Search for Heavy Neutral Leptons at SPS(’)

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on behalf of
Search for HIdden Particles - SHIP Collaboration

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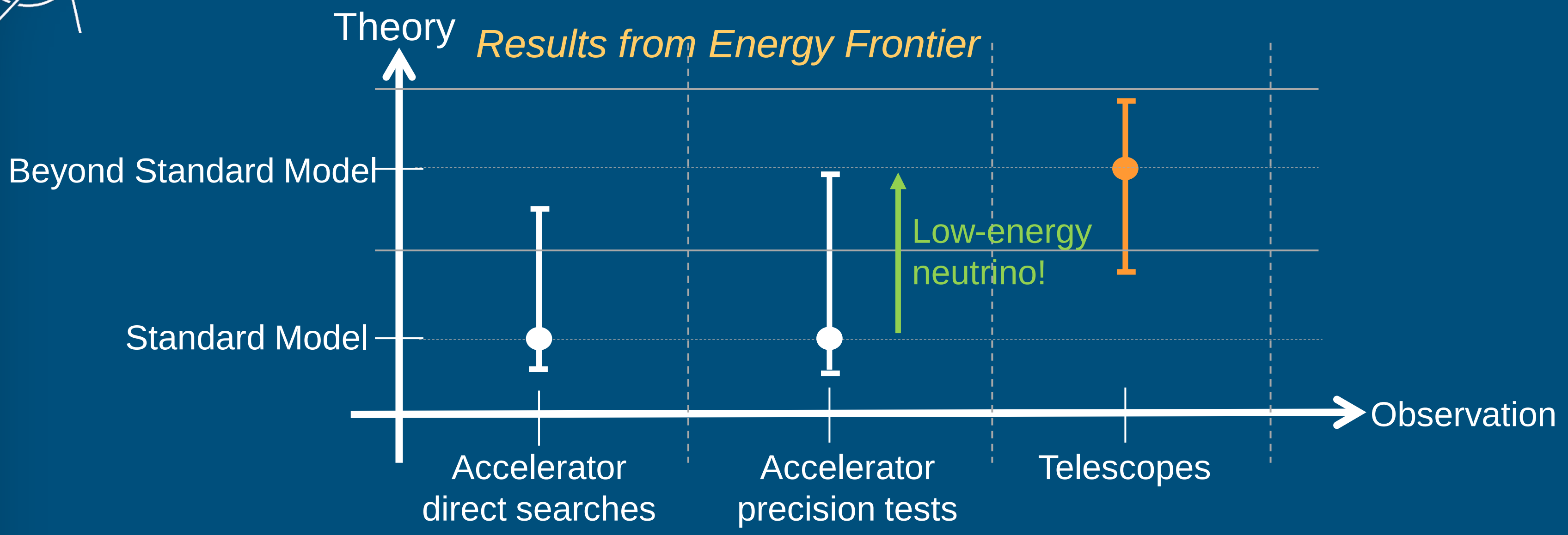
CERN-SPSC-2013-024 / SPSC-EOI-010 / arXiv:1310.1762v1 [hep-ex] 7 Oct 2013

Physics Situation after LHC Run 1



Theory

Results from Energy Frontier

Beyond Standard Model

Standard Model

Low-energy neutrino!

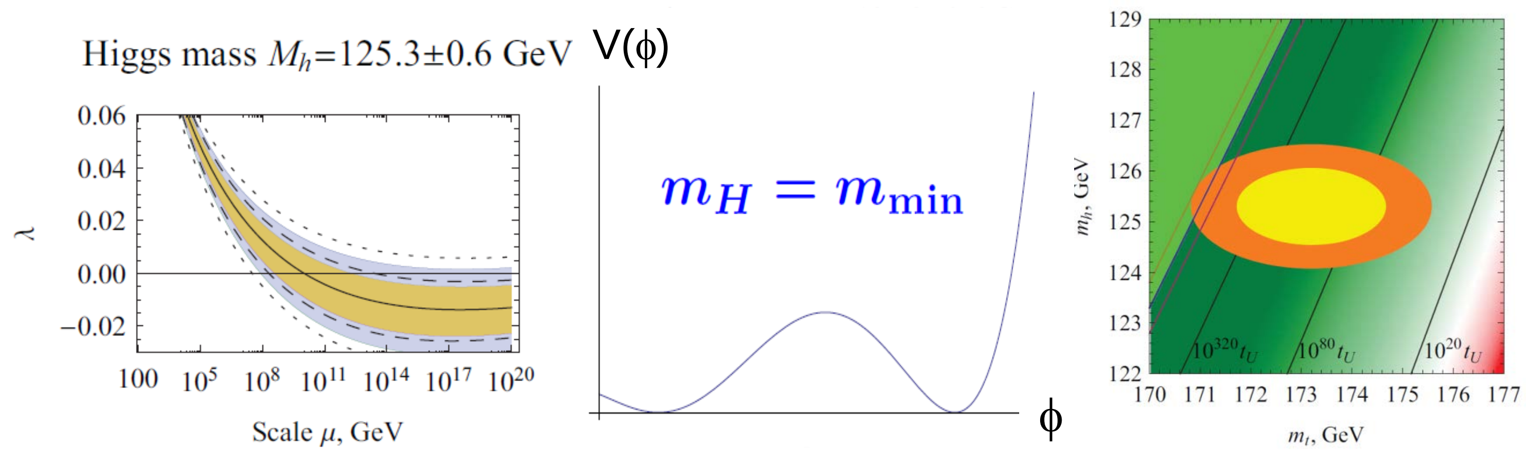
Observation

Accelerator direct searches

Accelerator precision tests

Telescopes

- Standard Model success: Higgs!
  - $m_H < 175\ GeV$: Landau pole in the self-interaction is above the quantum gravity scale M_{Pl} ~ 10^{19} GeV
  - $m_H > 111\ GeV$: Electroweak vacuum is sufficiently stable with a lifetime >>t_U



arXiv:0906.0954

Physics Situation after LHC Run 1

- *With a mass of the Higgs boson of 125 − 126 GeV the Standard Model is a self-consistent weakly coupled effective field theory up to very high scales (possibly up to the Planck scale) without adding new particles*

  ➔ No *need* for new particles *up to* Planck scale!?

Outstanding questions

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

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

  ➔ Most stringent bounds on the scale of New Physics from $B\bar{B}$ mixing…

Physics Situation after LHC Run 1

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

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

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

Many extensions predict very weakly interacting long-lived objects

➔ Complementary physics program consists of searches for these

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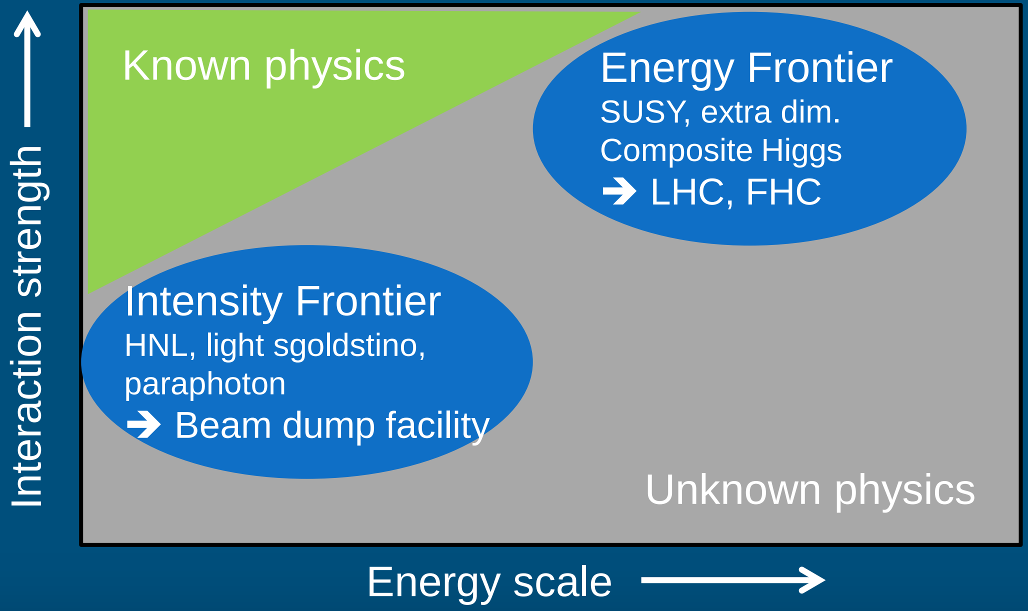
What about solutions to (some) these questions *below* Fermi scale and weak couplings?



