Modern colliders applications of the theory of elementary particles

About the course:

- ❖ This course is meant to supplement your standard courses in QFT and PhEP.
- ❖ You are free to choose to take it or not. No exam at the end.
- ❖ If you do:
  - ❖ Please actively participate in the lectures/discussions.
  - ❖ You will have to complete individual projects at the end

Today: Part I: Introduction

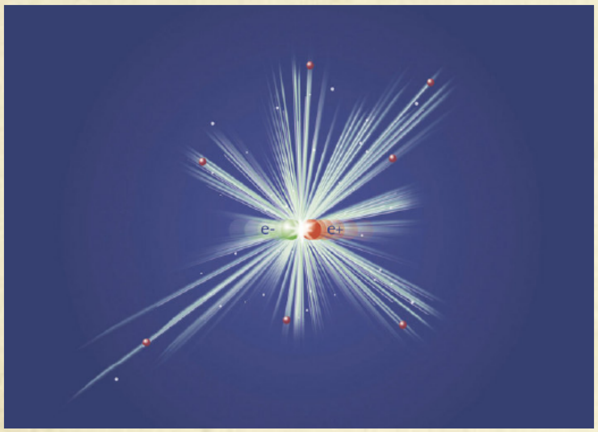
- ❖ What is measured at colliders?
- ❖ What fundamental questions can be answered at colliders?
- ❖ The role of theory

Alexander Mitov
Cavendish Laboratory

UNIVERSITY OF CAMBRIDGE

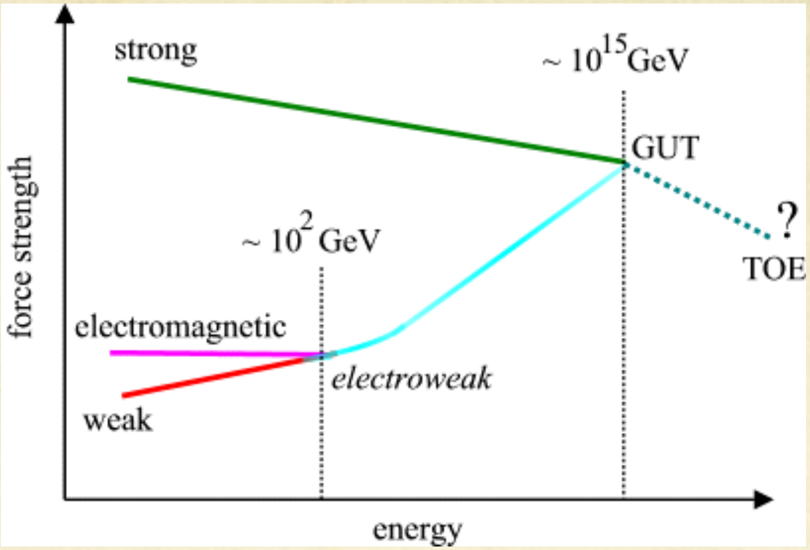
Contact: please talk to me after lectures or by email (google me)

Particle physics is driven by the belief that:



… are driven and described by the same microscopic forces

Here is the particle physicist's picture of the world:



It is all about the desert; what is it – what's its nature?

Is it merely a desert?

Or an oasis?

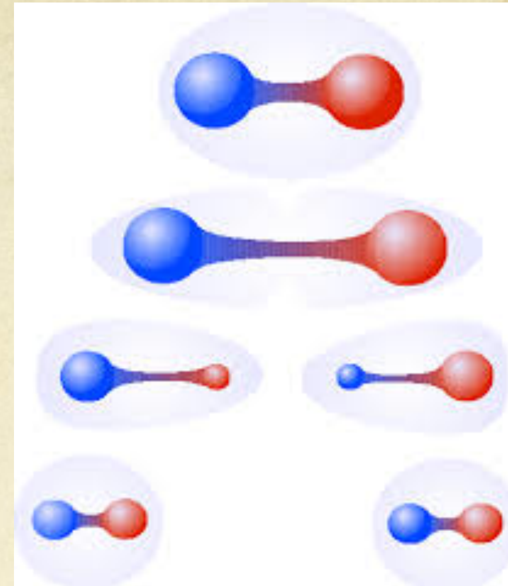
Or perhaps a jungle?

