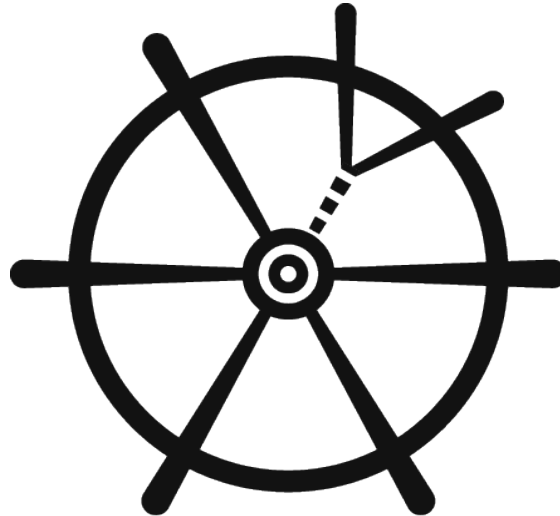


Search for long-lived, very weakly interacting particles - the proposed beamdump facility at the CERN SPS

Heiko Lacker, HU Berlin

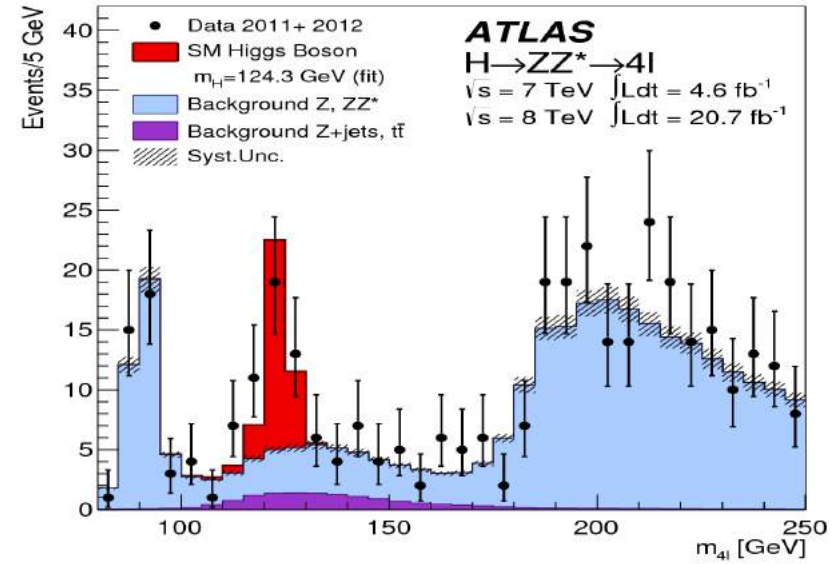
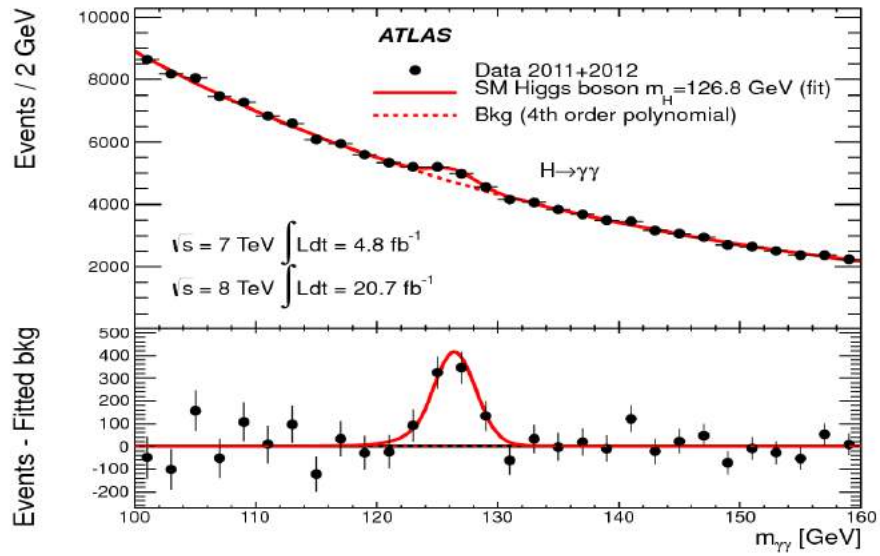
Dresden, 16.11.2017



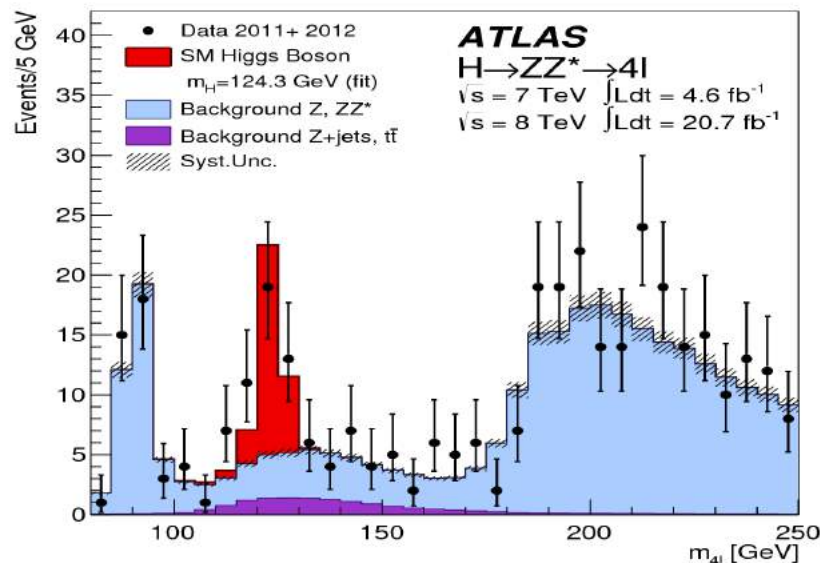
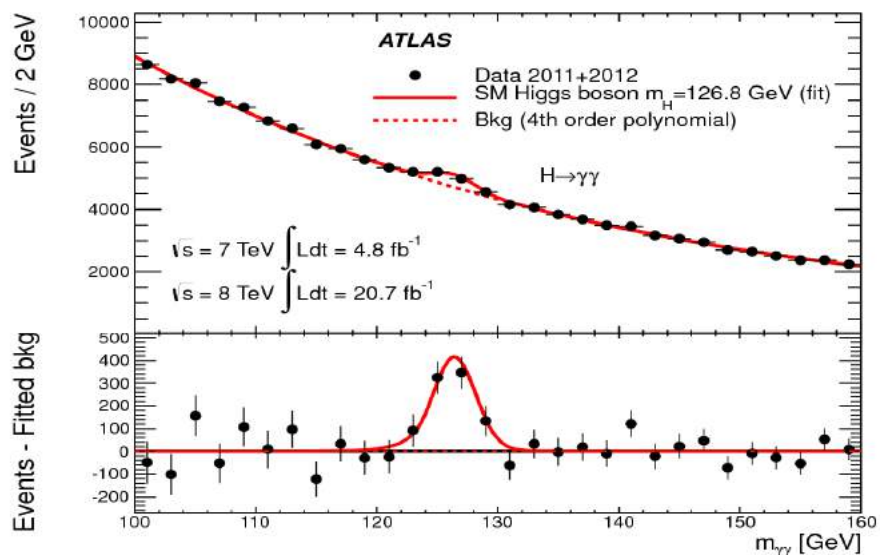
SHiP

Search for Hidden Particles

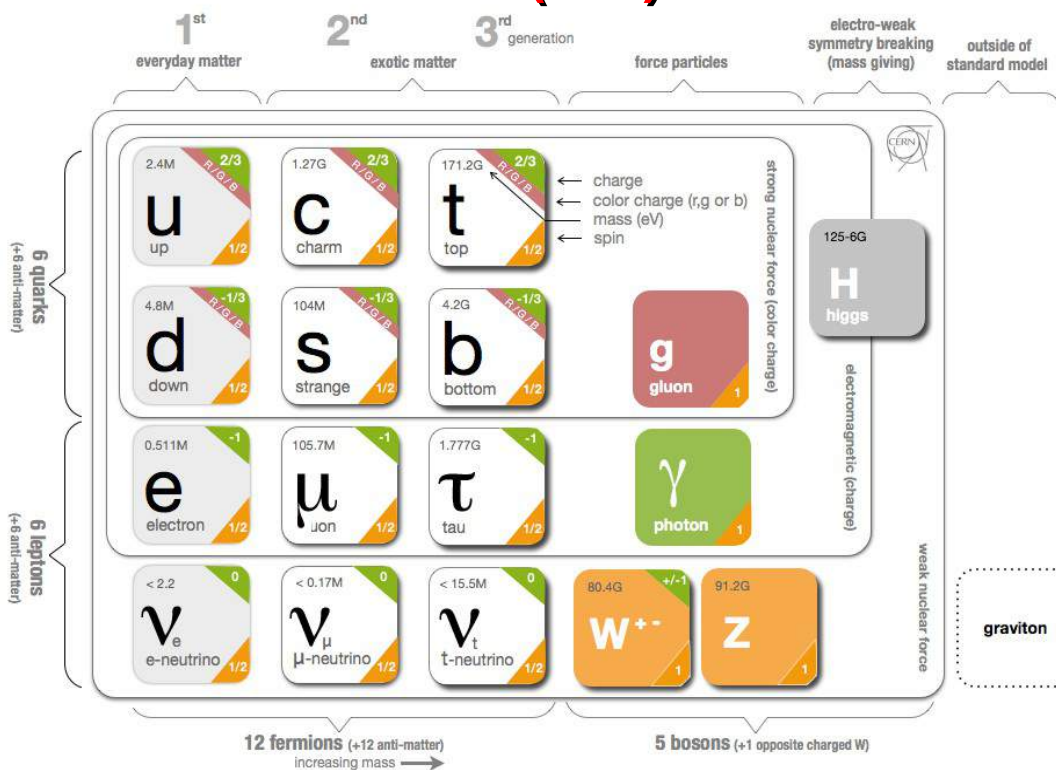
Higgs-boson discovery (2012): a scientific breakthrough



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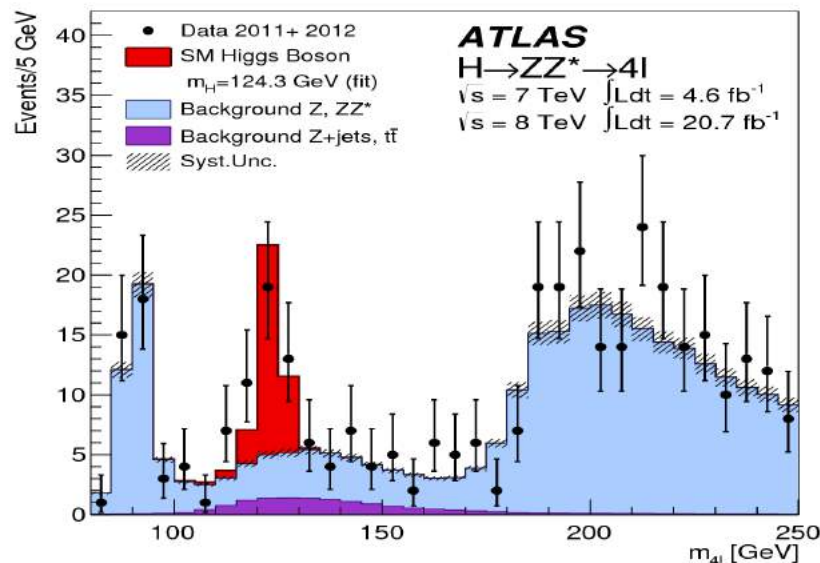
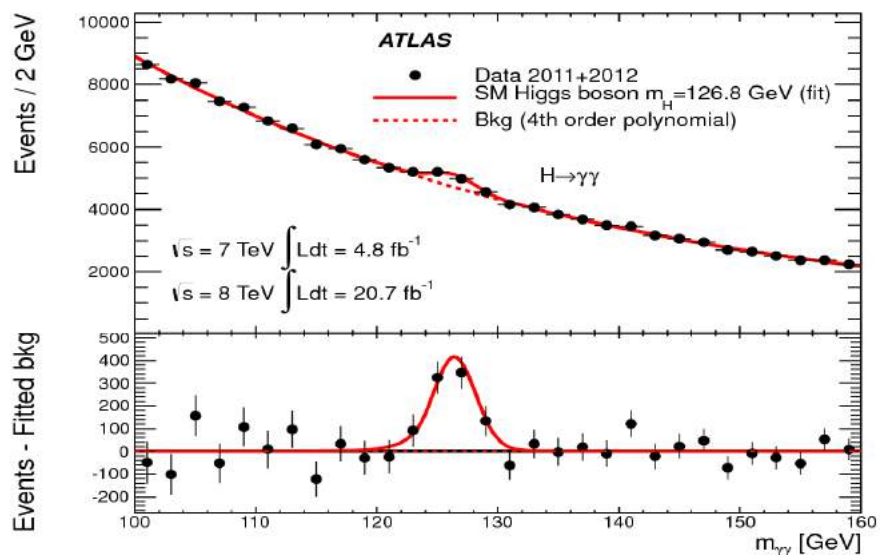


Standard Model (SM) of elementary particles physics “complete”:

