FLUCTUAT NEC MERGITUR

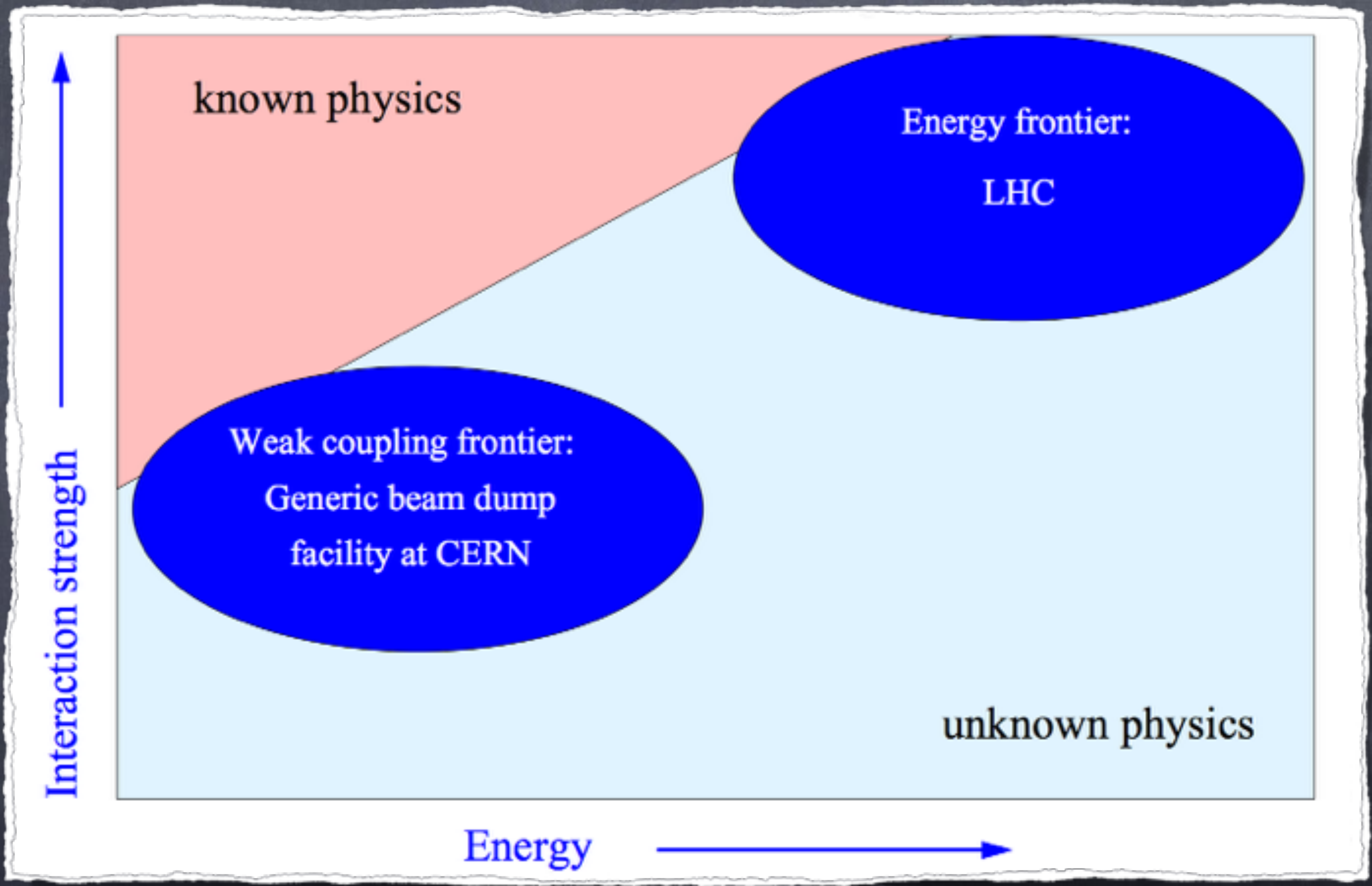
# SHiP: Searching for Hidden Particles

Nico Serra on behalf of the SHiP collaboration

X$^{th}$ Rencontres Du Vietnam
Flavour Physics

ICISE, Quy Nhon, 27$^{th}$ July - 2$^{nd}$ August 2014

# The high intensity frontier




New Particles are either heavy or very weakly coupled

See Oleg's presentation on Wednesday

# Portals to new physics

If new particles are light they must be singlet wrt SM, so they couple with SM particles via Portals (singlet composed operators)

- Neutrino portal: new heavy neutral lepton, coupling $YH^T\overline{N}L$
- Vector portal: new massive vector meson, coupling $\epsilon' B_{\mu\nu}F^{\mu\nu}$
- Higgs portal: new massive scalar, coupling $(\mu\chi + \lambda\chi^2)H^\dagger H$
- Axion portal: massive axion like particle

and others...

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# 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