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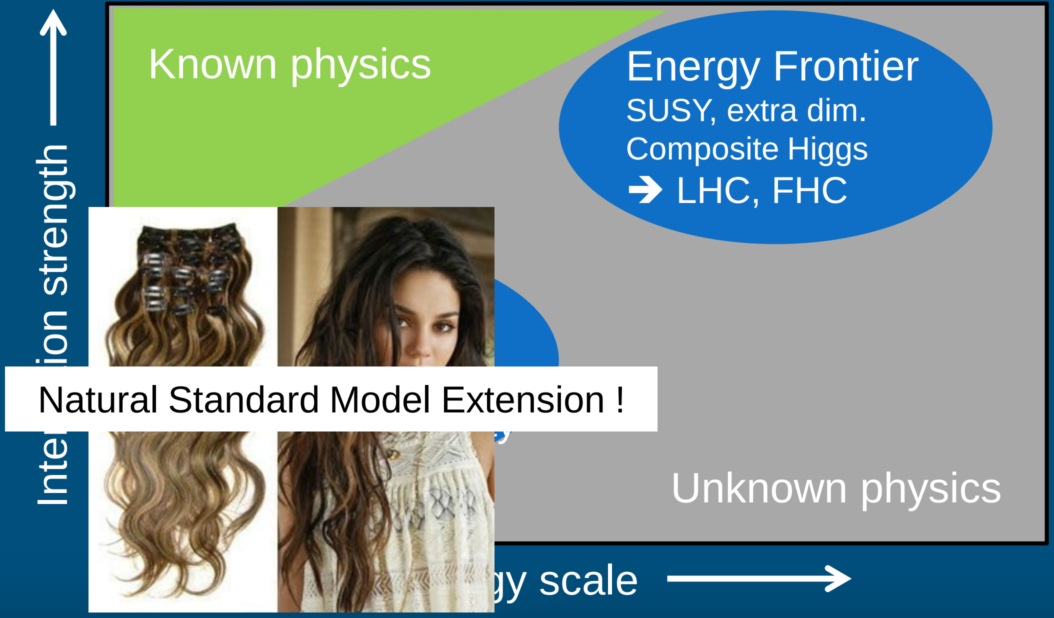


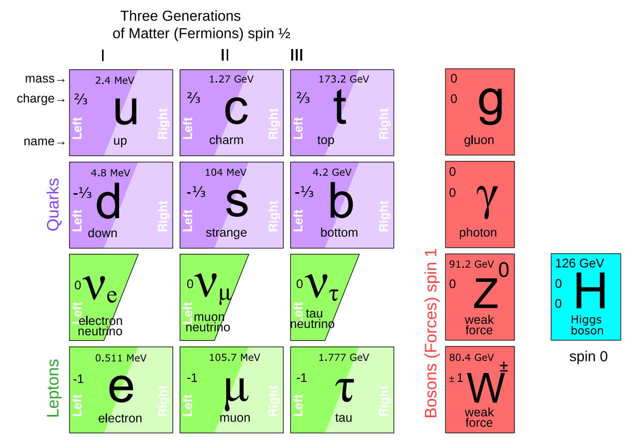
Known physics

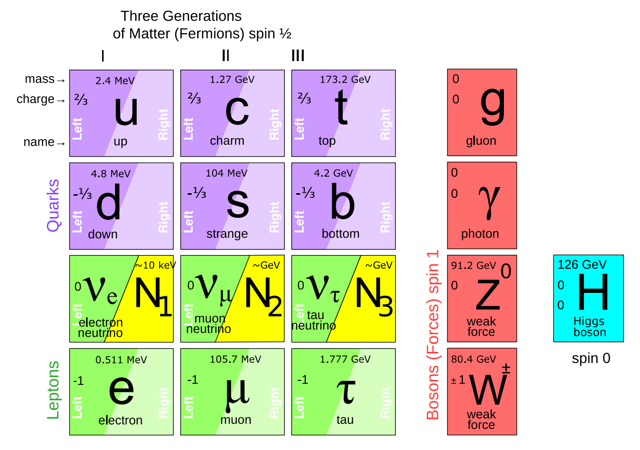
Energy Frontier
SUSY, extra dim.
Composite Higgs
➔ LHC, FHC

Natural Standard Model Extension !

Unknown physics

Ockham's Razor





- Introduce three neutral fermion singlets – right-handed Majorana leptons N_I with Majorana mass m_I^R ≡ "Heavy Neutral Leptons (HNL)"
  - Make the leptonic sector similar to the quark sector

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

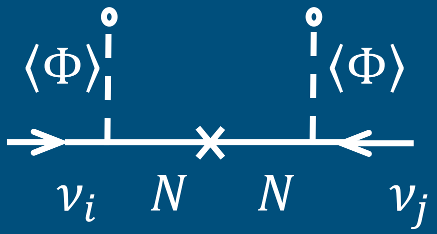
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{\substack{I=1,2,3; \\ \ell=1,2,3(e,\mu,\tau)}} i\bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\ell}\bar{N}_I \Phi^\dagger L_\ell - m_I^R \bar{N}_I^c N_I + h.c$$

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

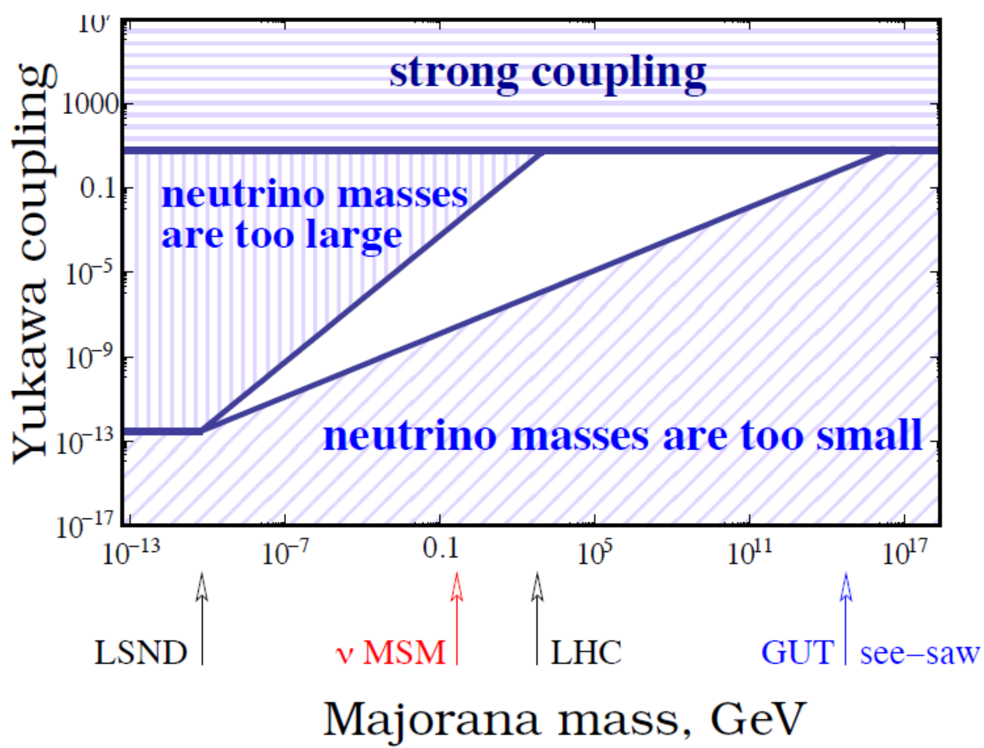
- Discovery of Higgs vital for the see-saw model! ➔ Responsible for the Yukawa couplings!