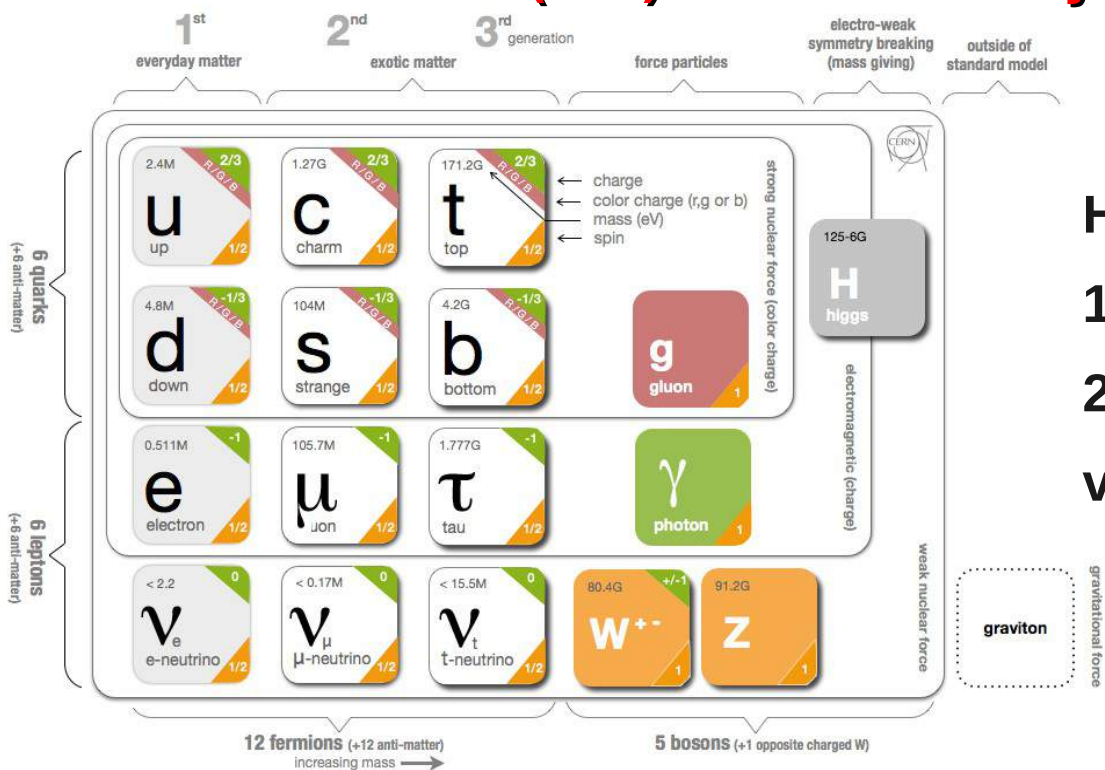


- Higgs mechanism gives masses to
1. W/Z bosons
 2. charged leptons & quarks
- via spontaneous symmetry breaking

Higgs-boson discovery (2012): a scientific breakthrough



Standard Model (SM) of elementary particles physics “complete”:



Higgs mechanism gives masses to

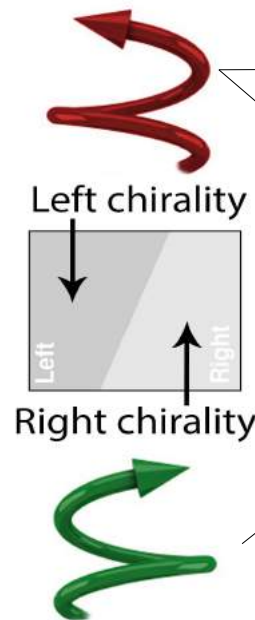
1. W/Z bosons,
2. charged leptons & quarks

via spontaneous symmetry breaking

However:

SM does not explain (tiny) neutrino masses

| | | | |
|---------|--|--|--|
| | 2.4 MeV $\frac{2}{3}$ u up Right | 1.27 GeV $\frac{2}{3}$ c charm Right | 171.2 GeV $\frac{2}{3}$ t top Right |
| Quarks | 4.8 MeV $-\frac{1}{3}$ d down Right | 104 MeV $-\frac{1}{3}$ s strange Right | 4.2 GeV $-\frac{1}{3}$ b bottom Right |
| | <0.0001 eV 0 ν_e electron neutrino Right | ~ 0.01 eV 0 ν_μ muon neutrino Right | ~ 0.04 eV 0 ν_τ tau neutrino Right |
| Leptons | 0.511 MeV -1 e electron Right | 105.7 MeV -1 μ muon Right | 1.777 GeV -1 τ tau Right |



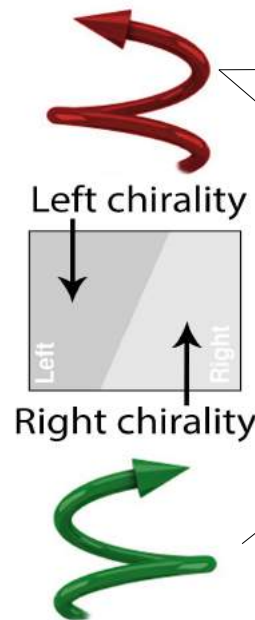
Only left-handed fermions couple weakly to W bosons

Left- & right-handed component needed to generate fermion mass:

$$m_f \bar{\psi}_L \psi_R$$

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| | | | |
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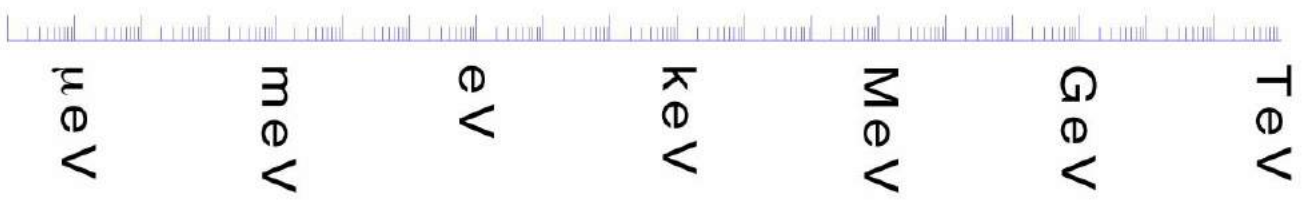
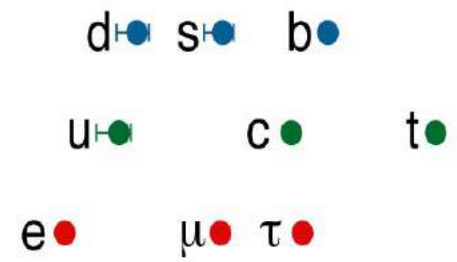
Only left-handed fermions couple weakly to W bosons

Left- & right-handed component needed to generate fermion mass:

$$m_f \bar{\Psi}_L \Psi_R$$

fermion masses

(large angle MSW)



Nobel Prize 2015: "Neutrinos have mass"

How is (tiny) neutrino mass generated:

Higgs mechanism?

Majorana particles?

Baryon-Antibaryon Asymmetry of the Universe (BAU)

Up to now: got off lightly in all “encounters” with other celestial bodies

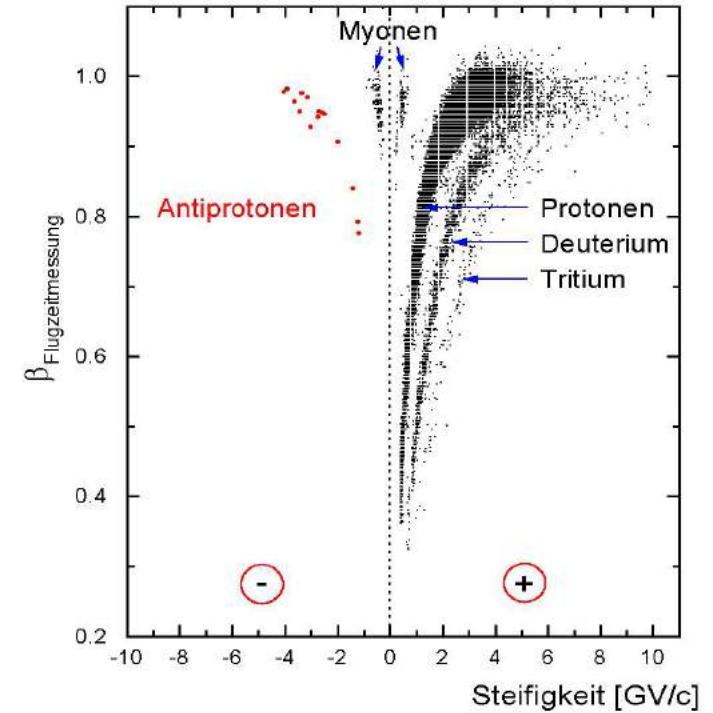
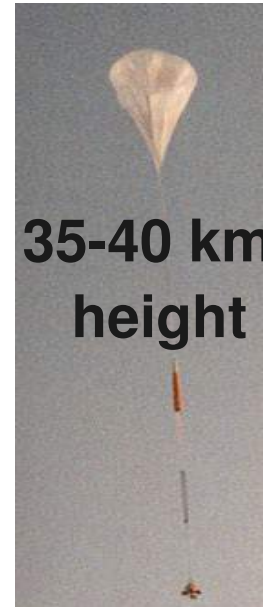


Baryon-Antibaryon Asymmetry of the Universe (BAU)

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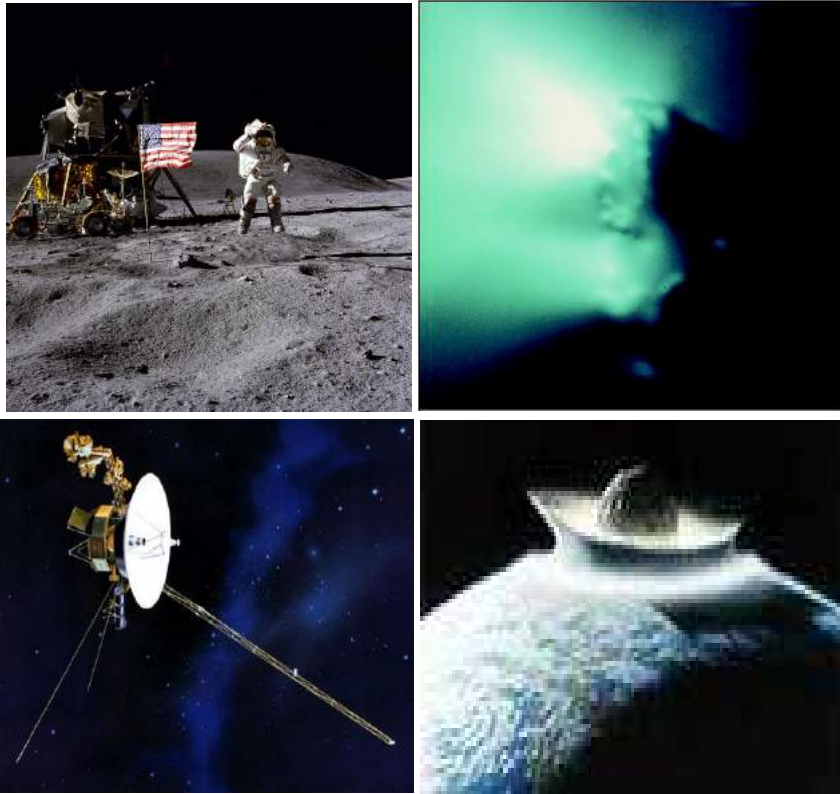


Up to now: no Anti-He in cosmic rays discovered

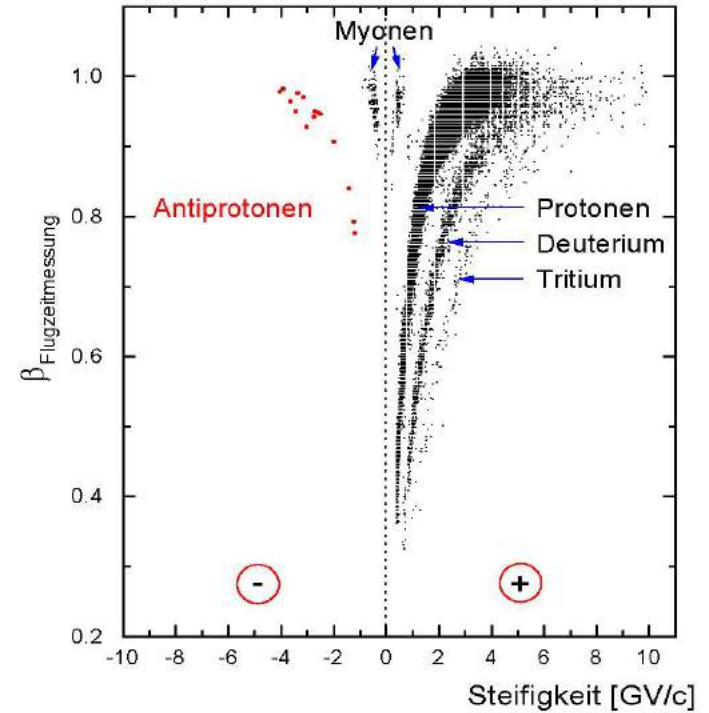


Baryon-Antibaryon Asymmetry of the Universe (BAU)

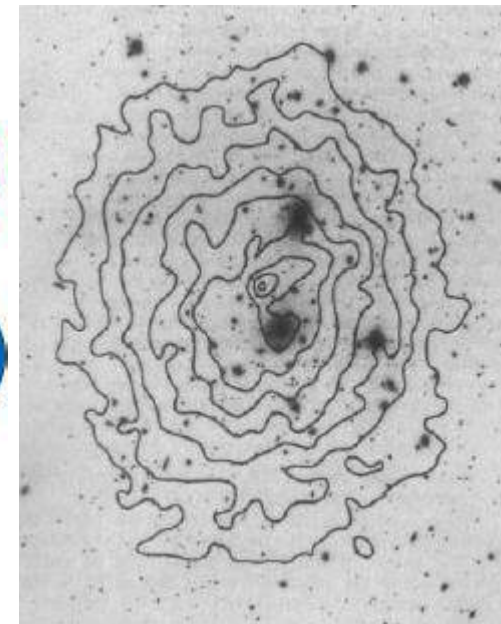
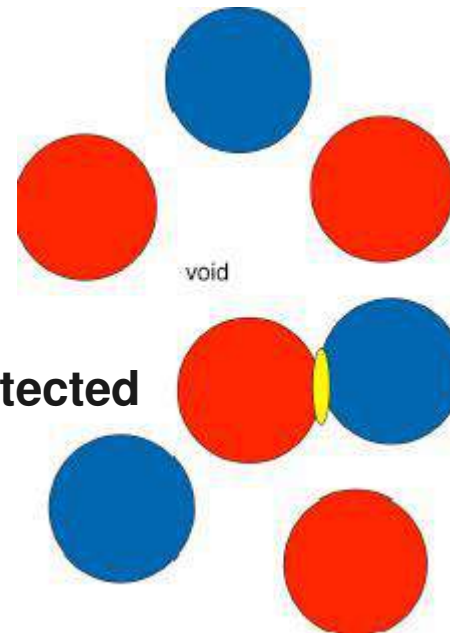
Up to now: got off lightly in all “encounters” with other celestial bodies



Up to now: no Anti-He in cosmic rays discovered



Up to now: no annihilation radiation from galaxy cluster borders (< 600 mio. light yrs) detected



Baryon-Antibaryon Asymmetry of the Universe (BAU)

Sakharov (1967): Dynamical generation possible for processes that:

- 1) violate Baryon Number
- 2) violate C and CP symmetry
- 3) are out of thermal equilibrium



