ESS Science Symposium, NPP@LPS

Low energy precision physics and the high energy frontier

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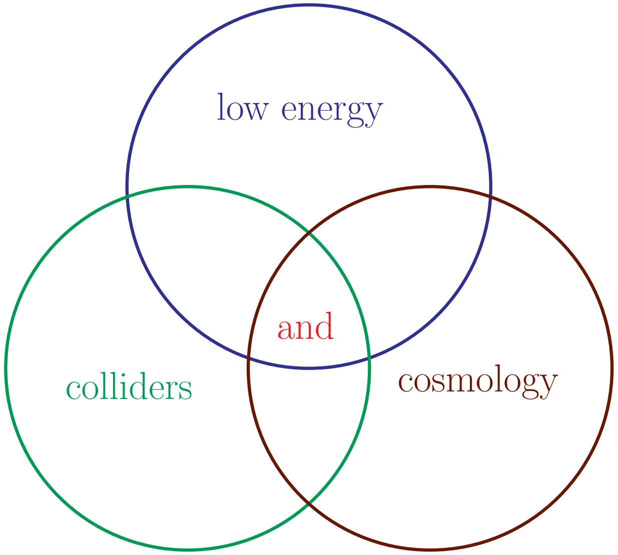
- most important word in title: “and” (and not “vs.”)



- lack of observation of BSM particles at LHC so far (no direct evidence)
- no indirect evidence of BSM physics whatsoever from colliders
- $\longrightarrow$ change of focus is under way, partially enforced
- $\longrightarrow$ take into account and try to combine all available information
- this will be even more important if no BSM signal after LHC upgrade $\rightarrow$ $13 - 14$ TeV

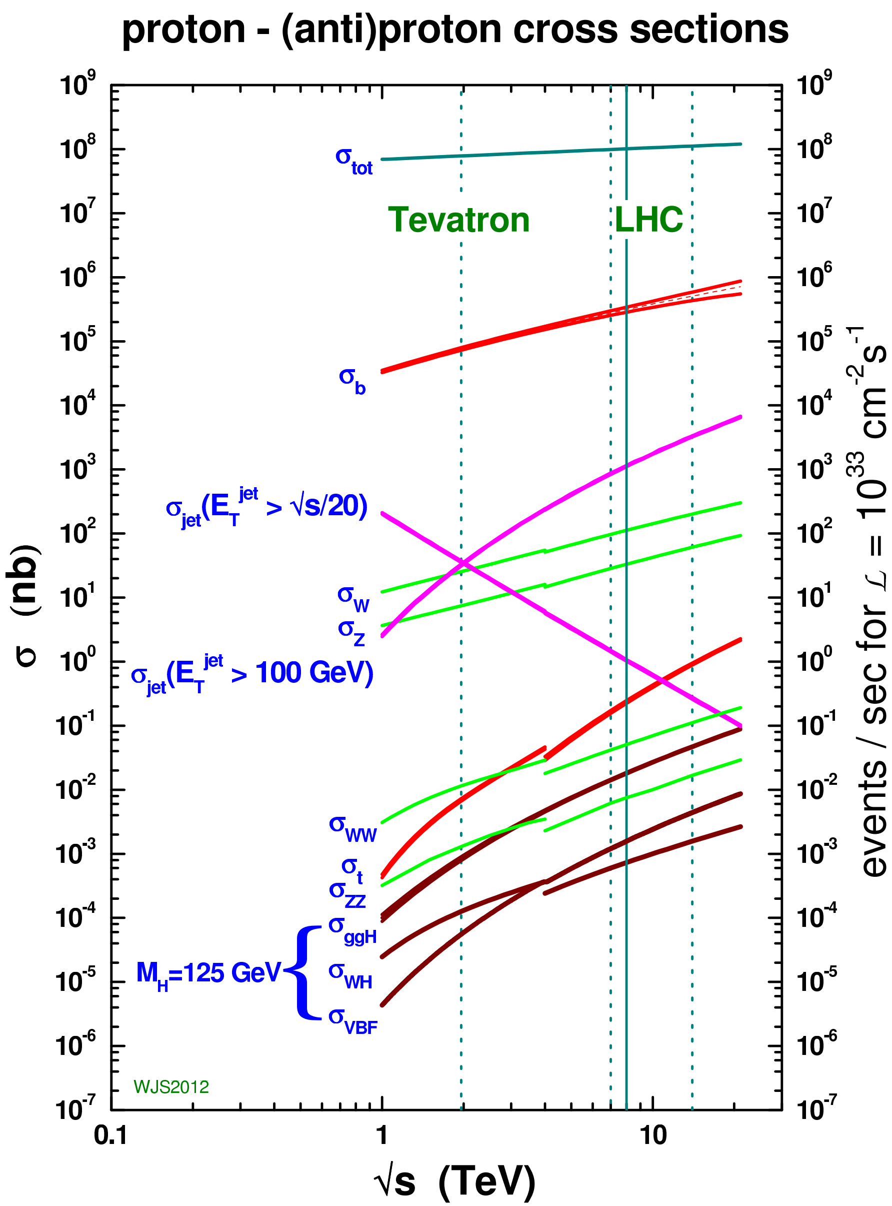
- high energy $\simeq$ direct
  BSM particles are explicitly produced and studied
- low energy $\simeq$ indirect $\simeq$ via effective theory
  consider the case where no new particles are produced in final state

- all particles of Standard Model (and only these) have been found
- up to electro-weak (EW) energies they behave as predicted by the SM
- further big step when LHC $\longrightarrow$ $13 - 14\ \mathrm{TeV}$
- long standing expectation: there is new physics at the TeV scale
  - NP real: some BSM particles explicitely produced
  - NP virtual: BSM effects through loops
- what if no deviations from SM are found at $14\ \mathrm{TeV}$ LHC

