experimental Setup

- Residual backgrounds:
  1. Neutrinos scattering (e.g. $\nu_\mu + p \rightarrow X + K_L \rightarrow \mu\pi\nu$) ➔ Detector under vacuum, accompanying charged particles (timing), topological
  2. Muon inelastic scattering ➔ Accompanying charged particles (timing), topological
  3. Muon combinatorial (e.g. $\mu\mu$ with μ mis-ID)➔ Tagging, timing and topological

Generic setup, not to scale!



p(400 GeV)

π,K

W-target ~1m

e.m, hadrons

Fe ~3m

muon

neutrino

Active muon filter (magnetic deflection) ~35m

Occupancy + combinatorial

K_L, K_S, Λ, n, γ

Ex.$N_{2,3}$

π

μ

K_L, K_S, Λ, n, ν

Vacuum

Detector volume ~100m

Crucial to study background in detailed simulation with full detector description

Schematic Principle of Experimental Setup

- Residual backgrounds:
  1. Neutrinos scattering (e.g. $\nu_\mu + p \to X + K_L \to \mu\pi\nu$) ➔ Detector under vacuum, accompanying charged particles (timing), topological
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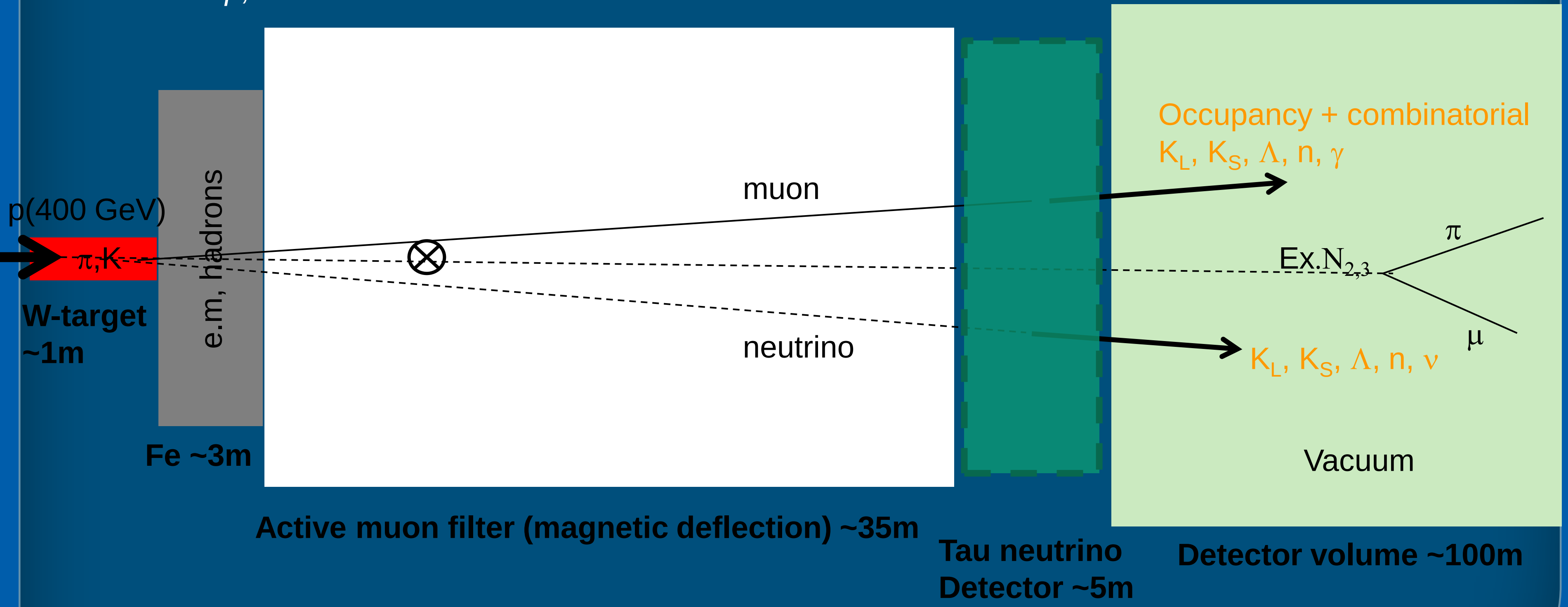
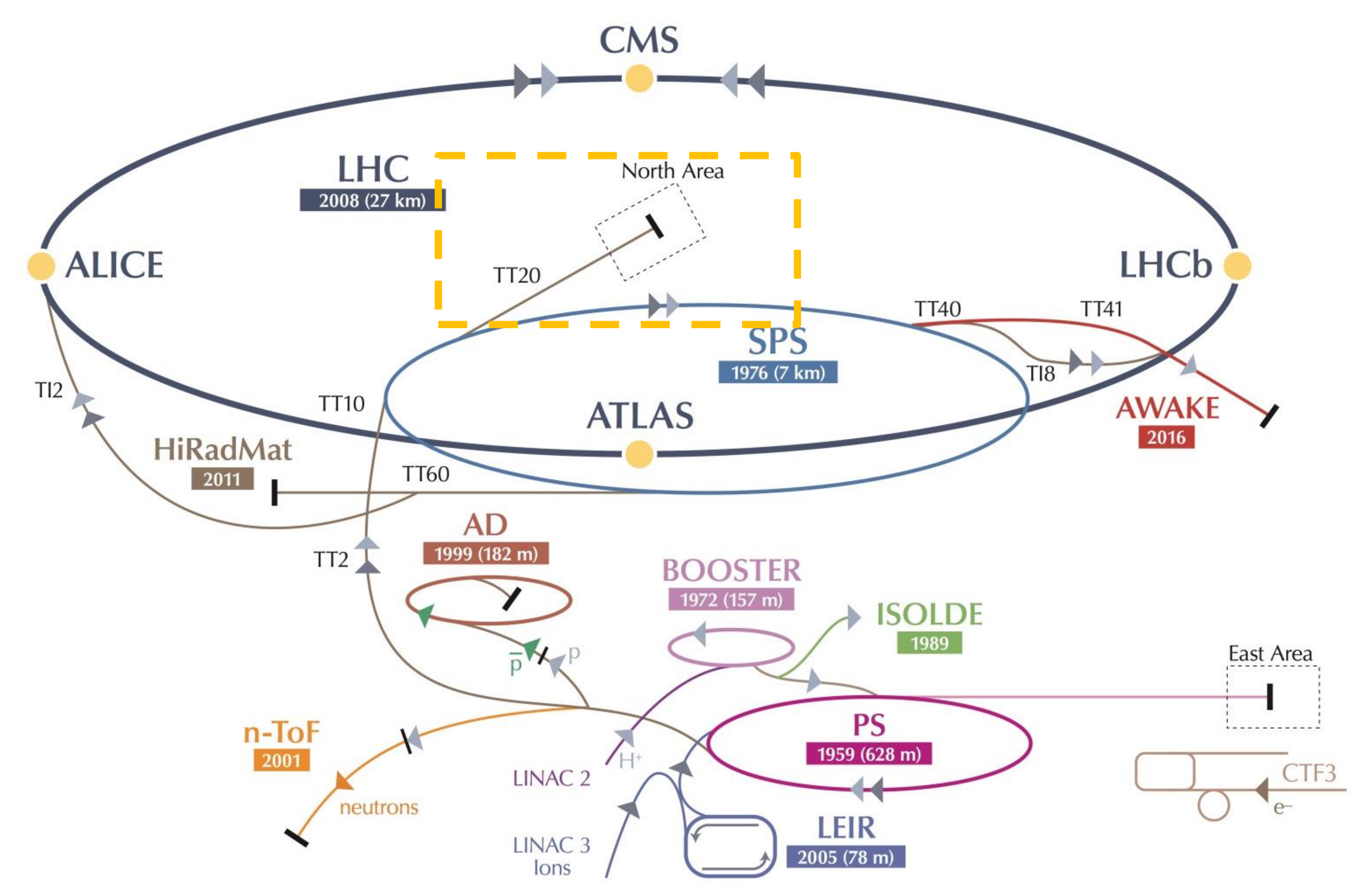
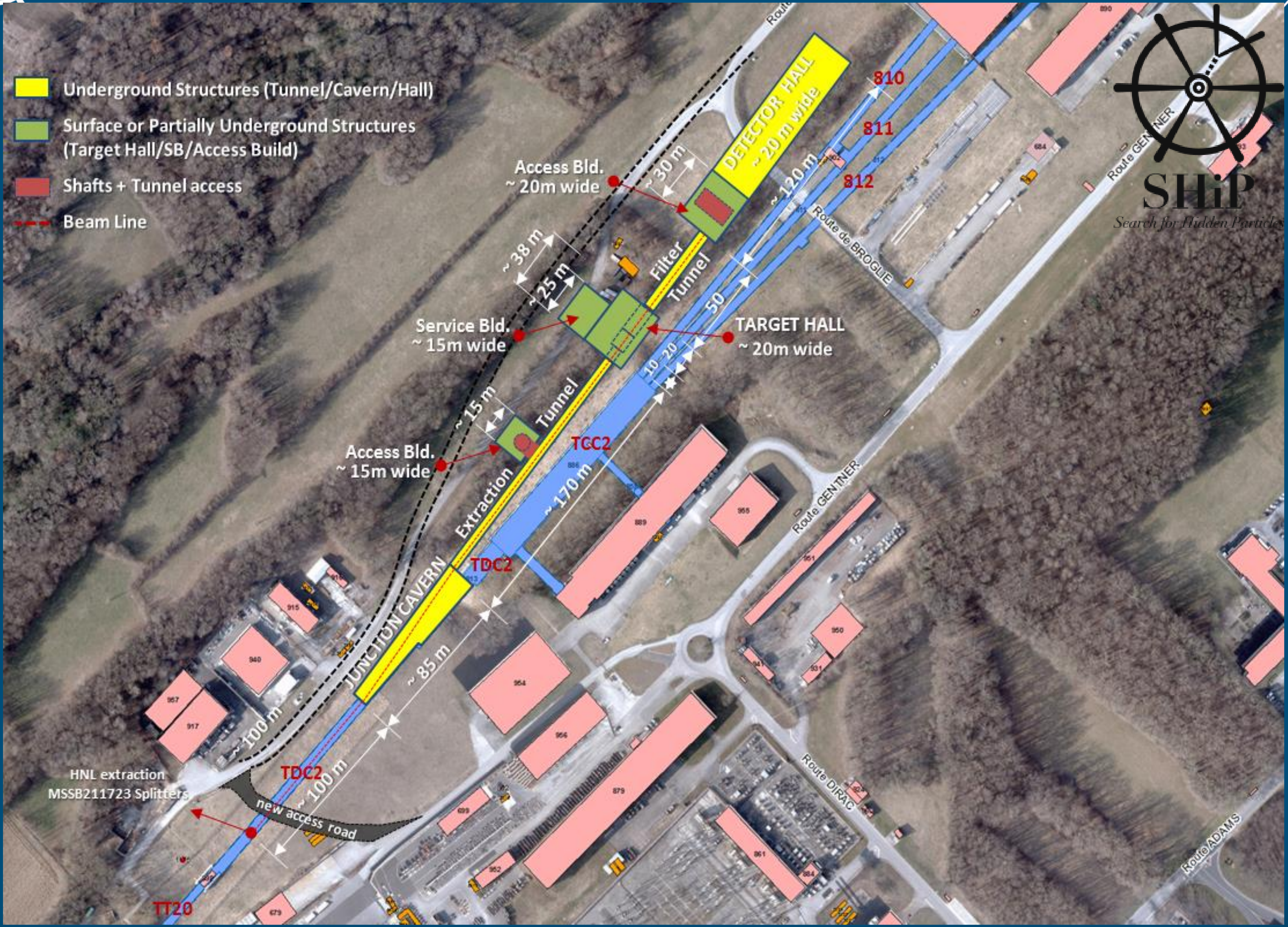


