Search for Heavy Neutral Leptons at SPS

- A "Lepton Flavour Experiment" -

on behalf of

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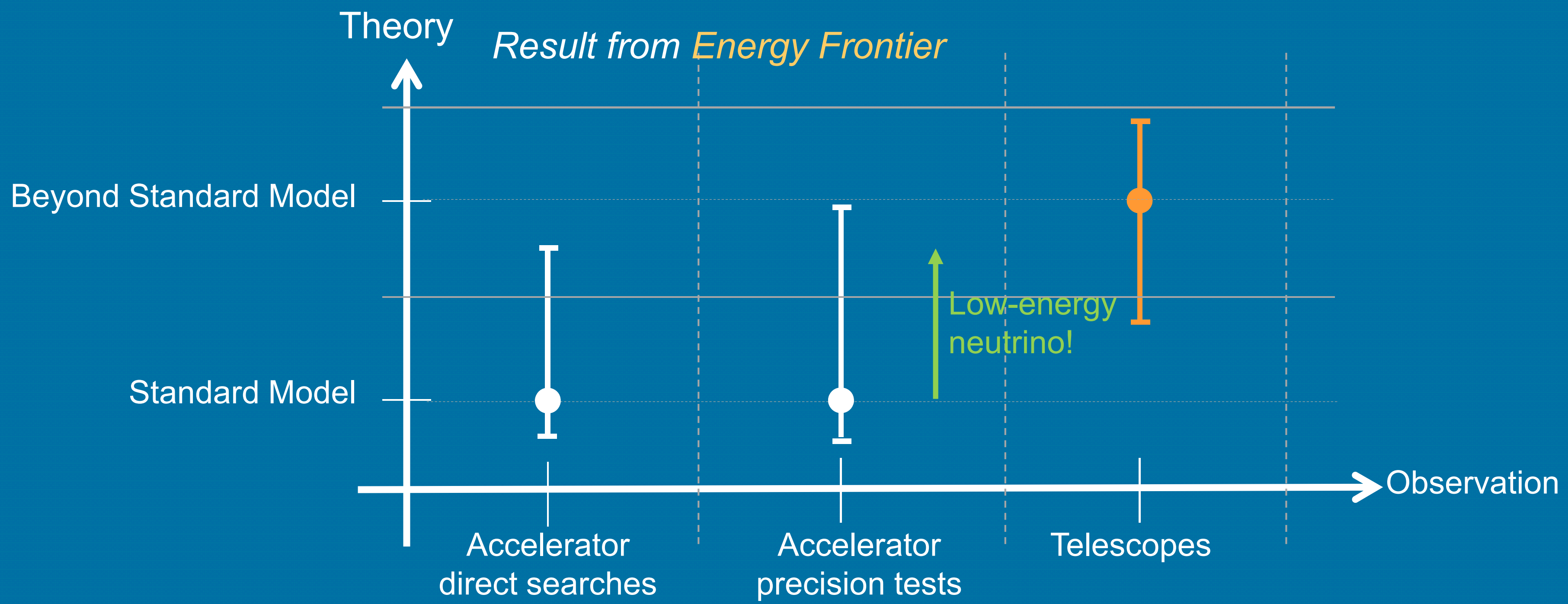
Expression of Interest presented at 111th Meeting of SPSC, October 22, 2013 :
CERN-SPSC-2013-024 / SPSC-EOI-010 / arXiv:1310.1762v1 [hep-ex] 7 Oct 2013

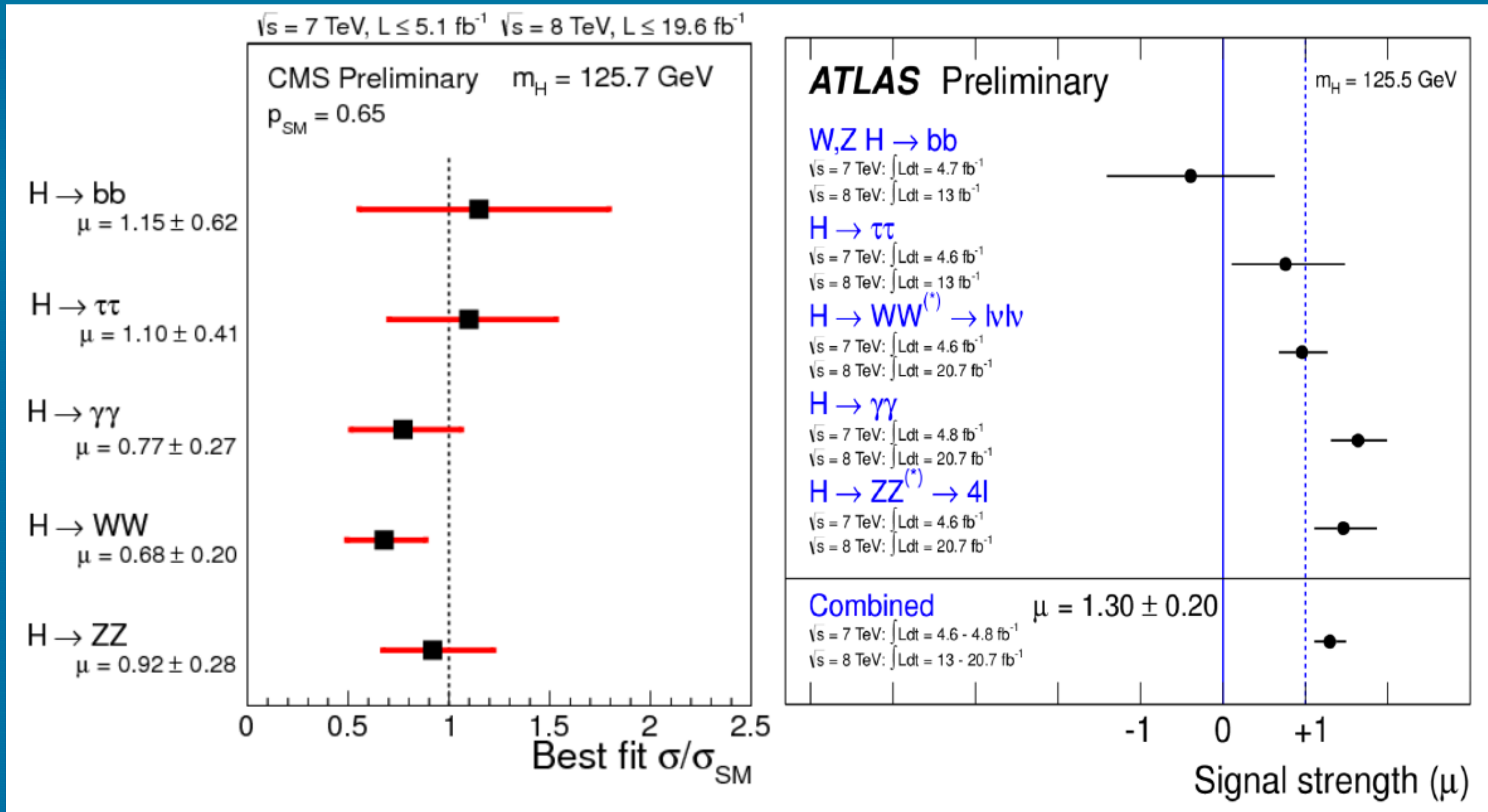
Physics Situation after LHC Run 1



➔ Standard Model success: Higgs!

Higgs Discovery

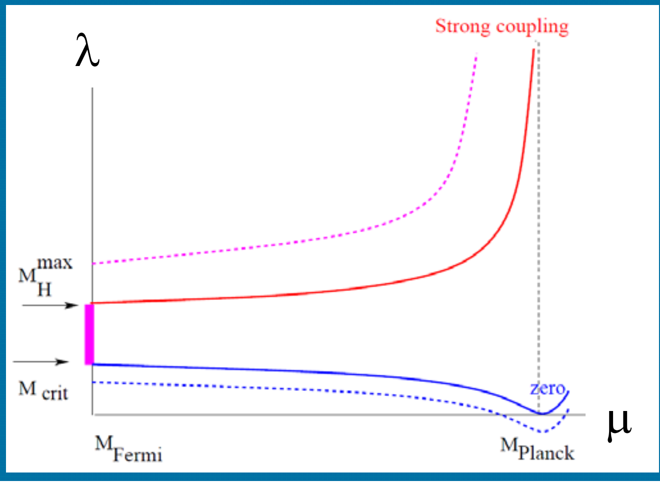
- It looks very much like THE Higgs boson:

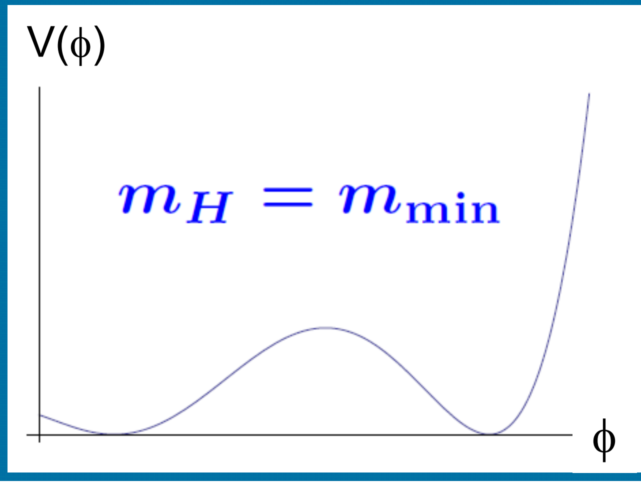


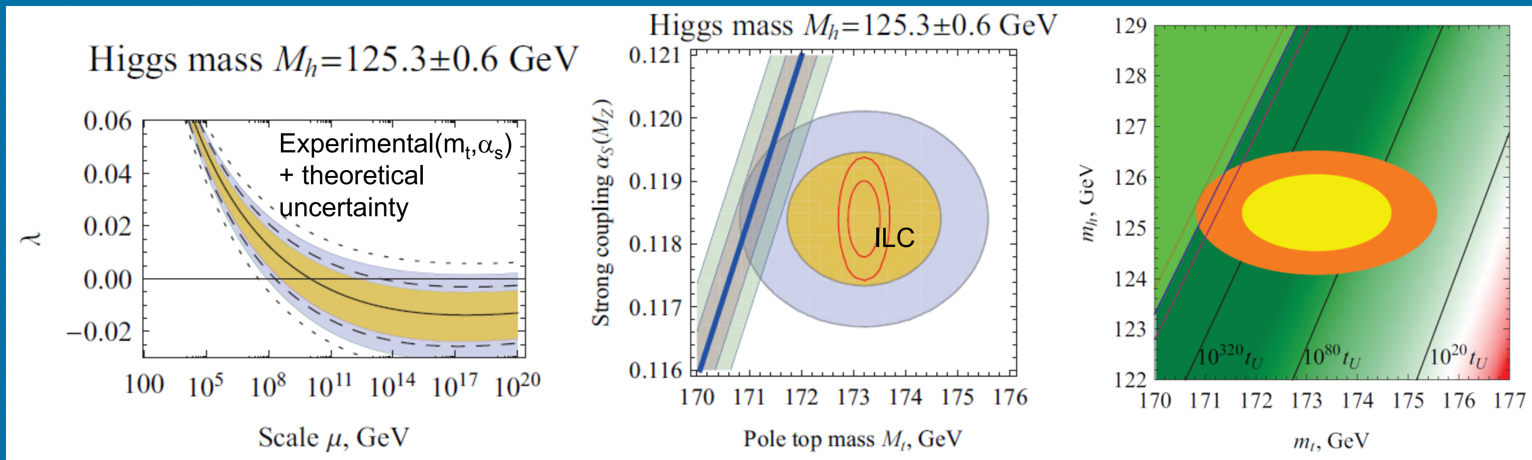
- To be done
  - Measure more precisely fermion couplings
  - Measure triple and quartic gauge couplings to reconstruct vacuum potential

SM Validity

- Requirement that the E.W. vacuum be the minimum of the potential up to a scale Λ, implies that $\lambda(\mu) > 0$ for any $\mu < \Lambda$.
- $M_H = 125.5 \pm 0.2_{stat}{}^{+0.5}_{-0.6\,syst} GeV$ (ATLAS) / $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{syst}\ GeV$ (CMS)
  - $m_H < 175\ GeV$: Landau pole in the self-interaction is above the quantum gravity scale M_{Pl}
  - $m_H > 111\ GeV$: Electroweak vacuum is sufficiently stable with a lifetime >>t_U



