Exploring the lifetime frontier at the LHC and beyond

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Based on: arXiv:1905.11889 and arXiv:1908.11741 with F. Deppisch, W. Liu

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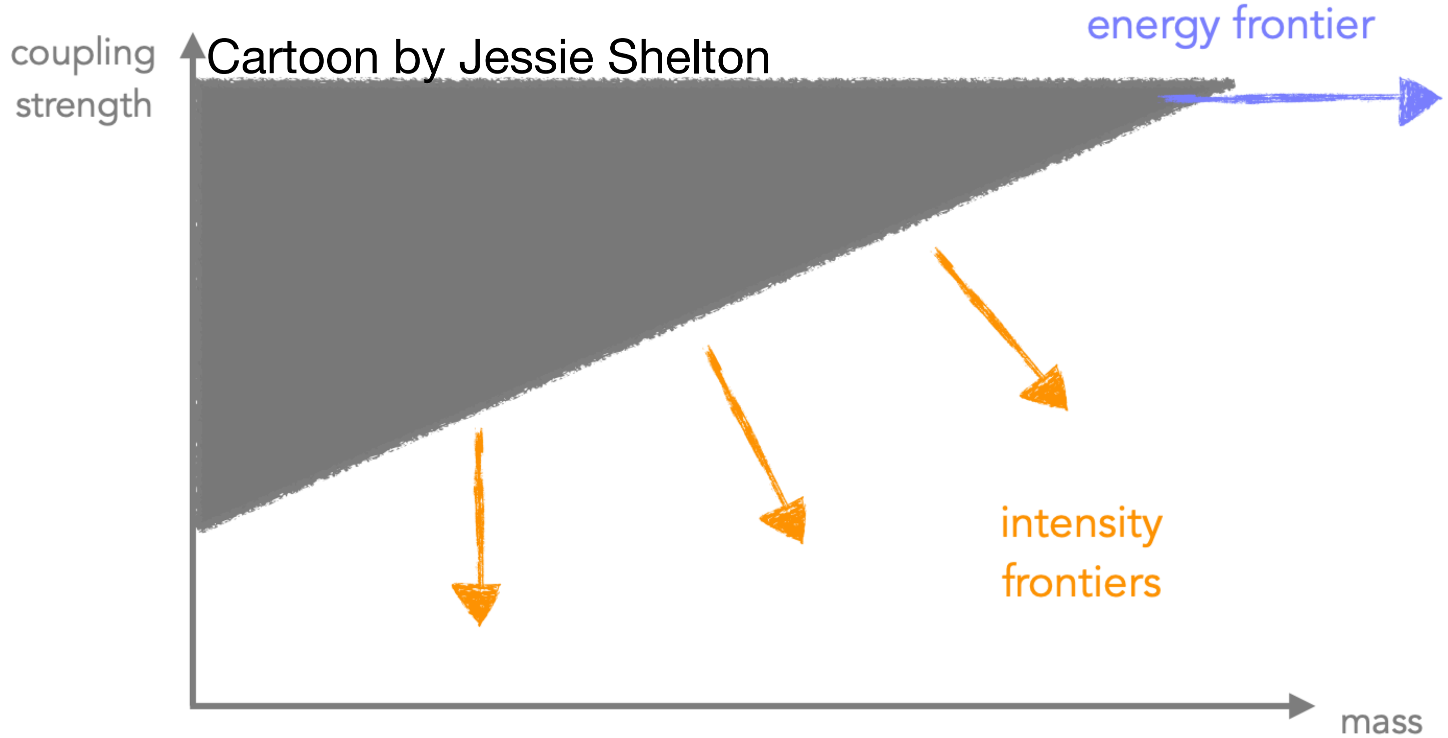
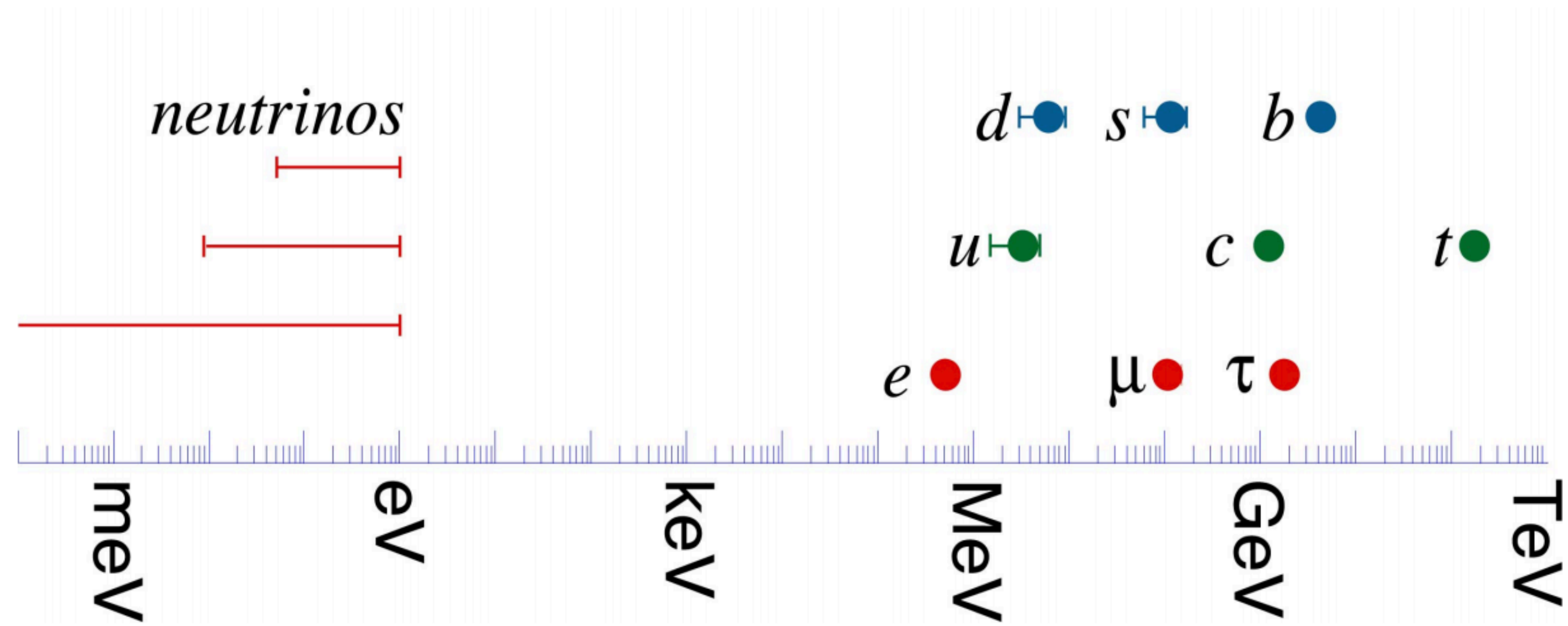
Beyond the standard model physics

Cartoon by Jessie Shelton



- Third dimension: lifetime!
- Not well explored at the LHC
- Long lived particle (LLP) searches: very little to no background

- LLP occur when either mass splitting between two particles is small or the coupling is suppressed
- Neutrino masses: Evidence of BSM physics
- Intimately related to new physics at lifetime frontier



Neutrino mass generation mechanisms

- SM + right handed fields

Tiny Yukawa →

- Small Dirac neutrino masses

- RH fields mass term

Lepton number violation →

- Baryogenesis through leptogenesis

$$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D \\ M_D^\mathsf{T} & M_N \end{pmatrix}$$

Dirac mass, usually small Y_ν

Majorana mass, can be heavy, can have $Y_N \sim 1$, introduces Lepton number violation

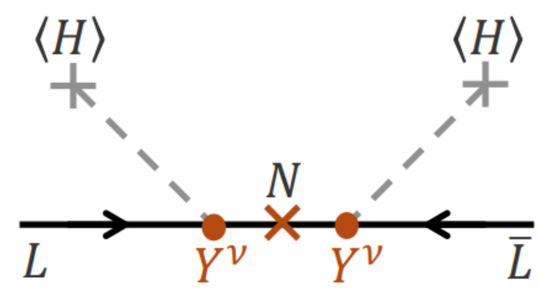
$$\mathcal{L} \supset Y_{ij}^{\nu} \overline{N}_i \ L_j \cdot H - \frac{1}{2} M_{ij} \overline{N}_i \ N_j^c$$

See e.g. Deppisch, New J. Phys. 17 (2015) 075019

Neutrino mass model probes

- Let us go to one extreme $M_N \approx 10^{14}$ GeV (GUT scale)

$$\mathcal{L} \supset Y^\nu_{ij}\bar{N}_i\; L_j\cdot H - \frac{1}{2}M_{ij}\bar{N}_i\; N_j^c \xrightarrow[\langle H\rangle \ll M_N]{} \frac{1}{2}(Y^\nu_{ki}M^{-1}_{kl}Y^\nu_{lj})(\bar{L}^c_i\cdot H)(H^T\cdot L_j)$$



- Light neutrino mass

$$m_\nu \approx 0.1\ \text{eV}\left(\frac{Y_\nu\langle H\rangle}{100\ \text{GeV}}\right)^2\left(\frac{10^{14}\ \text{GeV}}{M}\right)$$

- Heavy neutrino lifetime

$$L_N \approx 0.025\ \text{m}\cdot\left(\frac{10^{-6}}{V_{\mu N}}\right)^2\cdot\left(\frac{100\ \text{GeV}}{m_N}\right)^5$$

- Sterile neutrino mass scale M_N unknown
  - $\approx 10^{14}$ GeV — Naive seesaw, GUTs
  - $\gtrsim 10^9$ GeV — Thermal leptogenesis
  - $\approx 10^3$ GeV — Production at the LHC
  - ≈ 1 keV — Dark matter candidate
  - ≈ 1 eV — Oscillations, cosmology, 0νββ

Region of interest for this talk

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Neutrino masses - a simple model

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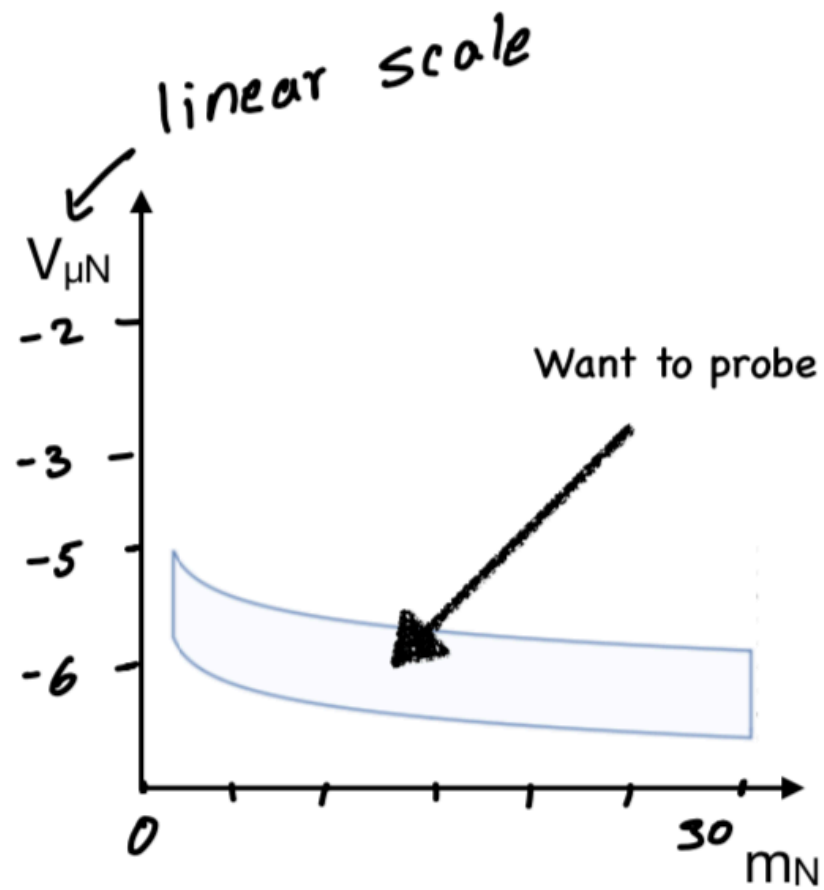
Mohapatra, Marshak (PRL 44 (1980) 1316 1319)

- Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
- Characteristics
  - **Particle content**: B-L gauge boson (Z'), Higgs boson (χ_{B-L}), 3 heavy neutrinos (N)
  - **Couplings**: g'_{B-L} (B-L coupling), $\sin\alpha$ (χ_{B-L}, Higgs mixing), V_{lN} (neutrino mixing)
  - **Free parameters**: 5 masses, 5 couplings (diagonal V_{lN})
    - Assume only light muon neutrino → 3 masses, 3 couplings
  - **Charges**: χ: +2; N: -1; q: 1/3; l:-1

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \qquad m_\nu \approx -\frac{M_D^2}{M_R} = -V_{lN}^2 M_R$$

- Heavy neutrino lifetime

$$L_N \approx 0.025\ \mathrm{m} \cdot \left(\frac{10^{-6}}{V_{\mu N}}\right)^2 \cdot \left(\frac{100\ \mathrm{GeV}}{m_N}\right)^5$$



B-L Lagrangian

Higgs sector

$$\mathcal{L} \supset (D^{\mu}H)^{\dagger}(D_{\mu}H) + (D^{\mu}\chi)^{\dagger}D_{\mu}\chi - \mathcal{V}(H,\chi),$$

$$\mathcal{V}(H,\chi) = m^2 H^{\dagger}H + \mu^2|\chi|^2 + \lambda_1(H^{\dagger}H)^2 + \lambda_2|\chi|^4 + \lambda_3 H^{\dagger}H|\chi|^2$$

$$D_{\mu} = \partial_{\mu} + ig_s \mathcal{T}_{\alpha} G^{\alpha}_{\mu} + igT_a W^a_{\mu} + ig_1 Y B_{\mu} + i(\tilde{g}Y + g'_1 Y_{B-L})B'_{\mu}$$

Kinetic term

$$\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu}$$

Abelian hyper-charge and B-L mixing terms set to zero

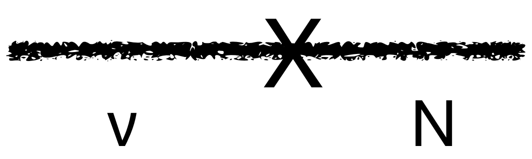
Right handed neutrino term

$$\mathcal{L} \supset i\overline{\nu_{Ri}}\gamma_{\mu}D^{\mu}\nu_{Ri}$$

Additional Yukawa terms

$$\mathcal{L} \supset -y^{\nu}_{ij}\overline{L_i}\nu_{Rj}\tilde{H} - y^{M}_{ij}\overline{\nu^c_{Ri}}\nu_{Rj}\chi + \text{h.c.}$$

B-L portals



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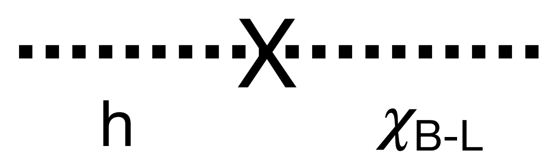

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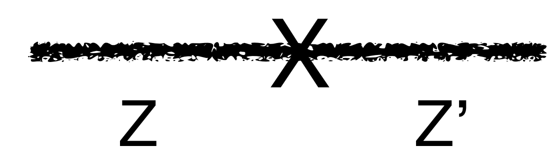

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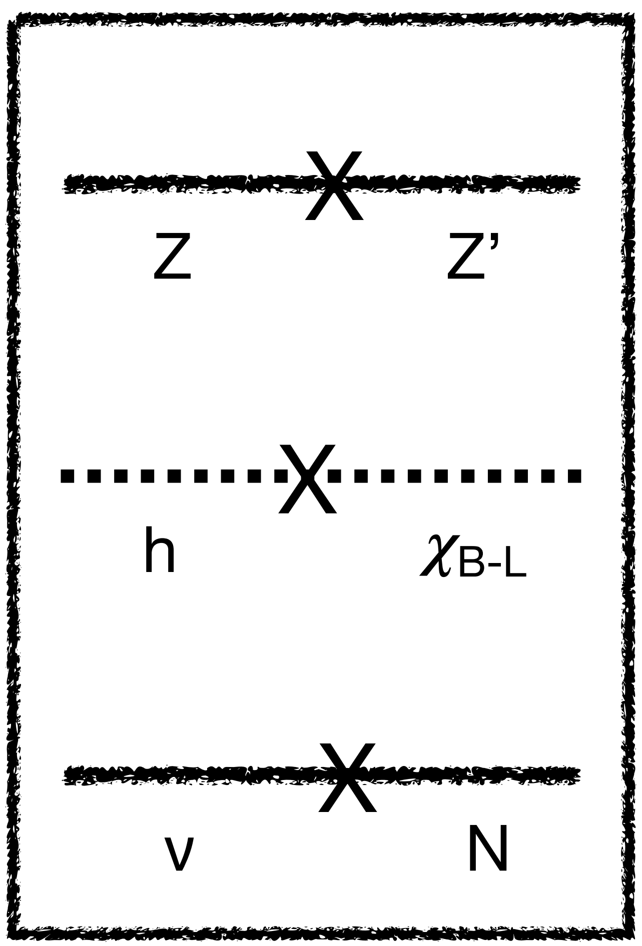
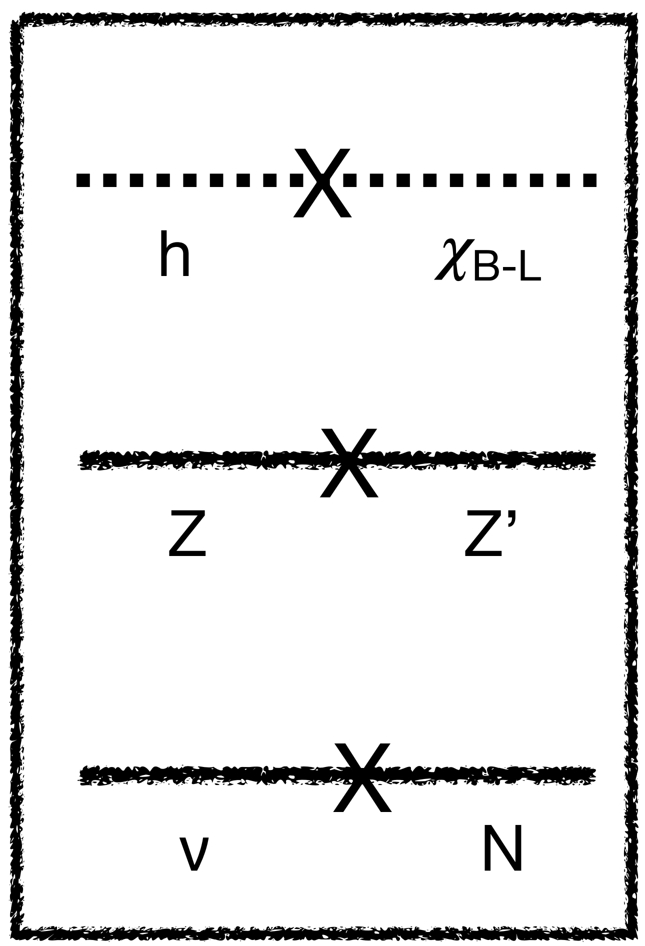
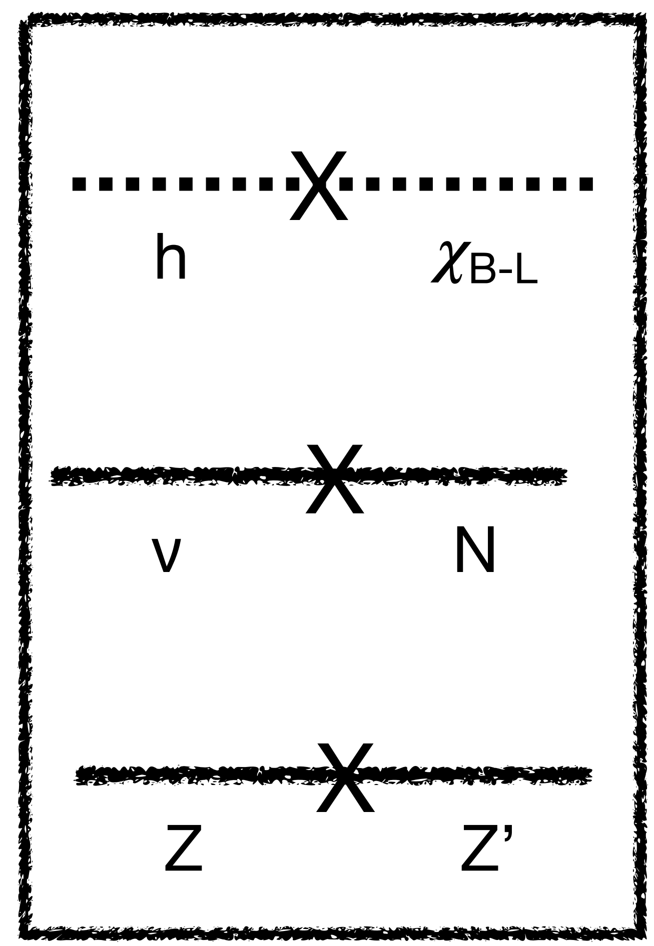
Different B-L mass hierarchies lead to different phenomenology







Z' portal

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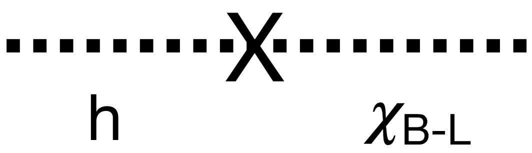

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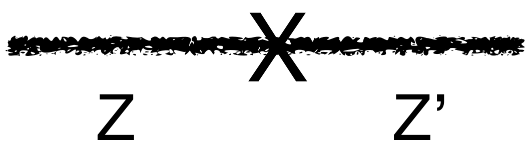

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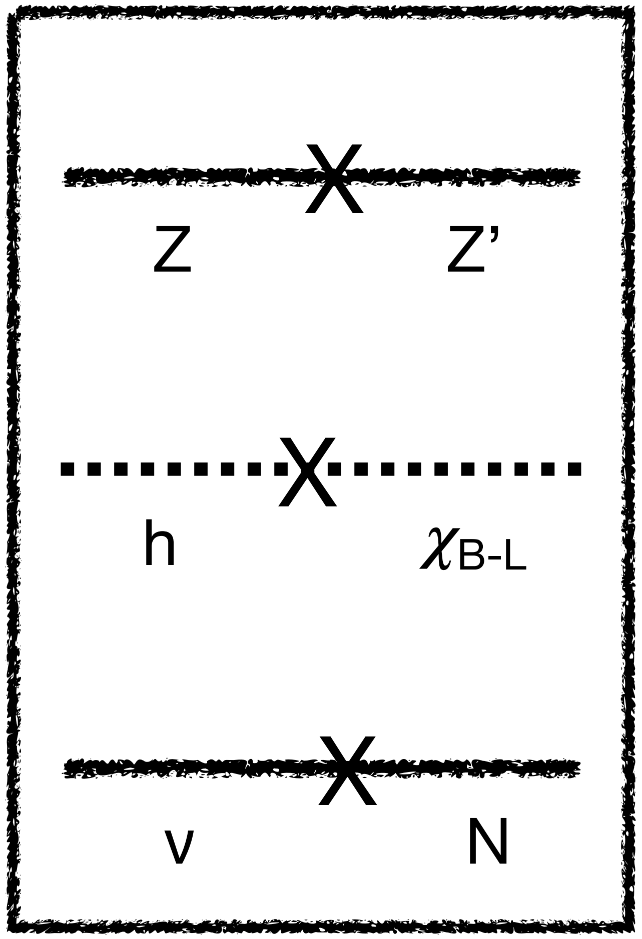
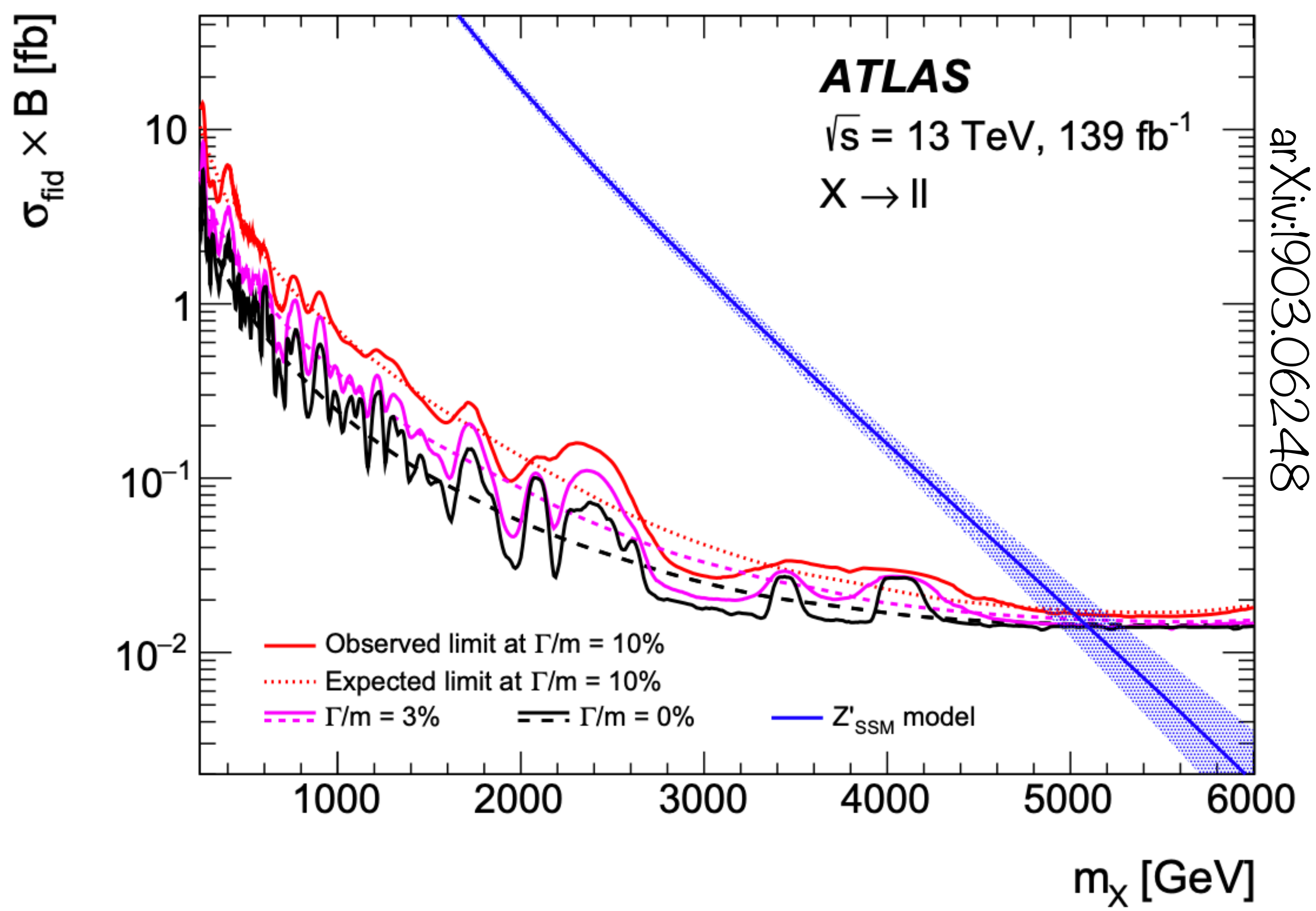
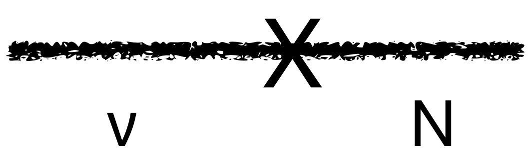
$M_{Z'}$ must at least be 125 GeV → strong constraints from dilepton searches





Heavy Higgs portal



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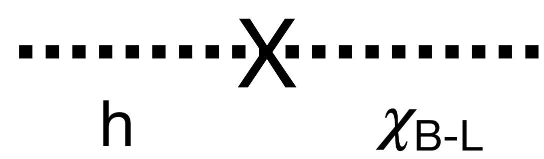

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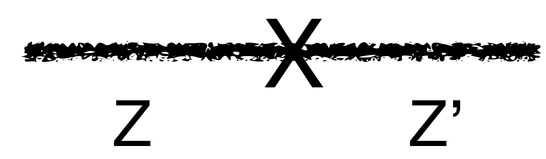

