Baryon Number as a Gauge Symmetry

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[arXiv: 1904.01017] PRD 100 (2019) 015017

[arXiv: 2003.09426] JHEP 07 (2020) 087

[arXiv: 2008.09116] JHEP 03 (2021) 185

[arXiv: 2112.02103] PRD 105 (2022) 095021

Aim of the talk

Discuss minimal gauge extensions of the SM that predict dark matter and new sources of CP-violation.

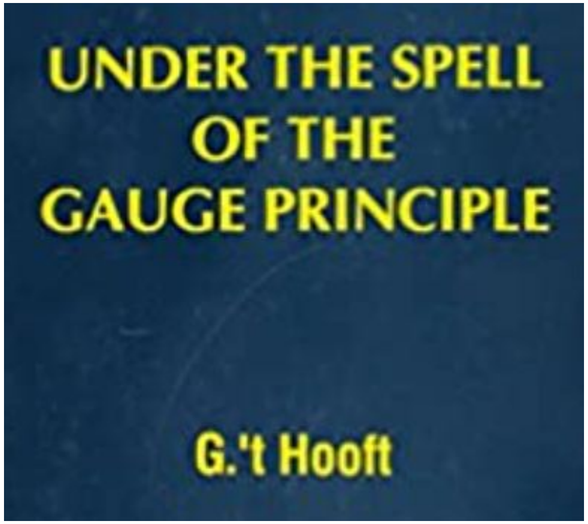
These theories must live at the low scale and can be fully probed in the near future.

New Gauge Symmetries at the Low Scale

- Anomalous symmetries, predict a new sector needed for Anomaly Cancellation

- Predict a Dark Matter candidate

- The new Symmetry Breaking Scale must be low to be in agreement with Cosmology



New Gauge Symmetries at the Low Scale

- Anomalous symmetries, predict a new sector needed for Anomaly Cancellation
- Predict a Dark Matter candidate
- The new Symmetry Breaking Scale must be low to be in agreement with Cosmology
- Predict new CP-violating interactions
- Can be complementary tested at LHC, dark matter and EDM experiments

$U(1)_B$

Gamma-ray lines, LHC pheno and EDMs

[Fileviez Perez, Golias, Li, Murgui, ADP 1904.01017]

[Fileviez Perez, Murgui, ADP 2003.09426]

[Fileviez Perez, ADP 2008.09116]

Gauging baryon number

- Baryon number is an accidental global symmetry in the SM
- Only broken by non-perturbative effects - SU(2) instantons
- Anomalous in the Standard Model

$$\underbrace{\mathrm{U}(1)_B}$$

Local gauge symmetry

gauge boson: Z_B

$$\langle S_B \rangle \neq 0$$

- Spontaneous breaking of baryon number
- Consistent completion of simplified models of dark matter

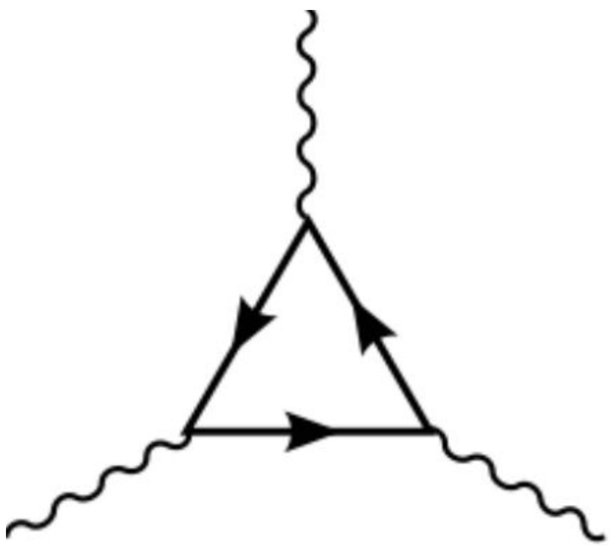
[Pais 1973]

[Fileviez Perez, Wise 2011]

Anomaly cancellation

- Baryon number broken in 3 units: $\Delta B=\pm 3$ interactions
  → No proton decay

- Need to add new fermions to cancel anomalies



$$\mathcal{A}_1\,(\mathrm{SU}(3)^2 \otimes \mathrm{U}(1)_B),\ \mathcal{A}_2\,(\mathrm{SU}(2)^2 \otimes \mathrm{U}(1)_B),$$
$$\mathcal{A}_3\,(\mathrm{U}(1)_Y^2 \otimes \mathrm{U}(1)_B),\ \mathcal{A}_4\,(\mathrm{U}(1)_Y \otimes \mathrm{U}(1)_B^2),$$
$$\mathcal{A}_5\,(\mathrm{U}(1)_B),\ \ \mathcal{A}_6\,(\mathrm{U}(1)_B^3),$$

In the SM the non-zero values are:

$$\mathcal{A}_2 = -\mathcal{A}_3 = 3/2$$

Anomaly-free model

[Fileviez Perez, Ohmer, Patel 1403.8029]

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
$\Psi_L = \begin{pmatrix} \Psi_L^+ \\ \Psi_L^0 \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	$\frac{3}{2}$
$\Psi_R = \begin{pmatrix} \Psi_R^+ \\ \Psi_R^0 \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	$-\frac{3}{2}$
$\Sigma_L = \frac{1}{\sqrt{2}} \begin{pmatrix} \Sigma_L^0 & \sqrt{2}\Sigma_L^+ \\ \sqrt{2}\Sigma_L^- & -\Sigma_L^0 \end{pmatrix}$	$\mathbf{1}$	$\mathbf{3}$	0	$-\frac{3}{2}$
χ_L^0	$\mathbf{1}$	$\mathbf{1}$	0	$-\frac{3}{2}$

Model with 6 representations: [Duerr, Fileviez Perez, Wise 1304.0576]

- Neutral fermion required for anomaly cancellation
- Automatically stable from remnant $U(1)_B \longrightarrow Z_2$ symmetry

→ DM Candidate  

Simplified Dark Matter

χ: Majorana DM

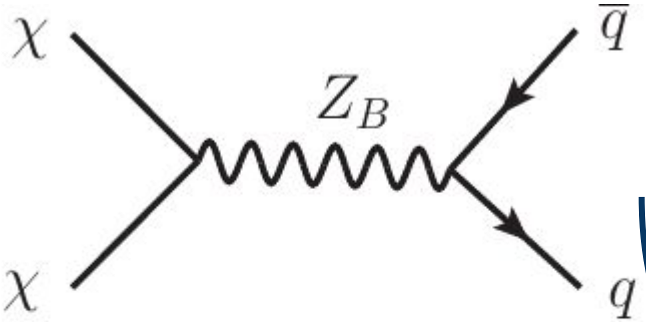
Z_B : Leptophobic mediator

$$\mathcal{L} \supset \frac{3}{4} g_B \bar{\chi} \gamma^\mu \gamma^5 \chi Z^B_\mu - \frac{1}{3} g_B \bar{q} \gamma^\mu q Z^B_\mu + \frac{M_\chi}{2 v_B} \sin\theta_B \bar{\chi}\chi h_1 - \frac{M_\chi}{2 v_B} \cos\theta_B \bar{\chi}\chi h_2$$

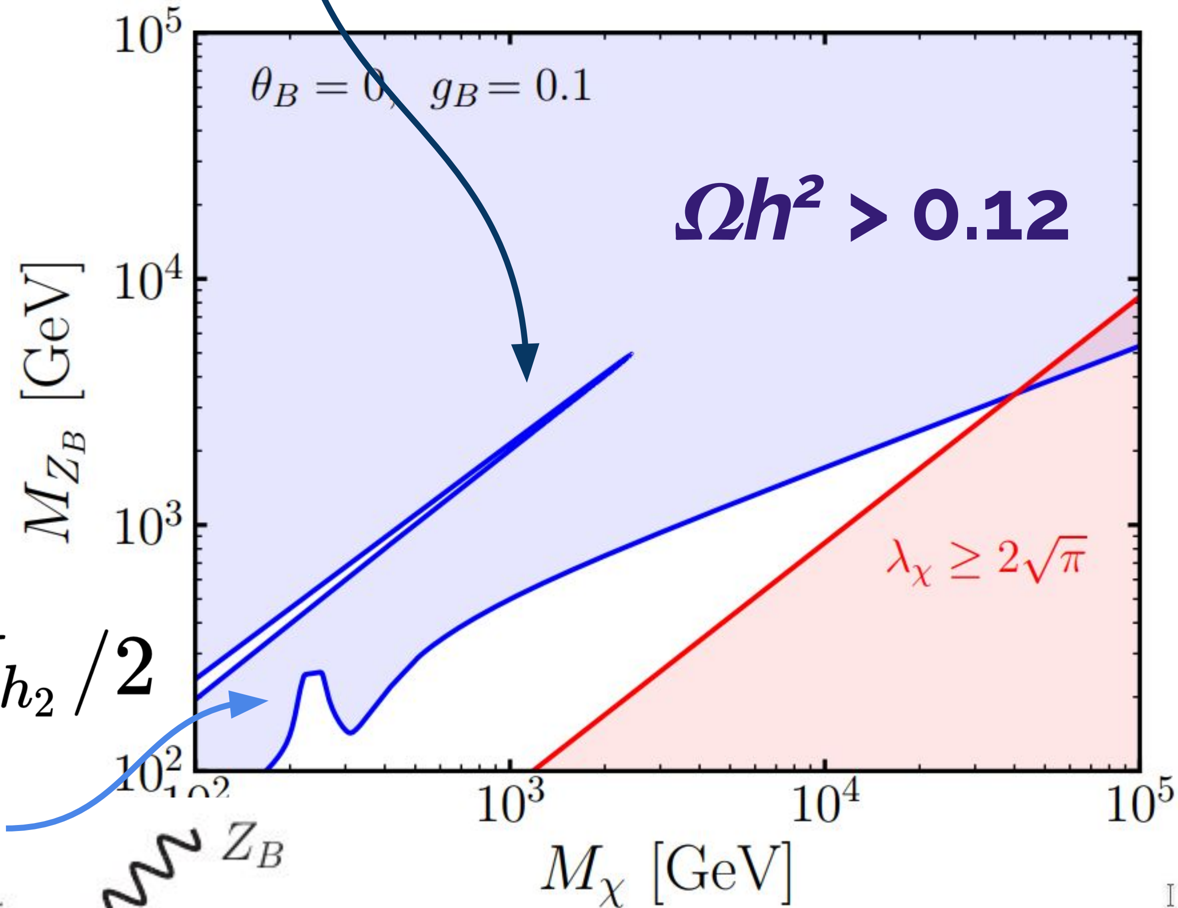
Axial (the $\frac{3}{4} g_B \bar{\chi} \gamma^\mu \gamma^5 \chi Z^B_\mu$ term) — **Vector** (the $\frac{1}{3} g_B \bar{q} \gamma^\mu q Z^B_\mu$ term)

the free parameters in the model are:

$$M_\chi, \quad M_{Z_B}, \quad M_{h_2}, \quad \theta_B, \quad g_B.$$



$$M_\chi \approx M_{Z_B}/2$$



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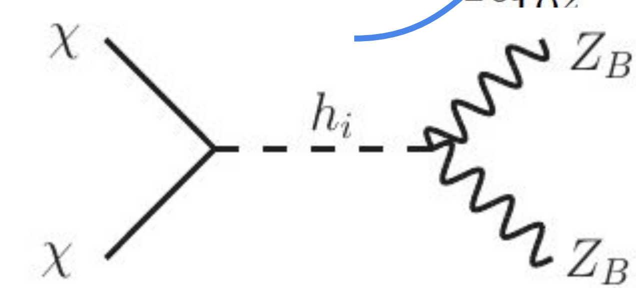
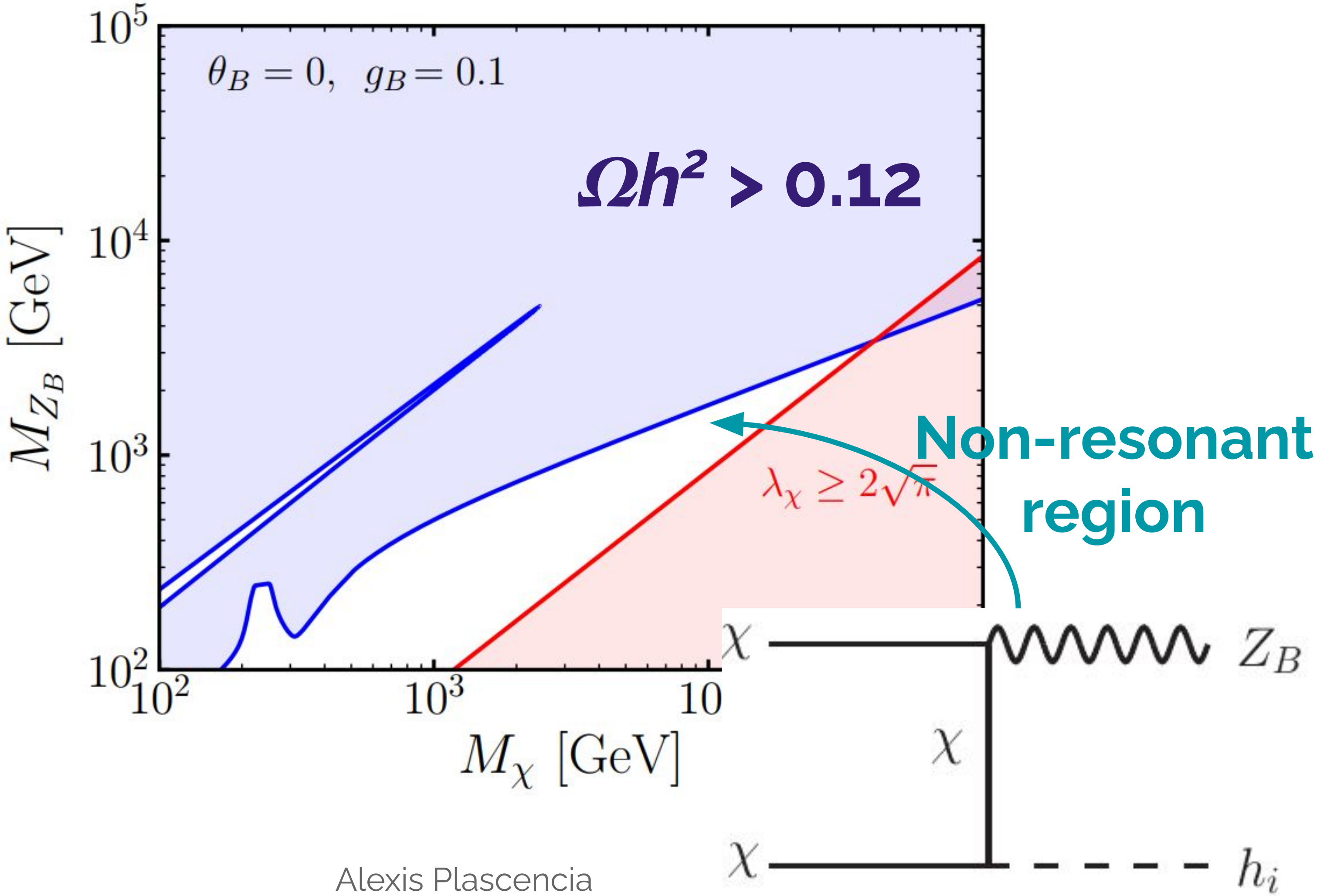
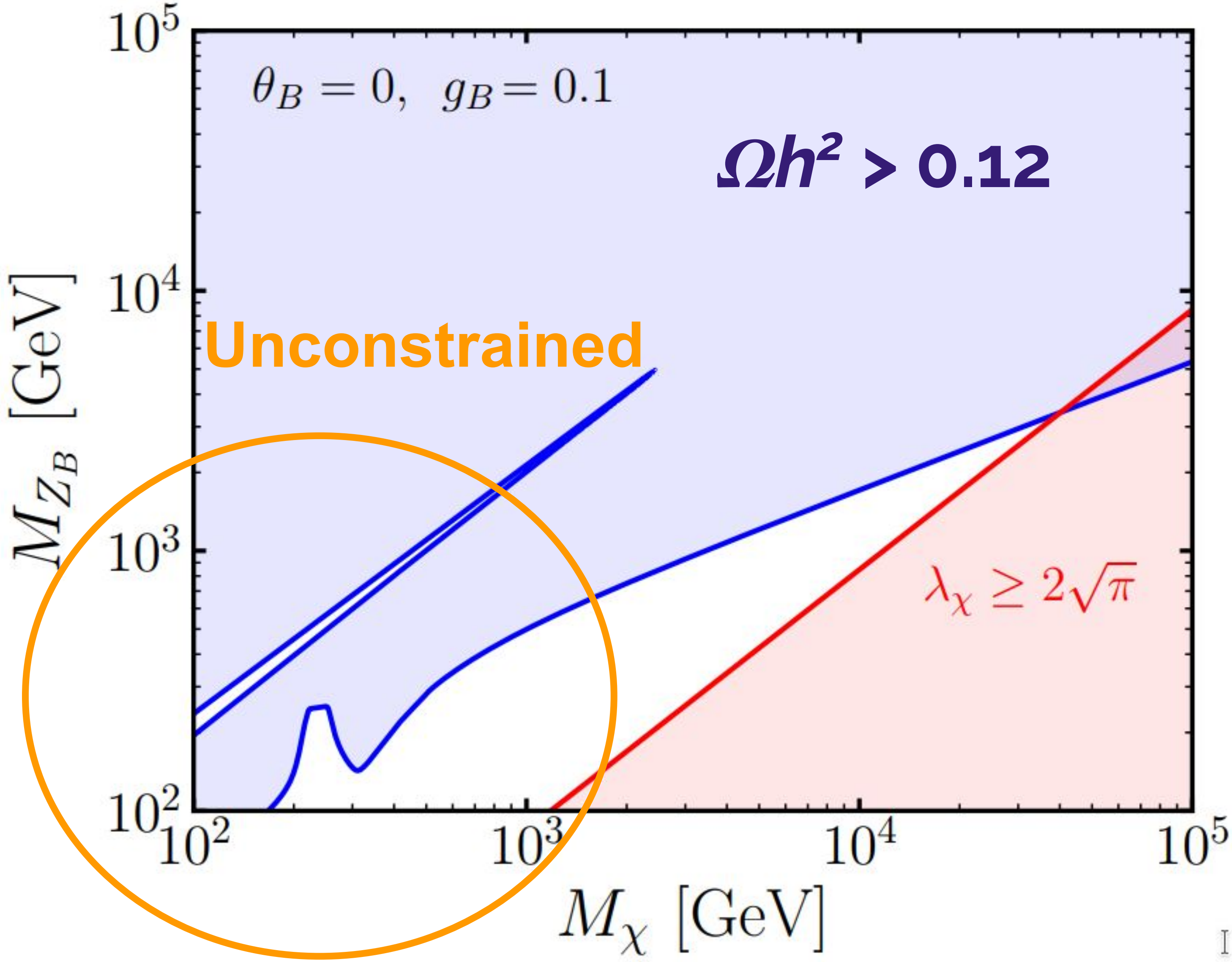




