MSSM4G scenario and vectorlike lepton @ LHC

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

chiral: $\mathcal{L} \ni y\langle H\rangle \bar{\psi}_{\mathrm{R}}\psi_{\mathrm{L}}$
vector-like: $\mathcal{L} \ni m\bar{\psi}_{\mathrm{R}}\psi_{\mathrm{L}}$

- Chiral q_4 ... disfavored by $\sigma(gg \to h)$
- Vectorlike q_4
  - Motivated by MSSM Higgs mass enhancement
  - Searched for at the LHC: $pp \to q_4\bar{q}_4 \to 2q + 2$ bosons
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- Vectorlike e_4
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  - Search-able at the (HL-)LHC

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■ SUSY = solution to Naturalness

old-days expectation :

Papucci, Ruderman, Weiler [1110.6926]

$$|\mu| \lesssim 200\,\mathrm{GeV}\left(\frac{\Delta^{-1}}{20\,\%}\right)^{-1/2}$$

$$\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2} \lesssim 600\,\mathrm{GeV}\frac{\sin\beta}{\sqrt{1+\alpha^2}}\left(\frac{\log(\Lambda/\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{\Delta^{-1}}{20\,\%}\right)^{-1/2}$$

$$m_{\tilde{g}} \lesssim 900\,\mathrm{GeV}\cdot\sin\beta\left(\frac{\log(\Lambda/\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{\Delta^{-1}}{20\,\%}\right)^{-1/2}$$

difficulties:

- LHC bounds
- radiative Higgs mass

Δ : “naturalness”

$\alpha = A_t/m_{\tilde{t}}$ (stop mixing parameter)

Λ : SUSY-breaking scale

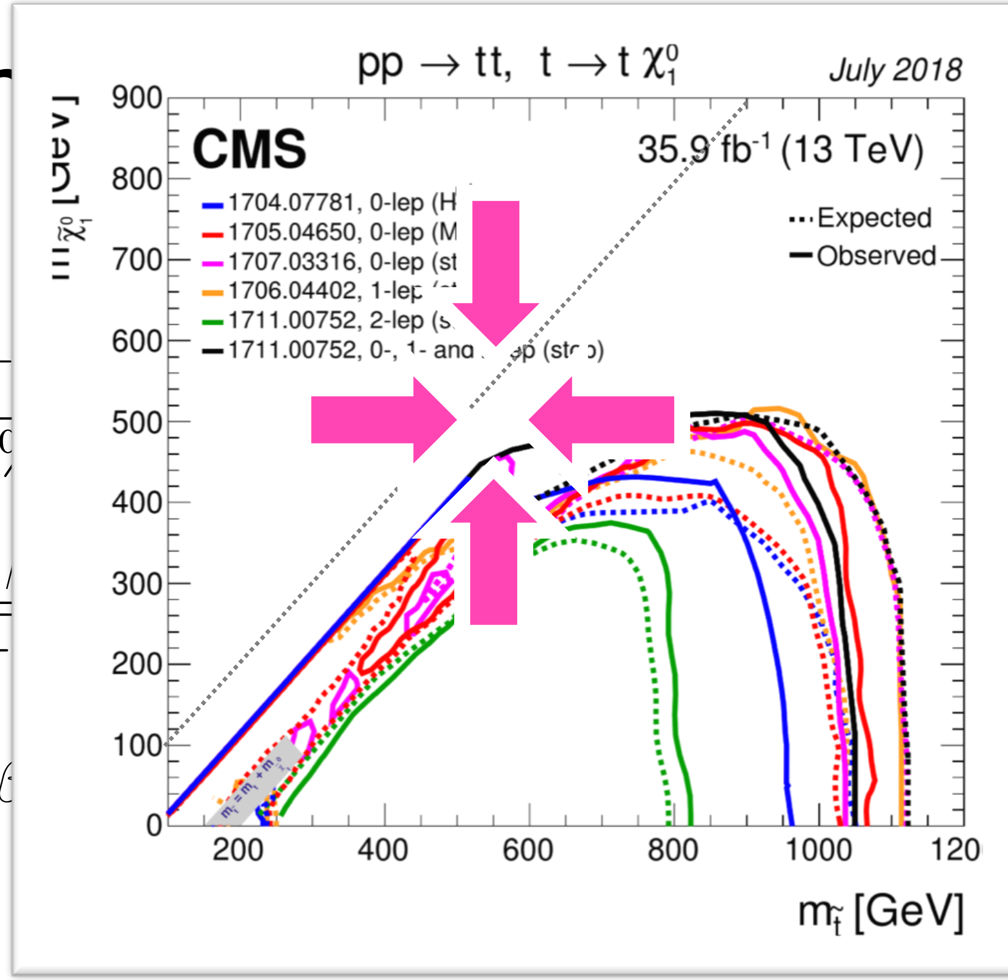
■ SUSY = solution

old-days expectation :

$$|\mu| \lesssim 200\,\mathrm{GeV}\left(\frac{\Delta^{-}}{20\,\%}\right.$$

$$\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2} \lesssim 600\,\mathrm{GeV}\,\frac{\sin}{\sqrt{1+}}$$

$$m_{\tilde{g}} \lesssim 900\,\mathrm{GeV}\cdot\sin$$



difficulties:

- LHC bounds ..."avoidable"
- radiative Higgs mass

Δ : “naturalness”

$a = A_t/m_{\tilde{t}}$ (stop mixing parameter)

Λ : SUSY-breaking scale

- MSSM prediction

$$m_h^2 \approx m_Z^2 \cos^2(2\beta) + \frac{3y_t^2 \sin^2\beta}{4\pi^2} m_t^2 \left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \alpha^2\left(1 - \frac{\alpha^2}{12}\right)\right]$$

$(125\text{GeV})^2$ $(91\text{GeV})^2$

SUSY-breaking effect from $W \ni y_t H_u q_3 \bar{u}_3$

$$\Longrightarrow m_{\tilde{t}} \gtrsim 1\,\text{TeV}$$

cf. Hall, Pinner, Ruderman [1112.2703] etc.

- To relax this constraint
  - add a scalar particle ("NMSSM")
  - add "another top" ... MSSM + vectorlike quark

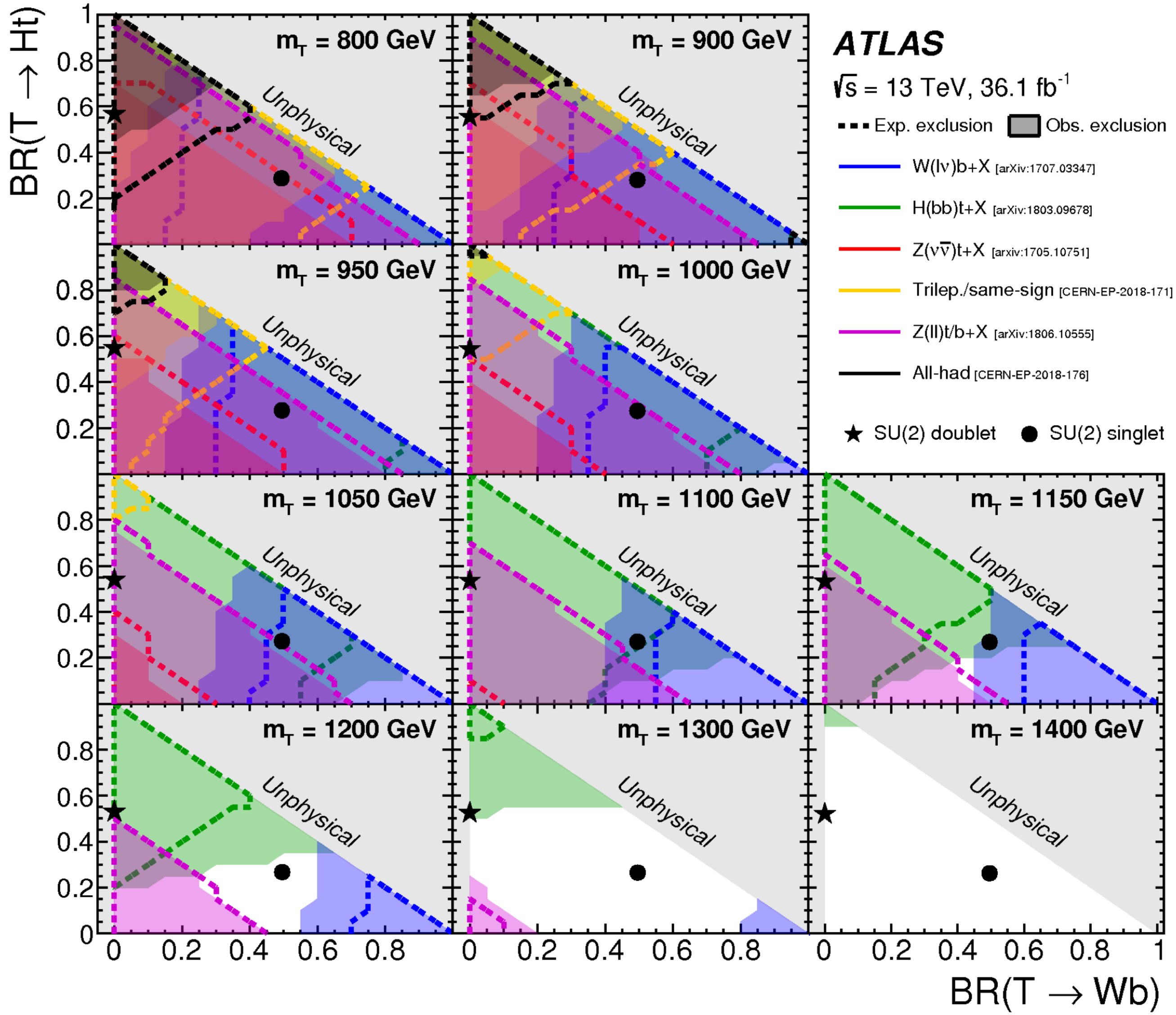
e.g. MSSM + q_4 + $\bar{u}_4$ + $\bar{q}_4$ + u_4:

$$W_{\text{VLQ}} = y' H_u q_4 \bar{u}_4 + M_{q_4} q_4 \bar{q}_4 + M_{u_4} u_4 \bar{u}_4$$

vectorlike mass terms

assuming $T \to Wb$ or Ht or Zt,

$m_T < 1100\,\mathrm{GeV}$ is excluded for any decay patterns (BRs).



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e.g. MSSM $+ q_4 + \bar{u}_4 + \bar{q}_4 + u_4$: GUT compatibility?

$W_{\text{VLQ}} = y' H_u q_4 \bar{u}_4 + M_{q_4} q_4$ ...

$5 = q + \bar{u} + \bar{e}$ in SU(5)-GUT

- MSSM4G scenario
  = use this e_4 to solve "bino overabuncance"

Abdullah, Feng [1510.06089]

If dark matter is $\tilde{\chi}^0$ and it is pure-Bino $\tilde{B}$,
it would give larger DM density than observed.

$\tilde{\chi}^0$: lightest neutralino

$$\tilde{\chi}^0 = \tilde{B} \oplus \widetilde{W}^0 \oplus \tilde{H}_d^0 \oplus \tilde{H}_u^0$$

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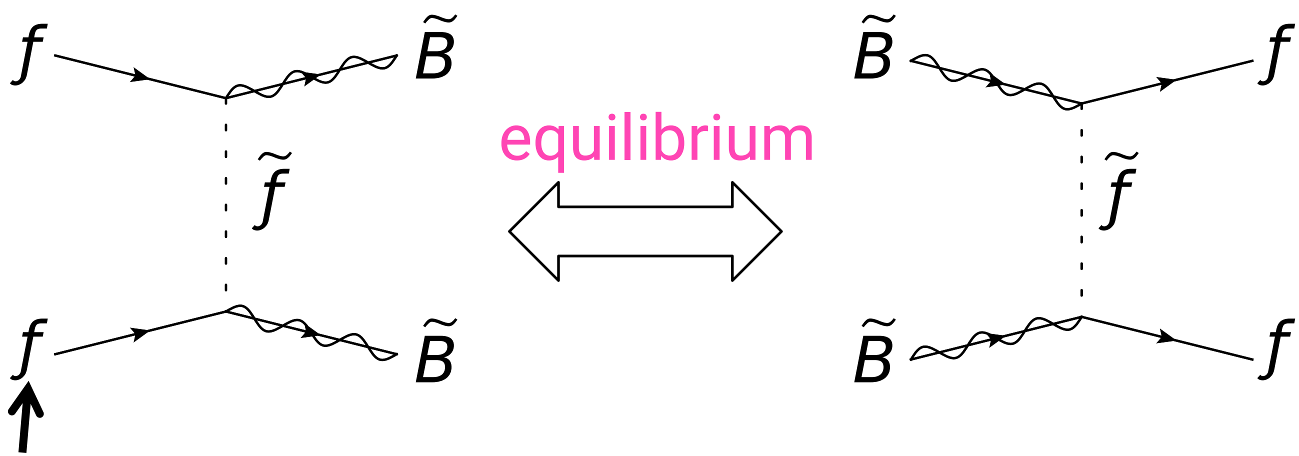
1) In early Universe with $T > m_{\tilde{B}}$ → DM "equilibrium"

pair creation ($f\bar{f} \to \tilde{B}\tilde{B}$) pair annihilation ($\tilde{B}\tilde{B} \to f\bar{f}$)



kinetic energy ~ T (> $m_{\tilde{B}}$)

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2) In early Universe after $T < m_{\tilde{B}}$ → DM decreases

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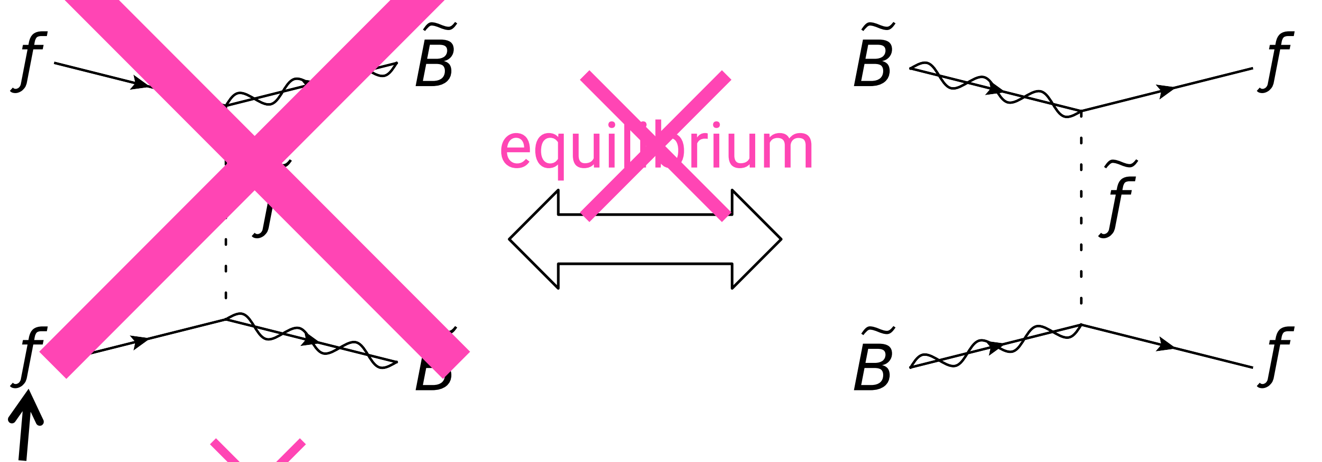

kinetic energy ~ T (~~> $m_{\tilde{B}}$~~)

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3) after $T < m_{\tilde{B}}/20$ → DM **frozen-out**

pair annihilation ($\tilde{B}\tilde{B} \to f\bar{f}$)

far apart due to

- pair annihilation
- Universe's expansion

- MSSM4G scenario
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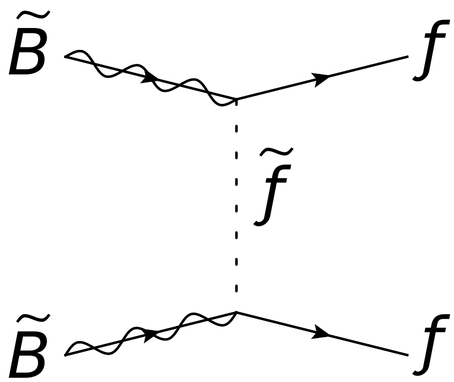


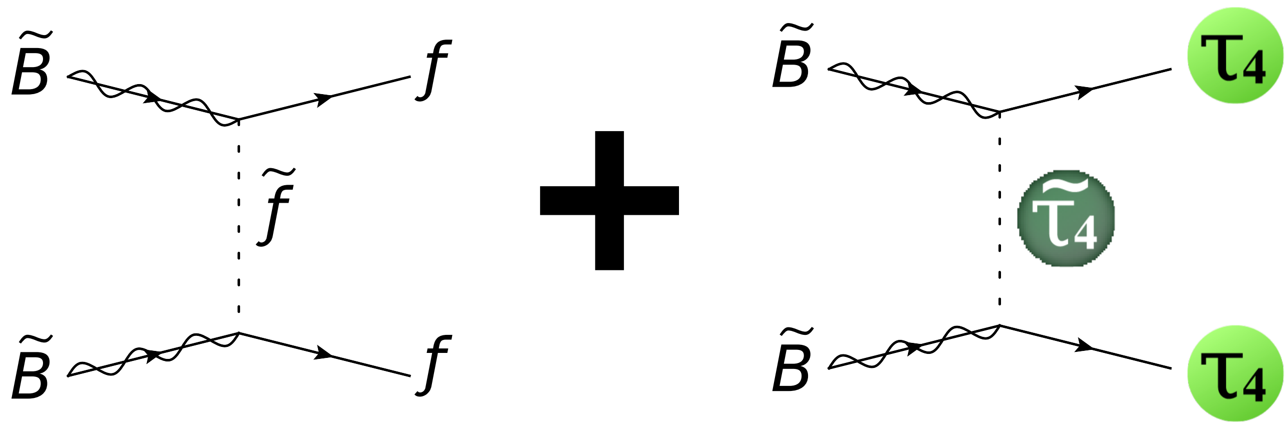
$\tilde{B}$: smaller cross section
→ **"overabundant problem"**
of Bino thermal relic DM

