Particle physics: present and future

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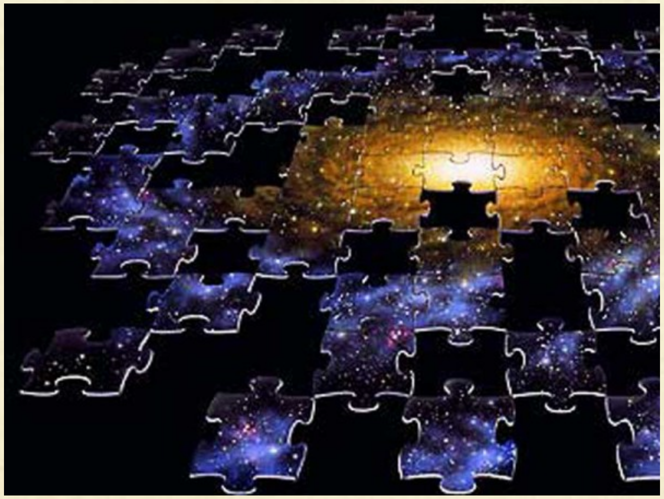
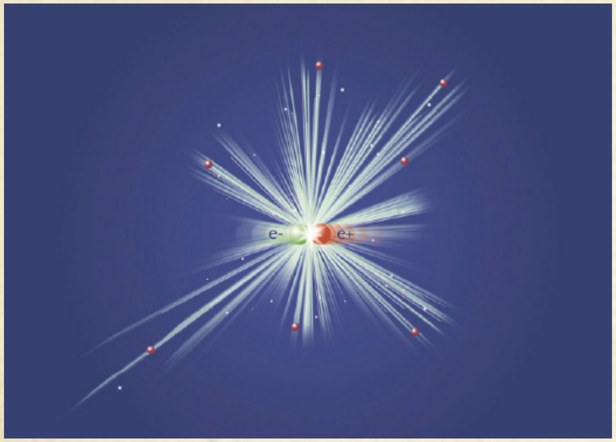
Plan for this talk:

- ✓ The Big picture
- ✓ The modern physics at particle accelerators
- ✓ Where is New Physics?
  - ✓ Searches
  - ✓ Precision applications
- ✓ Figuring out "the desert"
  - ✓ Help from the SM
  - ✓ Dark Matter

The Big Picture



Particle physics is driven by the belief that:



… are driven and described by the same microscopic forces

This, of course, is not a new idea:

The quest for understanding what is basic and fundamental is old and has been constantly evolving

- ✓ At first, electron and proton were fundamental.
- ✓ Then the neutron decay introduced the possibility of a new particle (neutrino)
- ✓ The number of fundamental particles “jumped” once antiparticles were predicted/discovered
- ✓ Detailed studies of cosmic rays and first accelerators led to the proliferation of new strongly interacting particles

The particle zoo of the 1950’s

100’s of strongly interacting particles; could not be described theoretically

It was a wild time: plenty of data that could not be fit by the then-models

Soon enough, and quite unexpectedly, this desperation turned into a major triumph:

- ✓ Non-abelian (Yang-Mills) theories were suggested
- ✓ Weinberg-Salam model
- ✓ Higgs mechanism (the big wild card)
- ✓ Asymptotic freedom for SU(3) gauge theory was discovered
- ✓ CKM paradigm was formulated

Then all collapsed neatly at the next fundamental level: the Standard Model.

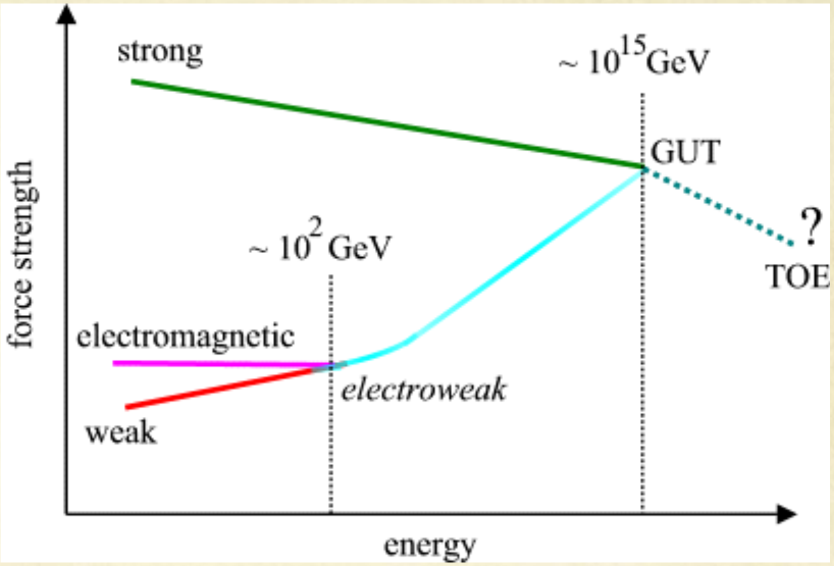
The world is actually simple; it consists of quarks and leptons and our theories DO work!

This is where we stand today

Of course, such a success was amazing; and since history repeats itself we can guess the next fundamental level:

GUT (Grand Unified Theory)

Simplify theory's structure (coupling unification):



It is all about the desert:

Is it merely a desert?

Or an oasis?

Or perhaps a jungle?

Since the idea of GUT was proposed, plethora of new ideas have appeared:

- ✓ SUSY
- ✓ New Strong Dynamics
- ✓ Extra Dimensions
- ✓ Including new formal developments (string theory)

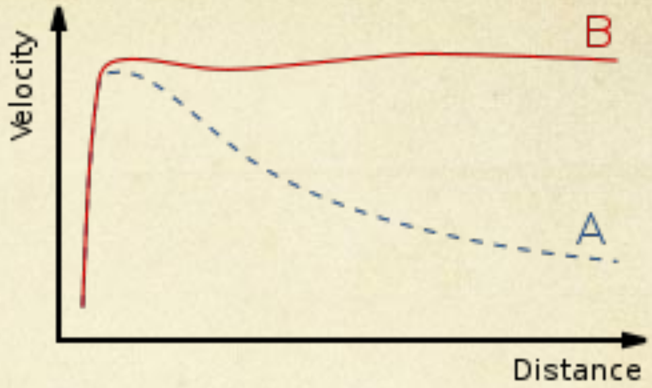
The funny thing is that today is kind of the opposite to the 1950's

- ✓ Plenty of data,
- ✓ Plenty of models and ideas
- ✓ But no deviations from our models.

Really?

The Dark Matter Problem

The famous galactic rotation curves problem:

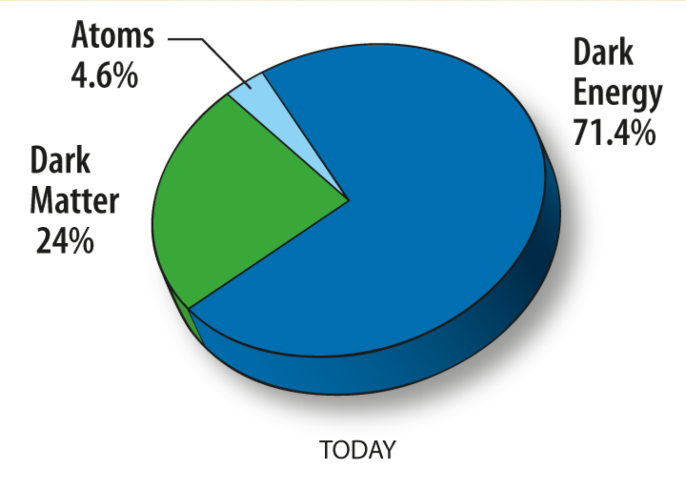


Fritz Zwicky '1933

Born Varna, Bulgaria

Dramatic departure from the expectation based on Newtonian dynamics

Especially after WMAP it became clear that:



8

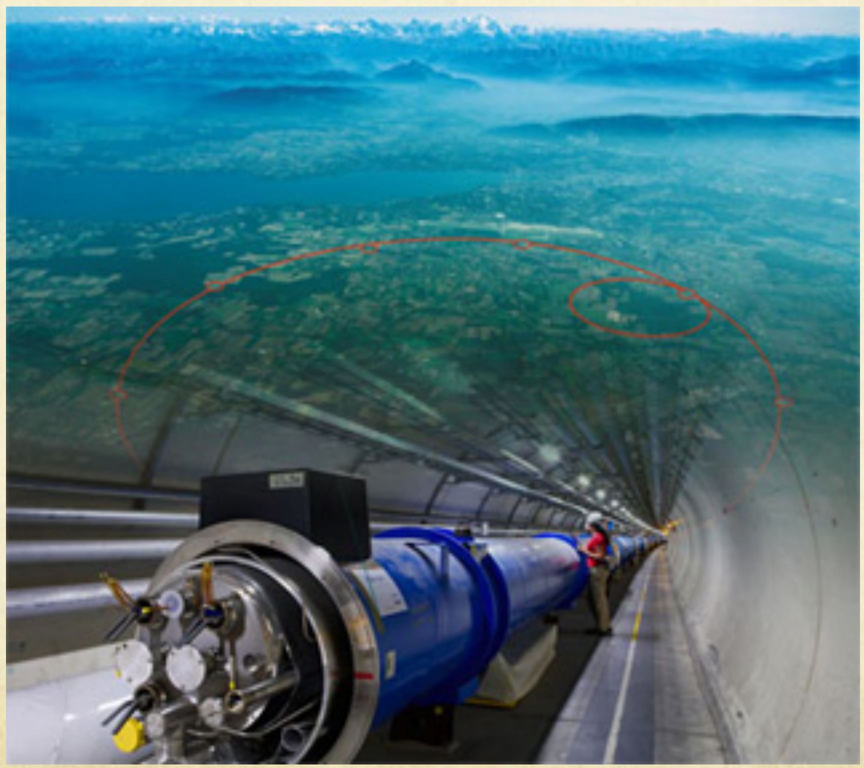
Why did I bring Dark Matter into this discussion?

- ✓ It is an important problem on its own right
- ✓ It has to have some microscopic explanation
- ✓ (more subtle) If there is a jungle of particles in the desert, then such new physics offers Dark Matter candidates.

In a way, conceptually, New Physics implies a resolution to the dark matter problem.

I should mention the opposite is not implied. Will return to this later.

The modern physics at particle accelerators

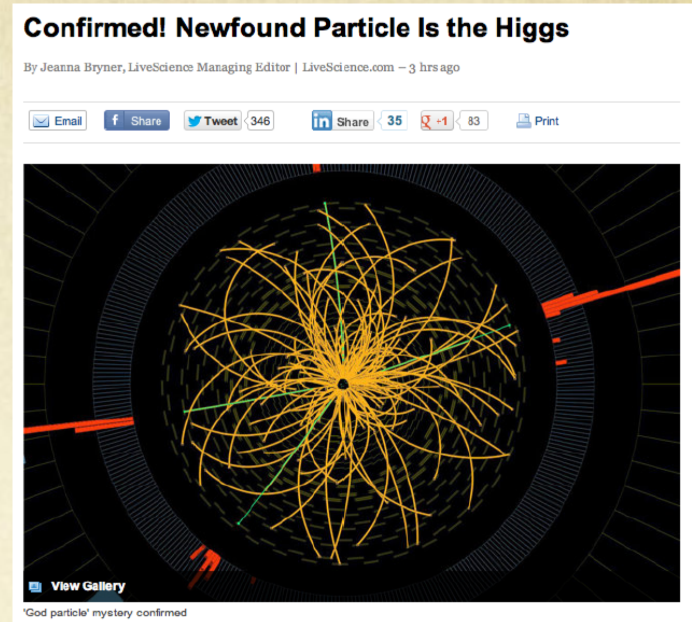


We have had great successes at accelerator-based physics in the recent past

Discovered the Higgs (-like) boson:

… established the CKM paradigm:

The biggest question today is: <u>what's the story with the Higgs?</u>



Well, look at the main news outlets today:

Well, not quite, but it depends on which experiment you ask ☺

CERN Press Release (14 march 2012):
"New results indicate that particle discovered at CERN is a Higgs boson"

- ✓ *CMS spokesperson Joe Incandela:*
  "The preliminary results with the full 2012 data set are magnificent and to me it is clear that we are dealing with a Higgs boson though we still have a long way to go to know what kind of Higgs boson it is."

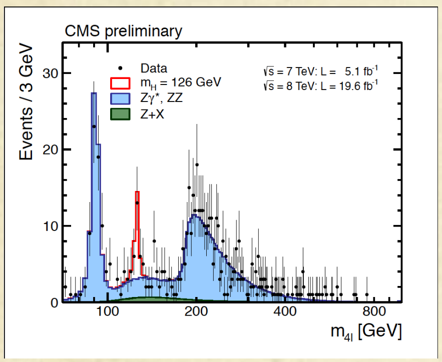
- ✓ *ATLAS spokesperson Dave Charlton:*
  "The beautiful new results represent a huge effort by many dedicated people. They point to the new particle having the spin-parity of a Higgs boson as in the Standard Model. We are now well started on the measurement programme in the Higgs sector".

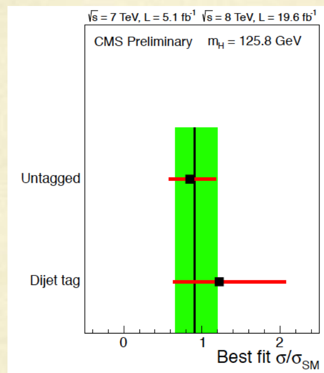
CMS: agrees well with SM Higgs boson with mass ~126 GeV

For Moriond 2013:

- $H \to ZZ \to 4\ell$
- $H \to WW \to 2\ell 2\nu$
- $H \to \gamma\gamma$

- Red: new update
- Blue: no new update





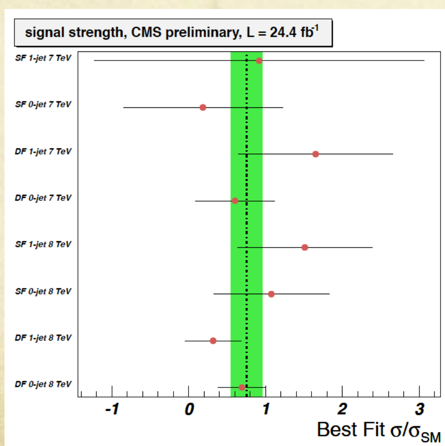
$H \to ZZ \to 4\ell$

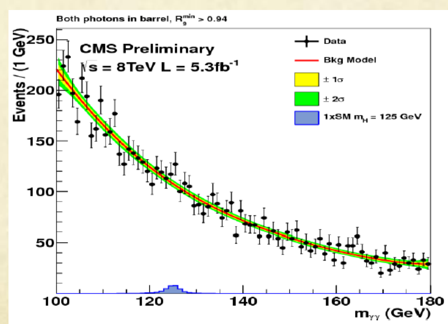
agrees well with SM in CMS

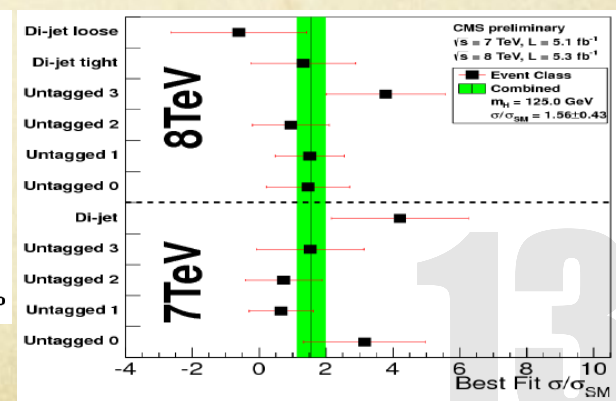
$H \to \gamma\gamma$

$H \to WW \to 2\ell 2\nu$

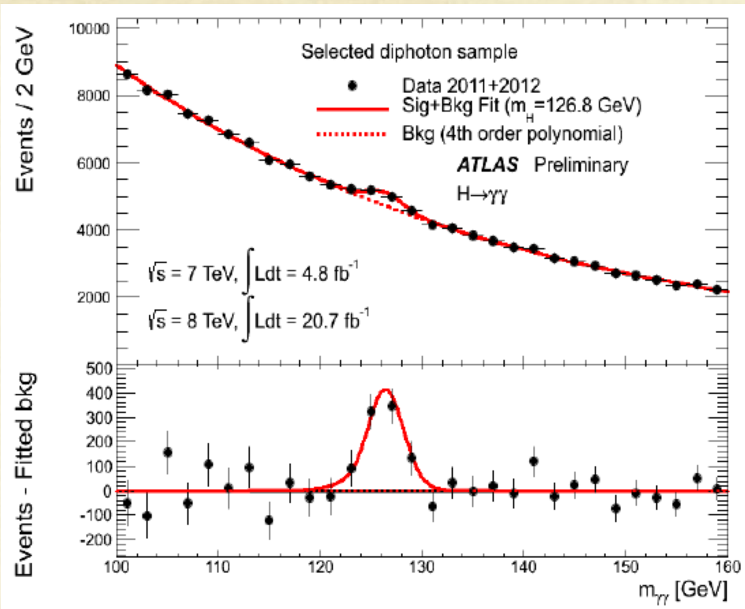
$\sigma/\sigma_{SM} = 0.76 \pm 0.21$

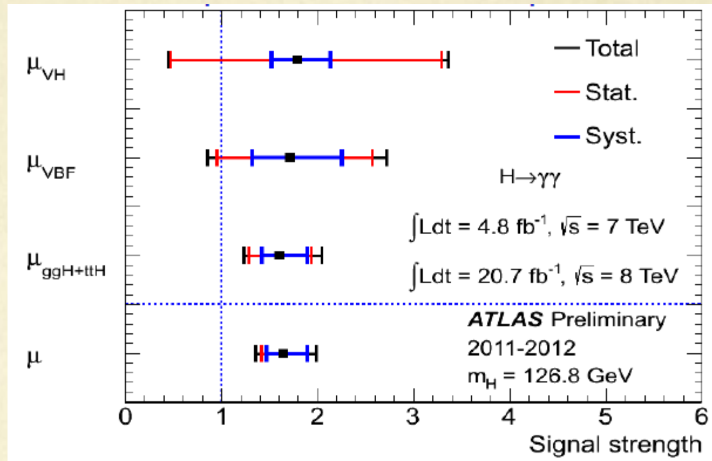


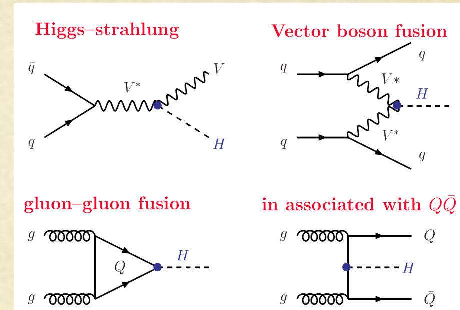




ATLAS **H→γγ**



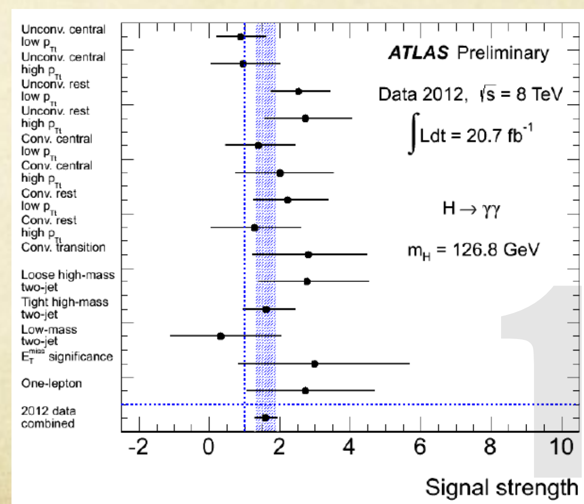




Best mass fit: 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV

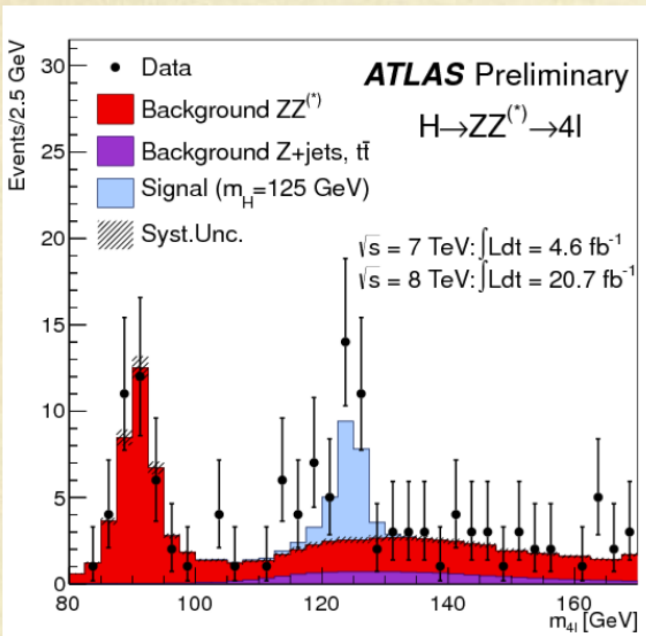
Exp/Theory: $\mu=1.65^{+0.34}_{-0.30}$ = 1.65 ± 0.24 (stat) $^{+0.25}_{-0.18}$ (syst)

2.3σ from SM Higgs + background hypothesis



14

ATLAS **$H \rightarrow ZZ^{(*)} \rightarrow 4l$**



- Observed local significance of the excess: **6.6σ**
  (4.4σ expected for SM Higgs)
- Best mass fit **$124.3^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV**
  [measurement dominated by 4μ – 0.2% systematics from p_T-scale]
- Signal strength @ this mass: **$\mu = 1.7^{+0.5}_{-0.4}$**
  [@ 125.5 GeV: μ =1.5 ± 0.4]

Note the persistent difference in Higgs masses extracted in the two decay channels

✓ We do not know yet what the resolution is.

✓ But such a discrepancy is great; it could be that something is just about to manifest itself!