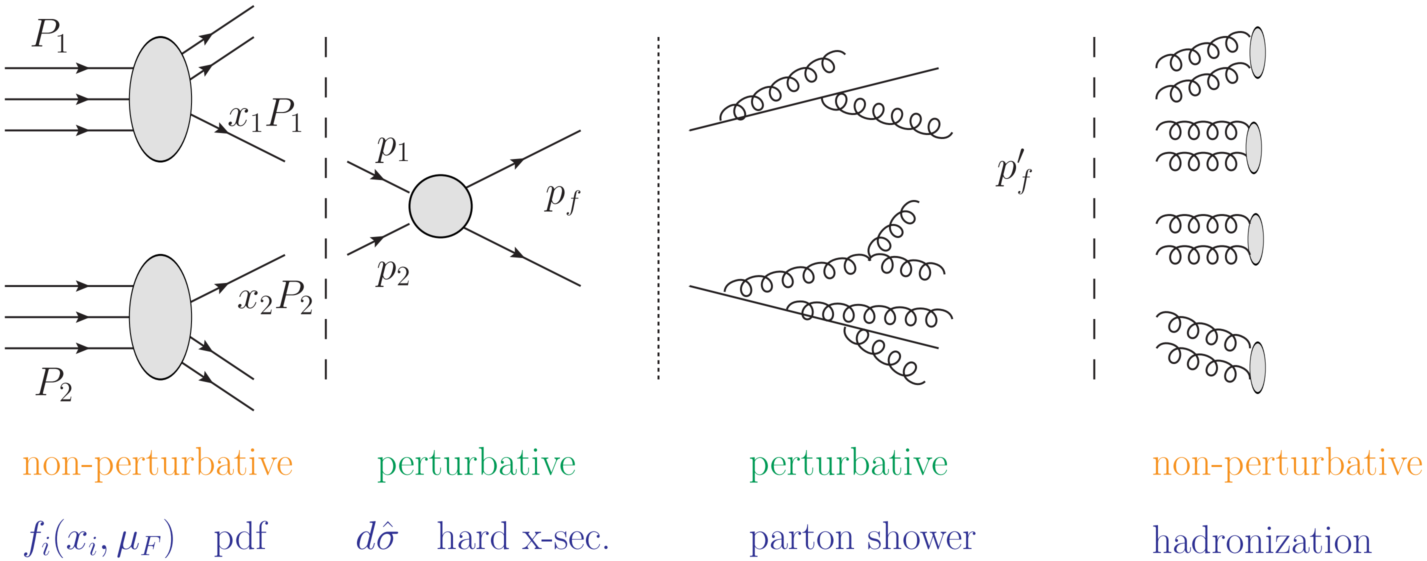
outline

precision at the LHC	• framework • theory status • precision of theory
SM and BSM as effective theory	• SM as an effective theory • limit of validity of SM • BSM as an effective theory
looking for BSM effects	• effective theory as common language • non-collider searches • collider searches • mixed collider/non-collider searches
conclusions	

- the LHC is ruled by QCD
- there is good agreement with SM (so far)
  $\Longrightarrow$ no huge deviations
- to find anything new
  - increase energy to directly produce new particles (upgrade to $13 - 14\ \mathrm{TeV}$)
  - increase precision to pin down cross sections etc. (this requires excellent understanding of QCD)
- here we focus on the precision



a process at the LHC



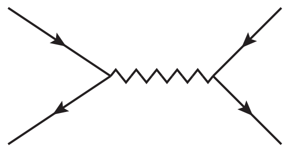
factorization theorem

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

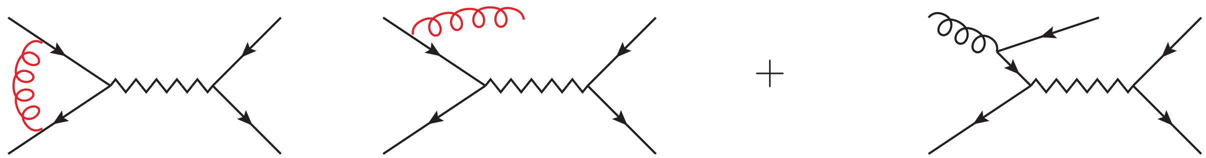
parton distribution functions	hard scattering cross section	higher twist
obtained from fits	compute as series in α_s	small for $Q \gg \Lambda_{\text{QCD}}$

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

LO

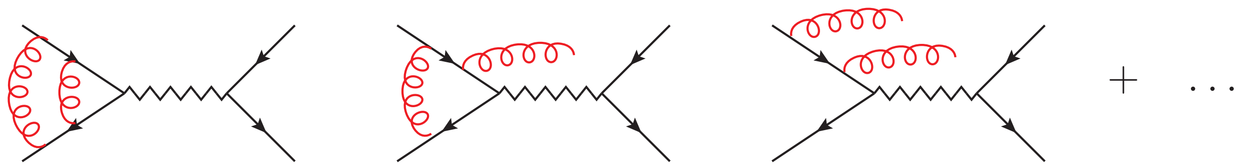


NLO



virtual | real | more channels

NNLO

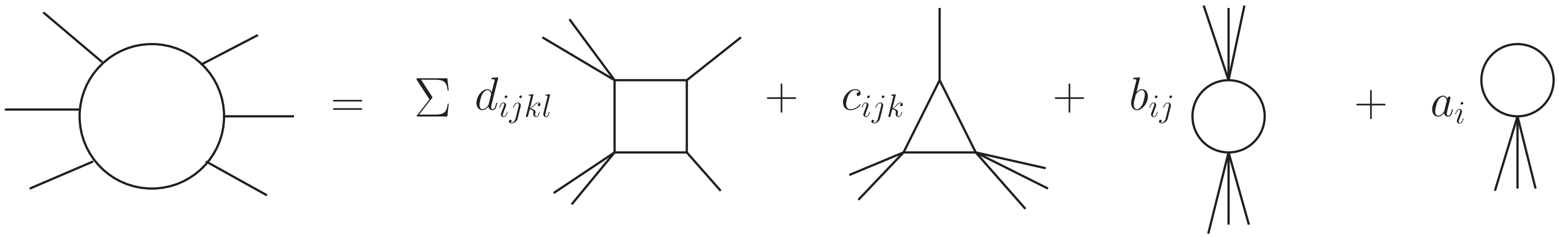


double virtual | virtual-real | double real

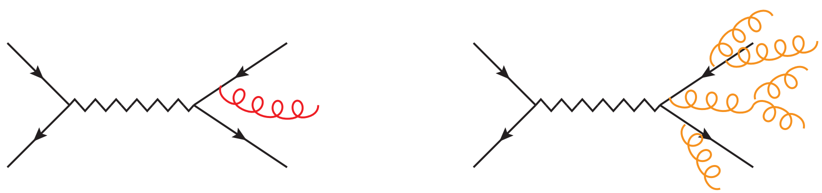
- structure simple at LO, but becomes rapidly much more complicated
- various parts (virtual, real) separately singular (soft/collinear emission)
  $\longrightarrow$ only combination is finite and physically meaningful

theory status [never-ending list of citations...]

- LO fully automatized and combined with parton showers (plug and play, even for BSM)
- NLO large degree of automatization and combined with parton showers
- huge progress in recent years [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)

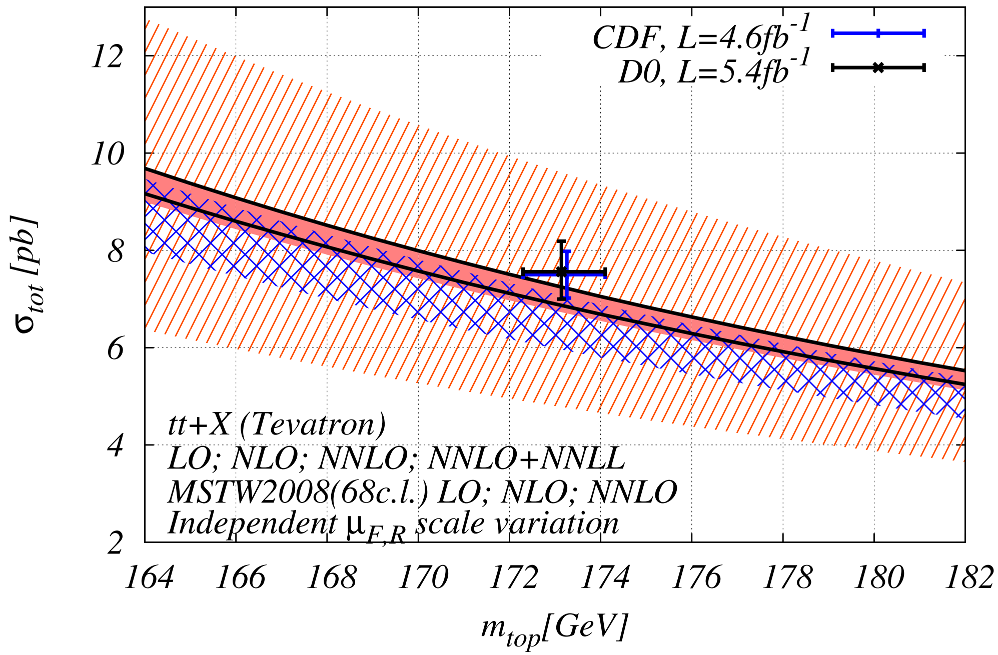


real corrections   parton shower

- NNLO: still “hand crafted” [current status $\sim 2 \to 2$]

