Electroweak Baryogenesis and Higgs Signatures

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(SLAC)
with Aaron Pierce

arXiv:1109.2604

with David Morrissey and Aaron Pierce

arXiv:1203.2924

DPF 2013
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Baryogenesis

- It is well established that there is a baryon asymmetry.

$$\frac{n_b - \overline{n}_b}{n_\gamma} \simeq 6 \times 10^{-10}$$

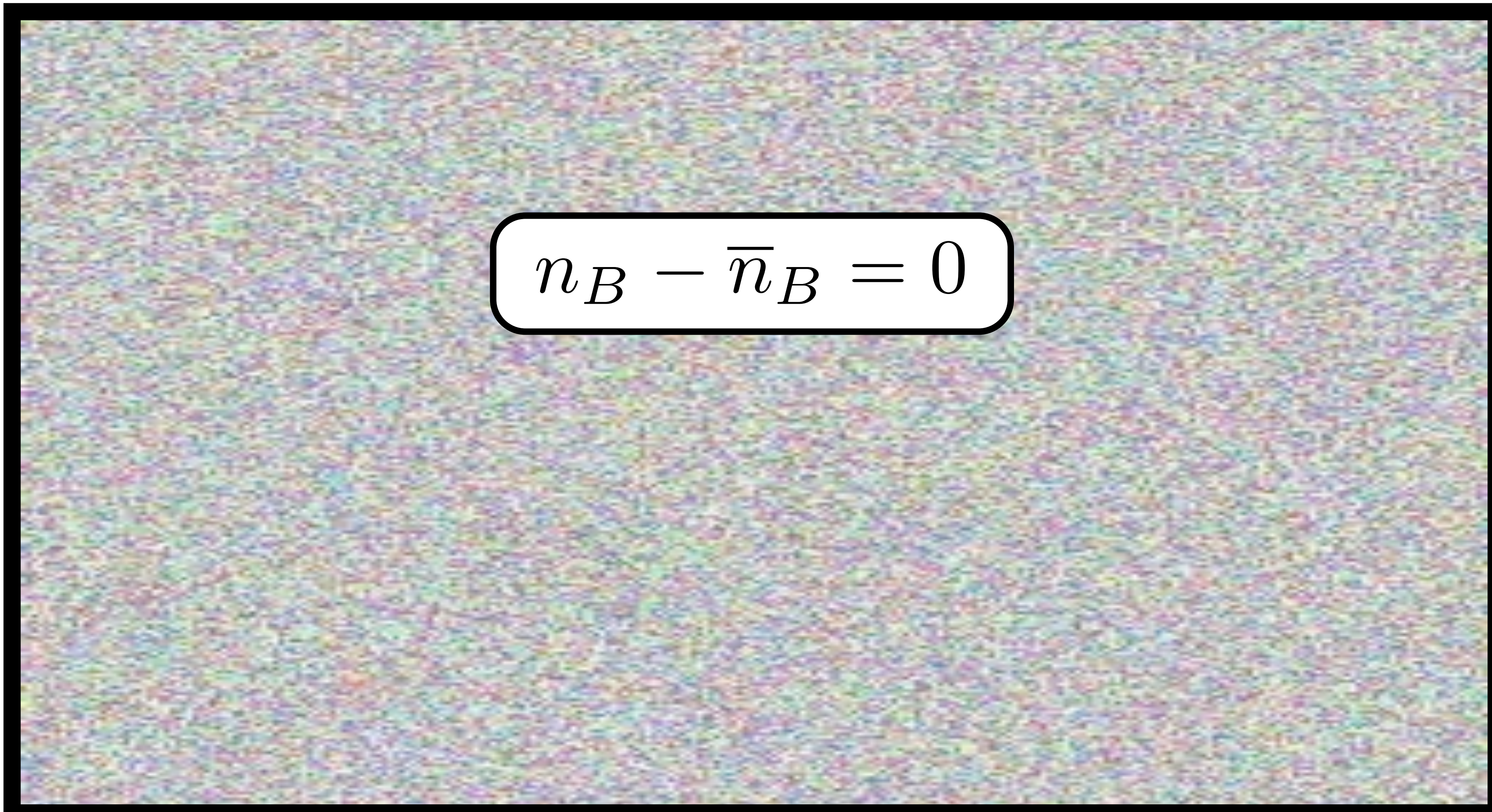
WMAP7 [arXiv:1001.4538]

- Models which generate this asymmetry must satisfy the Sakharov conditions: Sakharov [1967]
  i) Baryon number violation;
  ii) CP violation;
  iii) Departure from equilibrium.
- Many paradigms for baryogenesis:
  - Leptogenesis - lepton number from right handed neutrino decays;
  - Affleck-Dine - baryon number from the “decay” of flat directions;
  - Dark-o-genesis - simultaneous generation of baryon and dark matter asymmetries;
  - Electroweak Baryogenesis - baryon number generated at the electroweak phase transition.

Electroweak Baryogenesis

For a review see
Trodden [arXiv:hep-ph/9803479]

The Universe is a hot baryon symmetric thermal bath with $\langle H \rangle = 0$.



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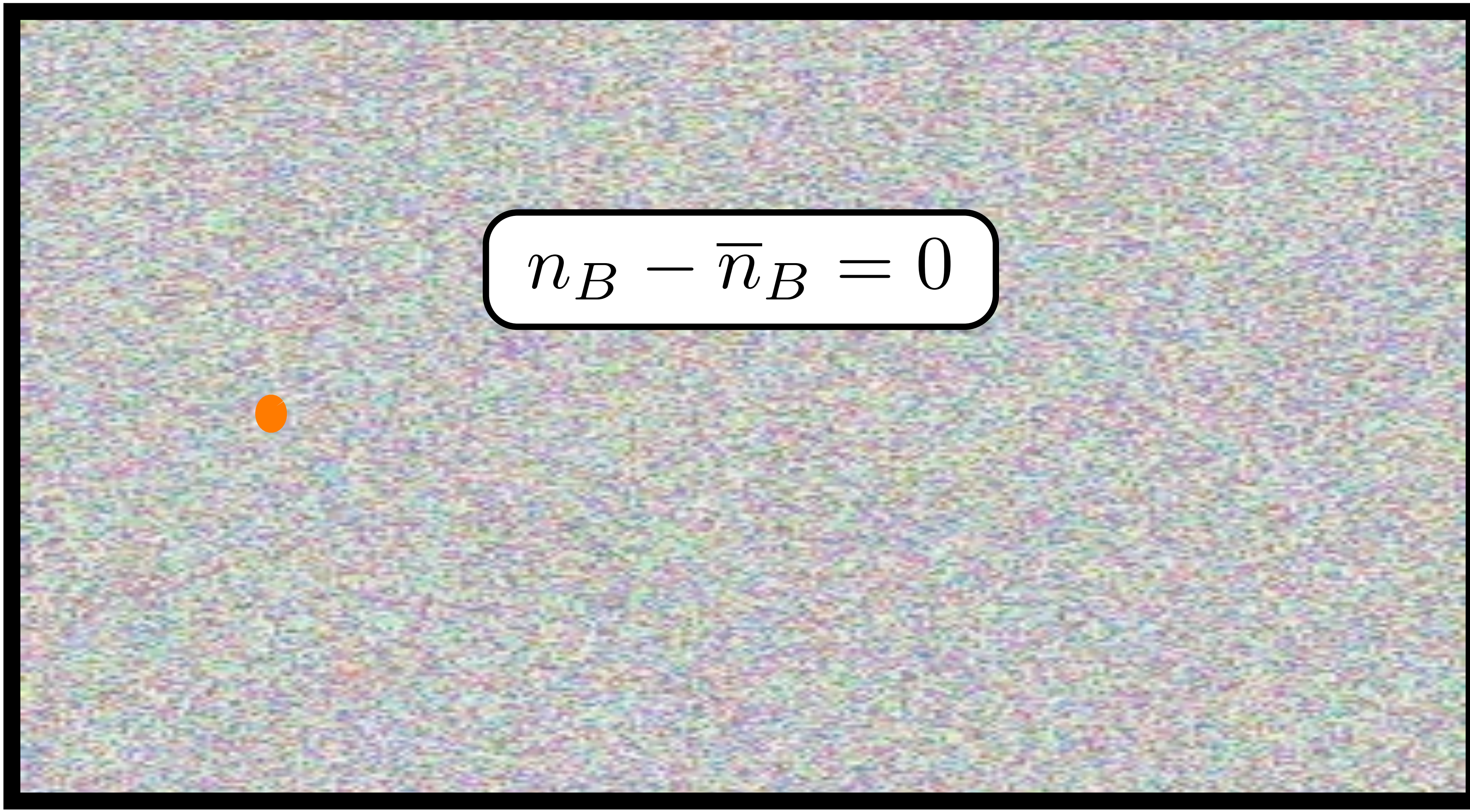
At the critical temperature T_C, bubbles of $\langle H \rangle \neq 0$ begin to percolate.



