WetB
SM

CERN TH Retreat
Les Houches
November 4 – 6, 2009

Benjamín Grinstein

Who am I?

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- I used to sleep with an elephant

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Work in previous 3-year period

- Minimal Lepton Flavor Violation
  - As extension of SM
  - And GUTs
- Unparticles: killing the bads (CFT reps from optical thm; local counterterms)
- Non-standard Higgs
  - Higgsinium
  - Baryogenesis
- Higher Derivatives
  - Extension of SM: hierarchy, flavor, EW
  - Unitarity: Longitudinal Vector scattering, Large N
  - Thermal Properties
  - Acausal or Non-local?
- Littlest-Higgs
  - Vacuum alignment
  - Fine tuning in top-quark Yukawa sector
  - Renormalization
- Heavy Quarks
  - XYZ: di-quarks as scalars in 'tHooft model, molecule Tevatron production
  - EFT (HQET/NRQCD/SCET) for charmonium production in B decays

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CERN TH colloquium
April 2, 2008

Pheno Club
Sep 17, 2009

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simple, easy to describe in
what must be 10 secs that remain

MLFV

- MFV is a good, if incomplete, solution to the flavor problem
- Can be formulated as an EFT for the SM, or for the 2HDM — D'A., Giudice, I, Strumia, NB645,155
  - Assume SM field content
  - Assume New Physics (NP) at scale $\Lambda \sim$ few TeV
  - Assume quark flavor symmetry $SU(3)^3$ is broken only by Yukawa mass terms
  - Add non-renormalizable terms consistent with symmetries, using Yukawa couplings as spurions
- Program: same for lepton sector
- Why?
  - Flavor symmetry mechanism could be the same in both sectors: test idea
  - Better?: MFV for quarks + GUT = MLFV
- Distinguish two cases, whether neutrino masses are
  - Dirac: copy of quark sector, no observable consequences
  - Majorana: lepton number (LN) is broken.

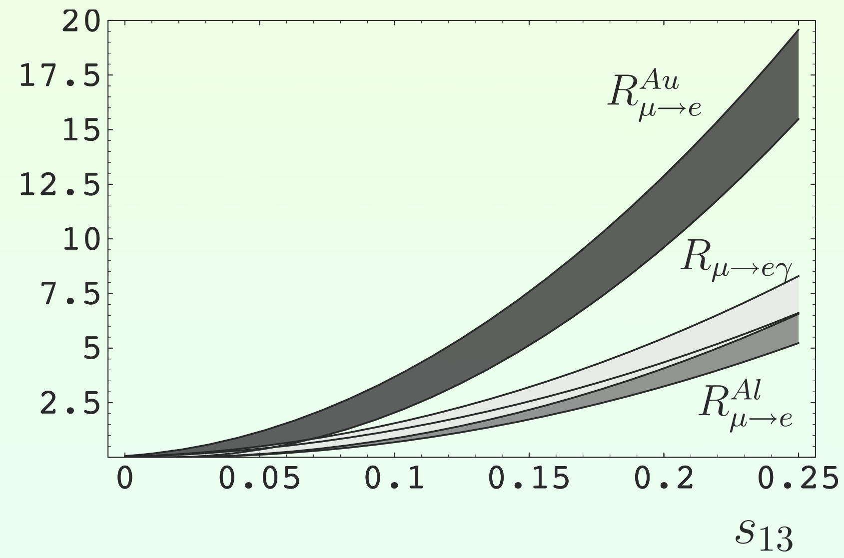
- LN breaking: at some scale M » Λ
  - Assume further right handed neutrinos have very large majorana LN-breaking mass M (for see-saw).
    - EFT only after integrating out right handed neutrinos
  - Do not assume majorana mass term for left handed neutrinos (a dim 5 operator) arises from integrating out right handed neutrinos, but some other LN breaking interaction at scale M
- In either case M < 10^{13} GeV for perturbative mass couplings