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

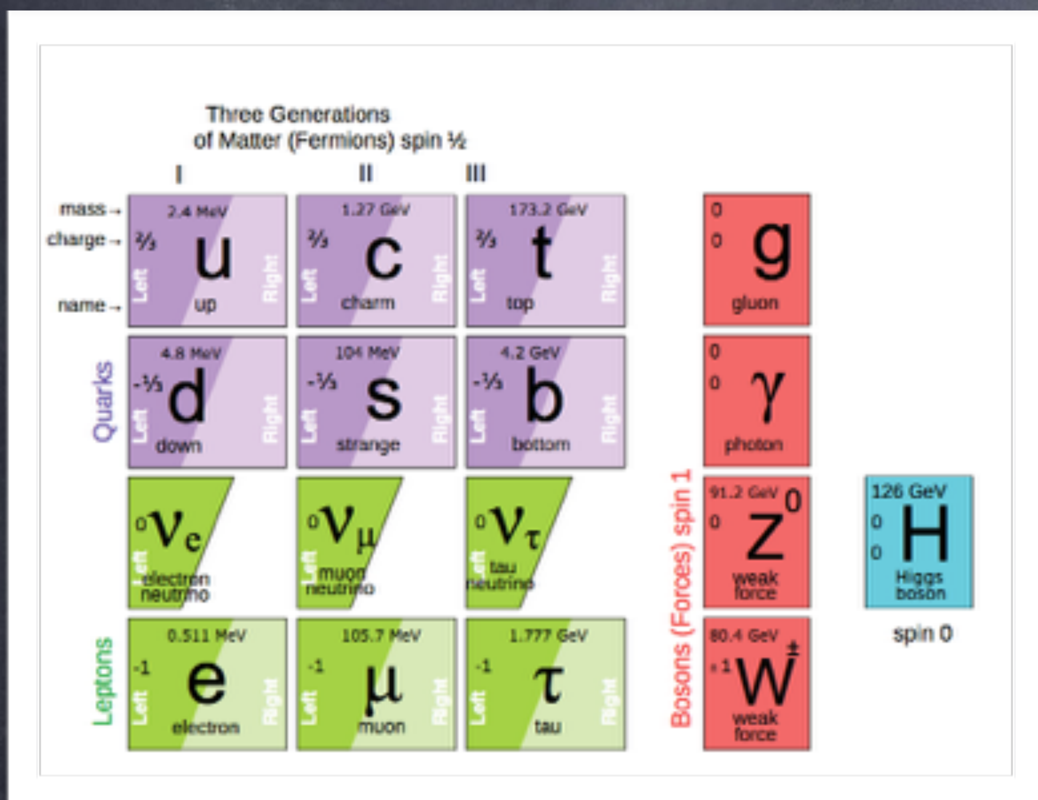
Kinetic term

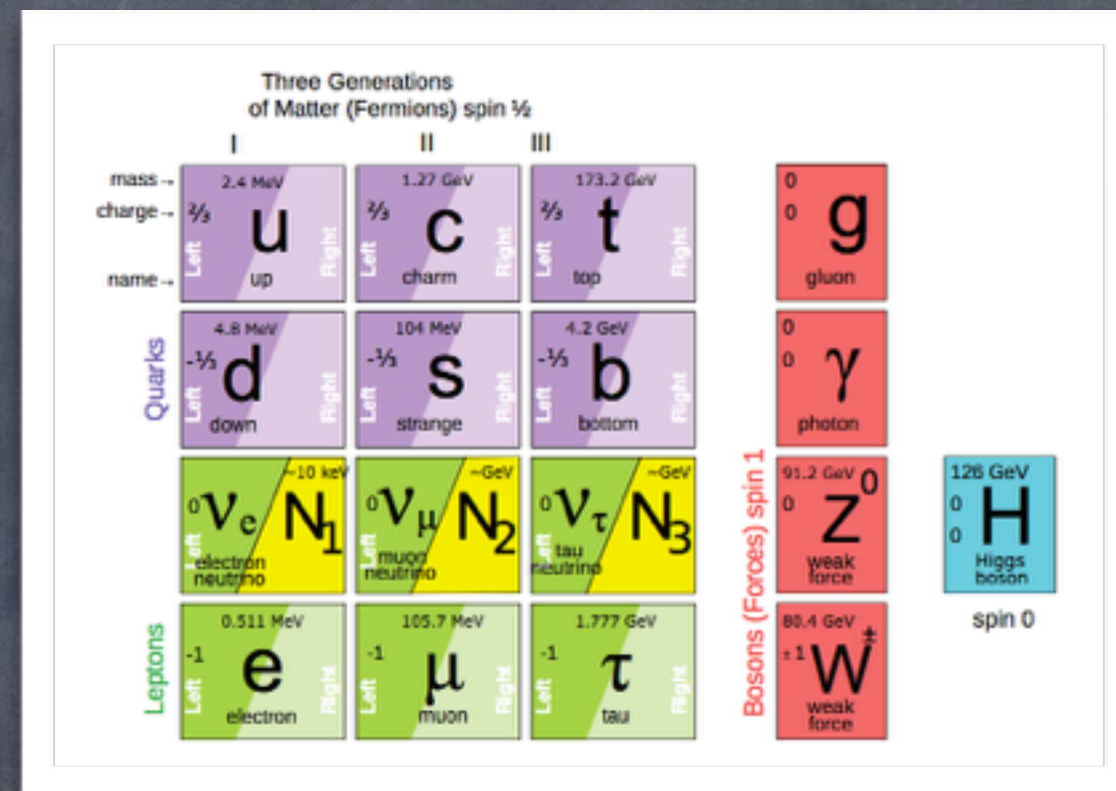
Majorana mass term

Yukawa coupling

See talk by B. Kayser yesterday

# The nuMSM



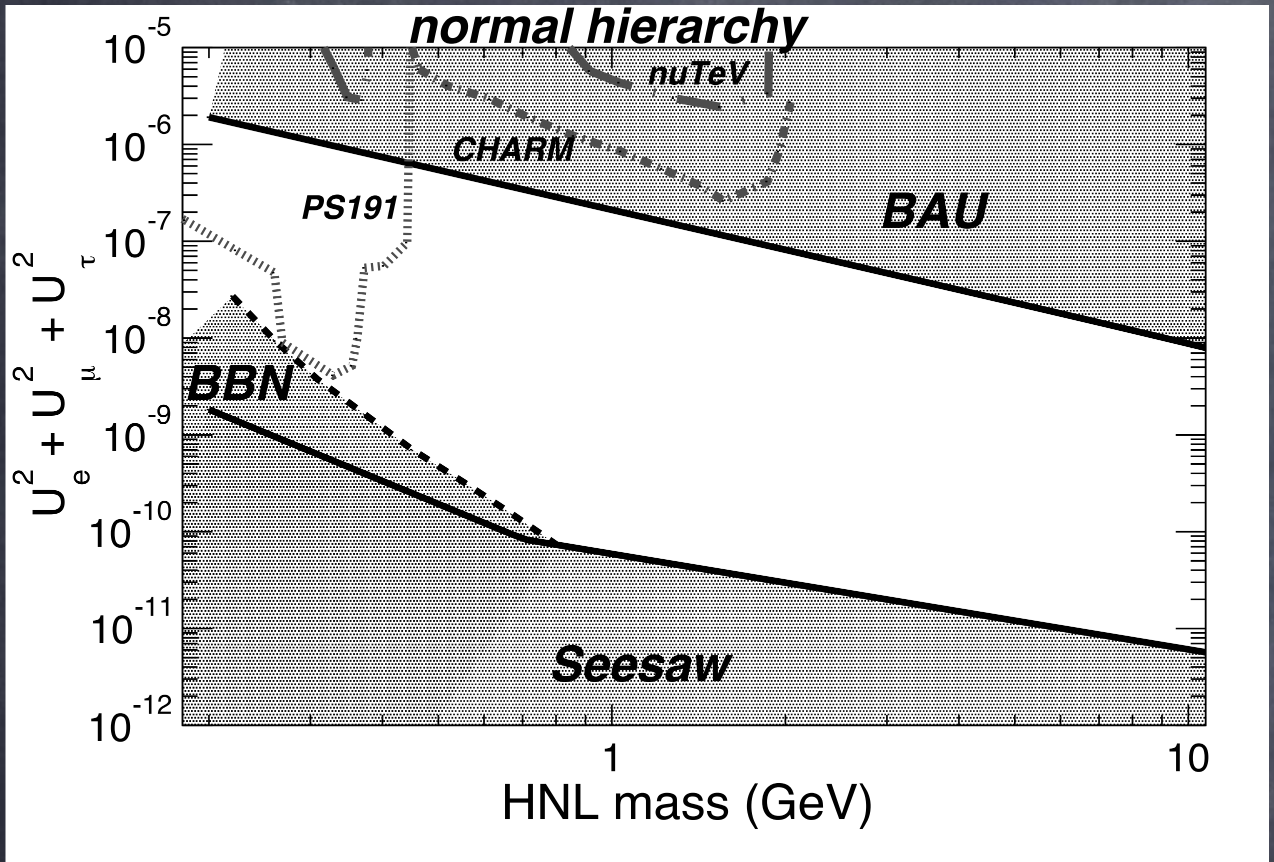



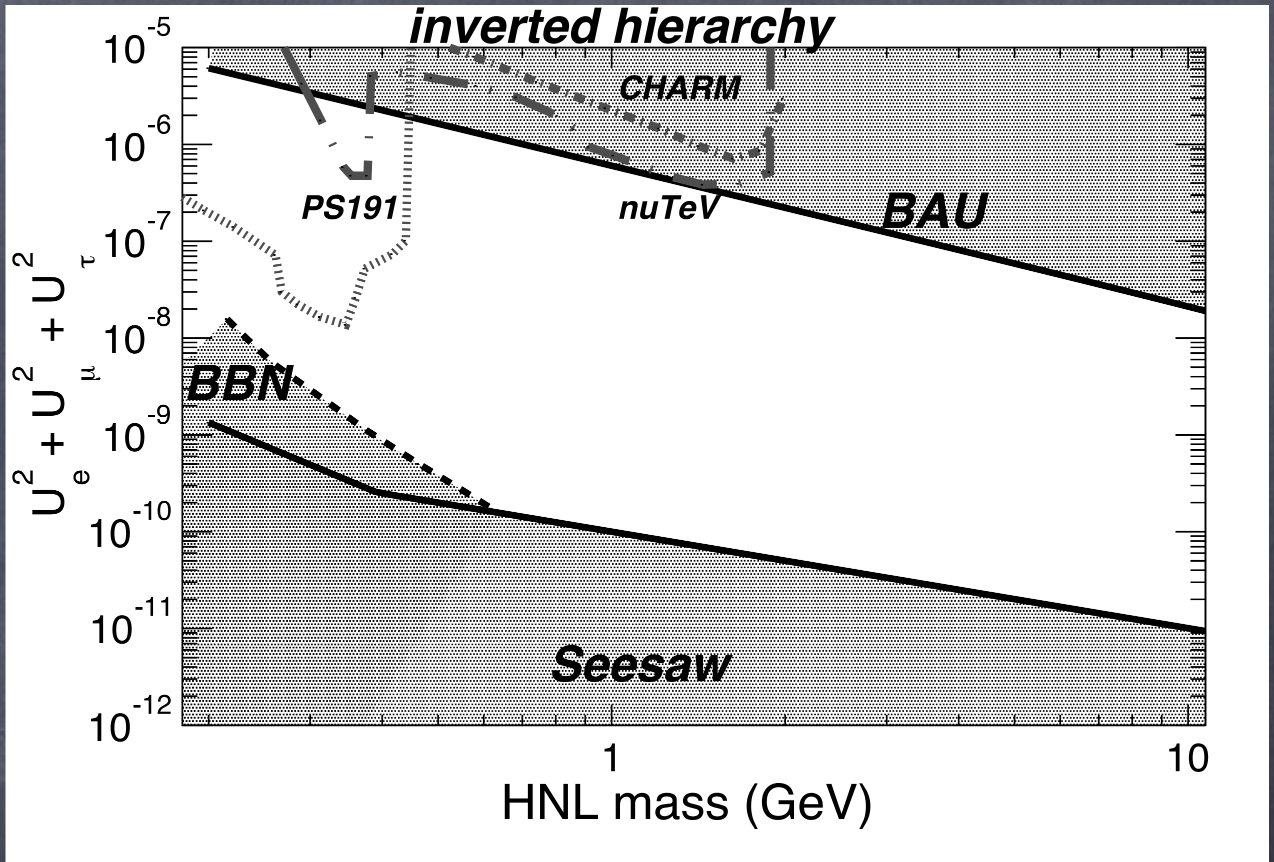

- $N_1$ with a mass in the KeV region plays the role of Dark Matter
- $N_{2,3}$ have mass in the GeV region, are quasi degenerate, give mass to active neutrinos and produce the baryon-antibaryon asymmetry in the Universe

See Oleg's presentation on Wednesday
See Dima's presentation later

See Dima's presentation later

# Present status

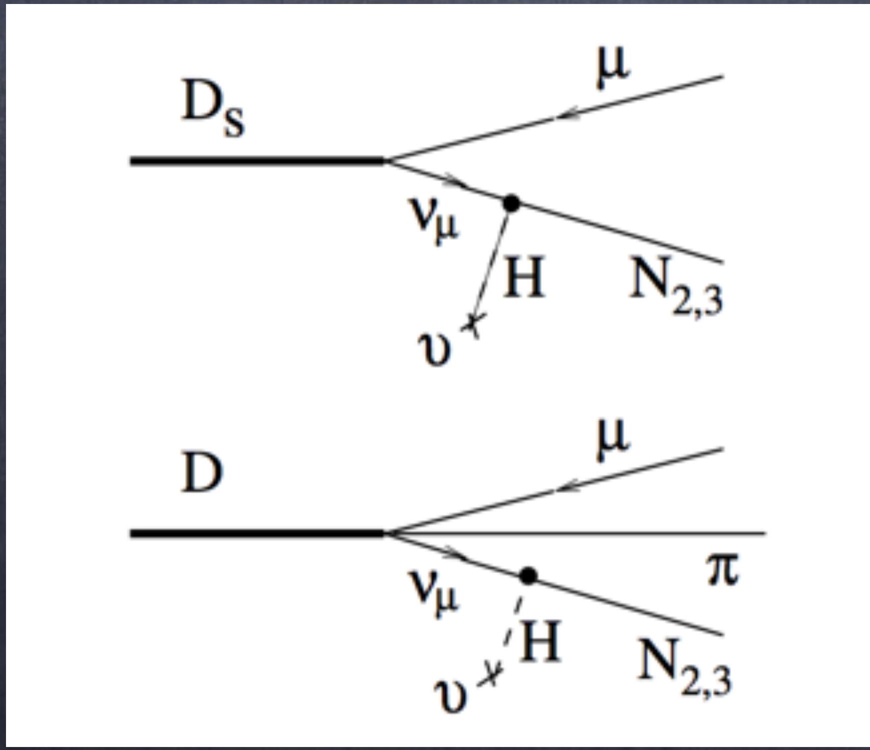


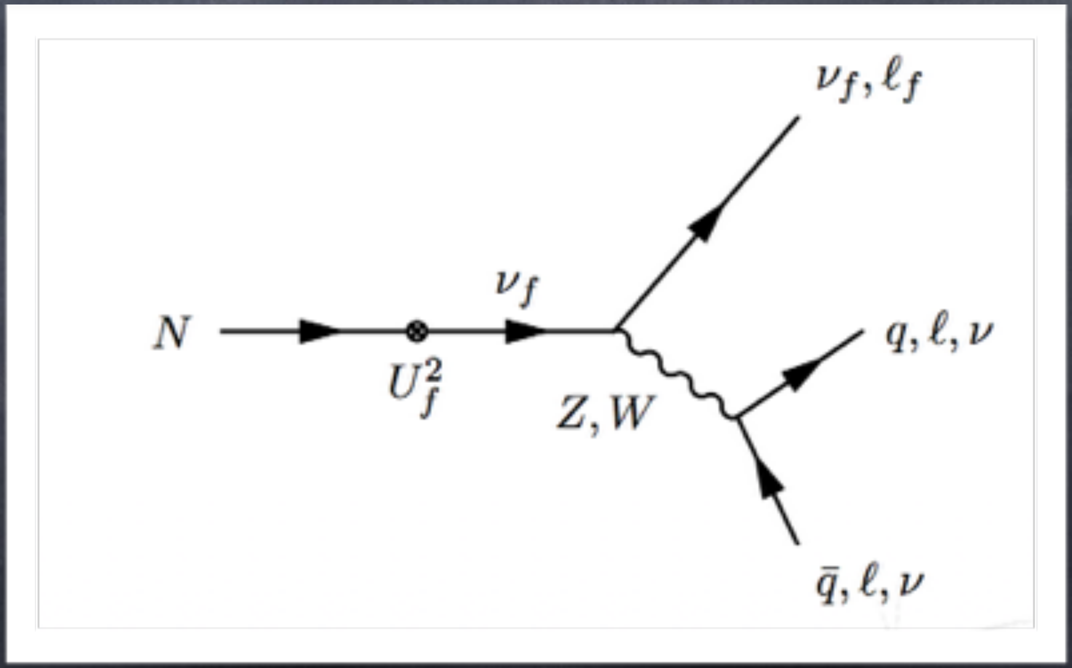




Constraints from Canetti, Drewesb, Frossardd and Shaposhnikov arXiv:1208.4607 and references therein

# Production and decays

- Produced via the (small) mixing with active neutrinos (mainly coming from D-meson decays)
- Typical lifetime of the order of 10$\mu$s, i.e. decay lenght O(Km)
- Number of events proportional to $U^4$




Decays $N_{2,3} \to \ell^- h^+,\ \ell^- \ell^+ \nu,\ h^0 \nu$

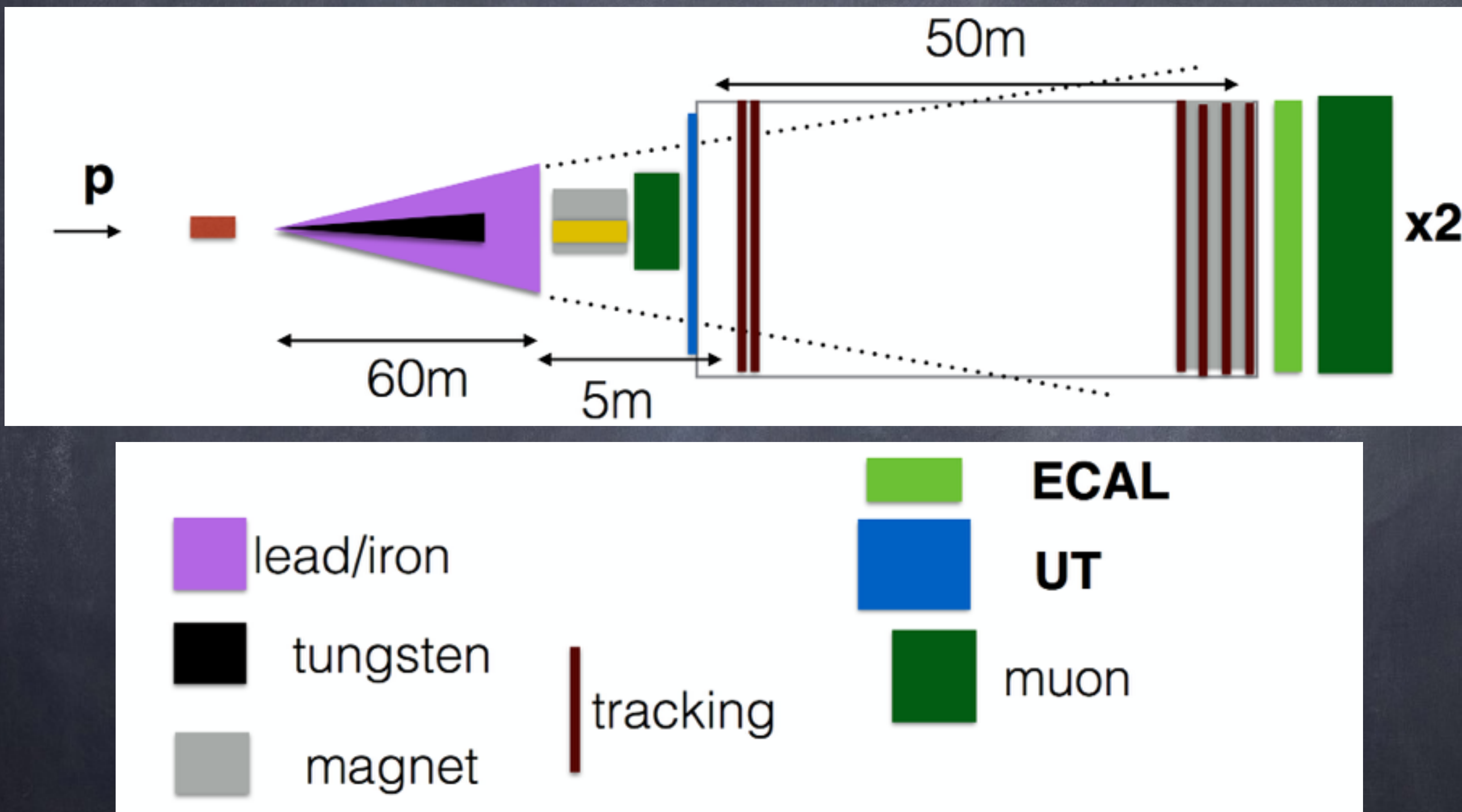
See Walter's presentation

# SHiP Experiment

Proposal for a fix target experiment at SPS (arXiv:1310.1762)

- Large number of protons on target $4 - 5 \times 10^{13}$ per 6-7s at 400GeV $\rightarrow$ $2 \times 10^{20}$ POT
- Slow beam extraction (1s) to minimize backgrund and occupancy
- Target consisting of heavy material to stop $\pi$ and $K$ before they decay in active neutrinos
- Long muon shield to range out the flux of muons
- Evacuated decay volume