Electroweak Baryogenesis

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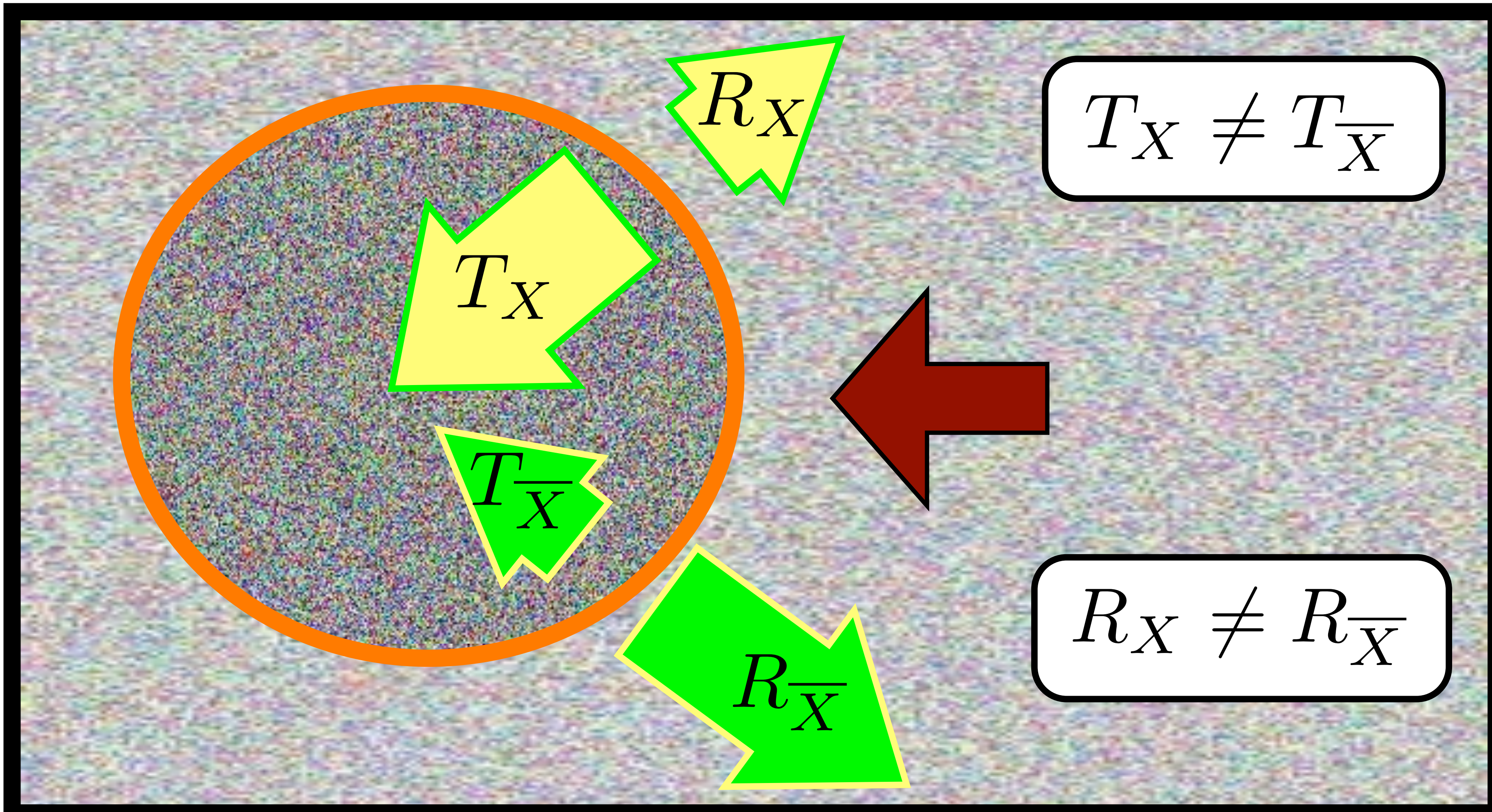
Scatterings with the (CP violating) bubble wall lead to non-zero, opposite chemical potentials inside and outside the bubbles.



Electroweak Baryogenesis

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Outside the bubbles: Electroweak sphalerons convert this charge asymmetry to a baryon asymmetry.

Electroweak Baryogenesis

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Inside the bubbles: Electroweak sphaleron rates are exponentially suppressed.

$$\Gamma_S \sim \mathrm{Exp}(-\phi_C/T_C)$$

$$\Gamma_S \sim T^4$$

Electroweak Baryogenesis

For a review see Trodden [arXiv:hep-ph/9803479]

A net baryon asymmetry is generated outside the bubbles.

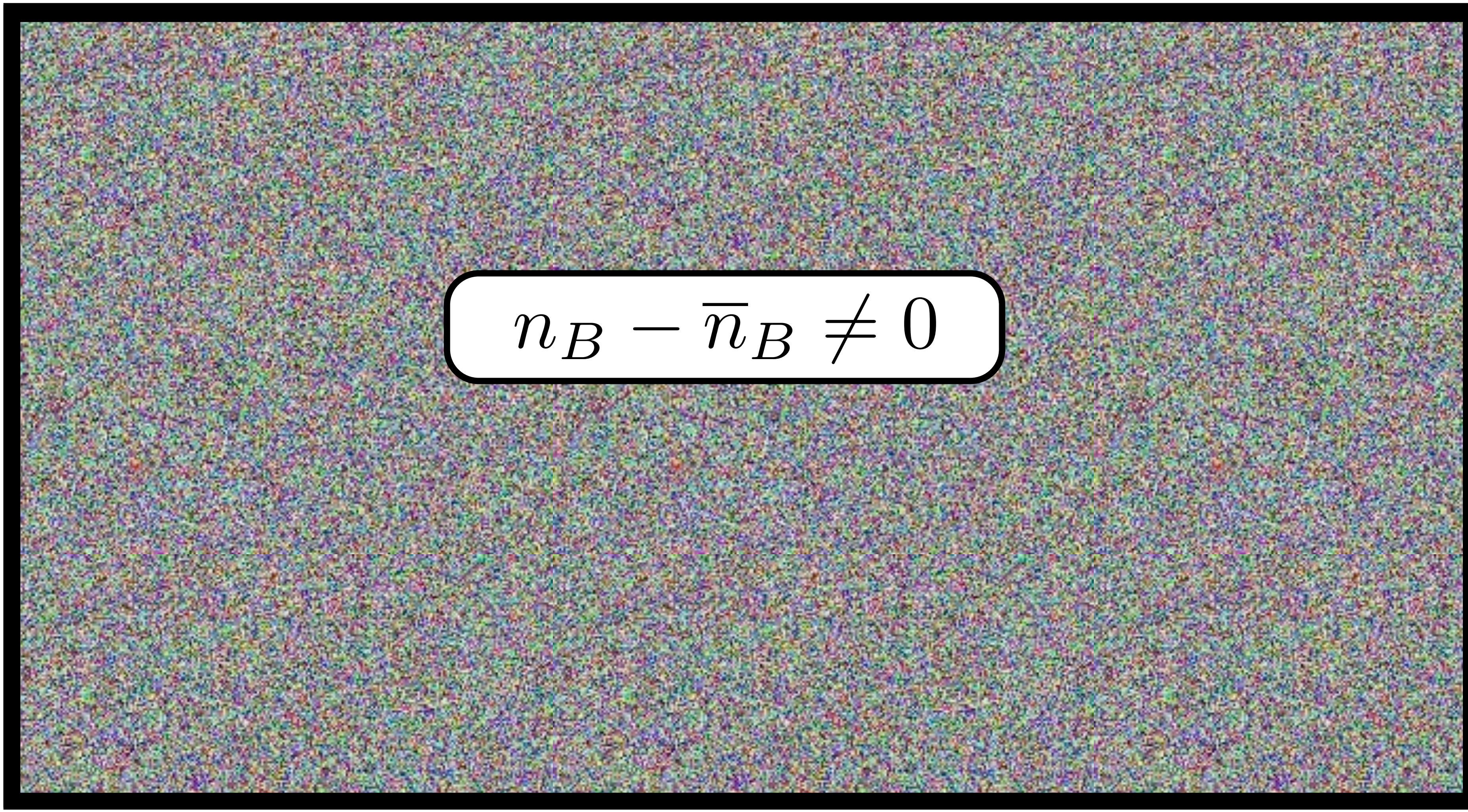
$$\Delta\left(n_B - \overline{n}_B\right) = 0$$

$$\Delta\left(n_B - \overline{n}_B\right) \neq 0$$

Electroweak Baryogenesis

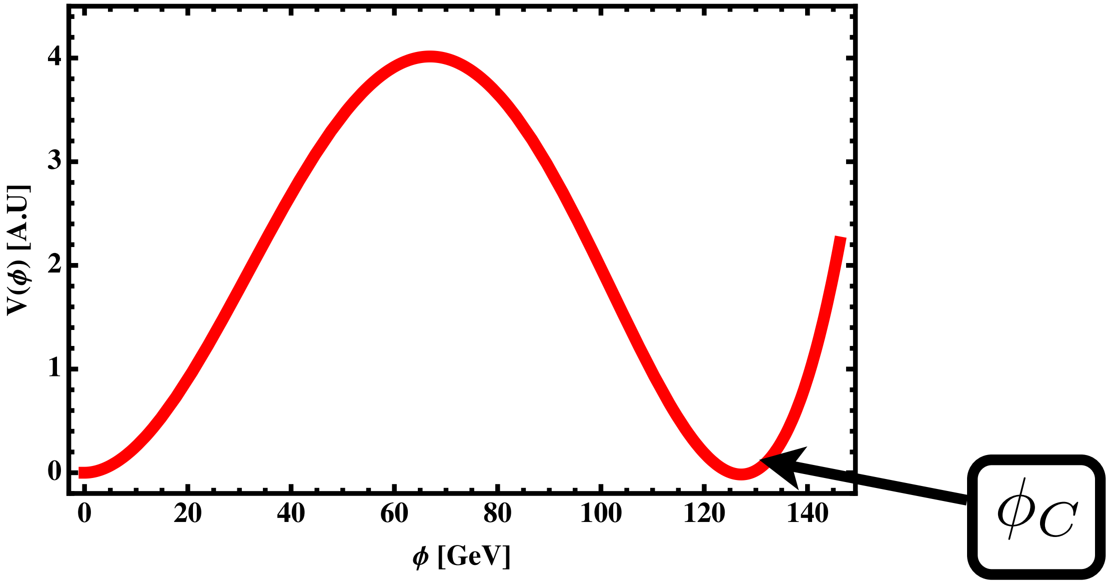
For a review see Trodden [arXiv:hep-ph/9803479]

The bubbles of broken phase overtake the Universe and the baryon asymmetry is frozen in.



The Electroweak Phase Transition

- A 1st order phase transition is characterized by the existence of a non-zero local minimum for the finite temperature Higgs potential.
- The temperature when this minimum is degenerate with the origin is the critical temperature T_C.



