Minimal dark matter model for muon g-2 with scalar lepton partners at the TeV scale

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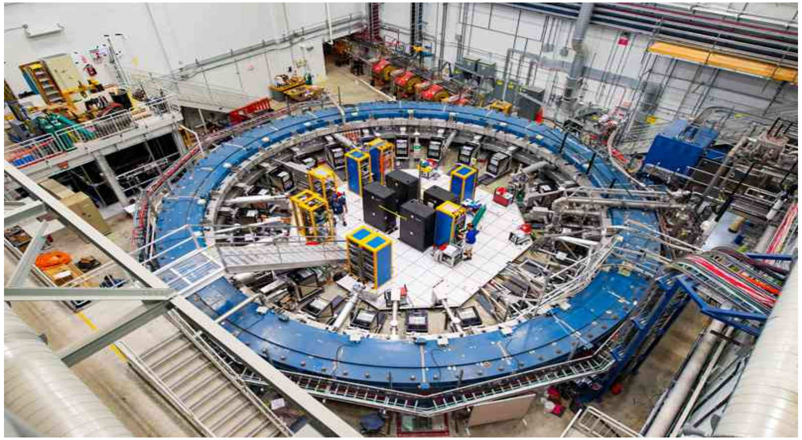
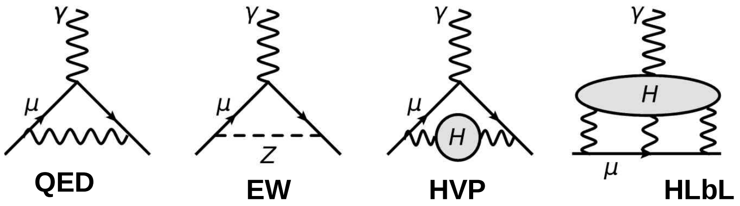
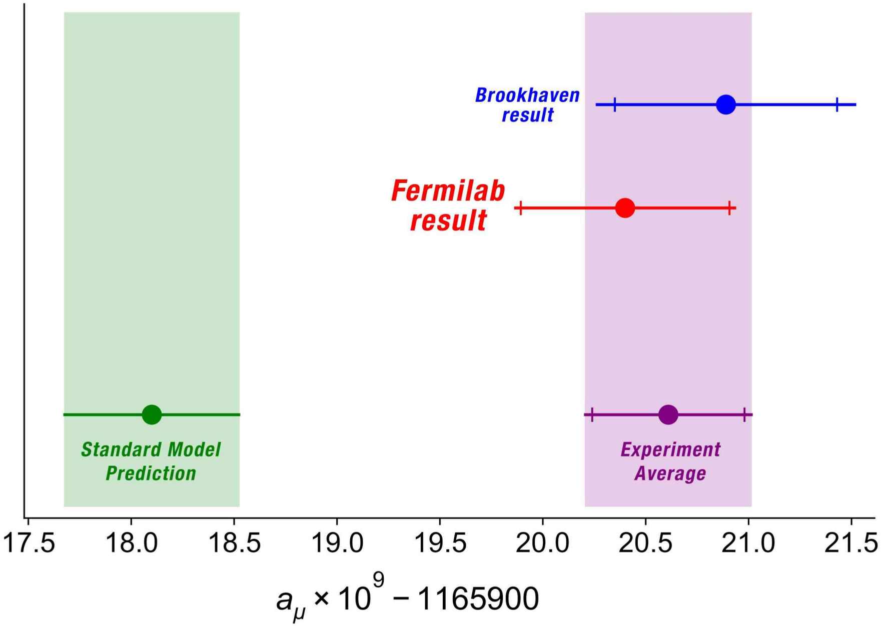
Outline

- Motivation: muon g-2 anomaly
- A minimal framework: two sets of muonic scalars and a Majorana
- DM production mechanism
- Theoretical consistency constraints
- Direct detection
- Conclusions

Motivation: FNAL measurement







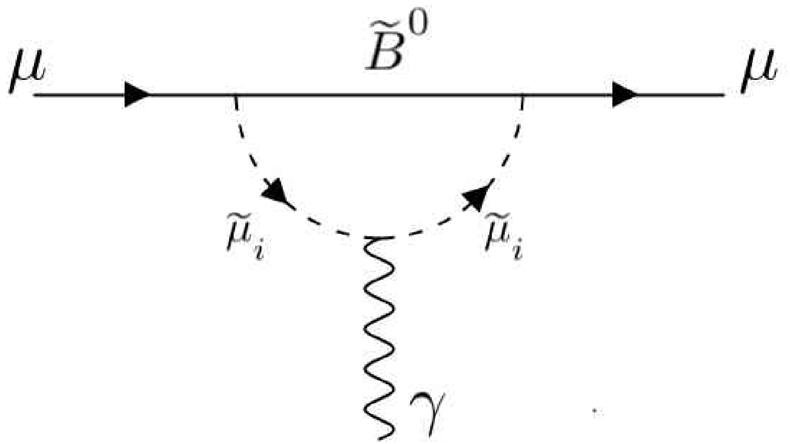
Hadronic contribution: Data-driven (dispersion relation) vs first-principles (lattice QCD; reduction to 1.5σ tension)

$$a_\mu(FNAL) = 116592040(54)\times 10^{-11}(0.46\ ppm)$$
$$a_\mu(BNL) = 116592080(54)(33)\times 10^{-11}(0.54\ ppm)$$
$$a_\mu(\exp) = 116592061(41)\times 10^{-11}(0.35\ ppm)$$
$$a_\mu(SM) = 116591810(43)\times 10^{-11}(0.37\ ppm)$$

$$a_\mu \equiv \frac{g-2}{2}$$

$$\Delta a_\mu = (25.1 \pm 5.9)\times 10^{-10}$$

Assume new physics



Particle	$SU(2)_L$	$U(1)_Y$	Z_2
$\tilde{l}_L=(\tilde{\nu}_\mu \;\; \tilde{\mu}_L)^T$	2	-1/2	-1
$\tilde{\mu}_R$	1	-1	-1
$l_L=(\nu_\mu \;\; \mu_L)^T$	2	-1/2	1
μ_R	1	-1	1
$\tilde{B}^0$	1	1	-1

