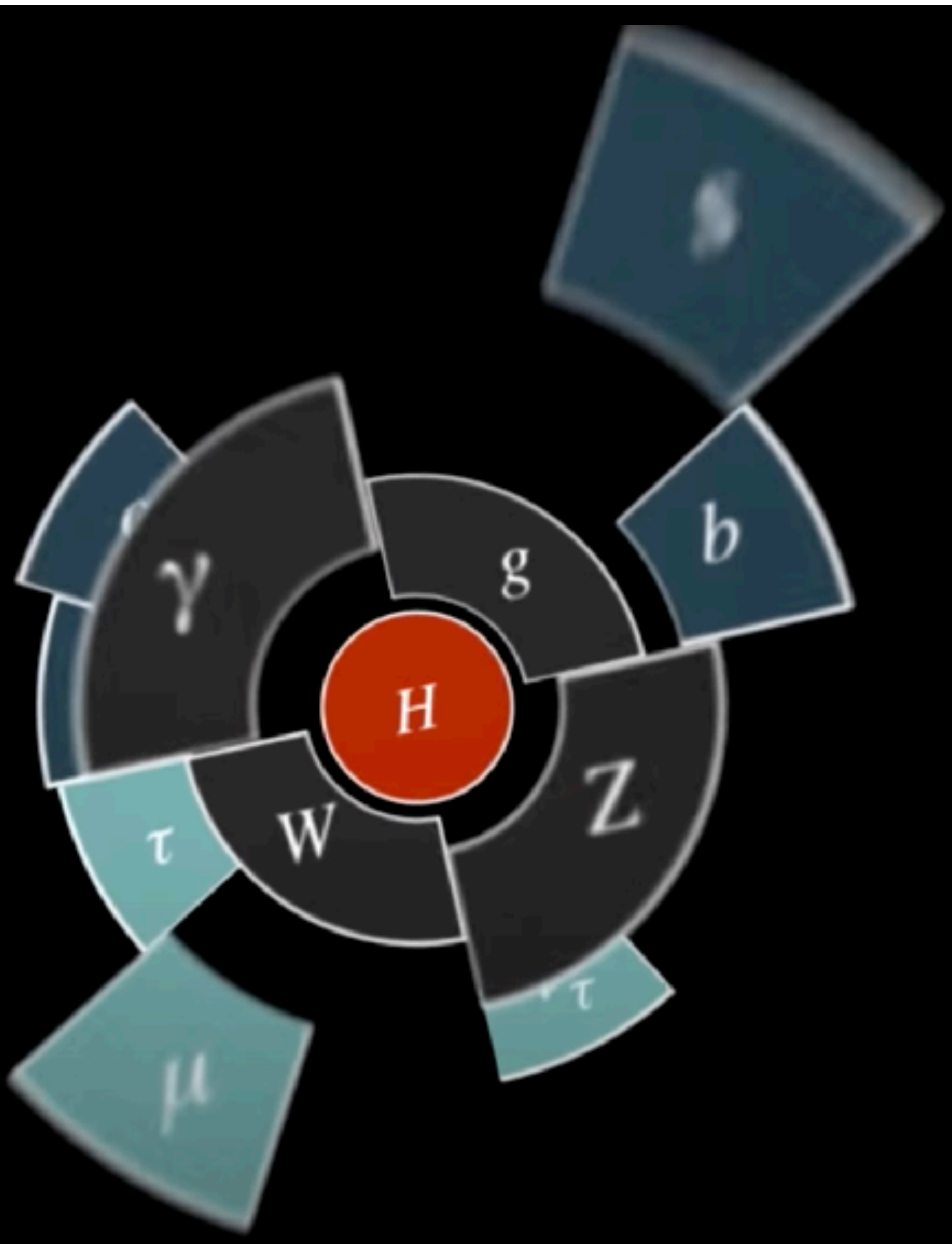

A concise review on some Higgs-related new physics models in light of current experiments

Sun Yat-sen University Zhuhai Campus
Jul 04, 2023.

Picture from the Screenshot of YouTube video: How Symmetry Shapes Nature's Laws Quantamagazine

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Based on arXiv: 2203.05719 [hep-ph], arXiv:2201.00156 [hep-ph]


HIGGS BOSON 10 YEARS ON: WHAT SCIENTISTS DO AND DON'T KNOW

nature

Vol 607 | 14 July 2022 | 221

Physicists are celebrating ten years since the Higgs boson's discovery. But many of its properties remain mysterious.

— **Elizabeth Gibney**

4 things scientists have learnt

- The Higgs boson's mass is 125 GeV.
- The Higgs boson is a spin-zero particle.
- The Higgs's properties rule out some theories that extend the standard model.
- The Universe is stable — but only just.

4 things scientists still want to know

- Can we make Higgs measurements more precise?
- Does the Higgs interact with lighter particles?
- Does the Higgs interact with itself?
- What is the Higgs boson's lifetime?

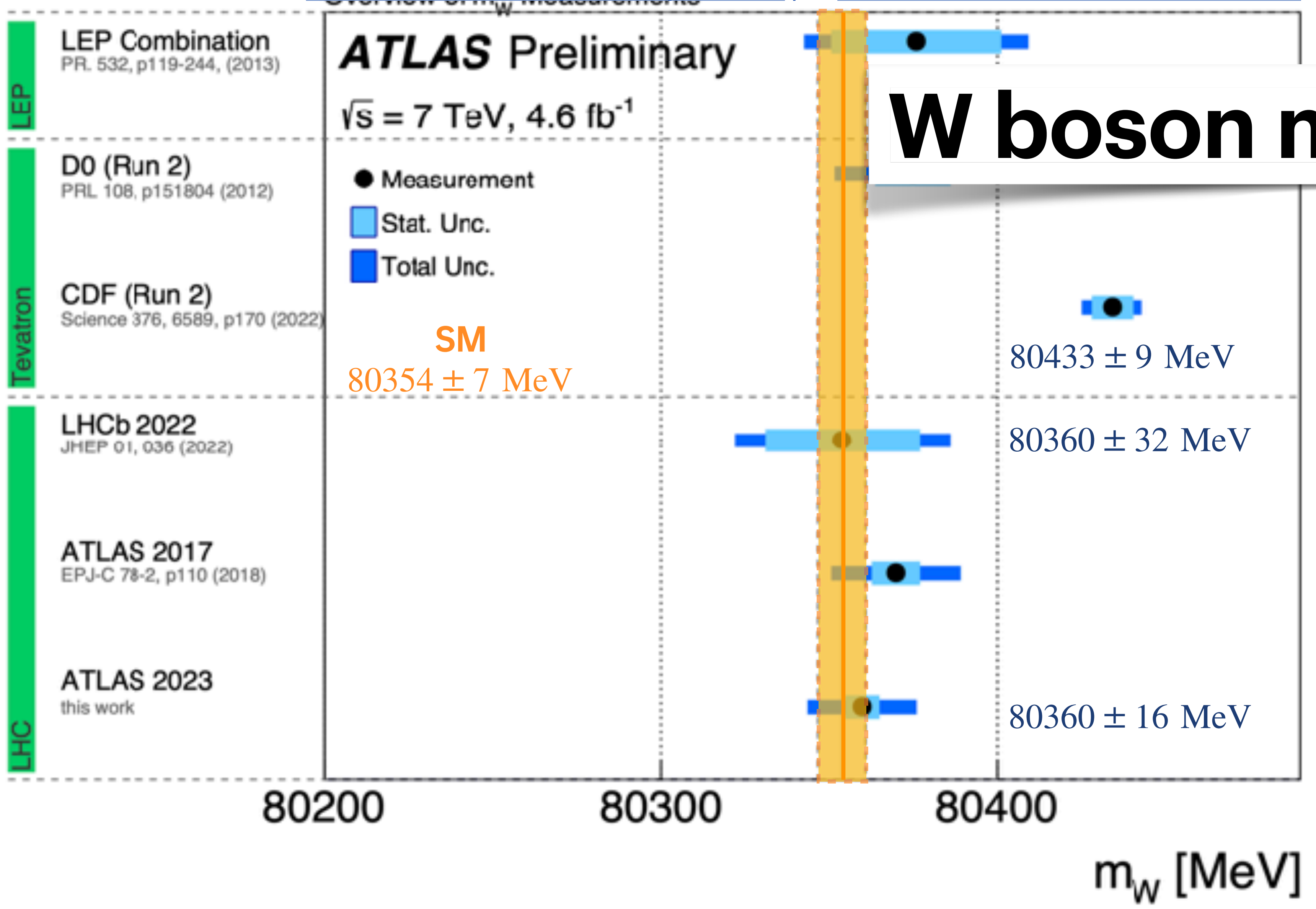
Shortcoming of SM:

- Hierarchy Problem: $\langle v \rangle \sim 246 \text{ GeV} \ll M_{\text{Planck}}$
- Naturalness Problem: Fine-tuning required for m_H.
- Vacuum Stability
- Lack of DM explanation: Higgs as a portal to cold DM, …
- Lack of Neutrino mass explanation. (Only in some SUSY topic, but not too much)
- Flavor Structure and Hierarchy. (Not in this talk)
- Baryon asymmetry of the universe: Strong first order EW phase transition is a solution to baryon asymmetry, but EWPT from SM Higgs is a smooth crossover.

…

Two recent anomalies from experimental side

Science 376 (2022) 6589, ATLAS-CONF-2023-004



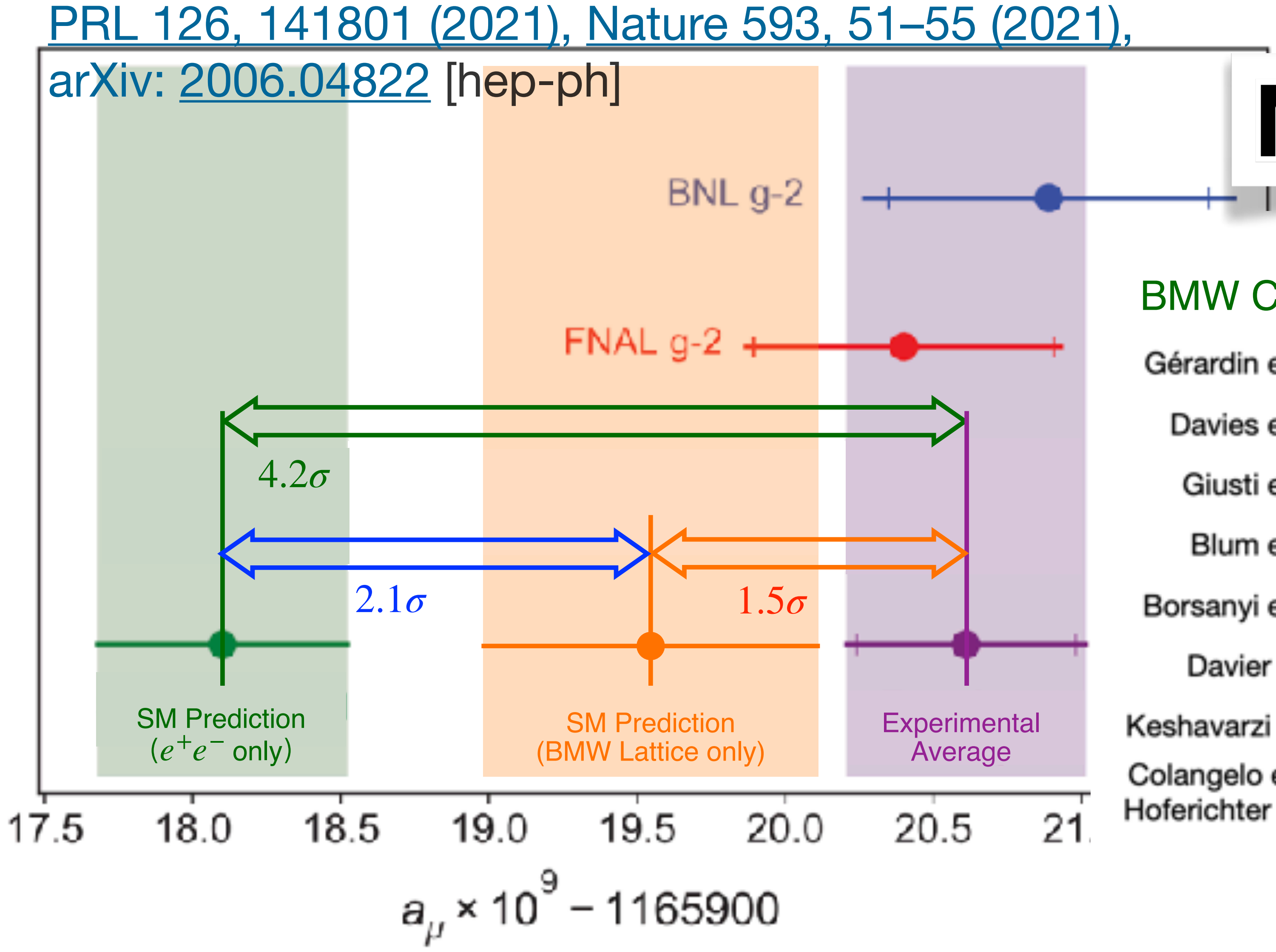
W boson mass anomaly

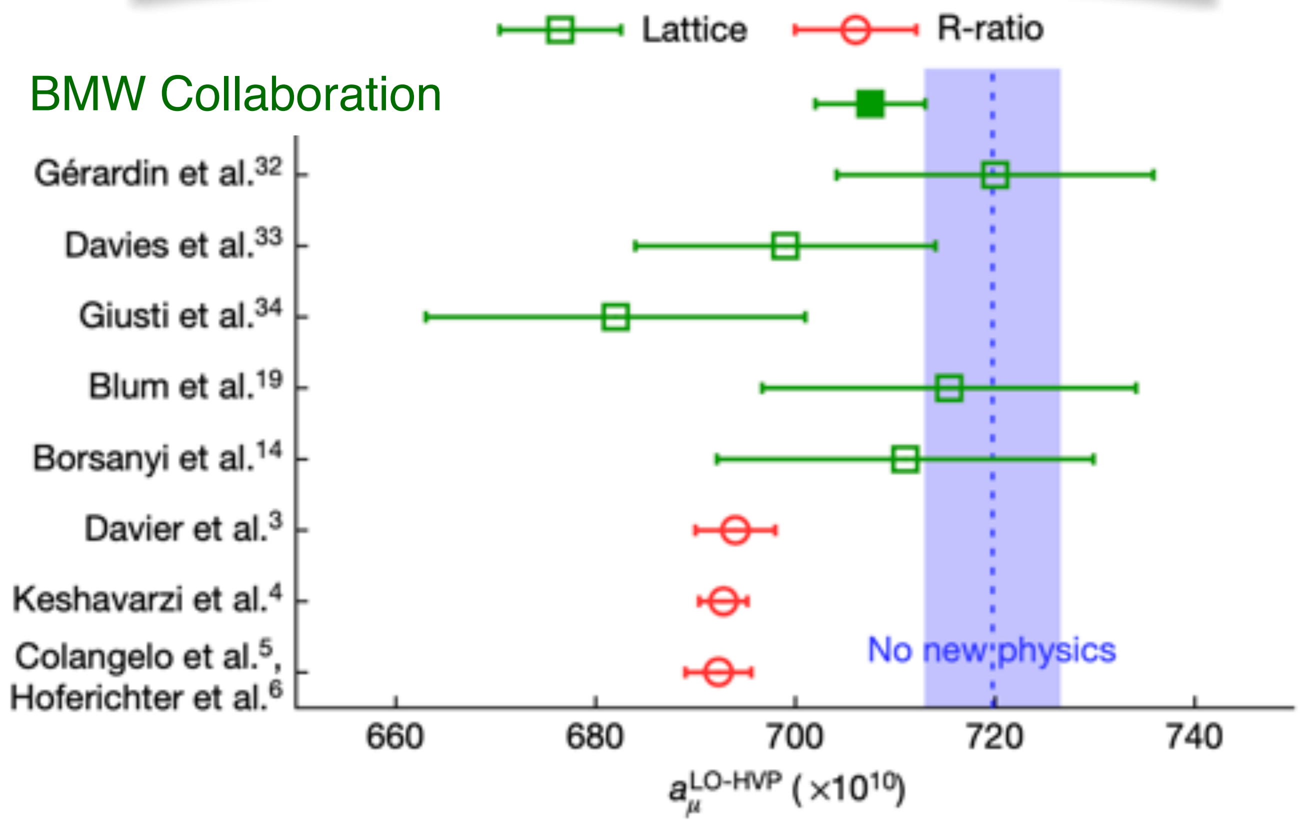
- CDF result (about 6σ deviation) disagrees with recent LHC measurement, in line with SM prediction.

- The lattice calculation for muon $g-2$ shifts the SM value, but has larger uncertainty. It relax the deviation from 4.2σ to 1.5σ. But showing a 2.1σ tension with the e^+e^- data-driven HVP contribution estimation.

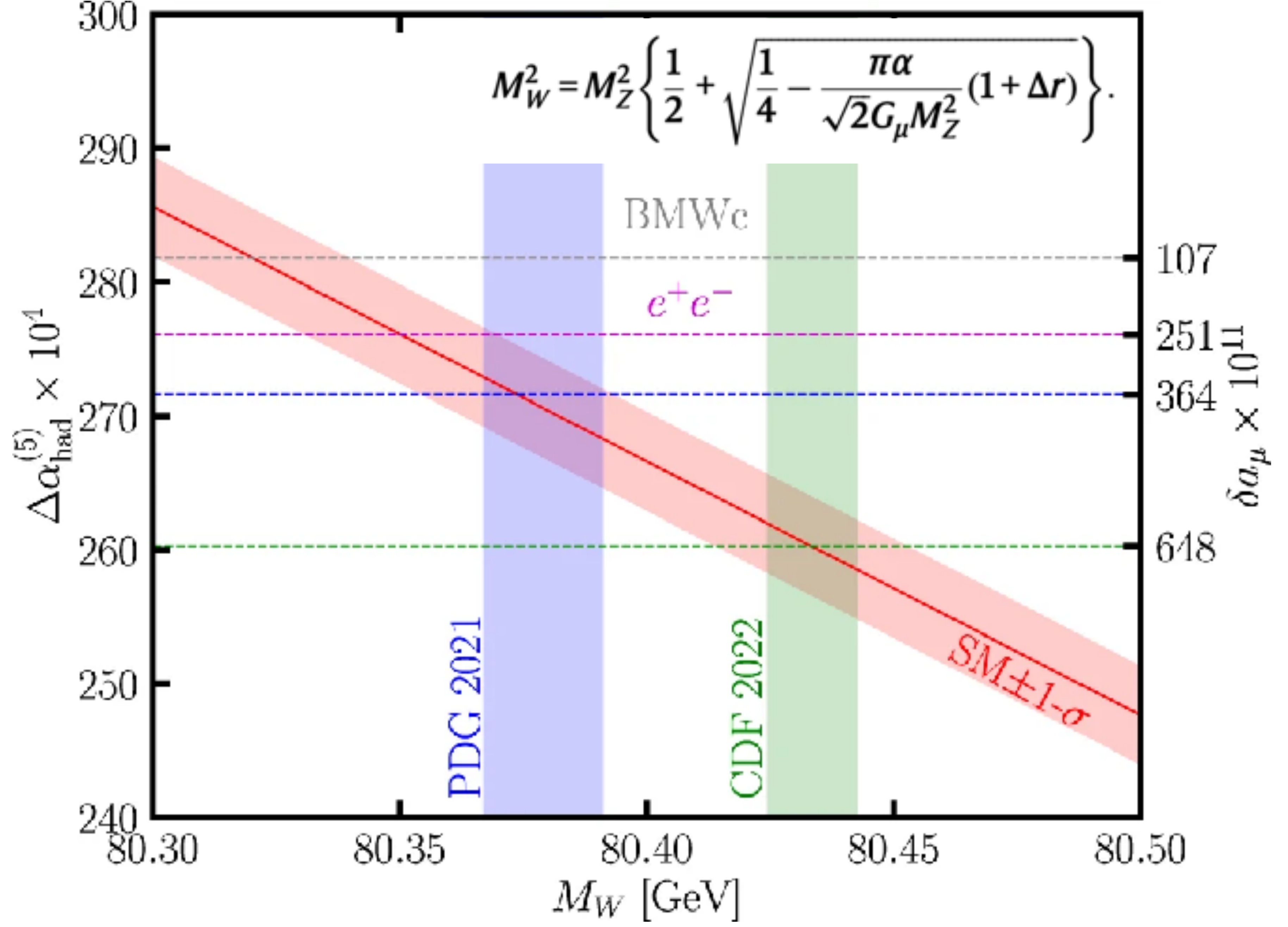
Muon g-2 anomaly

PRL 126, 141801 (2021), Nature 593, 51–55 (2021), arXiv: 2006.04822 [hep-ph]





arXiv: 2204.03996 [hep-ph]



- The m_W and muon $g-2$ calculations are in fact connected by the fact that both the hadronic contributions to the running of the fine structure constant $\Delta\alpha_{\rm had}$ and the HVP contributions $a_\mu^{\rm HVP}$.

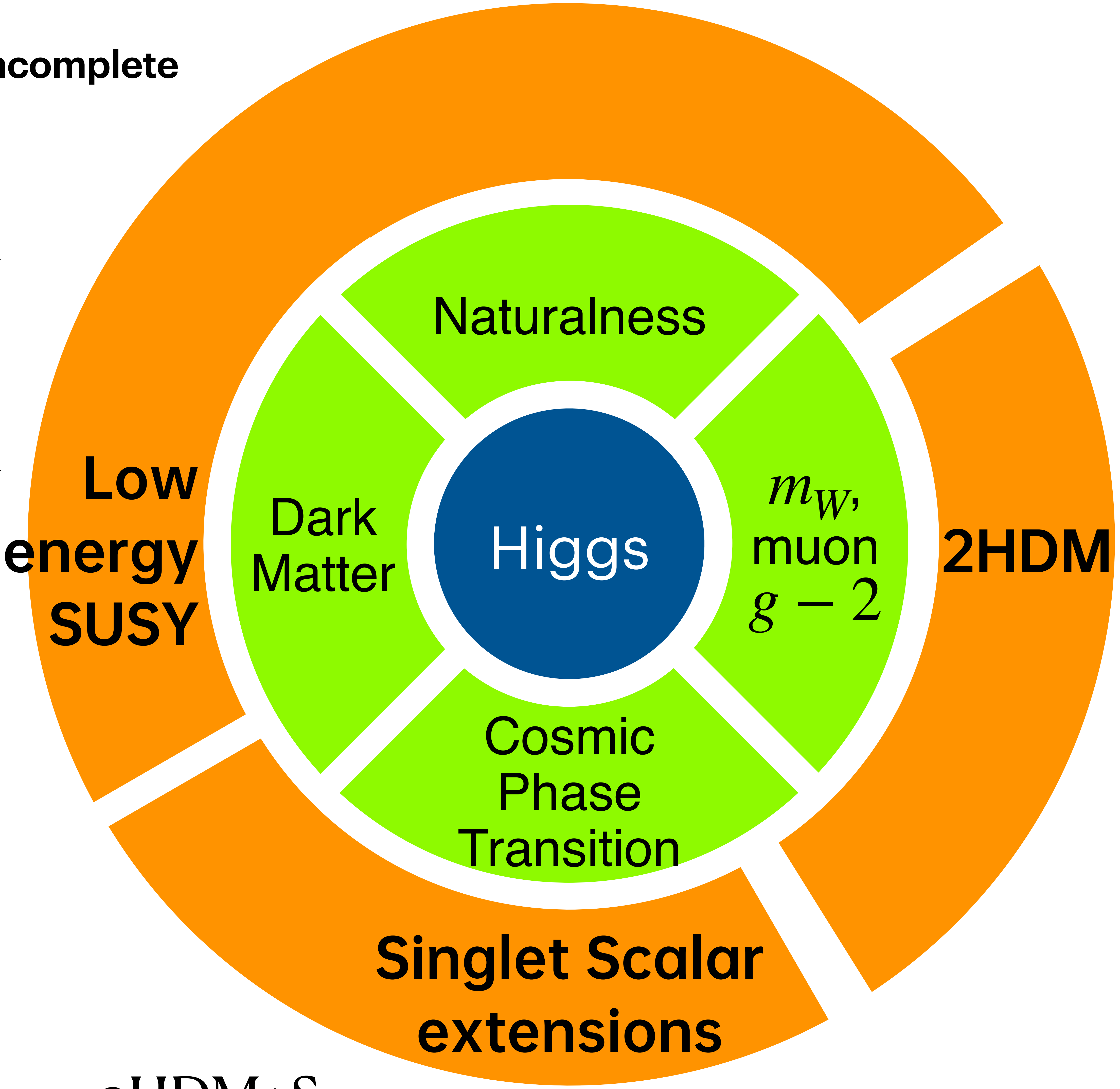
$$\Delta\alpha_{\rm had} = \frac{M_Z^2}{4\pi^2\alpha}\int_{m_{\pi^0}^2}^{\infty}\frac{{\rm d}s}{M_Z^2-s}\sigma_{\rm had}(\sqrt{s}), \qquad a_\mu^{\rm HVP} = \frac{m_\mu^2}{12\pi^3}\int_{m_{\pi^0}^2}^{\infty}\frac{{\rm d}s}{s}K(s)\sigma_{\rm had}(\sqrt{s}),$$

- The EW fit result demonstrate that including the $g-2$ measurement worsens the tension with the CDF measurement and conversely that adjustments that alleviate the CDF tension worsen the g – 2 tension beyond 5σ.

Contents

A philatelic collection, though incomplete

- Supersymmetric Standard Model (SSM)s
  - Minimal SSM
  - Next-to-Minimal SSM
- Seesaw extended SSMs:
  - Type-I seesaw
  - Inverse seesaw

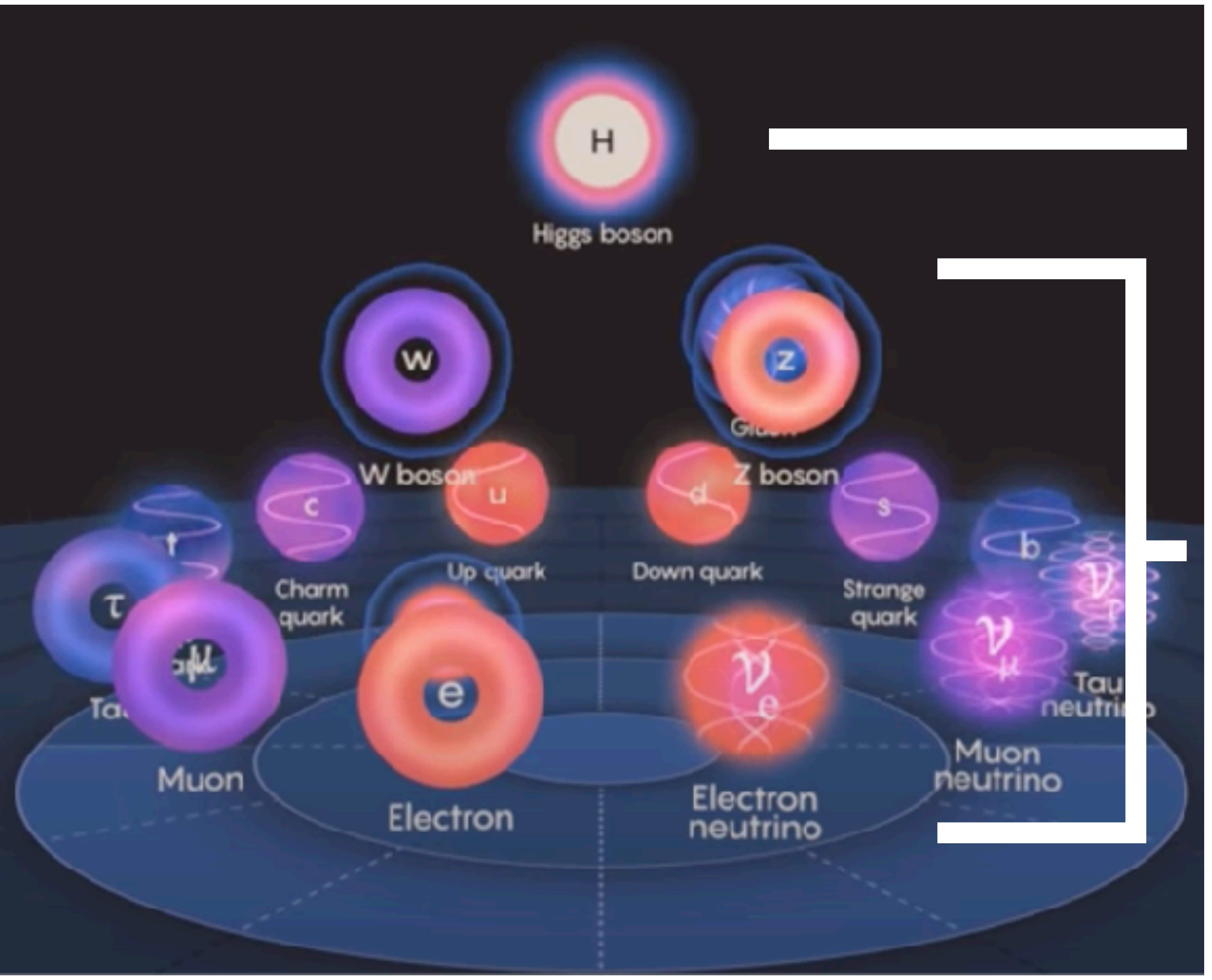


- Muon $g-2$ favored:
  - Type-II 2HDM
  - Type-X 2HDM
  - Flavor-aligned 2HDM
  - Muon-specific 2HDM
  - $\mu\tau$-flavor violating 2HDM

- 2HDM+S

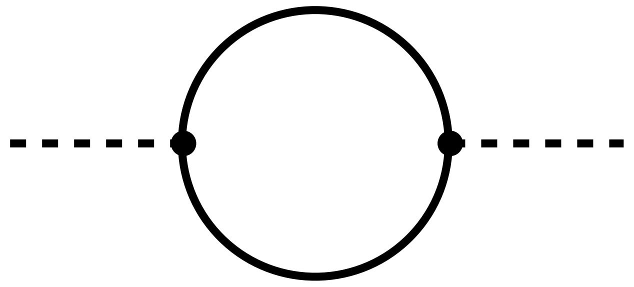
Low energy SUSY

A light Higgs boson in SM

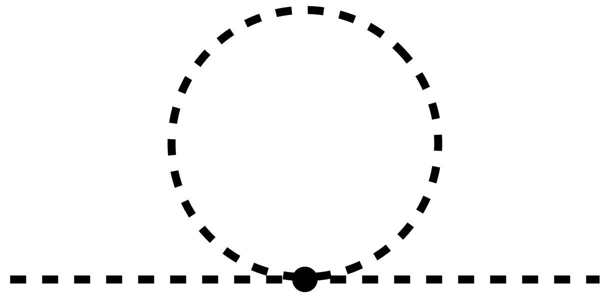


Picture from the Screenshot of YouTube video: The Standard Model of Particle Physics: A Triumph of Science Quantamagazine

- m_H is not protected by any symmetry, and it has a quadratic divergence from loop correction.
- The masses of fermions or gauge boson are prohibited by gauge or chiral symmetry.



$$\delta m_H^2 = -\frac{\left|\lambda_f\right|^2}{8\pi^2}\Lambda^2 + \cdots$$

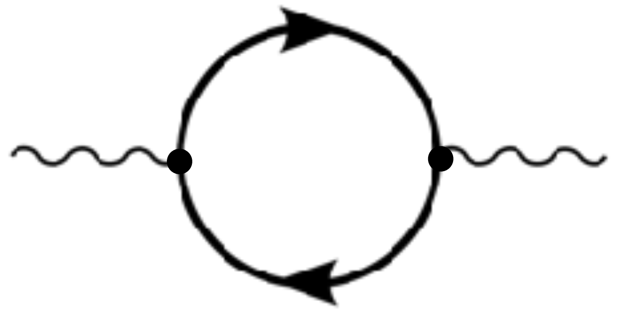


$$\delta m_H^2 = -\frac{\lambda_S}{16\pi^2}\left[\Lambda^2 - 2m_S^2\log\frac{\Lambda}{m_S} + \cdots\right]$$

electron self-energy

$$\pi_{ff}(0) = -4e^2 m_f \int \frac{\mathrm{d}^4k}{(2\pi)^4}\frac{1}{k^2(k^2-m_f^2)}$$

$$\delta m_f \simeq 2\frac{\alpha_{\mathrm{em}}}{\pi} m_f \log\frac{\Lambda}{m_f}$$



photon self-energy

$$\pi_{\gamma\gamma}^{\mu\nu}(0) = -4e^2 \int \frac{\mathrm{d}^4k}{(2\pi)^4}\frac{2k^\mu k^\nu - g^{\mu\nu}(k^2-m_f^2)}{(k^2-m_f^2)^2}$$

$$= 0$$ [1]

---

[1] The integral vanishes is manifest only in a regularization scheme that preserves gauge invariance, e.g. dimensional regularization.