Muon flux limit driven by emulsion based tau neutrino detector and “hidden particle” background

CERN Accelerator Complex



Prevessin North Area site



CERN Task force

Initiated by CERN Management after SPSC encouragement in January

Detailed investigation

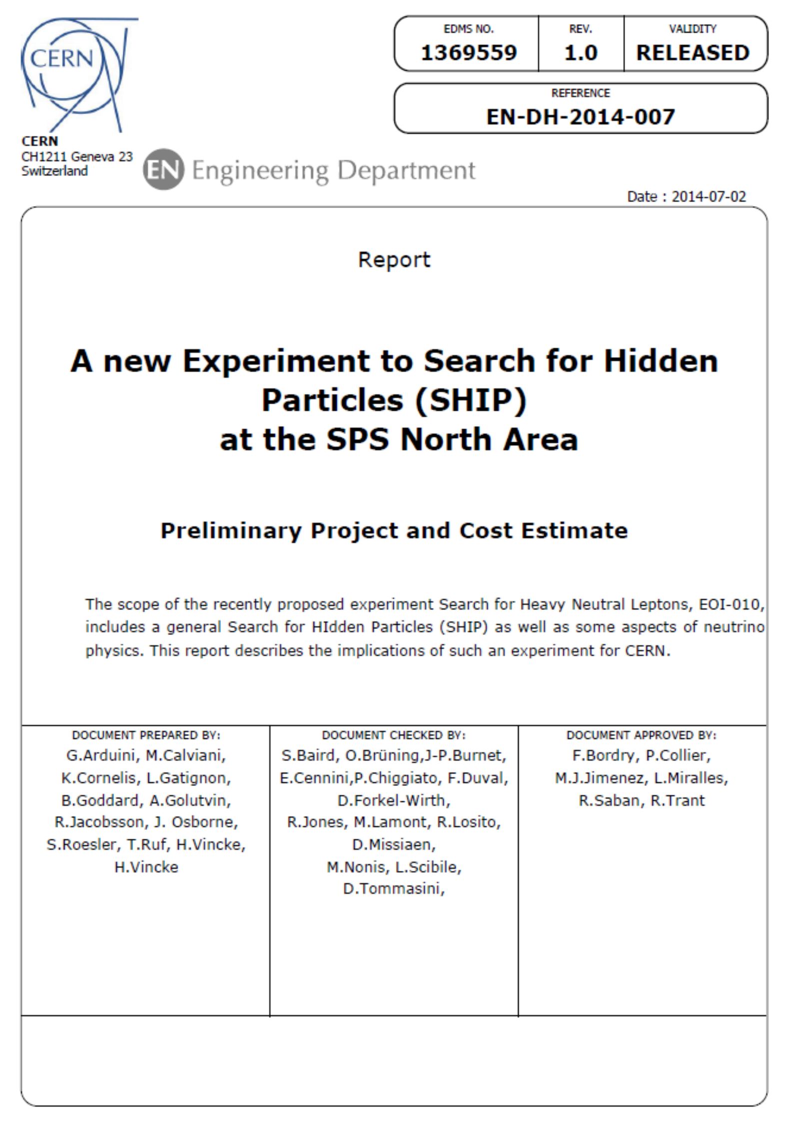
- Physics motivation and requirements
- Experimental Area
- SPS configuration and beam time
- SPS beam extraction and delivery
- Target station
- Civil engineering
- Radioprotection