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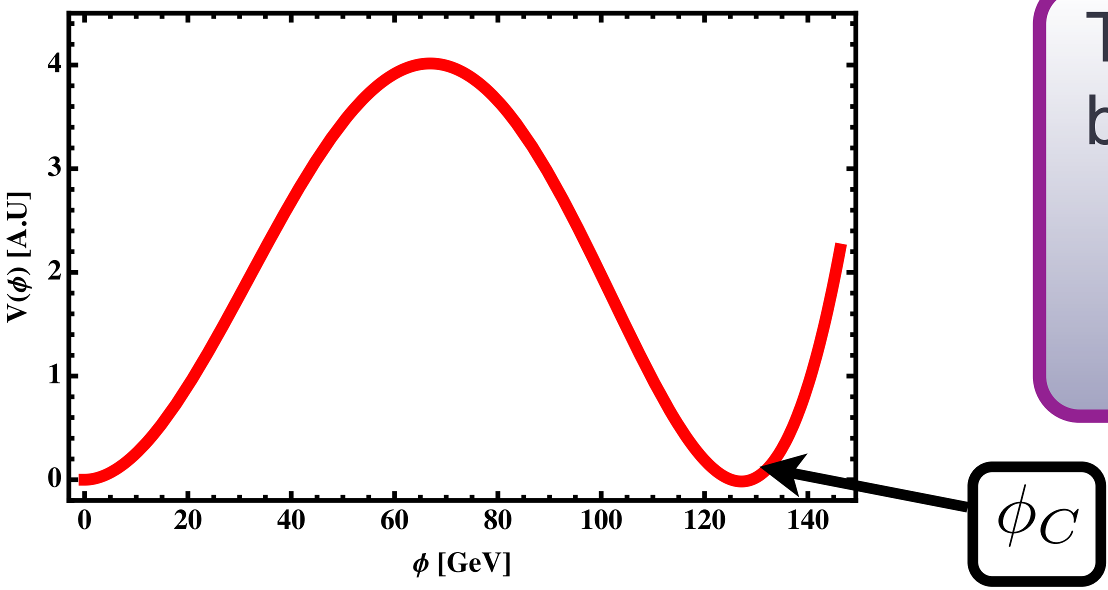

To realize electroweak baryogenesis:

$$\frac{\phi_C}{T_C} \gtrsim 0.9$$

Outline

I. Review: Finite Temperature Field Theory
II. New Colored Scalars
III. Correlating the EWPT with Higgs Signatures
IV. Applications to the MSSM
V. Collider Signatures
VI. Conclusions

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- Note: this talk will not address the new source of CP violation required for successful electroweak baryogenesis, e.g. in SUSY models, a non-zero $\arg(\mu\, M_2)$.

Review

Finite Temperature Field Theory

Imaginary Time and Matsubara Modes

- The Coleman-Weinberg potential at finite temperature:
  - Time is imaginary and periodic;
  - $E \to 2\pi i\, n\, T$ with integrals over energy replaced by sums.

For a nice review, see Quiros [arXiv:hep-ph/9901312]

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- The Higgs field coupled to a *scalar*

$$V(m,T) \supset \frac{1}{24} T^2 m^2 - \frac{1}{12\,\pi} T \left(m^2\right)^{3/2} - \frac{1}{64\,\pi^2} m^4 \log\left(\frac{\mu_{\text{ren}}^2}{a_b\, T^2}\right)$$

- The Higgs field coupled to a *fermion*

$$V(m,T) \supset \frac{1}{24} T^2 m^2 + \frac{1}{32\,\pi^2} m^4 \log\left(\frac{\mu_{\text{ren}}^2}{a_f\, T^2}\right)$$

$$m^2 \equiv m_{\text{bare}}^2 + Q/2\,\phi^2$$

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NEW SCALARS = NEW CUBIC TERM!

$$m^2 \equiv m^2_{\rm bare} + Q/2\, \phi^2$$

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Power Counting in T

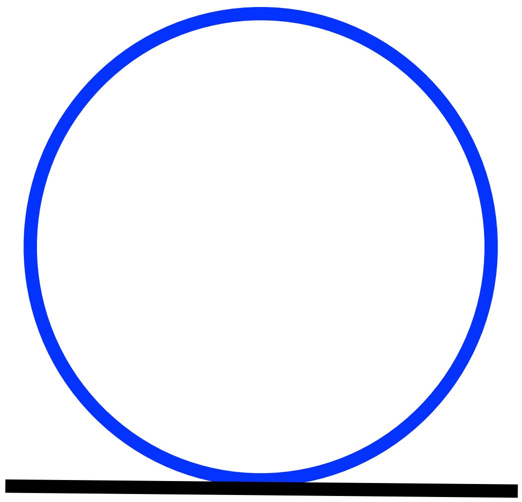
- Rescale all loop momenta and masses by T.
- A diagram with degree of divergence D goes as $T^D f(m/T)$.
- For diagrams
  - involving zero modes;
  - with IR divergences in the limit $M/T \to 0$,

  the only factor of T comes from the $\mathrm{d}E$ loop integration measure.

Weinberg [1974]; Fendley [1987]; Espinosa, Quiros, Zwirner [1992]

A Problematic Class of Diagrams

$$V = \frac{1}{2} M^2 \phi^2 + \frac{1}{4!} \lambda \phi^4$$



$$\sim \lambda T^2$$

Blue line = zero mode only.

Black line = sum over all modes.

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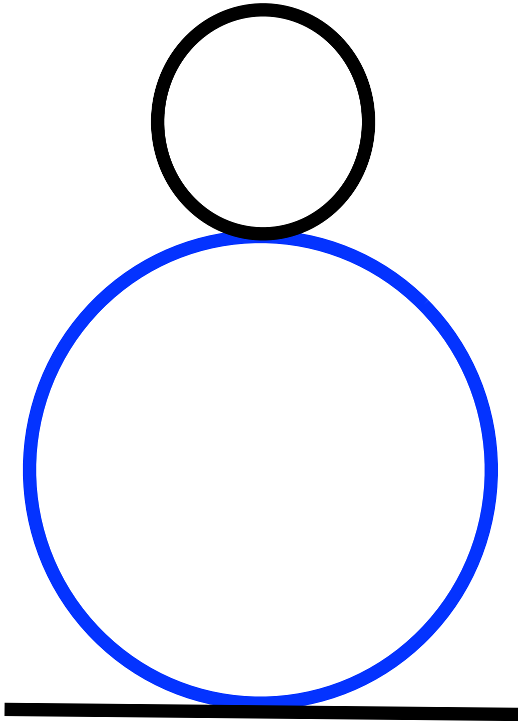

$$\sim \lambda T M \left(\frac{\lambda T^2}{M^2} \right)$$

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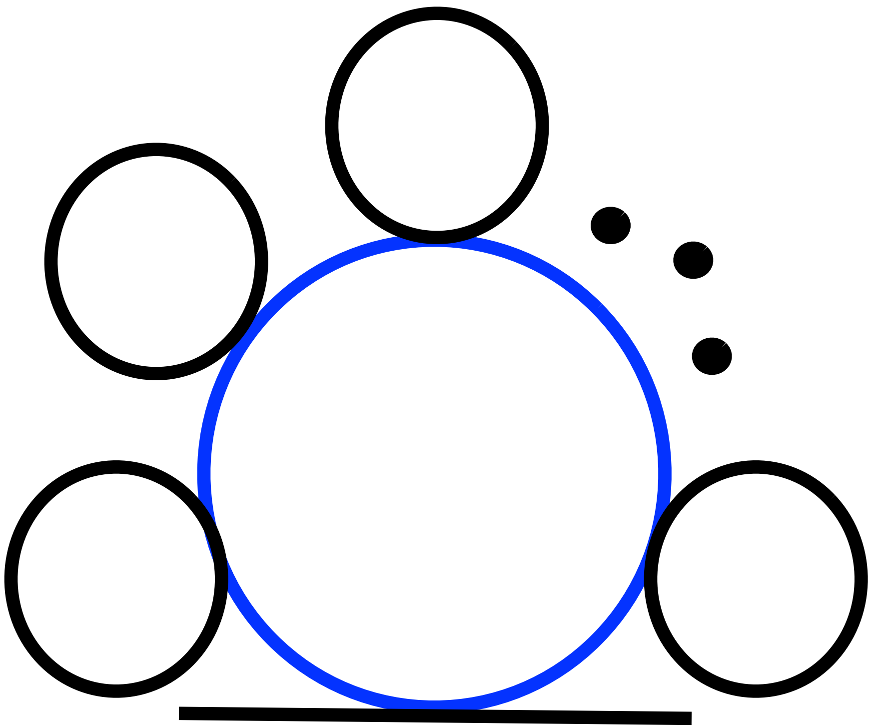

$$\sim \lambda T M \left(\frac{\lambda T^2}{M^2}\right)^n$$

Blue line = zero mode only.

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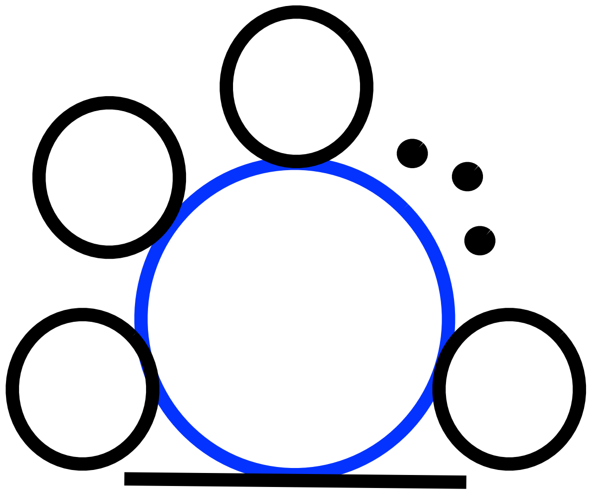
Daisy Resummation

A power of $\lambda T^2/M^2$ for each quadratically divergent bubble.



$$\sim \lambda T M \left(\frac{\lambda T^2}{M^2}\right)^n$$

- The critical temperature is given by $T_C \sim M/\sqrt{\lambda}$.
- Each additional bubble contributes

$$\lambda T_C^2/M^2 = \lambda(M^2/\lambda)/M^2 = 1$$

- No parametric suppression: we must resum!