DM candidate

$$\mathcal{L} \supset -\lambda_{\tilde{\mu}_R}\tilde{\mu}_R^*\bar{\tilde{B}}^0 P_R\mu - \lambda_{\tilde{\mu}_L}\tilde{\mu}_L^*\bar{\tilde{B}}^0 P_L\mu - \lambda_{\tilde{\nu}}\tilde{\nu}_\mu^*\bar{\tilde{B}}^0 P_L\nu_\mu + \text{H.c.}.$$

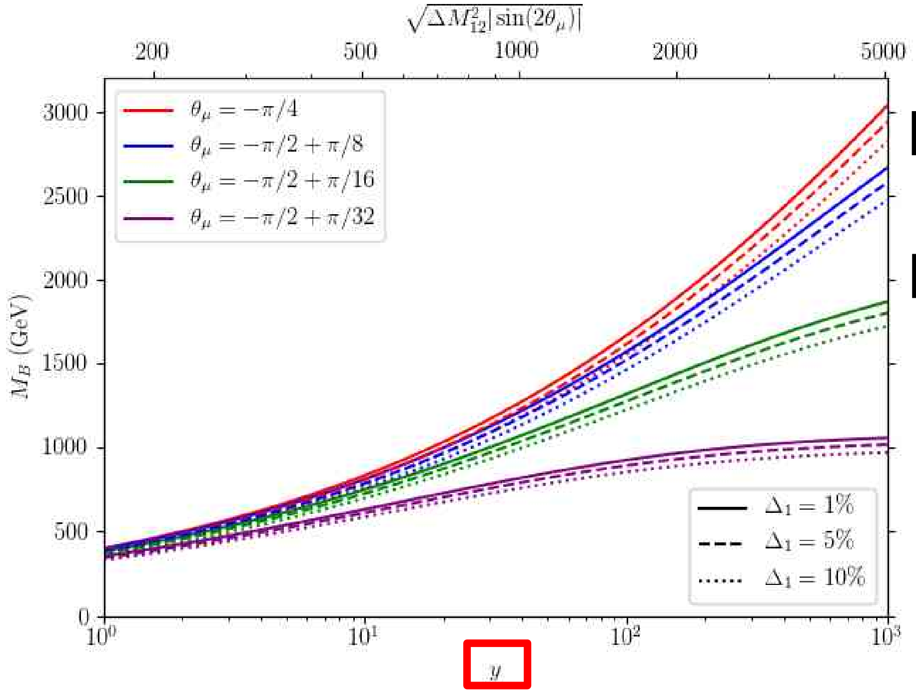
Generic LR mixing; origin yet unspecified

$$\mathcal{L} \supset -\begin{pmatrix} \tilde{\mu}_L^* & \tilde{\mu}_R^* \end{pmatrix} \begin{pmatrix} m_{LL}^2 & \boxed{m_{LR}^2} \\ m_{LR}^2 & m_{RR}^2 \end{pmatrix} \begin{pmatrix} \tilde{\mu}_L \\ \tilde{\mu}_R \end{pmatrix}$$

$$\begin{pmatrix} \tilde{\mu}_1 \\ \tilde{\mu}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{\mu}} & -\sin\theta_{\tilde{\mu}} \\ \sin\theta_{\tilde{\mu}} & \cos\theta_{\tilde{\mu}} \end{pmatrix} \begin{pmatrix} \tilde{\mu}_L \\ \tilde{\mu}_R \end{pmatrix}$$

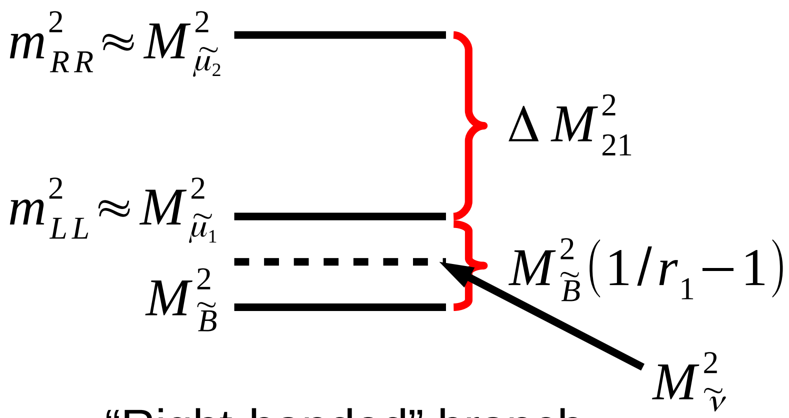
$$M_{\tilde{\nu}}^2 = M_{\tilde{\mu}_1}^2 + \Delta M_{21}^2 \sin^2\theta_{\tilde{\mu}} - M_W^2$$

Muon g-2 contribution

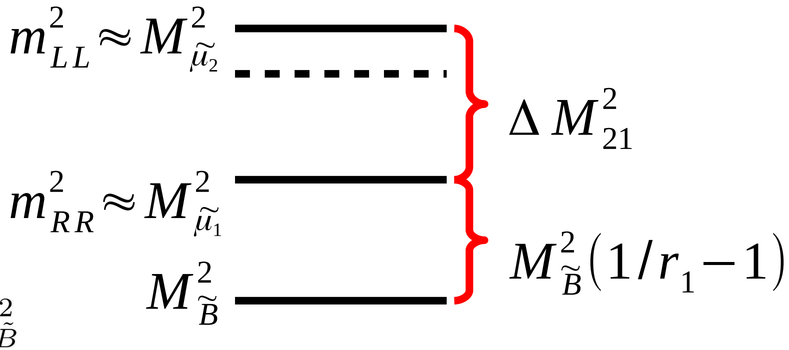


Parameter space:
M_B, Δ_1, y, θ

"Left-handed" branch



"Right-handed" branch



$$\frac{\Delta a_\mu}{25.1\times10^{-10}} \simeq \left(\frac{100\,\mathrm{GeV}}{M_{\tilde B}}\right)\left[-\frac{\sin(2\theta_{\tilde\mu})}{6.23\times10^{-2}}\right]\left[\frac{L_0(r_1)}{0.05}\right],\ \Delta M_{21}^2 \simeq M_{\tilde B}^2$$

$$\frac{\Delta a_\mu}{25.1\times10^{-10}} \simeq (0.068)\left(\frac{1\,\mathrm{TeV}}{M_{\tilde B}}\right)^3 \boxed{\left[-\frac{\Delta M_{21}^2\sin(2\theta_{\tilde\mu})}{4M_W^2}\right]}\left[\frac{L_1(r_1)}{0.083}\right],\ \Delta M_{21}^2 \ll M_{\tilde B}^2$$

