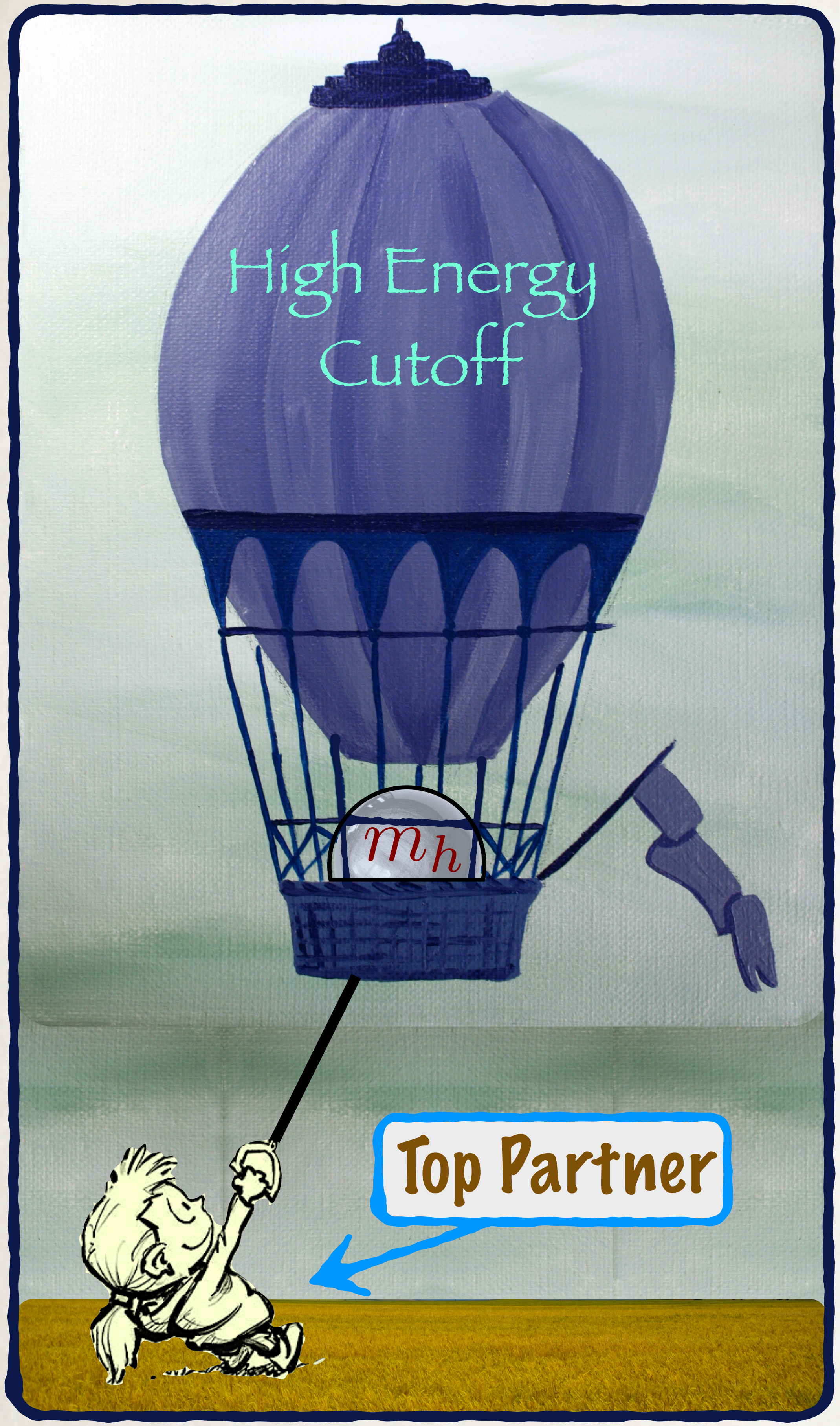



# THE HIGGS MASS, TOP PARTNERS, AND COLLIDERS: *WHAT WE LOSE BY LETTING GO*

Timothy Cohen

Princeton University
Institute for Advanced Study

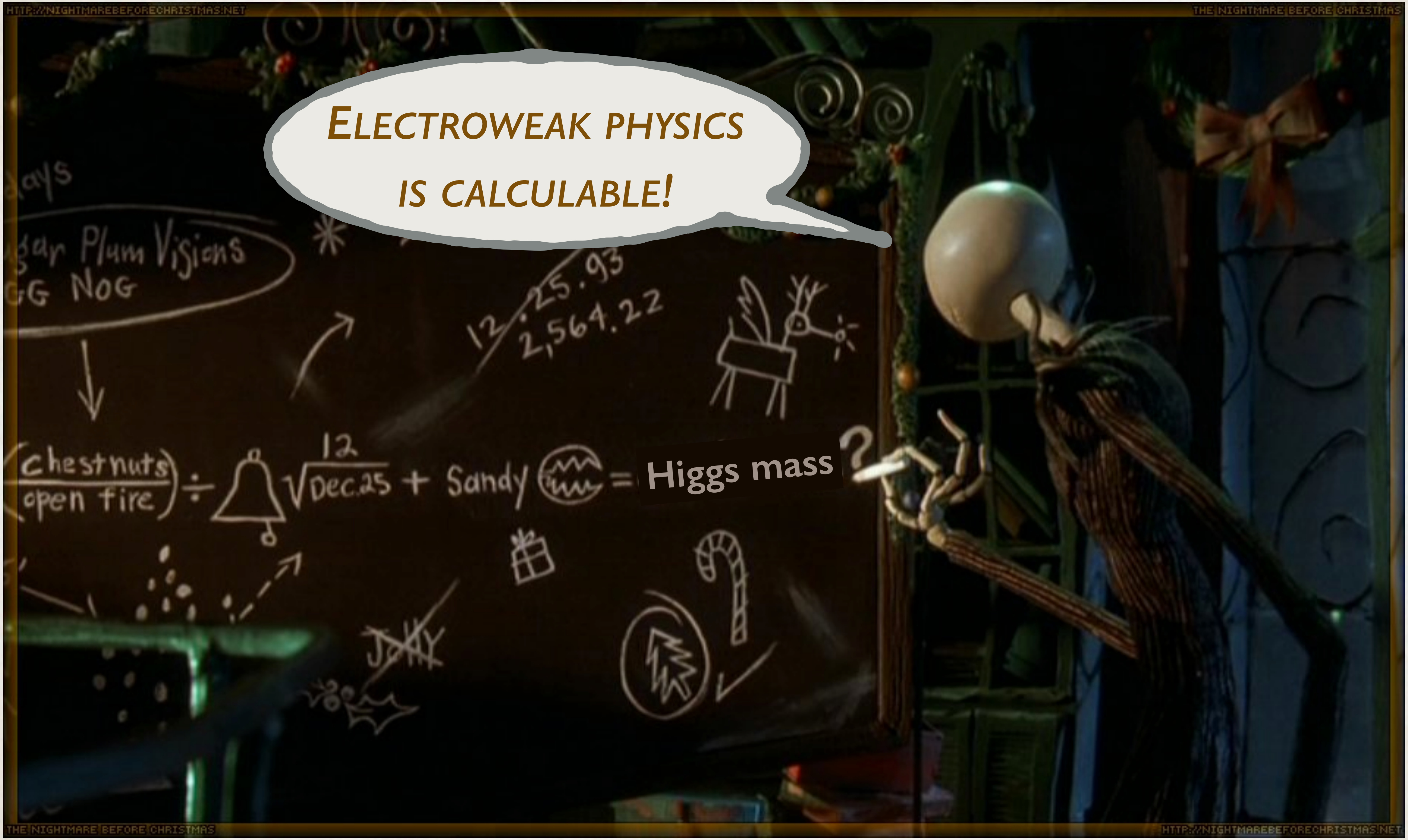
Fermilab Colloquium
March 4, 2015

# HIGGSDEPENDENCE DAY!

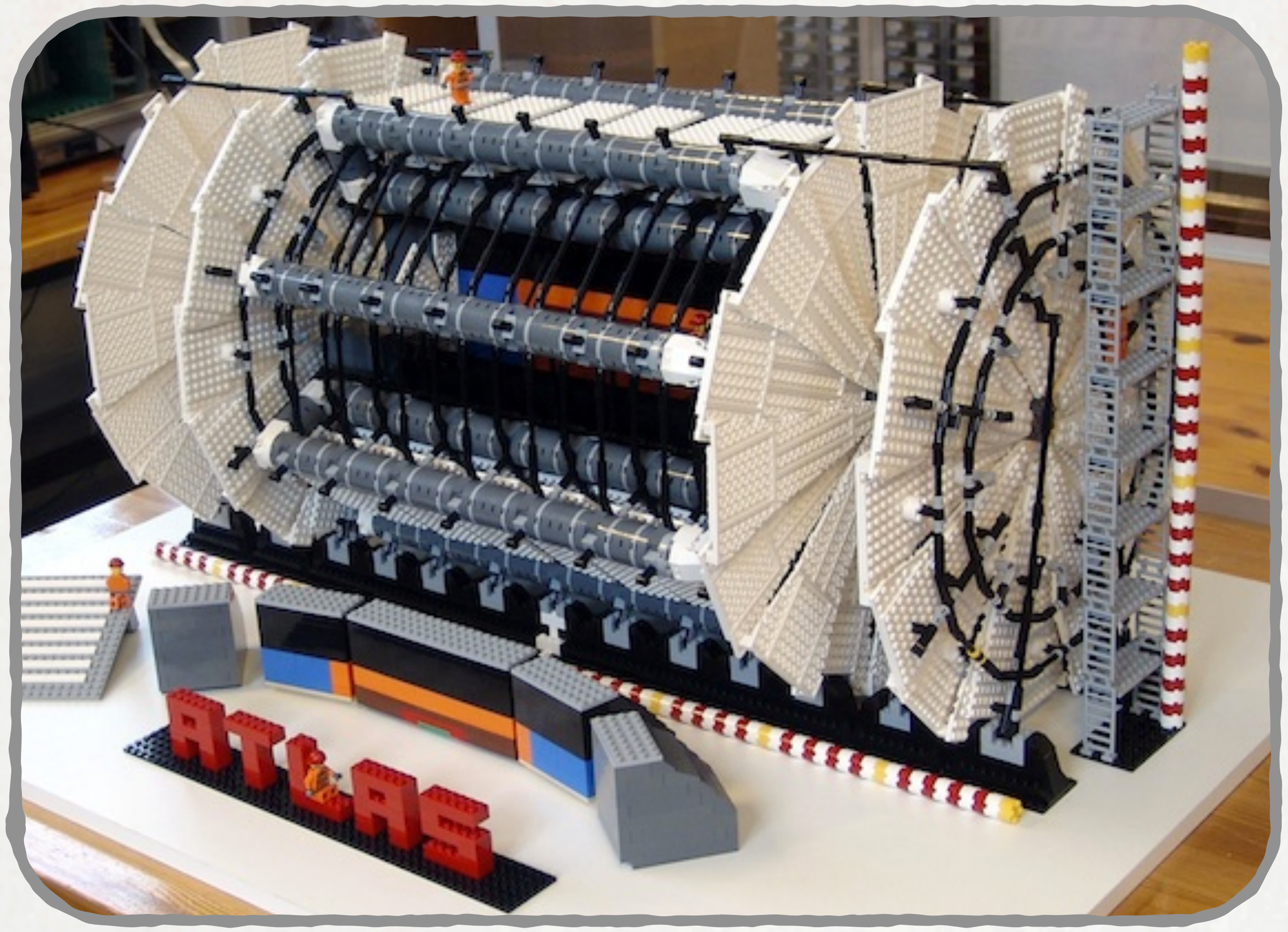
Most important lessons:

- Higgs boson exists!
- Weakly coupled!!

# HIGGSDEPENDENCE DAY!



# THE STANDARD MODEL IS A MODEL




Set the low energy Higgs mass and forget it.

Make predictions.

No conflict with experiment (so far).

# BRIEF SIDEBAR

# DIMENSIONFUL SCALES

**Relativity:**

Space $\equiv$ Time

Convert meters to seconds with speed of light: $c$.

Mass $\equiv$ Energy

Convert mass to energy with speed of light: $c$.

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**Quantum Mechanics:**

Energy $\equiv 1/$Time

Convert energy to time with Planck's constant: $\hbar$.

# DIMENSIONFUL SCALES

**Relativity:**

Space $\equiv$ Time

Convert meters to seconds with speed of light: $c$.

Mass $\equiv$ Energy

Convert mass to energy with speed of light: $c$.

**Quantum Mechanics:**

Energy $\equiv 1/$Time

Convert energy to time with Planck's constant: $\hbar$.

Large mass scales are like short distance scales.
The LHC is a giant microscope!

# END SIDEBAR

# REDUCTIONISM

What does it mean to have a *theory* for the Higgs mass?

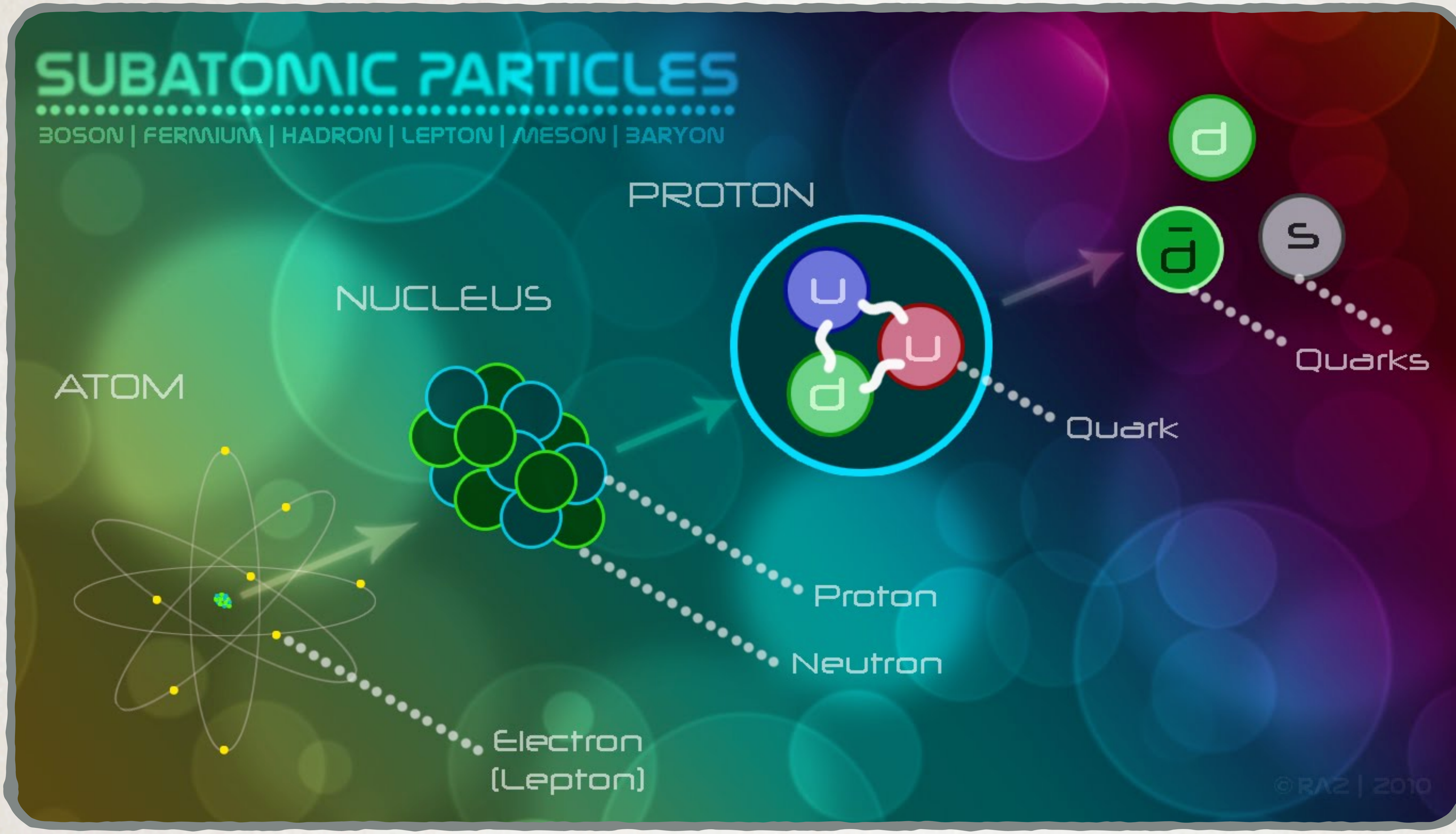
Higgs mass is a function of well defined (finite) inputs.
The Standard Model encompassed by larger framework.

***Naively: Higgs mass quadratically sensitive to new mass scales.***

**Historical precedent for reductionism:**

Underlies progress in fundamental physics.
New frameworks encompass the old, giving "reasons".

# REDUCTIONISM



# NEW SCALES?

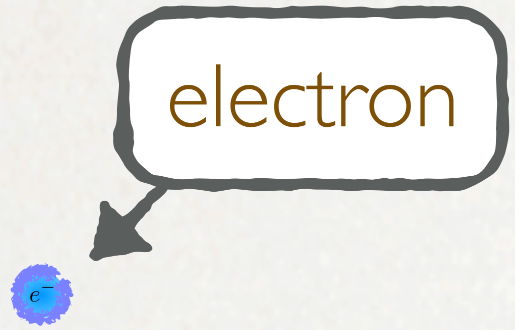
Evidence for physics beyond the Standard Model:

- dark matter
- matter/anti-matter asymmetry
- neutrino masses
- gravity

Very likely new dimensionful scale exists.

Want to protect the Higgs from physics at high energy scales.

# ELECTRON SELF-ENERGY



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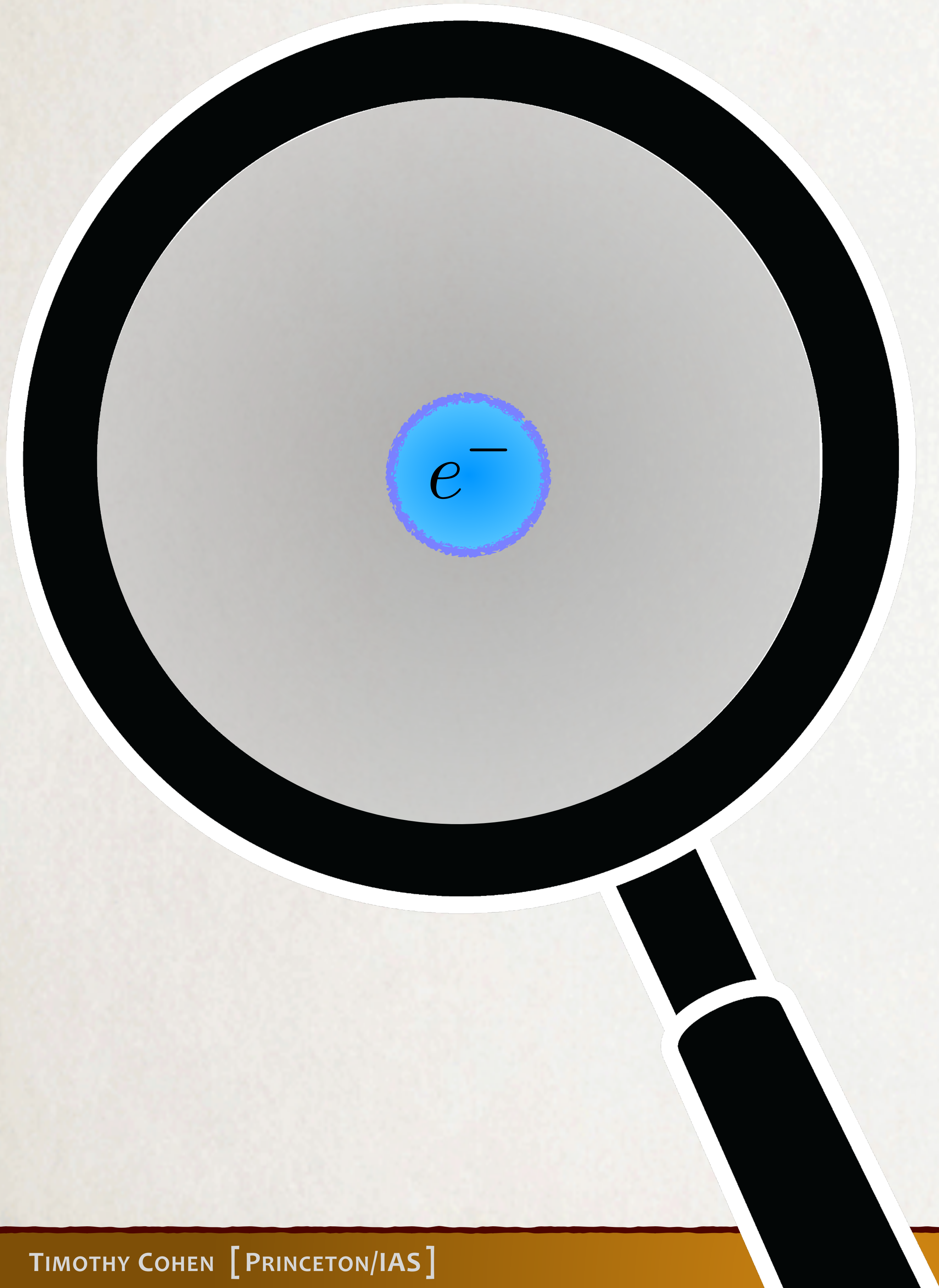


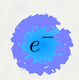

**CLASSICAL**

$$\Delta m_e \sim \frac{e^2}{r_e}$$

"electron radius"

$$\frac{\Delta m_e}{m_e} \sim 10^9 \left(\frac{r_{\text{Planck}}}{r_e}\right)$$

# ELECTRON SELF-ENERGY



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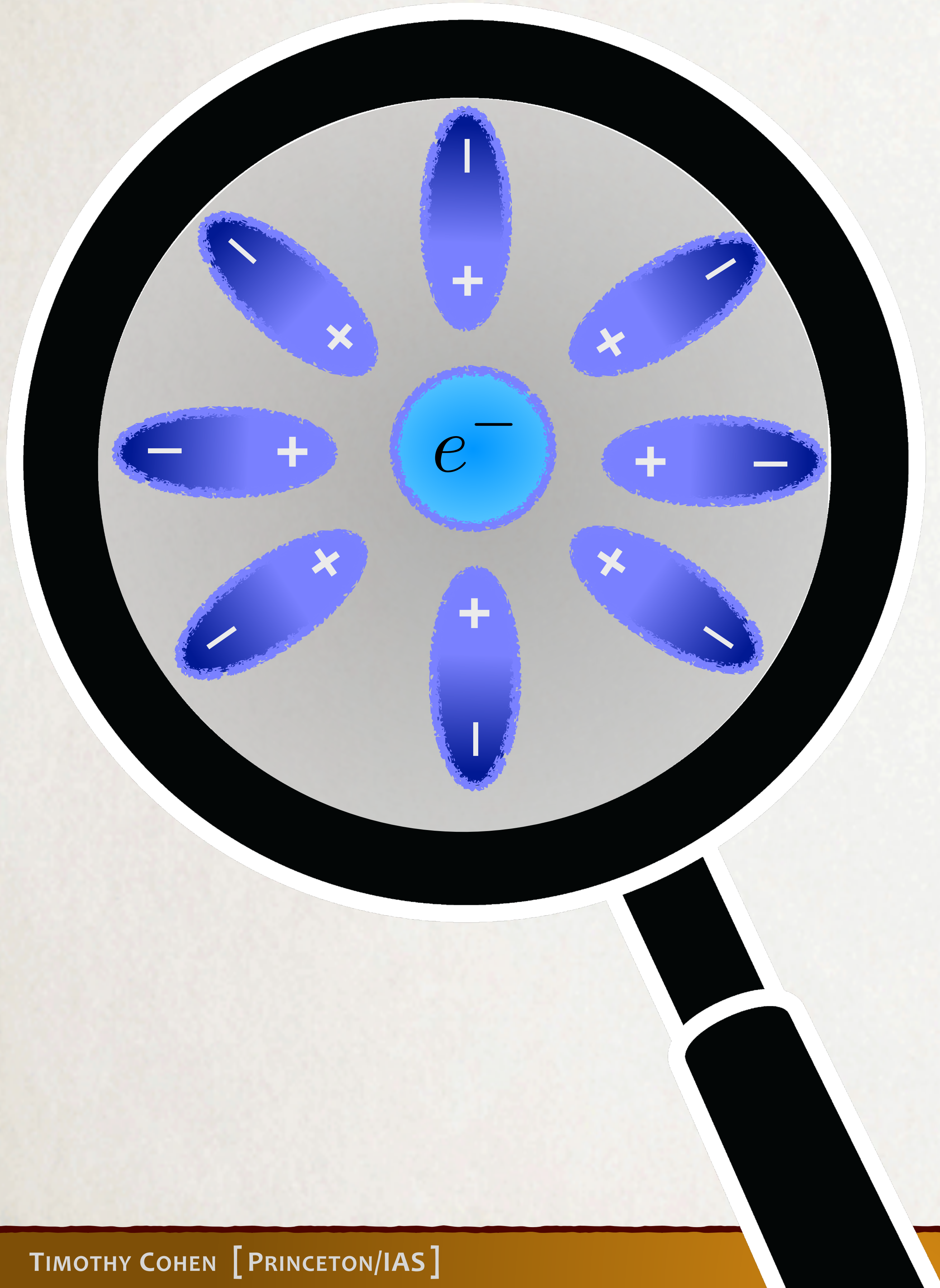


