On Heavy Supersymmetry

Timothy Cohen
[slac]

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Acknowledgements

Wino Dark Matter Under Siege:

TC, Mariangela Lisanti, Aaron Pierce, Tracy R. Slatyer

[arXiv:1307.4082]

SLAC simplified models (theory) team:

TC, Kiel Howe, Jay Wacker

Snowmass backgrounds team:

Aram Avetisyan, James Dolen, James Hirschauer,

Meenakshi Narain, Sanjay Padhi, Michael Peskin, John Stupak

Snowmass simplified models (experimental) team:

Tobias Golling, Mike Hance, Anna Henrichs,

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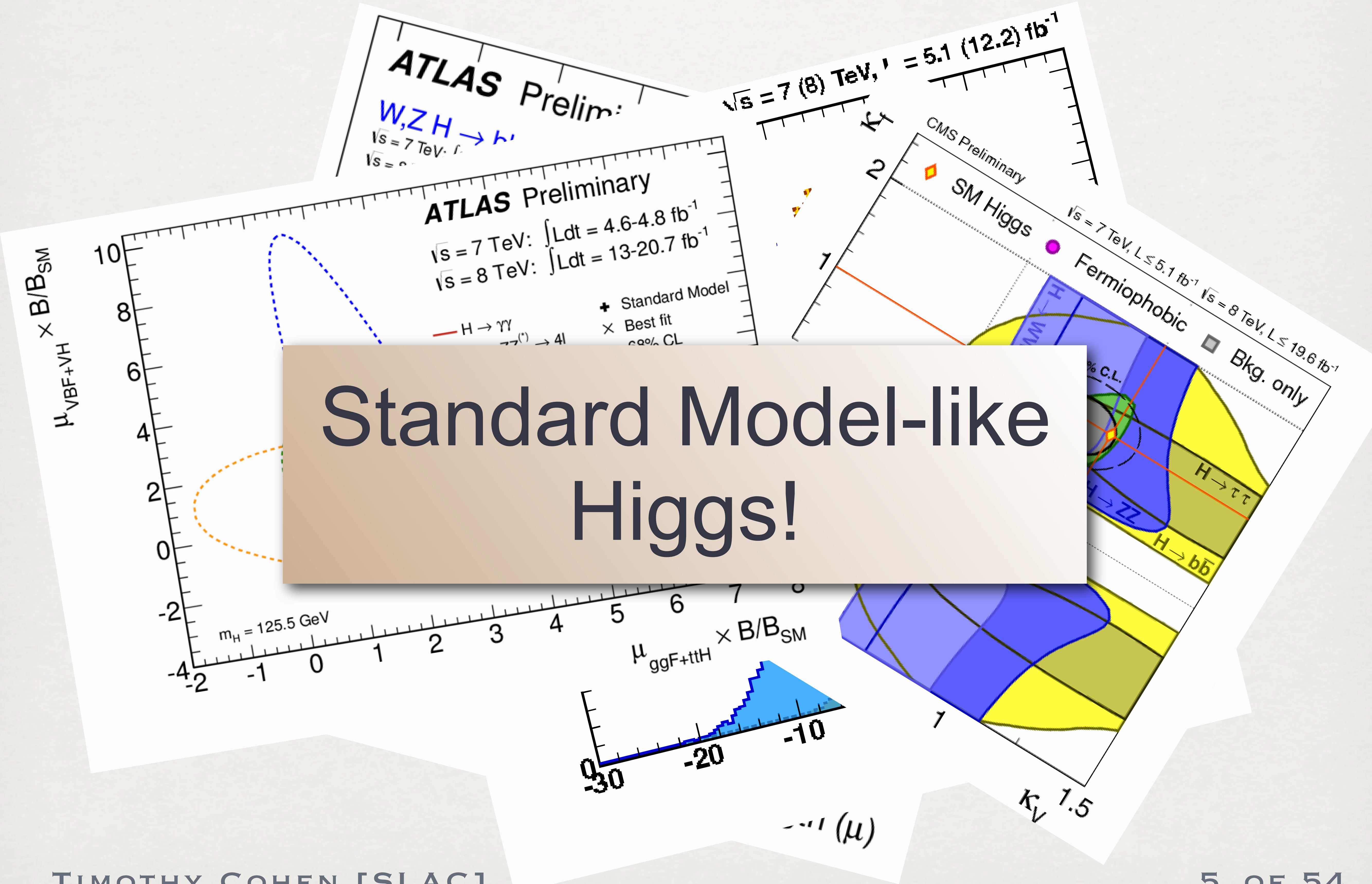
Backgrounds [arXiv:1308.1636]; Simplified Models 14 TeV, 33 TeV, and 100 TeV [arXiv:soon];
Simplified Models Summary [arXiv:1310.0077]

Outline

- Introduction
- Motivation
- Heavy SUSY Dark Matter
- Heavy SUSY at Colliders
- Conclusions

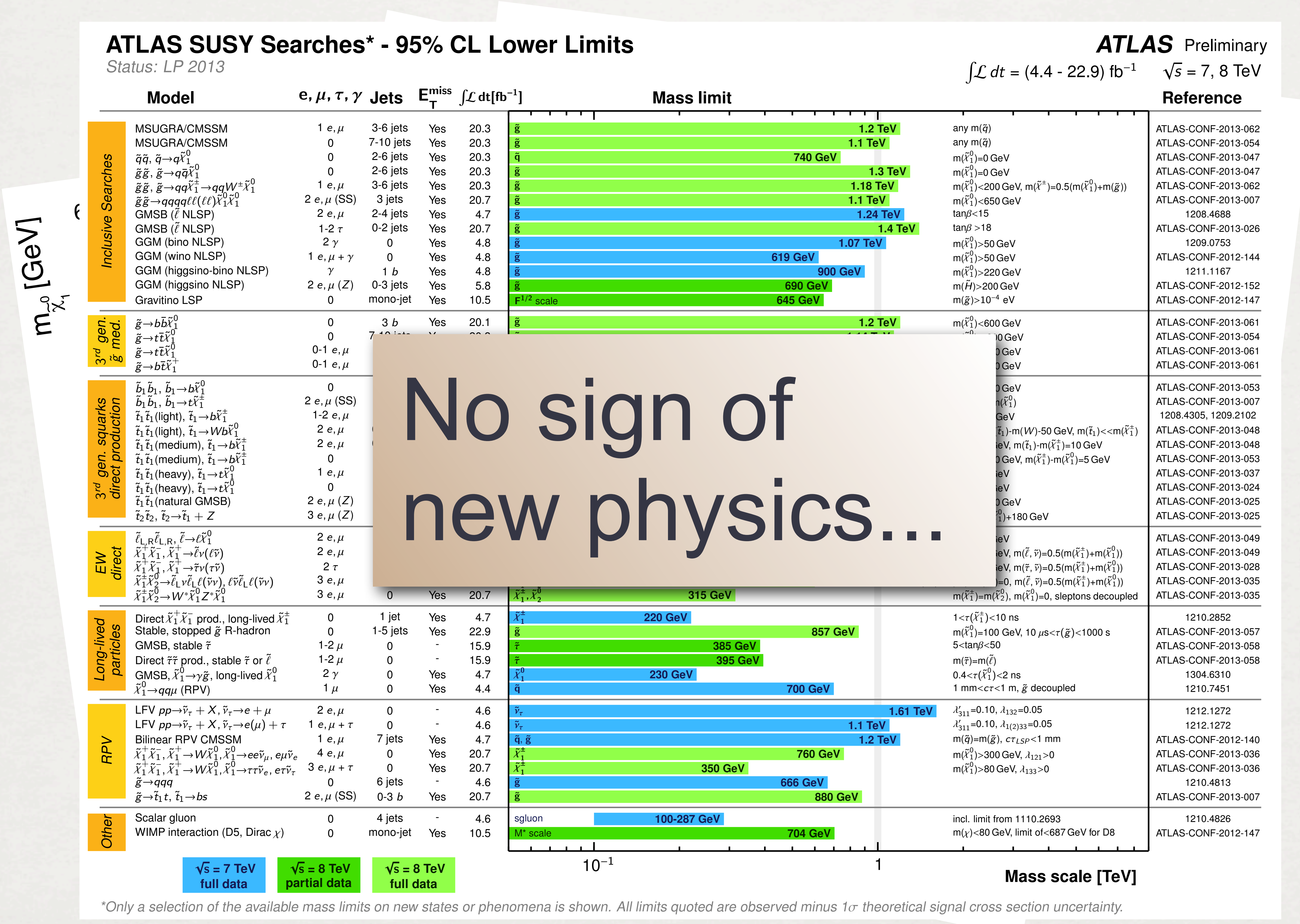
Introduction

Lessons from LHC8



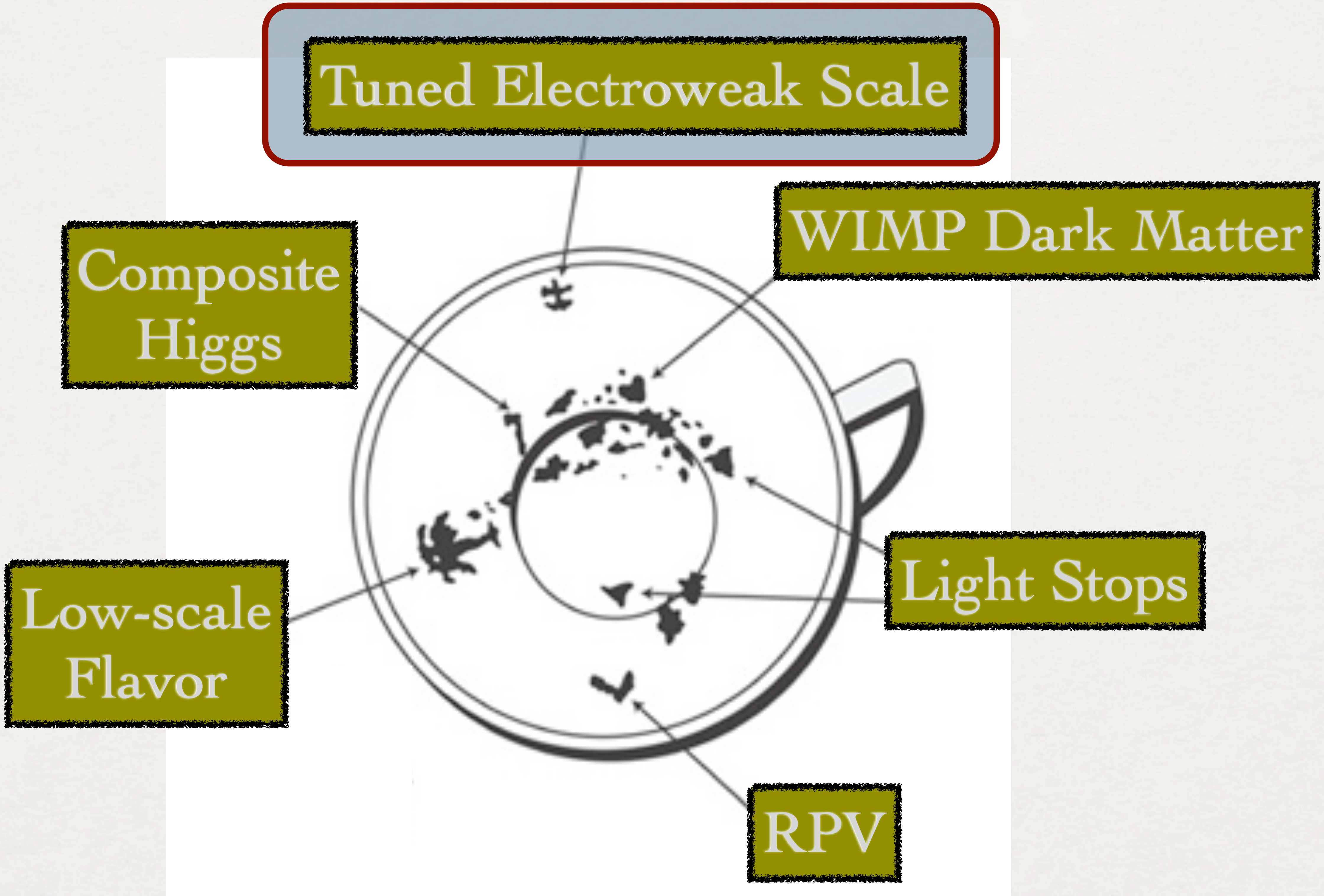
Standard Model-like Higgs!

Lessons from LHC8



No sign of new physics...

Reading the Tea Leaves



Motivation

Supersymmetry

Data consistent with fundamental scalar Higgs.

Mass should be protected from Planck slop.

SUSY to the rescue!

WIMP dark matter.

Gauge coupling unification.

Little hierarchy problem changing our view of SUSY.

SUSY Models

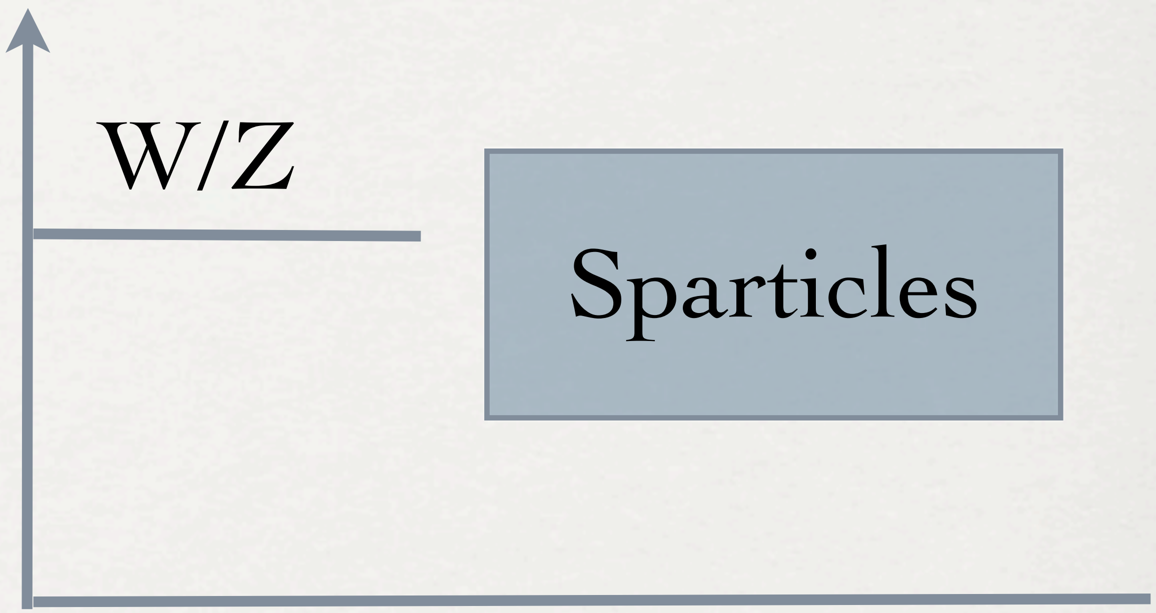
TeV scale SUSY

Model building challenges

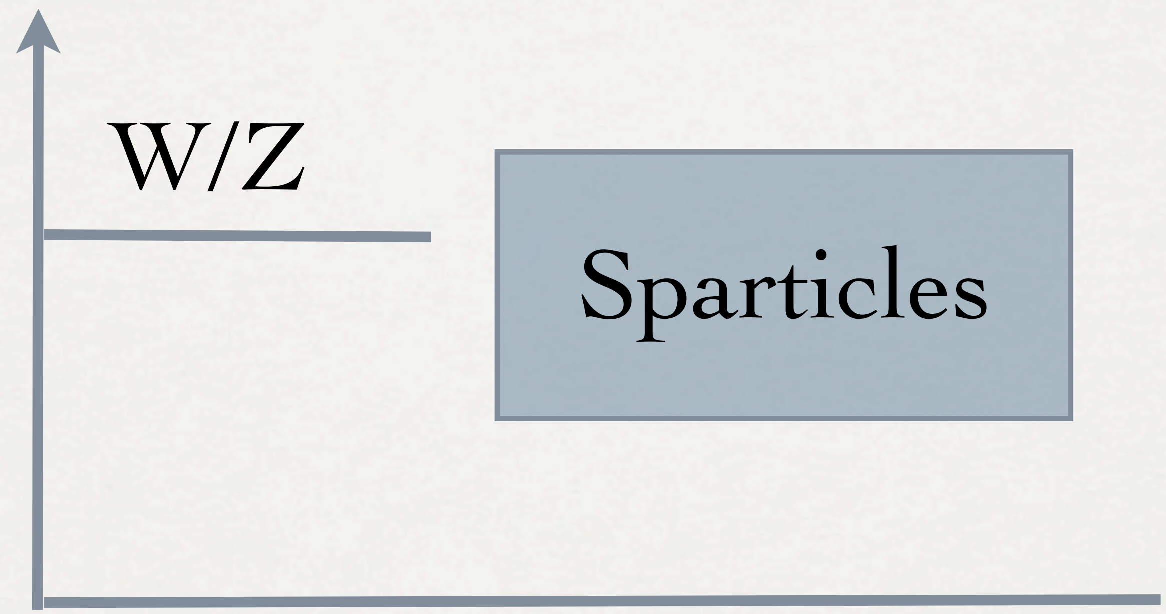
1) Flavor

2) CP Violation

3) 125 GeV Higgs boson



Complicated SUSY



Required Setup

Another Approach

PeV scale SUSY

Wells [arXiv:hep-ph/0411041]