Resummed Cubic Terms

- At 1-loop daisy resummation causes

$$V(m,T) \supset -\frac{1}{12\,\pi} T \left(m^2\right)^{3/2} \to -\frac{1}{12\,\pi} T \left(\overline{m}^2\right)^{3/2}$$

  - where $\overline{m}^2 \equiv m^2_{\text{bare}} + Q/2\,\phi^2 + \Pi(T)$

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- Why do we care?

$$m^2_{\text{bare}} + \Pi(T) \gg Q/2\,\phi^2 \Rightarrow T\left(\overline{m}^2\right)^{3/2} \simeq \left(3/4\,Q\,T\sqrt{m^2_{\text{bare}} + \Pi(T)}\right)\phi^2$$

  - while

$$m^2_{\text{bare}} + \Pi(T) \ll Q/2\,\phi^2 \Rightarrow T\left(\overline{m}^2\right)^{3/2} \simeq T\left(Q/2\right)^{3/2}\phi^3$$

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- We see that we only get a “cubic” term when $m^2_{\text{bare}} \simeq -\Pi(T)$
- This is how one “opens the baryogenesis window” of the MSSM.

Carena, Quiros, Wagner [arXiv:hep-ph/9603420]

Charge-color Breaking Vacuua

- We will be analyzing models which have negative values of the bare mass for a colored scalar.
- This opens the possibility of ending up in a charge color breaking (CCB) vacuum.
- We compute the 2-loop finite temperature potential in the CCB direction.
- Then we can check that $T_C^{\phi} > T_C^{X}$.
  - We also apply a correction to this condition due to the fact that the critical temperature is not exactly equal to the bubble nucleation temperature.

Carena, Nardini, Quiros, Wagner [arXiv:0806.4297]

New Colored Scalars

The Model

- We will study a model where we couple a new scalar, X to the Higgs boson through the "Higgs portal."

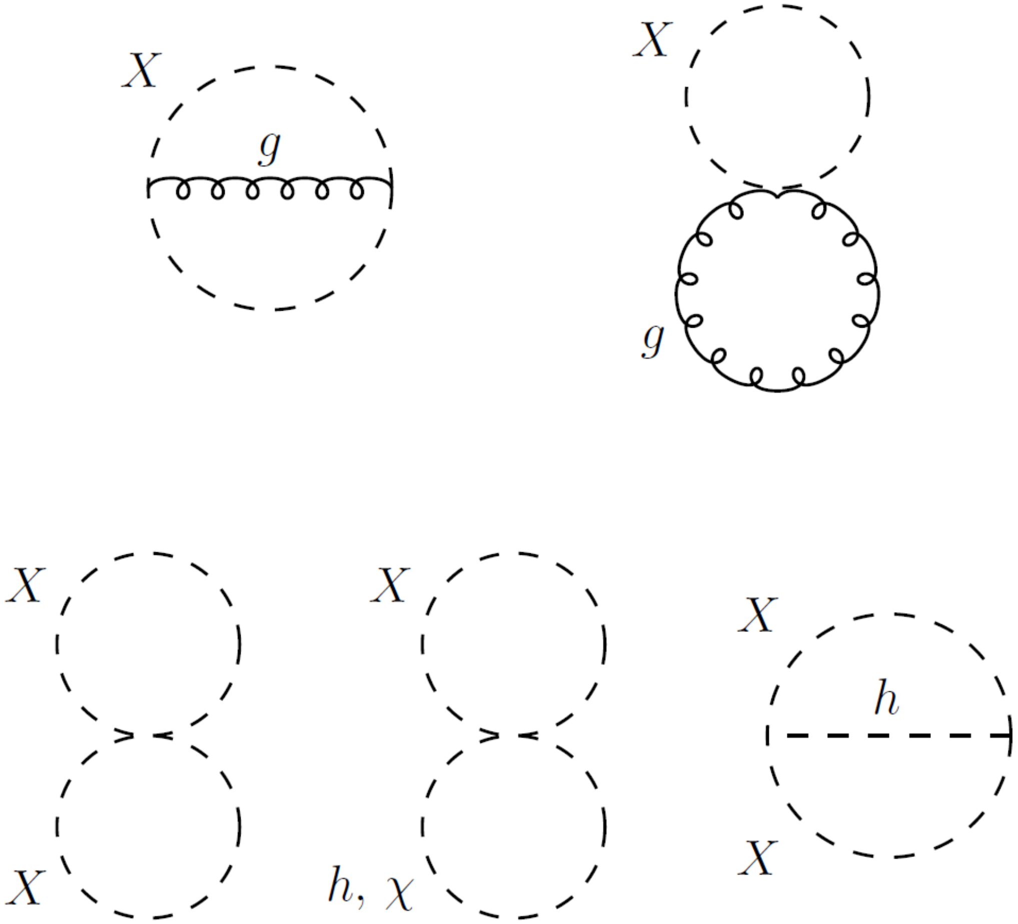
$$
\begin{aligned}
-\mathcal{L} \quad &\supset \quad M_X^2 |X|^2 + \frac{K}{6}|X|^4 + Q|X|^2|H|^2 \\
&\supset \quad M_X^2 |X|^2 + \frac{K}{6}|X|^4 + \frac{1}{2}Q\left(v^2 + 2\,v\,h + h^2\right)|X|^2
\end{aligned}
$$

- Then the physical mass of X is given by

$$
M_X^{\text{phys}} = \sqrt{M_X^2 + \frac{Q}{2}v^2}
$$

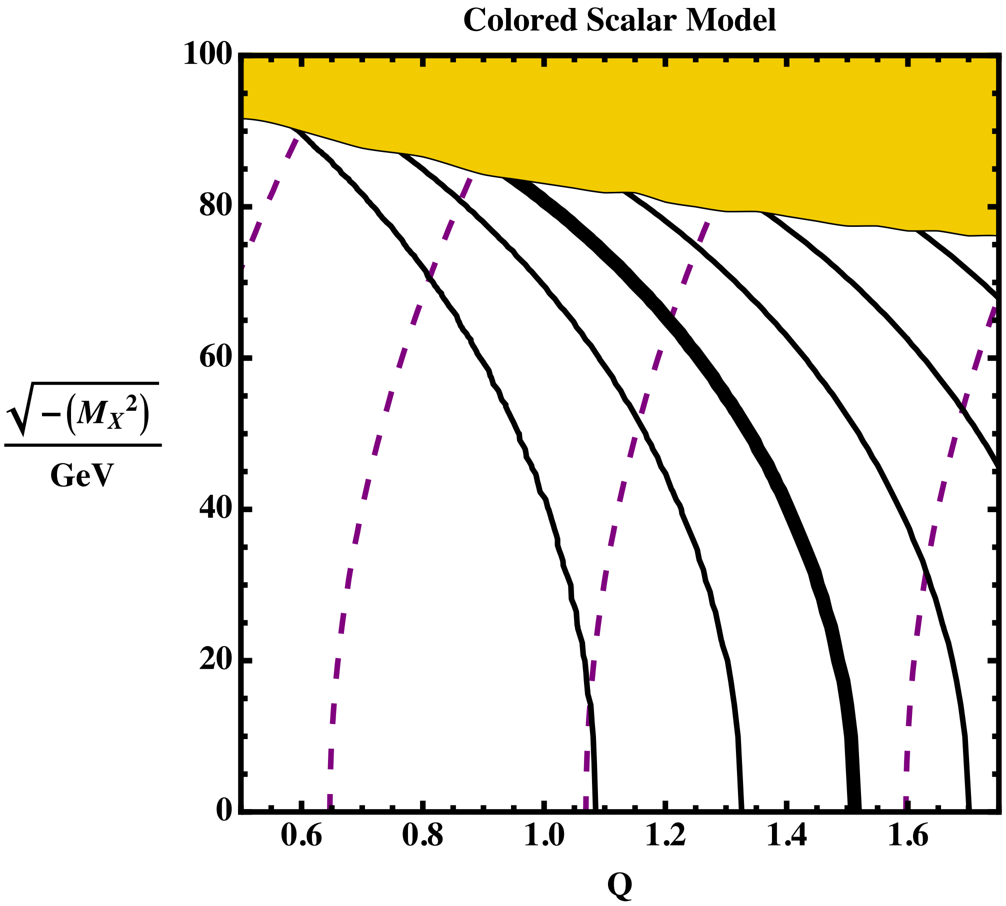
- We will usually take X to be a fundamental under $SU(3)$.
- This is similar to the "light stop effective theory" limit of the MSSM. Carena, Nardini, Quiros, Wagner [arXiv:0806.4297]

