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

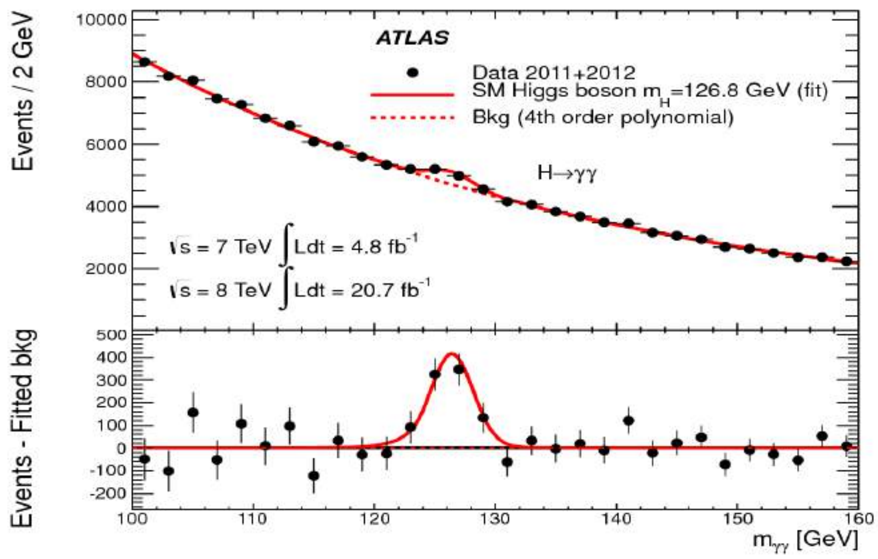
**Heiko Lacker, HU Berlin**

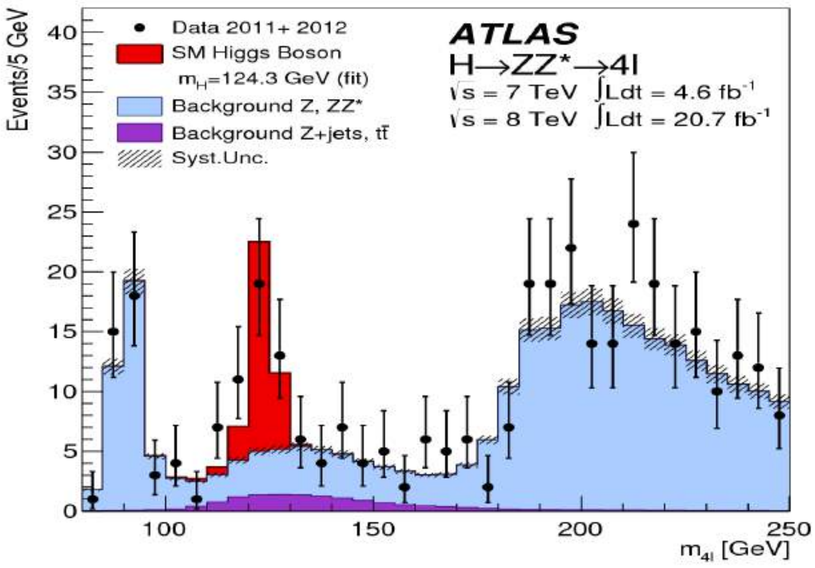
**Dresden, 16.11.2017**

SHiP

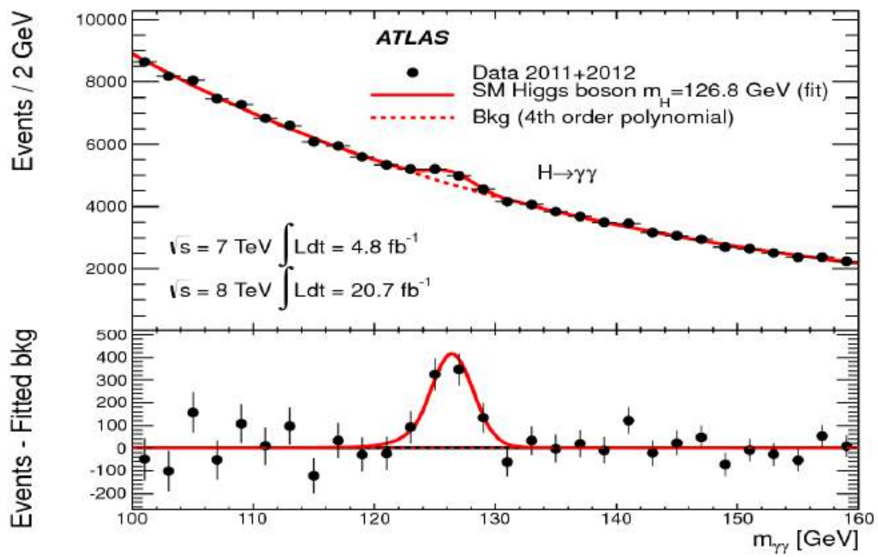
*Search for Hidden Particles*

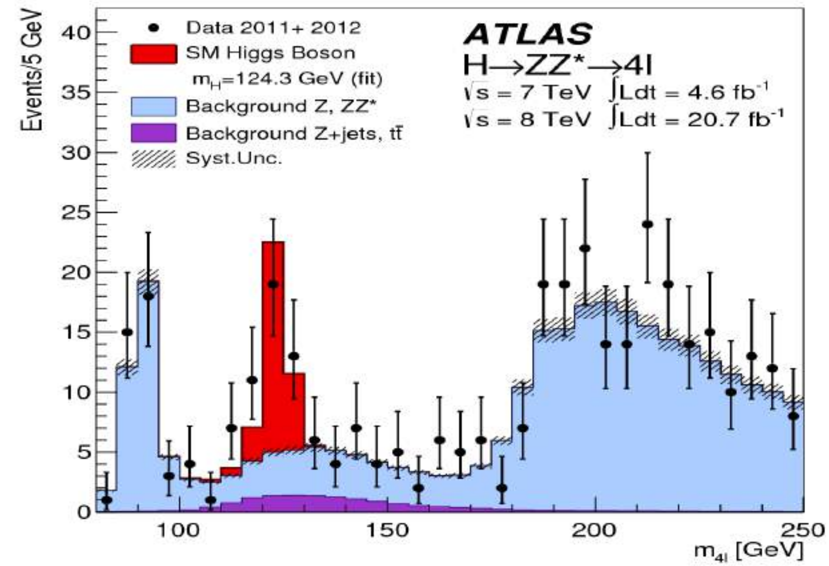
# Higgs-boson discovery (2012): a scientific breakthrough



