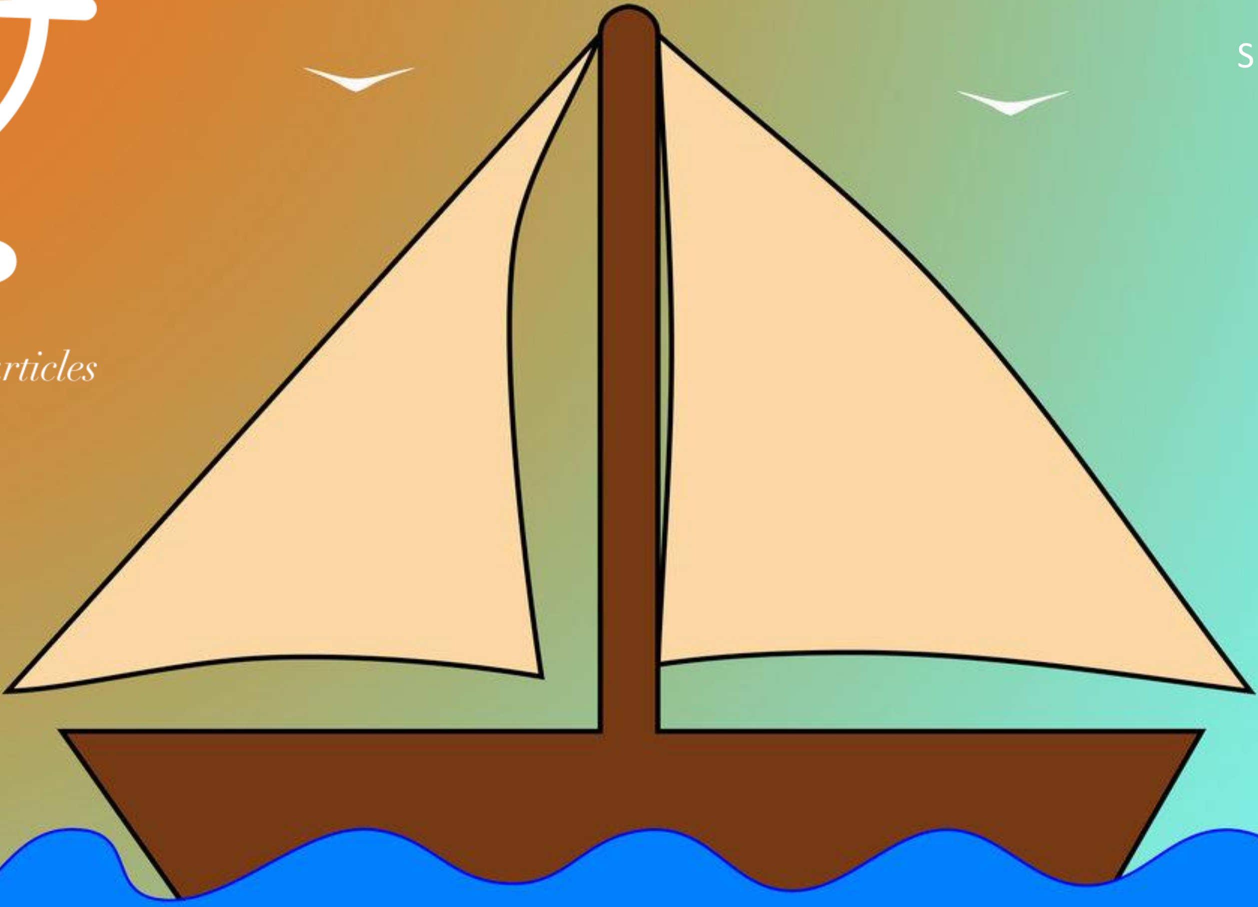
SHiP
Search for Hidden Particles

University of Zurich^UZH

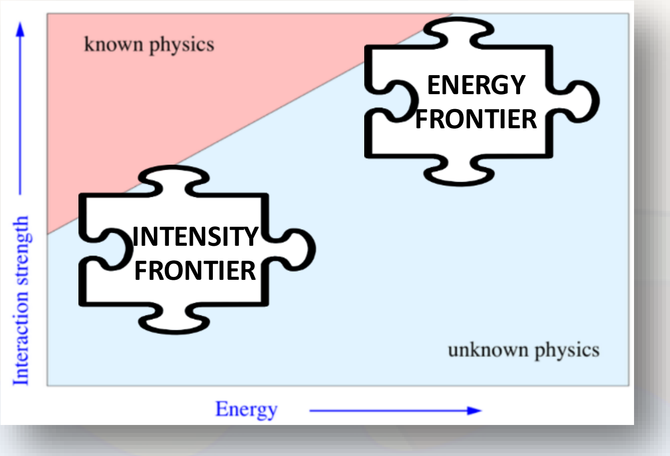
Elena Graverini
on behalf of the
SHiP collaboration



Exploring the Hidden Sector with the SHiP experiment

Physics motivation

- We know that the Standard Model is incomplete…
- …but we do not know yet the scale of New Physics.
- Dark matter might be **light**
- We may have a whole **Hidden Sector** (HS) of weakly interacting particles.



Long lived neutral (hidden) particles predicted in many BSM models. They can be searched for at:

energy frontier:
heavy particles,
high energy events

intensity frontier:
light particles,
very rare events

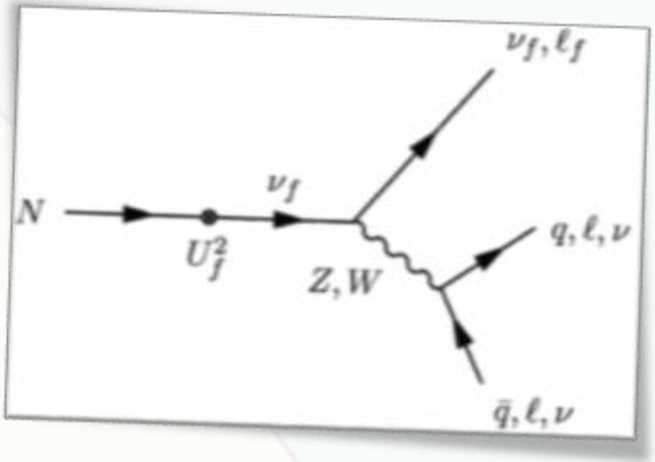
- Several ***portals*** to the HS: scalar portal, neutrino portal, vector portal, SUSY…
- All of these can be probed at the intensity frontier with **SHiP**!

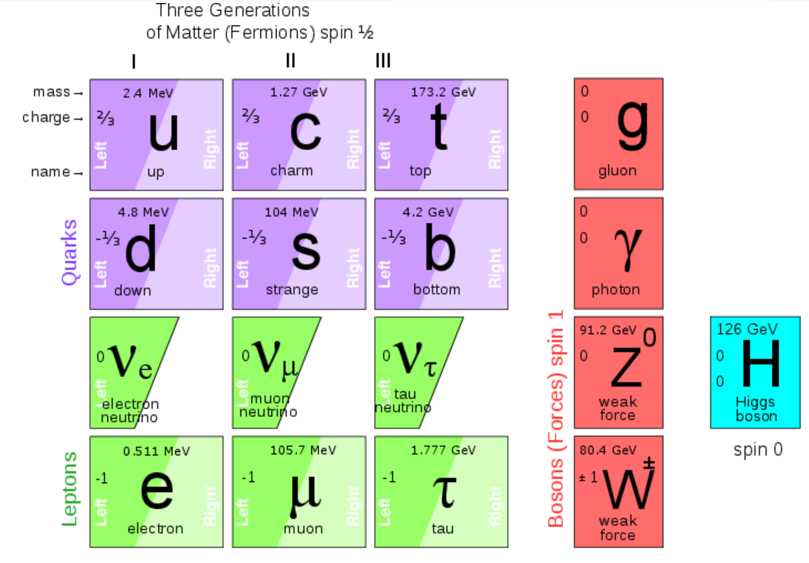
Neutrino portal

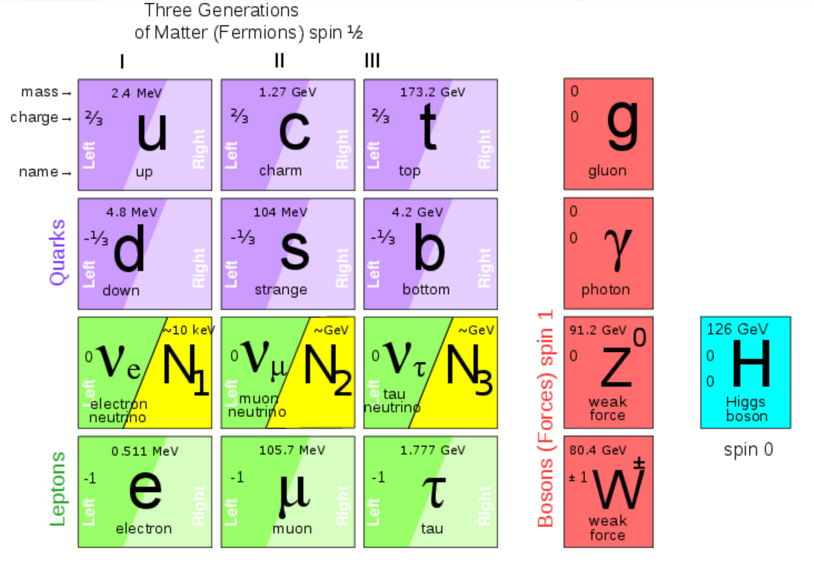
Complete the SM by adding **H**eavy **N**eutral **L**eptons:

- could explain **ν oscillations** and
- the **smallness** of ν masses (*seesaw*)
- could explain **baryon asymmetry**
- could explain **dark matter**

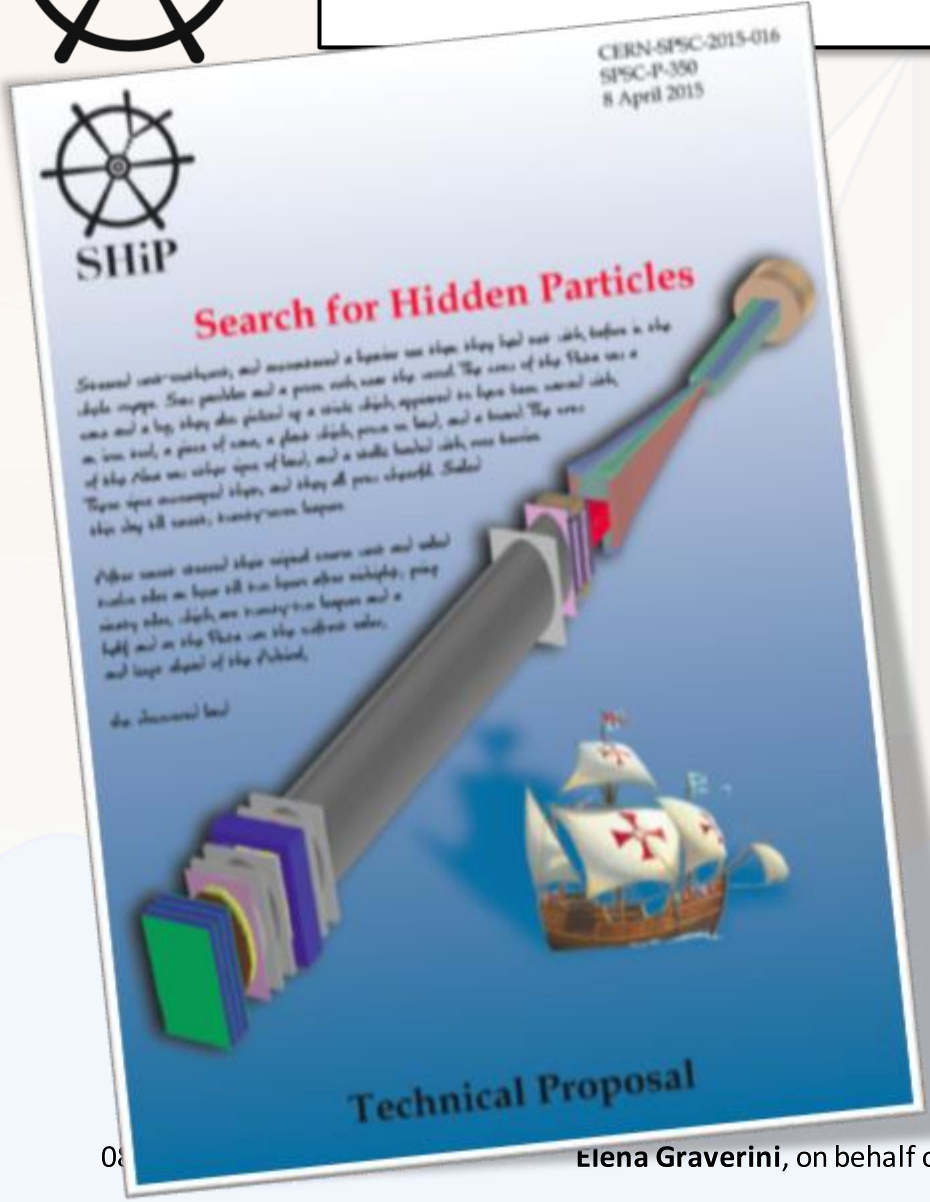
Production and decay through **HNL - ν** mixing







The SHiP experiment



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

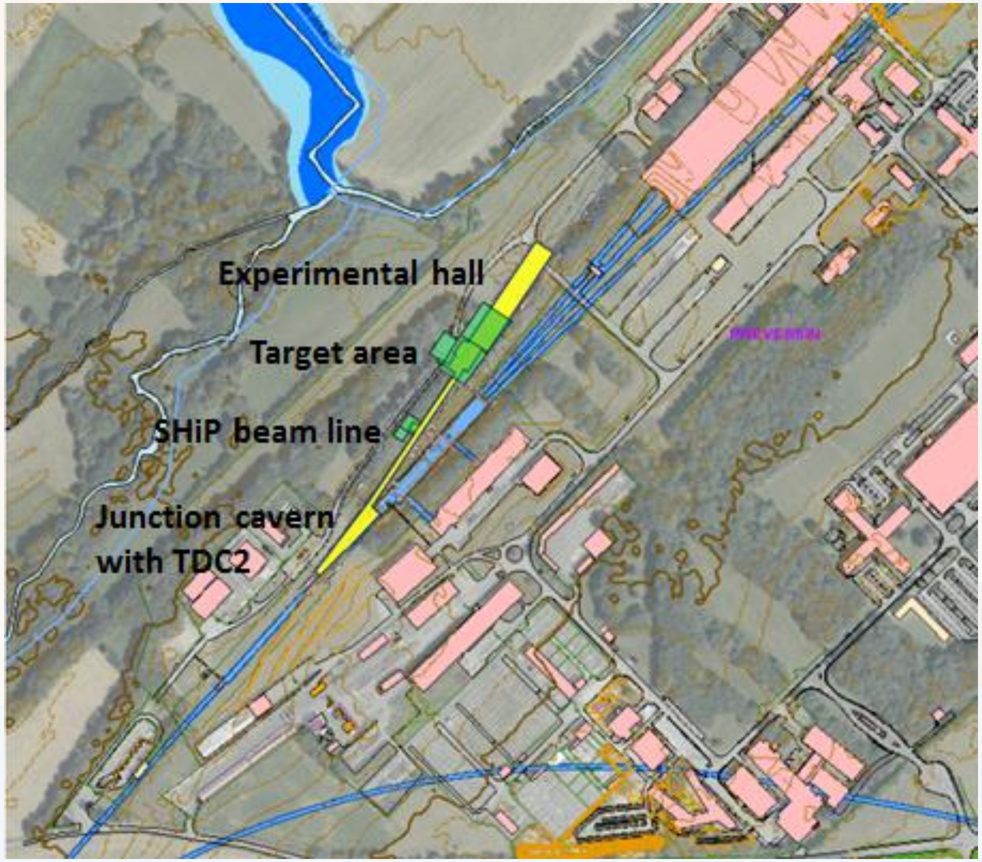
SHiP

Search for Hidden Particles

Technical Proposal

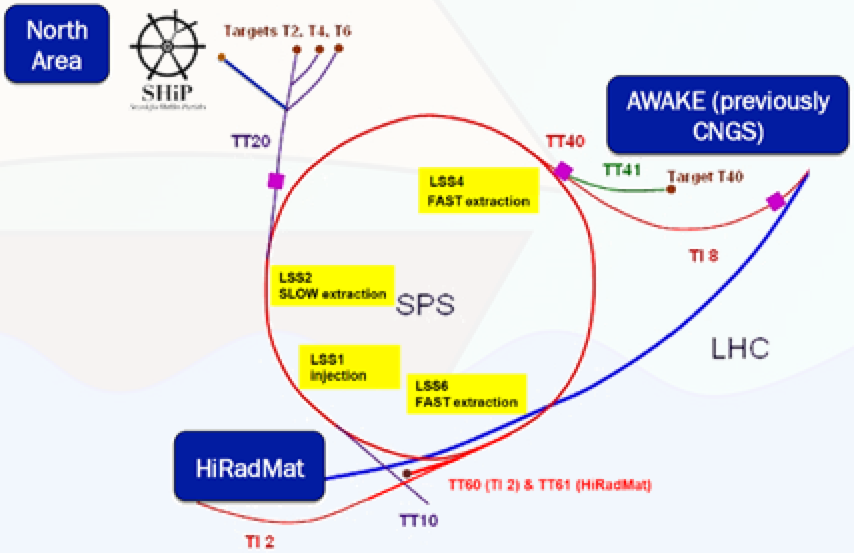
- Proposal for a new facility at the CERN SPS accelerator:
  - general purpose HS detector
  - ν_τ facility
- 235 experimentalists from 45 institutes and 15 countries + CERN
- Technical Proposal submitted in April (arXiv:1504.04956)
- Physics Proposal signed by 80 theorists (arXiv:1504.04855)
- Presently under scrutiny by the SPSC

The SHiP facility at the SPS



Proposed implementation at the CERN North Area, based on minimal modification to the SPS complex.

Share transfer line and slow extraction mode with existing facilities.

