Search for Hidden Particles (ShiP): an experimental proposal at the SPS

ship.web.cern.ch/ship

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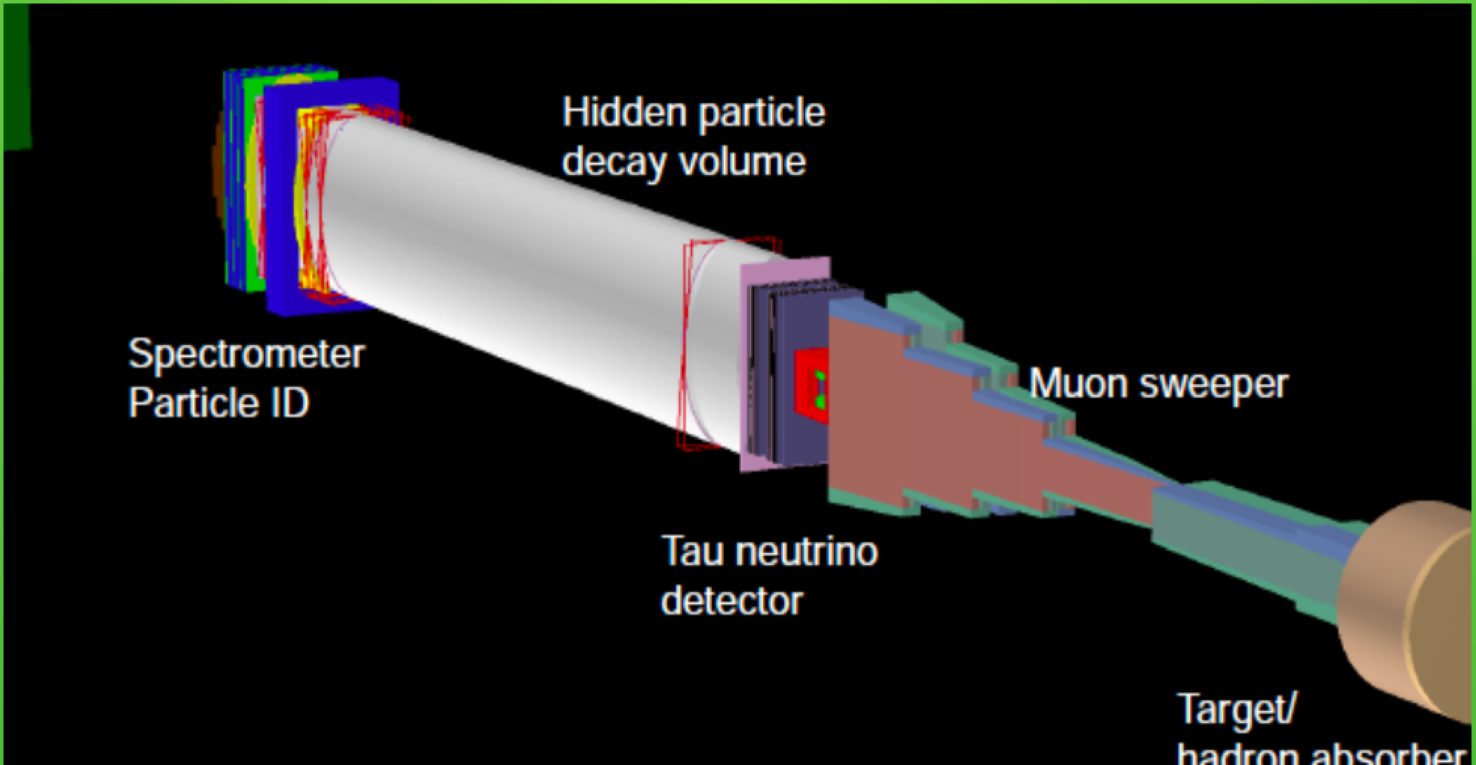
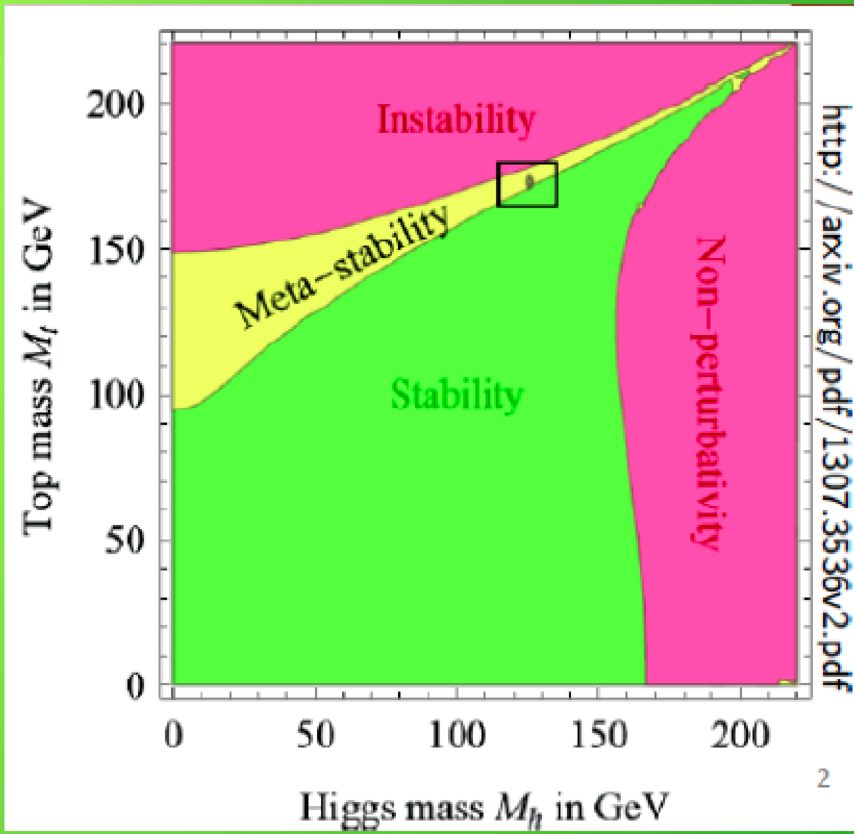


The Standard Model and beyond

- All SM particles have been discovered so far (apart from anti-ν_τ)
- Despite some anomalies, no compelling evidence of new physics found so far
- The Higgs mass points to a (meta-) stable universe
- The SM could be valid to the Plank scale
- Naturalness only a problem if we assume new particles between theEW and Plank scales



http://arxiv.org/pdf/1307.3536v2.pdf

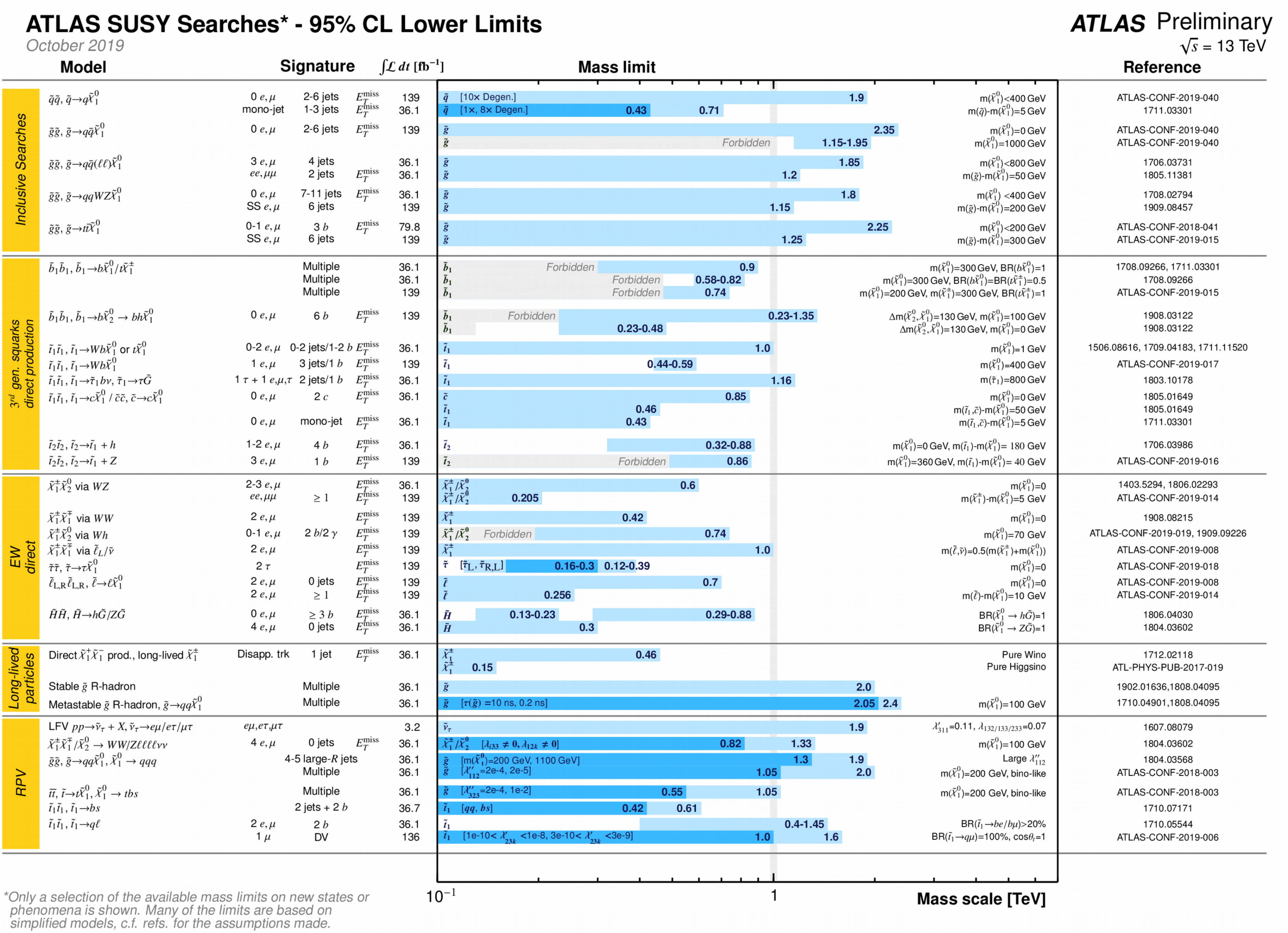
What we know we do not know

- Apart from naturalness, we do not understand:
  - Barion Asymmetry of the Universe
  - Dark Matter (indications are for cold, non-barionic)
  - The pattern of masses and mixings
  - Inflation

- Limits to masses of new particles being pushed in the TeV scale by the LHC.

  → “protection” against a small Higgs mass getting weaker

ATLAS limits for SUSY



ATLAS SUSY Searches* - 95% CL Lower Limits

October 2019

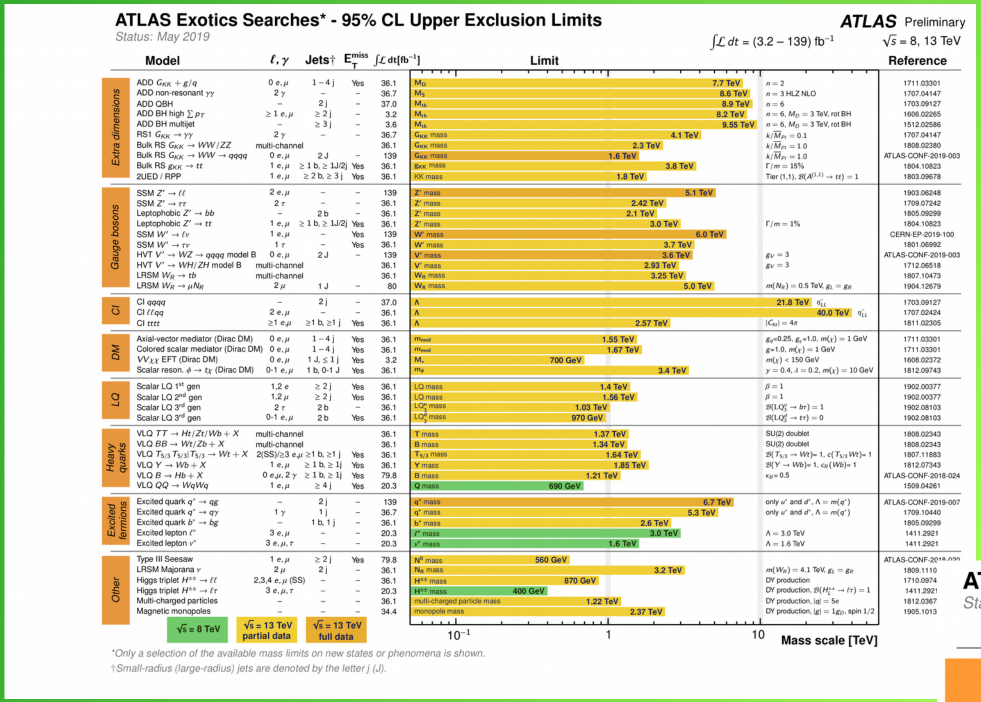
ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

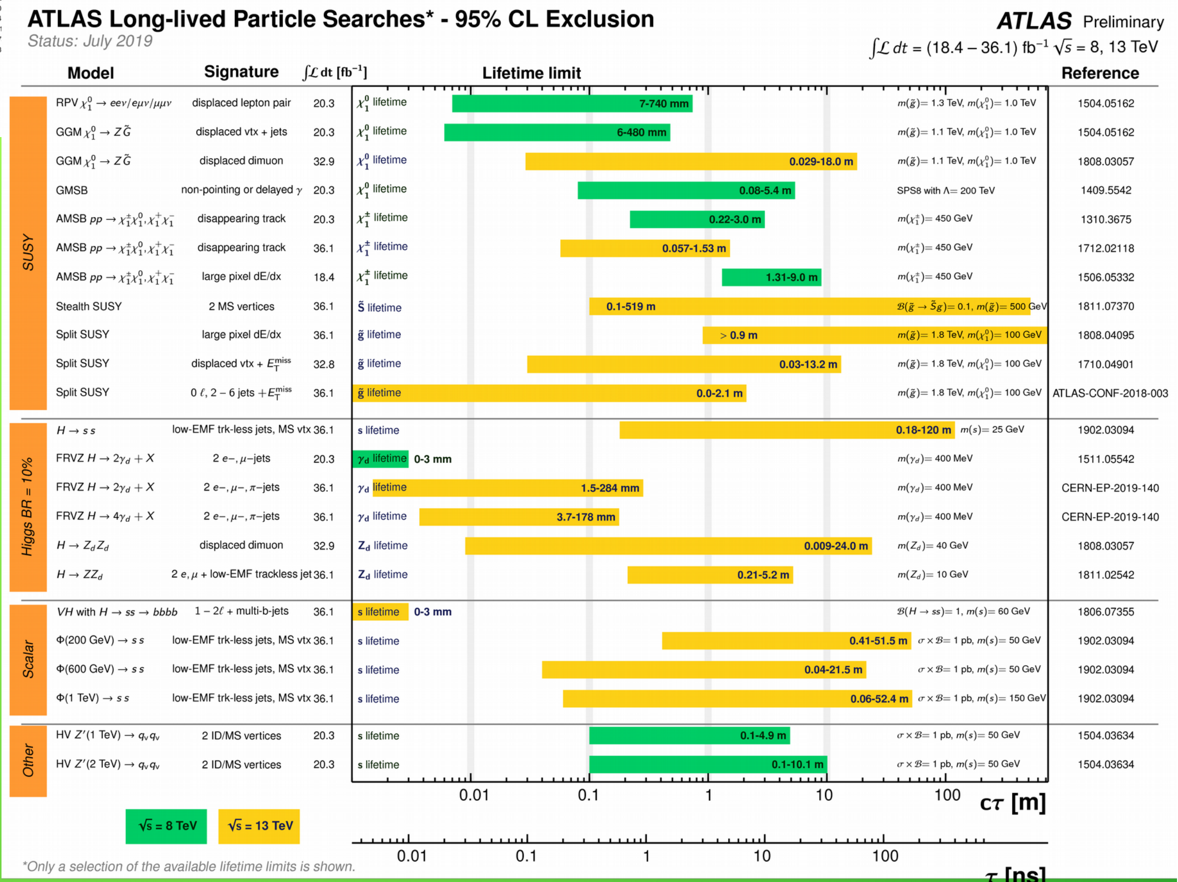
	Model	Signature			$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{q}$ [10× Degen.] 1.9	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	E_T^{miss}	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{g}$ 2.35	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2019-040
						$\tilde{g}$ Forbidden 1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	3 e,μ	4 jets		36.1	$\tilde{g}$ 1.85	m($\tilde{\chi}^0_1$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	E_T^{miss}	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	E_T^{miss}	36.1	$\tilde{g}$ 1.8	m($\tilde{\chi}^0_1$) <400 GeV	1708.02794
		SS e,μ	6 jets		139	$\tilde{g}$ 1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	E_T^{miss}	79.8	$\tilde{g}$ 2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	ATLAS-CONF-2019-015
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^\pm_1$)=0.5	1708.09266
			Multiple		139	$\tilde{b}_1$ Forbidden 0.74	m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1	ATLAS-CONF-2019-015
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$ Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
						$\tilde{b}_1$ 0.23-0.48	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	1908.03122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	E_T^{miss}	36.1	$\tilde{t}_1$ 1.0	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$ 0.44-0.59	m($\tilde{\chi}^0_1$)=400 GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	E_T^{miss}	36.1	$\tilde{t}_1$ 1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$ 0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	E_T^{miss}	36.1	$\tilde{t}_2$ 0.32-0.88	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	139	$\tilde{t}_2$ Forbidden 0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	ATLAS-CONF-2019-016
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	2-3 e,μ		E_T^{miss}	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.6	m($\tilde{\chi}^0_1$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	E_T^{miss}	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.205	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV	ATLAS-CONF-2019-014
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^\pm_1$ 0.42	m($\tilde{\chi}^0_1$)=0	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	0-1 e,μ	2 b/2 γ	E_T^{miss}	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ Forbidden 0.74	m($\tilde{\chi}^0_1$)=70 GeV	ATLAS-CONF-2019-019, 1909.09226
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^\pm_1$ 1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2019-008
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		E_T^{miss}	139	$\tilde{\tau}$ [$\tilde{\tau}_L$, $\tilde{\tau}_{R,L}$] 0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-018
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$ 0.7	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-008
		2 e,μ	≥ 1	E_T^{miss}	139	$\tilde{\ell}$ 0.256	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	ATLAS-CONF-2019-014
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	E_T^{miss}	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	E_T^{miss}	36.1	$\tilde{\chi}^\pm_1$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}^\pm_1$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$ 2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901,1808.04095
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82 1.33	m($\tilde{\chi}^0_1$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}^0_1, \tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	ATLAS-CONF-2019-006

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

“Exotics” limits

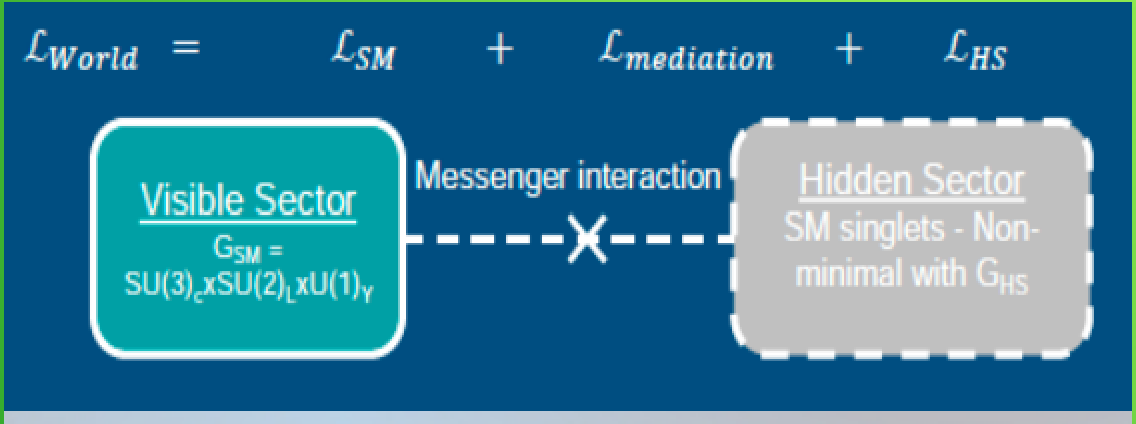


- Keep in mind: limits on particle lifetimes limited by size of LHC detectors



The “hidden sector” approach to new physics

- Maybe new particles have not been yet found not because they are heavy, but because their coupling is very small, or null
- If an additional term to the Lagrangian is not interacting with SM, there could be invisible particles contributing to dark matter, and no naturalness issues
- However, an interference term between the Lagrangians would allow a very small coupling:

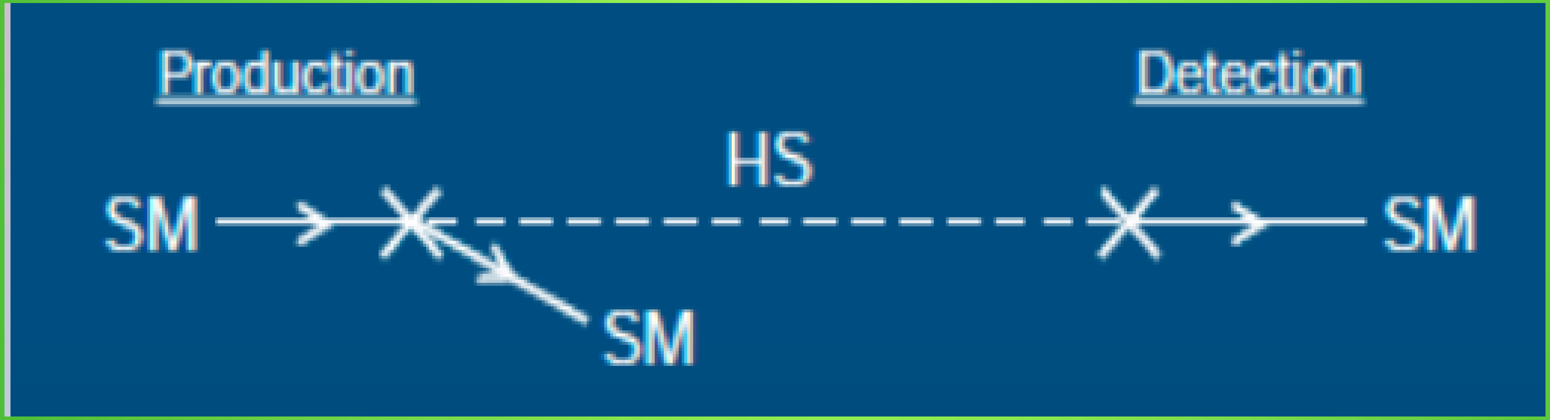


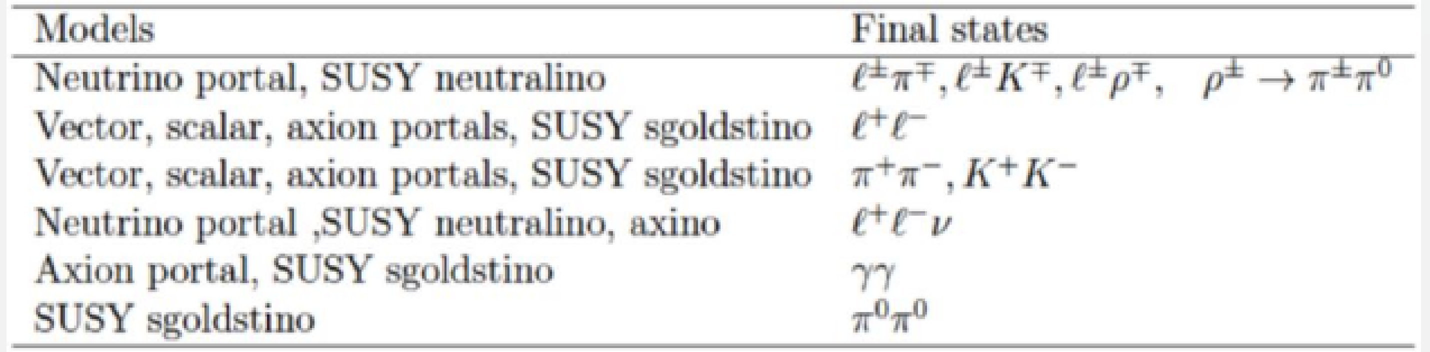
$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$

$$\mathcal{L}_{mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{O_{HS}^{(k)} O_{SM}^{(l)}}{\Lambda^n}$$

“Portals”

- Indications for a Hidden Sector may come from “ordinary” particles (SM, SUSY, axions etc.) acting as mediators with the HS Lagrangian
- The experimental signature is either missing energy or the appearance of SM particles very far away from its production, indicating an “oscillation” into the HS (and back)





Models	Final states
Neutrino portal, SUSY neutralino	$\ell^\pm\pi^\mp, \ell^\pm K^\mp, \ell^\pm\rho^\mp, \quad \rho^\pm \to \pi^\pm\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^+\ell^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-, K^+K^-$
Neutrino portal ,SUSY neutralino, axino	$\ell^+\ell^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

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

    ➔ Interaction with 'mirror world' constituting dark matter

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

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

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

  - **D = 5/2: Neutrino portal**
    - 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 pNGB, 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

