Z'_{BL} Portal Dark Matter and LHC Run-2 Results

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Ref: NO & S. Okada, PRD 93, 075003 (2016)
[arXiv:1601.07526 [hep-ph]]

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Problems in 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

EVEN after the LHC

However,

New Physics beyond SM is strongly suggested by both experimental & theoretical points of view

What is missing in the Standard Model?

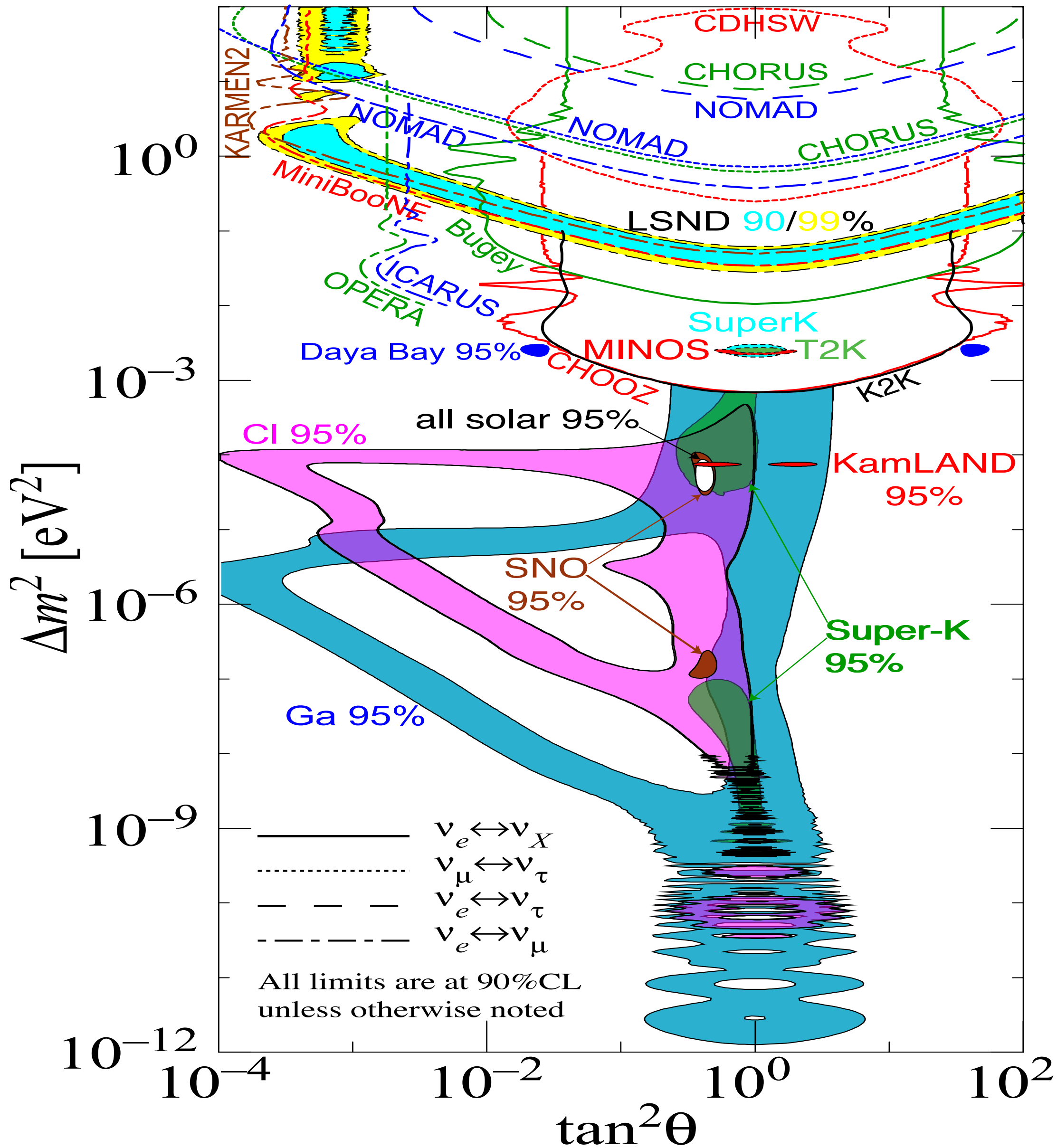
PDG

1. Neutrino masses and flavor mixings

$$\Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$$
$$\Delta m_{32}^2 = (2.44 \pm 0.06) \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2(2\theta_{12}) = 0.846 \pm 0.021$$
$$\sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018}$$
$$\sin^2(2\theta_{13}) = (9.3 \pm 0.8) \times 10^{-2}$$

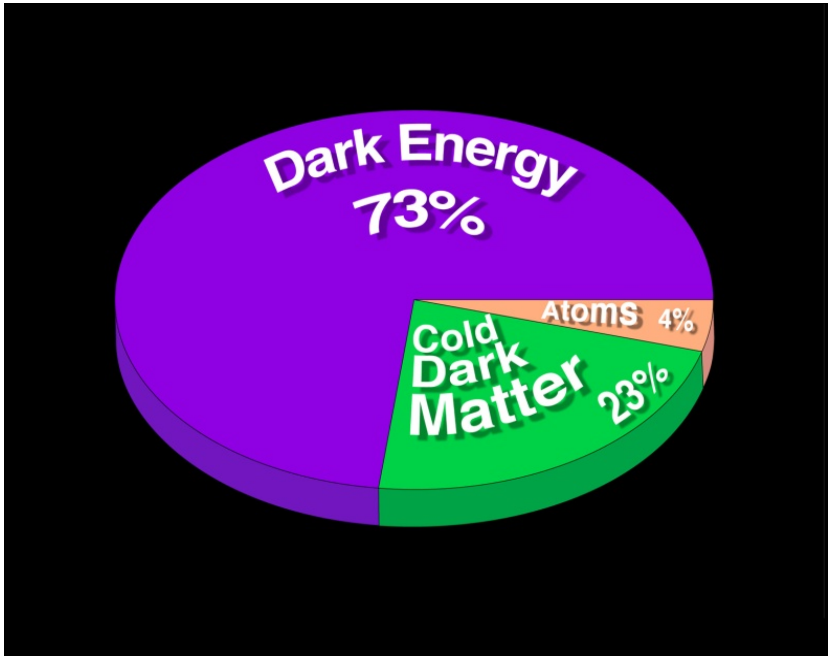
Neutrinos are massless in the Standard Model



2. Cosmological Dark Matter Problem

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 candidates in the SM

Minimal gauged B-L extension of the Standard Model

- To incorporate neutrino masses in the Standard Model (at the renormalizable level), we need right-handed neutrinos

