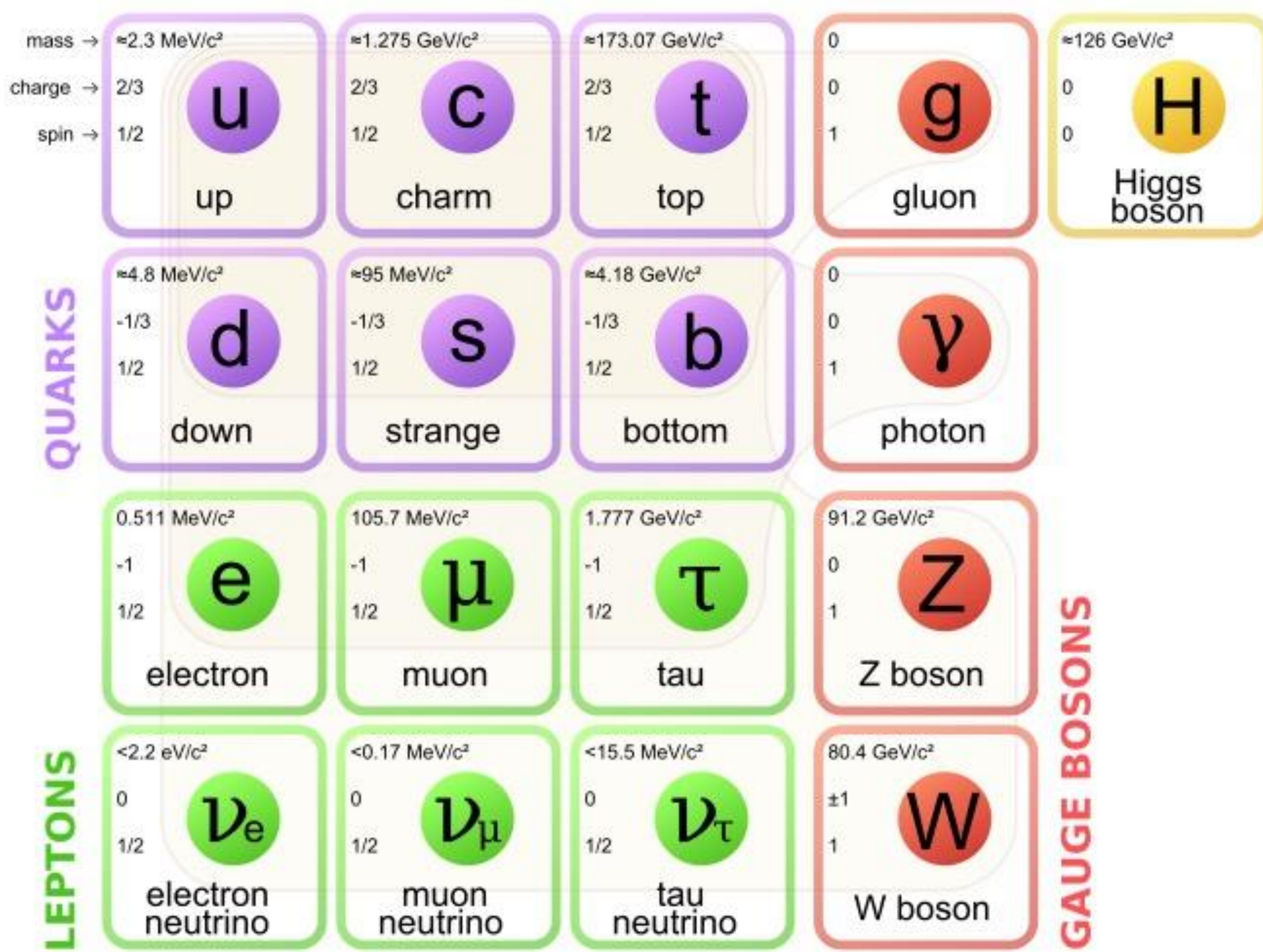
MSSM 4G scenario

Sho IWAMOTO（岩本　祥）

10 Nov. 2016
Seminar @ IPPP

Based on [1608.00283] in collaboration with
M. Abdullah, **J. L. Feng**, and **B. Lillard** (UC Irvine)

Universe =



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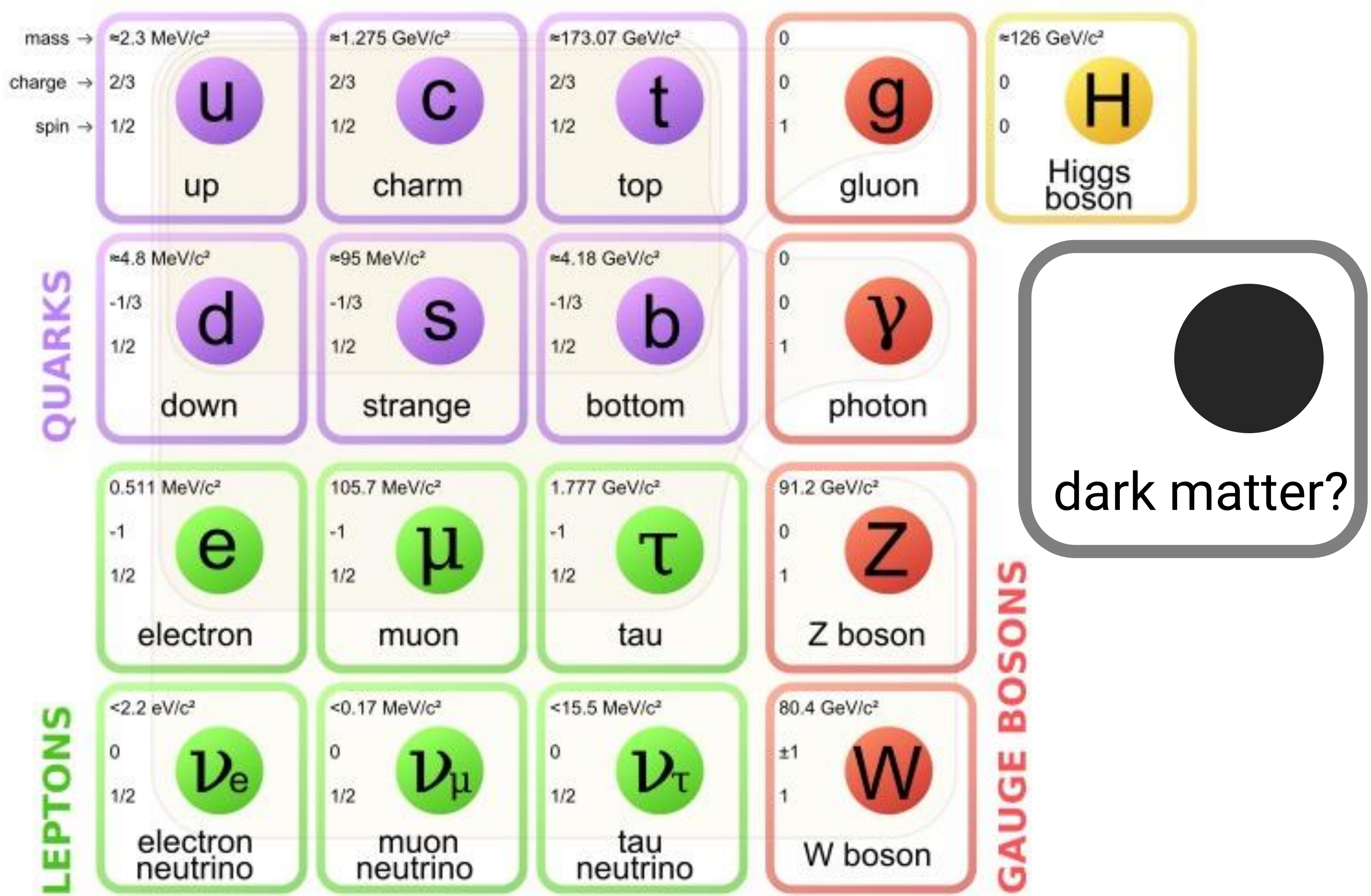
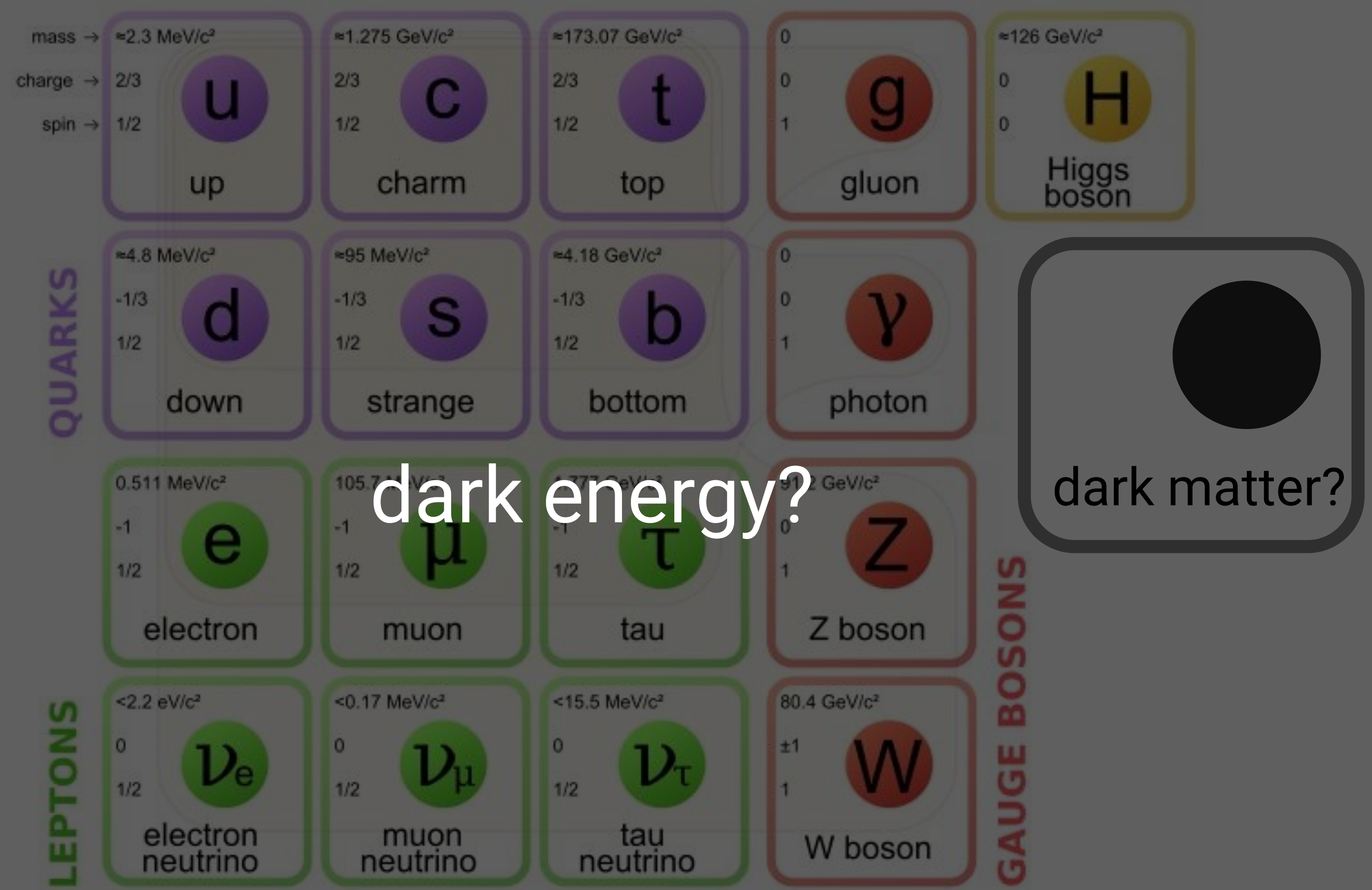

mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
dark matter?

Universe =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LEPTONS
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dark energy?
dark matter?

Hints of "New Physics"

- Dark matter
- Dark energy
- Neutrino mass
- Gauge coupling unification
- Higgs mass ("naturalness")
- Muon "$g - 2$"
- ...

New Physics Candidates

-
-
-
-

etc…

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New Physics Candidates

- SUSY [supersymmetry]
-
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etc…

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Please fill this list with your models / models you like

etc…

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- SUSY [supersymmetry]
- Gauge-Higgs unification
- Hidden strong SU(N)
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etc…

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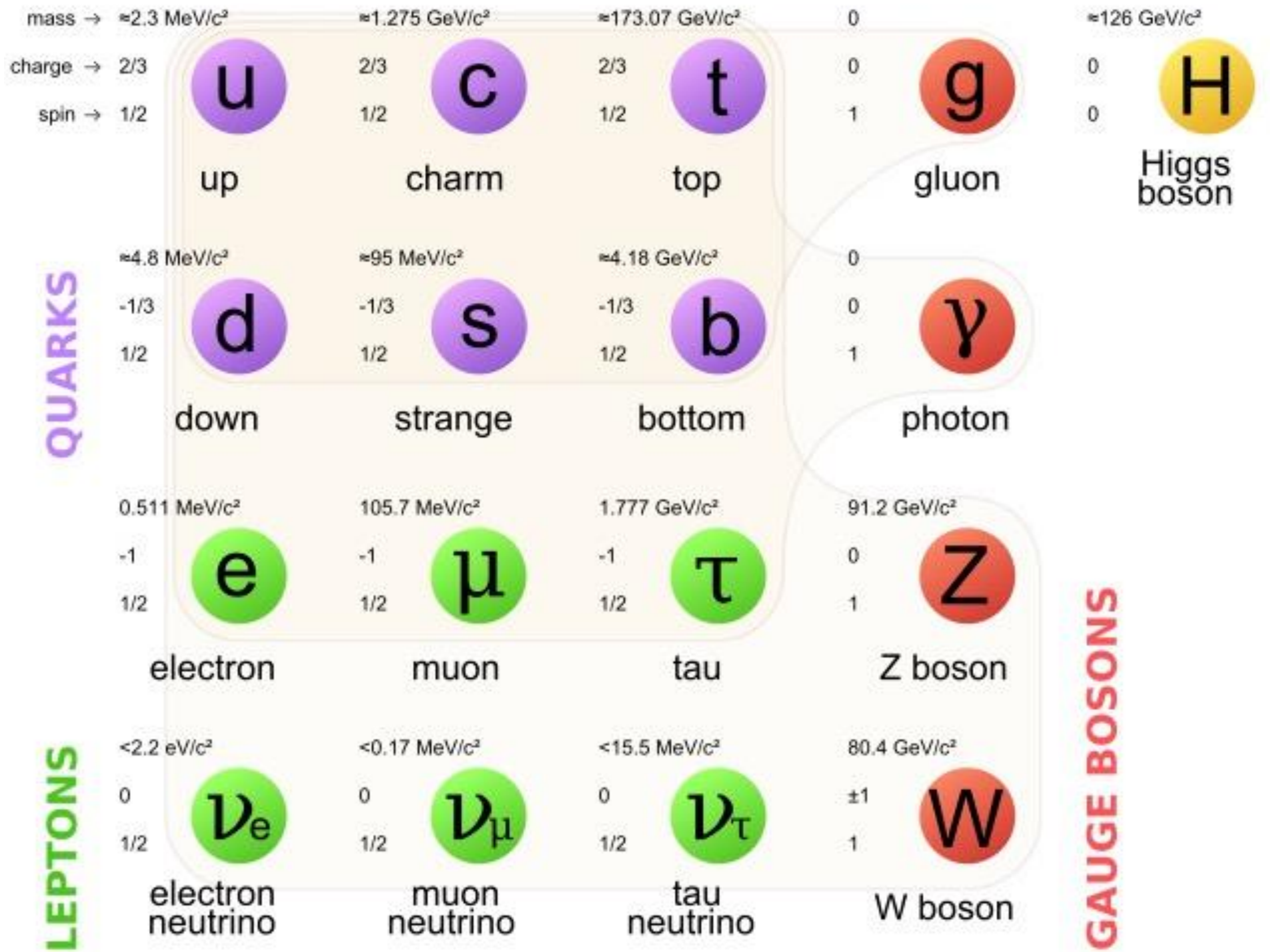
[Standard Model]

- SM =



[Minimal Supersymmetric Standard Model]

- MSSM =

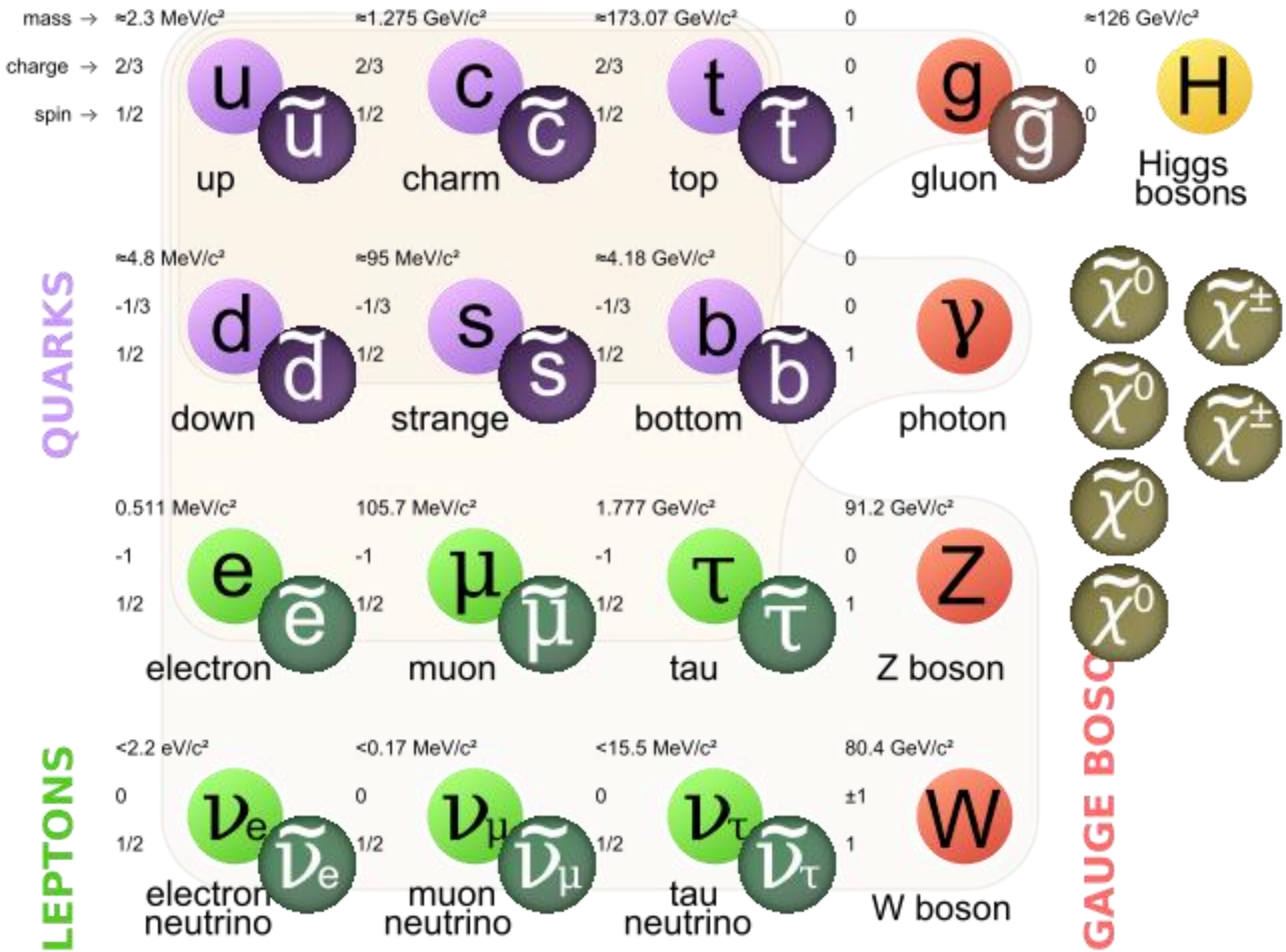
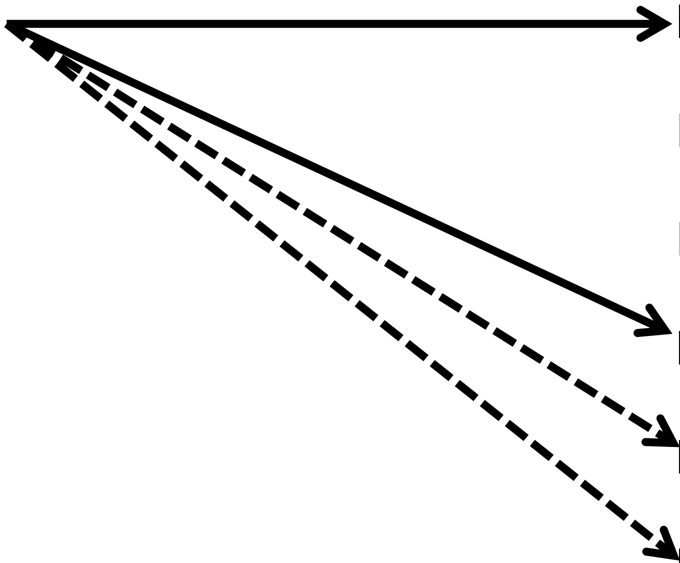


Image by MissBJ [CC BY 3.0], via Wikimedia Commons
(changes were made by S.I)

New Physics Candidates

- SUSY



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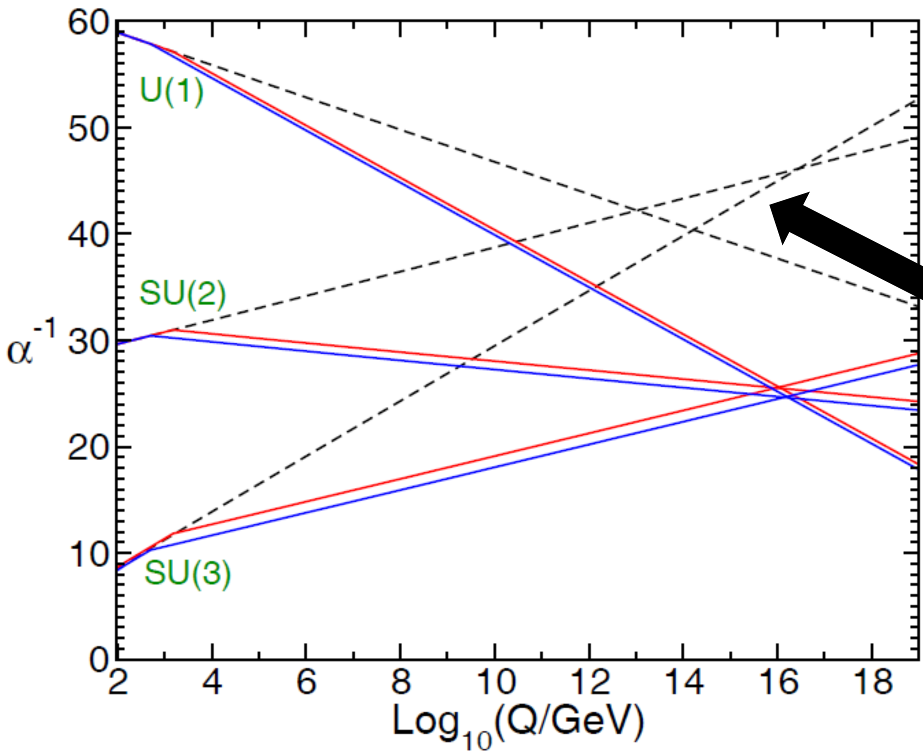
- SM ∋ 3 forces : U(1), SU(2), SU(3) [Why three?]