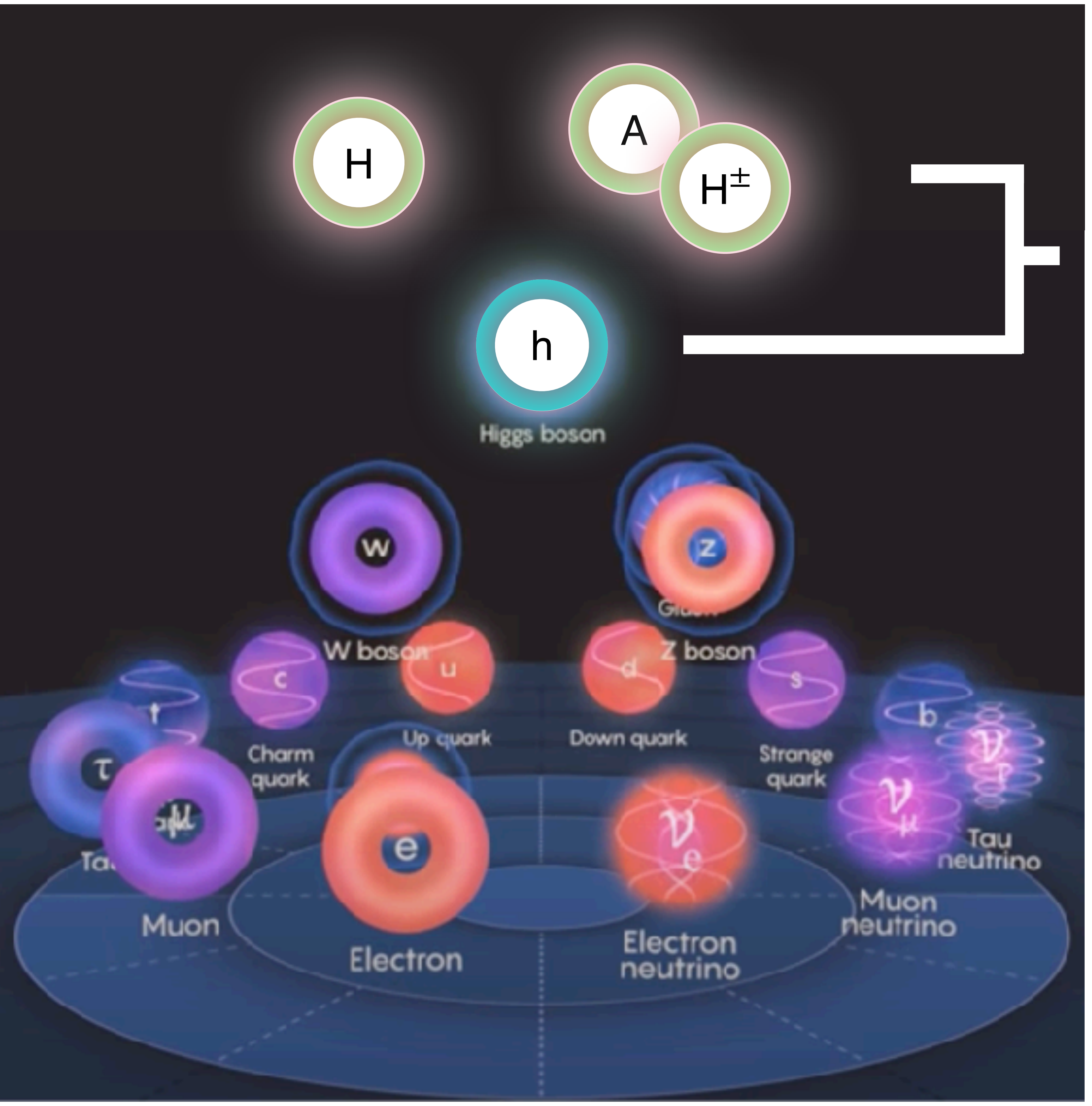
* arXiv: hep-ph/0410370

Low energy SUSY

A light Higgs boson in SUSY

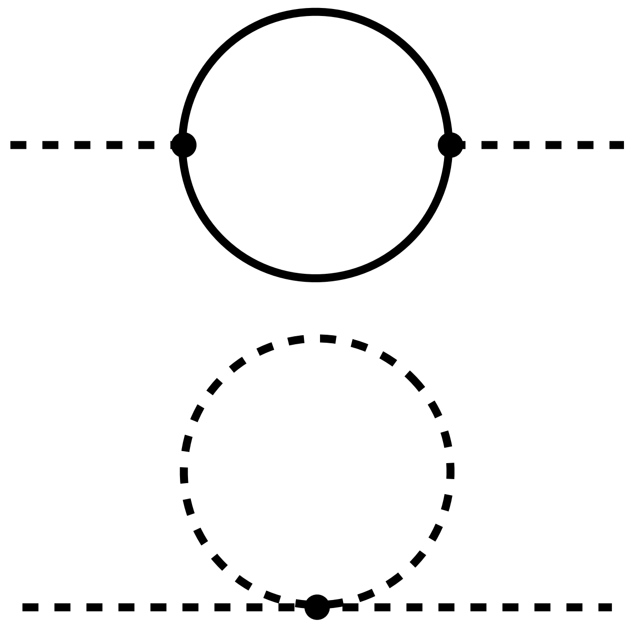
$$W_{\text{MSSM}} = y_u Q \cdot H_u \, \bar{u} - y_d Q \cdot H_d \, \bar{d} - y_e L \cdot H_d \, \bar{e} + \mu H_u \cdot H_d$$

- The holomorphicity requires the Higgs sector must be extended to two Higgs doublet H_u and H_d.



- The quadratic divergences from the loop corrections are “technically” canceled out and only logarithmic divergences remains.

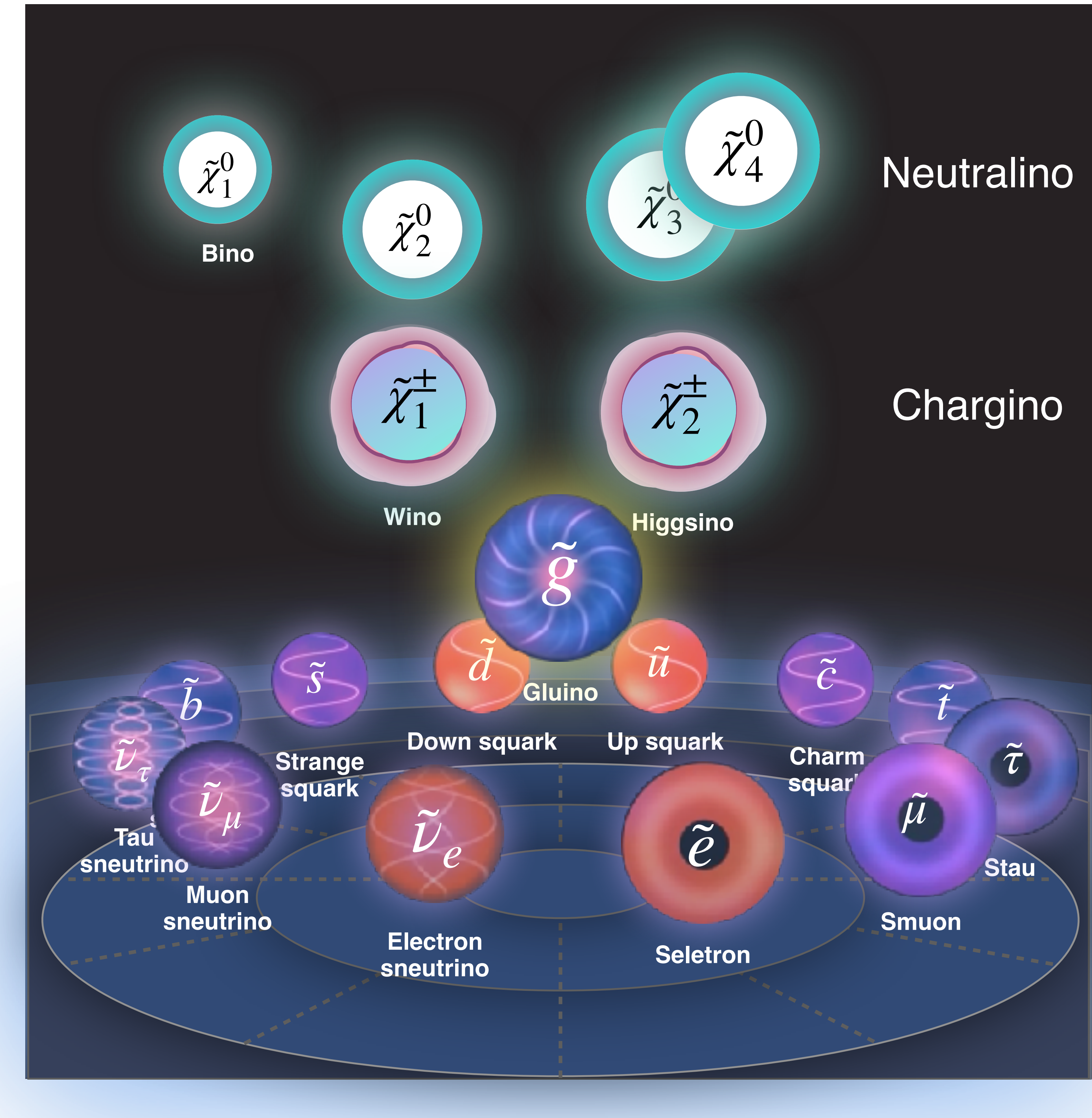
$$\lambda \equiv \lambda_S = \left|\lambda_f\right|^2$$



$$\delta m_H^2 = -\frac{\left|\lambda_f\right|^2}{8\pi^2}\cancel{\Lambda^2} + \cdots$$

$$\delta m_H^2 = -\frac{\lambda_S}{16\pi^2}\left[\cancel{\Lambda^2} - 2m_S^2 \log\frac{\Lambda}{m_S} + \cdots\right]$$

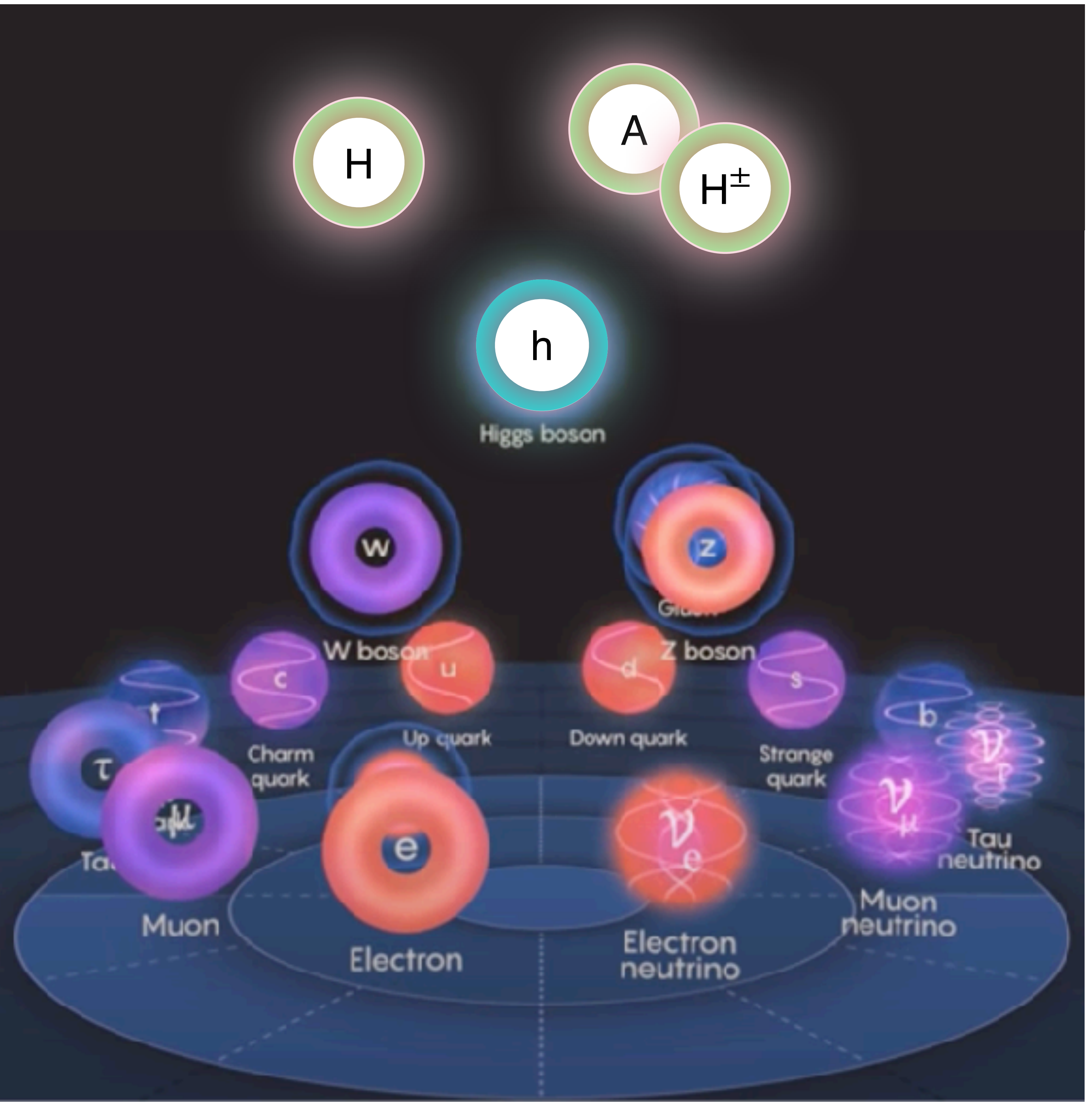
$$\delta m_H^2 = M_{\text{soft}}^2 \left[\frac{\lambda}{16\pi^2} \log\frac{\Lambda}{M_{\text{soft}}} + \cdots\right]$$



- arXiv: hep-ph/9709356
- arXiv: hep-ph/0410370

Low energy SUSY

A light Higgs boson in SUSY (MSSM)



$$v = \sqrt{v_u^2 + v_d^2} \approx 246\ \text{GeV}$$

$$v_u \equiv \langle H_u \rangle$$

$$v_d \equiv \langle H_d \rangle$$

$$\tan\beta \equiv v_u / v_d$$

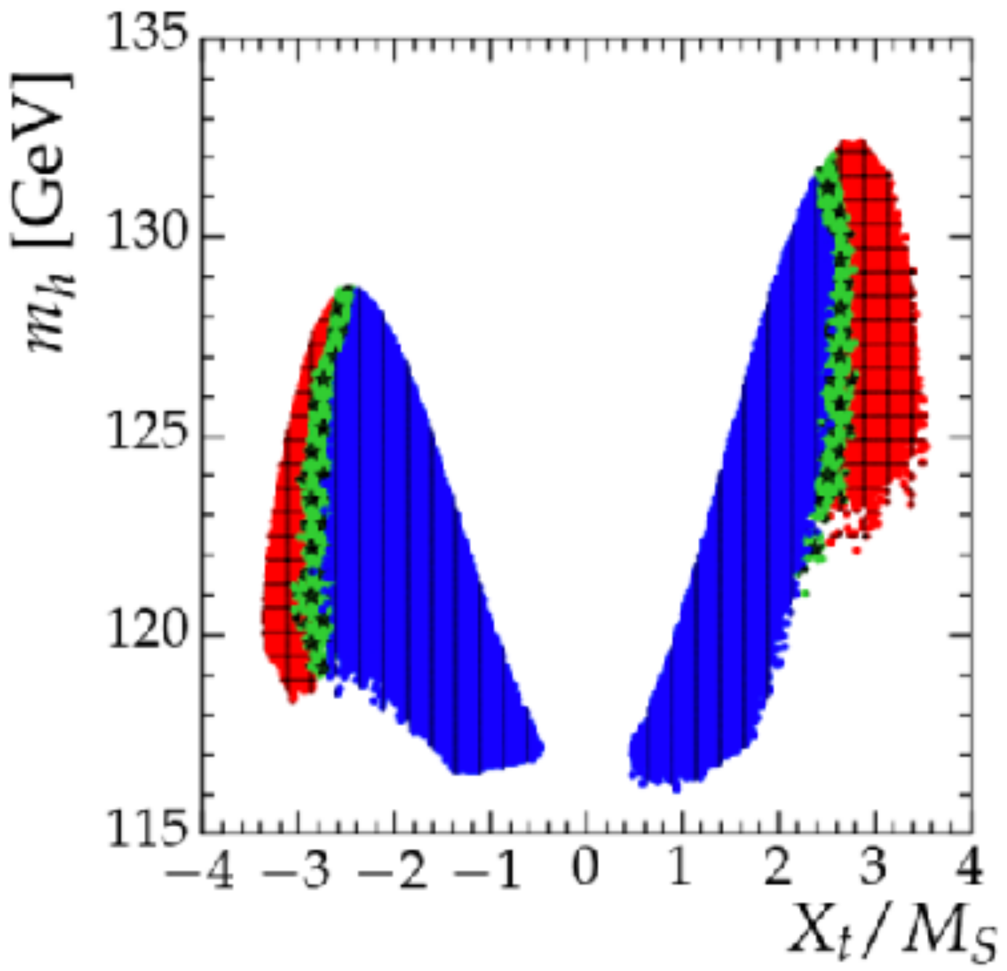
$$m_t \approx 173\ \text{GeV}$$

$$\overset{\text{Stop mixing parameter}}{X_t} = \underset{\text{Stop soft trilinear coupling}}{A_t} - \mu / \tan\beta$$

$$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

A typical scale of soft SUSY breaking parameter

$$m_h^2 \sim \underbrace{m_Z^2 \cos^2 2\beta}_{\text{tree level}} + \underbrace{\frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]}_{\text{loop level (dominated contribution from top-stop loop)}}$$



- $\left|X_t\right| \lesssim \sqrt{6} M_S$ required by charge & color breaking constraint.
- Large mixing term favored

* arXiv: 1310.1932 [hep-ph]

Low energy SUSY

A light Higgs boson in SUSY (MSSM)

$$m_h^2 \sim m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

$M_1 = M_2/2 = 1\ \text{TeV},$

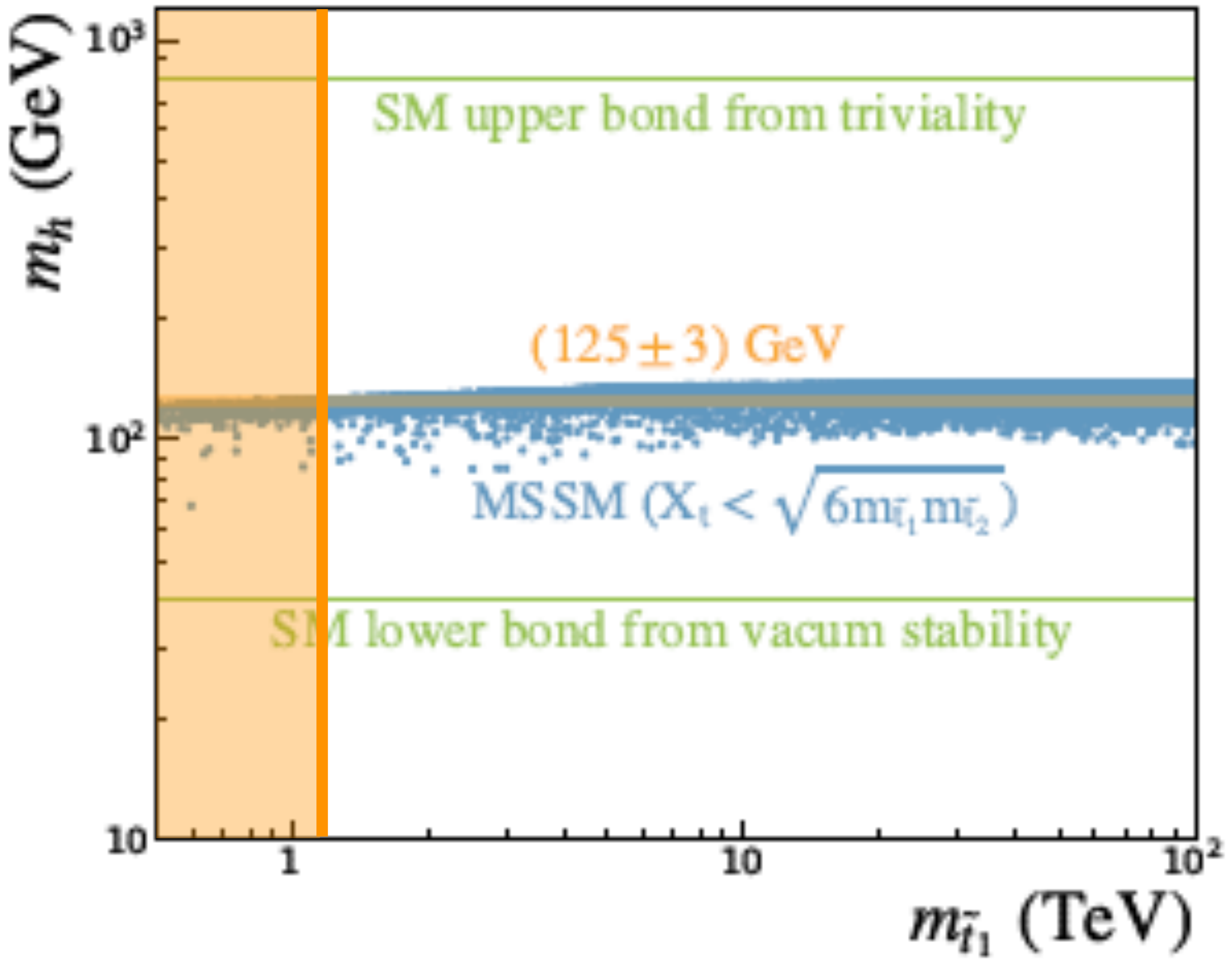
$100\ \text{GeV} \leq \mu \leq 300\ \text{TeV}$

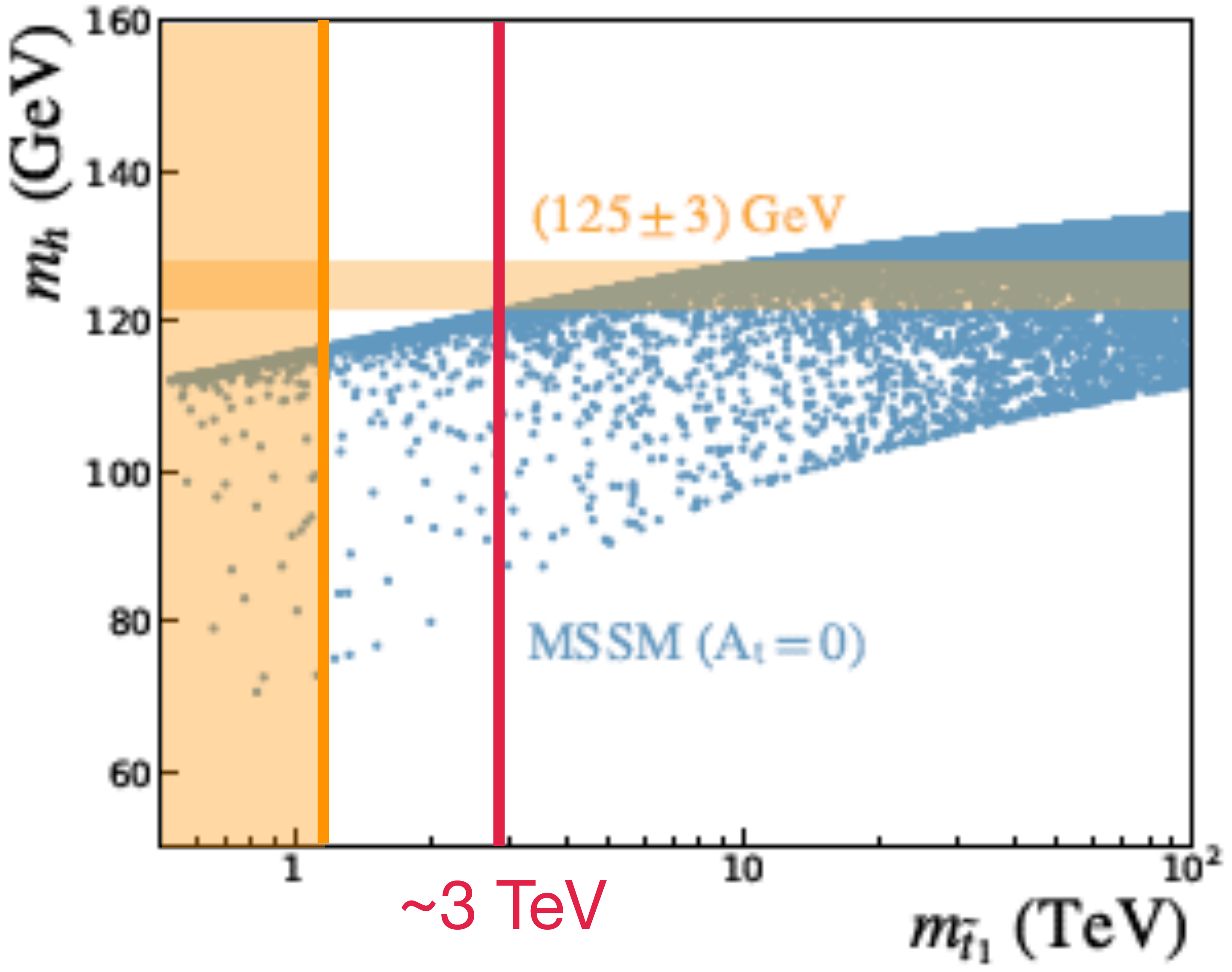
$1 \leq \tan\beta \leq 50$

$500\ \text{GeV} \leq M_{U_3} = M_{D_3} = M_{Q_3} \leq 100\ \text{TeV}$

$\left|X_t\right| \leq \sqrt{6}M_S$

Current LHC detection limit





~3 TeV

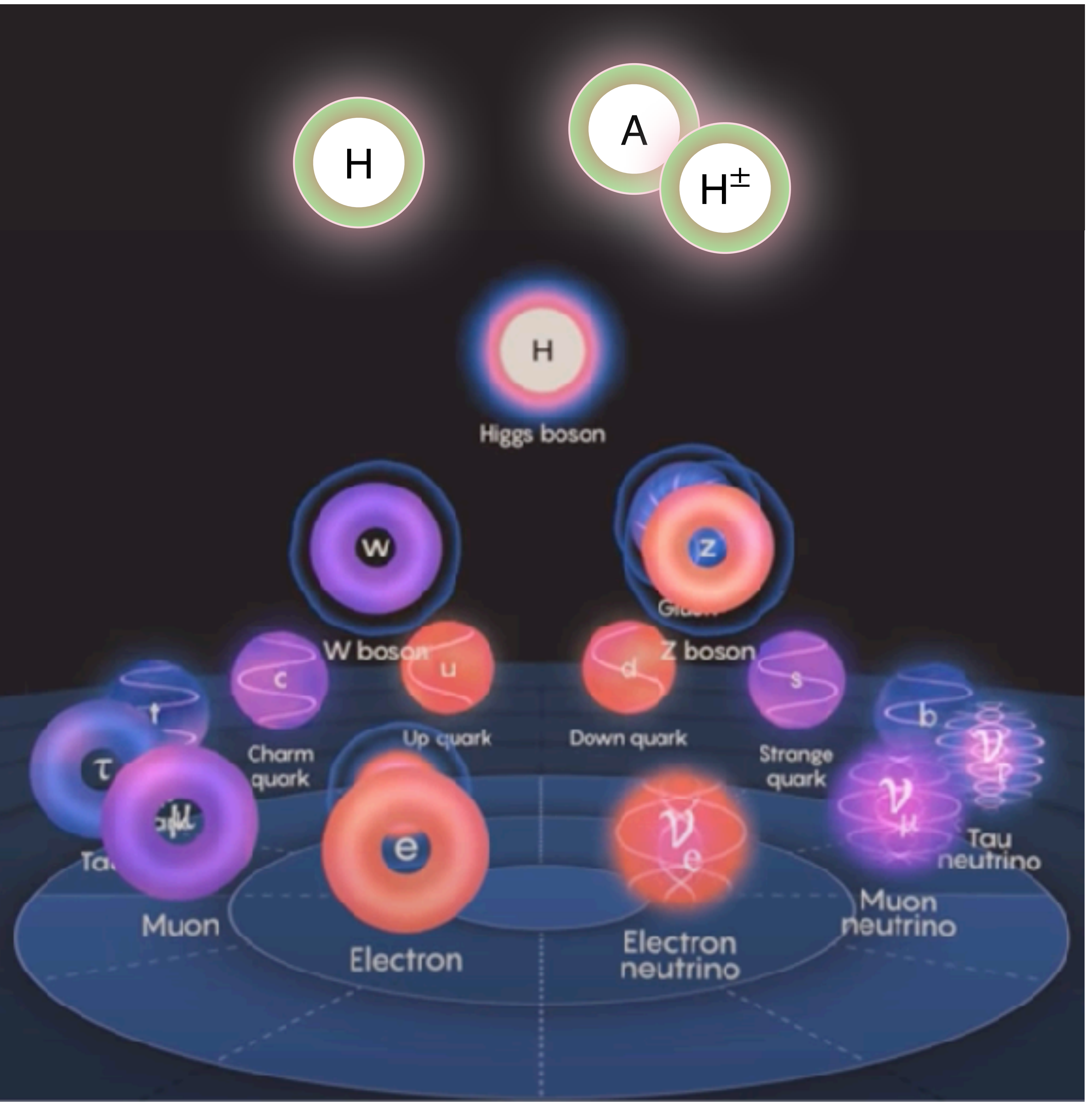
- 125 GeV Higgs is a great triumph of SUSY!
- Require top squark (colored sparticle) above TeV.
- LHC direct search not see any SUSY particle, and push the colored sparticle above TeV.
- They are in consistency!