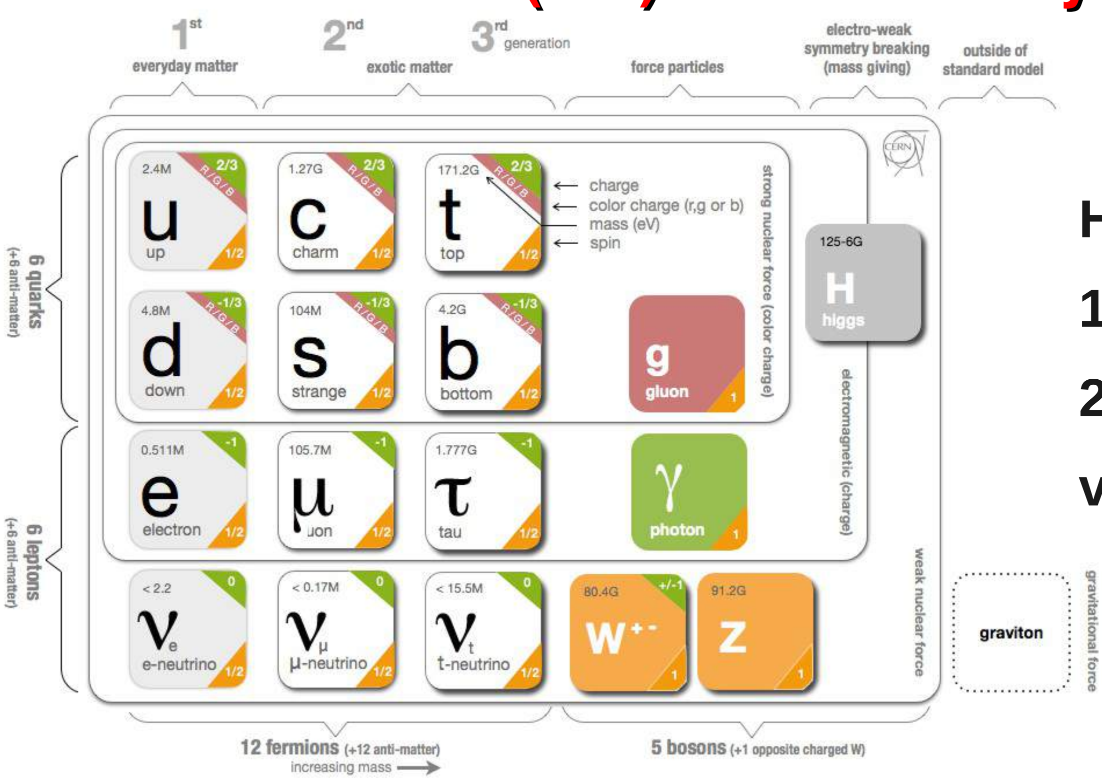



# Higgs-boson discovery (2012): a scientific breakthrough




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



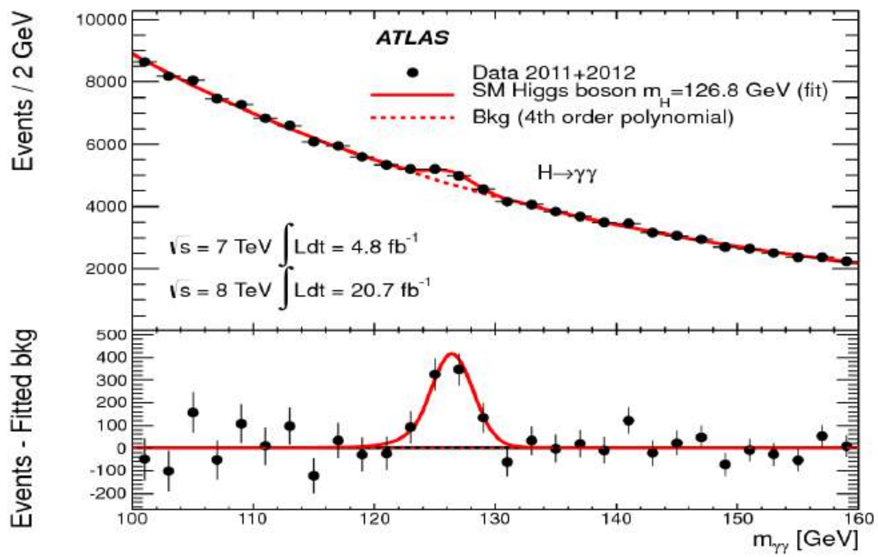

**Higgs mechanism gives masses to**

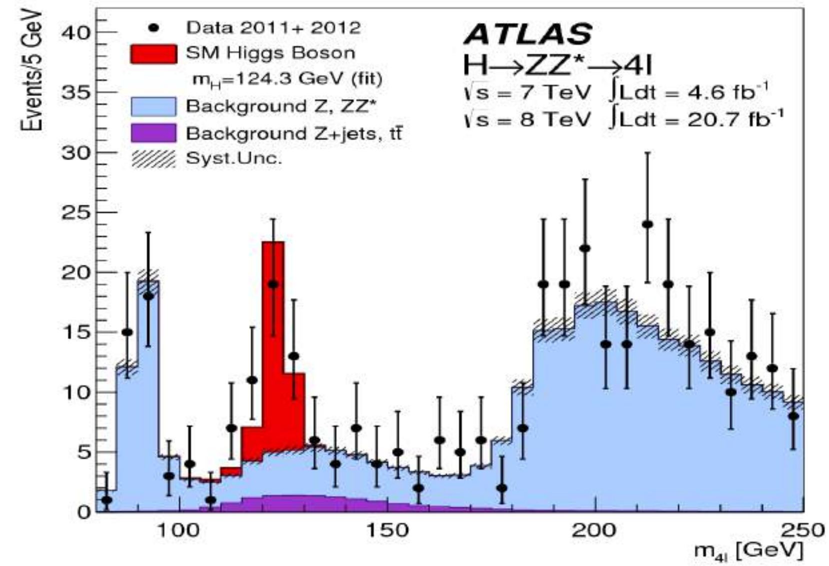
**1. W/Z bosons**

**2. charged leptons & quarks**

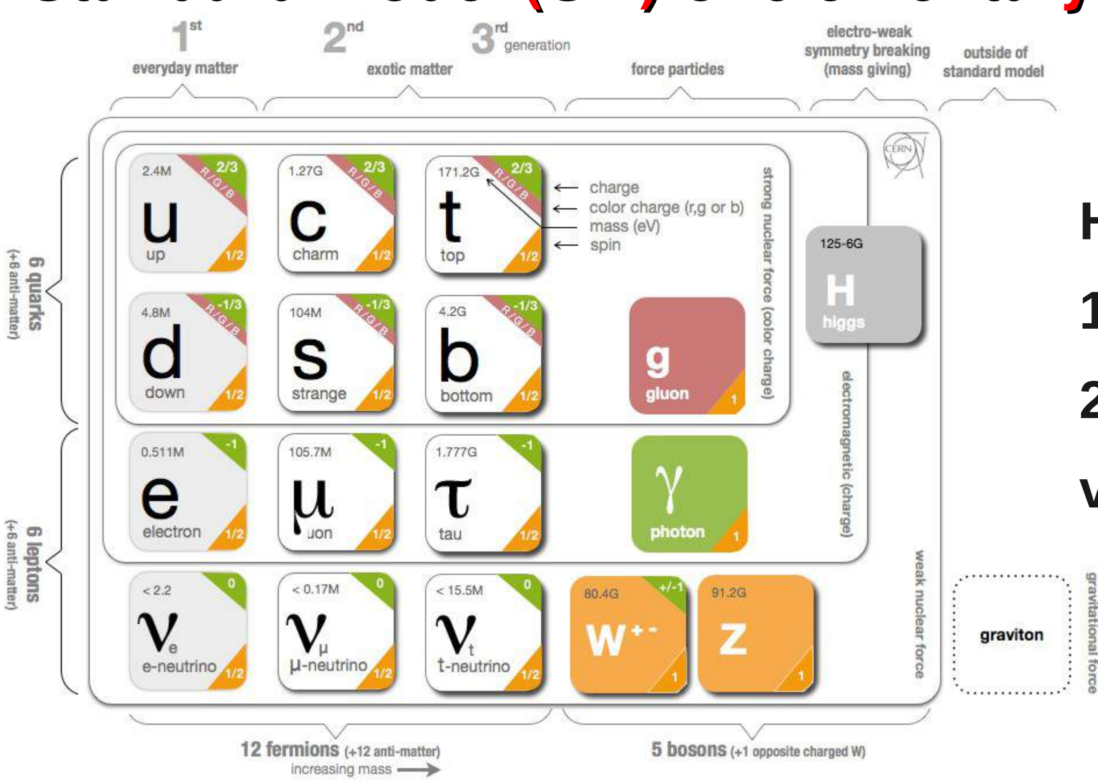
**via spontaneous symmetry breaking**

# Higgs-boson discovery (2012): a scientific breakthrough




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




**Higgs mechanism gives masses to**

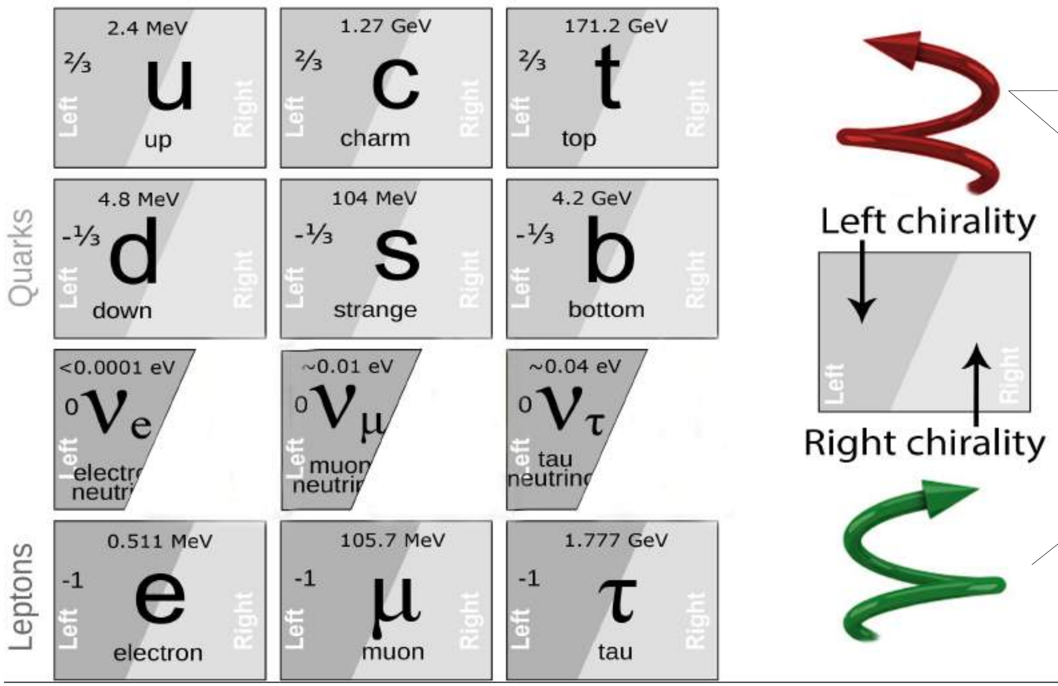
**1. W/Z bosons,**

**2. charged leptons & quarks**

**via spontaneous symmetry breaking**

# However:

# SM does not explain (tiny) neutrino masses

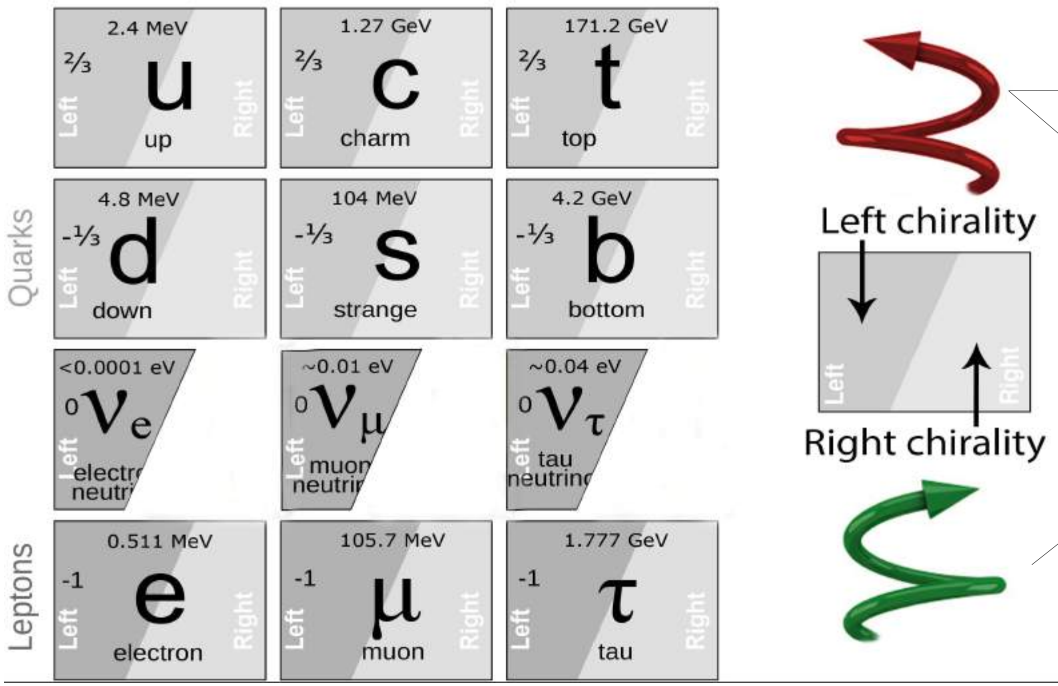



**Only left-handed fermions couple weakly to W bosons**

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

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

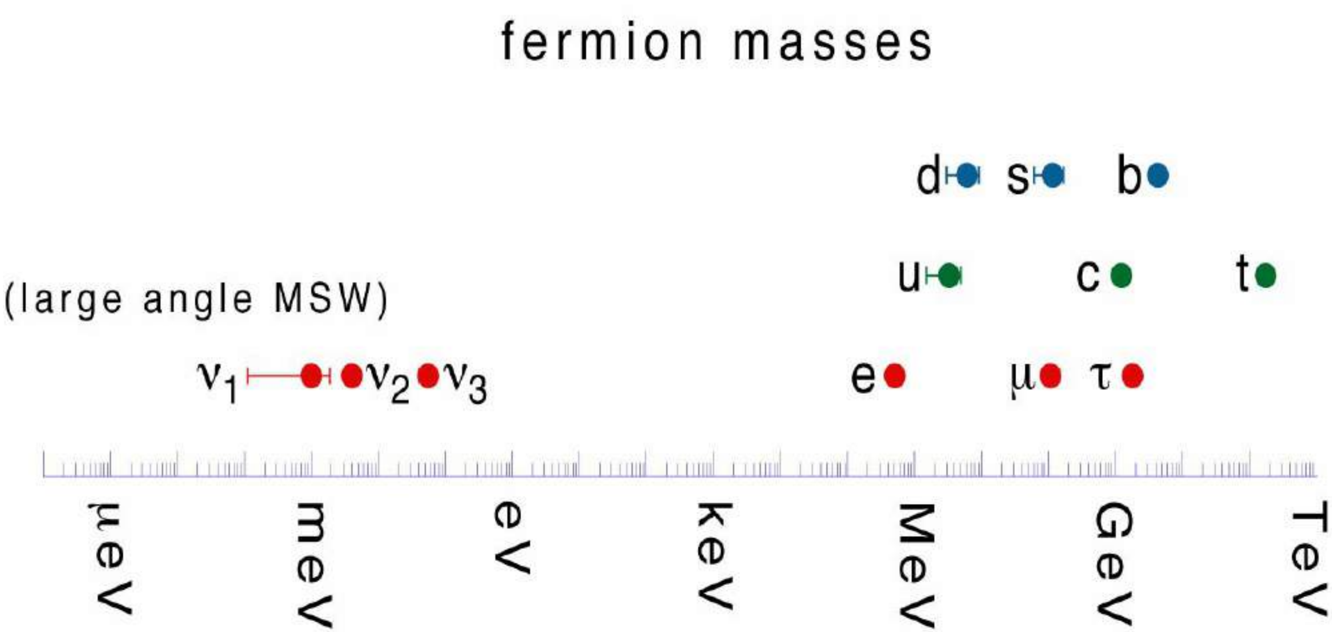
# SM does not explain (tiny) neutrino masses




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

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

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




**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**



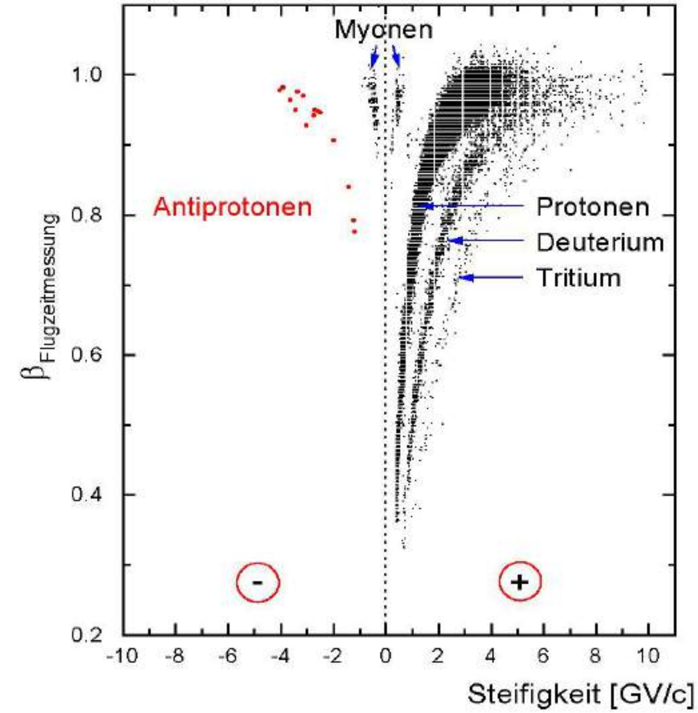

# Baryon-Antibaryon Asymmetry of the Universe (BAU)

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

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



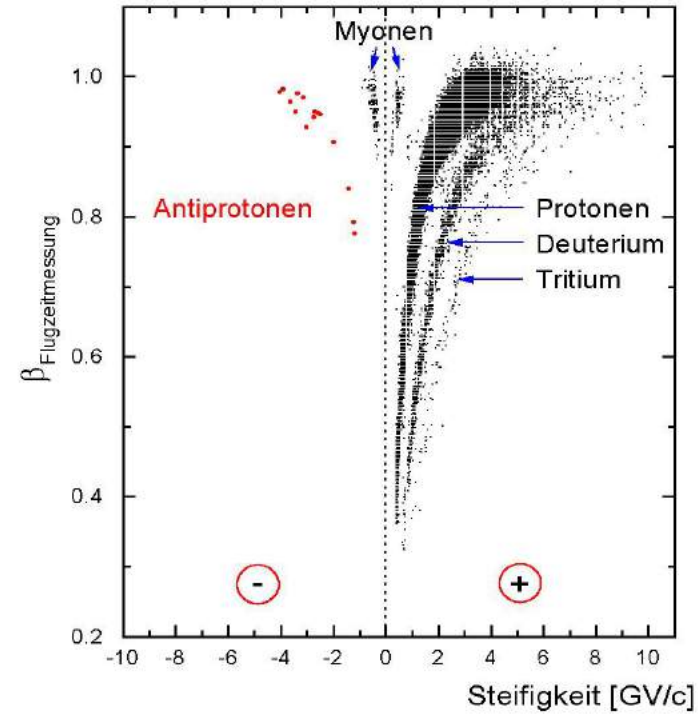




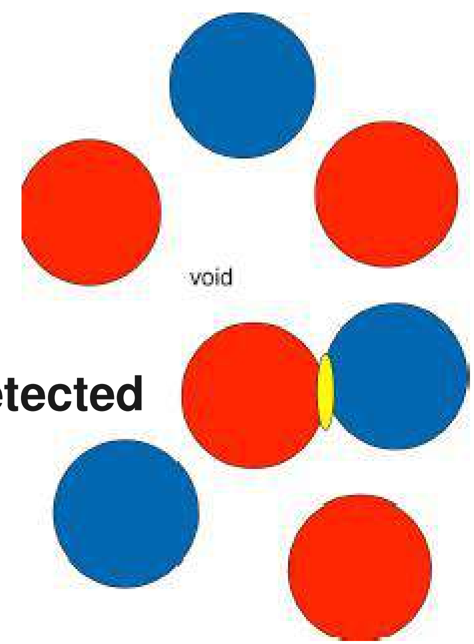
# Baryon-Antibaryon Asymmetry of the Universe (BAU)

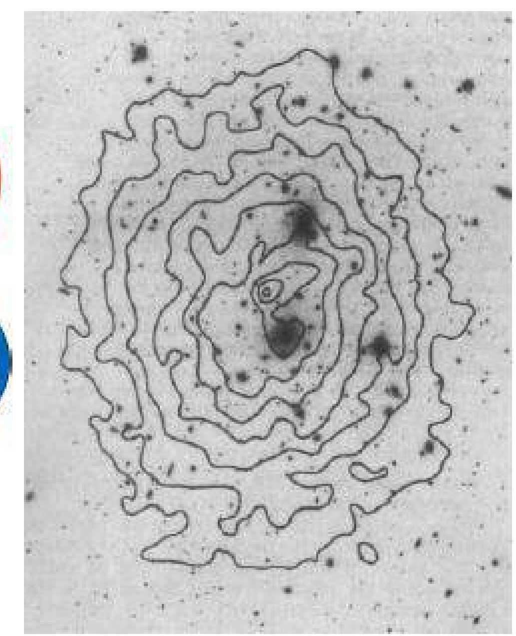
**Up to now: got off lightly in all "encounters" with other celestial bodies**

