# THE EIGHTH PARTICLE PHYSICS PHENOMENOLOGY WORKSHOP (PPP8) 2009

A simple model of neutrino masses, μ g-2, and some cosmological issues

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* Several deviations between theoretical predictions and experimental data appear both in Standard Model of Particle Physics and Cosmology due to precision measurement.
* Nentrino masses, anomalous μ magnetic moment, dark matter, ...
* Lithium problem, baryon asymmetry, dark energy, ...

# The model

- The evidence of dark matter $\longrightarrow$ $Z_2$ symmetry
- All the new particles besides SM sectors are $Z_2$ odd
- Scalar sector $\phi_{i=1,2}$ and $S^+$

  Fermion sector $L_i = \begin{pmatrix} N \\ E^- \end{pmatrix}_i$
- New Yukawa couplings

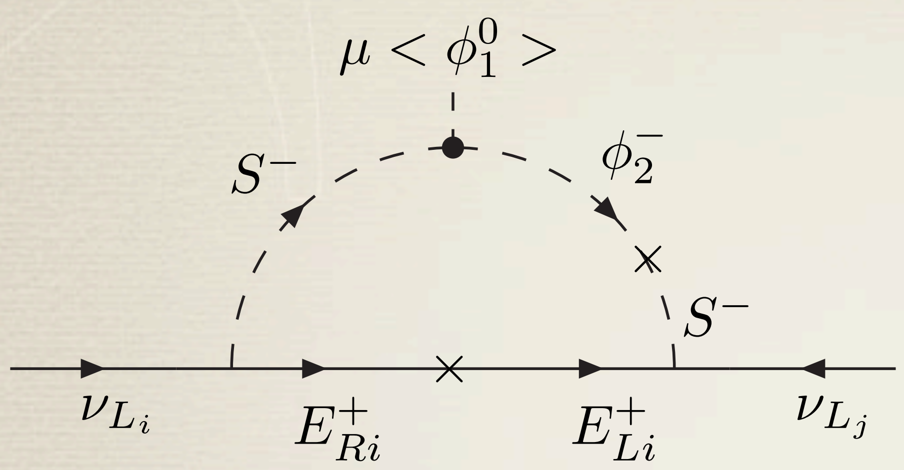
$$\begin{aligned} L_Y &= f_{\alpha i}\bar{l^c}_\alpha L_i S^+ + y_{\alpha i} l_{R\alpha} L_i \phi_2 + h.c. \\ &= \left[f_{\alpha i}(\bar{\nu_\alpha} E_i^- + l_\alpha^- \bar{N}_i^c)\right] S^+ + y_{\alpha i}\left[l_{R\alpha}^- E_i^+ \phi_2^0 + l_{R\alpha}^- N_i \phi_2^-\right] + h.c., \end{aligned}$$

- Potential

$$\begin{aligned} V(\phi_1, \phi_2, S^-) &= -\mu_1^2|\phi_1|^2 + \lambda_1|\phi_1|^4 + m_2^2|\phi_2|^2 + \lambda_2|\phi_2|^4 + \lambda_3|\phi_1|^2|\phi_2|^2 \\ &+ \lambda_4|\phi_1^\dagger\phi_2|^2 + \frac{\lambda_5}{2}\left[(\phi_1^\dagger\phi_2)^2 + h.c.\right] + m_s^2|S|^2 + \lambda_s|S|^4 \\ &+ \mu\left[(\phi_1^{0*}\phi_2^- - \phi_1^-\phi_2^0)S^+ + h.c.\right]. \end{aligned}$$

# Neutrino mass generation

* No tree level seesaw due to $Z_2$ symmetry, neutrino masses are generated in one-loop level




$$\begin{pmatrix} \phi_2^+ & S^+ \end{pmatrix} \begin{pmatrix} \mu_2^2 + \frac{\lambda_3 v^2}{2} & \frac{\mu v}{\sqrt{2}} \\ \frac{\mu v}{\sqrt{2}} & m_s^2 \end{pmatrix} \begin{pmatrix} \phi_2^- \\ S^- \end{pmatrix}$$

$$F(M^2) = \frac{1}{(M^2 - M_s^2)} + \frac{M^2}{(M^2 - M_s^2)^2} \ln \frac{M_s^2}{M^2}$$

$$\begin{aligned} (m_\nu)_{\alpha\beta} &= -i f_{\alpha i} f_{i\beta} M_{E_i} \mu^2 < \phi_1^0 >^2 \int \frac{d^4 q}{(2\pi)^4} \frac{1}{(q^2 - M_s^2)^2} \frac{1}{(q^2 - M_{\phi_2}^2)} \frac{1}{(q^2 - M_{E_i}^2)} \\ &= \frac{f_{\alpha i} f_{i\beta} \mu^2 v^2 M_{E_i}}{32\pi^2 (M_{E_i}^2 - M_{\phi_2}^2)} \left[ F(M_{E_i}^2) - F(M_{\phi_2}^2) \right] \qquad (9) \\ &\approx \frac{f_{\alpha i} f_{i\beta}}{64\pi^2} \left(\frac{v}{M_{E_i}}\right)\left(\frac{\mu^2}{M_{\phi_2}^2}\right) v \sim 10^{-3} \times f^2 \frac{\mu^2}{M_{E_i}}. \end{aligned}$$

