

Lectures on The Standard Model and Beyond

Nobuchika Okada

University of Alabama



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Day 2

Beyond the Standard Model (BSM)

Status of the Standard Model

The Standard Model (SM) is the best theory in describing the nature of elementary particle physics, which is in excellent agreement with almost of all current experimental results (including LHC Run results) as of TODAY

Discussion Day 1 completed!

Let's continue to Day 2

However,

There are problems that the SM cannot answer

Physics beyond the SM (BSM Physics) is strongly suggested by both experimental & theoretical points of view

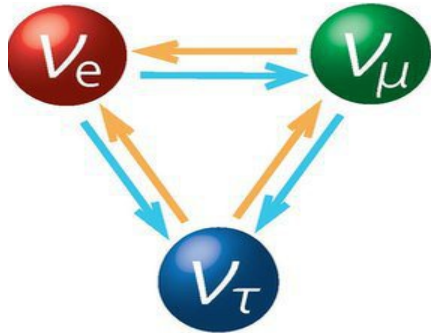
Some questions that the Standard Model cannot answer

Some questions that the Standard Model cannot answer

1. Why are **Neutrino Masses** are non-zero and so tiny?

Neutrino Mass problem

Neutrino Oscillation Phenomena



$$\Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{32}^2 = (2.44 \pm 0.06) \times 10^{-3} \text{ eV}^2$$

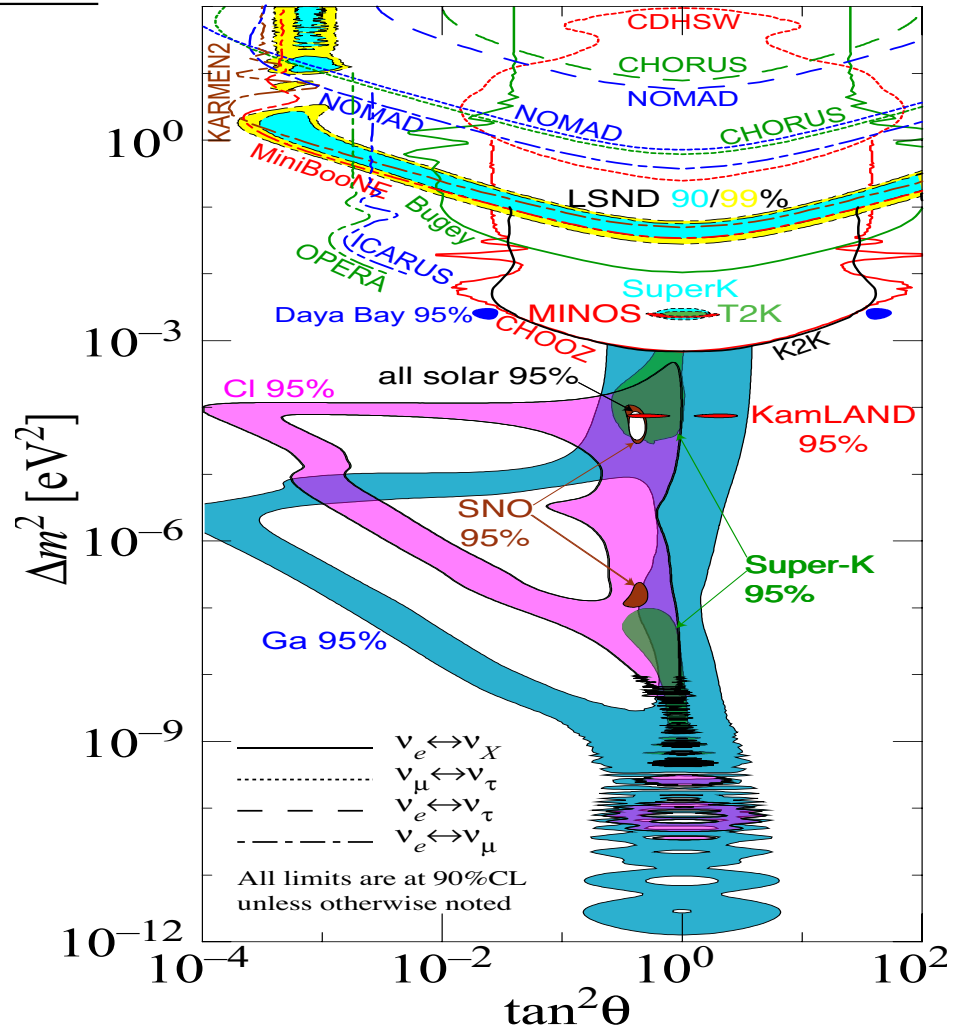
$$\sin^2(2\theta_{12}) = 0.846 \pm 0.021$$

$$\sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018}$$

$$\sin^2(2\theta_{13}) = (9.3 \pm 0.8) \times 10^{-2}$$

Neutrinos are massless
in the Standard Model

Particle Data Group



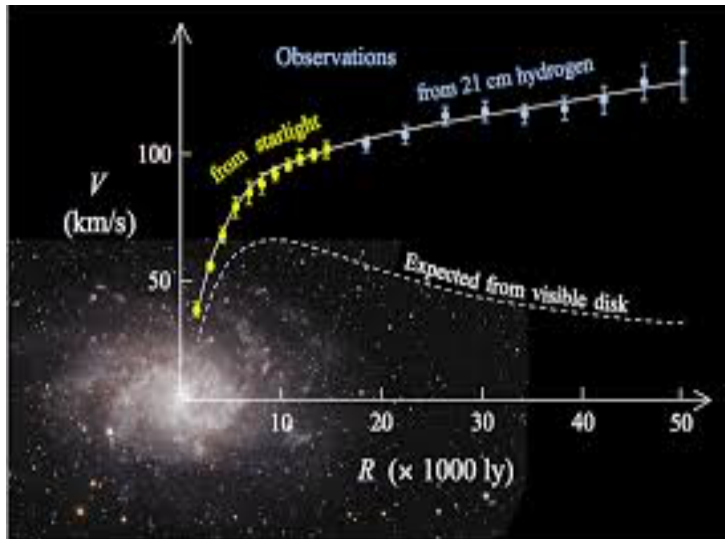
Some questions that the Standard Model cannot answer

1. Why are **Neutrino Masses** are non-zero and so tiny?
2. What is the nature of **Dark Matter**?

Dark Matter Problem

Evidence of dark matter

Galaxy rotation curve

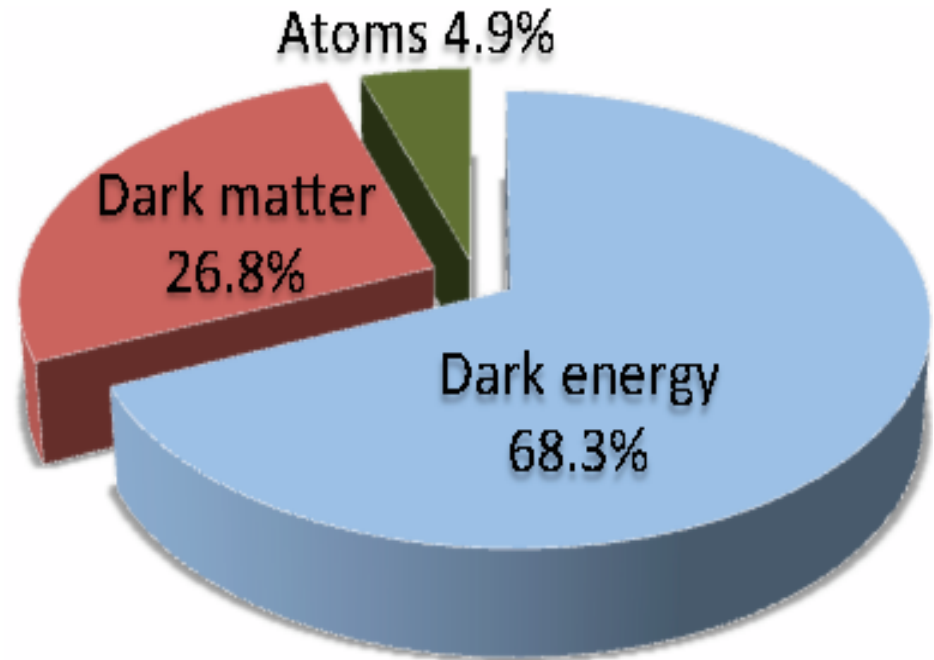


Bullet Cluster



Existence of Dark Matter has been established!

Energy budget of the Universe is precisely determined by recent CMB anisotropy observations (WMAP & Planck)



Dark Matter particle: non-baryonic
electric charge neutral
(quasi) stable $\tau_{DM} > t_U$

No suitable DM candidate in the Standard Model

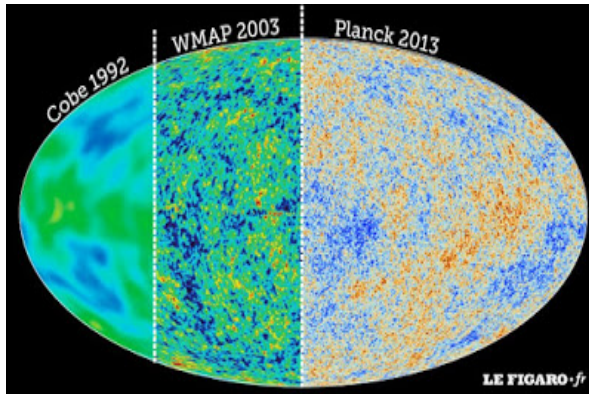
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1. Why are **Neutrino Masses** are non-zero and so tiny?
2. What is the nature of **Dark Matter**?
3. What drives **Cosmic Inflation** before Big Bang?

Cosmic Inflation

The problems of Big-Bang Cosmology

- Flatness problem
- Horizon problem
- Need to dilute unwanted topological defects
- Origin of the primordial density fluctuations



$$\frac{\delta T}{T} \simeq 10^{-5}$$

Seeds of the large scale structure

Solution: **Cosmic Inflation** before Big-Bang cosmology, driven by a scalar field (**inflaton**) which has a very flat potential

No suitable inflaton candidate in the SM

Some questions that the Standard Model cannot answer

1. Why are **Neutrino Masses** non-zero and so tiny?
2. What is the nature of **Dark Matter**?
3. What drives **Cosmic Inflation** before Big Bang?
4. What is the origin of **Matter-Antimatter asymmetry** in the Universe?

What is the origin of Matter-Antimatter Asymmetry?

Observations: (1) Big asymmetry $n_B \gg n_{\bar{B}}$

(2) Small ratio to entropy

$$\frac{n_B}{s} \simeq \frac{n_B - n_{\bar{B}}}{s} \simeq 10^{-10} \ll 1$$

What is the origin?