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

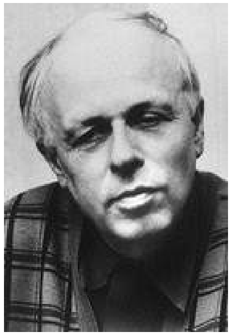

**Up to now: no annihilation radiation from galaxy cluster borders (< 600 mio. light yrs) detected**



# 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**

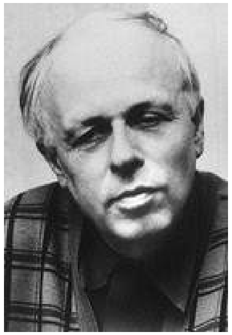
# Baryon-Antibaryon Asymmetry of the Universe (BAU)

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

1) violate Baryon Number

2) violate C and CP symmetry

3) are out of thermal equilibrium



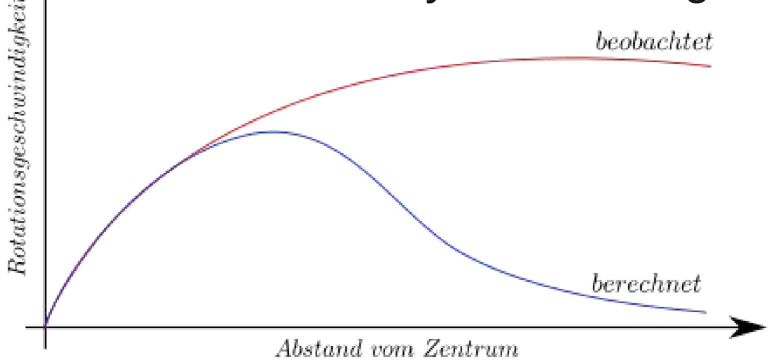
Standard Model fulfills in principle all conditions, but fails quantitatively:

2) CP violation many orders of magnitude too small

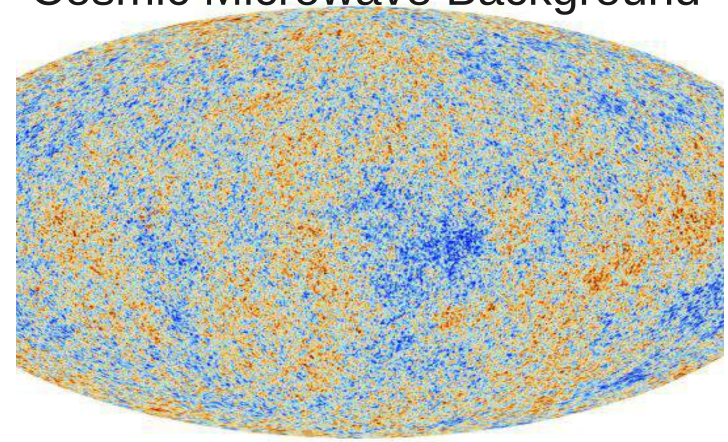
3) fulfilled for $m_{Higgs}$ < 70 GeV

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

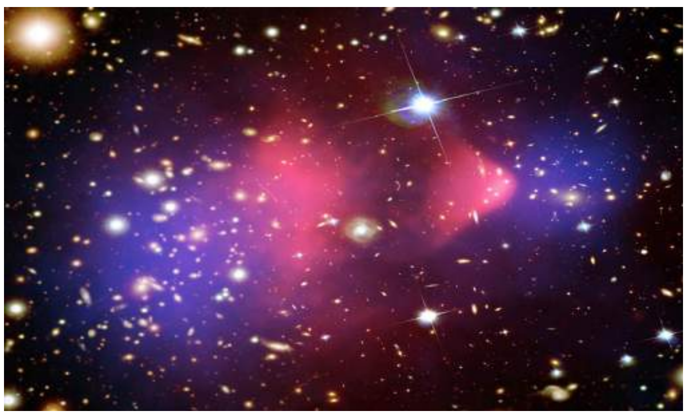
Rotational velocity of stars in galaxies



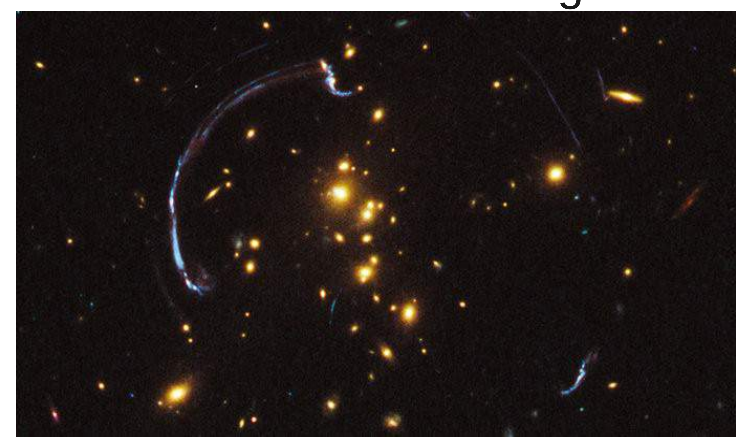

Cosmic Microwave Background



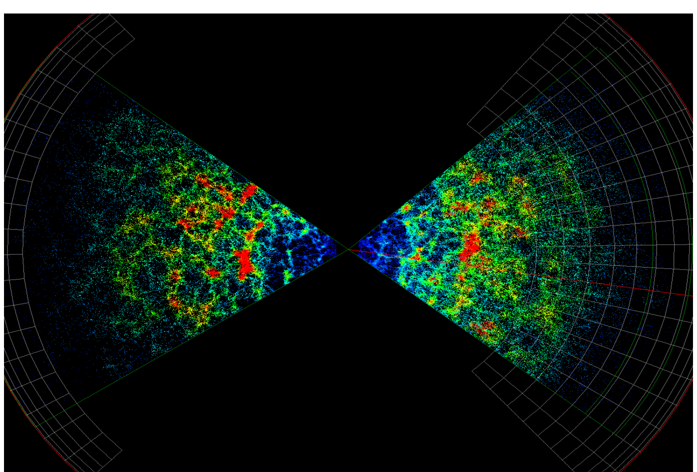
Bullet Cluster

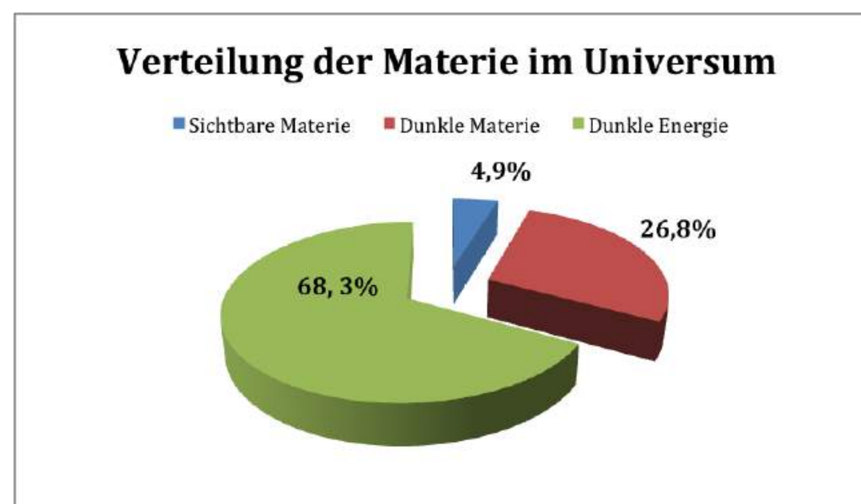


Gravitational Lensing

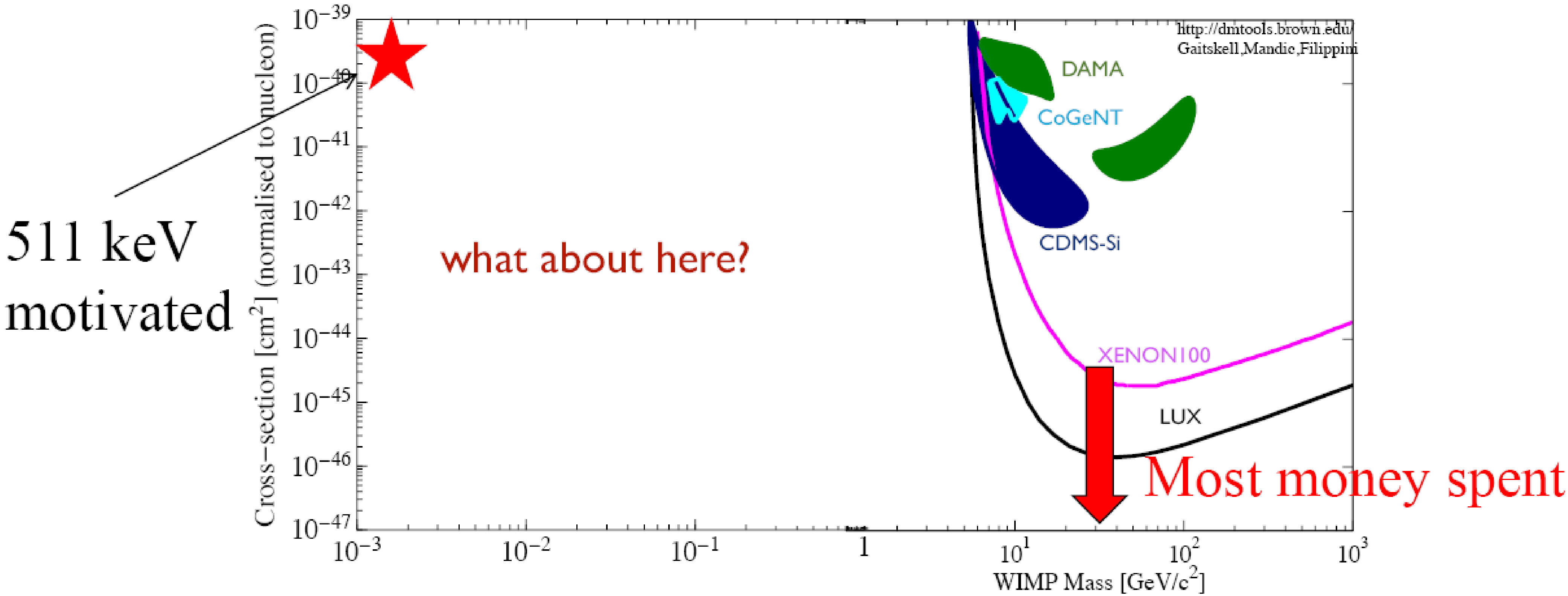


Matter distributions in the universe





# 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 $m_{Higgs}$=126 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

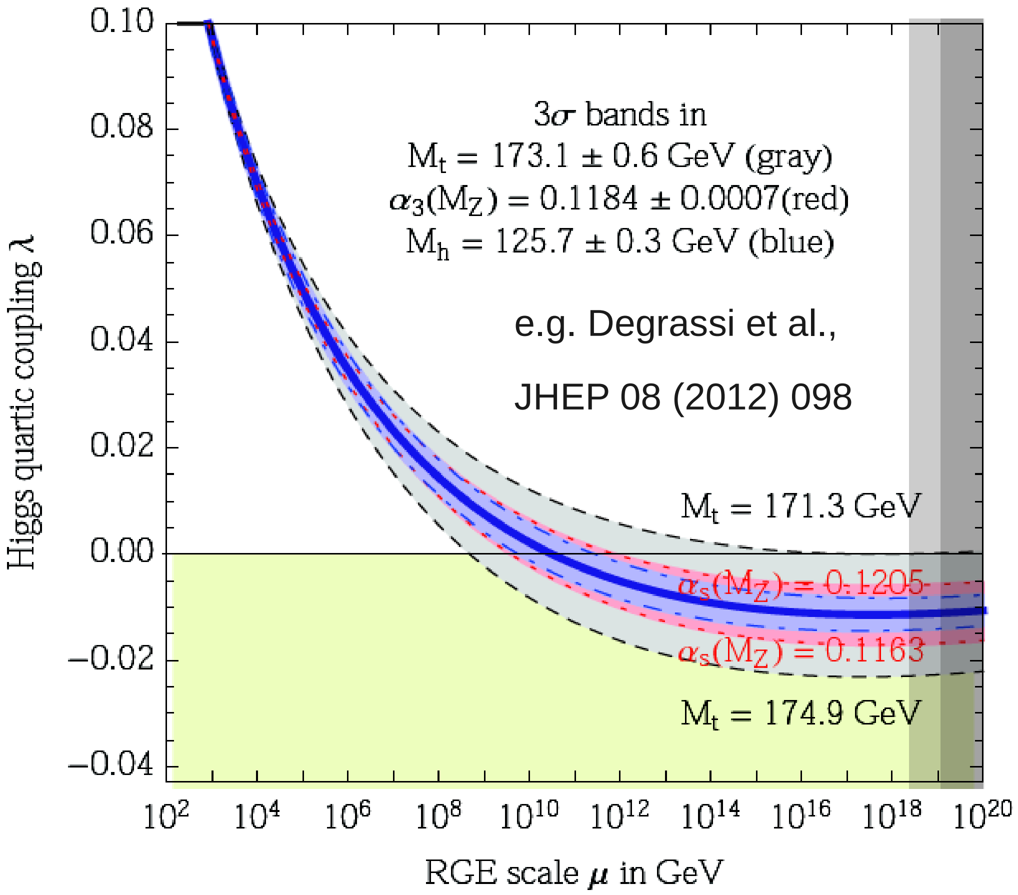
* Different sizes of interaction couplings