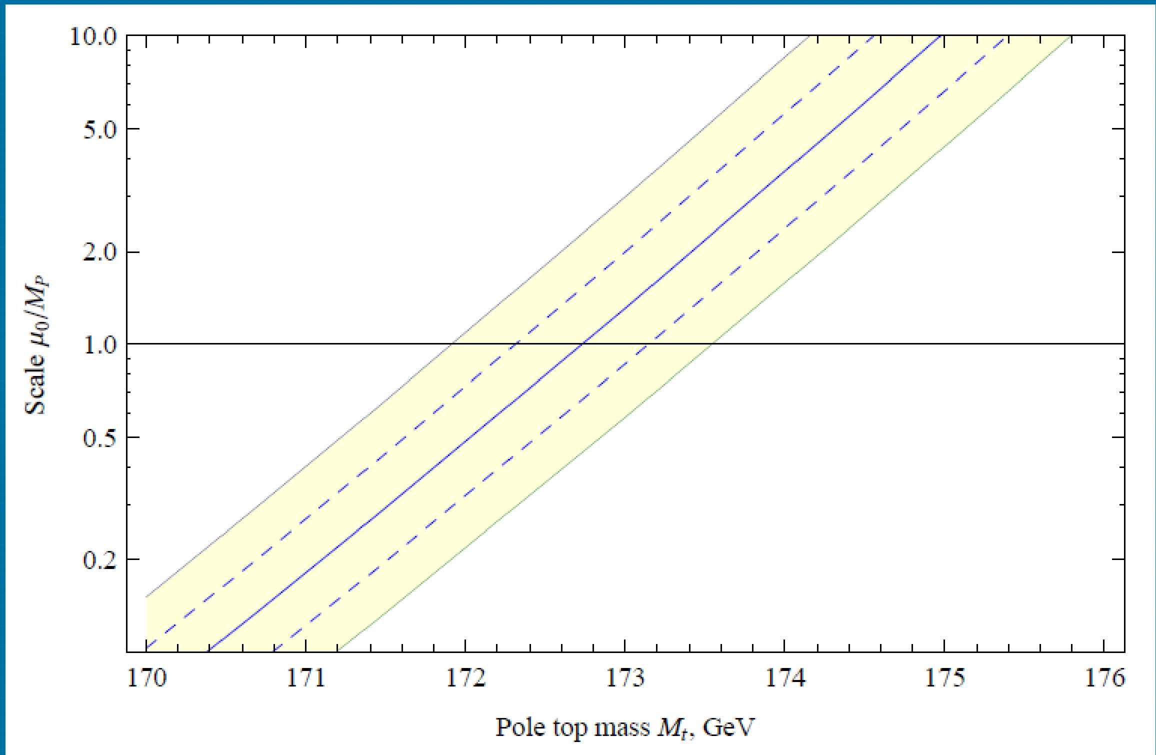




arXiv:0906.0954

SM Validity

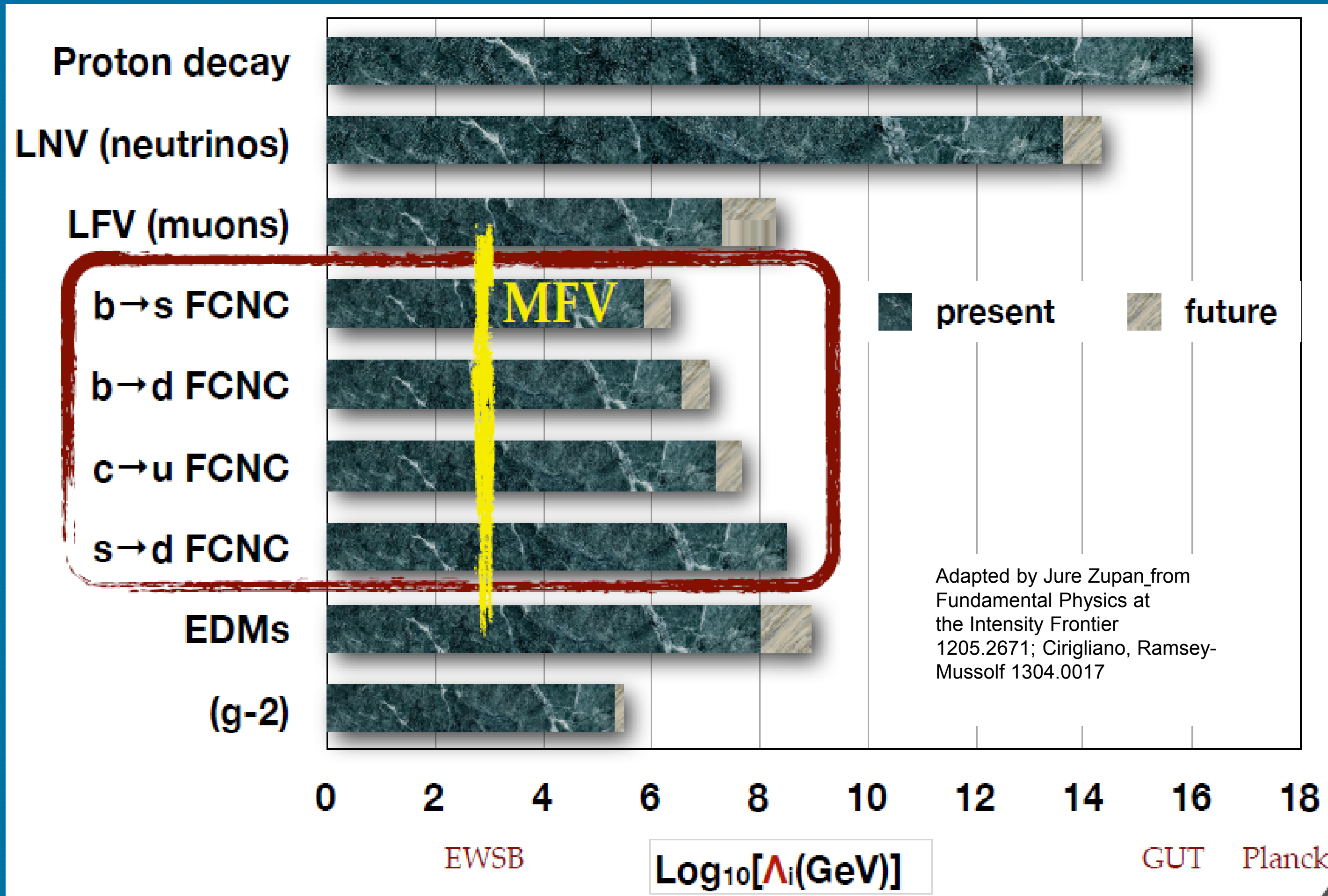
- Currently used values
  - Tevatron $m_t = 173.2 \pm 0.51_{stat} \pm 0.71_{syst} GeV$
  - ATLAS and CMS: $m_t = 173.4 \pm 0.4_{stat} \pm 0.9_{syst} GeV$
  - $\alpha_s = 0.1184 \pm 0.0007$
  - Measure more precisely!



- μ_0 determined from electroweak physics gives Planck scale!

Precision Flavour Physics

$$\sigma_{stat+sys+th} < \delta C[\frac{\epsilon^{NP}}{\Lambda^2_{NP}}]$$



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 (probably 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. Gauge hierarchy and stability of Higgs mass
6. SM flavour structure

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

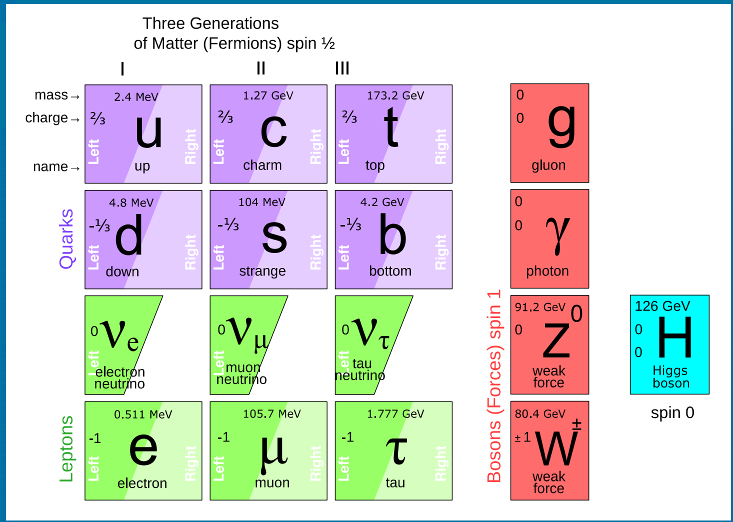
- Search for beyond Standard Model physics at the Energy Frontier:
  - Higgs and top (EW) precision physics
  - Flavour precision physics
  - Continued direct searches for new particles

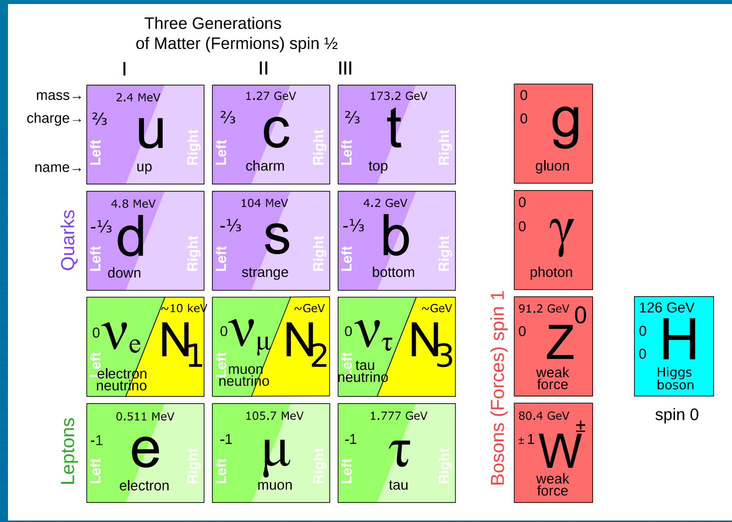
Alternative Path

- What about new particles *below* Fermi scale and weak couplings?

A Natural Standard Model Extension !

Ockham's Razor





- Introduce three neutral fermion singlets – right-handed Majorana leptons N_I with Majorana mass $m_I^R \equiv$ "Heavy Neutral Leptons (HNL)"
  - Make the leptonic sector similar to the quark sector
  - No electric, strong or weak charges ➔ sterile

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!

Four "popular" N mass ranges

➔ Irrespective of mass, the HNLs may explain neutrino oscillations and active neutrino mass

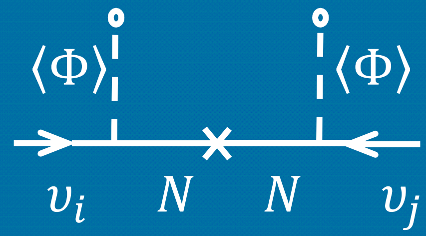
1. GUT see-saw ($10^9 < M_N < 10^{14}$ GeV) :
   - Motivated by GUT theories
   - BAU generated via sphalerons by CP violating decays of $N's$ to a lepton asymmetry
   - Large mass of HNLs results in fine-tuning problem for the Higgs mass

     ➔ Low energy SUSY but largely disfavoured by LHC results
   - No DM candidate and no way to probe in accelerator based experiments
2. E.W. see-saw ($M_N \sim 10^2 - 10^3$ GeV):
   - Motivated by hierarchy problem at the electroweak scale
   - BAU generated via resonant leptogenesis and sphalerons
   - No DM candidate
   - Part of parameter space may be explored in ATLAS and CMS
3. νMSM see-saw ($M_N \sim m_q/m_{l^\pm}$)
   - BAU via resonant leptogenesis and sphalerons
   - $\mathcal{O}(10)keV$ range DM candidate
4. eV see-saw ($M_N \sim$ eV)
   - Motivated by the 2-3σ anomalies observed in the short-baseline experiments
   - No BAU and no candidate for DM

Type I See-saw Trivia

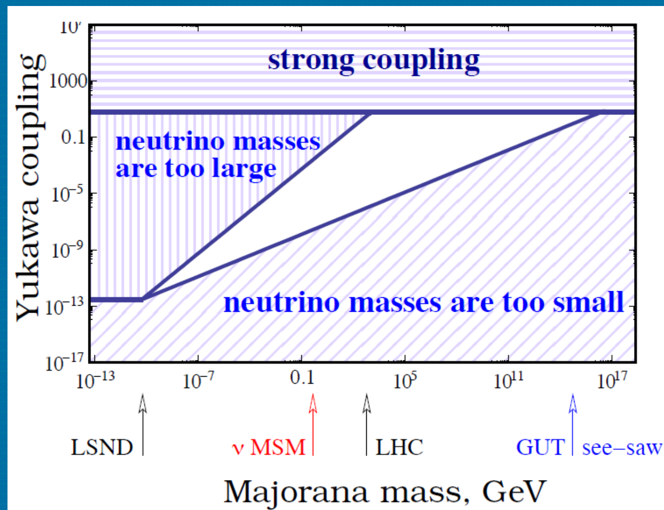
- $Y_{I\ell}\bar{N}_I\Phi^{\dagger}L_{\ell}$ lepton flavour violating term results in mixing between N_I and SM active neutrinos when the Higgs SSB develops the $< VEV > = v \sim 246\ GeV$
  - ➔ Oscillations in the mass-basis and matter-anti-matter asymmetry

- Mixing between N_I and active neutrino $\mathcal{U}_{I\ell} = \frac{Y_{I\ell}v}{m_I^R} \sim \frac{m_D}{m^R}$
  - Total strength of coupling $\mathcal{U}^2 = \sum_{\substack{I=1,2,3 \\ \ell=1,2,3(e,\mu,\tau)}} \frac{v^2|Y_{\ell I}|^2}{m_I^{R\,2}}$



- Type I See-saw with $m^R >> m_D (= Y_{I\ell}v)$ ➔ superposition of chiral states give
  - ➔ Active neutrino mass in mass basis $\tilde{m}_1 \sim \frac{m_D^2}{m^R} \sim m_v$
  - ➔ Heavy singlet fermion mass in mass basis $\tilde{m}_2 \sim m^R\left(1 + \frac{m_D^2}{m^{R^2}}\right) \sim m^R \sim M_N$

arXiv:1204.5379



- Assumption that N_I are $\mathcal{O}(m_q/m_{l^\pm})$ (νMSM)
  - ➔ Yukuawa couplings are very small
  - $Y_{I\ell} = \mathcal{O}\left(\frac{\sqrt{m_{atm}m_I^R}}{v}\right) \sim 10^{-8} \quad (m^R = 1\ GeV, m_v = 0.05\ eV)$
  - $\mathcal{U}^2 \sim 10^{-11}$

➔ Experimental challenge ➔ Intensity Frontier

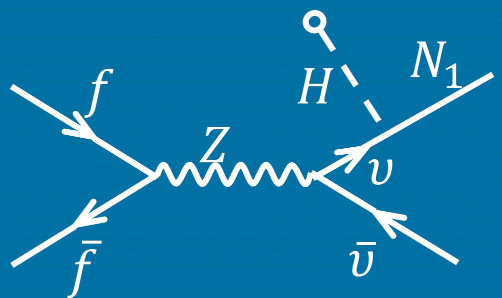
νMSM (Asaka, Shaposhnikov: hep-ph/0505013)

