- Abstract:
A new fixed-target experiment at the CERN SPS accelerator is being proposed that will use decays of charm mesons to search for Heavy Neutral Leptons (HNLs) and other hidden, very weakly interacting particles.
With the discovery of a light Higgs boson, the Standard Model could be a self-consistent effective field theory up to the Planck scale. In spite of the fact that the Standard Model is consistent with LHC experiments, it cannot be an ultimate theory of nature. It does not explain neutrino masses and oscillations, the baryon asymmetry of the universe, and there is no dark matter candidate.
I will discuss the theoretical motivations for such an experiment, its setup and sensitivity.

Expression of Interest:
Proposal to search for
Heavy Neutral Leptons at the SPS
and other very weakly interacting long lived particles

http://ship.web.cern.ch/ship/

(CERN-SPSC-2013-024 / SPSC-EOI-010)

W. Bonivento[1,2], A. Boyarsky[3], H. Dijkstra[2], U. Egede[4], M. Ferro-Luzzi[2], B. Goddard[2], A. Golutvin[4], D. Gorbunov[5], R. Jacobsson[2], J. Panman[2], M. Patel[4], O. Ruchayskiy[6], T. Ruf[2], N. Serra[7], M. Shaposhnikov[6], D. Treille[2] (‡)

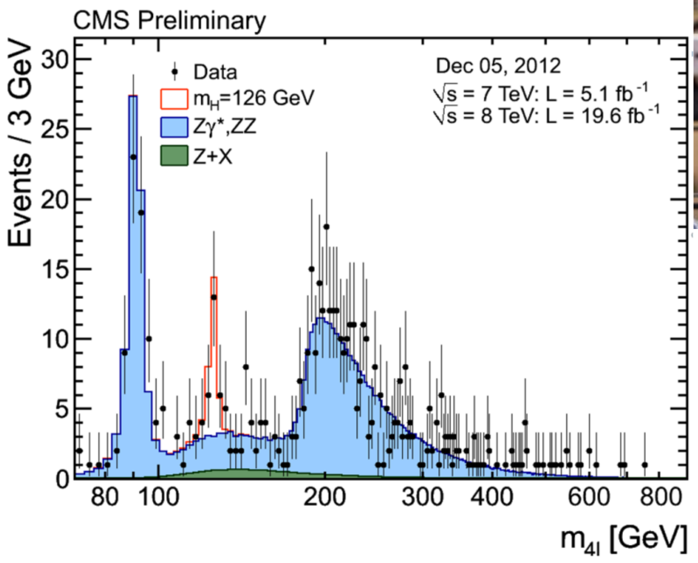
[1] *Sezione INFN di Cagliari, Cagliari, Italy*
[2] *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[3] *Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands*
[4] *Imperial College London, London, United Kingdom*
[5] *Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia*
[6] *Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[7] *Physik-Institut, Universität Zürich, Zürich, Switzerland*
(‡) *retired*

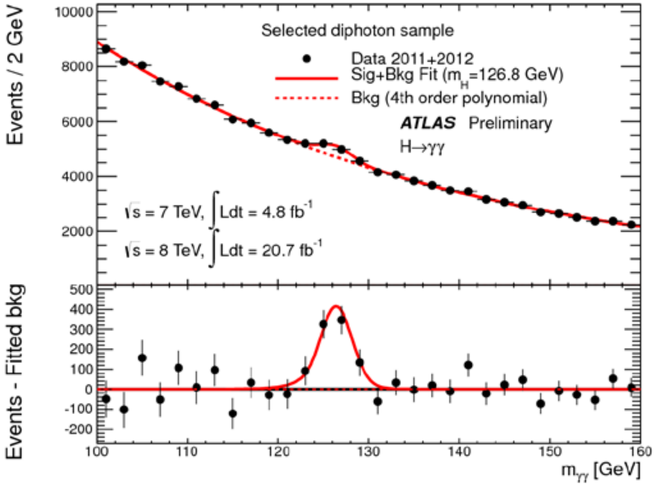
Outline

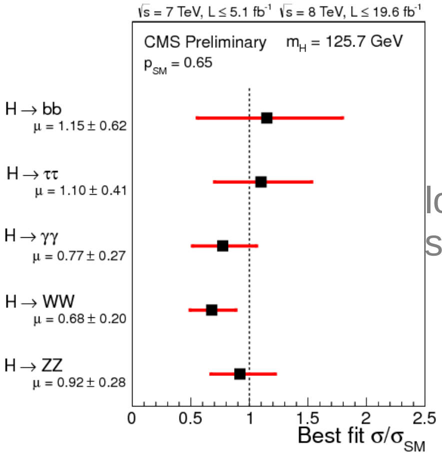
- Theoretical Motivation
- Production and Decay of Heavy Neutral Leptons
- Experimental Setup
- Extended Physics Program
- Time Line and Conclusion

Theoretical Motivation

- Discovery of the 126 GeV Higgs boson → Triumph of the Standard Model.







looks like the standard model Higgs,
smells like the standard model Higgs

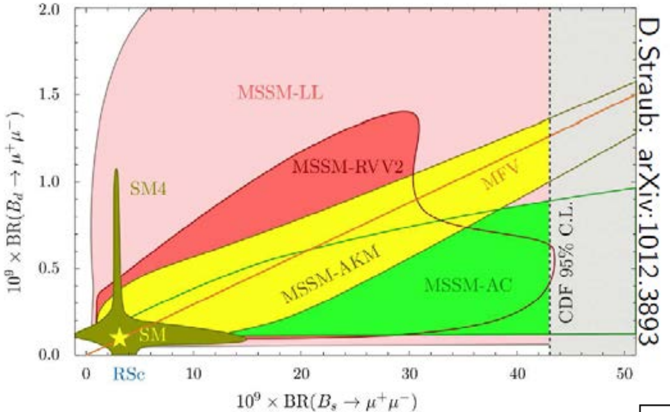
Pictures from the ATLAS / CMS official Web sites

Theoretical Motivation

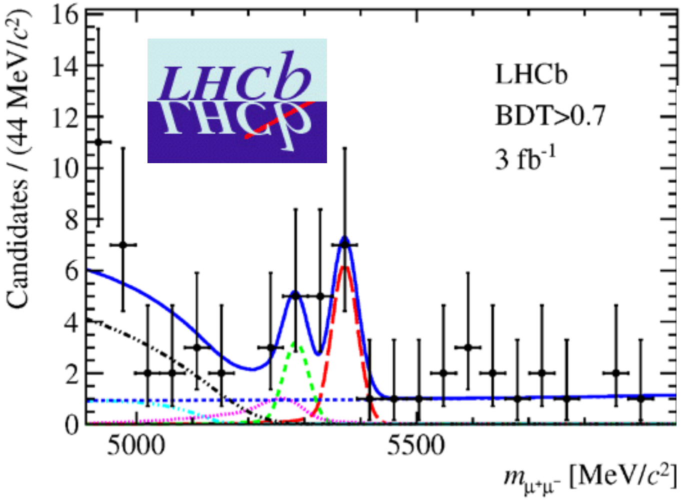
- Another success of the SM: Observation of the rarest B decay mode
  - Expected: $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$
    Phys. Rev. Lett. 109 (2012) 041801

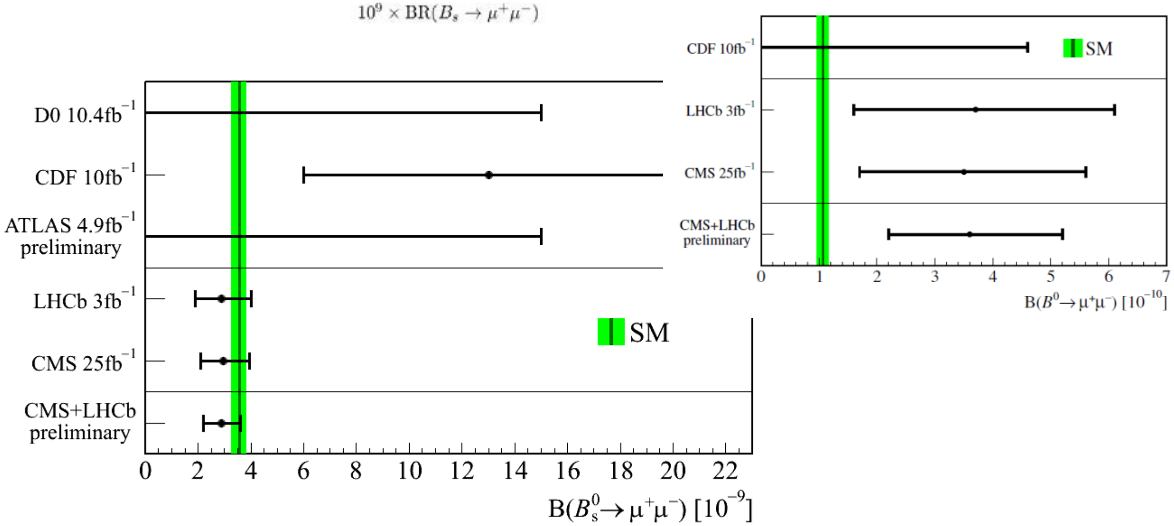
- MSSM: $\mathcal{B} \propto tan^6\beta / M^4_{A^0}$

Landscape before LHC:



D.Straub: arXiv:1012.3893

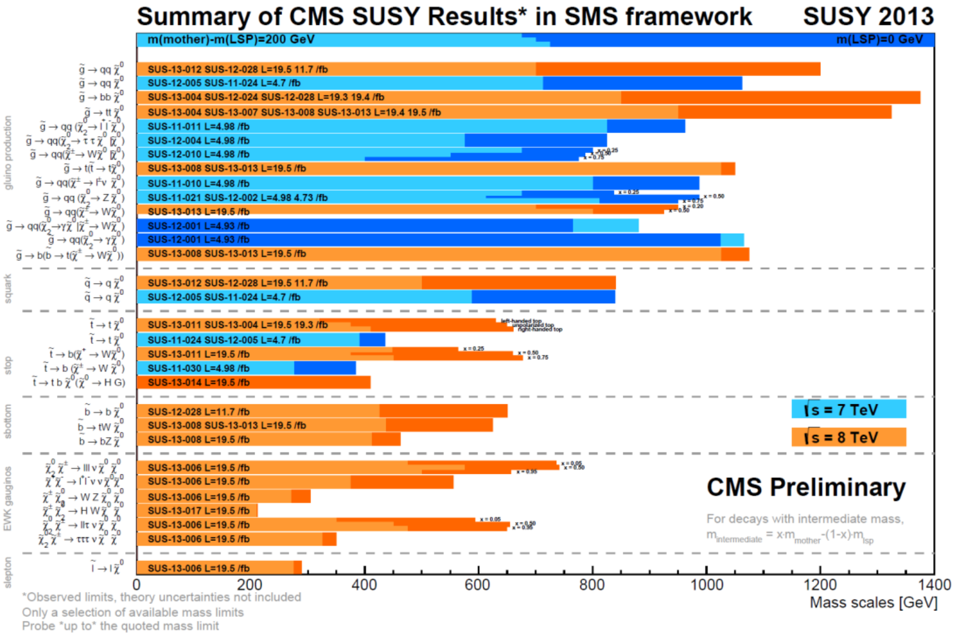


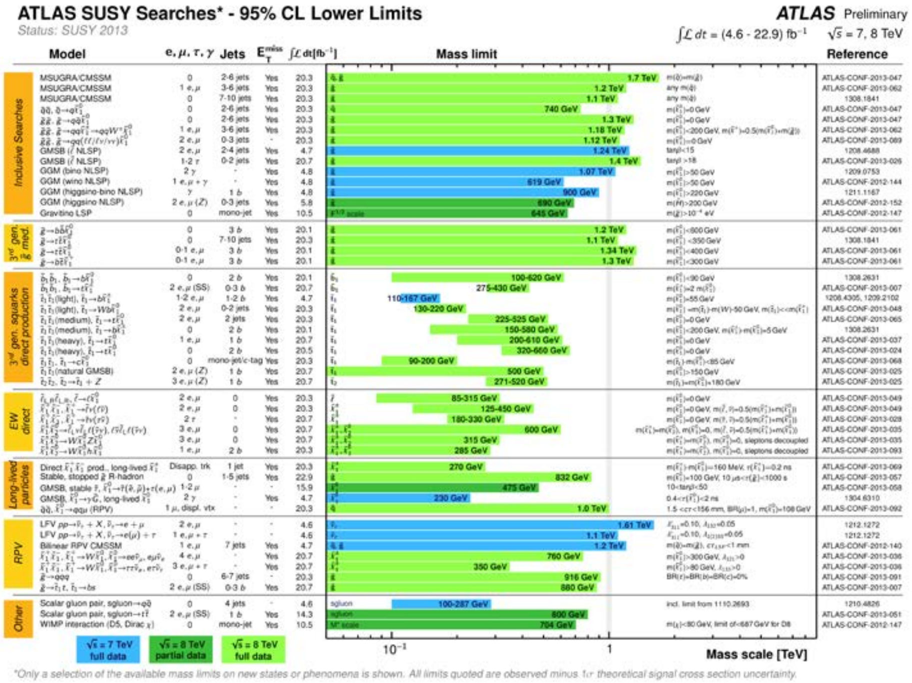


Pictures from the LHCb official Web site

Theoretical Motivation

- In parallel, many direct searches for new SUSY particles



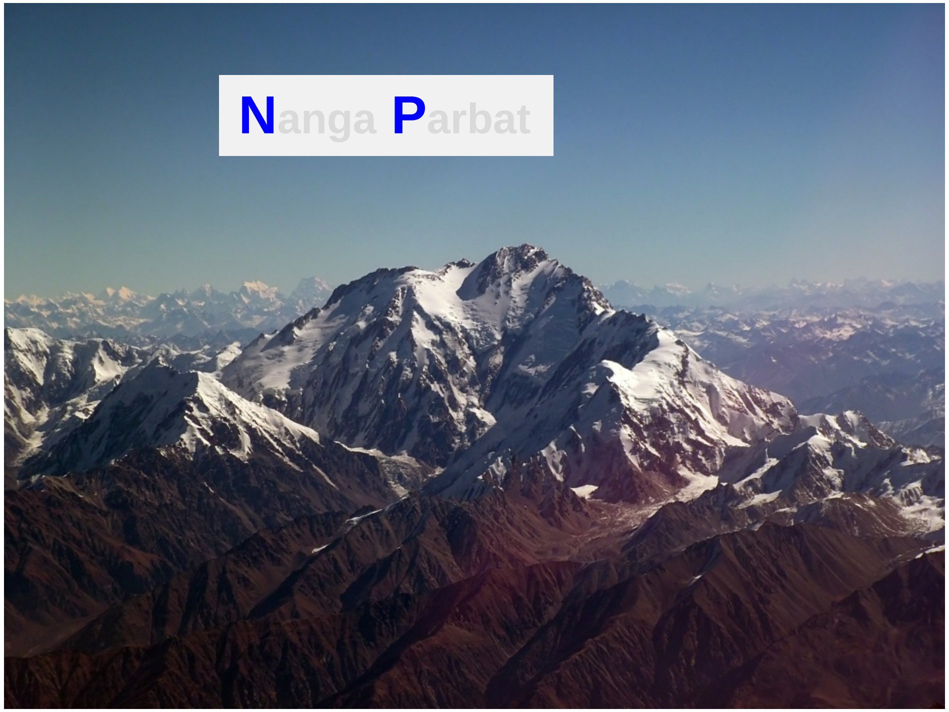


- Nothing found (yet) !

Theoretical Motivation

- No new particles (yet) in direct searches.
- Flavour physics, e.g. $\mathrm{B\overline{B}}$-mixing pushes scale for NP up to $0.5 - 10^4\ \mathrm{TeV}$ depending on assumptions of couplings.

- Air becomes thin for NP at TeV scale.

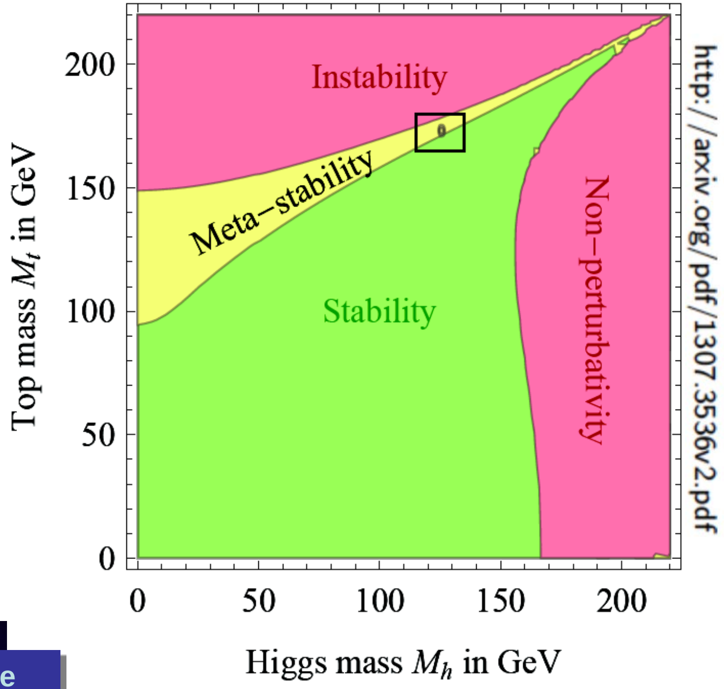


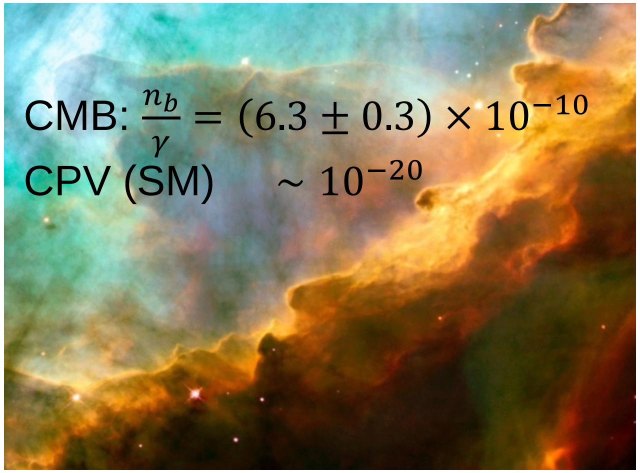
Waiting with suspense for the first LHC results with increased energy $\sqrt{s} \approx 13\ TeV$

