MSSM4G: MOTIVATIONS AND ALLOWED REGIONS

ATLAS SUSY WG Meeting

CERN

Jonathan Feng, University of California, Irvine
31 January 2018

Based on 1510.06089, 1608.00283 with Mohammad Abdullah (Texas A&M), Sho Iwamoto (Padua), Ben Lillard (UC Irvine)

OUTLINE

- Motivations
- QUE and QDEE Models
- Allowed Masses
- Neutralino Dark Matter Implications

[Collider Implications (Sho Iwamoto, next talk)]

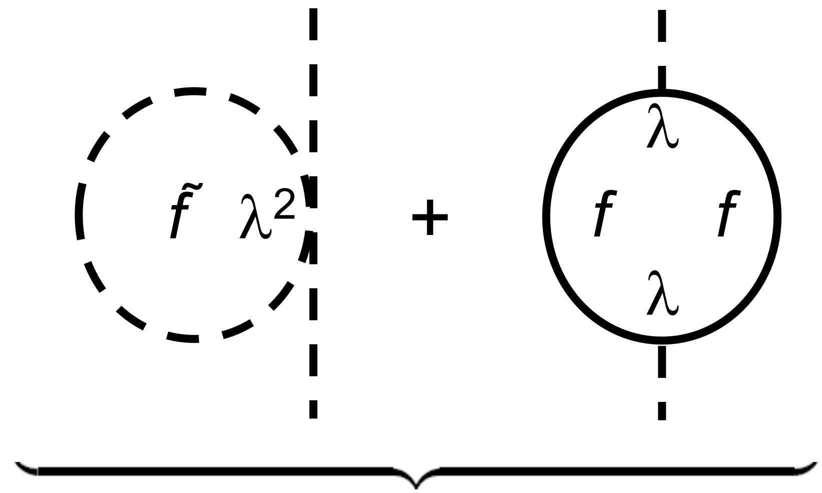
MOTIVATIONS

- For decades, the case for weak-scale SUSY has rested on 3 leading motivations.

- Recent results from the LHC motivate thinking about new SUSY theories beyond the MSSM that are consistent with these results, but also, ideally, preserve these motivations.

THE HIGGS BOSON MASS

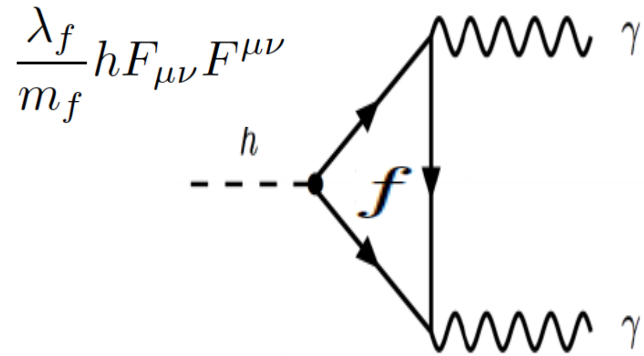
- At tree-level, the Higgs boson mass is maximally m_Z .
- To make it 125 GeV, need large radiative corrections. In the MSSM, this requires multi-TeV stops or large left-right stop mixing. Both options may be unnatural, and the first is certainly disappointing.



$$\frac{1}{16\pi^2}\lambda^2(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_h)$$

- An obvious solution: introduce more matter, e.g., extra top-like quarks and squarks, that gives additional radiative corrections. These can raise the Higgs mass without extremely heavy or highly mixed superpartners. Moroi, Okada (1991)