Decoupling solves

1) Flavor

2) CP Violation

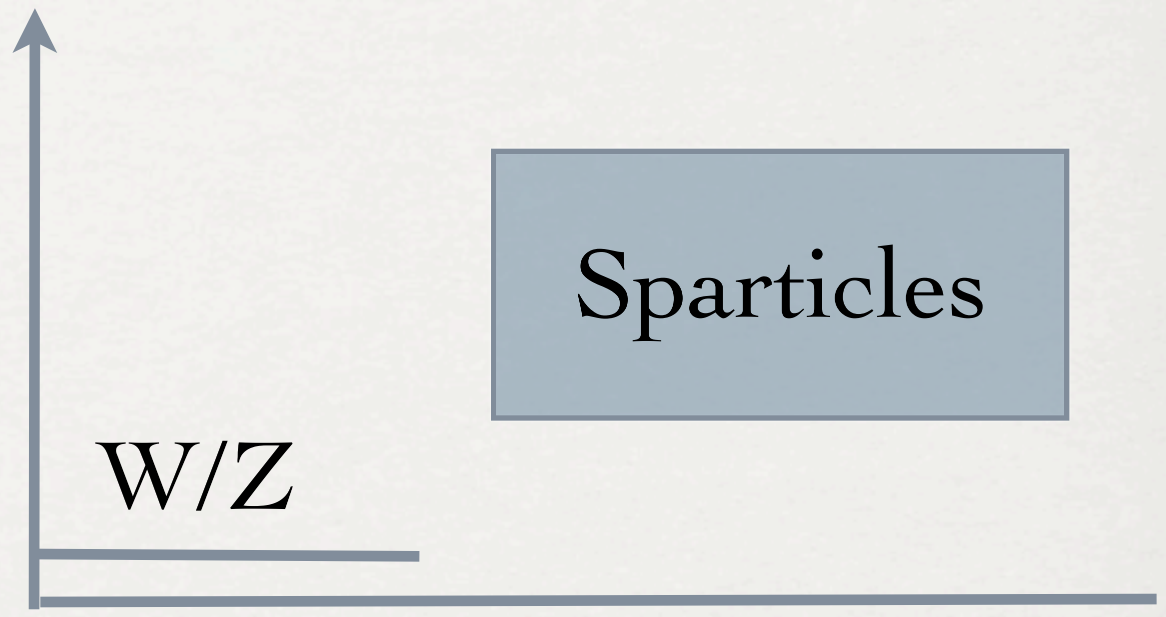
Consistent with

3) 125 GeV Higgs boson

Also get

dark matter candidate +

gauge coupling unification.



Some tuning...

but simple.

SUSY Breaking

Ignore preconceptions about fine-tuning.

Wells [arXiv:hep-ph/0411041]; Arkani-Hamed and Dimopoulos [arXiv:hep-th/0405159]; Giudice and Romanino [arXiv:hep-ph/0405159]

Explore "simplest" SUSY breaking scenarios.

Gravity mediation.

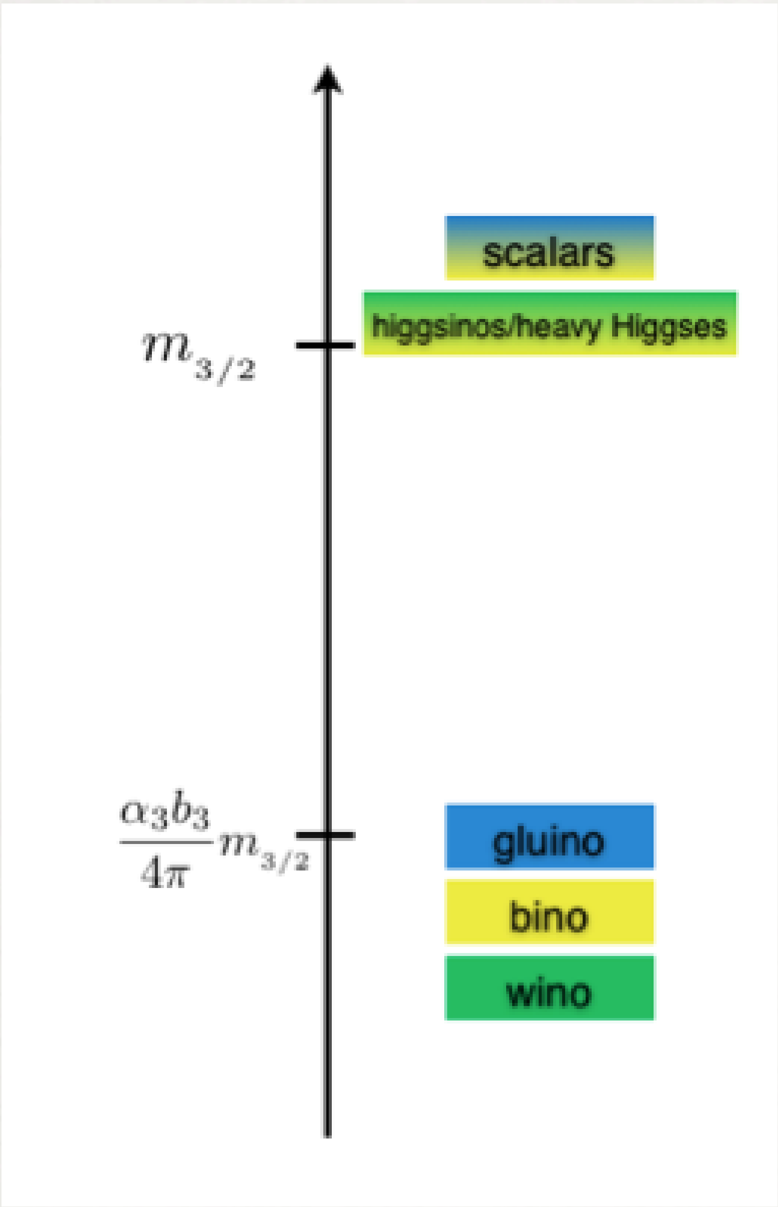
Assume SUSY breaking spurion is not gauge singlet.

Anomaly mediation and small *A*-terms.

Some examples since 125 GeV Higgs:
Arvanitaki, Craig, Dimopoulos [arXiv:1210.0555]; Hall, Nomura, Shirai [arXiv:1210.2395]; Kane, Kumar, Lu, Aheng [arXiv: 1112.1059]; Ibe, Yanagida [arXiv:1112.2462]; Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski [arXiv:1212.6971]

Anomaly + Gravity Mediation

Giudice, Luty, Murayama, Rattazzi [arXiv:hep-ph/9810442];
Randall and Sundrum [arXiv:hep-th/9810155]



1) Gravity mediation for scalars:

$$m_{\tilde{f}} \sim m_{3/2}$$

2) Anomaly mediation for gauginos:

$$m_{\tilde{\lambda}} \sim \frac{\alpha_i\, b_i}{16\,\pi^2} m_{3/2}$$

$$b_2 < b_1 < b_3 \Longrightarrow M_2 < M_1 < M_3$$

Wino or Higgsino LSP

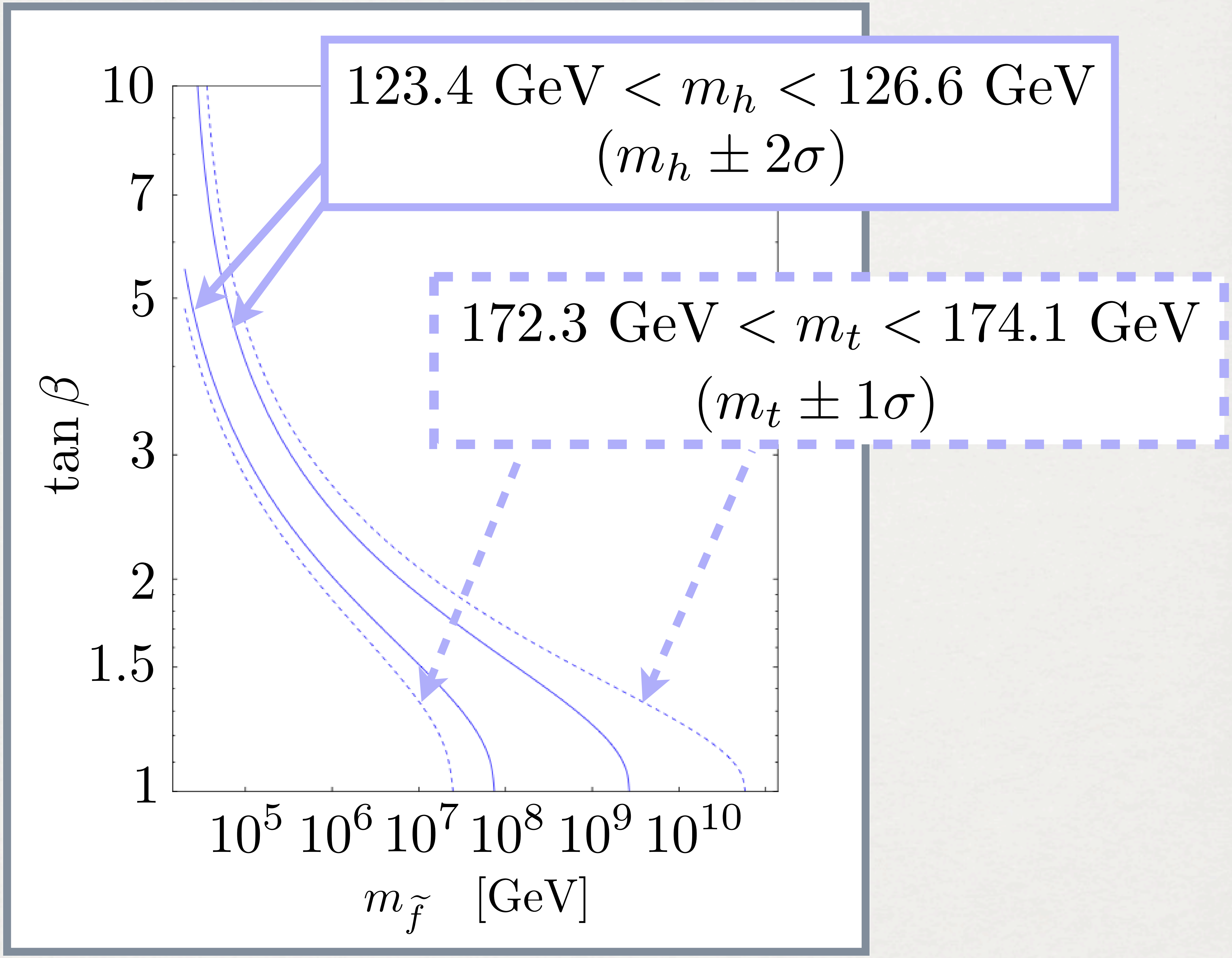
3) Giudice-Masiero $\Longrightarrow$ $\mu \sim m_{3/2}$

Wino LSP!

With Higgsino thresholds $\Longrightarrow$ $M_3 \simeq 6 \times M_2$

Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski [arXiv:1212.6971]

Higgs Mass

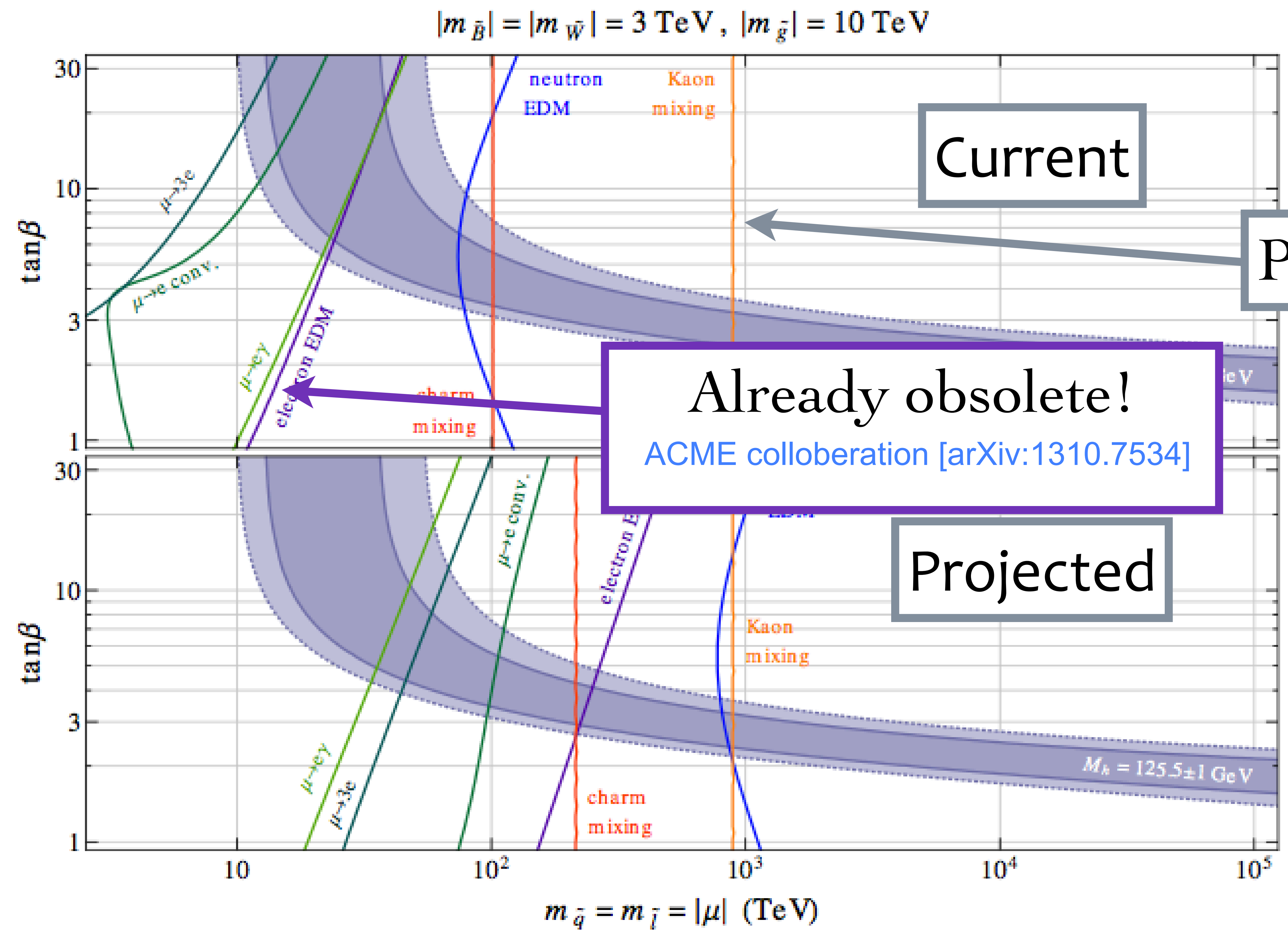


Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski [arXiv:1212.6971]

$\mathcal{O}(1)$ phases

Flavor

$(\delta_A)_{ij} = 0.3$



Already obsolete!

