2013 CHIPP Annual Plenary Meeting

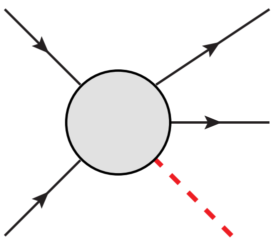
Testing the Standard Model
and waiting for Godot

Adrian Signer

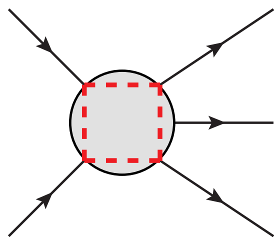
Paul Scherrer Institute & University of Zurich

24 JUNE 2013; CAMPUS SURSEE

- expectation was the LHC by now would have uncovered BSM more or less single-handedly with input from other sources to round off the picture
- all particles of Standard Model (and only these) have been found
- up to electro-weak (EW) energies they behave as predicted by the SM
- the SM is a (very successful) effective theory up to some energy scale $\Lambda_{\rm UV}$
- long standing expectation that there is new physics at the TeV scale ($\Lambda_{\rm UV} \sim \Lambda_{\rm EW}$) $\longrightarrow$ is being questioned recently
- further big step when LHC $\rightarrow$ $13 - 14\ {\rm TeV}$
  - option 1: many new particles produced
  - option 2: no new particle produced



option 1



option 2

- theory must be ready for both options

setting the stage

- gauge group $SU(3) \times SU(2) \times U(1)$, 3 families of matter fields, one scalar
- consider all gauge (and Lorentz) invariant operators
- $\mathcal{L}_{\rm SM}$ contains (renormalizable) operators with Dim ≤ 4

$$\mathcal{L}_{\rm SM} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \ldots + \hat{\theta}\, G^{\mu\nu} \tilde{G}_{\mu\nu} + i\left(\bar{\ell} \not{D}\, \ell + \bar{e} \not{D}\, e + \ldots\right)$$
$$+ (D_\mu \Phi)^\dagger (D^\mu \Phi) + \Lambda_{\rm UV}^2 \Phi^\dagger \Phi - \frac{\lambda}{2} (\Phi^\dagger \Phi)^2 - \left(Y_e\, \bar{\ell}\, e\, \Phi + \ldots + \text{h.c.}\right)$$

- treating BSM effects via effective theory:

$$\mathcal{L}_{\rm BSM}^{\rm ET} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(5)}}{\Lambda_{\rm UV}} \mathcal{O}_i^{(5)} + \sum \frac{c_i^{(6)}}{\Lambda_{\rm UV}^2} \mathcal{O}_i^{(6)} + \ldots$$

- $\Phi^\dagger \Phi$ requires a dimensionfull coefficient $\Lambda_{\rm UV}^2 \sim M_H^2$ $\Longrightarrow$ hierarchy problem
- from experiment θ extremely small (or 0?) $\Longrightarrow$ strong CP problem

	assume $\Lambda_{\rm UV} \sim \Lambda_{\rm EW}$	assume $\Lambda_{\rm UV} \gg \Lambda_{\rm EW}$
dilemma:	+ M_H as expected	− why is $M_H \ll \Lambda_{\rm UV}$
	− BSM physics seems to conspire	+ BSM effects naturally small
	many small problems	one big problem

outline

act 1: standard scenario

- $\Lambda_{\rm NP} \sim 1$ TeV, global market
- testing SM at energy frontier
- theory in very good shape
- further theory progress 'certain'