* 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

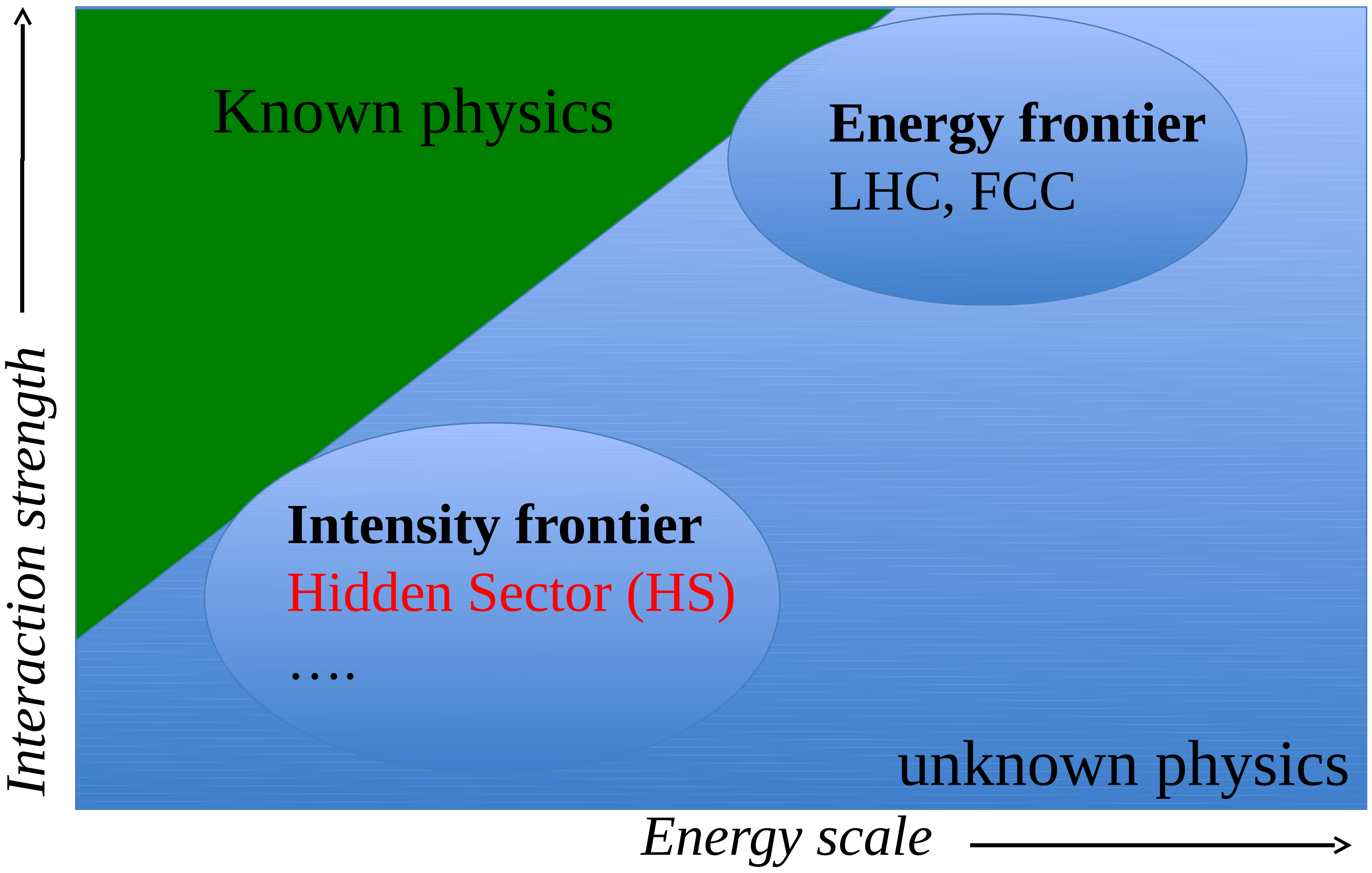
**Shaposhnikov, Wetterich (Phys. Lett. B683: 196-200, 2010): $M_{Higgs}$=126 GeV**




→ **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

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

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

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

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

- **Production through meson decays ($\pi$, 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 | $\ell^{\pm}\pi^{\mp}, \ell^{\pm}K^{\mp}, \ell^{\pm}\rho^{\mp}, \quad \rho^{\pm} \to \pi^{\pm}\pi^{0}$ |
| Vector, scalar, axion portals, SUSY sgoldstino | $\ell^{+}\ell^{-}$ |
| Vector, scalar, axion portals, SUSY sgoldstino | $\pi^{+}\pi^{-}, K^{+}K^{-}$ |
| Neutrino portal ,SUSY neutralino, axino | $\ell^{+}\ell^{-}\nu$ |
| Axion portal, SUSY sgoldstino | $\gamma\gamma$ |
| SUSY sgoldstino | $\pi^{0}\pi^{0}$ |

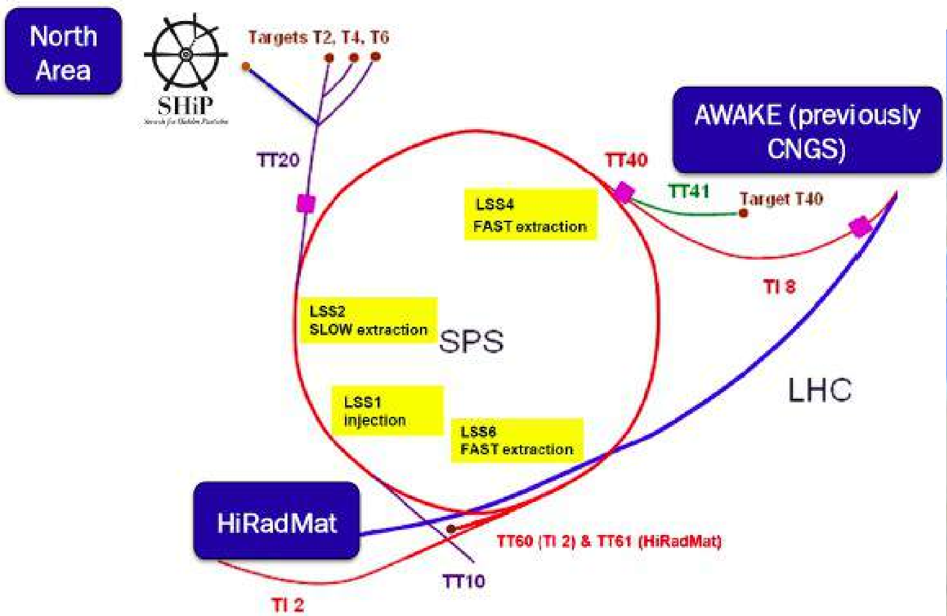
- **Full reconstruction and particle identification to distinguish btw models**

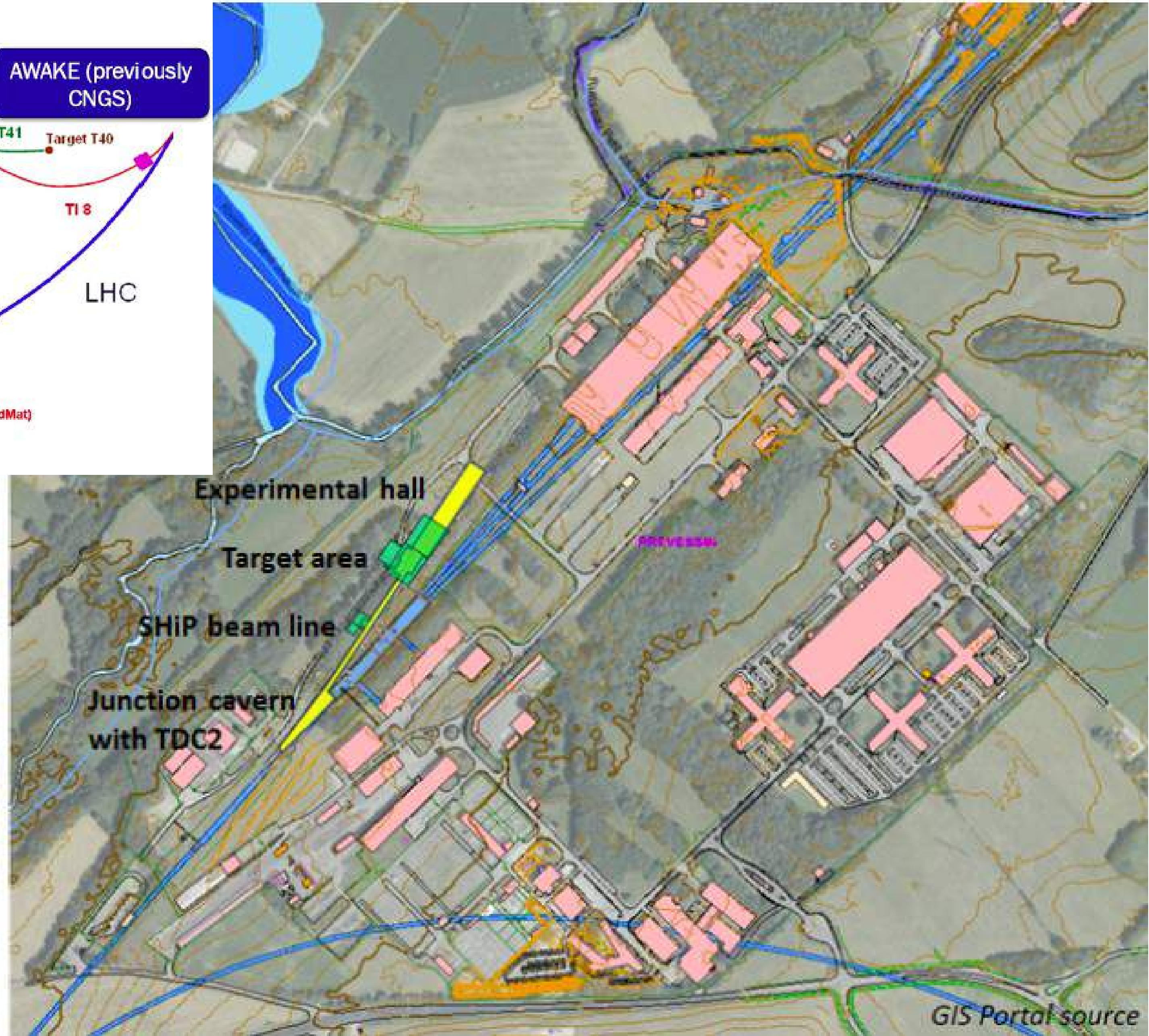
- **Goal: BG  < O(0.1)**

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

**Proposed implementation is based on minimal modification to the SPS complex**

High-intensity proton beam: $4\times10^{13}$ p/spill, $4\times10^{19}$ pot/yr, 5 years run → $2\times10^{20}$ pot