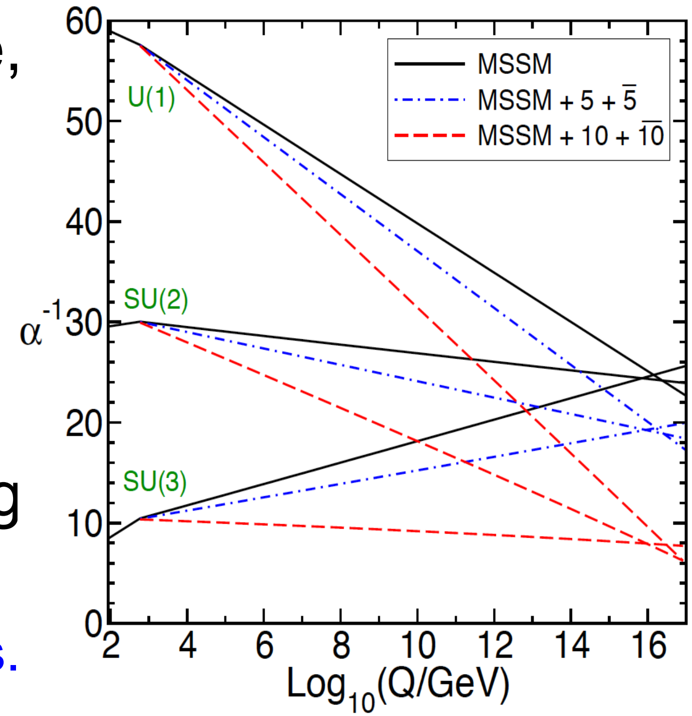
VECTOR-LIKE MATTER



- Unfortunately, extra *chiral* matter is essentially excluded.
- E.g., such matter contributes to h→ γγ, which is famously non-decoupling.
- The problem: for chiral matter, Q'_L is an SU(2) doublet, t'_R is an SU(2) singlet, so all mass comes from $\lambda h Q'_L t'_R$, $m_f \propto \lambda_f$.
- A solution: introduce vector-like matter, fields come in left-right pairs. E.g., Q'_L, t'_R *and* Q'_R, t'_L, so then also have vector-like masses $M_V Q'_L Q'_R$ and $M_V t'_L t'_R$ without coupling to Higgs field.
- We need to keep large Yukawa couplings to give large radiative corrections to the Higgs mass, but we can simultaneously take M_V large enough to satisfy all constraints (Higgs properties, electroweak precision, etc.).

QUE and QDEE MODELS

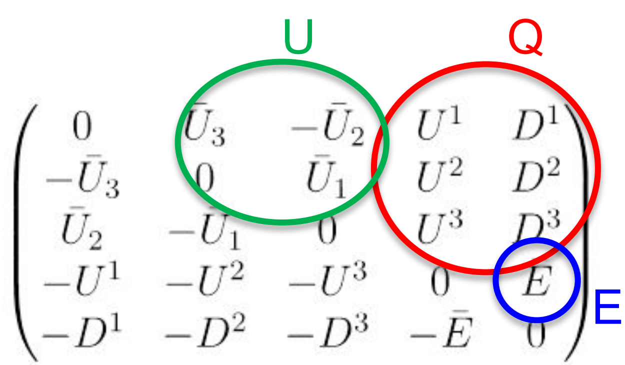
- Vector-like fermions are anomaly-free, so we don’t need complete generations. Too many possibilities?



- But we want to keep gauge coupling unification. This suggests complete SU(5) multiplets: 5s or 10s. Requiring couplings perturbative to GUT scale:
  - 5s do not give sufficient m_{Higgs} corrections.
  - at most one vector-like 10 is allowed.

  This is the QUE model.

- There is also a “flipped SU(5) possibility”: the QDEE model.



Martin (2010)

QUE AND QDEE MODELS

- Summary so far: remarkably, there are only two models that give (1) large Higgs mass corrections and (2) preserve gauge coupling unification. E.g., the QUE model:

$$\begin{aligned} \text{Dirac fermions:} &\quad T_4, B_4, t_4, \tau_4 \\ \text{Complex scalars:} &\quad \tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{t}_{4L}, \tilde{t}_{4R}, \tilde{\tau}_{4L}, \tilde{\tau}_{4R} \end{aligned}$$

[upper case: SU(2) doublet, lower case: SU(2) singlet]