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

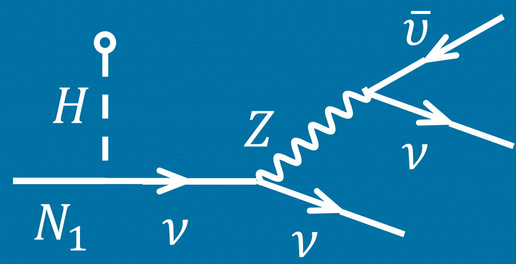
Role of N_2 and N_3 with a mass of $\mathcal{O}(m_q/m_{l^\pm})$ (100 MeV – GeV):
➔ Neutrino oscillations and mass, and BAU

- 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
    - ➔ Decouples from the primordial plasma very early
  - Produced relativistically out of equilibrium in the radiation dominant epoque ➔ erase density fluctuations below free-streaming horizon ➔ sterile neutrinos are redshifted to be non-relativistic before end of radiation dominance (Warm Dark Matter → CDM)
    - ➔ Temperature dependent : Production suppressed at T>100 MeV
  - ➔ Decaying Dark Matter

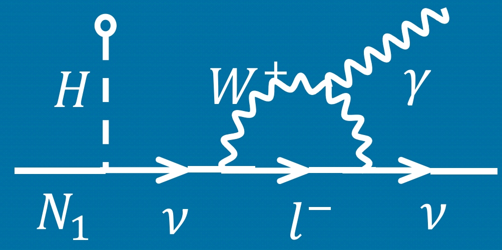
Production from υ ↔ N oscillations



Dominant decay



Subdominant radiative decay

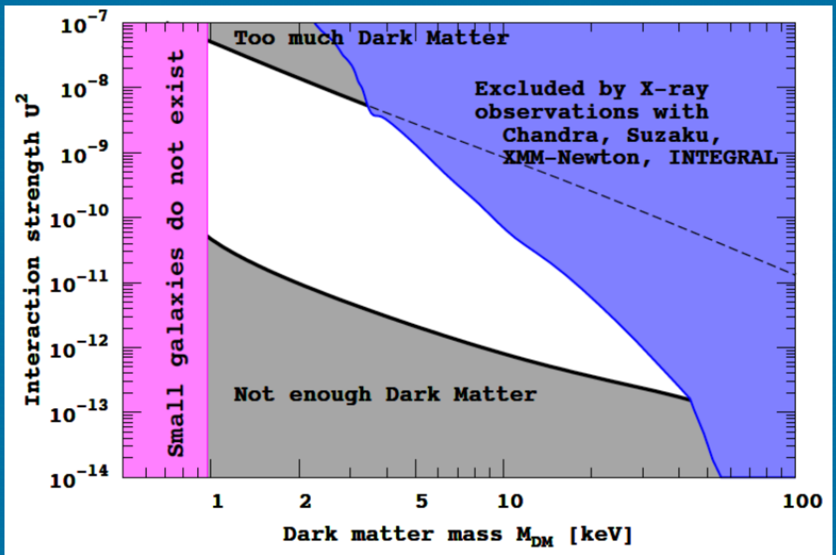


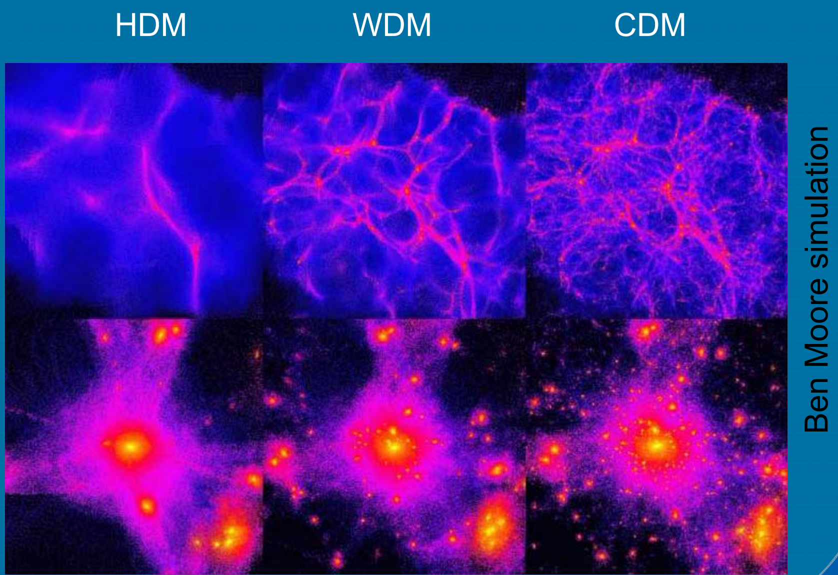
$$E_\gamma = \frac{M_{N_1} c^2}{2}$$

Dark Matter Constraint and Search

1. Tremaine-Gunn bound: average phase-space density for fermionic DM particles cannot exceed density given by Pauli exclusion principle
   ➔ For smallest dark matter dominated objects such as dwarf spheroidal galaxies of the Milky Way
2. X-ray spectrometers to detect mono-line from radiative decay
   - Large field-of-view ~ ~ size of dwarf spheroidal galaxies ~ 1°
   - Resolution of $\frac{\Delta E}{E} \sim 10^{-3} - 10^{-4}$ coming from width of decay line due to Doppler broadening

   ➔ Proposed/planned X-ray missions: Astro-H, LOFT, Athena+, Origin/Xenia
3. Lyman-α forest
   - Super-light sterile neutrino creates cut-off in the power spectrum of matter density fluctuations due to sub-horizon free-streaming $d_{FS} \sim 1\ \text{Gpc}\ m_{eV}^{-1}$
   - Fitted from Fourier analysis of spectra from distant quasars propagating through fluctuations in the neutral hydrogen density at redshifts 2-5

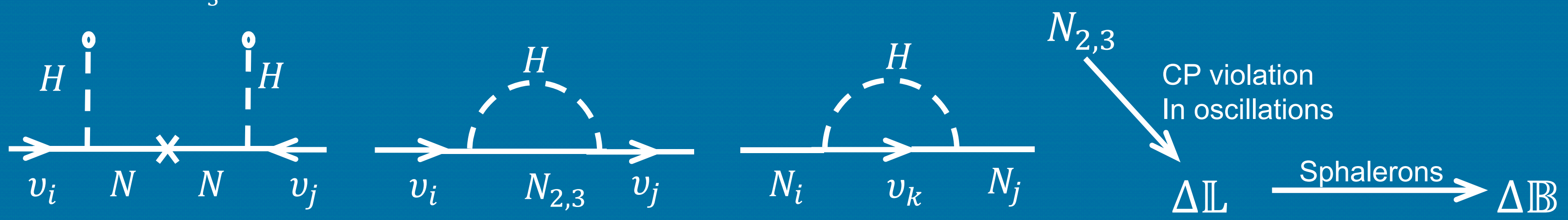




N_2 and N_3

- 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:
      - 2 Majorana masses
      - 2 diagonal Yukawa couplings as Dirac masses
      - 4 mixing angles
      - 3 CP violating phases (only one in SM in quark sector)
      - ➔ Two mixing angles related to active neutrinos and mass difference measured in low-energy neutrino experiment

- Generation of BAU with N_2 and N_3 (Akhmedov, Rubakov, Smirnov; Asaka, Shaposhnikov)
  1. Leptogenesis from coherent resonant oscillations with interference between CP violating amplitudes
     - ➔ Two fermion singlets should be quasi-degenerate
  2. Sterile neutrinos out of equilibrium ($\Gamma_{N_{2,3}}$ < Hubble rate of expansion) at the E.W. scale above the 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



Thermal History in νMSM

(arXiv:1208.4607)

T

zero abundance of N_I

thermal production of N_2, N_3

→ lepton asymmetry generated

200 GeV T_{EW} **Electroweak Symmetry Breaking**

→ lepton Asymmetry converted to baryon asymmetry

T_+ N_2, N_3 reach equilibrium

→ lepton asymmetry washed out

few GeV T_- N_2, N_3 freeze out

→ lepton asymmetry generated

T_d N_2, N_3 decay

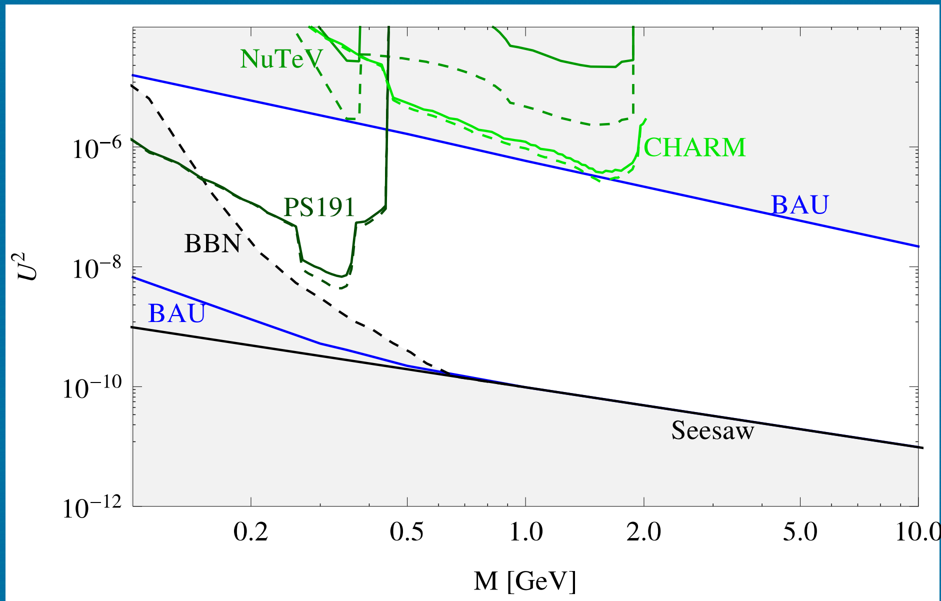
→ lepton asymmetry generated

100 MeV T_{DM} **resonant N_1 Dark Matter production**

t

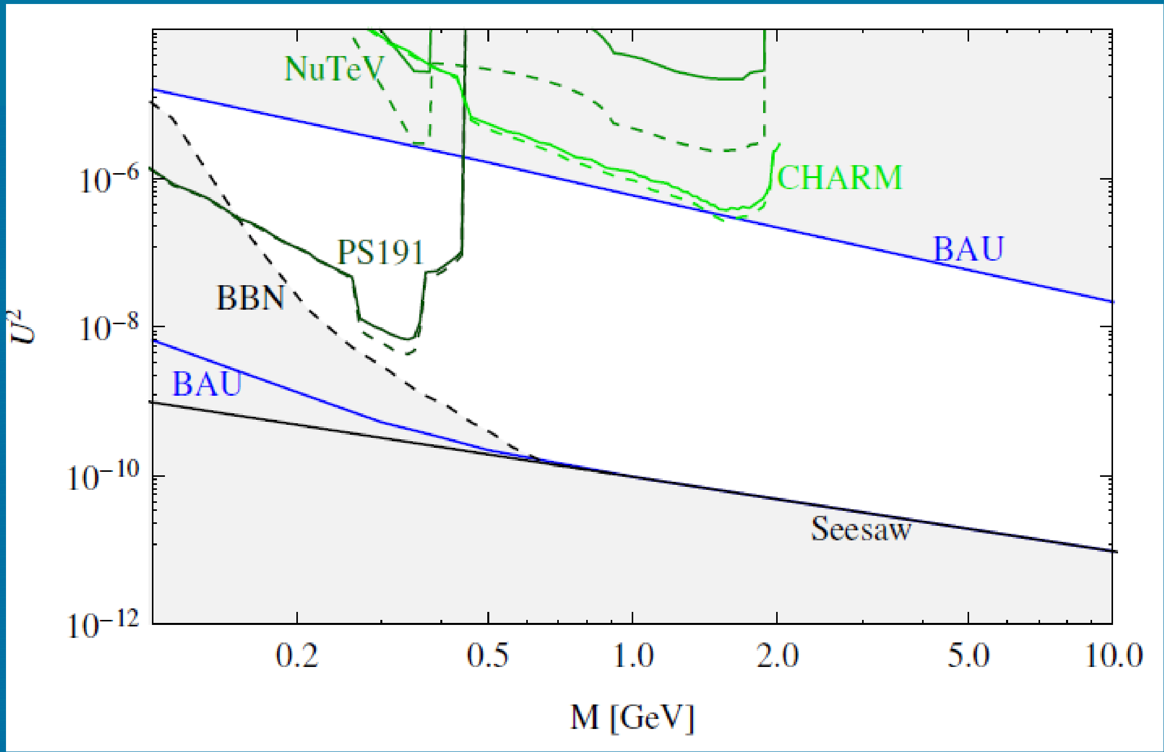
N_2 and N_3 Constraints in νMSM

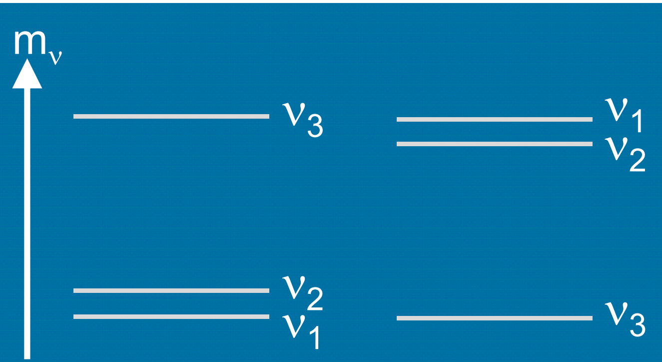
1. See-saw: Lower limit on mixing angle with active neutrinos to produce oscillations and masses
2. BAU: Upper limit on mixing angle to guarantee out-of-equilibrium oscillations
3. BBN: Decays of N_2 and N_3 must respect current abundances of light nuclei
   ➔ Limit on lifetime $\tau_{N_{2,3}} < 0.1s \ (T > 3\ MeV)$
4. Experimental: No observation so far
   ➔ Constraints 1-3 now indicate that previous searches were largely outside interesting parameter space
   - PS191, BEBC, CHARM, CCFR, NuTeV