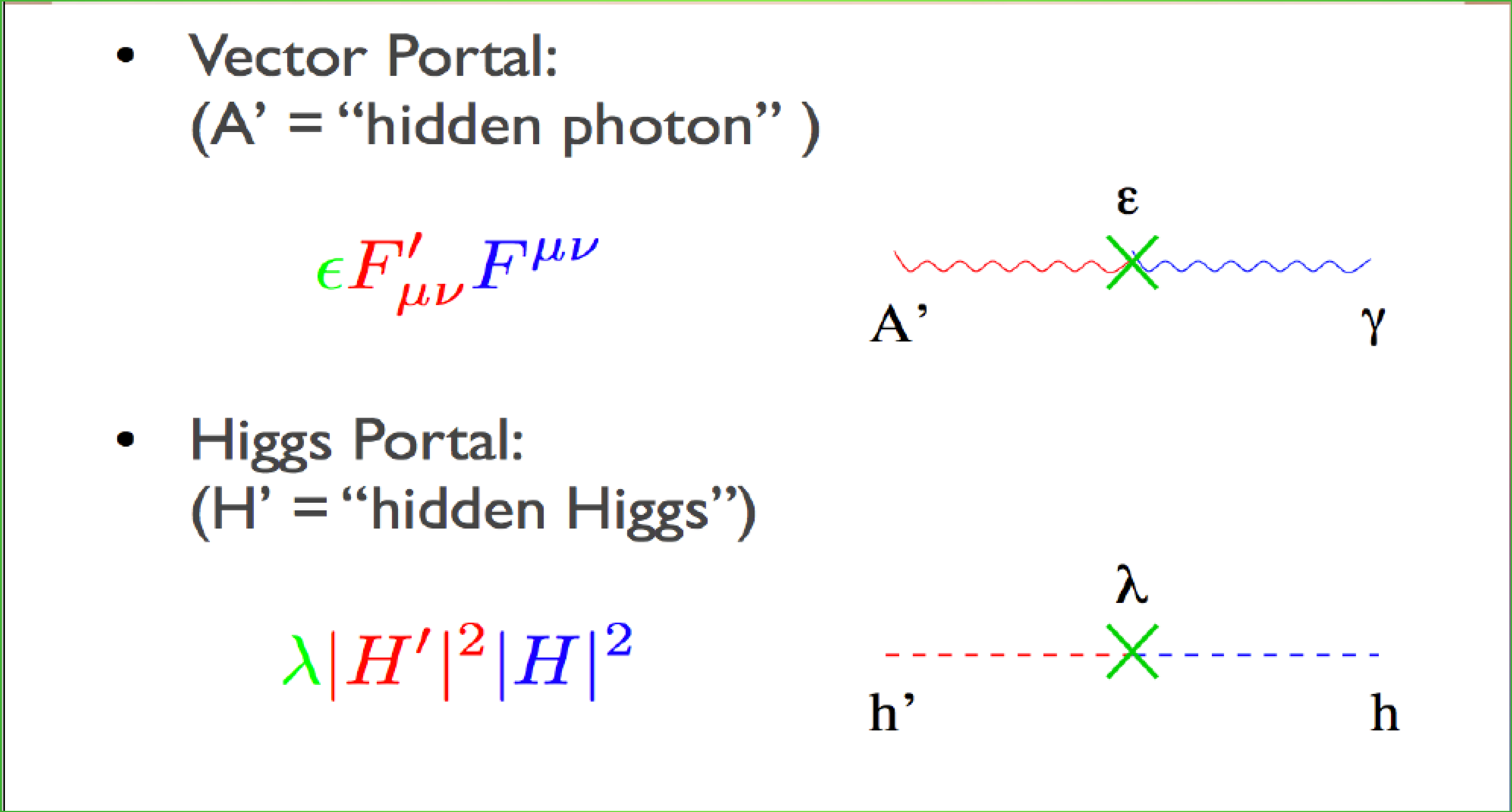
    ➔ Solve strong CP problem, Inflaton

  - 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

Vector and scalar portals



- Vector Portal:
  (A’ = “hidden photon”)

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

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

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

Sterile neutrinos

Fermions get mass via the Yukawa couplings:

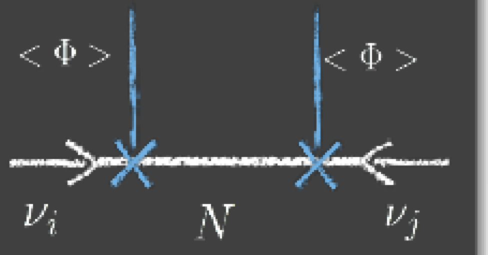
$$-\mathcal{L}_{\text{Yukawa}} = Y^d_{ij}\overline{Q_{Li}}\phi D_{Rj} + Y^u_{ij}\overline{Q_{Li}}\tilde{\phi}U_{Rj} + Y^\ell_{ij}\overline{L_{Li}}\phi E_{Rj} + \text{h.c.},$$

If we want the same coupling for neutrinos, we need right-handed (sterile) neutrinos… the most generic Lagrangian is

$$\mathcal{L}_N = i\overline{N}_i\partial_\mu\gamma^\mu N_i - \frac{1}{2}M_{ij}\overline{N^c}_i N_j - Y^\nu_{ij}\overline{L_{Li}}\tilde{\phi}N_j$$

Kinetic term — Majorana mass term — Yukawa coupling

$$U_{I\ell} \sim \frac{M_D^\ell}{M_N^I} = \frac{Y_{I\ell}v}{M_N^I}$$



Seesaw mechanism:

$$\mathcal{V} = (\nu_{Li}, N_j)$$

$$-\mathcal{L}_{M_\mathcal{V}} = \frac{1}{2}\overline{\mathcal{V}}M_\mathcal{V}\mathcal{V} + h.c.$$

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D{}^T & M_N \end{pmatrix}$$

$$\lambda_\pm = \frac{M_N \pm \sqrt{M_N^2 + 4M_D^2}}{2}$$

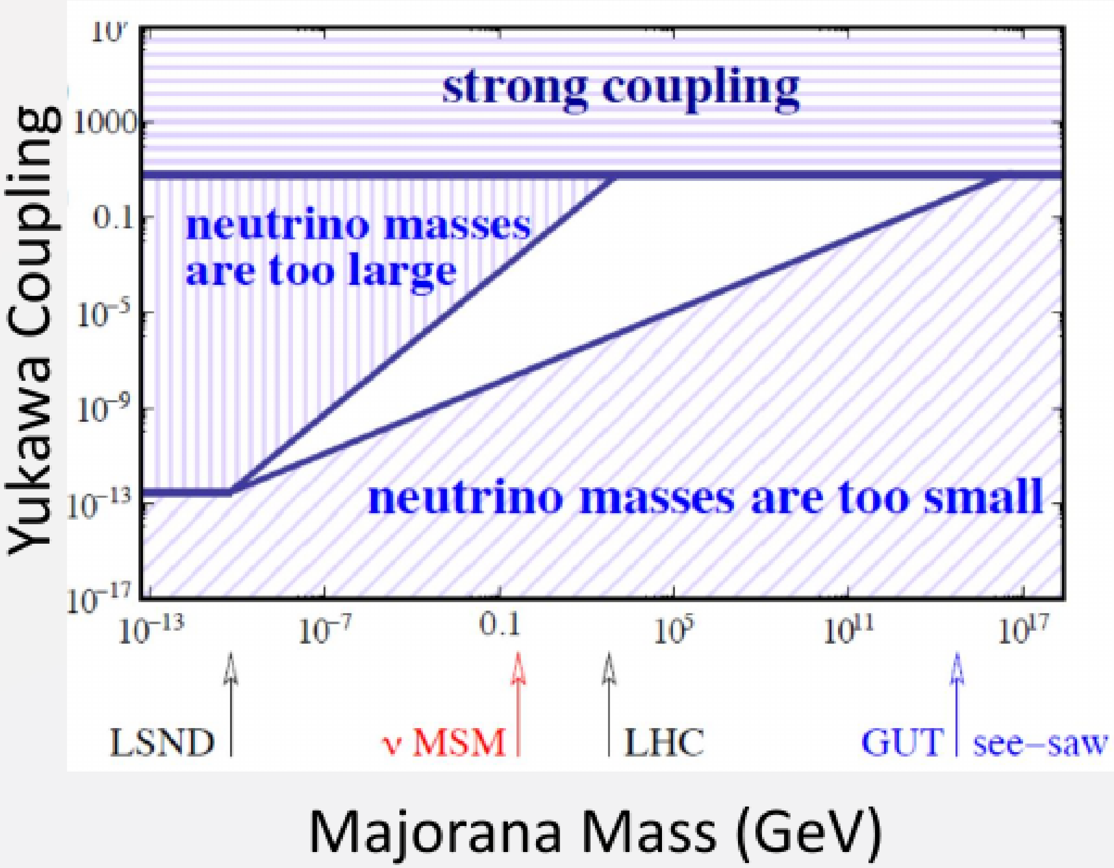
if $M_N \gg M_D$:

$$\lambda_- \sim \frac{M_D^2}{M_N}$$

$$\lambda_+ \sim M_N$$

The see-saw mechanism

Seesaw formula $m_D \sim Y_{I\alpha} < \phi >$ and $m_\nu = \frac{m_D^2}{M}$

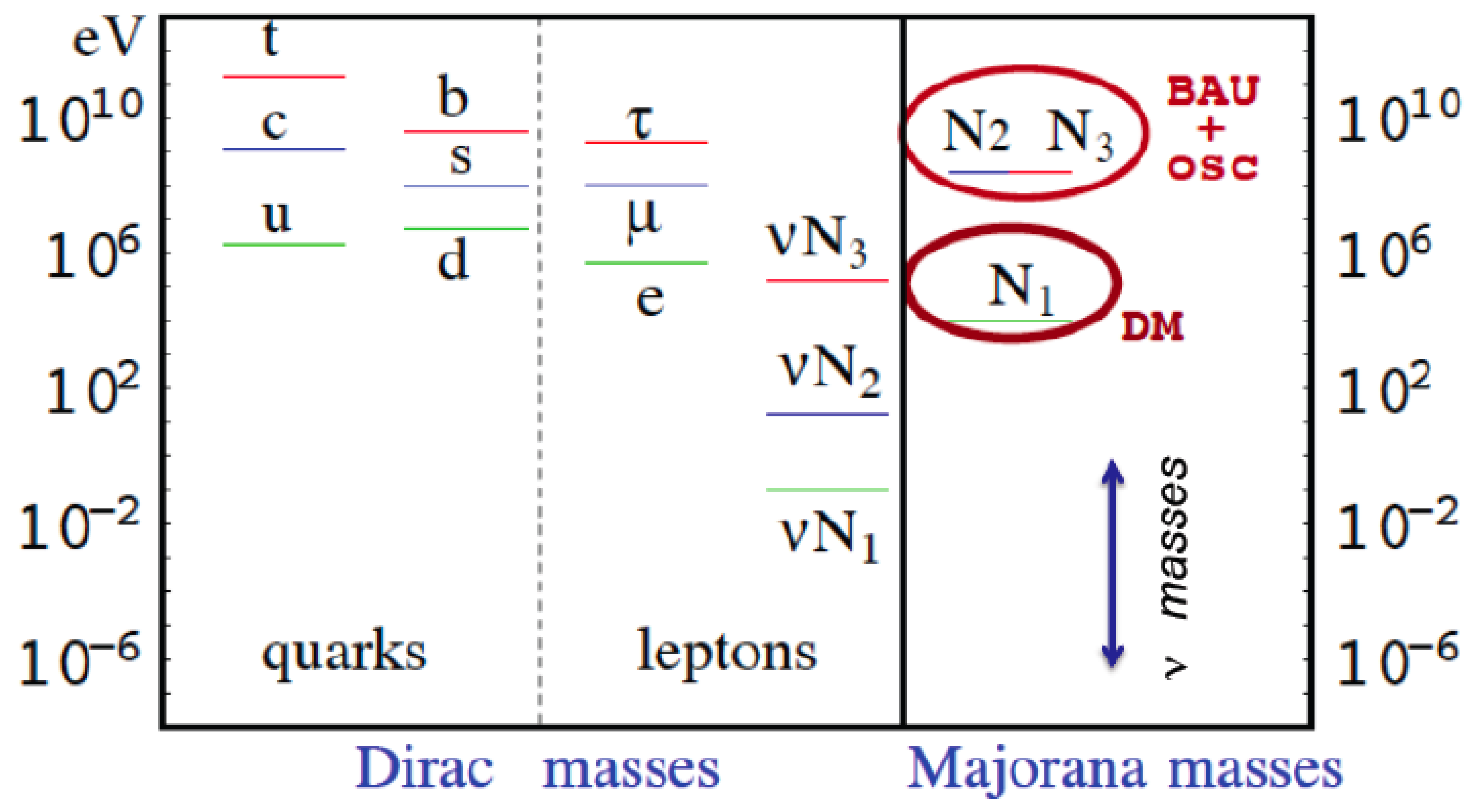


- Assuming $m_\nu = 0.1\text{eV}$
- if $Y \sim 1$ implies $M \sim 10^{14}\text{GeV}$
- if $M_N \sim 1\text{GeV}$ implies $Y_\nu \sim 10^{-7}$

remember $Y_{top} \sim 1.$ and $Y_e \sim 10^{-6}$

If we want to explain the smallness of neutrino masses (in a natural way) the mass of sterile neutrinos should be at least at the GeV scale

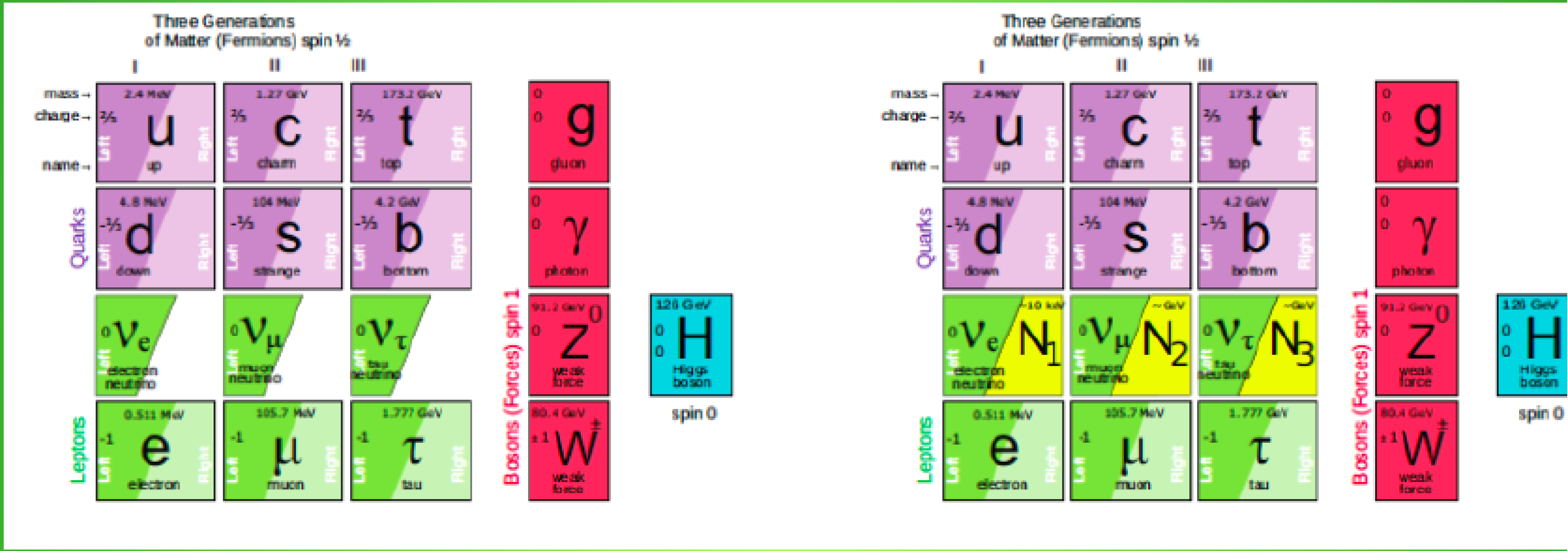
Resulting mass ranges



- Sterile neutrinos could have masses and couplings similar to those of the ordinary charged leptons

The νMSSM

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

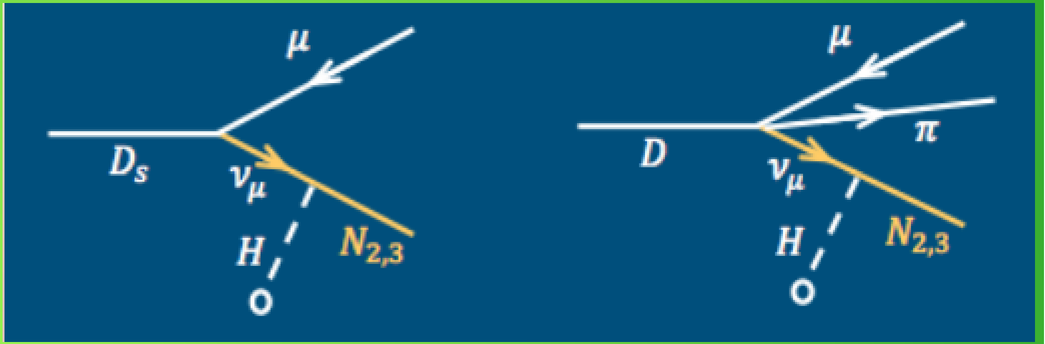


Particle content of SM made symmetric by adding 3 HNL: N_1, N_2, N_3

With M(N) ~ few KeV, it is a good DM candidate (or DM can be generated outside of this model through decay of inflaton)

With M(N , N) ~ GeV, could explain Barion Asymmetry of Universe (via leptogenesis), and generate neutrino masses through see-saw.

HNL production mechanism

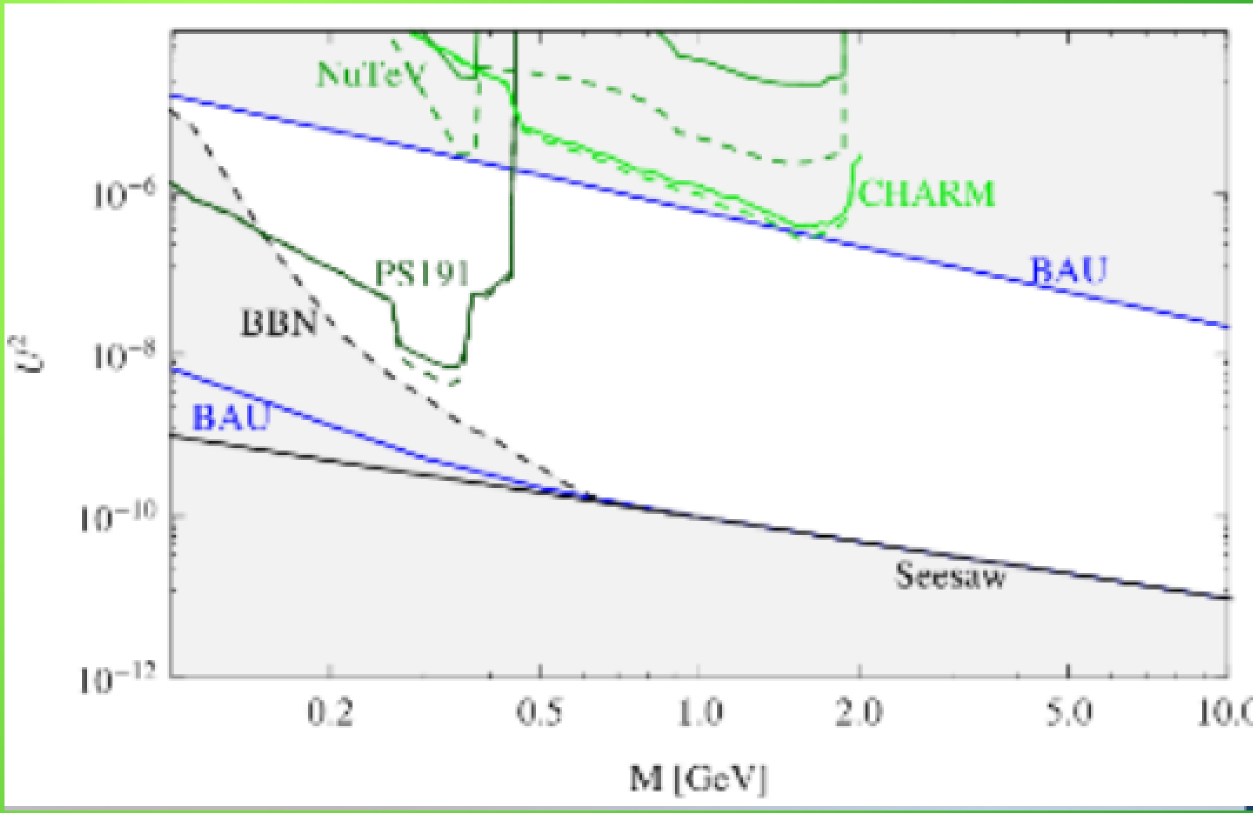


Interaction with Higgs vev leads to a mixing with active neutrinos

Several past searches; PS191 used neutrinos from K decays, while other experiments not sensitive to mixings of cosmological interest.

Latest result: LHCb with B decays obtained U2≈10-4, arXiv:1401.5361

Further exploration needed of the region with higher masses and smaller mixings

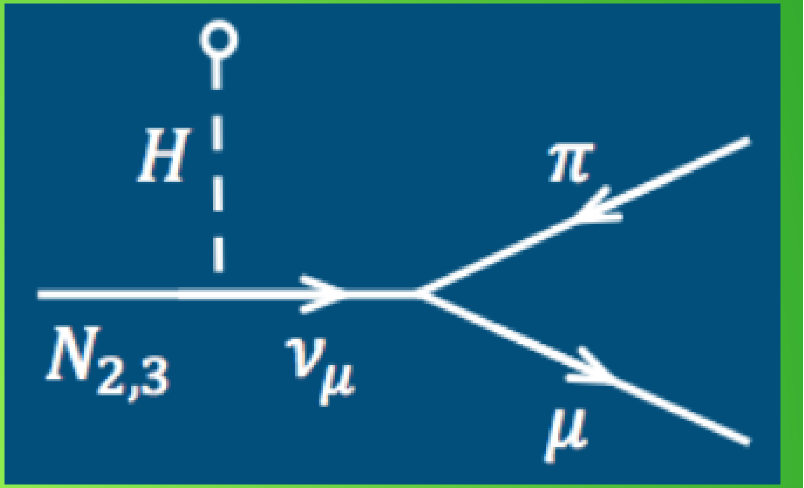


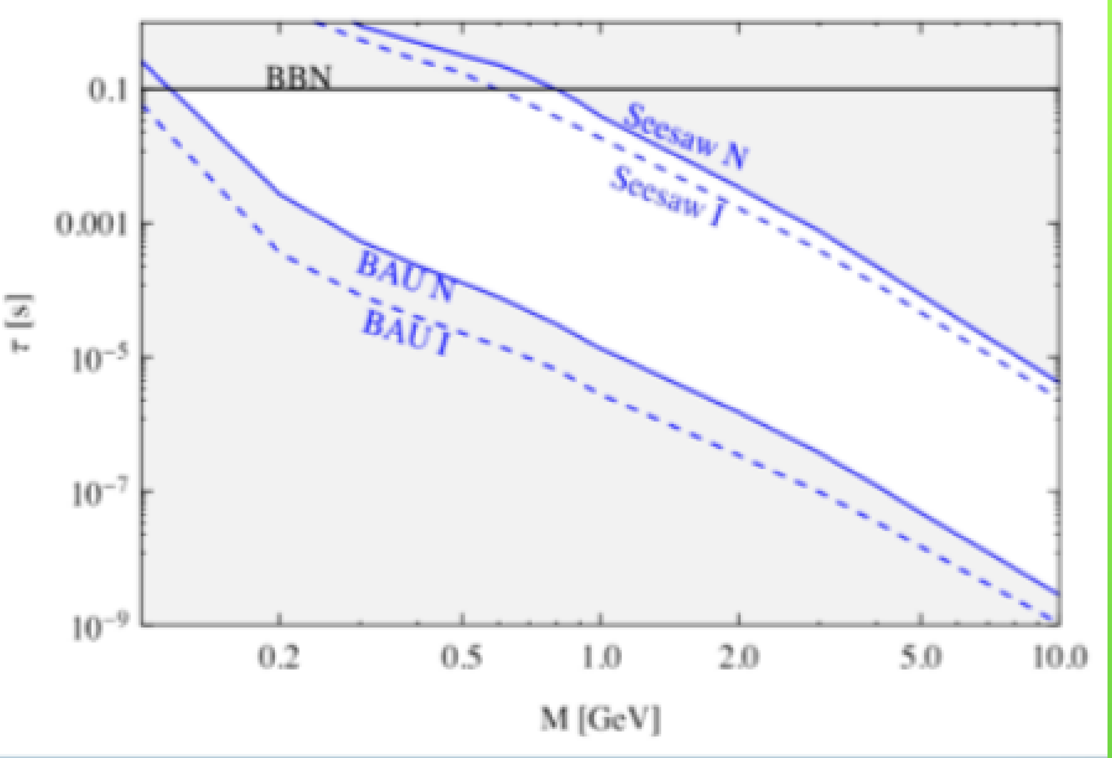
HNL decay modes

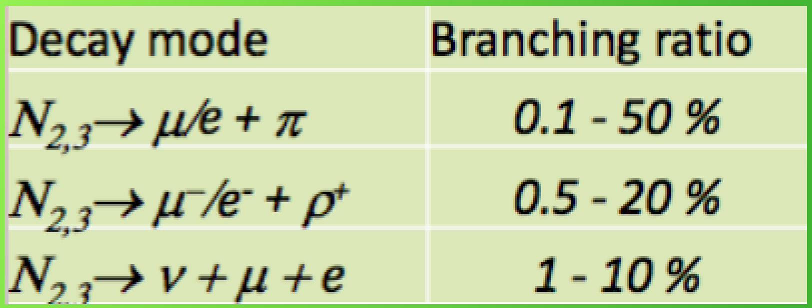
Interaction with Higgs vev would make it oscillate back into a virtual neutrino, that produces a muon and a W (→ hadrons, eg pions)