* arXiv: 1202.5821 [hep-ph]

Low energy SUSY

the measured value of m_h is close to this upper mass limit implies that the SUSY breaking scale M_S might be rather high.

Heavy Higgs states H, A & H$^{\pm}$ (hMSSM approach)



hMSSM:

$$m_h \approx 125\ \text{GeV}$$

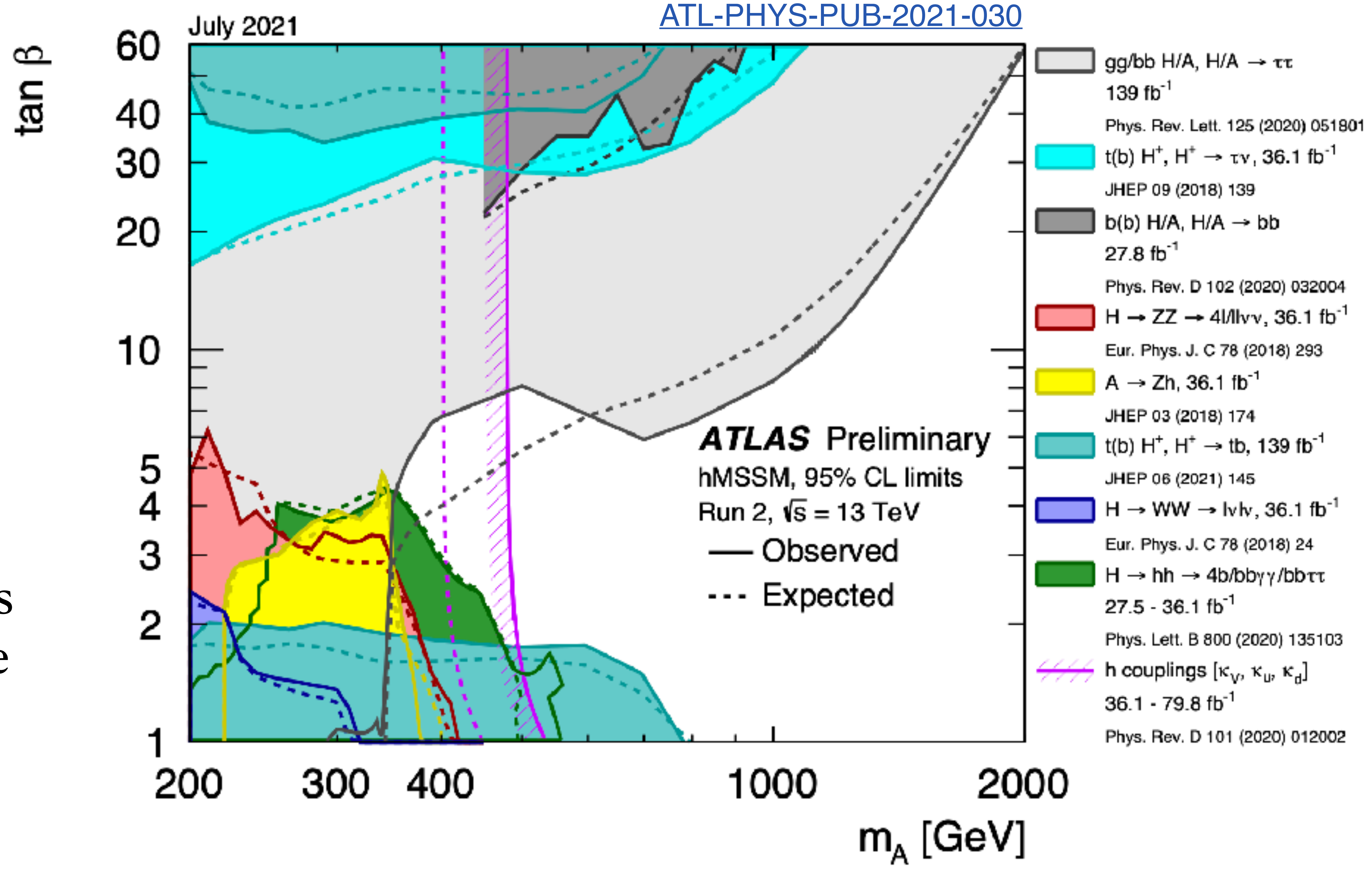
$$M_S \gtrsim 1\ \text{TeV}$$

$$m_H \sim m_A \sim m_H^{\pm}$$

$$\alpha + \beta \sim \frac{\pi}{2}$$

trade the effective Higgs coupling measure to the heavy Higgs states.

- arXiv: 1202.5998 [hep-ph]
- arXiv: 1307.5205 [hep-ph]
- arXiv: 1502.05653 [hep-ph]
- arXiv: 2201.00070 [hep-ph]



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Low energy SUSY

$\tilde{\chi}_1^0$

Neutralino Dark matter

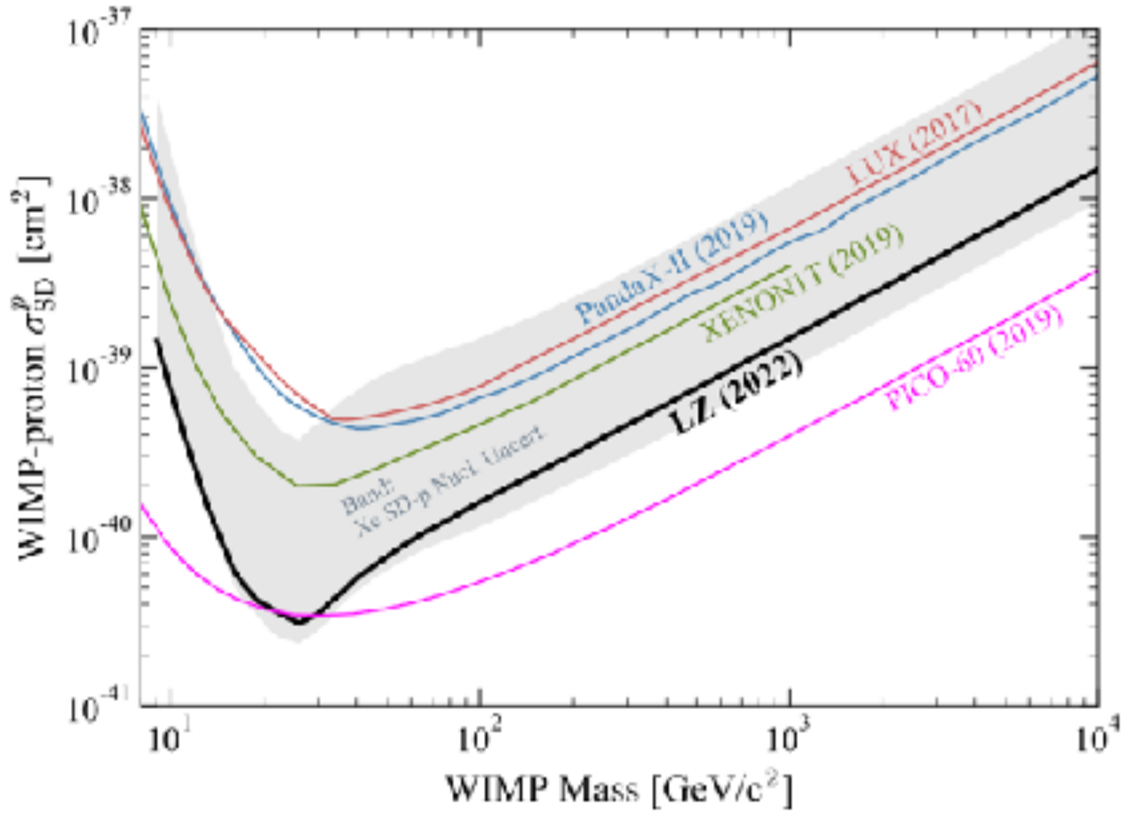
- Neutralino DM candidate is a typical WIMP.
- WIMP miracle:

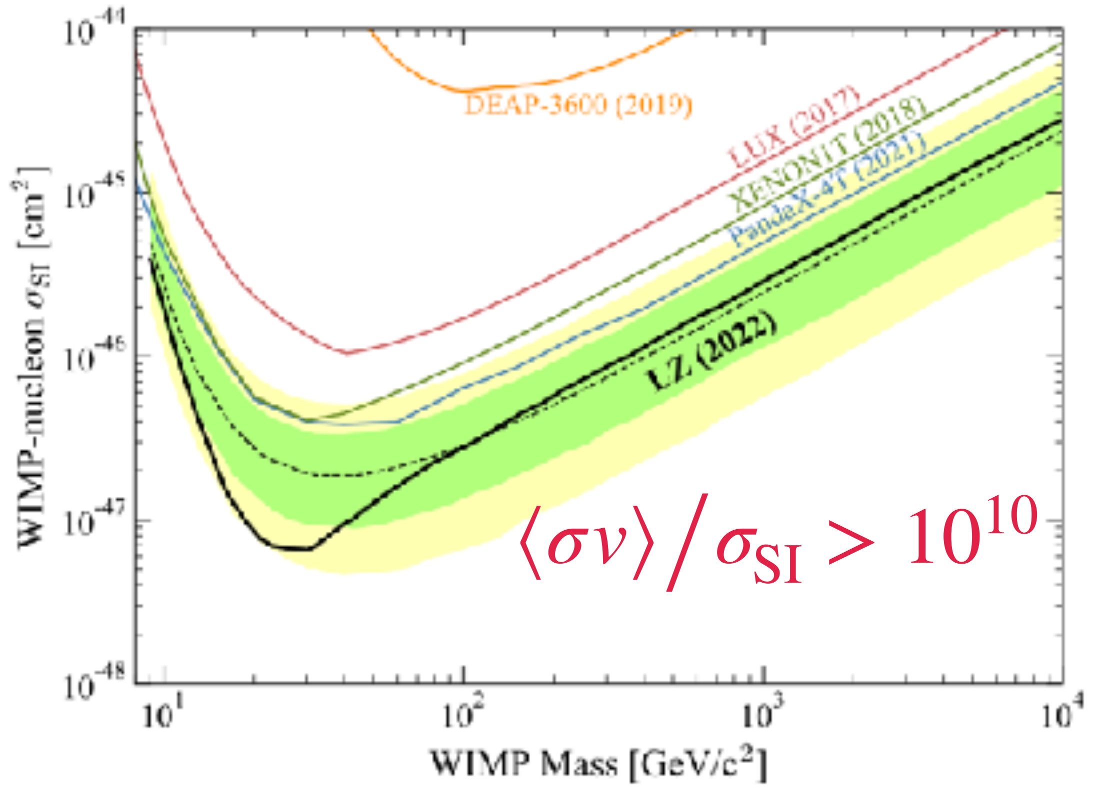
$$\Omega_{\rm DM}h^2 \simeq \frac{3\times10^{-27}{\rm cm}^3s^{-1}}{\langle\sigma v\rangle}$$

$$\langle\sigma v\rangle \sim \frac{g^4}{16\pi}\frac{1}{M^2} \sim 2.6\times10^{-26}\ {\rm cm^3s^{-1}}$$

$$\simeq \left(\frac{g}{0.5}\right)^4\left(\frac{500\ {\rm GeV}}{M}\right)^2\cdot 6\times10^{-26}\ {\rm cm^3s^{-1}}$$

- Constraints from DM-nucleon scattering rate measurement



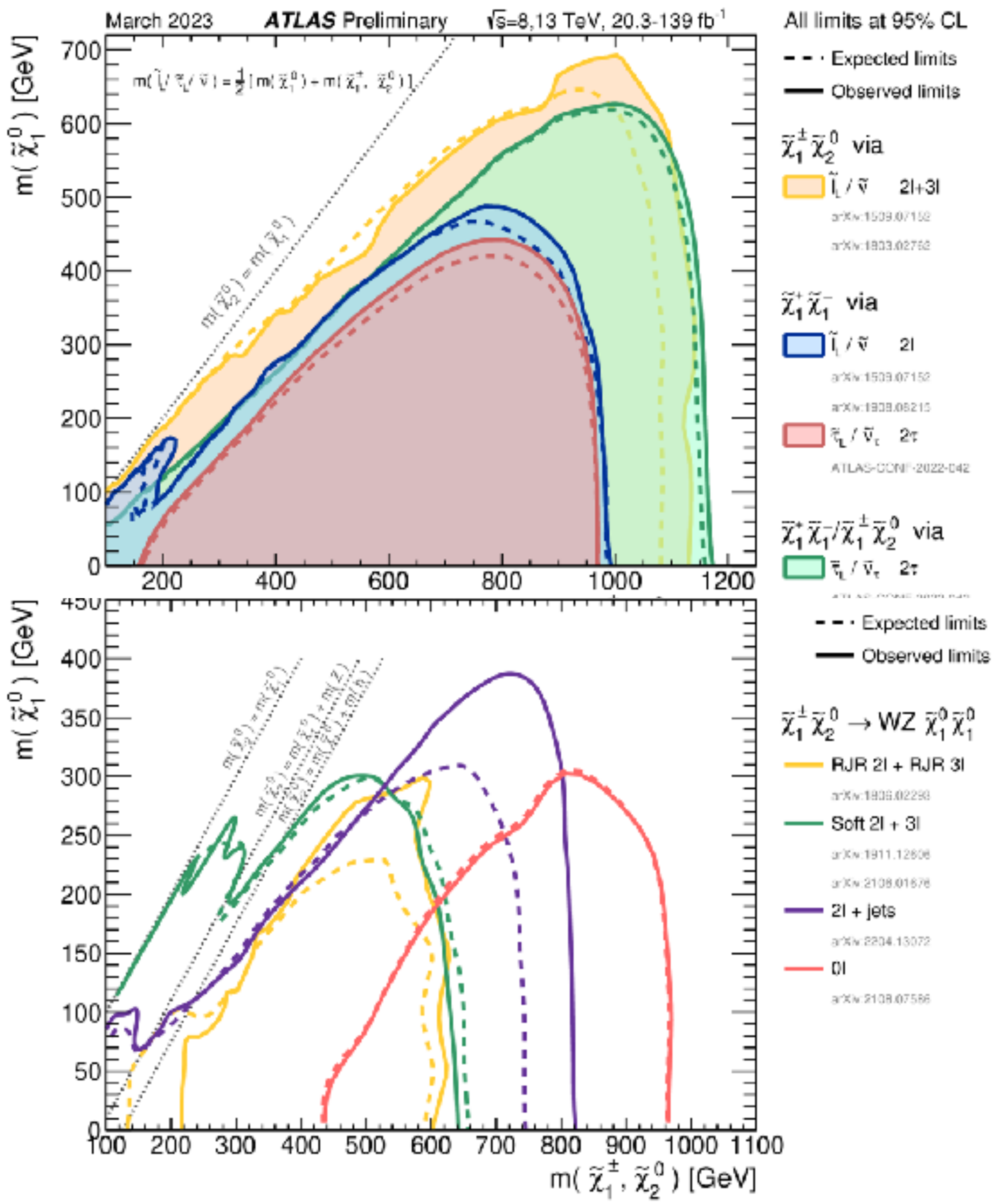


$\langle\sigma v\rangle/\sigma_{\rm SI} > 10^{10}$

- Roughly speaking, Bino/Wino DM need tuning to escape the $\sigma_{\rm SD}$ constraint, Higgsino need tuning to escape the $\sigma_{\rm SI}$

Collider constraints

- Current LHC is a great machine to test the Neutralino DM.
- Testing Electroweakino sector in final states of multi-leptons $+E_{\rm T}^{\rm miss}$.



ATL-PHYS-PUB-2023-005

- Neutralino DM is still OK, but need fine-tuning, especially for $m_{\tilde\chi} \lesssim 500$ GeV.
- Compressed spectrum is favored by the current LHC.

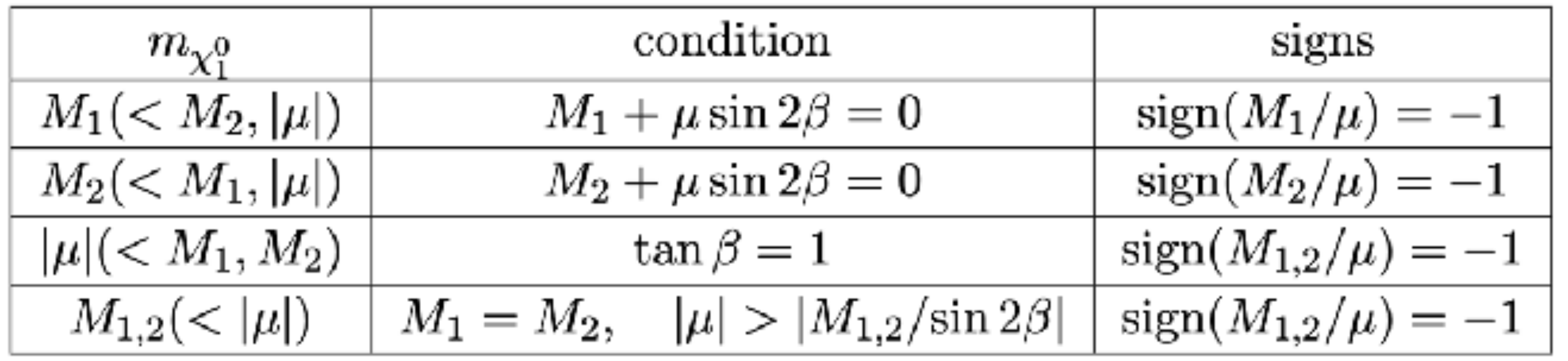
- arXiv: 2207.03764 [hep-ph]
- arXiv: 2303.02169 [hep-ph]
- arXiv: hep-ph/0512090
- arXiv: hep-ph/9506380
- arXiv: 1001.3651 [hep-ph]

Low energy SUSY

BS needs fine-tuning of SUSY parameter to escape DM experiments !!!

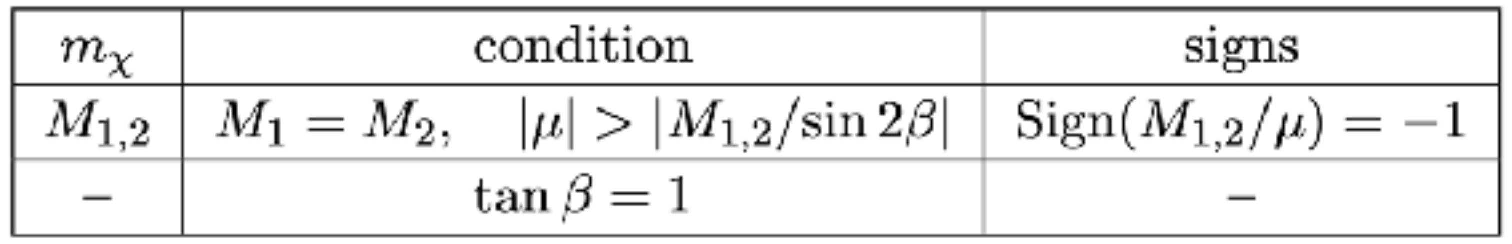
MSSM DM (Blind spot condition case)

- **Relic density aspect:**
  - **Pure-bino DM:** almost no interaction, over abundant.
  - **Pure-Higgsino DM:** $m_{\mathrm{LSP}} \gtrsim 1$ TeV for correct abundance
  - **Pure-Wino DM:** $m_{\mathrm{LSP}} \gtrsim 2.5$ TeV for correct abundance
- **DM-nucleon scattering aspect (DM direct detection):**
  - **Blind spot (BS) condition:**



$m_{\chi_1^0}$	condition	signs
$M_1(< M_2, \lvert\mu\rvert)$	$M_1 + \mu \sin 2\beta = 0$	$\mathrm{sign}(M_1/\mu) = -1$
$M_2(< M_1, \lvert\mu\rvert)$	$M_2 + \mu \sin 2\beta = 0$	$\mathrm{sign}(M_2/\mu) = -1$
$\lvert\mu\rvert(< M_1, M_2)$	$\tan\beta = 1$	$\mathrm{sign}(M_{1,2}/\mu) = -1$
$M_{1,2}(< \lvert\mu\rvert)$	$M_1 = M_2, \quad \lvert\mu\rvert > \lvert M_{1,2}/\sin 2\beta\rvert$	$\mathrm{sign}(M_{1,2}/\mu) = -1$

The spin-independent blind spot mass relation

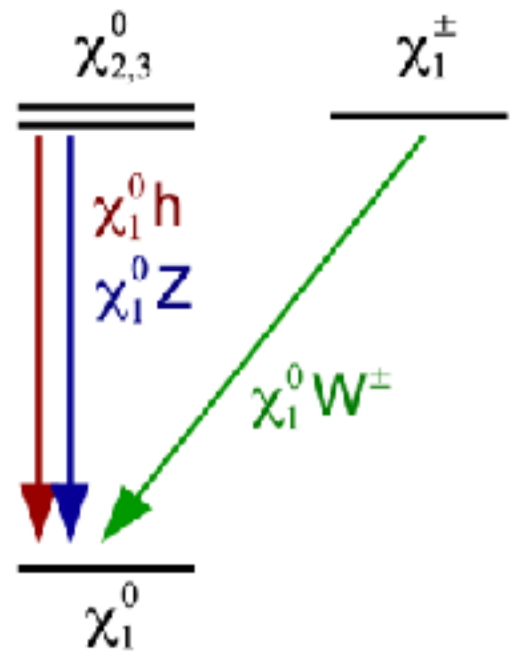


m_χ	condition	signs
$M_{1,2}$	$M_1 = M_2, \quad \lvert\mu\rvert > \lvert M_{1,2}/\sin 2\beta\rvert$	$\mathrm{Sign}(M_{1,2}/\mu) = -1$
–	$\tan\beta = 1$	–

The spin-dependent blind spot mass relation

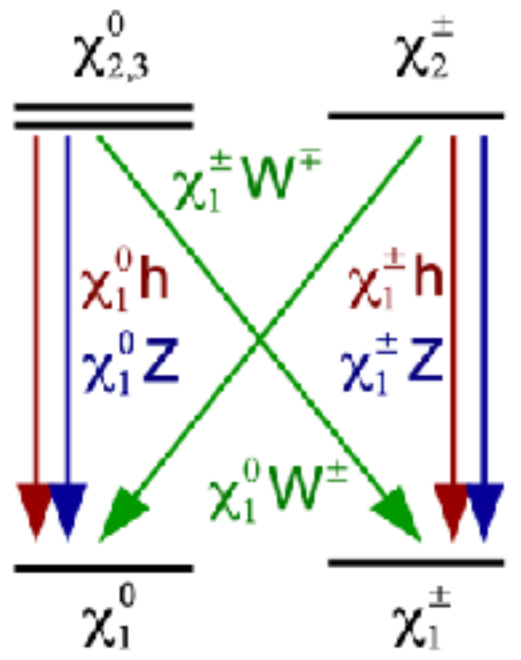
- **Case A: SI BS**

$$M_1 + \mu \sin 2\beta = 0$$
$$m_{\tilde{\chi}_1^0} = M_1$$
$$\mathrm{sgn}\left(M_1/\mu\right) = -1$$



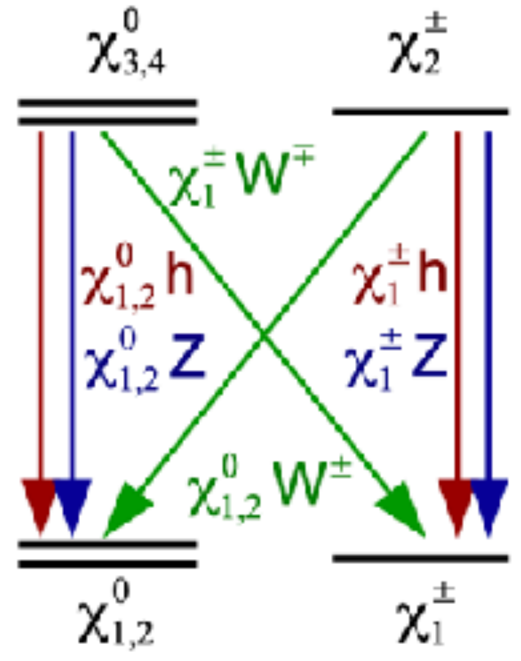
- **Case B: SI BS**

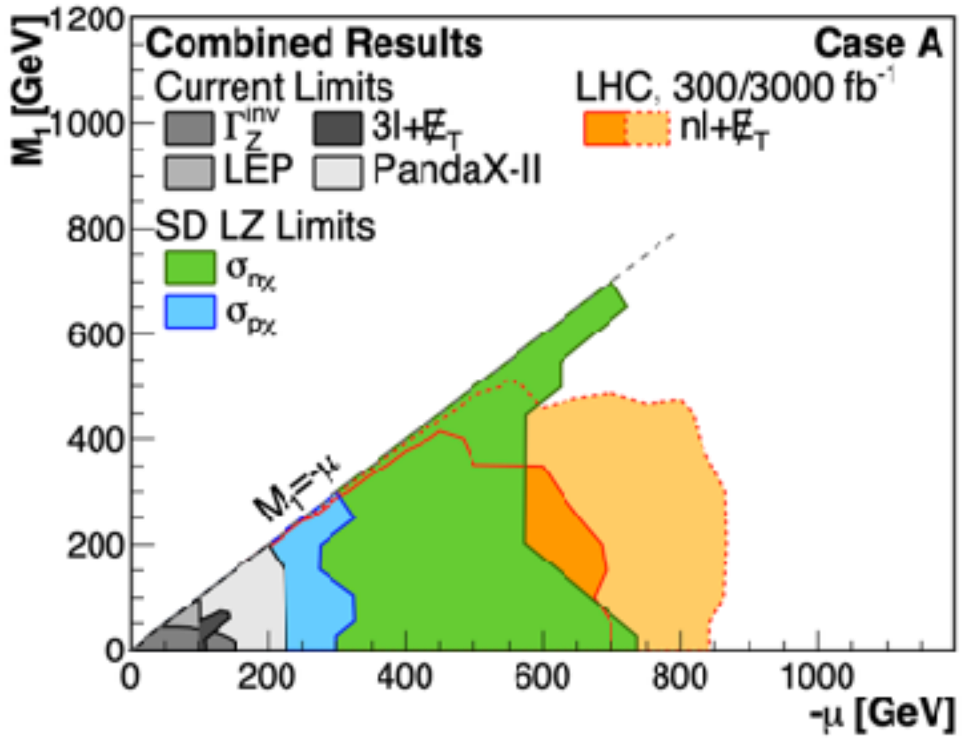
$$M_2 + \mu \sin 2\beta = 0$$
$$m_{\tilde{\chi}_1^0} = M_2$$
$$\mathrm{sgn}\left(M_2/\mu\right) = -1$$