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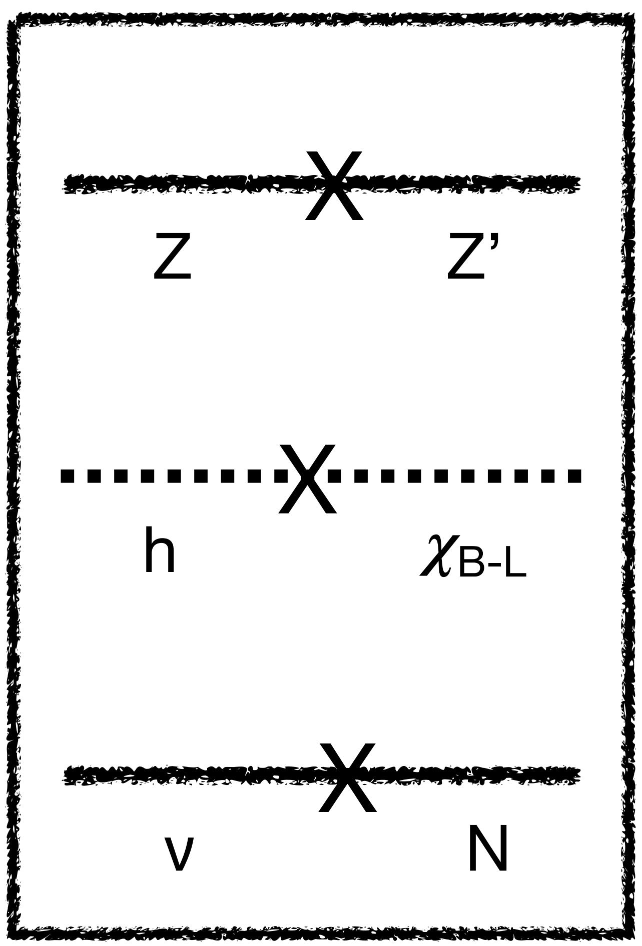
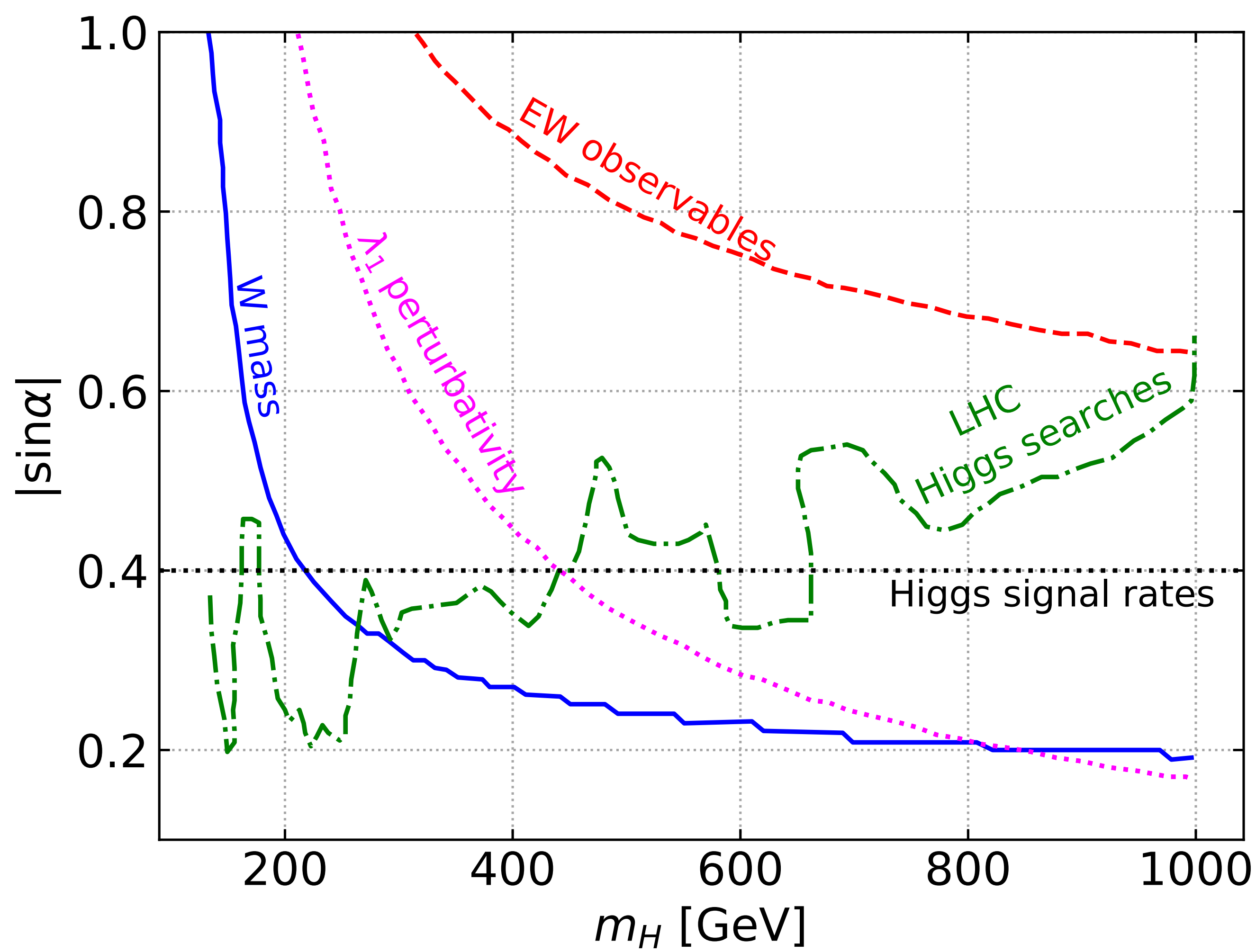
Constraints from heavy Higgs searches, EW observables and theory considerations





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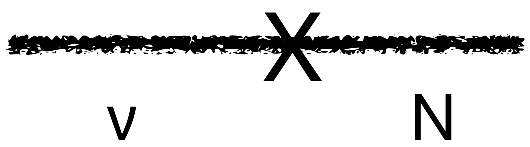

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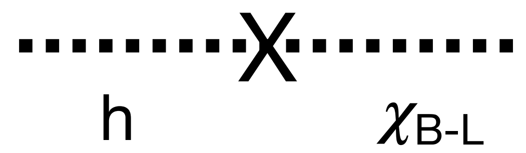

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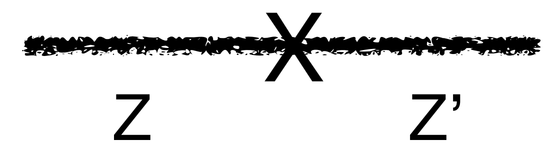

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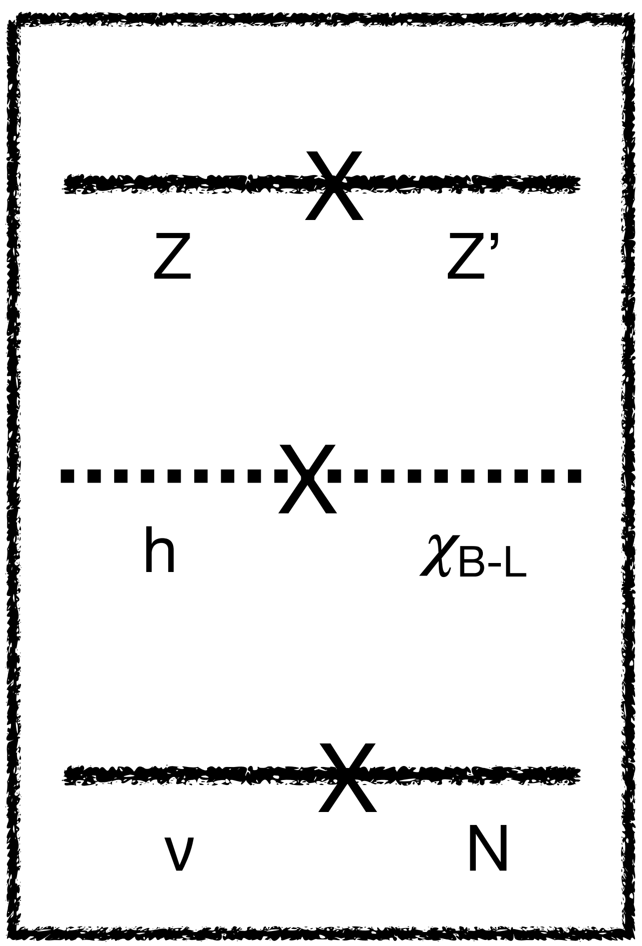
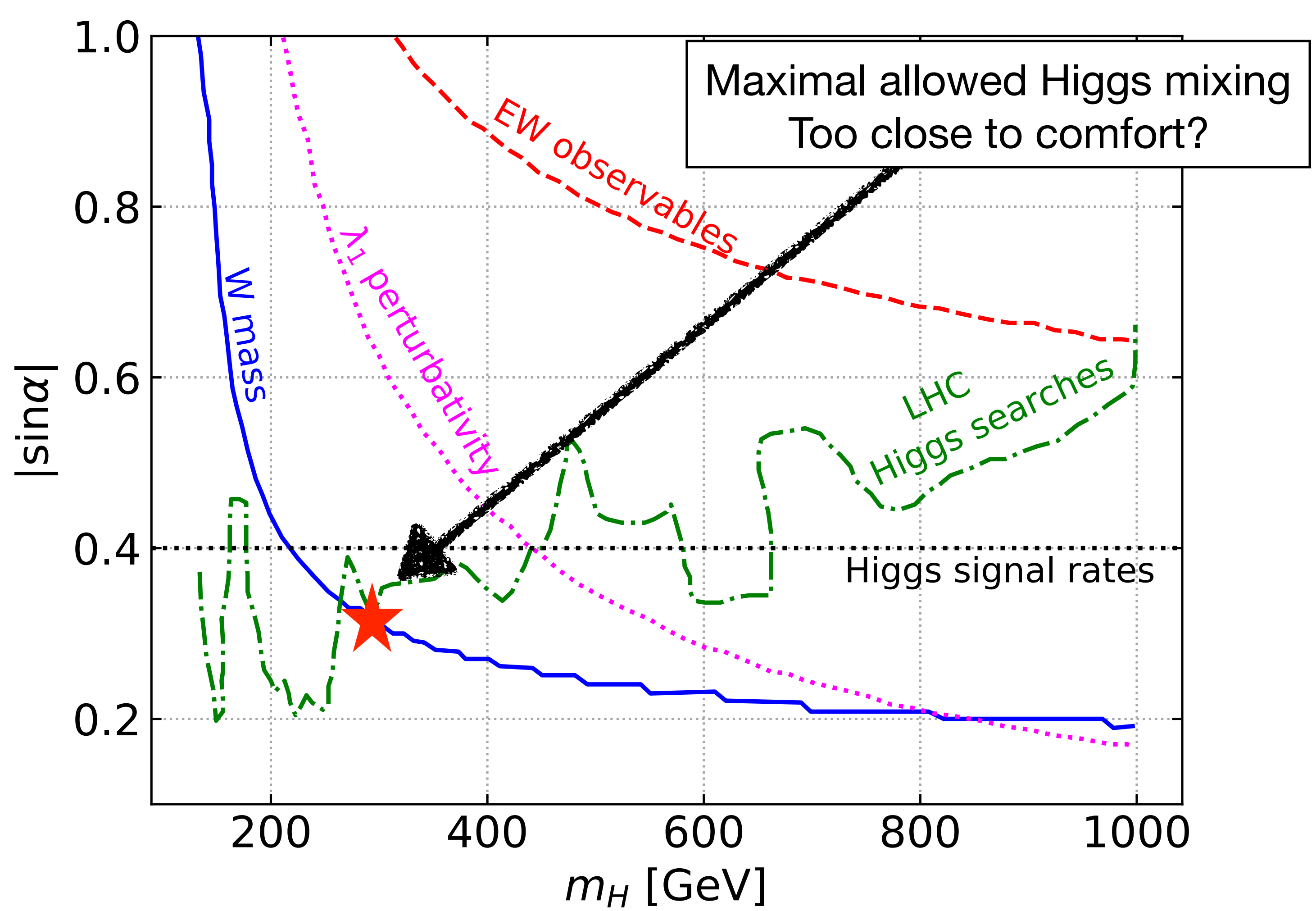
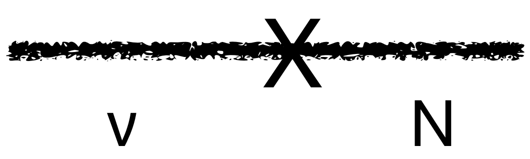




Heavy Higgs portal



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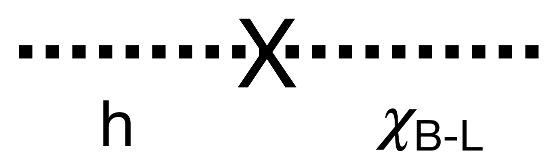

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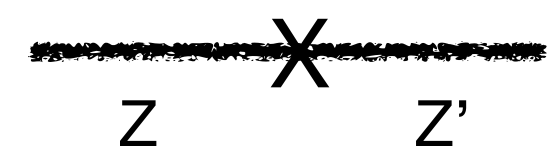

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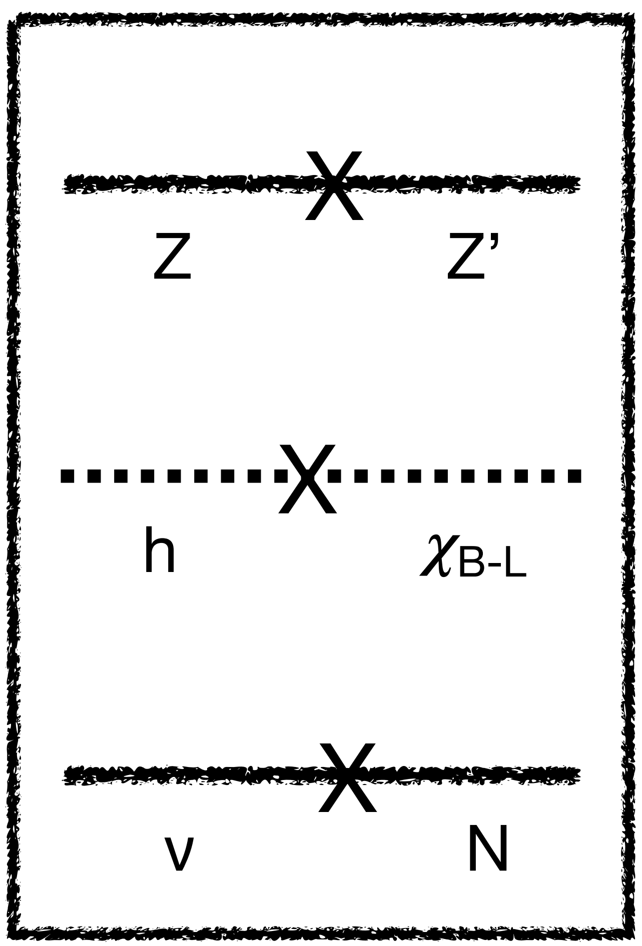
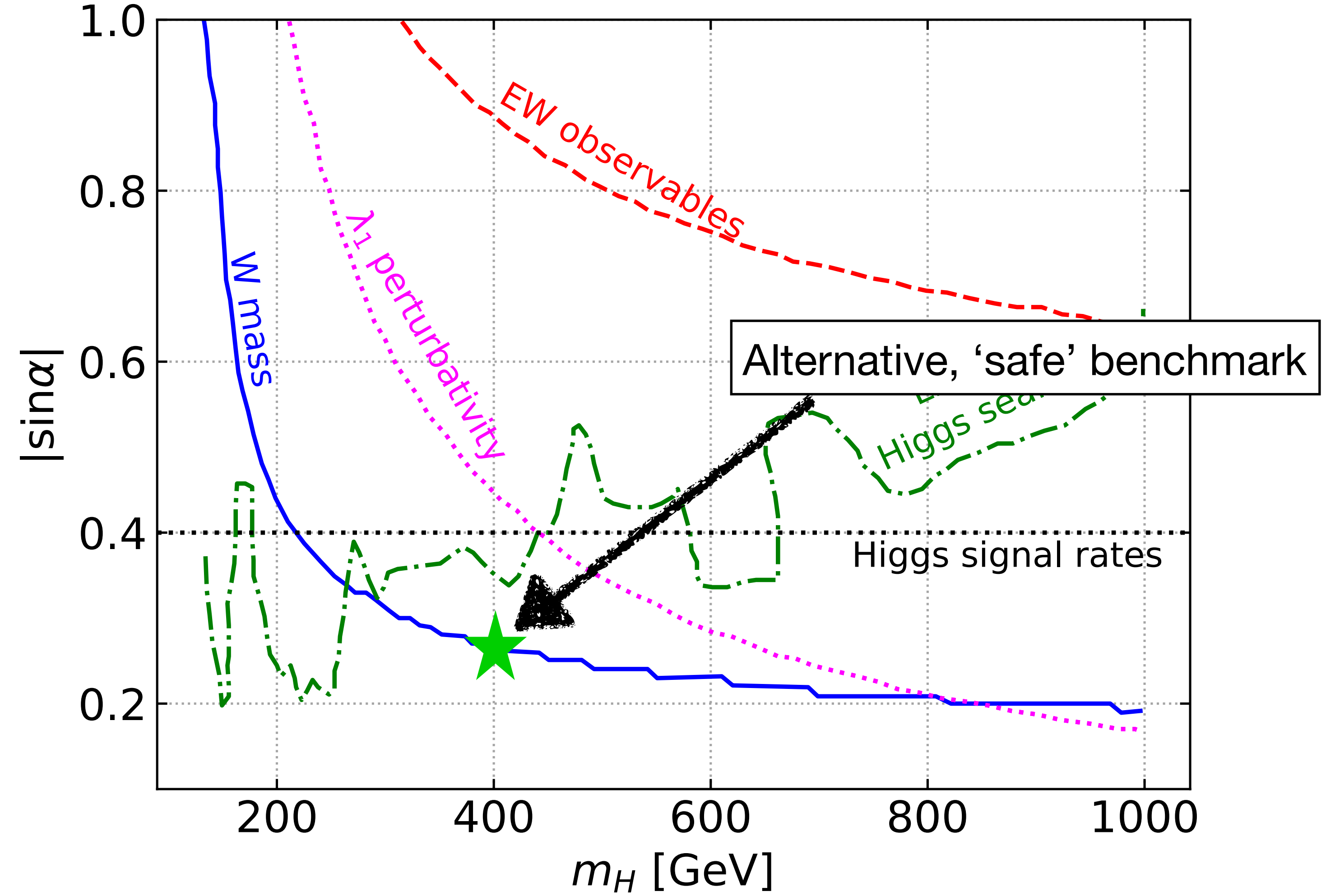
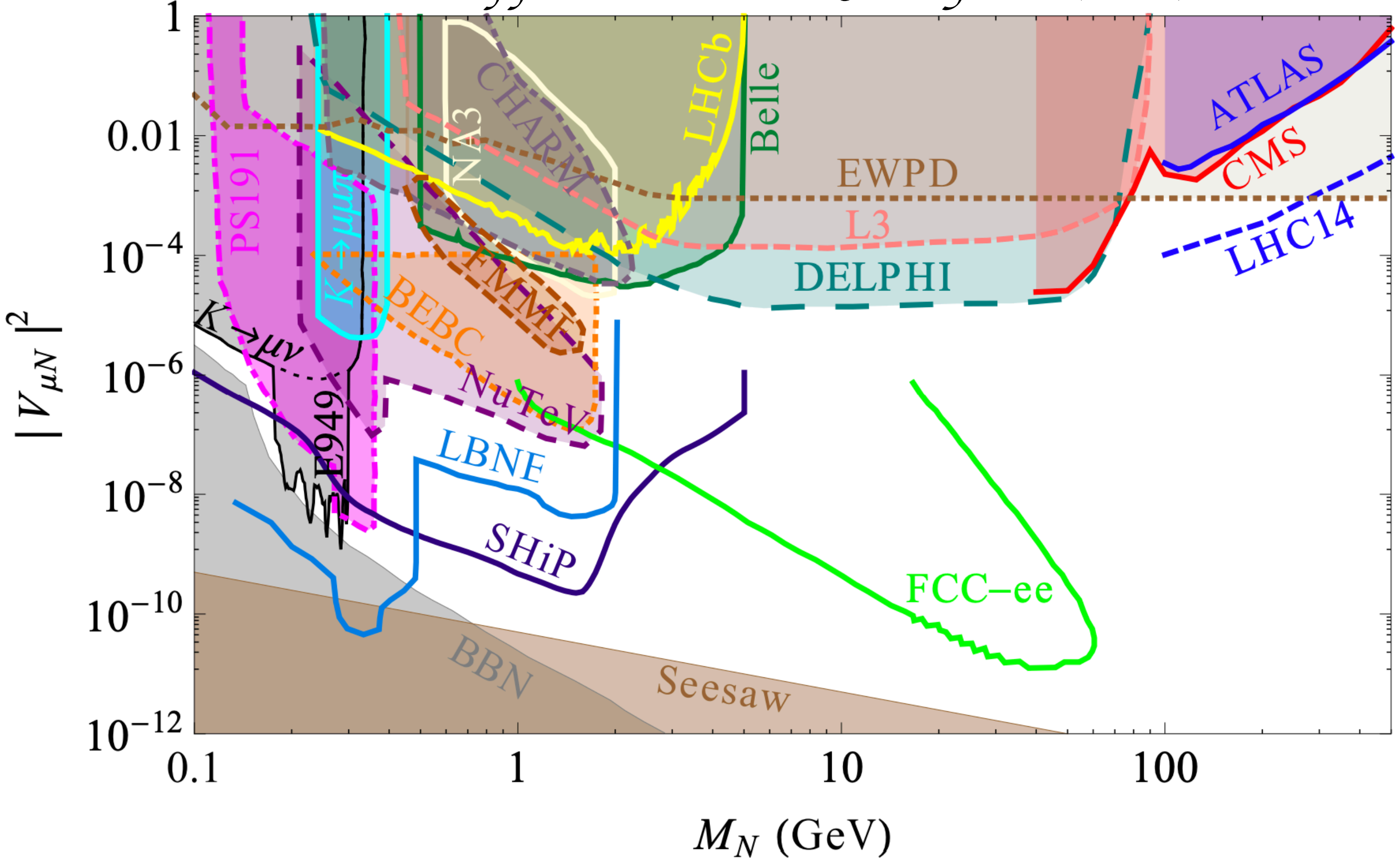
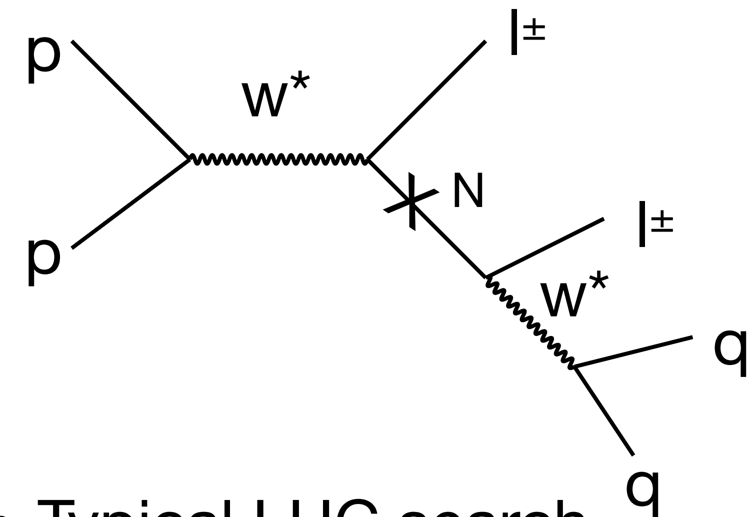




Neutrino portal

Deppisch et al, New J. Phys. 17 (2015) 075019



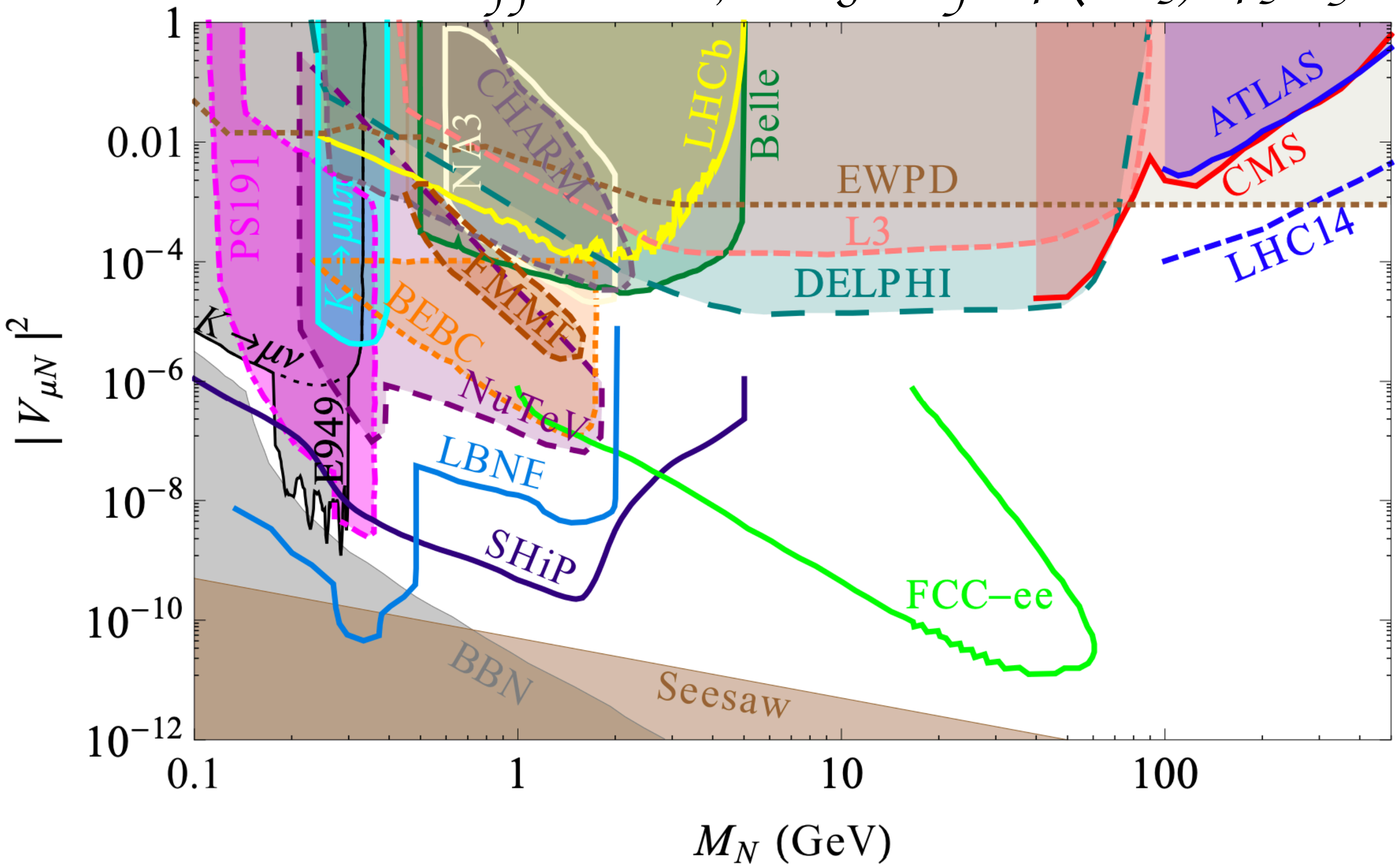


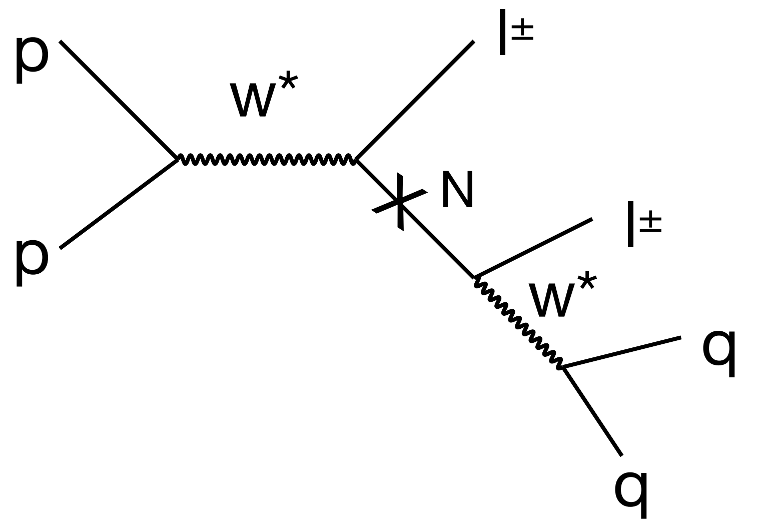
- Typical LHC search
- Minimal process
- Prompt lepton requirement