- Right-handed neutrinos are singlet, and only for generating neutrino mass

Gauged B-L extension of the Standard Model

- B-L is the unique anomaly free global symmetry

- Gauging the global B-L symmetry looks natural

- Anomaly free requirement → 3 right-handed neutrinos

Minimal Gauged B-L Extension of the SM

Mohapatra & Marshak;
Wetterich; others

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

Particle Contents

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

New terms in Lagangian

$$\mathcal{L} \supset -Y_D^{ij} N^{ci} \ell^j H - f_i \Phi N^{ci} N^{cj}$$

B-L symmetry breaking via $\langle \Phi \rangle = \frac{v_{\rm BL}}{\sqrt{2}}$

→ B-L gauge boson (Z' boson) mass

$$M_{Z'} = 2 g_{\rm BL} v_{\rm BL}$$

Mass scale is controlled by B-L Sym. Br. scale

Majorana neutrino mass

$$M_R^i = \sqrt{2} f_i v_{\rm BL}$$

B-L sym breaking also generates NR mass

Seesaw Mechanism

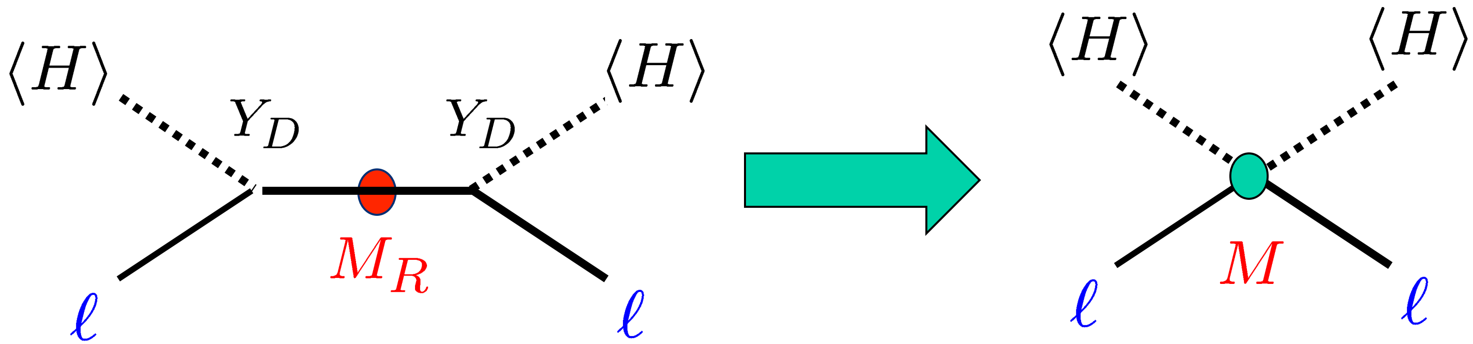
Minkowski; Yanagida; Gell-Mann, Ramond & Slansky; Mohapatra & Senjanovic; others

We introduce right-handed neutrinos and Majorana masses

$$\mathcal{L} \supset -Y_D N^c \ell H - \frac{1}{2} M_R N^c N^c$$

Integrating out the heavy Majorana neutrino

SM singlet fermion



$$\frac{Y_D^2}{M_R} = \frac{1}{M}$$

What is the Majorana mass scale?

$$\frac{Y_D^2}{M_R} = \frac{1}{M} \sim \frac{1}{10^{14}\text{GeV}}$$

Broad range of Majorana mass, depending on Dirac mass scale

Example:

$$Y_D v \sim m_e \rightarrow \boxed{M_R \sim 1\text{TeV}}$$

$$Y_D v \sim m_t \rightarrow \boxed{M_R \sim 10^{14}\ \text{GeV}}$$

Minimal B-L @ TeV is well-motivated in terms of the LHC

Natural realization of the TeV scale B-L model (Example)

SUSY extension

chiral superfield	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
Q^i	$\mathbf{3}$	$\mathbf{2}$	$+1/6$	$+1/3$
U_i^c	$\mathbf{3}^*$	$\mathbf{1}$	$-2/3$	$-1/3$
D_i^c	$\mathbf{3}^*$	$\mathbf{1}$	$+1/3$	$-1/3$
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1
N_i^c	$\mathbf{1}$	$\mathbf{1}$	0	$+1$
E_i^c	$\mathbf{1}$	$\mathbf{1}$	-1	$+1$
H_u	$\mathbf{1}$	$\mathbf{2}$	$+1/2$	0
H_d	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
Φ	$\mathbf{1}$	$\mathbf{1}$	0	-2
$\bar{\Phi}$	$\mathbf{1}$	$\mathbf{1}$	0	$+2$

New superpotential terms

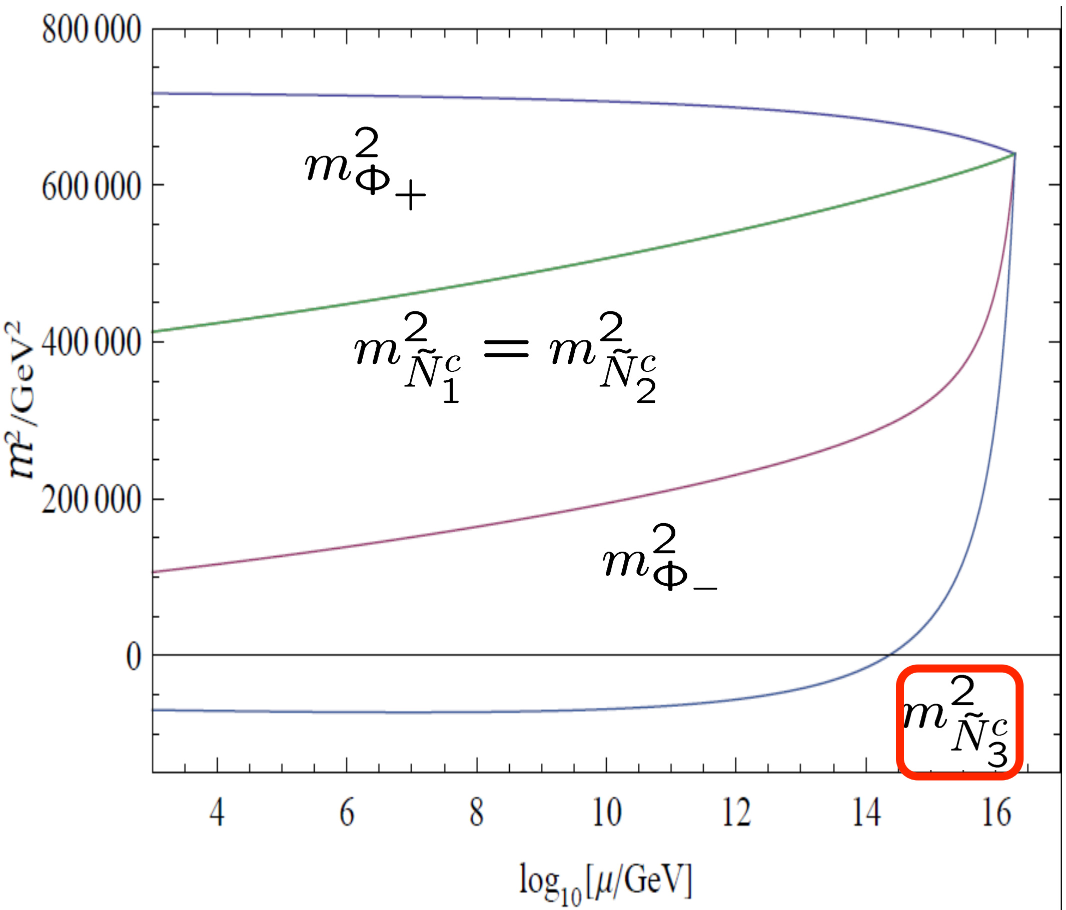
$$W \supset y_D^{ij} N_i^c L_j H_u + f_k \Phi N_k^c N_k^c + \mu \Phi \bar{\Phi}$$

Radiative B-L symmetry breaking @ TeV

Kharlil & Masiero, PLB 665 (2008) 374

$$\mathcal{L}_{\rm soft} = -\left(\frac{1}{2}M_{BL}\lambda_{BL}\lambda_{BL} + h.c.\right) - \left(\sum_{k=1}^{3} m^2_{\tilde{N}^c_k}|\tilde{N}^c_k|^2 + m^2_{\Phi}|\Phi|^2 + m^2_{\bar{\Phi}}|\bar{\Phi}|^2\right) + \left(B_\Phi \bar{\Phi}\Phi + \sum_{k=1}^{3} A_k \Phi \tilde{N}^c_k \tilde{N}^c_k + h.c.\right).$$