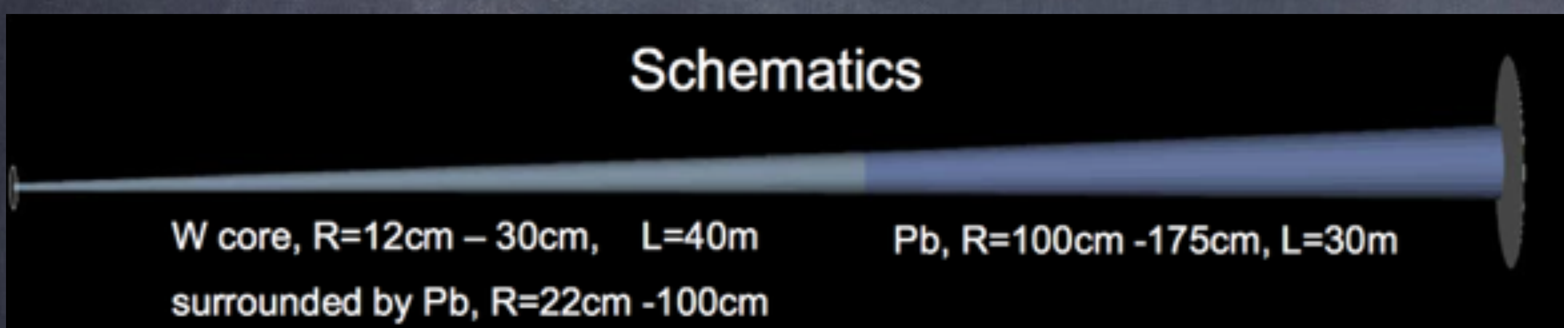
# Concept of the experiment

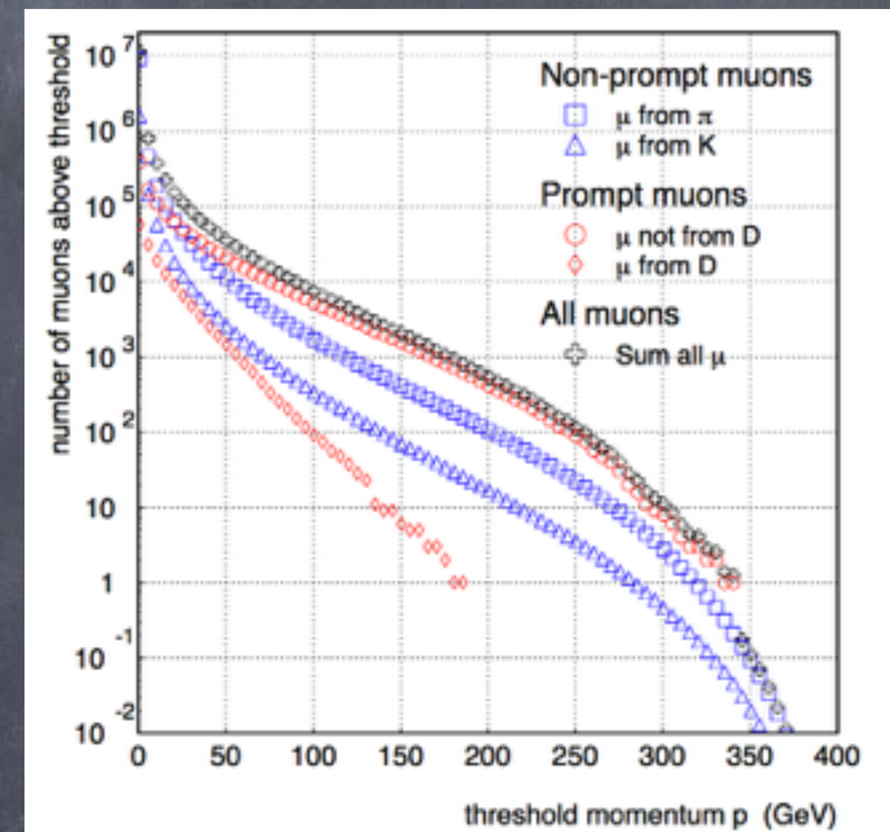


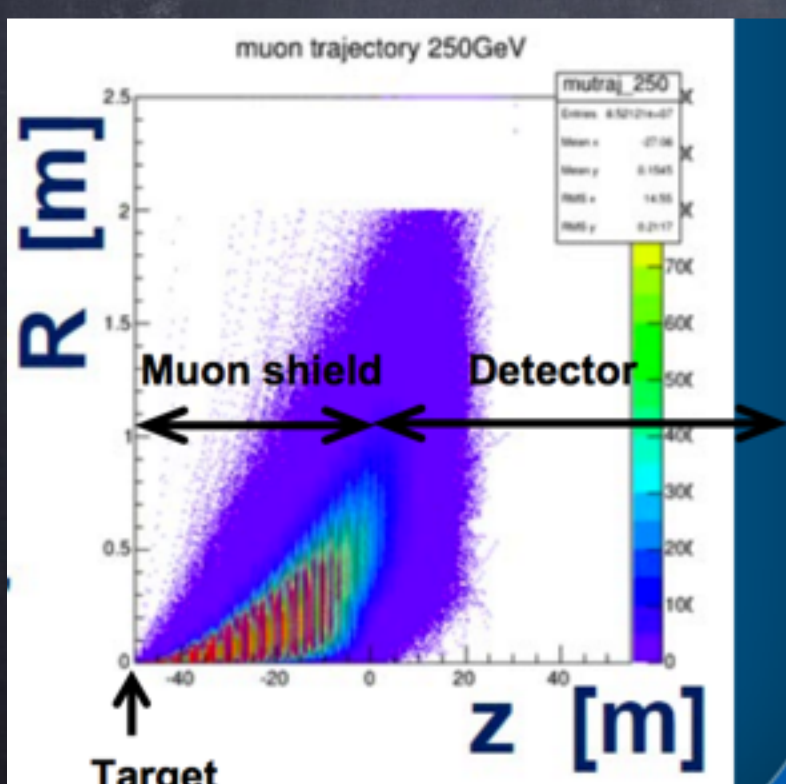
# Muon Shield

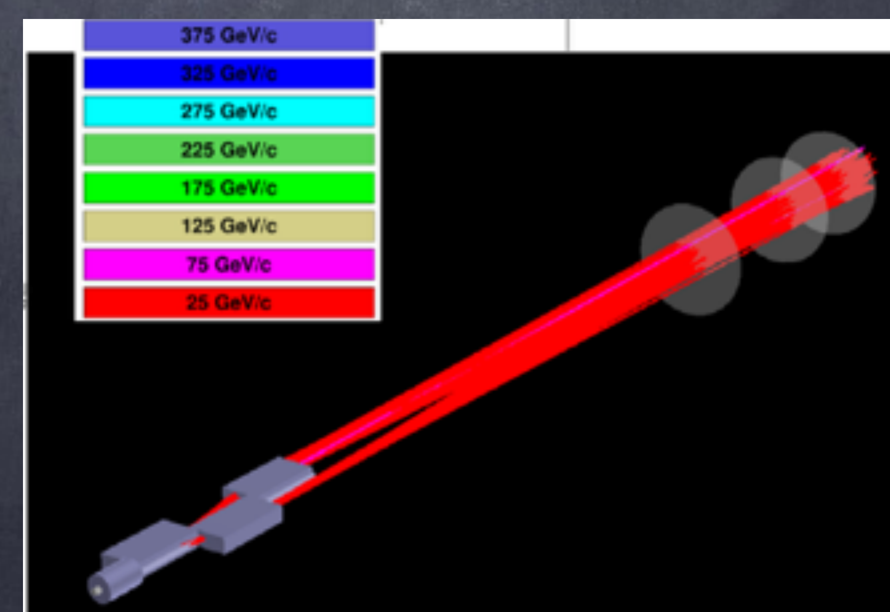
Muon rate $5 \times 10^9$ muons/spill

- Acceptable rate $< 10^5$ muons per spill
- Main source of muons from $\eta$, $\eta'$, $\omega$, etc...
- Studying solution with passive or active filter

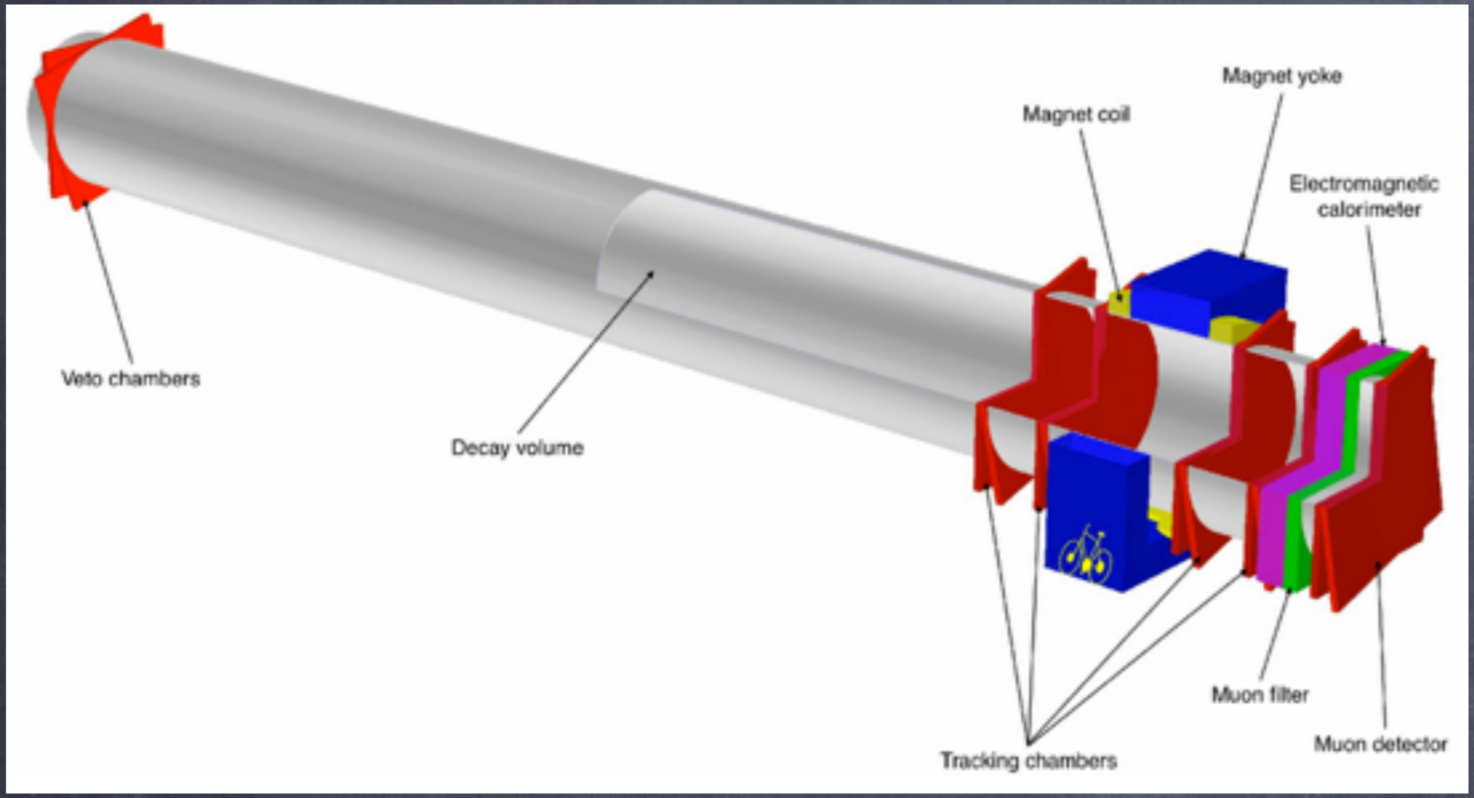


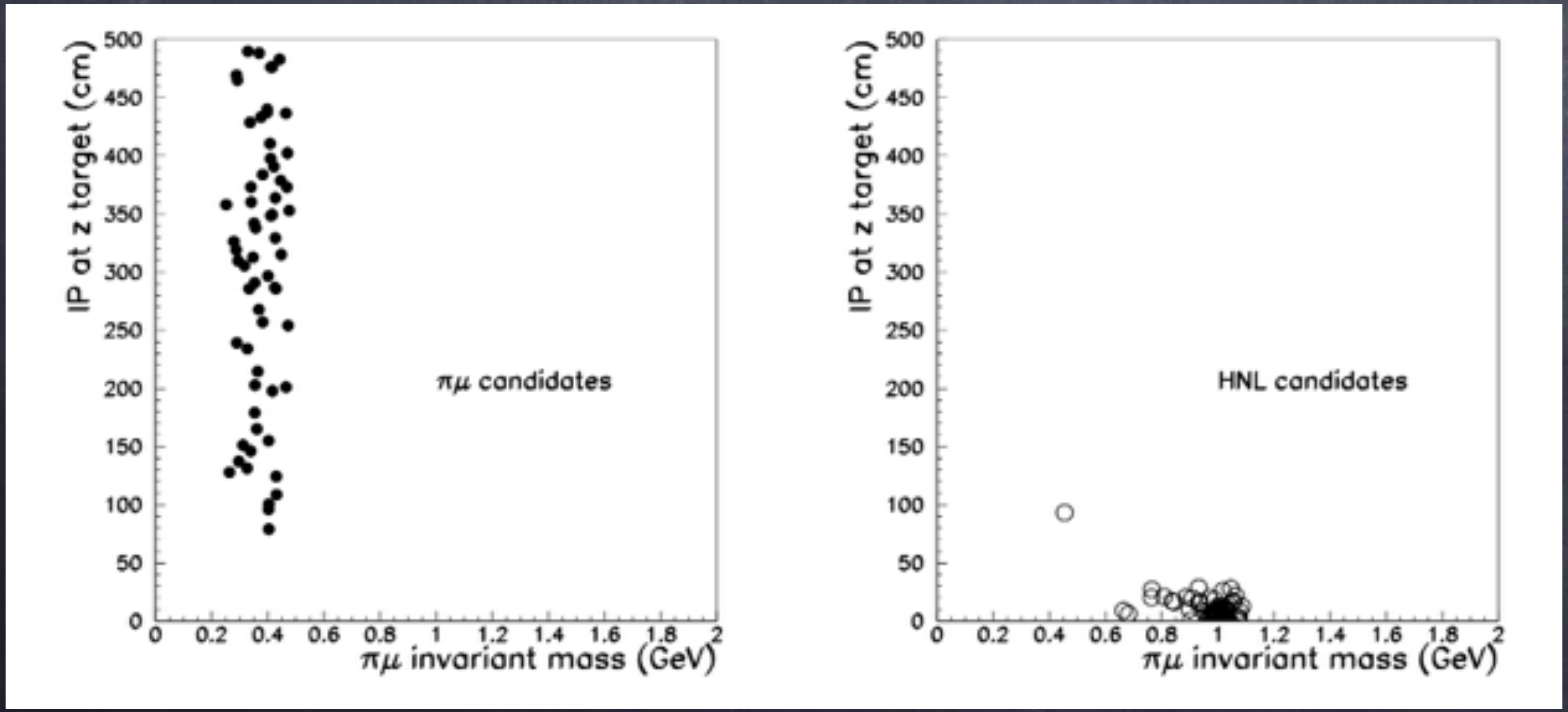
# Decay Volume




- Vacuum tank (similar to NA62) with 1e-2 mbar (instead of 1e-5 mbar)
- NA62-like straw chambers, 120um resolution and 0.5% X0/X
- LHCb-like magnet 0.5Tm over 5m
- LHCb-like shashlik calorimeter
- Veto chambers at the entrance of the vacuum tank to veto muons and strangeness from surroundings