*Baryogenesis in the SM context: [Electroweak Baryogenesis](#)
Unfortunately, it doesn't work with the 125 GeV Higgs mass

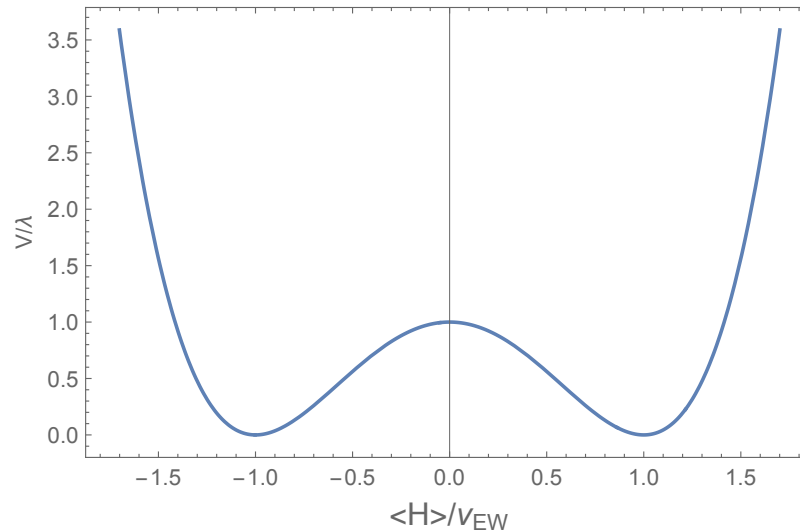
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2. What is the nature of **Dark Matter**?
3. What drives **Cosmic Inflation** before Big Bang?
4. What is the origin of **Matter-Antimatter asymmetry** in the Universe?
5. What derives the **Electroweak Symmetry Breaking**?

5. What drives the Electroweak symmetry breaking?

SM Higgs potential with a negative mass squared:

$$V = -m_H^2(H^\dagger H) + \lambda(H^\dagger H)^2 + \text{const}$$



Any “dynamical” reason for $-m_H^2$?

Research on BSM may include

1. Consider new framework to solve the SM's mysteries and how to experimentally confirm it
2. Discuss new theoretically interesting paradigm, its prediction and possible ways to experimentally confirm it
3. Consider a way to discriminate different scenarios by experiment

Direction 1

Consider new framework to solve the SM's mysteries
and how to experimentally confirm it

Some attempt to saving several mysteries

Simple solution to the neutrino mass problem

Seesaw Mechanism

Minkowski; Yanagida; Mohapatra & Senjanovic; Gell-Mann, Ramond & Slansky

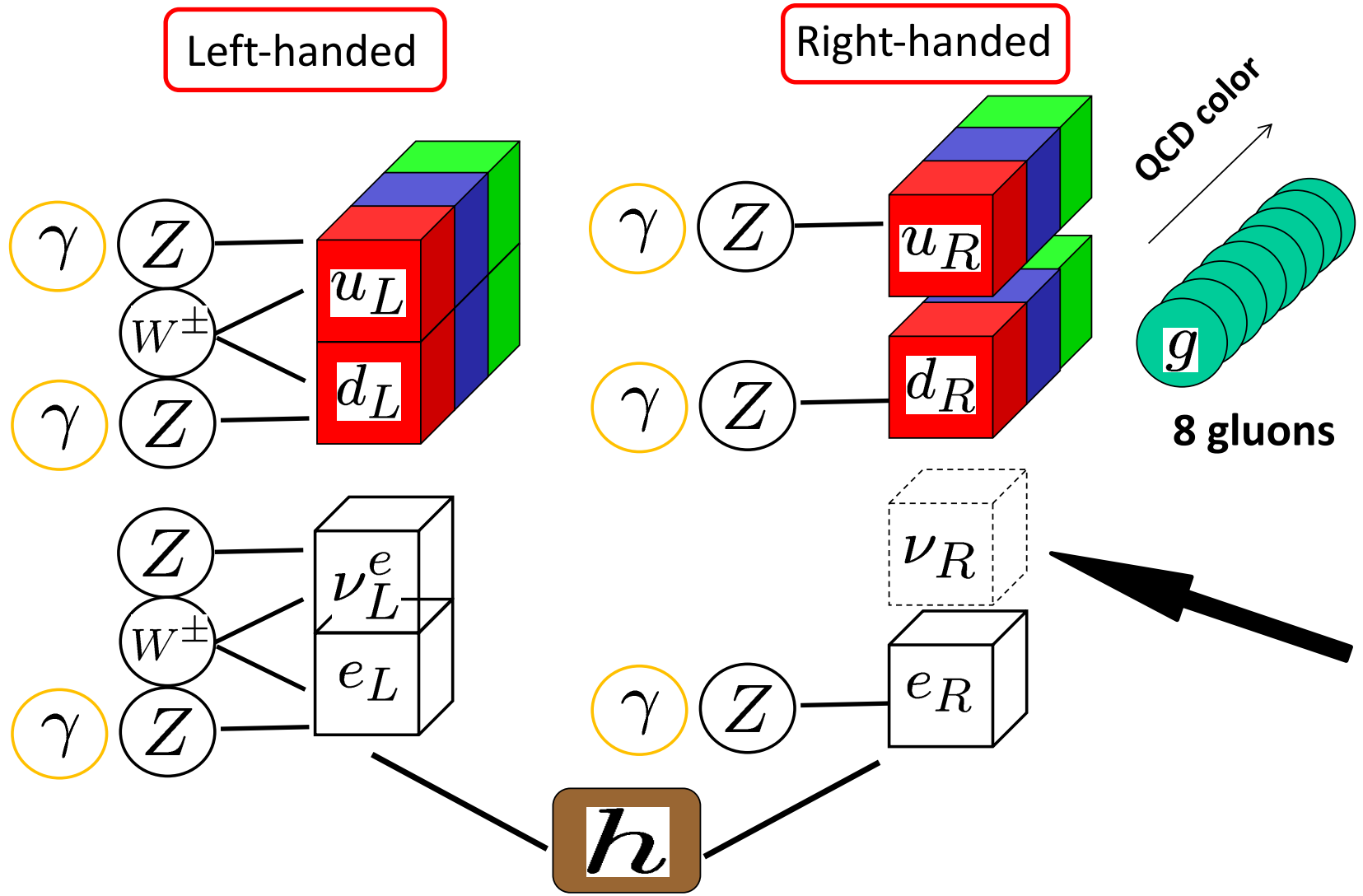
The Standard Model + **heavy Right-Handed Neutrinos**

$$M_\nu = \begin{bmatrix} 0 & m_D \\ m_D & M \end{bmatrix} \quad \begin{array}{l} m_D \text{ from SM Higgs VEV} \\ M : \text{RHN mass} \end{array}$$

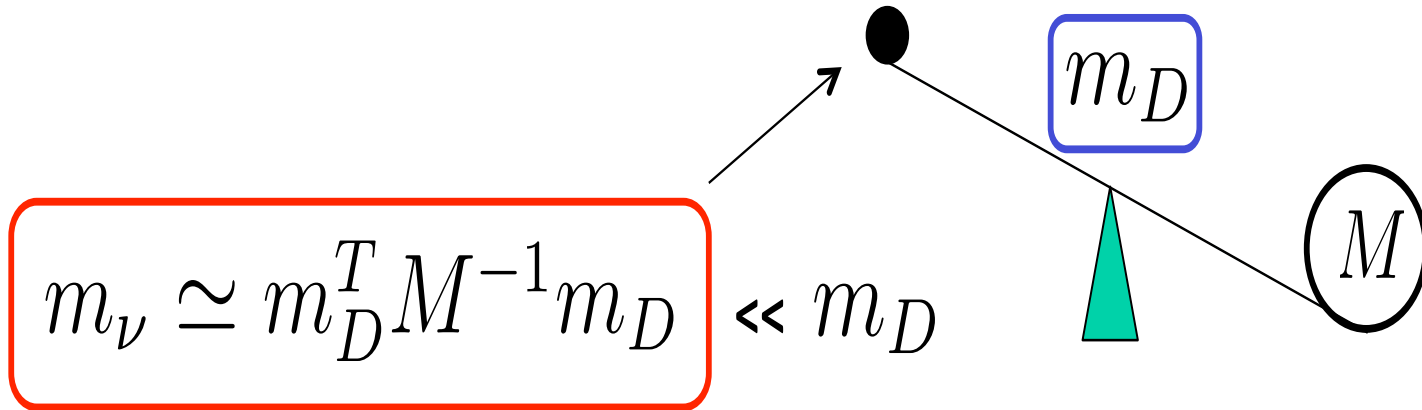
If we have a hierarchy between $m_D \ll M$

$$M_\nu = \begin{bmatrix} 0 & m_D \\ m_D & M \end{bmatrix} \rightarrow \begin{bmatrix} m_D \frac{m_D}{M} & 0 \\ 0 & M \end{bmatrix}$$

The structure of the SM (1st generation)



Seesaw Mechanism



$$\left. \begin{array}{l} m_D \sim 100 \text{ GeV} \\ M \sim 10^{14} \text{ GeV} \end{array} \right\}$$

$$m_\nu \sim m_D \frac{m_D}{M} \sim 0.1 \text{ eV}$$

- Neutrinos are Majorana particles
- Theoretical connection between tiny neutrino mass & high scale phys.