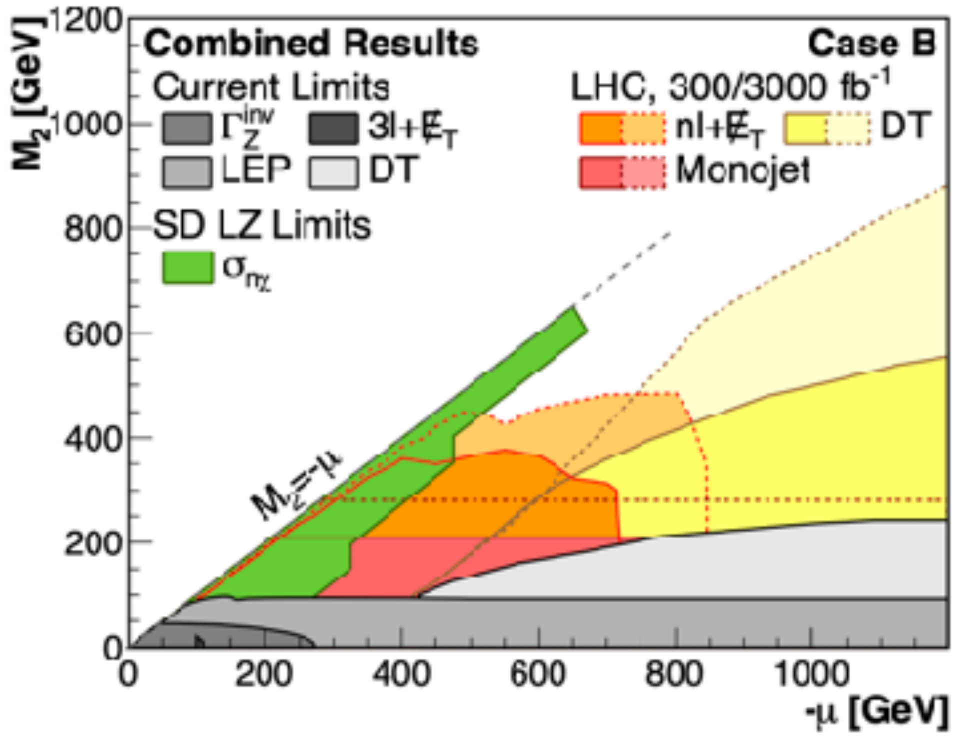


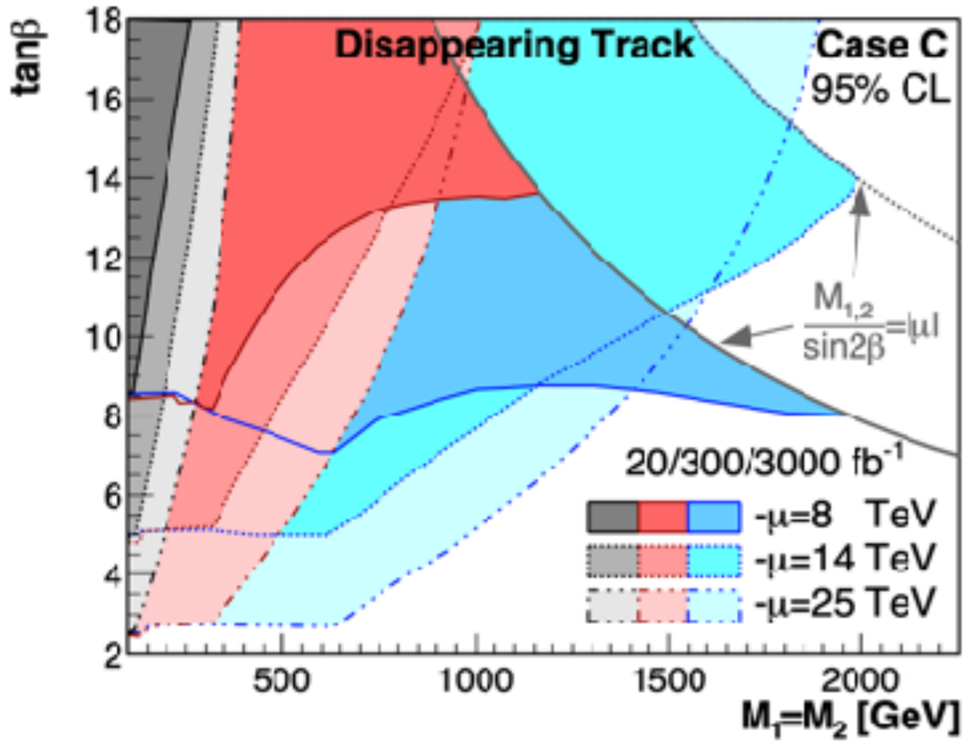
- **Case C: SI&SD BS**

$$M_1 = M_2$$
$$\left|\mu\right| > \left|M_{1,2}/\sin 2\beta\right|$$
$$\mathrm{sgn}\left(M_{1,2}/\mu\right) = -1$$









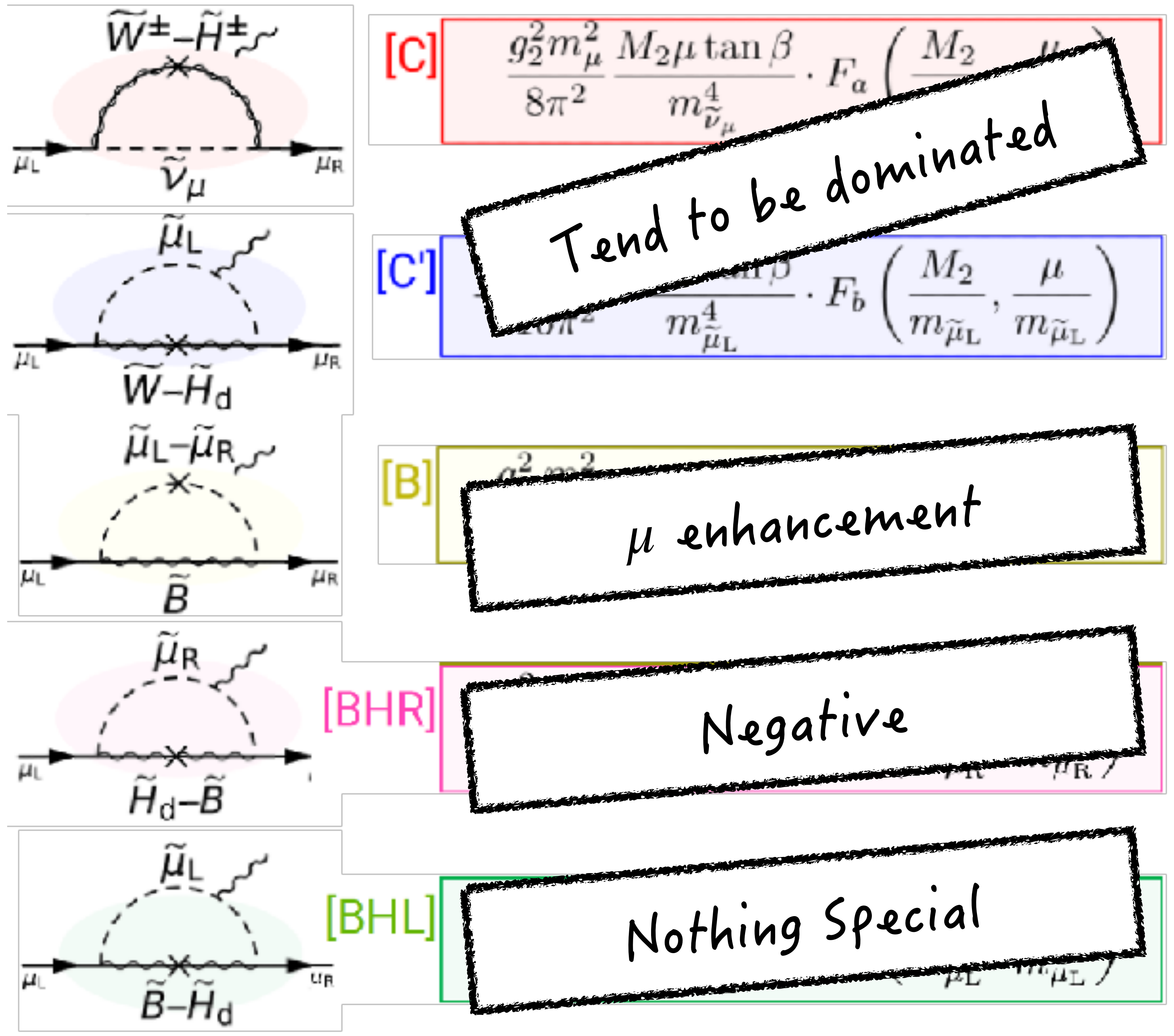
* arXiv: 1612.02387[hep-ph]

Low energy SUSY

Muon (g-2) in SUSY

$$a_\mu^{\mathrm{SUSY}} \simeq \mathrm{sgn}(\mu)\,\frac{\alpha(m_Z)}{8\pi \sin^2\theta_W}\frac{m_\mu^2}{m_{\mathrm{SUSY}}^2}\tan\beta\left(1-\frac{4\alpha}{\pi}\ln\frac{m_{\mathrm{SUSY}}}{m_\mu}\right)$$

$$\simeq \mathrm{sgn}(\mu)\;130\times10^{-11}\cdot\left(\frac{100\ \mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^2\tan\beta$$



Tend to be dominated

μ enhancement

Negative

Nothing Special

Collider constraints

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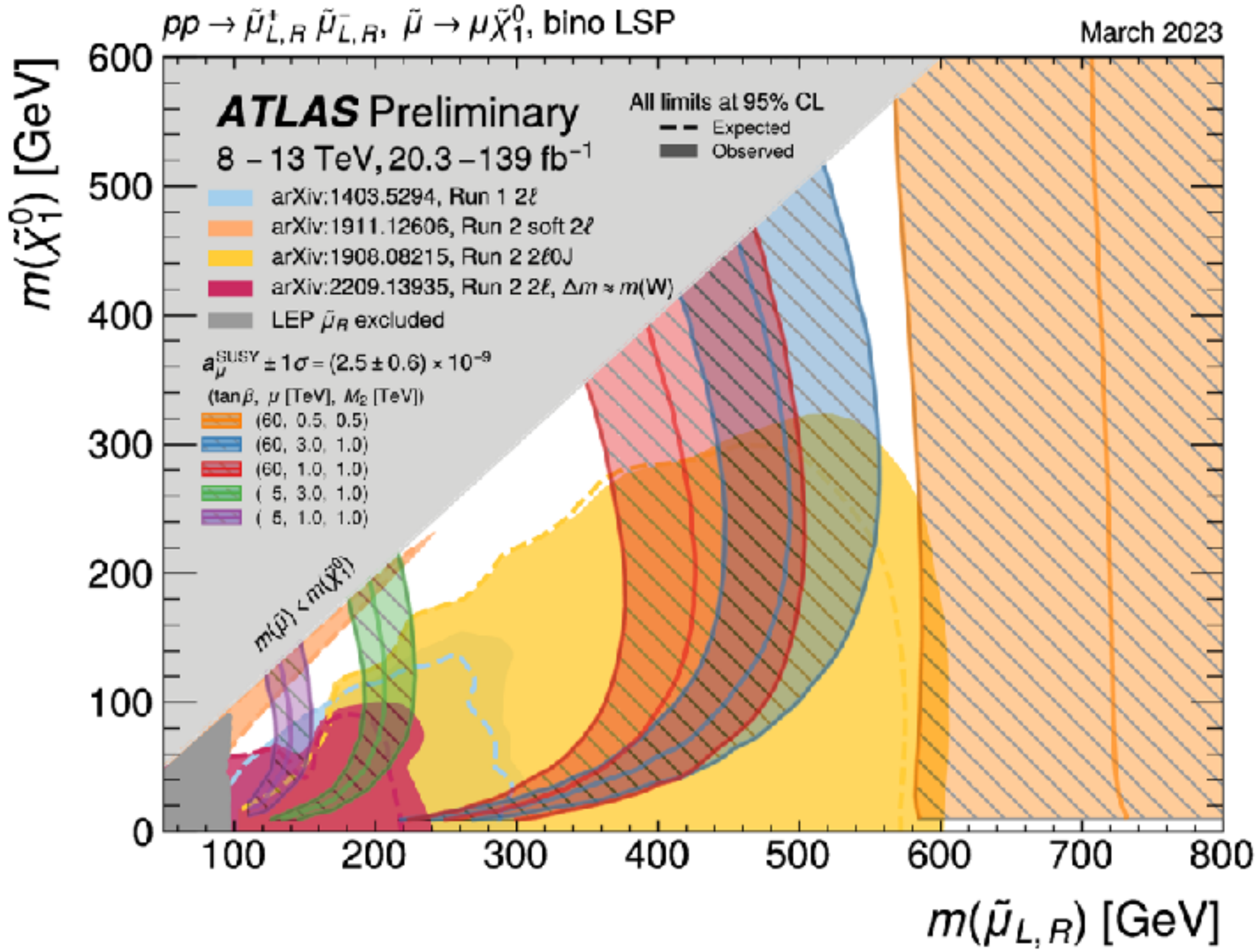


- Requires light sleptons & light electroweakinos.
- We are in the muon g-2 era !!

-Sho Iwamoto

- arXiv: hep-ph/9512396
- arXiv: hep-ph/0102122
- arXiv: hep-ph/0609168
- arXiv: 1704.05178[hep-ph]
- arXiv: 2104.03217[hep-ph]

Low energy SUSY

MSSM DM in Muon (g-2) parameter space

- **Bino-dominated DM candidate**

three annihilation mechanism can fulfill the DM relic density

1. **co-annihilate with Wino:**

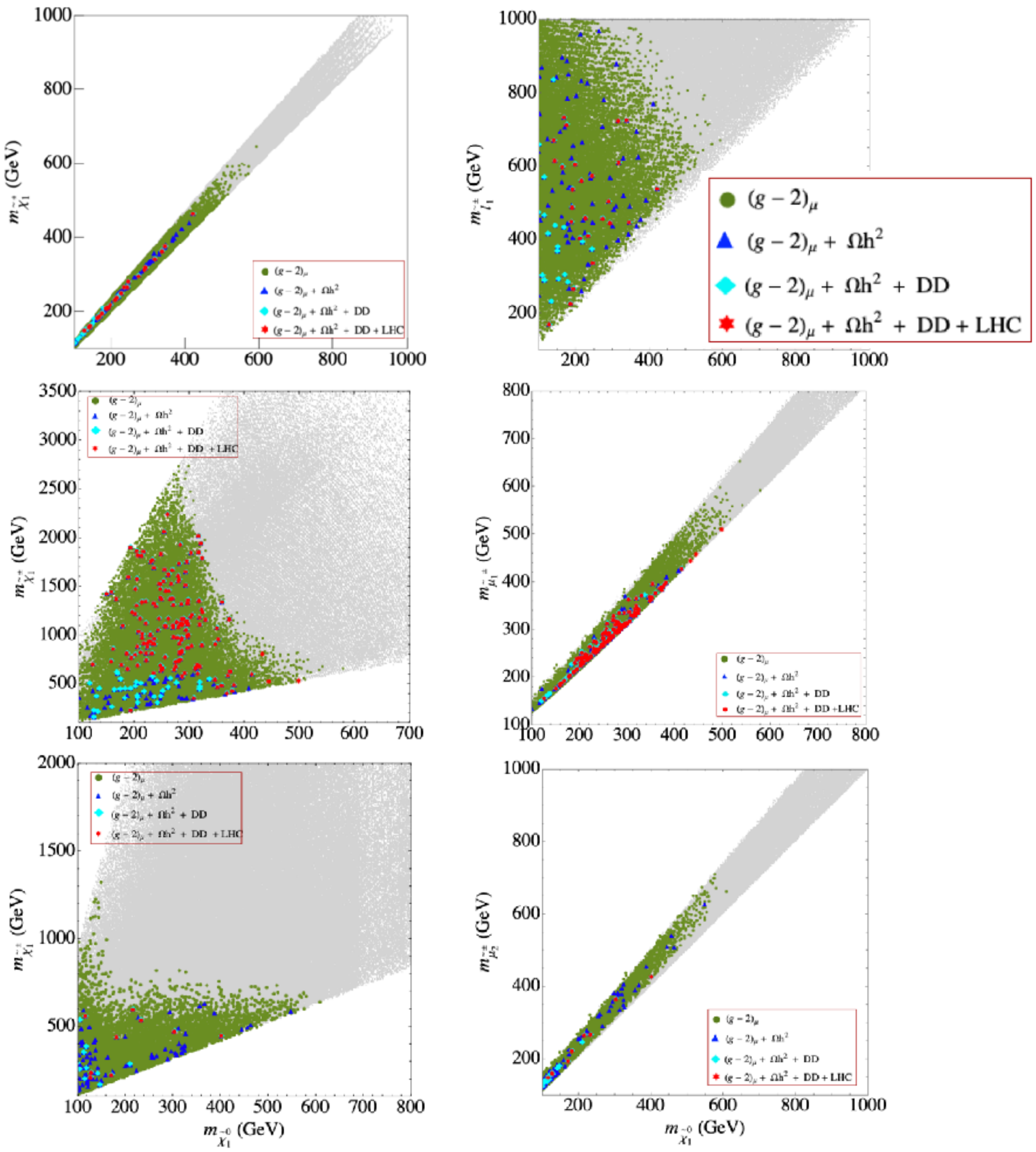
$$M_1 \lesssim M_2 \qquad m_{\rm (N)LSP} \lesssim 650\ (700)\ {\rm GeV}$$

2. **co-annihilate with Left-handed smuon:**

$$M_1 \lesssim m_{\tilde{\mu}_L} \qquad m_{\rm (N)LSP} \lesssim 650\ (700)\ {\rm GeV}$$

3. **co-annihilate with Right-handed smuon:**

$$M_1 \lesssim m_{\tilde{\mu}_R} \qquad m_{\rm (N)LSP} \lesssim 650\ (700)\ {\rm GeV}$$



- arXiv: 2006.15157[hep-ph]
- arXiv: 2103.13403[hep-ph]
- arXiv: 2104.03287[hep-ph]
- arXiv: 2105.06408[hep-ph]
- arXiv: 2112.01389[hep-ph]

Low energy SUSY

MSSM DM in Muon (g-2) parameter space

- **Wino-dominated DM candidate**

the DM relic density is only an upper bound, (The full relic density implies $m_{\tilde{\chi}_1^0} \sim 3\ \text{TeV}$, which cannot explain muon g-2)

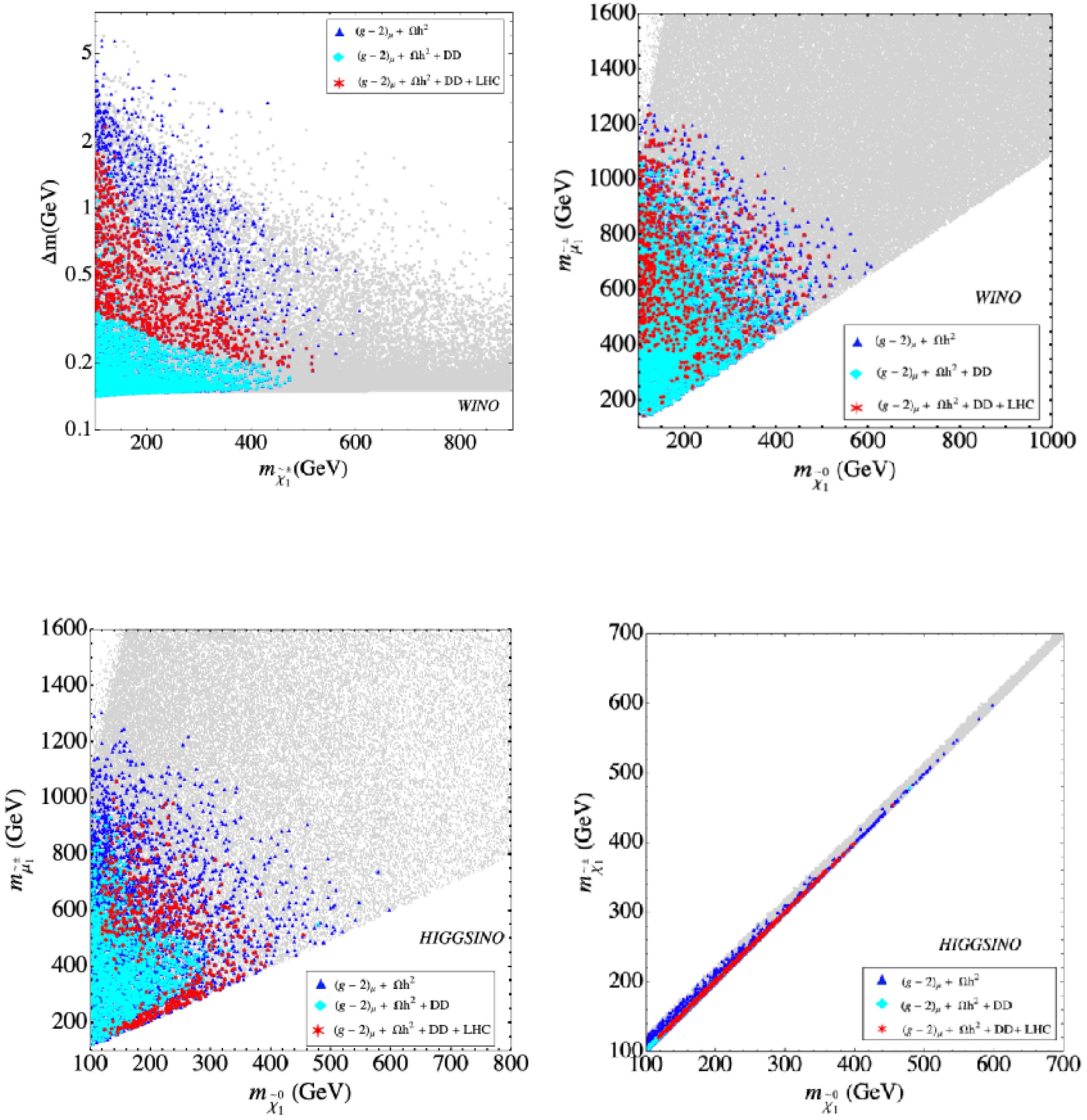
$$M_2 \lesssim M_1, \mu, m_{\tilde{\mu}_L}, m_{\tilde{\mu}_R}$$
$$m_{\text{(N)LSP}} \lesssim 600\ \text{GeV}$$
$$m_{\text{NLSP}} - m_{\text{LSP}} \sim 0.3\ \text{GeV}$$

- **Higgsino-dominated DM candidate**

the DM relic density is only an upper bound, (The full relic density implies $m_{\tilde{\chi}_1^0} \sim 1\ \text{TeV}$, which cannot explain muon g-2)

$$\mu \lesssim M_1, M_2, m_{\tilde{\mu}_L}, m_{\tilde{\mu}_R}$$
$$m_{\text{(N)LSP}} \lesssim 500\ \text{GeV}$$
$$m_{\text{NLSP}} - m_{\text{LSP}} \sim 5\ \text{GeV}$$

- arXiv: 2006.15157[hep-ph]
- arXiv: 2103.13403[hep-ph]
- arXiv: 2104.03287[hep-ph]
- arXiv: 2105.06408[hep-ph]
- arXiv: 2112.01389[hep-ph]



Low energy SUSY

MSSM Muon (g-2) & Electron (g-2)

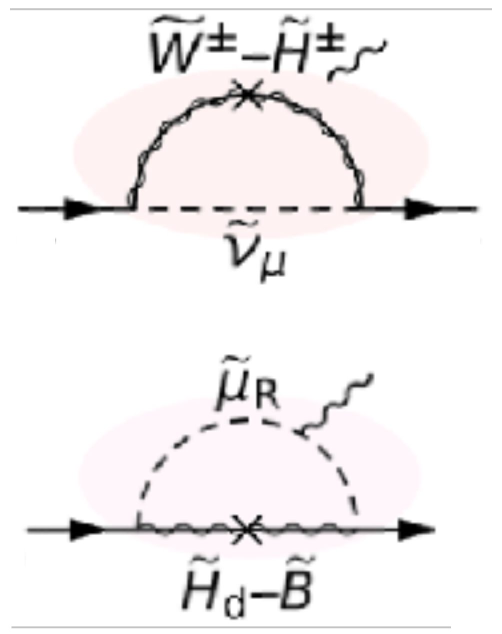
$$\Delta a_e(\mathrm{Rb}) = 48(36) \times 10^{-14}$$

$$\Delta a_e(\mathrm{Cs}) = -88(36) \times 10^{-14}$$

- **Two anomalies are highly correlated**

$$\frac{a_e^{\mathrm{NP}}}{a_\mu^{\mathrm{NP}}} \sim \frac{m_e^2}{m_\mu^2} \qquad \frac{\Delta a_e(\mathrm{Cs})}{\Delta a_\mu}\frac{m_\mu^2}{m_e^2} \sim -15$$

- **MSSM solution without Lepton flavor violation**



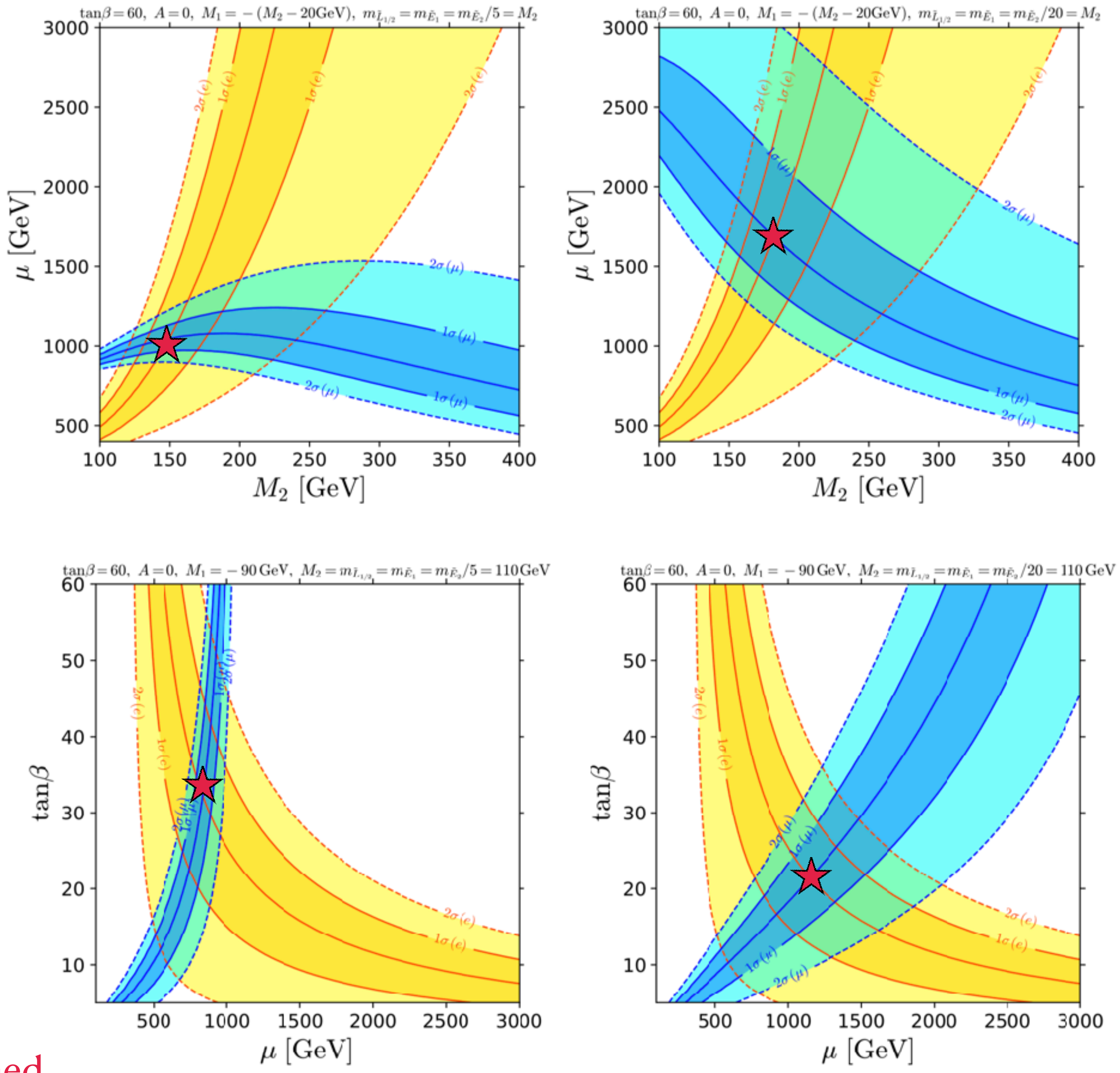
$\propto m_\mu^2 \; M_2 \mu \tan\beta$

$\propto m_e^2 \; M_1 \mu \tan\beta$

$\mathrm{Sgn}(M_2 M_1) < 0$

Large μ, large $\tan\beta$

Non-univeral soft slepton parameter



* arXiv: 1908.03607 [hep-ph]
* arXiv: 2107.04962 [hep-ph]

No global-fit result performed.
Still OK in MSSM, but hard.