Additional gauge invariant terms and MFV

- Interactions of extra states with SM gauge fields are implied
- Take MSSM as benchmark
- Only 1 light SM Higgs-like state
- **LR mixing comes from the A-term**

$$\mathcal{L} \supset m_Z^2 \sum_j \mathcal{S}_j^\dagger \left(\hat{T}_3 - \hat{Q}_{em} s_W^2\right) \mathcal{S}_j \left(1 + \frac{h}{v}\right)^2$$

$$\boxed{-\frac{m_{LR}^2}{v}} h(\tilde{\mu}_L \tilde{\mu}_R^\dagger + \text{h.c.})$$

$A_\mu = m_{LR}^2/v = gM_W\, y$

cf. **Minimal flavor violation (MFV) +**

weak scale-TeV dimensionful coupling

$A_\mu \sim$ (muon Yukawa)(weak scale)

Take home message: We are working in the "large y" regime where MFV assumption is relaxed!

DM production mechanism

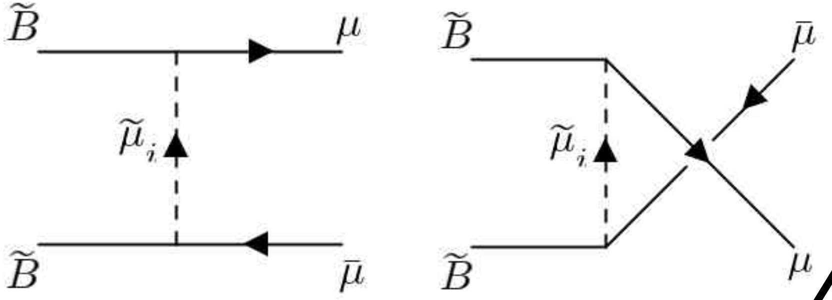
Standard lore:

S-wave annihilation
- need mass insertion ($\sim m_\mu^2/M^2$) to conserve angular momentum or LR mixing of scalars (killed by MFV)

P-wave annihilation
- leads to O(1) pb cross section for ~100 GeV sleptons; excluded by collider searches

"Incredible bulk"[1]
- MFV is relaxed, y can be large
- s-wave cross section is correlated with Δa_μ

WIMP thermal freeze-out?



Remark: Could be saved by CPV phase (enters as $1/\cos^2\varphi$)

$$\Omega h^2 \sim 0.1 \left(\frac{1\ \text{pb}}{\langle \sigma v\rangle (T_f)}\right)$$

$$\begin{aligned}\langle \sigma v\rangle_0 &= \frac{32\pi^3}{m_\mu^2}(\Delta a_\mu)^2\,\mathcal{F}\\ &= \boxed{(2.25\times 10^{-4}\ \text{pb})}\boxed{\left(\frac{\Delta a_\mu}{25\times 10^{-10}}\right)^2}\mathcal{F},\end{aligned}$$

$$\mathcal{F} \equiv \frac{1}{[L(M_B^2/m_1^2) - L(M_B^2/m_2^2)]^2}\left(\frac{1}{1+m_1^2/M_B^2} - \frac{1}{1+m_2^2/M_B^2}\right)^2$$

[1] Fukushima, K., Kelso, C., Kumar, J., Sandick, P., & Yamamoto, T. (2014). MSSM dark matter and a light slepton sector: The incredible bulk. Physical Review D, 90(9), 095007.

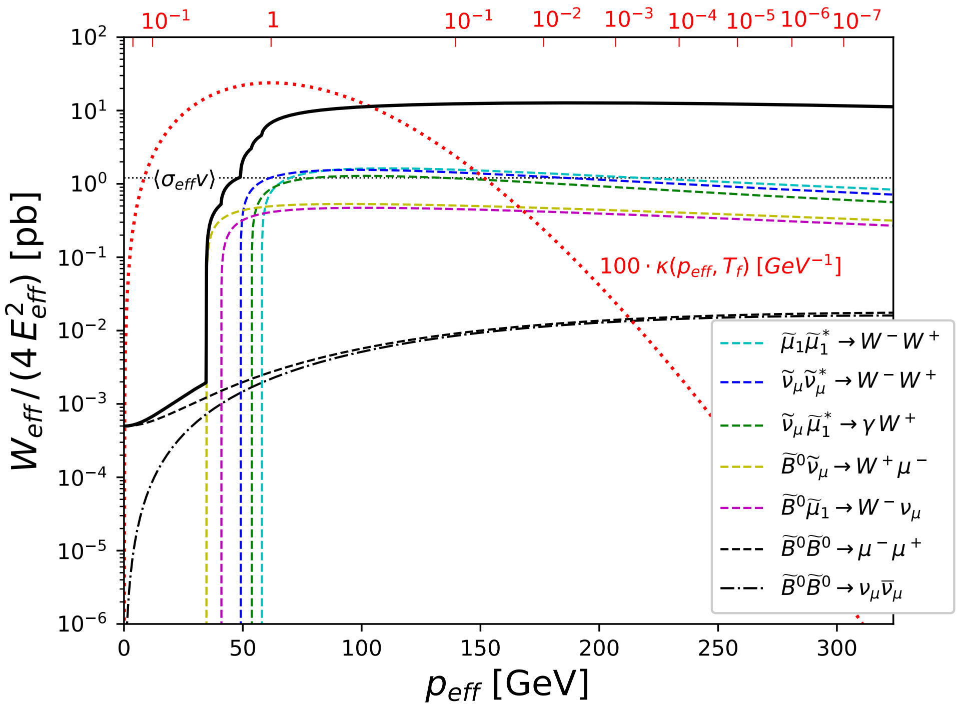
DM production mechanism

Coannihilations

$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle_{eff}\left(n^2 - n_{eq}^2\right)$$