$\theta_B = 0, \;\; g_B = 0.1$
$\Omega h^2 > 0.12$
$\lambda_\chi \geq 2\sqrt{\pi}$
Non-resonant region
M_{Z_B} [GeV]
M_χ [GeV]
χ
χ
χ
Z_B
h_i

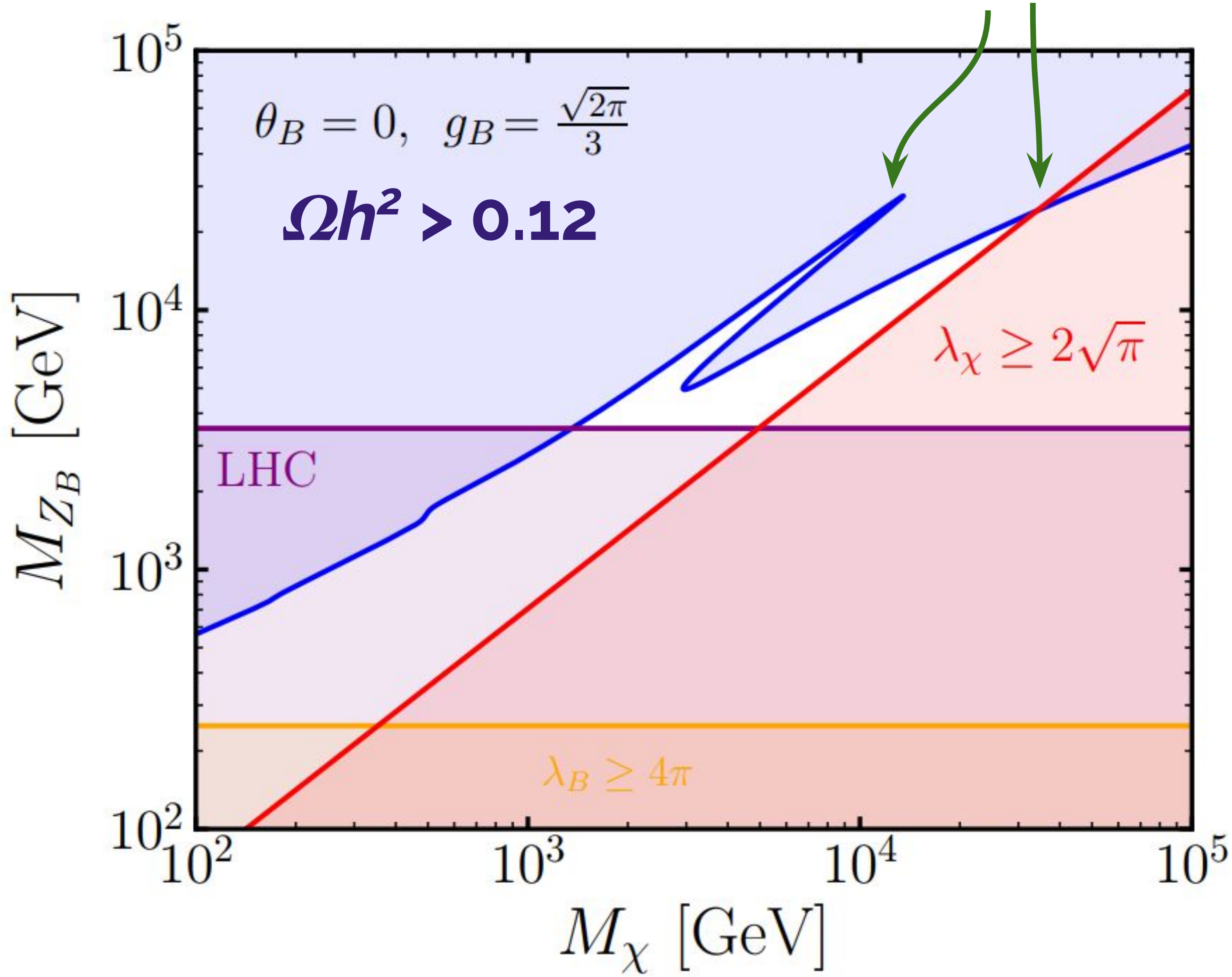
Results



[Fileviez Perez, Golias, Li, Murgui, ADP 1904.01017]

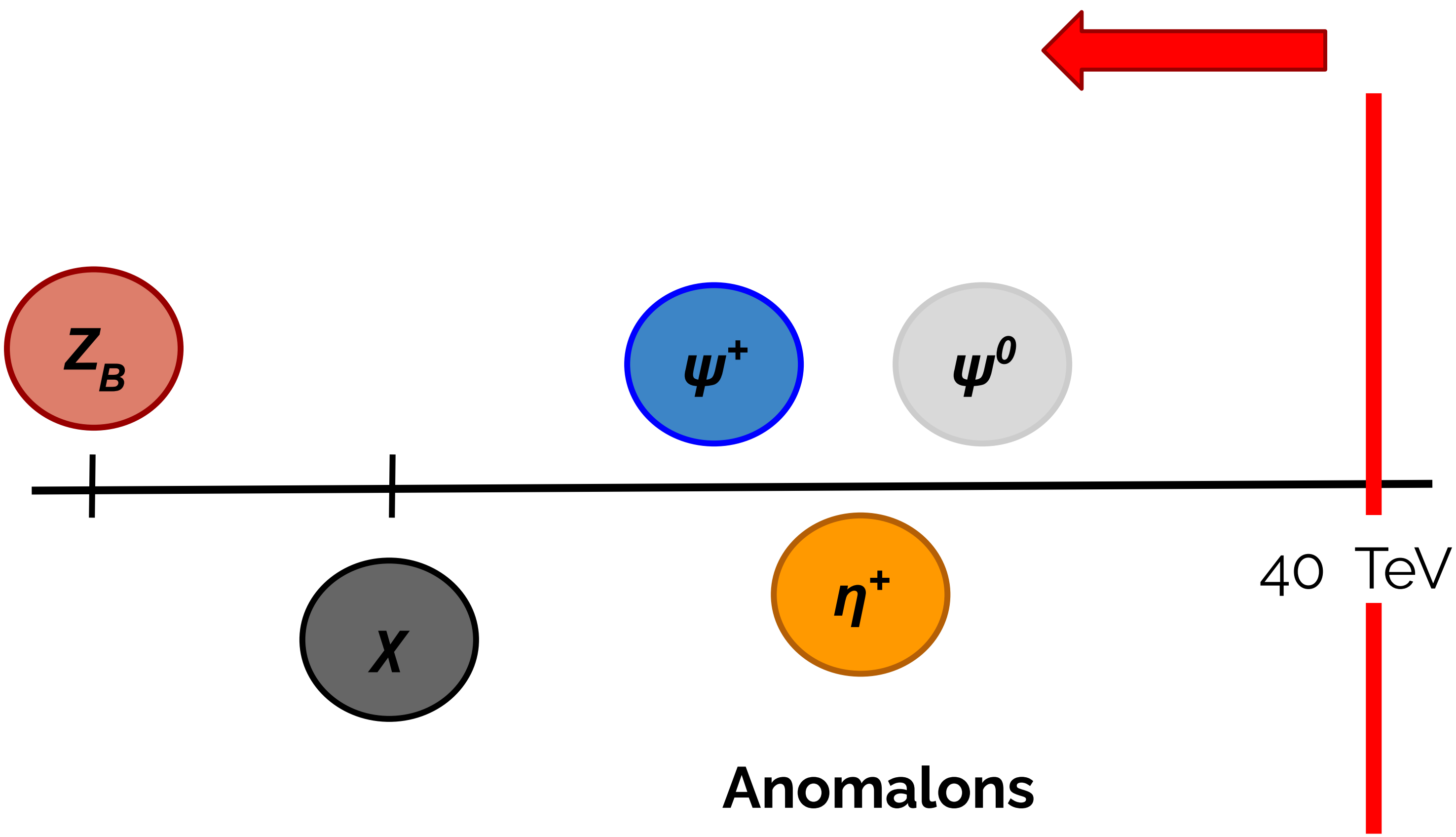
Perturbativity $g_B \leq \frac{\sqrt{2\pi}}{3} \approx 0.84$ and $\Omega h^2 \leq 0.12$

Give an upper bound on the scale



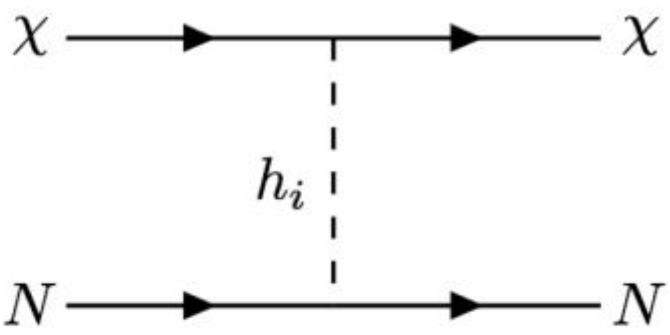
Upper bound on baryon number breaking scale

All masses connected to v_B , and hence, there is an upper bound for the full model



Direct Detection

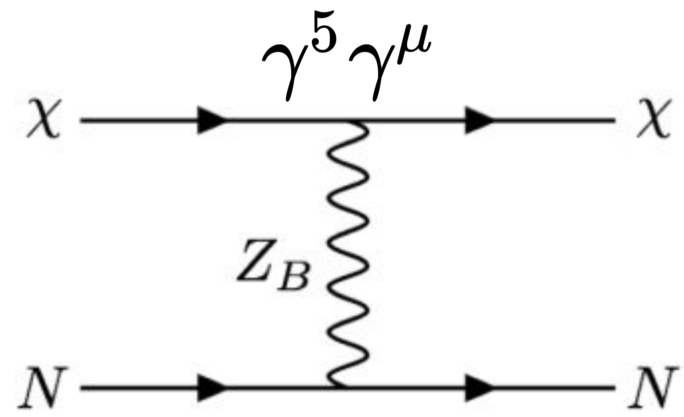
$$\sigma_{\chi N}^{\rm TOT} = \sigma_{\chi N}(h_i) + \sigma_{\chi N}^{0}(Z_B) v^2$$



