Dark matter and flavor

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Fermilab Astrophysics Seminar
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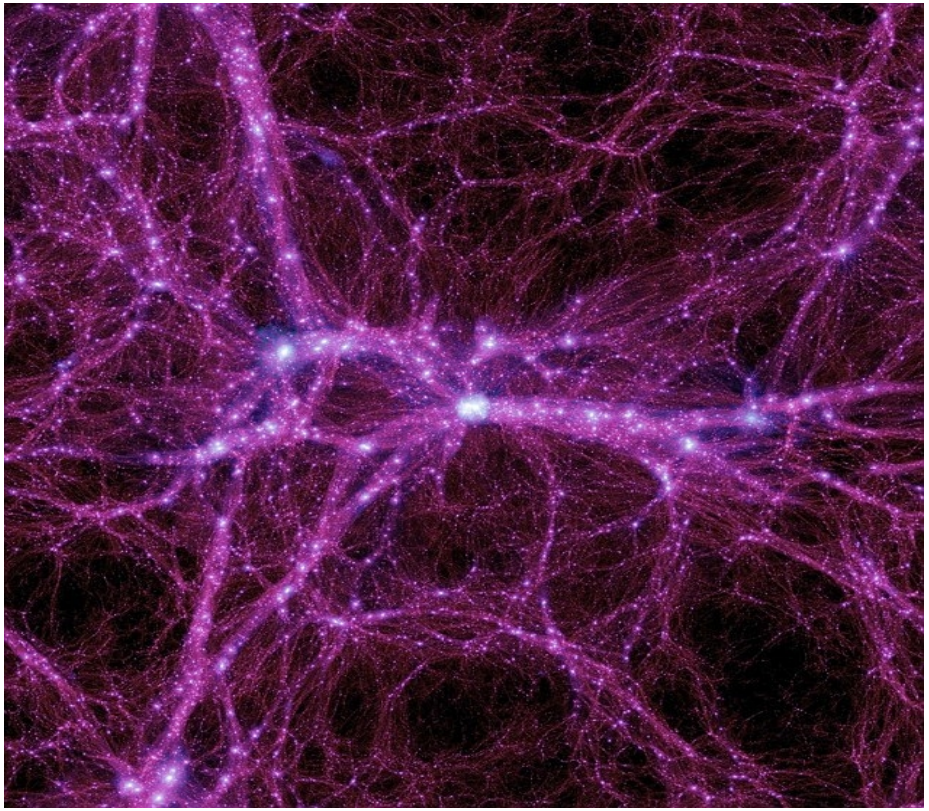
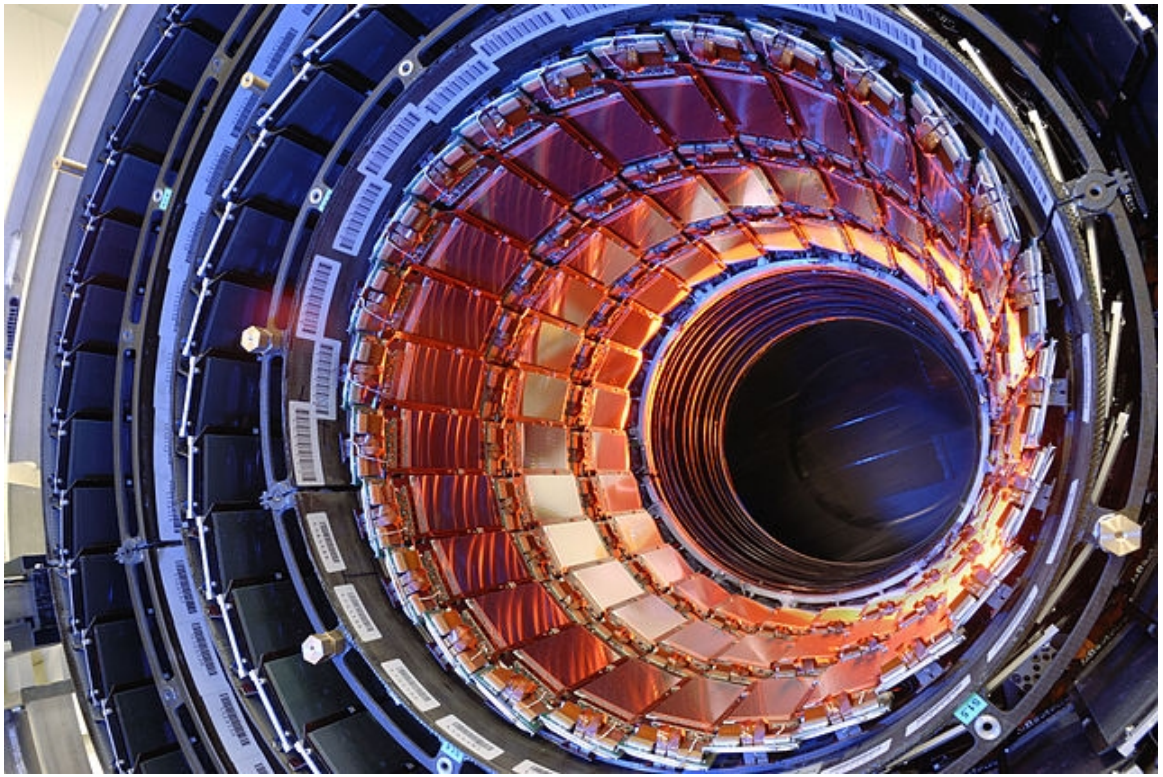
Dark matter is out there!

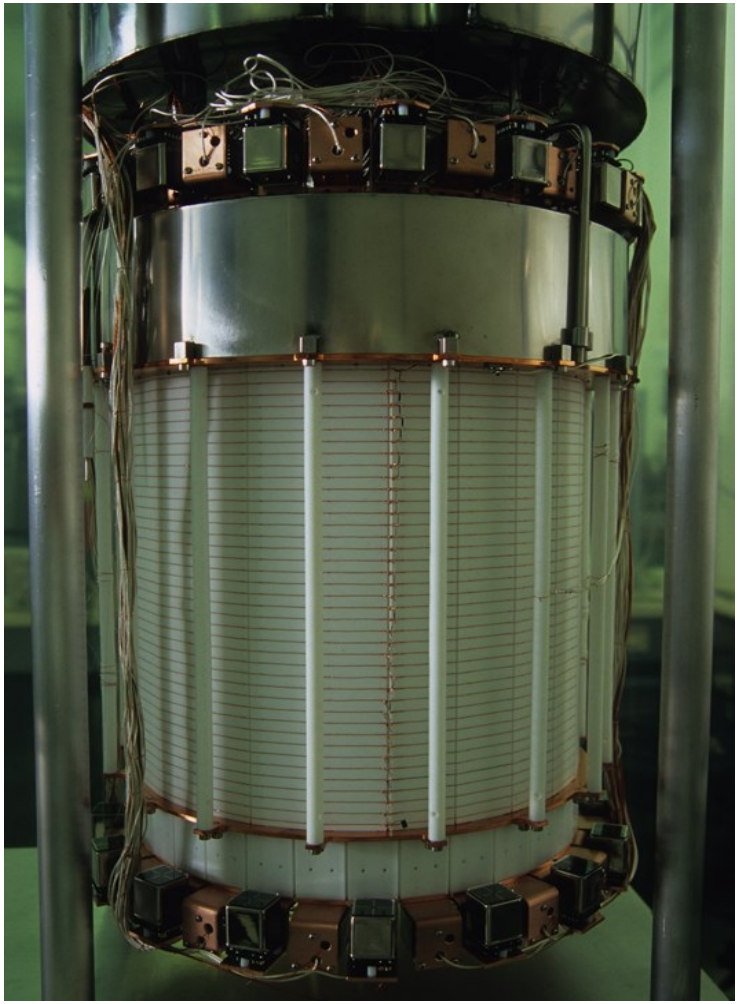
measurement



(educated) guess

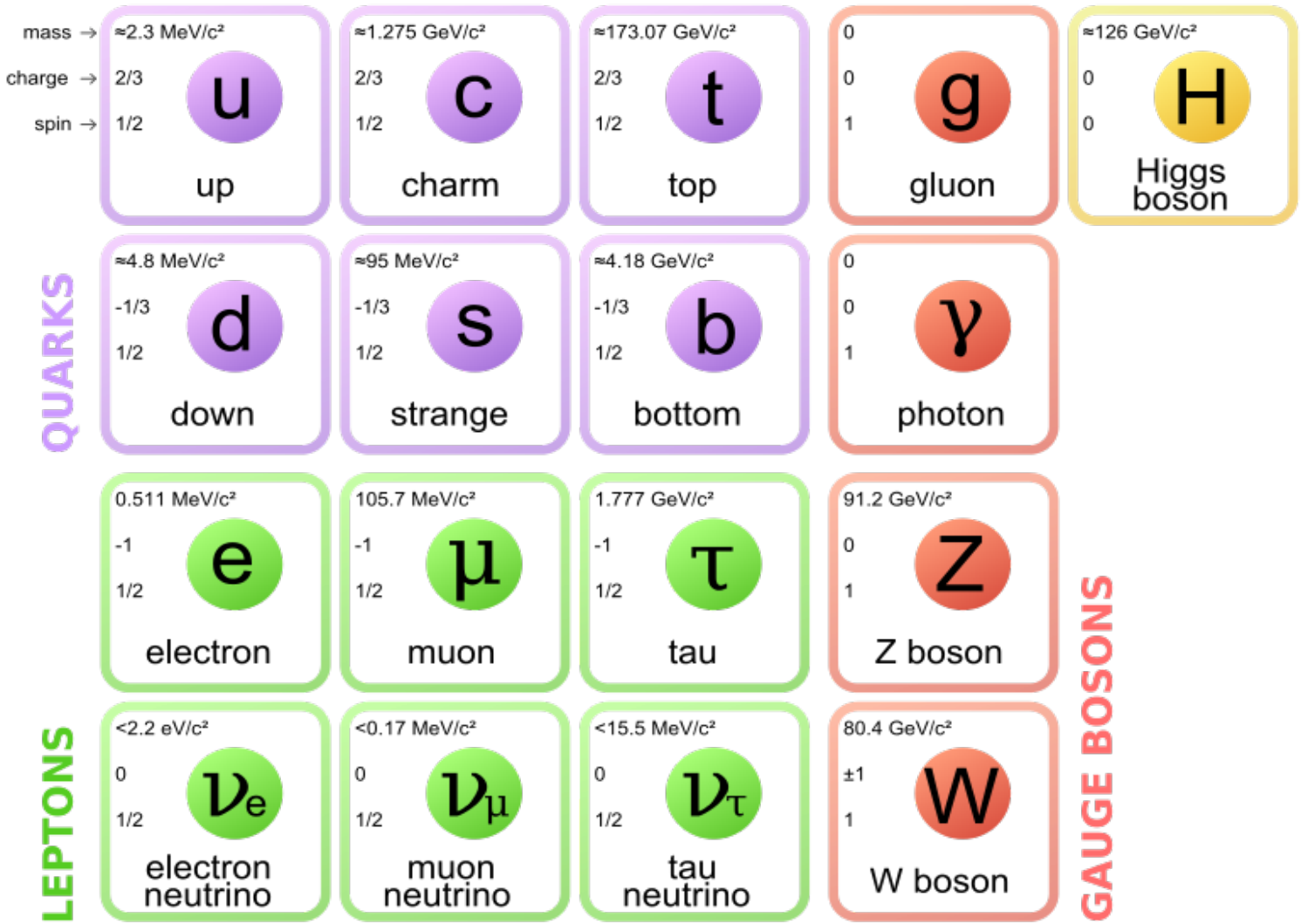
How do we find dark matter?





How do we find dark matter?