➔ Aimed at overall feasibility, identifying options/issues, resource estimate

➔ Document completed with 80 pages on July 2

➔ Detailed cost, manpower and schedule

➔ Compatible with commissioning runs in 2022, data taking 2023



EDMS NO.	REV.	VALIDITY
1369559	1.0	RELEASED

REFERENCE
EN-DH-2014-007

CERN
CH1211 Geneva 23
Switzerland

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

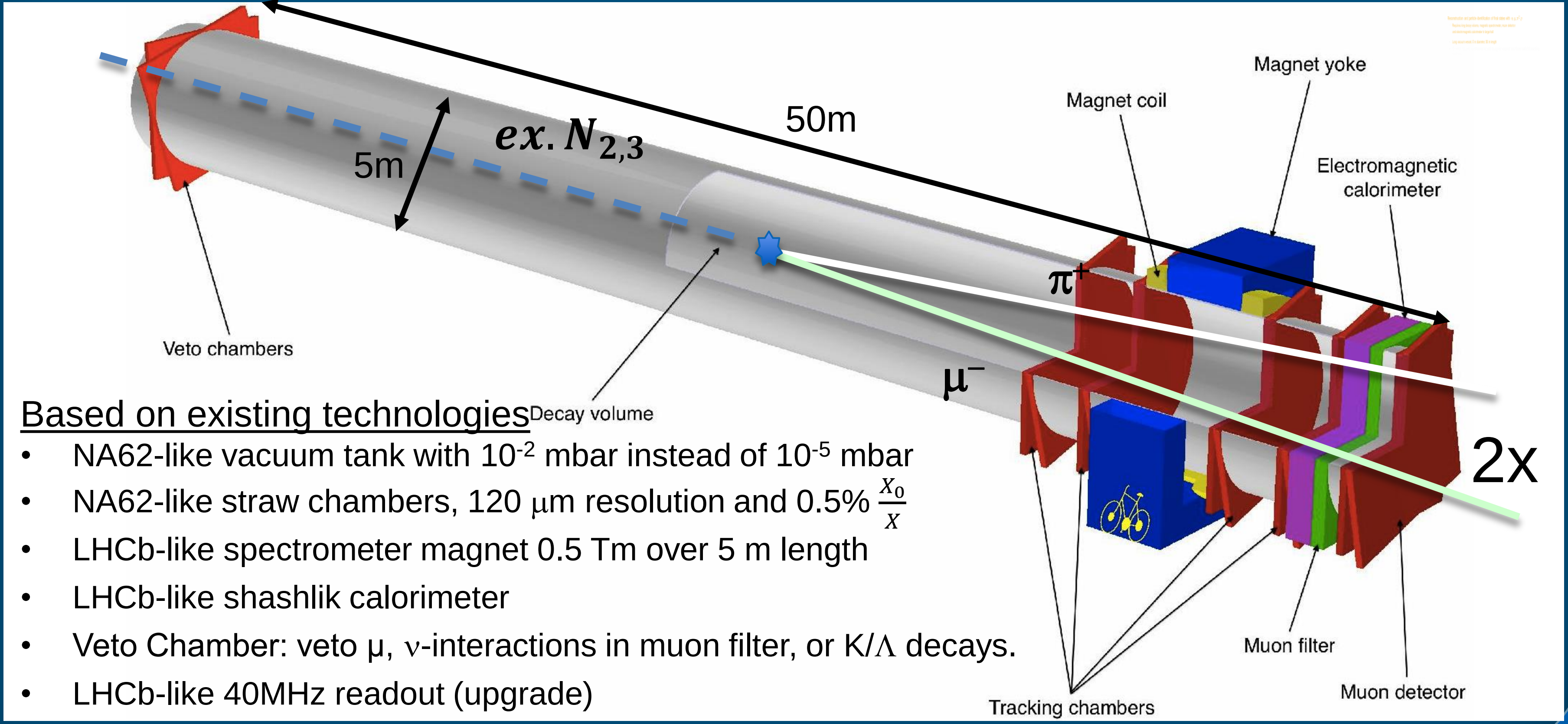
The scope of the recently proposed experiment Search for Heavy Neutral Leptons, EOI-010, includes a general Search for HIdden Particles (SHIP) as well as some aspects of neutrino physics. This report describes the implications of such an experiment for CERN.

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
G.Arduini, M.Calviani, K.Cornelis, L.Gatignon, B.Goddard, A.Golutvin, R.Jacobsson, J. Osborne, S.Roesler, T.Ruf, H.Vincke, H.Vincke	S.Baird, O.Brüning,J-P.Burnet, E.Cennini,P.Chiggiato, F.Duval, D.Forkel-Wirth, R.Jones, M.Lamont, R.Losito, D.Missiaen, M.Nonis, L.Scibile, D.Tommasini,	F.Bordry, P.Collier, M.J.Jimenez, L.Miralles, R.Saban, R.Trant

Detector Concept

- Reconstruction and particle identification of final states with e, $\mu, \pi^{\pm}, \gamma$
  - ➔ Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter in large hall

- Long vacuum vessel, 5 m diameter, 50 m length
- 10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers

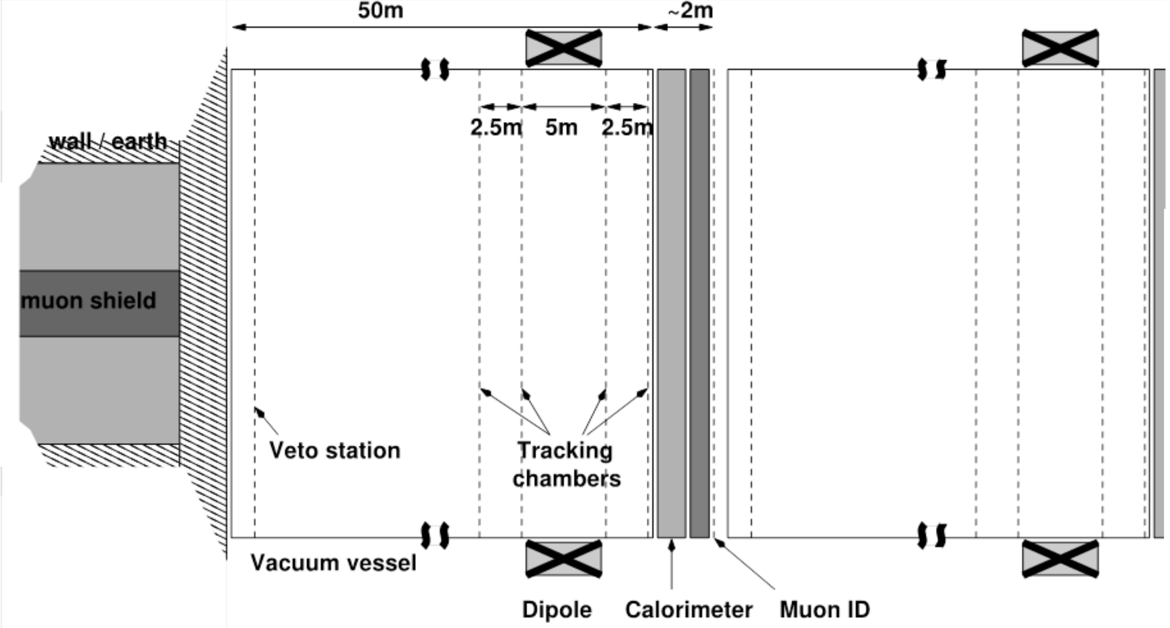


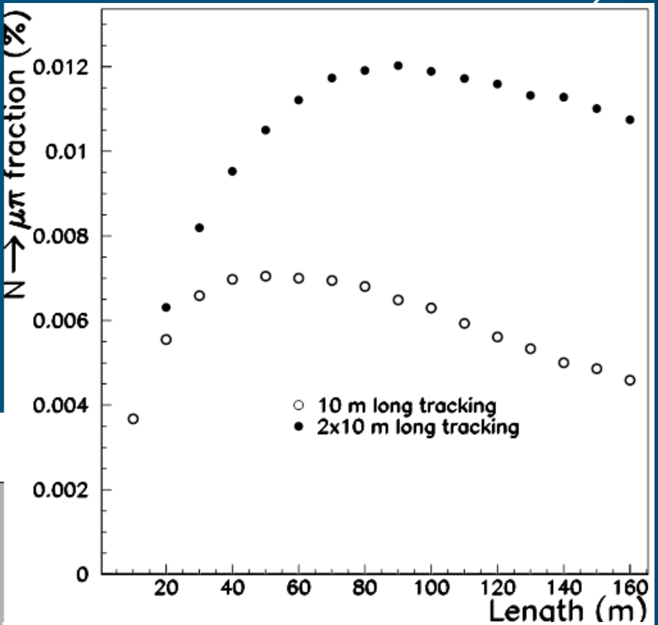
Based on existing technologies

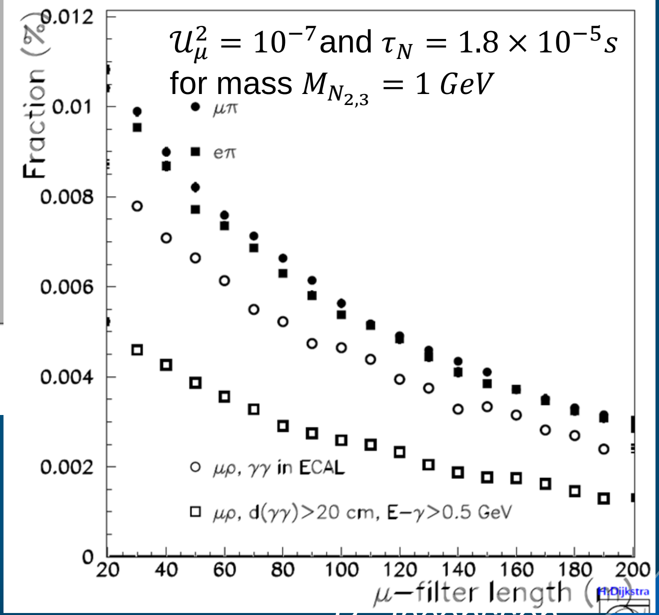
- NA62-like vacuum tank with 10^{-2} mbar instead of 10^{-5} mbar
- NA62-like straw chambers, 120 μm resolution and 0.5% $\frac{X_0}{X}$
- LHCb-like spectrometer magnet 0.5 Tm over 5 m length
- LHCb-like shashlik calorimeter
- Veto Chamber: veto μ, ν-interactions in muon filter, or K/Λ decays.
- LHCb-like 40MHz readout (upgrade)

Detector Concept

- Geometric acceptance
  - Saturates for a given $N_{2,3}$ lifetime as a function of the detector length
  - The use of two magnetic spectrometers increases the acceptance by 70%
  - Detector has two almost identical elements







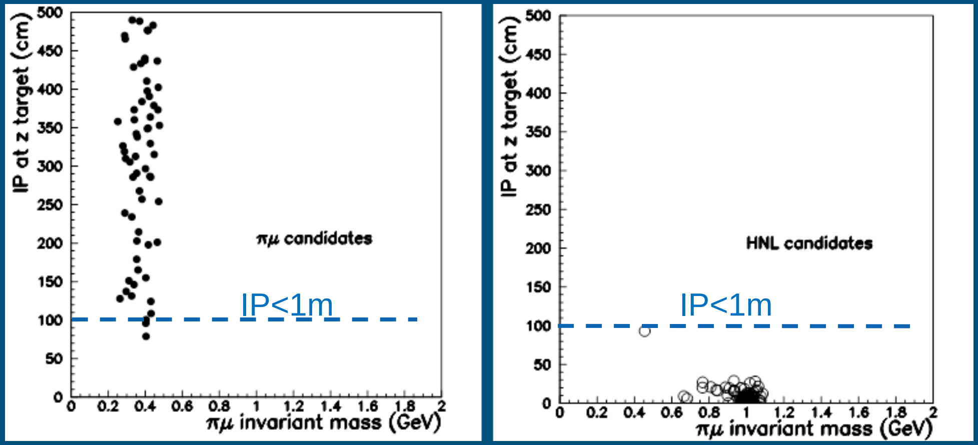
$\mathcal{U}_\mu^2 = 10^{-7}$ and $\tau_N = 1.8 \times 10^{-5} s$ for mass $M_{N_{2,3}} = 1\, GeV$

Ex. Background Suppression

- 2×10^4 neutrino interactions per 2×10^{20} p.o.t. in the decay volume at atmospheric pressure
  - ➔ Becomes negligible at 0.01 mbar

- Neutrino (muon) interactions in the final part of the muon shield
  - $\nu_\mu + p \rightarrow X + K_L \rightarrow \mu\pi\nu$
  - Yields CC(NC) rate of ~$6(2) \times 10^5$ / λ_{inter} / 2×10^{20} p.o.t.
  - ~10% of neutrino interactions produce Λ or K^0 in acceptance
  - Majority of decays occur in the first 5 m of the decay volume
  - ➔ Requiring μ-identification for one of the two decay products: 150 two-prong vertices in 2×10^{20} p.o.t.
  - For 0.5 Tm field integral σ_{mass} ~ 40 MeV for p < 20 GeV

➔ E.g. background reduction by impact parameter



- The IP cut will also be used to reject backgrounds induced by neutrino interactions in the material surrounding the detector, cosmics etc
- Similar for muon inelastic interactions in the vicinity of the detector

Expected Event Yield $N_{2,3} \rightarrow \mu\pi$

- Integral mixing angle $\mathcal{U}^2 = \mathcal{U}_e^2 + \mathcal{U}_\mu^2 + \mathcal{U}_\tau^2$