ACME colloberation [arXiv:1310.7534]

Altmannshofer, Harnik, Zupan [arXiv:1308.3653]

Simplest Scenario

Where has simplicity led us?

1) A thermal wino relic with a 3 TeV mass

or

Allow non-thermal/subdominant winos.

2) Gluino with a ~ 16 TeV mass (likely displaced decays).

3) Scalars a loop factor heavier with O(100 TeV) masses.

No problems!

How can we test this model?!?

Heavy SUSY Dark Matter

Wino Dark Matter

Introduce an electroweak triplet fermion χ ,

with the Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \bar{\chi}\left(i\not{D} + M_2\right)\chi$$

In components:

$$\chi = \begin{pmatrix} \chi^+ \\ \chi^0 \\ \chi^- \end{pmatrix}$$

Mass Splitting

Electroweak symmetry breaking splits chargino and neutralino.

In pure wino limit (with $M_2 = 2\ \text{TeV}$)

$$\delta = 0.1645 \pm 0.0004\ \text{GeV}$$

to two-loop order.

Ibe, Matsumoto, Sato [arXiv:1212.5989]

What about tree-level mixing?

$$\mu \sim m_{3/2} \sim O(100\ \text{TeV})$$

Leading splitting operator is dimension 7:

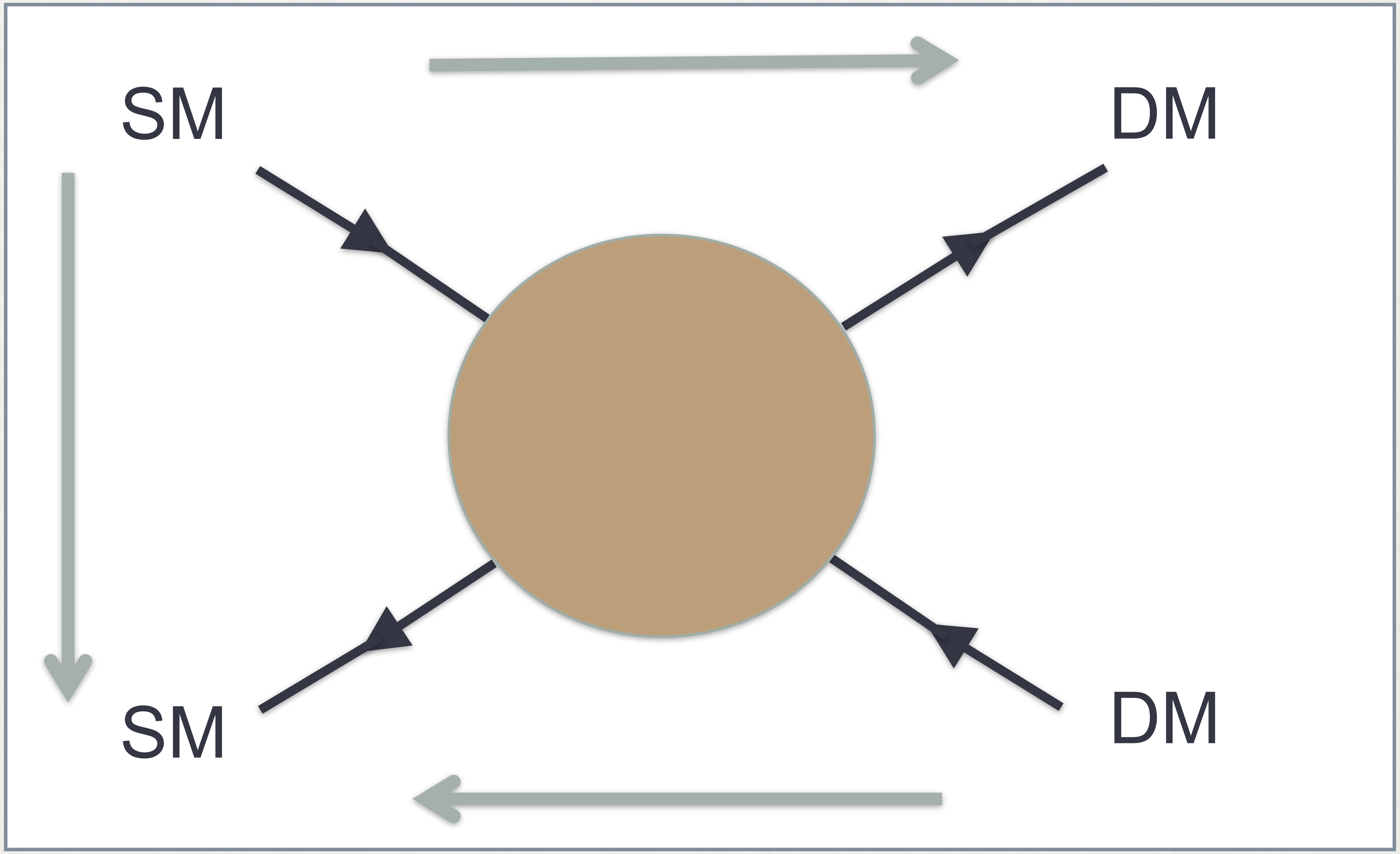
$$\mathcal{O}_\delta \sim \chi^a \chi^b \left(H^\dagger T^a H\right) \left(H^\dagger T^b H\right)$$

Implying $\delta \simeq 0.17\ \text{GeV}$ is a robust prediction.

Observing winos

Colliders:
(don't) see missing energy

Direct Detection:
see nuclear recoils



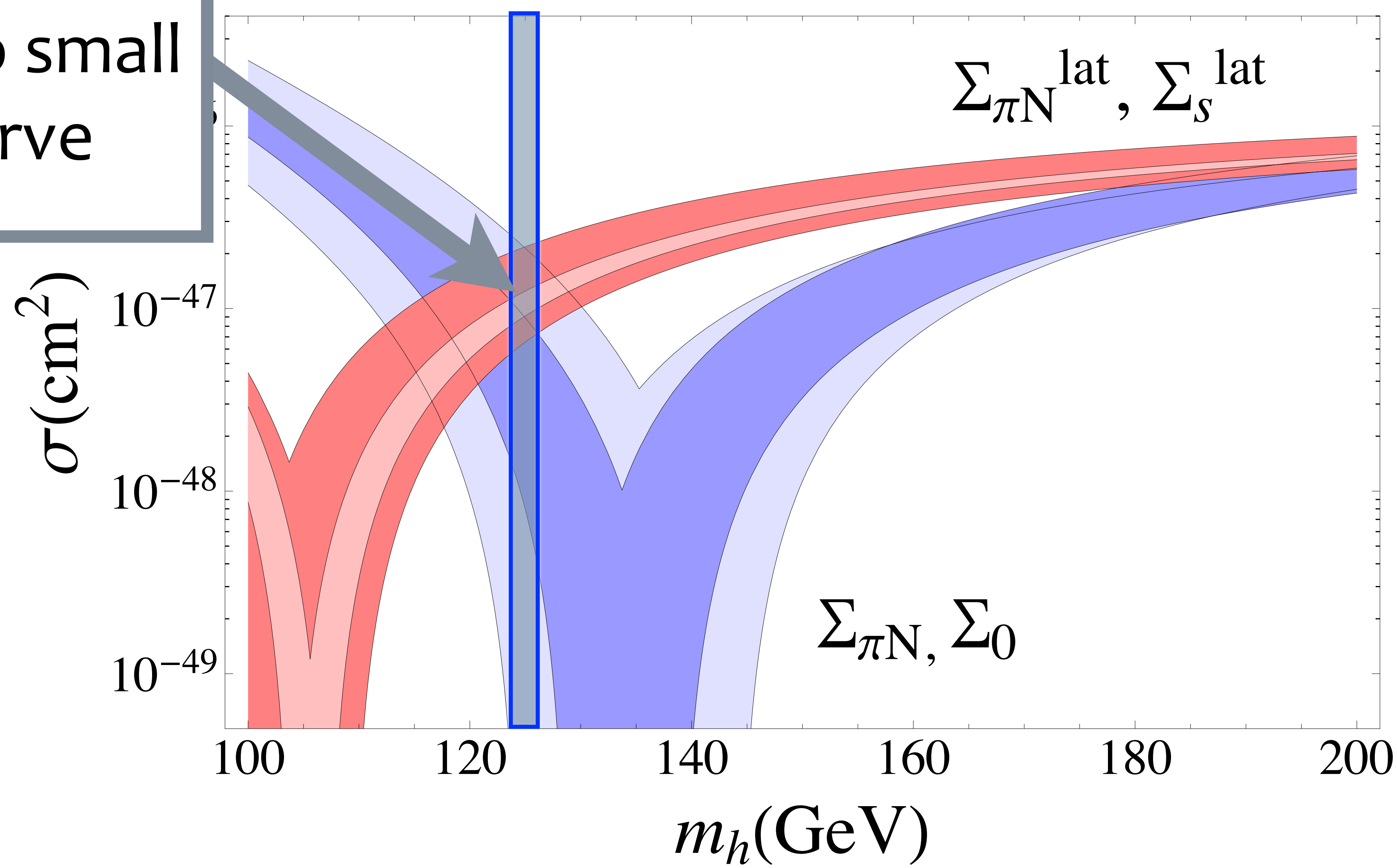
Indirect Detection:
see cosmic rays

Hill and Solon [arXiv:1111.0016, 1309.4092]

No tree couplings to the Z or the Higgs

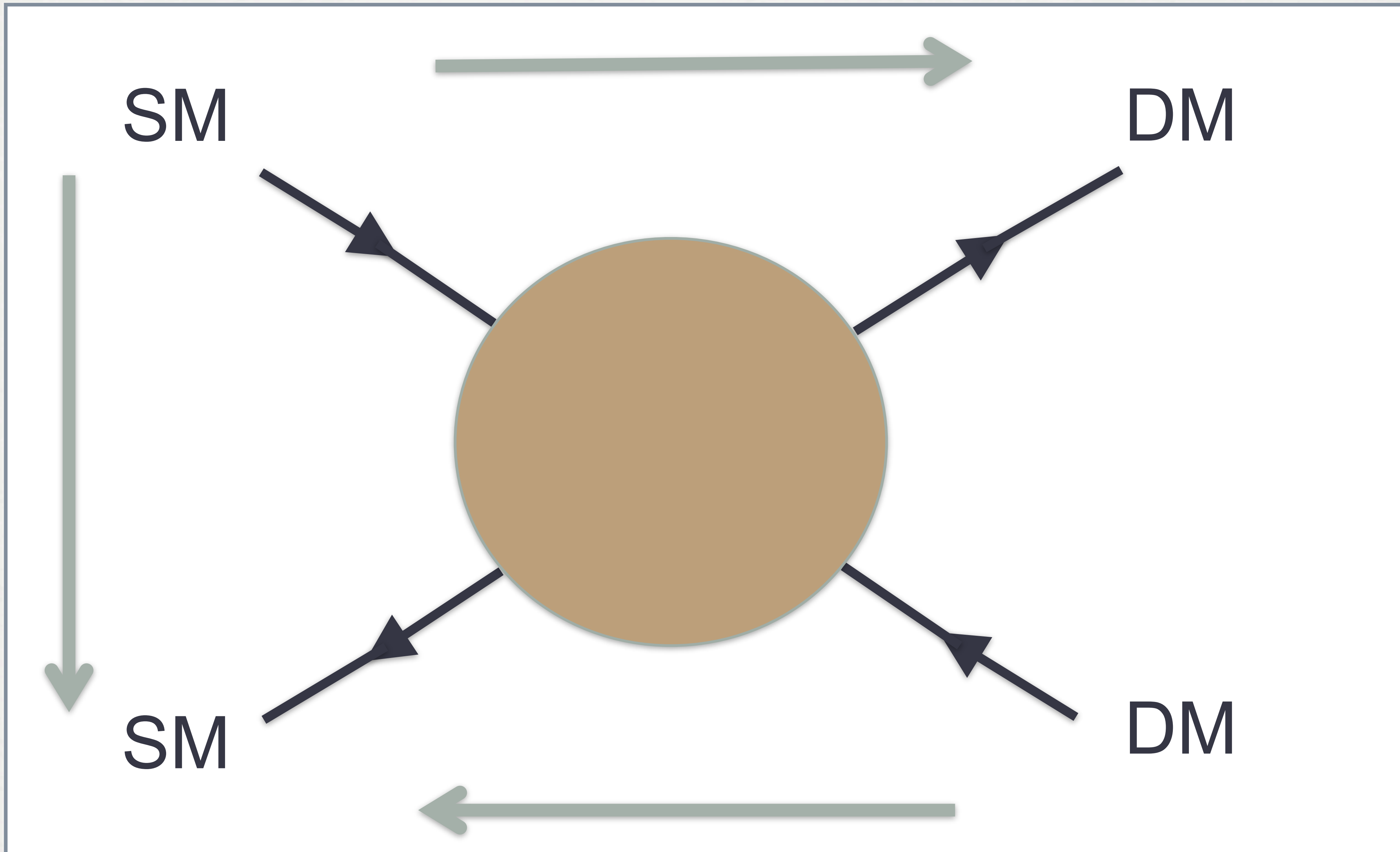
Leading process at 1-loop:

10^{-47} cm^2
almost too small
to observe



Observing winos

Colliders:
(don't) see missing energy



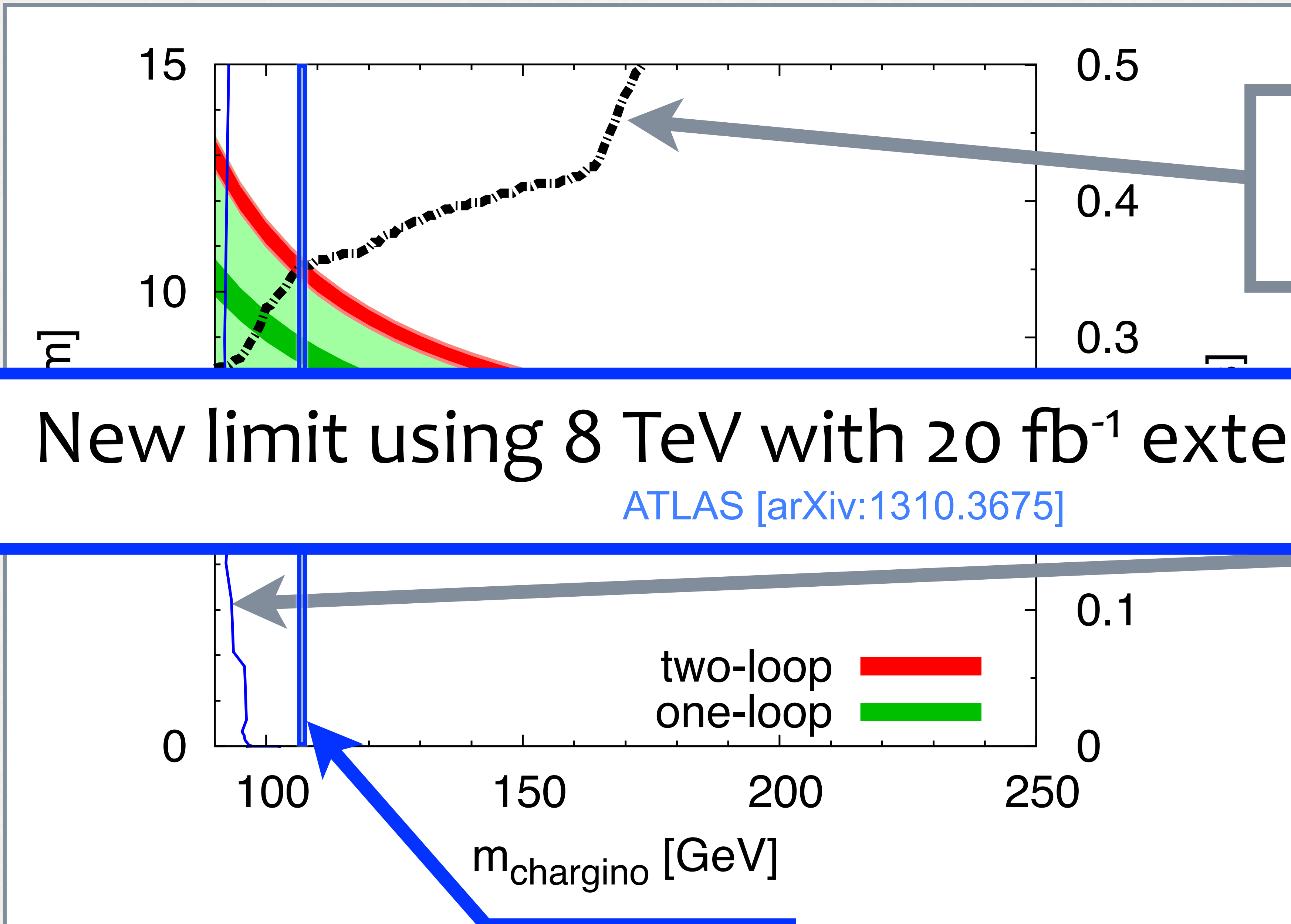
Direct Detection: see nuclear recoils

Indirect Detection: see cosmic rays

Winos at colliders

Ibe, Matsumoto, Sato [arXiv:1212.5989]

LHC searches for charged stubs in the tracker



7 TeV with 5 fb^{-1}

ATLAS [arXiv:1210.2852]

New limit using 8 TeV with 20 fb^{-1} extends to 280 GeV

ATLAS [arXiv:1310.3675]

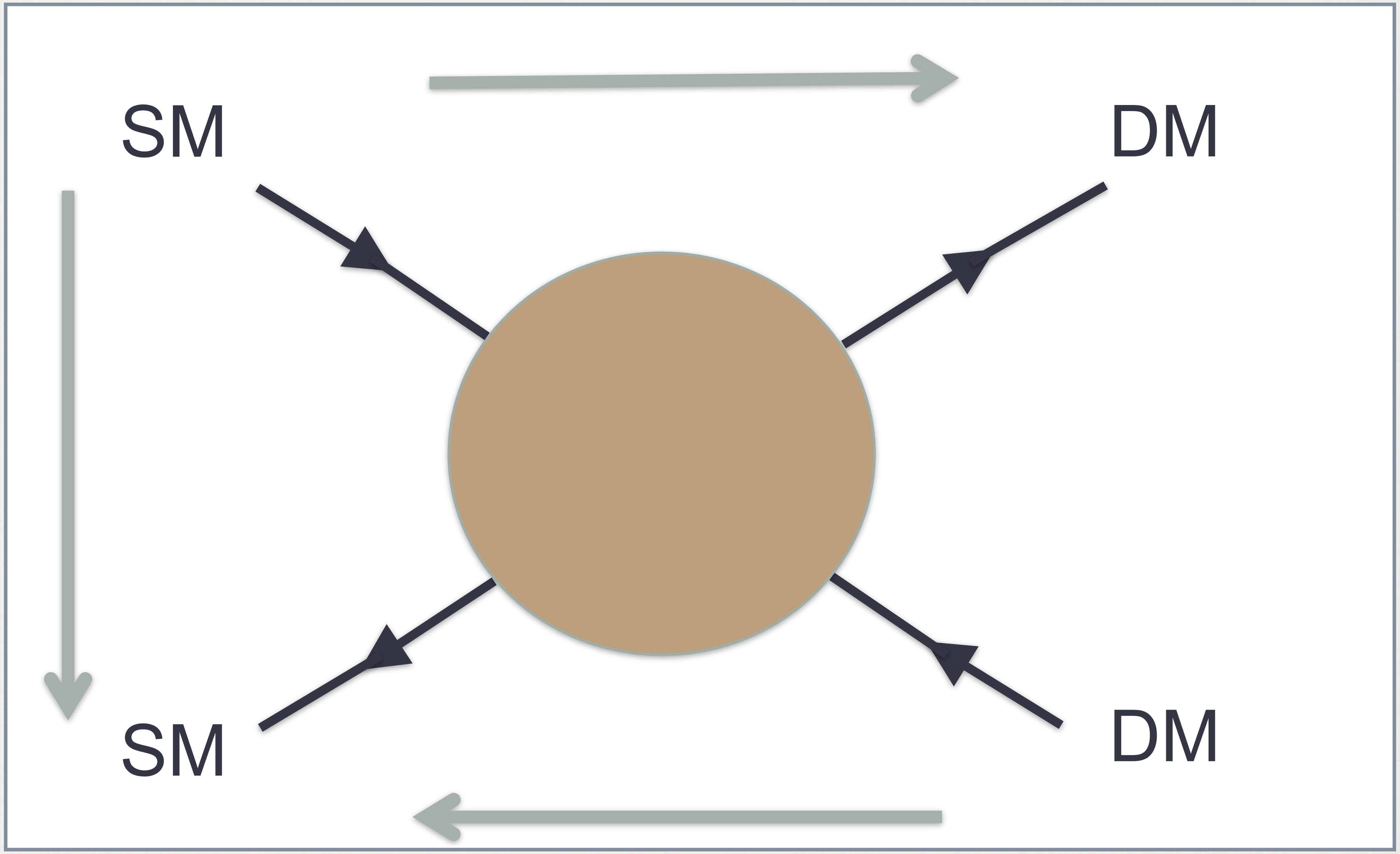
LEP

108 GeV

Observing winos

Colliders:
(don't) see missing energy

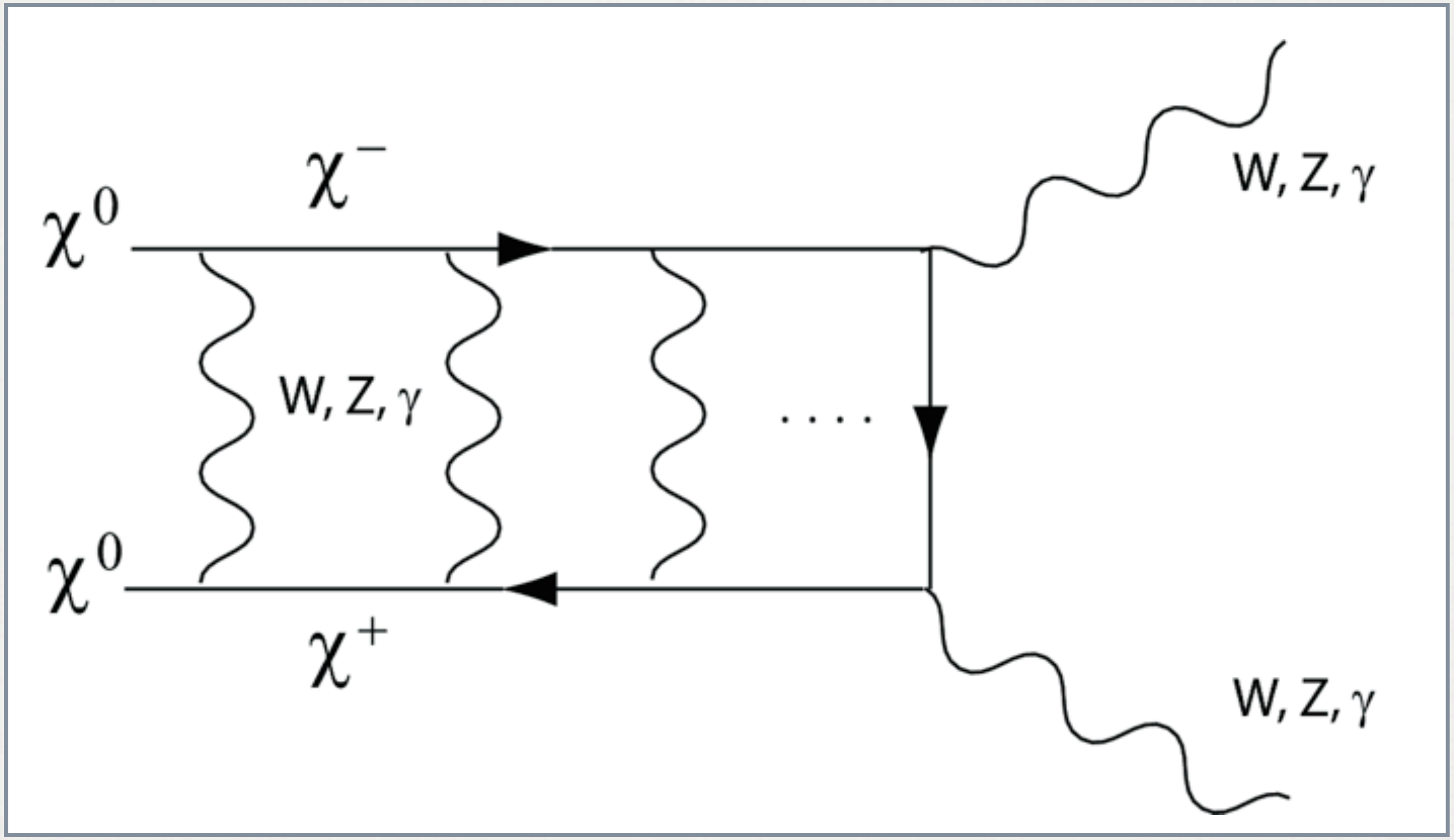
Direct
Detection:
see nuclear
recoils



Indirect Detection:
see cosmic rays

Sommerfeld Enhancement

Non-perturbative effect at low velocities



$$S \sim \frac{\alpha}{v}$$

Computing Cross Section

Hisano, Matsumoto, Nagai, Saito, Senami [arXiv:hep-ph/0610249]

Take non-relativistic limit and assume *s*-wave.

Example: Spin singlet neutralino-chargino system.

Want to solve

$$\psi''(x) = \left(\frac{V(x)}{E} - 1\right)\psi(x)$$

with

$$\frac{V(x)}{E} = \begin{pmatrix} 0 & -\sqrt{2}\left(\frac{\alpha_W\, m_\chi}{x\, p}\right) e^{-\frac{m_W\, x}{p}} \\ -\sqrt{2}\left(\frac{\alpha_W\, m_\chi}{x\, p}\right) e^{-\frac{m_W\, x}{p}} & \frac{2\, m_\chi\, \delta}{p^2} - \frac{\alpha_W\, m_\chi\, s_w^2}{x\, p} - \left(\frac{\alpha_W\, m_\chi\, c_w^2}{x\, p}\right) e^{-\frac{m_Z\, x}{p}} \end{pmatrix}$$

Yukawa

Mass splitting

Coulomb

Potential matrix index structure:
1 = neutralino + neutralino; 2 = chargino + chargino

Computing Cross Section

Boundary Conditions:

$$\psi_i(0) = \delta_{ij}$$

and

$$\psi_i(\infty) = \begin{cases} \text{outgoing wave [above threshold]} \\ \text{exponentially falling [below threshold]} \end{cases}$$

Hard annihilation matrix

Sommerfeld matrix: $s_{ij} = \psi_i(\infty)$

Cross section: $\sigma_i\, v = c_i \sum_{j,j'} s_{ij}\, \Gamma_{jj'}\, s^*_{ij'}$

$c = 2\,(1)$ for identical (distinct) particles.

Index structure: 1 = neutralino + neutralino; 2 = chargino + chargino

Sommerfeld Resonance

Resonant enhancement:

mass splitting $\simeq$ binding energy

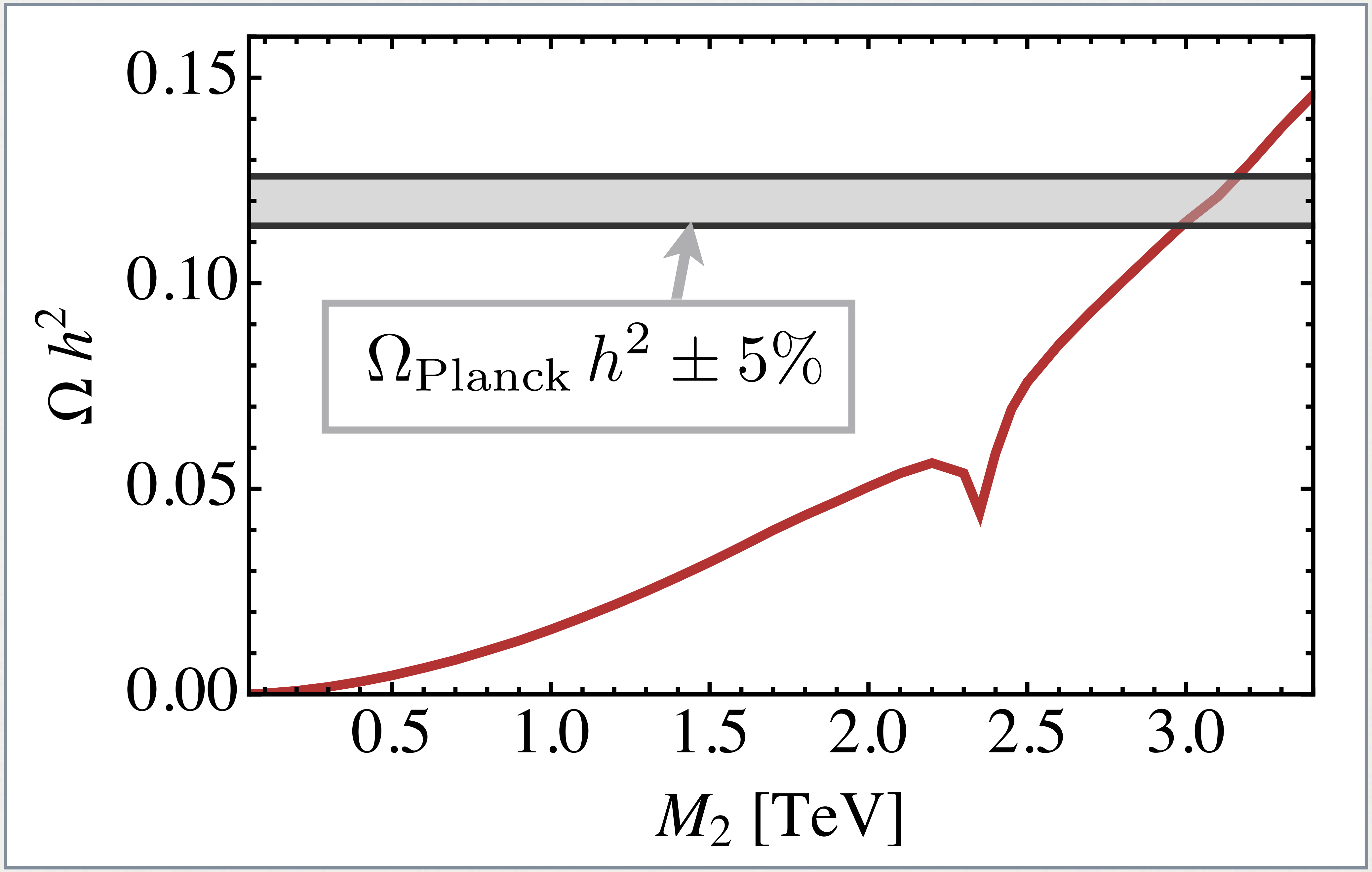
Position of resonance sensitive to mass splitting