Two Loop Contributions



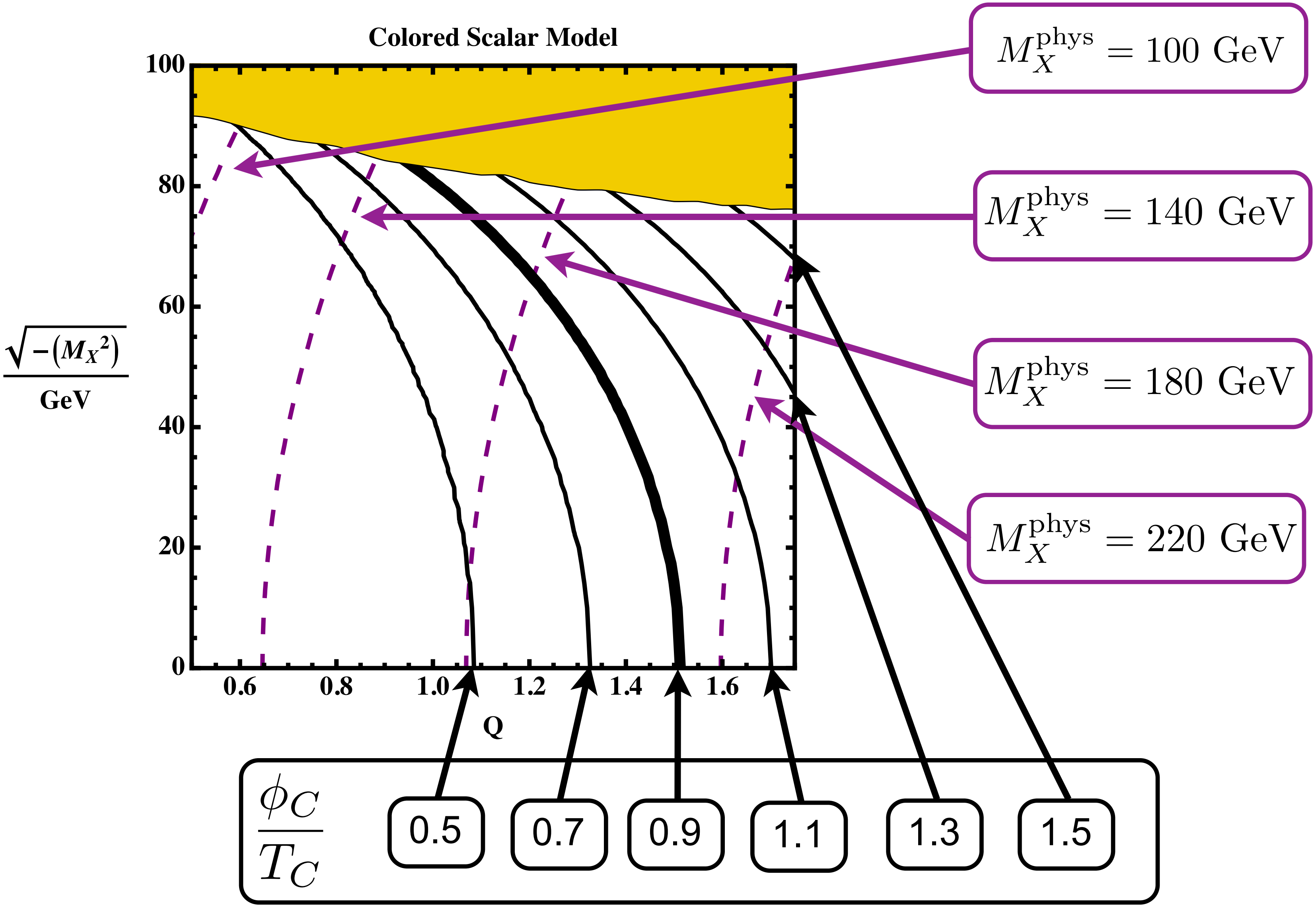
Espinosa [arXiv:hep-ph/9604320]; Carena, Quiros, Wagner [arXiv:hep-ph/9710401]; Carena, Nardini, Quiros, Wagner [arXiv:0806.4297]

EWPT with Colored Scalars



- The other parameters are taken to be $K = 1.6,\ m_h = 115\ \text{GeV}$.

EWPT with Colored Scalars



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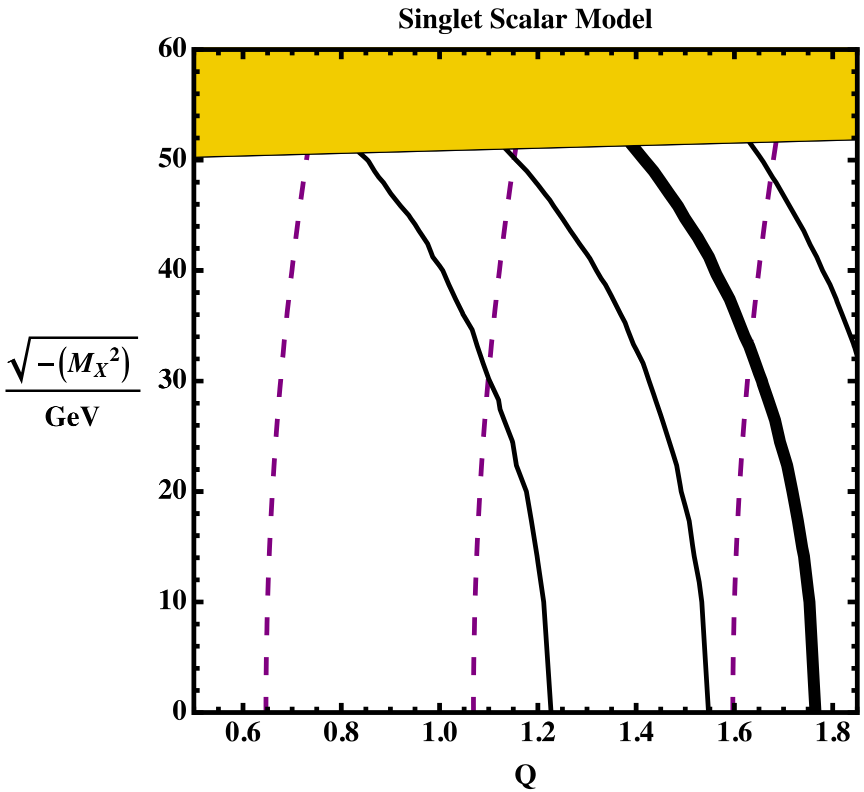
- For 6 singlet scalars:



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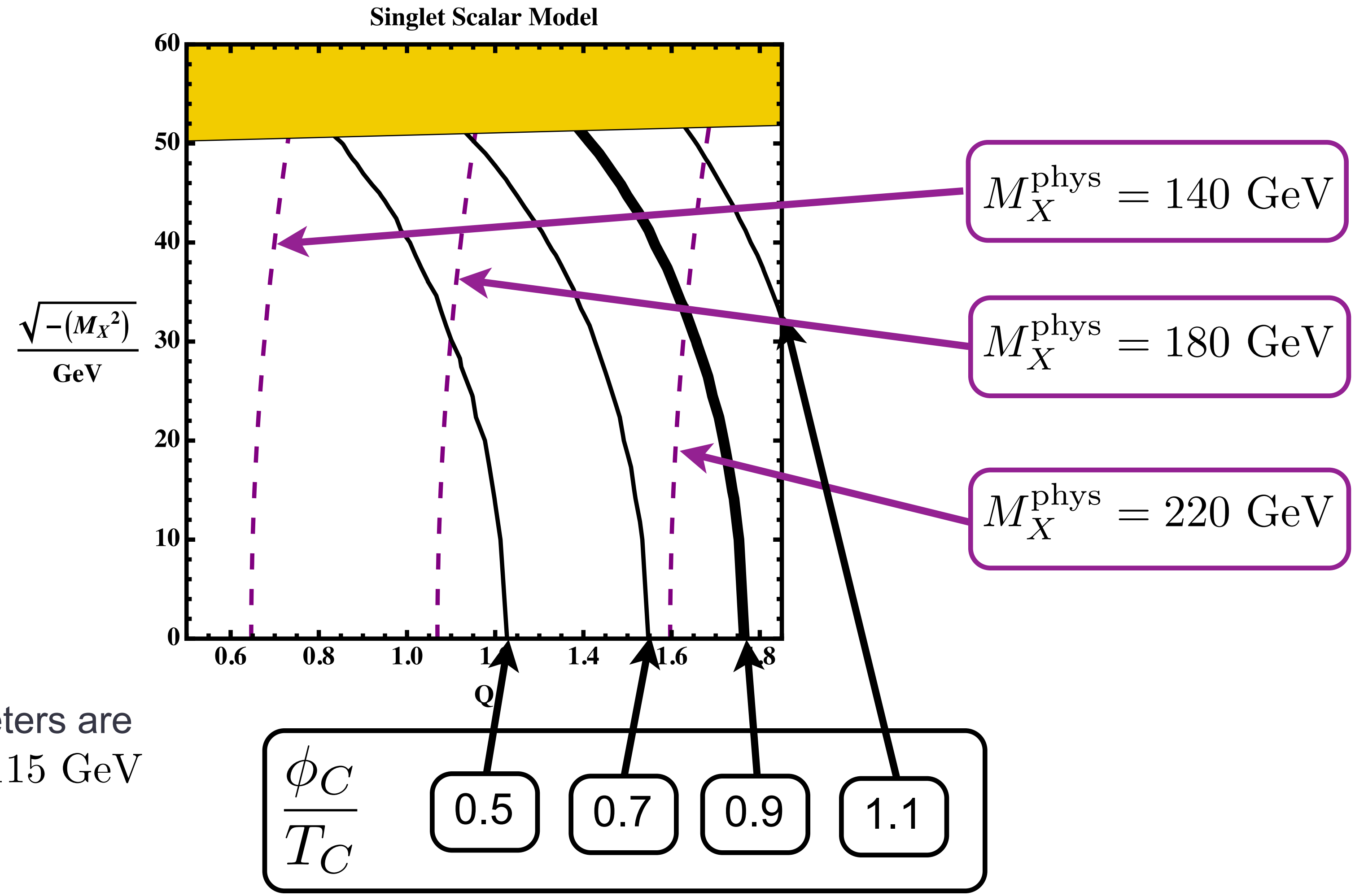

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The Punchline

- Two-loop corrections to ϕ_C/T_C can be very important.

  Dine, Leigh, Huet, Linde, Linde [arXiv:hep-ph/9203201]

- Colored scalars are "better" than singlet scalars:
  - i) Automatically get 6 degrees of freedom;
  - ii) Larger 2-loop enhancements due to loops involving gluons;
  - iii) *These models make observable predictions!*

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- Models with
  - a *single* vacuum expectation value;
  - a coupling to colored scalars via the Higgs portal;

  can result in a strong enough EWPT for electroweak baryogenesis.
- (Note that this is not the only way to get a strong EWPT.)
- The rest of this talk will be devoted to the resultant phenomenology of this model.