Credit http://de.wikipedia.org/wiki/Datei:Nanga_Parbat_from_air.jpg

Theoretical Motivation

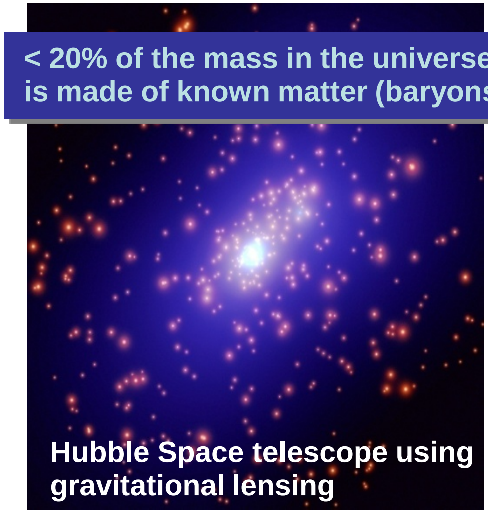
- Higgs (126 GeV) and Vacuum Stability
  - Vacuum is stable or has $\tau \gg \tau_{universe}$ *(Espinosa et al)*
  - Top mass biggest uncertainty
- **The SM may work successfully up to the Planck scale !**
- **However, we are missing explanations for**
  - **Baryon Asymmetry of the Universe**
  - **Dark matter**
  - **Neutrino mixing / masses**





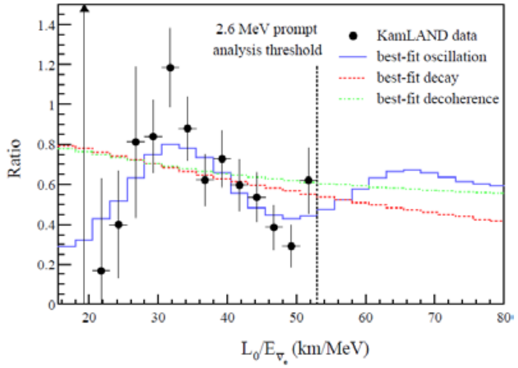
CMB: $\frac{n_b}{\gamma} = (6.3 \pm 0.3) \times 10^{-10}$

CPV (SM) $\sim 10^{-20}$



< 20% of the mass in the universe is made of known matter (baryons)

Hubble Space telescope using gravitational lensing

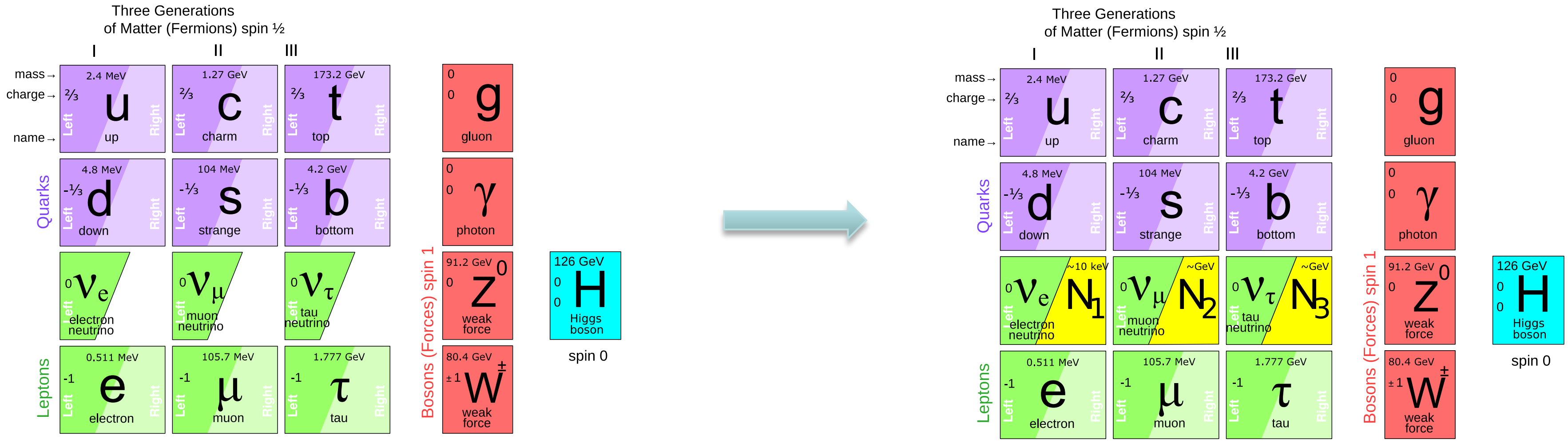


Phys.Rev.Lett. 94 (2005) 081801

The Neutrino Minimal Standard Model

- The most economical solution, only add what is needed

νMSM*: *T.Asaka, M.Shaposhnikov PL B620 (2005) 17



- Adding three new fundamental fermions, right-handed Majorana **H**eavy **N**eutral **L**eptons (HNL): $\mathbf{N_1}, \mathbf{N_2}$ and $\mathbf{N_3}$
  - $\mathbf{N_1}$ **dark matter candidate** $\mathbf{M \approx 10\ keV}$
  - $\mathbf{N_{2,3}}$ **give masses to neutrinos via seesaw mechanism,** $\mathbf{M \approx 1\ GeV}$ **and produce Baryon Asymmetry of the Universe via leptogenesis**
  - **Higgs: give masses to quarks, leptons, Z, W and inflate the Universe**

See-saw generation of neutrino masses

- Most general renormalisable Lagrangian with 3 right-handed neutrinos N_I:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{\substack{I=1,2,3 \\ \alpha=e,\mu,\tau}} i\bar{N}_I \delta_\mu \gamma^\mu N_I - Y_{I\alpha} \bar{N}_I^c \tilde{H} L_\alpha^c - \frac{M_I}{2} \bar{N}_I^c N_I + h.c.$$

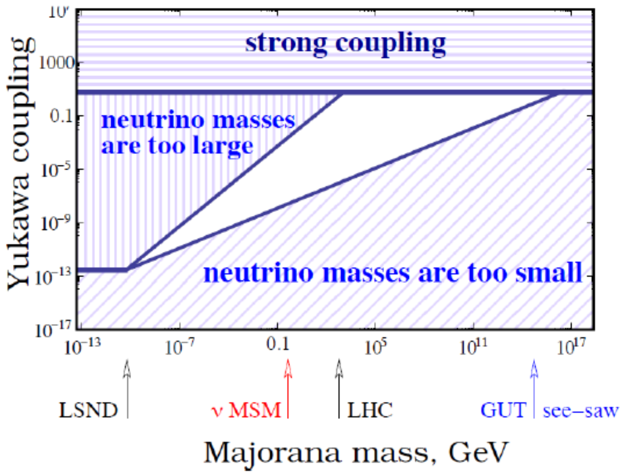
Yukawa term: mixing of $\boldsymbol{N_I}$ with active neutrinos to explain ν-oscillations

Majorana term which carries no gauge charge

- Dirac mass term: $m_D \sim Y_{I\alpha} v$
- Scale of active neutrino masses given by seesaw formula: $m_\nu \sim \frac{m_D^2}{M}$
- For HNL mass $\sim$1 GeV
  and $m_\nu \sim 0.05$ eV

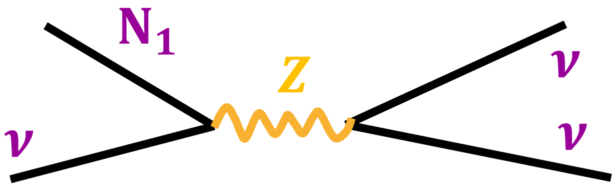
  $\Rightarrow$

  $m_D \sim 10$ keV and Yukawa coupling $\sim 10^{-7}$



N_1: The Dark Matter candidate

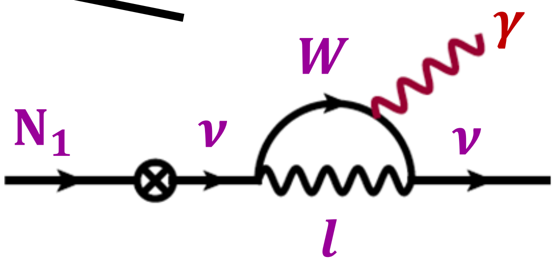
- Does not contribute to seesaw mechanism
- Yukawa couplings are small, therefore N_1 can be very stable, $\tau \gg \tau_{\mathrm{universe}}$
  - Main decay mode: $\mathbf{N \rightarrow 3\nu}$



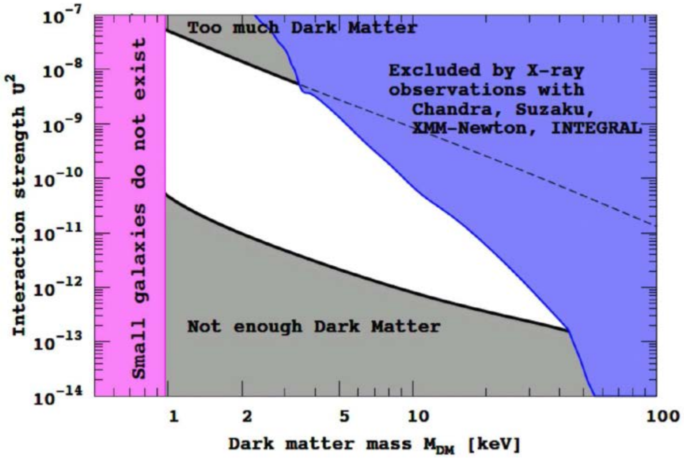
For one flavor:

$$\tau = \frac{96\,\pi^3}{G_F^2 M^5 U^2} \approx 10^{14} years \left(\frac{10\ keV}{M}\right)^5 \left(\frac{10^{-8}}{U^2}\right)$$

  - Radiative decay:



$$\Gamma_{rad}/\Gamma_{tot} = \frac{27\ \alpha_{EM}}{8\ \pi} \sim 1/128$$

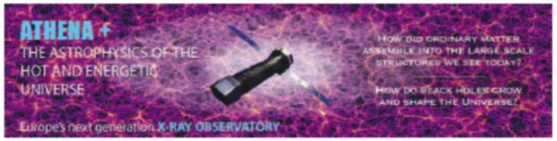


  - $\mathbf{E_\gamma} \sim \frac{M}{2}$, X-ray detection:
    - Astrophysics experiments, proposed missions:
    - Spectral resolution required $\Delta E/E \sim 10^{-3}$

Astro-H

LOFT

Athena+

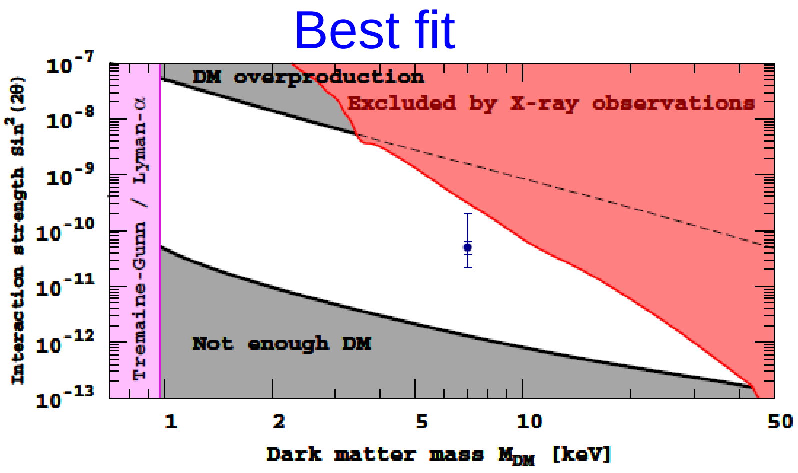


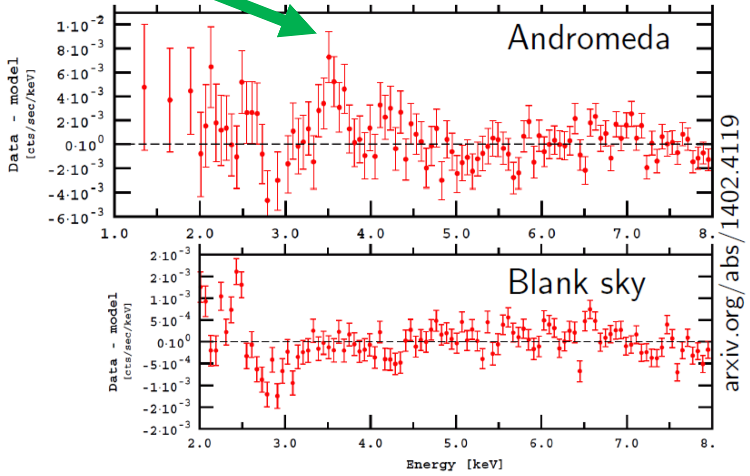
Origin/Xenia

$$U = \frac{Y_{I\alpha} v}{M_N} = \frac{m_D}{M_N}$$

(Interlude)

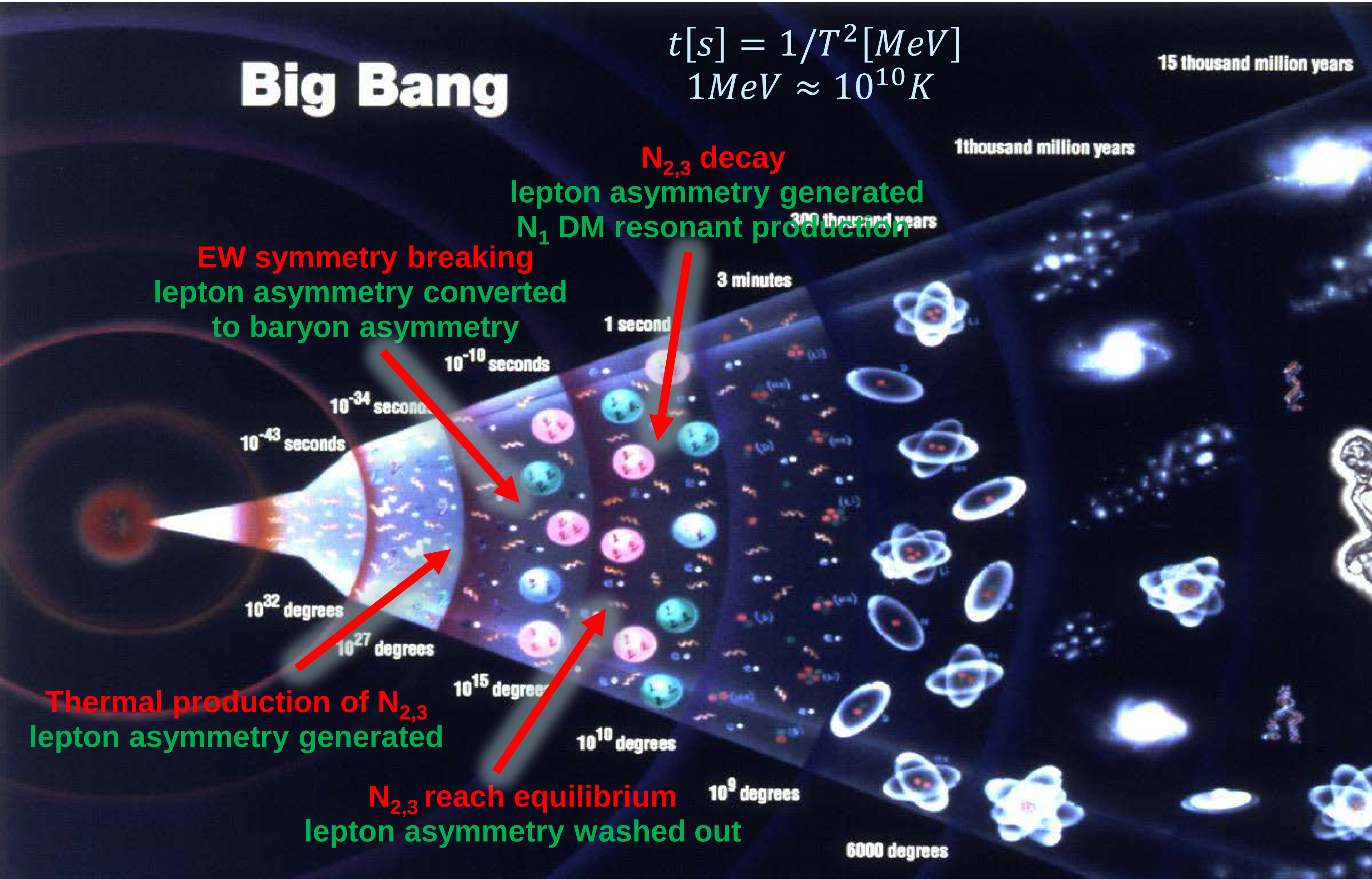
- Recent observations, Feb 2014, two independent teams come to same conclusion:
  - arxiv.org/abs/1402.2301: **Detection of an Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters**, $E_\gamma \sim 3.56\ keV$, Harvard-Smithsonian Center for Astrophysics & NASA Goddard Space Flight Center
  - arxiv.org/abs/1402.4119: **An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster**, $E_\gamma \sim 3.5\ keV$, *Alexey Boyarsky, Oleg Ruchayskiy, Dmytro Iakubovskyi, Jeroen Franse*





- Astro-H, 2015 launch, will confirm / rule-out the DM origin of this signal

BAU and DM in the νMSM



$$t[s] = 1/T^2[MeV]$$
$$1MeV \approx 10^{10}K$$

$N_{2,3}$ decay
lepton asymmetry generated
N_1 DM resonant production

EW symmetry breaking
lepton asymmetry converted
to baryon asymmetry

Thermal production of $N_{2,3}$
lepton asymmetry generated

$N_{2,3}$ reach equilibrium
lepton asymmetry washed out

Baryon Asymmetry and BBN

- $N_{2,3}$ oscillations are the source of baryon asymmetry
  - $\mathbf{N_{2,3}}$ are created in the early universe
  - At T > 100 GeV, due to small couplings, they are out of thermal equilibrium
  - Oscilatte in a coherent way with CPV ♣, 6 new CPV phases available
  - CPV produces lepton asymmetries, flavored leptogenesis
  - Lepton number of active left-handed neutrinos is transferred to baryons due to equilibrium sphaleron processes