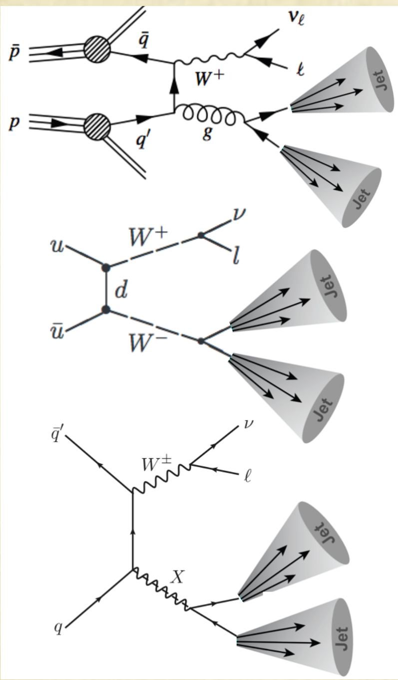
Or, it could be a combination of

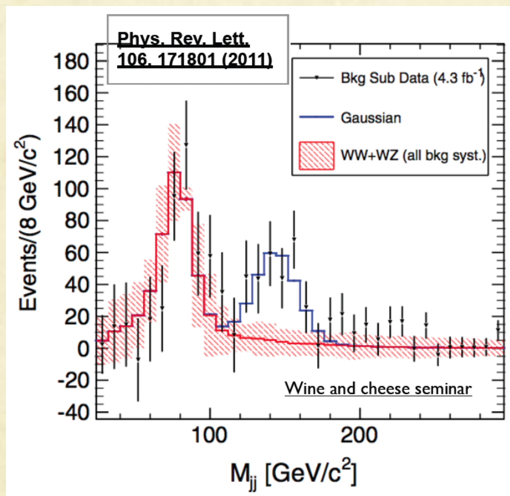
- ✓ Modeling
- ✓ Statistics
- ✓ …

<u>In the past we have had plenty of examples to learn from</u>

For example, just 2 weeks ago, an outstanding puzzle from the Tevatron was resolved:

W+jj production





Bump disappeared after improved:

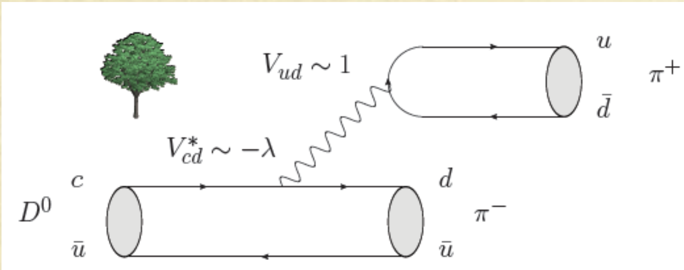
- ✓ Modeling of quark/gluon jets
- ✓ Modeling of fake electrons

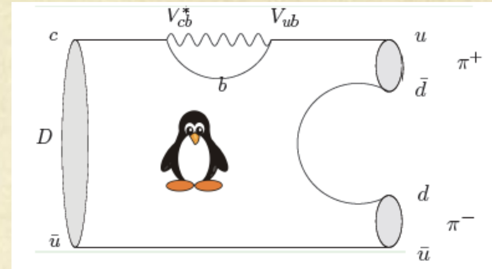
A 3.2σ bump close to the Higgs mass!
(both in muon and electron samples)

See talk M. Trovato
La Thuile 2013

Where is the New Physics?

The believe was, that measurable CP violation in charm would mean bSM physics.





Then LHCb reported CP violation that was much too large to explain.

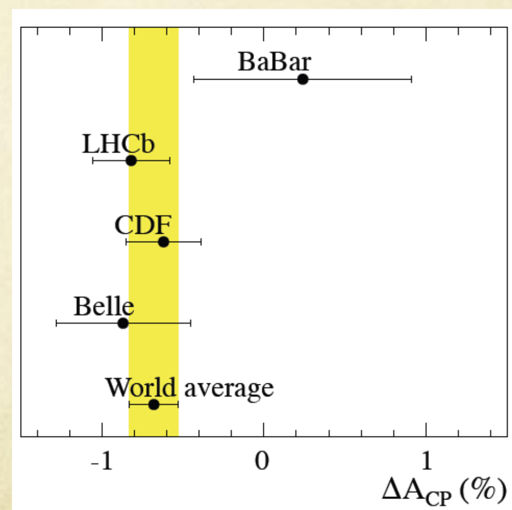
Yet, no bSM was proclaimed. Why? Hard to control non-perturbative effects.

Measure the time-integrated difference (detector and production asymmetries cancel):

$$\Delta A_{CP} \equiv A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$$

$$A_{CP}(f;\, t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)}$$

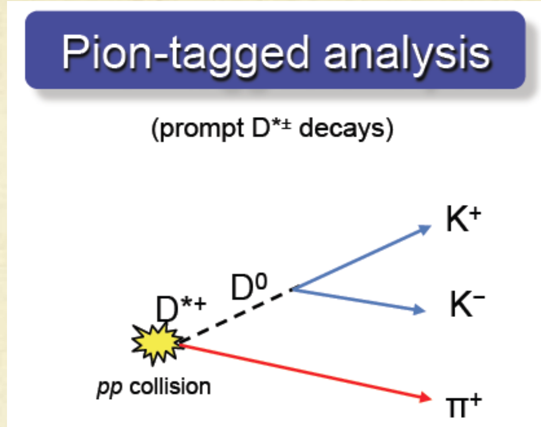
A number of measurements now available:

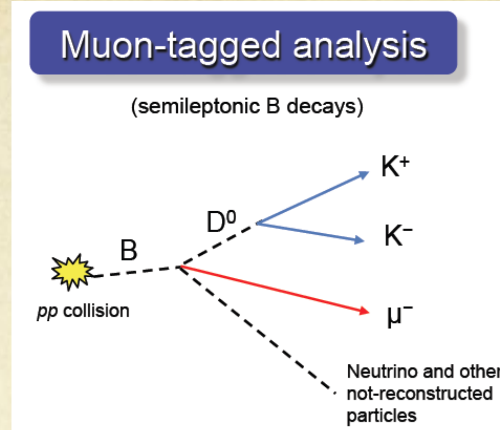


Just reported: new LHCb results

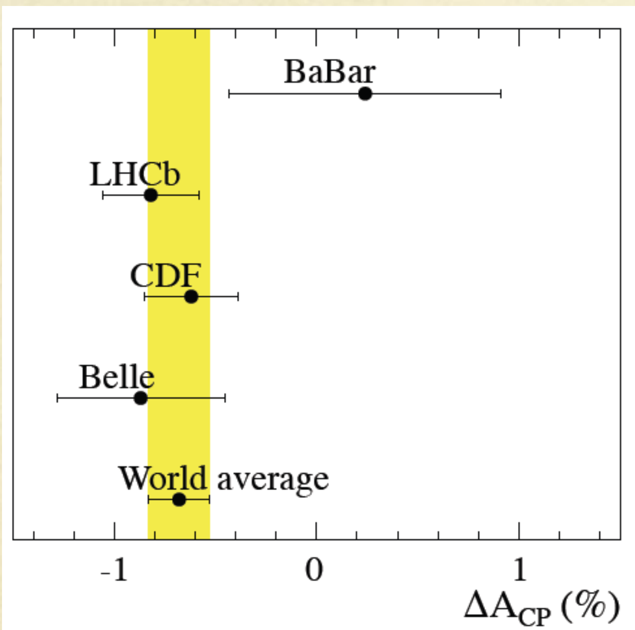
New: 1303.2614

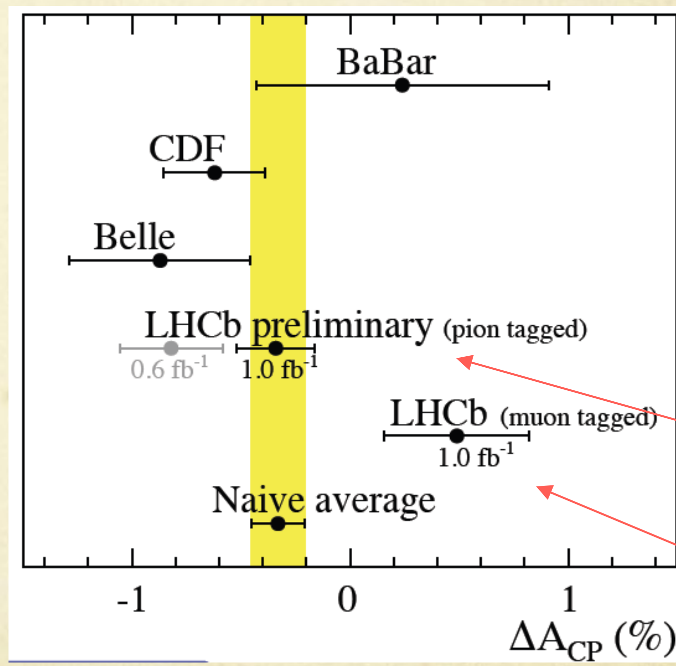
Two independent analyses:





Just presented by LHCb (CERN seminar; Moriond)



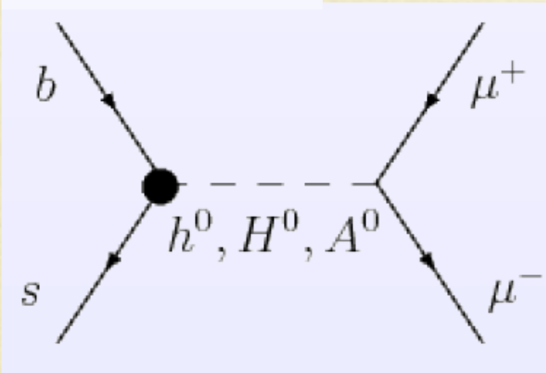


Differ by 2.2σ

Now closer to SM… but things seem to be even more confusing. Help from Belle II ?

Among the 100's of bSM searches, there is one I'd really like to discuss …

$B_s \to \mu^+\mu^-$



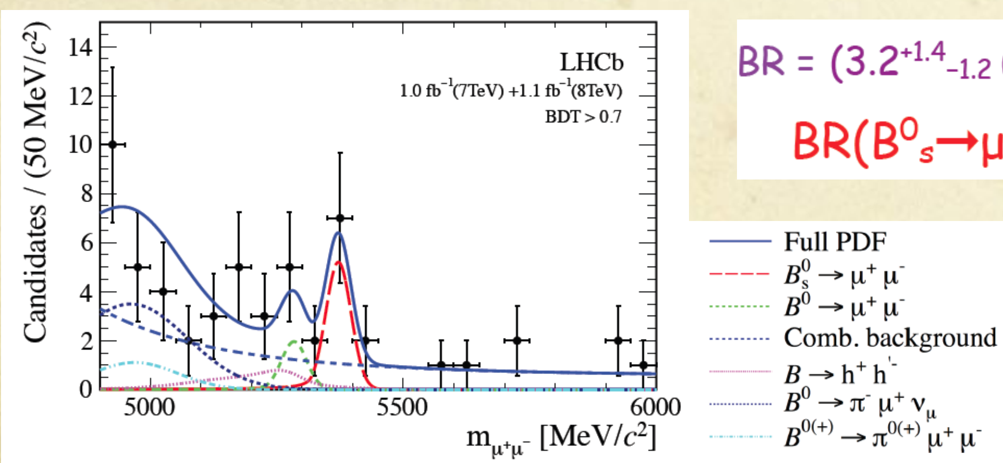
Very strongly suppressed in the SM

Easy theoretically:
✓ Purely leptonic final state

Very hard measurement:
✓ Tiny rate

Main feature: any bSM contribution inside the loops can significantly modify the rate.

After a long search, months ago, the rate was measured:



BR = $(3.2^{+1.4}_{-1.2}$ (stat) $^{+0.5}_{-0.3}$ (syst)$)\times10^{-9}$ **fully dominated by stat error**

$BR(B^0_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2})\times10^{-9}$

SM expectation
$(3.54\pm0.30)\times10^{-9}$

Main feature: any bSM contribution inside the loops can significantly modify the rate.

$B_s \to \mu^+\mu^-$

BR = $(3.2^{+1.4}_{-1.2}\,(\text{stat})\,^{+0.5}_{-0.3}\,(\text{syst}))\times10^{-9}$ **fully dominated by stat error**

$BR(B^0_s\to\mu^+\mu^-) = (3.2^{+1.5}_{-1.2})\times10^{-9}$

SM expectation
$(3.54\pm0.30)\times10^{-9}$

The measured rate agrees with SM. But there is more:

- Rate could have been different by orders of magnitude; yet agrees with SM within 30%
- Rate could have been even below SM; apparently it is not (at least not by much)

What should we take from this?

➔ Nature is unkind to us?

The hard lesson seems to be that whatever is going on:

- It is becoming increasingly unlikely that large deviation from the SM will be seen.
- Future searches will need high precision (theoretically and experimentally).

(and this was not obvious, or expected, until recently)

Is precision all we have left?

It might seem hard, but is doable …

NNLO: the new wave in hadron collider physics

Precision SM application to bSM searches: stealthy stop

- ✓ SUSY scenario of broad interest: stop → top + missing energy
  - ✓ m_stop small: just above the top mass.
  - ✓ Stop mass < 225 GeV is allowed by current data
  - ✓ Usual wisdom: the stop signal hides in the top background

Czakon, Mitov `12-13

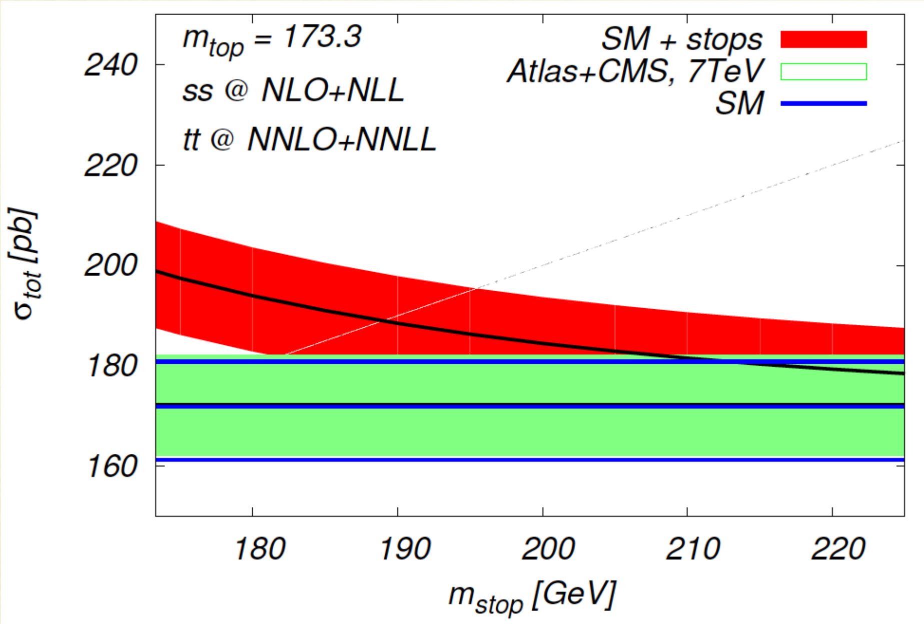
- ✓ The idea: use the very precisely known top quark x-section to derive a bound on the stop mass.
  Assumptions:
  - ✓ Same experimental signature as pure tops
  - ✓ the measured x-section is a sum of top + stop
  - ✓ Use precise predictions for stop production @ NLO+NLL