Type I See-saw

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



- Assumption that N_I are $\mathcal{O}(m_q/m_{l^\pm})$ (νMSM)
  - ➔ Yukawa couplings are very small
    - $Y_{I\ell} = \mathcal{O}\left(\frac{\sqrt{m_{atm} m_I^R}}{v}\right) \sim 10^{-8}$
    - $\mathcal{U}^2 \sim 10^{-11}$



arXiv:1204.5379

➔ Experimental challenge ➔ Intensity Frontier

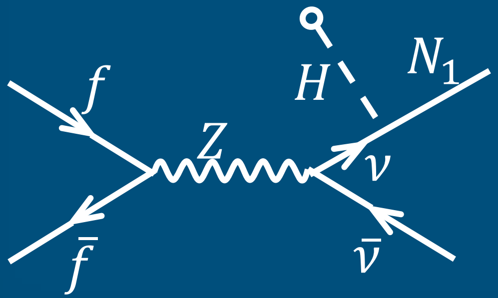
νMSM (Asaka, Shaposhnikov: hep-ph/0505013)

Role of N_1 with a mass of $\mathcal{O}$(10 keV)
➔ Dark Matter

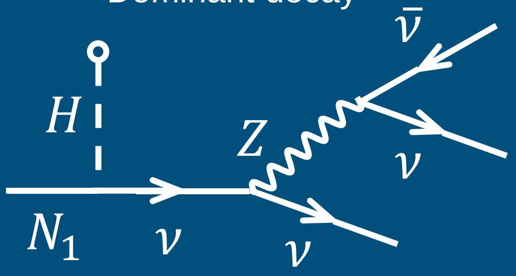
Role of N_2 and N_3 with quasi-degenerate mass of $\mathcal{O}(m_q/m_{l^\pm})$ (100 MeV – GeV's):
➔ Neutrino oscillations and mass, and BAU

- Assume lightest singlet fermion N_1 has a very weak mixing with the other leptons
  - Mass $M_1 \backsim \mathcal{O}(10) keV$ and very small coupling
    - ➔ Sufficiently stable to act as Dark Matter candidate
    - ➔ Give the right abundance
    - ➔ Decaying Dark Matter

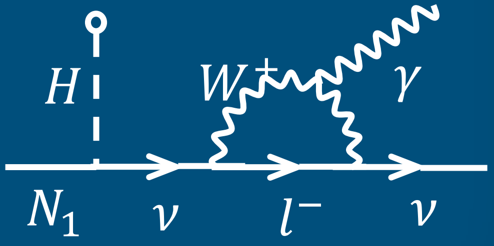
Production from υ ⟷ N oscillations



Dominant decay



Subdominant radiative decay

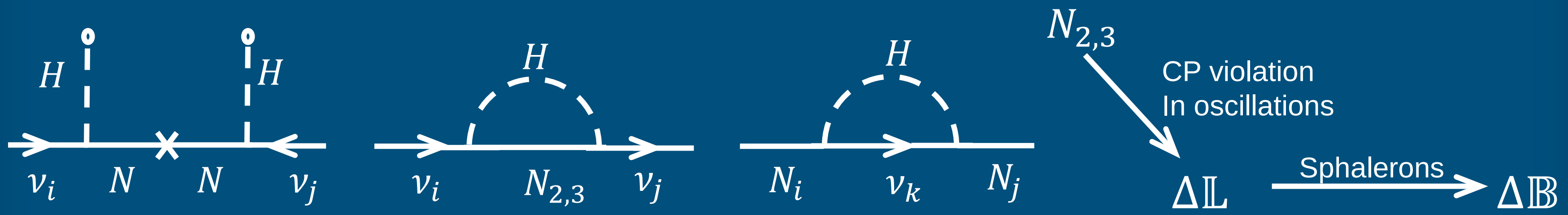


$$E_\gamma = \frac{M_{N_1} c^2}{2}$$

N_2 and N_3 in νMSM

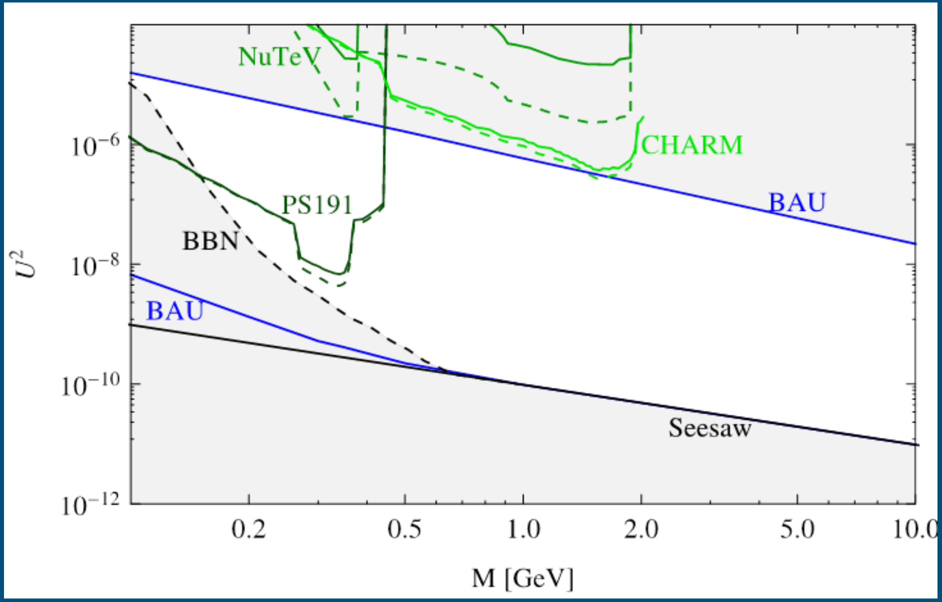
- N_1 as DM ($M_{N_1} \ll M_{N_2} \approx M_{N_3}$) gives no contribution to active neutrino masses
  - ➔ Neglect for the rest
  - ➔ Reduces number of effective parameters for Lagrangian with $N_{2,3}$
    - 18 parameters ➔ 11 new parameters with 3 CP violating phases
      - ➔Two mixing angles related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

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



N_2 and N_3 Constraints in νMSM

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



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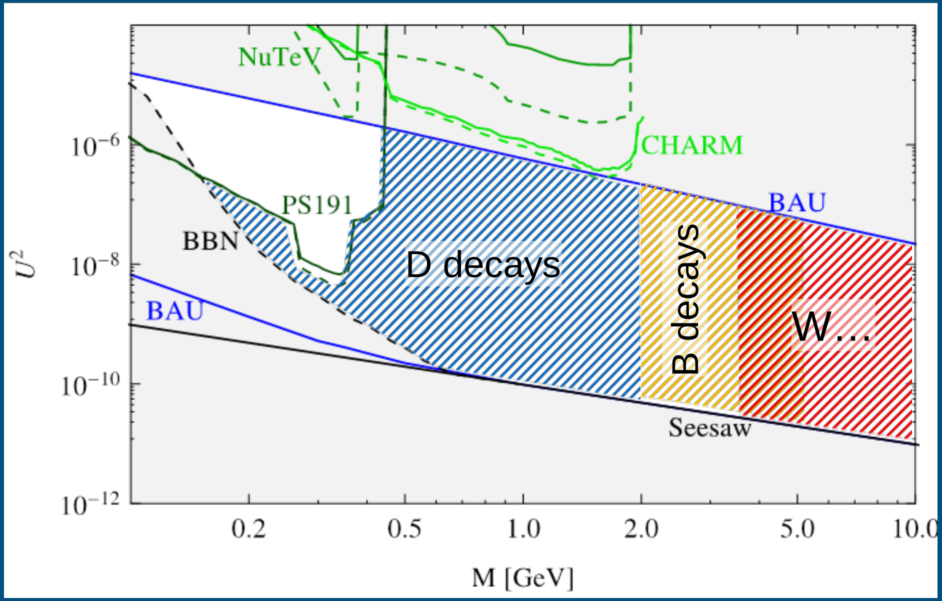


- Large fraction of interesting parameter space can be explored in accelerator based search
  - $m_\pi < M_N < 2$ GeV
  - $M_N > 2$ GeV is not reachable at any operating facility

$N_{2,3}$ Production

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

➔ For the sake of determining a search strategy, assume scenario with a predominant coupling to the muon flavour (arXiv:0705.1729)