measured theoretical prediction



- Gauge coupling unification

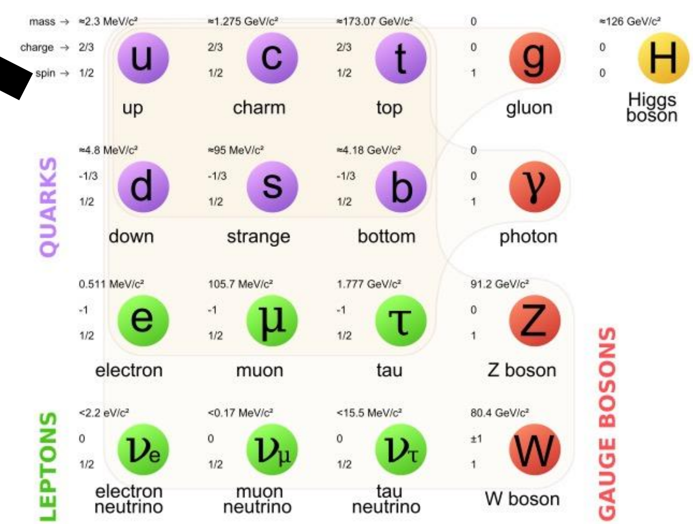


Figure from S. P. Martin, *A Supersymmetry Primer*, hep-ph/9709356

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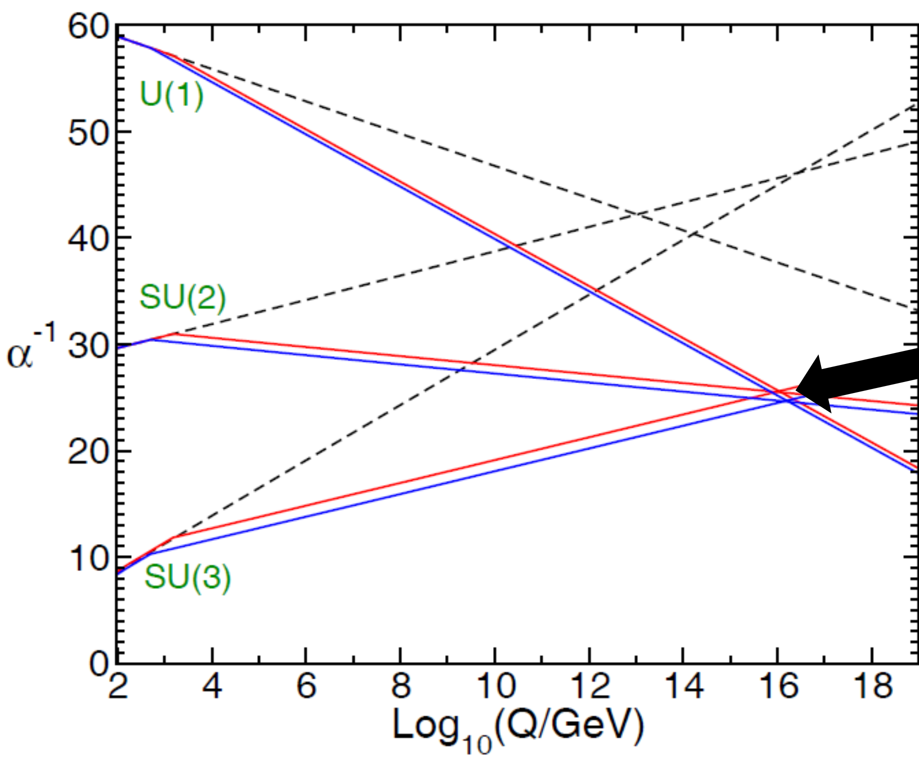

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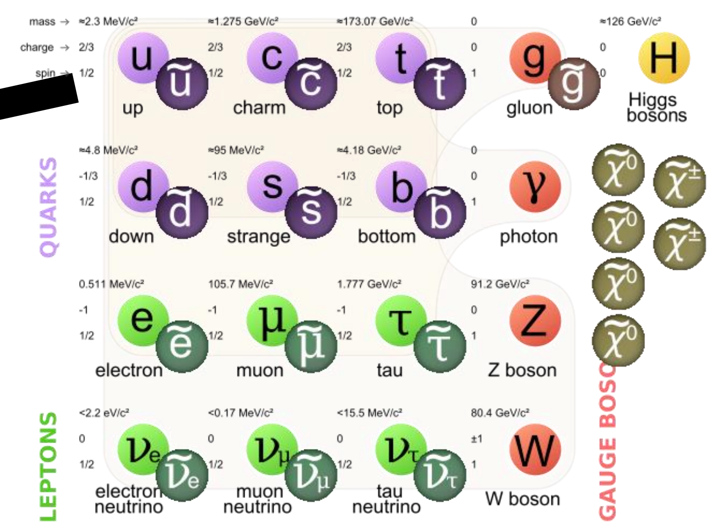

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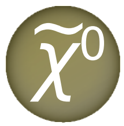
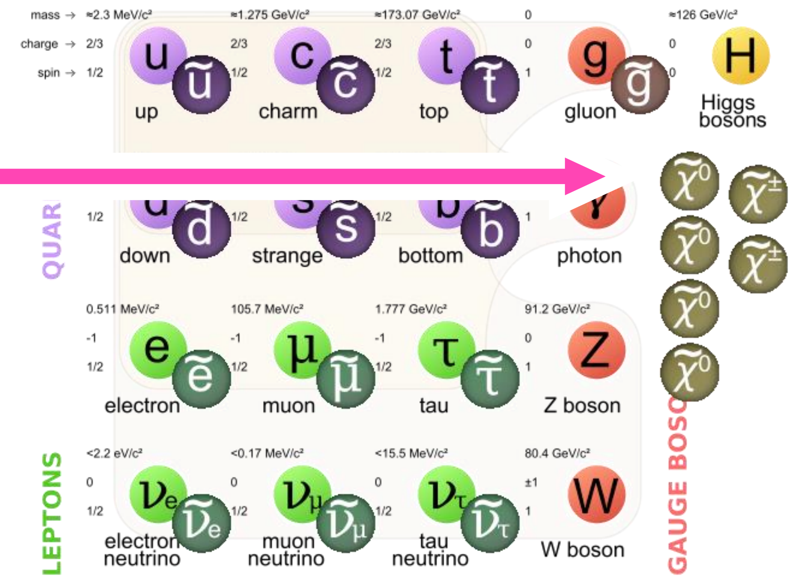
- MSSM $\ni$ Dark matter candidate





- Dark matter?
  - stable (at least 10^{10} yr)
  - ✓ charge neutral
  - density $\Omega h^2 = 0.12$
  - not detected by astrophysics / direct search / LHC

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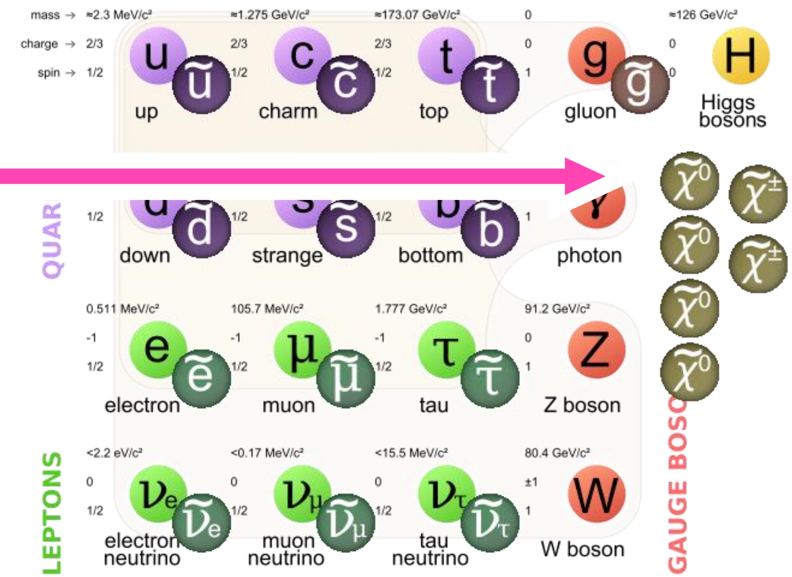

- Dark matter?

if we introduce R-parity

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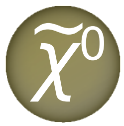

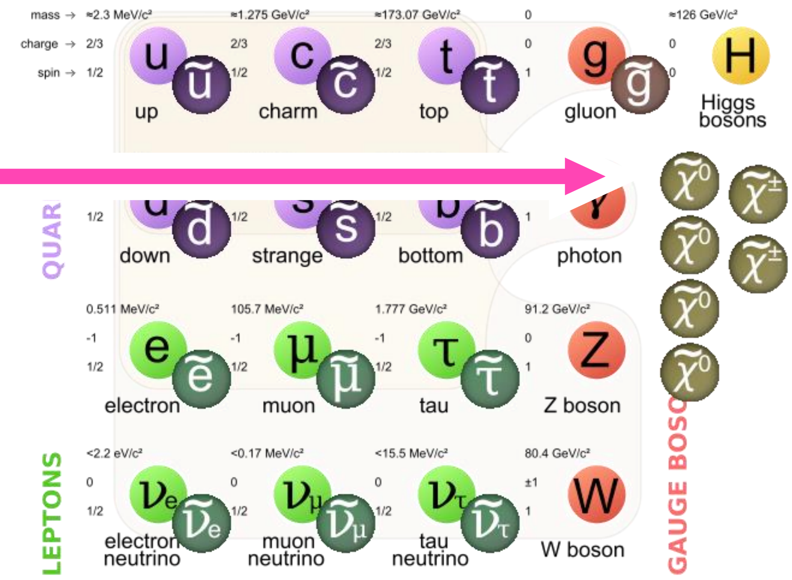

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$$\tilde{\chi}^0 = \tilde{B} \oplus \widetilde{W}^0 \oplus \tilde{H}^0_{\mathrm{d}} \oplus \tilde{H}^0_{\mathrm{u}}$$

- $\tilde{B}$-like? → "overabundant" problem

$$\Omega h^2 \gg 0.12$$

- $\widetilde{W}$-like?
- $\tilde{H}$-like?

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- $\tilde{B}$-like? → "overabundant" problem
- $\widetilde{W}$-like?
- $\tilde{H}$-like?

$$\Omega h^2 \gg 0.12$$

⇒ **MSSM4G model**

Introduction: why overabundant?

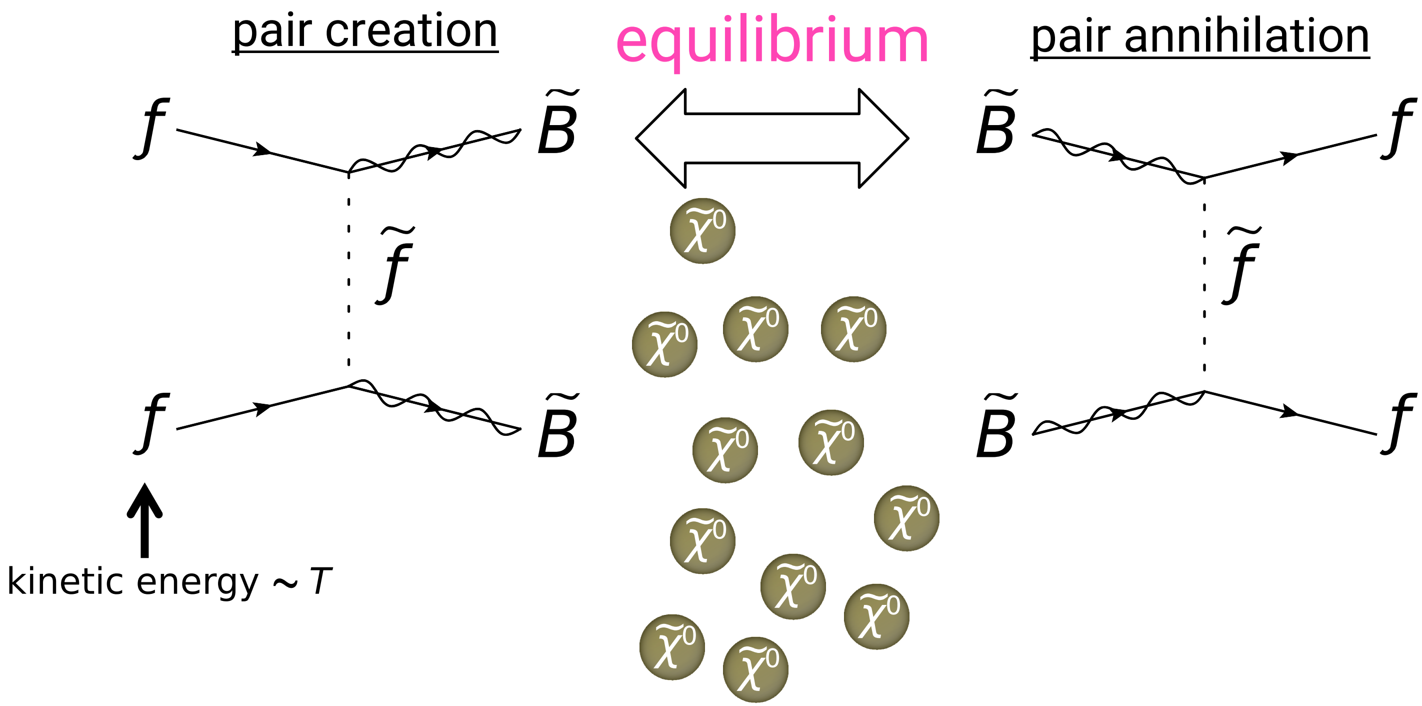
Model: **MSSM4G** solves overabundance.

Analysis:

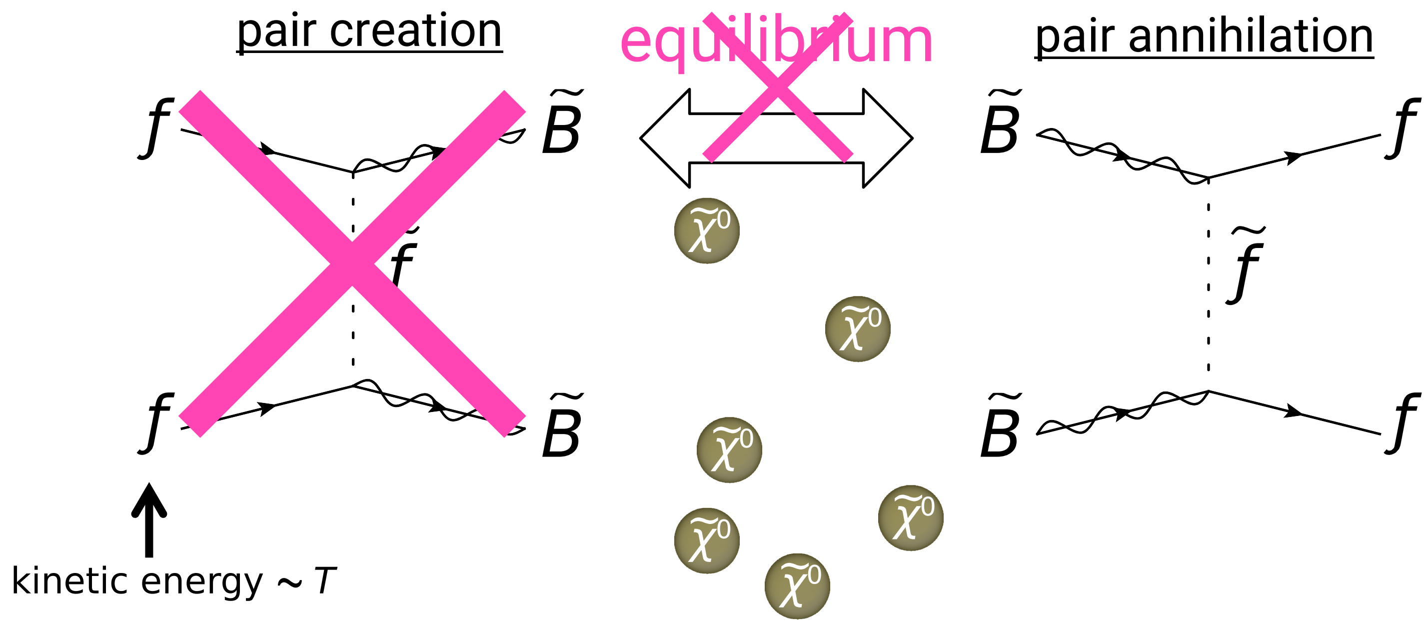
- cosmic rays (CTA, Fermi, MAGIC)
- colliders (LHC)
- direct detection (LUX)

Summary with discussion seeds

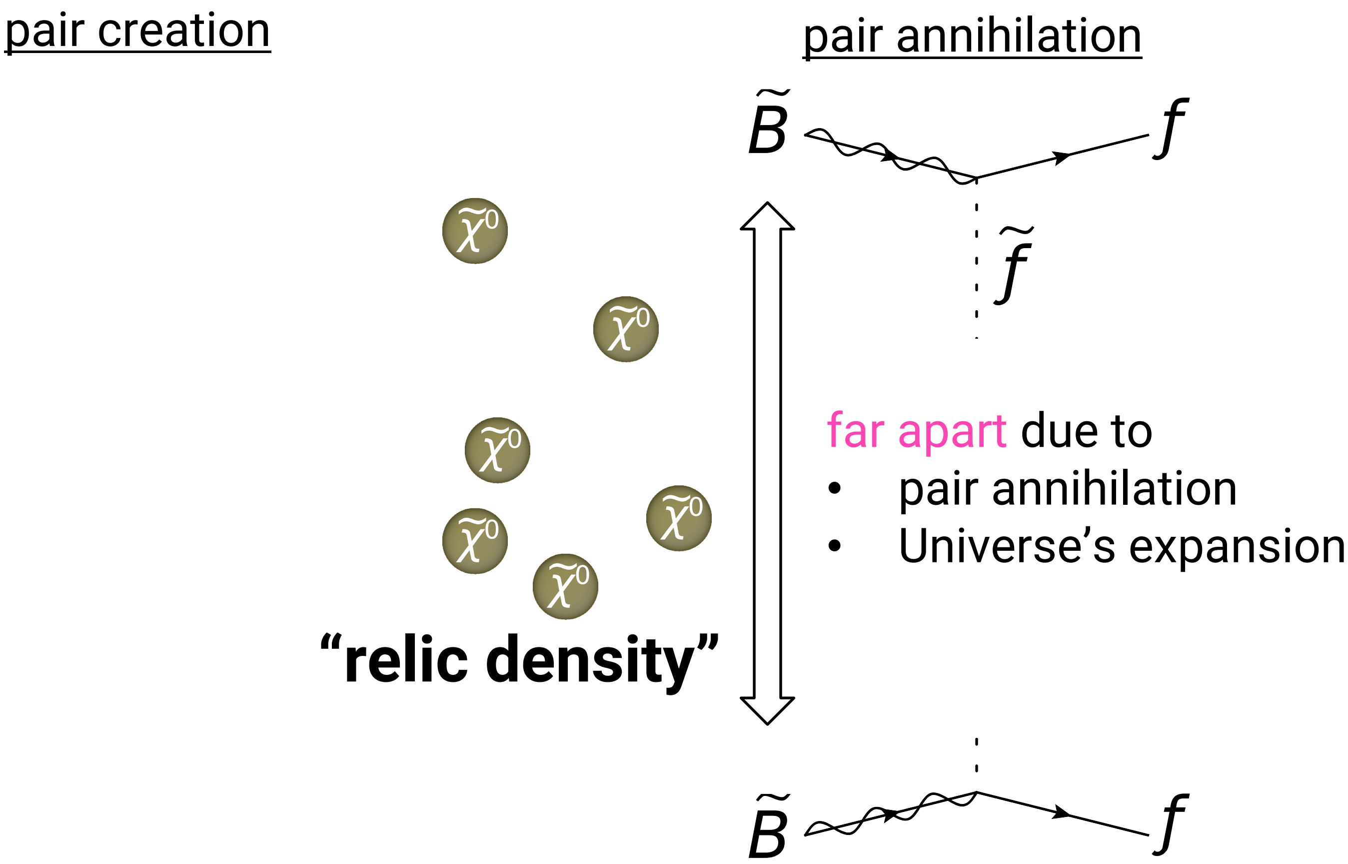
- Early Universe with $T > m_{\tilde{B}}$