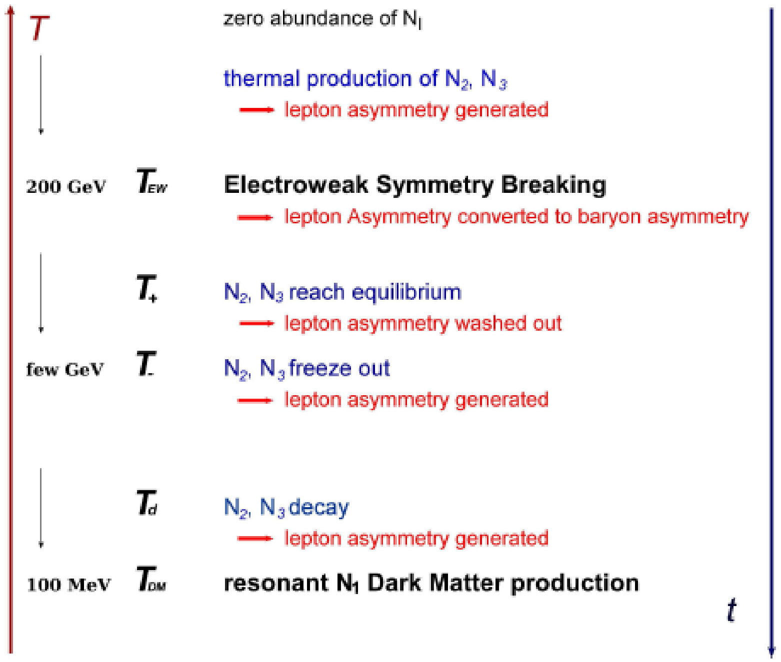


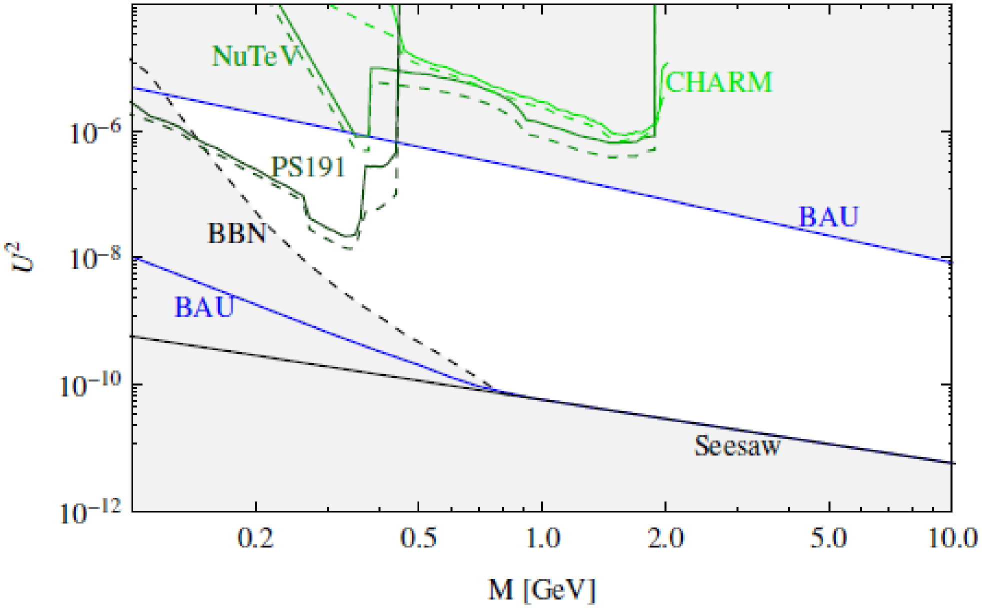
Figure 1: *The thermal history of the universe in the νMSM.*

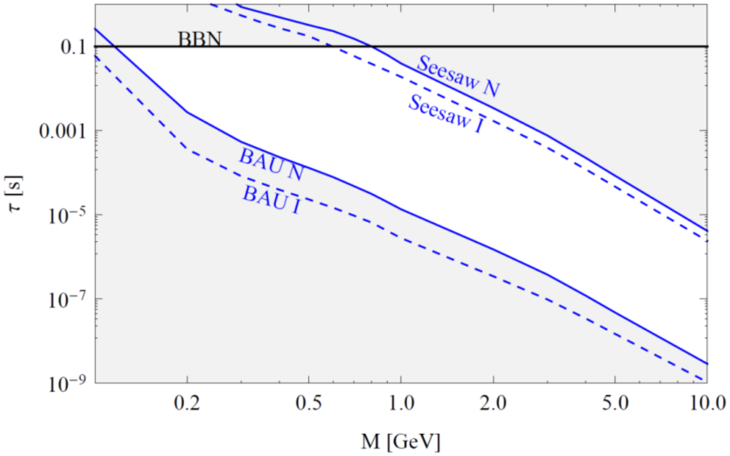
♣ Mass degenerated $N_{2,3}$ greatly enhance CPV and needed for resonant N_1 production

Baryon Asymmetry and BBN

Constraints

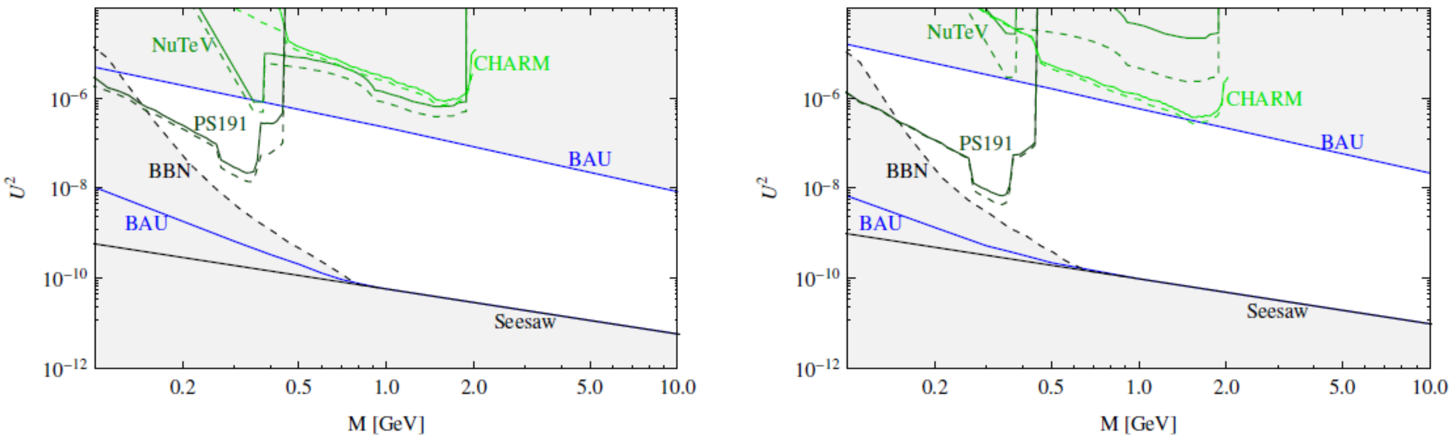
- **BAU requires out of equilibrium**: mixing angle of $\mathbf{N_{2,3}}$ to active neutrino cannot be too large
- **Neutrino masses:** Mixing angle cannot be too small
- **Big Bang Nucleosynthesis**: Decays of HNL must not spoil BBN $\tau_{N_{2,3}} < 0.1s$, otherwise nucleosynthesis affected by $\mathbf{N_{2,3}}$ decays (75/25 % H/He-4)





Present Experimental Constraints

- Previous experiments
  - **PS191** (CERN 1988), E_{beam}= 19 GeV, 1.4×10^{19} pot, 128m from target
  - **CHARM** (CERN 1986), E_{beam}= 400 GeV, 2.4×10^{18} pot, 480m from target
  - NuTev (Fermilab 1999), E_{beam}= 800 GeV, 2.5×10^{18} pot, 1.4km from target

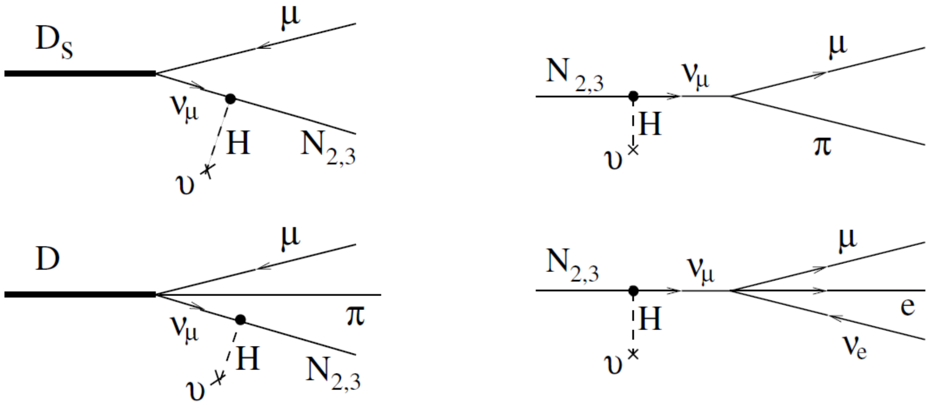


- Large area allowed by cosmology with $\mathbf{M_N < 2\ GeV}$ is still unexplored

Todays Production and Decay of HNLs

- **$N_{2,3}$** mix with normal neutrinos and can be "copiously" produced in (semi) leptonic hadron decays: $K \to \mu\nu, D \to K(\pi)\mu\nu, B \to D(\pi)\mu\nu$
  - **$M_N < 0.5$ GeV** with K, **$M_N < 2$ GeV** with charm, **$M_N < 3 - 5$ GeV** with beauty

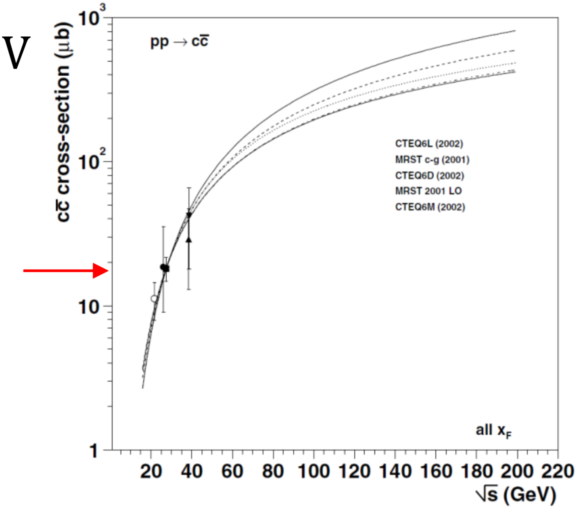
- **$N_{2,3}$** production in charm and subsequent decays



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

Todays Production and Decay of HNLs

- Large source of charm provided by proton (400 GeV) $\rightarrow$ fix target collisions
  - Sufficient large charm cross section, $\sqrt{s} = 27.4\ \mathrm{GeV}$
  - high intensity beam ($\sim 5 \times 10^{13}$ p every 10 sec)
    2×10^{20} pot in 3-4 years (CNGS):
    2×10^{17} c-hadrons
  - Large detector acceptance due to boost
    $\boldsymbol{\tau}_{\mathbf{N}_{2,3}} \propto \boldsymbol{U}^{-2}$, i.e. $\boldsymbol{c\tau} \propto \boldsymbol{O}(\mathrm{km})$



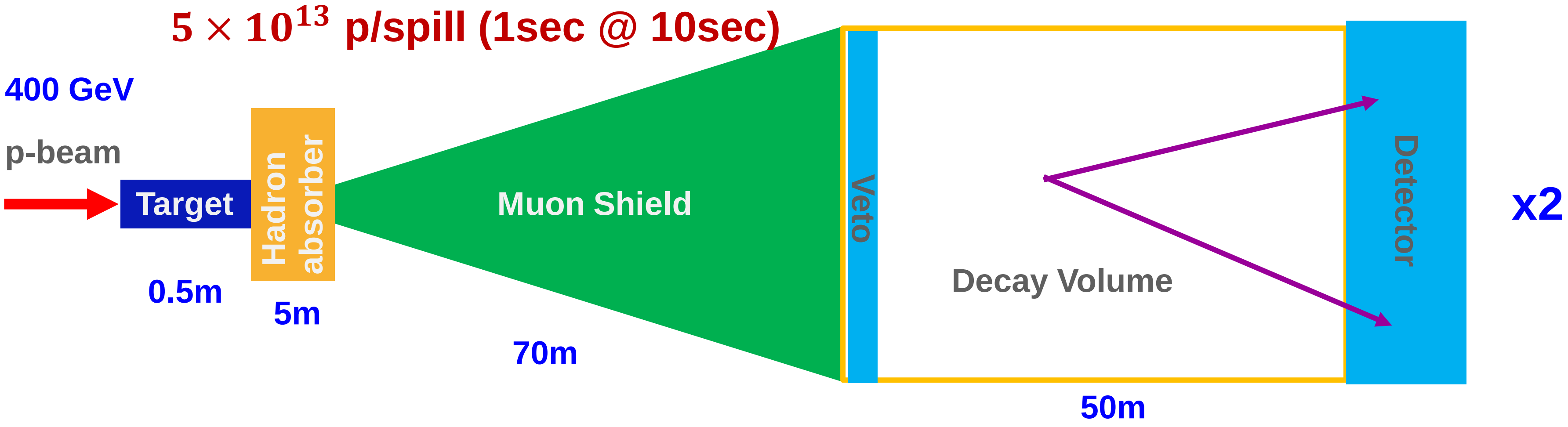
2004 *J. Phys. G: Nucl. Part. Phys.* 30 S315

- Other sources:
  - LHC ($\sqrt{s} = 14\ \mathrm{TeV}$), ~50 collisions / 25ns and 500 x $\sigma_{c\bar{c}}$
    2×10^{16} c-hadrons in 3-4 years in 4π, but almost no acceptance
  - Fermilab ($120\ \mathrm{GeV}$), 10 x smaller $\sigma_{c\bar{c}}$, 10x pot for LBNE by 2025 (?), but HNL operation not compatible with neutrino physics

The Experimental Setup

- Concept
- Beamline & Target
- Muon Shield
- Decay Volume and Spectrometer
- Detector Technologies

Concept of Experimental Setup



5×10^{13} p/spill (1sec @ 10sec)

400 GeV

p-beam

Target

Hadron absorber

Muon Shield

Veto

Decay Volume

Detector

x2

0.5m

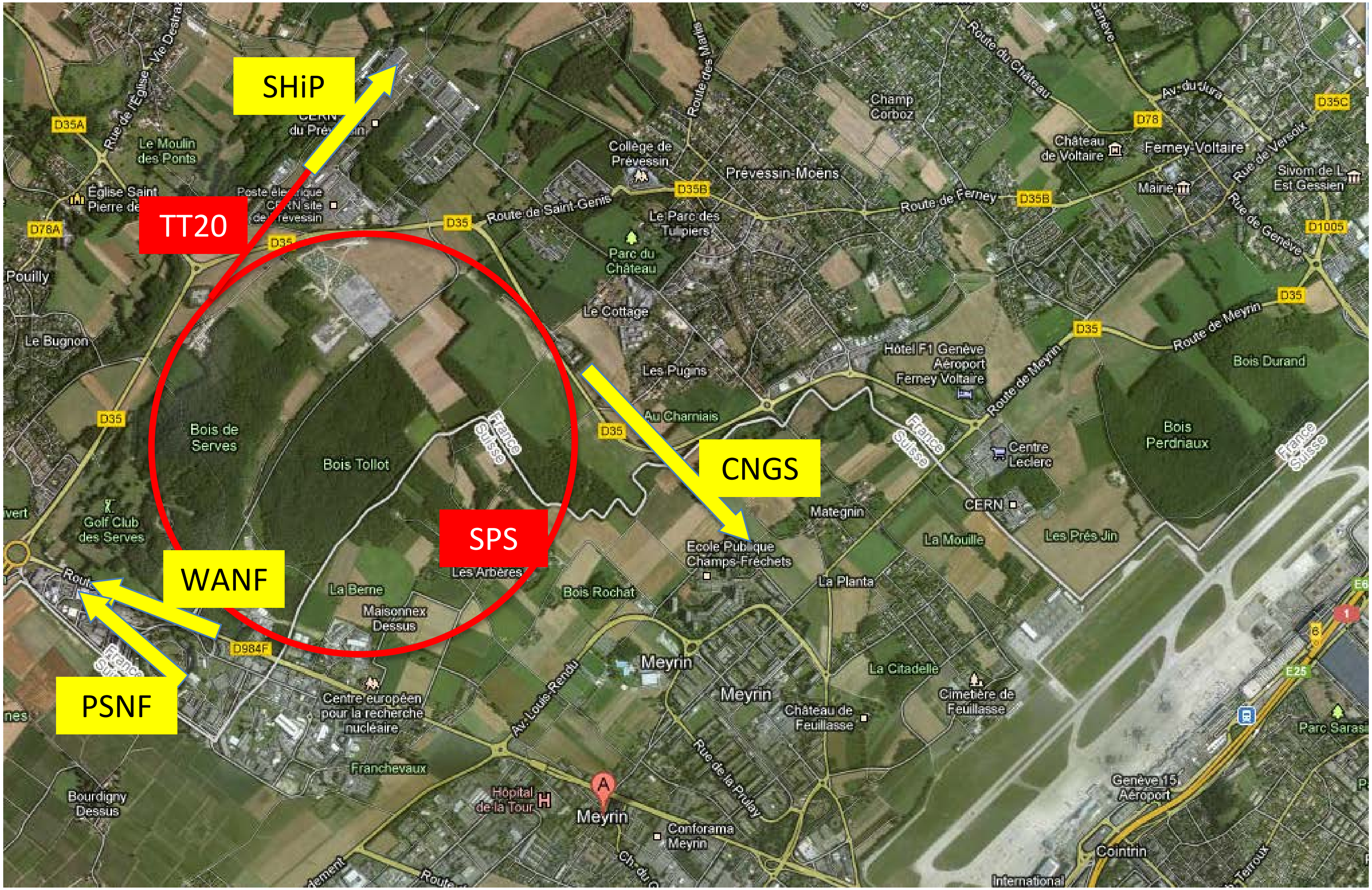
5m

70m

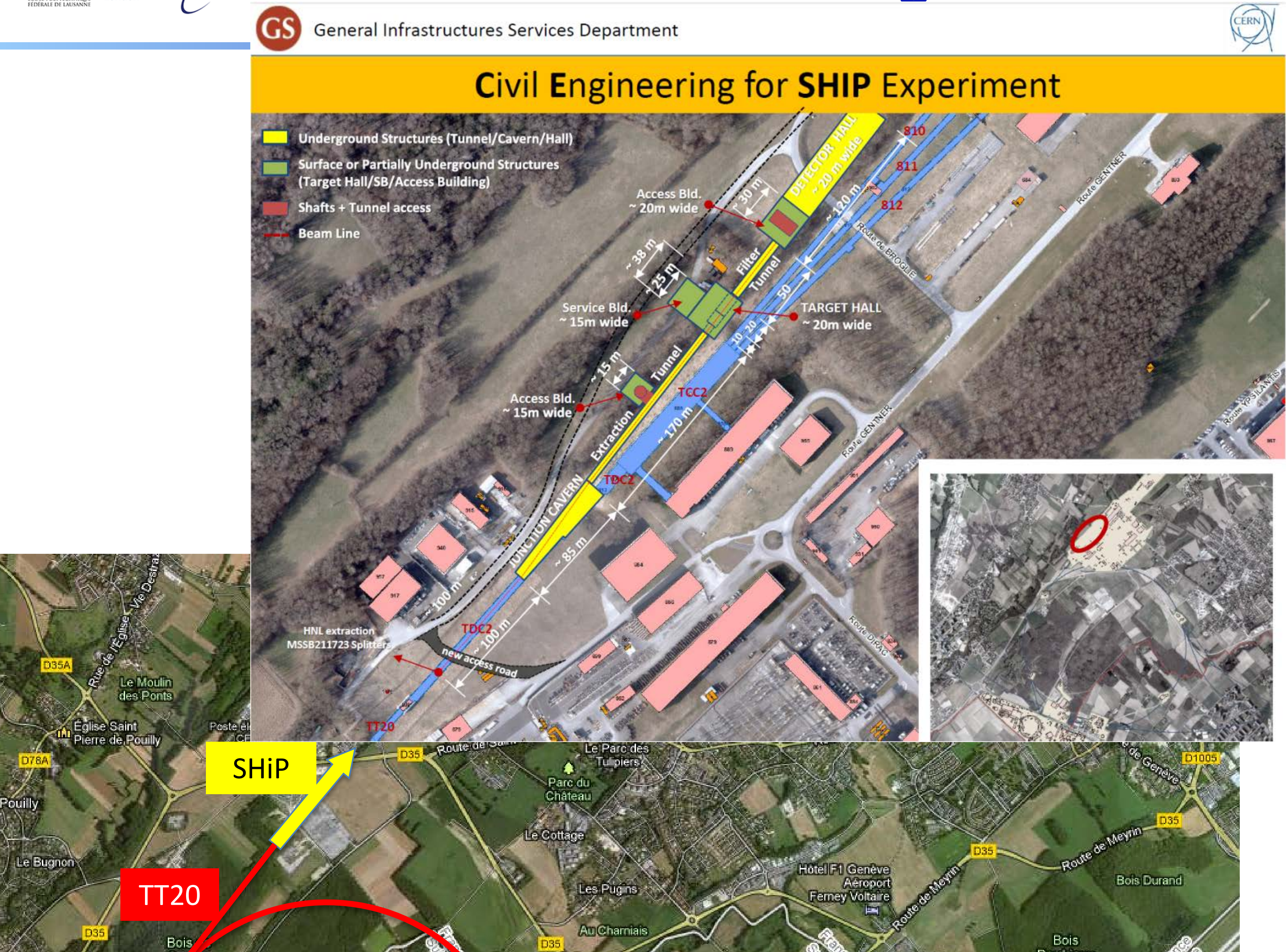
50m

- For reducing muon and neutrino background, would like to stop pions/kaons before they decay, ⇒ need heavy target = tungsten
- For radiation protection: need hadron absorber
- Detector needs to be shielded for still large flux of muons $\approx 10^{11}$/spill, for acceptance reasons as short as possible
  - passive shielding (W+Pb) or active shielding (magnets)
- Empty decay volume followed by a detector measuring the HNL decay products, charged and neutral.
  - Veto detector to identify background originating from muon shield
- To increase statistics, repeat (veto + decay volume + detector)