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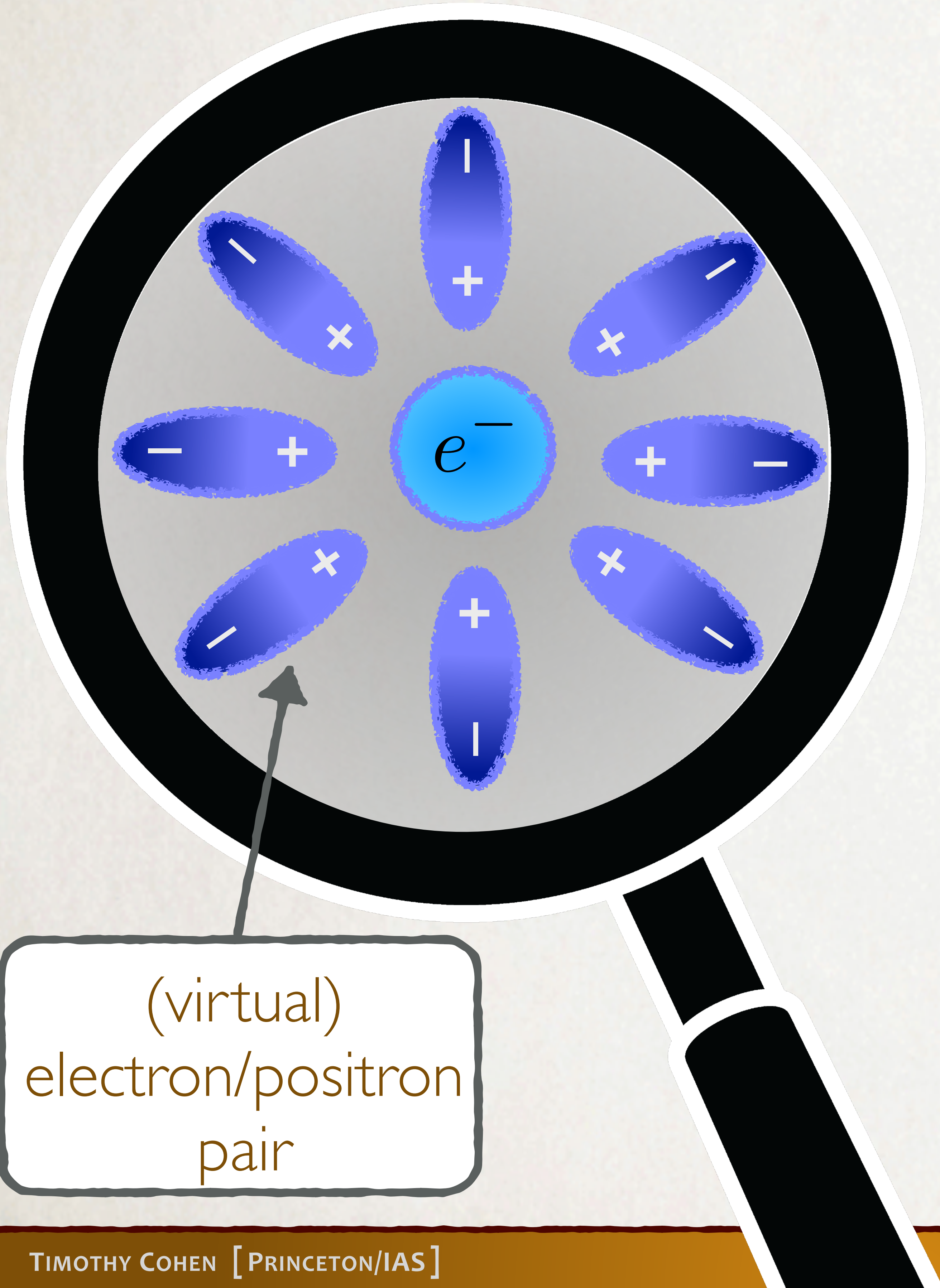
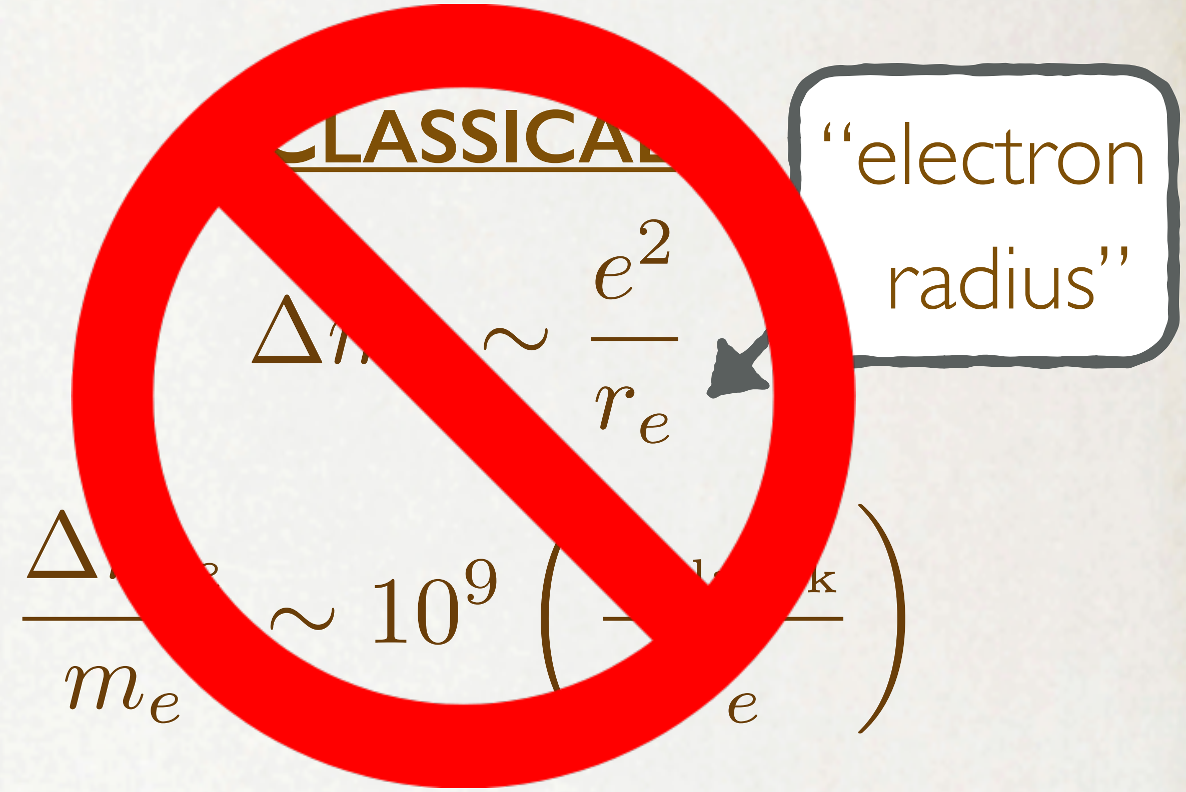
**QUANTUM**

$$\Delta m_e \sim m_e \frac{e^2}{16\pi^2} \log\left(m_e\, r_e\right)$$

$$\frac{\Delta m_e}{m_e} \sim 10^{-2}$$

# ELECTRON SELF-ENERGY

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$$\frac{\Delta m_e}{m_e} \sim 10^{-2}$$

***Requires new particle!***

# OUTLINE

I. The Higgs and its Potential

II. Supersymmetry: An Example Theory

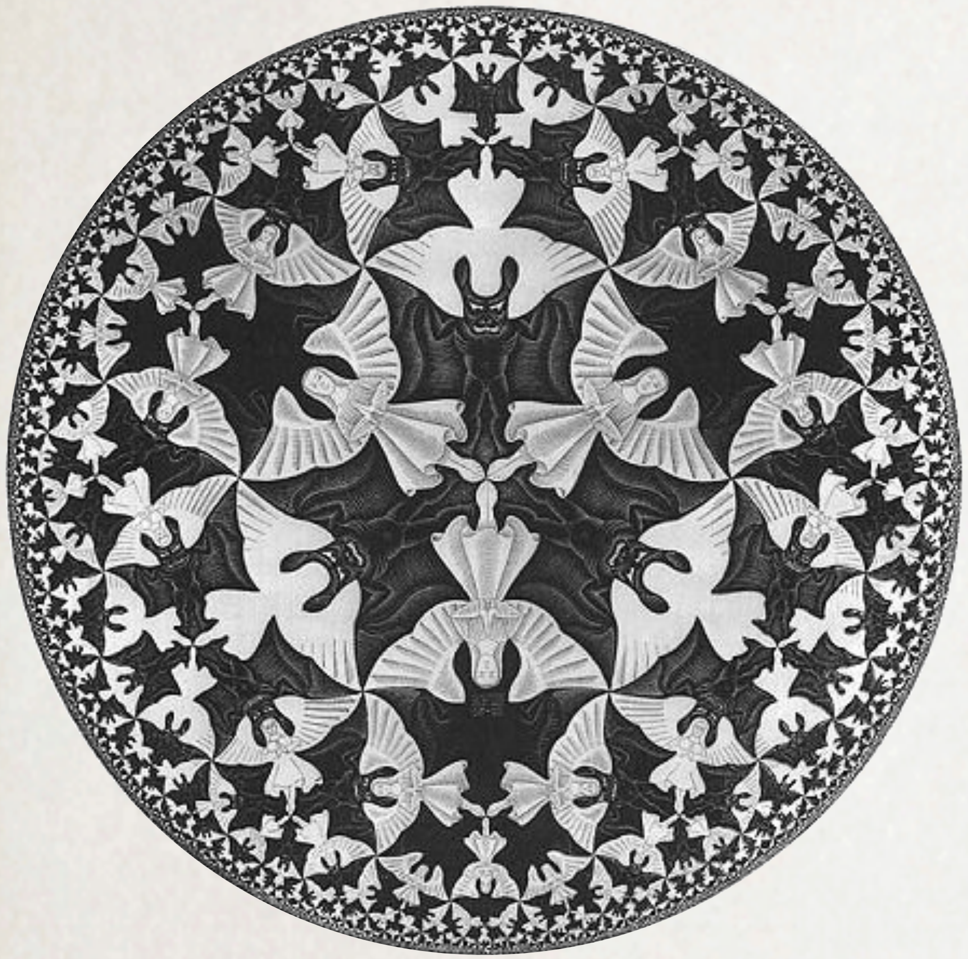
III. SUSY Naturalness Confronts Experiment

IV. Alternative Theories

V. Summary

# I. THE HIGGS AND ITS POTENTIAL

# CHARGED SCALAR



Introduce a charged scalar state: $\phi$ .

"$\phi$ carries a charge"

is equivalent to

$$\phi \rightarrow \phi' = e^{i\, q_\phi\, \xi}\, \phi$$

under a symmetry (gauge) transformation.

"Charge is conserved"

is equivalent to

Lagrangian $\mathcal{L}$ invariant under transformation.

$\phi$ and $\phi^*$ have opposite charge.

# SCALAR MASS

Scalar mass always phase rotation invariant:

$$\mathcal{L} \supset m^2 |\phi|^2$$

No phase rotation can forbid mass.

***Anything can happen in quantum mechanics!***

Implication:
If $\phi$ interacts, quantum corrections can generate a mass.


$$\sim \frac{\text{coupling}^2}{16\pi^2}\Lambda^2$$

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The *cutoff*: $\Lambda \to \infty$

Problem for Higgs boson!

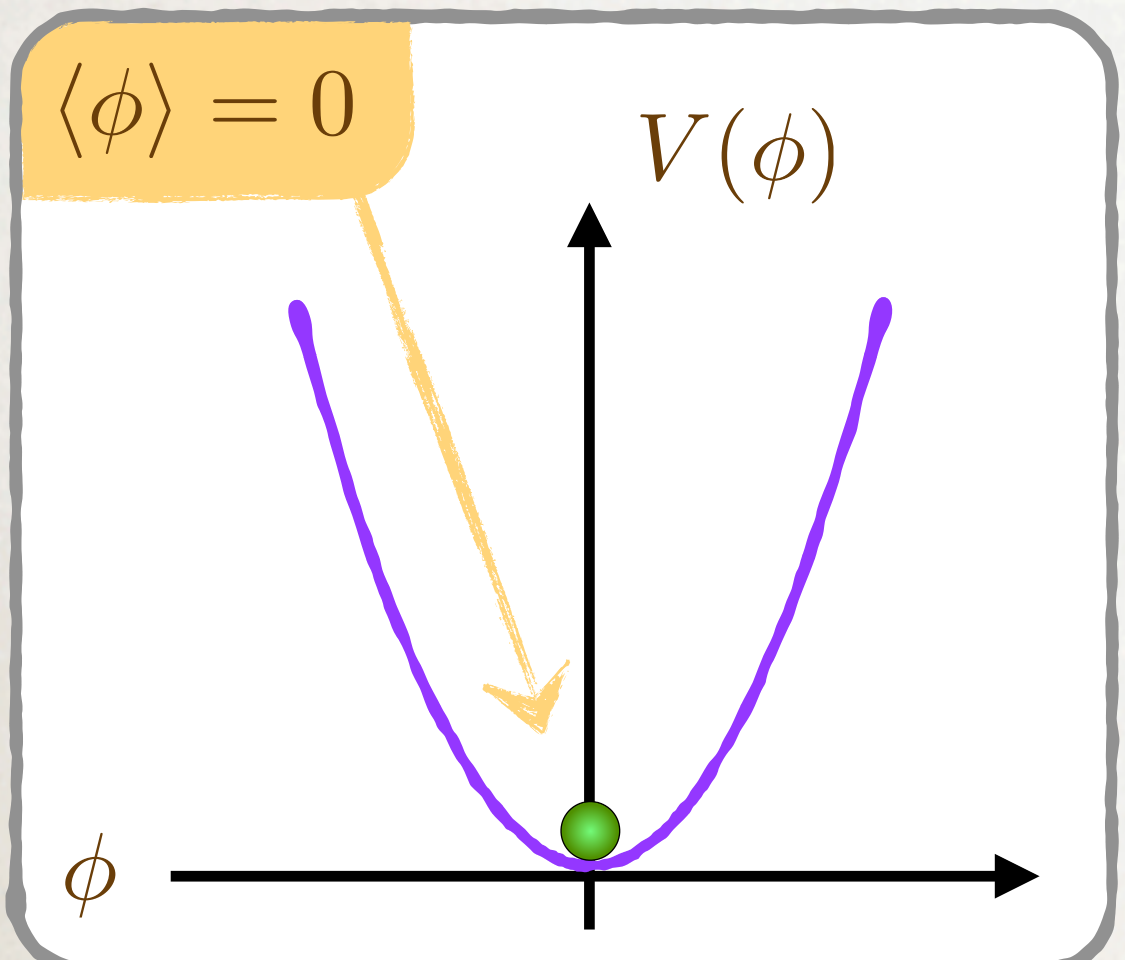
# SCALAR VEV

Add quartic for scalar (phase rotation invariant):

$$\mathcal{L} \supset \underbrace{m^2|\phi|^2 + \frac{\lambda}{4}|\phi|^4}$$

The "potential" $V(\phi)$.

$m^2 > 0$

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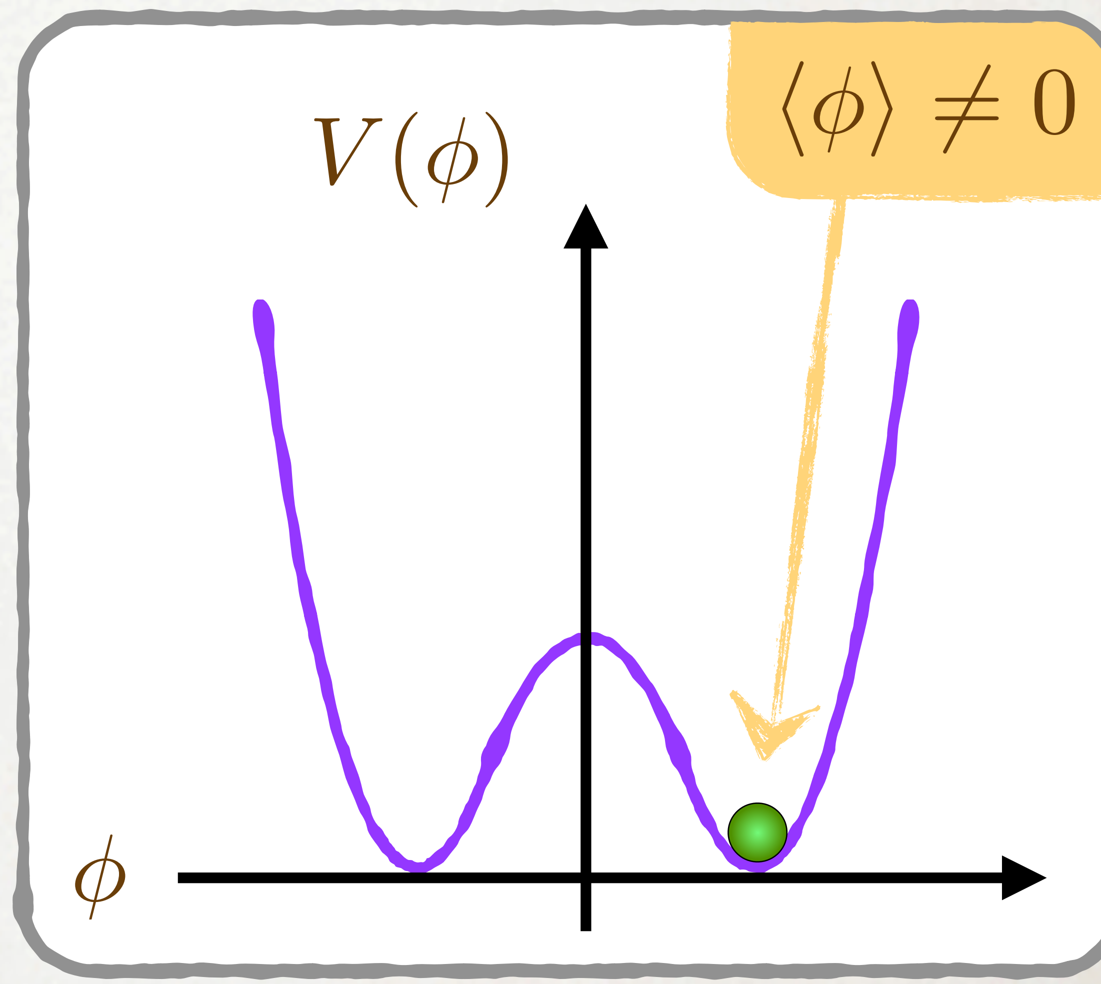
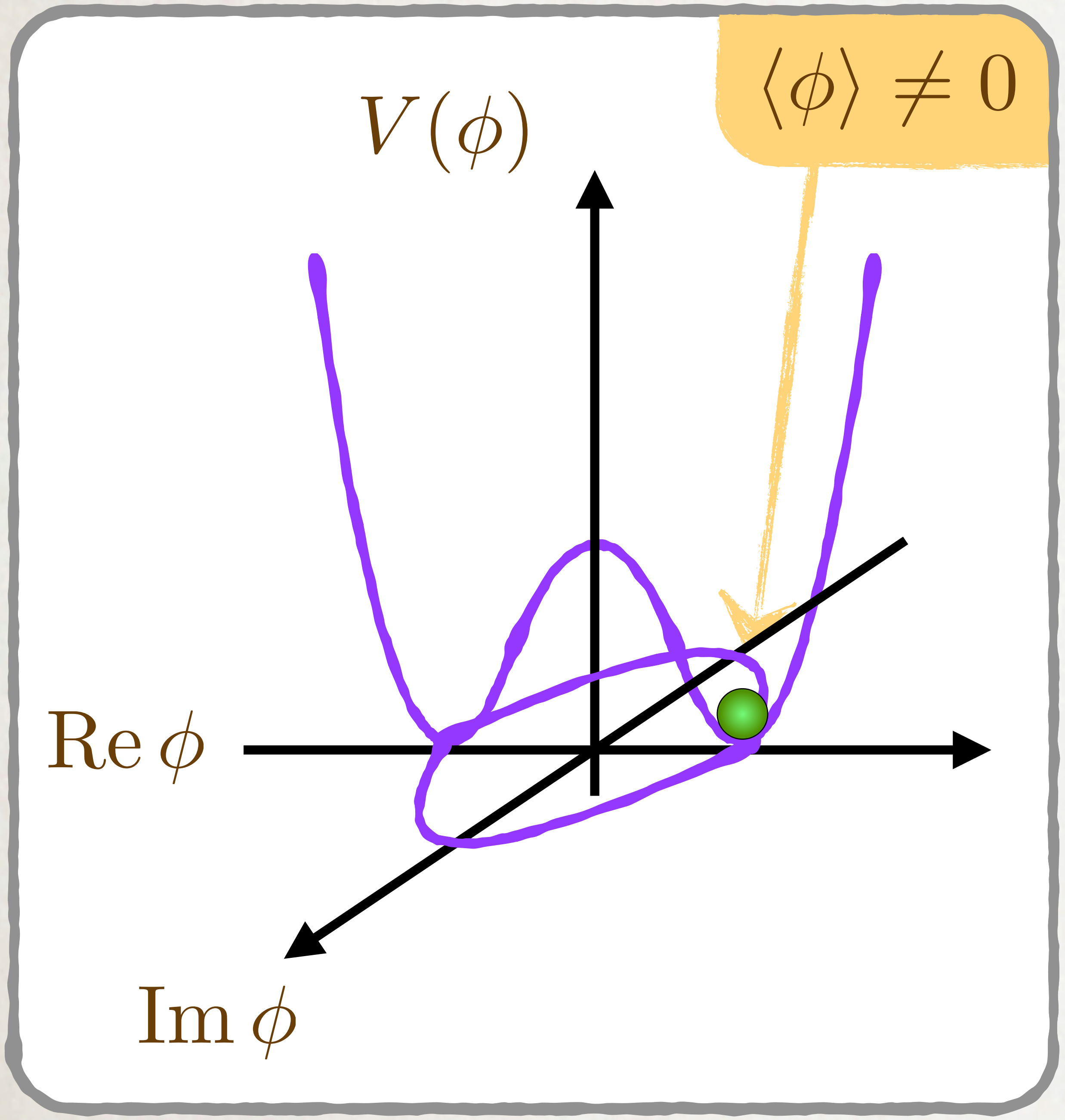


# VACUUM EXPECTATION VALUE

$\langle \phi \rangle$ : vacuum expectation value (vev).




Vacuum "sees" the phase.

The vev spontaneously breaks the symmetry.

This is how the Higgs vev breaks electroweak symmetry.

# THE HIGGS BOSON

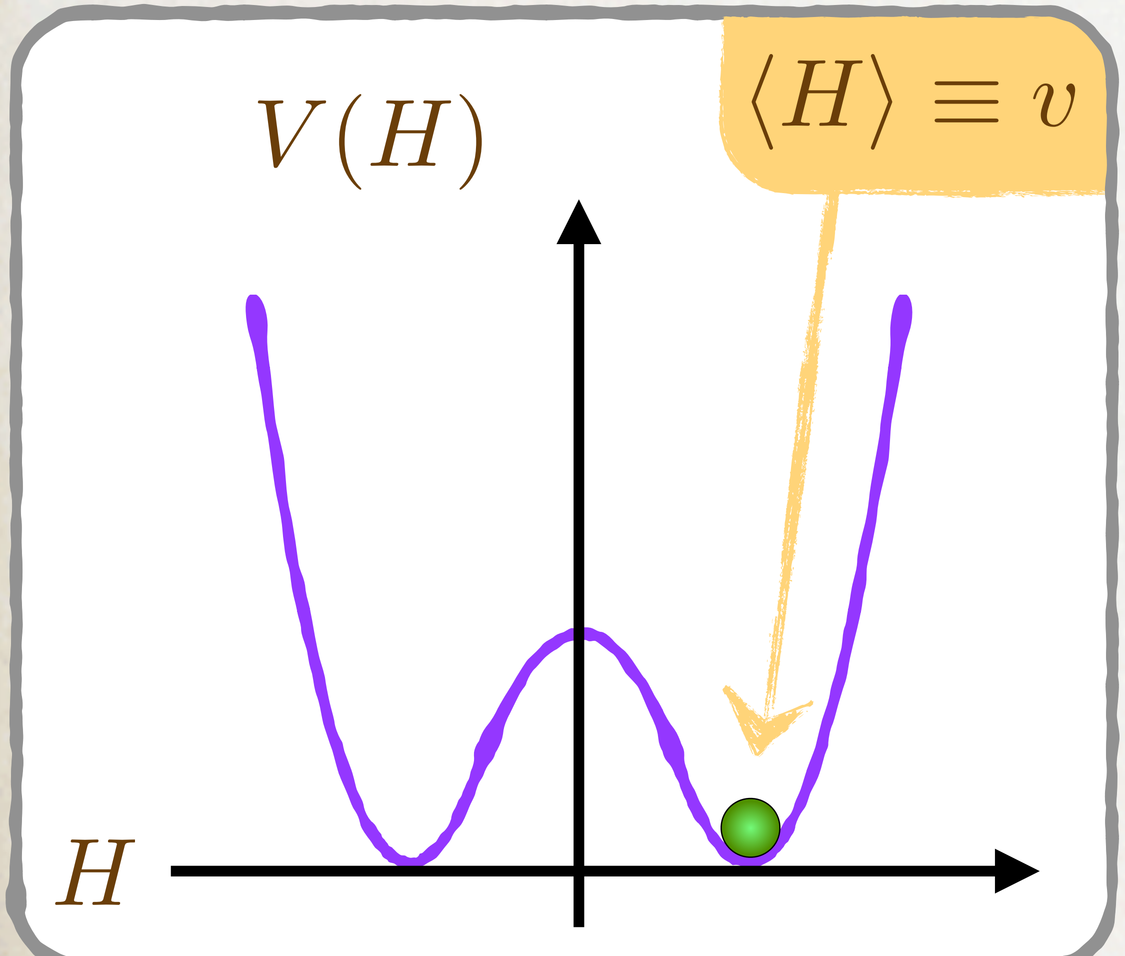
$$\phi \to H$$

# HIGGS POTENTIAL

$$V(v,H) = -\frac{\mu^2}{2}|v+H|^2 + \frac{\lambda_H}{16}|v+H|^4$$

Solving $\dfrac{\partial V(v,0)}{\partial v} = 0 \Rightarrow v^2 = \dfrac{2\,\mu^2}{\lambda_H}$

Solving $\dfrac{\partial^2 V(v,0)}{\partial v^2} = m_H^2 \Rightarrow m_H^2 = 2\,\mu^2$




$W^\pm$ mass $\Rightarrow$ $v \simeq 246$ GeV

Higgs mass $\Rightarrow$ $m_H \simeq 125$ GeV

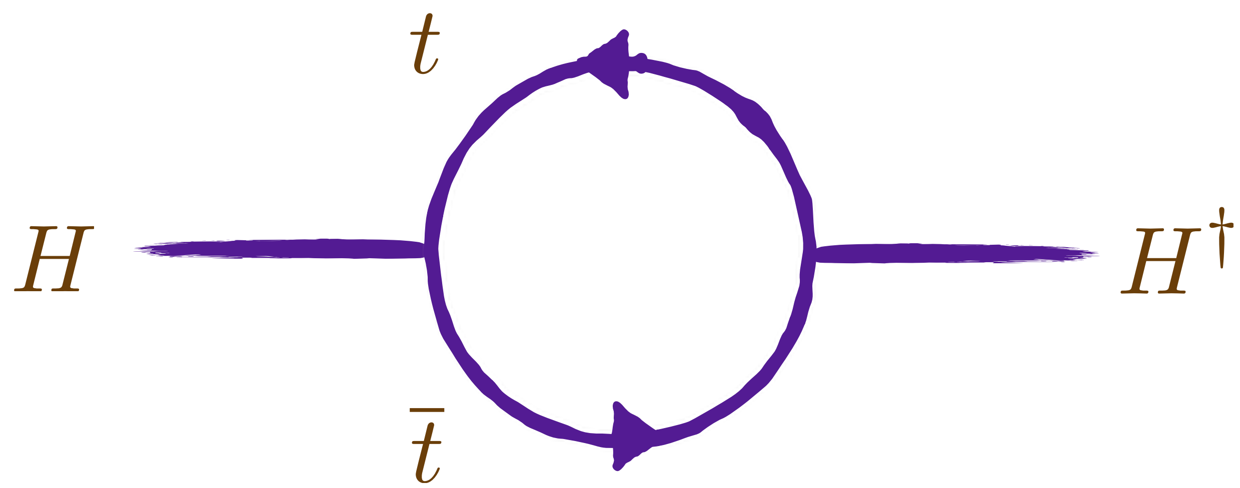
Yields $\lambda_H \simeq 0.26$, $\mu \simeq 88$ GeV

***Value for all SM parameters known!***

# HIGGS MASS CORRECTIONS

$$\mathcal{L} \supset y_t \, H \, \bar{t} \, t \quad \Rightarrow \quad m_t = \frac{y_t}{\sqrt{2}} \langle H \rangle$$

Top quark is heaviest particle; has strongest coupling to Higgs.




$$\sim \frac{y_t^2}{16\,\pi^2} \, \Lambda^2 \, |H|^2$$

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# TAME THE CUTOFF

To make sense of the model, "renormalize."

$$m^2_{\text{finite}} = m^2_{\text{bare}} + m^2_{\text{loop}}$$

$$\mu^2 \qquad \frac{y_t}{16\,\pi^2}\Lambda^2 + \mu^2 \qquad -\frac{y_t}{16\,\pi^2}\Lambda^2$$

free parameter in Lagrangian

computed from loops

Recall: $\mu^2 = (88 \text{ GeV})^2$ extracted from experiment.