- Early Universe with $T \lesssim m_{\tilde{B}}$

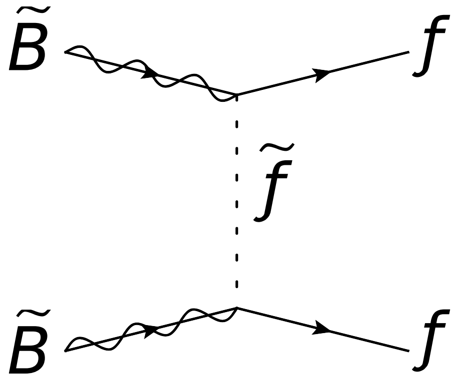


- Early Universe with $T \lesssim m_{\tilde{B}}/20$



- “observed” relic density Ωh^2

$\Leftarrow$ “proper” crosssection $\langle\sigma v\rangle$ of (DM)(DM)→SM



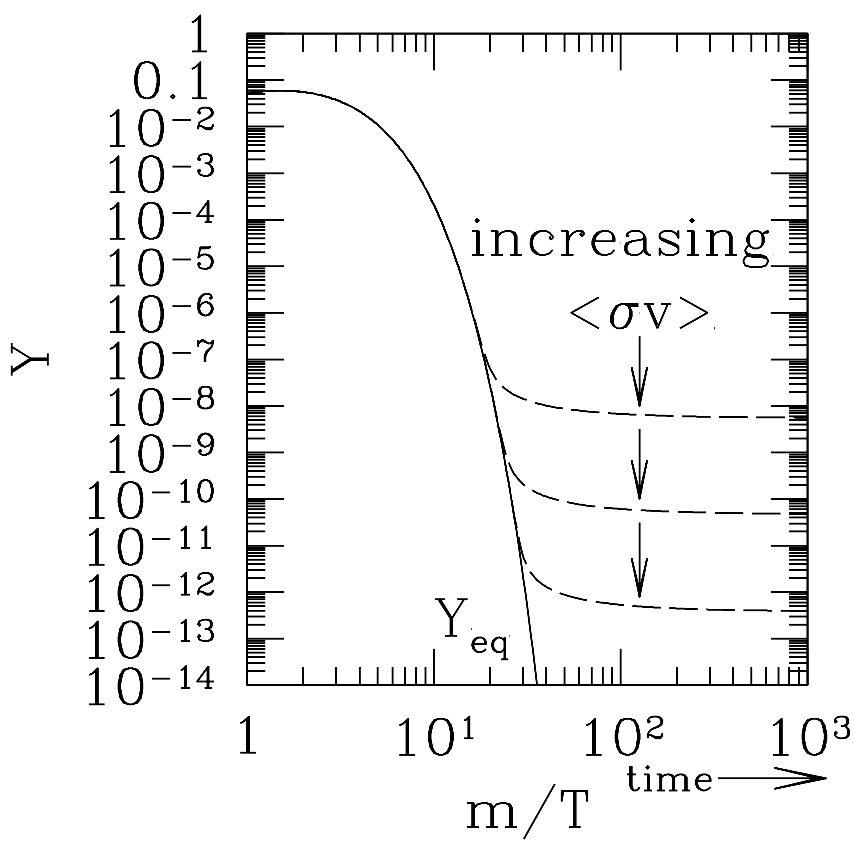
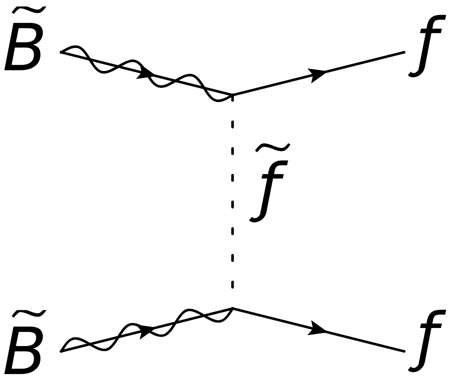


Figure from Gelmini and Gondolo, [1009.3690]

- "observed" relic density Ωh^2

  ⇦ "proper" crosssection $\langle \sigma v \rangle$ of (DM)(DM)→SM



- pure $\tilde{B}$-DM (i.e., LSP $\tilde{\chi}^0$ is $\tilde{B}$-like)
  - $\langle \sigma v \rangle$ strongly depends on $m_{\tilde{f}}$

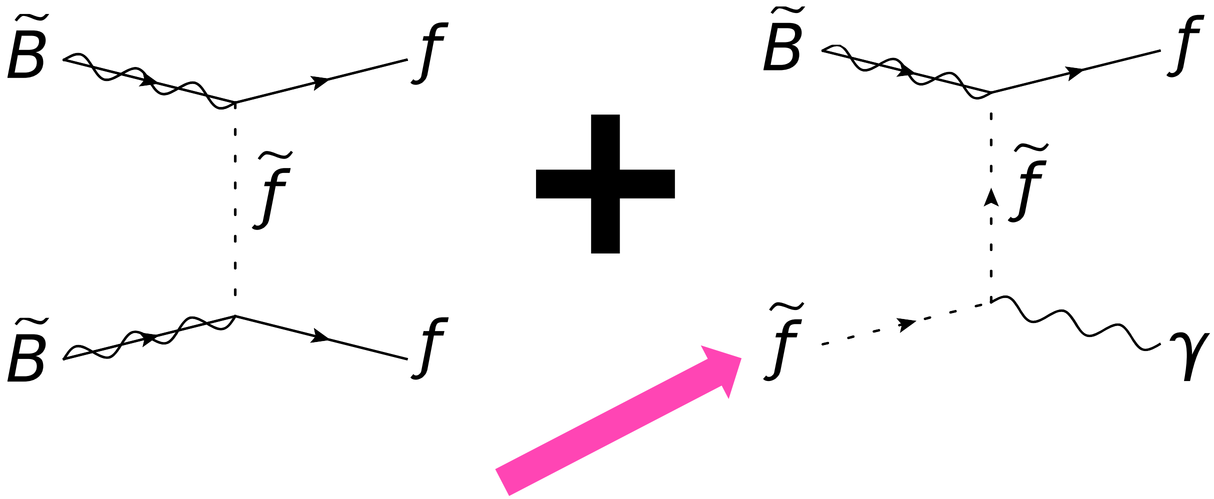
  ↳ $m_{\tilde{f}}$ should be ~100 GeV

$$m_{\tilde{f}} \gg 100\ \text{GeV} \Longrightarrow \langle \sigma v \rangle \text{ too small}$$

$$\Longrightarrow \text{"overabundant" problem}$$

(i.e., $m_{\tilde{B}\text{-DM}} \lesssim 100$ GeV)

- An old solution to increase $\langle \sigma v \rangle$: "co-annihilation"



mass splitting $\dfrac{m_{\tilde{f}} - m_{\tilde{B}}}{m_{\tilde{B}}} \ll 1$

- An c

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An example in CMSSM with $\tilde{\tau}$-coann.:

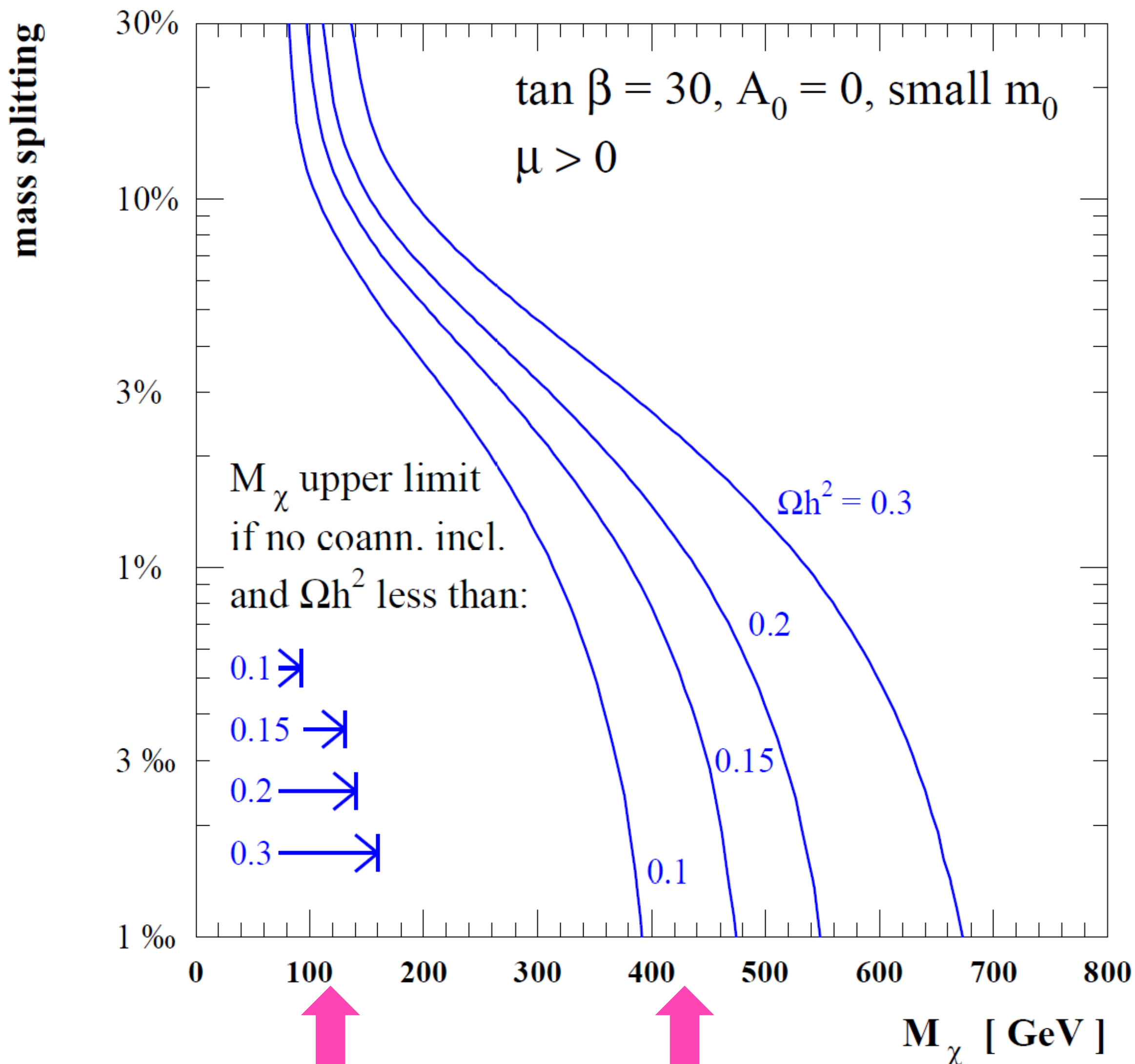


Figure from Edsjö, Schelke, Ullio, Gondolo, hep-ph/0301106

Introduction: why overabundant?

Model: MSSM4G solves overabundance.

Analysis:

- cosmic rays (CTA, Fermi, MAGIC)
- colliders (LHC)
- direct detection (LUX)

Summary with discussion seeds

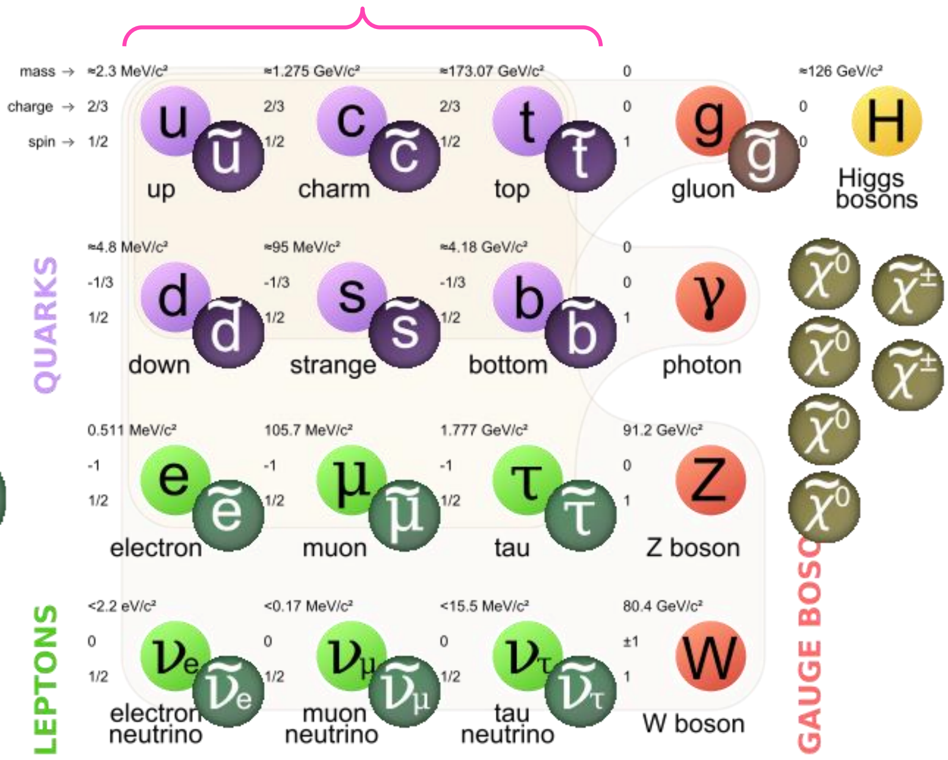
- MSSM = **3G**enerations

+

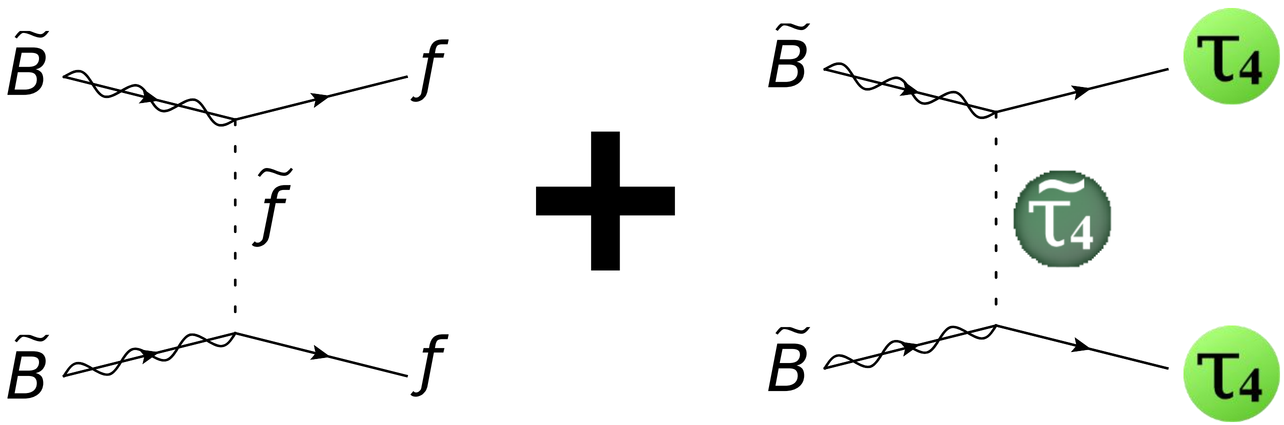
extra vector-like
4th**-G**eneration lepton

=

MSSM4G



- A new solution to increase $\langle\sigma v\rangle$: MSSM4G



extra annihilation channel
→ larger $\langle\sigma v\rangle$
→ "proper" Ωh^2

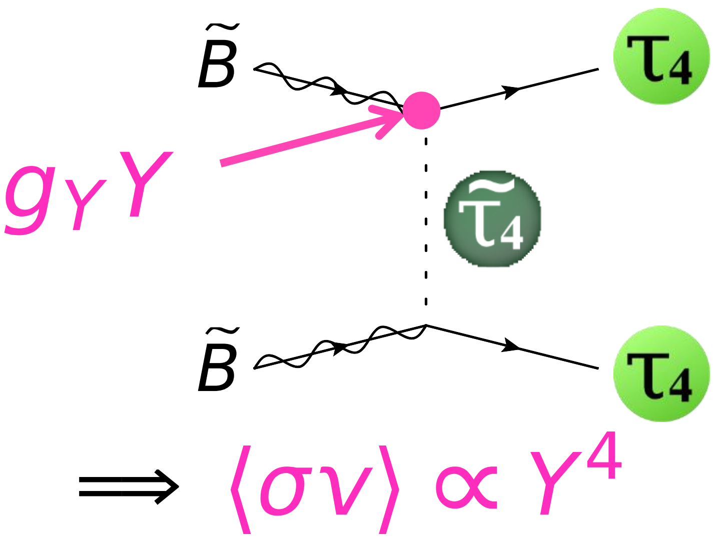
if $\tilde{\tau}_4 \gtrsim \tilde{B} > \tau_4$

$$\langle\sigma v\rangle_{s\text{-wave}} = \frac{g_Y^4 (Y_\mathrm{L}^2 + Y_\mathrm{R}^2)^2}{8\pi} \frac{m_f^2}{m_{\tilde{B}}} \frac{\sqrt{m_{\tilde{B}}^2 - m_f^2}}{(m_{\tilde{B}}^2 + m_{\tilde{f}}^2 - m_f^2)^2}$$

$$(Q_i, \bar{U}_i, \bar{D}_i, L_i, \bar{E}_i) + (H_u, H_d)$$ [MSSM]

$(i = 1 \dots 3)$

$$+(E_4, \bar{E}_4)$$ [MSSM4G]

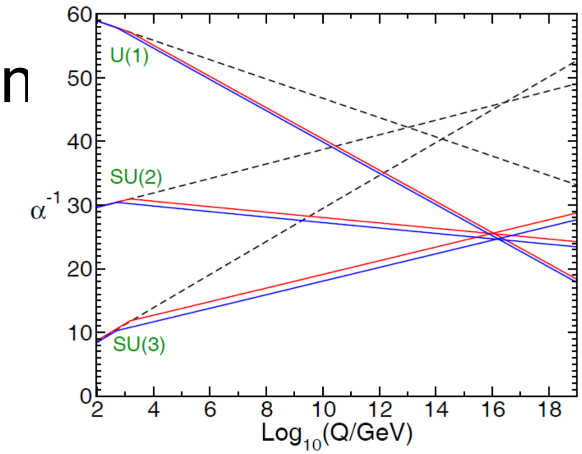


	$SU(3)_{color}$	$SU(2)_{weak}$	$U(1)_Y$
Q_i	$\mathbf{3}$	$\mathbf{2}$	$1/6$
$\bar{U}_i$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$
$\bar{E}_i$	$\mathbf{1}$	$\mathbf{1}$	1
$\bar{D}_i$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
H_u	$\mathbf{1}$	$\mathbf{2}$	$1/2$
H_d	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$\bar{E}_4$	$\mathbf{1}$	$\mathbf{1}$	1
E_4	$\mathbf{1}$	$\mathbf{1}$	-1

$$W = Y_u H_u Q \bar{U} + Y_d H_d Q \bar{D} + Y_e H_d L \bar{E}$$

$$+ M_{E_4} E_4 \bar{E}_4 + \epsilon_i H_d L_i \bar{E}_4$$

[vector-like mass] [mixing with SM leptons]



- MSSM + $E\bar{E}$ → breaks coupling unification

- QUE model : MSSM + $Q\bar{Q}U\bar{U}E\bar{E}$
  - ✓ gauge coupling unification
  - ✓ SU(5) GUT
  - ➢ extra $H_u Q_4 \bar{U}_4$ interaction → m_h UP

- QDEE model : MSSM + $Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$
  - ✓ gauge coupling unification
  - ✗ SU(5) GUT
  - ➢ extra $H_d Q_4 \bar{D}_4$ coupling → m_h slightly UP

- MSSM + $E\bar{E}$ → breaks coupling unification

- QUE model : MSSM + $Q\bar{Q}U\bar{U}E\bar{E}$

⇨ MSSM + $T_4, B_4, t_4, \tau_4,$

$\tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{t}_{4L}, \tilde{t}_{4R}, \tilde{\tau}_{4L}, \tilde{\tau}_{4R}$

- QDEE model : MSSM + $Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$

⇨ MSSM + $T_4, B_4, b_4, \tau_4, \tau_5,$

$\tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{b}_{4L}, \tilde{b}_{4R}, \tilde{\tau}_{4L}, \tilde{\tau}_{4R}, \tilde{\tau}_{5L}, \tilde{\tau}_{5R}$

- MSSM + $E\bar{E}$ → breaks coupling

Other working assumptions

- $M_1 \ll \mu \ll M_2$
  → LSP $\tilde{\chi}_1^0$ is $\tilde{B}$-like
- All the other SUSY particles & extra Higgses are decoupled.

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$\tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{t}_{4L}, \tilde{t}_{4R}, \tilde{\tau}_{4L}, \tilde{\tau}_{4R}$

assumed to be "decoupled" (very heavy) and we will ignore them.

