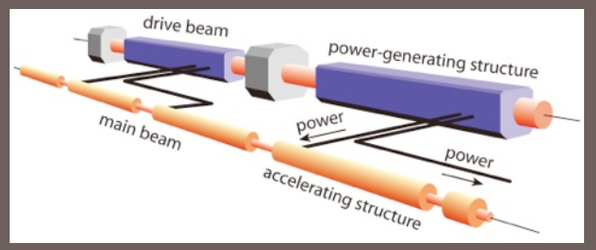
TRIUMF

Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Probing New Physics at Linear Colliders



David Morrissey | Research Scientist | TRIUMF

Linear Collider Science

Beyond the Standard Model

- dark matter
- excess of matter over anti-matter
- neutrino masses and mixings
- experimental anomalies? (e.g. $(g-2)_\mu$)

- naturalness of the weak scale
- quantum theory of gravity at high energies
- origin of flavor mixing and CP violation
- something we have not thought of yet ...

Electroweak Naturalness

- The Higgs discovery completes the Standard Model.
- It is the only known fundamental "scalar" (spin = 0).
- Higgs potential:

$$V_{eff} = -M_H^2|H|^2 + \lambda|H|^4$$

- Higgs boson mass:

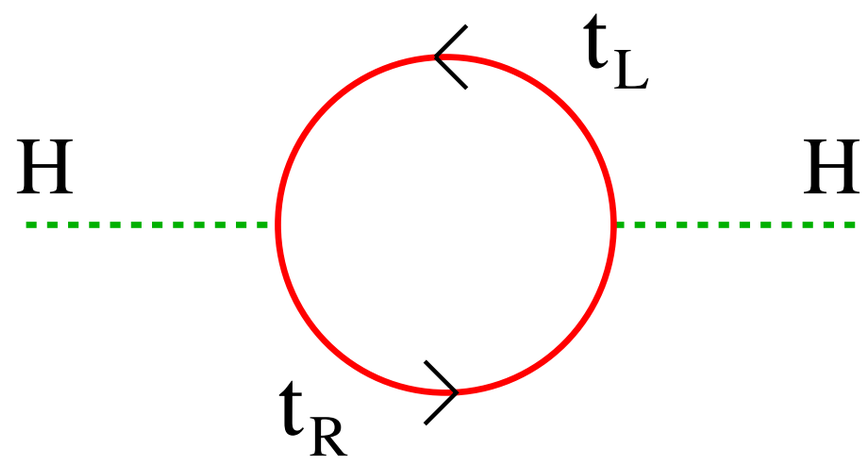
$$m_h = \sqrt{2}M_H \simeq 125\,\mathrm{GeV}$$

- Problem: M_H is very sensitive to quantum corrections from physics at higher energies.

Electroweak Naturalness

- Naive extrapolation of the SM to energies $\Lambda \gg m_W$:

$$\Delta M_H^2 = \frac{3y_t^2}{8\pi^2}\Lambda^2 + \ldots$$



$|\Delta M_H^2| \gg M_H^2$ would be surprising.

- "Naturalness": new physics should prevent this.

$$\Lambda^2 \lesssim \frac{4\pi^2}{3y_t^2} m_h^2 \sim (500\,\mathrm{GeV})^2$$

Electroweak Naturalness

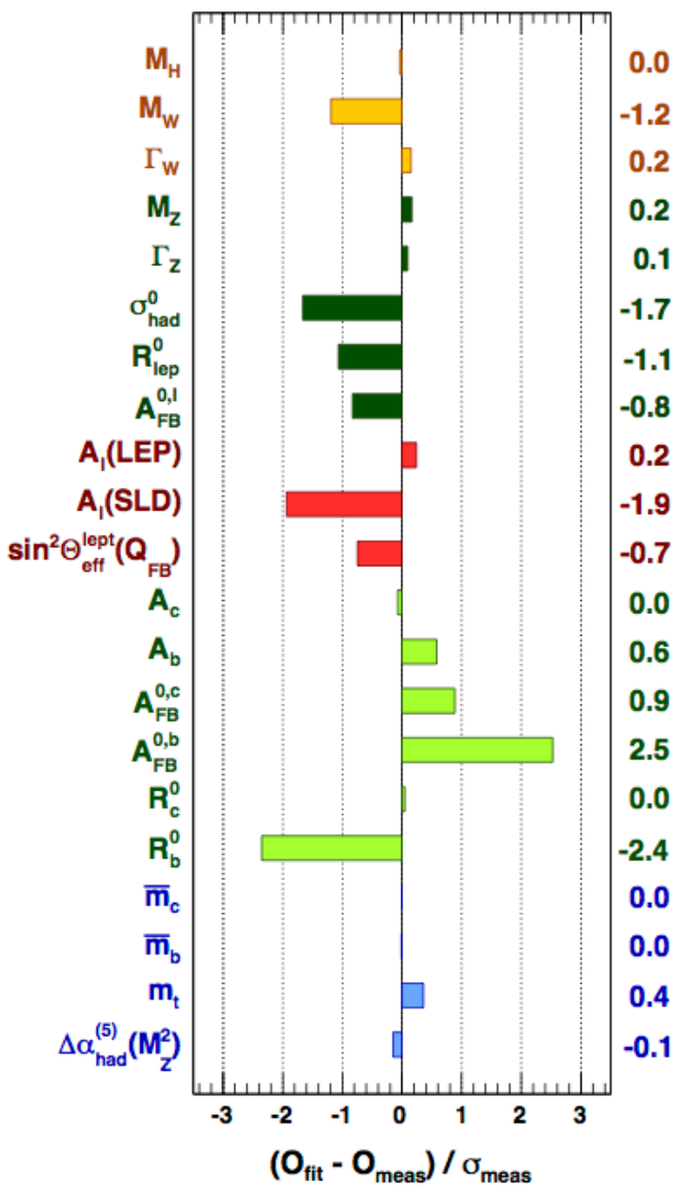
- New Physics for naturalness?

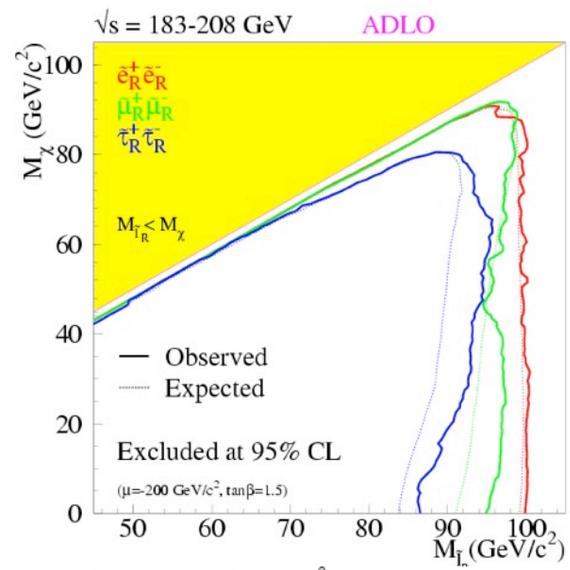
- Two classes of solutions:
  1. Cancellations with new partner particles:
     Supersymmetry, Little Higgs, Twin Higgs, ...
  2. Compositeness: Higgs is not a fundamental scalar:
     Composite Higgs, Warped Extra Dimension (RS)

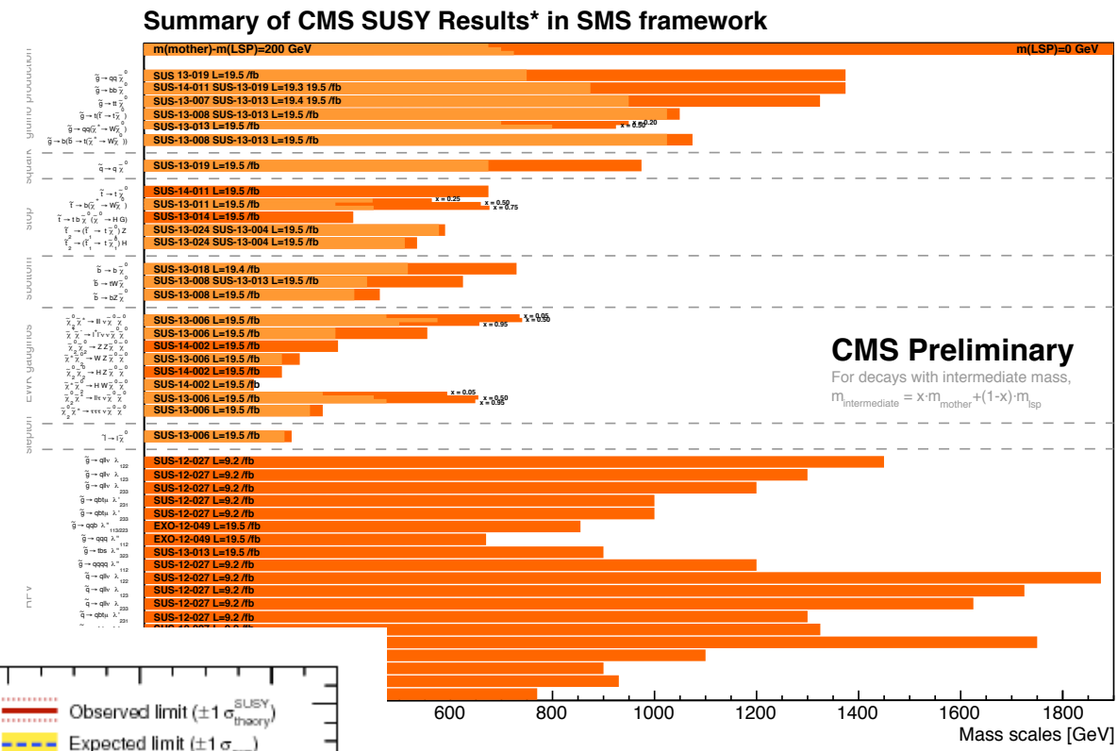
- Linear colliders will be essential to understand both.

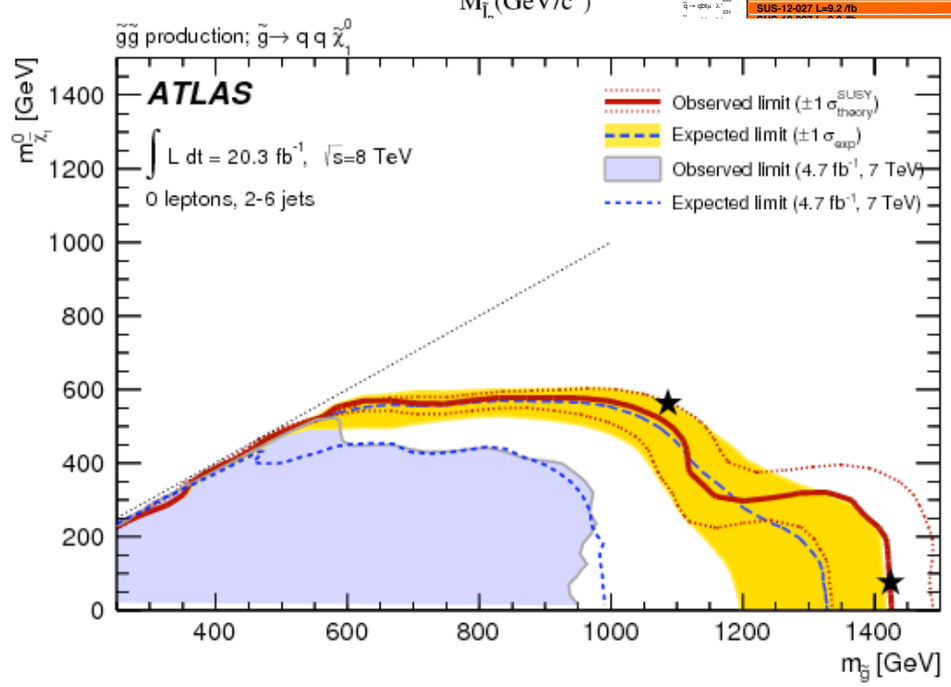
SLC/D, LEP, Tevatron, and LHC

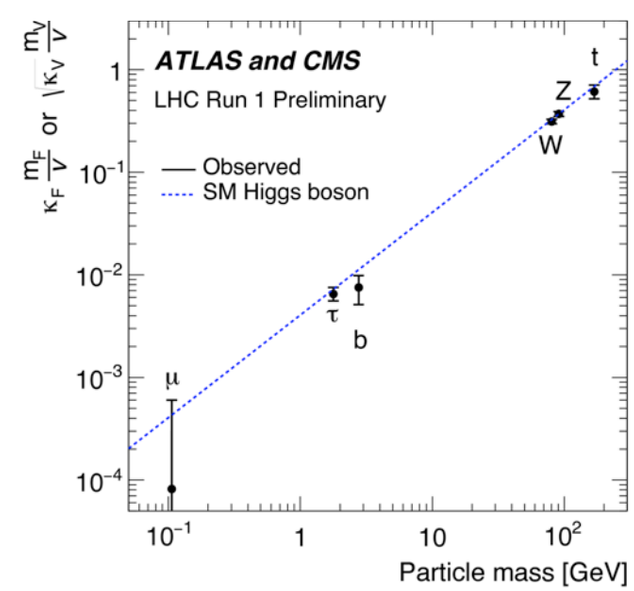
- No evidence for BSM physics so far, but strong limits:









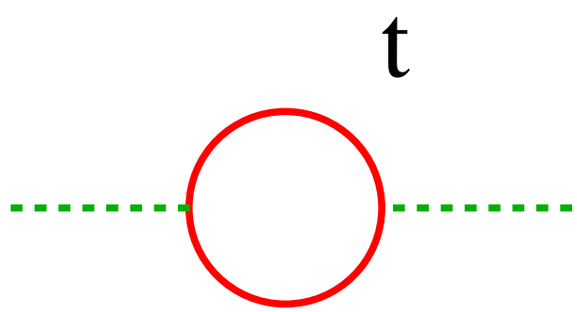


Five Linear Collider Stories

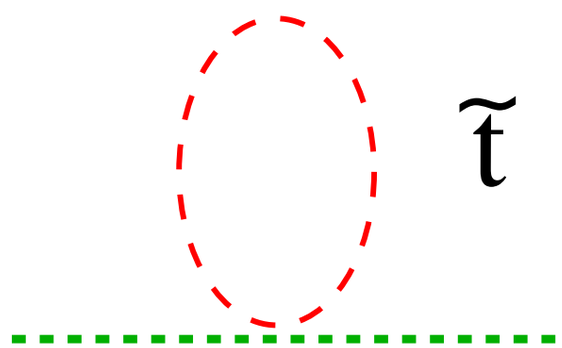
1. Discovery of SUSY Higgsinos
2. Precision Measurements of SUSY
3. Indirect Probes of a Composite Higgs
4. Neutral Naturalness through the Higgs Portal
5. Testing Matter Creation

SUSY Naturalness

- Naturalness Solution #1: Supersymmetry (SUSY)
  Cancellations between particles and superpartners:

$(\Delta M_H^2)_t =$ 

$$\frac{3y_t^2}{8\pi^2}\Lambda^2$$

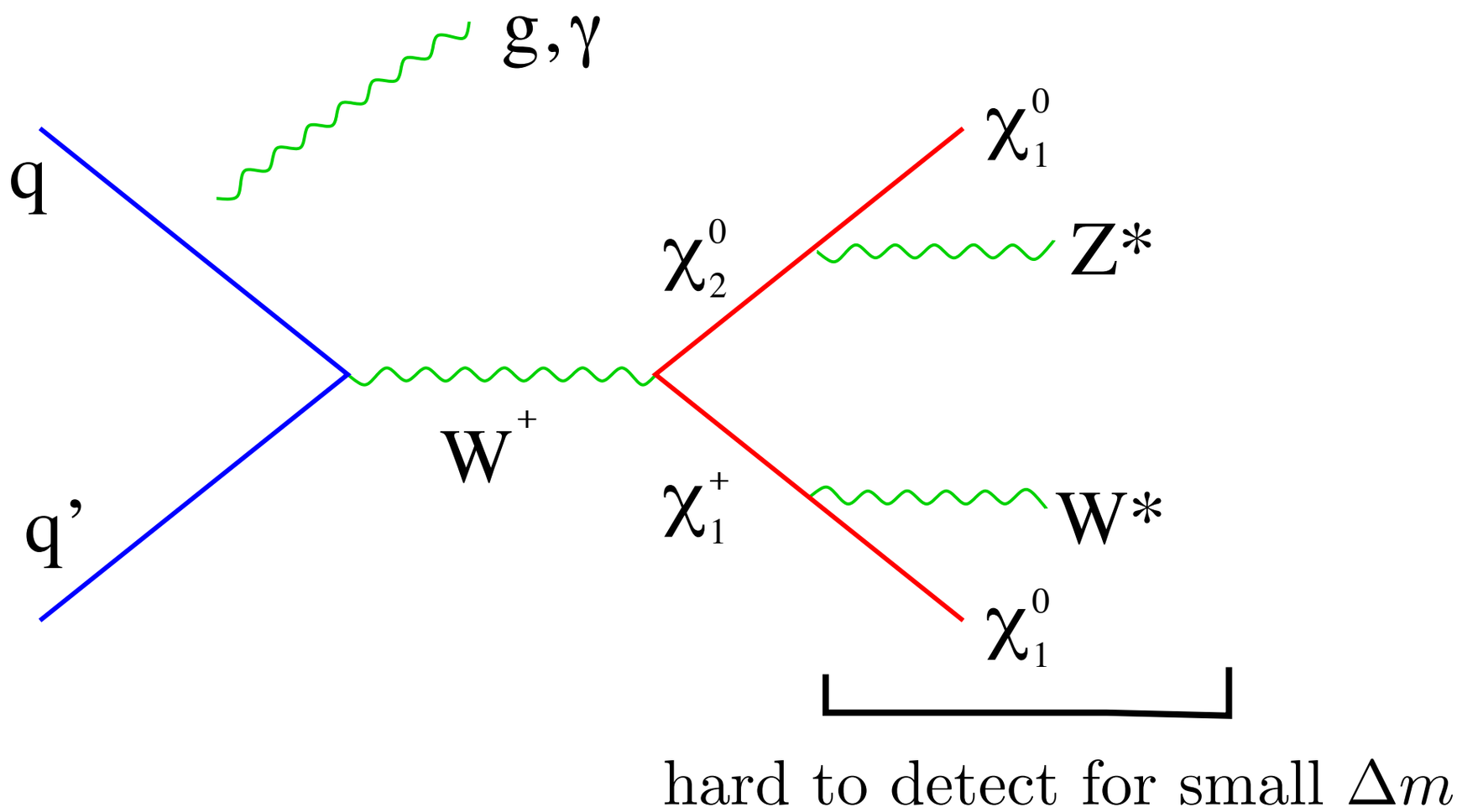
$(\Delta M_H^2)_{\tilde{t}} =$ 

$$-\frac{3y_t^2}{8\pi^2}\Lambda^2 + \frac{3y_t^2 m_{\tilde{t}}^2}{4\pi^2}\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

$$(\Delta M_H^2)_{\text{total}} = \frac{3y_t^2 m_{\tilde{t}}^2}{4\pi^2}\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

Higgsino Discovery

- Natural SUSY requires light higgsinos below 300 GeV.
- Four higgsino states: $\chi_1^0, \chi_2^0, \chi_1^\pm$.
- Close in mass if other SUSY is heavier: $\Delta m \lesssim 30\,\mathrm{GeV}$.



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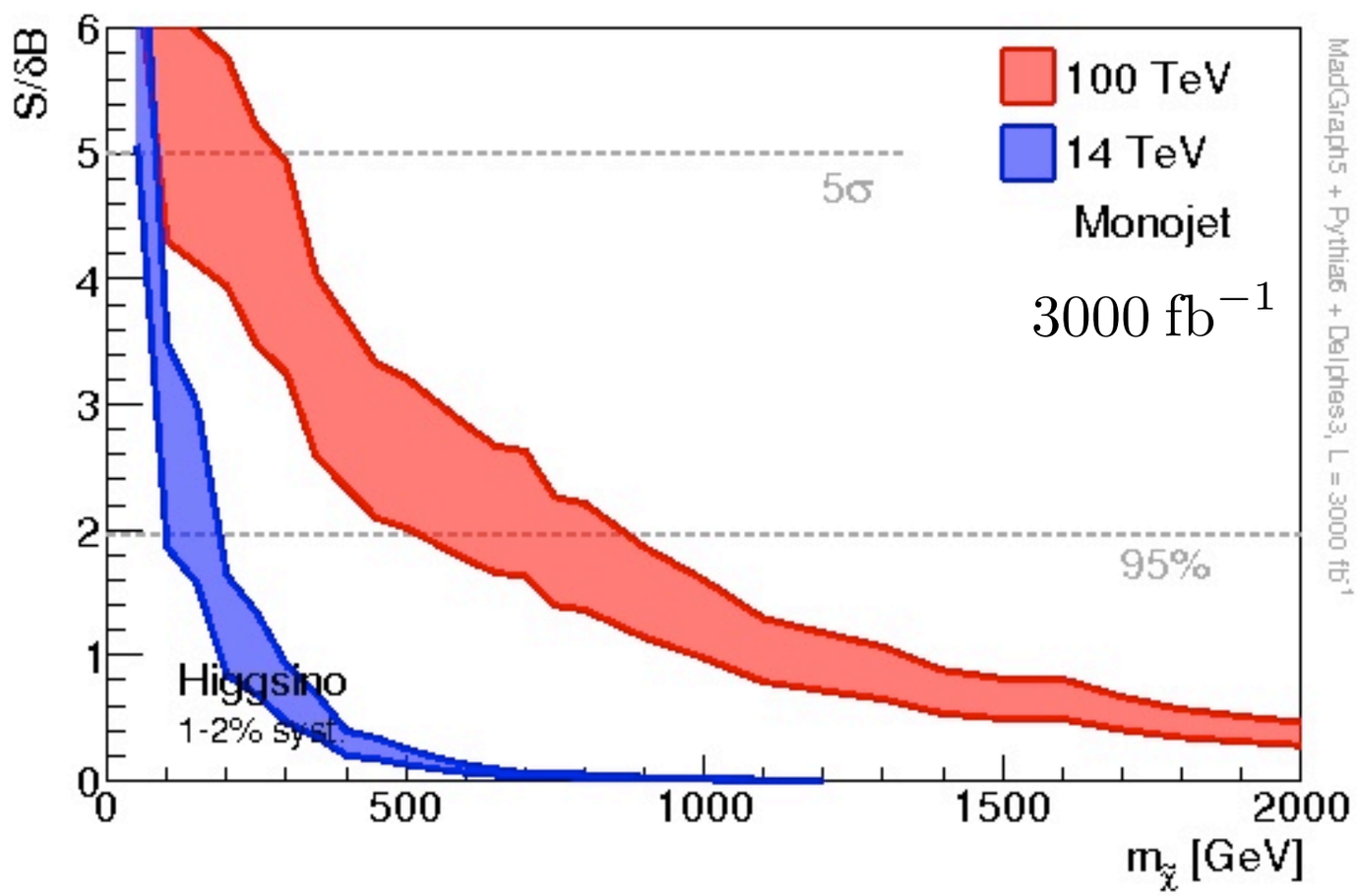
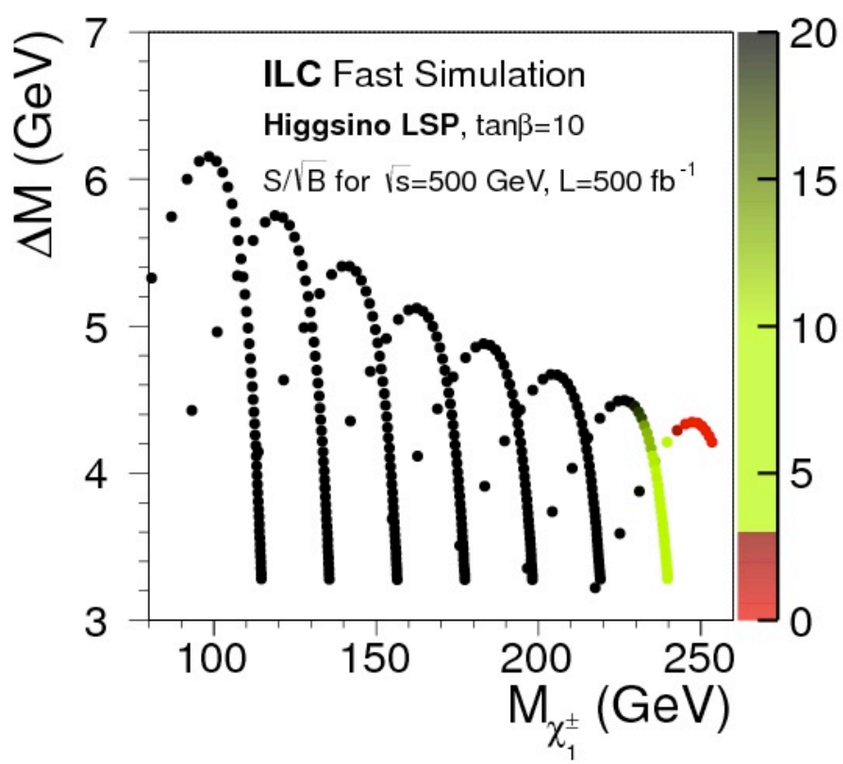