$\mu$ is $O(1) \sim O(100) GeV$ we have $f \sim 10^{-2} - 10^{-4}$

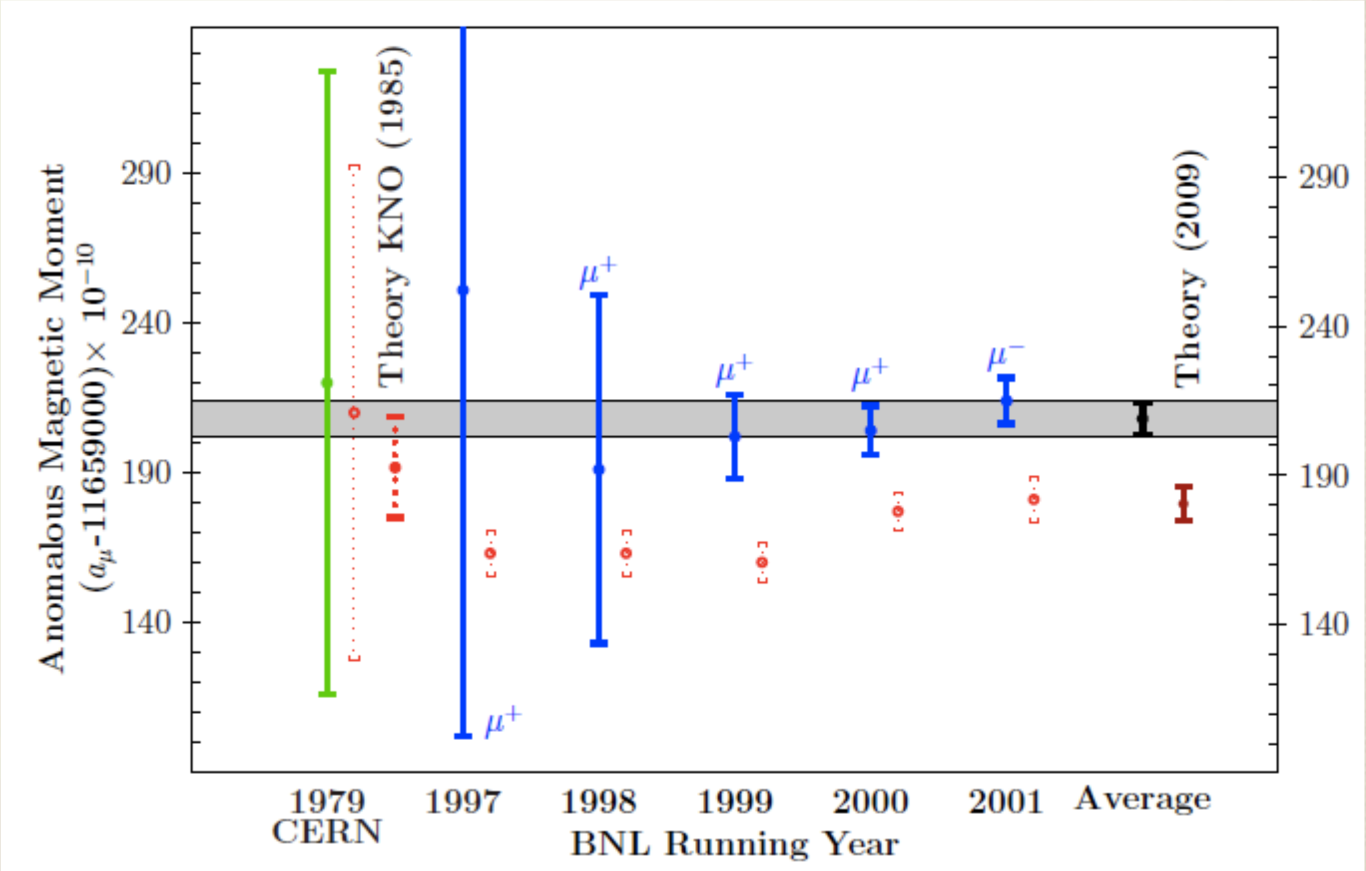
The masses of all new particles are around TeV scale

# Muon g-2

- μ anomalous magnetic moment is one of the most precisely measured quantities in particle physics.
- A recent experiment at Brookhaven it has been measured with a remarkable 14-fold improvement of the previous CERN result.

| Contribution | Value | Error |
|---|---|---|
| QED incl. 4-loops+LO 5-loops | 116 584 718.1 | 0.2 |
| Leading hadronic vacuum polarization | 6 903.0 | 52.6 |
| Subleading hadronic vacuum polarization | -100.3 | 1.1 |
| Hadronic light–by–light | 116.0 | 39.0 |
| Weak incl. 2-loops | 153.2 | 1.8 |
| | | |
| Theory | 116 591 790.0 | 64.6 |
| Experiment | 116 592 080.0 | 63.0 |
| Exp. - The. 3.2 standard deviations | 290.0 | 90.3 |

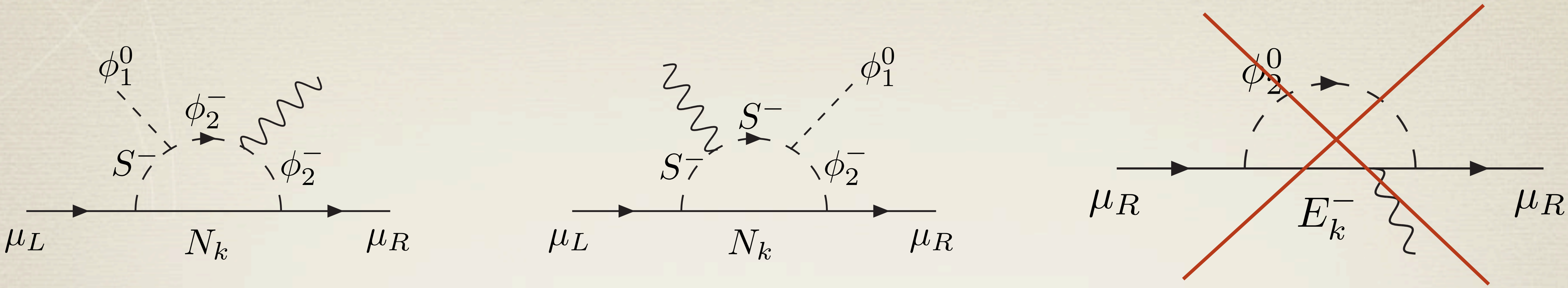
3.2σ



# Neutrino masses and μ g-2

$$\Delta a_\mu = (290 \pm 90) \times 10^{-11}$$

- A similar mechanism




$$\Delta a^{NP}_{\mu(N_k)} = -\frac{\sin\delta\cos\delta}{16\pi^2}\sum_k (f_{\mu k} y_{\mu k})\frac{m_\mu}{M_k}\left[F(x_{P_1}) - F(x_{P_2})\right]$$