suppressed by Higgs mixing

$\theta < 0.3$ for $M_{H2} > 200$ GeV

For lighter M_{H2} stronger bound

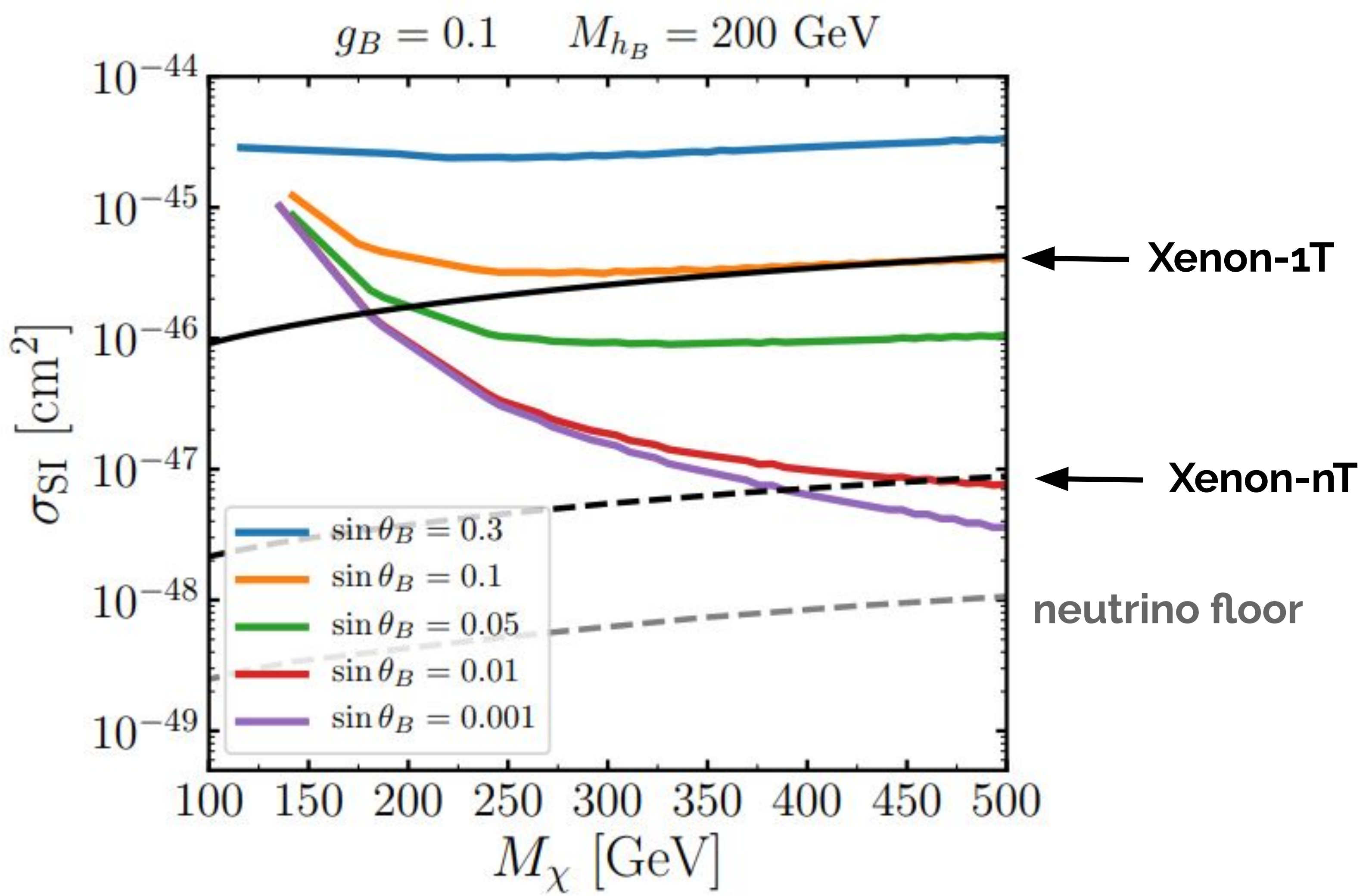


Due to axial coupling,

velocity suppressed $v \sim 10^{-3}$

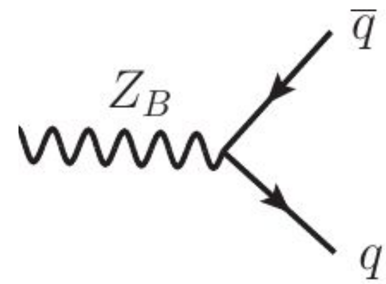
Direct Detection

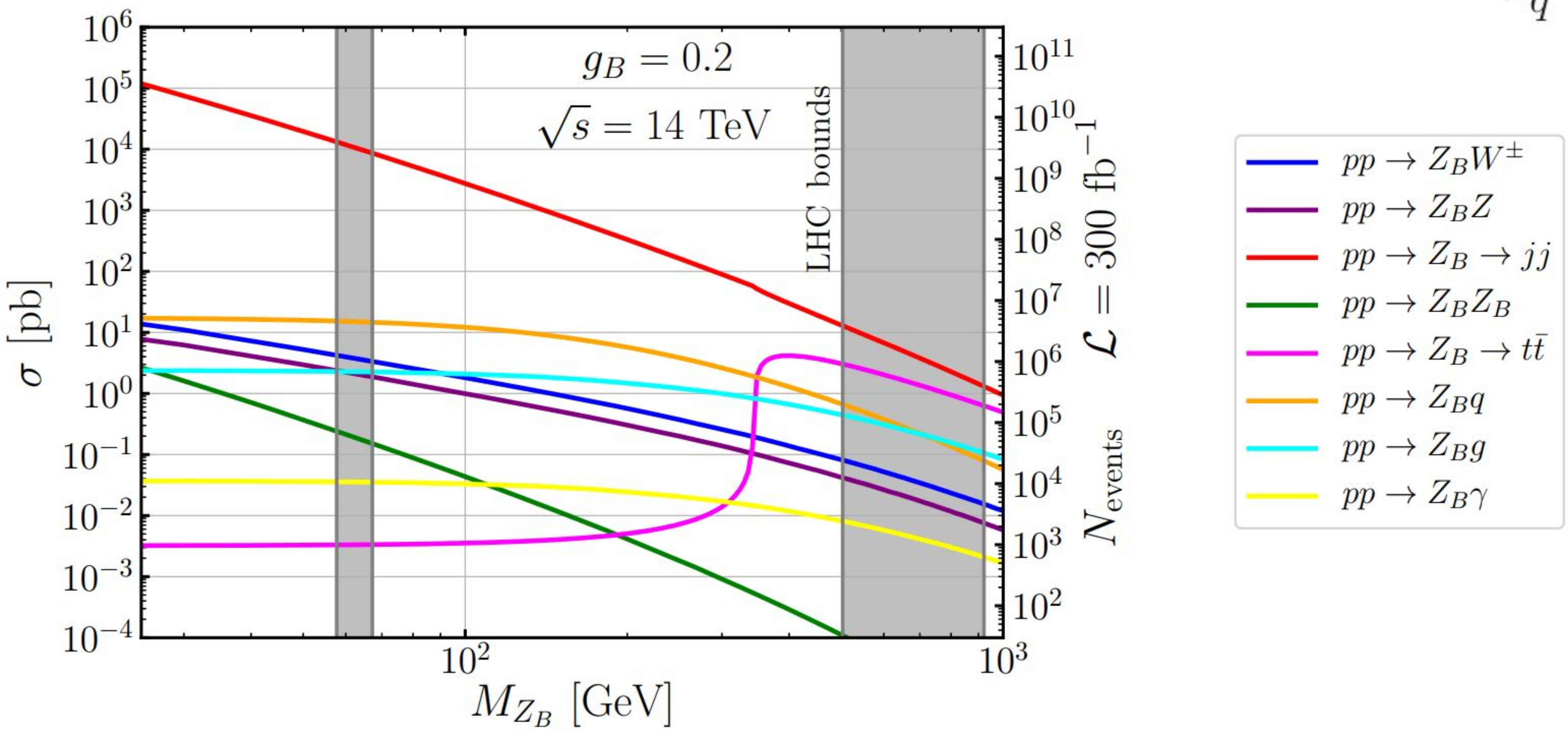
All points satisfy: $\Omega h^2 = 0.12 \pm 0.0022$



2. LHC Phenomenology

LHC production cross-sections

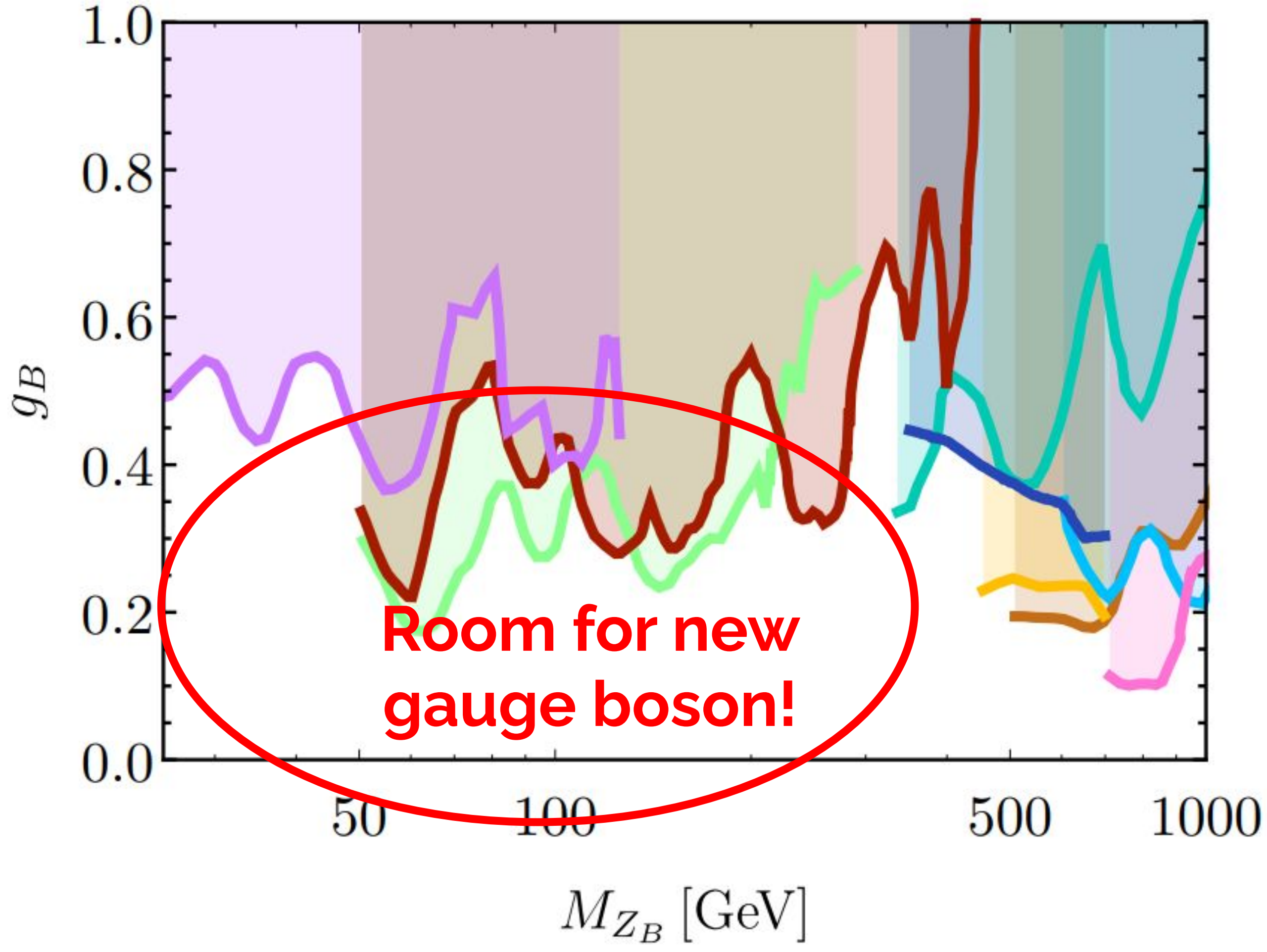




[Fileviez Perez, Golias, Murgui, ADP 2003.09426]

LHC bounds on leptophobic gauge boson

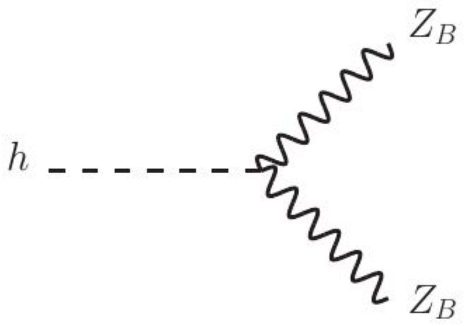
- Di-jet resonance searches by CMS and ATLAS - Run I & II



[Fileviez Perez, Murgui, ADP 2003.09426]

Exotic Higgs decays

When $M_{Z_B} \leq M_h/2$:



$$hZ_B^{\mu}Z_B^{\nu} :\ 2i\frac{M_{Z_B}^2}{v_B}g^{\mu\nu}\sin\theta_B,$$

$$\mathrm{BR}(h \to \mathrm{BSM}) \leq 0.34$$

[ATLAS & CMS 1606.02266]

Exotic Higgs decays

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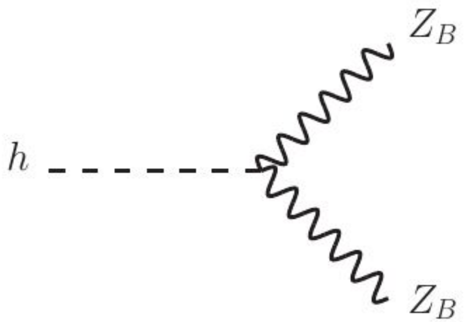
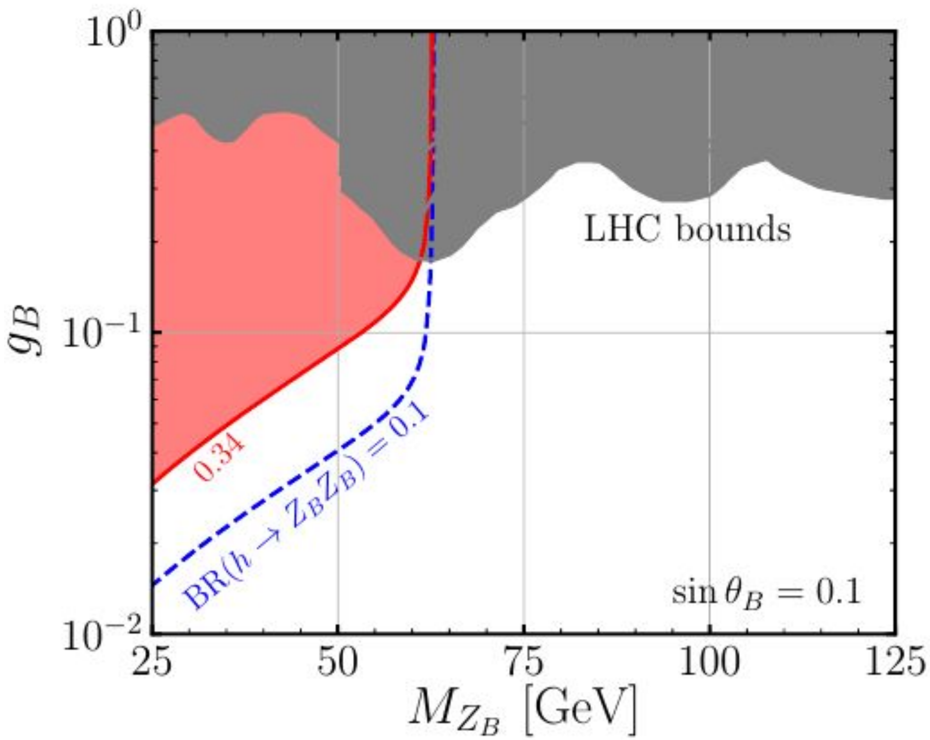


$$hZ_B^\mu Z_B^\nu : \; 2i\frac{M_{Z_B}^2}{v_B} g^{\mu\nu} \sin\theta_B,$$

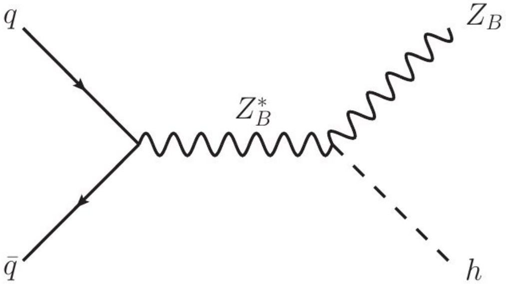
$$\mathrm{BR}(h \to \mathrm{BSM}) \leq 0.34$$

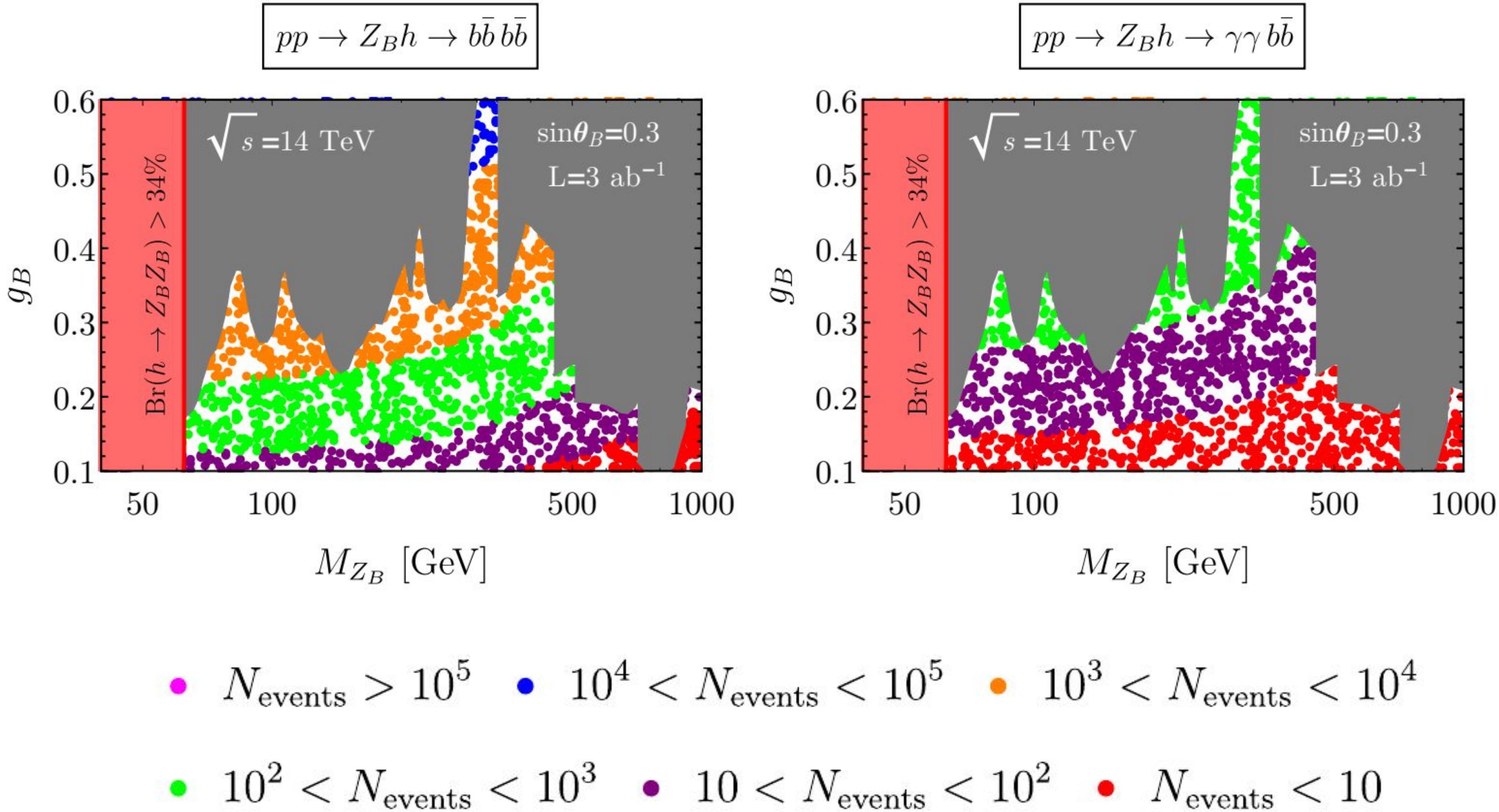
[ATLAS & CMS 1606.02266]