- MSSM4G scenario

  Abdullah, Feng [1510.06089]

  = use this e_4 to solve "bino overabuncance"

  ↳ τ_4 $\tilde{\tau}_4$



extra annihilation channel

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

→ abundance reduced

$$\langle \sigma v \rangle = \frac{g_Y^4 Y_L^2 Y_R^2}{2\pi} \frac{m_f^2}{m_{\tilde{B}}} \frac{\sqrt{m_{\tilde{B}}^2 - m_f^2}}{\left(m_{\tilde{B}}^2 + m_{\tilde{f}}^2 - m_f^2\right)^2}$$

$Q : (\mathbf{3}, \mathbf{2}, \ \ 1/6)$	$\bar{Q} : (\bar{\mathbf{3}}, \mathbf{2}, -1/6)$
$\bar{U} : (\bar{\mathbf{3}}, 1, -2/3)$	$U : (\mathbf{3}, 1, \ \ 2/3)$
$\bar{D} : (\bar{\mathbf{3}}, 1, \ \ 1/3)$	$D : (\mathbf{3}, 1, -1/3)$
$\bar{E} : (1, 1, \ \ 1)$	$E : (1, 1, -1)$
(same as SM)	(vectorlike partners)

- MSSM4G scenario
  = use this e_4 to solve "bino ov

- 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

- **MSSM4G scenario**

  = use this e_4 to solve "bino ov

(same as SM)	(vectorlike partners)
$Q : (\mathbf{3}, \mathbf{2}, \quad 1/6)$	$\bar{Q} : (\bar{\mathbf{3}}, \mathbf{2}, -1/6)$
$\bar{U} : (\bar{\mathbf{3}}, 1, -2/3)$	$U : (\mathbf{3}, 1, \quad 2/3)$
$\bar{D} : (\bar{\mathbf{3}}, 1, \quad 1/3)$	$D : (\mathbf{3}, 1, -1/3)$
$\bar{E} : (1, 1, \quad 1)$	$E : (1, 1, -1)$

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

  ✓ gauge coupling unification

  ✓ SU(5) GUT

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vectorlike mass terms

$$W_{\rm QUE} = y' H_{\rm u} Q_4 \bar{U}_4 - y'' H_{\rm d} \bar{Q}_4 U_4 + \overbrace{M_Q Q_4 \bar{Q}_4 + M_U U_4 \bar{U}_4 + M_E E_4 \bar{E}_4}^{\text{vectorlike mass terms}}$$

$$+ \underbrace{\epsilon_i H_{\rm u} Q_i \bar{U}_4 + \epsilon'_i H_{\rm u} Q_4 \bar{U}_i - \epsilon''_i H_{\rm d} L_i \bar{E}_4}_{\text{SM–Vectorlike mixings}}$$

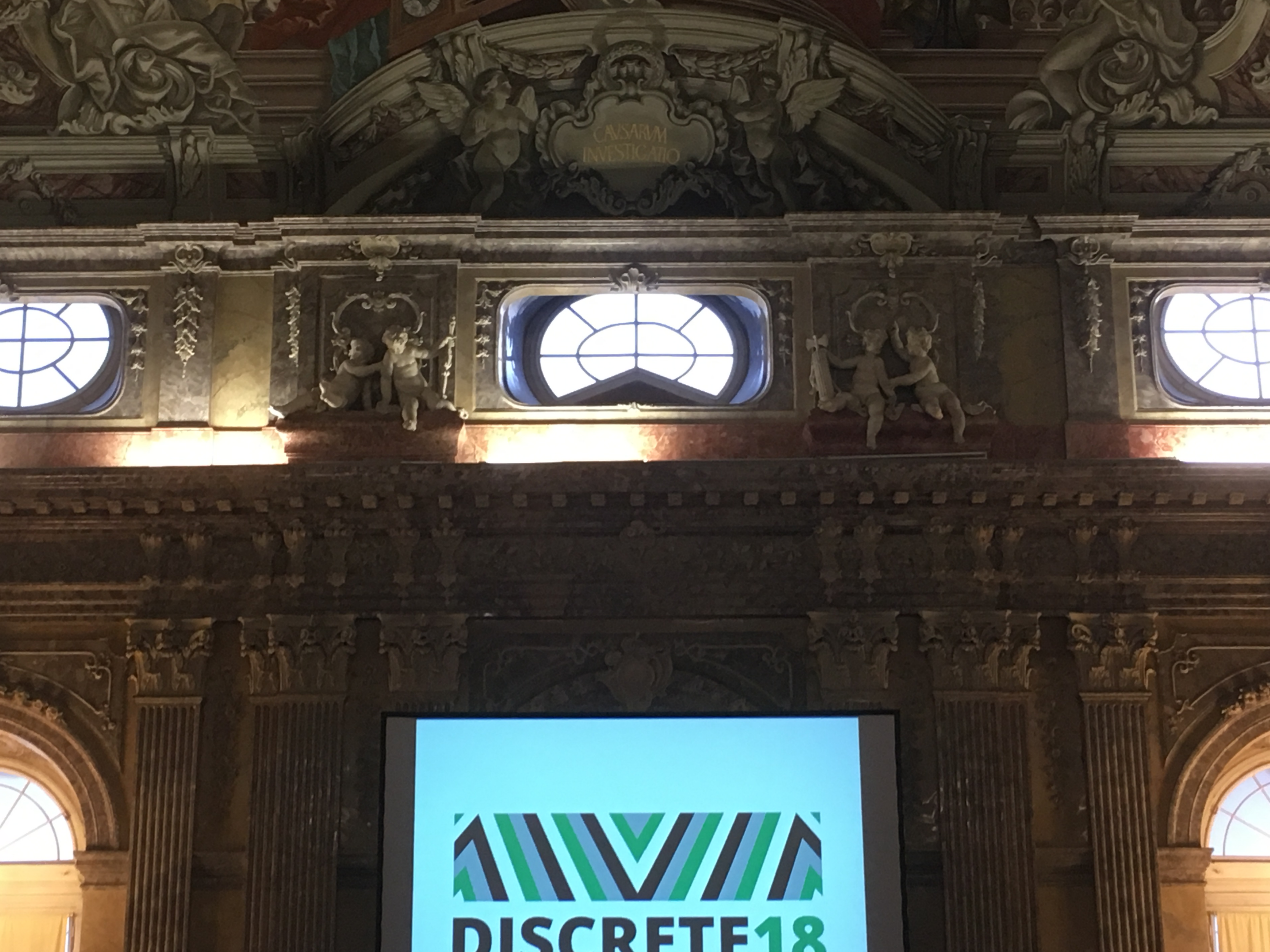
SM−Vectorlike mixings

- **dangerous** : induce flavor violations
- **necessary** : let VLF decay

... we need an approximate

DISCRETE Z_2

(SM: even, VLF: odd)


CAVSARVM
INVESTIGATIO
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$Q:(\mathbf{3},\mathbf{2},\ \ 1/6)$	$\bar{Q}:(\bar{\mathbf{3}},\mathbf{2},-1/6)$
$\bar{U}:(\bar{\mathbf{3}},1,-2/3)$	$U:(\mathbf{3},1,\ \ 2/3)$
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- MSSM4G scenario
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- QUE model : MSSM + $Q\bar{Q}U\bar{U}E\bar{E}$

$$W_{\rm QDEE} = y' H_{\rm u}\bar{Q}_4 D_4 - y'' H_{\rm d} Q_4 \bar{D}_4 \ + \ M_Q Q_4 \bar{Q}_4 + M_D D_4 \bar{D}_4 + M_E E_4 \bar{E}_4 + M'_E E_5 \bar{E}_5$$

$$- \epsilon_i H_{\rm d} Q_i \bar{D}_4 - \epsilon'_i H_{\rm d} Q_4 \bar{D}_i - \epsilon''_i H_{\rm d} L_i \bar{E}_4 - \epsilon'''_i H_{\rm d} L_i \bar{E}_5$$

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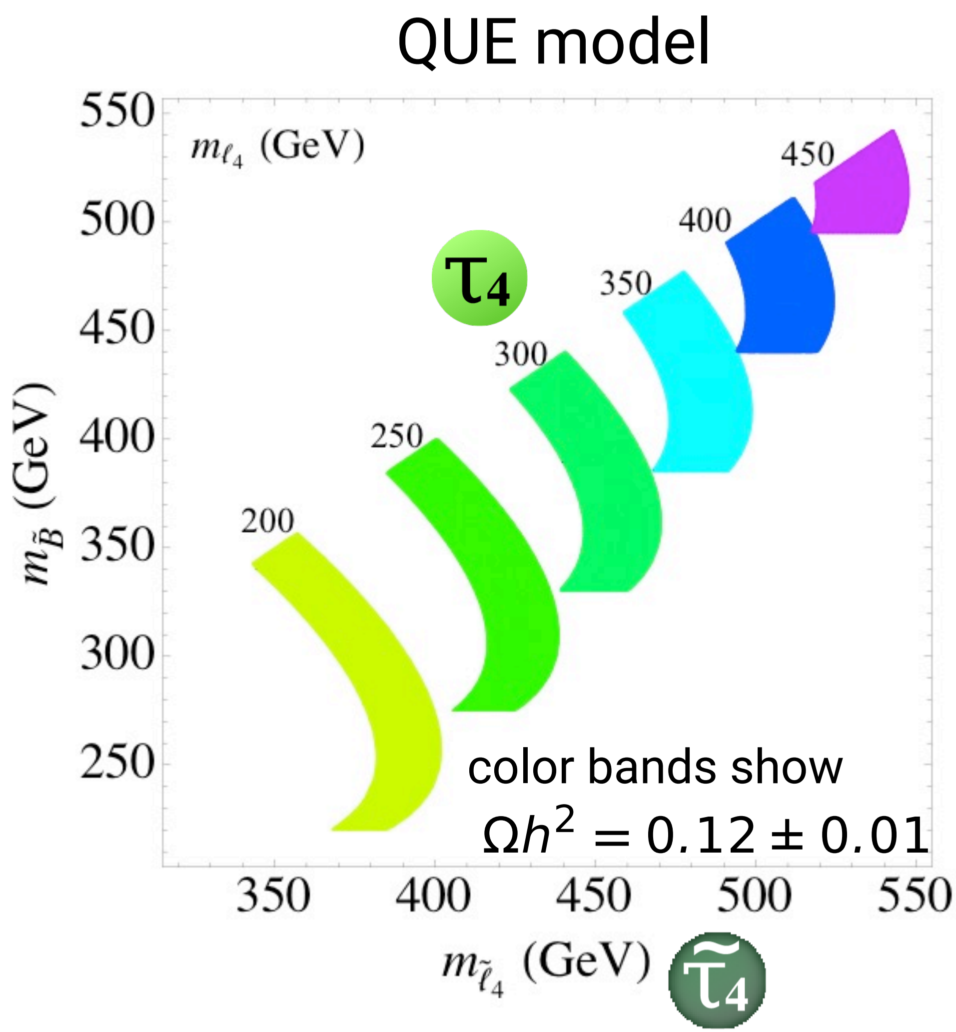
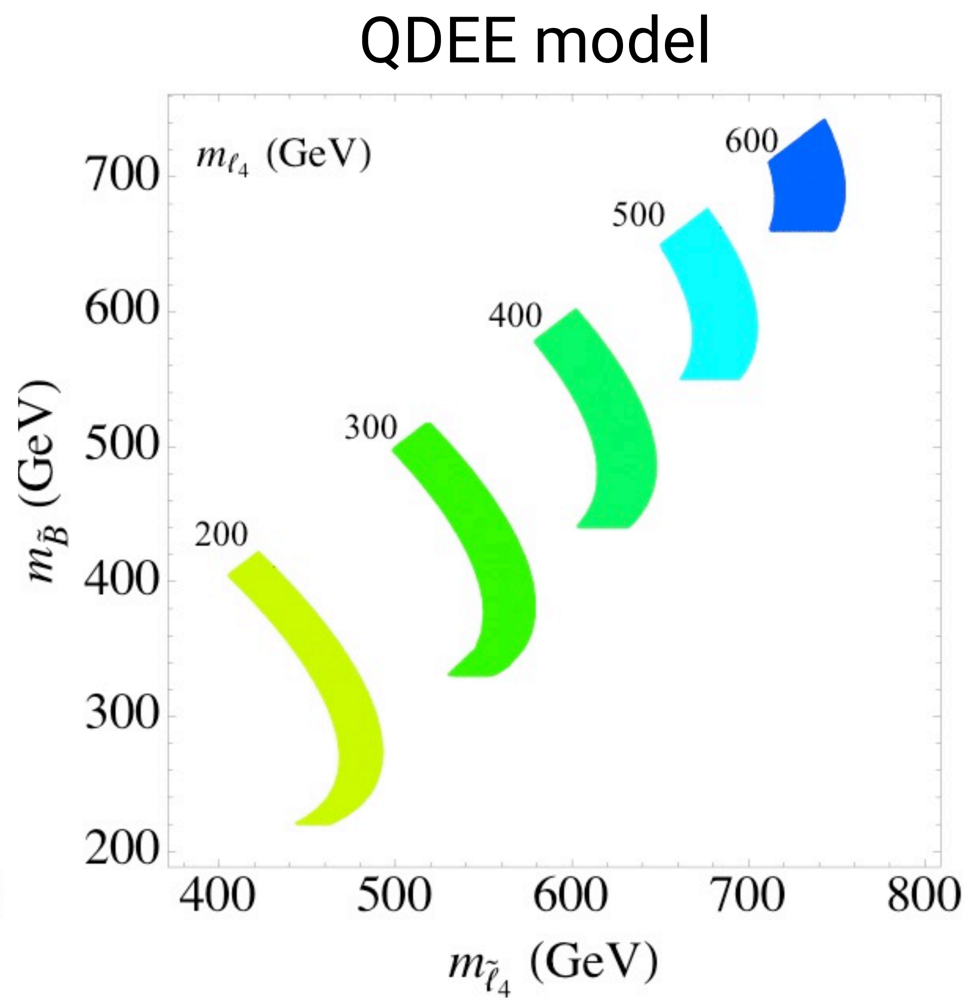
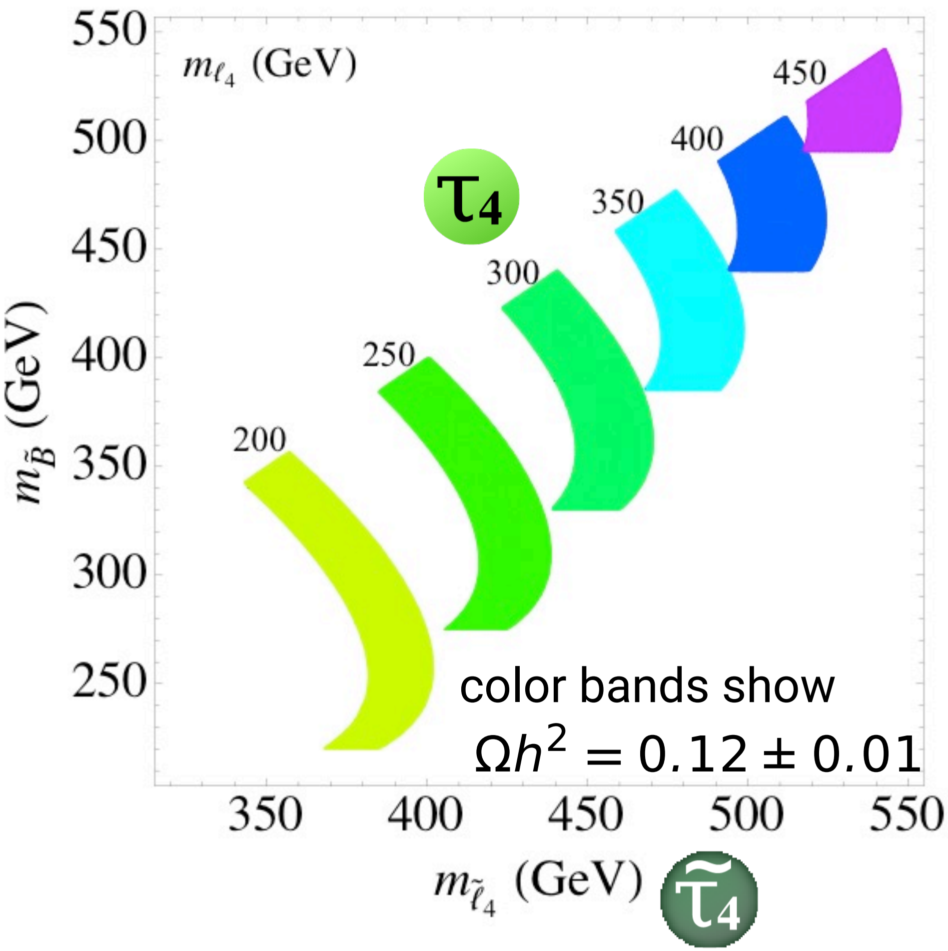




$\tilde{\tau}_4 \gtrsim \tilde{B} > \tau_4$

QUE model



- **LHC searches**
  - Searches for VL-slepton $\tilde{\tau}_4$
    → 2 lepton + mET search
  - Searches for VLL τ_4

- **Gamma-ray observation**
  - from τ-leptons coming from
    (DM)+(DM) → $\tau_4 \bar{\tau}_4$
    → $(Z\tau)(Z\bar{\tau})$

- **(DM direct detection)**
  - LZ, DARWIN, ...