Low energy SUSY

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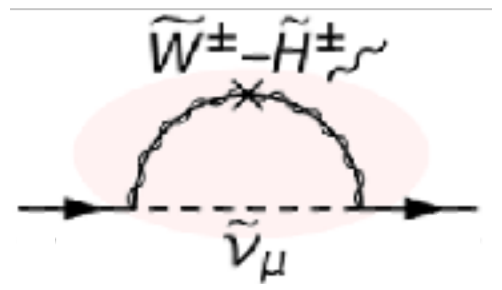
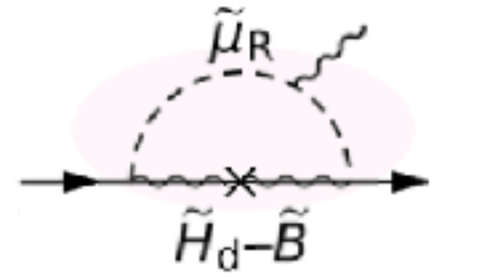


$$\propto m_e^2\ M_2 \mu \tan\beta$$

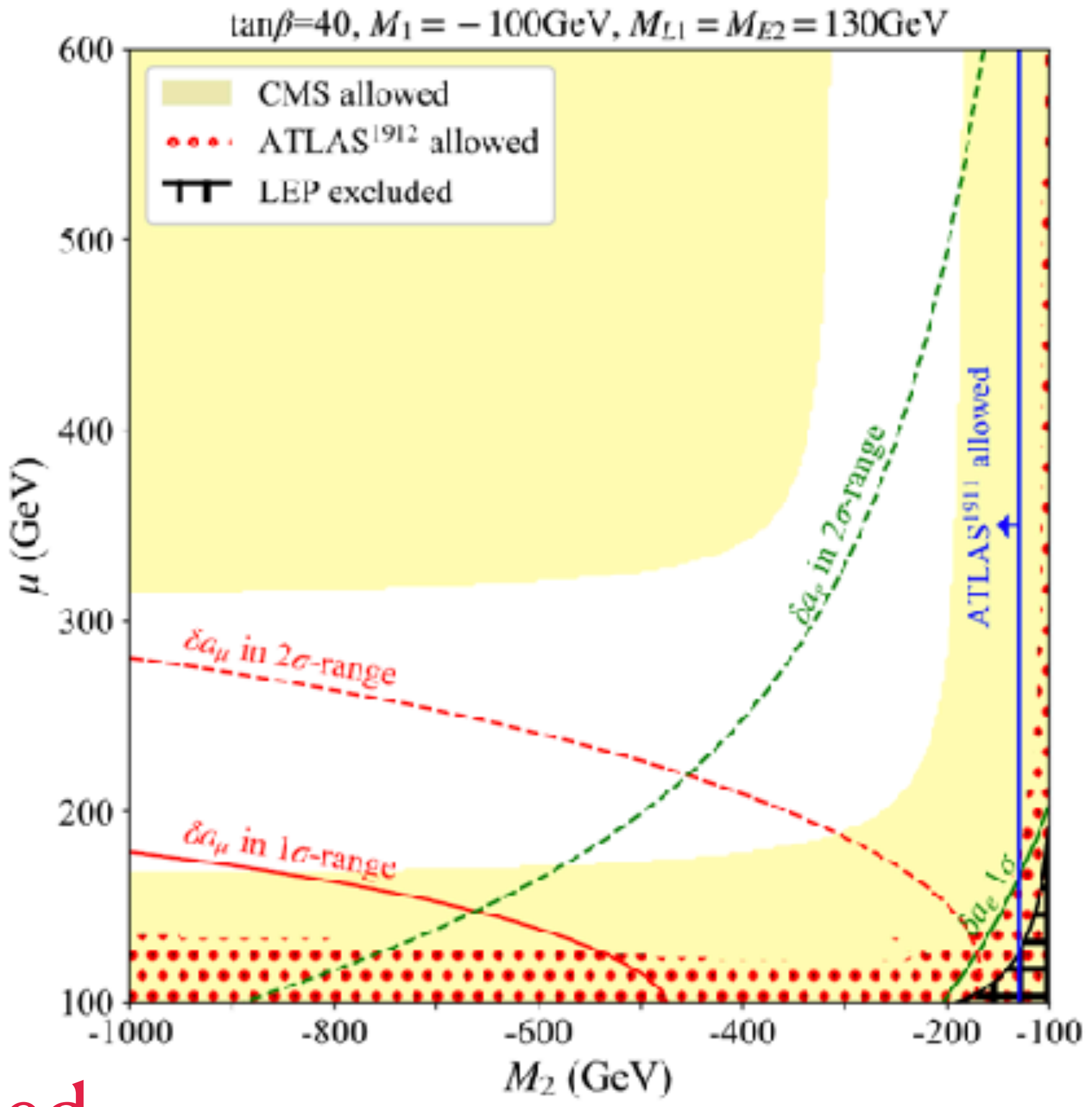


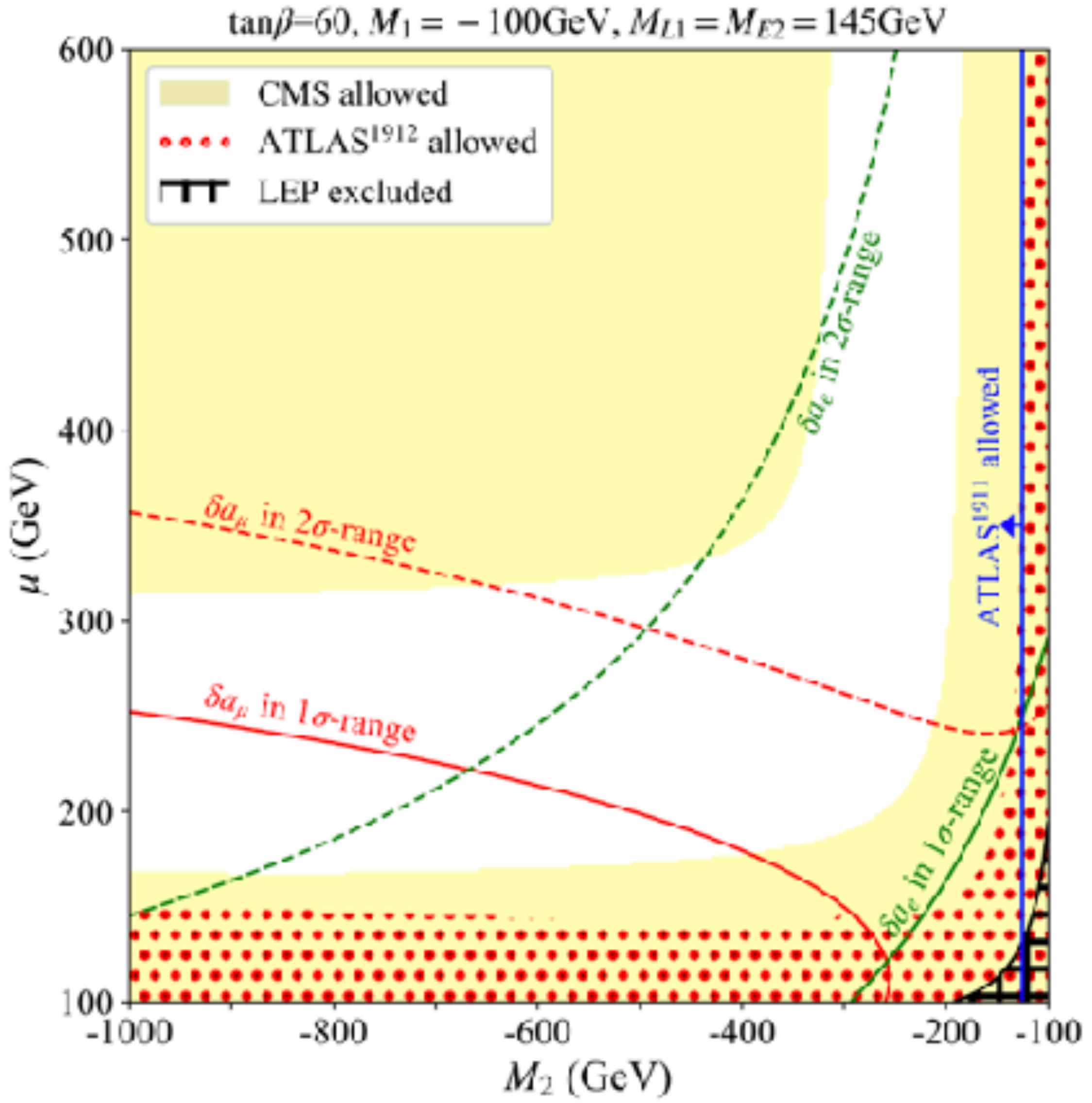
$$\propto m_e^2\ M_1 \mu \tan\beta$$

$\mathrm{Sgn}(M_2 M_1) > 0$

Large μ, large $\tan\beta$

Non-univeral soft slepton parameter





* arXiv: 1908.03607 [hep-ph]
* arXiv: 2107.04962 [hep-ph]

No global-fit result performed.
Still OK in MSSM, but hard.

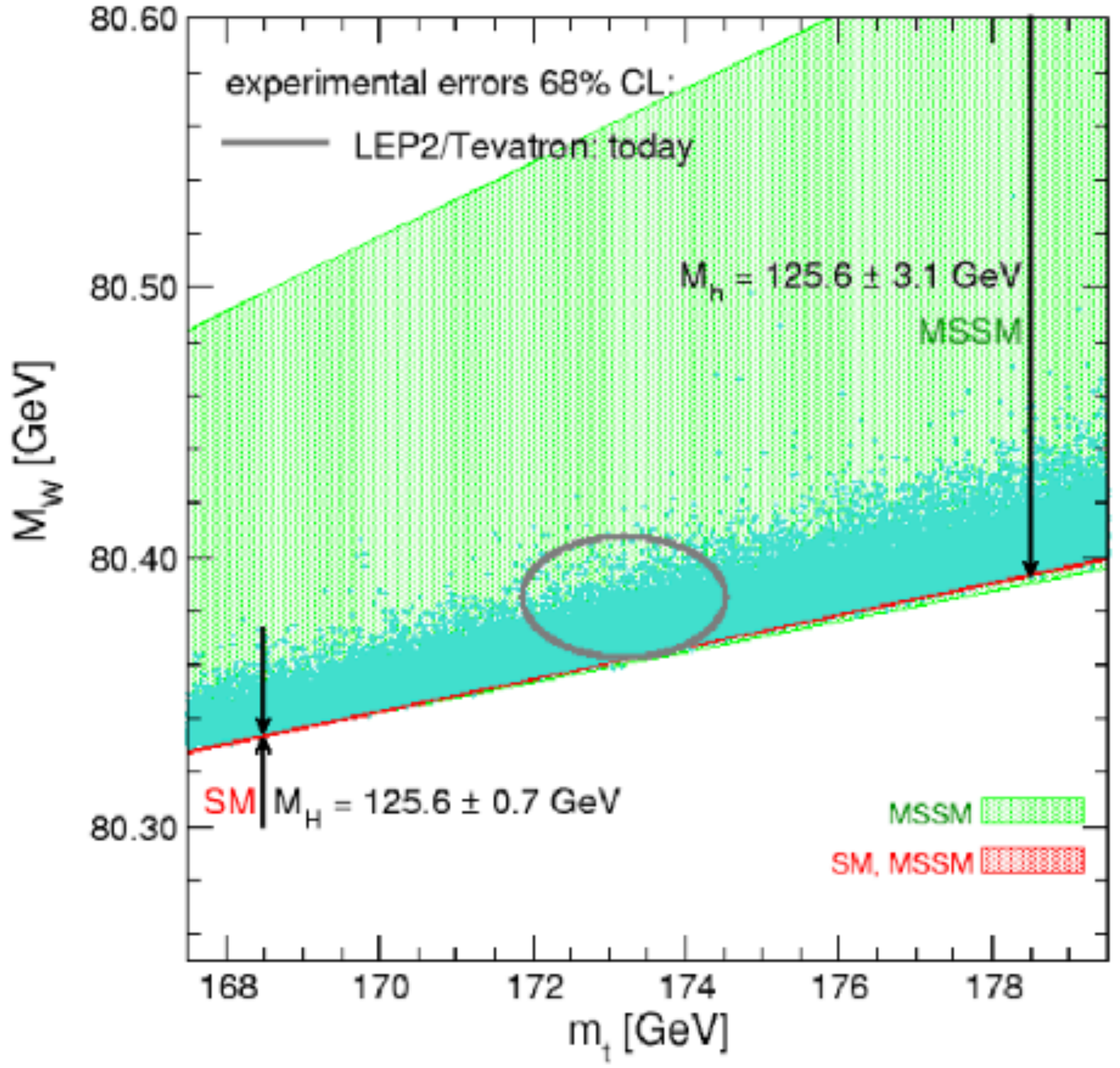
Low energy SUSY

DM, Muon (g-2) & W-mass Anomaly

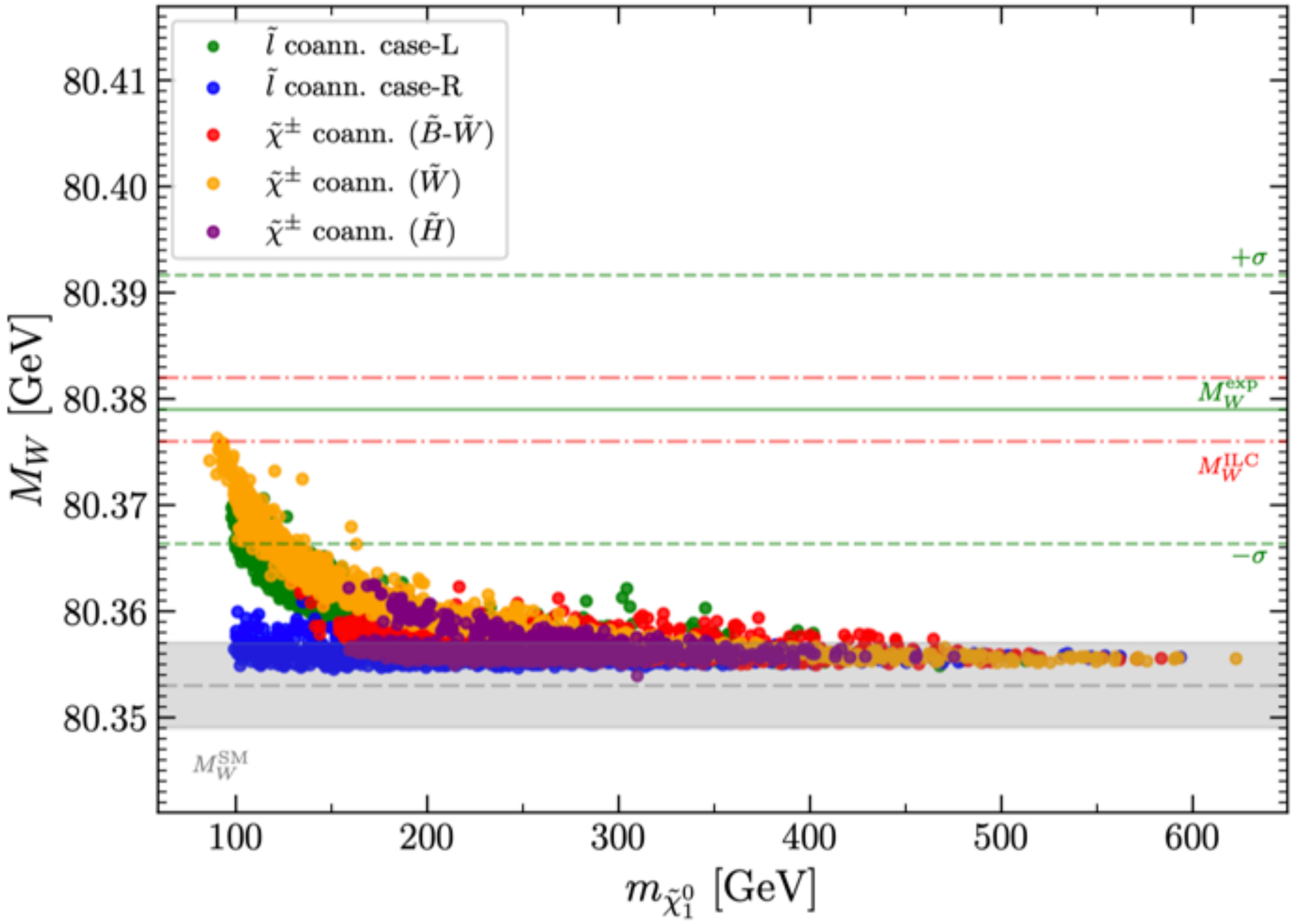
$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r),\qquad \Delta r=\Delta\alpha-\frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho+\cdots,\qquad \delta M_W\simeq\frac{M_W}{2}\frac{\cos^2\theta_W}{\cos^2\theta_W-\sin^2\theta_W}\Delta\rho.$$

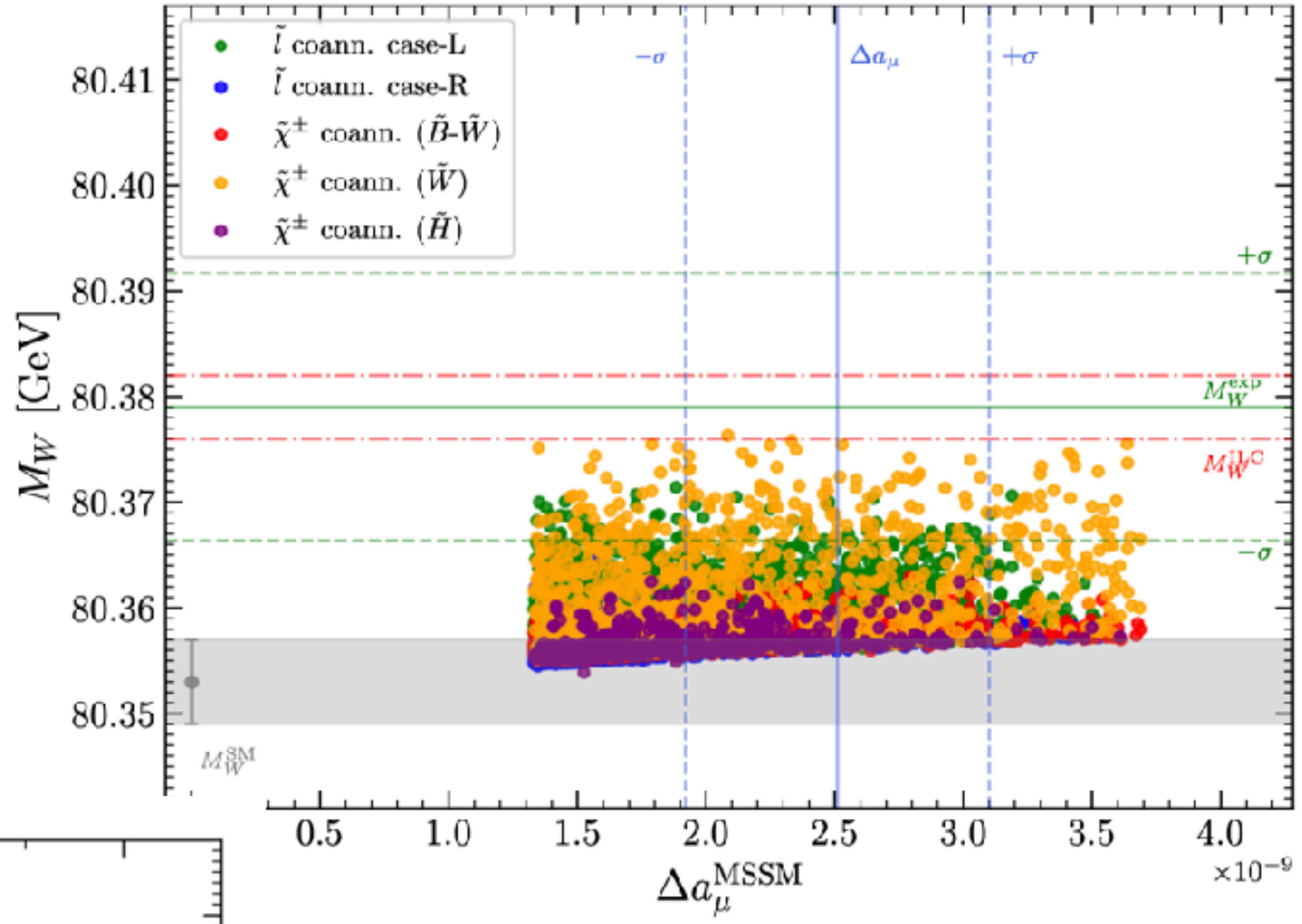
Δr is the sum of the loop corrections, $\Delta\alpha$ the shift of fine-structure constant.

$\Delta\rho$ is sensitive to the mass splitting of the isospin super-partners, like $\Delta(m_{\tilde t}, m_{\tilde b})$



- SUSY is a decoupled theory, larger m_W needs lighter SUSY particle.
- Light blue point: $m_{\tilde{t}/\tilde{b}} > 500$ GeV, $m_{\tilde{q}} > 1.2$ TeV & $m_{\tilde{g}} > 1.2$ TeV.





- Very light SUSY DM favored by the CDF-II measurement of m_W.
- The Δa_μ favored parameter space is hard to explain the CDF anomaly.
- LHC and DM phenomenology put very strong constraints.

- arXiv: 1311.1663 [hep-ph]
- arXiv: 2203.15710 [hep-ph]
- arXiv: 2204.04204 [hep-ph]

Low energy SUSY

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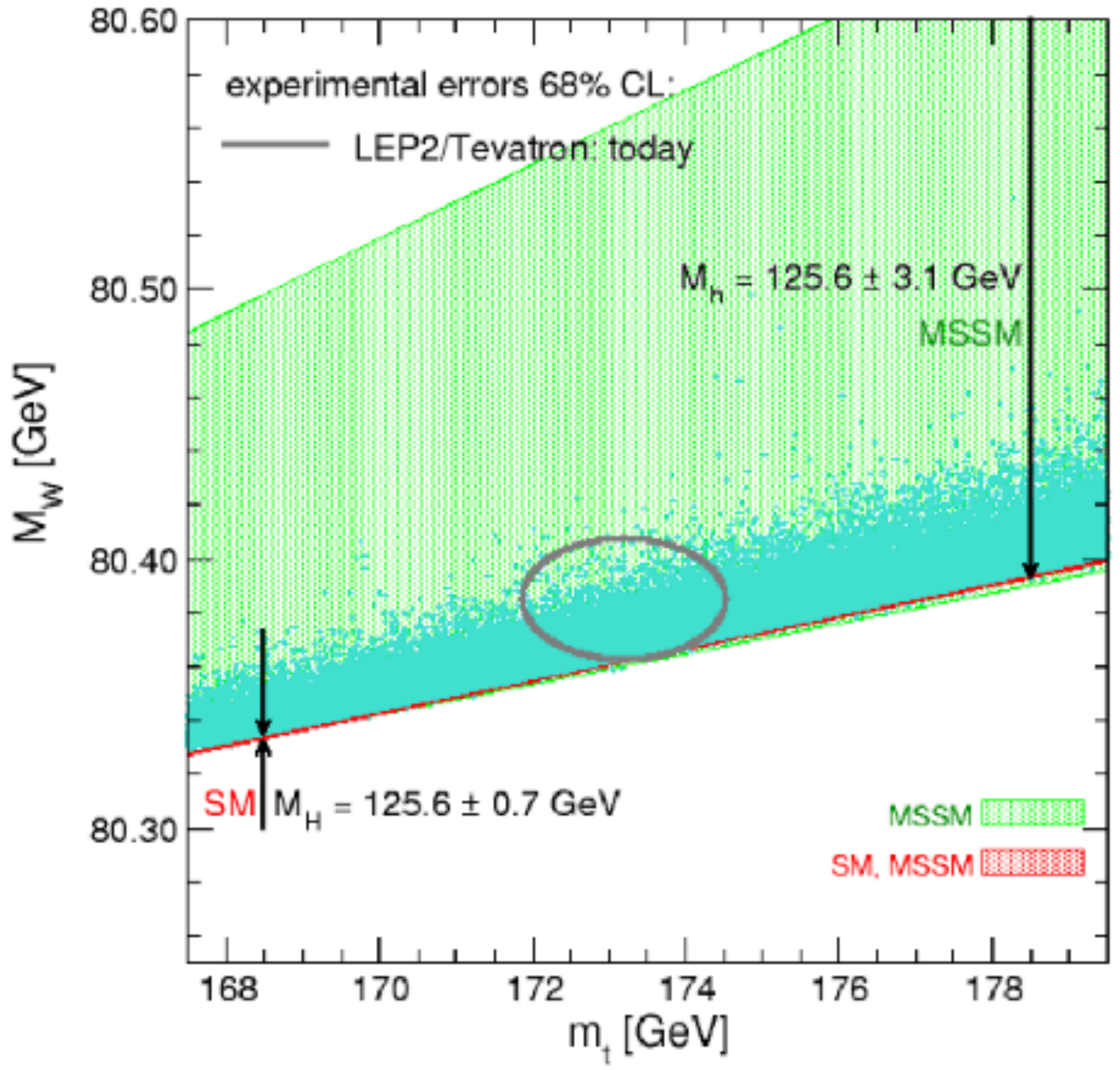
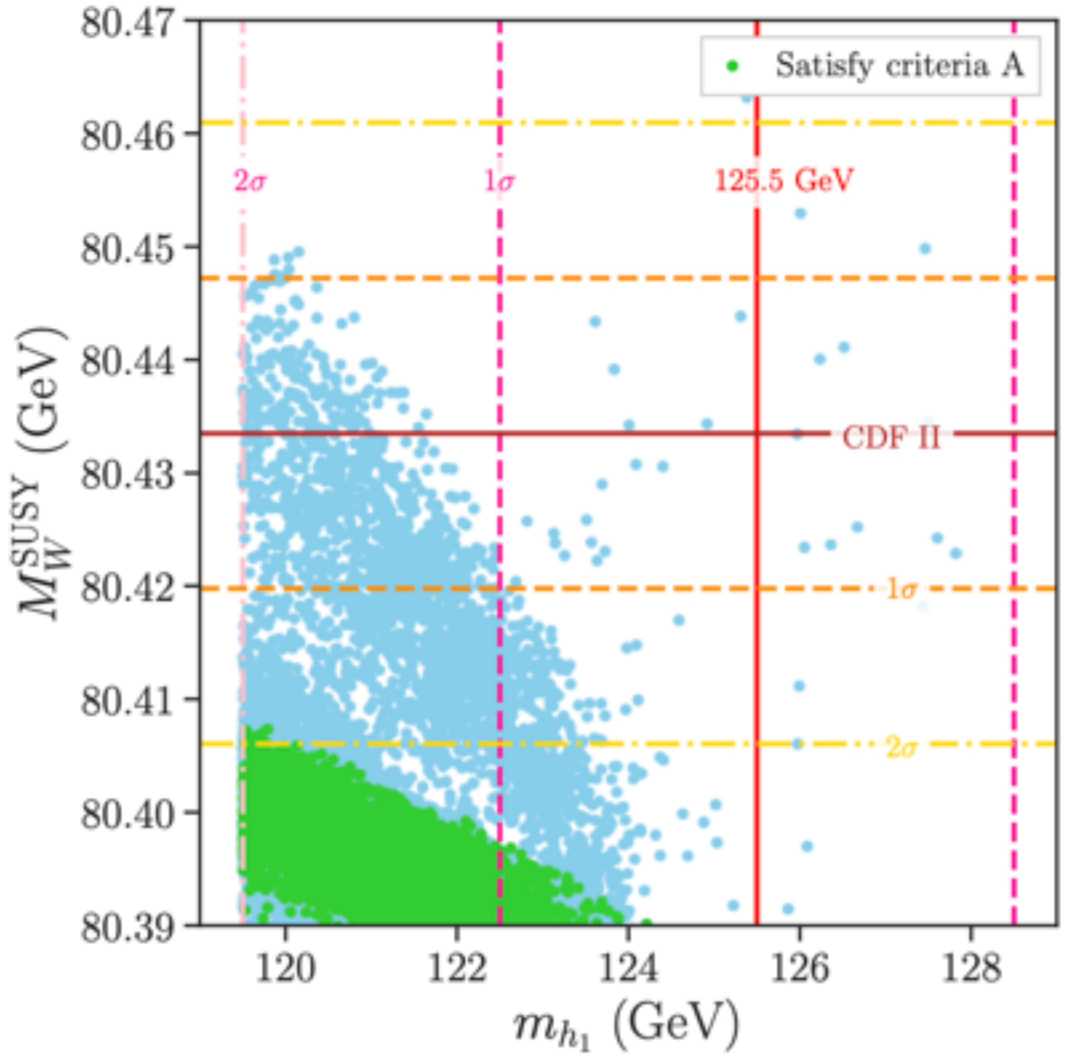
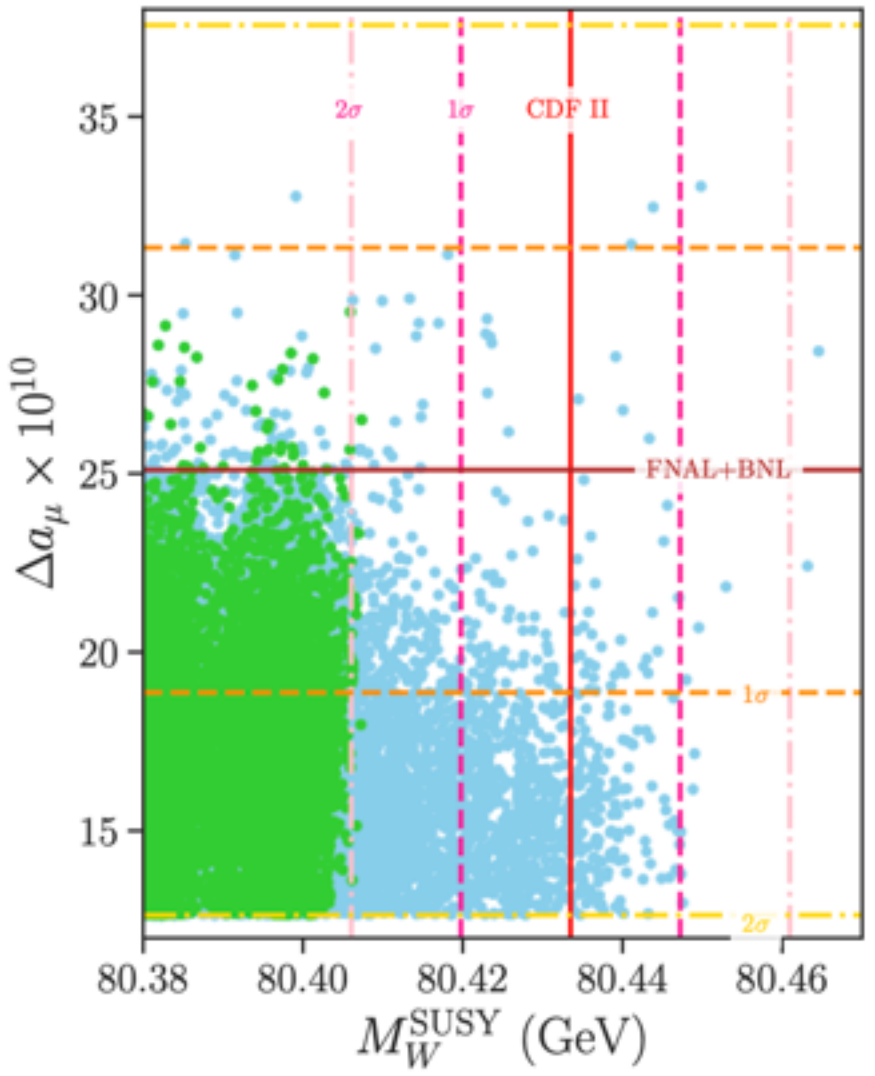


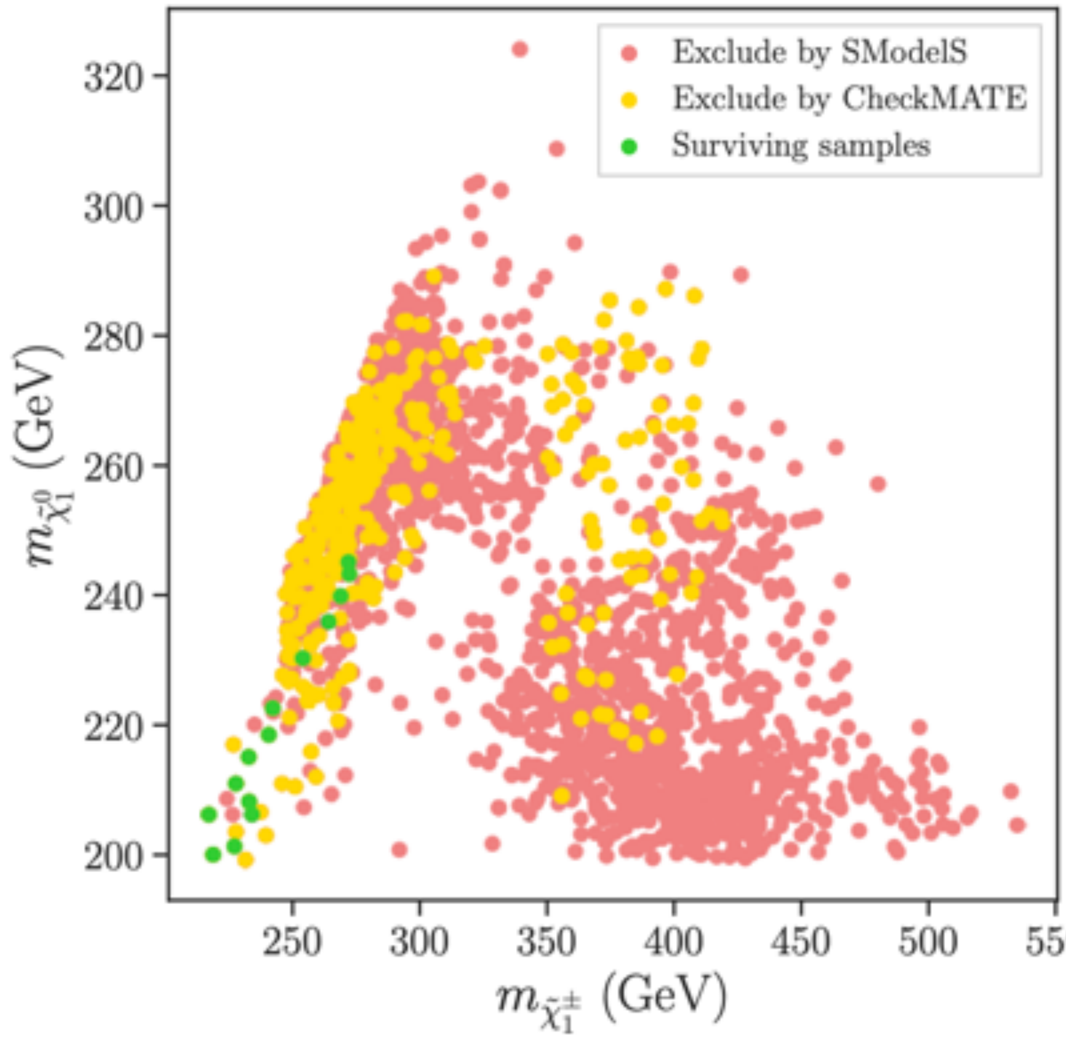
- SUSY is a decoupled theory, larger m_W needs lighter SUSY particle.
- Light blue point: $m_{\tilde{t}/\tilde{b}} > 500$ GeV, $m_{\tilde{q}} > 1.2$ TeV & $m_{\tilde{g}} > 1.2$ TeV.