Assume only EW contribution to splitting

Loop factor times W-mass → $\alpha_W \, m_W \simeq \alpha_W^2 \, M_2$ ← "Rydberg" constant

$$(M_2)_{\rm res} \simeq \frac{m_W}{\alpha_W} \simeq 2.4 \text{ TeV}$$

Thermal Wino



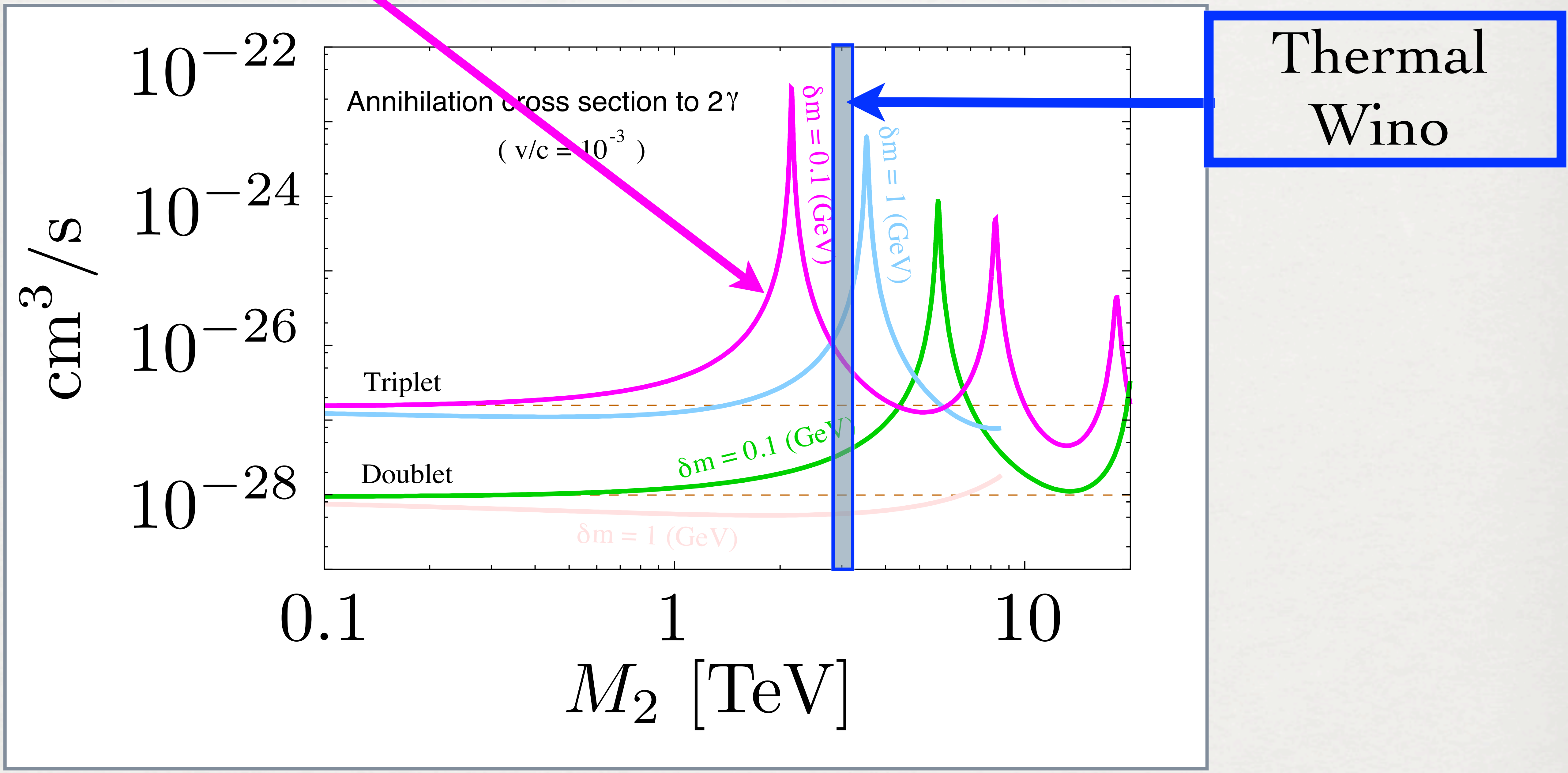
Planck Collaboration [arXiv:1303.5076]

Mass of "thermal wino": $(M_2)_{\text{thermal}} \simeq 3.1\ \text{TeV}$

Sommerfeld Enhancement

$\delta = 0.1$ GeV

$$\chi^0 \chi^0 \to \gamma\gamma$$



Hisano, Matsumoto, Nojiri [arXiv:hep-ph/0307216]

Indirect Detection

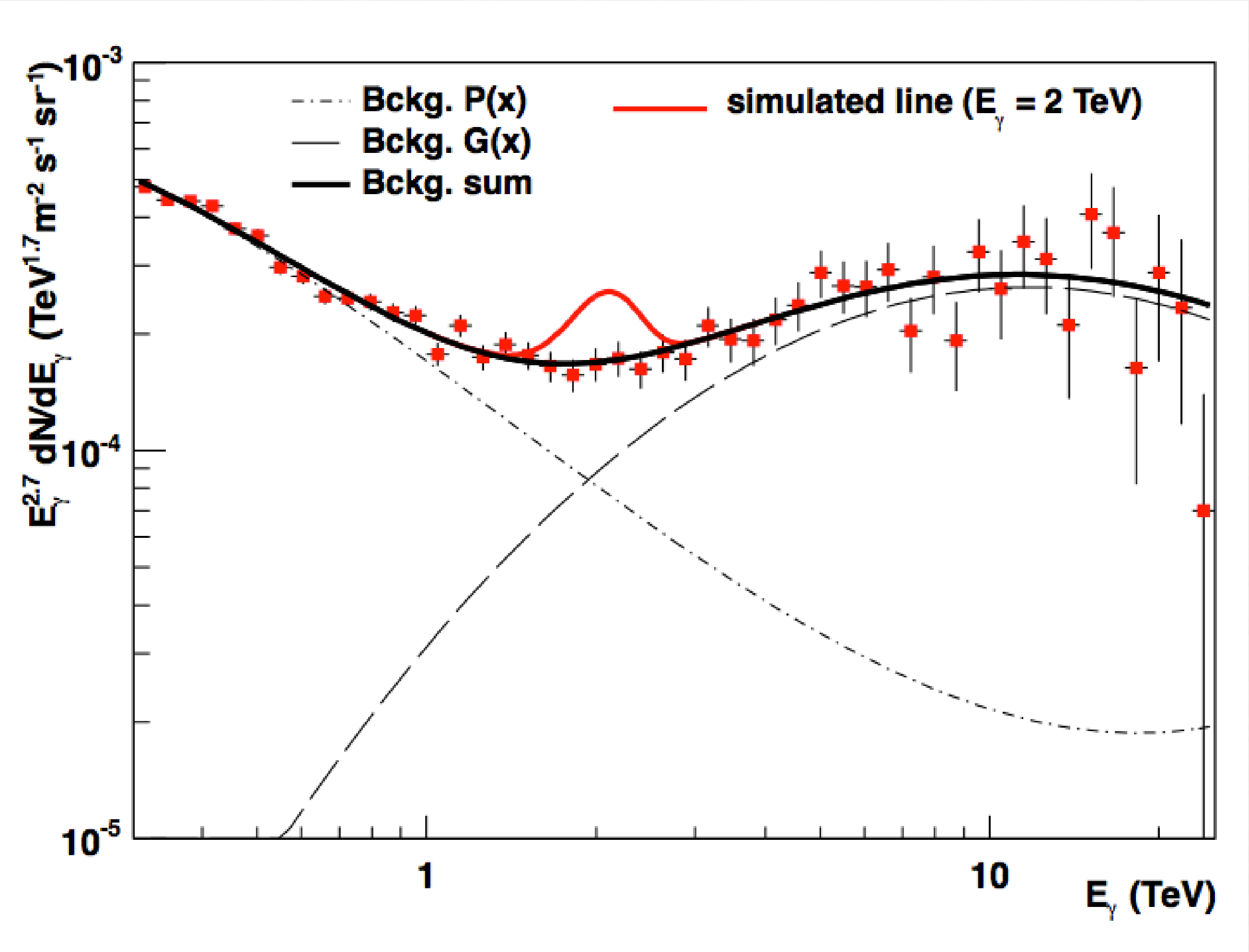
H.E.S.S. Line Search

H.E.S.S. Collaboration [arXiv:1301.1173]

Ground based imaging atmospheric Cherenkov telescope

Search in 1 degree region at galactic center (plane excluded)

Assuming NFW profile



Indirect Detection

Fermi Stacked Dwarf Limit

Fermi Collaboration [arXiv:1108.3546]

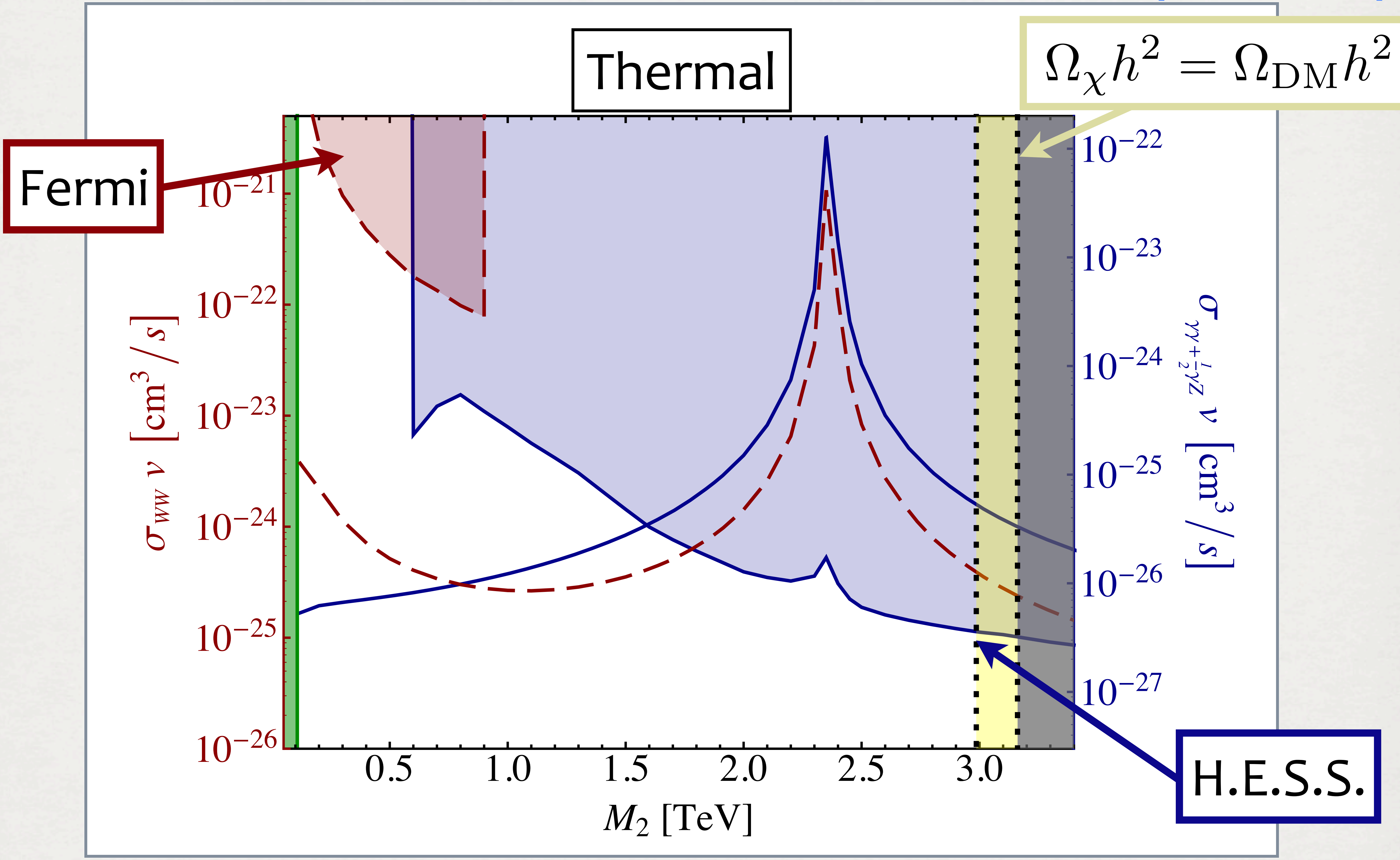
10 Milky Way satellite galaxies

24 months of data

Marginalizes over profile uncertainty

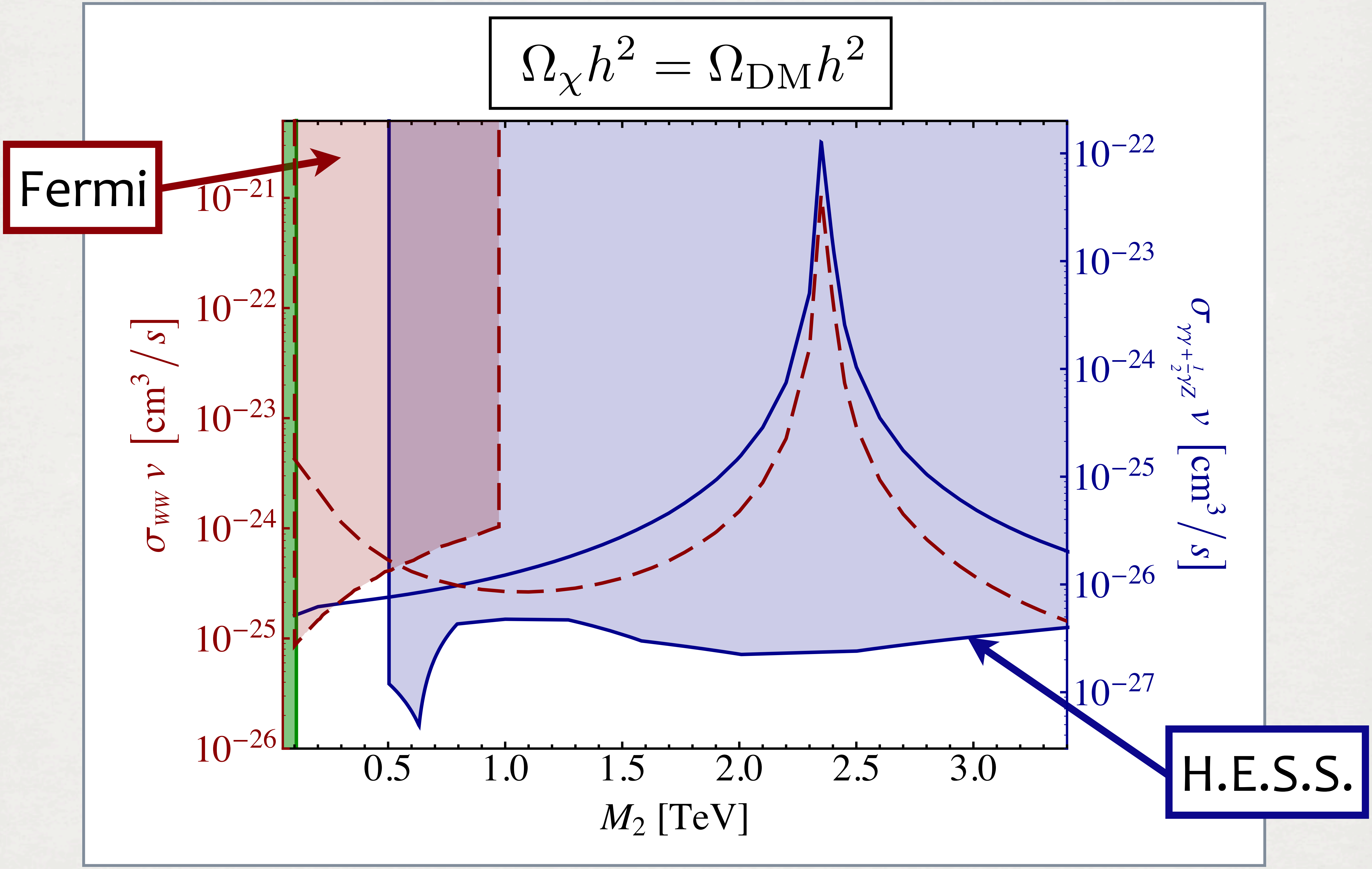
Constraints

See also Fan and Reece [arXiv:1307.4400]