Baryon-Antibaryon Asymmetry of the Universe (BAU)

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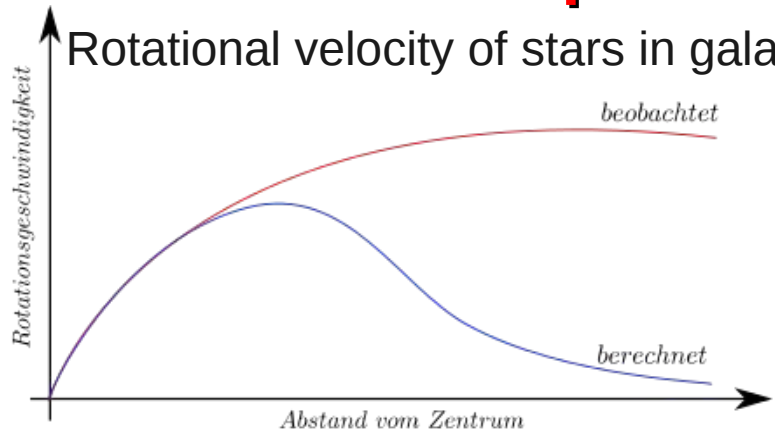


Standard Model fulfills in principle all conditions, but fails quantitatively:

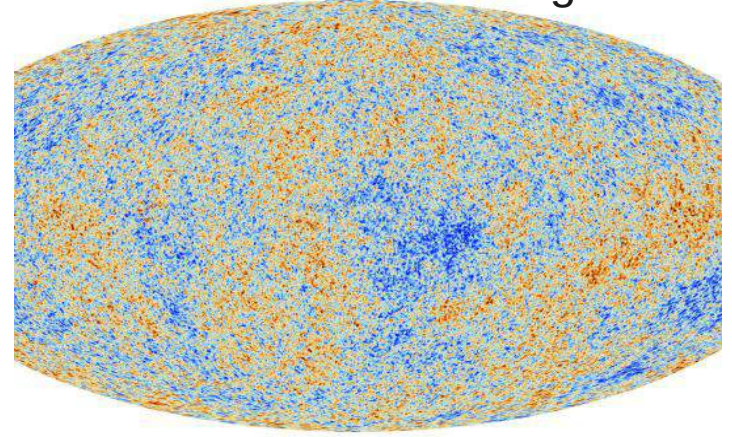
- 2) CP violation many orders of magnitude too small
- 3) fulfilled for $m_{\text{Higgs}} < 70 \text{ GeV}$

SM fails in explaining Dark Matter (DM) (& Dark Energy)

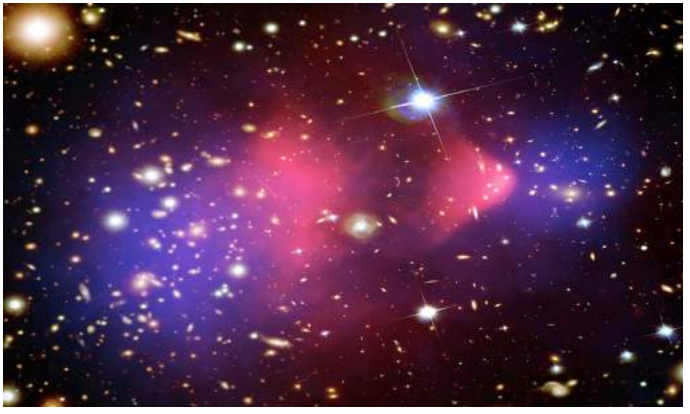
Rotational velocity of stars in galaxies



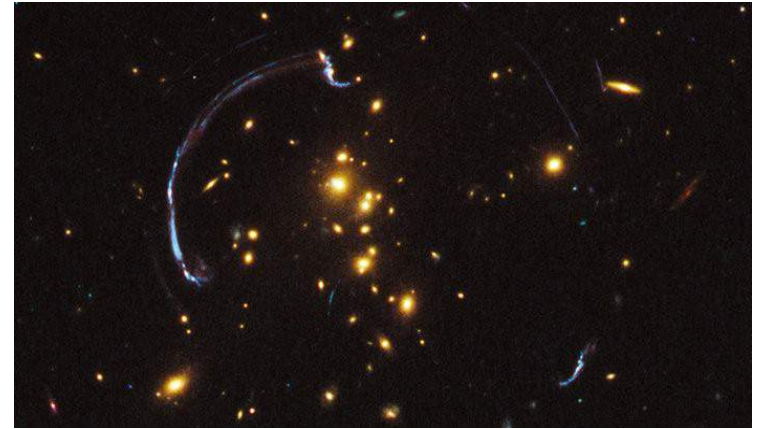
Cosmic Microwave Background



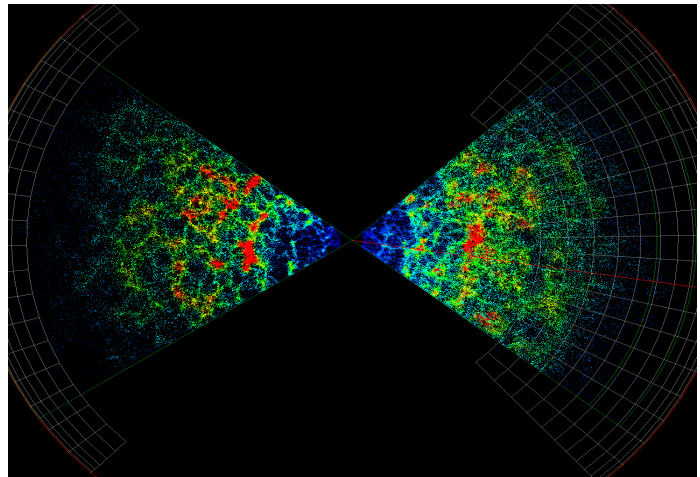
Bullet Cluster



Gravitational Lensing

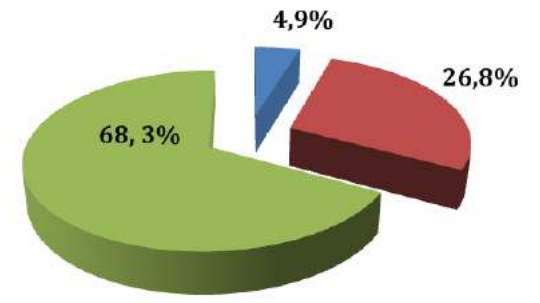


Matter distributions in the universe

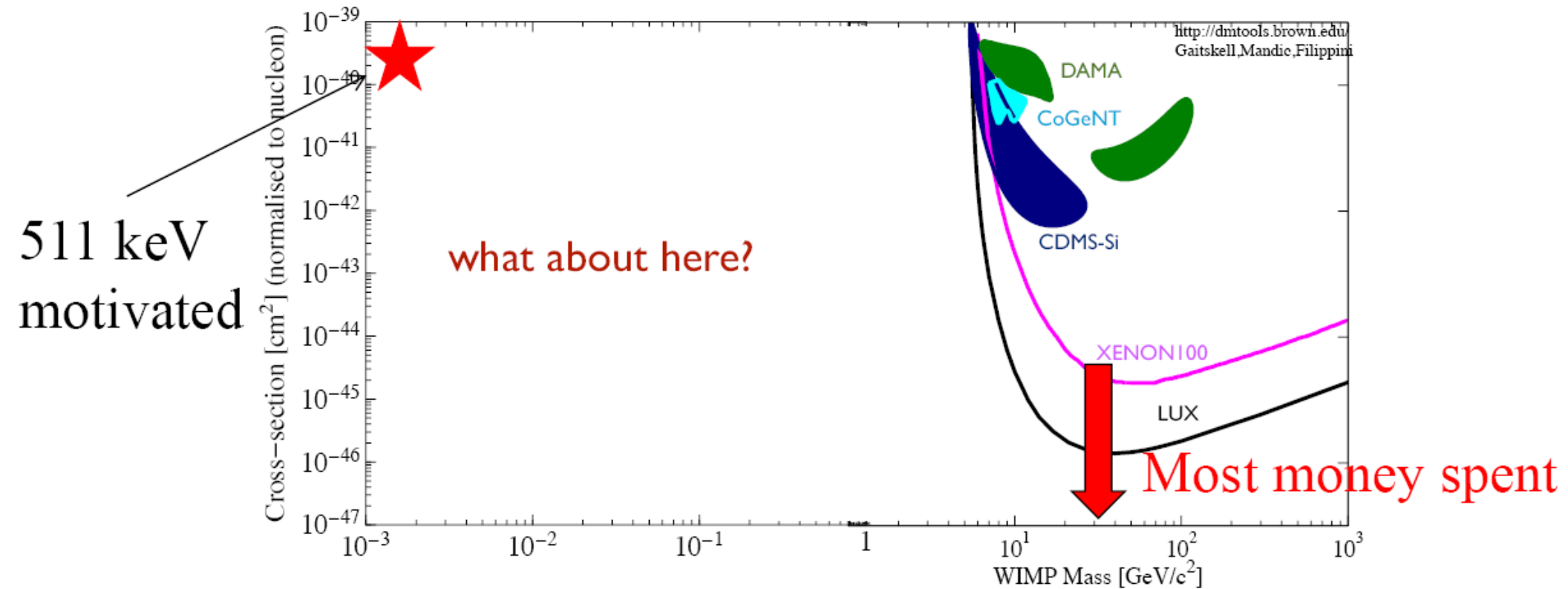


Verteilung der Materie im Universum

■ Sichtbare Materie ■ Dunkle Materie ■ Dunkle Energie



Light DM: Difficult to detect in nuclear-recoil experiments



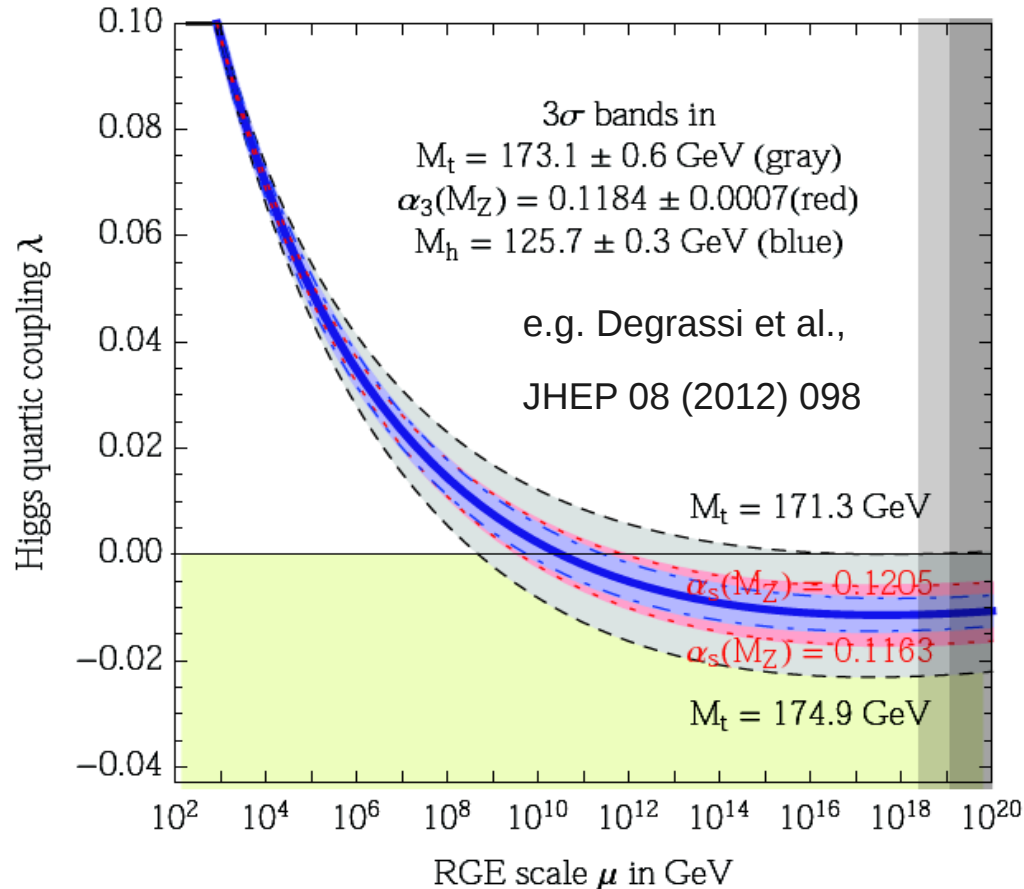
Courtesy: Maxim Pospelov

Theoretical shortcomings of the Standard Model

- * Higgs mechanism w/o dynamical explanation (“deus ex macchina”) (Analogy: Superconductivity w/o Cooper pairs & solid state body)
- * Why $m_{\text{Higgs}} = 126 \text{ GeV}$ and not 10^{19} GeV (Hierarchy problem!?) ?
If a problem: New Physics likely to be found @ TeV scale
- * Origin of Flavour: Why 3 generations?
Masses & mixing patterns of quarks & leptons
- * Strong CP problem
- * Quantization of electric charge
- * Different sizes of interaction couplings
- * What is the quantum field theory of gravity?
- * ...