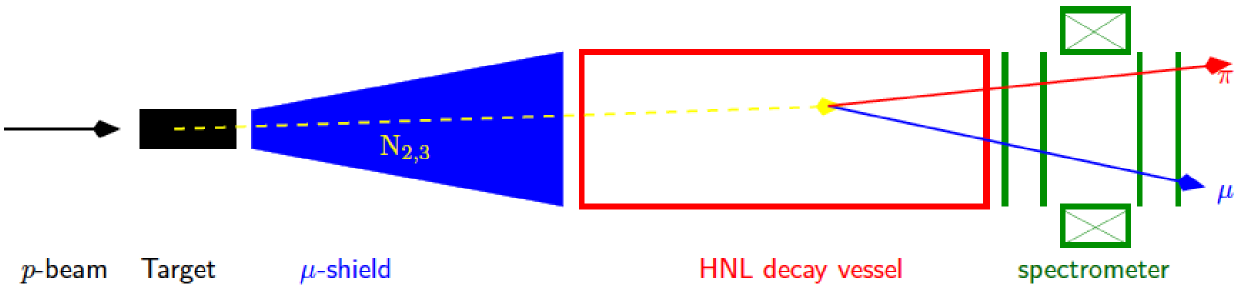



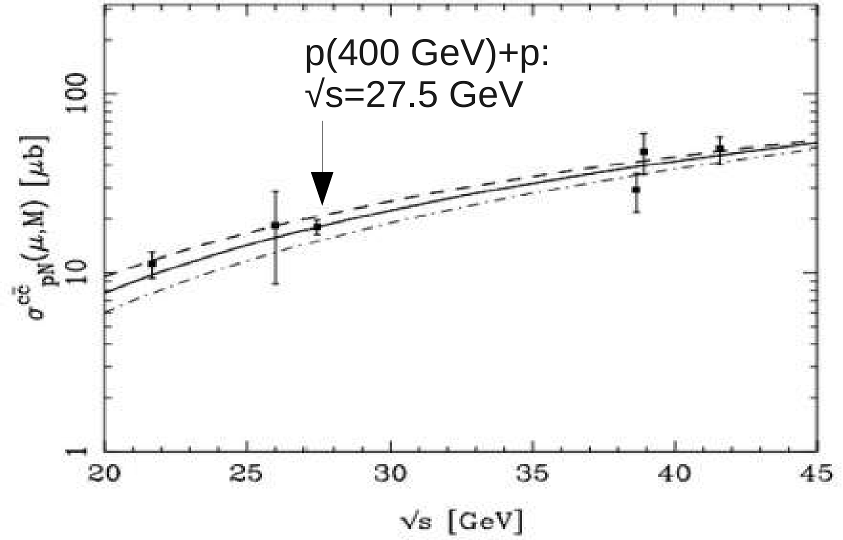

**The SHiP facility would share the TT20 transfer line and slow extraction mode with the fixed-target programmes**

# General experimental requirements

- **HS particles produced in c/b-quark decays**

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

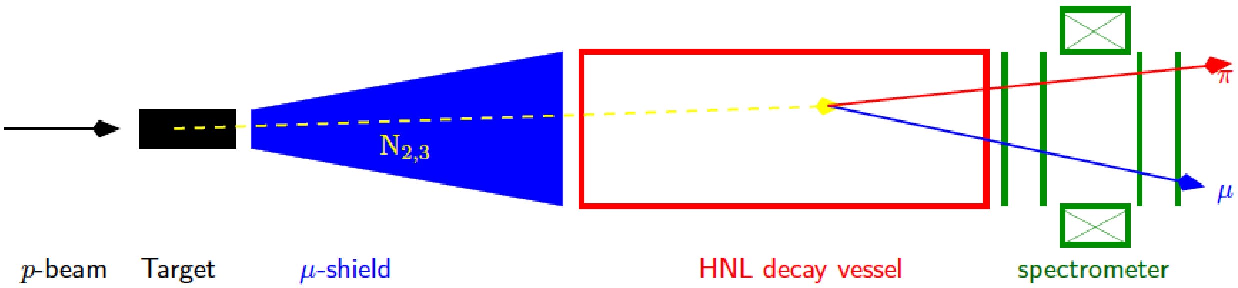


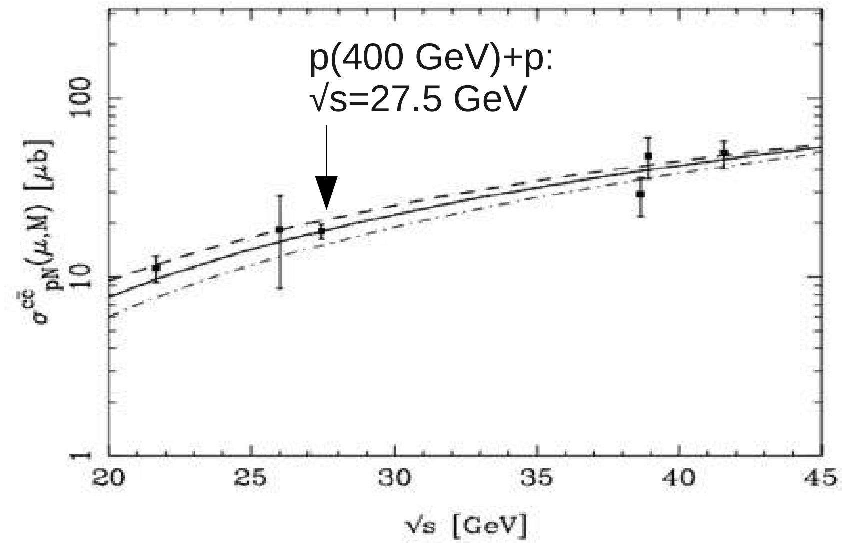



# General experimental requirements

- **HS particles produced in c/b-quark decays**

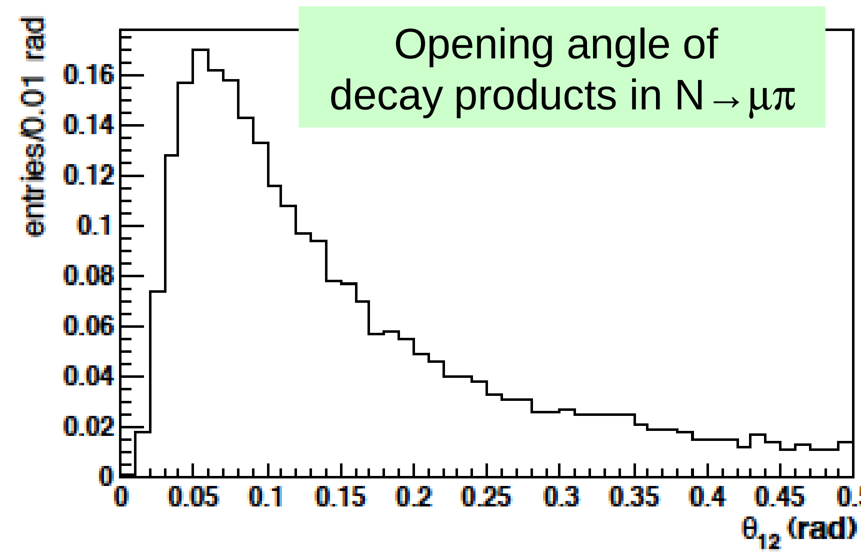
  → **CERN SPS well suited:**
  **High-intensity 400 GeV proton beam**




- **HS particles from c/b-hadron decays have significant transverse momenta**

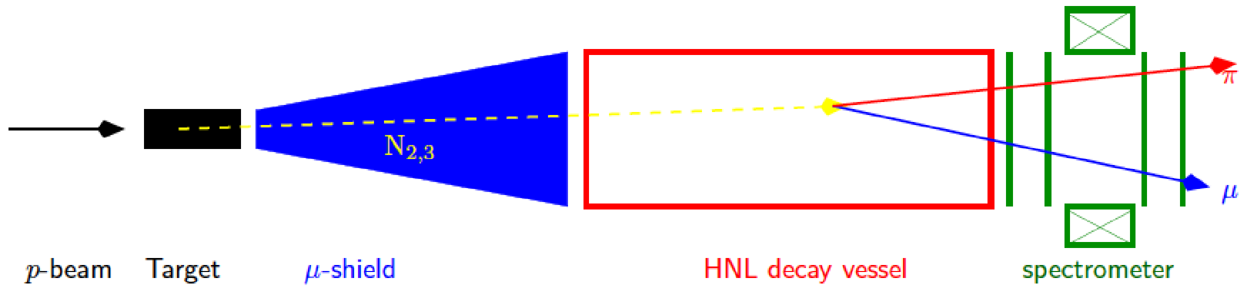
- **Decay products from HS particle decays have significant transverse momenta**

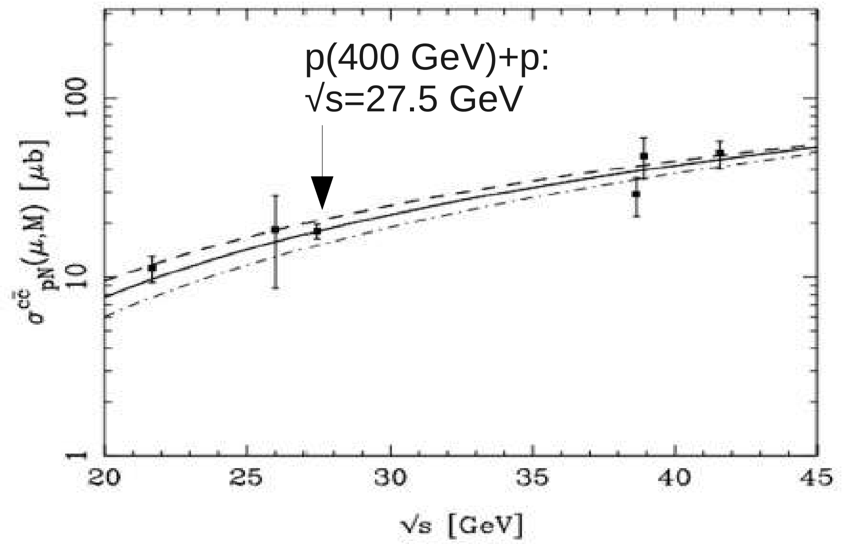


# General experimental requirements

- **HS particles produced in c/b-quark decays**

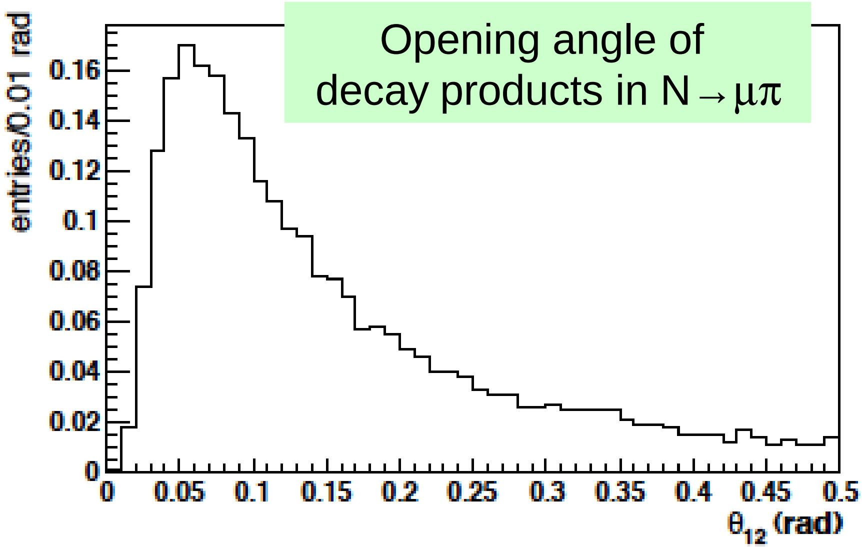
  → **CERN SPS well suited:**
  **High-intensity 400 GeV proton beam**




- **HS particles from c/b-hadron decays have significant transverse momenta**

- **Decay products from HS particle decays have significant transverse momenta**



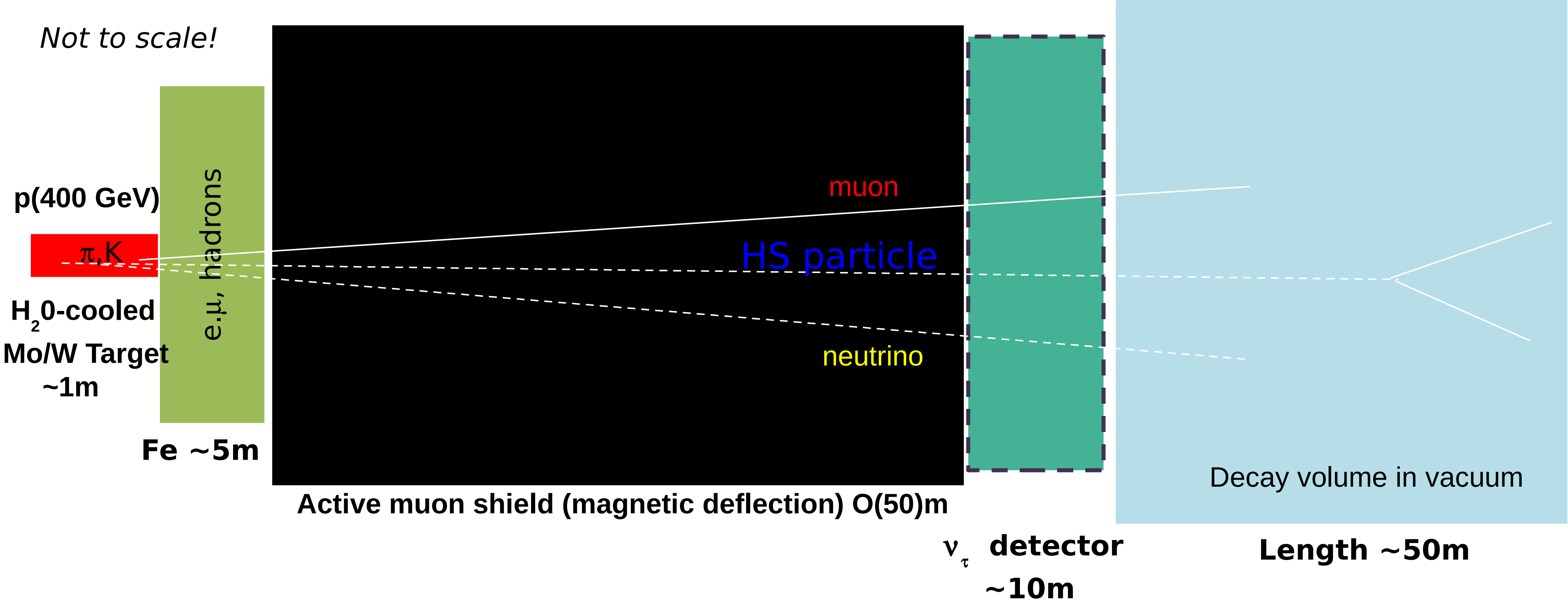

- **Detector must be close to the target to maximize geometrical acceptance**

ü **Effective (and “short”) muon shield is essential to reduce μ-induced backgrounds**

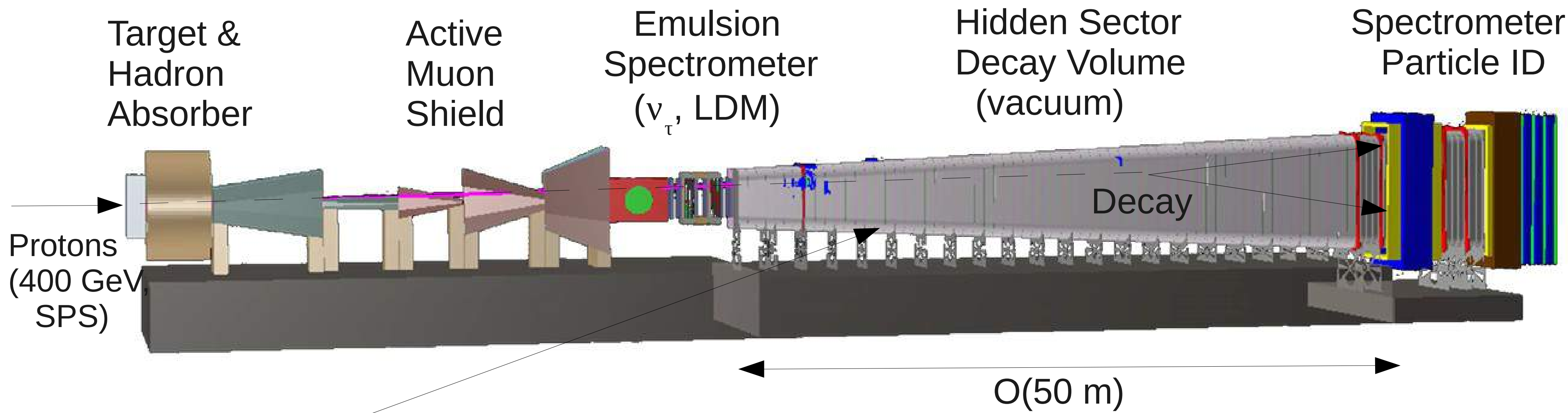
# SHiP beamline

**Initial reduction of beam induced backgrounds**

- Heavy target → large c/b-quark production & reduces neutrinos from $\pi/K \rightarrow \mu\nu$
- Hadron absorber
- Effective muon shield (w/o shield: $\mu$ rate ~$10^{10}$ per spill of $4\times10^{13}$ pot)
- Slow (and uniform) beam extraction (~1s) to reduce occupancy in the detector and power deposit in the target (2-3 MW)