- 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

Constraints - Inverted Hierarchy

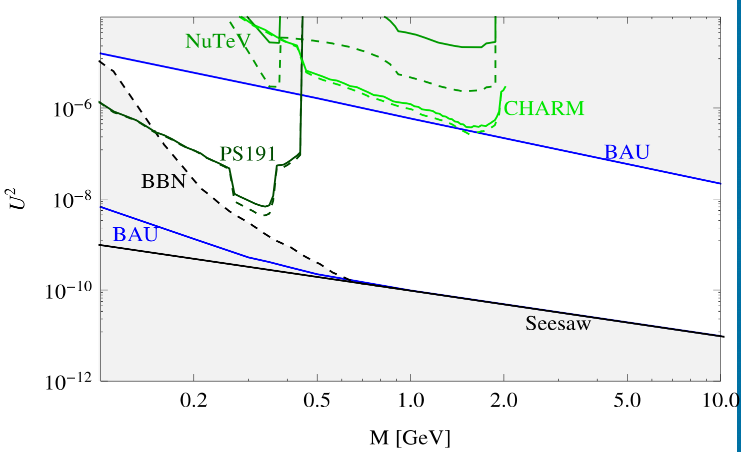




Constraints in Variants of νMSM (references at end)

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 constrints 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

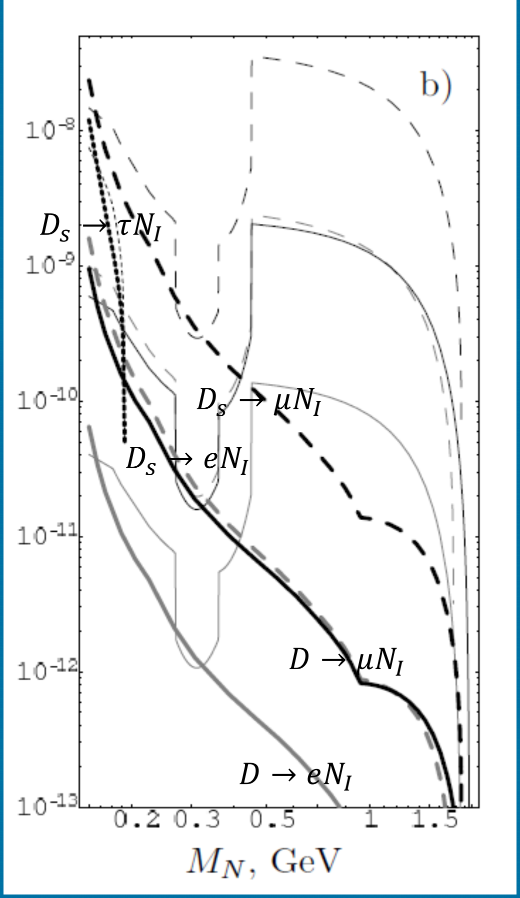


$N_{2,3}$ Production

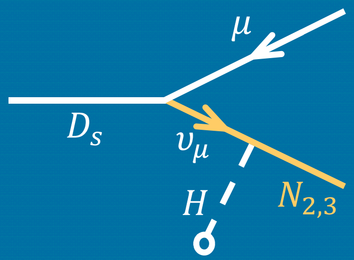
- Production in mixing with active neutrino from leptonic/semi-leptonic weak decays of charm mesons
  - Total production depend on $\mathcal{U}^2 = \sum_{\substack{I=1,2 \\ \ell=e,\mu,\tau}} |\mathcal{U}_{\ell I}|^2$
  - Relation between $\mathcal{U}_e^{\,2}, \mathcal{U}_\mu^{\,2}$ and $\mathcal{U}_\tau^{\,2}$ depends on exact flavour mixing
  - Ratio of Yukawa couplings can be expressed through the elements of the active neutrino mixing matrix (arXiv:0605047)

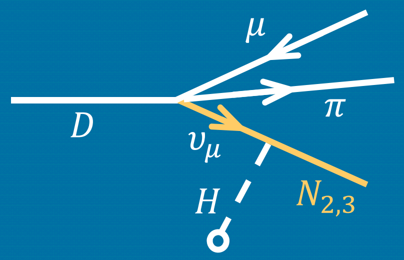
    ➔ For the sake of determining a search strategy, assume scenario with a predominant coupling to the muon flavour

Benchmark model II: muon flavour dominance



arXiv:0705.1729





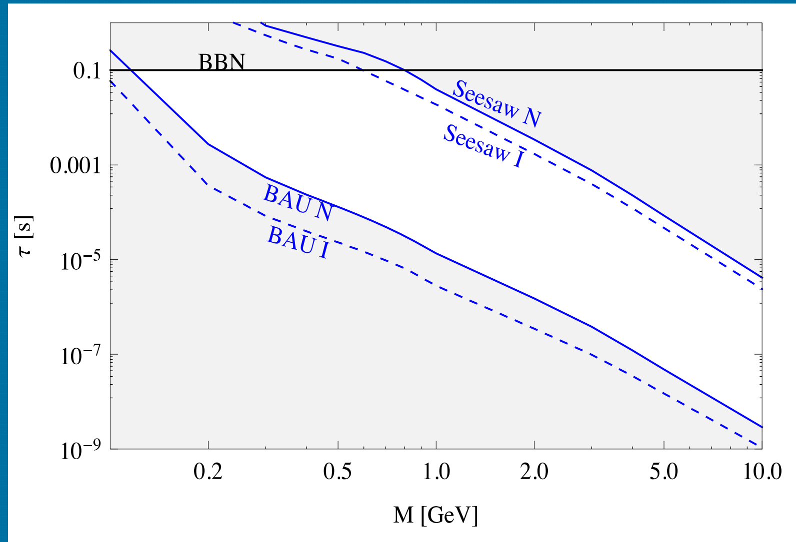
- Production mechanism probes $\mathcal{U}_\mu^{\,2} = \sum_{I=2,3} \frac{v^2 |Y_{\mu I}|^2}{m_I^{R\,2}}$

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

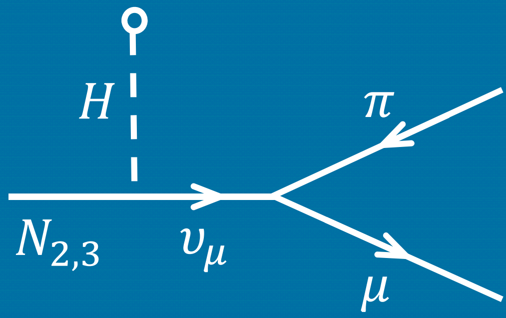
$N_{2,3}$ Decay

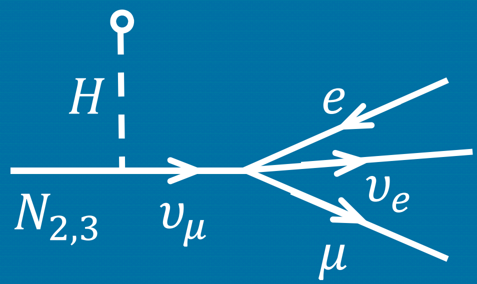
- Very weak sterile-active neutrino mixing → $N_{2,3}$ much longer lived than SM particles
  - ➔ Typical lifetimes > 10 ms for $M_{N_{2,3}} \sim 1\ GeV$ → Decay distance $\mathcal{O}(km)$
- Decay modes:
  - $N \rightarrow \mu e \upsilon, \pi^0 \upsilon, \pi e, \mu\mu\upsilon, \pi\mu, Ke, K\mu, \eta\nu, \eta'\nu, \rho\nu, \rho e, \rho\mu, \ldots$
  - 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 %
$N_{2,3} \rightarrow \upsilon + \mu + e$	1 - 10 %



E.g.





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

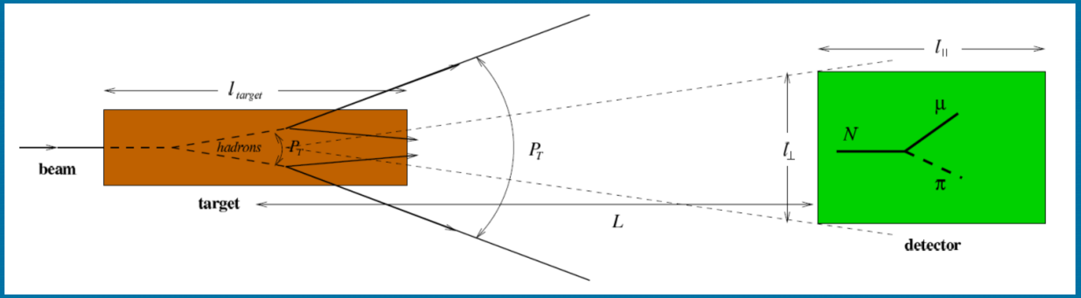
Experimental Requirements

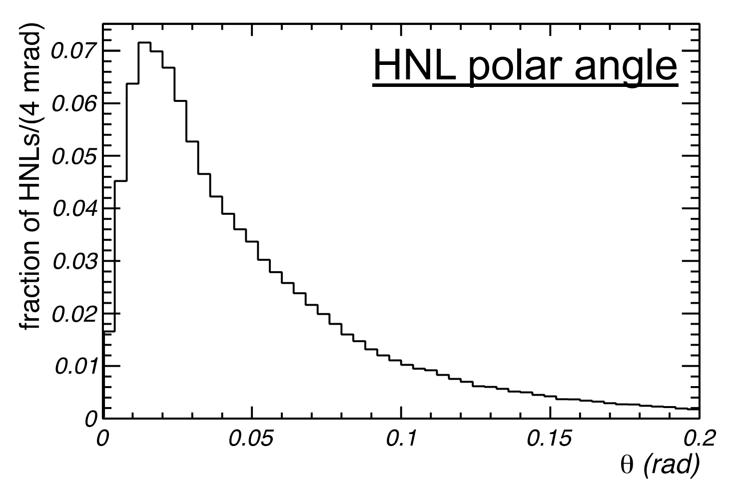
Proposal: beam dump experiment at the SPS

1. Sensitivity ∝ $\mathcal{U}^4$ → Number of protons on target (p.o.t.)
   - ➔ SPS: 4-5x10^{13} / 6-7s = 500 kW → 2x10^{20} in 4-5 years
   - ➔ 400 GeV beam energy ($\sqrt{s} = 27.5 GeV$) compromise between σ_{charm} and background conditions
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 reduce 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

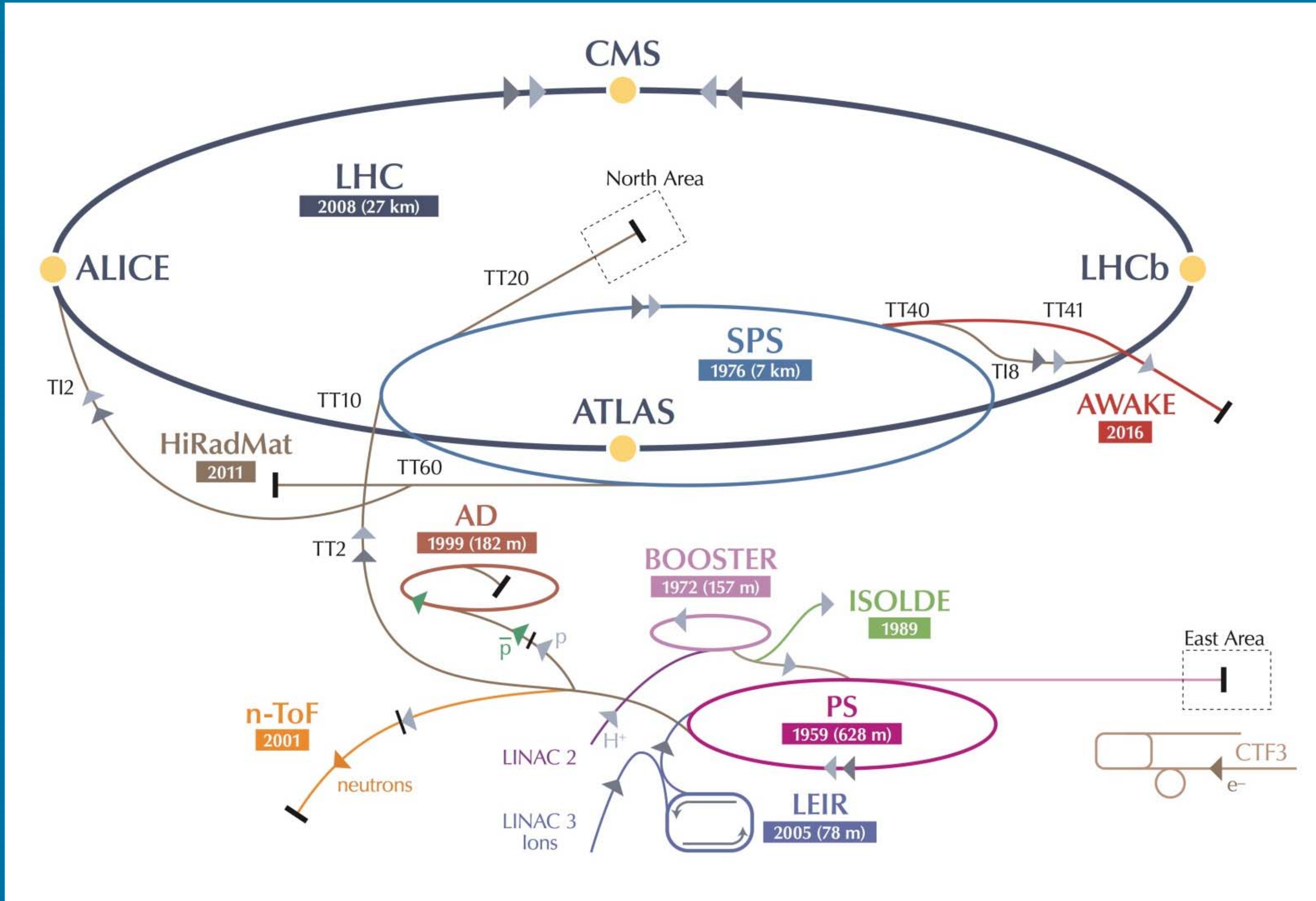
➔ Incompatible with conventional neutrino facility