[Fileviez Perez, Golias, Murgui, ADP 2020]

Associated Higgs Production





[Fileviez Perez, Murgui, ADP 2003.09426]

The Higgs of Baryon Number h_B

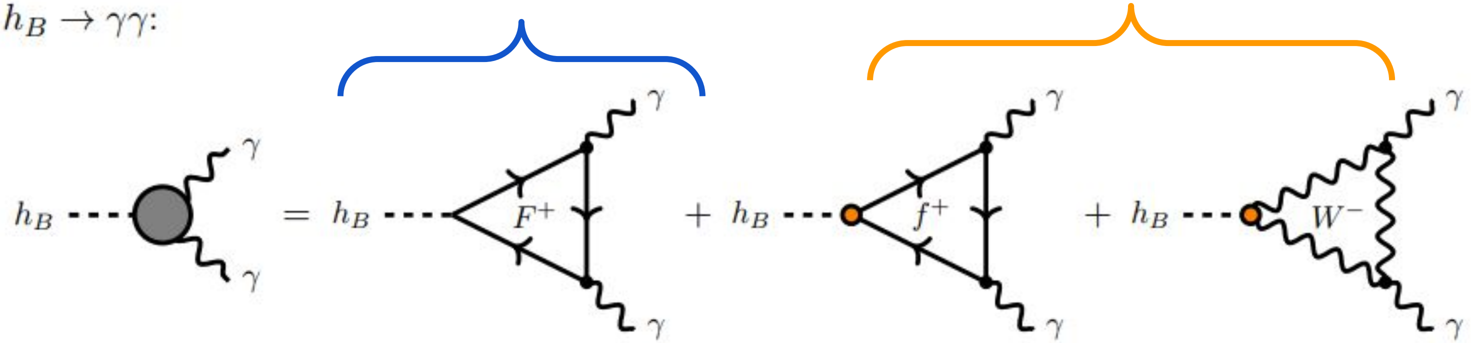
We calculated full one-loop decays

Second Higgs can have a large branching ratio into pair of photons

Anomaly-canceling fermions run in the loop!

- $h_B \to \gamma\gamma$:

small mixing **large mixing with SM *h***



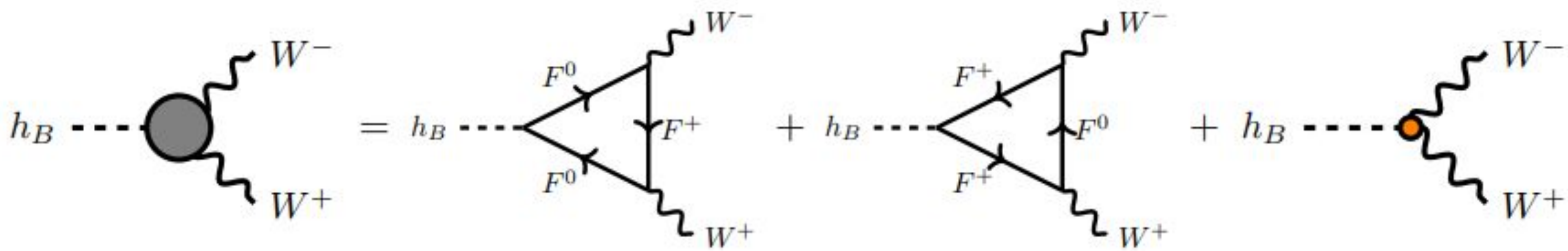
$$\Gamma(h_B \to \gamma\gamma) = \frac{\alpha^2}{64\pi^3 M_{h_B}^5} \left| \cos\theta_B \sum_{F^+} \frac{3 g_B M_{F^+}^2}{M_{Z_B}} F_{F^+} + \frac{\sin\theta_B}{v_0} \left(\sum_{f^+} N_c^f Q_f^2 m_{f^+}^2 F_{f^+} - F_W \right) \right|^2 .$$

[Fileviez Perez, Murgui, ADP 2012.06599]

The Higgs of Baryon Number h_B

small mixing with SM h | large mixing

- $h_B \to WW$:



$$\Gamma(h_B \to WW) = \frac{\sqrt{M_{h_B}^2 - 4M_W^2}}{16\pi M_{h_B}^2 M_W^4} \left(\cos^2\theta_B \frac{9g_B^2}{M_{Z_B}^2} \left| \sum_F g_{WF}^2 B_F[W] \right|^2 + 2(M_{h_B}^2 - 2M_W^2) \times \right.$$

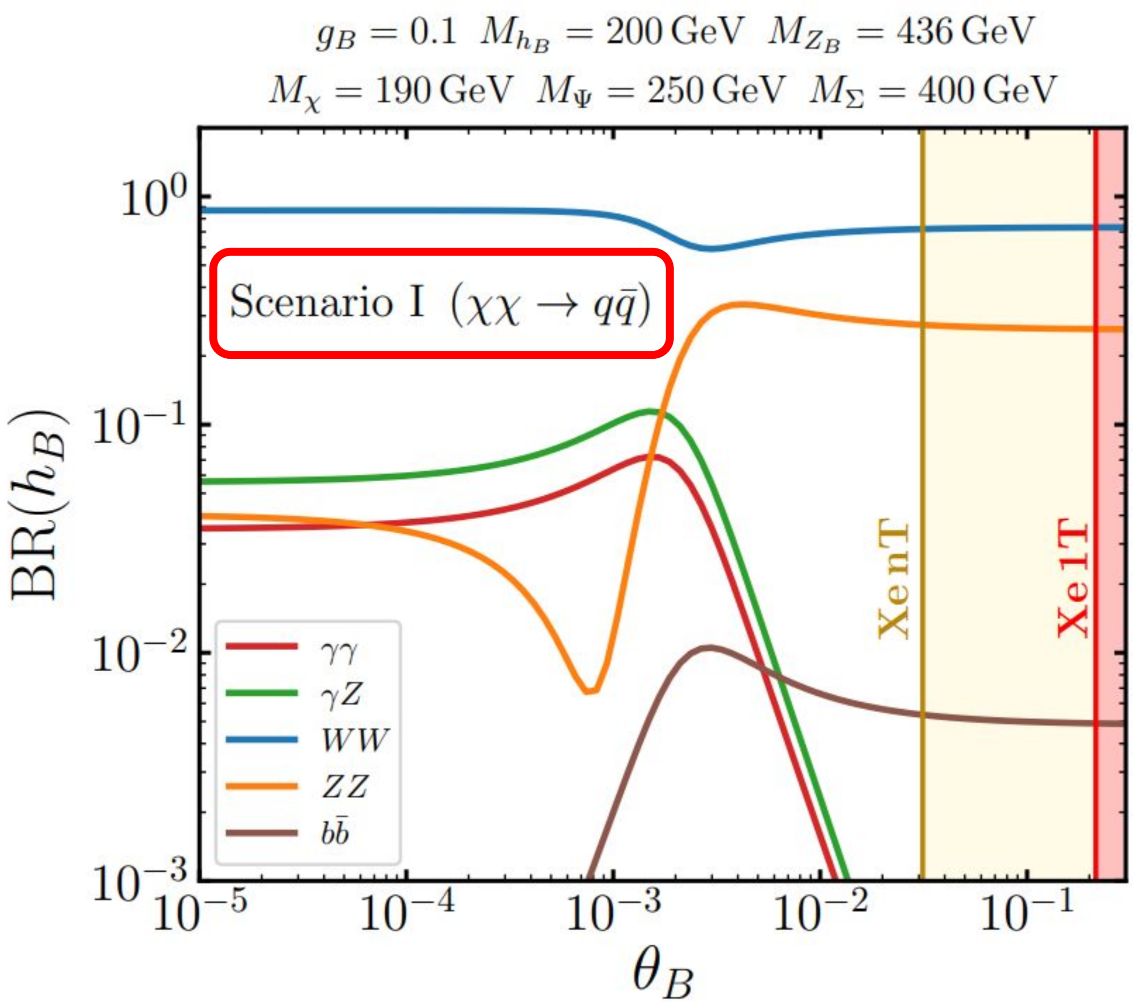
$$\mathrm{Re}\left\{ \cos\theta_B \frac{3g_B}{M_{Z_B}} \sum_F g_{WF}^2 B_F[W] \left(\cos\theta_B \frac{3g_B}{M_{Z_B}} \sum_F g_{WF}^2 C_F^*[W] + \frac{\sin\theta_B}{v_0} M_W^2 \right) \right\}$$

$$\left. + \left| \cos\theta_B \frac{3g_B}{M_{Z_B}} \sum_F g_{WF}^2 C_F[W] + \frac{\sin\theta_B}{v_0} M_W^2 \right|^2 (M_{h_B}^4 - 4M_{h_B}^2 M_W^2 + 12 M_W^4) \right) .$$

[Fileviez Perez, Murgui, ADP 2012.06599]

The Higgs of Baryon Number h_B

Correlation between dark matter and the properties of the second Higgs



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

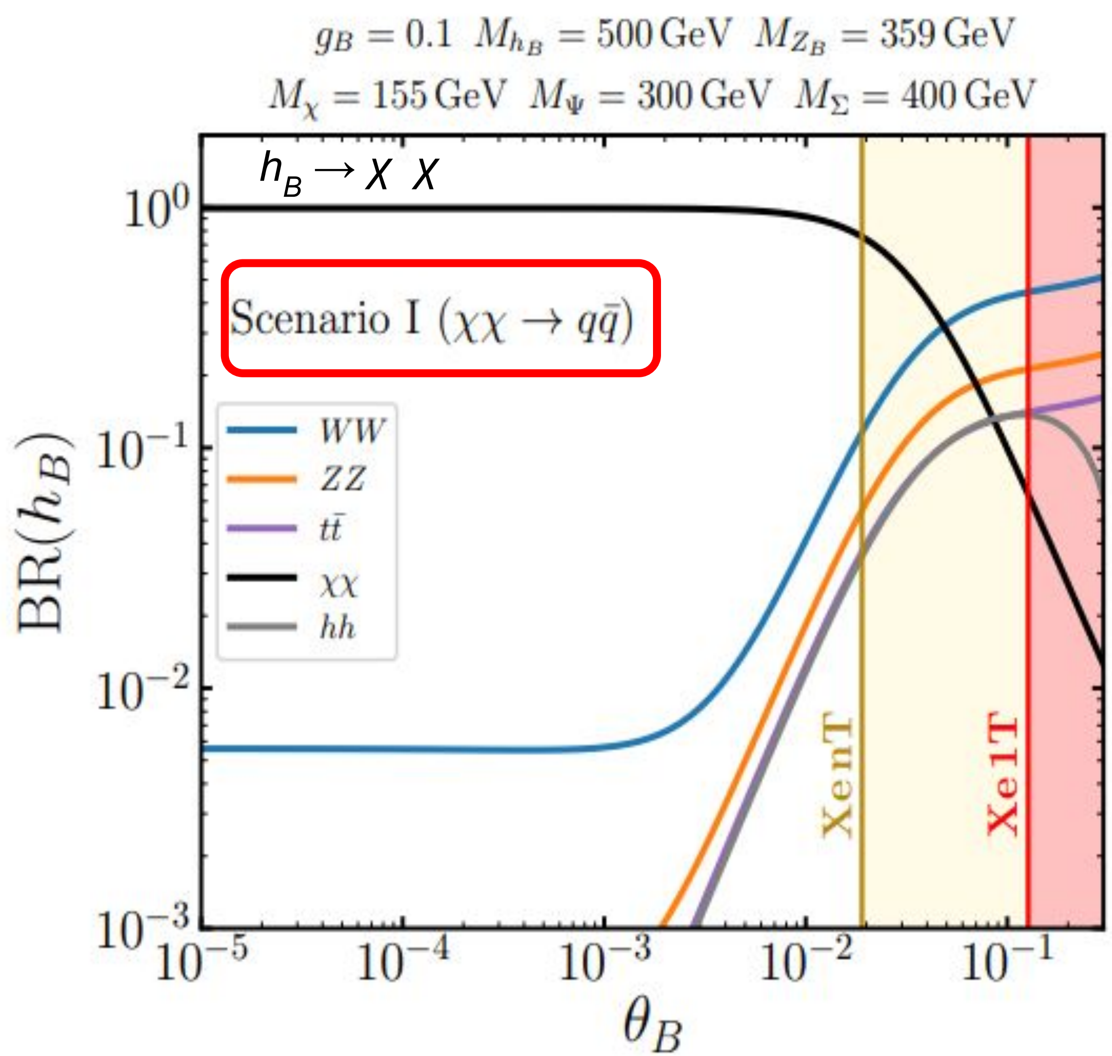
$$\mathrm{Br}(h_B \to \gamma\gamma) \simeq 5\%$$

Large di-photon decay!