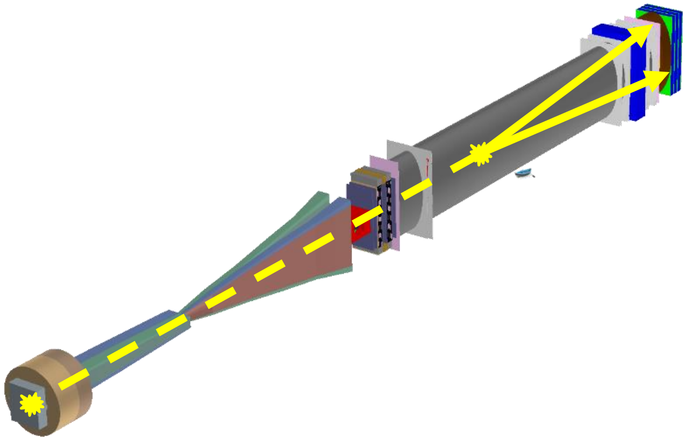


SHiP requirements

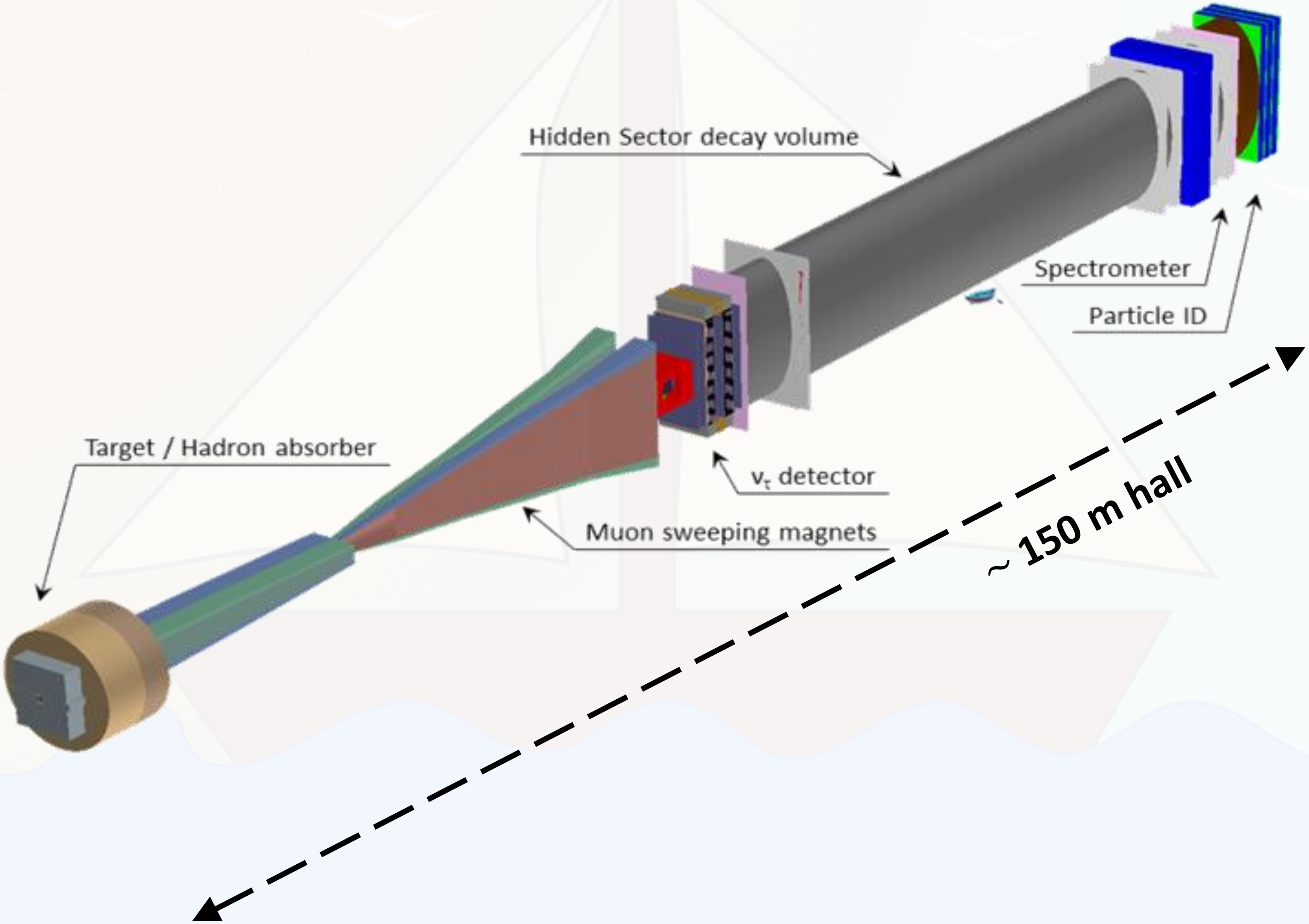
- High intensity beam dump experiment ⇒ K, D, B mesons
- Long-lived, weakly interacting particles require:
    - large decay volume
    - shielded from SM particles
- Spectrometer, Calorimeter, PID

Signal signature:

- charged tracks forming an isolated vertex inside the fiducial volume
- candidate momentum pointing back to the target
- “silent” VETO detectors



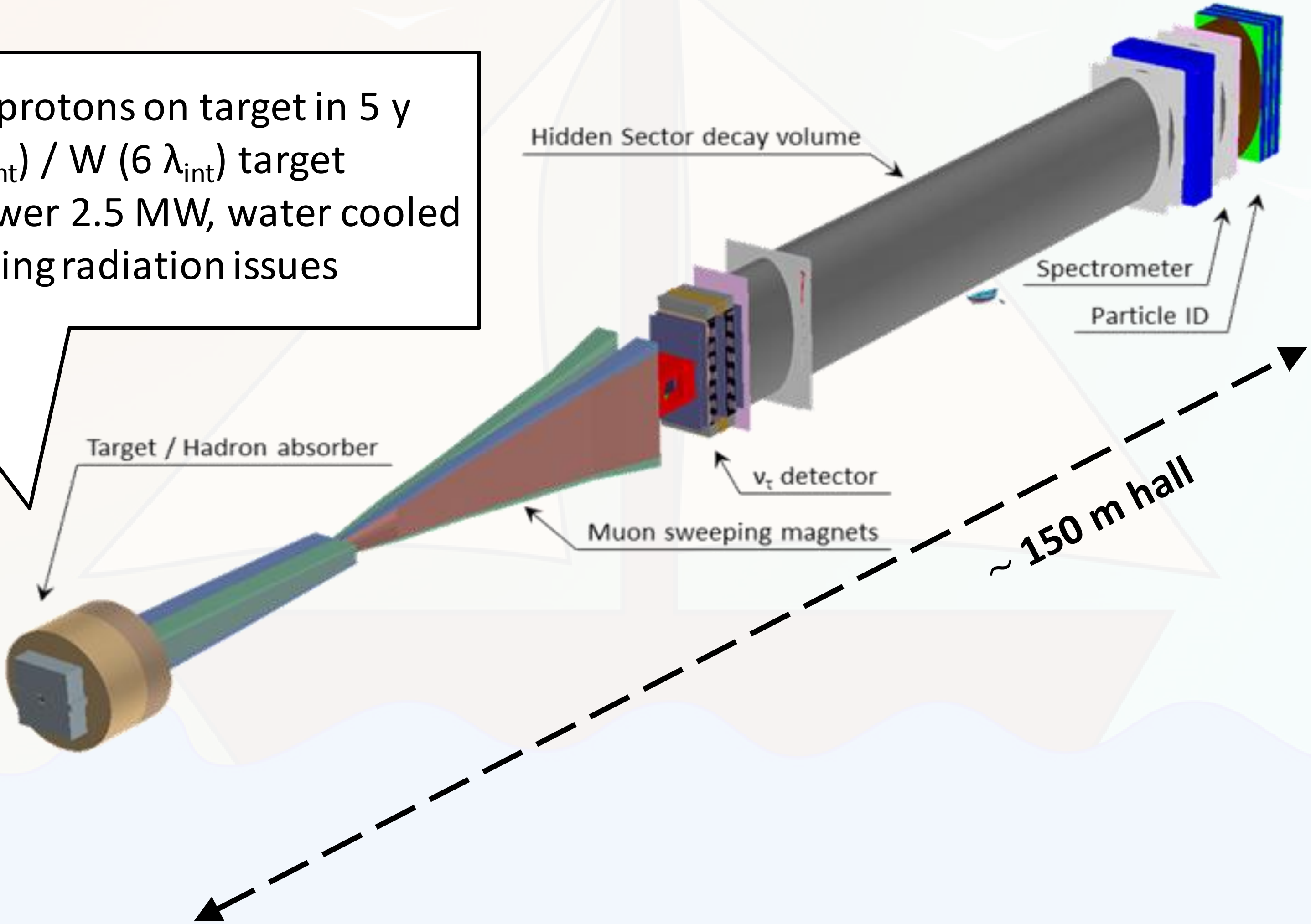
The SHiP experiment



Elena Graverini, on behalf of the **SHiP** collaboration

The SHiP experiment

- 2 x 10^{20} protons on target in 5 y
- Mo (4 λ_{int}) / W (6 λ_{int}) target
- peak power 2.5 MW, water cooled
- challenging radiation issues



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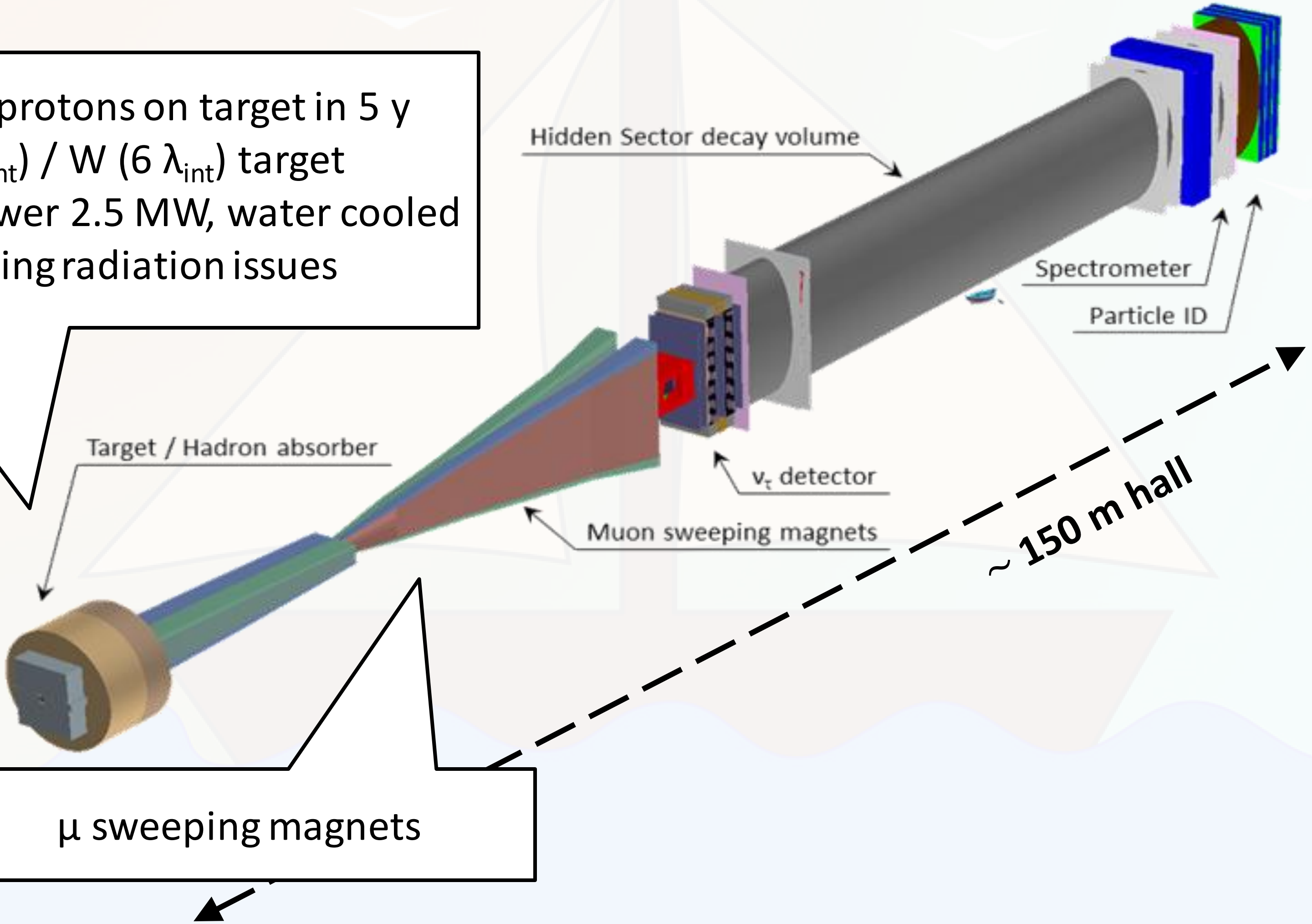

µ sweeping magnets

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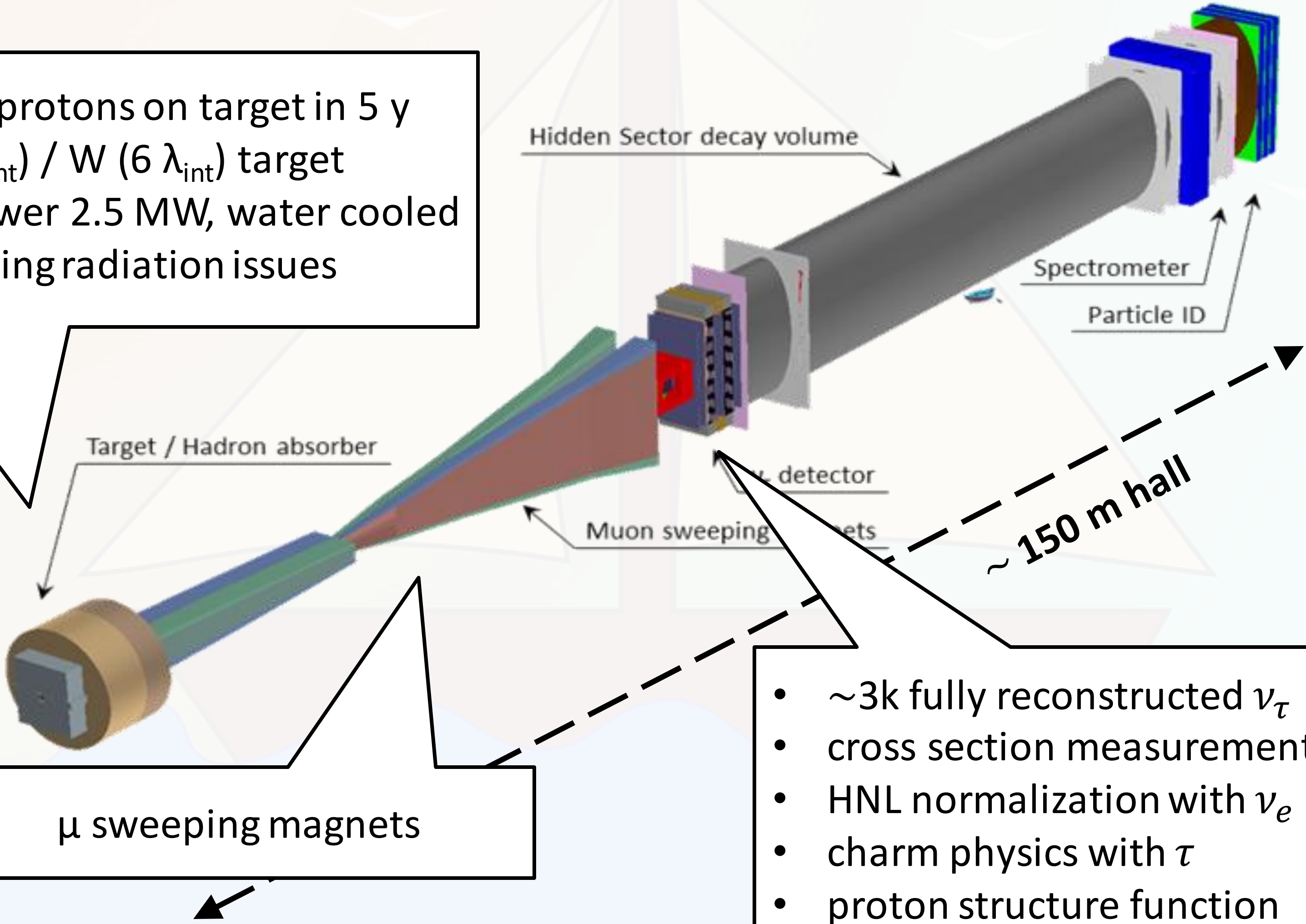
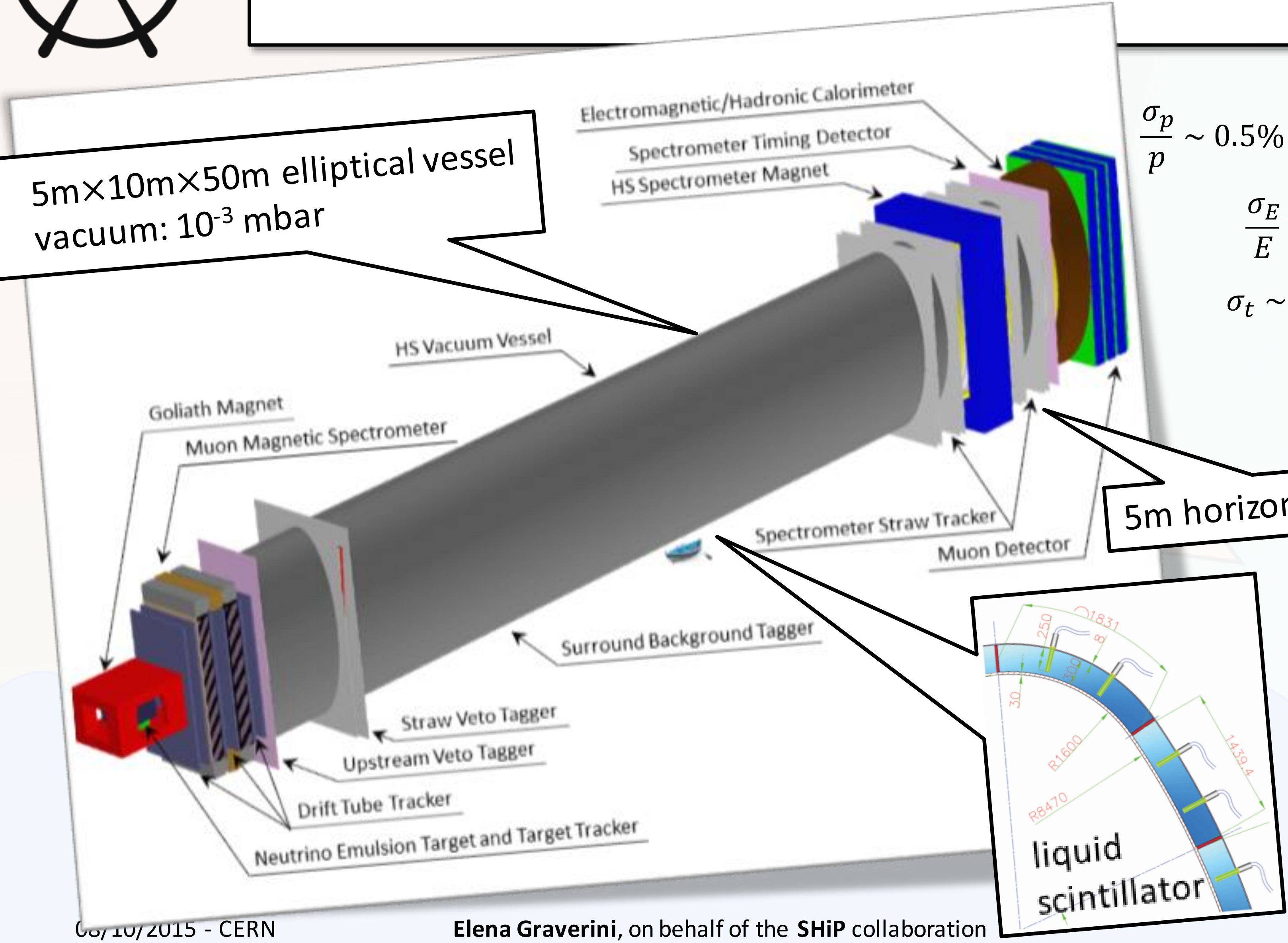


μ sweeping magnets

- ~3k fully reconstructed ν_τ
- cross section measurements
- HNL normalization with ν_e
- charm physics with τ
- proton structure function