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

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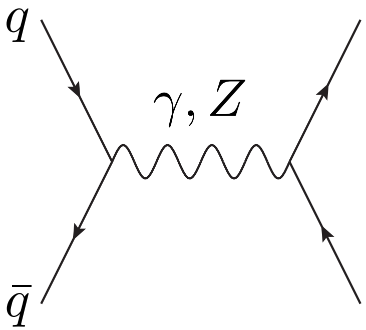
- Vector-like lepton τ_4
  - Lagrangian $\mathcal{L}_{\text{extra}} = \epsilon_i H L_i \bar{\tau}_4 + m \bar{\tau}_4 \tau_4 + (\text{kinetic})$
  - production & decay:

$$pp \to \tau_4 \bar{\tau}_4, \quad \tau_4 \to W^- \nu_i,\ Z\, l_i^-,\ h\, l_i^-$$

"Drell-Yan" production

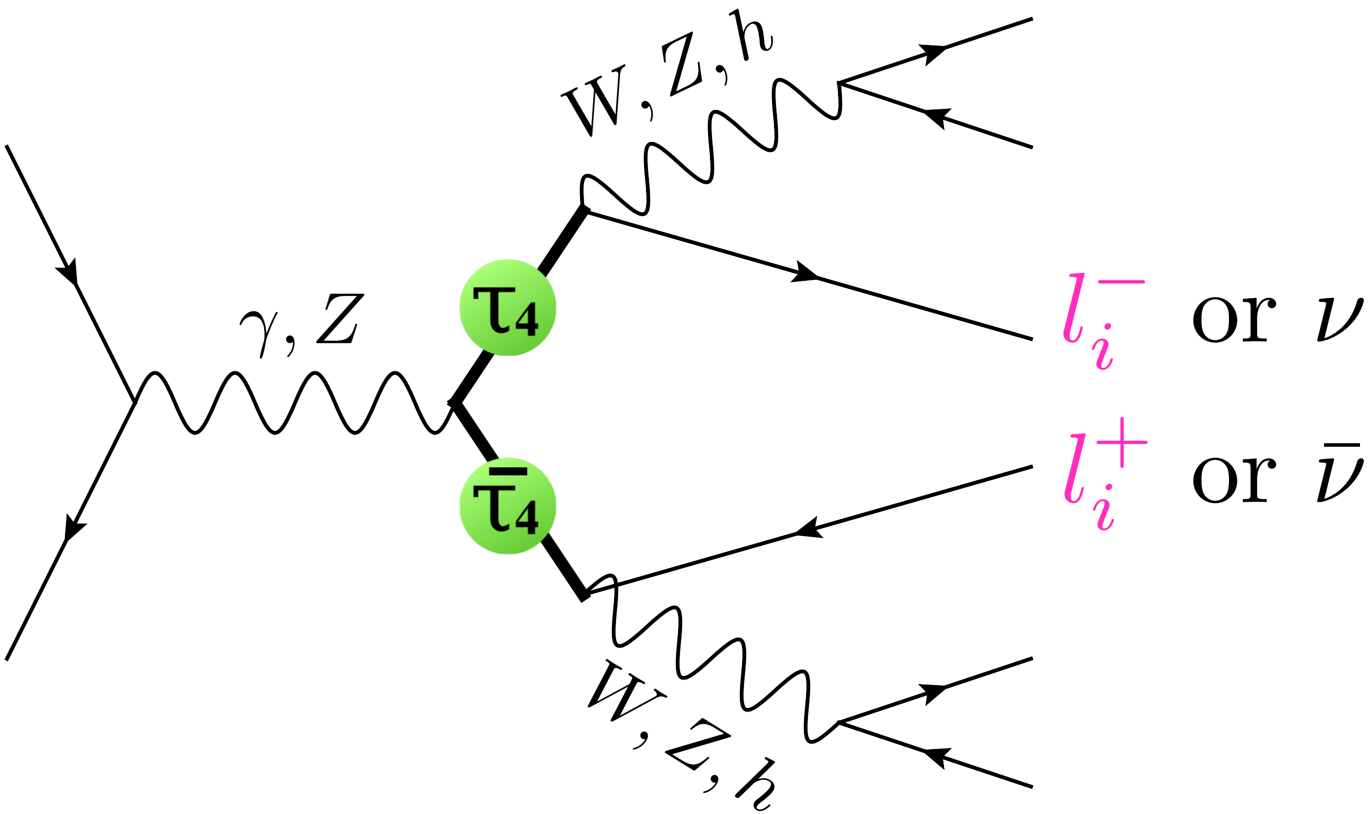
Decay through "SM-4G mixing"



- 3 benchmark scenarios assuming hierarchical ε_i
  (if not → flavor-violation constraints)
  - $\mathrm{Br}(\tau_4 \to e \text{ or } \nu_e) \approx 100\%$
  - $\mathrm{Br}(\tau_4 \to \mu \text{ or } \nu_\mu) \approx 100\%$
  - $\mathrm{Br}(\tau_4 \to \tau \text{ or } \nu_\tau) \approx 100\%$

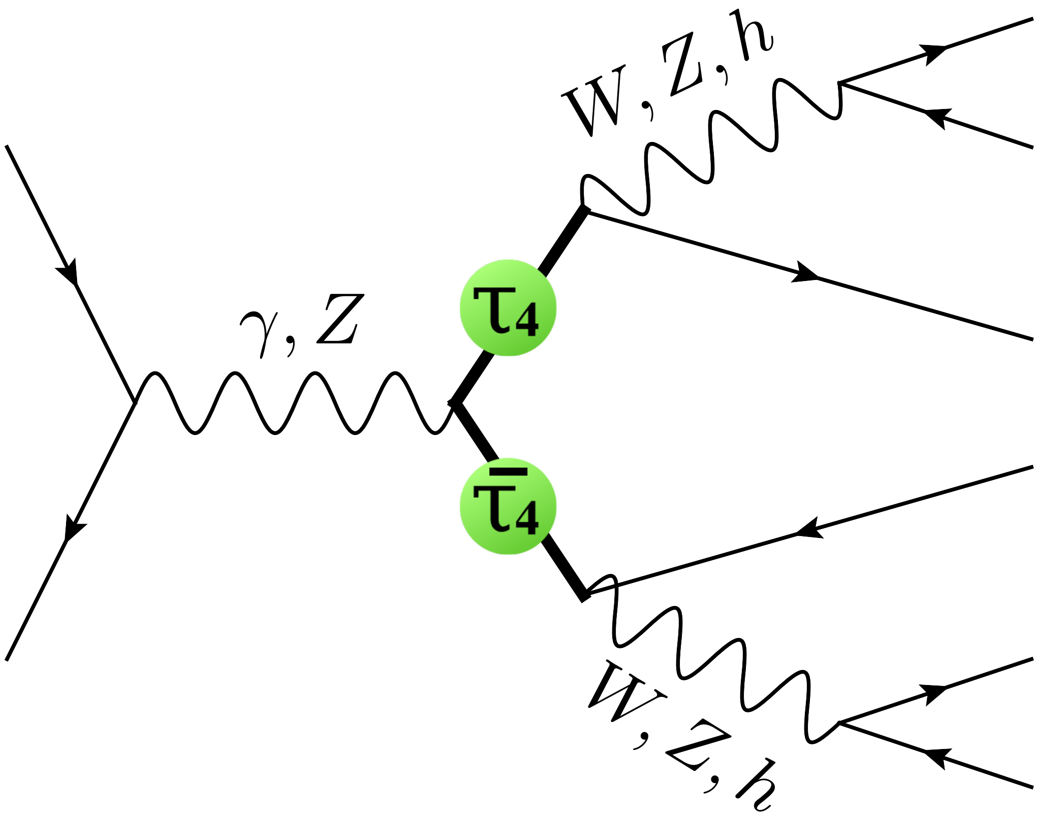
cf. $\mathrm{Br}(W) : \mathrm{Br}(Z) : \mathrm{Br}(h) \approx 2 : 1 : 1$

- Vector-like lepton : $pp \to \tau_4 \bar{\tau}_4$ $\tau_4 \longrightarrow Z\, l_i^-,\ W^- \nu_i,\ h\, l_i^-$



How do you capture this signature?

- Vector-like lepton : $pp \to \tau_4 \bar{\tau}_4$, $\tau_4 \longrightarrow Z\, l_i^-,\ W^-\nu_i,\ h\, l_i^-$



$3l$	$4l$		$6l$
Z (l^+l^-)	Z (l^+l^-)	Z (l^+l^-)	Z (l^+l^-)
l^-	l^-	l^-	l^-
$\bar{\nu}$	$\bar{\nu}$	l^+	l^+
W (jj)	W $(l^+\nu)$	Z (jj)	Z (l^+l^-)

- Vector-like lepton : $pp \to \tau_4 \bar{\tau}_4$, $\tau_4 \longrightarrow Z\, l_i^-,\ W^- \nu_i,\ h\, l_i^-$
  - Our "most basic" approach: **multi-$\ell^\pm$ (3−5$\ell^\pm$) search**

→ HL-LHC may exclude m_{τ_4} < 350 GeV **if VLL decays to e or *μ*.** (= "mixes with")

details for experts

	$WZ(j)$	$WZ(\ell)$	$ZZ(j)$	$ZZ(\ell)$	
N_ℓ	≥ 3	≥ 4	≥ 4	≥ 5	
N_j	≥ 2	< 2	≥ 2	—	
$\lvert m_{jj} - m_W \rvert$	< 20 GeV	—	—	—	←*W*/*Z*-like jet pair
$\lvert m_{jj} - m_Z \rvert$	—	—	< 40 GeV	—	
$\not{E}_T$	> 60 GeV	> 100 GeV	—	—	←Large mET from *ν*&*W*
$N_{Z(\ell\ell)}$	—	—	≥ 1	≥ 1	←Z-like lepton pair

- Snowmass BKG set is used.
  - MG5−Pythia−Delphes + NLO *K*-factor
  - di-boson + *tt* dominated
- Signal by FR−MG5aMC−Pythia−Delphes (LO)
- PT cut: $(\ell_1, \ell_2, \ell_i) > (120, 60, 20)$ GeV, $(j) > 20$ GeV.
- **tau-tag / b-tag not used (avoided)**
- Uncertainties = stat. + 20% syst.

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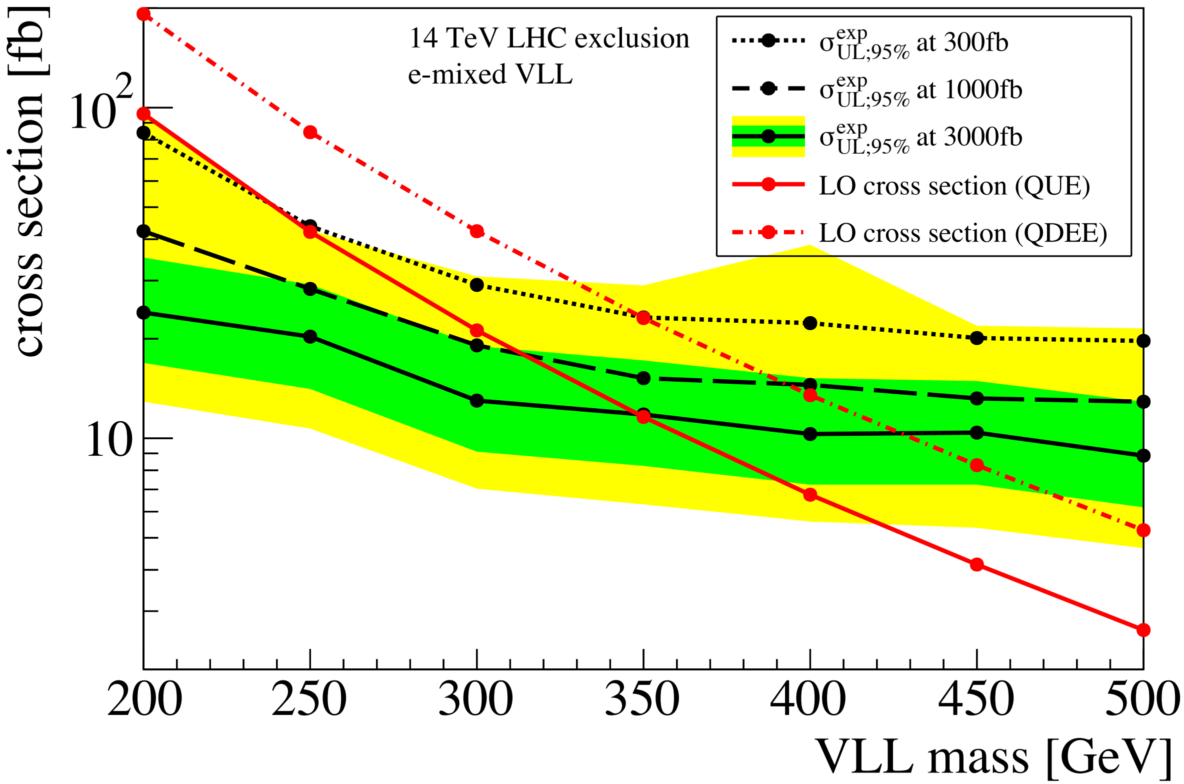

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if VLL decays to e or *μ*.
(= "mixes with")

- Possible (by expm. physicists) improvements
  - **This bound is for "right-handed" VLL.**
    → stronger bound expected for left-handed VLL.
  - Use τ-tagging to capture VLL mixed with τ.
  - Use Higgs-tagging to capture VLL decays to *h*.

Vectorlike q_4

- m_h (MSSM) 

; excluded up to 1.1TeV

Vectorlike e_4

$$\mathcal{L}_{\rm extra} = \epsilon_i H L_i \bar{\tau}_4 + m \bar{\tau}_4 \tau_4 + ({\rm kinetic})$$

- MSSM4G model: solves Bino-overabundance
- HL-LHC expectation : **350 GeV** if "right-handed" & mixed with *e* or μ

What I skipped

- MSSM4G is testable also by **DM-direct** and **Gamma-ray**.

■ Vectorlike q_4

➢ m_h (MSSM) UP ; excluded up to 1.1TeV

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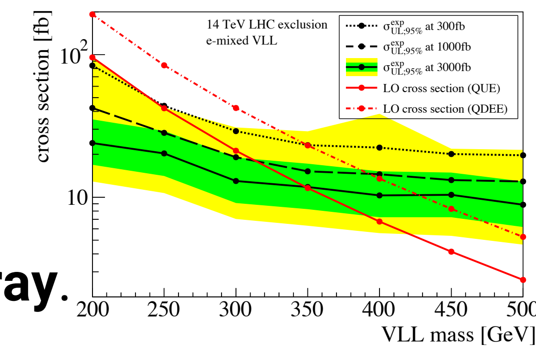
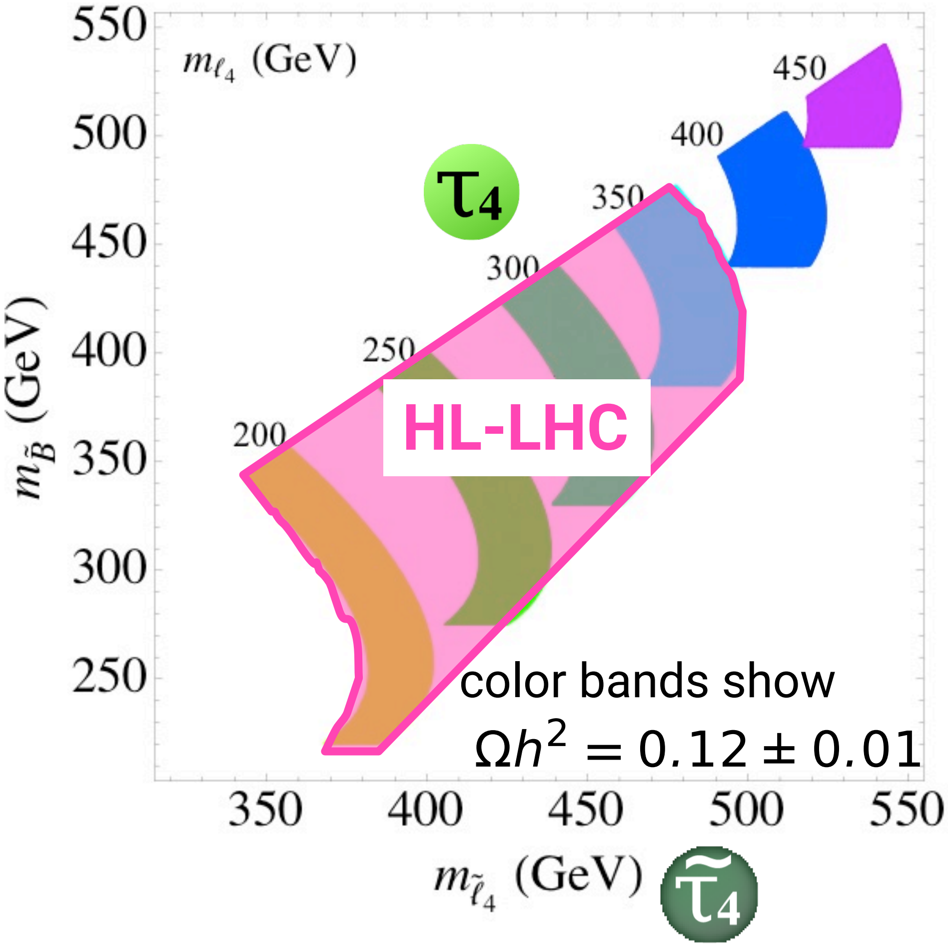