WIMP scenario for Dark Matter Problem

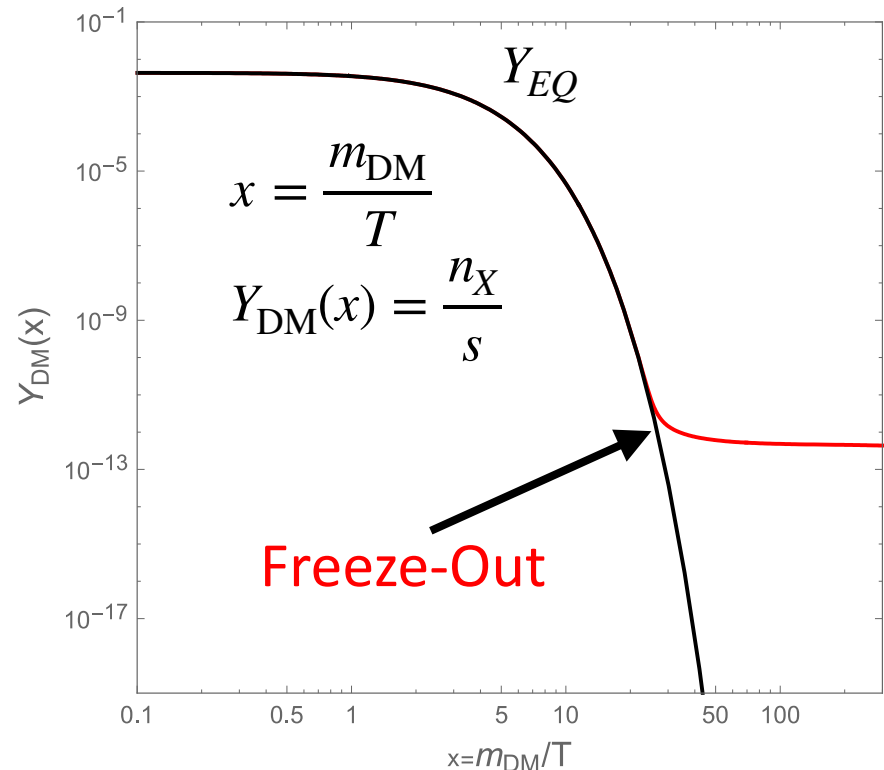
DM candidate: Weakly Interacting Massive Particle (WIMP)
with

$$Q_X = 0 \text{ and } \tau_X \gg \tau_U$$

Decoupling from
the SM thermal plasma:

Boltzmann equation

$$\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma_{X\bar{X}} v_{rel} \rangle \left(n_X^2 - \left(n_X^{EQ} \right)^2 \right)$$



The DM relic density:

$$\Omega_{DM}h^2 = \frac{m_\chi s_0 Y(\infty)}{\rho_c/h^2},$$

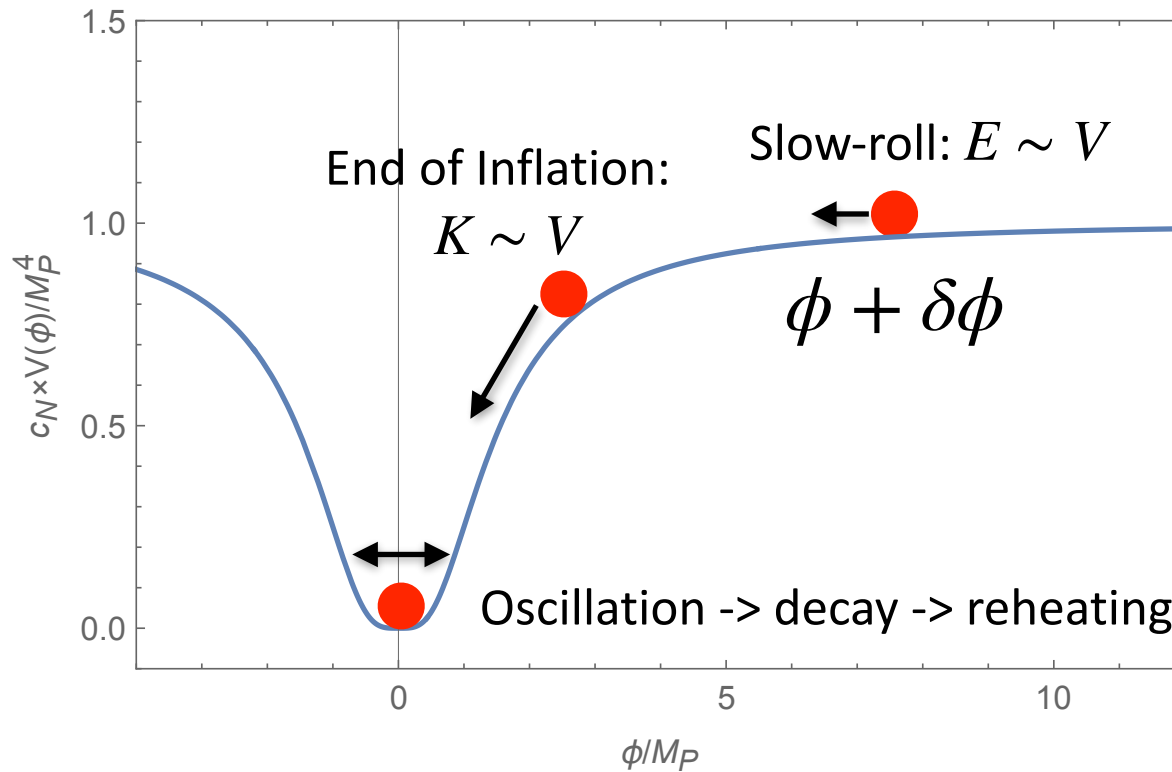
where $s_0 = 2890 \text{ cm}^{-3}$

$$\rho_c/h^2 = 1.05 \times 10^{-5} \text{ GeV/cm}^3$$

This should reproduce the observed DM density measured by Planck 2018

$$\Omega_{DM}h^2 = 0.12$$

Slow-roll inflation to drive the cosmic inflation



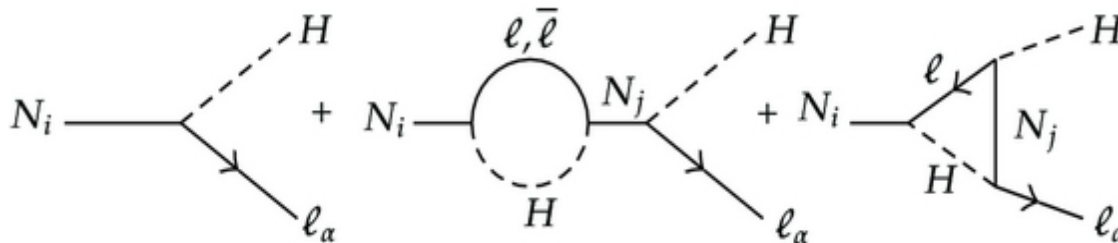
- Inflation takes place during slow-roll: $a(t) \propto e^{H_{inf}t}$
- Quantum fluctuation $\delta\phi$ is magnified to a macroscopic scale
—> primordial density fluctuation

Simple scenario: Baryogenesis via Leptogenesis

Fukugita & Yanagida (1986)

- Right-handed neutrino decay in the early Universe generates lepton asymmetry
- Lepton asymmetry is converted to Baryon asymmetry by the SM non-perturbative effect (Sphaleron processes)

CP-asymmetric out-of-equilibrium decay of heavy neutrinos



Radiative Symmetry Breaking

Toy U(1) gauge model: $\frac{\quad}{\Phi} \left| \begin{array}{c} \text{U(1)} \\ +2 \end{array} \right.$

By imposing “Classical Conformal Symmetry”

$$V_{tree} = \lambda_{\Phi} (\Phi^{\dagger} \Phi)^2$$

*define this theory as “Massless Theory”

Coleman-Weinberg mechanism

Coleman & Weinberg,
PRD 7 (1973) 1888

$$V_{CW} = V_{tree} + V_{1-loop}$$
$$= \frac{\lambda_{\Phi}}{4} \phi^4 + \frac{\beta_{\Phi}}{8} \phi^4 \left(\ln \left[\frac{\phi^2}{v_{\phi}^2} \right] - \frac{25}{6} \right),$$

where $\Phi = \frac{1}{\sqrt{2}} (\phi + i\chi)$, $\beta_{\Phi} = \frac{1}{16\pi^2} 96g^4$

➤ Radiative U(1) symmetry breaking at $\phi = v_{\phi}$

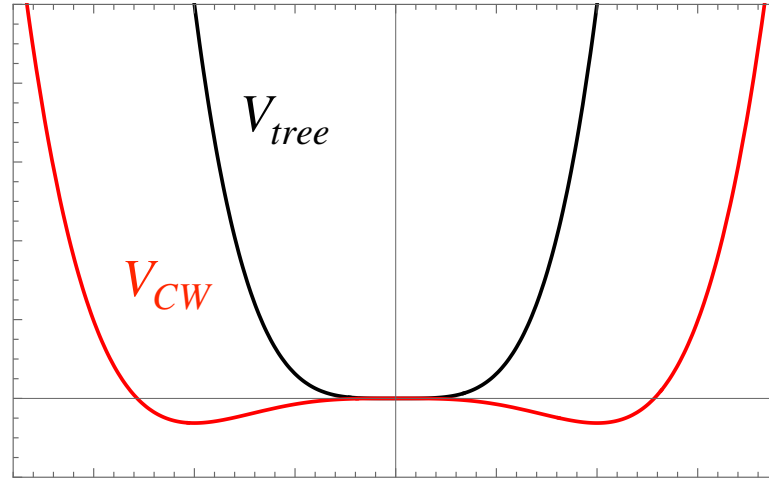
➤ Parameter relations: $\lambda_{\Phi} = \frac{11}{6} \beta_{\Phi}$

$$m_{\phi}^2 = \left. \frac{d^2 V_{CW}}{d\phi^2} \right|_{\phi \rightarrow v_{\phi}} \rightarrow \frac{3}{2\pi^2} g^2 M_{Z'}^2$$

Interesting properties:

- Origin of gauge symmetry breaking?
quantum corrections (QM system knows where to be)

$$\frac{d^2 V_{CW}}{d\phi^2} \Big|_{\phi \rightarrow 0} = 0$$



- Predictability

Relation between Higgs mass and U(1) gauge boson mass

Toward solving the some SM mysteries

Extension of the Standard Model with

- New scalar for inflation
- Right-Handed neutrinos

Seesaw Mechanism

Baryogenesis via Leptogenesis

- Dark Matter Candidate
- Dynamical origin of the Higgs VEV generation

Minimal gauged B-L extension of the SM

Davidson (1979);

Mohapatra & Marshak (1980)

B-L (Baryon number minus Lepton number)

Based on $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

Particle Content

New Force!