[Low, Wang, JHEP 1408 (2014) 161]

Higgsino Discovery

- LC sensitivity to higgsinos is close to $m_{higgsino} \sim \sqrt{s}$.
- Larger $\Delta m \in [10, 30]\,\mathrm{GeV}$: look for decay products from cascade decays. [Baer et al, JHEP1406 (2014)172]
- Smaller $\Delta m \lesssim 10\,\mathrm{GeV}$: search for a hard photon, missing energy, and limited extra visible energy.



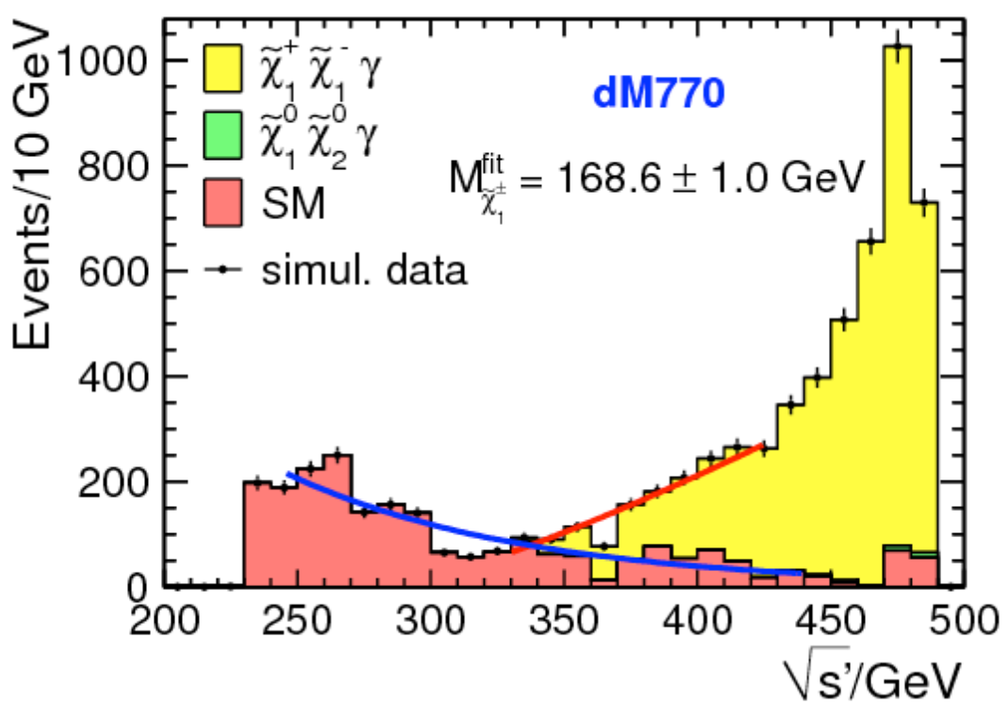
[Berggren et al, Snowmass 2013 1307.3566]

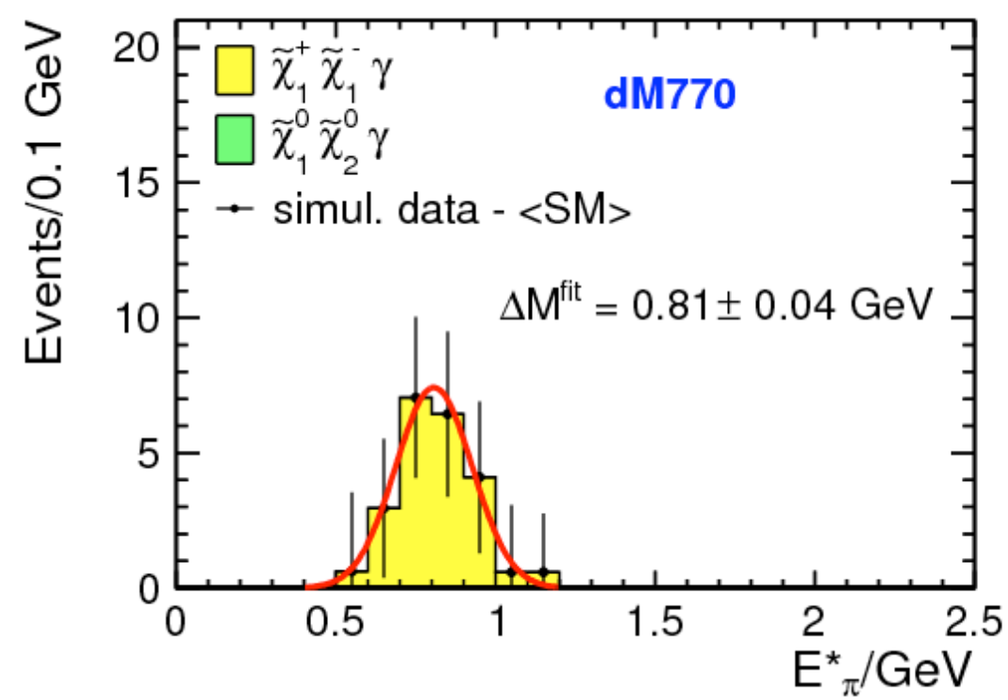
Precision Supersymmetry

- What are the masses of the superpartners?
- e.g. light higgsino $\chi_1^{\pm}$, χ_1^0 [Berggren et al, EPJ C73 (2013) 12, 2660]

$$m_{\chi_1^{\pm}} = 167.36\,\mathrm{GeV}, \quad m_{\chi_1^{\pm}} - m_{\chi_1^0} = 0.77\,\mathrm{GeV}$$

$$e^+e^- \to \gamma\, \chi_1^+ \chi_1 -, \quad \chi_1^+ \to \pi^+ \chi_1^0$$





Precision Supersymmetry

- What are the superpartner couplings and parameters?
- e.g. light higgsino $\chi_1^{\pm}$, χ_1^0 [Berggren et al, EPJ C73 (2013) 12, 2660]

$$m_{\chi_1^{\pm}} = 167.36\,\mathrm{GeV}, \quad m_{\chi_1^{\pm}} - m_{\chi_1^0} = 0.77\,\mathrm{GeV}$$

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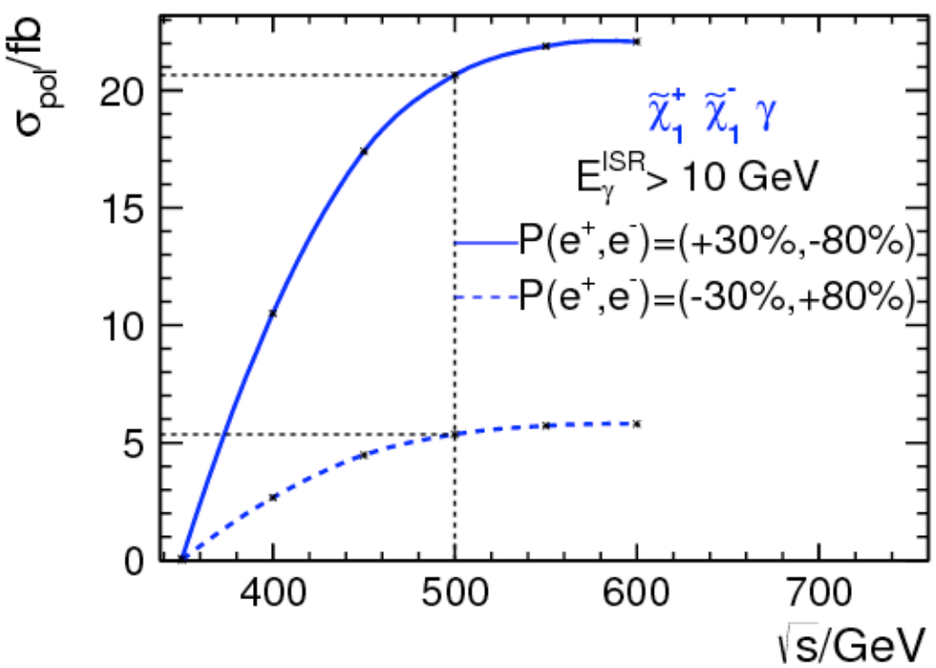
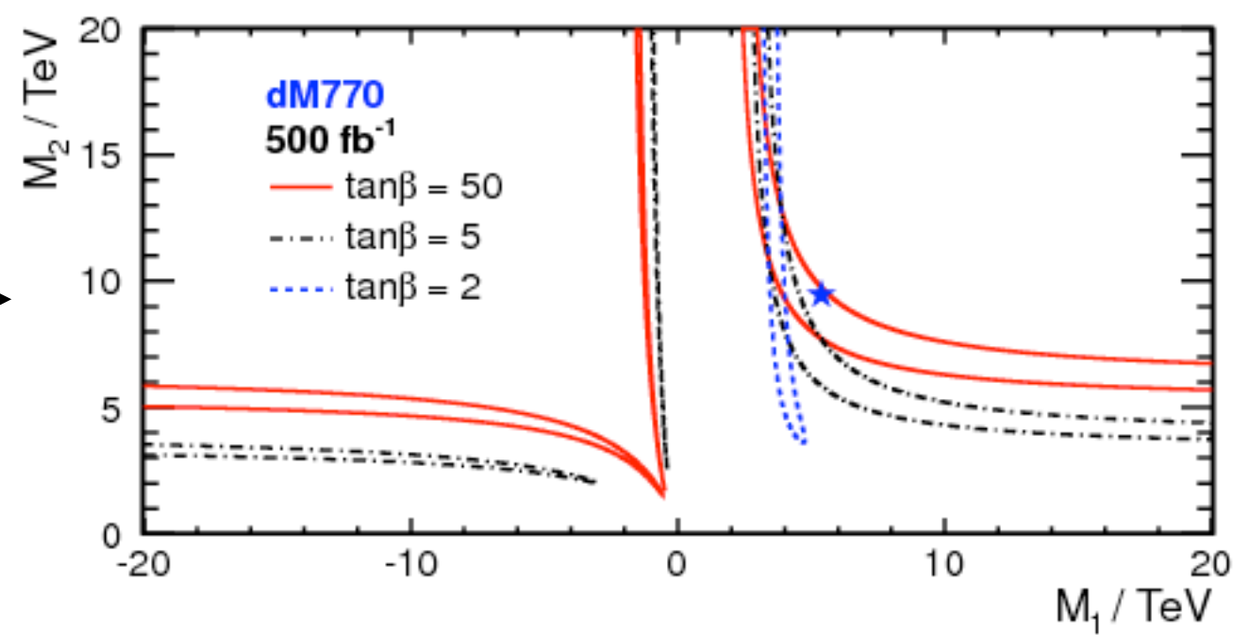




Precision Supersymmetry

- And much more: [Review: Moorgat-Pick et al, EPJ C75 (2015) 8, 371]
  - Spins from angular distributions and thresholds.
  - Asymmetries give indirect sensitivity to heavy SUSY.
  - High precision direct and indirect measurments.