Beamline & Target



Beamline & Target



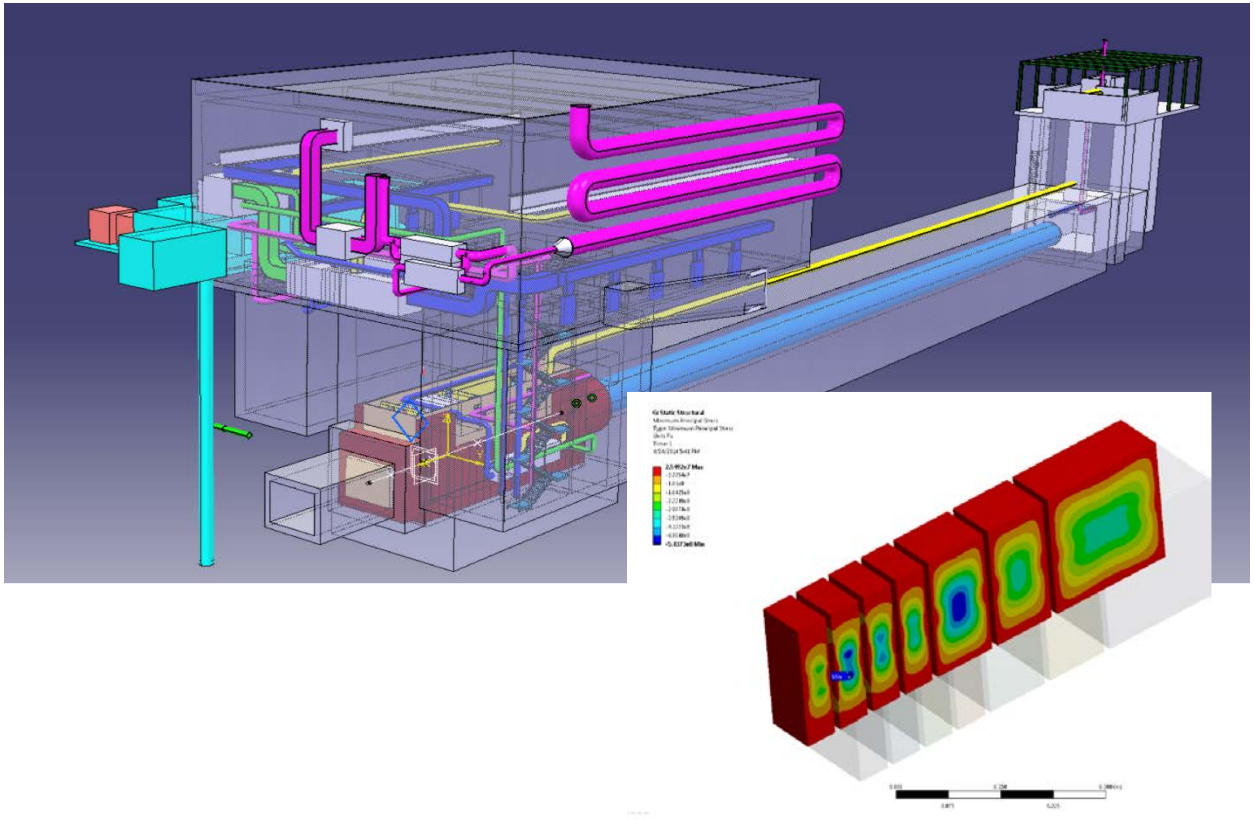
General Infrastructures Services Department

Civil Engineering for **SHIP** Experiment

- 🟨 Underground Structures (Tunnel/Cavern/Hall)
- 🟩 Surface or Partially Underground Structures (Target Hall/SB/Access Building)
- 🟥 Shafts + Tunnel access
- Beam Line

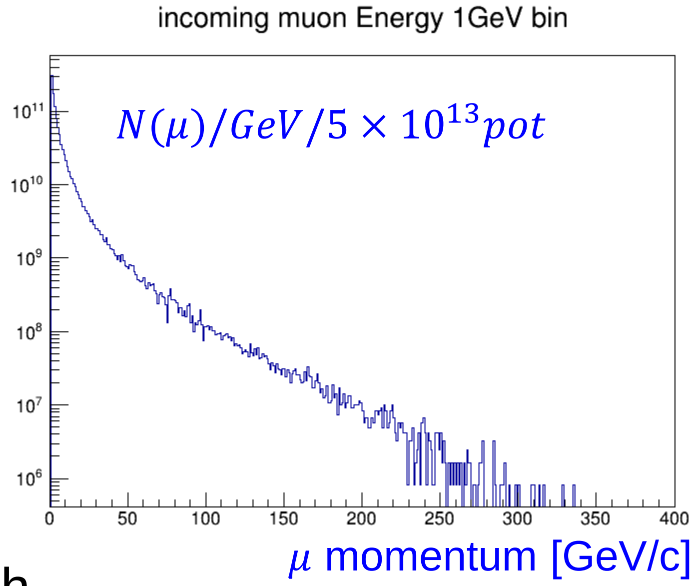
Beamline & Target

- An engineering design for a target station had already been worked out for the CERN neutrino R&D facility, used now as a starting point for SHiP.
- Challenge are the mechanical stresses and cooling
  - 500 kW power deposition in the W target during ~1s, every 10s
  - 200 kW power in the hadron absorber
  - Results of a thermo-mechanical design study expected by June.
  - Most probably, target needs to be segmented



Muon Shield

- Muon rate after target and hadron absorber **$\approx 10^{11}$/spill**
- For occupancy reasons, with 1s spill duration & typical 100ns readout times, could accept **50 x 10^6 μ's** / spill
- More stringent limit arise from muons interacting in the last cm's of the muon shield producing $K_S, \Lambda, \boldsymbol{K_L}$. To have < 100 events with the decay products recorded by the detector for the full lifetime of the experiment (2x10^{20} pot), require **< 10^5 μ's** / spill.



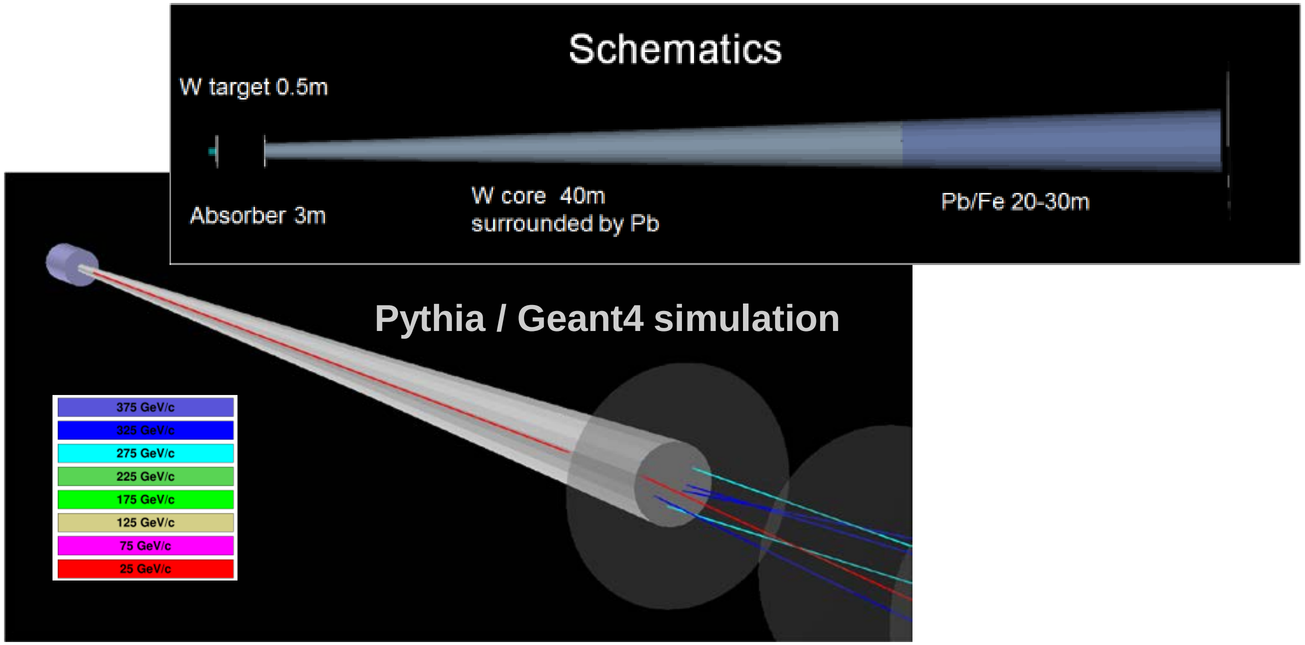
- Two solutions are under study, a pure passive shielding with heavy materials and a mixture of active shielding with dipole magnets and passive shielding.

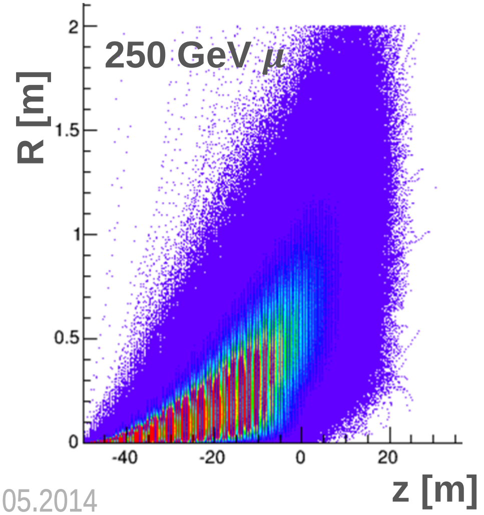
Muon Shield, Passive

- Stop muons through ionization, use dense material to minimize distance to target, 50m ⇒70m, loose 13% in signal acceptance
  - Tungsten first choice
    - Robust and simple, no operational cost
  - Multiple scattering requires increase of volume as function of distance
    - € constraint, add Pb
  - Current baseline, residual muon rate < 10^5 / $5\mathrm{x}10^{13}$ pot 100t W and 2500t Pb

- Ranges

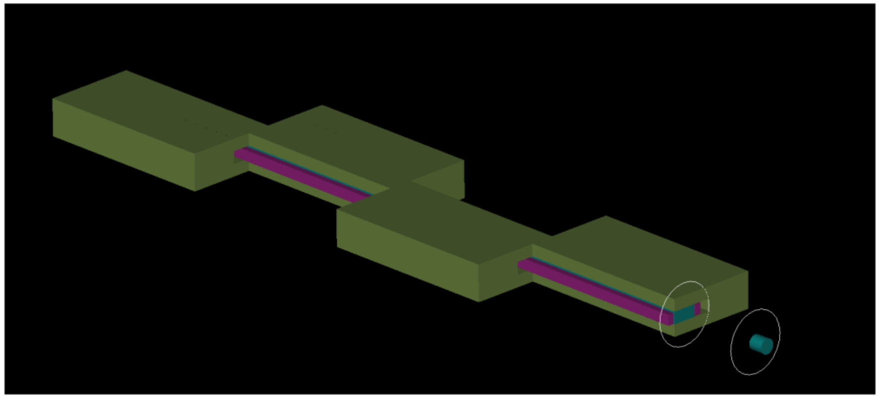
	E_μ = 50GeV	200GeV	400GeV
Ir (22.4 t/m^3):	12.0m	31.8m	46.2m
Os (22.57 t/m^3):	11.9m	31.8m	46.3m
Au (17.3 t/m^3):	13.8m	36.5m	52.9m
U (19 t/m^3):	14.3m	36.8m	52.5m
W (19.3 t/m^3):	13.8m	37.1m	54.0m
Hg (13.5 t/m^3):	19.6m	51.8m	75.1m
Pb (11.3 t/m^3):	23.4m	61.5m	89.0m
Ag (10.5 t/m^3):	23.8m	69.4m	107m
Cu (8.96 t/m^3):	27.2m	85m	137m
Fe (7.87 t/m^3):	30.3m	96.2m	157m
Concrete:	86.7m	300m	540m
H_20:	192.3m	680m	1243m

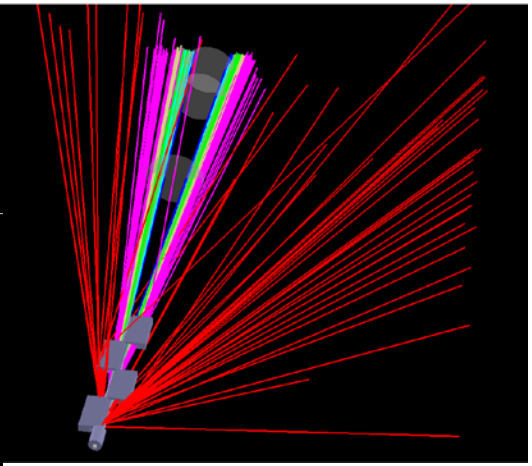


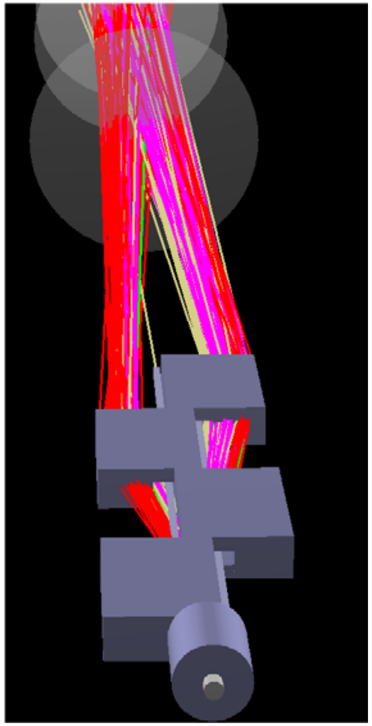


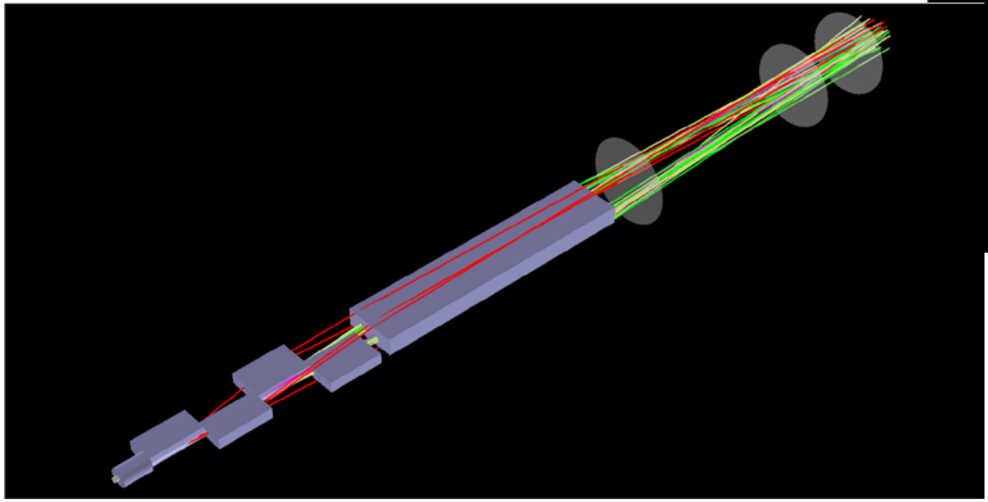
Muon Shield, Active

- Use magnetic field to deflect muons
  - Need ≈ 30Tm for 350 GeV muons
  - Cheap option, dipole magnets with saturated iron, B_{max}=1.8T, 4(3) x 6m
  - Big problem: return field
  - Need to add passive shield, iron block to stop low momentum muons < 100 GeV
  - Optimizaton ongoing