# IS THERE A PHYSICAL INTERPRETATION OF THE CUTOFF?!?

WILL SEE THAT THIS REQUIRES A *THEORY* OF THE HIGGS *MASS*.

# II. SUPERSYMMETRY: AN EXAMPLE THEORY

# FERMION MASS

Fermions have spin 1/2.

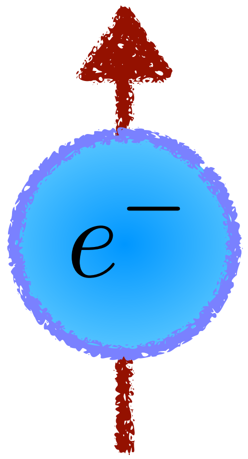
Is my fermion left or right handed?

# FERMION MASS

Fermions have spin 1/2.

Is my fermion left or right handed?

Take an electron spinning "up".

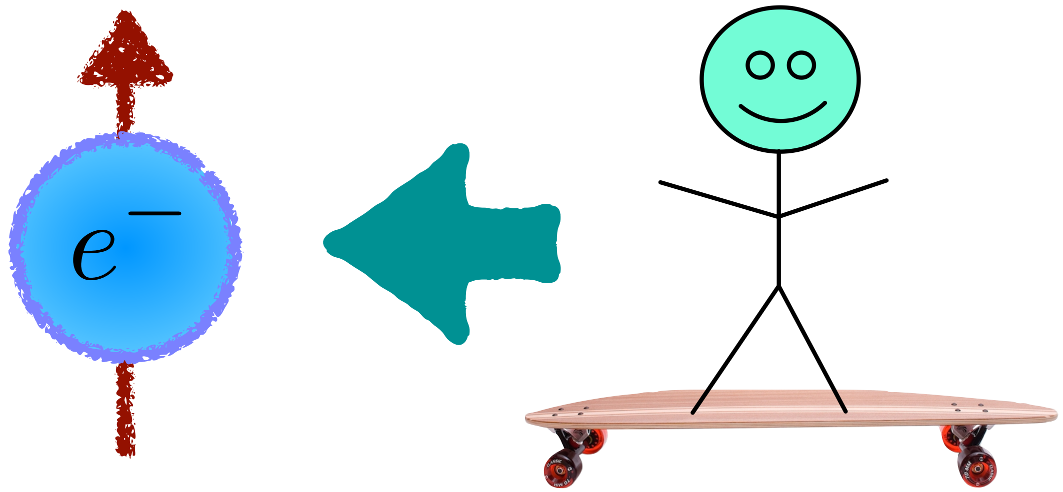


# FERMION MASS

Fermions have spin 1/2.

Is my fermion left or right handed?

Move into its rest frame.

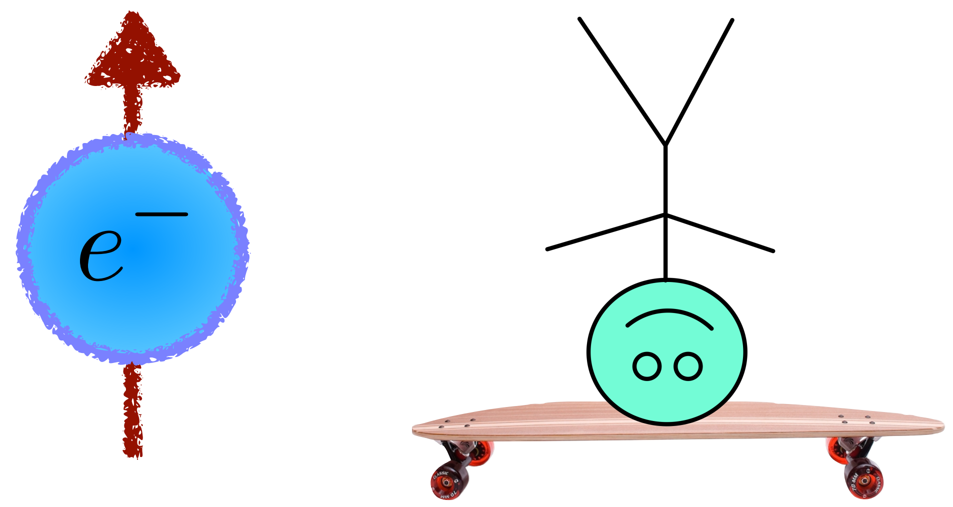


# FERMION MASS

Fermions have spin 1/2.

Is my fermion left or right handed?

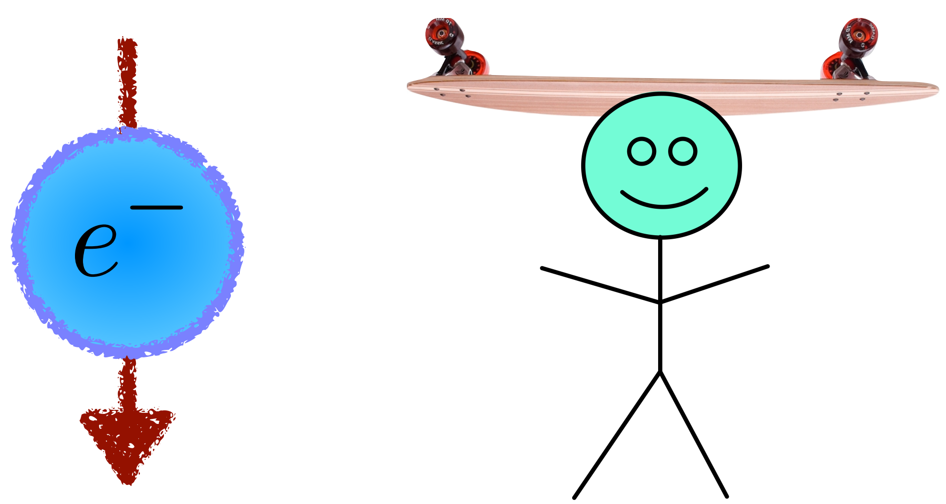
Stand on your head.



# FERMION MASS

Fermions have spin 1/2.
Is my fermion left or right handed?

From your point of view,
chirality is flipped.



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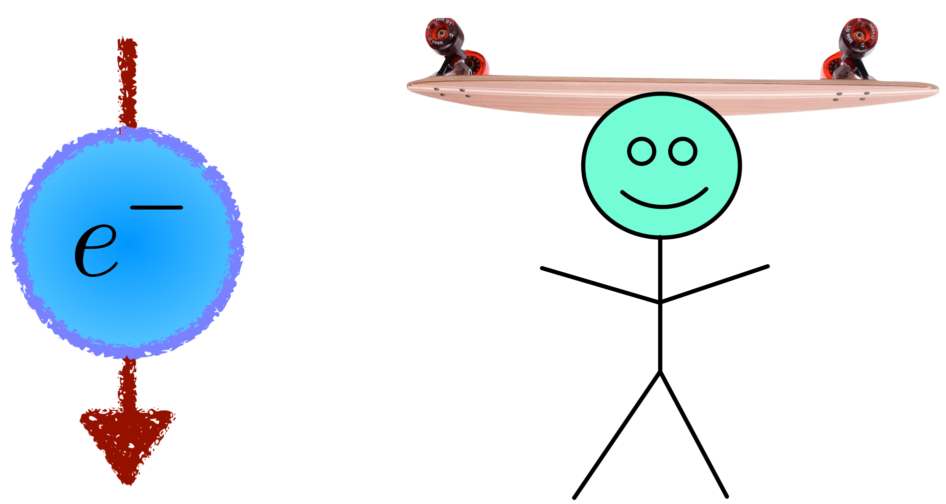


Going to rest frame is crucial step:
flipping chirality requires mass.

$$\mathcal{L} \supset m\,\psi_L\,\psi_R$$

Fermion mass mixes left and right chiralities.

# FERMION MASS

Recall, scalar mass always symmetric under phase rotation.

$$\mathcal{L} \supset m_\phi \, |\phi|^2$$

What about fermion mass?

$$\mathcal{L} \supset m_\psi \, \psi_L \, \psi_R$$

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Recall, scalar mass always symmetric under phase rotation.

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What about fermion mass?

$$\mathcal{L} \supset m_\psi \, \psi_L \, \psi_R$$

"Chiral" rotation:

$$\psi_R \to \psi_R' = e^{i\,\zeta} \, \psi_R$$

$$\psi_L \to \psi_L' = e^{i\,\zeta} \, \psi_L$$

$$\mathcal{L} \to \mathcal{L}' \subset e^{2\,i\xi} \, m_\psi \, \psi_L \, \psi_R$$

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Recall, scalar mass always symmetric under phase rotation.

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What about fermion mass?

$$\mathcal{L} \supset m_\psi \, \psi_L \, \psi_R$$

"Chiral" rotation:

$$\psi_R \to \psi'_R = e^{i\,\zeta} \, \psi_R$$

$$\psi_L \to \psi'_L = e^{i\,\zeta} \, \psi_L$$

$$\mathcal{L} \to \mathcal{L}' \subset e^{2\,i\xi} \, m_\psi \, \psi_L \, \psi_R$$

Chiral symmetry can forbid fermion mass.

Fermion mass correction proportional to $m_\psi$.

***Cutoff does not infect fermion masses!***

# “CHIRALITY” FOR SCALARS


Scalars inherit chirality of partner fermions.

Calculability of fermion masses inherited by scalars.

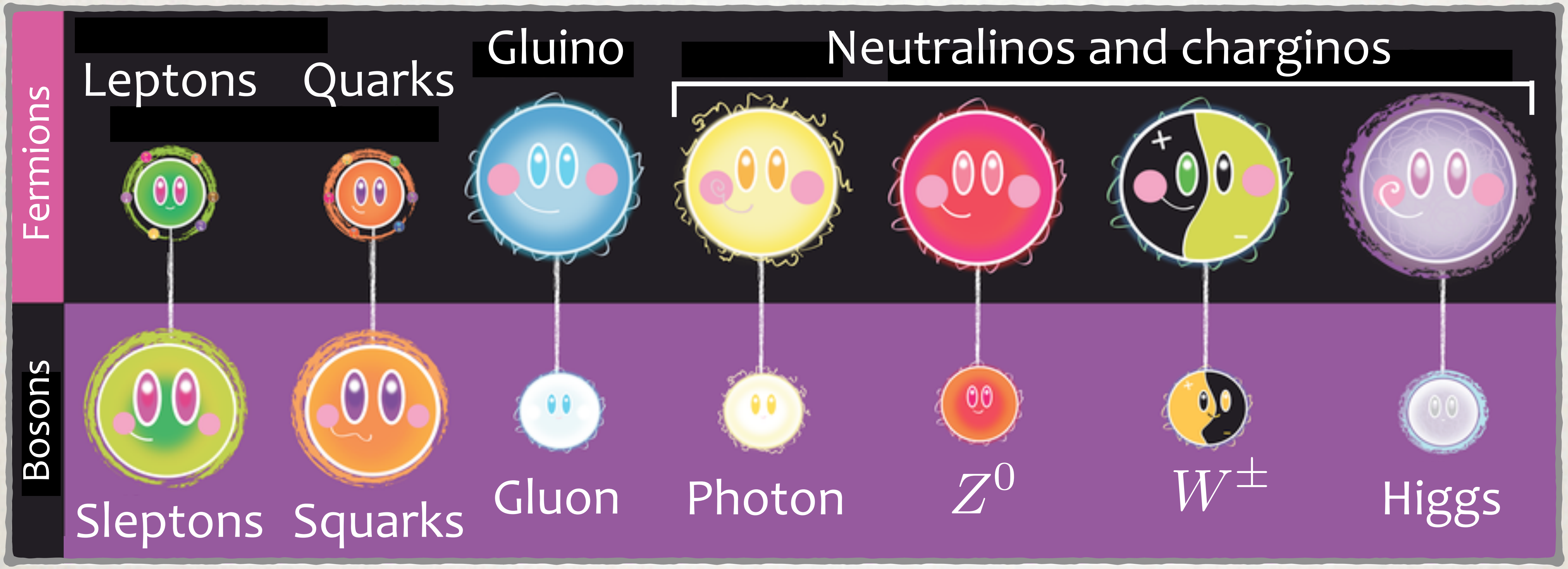
# A NEW KIND OF SYMMETRY

**Gauge invariance:**

Phase rotation compensated by states of opposite charge: electron needed positron.

**Supersymmetry:**

"Rotation" compensated by states of different spin



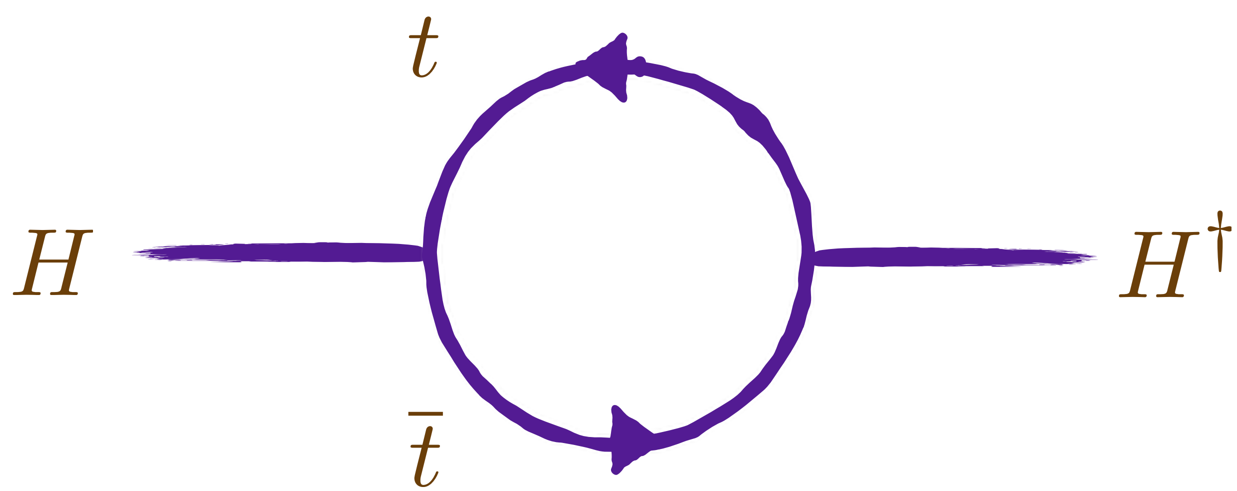
# THE TOP GETS A PARTNER


Top is a massive fermion; has $L$ and $R$ chirality.
Consistency requires introducing two stops: $\tilde{t}_L$ and $\tilde{t}_R$ .
Free parameters: two masses and a mixing angle.

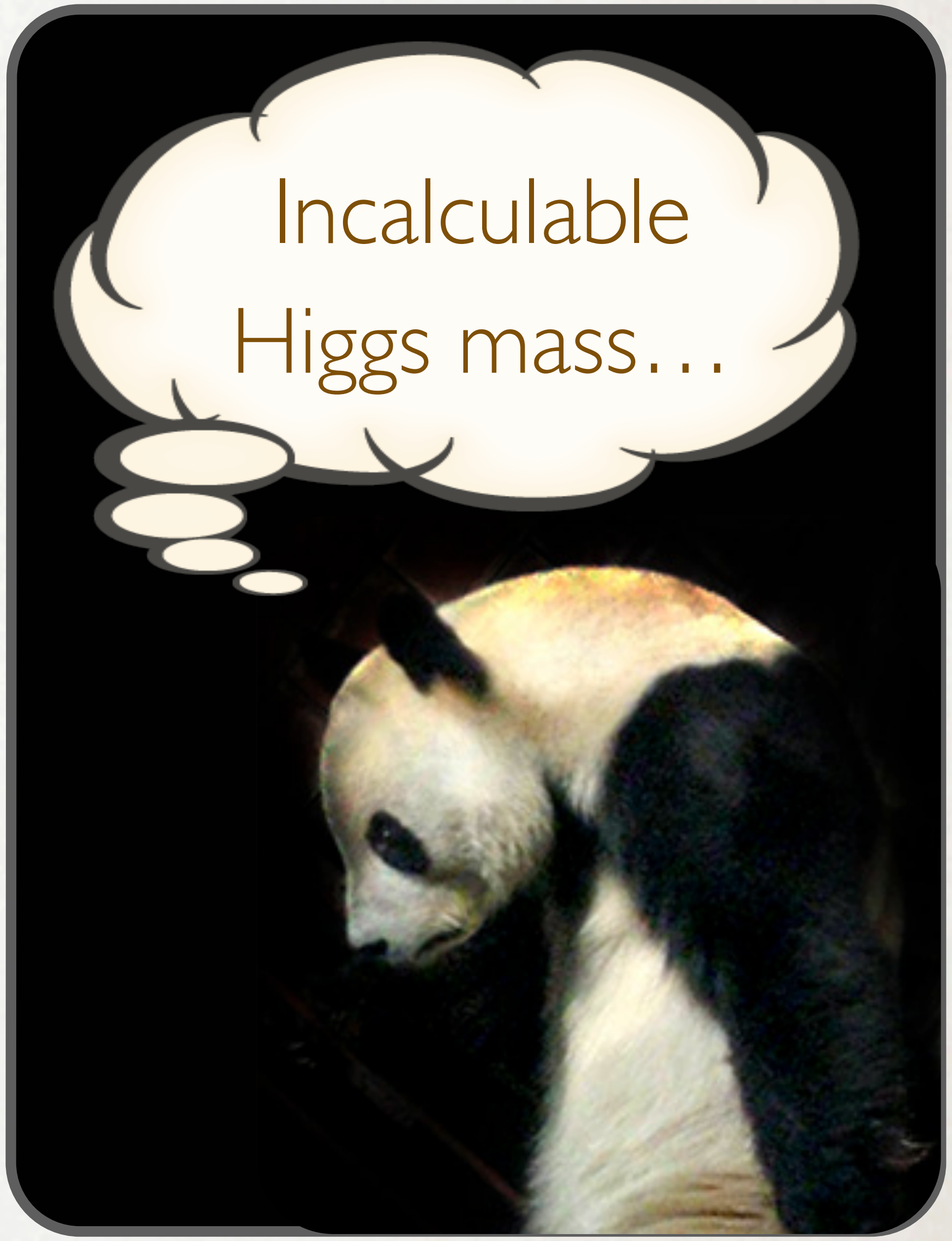
Top coupling to the Higgs: $y_t$.

Strength of top partner coupling to the Higgs set by $y_t$.

# HIGGS MASS CORRECTIONS




$$\sim \frac{y_t^2}{16\,\pi^2}\,\Lambda^2\,|H|^2$$



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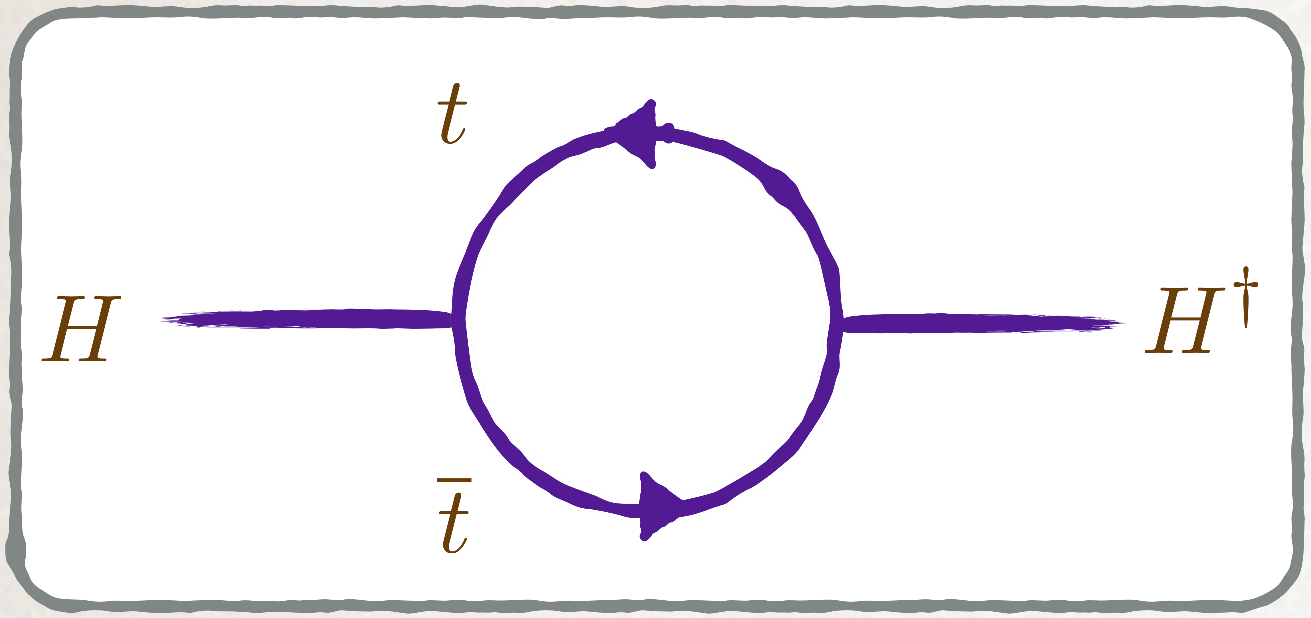
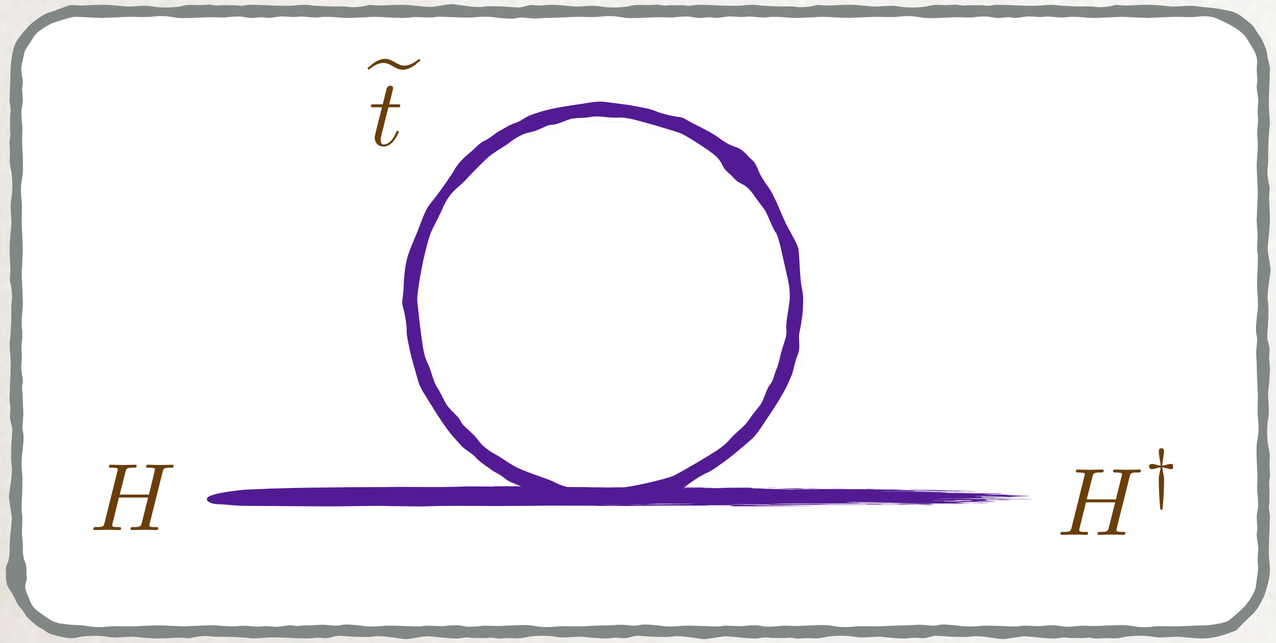



$$\sim \frac{y_t^2}{16\,\pi^2}\,\Lambda^2|H|^2$$

$+$




$$\sim -\frac{y_t^2}{16\,\pi^2}\left(\Lambda^2 + c\, m_{\tilde{t}}^2\right)|H|^2$$

# HIGGS MASS CORRECTIONS

# SUSY HIGGS POTENTIAL*

"Naturalness in SUSY"

$$V \simeq \overbrace{\left(m_H^2 - \frac{3}{4\,\pi^2}\, y_t^2\, m_{\tilde{t}}^2\right)}\left|H\right|^2$$

Calculable Higgs mass.

Stop mass give physical meaning to quadratic divergence.

Heavier stops imply larger cancellation.

***Stop mass below ~1 TeV extremely plausible!***

* in a simplified limit

# SUSY HIGGS POTENTIAL*

$$V \simeq \left(m_H^2 - \frac{3}{4\,\pi^2}\, y_t^2\, m_{\tilde{t}}^2\right)|H|^2$$
$$+\left(\frac{g^2 + g'^2}{8} + \frac{3}{8\,\pi^2}\, y_t^4 \log\frac{m_{\tilde{t}}}{m_t}\right)|H|^4$$

Calculable Higgs mass.

Stop mass give physical meaning to quadratic divergence.

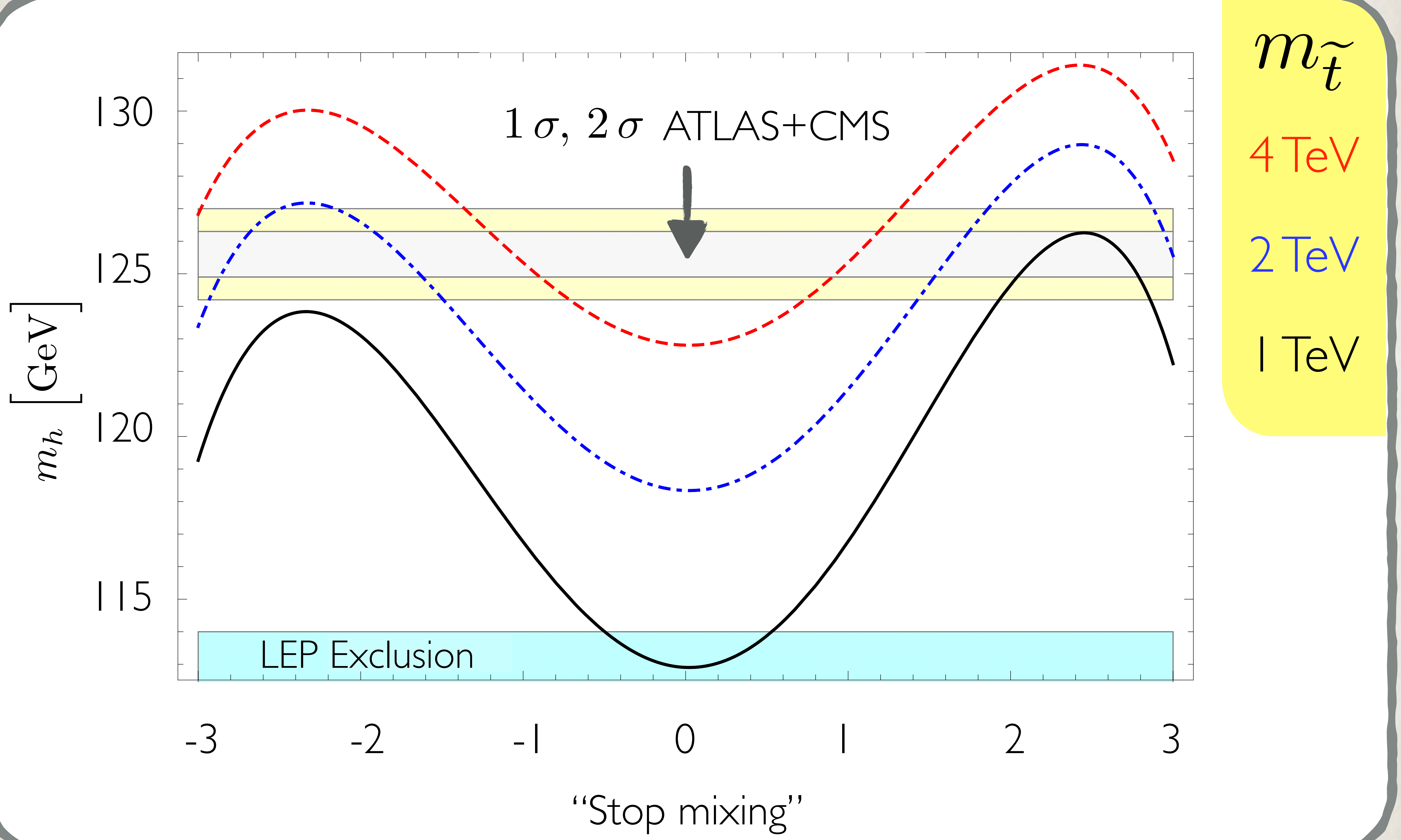
Heavier stops imply larger cancellation.