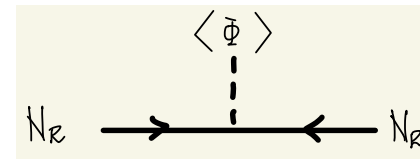
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
q_L^i	3	2	+1/6	+1/3
u_R^i	3	1	+2/3	+1/3
d_R^i	3	1	-1/3	+1/3
ℓ_L^i	1	2	-1/2	-1
N_R^i	1	1	0	-1
e_R^i	1	1	-1	-1
H	1	2	-1/2	0
Φ	1	1	0	+2

3 RHNs

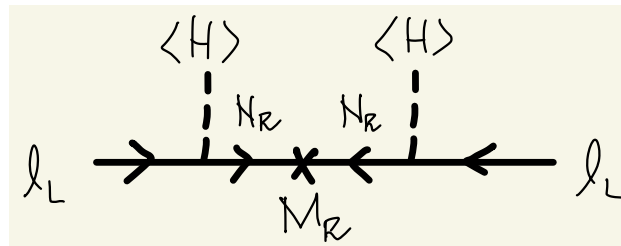
B-L Higgs field

Properties of Minimal B-L Model

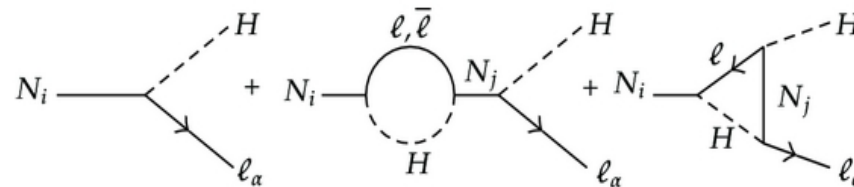
- Anomaly-free global B-L symmetry in the SM is gauged
- Right-handed neutrinos to cancel gauge/gravitational anomaly
- Spontaneous B-L gauge symmetry breaking to generate Majorana mass for RHNs



- Seesaw mechanism after electroweak symmetry breaking



- Leptogenesis via CP-asymmetric out-of-equilibrium NR decay



Classically Conformal extension of Minimal B-L Model

Iso, NO & Orikasa (2009)

$$V = \lambda_H (H^\dagger H)^2 + \lambda_\Phi (\Phi^\dagger \Phi)^2 - \lambda_{\text{mix}} (H^\dagger H) (\Phi^\dagger \Phi)$$

- ▶ No mass terms due to the conformal invariance
- ▶ We set $\lambda_{H,\Phi,\text{mix}} > 0$
- ▶ No symmetry breaking at the tree-level

Assuming a small mixing quartic coupling, the symmetry breaking occurs in the following way.....

Symmetry Breaking

1st: Radiative U(1) breaking by Coleman-Weinberg mechanism

$$V(\phi) = \frac{\lambda_{\Phi}}{4} \phi^4 + \frac{12g_X^4}{16\pi^2} \phi^4 \left(\ln \left[\frac{\phi^2}{v_X^2} \right] - \frac{25}{6} \right) \quad \phi = \sqrt{2} \text{Re} [\Phi]$$

$$\langle \Phi \rangle = \frac{v_X}{\sqrt{2}}$$

2nd: Electroweak symmetry breaking is triggered

$$V \supset -\lambda_{\text{mix}} (\Phi^\dagger \Phi) (H^\dagger H) + \lambda_H (H^\dagger H)^2$$
$$\rightarrow -\lambda_{\text{mix}} \langle \Phi^\dagger \Phi \rangle (H^\dagger H) + \lambda_H (H^\dagger H)^2$$

Negative mass squared generated!

Extension of B-L Model with a DM candidate

- Z_2 parity & Z_2 -odd RHN DM

NO & Seto (2009)

$J=1,2$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$	Z_2
N_R^j	1	1	0	-1	+
N_R	1	1	0	-1	-
Φ	1	1	0	+2	+

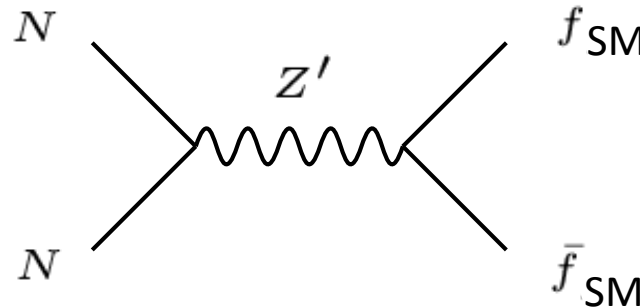
Z_2 -odd RHN is stable \rightarrow DM
The others are even

3 RHNs \rightarrow 2 RHNs for Minimal Seesaw

+

1 B-L Higgs/ Z' -portal WIMP DM

King, NPB 576 (2000) 85;
Frampton, Glashow & Yanagida,
PLB 548 (2002) 119



NO & Orikasa (2012);
NO & Burell (2015);
NO & S. Okada (2015)
NO, S. Okada & Raut (2017)
Oda, NO & Takahashi (2017)

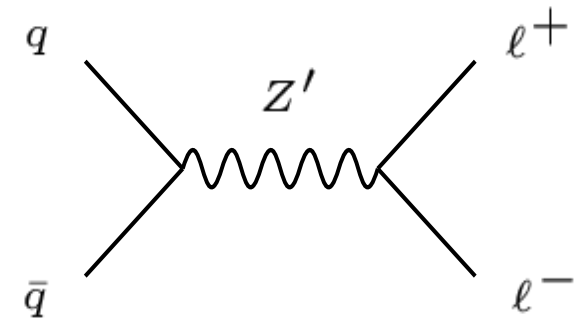
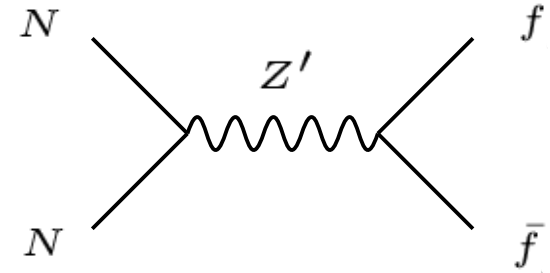
Complementarity between DM physics and LHC

(1) Z' -portal RHN DM

RHN DM communicates with the SM particles through Z' boson mediated processes

(2) Z' boson search at the LHC Run-2

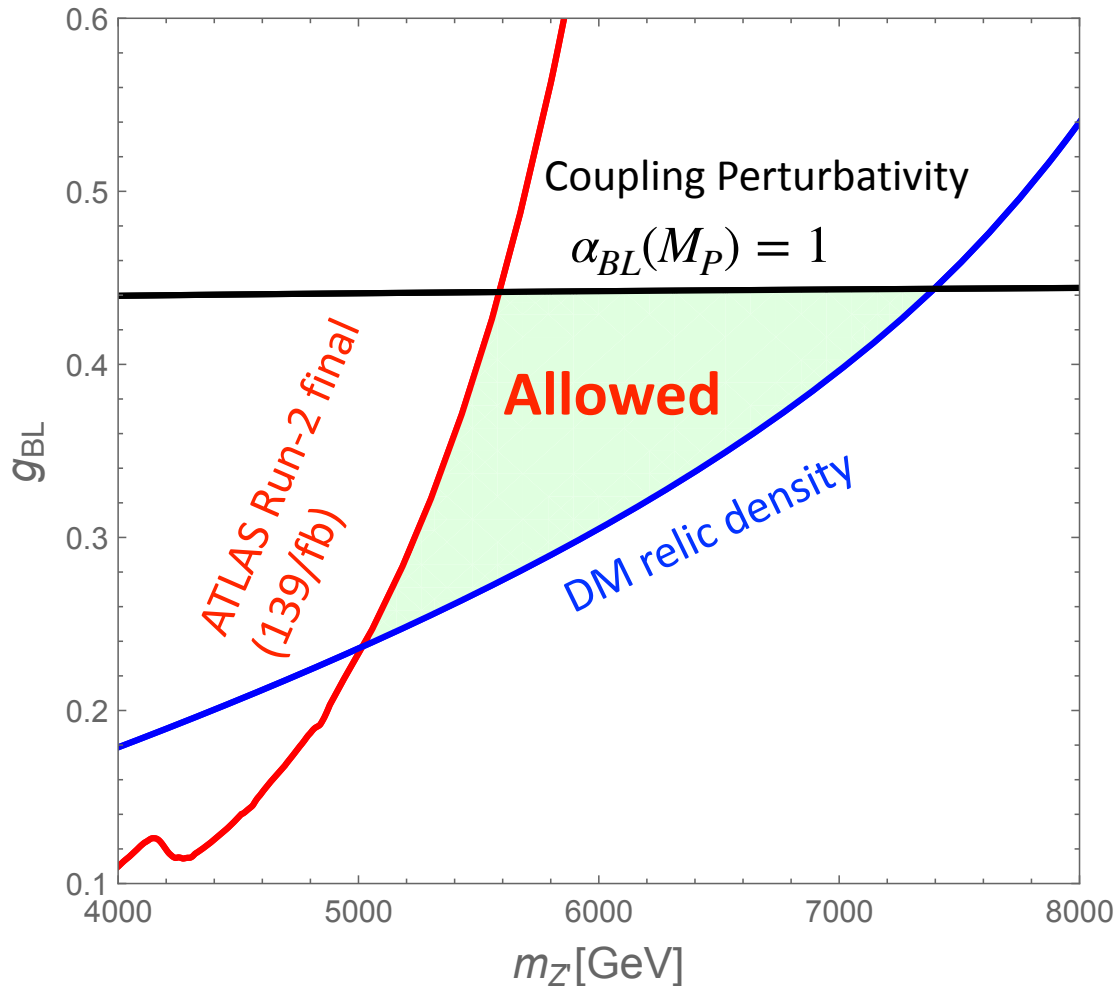
Search for a narrow resonance with the di-lepton final state at ATLAS and CMS with LHC Run-2



Both processes are controlled essentially by only two free parameters: g_{BL} and $m_{Z'}$.

* For a high mass Z' , $m_{DM} \simeq m_{Z'}/2$ is necessary to reproduce the observed DM relic density

Combining Cosmological & LHC Run-2 Constraints with the gauge coupling perturbativity until Planck

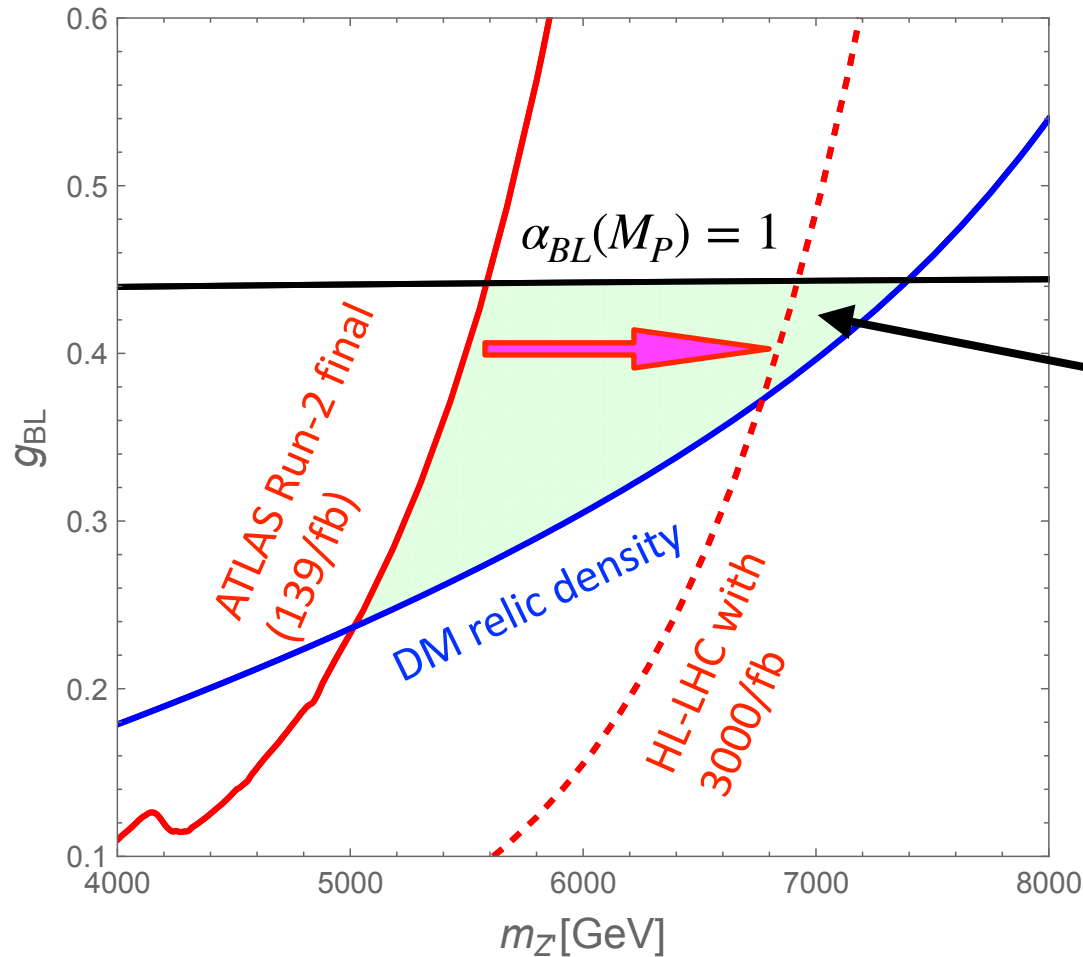


Allowed Region:

$$0.236 \leq g_{BL} \leq 0.444$$

$$5.0 \leq m_{Z'} [\text{TeV}] \leq 7.4$$

High-Luminosity LHC will push the bound with $\sqrt{s} = 14 \text{ GeV}$ and Goal Luminosity of 3000/fb



Inflation in Minimal B-L Model

- B-L Higgs as Inflaton

NO, Rehman & Shafi (2011)
NO & Raut (2015)

Introduce non-minimal gravitational coupling to the B-L Higgs:

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[-\frac{1}{2} M_P^2 f R + \partial_\mu \Phi^\dagger \partial^\mu \Phi - V(\Phi) \right]$$

where $f = 1 + 2\xi \frac{\Phi^\dagger \Phi}{M_P^2}$

- $v_{BL} \ll M_P$
- During the inflation, the inflation potential is dominated by
$$V \sim \lambda_\Phi (\Phi^\dagger \Phi)^2$$

In Einstein frame:
$$V_E(\phi) = \frac{\lambda_\Phi (\Phi^\dagger \Phi)^2}{(1 + \xi (\Phi^\dagger \Phi))^2}$$

A robust prediction from more accurate calculations

Kawai, NO & Shafi, PRD 109 (2024) 3, 035026

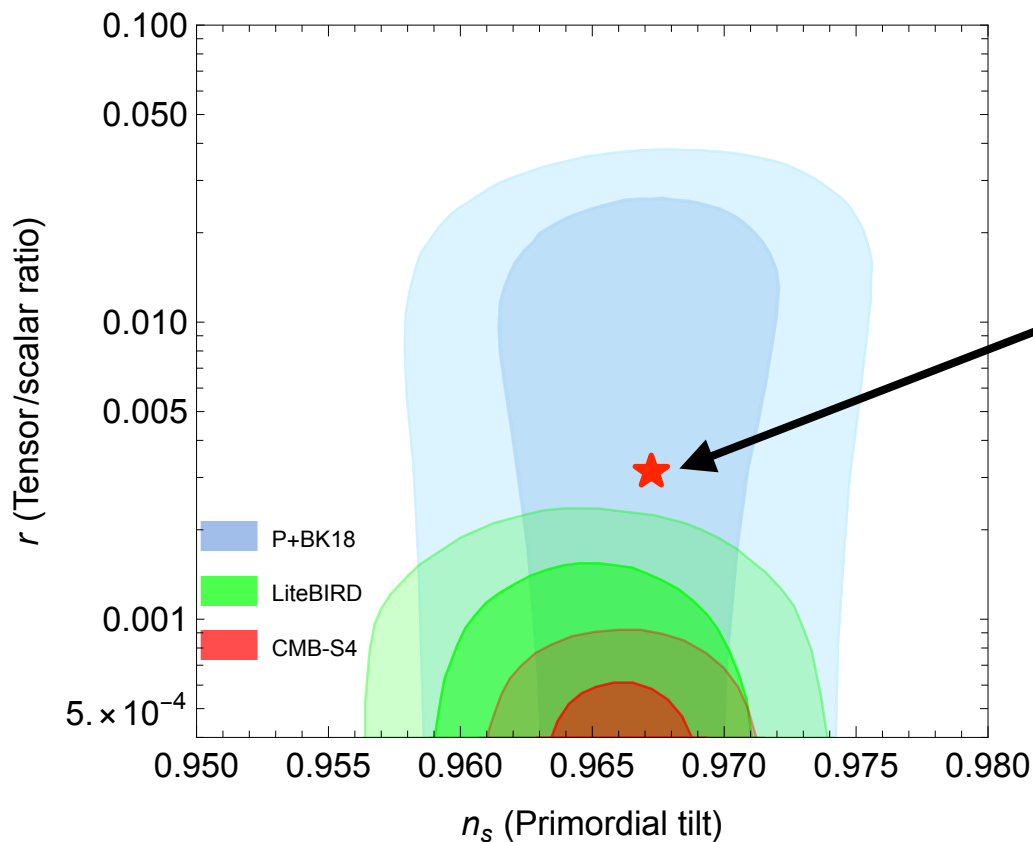
$$N_k \equiv \ln \frac{a_e}{a_k} = 66.5 - \ln h - \ln \frac{k}{a_0 H_0} + \frac{1 - 3w}{12(1 + w)} \ln \frac{\rho_{\text{th}}}{\rho_e} \\ + \frac{1}{4} \ln \frac{V_k}{\rho_e} + \frac{1}{4} \ln \frac{V_k}{M_{\text{P}}^4} + \frac{1}{12} (\ln g_*^{\text{eq}} - \ln g_*^{\text{th}})$$

Benchmark

- DM density reproduced
- Consistent with LHC Z' search

$$g_X = 0.24$$

$$M_{Z'} = 5 \text{ TeV}$$



For the allowed values,
reheating process is very
efficient (violent preheating):

Ema, Jinno, Mukaida, and
Nakayama, JCAP 1505 (05), 038

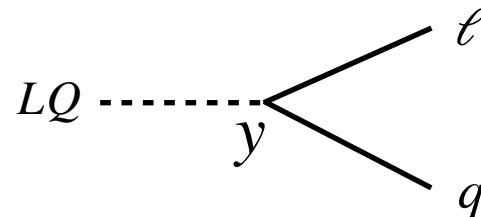
- Gauged U(1) B-L extended SM can solve several problems of the SM:
 - ☑ Why are **Neutrino Masses** are non-zero and so tiny?
 - ☑ What is the nature of **Dark Matter**?
 - ☑ What drives **Cosmic Inflation** before Big Bang?
 - ☑ What is the origin of **Matter-Antimatter asymmetry** in the Universe?
 - ☑ What drives **Electroweak Symmetry Breaking**?

Direction 2

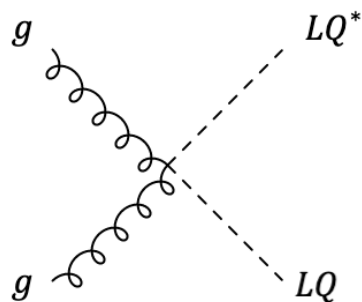
We may discuss new theoretically interesting paradigm, its prediction and possible ways to experimentally confirm it.

Discussion about a hypothetical “**Scalar Leptoquark**”

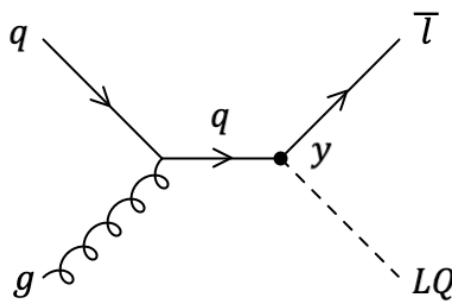
- hypothetical scalar particle **simultaneously** couples to quarks and leptons



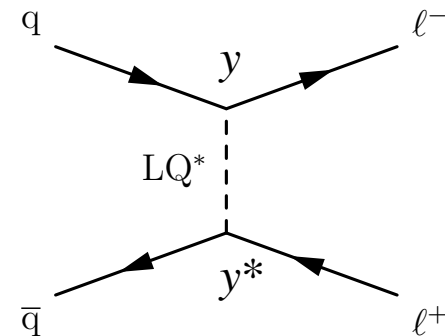
- has been searched for at LHC through a variety of processes



