SHiP

SEARCH FOR HIDDEN PARTICLES

A new experiment proposal

Neutrino Physics with the SHiP experiment

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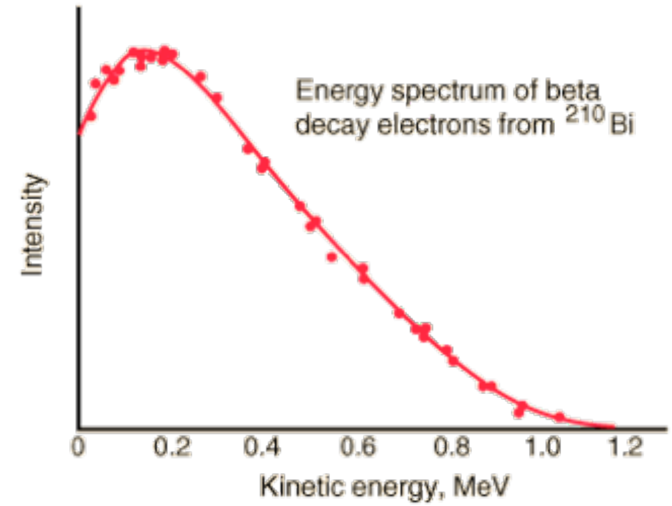
Outline of the talk

- The physics case for a beam dump facility
- The SHiP experiment
  - The detector for hidden particles
  - The tau neutrino detector
- Neutrino physics program: active neutrinos and heavy neutral leptons

History lesson - 1930s:

- Back then, the "Standard Model" was photon, electron, nucleons

- Beta decay: $n \to p + e^-$



Continuous spectrum!

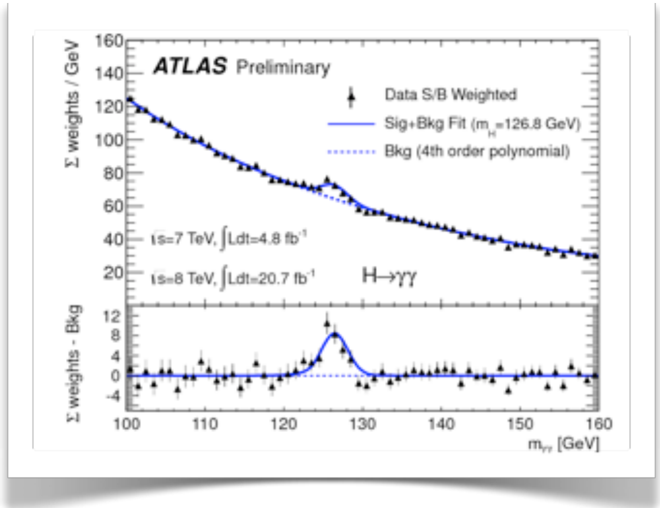
- Pauli proposes a radical solution - the neutrino!

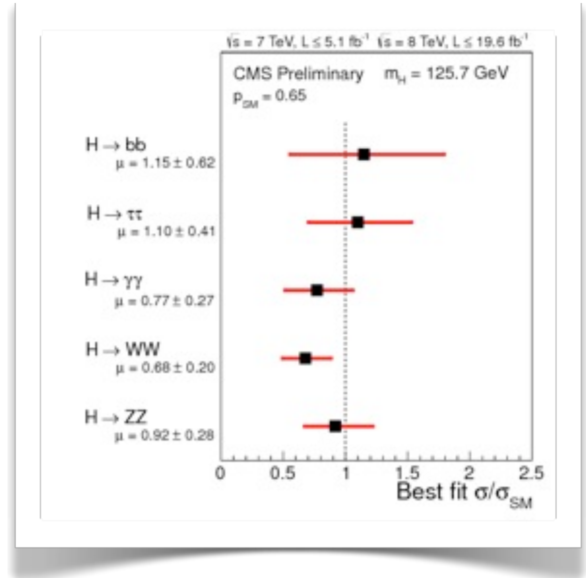
$$n \to p + e^- + \bar{\nu}$$

- Great example of a hidden sector!
    - neutrino is electrically neutral (QED gauge singlet)
    - very weakly interacting and light
    - interacts with "Standard Model" through "portal" - $(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu)$

Today, 2014 - Where are we?

- Higgs!
- Triumph of the Standard Model!





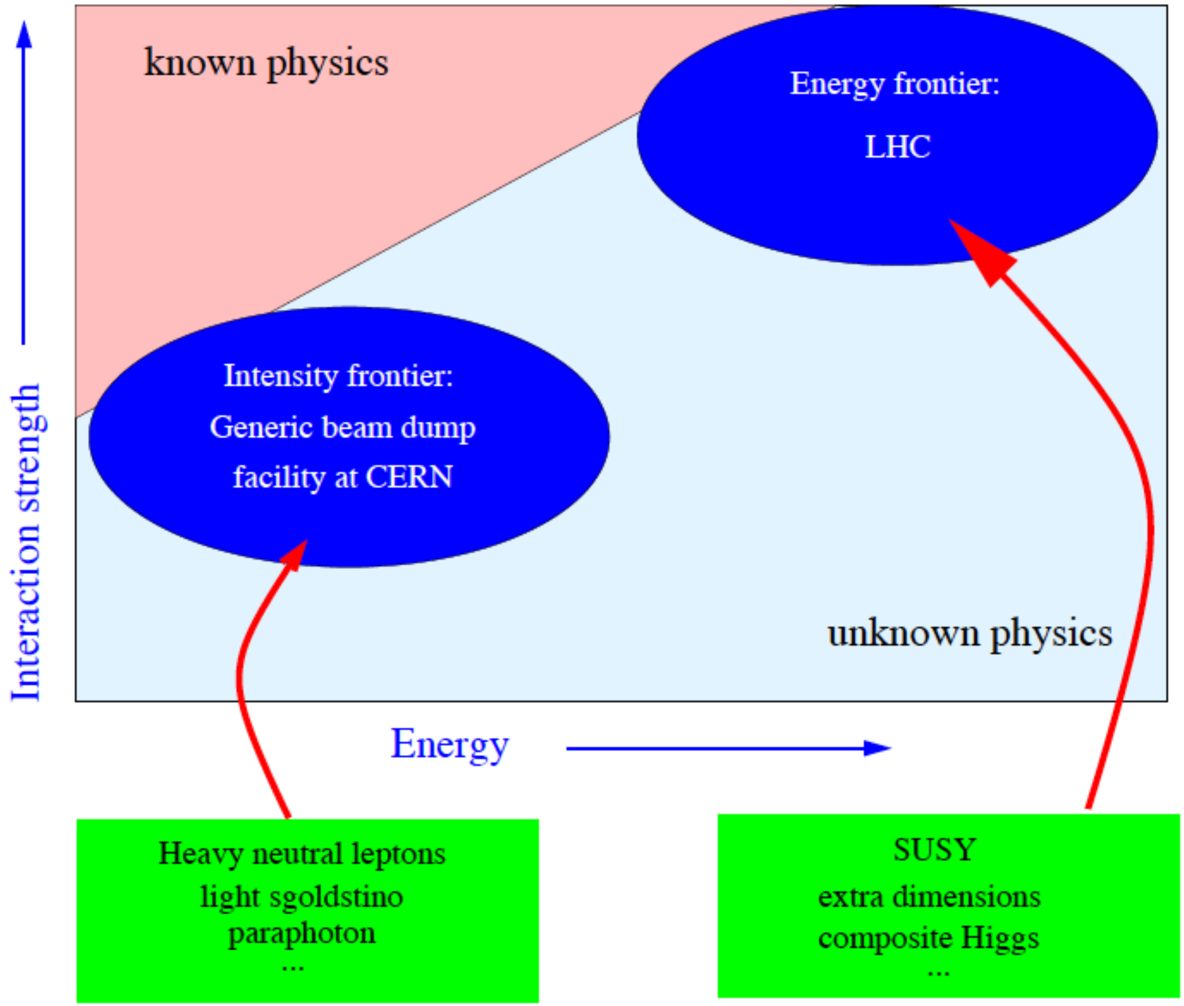
- Still, many reasons to believe there is new physics

Theoretical: naturalness (Higgs, CC), flavor, Strong CP, Unification, Gravity ...

Empirical: Dark Matter, Neutrino Oscillations, Baryon Asymmetry

- Unfortunately, there are no guarantees of discovery
- All searches for new physics are now fishing expeditions!

Search for new physics with accelerators: Physics case for a beam dump facility

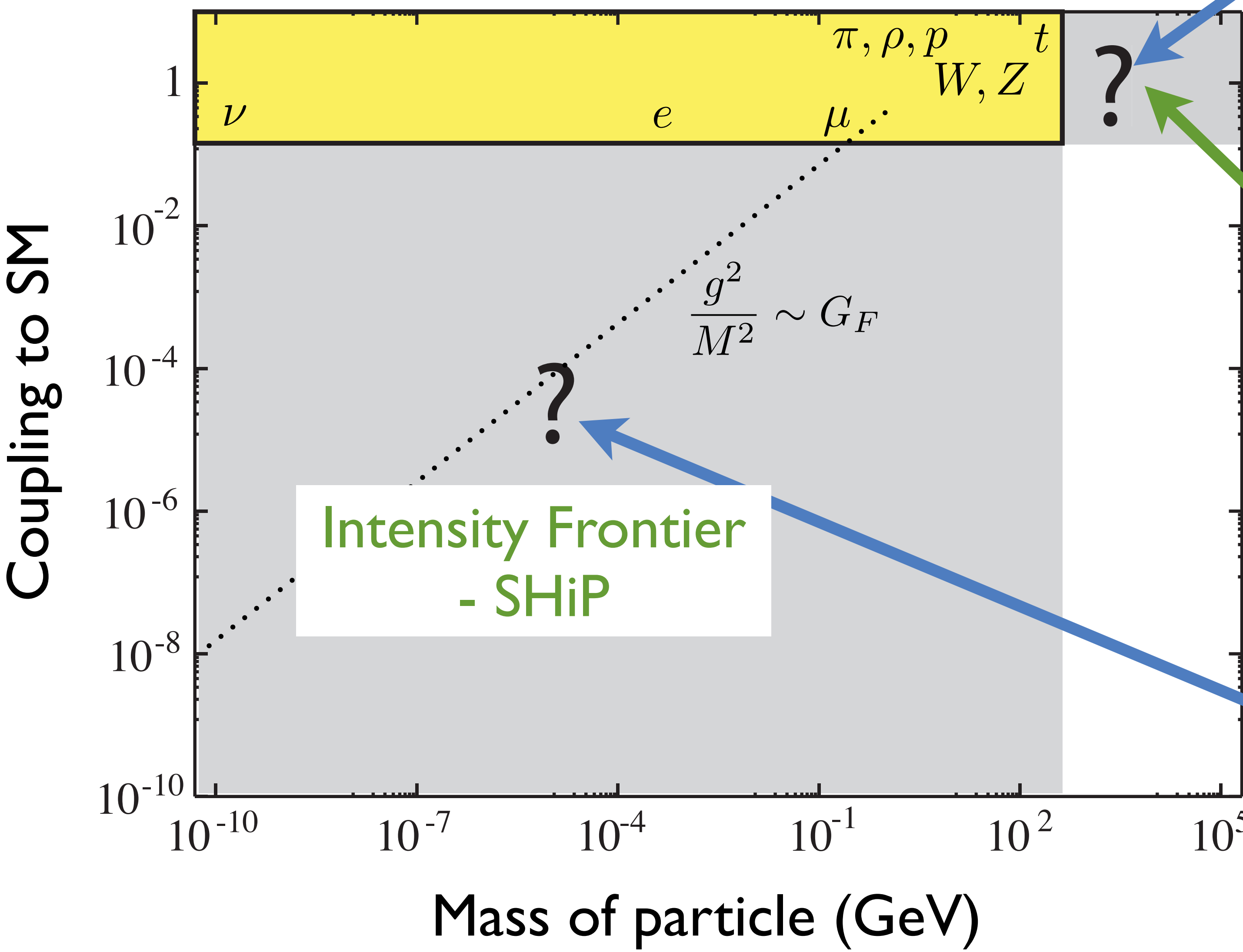


hidden sector:
HNL: baryon asymmetry of the Universe, dark matter, neutrino masses
sgoldstino, light neutralino: SUSY
paraphoton: mirror matter, dark matter

Physics case for a beam dump facility

Where is the new physics?

EWSB, Hierarchy
WIMP DM ...



Energy Frontier - LHC

RH neutrinos
Dark Matter
Hidden sector
...

Light Hidden particles → singlets with respect to the SM gauge group
→ couple to different singlet composite operators (**Portals**) of the SM

Renormalizable

$$LHN$$ Neutrino portal

$$(\mu S + \lambda S^2) H^\dagger H$$ Higgs Portal

$$-\frac{\kappa}{2} B_{\mu\nu} V^{\mu\nu}$$ Vector Portal

Higher dimension operators

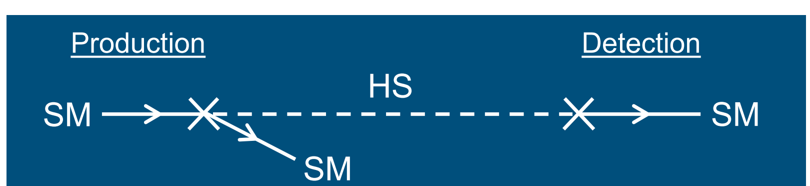
$$\frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$ Axion Portal

$$\frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q + \ldots ,$$ Dark Matter

Light mediator

$$g_\chi \phi \bar{\chi} \chi + g_q \phi \bar{q} q + \ldots$$

Direct detection:

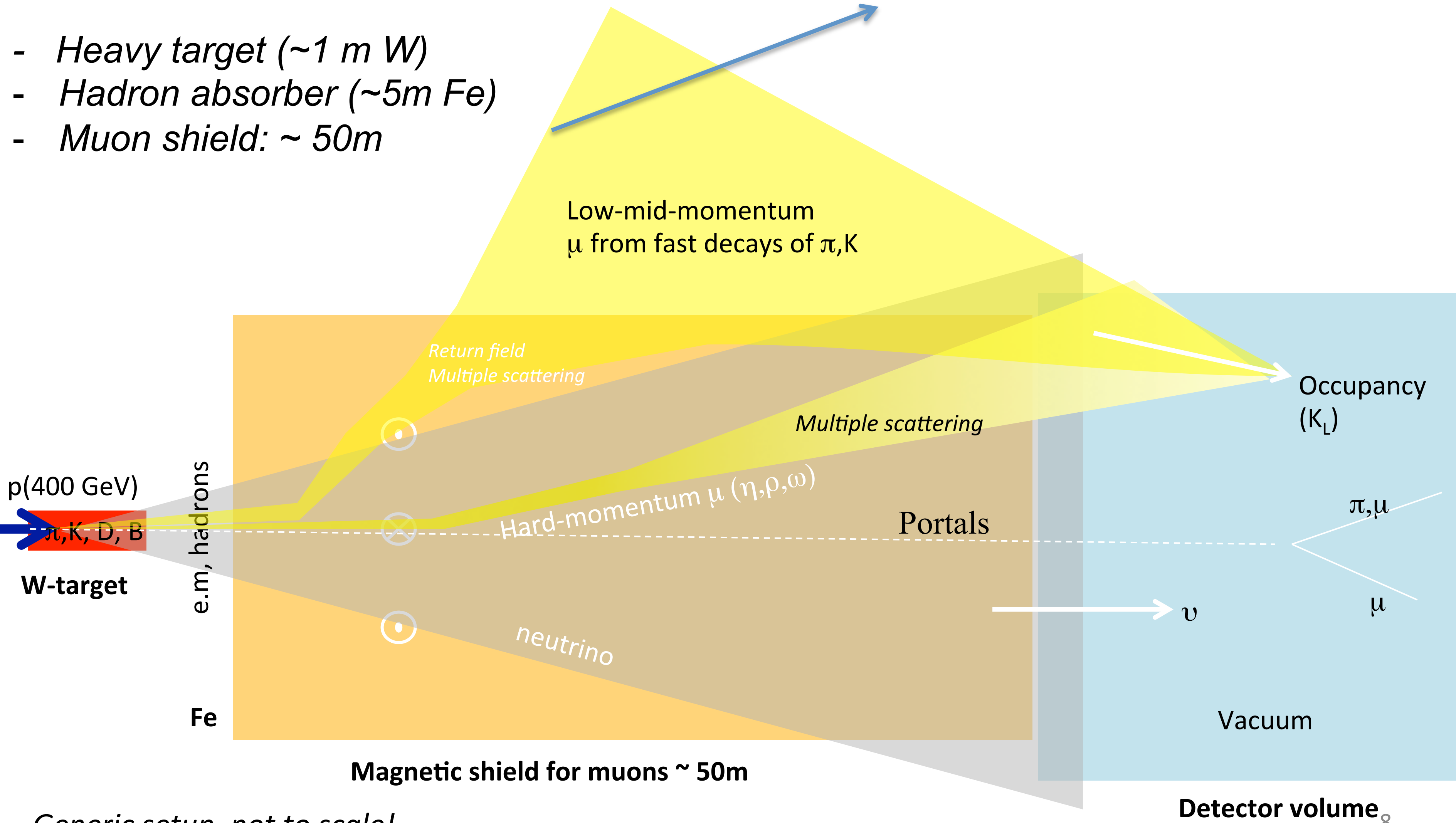


Beam dump facility
(different from a conventional neutrino facility)

Initial reduction of beam induced backgrounds

- *Heavy target (~1 m W)*
- *Hadron absorber (~5m Fe)*
- *Muon shield: ~ 50m*

One spill of 5×10^{13} p.o.t.
spill duration 1s ~ 5×10^{9} muons



Generic setup, not to scale!