Exact branching fractions depend n flavor mixing

Due to small couplings, ms lifetimes, decay paths O(km)



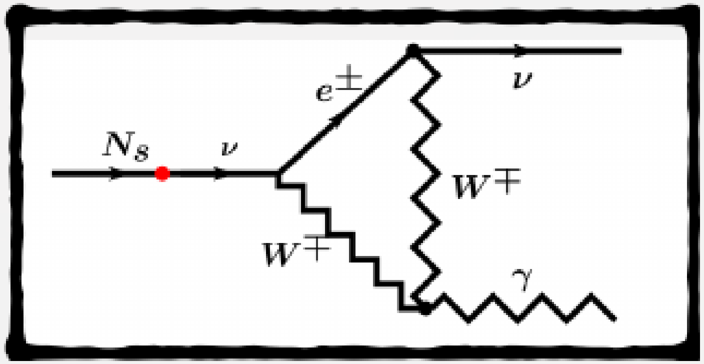


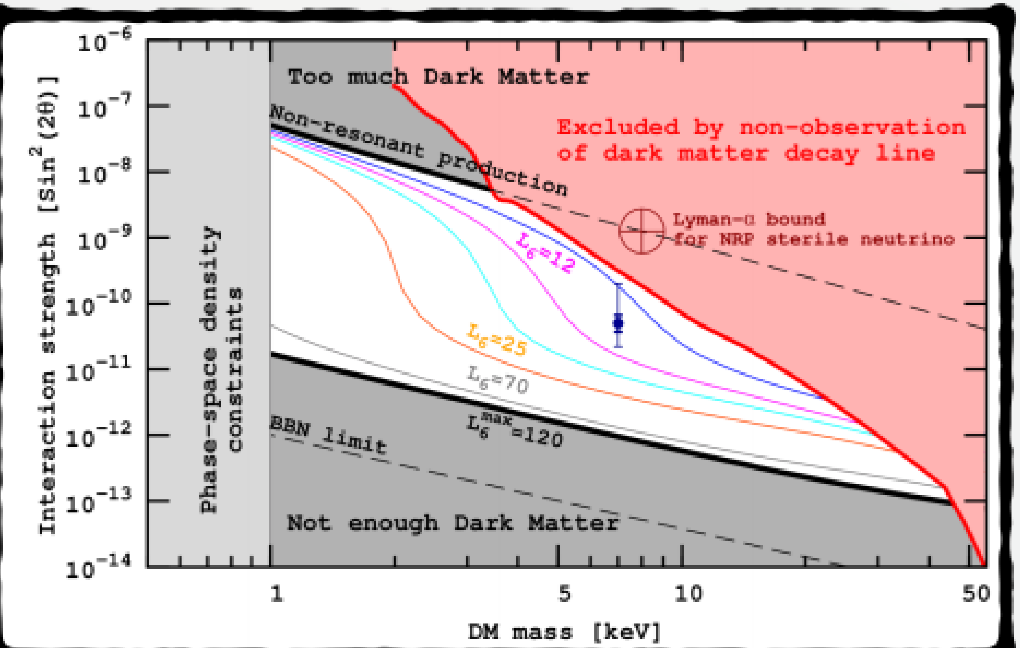


Decay mode	Branching ratio
$N_{2,3} \rightarrow \mu/e + \pi$	0.1 - 50 %
$N_{2,3} \rightarrow \mu^-/e^- + \rho^+$	0.5 - 20 %
$N_{2,3} \rightarrow \nu + \mu + e$	1 - 10 %

Constraints on N_1 mass

DM sterile neutrinos decay subdominantly as $N_1 \to \nu\gamma$ with a branching ration $\mathcal{B}(N_1 \to \gamma\nu) \sim \frac{1}{123}$





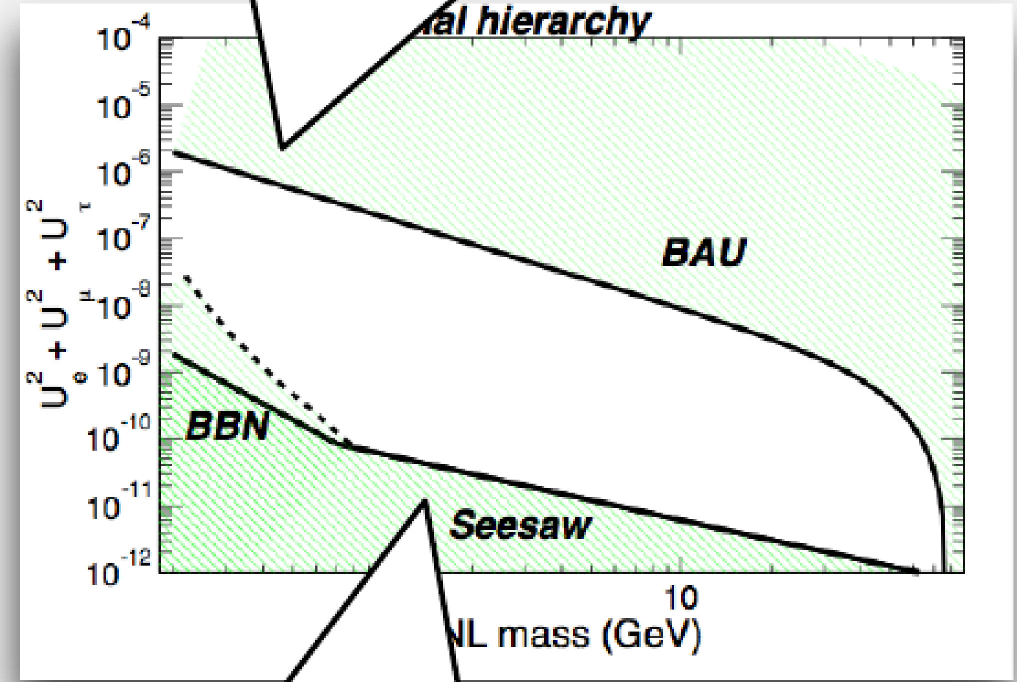
Discussion in the community, not yet clear if this is a “good” signal, needs confirmation

Bulbul et al. 2014 (arXiv:1402.2301)

Boyarsky et al. 2014 (arXiv:1402.4119)

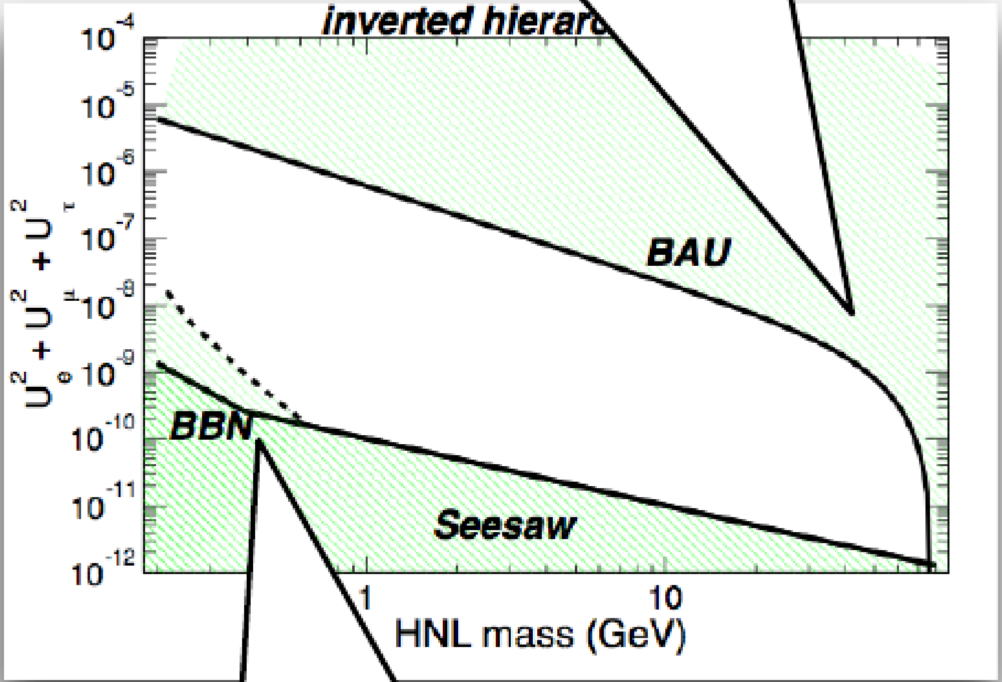
Constraints on N_2, N_3 masses

If U^2 is too large, $N_{2,3}$ are in **thermal equilibrium** during the expansion of the Universe



The **seesaw** limit defines the region where $N_{2,3}$ can explain the observed active neutrino Δm^2

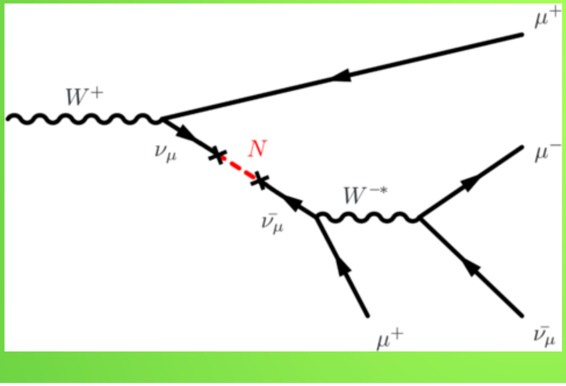
At $M_N \geq M_W$ the rate is **enhanced** by $N \rightarrow Wl$ leading to stronger constraints on U^2

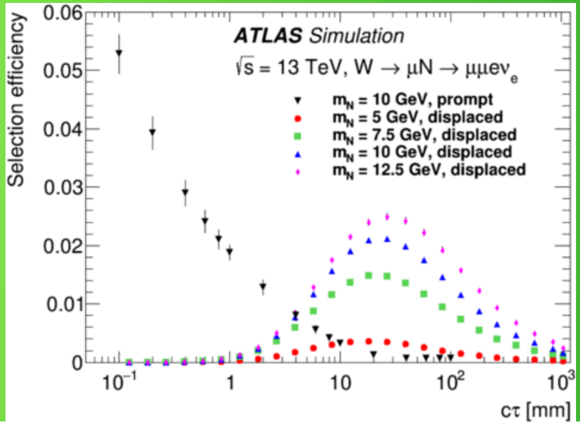


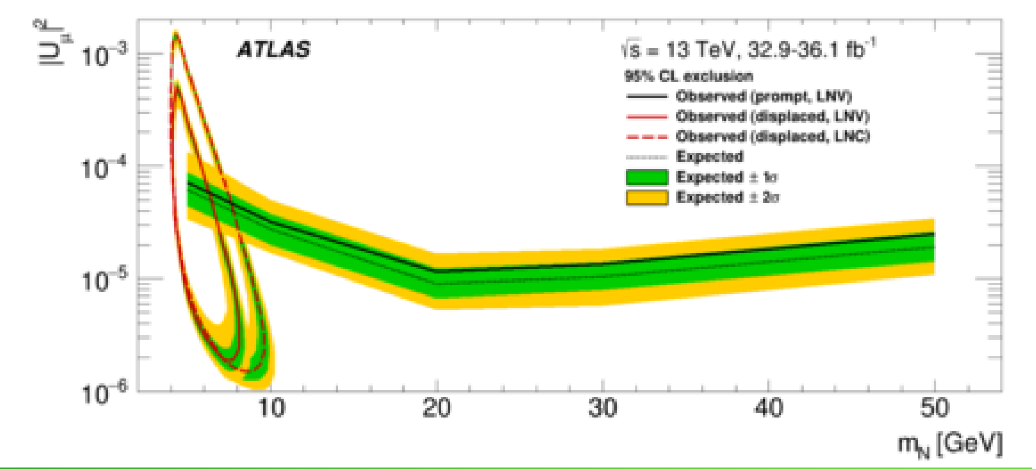
If $\tau(N_2, N_3) < 0.1\ s$, they cannot affect the **Big Bang nucleosynthesis**

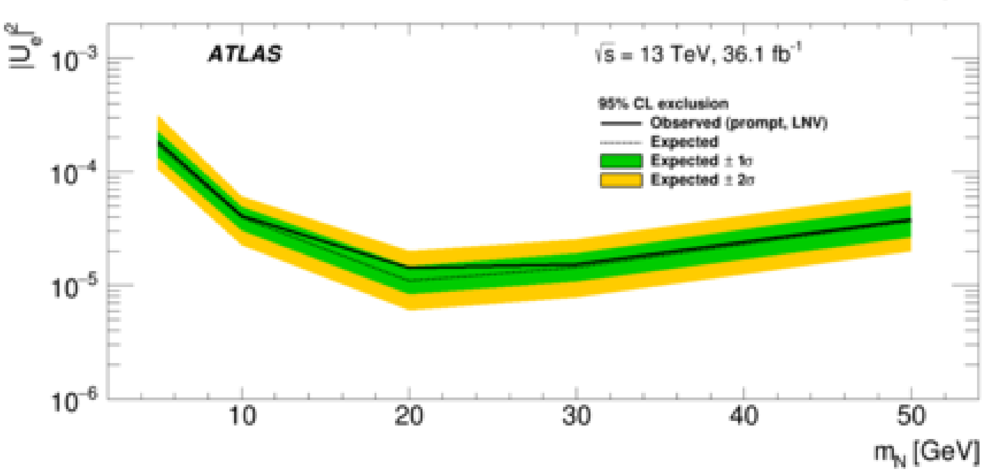
High-mass searches at the LHC

- Explore HNL mass range above 10 GeV
- Search for two same-sign leptons and no MET
- ATLAS paper JHEP 10(2019) 265 uses both prompt and displaced signatures

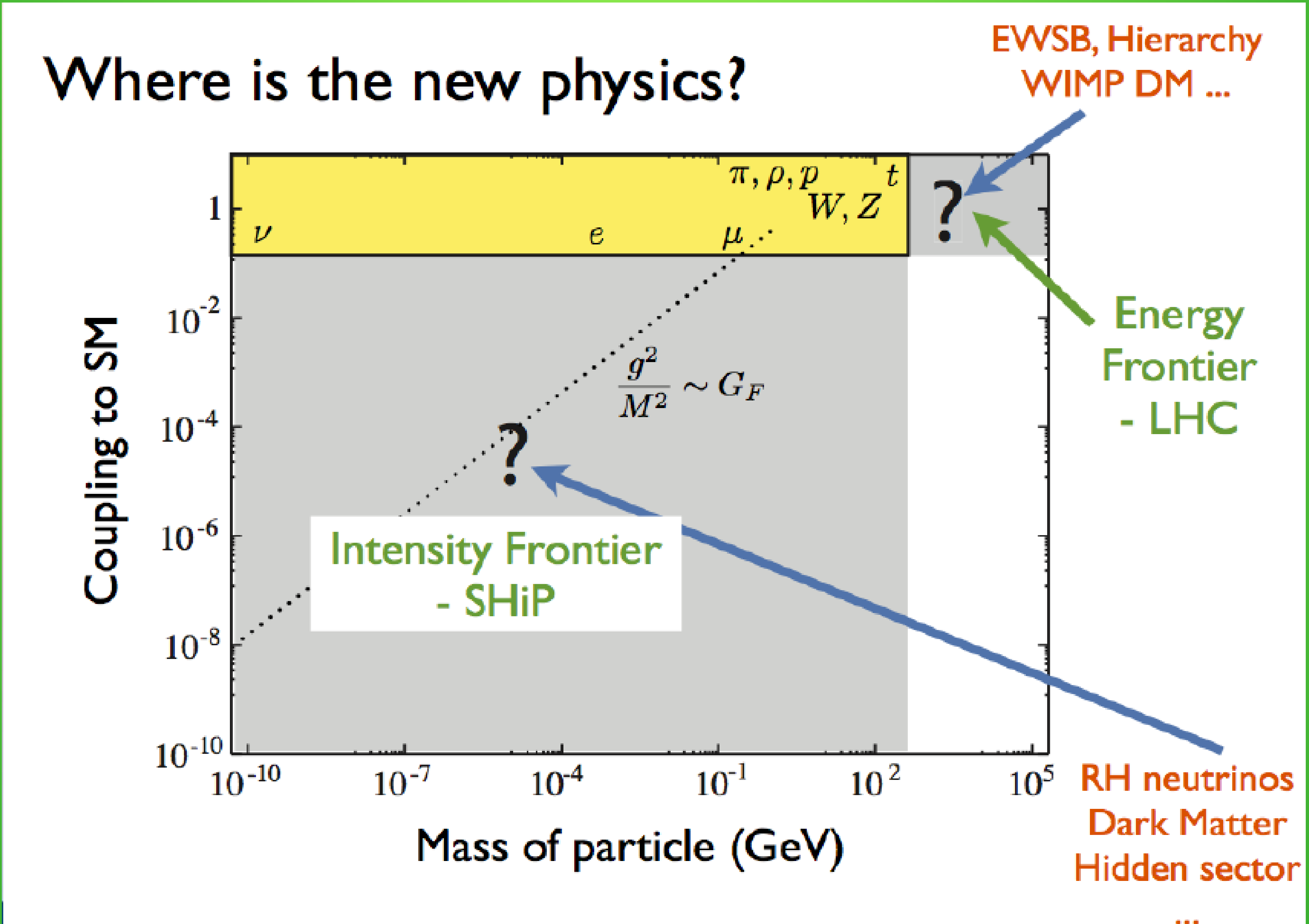








Searches in the cosmologically-interesting region



Where is the new physics?

EWSB, Hierarchy
WIMP DM ...

Energy
Frontier
- LHC

Intensity Frontier
- SHiP

RH neutrinos
Dark Matter
Hidden sector

Model-independent experimental considerations

We have to look for very weakly interacting particles:

- Production BR O(1E-10)
- Lifetimes O(km)
- Can travel through ordinary matter

Cosmologically interesting masses O(GeV)

- Produced through decays of mesons
- Can decay to mesons or charged leptons
- Full final-state reconstruction and particle ID

To have high intensities:

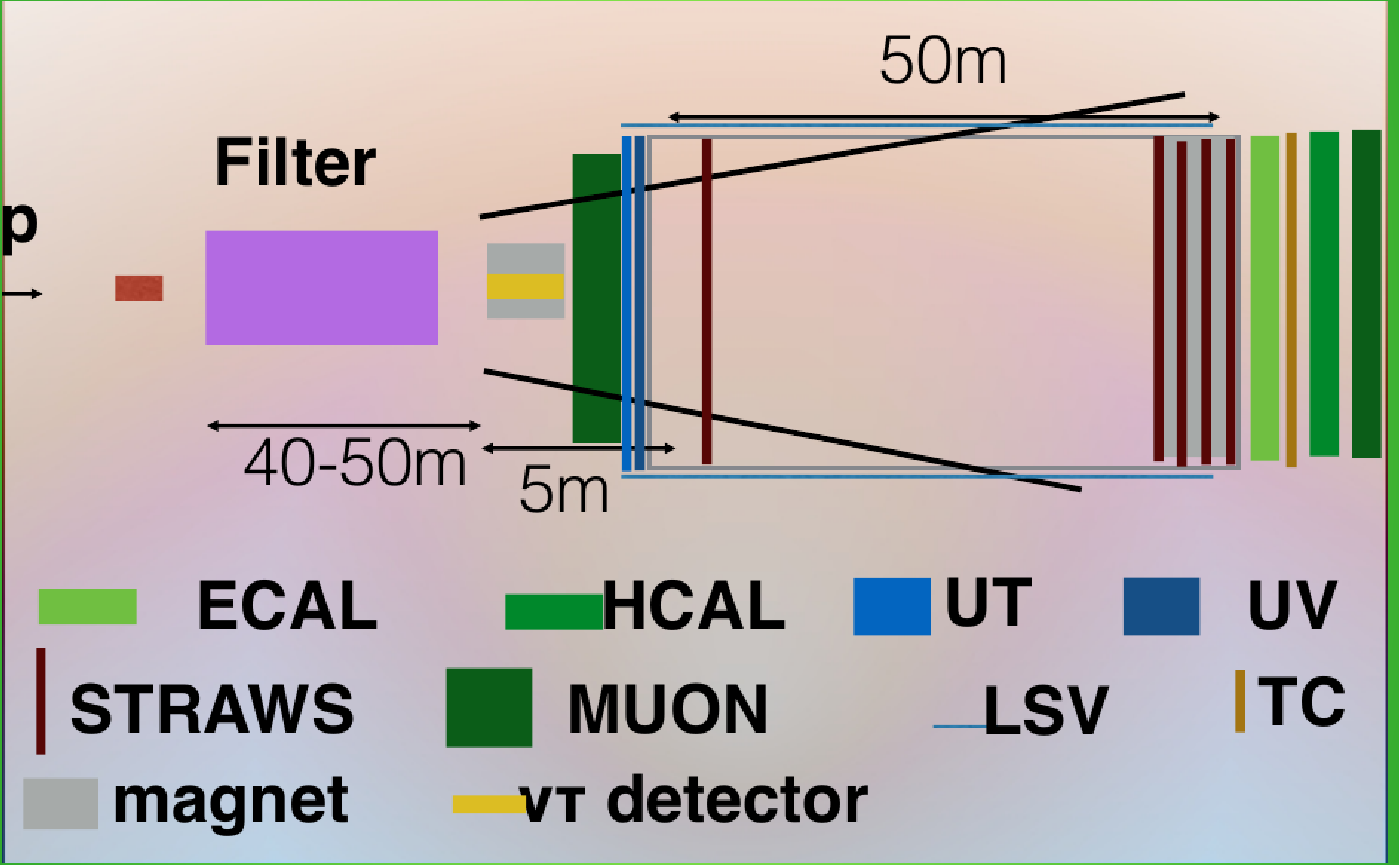
- fixed-target against a beam dump
- followed by a long decay tunnel and a spectrometer at the end

An experiment in practice

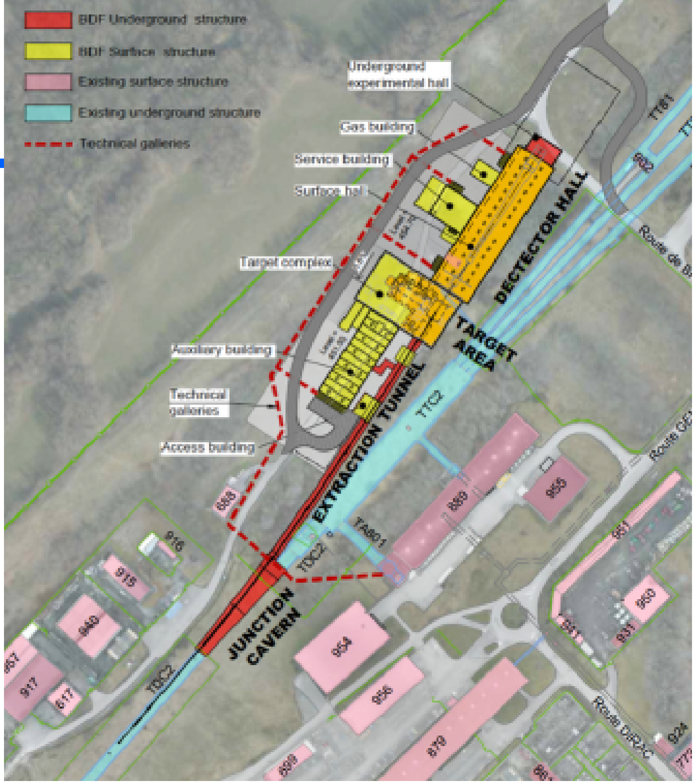
Use protons from CERN's SPS: 500 kW is 4x1E13 protons/7 s ->2E20 in 5y

- Slow (ms → 1s) and uniform extraction to reduce detector occupancy and combinatorics
- HS particles produced by mesons (mainly charm) decays; need to absorb all SM decay products to minimise BG → heavy material thick target, with wide beam to dilute energy deposition (different from neutrino facility)
- Muons cannot be absorbed by target: muon shield, possibly magnetised
- Long decay tunnel away from external walls to minimise rescattering of muons and neutrons close to detector
- Vacuum in decay tunnel to reduce neutrino interactions
- Far-away detector with good PID and resolutions

Schematically...