- Hard to achieve $m_h \sim 125$ GeV and $m_W \gtrsim 80.4$ GeV simultaneously.
- The Δa_μ favored parameter space is hard to explain the CDF anomaly.
- LHC and DM phenomenology put very strong constraints. LHC-Run III or HL-LHC will probe the surviving parameter space.

1. Need more precise theoretical calculation;
2. Global-fit is needed!





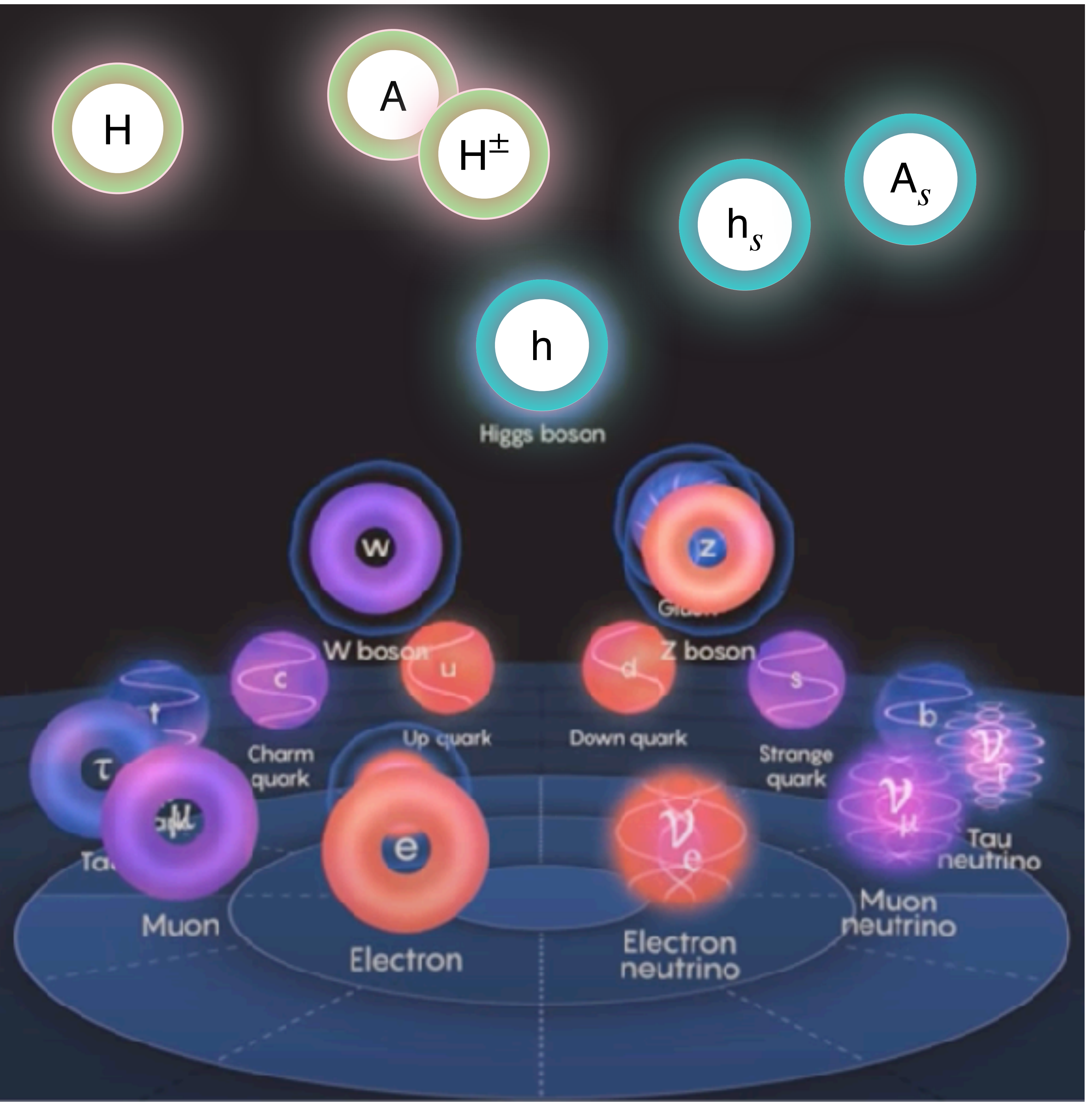


- arXiv: 1311.1663 [hep-ph]
- arXiv: 2203.15710 [hep-ph]
- arXiv: 2204.04204 [hep-ph]

Low energy SUSY

$$W_{\rm NMSSM} = y_u Q\cdot H_u\,\bar{u} - y_d Q\cdot H_d\,\bar{d} - y_e L\cdot H_d\,\bar{e} + \underbrace{\lambda S}_{\mu_{\rm eff} = \lambda\langle S\rangle \text{ after EWSB}} H_u\cdot H_d + \frac{\kappa}{3}S^3$$

A light Higgs boson in Next-to-Minimal SSM (NMSSM)

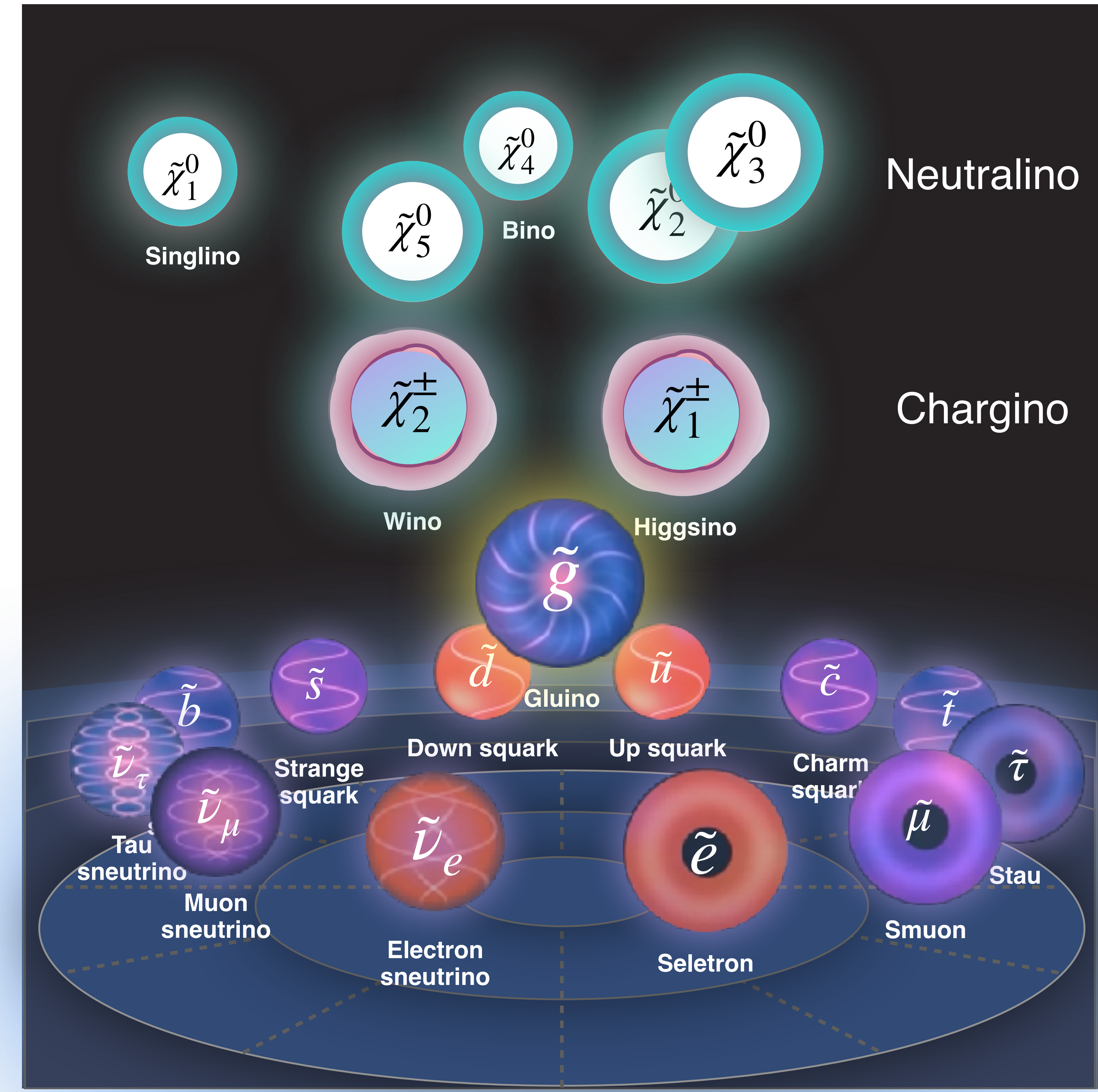


Two extra Higgs boson (h_s, A_s), and one extra Neutralino.

$$m_h^2 \approx m_Z^2\cos^2 2\beta + \Delta_t \boxed{+\lambda^2 v^2 - \frac{\lambda^2}{\kappa^2}v^2\left(\lambda - \kappa\sin 2\beta\right)^2}$$

Additional contribution compared with MSSM.

- **Singlino DM:** like pure-Bino case, but the mixing term with other electroweakino are controlled by one free parameter λ.
- New DM annihilation channels:
  - A. $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h_s A_s$
  - B. Co-annihilated with Higgsino $\lambda \simeq 2|\kappa|$
  - C. Annihilate via the charged Higgsino in t-channel.
- New blind spot condition due to the light h_s, which relax the stress from dark matter



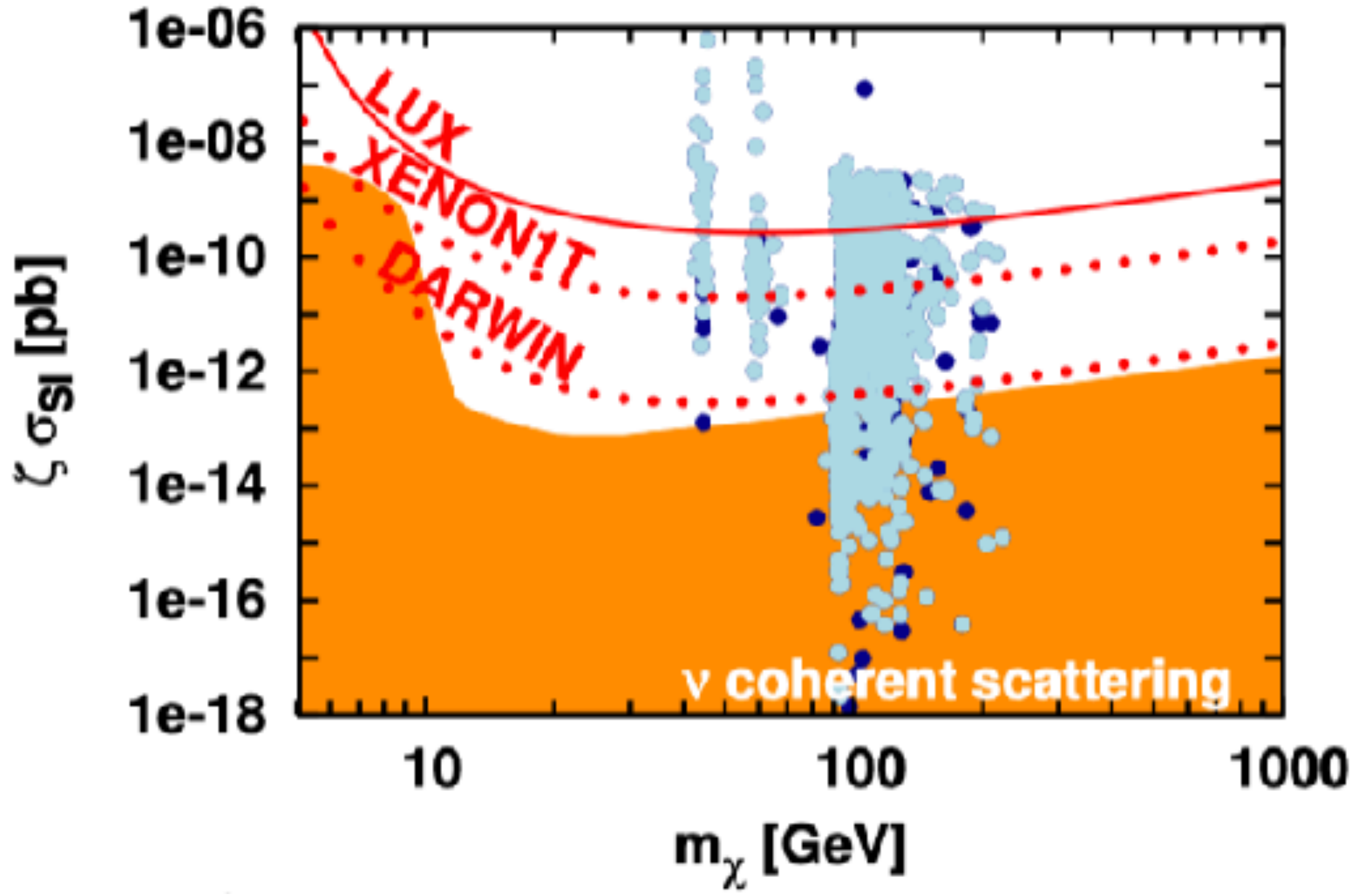
- arXiv: 0910.1785 [hep-ph]
- arXiv: 1612.06574 [hep-ph]
- arXiv: 1806.09478 [hep-ph]
- arXiv: 1810.09143 [hep-ph]
- arXiv: 2102.05309 [hep-ph]

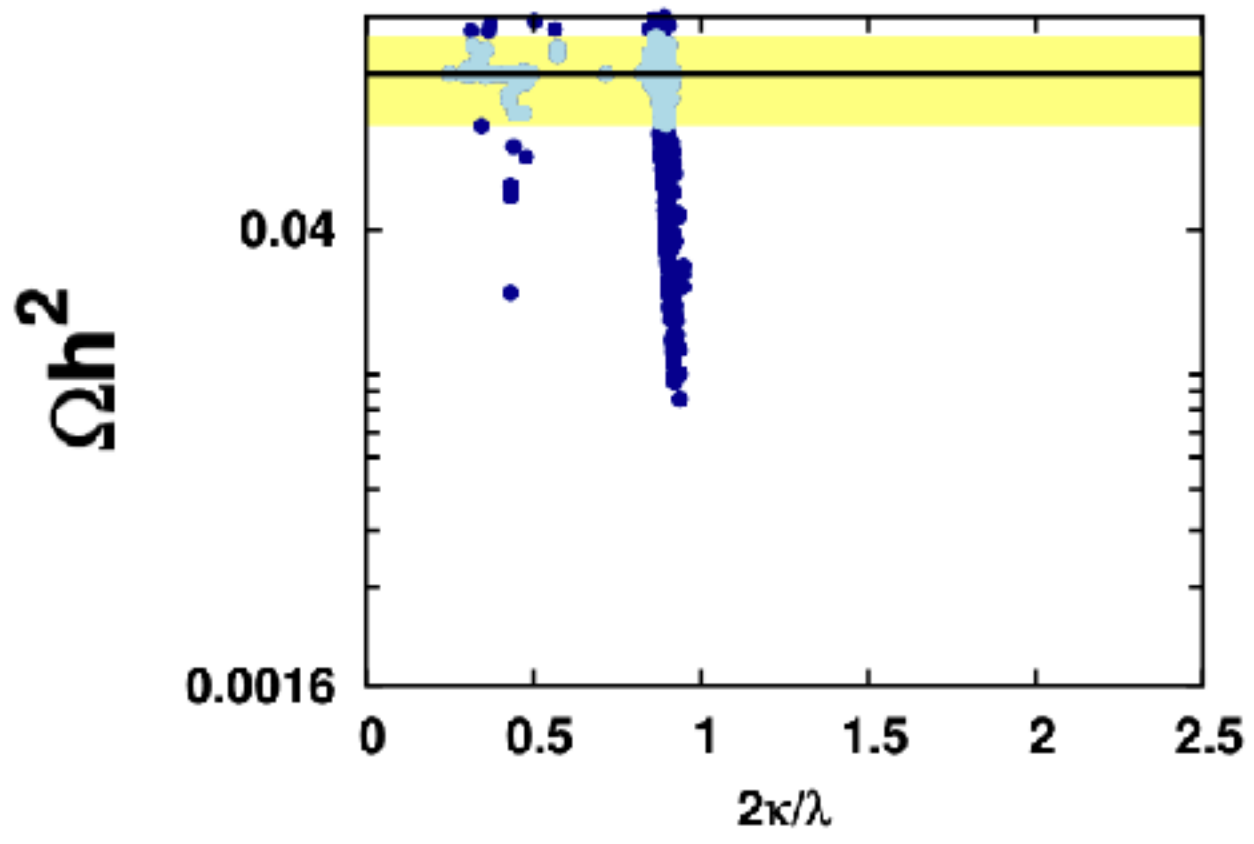
Low energy SUSY

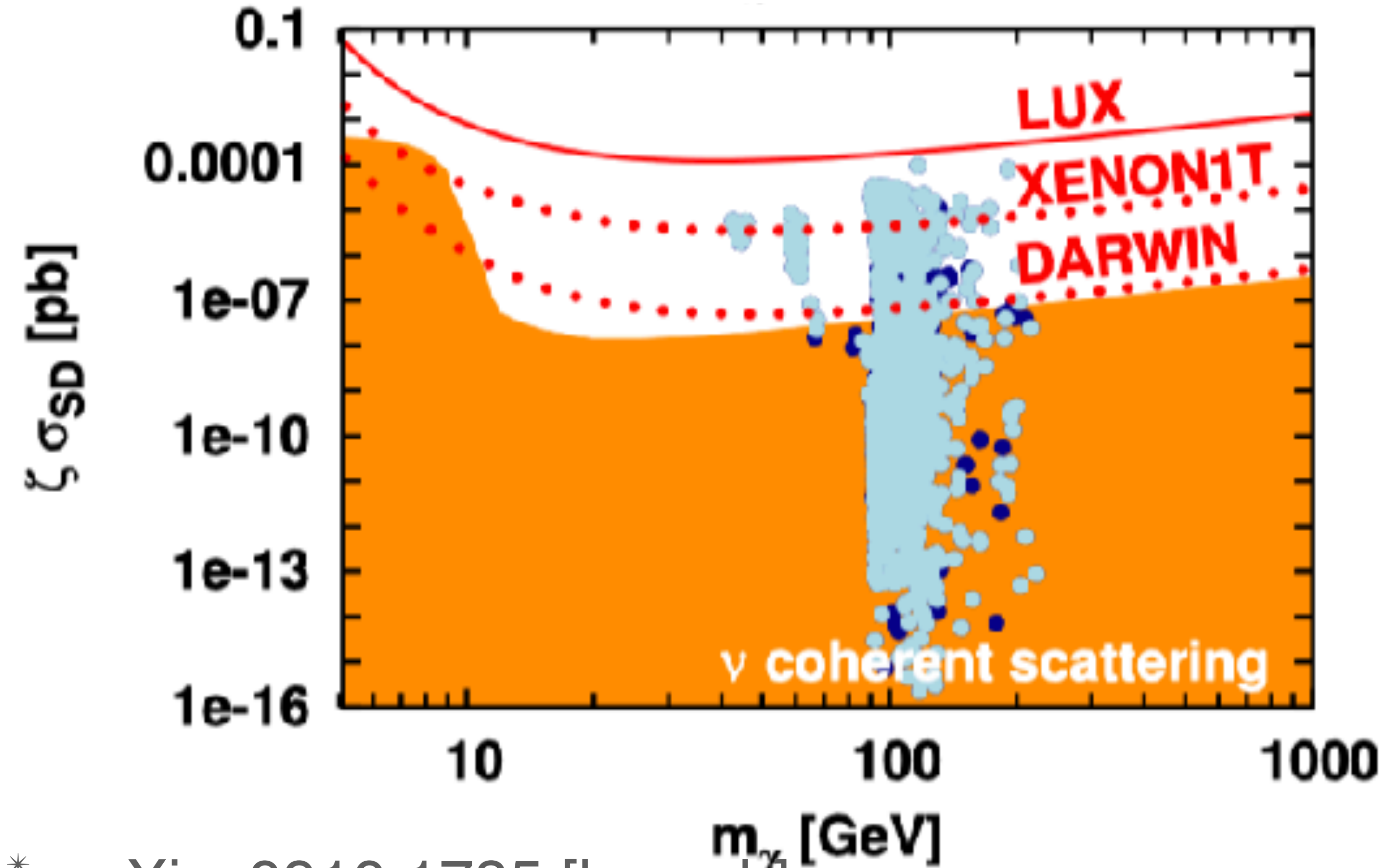
$$W_{\text{NMSSM}} = y_u Q \cdot H_u\, \bar{u} - y_d Q \cdot H_d\, \bar{d} - y_e L \cdot H_d\, \bar{e} + \lambda S H_u \cdot H_d + \frac{\kappa}{3} S^3$$

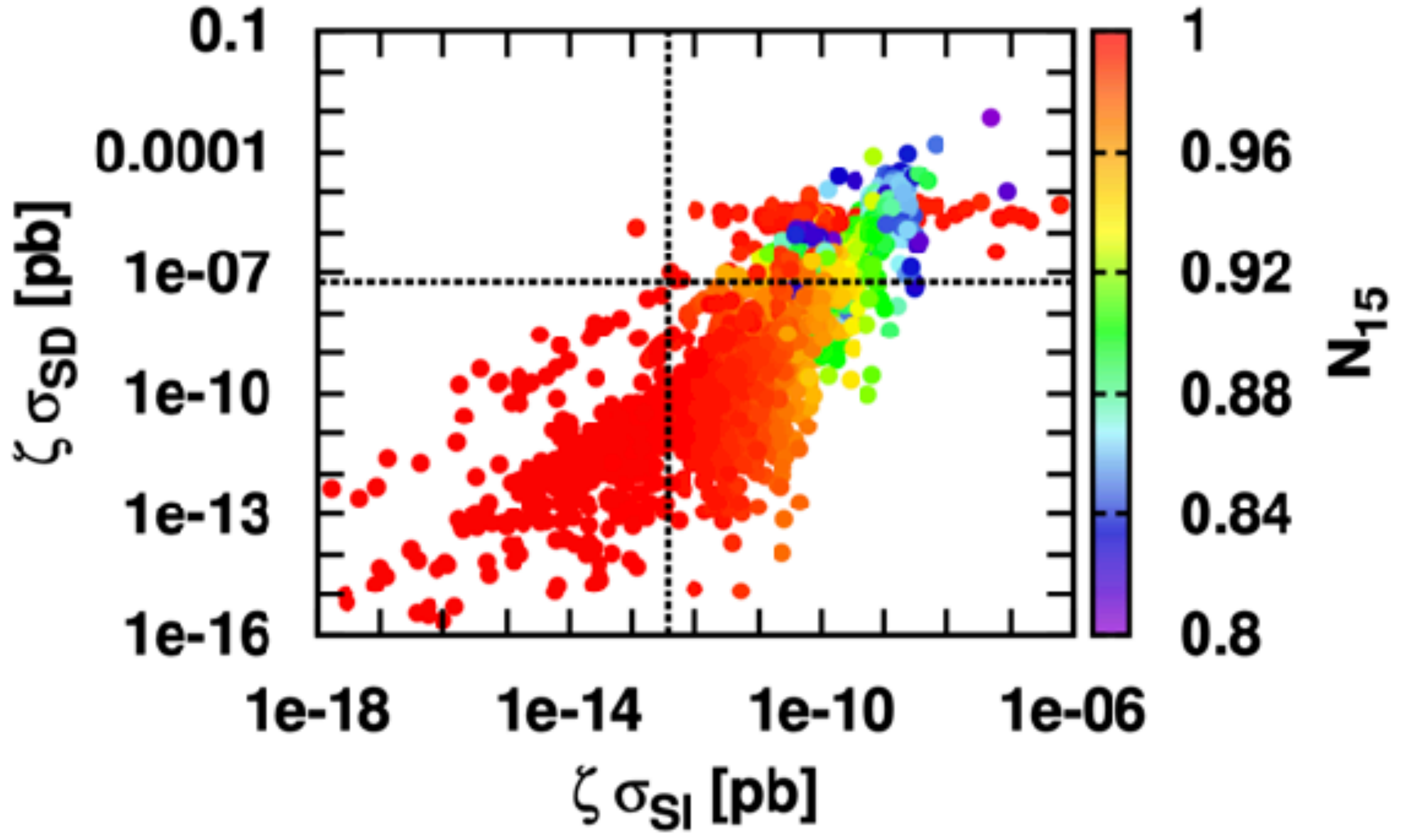
$\mu_{\text{eff}} = \lambda\langle S\rangle$ after EWSB

Singlino DM in NMSSM









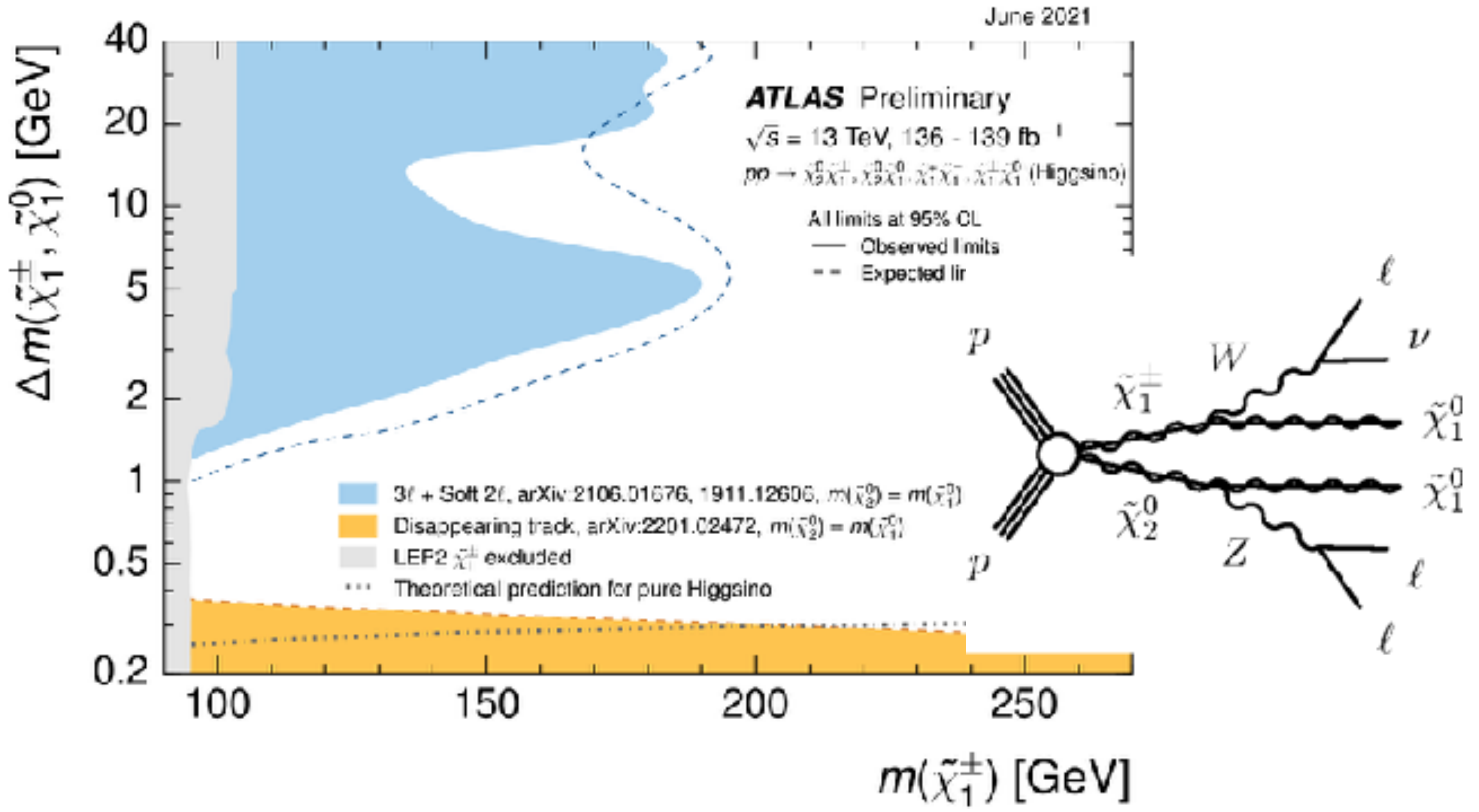
- **Status of Singlino DM in NMSSM prefers to:**