0.1% for SM Higgs

[Fileviez Perez, Murgui, ADP 2012.06599]

$M_\chi < M_{h_B}/2$ **Dominant invisible decay**

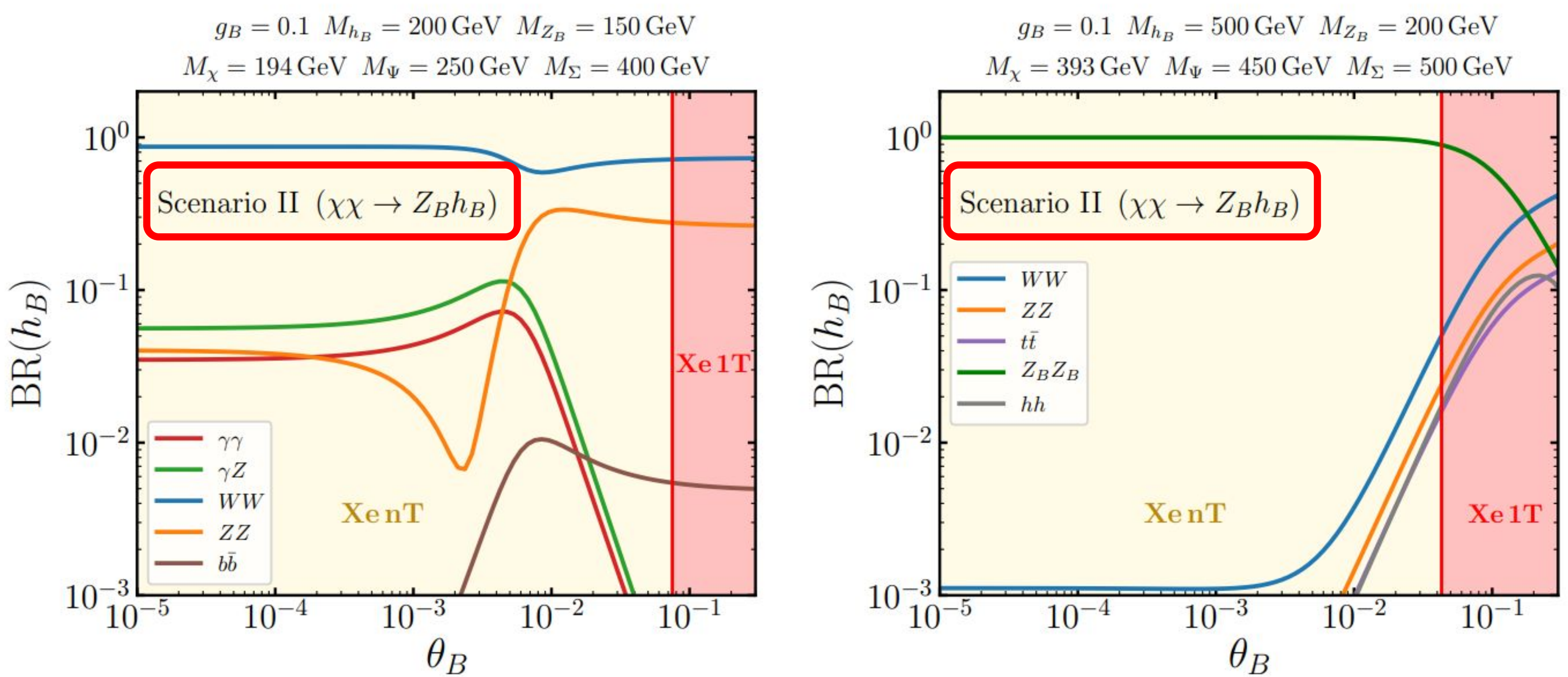


[Fileviez Perez, Murgui, ADP 2012.06599]

The Higgs of Baryon Number h_B

Correlation between dark matter and the properties of the second Higgs

$$h_B \longrightarrow Z_B Z_B$$



[Fileviez Perez, Murgui, ADP 2012.06599]

EDM

3. CP Violation and Electric Dipole Moments

[Fileviez Perez, ADP 2008.09116]

[Fileviez Perez, ADP 2112.02103]

CP violation and EDMs

$$-\mathcal{L} \supset y_1 \bar{\Psi}_R H \chi_L + y_2 H^\dagger \Psi_L \chi_L + y_3 H^\dagger \Sigma_L \Psi_L + y_4 \bar{\Psi}_R \Sigma_L H$$
$$+ \lambda_\Psi \bar{\Psi}_R \Psi_L S_B^* + \frac{\lambda_\chi}{\sqrt{2}} \chi_L \chi_L S_B + \lambda_\Sigma \mathrm{Tr}(\Sigma_L \Sigma_L) S_B + \mathrm{h.c.},$$

CP violation and EDMs

$$-\mathcal{L} \supset y_1 \bar{\Psi}_R H \chi_L + y_2 H^\dagger \Psi_L \chi_L + y_3 H^\dagger \Sigma_L \Psi_L + y_4 \bar{\Psi}_R \Sigma_L H + \lambda_\Psi \bar{\Psi}_R \Psi_L S_B^* + \frac{\lambda_\chi}{\sqrt{2}} \chi_L \chi_L S_B + \lambda_\Sigma \mathrm{Tr}(\Sigma_L \Sigma_L) S_B + \mathrm{h.c.},$$

$$-\mathcal{L} \supset \begin{pmatrix} \overline{\Sigma_R^+} & \overline{\Psi_{2R}^+} \end{pmatrix} \mathcal{M}_C \begin{pmatrix} \Sigma_L^+ \\ \Psi_{1L}^+ \end{pmatrix} + \mathrm{h.c.}$$

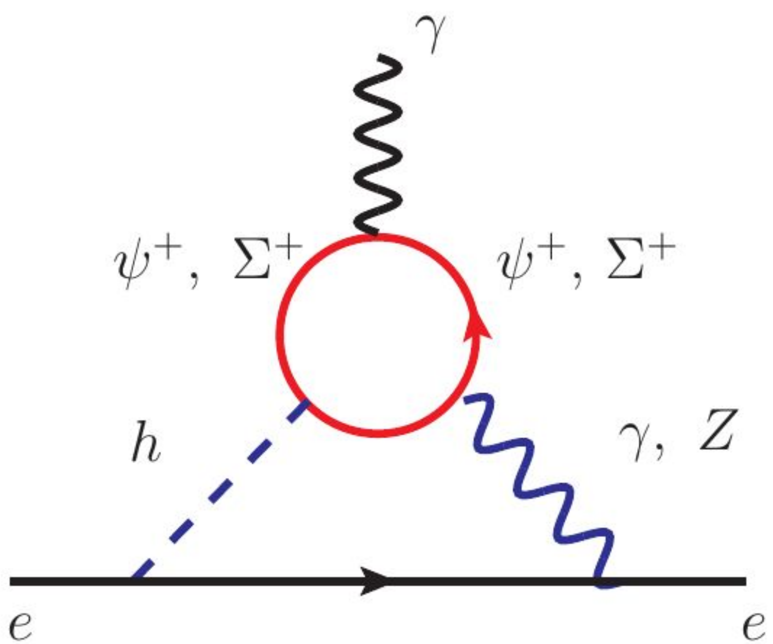
$$\mathcal{M}_C = \begin{pmatrix} \sqrt{2} y_\Sigma v_B & \frac{y_3 v}{\sqrt{2}} \\ \frac{y_4 v}{\sqrt{2}} & \frac{y_\Psi v_B}{\sqrt{2}} \end{pmatrix}$$

$$\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi)$$

[Fileviez Perez, ADP 2008.09116]

CP violation and EDMs

- This new CP-violating phase contributes to the electron and neutron electric dipole moments
- The new contribution comes from two-loop Barr-Zee diagrams with the charged anomaly-canceling fermions in the loop



$$\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi)$$

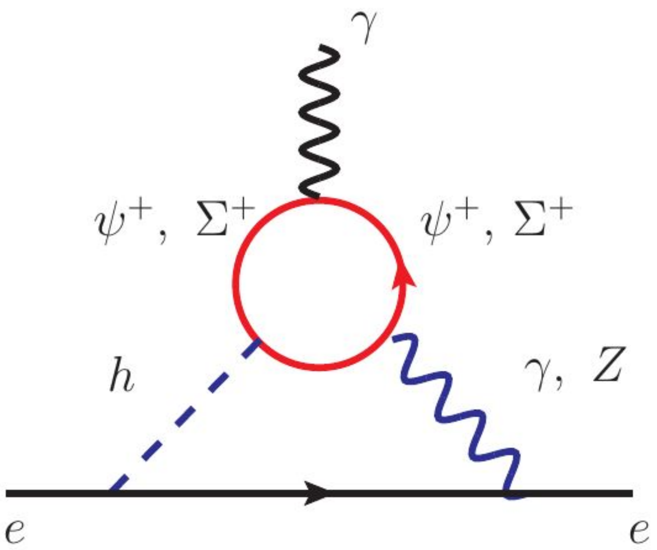
[Fileviez Perez, ADP 2008.09116]

CP violation and EDMs

$$d_e^{\gamma h} = \frac{\alpha^2 \cos\theta_B \, Q_e \, m_e}{8\pi^2 s_W \, m_h^2 \, m_W} \sum_{i=1}^{2} M_{\chi_i^\pm} \, \mathrm{Im}[C_h^{ii}] \, I_{\gamma h}^i(M_{\chi_i^\pm})$$

$$C_h^{ij} = \frac{1}{\sqrt{2}} \cos\theta_B \left[y_3 (V_R^{1i})^* V_L^{2j} + y_4 (V_R^{2i})^* V_L^{1j} \right] + \frac{1}{\sqrt{2}} \sin\theta_B \left[y_\Psi (V_R^{2i})^* V_L^{2j} + 2 y_\Sigma (V_R^{1i})^* V_L^{1j} \right]$$

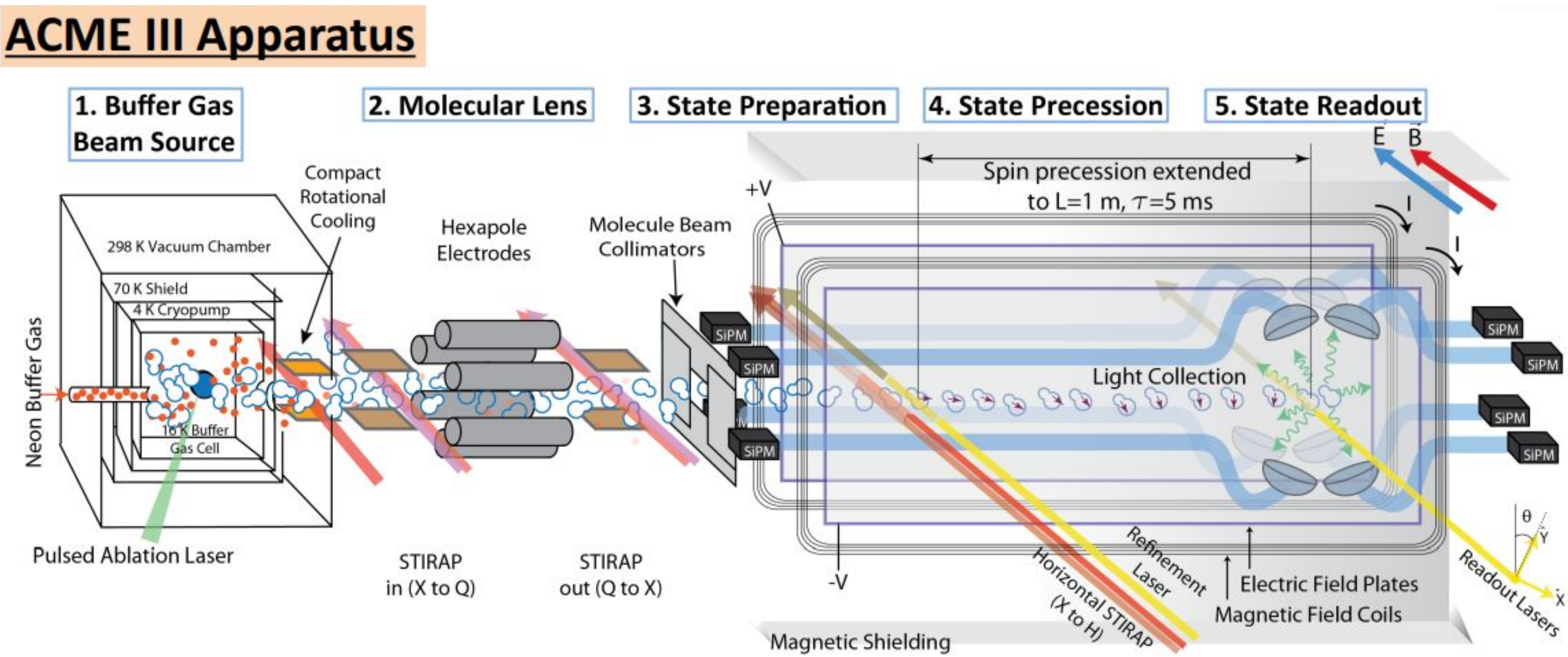
$$I_{\gamma h}^i(M_{\chi_i^\pm}) = \int_0^1 \frac{dx}{x} j\left(0, \frac{M_{\chi_i^\pm}^2}{m_h^2} \frac{1}{x(1-x)}\right)$$



[Fileviez Perez, ADP 2008.09116] **[Nakai, Reece 1612.08090]**

ACME experiment

- Measures the electron EDM
- Beam of thorium monoxide molecule
- ThO has a strong internal electric field



[ACME collaboration]

ACME experiment

$$\frac{|d_e|}{e} < 1.1 \times 10^{-29} \text{ cm}$$

[ACME, Nature 2018]

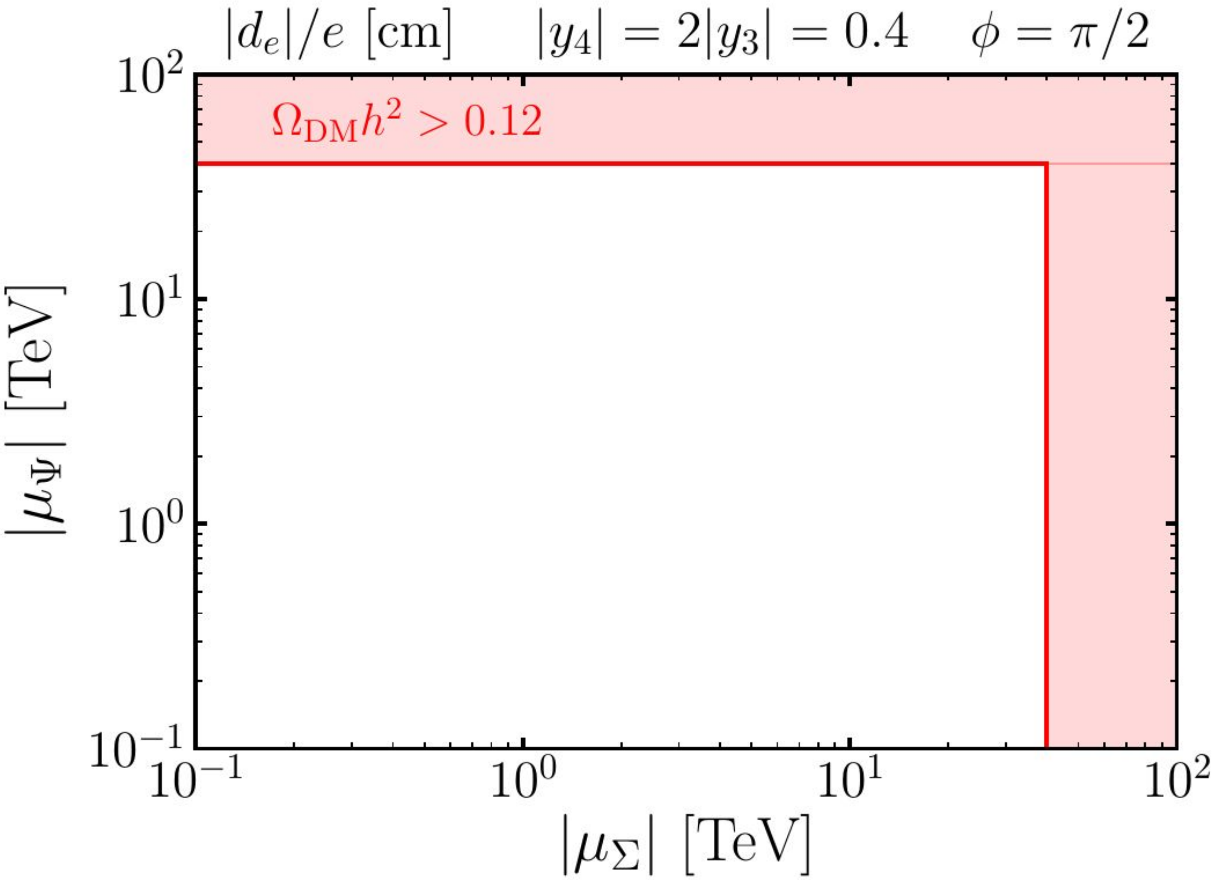
Naive tree-level contribution:

$$d_e \approx \frac{e m_e}{\Lambda^2} \approx \frac{\text{TeV}^2}{\Lambda^2} 10^{-23}\, e\,\text{cm}$$