The Hidden Sector detector



- 5m×10m×50m elliptical vessel
- vacuum: 10^{-3} mbar

5m horizontal straws

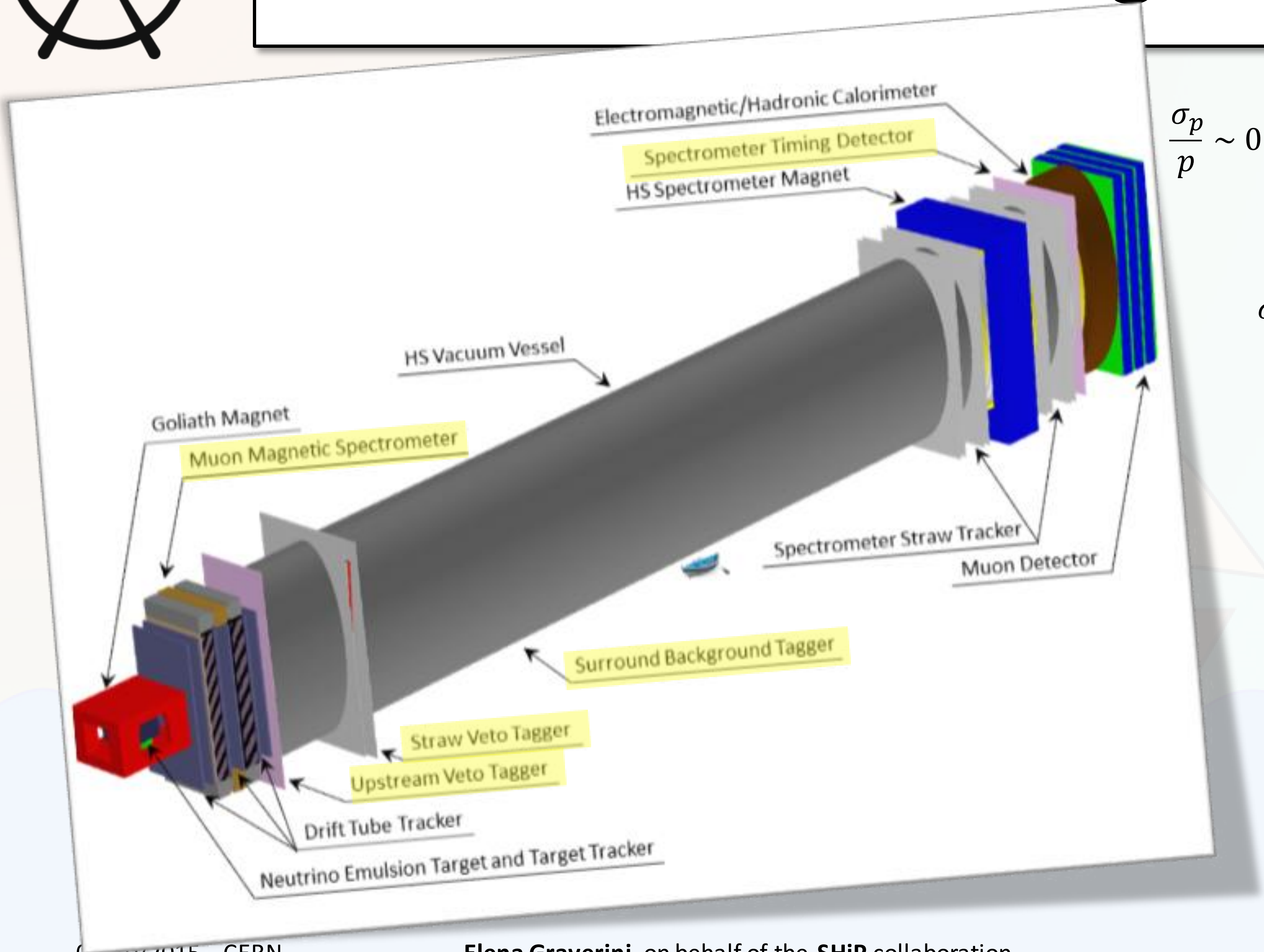
liquid scintillator

$$\frac{\sigma_p}{p} \sim 0.5\% \oplus 0.02\% \times p$$

$$\frac{\sigma_E}{E} \sim \frac{6\%}{\sqrt{E}}$$

$$\sigma_t \sim 100\ \mathrm{ps}$$

How to kill HS background



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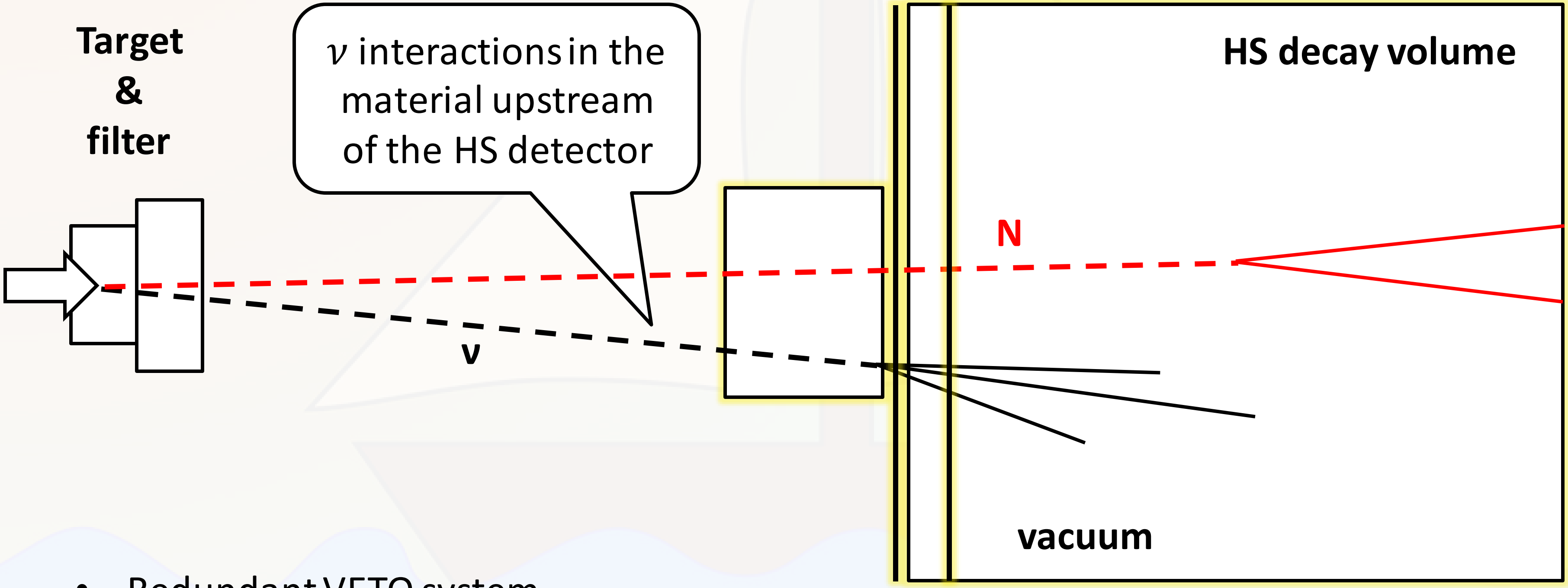
Background rejection

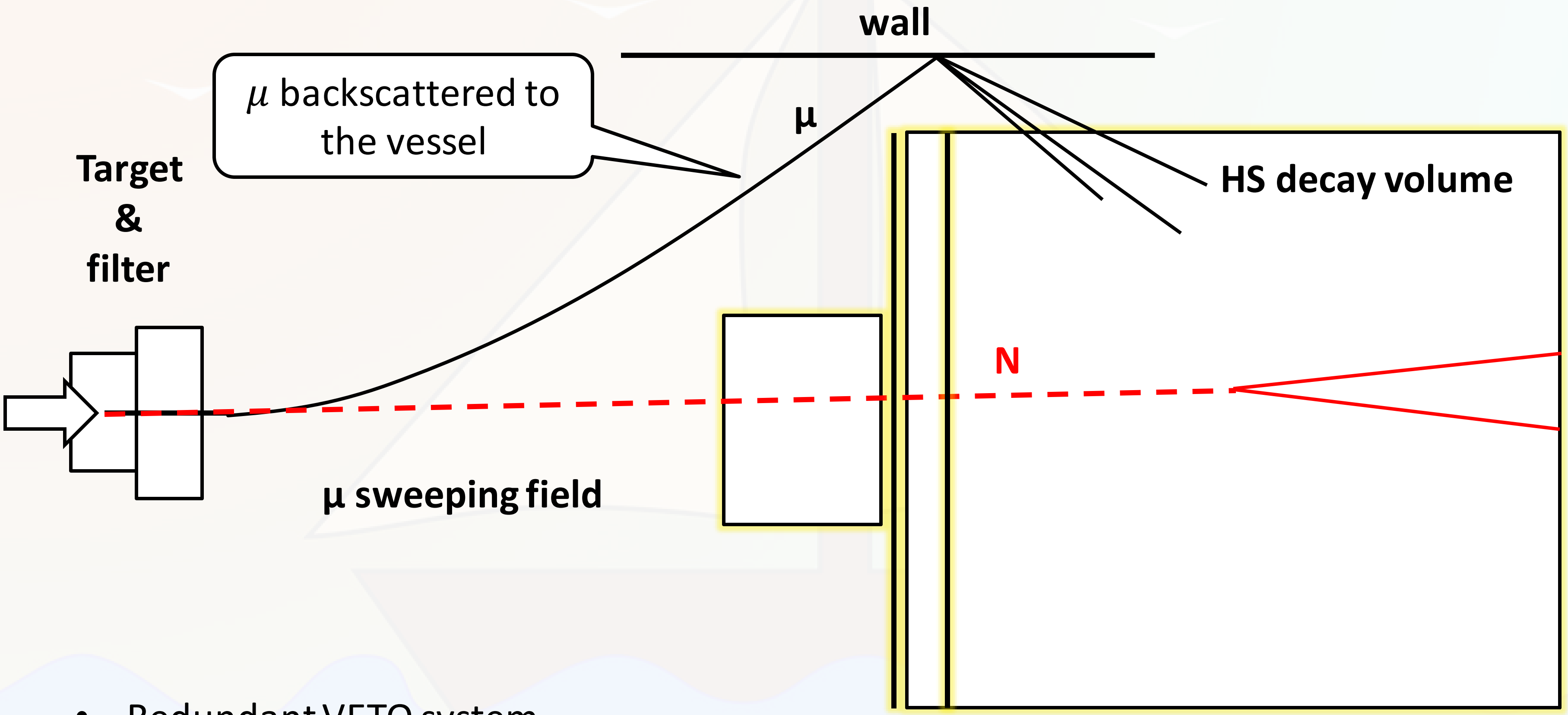


- Redundant VETO system
- Combinatorial rejected by timing detector
- Impact parameter to the target

After selections:

≤ 0.1 bkg / 5 y

Background rejection



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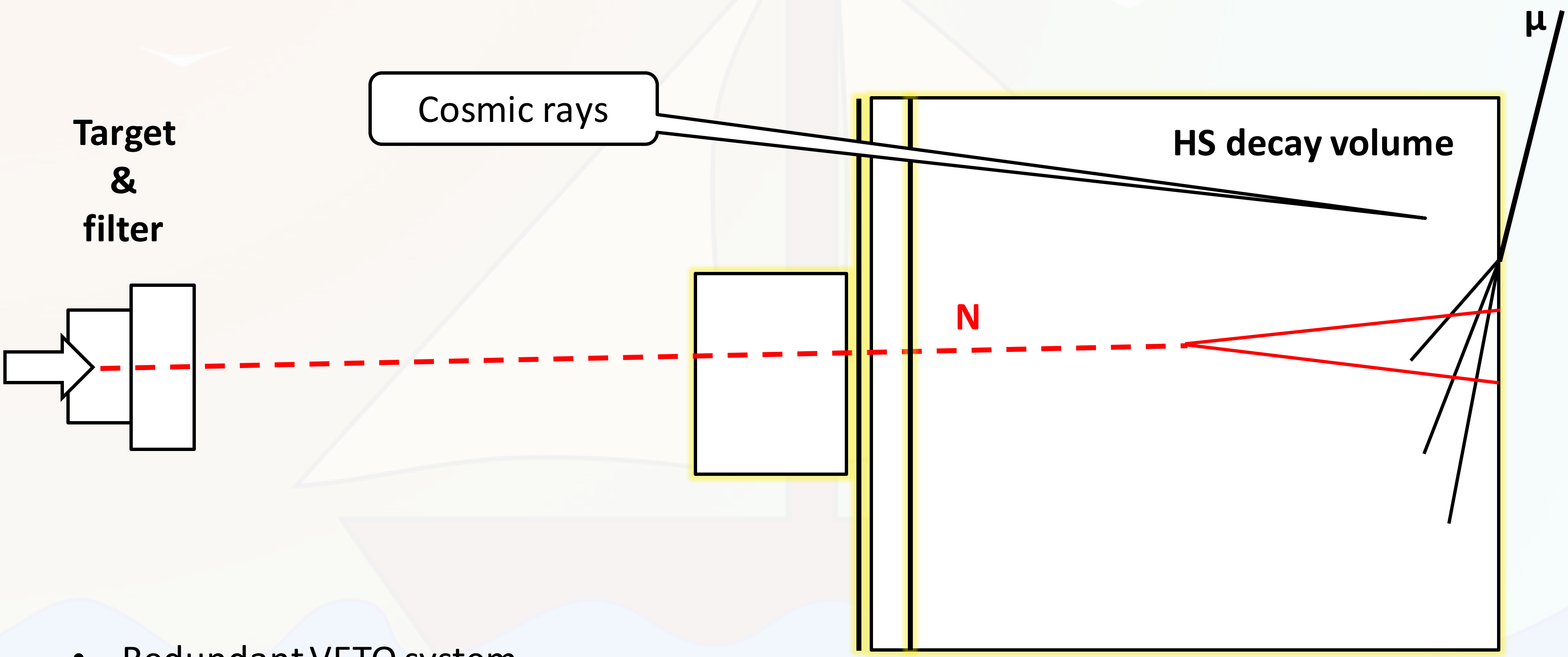


- Redundant VETO system
- Combinatorial rejected by timing detector
- Impact parameter to the target

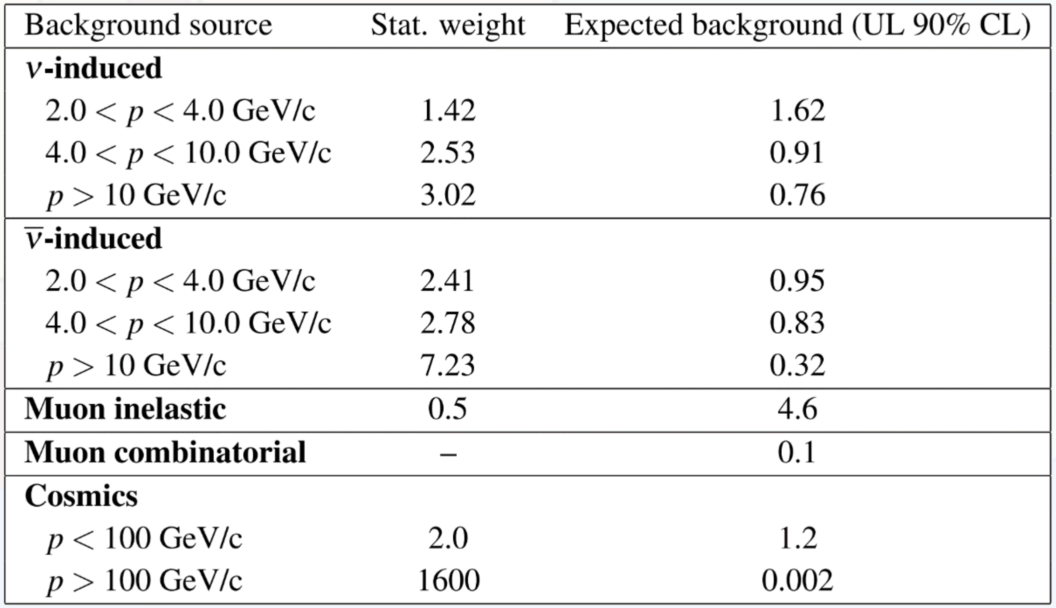
After selections:

≤ 0.1 bkg / 5 y

Background summary

Online selections: upstream veto, straw veto, RPC, liquid scintillator
Offline selections: fiducial volume, track multiplicity, track and vertex quality, impact parameter to the target, coincidence

- background MC samples mimic $\geq$ 5 years of data taking, when possible
- after applying selections we are left with 0 events for each background source
- we can set upper limits based on the generated statistics
- limits expected to decrease with larger MC samples

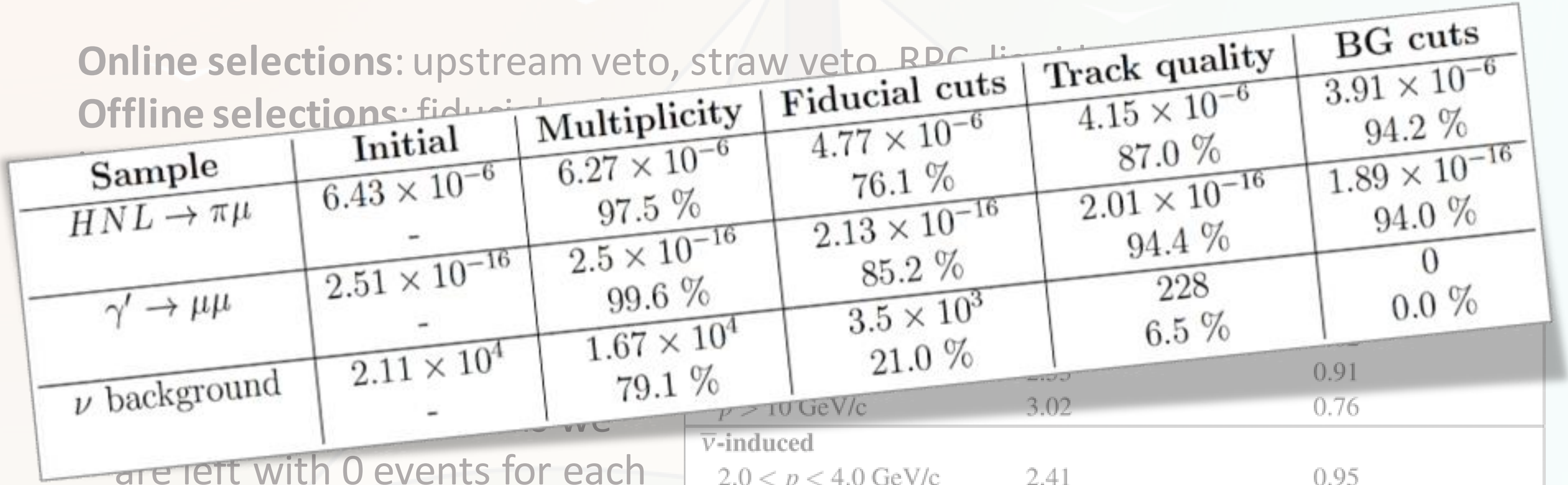


Background source	Stat. weight	Expected background (UL 90% CL)
ν-induced		
$2.0 < p < 4.0$ GeV/c	1.42	1.62
$4.0 < p < 10.0$ GeV/c	2.53	0.91
$p > 10$ GeV/c	3.02	0.76
$\overline{\nu}$-induced		
$2.0 < p < 4.0$ GeV/c	2.41	0.95
$4.0 < p < 10.0$ GeV/c	2.78	0.83
$p > 10$ GeV/c	7.23	0.32
Muon inelastic	0.5	4.6
Muon combinatorial	–	0.1
Cosmics		
$p < 100$ GeV/c	2.0	1.2
$p > 100$ GeV/c	1600	0.002

Signal efficiency

Online selections: upstream veto, straw veto, RPC

Offline selections: fi

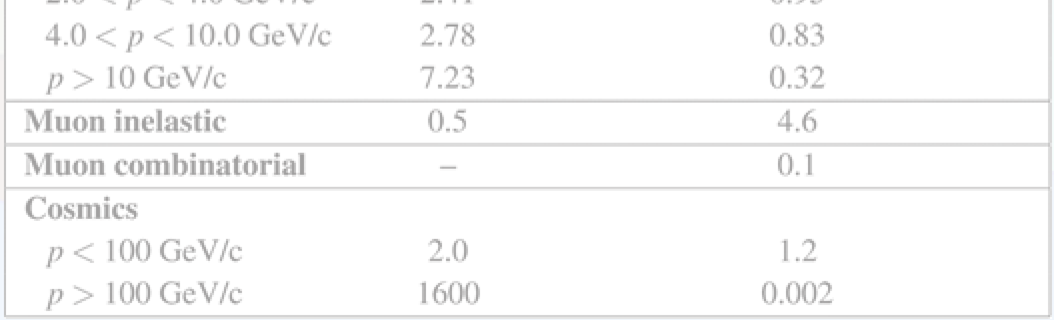


Sample	Initial	Multiplicity	Fiducial cuts	Track quality	BG cuts
$HNL \to \pi\mu$	6.43×10^{-6} -	6.27×10^{-6} 97.5 %	4.77×10^{-6} 76.1 %	4.15×10^{-6} 87.0 %	3.91×10^{-6} 94.2 %
$\gamma' \to \mu\mu$	2.51×10^{-16} -	2.5×10^{-16} 99.6 %	2.13×10^{-16} 85.2 %	2.01×10^{-16} 94.4 %	1.89×10^{-16} 94.0 %
ν background	2.11×10^{4} -	1.67×10^{4} 79.1 %	3.5×10^{3} 21.0 %	228 6.5 %	0 0.0 %

we

are left with 0 events for each background source

- we can set upper limits based on the generated statistics
- limits expected to decrease with larger MC samples