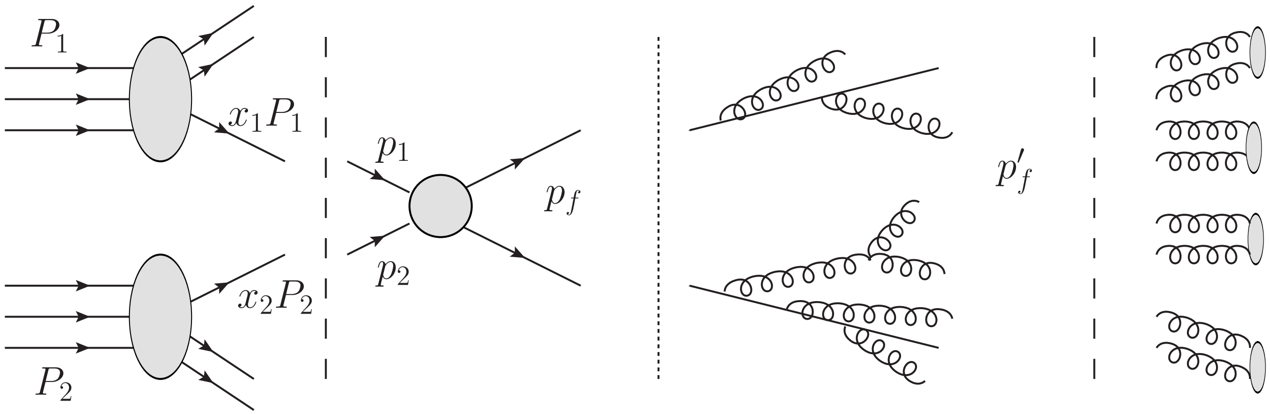
act 2: 'what if' scenario

- $\Lambda_{\rm NP} \gg 1$ TeV, niche market
- testing SM at precision frontier
- some flagship tests
- combining all possible information
- no theory steamroller available

curtain

- conclusions

a process at the LHC clear theoretical picture



non-perturbative	perturbative	perturbative	non-perturbative
$f_i(x_i, \mu_F)$ pdf	$d\hat\sigma$ hard x-sec.	parton shower	hadronization