- Precision answers fundamental questions:
  - Do couplings satisfy SUSY relations?
  - Are the neutralinos Dirac or Majorana?
  - What is the mechanism of SUSY breaking?
  - Connections to dark matter and baryogenesis.

Composite Naturalness

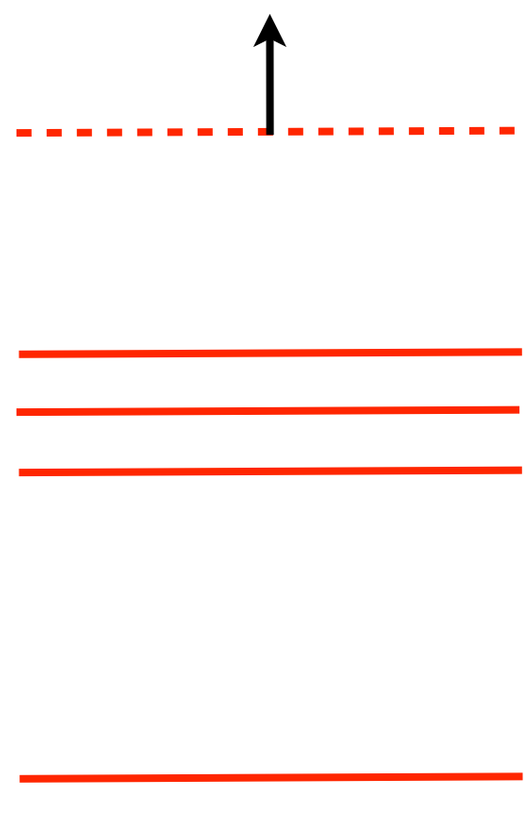
- Naturalness Solution #2: Composite Higgs
  Higgs is a bound state of new strong dynamics.

  QCD Analogy

$q,\, g:$ few GeV

$\rho:\ g_\rho f_\pi \sim$ GeV

$\pi^{0,\pm}:\ f_\pi \sim 0.1\,\mathrm{GeV}$



techniquarks (?)

warped XD stuff (?)

resonances :

$4\pi\, f \sim$ few TeV

$H:\ f \sim 200\,\mathrm{GeV}$

Tests of a Composite Higgs

- Higgs boson is now a composite bound state.
- EW and Higgs couplings are modified by:

$$\xi = \left(\frac{v}{f}\right)^2$$

$g_\rho f =$ compositeness scale ($g_\rho \sim 4\pi$)

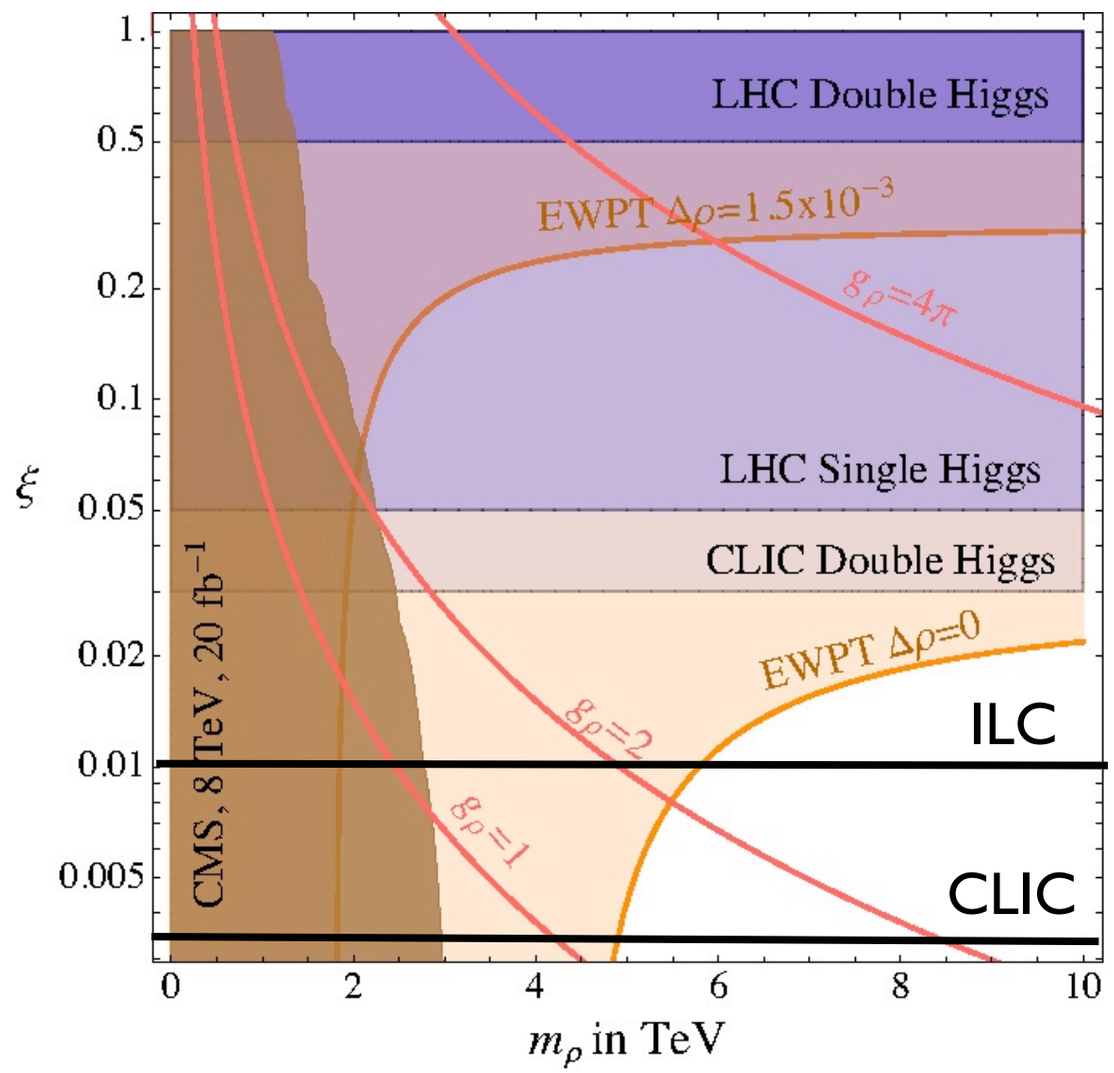
$v = 246\,\mathrm{GeV}$

- New resonances are expected with mass $\sim g_\rho f$. These are probably out of range.

- Linear colliders provide very strong indirect tests.

Tests of a Composite Higgs

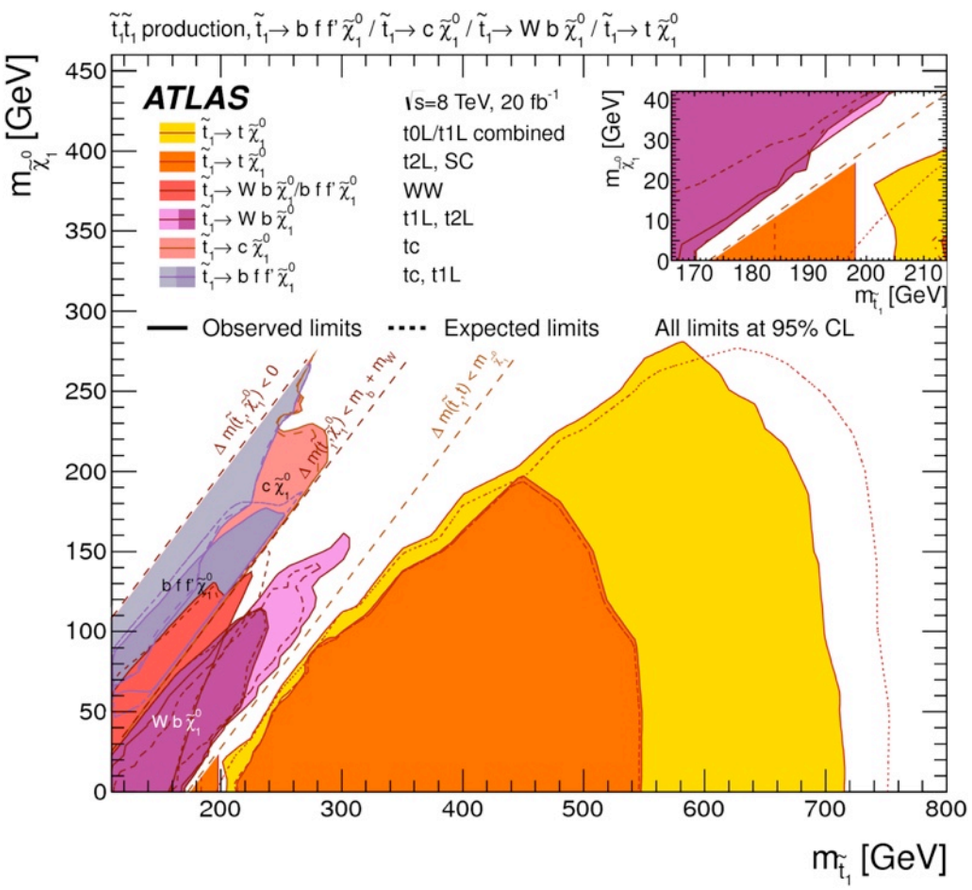
- Higgs couplings (talks by S. Gori, M. Peskin):

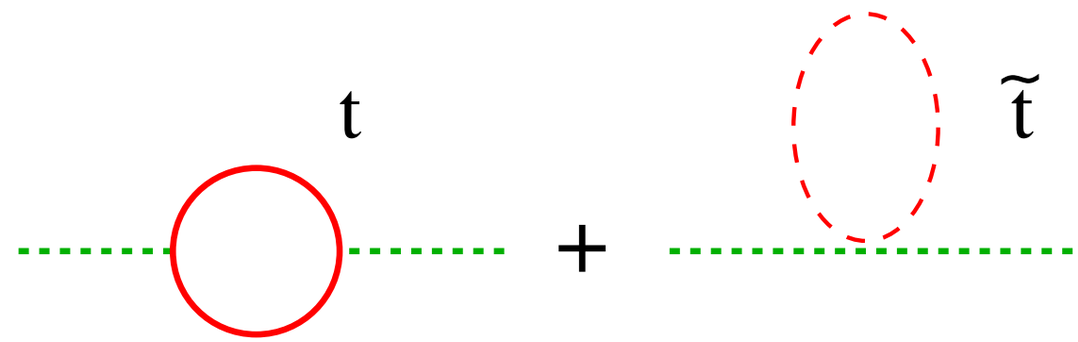


[Contino et al, JHEP 1402 (2014) 006]

Neutral Naturalness

- LHC bounds on top partners imply naturalness tension in SUSY and beyond:





$$\Delta M_H^2 = \frac{3y_t^2 m_{\tilde{t}}^2}{4\pi^2} \ln\left(\frac{\Lambda}{m_t}\right)$$

- These bounds would be much weaker if the top partners did not carry $SU(3)_c$ charge.