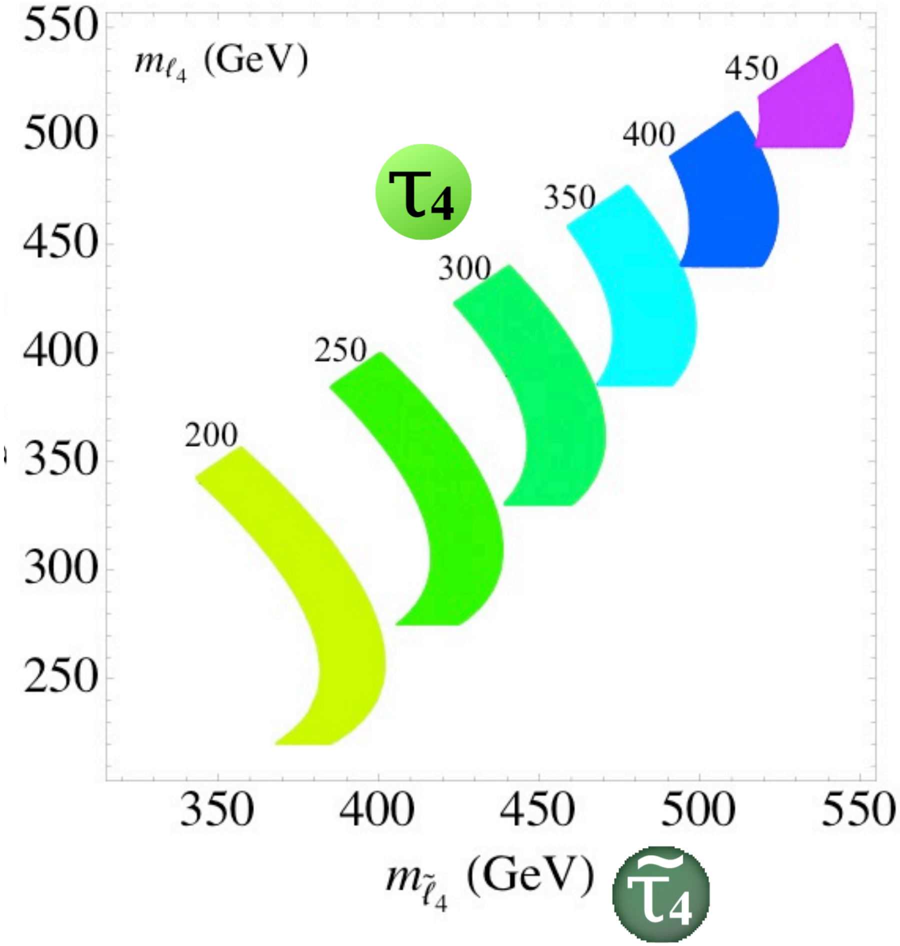
What I skipped

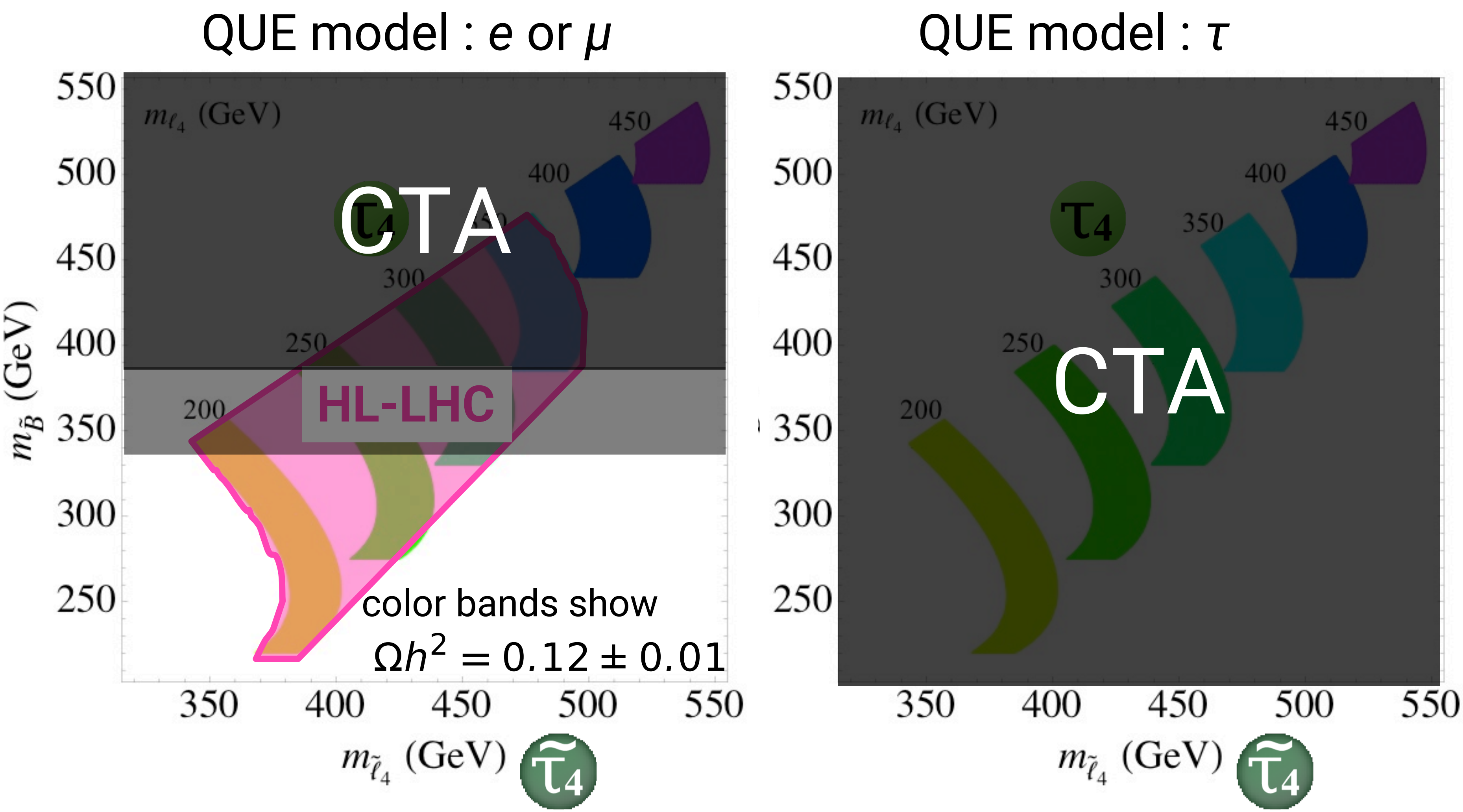
➢ MSSM4G is testable also by **DM-direct** and **Gamma-ray**.

QUE model : e or μ



QUE model : τ




QUE model : e or μ
QUE model : τ
CTA
HL-LHC
CTA
color bands show
$\Omega h^2 = 0.12 \pm 0.01$
m_{ℓ_4} (GeV)
200
250
300
350
400
450
$m_{\tilde{B}}$ (GeV)
$m_{\tilde{\ell}_4}$ (GeV)
$\tilde{\tau}_4$
τ_4
350
400
450
500
550
250
300
350
400
450
500
550

■ Vectorlike q_4

- m_h (MSSM) 

; excluded up to 1.1TeV

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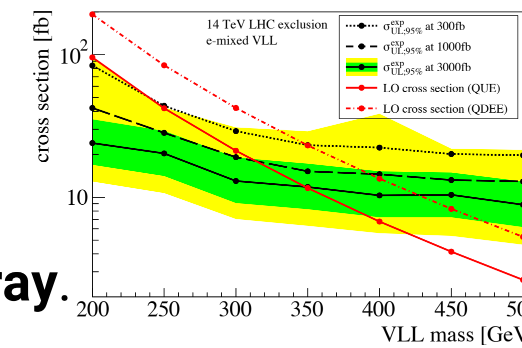
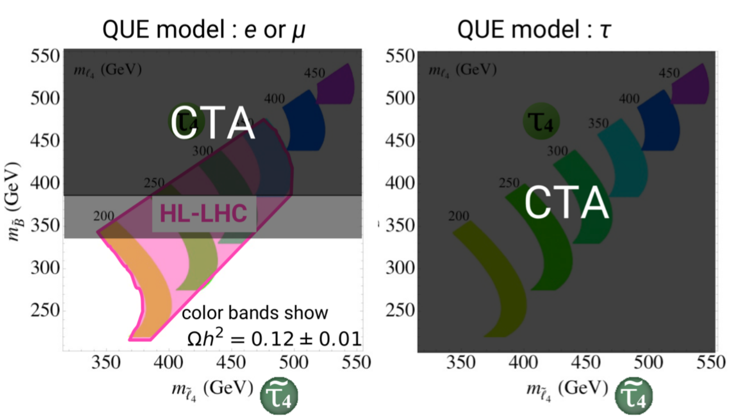
- HL-LHC expectation : **350 GeV** if "right-handed" & mixed with *e* or *μ*



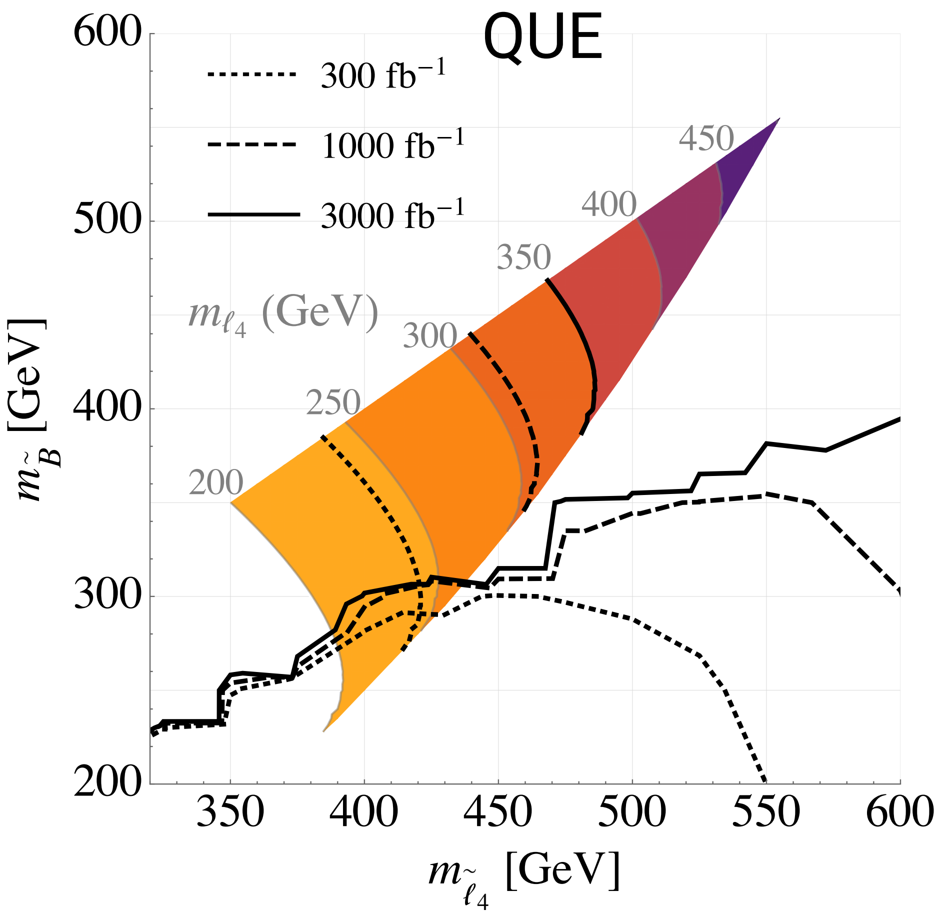
What I skipped

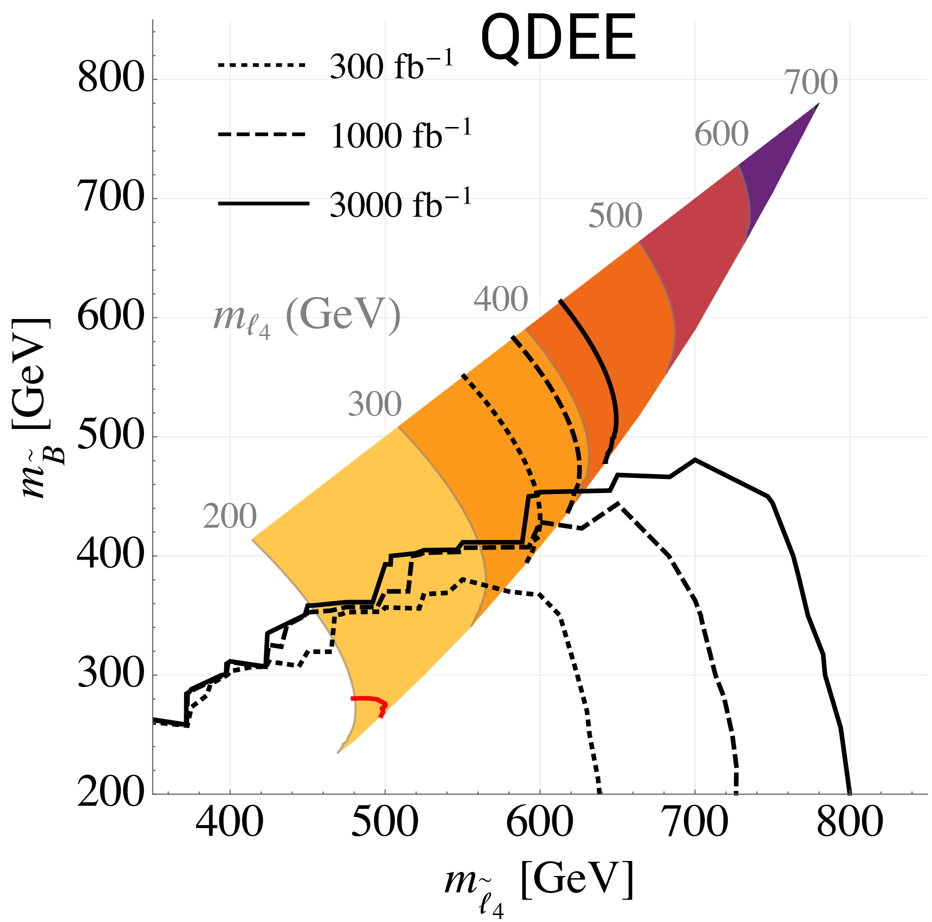
- MSSM4G is testable also by **DM-direct** and **Gamma-ray**.



MSSM4G "official" space

■ if 4G lepton decays to electron or muon

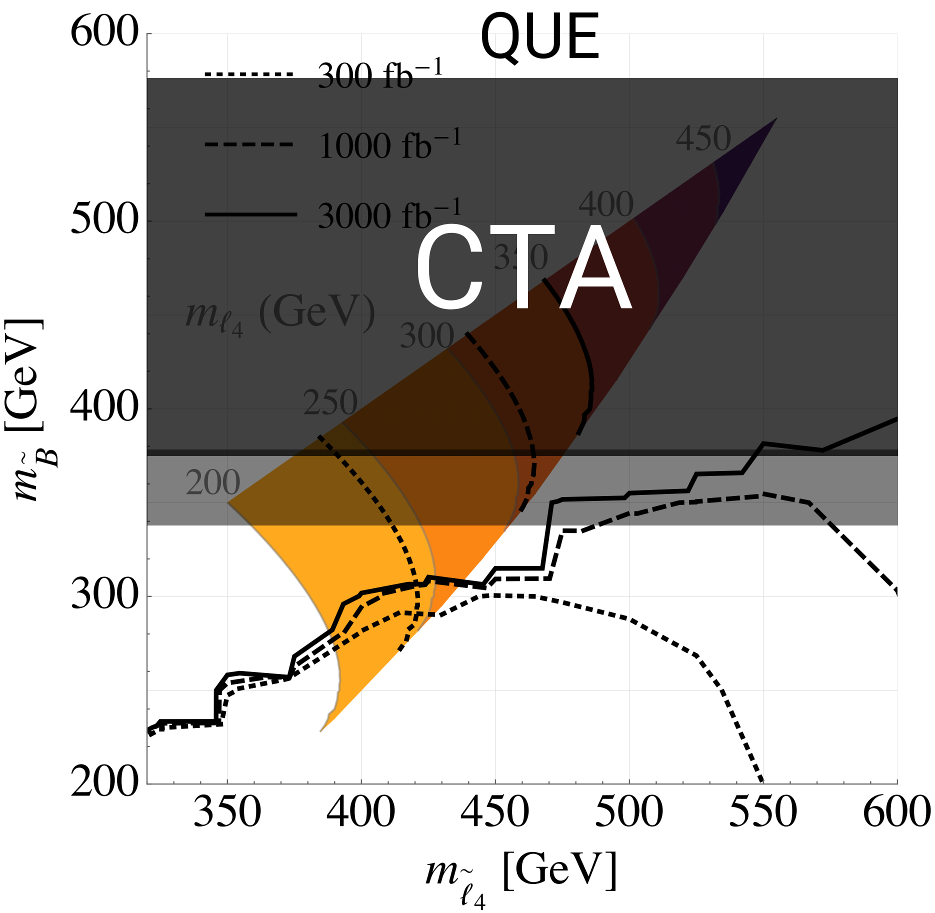


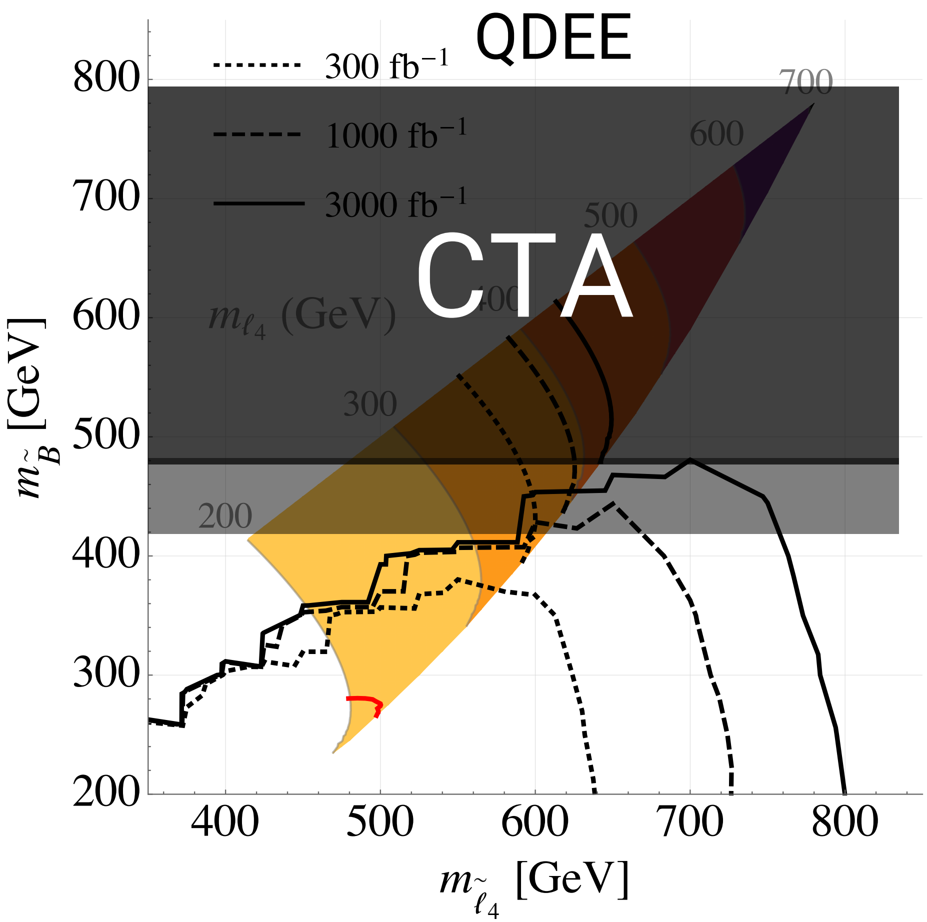


■ if 4G lepton decays to tau-lepton

LHC insensitive … (´・ω・`)