Burell & N.O, PRD 85 (2012) 055011



$M_{1/2} = 500$ GeV

$m_0 = 800$ GeV

$A_0 = 0$ GeV

$f_1 = f_2 = 0.45$

$f_3 = 3$

$g_{BL}(M_{GUT}) = 0.53$

Fileviez Perez & Spinner, PRD 83 (2009) 035004

- Most of parameter space, R-parity is also broken

DM candidate is still missing

There have been many proposal for introduction of DM particles

Concise model: no extension of the particle content

Instead, introduce a parity

NO & Seto,
PRD 82 (2010) 023507

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	+

- Assigning odd parity for one N_R
- The others are all even

Enhancement of symmetry: $\mathcal{L} \supset Y_D^{3j} N_3^c \ell_j H$ $\quad Y_D^{3j} \to 0$

Minimal B-L model with NR dark matter

- 3 right-handed neutrinos → 2+1

  2 NRs for the minimal seesaw

  Frampton, Glashow & Yanagida, PLB 548 (2002) 119

  ✓ Neutrino oscillation data with one massless eigenstate

  ✓ leptogenesis at TeV

  Enhancement of epsilon necessary
  → Resonant leptogensis

  Suppression of lepton asymmetry via Z' interaction
  → some more enhancement by Y_D

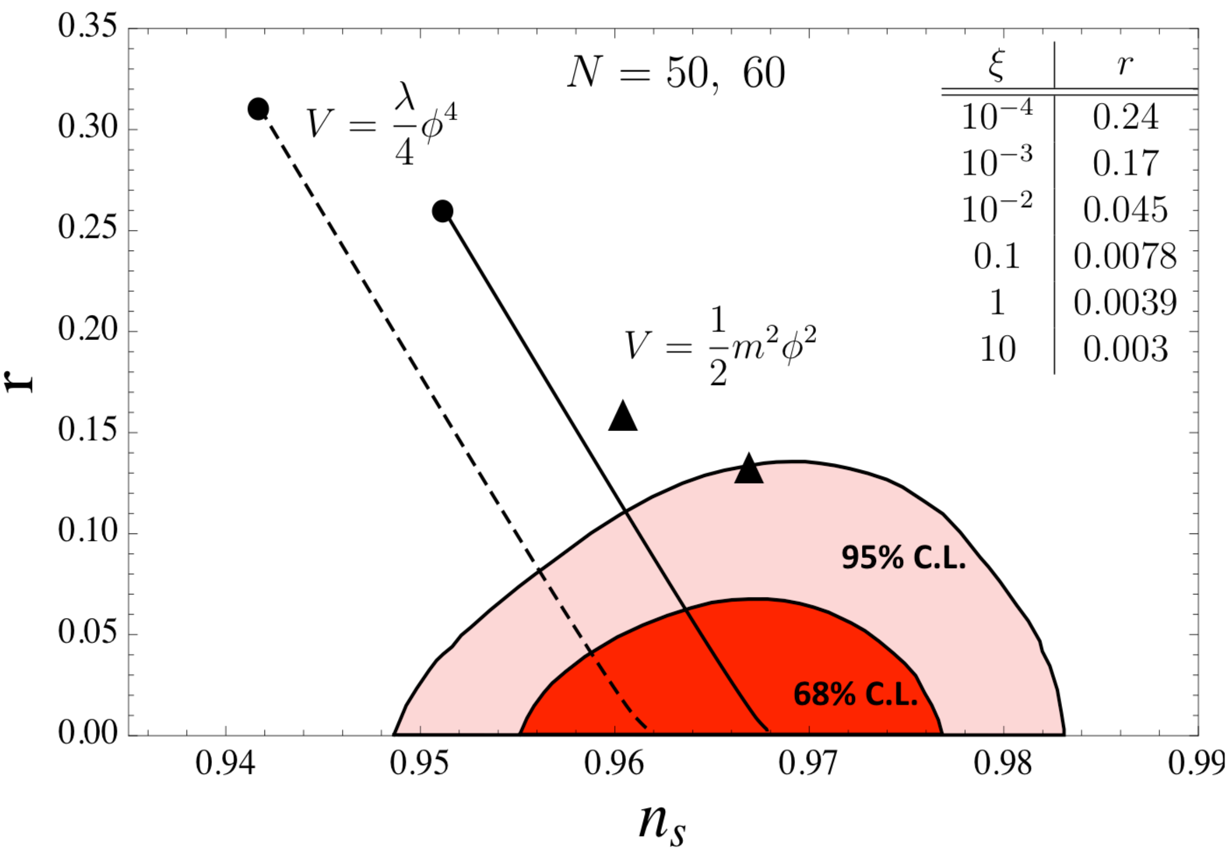
  Iso, NO & Orikasa, PRD 83 (2011) 093011

  1 NRs for thermal Dark Matter

- B-L Higgs can play the role of inflation

NO, Rheman & Safhi, PLB 701 (2011) 520

$$S_J^{tree} = \int d^4x\sqrt{-g}\Big[-\left(\frac{m_P^2}{2}+\xi_H H^\dagger H+\xi\Phi^\dagger\Phi\right)\mathcal{R}$$
$$+(D_\mu H)^\dagger g^{\mu\nu}(D_\nu H)-\lambda_H\left(H^\dagger H-\frac{v^2}{2}\right)^2$$
$$+(D_\mu \Phi)^\dagger g^{\mu\nu}(D_\nu \Phi)-\lambda\left(\Phi^\dagger\Phi-\frac{v_{B-L}^2}{2}\right)^2-\lambda'(\Phi^\dagger\Phi)(H^\dagger H)\Big]$$



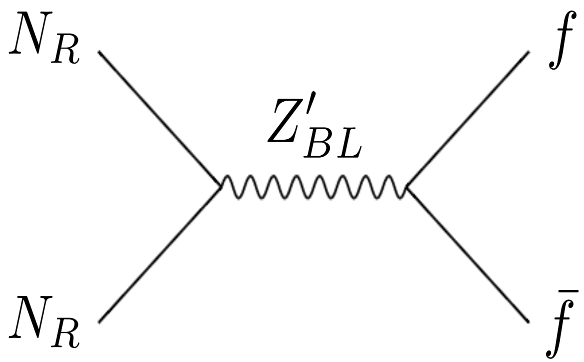
ξ	r
10^{-4}	0.24
10^{-3}	0.17
10^{-2}	0.045
0.1	0.0078
1	0.0039
10	0.003

Suitable choice of non-minimal coupling, the inflationary predictions are consistent with Planck 2015 results

Z'_{BL} portal NR dark matter

NO & S. Okada, PRD 93(2016) 075003
arXiv: 1601.07526

➢ The NR dark matter communicate with the SM particles through its B-L gauge interaction



➢ For Dark Matter physics, only 3 free parameters are involved

- B-L gauge coupling (α_{BL})
- Z'_{BL} boson mass ($m_{Z'}$)
- dark matter mass (m_{DM})

Note that the NR dark matter has B-L charge -1

Cosmological constraint on Z' portal DM

Observed Relic Abundance: $\Omega_{DM}h^2 = 0.1198 \pm 0.0015$

Planck 2015 (68% CL)