- Estimate of the sensitivity is obtained by considering different scenarios for the hierarchy of flavour coupling (arXiv:0605047)
  - Conservative: Consider only the decay $N_{2,3} \rightarrow \mu\pi$ with production mechanism $D \rightarrow \mu N_{2,3} X$, which probes $\mathcal{U}_\mu^4$

- Expected number of signal events

$$N_{signal} = n_{pot} \times 2\chi_{cc} \times Br(\mathcal{U}_\mu^2) \times \varepsilon_{det}(\mathcal{U}_\mu^2)$$

$n_{pot} = 2 \times 10^{20}$

$\chi_{cc} = 0.45 \times 10^{-3}$

- $Br(\mathcal{U}_\mu^2) = \mathrm{Br}\big(D \rightarrow \mu N_{2,3} X\big) \times Br(N_{2,3} \rightarrow \mu\pi)$,
  - $Br(N_{2,3} \rightarrow \mu\pi)$ is assumed to be 20%
  - Br$(D \rightarrow NX) \sim 10^{-8} - 10^{-12}$
- $\varepsilon_{det}(\mathcal{U}_\mu^2)$ is the probability that $N_{2,3}$ decays in the fiducial volume, and μ and π are reconstructed

  ➔ Detection efficiency entirely dominated by the geometrical acceptance $(8 \times 10^{-5}$ for $\tau_N = 1.8 \times 10^{-5} s)$

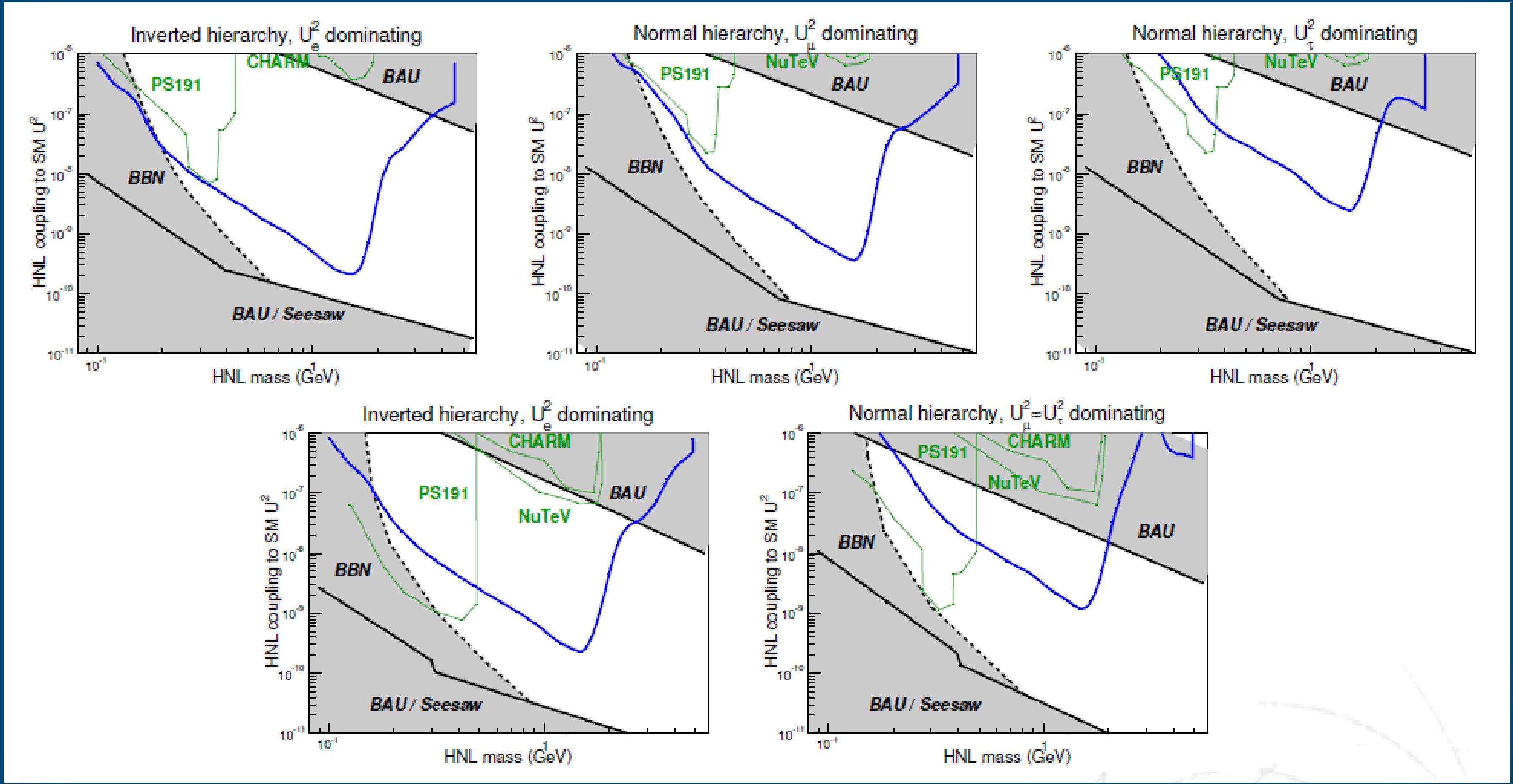
Ex. Expected Sensitivity to $N_{2,3} \to \mu\pi$

Sensitivity based on current SPS with 2x10^{20} p.o.t in ~5 years of CNGS-like operation

- Ex. $\mathcal{U}_\mu^2 = 10^{-7}$ (corresponding to strongest current experimental limit for $M_{N_{2,3}} = 1\ GeV$) ($\tau_N = 18\ \mu s$)

➔ ~12k fully reconstructed $N_{2,3} \to \mu\pi$ events are expected for $M_{N_{2,3}} = 1\ GeV$

➔ ~120 events for cosmologically favoured region: $\mathcal{U}_\mu^2 = 10^{-8}$ and $\tau_N = 180\ \mu s$