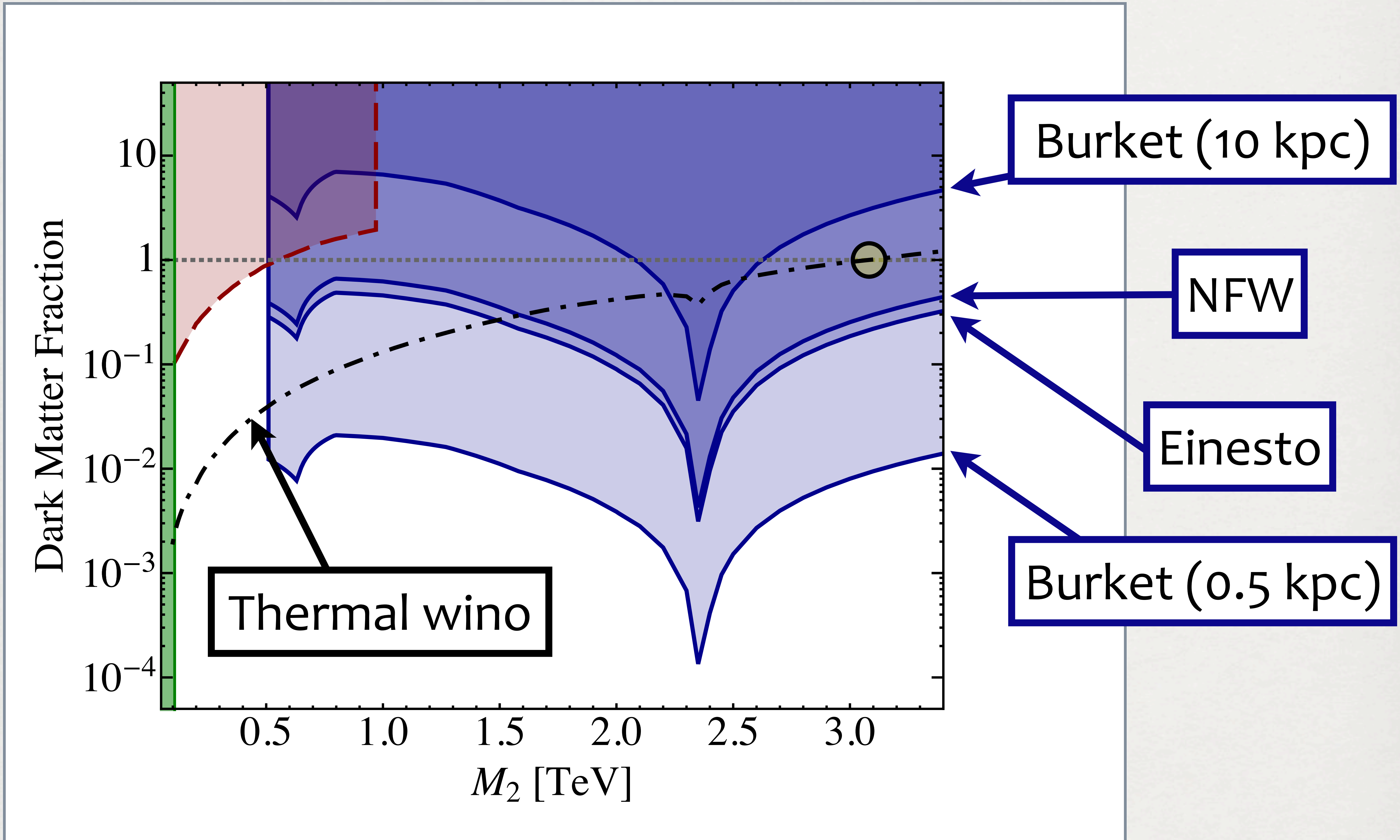


CONSTRAINTS

See also Fan and Reece [arXiv:1307.4400]

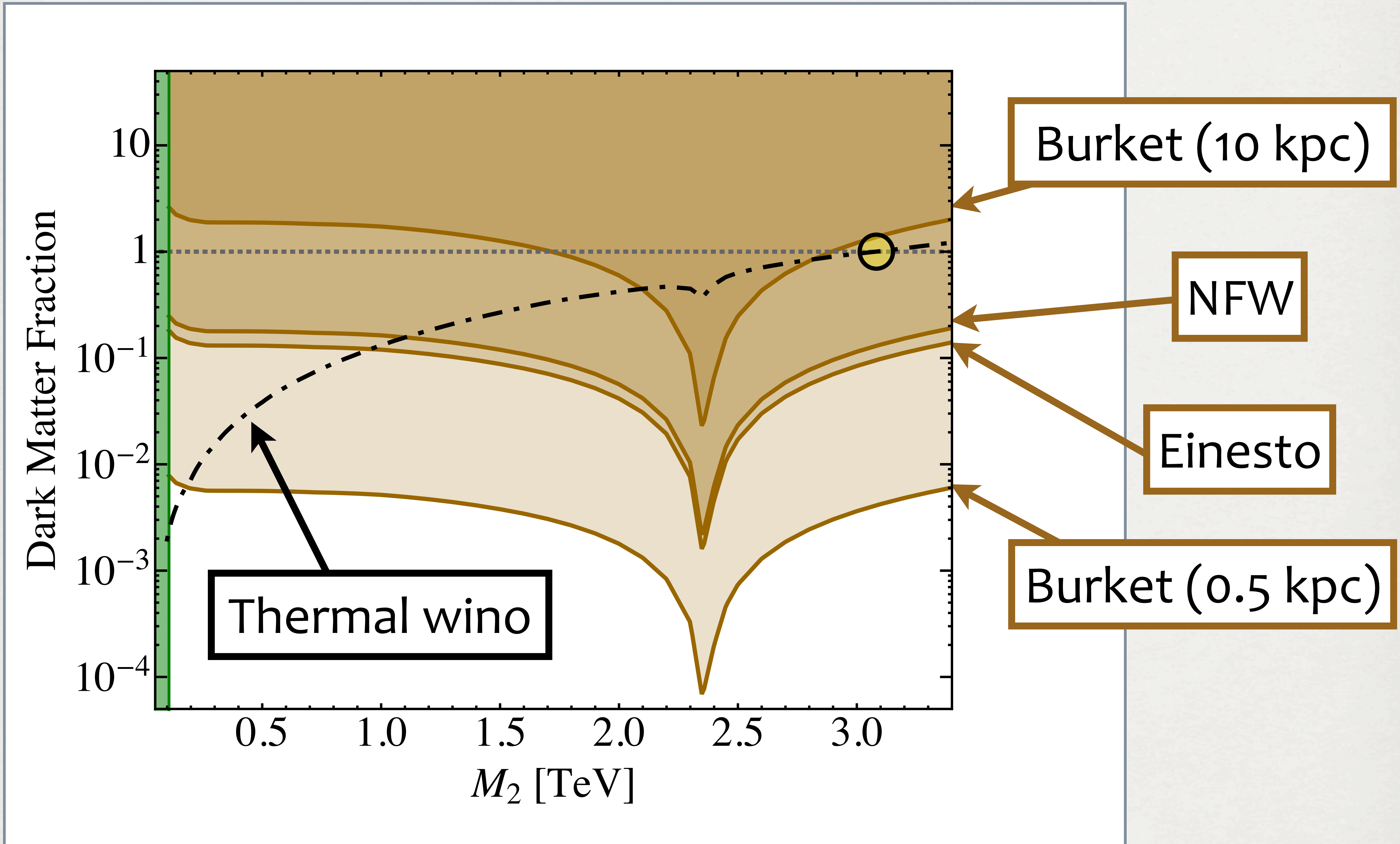


Caveat: Halo Profile



Using CTA

Bergstrom, Bertone, Conrad, Farnier, and Weniger [arXiv:1207.6773]



Caveat: NLO

Results use Sommerfeld enhanced tree-level hard annihilation cross section

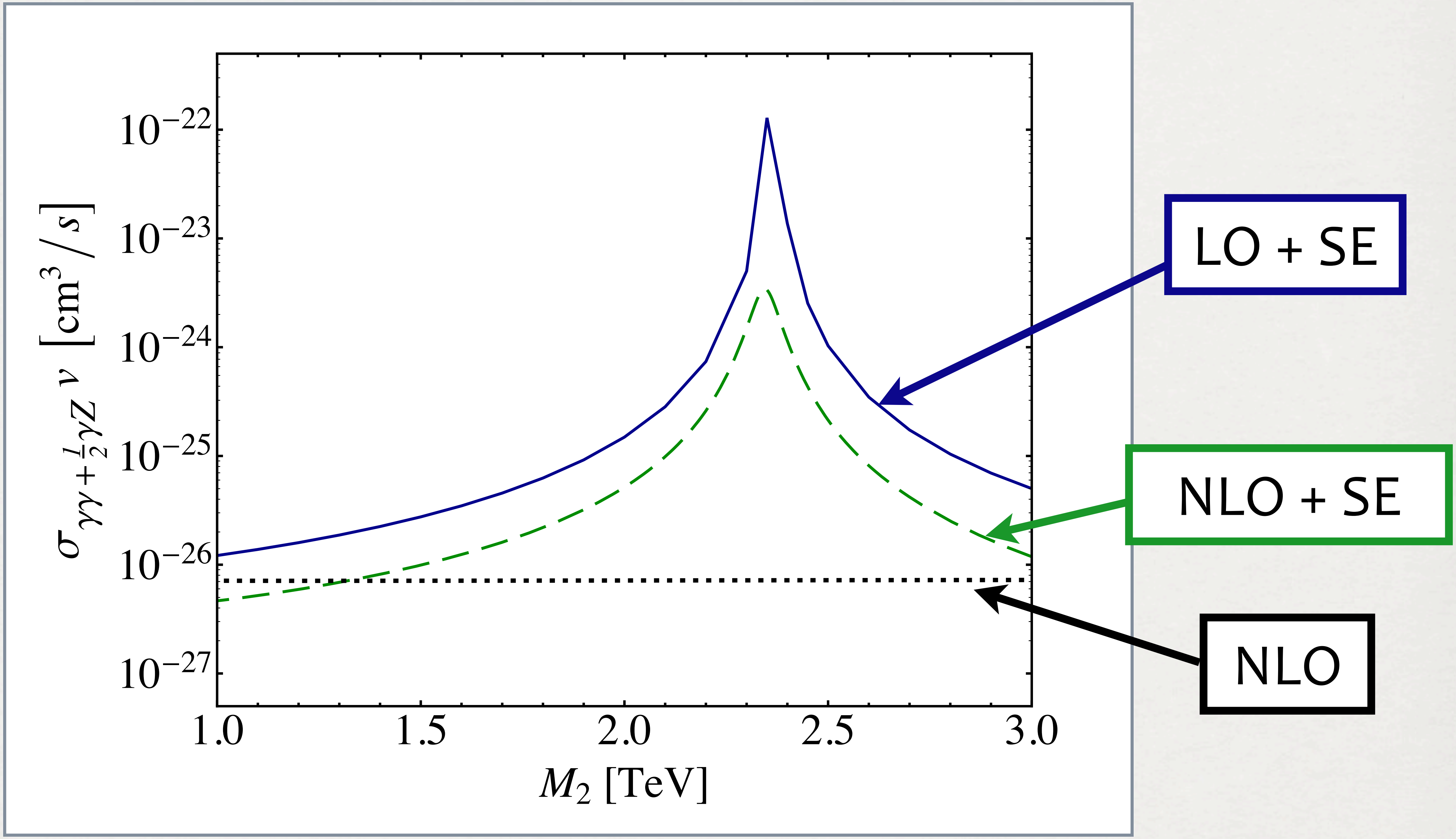
What is the impact of including NLO corrections to hard annihilation cross section?

$$\sigma_i\, v = c_i \sum_{j,j'} s_{ij}\, \Gamma_{jj'}\, s^*_{ij'}$$

Subtlety in order to not double count.

Hryczuk & Iengo [arXiv:1111.2916]

Caveat: NLO



Factor of ~ 4 reduction for thermal wino.
Large logs: breakdown of perturbation theory?

Hryczuk & Iengo [arXiv:1111.2916]

SUMMARY

Wino dark matter is well motivated.

(Resonant) Sommerfeld enhancement is important.

Indirect detection places strong constraints.

Thermal scenario: probed above 1.6 TeV;

Gluinos below ~ 10 TeV!

Non-thermal scenario: probed full mass range.