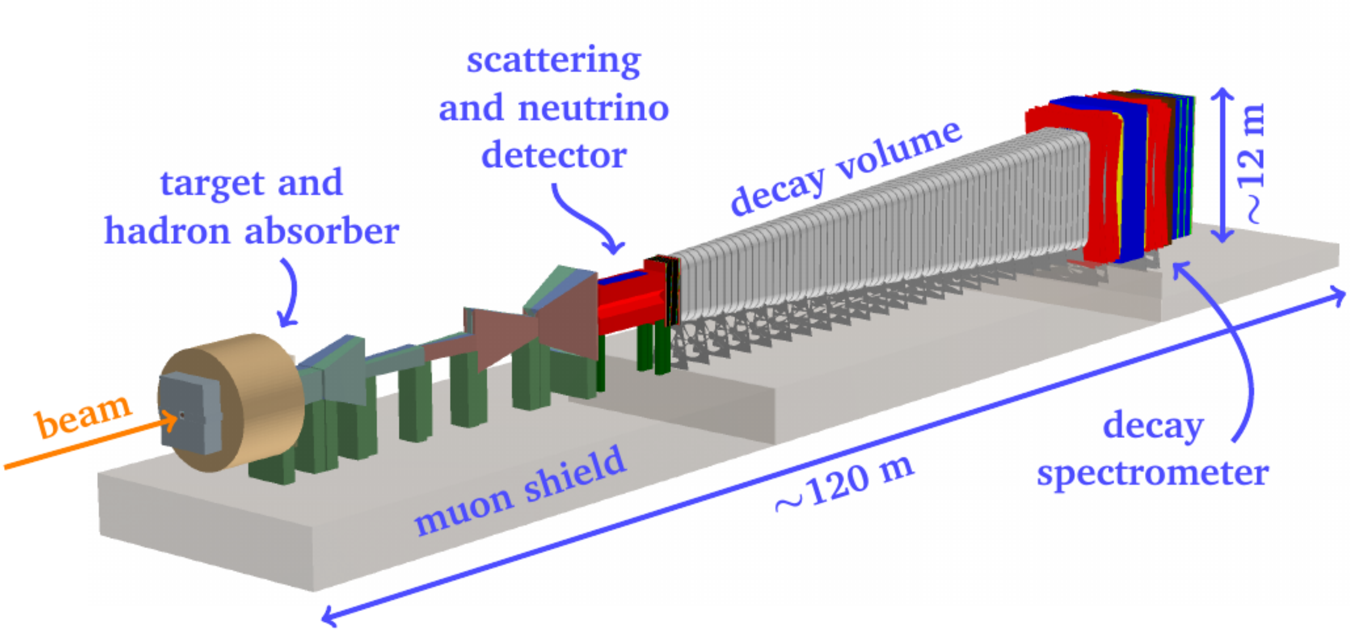
The SHiP experiment



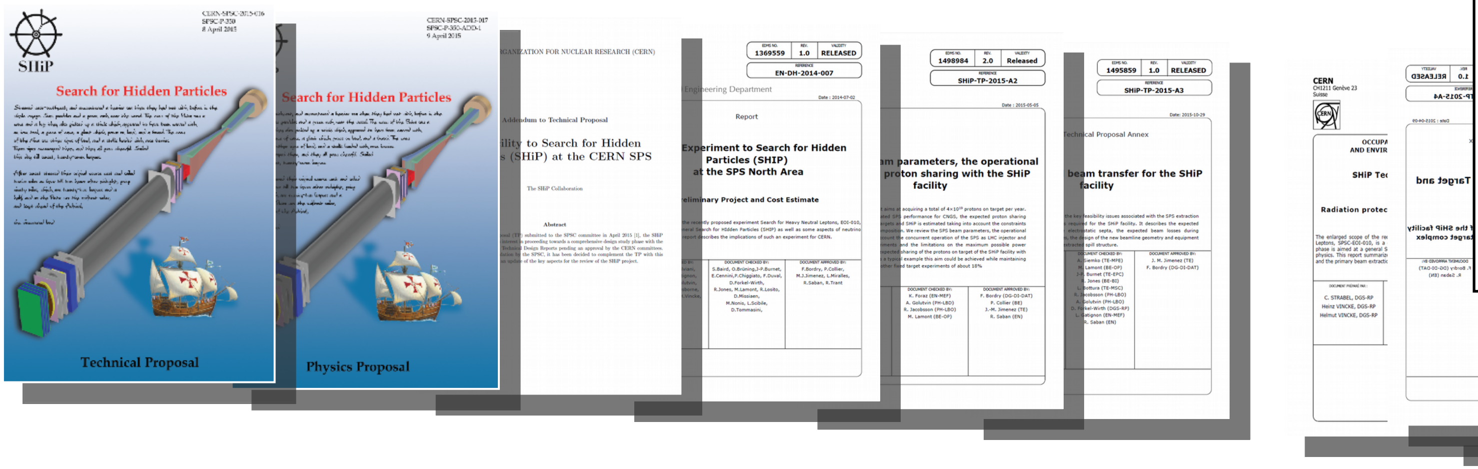
Dedicated detector for weakly coupled long-lived particles, plus tau neutrino and LDM scattering, to be run at future beam-dump facility at CERN.

The spectrometer is located ~100m downstream of the target, after a magnetised muon shield, the scattering and neutrino detector and a long decay volume

Aim for a 0-BG experiment (2 events → discovery)



SHiP history



CERN-SPSC-2015-016
SPSC-P-350
8 April 2015

SHiP

Search for Hidden Particles

Technical Proposal

CERN-SPSC-2015-017
SPSC-P-350-ADD-1
9 April 2015

Search for Hidden Particles

Physics Proposal

Addendum to Technical Proposal

The SHiP Collaboration

EDMS NO.	REV.	VALIDITY
1369559	1.0	RELEASED

REFERENCE EN-DH-2014-007

Date : 2014-07-02

Report

Preliminary Project and Cost Estimate

EDMS NO.	REV.	VALIDITY
1498984	2.0	Released

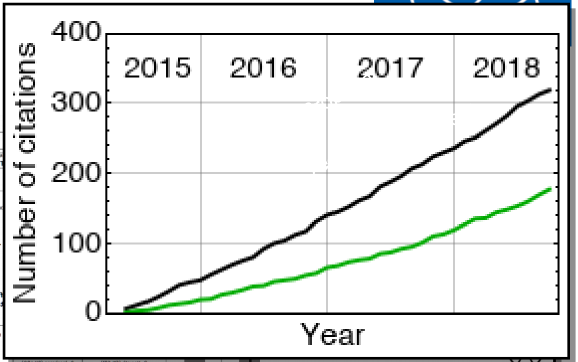
REFERENCE SHiP-TP-2015-A2

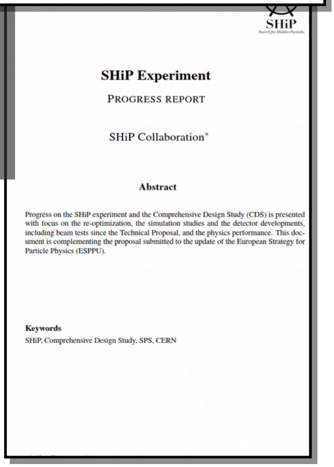
Date : 2015-05-05

EDMS NO.	REV.	VALIDITY
1495859	1.0	RELEASED

REFERENCE SHiP-TP-2015-A3

Date: 2015-10-29





SHiP
Search for Hidden Particles

SHiP Experiment

PROGRESS REPORT

SHiP Collaboration*

Abstract

Progress on the SHiP experiment and the Comprehensive Design Study (CDS) is presented with focus on the re-optimization, the simulation studies and the detector developments, including beam tests since the Technical Proposal, and the physics performance. This document is complementing the proposal submitted to the update of the European Strategy for Particle Physics (ESPPU).

Keywords
SHiP, Comprehensive Design Study, SPS, CERN

<u>2013 Oct</u>: EOI with SHiP@SPS NA

<u>2014 Jan</u>: Encouraged to produce TP and inter-departmental task force setup to study feasibility of proposed facility

<u>2015 Apr:</u> TP with ~700 pages by SHiP theorists, experimentalists, and CERN accelerator, engineering, and safety departments

<u>2016 Jan:</u> Recommendation by CERN SPSC to proceed to 3-year CDS

<u>2016 Apr:</u> CERN management launch of Beyond Collider Physics study group

SHiP experimental facility included under PBC as <u>Beam Dump Facility</u>

<u>2018:</u> EPPSU contribution submitted by SHiP and BDF

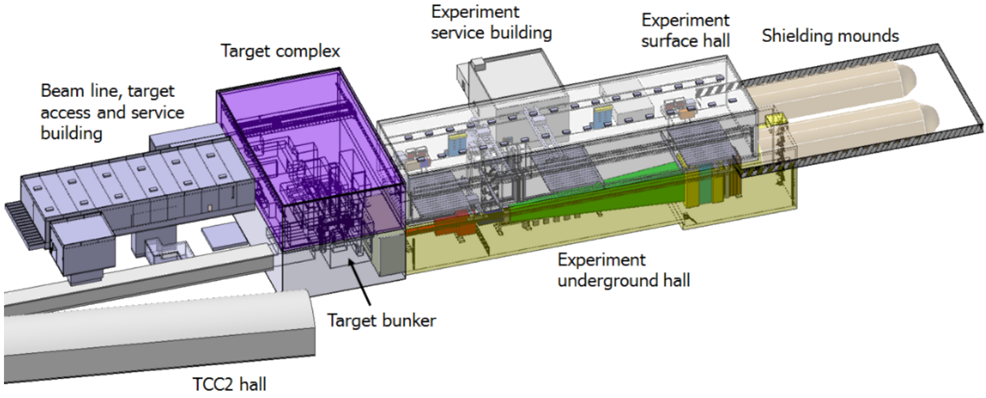
2019 Dec: CDS submitted: CERN-SPSC-2019-049 ; SPSC-SR-263

SHiP Collaboration: ***290 authors, 52 Institutes, 17 countries***

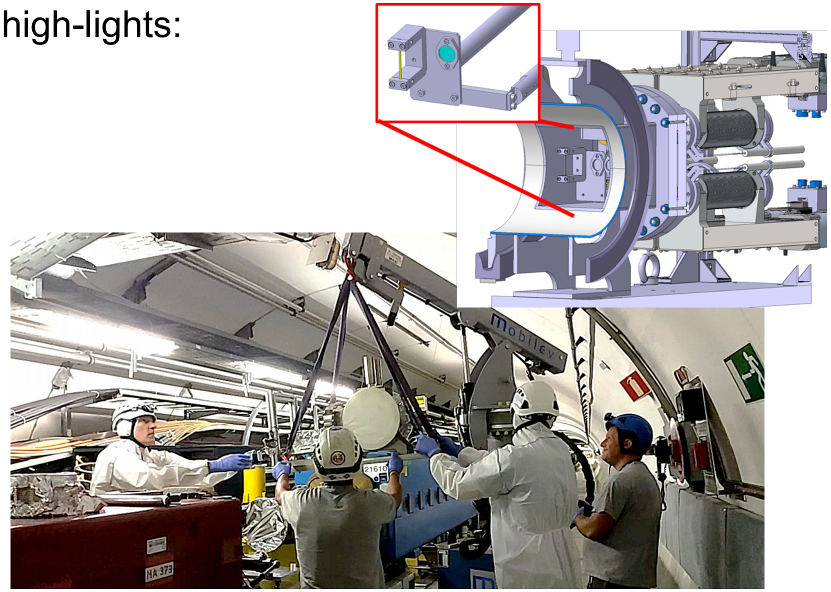
Status of Beam Dump Facility

3-year Comprehensive Design Study completed by BDF team

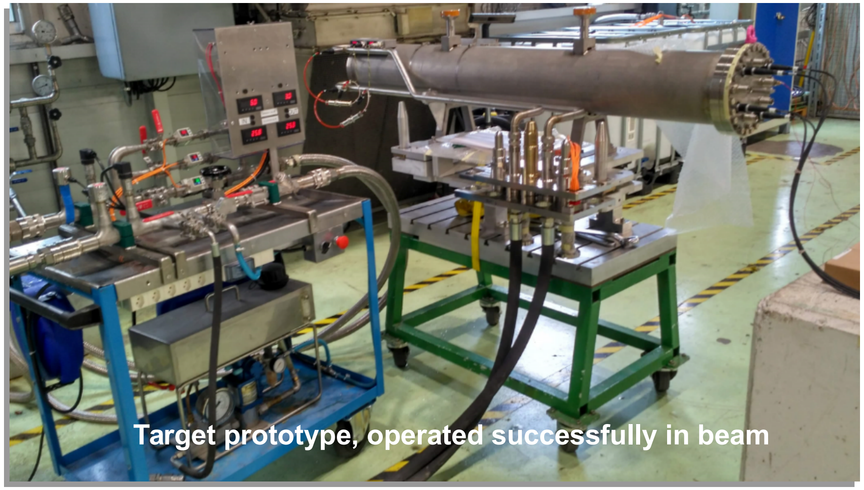
- In-depth feasibility study with prototypes of key elements
  - SPS extraction and proton delivery
  - Target system and target complex, including remote handling
  - Underground experimental area, layout of surface buildings for construction/installation and operation
  - Evaluations of the radiological aspects and safety
  - First iteration of detailed integration and civil engineering studies
  - Updated realistic schedule and cost, detailed project plan and resources for TDR phase
  - ➔ Documented in 580-page Yellow Report
  - ➔ BDF ready for 3-year TDR phase



A few high-lights:



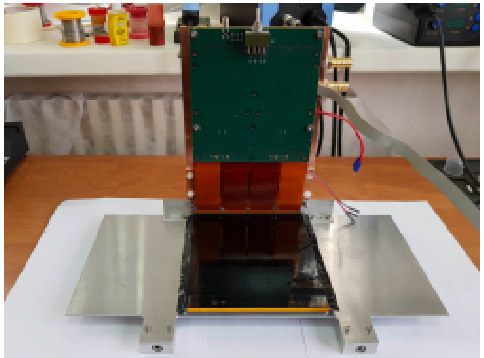
Crystal shadowing of extraction septum wires combined with improvements of beam dynamics and automated alignment achieved factor 3-4 less losses in SPS extraction, validating the SHiP requirements

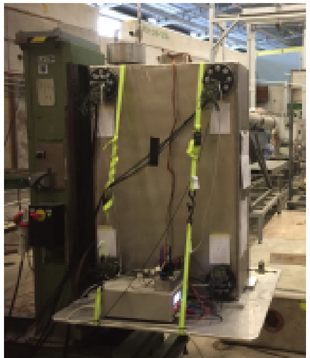


Target prototype, operated successfully in beam

Current status of the experiment

- Collaboration completed Comprehensive Design Study, then we expect to be requested a TDR
- Phase-1 prototypes for all sub-detectors built and tested on a beam in summer 2018
- From the summer 2019 ECFA newsletter:
  - Among them, the SPS Beam Dump Facility with the SHiP and (possibly) the TauFV experiment has been identified as having unique potential in the worldwide landscape for dark photon and heavy neutral lepton searches, as well as for third flavour physics (ντ interactions and τ rare decays). It is now mature and ready for an implementation decision pending the Strategy guidelines.
- Phase-2 prototypes under construction, to be tested on beam in 2019-21.



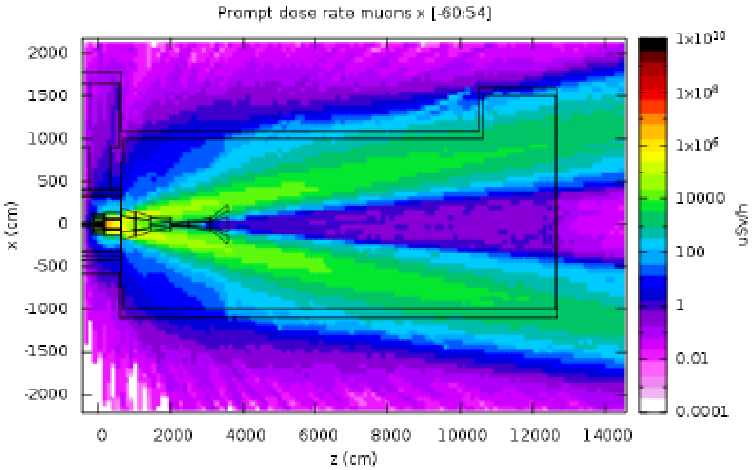


Target and shielding

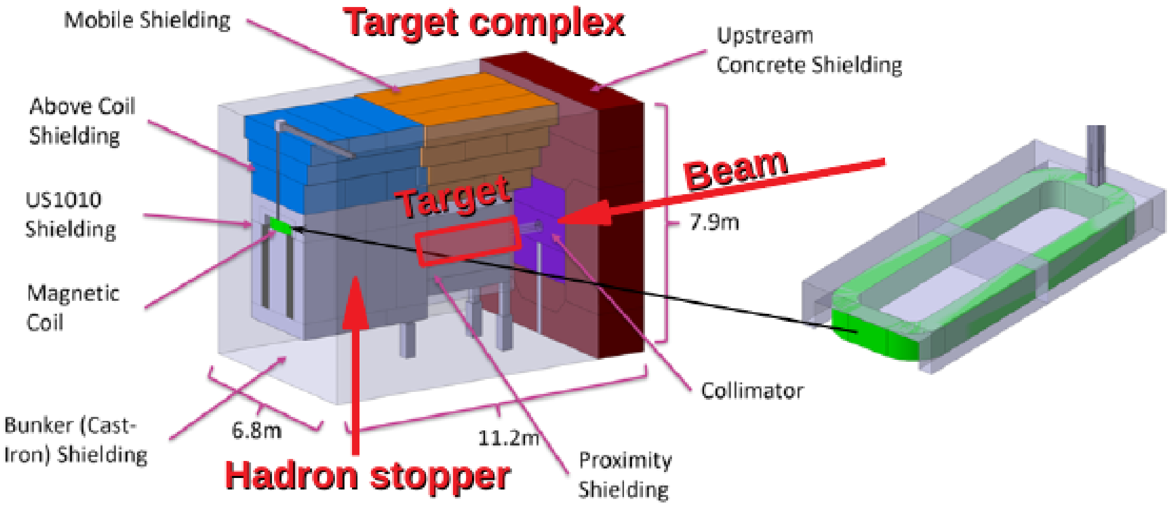
[JINST 12(2017)05 P05011]

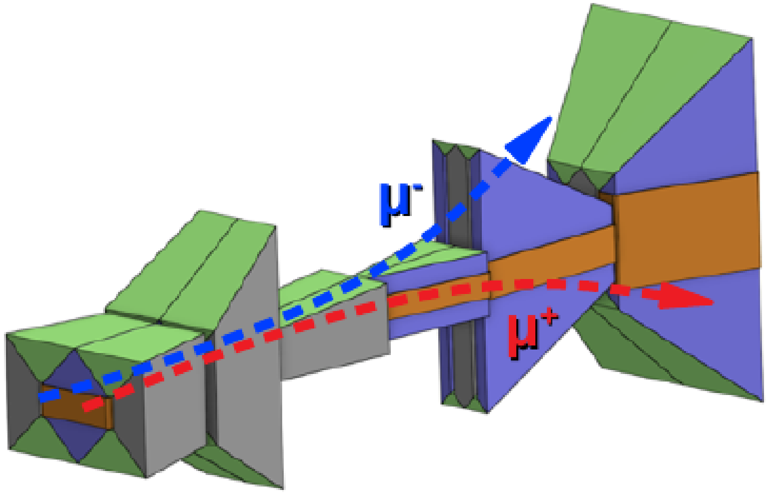
- heavy target to absorbe πs before decay
- magnetized hadron stopper: immediately separate $\mu^\pm$
- ideal muon shield configuration optimised with machine learning

  $\Longrightarrow$ μ rate reduced to $\sim$ 25 kHz



- μ spectrum validated with dedicated experiment in 2018



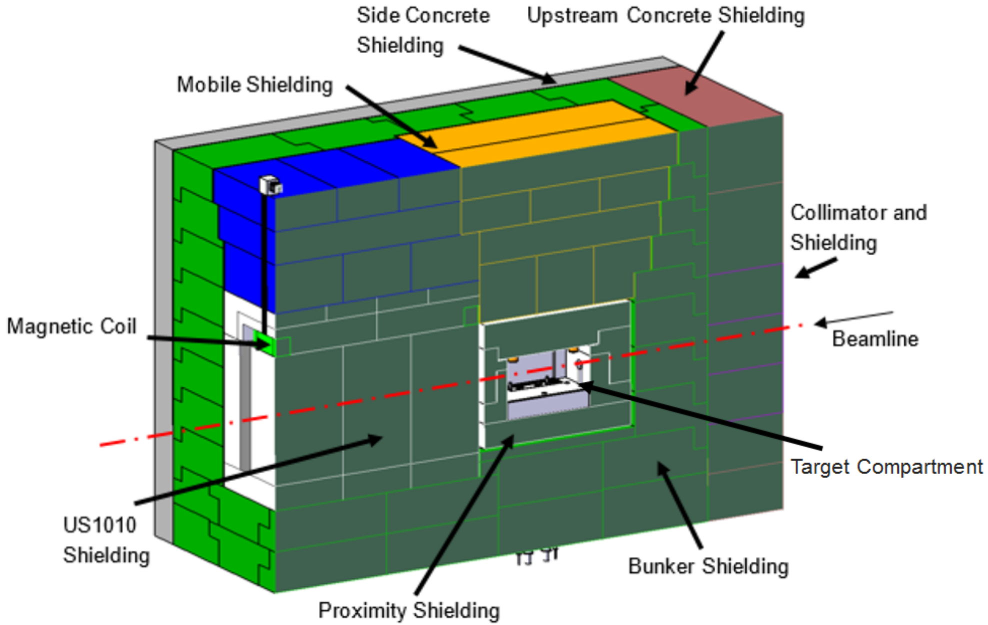


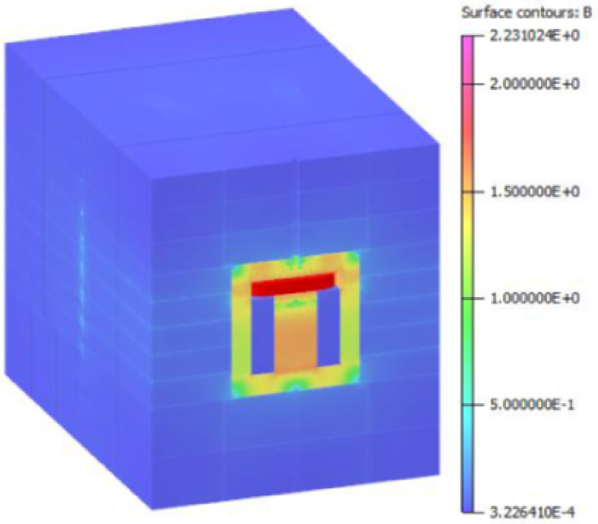
Magnetisation of hadron stopper

Detailed design study completed by RAL (V. Bayliss, J. Boehm, G. Gilley) through Collaboration Agreement with CERN

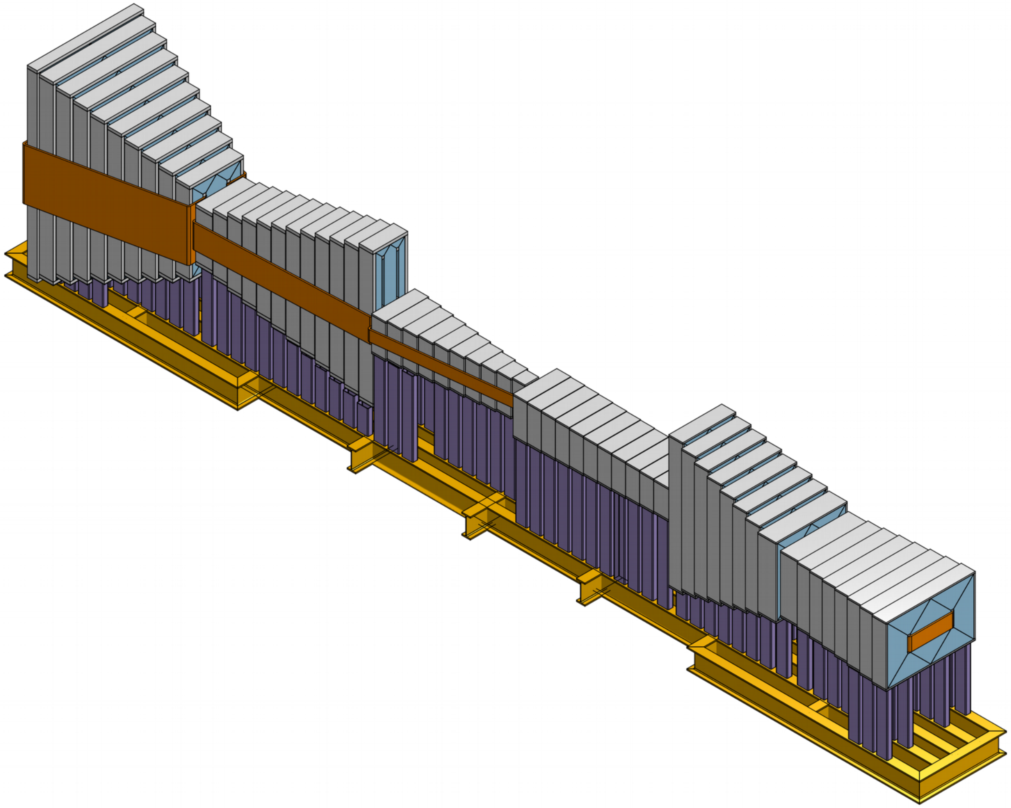
- Optimisation of the magnetic circuit
  - Simulated field maps for use in physics simulations and for optimisation of the subsequent free-standing muon shield
  - Hysteresis effects after multiple powering cycles;
  - Magnetic forces of the entire magnetized assembly and target shielding
  - Stray fields