pair production

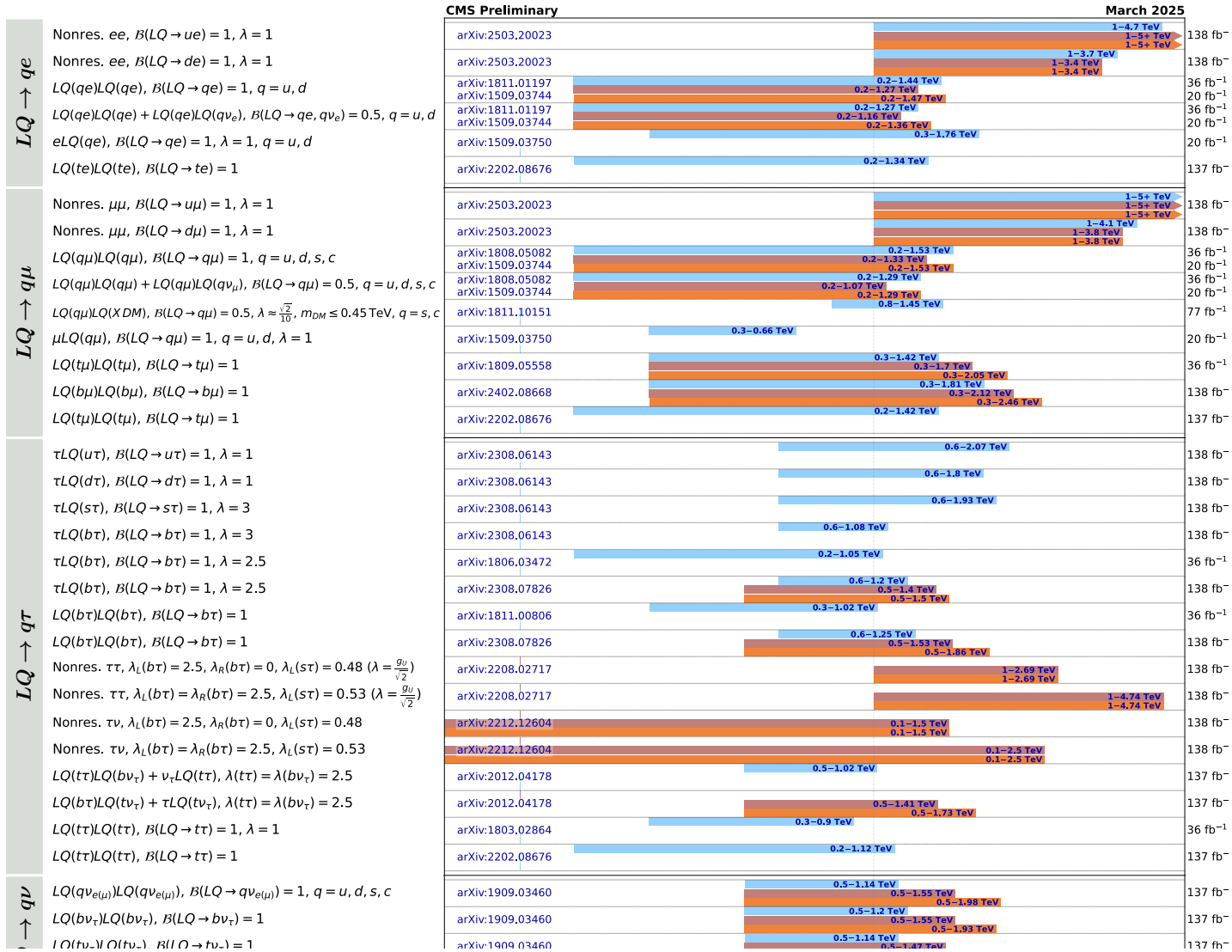


single production



LQ mediated process

CMS leptoquark summary (2025 Moriond)

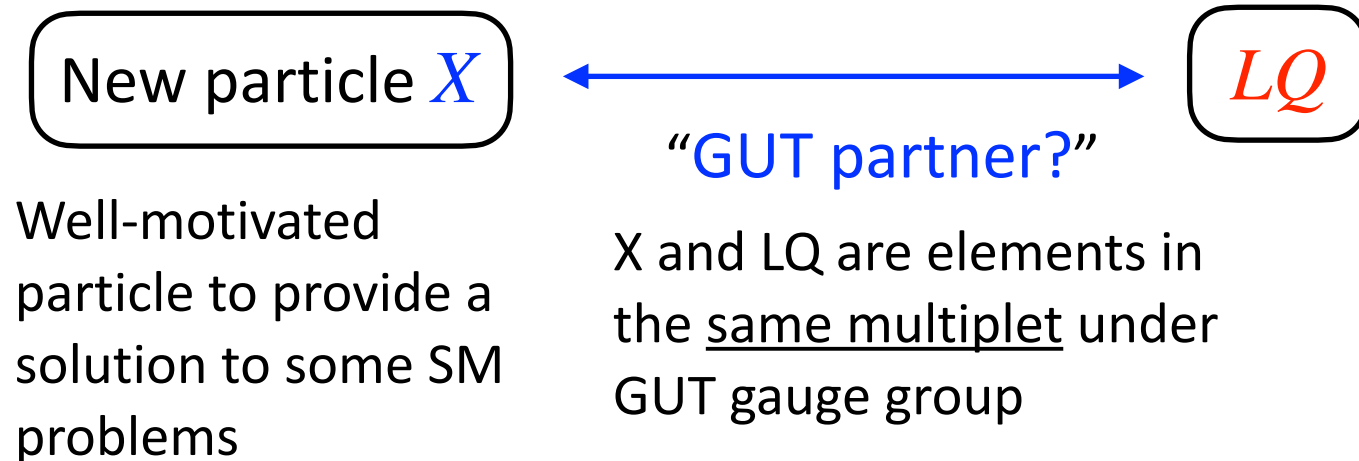


Theoretical Motivation

- What is a theoretical framework which provides/predicts the existence of LQ?
- Connection of LQ physics at LHC with other interesting physics?

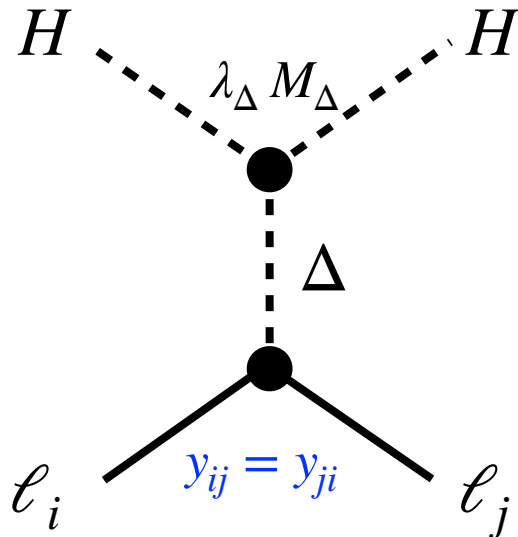
We consider SU(5) Grand Unification framework to answer to these questions

Basics idea/Theoretical structure



Type-II seesaw mechanism for neutrino mass generation

SM extension with a new heavy scalar $\Delta_{(1,3)} : (\mathbf{1}, \mathbf{3}, 1)$



Introduction of a new heavy scalar

$$\Delta_{(1,3)} : (\mathbf{1}, \mathbf{3}, 1)$$

$$m_\nu^{ij} = \lambda_\Delta y_{ij} \times \frac{v_{EW}^2}{M_\Delta} \propto y_{ij}$$

$$\mathcal{L} \supset Y_{ij} \overline{\ell^i} \Delta_{(1,3)} \ell^j - \lambda_\Delta M_\Delta H \Delta_{(1,3)}^\dagger H - M_\Delta^2 \text{tr} \left[\Delta_{(1,3)}^\dagger \Delta_{(1,3)} \right]$$

SU(5) Grand Unification Paradigm

SM gauge group of $SU(3)_c \times SU(2)_L \times U(1)_Y$ might be united into [a single gauge group](#) at high energies

How about $SU(5)$? (Georgi & Glashow, 1974)

- Mathematically very natural:

$$SU(5) \supset SU(3)_c \times SU(2)_L \times U(1)_Y$$

- Quarks and leptons are unified into SU(5) multiplets (5* + 10 plets) without any unknown/exotic fermions

$$\Psi_{5^*}^i = d^{Ci}(\mathbf{3}^*, \mathbf{1}, +1/3) + \ell^i(\mathbf{1}, \mathbf{2}, -1/2)$$

$$\Psi_{10}^i = u^{Ci}(\mathbf{3}^*, \mathbf{1}, -2/3) + q^i(\mathbf{3}, \mathbf{2}, 1/6) + e^{Ci}(\mathbf{1}, \mathbf{1}, +1)$$

- SM Higgs doublet is in 5-plet Higgs field

$$H_5 = H_c(\mathbf{3}, \mathbf{1}, -1/3) + H(\mathbf{1}, \mathbf{2}, 1/2)$$

$SU(5)$ GUT is very much the same as the SM

- It suffers from the neutrino mass problem
- Extension is necessary to generate the neutrino masses

Type-II seesaw extended SM

New scalar $\Delta_{(1,3)} : (\mathbf{1}, \mathbf{3}, 1)$



Type-II seesaw extended $SU(5)$ GUT

$$\Delta_{15} = \Delta_{(6,1)}(\mathbf{6}, \mathbf{1}, -2/3) + \Delta_{(3,2)}(\mathbf{3}, \mathbf{2}, 1/6) + \Delta_{(1,3)}(\mathbf{1}, \mathbf{3}, 1)$$

← GUT partner of $\Delta_{(1,3)}(\mathbf{1}, \mathbf{3}, 1)$

← type-II seesaw extension of SM

LQ $\Delta_{(3,2)}(\mathbf{3}, \mathbf{2}, 1/6)$ as a GUT partner of $\Delta_{(1,3)}(\mathbf{1}, \mathbf{3}, 1)$!

Theory Predictions

$$\mathcal{L} \supset Y_{ij} \overline{\ell^{iC}} \Delta_{(1,3)} \ell^j - \lambda_{\Delta} M_{\Delta} H \Delta_{(1,3)}^{\dagger} H - M_{\Delta}^2 \text{tr} \left[\Delta_{(1,3)}^{\dagger} \Delta_{(1,3)} \right]$$

$$\mathcal{L} \supset \boxed{y_{ij} \overline{\Psi_{5^*}^{iC}} \Delta_{15} \Psi_{5^*}^j} - \lambda_{\Delta} M_{\Delta} H_5 \Delta_{15}^{\dagger} H_5 - M_{\Delta}^2 \text{tr} [\Delta_{15}^{\dagger} \Delta_{15}]$$

$$y_{ij} (LQ_u) \overline{d}_R^i e_L^j + y_{ij} (LQ_d) \overline{d}_R^i \nu_L^j$$

Type-II seesaw mechanism

$$m_{\nu}^{ij} \propto y_{ij}$$

Flavor structure of LQ couplings with quarks and leptons is determined by the neutrino oscillation data!