total cross section for $p\bar{p} \to t\bar{t}$ at NNLO [Bärnreuther, Czakon, Mitov]

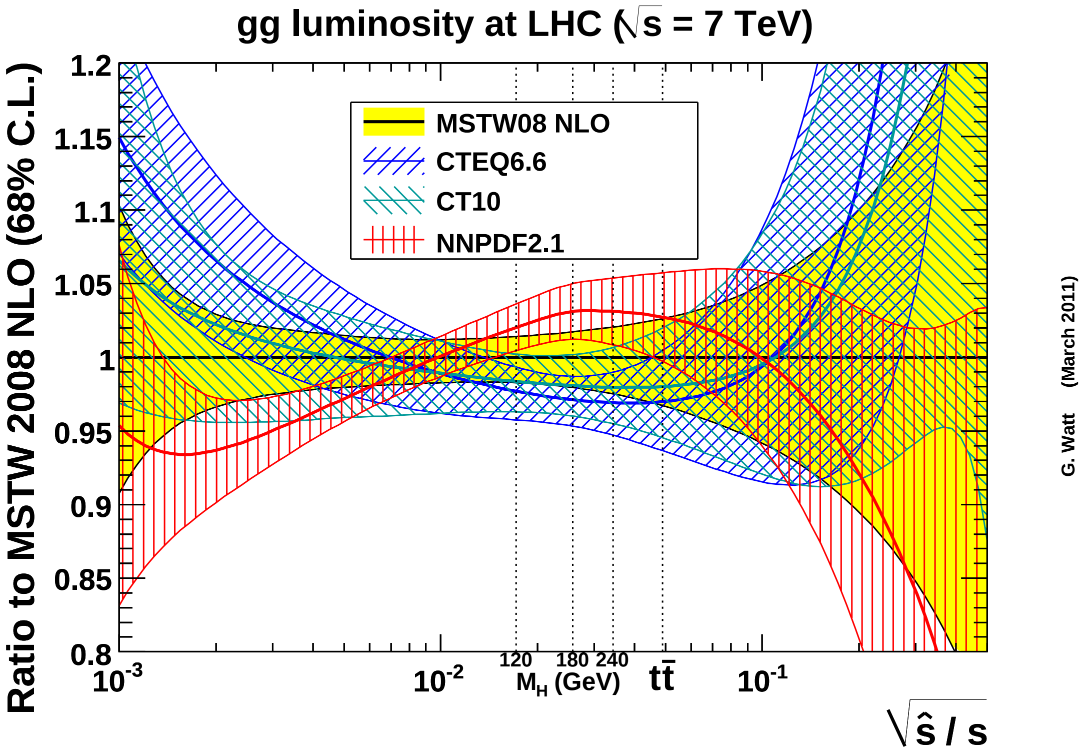
$$\hat{\sigma}_{ij} = \alpha_s^2 \Big[\sigma_{ij}^{(0)} + \alpha_s \Big(\sigma_{ij}^{(1,0)} + \sigma_{ij}^{(1,1)} \log(\mu^2/m^2) \Big) + \alpha_s^2 \Big(\sigma_{ij}^{(2,0)} + \sigma_{ij}^{(2,1)} \log(\mu^2/m^2) + \sigma_{ij}^{(2,2)} \log^2(\mu^2/m^2) \Big) \Big]$$



- state-of-the-art (numerical) NNLO calculation
- ever decreasing scale μ dependence, i.e. smaller theoretical error
- good agreement with experiment
- extraction of top-mass from total cross section becomes feasible

parton distribution functions

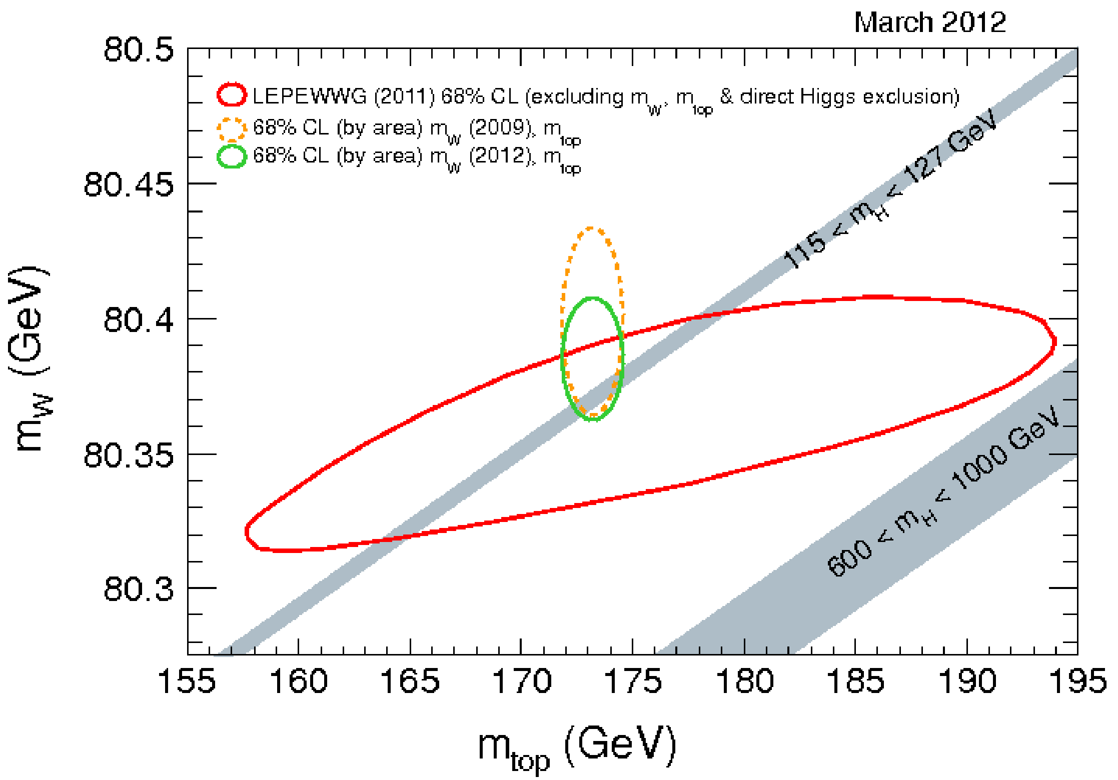
- pdf depend on order of calculation (LO, NLO, NNLO)
- several groups make global fits
- fairly good agreement between various groups
- pdf also introduce an error (sometimes the dominant 'theory' error)



plot from G.Watt (HepForge)

hadron-collider precision test

- typically theoretical error for hadron colliders $\sim 10 - 20\%$
- some quantities can be determined much more precisely e.g. [CMS Tevatron]