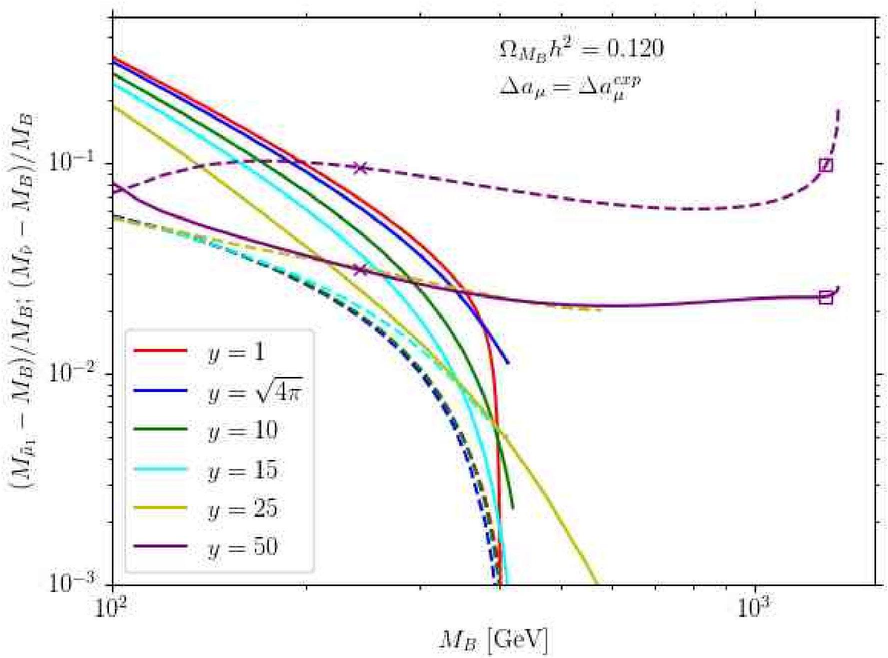
$$\langle\sigma_{\rm eff} v\rangle(T) = \sum_{ij}\langle\sigma_{ij}v\rangle(T)\frac{n_i^{\rm eq}(T)n_j^{\rm eq}(T)}{[n^{\rm eq}(T)]^2}$$
$$= \frac{\int_0^\infty dp_{\rm eff}\,p_{\rm eff}^2 W_{\rm eff}(s)K_1(\frac{\sqrt{s}}{T})}{m_1^4 T[\sum_i \frac{g_i}{g_1}\frac{m_i^2}{m_1^2}K_2(\frac{m_i}{T})]^2}$$

$$W_{\rm eff}(s) = \sum_{ij}\frac{p_{ij}}{p_{11}}\frac{g_i g_j}{g_1^2}W_{ij}$$
$$= \sum_{ij}\sqrt{\frac{[s-(m_i-m_j)^2][s-(m_i+m_j)^2]}{s(s-4m_1^2)}}\frac{g_i g_j}{g_1^2}W_{ij}$$

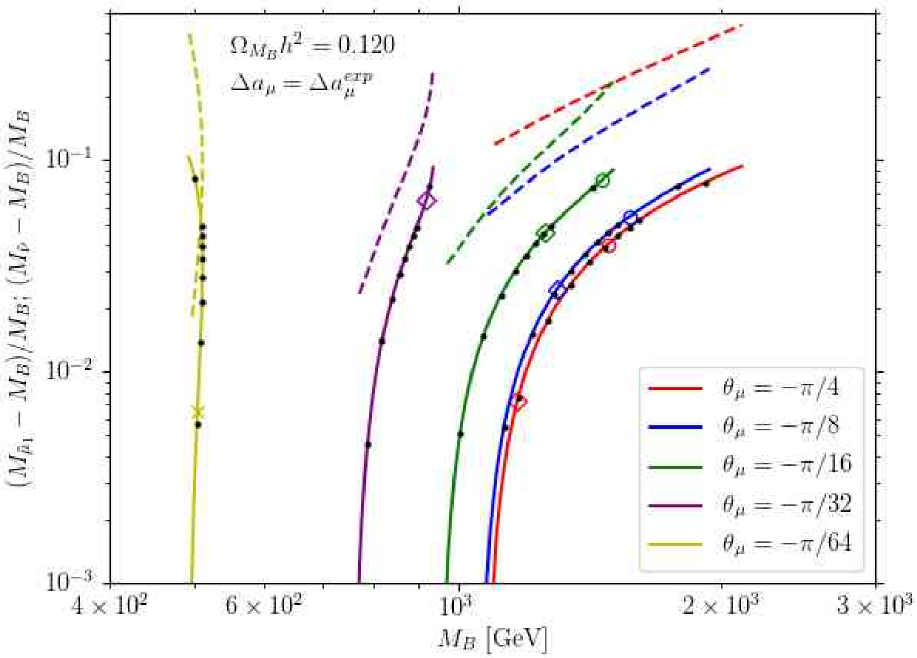


$$\langle\sigma_{\rm eff} v\rangle = \int_0^\infty dp_{\rm eff}\frac{W_{\rm eff}(p_{\rm eff})}{4E_{\rm eff}^2}\kappa(p_{\rm eff},T)$$

g-2 + relic density



LHB (fixed y)
(dashed curve:
sneutrino-bino
rel. mass split.)



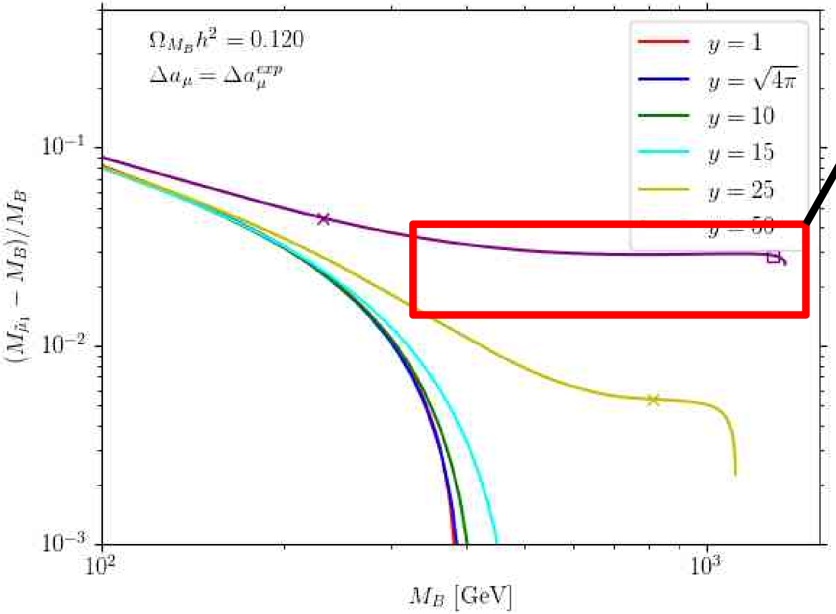
LHB (fixed θ)

$$\langle \sigma v \rangle_{eff} = \sum_{ij} \langle \sigma v \rangle_{ij} r_i r_j,$$