- With GUTs
  - New effects (*e.g.*, LFV even for Dirac neutrino)
  - Includes thoroughly studied models (*e.g.*, SUSY-GUTs)
  - Since $\lambda_u \propto \lambda_{10}$, $\lambda_d \propto \lambda_e^T \propto \lambda_5$
    spurions for *d* and *e* transform the same way: new FV structures (light quark masses fixed by trans-planckian operators)
  - Hence large effects even for smaller M

Sample results: $\mu \to e\gamma$, μ-to-e conversion

No GUTs yet:

$$B_{\ell_i \to \ell_j(\gamma)} = 10^{-50} \left(\frac{\Lambda_{\rm LN}}{\Lambda_{\rm LFV}}\right)^4 R_{\ell_i \to \ell_j(\gamma)}(s_{13}, \delta; c^{(i)})$$



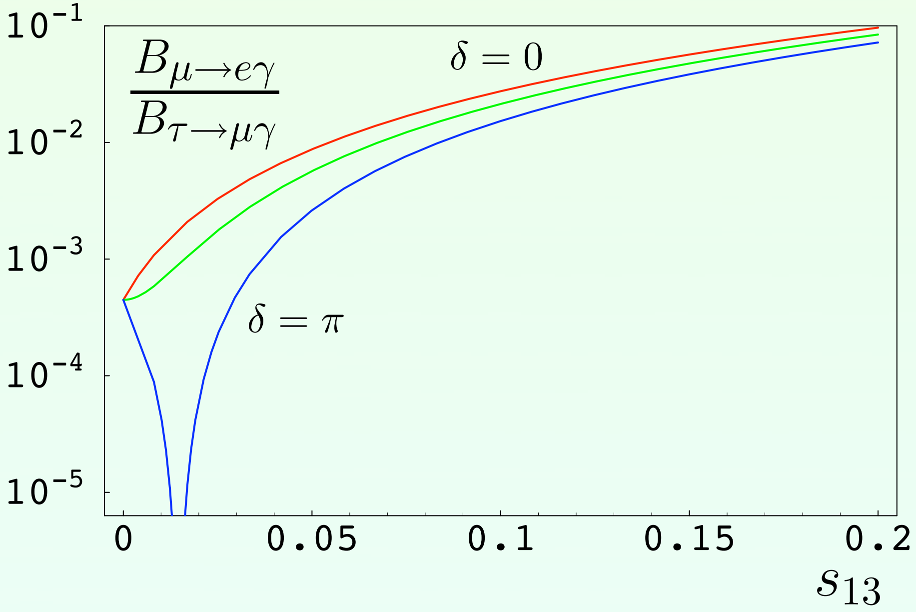
- since $\Delta \propto U(m_\nu)^2 U^\dagger$, only differences of $m_\nu^{\,2}$ enter; these are measured! (U = PMNS matrix)

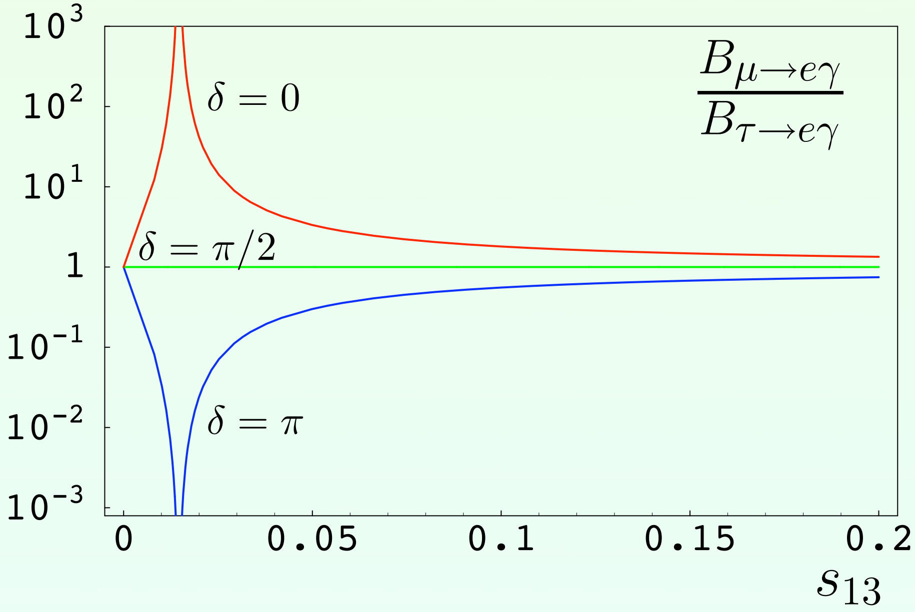
- s_{13} and δ unknown PMNS parameters (scan on δ)
- choose $c^{(i)}$ (coefficients of dim 6 operators) of order one for the estimate
- ratio of scales can be large:

  perturbative $g_\nu \Rightarrow$ $\Lambda_{\rm LN} \lesssim 3 \times 10^{13} (1~{\rm eV}/m_\nu)$ GeV
  so

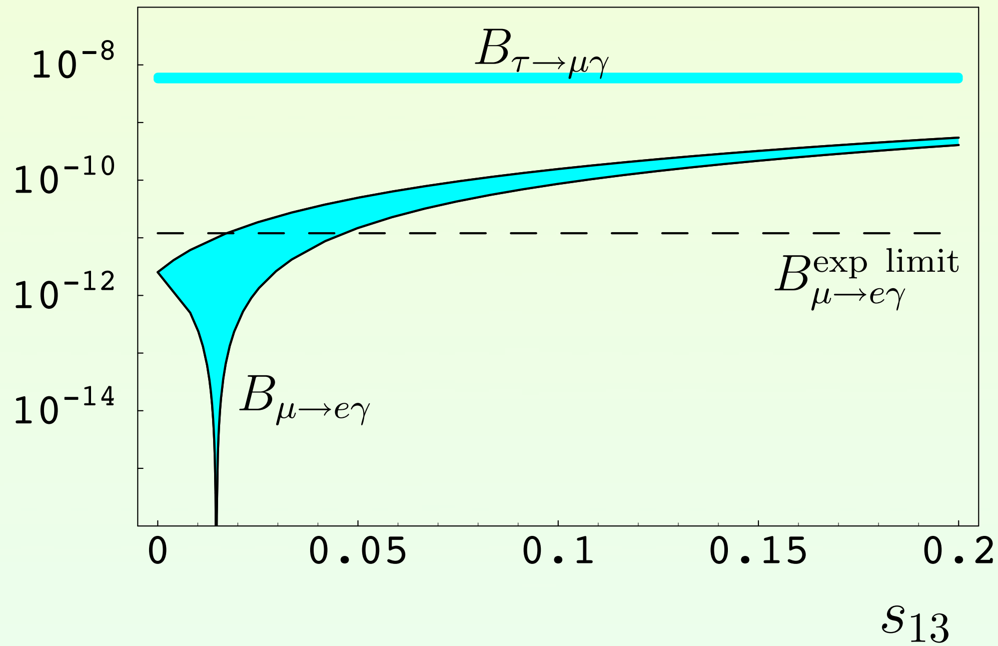
  $$\Lambda_{\rm LFV} \sim 1~{\rm TeV} \Rightarrow \Lambda_{\rm LN}/\Lambda_{\rm LFV} \lesssim 10^{10}$$

Predictive: $\ell \to \ell' \gamma$ patterns are independent of unknown input parameters (scales cancel in ratios, in this case $c^{(i)}$'s cancel too, and all other parameters are from long distance)





Overall normalization



If s_{13} is small, look at tau modes.