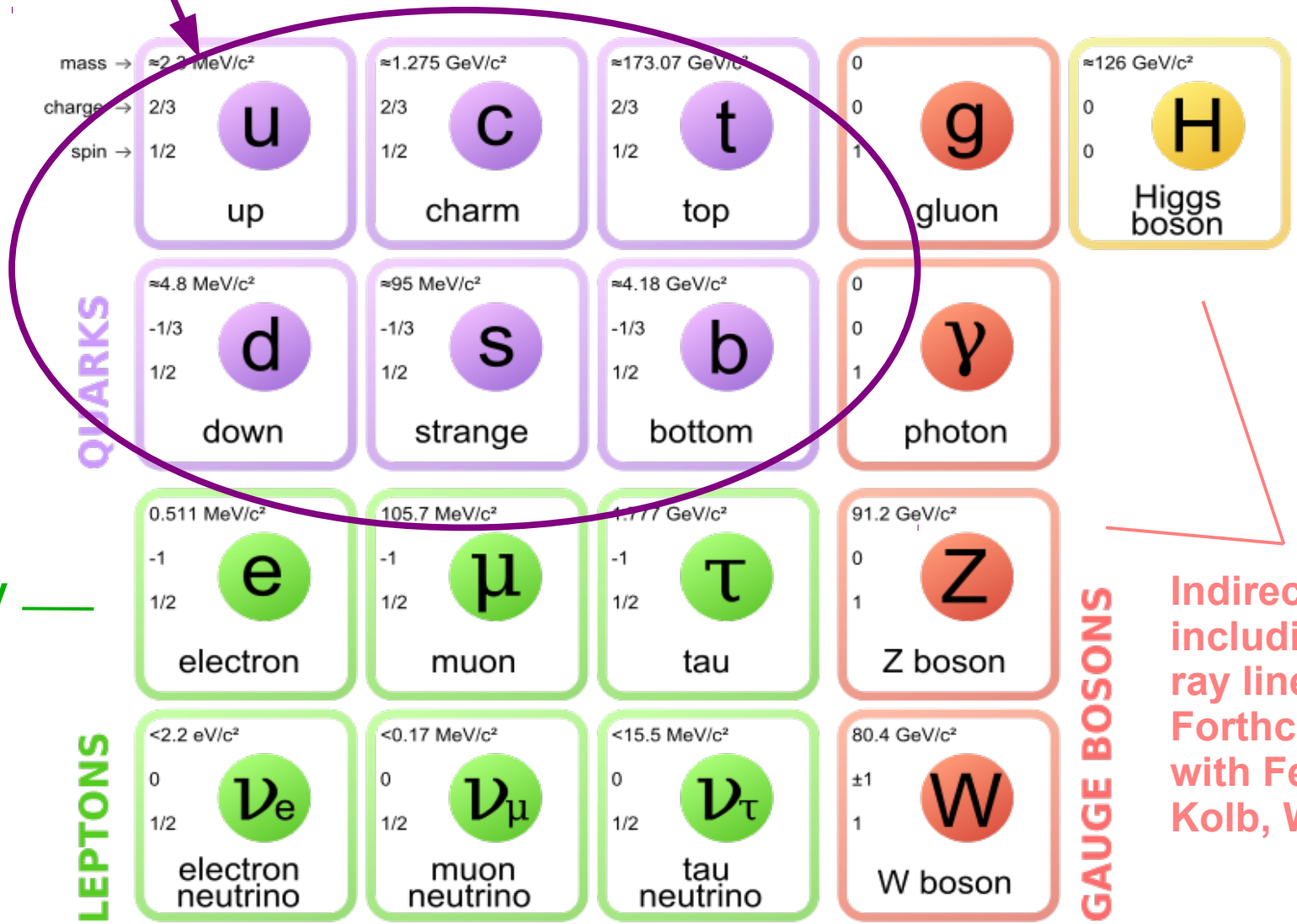
What does it interact with?



Focus of this talk

Can have indirect signals (gamma rays), direct detection, and collider signals.

How does DM interact w/ different quark flavors? Signals will differ!



cosmic-ray positrons

Indirect signals including gamma-ray lines. Forthcoming work with Fedderke, Lin Kolb, Wang.

Outline of talk

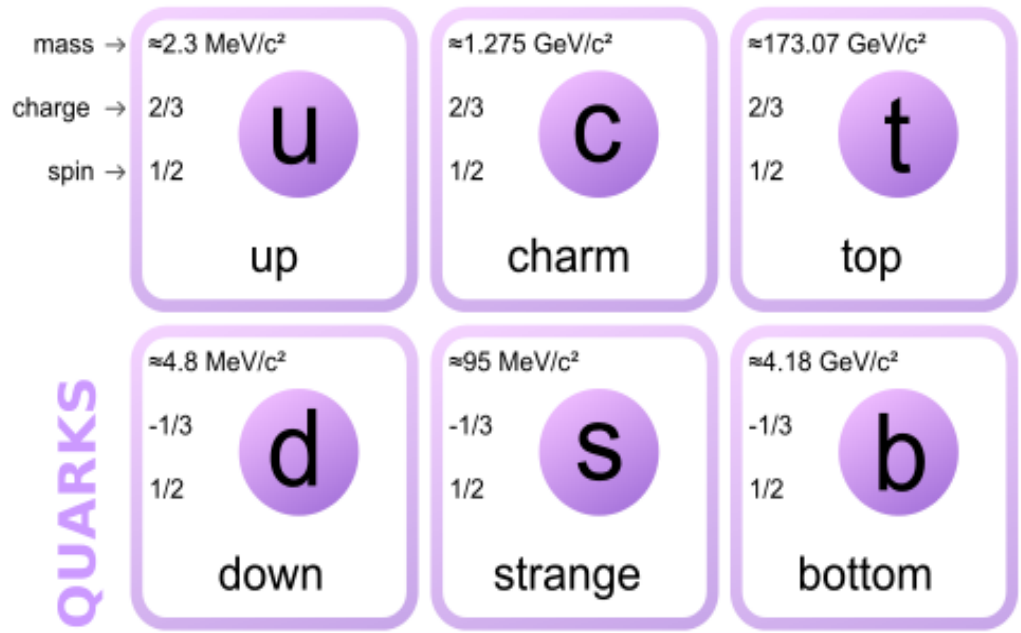
- Flavor in the Standard Model and Minimal Flavor Violation
- A model-independent example:
  - Mono-*b* (DM + heavy quark at colliders)
- An example of a model with tops:
  - Top-flavored DM
- Theoretical motivation for flavored dark matter in SUSY

Quark flavor in the Standard Model

Three generations

Up-type quarks →

Down-type quarks →



- Same QCD, electroweak charges across generations

Quark flavor in the Standard Model

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

+ right handed quarks

- Large flavor symmetry:

$$SU(3)_Q \times SU(3)_u \times SU(3)_d$$

(broken by quark masses)

- For most of the talk, working definition of flavor: label for which quark.

Flavor in the Standard Model

- Yukawa interactions break flavor symmetry:

$$\mathbf{Y_u}\bar{Q}H^\dagger u_R + \mathbf{Y_d}\bar{Q}Hd_R$$

(quark mass through Higgs vev)

- Source of CP violation and flavor violation in the SM

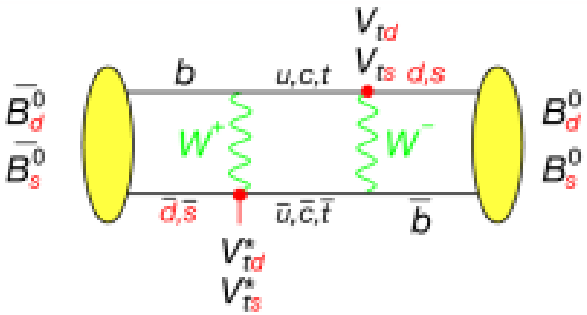
$$\mathbf{Y_u} \approx V_{CKM}^\dagger \begin{pmatrix} 10^{-5} & 0 & 0 \\ 0 & 10^{-2} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \mathbf{Y}_d \approx \begin{pmatrix} 10^{-5} & 0 & 0 \\ 0 & 10^{-3} & 0 \\ 0 & 0 & 10^{-2} \end{pmatrix}$$

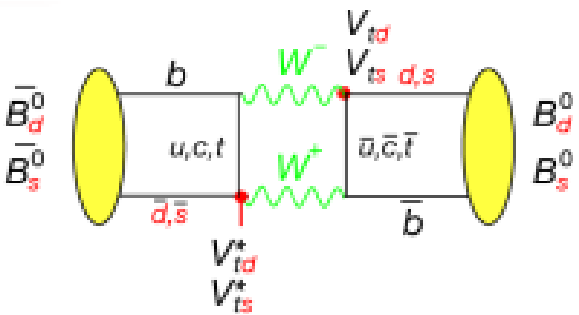
$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3/2 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Mixing between generations suppressed by $\lambda \sim 0.2$

CP/Flavor Violation

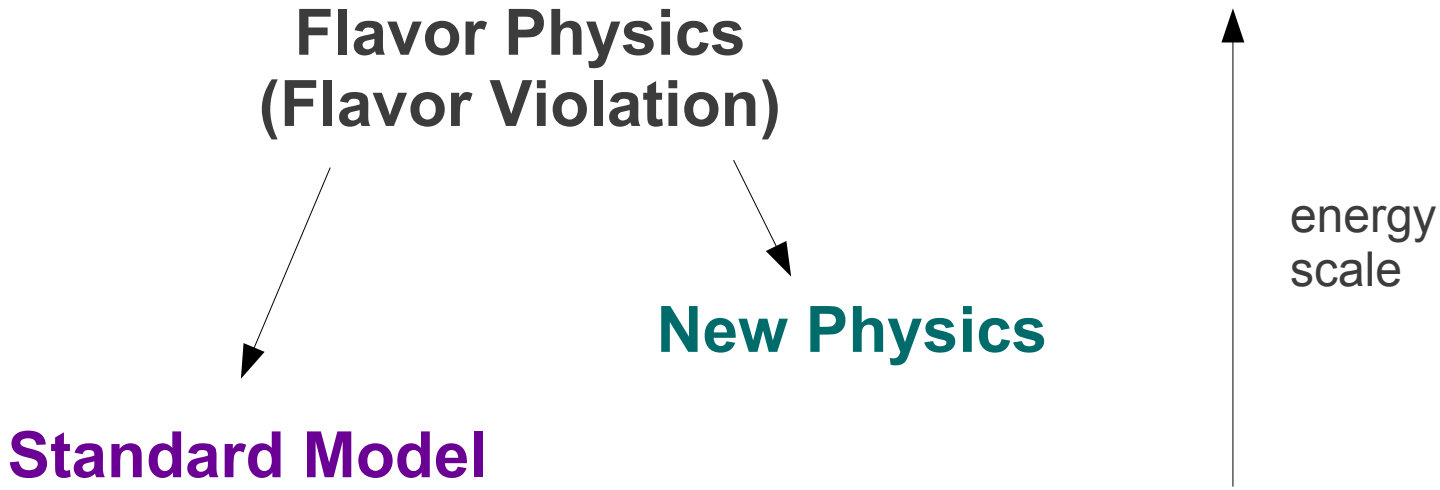
- Because of the structure of the Yukawas, flavor-changing neutral currents are very suppressed in the Standard Model
- Additional sources of CP/flavor violation are highly constrained by studies of B meson decays, neutral meson mixing, etc.
- Scale of new physics must be above hundreds of TeV





(e.g. D'Ambrosio, Giudice, Isidori, Strumia)

Minimal Flavor Violation (MFV)



- No **new** sources of flavor violation
- Flavor violation can be present, but only through SM Yukawa interactions Yu, Yd
- New interactions with quarks must respect gauge <u>and</u> flavor symmetry
- *Assumption* of many models (including in MSSM)

Minimal flavor violation and dark matter

- The assumption of MFV can imply large couplings to third generation (bottom and top) → study collider signals
  - Parts 2, 3 of this talk

- Flavor symmetry can also guarantee stability of dark matter, split the spectrum in the dark matter sector, and be embedded in SUSY
  - Part 3, 4 of this talk

- *See also: Batell et al., Kile, Agrawal et al., Kamenik and Zupan, etc...*

Dark matter and heavy quarks (at the LHC)

Study of collider signals of scalar operators:

MFV form of couplings

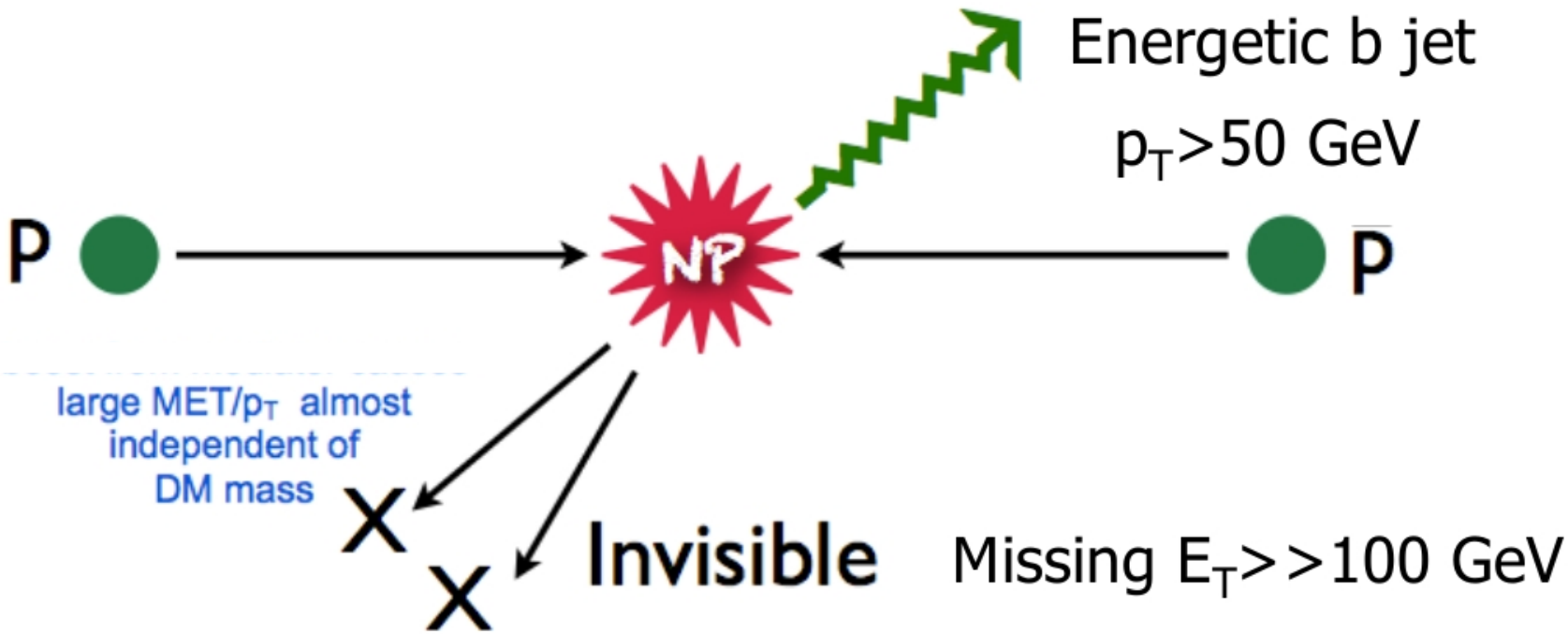
"Maverick" DM: Assume single effective operator

$$\mathcal{O} = \sum_q \frac{m_q}{M_*^3} \bar{q} q \bar{X} X$$

In collaboration with:

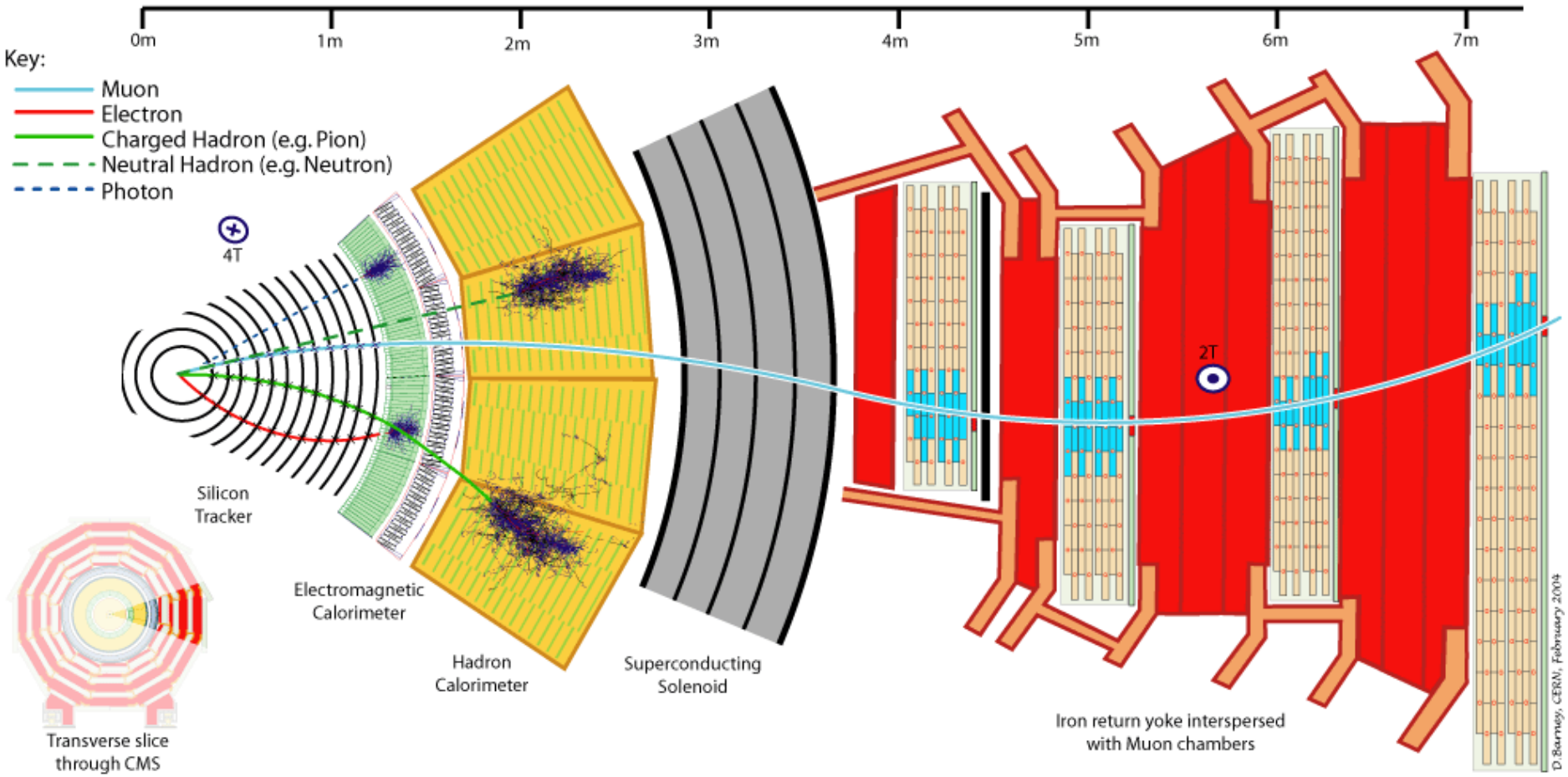
- T. Lin, Rocky Kolb, Liantao Wang, arXiv: 1303.6638
- Giacomo Artoni, T. Lin, Bjoern Penning, Gabriella Sciolla, Alessio Venturini, arXiv: 1307.7834

“Mono (b)-jet” searches



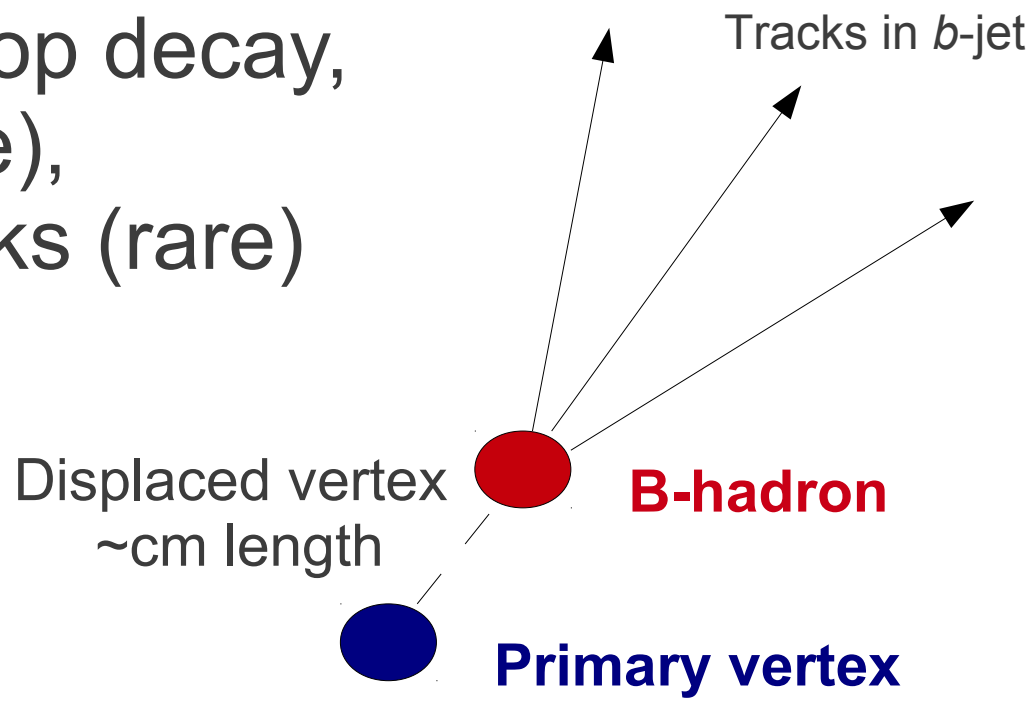
[Graphic from G. Sciolla]

See also: monojet, monophoton, mono-W/Z, razor search for DM, etc.


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

b-jets

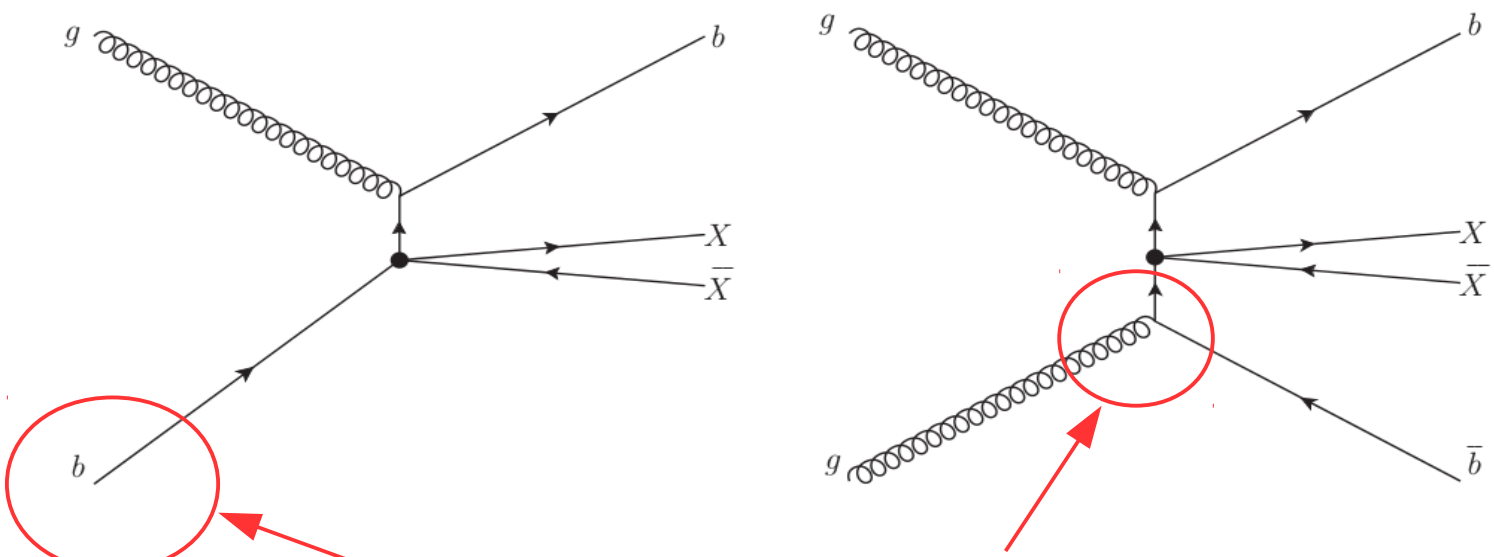
- Hadrons with *b*-quarks are long lived, heavy.
- Displaced vertex can be used to tag *b*'s.
  (efficiency ~ 50-70%)
- Observe *b*'s from top decay,
  gluon splitting (rare),
  mis-identified quarks (rare)