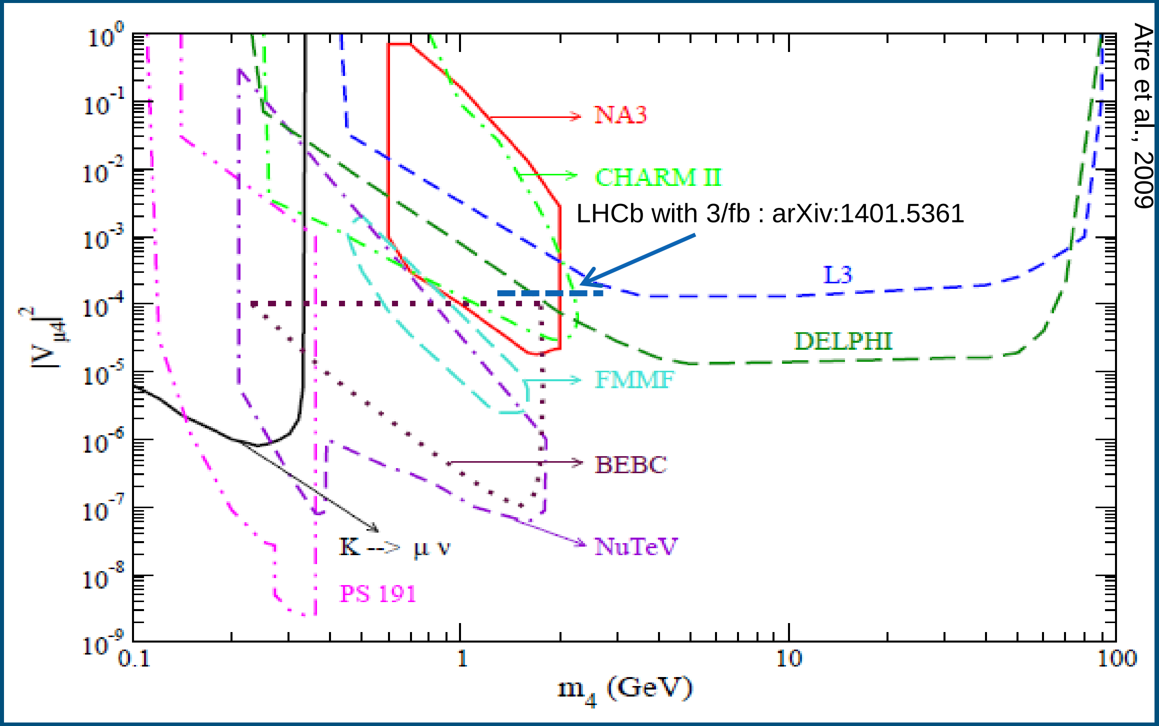


Sensitivity to $N_{2,3}$ - other experiments

→ Colliders out of luck with low mass / long lifetimes

- LHC ($\sqrt{s}$ = 14 TeV): with 1 ab^{-1}, i.e. 3-4 years: ~ 2×10^{16} in 4π
- SPS@400 ($\sqrt{s}$ = 27 GeV) with 2×10^{20} pot, i.e. ~5 years: ~ 2×10^{17}

Summary of past Searches for N_I

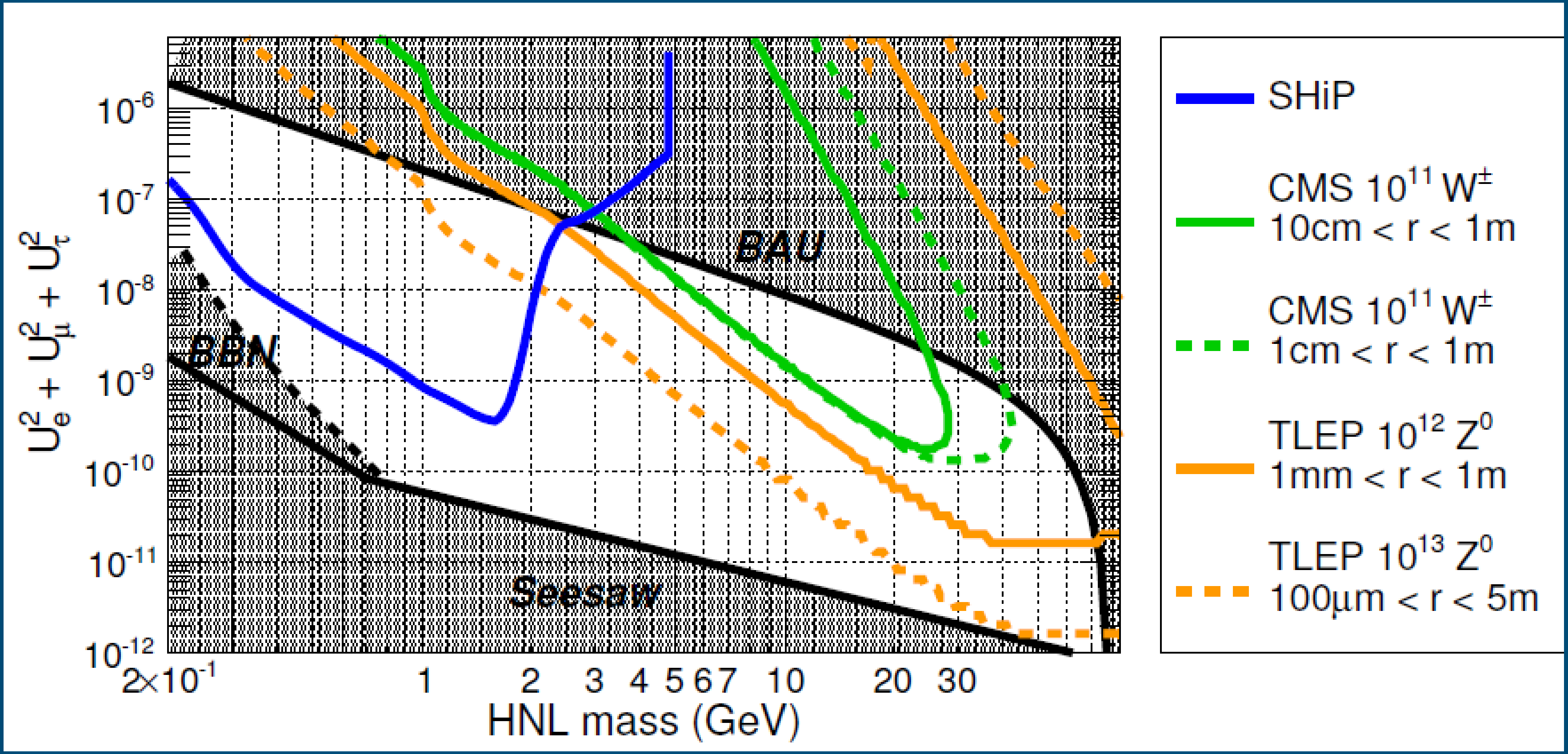


LHCb with 3/fb : arXiv:1401.5361

Atre et al., 2009

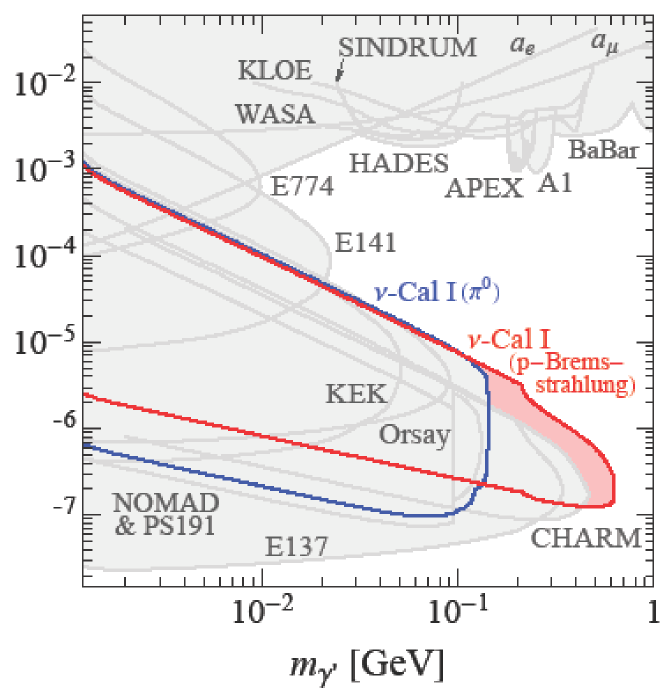
Future

- Towards closing allowed region
  - W ➔ ℓN at LHC: extremely large BG, difficult triggering/analysis.
  - Z ➔ N at e^+e^- collider [M. Bicer et al. 2013]: clean signature, low BG