Thermal DM relic abundance is determined by the Boltzmann equation:

$$\frac{dY}{dx} = -\frac{s\langle\sigma v\rangle}{xH(m_{DM})}\left(Y^2 - Y_{EQ}^2\right)$$

$$s = \frac{2\pi^2}{45} g_\star \frac{m_{\rm DM}^3}{x^3}$$

$$H(m_{\rm DM}) = \sqrt{\frac{4\pi^3}{45} g_\star} \frac{m_{\rm DM}^2}{M_{\rm Pl}}$$

$$sY_{\rm EQ} = \frac{g_{\rm DM}}{2\pi^2} \frac{m_{\rm DM}^3}{x} K_2(x)$$

$x = m_{DM}/T$

$M_{Pl} = 1.22 \times 10^{19}\,\mathrm{GeV}$: the Planck mass

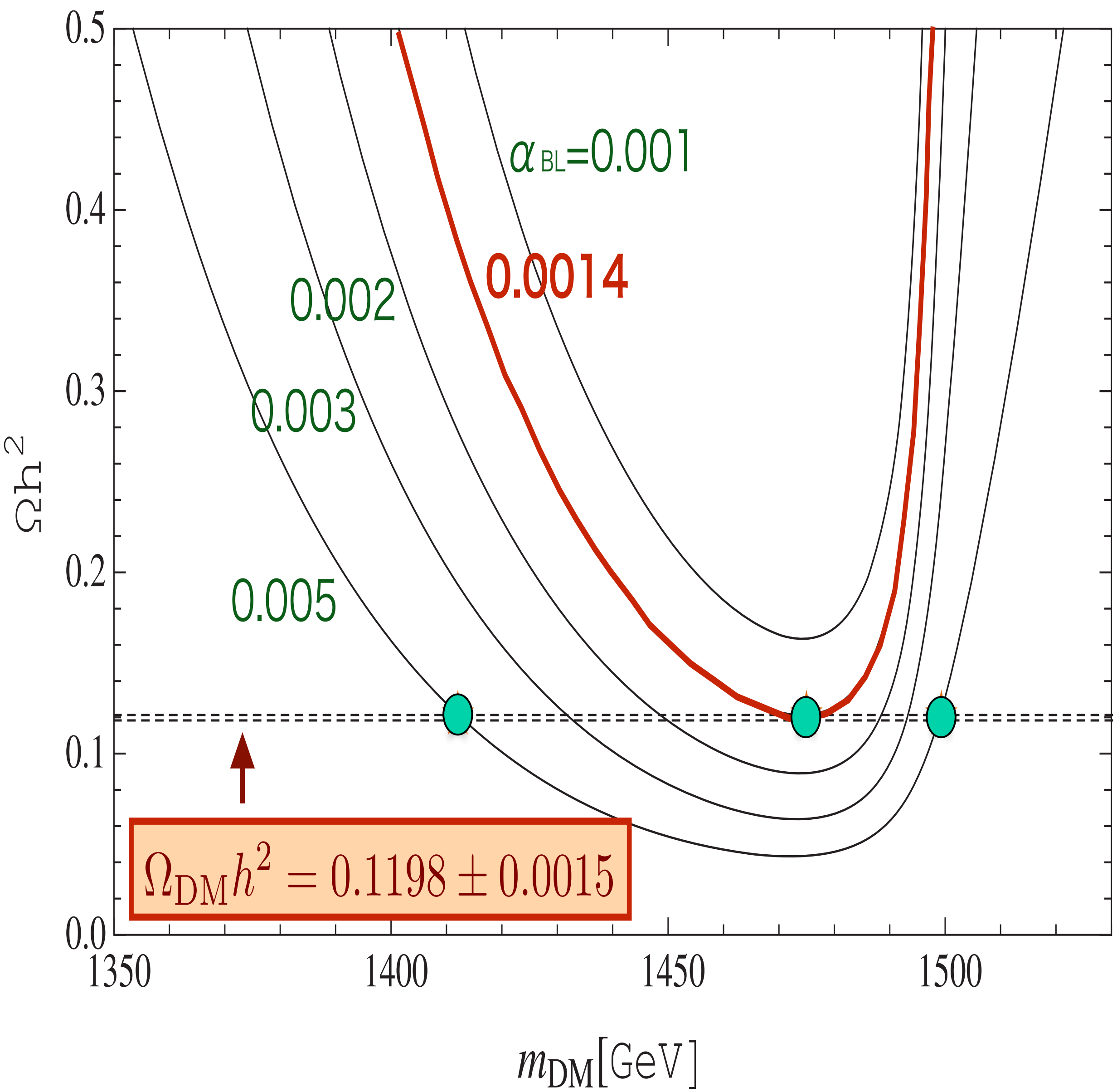
$g_{DM} = 2$: the number of DM d.o.f

$g_* = 106.75$: for the SM particles

K_2 : the modified Bessel function

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

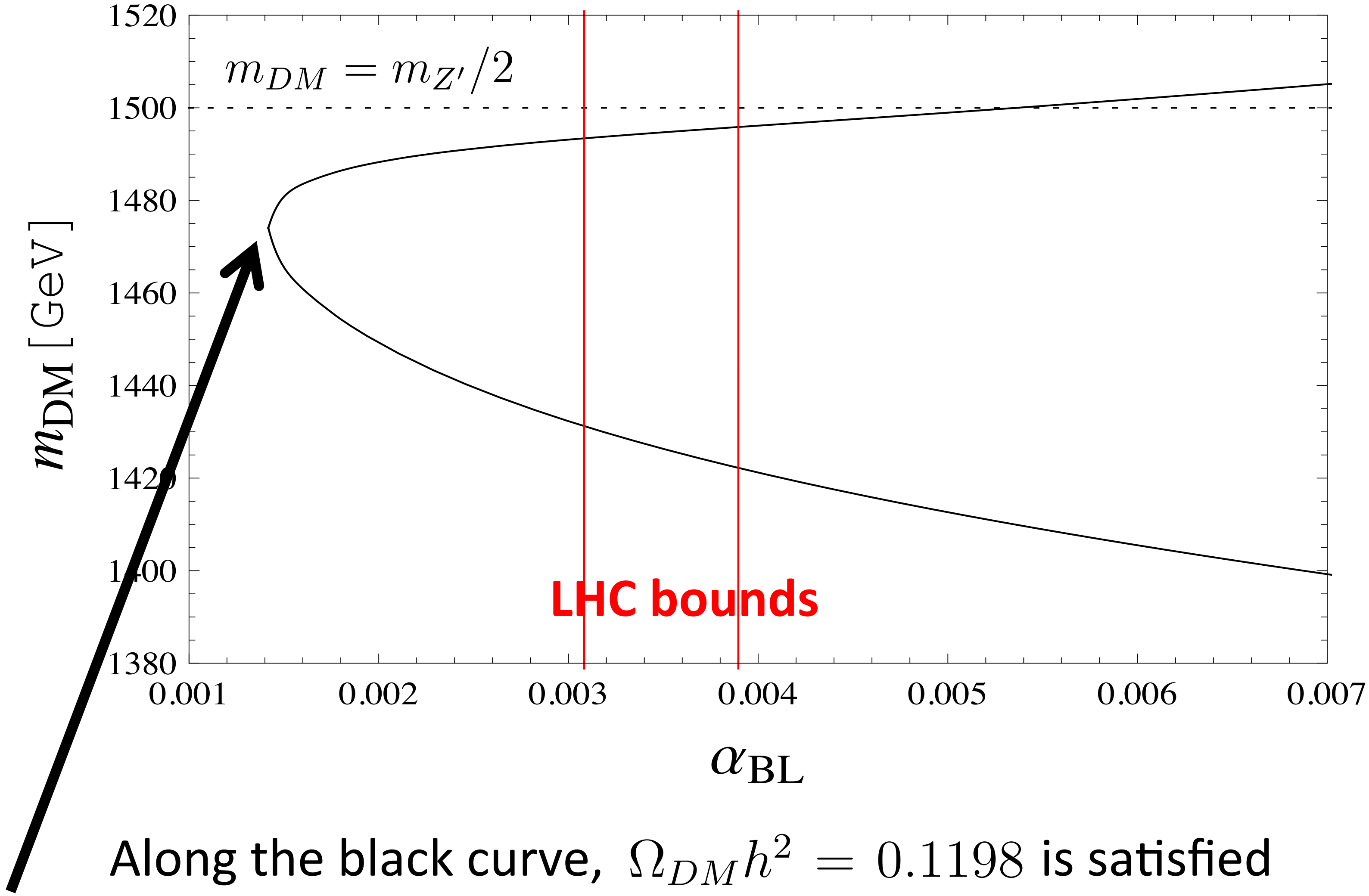
Results for various B-L gauge coupling values for $m_{Z'}=3$ TeV



As we lower α_{BL}, relic abundance becomes larger.