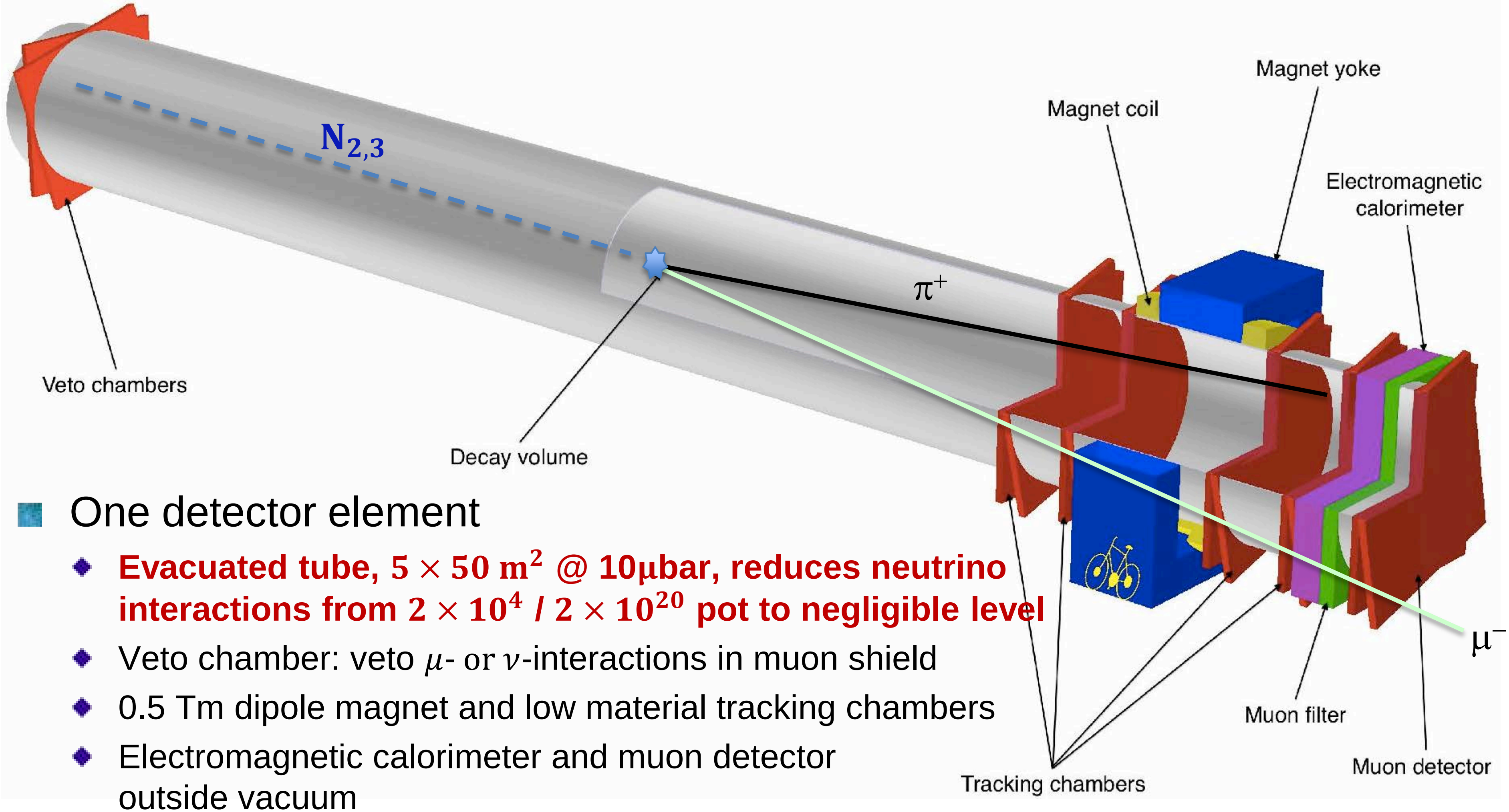






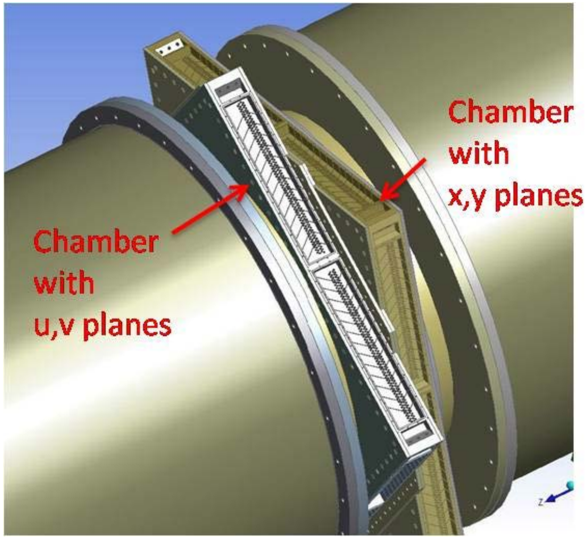


Decay Volume and Spectrometer



- One detector element
  - **Evacuated tube, $5 \times 50\ \mathrm{m}^2$ @ 10μbar, reduces neutrino interactions from 2×10^4 / 2×10^{20} pot to negligible level**
  - Veto chamber: veto μ- or ν-interactions in muon shield
  - 0.5 Tm dipole magnet and low material tracking chambers
  - Electromagnetic calorimeter and muon detector outside vacuum
  - Detector components are based on existing technologies

Vacuum tank and straw tracker
NA62 ($K^+ \rightarrow \pi^+\nu\bar{\nu}$)

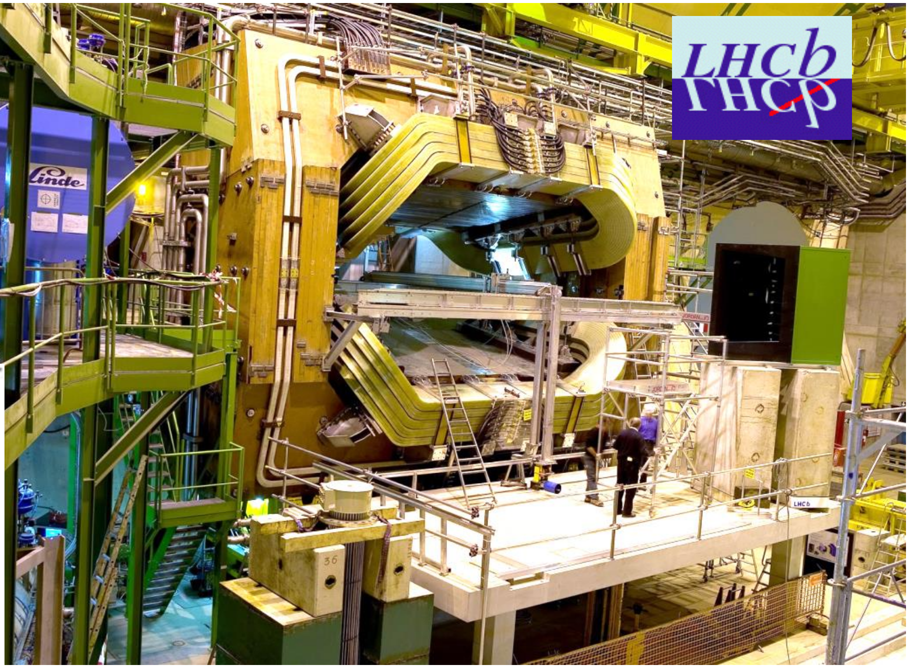


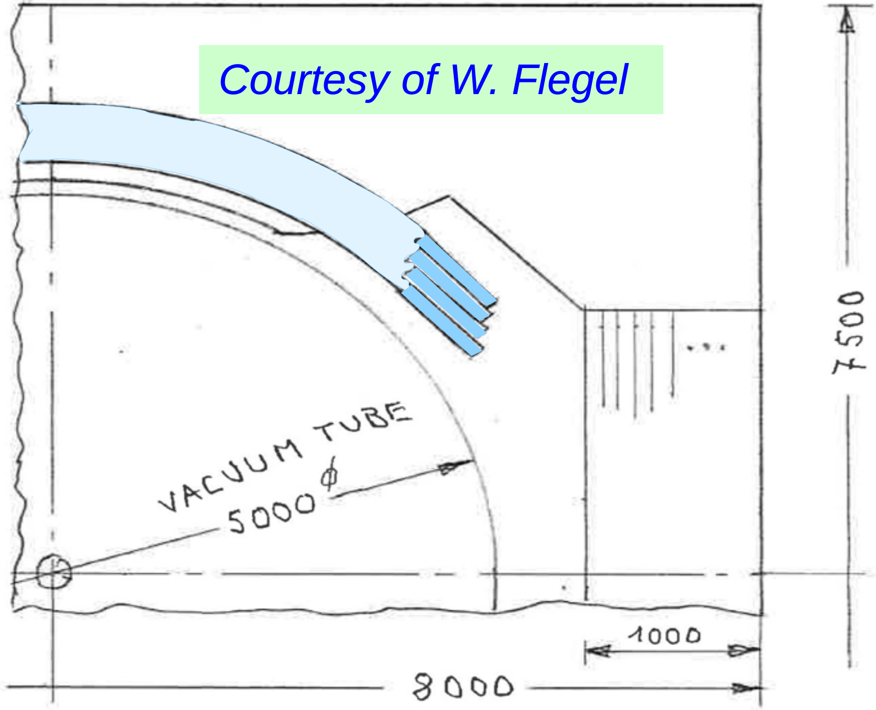
- 2m Ø @ 0.01μbar
- Straw tubes with $120\ \mu\mathrm{m}$ spatial resolution
- $0.5\%\ X/X_0$ for 4 stations
- Demonstrated to work in vacuum

For SHiP, needs to be extrapolated to 5m Ø

Magnet

- Similar to LHCb design but with ~40% less iron and three times less power
- Peak field ~0.2T, integral field of ~0.5 Tm
- Need $\approx 20\mathrm{m}^2$ aperture, LHCb has $16\mathrm{m}^2$ exit aperture

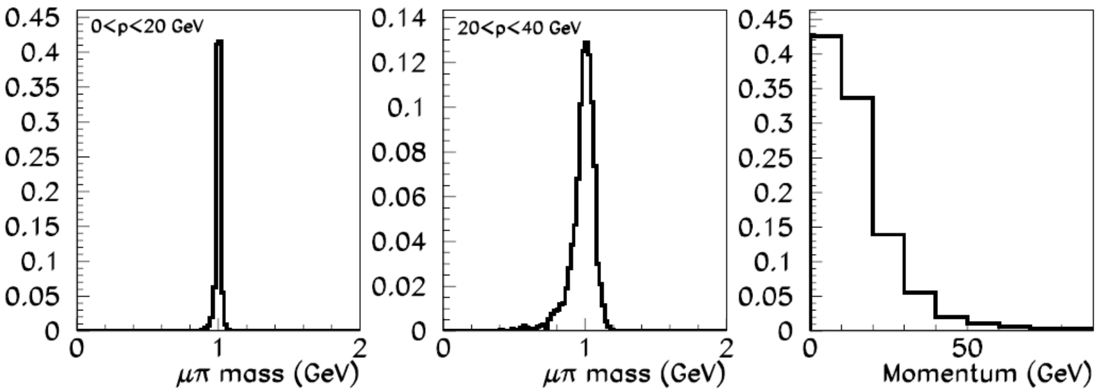



Courtesy of W. Flegel

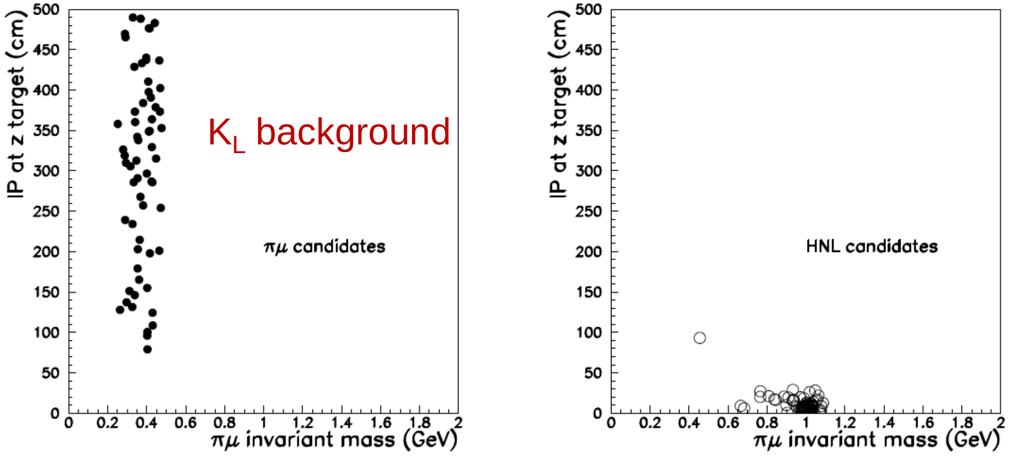
Mass Resolution

- Expected resolution for 1 GeV $\mathbf{N \rightarrow \mu^+\pi^-}$, momentum window for highest momentum track

$\sigma_M \approx 40$ MeV for p < 20 GeV tracks



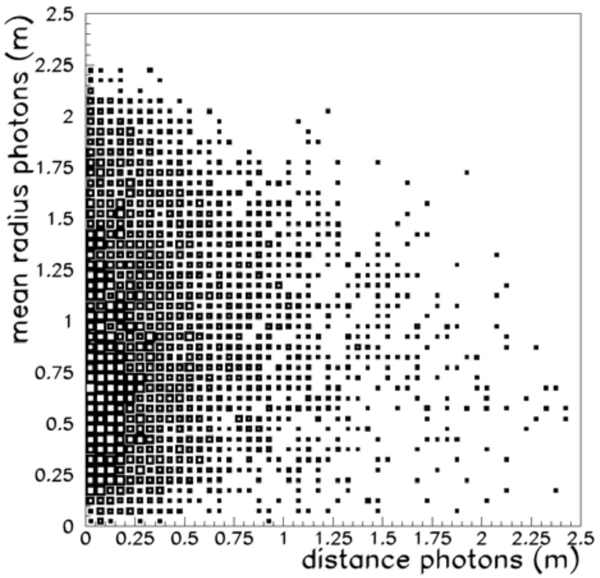
- Pointing requirement for K_L background suppression

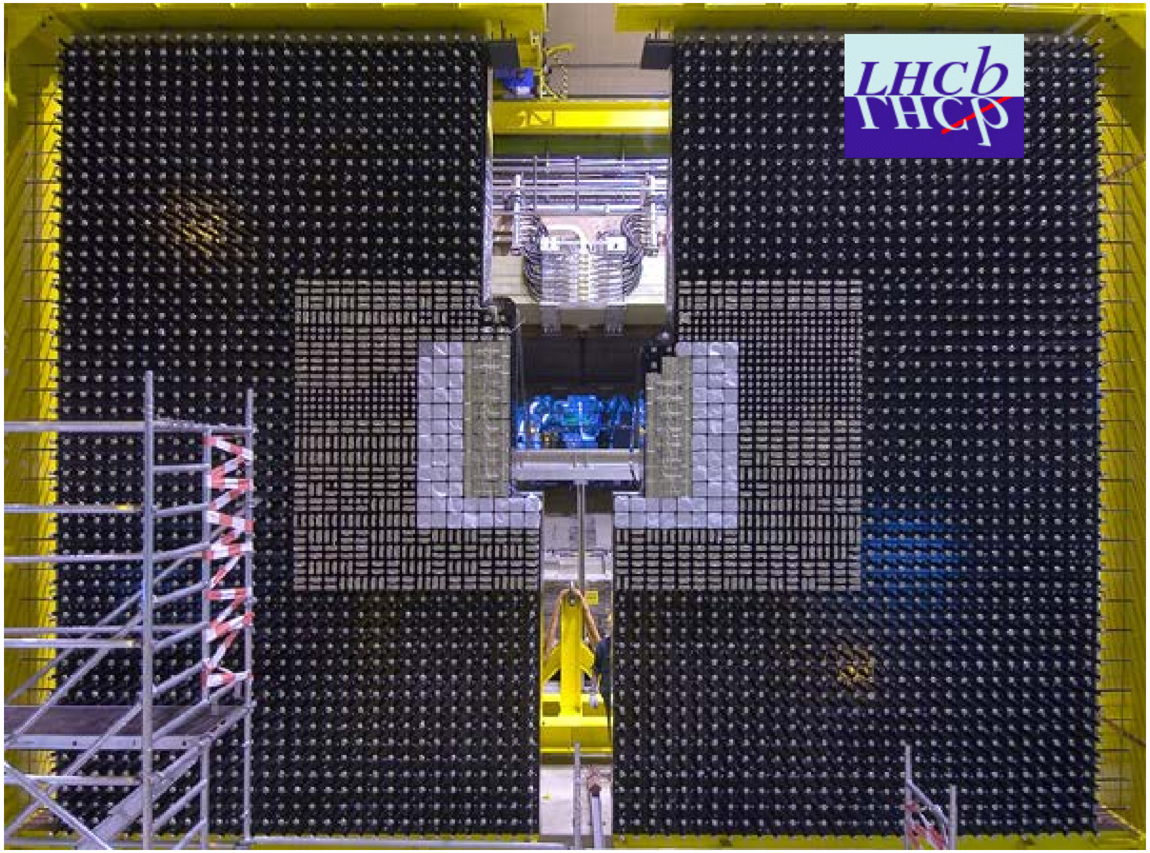


Electromagnetic Calorimeter

- LHCb Shashlik
  - $6.3 \times 7.8\ \mathrm{m}^2$
  - $\frac{\sigma(E)}{E} < 10\%/\sqrt{E} < \oplus\, 1.5\%$
- Larger / better than required

- For $\mathbf{N} \rightarrow \boldsymbol{\mu}^{+}\boldsymbol{\rho}^{-}(\boldsymbol{\pi}^{-}\boldsymbol{\pi}^{0}(\boldsymbol{\gamma\gamma}))$, need small cells $(10 \times 10\ c\mathrm{m}^2)$ everywhere:



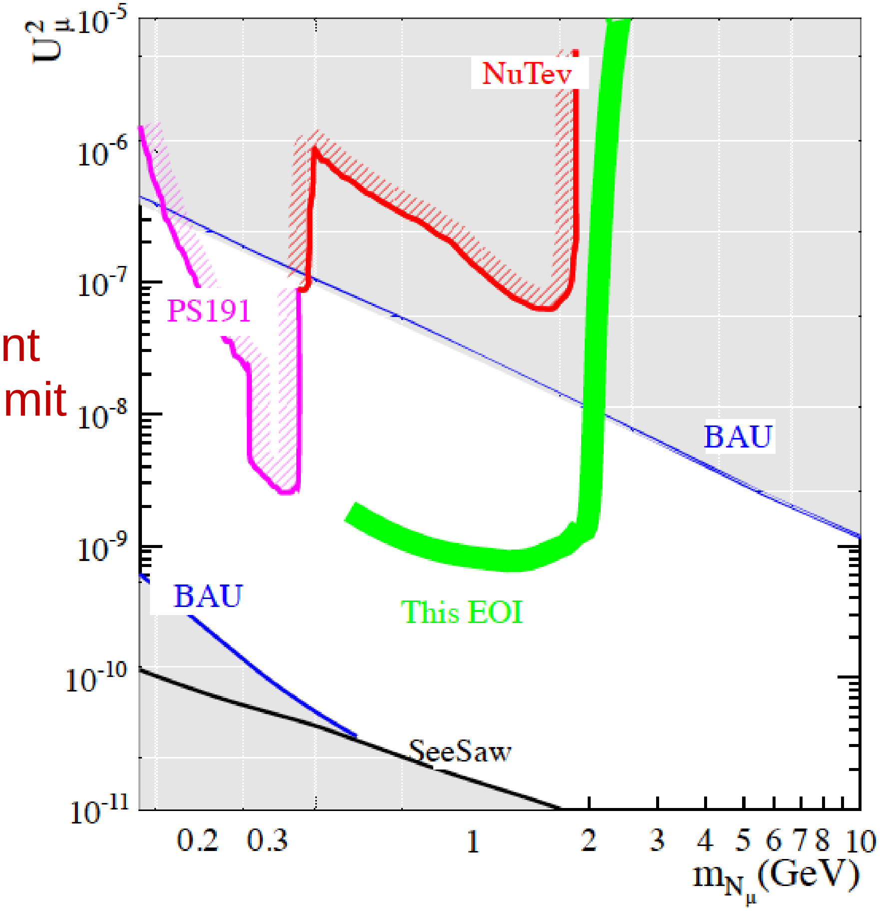


Expected Event Yield

- Only $\mathbf{N_{2,3} \rightarrow \mu^+\pi^-}$
  - 400 GeV, 2×10^{20} pot (3-4yrs)
  - $\mathcal{B}(\mathrm{N} \rightarrow \mu^+\pi^-) = 20\%$
  - $\mathrm{M_N} = 1$ GeV