Neutral Naturalness

- e.g. New complex scalars X

[Craig, Englert, McCullough, PRL111 (2013) 12, 121803]

$$-\mathcal{L} \supset \lambda_X |X|^2 |H|^2$$

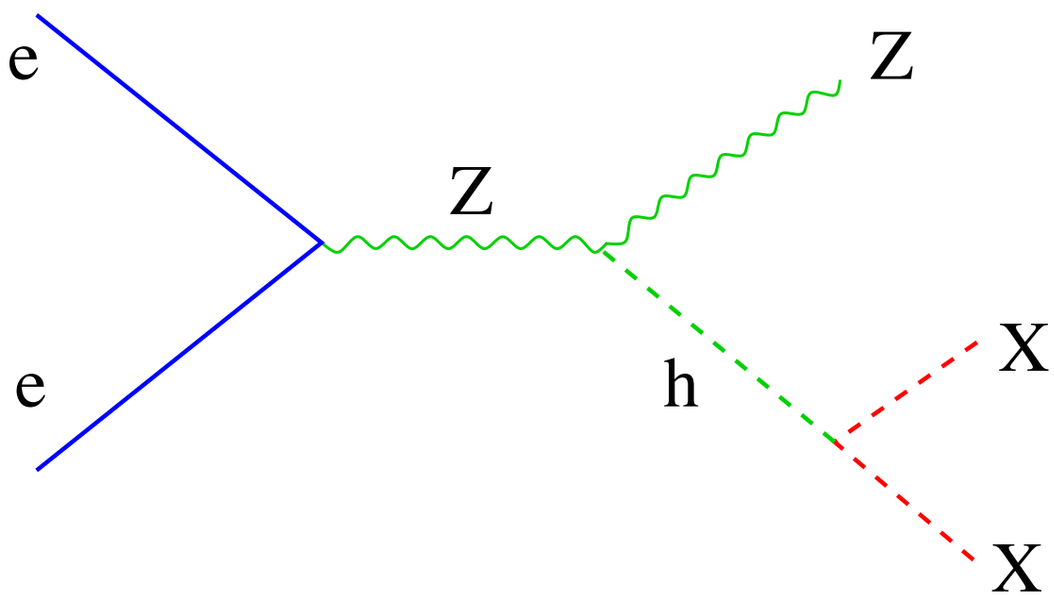
$$\Delta M_H^2 = \frac{3y_t^2}{8\pi^2}\Lambda^2 - \frac{N_X \lambda_X^2}{16\pi^2}\Lambda^2 + \frac{N_X \lambda_X^2}{8\pi^2} m_X^2 \ln\left(\frac{\Lambda}{m_X}\right)$$

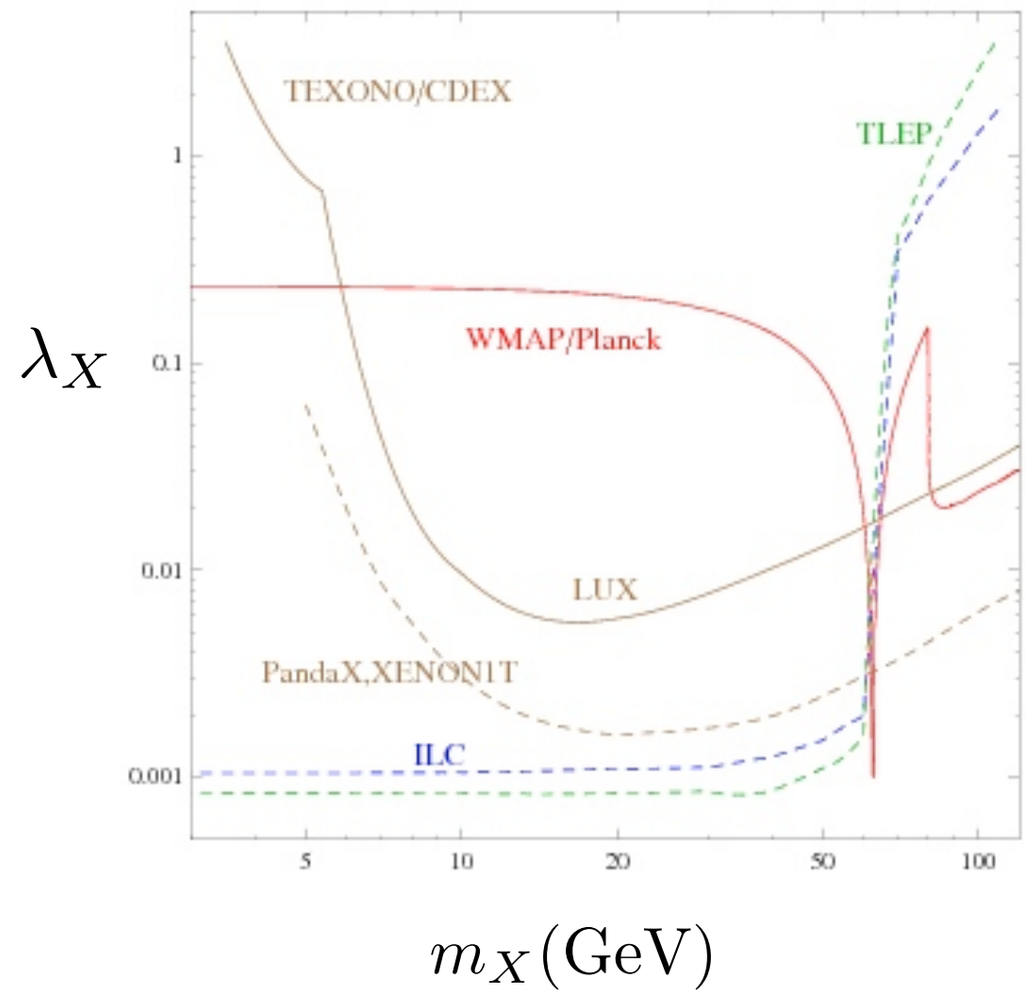
Want $N_X \lambda_X^2 = 6y_t^2$, moderate $m_X \lesssim 500\,\mathrm{GeV}$.

X need not have $SU(3)_c$ charge! (e.g. F-SUSY)

Neutral Naturalness

- Production via the Higgs boson:





- Note: plot for $N_X = 1/2$.

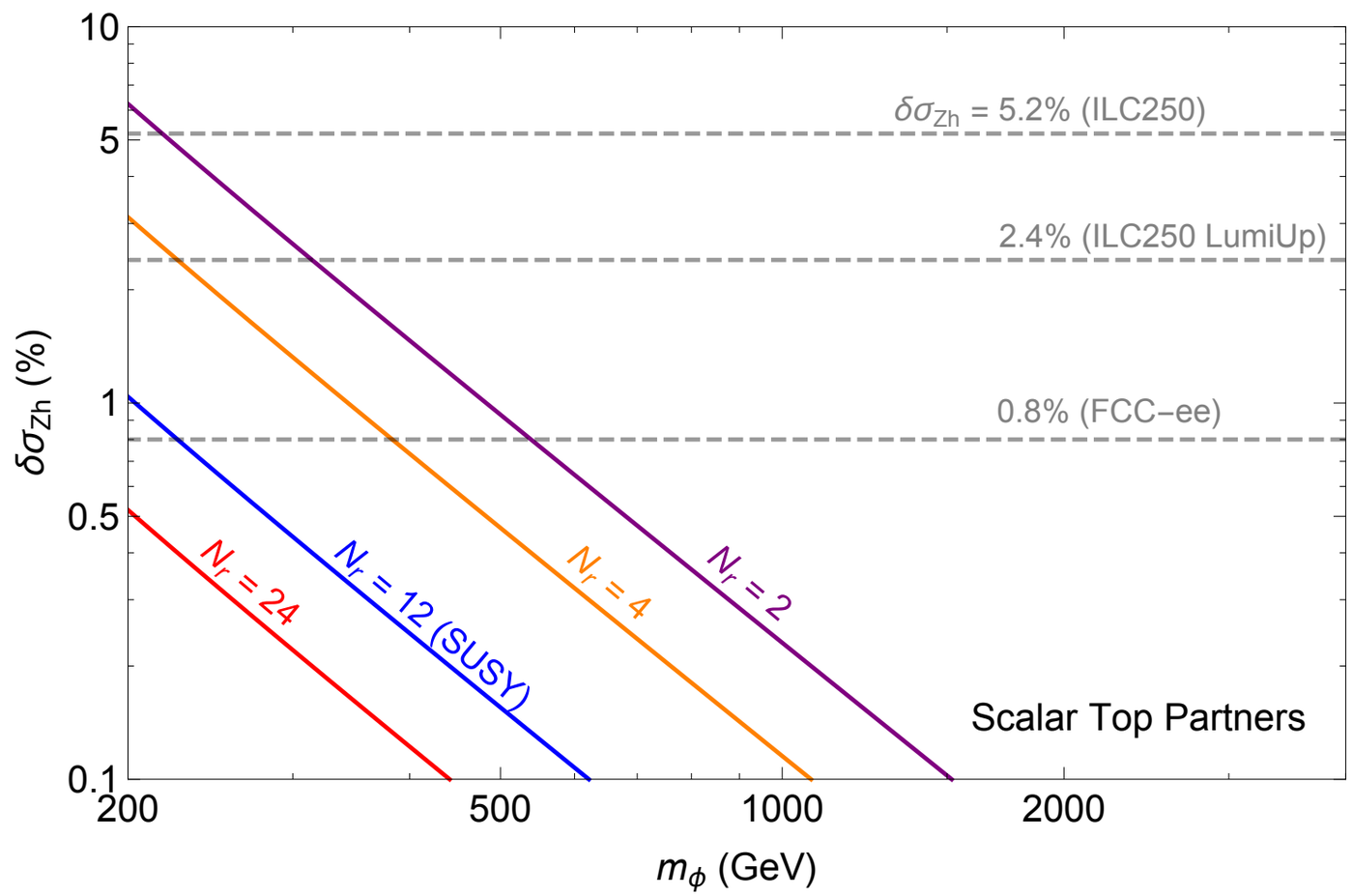
[Chacko, Cui, Hong, PLB732 (2014) 75]

Neutral Naturalness

- Loops of X will also modify Higgs couplings:

$$\delta\sigma_{Zh} = \Delta\sigma_{Zh}/\sigma_{Zh} \simeq \frac{N_X \lambda_X^2}{48\pi^2}\frac{v^2}{m_X^2}$$

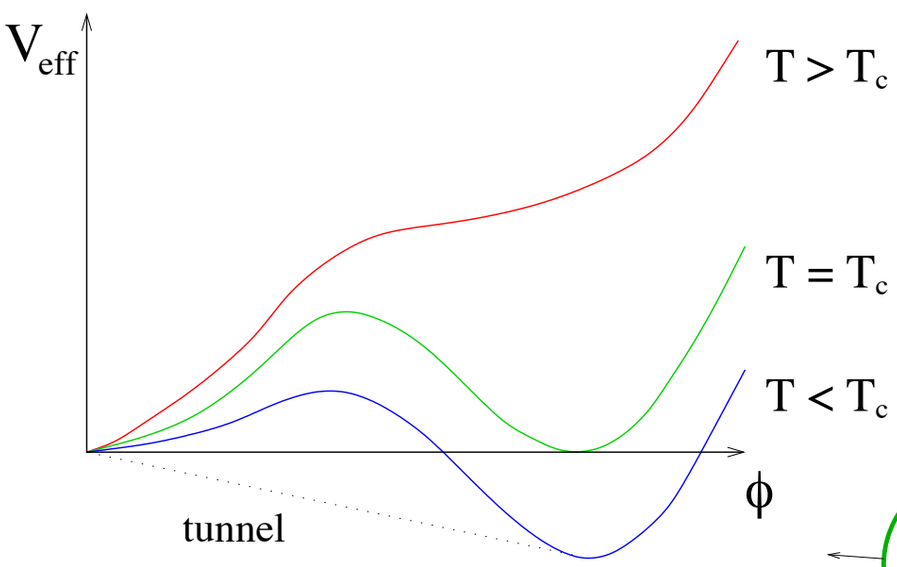
[Craig, Englert, McCullough, PRL111 (2013) 12, 121803]