- **if 4G lepton decays to electron or muon**



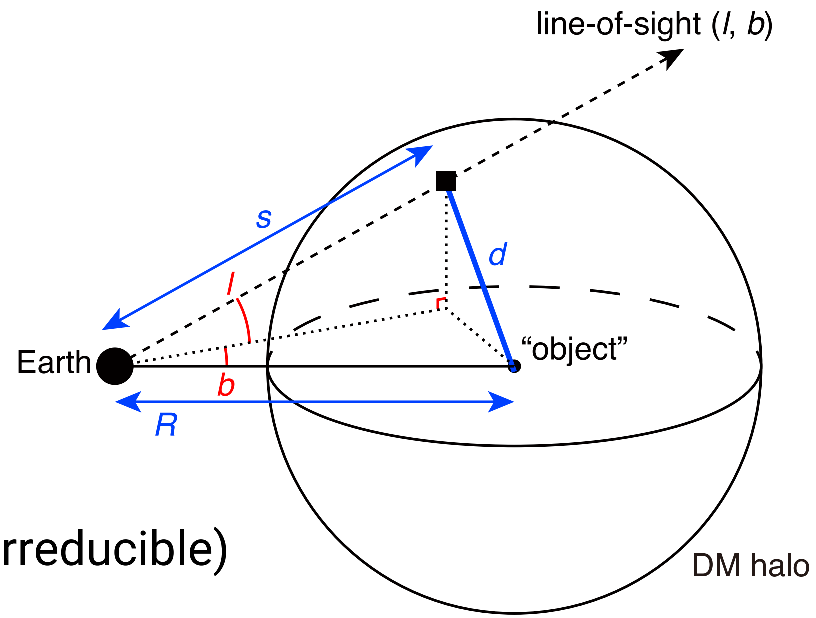


- **if 4G lepton decays to tau-lepton**

LHC insensitive … (´・ω・`)

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)



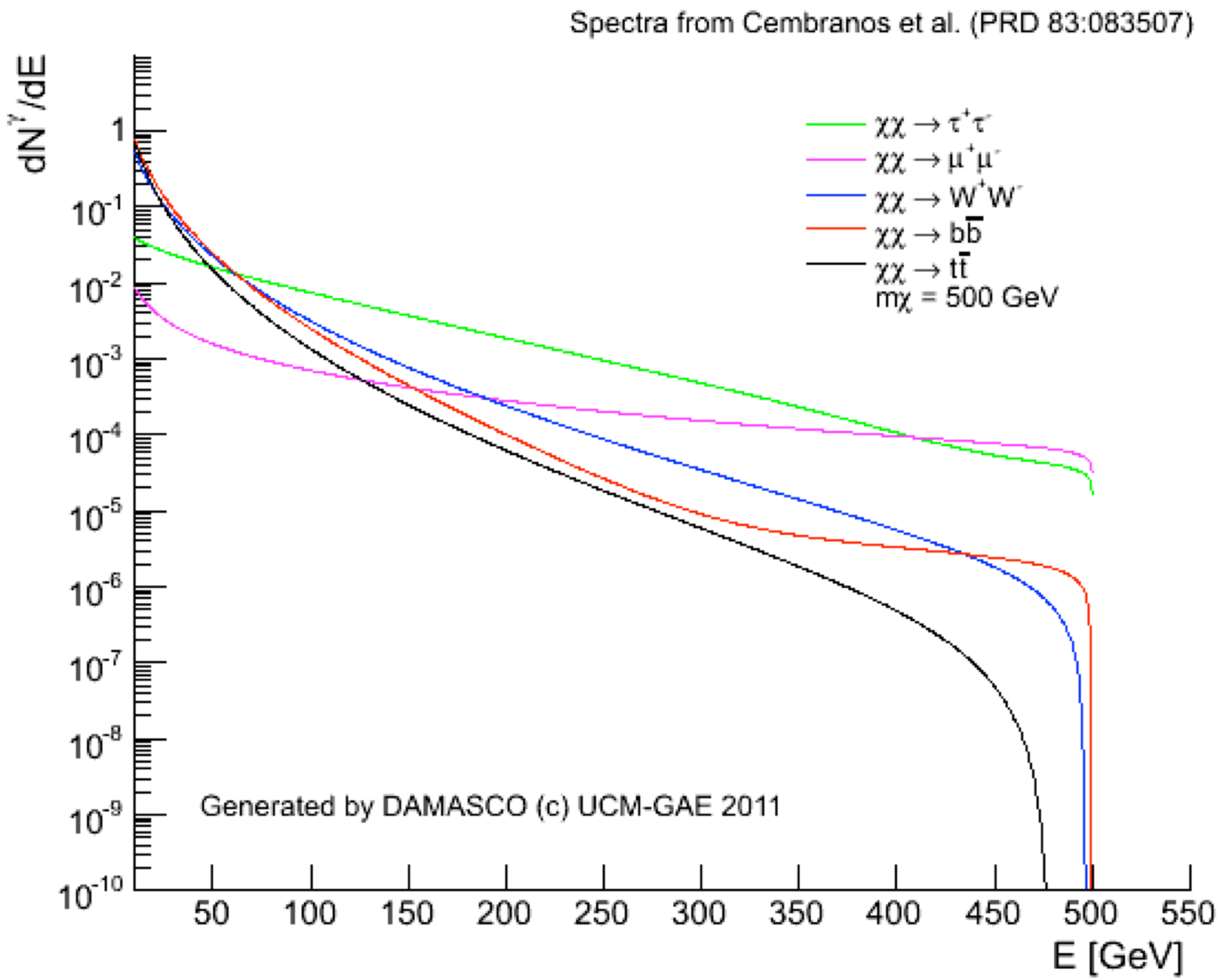
$$J = \int \mathrm{d}\Omega_{l,b} \int_0^\infty \mathrm{d}s\, \rho(d)^2$$

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

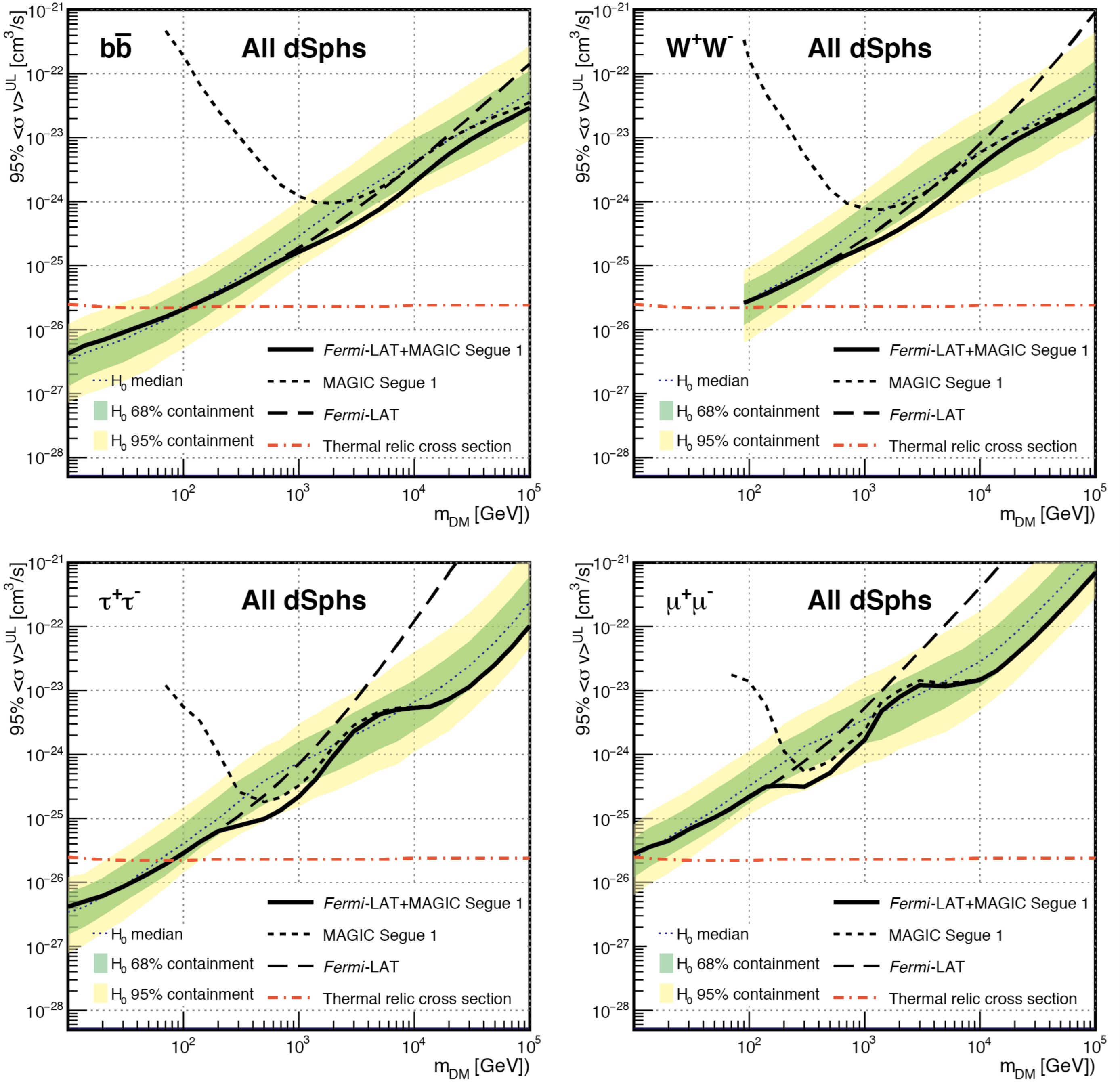
- < 100 GeV : satellites
  - full-sky, ~1m^2, 5–10% energy resolution
  - Fermi-LAT (2008) : gamma-ray to electron conversion

- > 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]

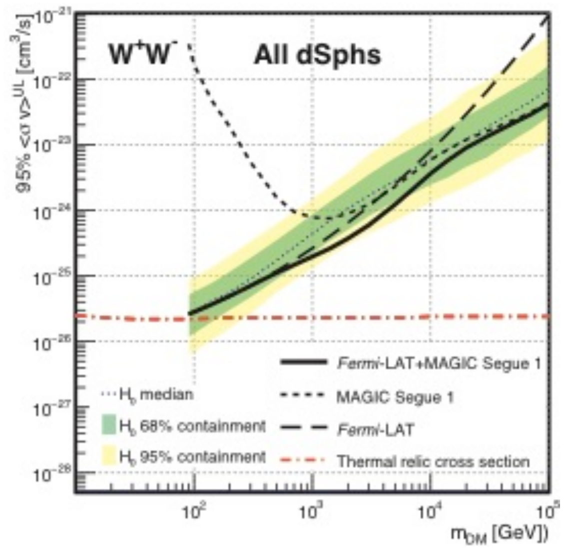
Original data of Fermi-MAGIC constraints