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

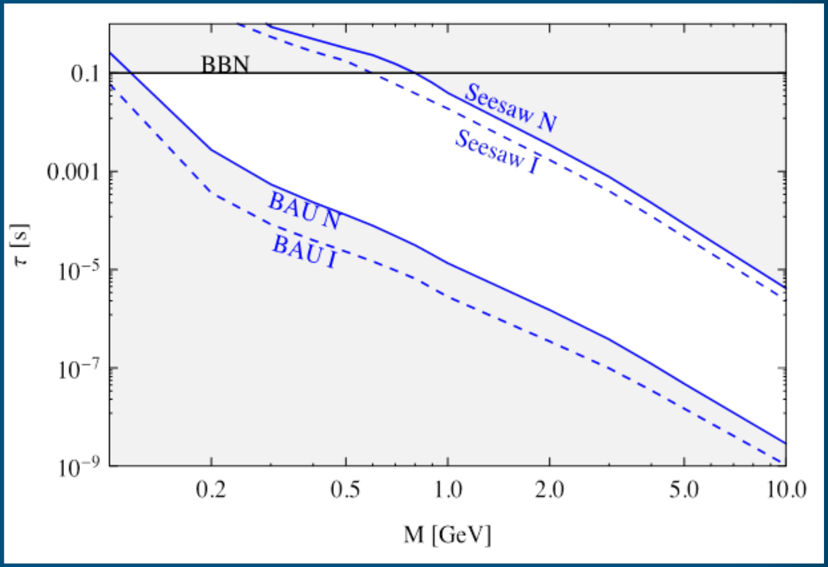
➔ $\mathrm{Br}(D \to NX) \sim 10^{-8} - 10^{-12}$

$N_{2,3}$ Decay

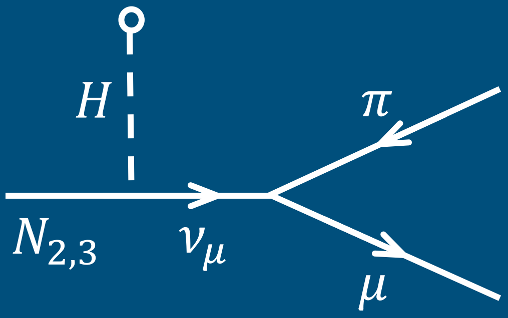
- Very weak HNL-active neutrino mixing → $N_{2,3}$ much longer lived than SM particles
  - ➔ Typical lifetimes > 10 ms for $M_{N_{2,3}} \sim 1\ GeV$ → Decay distance $\mathcal{O}(km)$

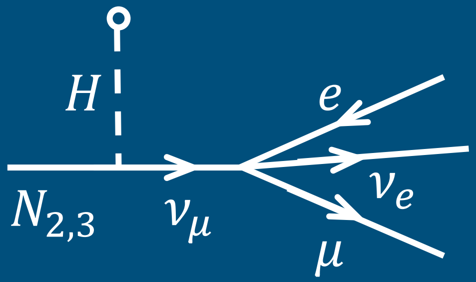
- Decay modes:
  - $N \rightarrow\ \mu e\nu, \pi^0\nu, \pi e, \mu\mu\nu, \pi\mu, Ke, K\mu, \eta\nu, \eta'\nu, \rho\nu, \rho e, \rho\mu, \ldots$
  - Branching ratios depend on flavour mixing (again)
  - Typical:

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



E.g.





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

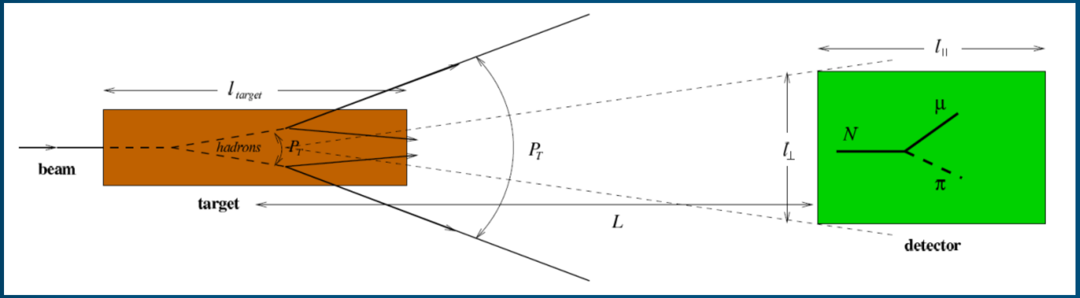
Experimental Requirements/Challenges

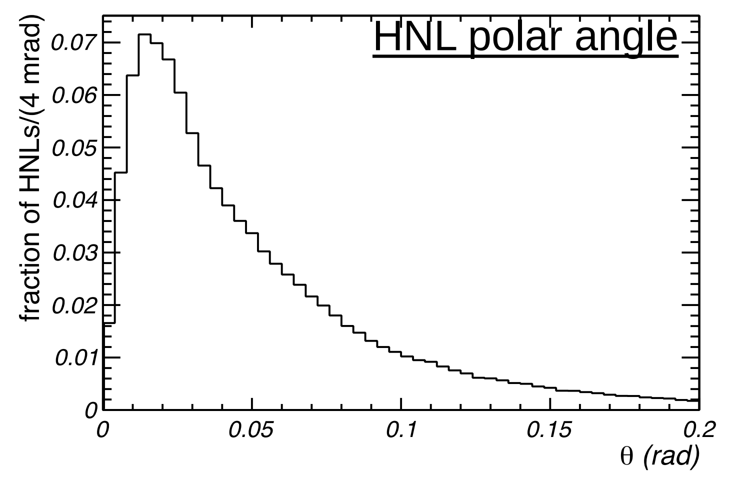
Proposal: beam dump experiment at the SPS

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

➔ Incompatible with conventional neutrino facility

Gorbunov, Shaposhnikov





Schematic Principle of Experimental Setup

- Initial reduction of beam induced background:
  - Heavy target
  - Hadron absorber
  - Muon deflection / shield

Muon flux at detector per spill of 5×10^{13} p.o.t.

No shield: 5×10^{9} muons

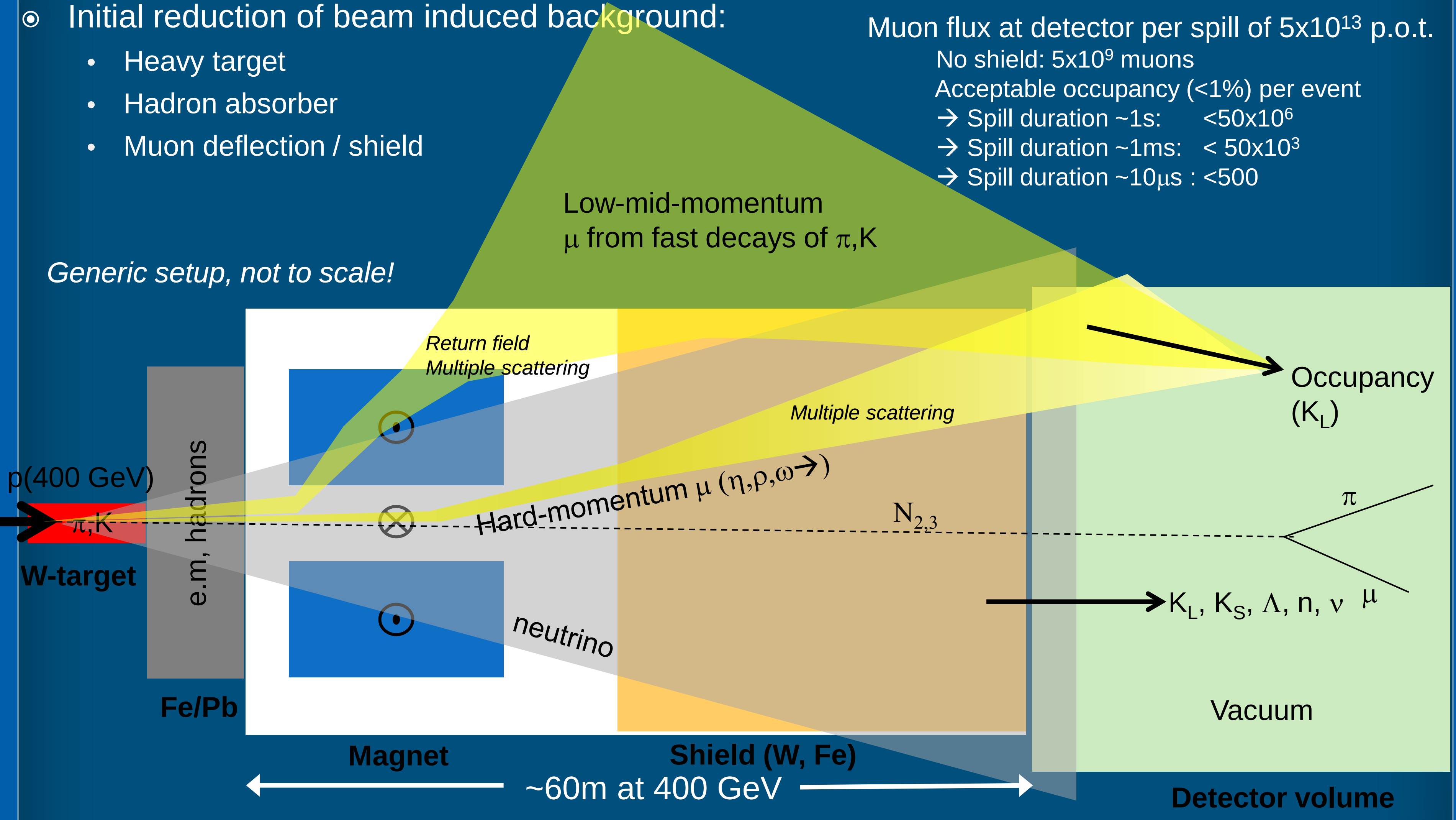
Acceptable occupancy (<1%) per event

→ Spill duration ~1s: $<50\times10^{6}$

→ Spill duration ~1ms: $< 50\times10^{3}$

→ Spill duration ~10μs : <500

Generic setup, not to scale!