Motivation for Heavy Neutral Leptons

See-saw generation of neutrino masses

Most general renormalisable Lagrangian of SM particles (+3 singlets wrt SM gauge group):

$$L_{singlet} = i\bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\alpha} \bar{N}_I^c \tilde{H} L_\alpha - M_I \bar{N}_I^c N_I + h.c.$$

Yukawa term: mixing of N_I with active neutrinos to explain oscillations

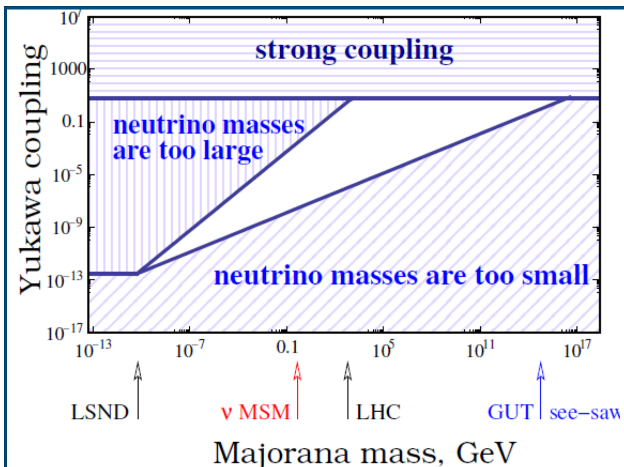
Majorana term which carries no gauge charge

$$v \sim 246 \text{ GeV}$$

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

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

Four "popular" N mass ranges

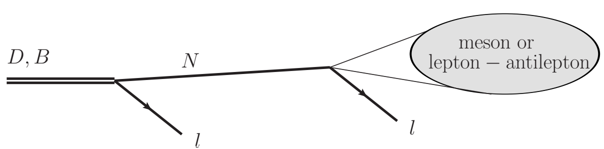


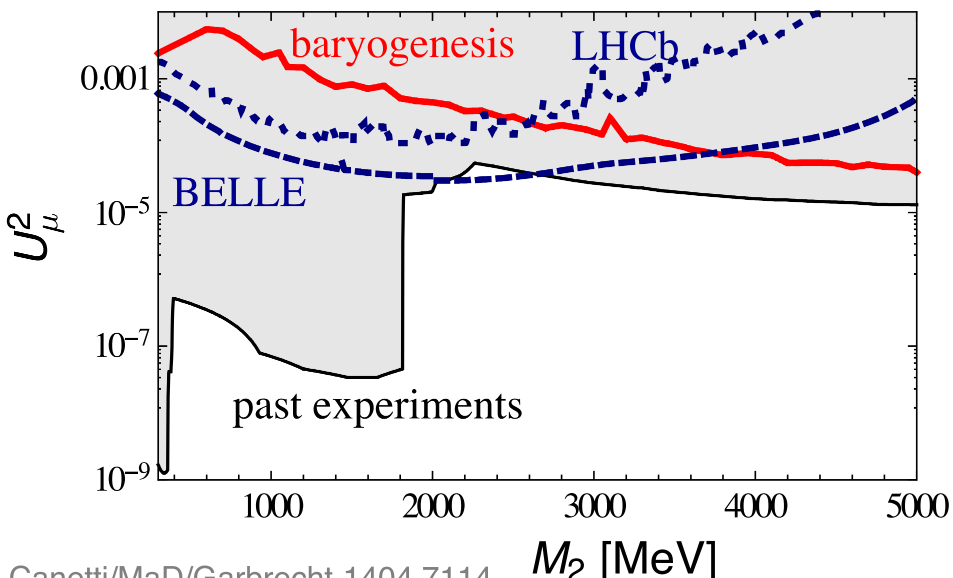
	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

Leptogenesis with 3 RH neutrinos

Marco Drewes, PRL 110 (2013) 6, 061801
Review: Int. J. Mod. Phys. E22 (2013) 1330019

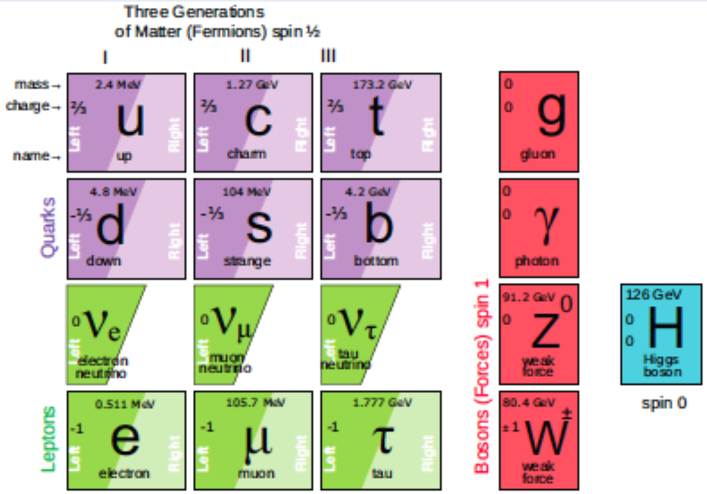
- Model not pretending to explain dark matter too
- Dark matter can be something else (4^{th} RH neutrino, axion, …)
- It does not require N_2 and N_3 to be quasi-degenerate, CP-violation does not need to be enhanced by mass degeneracy
- BAU explained also if $|Y_{\alpha I}|$ are not so small
- Individual $|Y_{\alpha I}|$ can be very different

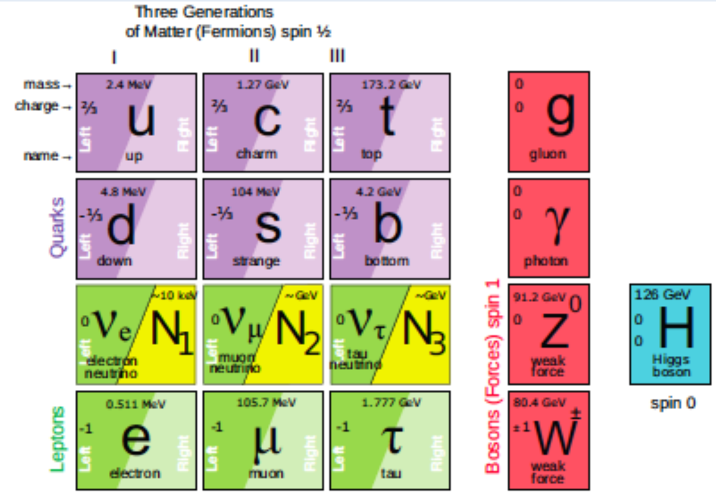




$M_1 = 1$ GeV, $M_3 = 3$ GeV plot updated from Canetti/MaD/Garbrecht 1404.7114
CP-violation may also be measurable Cvetic/Kim/Zamora-Saa 1403.2555

The νMSM model: leptogenesis and dark matter





N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter

Role of $N_2, \ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

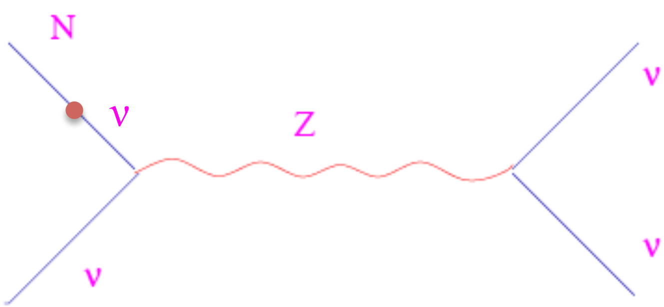
*νMSM: T.Asaka, M.Shaposhnikov PL **B620** (2005) 17*
M.Shaposhnikov Nucl. Phys. B763 (2007) 49

global lepton-number symmetry broken at the level of O(10^{-4}) leads to the required pattern of sterile neutrino masses consistent with neutrino oscillations data

Dark Matter candidate HNL N_1

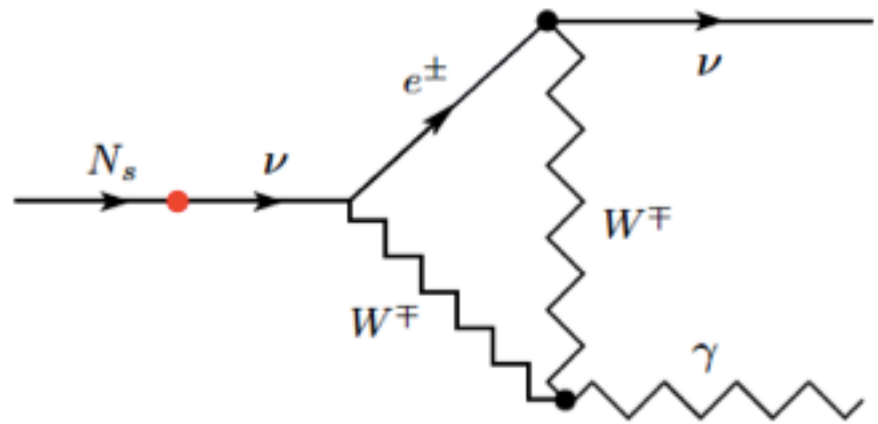
- **N_1 can be sufficiently stable to be a DM candidate, $M(N_1)$~10keV**

Yukawa couplings are small $\rightarrow$ N can be very stable.



Main decay mode: $N \rightarrow 3\nu$.

Subdominant radiative decay channel: $N \rightarrow \nu\gamma$.



Photon energy:

$$E_\gamma = \frac{M}{2}$$

Radiative decay width:

$$\Gamma_{\rm rad} = \frac{9\,\alpha_{\rm EM}\,G_F^2}{256 \cdot 4\pi^4}\,\sin^2(2\theta)\,M_N^5$$

Interaction strength

New line in photon galaxy spectrum at 3.5 keV? To be checked with higher accuracy

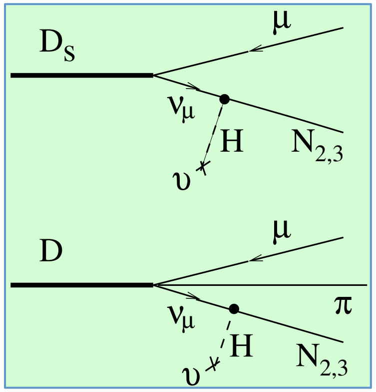
Masses and couplings of HNLs

- ***$M(N_2) \approx M(N_3)$ ~ a few GeV→ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)***

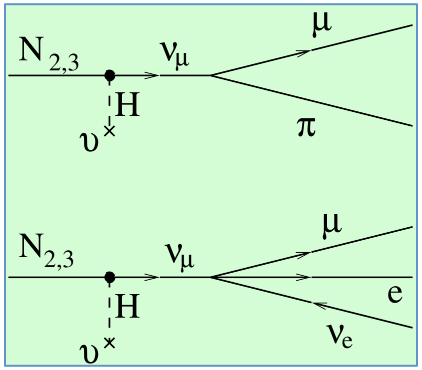
Very weak $N_{2,3}$-to-ν mixing (~ U^2) → $N_{2,3}$ are much longer-lived than SM particles

- Produced in semi-leptonic decays, $K \to \mu\nu,\ D \to \mu\pi\nu,\ B \to D\mu\nu$
- $\propto \sigma_D \times U^2$
- $U_2^2 = U_{2,\nu_e}^2 + U_{2,\nu_\mu}^2 + U_{2,\nu_\tau}^2$

Example:
$N_{2,3}$ production in charm



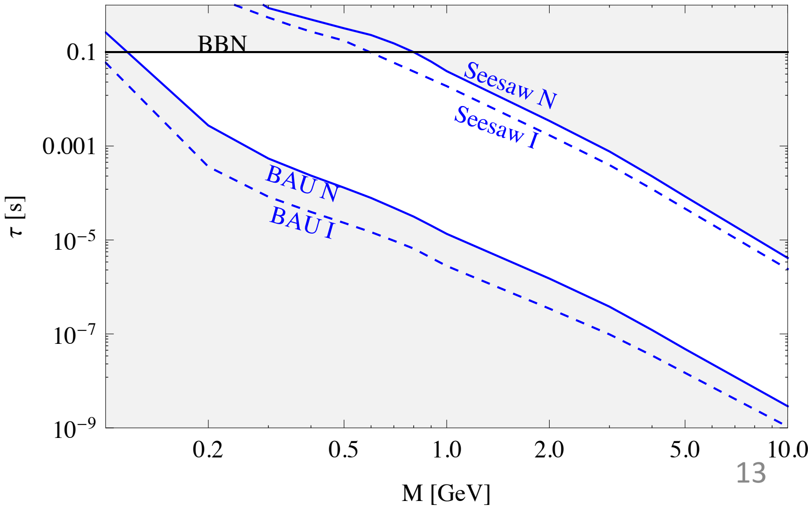
and subsequent decays



- *Typical lifetimes > 10 μs for $M(N_{2,3})$ ~ 1 GeV*
  Decay distance O(km)

- *Typical BRs (depending on the flavour mixing):*

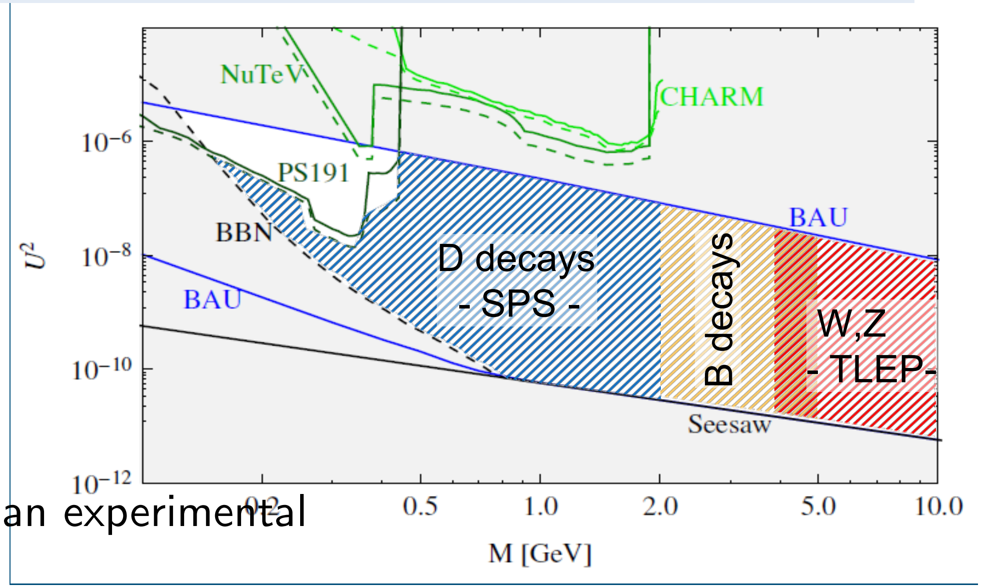
  Br(N → μ/e π) ~ 0.1 – 50%
  Br(N → $\mu^-/e^-\ \rho^+$) ~ 0.5 – 20%
  Br(N → νμe) ~ 1 – 10%



Experimental and cosmological constraints

Already searches in K/D-decay performed:

- PS191('88)@PS 19.2 GeV, 1.4×10^{19} pot, 128 m from target.
- CHARM('86)@SPS 400 GeV, 2.4×10^{18} pot, 480 m from target.
- NuTev('99)@Fermilab 800 GeV, 2.5×10^{18} pot, 1.4 km from target.
- BBN, BAU and Seesaw constrain more than experimental searches for $M_N > 400$ MeV.