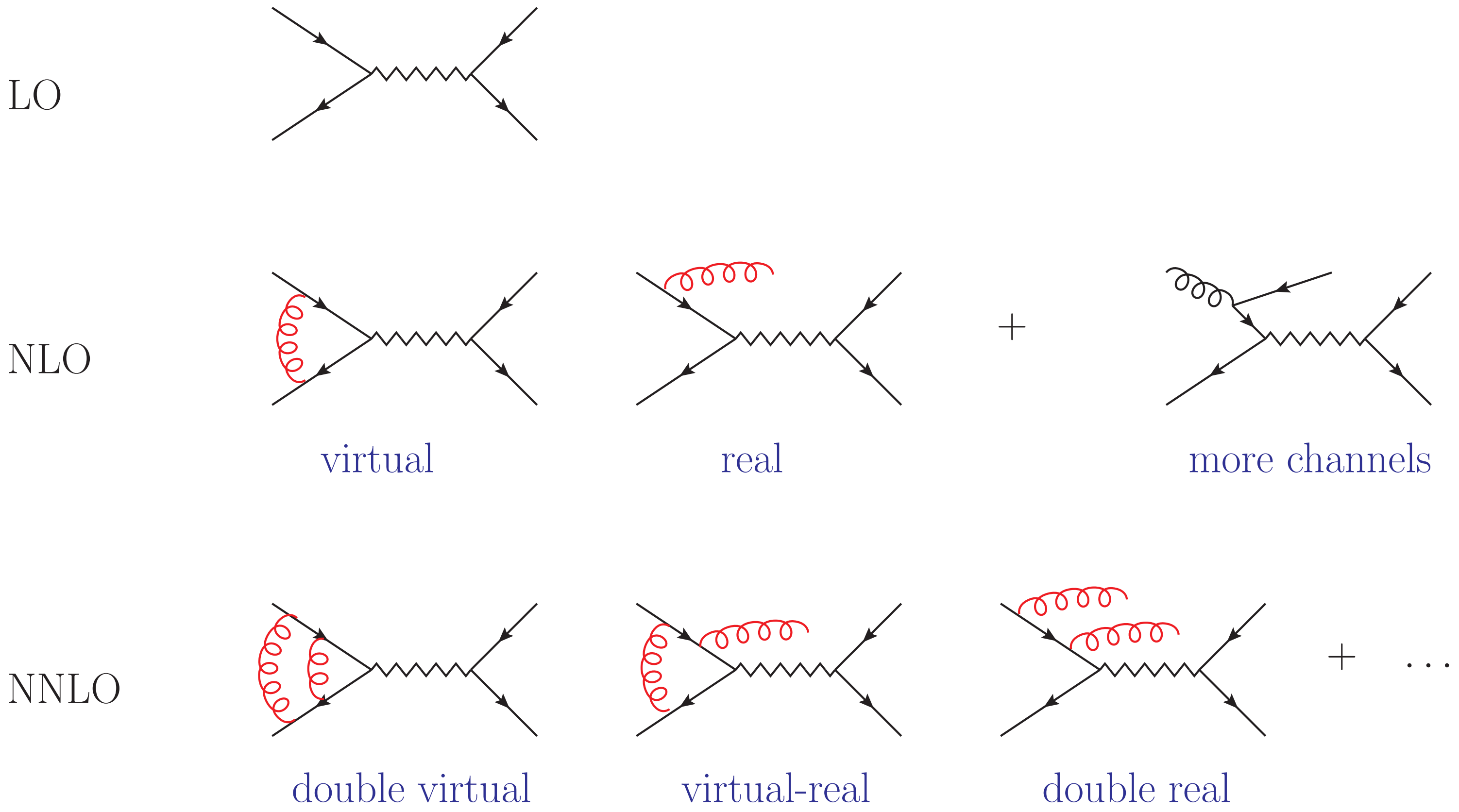
factorization theorem

$$d\sigma = \int dx_1 f_1(x_1, \mu_F) \int dx_2 f_2(x_2, \mu_F)\, d\hat\sigma(p_1 p_2 \to p_f; \mu_F, \mu_R)\, \text{Obs}(p_f) + \mathcal{O}\left(\frac{\Lambda}{Q}\right)$$

parton distribution functions	hard scattering cross section	higher twist
obtained from fits	compute as series in α_s	small for $Q \gg \Lambda$

hadronization: not much progress, but less and less important

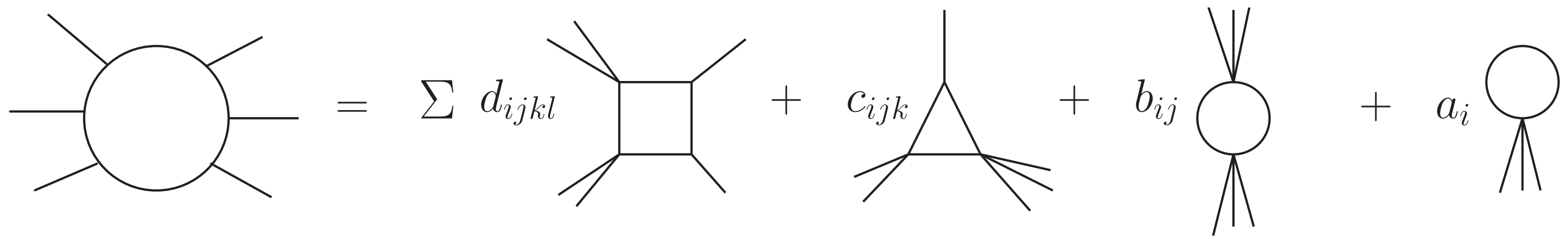
perturbative expansion of $d\hat{\sigma}$



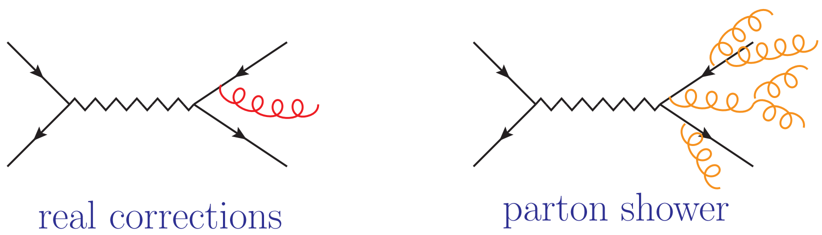
- structure simple at LO, but becomes rapidly much more complicated
- various parts (virtual, real) separately singular (soft/collinear emission)
  $\rightarrow$ only combination is finite and physically meaningful

theory status

- LO fully automatized and combined with parton showers (and hadronization)
- NLO large degree of automatization and combined with parton showers
- huge progress in recent years NLO revolution [current status $\sim 2 \to 4/5$]
  - in calculation of NLO virtual corrections: decompose one-loop amplitude into box-, triangle-, bubble- and tadpole-integrals



    determine coefficients numerically
  - in combining one-loop with parton showers (solve double counting issues)