$$\Rightarrow \quad \Lambda \geq 1{,}000 \text{ TeV}$$

Electron EDM

$$\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi) = \pi/2$$

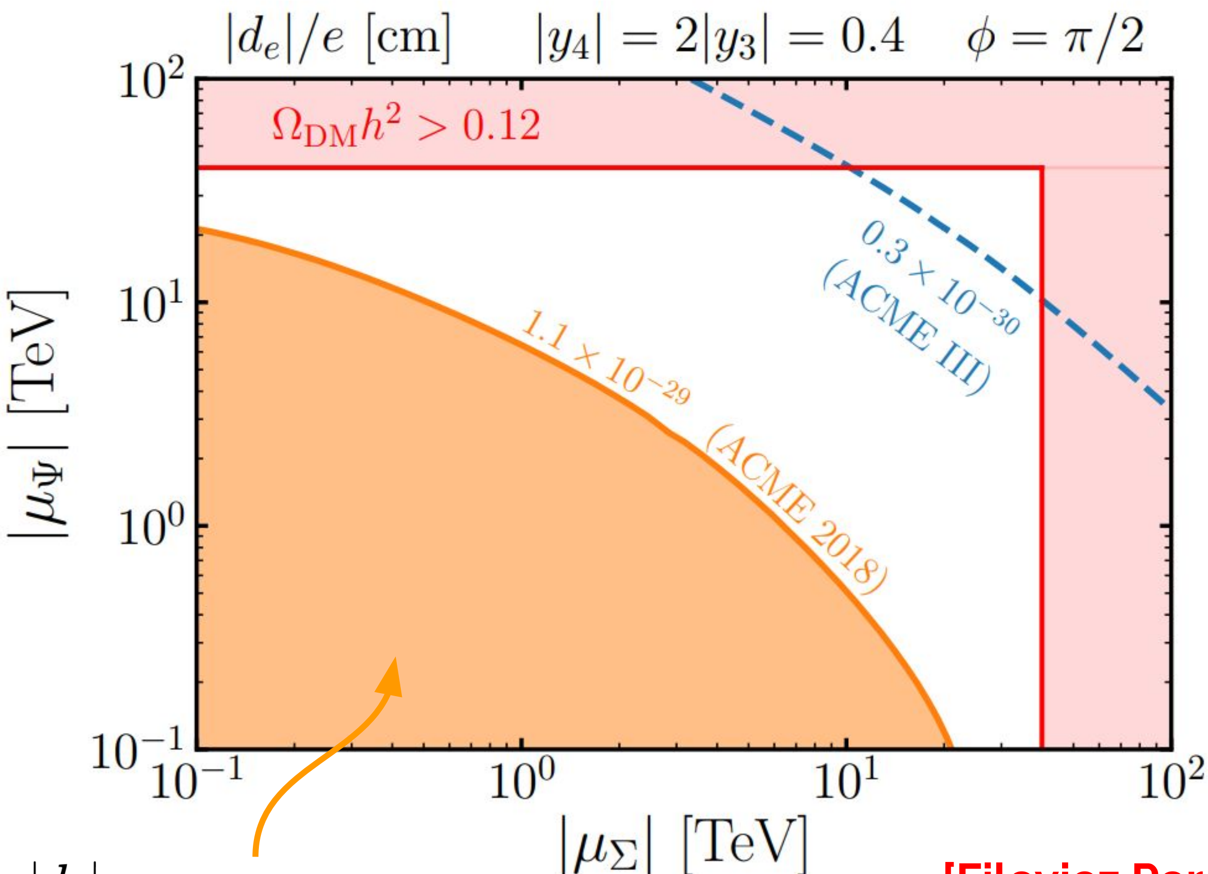


DM relic density requires:

$$|\mu_\Sigma|, |\mu_\Psi| < 40 \text{ TeV}$$

Electron EDM

$$\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi) = \pi/2$$



DM relic density requires:

$$|\mu_\Sigma|, |\mu_\Psi| < 40 \text{ TeV}$$

ACME bound implies:

$$|\mu_\Sigma|, |\mu_\Psi| > 20 \text{ TeV}$$

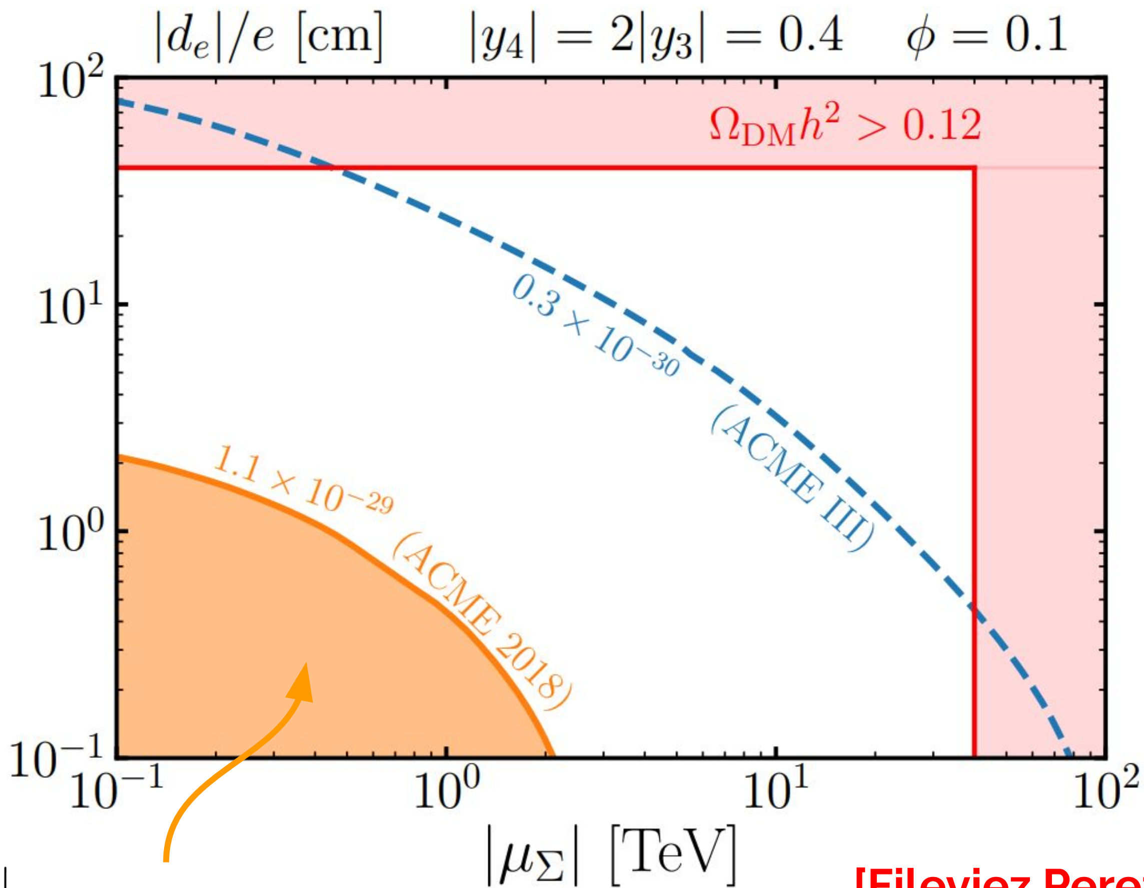
$$\frac{|d_e|}{e} < 1.1 \times 10^{-29} \text{ cm}$$

[ACME, Nature 2018]

[Fileviez Perez, ADP 2008.09116]

Electron EDM

$$\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi) = 0.1$$



DM relic density requires:

$$|\mu_\Sigma|, |\mu_\Psi| < 40 \text{ TeV}$$

ACME bound implies:

$$|\mu_\Sigma|, |\mu_\Psi| > 2 \text{ TeV}$$

$$\frac{|d_e|}{e} < 1.1 \times 10^{-29} \text{ cm}$$

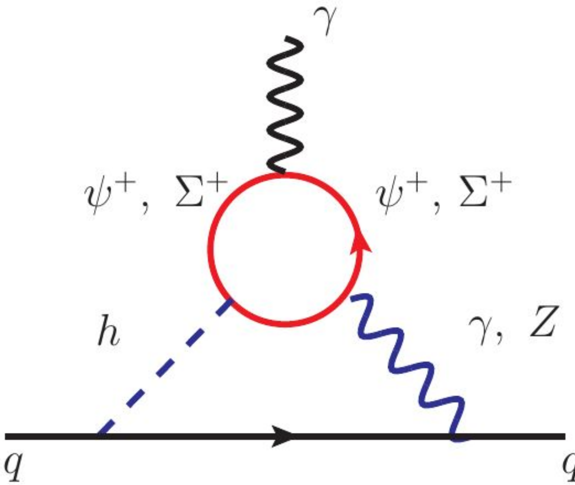
[ACME, Nature 2018]

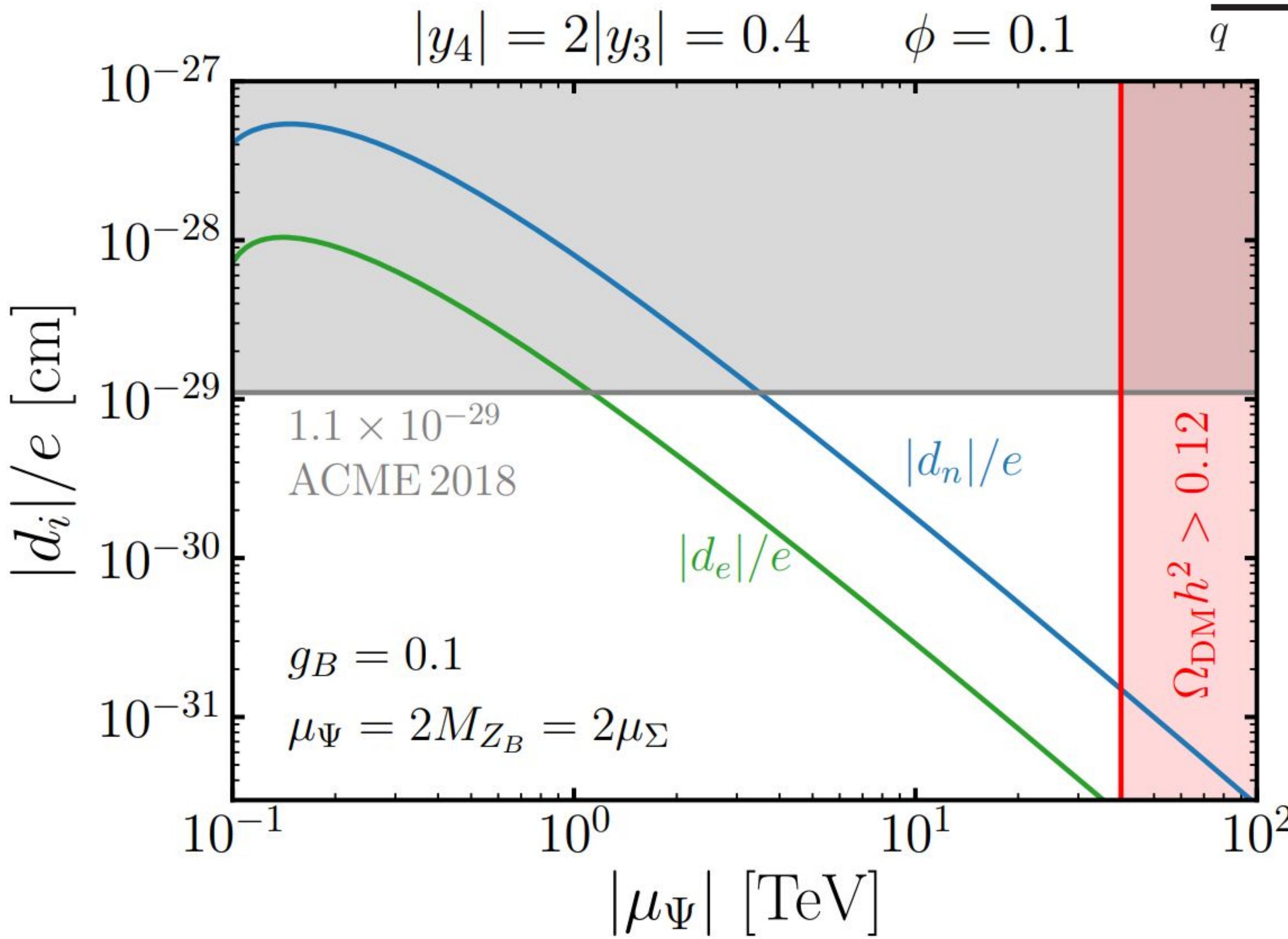
[Fileviez Perez, ADP 2008.09116]

Neutron EDM

$$d_n = (1.4 \pm 0.6)\,(d_d - 0.25 d_u)$$

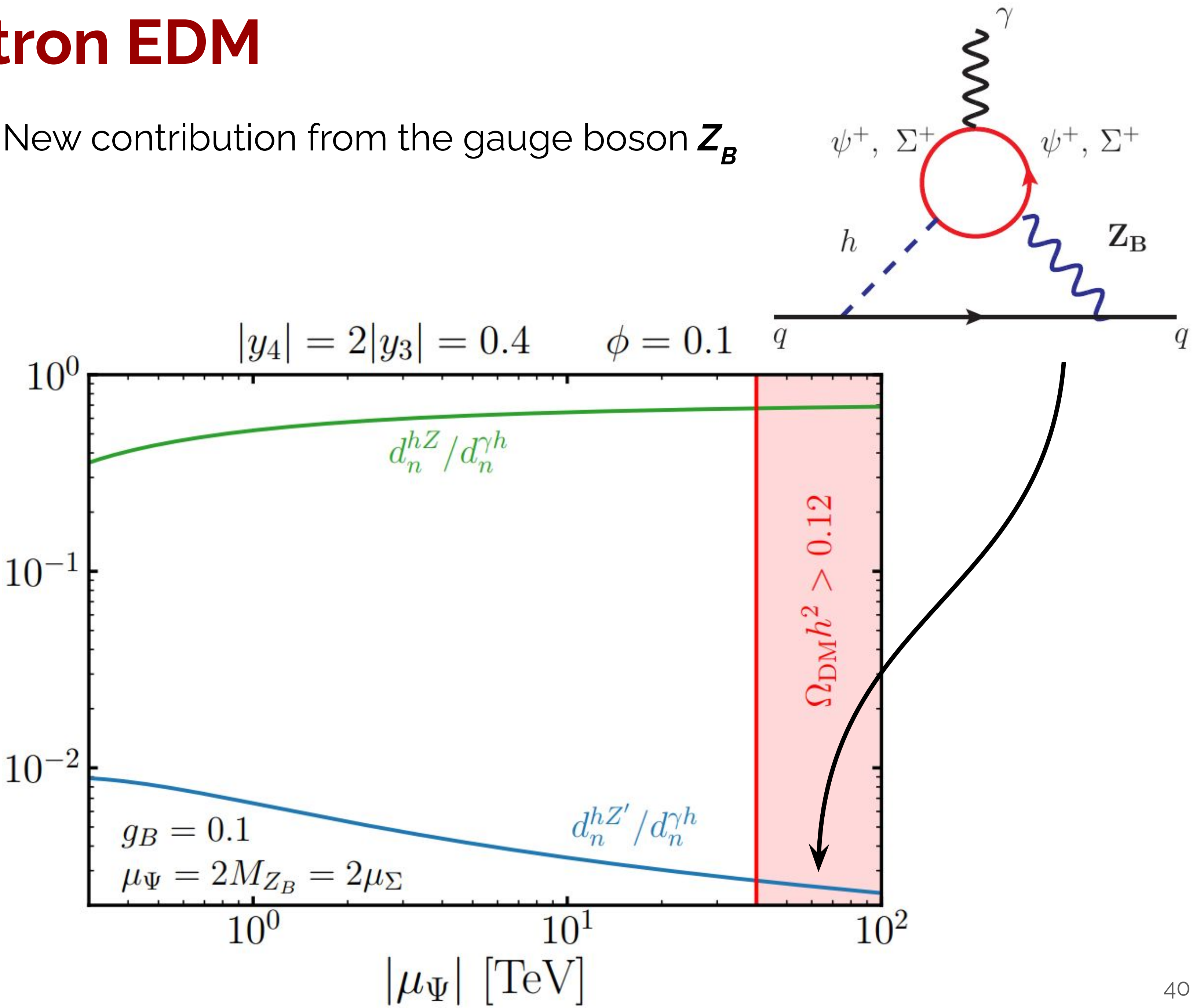
[Pospelov, Ritz 0504231]





Neutron EDM

- New contribution from the gauge boson $\boldsymbol{Z_B}$



Conclusions

- Promoting baryon and/or lepton number to local symmetries predicts a new sector from anomaly cancellation

- One of these new fermions is neutral and stable, and hence, a good dark matter candidate

- Not overproducing dark matter gives an upper bound on the full theory at the multi-TeV scale

- Leptophobic mediator leads to interesting phenomenology at the LHC

- New sources of CP violation that lead to large EDMs. Experiments such as ACME could fully probe the predictions for the electron EDM

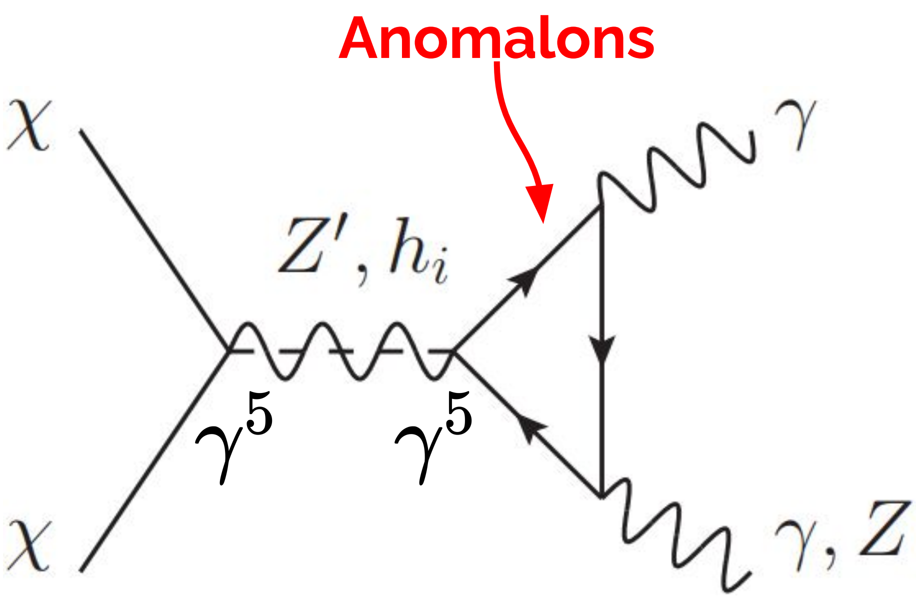
Thank you!