- ***Recent progress in cosmology***

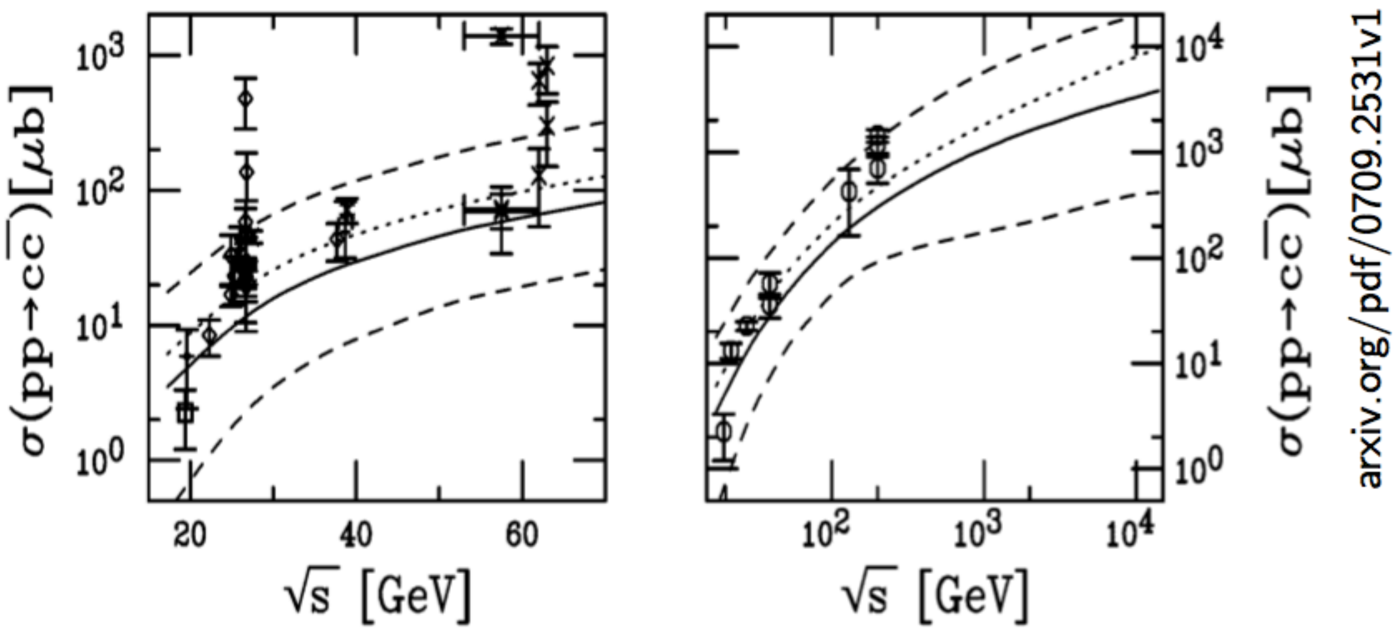
  - *The sensitivity of previous experiments did not probe the interesting region for HNL masses above the kaon mass*

→ *Strong motivation to explore cosmologically allowed parameter space*

Experimentally this domain has been only marginally explored!

Sensitivity for $N_{2,3} \propto U^4$

- PS-191: Used K decays → limited to 500 MeV (PLB 203 (1988) 332)
- Goal: Extend mass range to ~ 2 GeV by using charmed hadron decays
- B-decays: 20÷100 smaller σ, and B → Dμν, i.e. limited to ~ 3 GeV still



Where to produce charmed hadrons?

LHC ($\sqrt{s} = 14$ TeV): with 1 ab^{-1} (~ 3-4 years): $\sim 2 \times 10^{16}$ in 4π

SPS (400 GeV p-on-target (pot) $\sqrt{s} = 27$ GeV): with 2×10^{20} pot (~ 3-4 years): $\sim 2 \times 10^{17}$

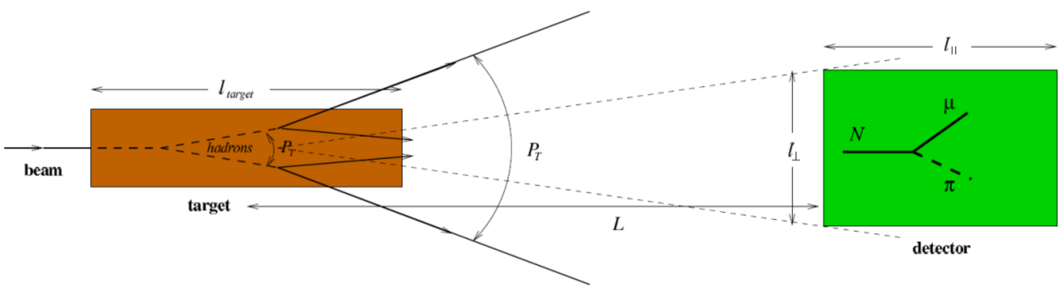
The acceptance of a beam dump facility is much larger for long lived particles

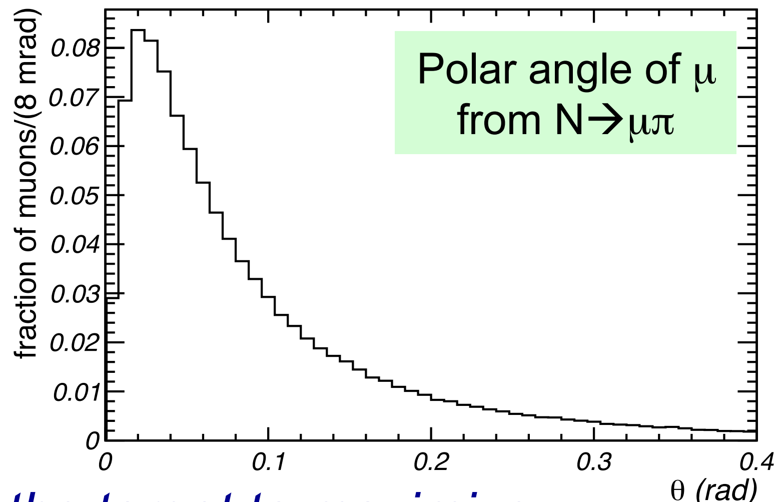
Experimental requirements

- *Search for HNL in Heavy Flavour decays*

→ *Beam dump experiment at the SPS with a total of 2×10^{20} protons on target (pot) to produce a large number of charmed hadrons*
CNGS: 1.8×10^{20} pot, 2011 run: 4.8×10^{19} pot

- *HNLs produced in charm decays have significant P_T*

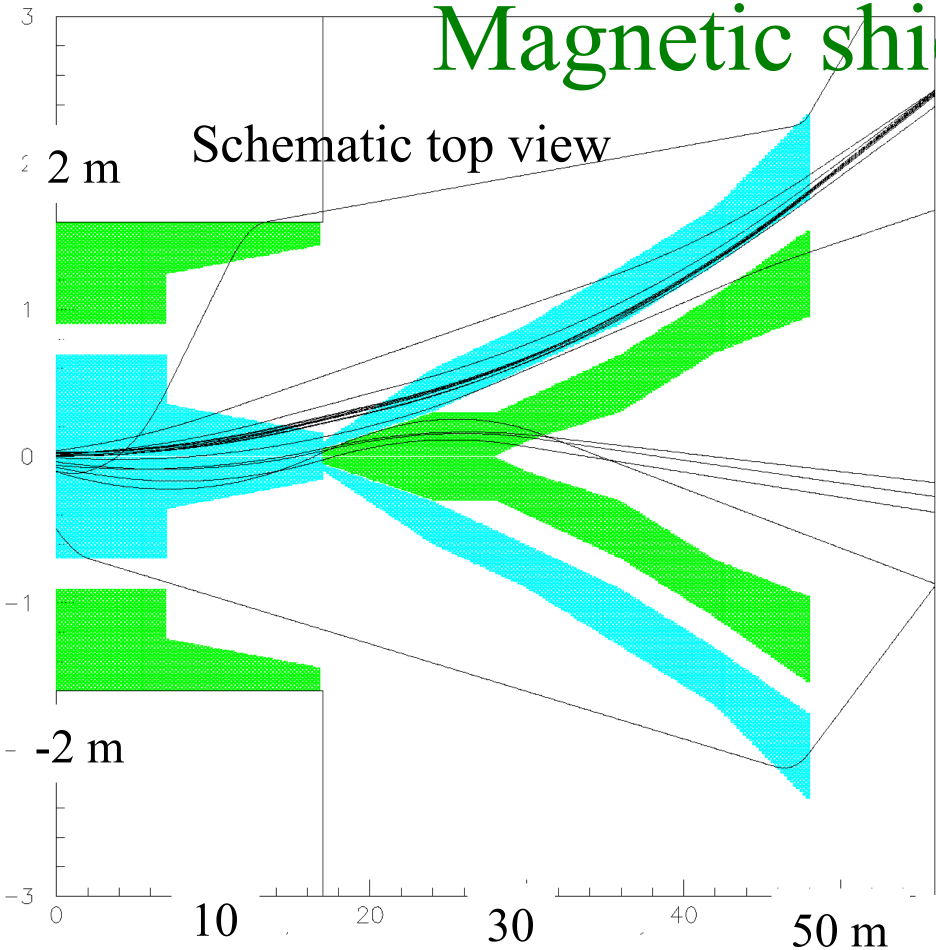


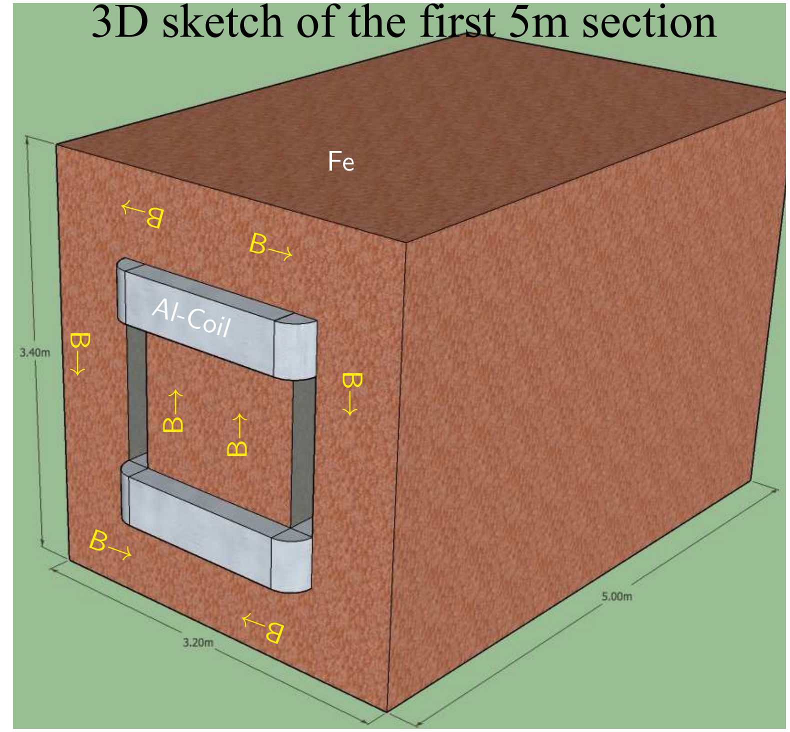


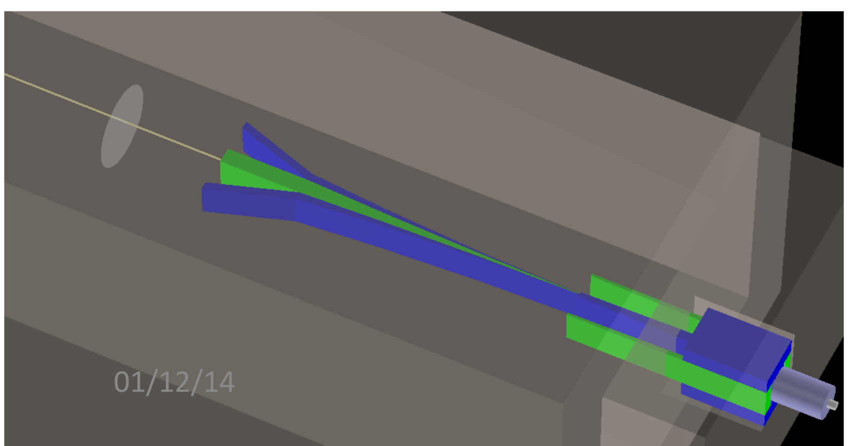
→ *Detector must be placed close to the target to maximize geometrical acceptance*

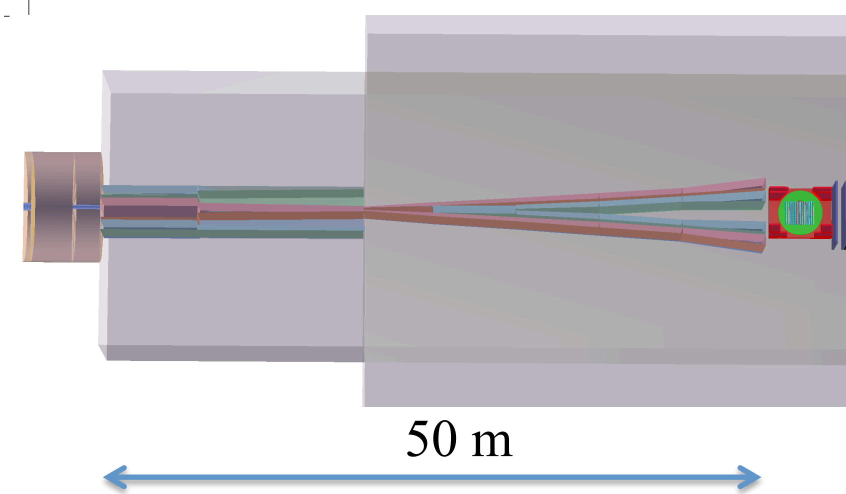
→ *Effective (and "short") muon shield is essential to reduce muon-induced backgrounds (mainly from short-lived resonances accompanying charm production)*