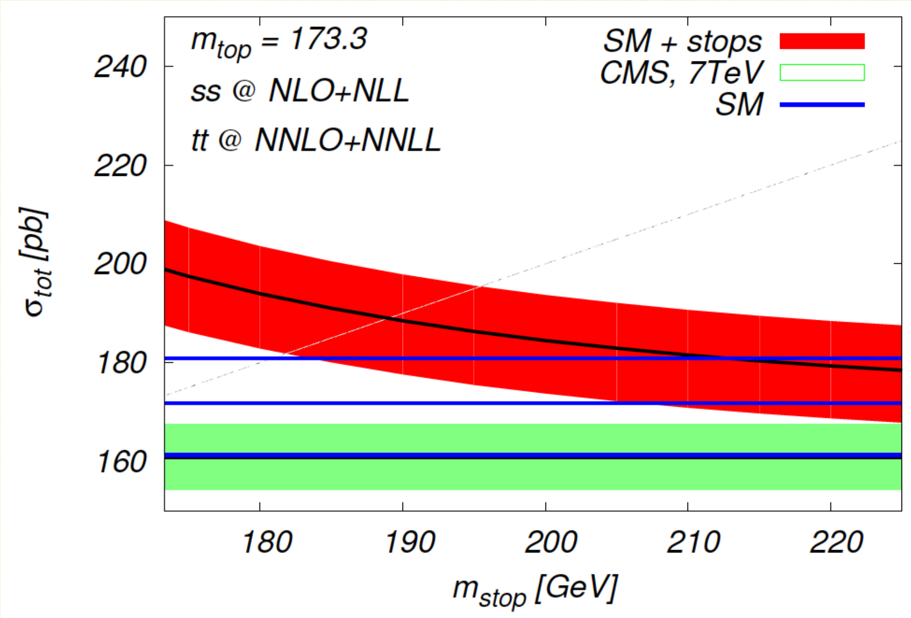
    Krämer, Kulesza, van der Leeuw, Mangano, Padhi, Plehn, Portell `12
  - ✓ Total theory uncertainty: add SM and SUSY ones in quadrature.

Applications to the bSM searches: stealth stop

✓ Predictions

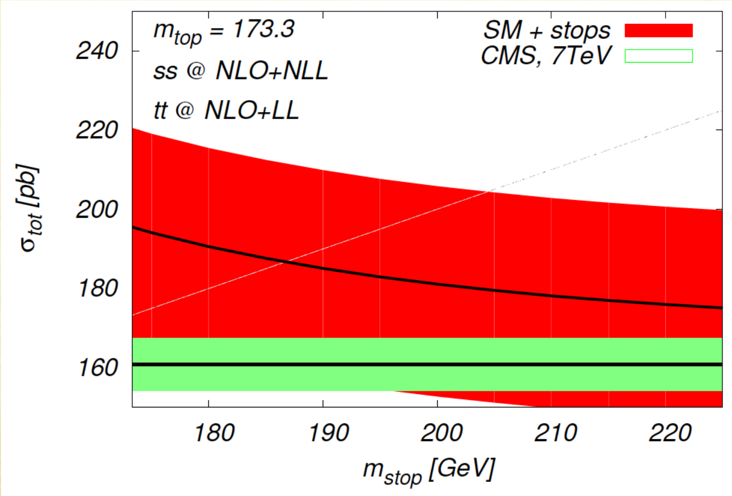
Preliminary; presented at La Thuile '13





Wonder why limits were not imposed before?

Here is the result with "NLO+shower" accuracy :

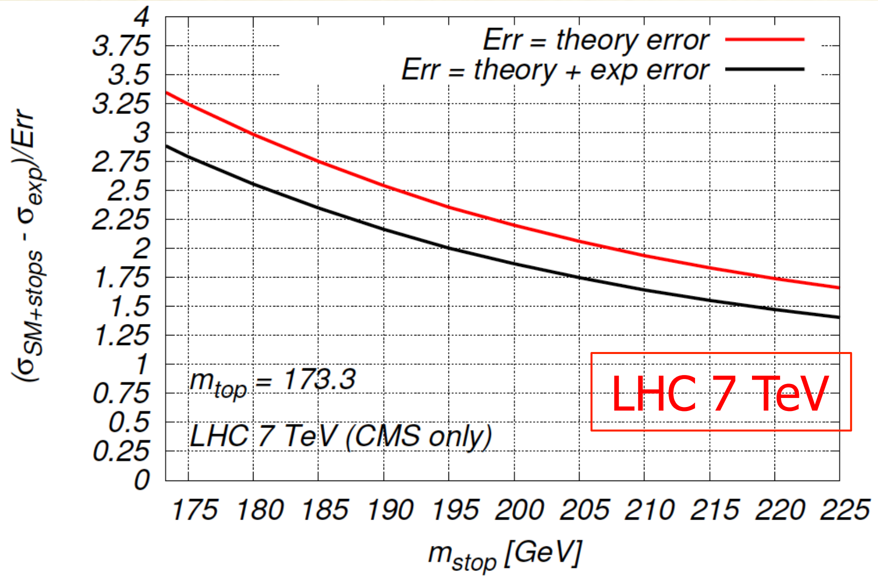


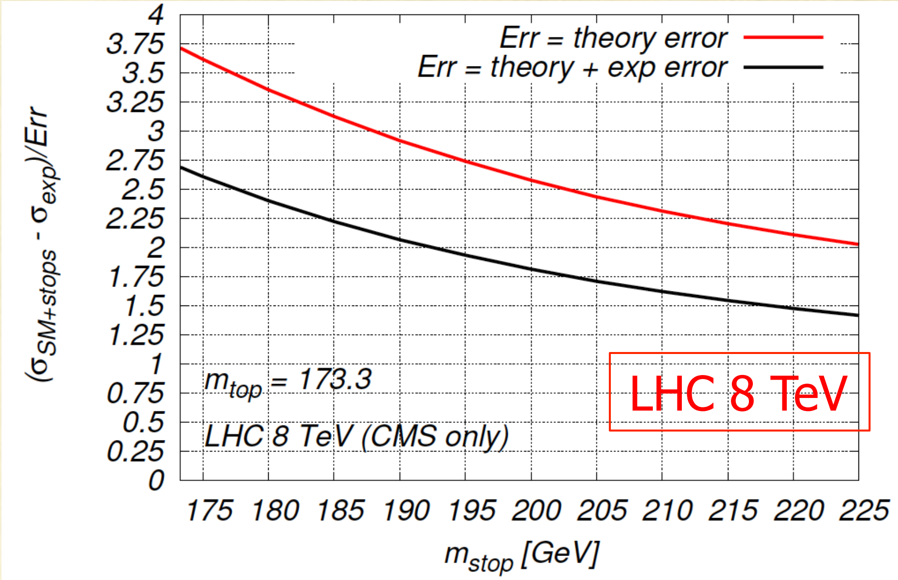
Improved NNLO accuracy makes all the difference

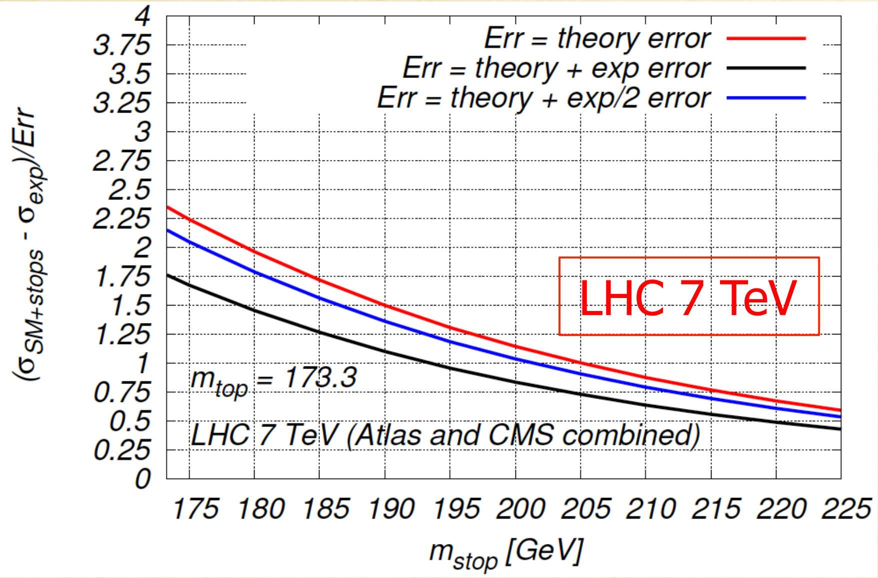
Applications to bSM searches: stealth stop

✓ How strong exclusions can be placed?