Here $\Lambda_{LN}/\Lambda_{LFV} = 10^{10}$ and $c^{(1)}_{RL} - c^{(2)}_{RL} = 1$

Belle and BaBar have bounds (summer '05)
of a few × 10^{-7} for $\mathrm{Br}(\tau \to \ell\gamma)$ and $\mathrm{Br}(\tau \to \ell\ell\ell)$

GUTs example $\tau \to \mu\gamma, \quad \tau \to e\gamma \quad \& \quad \mu \to e\gamma$

$$\Delta\mathcal{L}_{\rm eff} = \frac{v}{\Lambda^2}\bar{e}_R \Big[\; c_1 \; \lambda_e \lambda_1^\dagger \lambda_1 \; + \; c_2 \; \lambda_u \lambda_u^\dagger \lambda_e \; + \; c_3 \; \lambda_u \lambda_u^\dagger \lambda_d^T \; \Big] \sigma^{\mu\nu} e_L F_{\mu\nu}$$

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just like MLFV above

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Generalizes B, H & Strumia ($\lambda_5' = 0, C = G = 1$)

New mixing structures

$$C = V_{e_R}^T V_{d_L}$$

$$G = V_{e_L}^T V_{d_R}$$

Independent of M_ν

Hierarchical

$$\left(\frac{m_t^2}{v^2}\right) \times \begin{cases} \lambda^2(m_\tau/v), & (\tau \to \mu) \\ \lambda^3(m_\tau/v), & (\tau \to e) \\ \lambda^5(m_\mu/v), & (\mu \to e) \end{cases}$$

$(\lambda = 0.22)$

Large: for Λ=10TeV

$$\mathrm{Br}(\mu \to e\gamma) \sim 10^{-12}$$

R. Barbieri, L.J. Hall, Phys. Lett. B 338 (1994) 212
R. Barbieri, L.J. Hall, A. Strumia, Nucl. Phys. B 445 (1995) 219

Non-standard Higgs

- EFT approach to NP
  - Assume SM field content
  - Add non-renormalizable terms for these fields
  - Scale of NP $\Lambda \sim$ few TeV
- Focus on terms that modify Higgs sector
  - Manohar studied H coupling to photons, gluons
  - Focus on *H* self couplings
    - New potential terms
    - New derivative terms
    - Both shift or rescale *h* couplings (after shifting higgs field by VEV)
  - Mass relation relaxed: $m^2 = \lambda v^2$ + order (v^2/Λ^2)

Higgsinium

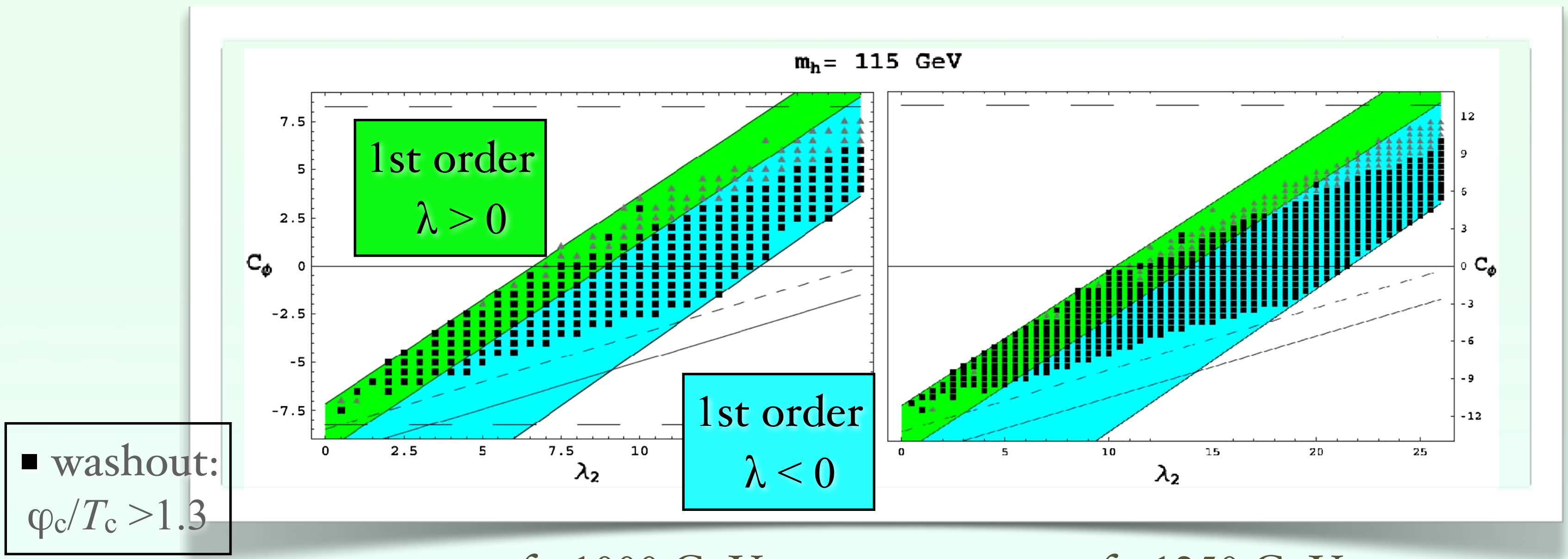
- Self interacting scalar can form bound state
  - Quartic self-interaction repulsive, ~ λ
  - Cubic self-interaction gives scalar exchange, attractive, ~ λ^2
  - Need self interaction large enough for binding
- In SM this is for heavy higgs
  - Very short lived higgs, formation slower than decay
- In EFT, mass relation relaxed, binding for lighter higgs may be possible
- Quantitative study complicated by non-perturbative relativistic bound state equation: assume non-relativistic and truncate BS kernel