***Stop mass below ~1 TeV extremely plausible!***

Heavier stops yield larger quartic.

* in a simplified limit

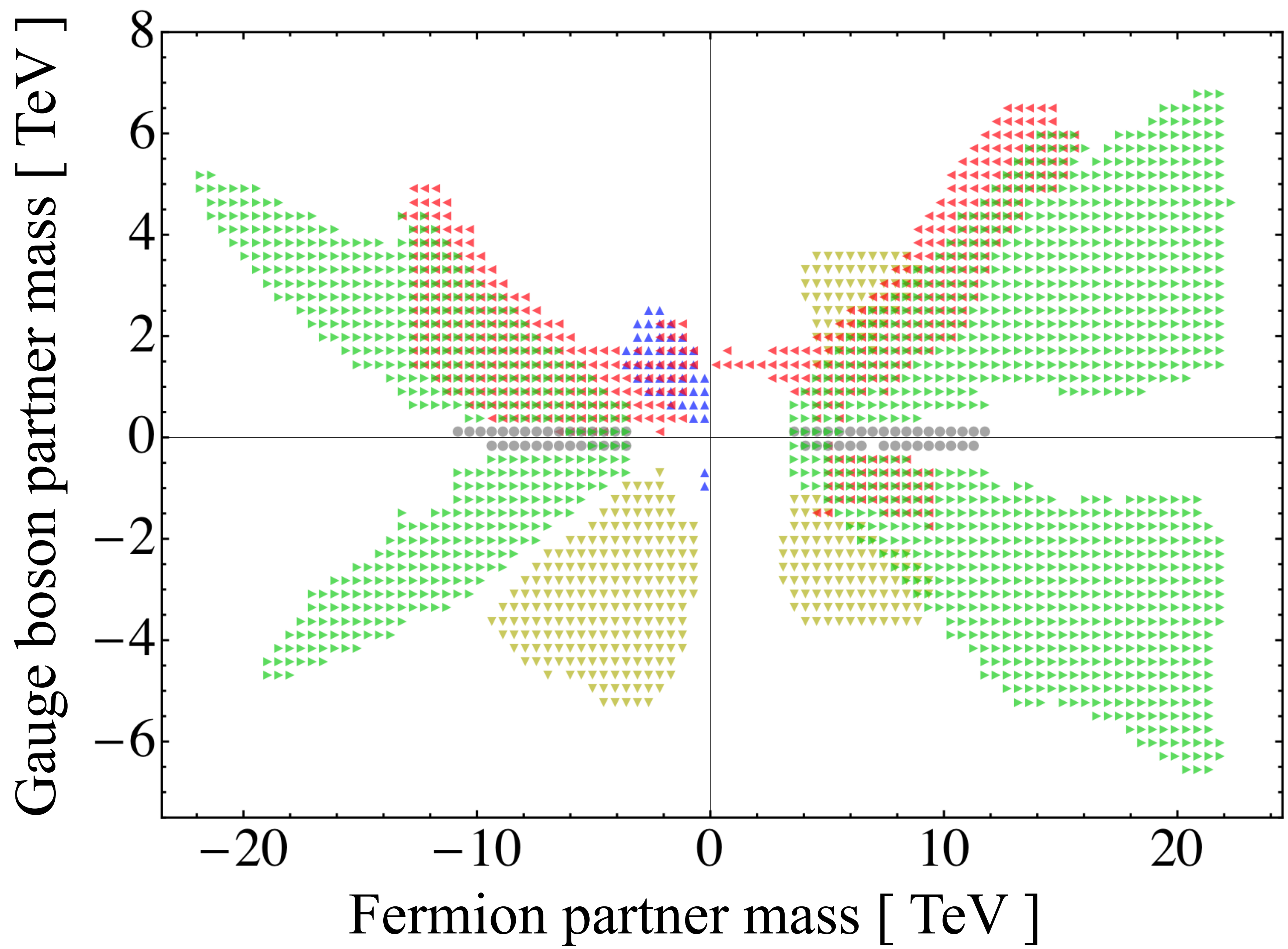
# HIGGS MASS IN MSSM




Draper, Lee, Wagner [arXiv:1312.5743]

# SUSY PARAMETER SPACE

Highly simplified assumption for inputs (the CMSSM).




Boundaries from requiring Higgs mass and relic density of dark matter.

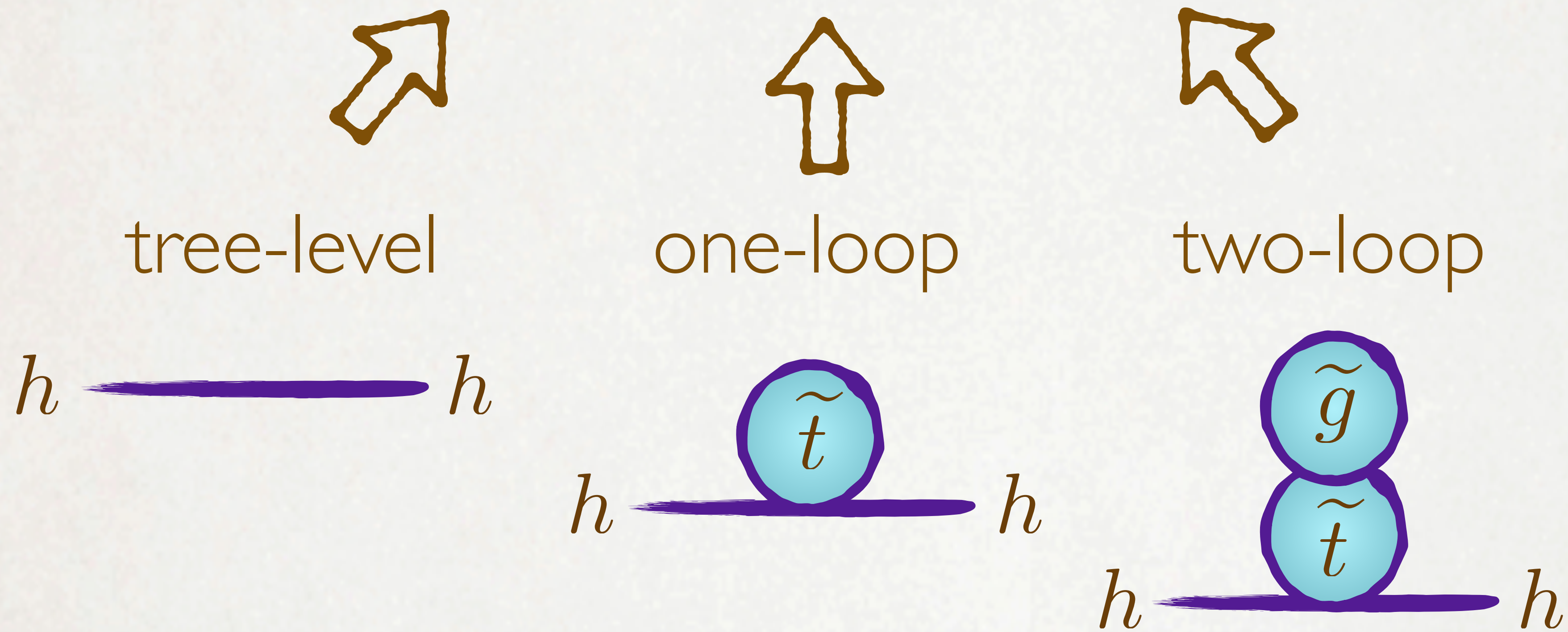
TC, Wacker [arXiv:1305.2914]

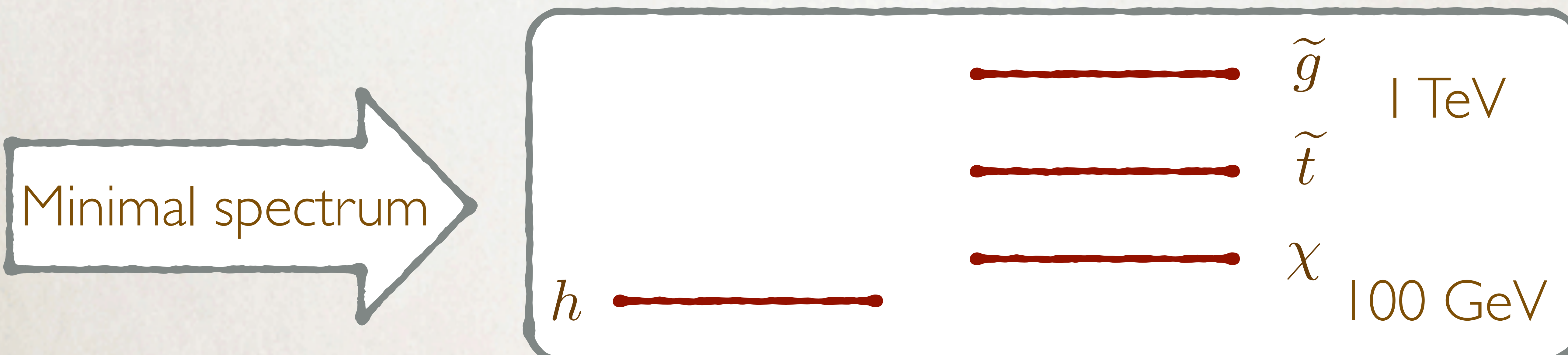
# III. SUSY NATURALNESS CONFRONTS EXPERIMENT

# MINIMAL INGREDIENTS

Biggest contributions to Higgs mass, ordered by size:

$$m_H^2 = m_{\text{Higgsino}}^2 + m_{\text{stop}}^2 + m_{\text{gluino}}^2 + \ldots$$

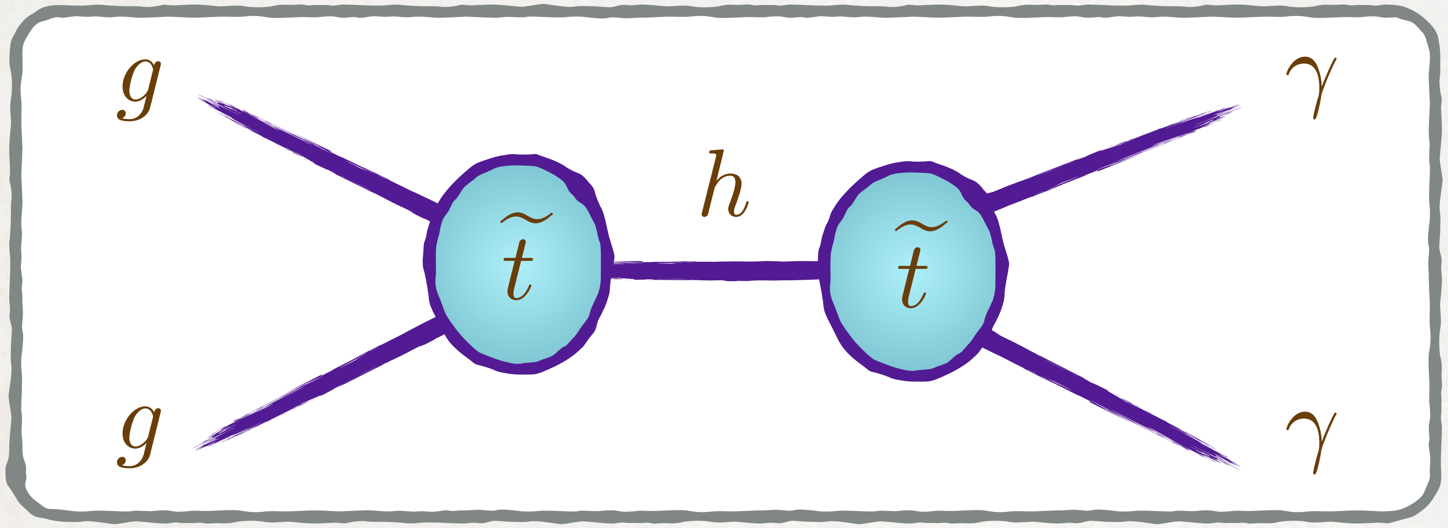


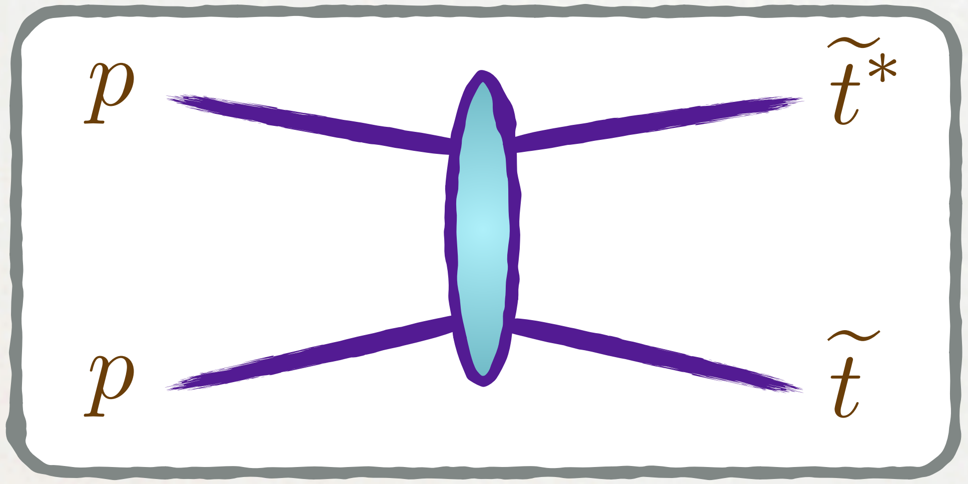
# NATURAL THEORIES HAVE OBSERVABLES

Existence of top partners ⇨ physical observables!

Loop corrections to Higgs properties.

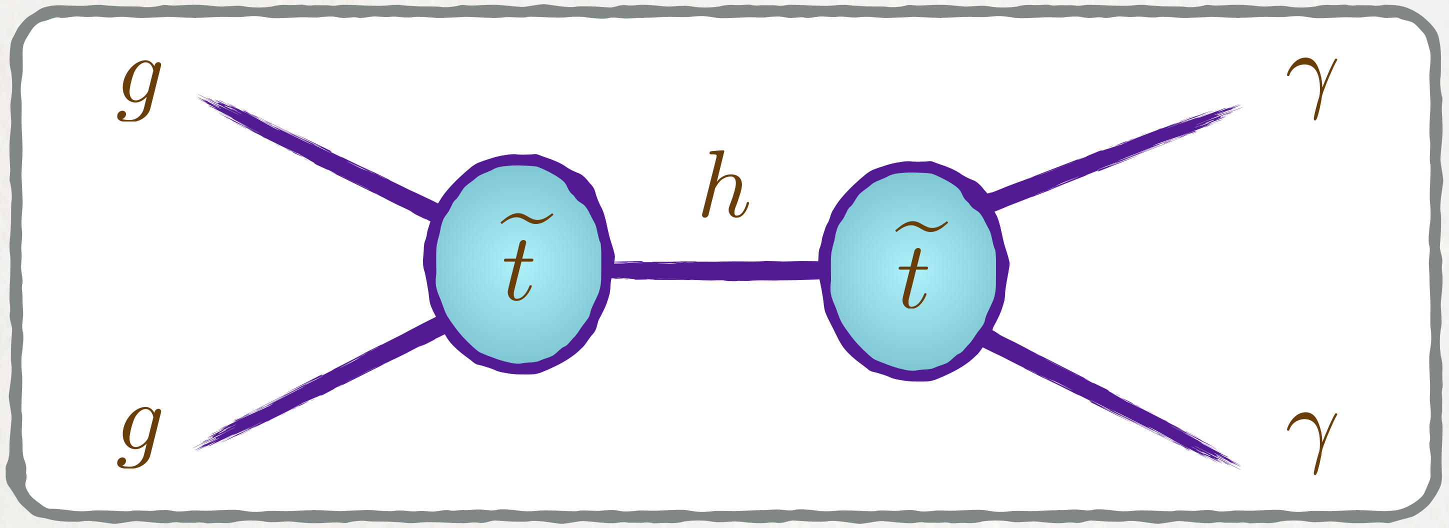



Direct production in proton collisions.



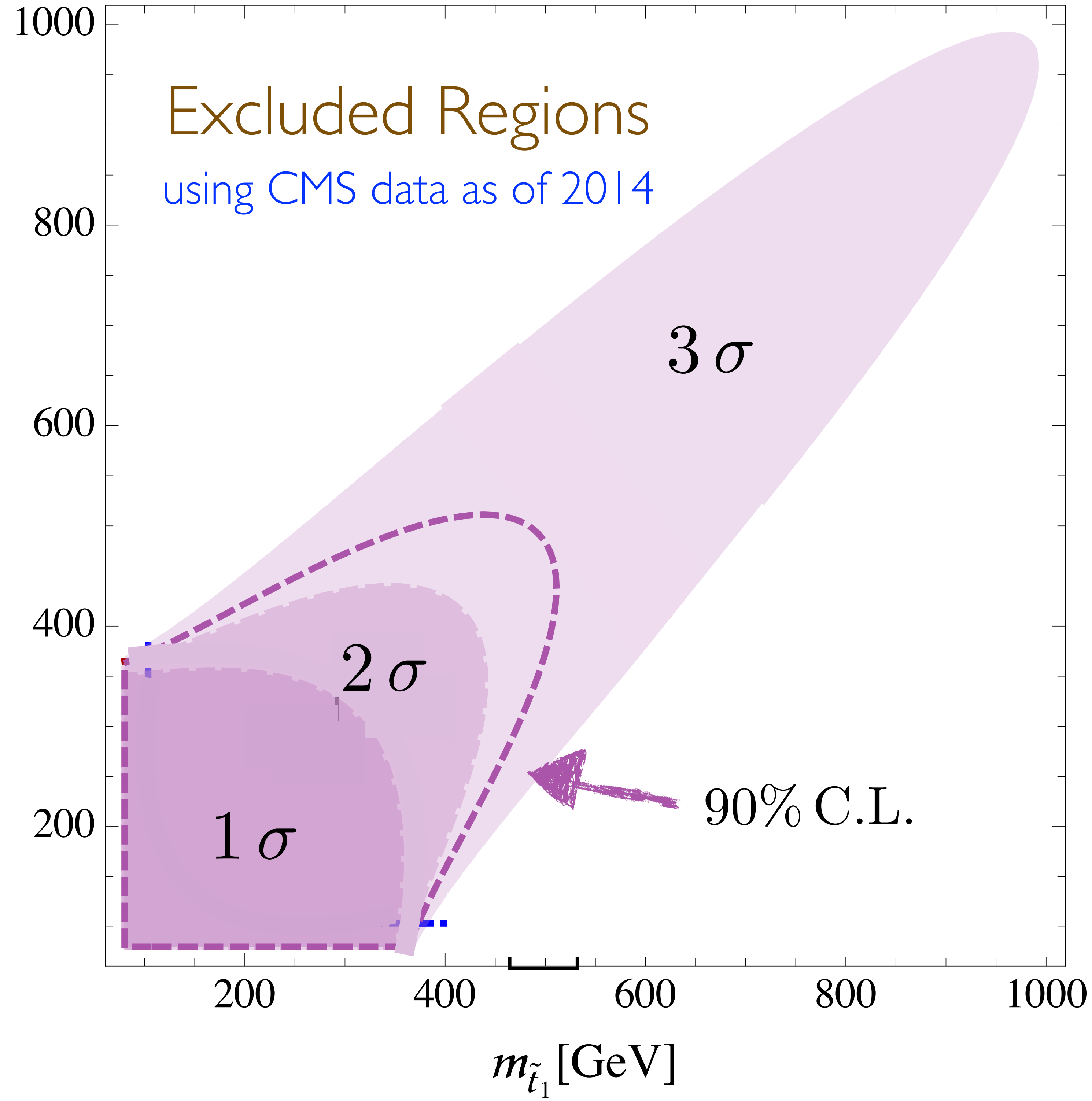
# HIGGS COUPLINGS

Modification to Higgs production and decay.




Yields bounds independent of stop decay modes.

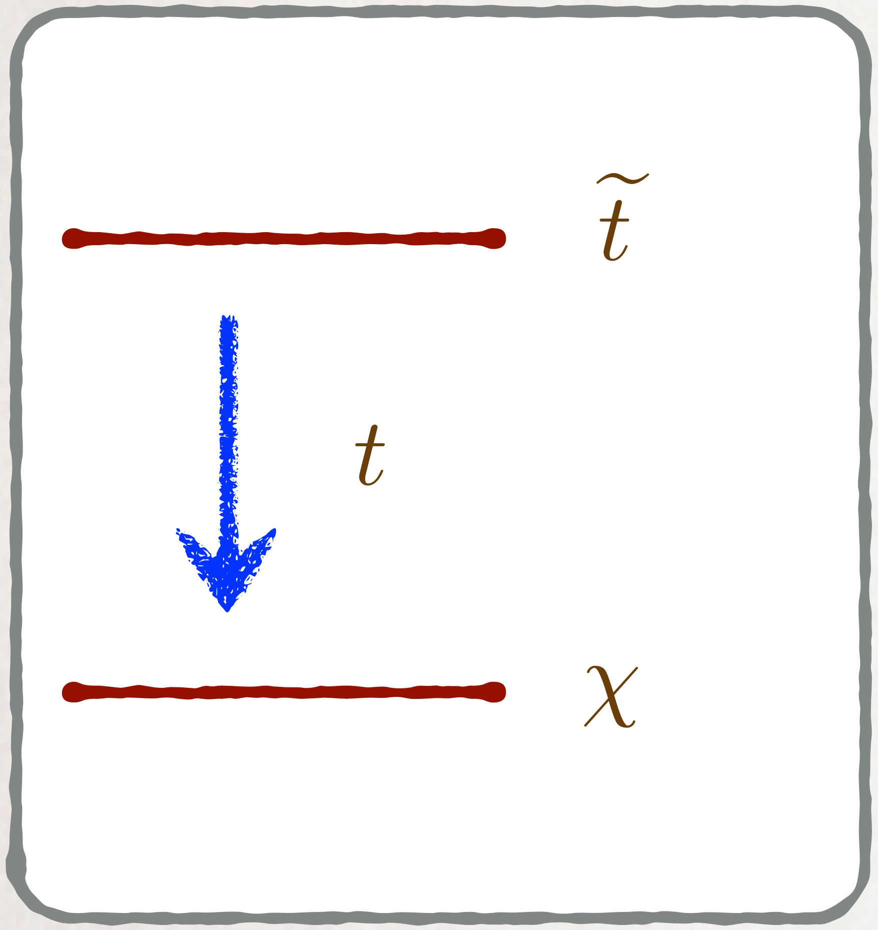
# CONSTRAINTS



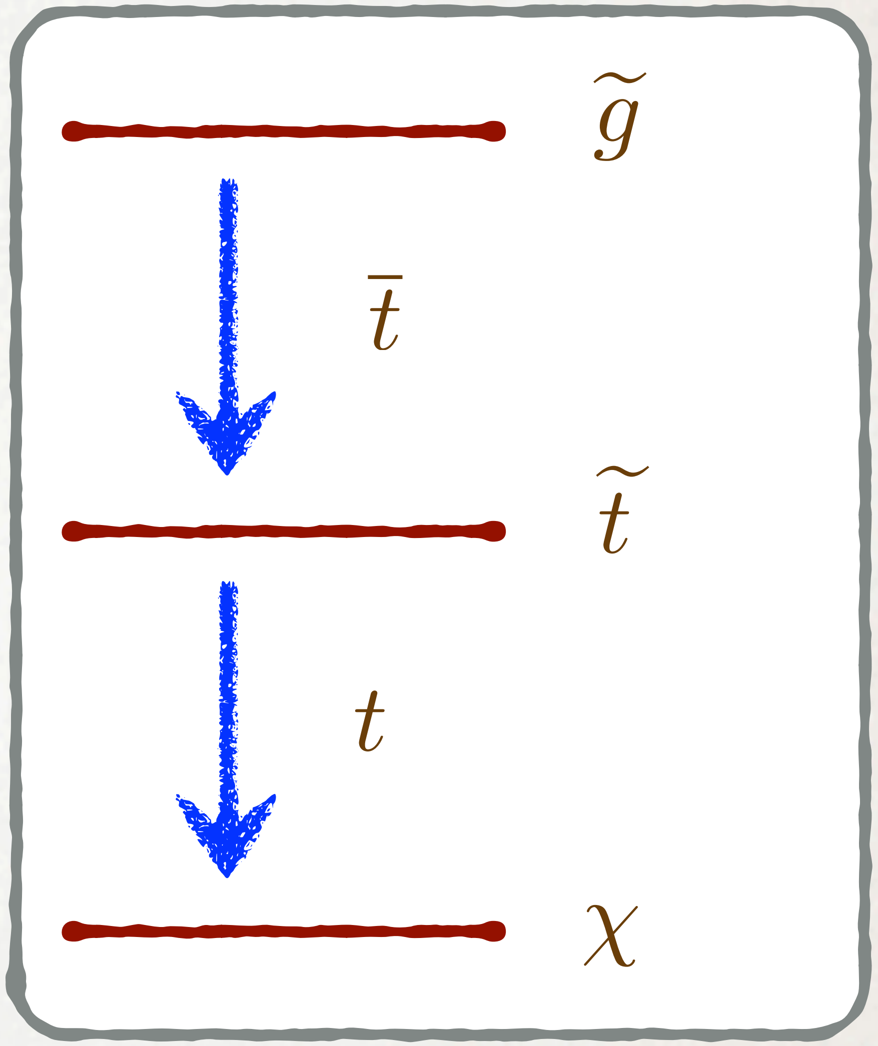

Reece, Fan [arXiv:1401.7671]

# SIMPLIFIED MODEL FOR PROTON COLLIDERS

Stop-neutralino




Gluino-stop-neutralino




Essig, Izaguirre, Kaplan, Wacker [arXiv:1110.6443]; Papucci, Ruderman, Weiler [arXiv:1110.6926]