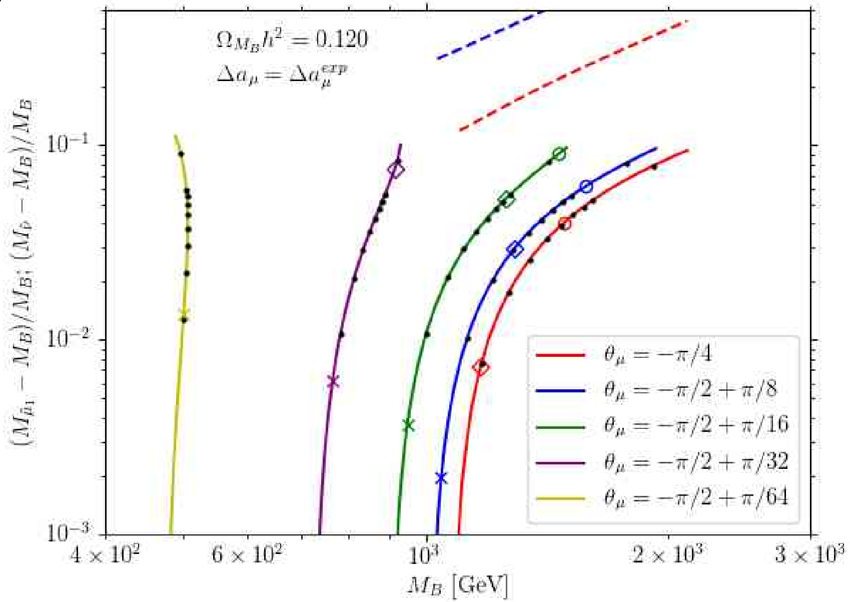
$$r_i \equiv \frac{\frac{g_i}{g_{\rm LSP}} (1+\Delta_i)^{3/2} \exp(-x\Delta_i)}{1 + \sum_{k \neq {\rm LSP}} \frac{g_k}{g_{\rm LSP}} (1+\Delta_k) \exp(-x\Delta_k)}$$

g-2 + relic density

Large *y*: What's happening here???



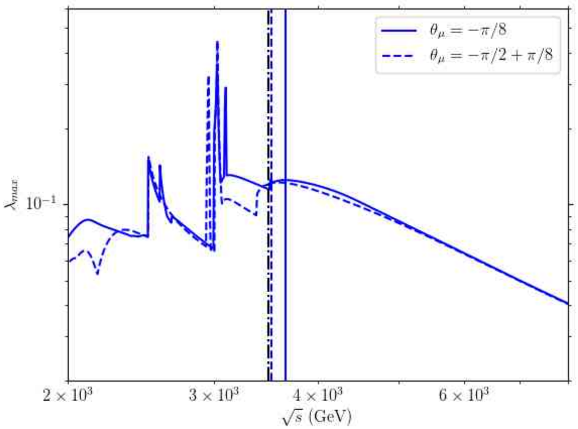
RHB (fixed y)



RHB (fixed θ)

Take home message: Low *y* explored in old MSSM scans; relaxing MFV and considering compressed spectra leads to TeV scale particles

Theoretical consistency: Perturbative unitarity

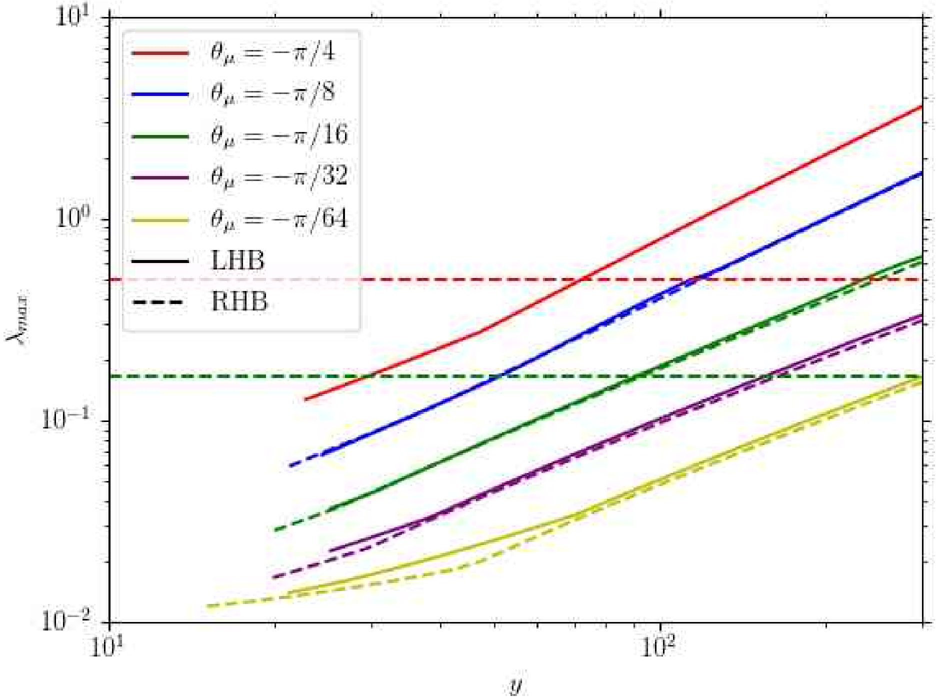


$$a_{fi,J}(s) \equiv \frac{1}{32\pi}\sqrt{\frac{4p_1p_3}{2^{\delta_{12}}2^{\delta_{34}}s}}\int_{-1}^{1} d(\cos\theta)T_{fi}(s,\cos\theta)P_J(\cos\theta)$$

$$2\mathrm{Im}\{a_{fi,J}\} \leq \sum_k a^*_{kf,J}a_{ki,J}$$

Criterion: Max eigenvalue < 0.5

Implemented using SARAH-SPheno interfacing



Careful not to pick up the poles and thresholds!