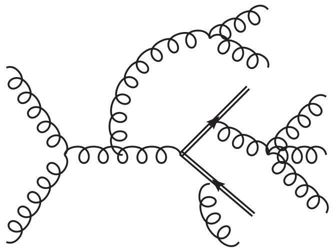


- NNLO: still “hand crafted”, gearing up for another revolution [current status $\sim 2 \to 2$]

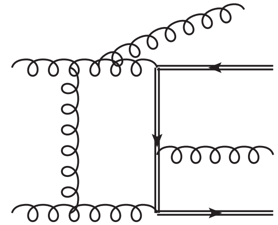
act 1

example $t\bar{t}$ + jets

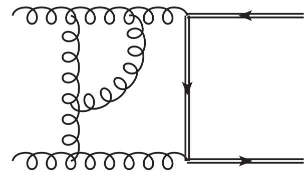
- LO: $t\bar{t} + 6$ jets
- NLO: $t\bar{t} + 2$ jets
- NNLO: $t\bar{t} + 0$ jets



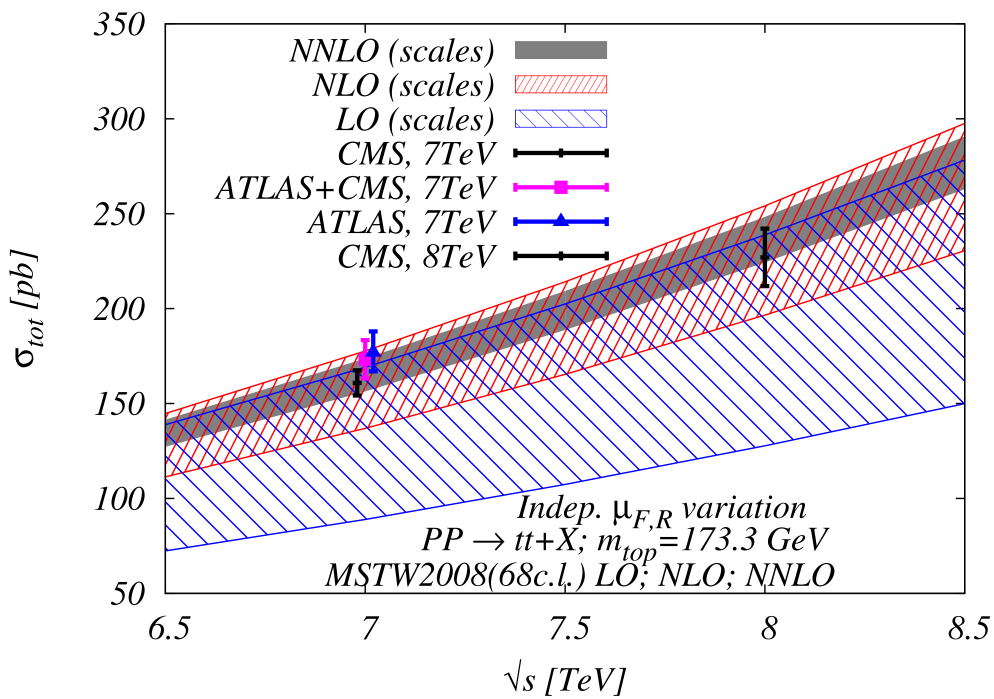
$t\bar{t} + 6j$ LO



$t\bar{t} + 2j$ NLO



$t\bar{t} + 0j$ NNLO

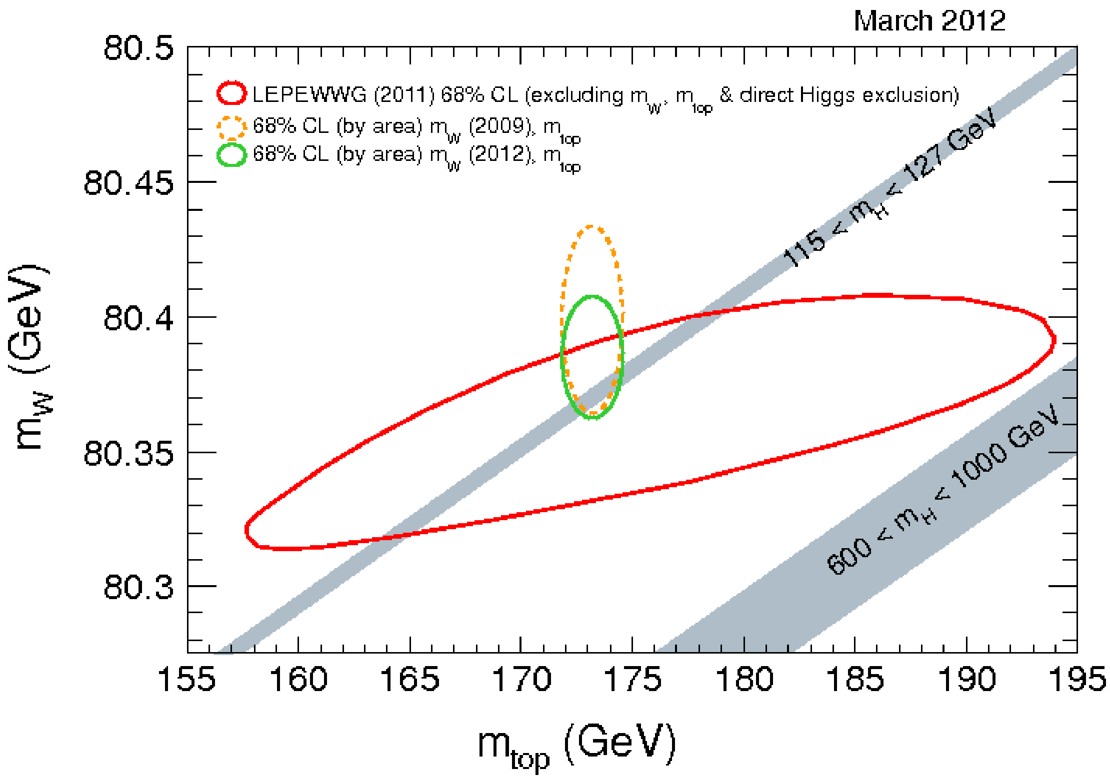


[Czakon et al. 1305.3892]

- state-of-the-art (numerical) NNLO calculation for total cross section
- ever decreasing scale dependence, i.e. smaller theoretical error
- good agreement with experiment
- differential cross section calculation on its way

a flagship precision test at high energies $m_W \leftrightarrow m_t \leftrightarrow m_H$

- currently $\delta m_W \sim 15$ MeV and $\delta m_t \sim 1$ GeV
- relation between m_W, $m_{\rm top}$ and m_H in the SM confirmed



- future possibilities with linear collider: $\delta m_W \sim 5$ MeV and $\delta m_t \sim 100$ MeV or maybe even better ?? (would require substantial theory improvements)

summary act 1

- theory for collider physics in very good shape
- theory ’collaborations’ ($\sim$ 5-10 or more people)
- very productive and highly efficient ’industry’ (automatization)
- huge progress in recent years (Les Houches NLO wishlist closed)
- further progress ’guaranteed’