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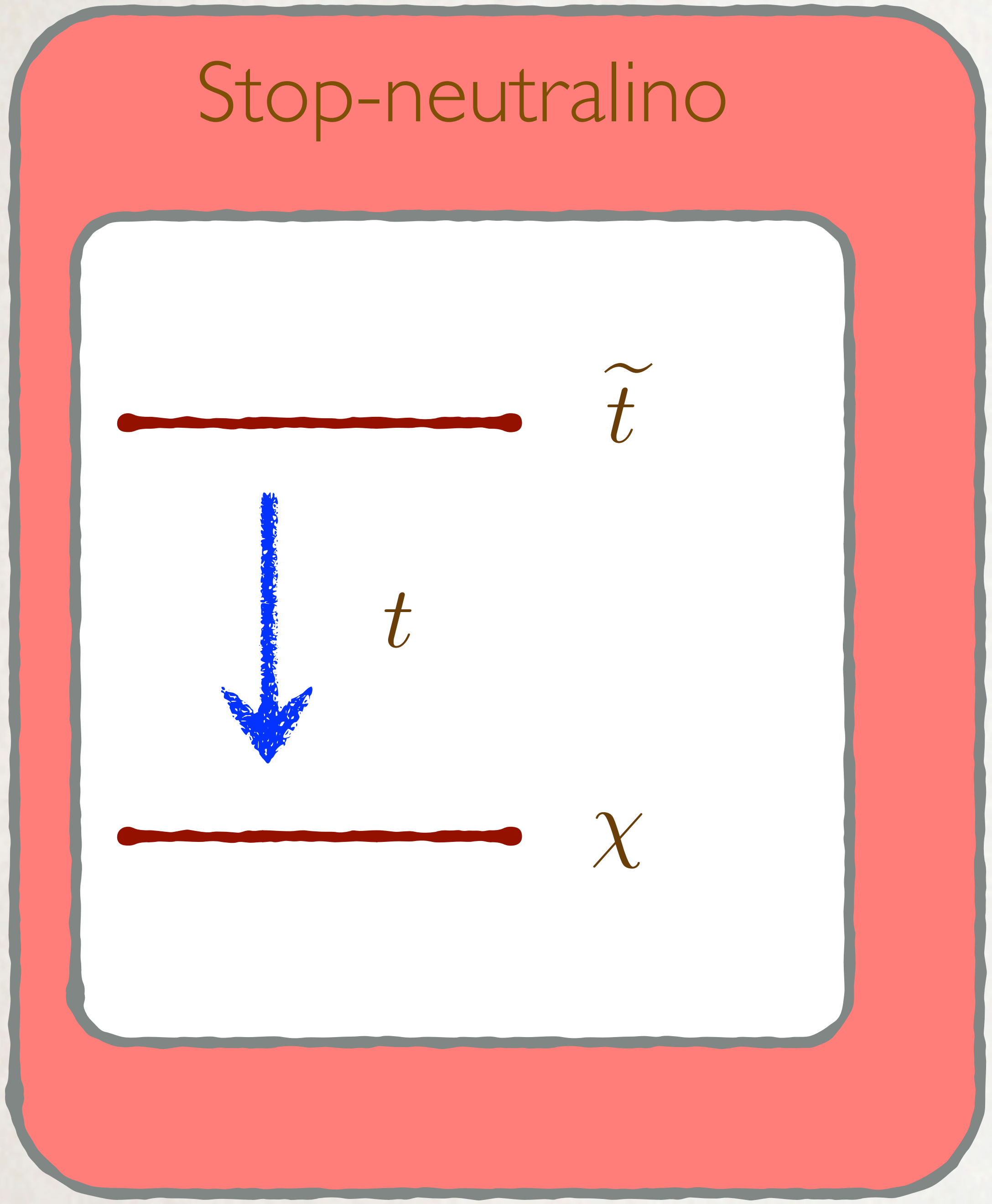
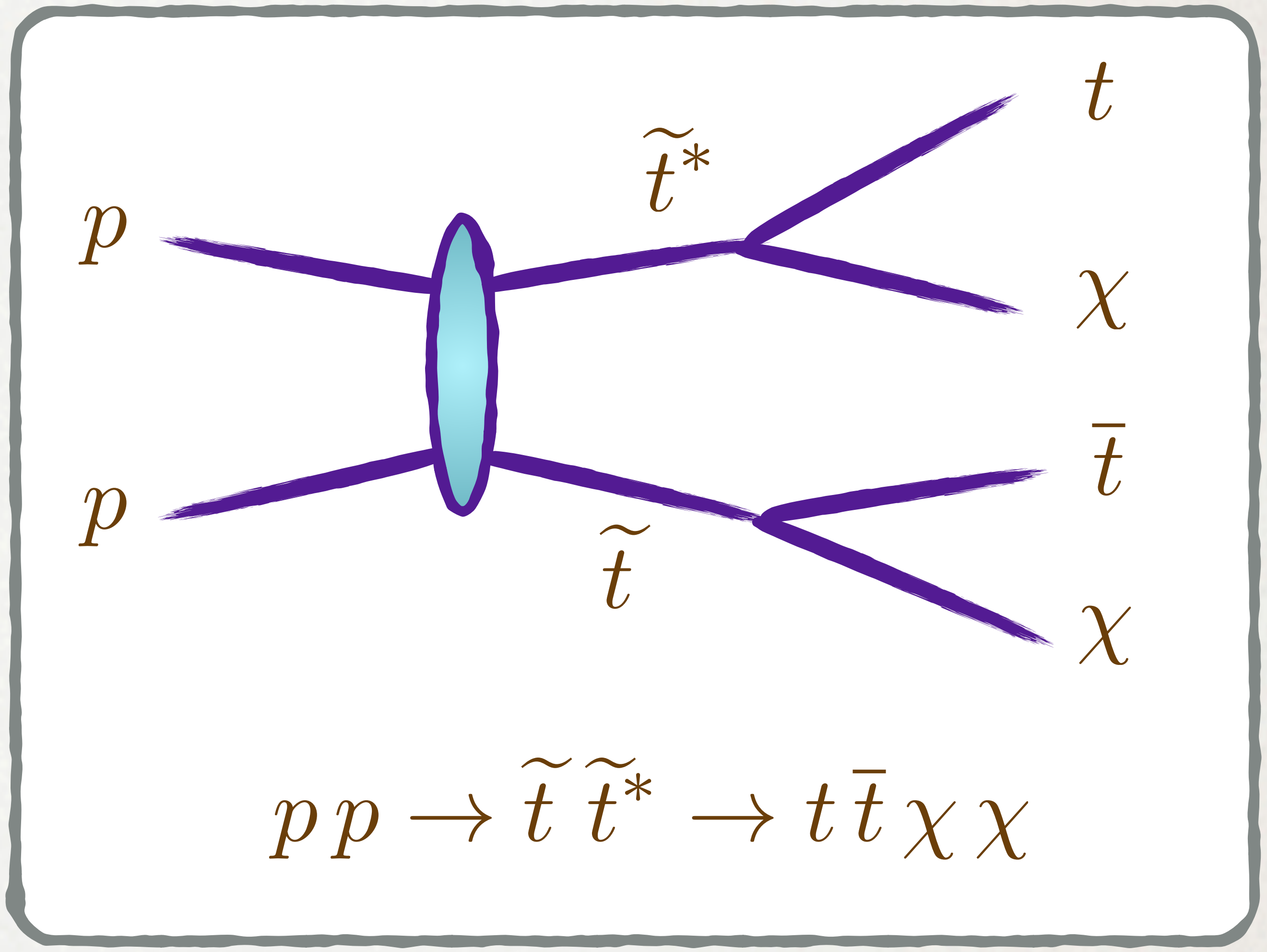
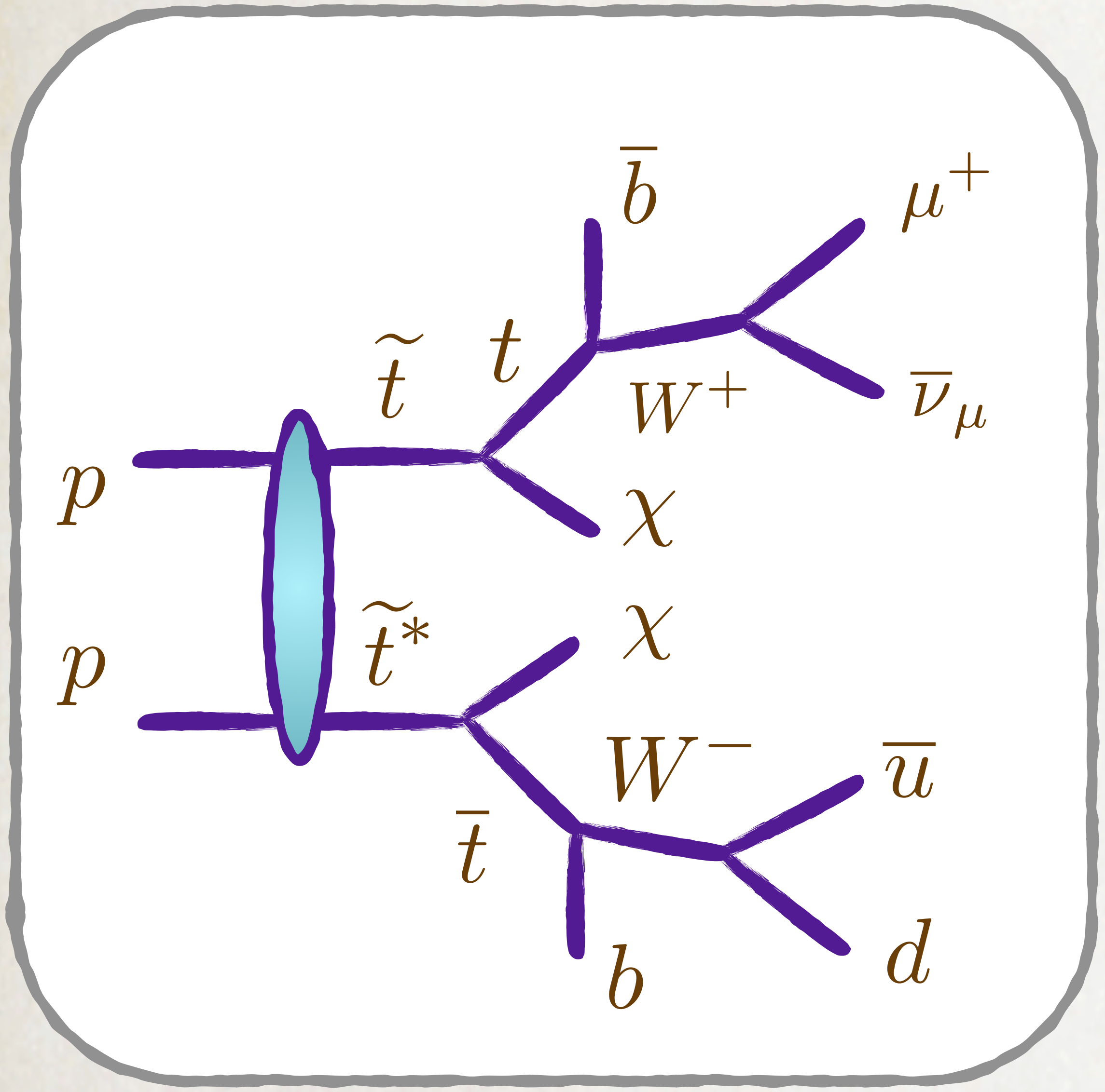



Essig, Izaguirre, Kaplan, Wacker [arXiv:1110.6443]; Papucci, Ruderman, Weiler [arXiv:1110.6926]

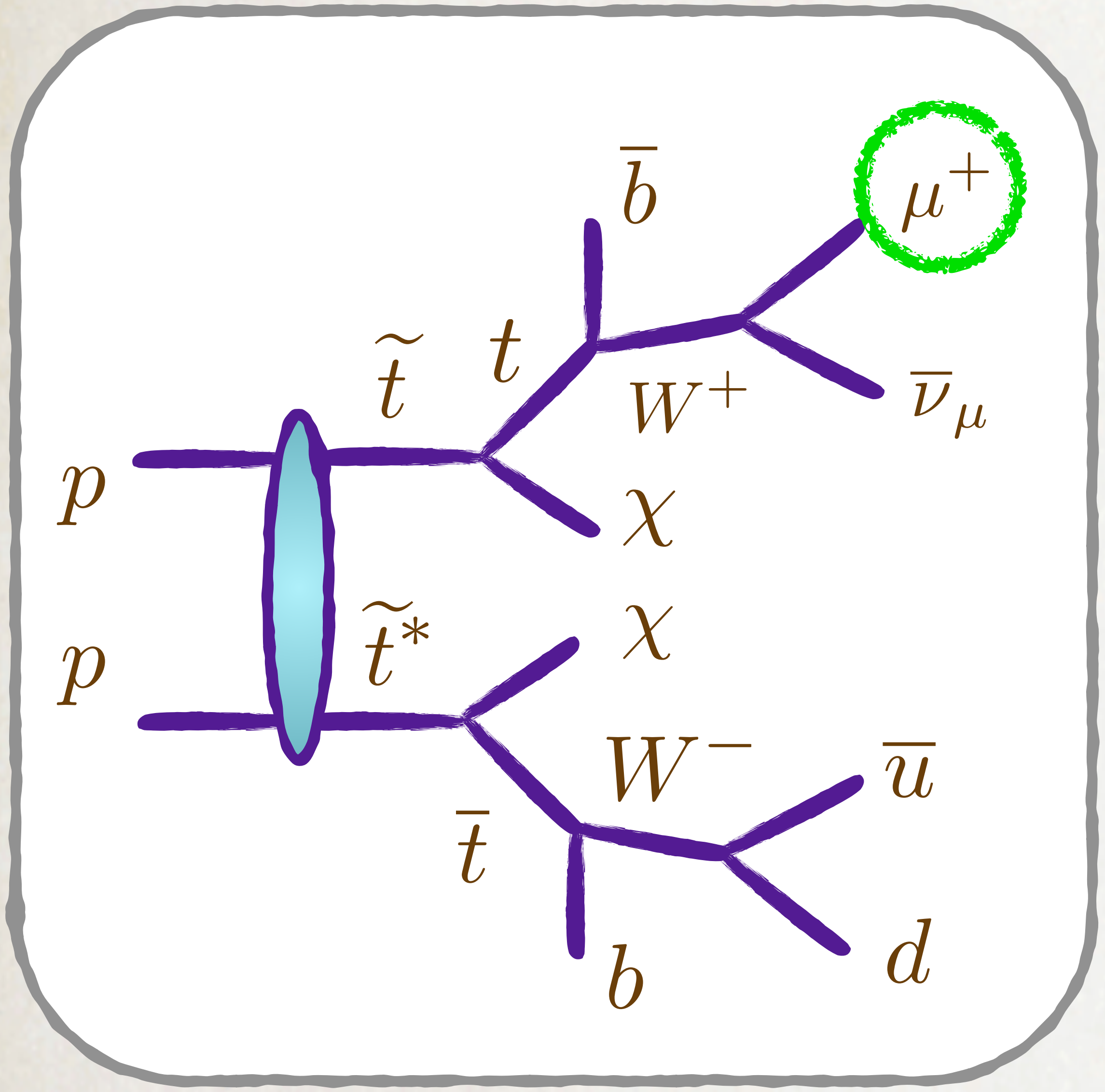
# SEARCH STRATEGY

## MAIN REQUIREMENTS




ATLAS [arXiv:1407.0583];
see also CMS [arXiv:1502.00300]

# SEARCH STRATEGY

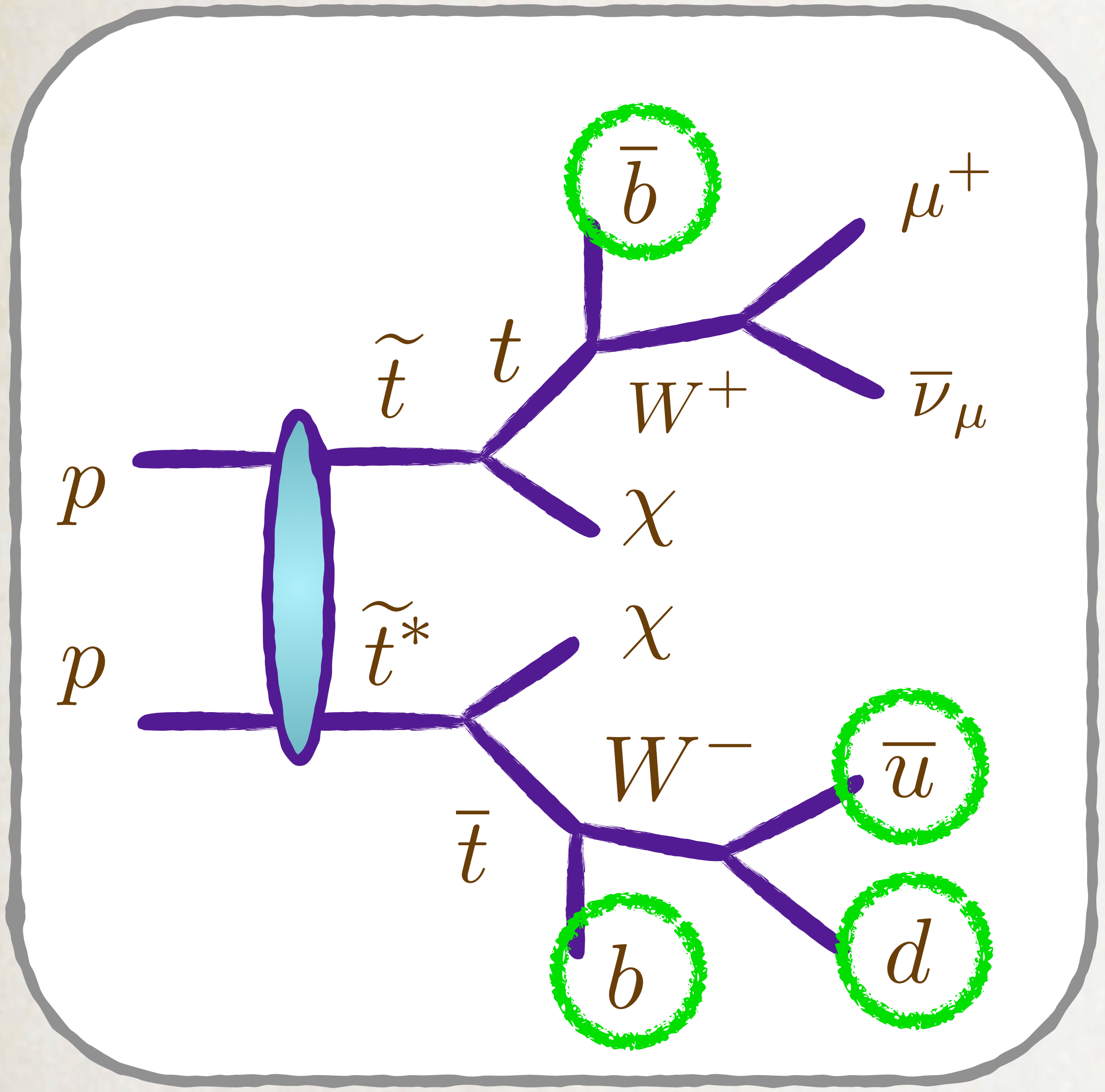



## Main requirements

- 1 lepton

ATLAS [arXiv:1407.0583];
see also CMS [arXiv:1502.00300]

# SEARCH STRATEGY




## Main requirements

- 1 lepton
- $\geq$ 4 jets

ATLAS [arXiv:1407.0583];
see also CMS [arXiv:1502.00300]

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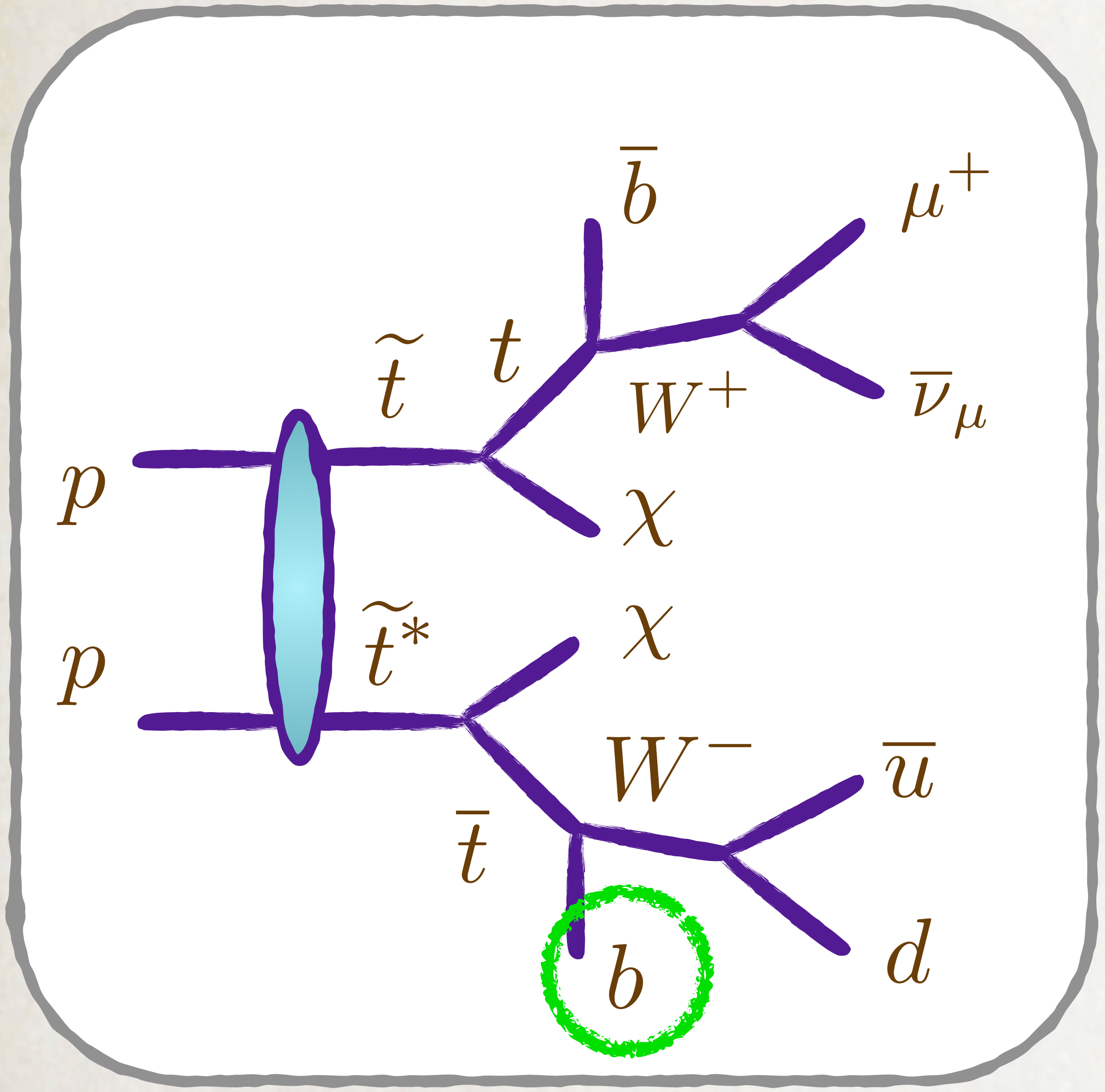


## Main requirements

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- $\geq$ 1 $b$-jet(s)

ATLAS [arXiv:1407.0583];
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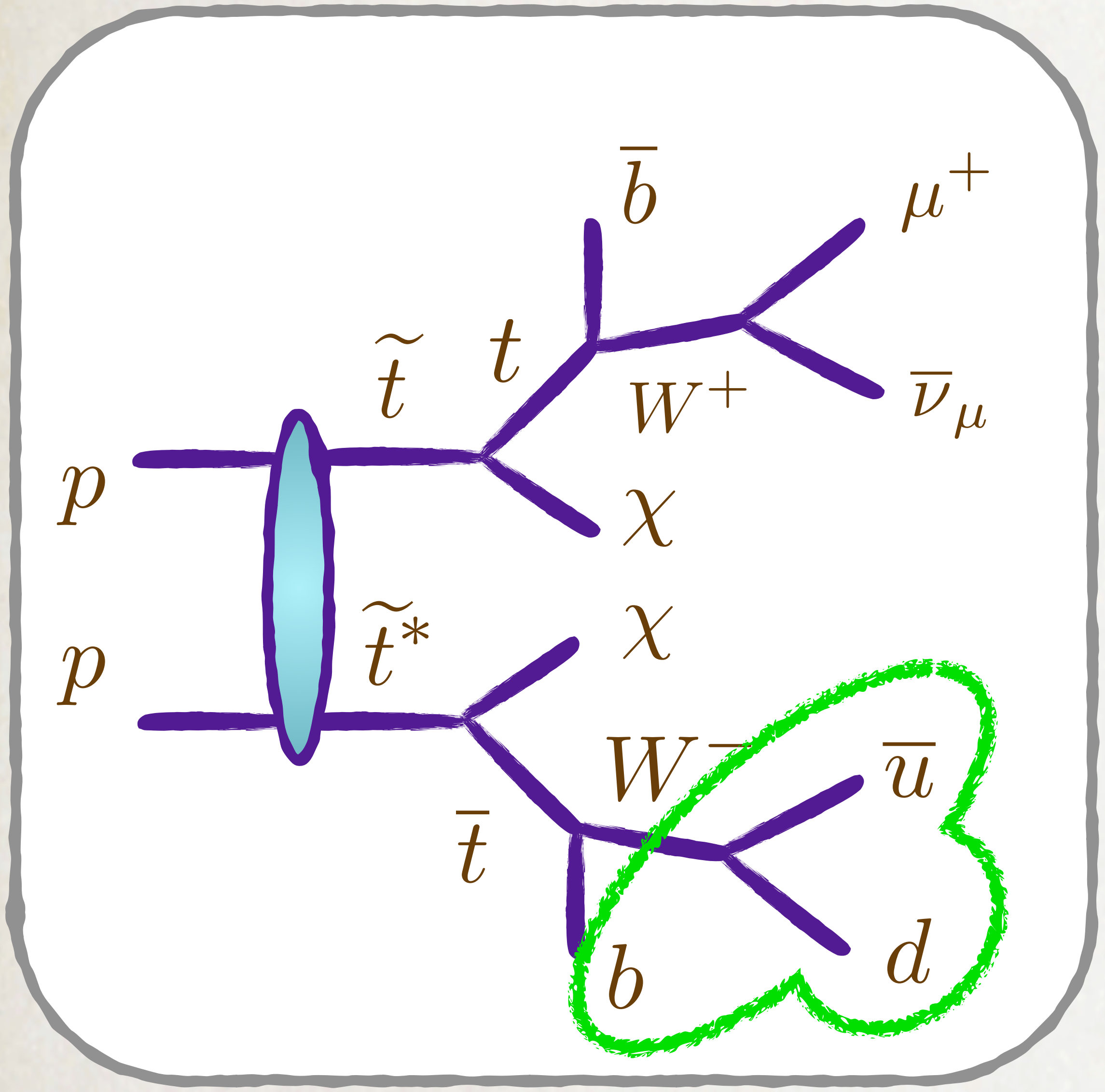


## MAIN REQUIREMENTS

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- One "hadronic top"