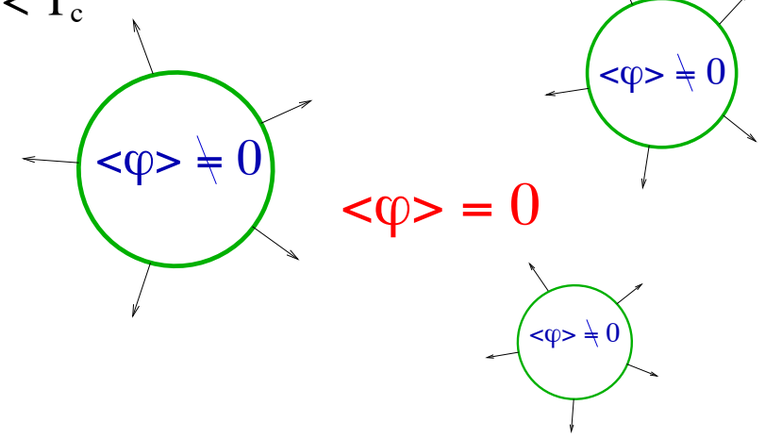


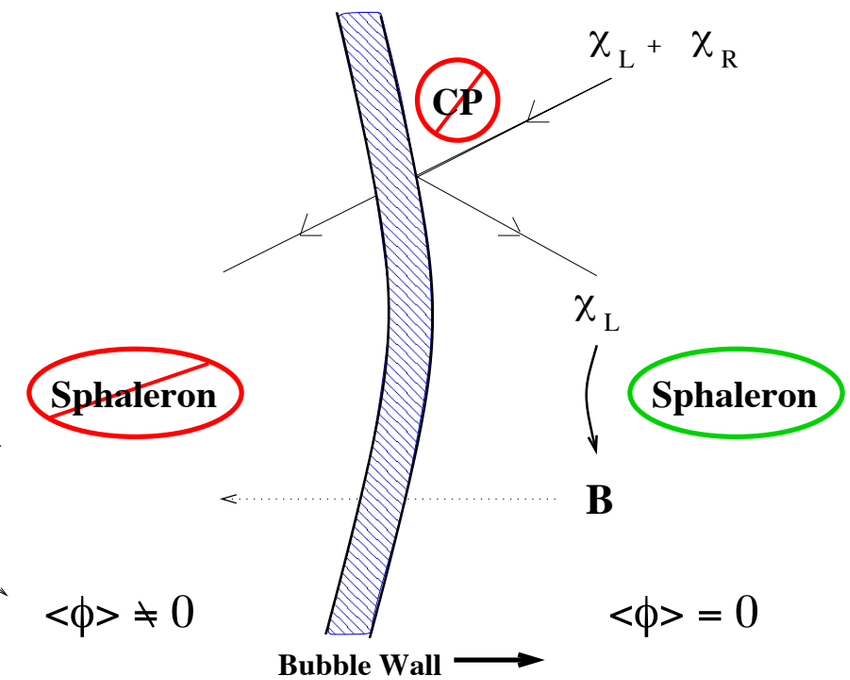
[Curtin, Saraswat, 1509.04284]

Testing Matter Creation

- Electroweak Baryogenesis (EWBG) can explain the excess of matter over antimatter.
- Baryons are created in a strongly first-order electroweak phase transition.







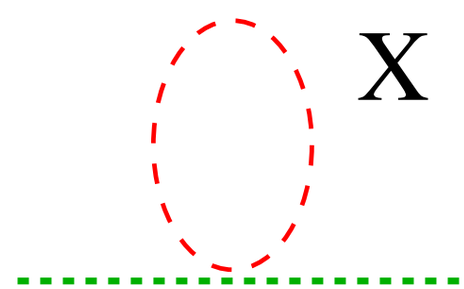
Testing Matter Creation

- A strongly first-order phase transition is needed for baryon creation in Electroweak Baryogenesis (EWBG).
- Standard Model: EW transition is second order.
- New physics is needed for EWBG.

  e.g. New scalars X [Carena et al, PLB380 (1996), 81; ...]

$$-\mathcal{L} \supset \lambda_X |X|^2 |H|^2$$

$\Delta V_H =$



$+ \ldots$

Can cause a strongly first-order EW phase transition.

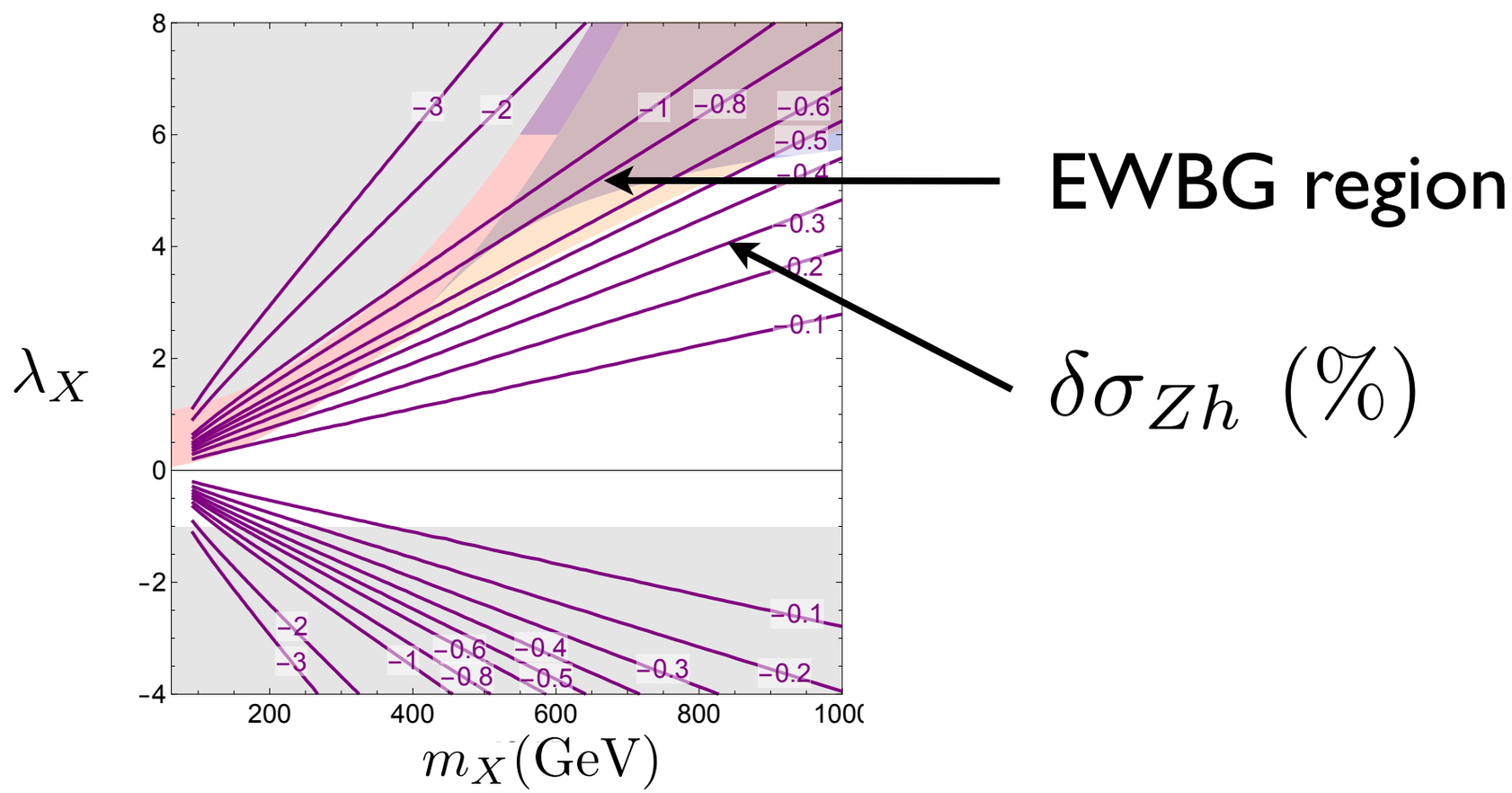
Testing Matter Creation

- Test EWBG by probing X:
  - Quantum numbers of (scalar) X can be anything.
  - X may be related to naturalness (e.g. SUSY stop).
  - EWBG only requires a large Higgs coupling.

- $SU(3)_c$ charged X is strongly constrained by LHC data.
  e.g. light scalar top superpartners in minimal SUSY
  Ruled out by Higgs rates [Cohen, DM, Pierce; Curtin, Jaiswal, Meade]
  Ruled out by direct stop searches [Krizka, Kumar, DM; Delgado et al.]
- Uncoloured X is largely unconstrained.

Testing Matter Creation

- Search strategy for X similar to neutral naturalness.
  - Direct searches via the Higgs coupling.
  - Indirect tests via precision Higgs couplings.
    e.g. Single real scalar X [Curtin, Meade, Yu JHEP 1411 (2014) 127]



Summary

- Naturalness is a strong motivator for new physics.
- It is essential to test the idea thoroughly.
  Precision Linear Colliders will be an essential tool.

- A Linear Collider will also be able to probe a wide range of New Physics I did not have time to cover:
  - dark matter (talk by P. Fox)
  - extended Higgs sectors (talk by S. Gori)
  - modified top couplings (talk by M. Peskin)
  - new gauge forces and more

Thank You! Merci!