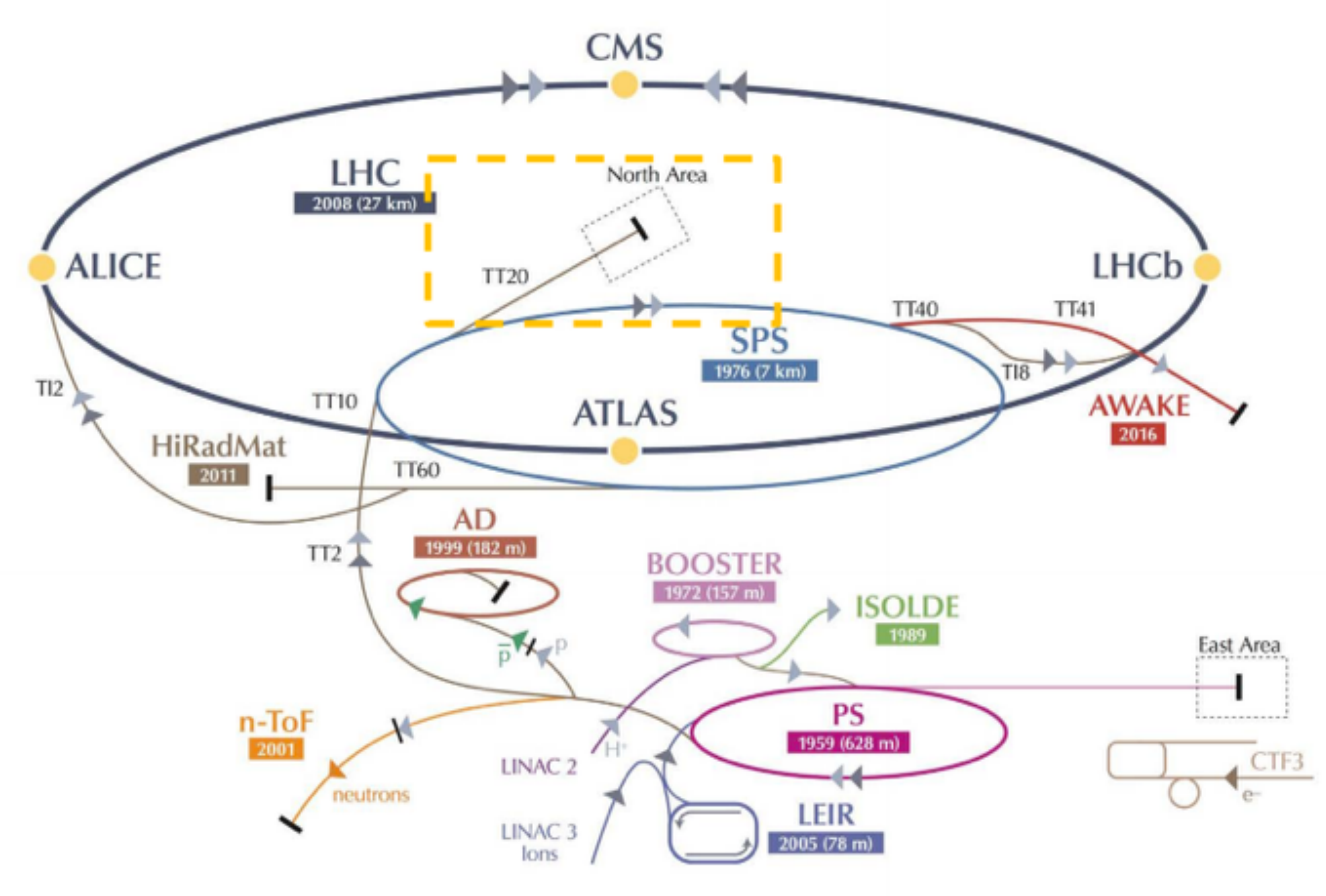
# Background rejection

- $2 \times 10^4$ neutrino interactions per $2 \times 10^{20}$POT in the decay volume at atmospheric pressure, negligible at $10^{-2}$mbar
- $K_L$ production from $\nu + A \rightarrow K_L(\rightarrow \mu\nu\pi)X$
- 10% $\nu$ interactions produce $\Lambda$ and $K^0$ in acceptance
- Majority of the decays in the first 5m of the decay volume
- Muon filter to reduce background from muon DIS to a negligible level



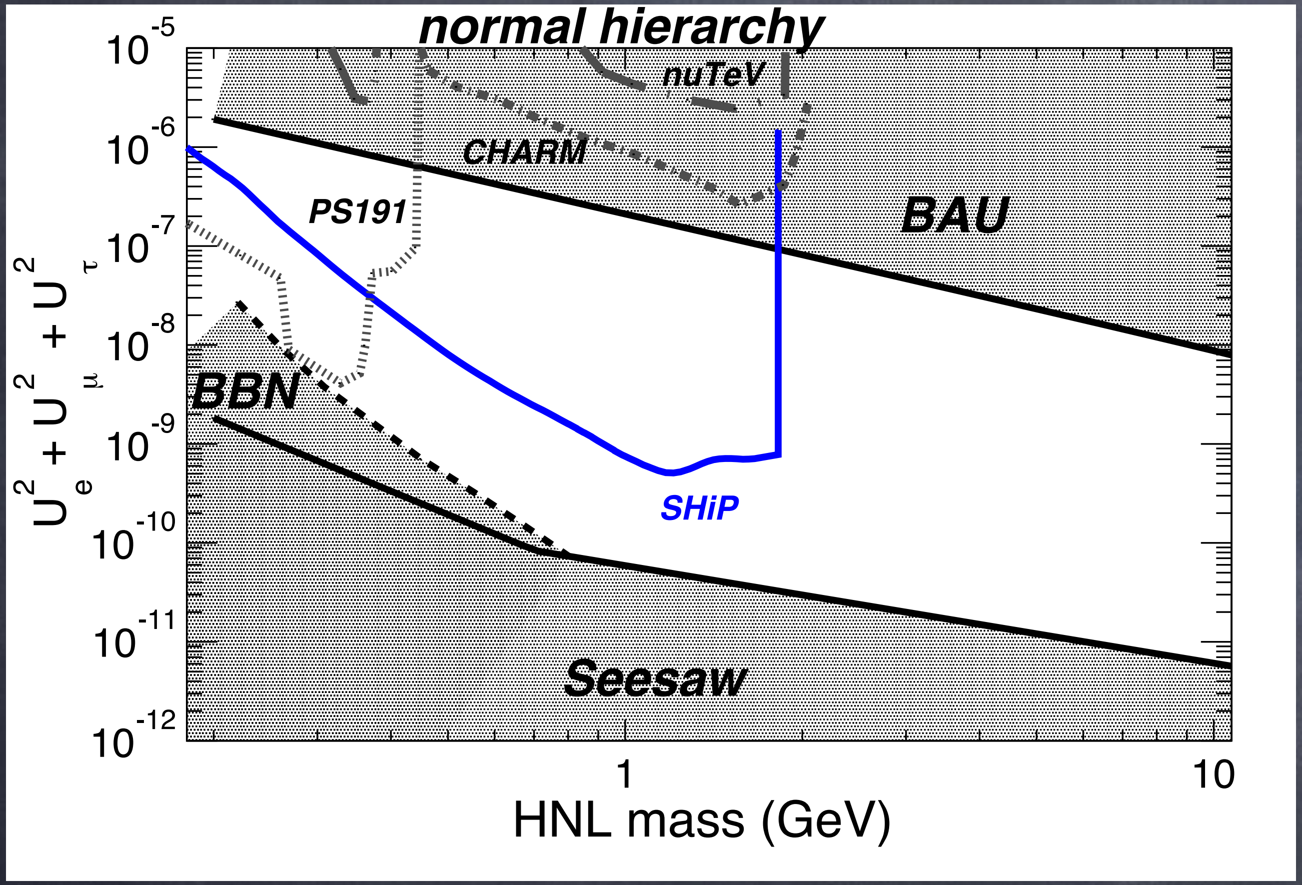

Fighting hard to design a zero background experiment

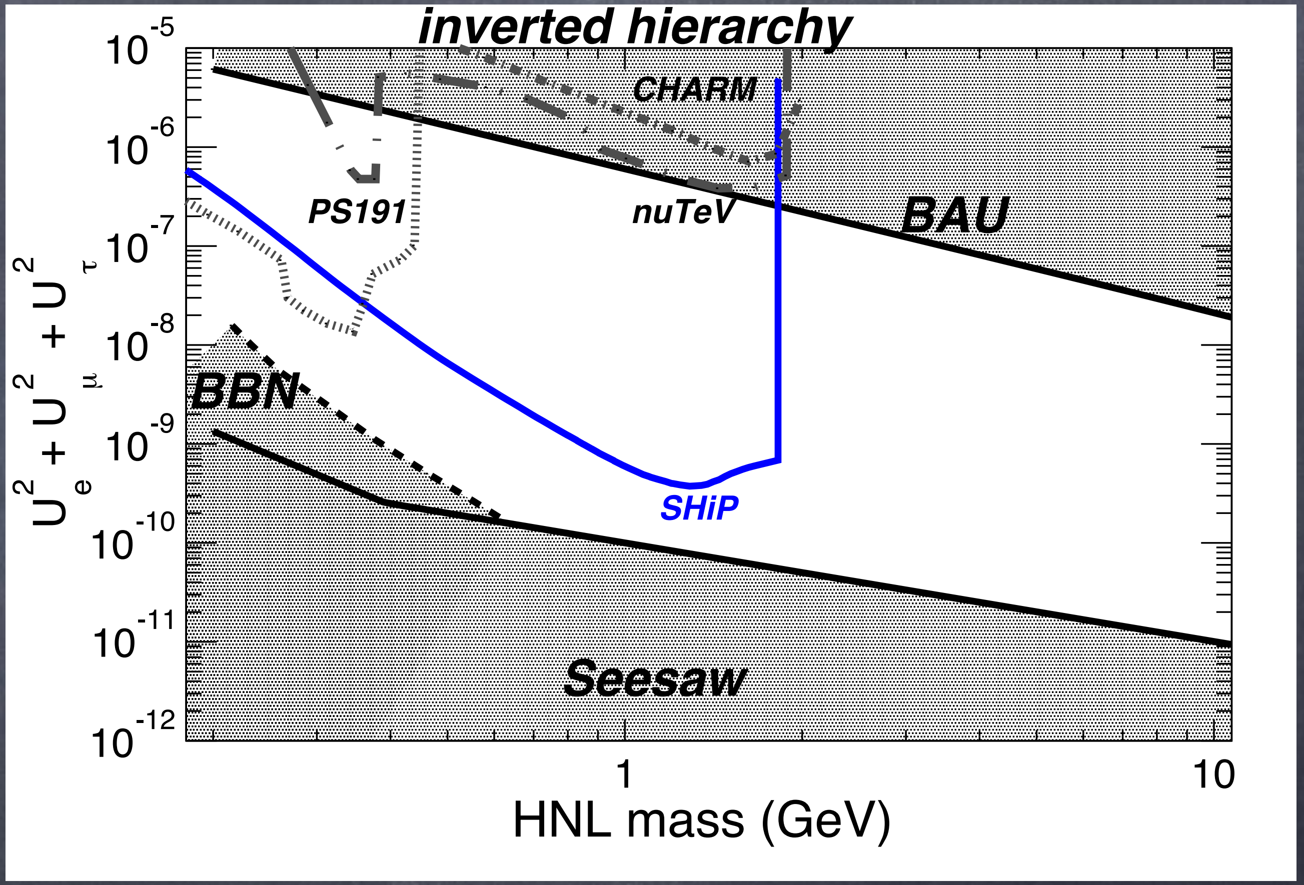
# CERN accelerator complex



Underground Structures (Tunnel/Cavern/Hall)
Surface or Partially Underground Structures (Target Hall/SB/Access Building)
Shafts + Tunnel access
Access Area + Car Park
New SHIP Beamline
Future SHIP Extension Area
DETECTOR HALL ~ 20 m wide
810
811
812
~ 40 m
~ 120 m
Access Bld. ~ 20m wide
~ 38 m
~ 25 m
Filter Tunnel
50
Service Bld. ~ 15m wide
TARGET HALL ~ 20m wide
Bypass tunnel
10
20
Technical Gallery
~ 140 m
Existing Technical Gallery GT801
~ 15 m
Tunnel
Access Bld. ~ 15m wide
TCC2
"Aux. Power Supply"
Extraction
~ 170 m
TDC2
JUNCTION CAVERN
~ 85 m
Splitter 2
TDC2
~ 100 m
SHIP extraction MSSB2117 Splitters
new access road
SHIP AREA on the French CERN Site in Prévessin

