# New physics models available for tesing with SHiP experiment

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HEPD seminar

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# Outline

1. Where is new physics ?
2. Neutrino oscillations: NP is below EW scale
3. Elusive NP: portals to a hidden World
   - To be tested at fixed target
   - $\nu$MSM: 3 in 1 flask
     (neutrino oscillations, dark matter, baryon asymmetry of the Universe)
   - Light Inflaton
   - Light sgoldstinos
   - Light neutralinos with *R*-parity violation
   - Para-, Dark, Hidden, Massive photon
4. Summary

# Standard Model: Success and Problems

Gauge fields (interactions): $\gamma$, $W^{\pm}$, $Z$, $g$

Three generations of matter: $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$, $e_R$; $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, $d_R$, $u_R$

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe
  - Neutrino oscillations
  - Dark matter ($\Omega_{DM}$)
  - Baryon asymmetry ($\Omega_B$)
  - Inflationary stage
  - Dark energy ($\Omega_\Lambda$)
  - Strong CP: boundary terms, new topology, ...
  - Gauge hierarchy: No new scales!
  - Quantum gravity

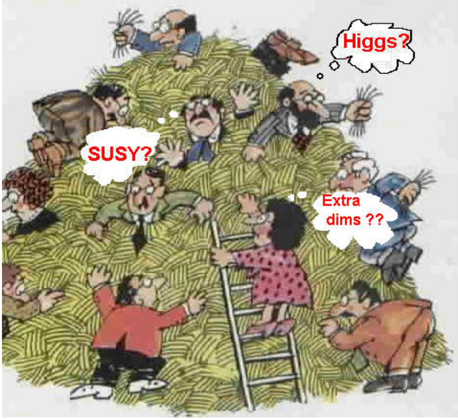
Try to explain all above

Low-energy supersymmetry ??

Planck-scale physics saves the day

# Outline

# Searches at LHC




Finally…
Higgs boson has been recognized

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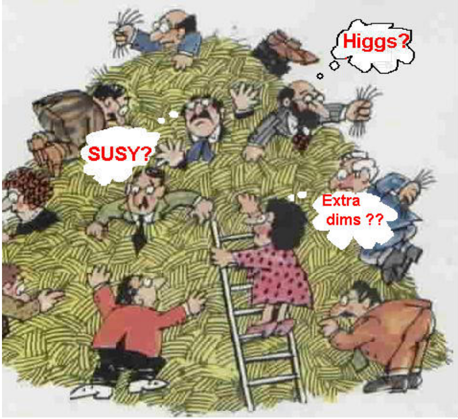


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# RG evolution of the SM couplings

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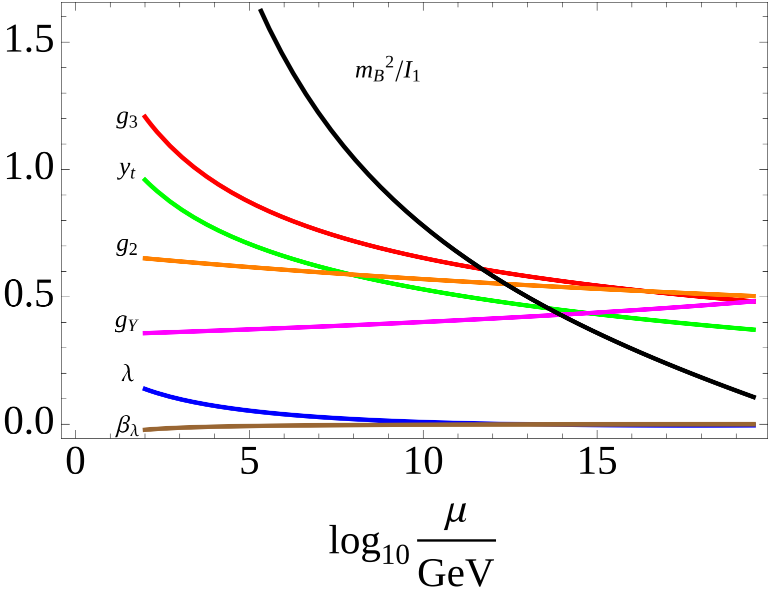
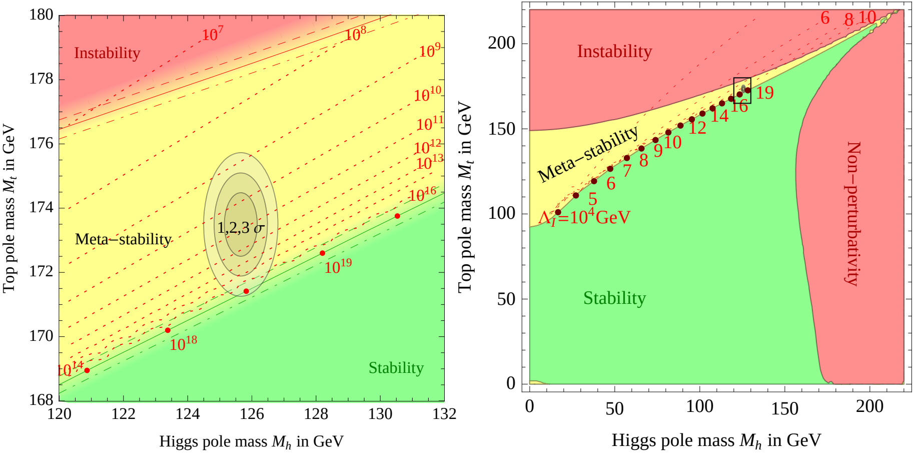


# How “natural” the 126 GeV. . .




1307.7879

# At the crossroads

## What we have at present

- We certainly need NP
- Any NP coupled to Higgs contribute
  to the Higgs boson mass, which is 126 GeV
- No clear signal of NP
  (no SUSY) at 8 TeV

## Logically possible ways out

- NP is lurking at 13 TeV
  (why hidden so well at 8 TeV ?)
  (why no hints in flavor ?)
- NP is
  at the gravity (Planck) scale
  and gravity
- NP is below EW scale

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# Active neutrino masses without new fields

Dimension-5 operator $\Delta L = 2$

$$\mathscr{L}^{(5)} = \frac{F_{\alpha\beta}}{4\Lambda} \bar{L}_\alpha \tilde{H} H^\dagger L^c_\beta + \text{h.c.}$$