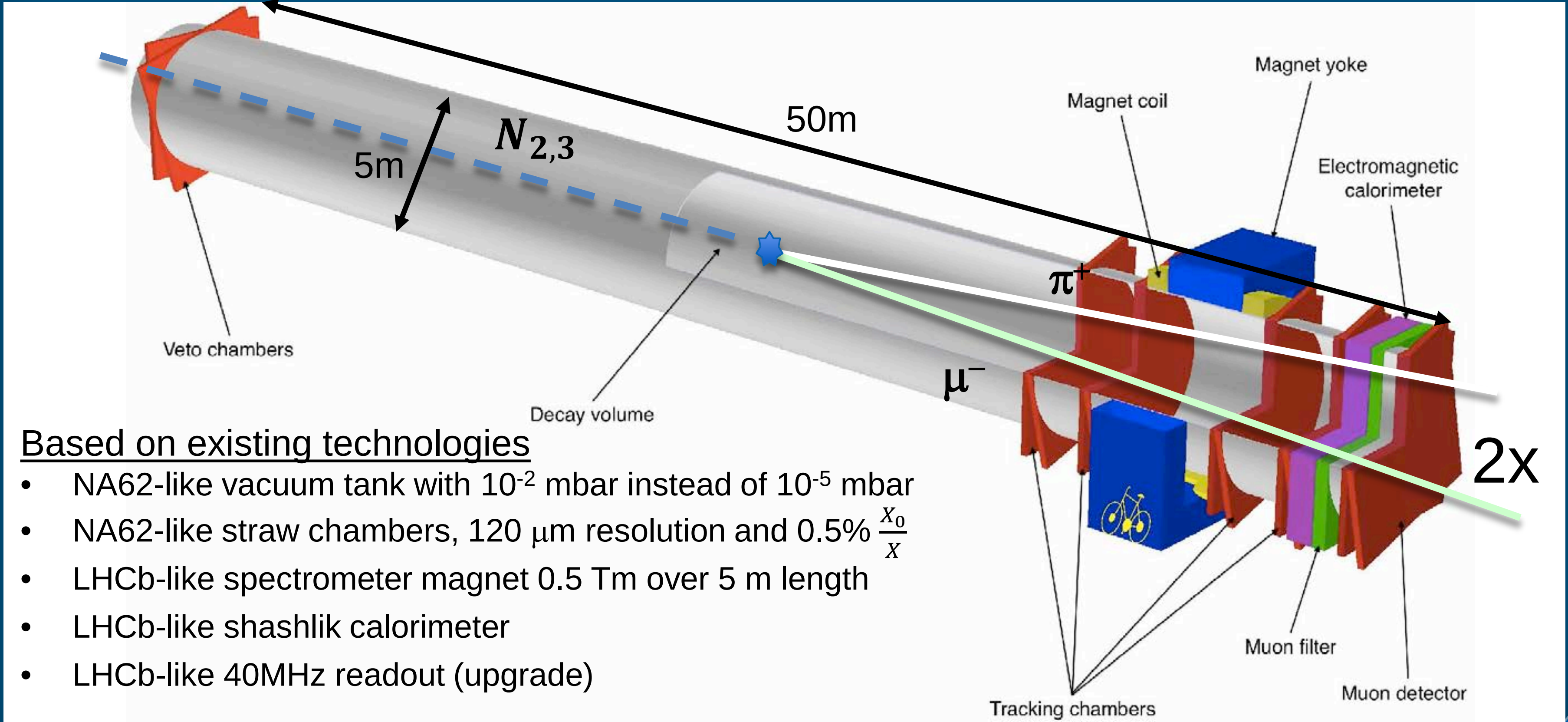


→ Multi-dimensional optimization: Beam energy is compromise between σ_{charm}, beam intensity, background conditions, acceptance, detector resolution

Detector Concept

- Reconstruction of the HNL decays in the final states: $\mu\pi, \mu\rho, e\rho$
  - ➔ Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter in large hall

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



Based on existing technologies

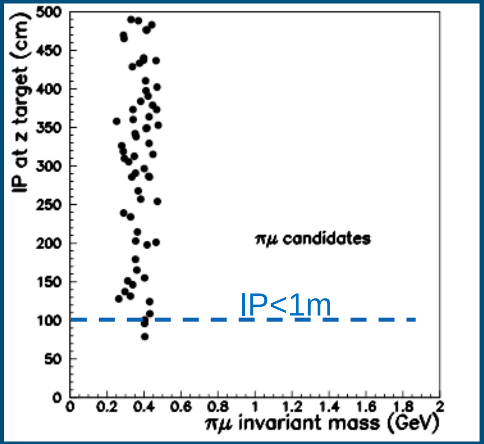
- NA62-like vacuum tank with 10^{-2} mbar instead of 10^{-5} mbar
- NA62-like straw chambers, 120 μm resolution and 0.5% $\frac{X_0}{X}$
- LHCb-like spectrometer magnet 0.5 Tm over 5 m length
- LHCb-like shashlik calorimeter
- LHCb-like 40MHz readout (upgrade)

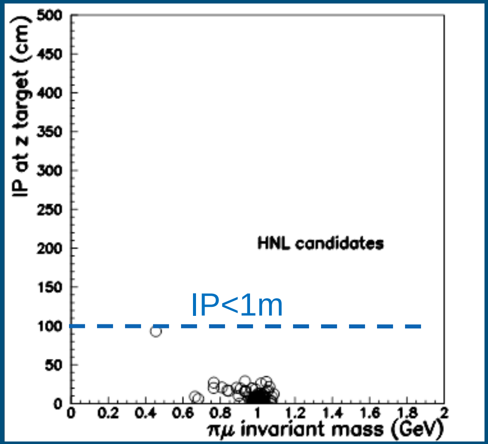
Background Suppression

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

- Charged Current and Neutral Current neutrino interaction in the final part of the muon shield
  - Yields CC(NC) rate of $\sim6(2)\times10^5$ / λ_{inter} / 2×10^{20} p.o.t.
  - ~10% of neutrino interactions produce Λ or K^0 in acceptance
  - Majority of decays occur in the first 5 m of the decay volume
  - ➔ Requiring μ-identification for one of the two decay products: 150 two-prong vertices in 2×10^{20} p.o.t.
  - For 0.5 Tm field integral σ_{mass} ~ 40 MeV for p < 20 GeV

➔ E.g. background reduction by impact parameter





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

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

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

- A conservative estimate of the sensitivity is obtained by considering only the decay $N_{2,3} \to \mu\pi$ with production mechanism $D \to \mu N_{2,3} X$, which probes $\mathcal{U}_\mu^4$