Magnetic shield for muons

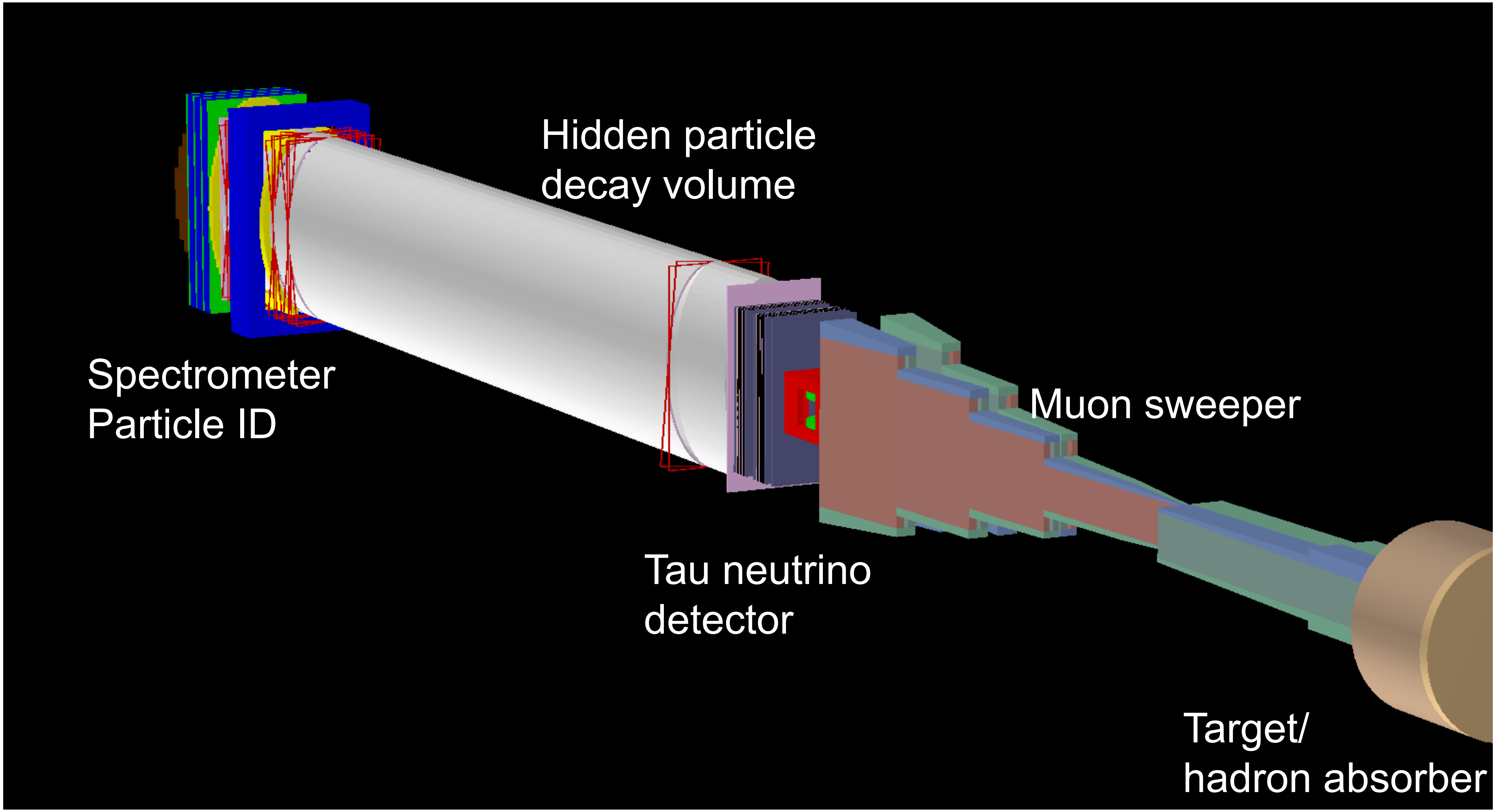








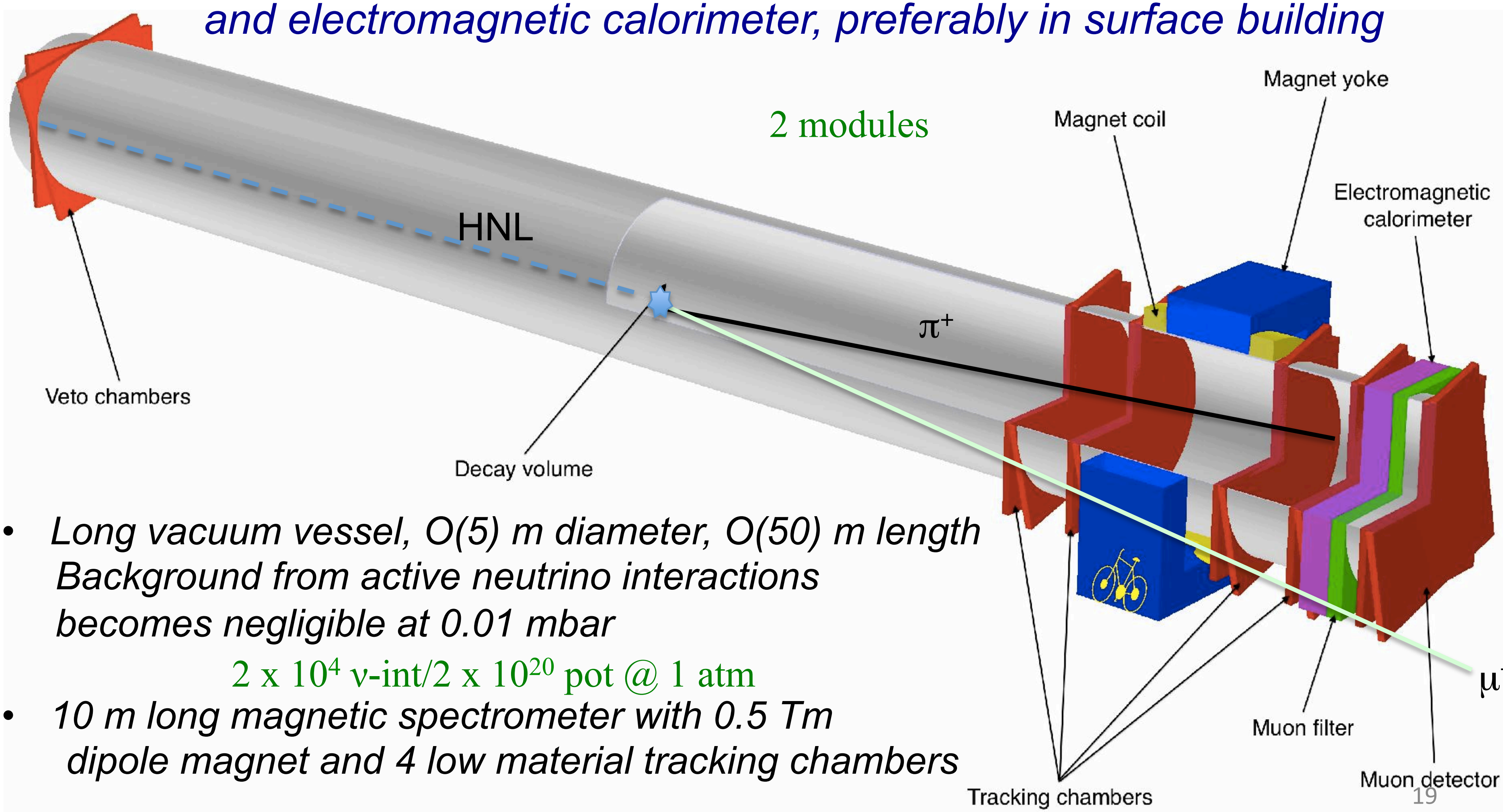
Experimental setup



Detector concept
(based on existing technologies)

- *Reconstruction of the HNL decays in the final states:* $\mu^-\pi^+$, $\mu^-\rho^+$ & $e^-\pi^+$

→ *Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter, preferably in surface building*



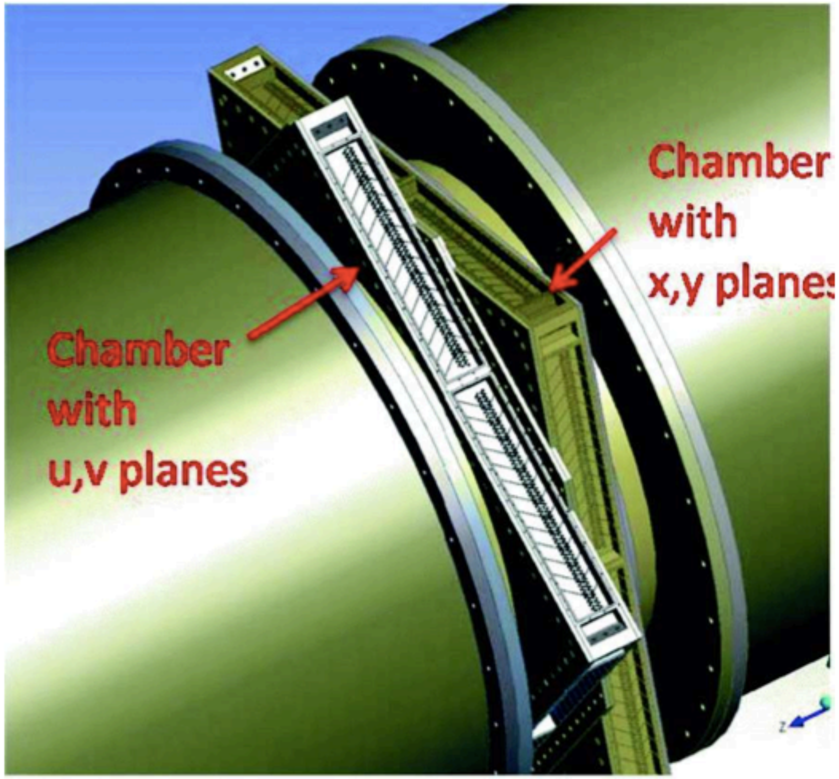
- *Long vacuum vessel, O(5) m diameter, O(50) m length Background from active neutrino interactions becomes negligible at 0.01 mbar*

  2×10^4 ν-int/2×10^{20} pot @ 1 atm

- *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

Tracking chambers

Same as NA62 $(K^+ \to \pi^+ \nu \bar{\nu})$
2m diameter vessel at 0.01 μbar
10 mm diameter straws made of PET → working well in vacuum
X/X_0 = 0.5% for 4 view stations
120 μm resolution/straw

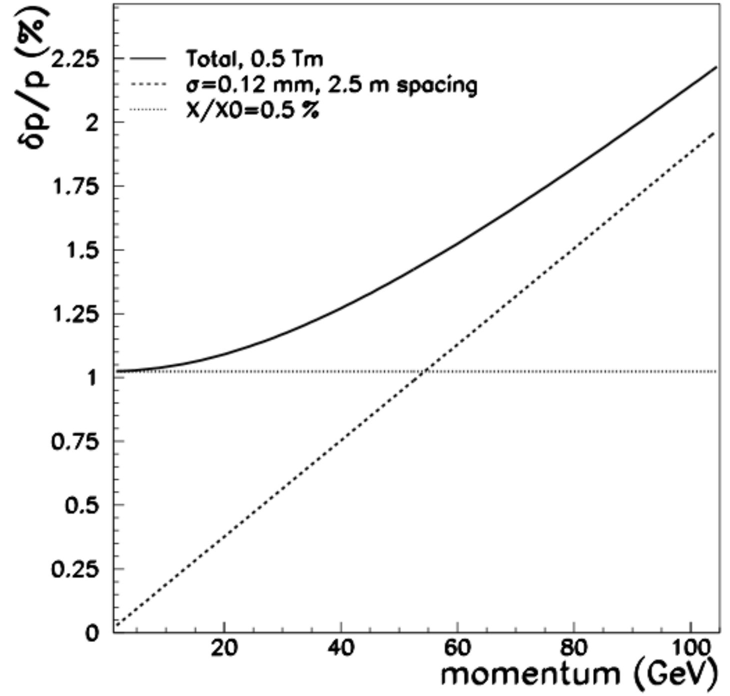


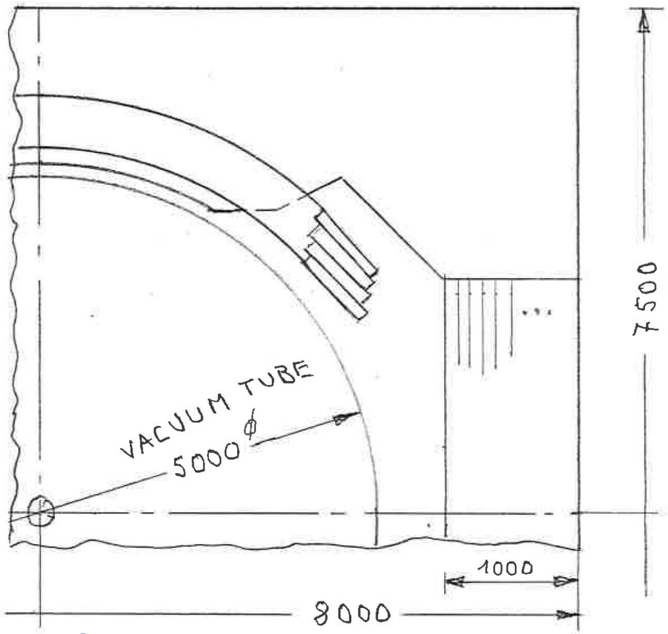
Magnet and e.m. calo

- With X/X0=$0.5\ \%$ chambers: modest 0.5 Tm
- Need $\sim 20\ \mathrm{m}^2$ aperture.

LHCb magnet: 4 Tm, $16\ \mathrm{m}^2$ aperture
Preliminary calculations (W.Flegel):

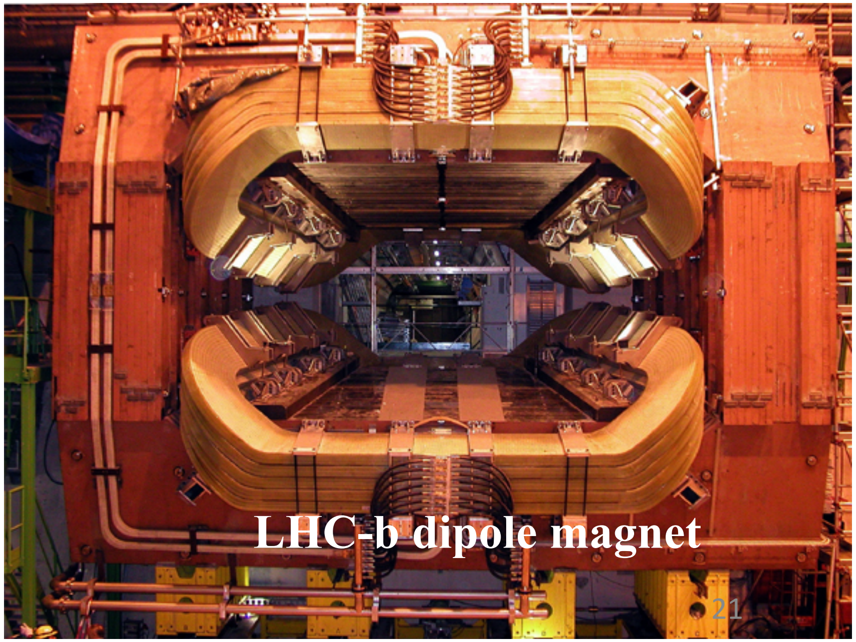
- Needs $30\ \%$ less iron/yoke than LHCb.
- Consumes 3 times less power.





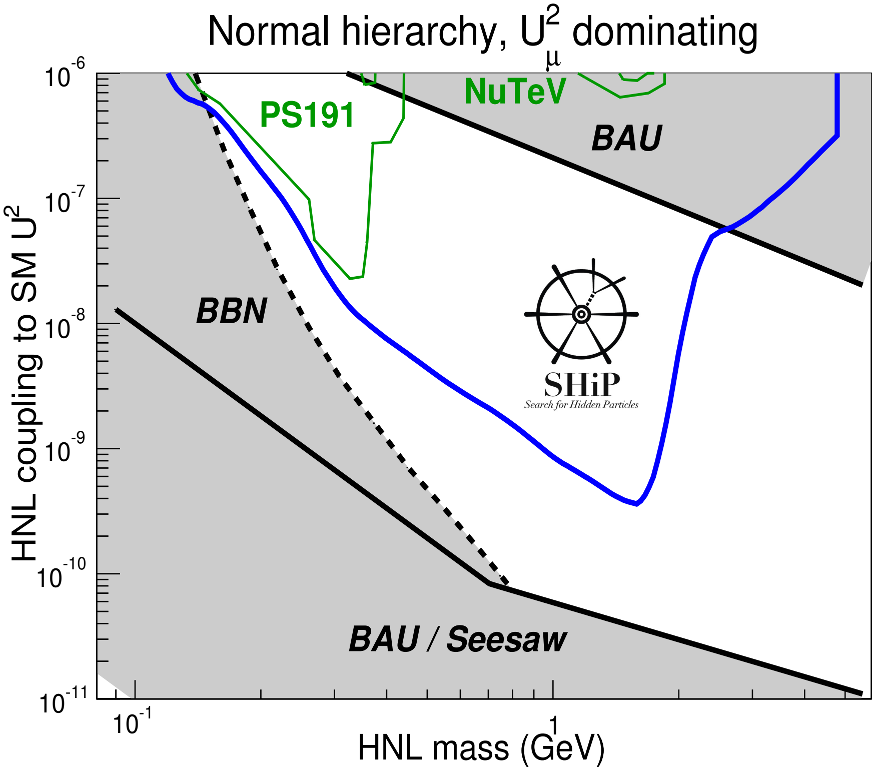
LHCb Shashlik ECAL:

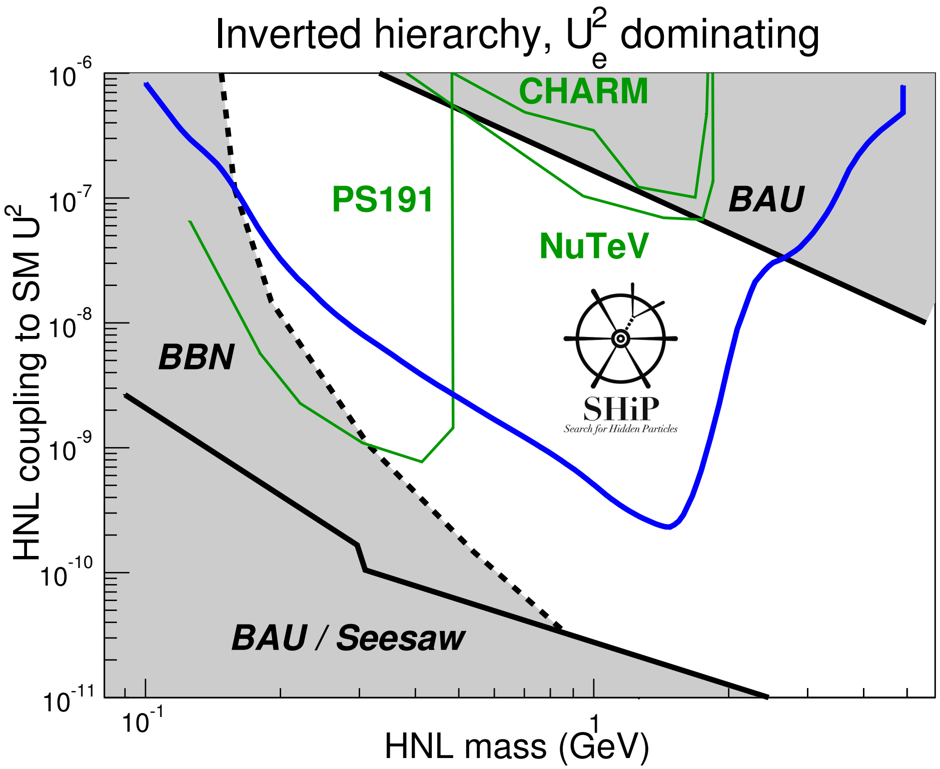
- $6.3{\times}7.8\ \mathrm{m}^2$
- $\frac{\sigma(E)}{E} < 10\%/\sqrt{E} \oplus 1.5\%$