For a fixed $m_{Z'}$ there is a lower bound on α_{BL} from the DM relic abundance constraint.

Results for various B-L gauge coupling values for $m_{Z'}=3$ TeV

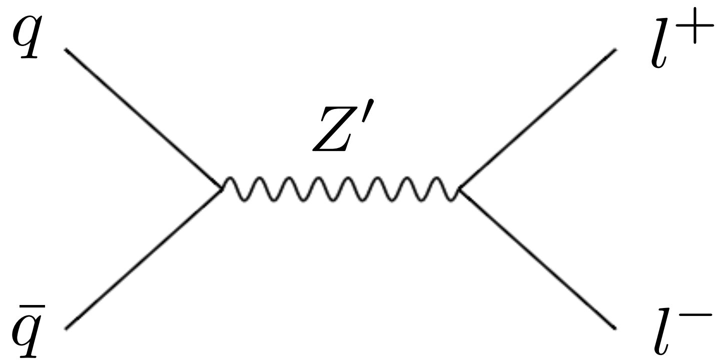


Along the black curve, $\Omega_{DM}h^2 = 0.1198$ is satisfied

The lower bound on α_{BL} as a function of Z'_{BL} mass

LHC Run-2 Constraints

pp → Z' +X → ll +X



- The ATLAS and CMS collaborations have been searching for Z' boson resonance with dilepton final state at the LHC Run-2

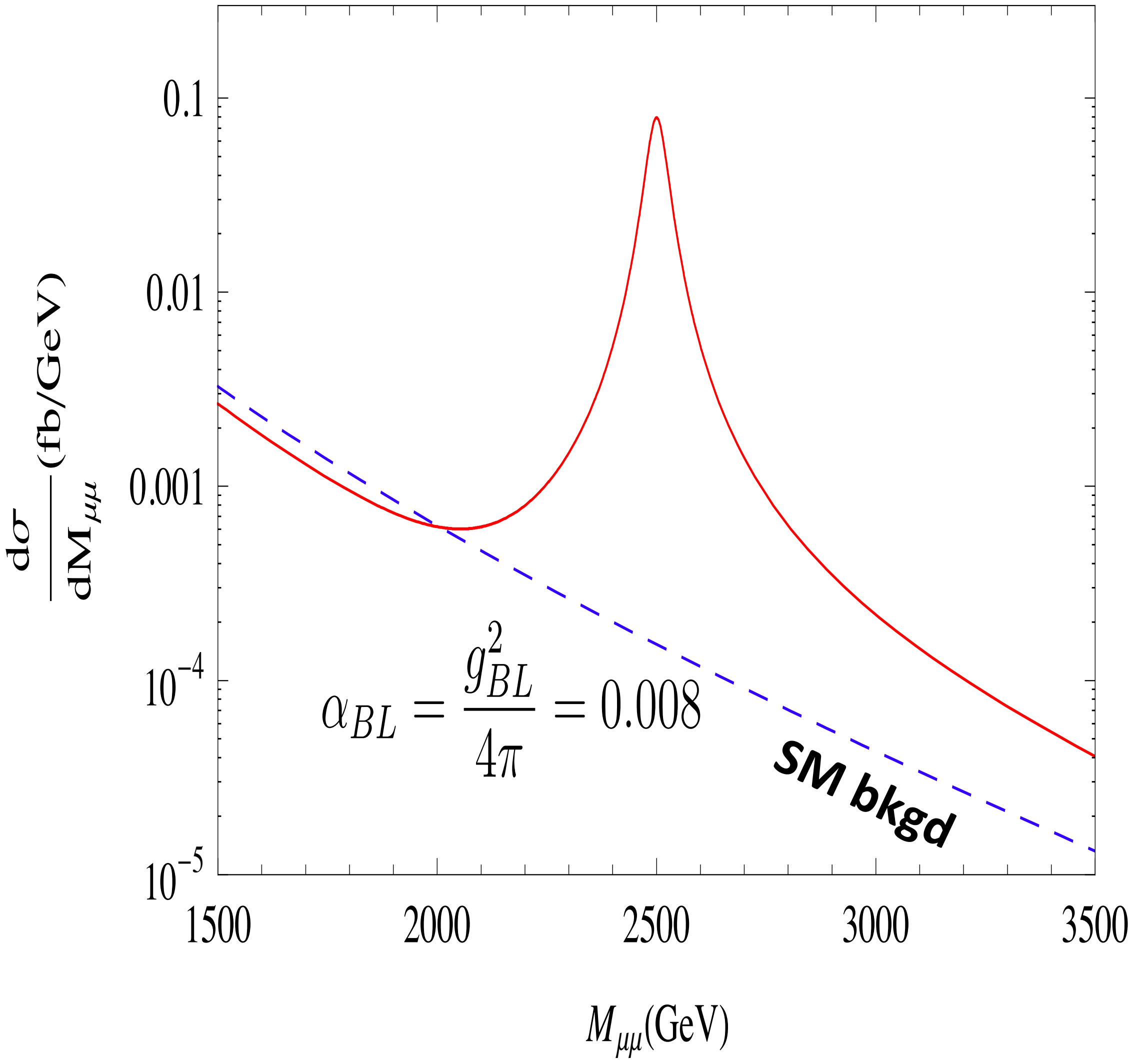
- Upper bounds on the cross section for the sequential Z' model have been obtained

Sequential Z' : heavy Z' boson with exactly the same coupling as the SM Z boson

We interpret the ATLAS & the CMS bounds to the B-L Z' boson

Sample

Final state dilepton invariant mass distribution for mz'=2.5 TeV



$$\frac{d\sigma}{dM_{\ell\ell}} = \sum_{a,b} \int_{\frac{M_{\ell\ell}^2}{E_{\rm CM}^2}}^{1} dx \frac{2M_{\ell\ell}}{xE_{\rm CM}^2} f_a(x, Q^2) f_b\left(\frac{M_{ll}^2}{xE_{\rm CM}^2}, Q^2\right)$$

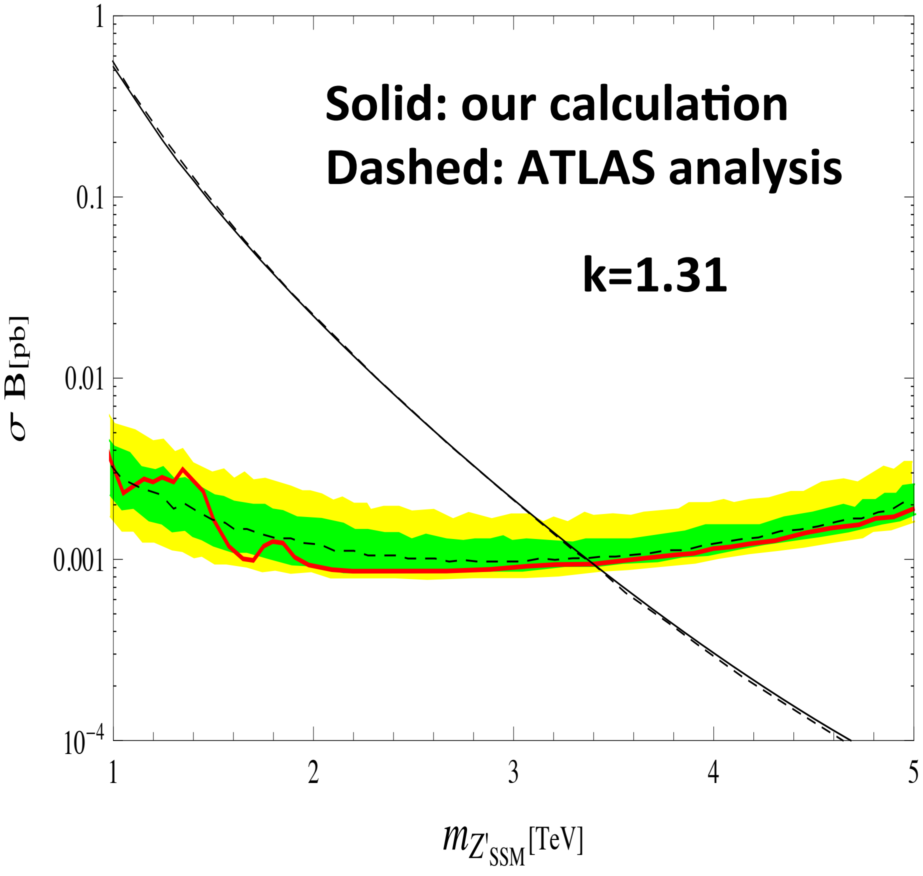
$$\text{x} \;\; \hat{\sigma}(q\bar{q} \to Z'_{BL} \to \ell^+\ell^-)$$