- relation between m_W, $m_{\rm top}$ and m_H in the SM confirmed

the Standard Model

input: gauge group $SU(3) \times SU(2) \times U(1)$: $G^{\mu\nu}$, $W^{\mu\nu}$, $B^{\mu\nu}$

3 families of matter fields (in fundamental representation): ℓ_L, q_L, e_R, u_R, d_R

one scalar doublet for good measure: Φ

output: all renormalizable (Dim ≤ 4), gauge invariant operators

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

- (mass) dimensions: $[m] = [\partial^\mu] = [A^\mu] = 1$ and $[\ell] = 3/2$ and we must have $[\mathcal{L}] = 4$.
- all operators have Dim 4, except for $\Phi^\dagger \Phi$ which requires a dimensionfull coefficient $\Lambda_{\rm UV}^2 \sim M_H^2 \quad \Longrightarrow$ hierarchy problem
- from experiment the (dimensionless) parameter θ is found to be extremely small (or 0?) $\Longrightarrow$ strong CP problem

- despite the phenomenal success of SM, it is not the theory of everything

  SM $\longrightarrow$ "only" an effective theory valid up to some scale $\Lambda_{\rm UV}$

  - dark matter, gravity, dark energy not part of SM $\Lambda_{\rm UV} = ??$
  - matter-antimatter asymmetry $\Lambda_{\rm UV} = ??$
  - strong CP problem $\Lambda_{\rm UV} \overset{?}{\sim} 10^{10}\ {\rm GeV}$
  - neutrino masses $\Lambda_{\rm UV} \sim 10^{10}\ {\rm GeV}$
  - hierarchy problem $\Lambda_{\rm UV} \sim \Lambda_{\rm EW}$
- however, BSM physics seems to be hiding very well at colliders $\Lambda_{\rm UV} \gg \Lambda_{\rm EW}$

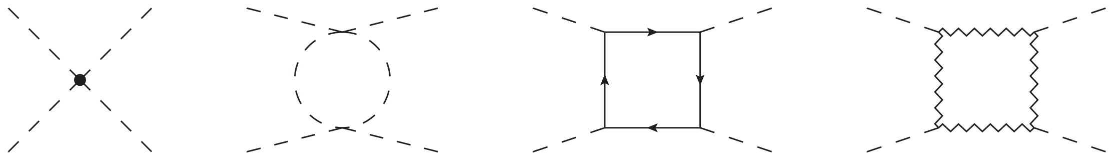
	assume $\Lambda_{\rm UV} \sim \Lambda_{\rm EW}$	assume $\Lambda_{\rm UV} \gg \Lambda_{\rm EW}$
dilemma:	$+$ M_H as expected	$-$ why is $M_H \ll \Lambda_{\rm UV}$
	$-$ BSM physics seems to conspire	$+$ BSM effects naturally small
	many small problems	one big problem

could it be the SM is valid to very high energies ?
only hierarchy problem points towards $\Lambda_{\rm NP} \sim \Lambda_{\rm EW}$

self-consistency of SM: the Higgs-Top miracle

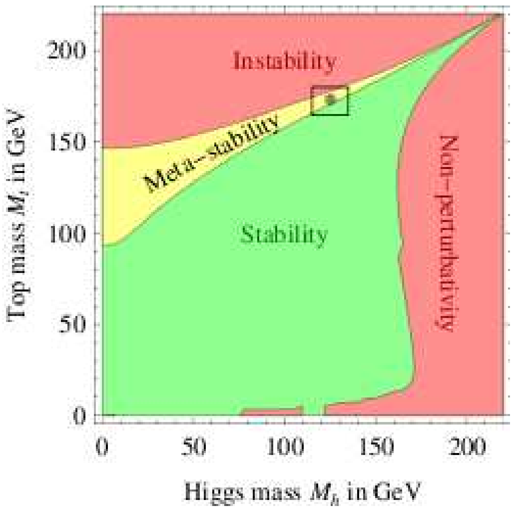
- consider self coupling of Higgs $\lambda(t)$ with $t = \ln \Lambda^2/Q_0^2$
- coupling runs:

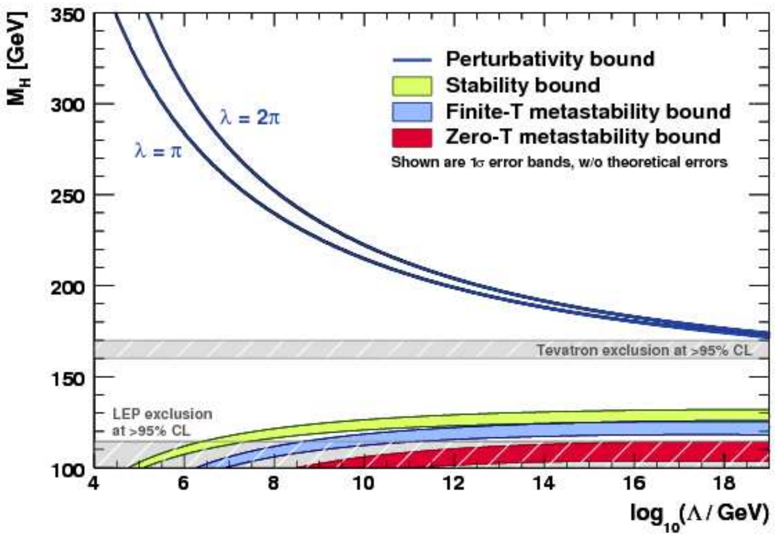
$$\frac{4\pi^2}{3}\frac{d\lambda(t)}{dt} = \lambda^2 - y_t^2 + \ldots$$



λ λ^2 y_t^4 g^4

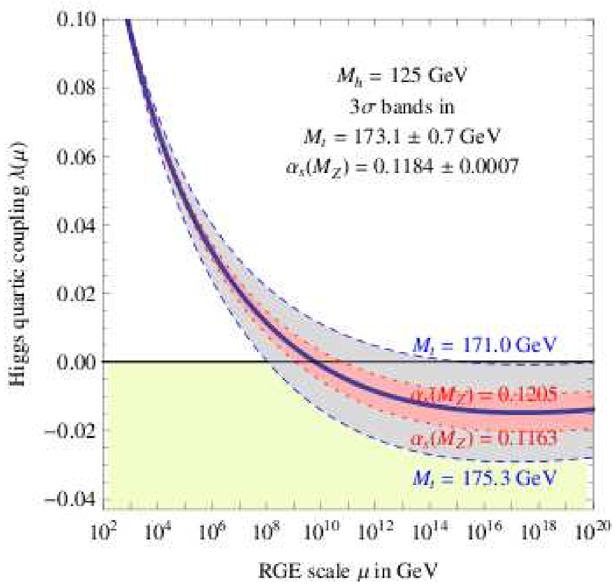
- triviality bound: $\lambda(\Lambda) = \dfrac{\lambda(Q_0)}{1 - 3/(4\pi^2)\,\lambda(Q_0)\,t} \implies 2\lambda(v)v^2 = M_H^2 < \dfrac{8\pi^2\,v^2}{3\ln(\Lambda^2/v^2)}$