- Several probes for heavy neutrinos (aka heavy neutral leptons; HNL)
- Intensity frontier typically covers low masses; small mixing angles
- Limit plot corresponds to HNL production via SM mediators, B-L charges not taken into account
- At the LHC, same sign leptons from production (decays) of heavy neutrinos via SM W boson
- Current LHC limits weak, rapidly changing situation

Neutrino portal

Deppisch et al, New J. Phys. 17 (2015) 075019



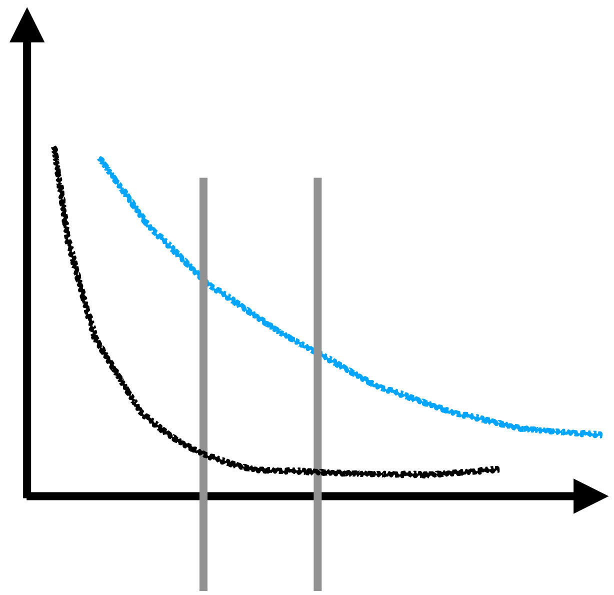


- Heavy neutrino decay length

$$L_N \approx 0.025\ \text{m} \cdot \left(\frac{10^{-6}}{V_{\mu N}}\right)^2 \cdot \left(\frac{100\ \text{GeV}}{m_N}\right)^5$$

- Build FCC!
- Heavy neutrino phenomenology at LHC necessitates exploration at lifetime frontier
- For neutrino masses ≈ 100's of GeV, $V_{\mu N} \approx 10^{-6} \rightarrow L_N \approx$ 25mm
- Problem: $V_{\mu N}$ suppression → have higher luminosity
- Neutrino mass of order 10 GeV, $V_{\mu N} \approx 10^{-6}$, $L_N \approx$ 100m, decays outside of the LHC → build bigger detectors; several proposals exist

LLP searches basics

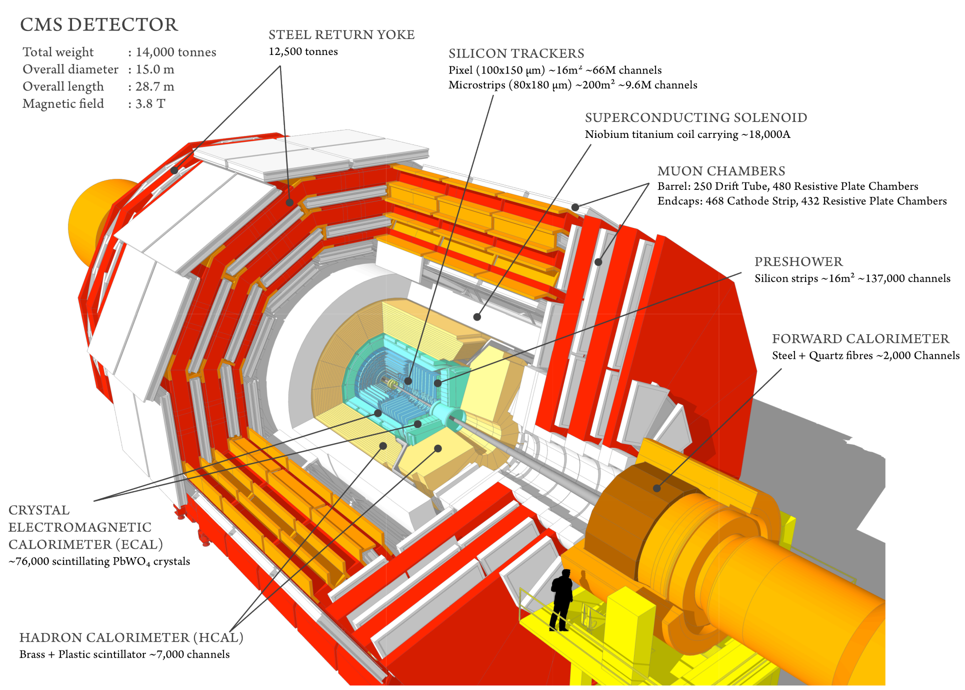


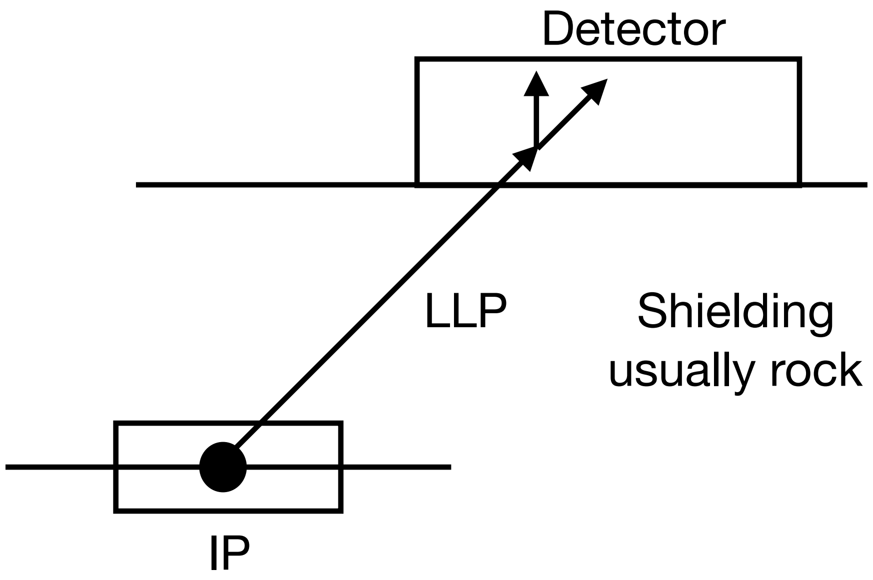
$$P_{\text{decay}}(b c\tau, L_1, L_2) = e^{-\frac{L_1}{bc\tau}} - e^{-\frac{L_2}{bc\tau}} \approx \frac{L_2 - L_1}{bc\tau} \quad \text{for } (L_2 - L_1) \ll bc\tau$$

- Boost depends on production mechanism and mass hierarchy between progenitor and decay product

$$N_{obs} \approx (\sigma_{sig}^{LHC} \mathcal{L})\, \epsilon_{LLP}^{detector}\, n_{LLP}\, \epsilon_{geometric}\, P_{decay}(\bar{b}c\tau, L_1, L_2)$$

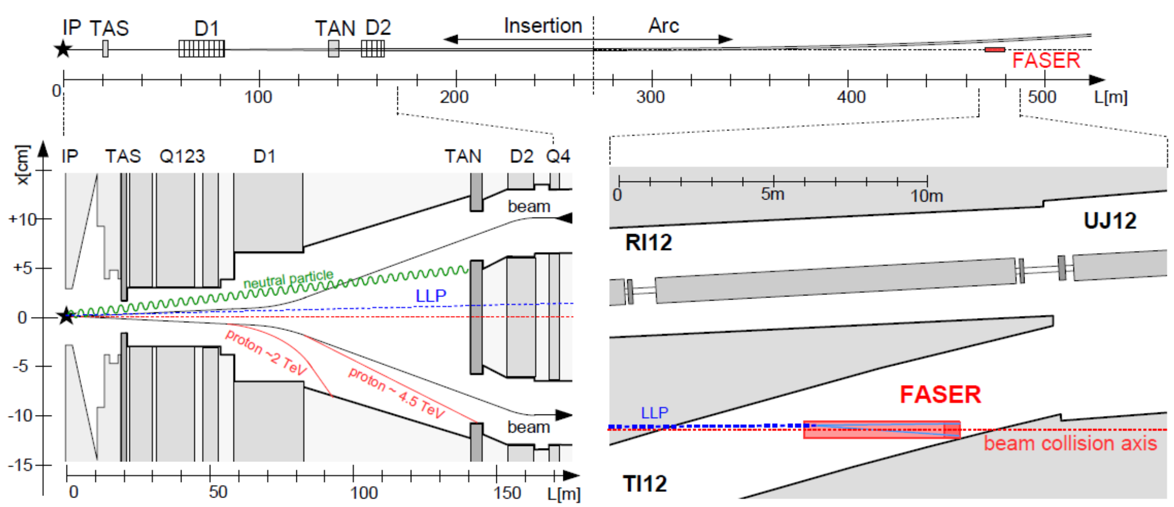
- Geometric acceptance depends on the distance and geometry of the detector



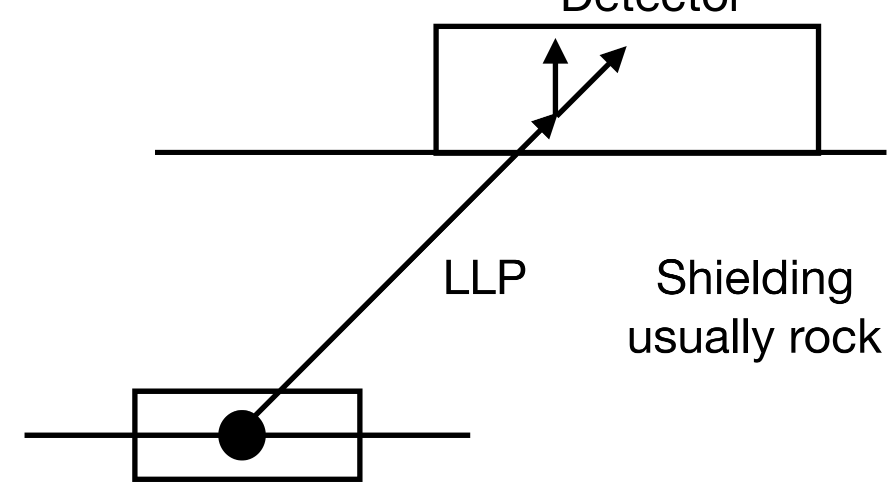


Proposed lifetime frontier detectors

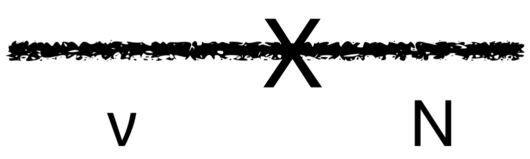
Detector	Location	Distance from IP (m)	Dimensions (m)	Luminosity (fb^{-1})
FASER-2	ATLAS	480	Cylinder 5 X1	3000
CODEX-b	LHC cavity	3	10 X 10 X 10	300
MAPP	LHCb/ MoEDAL	50	7 - 10 tunnel 5 - 25 degrees angle	300
MATHUSLA	CMS	100	200 X 200 X 20	3000



Approved experiment



B-L portals



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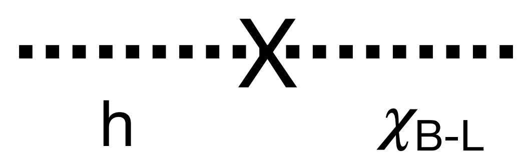
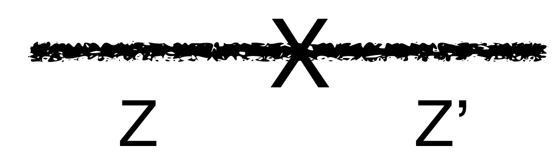


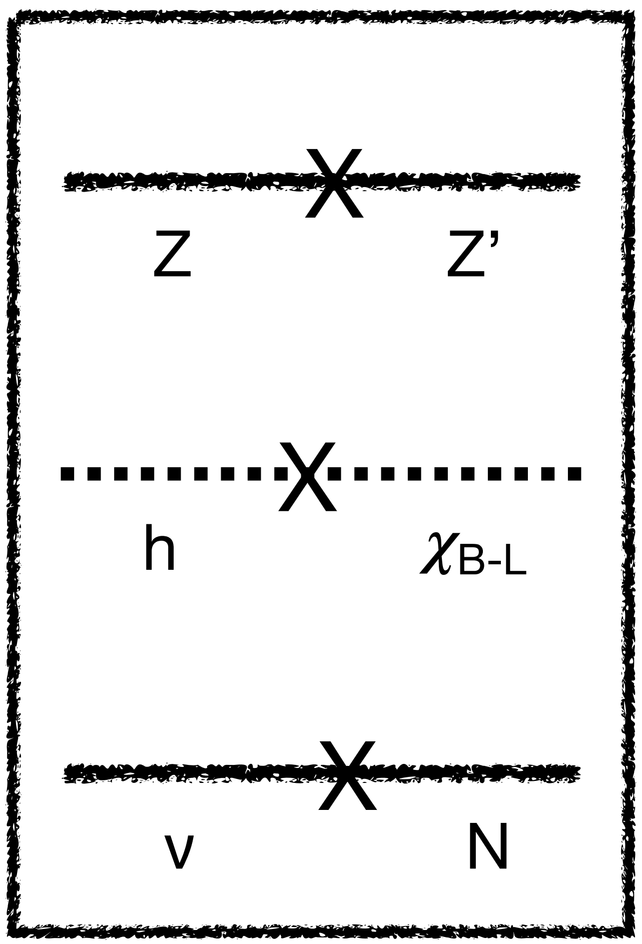
Suppressed by $\sin\alpha$

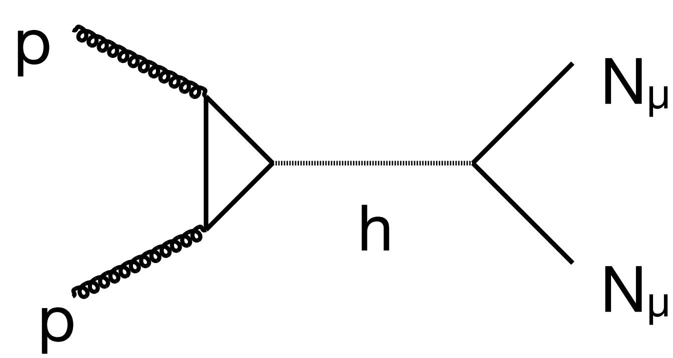


Suppressed by g'

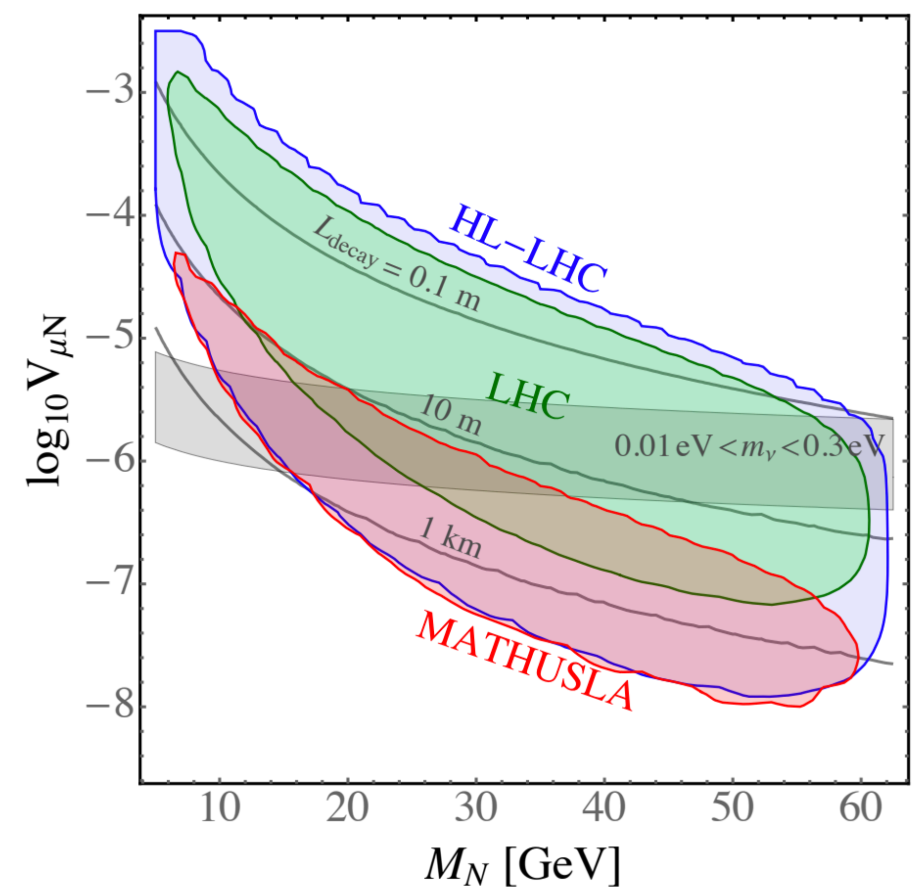
$h \to N\,N$ still possible if $\sin\alpha$ is large

$\sin\alpha = 0.3$, $g' \sim 0$





Deppisch et al, JHEP 1808 (2018) 181



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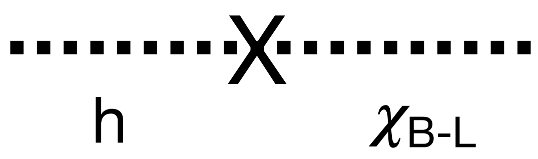

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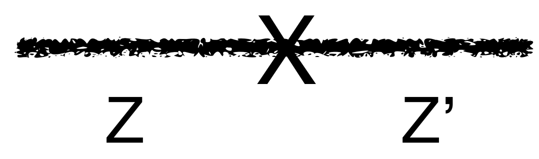
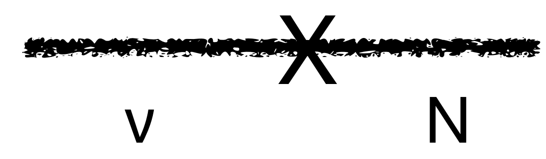
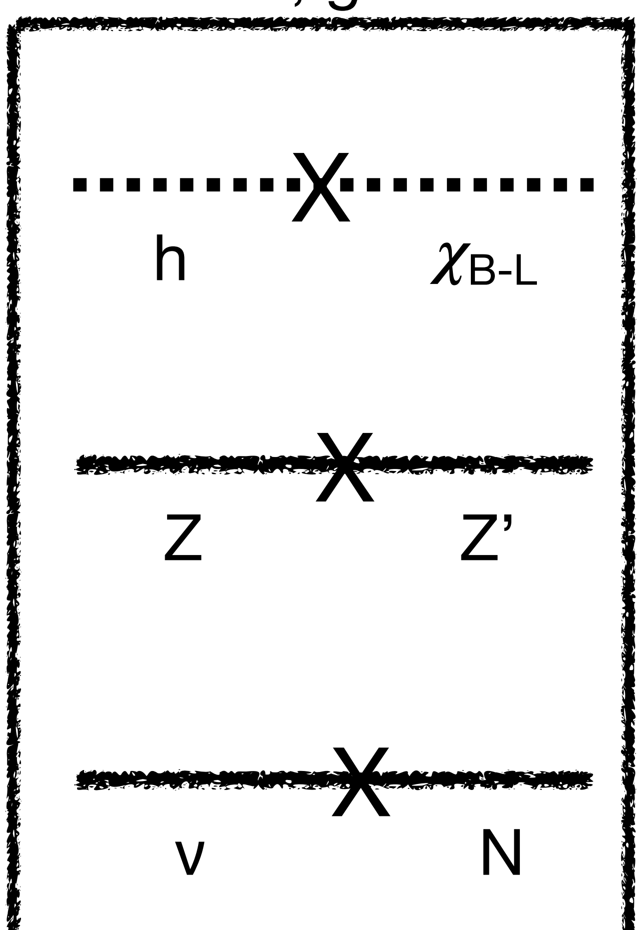


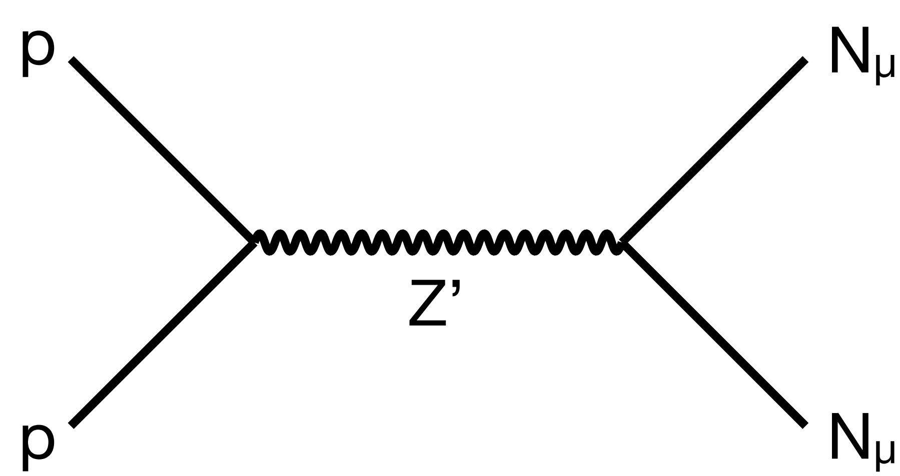
Suppressed by g’



Suppressed by $V_{\ell N}$

$\sin\alpha = 0$, $g' = 10^{-3}$



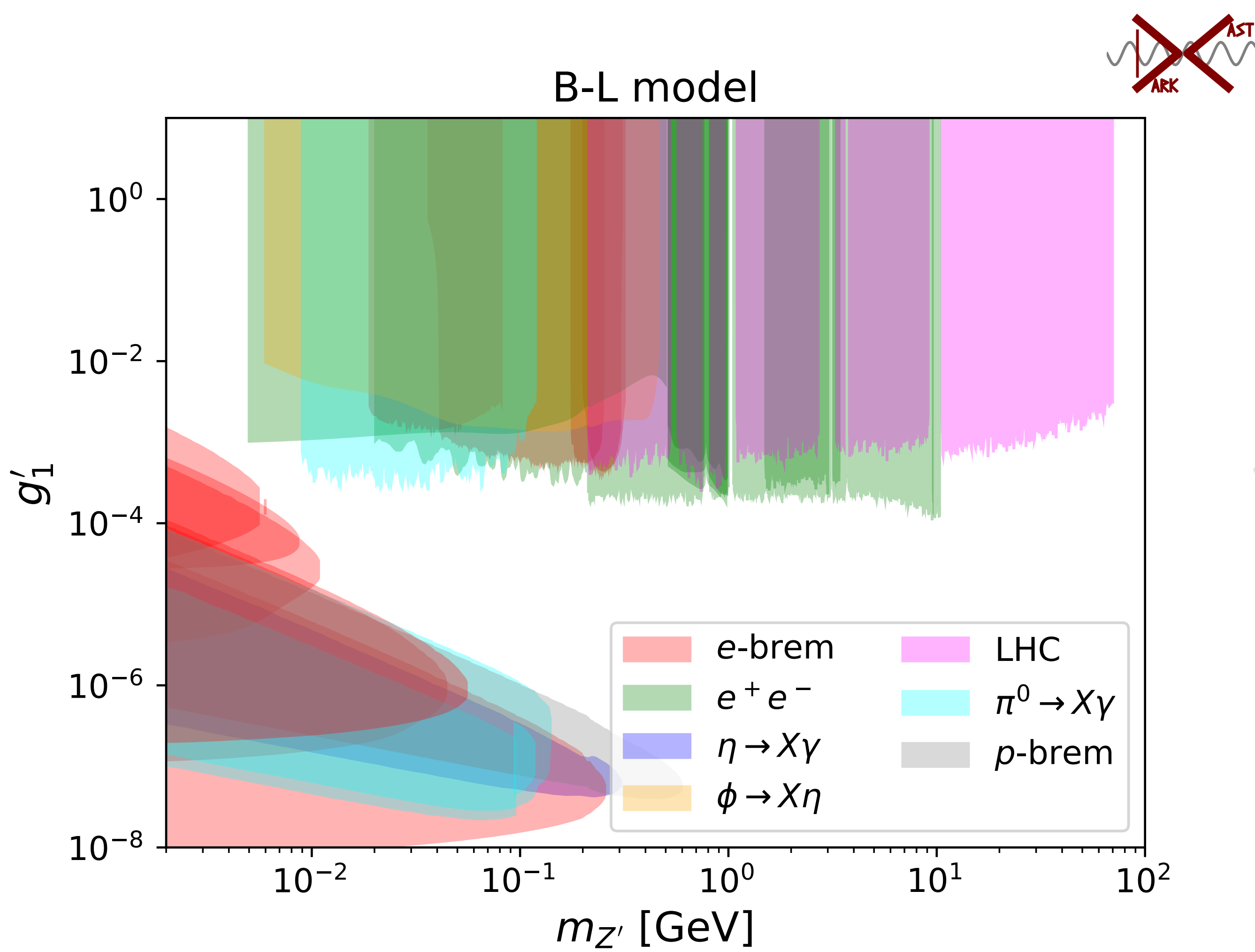


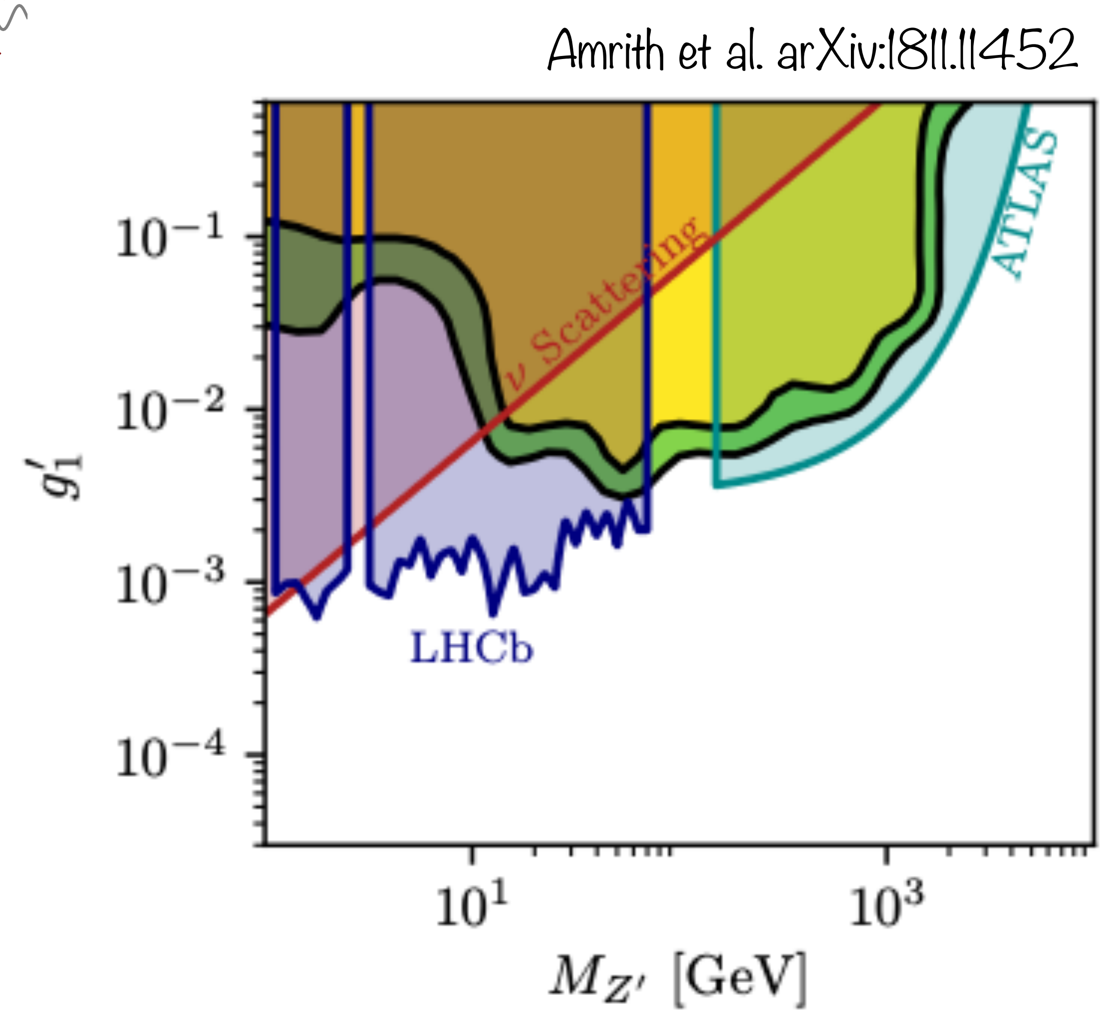
$M_{Z'} < M_h \rightarrow M_{Z'} < 100$ GeV;

What do the experiments have to say about this mass range?