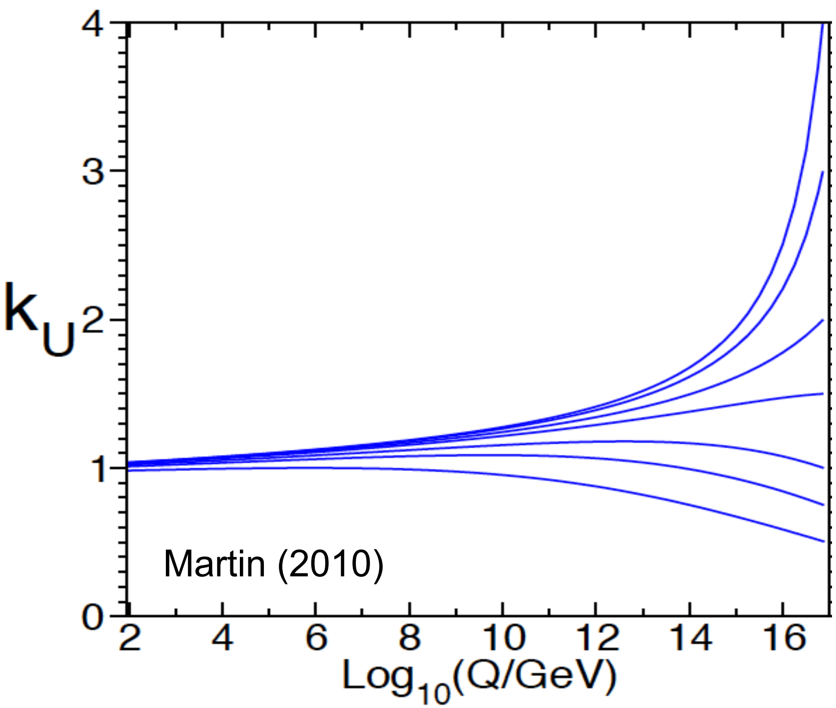
- Simple, but not that simple! Assume unified 4th generation squark, slepton, quark, and lepton masses:

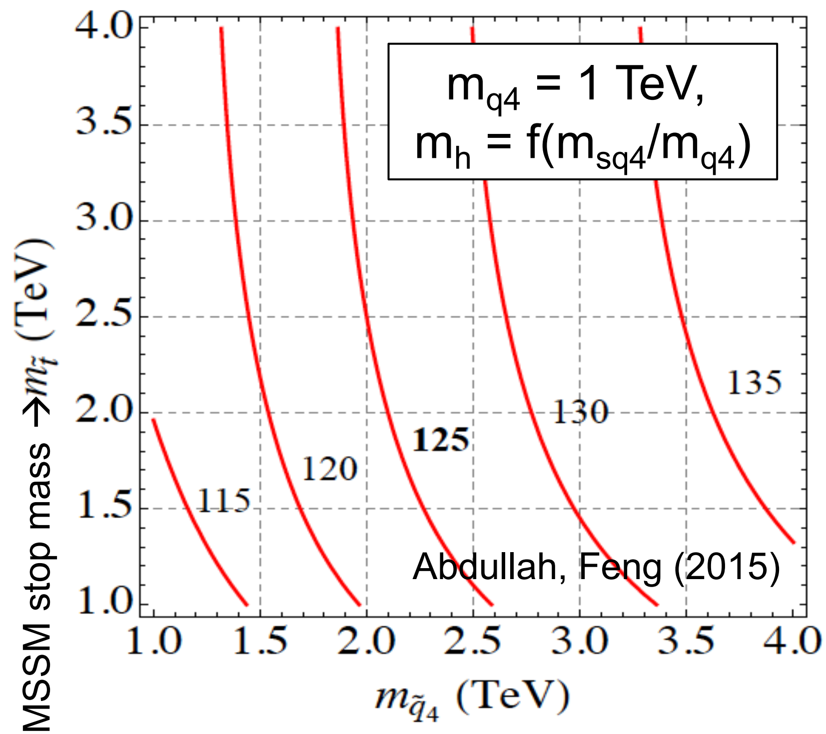
$$\begin{aligned} m_{\tilde{q}_4} &\equiv m_{\tilde{T}_{4L}} = m_{\tilde{T}_{4R}} = m_{\tilde{B}_{4L}} = m_{\tilde{B}_{4R}} = m_{\tilde{t}_{4L}} = m_{\tilde{t}_{4R}} \\ m_{\tilde{\ell}_4} &\equiv m_{\tilde{\tau}_{4L}} = m_{\tilde{\tau}_{4R}} \\ m_{q_4} &\equiv m_{T_4} = m_{B_4} = m_{t_4} \\ m_{\ell_4} &\equiv m_{\tau_4} \ . \end{aligned}$$

ALLOWED MASSES

- As with the top Yukawa in the MSSM, the 4th generation quark Yukawa couplings have quasi-fixed points.