On the other hand: Standard Model could be a self-consistent theory up to the Planck scale

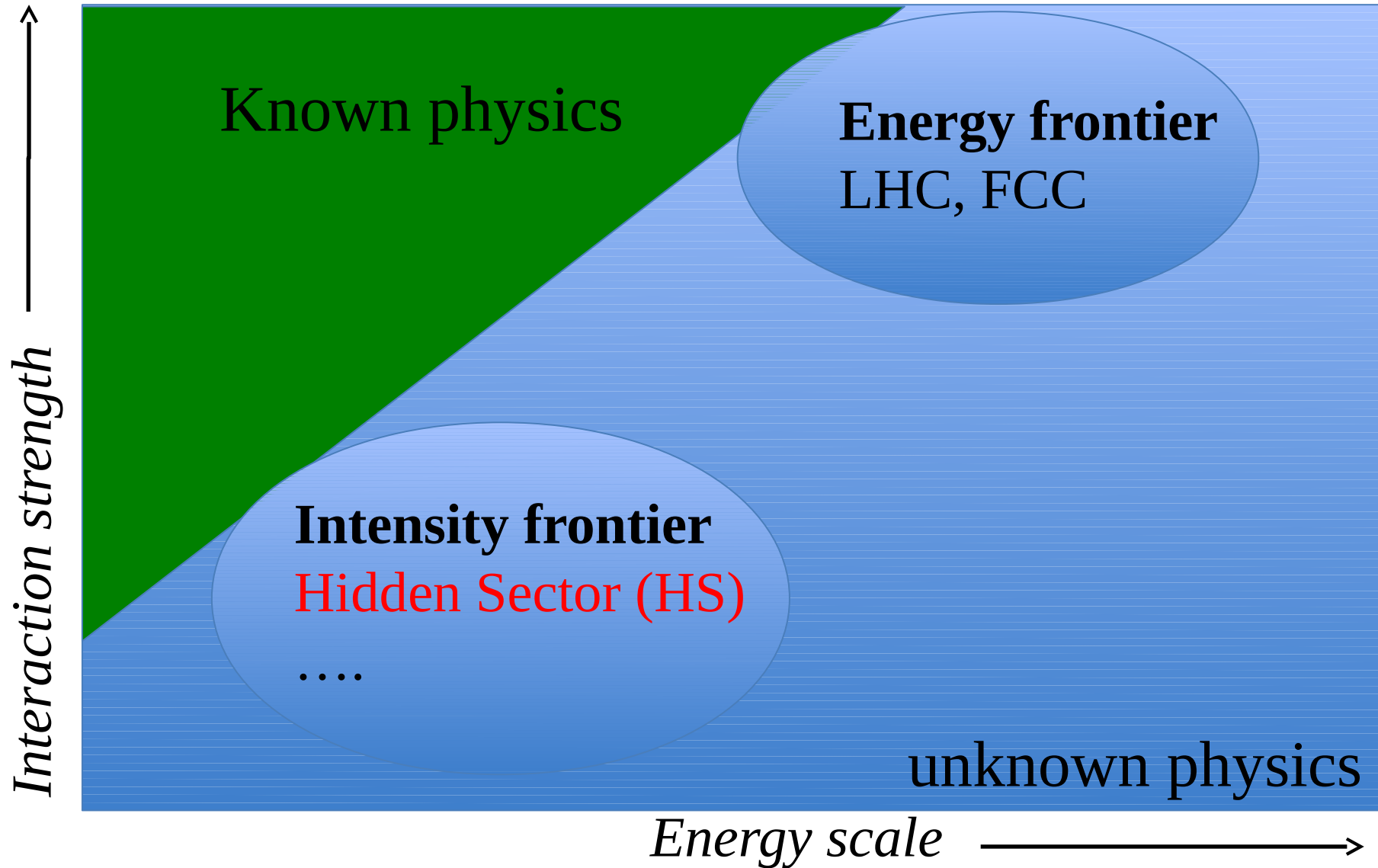
Shaposhnikov, Wetterich (Phys. Lett. B683: 196-200, 2010): $M_{\text{Higgs}} = 126 \text{ GeV}$



→ **Scale of New Physics ?**

→ **Couplings of New Physics to SM particles?**

Where to look for New Physics (very simplified) ?



Examples of light Hidden-Sector particles

$$L_{eff} = L_{SM} + L_{Mediator} + L_{HS} \text{ (e.g. DM } \chi \text{)}$$

| | | |
|----------------------------|--|-----------------------------------|
| Renormalizable | $\left\{ \begin{array}{l} \text{Right-handed Neutrinos} \\ (\mu S + \lambda S^2) H^+ H \\ -\frac{\epsilon}{2} F^{\mu\nu} F_{\mu\nu} \end{array} \right.$ | Neutrino portal |
| | | Higgs/Scalar portal |
| | | Vector portal ("dark" photons) |
| Higher-dimension operators | $\left\{ \begin{array}{l} \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi \\ \frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q + \dots \end{array} \right.$ | Axion Portal |
| | | Dark Matter |
| Light mediator | $g_\chi \phi \bar{\chi} \chi + g_q \phi \bar{q} q + \dots$ | |

RPV SUSY → Light, weakly interacting particles (e.g. Neutralino)

Experimental features for Hidden Sector (HS) searches @ proton beamdump

- Production through meson decays (π , K, D, B); proton bremsstrahlung, QCD ...
- - Production branching ratios $O(10^{-10})$
- Long-lived particles
- Travel quasi unperturbed through ordinary matter

| Models | Final states |
|--|--|
| Neutrino portal, SUSY neutralino | $l^\pm \pi^\mp, l^\pm K^\mp, l^\pm \rho^\mp, \rho^\pm \rightarrow \pi^\pm \pi^0$ |
| Vector, scalar, axion portals, SUSY sgoldstino | $l^+ l^-$ |
| Vector, scalar, axion portals, SUSY sgoldstino | $\pi^+ \pi^-, K^+ K^-$ |
| Neutrino portal, SUSY neutralino, axino | $l^+ l^- \nu$ |
| Axion portal, SUSY sgoldstino | $\gamma\gamma$ |
| SUSY sgoldstino | $\pi^0 \pi^0$ |

- Full reconstruction and particle identification to distinguish btw models
- Goal: BG < O(0.1)

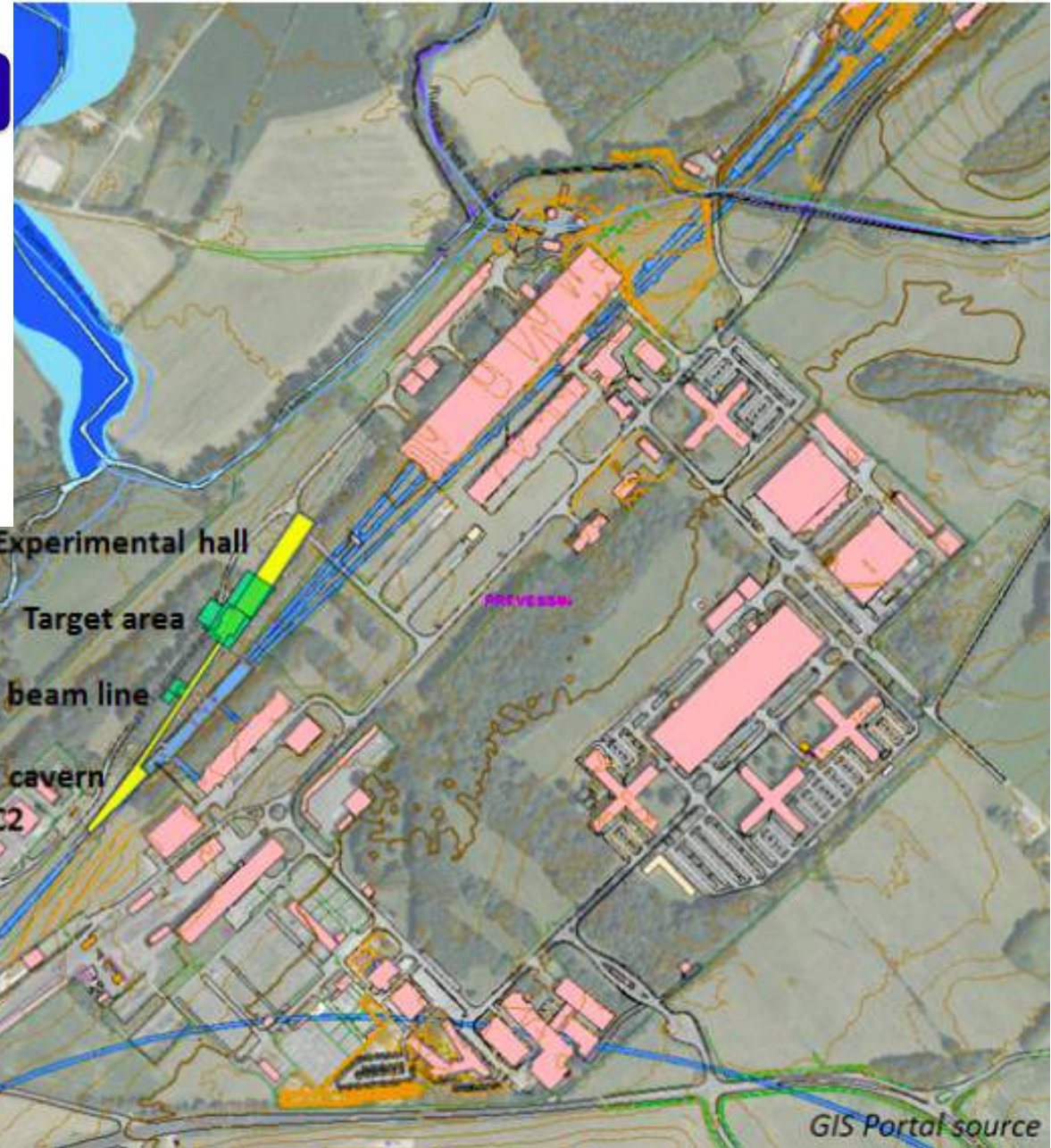
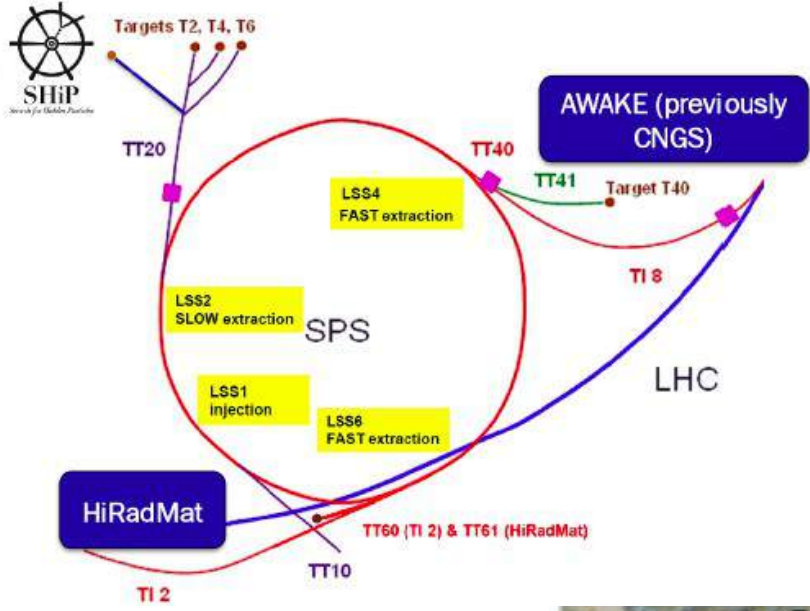


The Fixed-target facility at the SPS: Preveessin North Area site

Proposed implementation is based on minimal modification to the SPS complex

High-intensity proton beam: 4×10^{13} p/spill, 4×10^{19} pot/yr, 5 years run $\rightarrow 2 \times 10^{20}$ pot

North Area

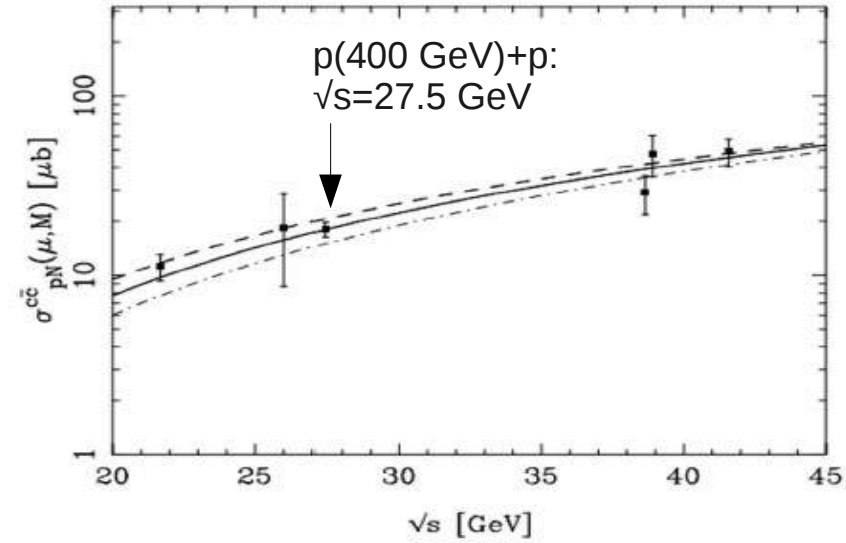
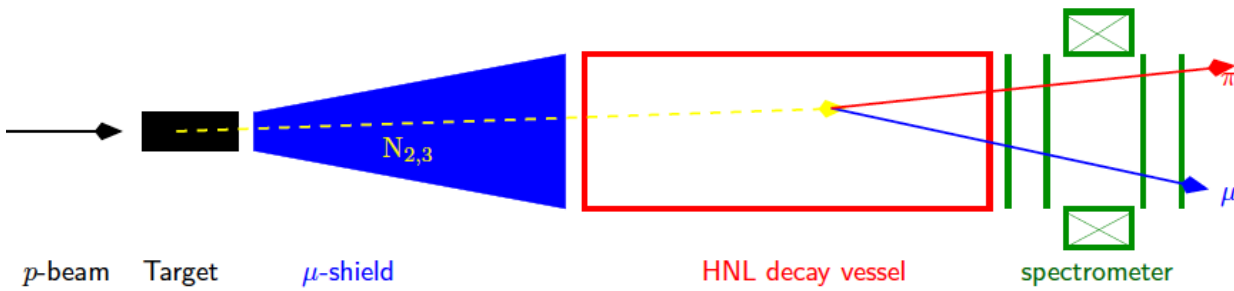


The SHiP facility would share the TT20 transfer line and slow extraction mode with the fixed-target programmes