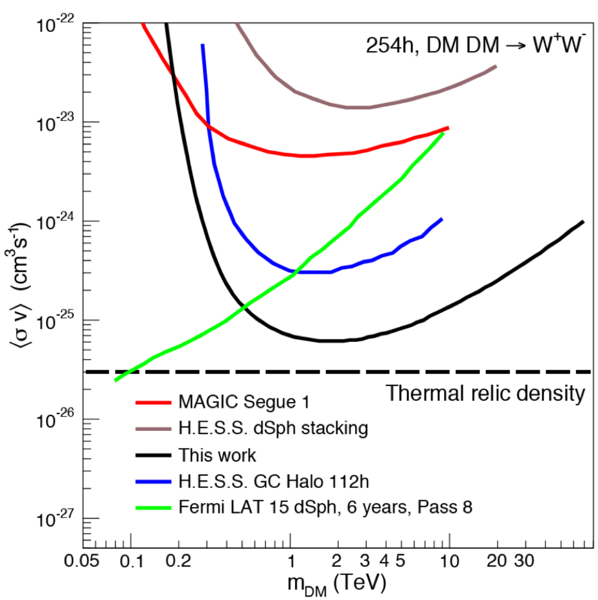


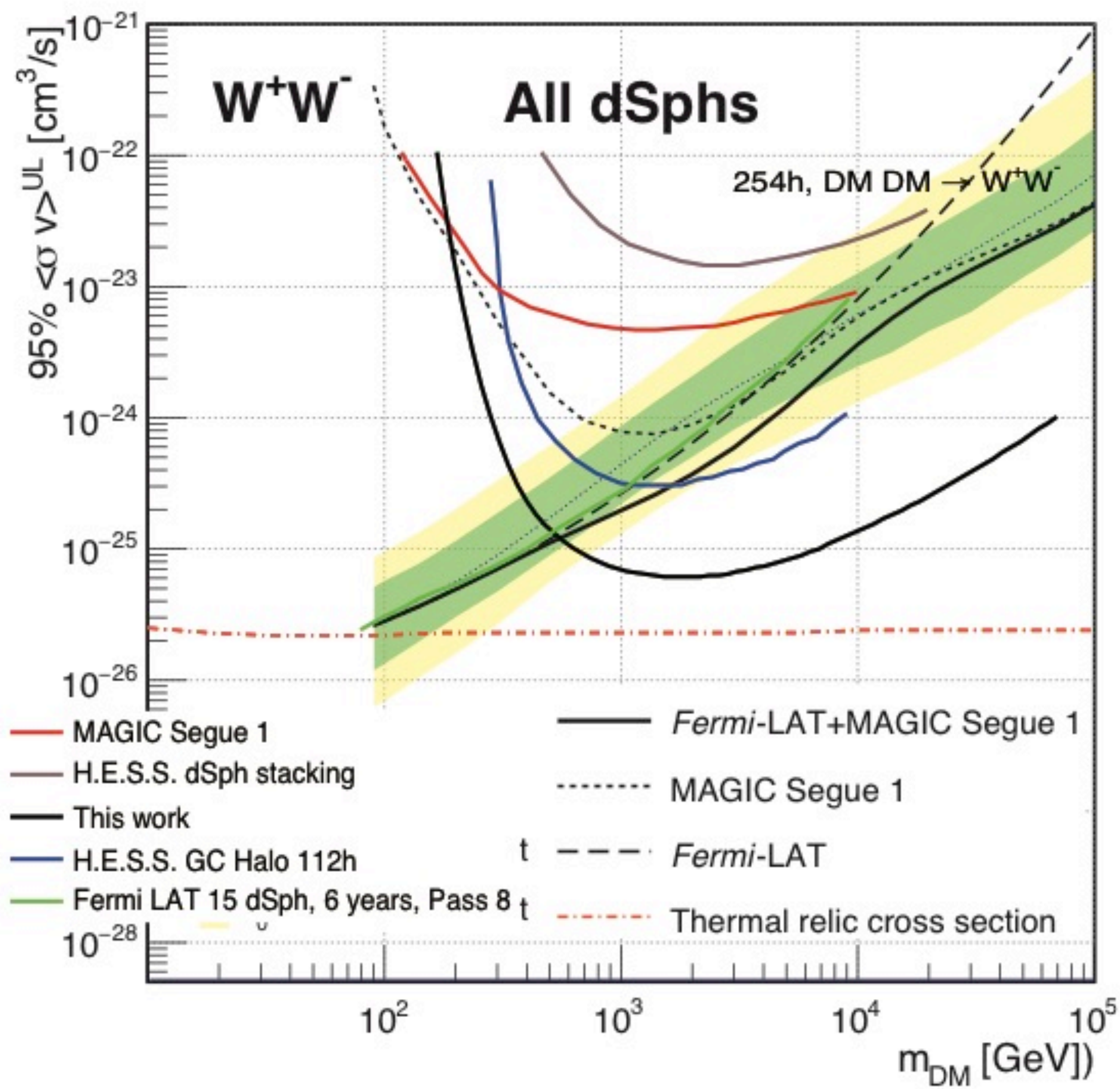
MAGIC:
158 hr of Segue 1

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

DM profile: NFW







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

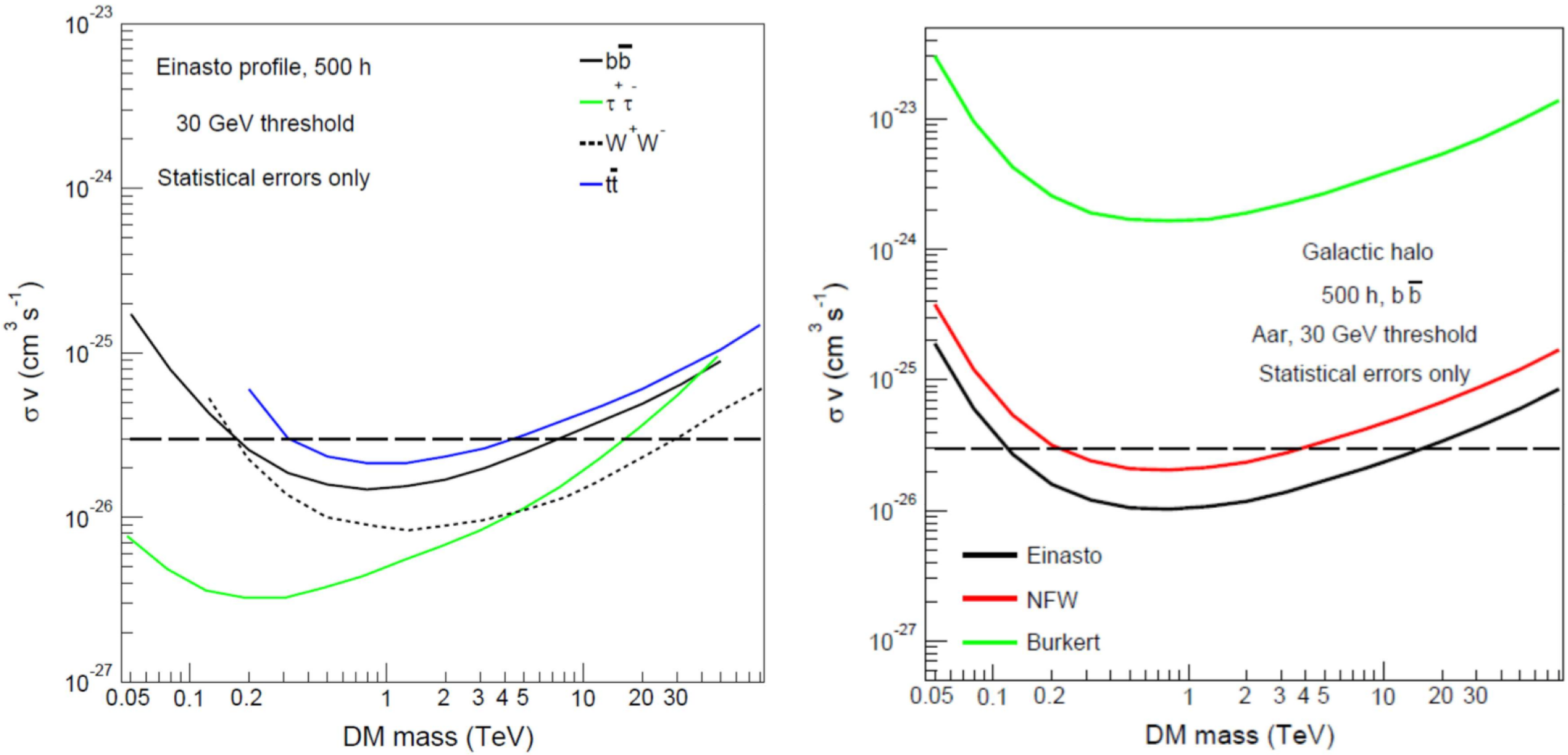
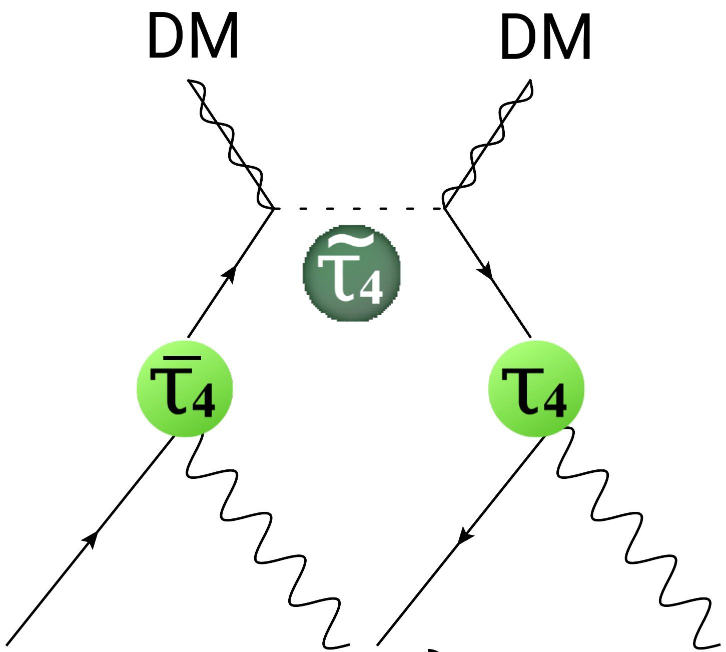


Figure1. Left: Sensitivity for σ v from observation on the Galactic Halo with Einsasto dark matter profile and for different annihilation modes as indicated. **Right**: for cuspy (NFW, Einasto) and cored (Burkert) dark matter halo profiles. For both plots only statistical errors are taken into account.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

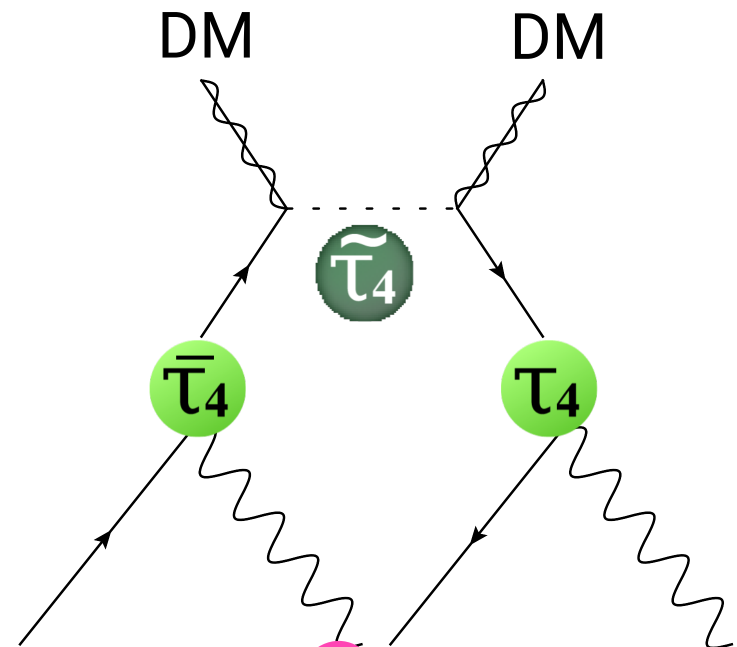
- DM indirect detection by Gamma-ray observation



$$\left.\begin{array}{ccc} \nu & + & W \\ l & + & h \\ l & + & Z \end{array}\right\} \sim 2:1:1$$

$$\begin{pmatrix} \nu = \nu_e, \nu_\mu, \nu_\tau \\ l = e, \mu, \tau \end{pmatrix}$$

- DM indirect detection by Gamma-ray observation



$\nu \quad + \quad W$

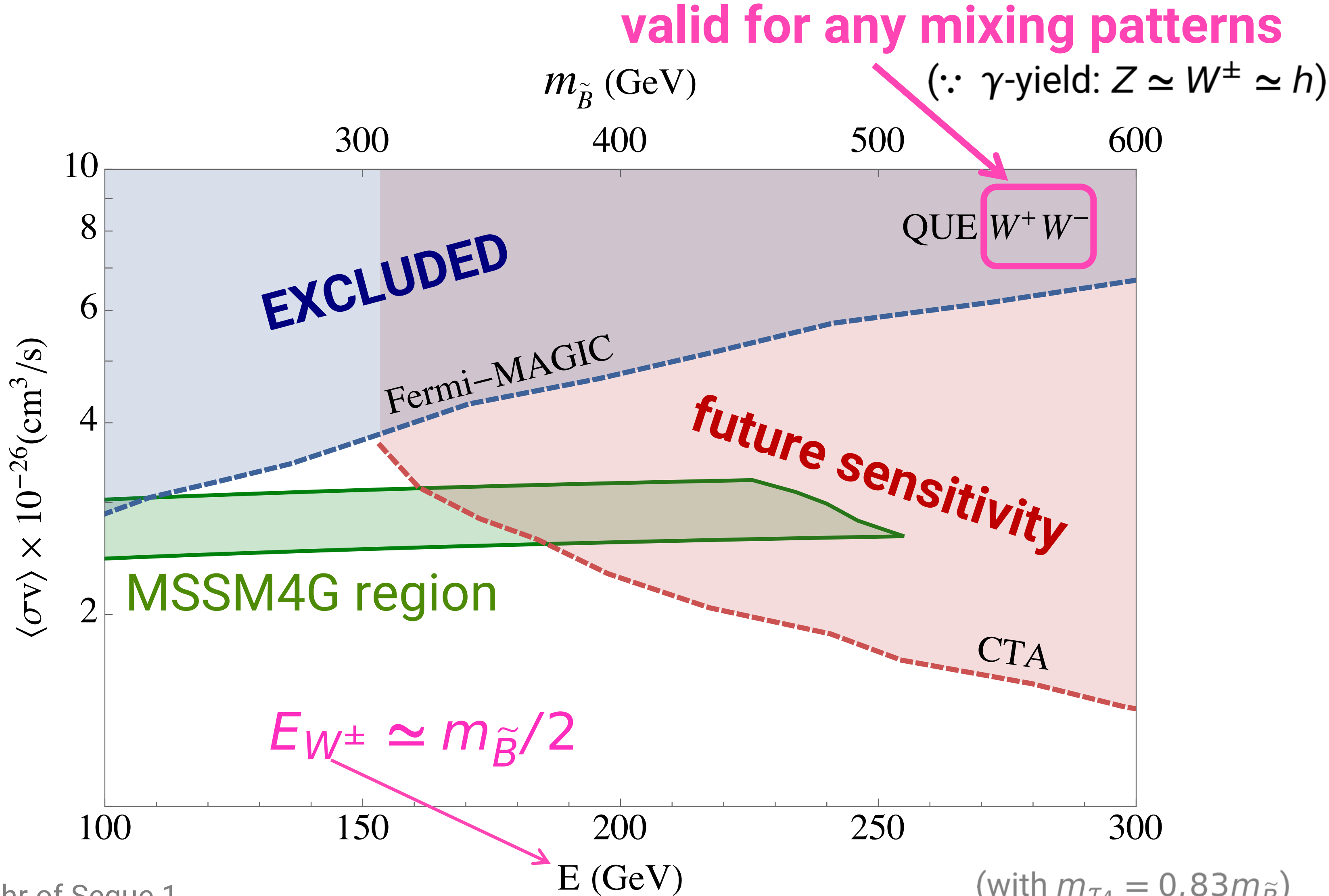
$l \quad + \quad h \quad \rightarrow \cdots \rightarrow \gamma$

$l \quad + \quad Z$

$$\begin{pmatrix} \nu = \nu_e, \nu_\mu, \nu_\tau \\ l = e, \mu, \tau \end{pmatrix}$$

⇒ Fermi-LAT (satellite)
MAGIC (Air Cherenkov telescope)

CTA (**future** A. C. Telescope)



MAGIC: 158 hr of Segue 1

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

DM profile: NFW

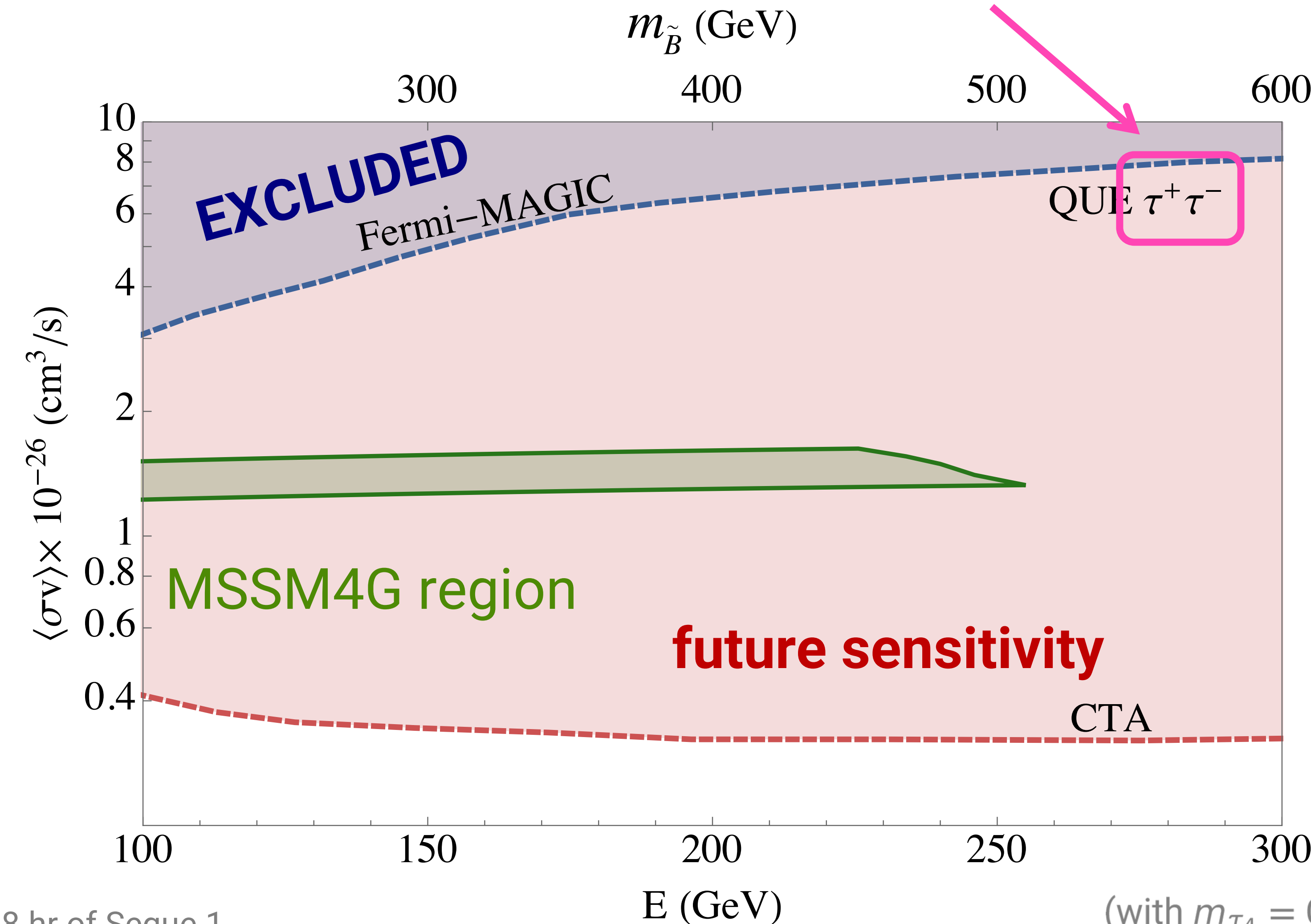
Fermi-LAT dominates MAGIC in almost all *E*-range.

CTA prospect : 500hr of Milky Way

DM profile: Einasto

No syst. unc. (stat only)

if 4G lepton decays to tau-lepton



(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.