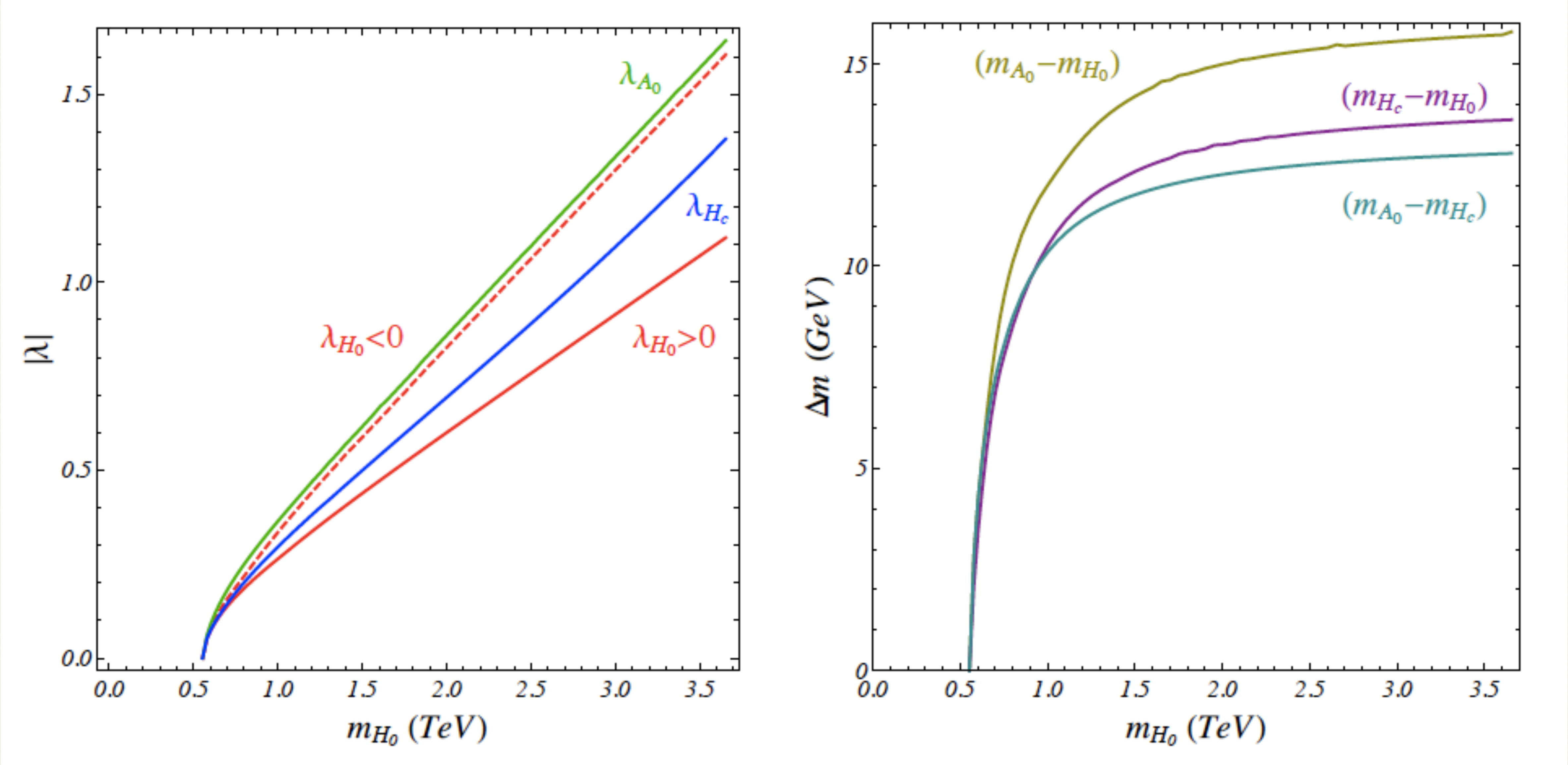
$$\sin\delta\cos\delta = \frac{\mu v}{\sqrt{2}(m^2_{P_1} - m^2_{P_2})} \qquad F(x) = \frac{1}{(1-x)^3}\left[1 - x^2 + 2x\ln x\right]$$

$$\sin\delta\cos\delta \times f_{\mu k} \sim 10^{-3\sim-4} \qquad m_\mu/(16\pi^2 M_k) \sim 10^{-5} \qquad y_{\mu k} \sim O(10^{-1} - 10^{-2})$$

# Dark matter, lithium problem, and leptogenesis

- A dark matter can be realized in the inert scalar doublet $\phi_2^0$
- Relic abundance ⟷ quartic couplings, μ ⟷ mass splitting

$M_{\phi_2^0} \geq 534 GeV.$ $\mu = \lambda v$ $M_{s^-} - M_{\phi_2^-} \leq O(1) GeV$

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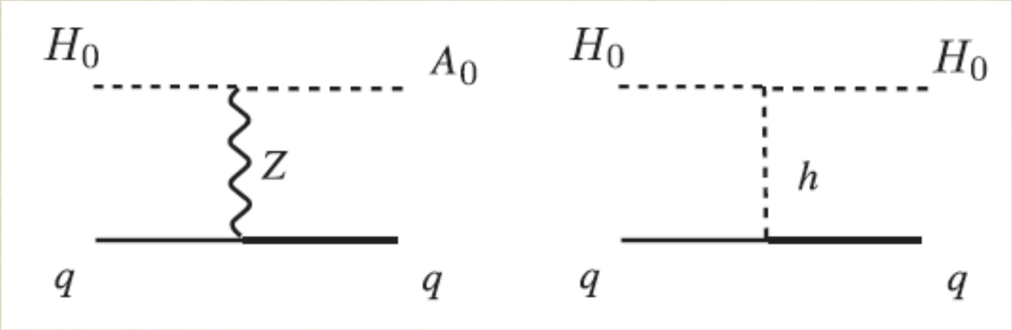
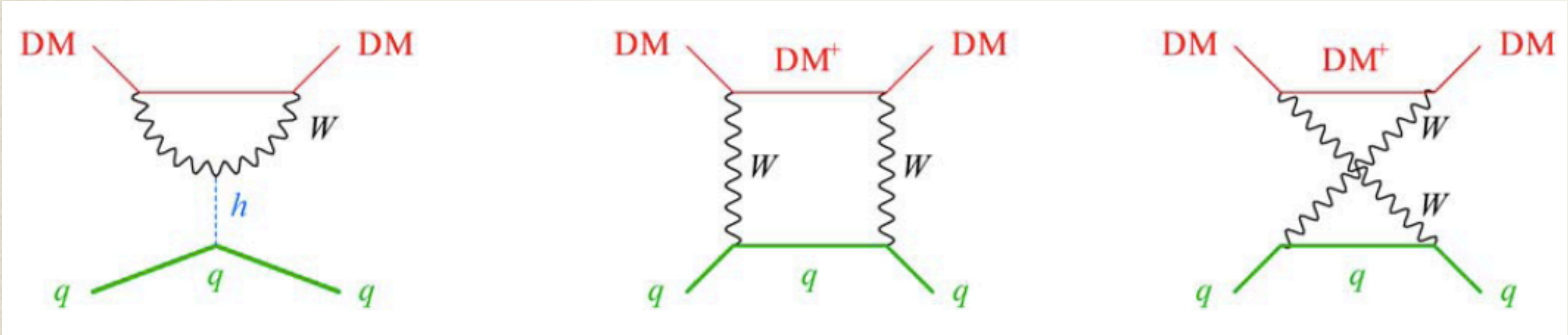
## * Direct detection