General experimental requirements

- HS particles produced in c/b-quark decays

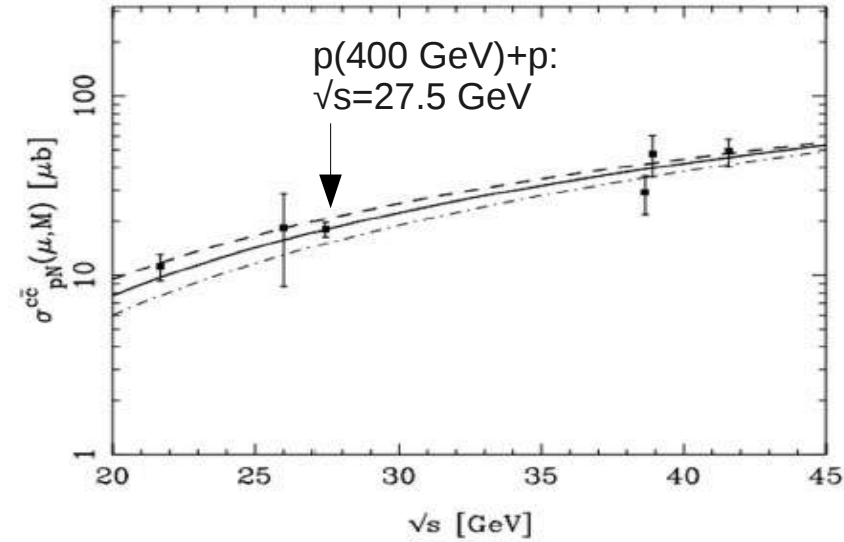
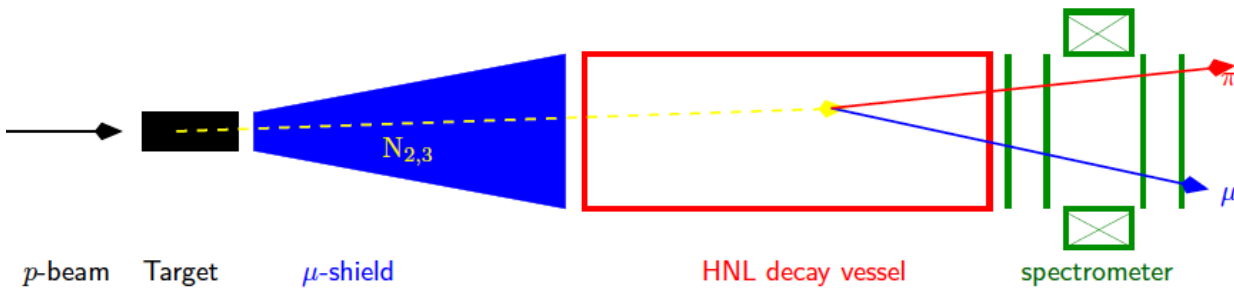
→ CERN SPS well suited:
High-intensity 400 GeV proton beam



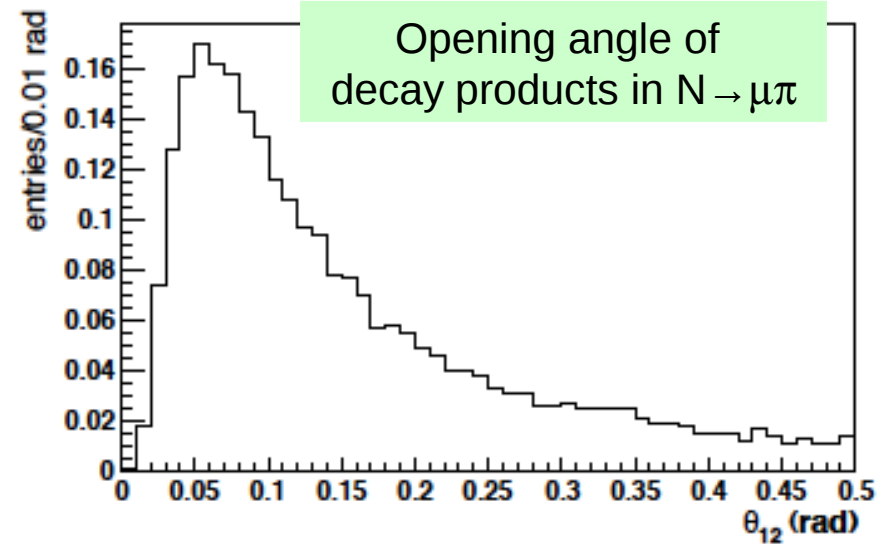
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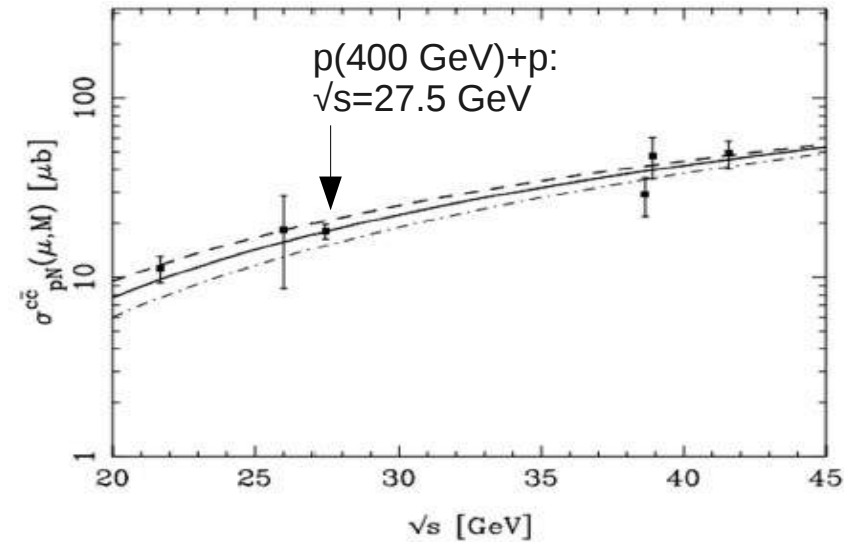
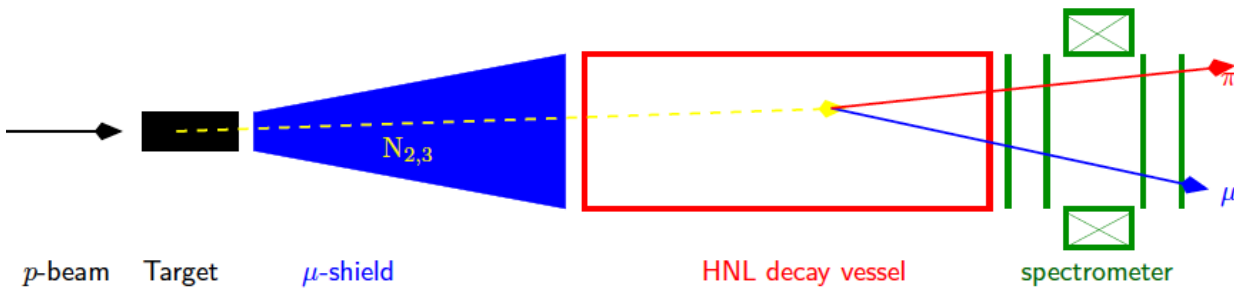
- HS particles from c/b-hadron decays have significant transverse momenta
- Decay products from HS particle decays have significant transverse momenta



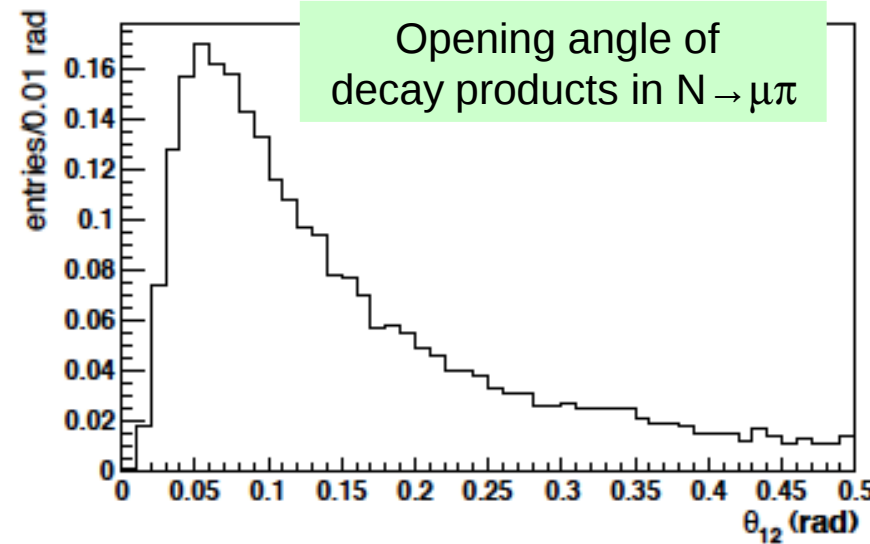
General experimental requirements

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→ CERN SPS well suited:
High-intensity 400 GeV proton beam



- HS particles from c/b-hadron decays have significant transverse momenta
- Decay products from HS particle decays have significant transverse momenta



- Detector must be close to the target to maximize geometrical acceptance
- Effective (and “short”) muon shield is essential to reduce μ-induced backgrounds

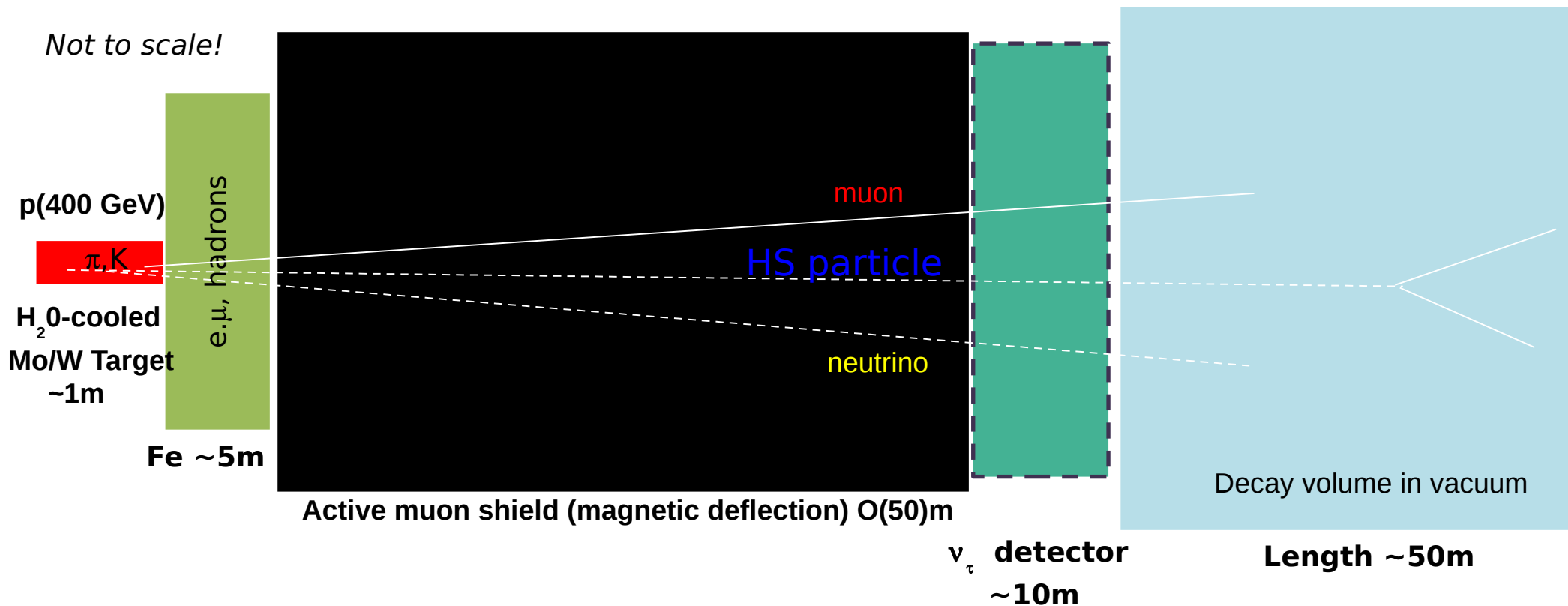


SHiP beamline

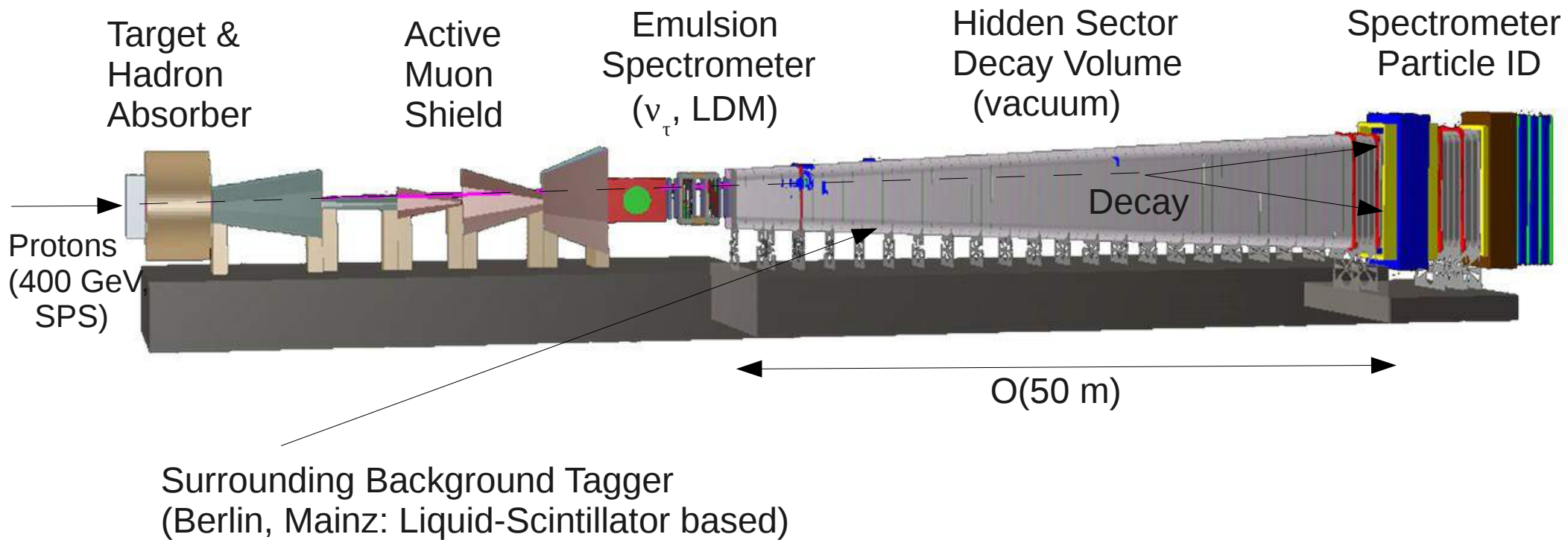
Initial reduction of beam induced backgrounds

- Heavy target \rightarrow large c/b-quark production & reduces neutrinos from $\pi/K \rightarrow \mu\nu$
- Hadron absorber
- Effective muon shield (w/o shield: μ rate $\sim 10^{10}$ per spill of 4×10^{13} pot)
- Slow (and uniform) beam extraction (~ 1 s) to reduce occupancy in the detector and power deposit in the target (2-3 MW)

Not to scale!