Scalar operator

$$\mathcal{O} = \sum_q \frac{m_q}{M_*^3} \bar{q} q \bar{X} X$$

Production mechanisms for b-quarks plus MET (DM)



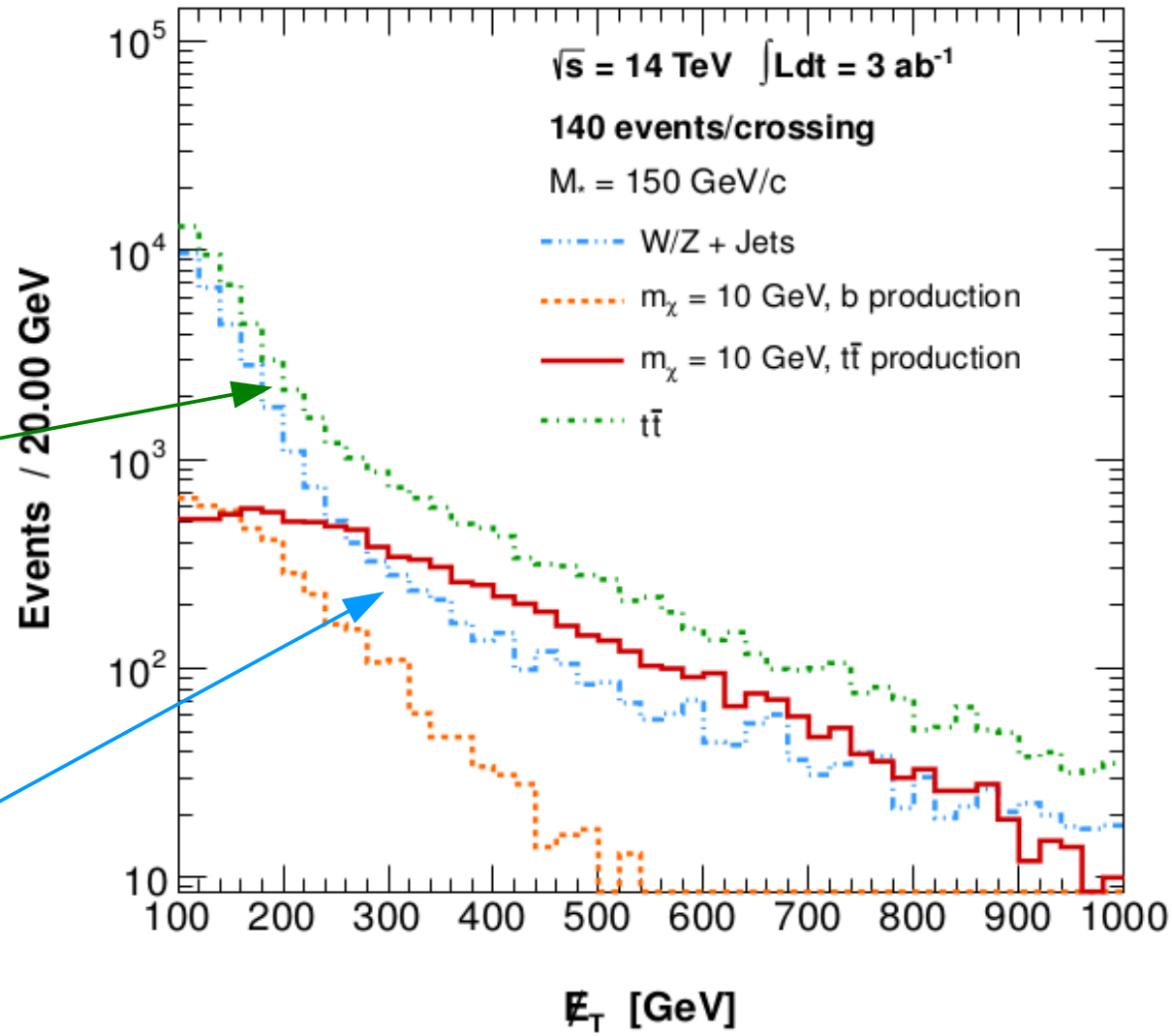
Although b-content of proton is small, and b-production is rare, this is (more than) made up by large couplings to b-quarks.

LHC search

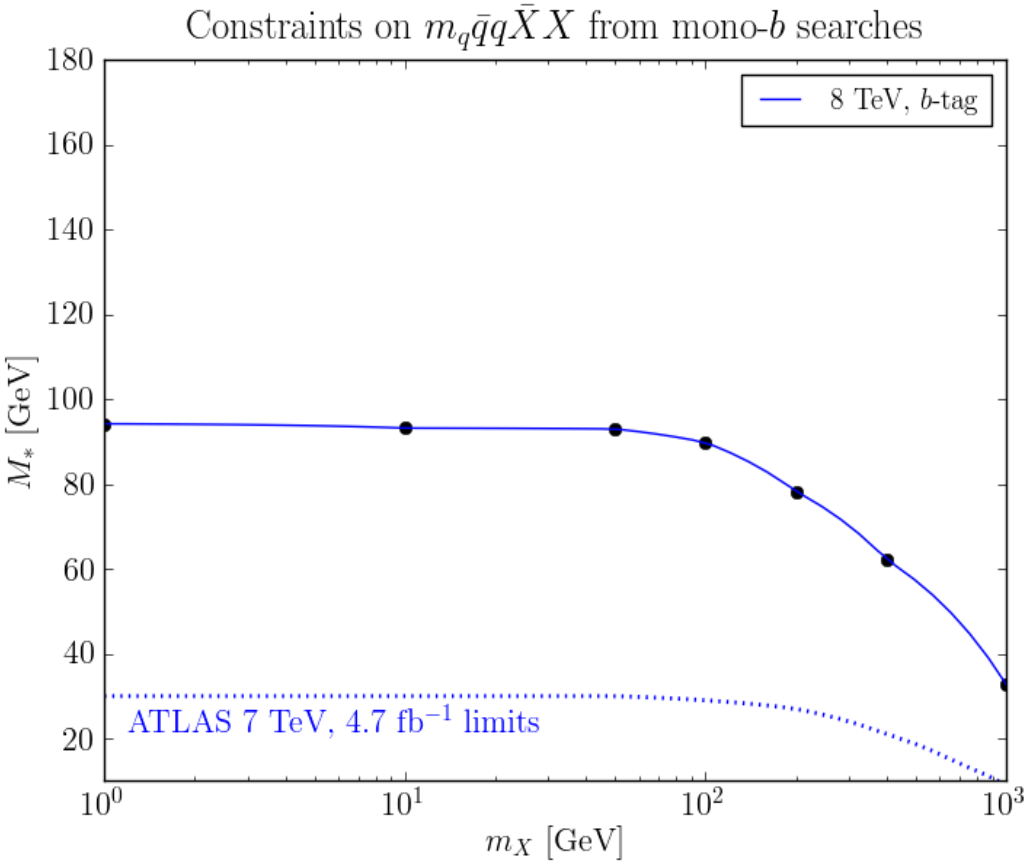
Requiring a *b*-tag cuts down backgrounds. Still have:

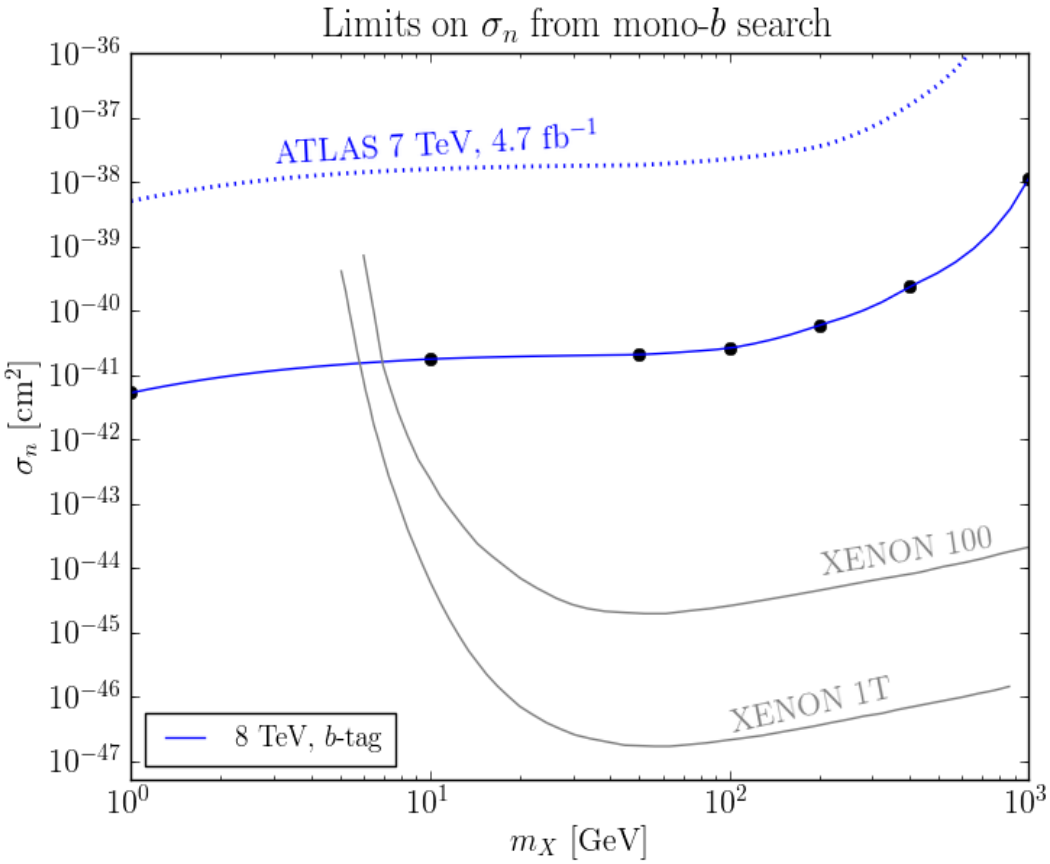
SM sources of b-quarks and missing transverse momentum: tops + jets.

SM sources of missing transverse momentum: W/Z(> neutrinos) + jets. Can have jet fake a b-jet.