- Preliminary engineering design compatible with the target complex and radiation environment
  - Power requirements
  - Thermal management (consideration of water and gas cooling)
  - Technical solution for connections of power cables, cooling, sensors etc.
  - Technical solution for the integration of magnetic iron blocks and remote handling of blocks and coils





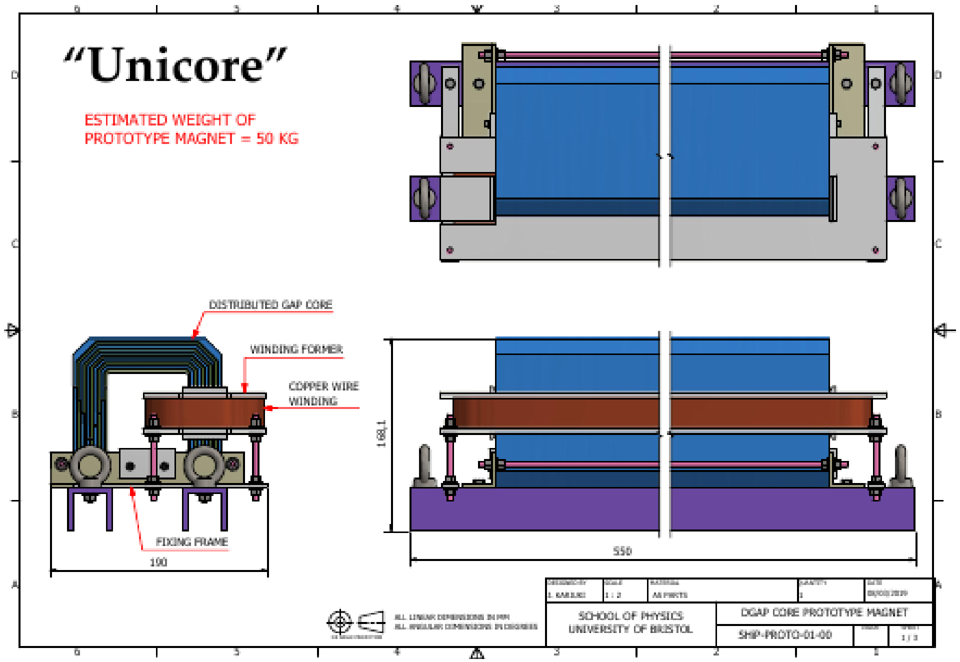
Magnetic Shield for SHiP (UK-Russia responsibility)



- about 600 individual modules (one block in the figure is 10 modules)
- total weight of about 10000 tons
- modules up to 6.5×4 m^2 in size
- about 2000 km of sheet cutting length

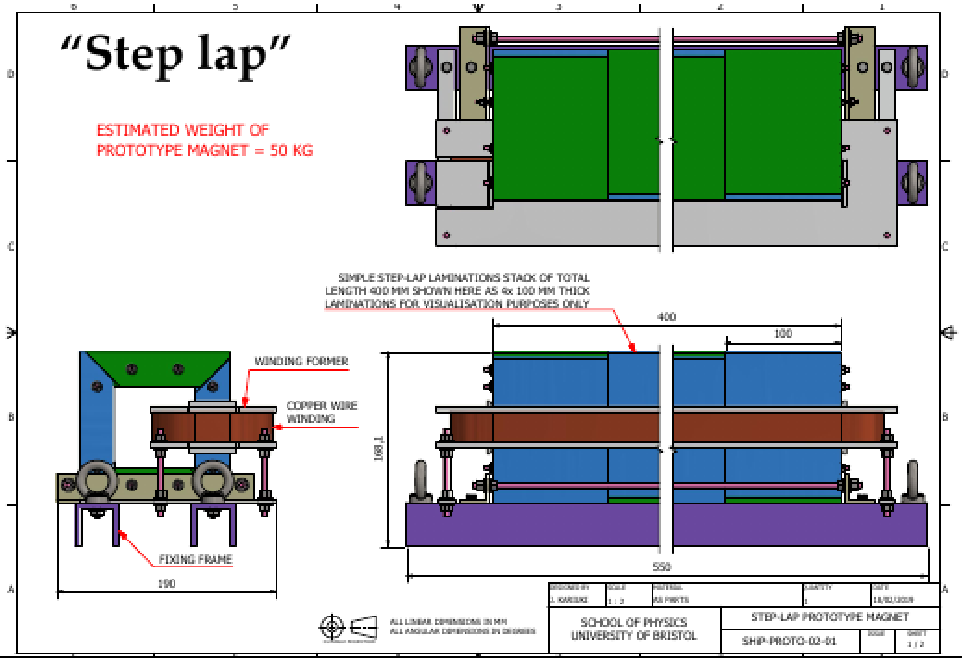
Magnet prototypes

- Two 50kg magnet prototypes have been constructed with different assembly techniques by UK companies using UK Grain Oriented Steel
  - Complementary approach to welding of laminations
  - Target field of ~1.8T with stacking factor >0.95
  - Test for loses of magnetic flux around the loop due to the different types of connections between laminations
- Awaiting delivery to CERN for testing



“Unicore”

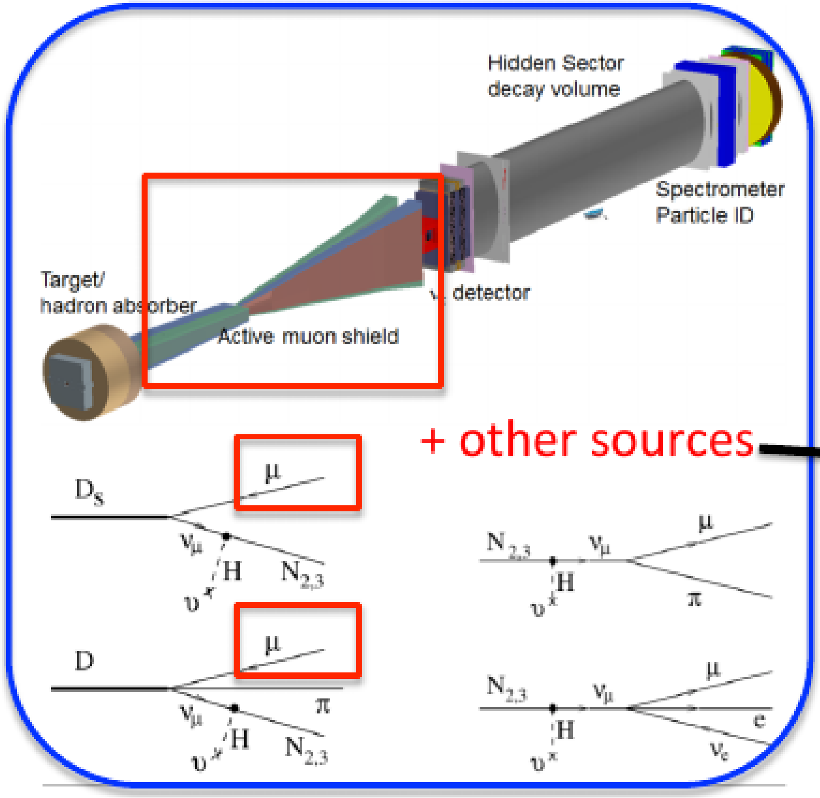
ESTIMATED WEIGHT OF PROTOTYPE MAGNET = 50 KG



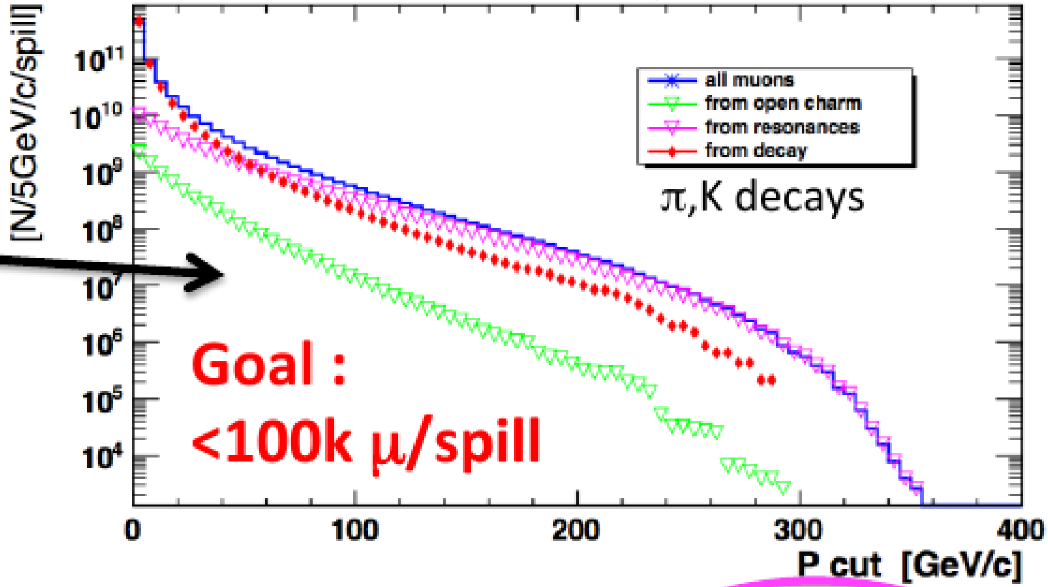
“Step lap”

ESTIMATED WEIGHT OF PROTOTYPE MAGNET = 50 KG

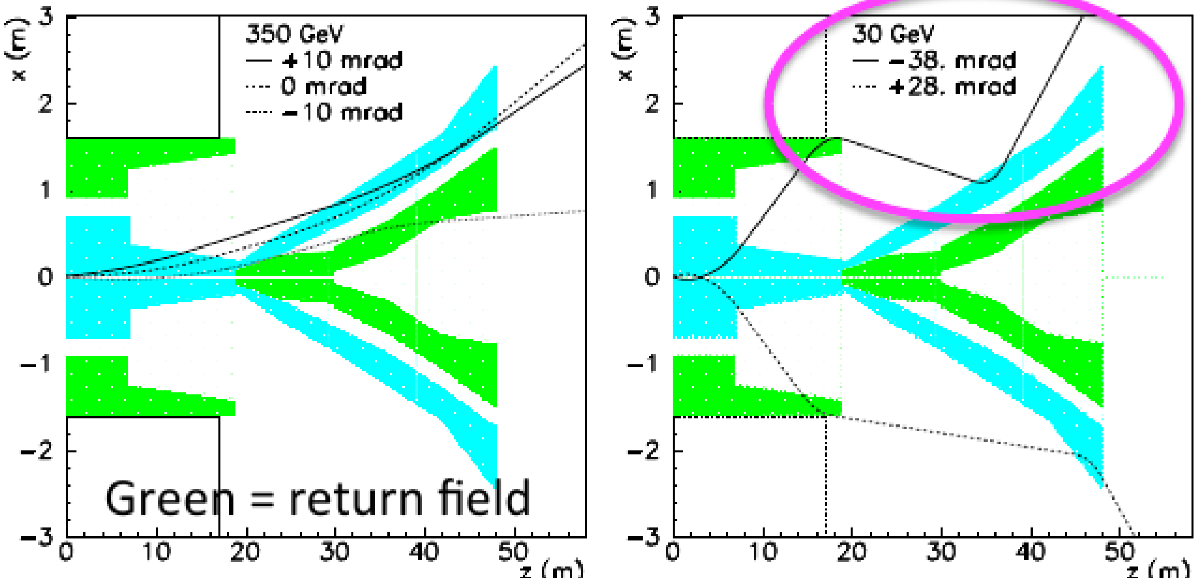
The muon filter



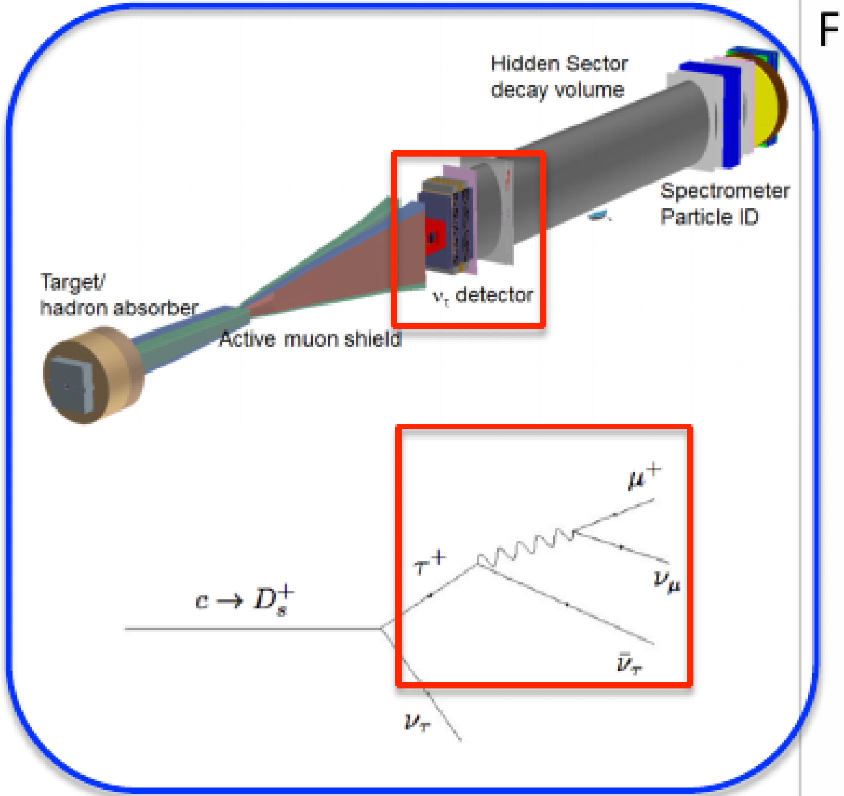
- **Clear the μ flux** to a level inferior to the ν-induced background and not to compromise the **occupancy limit** in the ν_τ detector

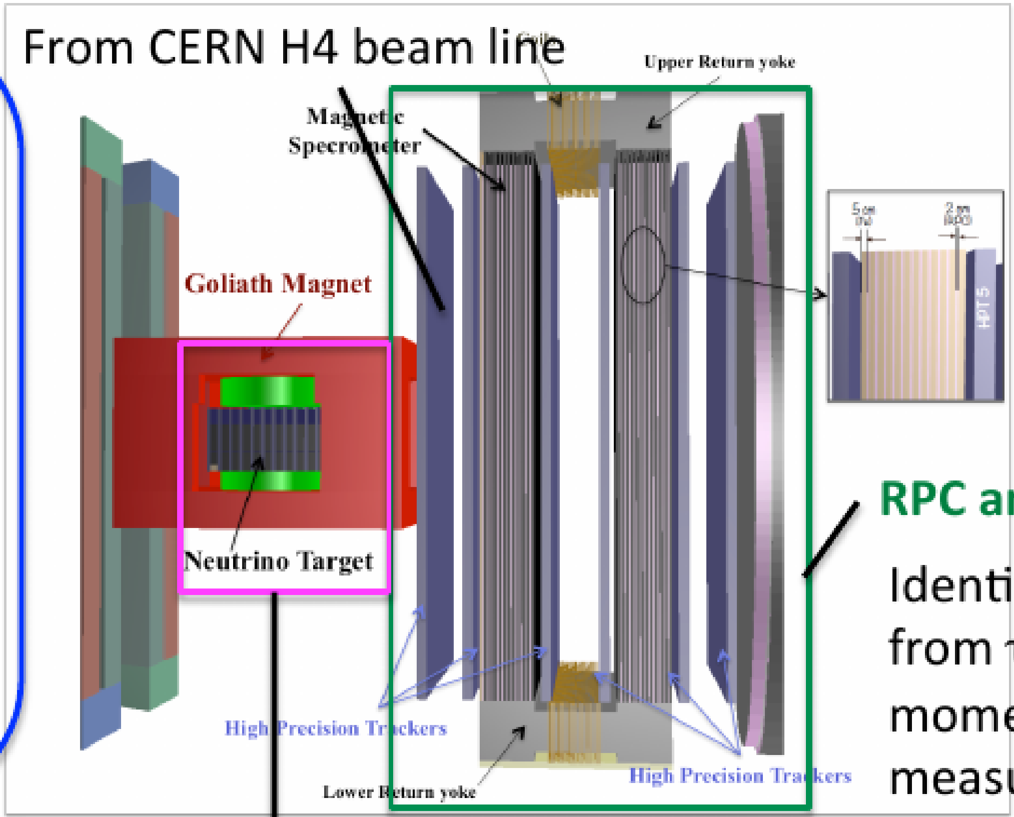


- **Active** muon filter made of two magnets (B_y = 40 Tm to bend out 350 GeV μ beyond the 5 m vacuum vessel aperture)
  - **1st part** to separate μ^+/μ^-
  - **2nd part** to bend the muons **further outward**



Bonus intermezzo: the ν_τ detector

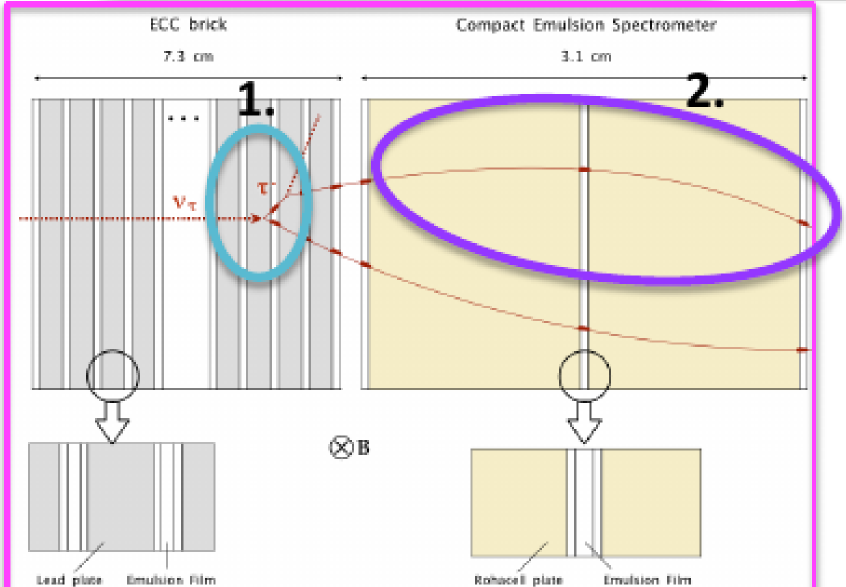




μ flux :
10^3 μ/mm^2
in 6 months

RPC and drift tubes

Identify μ coming from τ decays; μ momentum measurement

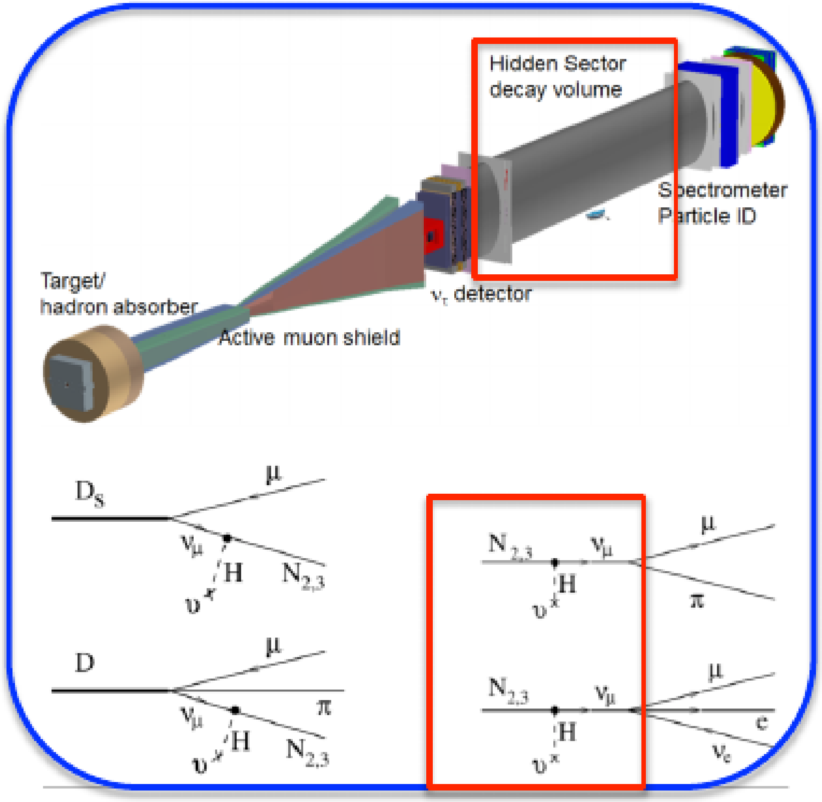


OPERA-type modules (emulsion cloud chambers (ECC))

- 1x1m, close to the beam line
- 2 parts : ECC brick and compact spectrometer

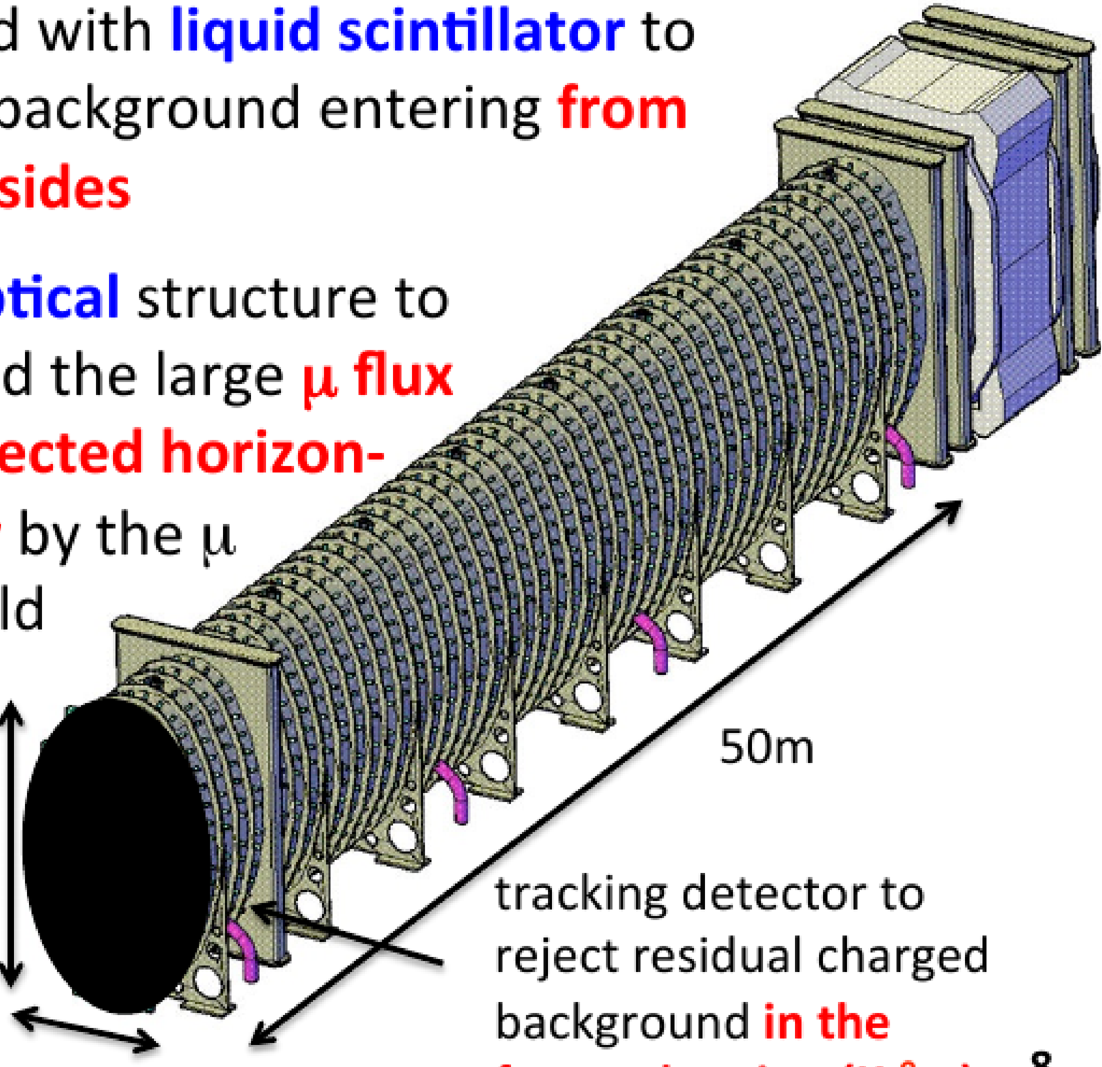
1. **ν interaction :** identified through **detection of τ production and decay** (contained within a brick due to short τ lifetime)
2. **distinguish ν_τ anti-ν_τ :** Look at the **charge of the τ decay** products