$L_\alpha$ are SM leptonic doublets, $\alpha = 1,2,3$, $\tilde{H}_a = \varepsilon_{ab} H^*_b$, $a,b = 1,2$; in a unitary gauge $H^T = \left(0, (v+h)/\sqrt{2}\right)$ and

$$\mathscr{L}^{(5)}_{\nu\nu} = \frac{v^2 F_{\alpha\beta}}{4\Lambda} \times \frac{1}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.} = m_{\alpha\beta} \times \frac{1}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.}$$

where

$\Lambda$ is the scale of new dynamics

$F_{\alpha\beta}$ is the strength of new dynamics

only their ratio is fixed by the scale of active neutrino masses

# Perturbative regime for model parameters

$$F_{\alpha\beta} \lesssim 1 \qquad \Longrightarrow \qquad \Lambda \lesssim 3\times 10^{14}\,\text{GeV} \times \left(\frac{3\times 10^{-3}\,\text{eV}^2}{\Delta m^2_{\text{atm}}}\right)^{1/2}$$

The model has to be UV-completed at the scale $\Lambda \to$ New physics

- The scale is certainly below the Planck (string) scale, and hence is most probably at (below) EW scale
- Why no hints recognized at this scale?

couplings to the SM fields are tiny

- which probably implies not a GUT-like new physics (all is $\propto g$) hence coupling to new gauge singlets
- those are usually nonrenormalizable interactions. . . however, there are exceptions. . .

thus we arrive at the portals

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# Outline

# Three Portals to the hidden World

Renormalizable interaction including SM field and new (hypothetical) fields singlets with respect to the SM gauge group

Attractive feature: couplings are insensitive to energy in c.m.f., hence low energy experiments (intensity frontier) are favorable

- Scalar portal: SM Higgs doublet $H$ and hidden scalar $S$

  the simplest dark matter

$$\mathscr{L}_{\text{scalar portal}} = -\beta H^\dagger H S^\dagger S$$

- Spinor portal: SM lepton doublet $L$, Higgs congugate field $\tilde{H} = \varepsilon H^*$ and hidden fermion $N$

  sterile neutrino !!

$$\mathscr{L}_{\text{spinor portal}} = -y \bar{L} \tilde{H} N$$

- Vector portal: SM gauge field of $U(1)_Y$ and gauge hidden field of abelian group $U(1)'$

$$\mathscr{L}_{\text{vector portal}} = -\frac{\varepsilon}{2} B_{\mu\nu}^{U(1)_Y} B_{\mu\nu}^{U(1)'}$$

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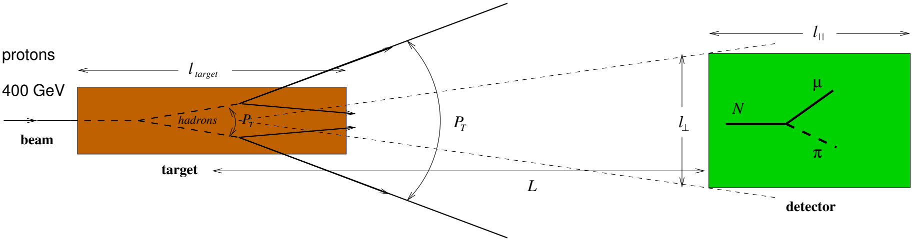
# The experiment under discussion: a scheme

fixed target | beam dump | vacuum volume



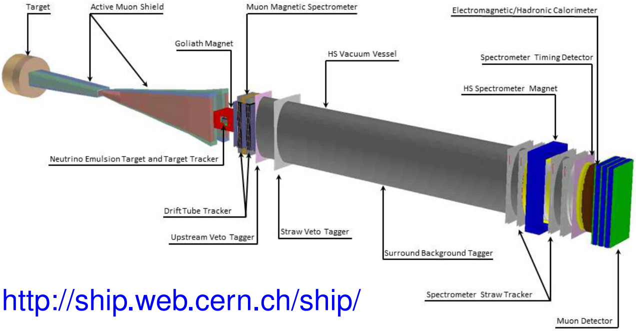

Searches for any BSM with

Neutral Unstable but Long Lived Particles Lighter than D-meson

# Towards the proposal

- $\nu$MSM: T.Asaka, S.Blanchet, M.Shaposhnikov (2005), T.Asaka, M.Shaposhnikov (2005),
- direct tests of $\nu$MSM: D.G., M.Shaposhnikov (2007)
- proposal for direct searches, to European Strategy Group, 2012 D.G., M.Shaposhnikov
- sketch of realistic experiment S.Gninenko, D.G., M.Shaposhnikov (2013)
- Expression Of Interests: Proposal to Search for Heavy Neutral Leptons at the SPS
  W. Bonivento, . . . D.G., et al, 1310.1762
- Technical Proposal and Physics Paper 1504.04956, 1504.04855
- included in the CERN GreyBook (2016) → 2026 46 institutes from 16 countries

SHiP
Search for Hidden Particles




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

# Physics to be tested

- weak interactions (neutrino beam scatterings off matter)
- light, feebly interacting, yet unstable particles:
  produced (in)directly on target, then decaying in the detector fiducial volume
  - light sgoldstinos (superpartners of goldstino in SUSY models)
    e.g., D.S. Gorbunov (2001) — e.g. $D \to \pi X$, then $X \to l^+ l^-$
  - R-parity violating neutralinos in SUSY models
    e.g., A. Dedes, H.K. Dreiner, P. Richardson (2001) — e.g. $D \to l \tilde{\chi}$, then $\tilde{\chi} \to l^+ l^- \nu$
  - massive paraphotons (in secluded dark matter models)
    e.g., M. Pospelov, A. Ritz, M.B. Voloshin (2008) — e.g. $\Sigma \to p V$, then $V \to l^+ l^-$
- light, fairly weakly interacting, unstable particles:
  produced in beam dump (rock), right in front of detector, then decaying in the detector fiducial volume
  - sterile neutrinos with transition dipole moments
    e.g., S.N. Gninenko (2009,2010) — $\nu A \to N A$, then $N \to \nu \gamma$

as compared to CHARM
longer lifetimes and smaller couplings will be accessible

Many examples can be found
in Physics Paper arXiv:1504.04855

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# Possible new physics: Sterile neutrinos