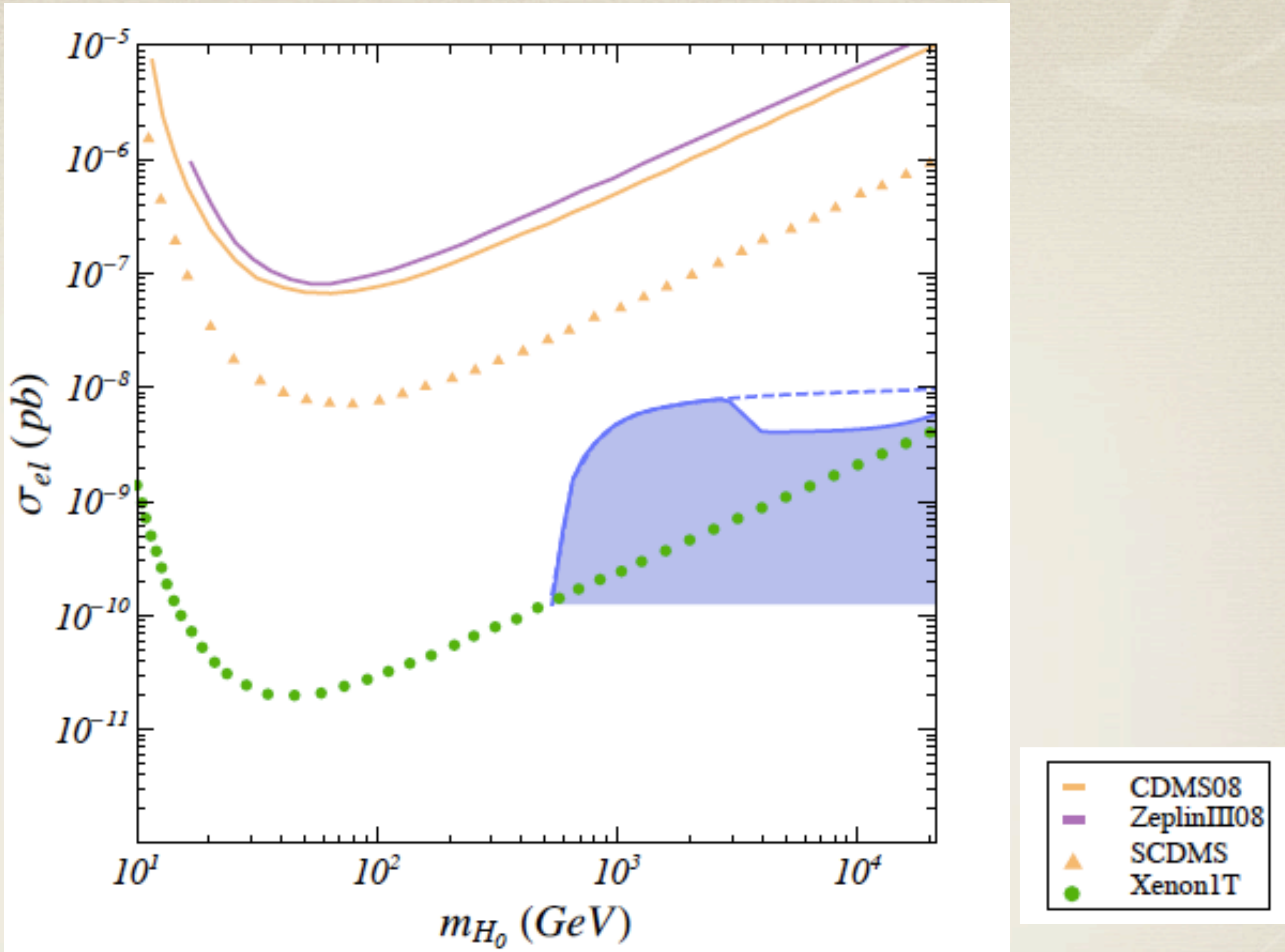

Experimental limit on Z exchange --
$M_{H^0} - M_{A^0} \sim (10^2)$KeV

$$\sigma^h_{DM-N} \approx \frac{f_N^2 \lambda^2_{\phi_2^0}}{4\pi}(\frac{m_N^2}{m_{DM} m_h^2})^2.$$




$$\sigma_{1-loop} = \frac{9 f_N^2 \pi \alpha_2^4 m_N^4}{64 M_W^2}(\frac{1}{M_W^2} + \frac{1}{m_h^2})^2.$$

Independent of DM mass




$\rho_0 = 0.3 GeV/cm^3$ $m_h$ = 120 GeV

Next generation experiment

# Lithium problem

- BBN was generally taken to be a three-parameter theory

| Baryon density | Neutron mean-life | Number of neutrino flavors |
| --- | --- | --- |

$\eta_{10}$(WMAP2008)=6.23±0.17 $T_n$=878.5±0.8 s

- SBBN $^{7}Li/H = (5.24^{+0.71}_{-0.62}) \times 10^{-10}$ and

  $^6$Li component is small $^{6}Li/^{7}Li \sim 3.3 \times 10^{-5}$

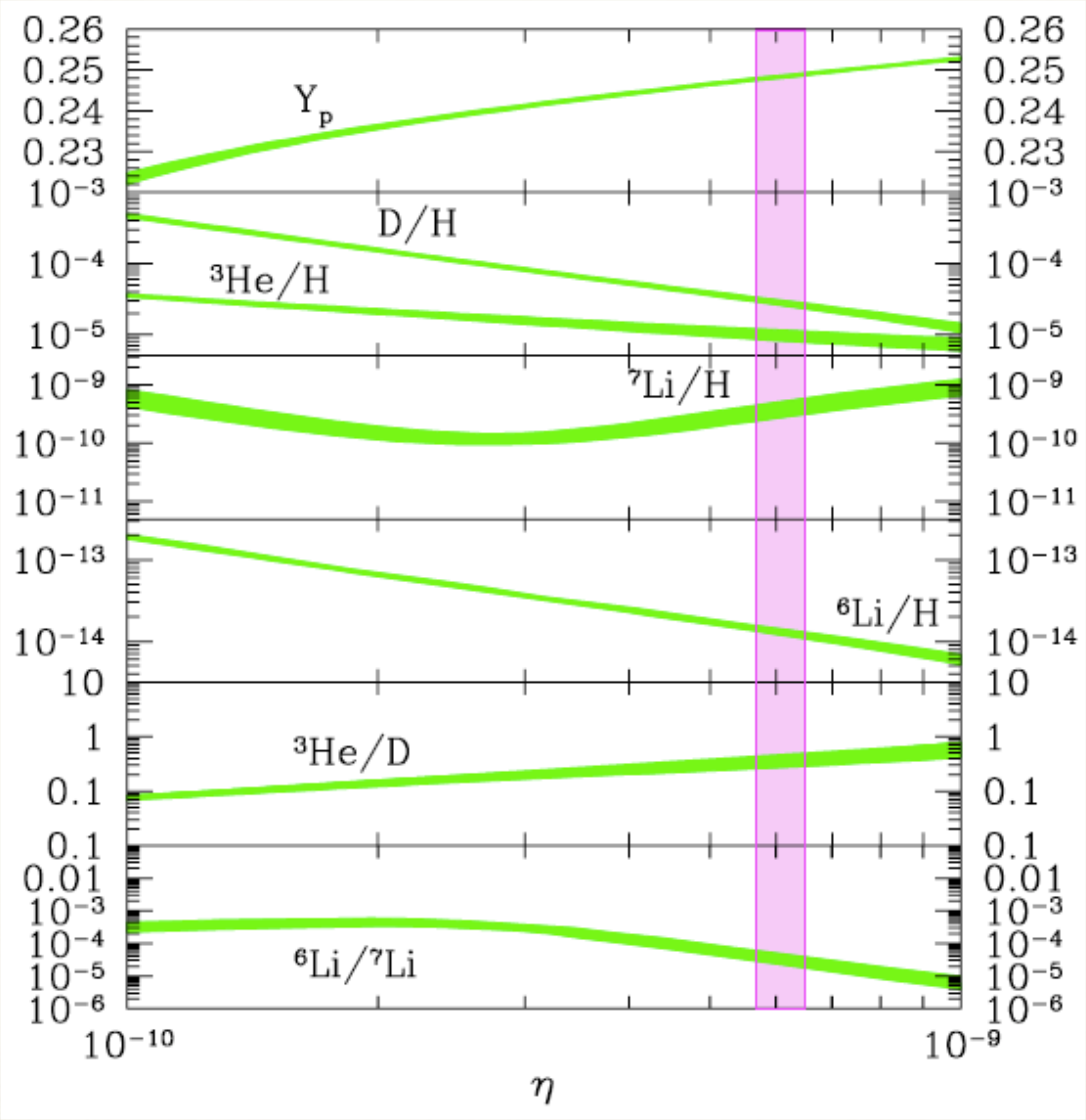
- Metal-poor halo stars --- $Li/H = (1 \sim 2) \times 10^{-10}$