There are several important problems that are in the realm of particle physics:

Ex: Confinement:

✓ An outstanding problem in the theory of strong interactions (QCD = Quantum ChromoDynamics).

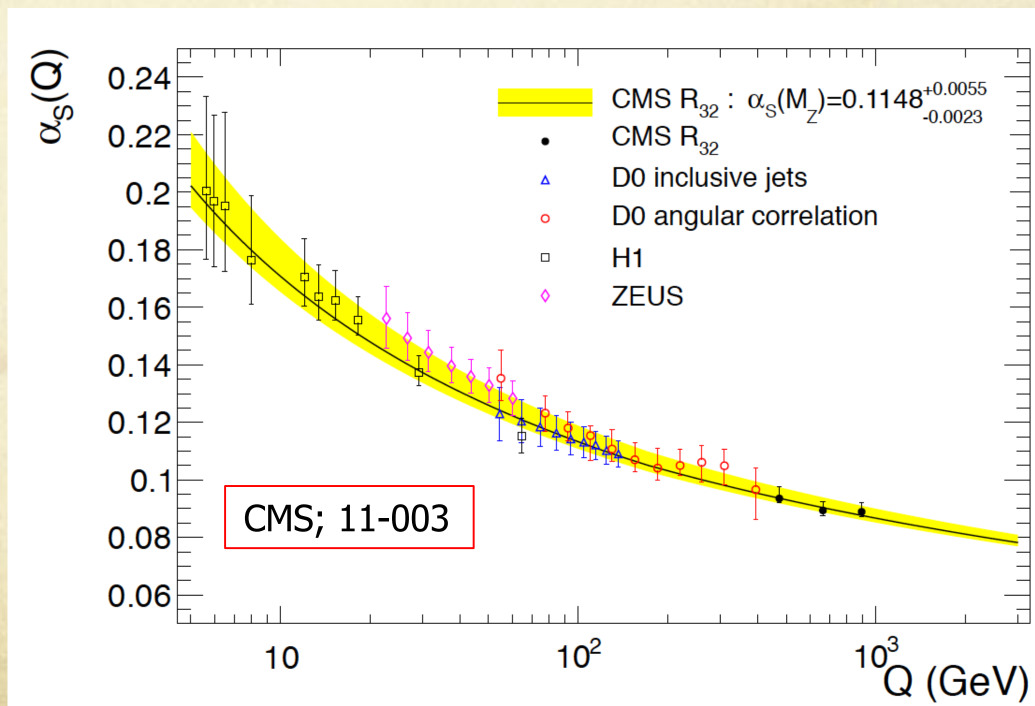
✓ Yet we know how to go around it and keep making progress.



Proof: The LHC

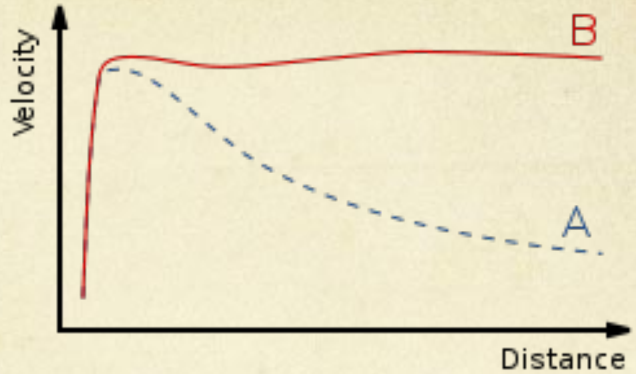
The energy dependence of the strong coupling constant:

Perfect agreement between theory predictions and experimental measurements



The Dark Matter Problem

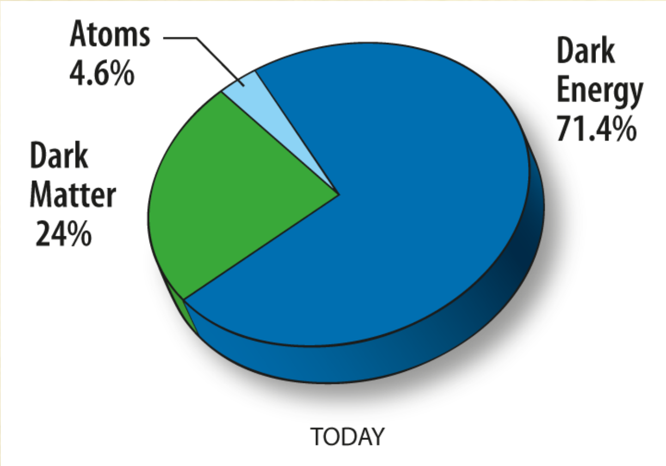
The famous galactic rotation curves problem:



Fritz Zwicky '1933

Dramatic departure from the expectation based on Newtonian dynamics

Especially after WMAP it became clear that:



Why did I bring Dark Matter into this discussion?

Dark matter is a different story:

- ✓ We do not know how to solve it
- ✓ And we do not know how to circumvent it …

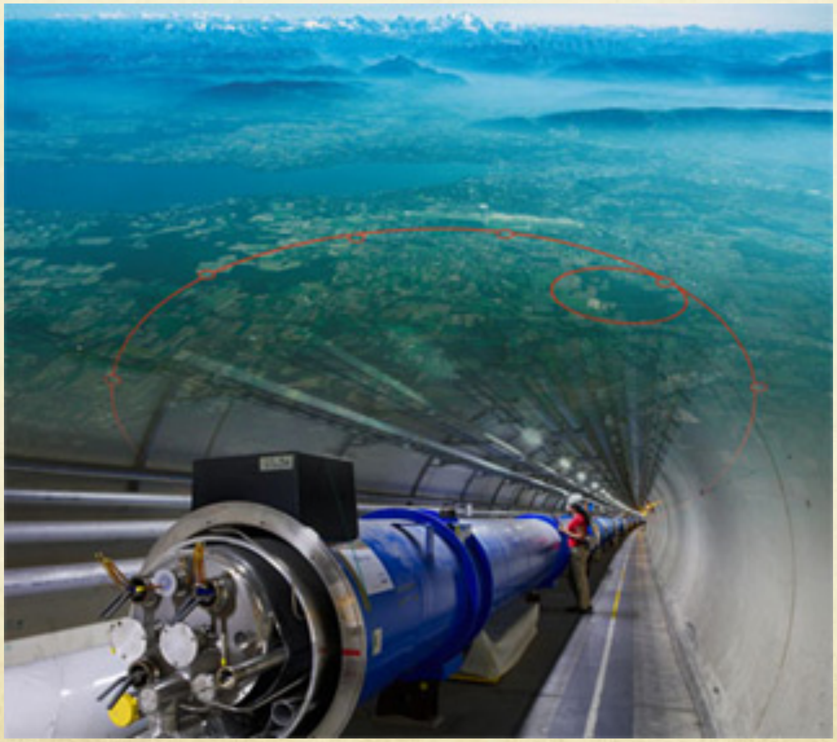
- ✓ It has to have some microscopic explanation
- ✓ (more subtle) If there is a jungle of particles in the desert, then such new physics offers Dark Matter candidates.

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

The opposite is not quite true:

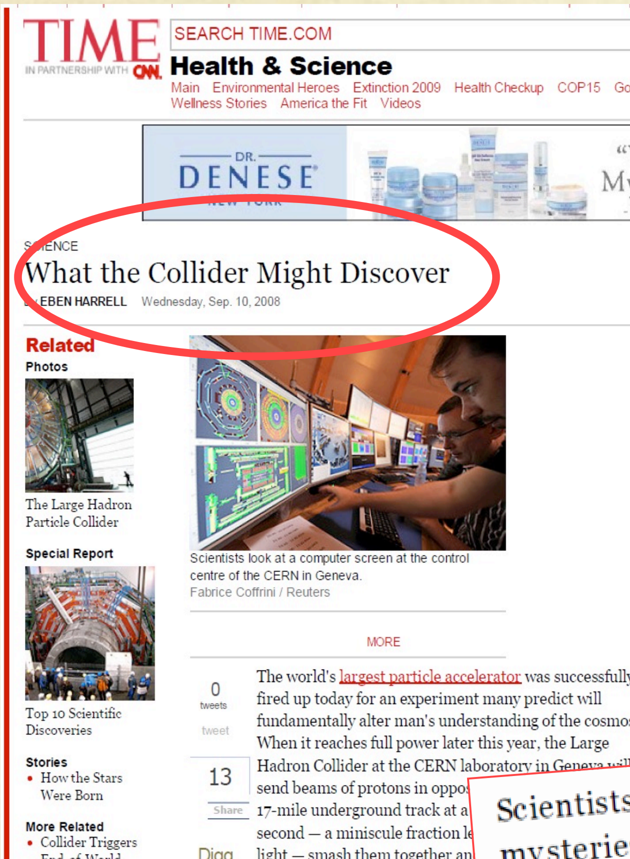
We should view the absence of bSM physics at the LHC, if it comes to that, as a strong guide for understanding the mystery of Dark Matter

The modern physics at particle accelerators



Particle colliders …

… everyone knows that colliders discover things!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Scientists look at a computer screen at the control centre of the CERN in Geneva.
Fabrice Coffrini / Reuters

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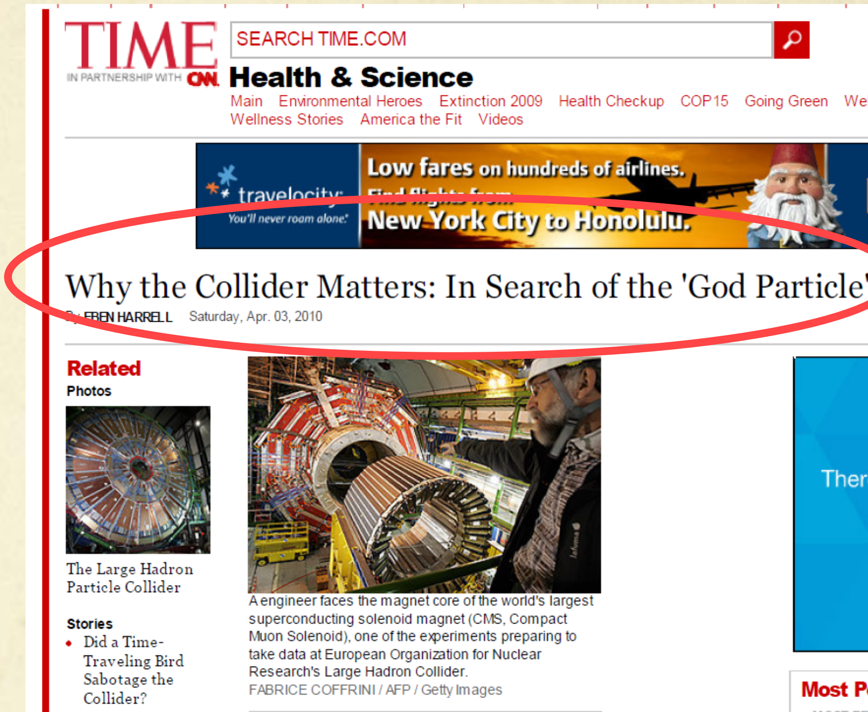
The world's largest particle accelerator was successfully fired up today for an experiment many predict will fundamentally alter man's understanding of the cosmos. When it reaches full power later this year, the Large Hadron Collider at the CERN laboratory in Geneva will send beams of protons in oppo… 17-mile underground track at a… second — a miniscule fraction le… light — smash them together an…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By EBEN HARRELL Saturday, Apr. 03, 2010