- Given the quasi-fixed point value, what masses give the desired Higgs mass? ~1-2 TeV squarks are sufficient. Current lower bound ~1.3 TeV (ATLAS, 1707.03347)



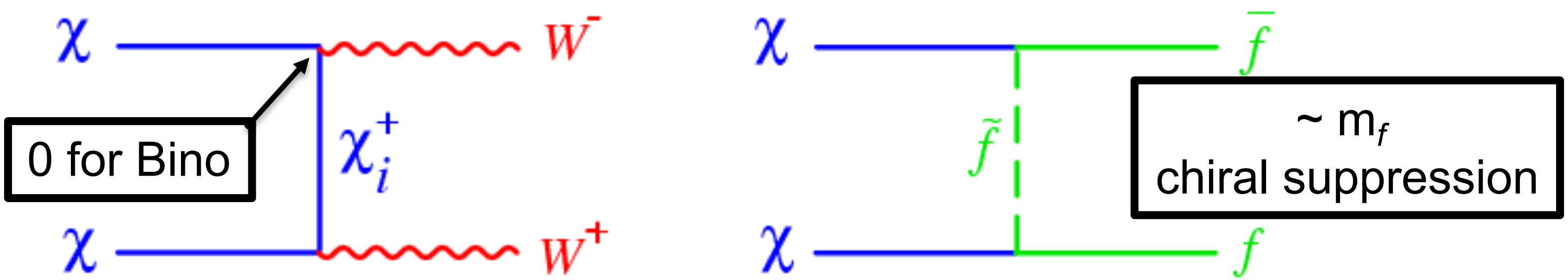


NEUTRALINO DARK MATTER

- 3rd SUSY motivation: requiring correct thermal relic density prefers certain masses, often provides upper limits:

$$\Omega_\chi \sim \frac{1}{\langle \sigma_{\rm ann} v \rangle} \sim \frac{m_\chi^2}{({\rm couplings})^4}$$

- In the MSSM, Bino DM annihilation is highly suppressed, typically get too much DM:



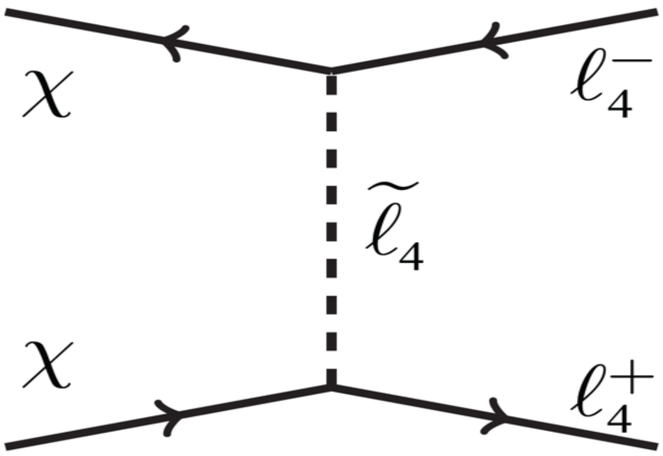
- Need to either raise the couplings (Higgsino/Wino mixing) or lower the mass (light Binos < 200 GeV, gluinos < 1.4 TeV)

MSSM4G DARK MATTER

- For MSSM4G, the situation is completely different. Assume neutralino LSP, annihilates to 4th generation leptons:

$$m_{\tilde{q}4}, m_{\tilde{\ell}_4}, m_{q4} > m_{\tilde{B}} > m_{\ell_4}$$

- Annihilation to 4th generation leptons is unsuppressed, completely dominates all O(100) SM diagrams, opens up new Bino DM parameter space.



- Note: No charged DM, so 4th generation leptons must mix with and decay to e/μ/τ, neutrinos; large range of lifetime.