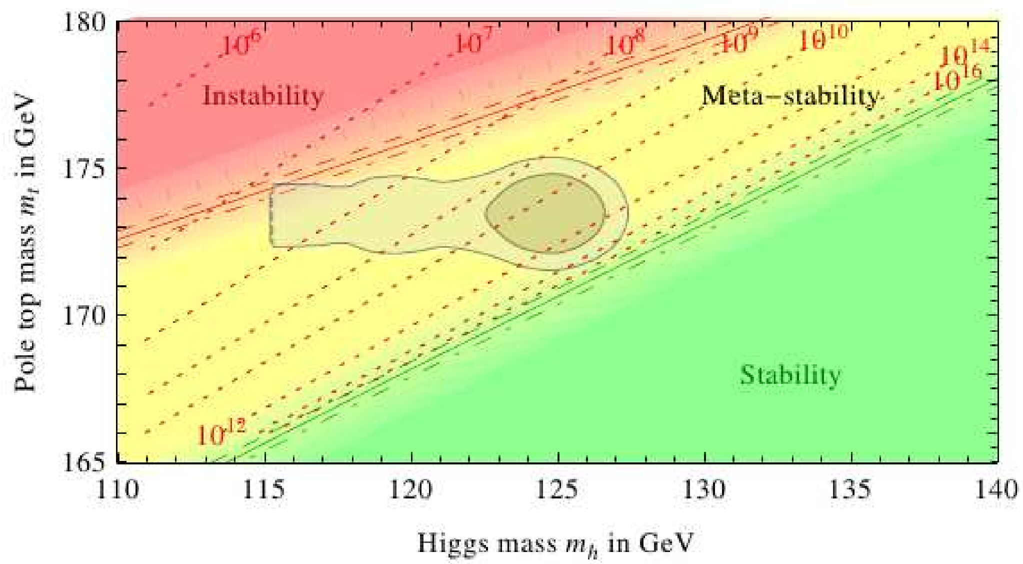




self-consistency of SM: the Higgs-Top miracle plots: [Degrassi et al. 1205.6497]

- vacuum stability: $\lambda(\Lambda) = \lambda(Q_0) - \frac{3}{4\pi^2}\, y_t^4\, t \overset{!}{>} 0 \quad\Longrightarrow\quad M_H^2 > \frac{3\, v^4\, y_t^4}{2\pi^2 v^2} \ln \frac{\Lambda^2}{v^2}$

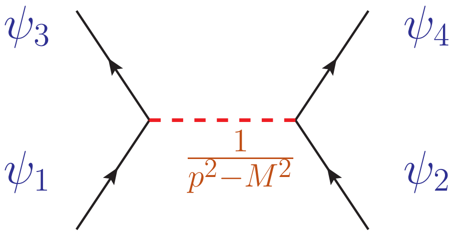




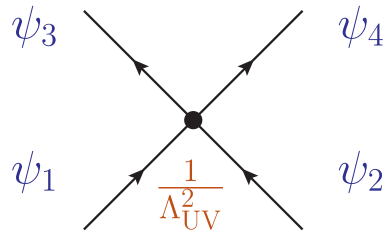
- for $M_H \sim 125$ GeV and $M_t \sim 173$ GeV the SM seems to be consistent up to very high energies $\Lambda_{\rm UV} \sim 10^9 - 10^{14}$ GeV
- is this a coincidence ?? (small M_H is not only a triumph for SUSY, but also for SM) M_t larger than expected, M_H smaller than expected, $\lambda(\Lambda_{\rm UV}) = \dot\lambda(\Lambda_{\rm UV}) = 0$

beyond the Standard Model

- standard option: new physics (particles) at a high scale $\Lambda_{\rm UV}$
- treat SM is an effective theory valid up to $\sim \Lambda_{\rm UV}$



$$\mathcal{O}^i = \frac{1}{\Lambda_{\rm UV}^2}(\bar\psi_3\Gamma^a\psi_1)\,(\bar\psi_4\Gamma^b\psi_2)$$



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

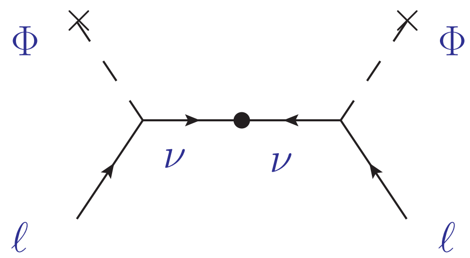
+ very general and systematic approach
– limited information, $\mathcal{L}_{\rm BSM}^{\rm ET}$ only applicable at energies $\ll \Lambda_{\rm UV}$
– not all BSM scenarios can be covered

- alternative: find the explicit model out of the infinitely many possibilities

– requires divine inspiration
+ more information, $\mathcal{L}_{\rm BSM}$ applicable at energies $\sim \Lambda_{\rm UV}$

neutrino masses

- add right handed singlet $\nu \equiv \nu_R$ to SM: $\mathcal{L}_{\rm SM} + \left(Y_\nu\, \bar\ell\, \nu_R\, \tilde\Phi + M \bar\nu\, \nu + \text{h.c.}\right)$
- Dirac mass term (as for all other fermions) $m \sim Y_\nu\, v$

  Majorana mass term (only for right-handed neutrino) $M \sim \Lambda_{\rm UV} \gg \Lambda_{\rm EW}$
- mass matrix $(\nu_L, \nu_R) \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$ eigenvalues $m_1 \sim \frac{m^2}{M}$ and $m_2 \sim M$
- view this as 

and integrate out heavy ν field
- $\Longrightarrow$ Dim 5 (Weinberg) operator: $\mathcal{L}^{\rm ET}_{\rm SM} + \frac{c^{(5)}}{M} (\bar\ell\, \tilde\Phi)(\bar\ell\, \tilde\Phi)$
- $M \sim \Lambda_{\rm UV} \sim 10^{11}$ GeV to generate masses consistent with experiment
- Weinberg operator is the only possible Dim 5 operator

axion the strong CP problem and dark matter

- $\mathcal{L}_{\rm SM} \supset \frac{\alpha_s}{8\pi}\bar\theta\, G^{\mu\nu}\tilde G_{\mu\nu}$ CP-violating term in QCD
- no effect in perturbation theory, but cannot be ignored
- bounds from experiment (neutron EDM) $\bar\theta \lesssim 10^{-10}$, why so small ??
- drastic measure: add new field, axion a (dynamical θ parameter)

$$\mathcal{L}_{\rm BSM} \supset \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{\alpha_s}{8\pi}\left(\bar\theta + \frac{a}{f_a}\right) G^{\mu\nu}\tilde G_{\mu\nu}$$

