QCD effects in New Physics

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Markov's Readings - 2018
MR'2018

INR RAS, Moscow, Russia

Widely accepted statements

- Standard Model nicely explains
  almost all results of particle physics experiments
- We definitely need New particle Physics
  - neutrino oscillations (Nobel Prize 2015)
  - baryon asymmetry
  - dark matter
  - inflation-like stage in the early Universe

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Markov heritage

- Hadron physics
- Calculations within QFT
- Neutrino physics
- Gravity and Cosmology
- Non-standard ideas in particle physics and gravity
  - noncommutativity
  - nonlocality
  - Planck-size black holes
  - friedmons, maximons, minimons, . . .

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Community

- BSM-people
  - ThD of INR
  - CMS, ATLAS, . . . collaborations
  - dedicated experiments: CAST, NA64, . . .
- Paper counting
  - yesterday's hep-ph: out of 37
  - BSM: 17
  - QCD: 16
  - exception or tendency. . . ?
- BSM-theorists & QCD-theorists naturally kept a distance
- but they harmoniously unite to engage experimentalists

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BSM $\to$ QCD

- $(g-2)$ of muon
- AdS/CFT for heavy ions
- $N = 1,2,4$ SUSY for calculating QCD asymptotics
- ...

QCD $\to$ BSM

- $(g-2)$ of muon
- anomalies in B-physics
- K^0-$\bar{K}^0$ mixing
- $0\nu\beta\beta$
- BSM (e.g. MSSM) Higgs sector
- Inevitable if BSM scale is ~ 1 GeV

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  - inflation-like stage in the early Universe
- New Heavy particle contribution to the Higgs boson mass lifts it up but miraculously $m_h \sim E_{EW}$

Guesswork: a logically possible option

- All the new particles are at (below) E_{EW}
  then quantum contributions to $m_h \sim E_{EW}$ are safe
- Why so far no evidences for such light New Particles ?
- They are only feebly coupled to the Standard Model
  - they are SM gauge singlets (not a GUT)
  - new Yukawa-type couplings ?
  - portal-like couplings ?

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Disclaimer and the main task

- There are no general theoretical motivation for the New Particles to be of (sub)GeV mass
  but for the feebly coupled light particle best place to show up is the intensity frontier fixed target experiment
- Moreover, there are many concrete BSM theories which suggest such theoretical motivations
- Then the problem is
  how to properly account for the new particle (SM gauge singlet) effective coupling to the SM strongly-interacting states
  - for $m \gg 1$ GeV it couples to partons
  - for $m \ll 1$ GeV it couples to hadrons
  - how to calculate
    the new particle production and decay rates for $m \simeq 1$ GeV ?
  - in the cincrete models
    "parton" and "hadron" answers often mismatch

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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 $U(1)'$

  hidden photon

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

Renormalizable inflaton at GeV scale

0912.0390

$$S_{XSM} = \int \sqrt{-g}\, d^4x \left(\mathscr{L}_{SM} + \mathscr{L}_{ext} + \mathscr{L}_{grav}\right),$$

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

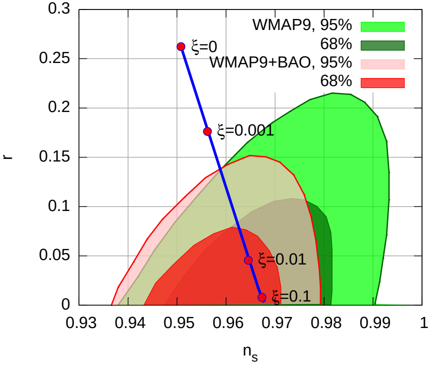
$$\mathscr{L}_{grav} = -\frac{M_P^2 + \xi X^2}{2} R,$$

inflaton mass

$$m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}} = \sqrt{\frac{\beta}{\lambda \theta^2}}.$$