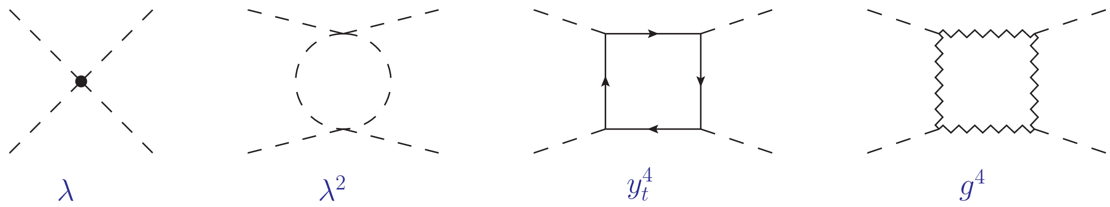
act 2, the 'what if' scenario

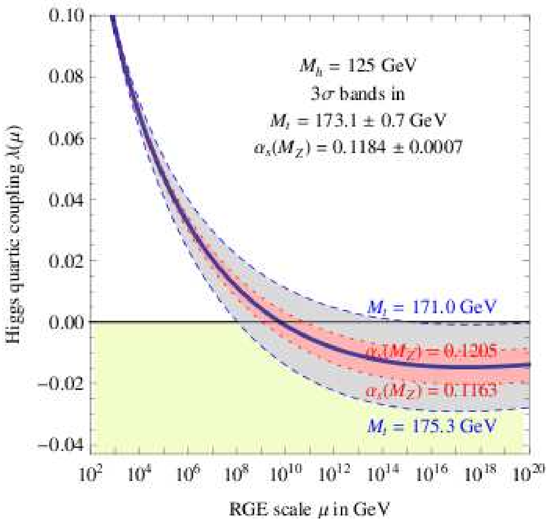
- could it be the SM is valid up to very high energies, say $\Lambda_{\rm UV} \sim 10^{10}$ GeV ??
- direct production hopeless $\longrightarrow$ precision option
- LHC still very important, but influence of other activities (cLFV, edm, dark matter . . .) will grow even bigger
- a combined effort (high-energy, high-precision, cosmology) is mandatory
- high-presicion observables often face the problem that potential BSM physics competes against 'dirty' SM physics (classic example $g-2$ of muon)
- move towards using an effective-theory approach to parametrize ignorance and look for weakest point in SM (scraping for information)

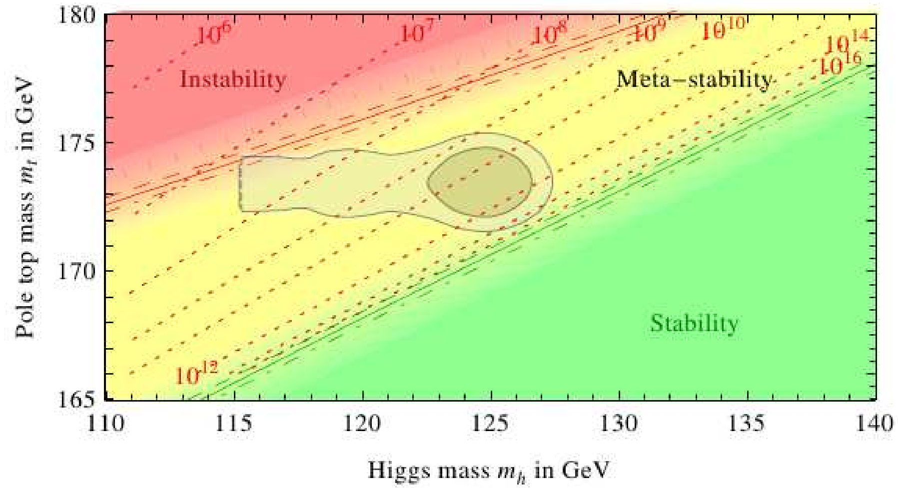
self-consistency of SM: the Higgs-Top miracle   plots: [Degrassi et al. 1205.6497]