		0.91
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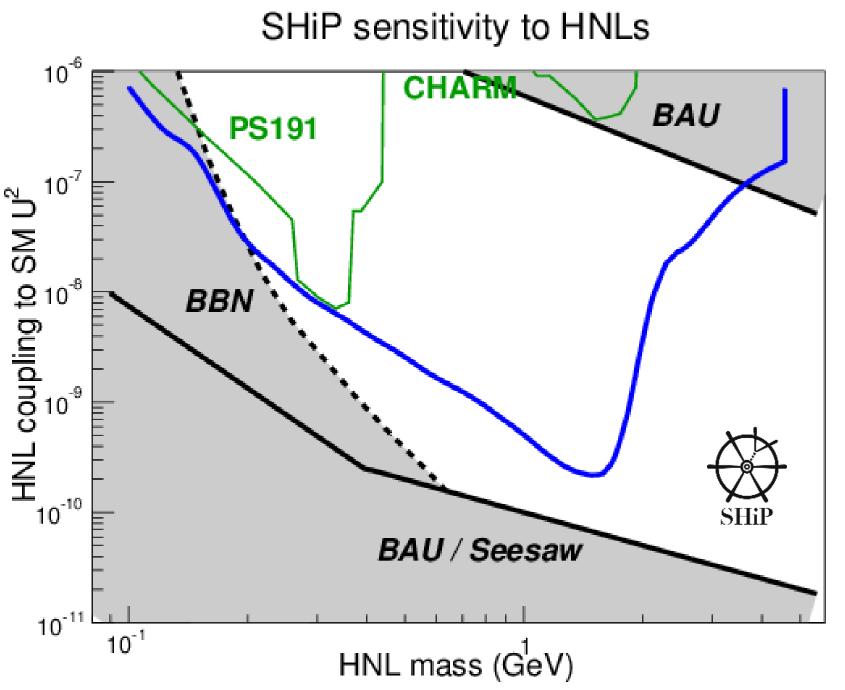
Sensitivity to HNLs



νMSM model: $U_e^2 : U_\mu^2 : U_\tau^2 = 52 : 1 : 1$**, inverted hierarchy**

- Critically improving present limits in U^2
- Access masses up to m_B
- Probe region of special interest:
  - left open by cosmological observations (BBN)
  - explains ν masses (seesaw)
  - explains matter-antimatter asymmetry (BAU)
- Sensitivity in all U_e, U_μ, U_τ channels

- **but the physics case is wider**

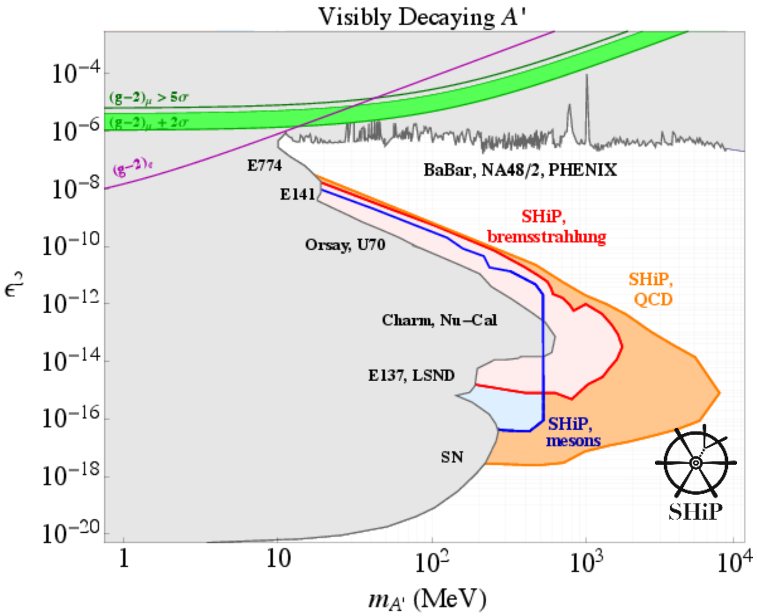
Theory bibliography:

- Gorbunov, Shaposhnikov hep-ph/0705.1729

Sensitivity to other portals

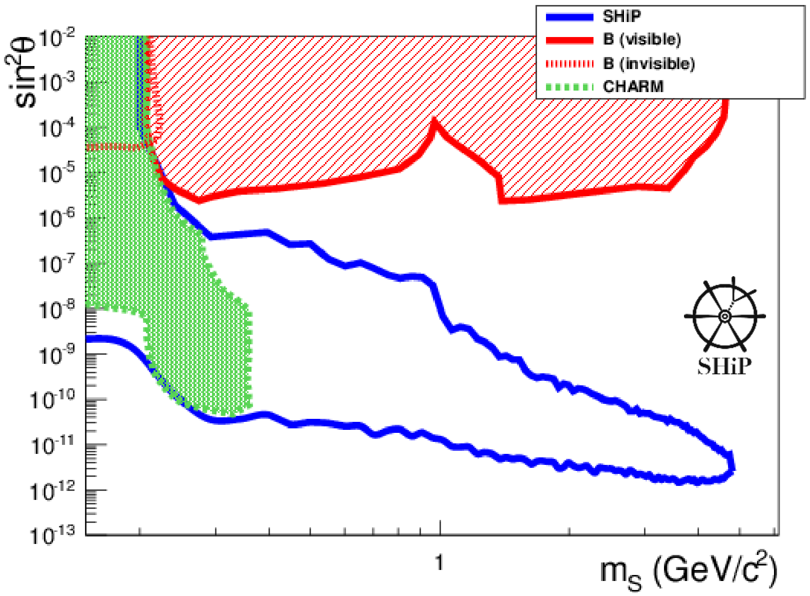
Dark photon

- sources: p bremsstrahlung, light meson decays, QCD
- decays to l^+l^-, $q\bar{q}$



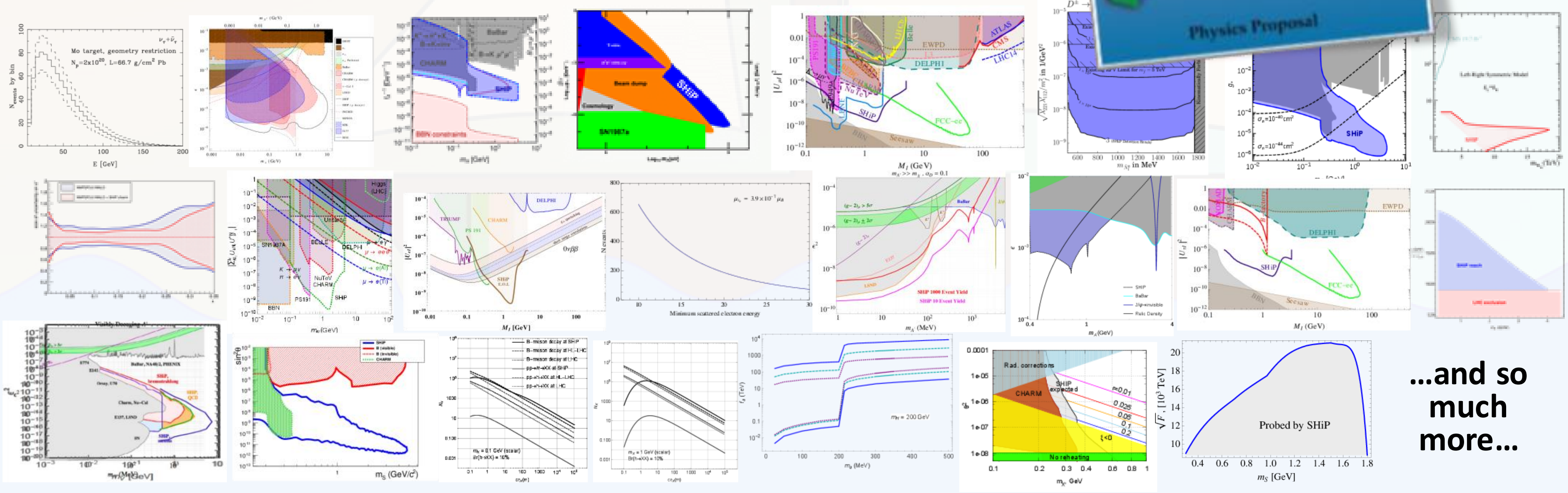
Dark scalar

- sources: B mesons
- decays to l^+l^-, $q\bar{q}$



A wide physics case…

Below, just a small extract from the
SHiP Physics Paper…



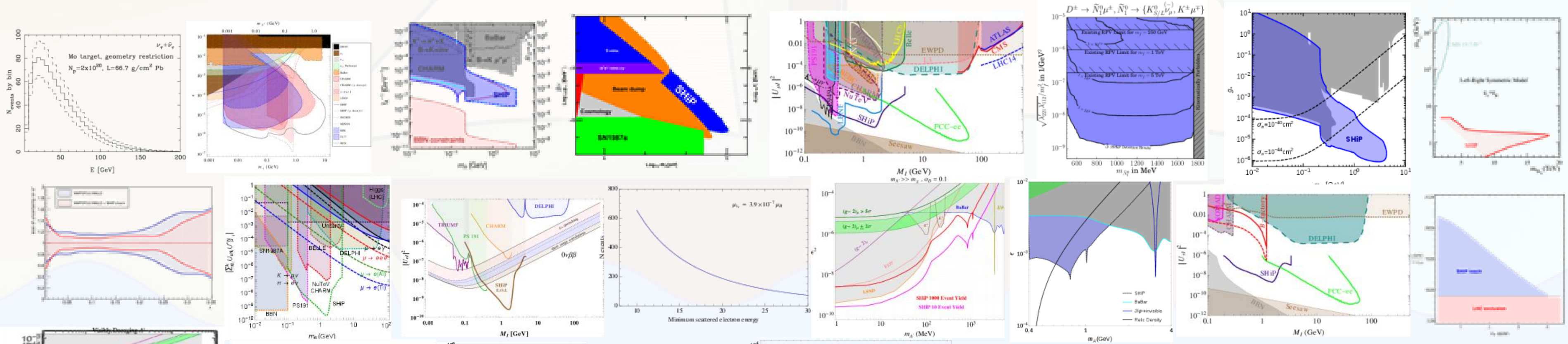
…and so much more…

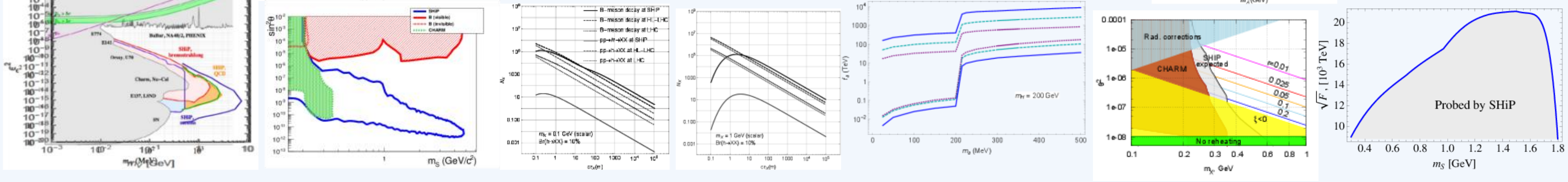
Conclusions

SHiP: a 400 GeV proton beam dumped with maximum intensity and followed by the closest, longest and widest possible decay tunnel!

- unprecedented sensitivity to many BSM models
- under review of the CERN SPSC committee, decision expected soon
- only 10 years to data taking!

Come on board!





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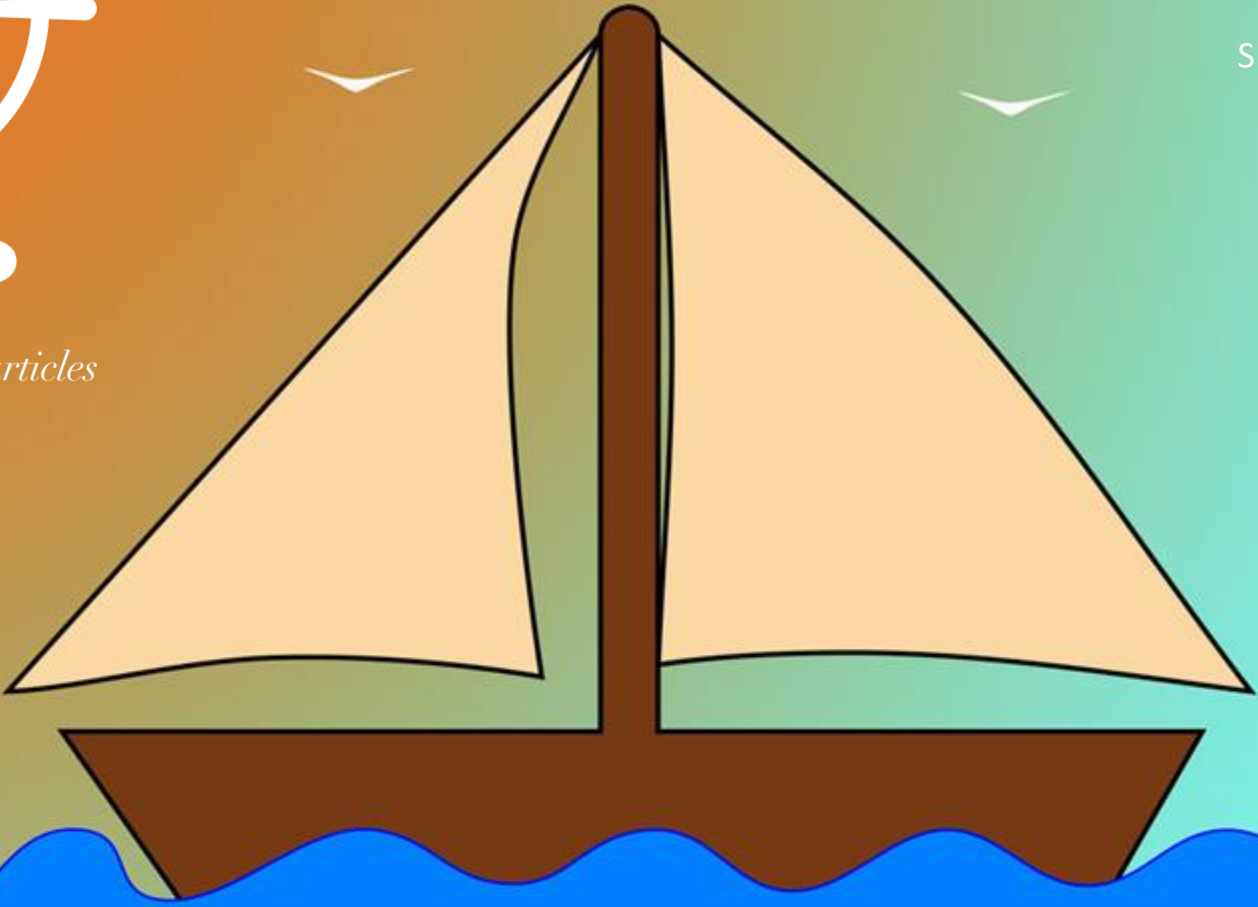
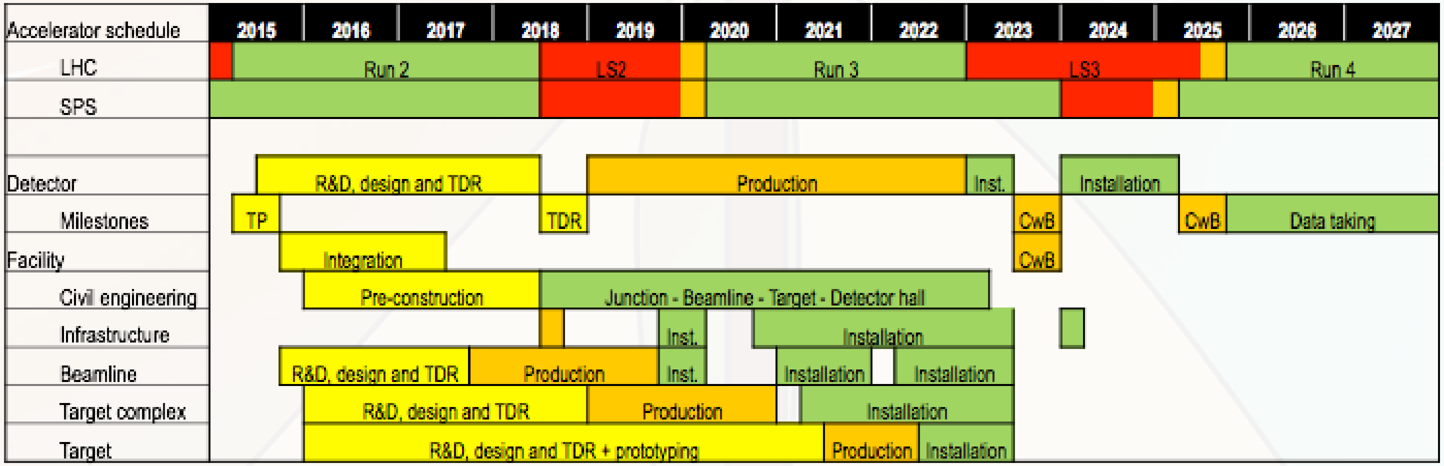


Thanks!
Questions?