Gorbunov, Shaposhnikov





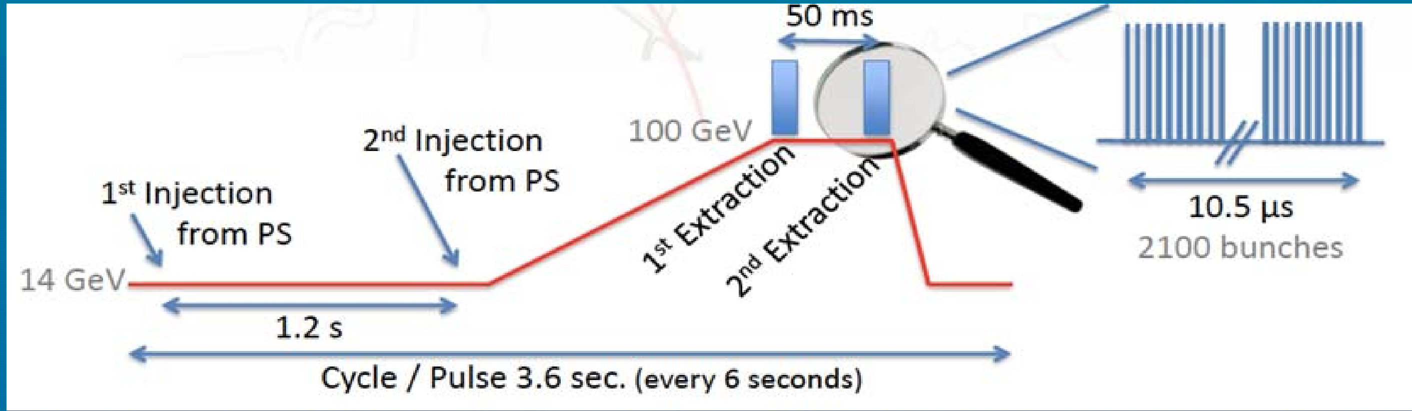
CERN Accelerator Complex

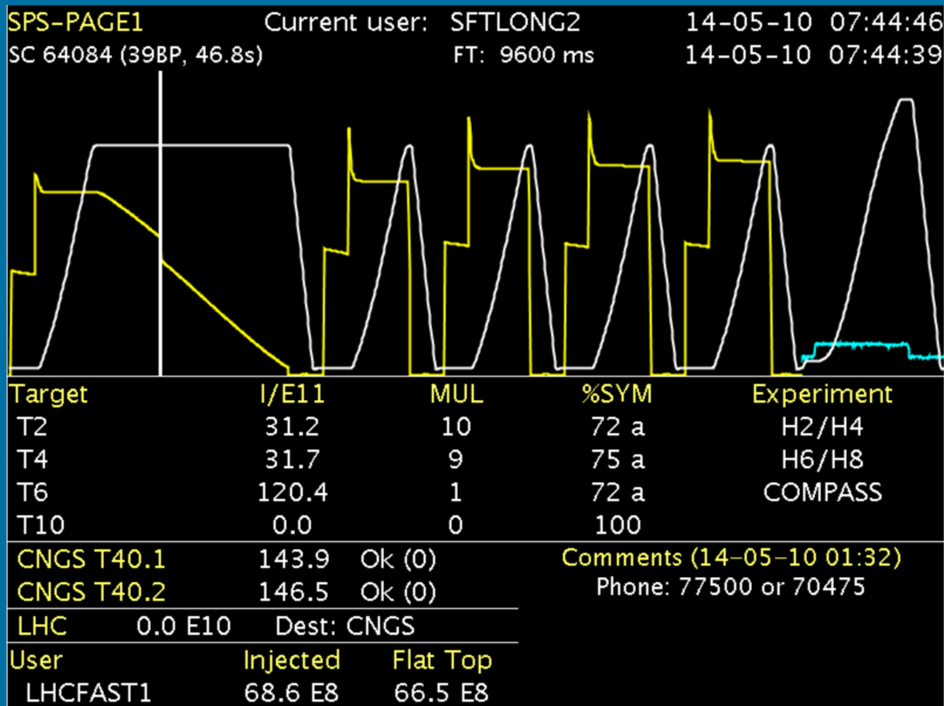


A Possible Site – CERN North Area

Beam Extraction 400 GeV

- Ex. CNGS: 4-4.5x10^{13} / 6s → 4.5x10^{19} p.o.t / year → 500 kW





Beam Extraction Options

- Fast extraction - low loss (0.05% obtained for CNGS)
  - - 2x 10.5 us spill
  - - spill shape rectangular
  - - 6 s FT cycle
  - - No NA FT beam in same SC
  - HW changes needed (interlocking, ...)
  - - New non-local extraction to demonstrate operationally (tested only concept)

- Fast-resonant extraction (non-coherent half-integer)
  - - High loss (3% obtained for WANF)
  - - 1-6 ms spill
  - - spill shape gaussian
  - - 6 s FT cycle
  - - Compatible with NA beam in same SC

- Fast-resonant extraction (coherent half-integer)
  - - High loss (5%)
  - - 0.1-1 us spill
  - - spill shape gaussian
  - - 6 s FT cycle
  - - Compatible with NA beam in same SC

- Slow extraction (incoherent third-integer)
  - - high loss (1%)
  - - 1 s spill
  - - spill shape rectangular
  - - 7.2 s FT cycle
  - - Compatible with NA beam in same SC

- Continuous-transfer extraction (fast shaving)
  - - High loss (7-10%?)
  - - 100-200 us spill
  - - spill shape approx. rectangular
  - - 6 s FT cycle
  - - Compatible with NA beam in same SC

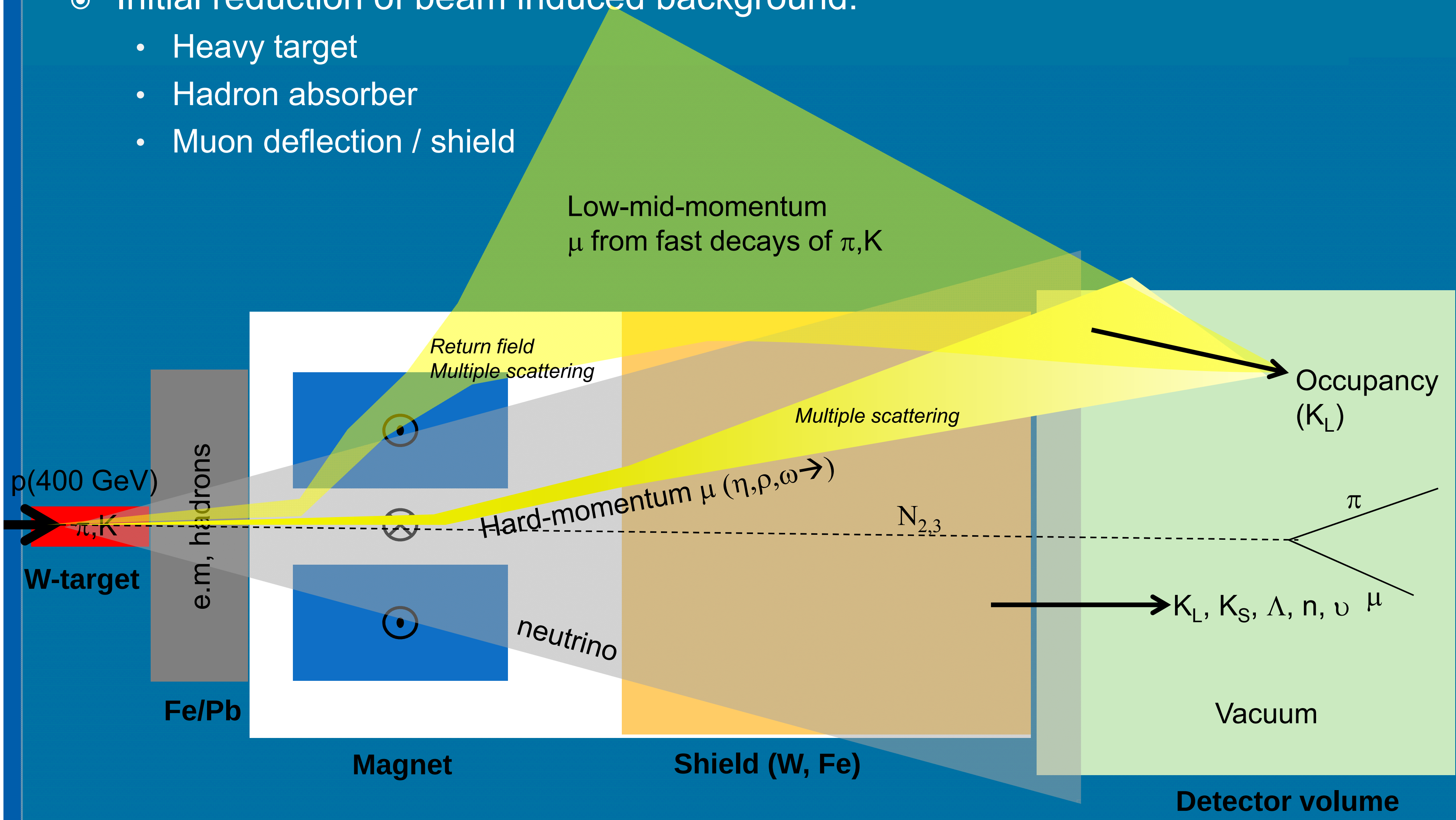
- MTE 4- or 5-turn extraction
  - - High loss (3-7%?) - check if this number is valid with bunched beam and kicker
  - - 100-125 us spill
  - - Spill shape approx. rectangular
  - - 6 s FT cycle
  - - Compatible with NA beam in same SC
  - - Extra HW needed (local kickers, multipoles)
  - - Untested and difficult beam physics concept needed (PS implementation difficult)

- Hybrid fast-shaving MTE-extraction
  - - Moderate loss (0.1-1%?) - to be studied in more detail as not clear
  - - Could hope for 20x 10.5 us spills (effectively 200 us)
  - - Spill shape approx. rectangular?
  - - 6 s FT cycle
  - - Compatible with NA beam in same SC
  - - Some extra HW maybe needed (multipoles?)
  - - Speculative idea, problem may be extra kicker HW needed to close the bump

- Stochastic extraction
  - - high loss (1%)
  - - 1 - 100 min. spill
  - - Spill shape rectangular
  - - 1 - 100 min FT cycle
  - - Compatible with NA beam in same SC
  - - No extra HW needed
  - - No new beam physics concept needed

Schematic Principle of Experimental Setup

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

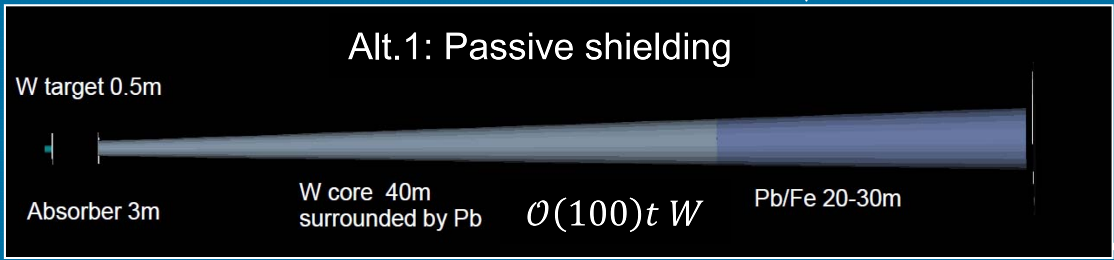


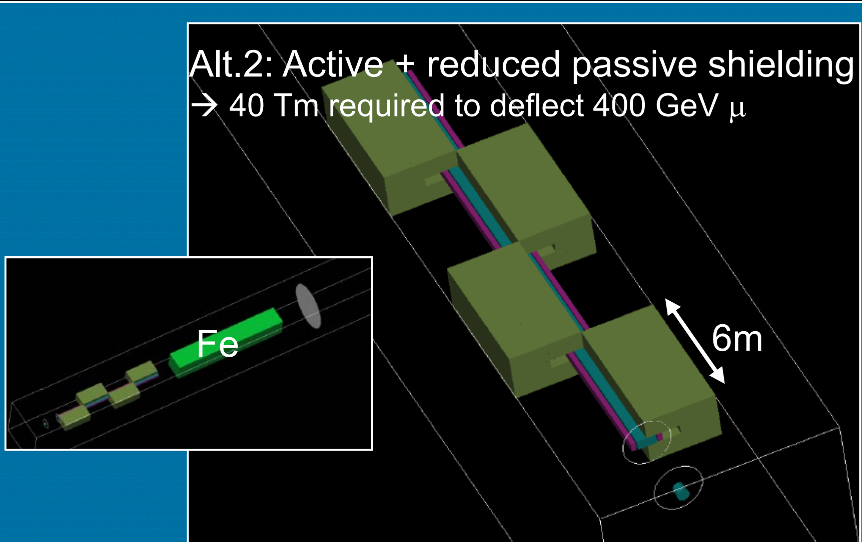
Generic setup, not to scale!