- QDEE model : MSSM + $Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$

⇨ MSSM + $T_4, B_4, b_4, \tau_4, \tau_5,$

$\tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{b}_{4L}, \tilde{b}_{4R}, \tilde{\tau}_{4L}, \tilde{\tau}_{4R}, \tilde{\tau}_{5L}, \tilde{\tau}_{5R}$

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⇨ SM + $\tilde{\chi}_1^0(\approx \tilde{B})$, τ_4, $\tilde{\tau}_{4L}, \tilde{\tau}_{4R}$

assumed to be equal-mass

- QDEE model : MSSM + $Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$

⇨ SM + $\tilde{\chi}_1^0(\approx \tilde{B})$, τ_4, τ_5, (assumed to be equal-mass)

$\tilde{\tau}_{4L}, \tilde{\tau}_{4R}, \tilde{\tau}_{5L}, \tilde{\tau}_{5R}$

assumed to be equal-mass

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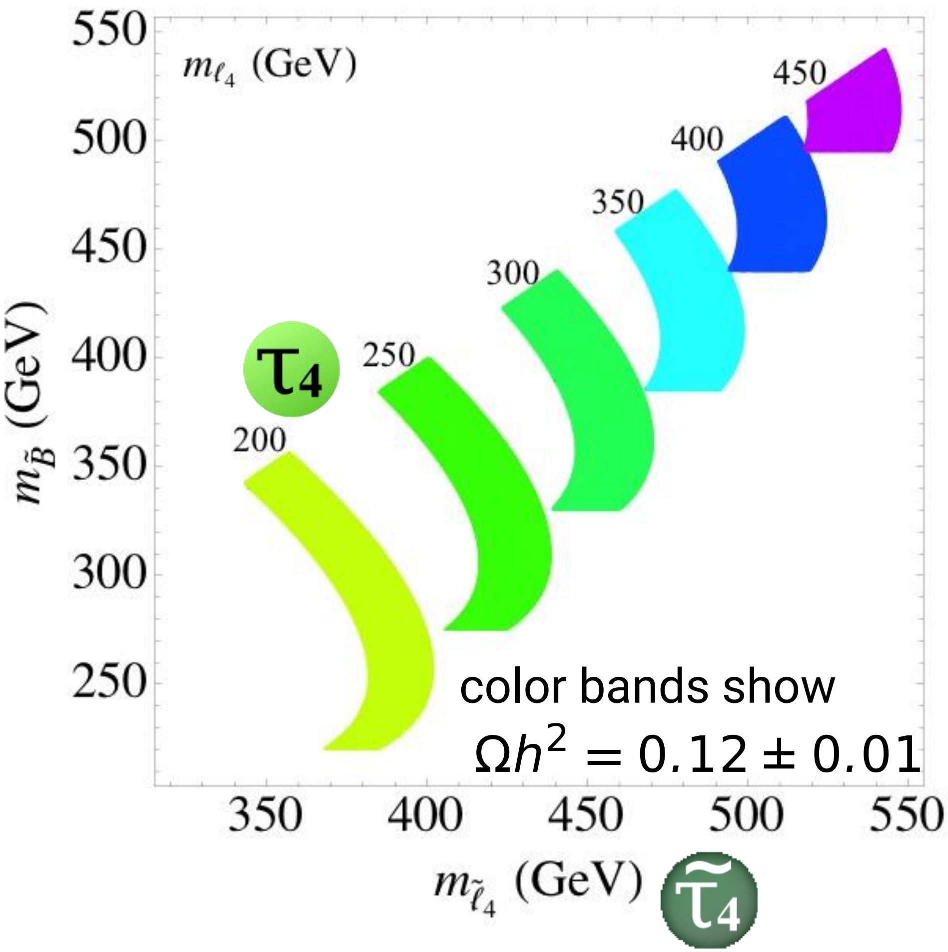
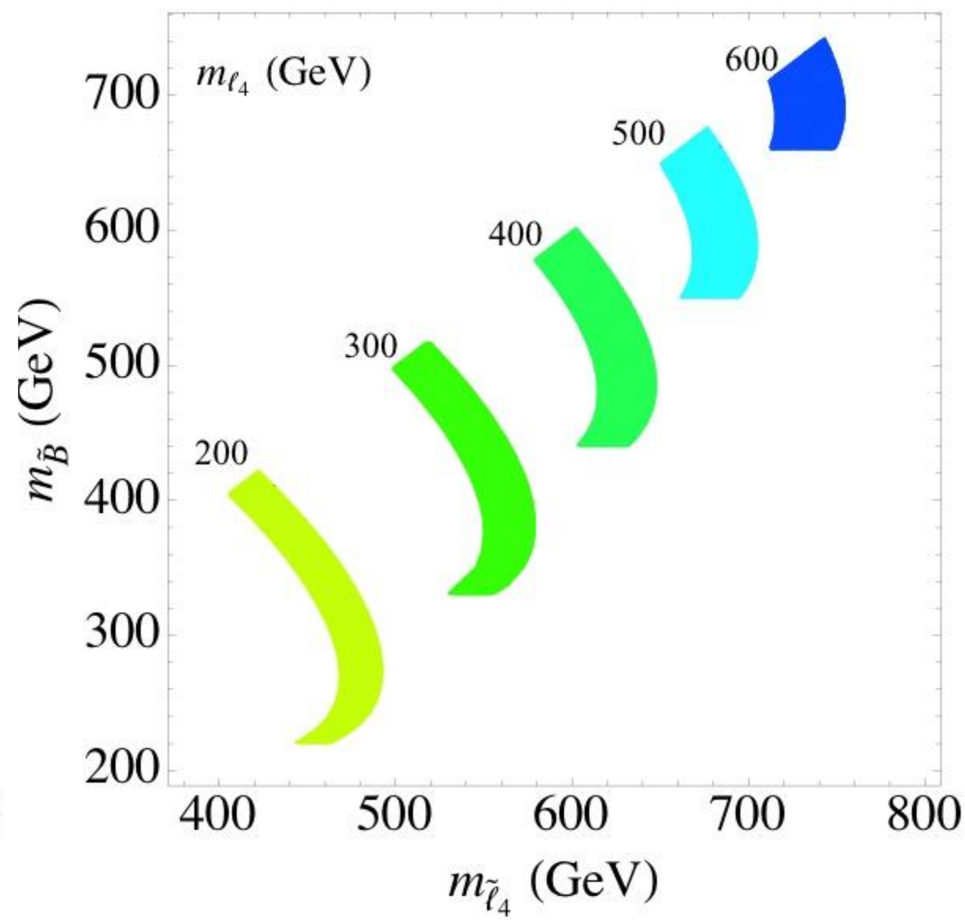
QUE model

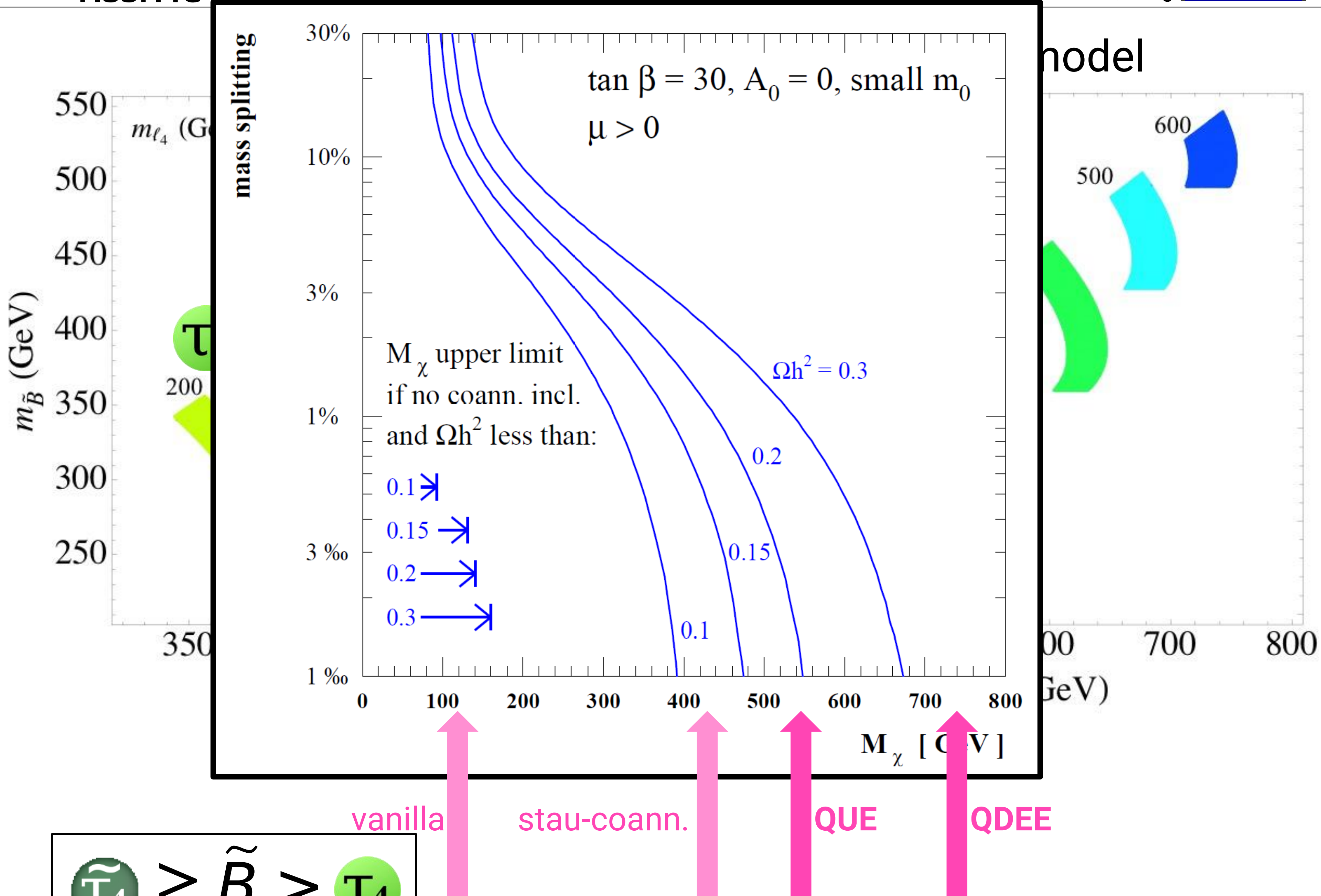


QDEE model



$\tilde{\tau}_4 \gtrsim \tilde{B} > \tau_4$

Abdullah, Feng [1510.06089]



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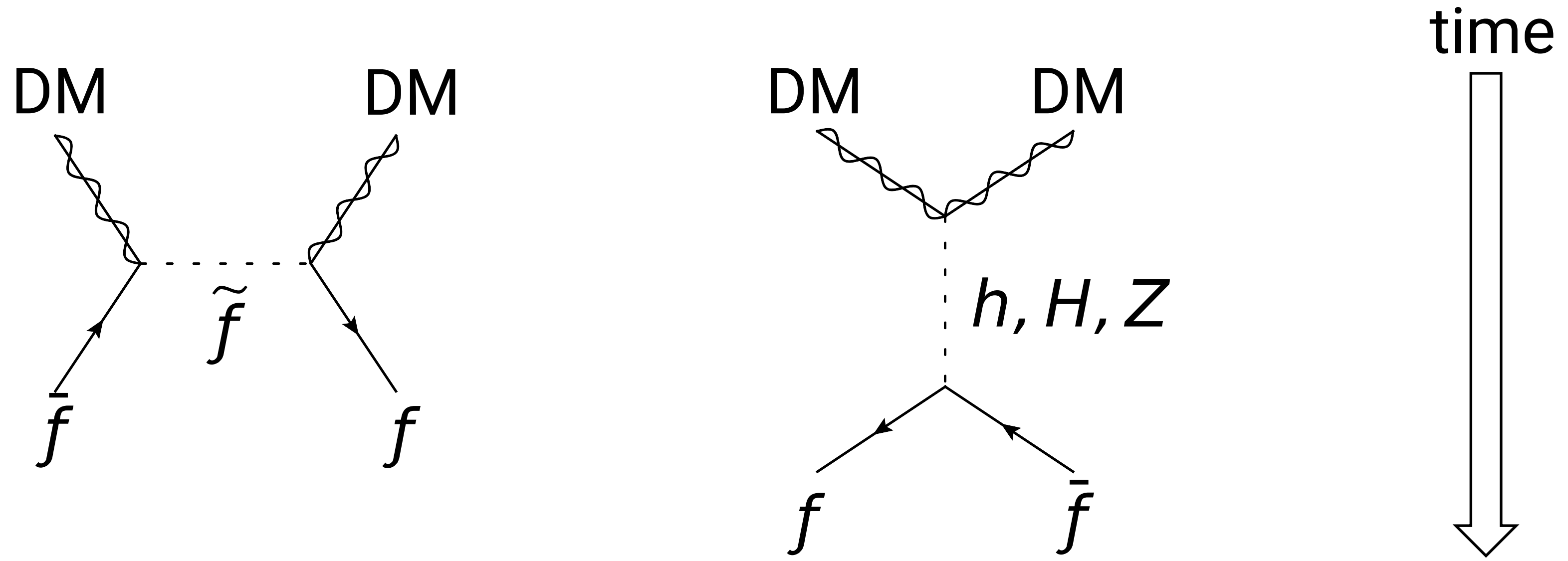

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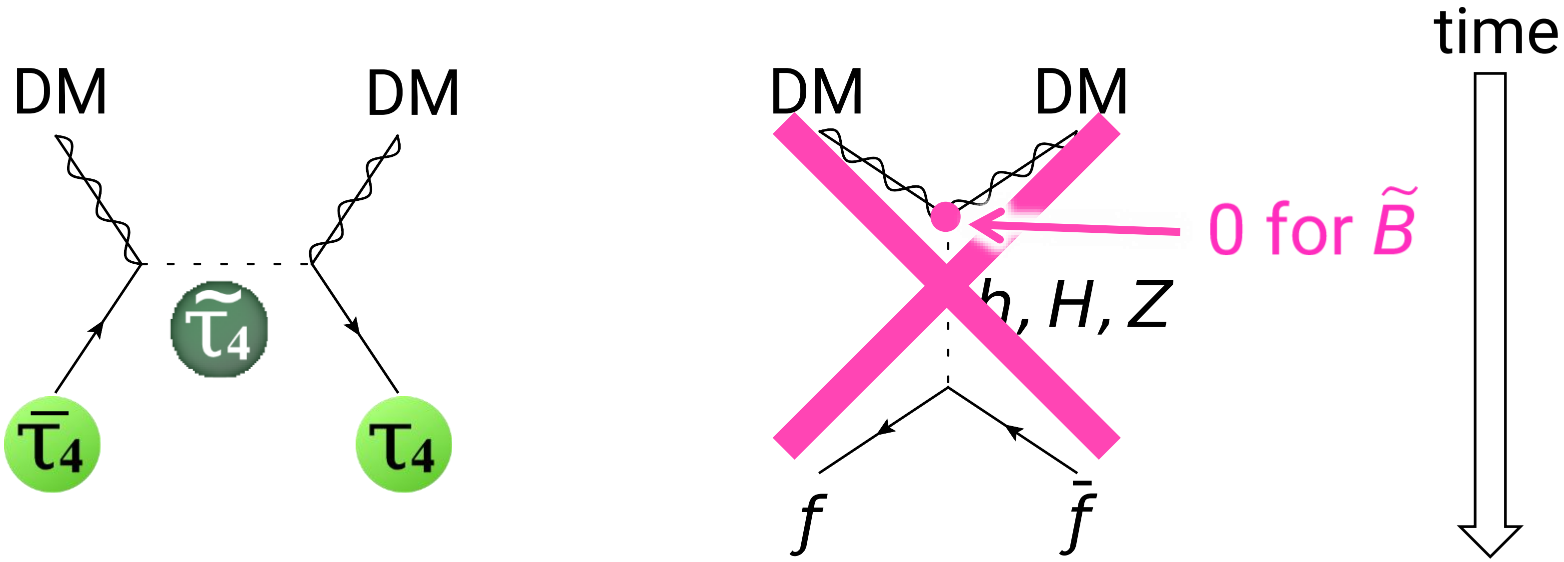
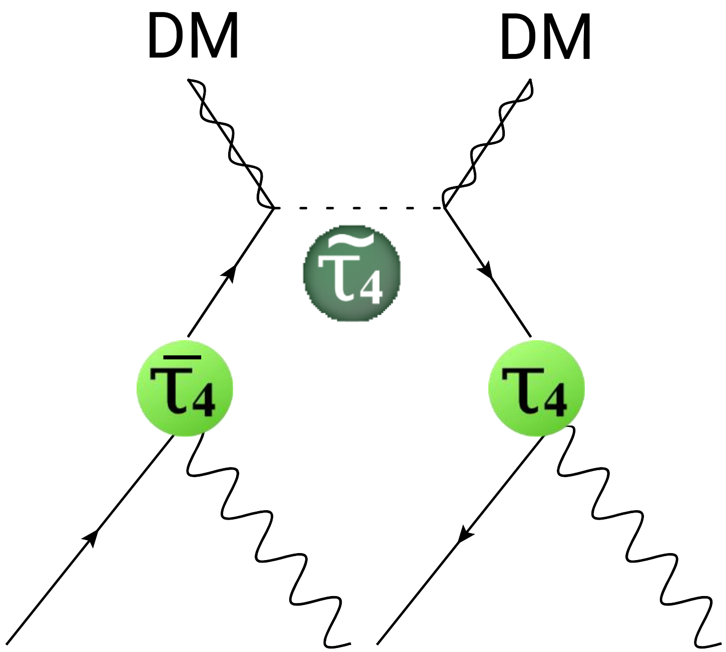


$$\langle \sigma v \rangle_{s\text{-wave}} = \frac{g_Y^4 (Y_L^2 + Y_R^2)^2}{8\pi} \frac{m_f^2}{m_{\widetilde{B}}} \frac{\sqrt{m_{\widetilde{B}}^2 - m_f^2}}{(m_{\widetilde{B}}^2 + m_{\widetilde{f}}^2 - m_f^2)^2}$$

- DM indirect detection (= searches for $\mathrm{DM\,DM} \to \tau_4 \bar{\tau}_4$)



$$\tau_4 \longrightarrow \begin{cases} W + \nu \\ Z + l \\ h + l \end{cases} \quad \begin{pmatrix} \nu = \nu_e, \nu_\mu, \nu_\tau \\ l = e, \mu, \tau \end{pmatrix}$$

$$W\nu : Zl : hl \sim 2 : 1 : 1$$

$$W \ni Y_e H_d L \bar{E} + M_{E_4} E_4 \bar{E}_4 + \epsilon_i H_d L_i \bar{E}_4$$

[vector-like mass] [mixing with SM leptons]

- DM indirect detection

$$W \ni Y_e H_d L \bar{E} + M_{E_4} E_4 \bar{E}_4 + \epsilon_i H_d L_i \bar{E}_4$$

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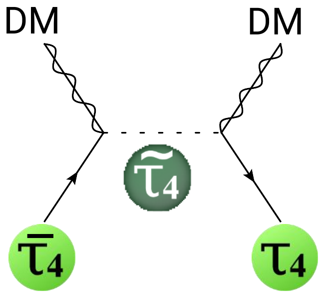
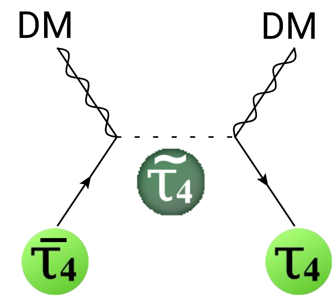


	DM DM→
$\tau_{4(5)}$ mixes with e	W^+W^- ZZ hh $\nu\bar{\nu}$ e^+e^-
$\tau_{4(5)}$ mixes with μ	W^+W^- ZZ hh $\nu\bar{\nu}$ $\mu^+\mu^-$
$\tau_{4(5)}$ mixes with τ	W^+W^- ZZ hh $\nu\bar{\nu}$ $\tau^+\tau^-$

- DM indirect detection

$$W \ni Y_e H_d L \bar{E} + M_{E_4} E_4 \bar{E}_4 + \epsilon_i H_d L_i \bar{E}_4$$

$W\nu : Zl : Hl \sim 2:1:1$



insensitive (IceCube)

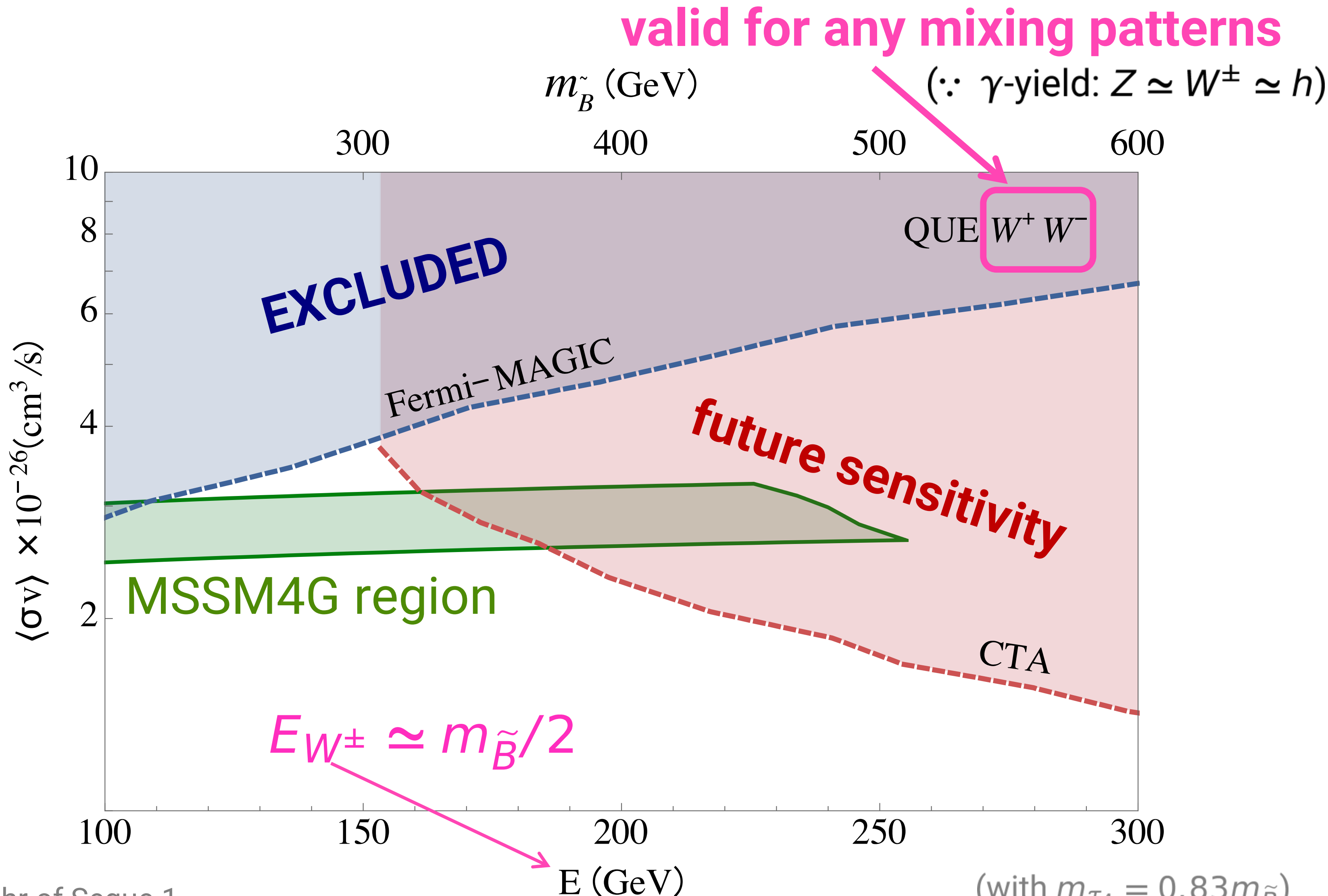
less sensitive / large BKG uncertainty

	DM DM→				
$\tau_{4(5)}$ mixes with e	W^+W^-	ZZ	hh	$\nu\bar{\nu}$	e^+e^-
$\tau_{4(5)}$ mixes with μ	W^+W^-	ZZ	hh	$\nu\bar{\nu}$	$\mu^+\mu^-$
$\tau_{4(5)}$ mixes with τ	W^+W^-	ZZ	hh	$\nu\bar{\nu}$	$\tau^+\tau^-$

$\rightarrow \cdots \rightarrow \gamma$

$\rightarrow \pi^0 \rightarrow \gamma$

Abdullah, Feng, SI, Lillard [1608.00283]



(with $m_{\tau_4} = 0.83 m_{\tilde{B}}$)

MAGIC: 158 hr of Segue 1

Fermi-LAT: 6 yr of 15 dSph (incl. Segue 1)

DM profile: NFW

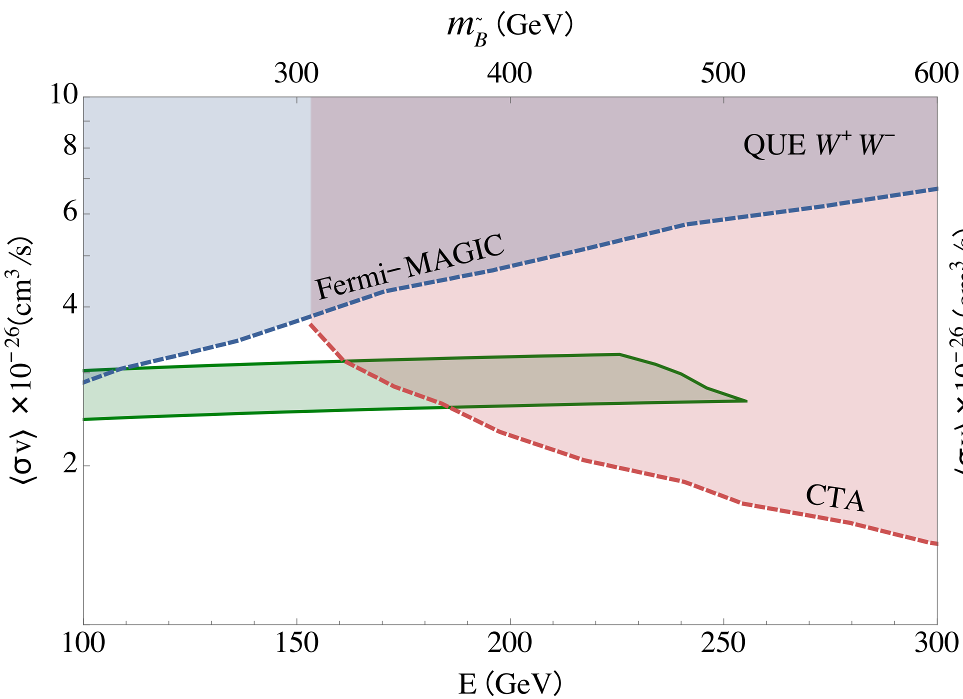
Fermi-LAT dominates MAGIC in almost all *E*-range.