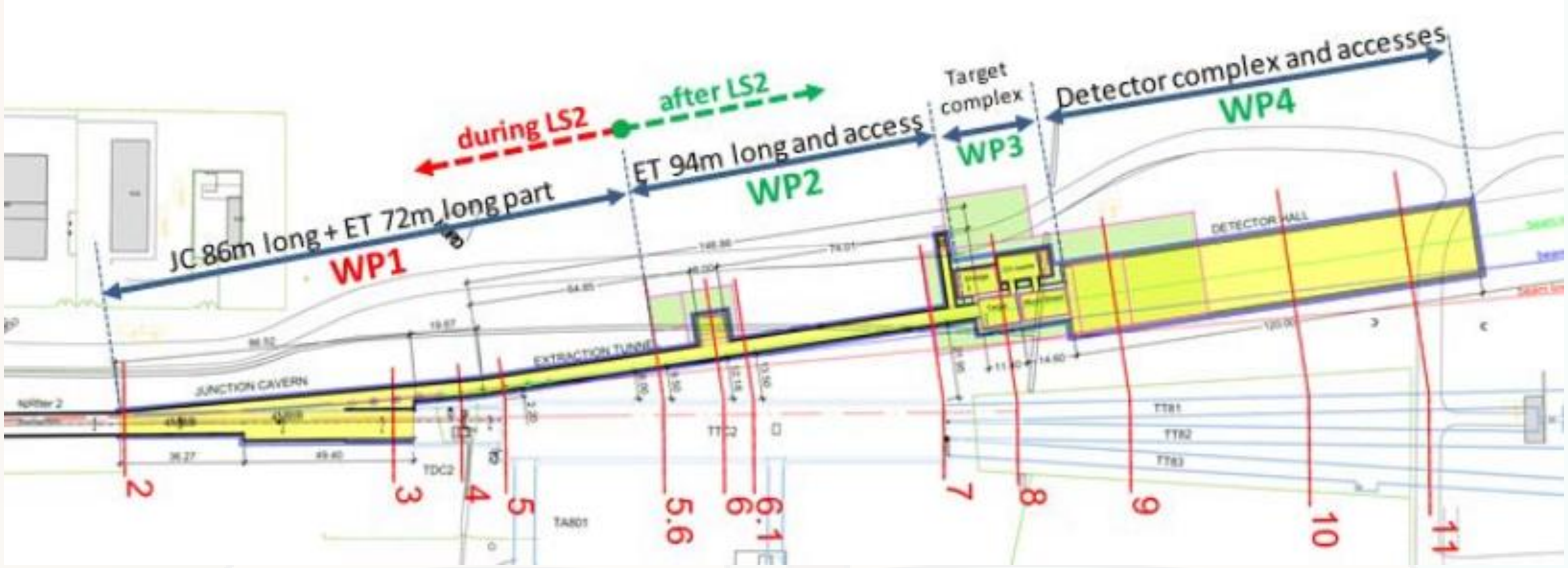
Time Schedule



10 years from TP to data taking

- ✓ *Schedule optimized for almost no interference with operation of North Area*
  - ➔ *Preparation of facility in four clear and separate work packages (junction cavern, beam line, target complex, and detector hall)*
  - ➔ *Maximum use of LS2 for junction cavern and first short section of SHiP beam line*
- ✓ *All TDRs by end of 2018*
- ✓ *Commissioning run at the end of 2023 for beam line, target, muon shield and background*
- ✓ *Four years for detector construction, plus two years for installation*
- ✓ *Updated schedule with new accelerator schedule (Run 2 up to end 2018, 2 years LS2) relaxes current schedule*
  - ➔ ***Data taking 2026***

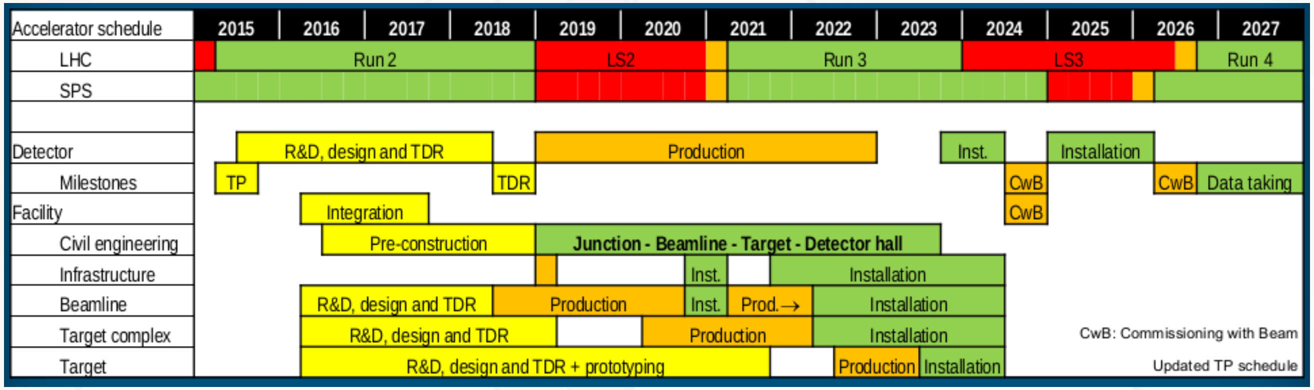
NA work packages



- Preparation of facility in four well-defined quasi-independent work packages
  - WP1: Junction cavern + 70m beam line for clearance during operation (21 months)
  - WP2 : Rest of beam line (12 months)
  - WP3 : Target complex (12 months)
  - WP4 : Experiment facility (18 months)
  - ➔ Only WP1 has to be done during a stop of the North Area only
  - ➔ WP1 associated with cool down, removal and re-installation of services and beam line (24-27 months)
  - ➔ Construction of facility has no interference with operation of SPS and LHC at any time

Updated time schedule

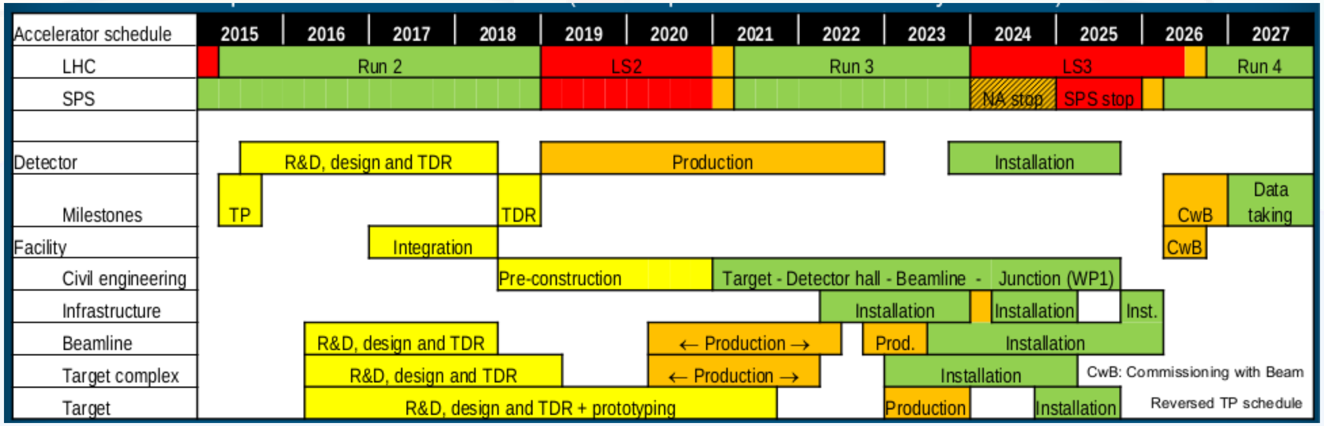
With new LHC schedule (run 2 up to 2018):



CwB: Commissioning with Beam

Updated TP schedule

With WP1 during LS3 (also reduces costs during the TDR phase):



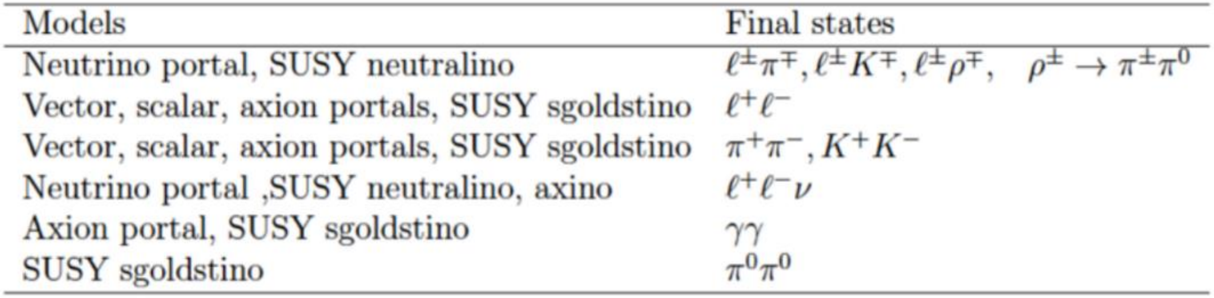
CwB: Commissioning with Beam

Reversed TP schedule

The Hidden Sector

$$L_{world} = L_{SM} + L_{mediation} + L_{HS}$$

- **Neutrino portal**: new Heavy Neutral Leptons coupling with Yukawa coupling, $L_{NP} = F_{\alpha I}\left(\bar{L}_{\alpha}\widetilde{\Phi}\right)N_I$
- **Vector portal**: massive dark photon coupling through loops of particles charged both under *U(1)* and *U'(1)*: $L_{VP} = \epsilon F'_{\mu\nu}F^{\mu\nu}$
- **Scalar portal**: light scalar mixing with the Higgs $L_{SP} = \left(\lambda_i S_i^2 + g_i S_i\right)\bar{\Phi}\Phi$
- **Axion portal**: axion-like particles, $L_{AP} = \frac{A}{4f_A}\epsilon^{\mu\nu\lambda\rho}F_{\mu\nu}F_{\lambda\rho}$
- **SUSY**: neutralino, sgoldstino, gaugino…



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	$\pi^{0}\pi^{0}$

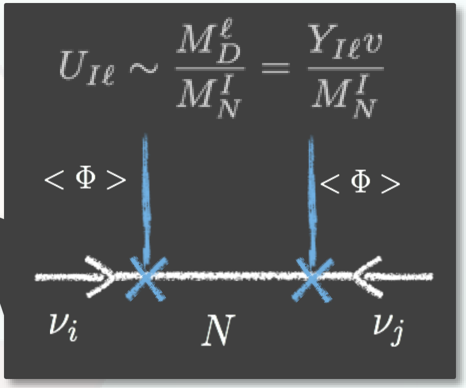
Sterile Neutrinos

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

$$\mathcal{L}_N = \underbrace{i\overline{N}_i\partial_\mu\gamma^\mu N_i}_{\text{Kinetic term}} - \underbrace{\frac{1}{2}M_{ij}\overline{N^c}_i N_j}_{\text{Majorana mass term}} - \underbrace{Y^\nu_{ij}\overline{L_{Li}}\tilde{\phi}N_j}_{\text{Yukawa coupling}}$$



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

Seesaw mechanism:

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

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

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

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

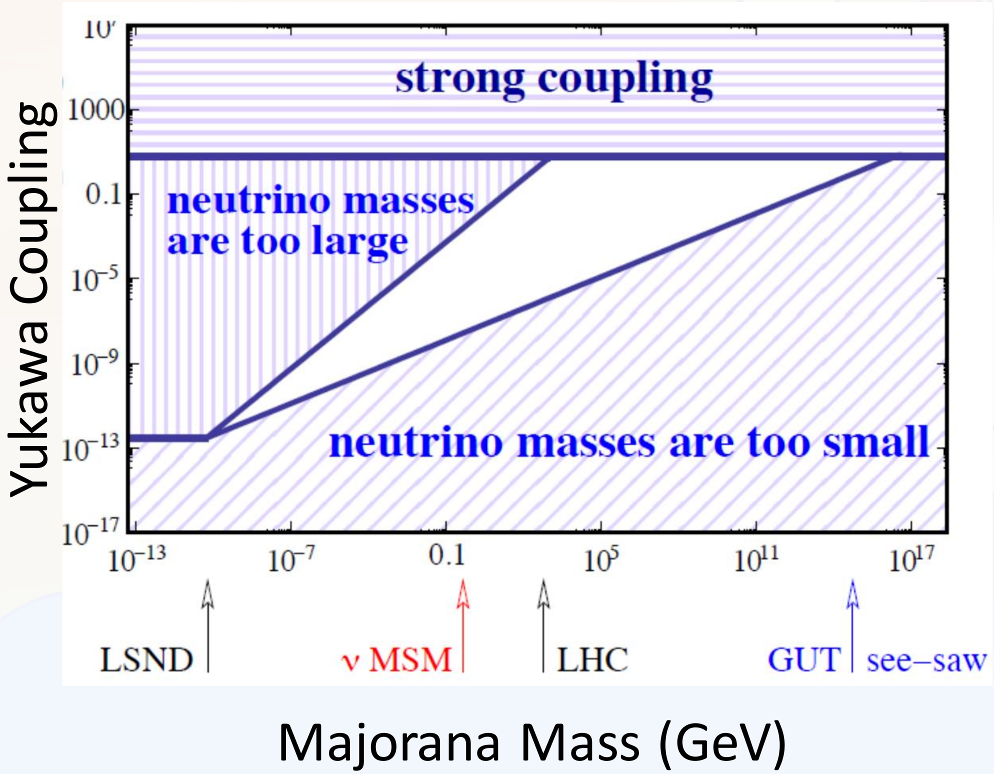
if $M_N \gg M_D$:

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

$$\lambda_+ \sim M_N$$

Sterile neutrino masses

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



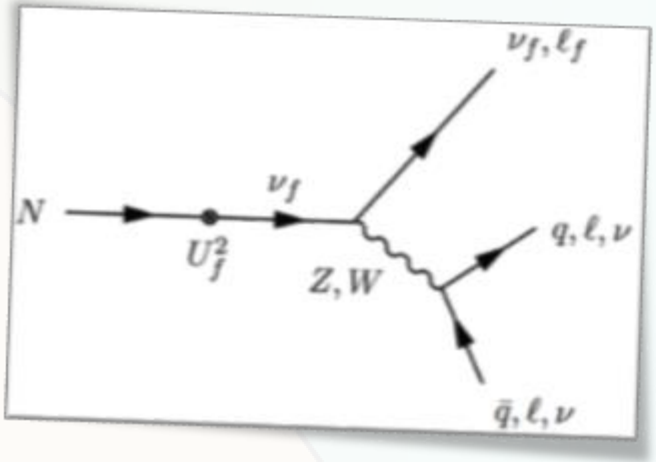
- Assuming $m_\nu = 0.1\text{eV}$
- if $Y \sim 1$ implies $M \sim 10^{14}\text{GeV}$
- if $M_N \sim 1\text{GeV}$ implies $Y_\nu \sim 10^{-7}$

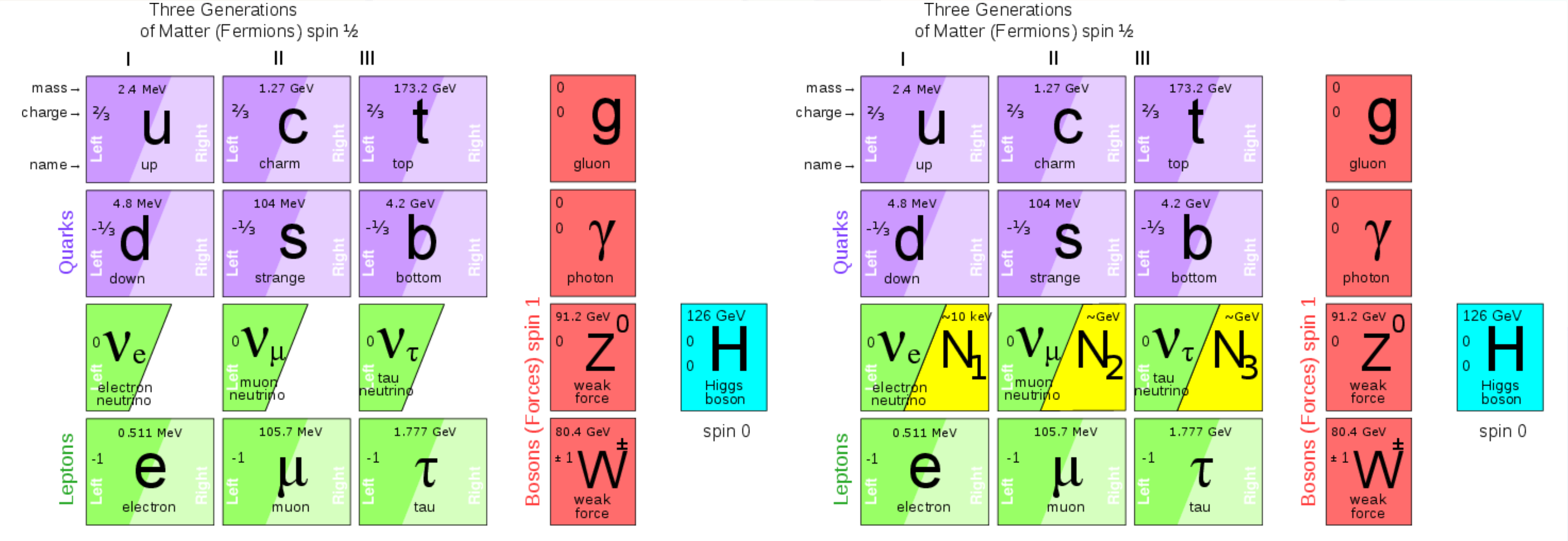
remember $Y_{top} \sim 1.$ and $Y_e \sim 10^{-6}$

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

Neutrino portal: the νMSM

- Complete the SM by adding RH neutrinos
- with **3** new right handed neutrinos:
  - 2 heavy quasi-degenerate HNLs explain **BAU** and **neutrino masses**
  - 1 lighter HNL could be **Dark Matter**
- Production and decay through HNL - ν mixing

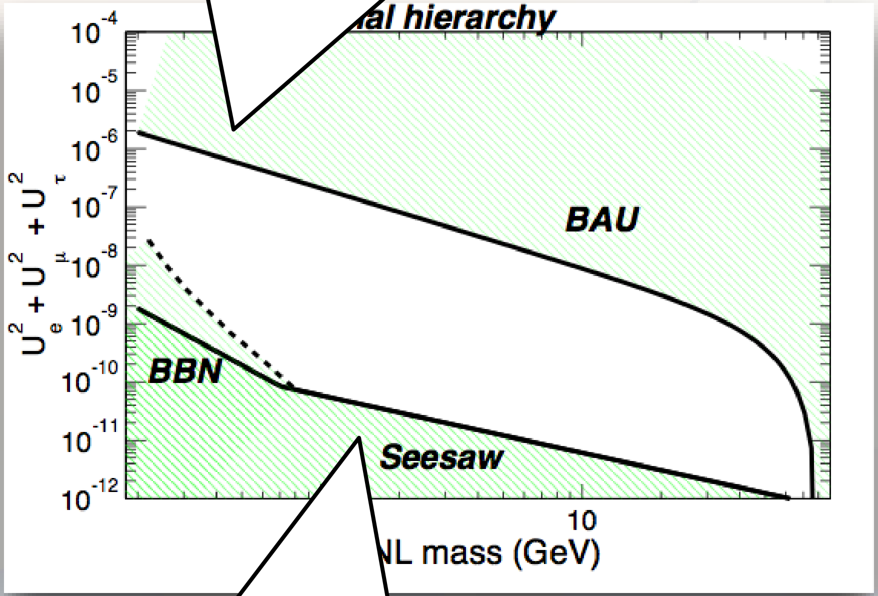


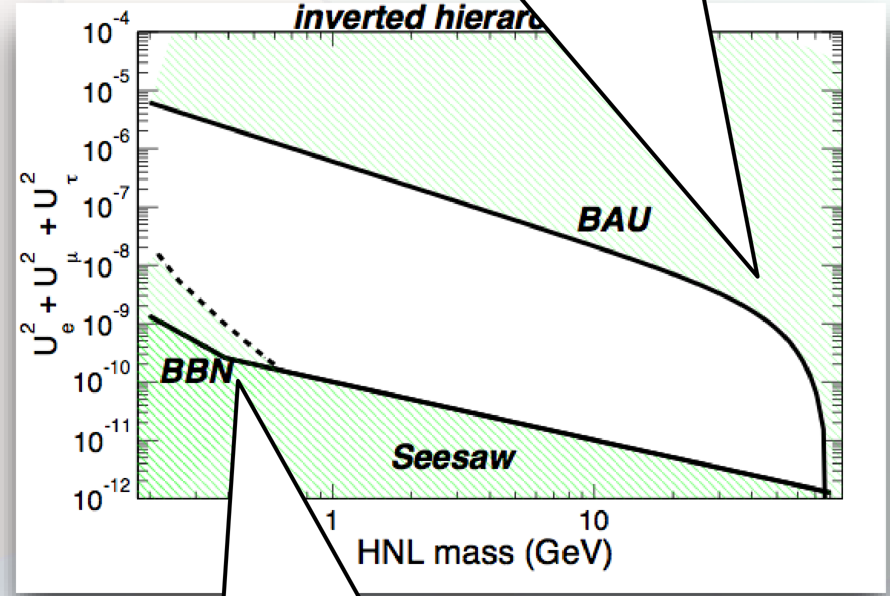


Constraints on N_2, N_3

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

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





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

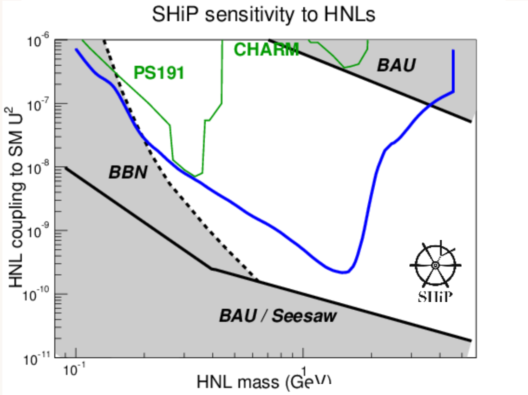
If $\tau(N_2, N_3) < 0.1\ s$, they cannot affect the **Big Bang nucleosynthesis**