$$\hat{\sigma} = \frac{4\pi\alpha_{BL}^2}{81} \frac{M_{\ell\ell}^2}{(M_{\ell\ell}^2 - m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2}$$

CTEQ6L for PDF

ATLAS & CMS bounds on sequential Z' model and the consistency of our analysis with their analysis

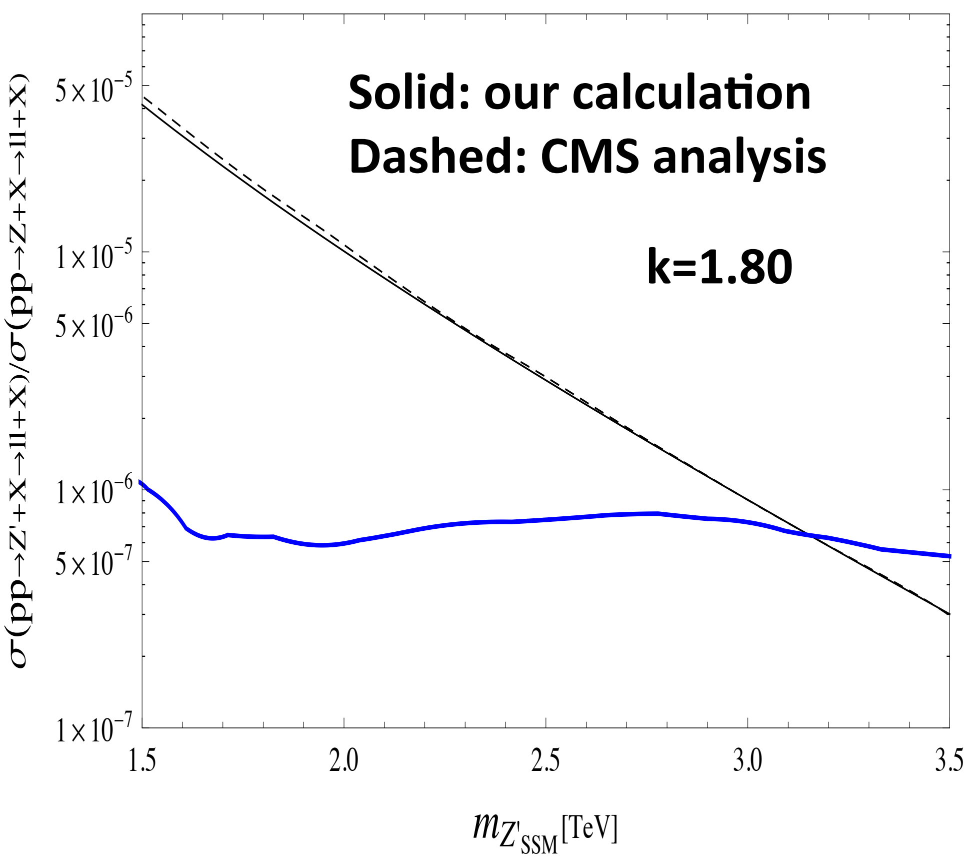
ATLAS-CONF-2015-070



Integrate the differential Xsec for

$$128\ \mathrm{GeV} \leq M_{\ell\ell} \leq 6000\ \mathrm{GeV}$$

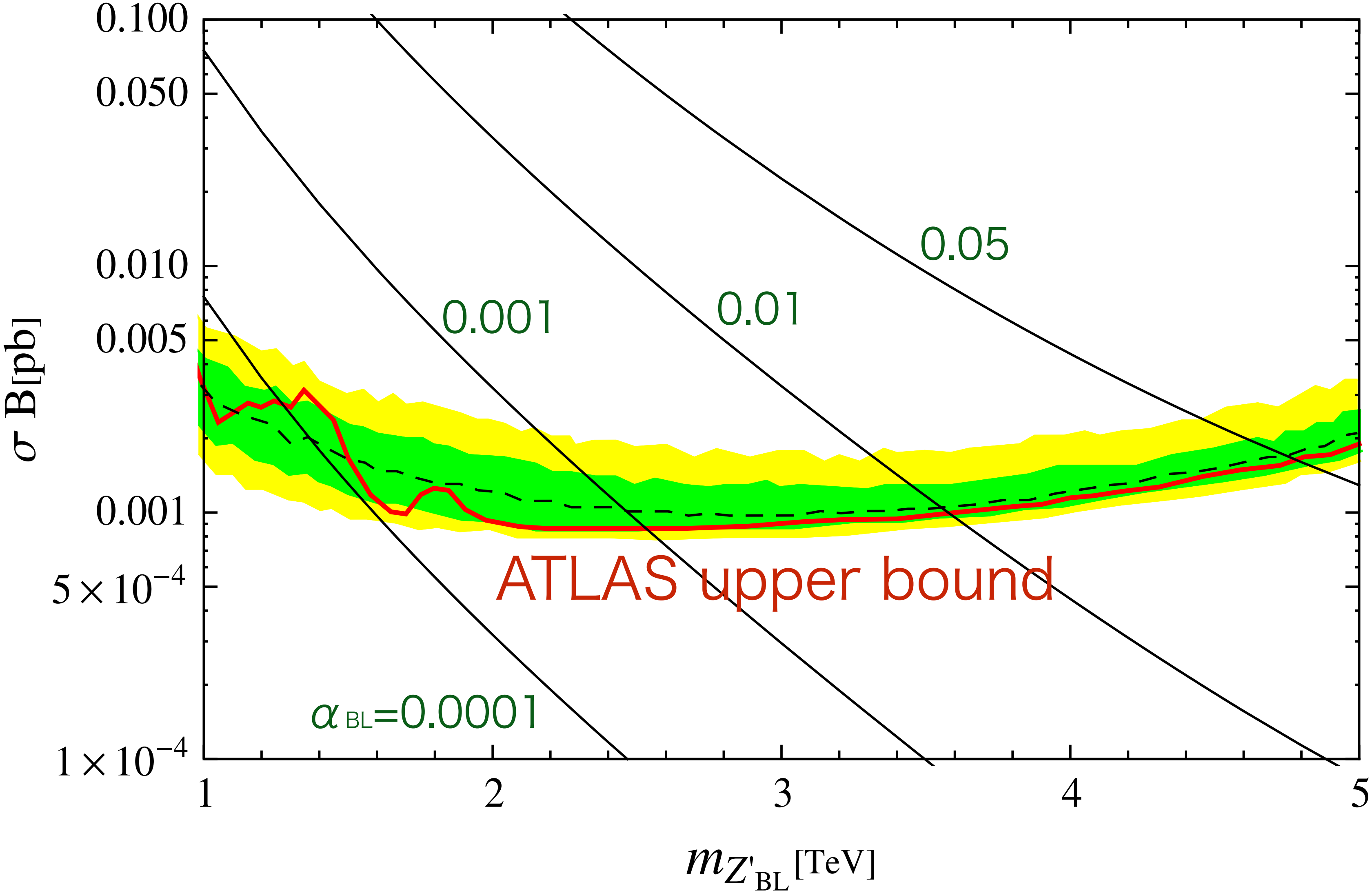