The vacuum vessel



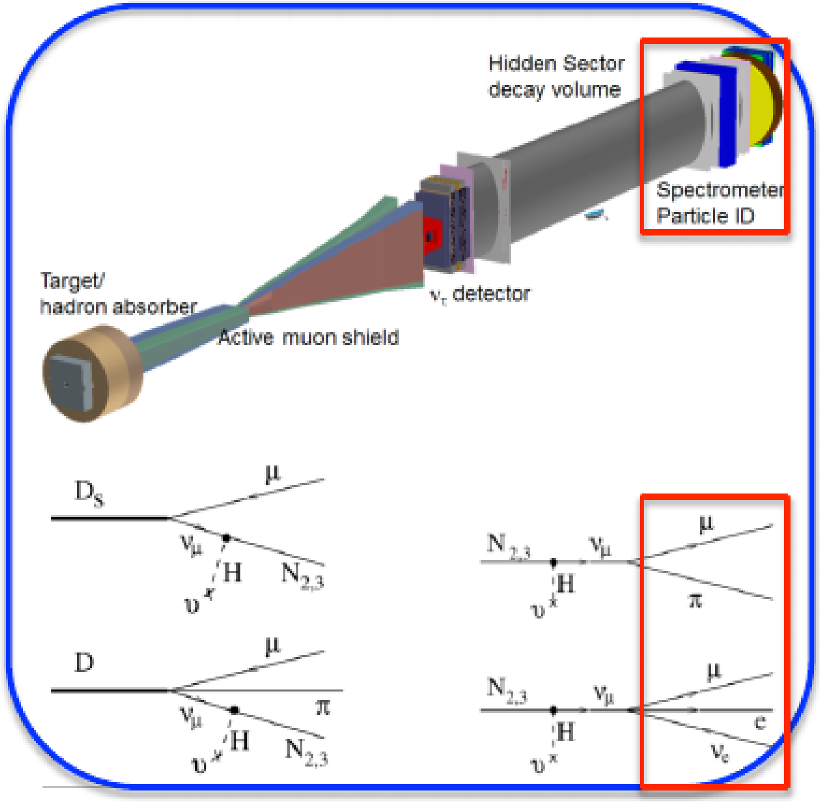
- **10^{-6} mbar vacuum** needed suppress the **neutrino interactions**
- Double-wall structure, space filled with **liquid scintillator** to tag background entering **from the sides**
- **Elliptical** structure to avoid the large **μ flux deflected horizontally** by the μ shield

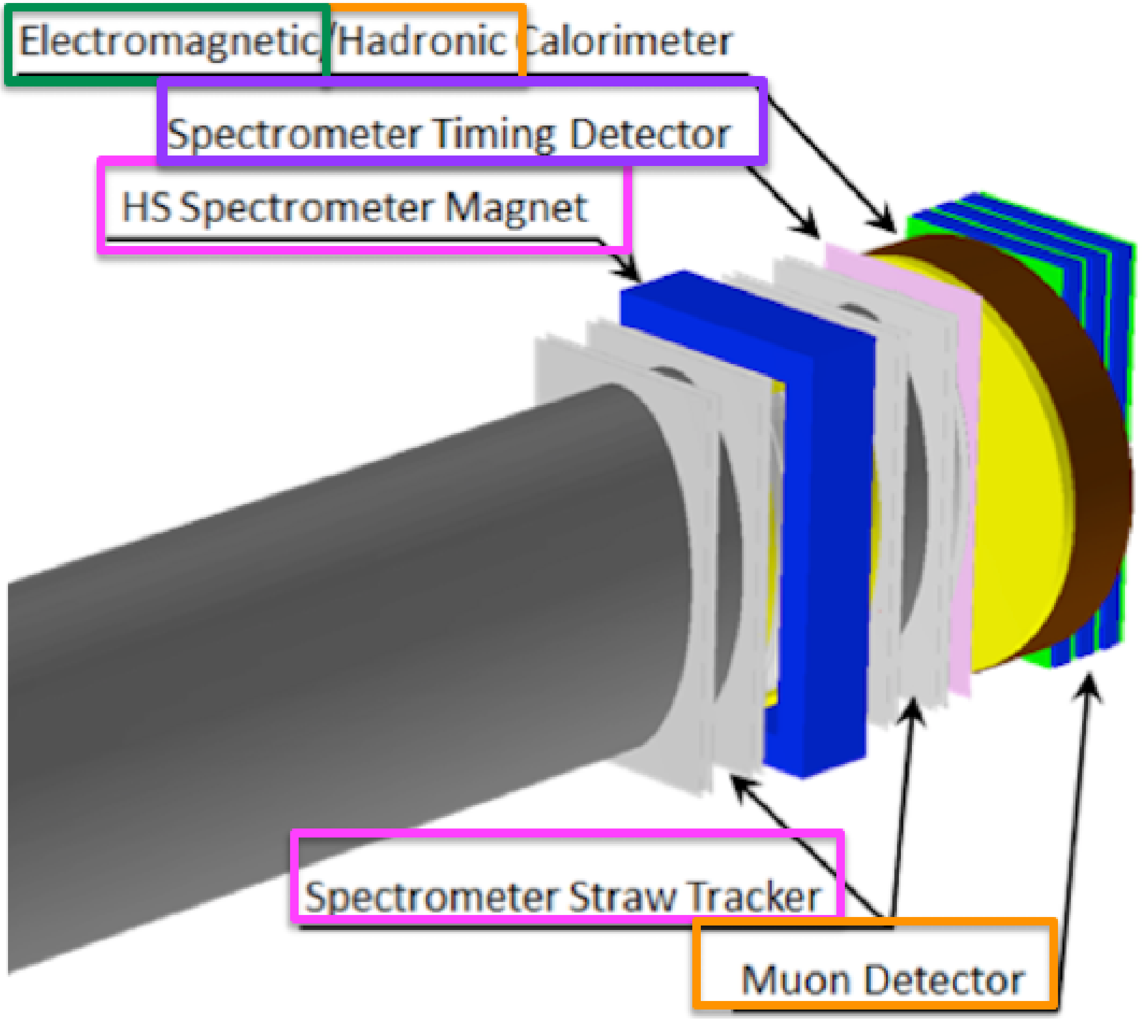
- **Veto tagger** located just after ν_τ detector to tag indirectly **neutral K** produced by ν and μ interactions in the passive material of the ν_τ detector and **μ entering the vessel from the front**



tracking detector to reject residual charged background **in the forward region (K_s^0,..)**

The spectrometer





Signal reconstruction and background rejection: warm magnet (LHCb) with 0.65Tm bending power; tracker (NA62) with horizontal straws and stereo angle

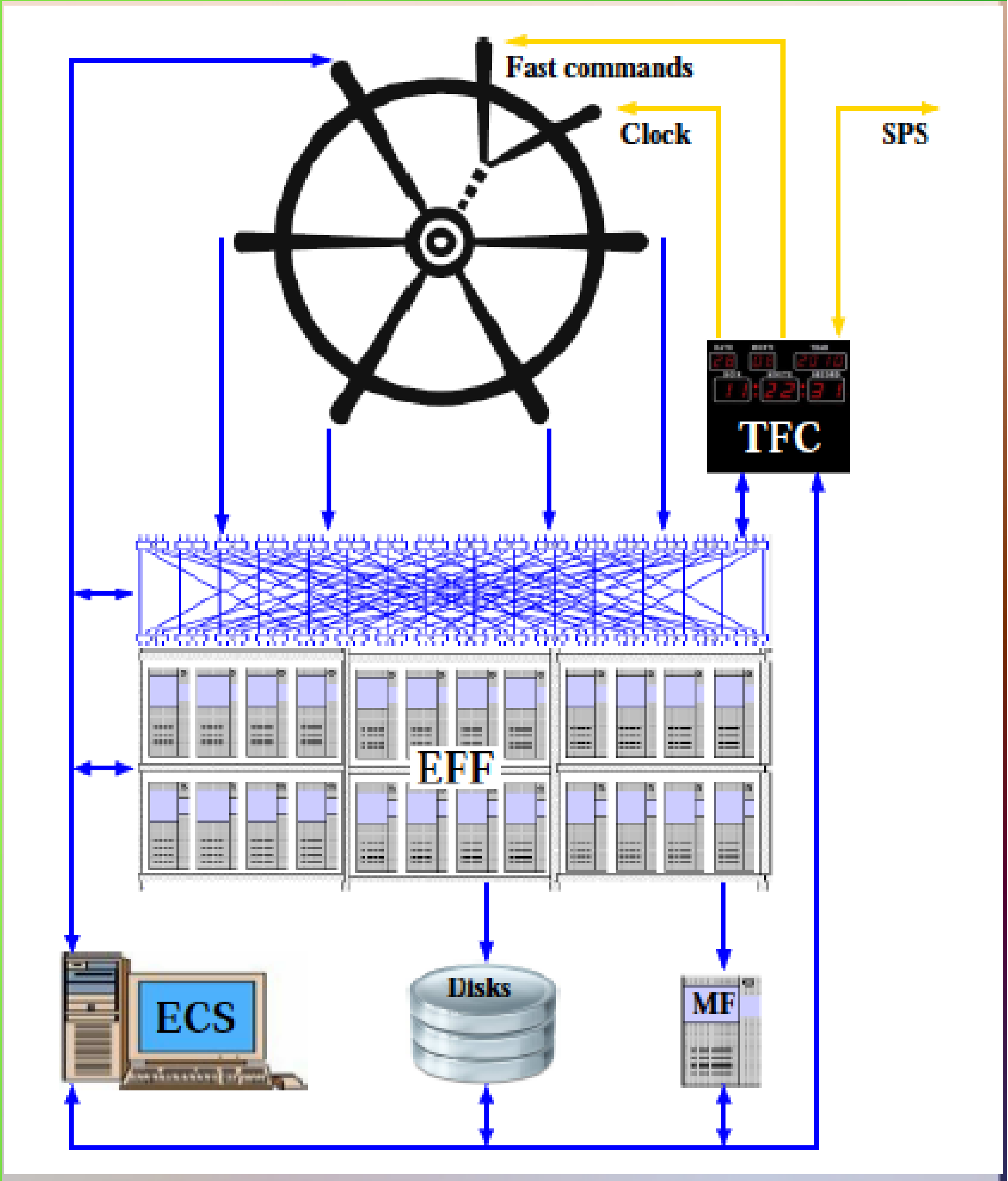
e/γ identification, π^0 and η reconstruction: ECAL (Shashlik technique, LHCb)

Veto anti-coincidence from combinatorial : timing detector (50ps resolution)

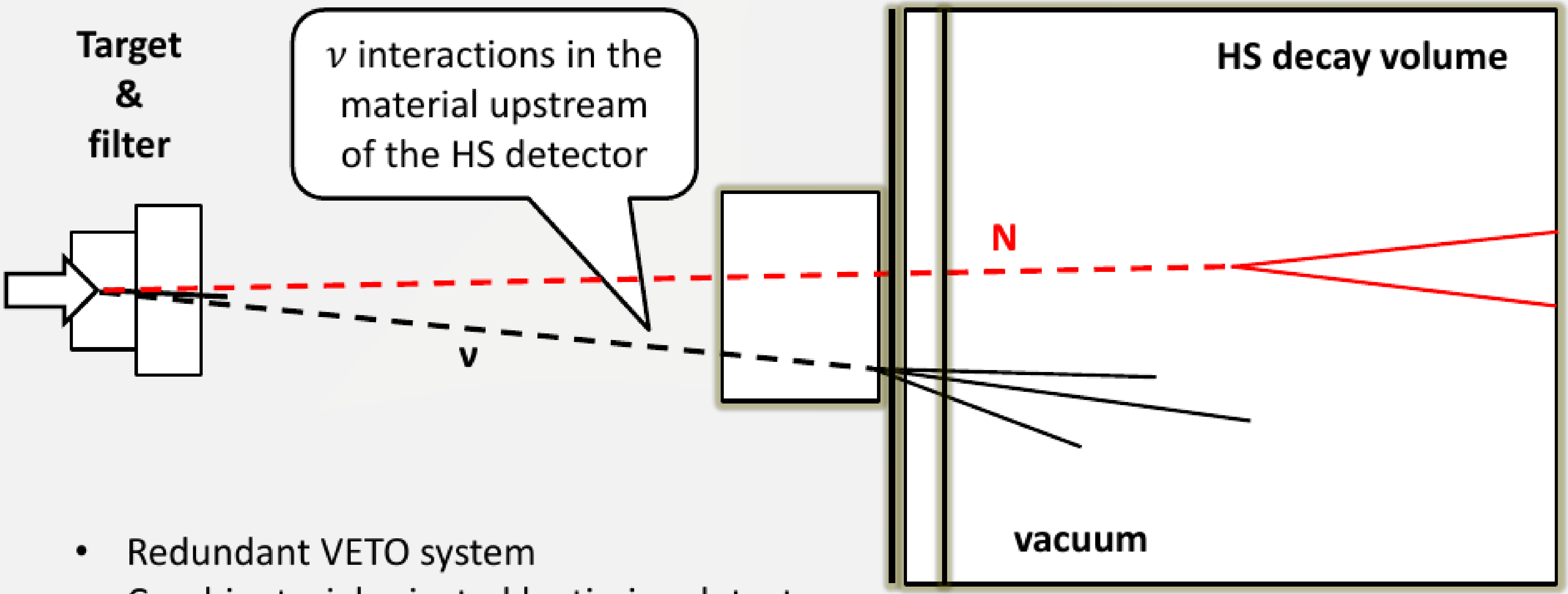
π/μ separation : hadronic calorimeter (similar technology as ECAL), muon detector (WLS fiber bars, MINOS)

Trigger and DAQ

- Trigger andEvent building on all data and trigger decision at EF
- TFC system generates the clock
- All sub-systems send data through ethernet links (no need for radiation hardness) to Event Filter Farm via a switch
- Fraction of data sent to Monitoring
- Farm to evaluate performance
- Smallest time slice that could potentially contain all data from one pot (100 ns)
- Since some events spread over more than one frame, 100 frames are combined into a “package”, with 1 overlap



Background rejection: upstream neutrino interactions

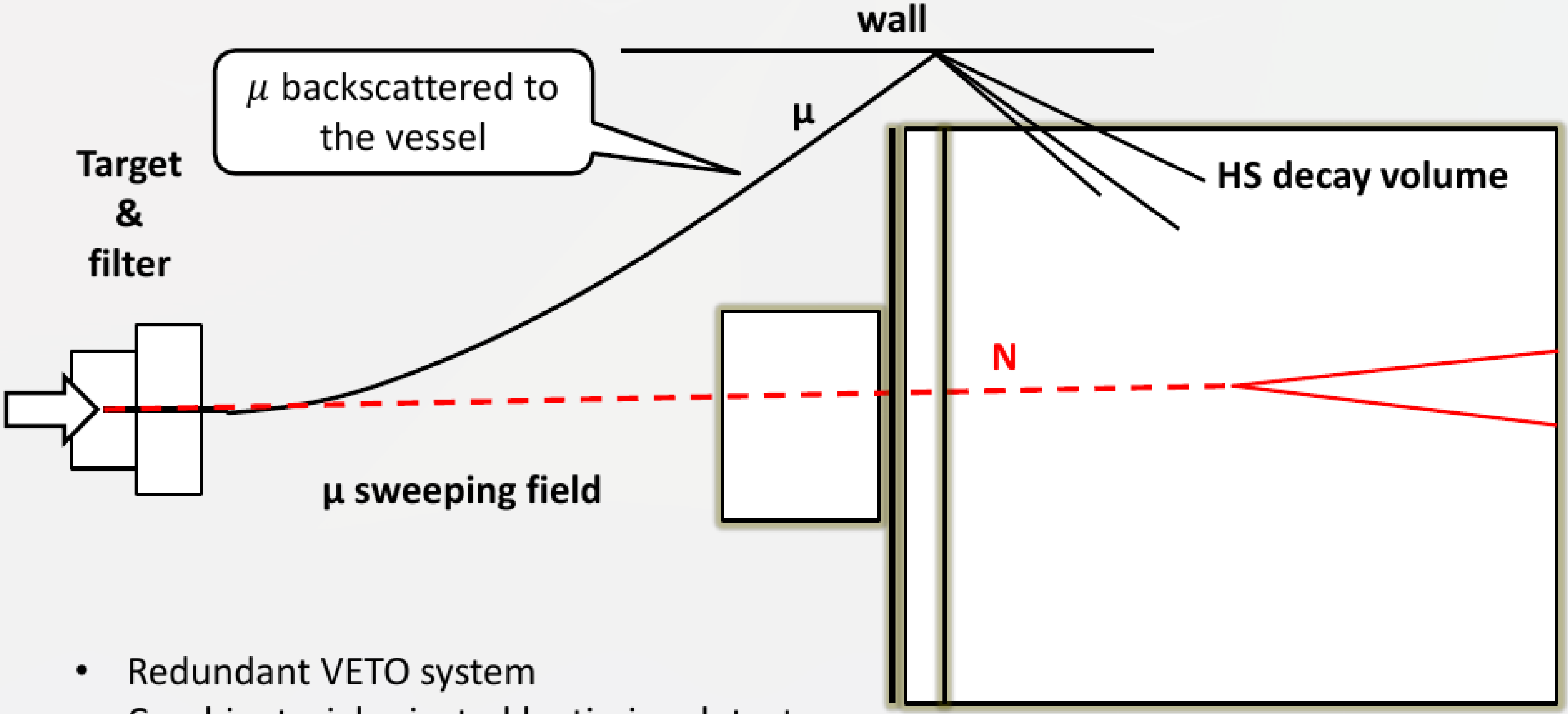


- Redundant VETO system
- Combinatorial rejected by timing detector
- Impact parameter to the target
- 75% selection efficiency for signal

After selections:

≤ 0.1 bkg / 5 y

Background rejection: interactions with experimental hall

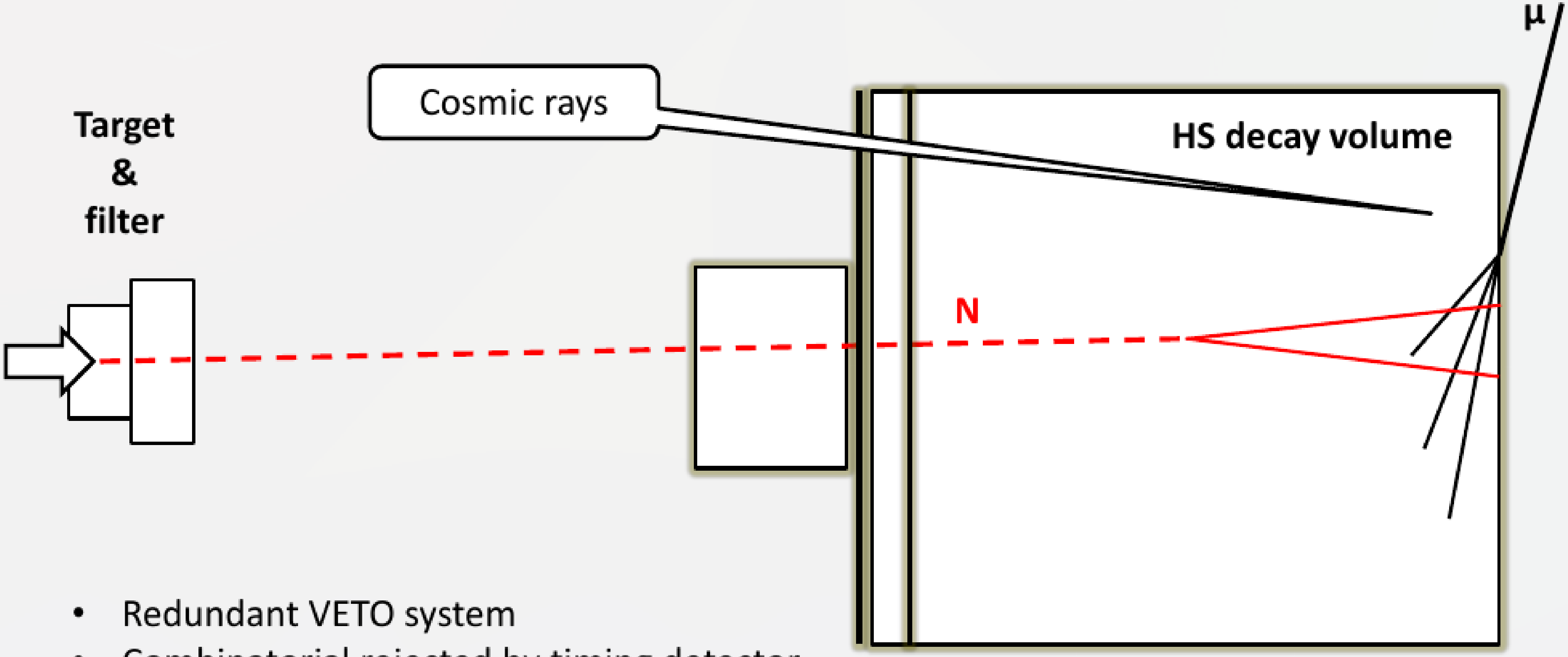


- Redundant VETO system
- Combinatorial rejected by timing detector
- Impact parameter to the target
- 75% selection efficiency for signal

After selections:

$\leq$ 0.1 bkg / 5 y

Background rejection: cosmics

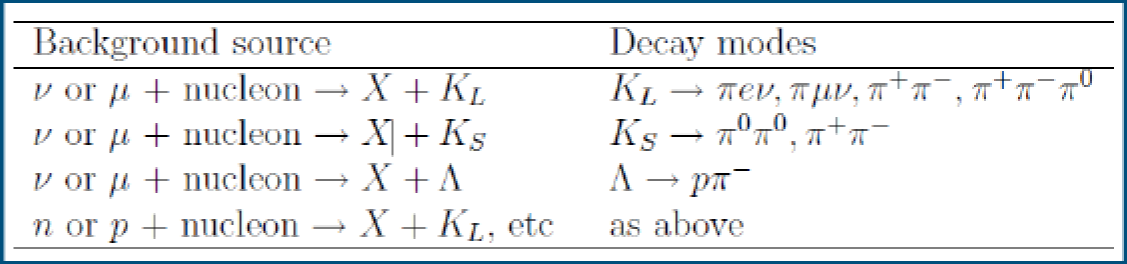


- Redundant VETO system
- Combinatorial rejected by timing detector
- Impact parameter to the target
- 75% selection efficiency for signal

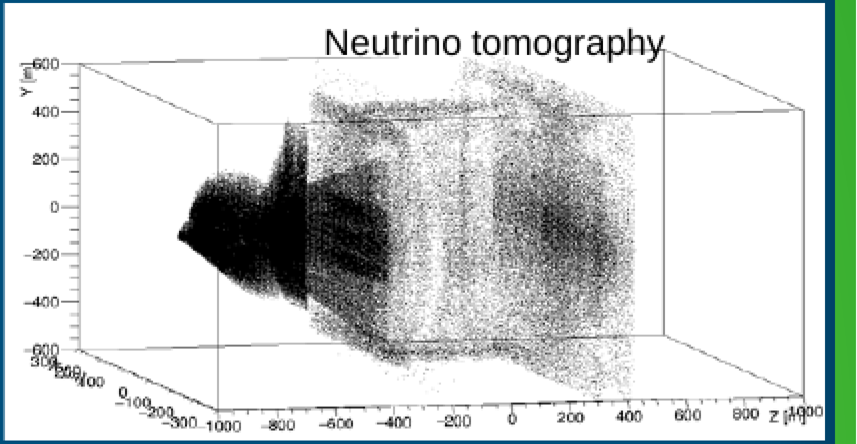
After selections:

≤ 0.1 bkg / 5 y

Backgrounds: summary

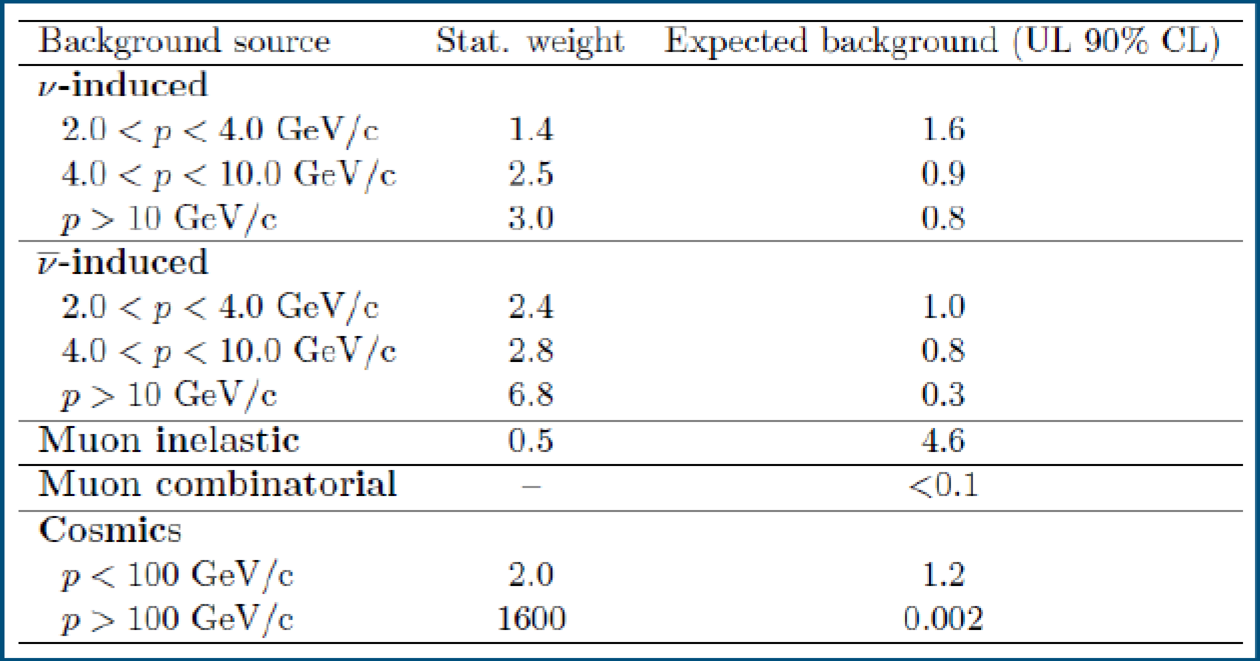


Background source	Decay modes
ν or μ + nucleon $\rightarrow X + K_L$	$K_L \rightarrow \pi e \nu, \pi \mu \nu, \pi^+\pi^-, \pi^+\pi^-\pi^0$
ν or μ + nucleon $\rightarrow X + K_S$	$K_S \rightarrow \pi^0\pi^0, \pi^+\pi^-$
ν or μ + nucleon $\rightarrow X + \Lambda$	$\Lambda \rightarrow p\pi^-$
n or p + nucleon $\rightarrow X + K_L$, etc	as above