Sensitivity to HNLs

Gorbunov, Shaposhnikov hep-ph/0705.1729

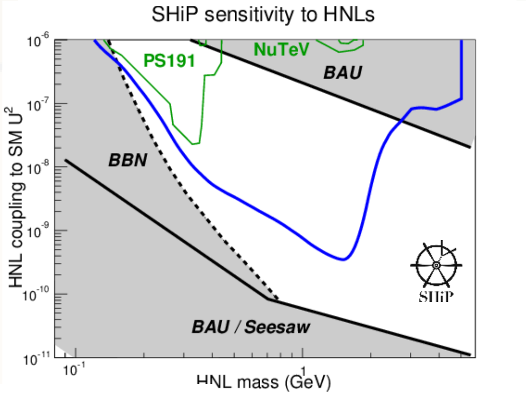
$U_e^2 : U_\mu^2 : U_\tau^2 = 52 : 1 : 1$

inverted hierarchy



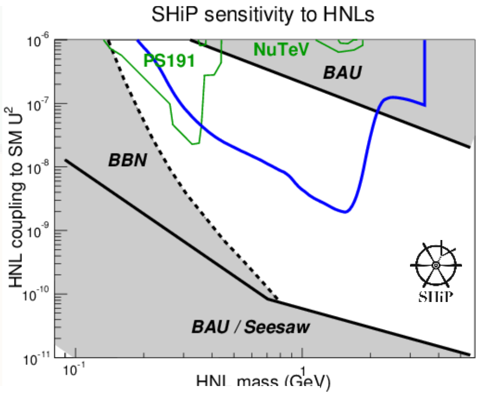
$U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8$

normal hierarchy



$U_e^2 : U_\mu^2 : U_\tau^2 = 0.061 : 1 : 4.3$

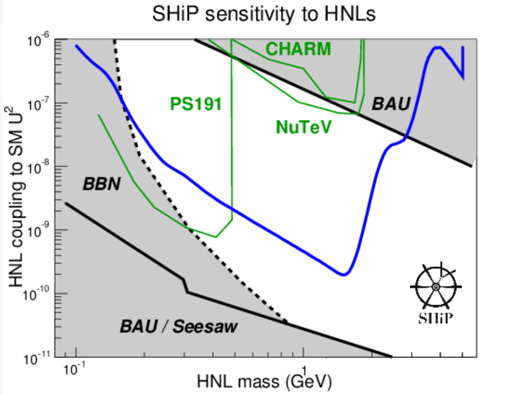
normal hierarchy



Canetti, Shaposhnikov hep-ph/1006.0133

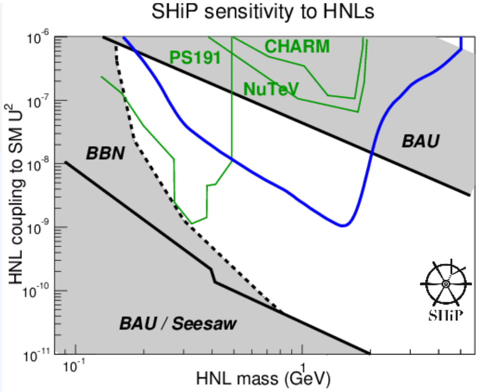
$U_e^2 : U_\mu^2 : U_\tau^2 = 48 : 1 : 1$

inverted hierarchy

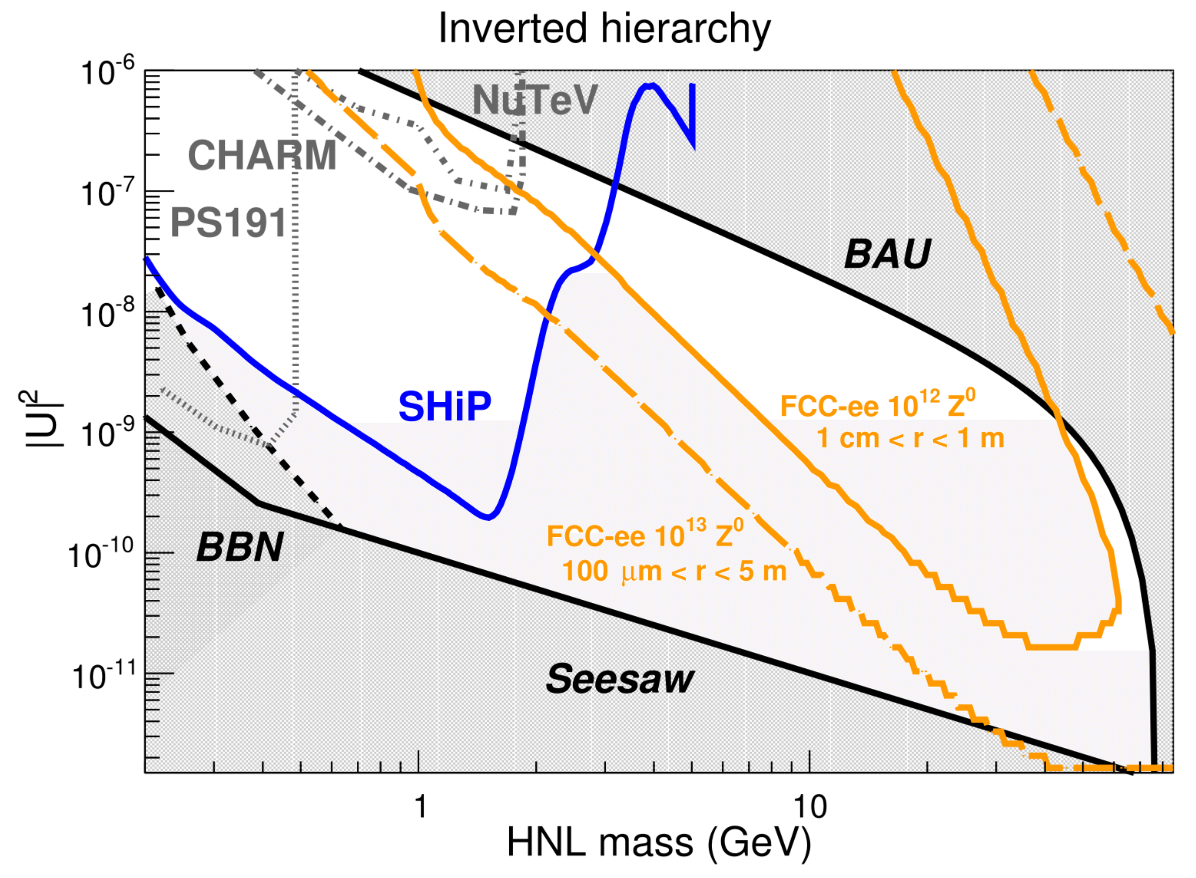


$U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 11 : 11$

normal hierarchy



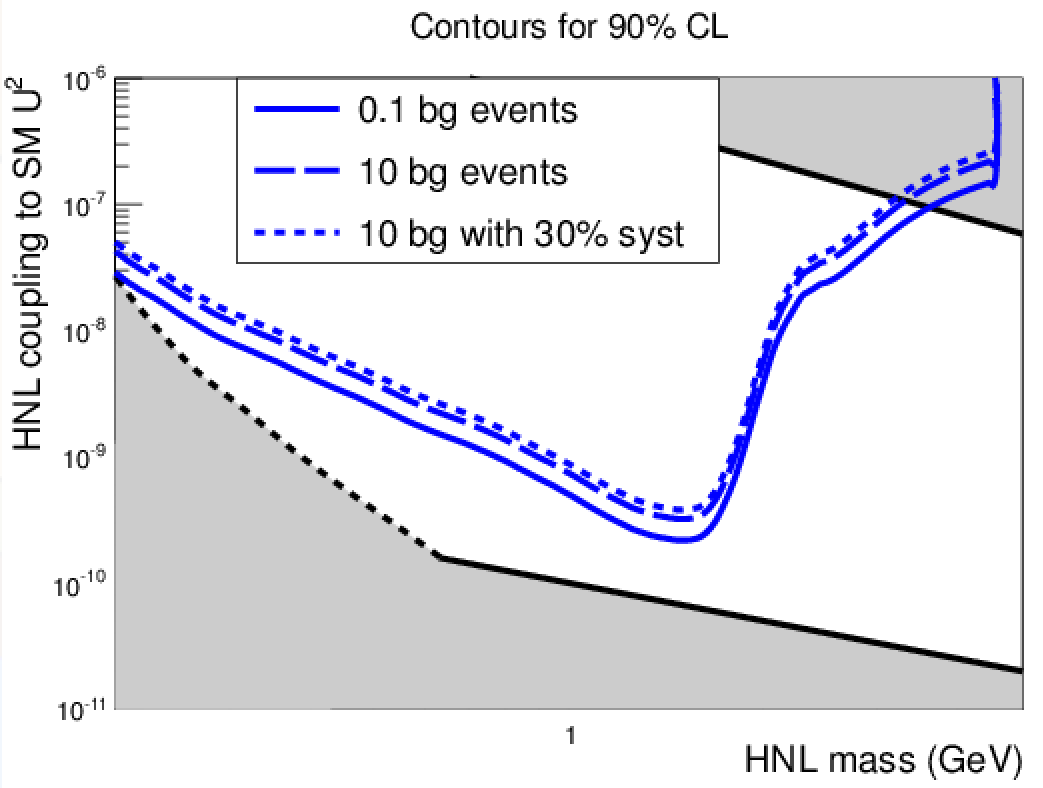
HNLs at future colliders



http://arxiv.org/abs/1411.5230
http://arxiv.org/abs/1503.08624

Sensitivity with background

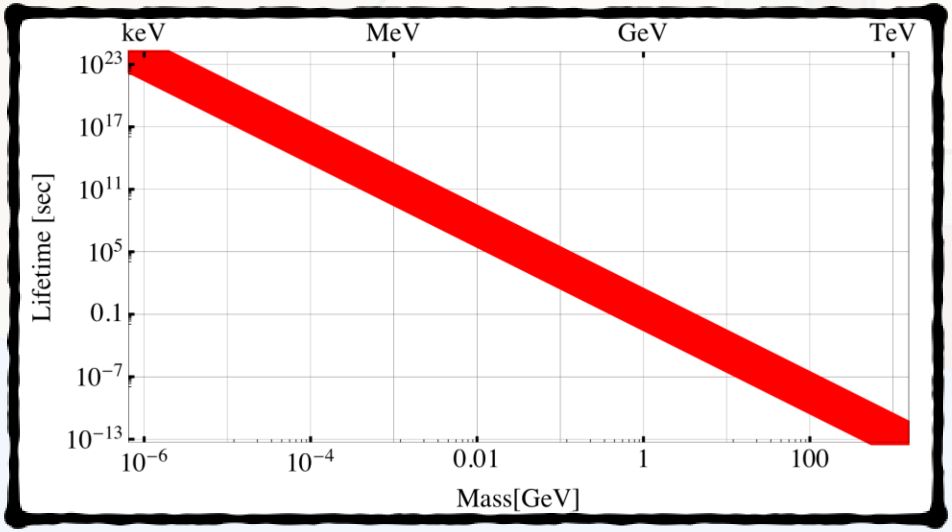
- U^2 scales with $\sqrt{N_S}$
- Need more than 100 background events to lose half an order of magnitude in U^2!



Constraints on N_1

The decay mode $N \to \nu\nu\nu$ is always present

$$LT = \left(\frac{U^2 G_F^2 M_N^5}{86\pi^3}\right)^{-1} \simeq 0.3 \left(\frac{1GeV}{M_N}\right)^4 sec$$

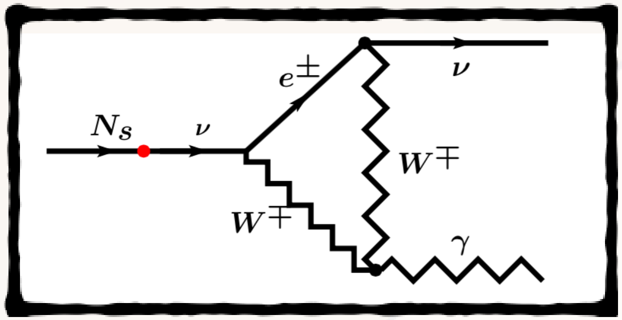


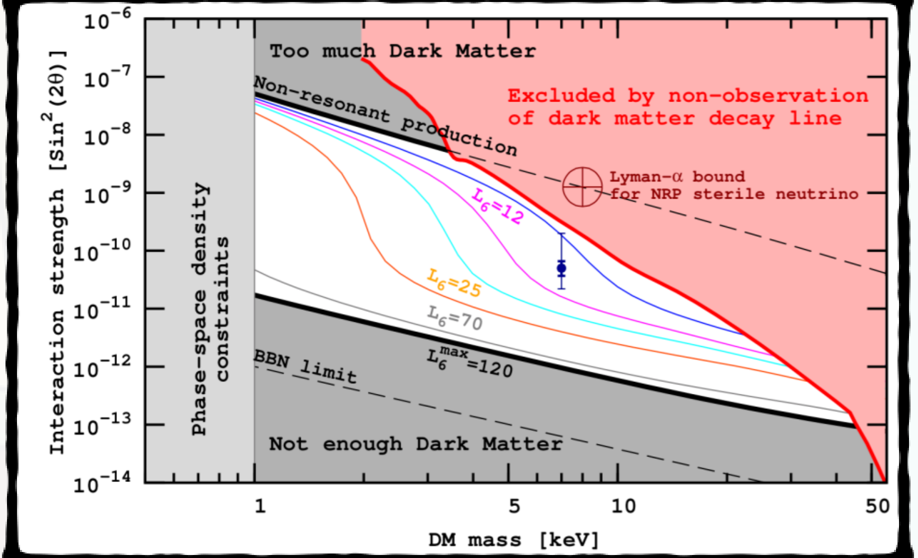
This gives an upper bound for the mass of the mass of the sterile neutrino Dark Matter

- $M_N \sim 1KeV \Longrightarrow \tau_N \sim 10^{24} sec$
- $\frac{\text{Age of the Universe}}{\tau_N} \sim 10^{-6}$

Constraints on N_1

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



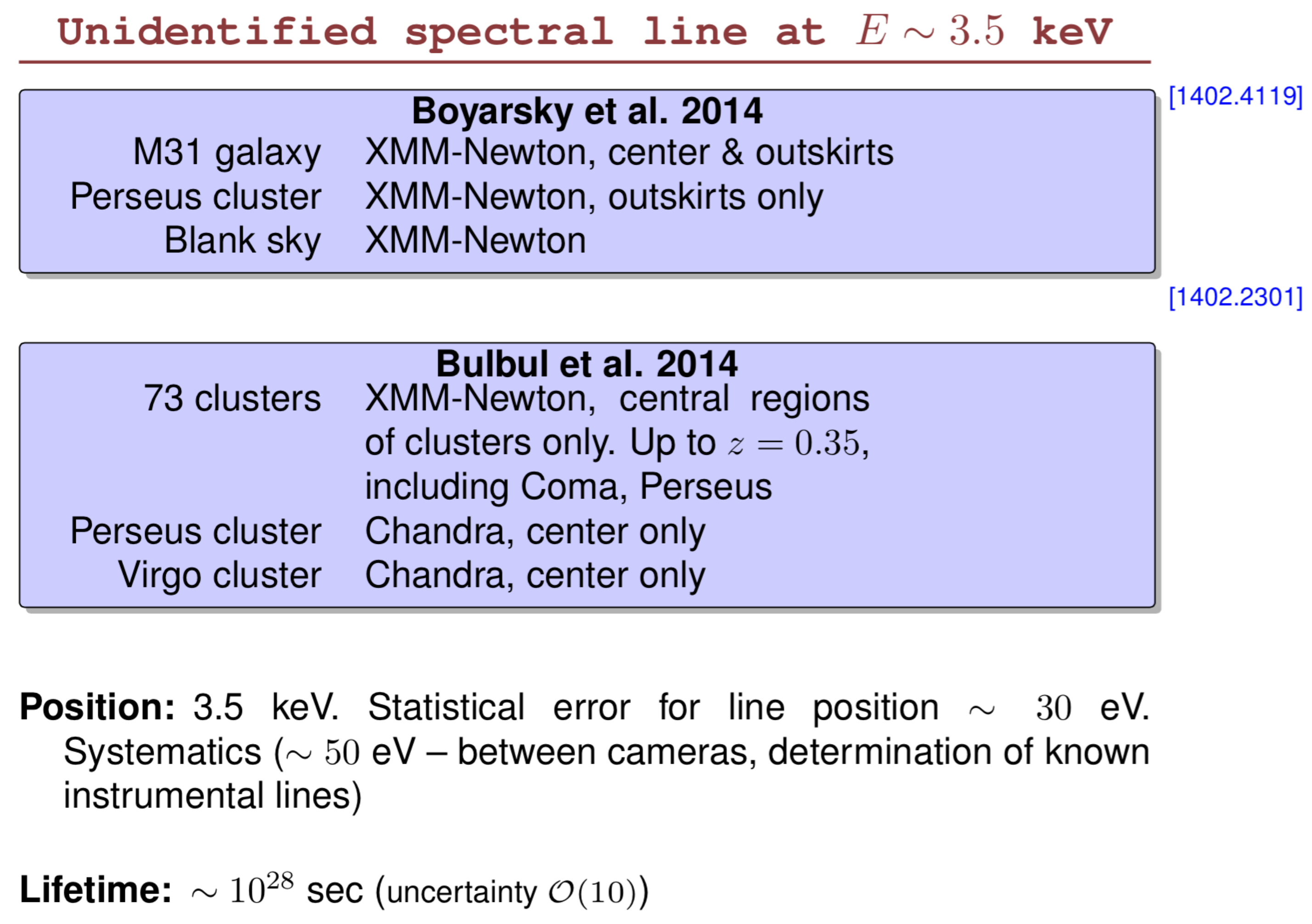


Discussion in the community, not yet clear if this is a “good” signal, needs confirmation

Bulbul et al. 2014 (arXiv:1402.2301)

Boyarsky et al. 2014 (arXiv:1402.4119)

Cosmology



Unidentified spectral line at $E \sim 3.5$ keV

[1402.4119]

Boyarsky et al. 2014

M31 galaxy	XMM-Newton, center & outskirts
Perseus cluster	XMM-Newton, outskirts only
Blank sky	XMM-Newton

[1402.2301]

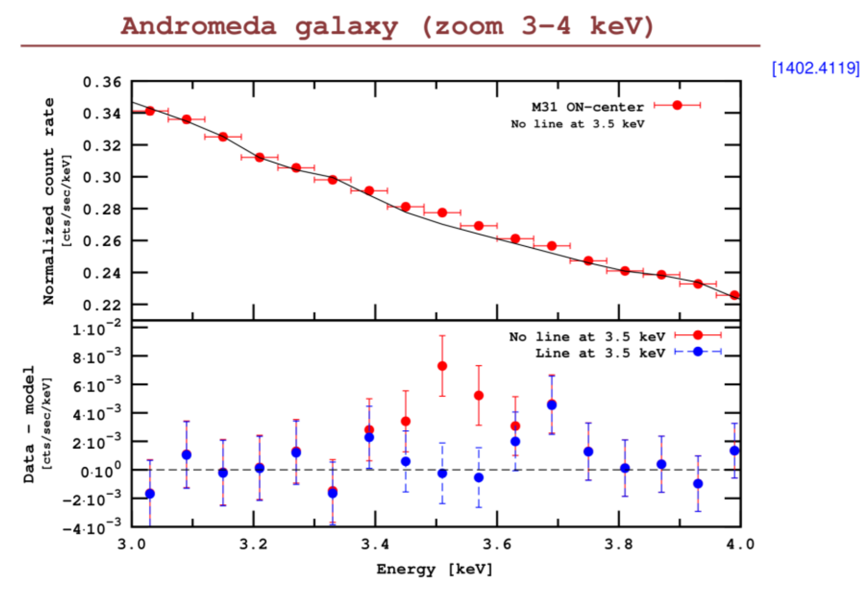
Bulbul et al. 2014

73 clusters	XMM-Newton, central regions of clusters only. Up to $z = 0.35$, including Coma, Perseus
Perseus cluster	Chandra, center only
Virgo cluster	Chandra, center only