- nontrivial potential s.t. $\langle \bar a\rangle \equiv \langle \theta + \frac{a}{f_a}\rangle = 0$, i.e. $V(0) < V(a)$

  excitations about minimum correspond to particle axion
- axion is pseudo-Goldstone boson
  - $\Longrightarrow$ with global Peccei-Quinn $U(1)$ symmetry broken at high scale f_a
  - $\Longrightarrow$ axion has very small mass $m_a \simeq m_\pi^2/f_a$ and slim interactions
- axion is a good dark matter candidate for $f_a \simeq 10^{10}\ {\rm GeV} \Longrightarrow m_a \simeq 10^{-3}\ {\rm eV}$

BSM via effective theory

- absence of large BSM effects “explained” by requiring $\Lambda_{\rm UV} \gg \Lambda_{\rm EW}$
- classify Dim 6 operators (~ 60) [Buchmüller, Wyler; Grzadkowski et al.]

$$\mathcal{L}^{\rm ET}_{\rm BSM} = \mathcal{L}^{\rm ET}_{\rm SM} + \frac{c^{(5)}}{\Lambda_{\rm UV}} (\bar\ell\,\tilde\Phi)(\bar\ell\,\tilde\Phi)$$

$$+ \frac{c^{(6)}_{0F}}{\Lambda^2_{\rm UV}}\, f\, G_\mu^{\ \nu} G_\nu^{\ \rho} G_\rho^{\ \mu} + \frac{c^{(6)}_{2F}}{\Lambda^2_{\rm UV}}\, \bar q \sigma^{\mu\nu} u\, \Phi G_{\mu\nu} + \frac{c^{(6)}_{4F}}{\Lambda^2_{\rm UV}}\, \bar q \Gamma q\, \bar e \Gamma e + \ldots$$

- can always link an explicit (large-scale) BSM model to ET, by calculating coefficients $c^{(6)}_{nF}$ of operators in ET
- within ET, the coefficients are independent and matrices in family space ($\longrightarrow$ lepton flavour violation)
- coefficients of SM operators are also free to deviate from SM values
  $\Longrightarrow$ tested e.g. in search for anomalous triple/quartic gauge couplings
- $\mathcal{L}^{\rm ET}_{\rm BSM}$ does not describe dynamics of BSM particles

classification of Dim 6 operators [Grzadkowski et al.]

- write everything in terms of left-handed L and right-handed R fermion fields
- 15 operators with 0 fermion fields
  - pure gauge e.g. $\epsilon^{IJK}\, W_\mu^{I\ \nu}\, W_\nu^{J\ \rho}\, W_\rho^{K\ \mu}$ $\longrightarrow$ anomalous triple/quartic gauge couplings
  - Higgs e.g. $(\Phi^\dagger D_\mu \Phi)^*(\Phi^\dagger D^\mu \Phi)$ $\longrightarrow$ anomalous Higgs couplings
- 19 operators with 2 fermion fields
  - anomalous currents e.g. $\bar\ell_p \sigma^{\mu\nu} e_r \phi\, B^{\mu\nu}$ $\longrightarrow$ lepton-flavour violation
  - Higgs e.g. $(\Phi^\dagger D_\mu \Phi)(\bar\ell_p \gamma^\mu \ell_r)$ $\longrightarrow$ anomalous Higgs-fermion couplings
- 25 operators with 4 fermion fields $(\bar L L)(\bar L L)$, $(\bar R R)(\bar R R)$ ...
  - e.g. $(\bar L L)(\bar R R)$: $(\bar\ell_p \gamma^\mu \ell_r)(\bar e_s \gamma^\mu e_t)$ $\longrightarrow$ contact interactions
  - e.g. $(\bar L R)(\bar R L)$: $(\bar\ell_p e_r)(\bar d_s q_t)$ $\longrightarrow$ contact interactions
- 'basis' not unique !!

  Fierz identities, equations of motions $\rightarrow$ many different conventions

charged current LFV

indirect tests @ LHC vs neutron/pion decay tests

- neutrino oscillation $\Longrightarrow$ lepton flavour violation
- test LFV also in charged sector
- Dim 6 operators in effective theory

$$\mathcal{L}_{\rm SM} + \frac{\alpha_{qde}}{\Lambda^2}(\bar\ell\, e)(\bar d q) + \frac{\alpha^t_{lq}}{\Lambda^2}(\bar\ell \sigma^{\mu\nu}\, e)(\bar q \sigma_{\mu\nu} u) + \ldots$$

- going to smaller energies (below EW breaking sale)
- these operators feed into anomalous charged current interactions $\alpha_i \to \epsilon_j$

$$\mathcal{L}_{\rm cc} = -\frac{G_F V_{ud}}{\sqrt{2}}\Big[(1+\epsilon_L)\, \bar e \gamma_\mu P_L \nu \cdot \bar u \gamma^\mu P_L d$$

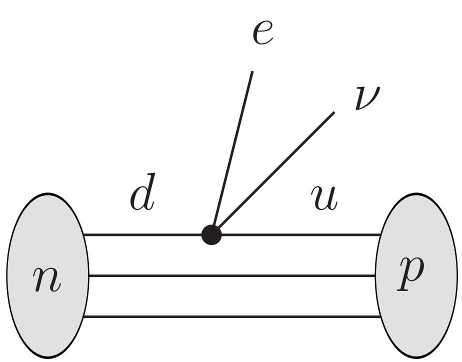
$$+ \epsilon_S\, \bar e P_L \nu \cdot \bar u d + \epsilon_T\, \bar e \sigma_{\mu\nu} P_L \nu \cdot \bar u \sigma^{\mu\nu} P_L d + \ldots\Big]$$

- this is a “standard procedure”, also used for tests on anomalous TGC, top couplings, Higgs couplings etc.