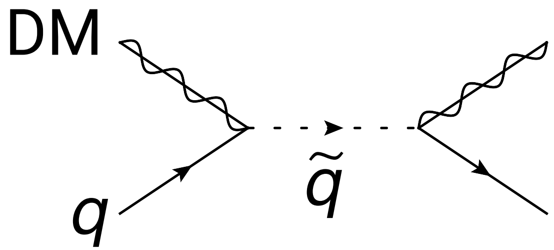
CTA prospect : 500hr of Milky Way

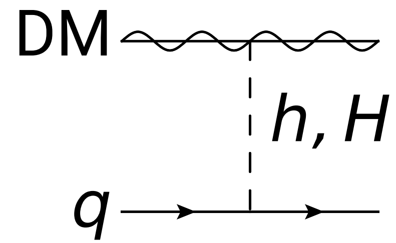
DM profile: Einasto

No syst. unc. (stat only)

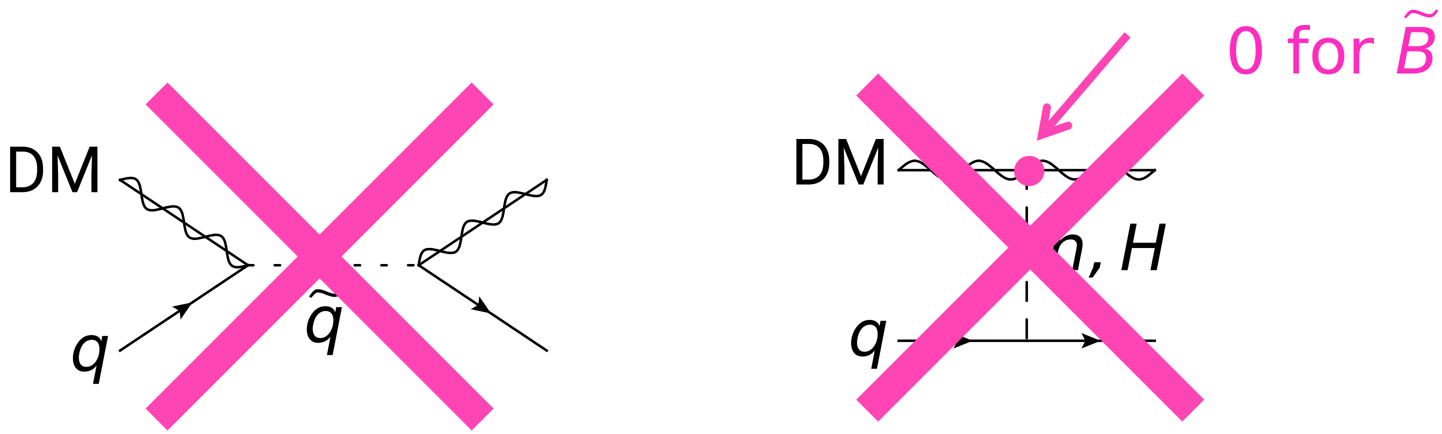
SI direct detection constraints

- spin-independent cross section $\sigma_{\rm SI}(N\tilde{\chi}_1^0 \to N\tilde{\chi}_1^0)$



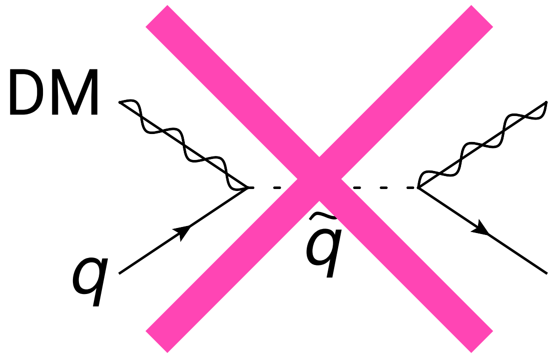


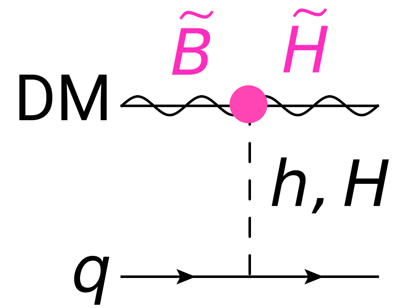
- spin-independent cross section $\sigma_{\rm SI}(N\tilde{\chi}_1^0 \to N\tilde{\chi}_1^0)$



if $\tilde{q}$ decoupled (as we assume)

- spin-independent cross section $\sigma_{\rm SI}(N\tilde{\chi}_1^0 \to N\tilde{\chi}_1^0)$





if $\tilde{q}$ decoupled (as we assume)

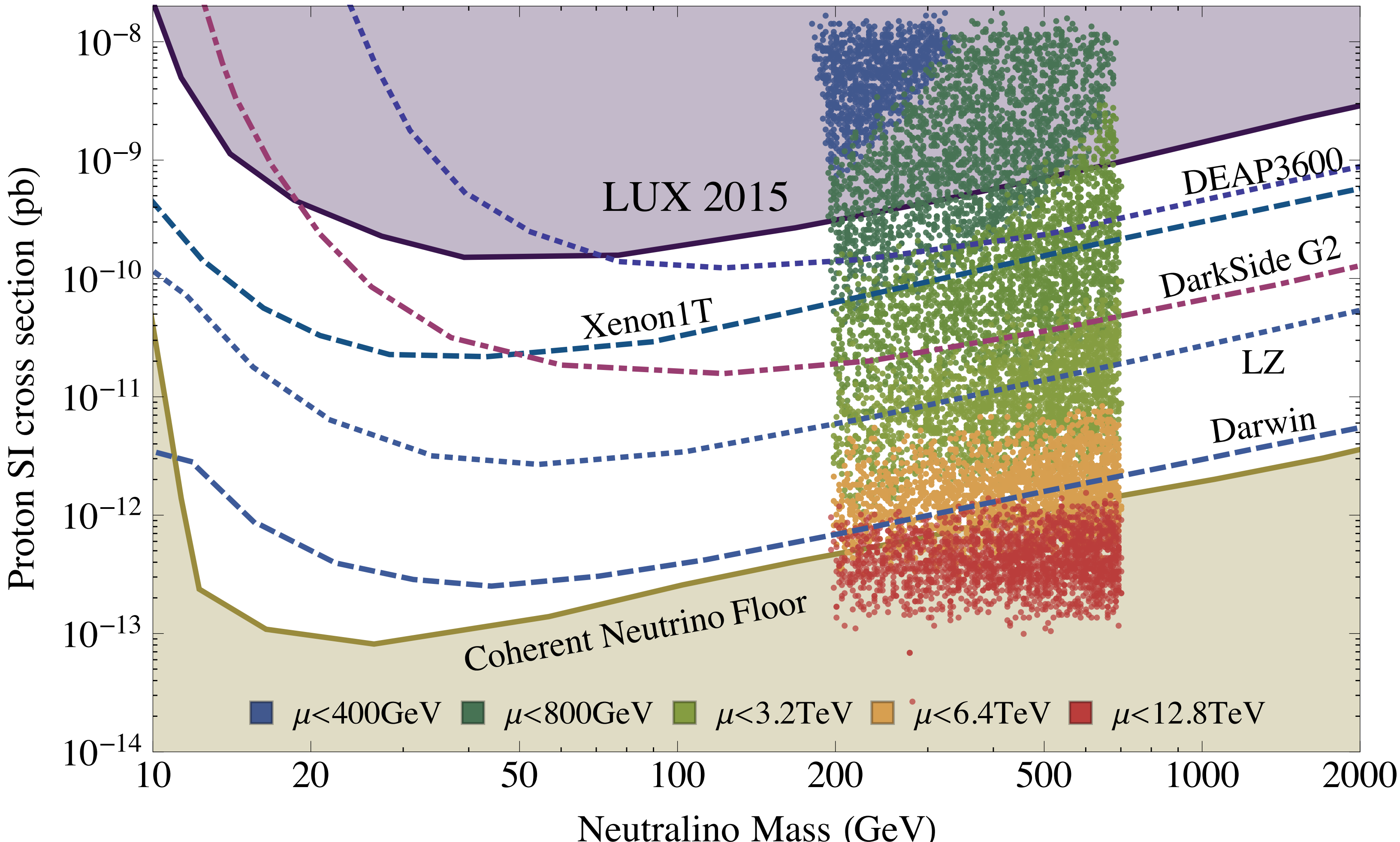
$\widetilde{W}$ in DM (~ 0) $\tilde{B}$ in DM (~ 1)

$$\sigma_{\rm SI} \propto \left[N_{41} \left(N_{21} - N_{11} \tan\theta_{\rm w} \right) \frac{g^2}{4 m_W m_h^2} \right]^2$$

$\tilde{H}$ in DM

$$\approx \left[\frac{M_1 m_Z s_{\rm w} t_{\rm w}}{\mu^2 - M_1^2 + m_Z^2 s_{\rm w}^2} \frac{g^2}{4 m_W m_h^2} \right]^2 \quad \left(M_1 \ll \mu \ll M_2, m_H \right)$$

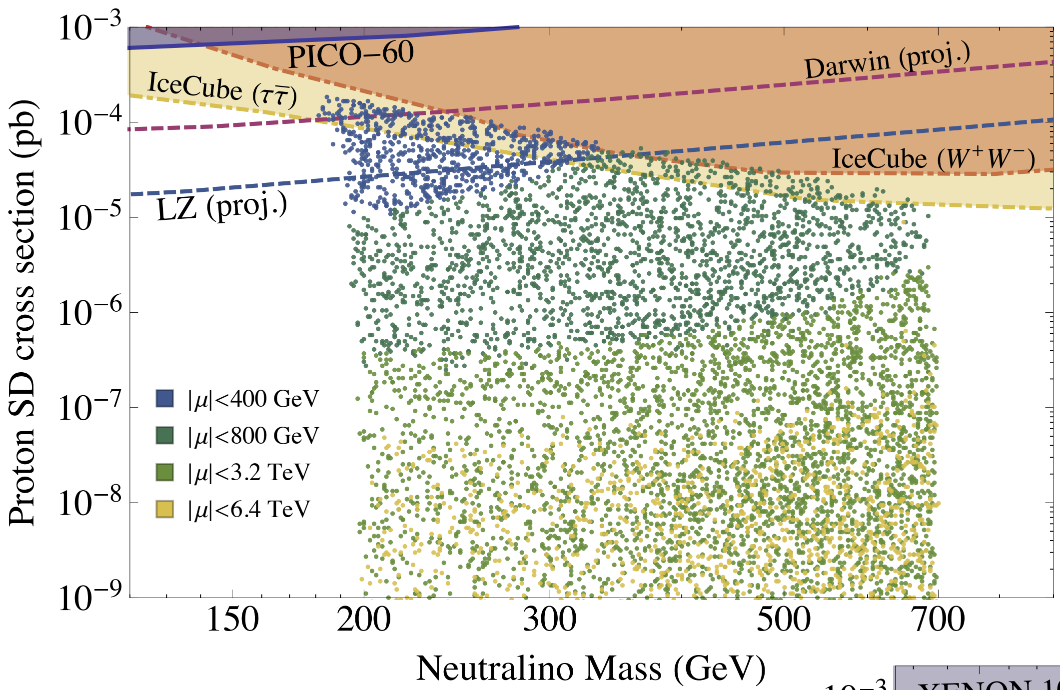
- spin-independent cross section



$$\approx \left[\frac{M_1 m_Z s_\mathrm{w} t_\mathrm{w}}{\mu^2 - M_1^2 + m_Z^2 s_\mathrm{w}^2} \frac{g^2}{4 m_W m_h^2} \right]^2 \quad \left(M_1 \ll \mu \ll M_2, m_H \right)$$

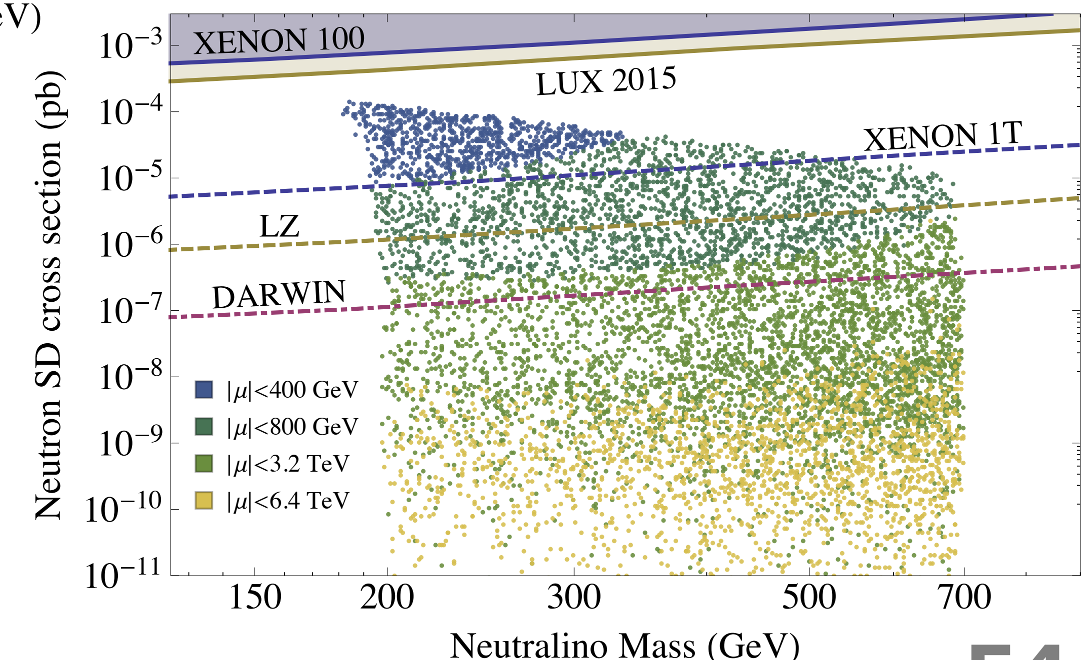
SD direct detection constraints

Spin-dependent direct detection constraints on MSSM4G scenario



Note

DM SI/SD constraints are the same as MSSM, but the parameter space is not preferred in the MSSM because of overabundance.



Vectorlike lepton search DATA

	$WZ(j)$	$WZ(\ell)$	$ZZ(j)$	$ZZ(\ell)$
N_ℓ	≥ 3	≥ 4	≥ 4	≥ 5
N_j	≥ 2	< 2	≥ 2	—
$\lvert m_{jj} - m_W \rvert$	$< 20\,\mathrm{GeV}$	—	—	—
$\lvert m_{jj} - m_Z \rvert$	—	—	$< 40\,\mathrm{GeV}$	—
$\not\!\!E_\mathrm{T}$	$> 60\,\mathrm{GeV}$	$> 100\,\mathrm{GeV}$	—	—
$N_{Z(\ell\ell)}$	—	—	≥ 1	≥ 1

TABLE IV: Selection flow of the background events in the vector-like lepton search. Upper bounds on the number of events in each SR, $N_{\rm UL}$, are shown for three values of integrated luminosity, where systematic uncertainty of 20% as well as statistical uncertainty is included.

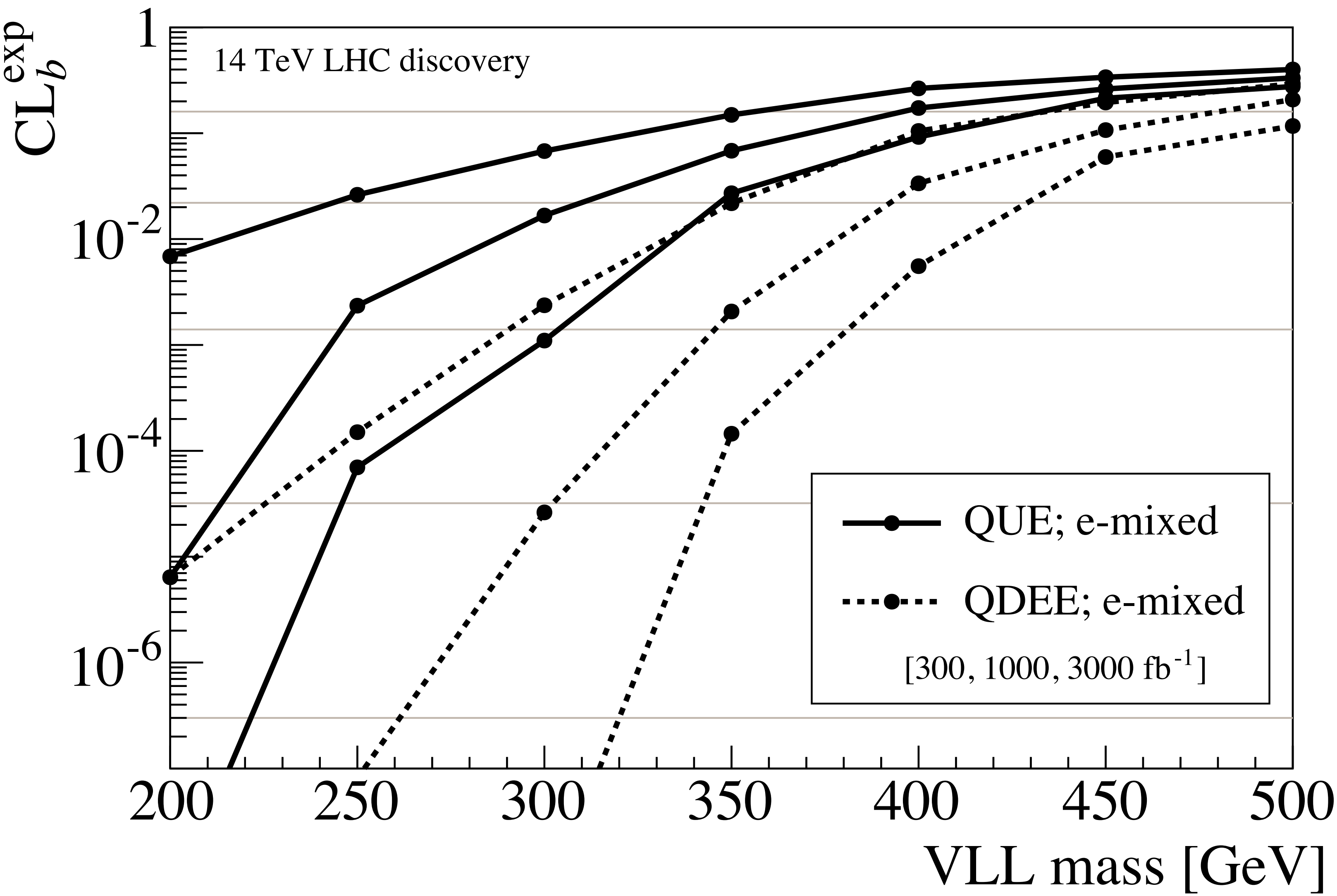
	background cross section [fb]				$N_{\rm UL}$		
	di-boson	tri-boson	top	total	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
$N_\ell \geq 3$	222	5.1	13.4	249	—	—	—
$WZ(j)^-$	0.071	0.013	0.082	0.166	25.1	70.4	200
$WZ(j)^Z$	0.643	0.071	0.183	0.898	111	359	1060
$WZ(\ell)^-$	0.014	0.025	0.017	0.056	11.9	27.4	71.1
$WZ(\ell)^Z$	< 0.001	0.005	0.003	0.008	5.1	7.9	14.5
$ZZ(j)^0$	0.194	0.016	0.058	0.268	37.2	111	321
$ZZ(j)^J$	0.064	0.007	0.022	0.093	16.4	41.8	114
$ZZ(j)^L$	0.182	0.012	0.024	0.218	31.2	91.7	263
$ZZ(j)^Z$	0.020	0.004	0.019	0.043	10.2	22.2	55.7
$ZZ(j)^{JL}$	0.060	0.005	0.009	0.075	14.2	35.3	94.3
$ZZ(j)^{JZ}$	0.008	0.001	0.008	0.017	6.7	11.9	25.6
$ZZ(j)^{LZ}$	0.020	0.004	0.019	0.043	10.2	22.2	55.9
$ZZ(j)^{JLZ}$	0.008	0.001	0.008	0.017	6.7	11.9	25.5
$ZZ(\ell)$	< 0.001	0.005	< 0.001	0.005	4.7	6.8	11.5
$ZZ(\ell)^{<2}$	< 0.001	0.003	< 0.001	0.004	4.2	5.8	9.2
$ZZ(\ell)^{<1}$	< 0.001	0.001	< 0.001	0.001	3.6	4.5	6.3