CTA prospect : 500hr of Milky Way

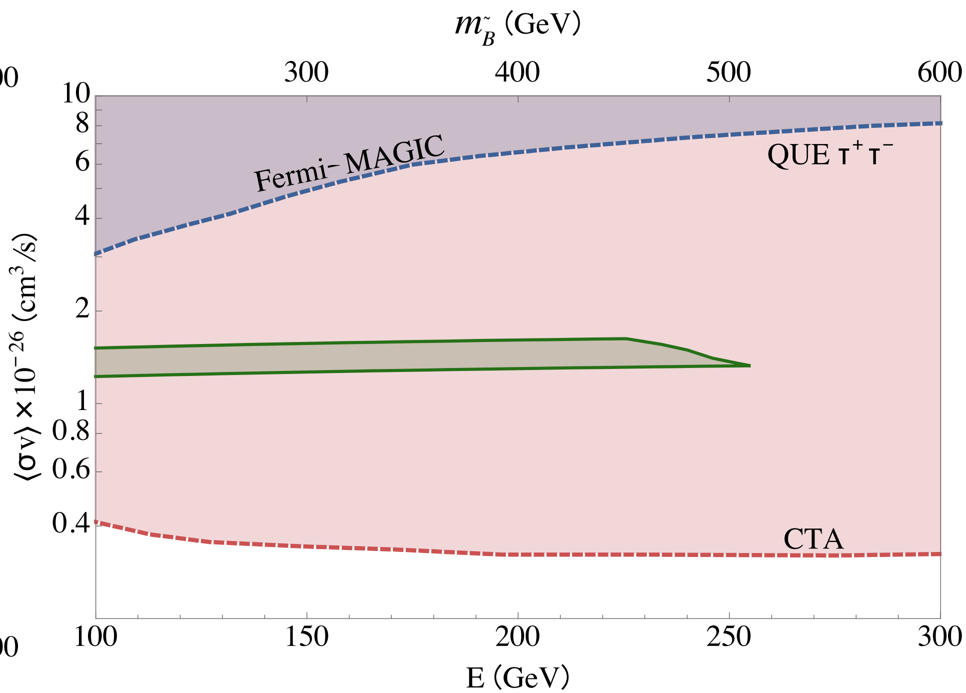
DM profile: Einasto

No syst. unc. (stat only)

WW (any mixing pattern)



ττ (only for τ-mixing cases)



✓ τ-mixing fully covered

✓ e/μ-mixing with $m_{\tilde{B}} > 340{-}380$ GeV covered

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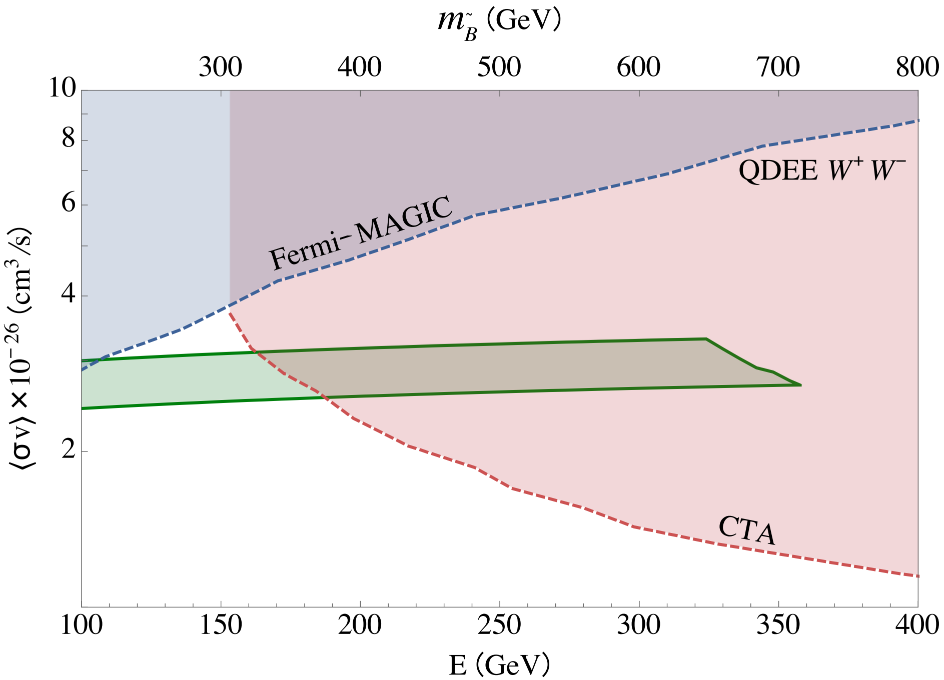

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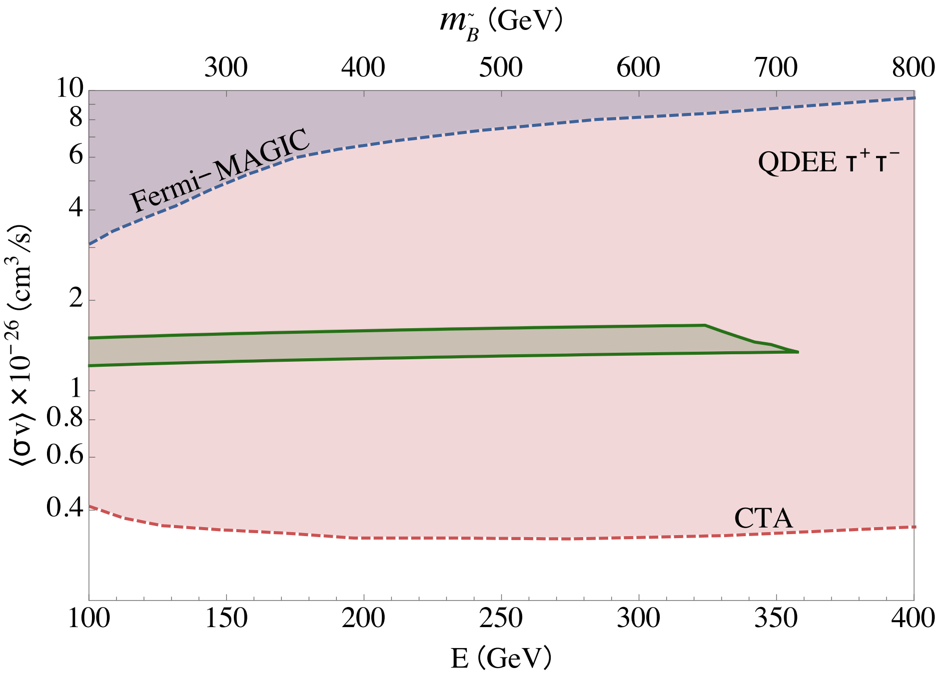

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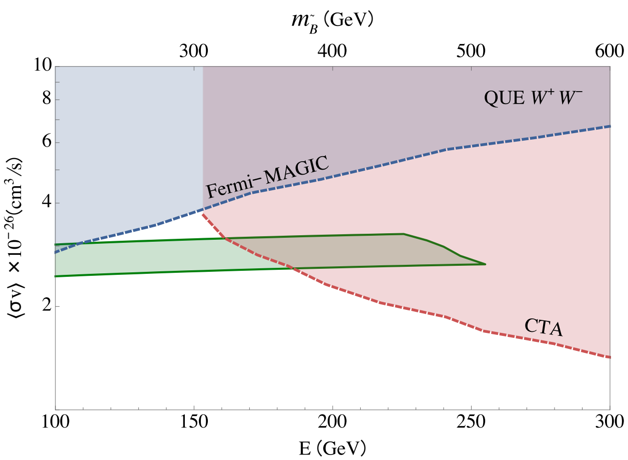
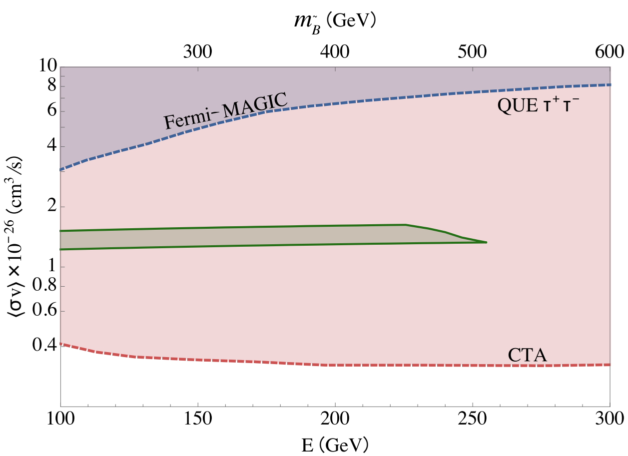
	e-mixing	μ-mixing	τ-mixing
CTA 500hr	covers $m_{\tilde{B}}$ > 340−380 GeV		**full coverage**
HL-LHC			

e/μ-mixing, QUE



τ/μ-mixing, QUE



Introduction: why overabundant?

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Analysis:

- cosmic rays (CTA, Fermi, MAGIC)
- colliders (LHC)
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Summary with discussion seeds

- MSSM + $E\bar{E}$ → breaks coupling unification

- QUE model : MSSM + $Q\bar{Q}U\bar{U}E\bar{E}$

⇨ SM + $\tilde{\chi}_1^0(\approx \tilde{B})$, τ_4,

$\underbrace{\tilde{\tau}_{4L}, \tilde{\tau}_{4R}}$ assumed to be equal-mass

- QDEE model : MSSM + $Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$

⇨ SM + $\tilde{\chi}_1^0(\approx \tilde{B})$, $\overbrace{\tau_4, \tau_5}$, assumed to be equal-mass

$\underbrace{\tilde{\tau}_{4L}, \tilde{\tau}_{4R}, \tilde{\tau}_{5L}, \tilde{\tau}_{5R}}$ assumed to be equal-mass

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assumed to be equal-mass

slepton search

extra lepton search

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assumed to be equal-mass

slepton search

$\tilde{\tau}_4 \not\to \tau_4 + \tilde{B}$

$\longrightarrow (e, \mu, \tau) + \tilde{B}$

$\equiv 2(4) \times \tilde{l}_R$

extra lepton search

$\tau_4 \to W\nu, Zl, hl$

(as discussed before)

standard searches for vectorlike leptons (but 2x in QDEE)

+ $Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$

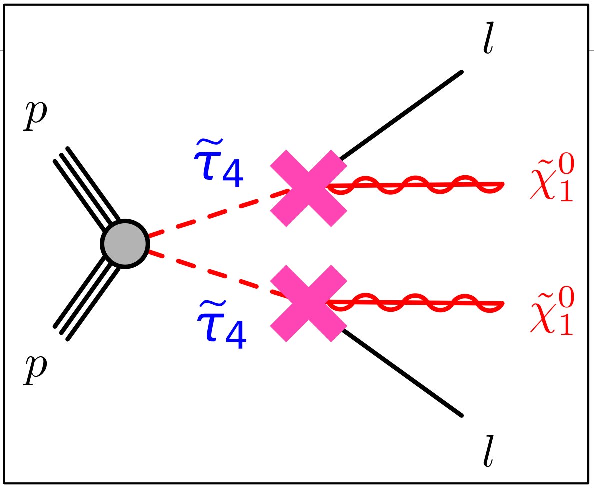
assumed to be equal-mass

τ_4, τ_5, $\tilde{\tau}_{4L}, \tilde{\tau}_{4R}, \tilde{\tau}_{5L}, \tilde{\tau}_{5R}$

assumed to be equal-mass

$$pp \to \tilde{\tau}_{4(,5)} \tilde{\tau}^*_{4,(5)} \equiv pp \to \tilde{l}_R \tilde{l}^*_R$$

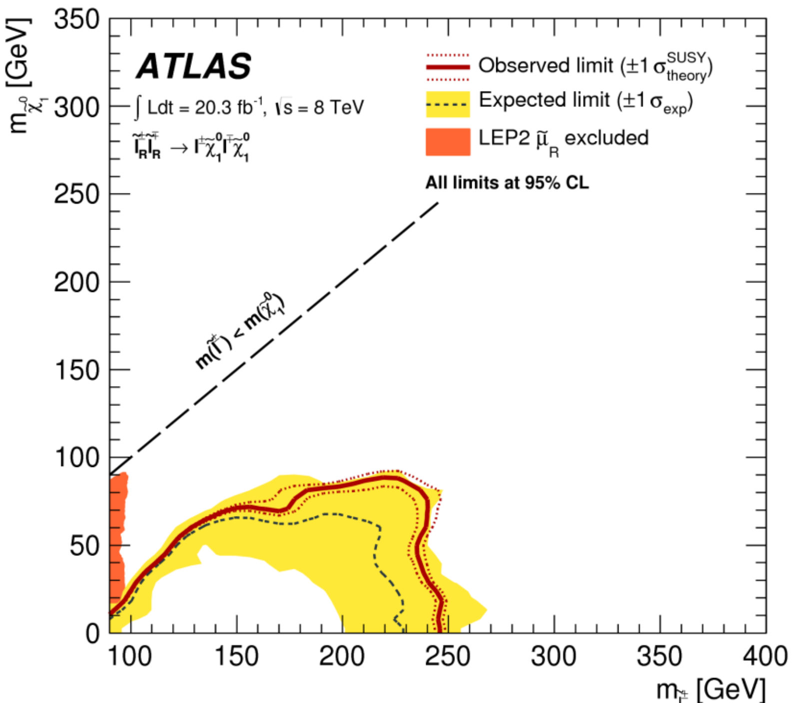
↑ determined by mixing parameters



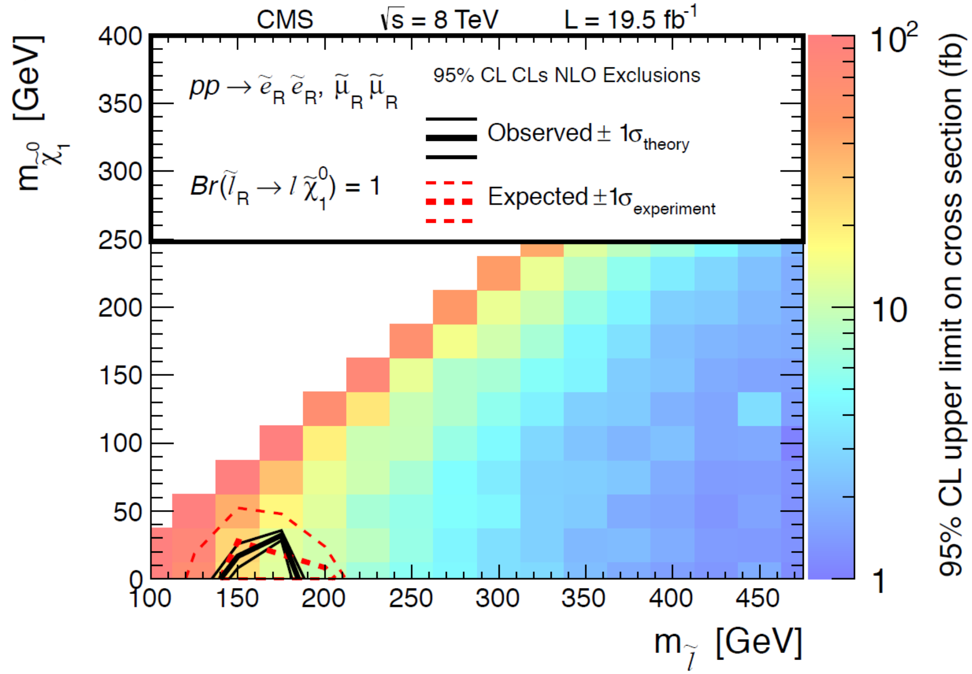
e/μ-mixing → slepton searches × 2 (4)
$(\tilde{e}_R, \tilde{\mu}_R)$

14 TeV prospects studied in 1408.2841 (Eckel, Ramsey-Musolf, Shepherd, Su)

→ re-interpreted



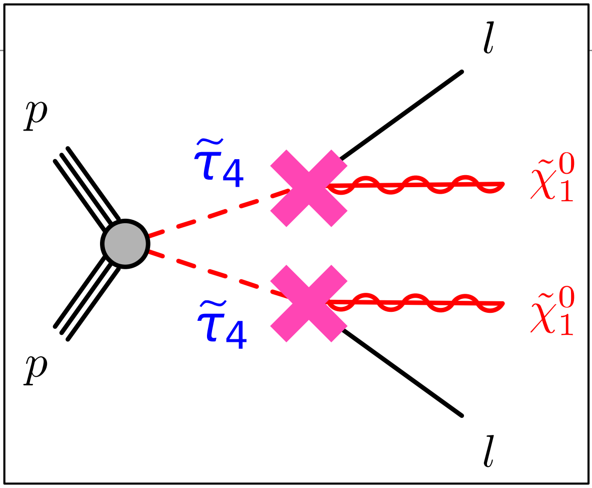
ATLAS (8TeV full) [1403.5294]



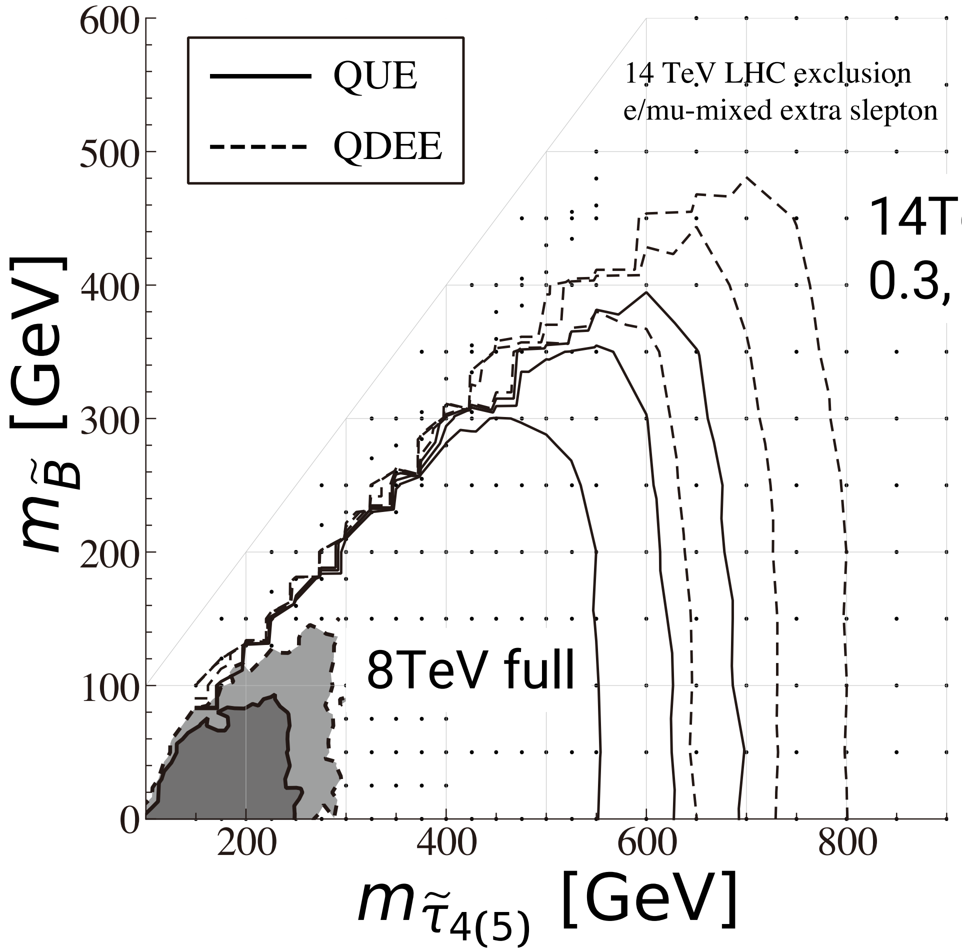
CMS (8TeV full) [1405.7570]

$$pp \to \tilde{\tau}_{4(,5)} \tilde{\tau}^*_{4,(5)} \equiv pp \to \tilde{l}_R \tilde{l}^*_R$$

determined by mixing parameters



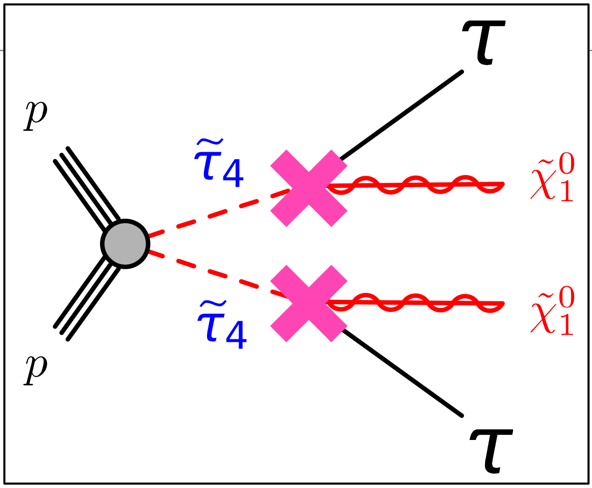
e/μ-mixing → slepton searches × 2 (4)
$(\tilde{e}_R, \tilde{\mu}_R)$



- 2 lepton + MET + mT2 + jet-veto
- BKG taken from 1408.2841
  - MG5−Pythia−Delphes (also for signal)
  - rescaled by NLO *K*-factor
  - di-boson dominates
- Signal events at LO level
- Uncertainties = stat. + 5% syst.

$$pp \to \tilde{\tau}_{4(,5)} \tilde{\tau}^*_{4,(5)} \equiv pp \to \tilde{l}_R \tilde{l}^*_R$$

↑ determined by mixing parameters



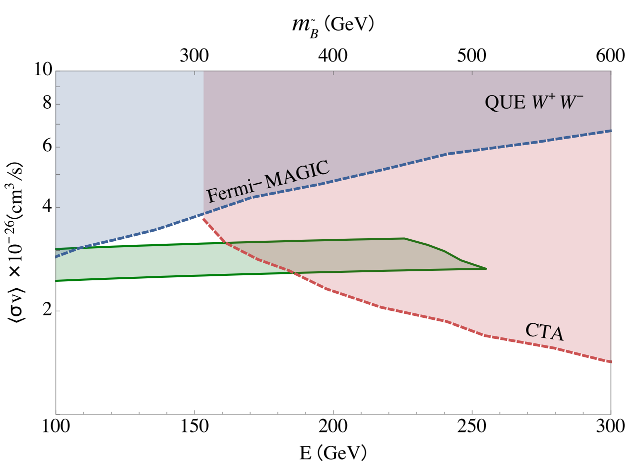
τ-mixing → stau searches × 2 (4)

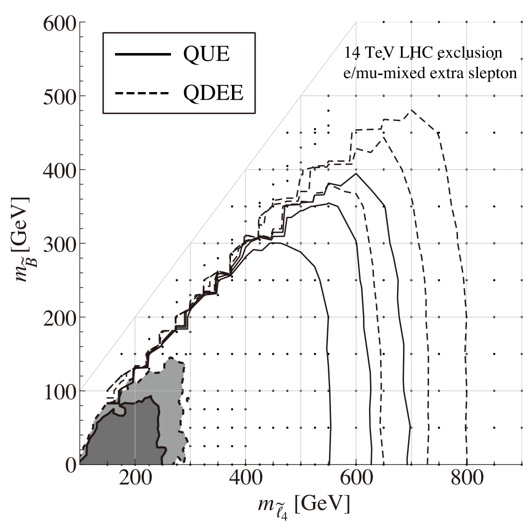
→ **No constraint expected.**

- LHC Run 1 provided no limit on MSSM stau mass.
- 14TeV, 3/ab LHC will not exclude MSSM4G parameter region.