Background summary: no evidence for any irreducible background

- No events selected in MC ➔ Expected background UL @ 90% CL

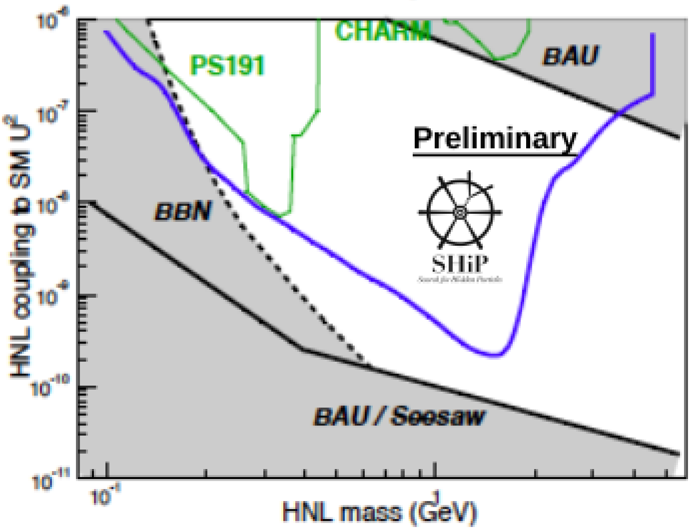


Background source	Stat. weight	Expected background (UL 90% CL)
ν-induced		
$2.0 < p < 4.0$ GeV/c	1.4	1.6
$4.0 < p < 10.0$ GeV/c	2.5	0.9
$p > 10$ GeV/c	3.0	0.8
$\overline{\nu}$-induced		
$2.0 < p < 4.0$ GeV/c	2.4	1.0
$4.0 < p < 10.0$ GeV/c	2.8	0.8
$p > 10$ GeV/c	6.8	0.3
Muon inelastic	0.5	4.6
Muon combinatorial	–	<0.1
Cosmics		
$p < 100$ GeV/c	2.0	1.2
$p > 100$ GeV/c	1600	0.002

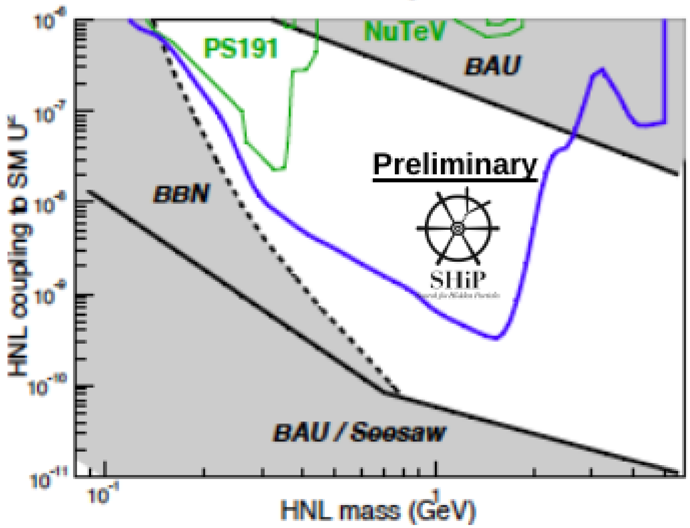
Sensitivity to HNL

- Visible decays = At least two tracks crossing the spectrometer
  - Ex. For m_N = 1 GeV with $\mathcal{U}^2$= 10^{-8} and $\mathcal{BR}(N \to \mu\pi)$ = 20%, expect ~330 signal events

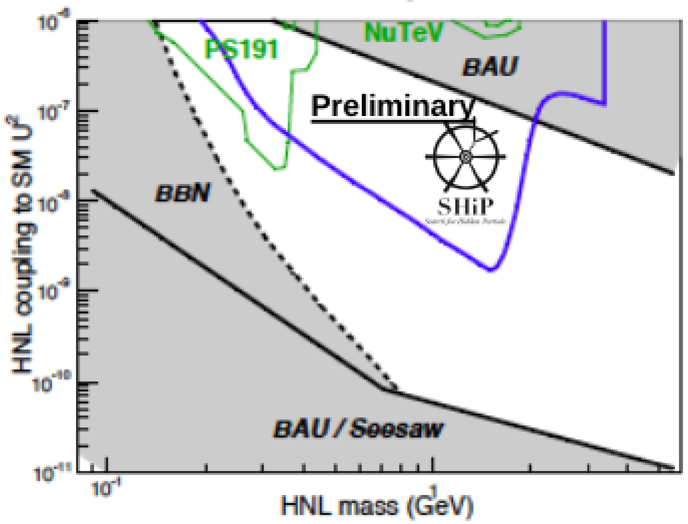
$U_e^2 : U_\mu^2 : U_\tau^2 \sim 52:1:1$, inverted hierarchy



$U_e^2 : U_\mu^2 : U_\tau^2 \sim 1:16:3.8$, normal hierarchy

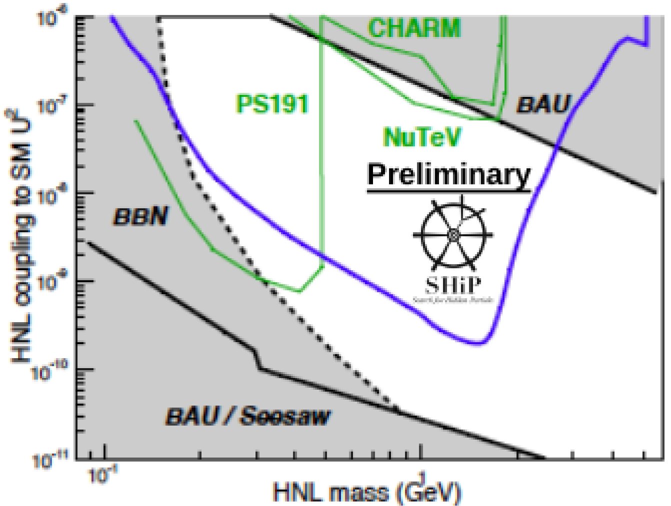


$U_e^2 : U_\mu^2 : U_\tau^2 \sim 0.061:1:4.3$, normal hierarchy

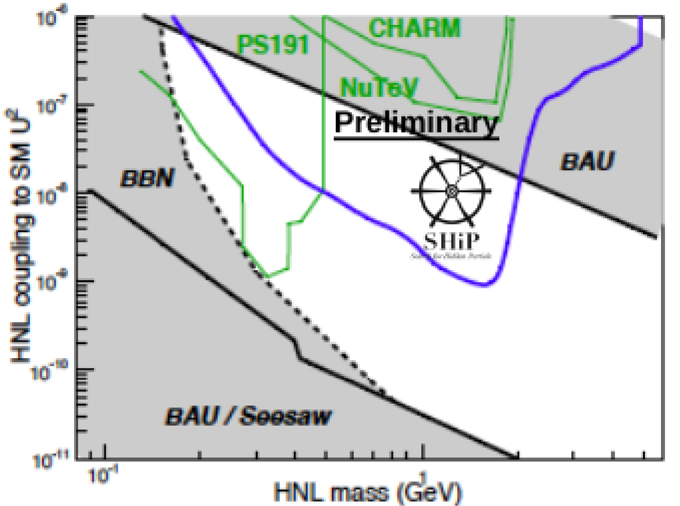


Scenarios for which baryogenesis was numerically proven

$U_e^2 : U_\mu^2 : U_\tau^2 \sim 48:1:1$, inverted hierarchy



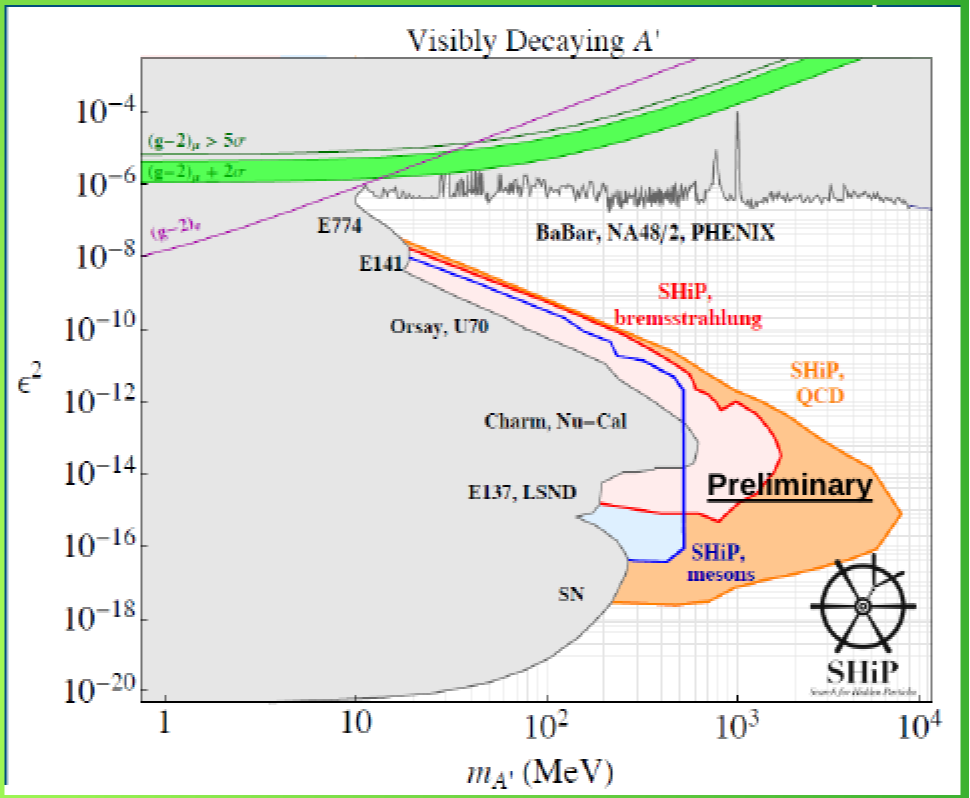
$U_e^2 : U_\mu^2 : U_\tau^2 \sim 1:11:11$, normal hierarchy

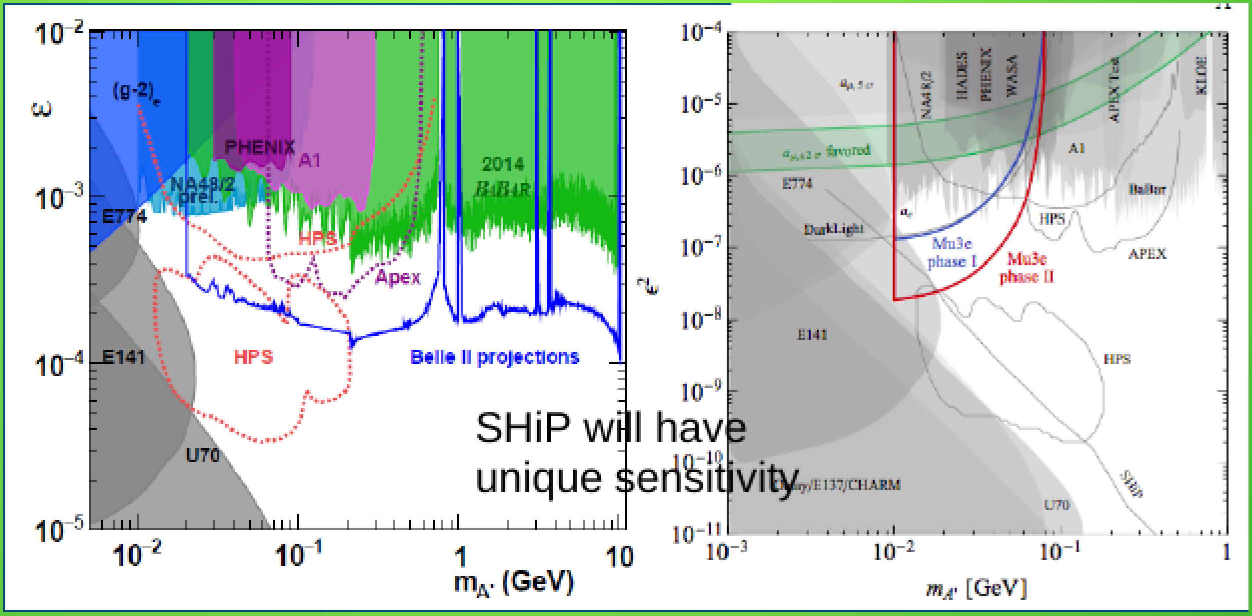


Sensitivity to dark photons

Production

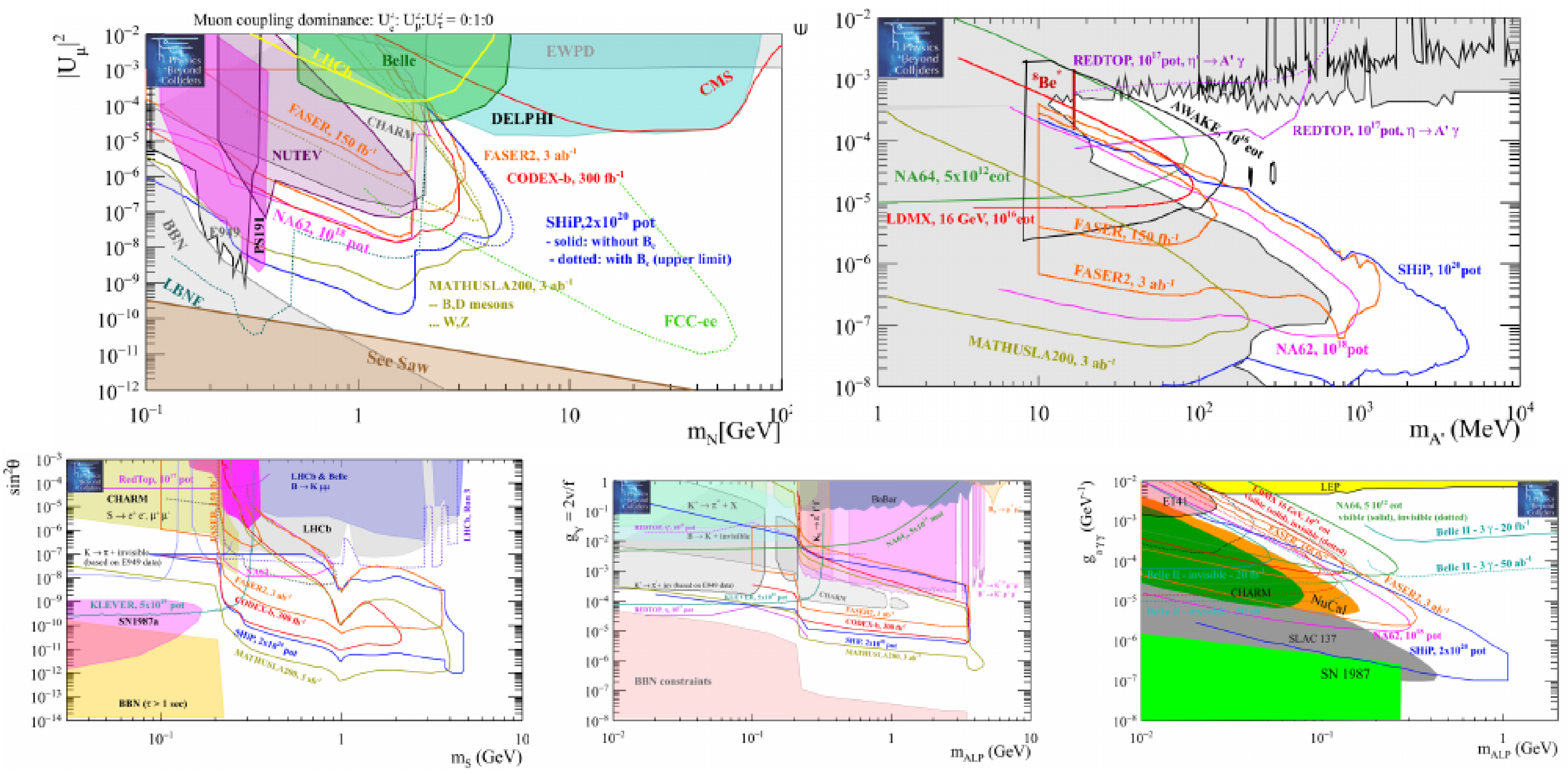
- Decays of $\pi^0 \rightarrow V\gamma$, $\eta \rightarrow V\gamma$, $\omega \rightarrow V\pi^0$
- Proton bremsstrahlung and parton bremsstrahlung above Λ QCD
- Decay into pair of SM particles





SHiP will have unique sensitivity

Updated physics reach



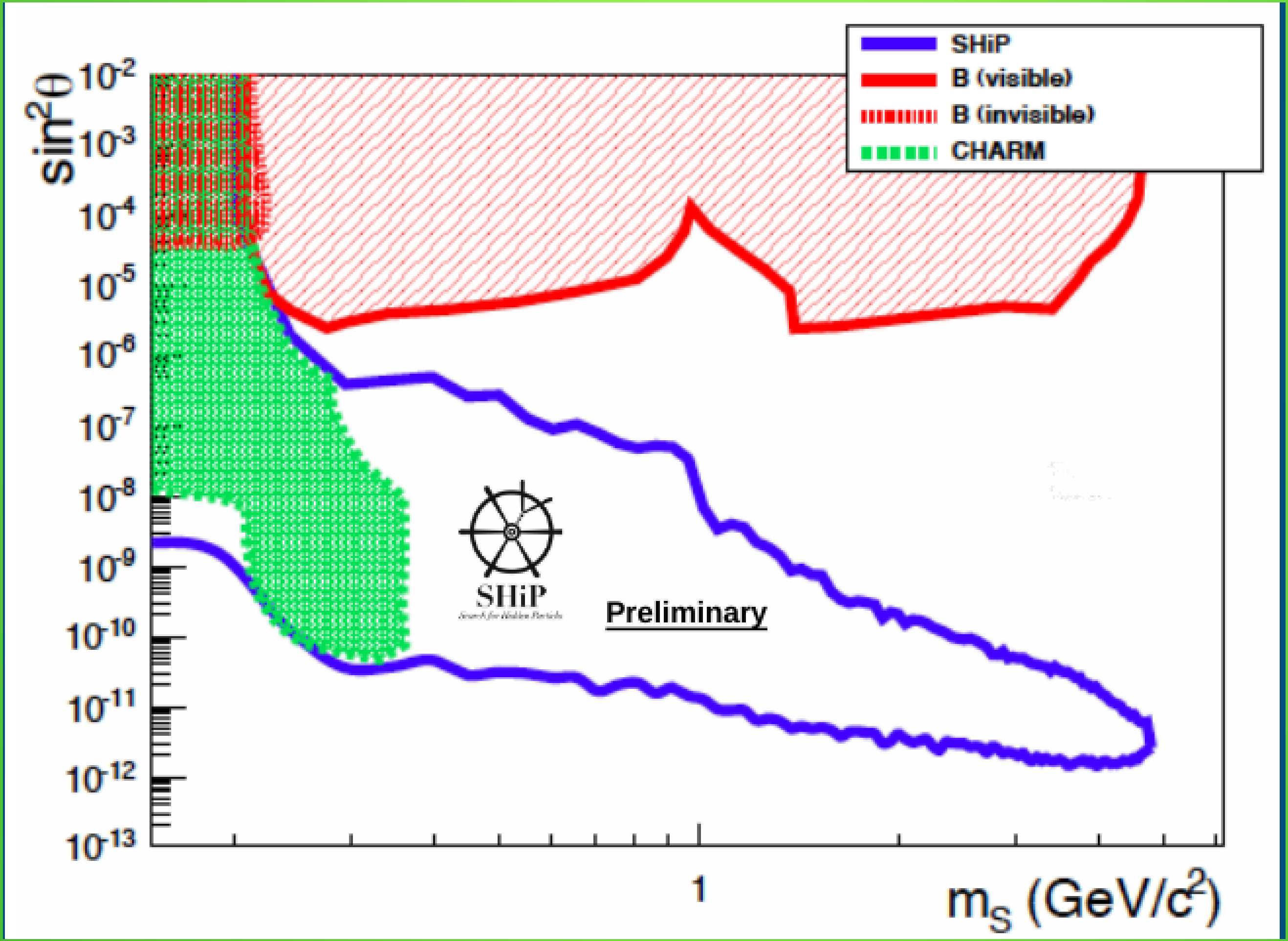
[1504.04956, 1504.04855, 1811.00930, 1901.09966]

- from top left: HNL (heavy meson decays), dark photon (decays + bremsstrahlung + QCD), scalar (*K* and *B* decays), ALPs coupled to fermions, ALPs coupled to photons

Hidden scalars

Production from B and K decays

Decay into fermion or meson pairs



Axion portal

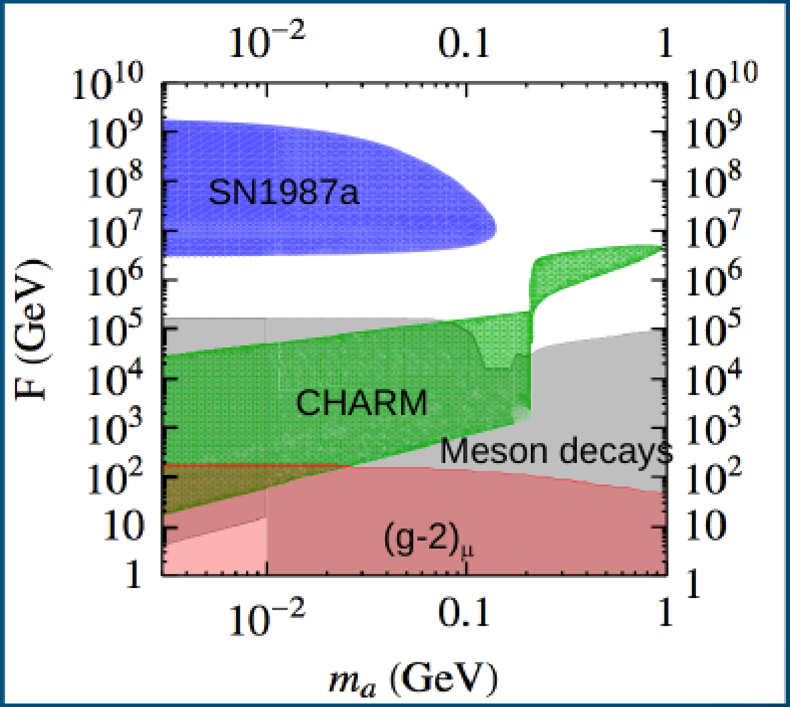
- Axion Like Particles, pseudo-scalars pNGB, axial vectors a
  - Appear in extended Higgs, SUSY breaking, motivated by coupling with dark sector, possibility of inflaton, etc
  - Generically light pseudo-scalars arise in spontaneous breaking of approximate symmetries at a high mass scale F

    ➔ Couplings suppressed by the breaking scale *F* and masses are light $\sim\Lambda/F^2$

  - SM portal through mixing with gauge bosons and fermions

$$\mathcal{L} = \frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu},\ \frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi\ \text{, etc}$$

- Production
  - Resonant production from Drell-Yan photons
  - Production from mixing with pions and heavy meson decays
- Decays
  - Decays to $e^+e^-, \mu^+\mu^-$, hadrons above 1 GeV
  - Decays to photon pair



PRD 82,113008 (2010)

Tau neutrino physics

- Charged current neutrino nucleon scattering

neutrino scattering

anti-neutrino scattering

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

Structure functions

- F_1
- F_2

→ More precise estimation from other experiments

- F_3

→ Opposite sign for **ν** and **anti-ν**

- F_4
- F_5

→ Dependent on the lepton mass. Suppressed in case of ν_μ interactions, becomes relevant for $\boldsymbol{\nu_\tau}$ interactions

- Evaluation of F_3
- First evaluation of F_4 and F_5, not accessible with lighter neutrinos

Some tau neutrino numbers

Current status of tau neutrino observations:

- DONUT observed 9 events (from charm) with a background of 1.5
- OPERA observed 4 events (from oscillations)
- No tau antineutrino has been even observed
- Ship can increase by 200 the current tau neutrino sample, and discover tau antineutrinos

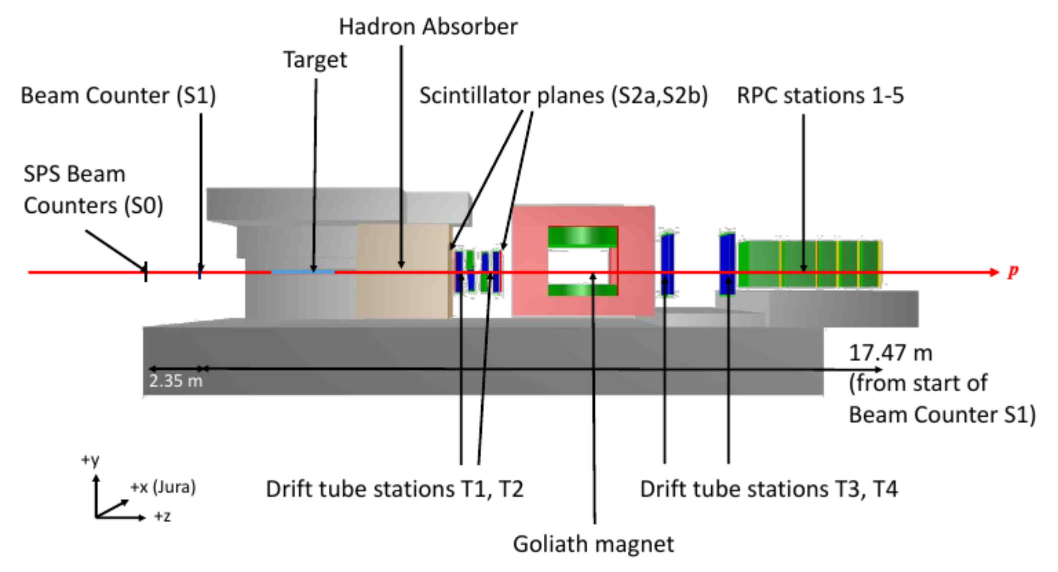
- Measurement of tau neutrino differential cross-section in CC interactions

- Measurement of charm production for muon neutrinos and antineutrino (factor of
- 100 increase wrt CHORUS)
- A good fraction of the old OPERA collaborators are joining SHiP to build the neutrino sub-detector and analyse its data.