- Expected number of signal events

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

$n_{pot} = 2 \times 10^{20}$
$\chi_{cc} = 0.45 \times 10^{-3}$

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

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

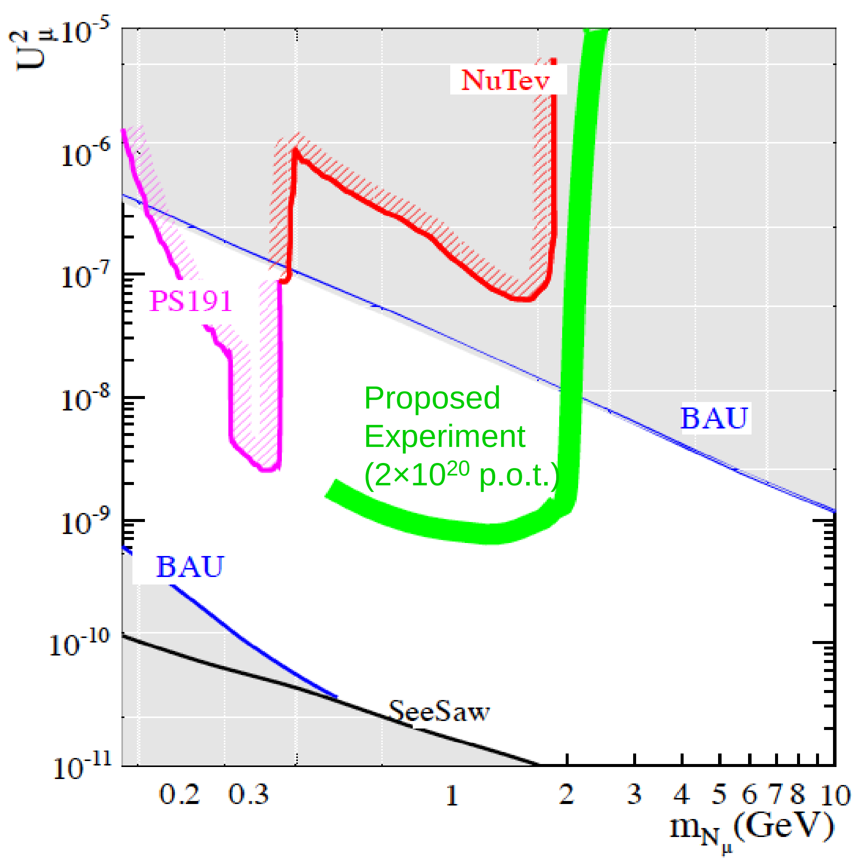
  - (Reconstruction efficiency for $N_{2,3} \to e\pi$ is about same as $\mu\pi$)
  - ($N_{2,3} \to \mu\rho$ is about 45% of $N_{2,3} \to \mu\pi$)

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

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

- For comparison, assume
  - $\mathcal{U}_\mu^2 = 10^{-7}$ (corresponding to the strongest current experimental limit for $M_{N_{2,3}} = 1\ GeV$)
  - $\tau_N = 1.8 \times 10^{-5} s$

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



- 120 events for cosmologically favoured region: $\mathcal{U}_\mu^2 = 10^{-8}$ and $\tau_N = 1.8 \times 10^{-4} s$

Evaluation of Full Physics Program

- General Purpose (Beam) Dump: Explore sensitivities to
  - *all less constraining "variants" of νMSM*
  - all BSM models with HNLs
  - all models with light, very weakly interacting, long-lived "exotic" particles out of reach at LHC
    - Sensitive to the same physics as CHARM and LHCb ➔ Longer lifetimes and smaller couplings
  - ν_τ physics with additional upstream emulsion detector: 1500 - 2000 events expected

Examples with mass~$\mathcal{O}(GeV)$ and production branching ratio ~ $\mathcal{O}(10^{-10})$

➔ Light super-goldstinos [Gorbunov, 2001] "Axion- and dilaton-like"

➔ $D \rightarrow \pi X,\ X \rightarrow \pi^+\pi^-,\ \pi^0\pi^0,\ l^+l^-$

- $N_{\pi^+\pi^-}(N_{pot} = 2 \times 10^{20}) \cong 2\ \times \left(\frac{1000\ TeV}{\sqrt{F}}\right)^8 \left(\frac{M_{\lambda g}}{3\ TeV}\right)^4 \left(\frac{m_X}{1\ GeV}\right)^2$

➔ R-parity violating neutralinos in SUSY [Dedes et al., 2001] "Heavy-neutrino like"

➔ $D \rightarrow l\tilde{\chi},\ \ \tilde{\chi} \rightarrow l^+l^-\nu$

- $N_{\mu^+\mu^-\nu}(N_{pot} = 2 \times 10^{20}) \cong 20\ \times \left(\frac{m_{\tilde{\chi}}}{1\ GeV}\right)^6 \left(\frac{\lambda}{10^{-8}}\right)^2 \left(\frac{BR(D\rightarrow l\tilde{\chi})}{10^{-10}}\right)$, λ is R-violating coupling

➔ Massive vectors in secluded dark matter models [Pospelov et al., 2008] "Paraphoton-like"

- Production of γ' through bremsstrahlung, J/ψ decay, $\gamma' \rightarrow l^+l^-$

➔ Specifying the full physics program is one of the main goals of the next few months

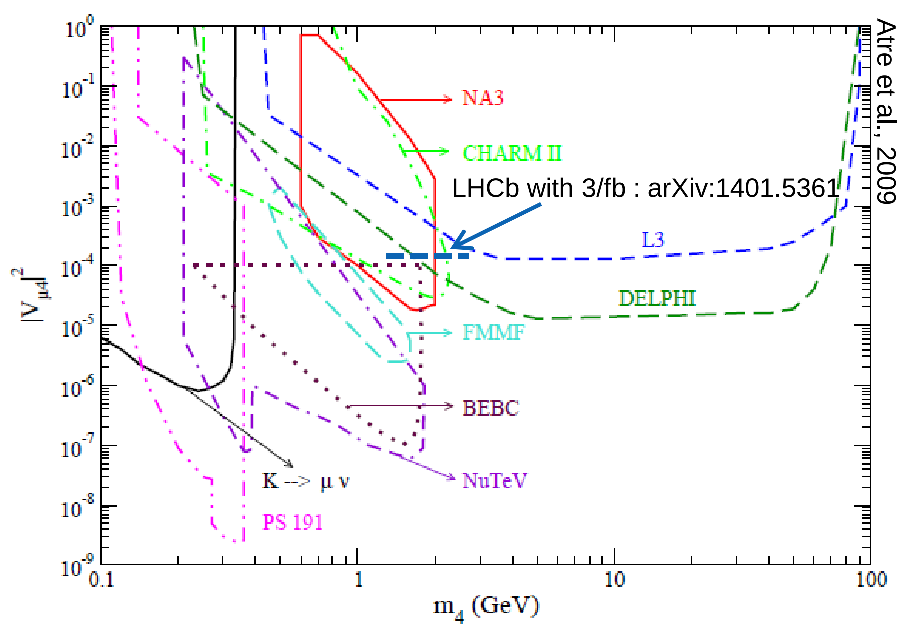
Prospects for Future

Current sensitivity based on current SPS with 2×10^{20} p.o.t in ~5 years of operation

- HNLs very constrained by simultaneously aiming at answering to neutrino masses, BAU and DM.

➔ Primary interest to reach seesaw limit

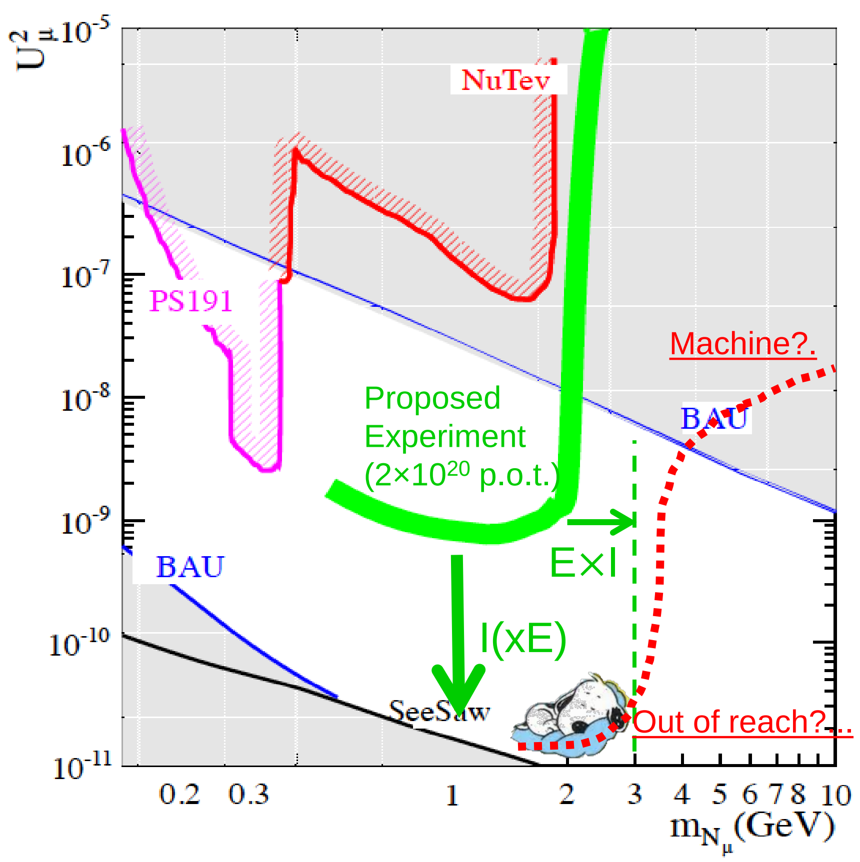
Summary of Searches for N_I



LHCb with 3/fb : arXiv:1401.5361

Atre et al., 2009

→ Colliders out of luck



Proposed Experiment (2×10^{20} p.o.t.)