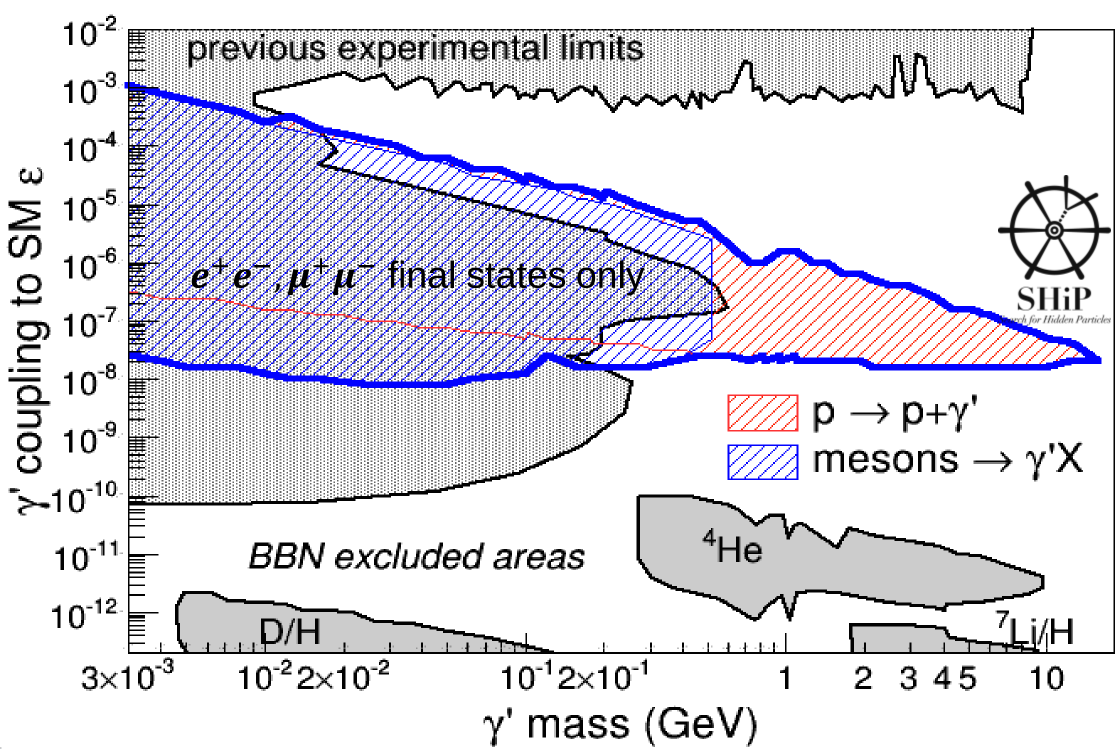


Ex. Expected sensitivity to Dark Photons

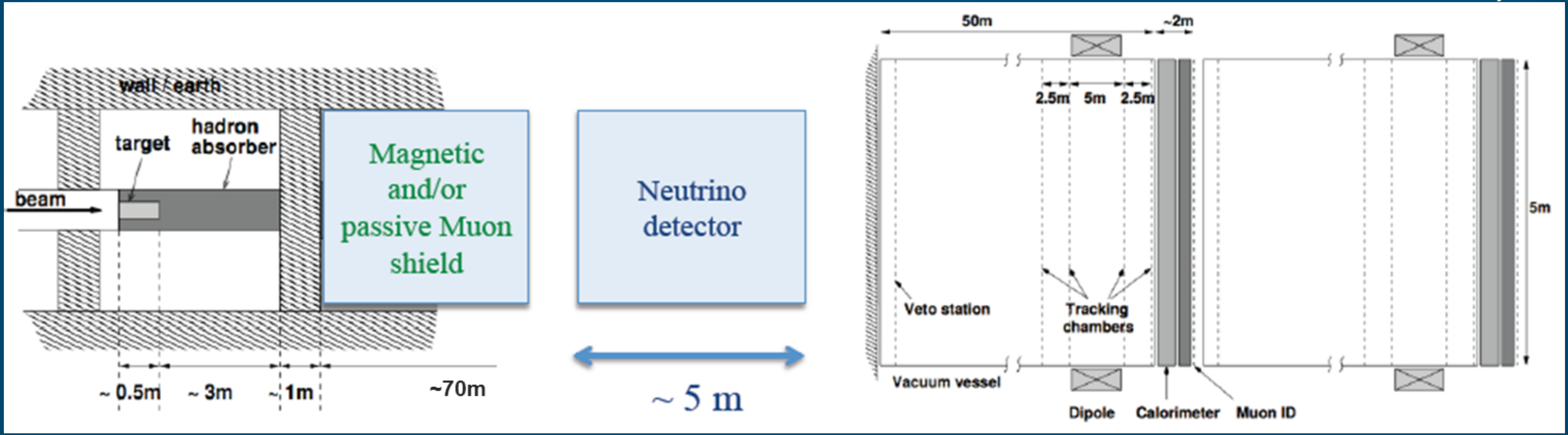
- Predominant dark photon production at SPS
  - Proton bremsstrahlung
  - Meson decays ($\pi^0, \eta,\ \omega,\ \eta', \ldots$)
  - Lifetime limit from BBN: $\tau_\gamma < 0.1s$
- Dark photon decays
  - $e^+e^-, \mu^+\mu^-, q\bar{q}\ (\pi^+\pi^-, \ldots), \ldots$



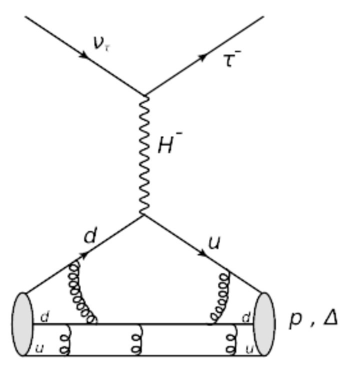
arXiv:1311.3870

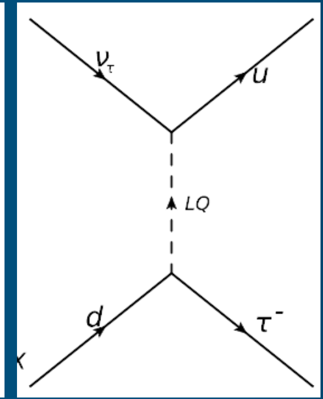


Prospects for ν_τ Physics



- Expecting $\mathcal{O}(3500)$ ν_τ interactions in 6 tons of emulsion target
  - Tau neutrino and anti-neutrino physics
- Charm physics with neutrinos and anti-neutrinos
  - ➔ ν_μ- induced charm production: 11 000 events
  - ➔ $\overline{\nu_\mu}$ - induced charm productoon: 3500 events
  - Electron neutrino studies (high energy cross-section and ν_e induced charm production ~ 2 x ν_μ induced)
    - **➔ Normalization for hidden particle search!**