# SHiP experiment (as implemented in GEANT4)



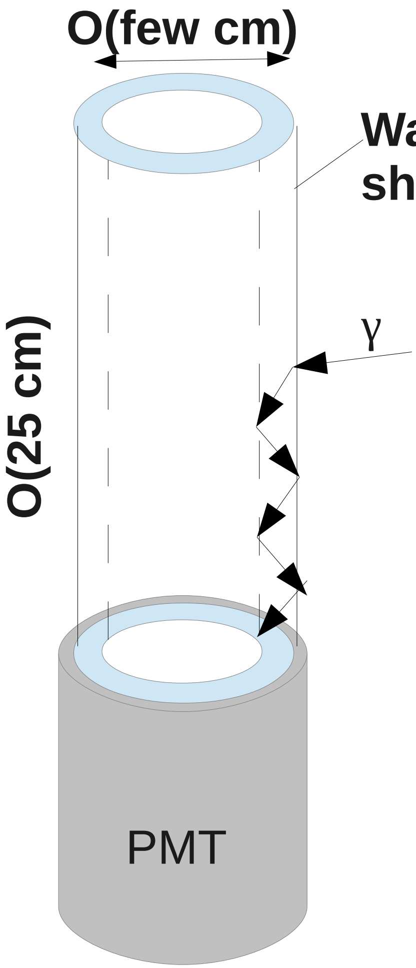

Surrounding Background Tagger
(Berlin, Mainz: Liquid-Scintillator based)

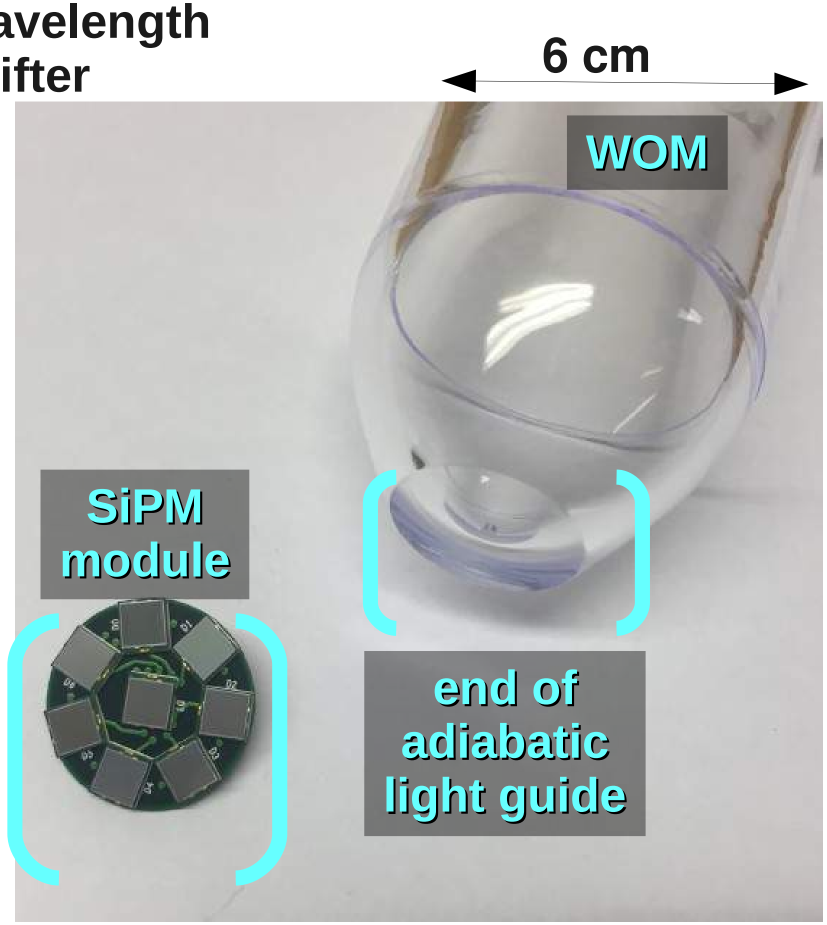
# Surrounding Background Tagger

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

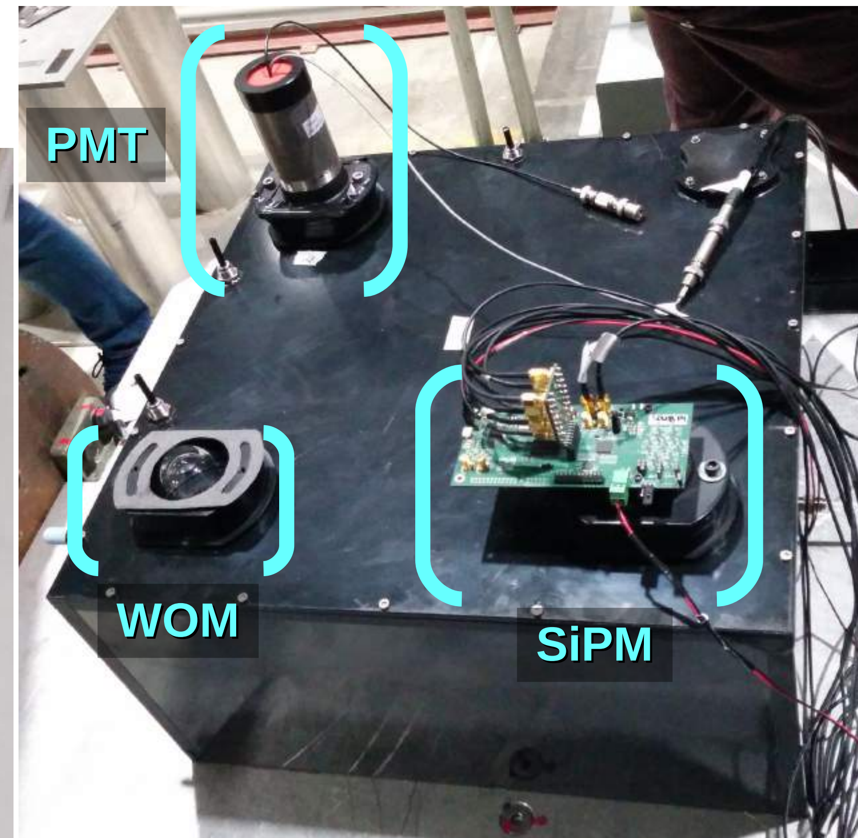
Increase effective photodetector area using Wavelength-shifting Opical Modules (WOM)

WOM principle




Test detector @ CERN SPS testbeam (September 2017)



# Neutrino Physics with the emulsion spectrometer

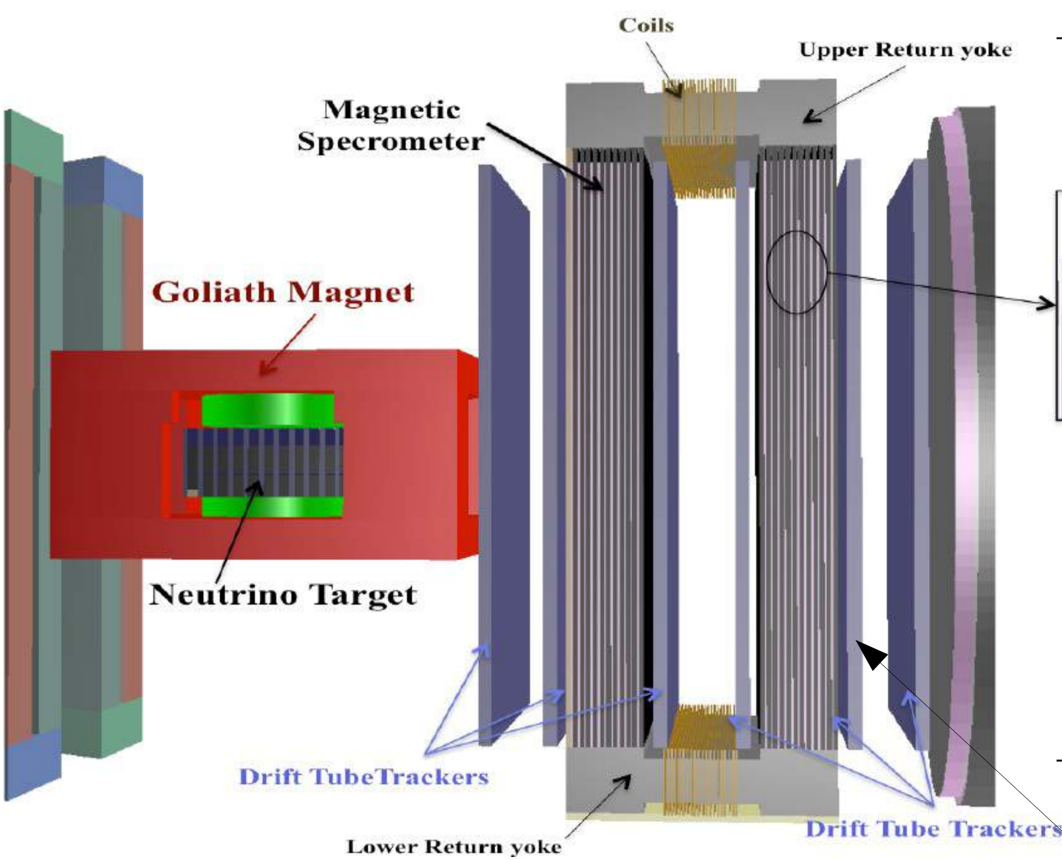
Up to now only a handful of $\nu_\tau$ interactions detected (DONUT, OPERA)

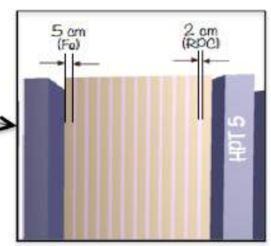
- 6700 $\nu_\tau$ + 3400 $\bar{\nu}_\tau$ (for the $1^{st}$ time) CC interactions in 5 years of running
- Deep-Inelastic Scattering: nucleon structure functions $F_{4,5}$ accessible for the $1^{st}$ time
- Limits on $\nu_\tau$ magnetic moment

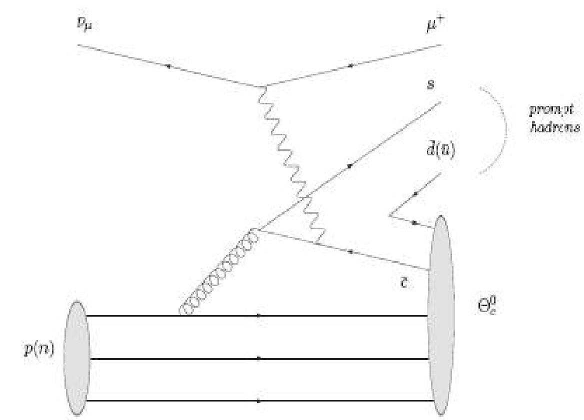
Huge flux of $\nu_\mu/\bar{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$ from $\pi$/K decays

→ $1.1 \times 10^5$ events with charm-quark hadrons:

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




Limit improvement wrt CHORUS: $10^3$

→ Check NuTeV anomaly with more precision

U Hamburg

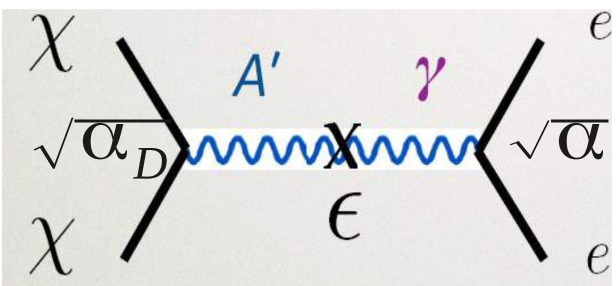
# Example of Dark matter search with the emulsion spectrometer

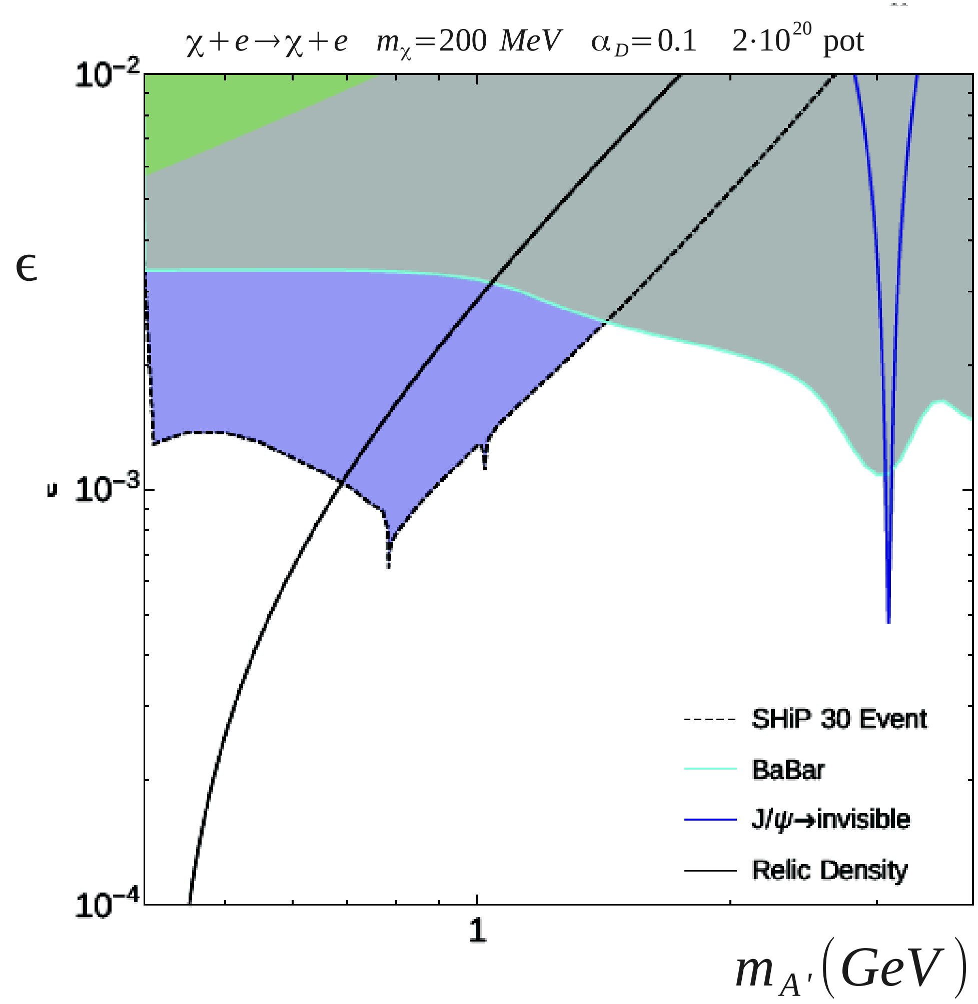
Dark matter ($\chi$) might couple to SM particles by "dark" photons A' (as mediator)