Muon Shield Optimization

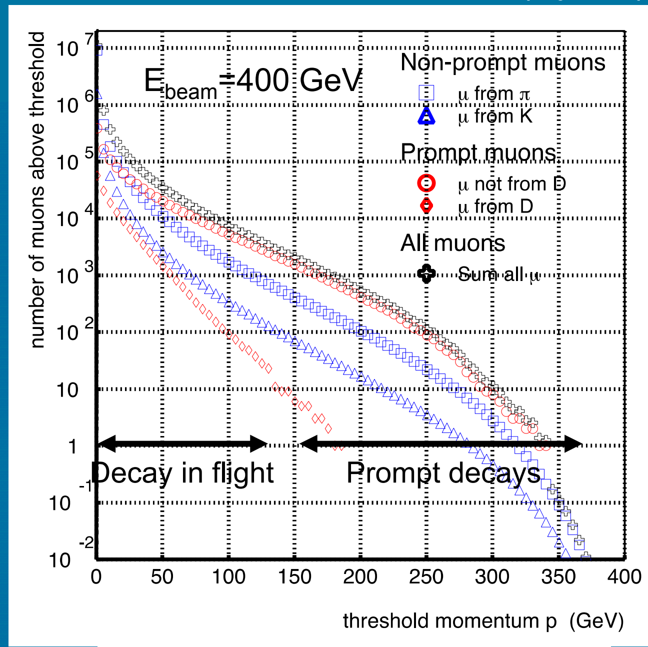
- No shield: Rate at detector 5×10^{9} muons / 5×10^{13} p.o.t.
  - Acceptable occupancy (<1%) per spill of 5×10^{13} p.o.t
  - → Spill duration ~1s: $<50\times10^{6}$ muons
  - → Spill duration ~1ms: $< 50\times10^{3}$ muons
  - → Spill duration ~10μs : <500 muons

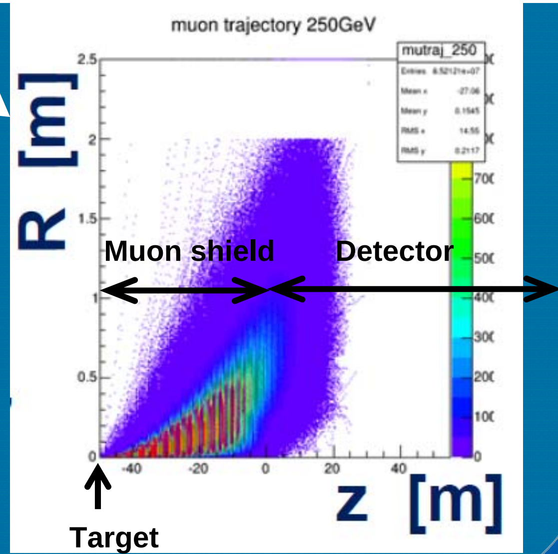
- Simulations with passive and active/passive shield
  - Stopping power of tungsten: 54m @ E_{μ}=400 GeV





Main sources of the muon flux (Pythia)

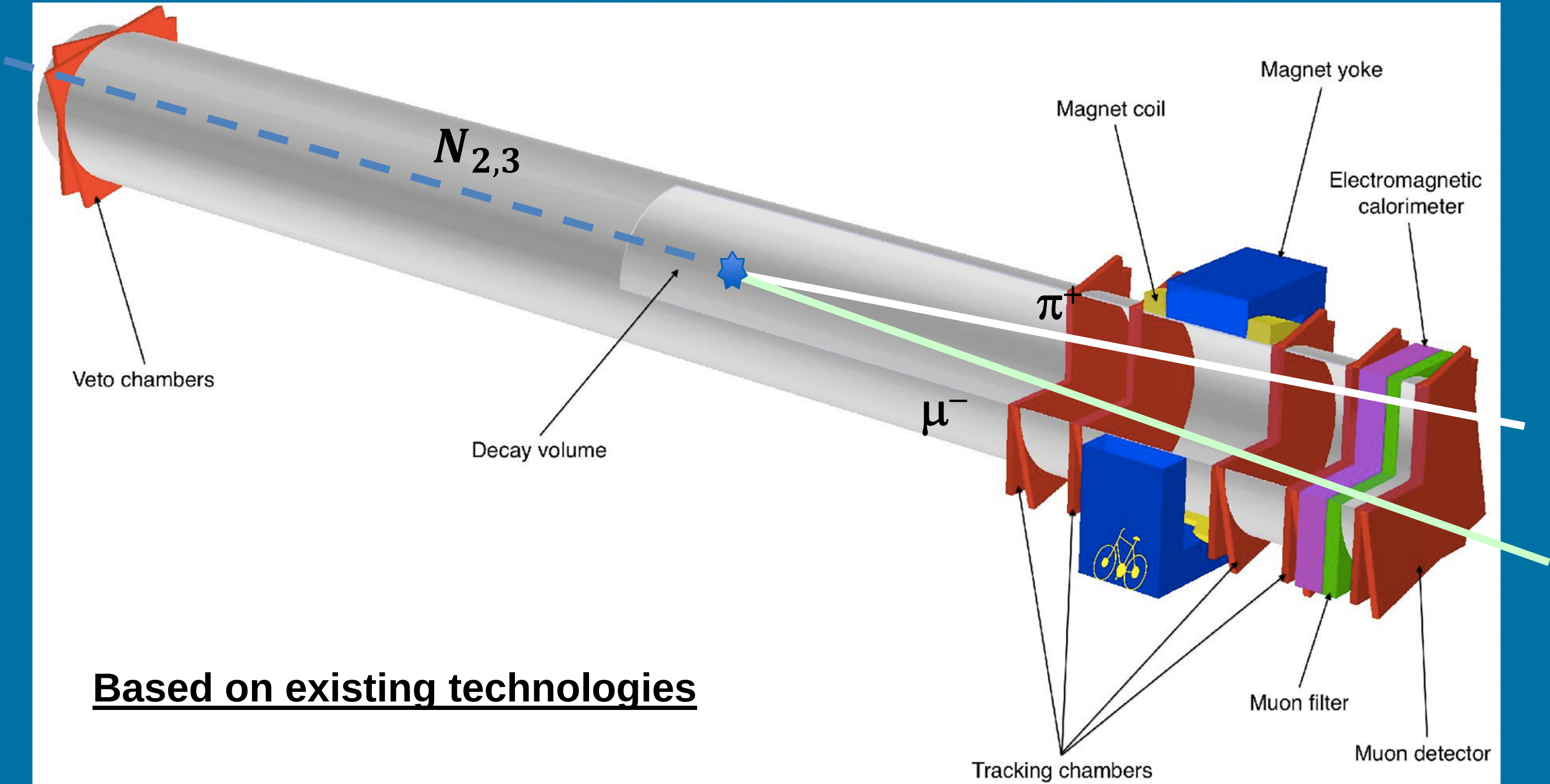




Detector Concept

- 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, preferably in surface building

- 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



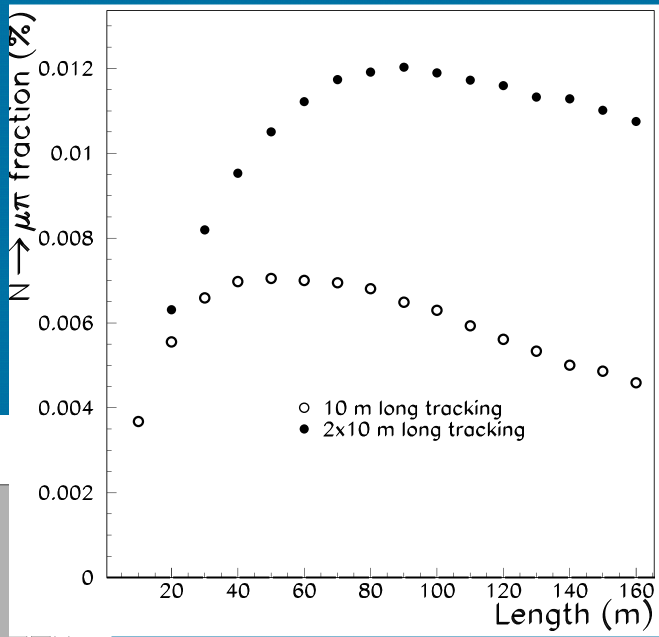
<u>Based on existing technologies</u>

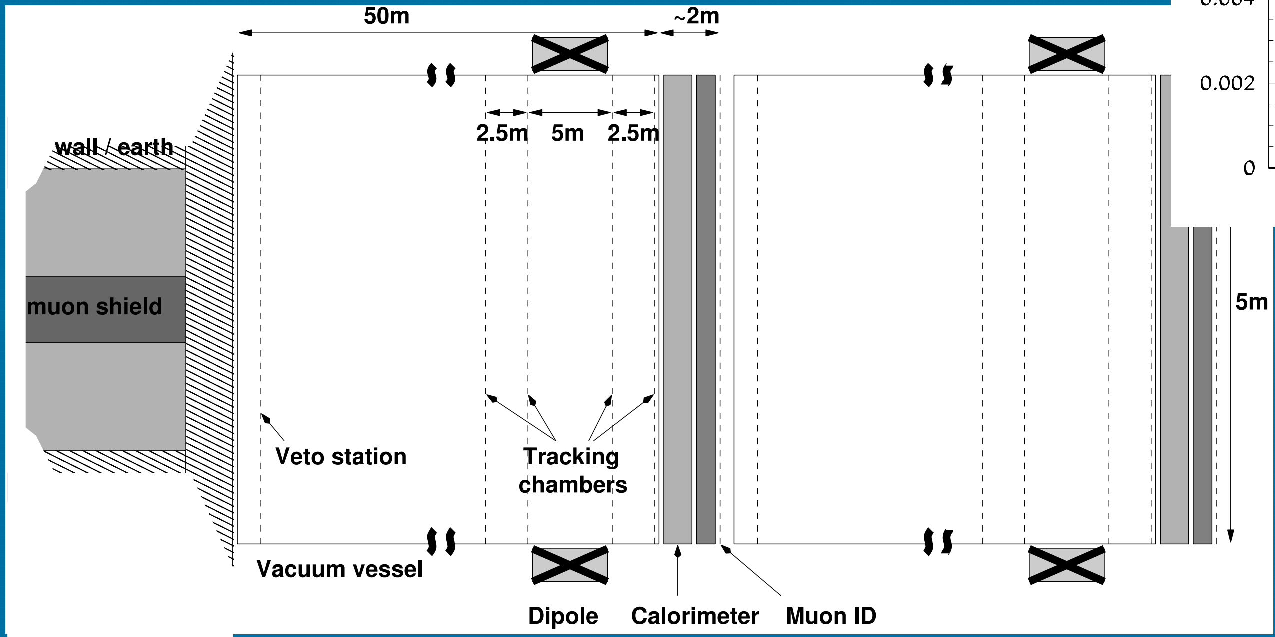
Detector Concept

- Geometric acceptance
  - Saturates for a given $N_{2,3}$ lifetime as a function of the detector length

  - The use of two magnetic spectrometers increases the acceptance by 70%

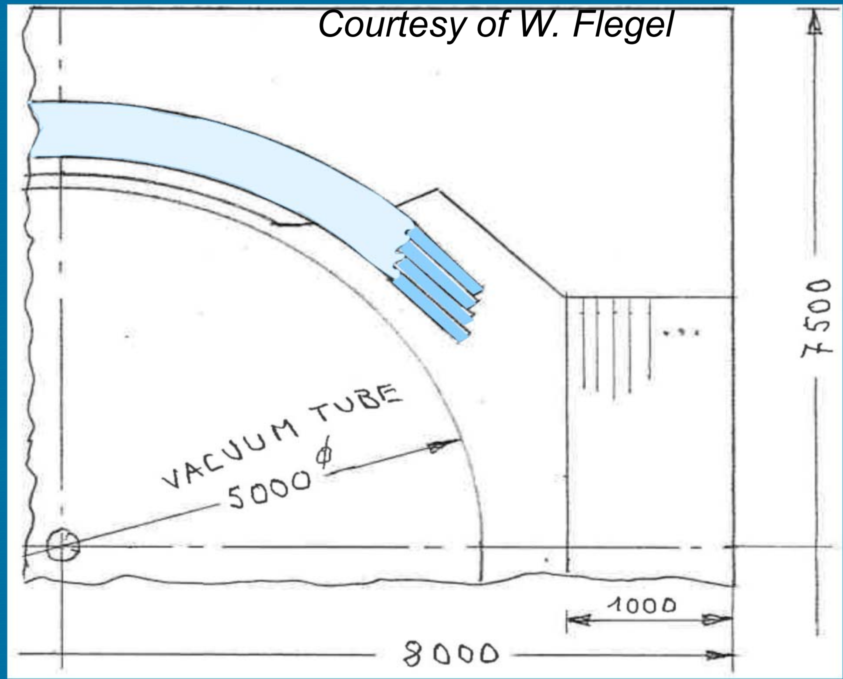
  - Detector has two almost identical elements





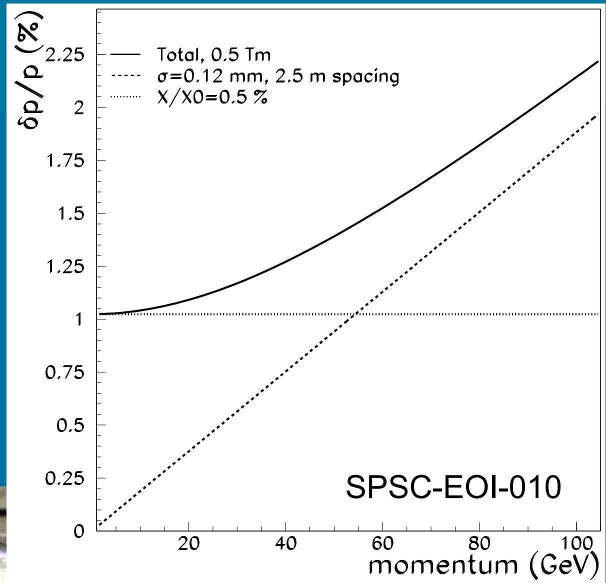
Detector Technologies

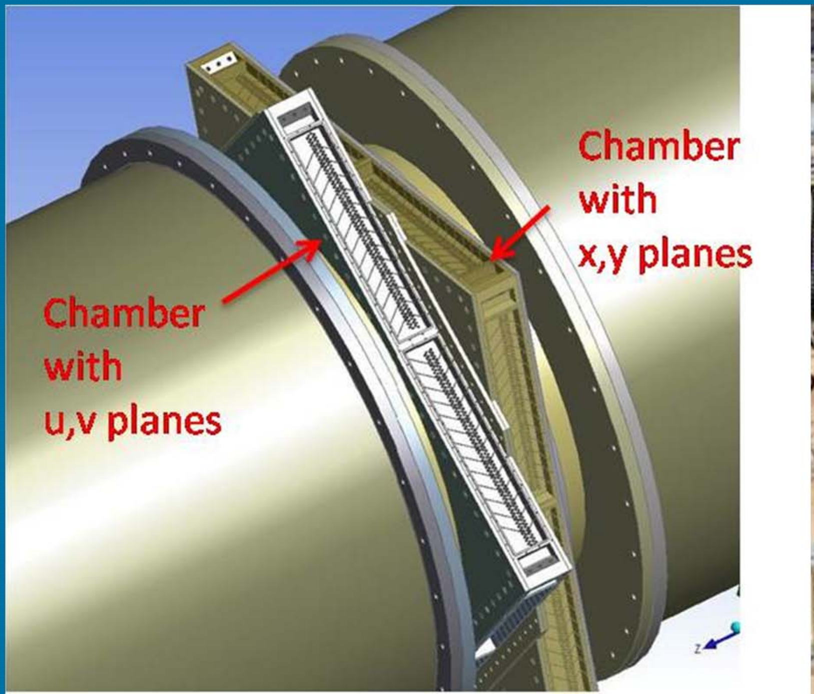
- Experiment requires a dipole magnet similar to LHCb design, but with ~40% less iron and three times less dissipated power
- Free aperture of ~ 16 m^2 and field integral of ~ 0.5 Tm
  - Yoke outer dimension: 8.0×7.5×2.5 m^3
  - Two Al-99.7 coils
  - Peak field ~ 0.2 T
  - Field integral ~ 0.5 Tm over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