COSMOLOGICALLY PREFERRED MASSES

- To get the correct thermal relic density, need

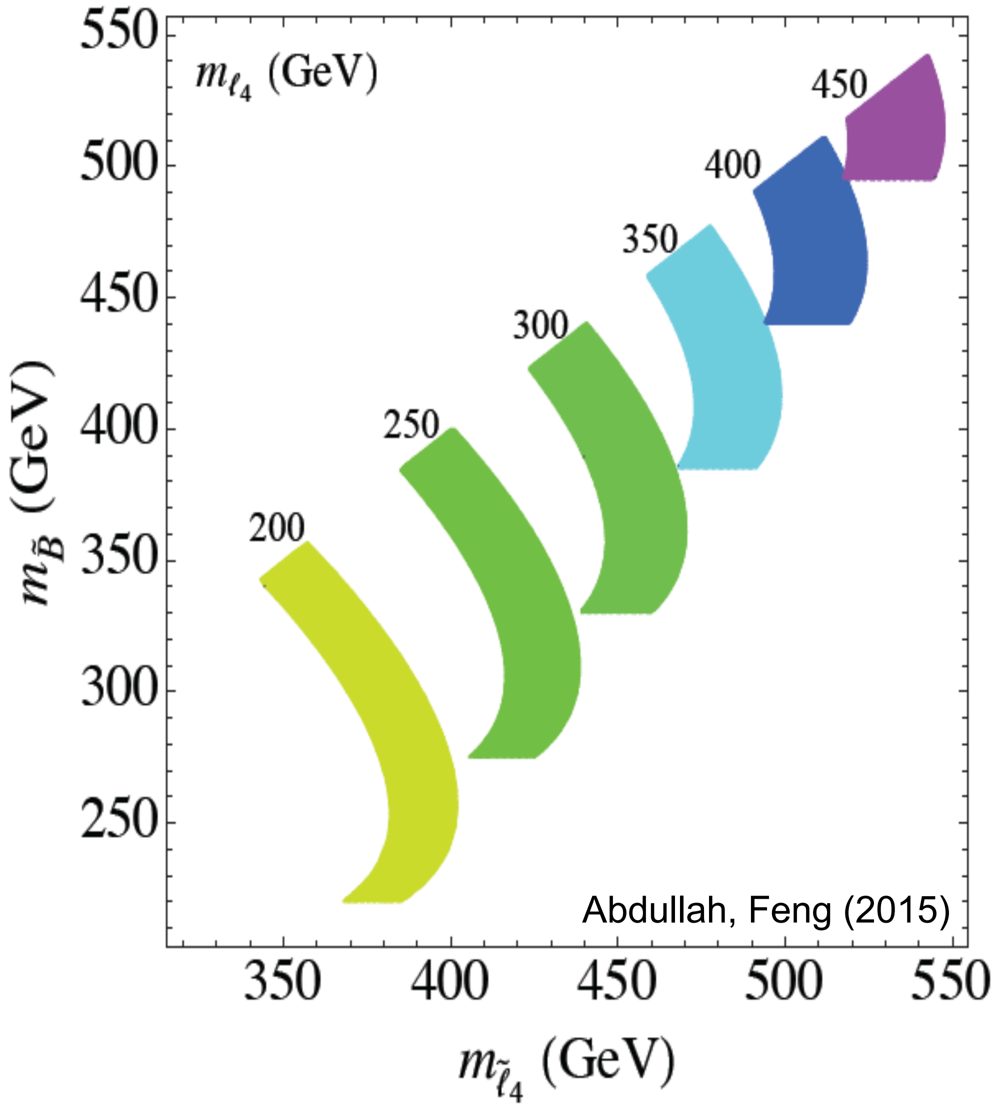