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 $\chi + e \rightarrow \chi + e$



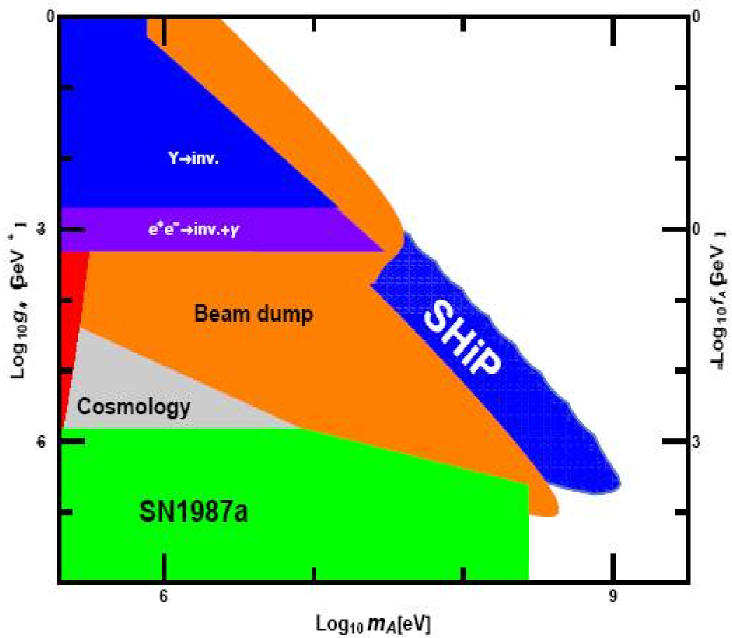




Relic density determined by annihilation XS:

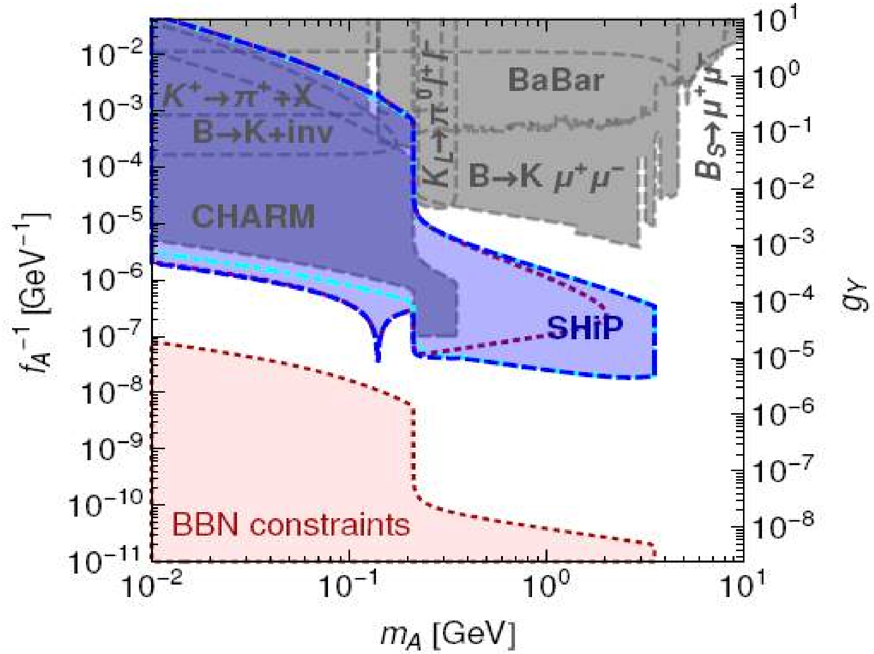
$$<\sigma \cdot v> \propto \alpha_D \epsilon^2 \alpha \frac{m_\chi^2}{m_{A'}^4}$$