➔ Search for Hidden Sector light objects ➔ Intensity Frontier

➔ Complementary by use of fixed target facility on FHC Injectors (fast cycling!)

- Fiducial volumes

Conclusions

- νMSM : Minimal SM extension with solutions to the main BSM questions with "*least prejudice*"
    - Origin of the baryon asymmetry of the Universe
    - Origin of neutrino oscillations and mass
    - Shed light on the nature of Dark Matter

- Evaluation of complete physics program with very weakly interacting and long-lived particles
    - General purpose beam dump facility
    - The proposed experiment perfectly complements the searches for NP at the LHC

- Sensitivity demonstrated with νMSM for $M_N < 2\ GeV$ and $2\text{x}10^{20}$ p.o.t.

    ➔ Discovery potential in cosmologically favoured region with $10^{-7} < \mathcal{U}_\mu^2 < a\ few\ \times 10^{-9}$
    - Improved with the additional decay modes
    - Improved with an SPS': $7\text{x}10^{13}$ p.o.t. and ms / second extraction
    - Below $\mathcal{U}^2 \sim 10^{-9}$ and $M_N > 2\ GeV$ → Clearly new machine! ➔ FHC Injectors with fixed-target facility

- The impact of a discovery of the HNLs on particle physics is difficult to overestimate !
    - Of course also true for any other BSM long-lived object!
    - Clearly requires a new machine ➔ Intensity
    - *Challenging experimental optimization*

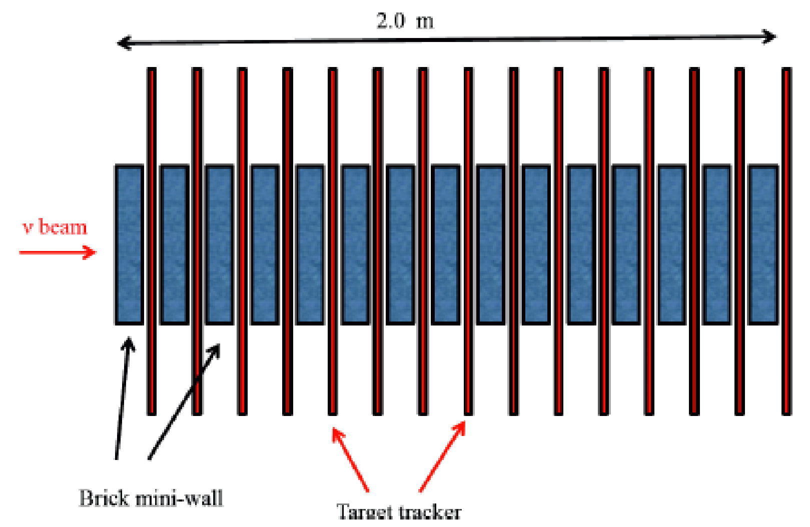
- SPSC recommendation Jan 2014: Encouragement to submit extended proposal (LoI)

    ➔ "SHIP" Workshop/Collaboration meeting June 10 – 12, 2014

Reserve slides

Prospects for ν_τ Physics

- Scaling from the DONUT experiment
  - 20 times more ν_τ CC interactions assuming the same neutrino fiducial mass
  - Realistic to increase fiducial mass from 260 kg (DONUT) to 3000 kg with OPERA style lead/emulsion bricks (3% of OPERA emulsion surface)
  - ➔ 1500 – 2000 events expected



➔ Negligible loss of acceptance for HNL detector

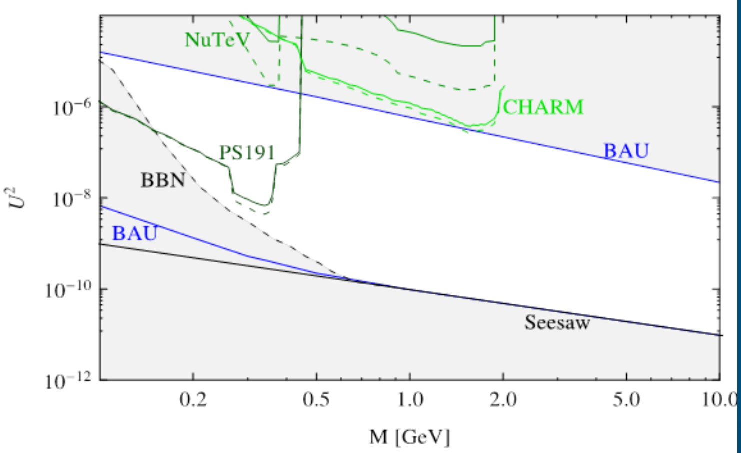
➔ HNL detector function as forward spectrometer for ν_τ physics program

➔ Use of calorimeter/muon detector allow tagging neutrino NC/CC interactions → normalization

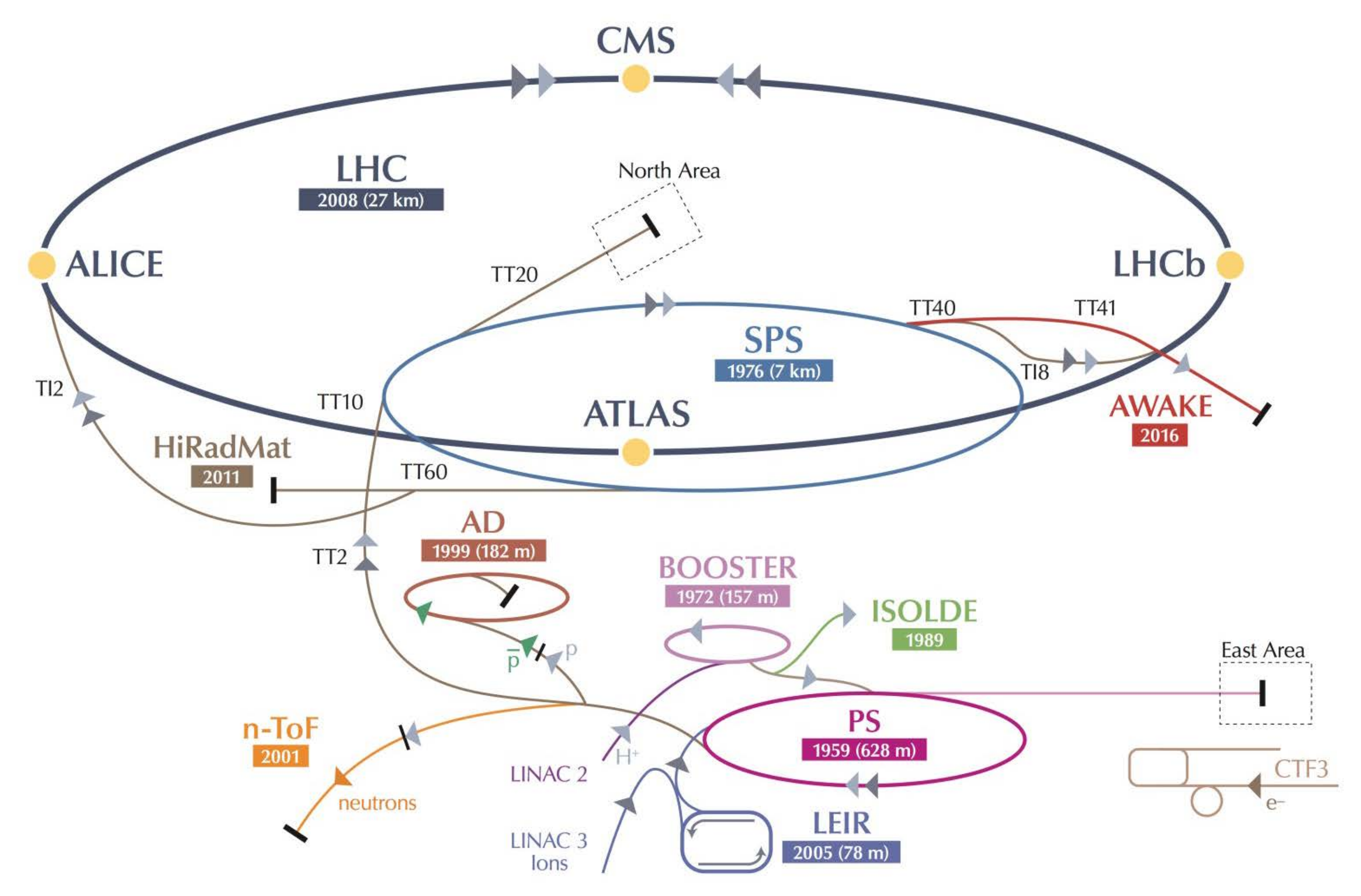
Constraints in Variants of νMSM

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

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



CERN Accelerator Complex



Primary Beam with current SPS

Experimental sensitivity based on 2x10^{20} protons on target, that is 5 years of equivalent CNGS operation