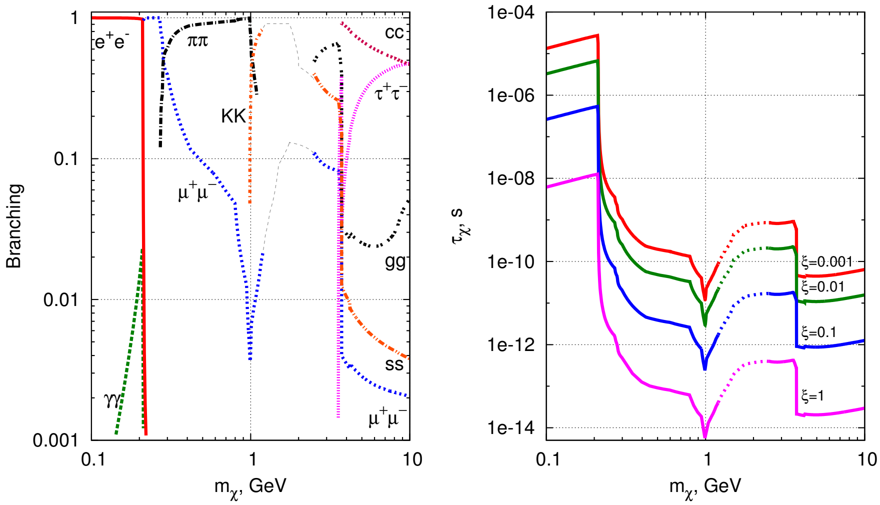
phenomenology is fixed by
mixing with Higgs

$$\theta^2 = \frac{2\beta v^2}{m_\chi^2} = \frac{2\alpha}{\lambda}.$$



QCD modes: claimed uncertainties upto 10^2

1303.4395

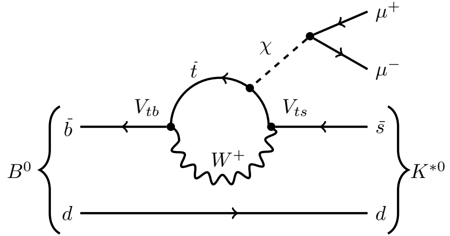


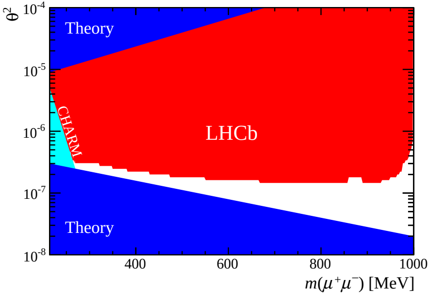
Interaction among the final hadronic states

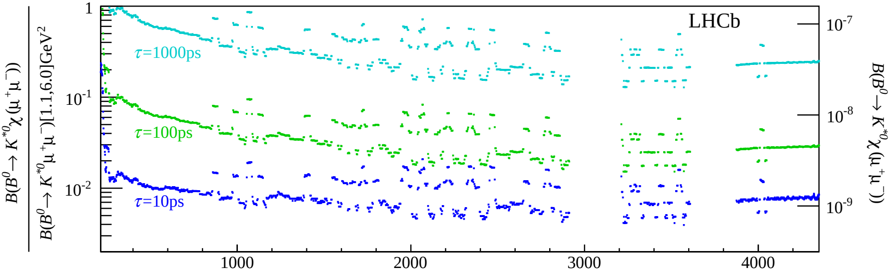
following J.Donoghue, J.Gasser and H Leutwyler (1990)

Limits from LHCb

1508.04094







Light sgoldstinos in SUSY models

SUSY is spontaneously broken

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)

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

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

Goldstone fermion: goldstino

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

Goldstino supermultiplet: (boson φ (sgoldstino), fermion ψ (goldstino))