  Galactic cosmic rays --- primordial value $Li/H = (1.23 \pm 0.06) \times 10^{-10}$

  Measurement from clusters (NGC 6397) --- $Li/H = (2.19 \pm 0.28) \times 10^{-10}$

- Recent high-precision measurements are sensitive to the tiny isotopic shift in Li absorption and indicate $^{6}Li/^{7}Li \leq 0.15$

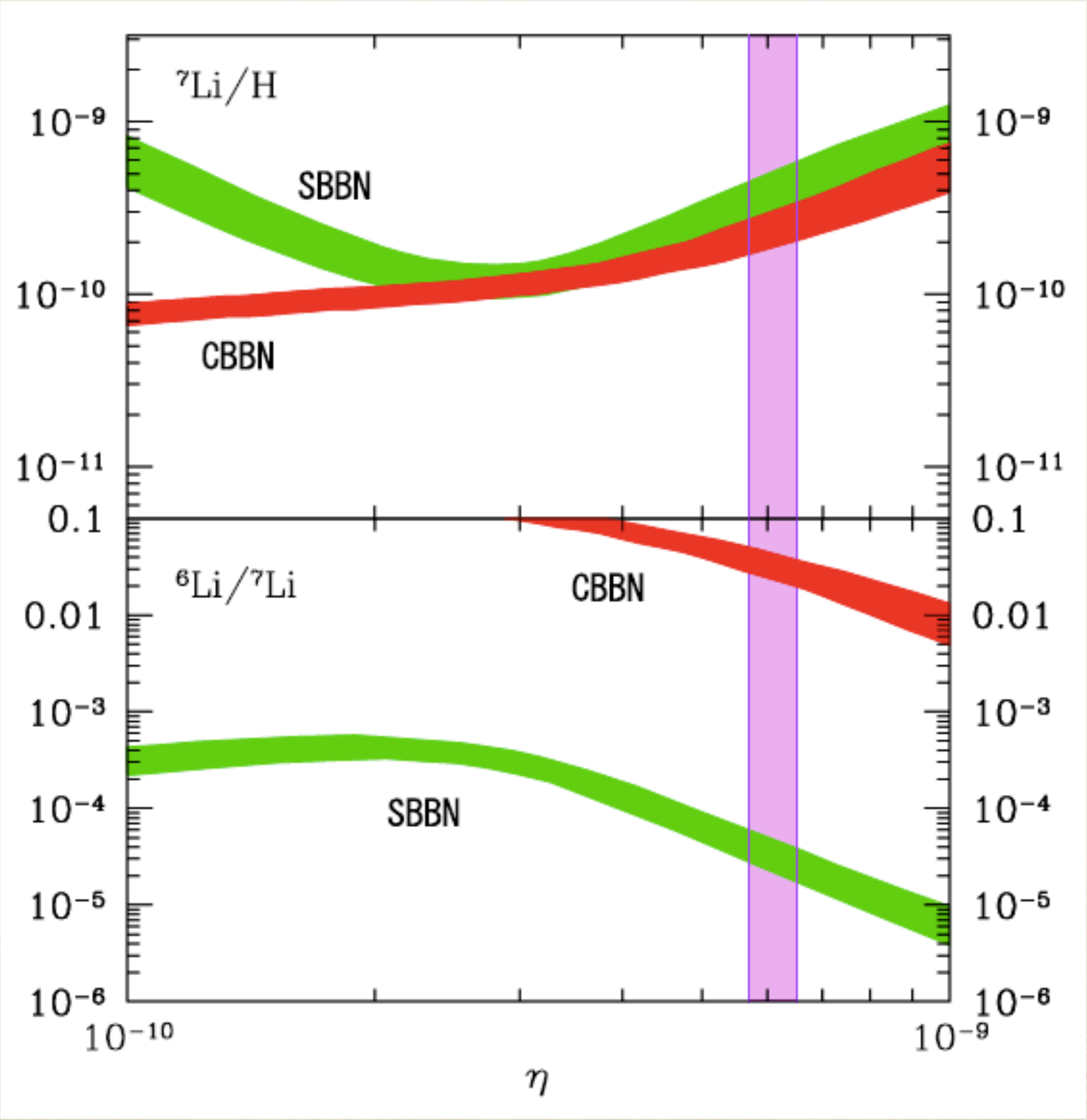
* Lithium problem : The SBBN predicts primordial $^6$Li abundance about 1000 times smaller than the observed abundance level and $^7$Li abundance a factor of 2-3 larger than when one adopts a value of η inferred from the WMAP data.



* Catalyzed BBN (CBBN) may provide the solution $S^-$.
* $$SBBN : {}^4He + D \to {}^6Li + \gamma$$

$$CBBN : \quad S^- \to ({}^4HeS^-) \to {}^6Li \quad \text{and} \quad S^- \to ({}^4HeS^-) \to ({}^8BeX^-) \to {}^9Be.$$

* $$({}^4HeS^-) + D \to {}^6Li + S^- \quad \text{and} \quad ({}^8BeS^-) + n \to {}^9Be + S^-.$$

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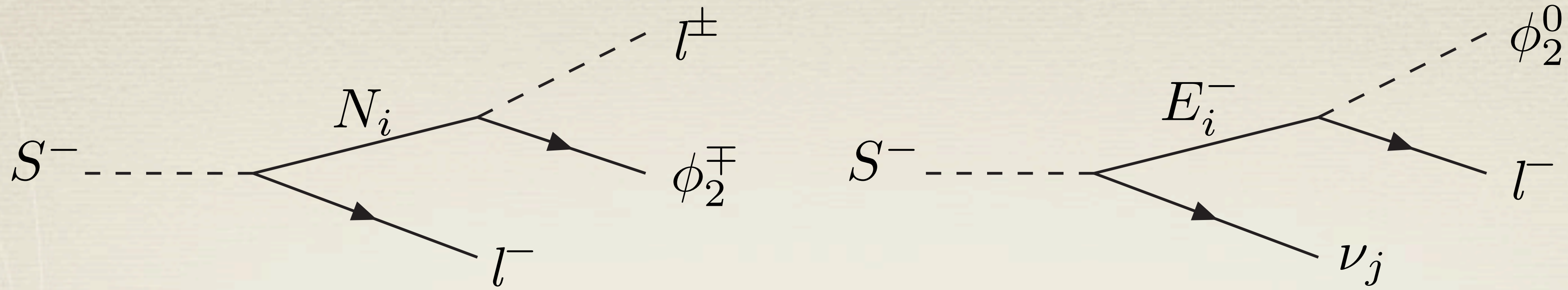
✳ A long-lived $S^+$ is needed ~ 1000 sec