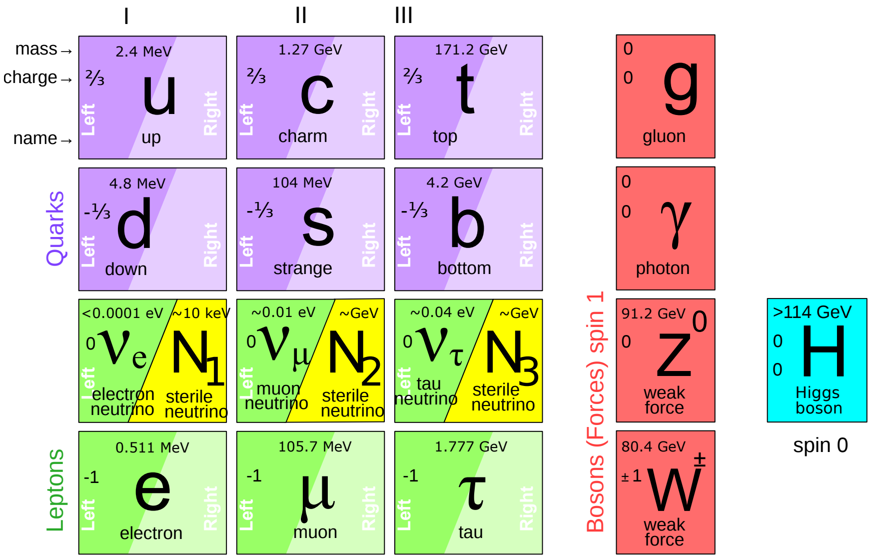
Minimal extension of SM to explain neutrino oscillations

sterile: new fermions uncharged under the SM gauge group
neutrino: explain observed oscillations by mixing with SM (active) neutrinos

Attractive features:

- only 3 Majorana fermions (6 d.o.f.) is enough
- true renormalizable theory not worth then the SM (e.g. may work up to the Planck scale)
- baryon asymmetry via leptogenesis through redistribution of the leptonic charge between active and sterile neutrinos and transfering of the lepton asymmetry into baryon asymmetry by electoweak sphalerons
- dark matter: lightest sterile neutrino (1-50 keV)

Three Generations
of Matter (Fermions) spin ½



# Seesaw type I mechanism: $M_N \gg m_{active}$

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.}$$

where $I = 1,2,3$ and $\alpha = e,\mu,\tau$ $\quad \tilde{H}_a = \varepsilon_{ab} H_b^*$

When Higgs gains $\langle H \rangle = v/\sqrt{2}$ we get in neutrino sector

$$\mathscr{V}_N = v\,\frac{f_{\alpha I}}{\sqrt{2}}\,\overline{\nu}_\alpha N_I + \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.} = \frac{1}{2}\left(\overline{\nu}_\alpha\,,\overline{N}_I^c\right)\begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^T}{\sqrt{2}} & \hat{M}_N \end{pmatrix}\left(\nu_\alpha^c\,,N_I\right)^{\mathrm{T}} + \text{h.c.}$$

Then for $M_N \gg \hat{M}_D = v\,\frac{\hat{f}}{\sqrt{2}}$ we find the eigenvalues:

$$\simeq \hat{M}_N \qquad \text{and} \qquad \hat{M}^\nu = -\hat{M}_D \frac{1}{\hat{M}_N}\hat{M}_D^T \propto f^2\,\frac{v^2}{M_N} \lll M_N$$

Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I} N_I$

active-active mixing: (PMNS-matrix $U$) $\qquad U^T \hat{M}^\nu U = diag\,(m_1\,,m_2\,,m_3)$

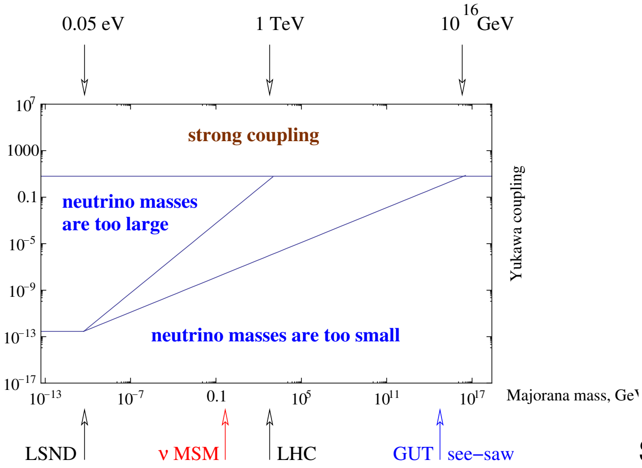
active-sterile mixing: $\qquad \theta_{\alpha I} = \frac{M_{D_{\alpha I}}}{M_I} \propto \hat{f}\,\frac{v}{M_N} \ll 1$

# Sterile neutrino mass scale: $\hat{M}_\nu = -v^2 \hat{f}^T \hat{M}_N^{-1} \hat{f}$

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}$ we can get a hierarchy in sterile neutrino masses, and 1 keV and even 1 eV sterile neutrinos

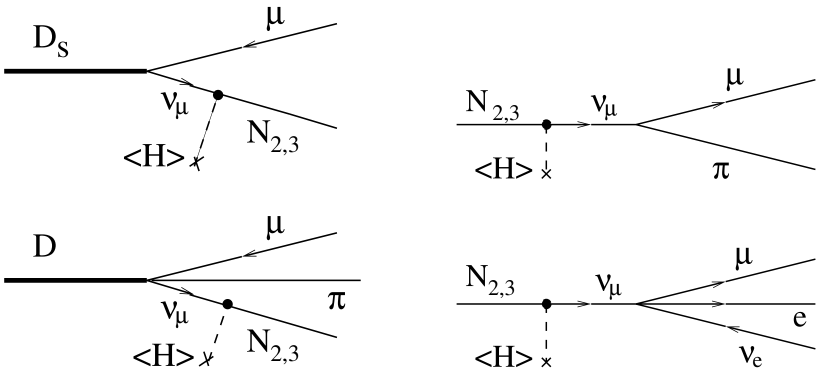
$L_e - L_\mu - L_\tau$ or discrete symmetries
Froggatt-Nielsen mechanism

Extended seesaw

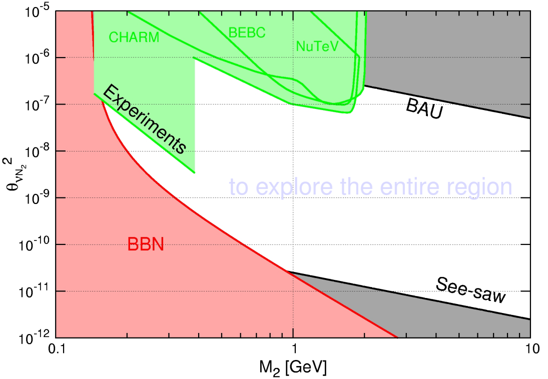



Seesaw diagram

# Sterile neutrinos: production and decays



# Probing leptogenesis SHIP upgrading to Aerocarrier




D.G, M.Shaposhnikov (2007)

lower bound at $\times 10^{-4}$

$$\mathrm{Br}\,(D \to lN) \lesssim 2 \cdot 10^{-8}$$

$$\mathrm{Br}\,(D_s \to lN) \lesssim 3 \cdot 10^{-7}$$

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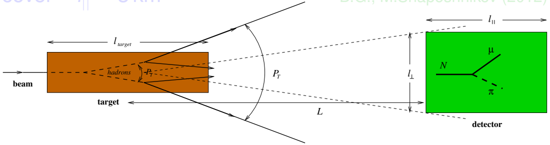
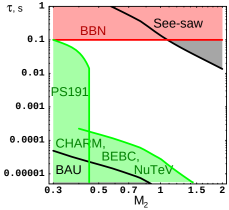
For $10^{20}$ PoT at 400 GeV (SPS) detectors have to cover $\quad l_{||} \sim 3$ km