# Expected SHiP sensitivity to nuMSM



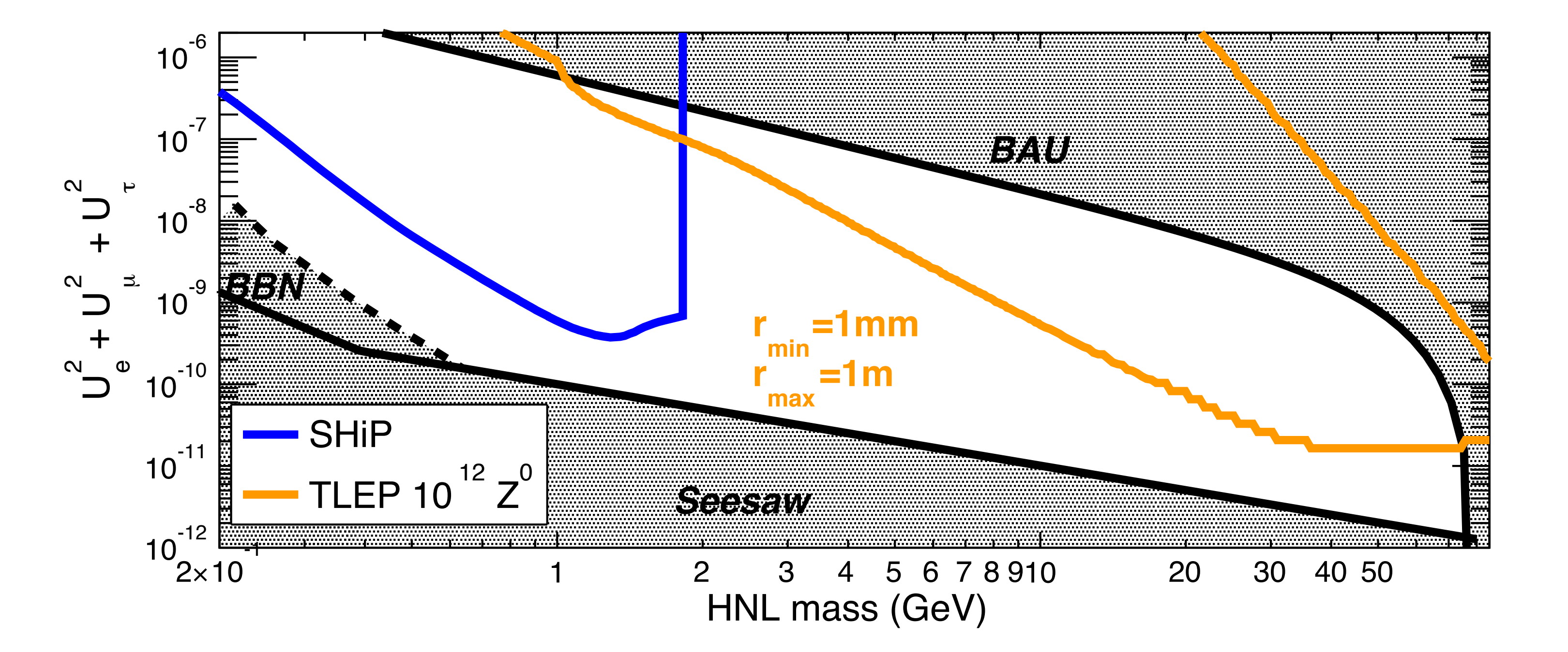

Scan most of the interesting region below the charm mass

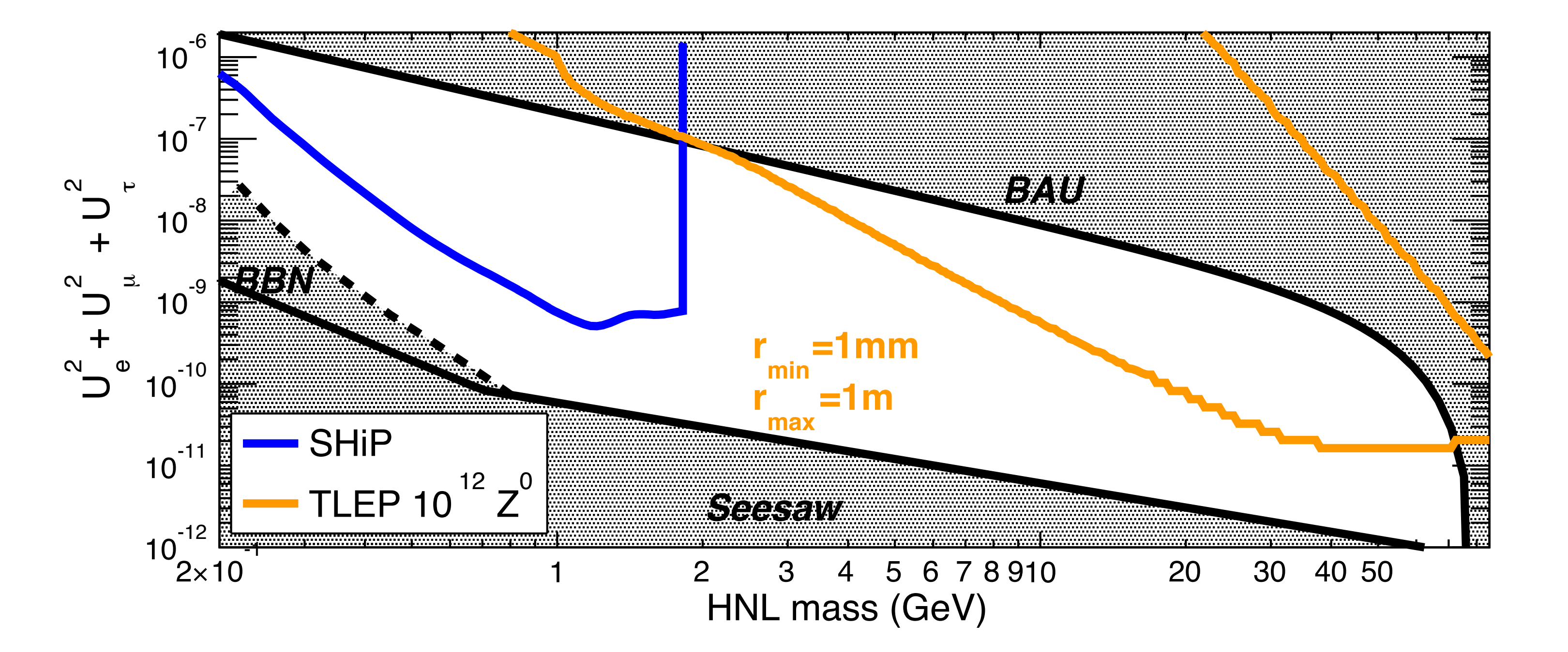
# What about higher masses

- Studied the sensitivity for TLEP, running at the $Z^0$ c.m.
- Assuming $10^{12-13}$ $Z^0$ produced (see talk by Alain Blondel at ICHEP)
- Experimental signatures:
  - 2 jets + lepton displaced from the PV
  - 2 leptons + (neutrino) displaced from the PV
- Assumption we can fight the $Z \to b\bar{b}$, $Z(Z/\gamma)^*$ and $W^*W^*$ backgrounds

# What about higher masses

*In collaboration with
E. Graverini, M. Shaposhnikov and A. Blondel



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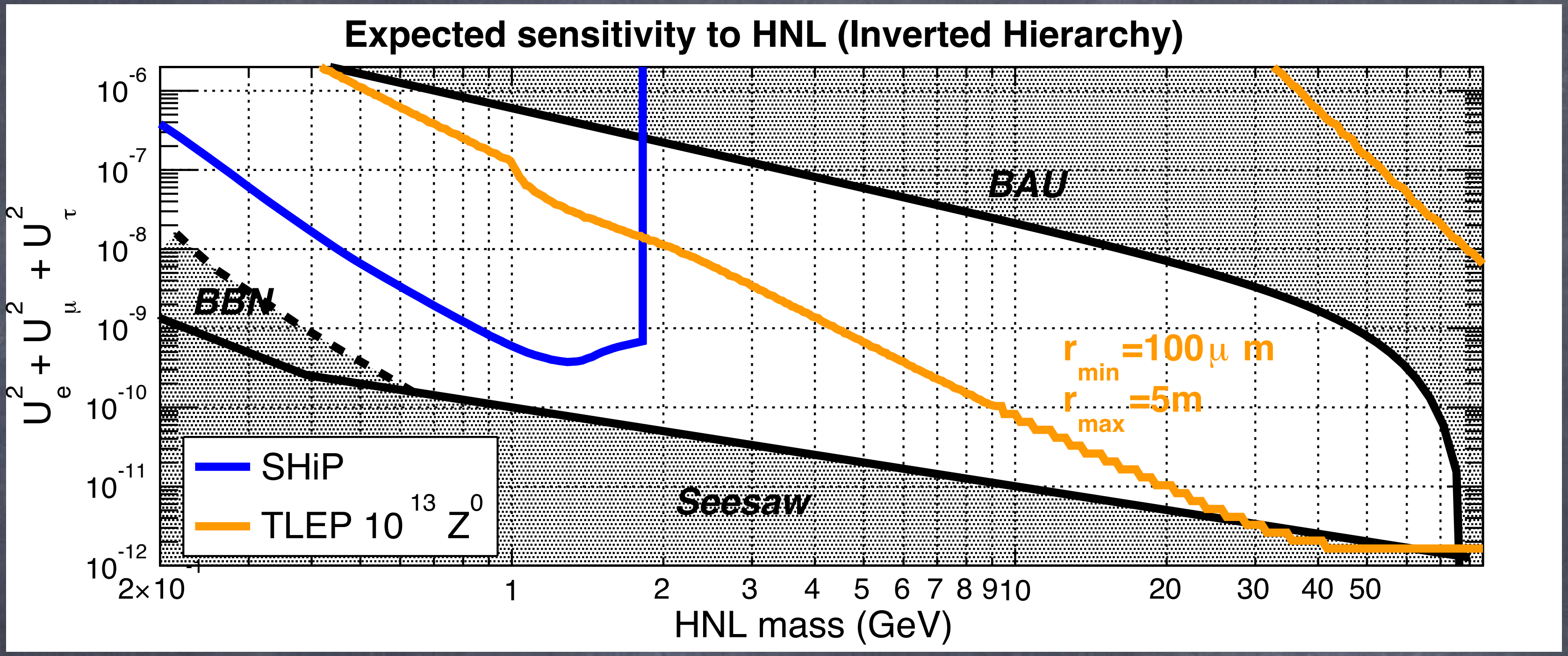
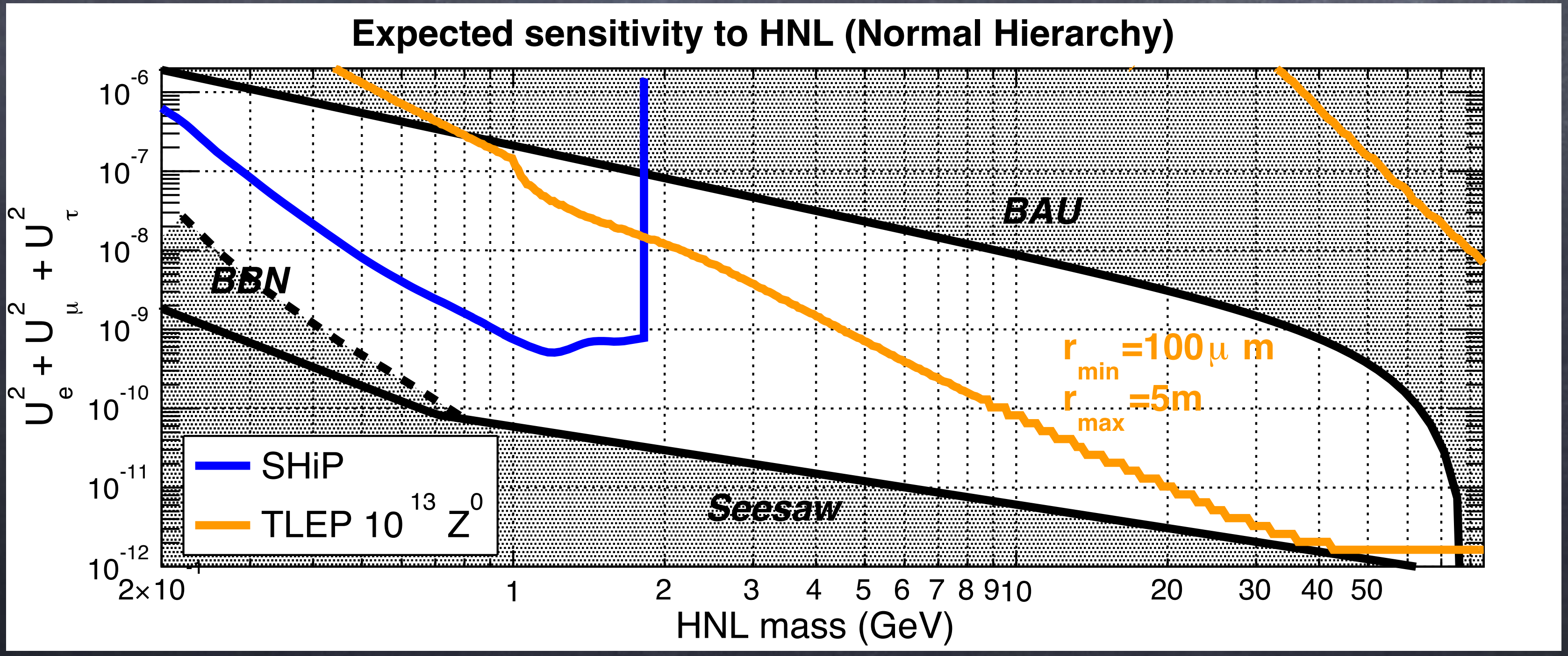
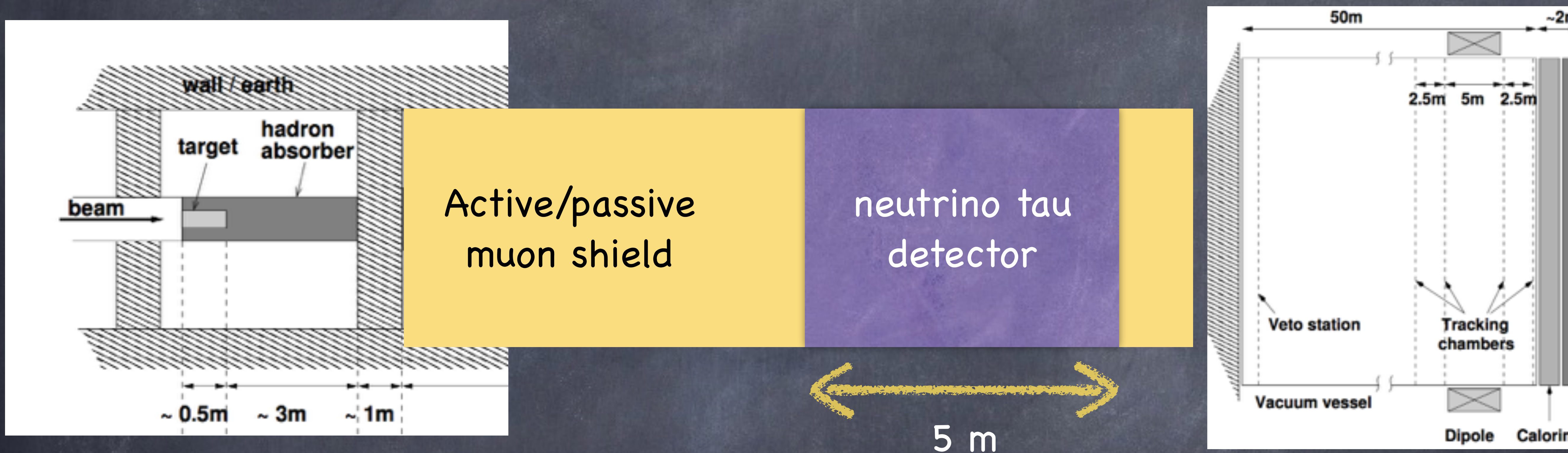