ATLAS [arXiv:1407.0583];
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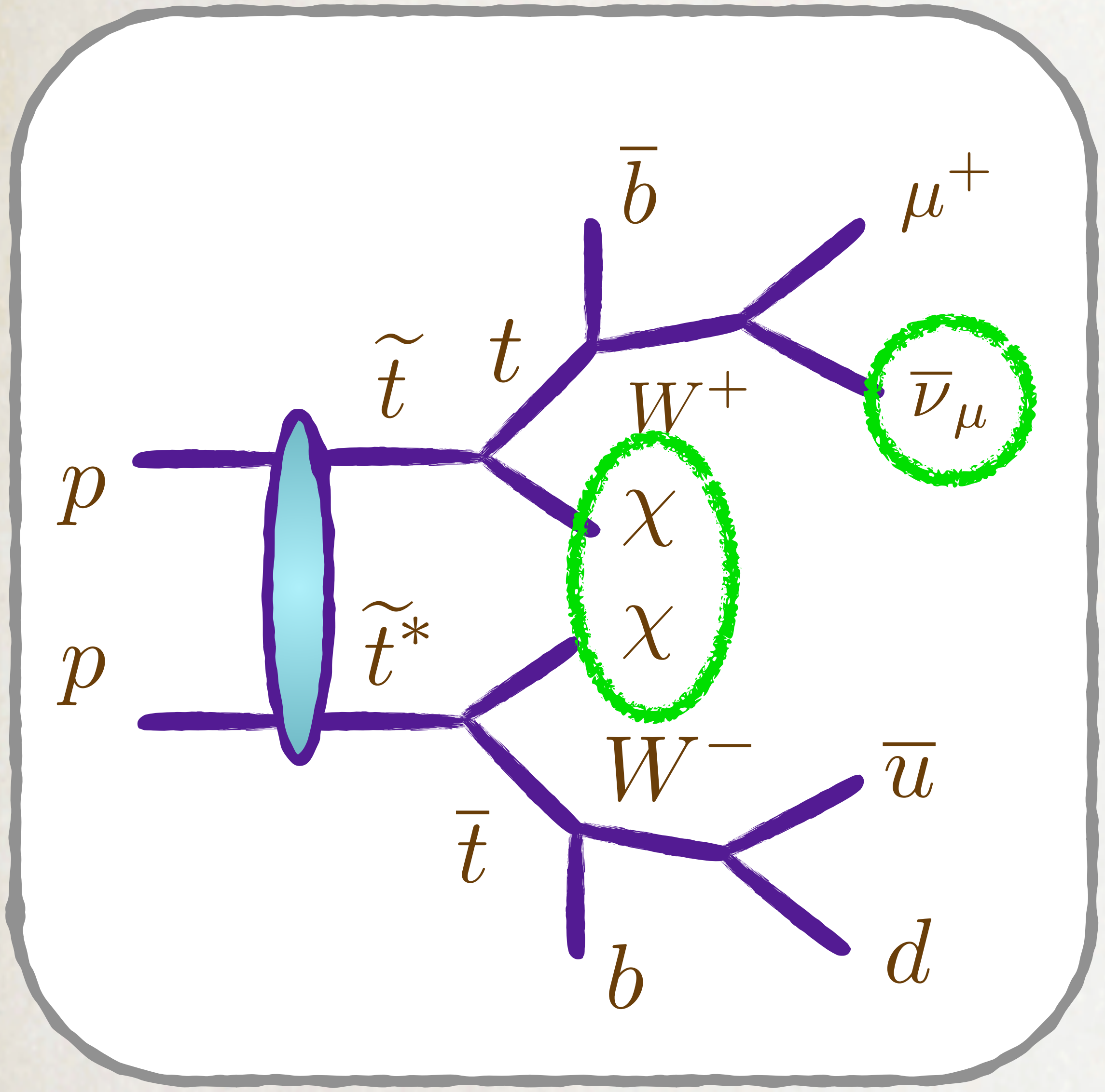


## Main requirements

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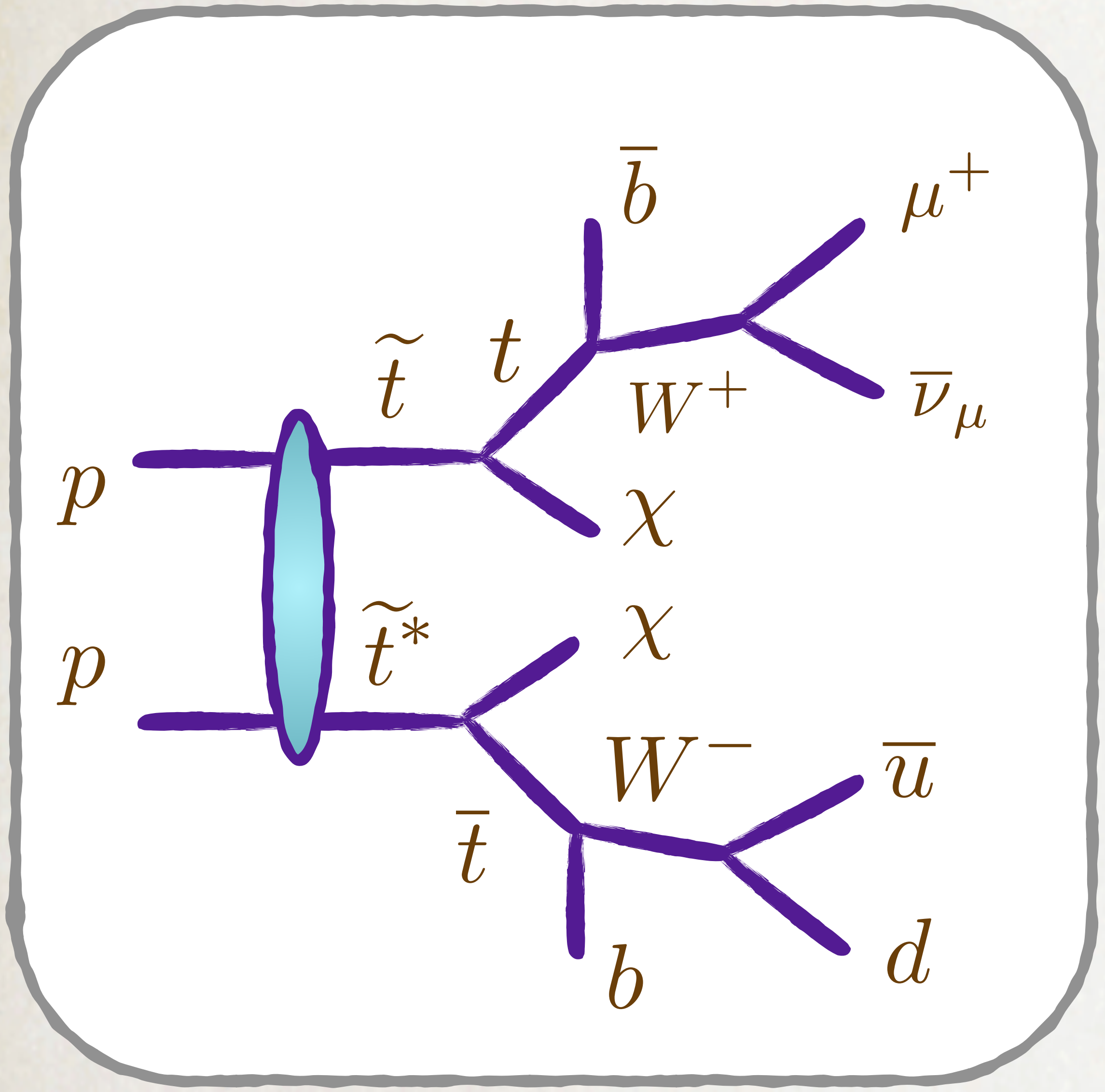


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- …

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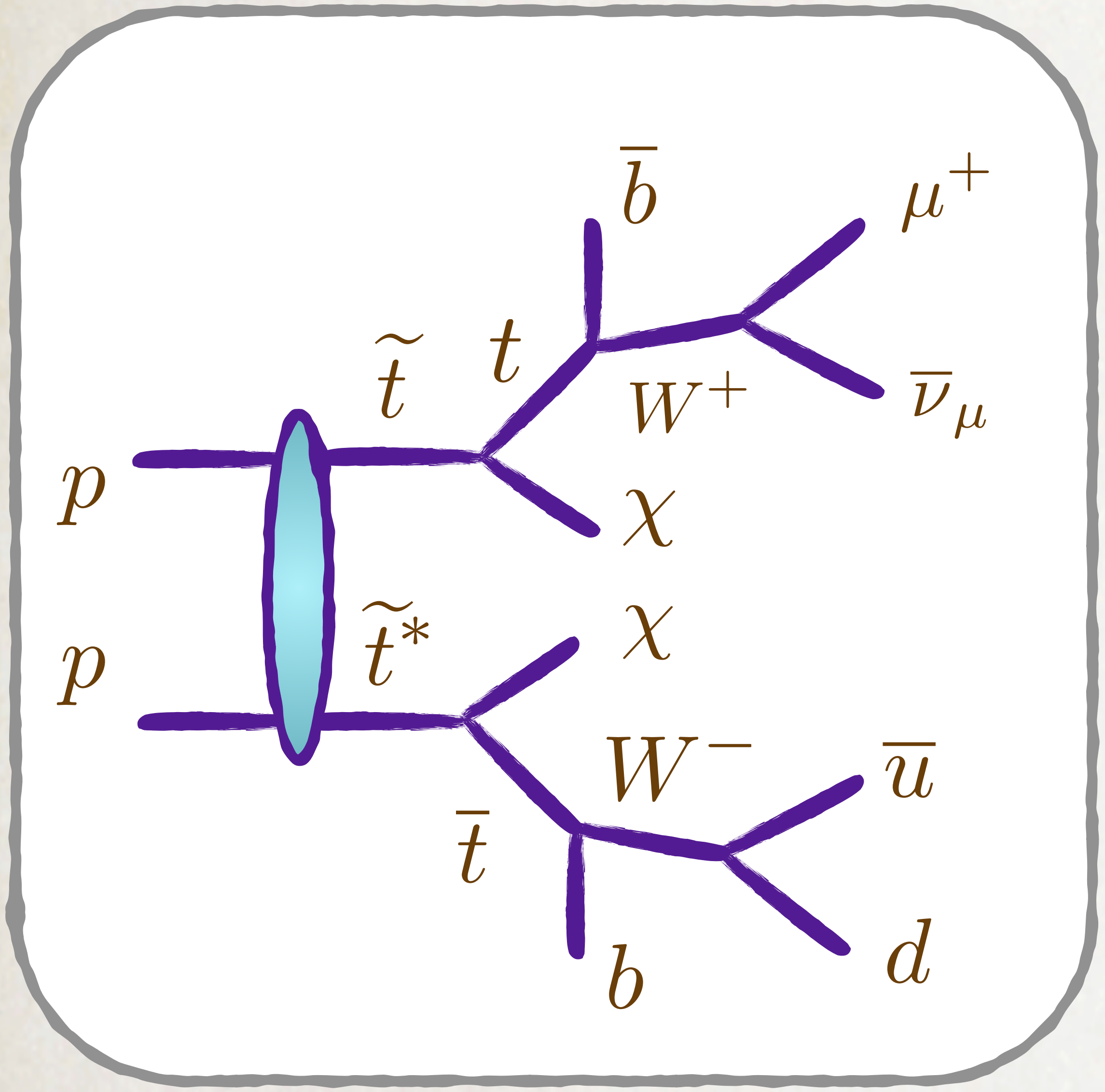


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ATLAS [arXiv:1407.0583];
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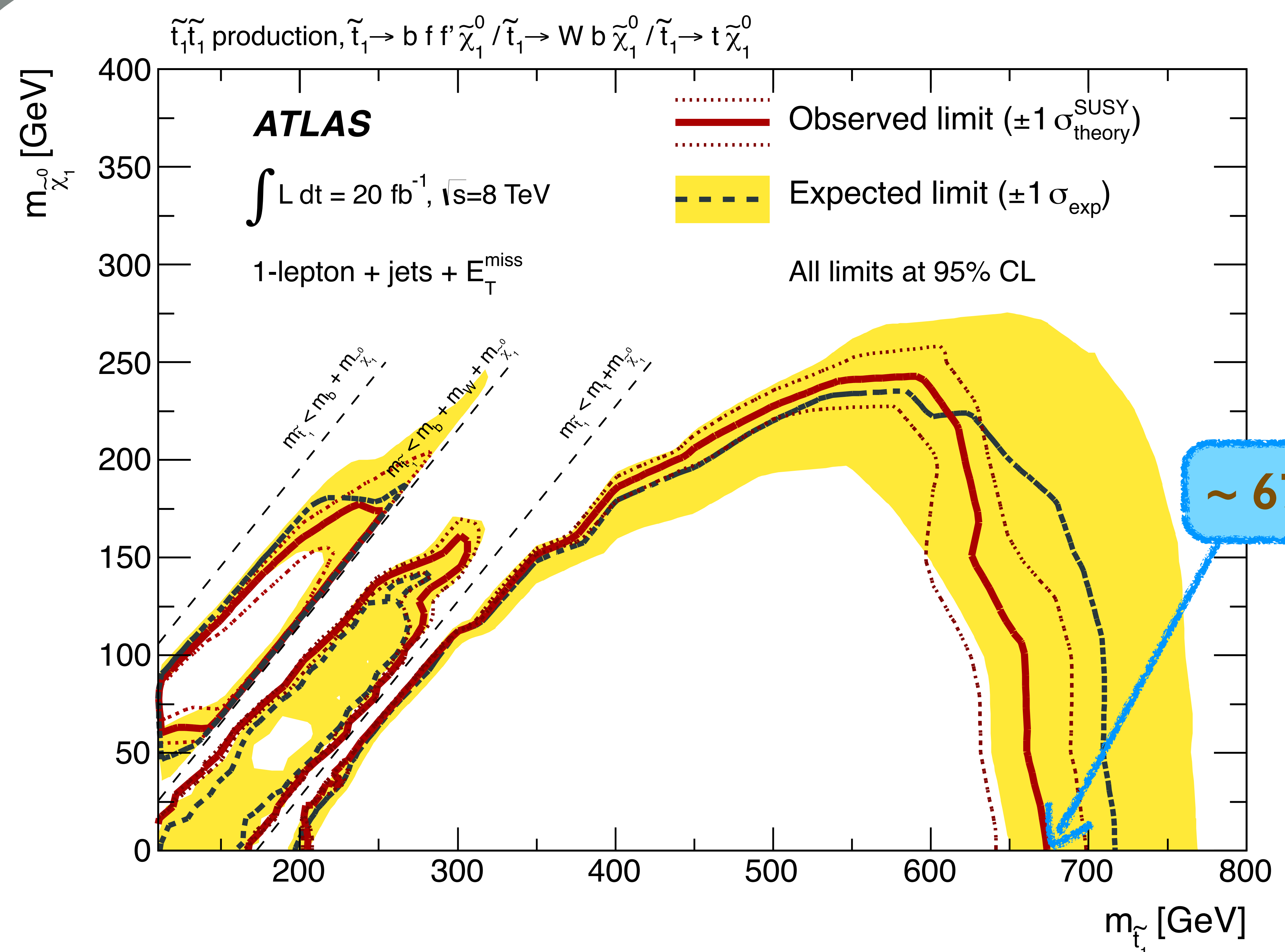
## Dominant backgrounds

$$t\,\bar{t}\,,\,W + \text{jets}, t\,\bar{t} + W/Z\,,\ldots$$

# 1-LEPTON RESULTS

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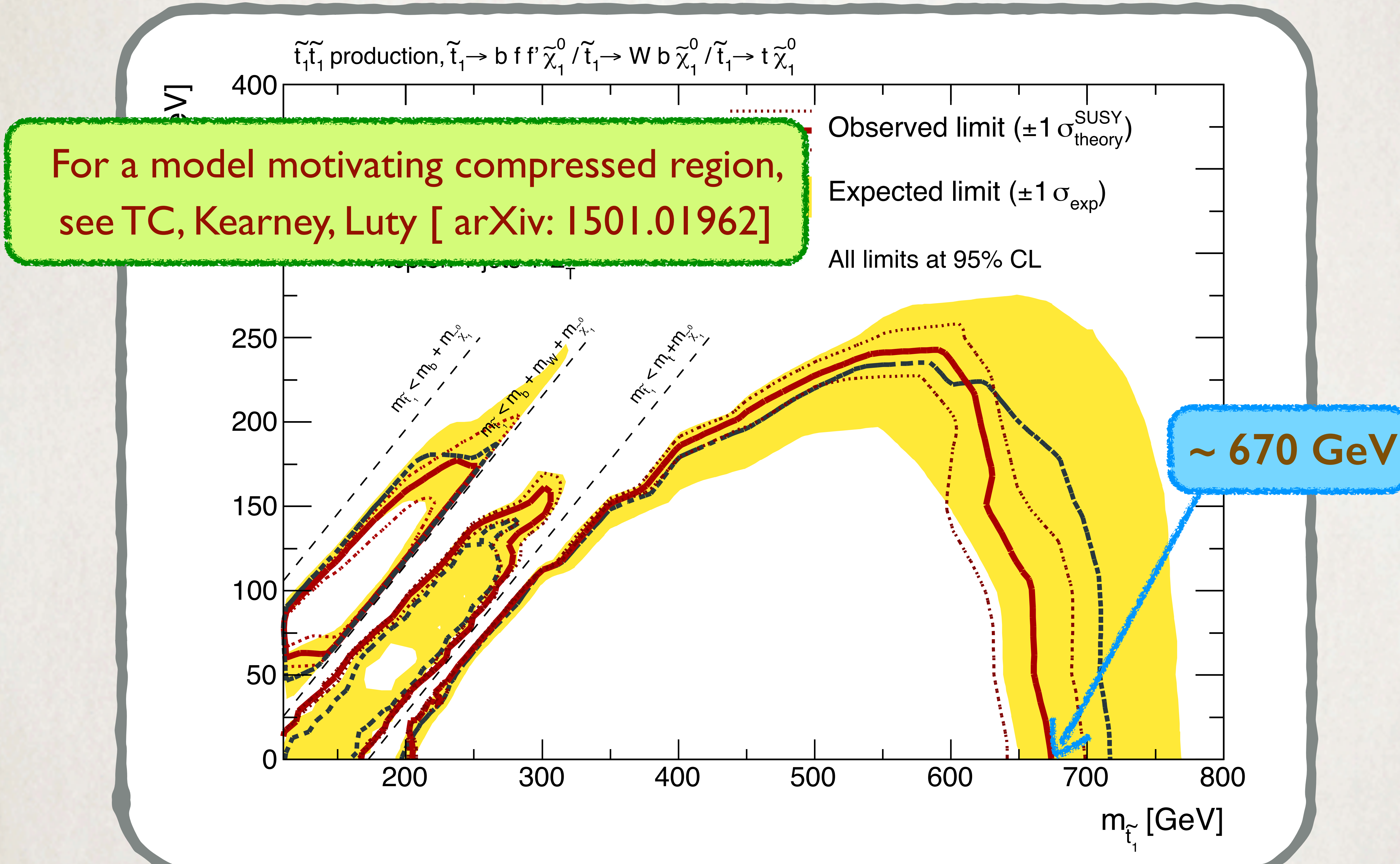
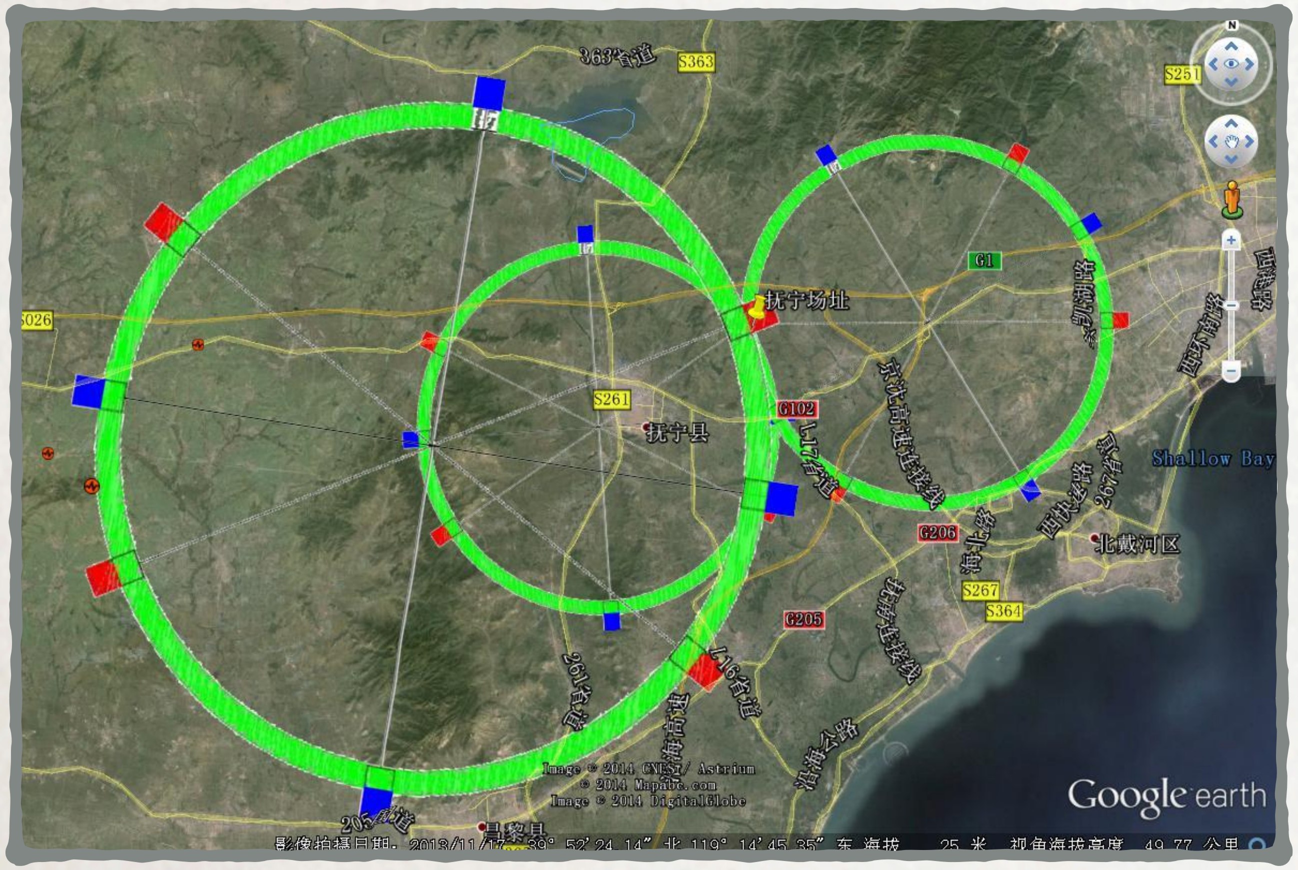



ATLAS [arXiv:1407.0583]; see also CMS [arXiv:1502.00300]

# FUTURE COLLIDERS

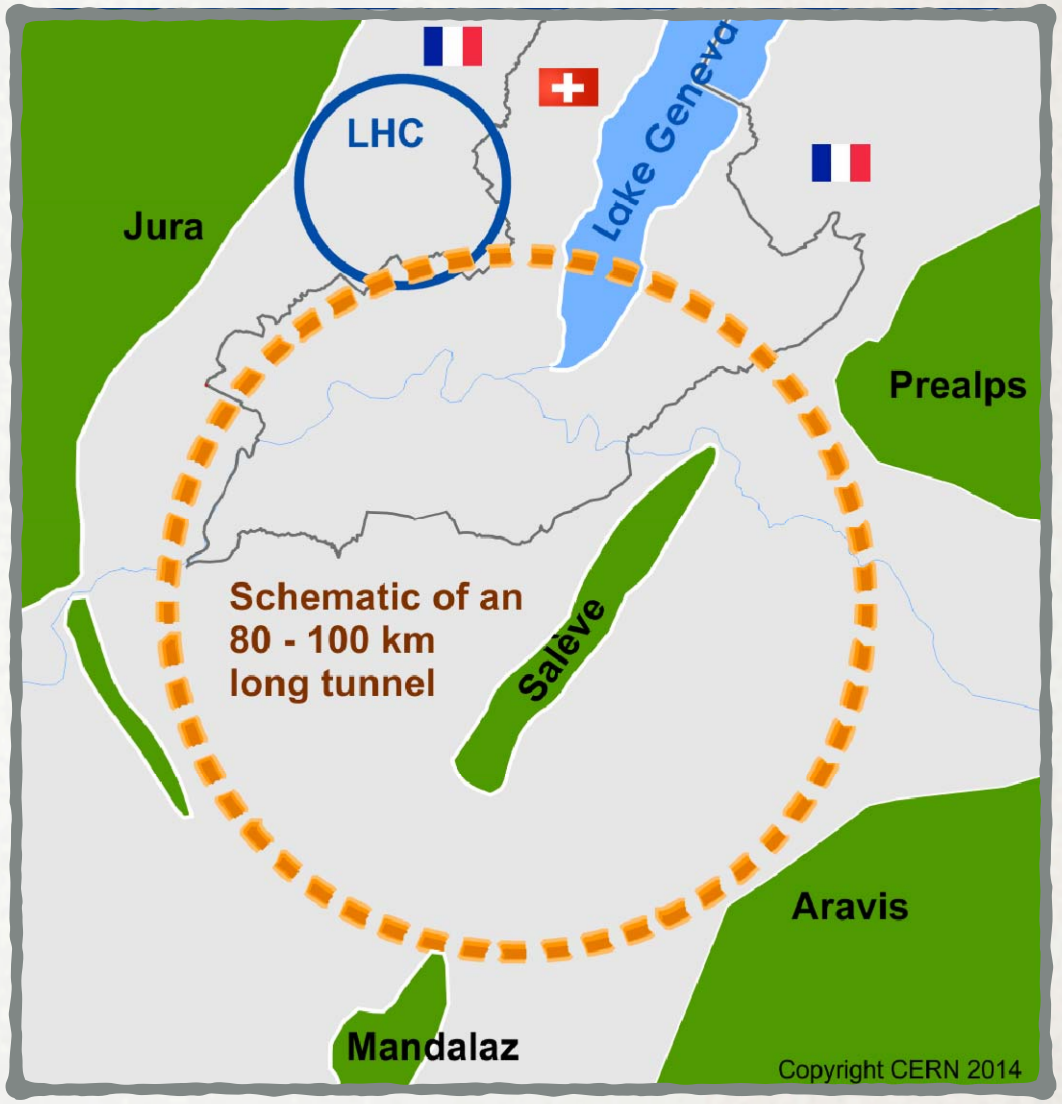
Higgs factory and
100 TeV proton collider?

IHEP in China?