D.G., M.Shaposhnikov (2012)



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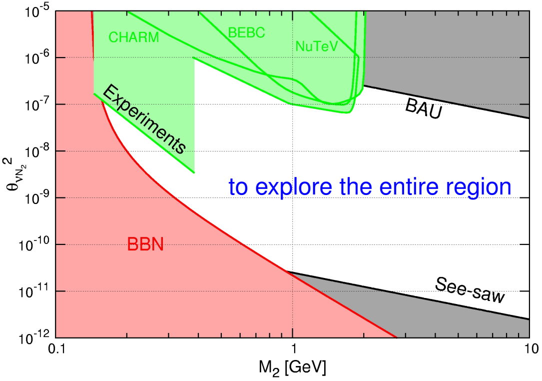


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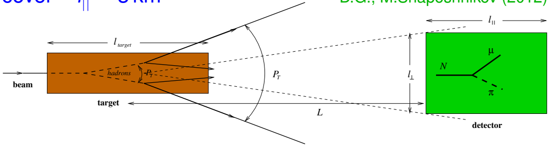
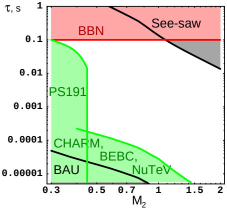
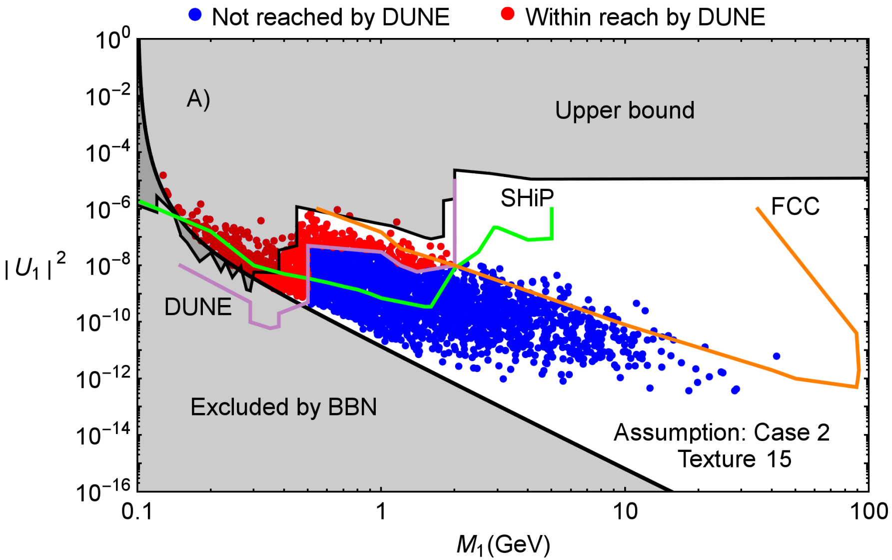


# Present status; $\sigma \propto \theta^2$, $\Gamma \propto \theta^2 M_N^5$

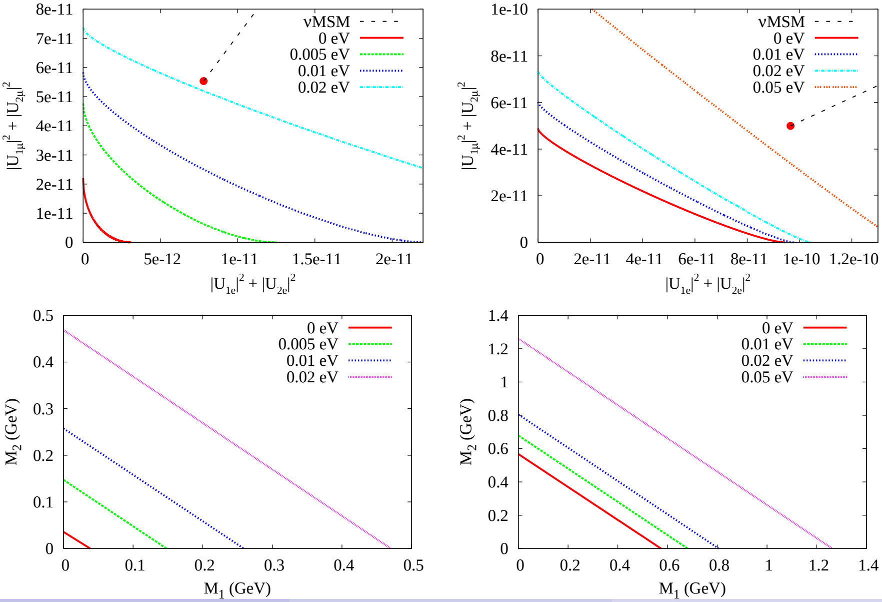
LBNE Collab (2011)




1607.07880

# Lowest mixing to falsify Seesaw type I

D.G., A.Panin (2013)



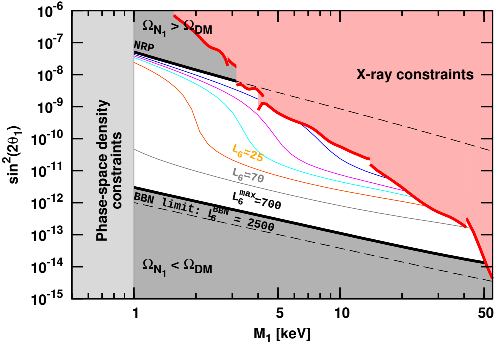
# Lightest sterile neutrino $N_1$ as Dark Matter

Non-resonant production (active-sterile mixing) is ruled out

D.G., A.Khmelnitsky, V.Rubakov (2008)