Projected limits for 8 TeV run

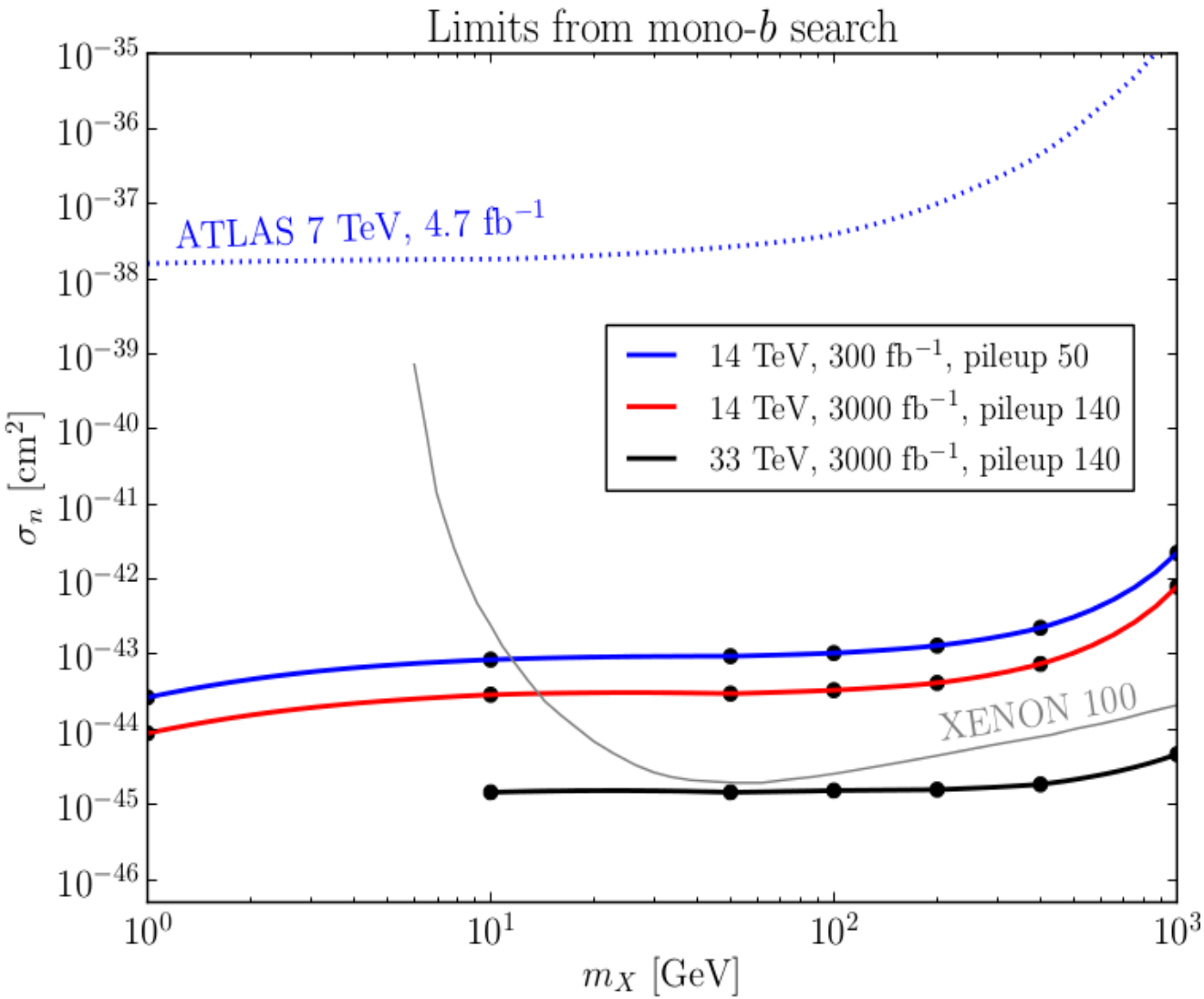




Spin-independent scattering:

$$\sigma_n = \frac{(0.38 m_n)^2 \mu_X^2}{\pi M_*^6} \approx 2 \times 10^{-38} \mathrm{cm}^2 \left(\frac{30 \text{ GeV}}{M_*} \right)^6$$

Prospects for DM+b searches



DM+heavy quark summary

- Collider studies of operator with MFV couplings to dark matter
- Improvement in limits, and direct probe of flavor structure of DM-quark interactions
- Effective operator analysis.

- Next: build a complete model (and get the right relic abudance)

Top-flavored DM
(super-flavored DM)

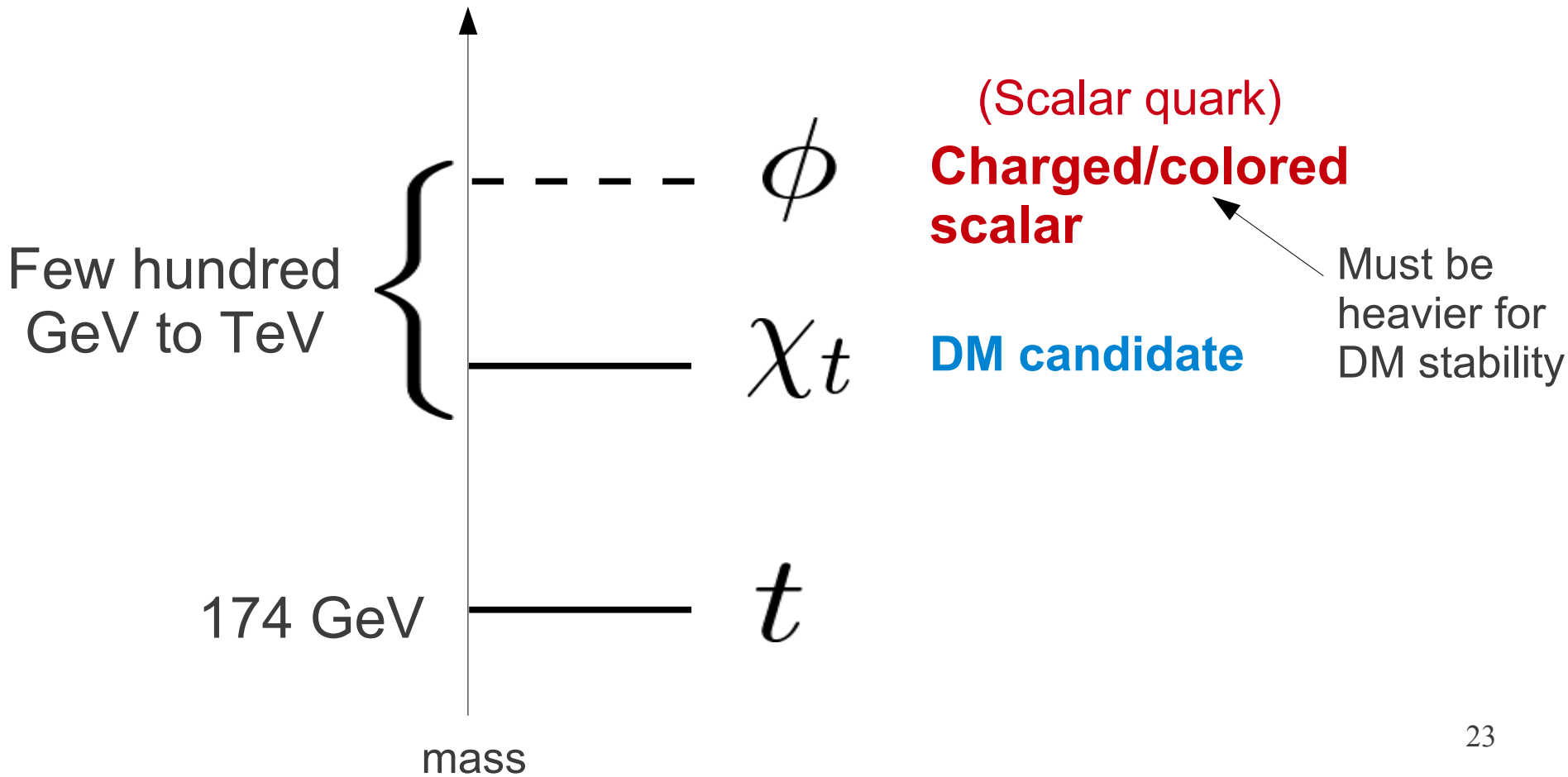
- Studied in context of MFV SUSY (more later)
- DM candidate coupling primarily to top quarks – required from MFV structure
- New “scalar quark” acting as mediator

In collaboration with:

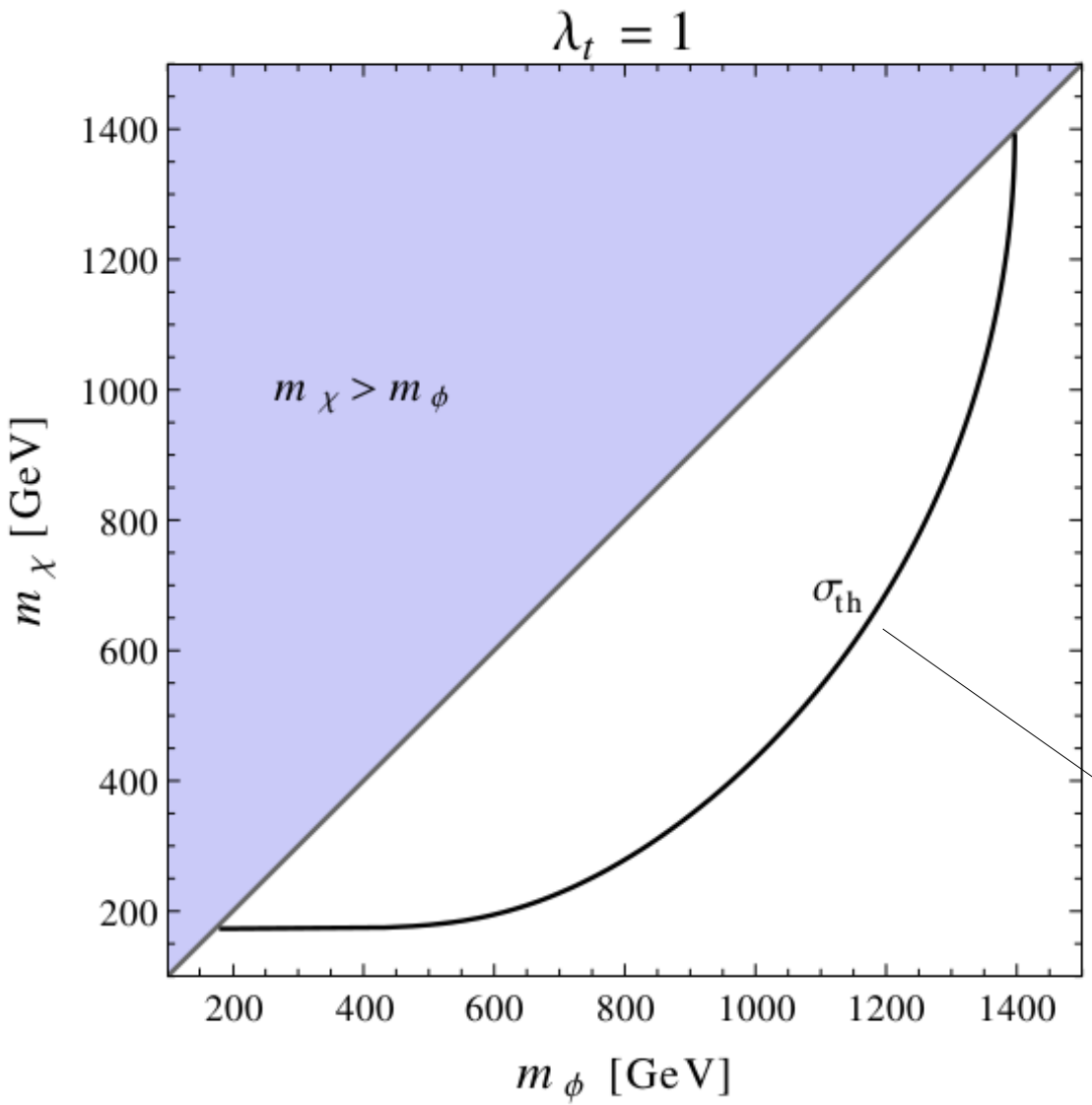
- Brian Batell, T. Lin, Liantao Wang, arXiv:1309.4462

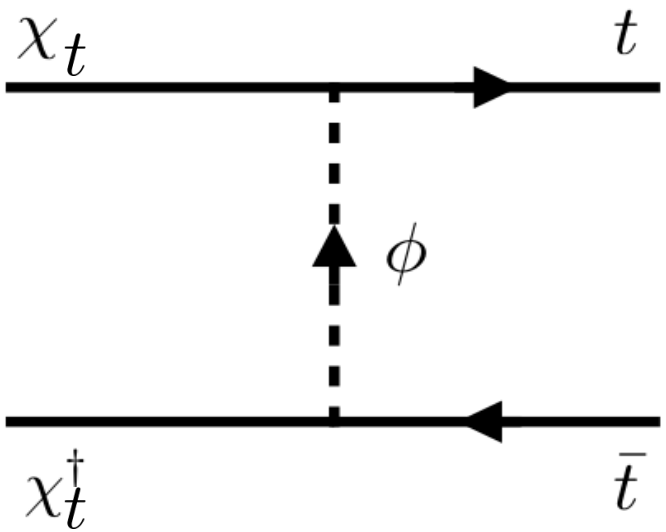
Top-flavored DM:
Spectrum & interactions