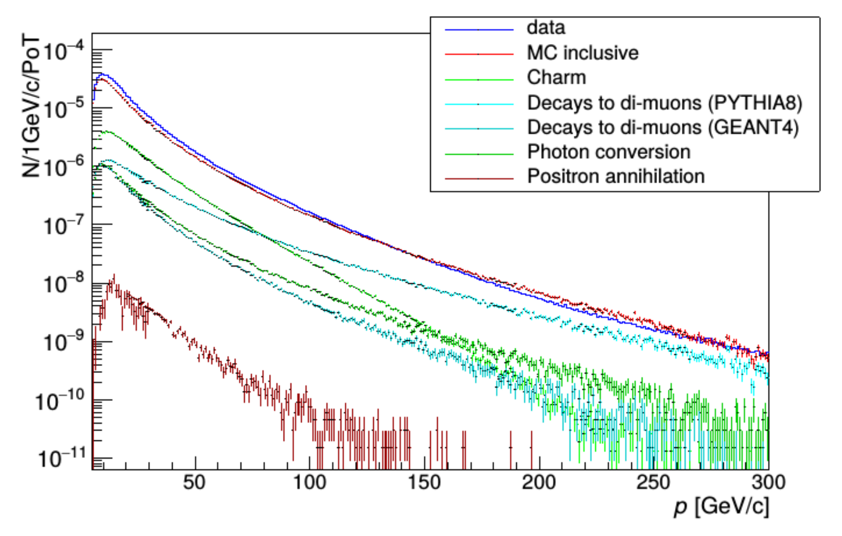
Muon flux measurement in 2018

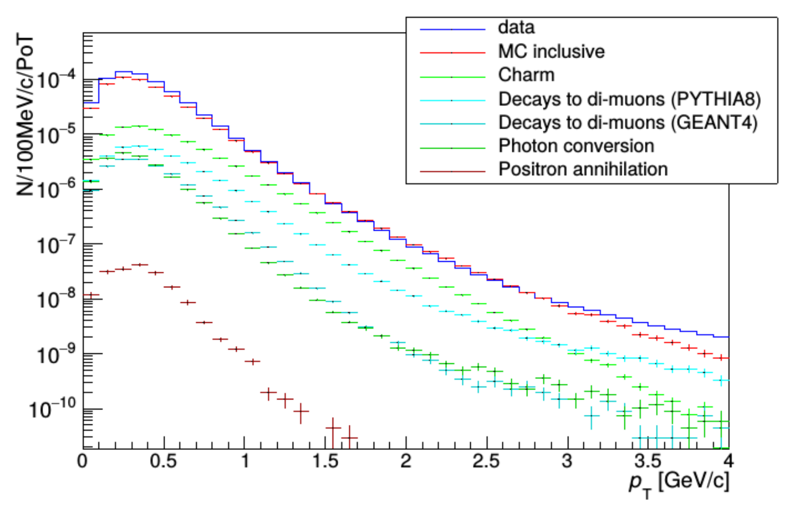
- To validate simulations for the fundamental muon BG, a prototype target and hadron absorber have been exposed to the SPS beam

JHEP 2001.04784



Reasonable agreement with simulation, but tails not well modeled (on 1% of SHiP spill)

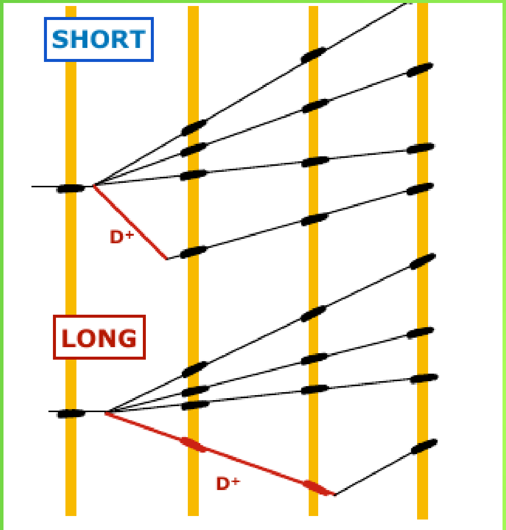




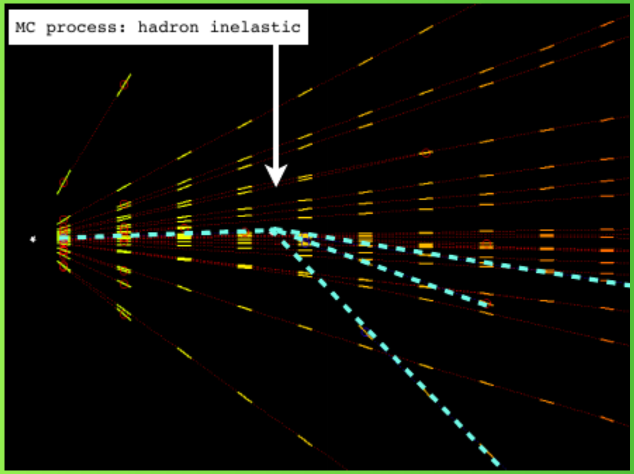
Double Charm production (preliminary)

- Used Emulsion Cloud Chambers to identify charm decay topology
- Pixel + SciFi + drift tubes to measure momentum, RPCs to identify muons

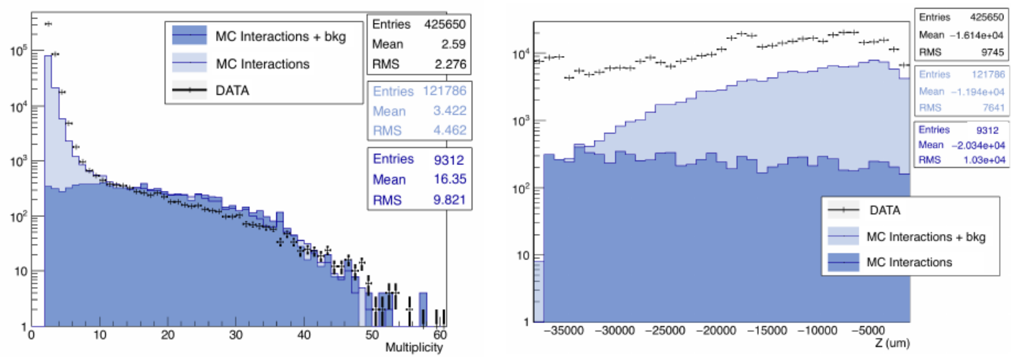
Charm interactions

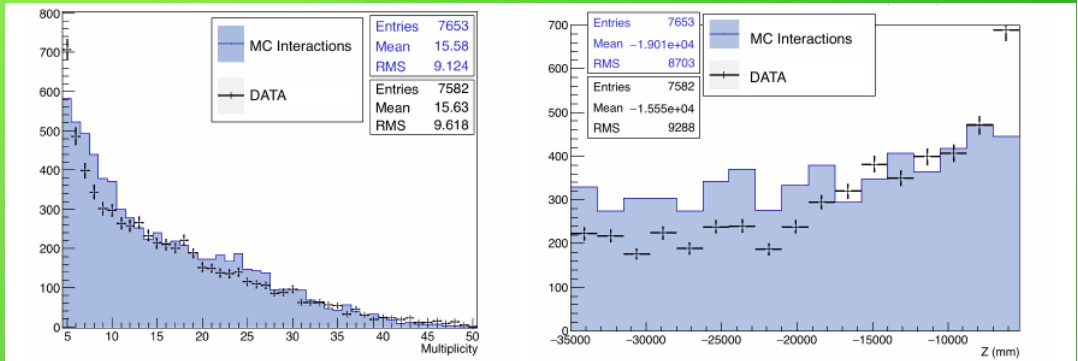


BG



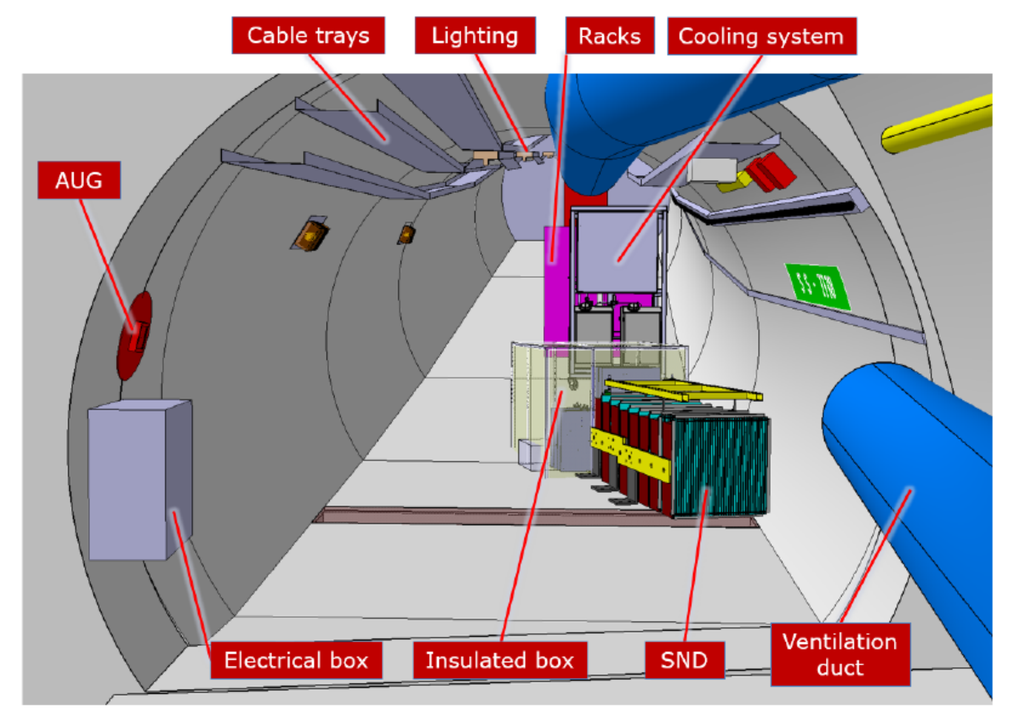
Multivariate techniques used to suppress background in vertex identification; charm analysis in emulsions still ongoing.

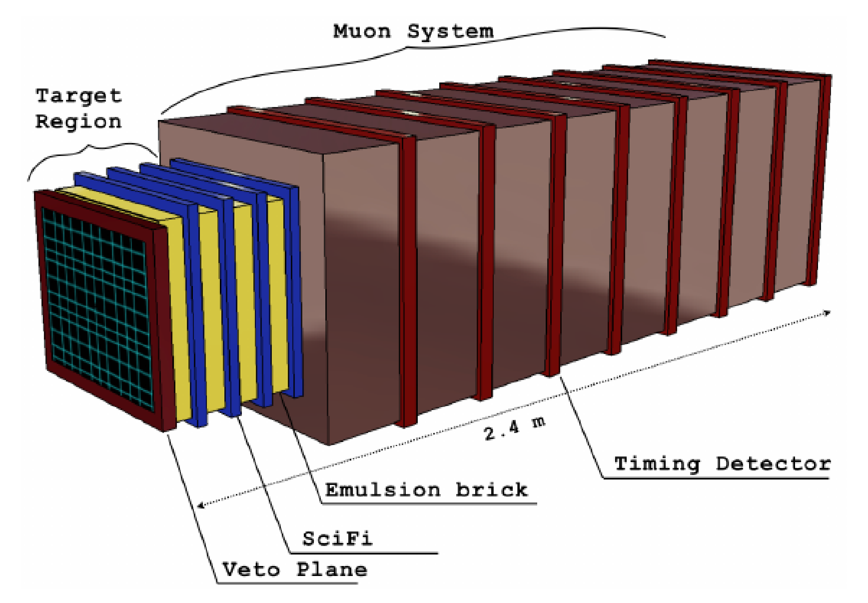




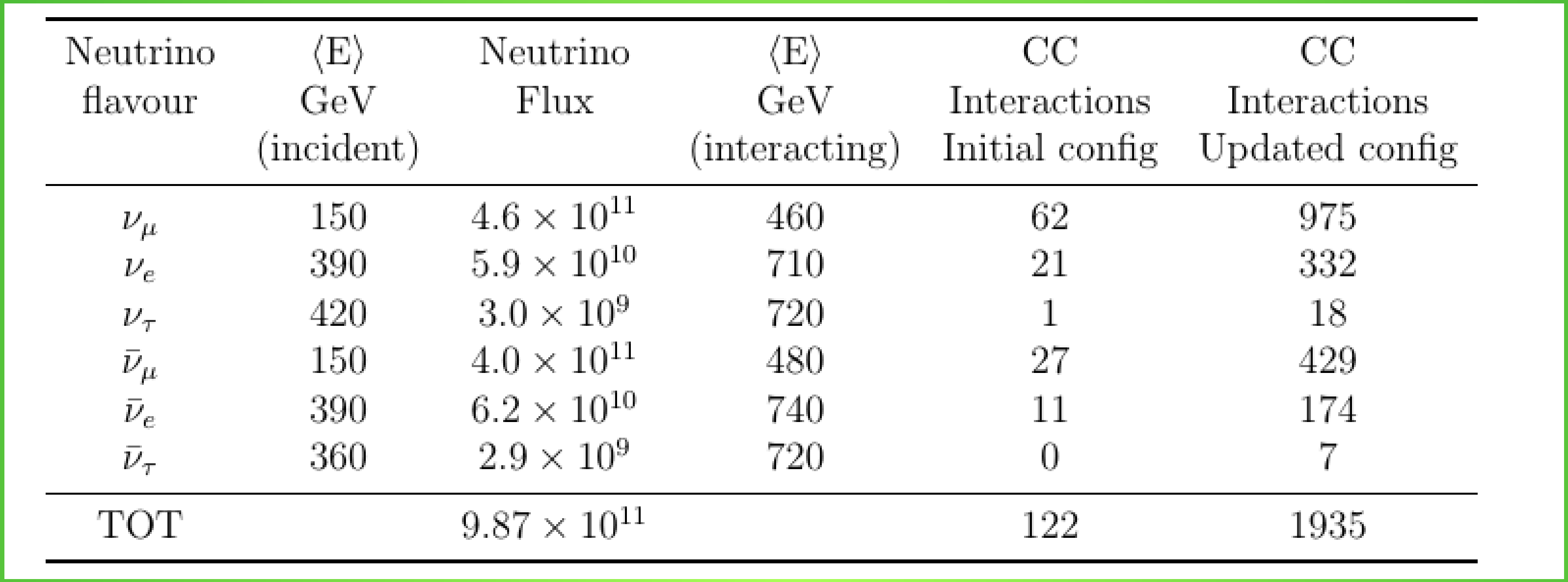
SND@LHC: arXiV 2002.08722

- A Scattering and Neutrino Detector to measure $pp \rightarrow \nu X$ at the LHC, to search for feebly interactive particles in an unexplored domain, using a prototype of the SHiP neutrino system in a LHC service tunnel covering $7.2 < \eta < 8.7$.

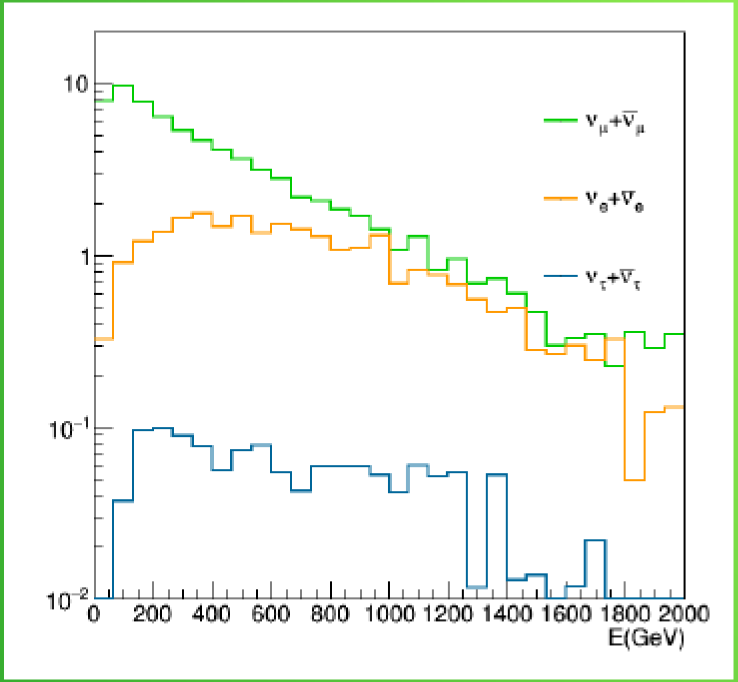




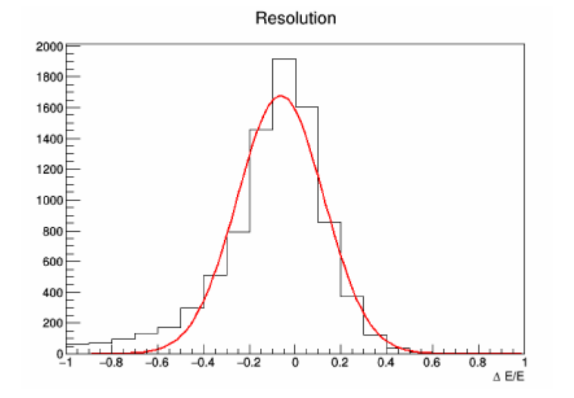
SND@LHC Neutrino physics



Neutrino flavour	⟨E⟩ GeV (incident)	Neutrino Flux	⟨E⟩ GeV (interacting)	CC Interactions Initial config	CC Interactions Updated config
ν_μ	150	4.6×10^{11}	460	62	975
ν_e	390	5.9×10^{10}	710	21	332
ν_τ	420	3.0×10^{9}	720	1	18
$\bar{\nu}_\mu$	150	4.0×10^{11}	480	27	429
$\bar{\nu}_e$	390	6.2×10^{10}	740	11	174
$\bar{\nu}_\tau$	360	2.9×10^{9}	720	0	7
TOT		9.87×10^{11}		122	1935

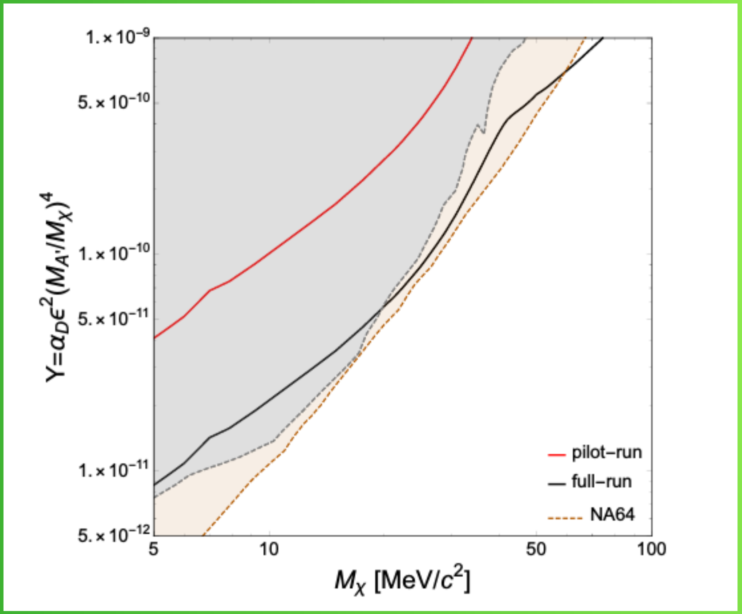


Tau identification efficiency about 50%, with BG (about 3 events) coming from charmed hadrons produced by other neutrino species.
Neutrino energies can be reconstructed with 20% resolution.

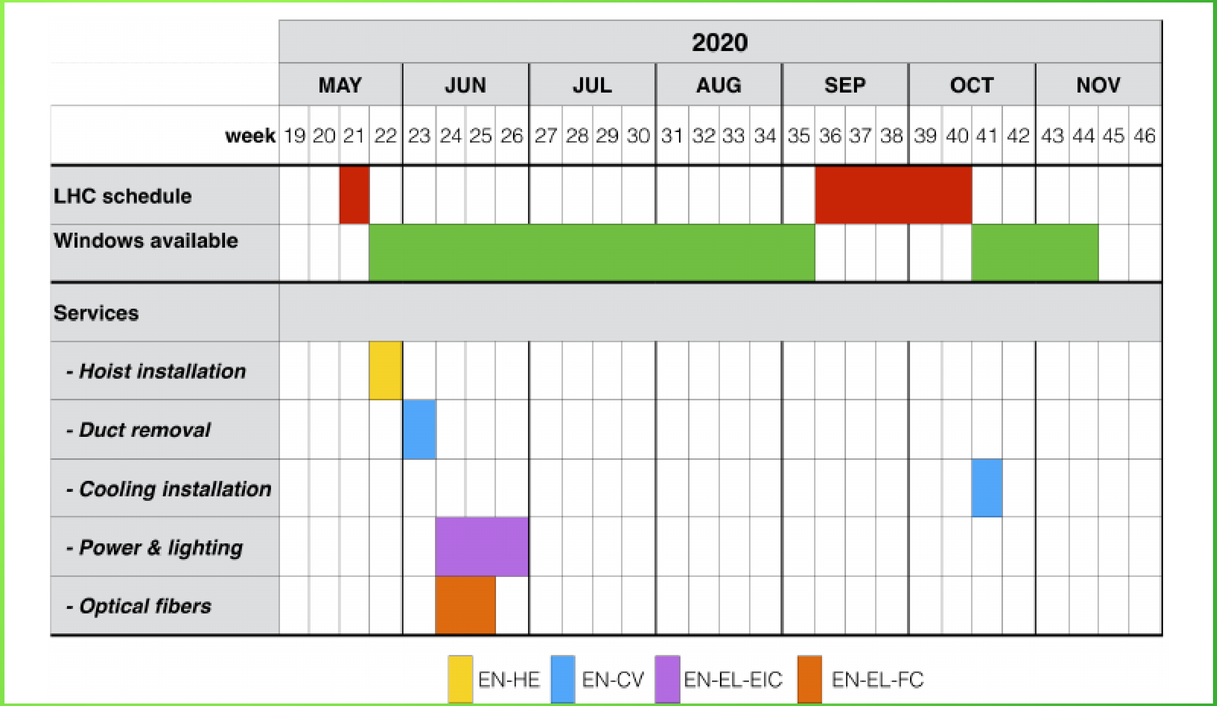


Light dark matter: Dark Photon

- Dark photons of ~ 1 GeV mass could be produced by meson decays or photon bremsstrahlung
- Decay mode into a pair of LDM candidates A’ → χχ’ followed by scattering in the emulsion target χ e- → χ e-



Limits in a 0-BG scenario, with m(A’) = 3 m(χ) and coupling α(D) = 0.1



	2020																											
	MAY				JUN				JUL				AUG				SEP				OCT				NOV			
week	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
LHC schedule			🟥															🟥	🟥	🟥	🟥	🟥						
Windows available				🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩		
Services																												
- Hoist installation				🟨																								
- Duct removal					🟦																							
- Cooling installation																							🟦					
- Power & lighting						🟪	🟪	🟪																				
- Optical fibers						🟧	🟧																					

🟨 EN-HE 🟦 EN-CV 🟪 EN-EL-EIC 🟧 EN-EL-FC

Very aggressive schedule, with installation of services already this summer!

Conclusions

- LHC Run 2 results geve no positive evidence for new physics
- We need an alternative approach to a next big brute-force, general-purpose high-energy collider
- Particle physics could reinvent itself in becoming smaller and smarter, designing experiments that target specific problems (dark matter, neutrinos, etc.)
- A detector like ShiP perfectly fits this philosophy
- Very positive feedback so far from CERN, we have just submitted a CDR and were a major player in the Physics Without Colliders initiative as well as in the European Strategy.
- Waiting for experiment approval, already interesting results from muon flux measurement, charm production, and tau neutrino physics from the proposed SND installation at the LHC