# Tau neutrinos

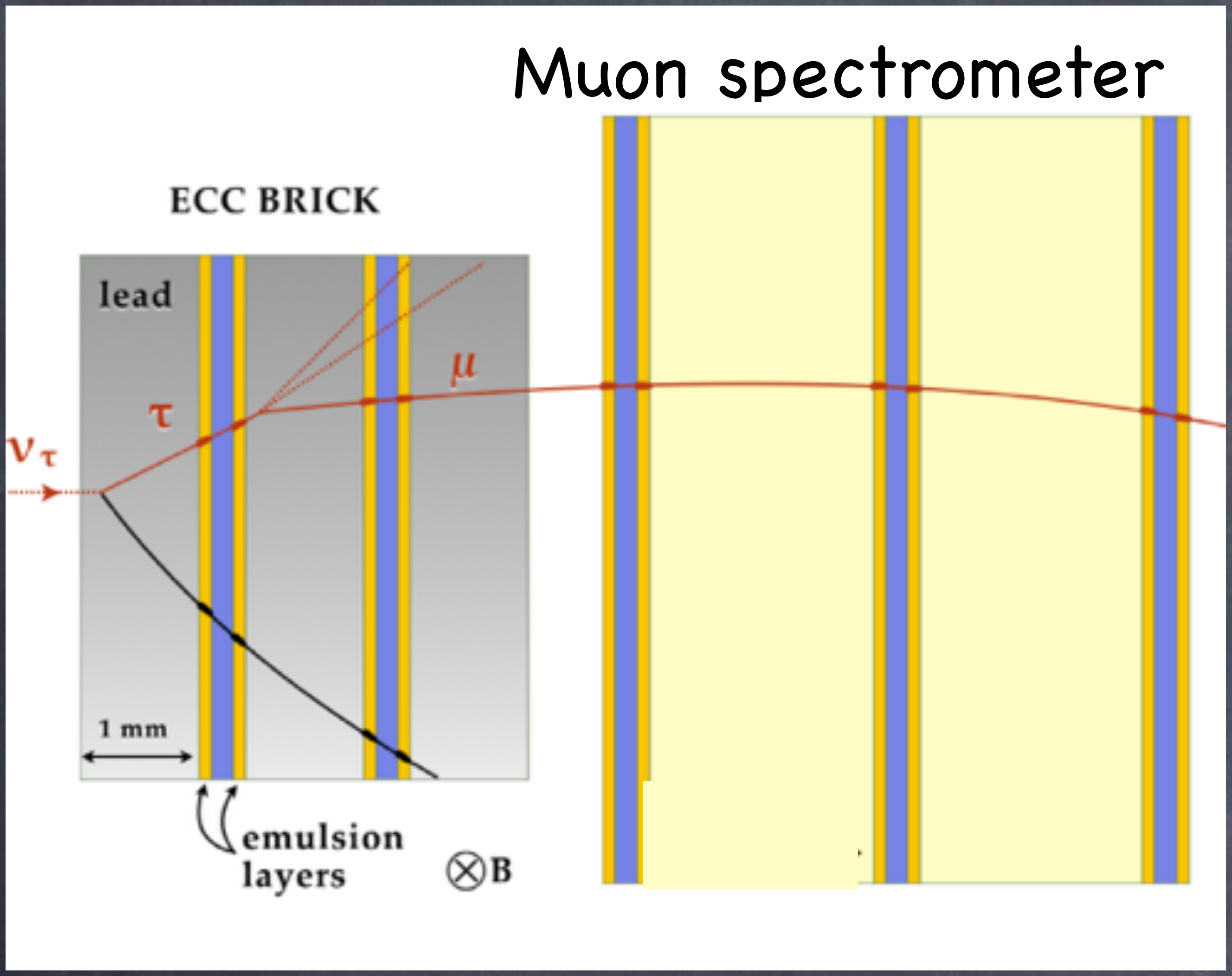


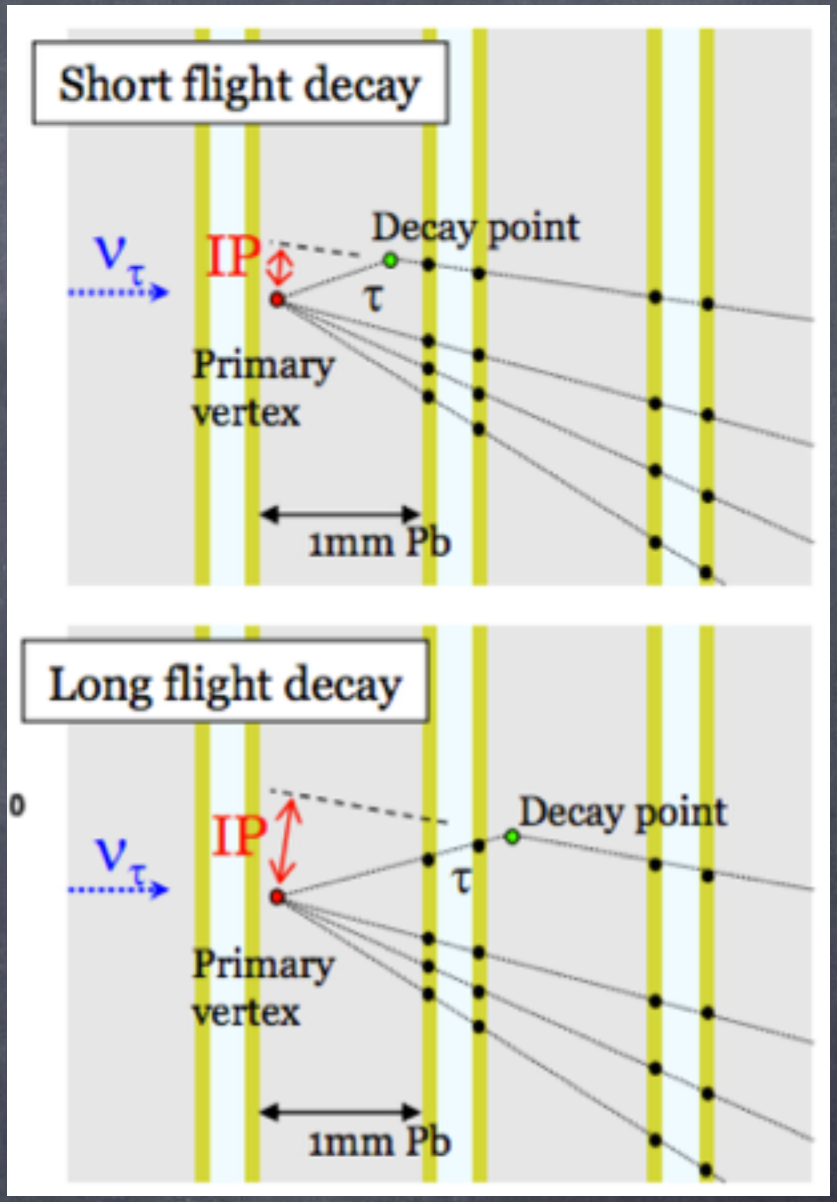

- The same optimization for sterile neutrinos in the GeV region also maximises the flux of $\nu_\tau$
- Source of $\nu_\tau$ and $\overline{\nu}_\tau$ is $D_s \to \tau\nu_\tau$
- Also high rate of $\nu_e$ from charm

# Tau neutrinos physics

- So far 4 $\nu_\tau$ events observed by OPERA and 9 by DONUT
- We expect between 3000-4000 reconstructed $\nu_\tau$ per $2 \times 10^{20}$ POT
- Physics goals:
  - First observation of $\overline{\nu}_\tau$, which has never been observed
  - $\tau_\nu$ and $\overline{\nu}_\tau$ cross section measurements
  - Charm physics with $\tau_\nu$ and $\overline{\nu}_\tau$
  - $\nu_e$ cross section at high energy to measure charm hadron production (possible normalization for HNLs)

# Tau neutrino detector



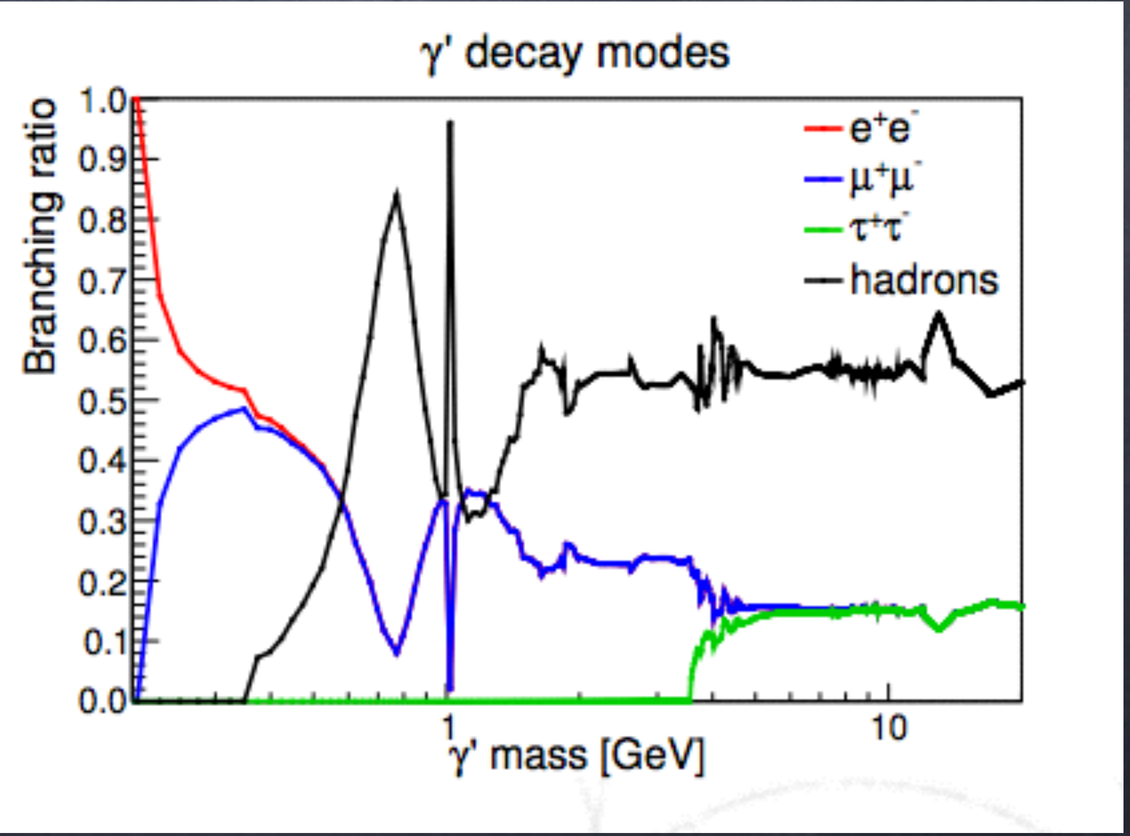




- $\nu_\tau$ target: Opera-like bricks, laminated lead and nuclear emulsions (for micrometric resolution)
- 750 Opera-like bricks, to be replaced 10 times
- Muon spectrometer to measure charge and momentum and give time stamp

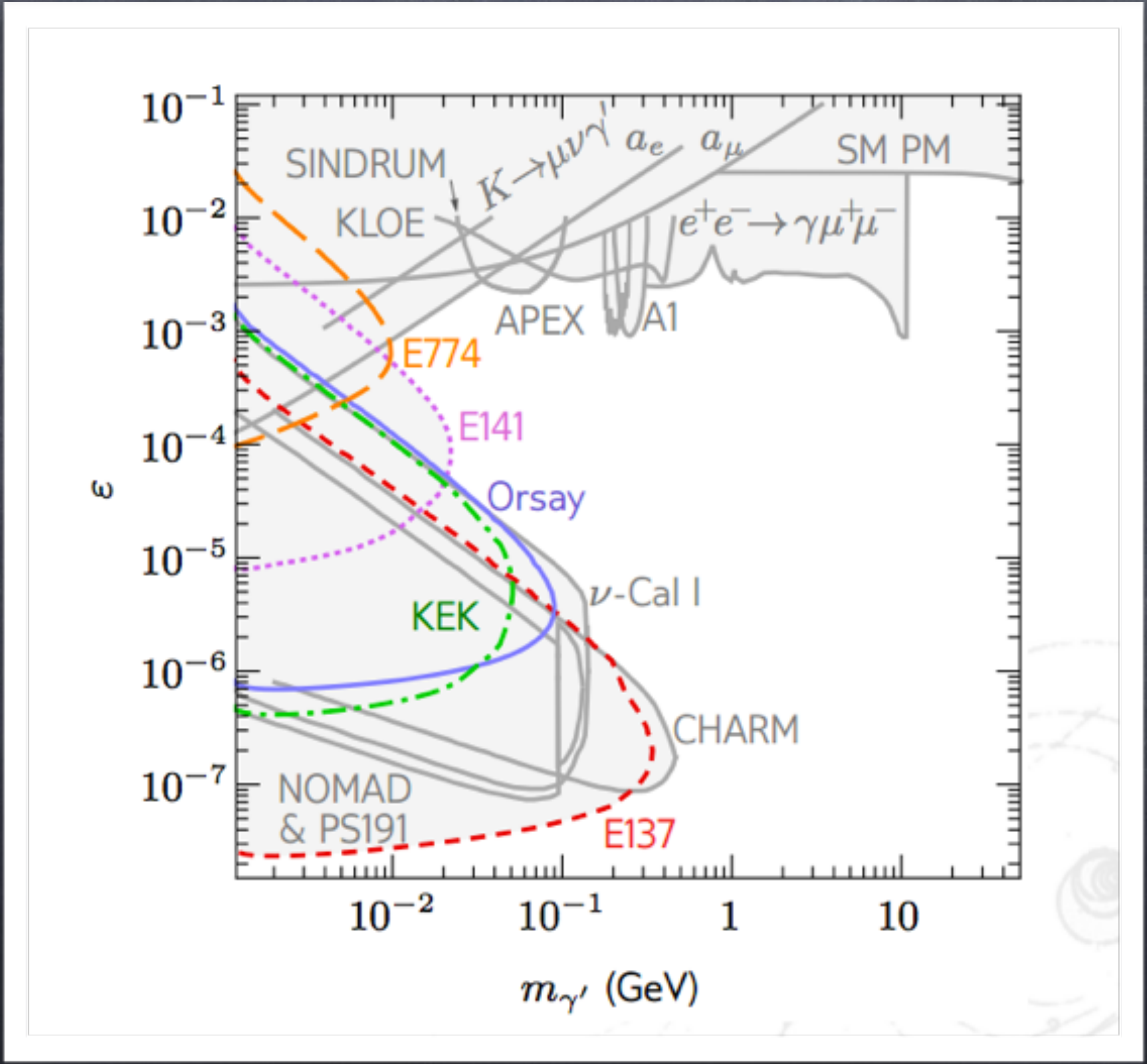
# Dark Photon

- Models with hidden sector offer a natural candidate for DM
- Many of these models predict the existence of a massive Dark Photon, which can mix with the SM photon, with a strengh $\epsilon$
- $\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_{hidden} + \frac{\epsilon}{2} A'_{\mu\nu} F^{\mu\nu}$
- Production:
  - $p + A \to p'\gamma + A$
  - Meson decays, e.g. $\pi^0 \to \gamma\gamma$