  Bino: 200–550 GeV

  Slepton: 350–550 GeV

  Lepton: 200–450 GeV

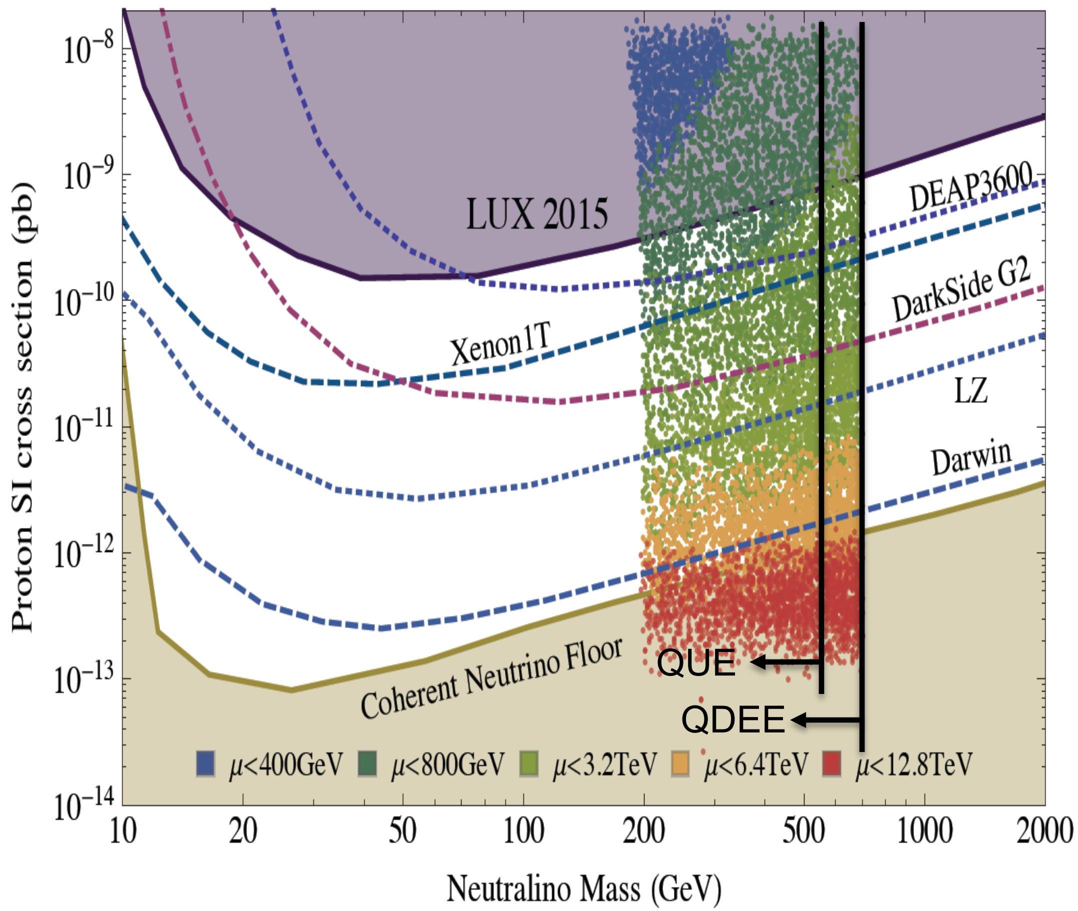
  [Gluino: 1.4-3.8 TeV]