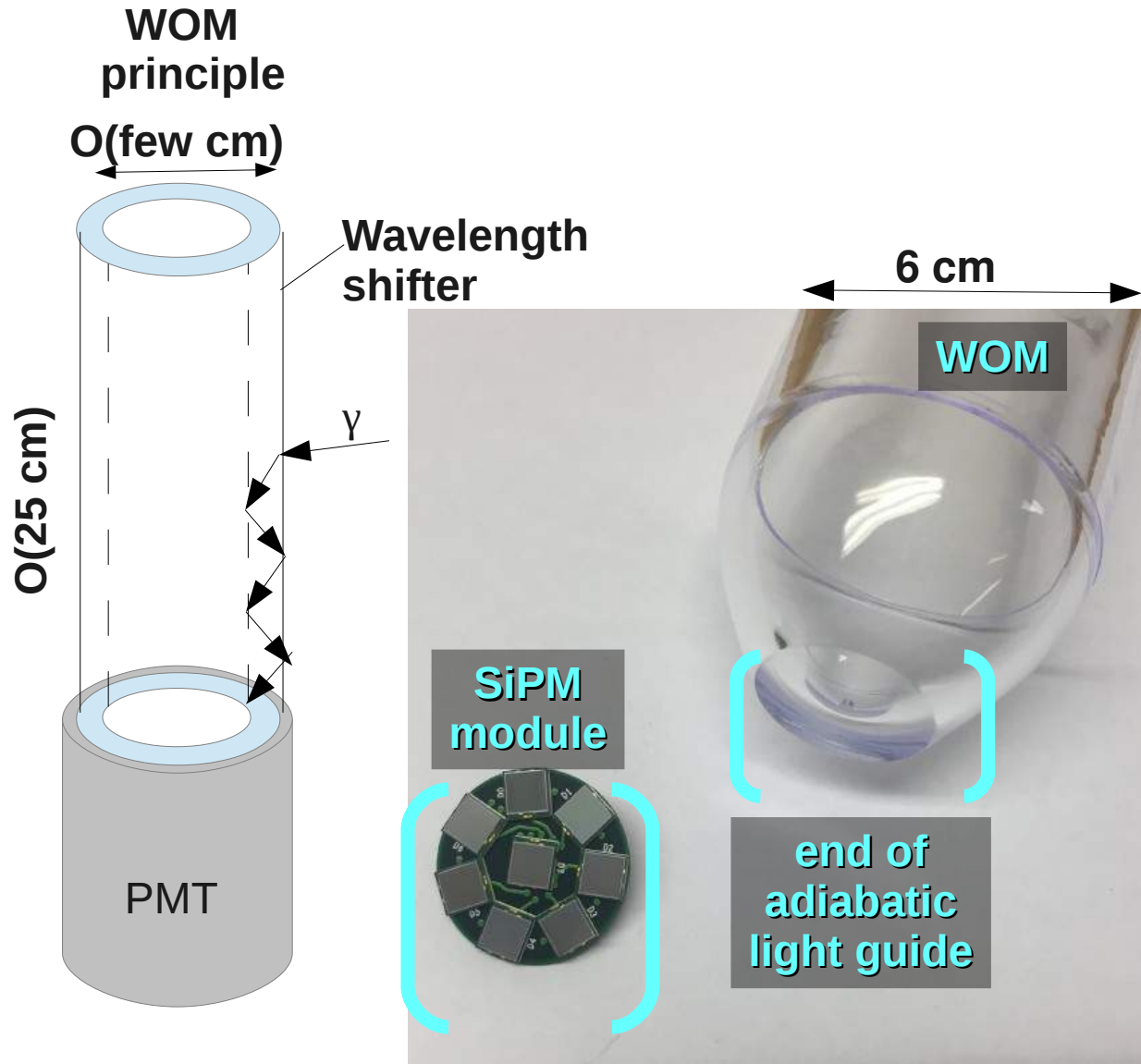
SHiP experiment (as implemented in GEANT4)



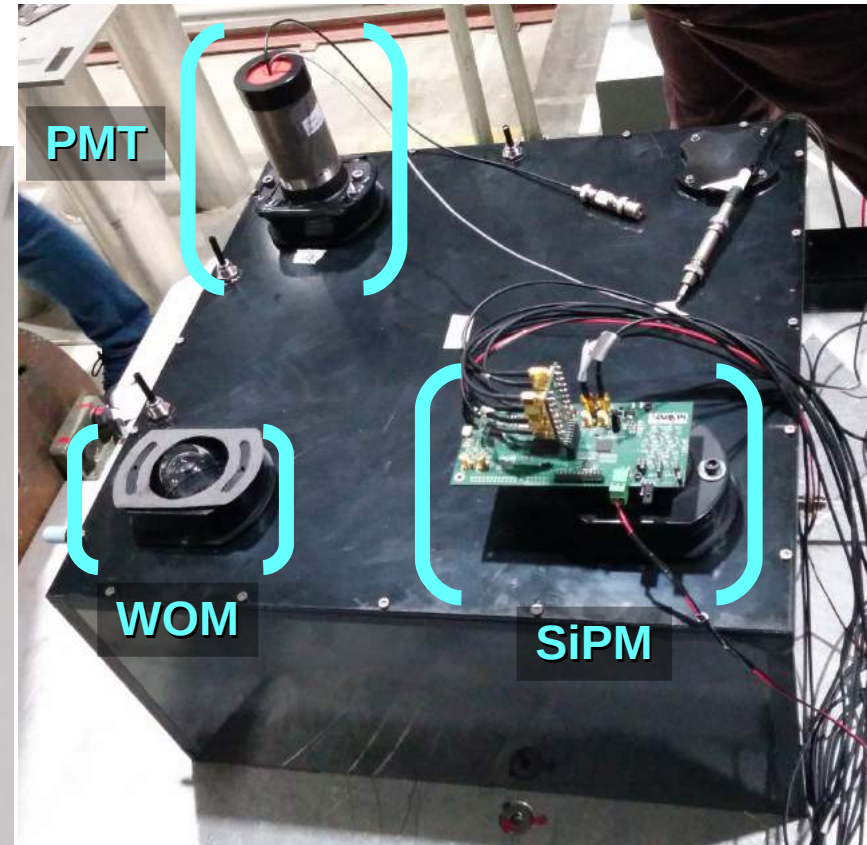
Surrounding Background Tagger

Liquid Scintillator (400 t): Linear Alkylbenzene (LAB) + 1.5 g/l Diphenyloxazole (PPO)

Increase effective photodetector area using Wavelength-shifting Optical Modules (WOM)



Test detector @ CERN SPS testbeam
(September 2017)





Neutrino Physics with the emulsion spectrometer

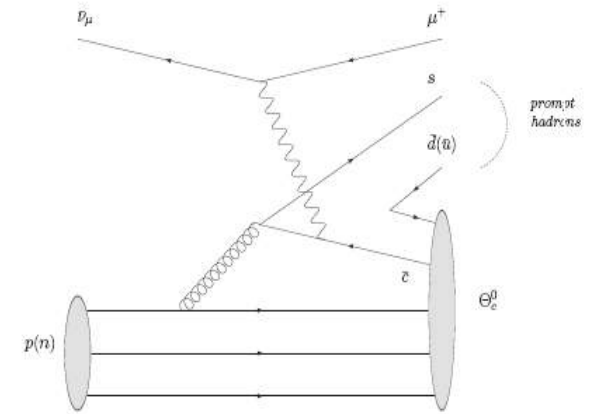
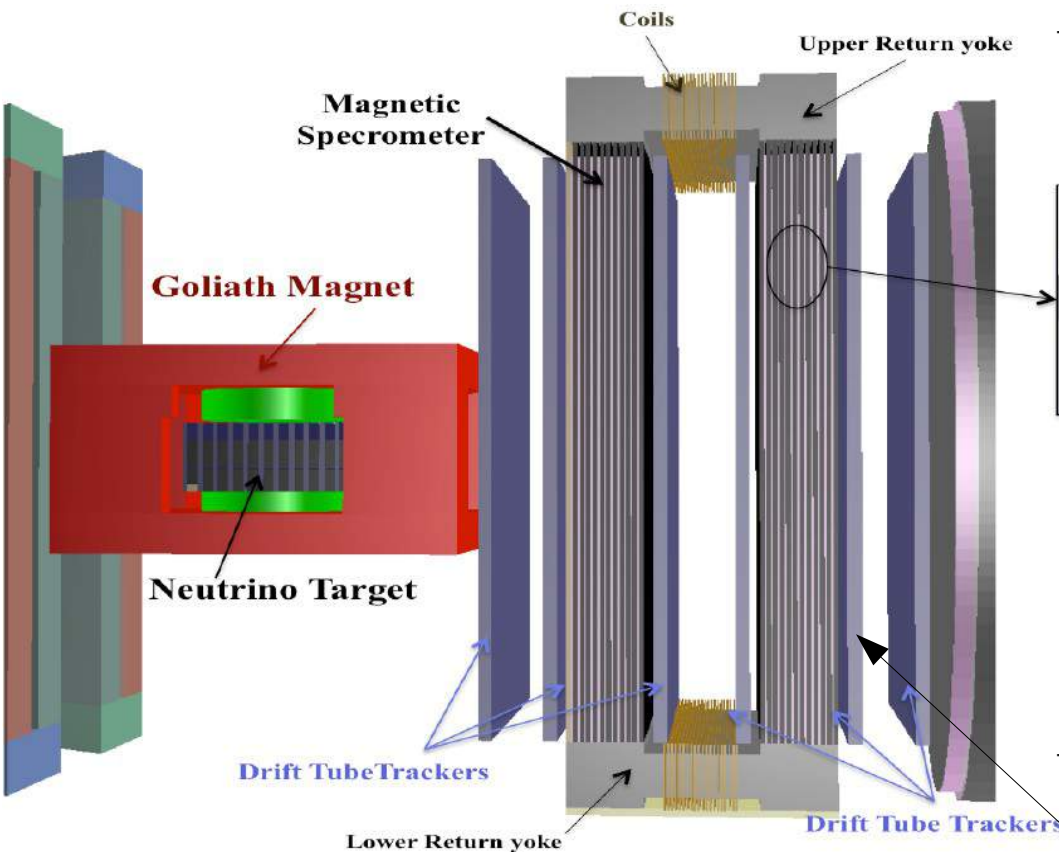
Up to now only a handful of ν_τ interactions detected (DONUT, OPERA)

- 6700 ν_τ + 3400 $\bar{\nu}_\tau$ (for the 1st time) CC interactions in 5 years of running
- Deep-Inelastic Scattering: nucleon structure functions $F_{4,5}$ accessible for the 1st time
- Limits on ν_τ magnetic moment

Huge flux of $\nu_\mu/\bar{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$ from π/K decays

→ 1.1x10⁵ events with charm-quark hadrons:

$s+\bar{s}, s-\bar{s}$; charmed pentaquarks



Limit improvement wrt CHORUS: 10³

→ Check NuTeV anomaly with more precision

U Hamburg

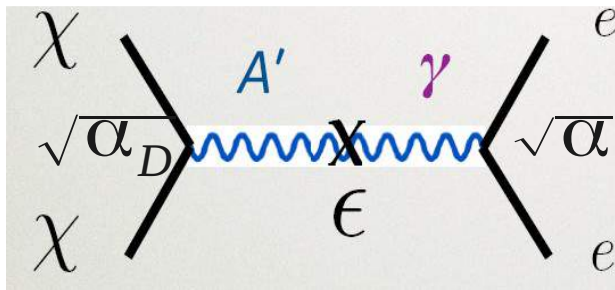
Example of Dark matter search with the emulsion spectrometer

Dark matter (χ) might couple to SM particles by “dark” photons A' (as mediator)

A' production in proton beamdump e.g. from $\pi^0/\eta^{(\prime)} \rightarrow A'\gamma$, $\omega \rightarrow A'\pi^0$

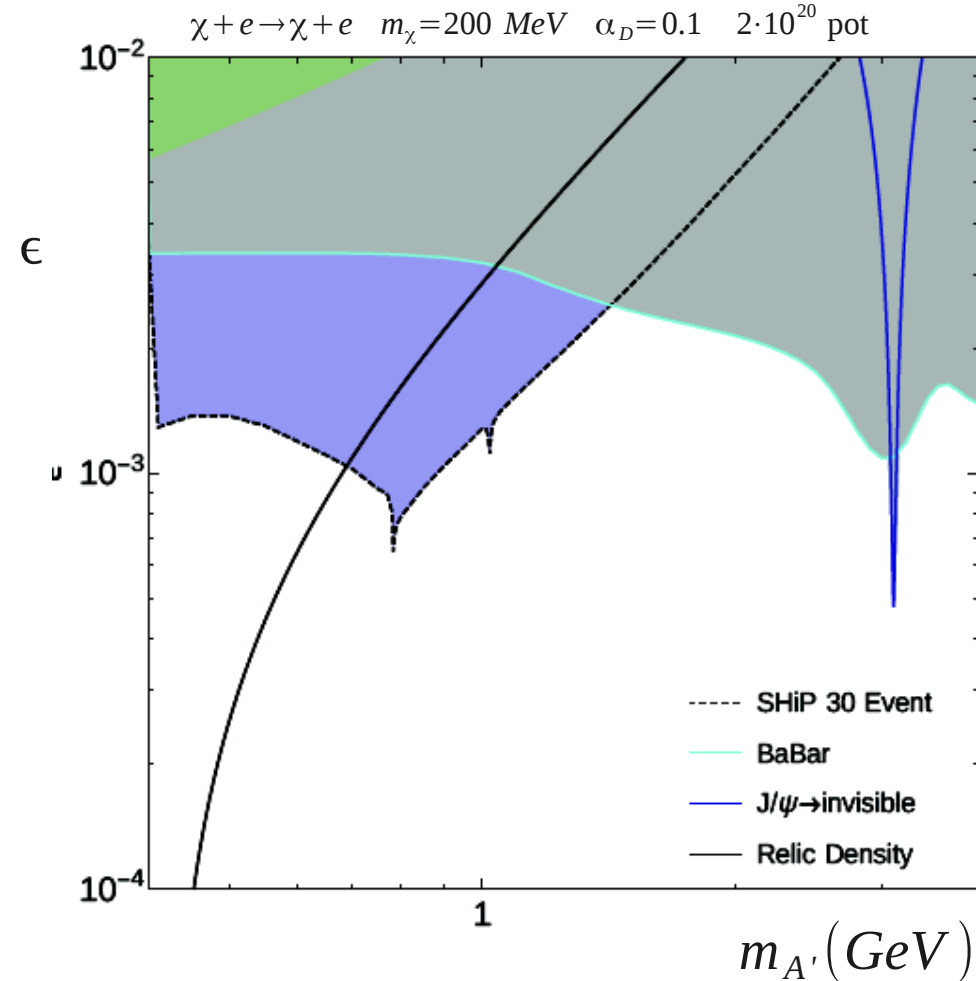
or proton bremsstrahlung and QCD

For $m_{A'} > 2m_\chi$: $A' \rightarrow \chi\bar{\chi}$ and detection in emulsion detector by $\chi + e \rightarrow \chi + e$