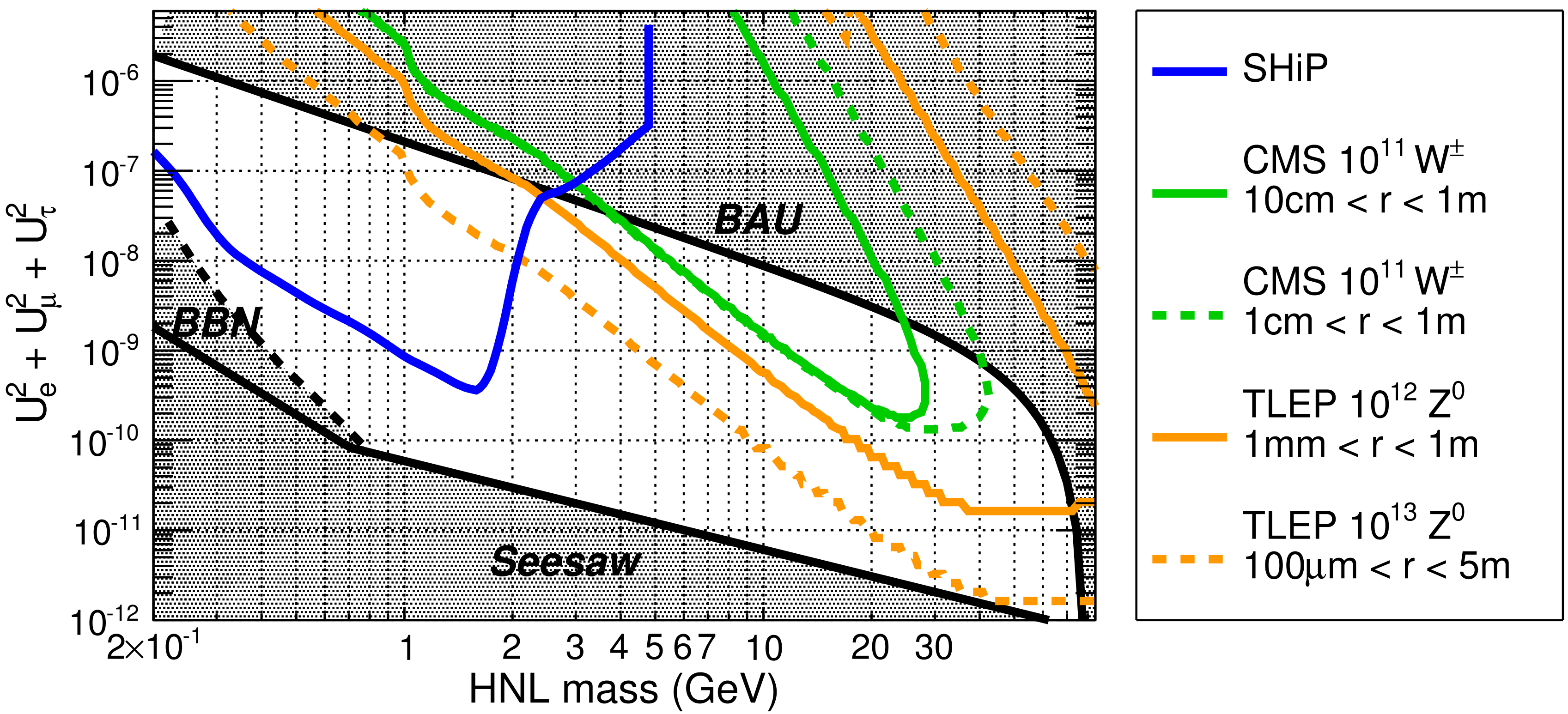
LHC-b dipole magnet

Expected exclusion limits





SHIP sensitive to a significant part of the parameter space

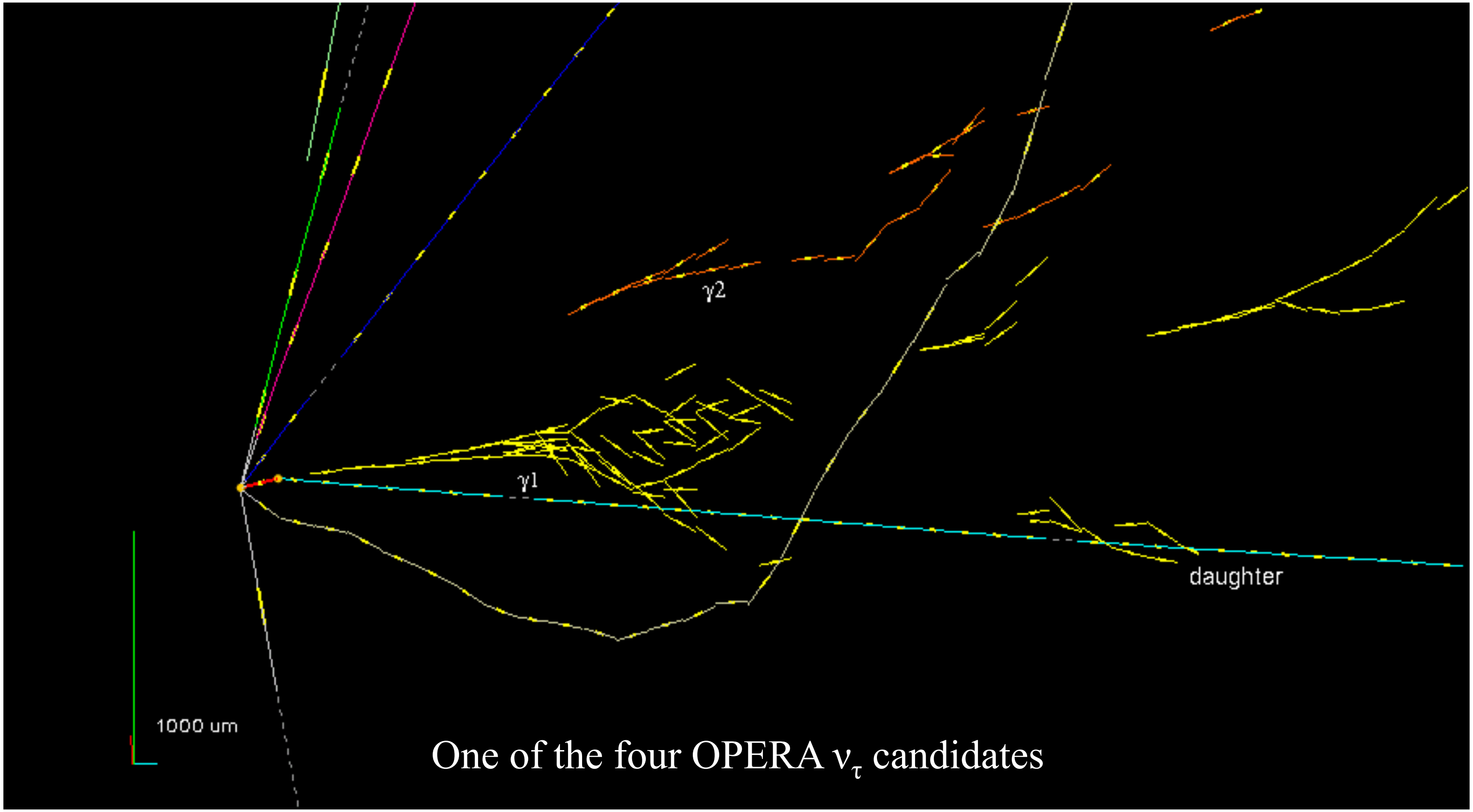


ν_τ: *the less know particle in the Standard Model*

DONUT: 9 observed ν_τ candidate events (leptonic number not measured)

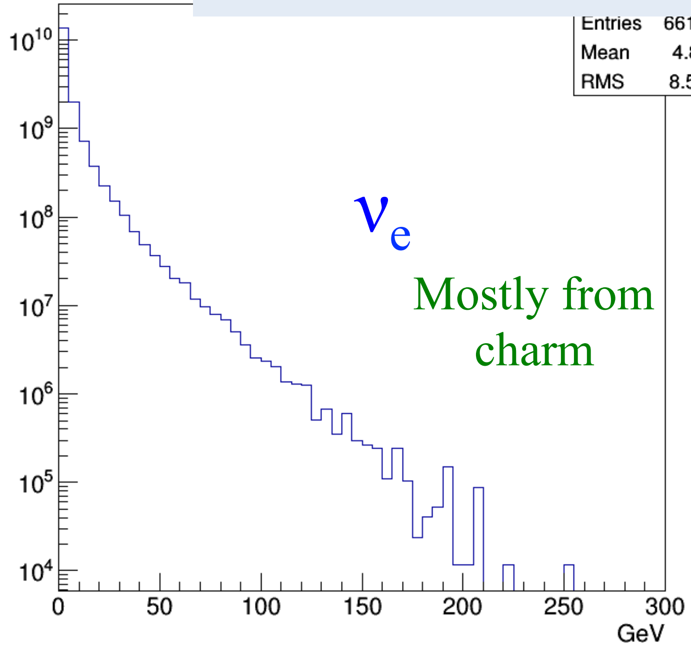
OPERA: First observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode (4.2σ result)

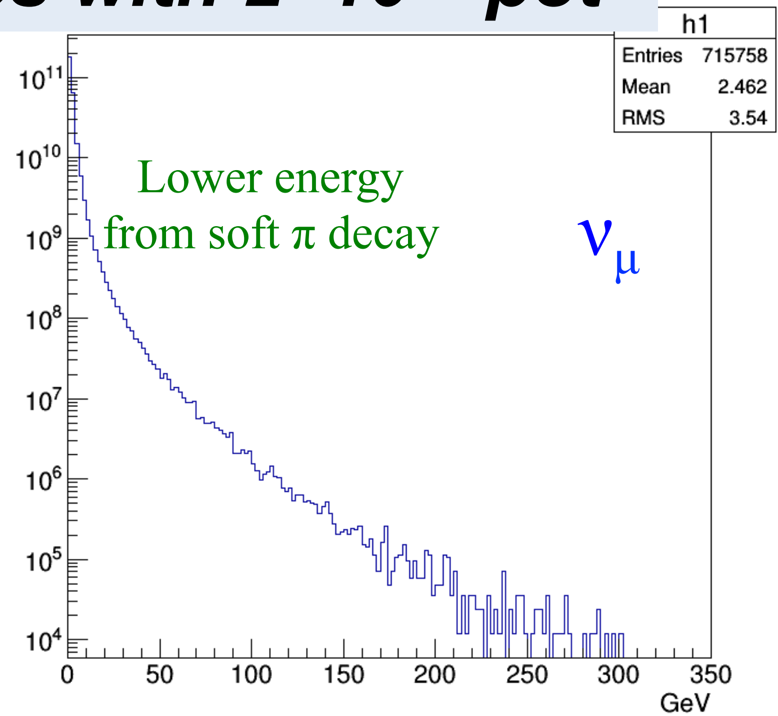
$\bar{\nu}_\tau$ not detected yet!

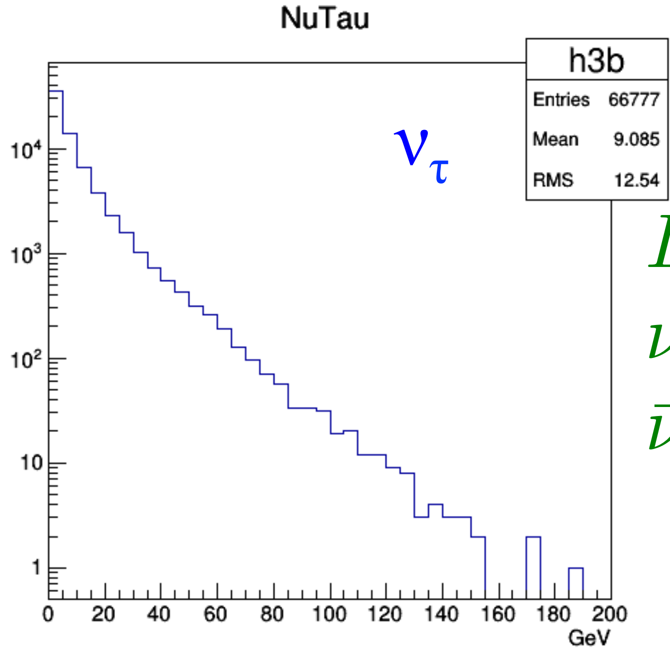


One of the four OPERA ν_τ candidates

Standard Model: ν_τ physics with 2×10^{20} pot







$D_s \to \tau\nu_\tau$, present configuration:

$\nu_e \simeq 7.1\%$, $\nu_\mu \simeq 92.5\%$, $\nu_\tau \simeq 0.4\%$

$\bar{\nu}_\mu/\nu_\mu \simeq 62\%$, $\bar{\nu}_e/\nu_e \simeq 1$, $\bar{\nu}_\tau/\nu_\tau = 1$

Standard Model: ν_τ physics with 2×10^{20} pot

- $\simeq 3500\ \nu_\tau$ interactions with 6 tons detector ($\simeq 5\%$ of OPERA films)
- Discovery of $\bar{\nu}_\tau$
- ν_τ and $\bar{\nu}_\tau$ cross-section
- ν_τ magnetic moment
- Structure functions (F_4 and F_5 never measured)
- F_1, F_2 and F_3 measured with $2 \times 10^6 \nu_\mu$ interactions