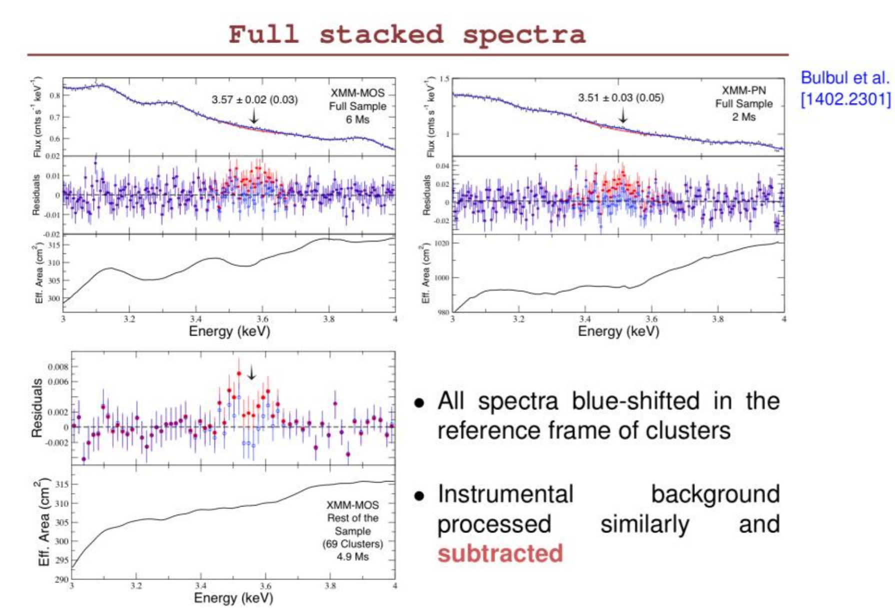
Position: 3.5 keV. Statistical error for line position $\sim$ 30 eV. Systematics (~ 50 eV – between cameras, determination of known instrumental lines)

Lifetime: $\sim 10^{28}$ sec (uncertainty $\mathcal{O}(10)$)

Cosmology


Andromeda galaxy (zoom 3–4 keV)

[1402.4119]


Full stacked spectra

Bulbul et al. [1402.2301]

- All spectra blue-shifted in the reference frame of clusters
- Instrumental background processed similarly and **subtracted**

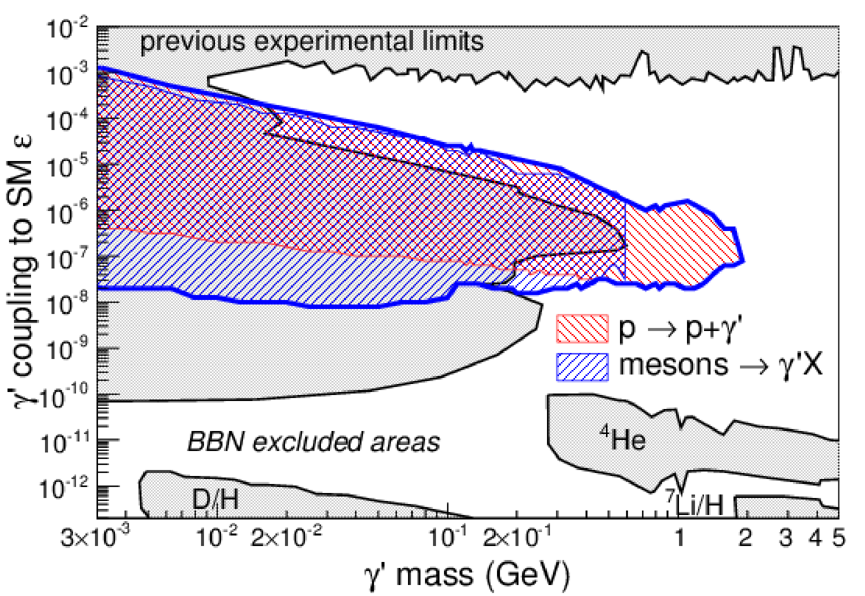
Sensitivity to other portals

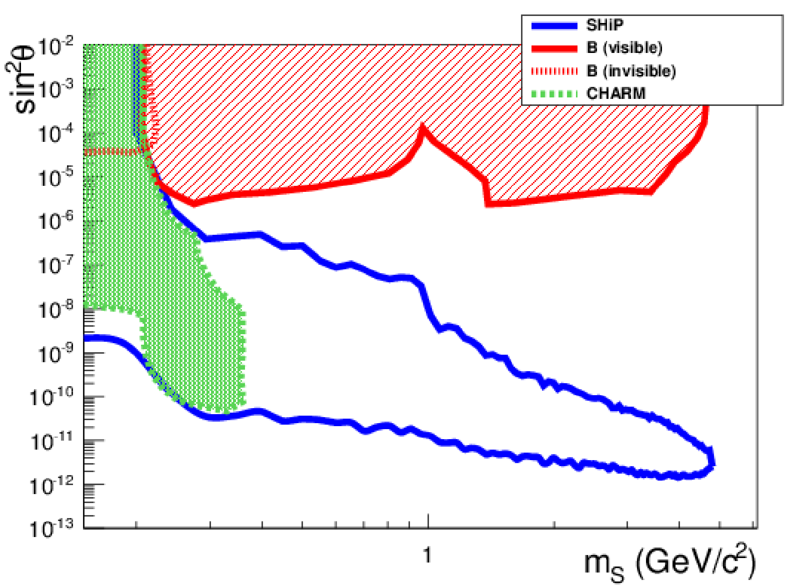
Dark photon

- sources: p bremsstrahlung, light meson decays
- decays to l^+l^-, $q\bar{q}$

Dark scalar

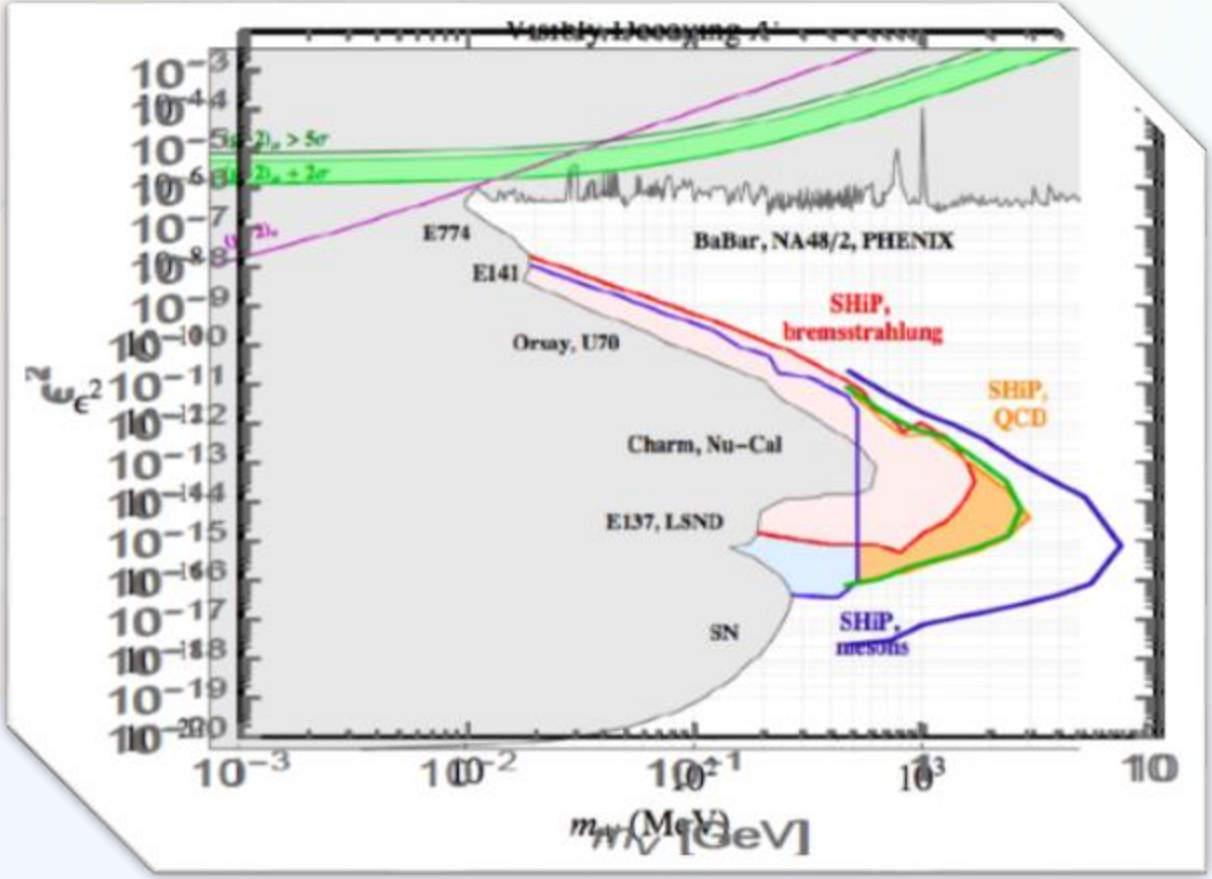
- sources: B mesons
- decays to l^+l^-, $q\bar{q}$





Dark photon

Updated computations show that **direct QCD production** is dominant at large masses. SHiP's sensitivity reaches $m_{\gamma} \sim 8$ GeV (work in progress).



ν_τ physics

- Charged current neutrino nucleon scattering

neutrino scattering

anti-neutrino scattering

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

Structure functions

- F_1
- F_2

→ More precise estimation from other experiments

- F_3

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

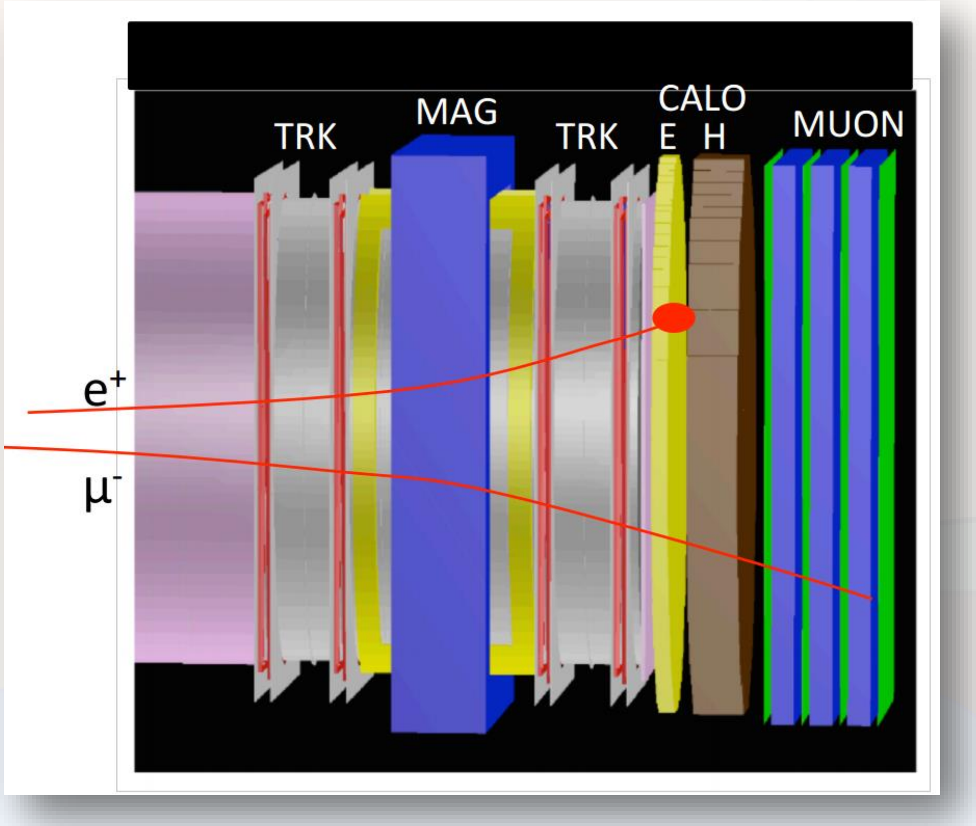
- F_4
- F_5

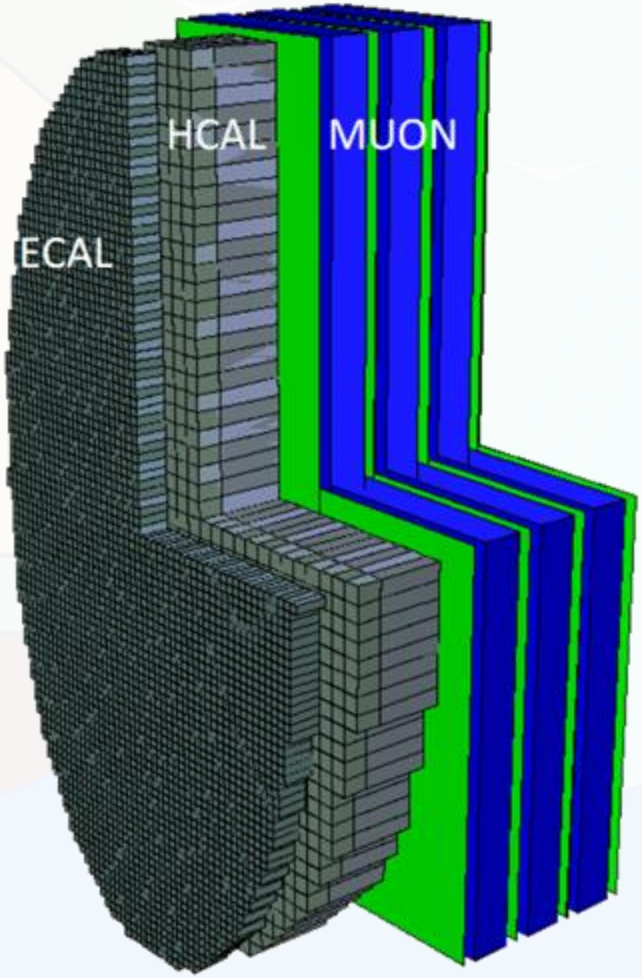
→ Dependent on the lepton mass. Suppressed in case of ν_μ interactions, becomes relevant for ν_τ interactions

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

The SHiP facility at CERN

SHiP detector: ECAL/HCAL

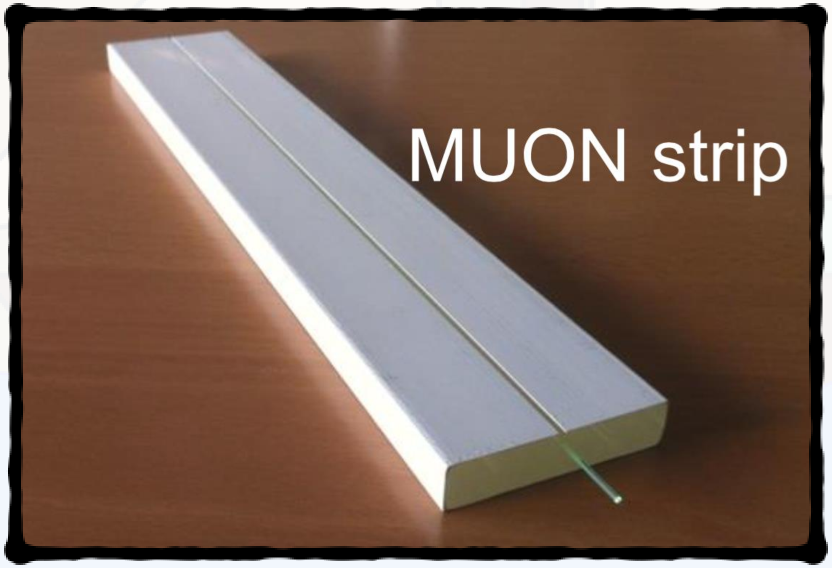




SHiP detector: MUON

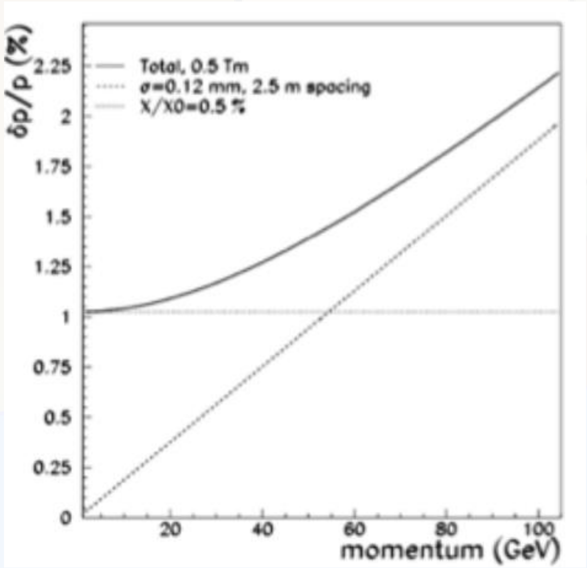
Possible Muon system:

- Four active stations (1 cm scintillators)
- interleaved with 60 cm (3.6 lambda) iron filter
- Strips: 5cm x 2cm x 270 cm



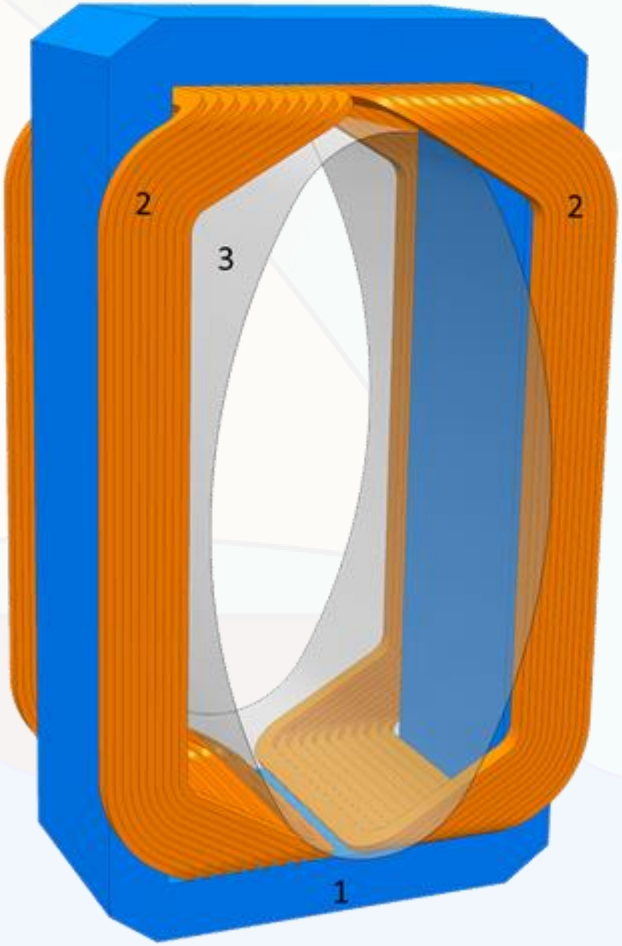
SHiP detector: TRACKER

NA62-like straw tubes with:
- 120 μm resolution
- 0.5% X_0/X
- 5 m length
- vacuum 10^{-2} mbar