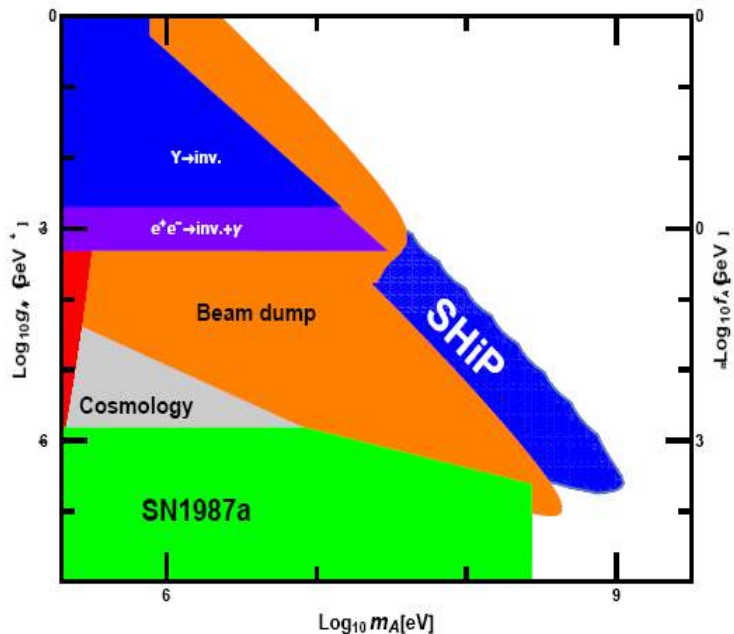
Relic density determined by annihilation XS:

$$\langle \sigma \cdot v \rangle \propto \alpha_D \epsilon^2 \alpha \frac{m_\chi^2}{m_{A'}^4}$$

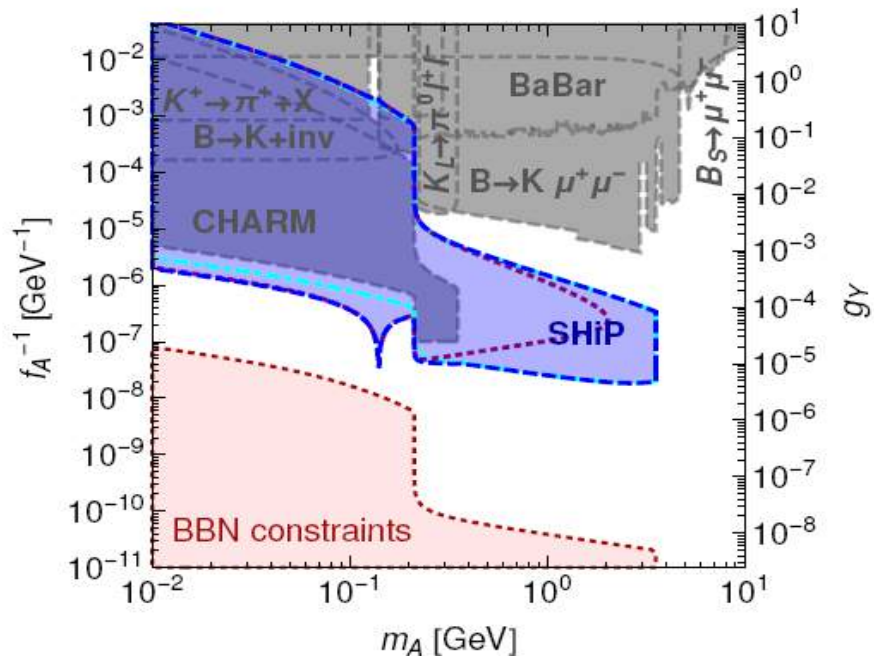


Physics reach with HS detector: selected examples

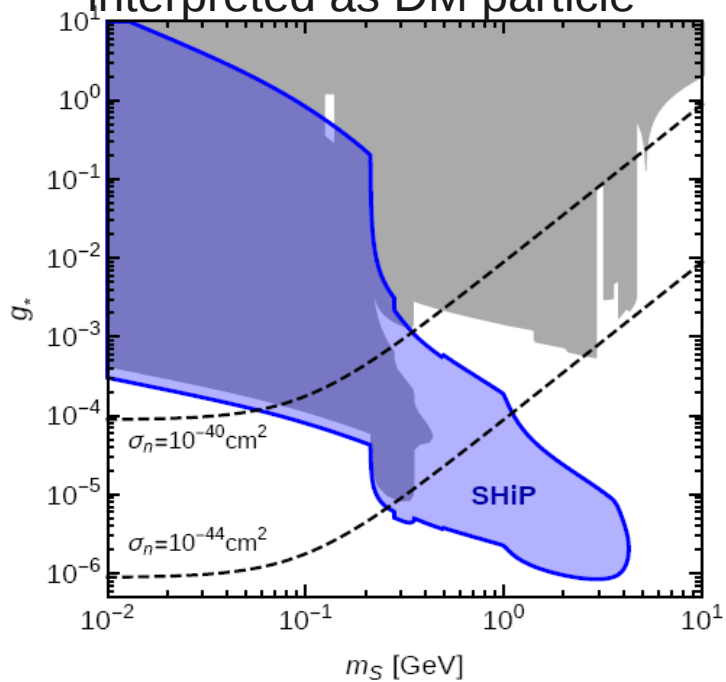
Pseudo-scalar ALP $\rightarrow \gamma\gamma/VV$



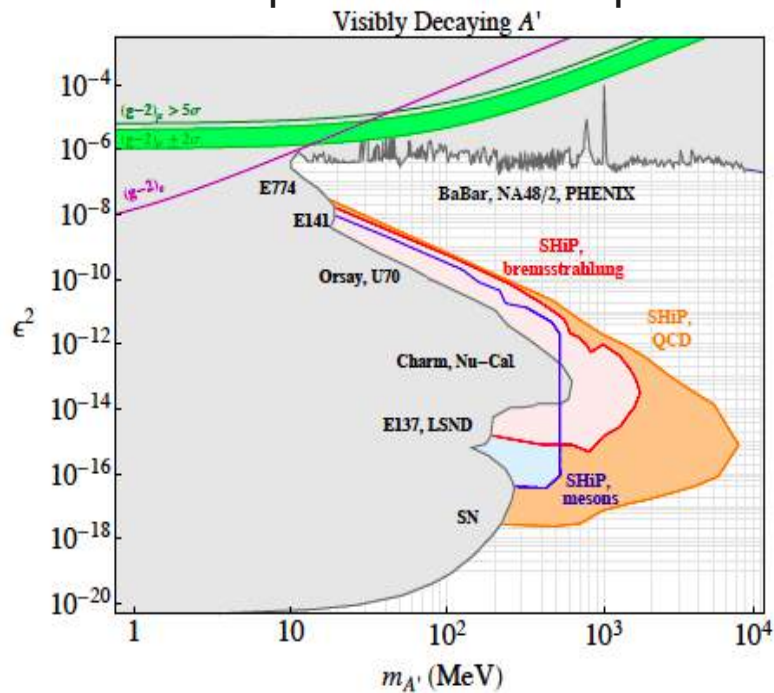
ALP \rightarrow fermion anti-fermion



Light scalar \rightarrow SM particles interpreted as DM particle

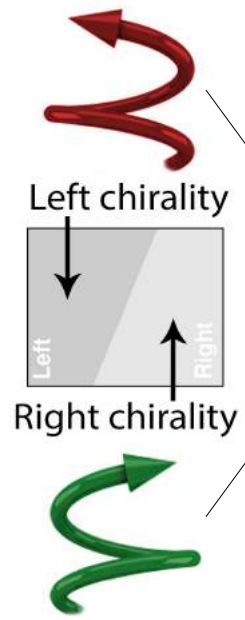


“Dark” photon A' \rightarrow SM particles



The ν MSM model

| | | | |
|---------|--|---|---|
| Quarks | 2.4 MeV $\frac{2}{3}$ Left u Right up | 1.27 GeV $\frac{2}{3}$ Left c Right charm | 171.2 GeV $\frac{2}{3}$ Left t Right top |
| | 4.8 MeV $-\frac{1}{3}$ Left d Right down | 104 MeV $-\frac{1}{3}$ Left s Right strange | 4.2 GeV $-\frac{1}{3}$ Left b Right bottom |
| | 0 Left ν_e Right electron neutrino | N_1 sterile neutrino | 0 Left ν_μ Right muon neutrino |
| Leptons | 0.511 MeV -1 Left e Right electron | 105.7 MeV -1 Left μ Right muon | 1.777 GeV -1 Left τ Right tau |
| | 0 Left ν_τ Right tau neutrino | N_2 sterile neutrino | N_3 sterile neutrino |



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

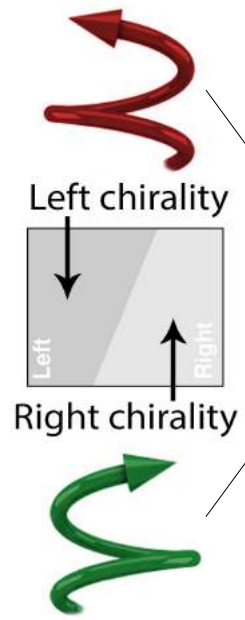
➔ Add 3 right-handed Majorana neutrinos
(Particle = Anti-Particle)

seesaw mechanism → tiny ν -masses:

$$m_\nu \approx m_D \frac{m_D}{M_M}, \quad m_N \approx M_M$$

The ν MSM model

| | | | |
|---------|--|--|--|
| | 2.4 MeV Left $\frac{2}{3}$ u Right up | 1.27 GeV Left $\frac{2}{3}$ c Right charm | 171.2 GeV Left $\frac{2}{3}$ t Right top |
| Quarks | 4.8 MeV Left $-\frac{1}{3}$ d Right down | 104 MeV Left $-\frac{1}{3}$ s Right strange | 4.2 GeV Left $-\frac{1}{3}$ b Right bottom |
| | ν_e N₁ electron neutrino sterile neutrino | ν_μ N₂ muon neutrino sterile neutrino | ν_τ N₃ tau neutrino sterile neutrino |
| Leptons | 0.511 MeV Left -1 e Right electron | 105.7 MeV Left -1 μ Right muon | 1.777 GeV Left -1 τ Right tau |

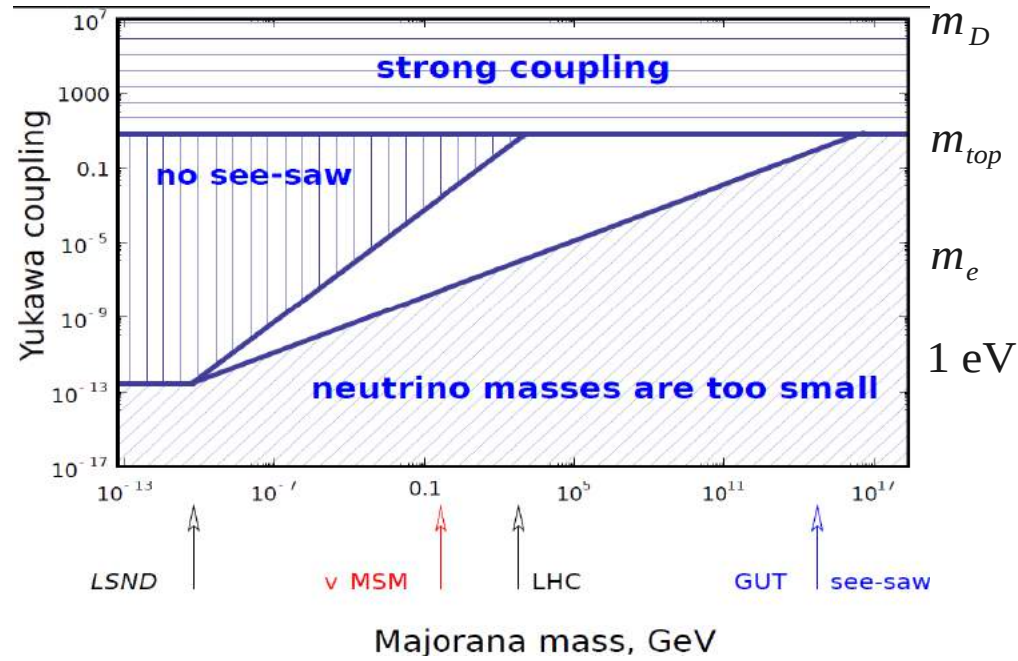


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M. Shaposhnikov Nucl. Phys. B763 (2007) 49

**Add 3 right-handed Majorana neutrinos
(Particle = Anti-Particle)**

seesaw mechanism \rightarrow tiny ν -masses:

$$m_\nu \approx m_D \frac{m_D}{M_M}, \quad m_N \approx M_M$$

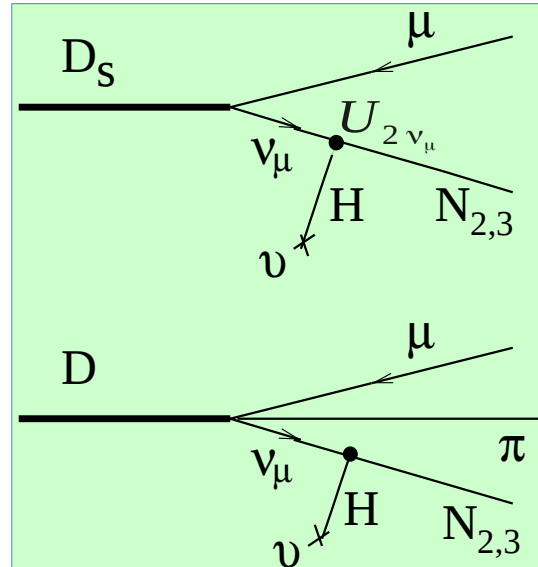


- $N_{2,3} \sim 0.1 - \text{several GeV}$: ν masses & BAU
- $N_1 \sim \text{O(keV)}$: dark matter candidate
(3.5 keV line in galaxies & galaxy clusters?)
- **Higgs:** - masses of quarks, leptons, Z/W
- inflaton