Preliminary







CMS data allows 2 sigma exclusion for

m_stop < 195 GeV

CMS and Atlas combined data (same as SM) allows 2 sigma exclusion for

m_stop < 177 GeV
(if combined exp error reduced by ½)

Clearly, theory permits exclusion; looking forward to future data improvements!

Back to the desert …

How can we tell if it is a desert or a jungle?

Hey, top mass measurement might help!

Top quark mass

Places where the top mass is crucial:

- Higgs-inflation

Bezrukov, Shaposhnikov '07-'08
De Simone, Hertzbergy, Wilczek'08

Assume non-minimal coupling to gravity:

$$\mathcal{L}_h = -|\partial H|^2 + \mu^2 H^\dagger H - \lambda (H^\dagger H)^2 + \xi H^\dagger H \, \mathcal{R}$$

Then: Higgs = inflaton provided:

1) $10^3 < \xi < 10^4$

2) $m_h > 125.7\,\mathrm{GeV} + 3.8\,\mathrm{GeV}\left(\frac{m_t - 171\,\mathrm{GeV}}{2\,\mathrm{GeV}}\right) - 1.4\,\mathrm{GeV}\left(\frac{\alpha_s(m_Z) - 0.1176}{0.0020}\right) \pm \delta$

3) $m_h \lesssim 190\,\mathrm{GeV}$

- Theory remains perturbative at high energy,
- Has been criticized for inconsistent inflation.

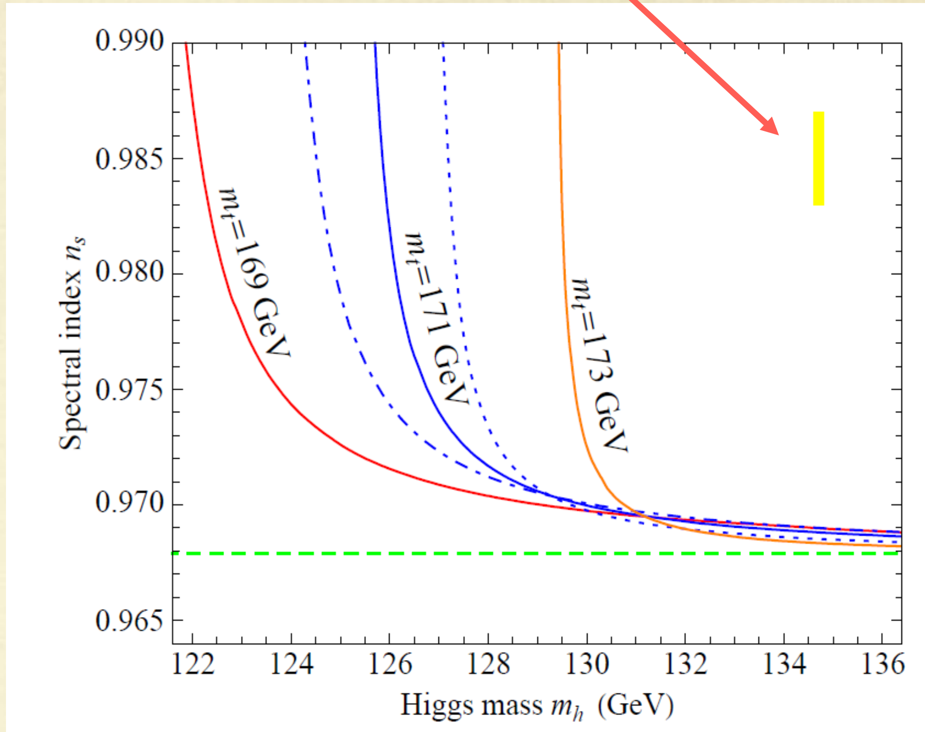
Top quark mass

Results from PLANK to be released ~ 1 week!

- Higgs-inflation

Bezrukov, Shaposhnikov '07-'08
De Simone, Hertzbergy, Wilczek'08

Provided it works ☺
the model is very predictive!



De Simone, Hertzbergy, Wilczek arXiv:0812.4946v2

Figure 1: The spectral index n_s as a function of the Higgs mass m_h for a range of light Higgs masses. The 3 curves correspond to 3 different values of the top mass: $m_t = 169\,\text{GeV}$ (red curve), $m_t = 171\,\text{GeV}$ (blue curve), and $m_t = 173\,\text{GeV}$ (orange curve). The solid curves are for $\alpha_s(m_Z) = 0.1176$, while for $m_t = 171\,\text{GeV}$ (blue curve) we have have also indicated the 2-sigma spread in $\alpha_s(m_Z) = 0.1176 \pm 0.0020$, where the dotted (dot-dashed) curve corresponds to smaller (larger) α_s. The horizontal dashed green curve, with $n_s \simeq 0.968$, is the classical result. The yellow rectangle indicates the expected accuracy of PLANCK in measuring n_s ($\Delta n_s \approx 0.004$) and the LHC in measuring m_h ($\Delta m_h \approx 0.2\,\text{GeV}$). In this plot we have set $N_e = 60$.

Yet another application of the top mass:

The fate of the Universe might depend on 1 GeV in M_{top}!

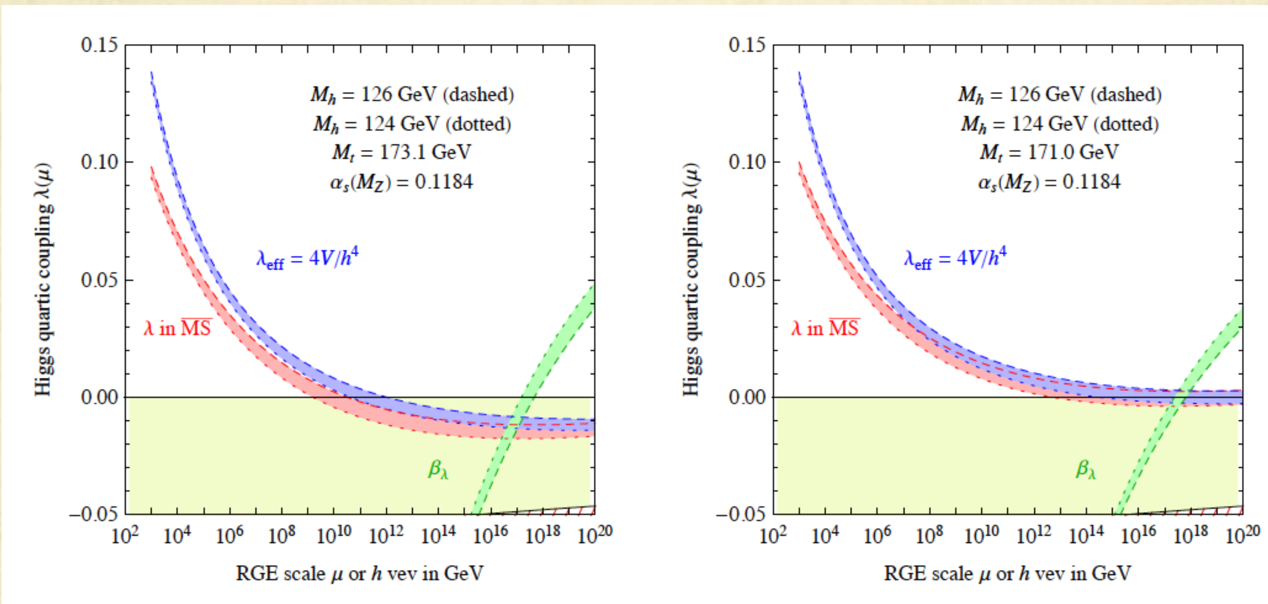
Higgs mass and vacuum stability in the Standard Model at NNLO.

Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia '12

Vacuum stability condition:

$$V_{\rm eff} = -\frac{m^2}{2}h^2 + \frac{\lambda}{4}h^4 + \Delta V$$

Quantum corrections (included)



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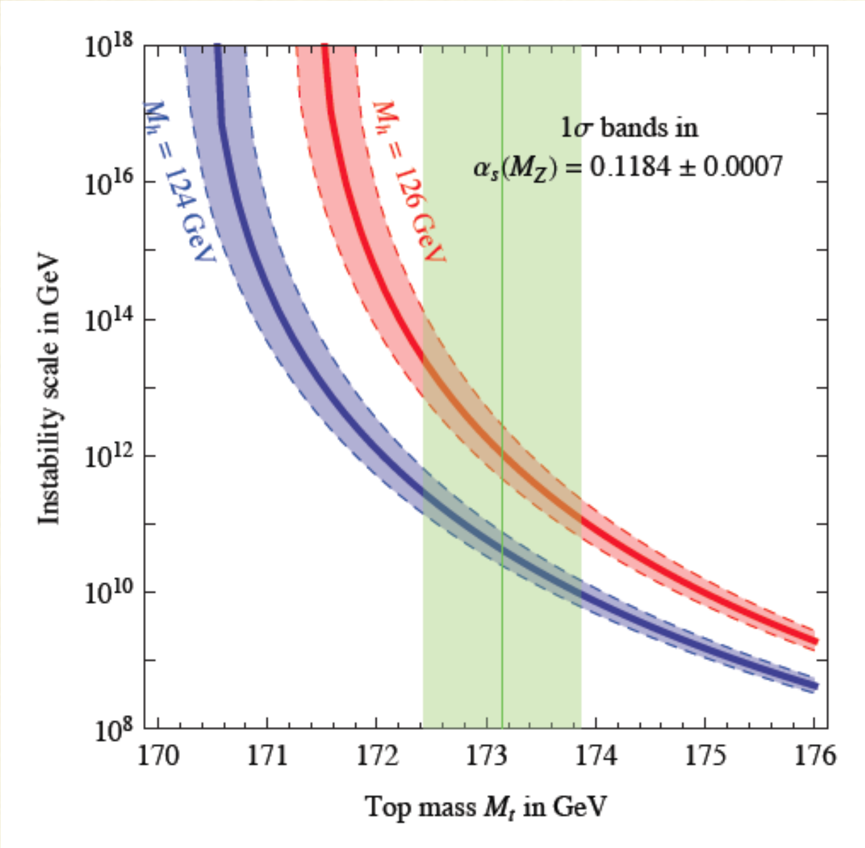

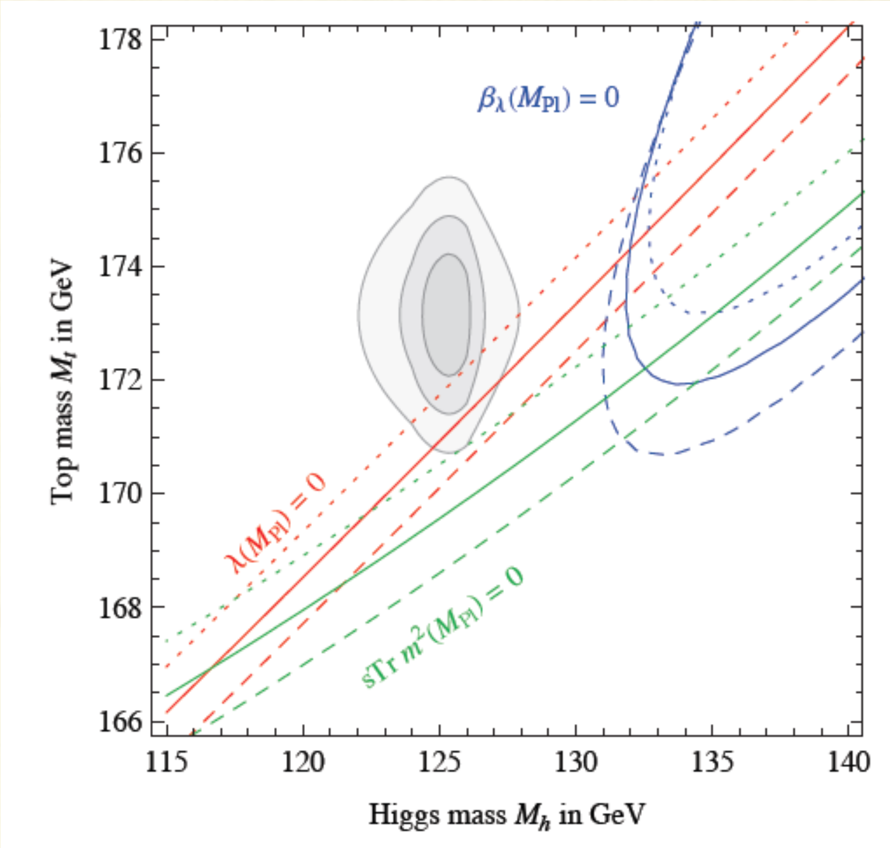

Possible implication:

For the right values of the SM parameters (and we are right there)
SM might survive the Desert and reach the gravity Oasis!

Currently a big push for better understanding of the top mass !

Back to the desert …

How can we tell if it is a desert or a jungle?

But what about the Dark Matter problem?

I mentioned that bSM physics strongly implies DM candidate. But not the opposite.

Let me elaborate:

While a particle explanation of DM is favored today we should recall that the evidence for DM comes from deviations w/r to gravity.

- The implication is then bold, but … plausible:

Modified gravity?

A very small scale indeed!

This is a long story…

- ✓ The basic idea is that at a scale $a_0 = 1.2\times10^{-10}\ ms^{-2}$ Newtonian gravity gets modified.
- ✓ If a theory generates such (new) scale, it can explain the galactic rotations curves.

- ✓ MOND, is an effective theory framework. What is the true theory behind it is unknown

Example: conformal gravity

The main critique about specific MOND models is that they fail to describe:

- Large scale structures
- Gravitational lensing
- Shape of CMB spectrum

Whatever the truth, MOND can be fun! Few fun facts to think about:

The MOND scale $a_0 = 1.2\times10^{-10}\ ms^{-2}$ is:

- ✓ With acceleration a_0, over the life of the Universe, one covers a distance ~ Universe.
- ✓ The Pioneer anomaly's uncertainty: $8.74 \pm 1.33\times10^{-10}\ m/s^2$

Summary

- ✓ Particle physics is undergoing a transformation:
  - ✓ SM is complete (if Higgs = SM Higgs)
  - ✓ Plenty of data from colliders and cosmological observations
  - ✓ No other (significant) deviations seen at colliders
  - ✓ Dark Matter problem is acute

About the future

- ✓ We'll keep searching. Plenty of (tight) spaces remain.
  - ✓ LHC has 15+ more years to run;
  - ✓ 100 times more data to collect.
- ✓ Future supplementary measurements; precision Higgs physics:
  - ✓ Belle II
  - ✓ ILC/CLIC/muon collider/LEP3/…

Conclusions

Thank you!

- ✓ We need to keep producing good ideas
- ✓ Precision is a key ability