indirect tests @ LHC vs neutron decay tests

can test the same BSM 4-fermion operator(s) in completely different contexts

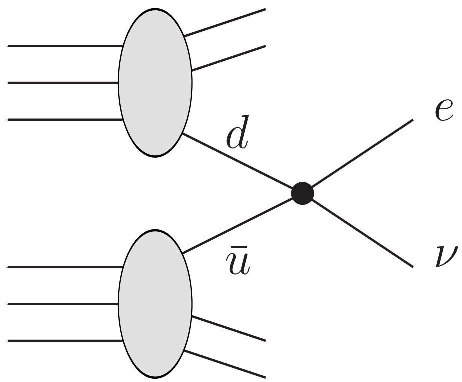
beta decay $n \to p\, e\, \nu$



via form factors $\langle p|\bar{u}d|n\rangle \sim g_{S/T}(\mu^2)$

SM-BSM interference leading $\sim \dfrac{1}{\Lambda_{\rm UV}^2}\dfrac{m_f}{E}$

$pp \to e\nu + X$ = $pp \to e +$ MET

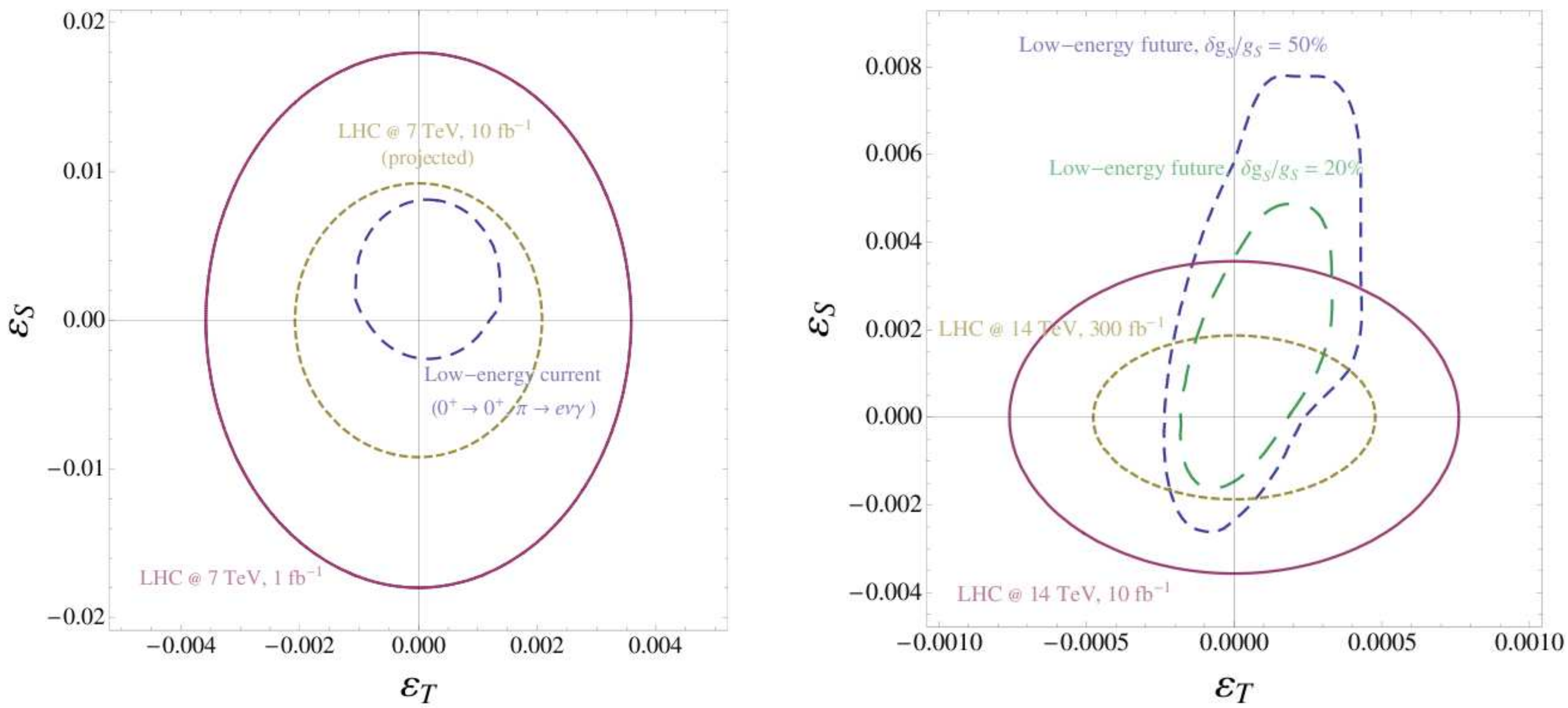


via pdf $\int dx_1 dx_2\, f_1(x_1) f_2(x_2) d\hat{\sigma}$

BSM-BSM leading $\sim \dfrac{\hat{s}}{\Lambda_{\rm UV}^4}$

also other form factors and other final-state flavour (LHC)

- “low energy” beta decay $n \to p\, e\, \nu$, requires non-perturbative input (form factors, from Lattice or measurements)
- “high energy” LHC $pp \to e + \mathrm{MET}$, requires non-perturbative input (parton distribution functions, from measurements)
- compare constraints [Cirigliano et al.] true complementarity

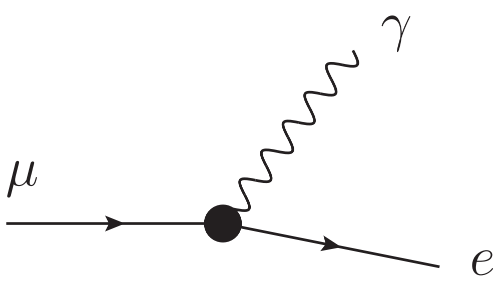


[Bhattacharya et al. 1110.6448]

indirect tests vs direct tests

- “virtual”/indirect tests for $\mu \to e\gamma$ and $\mu \to e\,e\,e$ extremely powerfull
- also done as “real”/direct test at LHC e.g. assuming R-parity violating sneutrino
- LHC bounds can/should also be interpreted as limit on 4-fermion operator

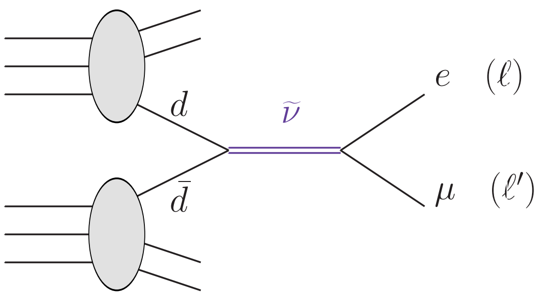
$\mu \to e\gamma$



much more constraining

could dig out tiny signal

$pp \to e\mu \quad (\ell\ell')$



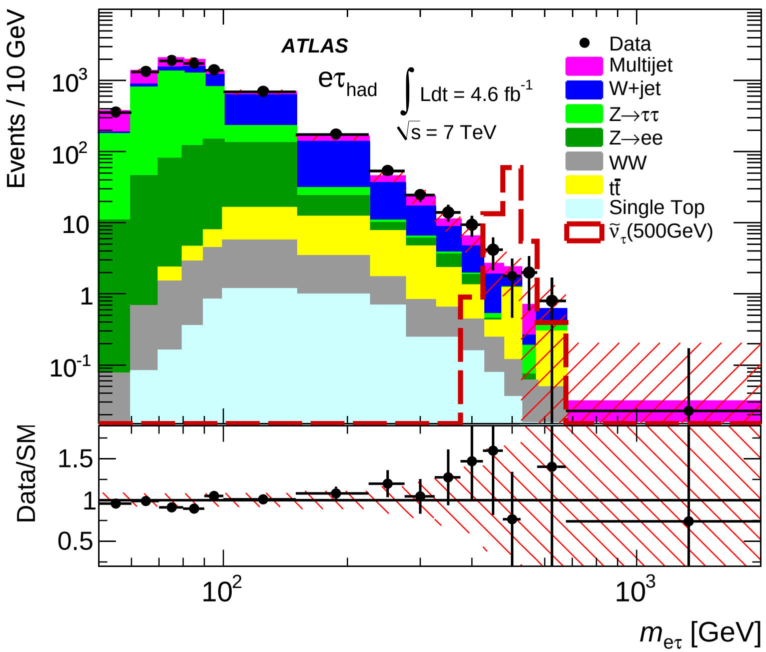
more general (all flavours)