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 $\frac{dP}{P}$

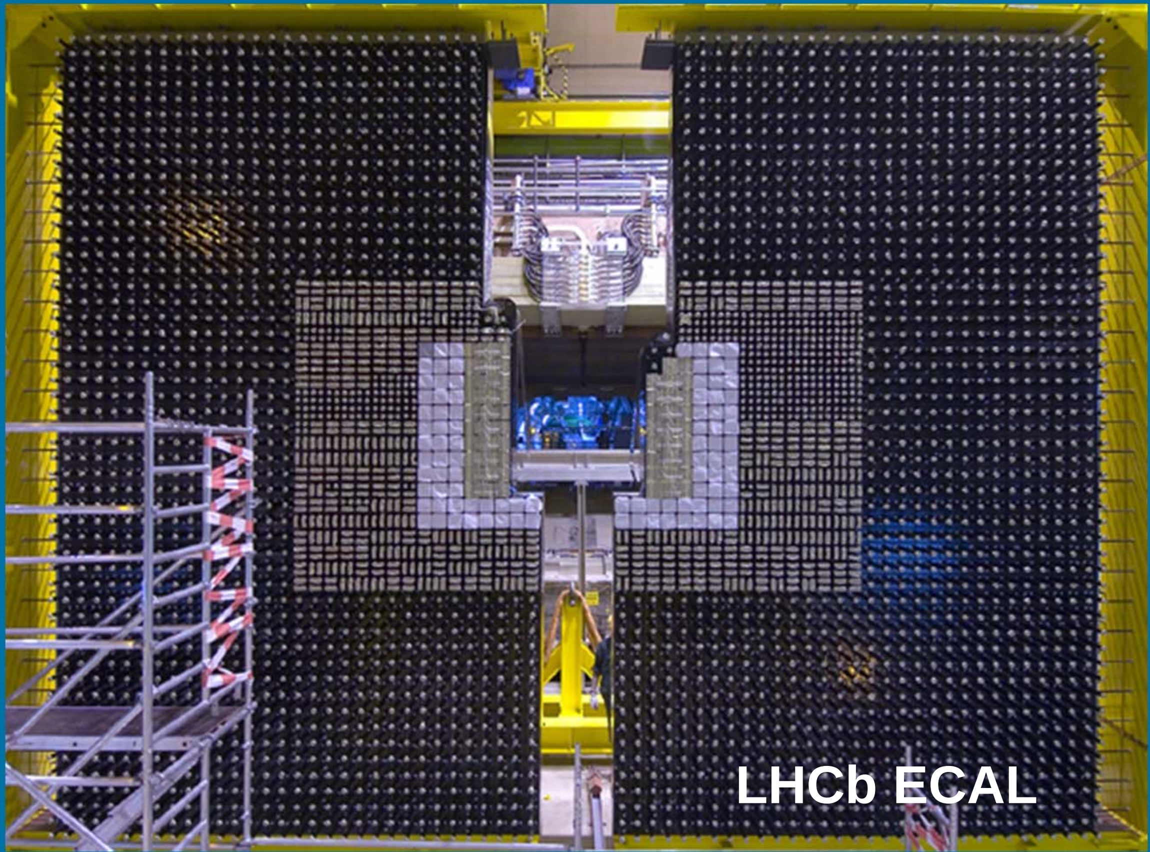




Detector Technologies

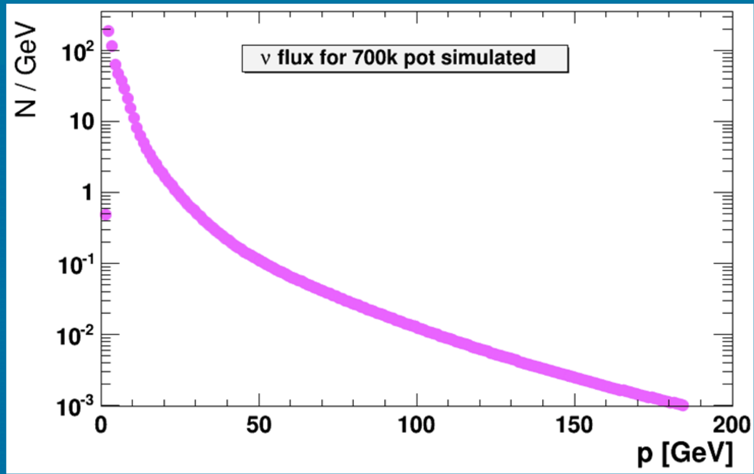
- LHCb electromagnetic calorimeter

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



Residual Backgrounds

- Momentum spectrum of the neutrino flux after the muon shield



→ 2×10^4 neutrino interactions per 2×10^{20} protons on target in the decay volume at atmospheric pressure

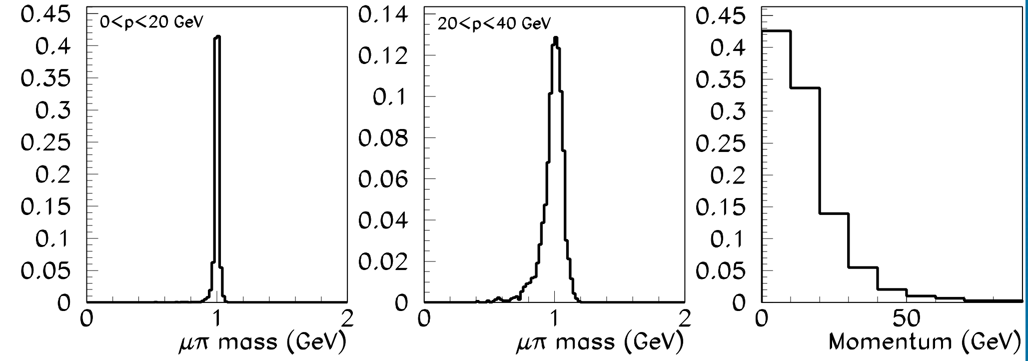
→ Becomes negligible at 0.01 mbar

- Charged Current and Neutral Current neutrino interaction in the final part of the muon shield
  - Simulated with GEANT and GENIE, and cross-checked with CHARM measurement
  - → Yields CC(NC) rate of ~$6(2)\times10^5$ / 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.
  - Instrumentation of the end-part of the muon shield allows the rate of CC + NC to be measured and neutrino interactions to be tagged

Residual Background

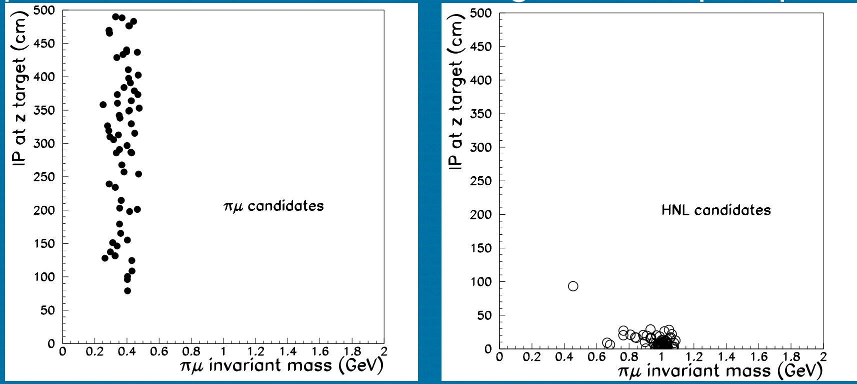
- Background reduction by mass
  - For 0.5 Tm field integral σ_{mass} ~ 40 MeV for p < 20 GeV
  - 75% of μ π decay products have both tracks with p < 20 GeV

Reconstruction of $N_{2,3}$ with mass of 1 GeV



→ Ample discrimination between high mass tail from small number of residual $K_L \to \pi\mu\nu$ and $N_{2,3}$ @ 1 GeV

- Background reduction by impact parameter
  - K_L produced in the final part of the muon shield have significant impact parameter



  - IP < 1 m is 100% eff. for signal and leaves only a handful of background events (no mass cut)
  - The IP cut will also be used to reject backgrounds induced in neutrino interactions in the material surrounding the detector, cosmics etc

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 $\mathcal{U}_\mu^4$
  - Benchmark model II with predominant muon flavour coupling (arXiv:0605047)

- Expected number of signal events

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

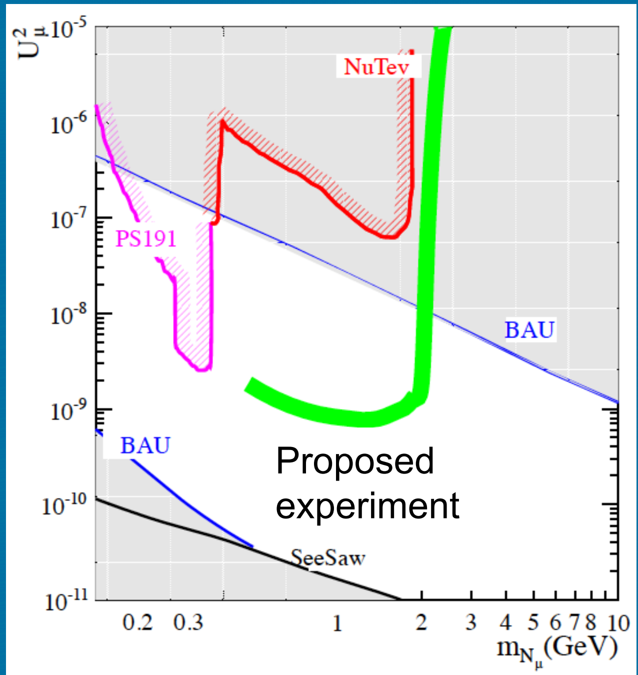
$n_{pot} = 2 \times 10^{20}$
$\chi_{cc} = 0.45 \times 10^{-3}$

- $Br(\mathcal{U}_\mu^2) = \mathrm{Br}(D \to \mu N_{2,3} X) \times Br(N_{2,3} \to \mu\pi)$ 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 effeciency entirely dominated by the geometrical acceptance

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

- 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 $N_{2,3} \rightarrow \mu\pi$ events are expected for $M_{N_{2,3}} = 1\ GeV$

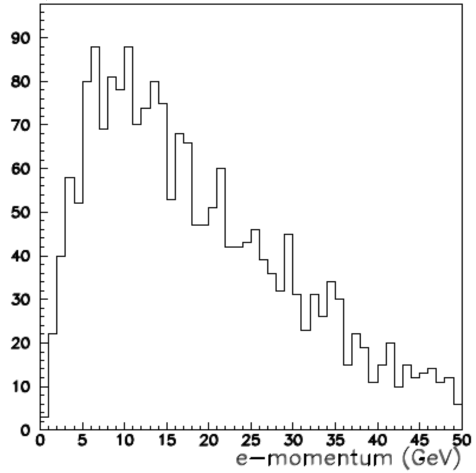


- 120 events for cosmologically favoured region: $\mathcal{U}_\mu^2 = 10^{-8}$ and $\tau_N = 1.8 \times 10^{-4} s$

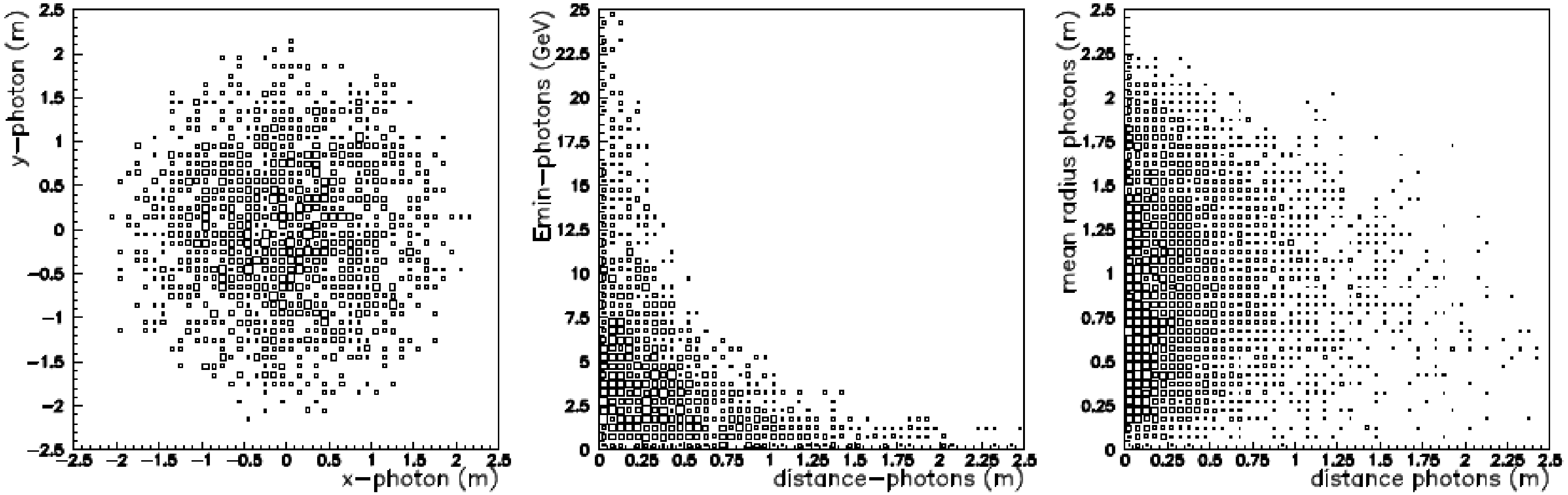
$N_{2,3} \to \mu\rho, e\pi$

- Calorimeter will allow reconstruction of additional decay modes
  - $N_{2,3} \to \mu^{\mp}\rho^{\pm}, \quad \rho^{\pm} \to \pi^{\pm}\pi^{0}$
  - $N_{2,3} \to e\pi$ allow probing $\mathcal{U}_e^2$
- E_e > 1. GeV: 99.9% for electron in acceptance
- Assume 10cm calorimeter cells:
  - To have resolved π^0 need at least 20 cm between photons
  - Need to require E > 0.5 GeV to distinguish from MIP