→ Basic experimental requirements

1. Maximum production of D mesons at an energy of ~400 GeV
   - Energy is driven by optimization between D cross-section, acceptance from boost, and amount of shield to range out muon flux.
2. 6s/7.2s SPS cycles with preference for longest possible extraction spill to reduce detector occupancy
   - Easing requirements on detector and reconstruction
3. Minimal beam induced background in terms of neutrinos and muons
   - Use of a heavy target material (tungsten) to stop pions and kaons
4. HNL production angles relaxes significantly the beam parameters (collimation and alignment)
   - Beam delivery line consisting mainly of drift space and dilution to ease tungsten target design

Based on these requirements, the proponents have investigated a realistic NA option in close contact with beam, target, radiology, and infrastructure experts

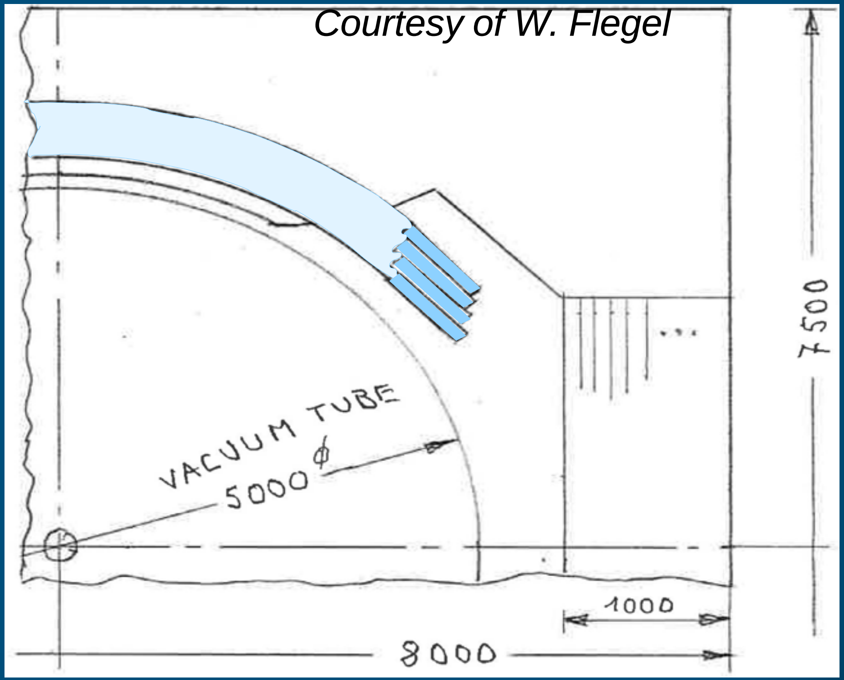
- SPS extraction in SPS-LSS2
  - Key study concerns optimal extraction type
- Beam splitting/switch at the top of SPS-NA transfer line (TT20)
  - Key study concerns the possibility of a combined splitter for COMPASS and the EOI-010 experiment transfer line
- A compact target bunker
  - Limited volume by the use of the hadron stopper closing the entrance to the muon shield tunnel
- Wide tungsten target head
  - Key study concerns the solid tungsten target design with heat extraction and mechanical stress
- 60 m tunnel housing optimised combination of passive/active muon shield

⦿ A significant fraction of studies performed for neutrino facilities are directly beneficial to the current proposal (extraction, TT20 reuse, transfer line, target station, civil engineering and radiological aspects)

Detector Technologies

- Experiment requires a dipole magnet similar to LHCb design, but with ~40% less iron and three times less dissipated power
- Free aperture of ~ 16 m^2 and field integral of ~ 0.5 Tm
    - Yoke outer dimension: 8.0×7.5×2.5 m^3
    - Two Al-99.7 coils
    - Peak field ~ 0.2 T
    - Field integral ~ 0.5 Tm over 5 m length

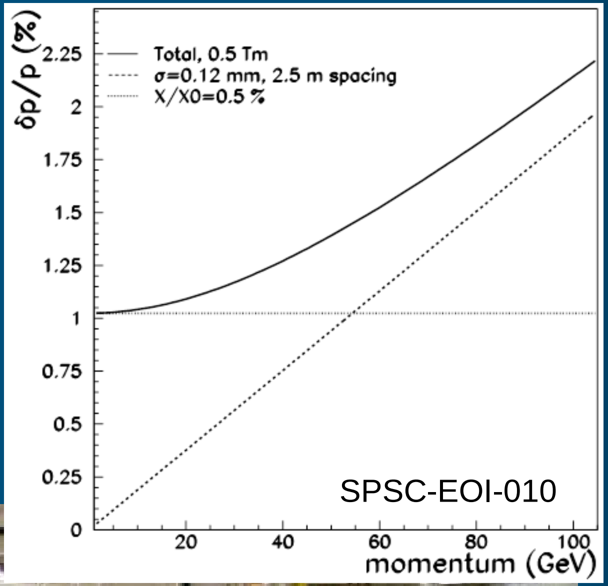
LHCb diplole magnet



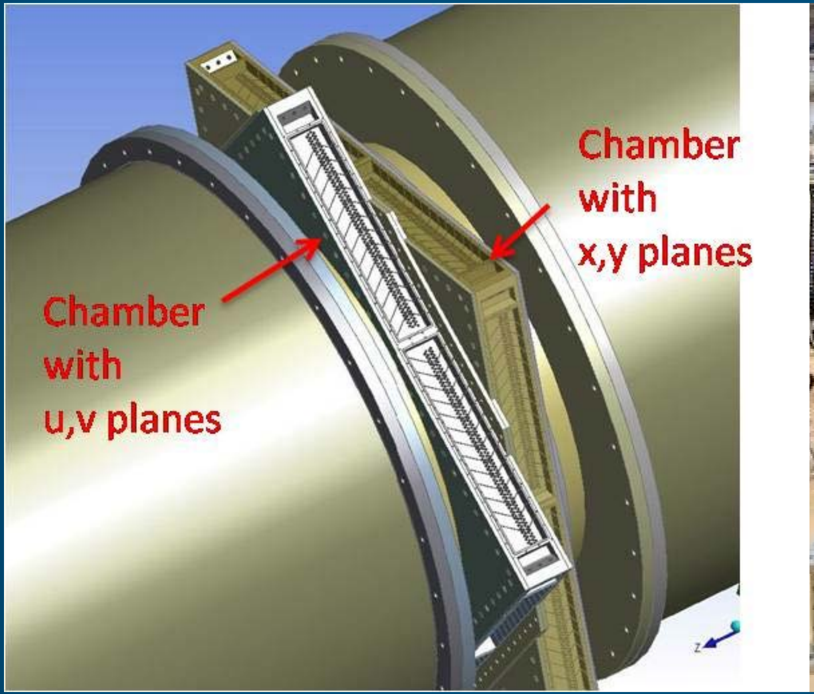
Courtesy of W. Flegel

Detector Technologies

- NA62 vacuum tank and straw tracker
  - < 10^{-5} mbar pressure in NA62 tank (cmp. 10^{-2} mbar)
  - Straw tubes with 120 μm resolution and 0.5% $\frac{X_0}{X}$ of material budget
  - Gas tightness of straw tubes demonstrated in long term tests
- Multiple scattering and spatial resolution of straw tubes give similar contribution to the overall $\frac{dP}{P}$



SPSC-EOI-010



Detector Technologies

- LHCb electromagnetic calorimeter

➔ Shashlik technology provides economical solution with good energy and time resolution