U_μ^2	$\tau_\mathrm{N}[sec]$	$\mu\pi$ events
10^{-7}	1.8×10^{-5}	12000
10^{-8}	1.8×10^{-4}	120
10^{-9}	1.8×10^{-3}	1

current exp limit



Additional sensitivity by using other decay channels, e.g. $\mathrm{N} \rightarrow \mu^+\rho^-$

For $U_\mu^2 = 10^{-10}$ would need:

- 10x more pot (and/or $> \sqrt{s}$)
- **AND** 10x larger acceptance

Status

- Oct'13: Submission of EOI *(CERN-SPSC-2013-024)* and presentation at SPSC
  - 4 referees assigned, came with a list of questions, answers delivered in Jan'14
- Jan'14: SPSC discussed our proposal and recognized the interesting physics potential. Endorsement to proceed towards technical design report, **with broader physics programme and stronger collaboration**.
- Feb'14: CERN management has set-up task force (machine & engineering departements + experiment)
  - **"Deliver report including the layout and the resources which are required to set-up the experiment and the calendar."**

- **In the meantime ...**

Proto-collaboration formed: Search for Hidden Particles

SHiP

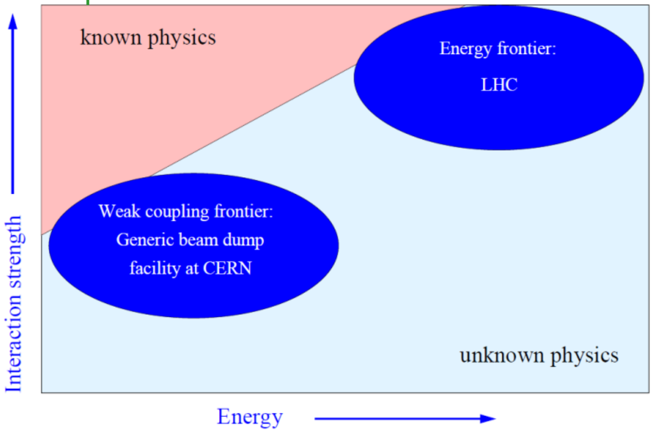
Search for Hidden Particles

Physics case for a general beam dump facility

- Different portals to hidden sector
  - **Vector**: para-photon, secluded photon
  - **Higgs**: dark scalar
  - **Axion**: pseudo-scalars**,** axion like particles
  - **Neutrino: Heavy Neutral Leptons**

Where is new physics?

Mikhail Shaposhnikov
https://indico.cern.ch/event/300293/

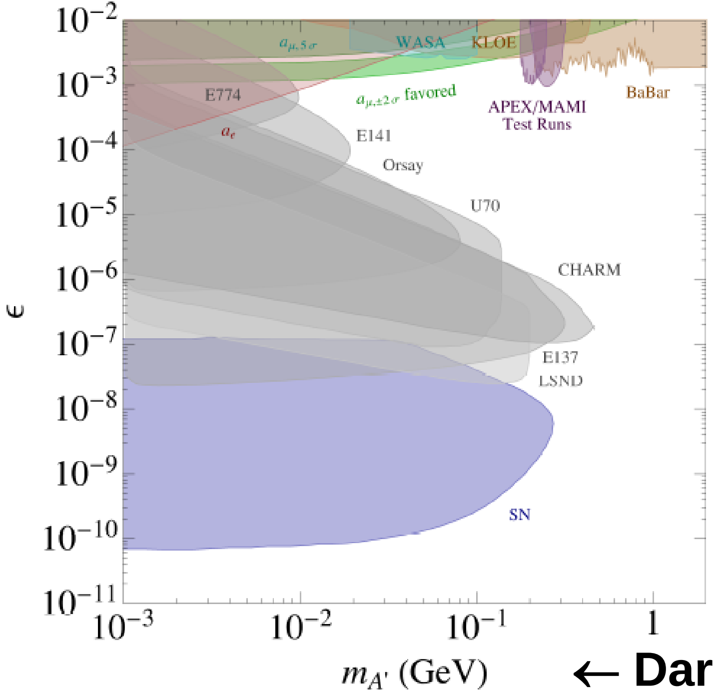


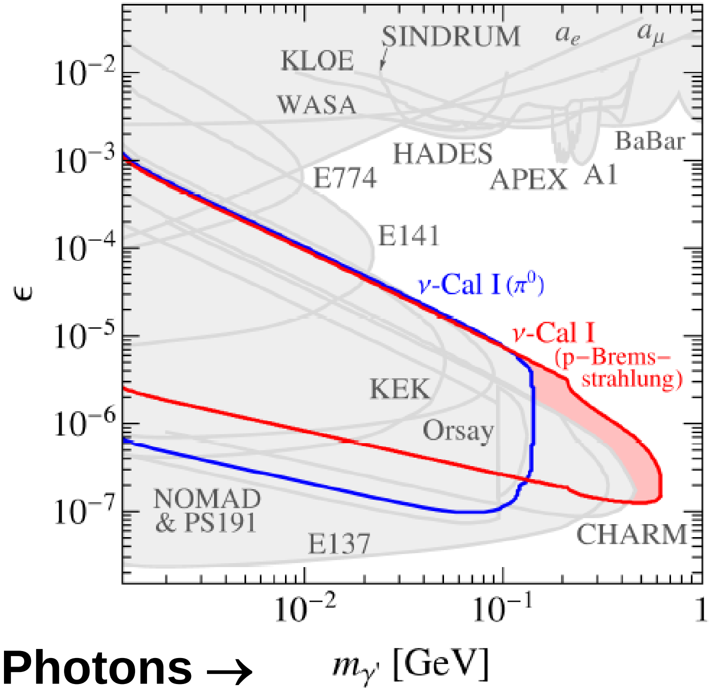
- Long lived weakly interacting particles:
  - Heavy masses, O(100 GeV): ATLAS and CMS via missing E_T
  - Small masses, O(1-10 GeV), direct observation,
    large couplings = short lifetimes (~1ns) : LHCb, meson-factories
  - **Small masses, O(1GeV), small couplings = long lifetimes: SHiP**
- **The SHiP beam dump experiment is complimentary to new particle searches at colliders, in the parameter space relevant for cosmology.**

Vector Portal

- Okun, Voloshin, Ellis, Schwarz, Tyupkin, Kolb, Seckel, Turner, Georgi,Ginsparg, Glashow, Foot, Volkas, Blinnikov, Khlopov, Gninenko,Ignatiev, Berezhiani,..
- Holdom, Galison, Manohar, Arkani-Hamed, Weiner, Schuster, Essig, Pospelov, Toro, Batell, Ritz, Andreas, Goodsell, Abel, Khoze,Ringwald, Fayet, Cheung, Ruderman, Wang, Yavin, Morrissey, Poland, Zurek, Reece, Wang, ...

A' → Standard Model





← Dark Photons →

arXiv:1311.0029, Adrian et al, arXiv:1311.3870, Bluemlein et al.

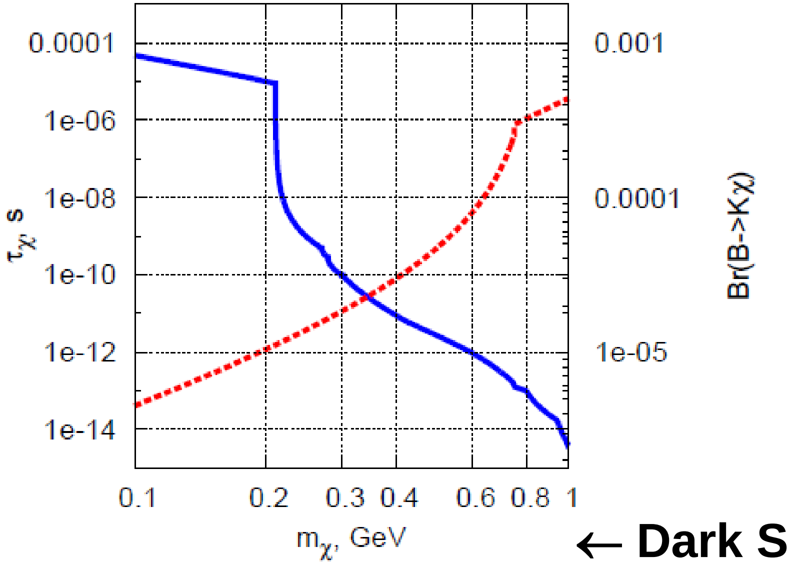
Mikhail Shaposhnikov
CERN Theory Seminar, 9th April 2014

This constrains can be greatly improved by SHiP

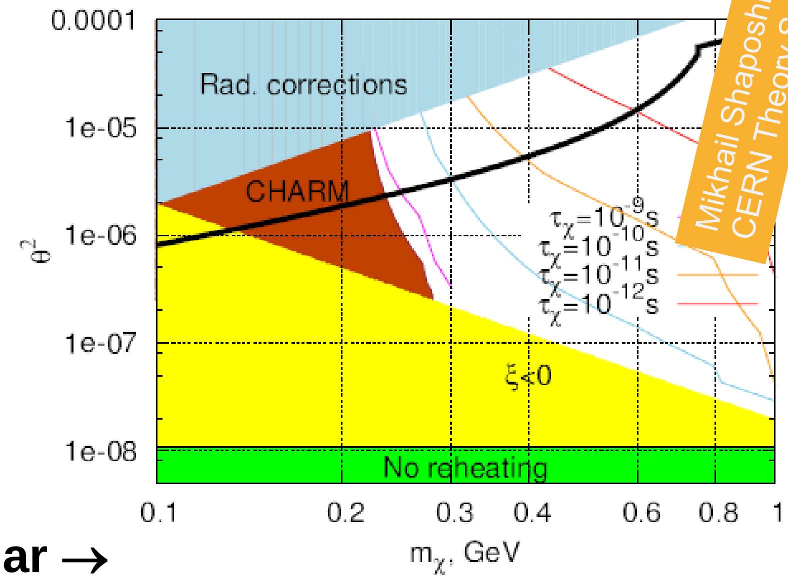
Higgs Portal

- Patt, Wilczek, Schabinger, Wells, No, Ramsey-Musolf, Walker, Khoze, Ro, Choi, Englert, Zerwas, Lebedev, Mambrini, Lee, Jaeckel, Everett, Djouadi, Falkowski, Schwetz, Zupan, Tytgat, Pospelov, Batell, Ritz, Bezrukov, Gorbunov, Gunion, Haber, Kane, Dawson,...

Mikhail Shaposhnikov
CERN Theory Seminar, 9th April 2014



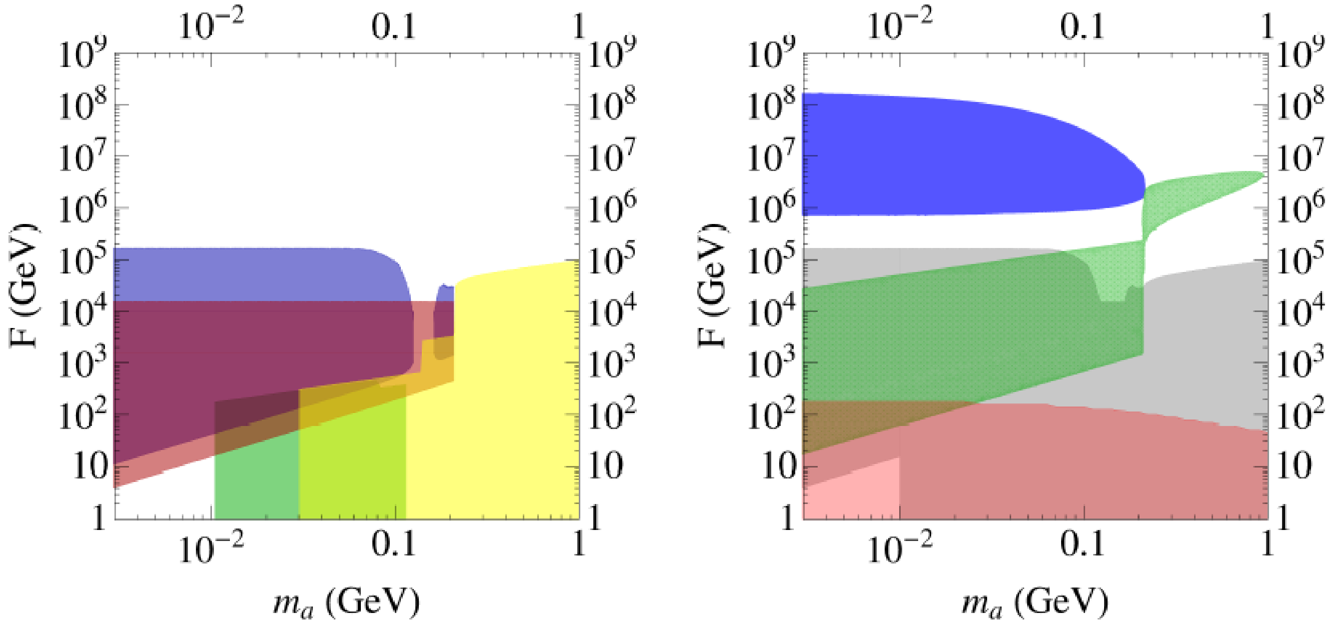
← **Dark Scalar** →



This constrains can be greatly improved by SHiP

Axion Portal

- Weinberg, Wilczek, Witten, Conlon, Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell, Cicoli, Goodsell, Ringwald, Lazarides, Shafi, Choi, Essig, Harnik, Kaplan, Toro, Gorbunov,...



Mikhail Shaposhnikov
CERN Theory Seminar, 9th April 2014

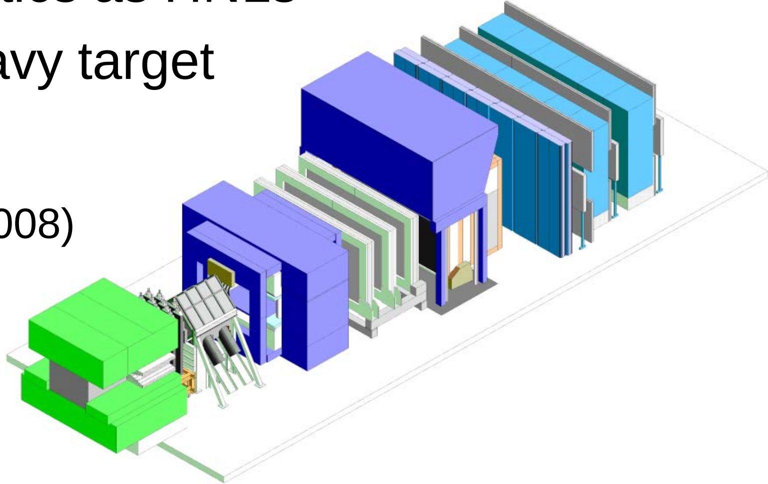
Left: $K^+ \to \text{anything} + e^+e^-$ (green); $K^+ \to \pi^+ +$ invisible (blue); $B^+ \to K^+ l^+ l^-$ (yellow) ($l = e, \mu$); $B^+ \to K^+ +$ invisible (red).

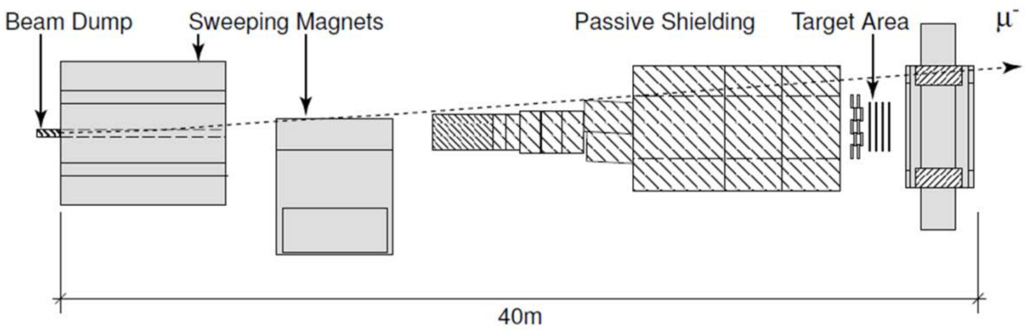
Right: Gray: the combined exclusion region from meson decays; green: CHARM; blue: supernova SN 1987a; red: muon anomalous magnetic moment.