  - Charged current neutrino nucleon scattering

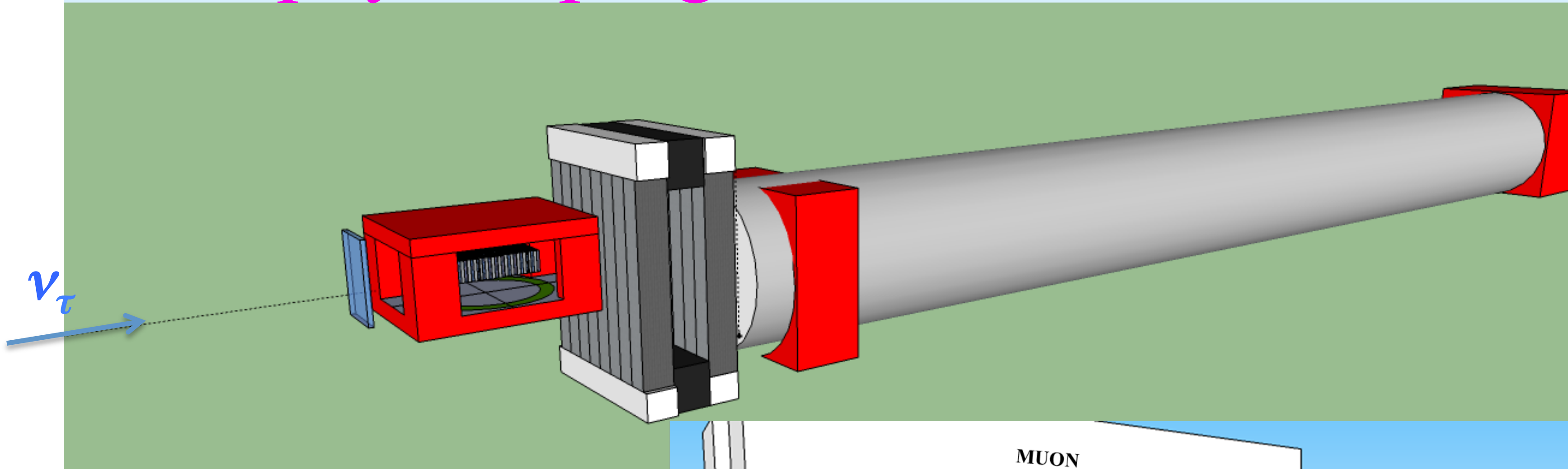
neutrino scattering

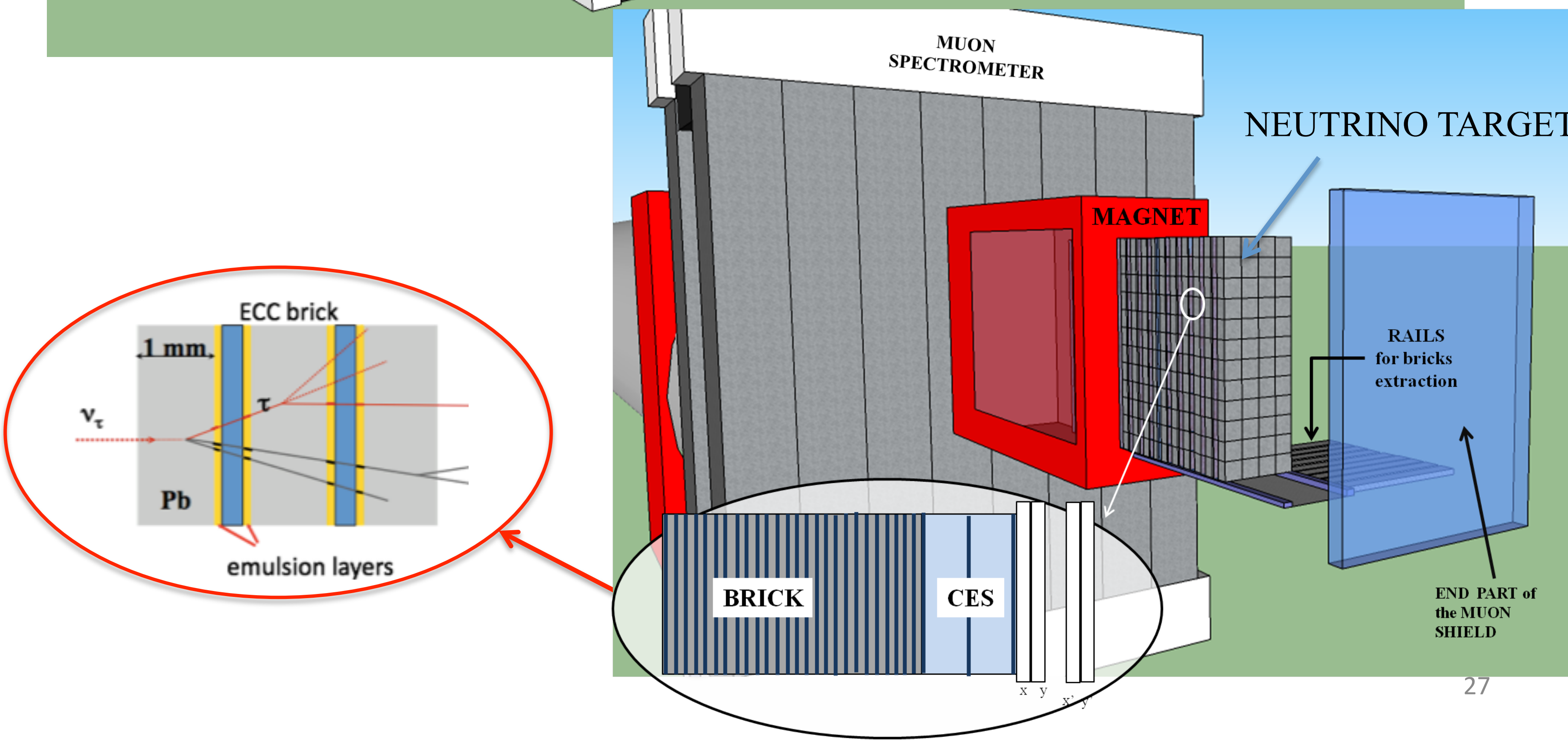
anti-neutrino scattering

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

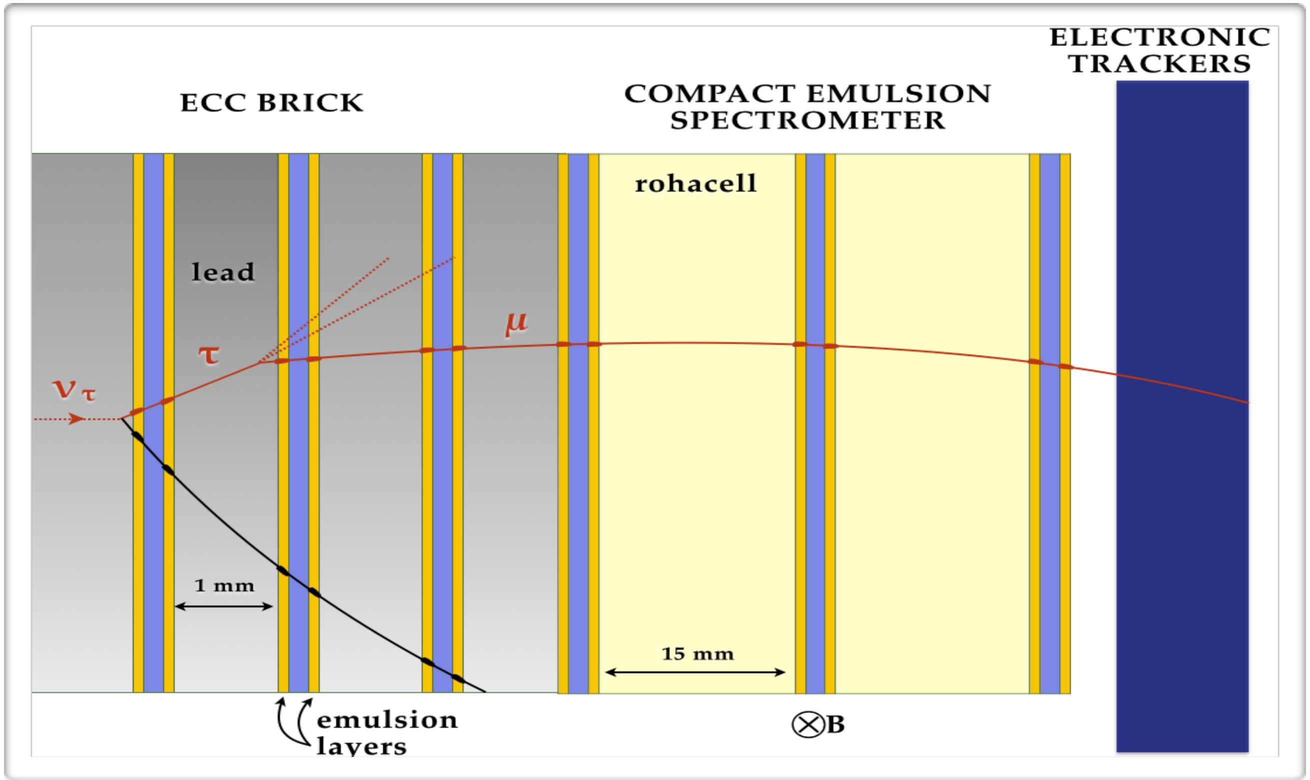
ν_e interactions (10^5) to measure charm production yield
$\rightarrow$ constraint normalization also for HNL

A SM physics program: tau neutrino detector





Hybrid detector principle

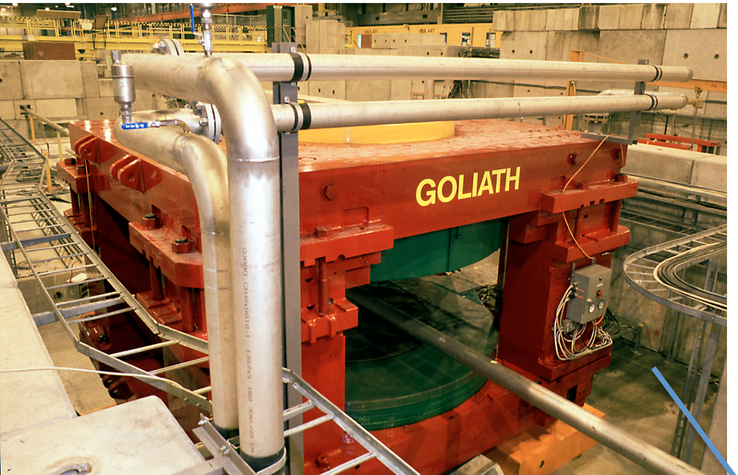


τ DECAY CHANNEL	BR (%)
τ →μ	17.7
τ →e	17.8
τ →h	49.5
τ →3h	15.0

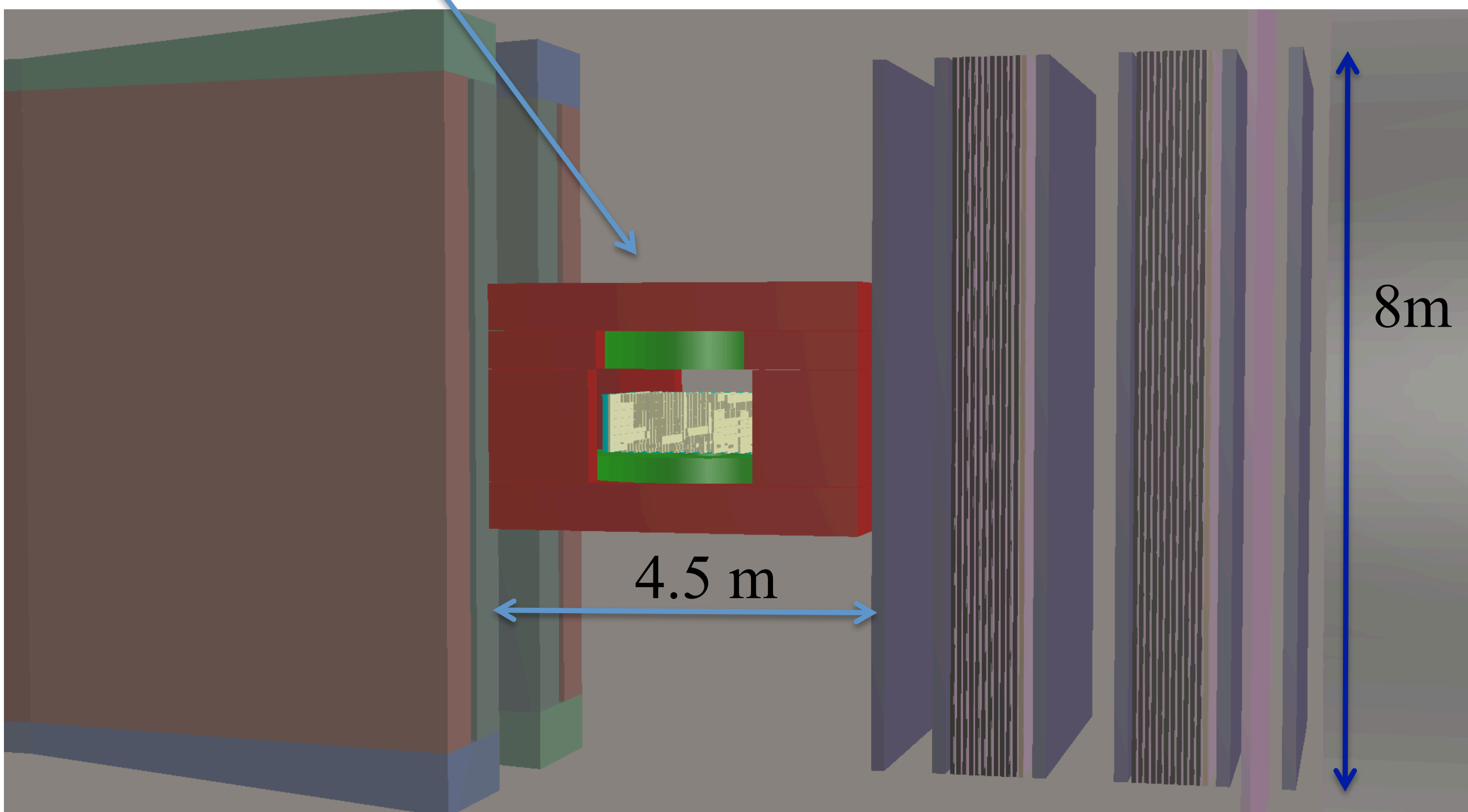
This configuration (ECC + an emulsion spectrometer) never used so far!
TESTS are needed to finalize the geometry and performances

- Nuclear emulsions as trackers with micrometric resolution
- Detect τ-lepton production and decay vertices
- Compact emulsion spectrometer to measure the charge of τ decays
- Electronic detectors to provide the "time stamp" and reconstruct μ charge/momentum

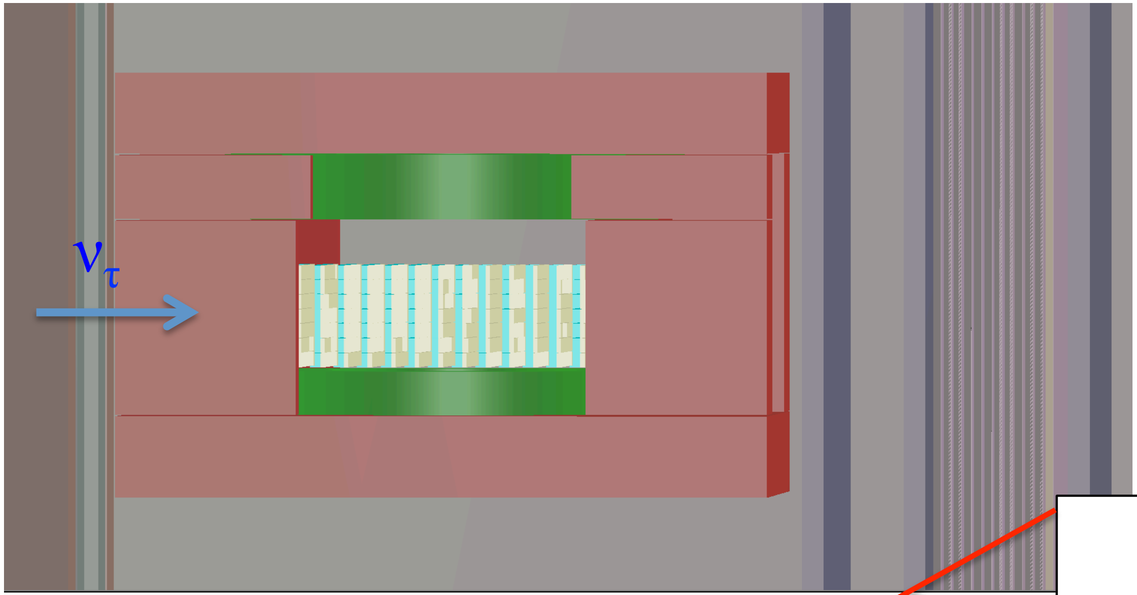
Magnetized neutrino target



Magnet available

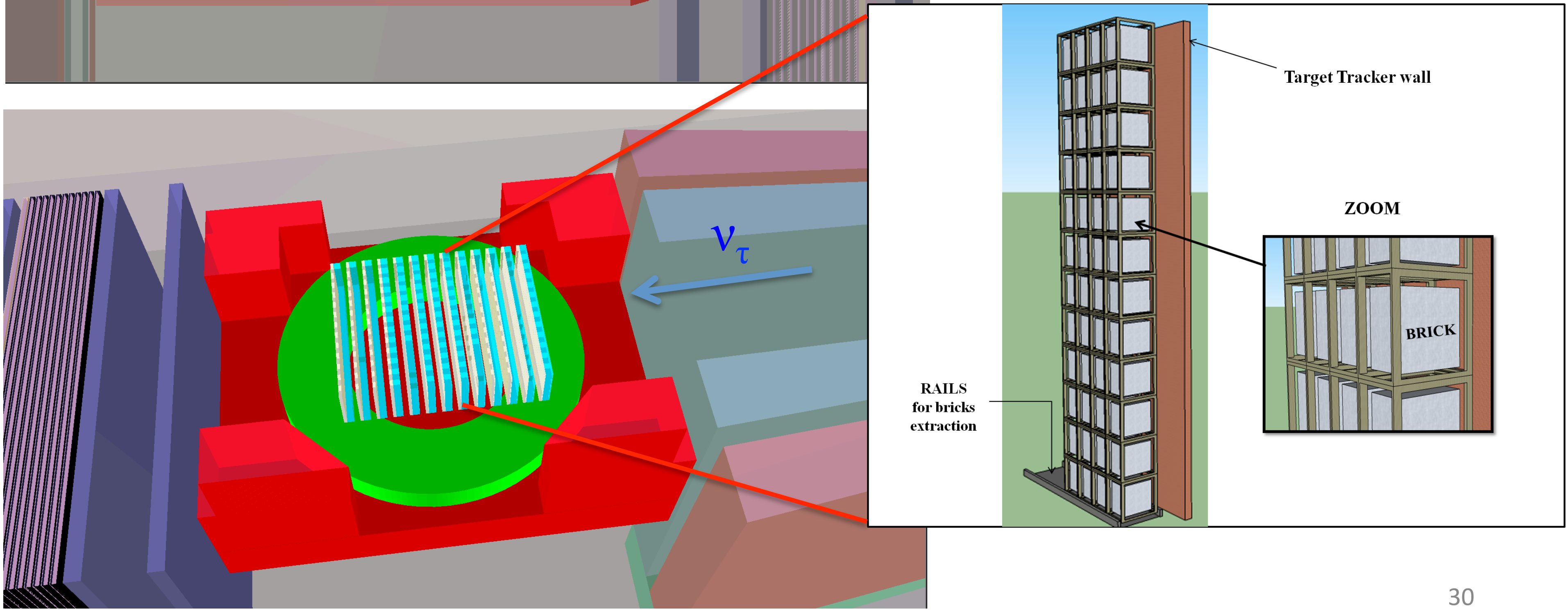


Detector design

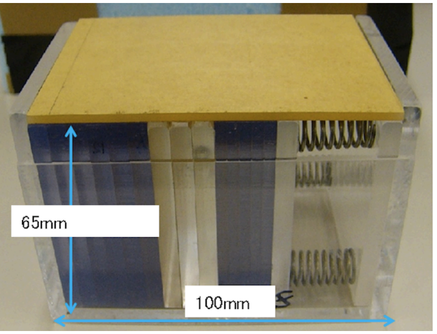


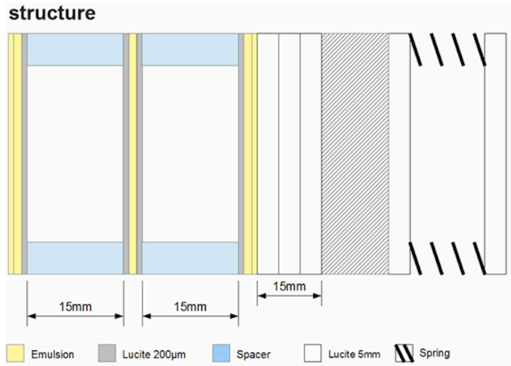
Target region: 15 mini-walls
One wall contains 48 bricks
target mass ~ 8.3 x 48 x 15 kg ~ 6 ton