# Physics reach with HS detector: selected examples

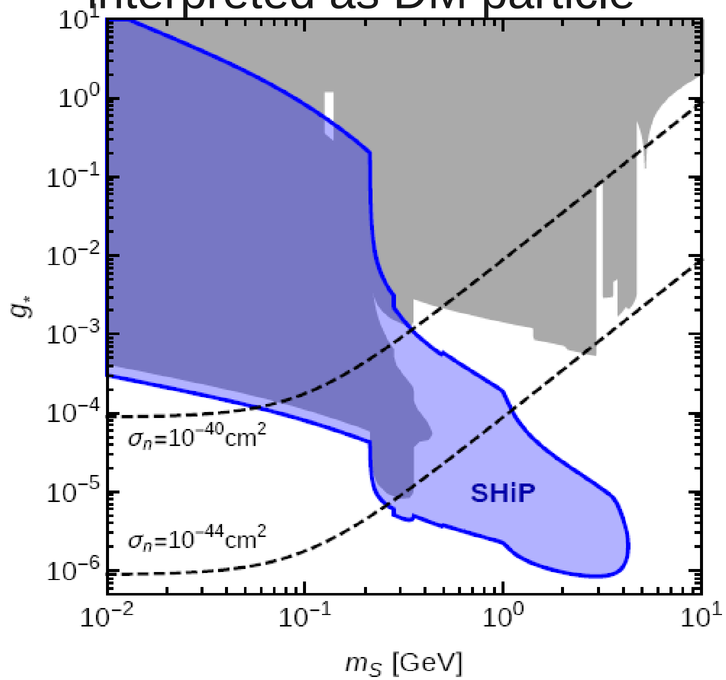
Pseudo-scalar ALP → γγ/VV



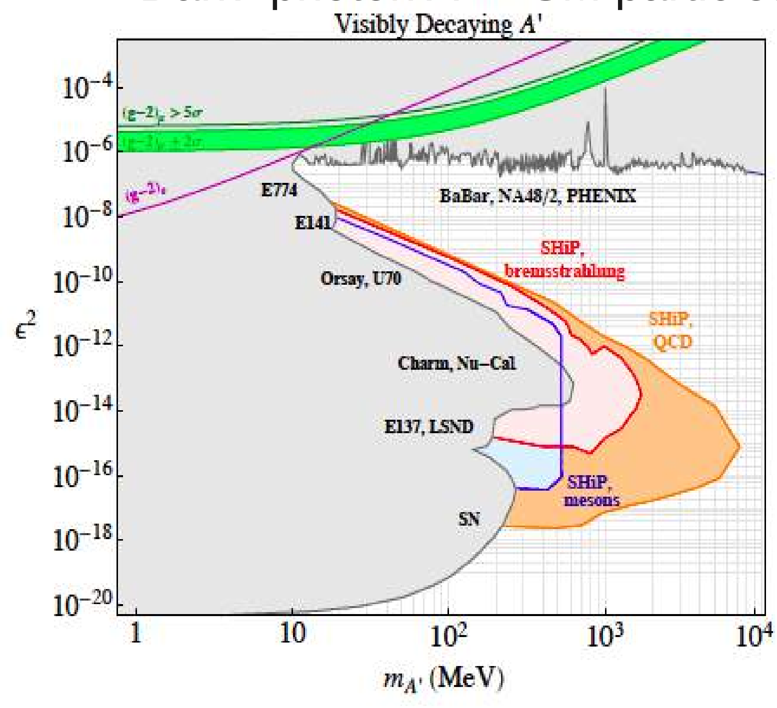

ALP → fermion anti-fermion



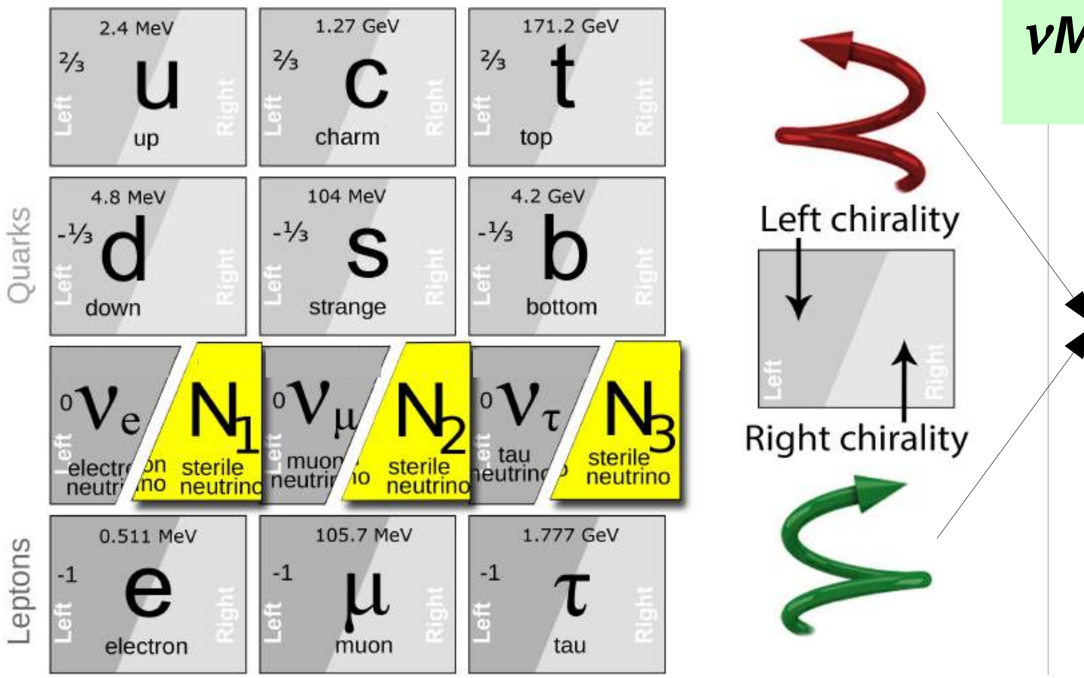

Light scalar → SM particles
interpreted as DM particle




“Dark” photon A' → SM particles



# The νMSM model



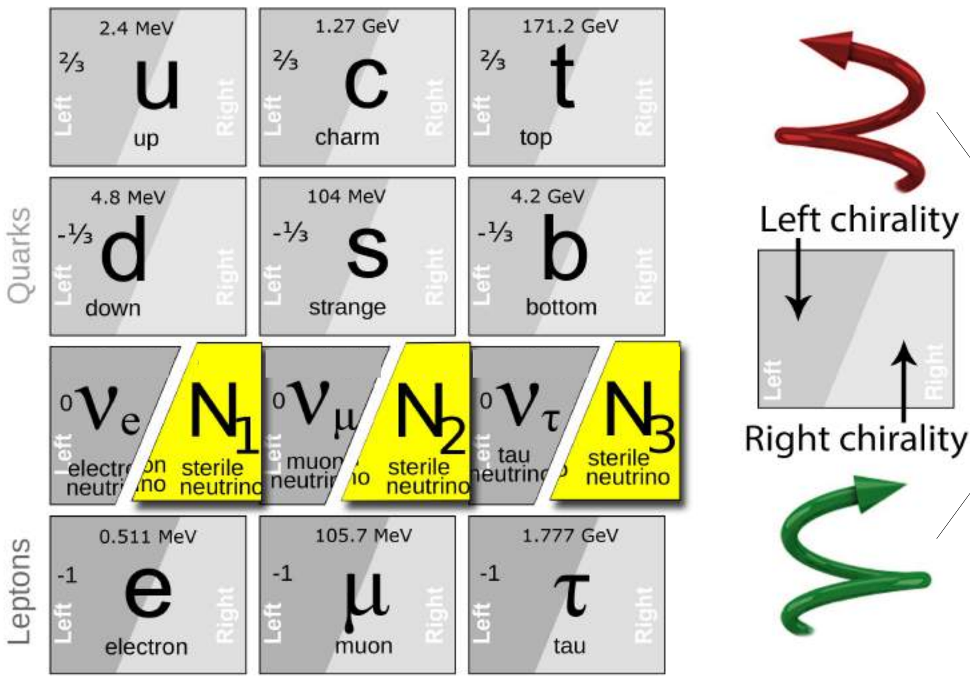

***νMSM:*** *T. Asaka, M. Shaposhnikov PL* ***B620*** *(2005) 17*
*M. Shaposhnikov Nucl. Phys. B763 (2007) 49*

**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 νMSM model

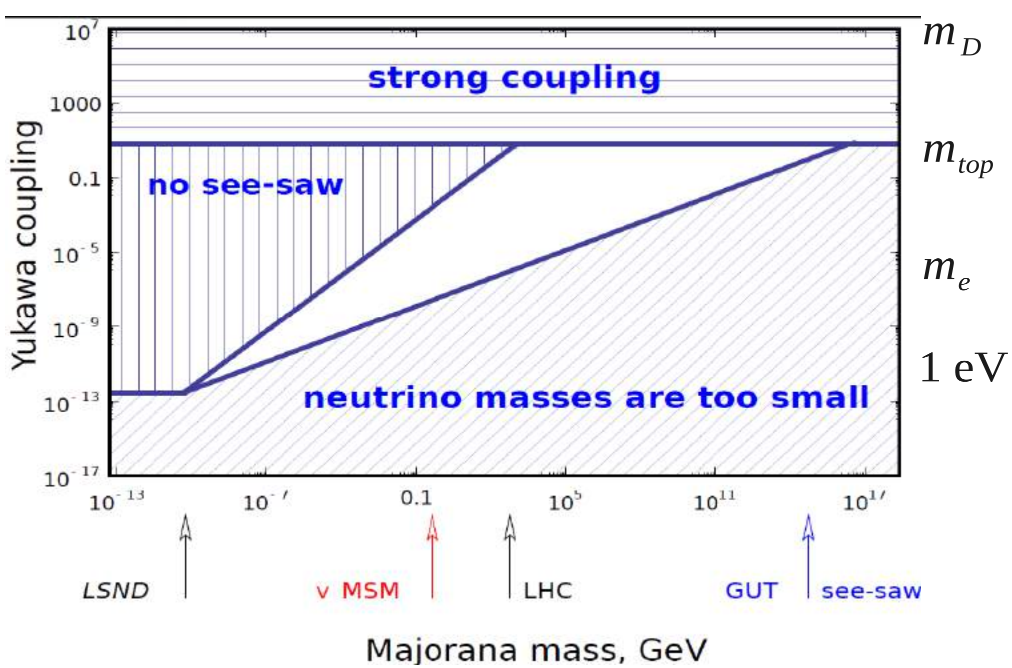



***νMSM:*** *T. Asaka, M. Shaposhnikov PL* ***B620*** *(2005) 17*
*M. Shaposhnikov Nucl. Phys. B763 (2007) 49*

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

**seesaw mechanism → tiny ν-masses:**

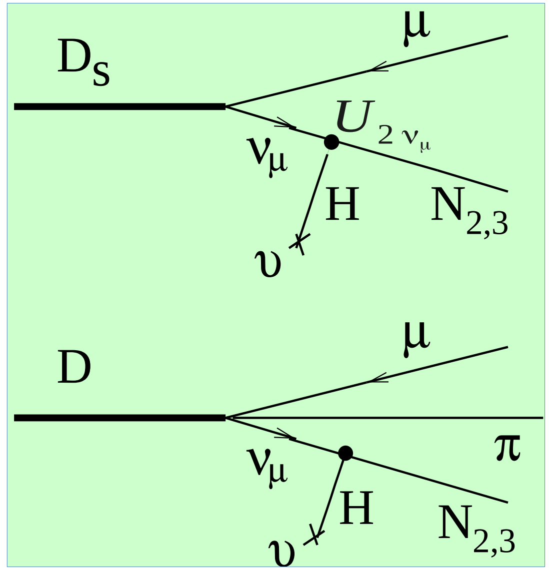
$$m_\nu \approx m_D \frac{m_D}{M_M}, \quad m_N \approx M_M$$



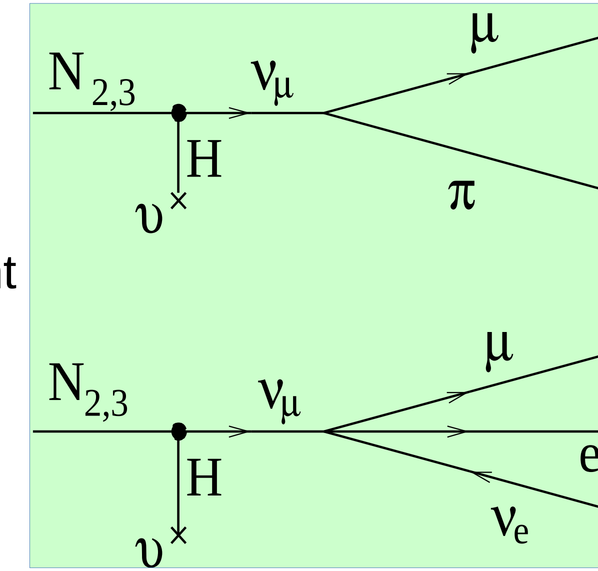

- **$N_{2,3}$ ~ 0.1 – several GeV: ν masses & BAU**
- **$N_1$ ~O(keV): dark matter candidate ( 3.5 keV line in galaxies & galaxy clusters?)**
- **Higgs: - masses of quarks, leptons, Z/W**
  **- inflaton**

# Masses and couplings of HNLs

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




and subsequent decays




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

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

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

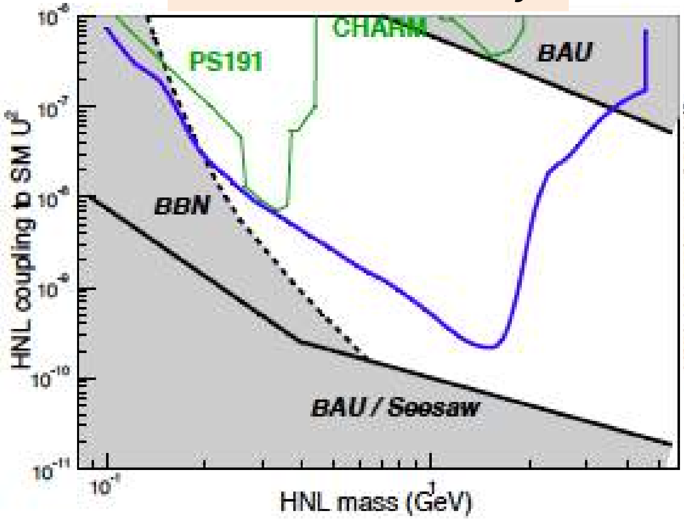
- **Typical lifetimes > 10 $\mu$s for M($N_{2,3}$) ~ 1 GeV**
  **Decay distance O(km)**

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

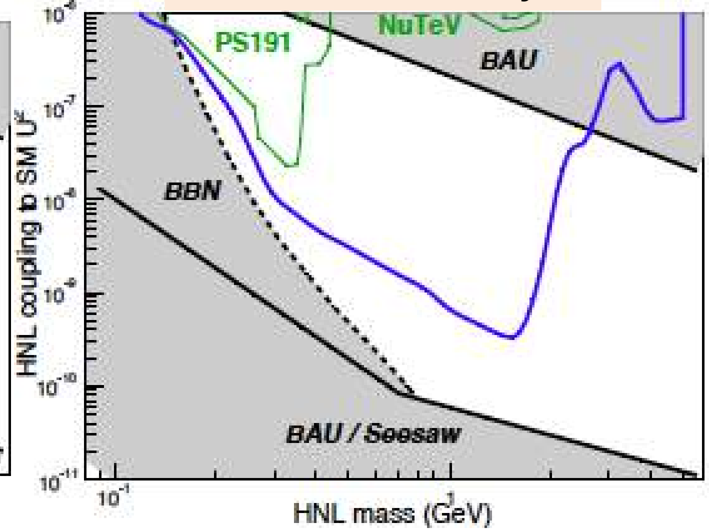
  **Br(N→ $\mu$/e $\pi$ ) ~ 0.1 – 50%**
  **Br(N →$\mu$/e $\rho$) ~ 0.5 – 20%**
  **Br(N →$\nu\mu$e) ~ 1 – 10%**

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

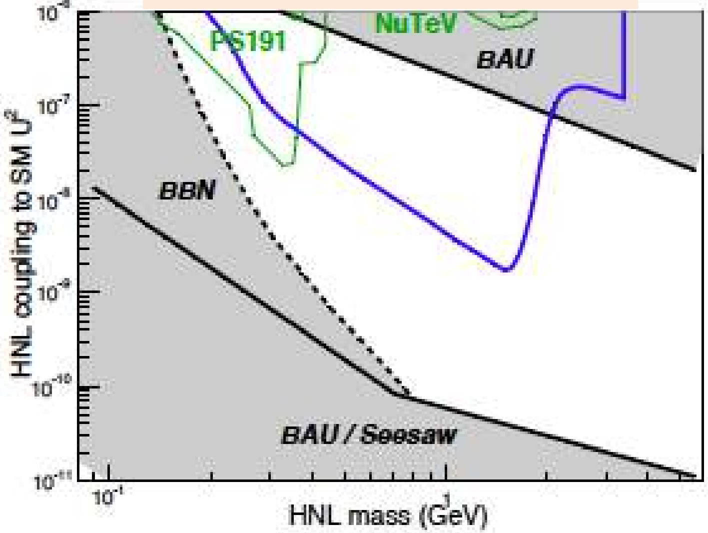
$U^2_e : U^2_\mu : U^2_\tau \sim 52:1:1$
*Inverted hierarchy*




$U^2_e : U^2_\mu : U^2_\tau \sim 1:16:3.8$
*Normal hierarchy*

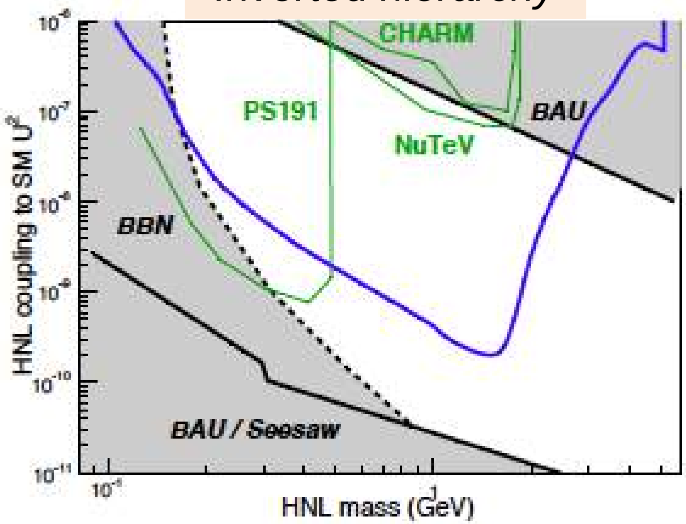



$U^2_e : U^2_\mu : U^2_\tau \sim 0.061:1:4.3$
*Normal hierarchy*

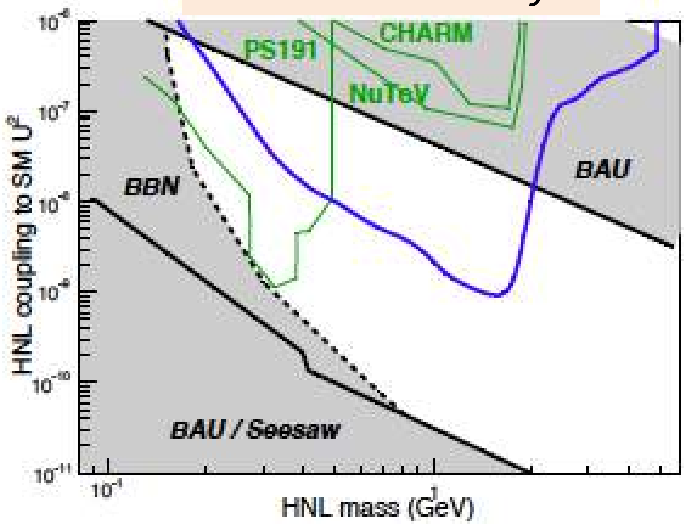



Model parameters for which BAU works

$U^2_e : U^2_\mu : U^2_\tau \sim 48:1:1$
*Inverted hierarchy*




$U^2_e : U^2_\mu : U^2_\tau \sim 1:11:11$
*Normal hierarchy*



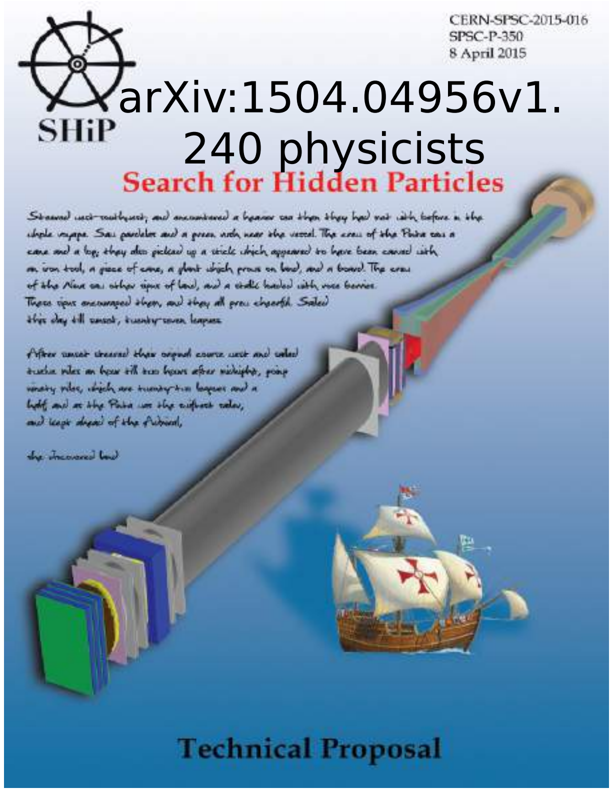
# Evolution of the Project

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

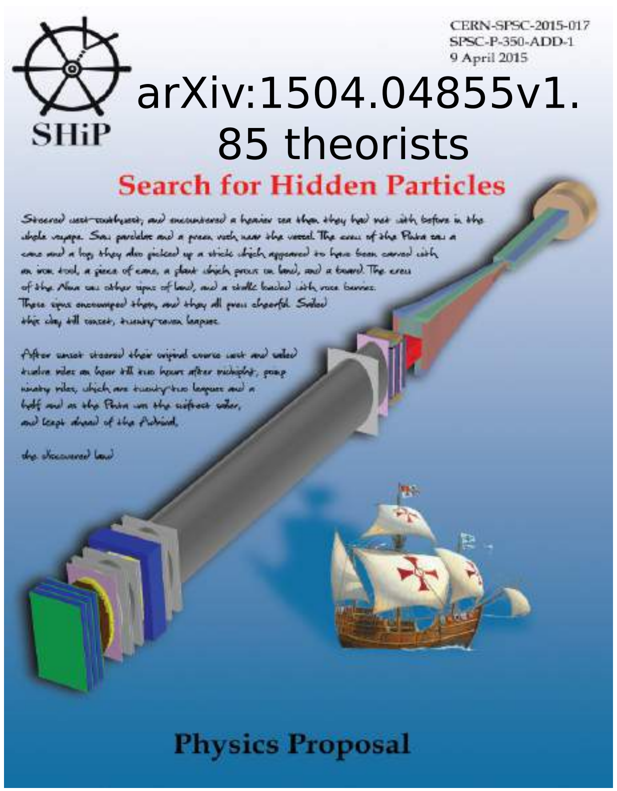
**12/2014: Foundation of the SHiP Collaboration**

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

**04/2015:**




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 $\nu_\tau$ physics
- SHiP will greatly complement NP searches at the energy frontier at CERN
- Interesting sensitivity (~$10^{-10}$) 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