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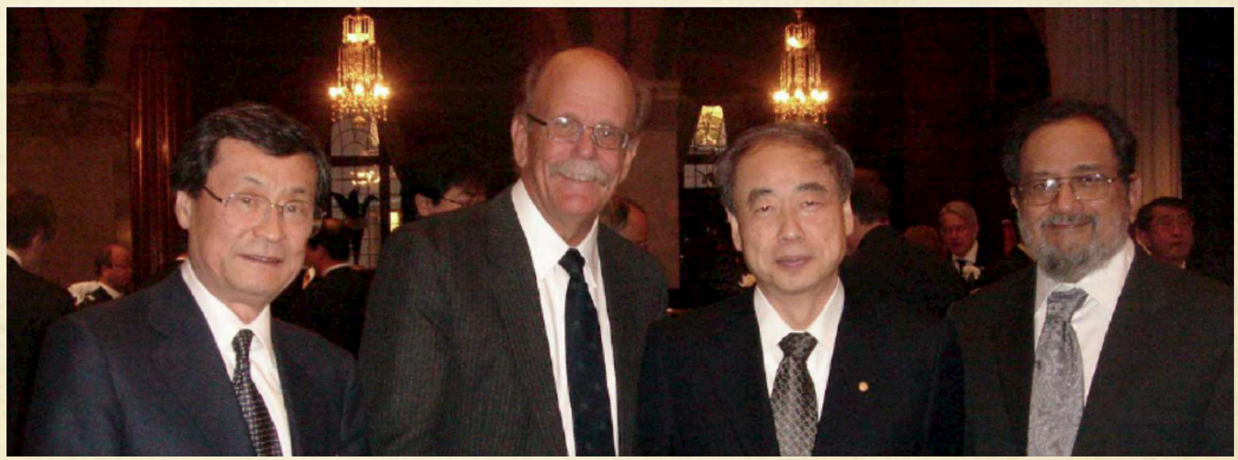
A engineer faces the magnet core of the world's largest superconducting solenoid magnet (CMS, Compact Muon Solenoid), one of the experiments preparing to take data at European Organization for Nuclear Research's Large Hadron Collider.
FABRICE COFFRINI / AFP / Getty Images

Scientists hope to unlock some of nature's most enduring mysteries: why is the universe expanding at an accelerating rate? What stops our own spiral galaxy, the Milky Way, from unraveling and spilling its contents across the universe? How does gravity work?
(See pictures of the Large Hadron Particle Collider.)

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

Discovered Higgs boson:

... established the CKM paradigm:



40 years of tireless scrutiny: no deviation from the SM so far

The apparent success of the SM can hardly by overstated

Phenomenology at colliders

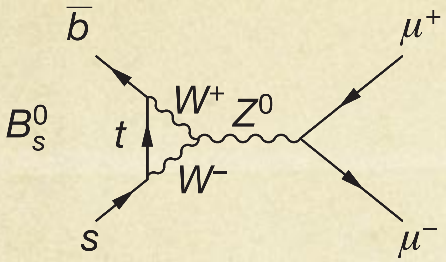
- ✓ Phenomenology = Provide testable predictions at experiments (mostly colliders).

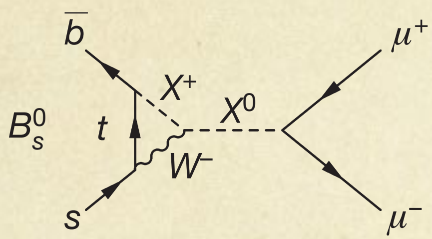
- ✓ Why the need for Phenomenology?
  - Theory becomes very complicated
  - Experiments become too complicated. “To conquer we need to divide”

- ✓ Why colliders?
  - ➢ They provide controlled environment!
    - You can repeat the same thing millions/billions of times and rigorously study what happens (with statistical methods).
    - Example of the opposite situation: astrophysical observations. There we witness events but cannot reproduce them!
  - ➢ Interpret data in terms of underlying models:
    - Which models are correct
    - Which ones are disfavored