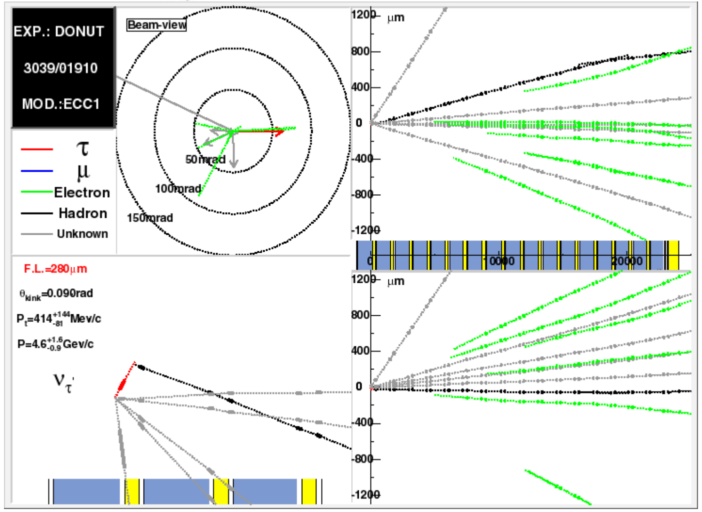
This constrains can be greatly improved by SHiP

Extended Physics Program

- Beam dump also ideal for the study of $\boldsymbol{\nu_\tau}$ scattering
  - $\boldsymbol{\nu_\tau}$ produced in $\mathbf{D_s}$ decays, similar kinematics as HNLs
  - $\boldsymbol{\nu_e}$ and $\boldsymbol{\nu_\mu}$ background is suppressed, heavy target
  - $\boldsymbol{\nu_\tau}$ factory with lowest background
- Experimental status: **DONUT**, PR D 78, 052002 (2008)
  - 3.6×10^{17} pot, 800 GeV,
    260 kg emulsion ν-target
  - 9 candidates, including 1.5 background

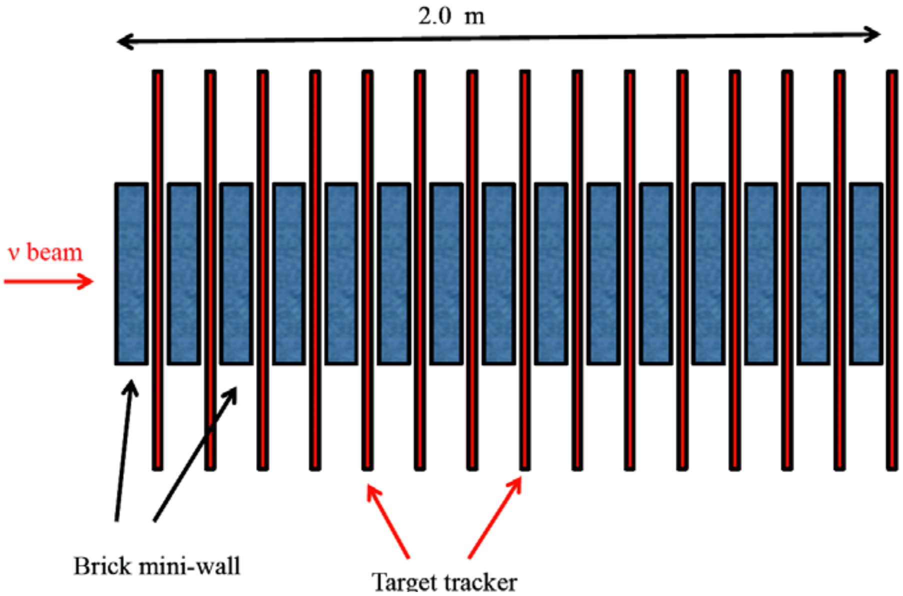






ν_τ Physics with 2×10^{20}pot

- With same ν-target mass as DONUT, will get 20x more CC events
- Can increase ν-target mass "easily" these days, 3% of OPERA



- Only small space required along beam-line, almost no loss for HNL physics
- HNL spectrometer used as forward spectrometer for ν-physics program
- ν-target tracker can be used as Veto against K_L induced background
- Expect 1500-2000 reconstructed CC ν_τ interactions
- In addition: $5 \times \nu_\mu$ CC charm events than CHORUS (2k)

NEXT

SHiP
Search for Hidden Particles

FIRST SHIP WORKSHOP

10 - 12 - JUNE - 2014 - ZÜRICH

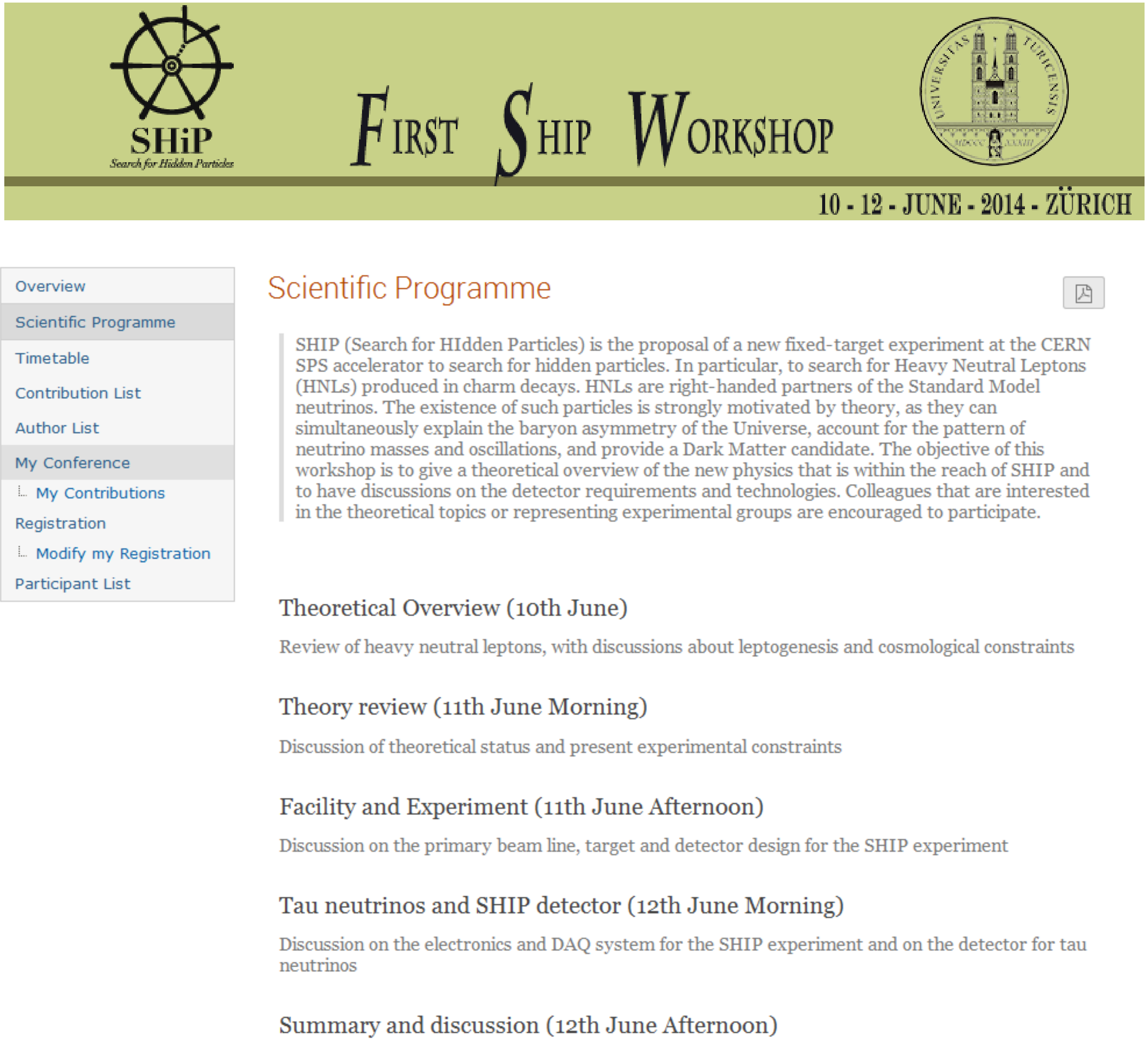
- Home
- Committees
- Scientific Program
- Accommodation
- Social Program
- Registration
- Timetable
- 1st Bulletin

News:

Registrations are now open!

SHIP (Search for HIdden Particles) is a new beam dump experiment at the SPS. It looks for very weakly interacting long lived particles including heavy neutral leptons - right-handed partners of the active neutrinos; light supersymmetric particles - sgoldstinos, etc; scalar, axion and vector portals to the hidden sector.

The objective of this meeting is to give a theoretical overview of the new physics that is within the reach of SHIP and to have discussions on the detector requirements and technologies. Colleagues that are interested in the theoretical topics or representing experimental groups are encouraged to participate.



Scientific Programme

> SHIP (Search for HIdden Particles) is the proposal of a new fixed-target experiment at the CERN SPS accelerator to search for hidden particles. In particular, to search for Heavy Neutral Leptons (HNLs) produced in charm decays. HNLs are right-handed partners of the Standard Model neutrinos. The existence of such particles is strongly motivated by theory, as they can simultaneously explain the baryon asymmetry of the Universe, account for the pattern of neutrino masses and oscillations, and provide a Dark Matter candidate. The objective of this workshop is to give a theoretical overview of the new physics that is within the reach of SHIP and to have discussions on the detector requirements and technologies. Colleagues that are interested in the theoretical topics or representing experimental groups are encouraged to participate.

Theoretical Overview (10th June)

Review of heavy neutral leptons, with discussions about leptogenesis and cosmological constraints

Theory review (11th June Morning)

Discussion of theoretical status and present experimental constraints

Facility and Experiment (11th June Afternoon)

Discussion on the primary beam line, target and detector design for the SHIP experiment

Tau neutrinos and SHIP detector (12th June Morning)

Discussion on the electronics and DAQ system for the SHIP experiment and on the detector for tau neutrinos

Summary and discussion (12th June Afternoon)

First Ship Workshop

10 - 12 - JUNE - 2014 - ZÜRICH

Scientific Programm

SHIP (Search for HIdden P
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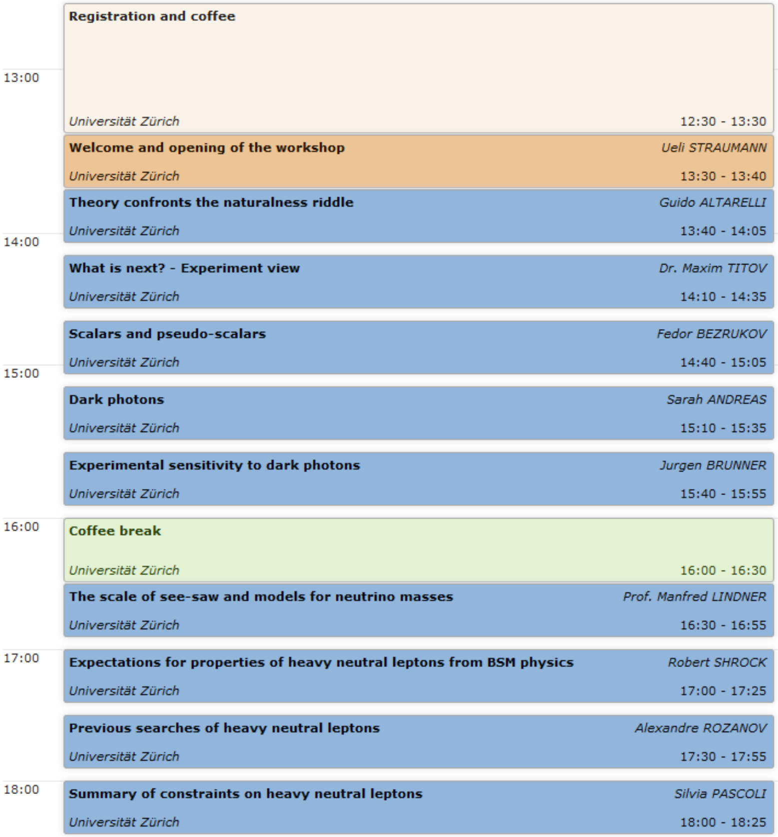
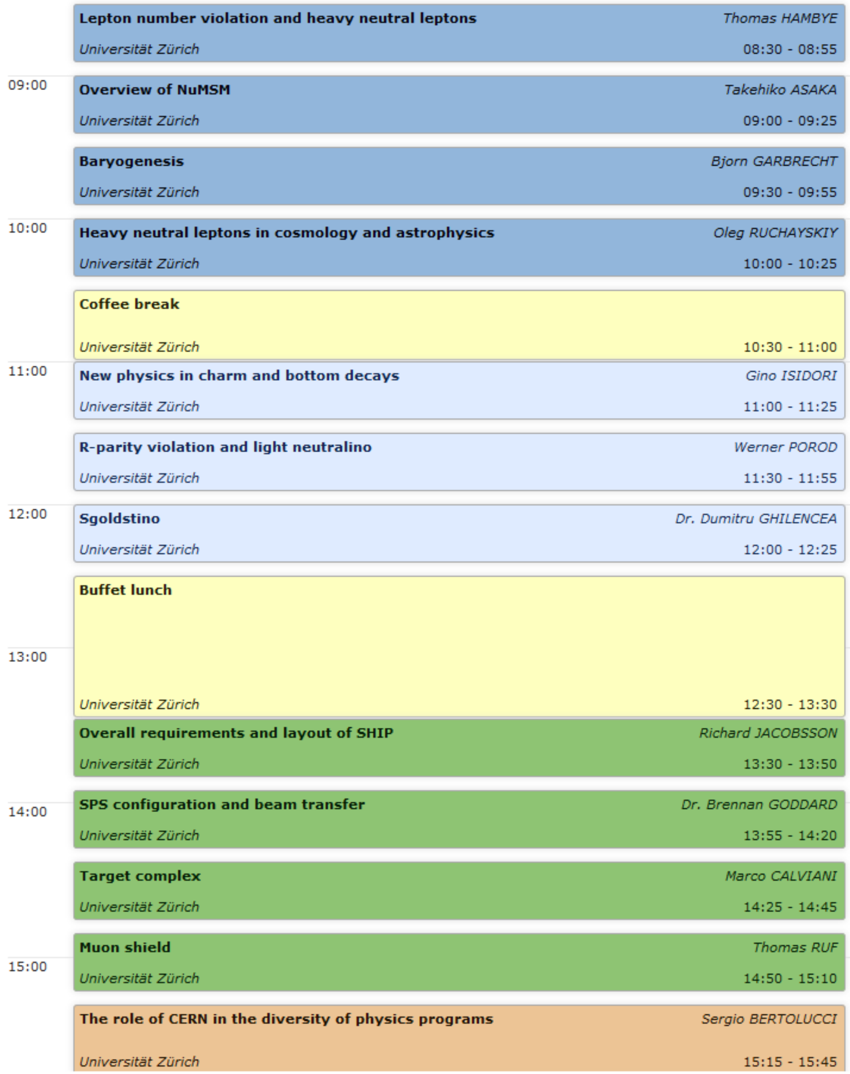


	Title	Speaker	Place	Time
13:00	**Registration and coffee**		*Universität Zürich*	12:30 - 13:30
	Welcome and opening of the workshop	*Ueli STRAUMANN*	*Universität Zürich*	13:30 - 13:40
	Theory confronts the naturalness riddle	*Guido ALTARELLI*	*Universität Zürich*	13:40 - 14:05
14:00	**What is next? - Experiment view**	*Dr. Maxim TITOV*	*Universität Zürich*	14:10 - 14:35
	Scalars and pseudo-scalars	*Fedor BEZRUKOV*	*Universität Zürich*	14:40 - 15:05
15:00	**Dark photons**	*Sarah ANDREAS*	*Universität Zürich*	15:10 - 15:35
	Experimental sensitivity to dark photons	*Jurgen BRUNNER*	*Universität Zürich*	15:40 - 15:55
16:00	**Coffee break**		*Universität Zürich*	16:00 - 16:30
	The scale of see-saw and models for neutrino masses	*Prof. Manfred LINDNER*	*Universität Zürich*	16:30 - 16:55
17:00	**Expectations for properties of heavy neutral leptons from BSM physics**	*Robert SHROCK*	*Universität Zürich*	17:00 - 17:25
	Previous searches of heavy neutral leptons	*Alexandre ROZANOV*	*Universität Zürich*	17:30 - 17:55
18:00	**Summary of constraints on heavy neutral leptons**	*Silvia PASCOLI*	*Universität Zürich*	18:00 - 18:25



	Title	Speaker	Place	Time
	Lepton number violation and heavy neutral leptons	*Thomas HAMBYE*	*Universität Zürich*	08:30 - 08:55
09:00	**Overview of NuMSM**	*Takehiko ASAKA*	*Universität Zürich*	09:00 - 09:25
	Baryogenesis	*Bjorn GARBRECHT*	*Universität Zürich*	09:30 - 09:55
10:00	**Heavy neutral leptons in cosmology and astrophysics**	*Oleg RUCHAYSKIY*	*Universität Zürich*	10:00 - 10:25
	Coffee break		*Universität Zürich*	10:30 - 11:00
11:00	**New physics in charm and bottom decays**	*Gino ISIDORI*	*Universität Zürich*	11:00 - 11:25
	R-parity violation and light neutralino	*Werner POROD*	*Universität Zürich*	11:30 - 11:55
12:00	**Sgoldstino**	*Dr. Dumitru GHILENCEA*	*Universität Zürich*	12:00 - 12:25
13:00	**Buffet lunch**		*Universität Zürich*	12:30 - 13:30
	Overall requirements and layout of SHIP	*Richard JACOBSSON*	*Universität Zürich*	13:30 - 13:50
14:00	**SPS configuration and beam transfer**	*Dr. Brennan GODDARD*	*Universität Zürich*	13:55 - 14:20
	Target complex	*Marco CALVIANI*	*Universität Zürich*	14:25 - 14:45
15:00	**Muon shield**	*Thomas RUF*	*Universität Zürich*	14:50 - 15:10
	The role of CERN in the diversity of physics programs	*Sergio BERTOLUCCI*	*Universität Zürich*	15:15 - 15:45

Time Line

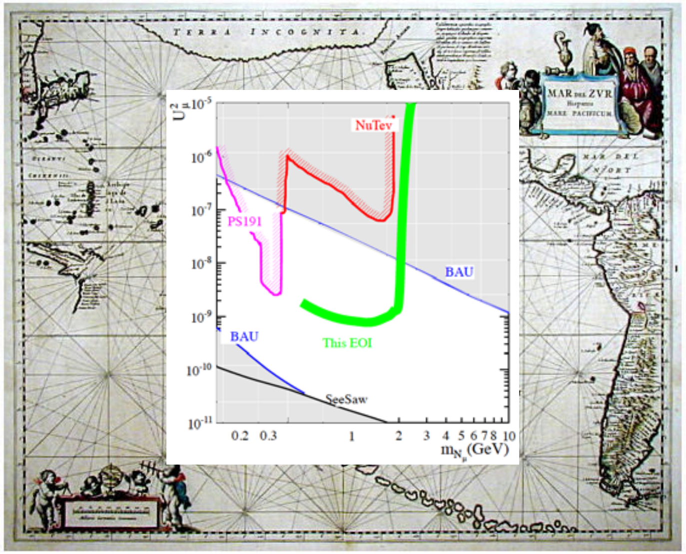
- **June 2014: collaboration kick-off meeting in Zurich**
- **Spring 2015: submission of technical design report**

- 2015-2017: R&D, starting civil engineering
- 2018-19 (LS2): Connection of extraction line to SPS, starting detector installation
- >2020: First beam

Conclusions

- SHiP will explore the unknown territory of very weakly interacting long-lived particles

- Detector is based on existing proven technologies
  - New ideas not excluded



- The impact of HNL discovery on particle physics is difficult to overestimate!
  - The origin of the baryon asymmetry of the Universe
  - The nature of Dark Matter
  - The origin of neutrino mass
- CERN directorate has set-up task force to study impact for CERN
- The SHiP collaboration is ready for boarding, first collaboration meeting June 10-12.