Correlating the EWPT with Higgs Signatures

Gluon Fusion and Di-photon Decays

- We will take ratios of our production and decay rates to the Standard Model values.
- NLO effects mostly cancel for $m_i > m_h/2$ since the relevant vertex is approximately point like.
  - Gluon fusion: $h\, G^a_{\mu\nu} G^{a,\,\mu\nu}$
  - Di-photon decay: $h\, F_{\mu\nu} F^{\mu\nu}$
- Therefore, we will only consider leading order effects.

Djouadi, Spira [arXiv:hep-ph/9912476];
Harlander, Steinhauser [arXiv:hep-ph/0307346, hep-ph/0308210, hep-ph/0409010];
Anastasiou, Beerli, Daleo [arXiv:0803.3065]

Gluon Fusion and Di-photon Decays

- Gluon fusion is dominated by the top. For $Q > 0$ there is constructive interference between the top and the X.

$$\Gamma_{gg} = \frac{\alpha_s^2}{128\pi^3}\frac{m_h^3}{m_W^2}\left|\sum_i g_i T_2^i\, F_{s_i}(\tau_i)\right|^2 \qquad g_X = \frac{2}{g}\left(\frac{m_W}{m_{\phi_i}}\right)^2 Q$$

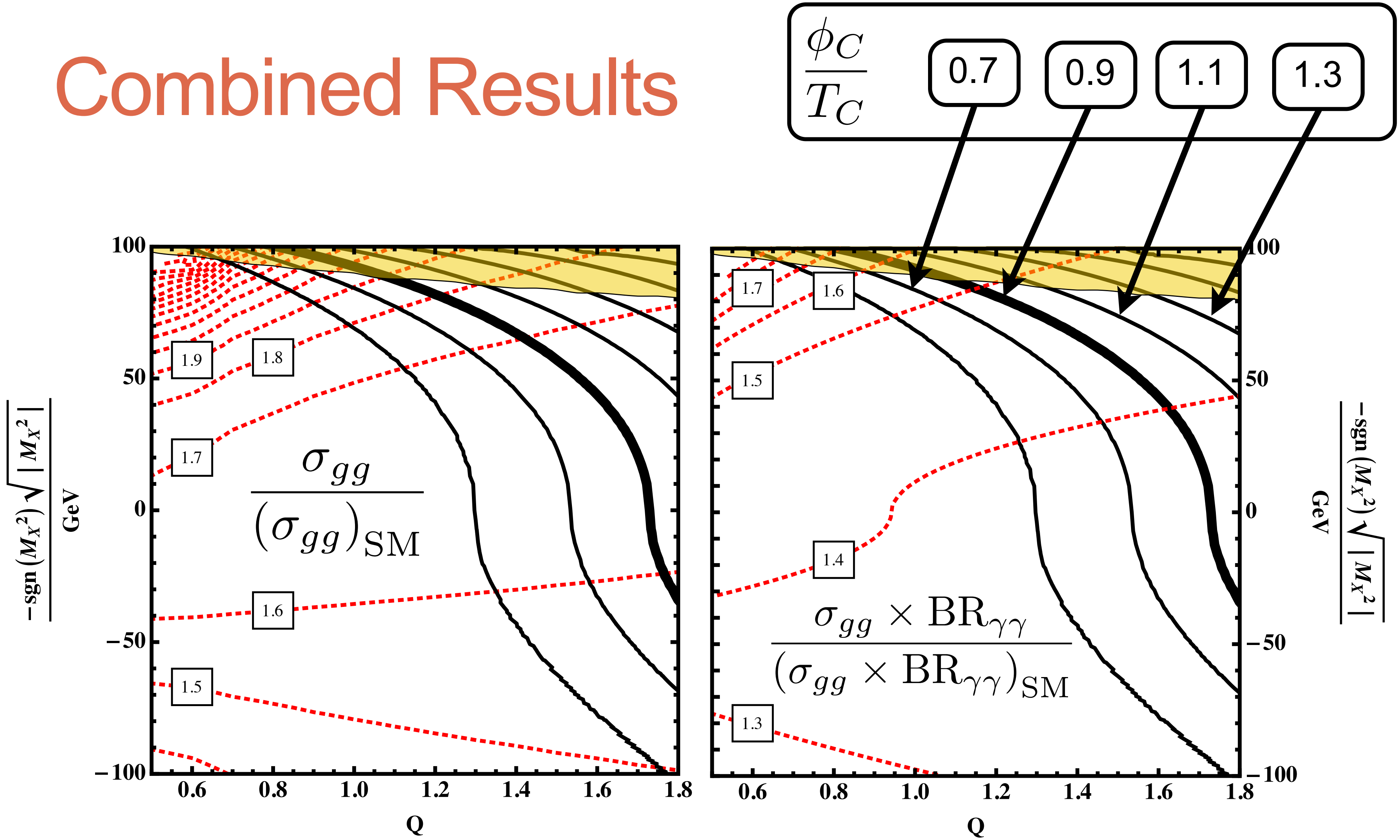
- Di-photon decay is dominated by the $W^\pm$ loop. For $q_X \lesssim 1$ there will be destructive interference between the $W^\pm$ and the X.

$$\Gamma_{\gamma\gamma} = \frac{\alpha^2}{1024\pi^3}\frac{m_h^3}{m_W^2}\left|\sum_i g_i {q_i}^2 d_i\, F_{s_i}(\tau_i)\right|^2 \qquad \tau_i = 4m_i^2/m_h^2$$

$$\begin{aligned} F_0(\tau) &= \tau[1-\tau f(\tau)] \\ F_{1/2}(\tau) &= -2\tau[1+(1-\tau)f(\tau)] \\ F_1(\tau) &= 2+3\tau+3\tau(2-\tau)f(\tau) \end{aligned} \qquad f(\tau) = \begin{cases} \left[\sin^{-1}(\sqrt{1/\tau})\right]^2 & ; \quad \tau \geq 1 \\ -\frac{1}{4}\left[\ln\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & ; \quad \tau < 1 \end{cases}$$

Gunion, Haber, Kane, Dawson [The Higgs Hunter's Guide]

Combined Results



- The other parameters are taken to be $K = 1.6$, $m_h = 125$ GeV.

Applications to the MSSM

MSSM-like Model

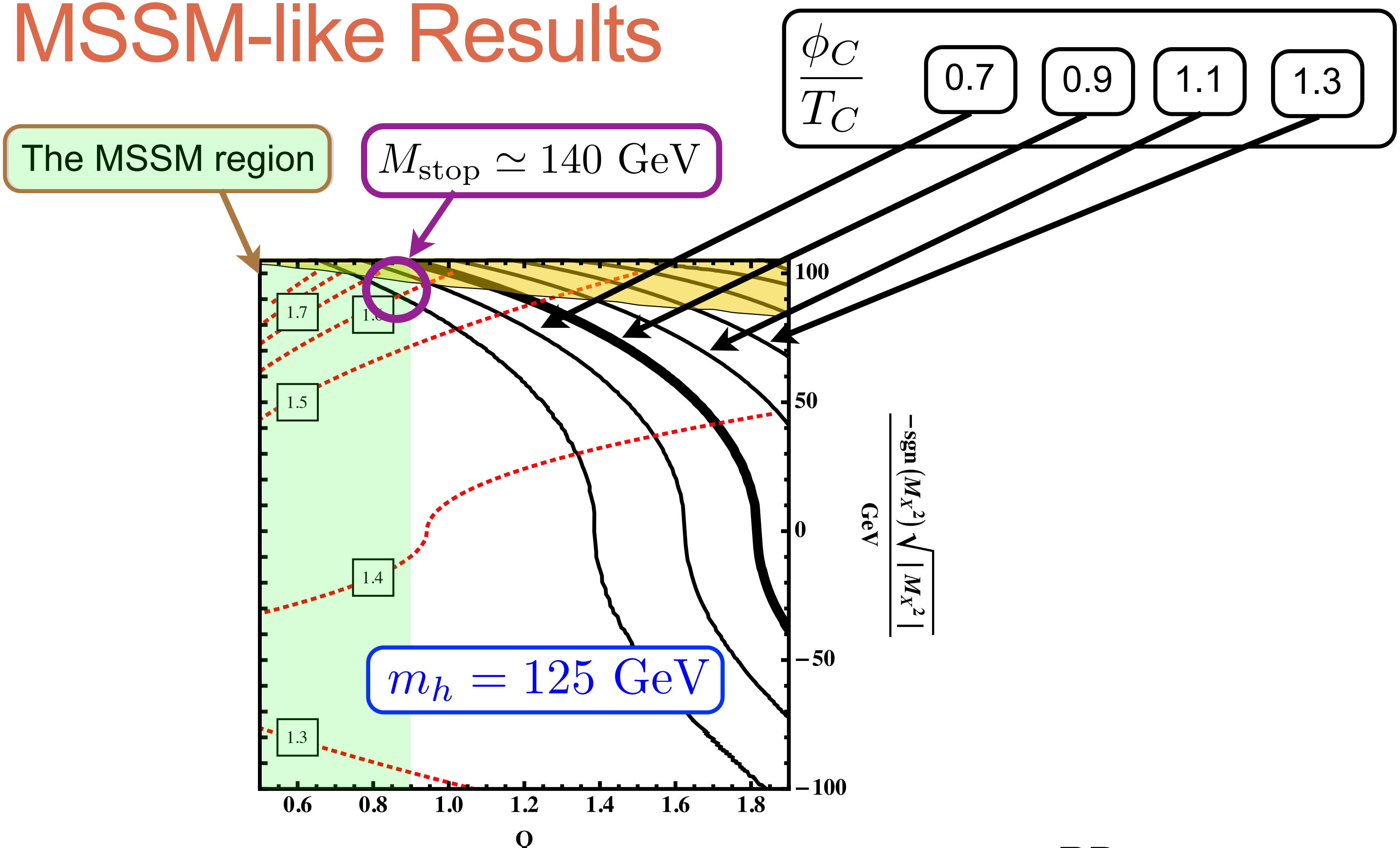
- In order to map onto the MSSM, we must include the Higgsino state and a Yukawa coupling $Y_t \overline{\tilde{H}_u Q_{L_3}} X^*$.
- We will take a typical value $Y_t = 0.8$.