- The masses cannot be higher, or there is too much DM



MSSM4G DARK MATTER DIRECT DETECTION

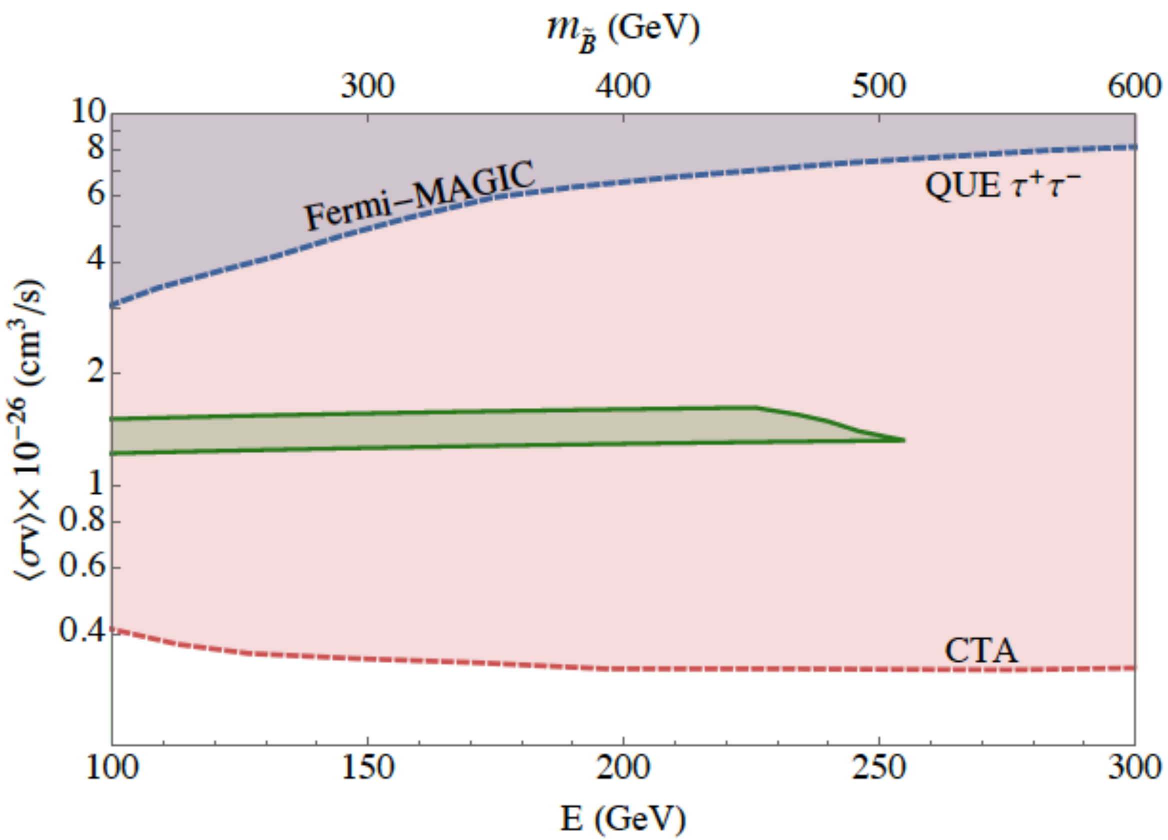
- MSSM4G DM direct detection cross sections naturally fall between current bounds and the neutrino floor



Abdullah, Feng, Iwamoto, Lillard (2016)

MSSM4G DARK MATTER INDIRECT DETECTION

- Halo DM annihilates to τ_4 pairs, which then decay to e/μ/τ, produce gamma rays. Decays to τ may be seen at CTA in the next few years. Decays to e and μ are harder for CTA, but better for the LHC.



Abdullah, Feng, Iwamoto, Lillard (2016)

MSSM4G AT THE LHC

- MSSM4G models imply a wealth of signals at the LHC (see next talk).
- 4th generation particles must decay, but can decay to any of the 1st three generations with a variety of lifetimes. Possible signals:
  - Quarks, squarks, gluinos in the 1-3 TeV range, cascading down to MET signatures
  - $\tau_4\,\tau_4$ Drell-Yan production, followed by decays $\tau_4 \rightarrow \tau Z$, νW, τh, etc.
  - $\tilde{\tau}_4\,\tilde{\tau}_4$ Drell-Yan production, followed by decays $\tilde{\tau}_4 \rightarrow e\,\chi$, $\mu\,\chi$, $\tau\,\chi$
  - $\tilde{\tau}_4\,\tilde{\tau}_4$ Drell-Yan production, leading to long-lived charged particles, displaced vertices

Parameter	QUE (GeV)
$M_{\tilde{B}}$	200 – 540
$m_{\tilde{q}_4}$	1000 – 4000
$m_{\tilde{\ell}_4}$	350 – 550
m_{q_4}	1000 – 2000
m_{ℓ_4}	170 – 450
$m_{\tilde{t}}$	1000 – 4000

Kumar, Martin (2015); Abdullah, Feng, Iwamoto, Lillard (2016)

CONCLUSIONS

- MSSM4G: extension of the MSSM to include 4th generation vector-like particles.
- Higgs mass and gauge coupling unification → only two models to consider: QUE and QDEE.
- ~1-2 TeV stops and 4th generation squarks raise Higgs mass to 125 GeV.
- Dark matter: 350–550 GeV sleptons, 200–550 GeV Binos, 170–450 GeV leptons give correct thermal relic density.
- Promising signals for direct detection, indirect detection, and LHC.