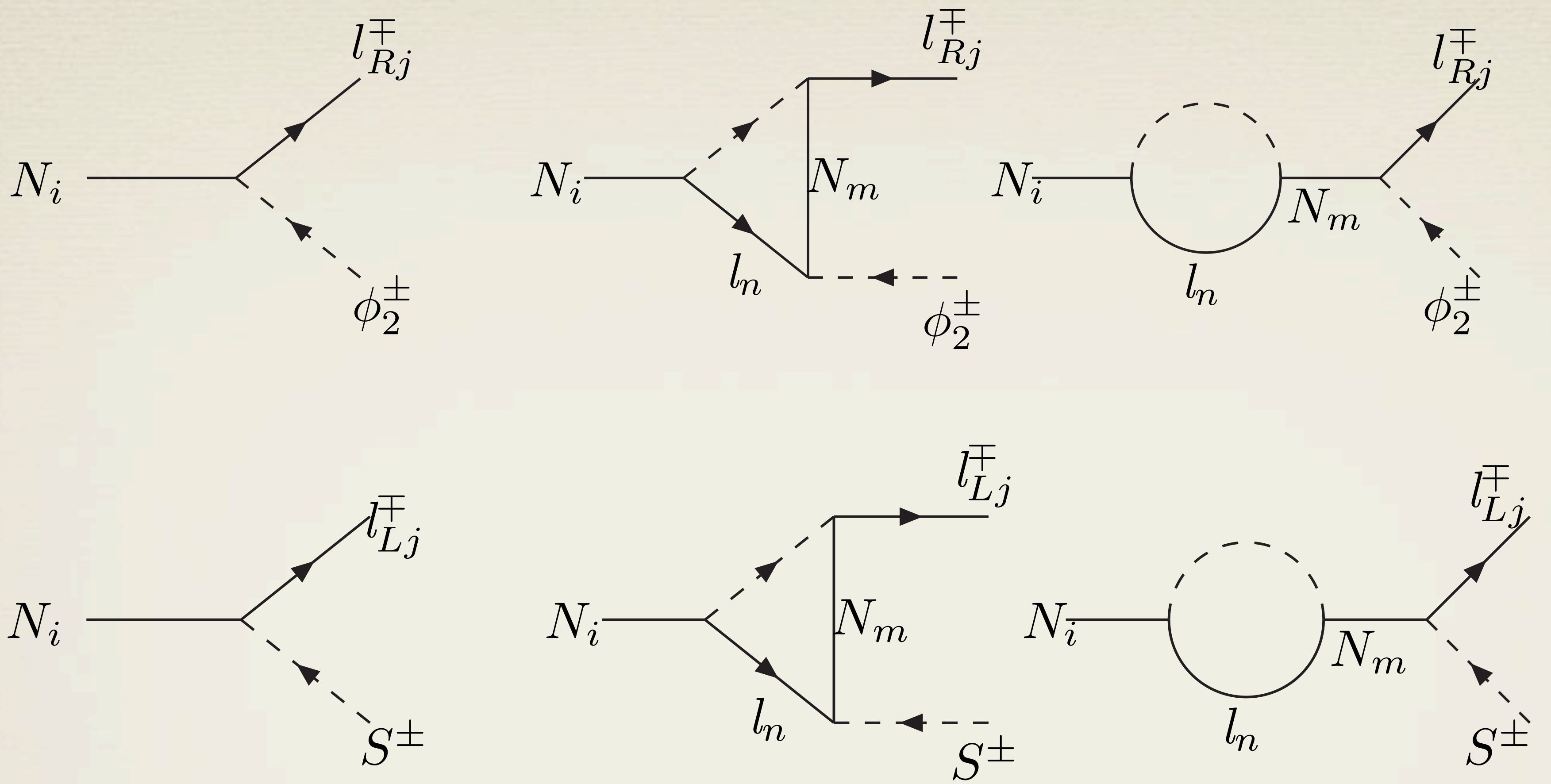

$$\Gamma_s|_{\alpha\beta(N_i)} \approx \frac{(f_{\alpha i}y_{i\beta})^2}{30\pi^3 M_{N_i}^4} \times (\delta m)^5 (1 - \frac{5m_l^2}{\delta m^2})$$
$$\approx f_{\alpha i}^2 y_{i\beta}^2 \times 10^{-15} (\frac{\delta m}{1GeV})^5 \mathrm{GeV},$$

$$\tau_{\alpha\beta} \approx 6.6 \times f_{\alpha i}^{-2} y_{i\beta}^{-2} \times (\frac{\delta m}{1GeV})^{-5} \times 10^{-10} s.$$

$f \sim 10^{-4\sim-5}$ $\delta m \leq 1GeV$ $y \sim 10^{-1} - 10^{-2}$

# Leptogensis

- Two contributions




$$\Gamma_{N_1} = \frac{\sum_\alpha (y_{1\alpha})^2}{16\pi} M_{N_1} \quad \text{and} \quad \Gamma_{N_1} = \frac{(f^\dagger f)_{11}}{8\pi} M_{N_1}$$

The right-handed sector is not constrained by neutrino masses

$$\epsilon_1 = \frac{\Gamma(N_1 \to l\phi_2^+) - \Gamma(N_1 \to \bar{l}\phi_2^-)}{\Gamma(N_1 \to l\phi_2^+) + \Gamma(N_1 \to \bar{l}\phi_2^-)} = \frac{1}{8\pi}\sum_{m\neq 1}\frac{Im[(y^\dagger y)^2_{1m}]}{\sum_\alpha (y^\dagger y)_{1\alpha}}\{f_v(\frac{M_m^2}{M_1^2}) + f_s(\frac{M_m^2}{M_1^2})\}$$

$$= \frac{3}{16\pi}\sum_{m\neq 1}\frac{Im[(y^\dagger y)^2_{1m}]}{\sum_\alpha (y^\dagger y)_{1\alpha}}\frac{M_1}{M_m}, \qquad (26)$$

If $\quad y^{(2)} = \sqrt{\frac{Im[(y_{1\alpha})(y^*_{2\alpha})]^2}{\sum_\alpha (y_{1\alpha})(y^*_{1\alpha})}} \geq 1.05 \times 10^{-3}\sqrt{\frac{M_{N_2}}{M_{N_1}}},$

One has $\quad \frac{n_B}{s} = -\frac{28}{79}\frac{n_L}{s} = -1.36 \times 10^{-3}\epsilon_1\eta = 9 \times 10^{-11},$