Carena, Nardini, Quiros, Wagner [arXiv:0806.4297]

- We will scan over a range of values for Q.
- Note that in the MSSM, $Q \lesssim 0.9$ for $M_X^2 = -(80\ \text{GeV})^2$, $\tan\beta = 10$, and $m_{Q_3} = 1000\ \text{TeV}$. Morrissey, Menon [arXiv:0903.3038]
- Non-zero *a*-terms for the stop reduce the value of Q.

The electroweak phase transition for the MSSM has been studied by e.g.,
Giudice [1992]; Anderson, Hall [1992];
Carena, Quiros, Wagner [arXiv:hep-ph/9603420]

MSSM-like Results

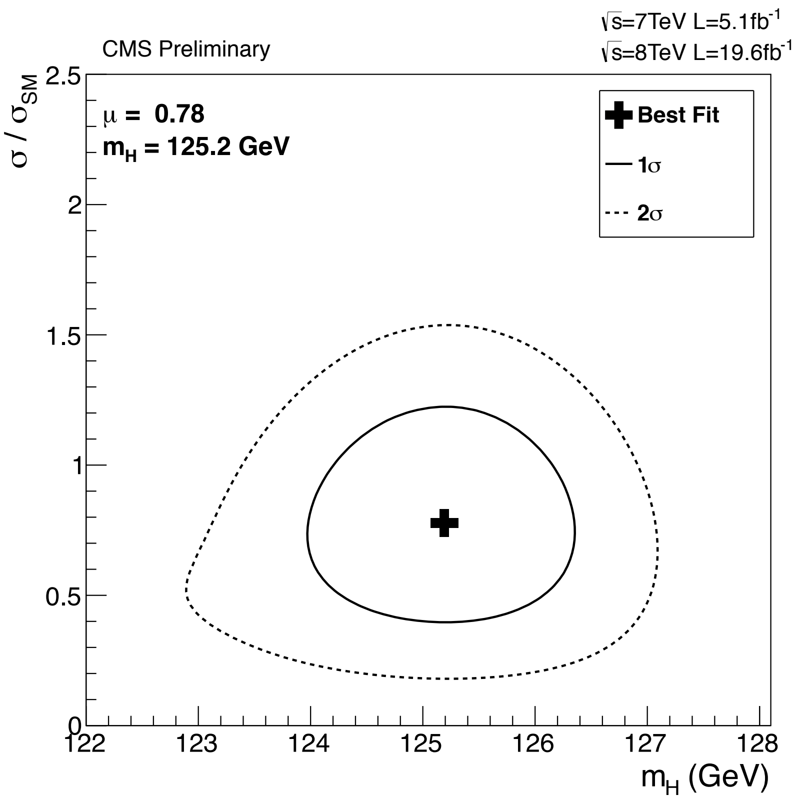


Red, dashed contours show $\frac{\sigma_{gg} \times \text{BR}_{\gamma\gamma}}{(\sigma_{gg} \times \text{BR}_{\gamma\gamma})_{\text{SM}}}$.

Collider Signatures

Measuring Higgs Properties

CMS-PAS-HIG-13-001



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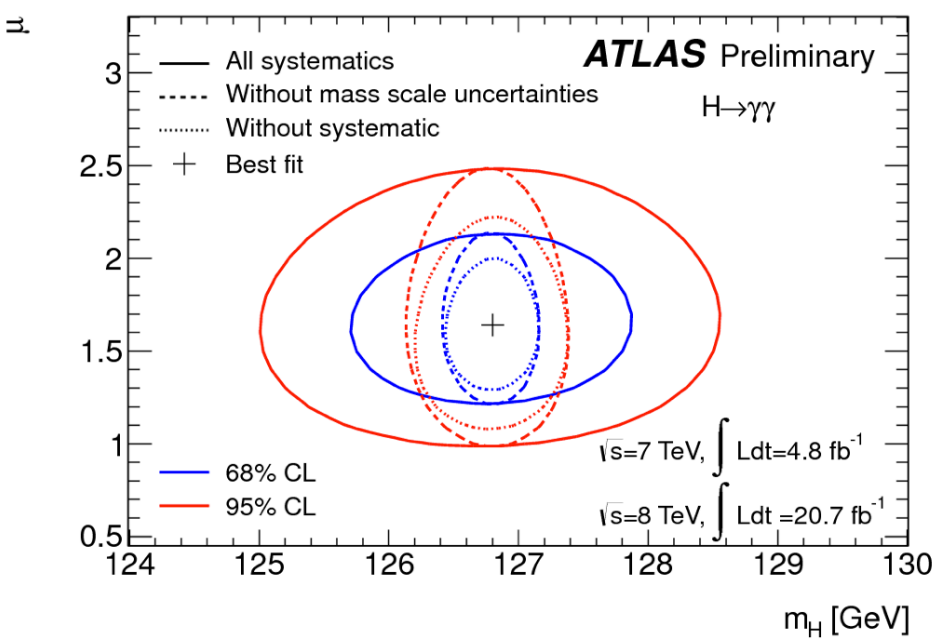
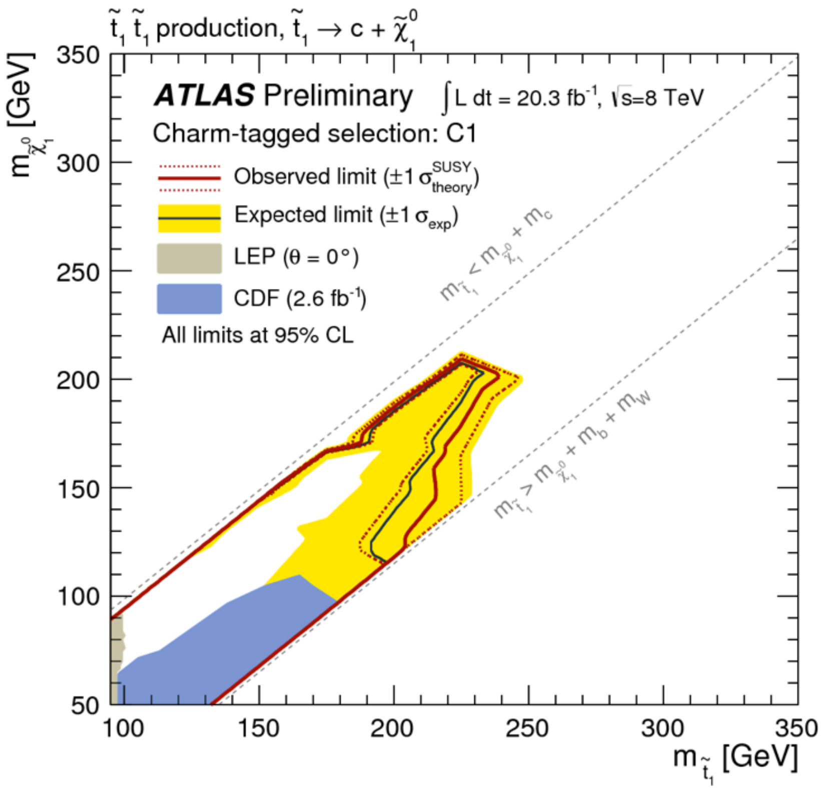


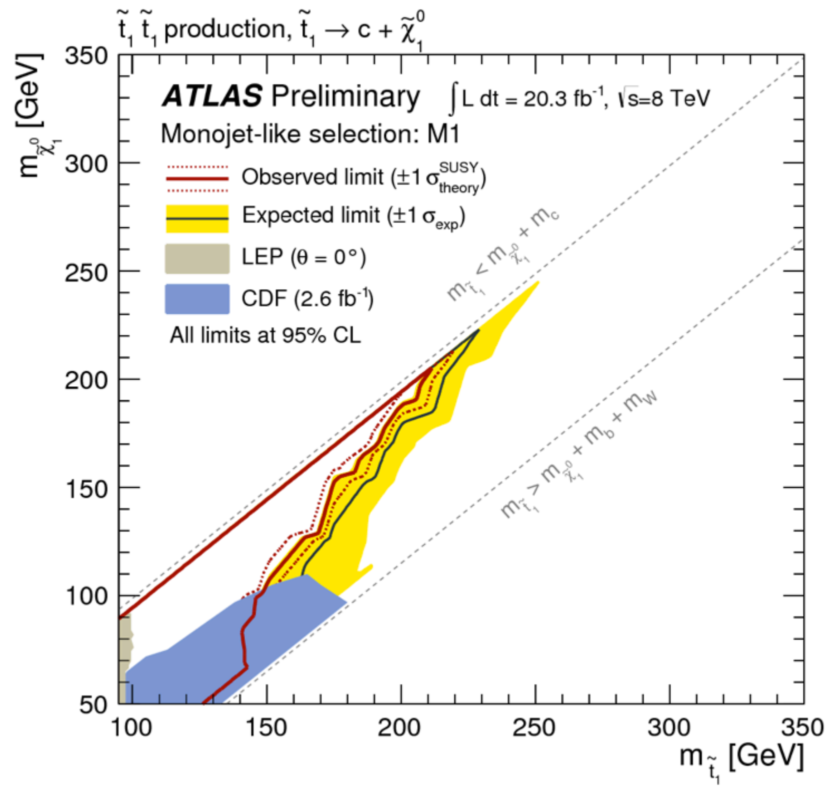
Future Measurements

- Dominate uncertainty in measuring the gluon fusion rate will be systematics limited by theory and PDFs at O(20%).
- Dominate uncertainty in measuring di-photon BR will be systematics limited by experimental effects. Maybe eventually measure the $q_X = 2/3,\ 4/3$ cases?
- We expect that this will be enough to “discover”/exclude the region of parameter space consistent with electroweak baryogenesis.
- Note: doing a global fit to the Higgs couplings, maybe we can measure various ratios to 10-40%?