Talk by X. Lou [Aspen Future Colliders Conference, 2015]

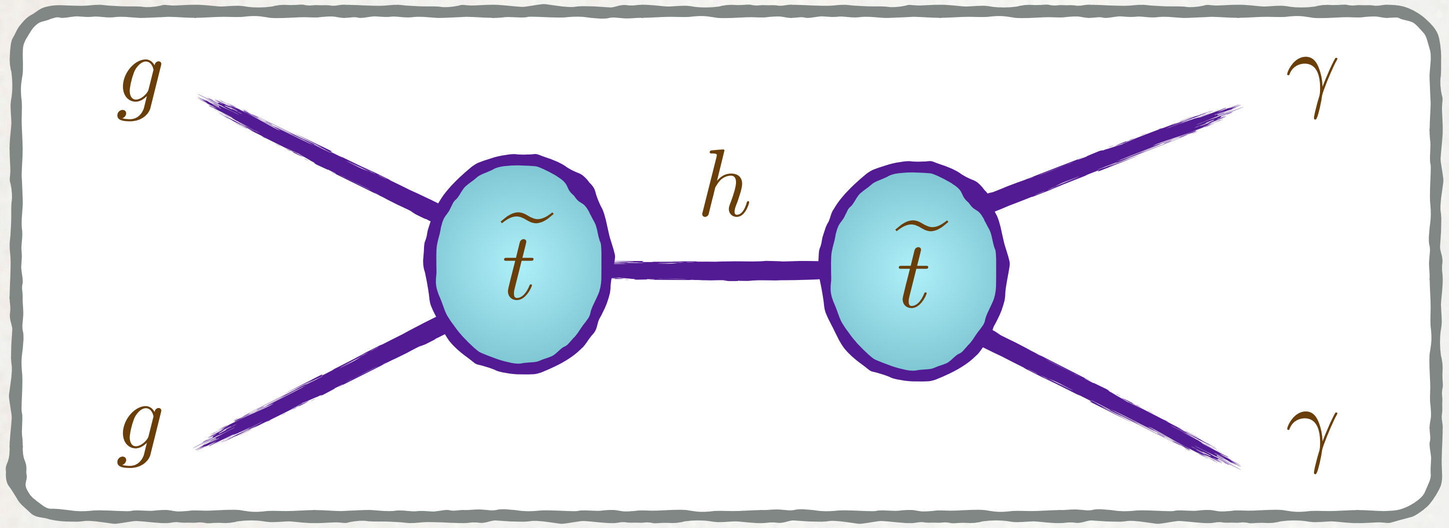
CERN in Europe?




Talk by M. Benedikt [Aspen Future Colliders Conference, 2015]

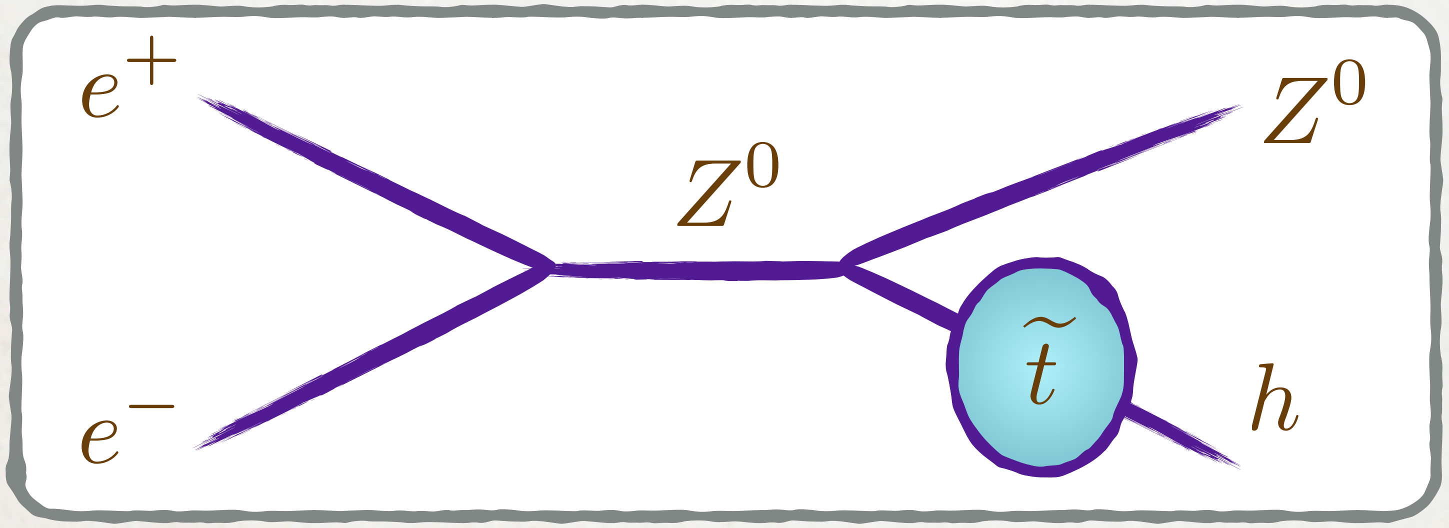
# MORE HIGGS MEASUREMENTS

Previous indirect probe required top partner be colored and charged.




Completely model independent probe:

Modification to $Z^0 - h$ associated production cross section $\delta\sigma_{\mathrm{Zh}}$.

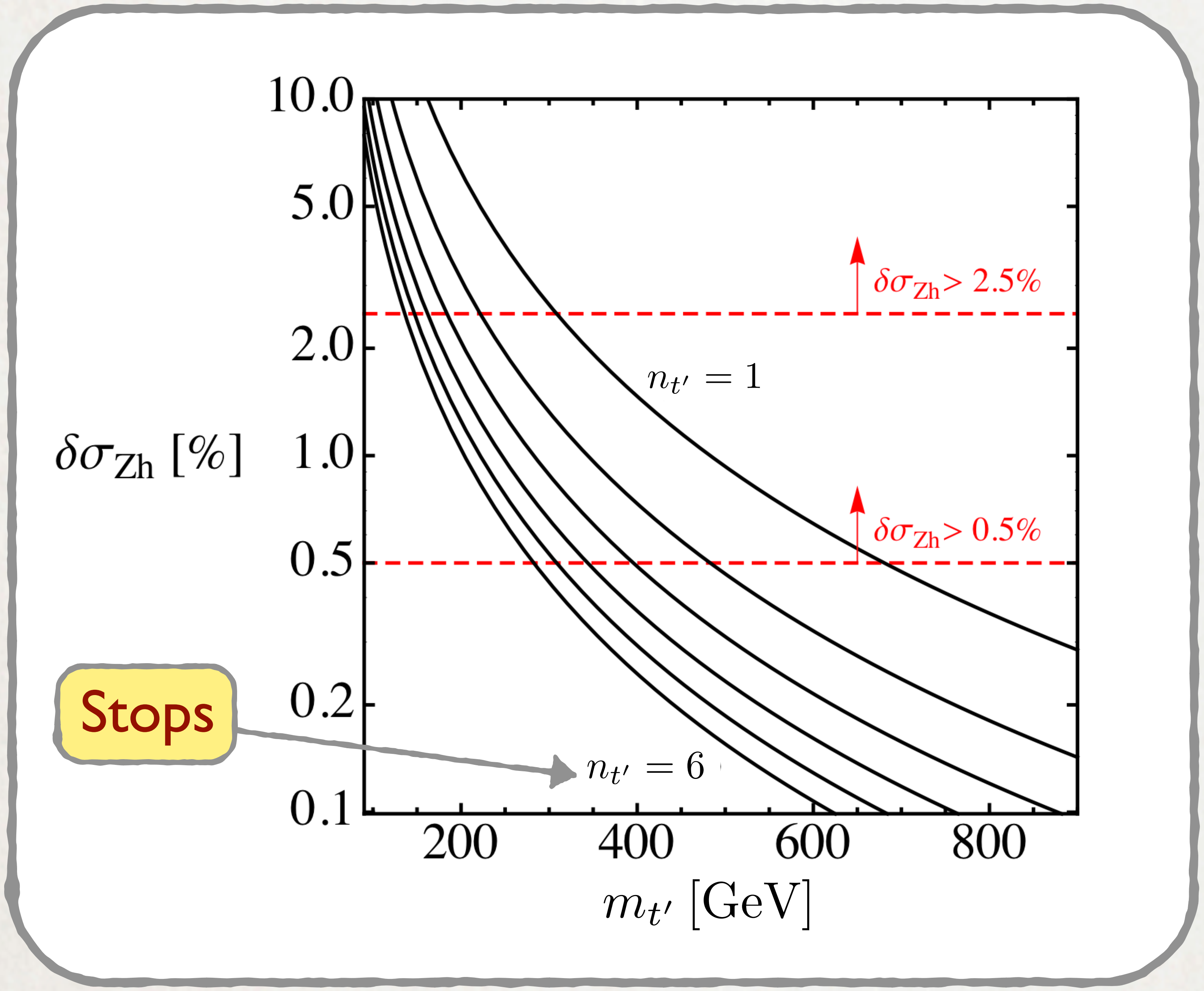



Craig, Englert, McCullough [arXiv:1305.5251]

# AT A FUTURE LEPTON COLLIDER

For a generic top partner $t'$,

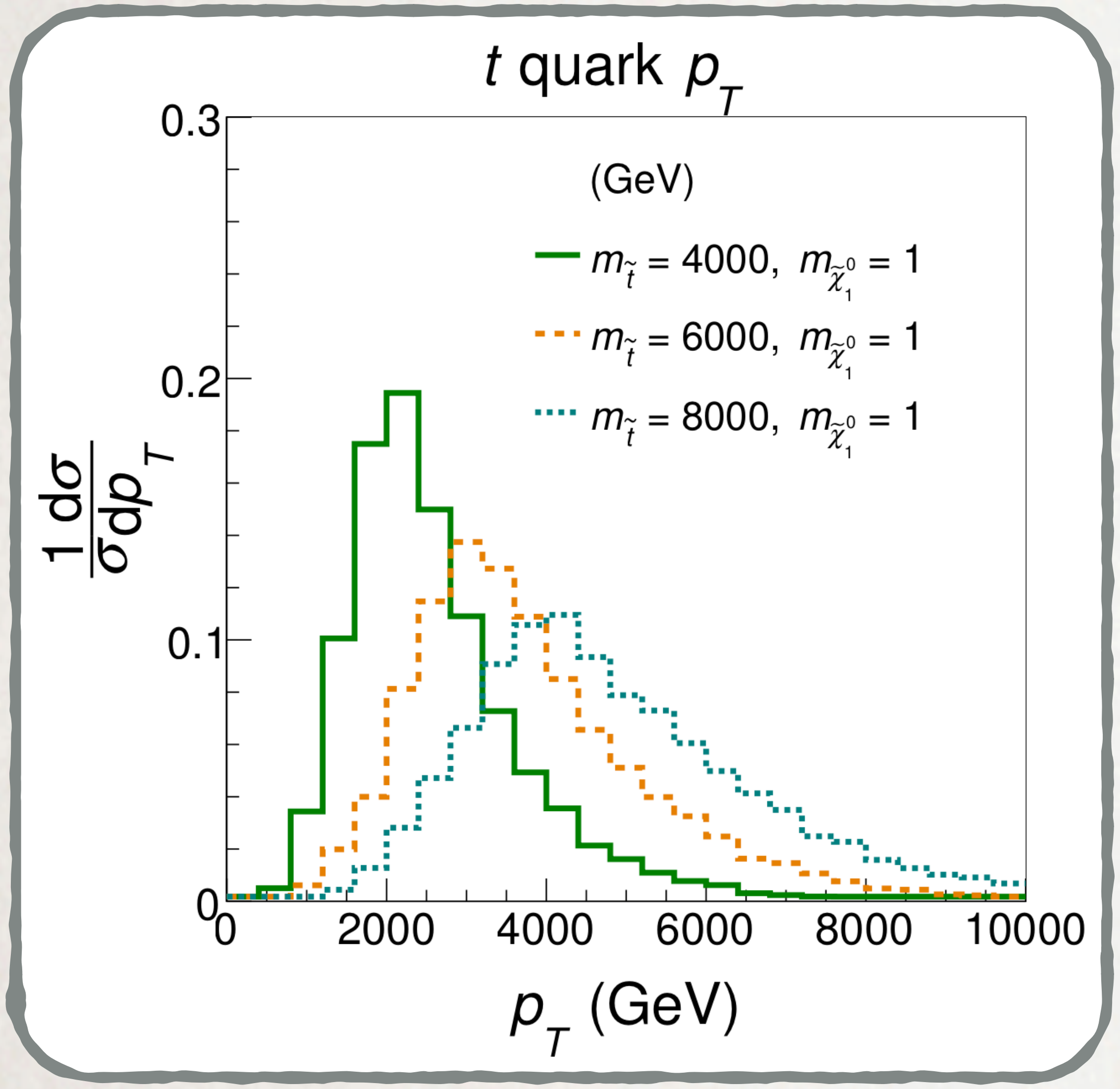
with number of degrees of freedom $n_{t'}$.

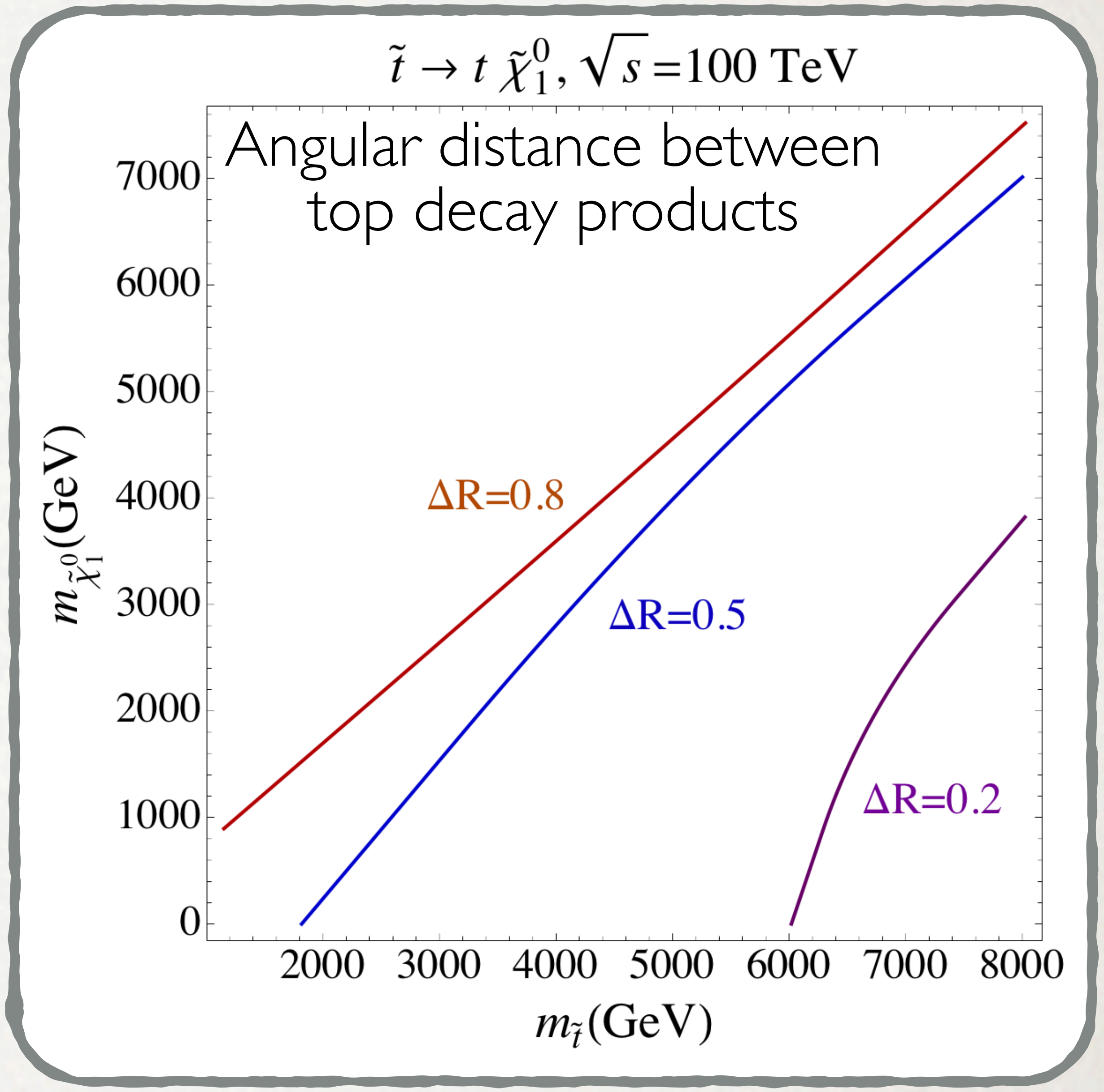



Craig, Englert, McCullough [arXiv:1305.5251]

# STOP DECAYS AT A 100 TEV COLLIDER

"Top is the new bottom."

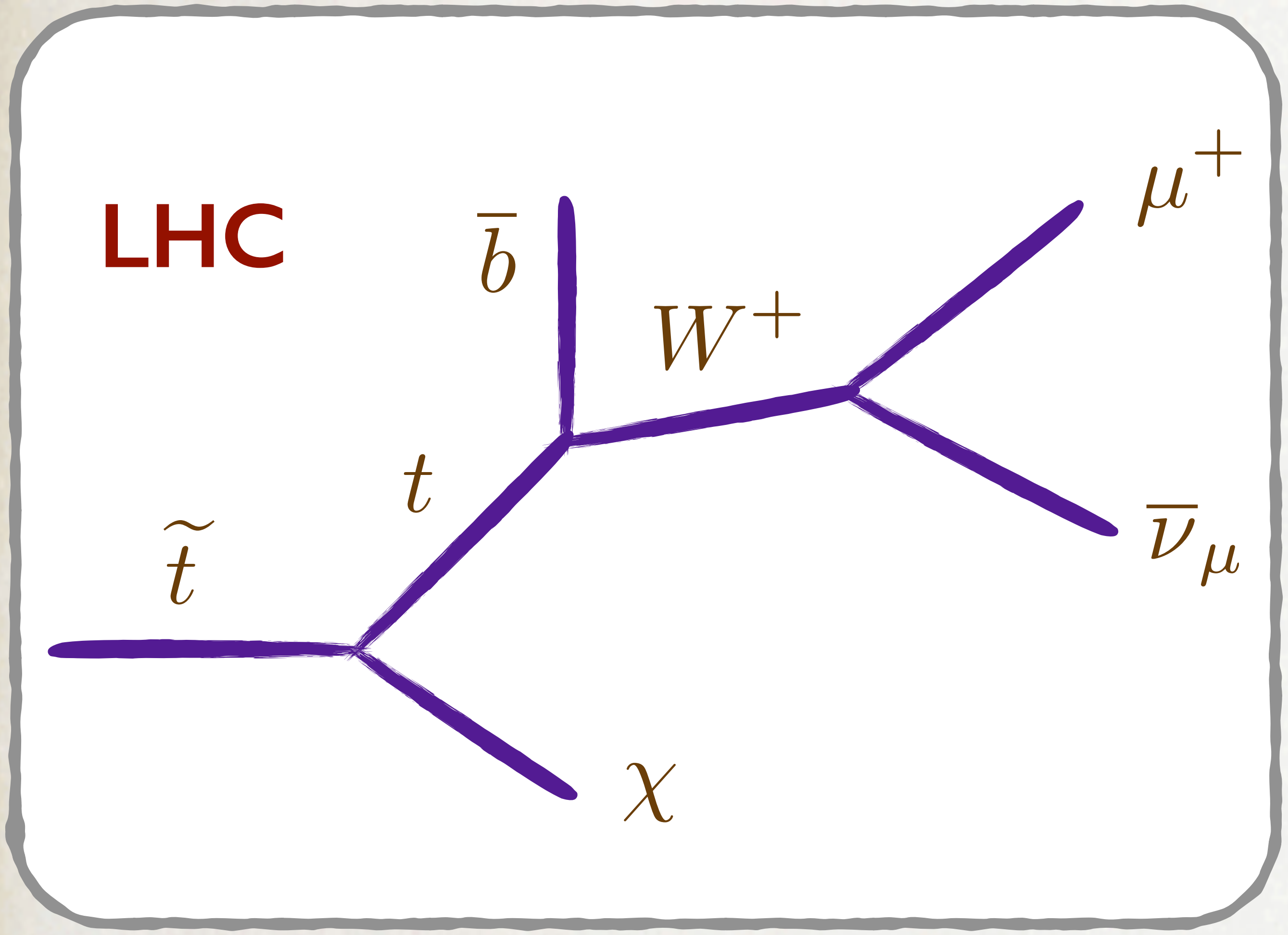


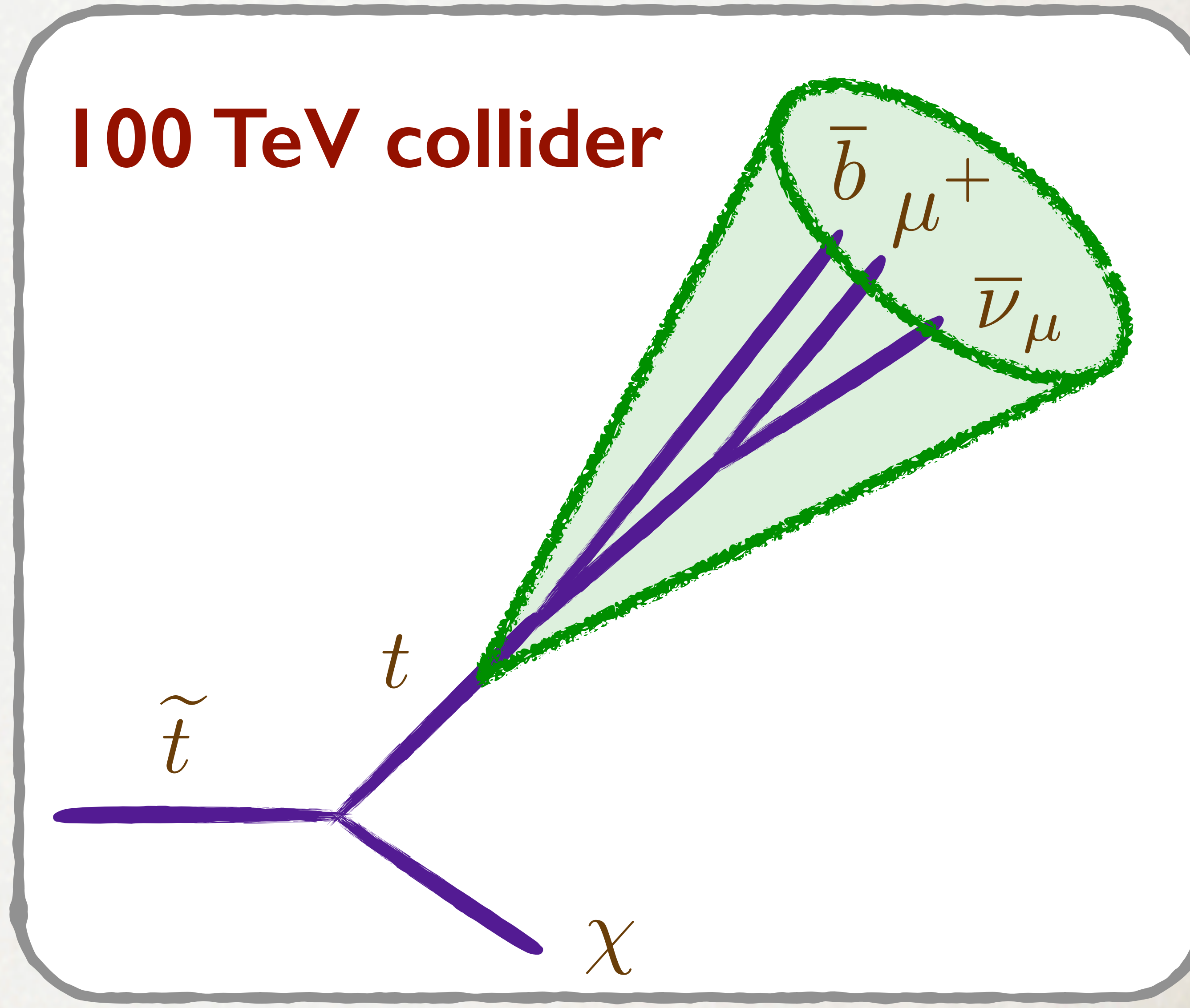

TC, D'Agnolo, Hance, Lou, Wacker [arXiv:1406.4512]

# SUPER BOOSTED TOP TAGGING

Require isolated lepton.




Require muon inside a jet.