$$\frac{m_h}{v} > \sqrt{\frac{16\pi - 4\lambda_2 \frac{v^2}{\mathcal{M}^2} + \frac{51N_c}{4\pi^2}\left(\frac{m_t^4}{v^4}\right)}{12 - 40C_h^K}}.$$

  $m_h < v$ possible for $C < 0$! (C is coefficient of dim 6 derivative operator)
- Also studied non-linear realization:
  - Strong EW breaking, but with a light higgs remnant (like σ in QCD: EFT has GBs (pions) plus σ, but not a linear σ-model)
  - Cubic and quartic self-couplings now free parameters
  - Binding for large parameter space with order 1 couplings

EW Baryogenesis

- Problems with SM's EW baryogenesis:
  - Strong 1st order phase transition requires $m_h < 70$GeV (again, $m_h^2 = \lambda v^2$)
  - Not enough CP in CKM model
- NP may solve both. Focus on order of transition
  - Shape of potential is modified (computed thermal, full SU(2) x U(1))
  - Drastic change: quartic self-coupling negative, stability from dim 6 term
    ➠ Easily strongly 1st order
  - Conservative: positive quartic



f = 1000 GeV
f = 1250 GeV

The End

13 slides including title and this

Higher Derivative FT

- non-Q FT or QFT with renormalizable Lagrangian + dim 6 terms with:
  - 4 derivatives (bosons)
  - 3 derivatives (fermions)
- Not a perturbation
- Better convergence properties of Feynman diagrams
- Issues:
  - Stability: exponential growth of solutions
  - Unitarity: ghosts (negative residues of poles in propagator)
  - Non-locality, apparent acausality
  - No GUT?
- Features
  - No quadratic divergence in higgs mass (solves big fine tuning problem)
  - No flavor problem
  - EW OK if at few TeV scale
  - Testable
  - Economical: no new fields, roughly doubled spectrum (a ghost per normal particle)
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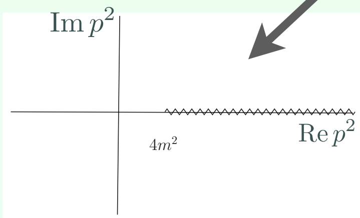
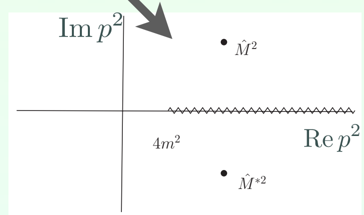
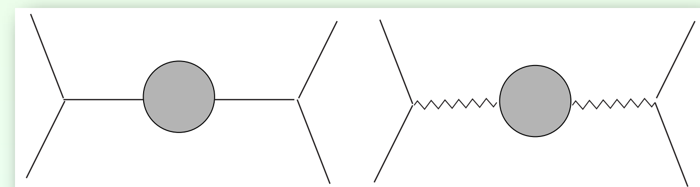
- Unitarity: ghosts and the Lee-Wick prescription
  - New poles with negative residue: ghosts (states with negative norm)
  - LW: interactions render would-be-ghosts unstable, no asymptotic states, hence no negative norm states
    - ➠ S matix may well be unitarity