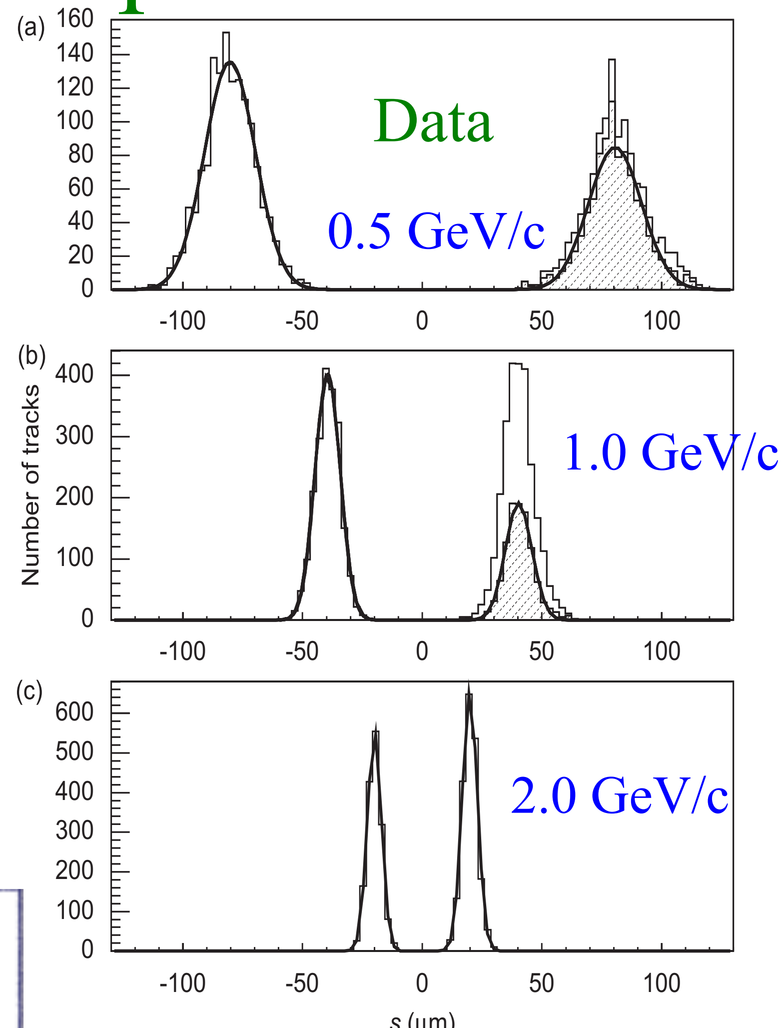
TARGET TRACKER:
- Scintillating fibres (250 μm diameter), read out by SiPMs,
- GEM
- Micromegas



Compact emulsion spectrometer



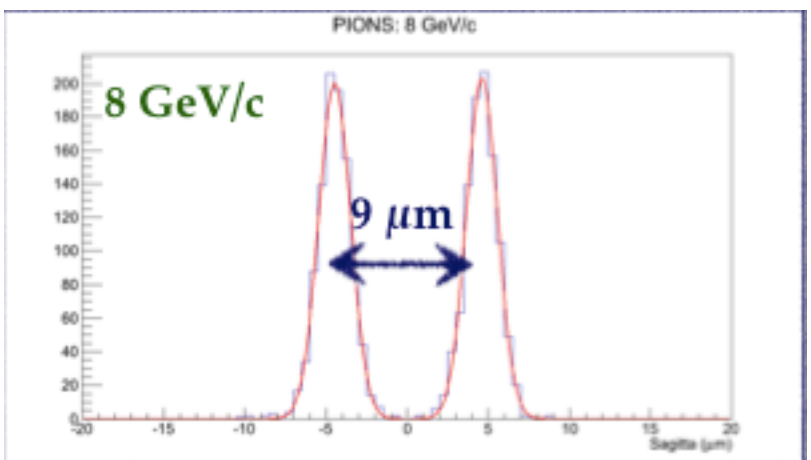




Sagitta measurement

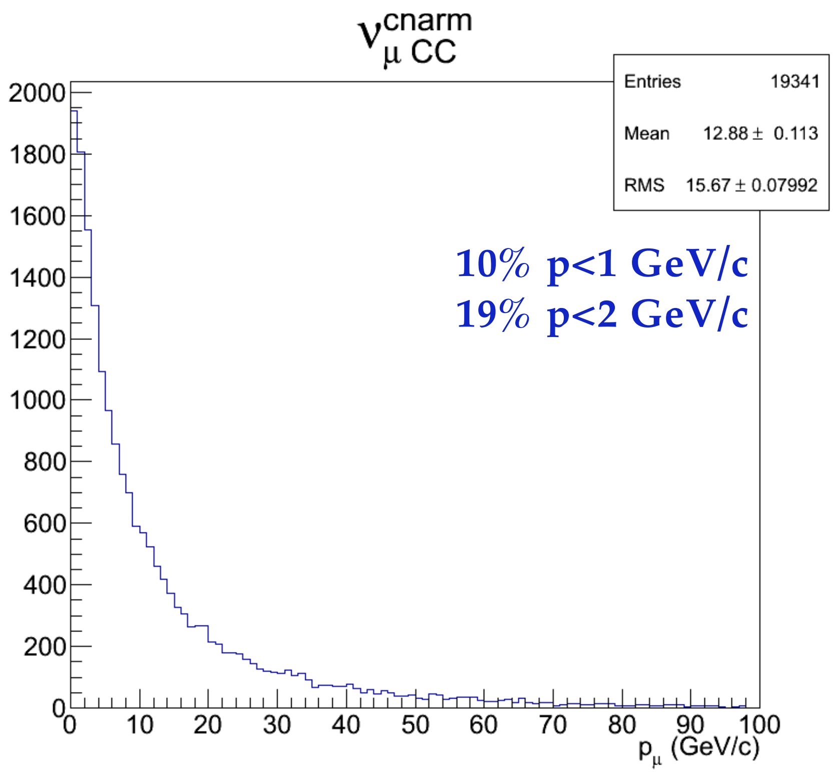
3 emulsion films interleaved with 1.5 cm air gap in a magnetic field (~ 1T), 3cm thick device, H. Shibuya et al NIM A592 (2008) 56

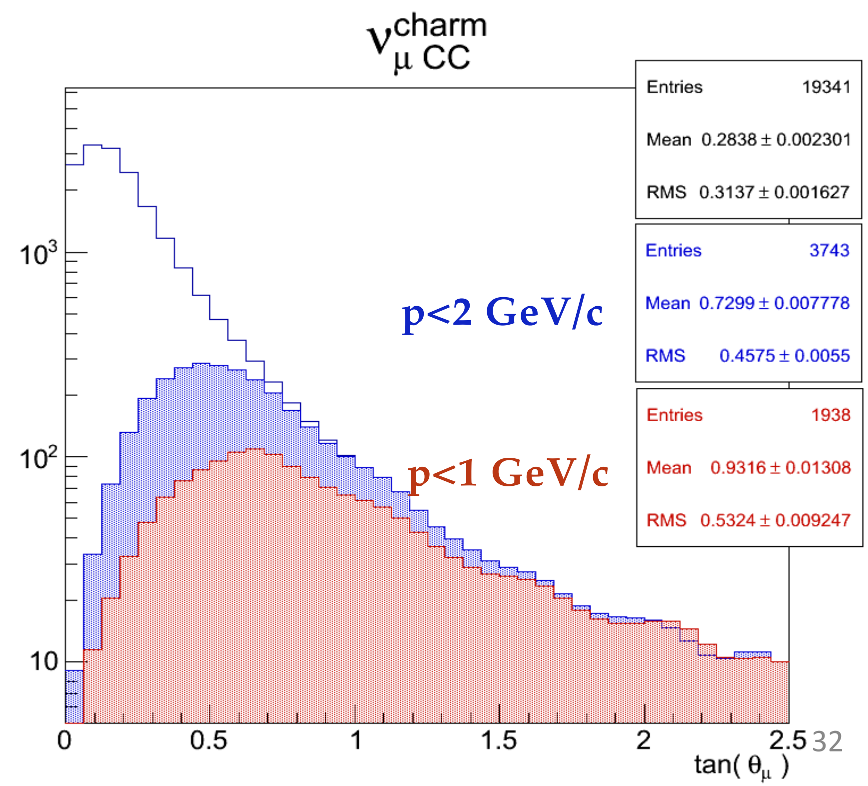
- Emulsion films alternated by low density material (Rohacell, 30÷100 kg/m^3)
- the charge of 8 GeV muons detectable (±4.5 μm) → require precise alignment



Muon detector requirements

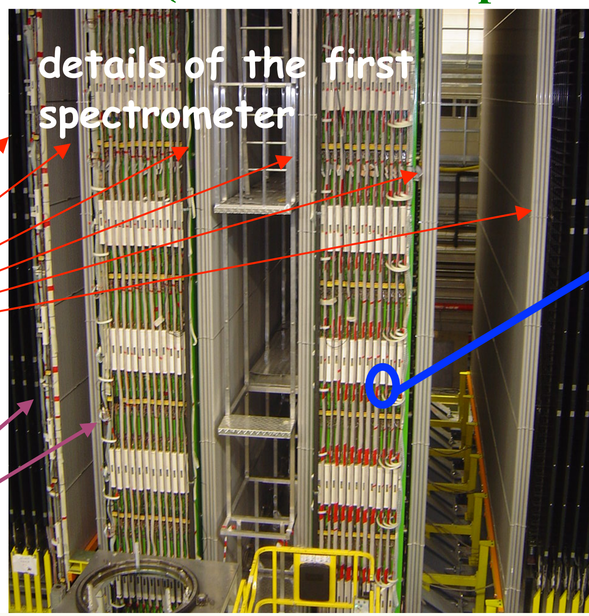
- Detector performances driven by background rejection → minimise muon misidentification
- Soft and large angle muons → difficult to be identified
- Large acceptance and fine graining to identify P < 2 GeV
- 4.5 x 4.5 m^2 to detect angles up to tan(ϑ)≤1
- High sampling to use momentum/range correlation

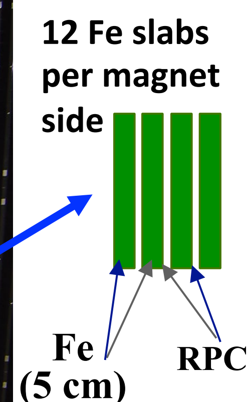


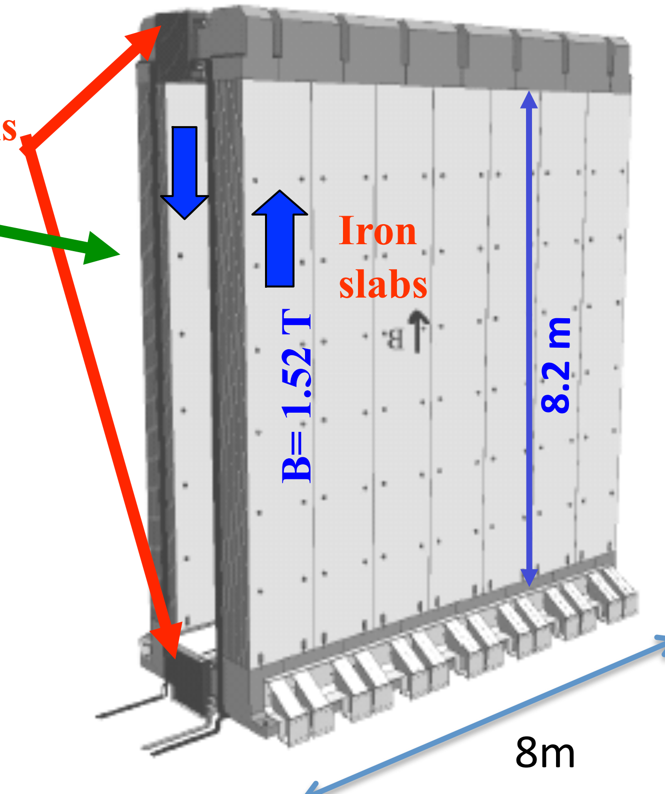


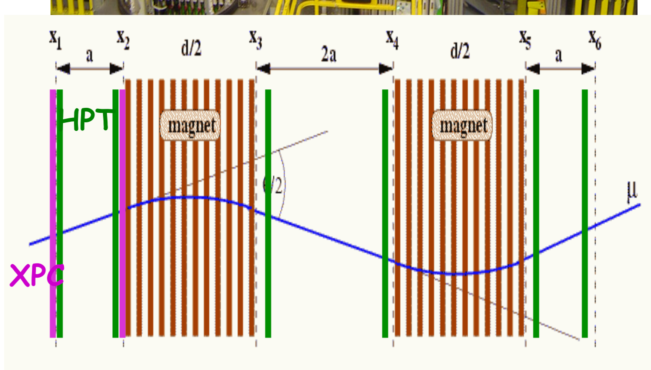
The magnetic spectrometer as a muon detector (OPERA one is an option)

One spectrometer is composed by:
1 dipolar magnet (1.52 T)
22 RPC layers as inner tracker inside magnetized iron
6 drift tubes stations (PT stations)
2 external XPC stations (RPCs with strips at ±43°)









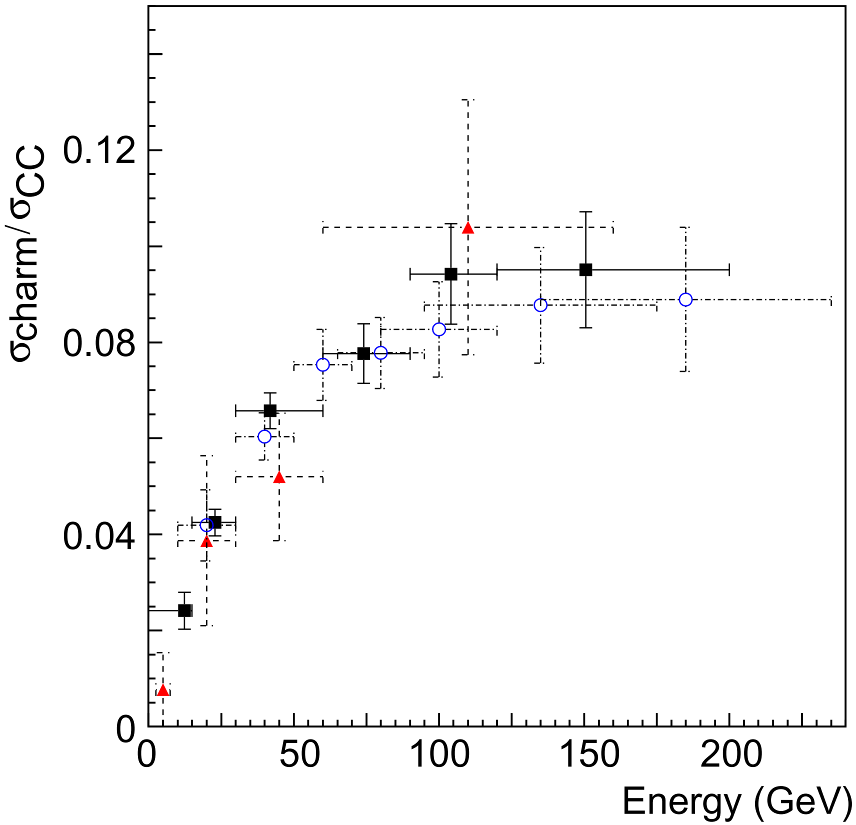
Charm bkg rejection in ν_μ CC events

Muon identification (with TT) > 95%

$\Delta p/p < 20\%$ for $p<30$ GeV

Charge misidentification < 0.3%

ν-induced charm production



CHORUS , New Journal of Physics 13 (2011) 093002

$$f(charm) = \frac{\int \Phi_{\nu_\mu} \sigma_{\nu_\mu}^{CC} \left(\frac{\sigma_{charm}}{\sigma_{\nu_\mu}^{CC}} \right) dE}{\int \Phi_{\nu_\mu} \sigma_{\nu_\mu}^{CC} dE} \approx 2\%$$