Heavy SUSY at Colliders

Future Proton Colliders

Want to study the following collider scenarios:

Know we get

14(ish) TeV LHC with 300 fb^{-1}

(50 mean pile-up)

Probably we get

14(ish) TeV LHC with 3000 fb^{-1}

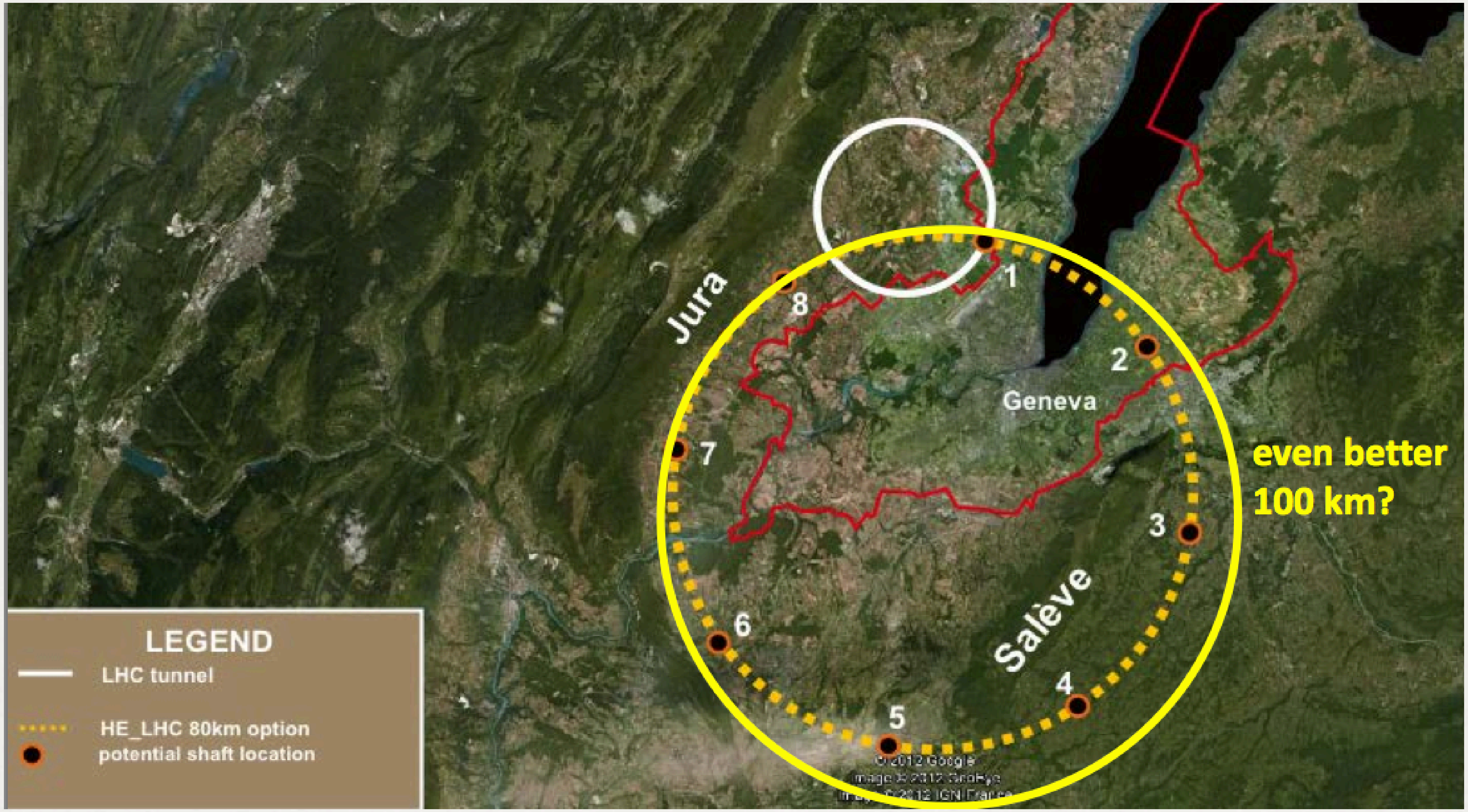
(140 mean pile-up)

Will ***hope*** for

33 to 100 TeV proton collider with 3000 fb^{-1}

(140 mean pile-up)

The next Proton collider?



100 km tunnel: CERN versus China?

100 TeV needs 16 Tesla magnets (100 km ring)

Current technology ~ 11 Tesla

A Monte Carlo Challenge

Generate top backgrounds:

$$\sigma_{\text{NLO}}(p\,p \to t\,\bar{t}) = 0.8 \text{ nb}$$

Require factor of 10 MC more than expected events

$$\mathcal{L} = 3 \text{ ab}^{-1}$$

$$10 \times \sigma \times \mathcal{L} = 2.4 \times 10^{10}$$

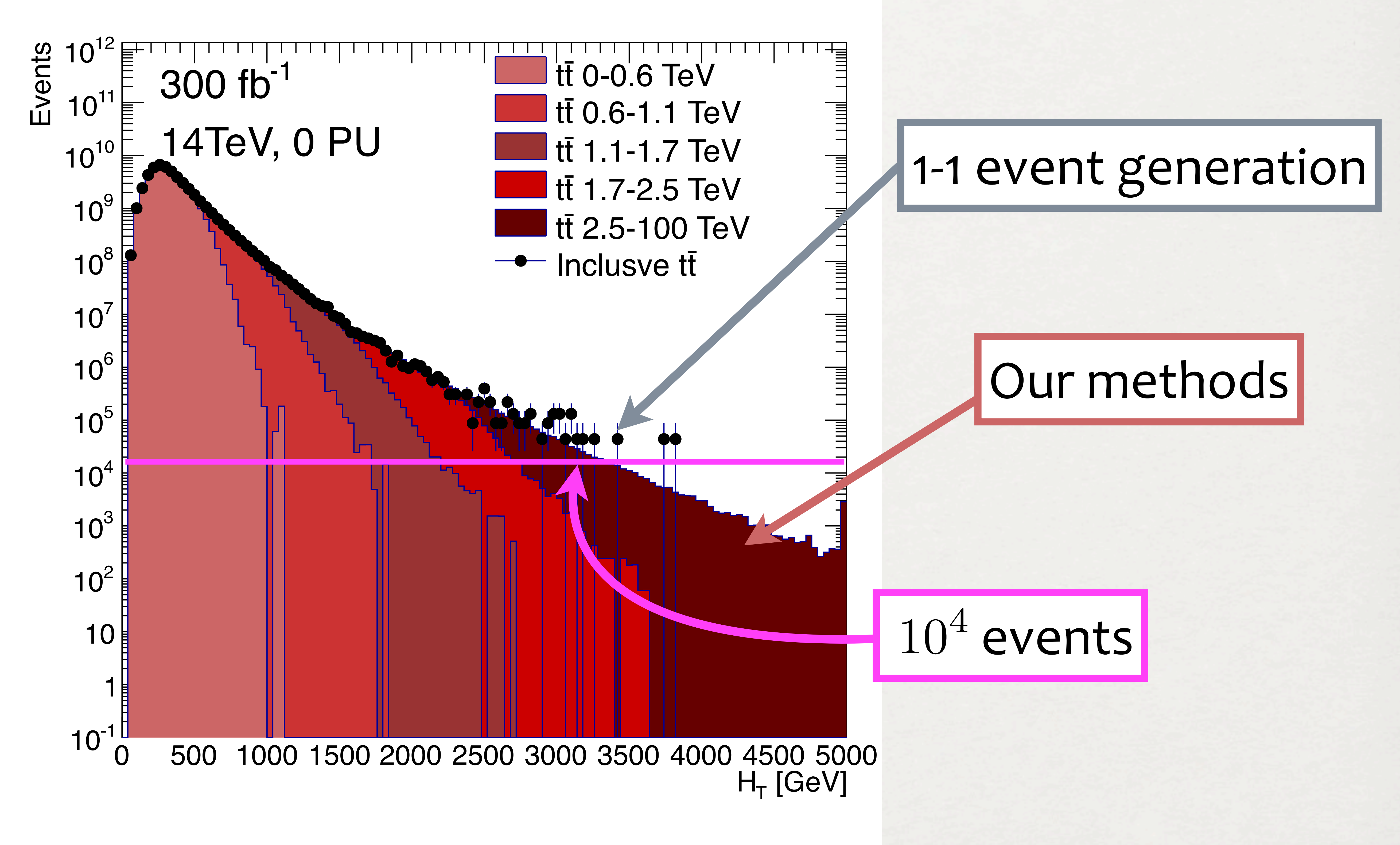
Each event ~ 1 kb

24 Terabytes for tops (per pileup setting)

Need new Monte Carlo approach!

After many months...

Avetisyan, Campbell, TC, Dhingra, et al [arXiv: 1308.1636]



Simplified Models

We have backgrounds

What should we do with them?

Want to assess reach of future machines

Want transparent results

Want to study all kinematic regions

Simplified Model	Decay channel
Gluino-neutralino with light flavor decays	$\widetilde{g} \to q\,\bar{q}\,\widetilde{\chi}_1^0$
Squark-neutralino	$\widetilde{q} \to q\,\widetilde{\chi}_1^0$
Gluino-squark with a massless neutralino	$\widetilde{g} \to (q\,\bar{q}\,\widetilde{\chi}_1^0 / q\,\widetilde{q}^*);\, \widetilde{q} \to (q\,\widetilde{\chi}_1^0 / q\,\widetilde{g})$
Gluino-neutralino with heavy flavor decays	$\widetilde{g} \to t\,\bar{t}\,\widetilde{\chi}_1^0$

(Assuming prompt decays)

Jets + MET

Preselection

- zero selected electrons or muons
- $E_T^{\text{miss}} > 100$ GeV
- at least 4 jets with $p_T > 60$ GeV

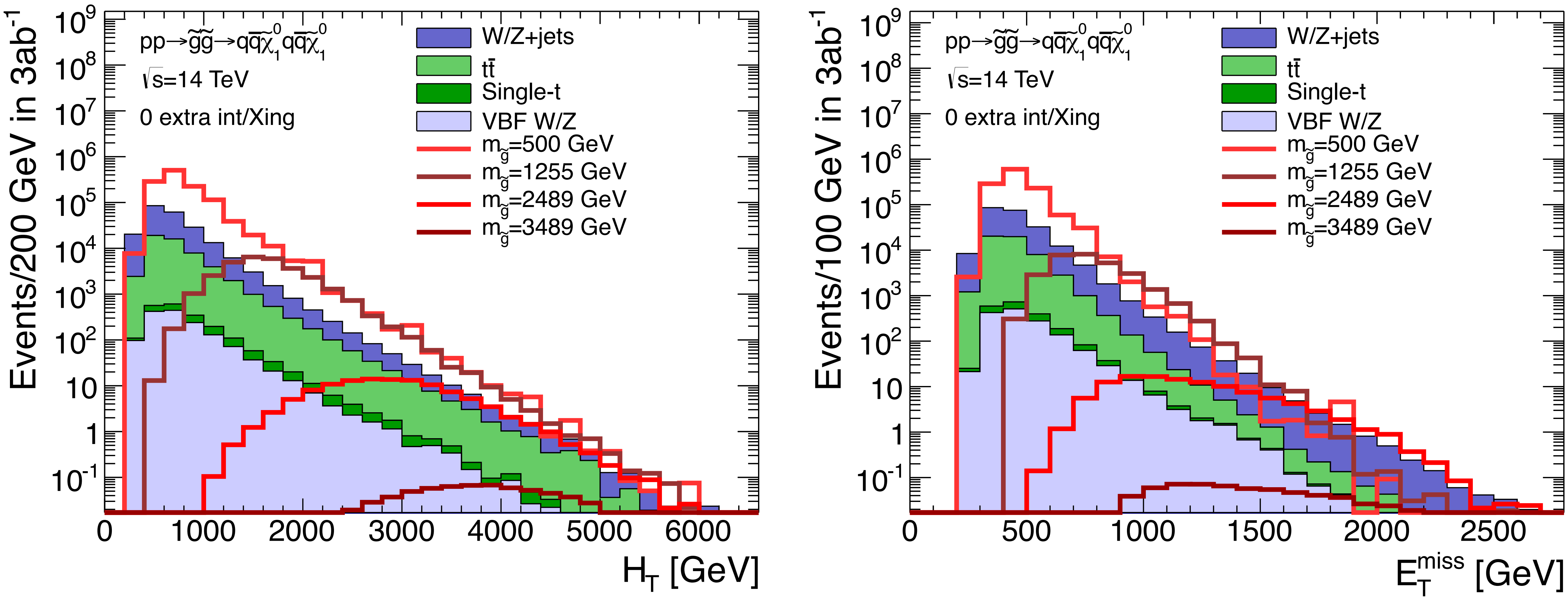
Search strategy

- $E_T^{\text{miss}}/\sqrt{H_T} > 15\ \text{GeV}^{1/2}$
- The leading jet p_T must satisfy $p_T^{\text{leading}} < 0.4\, H_T$
- $E_T^{\text{miss}} > (E_T^{\text{miss}})_{\text{optimal}}$
- $H_T > (H_T)_{\text{optimal}}$

Jets + MET

$\sqrt{s} = 14$ TeV

$p\,p \to \tilde{g}\,\tilde{g} \to \left(q\,\bar{q}\,\tilde{\chi}_1^0\right)\left(q\,\bar{q}\,\tilde{\chi}_1^0\right)$

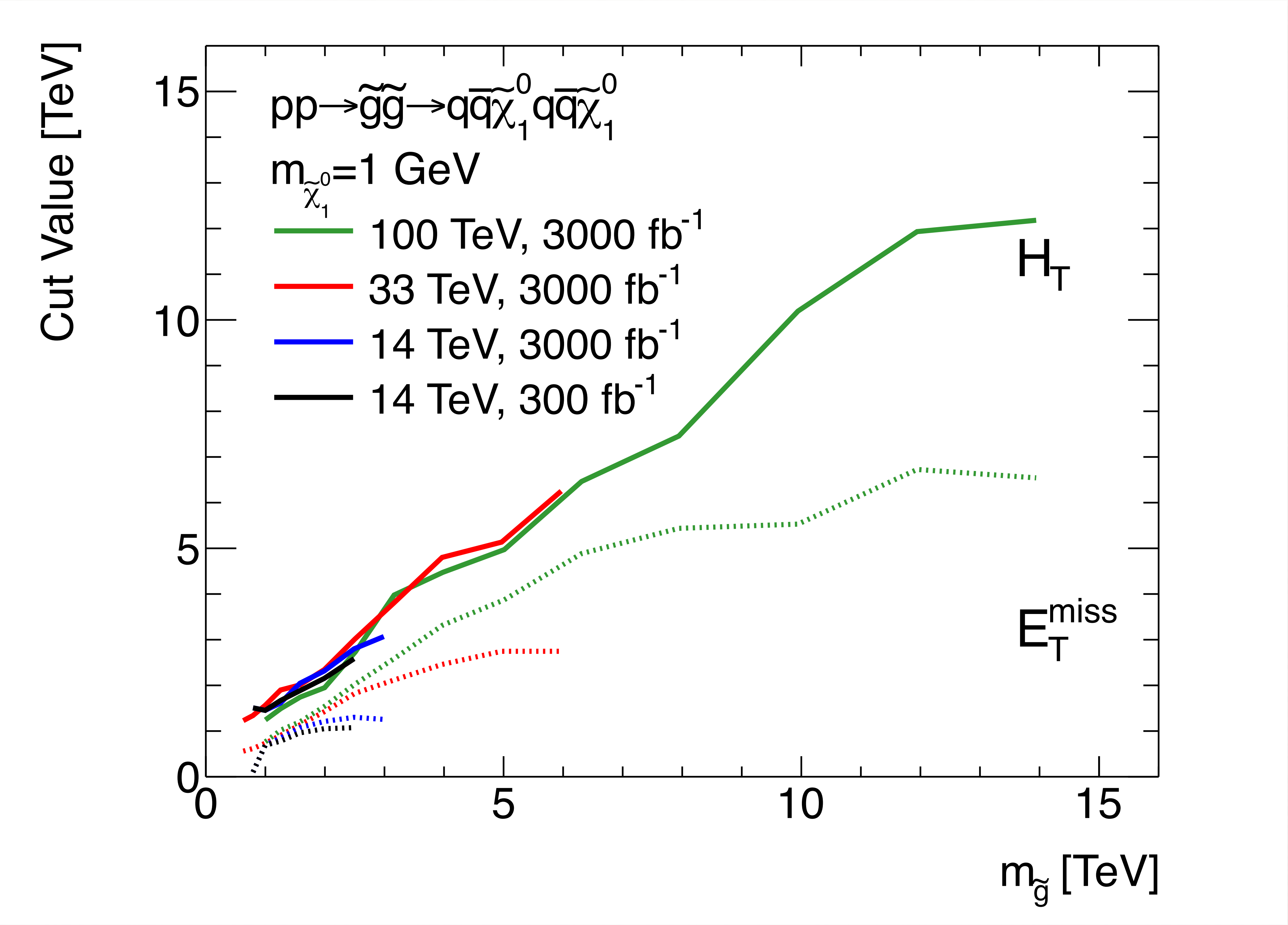


Dominant background:

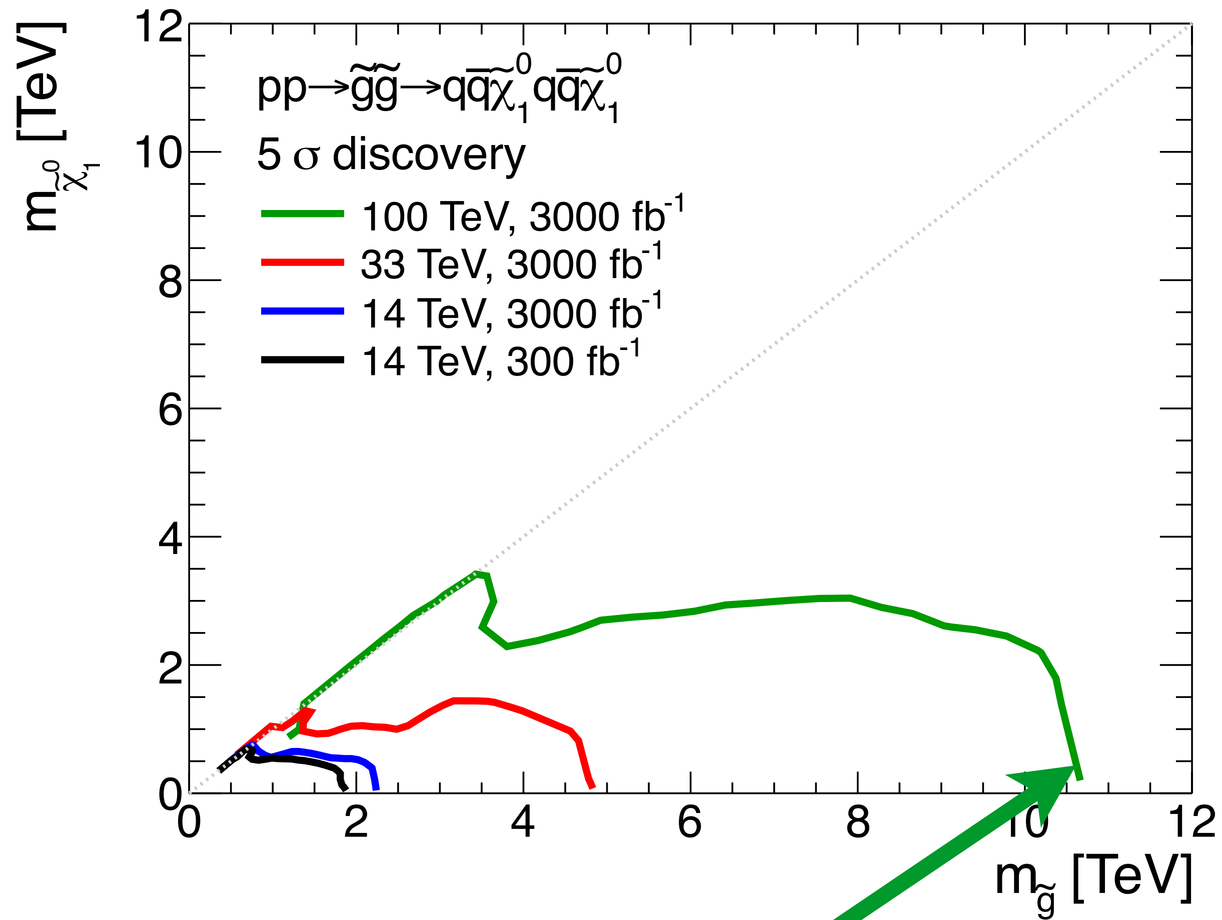
W/Z + jets @ 14 TeV

$t\,\bar{t}$ @ 100 TeV

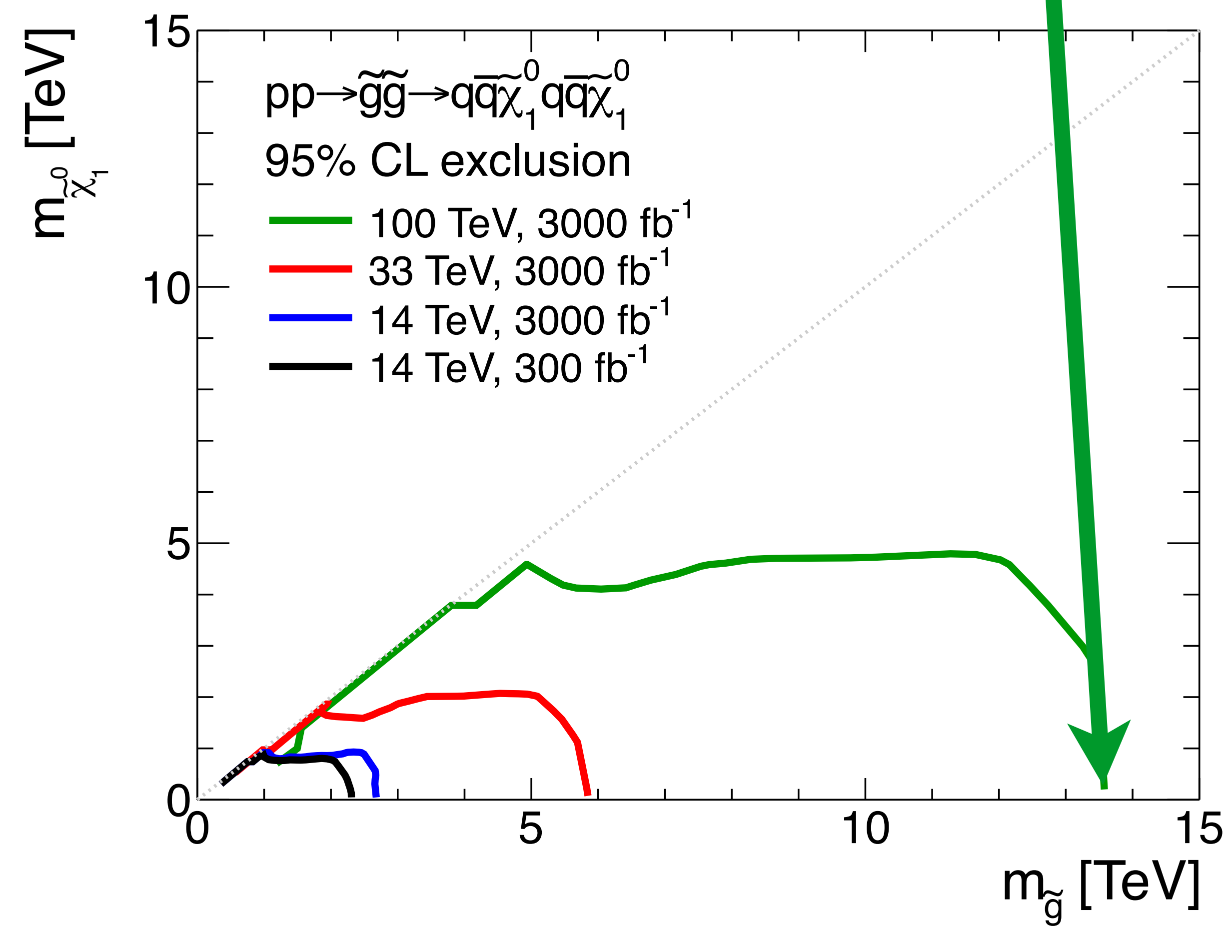
Optimal Cuts



Results

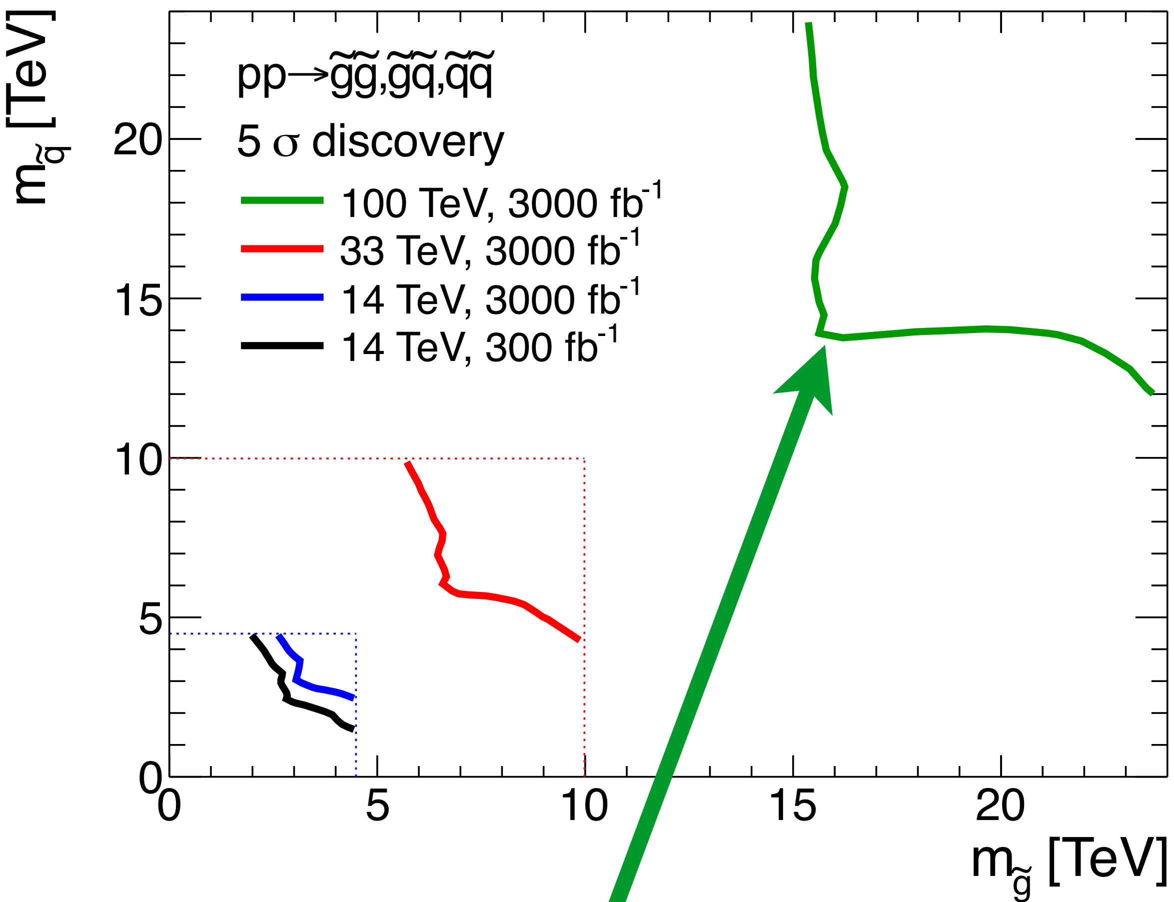


Exclude 13.5 TeV gluino!
(with 60 events)



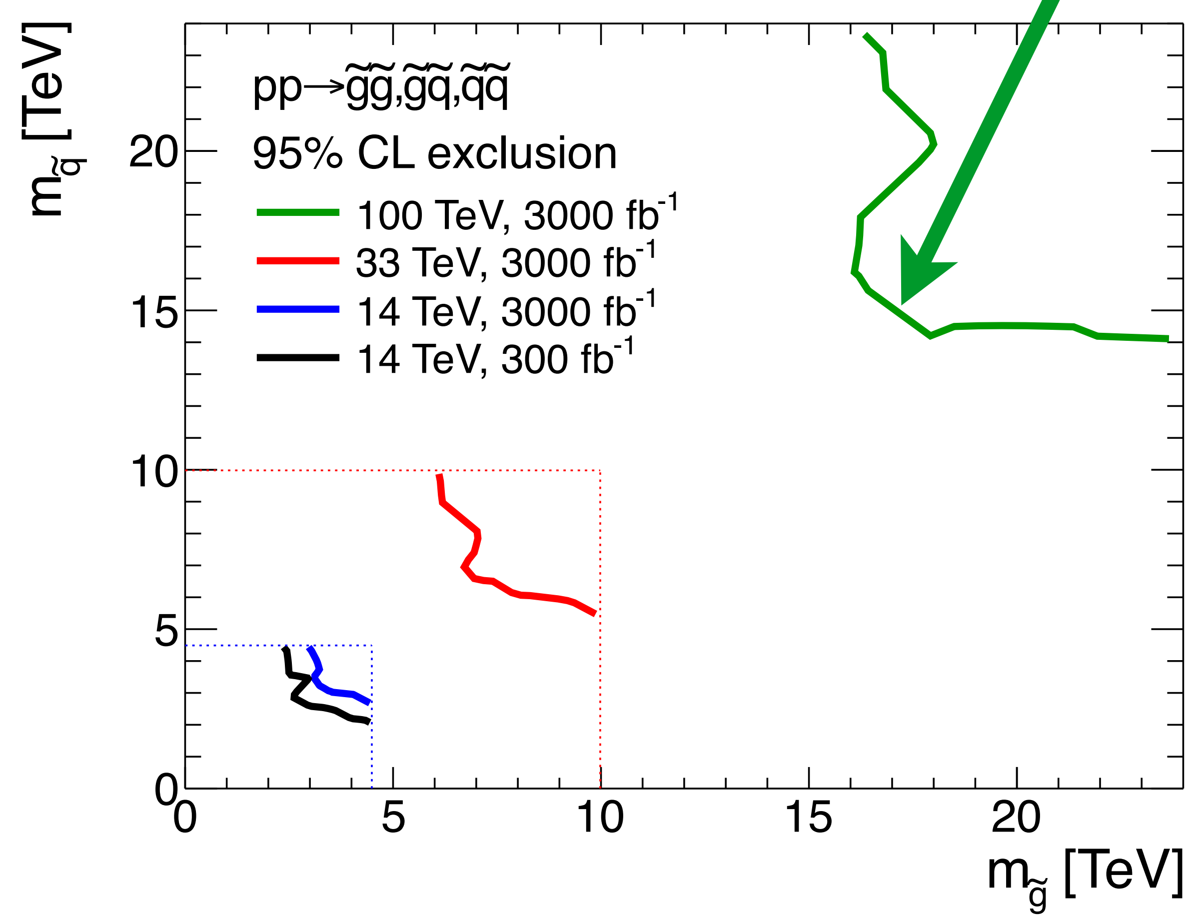
Discover 11 TeV gluino!

Results



Discover 15 TeV gluino; 13 TeV squarks!

Exclude 17 TeV gluino; 15 TeV squarks!



Summary

Interested in the reach of future colliders.

Simplified Models well suited to this task.

Overcame Monte Carlo challenges.

Among first realistic projections for 33 TeV and 100 TeV machines.

With 100 TeV, can discover 11 TeV gluinos.

Implications

Thermal winos below 1.6 TeV implies

gluinos below 10 TeV

Direct test of “simple” scenario!

Conclusions

Conclusions

Models of heavy SUSY are compelling.

Need concrete experimental tests.

Demonstrated wino dark matter can be probed with data.

Computed mass reach for future collider experiments.

Anticipating improved limits (discovery?) for winos using CTA!

Tons of interesting new physics questions to consider for proton collisions at 100 TeV!