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

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

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

Direct coupling to gluonic tensor

- For $M_S \ll 1$ GeV estimate coupling to pions through the triangle anomaly in $T_{\mu\mu}$
  M.Voloshin, V.Zakharov (1980)

$$-\langle \pi\pi \left| \frac{bg_s^2}{32\pi^2} G^a_{\mu\nu} G^a_{\mu\nu} \right| 0 \rangle = \langle \pi\pi \,|\, T_{\mu\mu} \,|\, 0 \rangle = q^2 \varphi^\alpha_\pi \varphi^\alpha_\pi / 2$$

  hence we get an amplification 1511.05403

$$\Gamma(S \to \pi^0\pi^0) \approx \frac{\alpha_s^2(M_3)}{\beta^2(\alpha_s(M_3))} \frac{\pi m_S^3 M_3^2}{4F^2} \sqrt{1 - \frac{4m^2_{\pi^0}}{m_S^2}},$$

- For $M_S \gg 1$ GeV we have gluons and a suppression $g_s^2 G^2_{\mu\nu}$ is a renorm-invariant

$$\Gamma(S \to gg) = \left(\frac{\alpha_s(m_S)\beta(\alpha_s(M_3))}{\beta(\alpha_s(m_S))\alpha_s(M_3)} \right)^2 \frac{m_S^3 M_3^2}{4\pi F^2}.$$

- The two rates mismatch by orders...

Massive vectors (paraphotons)

NA64

Vector portal to a secluded sector:

one more $U(1)'$ gauge group [spontaneously broken] in secluded sector

e.g. with Dark matter Ψ

0711.4866

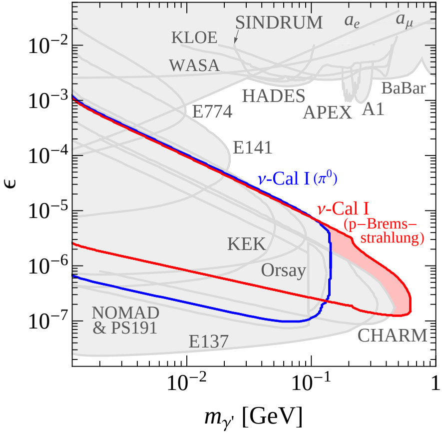
$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu \partial_\mu - e'\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m^2_{\gamma'}}{2}A'_\mu A'^\mu + \varepsilon A'_\mu \partial_\nu B^{\mu\nu}$$

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

- limit from BBN:

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

- light for $(g-2)$
- light for Pamela, Fermi, etc



1311.5104

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

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

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

Massive vectors: decays are under control

Decay into SM via mixing with photon

into leptons

$$\Gamma_{A'}^{l^+l^-} = \frac{1}{3}\alpha_{\text{QED}}\, m_{A'}\, \varepsilon^2 \sqrt{1 - \frac{4m_l^2}{m_{A'}^2}} \left(1 + \frac{2m_l^2}{m_{A'}^2}\right),$$

into hadrons

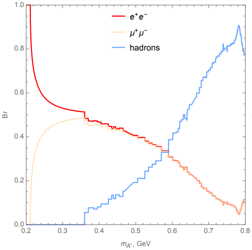
$$\Gamma_{A'}^{\text{hadrons}} = \frac{1}{3}\alpha_{\text{QED}}\, m_{A'}\, \varepsilon^2 \cdot R(m_{A'}),$$

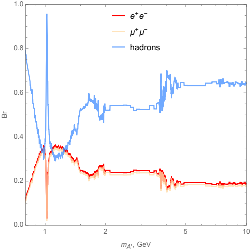
where

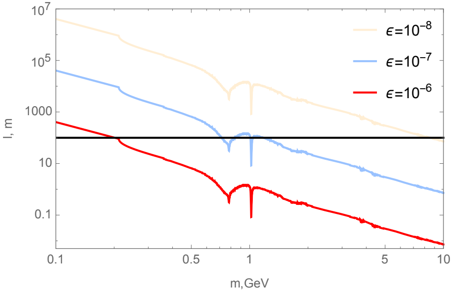
$$R(\sqrt{s}) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

and

$$\Gamma_{A'}^{\text{tot}} = \Gamma_{A'}^{e^+e^-} + \Gamma_{A'}^{\mu^+\mu^-} + \Gamma_{A'}^{\text{hadrons}}$$