Large Singlino purity: $N_{15}^2 > 0.99$

Co-annihilation with Higgsino: $2|\kappa|/\lambda \sim 1$

Nature may choose a singlet WIMP DM

- **Higgsino pair production at LHC/HL-LHC can probe it.**

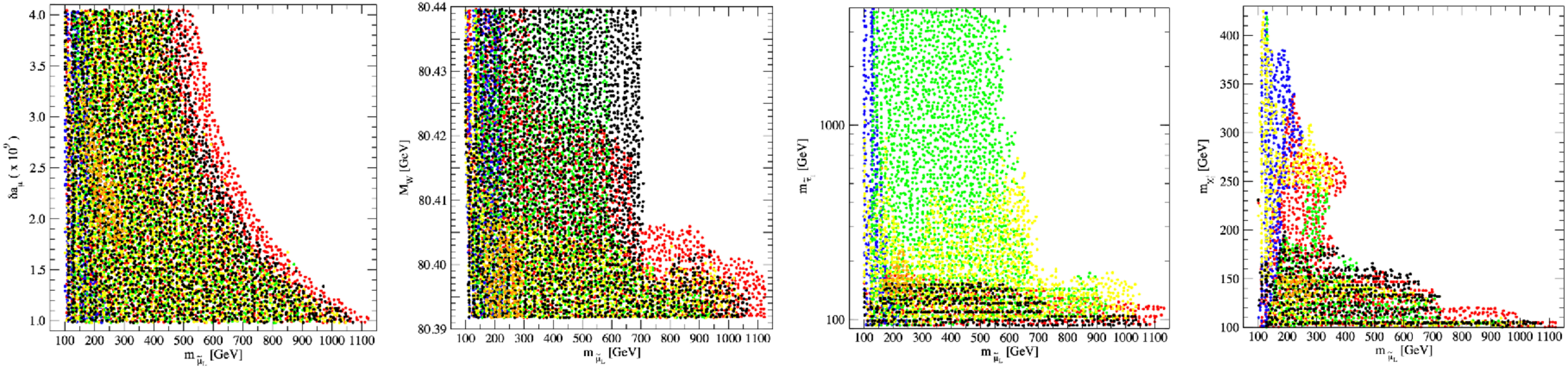


- arXiv: 0910.1785 [hep-ph]
- arXiv: 1703.01255 [hep-ph]
- arXiv: 1810.09143 [hep-ph]

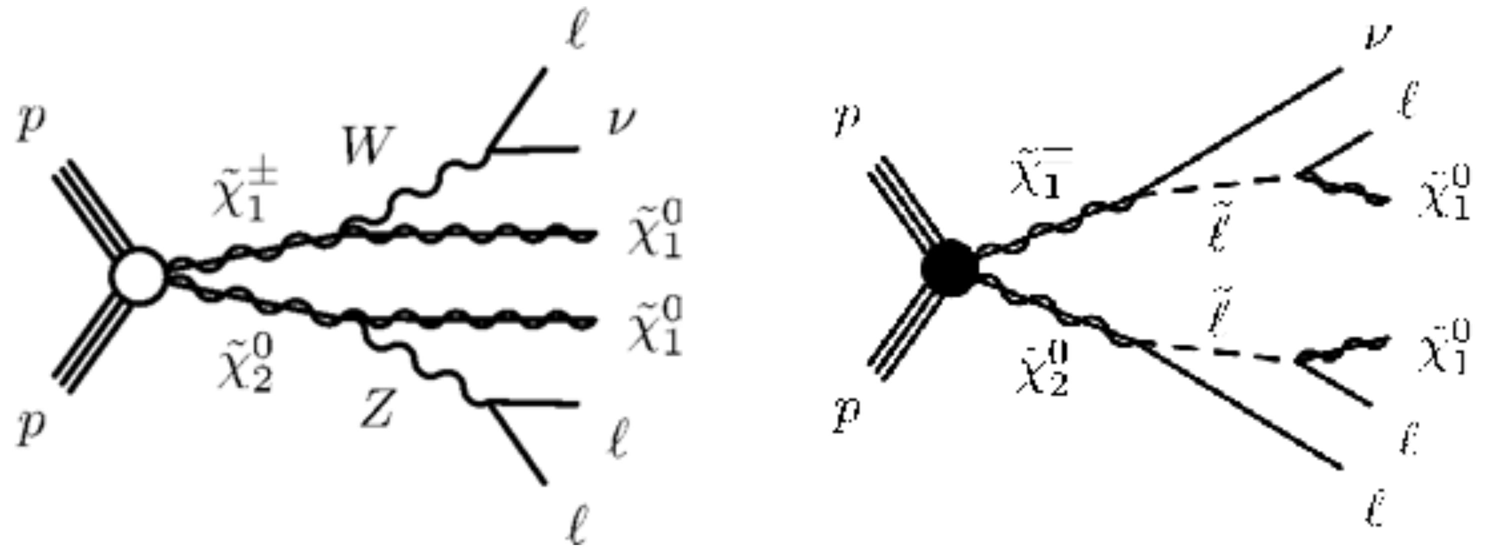
Low energy SUSY

$$W_{\mathrm{NMSSM}} = y_u Q \cdot H_u\, \bar{u} - y_d Q \cdot H_d\, \bar{d} - y_e L \cdot H_d\, \bar{e} + \lambda \underbrace{S}_{\mu_{\mathrm{eff}} = \lambda\langle S\rangle \text{ after EWSB}} H_u \cdot H_d + \frac{\kappa}{3} S^3$$

DM, W mass anomaly & Muon (g-2) in NMSSM



- DM is singlino-like
- Light stau, slepton and chargino are characterized to give a common explanation to *W* mass and muon (g-2).
- In principle, rich lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ signal predicted, which can be probed by LHC.



- arXiv: 0910.1785 [hep-ph]
- arXiv: 2209.03863 [hep-ph]
- arXiv: 2204.04356 [hep-ph]

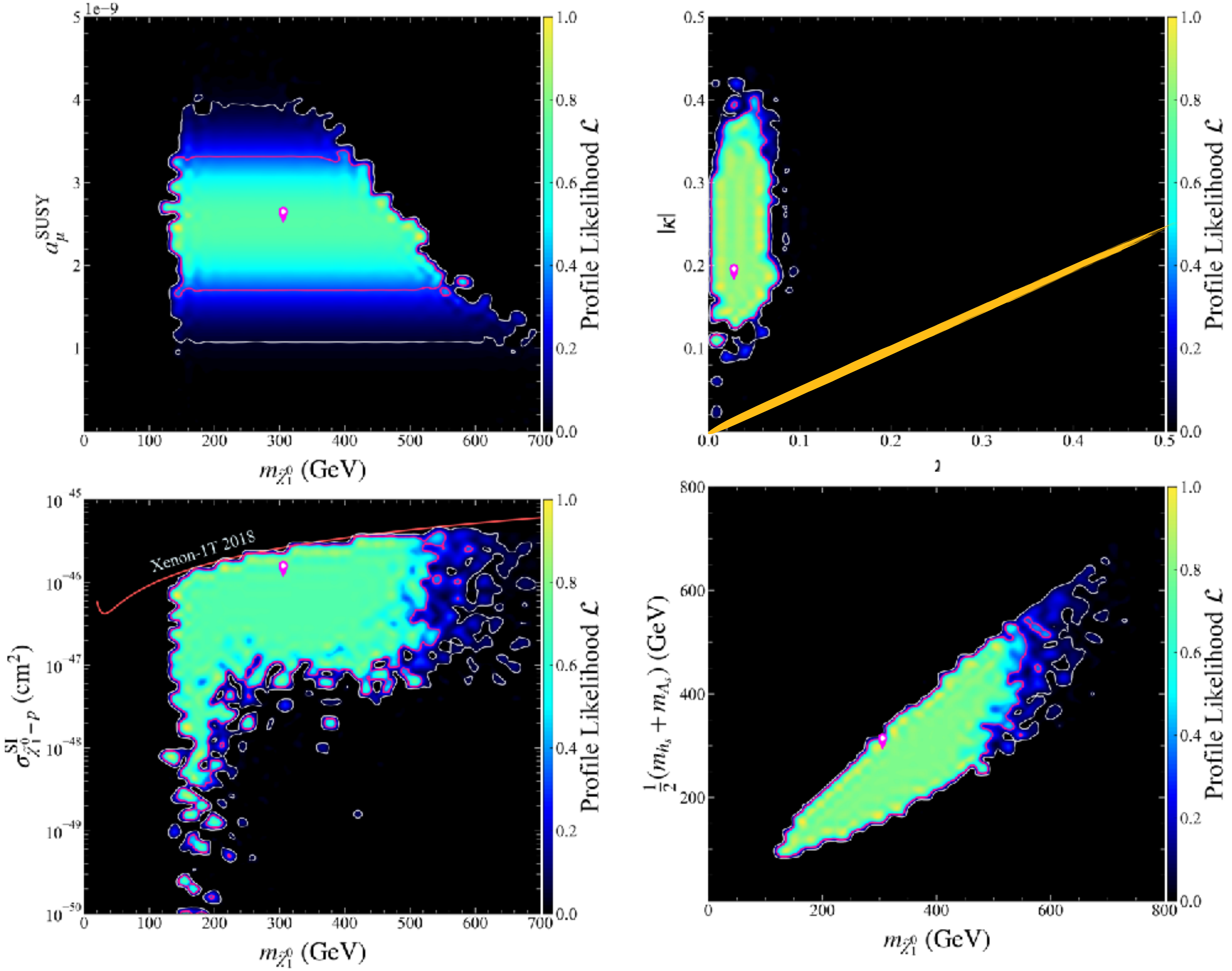
Low energy SUSY

$$W_{\text{GNMSSM}} = y_u Q \cdot H_u\, \bar{u} - y_d Q \cdot H_d\, \bar{d} - y_e L \cdot H_d\, \bar{e} + \underbrace{\left(\mu + \lambda S\right)}_{\mu_{\text{eff}} = \mu + \lambda\langle S\rangle \text{ after EWSB}} H_u \cdot H_d + \frac{\kappa}{3} S^3$$

General NMSSM: an alternative solution of singlino DM

- **Singlino DM:** like pure-Bino case, but the mixing term with other electroweakino are controlled by one free parameter λ.
- New DM annihilation channels:
  - A. $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to h_s A_s$
  - B. Co-annihilated with Higgsino $\lambda \simeq 2|\kappa|$
  - C. Annihilate via the charged Higgsino in t-channel.
- **LHC/HL-LHC can test this model with Higgsino pair production.**
- **Muon g-2 anomaly can be easily explained.**

* arXiv: 2104.03284[hep-ph]



Low energy SUSY

$$W_{\text{ISS NMSSM}} = W_{\text{Yukawa}} + \lambda \hat{S}\hat{H}_u \cdot \hat{H}_d + \frac{1}{3}\kappa \hat{S}^3 + \lambda_\nu \hat{S}\hat{\nu}\hat{X} + Y_\nu \hat{L} \cdot \hat{H}_u \hat{\nu} + \mu_X \hat{X}\hat{X}$$

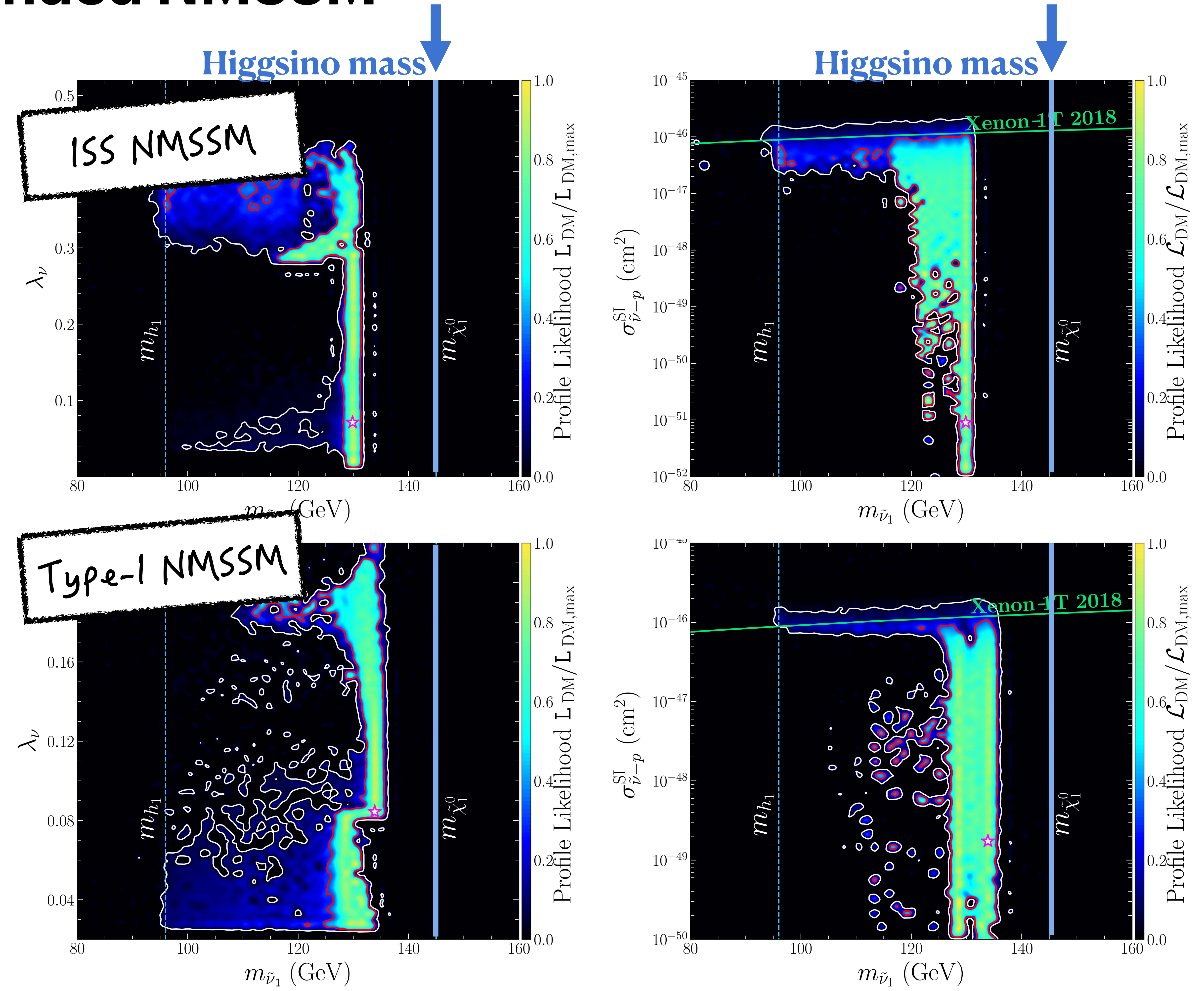
$$W_{\text{Type-I NMSSM}} = W_{\text{Yukawa}} + \lambda \hat{S}\hat{H}_u \cdot \hat{H}_d + \frac{1}{3}\kappa \hat{S}^3 + \lambda_\nu \hat{S}\hat{\nu}\hat{\nu} + Y_\nu \hat{L} \cdot \hat{H}_u \hat{\nu}$$

Sneutrino DM in Seesaw mechanism extended NMSSM

- **Same Higgs sector to NMSSM**

- **Sneutrino DM:** like singlino case in NMSSM, the right-handed sneutrino or the X-type sneutrino can be WIMP DM.
- New DM annihilation channels:
  - A. Co-annihilated with Higgsino
  - B. …
- DM direct detection rate is control by parameters λ_ν and Y_ν, currently $\lambda_\nu, Y_\nu < 0.1$

- **Light enough Higgsino NLSP favored, the phenomenology same to NMSSM without considering DM.**



* arXiv: 1910.14317[hep-ph]

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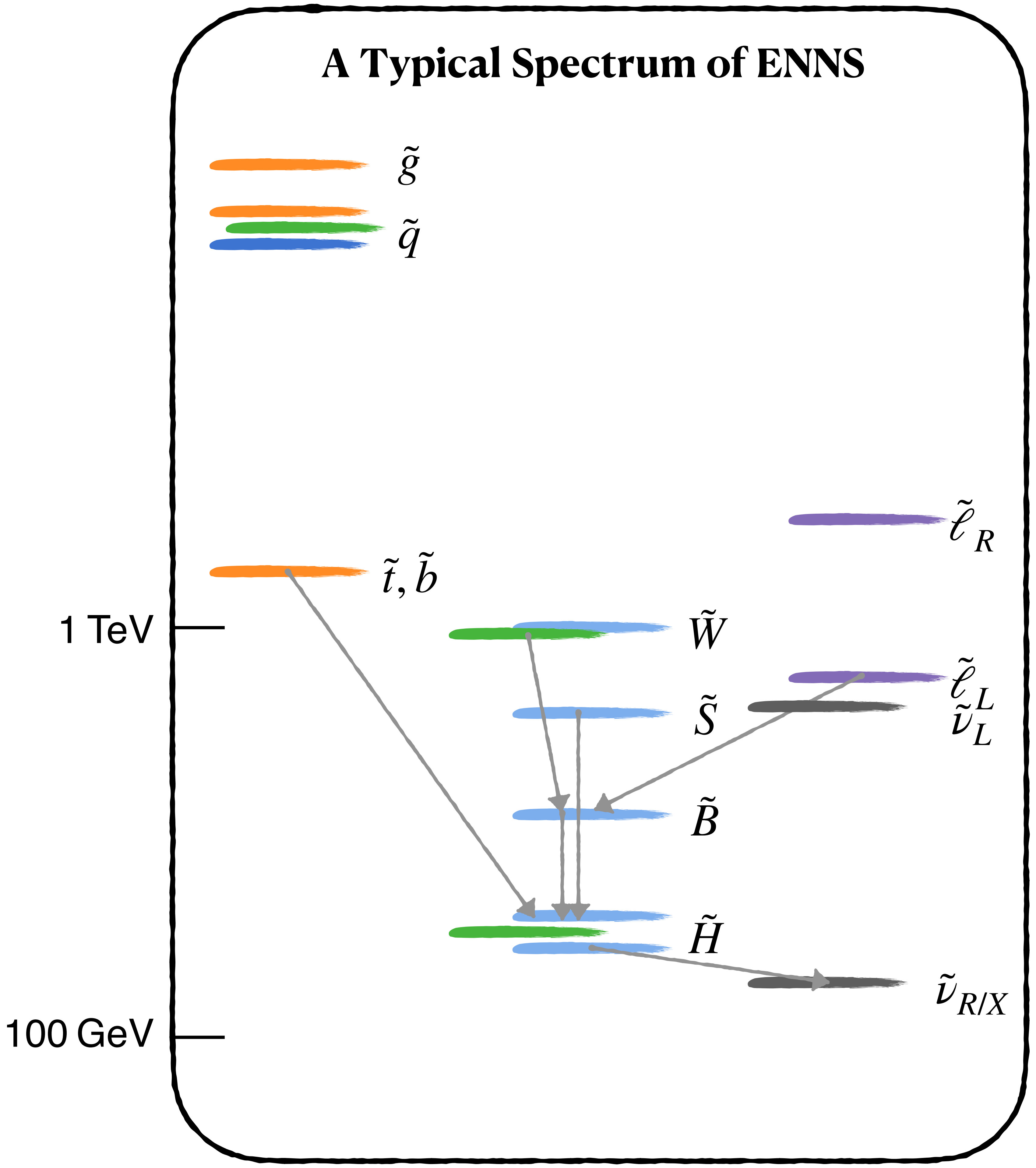

* arXiv: 1910.14317[hep-ph]

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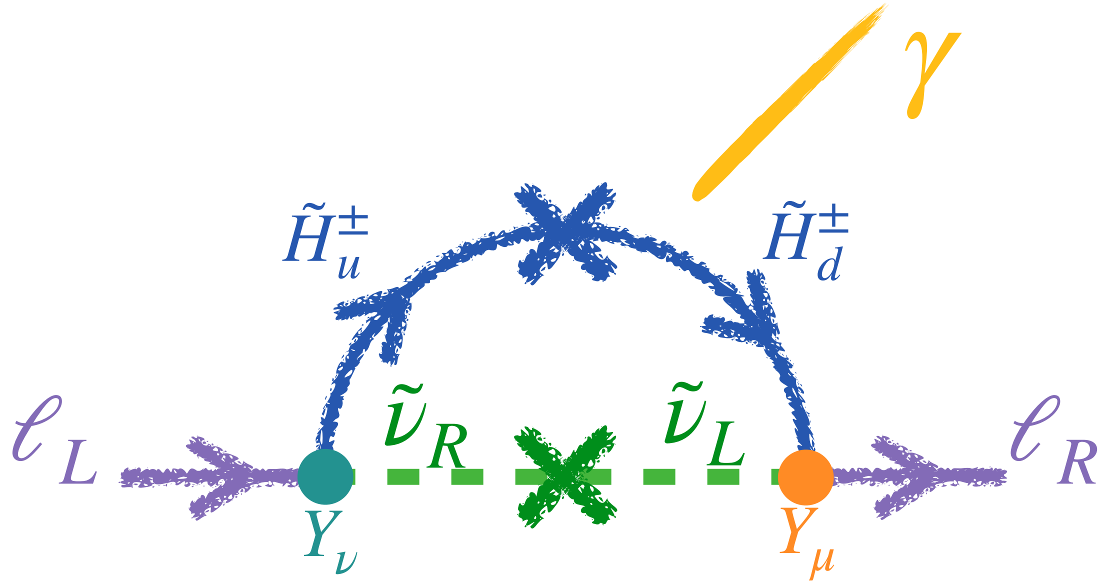
Neutrino Yukawa as the source of (g-2)

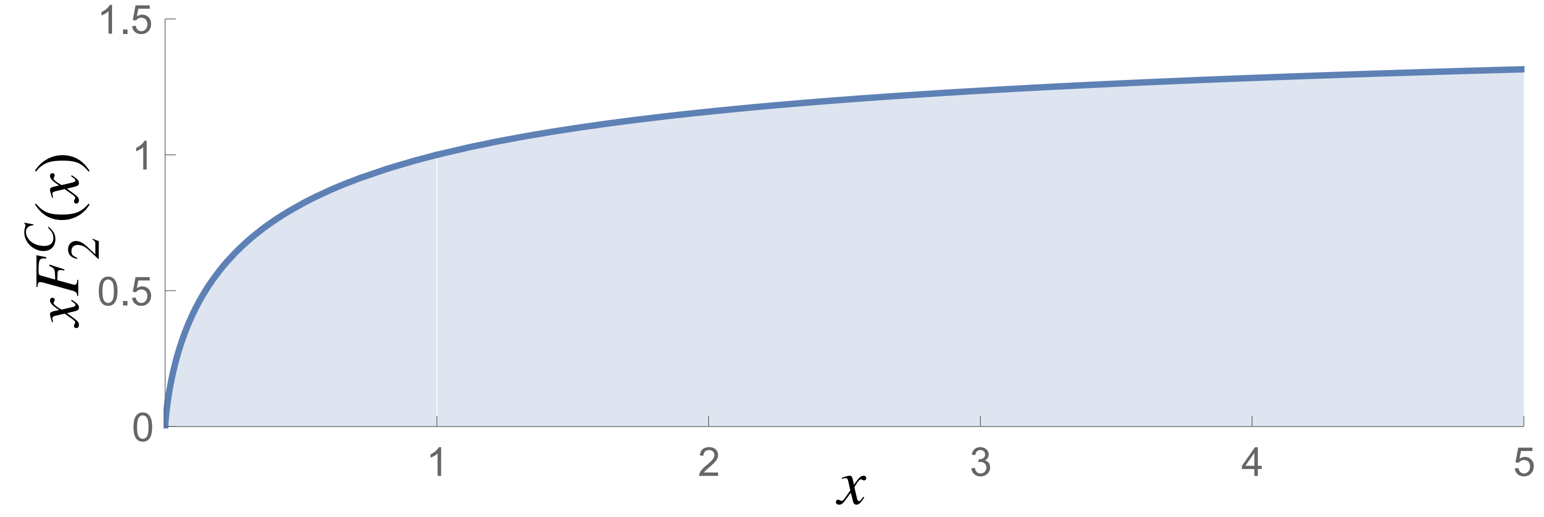


$$a_\mu^{\text{HS}} \approx m_\mu^2 \frac{1}{48\pi^2 v}\frac{Y_\nu}{\mu\cos\beta}\left\{\sum_n Z_{n1}Z_{n2}\cdot x_n F_2^C\left(x_n\right)\right\}, \quad x_n = \frac{\mu^2}{m^2_{\tilde{\nu}_n}}$$