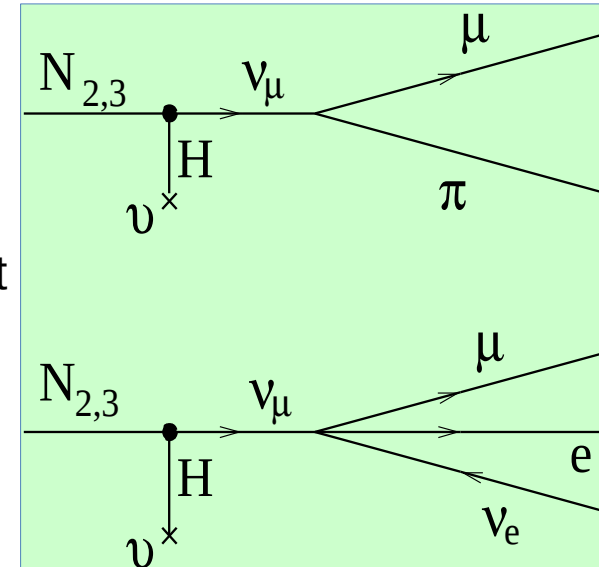
Masses and couplings of HNLs

Example:

$N_{2,3}$ production in charm



and subsequent decays



$$\sigma_D \times |U|^2$$

$$|U|^2 = |U_{2, \nu_e}|^2 + |U_{2, \nu_\mu}|^2 + |U_{2, \nu_\tau}|^2$$

$$\Gamma_N \propto |U|^2$$

- Typical lifetimes $> 10 \mu\text{s}$ for $M(N_{2,3}) \sim 1 \text{ GeV}$
Decay distance $O(\text{km})$
- Typical BRs (depending on flavour mixing):

$$\text{Br}(N \rightarrow \mu/e \pi) \sim 0.1 - 50\%$$

$$\text{Br}(N \rightarrow \mu/e \rho) \sim 0.5 - 20\%$$

$$\text{Br}(N \rightarrow \nu \mu e) \sim 1 - 10\%$$

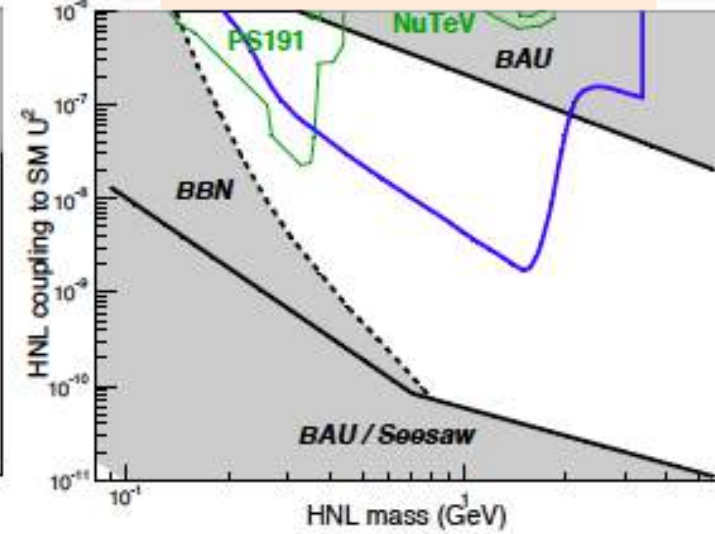
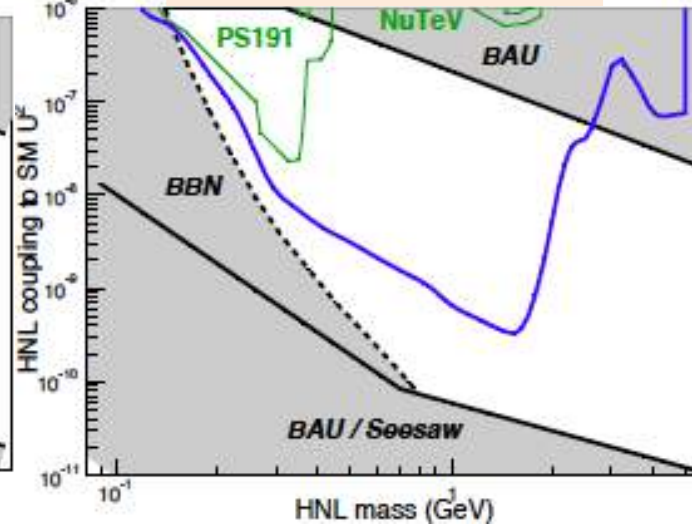
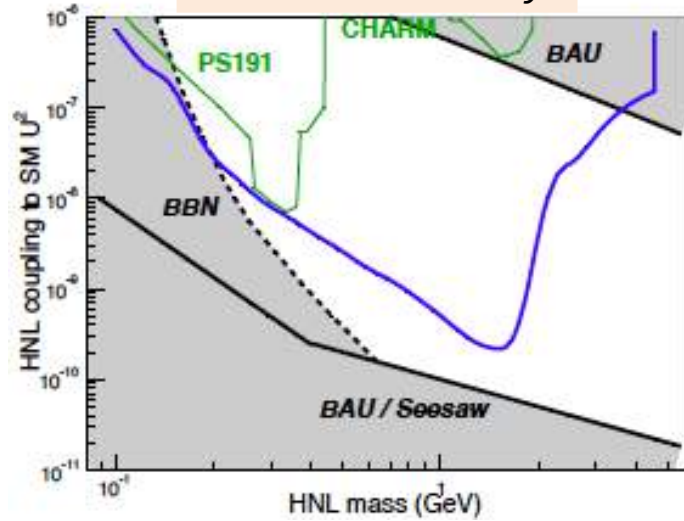


Sensitivity to HNLs for representative scenarios (approaching ultimate see-saw limit)

$U_e^2 : U_\mu^2 : U_\tau^2 \sim 52:1:1$
Inverted hierarchy

$U_e^2 : U_\mu^2 : U_\tau^2 \sim 1:16:3.8$
Normal hierarchy

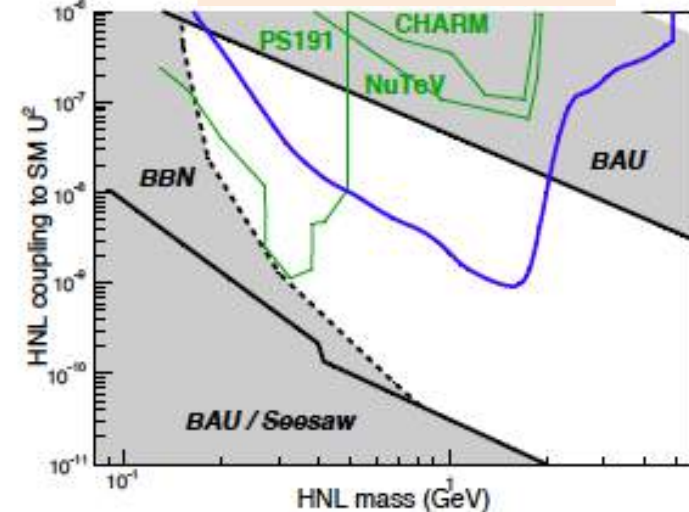
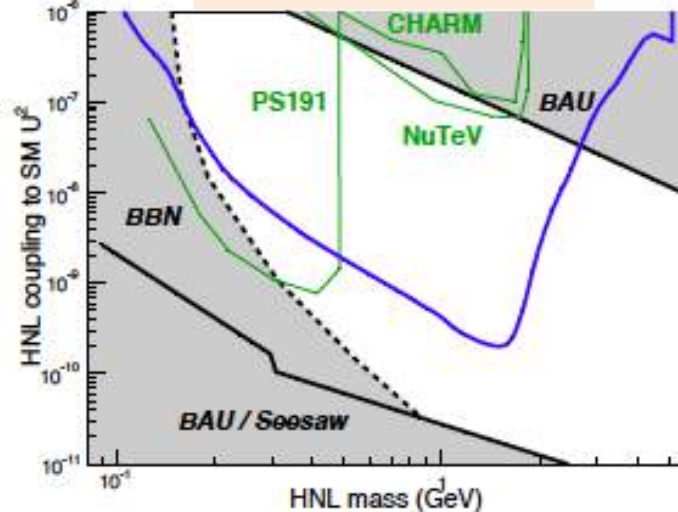
$U_e^2 : U_\mu^2 : U_\tau^2 \sim 0.061:1:4.3$
Normal hierarchy



$U_e^2 : U_\mu^2 : U_\tau^2 \sim 48:1:1$
Inverted hierarchy

$U_e^2 : U_\mu^2 : U_\tau^2 \sim 1:11:11$
Normal hierarchy

Model parameters
for which BAU works



Evolution of the Project

10/2013: EoI (16 physicists: Cagliari, CERN, Leiden, ICL, Moscow, EPFL, Zürich)

12/2014: Foundation of the SHiP Collaboration

(Bulgaria, Chile, Denmark, France, Germany, Italy, Japan, Russia, Sweden, CERN, Switzerland, Turkey, UK, Ukraine, US)

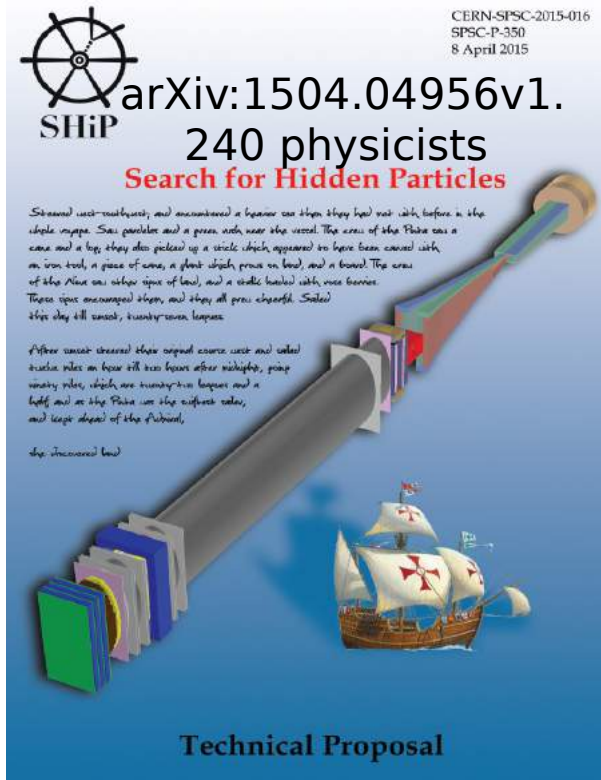
04/2015:

CERN-SPSC-2015-016
SPSC-P-350
8 April 2015

arXiv:1504.04956v1.
240 physicists
Search for Hidden Particles

Steered west-southwest, and encountered a heavier sea than they had met with before in the whole voyage. Saw parallel and a green rock near the vessel. The crew of the *Phaenon* on a canoe and a log, they also picked up a stick which appeared to have been carved with an iron tool, a piece of cane, a glass which proved to have been broken. The crew of the *Phaenon* saw other signs of land, and a small boat with three persons. These signs encouraged them, and they all grew cheerful. Said they they will coast, twenty-seven leagues.

After sunset steered their original course west and sailed twelve miles on board till ten hours after midnight, found twenty miles, which are twenty-two leagues and a half, and as the *Phaenon* on the surface water, and kept ahead of the *Phaenon*, and they discovered land.



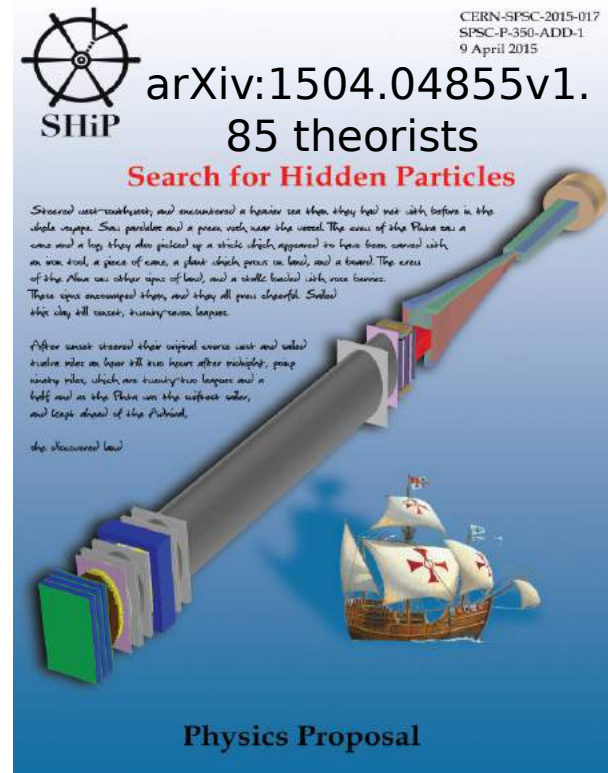
Technical Proposal

CERN-SPSC-2015-017
SPSC-P-350-ADD-1
9 April 2015

arXiv:1504.04855v1.
85 theorists
Search for Hidden Particles

Steered west-southwest, and encountered a heavier sea than they had met with before in the whole voyage. Saw parallel and a green rock near the vessel. The crew of the *Phaenon* on a canoe and a log, they also picked up a stick which appeared to have been carved with an iron tool, a piece of cane, a glass which proved to have been broken. The crew of the *Phaenon* saw other signs of land, and a small boat with three persons. These signs encouraged them, and they all grew cheerful. Said they they will coast, twenty-seven leagues.

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Physics Proposal

Germany:
Hamburg, HU Berlin
(+ Mainz, Bonn)

Germany:
DESY Zeuthen & Hamburg, Hamburg, Bonn,
TU Munich, Heidelberg, Dortmund, Tübingen

02/2016: SPSC recommendation → Comprehensive Design Report



Summary

- **SHiP is proposed to search for New Physics in the largely unexplored domain of new, very weakly interacting particles with masses $O(0.1-10)$ GeV**
- **Also unique opportunity for ν_τ physics**
- **SHiP will greatly complement NP searches at the energy frontier at CERN**
- **Interesting sensitivity ($\sim 10^{-10}$) for $\tau \rightarrow \mu\mu\mu$ at a future extension of the SHiP facility**
- **Technical feasibility of the SHiP facility demonstrated by a CERN task force**
- **SHiP officially recognised as a CERN experiment under study (included in midterm planning; dedicated budget; Greybook)**
- **Decision on approval: Update of European Strategy**
- **Goal: start of data taking in 2026**
- **Great opportunity for interested parties to “board” SHiP now**