Current neutrino oscillation data determines the neutrino mass matrix m_ν as a function of only the lightest neutrino mass (m_{lightest})

$$m_\nu = U^* D_\nu U^\dagger$$

Neutrino mixing matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Mass eigenvalue matrix: $D_\nu = \text{diag}(m_1, m_2, m_3)$

Mass ordering is to be determined by future experiments

Normal order: $m_{\text{lightest}} = m_1 < m_2 < m_3$

Inverted order: $m_{\text{lightest}} = m_3 < m_1 < m_2$

Best Fit values (NuFit-6.0, arXiv: 2410.05380)

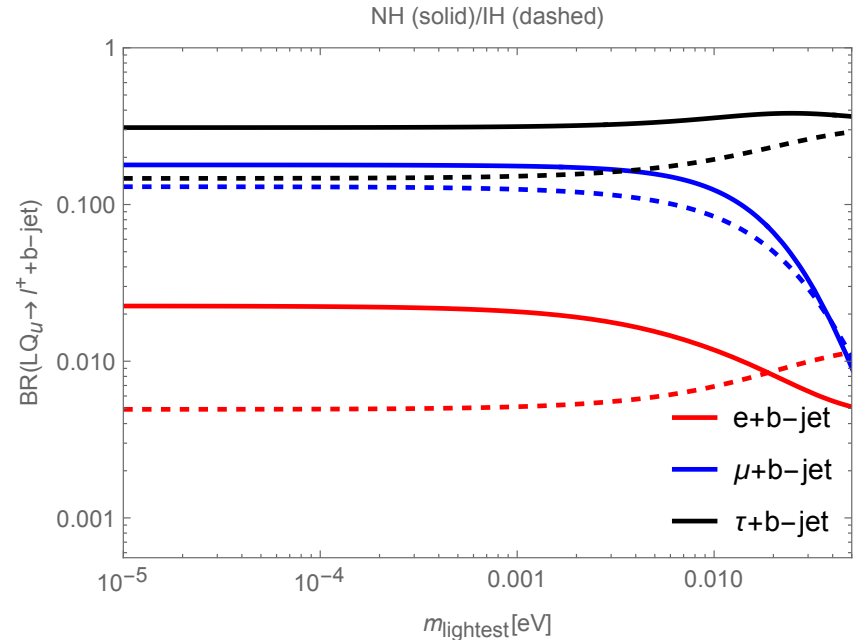
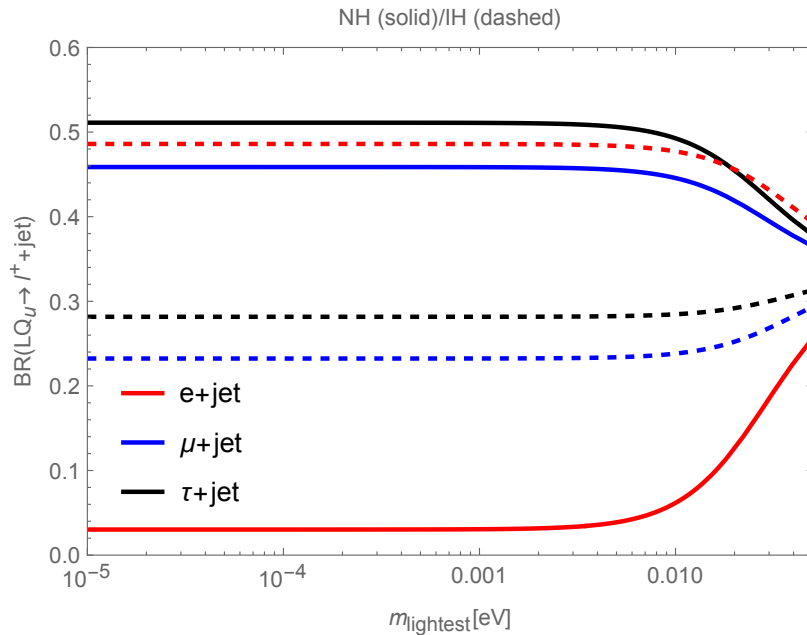
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.1$)		
	bf $\pm 1\sigma$	3σ range	bf $\pm 1\sigma$	3σ range	
IC24 with SK atmospheric data	$\sin^2 \theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \rightarrow 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \rightarrow 0.345$
	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \rightarrow 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \rightarrow 35.95$
	$\sin^2 \theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \rightarrow 0.585$	$0.550^{+0.012}_{-0.015}$	$0.440 \rightarrow 0.584$
	$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	$41.3 \rightarrow 49.9$	$47.9^{+0.7}_{-0.9}$	$41.5 \rightarrow 49.8$
	$\sin^2 \theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \rightarrow 0.02388$	$0.02231^{+0.00056}_{-0.00056}$	$0.02060 \rightarrow 0.02409$
	$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	$8.19 \rightarrow 8.89$	$8.59^{+0.11}_{-0.11}$	$8.25 \rightarrow 8.93$
	$\delta_{CP}/^\circ$	212^{+26}_{-41}	$124 \rightarrow 364$	274^{+22}_{-25}	$201 \rightarrow 335$
	$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \rightarrow 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \rightarrow 8.05$
	$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \rightarrow +2.578$	$-2.484^{+0.020}_{-0.020}$	$-2.547 \rightarrow -2.421$

* In the following analysis, we use the center values

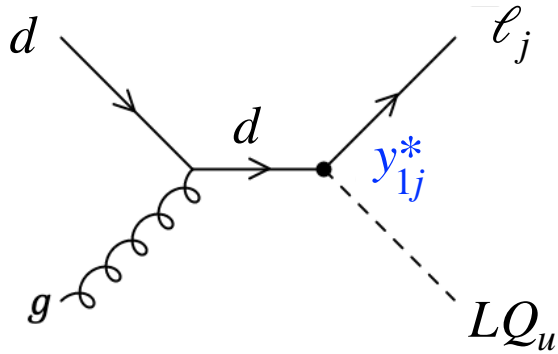
Flavor structure of LQ decay

Using the relation $y^{ij} \propto m_\nu^{ij}$,

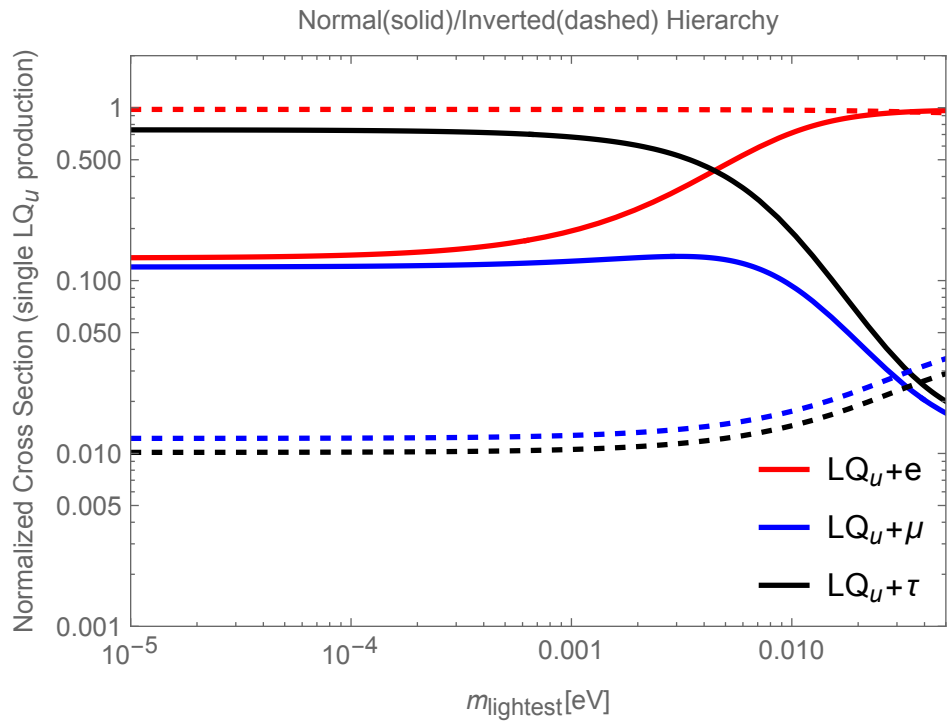
$$\text{BR}(LQ_u \rightarrow d^i + \ell^{+j}) = \text{BR}(LQ_d \rightarrow d^i + \nu^j) = \frac{|(m_\nu)_{ij}|^2}{\sum_k \sum_l |(m_\nu)_{kl}|^2}$$



Single LQ production process



$$\sigma(dg \rightarrow LQ_u + \ell_j) \propto |(m_\nu)^{1j}|^2$$



Normalized cross section

$$\frac{\sigma(LQ_u + \ell^i)}{\sum_{j=1}^3 \sigma(LQ_u + \ell^j)} = \frac{|m_\nu^{1i}|^2}{\sum_{j=1}^3 |m_\nu^{1j}|^2}$$

- The SU(5) paradigm with a type II seesaw extension predicts the existence of scalar leptoquarks.
- This framework has a direct connection to neutrino oscillation data.
- If such leptoquarks are discovered and their branching ratios are measured, we can test this GUT paradigm and its link to neutrino oscillation physics.
- In fact, collider measurements could even help determine the neutrino mass ordering, providing a powerful complement to future neutrino oscillation experiments.leptoquarks

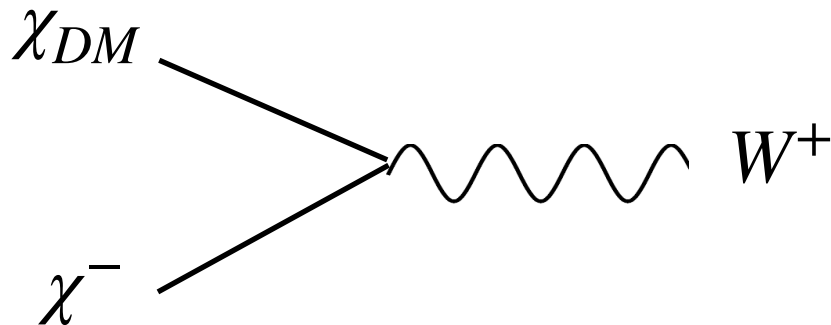
Direction 3

Consider a way to discriminate different scenarios by experiments

Let us consider a dark matter scenario

- In many dark matter scenarios, the stability of dark matter is ensured by a Z_2 discrete symmetry with odd-parity assigned to the DM particle
- A dark matter may couple to an SM particle along with its Z_2 -odd partner

Example:



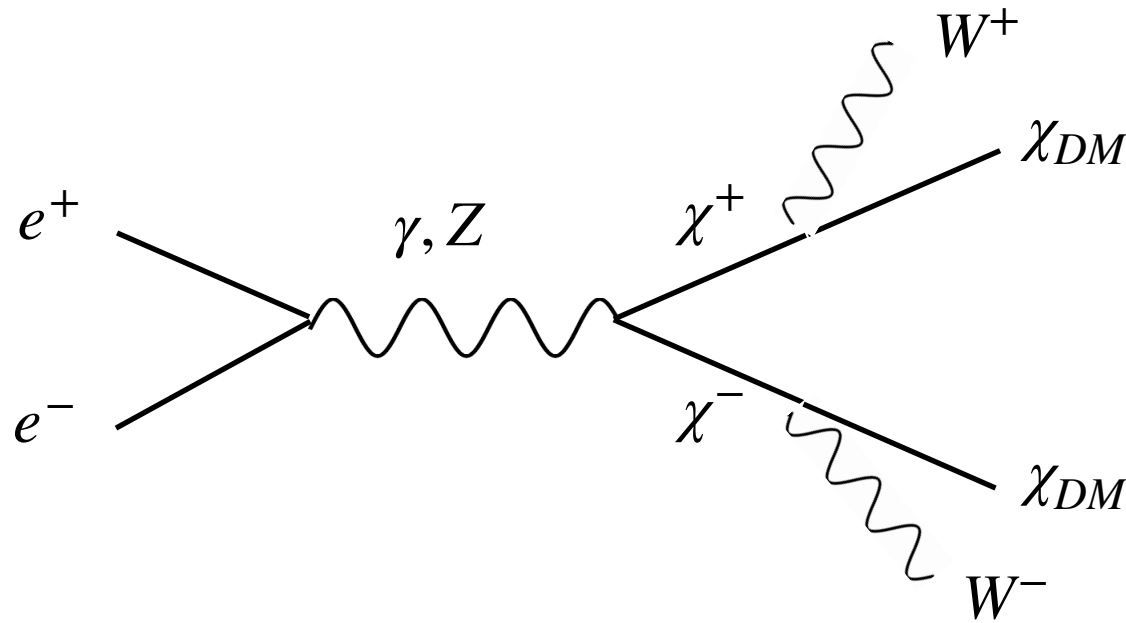
Known examples: (i) neutralino DM and chargino
(ii) Inert Higgs doublet model

Can we discriminate such models by collider experiments?