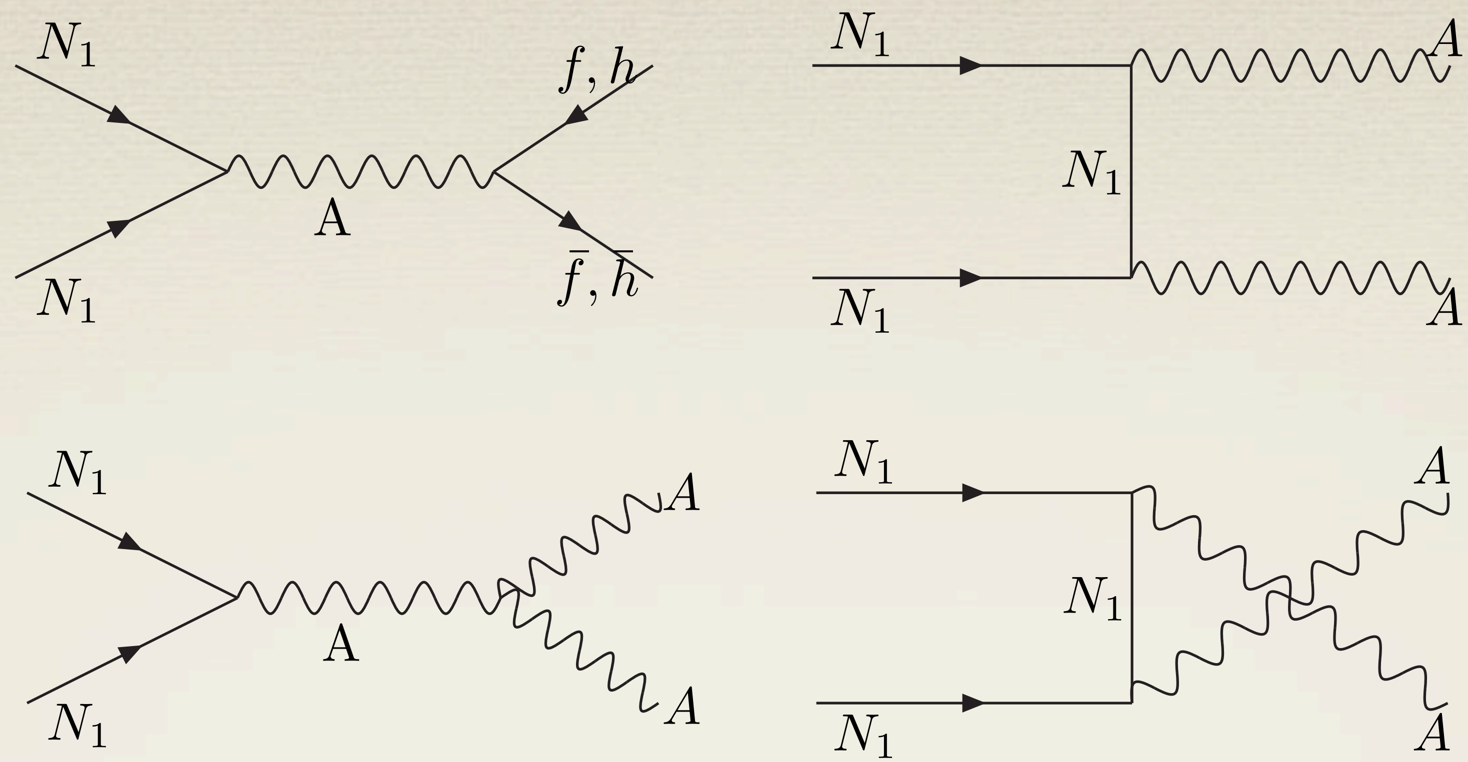
Out of equilibrium condition $\quad \Gamma_{N_1} < H(T) = \sqrt{\frac{4\pi^3 g_*}{45}}\frac{T^2}{M_{pl}}|_{T=M_{N_1}}.$

We have $\quad y^{(1)} = \sqrt{\sum_i |y_{1i}|^2} < 3 \times 10^{-4}\sqrt{\frac{M_{N_1}}{10^9 GeV}}.$

Hierarchy couplings : $\quad \frac{y^{(1)}}{y^{(2)}} < 0.28 \times \sqrt{\frac{M_{N_1}}{M_{N_2}}\frac{M_{N_1}}{10^9 GeV}}.$

$M_{N_1} = 1TeV$, $M_{N_2} = 5TeV$, $y^{(2)} \simeq 2.3 \times 10^{-3}$, and $y^{(1)} \simeq 3 \times 10^{-7}$.

* Washout effects from gauge interactions (Type II ,III seesaw mechanism)



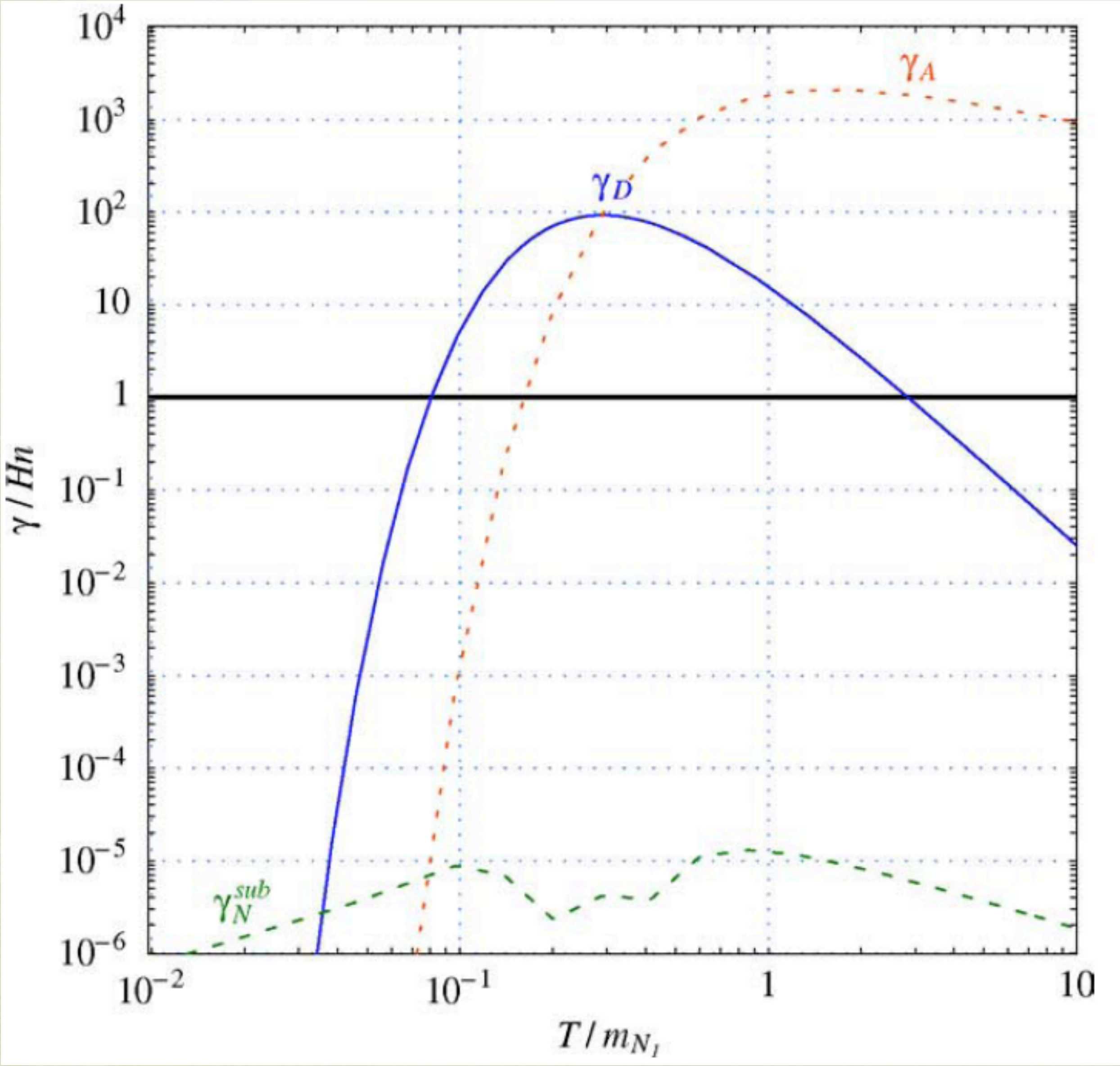

$$\hat{\sigma}_A(N_1N_1 \to D\bar{D}, AA) = \frac{6g_2^4}{\pi}\left(1+\frac{2}{x}\right)r + \frac{2g_2^4}{\pi}\left[-r\left(4+\frac{17}{x}\right)+3\left(1+\frac{4}{x}-\frac{4}{x^2}\right)\ln\frac{1+r}{1-r}\right],$$