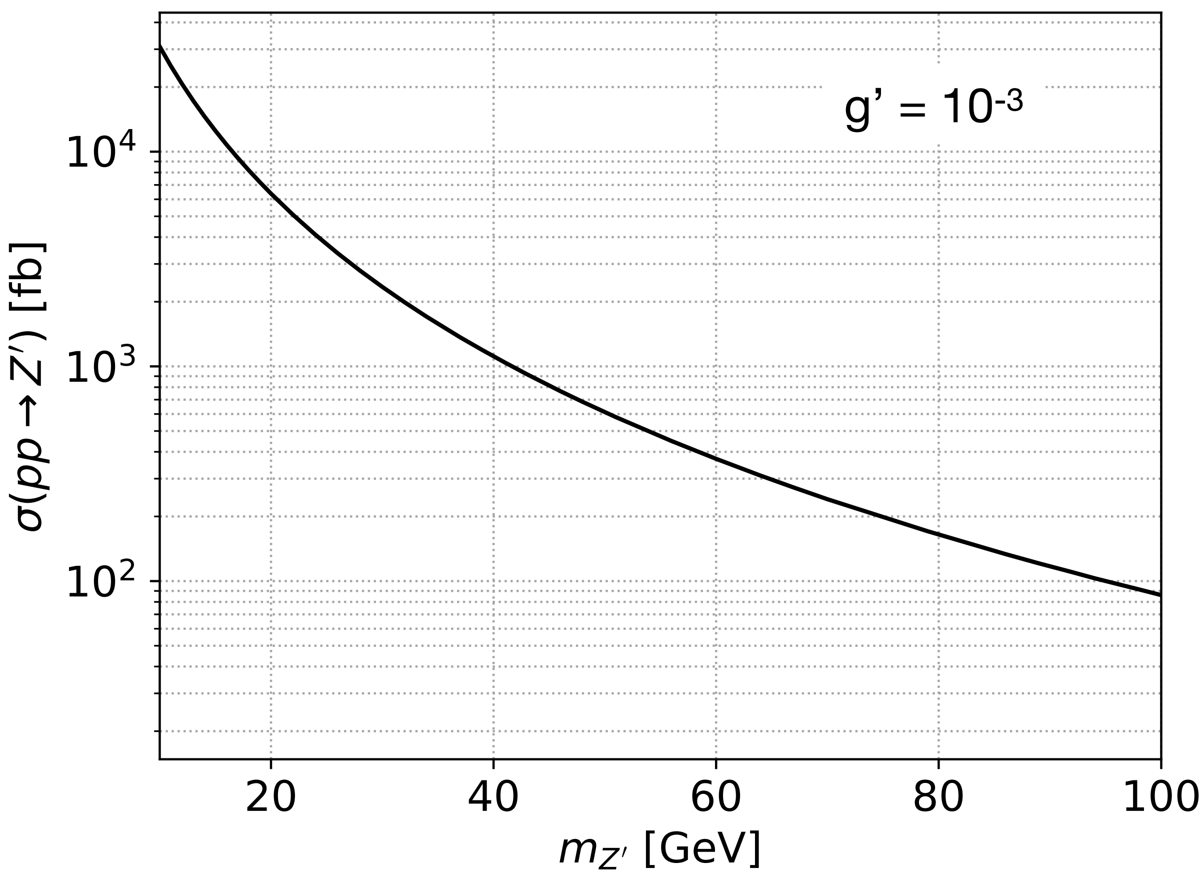
B-L existing constraints

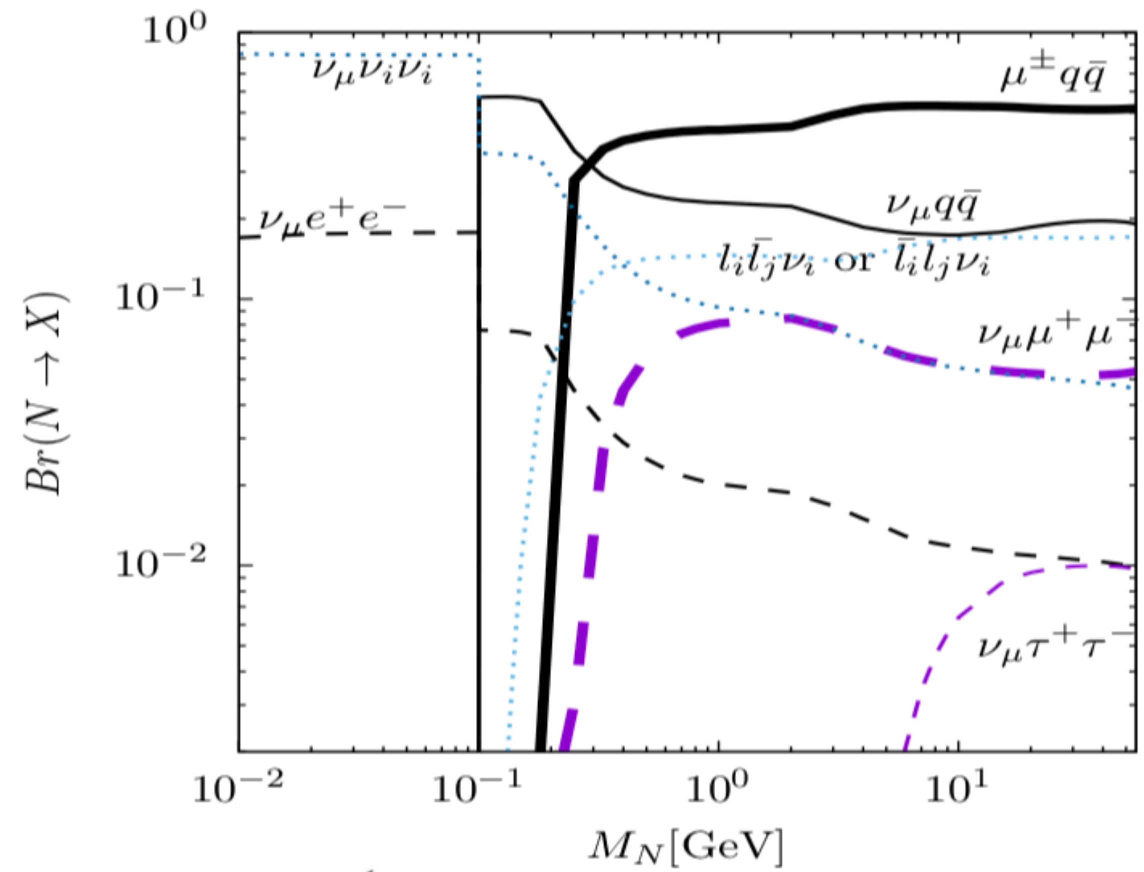
- Current constraints on the Z' masses come from LHC as well as fixed target experiments
- Reinterpretation of LHC SM searches done via CONTUR





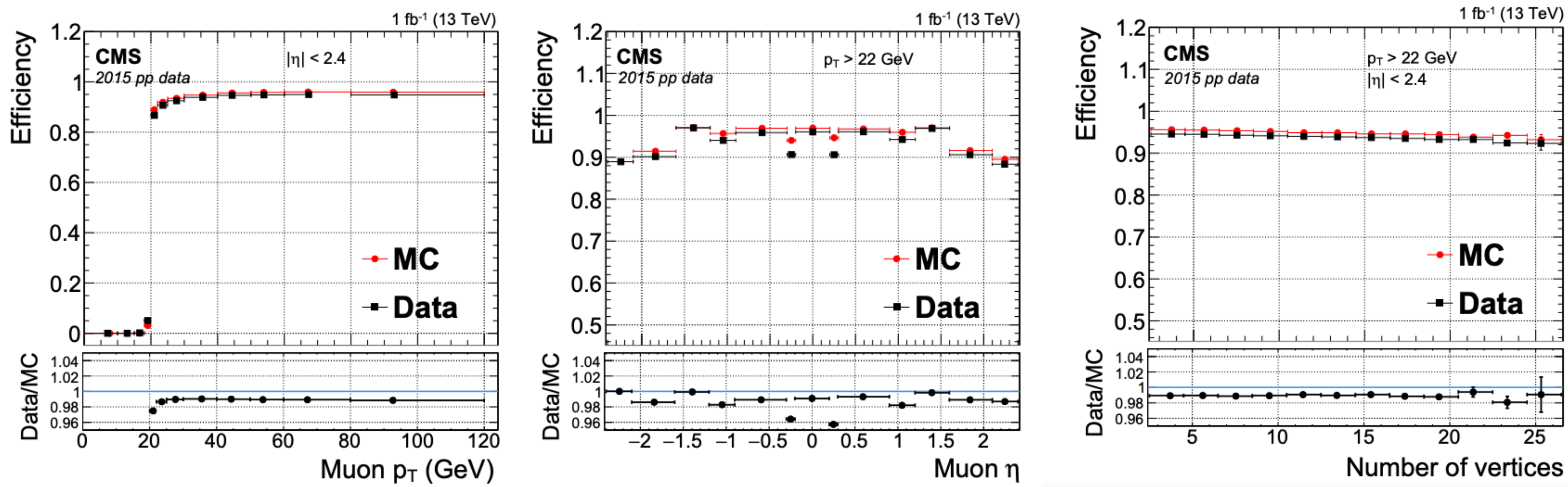
Some simple estimates





- Significant Z' production cross section
- BR(Z'→ N N) ~ 8% (per specie)
- Branching ratio N to at least one muon final state between 10 to 30%
- Typical HNL decay lengths ($V_{\mu N} \approx 10^{-6}$): O(100) m
- Potential for good reach in neutrino mixing angle at future facilities
- Concentrate on final state containing muons

Why muons?



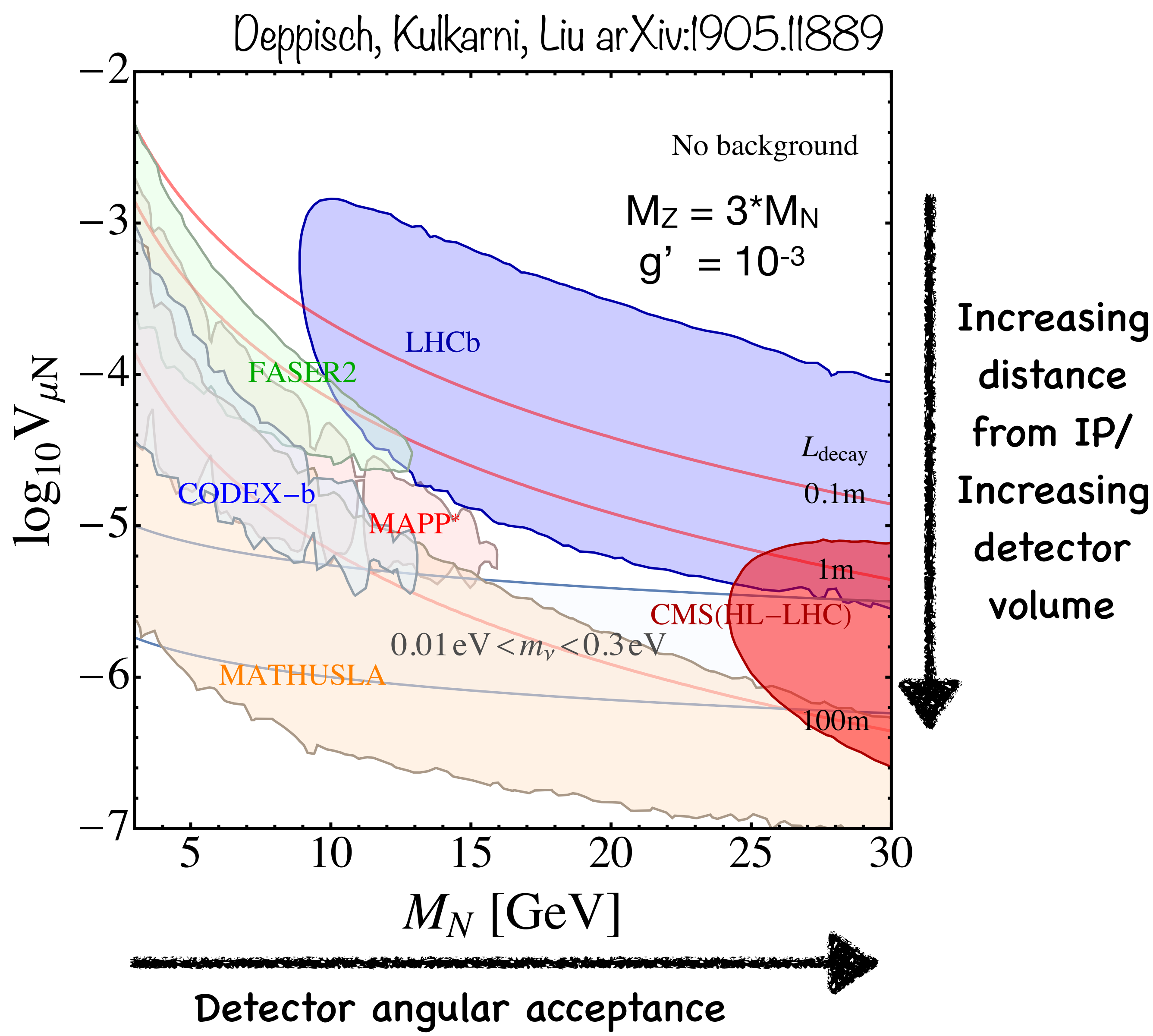
arXiv: 1804.04528.

- Electrons: absorbed in calorimeter (Electrons in muon system can appear as noise)
- Taus: decay, penalty due to tau branching fraction, challenging at LHC
- Jets: Not good resolution, larger trigger requirements compared to leptons
- Muons:
  - Excellent efficiencies for a large part
  - Lower background compared to hadrons
  - NB: situation is different for highly displaced muons

Decays via Z’

- Model implementation in MadGraph
- Decays and hadronization using Pythia8
- No detector simulation
- Final states under considerations:
  - LHCb: p p → N N → N μjj
  - General purpose LHC: p p → N N → N μμν
  - MATHUSLA, FASER, CODEX-b: p p → N N
- Cuts:
  - L_z = 480m, L_d = 1.5m, 5m, R = 1m, 5m [FASER]
  - L_z~30 - 60m, L_x~4 - 15m, L_y~-10 - 10m [MAPP*]
  - L_x = –100~100m L_y= 100~120m, L_z = 100~300m [MATHUSLA]

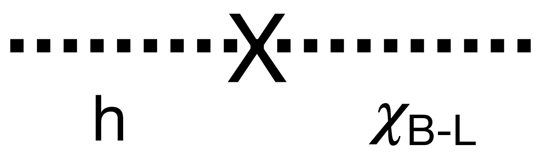
Decays via Z'



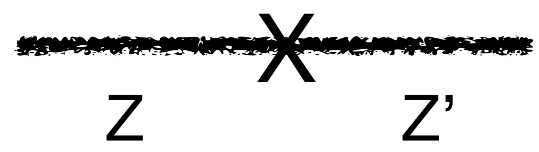
- For LHCb, use μjj final state; CMS μμν
- For other detector any final state allowed
- Look at the decay of only one heavy neutrino
- Apply some minimal cuts on the p_T and |η| of final state particles
- Assume all neutrino decays within the detector volume are detected
- Nice interplay of boost and lifetime
- Detector of maximal interest: MATHUSLA
- ATLAS/CMS trigger requirements too high

B-L portals

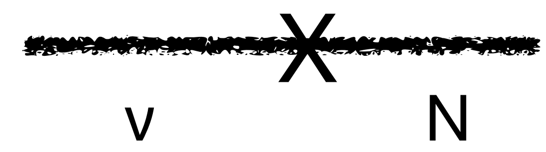
Deppisch, Kulkarni, Liu arXiv:1908.11741



Suppressed by sinα

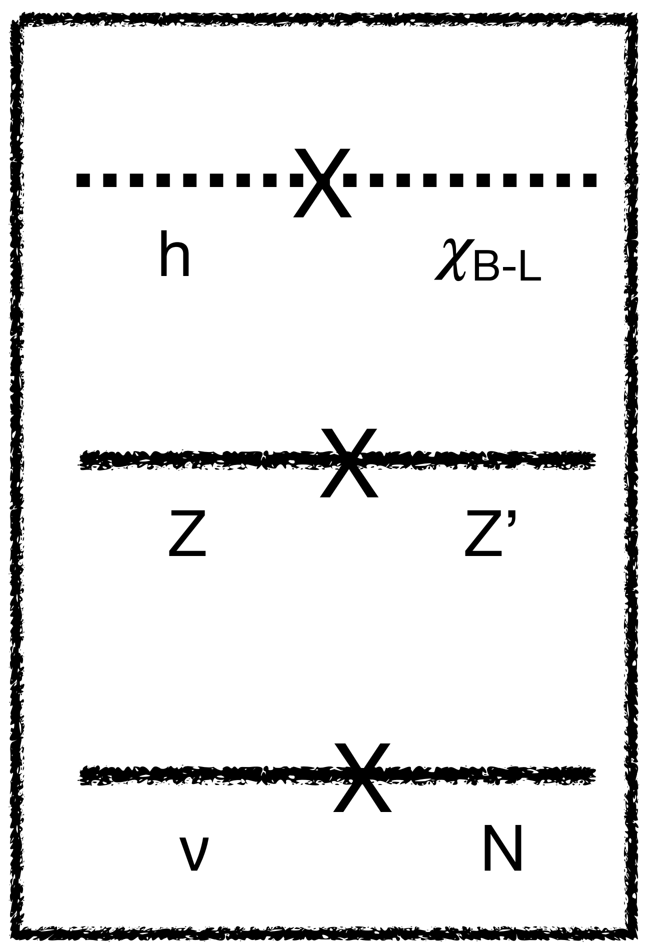


Suppressed by g'

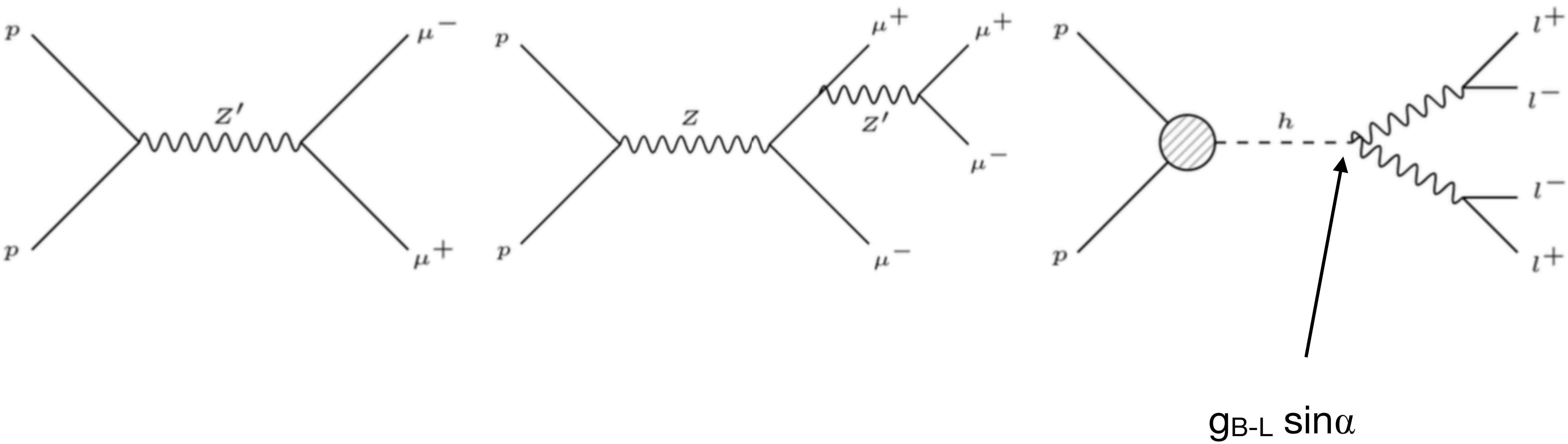


Suppressed by $V_{\ell N}$

sinα = 0.3, g' = 10^{-3}

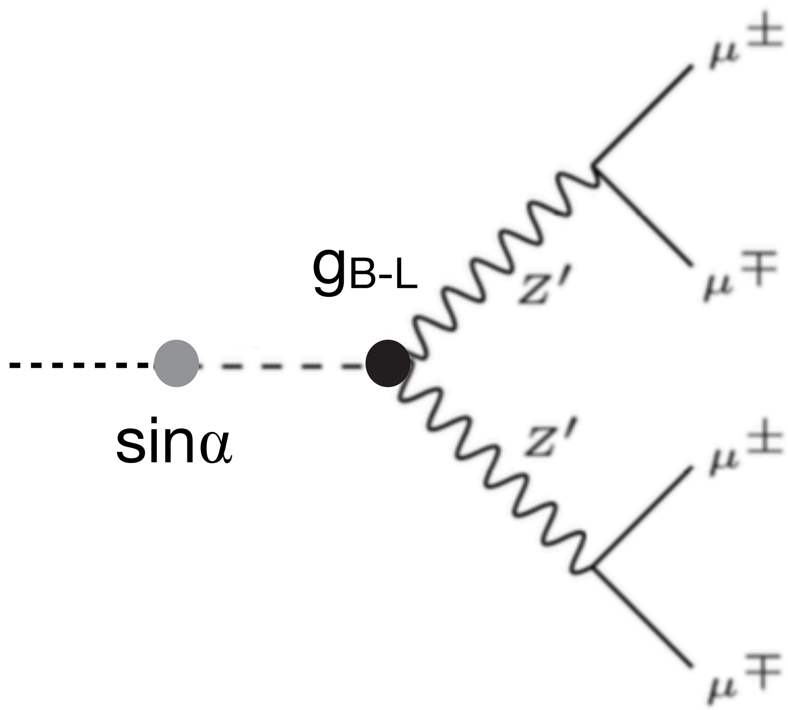


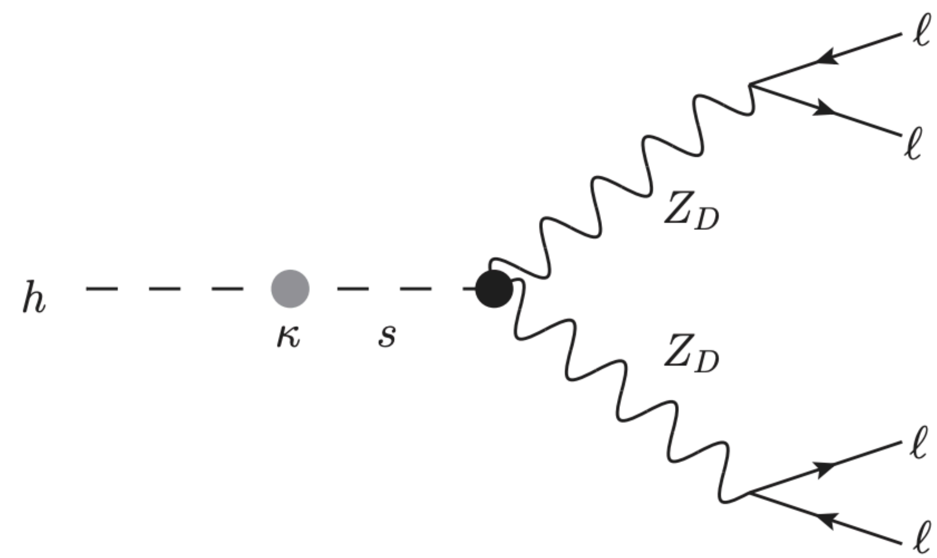
Higgs and Z' portal



- New channels to probe
- FSR process usually most attractive for L_μ -L_τ models, included here for completion
- Both CMS and ATLAS search for 4 muon final state, interpretations usually in NMSSM or dark photon scenarios
- Higgs and Z' mediated heavy neutrino production still a possibility