CMS-PAS-EXO-5-005



Integrate the differential Xsec for

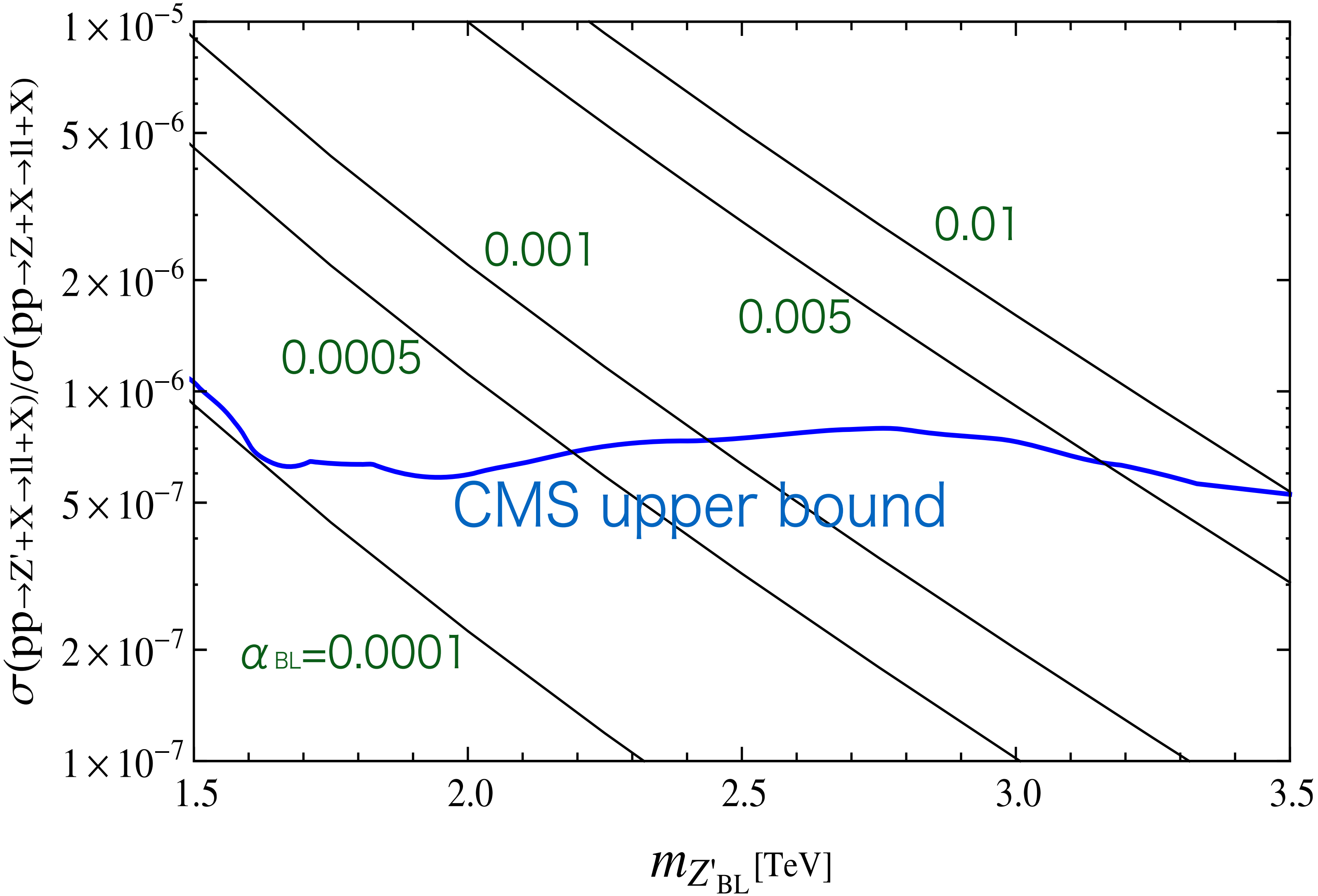
$$0.97\ m_{Z'_{SSM}} \leq M_{\ell\ell} \leq 1.03\ m_{Z'_{SSM}}$$

Bounds from ATLAS at LHC Run-2



The upper bound on α_{BL} as a function of Z'_{BL} mass

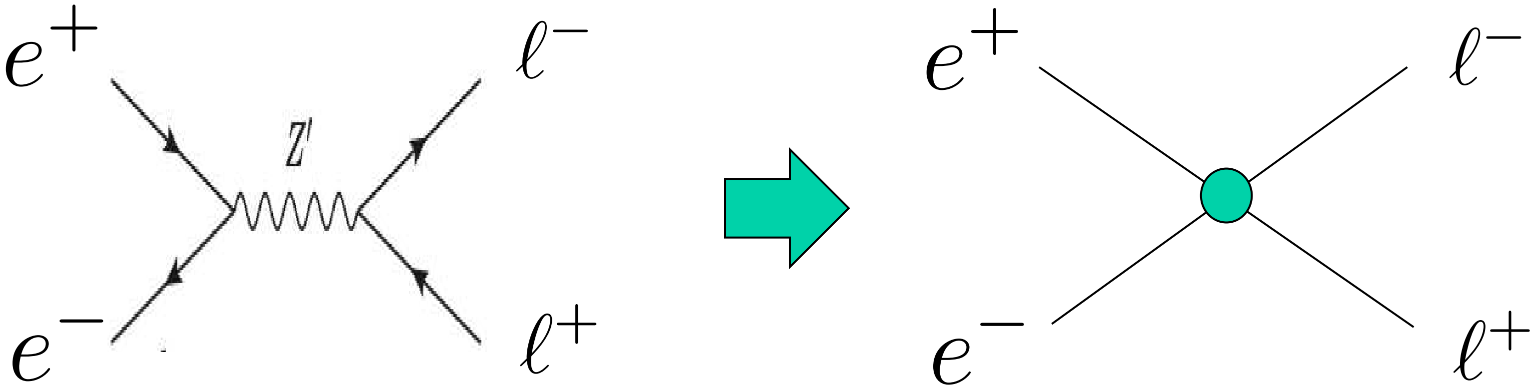
Bounds from CMS at LHC Run-2



The upper bound on α_{BL} as a function of Z'_{BL} mass

Other constraints

- LEP 2 bound on effective 4 Fermi interactions from Z'