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Extra Slides

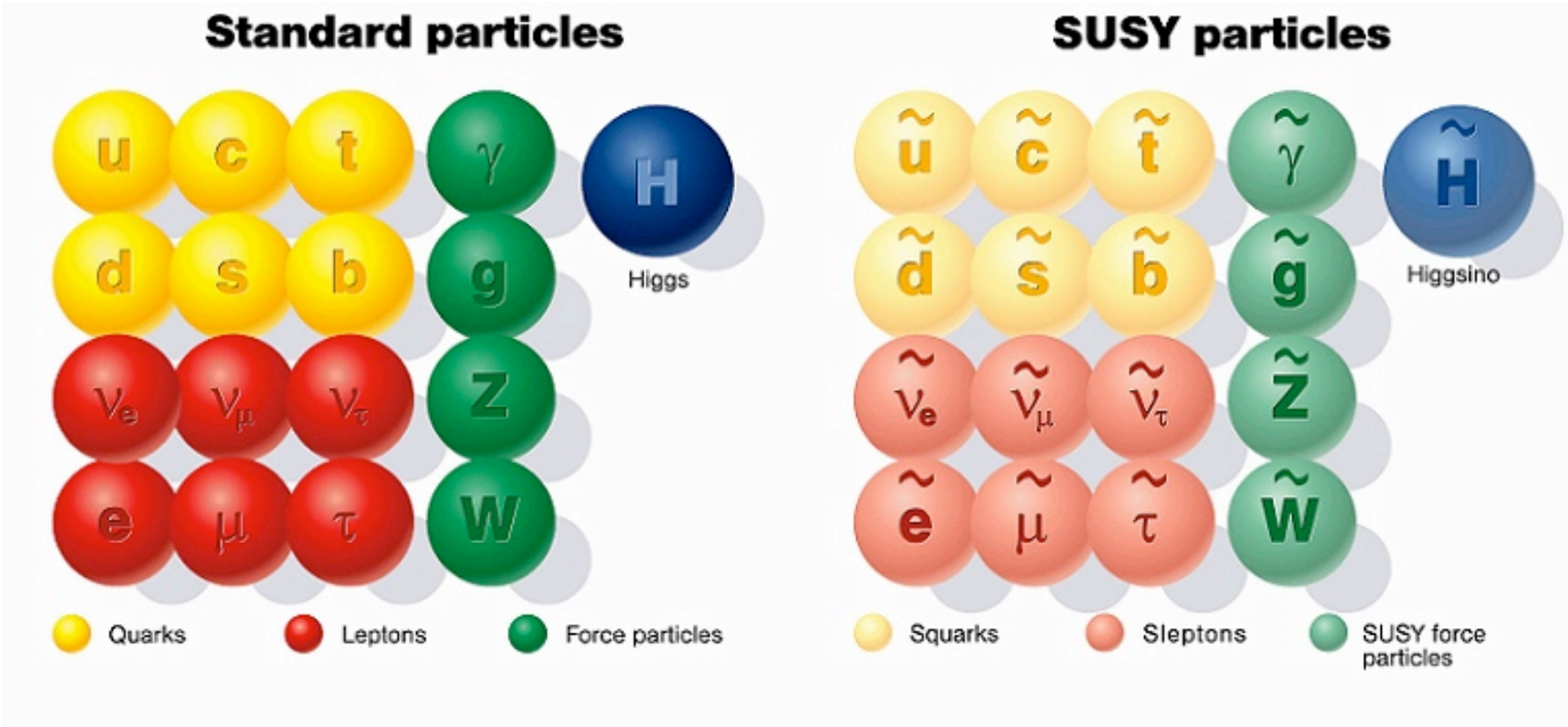
Search for Naturalness

[Mel Brooks el al, Spaceballs, 1987]

Supersymmetry

- Every SM particle has a superpartner:

$$
\begin{array}{rcl}
(s=1/2) & f \leftrightarrow \widetilde{f} & (s=0) \\
(s=1') & W^{\mu} \leftrightarrow \widetilde{W} & (s=1/2) \\
(s=0) & H \leftrightarrow \widetilde{H} & (s=1/2)
\end{array}
$$



Higgsino Discovery

- LHC limits:

$$m_{squark} \gtrsim 700-1500\,\mathrm{GeV} \qquad m_{gluino} \gtrsim 700-1500\,\mathrm{GeV}$$

$$m_{stop} \gtrsim 200-700\,\mathrm{GeV} \qquad m_{higgsino} \gtrsim 50-400\,\mathrm{GeV}$$

- SUSY naturalness:
  - higgsinos below 250 GeV
  - stops below 500 GeV
  - gluinos below 1500 GeV
  - light-flavour squarks below several TeV

Quadratic Sensitivity of Scalars

- Cutoff Λ dependence depends on regularization type and renormalization scheme.
- Consider instead the finite threshold correction from integrating out a massive state ψ with H coupling g_ψ:

$$\Delta M_H^2 \sim \pm \frac{g_\psi^2}{(4\pi)^2} M_\psi^2$$

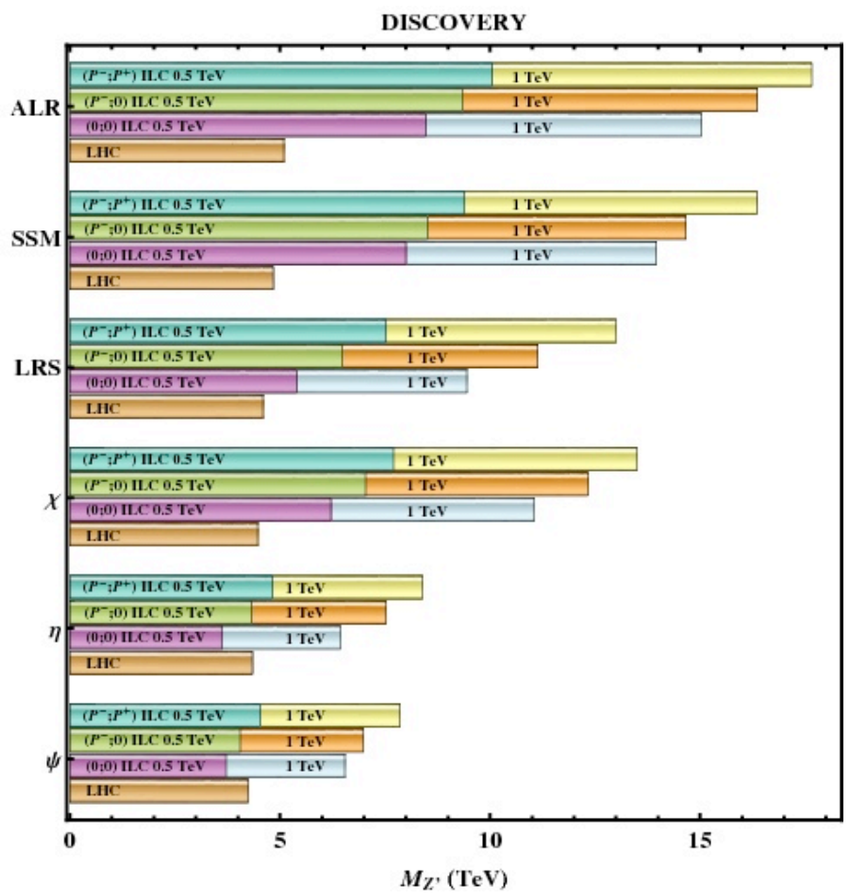
  Sign for fermion (boson).
- Any heavy new physics with moderate coupling can destabilize the Higgs potential.
- We expect this from quantum gravity, neutrino mass generation, grand unification, ...

Neutral Naturalness

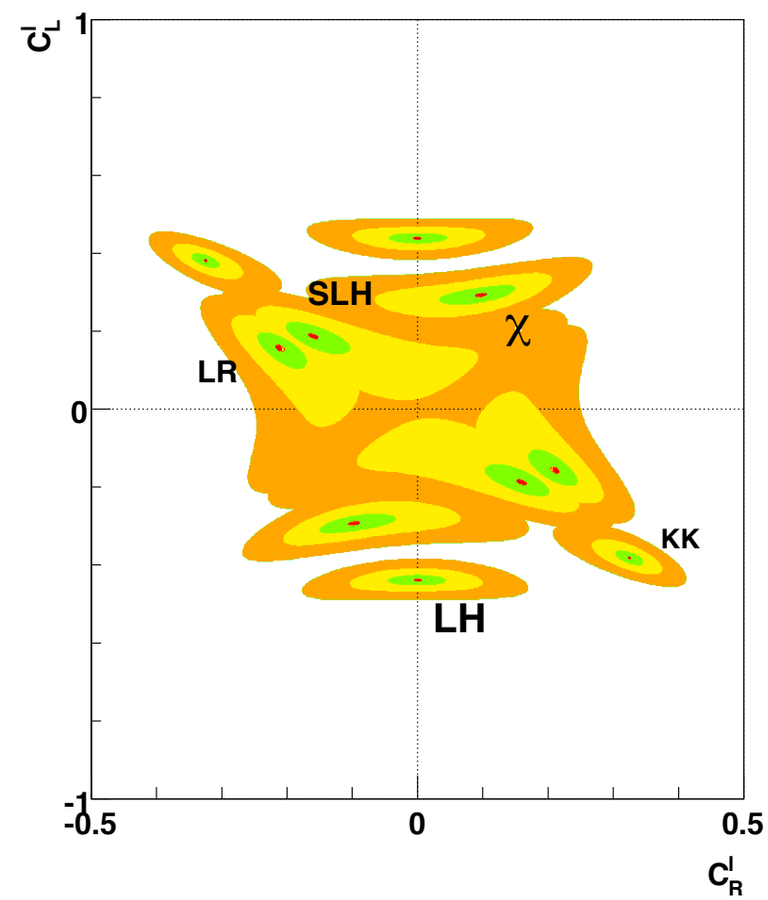
- SUSY enforces $N_X = 2N_c = 6,\ \lambda_X = y_t$.
- Folded SUSY:
  - F-stops are uncharged under $SU(3)_c$.
    They are charged under an exotic $SU(3)_{cX}$.
    $N_X = 2N_{cX} = 6, \quad \lambda_X \simeq y_t$
- More general realizations are possible.
- X partners may also:
  - carry electroweak charges
  - couple to new gauge forces
  - have spectacular, invisible, or displaced decays

New Gauge Forces

- New gauge forces can couple to SM states directly. e.g. Z' models
- Excellent indirect reach through $e^+e^- \to f\bar{f}$:



[Osland et al, EPJ C67 (2010) 191]



[Godfrey et al, hep-ph/0511335]

New Gauge Forces

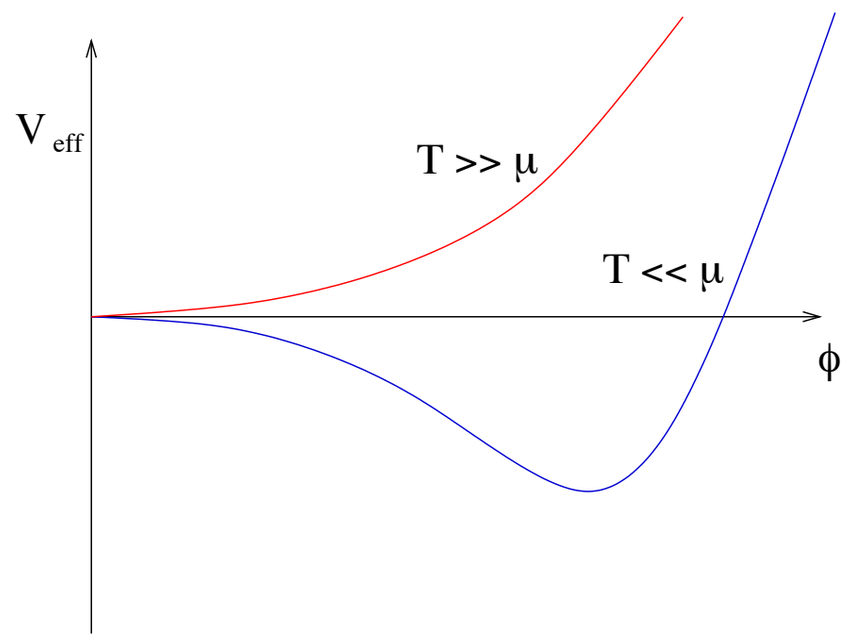
- New gauge forces might only couple indirectly to the Standard Model: dark (hidden) sectors.
  - Vector Portal: $\frac{\epsilon_Y}{2} B_{\mu\nu} X^{\mu\nu}$
    Test with precision electroweak, direct searches.
  - Higgs Portal: $\lambda_X |X|^2 |H|^2$
    (X charged under new force)
  - Neutrino Portal: $y_N L H N$

- May connect to dark matter or naturalness.