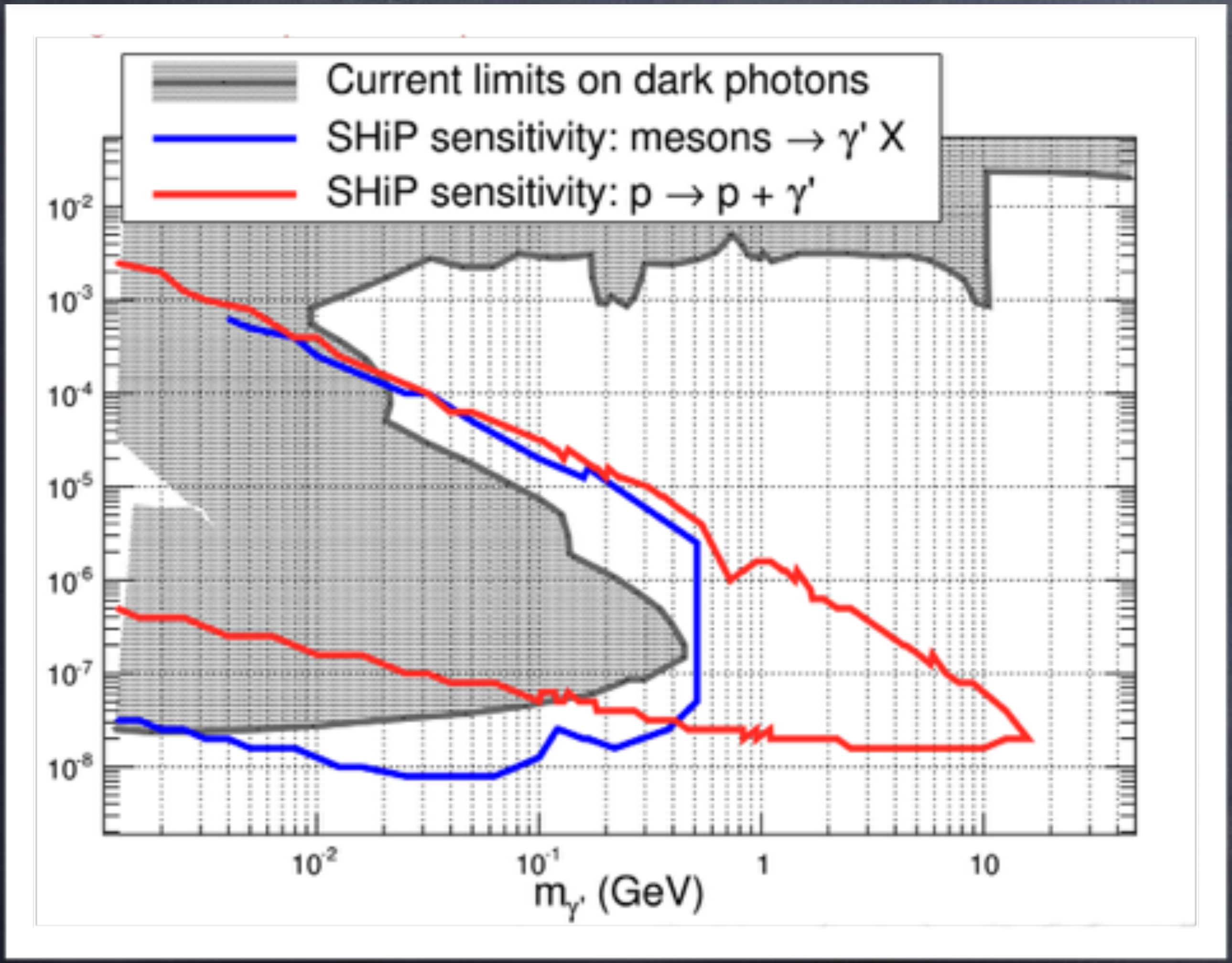
| Mass interval (GeV) | Process | $n_{\gamma'}/p.o.t$ |
|---|---|---|
| $m_{\gamma'} < 0.135$ | $\pi^0 \to \gamma\gamma'$ | $\varepsilon^2 \times 5.41$ |
| $0.135 < m_{\gamma'} < 0.548$ | $\eta \to \gamma\gamma'$ | $\varepsilon^2 \times 0.23$ |
| $0.548 < m_{\gamma'} < 0.648$ | $\omega \to \pi^0\gamma'$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

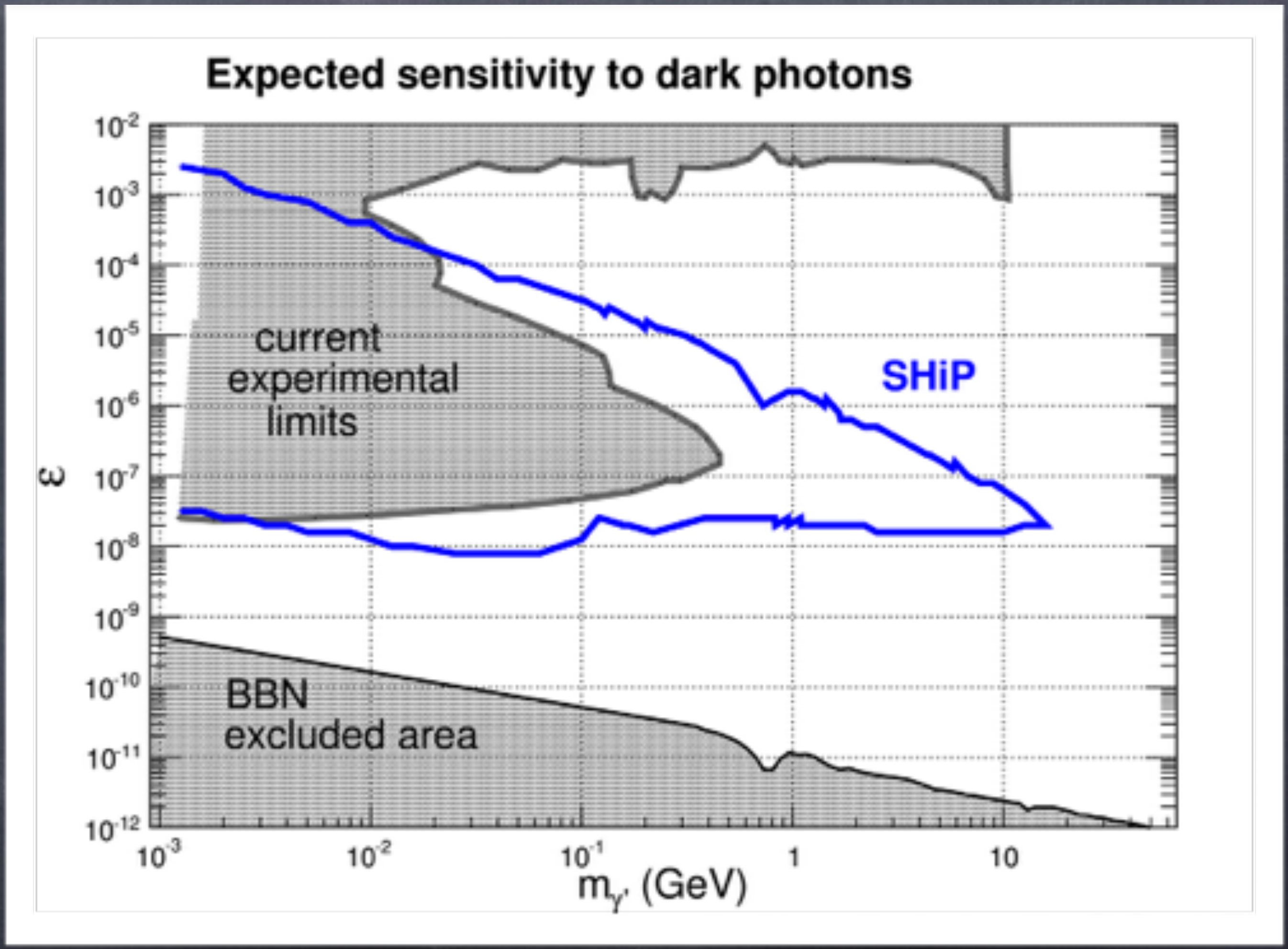


# Present status



# SHiP sensitivity to DP




SHiP can strongly improved bounds on Dark Photons

# Other searches

Many other models can be tested

- Models with light scalars mixing with the Higgs boson, i.e. 2HDM + singlet, light inflaton, ... see for instance J.Clarke arXiv:1310.8042, Bezrukov and Gorbunov arXiv:1303.4395
- Models with light pseudoscalars, see for instance arXiv:1008.0636
- Models with light sgoldstino, see for instance arXiv:hep-ph/0007325
- In general models with long leaved very weakly interacting particles

# Conclusions

- Good physics case for a new beam dump experiment at SPS
  - Search for sterile neutrinos in the GeV region, in particular $\nu$MSM
  - Search for long lived very weakly interacting particles
  - $\nu_\tau$ physics
- The SHiP collaboration submitted a Expression of Interest at SPSC, and aims to submit a Technical Proposal next year
- We had the first workshop and collaboration meeting in Zurich (cern.ch/ship/SHIP_workshop.html)
- More than 20 institutes expressed interest in participating to the TP

If you are interested get in touch!
www.cern.ch/ship

# Fluctuat nec mergitur


She is tossed by the waves but does not sink

# Beam

| | Baseline |
|---|---|
| Beam | protons |
| Momentum [GeV/c] | 395 or 405 |
| Beam Intensity [$10^{13}$ p/cycle] | 4.5 |
| Cycle length [s] | 7.2 |
| Spill duration [s] | 1.0 |
| Average power [kW] | 300 |
| Expected r.m.s. spot size (H/V) [mm] | 6/6 |

# Tracking

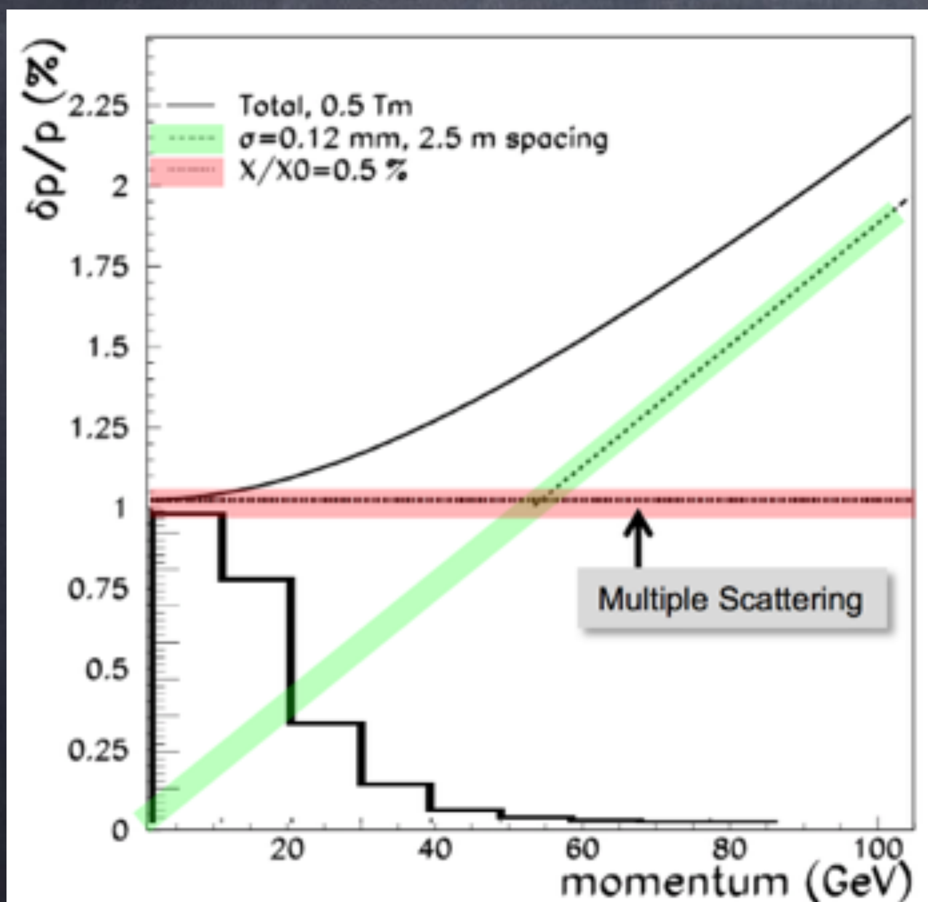
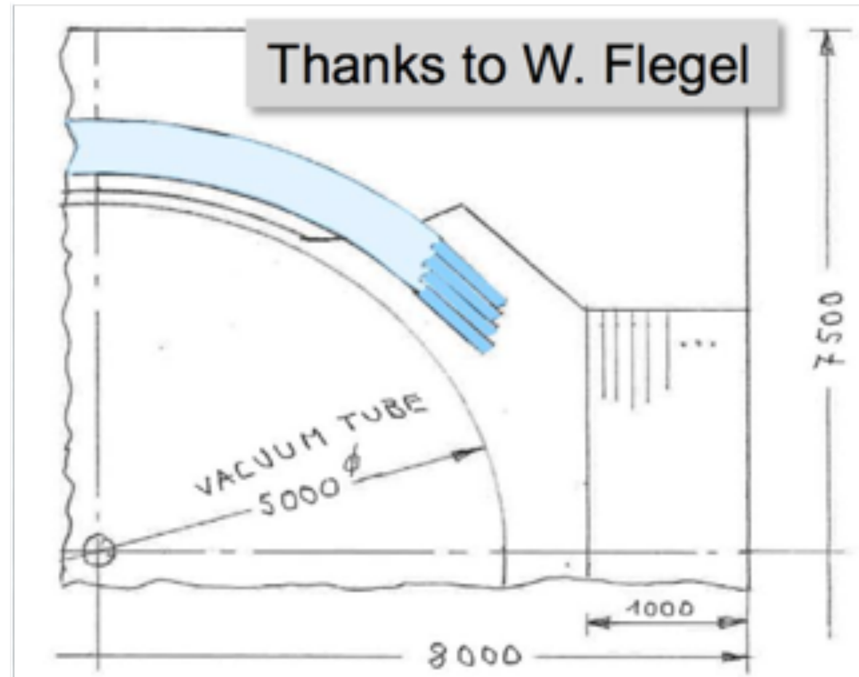



Figure 11: Estimated momentum resolution of the spectrometer (solid line) with separate contributions from multiple scattering (dotted line) and chamber resolution (dashed line).




Given such a magnet and tracker, we are still dominated by MS (0.5% total x/x0 for 4 views/station)

With a yoke with outer dimension of $8.0 \times 7.5 \times 2.5\,\mathrm{m}^3$, and two Al-99.7 coils, the proposed magnet provides a peak field of $\sim 0.2\,\mathrm{T}$, and a $\int BdL \approx 0.5\,\mathrm{Tm}$ over a length of $\sim 5\,\mathrm{m}$. For comparison, the LHCb magnet mentioned above contains $\sim 40\ \%$ more iron for its yoke, and dissipates three times more power.