- Yukawa interaction: $\lambda_t \bar{\chi}_t t_R \phi + h.c.$



Relic abundance

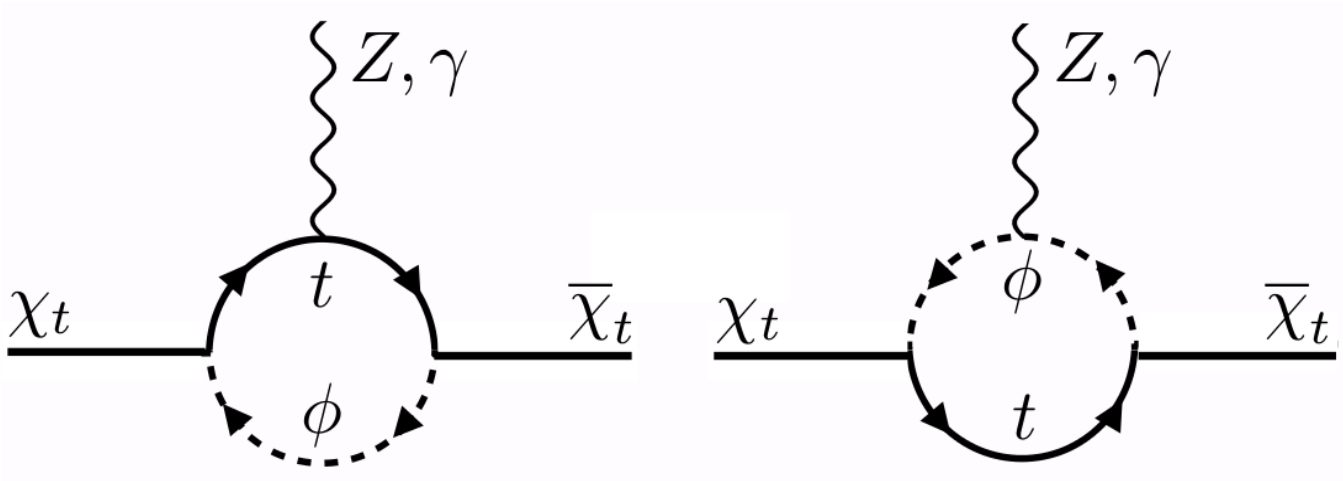


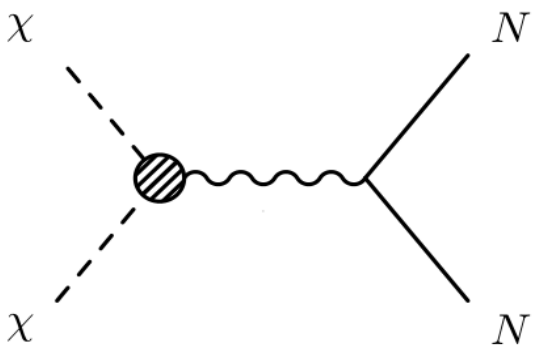


Outside σth curve: Relic abundance too high.

Direct Detection

- No direct detection at leading order.
- However, a loop with *Z* emission gives rise to sizable direct detection:





Direct Detection

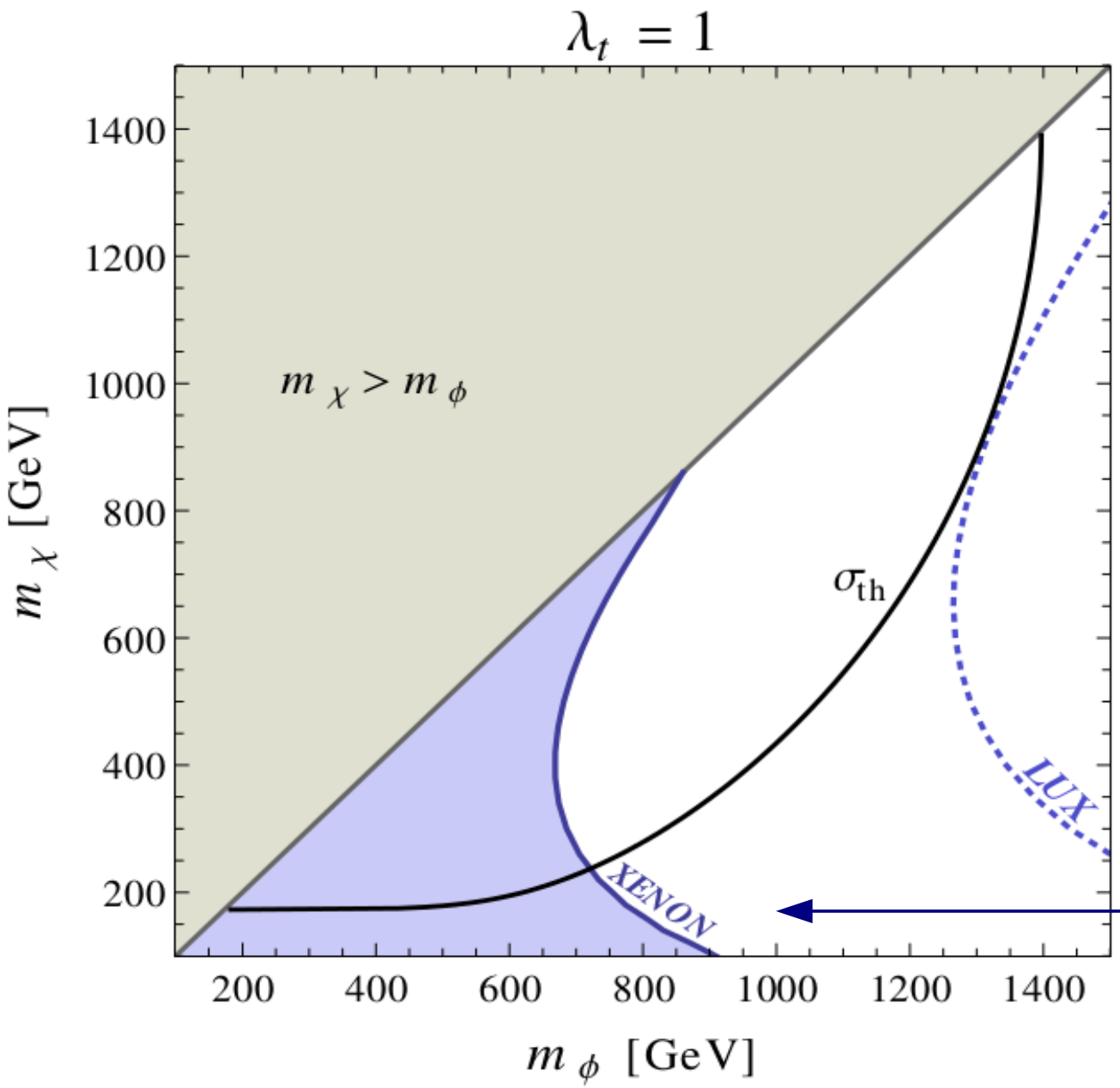
- Coupling to *Z* dominates:

$$g_Z Z^\mu \bar{\chi}_t \gamma^\mu P_L \chi_t$$

  - This loop is proportional to mass of the fermion in the loop. It's important that its top-flavored!
- Magnetic dipole moment from coupling to photon

$$\frac{\mu_\chi}{2} F_{\mu\nu} \bar{\chi}_t \sigma^{\mu\nu} \chi_t$$

  - Usually subdominant, although dipole-charge interactions can be important for large DM, scalar masses
  - Scattering from charge form factor also small



LUX projection with 10000 kg-day

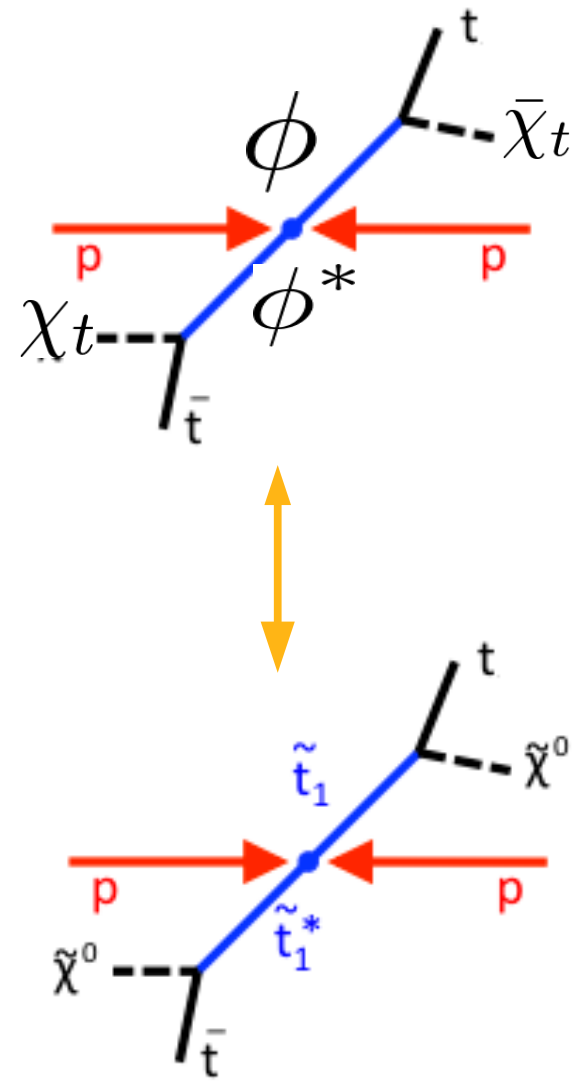
XENON100 limits

Collider signals

- Dark matter will be produced with tops: missing transverse momentum + heavy quarks
- Pair production of new colored scalar ϕ
- Scalar decays