$N_{2,3} \to e\pi$: Energy of electrons

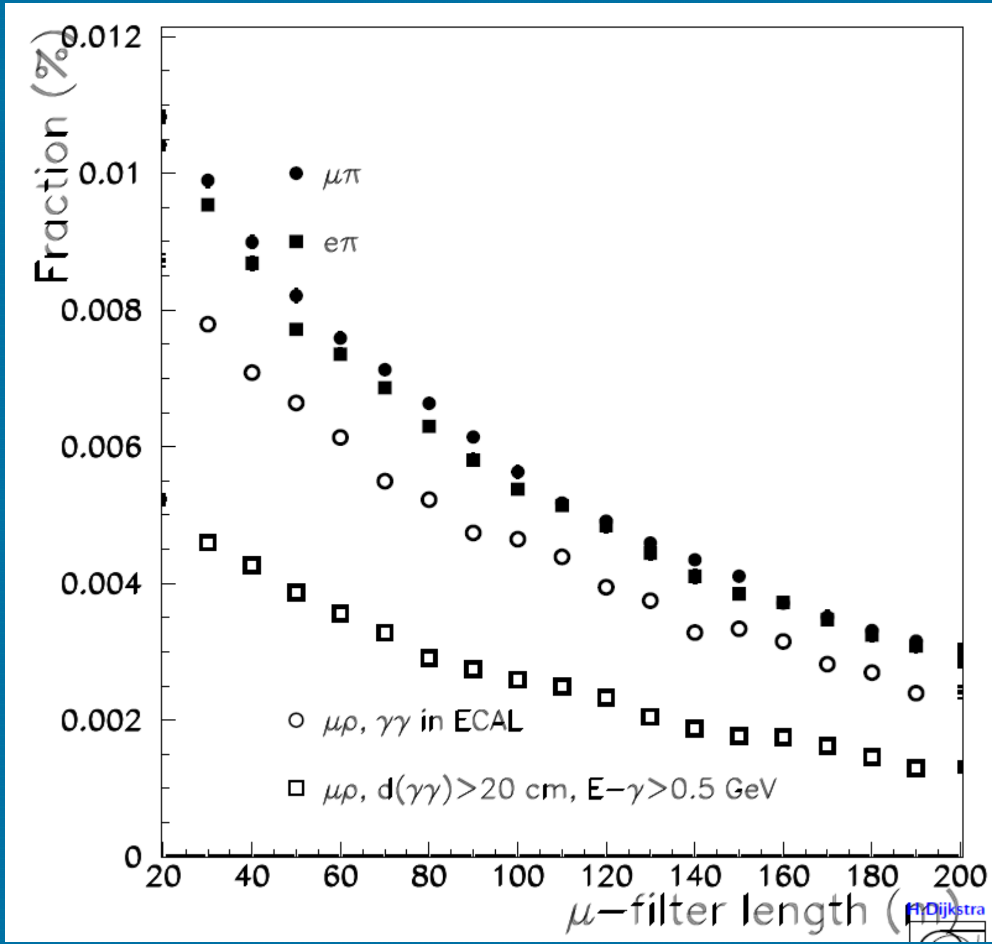


$N_{2,3} \to \mu\rho,\ \rho \to \pi\pi^0$: Position and energy of photons



Efficiency for $N_{2,3} \rightarrow e\pi, \mu\rho$

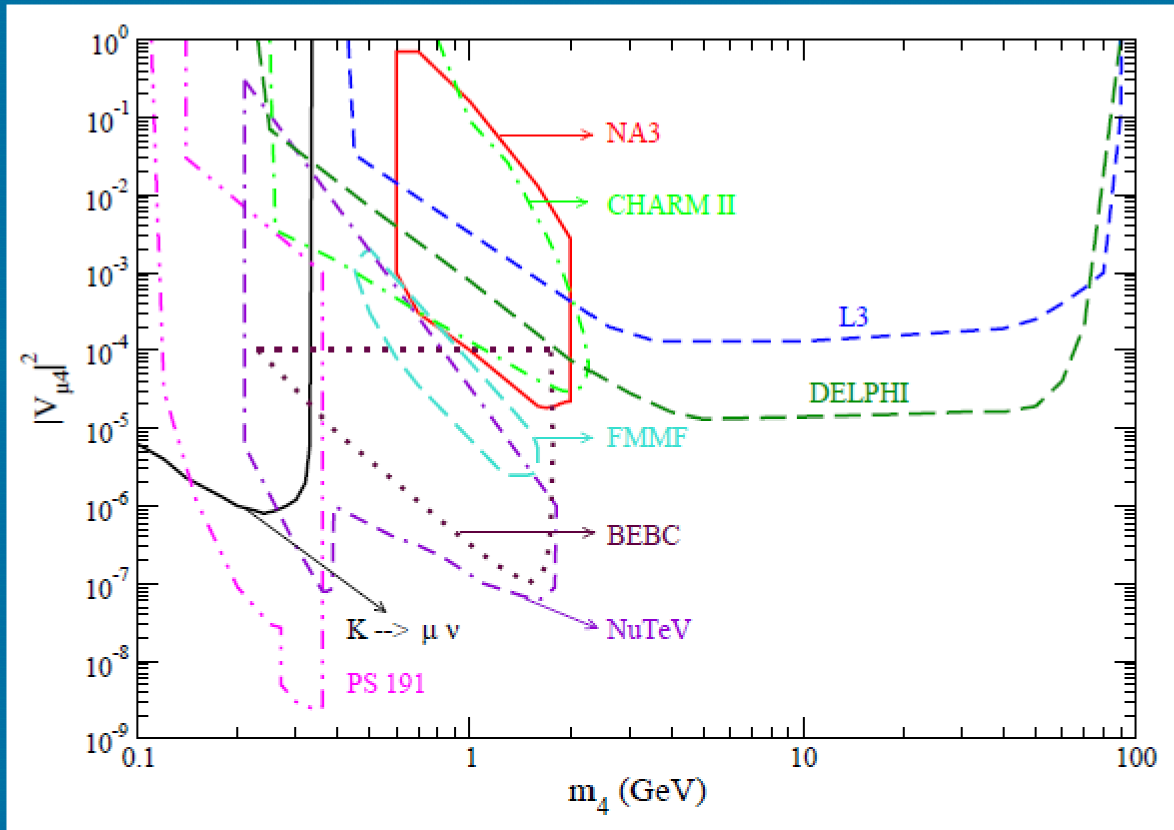
- Assume $\mathcal{U}_\mu^2 = 10^{-7}$and $\tau_N = 1.8 \times 10^{-5} s$ for mass $M_{N_{2,3}} = 1\ GeV$



- Reconstruction efficiency for $N_{2,3} \rightarrow \mu\rho$ is 45% of efficiency for $N_{2,3} \rightarrow \mu\pi$

Summary of Searches for N_I

- Atre et al., 2009



Other Possible SM Physics

Can the experiment be used as a facility for other physics?

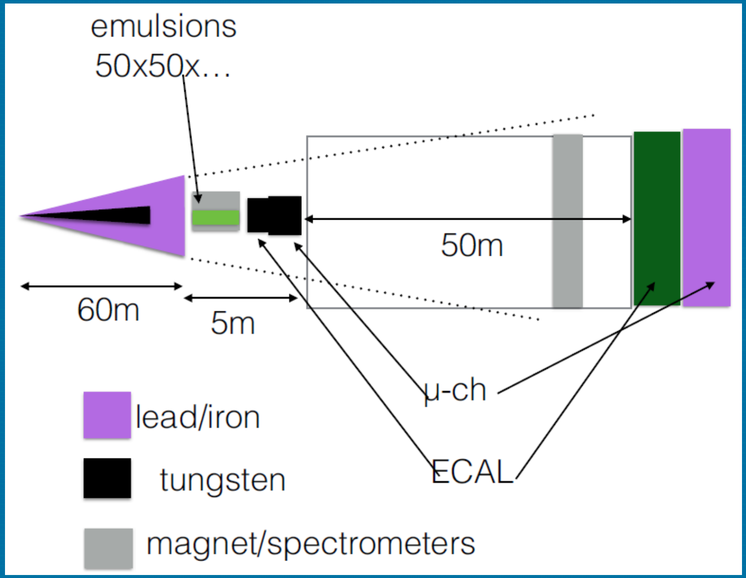
- E.g. Tau neutrino physics
  1. Precise tau neutrino cross section vs E and angular distributions (may be sensitive to New Physics)
  2. Anomalous tau neutrino magnetic moment
  3. Studies of charm production in neutrino interactions

  → Install emulsion at the end of the muon shield, e.g. 50 x 50 cm^2

  → Expect 20x more events compared to DONUT experiment at Fermilab at same neutrino target mass

  → Realistic to assume possibility in using >10x DONUT mass: 260 kg → 3000 kg

  → Expect 1700 events in full exposure



Other Possible BSM Physics

- Light, very weakly interacting, long lived particles out of the LHC reach
  - See e.g. [Batell et al., 2009] for exploring portals to hidden sector at fixed-target

→ Light sgoldstinos (superpartners of goldstino in SUSY): Axion- and dilaton-like

- e.g., [Gorbunov, 2001, LHCb: Aaij et al., 2013]

→ $D \to \pi X,\ X \to l^+ l^-$

→ $B_s \to PS, \quad P, S \to \pi^+\pi^-, \mu^+\mu^-$

→ R-parity violating neutralinos in SUSY: Heavy-neutrino like

- e.g., [Dedes et al., 2001]

→ $D \to l\tilde{\chi},\ \tilde{\chi} \to l^+ l^- \nu$

→ Massive vectors (in secluded dark matter models): Paraphoton-like

- e.g., [Pospelov et al., 2008]

→ $\Sigma \to pV,\ V \to l^+ l^-$

- Proposed experiment allows exploring longer lifetimes and smaller couplings compared to CHARM and LHCb

Conclusions

- Power of νMSM "framework"
  - 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
  - Many observable predictions in both accelerator based experiments and cosmological observations
  - A well constrained parameter space!

- For $M_N < 2\ GeV$ and 2x10^{20} p.o.t. the proposed experiment has discovery potential for the cosmologically favoured region with $10^{-7} < \mathcal{U}_\mu^2 < a\ few\ \times 10^{-9}$ for the decay $N_{2,3} \to \mu\pi$
  - May be improved with additional decay modes
  - $N_{2,3} \to e\pi$ allow probing $\mathcal{U}_e^2$

- The impact of a discovery of the HNLs on particle physics is difficult to overestimate !

- *Experiment also sensitive to other predictions of new, very weakly interacting and long-lived particles with masses below the Fermi scale*

- The proposed experiment perfectly complements the searches for NP at the LHC

Conclusions - Main Challenges

- Beam extraction
- Target bunker
- Target head
- Muon shield
- Potentially high occupancy

Conclusions – Next Steps

- Proposal presented to the CERN SPS Committee on October 22, 2013
  - Very well received
  - Follow-up questions being discussed with referees
  - Evaluation in progress
  - Proposal being discussed with:

European Organization for Nuclear Research (CERN)

France:	CEA Saclay, APC/LPNHE Universite Paris-Diderot
Italy:	Instituto Nazionale di Fisica Nucleare (INFN)
Netherlands:	National Institute for Subatomic Physics (NIKHEF, Amsterdam)
Poland:	Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences (Kracow)
Russia:	Institute for Nuclear Research of Russian Academy of Science (INR, Moscow), Institute for Theoretical and Experimental Physics ((ITEP, Moscow), Joint Institute for Nuclear Research (JINR, Dubna)
Sweden:	Stockholm University, Uppsala University
Switzerland:	Ecole Polytechnique Federale de Lausanne (EPFL), University of Zurich, University of Geneva
UK:	University of Oxford, University of Liverpool, Imperial College London, University of Warwick

➔ Open to further interest from new groups

Search for Heavy Neutral Leptons

Abstract:

A minimal extension of the Standard Model with three right-handed singlet Majorana leptons with masses below the Fermi scale (νMSM) allows incorporating a mechanism to generate the baryon asymmetry of the Universe, account for the pattern of small neutrino masses and oscillations, and potentially provide a Dark Matter candidate. This avoids introducing new energy scales between the Fermi scale and the Planck scale, the lack of which has also been shown to be compatible with the mass of the recently discovered Higgs boson. Considerations based on cosmological constraints and based on the data on neutrino oscillations favour a range of masses and couplings for these new heavy neutral leptons (HNL) which is largely accessible to experimental verification or falsification.

This paper outlines a proposal for a new fixed-target experiment at the CERN SPS to search for the HNLs, together with an introduction to the theoretical motivation, a description of the experimental setup with the associated beam line and detector, and a discussion of the background sources and the expected sensitivity. With an integrated total of 2x10^20 protons on target at 400 GeV, the experiment is able to achieve a sensitivity which is four orders of magnitude better than previous searches. In addition to HNLs, the experiment will be sensitive to many other types of physics models that predict weakly interacting long-lived exotic particles.

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Other BSM Physics

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