ILC/future lepton collider is a powerful tool to accomplish this task

Model (i) : χ_{DM}, χ^- are fermions (spin-1/2)

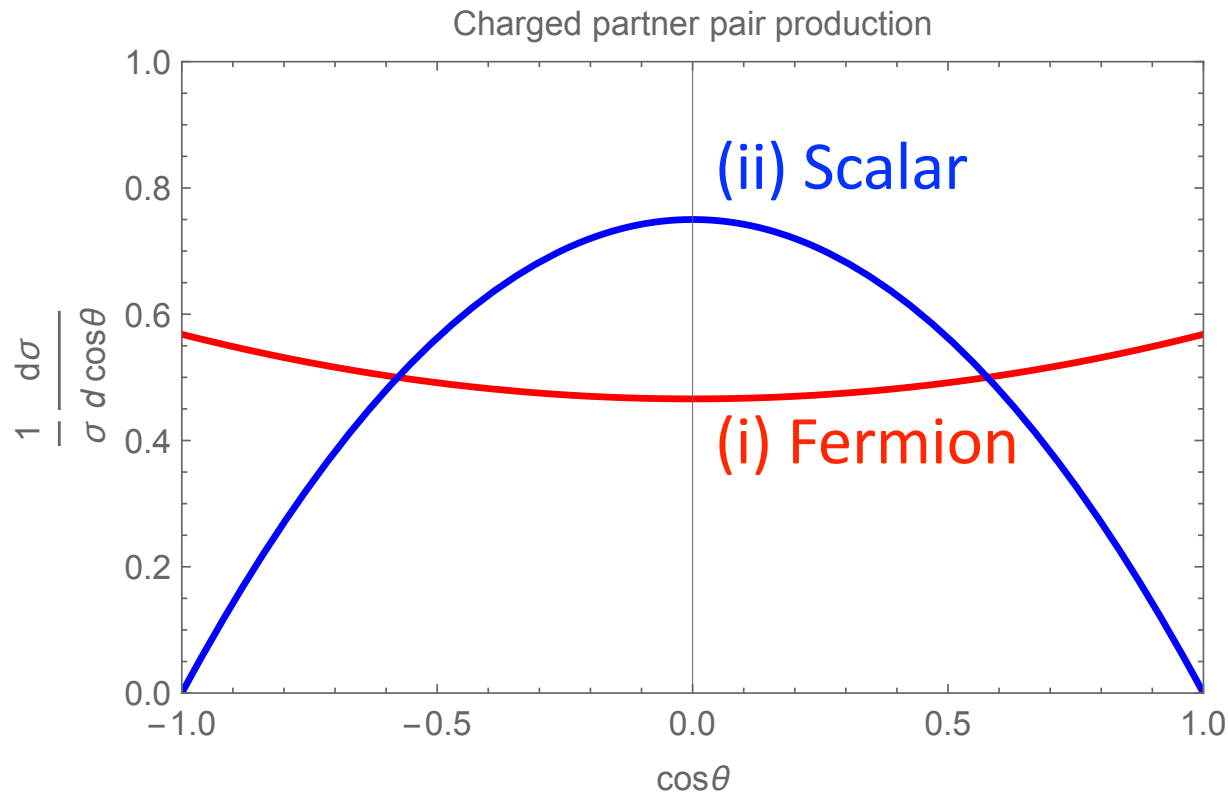
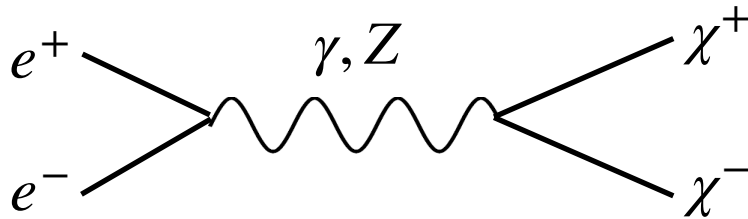
Model (ii) : χ_{DM}, χ^- are scalars (spin-0)



ILC/Future Lepton Collider study

For ILC simulations studies,
see Asano et al., PRD 84 (2011)
115003, arXiv: 1106.1932

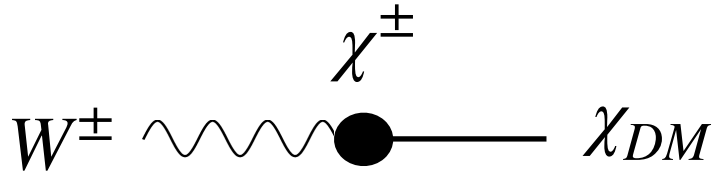
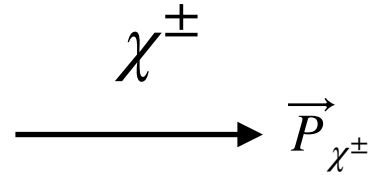
(i) Angular distributions



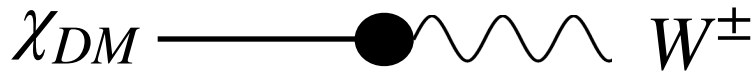
$\sqrt{s} = 500 \text{ GeV}$
 $m_{\chi^\pm} = 200 \text{ GeV}$

(ii) Determination of m_{χ^\pm} and $m_{\chi_{DM}}$

In Lab frame of χ^\pm

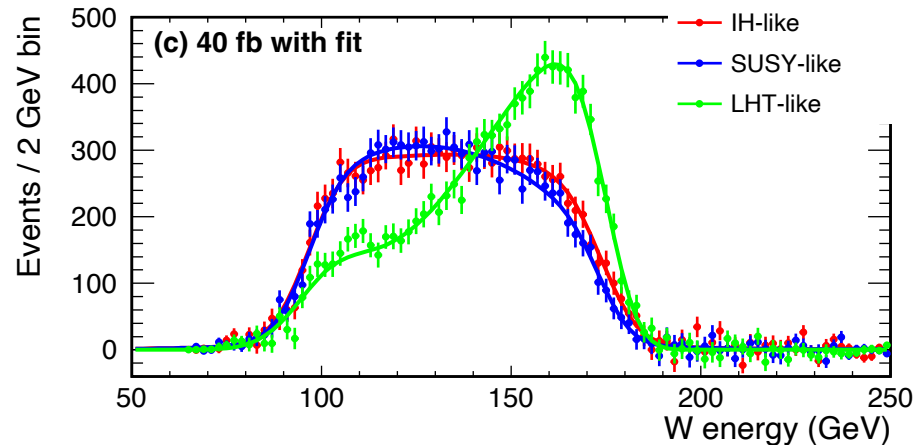


$$E_{\min} = \gamma_{\chi^\pm} E_W^* - \beta_{\chi^\pm} \gamma_{\chi^\pm} p_W^*$$



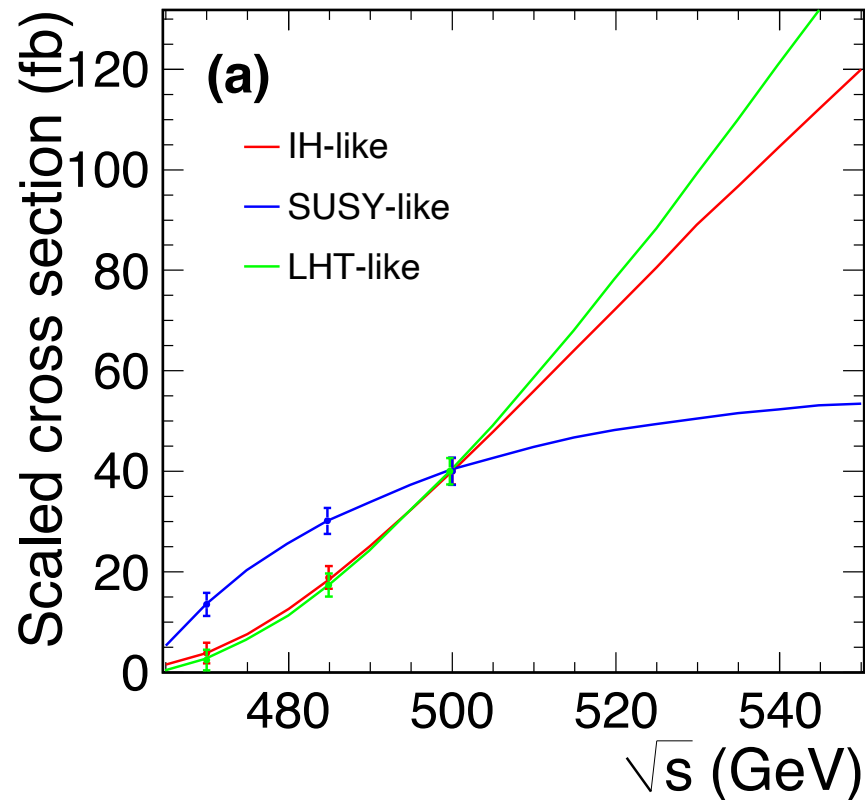
$$E_{\max} = \gamma_{\chi^\pm} E_W^* + \beta_{\chi^\pm} \gamma_{\chi^\pm} p_W^*$$

Produced W energy,
 $E_{\max/\min}$ is a function
of \sqrt{s} , m_{χ^\pm} , $m_{\chi_{DM}}$



(iii) Threshold scan for produced χ^\pm

Tunable energy of ILC/Future Lepton Colliders allows us to scan the χ^\pm production near production threshold



Summary

For the future of Particle Physics

The Standard Model (SM):

Pursue increasingly precise measurements of the Higgs boson properties to deepen and complete our understanding of the SM.

Beyond the Standard Model (BSM):

Continue exploring new physics scenarios to uncover what lies beyond the SM and to understand how nature extends past its current theoretical framework.

In this endeavor, collider experiments, particularly the ILC and other future lepton colliders, will play a crucial role by providing the precision measurements necessary to fully test the Standard Model and to probe possible signs of new physics. exploring new physics scenarios to uncover what lies beyond the SM and to understand how nature extends past its current theoretical framework.

*Thank you
for your attention!*