Resonant production (lepton asymmetry) requires $\Delta M_{2,3} \lesssim 10^{-16}$ GeV

arXiv:0804.4542, 0901.0011, 1006.4008




Dark Matter production from inflaton decays in plasma at $T \sim m_\chi$

M.Shaposhnikov, I.Tkachev (2006)

$$M_{N_I} \bar{N}_I^c N_I \leftrightarrow f_I X \bar{N}_I N_I$$

Can be "naturally" Warm

F.Bezrukov, D.G. (2009)

$$M_1 \lesssim 15 \times \left( \frac{m_\chi}{300 \text{ MeV}} \right) \text{keV}$$

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# Inflation & Reheating: the model

$$\mathscr{L}_{XN} = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2} m_X^2 X^2 - \frac{\beta}{4} X^4 - \lambda \left( H^\dagger H - \frac{\alpha}{\lambda} X^2 \right)^2$$

The SM-like vacuum of the scalar potential

$$v = \sqrt{\frac{2\alpha}{\beta\lambda}} m_X = 246 \text{ GeV}\,, \quad m_h = \sqrt{2\lambda}\, v\,, \quad m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}}$$

Higgs-inflaton ($h-\chi$) mixing angle

$$\theta = \sqrt{\frac{2\alpha}{\lambda}} = \frac{\sqrt{2\beta}\, v}{m_\chi} \sim 10^{-3} \times \left( \frac{100 \text{ MeV}}{m_\chi} \right)$$

Amplitude of primordial perturbations: $\beta \approx 1.5 \cdot 10^{-13}$

Only one free parameter!

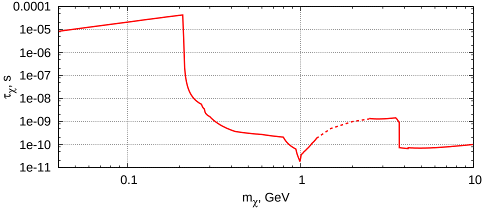
study of reheating:
A.Anisimov, Y.Bartocci, F. Bezrukov (2008)

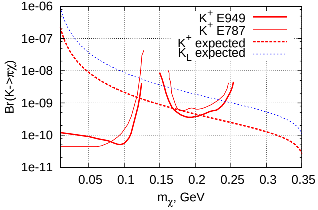
F.Bezrukov, D.G. (2009)

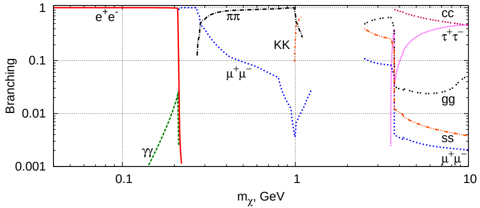
$30 \text{ MeV} \lesssim m_\chi \lesssim 1.8 \text{ GeV}$

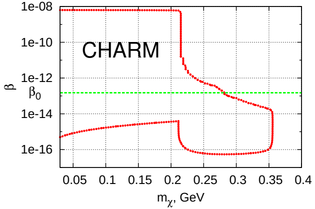
$T_{reh} > 100$ GeV, $m_h < 190$ GeV
Landau pole above inflation scale

# Phenomenlogy: Higgs-inflaton mixing!




$m_\chi \lesssim 250$ MeV is already excluded ! from $K \to \pi\chi$ and $pN \to \ldots\chi(\chi \to \mu^+\mu^-)$

# Inflaton Phenomenlogy: direct searches

$$\mathrm{Br}\left(B\to\chi X_s\right)\simeq 0.3\,\frac{\left|V_{ts}V_{tb}^*\right|^2}{\left|V_{cb}\right|^2}\left(\frac{m_t}{M_W}\right)^4\left(1-\frac{m_\chi^2}{m_b^2}\right)^2\theta^2$$

$$\simeq 10^{-6}\cdot\left(1-\frac{m_\chi^2}{m_b^2}\right)^2\left(\frac{300\text{ MeV}}{m_\chi}\right)^2,$$

Recent sensitivity: Belle

$\mathrm{Br}(B\to K^{(*)}l^+l^-)\gtrsim 10^{-7}$ $250\text{ MeV}\lesssim m_\chi\lesssim 1.8\text{ GeV}$

Expectation for the Inflaton:

scalar channel $B\to K\chi$

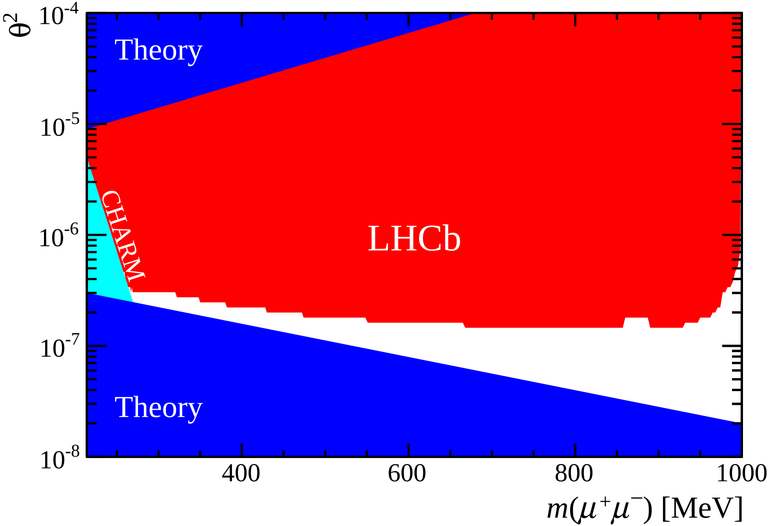
displaced decay vertex $c\tau_\chi\sim 3-30\,\text{cm}$

peaks at a given energy for $\mu^+\mu^-$, $\pi^+\pi^-$, $K^+K^-$

This INFLATIONARY model can be directly and fully explored

thanks to B-physics!