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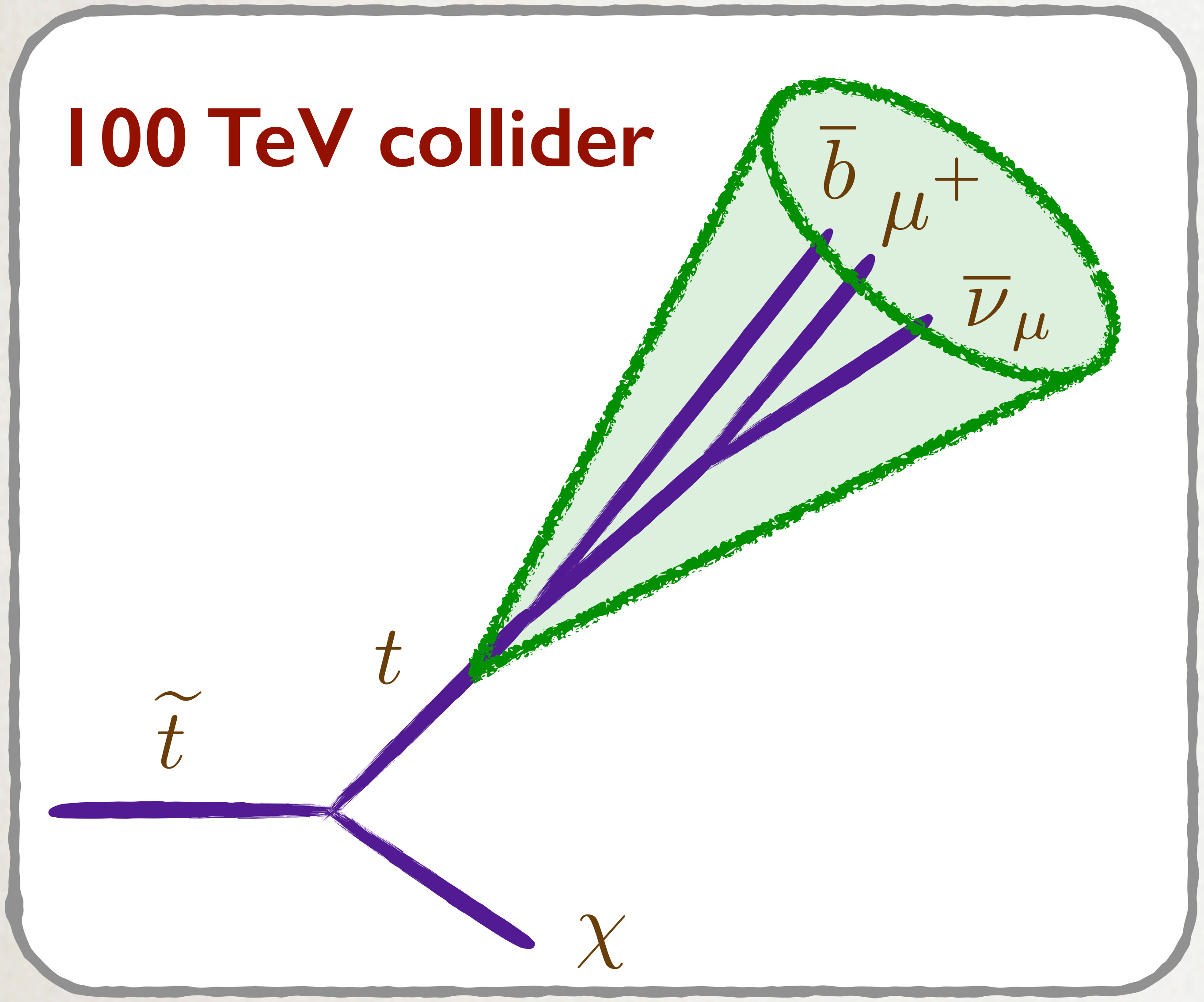


## Main requirements

- $\geq 2$ jets
- $\geq 1$ muon inside a jet
- $0$ isolated leptons
- Few TeV missing energy
- $\ldots$

## Dominant background

$$t\,\bar{t} + W/Z, \ldots$$

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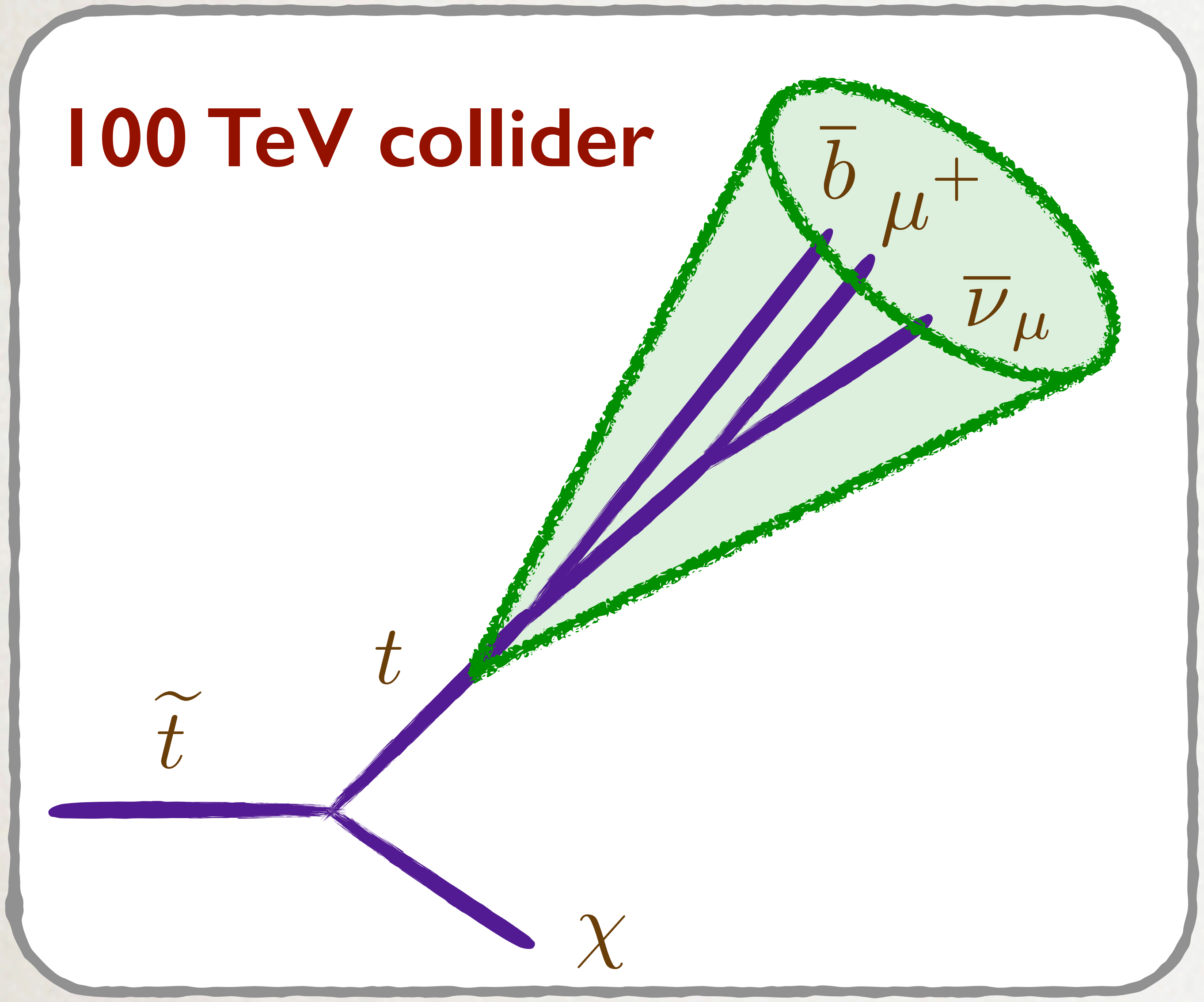


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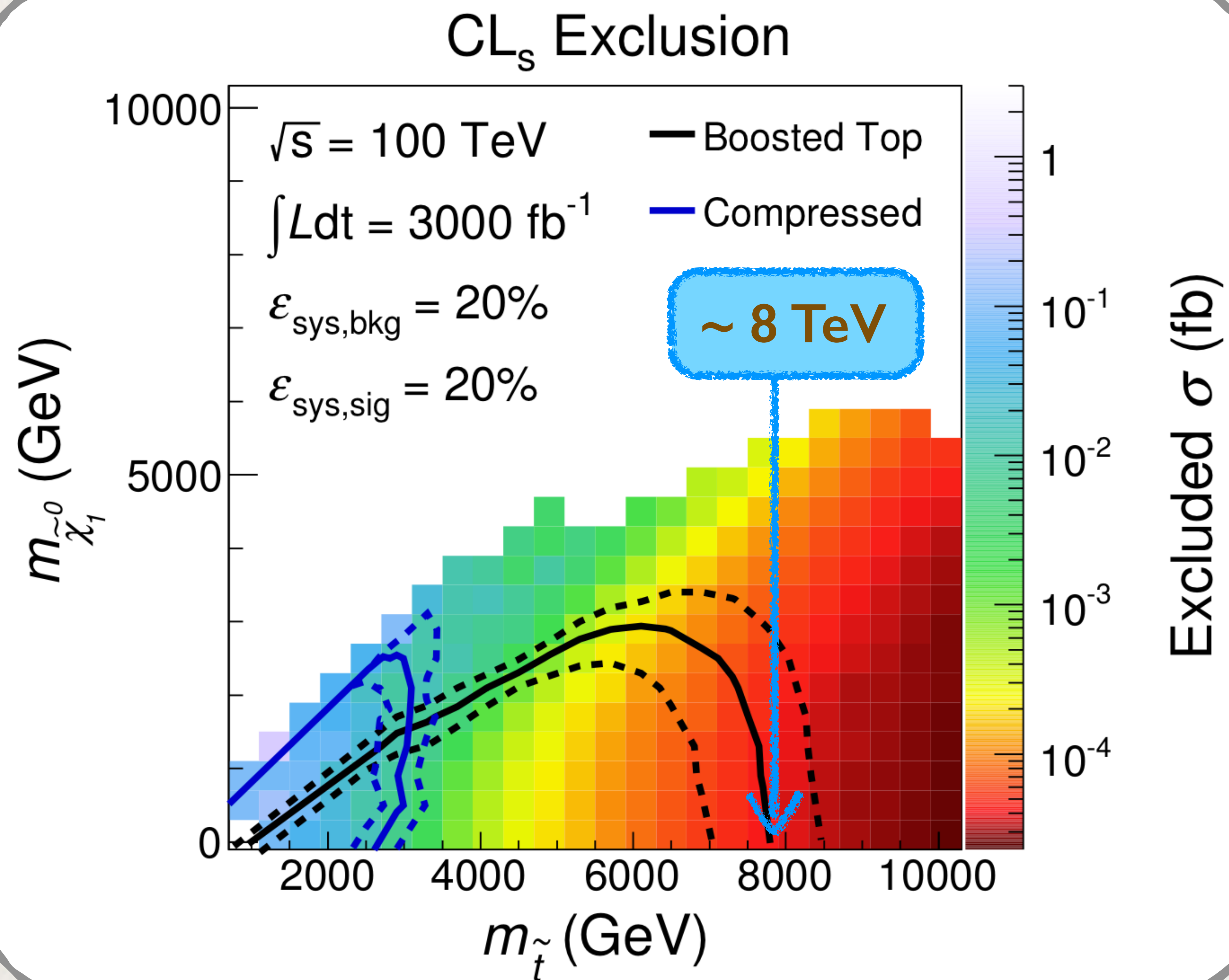
# PROJECTED LIMITS



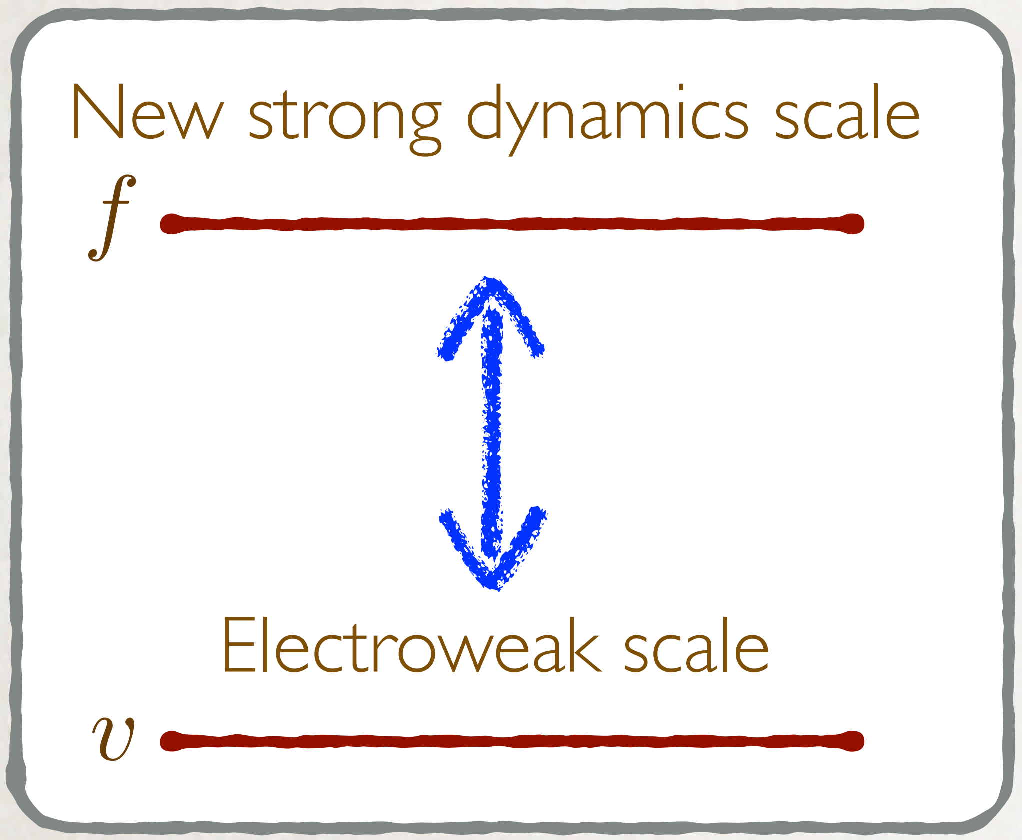

TC, D'Agnolo, Hance, Lou, Wacker [arXiv:1406.4512]

# ALTERNATIVE THEORIES

# COMPOSITE HIGGS

What if the Higgs were **not** an elementary scalar?

Requires new strong dynamics.





Kaplan, Georgi [1984];
Kaplan, Georgi, Dimopoulous [1984]; …
for a recent review: Bellazzini, Csaki, Serra [arXiv:1401.2457]

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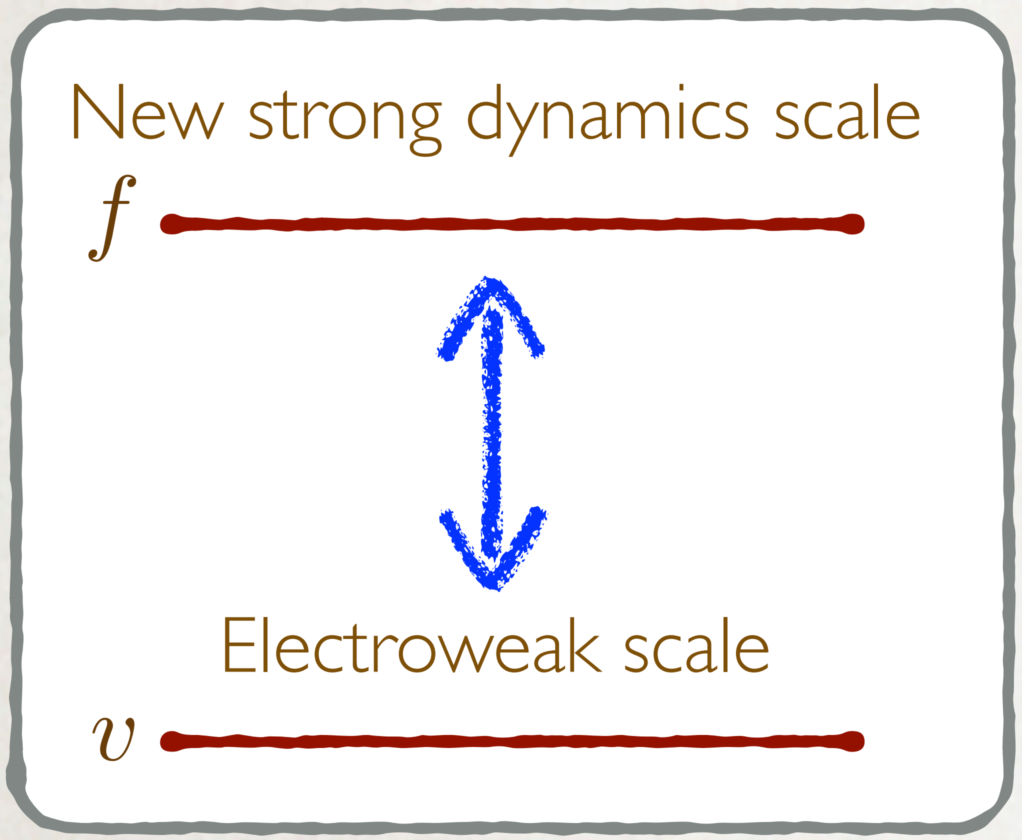


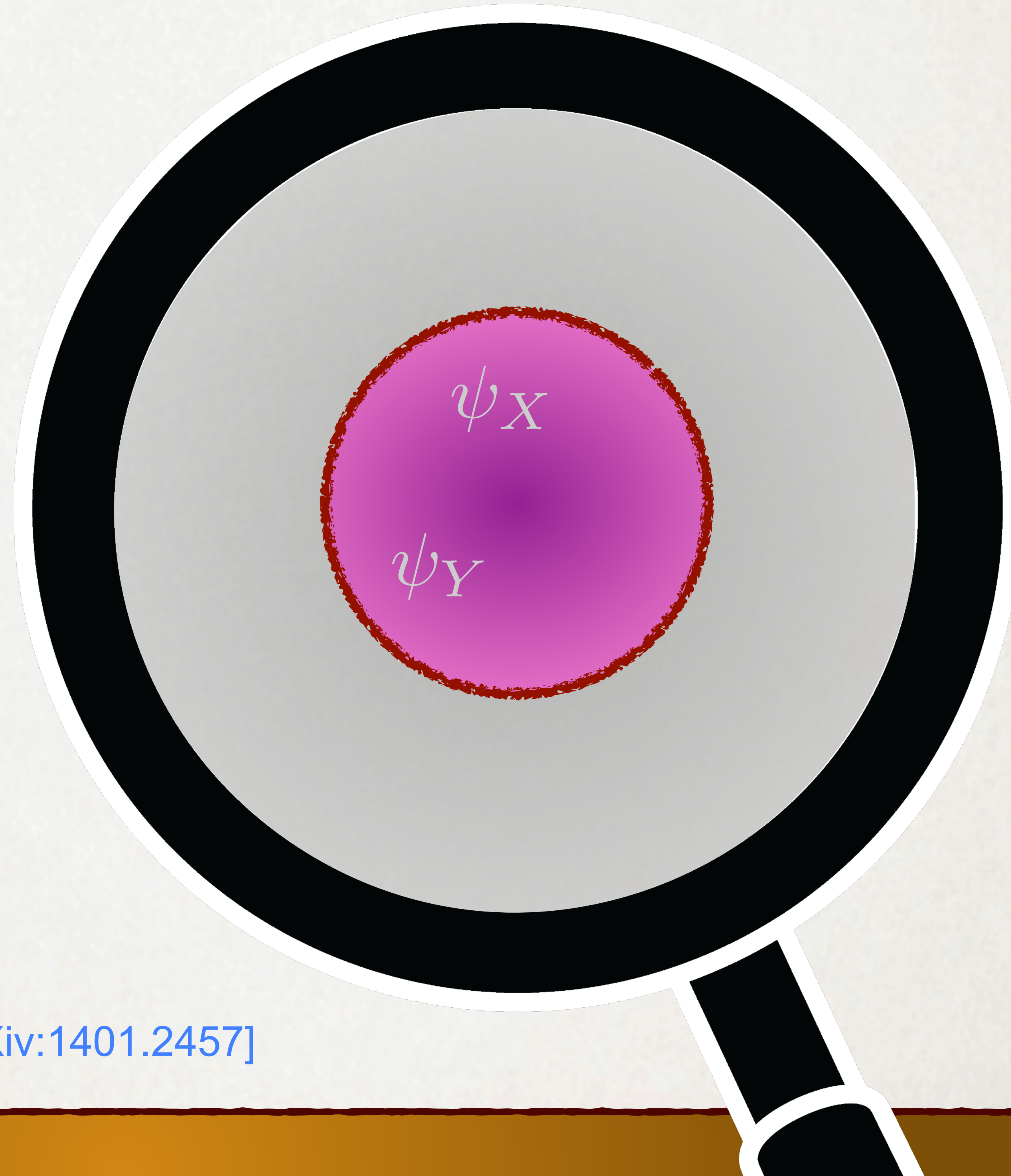


Kaplan, Georgi [1984];
Kaplan, Georgi, Dimopoulous [1984]; …
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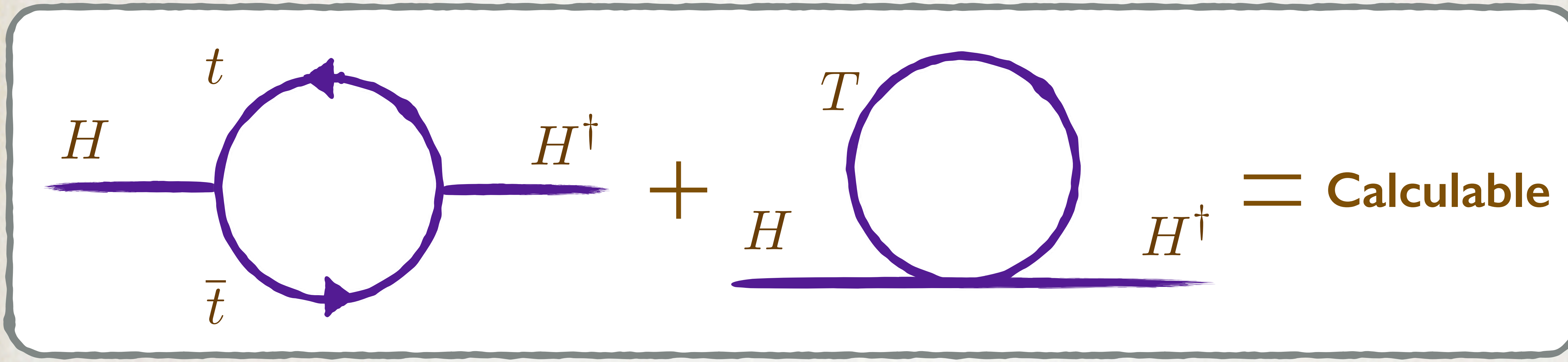
# FERMIONIC TOP PARTNERS

Calculable requires new fermions, $T$.

Quadratic divergences canceled by fermionic top partner loops.

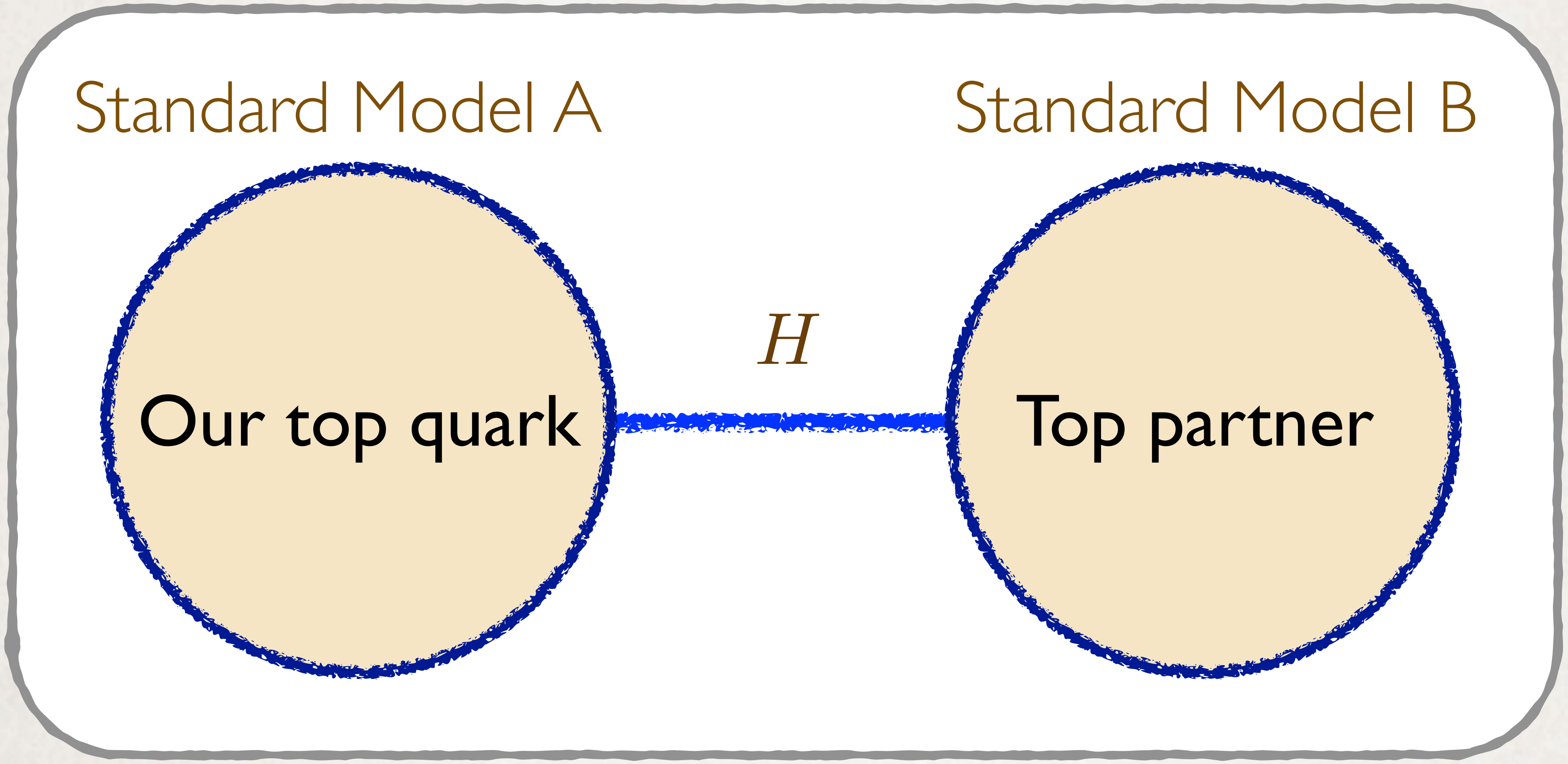



## Observables

- Search for top partners:
  $T \to t + Z^0, T \to t + H, T \to \bar{b} + W^+, \ldots$
- Modified Higgs properties set by $v/f$.

# NEUTRAL NATURALNESS

Do top partners have to be colored?




**Two options**

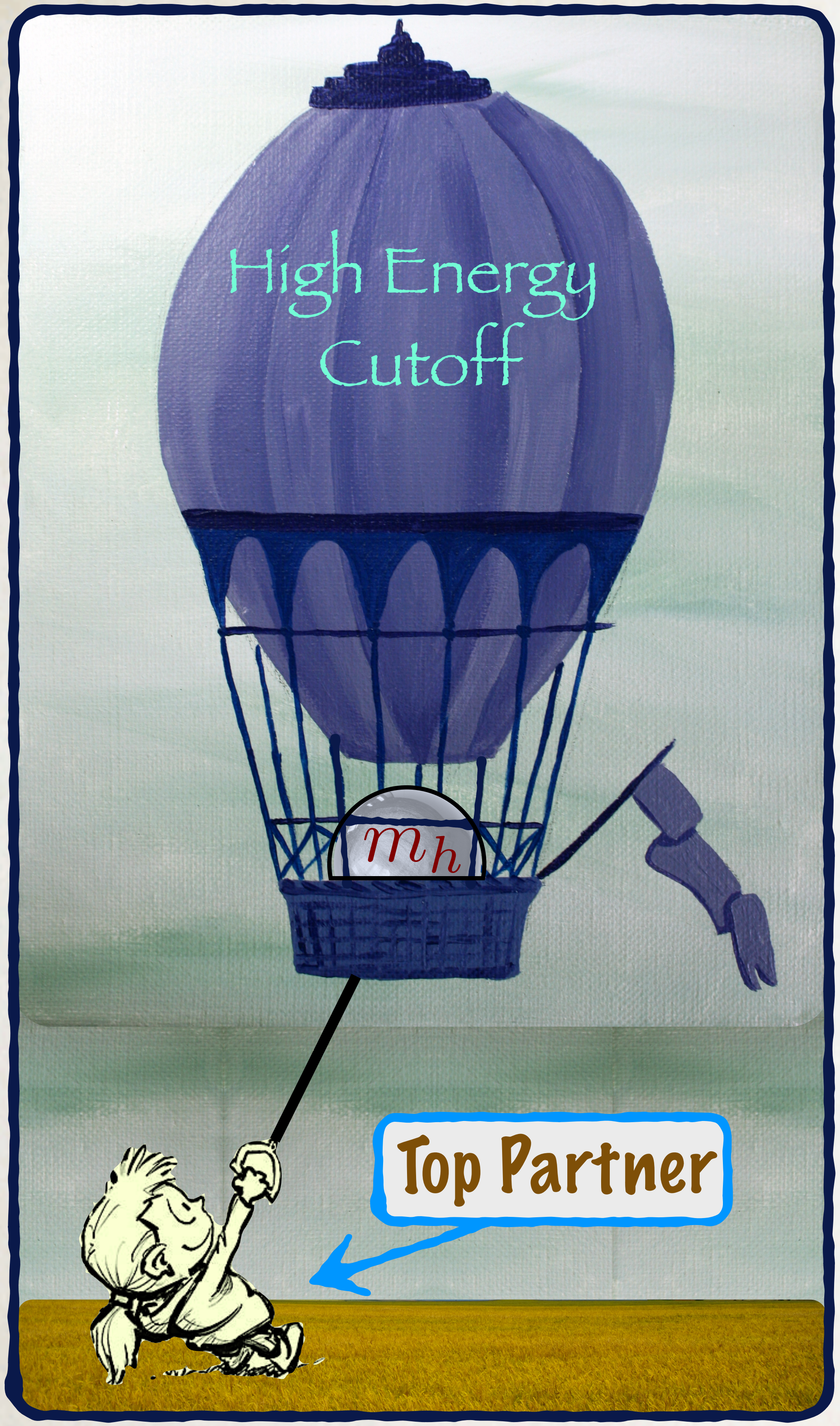
- Fermionic neutral top partners: Twin Higgs

  Chacko, Goh, Harnik [arXiv:hep-ph/0506256]

- Scalar neutral top patterns: Folded Supersymmetry

  Burdman, Chacko, Goh, Harnik [arXiv:hep-ph/0609152]

# SUMMARY




# SUMMARY

Reductionism:
Want "theory" of the Higgs potential.

Loops of top partners
render Higgs mass calculable.

**MANY MANIFESTATIONS:**

- Supersymmetry: stops (scalars)
- Composite Higgs: $T$ (fermions)
- SM x SM: neutral scalars or fermions

**TESTABLE CONSEQUENCES:**

- Direct production at colliders
- Modification of Higgs properties