1411.4007

Massive vectors: production by protons

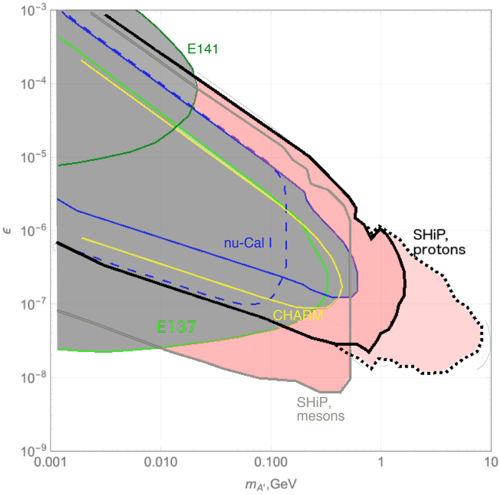
- decays of π^0, η^0 and $\rho^{\pm}$, ρ^0, ω

$$\mathrm{Br}_{\pi^0\to A'\gamma} \simeq 2\varepsilon^2 \left(1-\frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathrm{Br}_{\pi^0\to\gamma\gamma}$$

- proton bremsstrahlung
  concervatively corrected by the Dirac (electric) form factor of proton

$$F_1 = \frac{1}{\left(1+\frac{q^2}{m_D^2}\right)^2} \to \frac{1}{m_{A'}^4}$$

  with Dirac mass squared $m_D^2 = 12/r_D^2$ and the Dirac radius $r_D \approx 0.8\,\mathrm{fm}$
- quark bremsstrahlung



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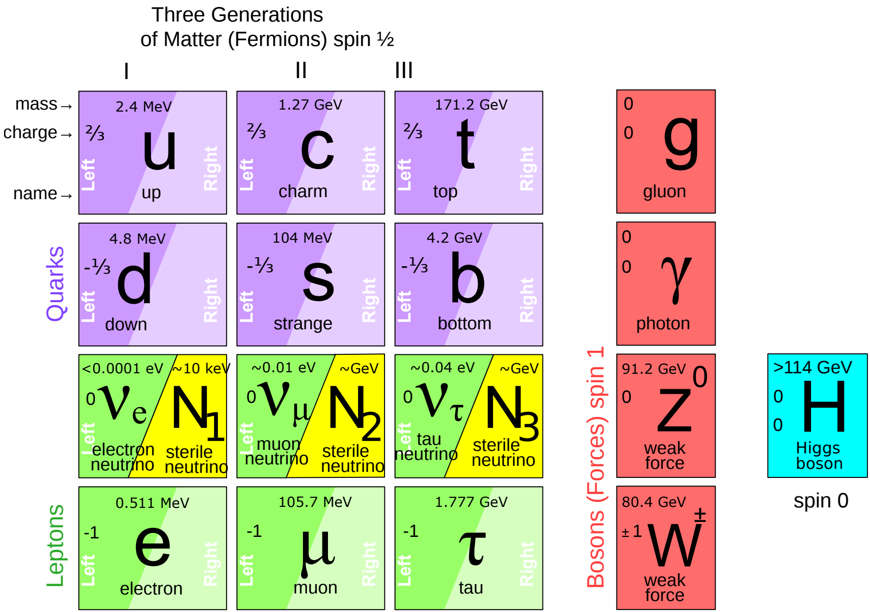
Summary

- QCD-effects MUST BE properly accounted for
- help from QCD-people are welcome !!
- some work is underway…


Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
top
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
Quarks
<0.0001 eV
~10 keV
0
νe
N1
electron neutrino
sterile neutrino
~0.01 eV
~GeV
0
νμ
N2
muon neutrino
sterile neutrino
~0.04 eV
~GeV
0
ντ
N3
tau neutrino
sterile neutrino
0.511 MeV
-1
e
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
Leptons
Left
Right
0
0
g
gluon
0
0
γ
photon
91.2 GeV
0
Z0
weak force
80.4 GeV
±1
W±
weak force
Bosons (Forces) spin 1
>114 GeV
0
0
H
Higgs boson
spin 0