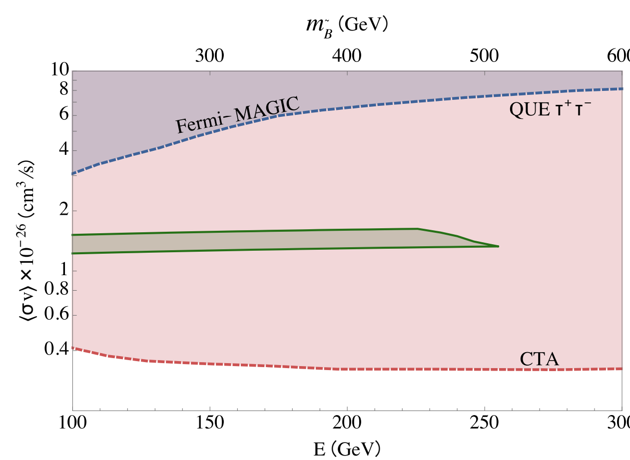
	e-mixing	μ-mixing	τ-mixing
CTA 500hr	covers $m_{\tilde{B}}$ > 340–380 GeV		**full coverage**
HL-LHC (slepton)	covers $m_{\tilde{B}}$ < 400 (480) GeV (but not “degenerate” region)		–
HL-LHC (lepton)			

e/μ-mixing

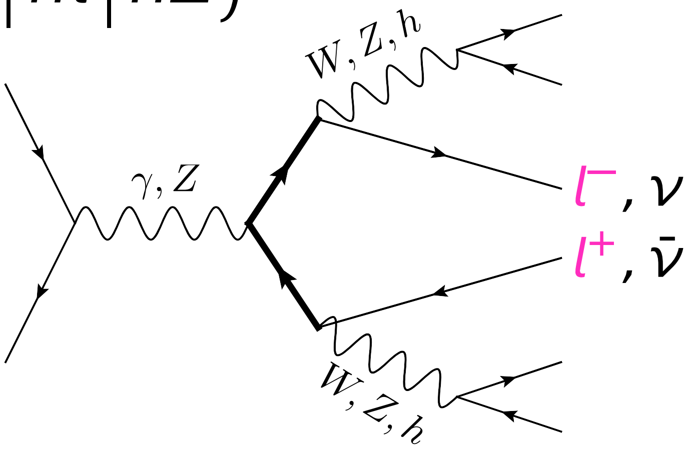




τ/μ-mixing, QUE



$$pp \to \tau^+_{4(,5)}\tau^-_{4,(5)} \to (W\nu | hl | Zl)(W\nu | hl | hZ)$$



e/μ-mixing case

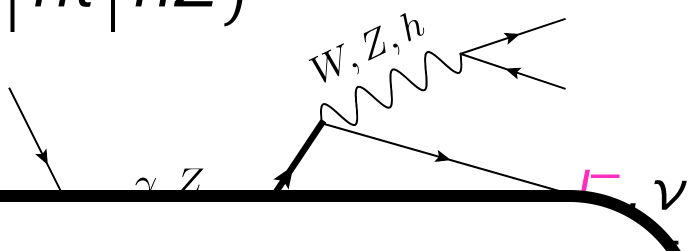
"vectorlike lepton searches" by
multi-$\ell^\pm$ signature (3−5$\ell^\pm$)

[Cf. ATLAS collaboration, 1506.01291]

$$\begin{cases} W\nu Z\ell \to 3\ell\ (1.3\%) \\ W\nu h\ell \to 3\ell\ (0.6\%) \\ h\ell Z\ell \to 3\ell\ (0.8\%) \\ h\ell h\ell \to 3\ell\ (0.8\%) \end{cases} \quad \begin{cases} W\nu Z\ell \to 4^+\ell\ (0.4\%) \\ h\ell Z\ell \to 4^+\ell\ (1.0\%) \\ Z\ell Z\ell \to 4^+\ell\ (0.8\%) \\ h\ell h\ell \to 4^+\ell\ (0.2\%) \end{cases}$$

→ Monte Carlo simulation

$$pp \to \tau^{+}_{4(,5)}\tau^{-}_{4,(5)} \to (W\nu|hl|Zl)(W\nu|hl|hZ)$$



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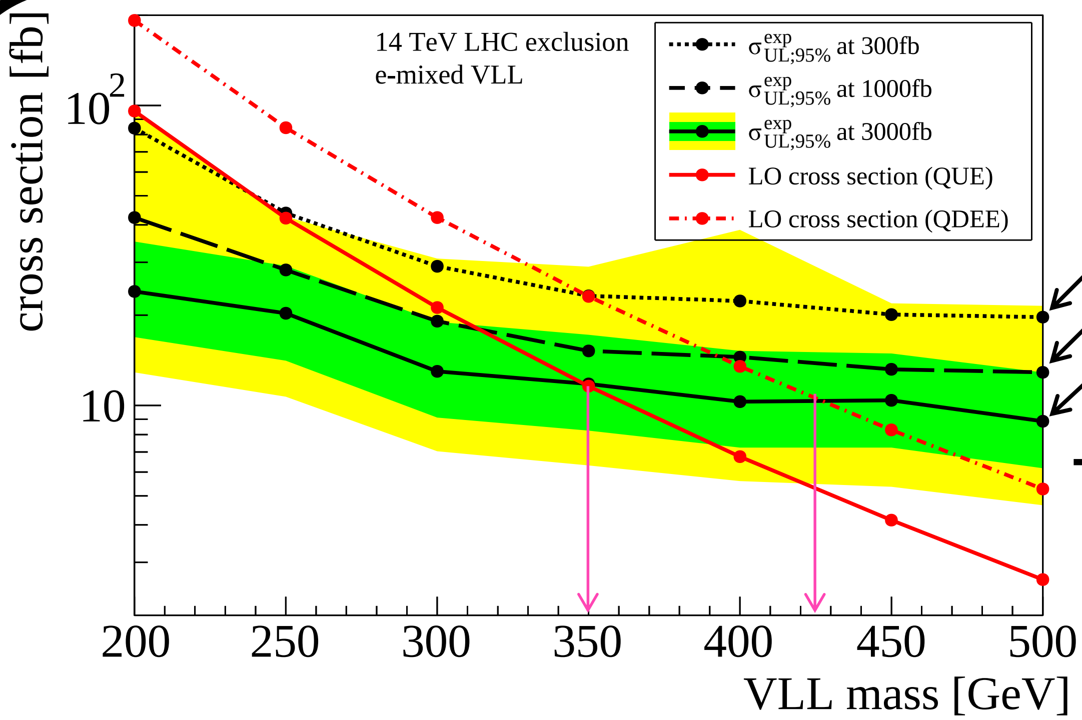
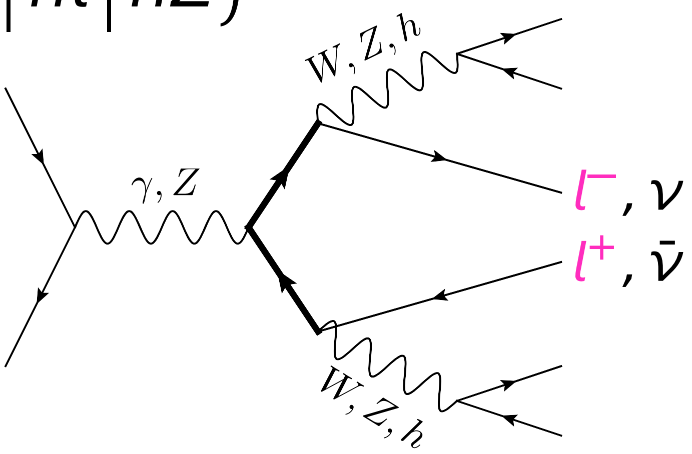


0.3/ab
1/ab
3/ab (with 1&2σ band)

→ 14TeV, 3/ab covers $m_{\tau_4} < 350\ (425)$ GeV
QUE QDEE

- Snowmass BKG set is used.
  - MG5−Pythia−Delphes + NLO *K*-factor
  - di-boson + *tt* dominated
- Signal by FR−MG5aMC−Pythia−Delphes (LO)
- SR dedicated for WZ / ZZ + leptons
  - 3L, 4L for WZ, and 4L, 5L for ZZ
  - tau-tag / b-tag not used (avoided)
- Uncertainties = stat. + 20% syst.

$$pp \to \tau^+_{4(,5)} \tau^-_{4,(5)} \to (W\nu | hl | Zl)(W\nu | hl | hZ)$$



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→ 14TeV, 3/ab covers
$m_{\tau_4} <$ 350 (425) GeV
QUE QDEE

τ-mixing case

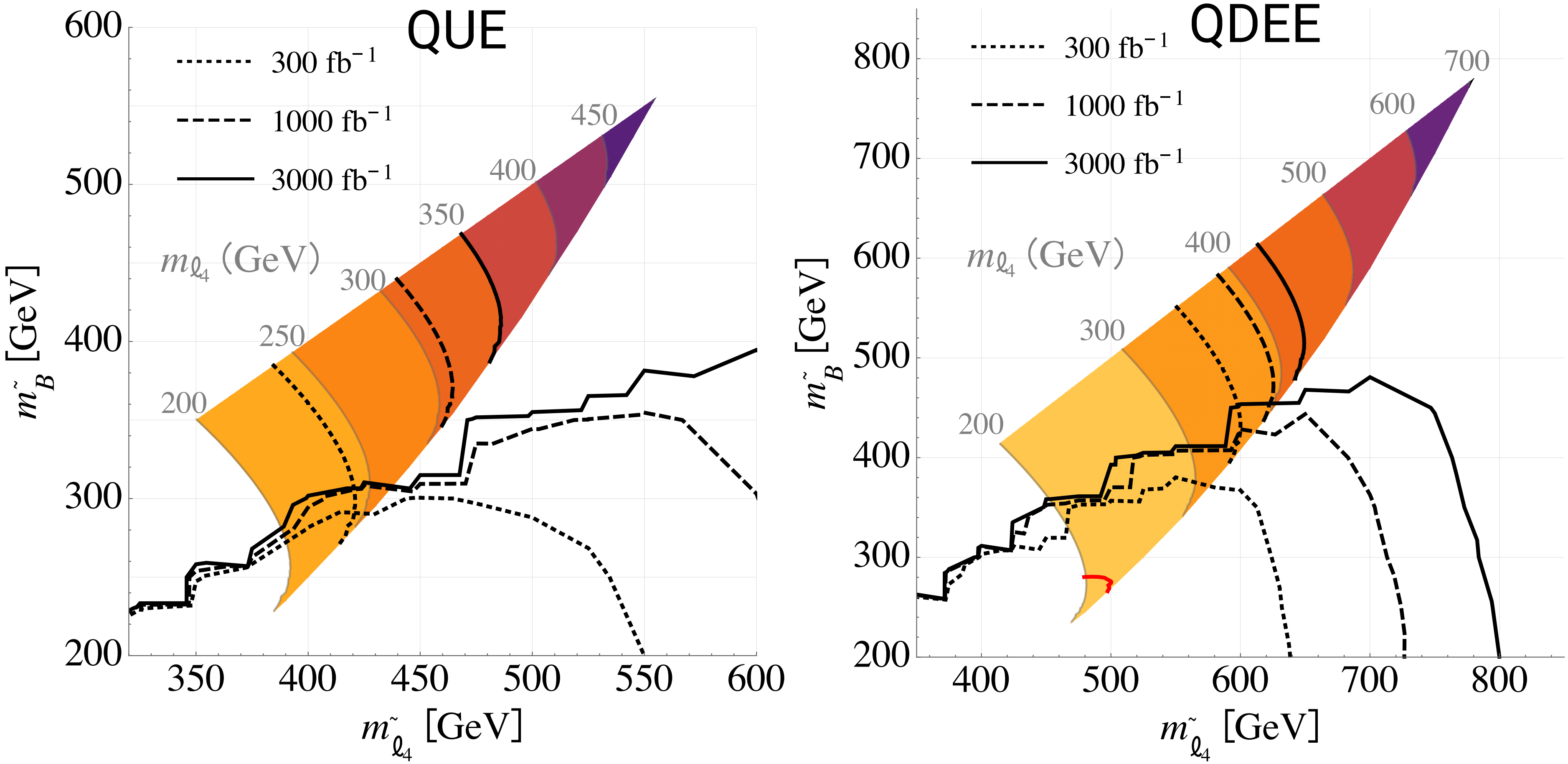
✓ 1510.03456 (Kumar and Matrin)

- SRs: 4(e, mu, had-tau)
- Signal and BKG by their MC (FR−MG5−Pythia−Delphes)
- no prospects for exclusion if BKG syst. unc. > 10%

→ 13 TeV, 3/ab covers
$m_{\tau_4} <$ 234 (264) GeV

with "a very optimistic BKG estimation"

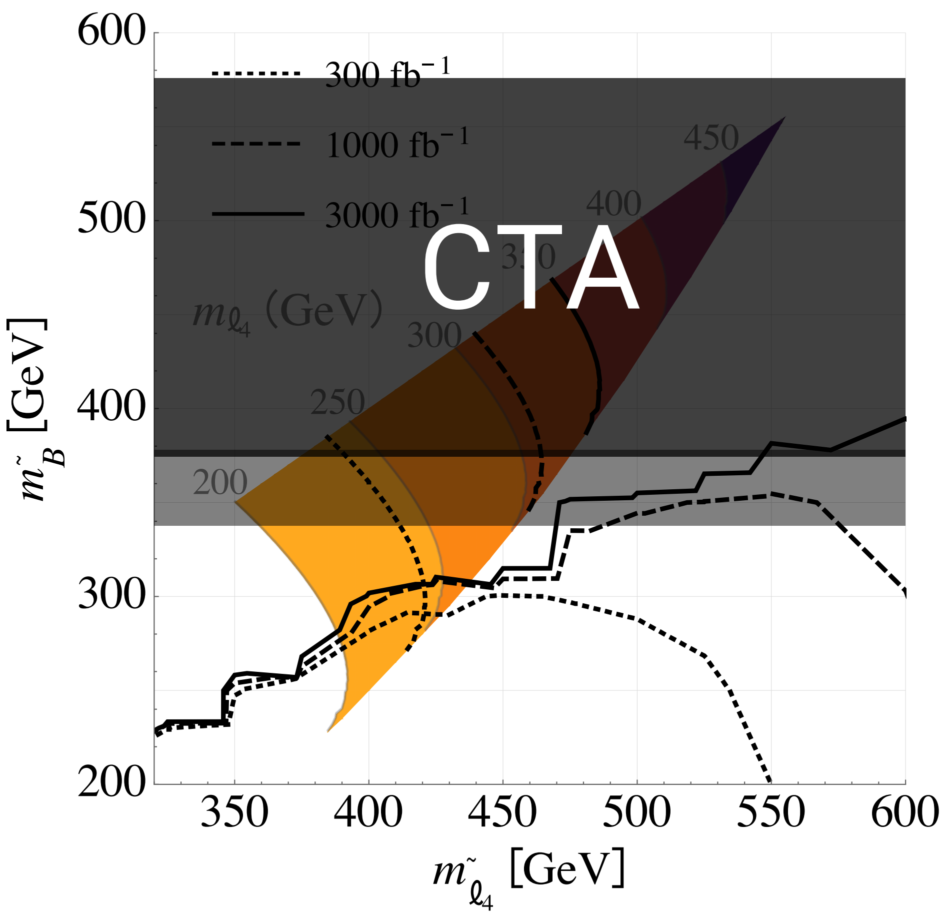
e/μ-mixing cases

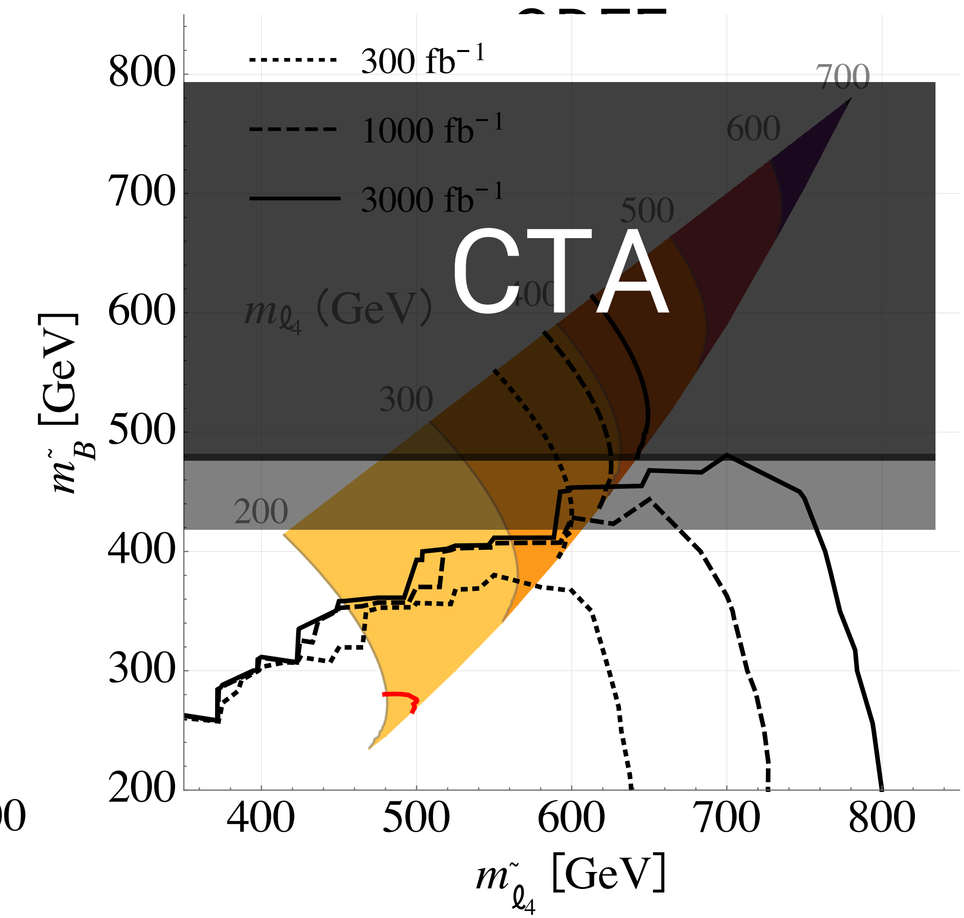


τ-mixing case

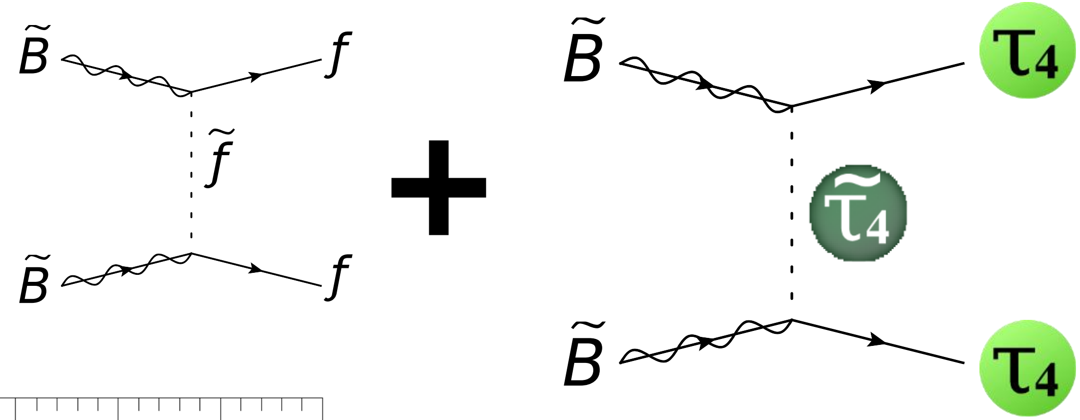
- LHC insensitive … (´ • ω • `)