Duhrssen, Heinemeyer, Logan, Rainwater, Weiglen, Zeppenfeld [arXiv:hep-ph/0406323]; Lafaye, Plehn, Rauch, Zerwas, Duhrssen [arXiv:0904.3866]

Decay Mode: $X \to c\,\chi$





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- χ is a new neutral state (may be a remnant of the CP violating sector).
- Multi-jet and Mono charm jet analyses.

Decay Mode: $X \rightarrow q\, q$

- The search is more difficult.
- There was an early ATLAS result using $34\ \mathrm{pb}^{-1}$, looking for scalar octets. Zhu [Talk at SUSY 2011]
  - No bound applies for $SU(3)_c$ fundamental scalars.
  - Extending this analysis for the larger data set is challenging due to harder trigger level cuts.
- ATLAS analysis for double jet resonance. ATLAS [1210.4826]
  - Only using 7 TeV data.
  - Needs to improve by factor of O(2) to be sensitive.
- There is an open widow for this decay mode.

CONCLUSIONS

Conclusions

- We are interested in simple extensions of the standard model Higgs sector with a strong enough phase transition for viable electroweak baryogenesis.
- We studied the model with new colored scalars which couple via the Higgs portal.
- 2-loop corrections are vital for accurate computations of the strength of the EWPT.
- The viable regions of parameter space lead to changes in the Higgs gluon fusion rate and branching ratio to di-photons of O(50%) or more with respect the standard model values.
- This statement applies to the MSSM in the baryogenesis window.
- These modification to the Higgs properties can potentially be observed at the LHC.
- The new scalars can also be searched for directly at the LHC.

Backup Slides

Resummation at 2-Loops

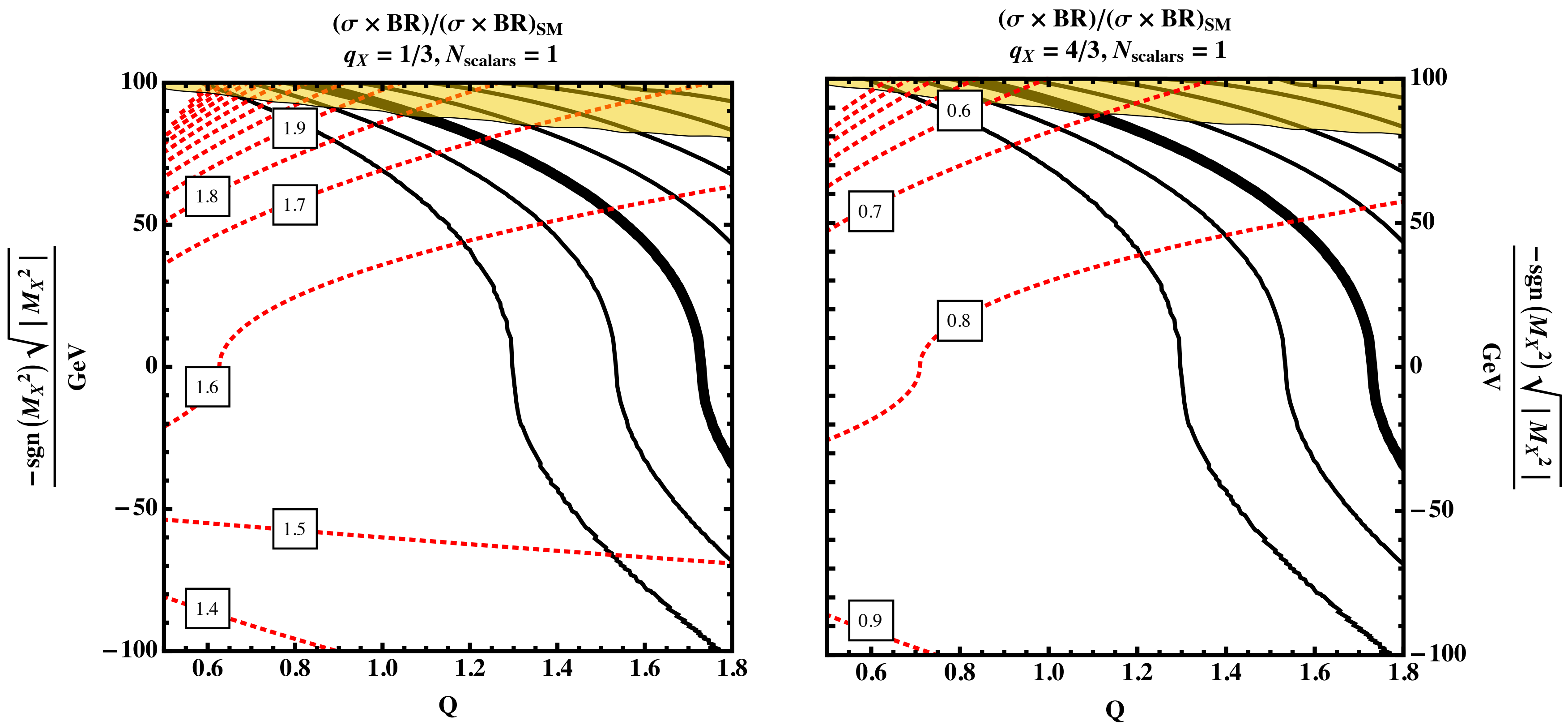
- The trick for making computations tractable is to separate out zero modes from non-zero modes:

$$\frac{1}{\vec{k}^2 + m^2(\phi)} \rightarrow \frac{1}{\vec{k}^2 + \overline{m}^2(\phi, T)}$$

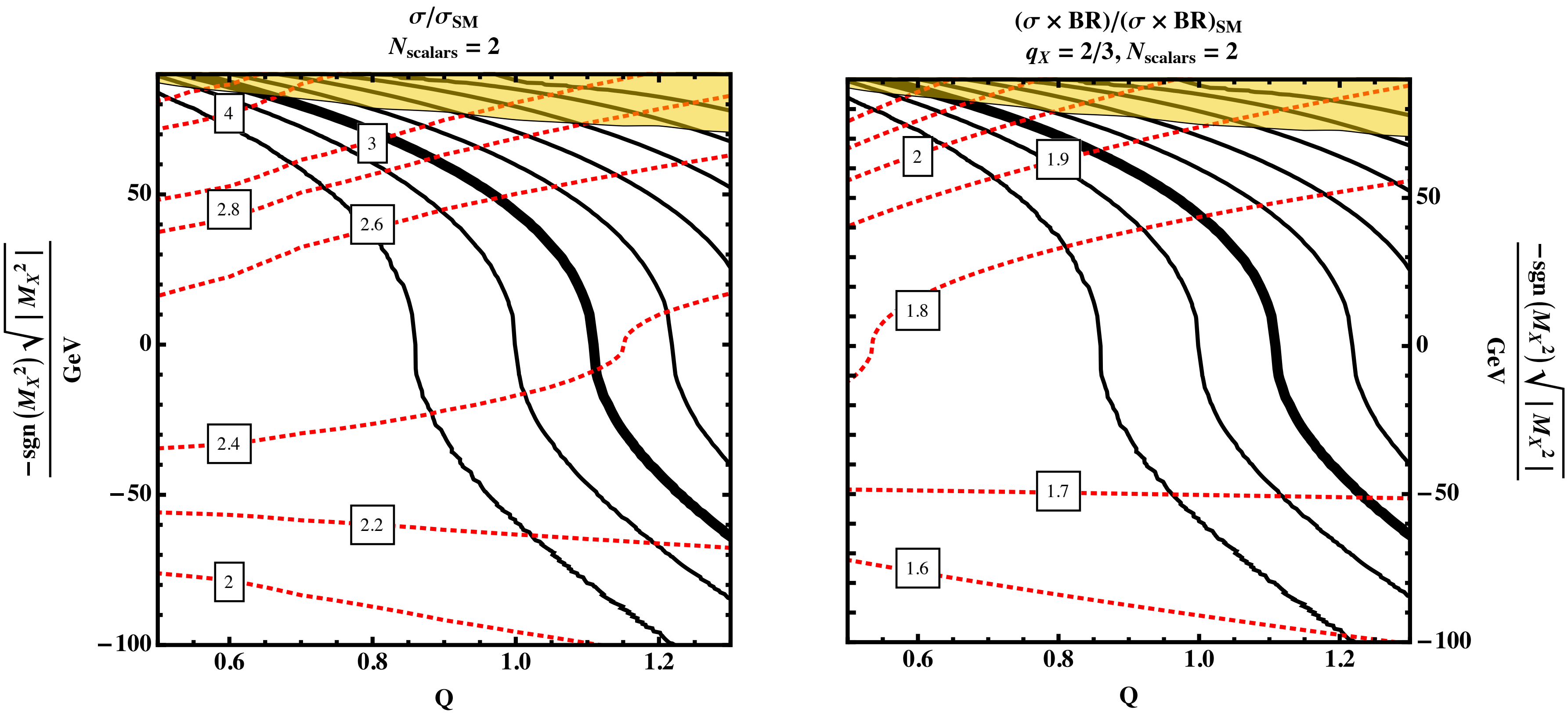
$$\frac{1}{(2\,n\,\pi\,T)^2 + \vec{k}^2 + m^2(\phi)} \rightarrow \frac{1}{(2\,n\,\pi\,T)^2 + \vec{k}^2 + m^2(\phi)} \qquad (n \neq 0)$$

- This procedure introduces temperature dependent counterterms which must be included for consistency.
- All longitudinal gauge boson zero modes must also be resummed.
- Derivative couplings to the longitudinal gauge boson zero modes vanish since $\partial^0 \sim n = 0$ for zero modes.

Other electric charges



Two Colored Scalars



X-onium

- Requires the new colored state to be long lived so it can hadronize.
- Recently there has been theoretical progress in computing the properties for stoponium. Martin [arXiv:0801.0237]
- An analysis using LHC data shows bounds on the order of $m_X \lesssim 100\ \mathrm{GeV}$. Barger, Ishida, Keung [arXiv:1110.2147]
- If the X-onium decays to the Higgs it will be even harder to find. Barger, Keung [1988]