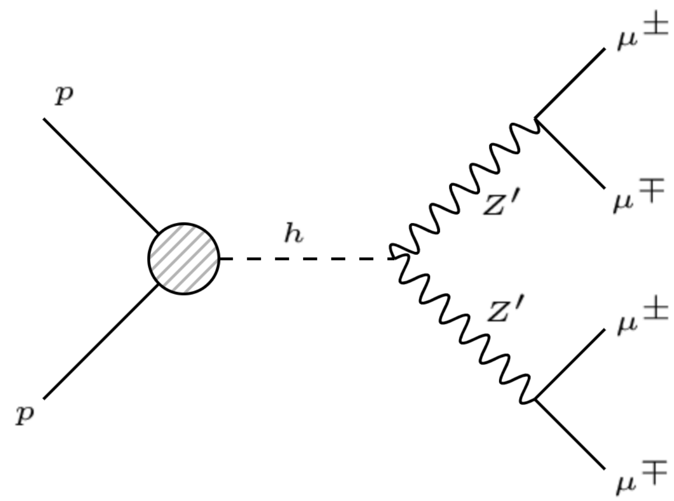
Differences with dark photon model

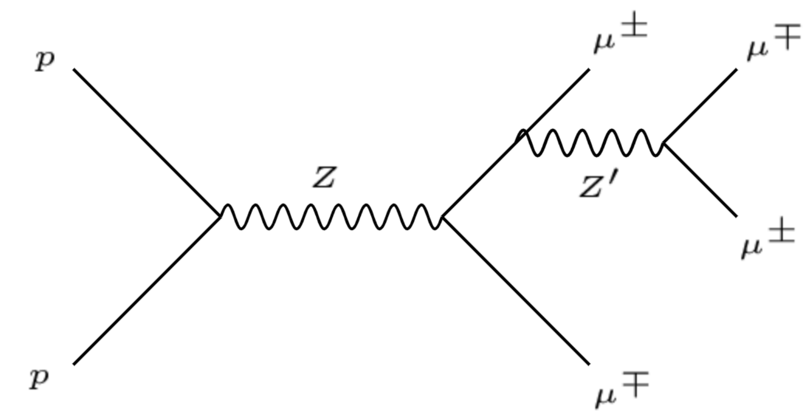


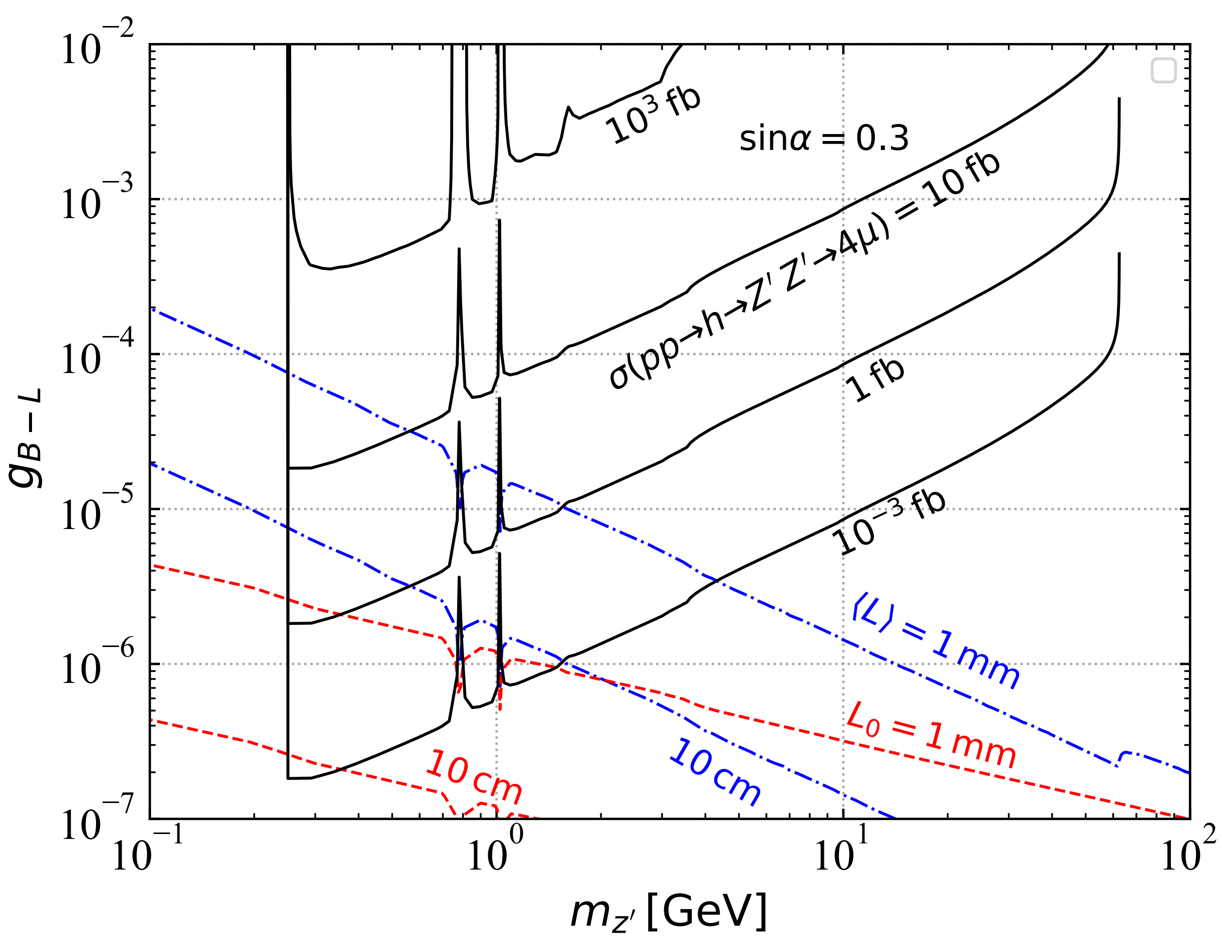


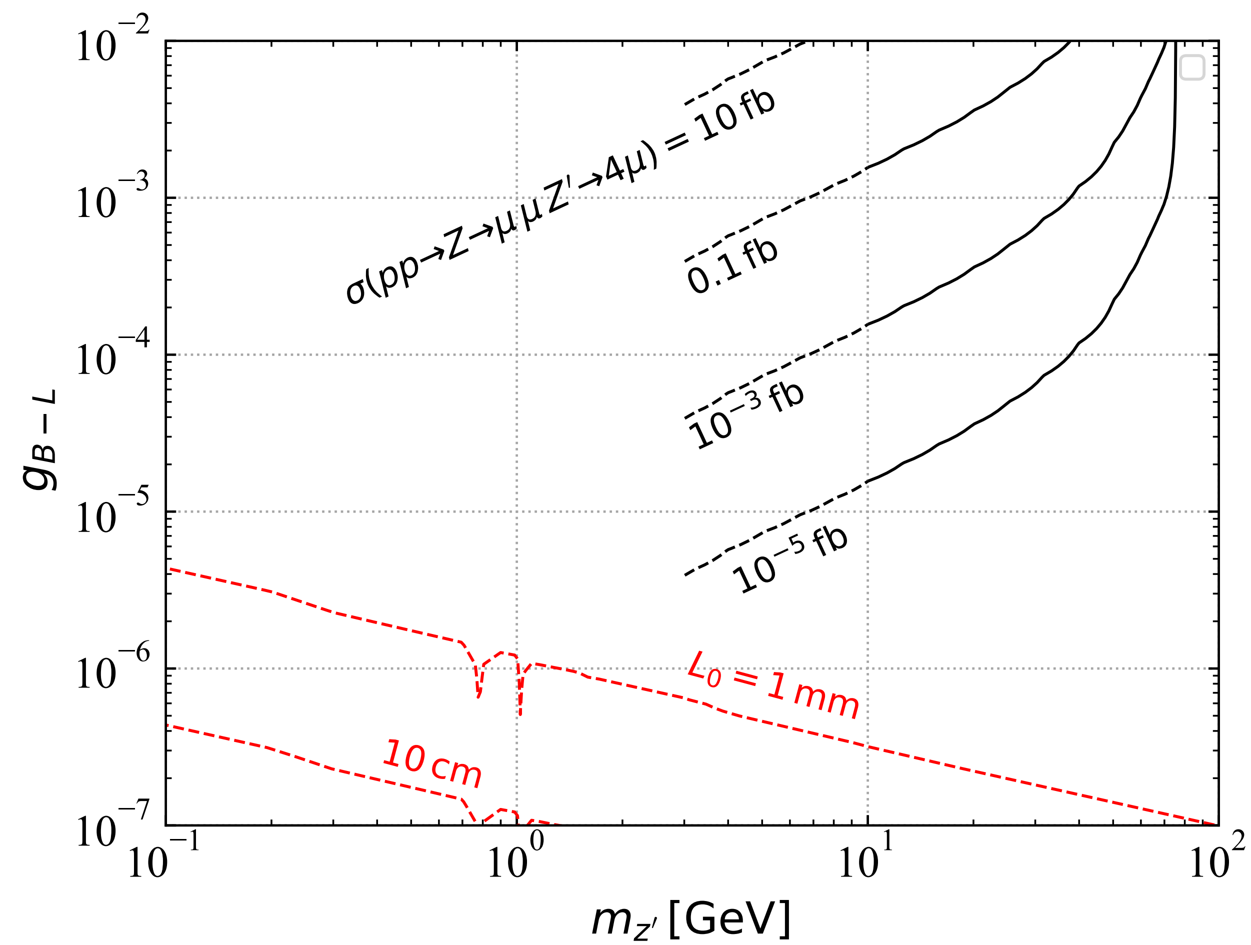
- In B-L model the term responsible for generating Z' mass is also responsible for mediating SM - B-L interactions
- Z' lifetime also controlled by $g_{B\text{-}L}$.
- This is not the case for dark photon models, mass generated by dark Higgs also mediated interactions
- Lifetime of Z_D controlled by mixing parameter ϵ

Z' Cross section and lifetimes



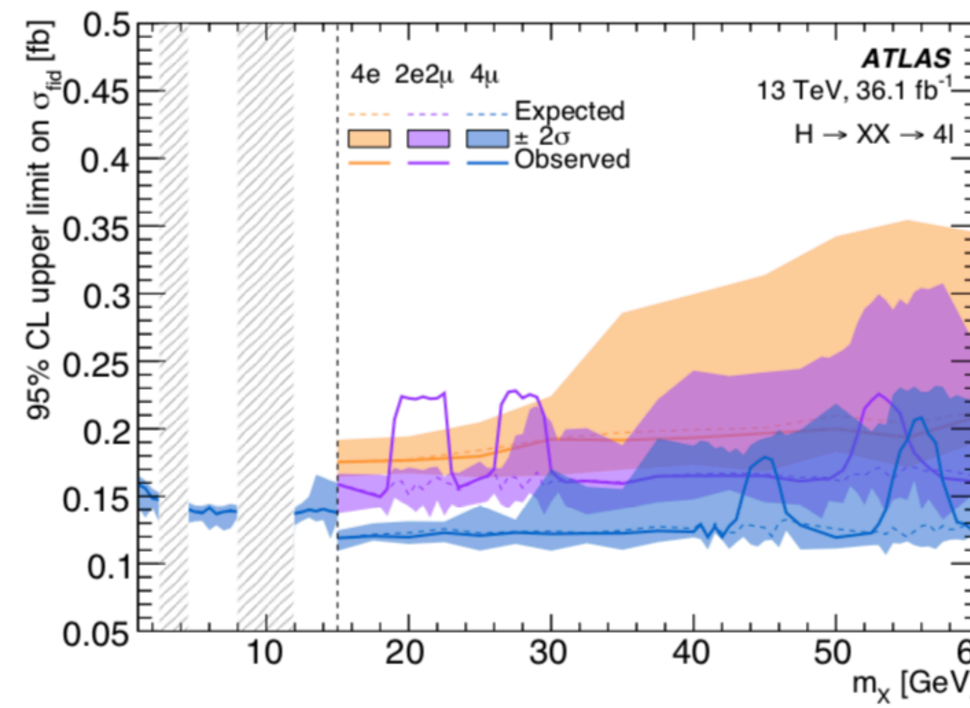




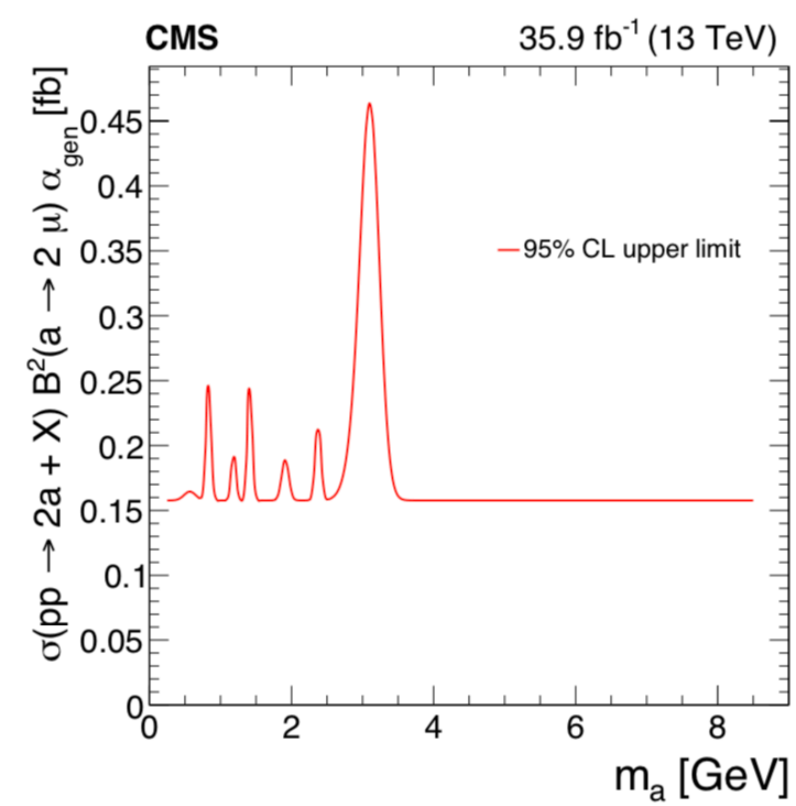


Analysis details

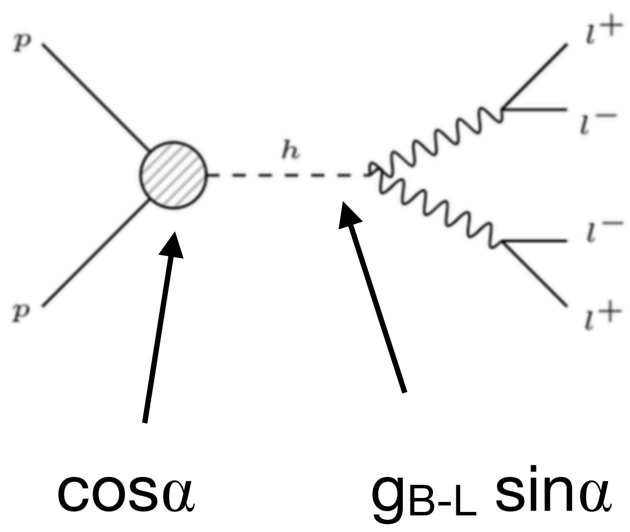
- **ATLAS-EXOT-2016-22 (13 TeV, 36.1 fb^{-1}):**
  - Analysis for Higgs decays to pair of dark photons
  - Searches for Z_D decays to pair of electrons or muons
  - Presents fiducial cross sections and limits on Higgs Z_D branching fraction
  - Z_D mass between 1 to 60 GeV

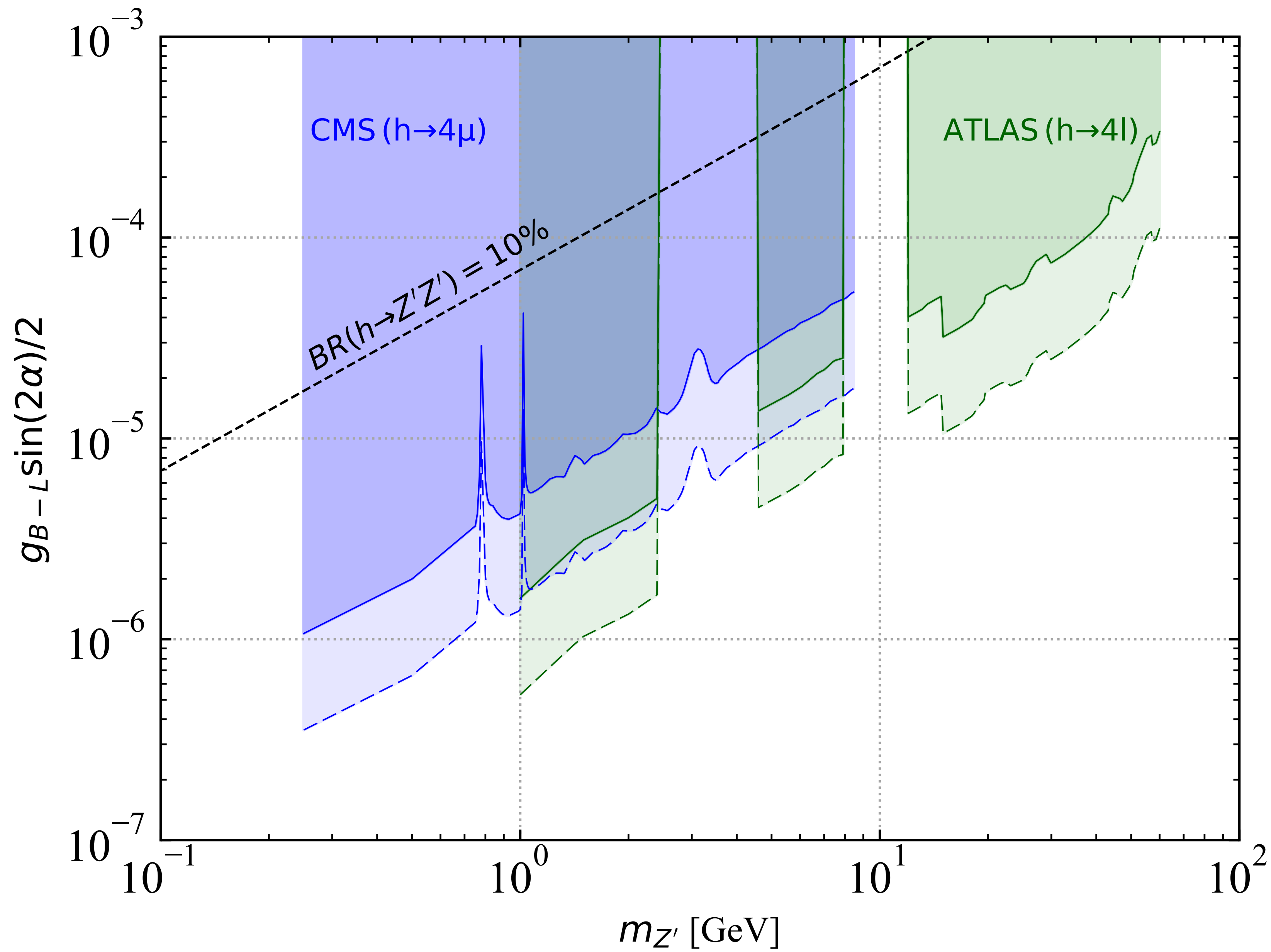


- **CMS-HIG-18-003 (13 TeV, 35.9 fb^{-1}):**
  - Searches for pair production of light bosons
  - Considers NMSSM models
  - Also sensitive to moderate displacements L_{xy} < 10 cm
  - Presents fiducial cross sections and model specific limits
  - Z_D mass between 0.25 to 8.5 GeV



‘Effective’ coupling constraints

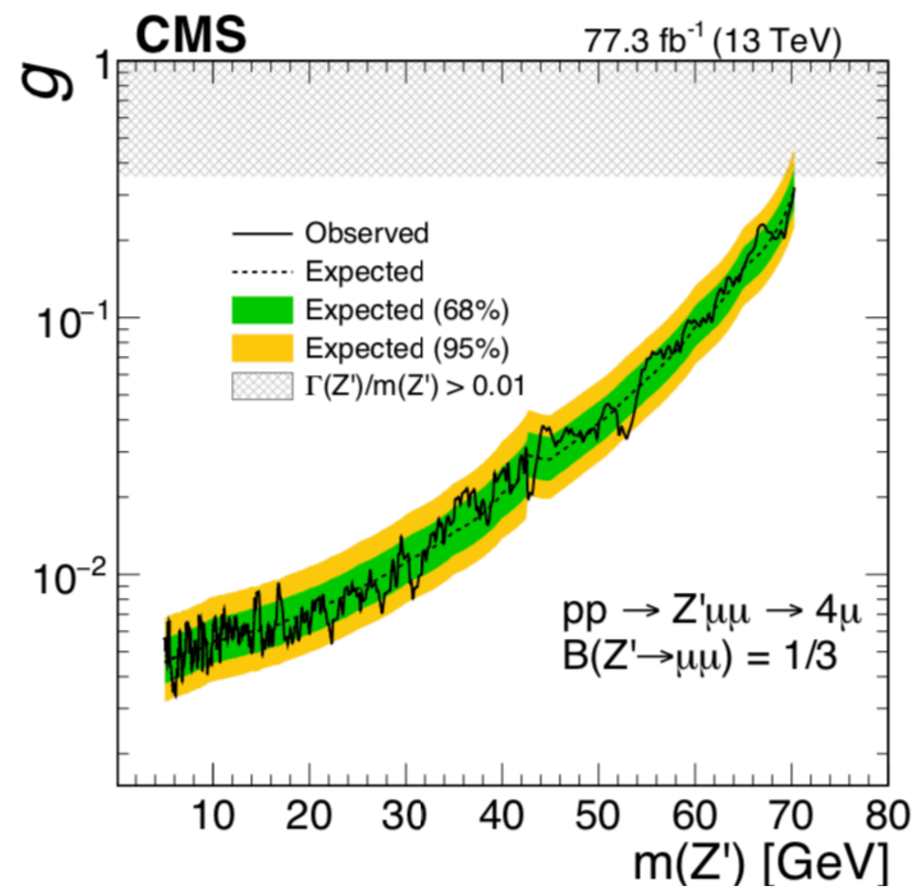


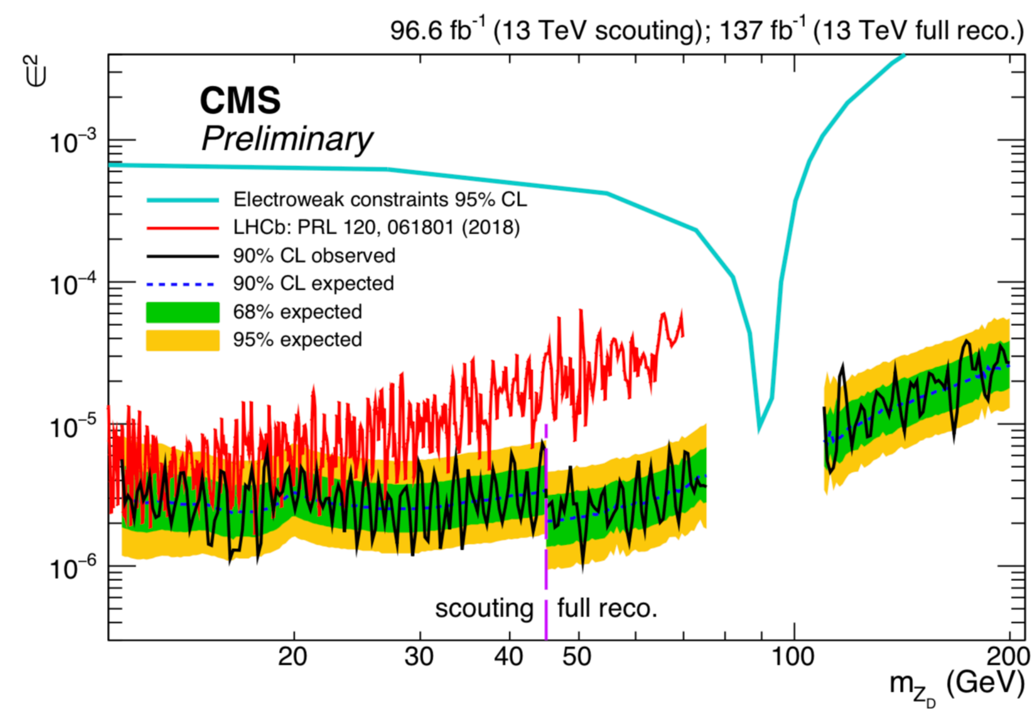


- For Higgs mediated Z’ production, constraints on the product of coupling
- Easy way to rescale limits given g_{B-L} or sinα value
- Important: rescaling to be taken with caution, different treatment for displaced regime

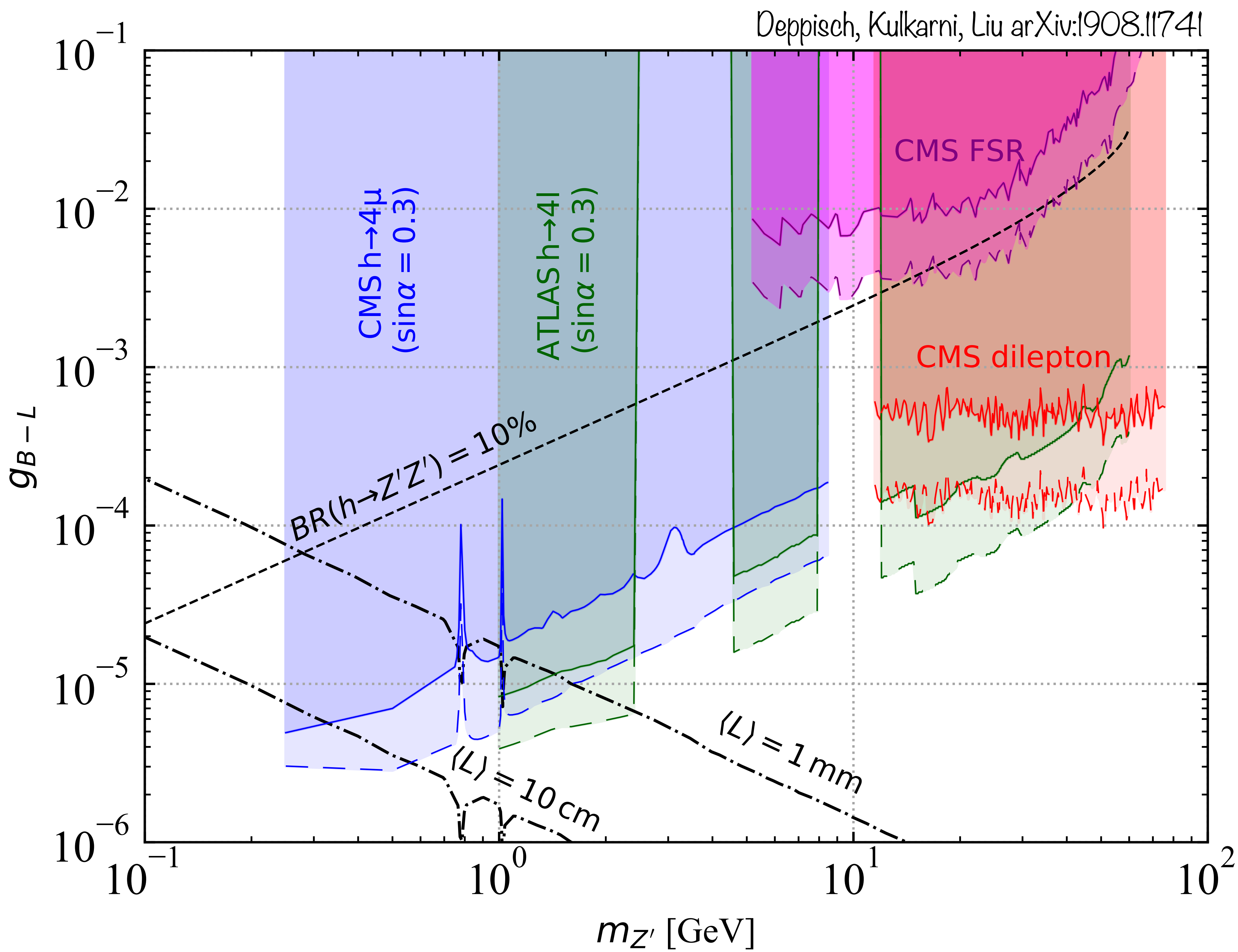
Analysis details

- **CMS-EXO-18-008 (13TeV, 77.3 fb^{-1}):**
  - Final state radiation of Z’ in DY Z production
  - Muon final state only
  - Particularly useful for L_μ - L_τ
  - Limits on the L_μ - L_τ z’ coupling as a function of mass, easy to rescale
  - Mass range between 6 to 70 GeV
- **CMS-EXO-19-018 (13TeV, 137 fb^{-1}):**
  - Latest and greatest CMS muon scouting analysis
  - Search for narrow resonance decaying to pair of muons
  - Scouting and full reach analysis
  - Mass range 10 to 200 GeV