- consider self coupling of Higgs $\lambda(t), \quad t = \ln \Lambda^2/Q_0^2$

$$\frac{d\lambda(t)}{dt} \sim \lambda^2 - y_t^2 + \ldots$$





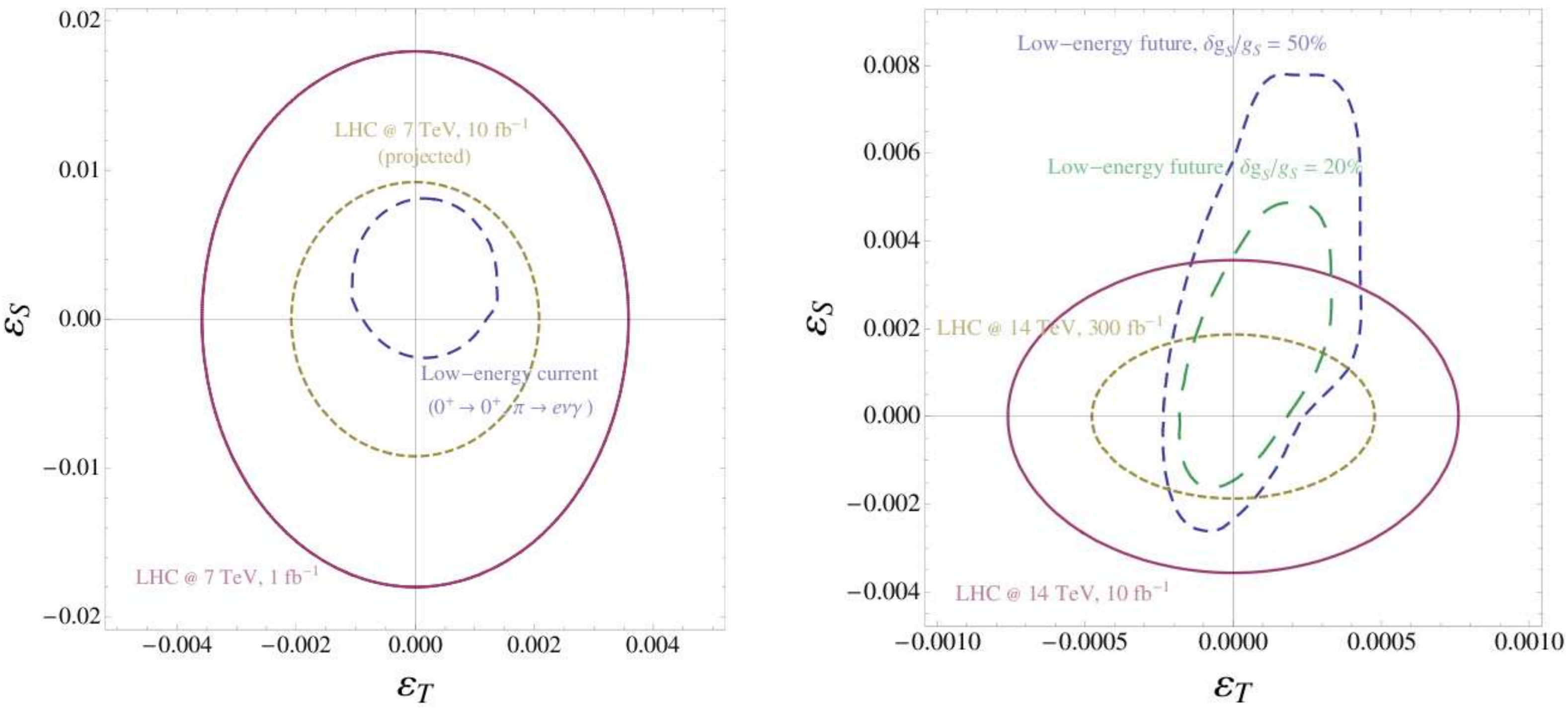


- for $m_H \sim 125$ GeV and $m_t \sim 173$ GeV the SM seems to be consistent $\lambda > 0$ (and perturbative $\lambda \ll 1$) up to very high energies   coincidence ??