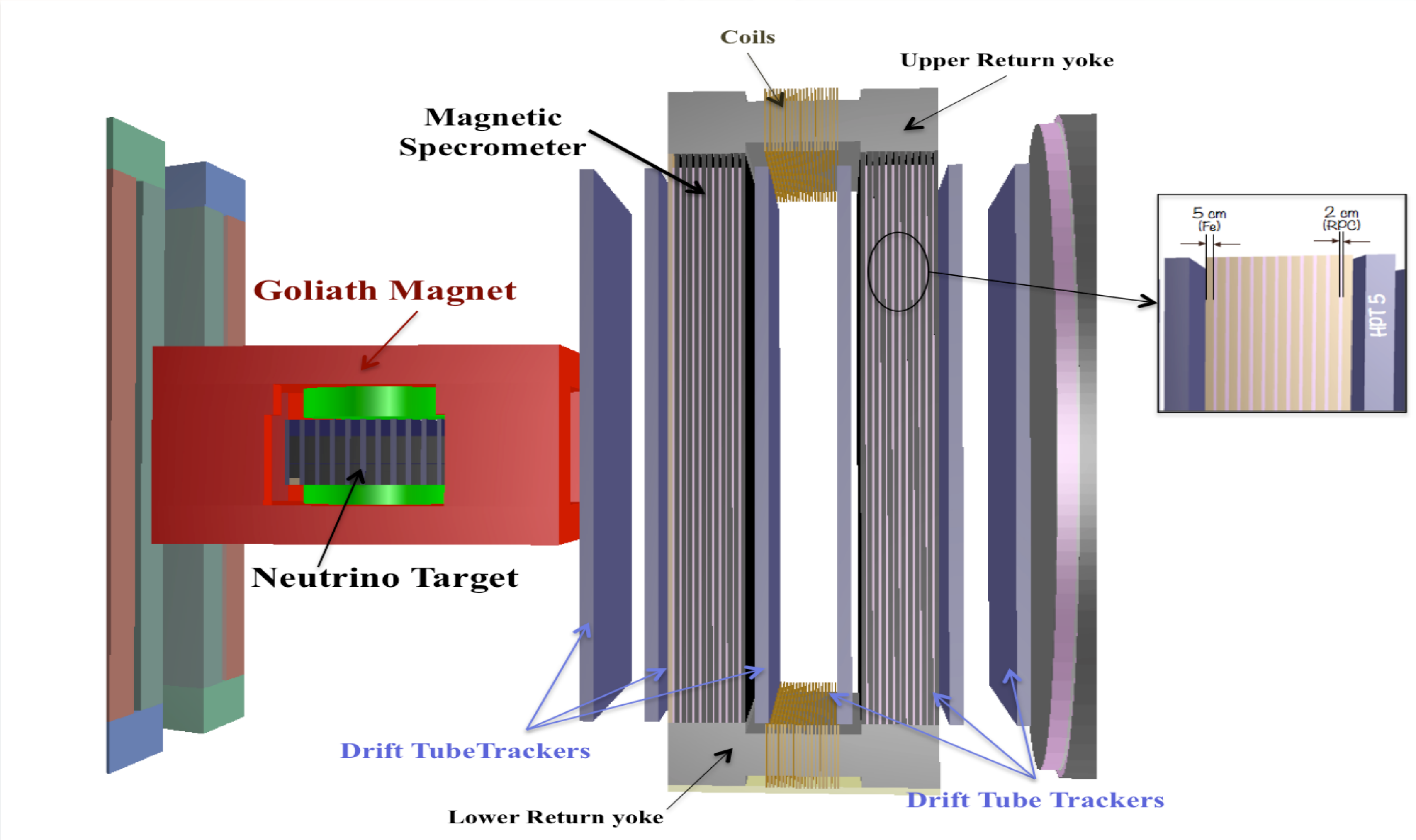


Tracker magnet

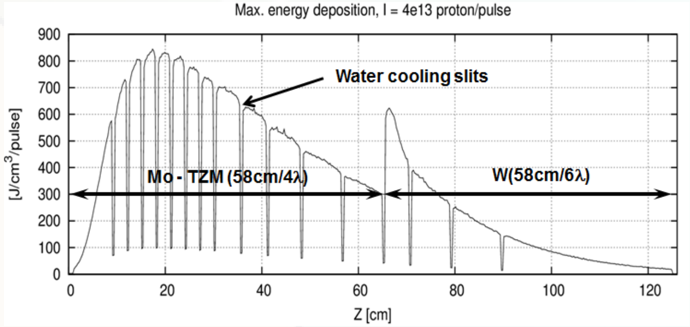
- Dipole magnet similar to LHCb magnet, but with 40% less iron and three times less power
- LHCb: 4Tm and aperture of $16m^2$
- This design:
  - aperture 20 m^2
  - Peak B-field 0.2T
  - Field integral 0.5Tm over 5m



Neutrino detector



Target

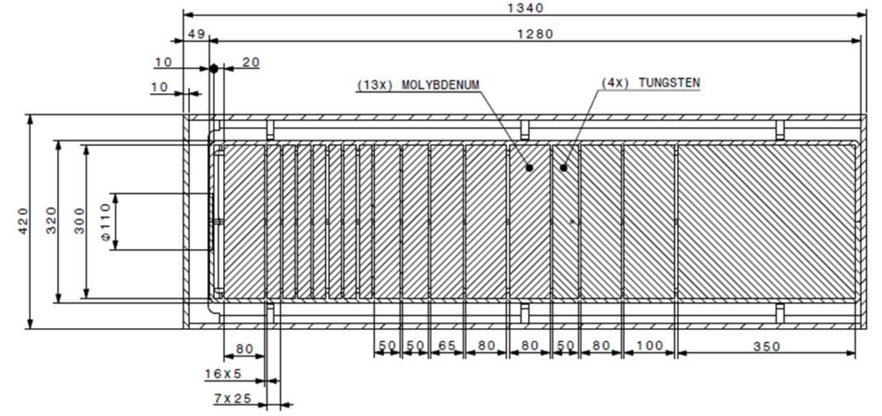


Design consideration

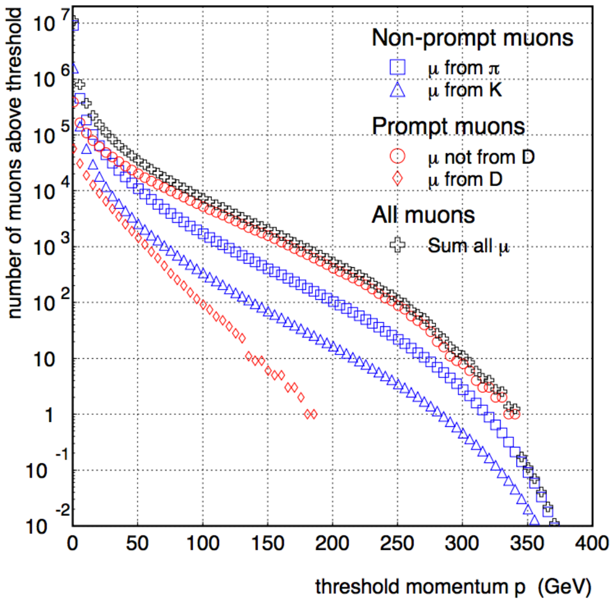
- ✓ *High temperature*
- ✓ *Compressive stresses*
- ✓ *Erosion/corrosion*
- ✓ *Material properties as a function of irradiation*
- ✓ *Remote handling*

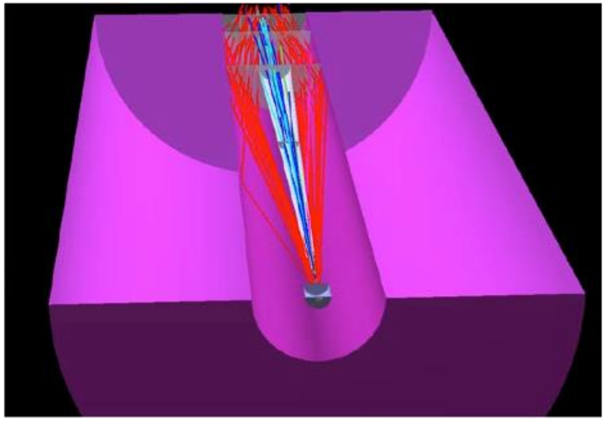
Layers of Titanium / Zirconium / Molibdenum for 4λ_{int} followed by layers of pure W

Longitudinal cross-cut



Muon background





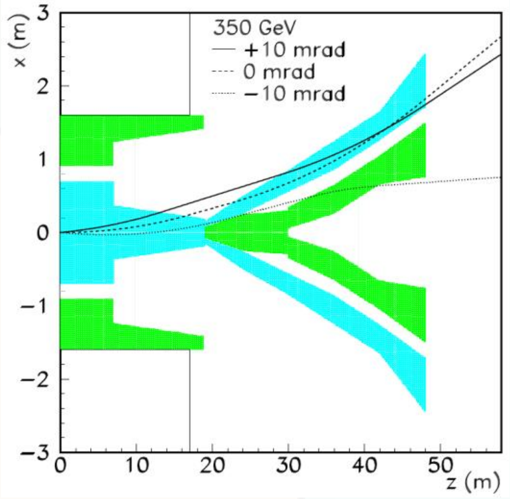
- Heavy target stops hadrons before they decay. After the target and the hadron absorber only muons survive
- Muons come mainly from η, η' and ω
- Without muon filter rate would be 5×10^9muons/spill (1 spill is 5×10^{13} POT)
- Under study solution with passive and active filter. Active filter preferred.

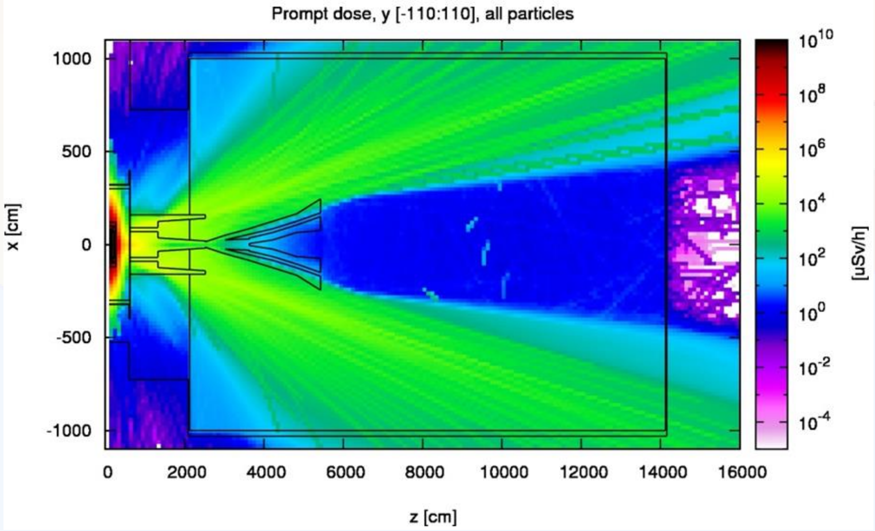
Active μ shield

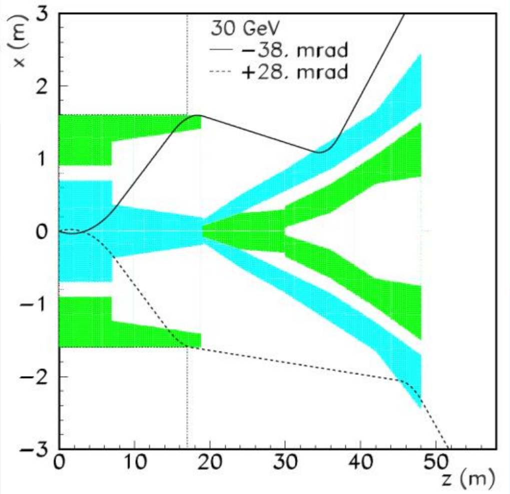
Muon flux is dangerous:

- background for HS physics
- ageing of ν_τ emulsions

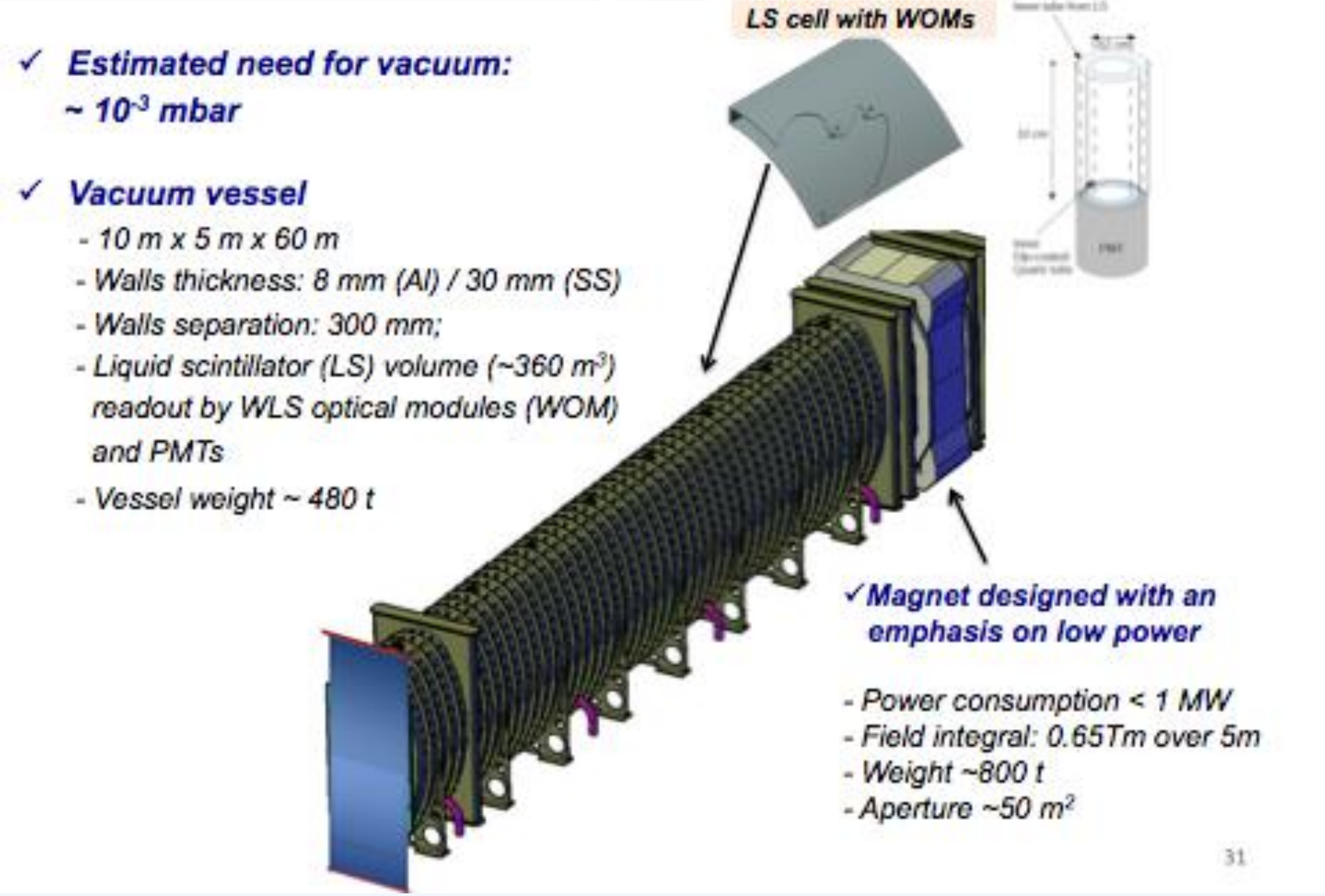
Active muon shield based on sweeping magnets with a vertical magnetic field of 86.4 Tm







Vacuum vessel

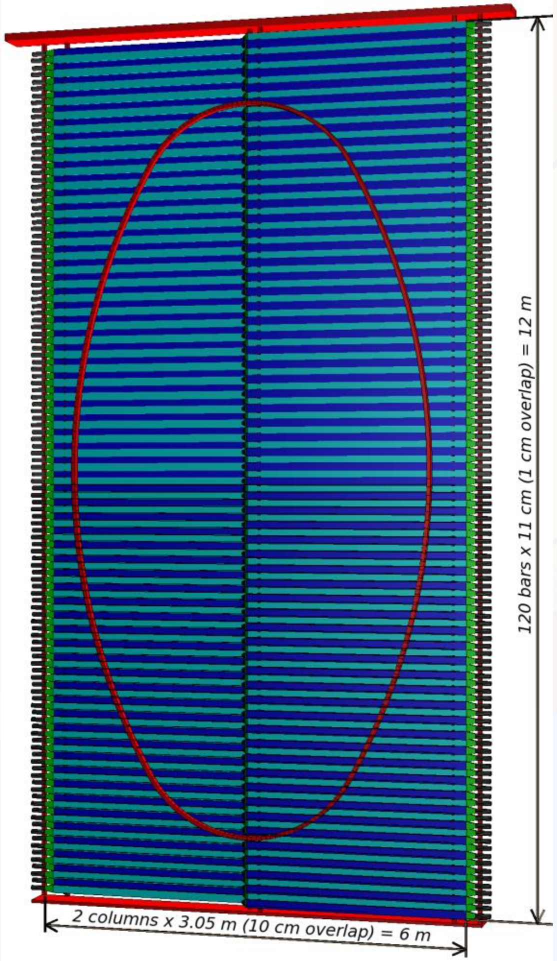


LS cell with WOMs

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

- ✓ *Magnet designed with an emphasis on low power*
  - Power consumption < 1 MW
  - Field integral: 0.65Tm over 5m
  - Weight ~800 t
  - Aperture ~50 m^2

Timing detector



Challenges:

- large area
- required resolution < 100 ps

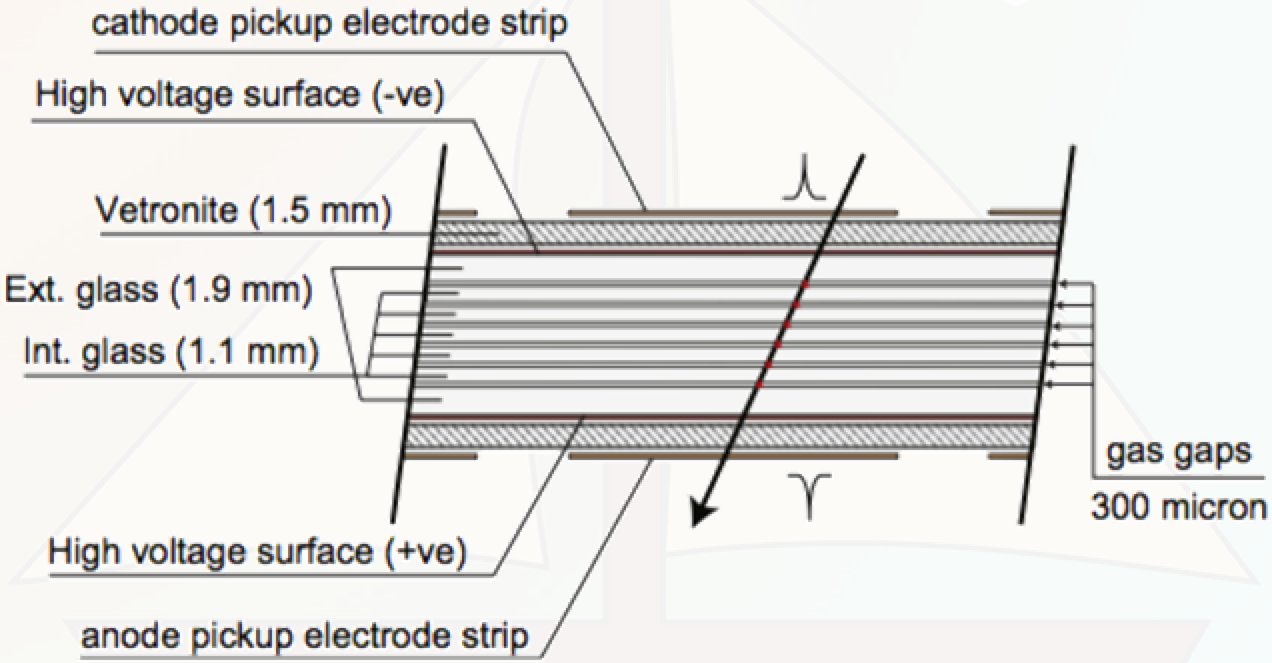
NA61/SHINE ToF:

- 100 ps resolution
- size of scint. counter 120 x 10 x 2.5 cm^3
- total active area 1.2 x 7.2 m^2

Energy loss in plastic: dE/dx min = 2 MeV/cm,
light yield: 10000 photons/MeV ⇒
for 2.5 cm bar: $N\gamma$= 2.5 x 2 x 10k = 50 k

For long bars, mainly photons with total internal reflection ($\theta > 39^o$) are detected

Timing detector: MRPC option



61 chambers x 120 cm strips, 3 cm pitch

Based on the EEE project

50 ps resolution achievable