Theoretical consistency: EW vacuum stability

$$V_2 = \frac{m_{LL}^2}{2}(X^2 + Y^2) + \frac{m_{RR}^2}{2} Z^2 + \frac{\mu^2}{2} h^2$$

$$V_{\rm mix} = \frac{k_s}{\sqrt{2}} hYZ$$

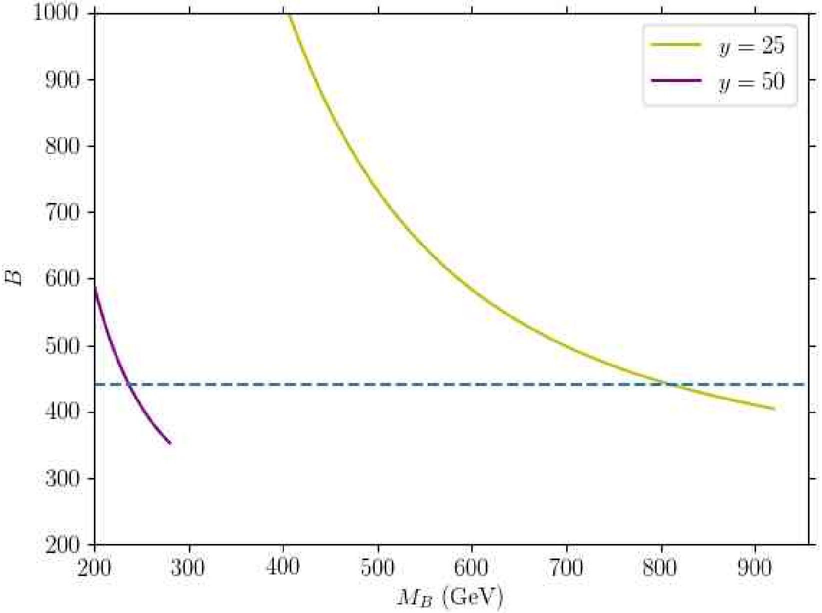
$$V_D^{(1)} = \frac{g'^2}{32}[h^2 - (X^2 + Y^2) + 2Y_R Z^2]^2$$

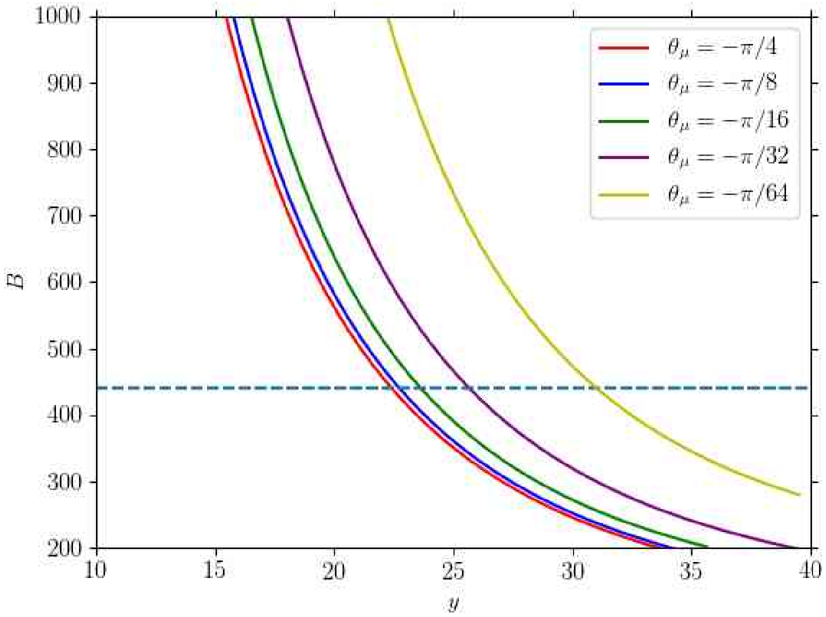
$$V_D^{(2)} = \frac{g^2}{32}[h^4 - 2h^2(X^2 - Y^2) + (X^2 + Y^2)^2].$$

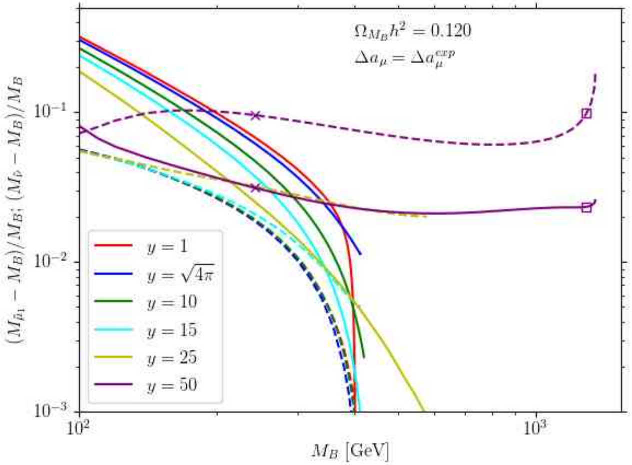
- Absolute stability
- Metastability
  - Equivalent to setting the bounce action B at least 440
- Used FindBounce to compute B

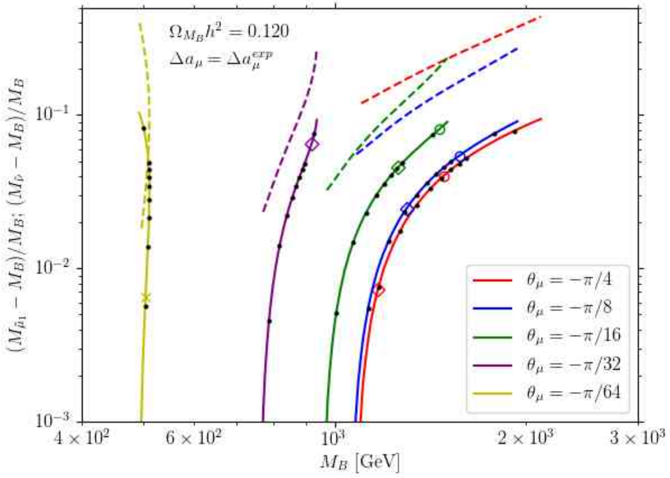
$$B = \int_0^\infty d\rho[\mathcal{T} + \mathcal{V}], \qquad \mathcal{T} = \frac{\pi^2}{2}\rho^3 \left[\frac{1}{2}\sum_{\phi=h,Y,Z}\left(\frac{d\phi}{d\rho}\right)^2\right],$$

$$\mathcal{V} = \frac{\pi^2}{2}\rho^3 V_{\rm tot}(h, Y, Z)$$


$y = 25$
$y = 50$
B
M_B (GeV)