$r = \sqrt{1-4/x}$. $x = s/M_1^2$.

* Boltzmann eqs.

$$sHz\frac{dY_{N_1}}{dz} = -\left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}} - 1\right)\gamma_D - \left(\frac{Y_{N_1}^2}{Y_{N_1}^{2\rm eq}} - 1\right)\gamma_A$$

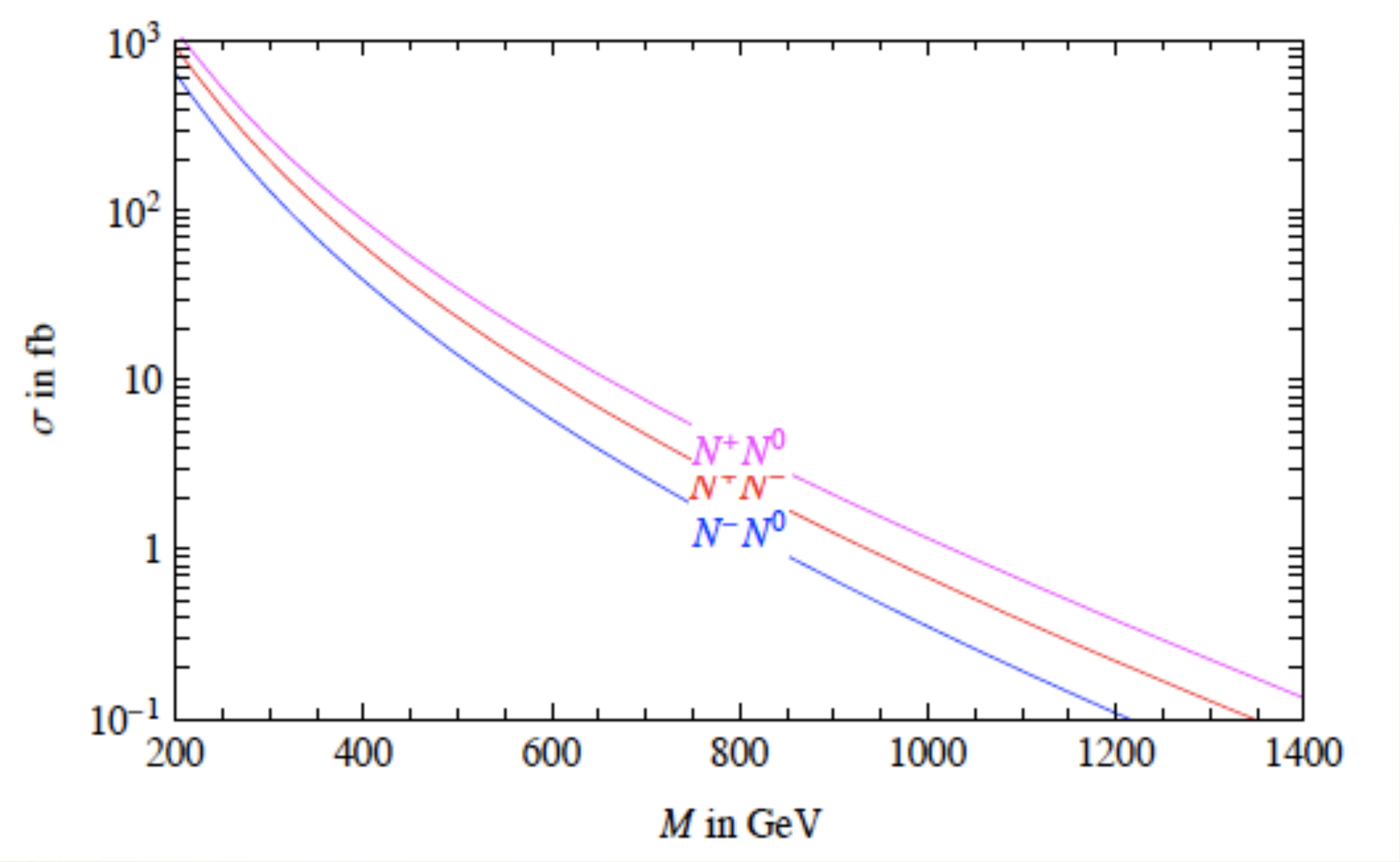
$$sHz\frac{dY_{\mathcal{B}-\mathcal{L}}}{dz} = -\gamma_D\varepsilon_{N_1}\left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}} - 1\right) - \frac{Y_{\mathcal{B}-\mathcal{L}}}{Y_L^{\rm eq}}\left(\frac{\gamma_D}{2} + 2\gamma_N^{\rm sub}\right)$$




Boltzmann suppression factor in gauge fields at low scale

Left-handed leptogenesis
Contribute constrained by
Neutrino masses -- subleading

* Some Collider phenomena
* The new particles are all reachable at LHC.




ΔM = 166 MeV
Splitting by gauge interactions

Long-lived to leave the tracks
In detectors

$$\Gamma(N^\pm \to N^0\pi^\pm) = \frac{2G_F^2 V_{ud}^2 \Delta M^3 f_\pi^2}{\pi}\sqrt{1-\frac{m_\pi^2}{\Delta M^2}}$$

$$\Gamma(N^\pm \to N^0 e^\pm \overset{(-)}{\nu}_e) = \frac{2G_F^2 \Delta M^5}{15\pi^3},$$

$$\Gamma(N^\pm \to N^0 \mu^\pm \overset{(-)}{\nu}_\mu) = 0.12\,\Gamma(N^\pm \to N^0 e^\pm \overset{(-)}{\nu}_e)$$

# Conclusions

* The neutrino masses generated through the radiative seesaw mechanism with double GIM suppression is presented.
* Anomalous muon magnetic moment is given through the mechanism similar to neutrino masses generation.
* Dark matter candidate is realized in inert doublet scalar, and a direct measurement is possible in next-generation experiments.
* Lithium problem can be solved by a long-lived single charged scalar $S^-$ to by Catalyzed BBN method.
* TeV-scale leptogenesis utilizing right-handed lepton sector as well as left-handed is presented.
* The model can be tested in near future at collider.