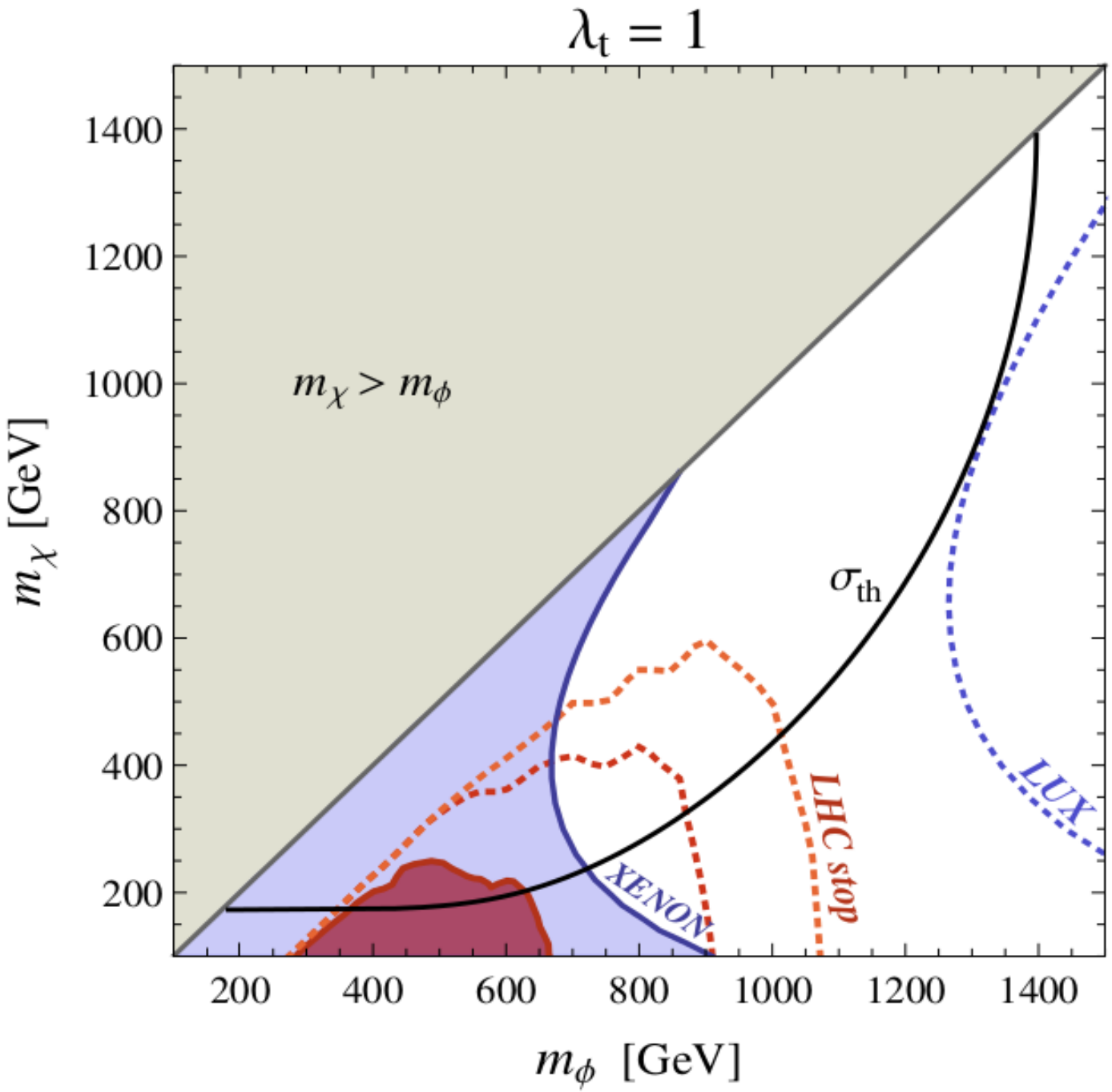
$$\phi \to t\ \bar{\chi}_t$$

- SUSY s(calar)-top search applies



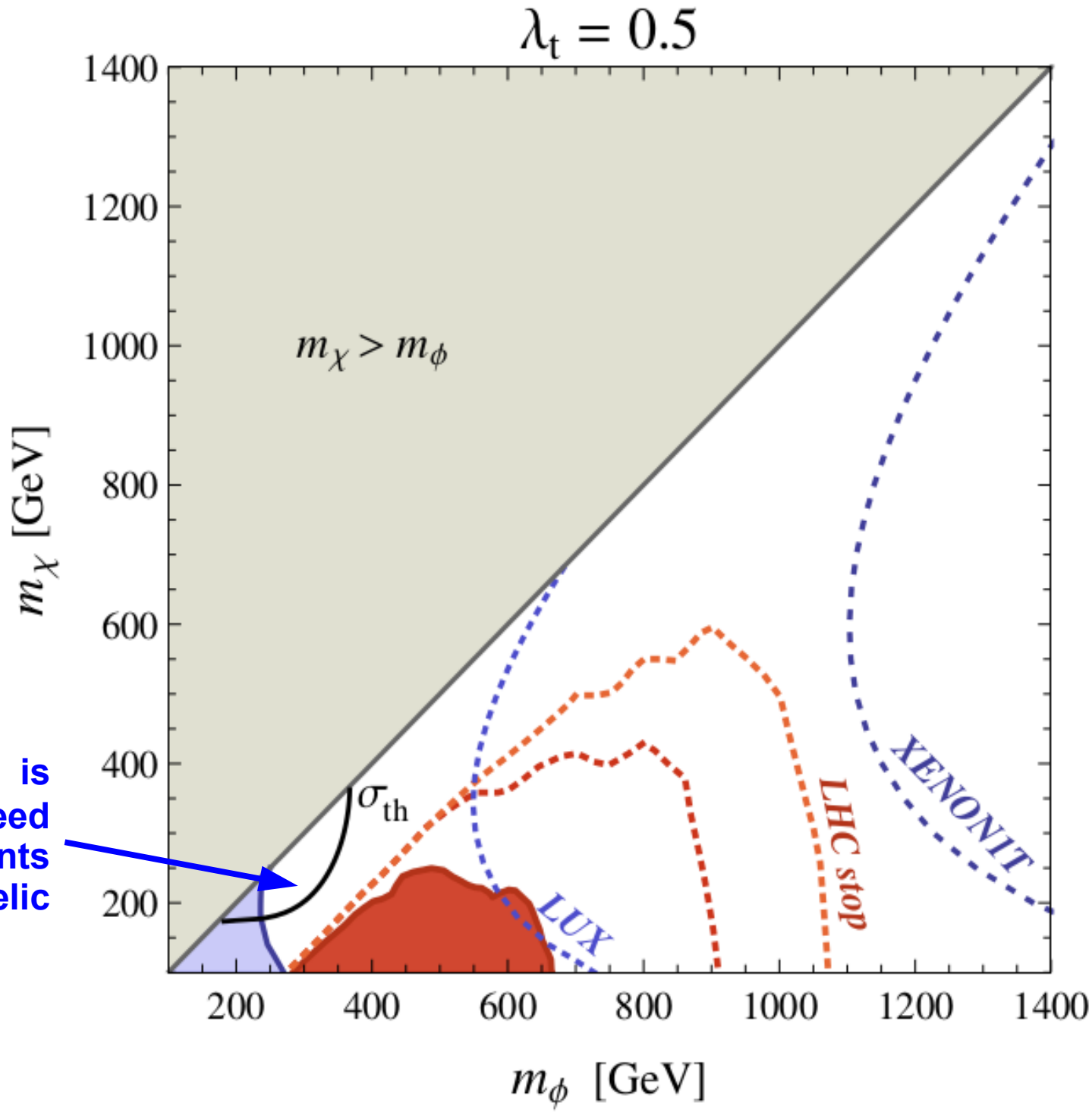
Prospects for model

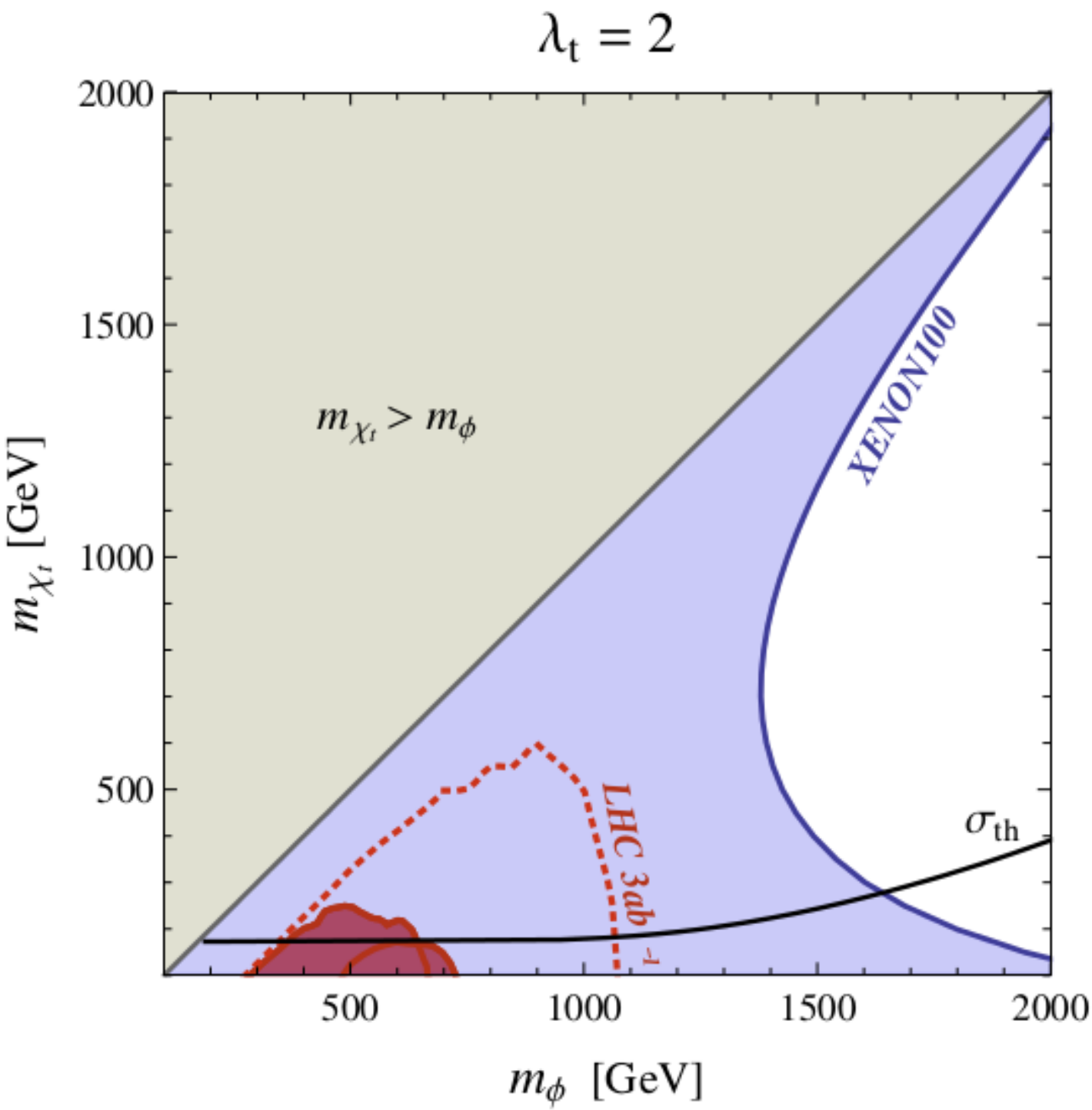
- For a thermal relic, can be tested by combination of LUX/Xenon1T, and to a lesser extent LHC
- Indirect signals more difficult in near future since large DM masses



LHC constraints more relevant here! (But these are 3000/ab projections.)

If the coupling λ is much smaller, need additional ingredients to get the right relic abundance





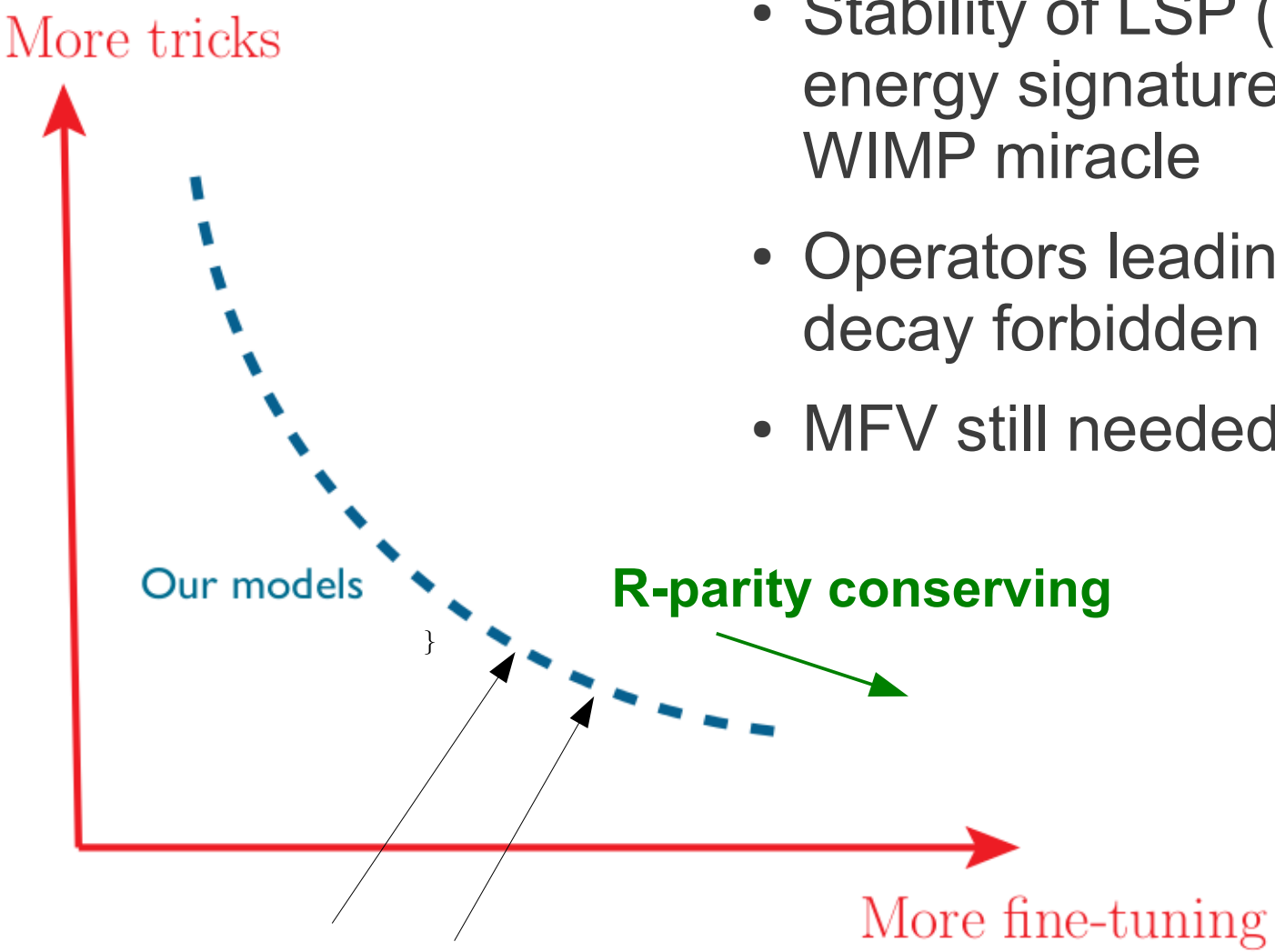
For larger coupling, DM and scalar masses are pushed beyond TeV range

Why top-flavored DM?