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

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

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

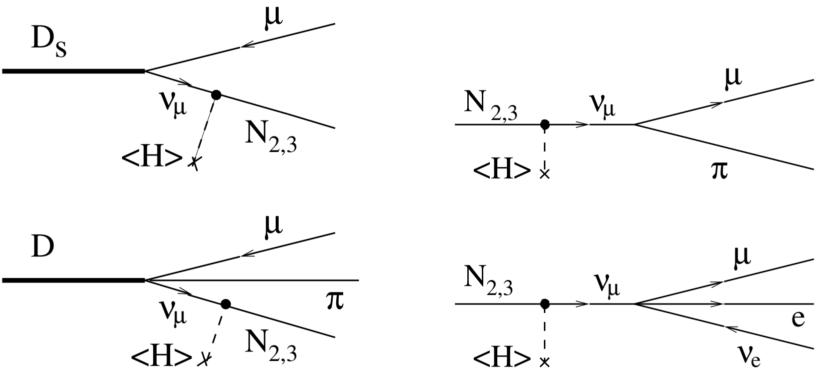
$$\simeq \hat{M}_N \qquad \text{and} \qquad \hat{M}^\nu = -\hat{M}_D \frac{1}{\hat{M}_N}\hat{M}_D^T \propto f^2\frac{v^2}{M_N} \lll M_N$$

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

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

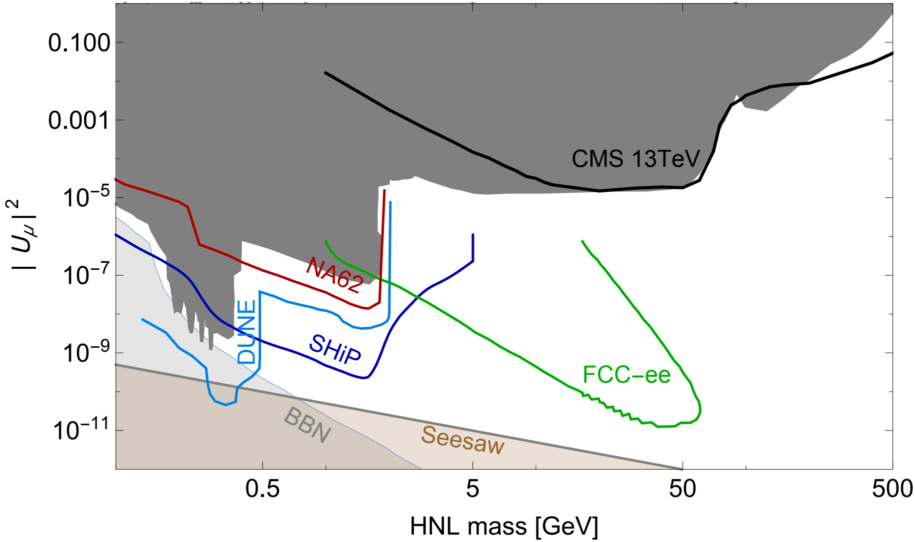
active-sterile mixing: $\qquad \theta_{\alpha I} = \frac{M_{D_{\alpha I}}}{M_I} \propto \hat{f}\,\frac{v}{M_N} \ll 1$

Sterile neutrinos: production and decays



Limits and sensitivities

1805.xxxxx



Only decays...