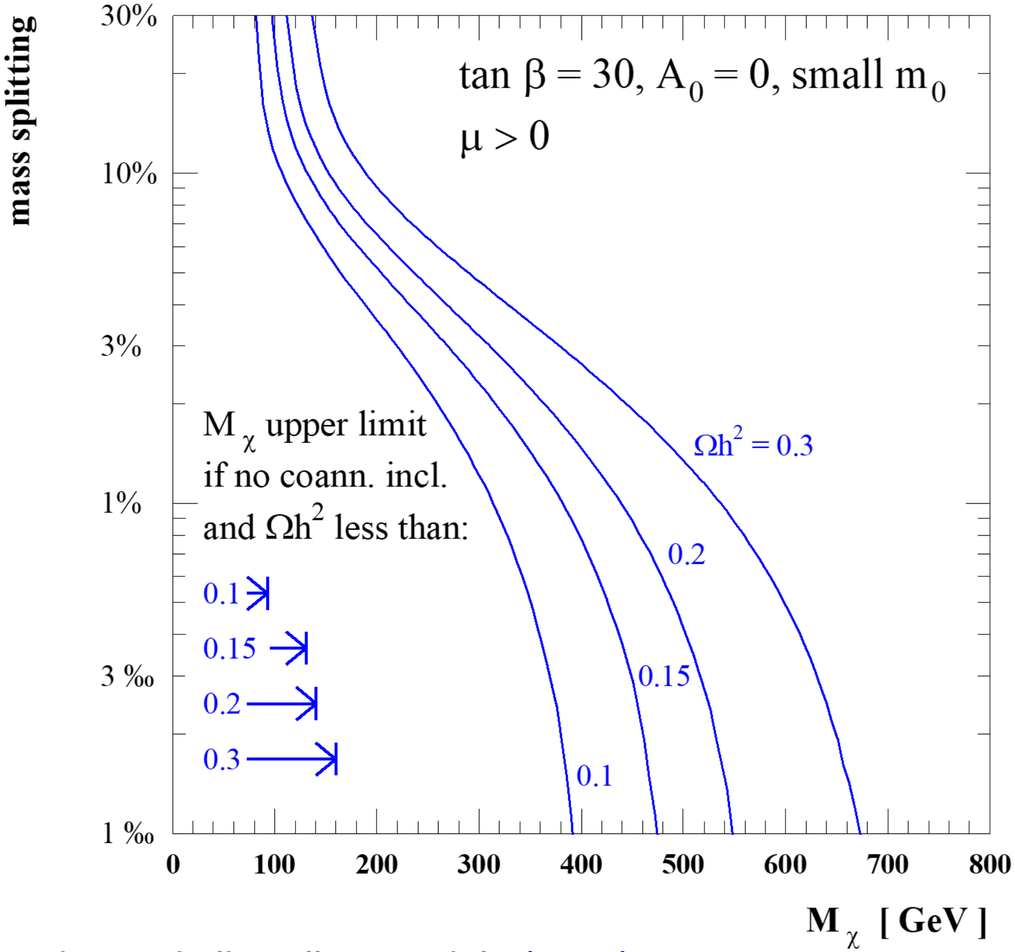
- e/μ-mixing cases





- τ-mixing case
  - LHC insensitive, but CTA covers full region





extra annihilation channel

→ larger Ωh^2

→ "proper" $\langle \sigma v \rangle$

if $\tilde{\tau}_4 \gtrsim \tilde{B} > \tau_4$

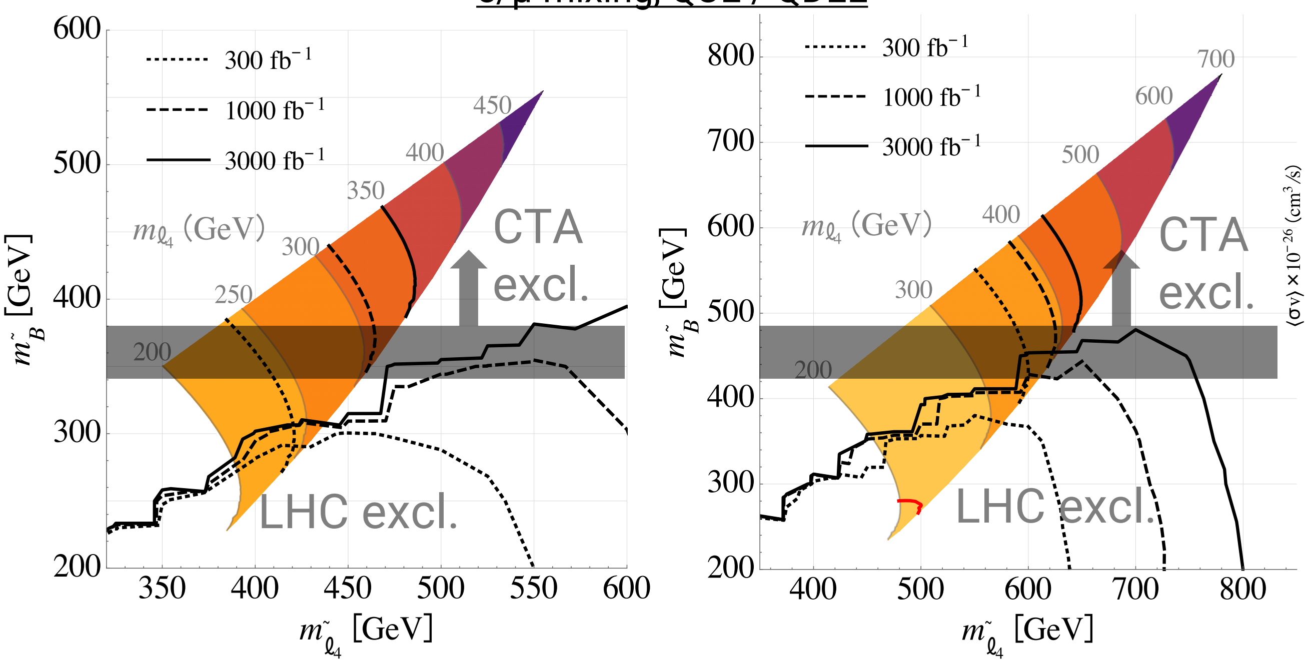
$$\langle \sigma v \rangle \propto Y^4 \Longrightarrow \text{MSSM} + E\bar{E}$$

$$Y_{\rm u} H_{\rm u} Q \bar{U} + Y_{\rm d} H_{\rm d} Q \bar{D} + Y_{\rm e} H_{\rm d} L \bar{E}$$
$$+ M_{E_4} E_4 \bar{E}_4 + \epsilon_i H_{\rm d} L_i \bar{E}_4$$

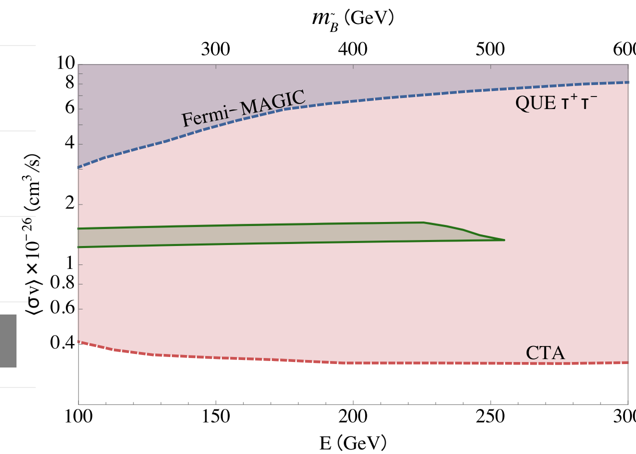
Edsjö, Schelke, Ullio, Gondolo, hep-ph/0301106

	e-mixing	μ-mixing	τ-mixing
CTA 500hr	covers $m_{\tilde{B}}$ > 340−380 GeV		**full coverage**
HL-LHC (slepton)	covers $m_{\tilde{B}}$ < 400 (480) GeV (but not “degenerate” region)		−
HL-LHC (lepton)	covers m_{τ_4} < 350 (430) GeV equivalent to $m_{\tilde{B}}$ < 380 (480) GeV		−

e/μ-mixing, QUE / QDEE



τ/μ-mixing, QUE



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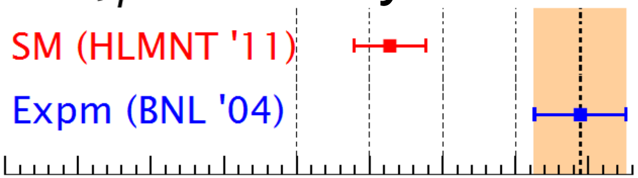
Summary with discussion seeds

: “muon $g{-}2$ problem”

$$\left(a_\mu := \frac{g_\mu - 2}{2}\right)$$

- $(g-2)_\mu$ anomaly



Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149]

$$a_\mu^{\mathrm{SM}} = (116\,591\,828 \pm 49) \times 10^{-11}$$

$$a_\mu^{\mathrm{exp}} = (116\,592\,089 \pm 63) \times 10^{-11}$$

3.3σ discrepancy

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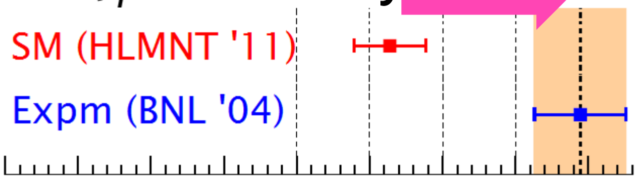
- $(g-2)_\mu$ anomaly

PUSH UP



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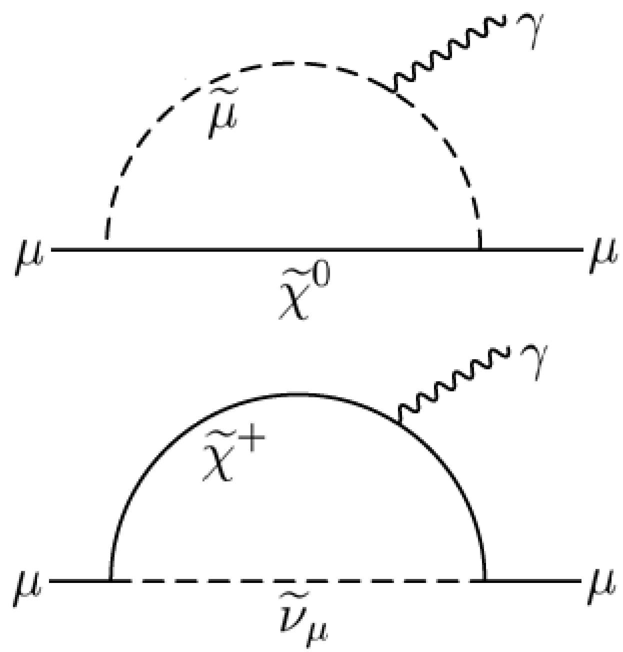
3.3σ discrepancy

MSSM: extra contribution → MSSM **may** explain this anomaly.



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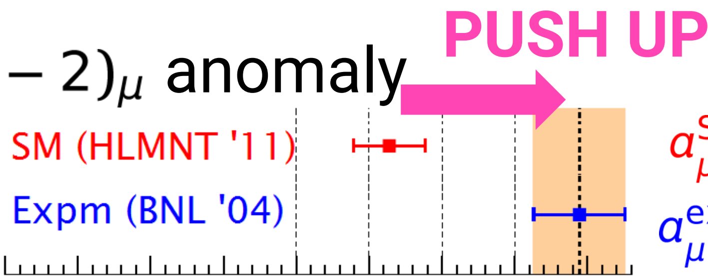

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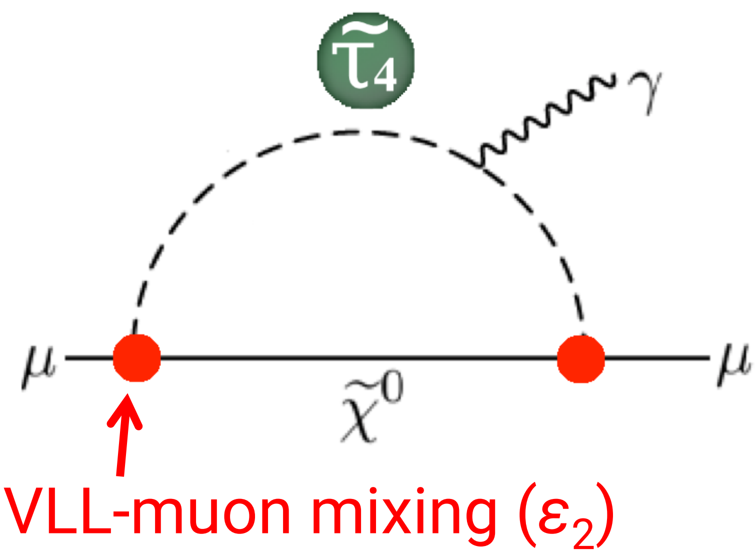
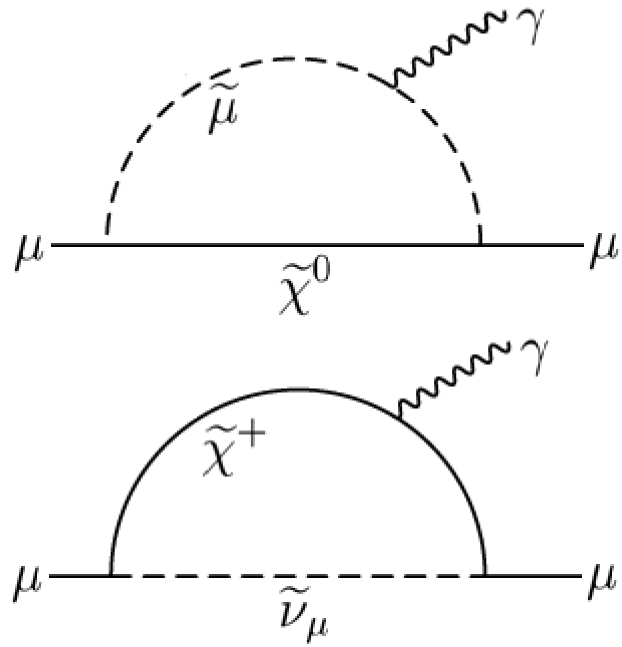
4G extra contribution?

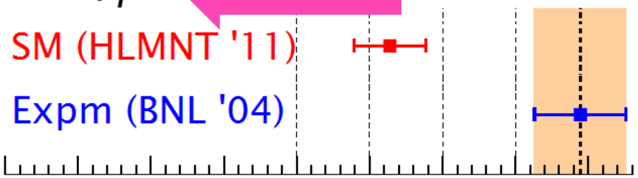




$$\left(a_\mu := \frac{g_\mu - 2}{2}\right)$$

- $(g-2)_\mu$ anomaly

PUSH DOWN



Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149]

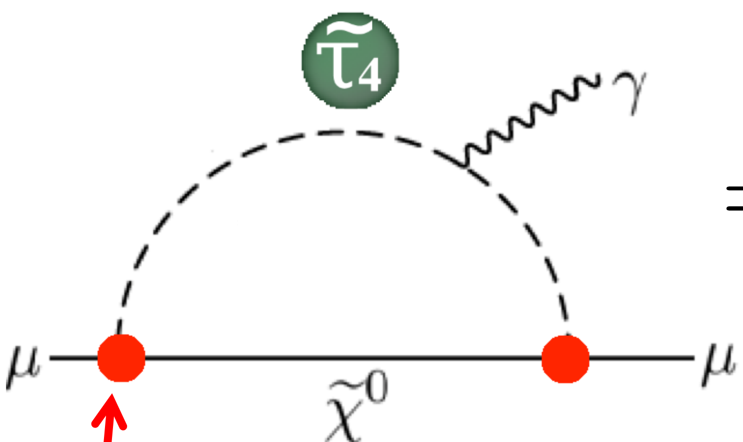
$$a_\mu^{\text{SM}} = (116\,591\,828 \pm 49) \times 10^{-11}$$

$$a_\mu^{\text{exp}} = (116\,592\,089 \pm 63) \times 10^{-11}$$

3.3σ discrepancy

MSSM: extra contribution → MSSM **may** explain this anomaly.

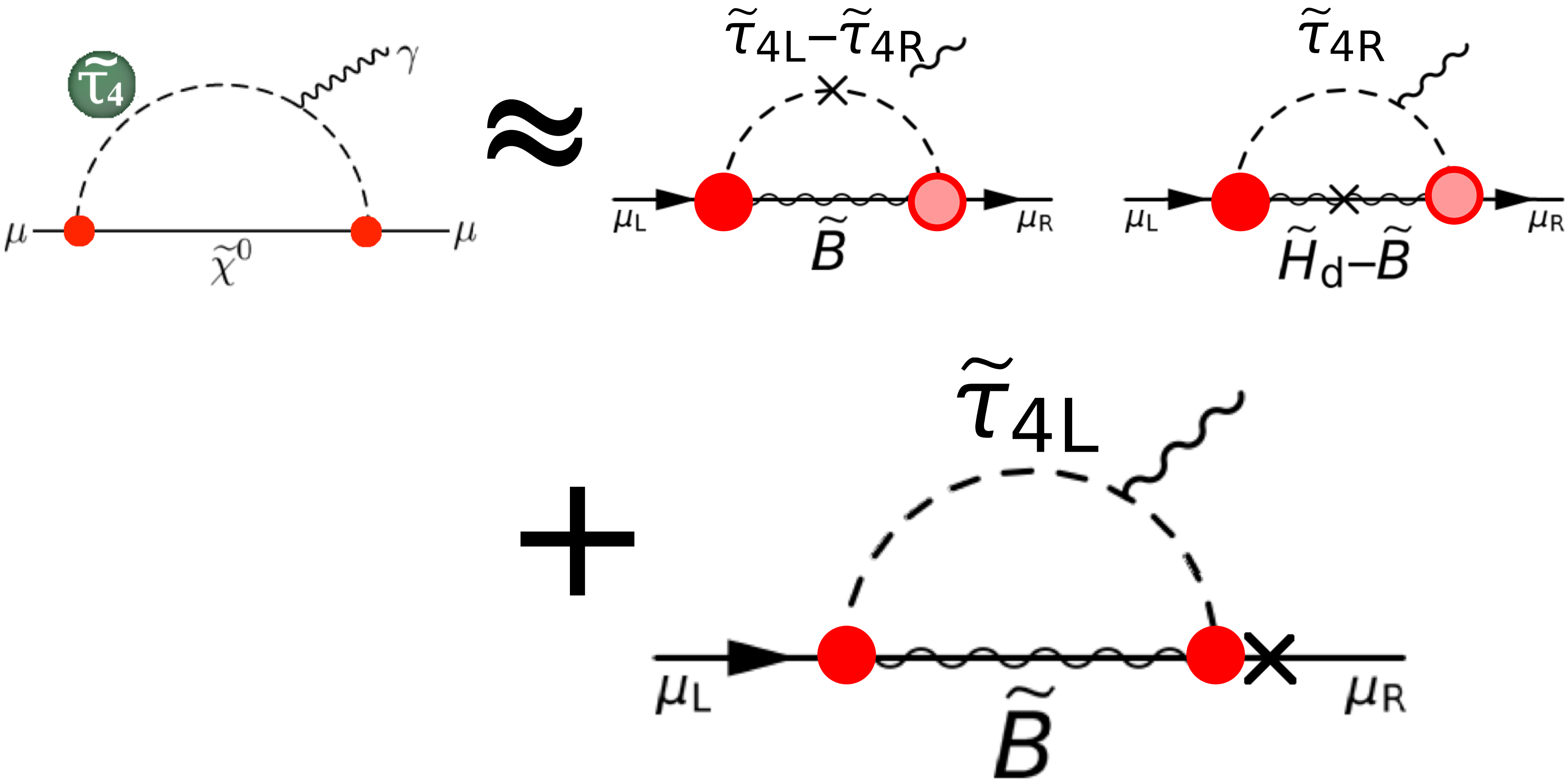
4G extra contribution?



$$= -|\epsilon_2|^2 \times (\text{loop func.})$$

VLL-muon mixing (ε_2)

- Why always negative?