  - Wick rotation/contour prescription: starting from free theory with usual Feynman contour, turn on interactions and deform contour to avoid poles as they move off the real axis
  - CLOP: to avoid pinches and maintain covariance, take complex conjugate poles as independent

$$iA = -ig^2\left[\frac{1}{p^2 - m^2 + \Pi} - \frac{1}{p^2 - M^2 - \Pi}\right]$$







$$G^{(2)} = -\frac{A}{p^2 - \hat{M}^2} - \frac{A^*}{p^2 - \hat{M}^{*2}} + \int_{4m^2}^{\infty} d\mu^2 \, \frac{\rho(\mu^2)}{p^2 - \mu^2}$$

- Does this really work?
  - CLOP checked that it does for some topologies of Feynman graphs
  - We showed the O(N) model, in leading order of $1/N$, satisfies the optical theorem
  - General proof missing. Non-perturbative formulation missing

- Unitarity: High Energy longitudinal vector scattering
  - In YM with vector mass added "by hand" amplitude grows with energy. This can be traced back to

    $$\epsilon_L^\mu(p) = 1/M(p, 0, 0, E)$$

    One factor of E per external leg, so in LL → LL naive growth is E^4
  - Gauge invariance helps:

    $$\epsilon_L^\mu(p) = p^\mu/M + (M/2E)n^\mu$$

    but with hard mass added there is no gauge invariance
  - HD theory has a ghost that is like a vector with a mass added by hand. But the theory IS gauge invariant.
  - Checked: no $2 \to 2$ amplitudes grow with E
  - Used WI to generalize to any amplitude

- Thermal HD theory

- For unitarity need LW-CLOP prescription.
- No Green functions, only S-matrix
- Thermodynamics from S-matrix possible (Dashen, Ma & Bernstein, Phys. Rev. 187: 345, 1969)

- At weak coupling scalar HD theory gives extra contribution to thermodynamic potential:

$$\Omega_{\rm LW} = -\frac{V}{\beta}\int \frac{{\rm d}^3P}{(2\pi)^3}\ln\left(1 - e^{-\beta\sqrt{M^2+\mathbf{P}^2}}\right)$$

Hence negative density and negative pressure

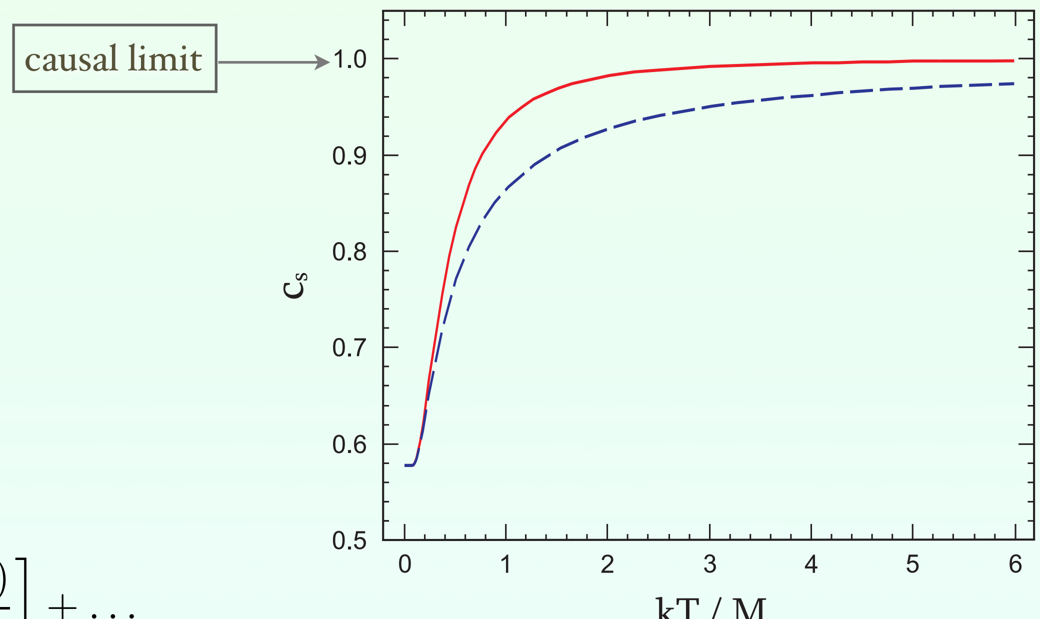
High T expansions:

$$\rho_{\rm LW} = -\left[\frac{\pi^2(kT)^4}{30} - \frac{M^2(kT)^2}{24}\right] + \dots$$

Cancel normal

Equal and positive e.o.s.: $w = 1$

$$p_{\rm LW} = -\left[\frac{\pi^2(kT)^4}{90} - \frac{M^2(kT)^2}{24} + \frac{M^3(kT)}{12\pi}\right] + \dots$$



speed of sound $c_s = \sqrt{dp/d\rho}$

presently studying spin-1/2 case,

problematic, seem to get negative energy density at large T

Littlest-Higgs

- Vacuum alignment
  - Common procedure:
    - weakly gauged interactions determine alignment
    - other interactions treated as perturbations in that vacuum
  - Top quark yukawa larger than weak gauge couplings
    - if only top-yukawa used to determine alignment, find two degenerate vacuua at lowest order (quadratic in cutoff):
      - the usual one, Σ_{ew}, with $SU(2)$ x $SU(2)$ x $U(1)$ x $U(1)$ → $SU(2)$ x $U(1)$
      - novel one, Σ_t, with $SU(2)$ x $SU(2)$ x $U(1)$ x $U(1)$ → $U(1)$ x $U(1)$
    - when Coleman-Weinberg ($m^4 \ln m$) is included, new one (Σ_t) has lower energy
    - gauge interactions favor Σ_{ew}
      ➠ Desired vacuum only if $U(1)$ gauge interaction is strong enough

$$g_1'^2 + g_1^2 > \frac{2N_c}{3\pi^2 c}\,\lambda_1^2\,\lambda_2^2\left[\ln\left(\frac{\Lambda^2}{(\lambda_1^2+\lambda_2^2)F^2}\right)+\frac{\hat{c}'}{2}\right]$$

  - Interesting result for PPP model (based on $SU(2)$ x $SU(2)$ x $U(1)$): vacuum alignment into Σ_{ew} (plus EW coupling values) requires $g_1 \gg g_2$ which is the same condition as for low F (while consistent with EW precision)
  - Cosmology; metastable vs stable vacuua, which does the universe cool to?

- Fine tuning in top Yukawa sector
  - Collective symmetry: no quadratically divergent higgs mass at 1-loop
    - Automatic in gauge sector
    - Artificially enforced in yukawa sector: need $\lambda_1 = \lambda_1'$ in $\mathcal{L}_{\rm top} = -\lambda_1 f \bar{q}_L{}^i \epsilon^{xy} \Sigma_{ix} \Sigma_{3y} q_R - \frac{1}{2} \lambda_1' f \bar{u}_L \epsilon^{3jk} \epsilon^{xy} \Sigma_{jx} \Sigma_{ky} q_R - \lambda_2 f \bar{u}_L u_R + \text{h.c.}$
  - Is there an extension of the model for which it may be an accidental symmetry or the result of a gauge symmetry?
    - Ans: No
      (Used only group theory and minimal requirements of a theory with a collective symmetry and a higgs)
  - Out?
    - The name of the game: collective symmetry can be imposed
    - Find a new mechanism to suppress top contribution to higgs mass