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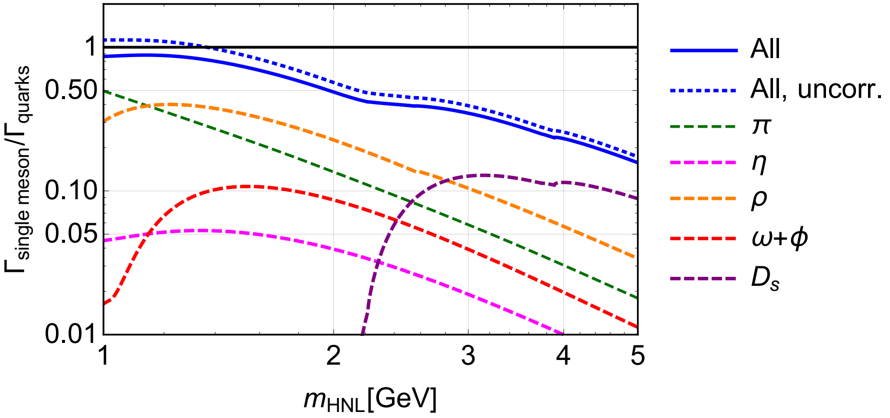
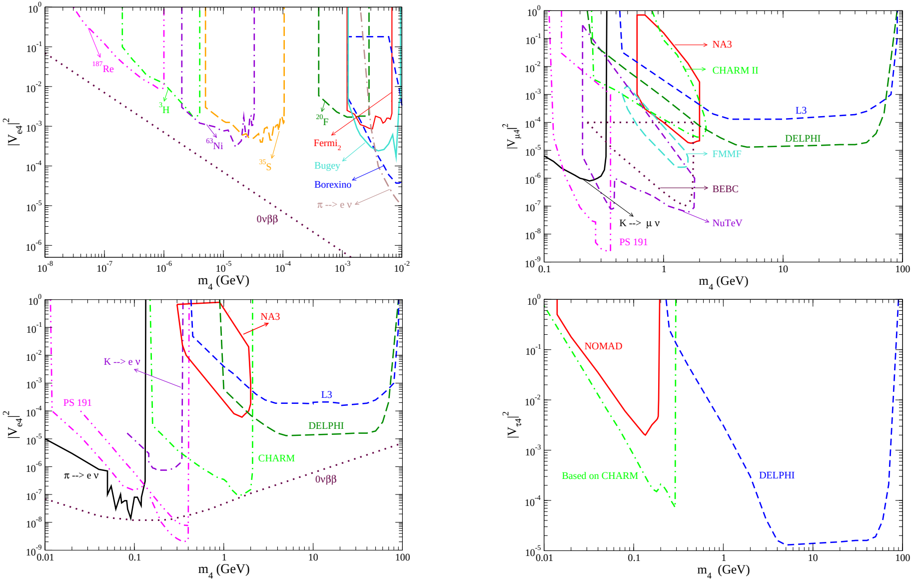


Backup slides

Present limits

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

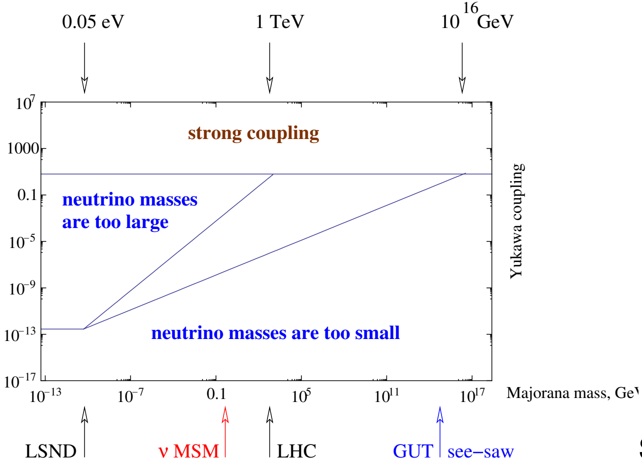


Sterile neutrino mass scale: $\hat{M}_\nu = -v^2 \hat{f}^T \hat{M}_N^{-1} \hat{f}$

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



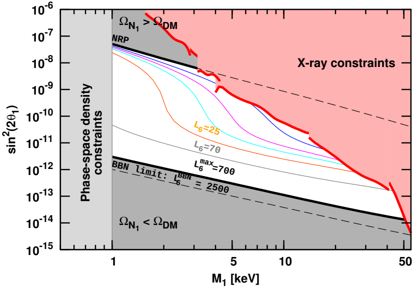
Seesaw diagram

Lightest sterile neutrino N_1 as Dark Matter

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

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 $T \sim m_\chi$

Not seesaw neutrino!

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 ($250\,\text{MeV} < m_\chi < 1.8\,\text{GeV}$)

F.Bezrukov, D.G. (2009)

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