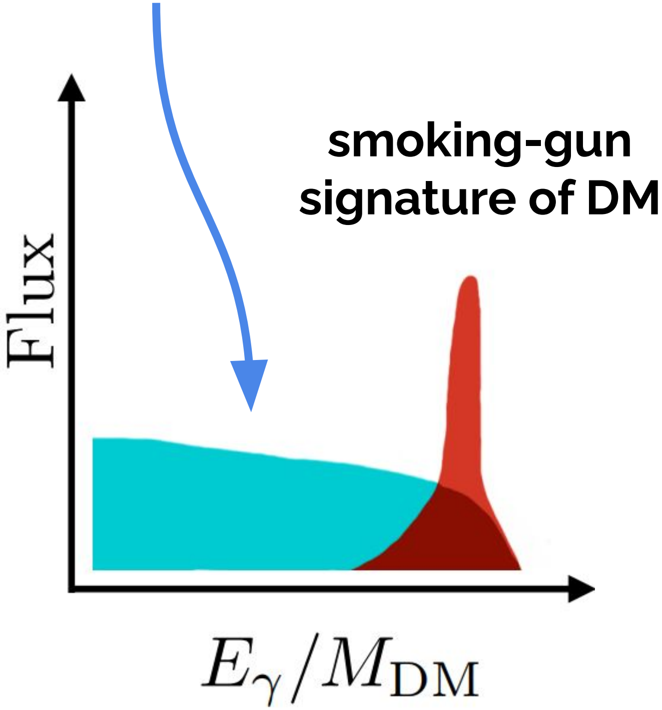

thank you
danke
謝謝
ngiyabonga
teşekkür ederim
gracias
merci
obrigado
bedankt
dziękuję
go raibh maith agat
mochchakkeram
sukriya
kop khun krap
terima kasih
grazie
arigatô
takk
dakujem
tapadh leat
dank je
спасибо
Баярлалаа
рахмат
mersi
kia ora
barka
welalin
tack
spas
faafetai lava
vinaka
спасибі
blagodaram
misaotra
matondo
paldies
grazzi
mahalo
хвала
asante
manana
obrigada
murakoze
tenki
kiitos
dankie
nanni
nandri
dhanyavad
mauruuru
köszönöm
hvala
gràçie
bayarlalaa
enkosi
akun
dankon
djiere dieuf
tau
дякую
mamnun
chokrane
chnorakaloutioun
gratias ago
gràcies
sulpáy
taiku
sobodi
děkuji
mèsi
didi madloba
sağolun
najis tuke
ありがとう
tanemirt
rahmet
trugarez
kam sah hamnida
rahmat
감사합니다
xièxie
ευχαριστώ
diolch
dhanyavadagalu
shukriya
mercê
мерси
তোমাকে ধন্যবাদ

Back-up

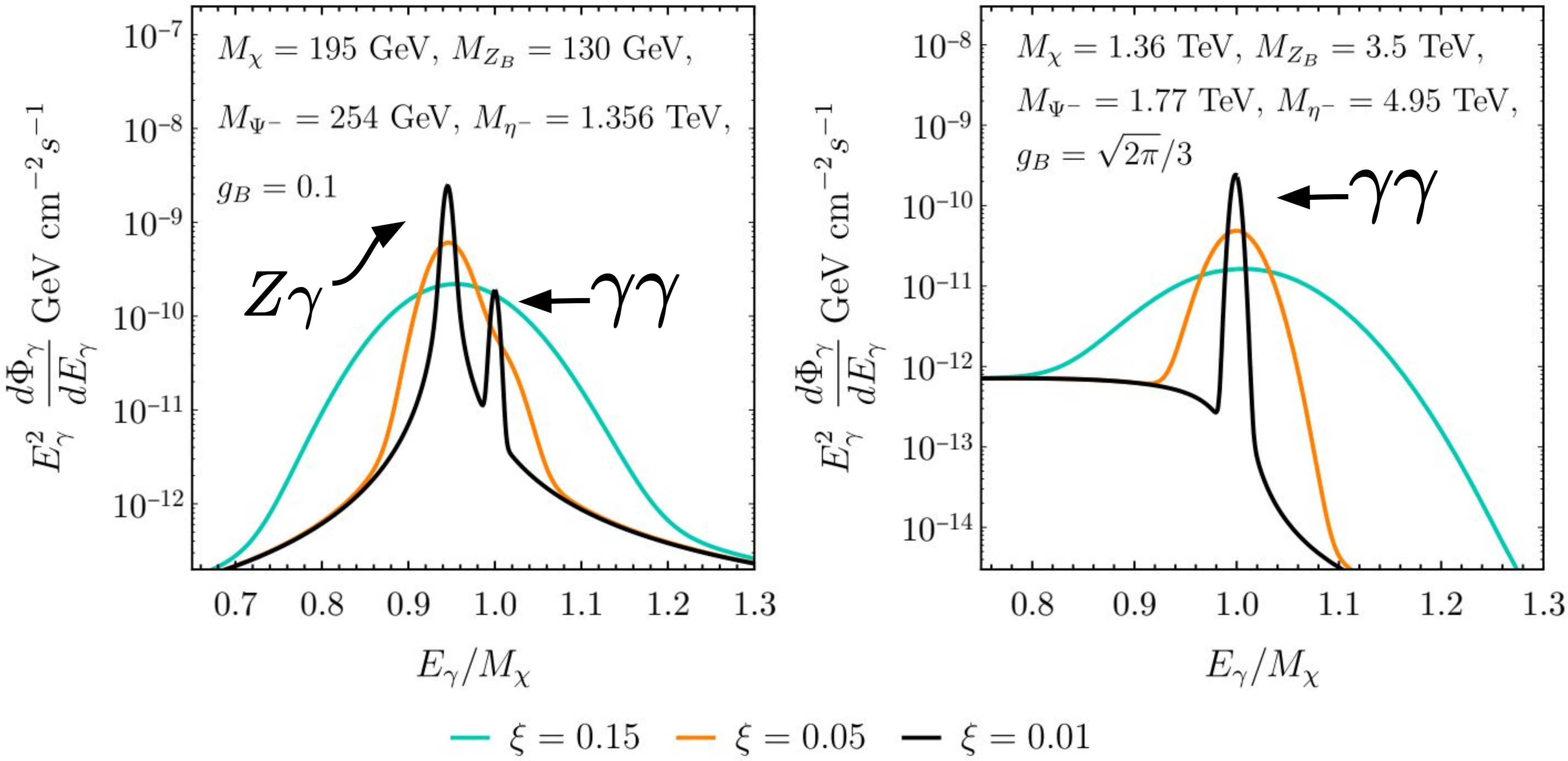
Gamma lines

- DM annihilation into $\gamma\gamma$ possible. Thanks to new fermions required for anomaly cancellation in the loop.
- Peak at $E = M_{DM}$ in the gamma spectrum
- Continuum is velocity suppressed, because of axial coupling





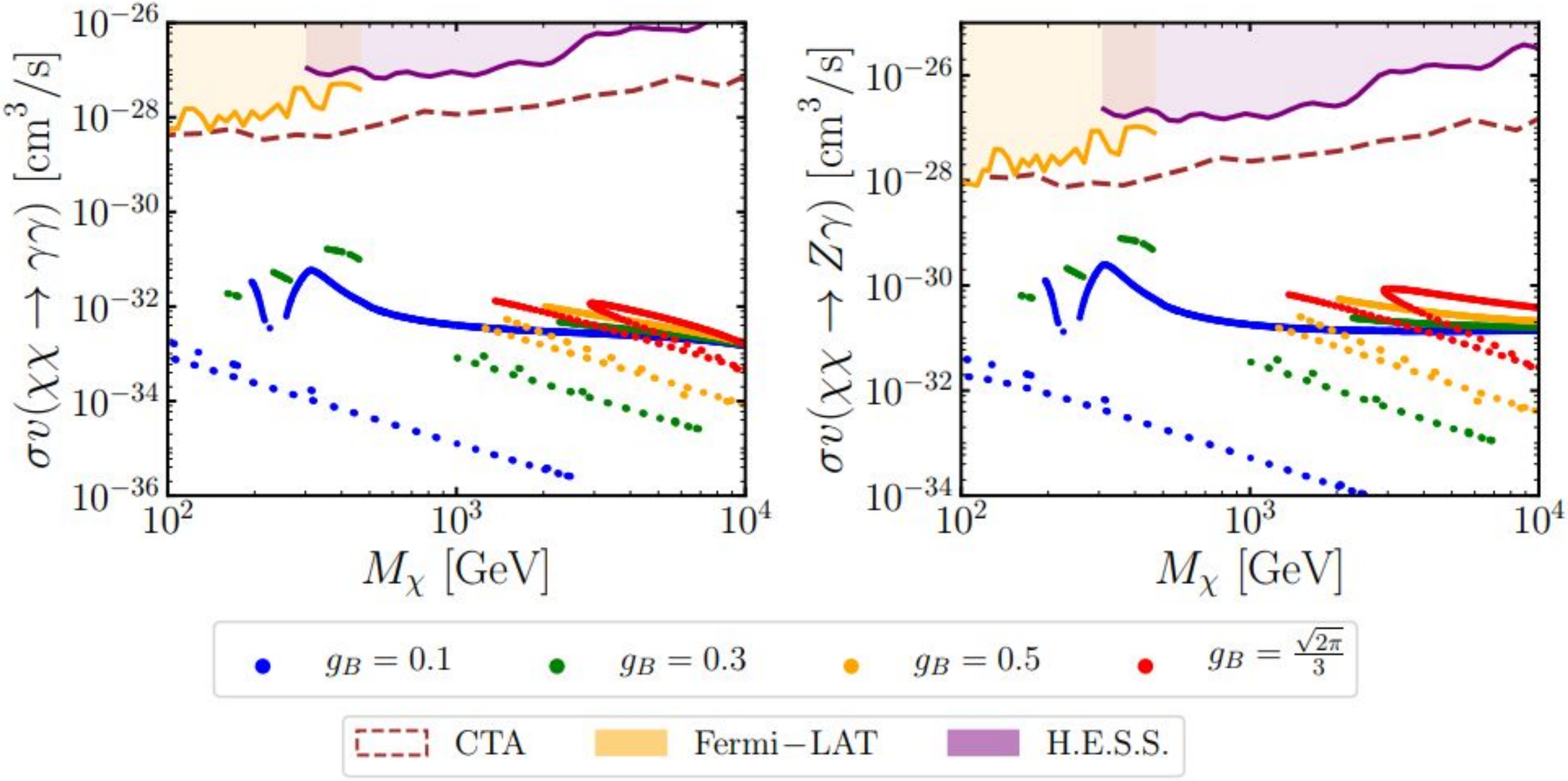
Gamma lines $\Omega h^2 = 0.12$



[Fileviez Perez, Golias, Li, Murgui, ADP 1904.01017]

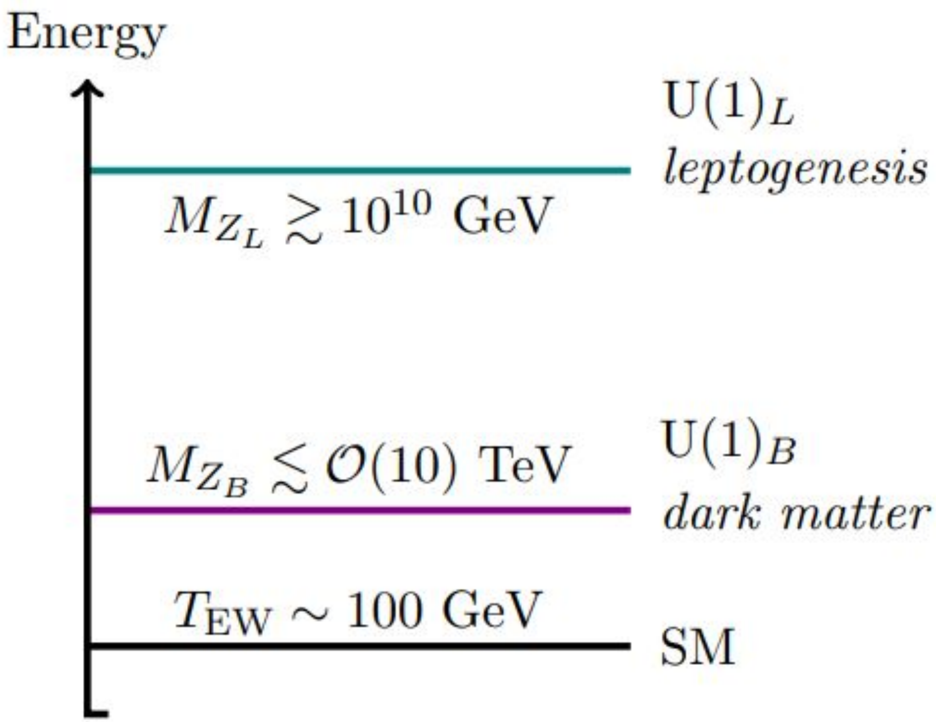
Gamma lines

All points satisfy: $\Omega h^2 = 0.12 \pm 0.0022$



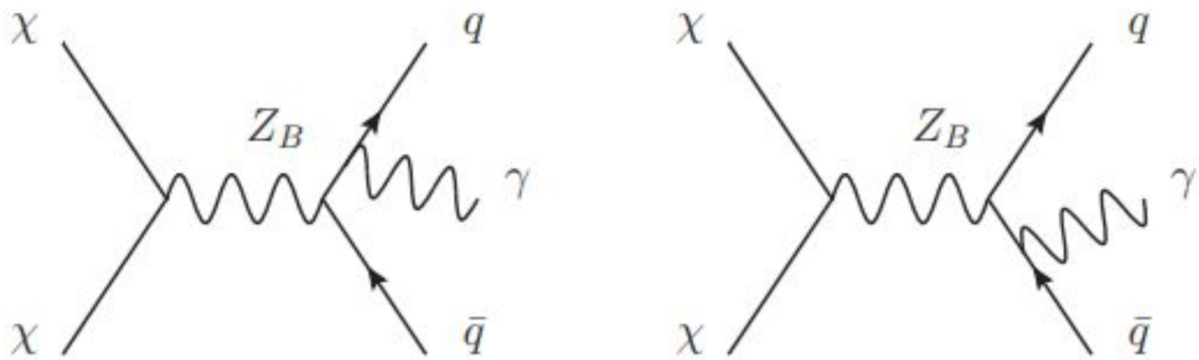
[Fileviez Perez, Golias, Li, Murgui, ADP 1904.01017]