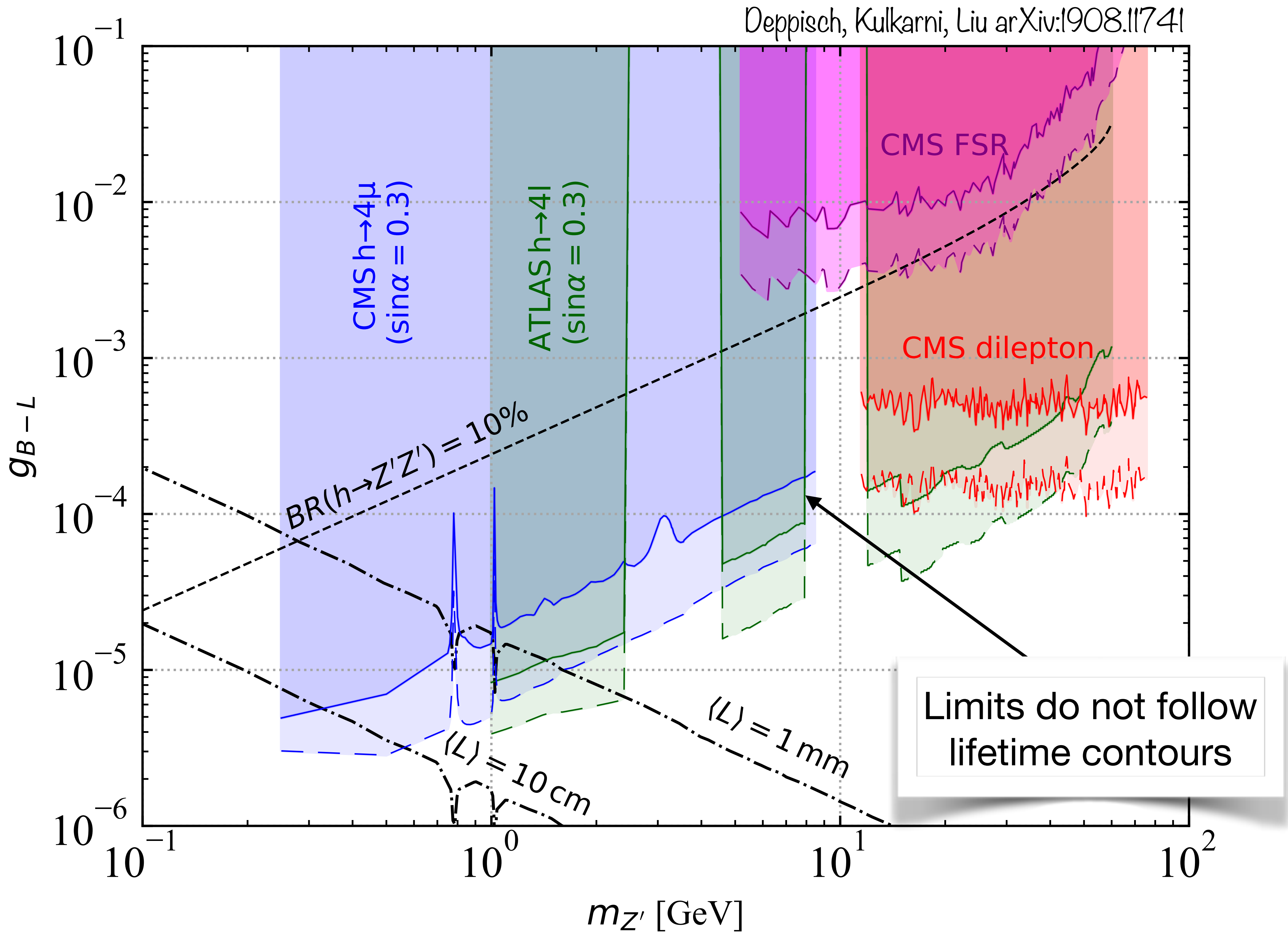




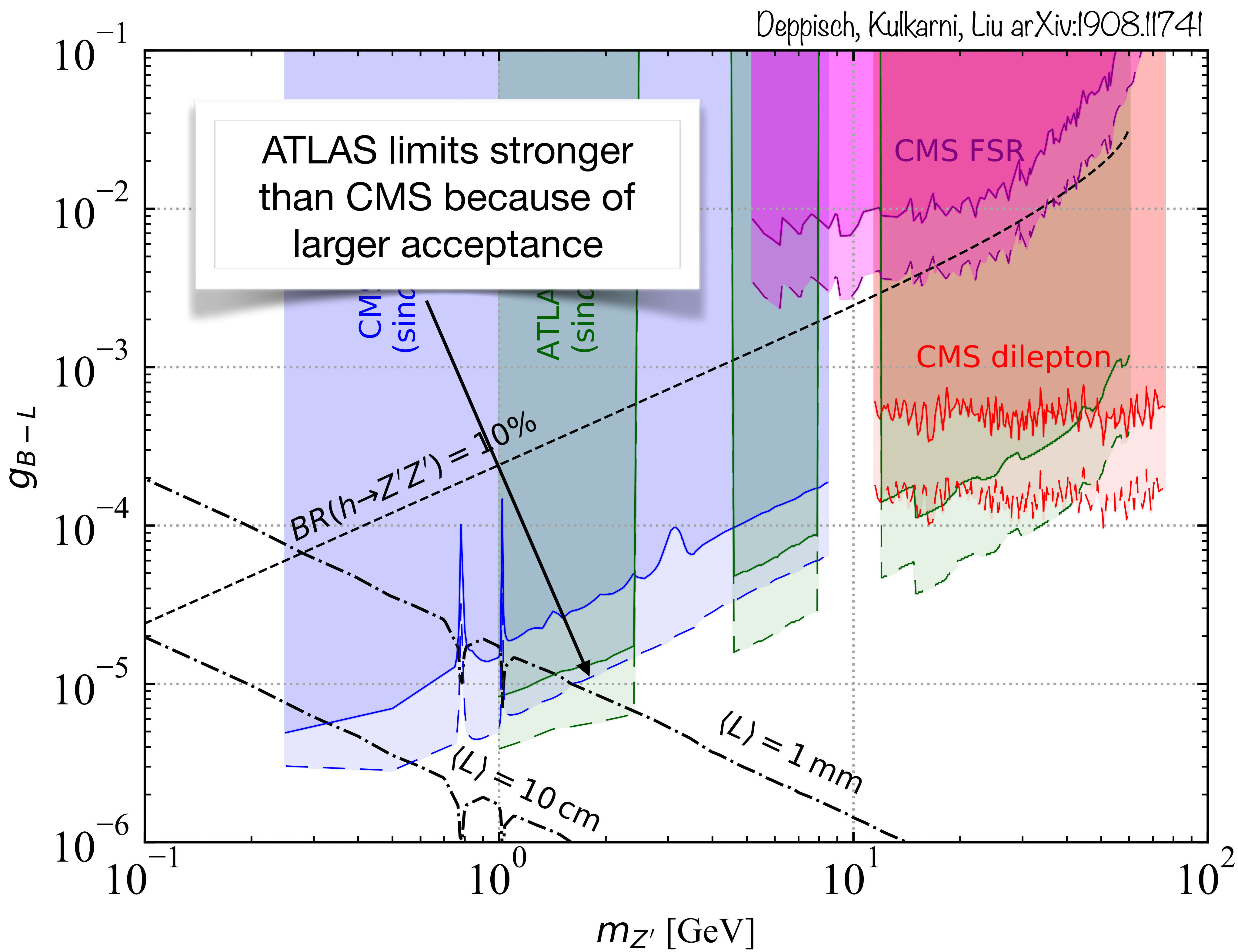
Results


Deppisch, Kulkarni, Liu arXiv:1908.11741
CMS h→4μ (sinα = 0.3)
ATLAS h→4l (sinα = 0.3)
CMS FSR
CMS dilepton
BR(h→Z'Z') = 10%
⟨L⟩ = 1 mm
⟨L⟩ = 10 cm
g_{B-L}
$m_{Z'}$ [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{0}
10^{1}
10^{2}

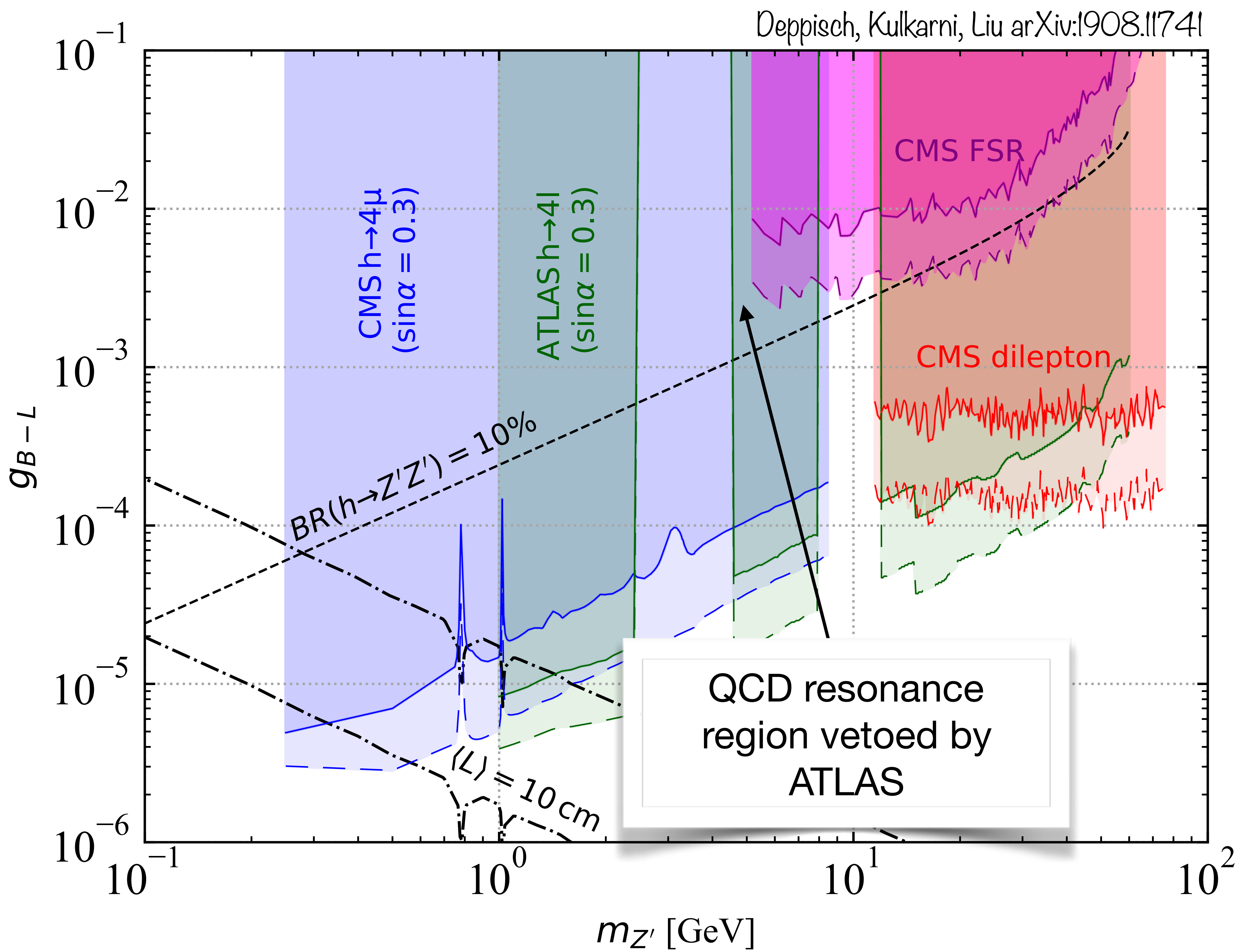
Results


Deppisch, Kulkarni, Liu arXiv:1908.11741
CMS h→4μ (sinα = 0.3)
ATLAS h→4l (sinα = 0.3)
CMS FSR
CMS dilepton
BR(h→Z′Z′) = 10%
⟨L⟩ = 1 mm
⟨L⟩ = 10 cm
g_{B-L}
$m_{Z'}$ [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{0}
10^{1}
10^{2}
Limits do not follow lifetime contours

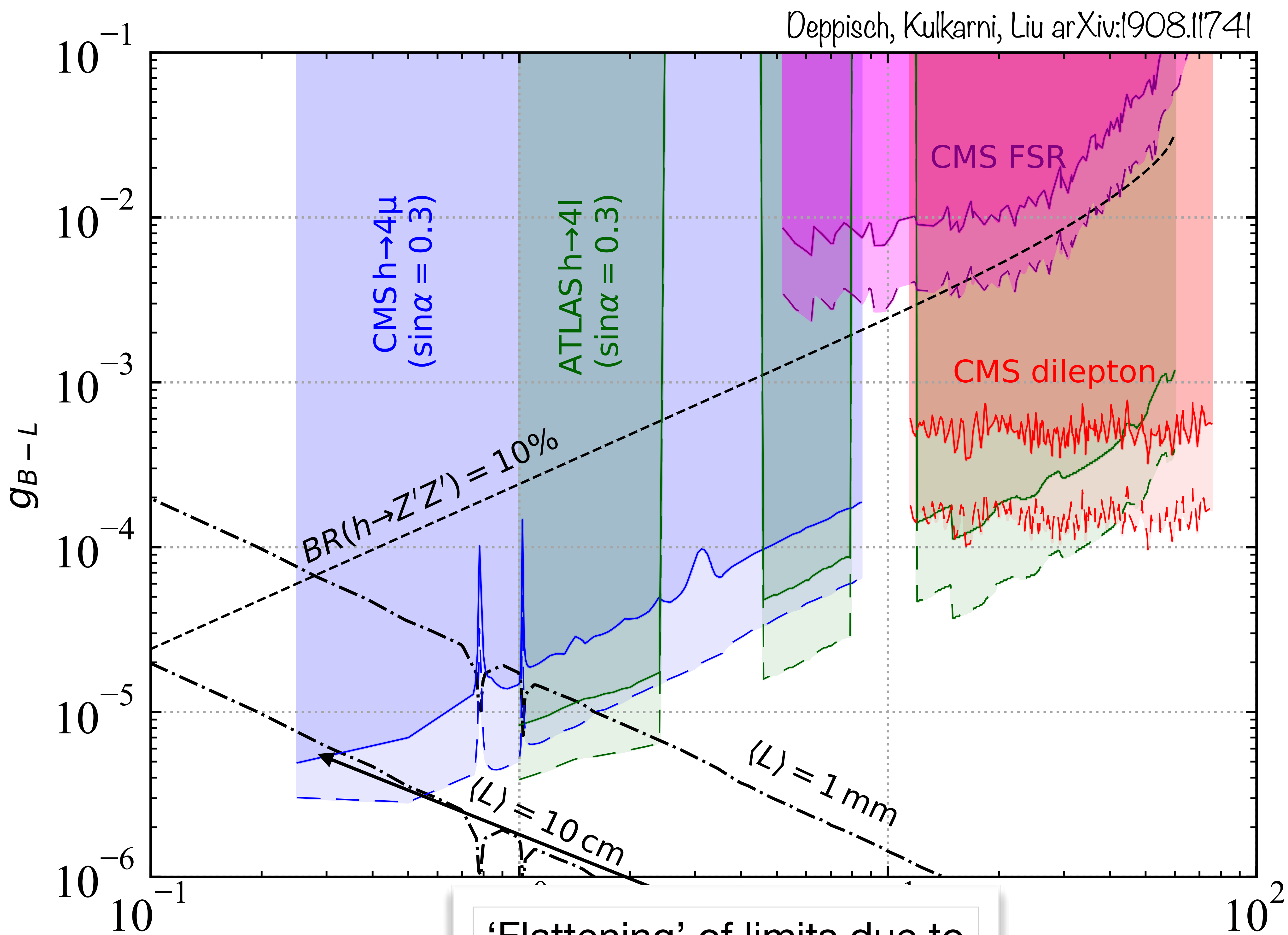
Results


Deppisch, Kulkarni, Liu arXiv:1908.11741
ATLAS limits stronger than CMS because of larger acceptance
CMS FSR
CMS dilepton
BR(h→Z'Z') = 10%
⟨L⟩ = 1 mm
⟨L⟩ = 10 cm
g_{B-L}
$m_{Z'}$ [GeV]

Results

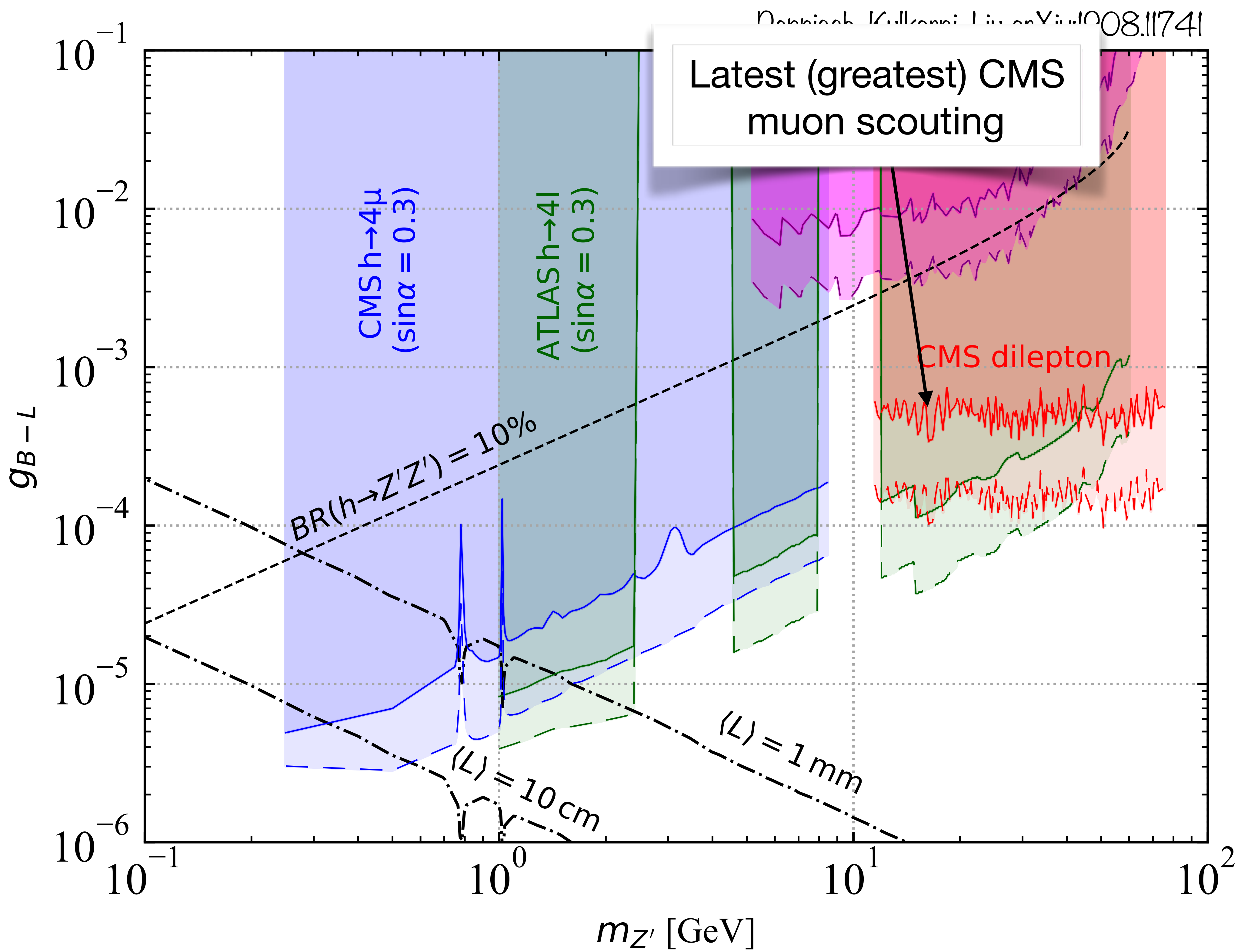

Deppisch, Kulkarni, Liu arXiv:1908.11741
CMS h→4μ (sinα = 0.3)
ATLAS h→4l (sinα = 0.3)
CMS FSR
CMS dilepton
BR(h→Z'Z') = 10%
⟨L⟩ = 10 cm
QCD resonance region vetoed by ATLAS
g_{B-L}
$m_{Z'}$ [GeV]

Results

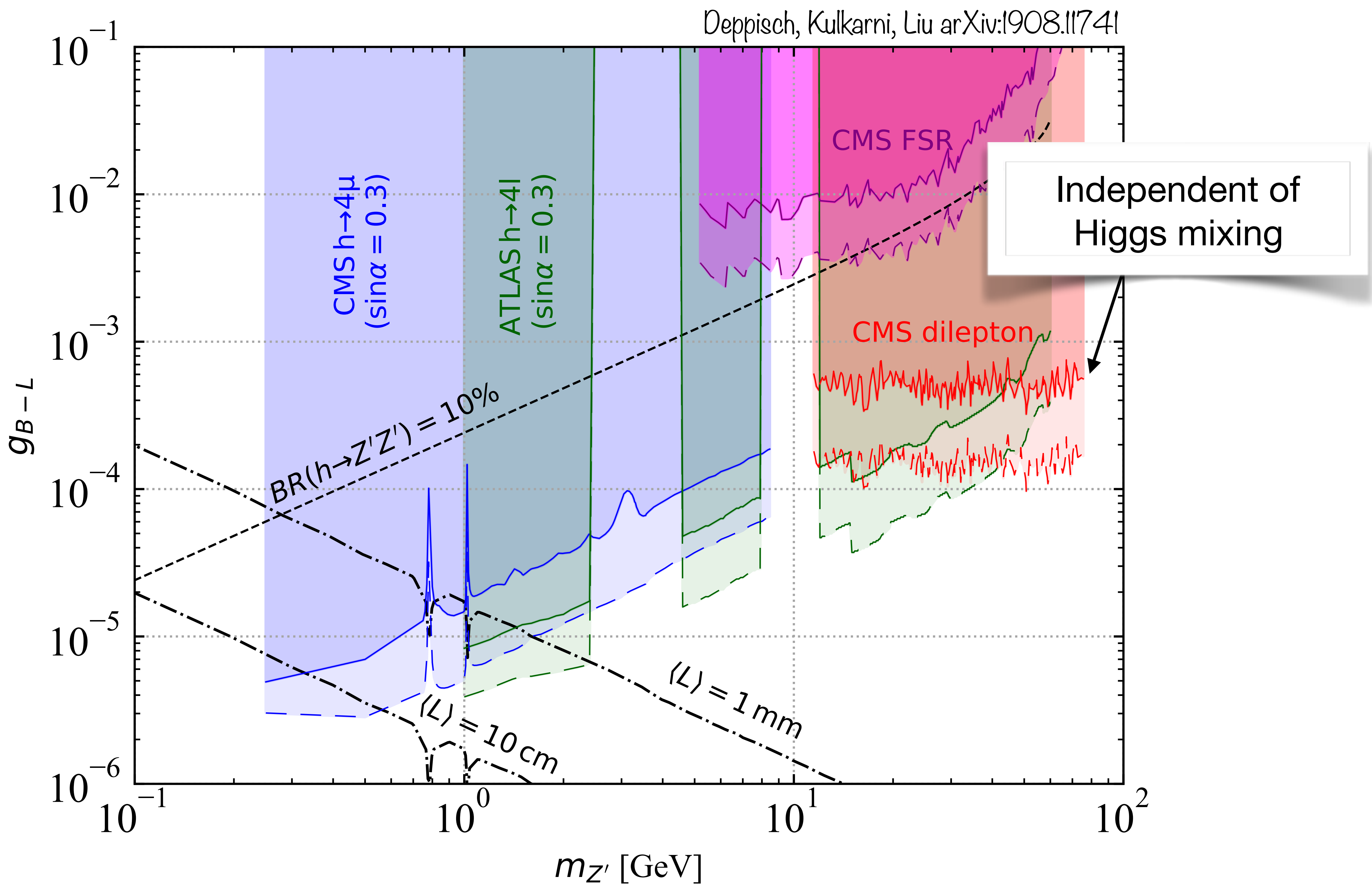


'Flattening' of limits due to displaced regime

Results

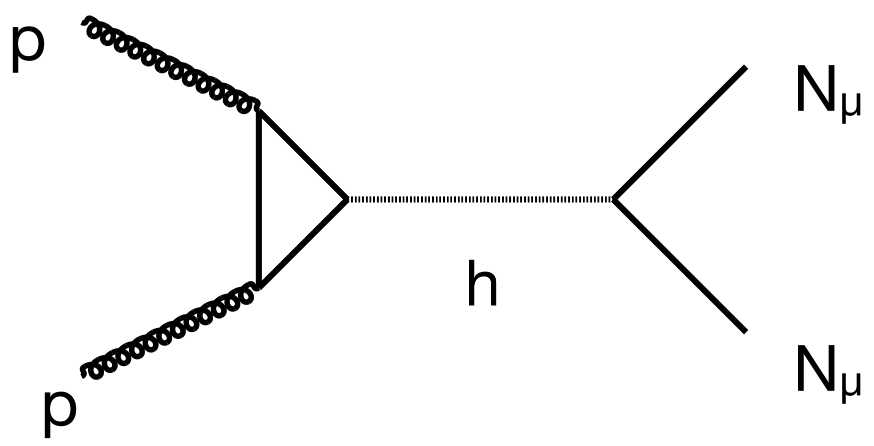

Latest (greatest) CMS muon scouting
CMS h→4μ (sinα = 0.3)
ATLAS h→4l (sinα = 0.3)
CMS dilepton
BR(h→Z'Z') = 10%
⟨L⟩ = 1 mm
⟨L⟩ = 10 cm
g_{B-L}
$m_{Z'}$ [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-1}
10^{0}
10^{1}
10^{2}

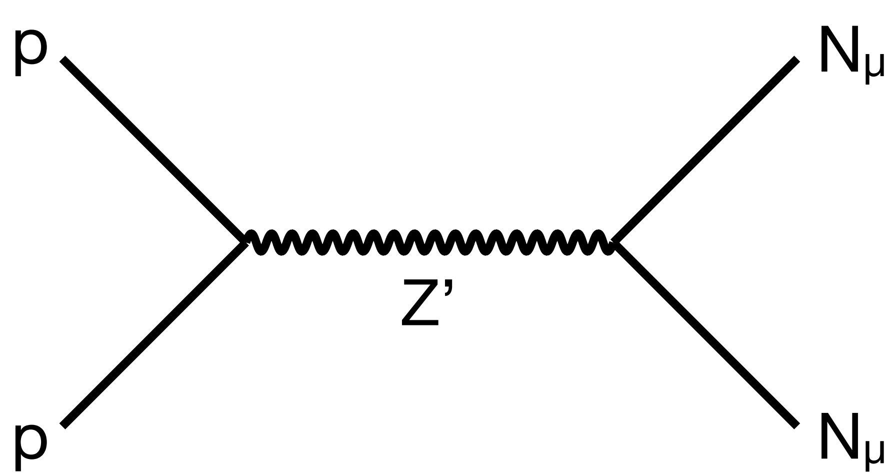
Results

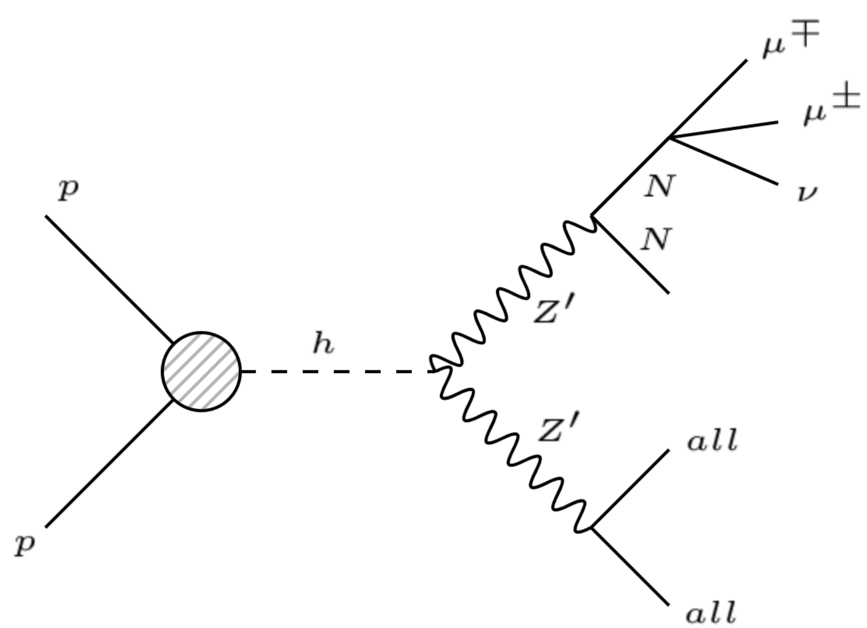


Deppisch, Kulkarni, Liu arXiv:1908.11741
CMS FSR
CMS h→4μ (sinα = 0.3)
ATLAS h→4l (sinα = 0.3)
CMS dilepton
Independent of Higgs mixing
BR(h→Z′Z′) = 10%
⟨L⟩ = 1 mm
⟨L⟩ = 10 cm
g_{B-L}
$m_{Z'}$ [GeV]