# LHCb results, NA62 is next




LHCb Collab., 1508.04094

# Outline

# Light sgoldstinos in SUSY models

SUSY is spontaneously broken (no scalar electron with mass of 510 keV !! )

breaking of $SU(2)_W \times U(1)_Y$ by the $\langle H \rangle = v$

Goldstones bosons couple to all massive fields

(Goldberger–Treiman formula like for pion)

$$\mathscr{L} = \frac{1}{v} J^{\mu}_{SU(2)_W \times U(1)_Y} \partial_\mu H$$

Higgs mechanism: three modes of $H$ are eaten giving masses to $Z$, $W^{\pm}$

breaking of SUSY by $\langle F_\varphi \rangle = F$

Goldstone fermion: goldstino

$$\mathscr{L}_\psi \propto \frac{1}{F} J^{\mu}_{SUSY} \partial_\mu \psi$$

Super-Higgs mechanism: goldstino is eaten giving mass to gravitino

$\psi$ — goldstino $\overset{SUGRA}{\longrightarrow}$ longitudinal gravitino

Physics of Goldstino supermultiplet: (boson $\varphi$ (sgoldstino), fermion $\psi$ (goldstino))

~~SUSY~~ $\longleftrightarrow$ $F \equiv \langle F_\varphi \rangle \neq 0$ $\qquad \Phi = \varphi + \sqrt{2}\theta\psi + F_\varphi \theta\theta$ $\qquad \frac{1}{\sqrt{2}}\left(\varphi + \varphi^\dagger\right) \equiv S$ — scalar

sgoldstino: $\qquad \mathscr{L}_{S,P} \propto \frac{M_{soft}}{F}$ $\qquad F \sim$ (~~SUSY~~ scale)$^2$ $\qquad \frac{1}{i\sqrt{2}}\left(\varphi - \varphi^\dagger\right) \equiv P$ — pseudoscalar

$M_{soft}$: MSSM soft terms

superpartner masses and trilinear couplings,

massless at tree level
naturally may be light...

gauginos:

$$M_\lambda \lambda\lambda \longrightarrow \frac{M_\lambda}{F} S F_{\mu\nu} F^{\mu\nu}, \quad \frac{M_\lambda}{F} P F_{\mu\nu} \tilde{F}^{\mu\nu}$$

squarks, sleptons:

$$A_{ij} h_u \tilde{q}_i \tilde{u}_j \longrightarrow \frac{A_{ij}}{F} S h_u q_i u_j, \quad \frac{A_{ij}}{F} P h_u q_i u_j$$

# Light sgoldstinos at the new fixed-target

Why is it interesting?

- allows to probe the scale of SUSY breaking
- *R*-even, hence single production and decay into SM particles
- responsible (?) for HyperCP anomaly in $\Sigma \to p\mu^+\mu^-$: $m_P = 214.3$ MeV hep-ph/0509147
- mixing with neutral Higgs bosons 1211.5609, 1207.0803, 1411.6222

Phenomenology is defined by MSSM soft terms and scale of SUSY breaking

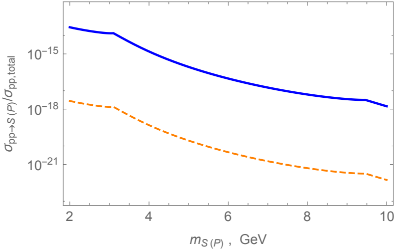
sgoldstinos produced in heavy meson decays

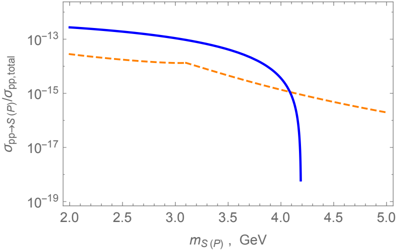
hep-ph/0610066 : tested at Belle (1005.1450)
1112.5230: tested at LHCb (1303.1092)

At the beam-dump experiment

Sgoldstino production and lifetime are naturally dominated by gluons

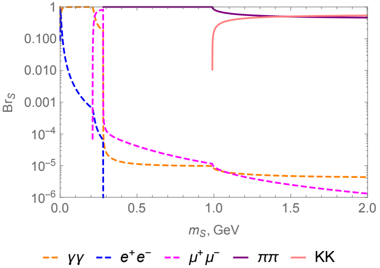
produced in D-meson decays fly for several kilometers and then decay K.Astapov, D.G. (2015)

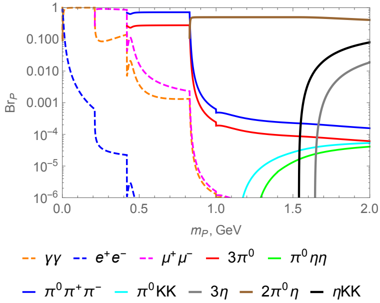


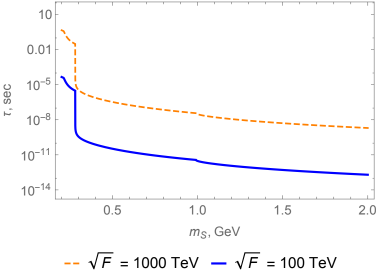



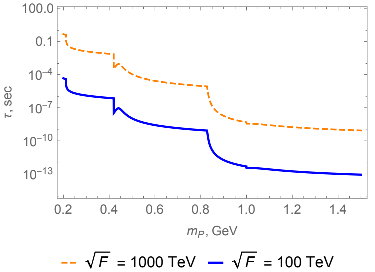
# Scalar and Pseudoscalar Sgoldstinos

K.Astapov, D.G. (2015)



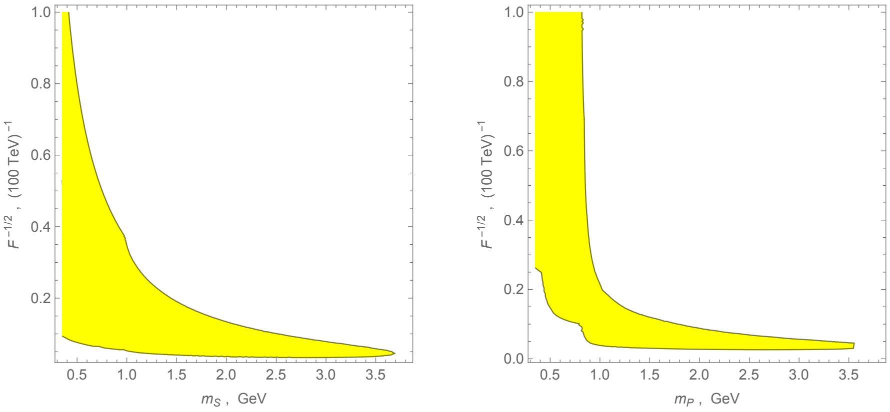



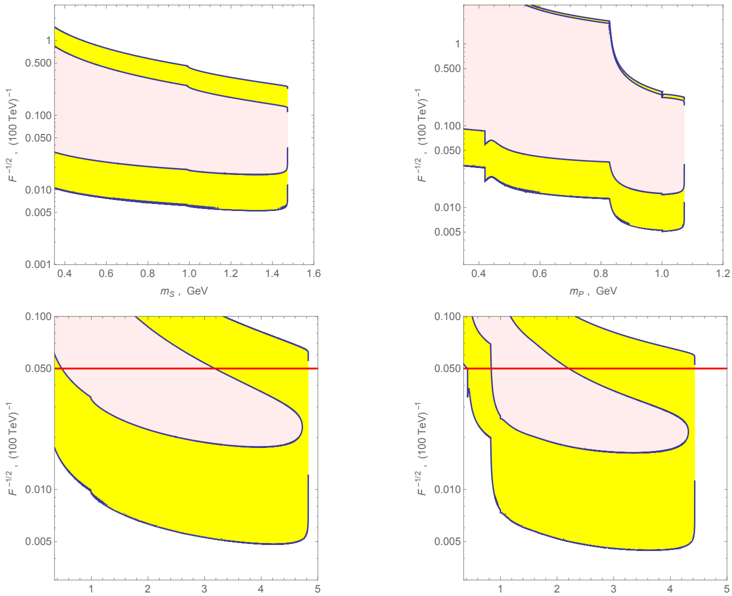
# Flavor conserving couplings

K.Astapov, D.G. (2015)