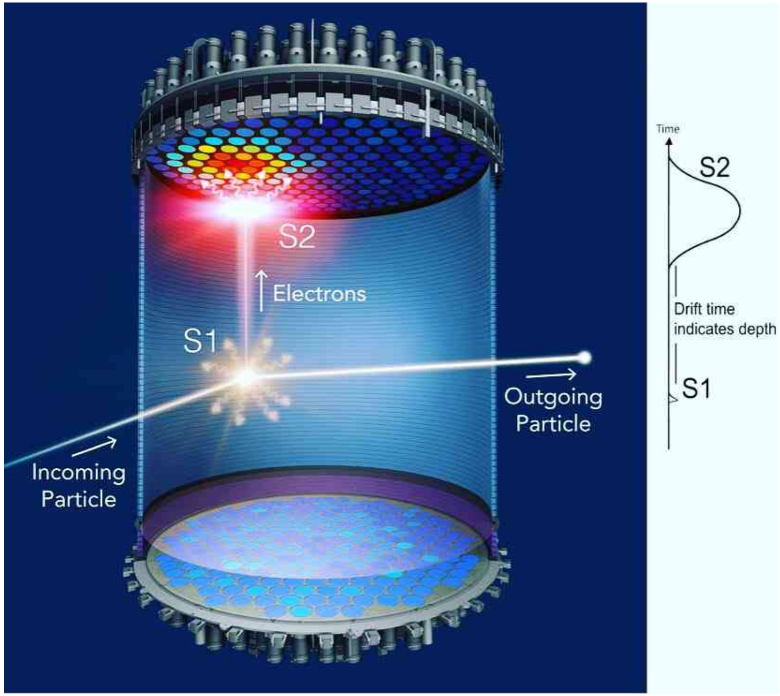

$\theta_\mu = -\pi/4$
$\theta_\mu = -\pi/8$
$\theta_\mu = -\pi/16$
$\theta_\mu = -\pi/32$
$\theta_\mu = -\pi/64$
B
y


$\Omega_{M_B} h^2 = 0.120$
$\Delta a_\mu = \Delta a_\mu^{exp}$
$y = 1$
$y = \sqrt{4\pi}$
$y = 10$
$y = 15$
$y = 25$
$y = 50$
$(M_{\tilde{\mu}_1} - M_B)/M_B;\ (M_{\tilde{\nu}} - M_B)/M_B$
M_B [GeV]


$\Omega_{M_B} h^2 = 0.120$
$\Delta a_\mu = \Delta a_\mu^{exp}$
$\theta_\mu = -\pi/4$
$\theta_\mu = -\pi/8$
$\theta_\mu = -\pi/16$
$\theta_\mu = -\pi/32$
$\theta_\mu = -\pi/64$
$(M_{\tilde{\mu}_1} - M_B)/M_B;\ (M_{\tilde{\nu}} - M_B)/M_B$
M_B [GeV]

Direct detection

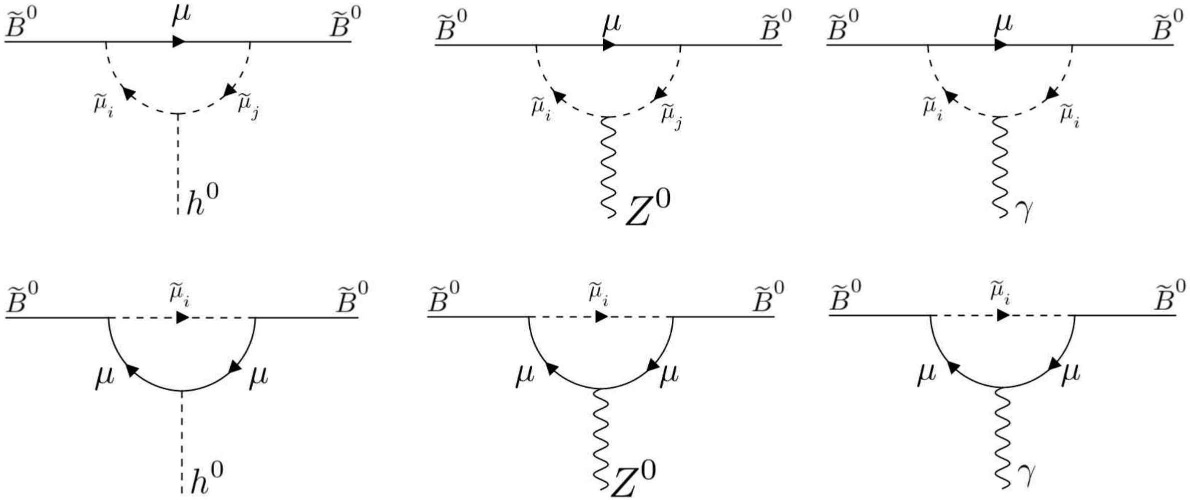
$$\mathcal{L}_{\tilde{B}^0 q} = c_q^{(0)} \bar{\tilde{B}}^0 \tilde{B}^0 \; m_q \bar{q} q + c_q^{(1)} \bar{\tilde{B}}^0 \gamma_\mu \gamma^5 \tilde{B}^0 \; \bar{q}\gamma^\mu \gamma^5 q$$
$$+ eQ_q c_A(k^2) \bar{\tilde{B}}^0 \gamma_\mu \gamma^5 \tilde{B}^0 \; \bar{q}\gamma^\mu q$$