# Straw mass production: main parameters

**Material:**

Mylar (PET), 36 μm with Al (0.75 μm at both side)
or Cu+Au: (0.050+0.020 μm )

**Material budget (per view):**

| | |
|---|---|
| Straws | - (0.93% - 0.95) $\%X_0$ (450 straws) |
| Wires | - 0.0046 $\%X_0$ (Luma 861) |
| Gas mixture | - 0.010 $\%X_0$ ($CO_2$ 80%+$CF_4$ 5%+Isobutene 5% or Ar 70%+$CO_2$ 30%) |
| Inner supports | - 0.020 $\%X_0$ (Ultem bushes) |

**Straw dimensions and quality:**

| | |
|---|---|
| ∅ | - 9.775±0.025 mm (9.2 mm effective area) |
| Length | - 2360 mm (2100 mm active area) |
| Straightness | - 0.1 mm |
| Elongation | - 2.0 mm per m at 1 bar |
| ∅ increasing | - 0.08 mm per 1 atm overpressure |
| Gas flow | - 2.56 $cm^3$/min (70 $cm^3$/min per view) |

**Production technology and rate:**

Ultrasonic welding, up to 400 mm straw per 1 minute

# Geometry

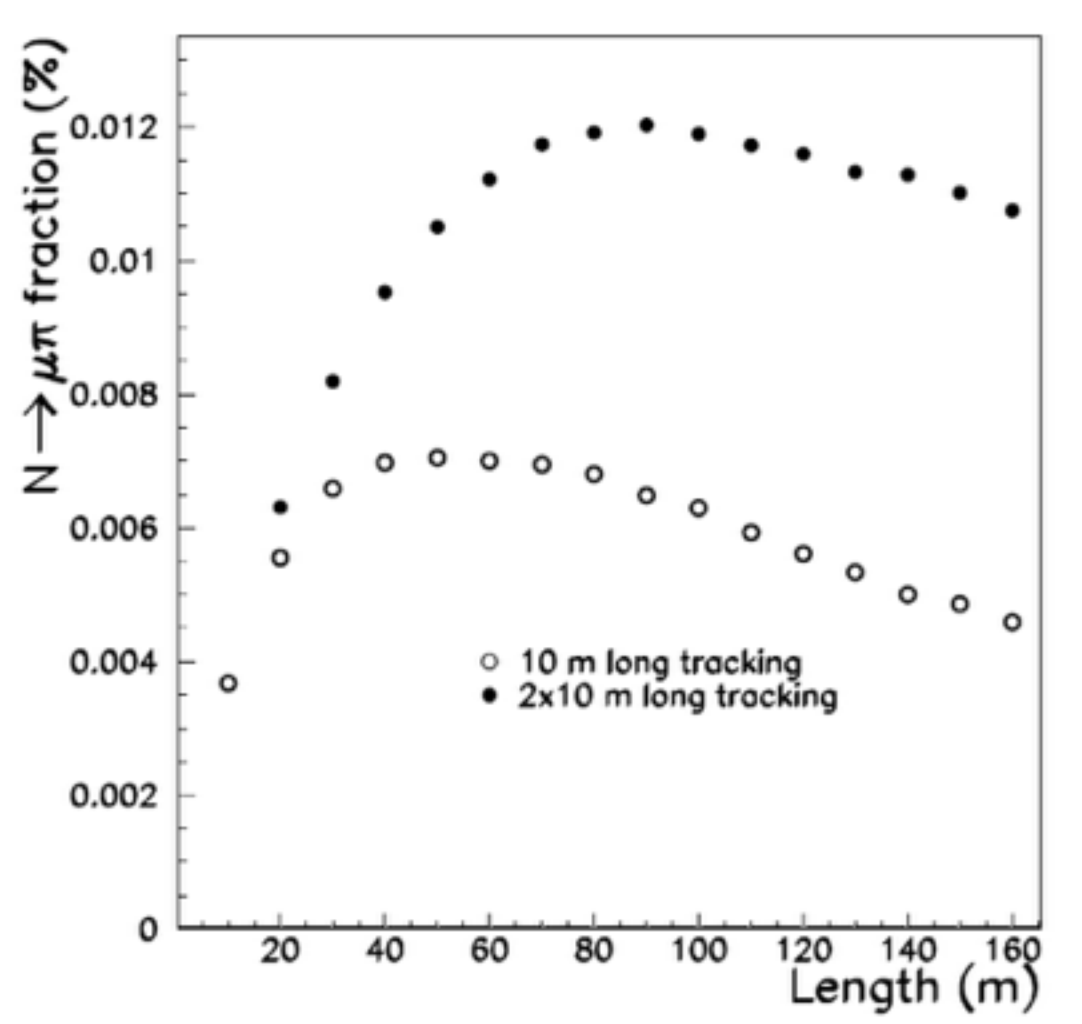
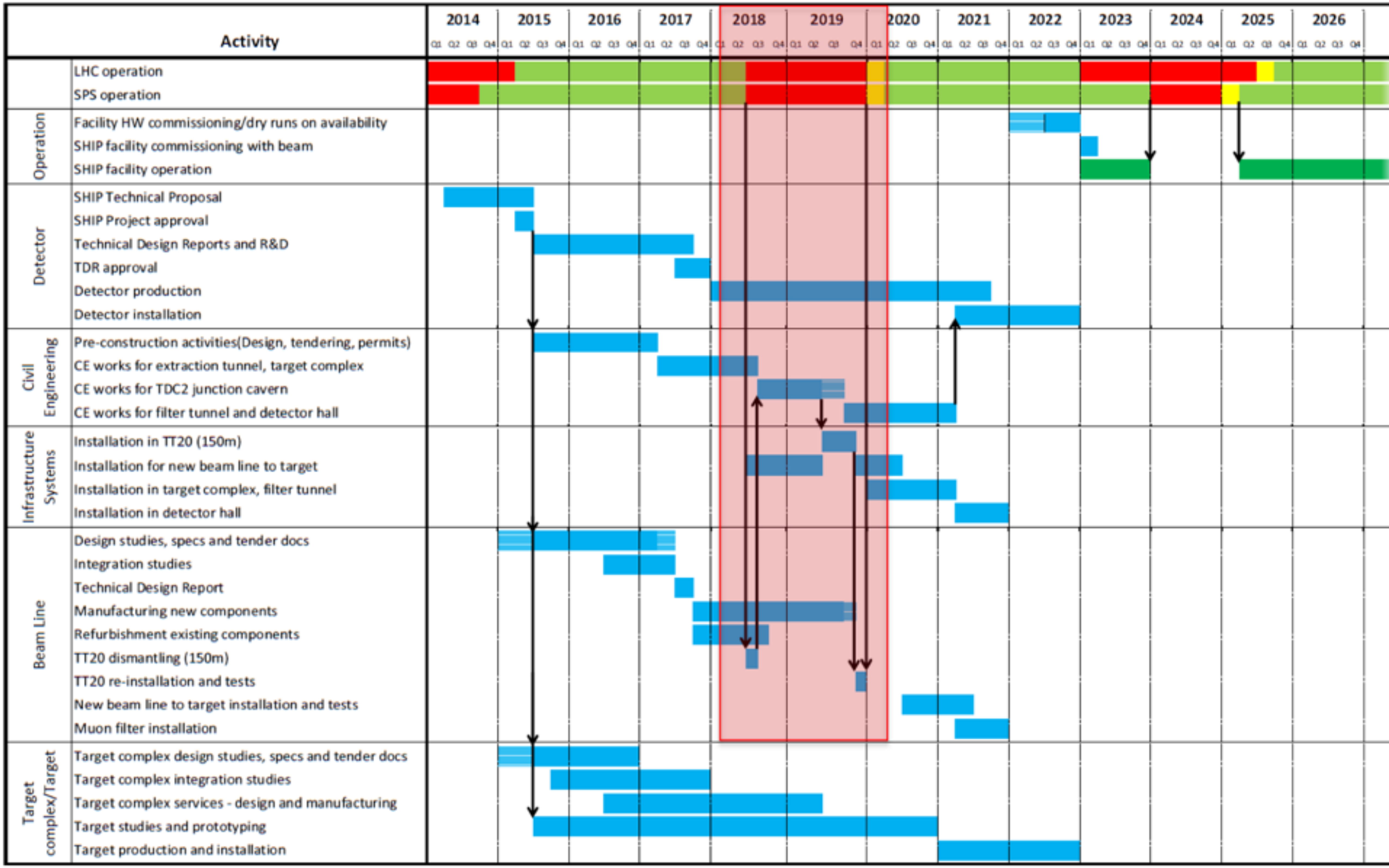



Figure 8: Fraction of HNL in the detector acceptance as a function of the length of the fiducial volume. Open circles: a single spectrometer following a fiducial volume of a given length. Full circles: two spectrometers in series, each following a fiducial volume of half the given length. The spectrometer length is fixed to 10 m.


Activity
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
Q1 Q2 Q3 Q4
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

SHiP

# Trigger

Compare SHiP↔LHCb-upgrade again:

- SHiP: $10^5$ $\mu$/s (/spill of 7 s), only 1 track/event.
- LHCb (2019): $10^9$ tracks/s, in complicated events.
  Estimated CPU-farm: $\sim 3-4$ MCHF.

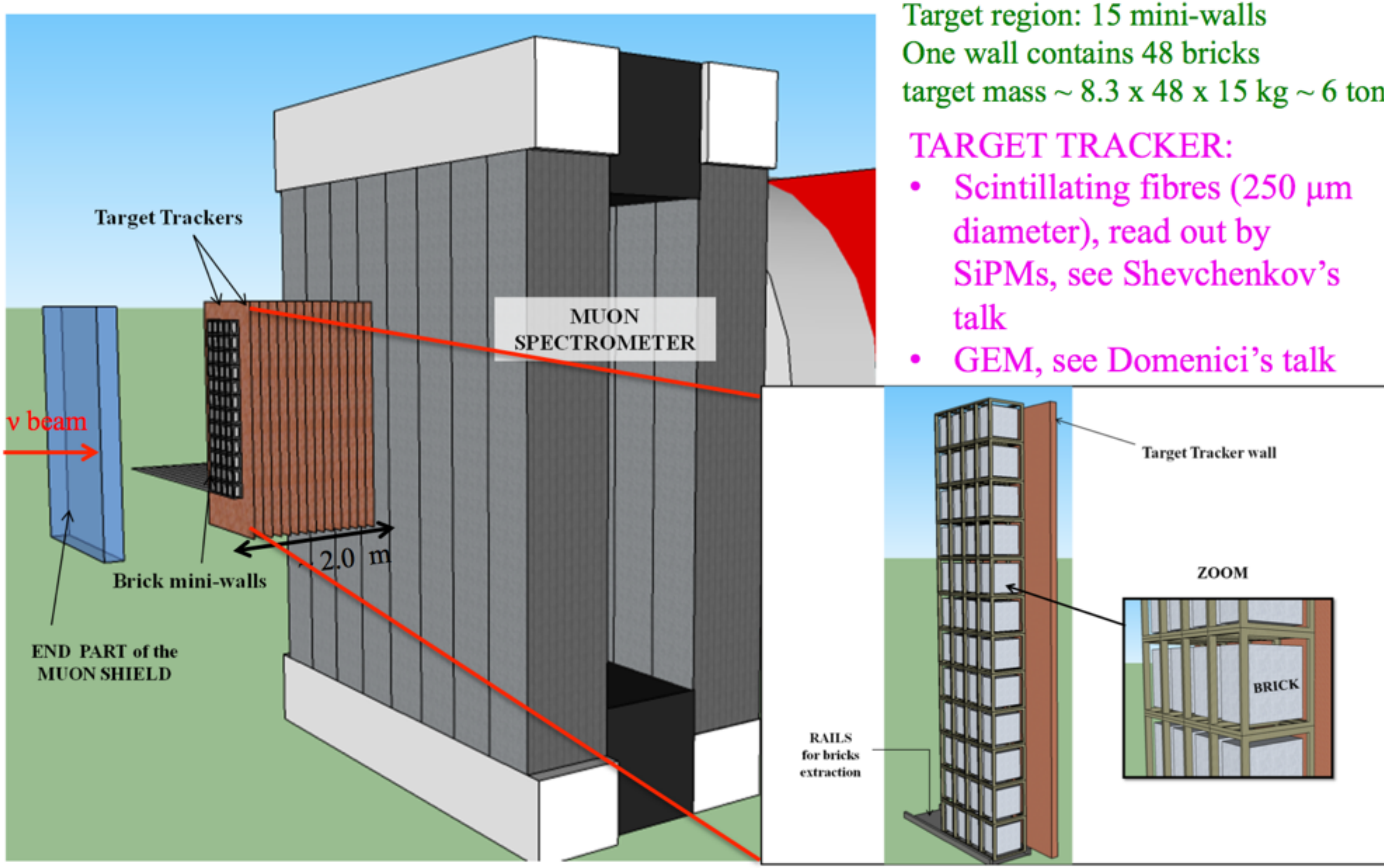
Conclusion: SHiP "farm" is tiny, i.e. one node with few dozen CPU cores.

Storage: write all "events" (10 kB/event?), with at least 1 track reconstructed.

- SHiP: $10^5 \times 10$ kB $\times 10^6$ spills= 1 pB/year.
- LHCb-upgrade: 20(?) kHz $\times 100$ kB/event $\times 5.10^6$ s=10 pB/year.

Or, if we do not like to write 1 pB/year:
Veto events with hits in VETO, which do not point at emulsion: order(s) of magnitude less?

# Detector design: first option




Target region: 15 mini-walls
One wall contains 48 bricks
target mass ~ 8.3 x 48 x 15 kg ~ 6 ton

TARGET TRACKER:

- Scintillating fibres (250 μm diameter), read out by SiPMs, see Shevchenkov's talk
- GEM, see Domenici's talk

Wall thickness ~ 13 cm: 8 cm brick + 5 cm tracker plane

# Working hypotheses

- Detector located ~60m from the proton target
- Charm production cross-sections in p-W affected by large uncertainties
- Compare with DONUT to extrapolate the expected numbers
- Energy dependence of $\sigma_{cc}$ and $\nu_\tau$ cross-section, acceptance: production ~ 0.36, detector acceptance ~ 0.2, energy dependence of the $\nu_\tau$ cross-section ~0.52 → DONUT/SHIP ~ 26
- 2 x $10^{20}$ pot for SHIP compared to 3.6 x $10^{17}$ DONUT → ~ 550 in favour of SHIP
- Overall rate SHIP/DONUT ~ 20
- DONUT observed 9 events with a background of 1.5 → 7.5±3 (40% error)
- 150 events expected with the same mass (260 kg)
- Measurement of $\nu_\tau$ and anti-$\nu_\tau$ cross-section, including the study of structure functions sets the scale for the mass: ~ 6 tons for ~ 3400 $\nu_\tau$ interactions
- Assume OPERA-like bricks (8.3 kg) and wall target structure: ~ 750 bricks

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