Who would like to sign on for the journey ?

Institutes potentiall interested, April'14

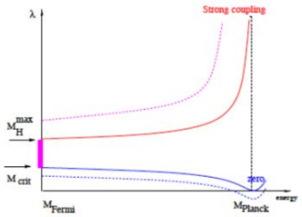
- *European Organization for Nuclear Research (CERN)*
- *Germany:*
  - *Humboldt Universität Berlin, Dresden*
- *France:*
  - *CEA Saclay, APC/LPNHE Universite Paris-Diderot*
- *Italy:*
  - *Instituto Nazionale di Fisica Nucleare (INFN)*
- *Netherlands:*
  - *National Institute for Subatomic Physics (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*

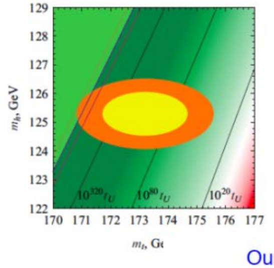
Backups

Higgs/Top/Vacuum stability

The main LHC result: SM is a consistent effective theory all the way up to the Planck scale

- No signs of new physics beyond the SM are seen
- $M_H < 175$ GeV : SM is a weakly coupled theory up to Planck energies
- $M_H > 111$ GeV: Our EW vacuum is stable or metastable with a lifetime greatly exceeding the Universe age. Espinosa et al





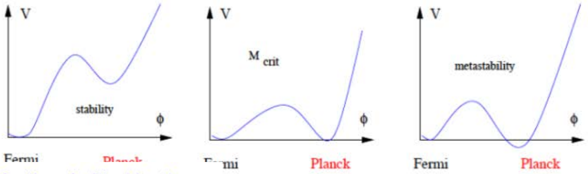
The mass of the Higgs boson is very close to the stability bound on the Higgs mass* (95'), to the Higgs inflation bound** (08'), and to asymptotic safety value for M_H*** (09'):

$$M_{crit} = [129.3 + \frac{y_t(M_t) - 0.9361}{0.0058} \times 2.0 - \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \times 0.5]\ \mathrm{GeV}$$

$y_t(M_t)$ - top Yukawa in $\overline{\mathrm{MS}}$ scheme

Matching at EW scale	Central value	theor. error
Bezrukov et al, $\mathcal{O}(\alpha\alpha_s)$	129.4 GeV	1.0 GeV
Degrassi et al, $\mathcal{O}(\alpha\alpha_s, y_t^2\alpha_s, \lambda^2, \lambda\alpha_s)$	129.6 GeV	0.7 GeV
Buttazzo et al, complete 2-loop	129.3 GeV	0.07 GeV

Chetyrkin et al, Mihaila et al, Bednyakov et al, 3 loop running to high energies



* Froggatt, Nielsen

** Bezrukov et al, De Simone et al

*** Wetterich, MS

Cosmology: theory – p. 2
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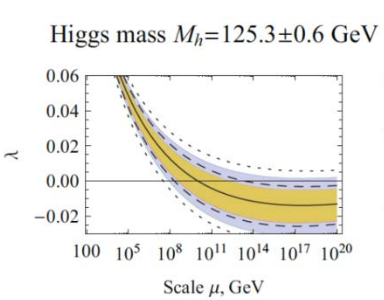
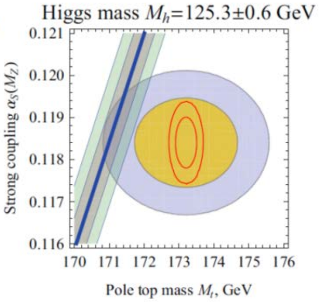
Our vacuum may be absolutely stable - this is perfectly admitted by the present data:





A.Golutvin / D.Gorbunov

errors in y_t: theory + experiment

Tevatron: $M_t = 173.2 \pm 0.51 \pm 0.71$ GeV

ATLAS and CMS: $M_t = 173.4 \pm 0.4 \pm 0.9$ GeV

$\alpha_s = 0.1184 \pm 0.0007$

Cosmology: theory – p. 3
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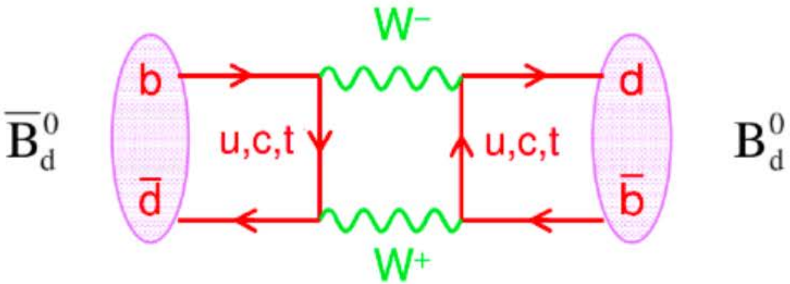
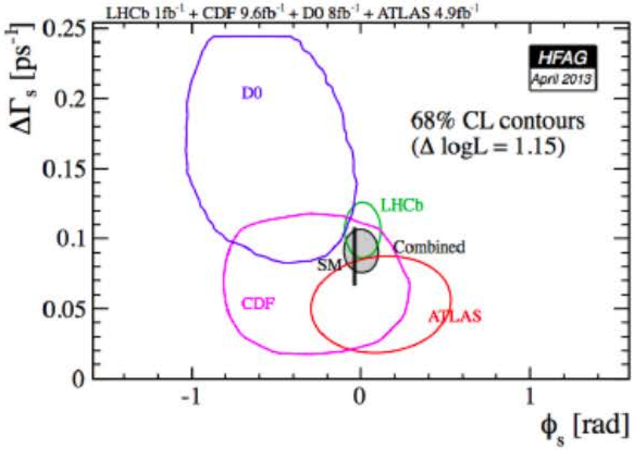
Bounds on the scale of New Physics

Most stringent limits come from observables in $B\bar{B}$ mixing





$$M(B_d - \bar{B}_d) \sim \frac{(y_t^2 V_{tb}^* V_{td})^2}{16\pi^2 m_t^2} + c_{NP}\frac{1}{\Lambda^2}$$

c_{NP}

$$\sim 1 \xrightarrow{\text{tree/strong + generic flavor}} \Lambda \gtrsim 2\times10^4 \text{ TeV [K]}$$

$$\sim 1/(16\pi^2) \xrightarrow{\text{loop + generic flavor}} \Lambda \gtrsim 2\times10^3 \text{ TeV [K]}$$

$$\sim (y_t V_{ti}^* V_{tj})^2 \xrightarrow{\text{tree/strong + “alignment”}} \Lambda \gtrsim 5 \text{ TeV [K \& B]}$$

$$\sim (y_t V_{ti}^* V_{tj})^2/(16\pi^2) \xrightarrow{\text{loop + “alignment”}} \Lambda \gtrsim 0.5 \text{ TeV [K \& B]}$$

Type 1 Seesaw Models

SHiP

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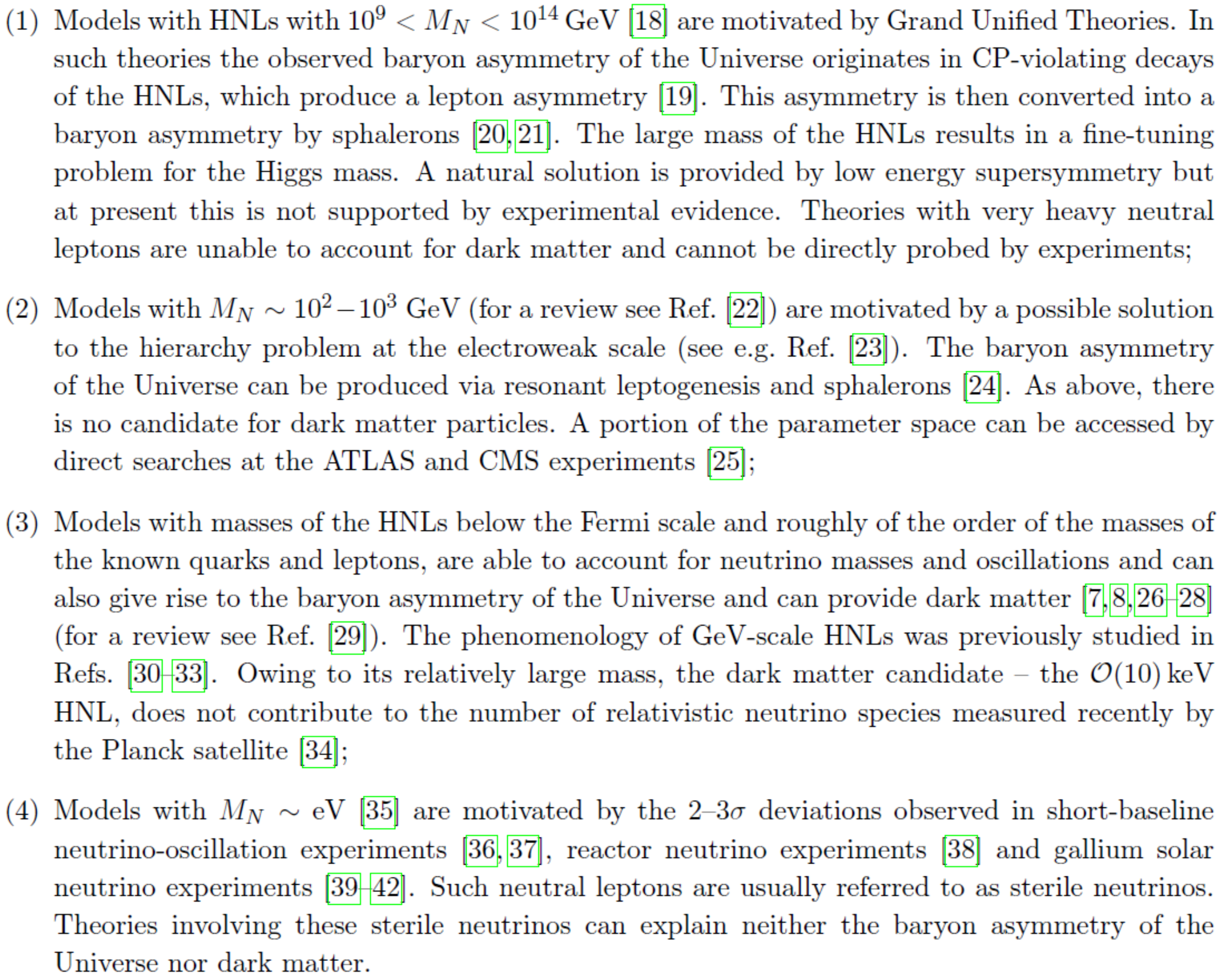

(1) Models with HNLs with $10^9 < M_N < 10^{14}$ GeV [18] are motivated by Grand Unified Theories. In such theories the observed baryon asymmetry of the Universe originates in CP-violating decays of the HNLs, which produce a lepton asymmetry [19]. This asymmetry is then converted into a baryon asymmetry by sphalerons [20, 21]. The large mass of the HNLs results in a fine-tuning problem for the Higgs mass. A natural solution is provided by low energy supersymmetry but at present this is not supported by experimental evidence. Theories with very heavy neutral leptons are unable to account for dark matter and cannot be directly probed by experiments;

(2) Models with $M_N \sim 10^2 - 10^3$ GeV (for a review see Ref. [22]) are motivated by a possible solution to the hierarchy problem at the electroweak scale (see e.g. Ref. [23]). The baryon asymmetry of the Universe can be produced via resonant leptogenesis and sphalerons [24]. As above, there is no candidate for dark matter particles. A portion of the parameter space can be accessed by direct searches at the ATLAS and CMS experiments [25];

(3) Models with masses of the HNLs below the Fermi scale and roughly of the order of the masses of the known quarks and leptons, are able to account for neutrino masses and oscillations and can also give rise to the baryon asymmetry of the Universe and can provide dark matter [7, 8, 26–28] (for a review see Ref. [29]). The phenomenology of GeV-scale HNLs was previously studied in Refs. [30–33]. Owing to its relatively large mass, the dark matter candidate – the $\mathcal{O}(10)$ keV HNL, does not contribute to the number of relativistic neutrino species measured recently by the Planck satellite [34];

(4) Models with $M_N \sim$ eV [35] are motivated by the 2–3σ deviations observed in short-baseline neutrino-oscillation experiments [36, 37], reactor neutrino experiments [38] and gallium solar neutrino experiments [39–42]. Such neutral leptons are usually referred to as sterile neutrinos. Theories involving these sterile neutrinos can explain neither the baryon asymmetry of the Universe nor dark matter.

cc and bb x-sections

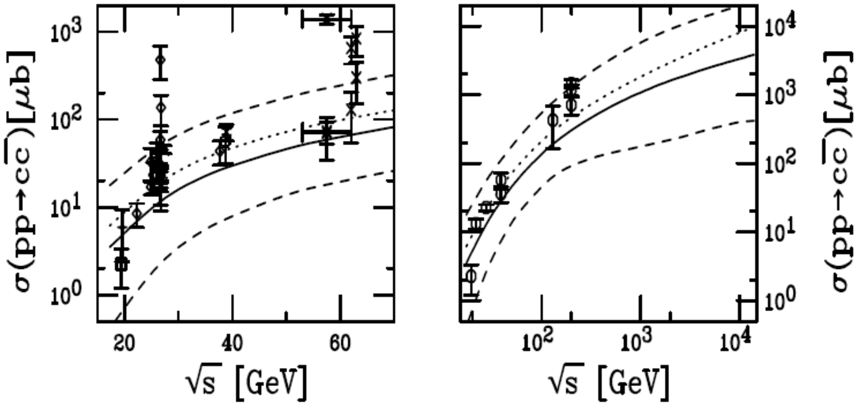

Fig. 2. The NLO total $c\bar{c}$ cross sections as a function of $\sqrt{S}$ for $\sqrt{S} \leq 70$ GeV (left-hand side) and up to 14 TeV (right-hand side) calculated with the CTEQ6M parton densities. The solid curve is the central result; the upper and lower dashed curves are the upper and lower edges of the uncertainty band. The dotted curves are calculations with $m = 1.2$ GeV, $\mu_F = \mu_R = 2m$.

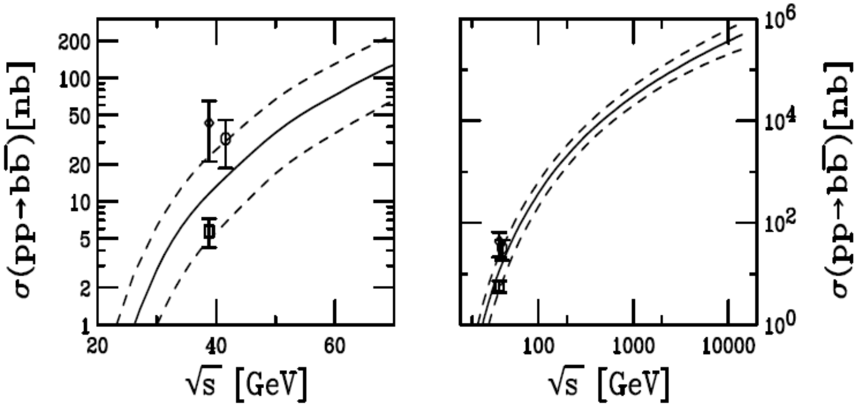

Fig. 3. The NLO total $b\bar{b}$ cross sections as a function of $\sqrt{S}$ for $\sqrt{S} \leq 70$ GeV (left-hand side) and up to 14 TeV (right-hand side) calculated with the CTEQ6M parton densities. The solid curve is the central result; the upper and lower dashed curves are the upper and lower edges of the uncertainty band.

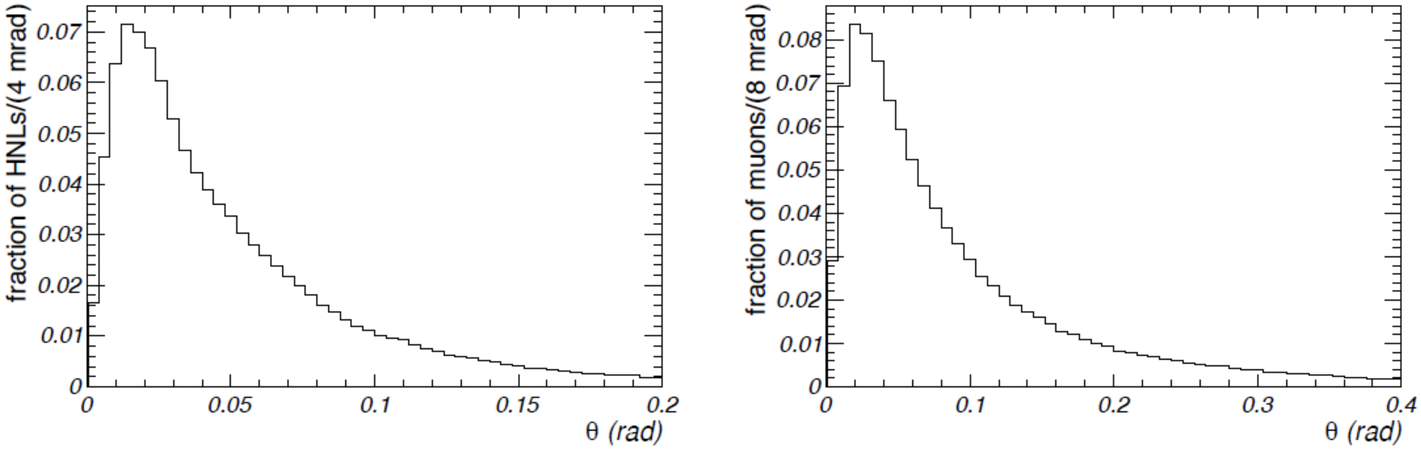

Figure 5: Polar angle distribution (left) of the HNLs and (right) of the muons and pions from the decay $N \to \mu^- \pi^+$ in simulated HNL decays with $M_N = 1$ GeV.

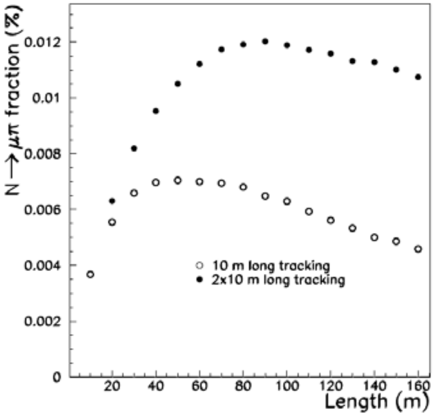

Figure 8: Fraction of HNL in the detector acceptance as a function of the length of the fiducial volume. Open circles: a single spectrometer following a fiducial volume of a given length. Full circles: two spectrometers in series, each following a fiducial volume of half the given length. The spectrometer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