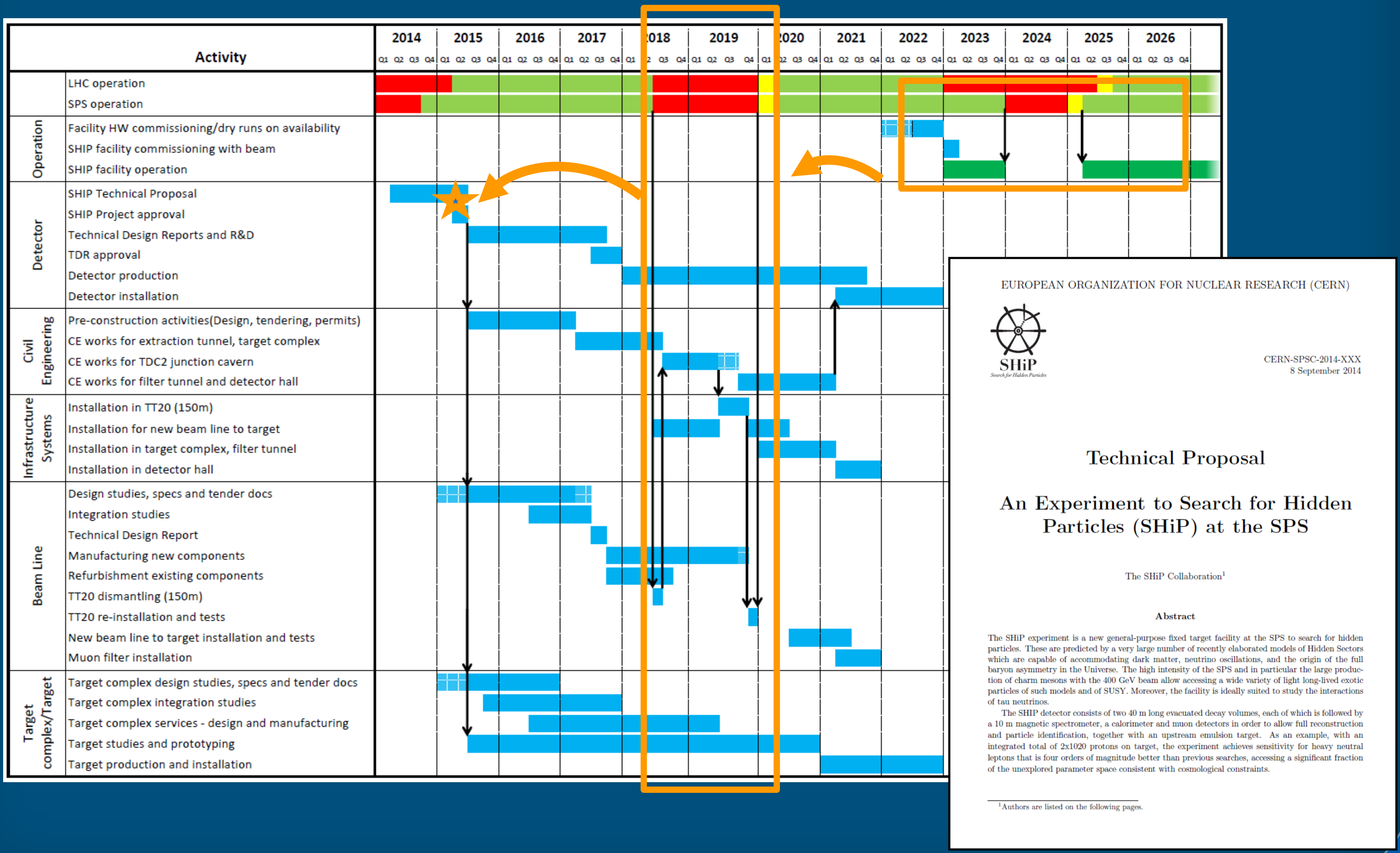
- ➔ Negligible loss of acceptance for Hidden Sector detector
- ➔ Hidden Particle detector function as forward spectrometer for ν_τ physics program
- ➔ Use of calorimeter/muon detector allow tagging neutrino NC/CC interactions ➔ normalization

History and Current Status

- Oct 2013: submitted our EOI: CERN-SPSC-2013-024 ; arXiv:1310.1762 ; SPSC-EOI-010
  - ➔ EOI stimulated a lot of interest
- January 2014: EOI discussed at SPSC
  - Encouraged to produce "*an extended proposal with further developed physics goals, a more detailed technical design and a stronger collaboration.*"
- January 2014: Meeting with CERN Research Director S. Bertolucci
  - ➔ Proposed a task force to evaluate feasibility and required resources at CERN within ~3months
  - ➔ Supportive to the formation of a Collaboration and agreed to CERN signing
- Work towards Technical Proposal in full swing
  - Extension of physics program
  - Signal background studies and optimization
  - Detector specification, simulation and even some detector R&D
  - Optimization of Experimental Facility - beam line, target, and muon filter, RP, overall layout
- 1st SHiP Workshop in Zurich in June with a 100 experimentalists and theorists
  - 41 institutes from 14 countries expressed interest to contribute to the Technical Proposal
- 2nd SHiP Workshop/Collaboration meeting at CERN September 24-26
  - Revise progress in Working Groups
  - Extend physics of a general purpose facility: Tau neutrino, LFV and direct Dark Matter search

Schedule and Technical Proposal

- Aim full force at submitting TP at beginning April 2015
  - Design of facility must start next summer (CE, beam, target, infra)



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

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP
Search for Hidden Particles

CERN-SPSC-2014-XXX
8 September 2014

Technical Proposal

An Experiment to Search for Hidden Particles (SHiP) at the SPS

The SHiP Collaboration[1]

Abstract

The SHiP experiment is a new general-purpose fixed target facility at the SPS to search for hidden particles. These are predicted by a very large number of recently elaborated models of Hidden Sectors which are capable of accommodating dark matter, neutrino oscillations, and the origin of the full baryon asymmetry in the Universe. The high intensity of the SPS and in particular the large production of charm mesons with the 400 GeV beam allow accessing a wide variety of light long-lived exotic particles of such models and of SUSY. Moreover, the facility is ideally suited to study the interactions of tau neutrinos.

The SHIP detector consists of two 40 m long evacuated decay volumes, each of which is followed by a 10 m magnetic spectrometer, a calorimeter and muon detectors in order to allow full reconstruction and particle identification, together with an upstream emulsion target. As an example, with an integrated total of 2x1020 protons on target, the experiment achieves sensitivity for heavy neutral leptons that is four orders of magnitude better than previous searches, accessing a significant fraction of the unexplored parameter space consistent with cosmological constraints.

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[1] Authors are listed on the following pages.

Conclusions

- Proposed general purpose experiment for Hidden Sector exploration in largely unexplored domain ➔ Increased interested for Hidden Sector after LHC Run 1
  - A very significant physics reach beyond past and current experiments in the cosmologically interesting region

➔ Extension to general purpose "Flavour Facility"

  - Unique opportunity for ν_τ physics
  - Lepton Flavour Violation ($\tau \rightarrow 3\mu$)
  - Also direct search for Dark Matter being looked into

- Further extension of complete physics program still ongoing
  - Very welcome to suggest searching for your favourite particle!

- The proposed experiment perfectly complements the searches for NP at the LHC

- Studies of the implementation of the experimental facility and resources in full swing as initiated by CERN management
  - Facility and physics case based on the current injector complex and SPS
  - 2×10^{20} in 5 nominal years by inheriting CNGS share of the SPS beam time from 2023

- Intense work for Technical Proposal : join!