Z-flag for $WZ(j)$: a Z-like $\ell\ell$ (SFOS, $|m_{\ell\ell} - m_Z| < 10\,\text{GeV}$)
Z-flag for $WZ(\ell)$: a Z-like $\ell\ell$ in 3^+rd-leading leptons
J-flag for $ZZ(j)$: a Z-like jj (10 GeV)
L-flag for $ZZ(j)$: a Z-like $\ell\ell$ in 2^+nd-leading leptons
Z-flag for $ZZ(j)$: leading-lepton does NOT form Z-like pairs
$ZZ(\ell)$ divided by number of jets

TABLE V: Selection flow of the signal events in searches for the e- or μ-mixed τ_4 in the QUE model, displayed as a signal cross section in fb. SRs marked with $*$, $\dagger$ and $\ddagger$ are the most sensitive for exclusion at $\mathcal{L} = 300$, 1000, and 3000 fb^{-1}, respectively.

m_τ [GeV], mixing	200, e	200, μ	300, e	300, μ	400, e	400, μ
total	95.7	96.0	21.2	21.2	6.76	6.74
$N_\ell \geq 3$	2.23	2.42	0.634	0.671	0.231	0.230
$WZ(j)^-$	0.018	0.022	0.020	0.024	0.011	0.012
$WZ(j)^Z$	0.049	0.063	0.034	0.036	0.014	0.014
$WZ(\ell)^Z$	0.012	0.014	$0.008^\ddagger$	0.008	0.003	$0.004^\ddagger$
$ZZ(j)^0$	0.066	0.065	0.035	0.044	0.015	0.015
$ZZ(j)^J$	0.035	0.033	0.018	0.023	0.008	0.007
$ZZ(j)^L$	0.045	0.048	0.026	0.031	0.011	0.012
$ZZ(j)^Z$	0.039^*	0.042^*	$0.025^{*\dagger}$	$0.029^\dagger$	0.010^*	$0.012^\dagger$
$ZZ(j)^{JL}$	0.025	0.025	0.013	0.016	0.006	0.006
$ZZ(j)^{JZ}$	0.021	0.022	0.013	$0.015^\ddagger$	0.005	0.006
$ZZ(j)^{LZ}$	0.039	0.042	0.025	0.029^*	$0.010^\dagger$	0.012^*
$ZZ(j)^{JLZ}$	0.021	0.022	0.013	0.015	0.005	0.006
$ZZ(\ell)$	$0.015^{\dagger\ddagger}$	$0.014^{\dagger\ddagger}$	0.005	0.007	$0.003^\ddagger$	0.002
$ZZ(\ell)^{<2}$	0.010	0.009	0.003	0.004	0.002	0.001
$ZZ(\ell)^{<1}$	0.004	0.003	0.001	0.002	8×10^{-4}	6×10^{-4}

Z-flag for $WZ(j)$: a Z-like $\ell\ell$ (SFOS, $|m_{\ell\ell} - m_Z| < 10$ GeV)
Z-flag for $WZ(\ell)$: a Z-like $\ell\ell$ in 3^+rd-leading leptons
J-flag for $ZZ(j)$: a Z-like jj (10 GeV)
L-flag for $ZZ(j)$: a Z-like $\ell\ell$ in 2^+nd-leading leptons
Z-flag for $ZZ(j)$: leading-lepton does NOT form Z-like pairs
$ZZ(\ell)$ divided by number of jets

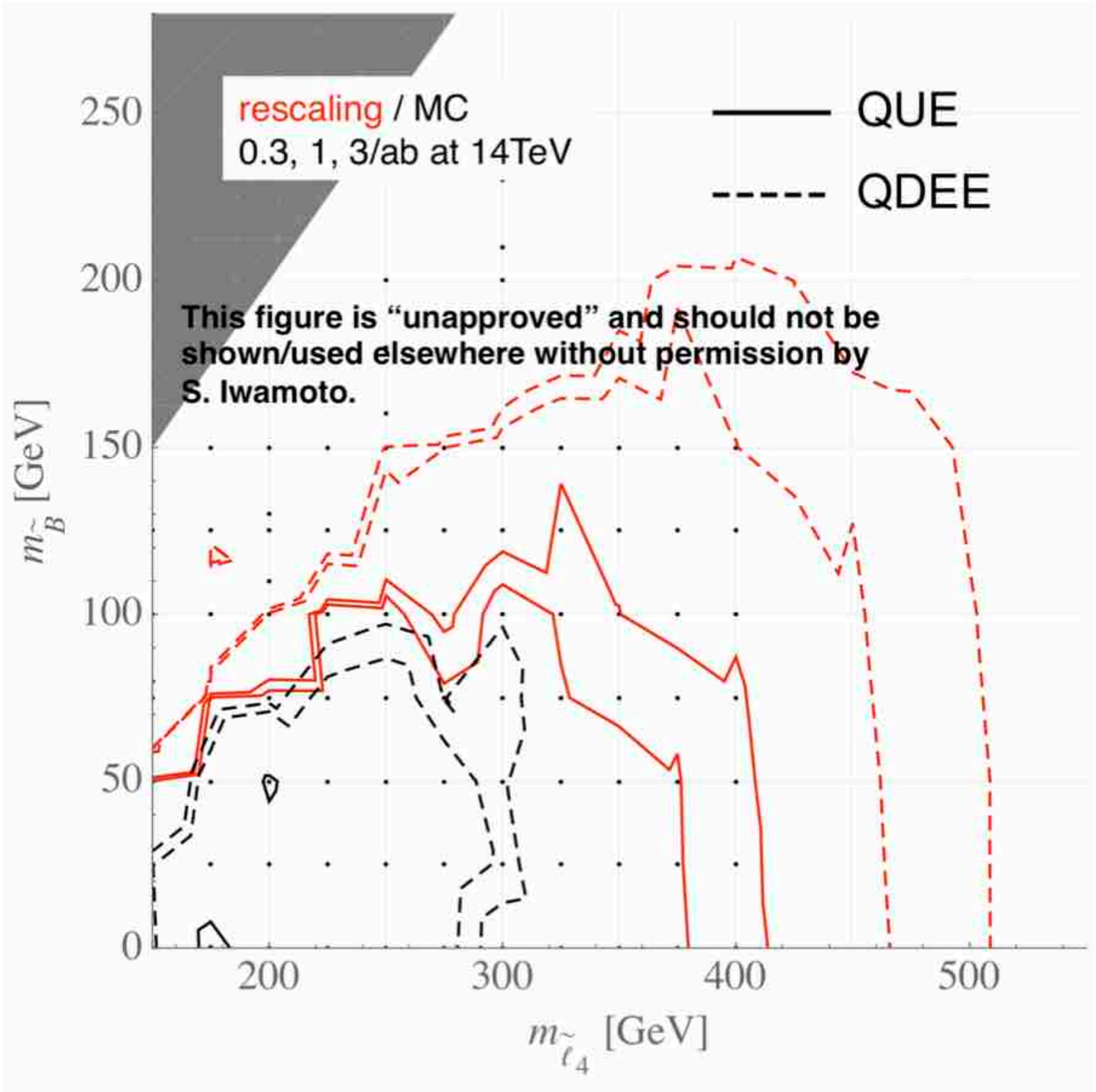


CL_b^{exp}
1
10^{-2}
10^{-4}
10^{-6}
14 TeV LHC discovery
QUE; e-mixed
QDEE; e-mixed
[300, 1000, 3000 fb^{-1}]
200
250
300
350
400
450
500
VLL mass [GeV]

TABLE II: Future prospects for searches for vector-like leptons at the 14 TeV LHC for three values of integrated luminosity. The first table is for the QUE models, and the second for the QDEE models. We consider vector-like leptons with a mass $m_{\ell_4} \geq 200$ GeV; the expressions 0^{+250} GeV etc. show that the central value of exclusion or discovery limit is below our model points and we may achieve the limit of 250 GeV with 1σ statistical fluctuation. In the dashed entries the upper limit is less than 200 GeV even with 1σ statistical fluctuation. The CL_s method is used for statistical treatment, where the statistical uncertainty and a 20% systematic uncertainty for the background contribution are taken into account, while the theoretical uncertainty on the signal cross section as well as the NLO correction are not considered. See Appendix B for further details.

QUE model		$300\ \mathrm{fb}^{-1}$	$1000\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
95% CL exclusion	e-mixed	240^{+60} GeV	310^{+50}_{-60} GeV	350^{+40}_{-40} GeV
	μ-mixed	270^{+50} GeV	330^{+40}_{-60} GeV	370^{+40}_{-40} GeV
3σ discovery	e-mixed	0^{+250} GeV	250^{+60}_{-40} GeV	300^{+50}_{-50} GeV
	μ-mixed	0^{+280} GeV	260^{+70}_{-60} GeV	320^{+50}_{-40} GeV
5σ discovery	e-mixed	—	0^{+210} GeV	220^{+20}_{-20} GeV
	μ-mixed	—	0^{+210} GeV	240^{+20}_{-20} GeV

QDEE model		$300\ \mathrm{fb}^{-1}$	$1000\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
95% CL exclusion	e-mixed	350^{+40}_{-50} GeV	390^{+40}_{-40} GeV	430^{+40}_{-40} GeV
	μ-mixed	360^{+40}_{-40} GeV	400^{+40}_{-40} GeV	440^{+40}_{-40} GeV
3σ discovery	e-mixed	290^{+60}_{-70} GeV	340^{+60}_{-40} GeV	380^{+50}_{-40} GeV
	μ-mixed	310^{+60}_{-50} GeV	360^{+40}_{-30} GeV	400^{+40}_{-30} GeV
5σ discovery	e-mixed	0^{+200} GeV	260^{+40}_{-50} GeV	310^{+20}_{-30} GeV
	μ-mixed	0^{+260} GeV	280^{+30}_{-30} GeV	320^{+40}_{-20} GeV



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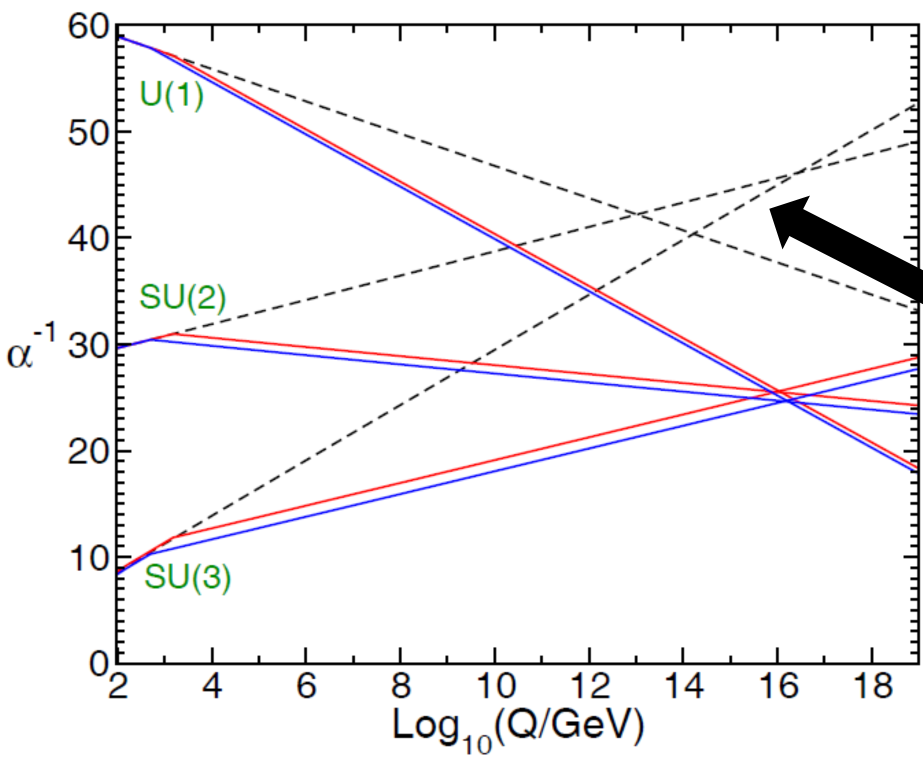
- SM ∋ 3 forces : U(1), SU(2), SU(3) [Why three?]

measured theoretical prediction



- Gauge coupling unification

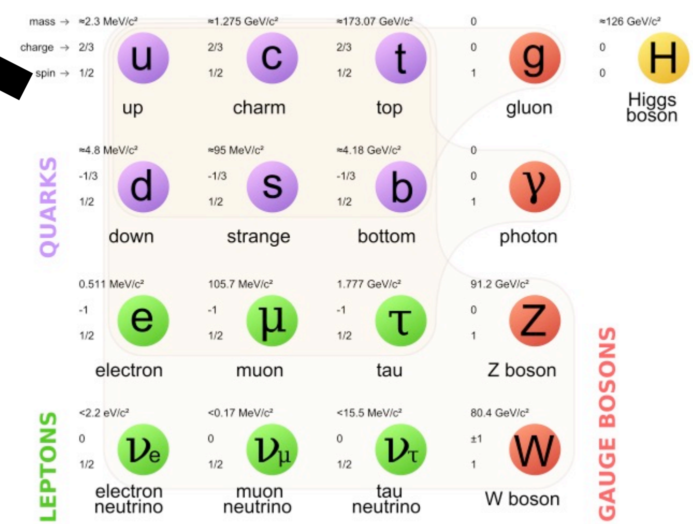
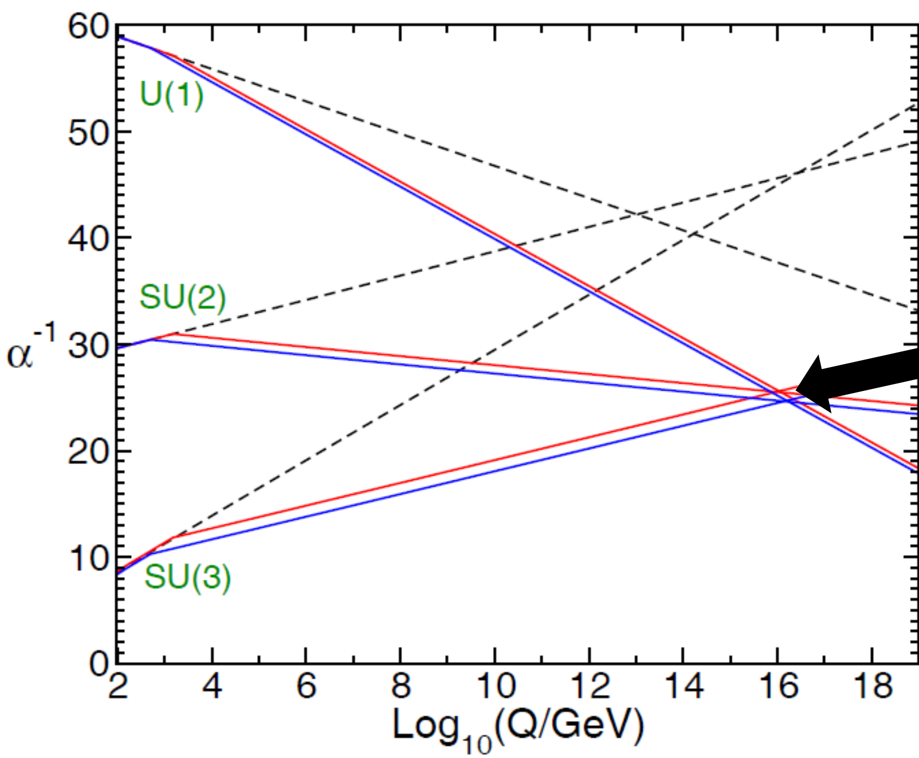


Figure from S. P. Martin, *A Supersymmetry Primer*, hep-ph/9709356

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

measured theoretical prediction



- Gauge coupling unification

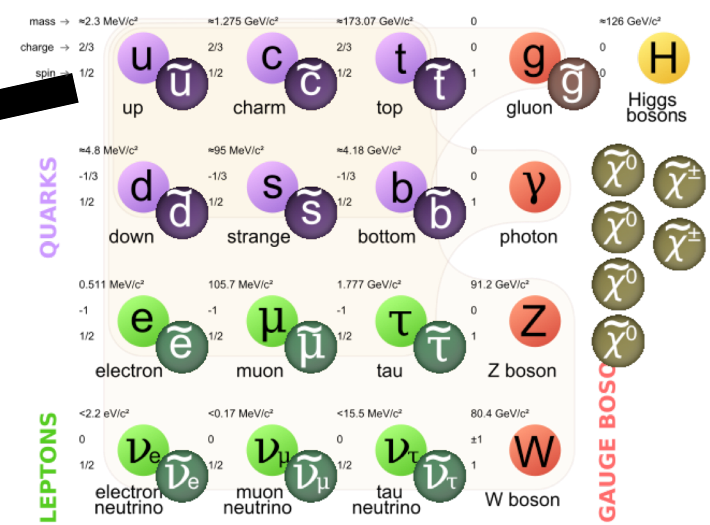


Figure from S. P. Martin, *A Supersymmetry Primer*, hep-ph/9709356