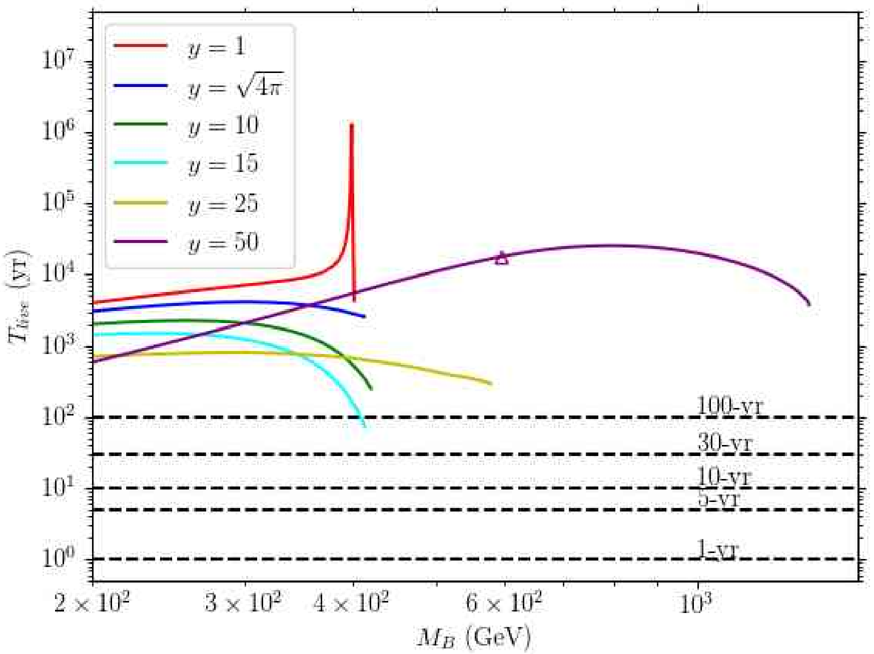
LZ Dark Matter Twitter Page,
Retrieved from https://twitter.com/lzdarkmatter/status/1251610953231335430

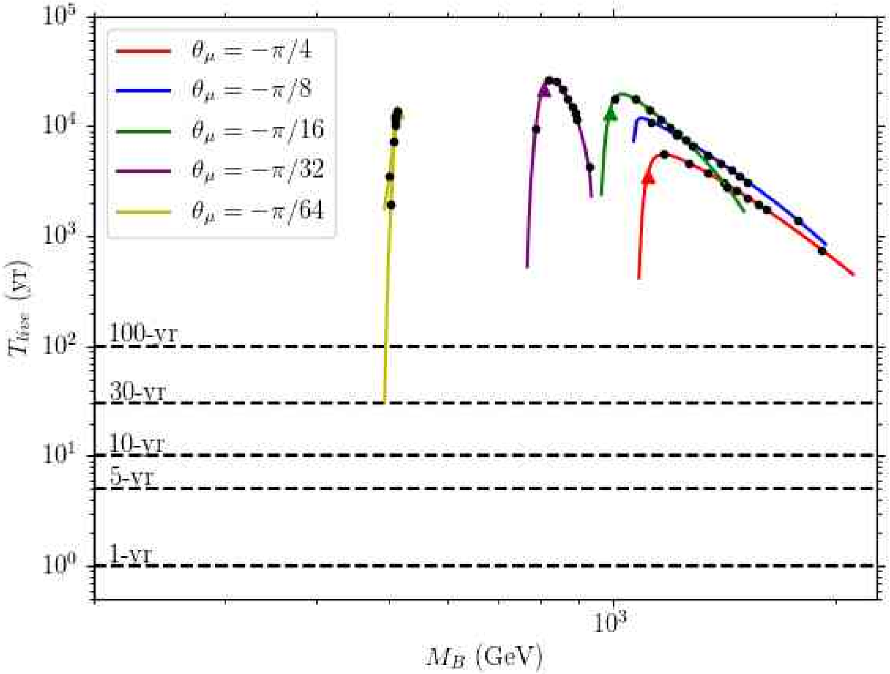
$$\mathcal{L}_{\text{NREFT}} = \sum_{N=p,n} [c_N^{(0)} \mathcal{O}_1^{(N)} - 4c_N^{(1)} \mathcal{O}_9^{(N)}]$$
$$- ec_A(k^2)[2\mathcal{O}_8^{(p)} - 2\mathcal{O}_9^{(p)}],$$

$$\mathcal{O}_8 \equiv \vec{S}_\chi \cdot \vec{v}^\perp,$$
$$\mathcal{O}_9 \equiv i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{k}}{m_N}\right)$$



Direct detection: bino-like DM





$$c_q^{(0)} \simeq \frac{g^2\, y_{H_2^0 11}}{32\pi^2 M_{H^0}^2 M_{\tilde{B}}} \left(\lambda_{\tilde{\mu}R}^2 \sin^2(\theta_{\tilde{\mu}}) + \lambda_{\tilde{\mu}L}^2 \cos^2(\theta_{\tilde{\mu}})\right) \left[1 + \frac{1-r_1}{r_1} \ln(1-r_1)\right]$$

$$c_A \approx \frac{e}{48\pi^2} \sum_{i=1,2} \alpha_\mu^{(i)} \beta_\mu^{(i)} \int_0^1 dx \frac{3x-2}{x+(1-x)t_i - x(1-x)r_i}$$

$$L_A(r_i,t_i) \approx \begin{cases} \left(2 - \frac{2}{t_i} - 3\ln t_i\right) + \left(4 + \frac{1}{t_i^2} - \frac{5}{t_i} - 3\ln t_i\right)(1-r_i) + \mathcal{O}((1-r_i)^2), \\ (3 - 3t_i + 2\ln t_i) + \left(\frac{7}{2} - 5t_i + \frac{3t_i^2}{2} + 2\ln t_i\right) r_i + \mathcal{O}(r_i^2). \end{cases}$$

Summary

- We assessed the viability of a minimal setup involving two muonic scalars and a Majorana fermion to resolve the muon g-2 anomaly and provide for a DM candidate
- Relaxing MFV + compressed spectra at TeV = DM production through coannihilations
- Deviating too much from MFV may violate perturbative unitarity and EW vacuum (meta)stability
- Direct detection weakly constrains the model, warrants alternative ways of probing the model, e.g. lepton collider, NS heating

Thank you for your attention.

謝謝大家的關注。