- We studied this model in the context of supersymmetry with R-parity violation (RPV) and minimal flavor violation (MFV)
- Adding dark matter to MFV SUSY:
  - Stabilisation of DM if DM is a flavor multiplet
  - Spectrum, couplings of dark matter determined by MFV and holomorphy of superpotential
  - Naturally get DM candidate coupling to tops

R-parity conservation

- Stability of LSP (missing energy signatures @ LHC), WIMP miracle
- Operators leading to proton decay forbidden
- MFV still needed



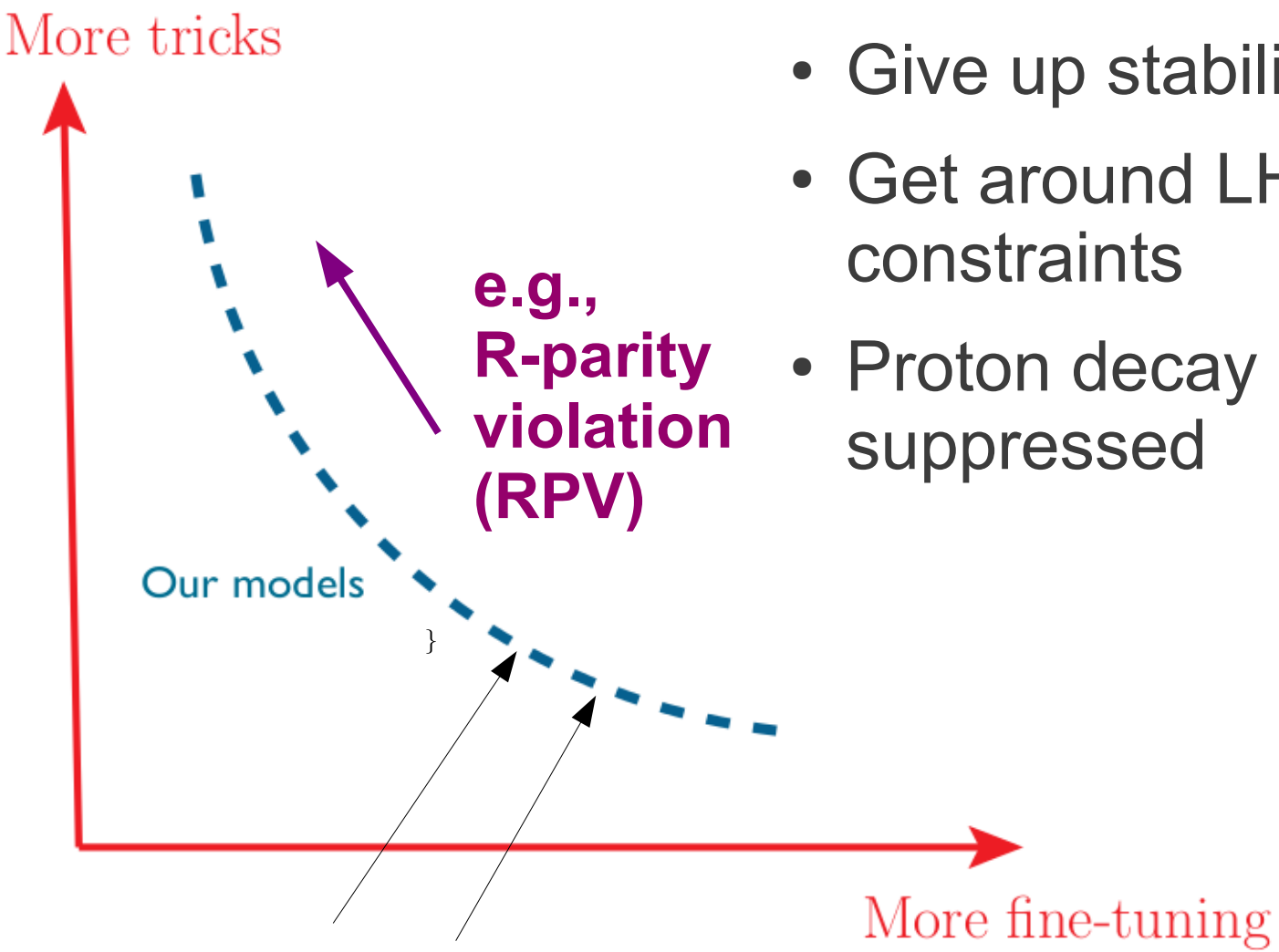
LHC constraints are pushing this curve out

[“Plot” from L.T. Wang]

Csaki, Grossman, Heidenreich 2012

RPV plus MFV

- Give up stability of LSP
- Get around LHC constraints
- Proton decay also suppressed



LHC constraints are pushing this curve out

R-parity

- R-parity

$$P_R = (-1)^{3(B-L)+2s}$$

  - Lightest superpartner stable

Lead to proton decay

$$\tau_p \sim 10^{33}\,\mathrm{yr}\left(\frac{10^{-19}}{\lambda'}\right)^2\left(\frac{10^{-8}}{\lambda''}\right)^2\left(\frac{m_{\tilde{q}}}{\mathrm{TeV}}\right)^4$$

- R-parity violation

$$W' = \lambda L L \bar{e} + \lambda' Q L \bar{d} + \lambda'' \bar{u}\bar{d}\bar{d} + \mu' L H_u$$

- In MFV SUSY:

Yukawas are spurions; holomorphic couplings

$$W' = w''(Y_u \bar{u})(Y_d \bar{d})(Y_d \bar{d})$$

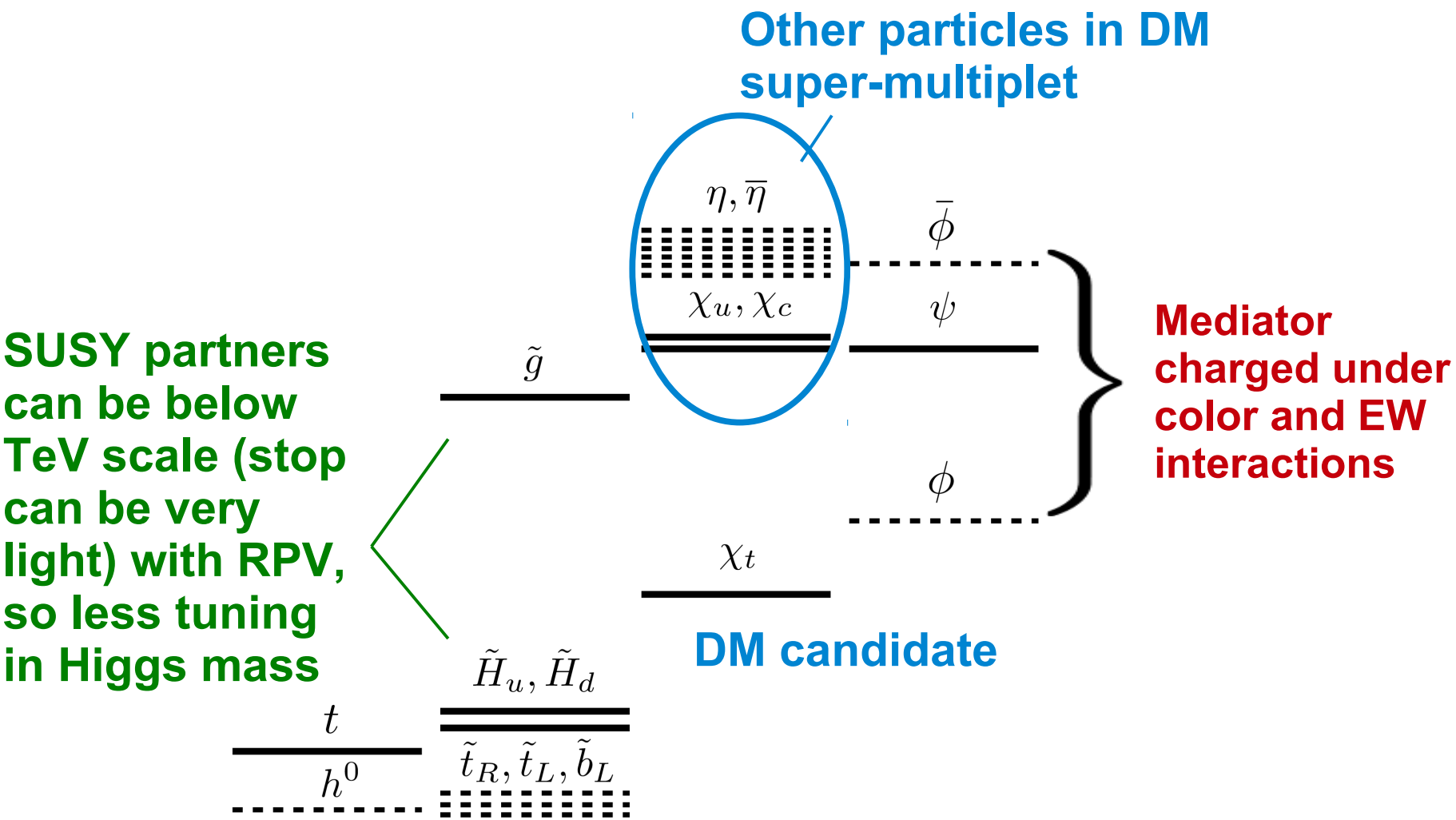
DM stability from flavor

- MFV SUSY: the LSP (WIMP candidate) is no longer stable
- However, flavor symmetry may be why dark matter is stable! DM may be in flavor multiplet. (Batell, Pradler, Spannowsky)
- Flavor triality: DM is lightest particle charged under this symmetry

$$U \equiv \left(e^{4\pi i/3}\right)_{\text{color}} \times \left(e^{2\pi i/3}\right)_{Q} \times \underbrace{\left(e^{2\pi i/3}\right)_{u} \times \left(e^{2\pi i/3}\right)_{d}}_{\text{Rotation in “flavor space”}}$$

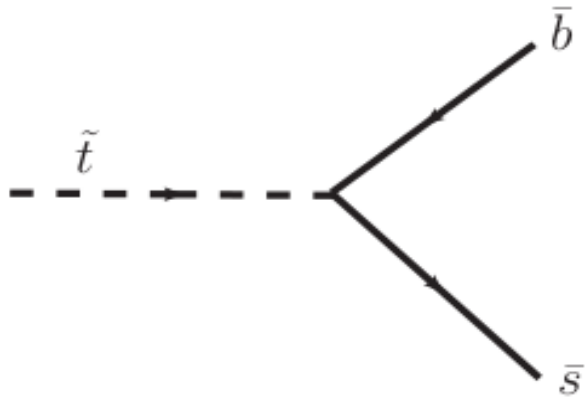
Yukawa, SM particles
neutral WRT flavor triality.

Full spectrum of top-flavored DM



Collider signals

- The LSP could be the stop, which decays through the RPV coupling:



- As in the R-parity conserving MSSM, there are missing energy signals from DM. However, the LHC constraints are no longer tied to naturalness (or at least less directly)

Summary

- Flavor violation is suppressed in the SM – very sensitive to any structure in new physics
- Assume minimal flavor violation and study DM couplings to different quark flavors
- Discussed few different directions
  - Effective (scalar) operator with MFV couplings
  - Super-flavored dark matter (in MFV SUSY)
  - Model of top-flavored dark matter

DM and flavor: outlook

- Plenty to do in this direction: collider phenomenology, flavor observables
  - Collider searches: not (always) just re-interpreting SUSY searches – depends on kinematics
  - Also, other searches for flavor violation, such as flavor violating top decays, monotop
- Focus here on third generation quarks (especially top-flavored). Other authors have thought about other possibilities, including lepton-flavored.