Energy Scales of New Physics



[Fileviez Perez, Murgui, ADP 2103.13397]

Final State Radiation



$$|\mathcal{M}|^2_{\rm FSR} = \frac{M_q^2}{M_{Z_B}^2} A + v^2 B + \mathcal{O}(v^4),$$

$$A = 12\pi\,\alpha\, g_B^4 Q_q^2 (M_{Z_B}^2 - 4M_\chi^2)^2 \frac{(E_q + E_\gamma - M_\chi)^2\left(2(E_q - M_\chi)(E_q + E_\gamma - M_\chi) - 3M_q^2\right)}{M_{Z_B}^2 (E_q - M_\chi)^2 (E_q + E_\gamma - M_\chi)^2 ((4M_\chi^2 - M_{Z_B}^2)^2 + \Gamma_{Z_B}^2 M_{Z_B}^2)}, \qquad (32)$$

$$B = 12\pi\,\alpha\, g_B^4 M_\chi^2 Q_q^2 \times$$
$$\frac{\left(2E_q M_\chi (E_\gamma^2 - 3E_\gamma M_\chi + 2M_\chi^2) - 2E_q^4 - 2E_q^3 (E_\gamma - 2M_\chi) - E_q^2 (E_\gamma^2 - 6E_\gamma M_\chi + 6M_\chi^2) - 2M_\chi^2 (E_\gamma - M_\chi)^2\right)}{M_{Z_B}^2 (E_q + E_\gamma - M_\chi)^2 ((4M_\chi^2 - M_{Z_B}^2)^2 + \Gamma_{Z_B}^2 M_{Z_B}^2)}. \qquad (33)$$

Model with 6 representations

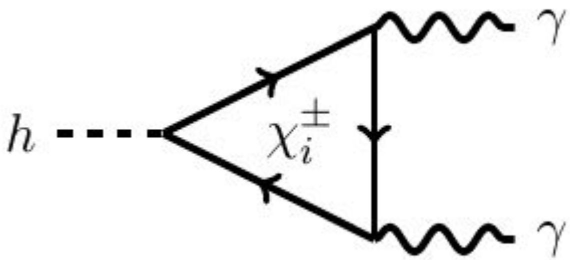
Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
$\Psi_L = \begin{pmatrix} \Psi_L^0 \\ \Psi_L^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	B_1
$\Psi_R = \begin{pmatrix} \Psi_R^0 \\ \Psi_R^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	B_2
η_R	$\mathbf{1}$	$\mathbf{1}$	-1	B_1
η_L	$\mathbf{1}$	$\mathbf{1}$	-1	B_2
χ_R	$\mathbf{1}$	$\mathbf{1}$	0	B_1
χ_L	$\mathbf{1}$	$\mathbf{1}$	0	B_2

Dirac dark matter

[Duerr, Fileviez Perez & Wise 2013]

$$B_1 - B_2 = -3$$

SM Higgs diphoton decay rate



This modifies the SM Higgs diphoton decay rate!

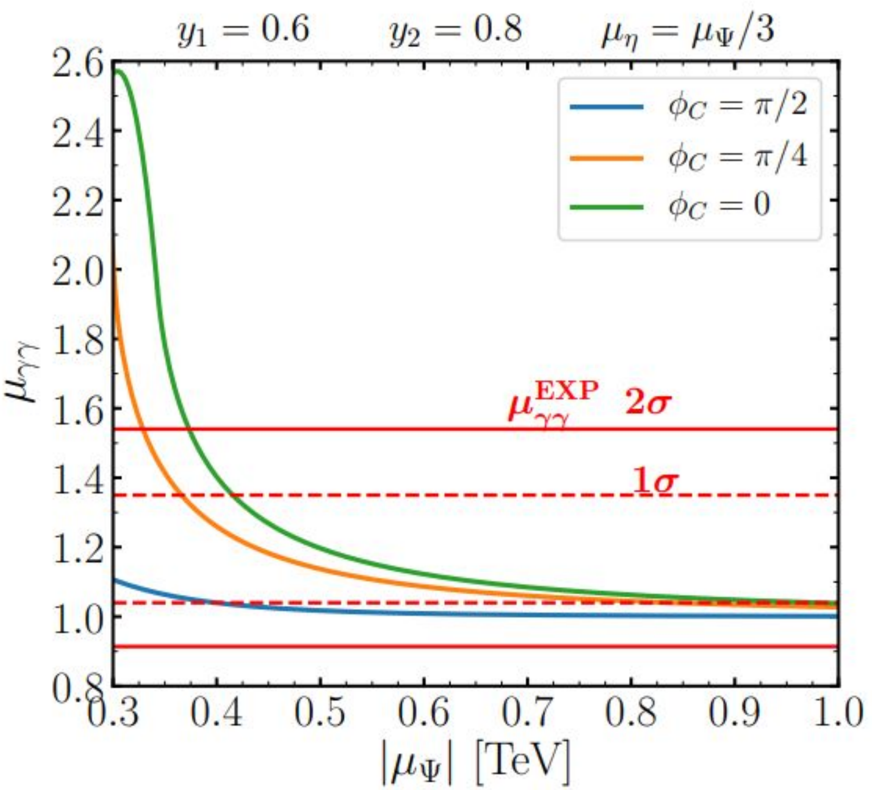
BSM + SM interference can be large!

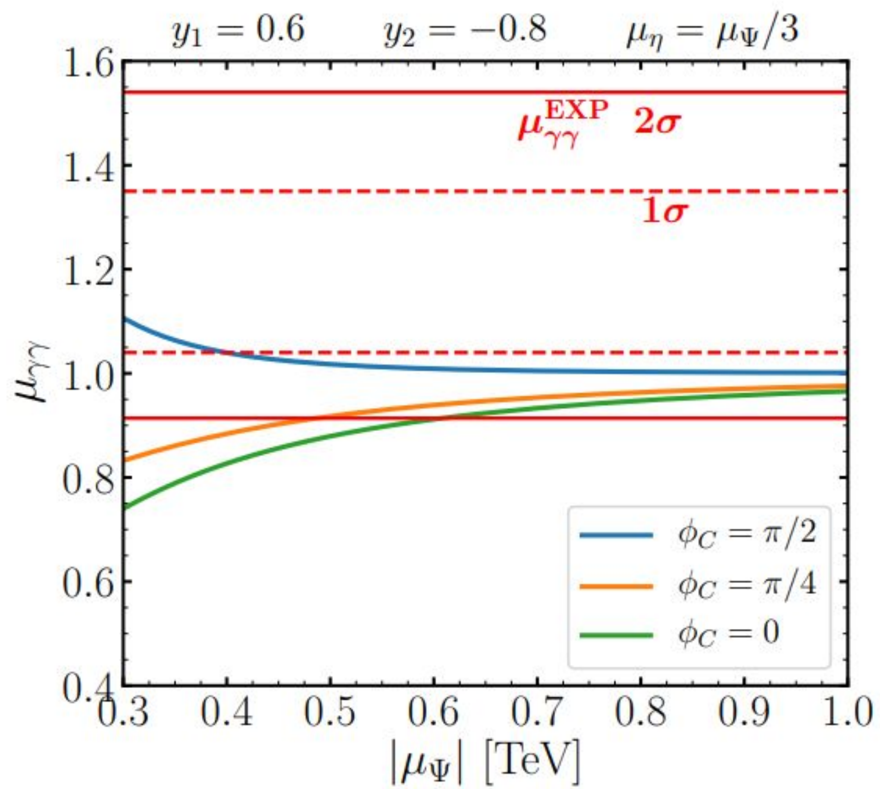
$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2}{64\pi^3 M_h^5} \left| \sum_{i=1}^{2} M_{\chi_i^\pm} \mathrm{Re}[C_{hc}^{ii}]\, F_{\chi_i^\pm} + \frac{\cos\theta_B}{v_0} \left(\sum_{f^+} N_c^f Q_f^2 m_{f^+}^2 F_{f^+} - F_W \right) \right|^2$$
$$+ \frac{\alpha^2}{64\pi^3 M_h} \left| \sum_{i=1}^{2} M_{\chi_i^\pm} \mathrm{Im}[C_{hc}^{ii}]\, G_{\chi_i^\pm} \right|^2 , \qquad (4.1)$$

[Fileviez Perez, ADP 2112.02103]

Results

ATLAS: $\mu_{\gamma\gamma} = 1.16 \pm 0.14$ **CMS:** $\mu_{\gamma\gamma} = 1.18^{+0.17}_{-0.14}$

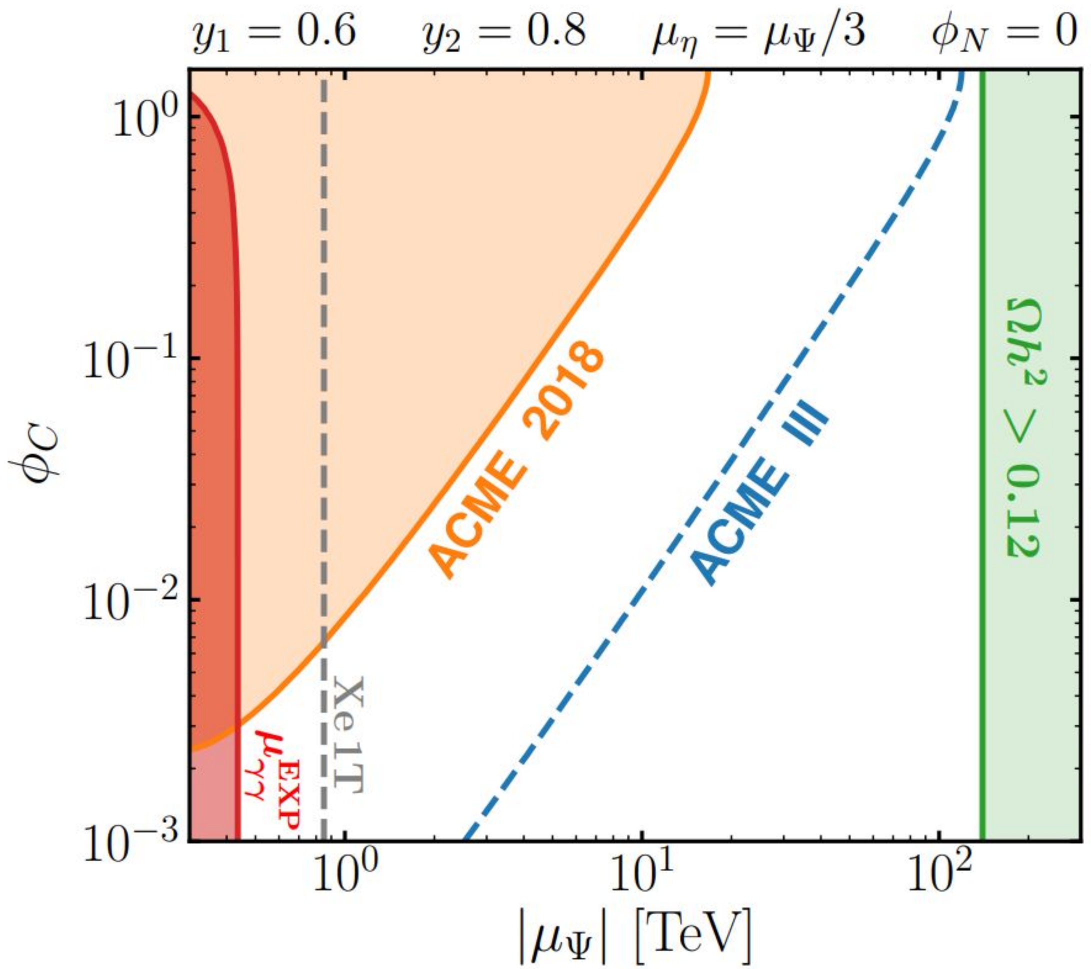




[Fileviez Perez, ADP 2112.02103]

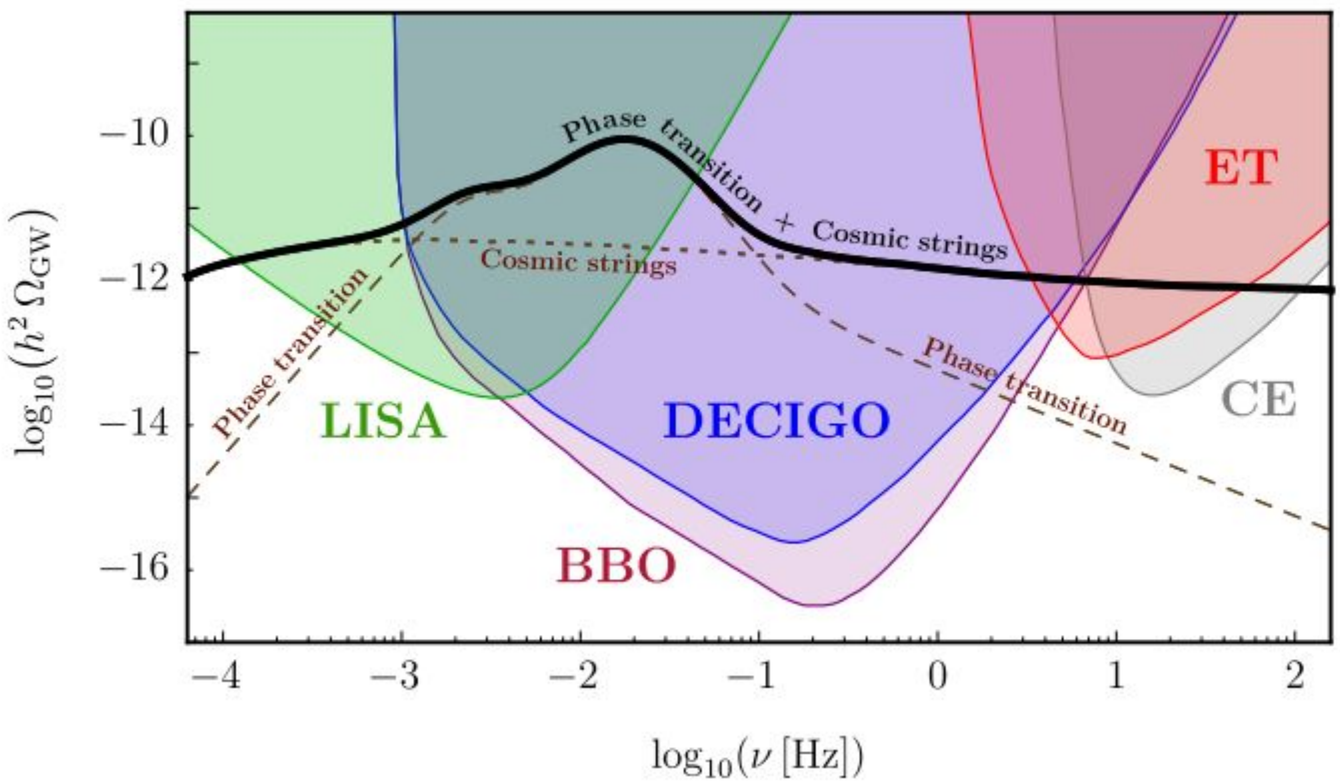
Results

Complementarity between measuring Electric Dipole Moments and the SM Higgs diphoton decay rate



[Fileviez Perez, ADP 2112.02103]

Gravitational Waves



[Fornal & Shams Es Haghi 2008.05111]