may reach $\Lambda_{\rm UV} \sim m_{\tilde{\nu}}$

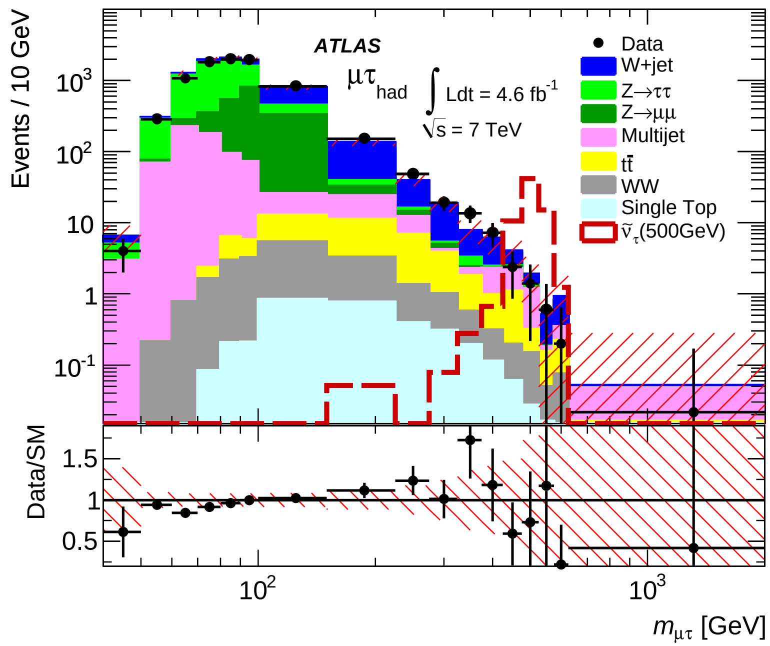
indirect tests vs direct tests

- e.g. ATLAS search for narrow resonances decaying to $e\mu$, $e\tau$ or $\mu\tau$
- compare observation with SM and signal simulation $m_{\ell\ell'} = 500\ \mathrm{GeV}$ in R-parity violating $\tilde{\nu} \to \ell\,\ell'$ [Atlas: 1212.1272]

$pp \to e\tau$



$pp \to \mu\tau$

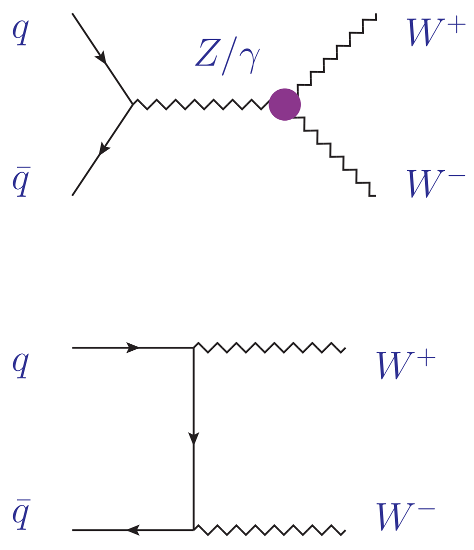


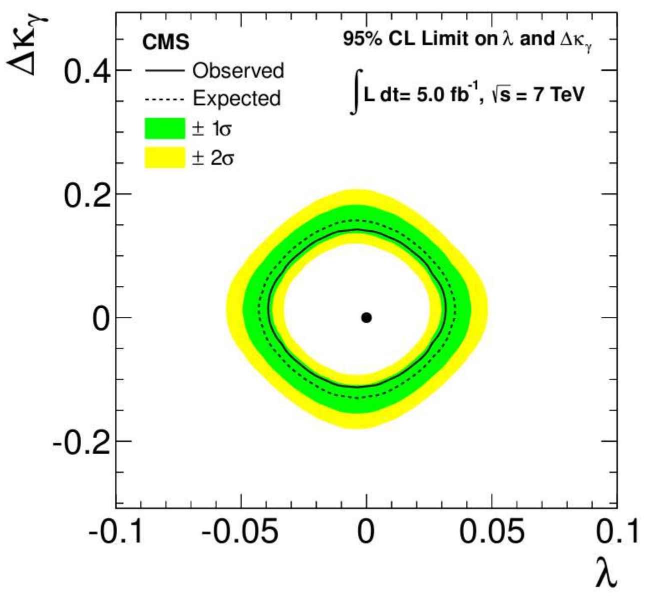
tests of triple gauge couplings (TGC) at LEP/Tevatron/LHC

- consider subset of $\mathcal{L}_{\rm SM}^{\rm ET}$, $\quad V \in \{\gamma, Z\}$

$$\mathcal{L} \simeq (1+\Delta g_v) W_{\mu\nu} W^{\mu} V^{\nu} + (1+\Delta\kappa_v) W_{\mu} W_{\nu} V^{\mu\nu} + \frac{\lambda_V}{\Lambda^2} W_{\mu\nu} W^{\nu}_{\rho} V^{\rho\nu}$$

- ET: insist on $SU(2)\times U(1)$ gauge invariance $\Longrightarrow$ constraints $\Delta g_\gamma = 0$ and $\lambda_\gamma = \lambda_Z$
- measure WW,WZ, $W\gamma \ldots$ cross section and obtain limits on (or find) anomalous couplings Δg_v, $\Delta\kappa_v$, λ_V (but form factors needed)
- recent example for $\sigma_{WW} + \sigma_{WZ}$ [CMS, 1210.7544]





Lorentz and CPT violation via effective theory

- assume spontaneous Lorentz breaking in underlying fundamental theory at very high scale $\Lambda \sim M_{\rm P}$ [Colladay, Kostelecky]
- SM/QED Lagrangian modified: $\mathcal{L}_{\rm QED}^{\rm eff} = i\,\bar\psi\gamma_\mu^{\rm eff} D^\mu \psi - \bar\psi m^{\rm eff}\psi$

$$\gamma_\mu^{\rm eff} = \gamma_\mu + c_{\mu\nu}\gamma^\nu + d_{\mu\nu}\gamma_5\gamma^\nu + e_\mu + \ldots$$

$$m^{\rm eff} = m + a^\nu\gamma_\nu + b^\nu\gamma_\nu\gamma_5 + \ldots$$

- induced parameters $c_{\mu\nu}$, $d_{\mu\nu}$, a^ν etc $\Longrightarrow$ (particle) Lorentz-violating and CPT-violating extension of SM
- theory still invariant under observer Lorentz transformations
- can test Lorentz and CPT invariance without having to understand Planck-scale physics !
- tests/limits on all energy scales: from study of hydrogen spectrum to effects in top quark (e.g. m_t vs $m_{\bar t}$)

conclusions

- maybe the SM is even better than we think, $\Lambda_{\rm NP} \gg \Lambda_{\rm EW}$ is a possibility!
- if we can directly access BSM physics
  - with an explicit model coefficients of ET-operators can be computed
  - consistency checks between various observables (high-energy vs low energy)
- if we cannot directly access BSM physics
  - ET approaches offer a method to study large classes of BSM effects
  - ET applied at different levels, depending on what is integrated out and what is kept dynamical
- not everything can be covered by ET approach but for many/most cases ET provides a common language
- recently a move towards using ET-framework in many different areas at LHC (Higgs, Top, EW-bosons, LFV . . .)

$\Longrightarrow$ good news for combining high-energy, high-precision and cosmology frontier