Large $Y_\nu \sim \mathcal{O}(0.1) - \mathcal{O}(1)$

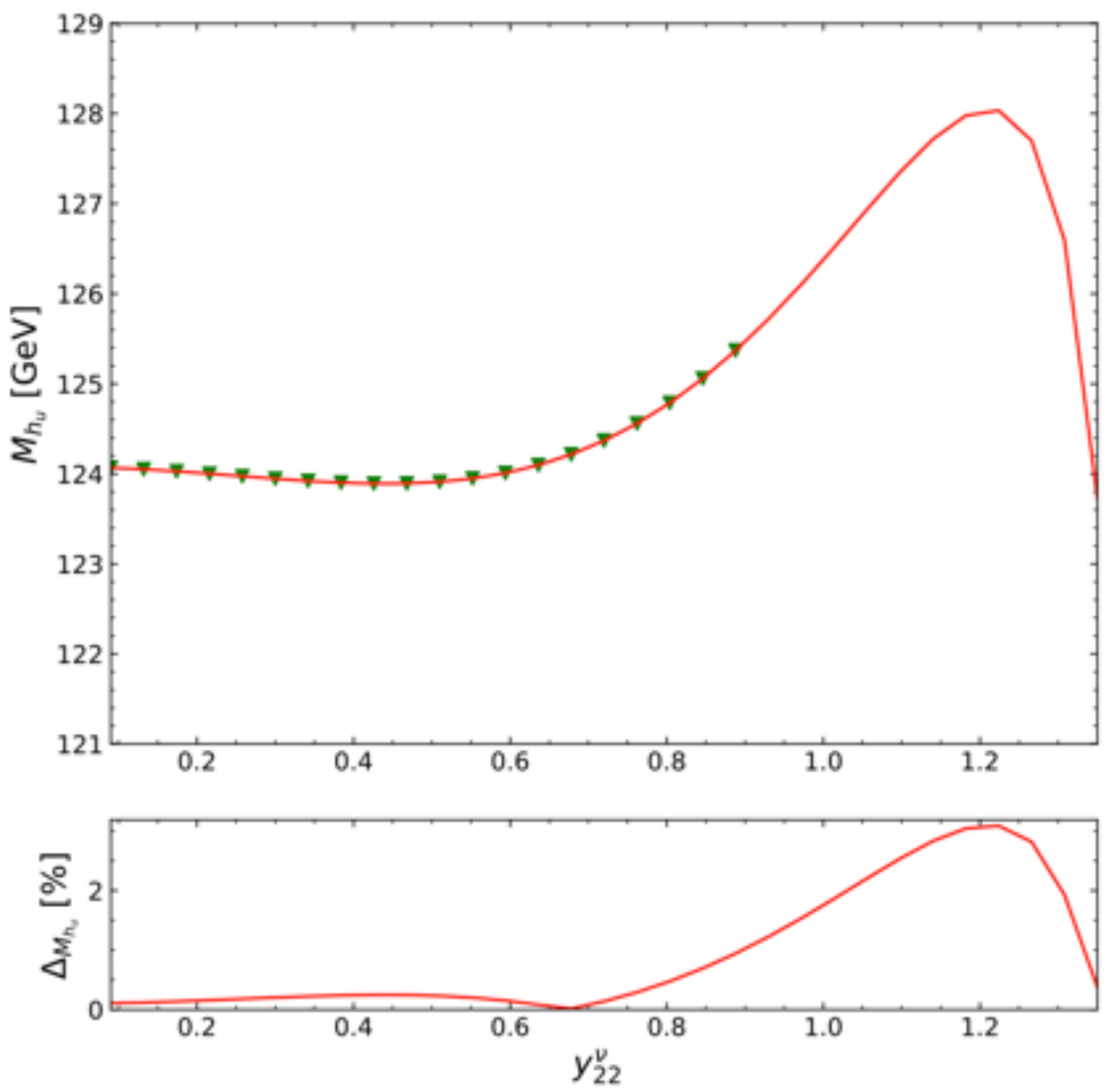
Small $|\mu|$, large $\tan\beta$

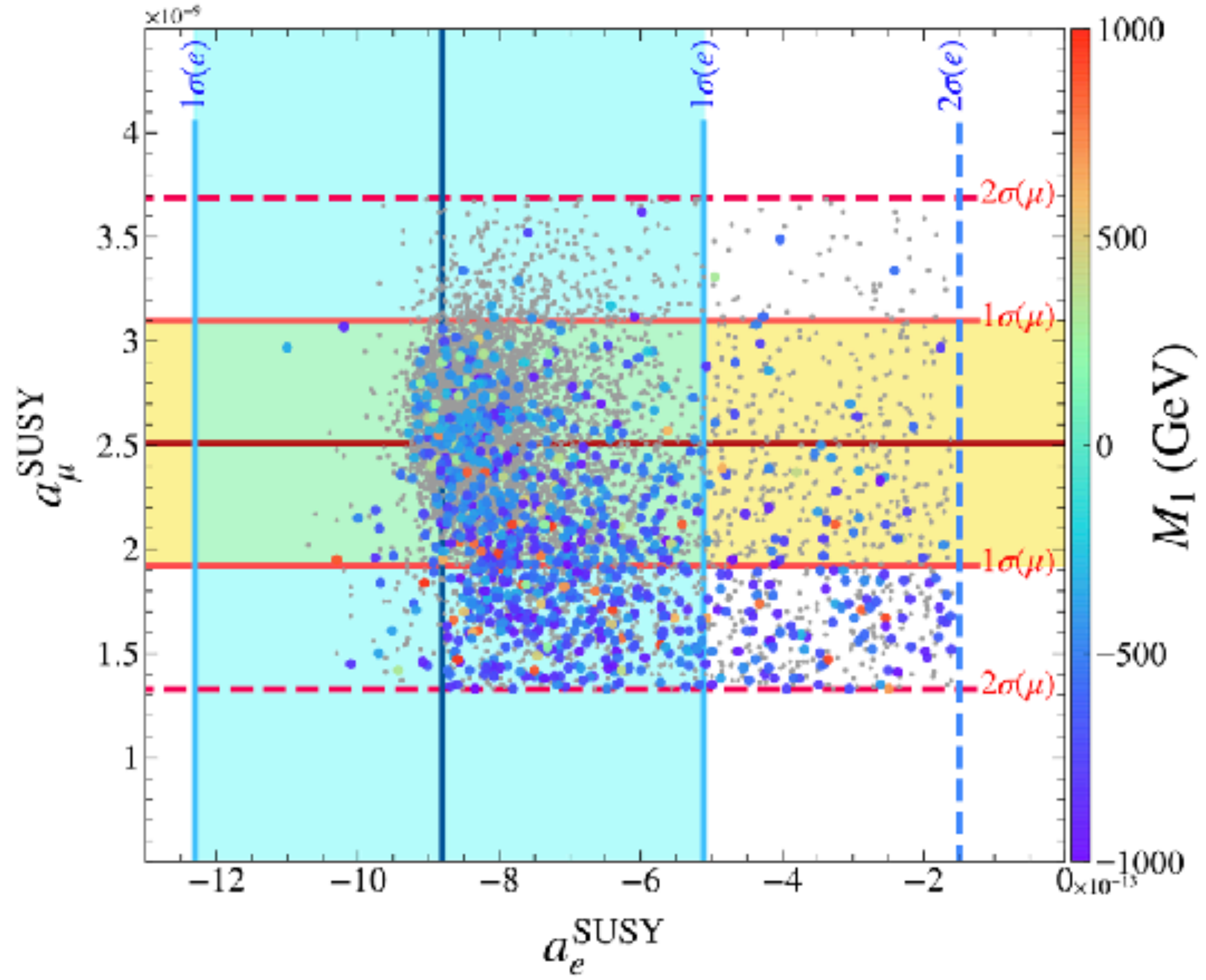
Independent of $\mathrm{Sgn}(\mu)$



- $Y_\nu \lesssim 1.4$: **due to the negative mass correction to Higgs boson**

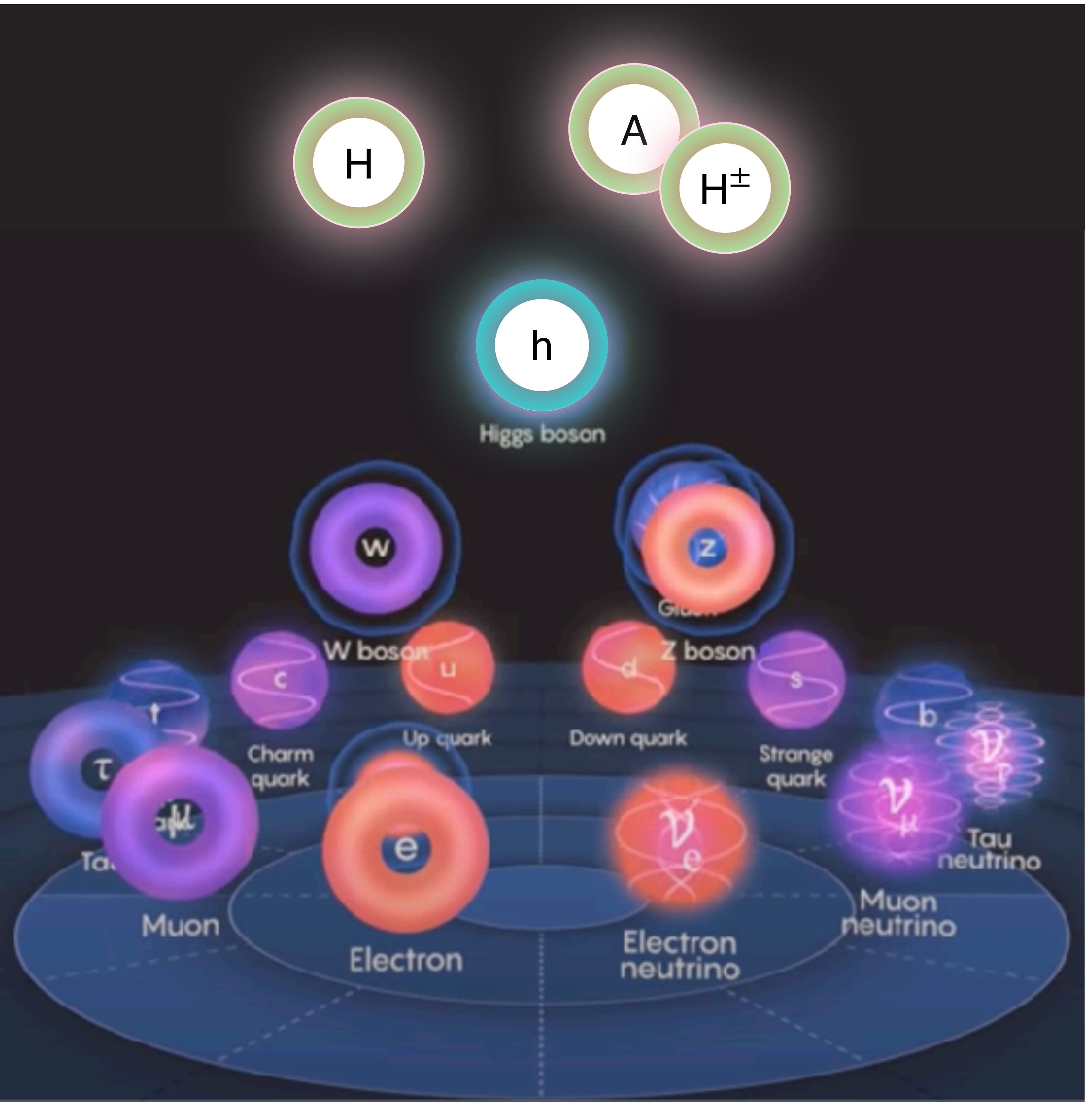
- **Can easily explain** $\Delta a_e(\mathrm{Cs})$ **&** Δa_μ **simultaneously without introducing lepton flavor violation**





- * arXiv: 1912.10225 [hep-ph]
- * arXiv: 2102.11355 [hep-ph]
- * arXiv: 2207.12618 [hep-ph]

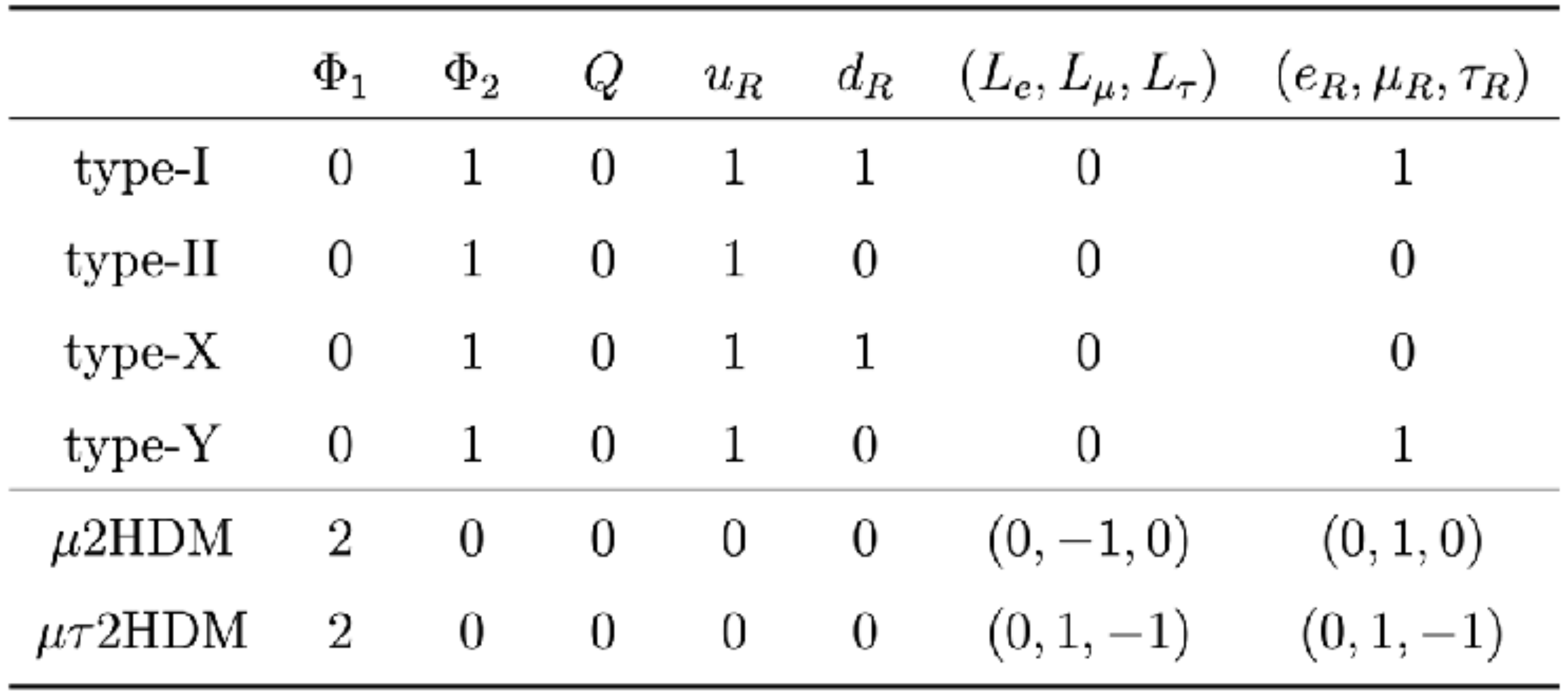
Two Higgs double model (2HDM)



First proposed by T. D. Lee in 1973.

The 2HDM appears as a low-energy effective scalar sector of many UV-complete theories, like SUSY, Pati-Salam model, little Higgs model, left-right model, etc.

- **Discrete symmetry (mostly Z_2) or Flavor alignment imposed to avoid FCNC at tree-level, accordingly:**
  - Type-I 2HDM:
  - Type-II 2HDM:
  - Type-X (Lepton-specific) 2HD
  - Lepton-specific 2HDM:
  - Muon-specific 2HDM (Z_4):
  - $\mu\tau$-flavor violating 2HDM:
  - Inert Double model
  - …



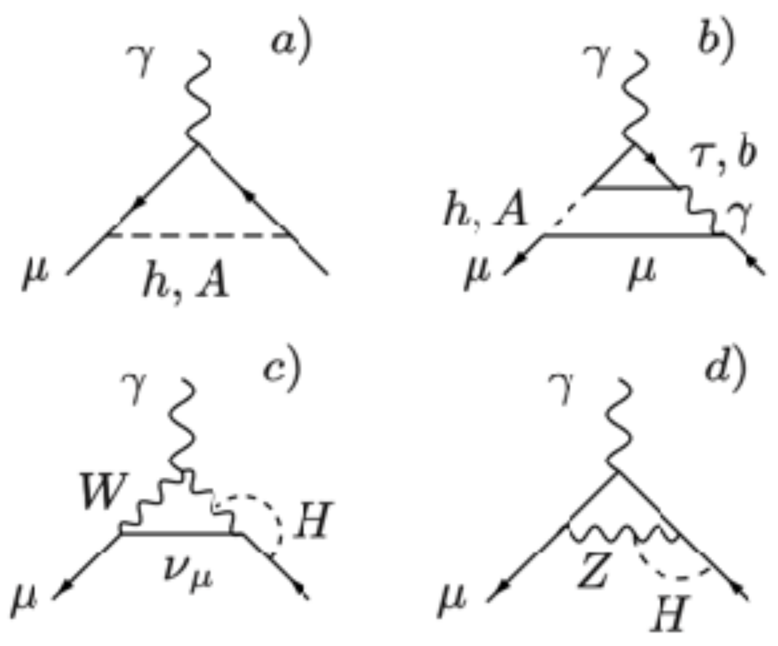
	Φ_1	Φ_2	Q	u_R	d_R	(L_e, L_μ, L_τ)	(e_R, μ_R, τ_R)
type-I	0	1	0	1	1	0	1
type-II	0	1	0	1	0	0	0
type-X	0	1	0	1	1	0	0
type-Y	0	1	0	1	0	0	1
μ2HDM	2	0	0	0	0	$(0, -1, 0)$	$(0, 1, 0)$
$\mu\tau$2HDM	2	0	0	0	0	$(0, 1, -1)$	$(0, 1, -1)$

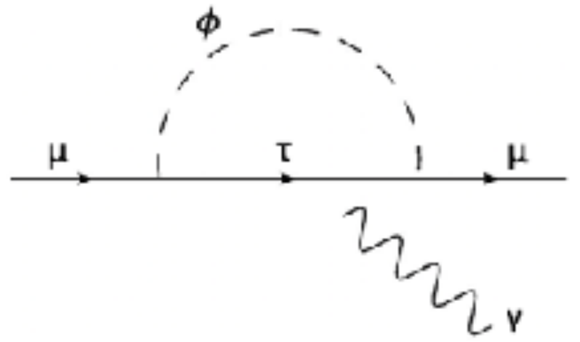
The charge assignments under the discrete symmetry

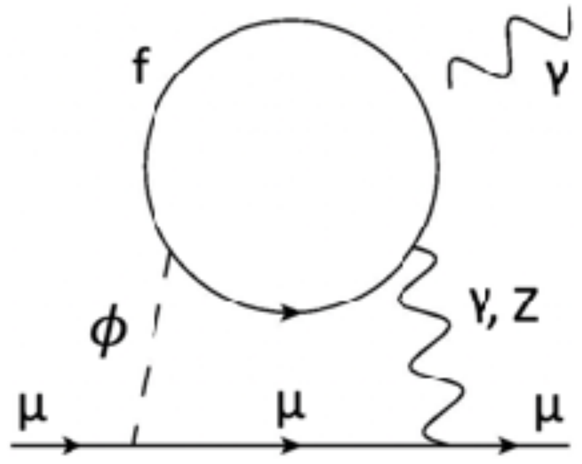
* PRD 8 (1973) 1226.
* arXiv: 2304.09887 [hep-ph]
* arXiv: 2203.07244 [hep-ph]

Two Higgs double model (2HDM)

Muon g-2 in 2HDM







Type-II & Type-X: $\tan\beta$ enhance

$$a_\mu^{(2)\text{2HDM}}(h) \simeq \frac{\sqrt{2}G_F m_\mu^2}{4\pi^2}\tan^2\beta\frac{m_\mu^2}{m_h^2}\left(\ln\frac{m_h^2}{m_\mu^2}-\frac{7}{6}\right)$$

$$a_\mu^{(2)\text{2HDM}}(A) \simeq \frac{\sqrt{2}G_F m_\mu^2}{4\pi^2}\tan^2\beta\frac{m_\mu^2}{m_A^2}\left(-\ln\frac{m_A^2}{m_\mu^2}+\frac{11}{6}\right)$$

Insensitive to $\tan\beta$

$$\delta a_\mu^\tau \simeq \frac{m_\mu^2}{16\pi^2}\rho_e^{\mu\tau}\rho_e^{\tau\mu}\frac{m_\tau}{m_\mu}\left(\frac{\log\frac{m_H^2}{m_\tau^2}-\frac{3}{2}}{m_H^2}-\frac{\log\frac{m_A^2}{m_\tau^2}-\frac{3}{2}}{m_A^2}\right)$$

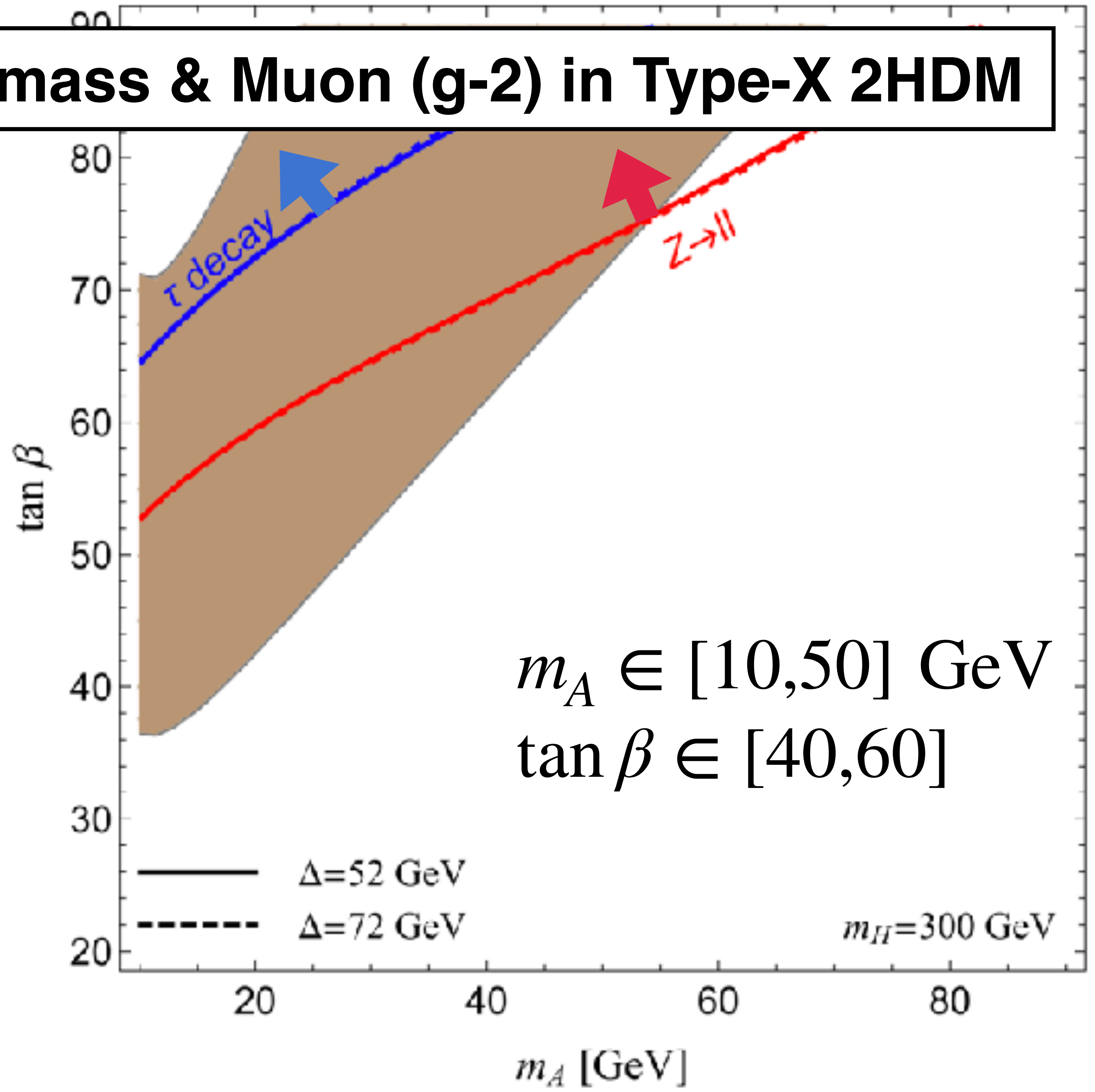
Dominated in Type-X

$$a_\mu^{(4)\text{2HDM}}(\text{Barr}-\text{Zee}) \simeq \frac{\sqrt{2}G_F m_\mu^2}{16\pi^2}\frac{\alpha}{\pi}4\tan^2\beta\sum_{i=h,A;f}N_{cf}Q_f^2F_i(x_{if})$$

	Δa_μ	mass range
Type-X 2HDM	2 loop	$m_A = \mathcal{O}(10)\,\text{GeV} \ll m_H = m_{H^\pm}$
FA2HDM	2 loop	$m_A = \mathcal{O}(10)\,\text{GeV} \ll m_H = m_{H^\pm}$
μ2HDM	1 loop	$900\,\text{GeV} \le m_{A,H} \le 1000\,\text{GeV}$
$\mu\tau$2HDM	1 loop	$500\,\text{GeV} \le m_{A,H} \le 1600\,\text{GeV}$

2HDM scenarios which can accommodate the muon g – 2 anomaly.

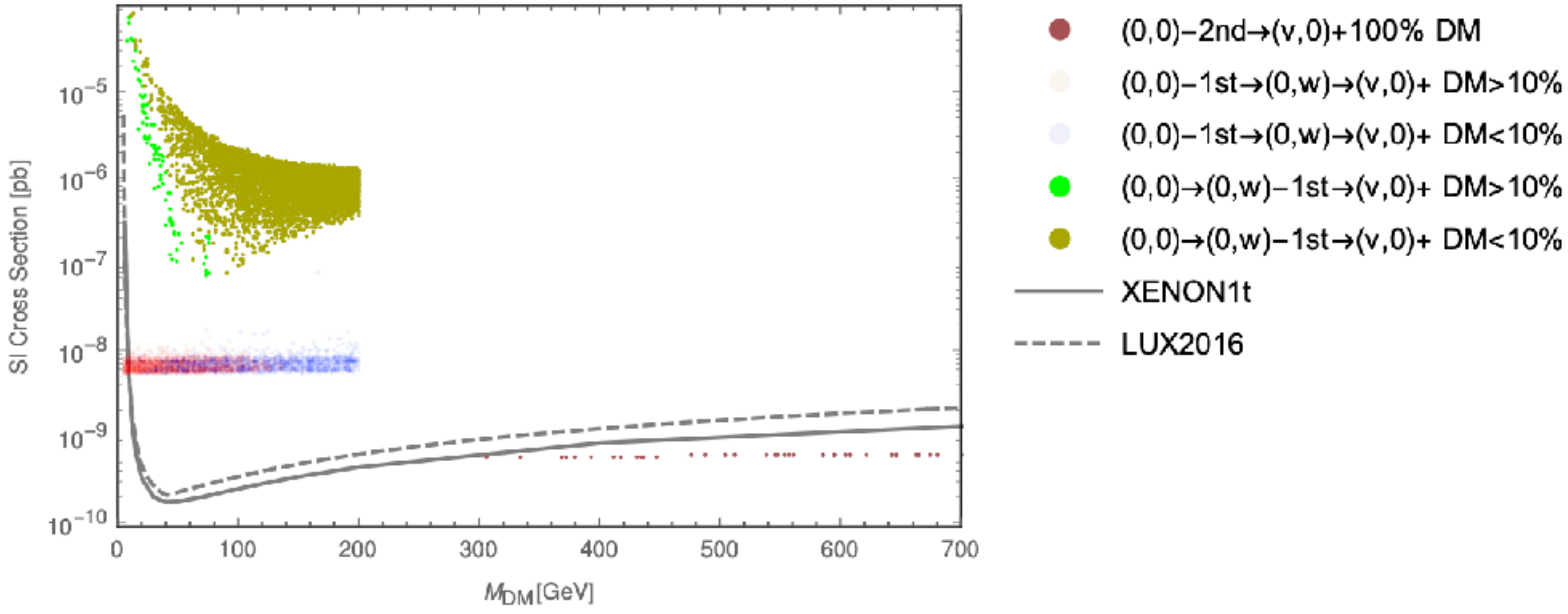
W mass & Muon (g-2) in Type-X 2HDM



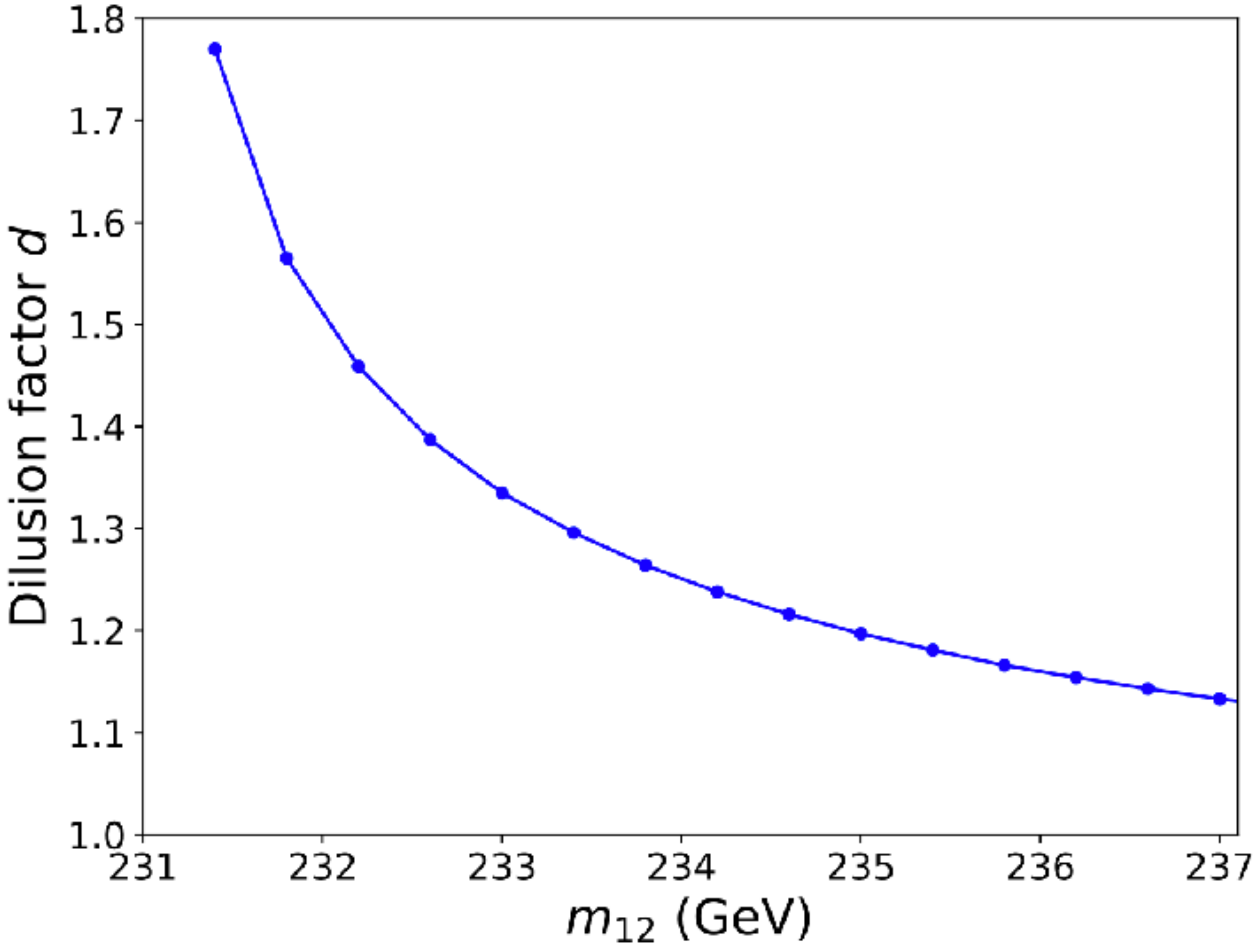
$m_A \in [10,50]$ GeV
$\tan\beta \in [40,60]$

- arXiv: 2304.09887 [hep-ph]
- arXiv: 2205.01437 [hep-ph]

Thermal History & DM



An example in 2HDM+S



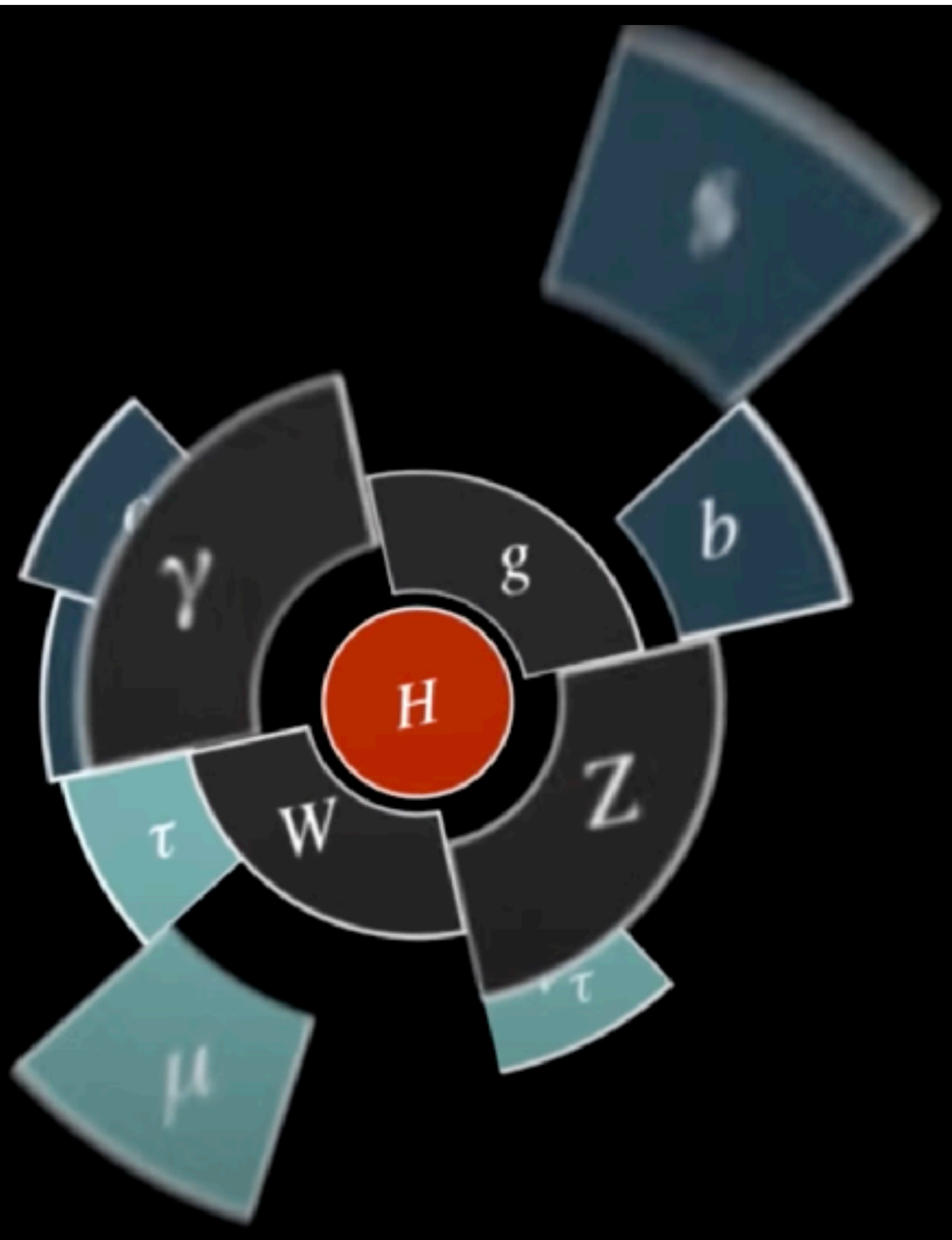
When the temperature at electroweak first-order phase transition close to the DM freeze-out temperature, the DM density will change:

1. The deviation from the thermal equilibrium cause by phase transition may affect the size of the universe, then change the DM relic density.
2. The particle mass (determines how particle decay) will change after the phase transition.
3. The bubble wall formed by phase transition may filter out most of the DM, leaving only a small number of DM.

- The Case in 2HDM+S:

  The entropy released by EW first-order phase transition can dilute the DM relic density to one-third.

- arXiv: 2010.15708 [hep-ph]
- arXiv: 2301.09283 [hep-ph]
- arXiv: 1712.03962 [hep-ph]
- arXiv: 2207.14519 [hep-ph]



Thank you !!!

Sun Yat-sen University Zhuhai Campus
Jul 04, 2023.

Picture from the Screenshot of YouTube video: How Symmetry Shapes Nature's Laws Quantamagazine

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In collaboration with Lei Wang, Jin-Min Yang, Yang Zhang, Rui Zhu

Based on arXiv: 2203.05719 [hep-ph], arXiv:2201.00156 [hep-ph]