$$\frac{m_{Z'}}{g_{BL}} \geq 6.9 \text{ TeV}$$

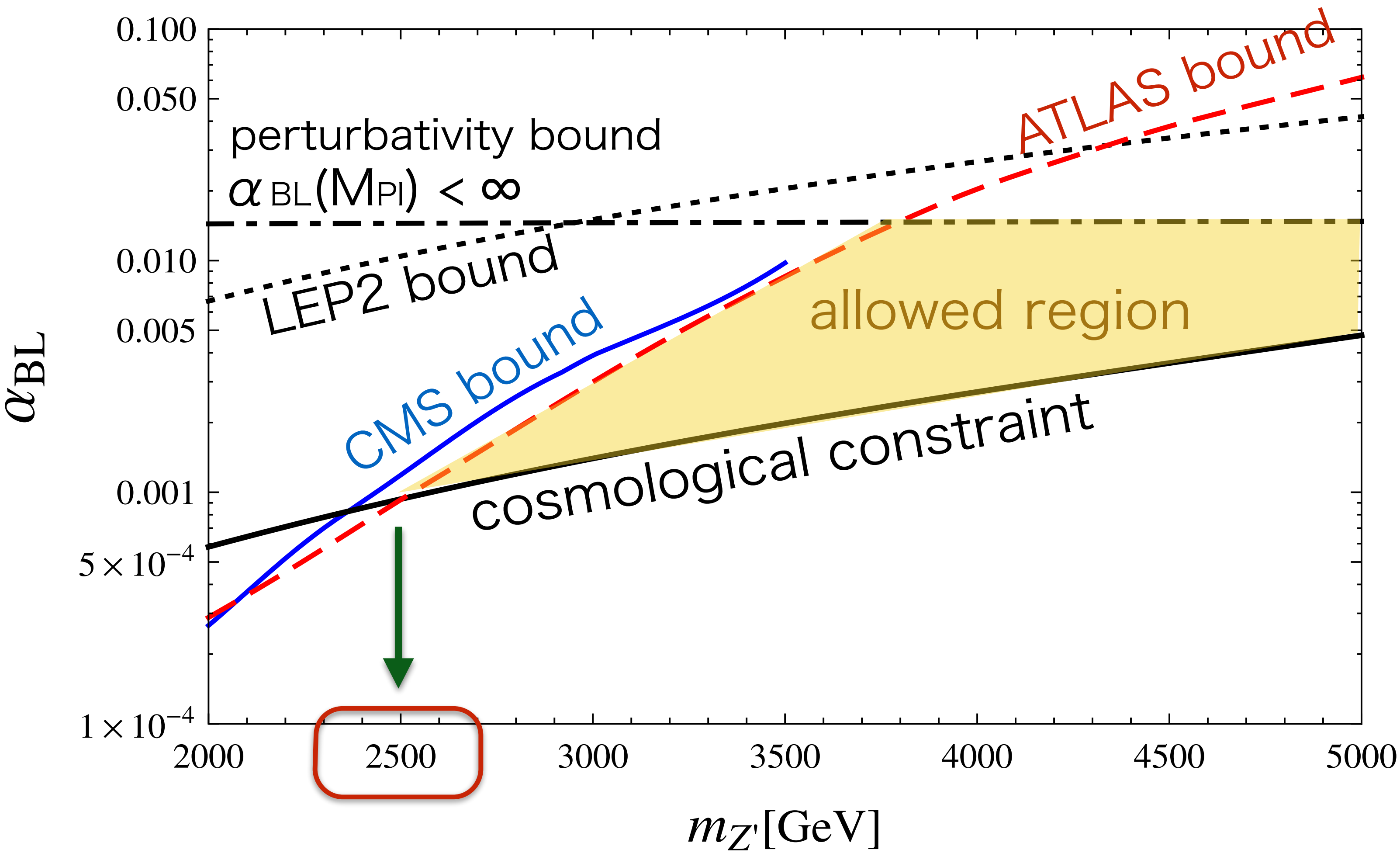
Carena et al., PRD 70 (2004) 093009
Heeck, PLB 739 (2014) 256

- Perturbativity of the B-L coupling up to the Planck scale

$$\alpha_{BL} < \frac{\pi}{6 \ln \left[\frac{M_{Pl}}{m_{Z'}} \right]}$$

1 loop RGE

Combining all constraints



We found the lower bound on the $Z'_{\rm BL}$ boson mass

$m_{Z'}$ > 2.5 TeV.

Conclusions

We have considered the minimal gauged B-L extension of the standard model with a right-handed neutrino dark matter.

In this model, the dark matter particle communicates with the standard model particles through the B-L gauge boson(Z'_{BL} boson), and this "Z'_{BL} portal" dark matter scenario is controlled by only three parameters,

- gauge coupling
- Z'_{BL} boson mass
- dark matter mass

We have considered a variety of phenomenological constraints on this "Z'_{BL} portal" dark matter scenario.

- relic abundance constraint
- LHC Run-2 bounds
- LEP2 bound
- perturbativity bound of running gauge coupling up to Planck mass

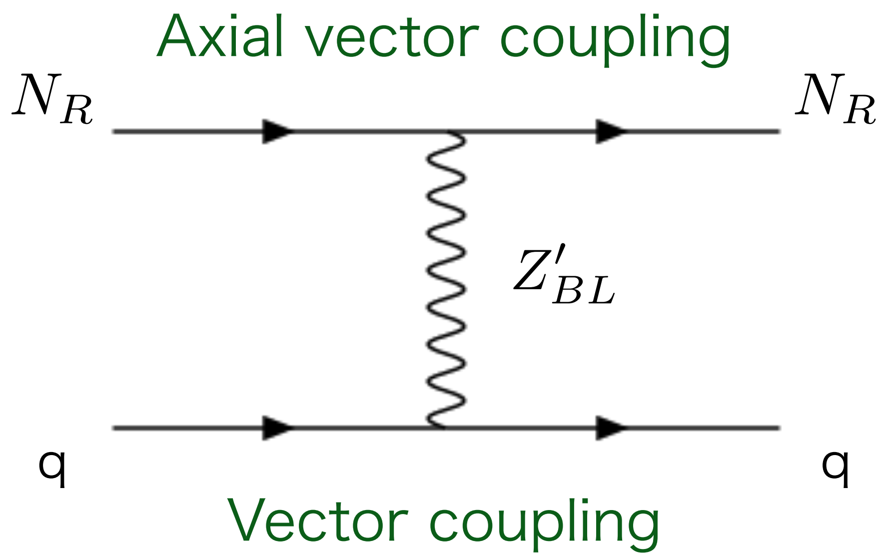
We have found the lower bound on the Z'_{BL} boson mass of **$m_{Z'} > 2.5$TeV**.

Thank you

for your attention!

Backup slides

Direct and indirect detection

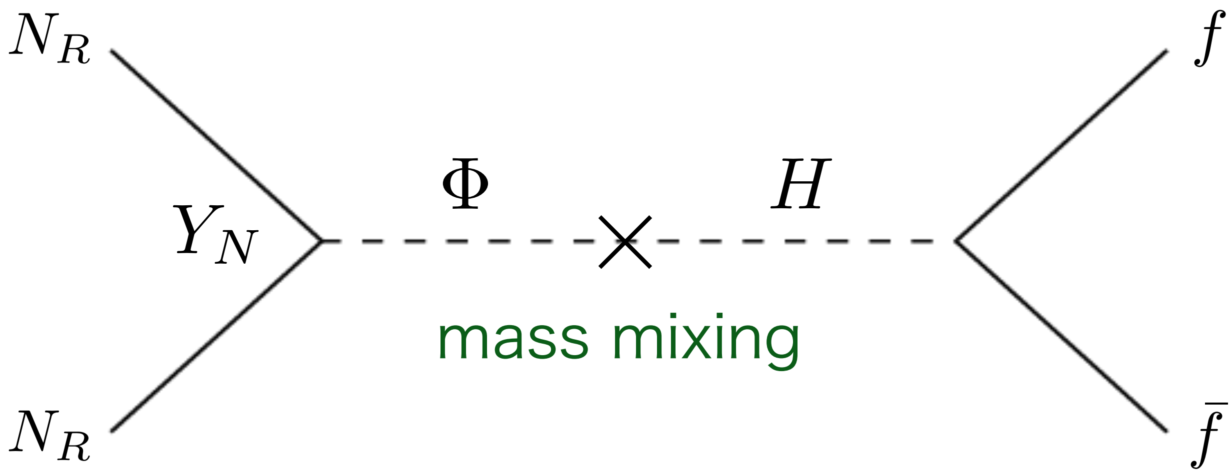


In non-relativistic limit,
the scattering cross section of DM with nucleon is vanishing.

$$\sigma(N_R q \to N_R q) \to 0$$

B-L Higgs portal dark matter

B-L Higgs portal dark matter is also possible.



Free parameters

- B-L Higgs mass (m_Φ)
- Φ-H mixing mass
- dark matter mass (m_{DM})