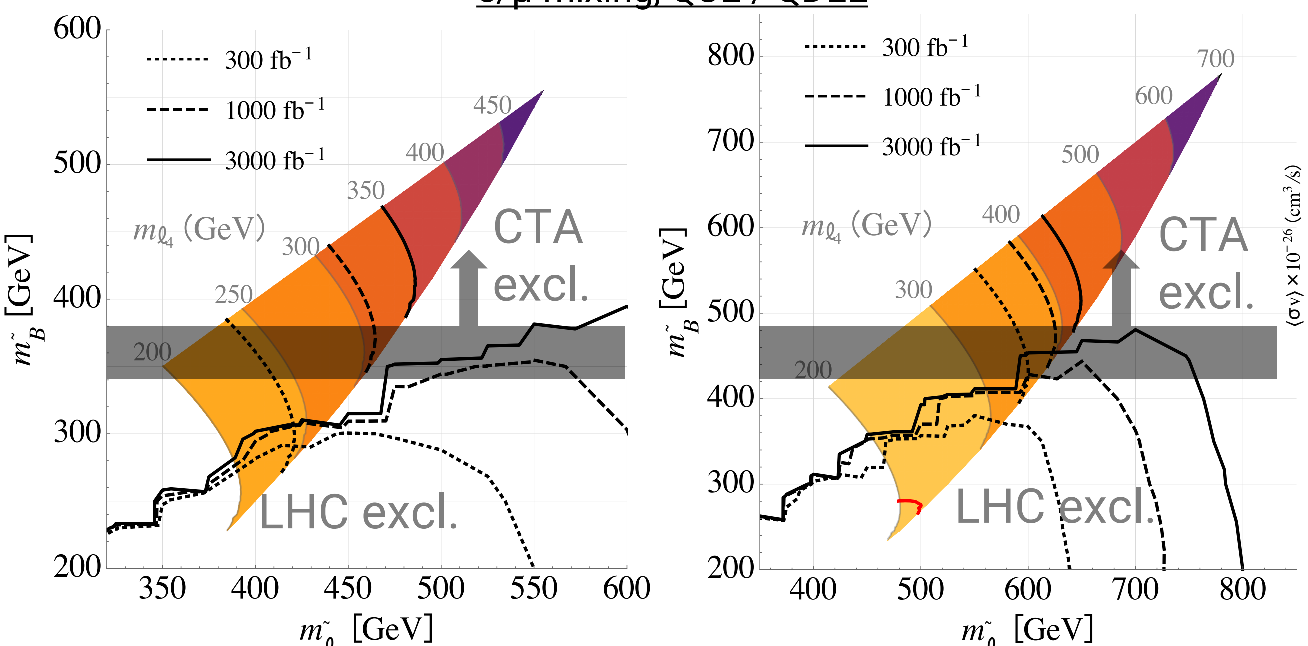


$$= -\frac{|\epsilon|^2}{16\pi^2}\frac{m_\mu^2}{6(|M_E|^2+m^2_{\tilde{E}^c})}N_1\left(\frac{\mu^2}{|M_E|^2+m^2_{\tilde{E}^c}}\right)$$

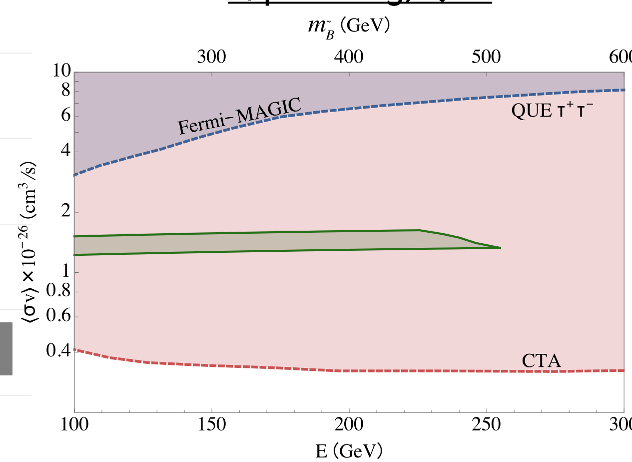
Summary : Future prospects

	e-mixing	μ-mixing	τ-mixing
CTA 500hr	covers $m_{\tilde{B}}$ > 340−380 GeV		**full coverage**
HL-LHC (slepton)	covers $m_{\tilde{B}}$ < 400 (480) GeV (but not “degenerate” region)		−
HL-LHC (lepton)	covers m_{τ_4} < 350 (430) GeV equivalent to $m_{\tilde{B}}$ < 380 (480) GeV		−

e/μ-mixing, QUE / QDEE

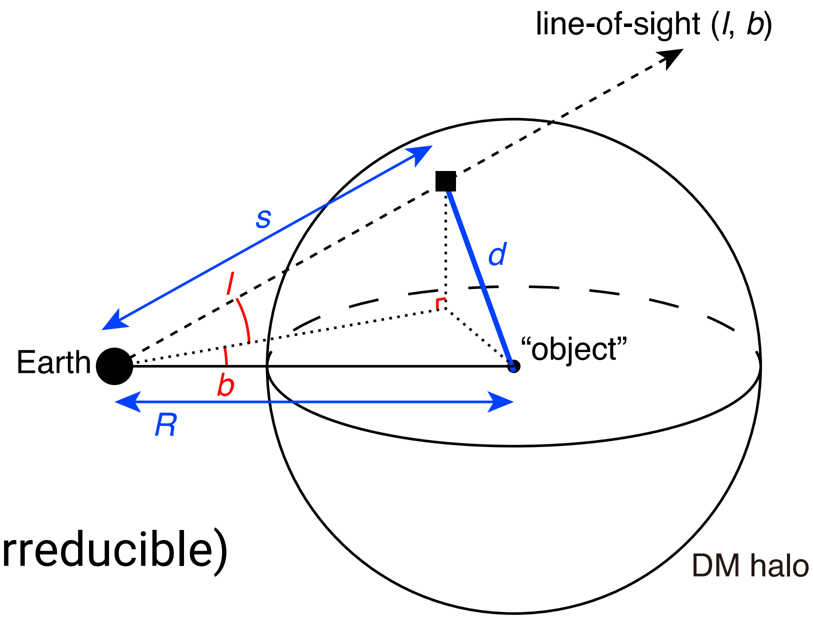


τ/μ-mixing, QUE



DM indirect detection Backup

- charged particles → diffusion
  - e : ~ 1 kpc are observable
  - P : ~ O(10) kpc ~ Milky Way
- neutral particles
  - from (neighbor of) galactic center
    - larger density, huge BKG (miss-ID & irreducible)
    - J ~ 10^{22} GeV^2/cm^5 (NFW; cuspy)
  - from dwarf spheroidals (mini-galaxies near MW)
    - DM rich, less baryon → low BKG
    - J < 10^{19-20} GeV^2/cm^5 (smaller profile dependence)



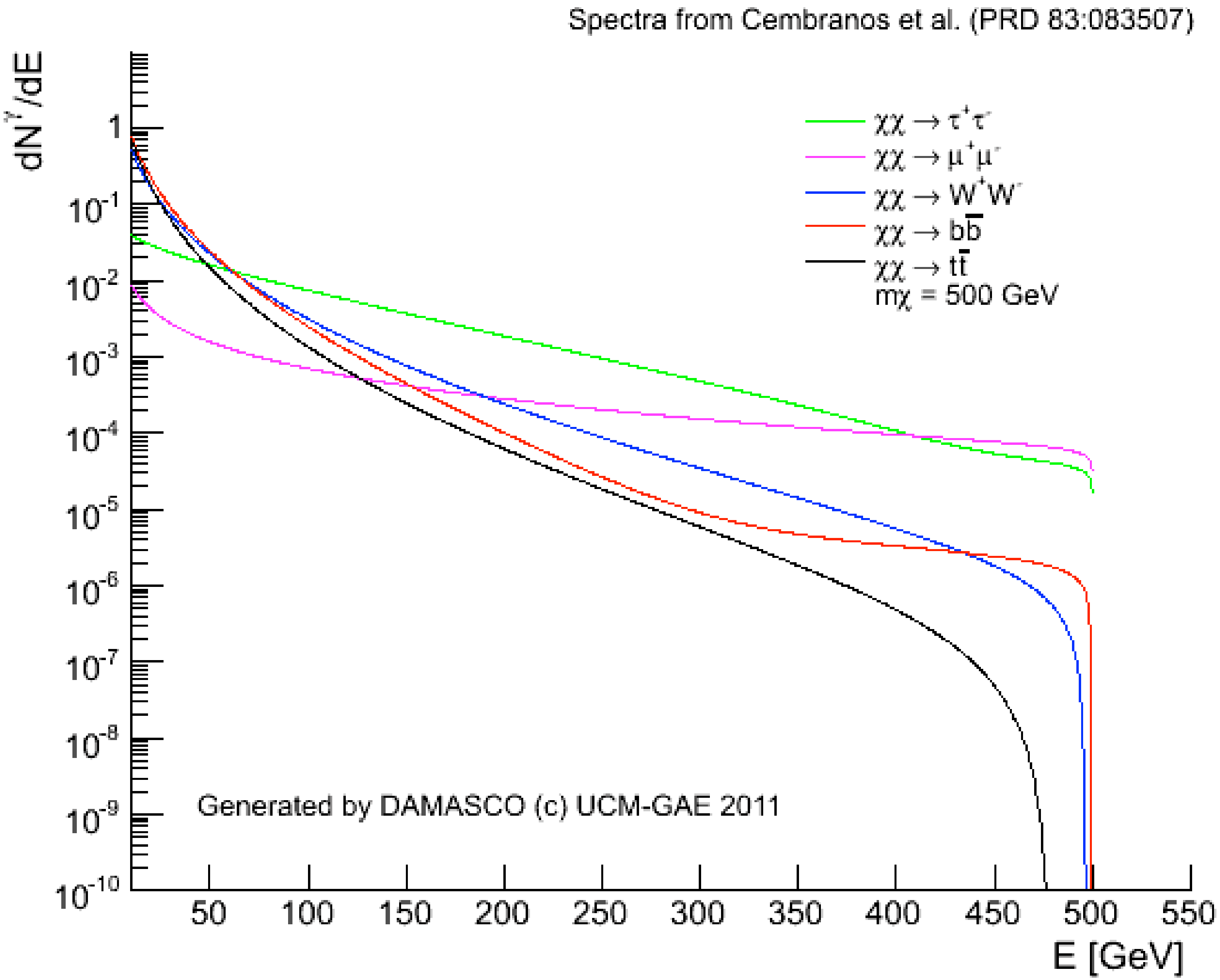
$$J = \int \mathrm{d}\Omega_{l,b} \int_0^\infty \mathrm{d}s\, \rho(d)^2$$

$$\left(d^2 = s^2 + R^2 - 2Rs \cos b \cos l\right)$$

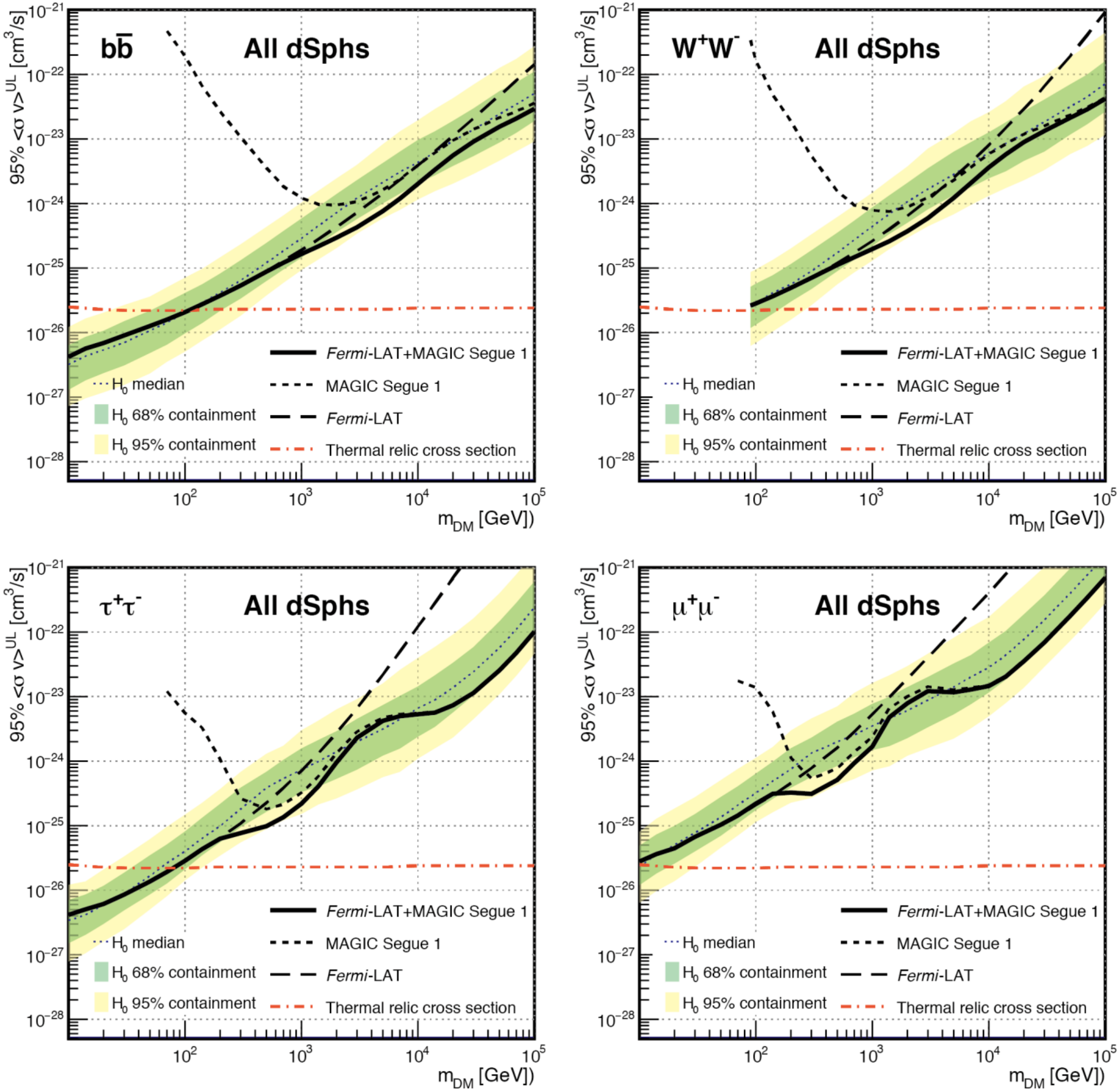
- < 100 GeV : satellites
  - full-sky, ~1m^2, 5–10% energy resolution
  - Fermi-LAT (2008) : gamma-ray to electron conversion

- > 100 GeV : ground-based Air Cherenkov Telescopes
  - several degree, 10^{5-6} m^{2,} ~20% energy resolution
  - VERITAS : 4x12m telescopes, Crab 36σ/√hr = 1%Crab in 35h
  - MAGIC : 2x17m telescope, 19σ/√hr = 2.2%Crab in 50h
  - HESS : 4x12m + 28m telescopes, 43σ/√hr

- > 10 TeV : ground-based Water Cherenkov
  - HAWC : 2/3-sky, effective area similar to ACT but worse resolution


Spectra from Cembranos et al. (PRD 83:083507)
dN^γ/dE
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
χχ → τ⁺τ⁻
χχ → μ⁺μ⁻
χχ → W⁺W⁻
χχ → bb̄
χχ → tt̄
mχ = 500 GeV
Generated by DAMASCO (c) UCM-GAE 2011
50
100
150
200
250
300
350
400
450
500
550
E [GeV]

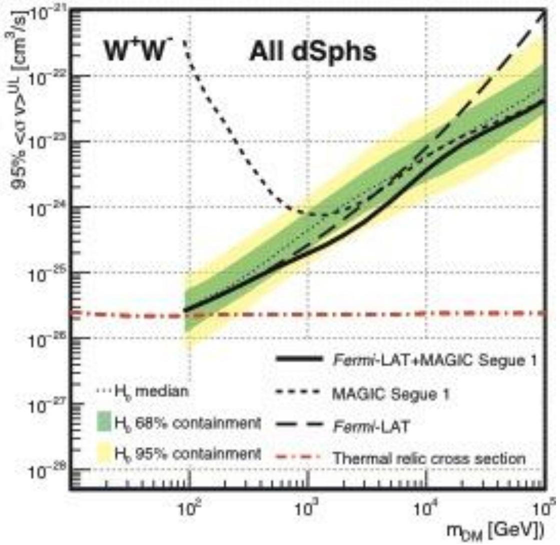
Ahnen et al. [1601.06590]

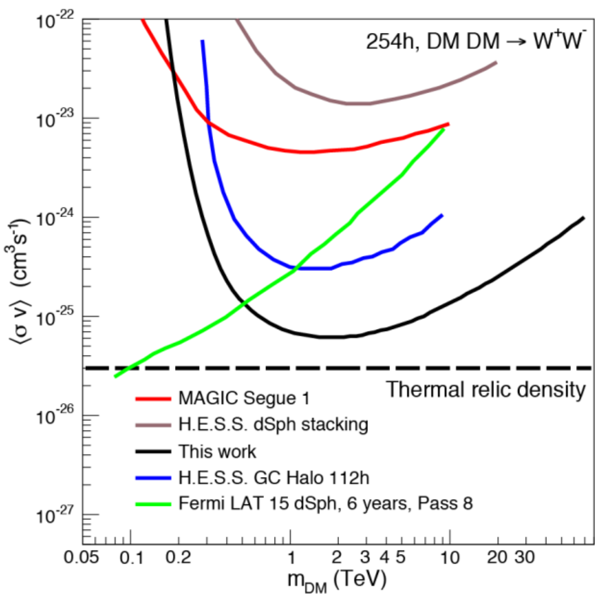


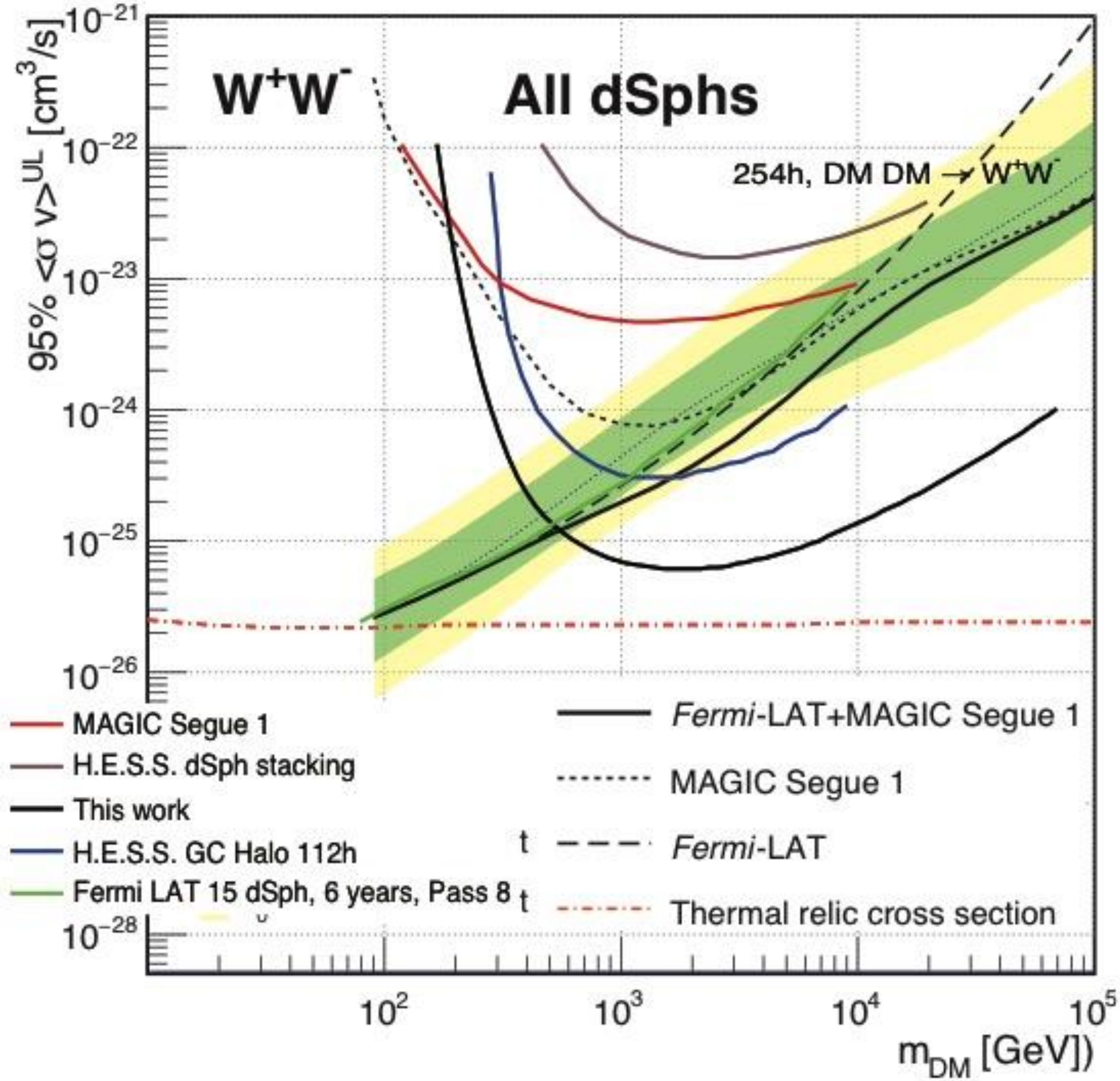
MAGIC:
158 hr of Segue 1

Fermi-LAT:
6 yr of 15 dSph
(incl. Segue 1)

DM profile: NFW







HESS assumes Einasto profile; for NFW weaker by factor ~2.

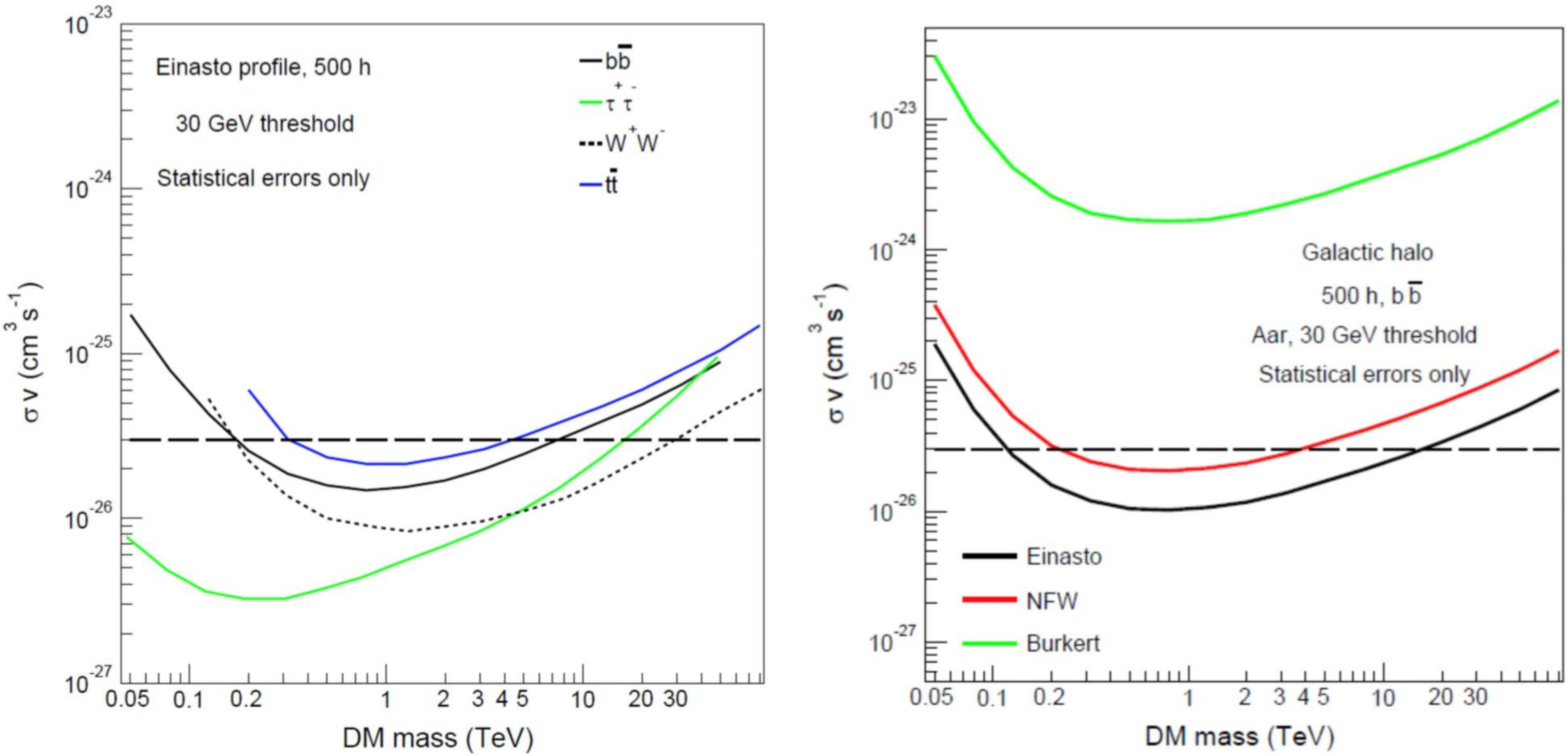


Figure1. Left: Sensitivity for σ v from observation on the Galactic Halo with Einsasto dark matter profile and for different annihilation modes as indicated. **Right**: for cuspy (NFW, Einasto) and cored (Burkert) dark matter halo profiles. For both plots only statistical errors are taken into account. The dashed horizontal lines indicate the level of the thermal cross-section of 3×10^{-26} cm^3 s^{-1}.