HNL production



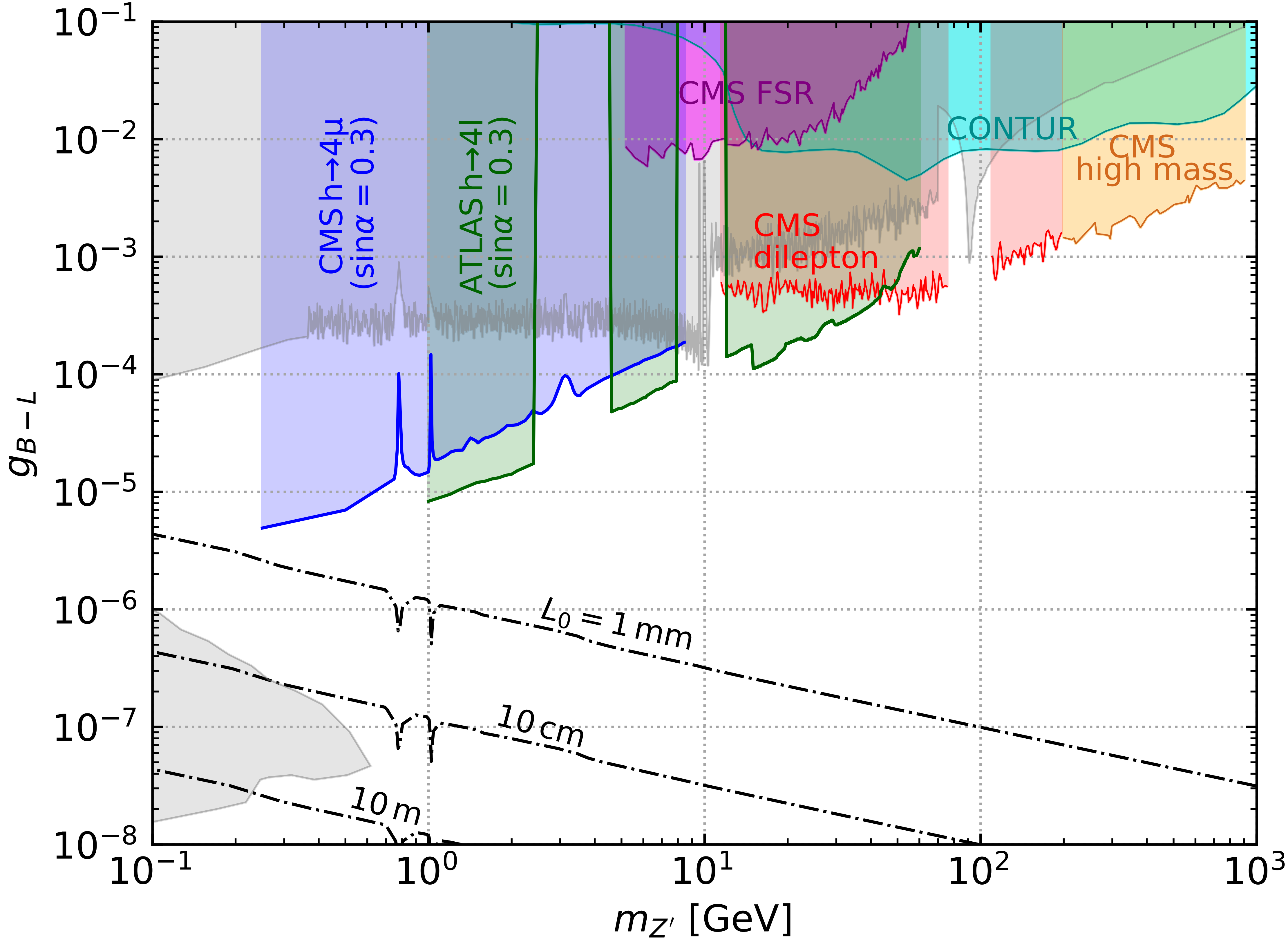




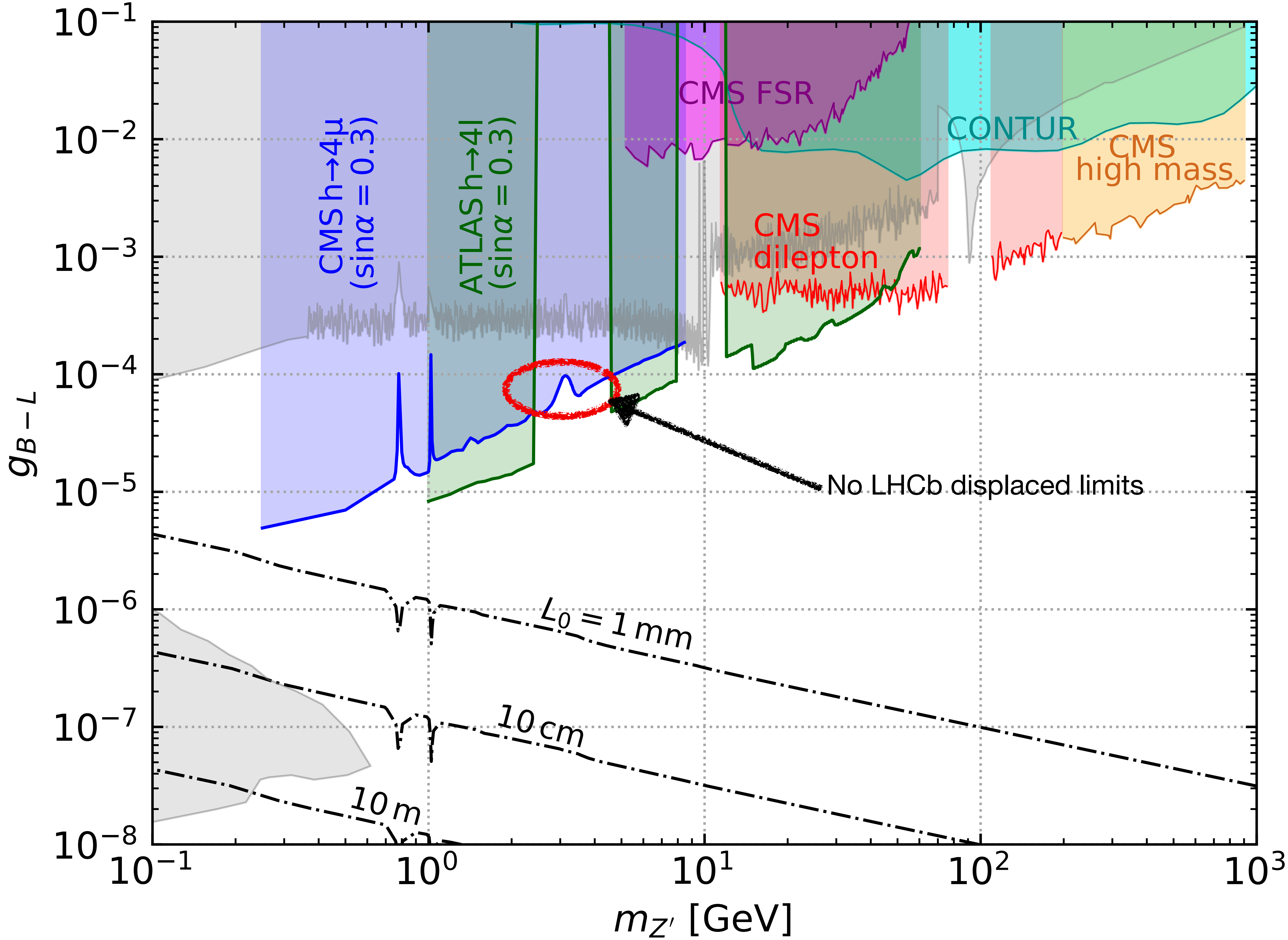
Vertex	Feynman rule
Z' - l - l	g_{B-L}
h - Z' - Z'	$g_{B-L} \cos\alpha \, m_{Z'}$
h - N - N	$g_{B-L} \cos\alpha \, m_N/m_{Z'}$
Z' - N - N	g_{B-L}

- All vertices **α** g_{B-L}
- Improved constraints on g_{B-L} → decreased heavy neutrino production rate via h and Z' mediators
- h and Z' mediators remain interesting option in limiting cases

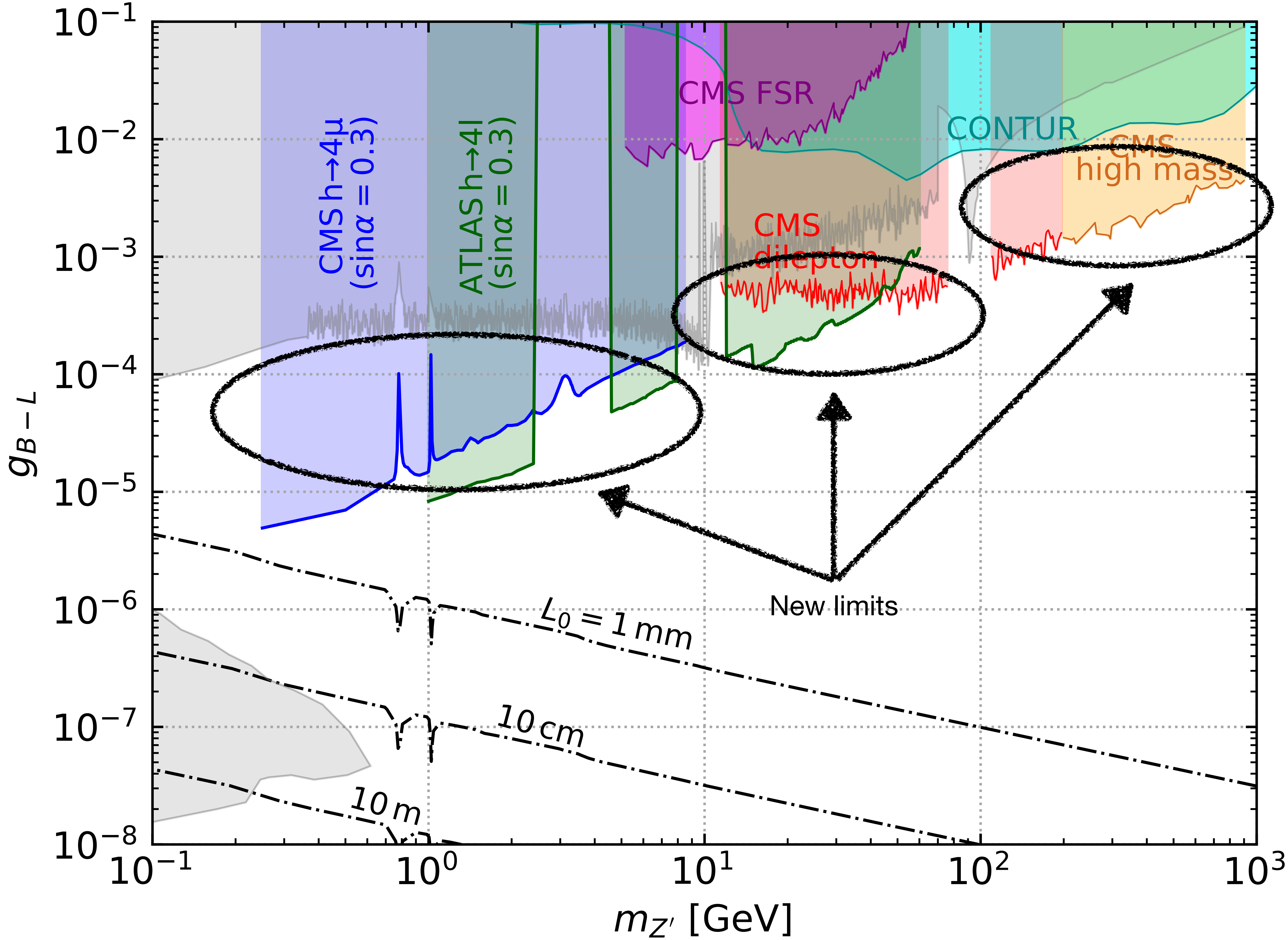
The global picture



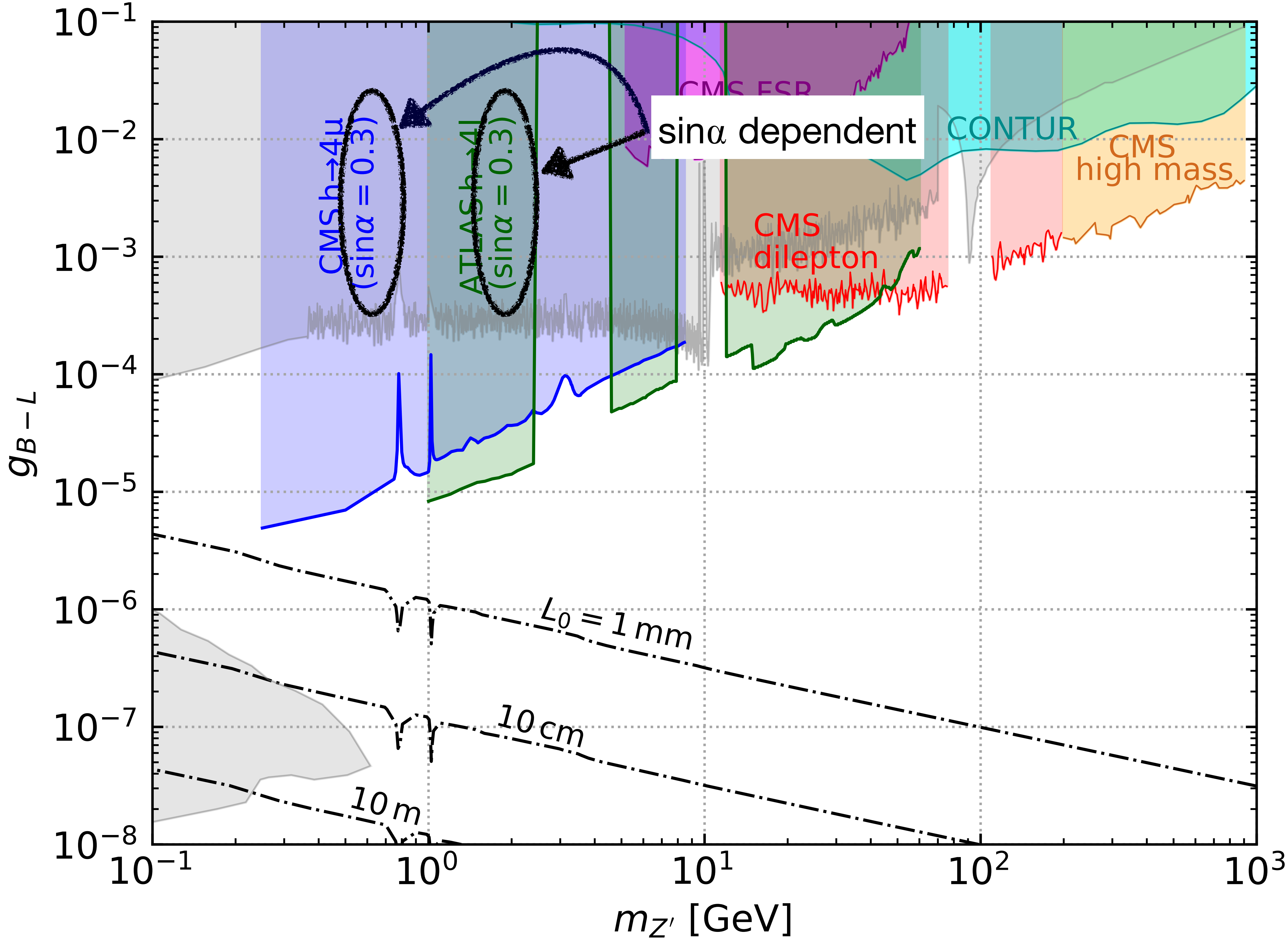
The global picture



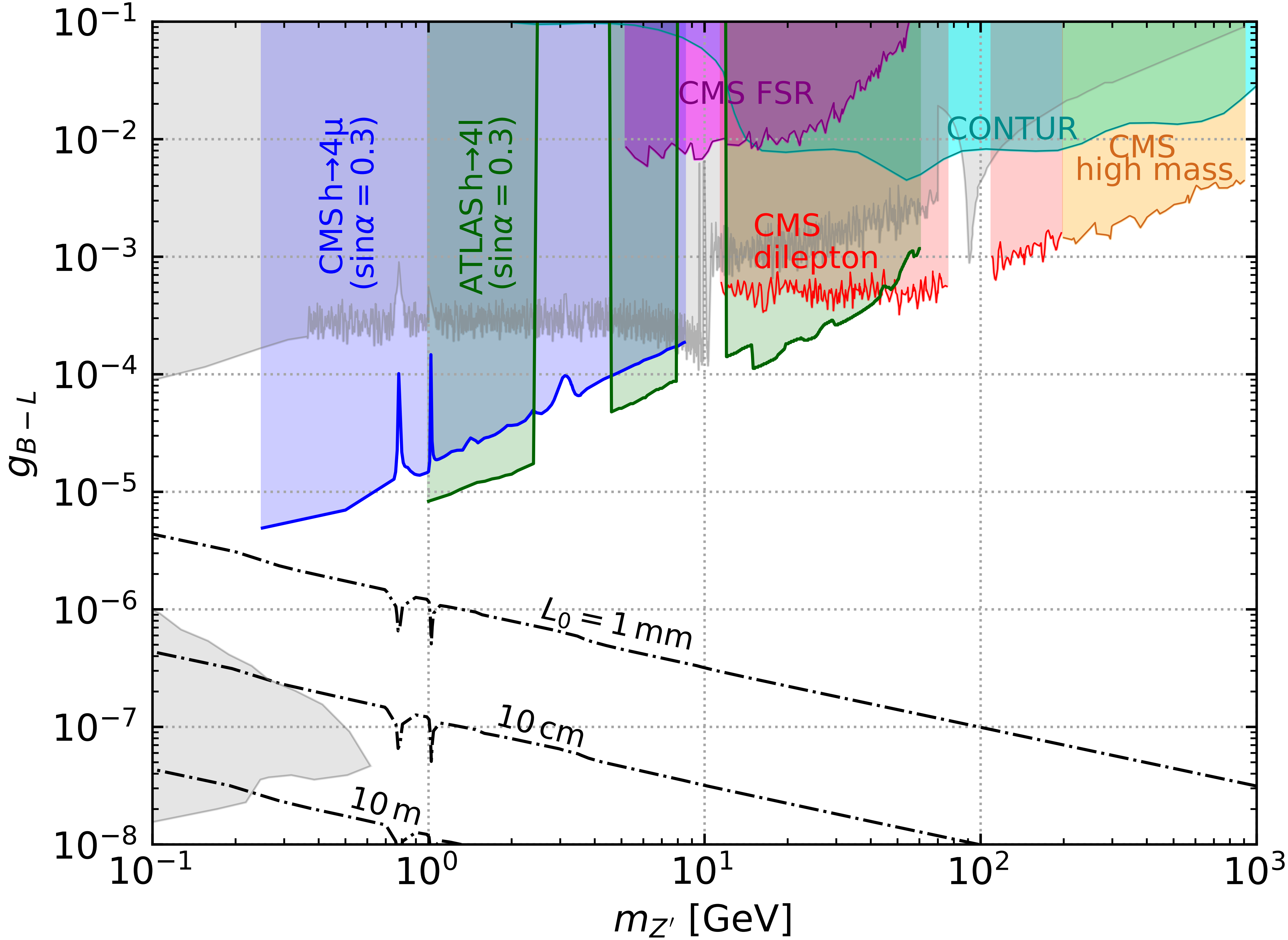
The global picture



The global picture



The global picture



Conclusions

- B-L models one of the simplest extensions of SM physics providing explanations of neutrino masses
- Heavy neutrino production can take place via SM Higgs or B-L Z' decays and probe different regions of B-L parameter space
- Have potential to probe neutrino mixing angles responsible for neutrino mass generations
- Z' production via SM Higgs tightly constrained via 'lepton-jet' searches. If Z' production via Higgs is possible, heavy neutrino production is suppressed
  - ATLAS analyses consider both electron and muon lepton-jets
  - Prompt analyses constrain parameter space where Z' is displaced
  - Interpretation for displaced regime not always straightforward
  - Model independent fiducial cross section limits from collaborations are very welcome for reinterpretation exercises
  - Careful reconsideration of information for exotic searches specially trigger and object level efficiencies necessary

Thank you!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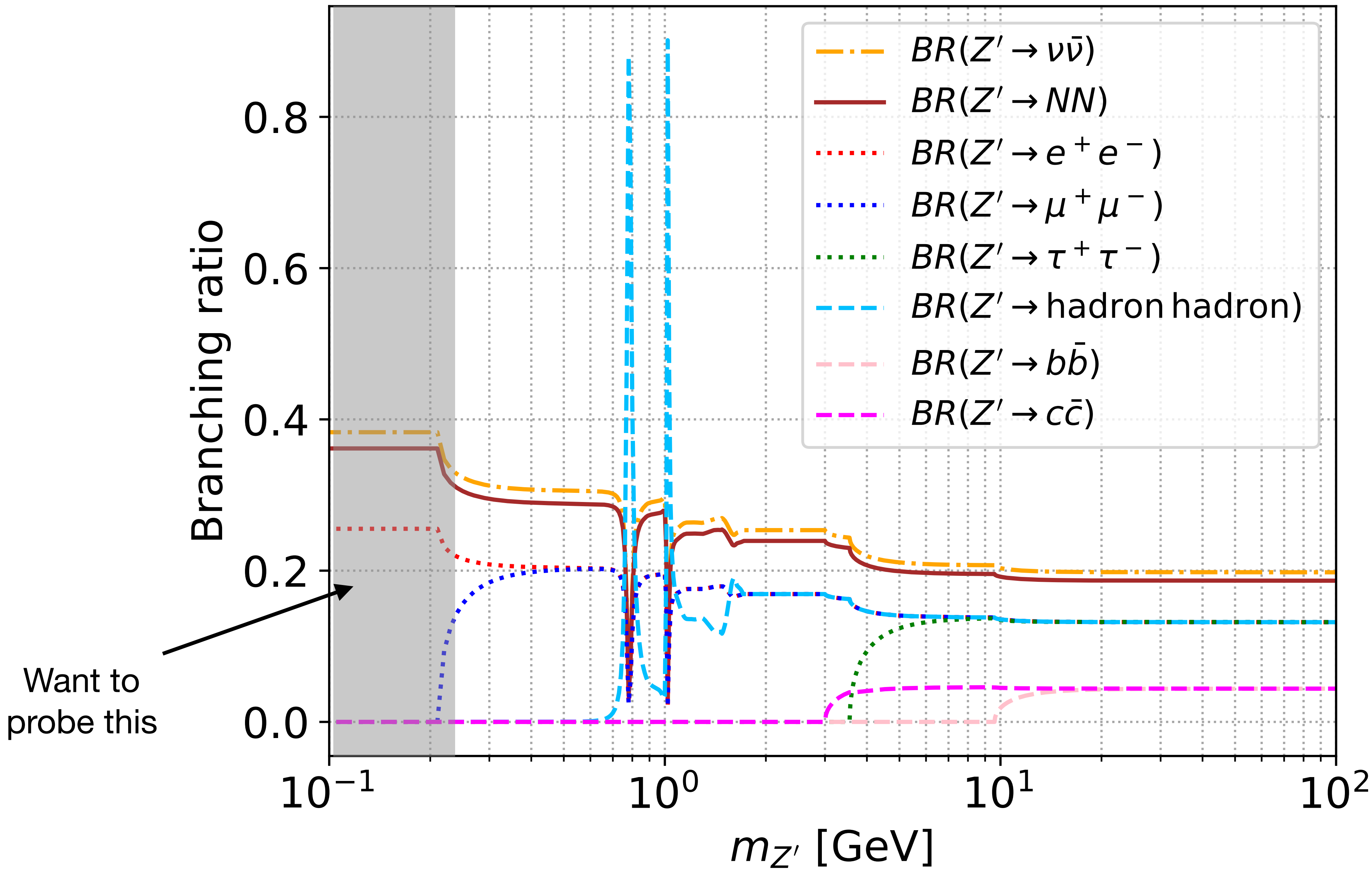
CoghillCartooning.com

Going for extremely light masses

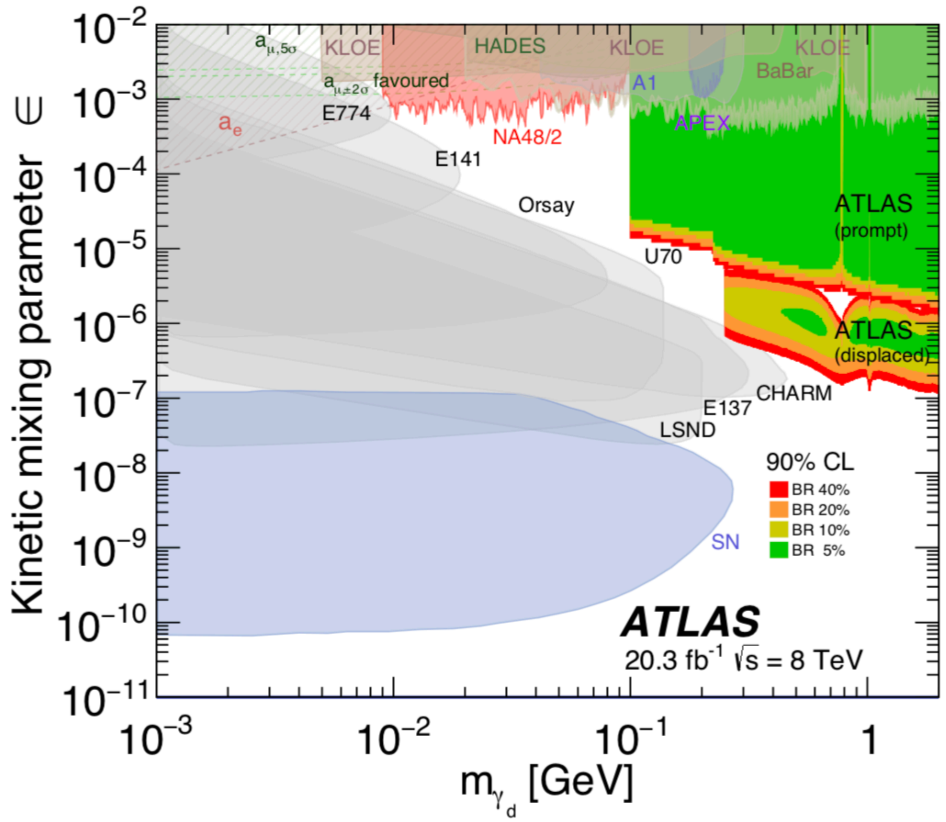


- Possibility of extending Higgs portal analyses for electron final states?
- Mono-jet constraints?