In ν_μ interactions: σ_{charm} ~ 2%, ~ 11000 charm

In anti-ν_μ interactions:
anti-ν_μ /ν_μ ~ 63%, $\sigma_{\nu\text{-bar}}/\sigma_\nu$ = 0.5 ~ 3500 events
only 32 observed by CHORUS

- Strange quark content obtained by the comparison of charm production in neutrino and anti-neutrino interactions
- Charm production with electronic detector tagged by dimuon events (high energy cut to reduce background): insensitive to the low energy region, slow-rescaling threshold → charm quark mass

Search for multi-quark states in ν interactions: charmed pentaquarks

Weakly decaying charmed hadron (below 2.8 GeV)

Unlike other processes like e+ e- scattering, the θ^0_c production in anti-neutrino interactions is favoured by the presence of three valence quarks

G. De Lellis et al. / Nuclear Physics B 763 (2007) 268–282

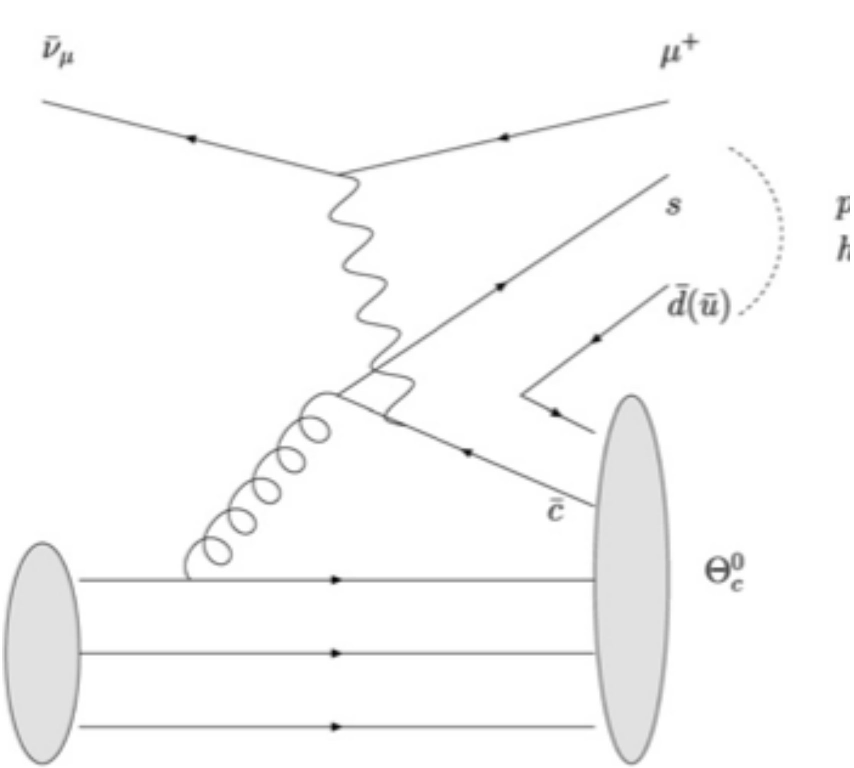


Fig. 1. Θ^0_c production in $\bar{\nu}_\mu$ interactions.

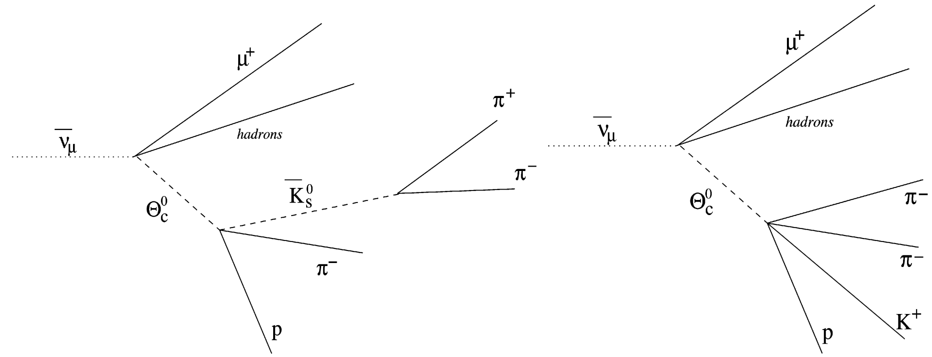


Fig. 2. Decay topology of Θ^0_c events produced in $\bar{\nu}_\mu$ interactions with two and four prongs.

$$\sigma_{\Theta^0_c}/\sigma_{\bar{\nu}} < 0.039 \text{ at } 90\% \text{ C.L.}$$

lifetime equal to $0.5\tau_{D^0}$

Not a tight bound, larger than D^0 prod,
Limited by the anti-nu statistics
SHiP: 2 orders of magnitude better

CERN task force to evaluate required infrastructure

- Following the SPSC encouragement in January 2014, CERN DG formed a dedicated Task Force
- The Task Force report (80 pages document) published and discussed at the extended CERN directorate meeting on July 18^{th}
- Detailed cost, manpower and schedule
- Encouraged to go ahead and report a Technical Proposal by next Spring

SHiP is currently a collaboration of 41 Institutes from 14 Countries.

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EN Engineering Department

EDMS NO.	REV.	VALIDITY
1369559	1.0	RELEASED

REFERENCE
EN-DH-2014-007

Date : 2014-07-02

Report

A new Experiment to Search for Hidden Particles (SHIP) at the SPS North Area

Preliminary Project and Cost Estimate

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

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
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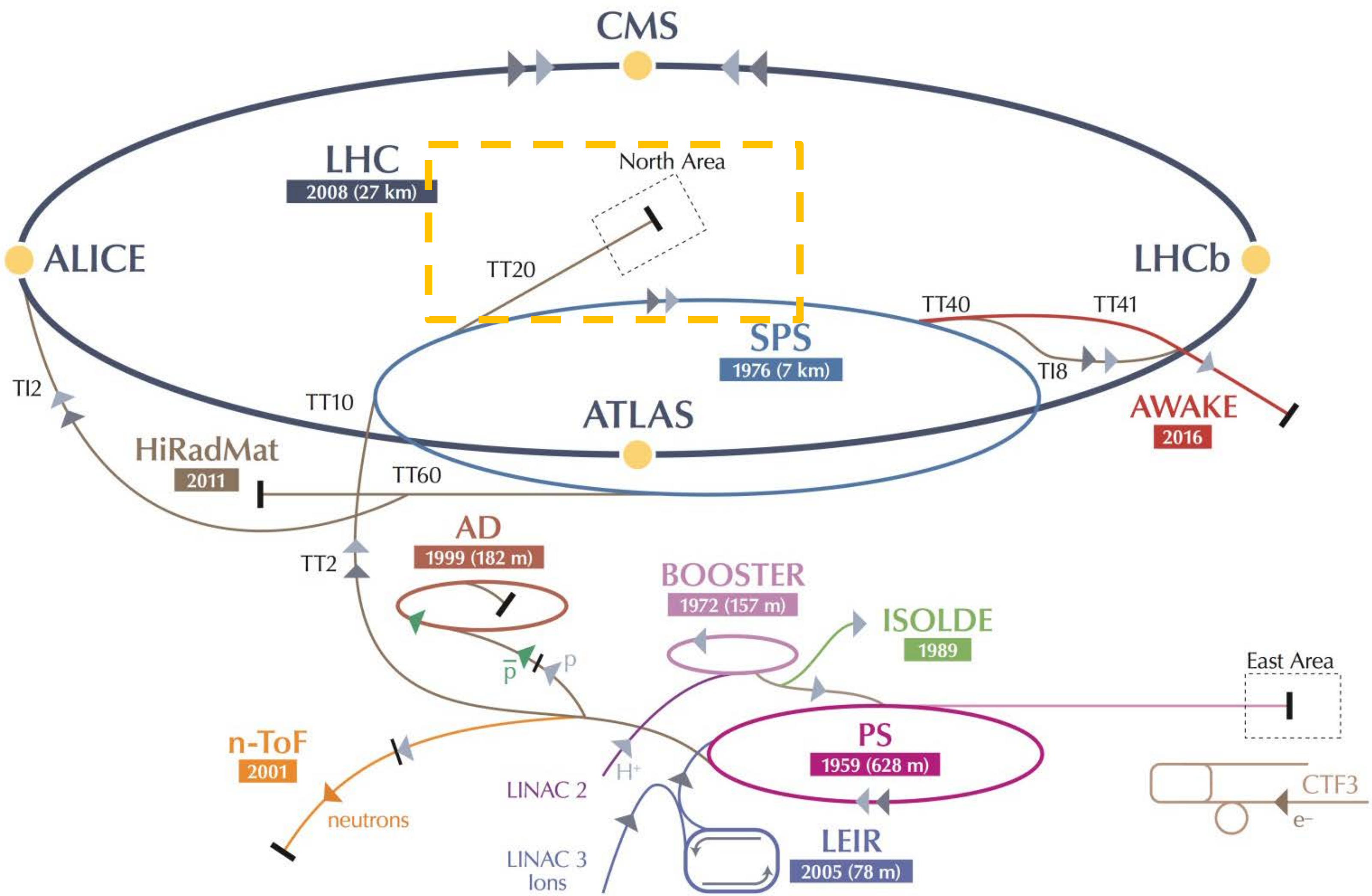
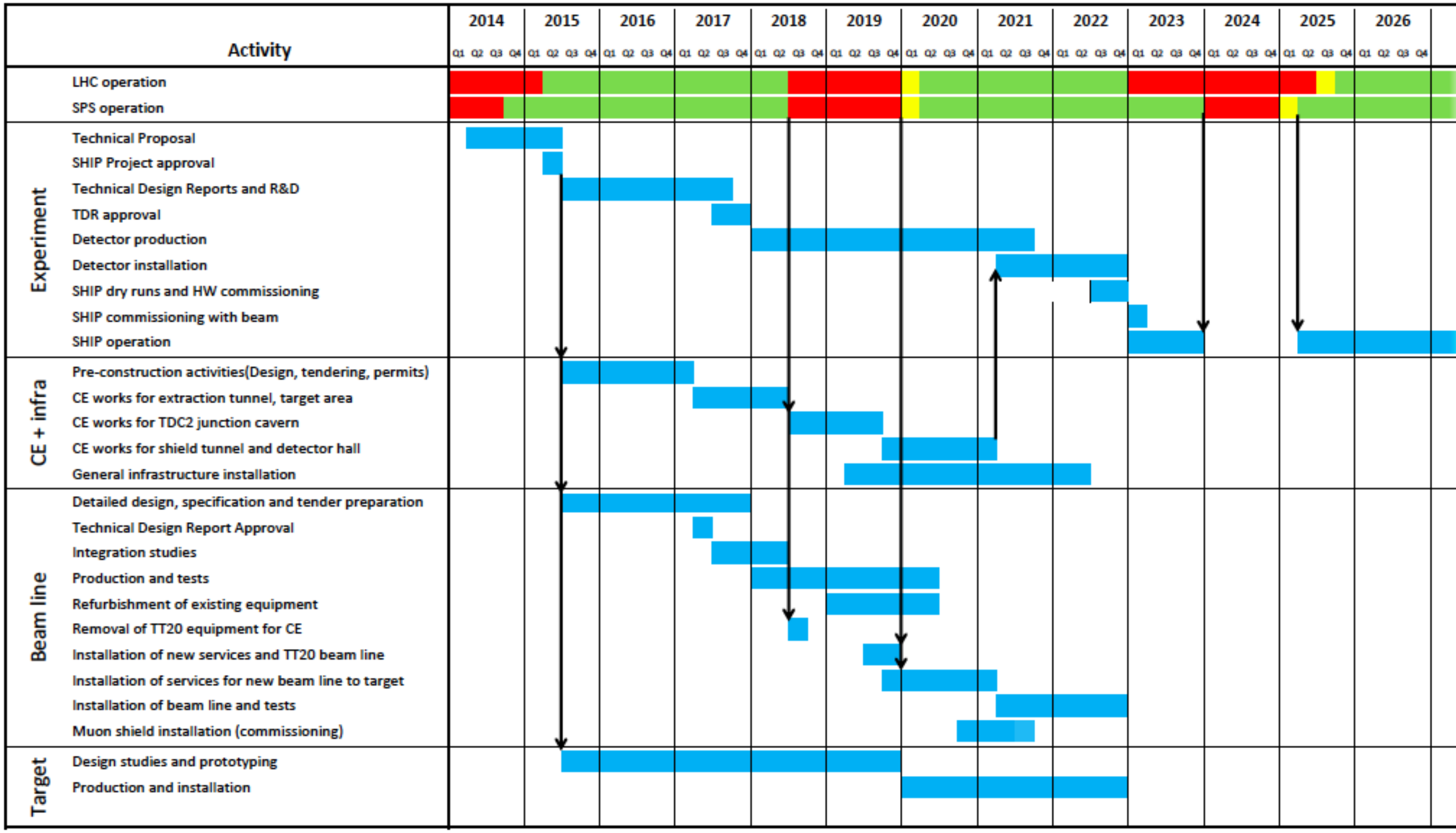
CERN Accelerator complex

proposed location by CERN beams and support department



Prevessin North Area from task force report

Planning schedule of the SHIP facility



A few milestones:

- ✓ *Form SHIP collaboration* → *June-September 2014*
- ✓ ***Technical proposal*** → ***2015***
- ✓ *Technical Design Report* → *2018*
- ✓ *Construction and installation* → *2018 – 2022*
- ✓ *Commissioning* → *2022*
- ✓ *Data taking and analysis of 2×10^{20} pot* → *2023 - 2027*

Theoretical paper: exploiting physics case

2 Physics case

- 2.1 Tau neutrino physics — F. Tramontano
- 2.2 Neutrino portal — M. Shaposhnikov
  - 2.2.1 Particle physics notations
  - 2.2.2 Seesaw Lagrangian
  - 2.2.3 Seesaw formula and scale of seesaw
  - 2.2.4 Dirac and Majorana masses: HNL phenomenology
  - 2.2.5 HNL and baryon asymmetry of the Universe
  - 2.2.6 HNL and dark matter — F. Vissani
  - 2.2.7 νMSM
  - 2.2.8 HNL in astrophysics
- 2.3 Vector portal — Maxim Pospelov
  - 2.3.1 Dark photons
  - 2.3.2 Z'
  - 2.3.3 Millicharge fermions
  - 2.3.4 Chern-Simons portal
- 2.4 Scalar portal — Christophe Grojean
  - 2.4.1 2HDM, 3HDM
- 2.5 Axion-like particles — Joerg Jaeckel
- 2.6 SUSY models
  - 2.6.1 R-parity violating models
  - 2.6.2 Sgoldstino

Tau neutrino physics

- S. Alekhin, Protvino, Higher order QCD corrections for DIS, strangeness, α_s, global fit sensitivity (ABMPDF)
- A. Guffanti, Copenhagen, Strangeness, α_s determination, global fit sensitivity (NNPDF)
- Sven-Olaf Moch, Hamburg, Higher order QCD corrections for DIS, strangeness, α_s, global fit sensitivity (ABMPDF)
- E. Roberto Nocera, Milano, Strangeness, α_s determination, global fit sensitivity (NNPDF)
- Emmanuel Paschos, Dortmund, Electroweak parameters
- Mary Hall Reno, Iowa, USA, Neutrino flux and cross-section, Target mass corrections
- Ingo Schienbein, Grenoble, Target mass corrections
- Francesco Tramontano, Naples (Convener), Exotic charmed baryon production

Conclusions

- Searches for new physics beyond SM: explore the high intensity frontier
- SM guaranteed physics program: $\bar{\nu}_\tau$ discovery, ν_τ cross-section studies and more
- Technical proposal in preparation (Spring 2015)