# Flavor violating couplings

K.Astapov, D.G. (2015)



# Outline

# R-parity violating neutralinos in SUSY models

Superpotential (SUSY-invariant part) gives Yukawa-like couplings for SM fermions

$$W_{\not R} = \lambda_{ijk} L_i^a \varepsilon_{ab} L_j^b \bar{E}_k + \lambda'_{ijk} L_i^a \varepsilon_{ab} Q_j^b \bar{D}_k + \lambda''_{ijk} \bar{U}_i^\alpha \varepsilon_{\alpha\beta\gamma} \bar{D}_j^\beta \bar{D}_k^\gamma$$

Yet the proton is stable if $\lambda'' = 0$ (baryon parity), or $\lambda, \lambda' = 0$ (lepton parity) and proton is lighter than LSP: $R_p = (-1)^{(3B+L+2S)}$

But LSP is unstable in these models, so no problems with overproduction (but we need another candidate to be dark matter. . . )

Nevertheless cosmology and astrophysics exclude

BBN: $0.1\,\text{s} < \tau_{\text{LSP}}$ cosmic $\gamma$-rays (FERMI): $\tau_{\text{LSP}} < 10^{18}\,\text{yr}$

hence, the excluded range is

$$3 \times 10^{-23} < (\lambda, \lambda', \lambda'') < 3 \times 10^{-10}$$

Direct searches at LHC (and TeVatron) probe:

$$(\lambda, \lambda', \lambda'') > 10^{-6}$$

otherwise LSP decays outside ATLAS and CMS

# R-parity violating neutralinos at the fixed-target

$$3\times 10^{-10} < (\lambda,\lambda',\lambda'') < 10^{-6}$$

production in meson decays: — probed by BaBar, Belle

$B^{\pm}\to l^{\pm}\tilde{\chi}_0,\ B^0\to \nu\tilde{\chi}_0$ A.Dedes, H.Dreiner, P.Richardson (2009) — $R$-violating

$D^{\pm}\to l^{\pm}\tilde{\chi}_0,\ D^0\to \nu\tilde{\chi}_0$ D.G., I.Timiryasov (2015)

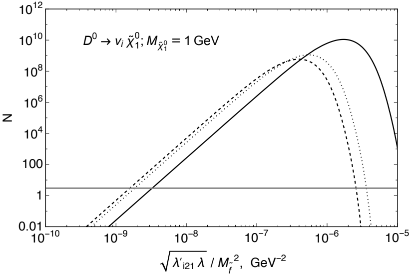
neutralinos decay into SM particles, e.g. — $R$-violating

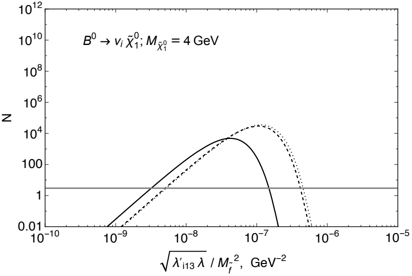
$\tilde{\chi}_0\to l^+l^-\nu$ (solid) H.Dreiner, P.Richardson, M.Seymour (1999)

$\tilde{\chi}_0\to l^{\pm}K^{\mp}$ (dotted) SHiP's Physics Paper (2015)

$\tilde{\chi}_0\to \nu K^0,\ \tilde{\chi}_0\to l^{\pm}\pi^{\mp}$, (dashed) $\tilde{\chi}_0\to\nu\pi^0$, D.G., I.Timiryasov (2015)

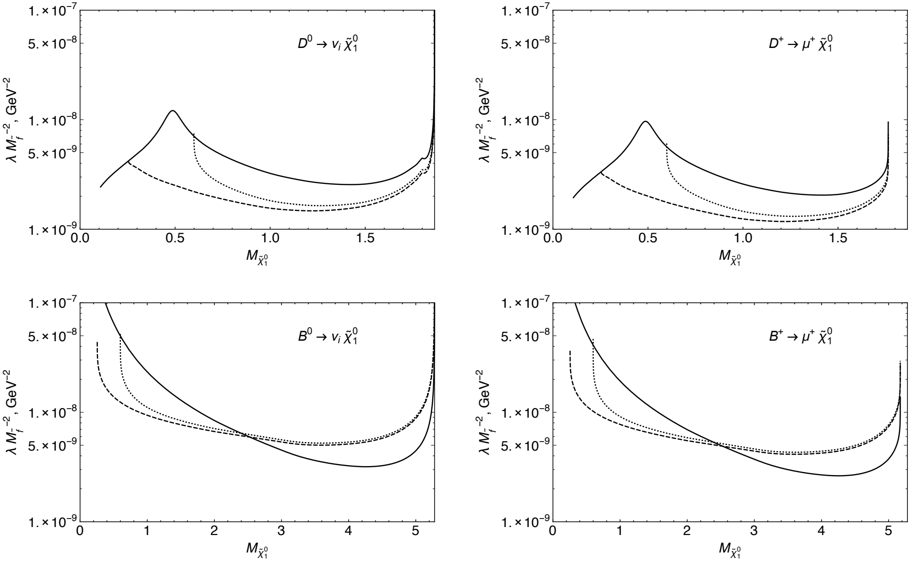
$\lambda\neq 0$ was discussed after NuTeV dimuon events hep-ex/0104037, hep-ph/0007195