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

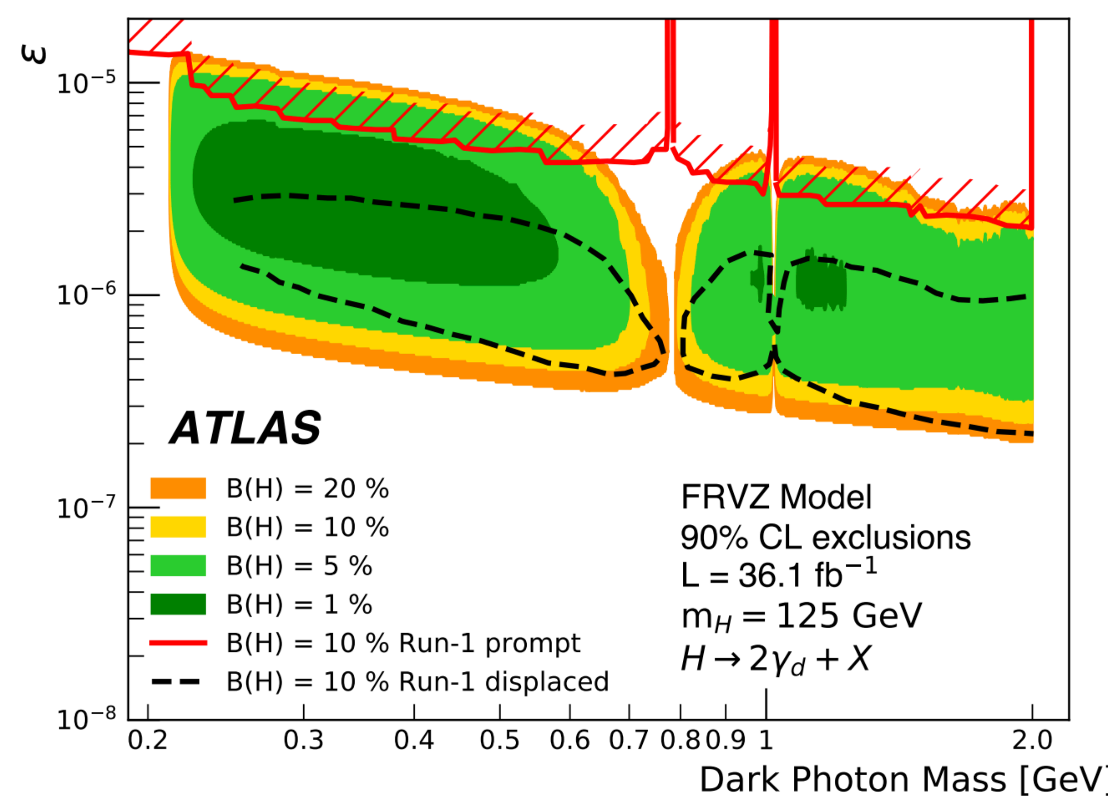
ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

Additional ATLAS analyses



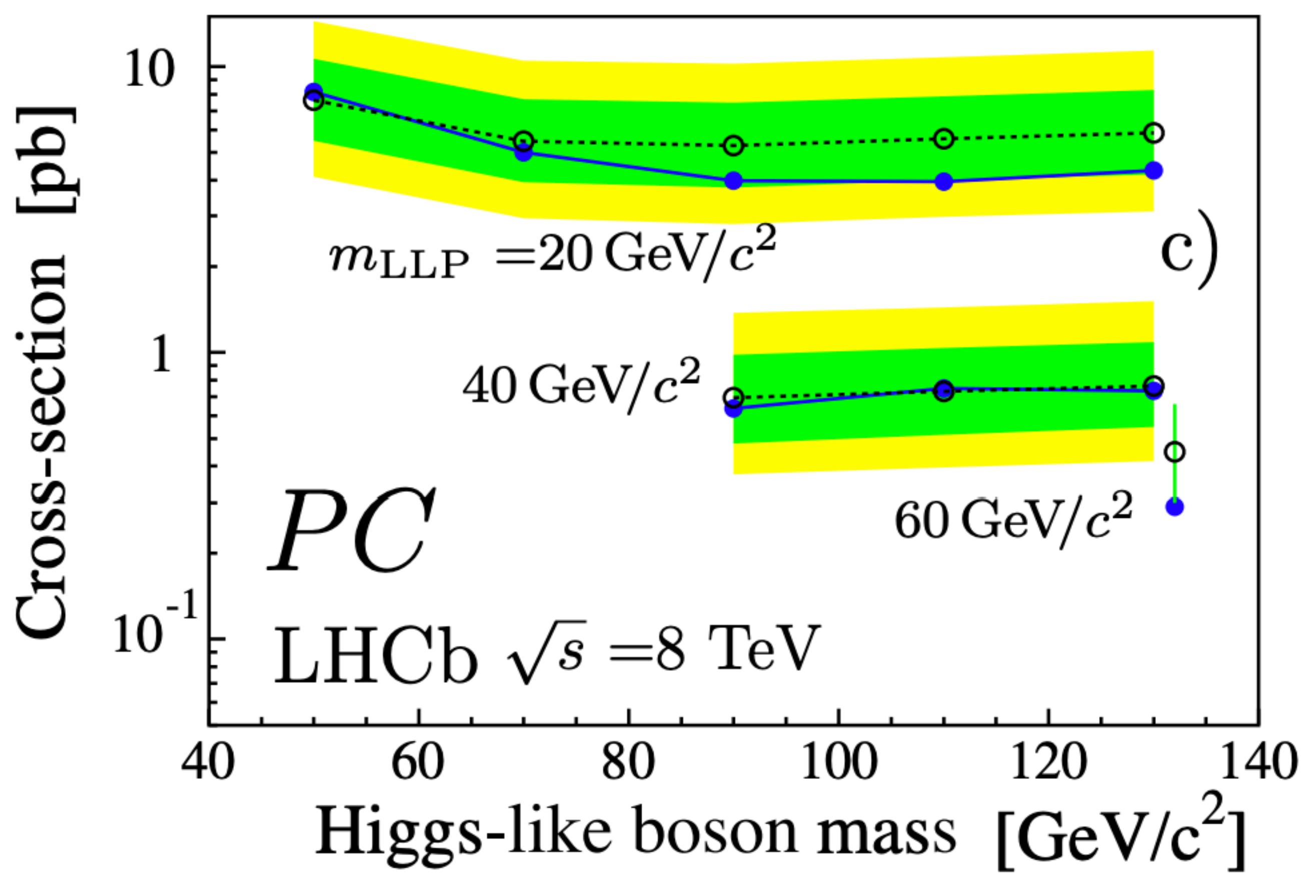
- **ATLAS-EXOT-2014-09 (8 TeV, 20.3 fb^{-1})**
  - Prompt lepton - jets analysis
  - Limits as a function of FRVZ Z_D mass
  - Both electron and muon final states
  - Mass range from 0.25 to 1.5 GeV
  - Competitive (but not better) limits than CMS at low mass

- **ATLAS-EXOT-2017-28 (13 TeV, 36 fb^{-1})**
  - Displaced lepton - jets analysis
  - Electron and muon LJ
- Prompt analysis as sensitive as CMS analysis
- Displaced analysis 8 TeV not sensitive; 13 TeV potentially sensitive
  - 13 TeV analysis hard to reinterpret



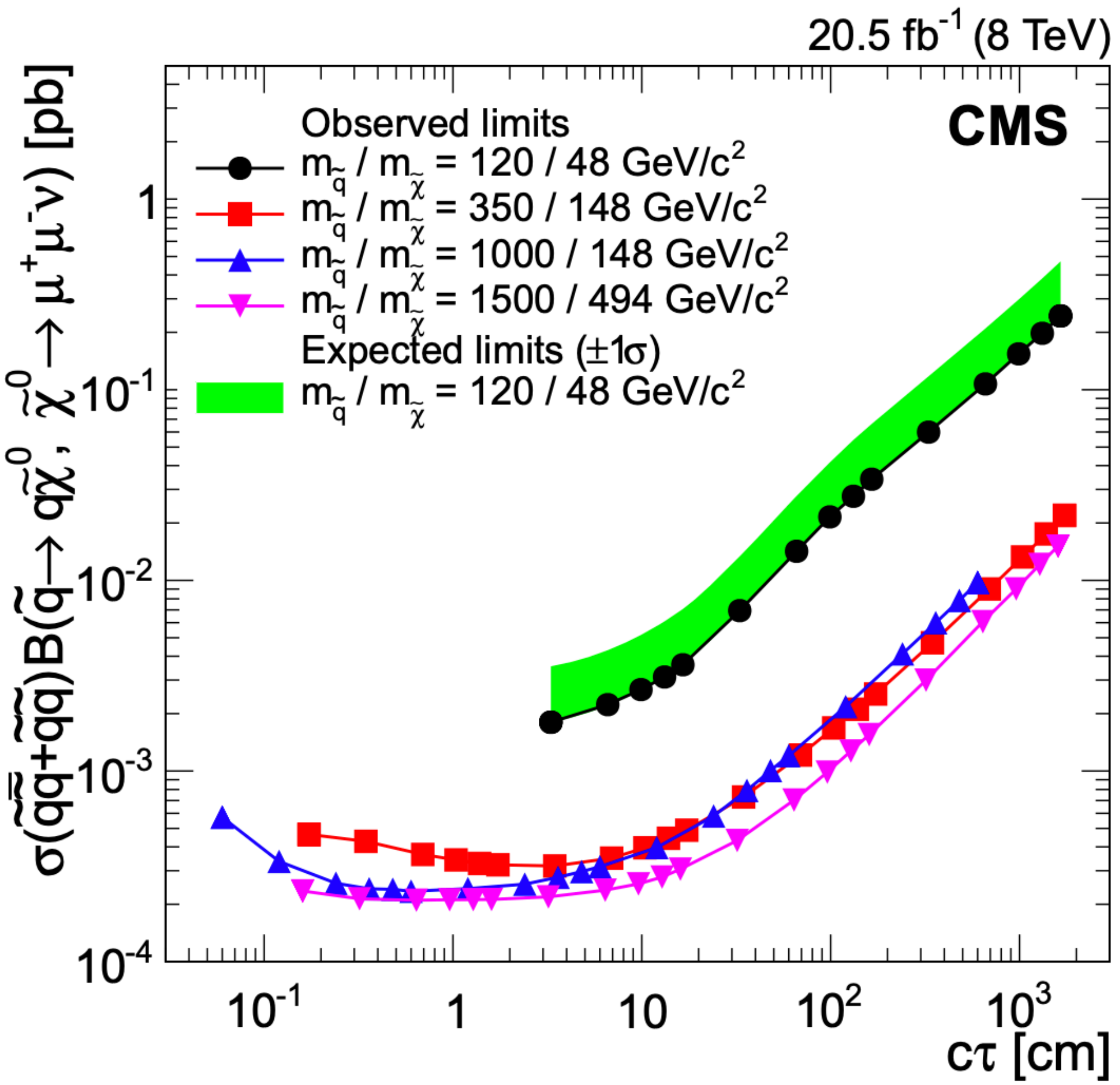
LHCb DV search

- LHCb-PAPER-2016-047: (7+8 TeV, 3 fb^{-1})
  - 'Inclusive displaced vertex search'
  - Trigger muons pT > 10 GeV
  - Final state muon and two jets
  - $p_T(\mu)$ > 12 GeV, d_{IP} > 0.25 mm, Rxy > 0.55 mm
  - Invariant mass of tracks > 4.5 GeV
  - Interpretation in terms of GUT scale SUSY RPV models



CMS DV search

- CMS-EXO-12-037: (8 TeV, 20 fb^{-1})
  - Inclusive displaced vertex search for pair of electron or muon final states
  - Electron E_T > 36 (22) GeV; Muon p_T > 23 GeV (reconstructed in muon detectors)
  - Generated Lvtx < 50 cm
  - $p_T(\mu)$ > 12 GeV, d_{IP} > 0.25 mm, Rxy > 0.55 mm
  - Interpretation for three body decays

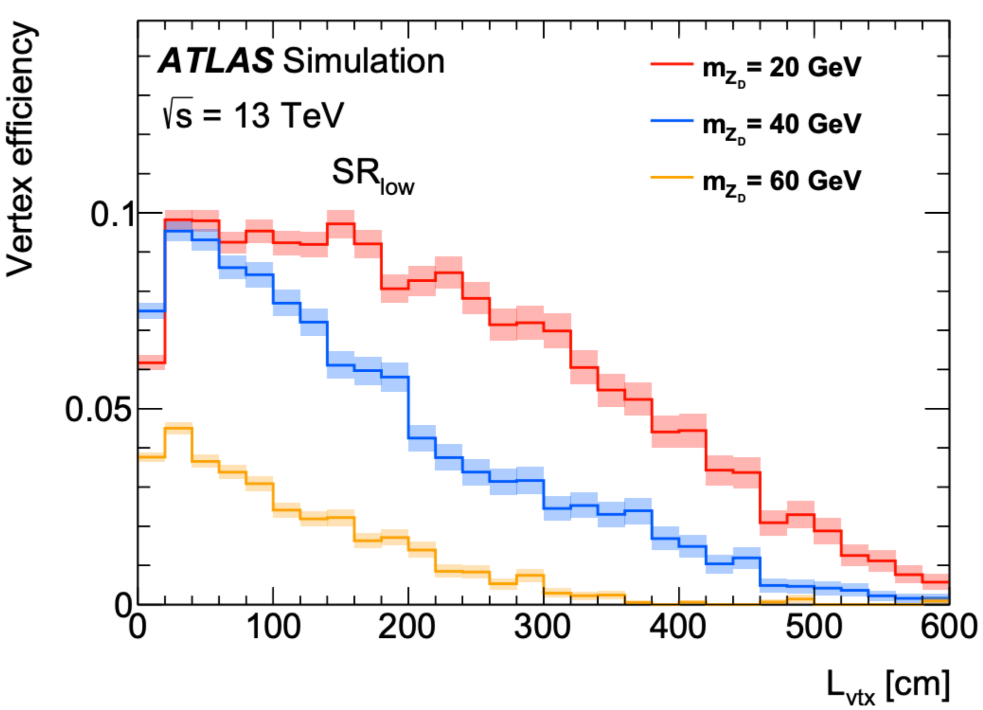


ATLAS DV search

- **ATLAS-EXOT-2017-03 (13 TeV, 32.9 fb^{-1})**
  - Inclusive search in displaced muon vertex

Signal type	Trigger	Description	Thresholds
High mass	E_T^{miss} single muon	missing transverse momentum single muon restricted to the barrel region	$E_T^{miss} > 110$ GeV muon $\|\eta\| < 1.05$ and $p_T > 60$ GeV
Low mass	collimated dimuon trimuon	two muons with small angular separation three muons	p_T of muons > 15 and 20 GeV and $\Delta R_{\mu\mu} < 0.5$ $p_T > 6$ GeV for all three muons

+



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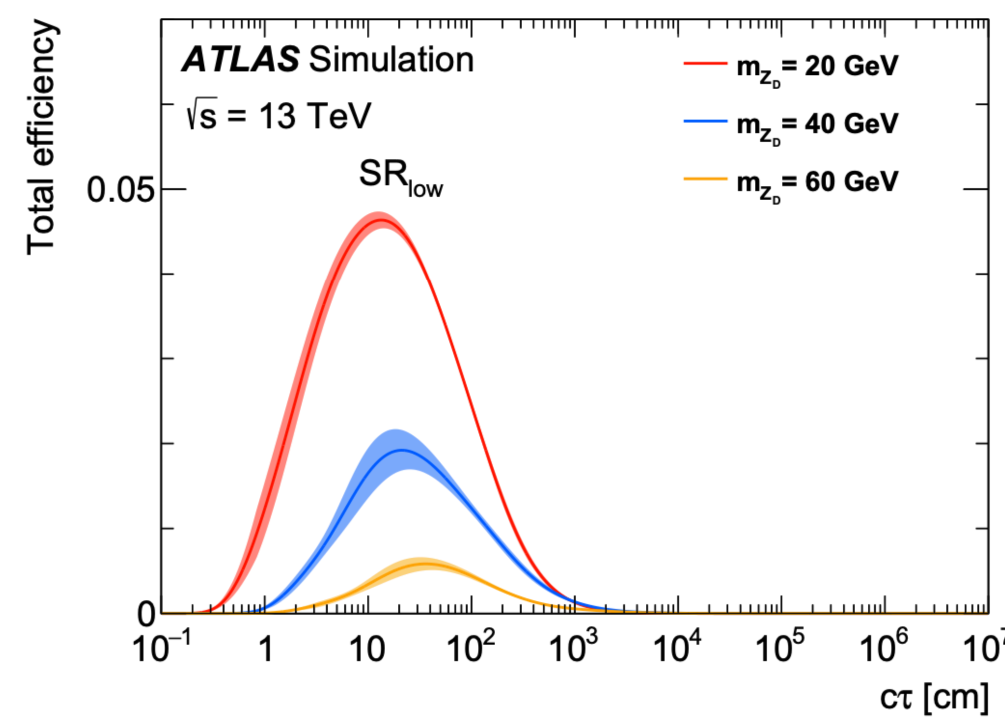
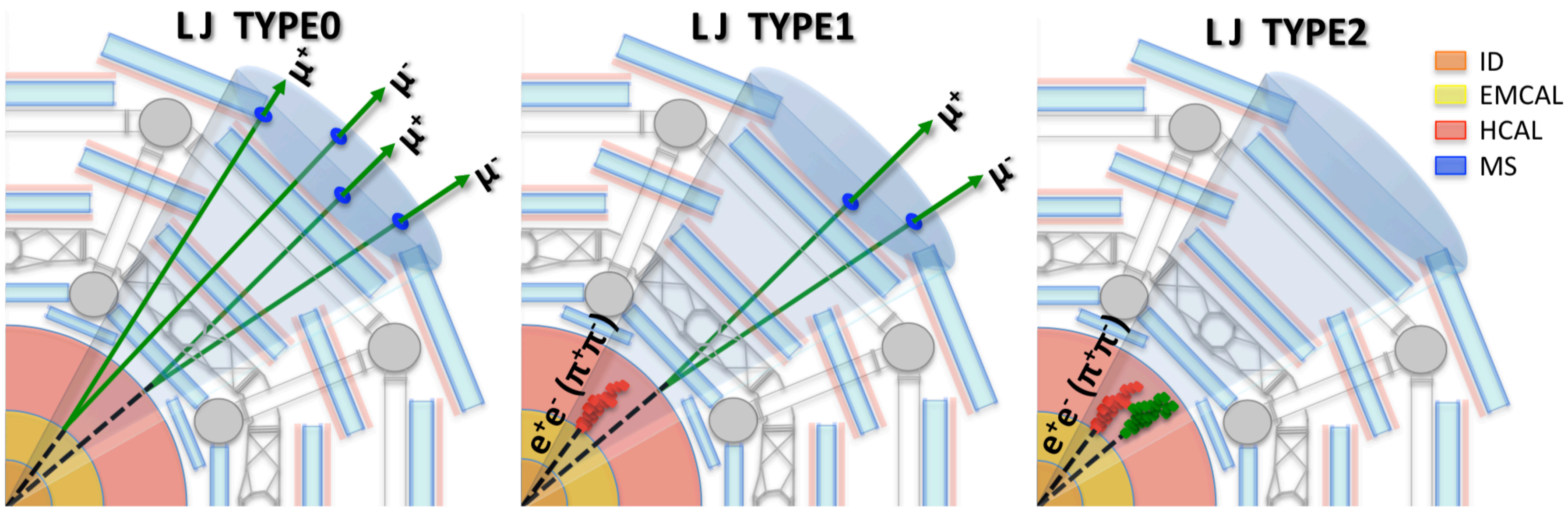


ATLAS LJ search

- **ATLAS-EXOT-2013-22 (sqrt 13 TeV, 20 fb^{-1})**

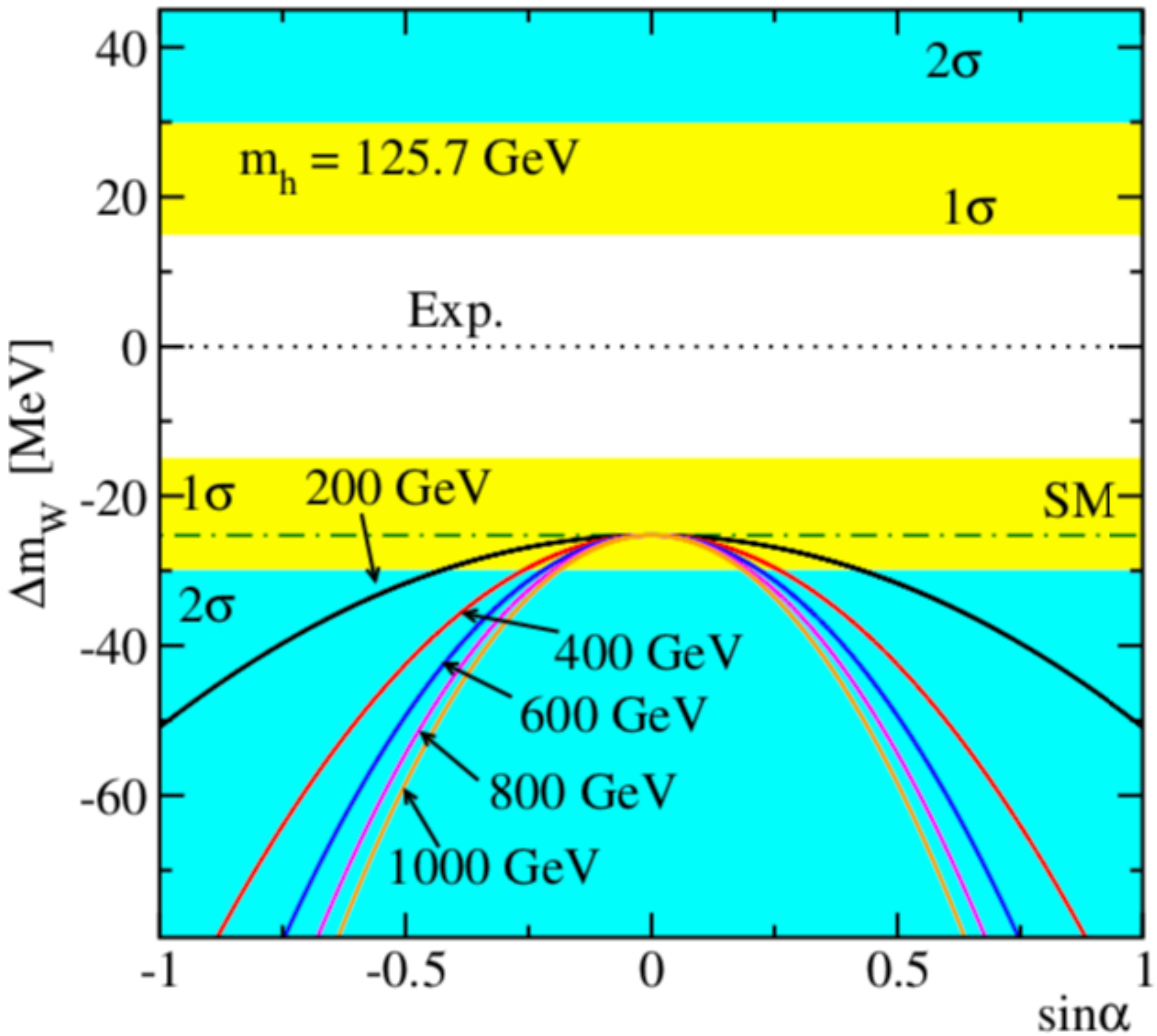


- Categorization of lepton jets:
  - Electron-jet if at least one electron candidate with E_T>10 GeV, 2 or more tracks w/ p_T>10 GeV, no muons
  - Muon-jet if at least 2 muons with pT>10 GeV and no electrons
  - Mixed-jet if at least one electron w/ E_T>10 GeV and at least one muon with p_T>10 GeV
- Triggers:
  - Single e w/ E_T>60 or double e w/ E_T>35/25 GeV
  - Single μ w/ p_T>36 or double μ w/ p_T>13/13 GeV

- **No equivalent CMS electron LJ search yet**

W mass constraint

Lopez-Val, Robens arXiv:1406.1043



$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha_{EM}}{\sqrt{2}G_F}(1+\Delta r)$$

$$\Delta m_W=-\frac{1}{2}m_W\frac{\sin^2\theta_W}{\cos^2\theta_W-\sin^2\theta_W}\delta(\Delta r)$$

- Constraints can be derived when lighter or heavier Higgs is 125 GeV
- Much stronger constraints when lighter Higgs is 125 GeV and heavier Higgs is heavy
- Driven by discrepancy between observed and predicted value of W mass
- When lighter Higgs is at 125 GeV, higher order EW corrections increase the discrepancy
- When heavy Higgs is at 125 GeV, somewhat better situation however, it is strongly constrained by Higgs signal strengths

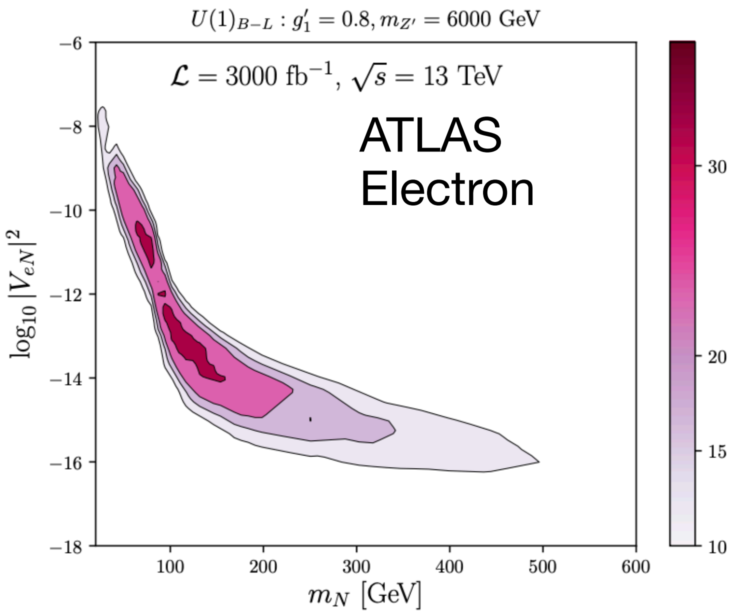
HNL high mass region

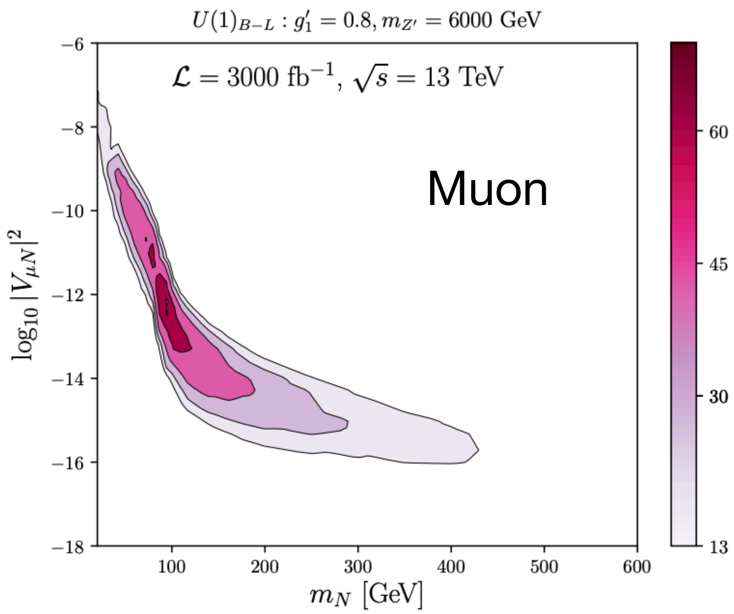
ATLAS

Trigger	Muon: $\lvert\eta\rvert < 1.07$ and $p_T > 55$ GeV. Electron: $p_T > 120$ GeV
DV region	DV within 4 mm $< r_{DV} <$ 300 mm and $\lvert z_{DV}\rvert <$ 300 mm
DV selection	Made from tracks with $\lvert d_0\rvert > 2$ mm and with $p_T > 1$ GeV
	DV track multiplicity $N_{trk} \geq 4$ and invariant mass $m_{DV} \geq 5$ GeV

CMS

Trigger	$H_T > 1000$ GeV
Jet selection	At least 4 jets with $p_T > 20$ GeV and $\lvert\eta\rvert < 2.5$
DV region	2 DVs within 0.1 mm $< r_{DV} <$ 20 mm and $d_{VV} > 0.4$ mm
DV selection	Made from tracks with $\lvert d_0\rvert \geq 0.1$ mm, $p_T > 20$ GeV and $\lvert\eta\rvert < 2.5$.
	$\sum p_T \geq 350$ GeV, correcting for b quarks.



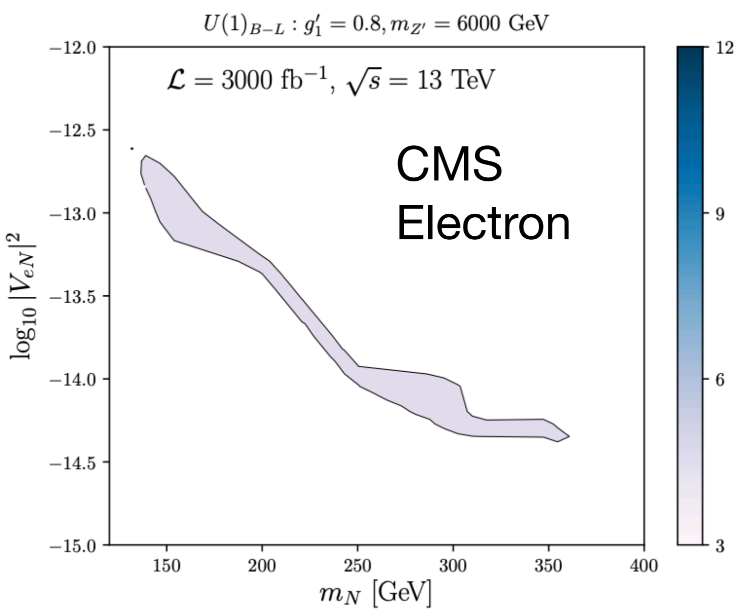


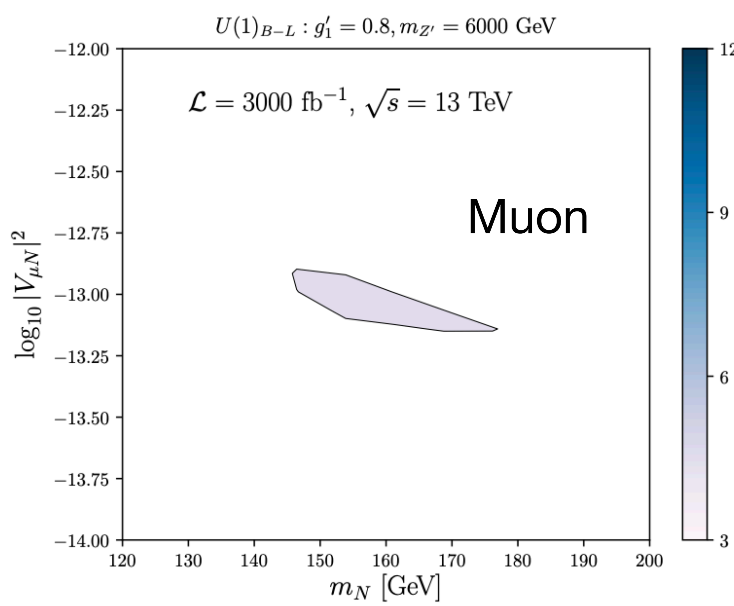
At least one DV in inner tracker

Efficiencies derived by ‘fitting’ to the limits

Exactly two DVs

Gen level selection + approximate event level efficiencies





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