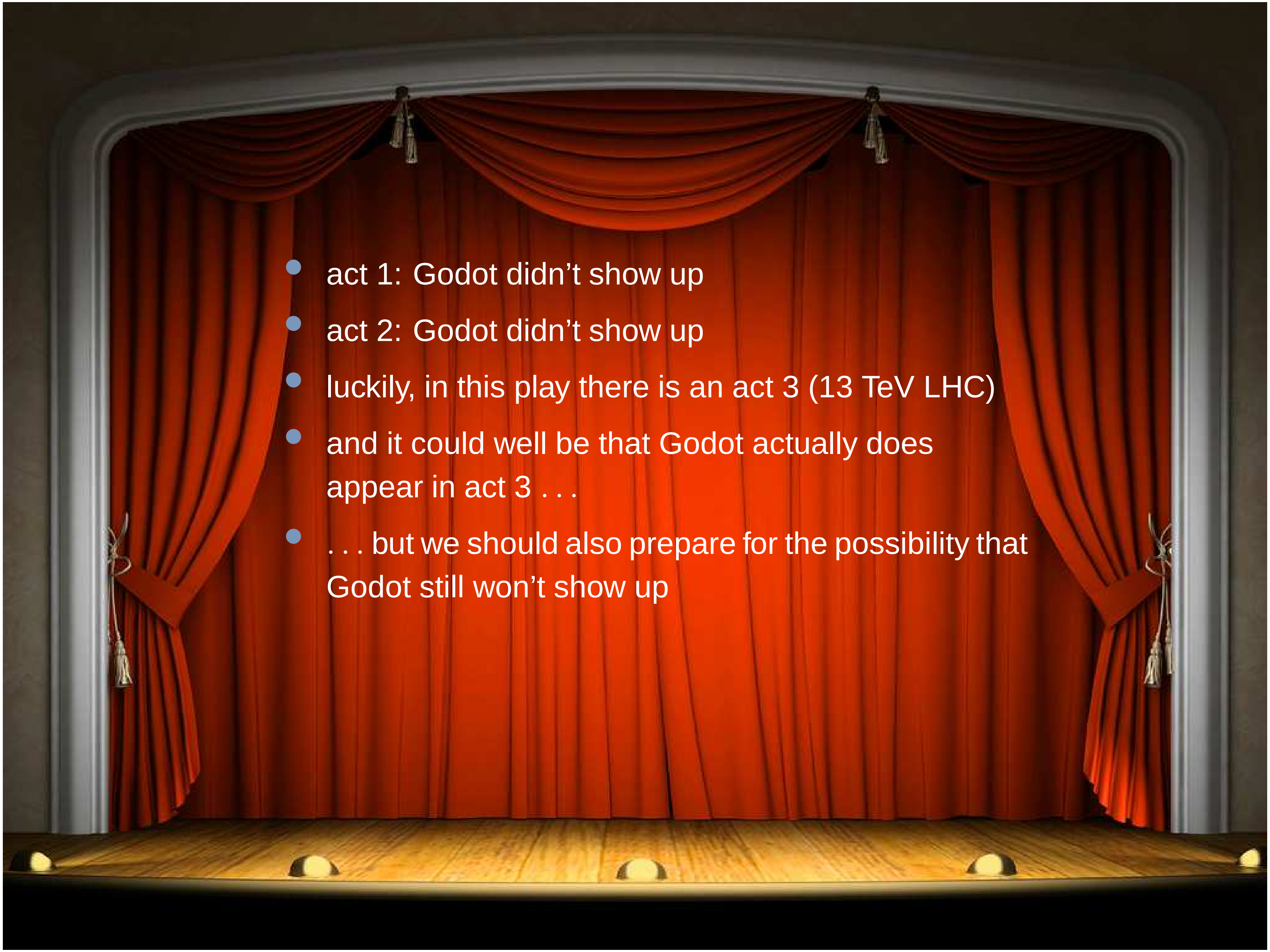
- Dim 6 operators ($+\frac{\alpha_{qde}}{\Lambda^2}(\bar{\ell}\, e)(\bar{d} q) + \frac{\alpha^t_{lq}}{\Lambda^2}(\bar{\ell}\sigma^{\mu\nu}\, e)(\bar{q}\sigma_{\mu\nu} u) + \ldots$) feed into anomalous charged current interactions $\alpha_i \to \epsilon_j$

$$\mathcal{L}_{cc} \sim \Big[(1+\epsilon_L)\, \bar{e}\gamma_\mu\nu \cdot \bar{u}\gamma^\mu d + \epsilon_S\, \bar{e}\gamma_\mu\nu \cdot \bar{u} d + \epsilon_T\, \bar{e}\sigma_{\mu\nu}\nu \cdot \bar{u}\sigma^{\mu\nu} d + \ldots\Big]$$

- “low energy” beta decay $n \to p\, e\, \nu$, requires non-perturbative input (form factors)
- “high energy” LHC $pp \to e + \mathrm{MET}$, requires non-perturbative input (pdf)
- compare constraints [Bhattacharya et al. 1110.6448] true complementarity



conclusions



- act 1: Godot didn't show up
- act 2: Godot didn't show up
- luckily, in this play there is an act 3 (13 TeV LHC)
- and it could well be that Godot actually does appear in act 3 . . .
- . . . but we should also prepare for the possibility that Godot still won't show up