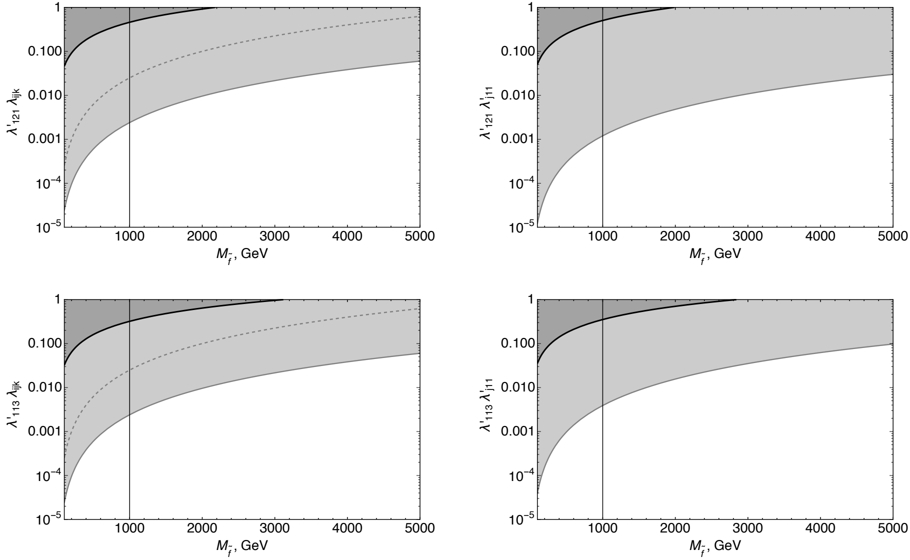
# SHiP sensitivity to LPV neutralinos

D.G., I.Timiryasov (2015)



# SHiP sensitivity vs CHARM (dotted)

D.G., I.Timiryasov (2015)



# Outline

# Massive vectors (paraphotons)

Vector portal to a secluded sector: e.g. with Dark matter $\Psi$

one more $U(1)'$ gauge group [spontaneously broken] in secluded sector: mixing with $U(1)_Y$ is naturally expected and unsuppressed by high energy scale 0711.4866

$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu\partial_\mu - e'\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m_{\gamma'}^2}{2}A'_\mu A'^\mu + \epsilon A'_\mu \partial_\nu B^{\mu\nu}$$

when $m_\Psi > m_{\gamma'} \sim 1\,\text{GeV}$

Cosmology:

- Limits from BBN:

$$\tau_V < 1\,\text{s}, \implies \epsilon^2\left(\frac{m_{\gamma'}}{1\,\text{GeV}}\right) \gtrsim 10^{-21}$$

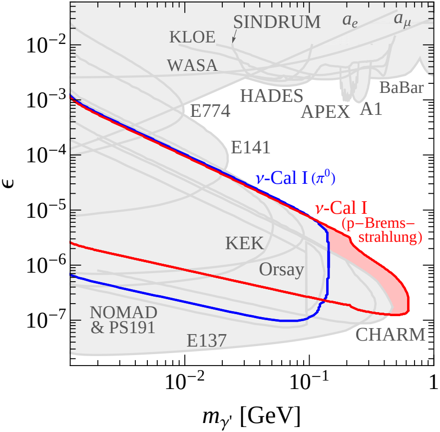
- For DM particles to be in thermal equilibrium in primordial plasma:

$$\epsilon^2\left(\frac{m_{\gamma'}}{1\,\text{GeV}}\right) \gtrsim 10^{-11} \times \left(\frac{m_\Psi}{500\,\text{GeV}}\right)^2$$

Production by virtual photon $\sigma \propto \epsilon^2$

Decay through virtual photon, $\Gamma \propto \epsilon^2$

$V \to e^+e^-$, $\mu^+\mu^-$, etc

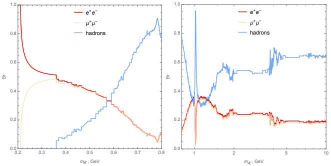


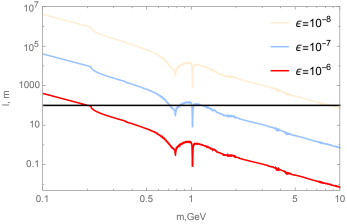

1311.5104

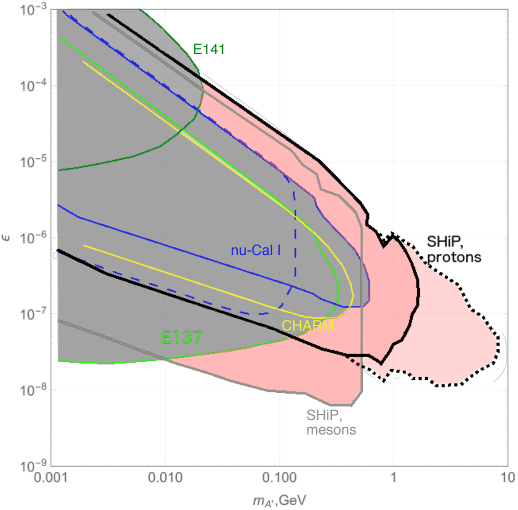
# Paraphotons: improvement of CHARM

$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu \partial_\mu - e'\,\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m^2_{\gamma'}}{2}A'_\mu A'^\mu + \epsilon A'_\mu \partial_\nu B^{\mu\nu}$$

when $m_\Psi > m_{\gamma'} \sim 1$ GeV




D.G., A.Makarov, I.Timiryasov (2014)

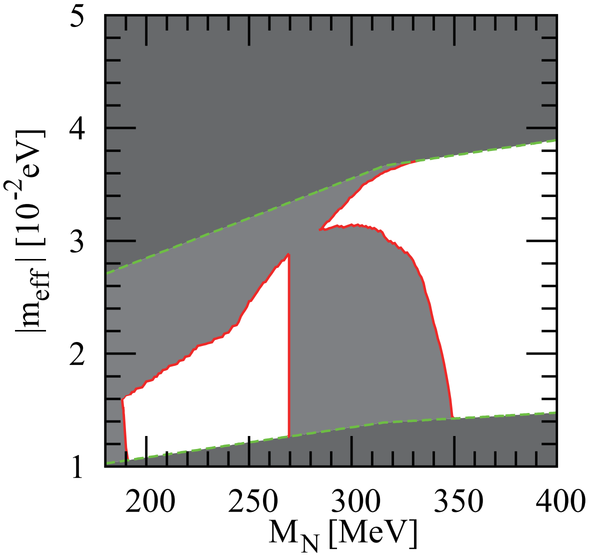
# Outline

# Summary

- Much more models in SHiP Physics Paper 1504.04855
- Still more to come. . .
- DUNE setup. . .
- $\nu_\tau$-detector at SHiP. . .

# Backup slides

# Leptogenesis in $2+1$ scheme: $0\nu2\beta$ decay region




Inverse hierarchy 1308.3550

# Present limits

0901.3589: 1) $0\nu\beta\beta$-bound is stronger by 10, 1205.3867 2) limits from LHCb and CMS