EWBG Step 1: Bubbles

- The effective Higgs potential is modified in the early Universe by thermal effects at temperature T:

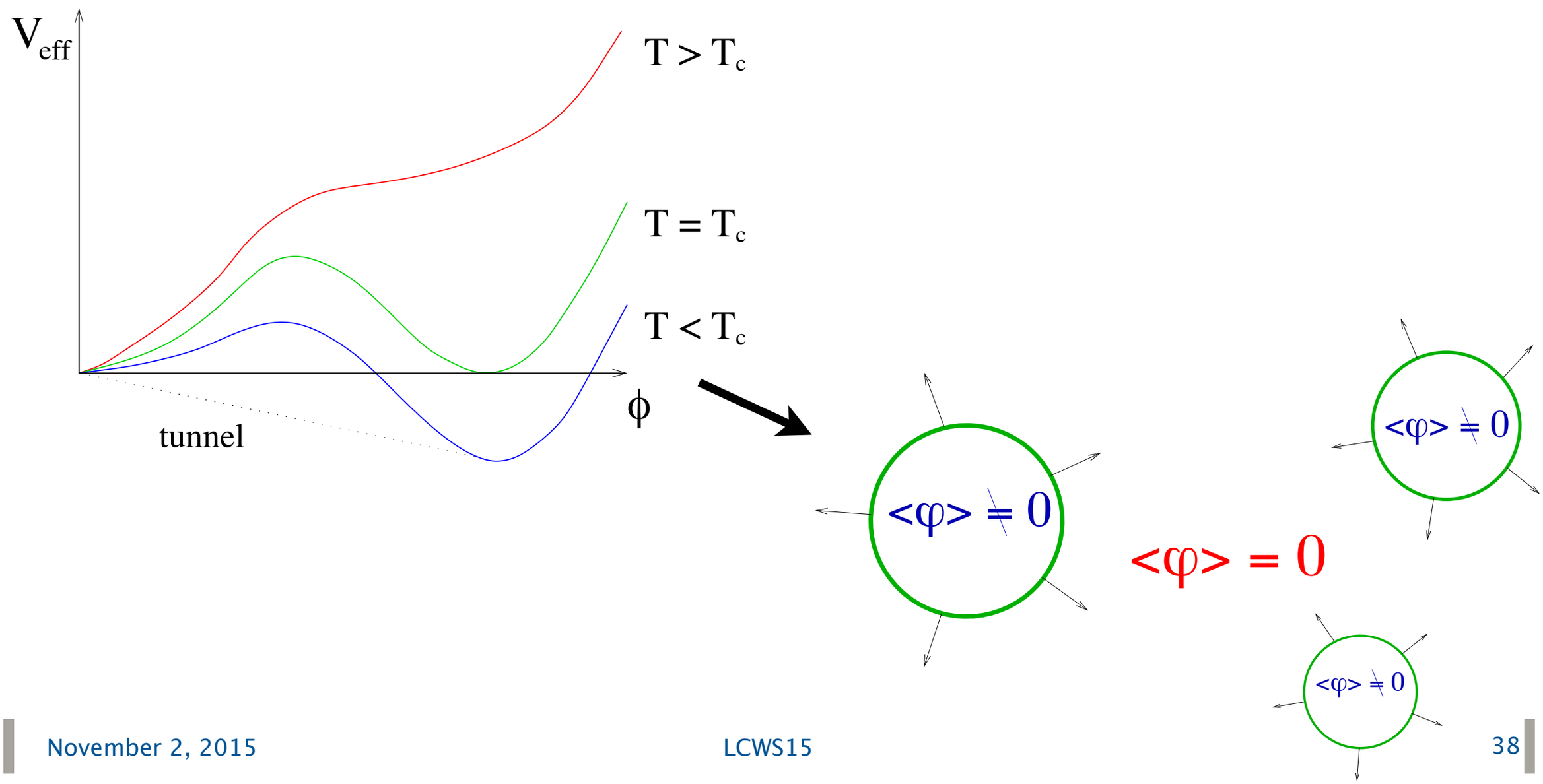
$$V(H,T) \simeq -\frac{1}{2}(\mu^2 - \zeta T^2)H^2 - \gamma T H^3 + \frac{\lambda}{4}H^4$$



- High T: $\langle H \rangle = 0$
- Low T: $\langle H \rangle = \sqrt{(\mu^2 - \zeta T^2)/\lambda} \neq 0$

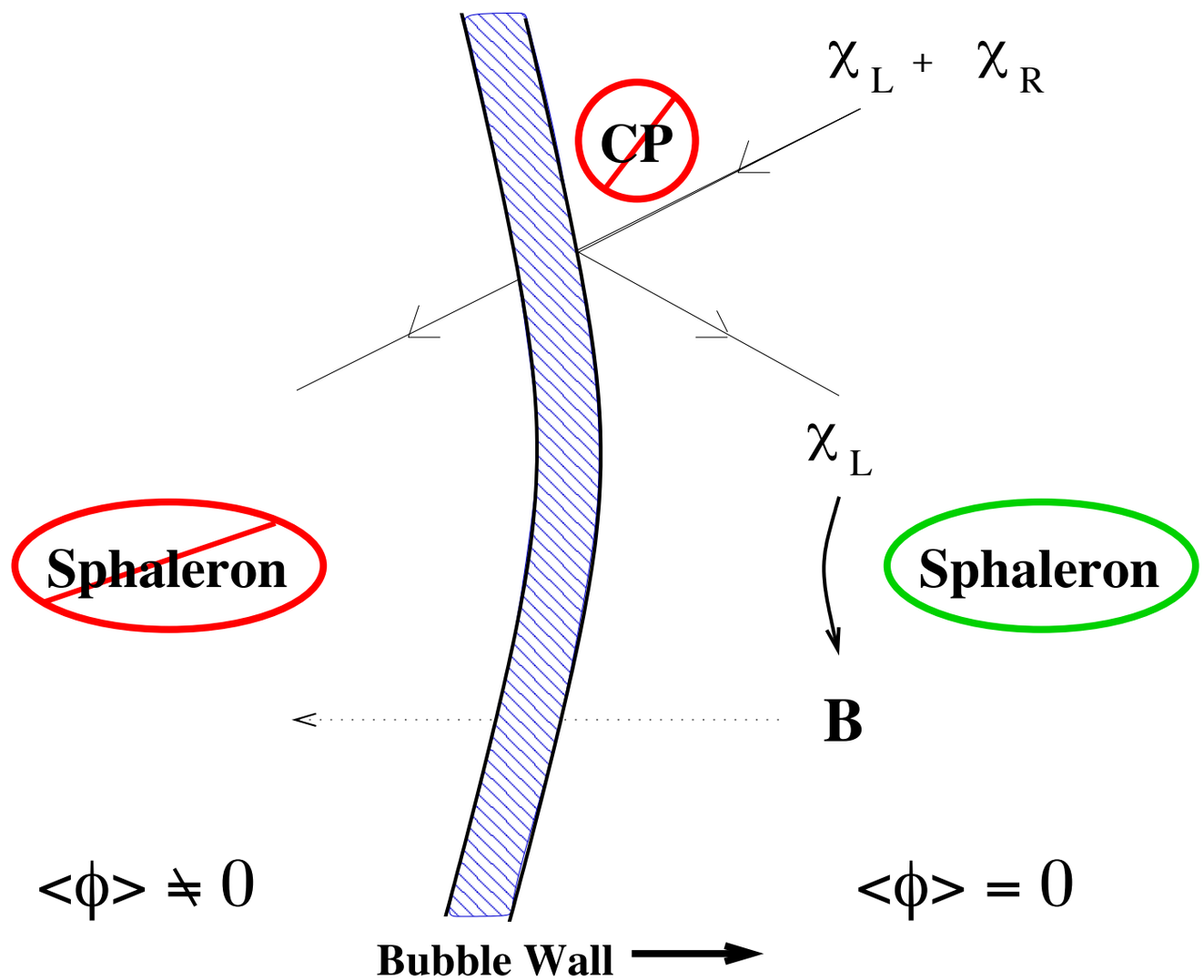
EWBG Step 1: Bubbles

- First-order phase transition.
  Bubbles of broken phase are nucleated at T < Tc.



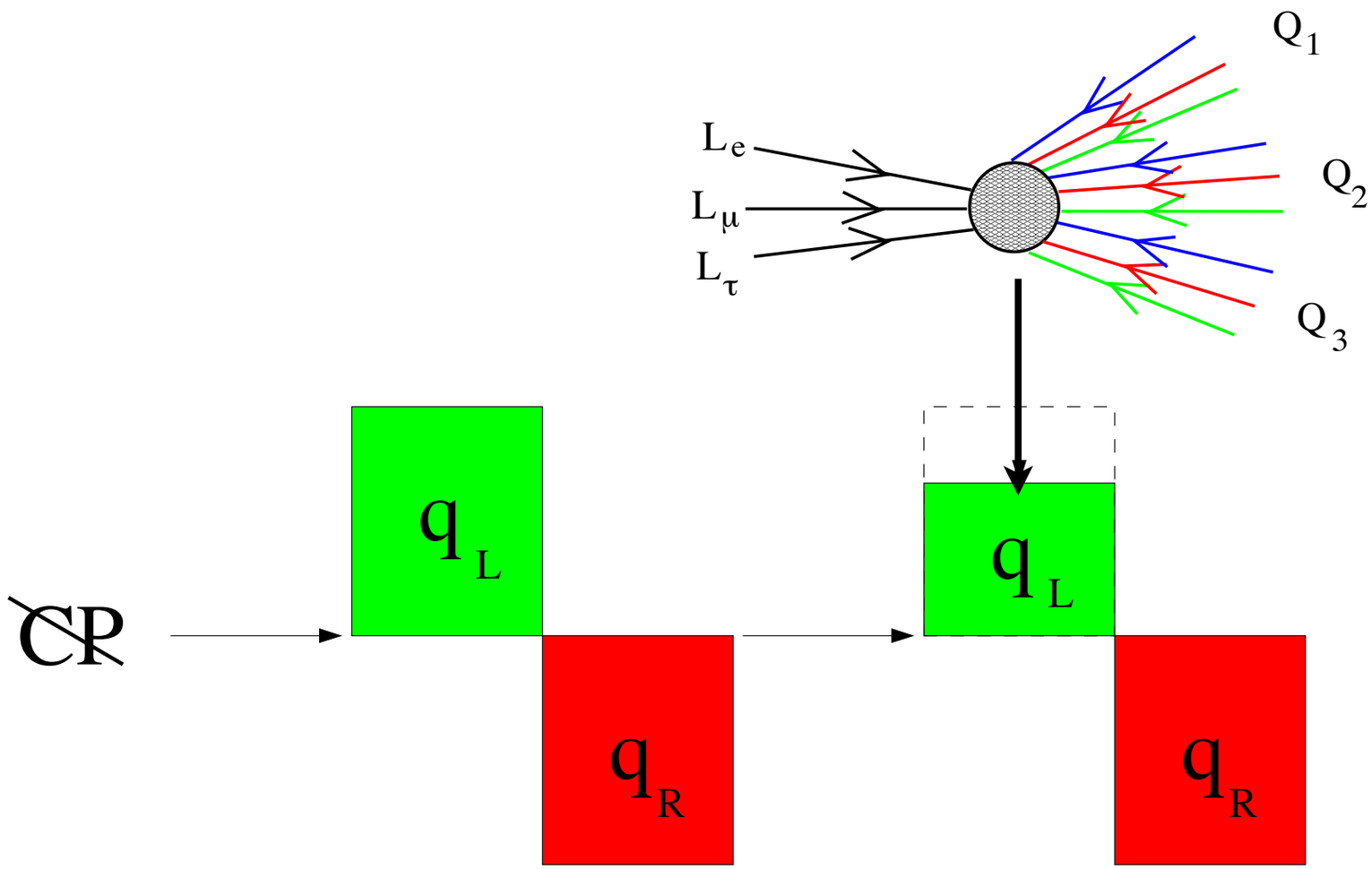
EWBG Step 2: CP Asymmetries

- Particles in the plasma scatter off the bubbles. C+CP violation can lead to charge asymmetries.



EWBG Step 3: Sphalerons

- Sphaleron transitions are active outside the bubbles. Charge asymmetries bias them to make more baryons.



- Baryons are swept up by bubbles where they are stable.