Searches for New Physics at Colliders

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





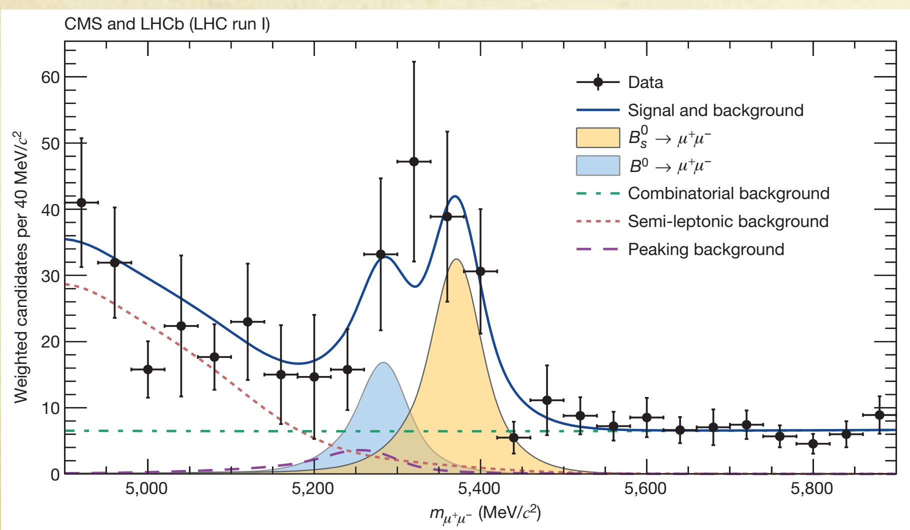
Very strongly suppressed in the SM

Easy theoretically:
✓ Purely leptonic final state

Very hard measurement:
✓ Tiny rate

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

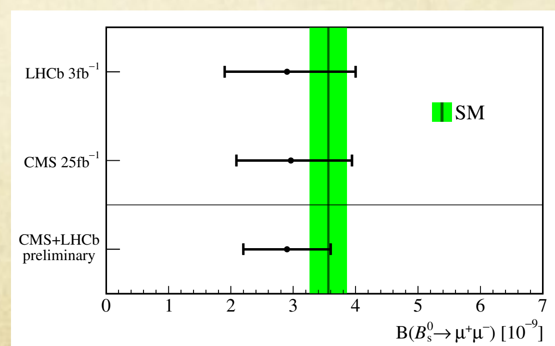
After a long search the rate was finally measured:



Bobeth et al arXiv:1311.0903

SM: $\overline{\mathcal{B}}(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

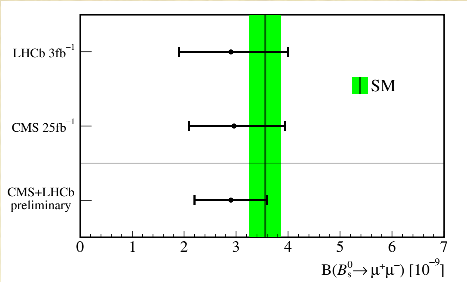
Exp: $\overline{\mathcal{B}}_{s\mu} = (2.9{\pm}0.7){\times}10^{-9}$



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

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

$$\overline{\mathcal{B}}_{s\mu} = (2.9 \pm 0.7) \times 10^{-9}$$



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

- Rate could have been different by orders of magnitude; yet agrees well with SM
- 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 less likely 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)

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:

Bezrukov, Shaposhnikov '07-'08

- Higgs-inflation

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

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

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

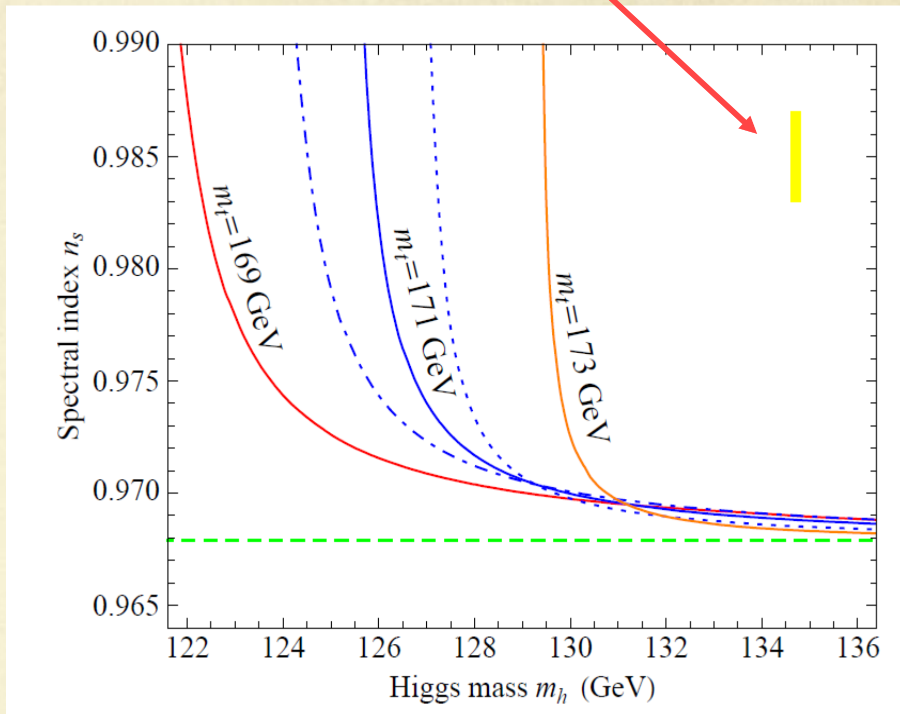
Top quark mass

Results from PLANK (past expectation – not the actual result)

- Higgs-inflation

Bezrukov, Shaposhnikov '07-'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: $m_t = 169\,\mathrm{GeV}$ (red curve), $m_t = 171\,\mathrm{GeV}$ (blue curve), and $m_t = 173\,\mathrm{GeV}$ (orange curve). The solid curves are for $\alpha_s(m_Z) = 0.1176$, while for $m_t = 171\,\mathrm{GeV}$ (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 ($\Delta m_h \approx 0.2\,\mathrm{GeV}$). In this plot we have set $N_e = 60$.

Yet another application of the top mass:

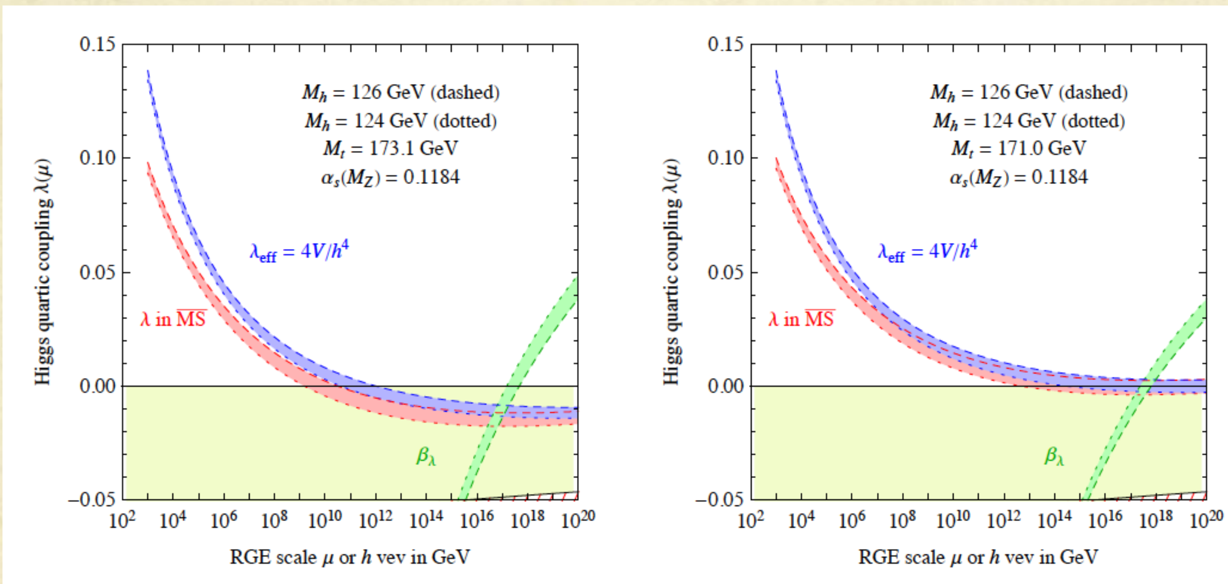
The fate of the Universe might depend on 1 GeV in M_{top}!

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

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

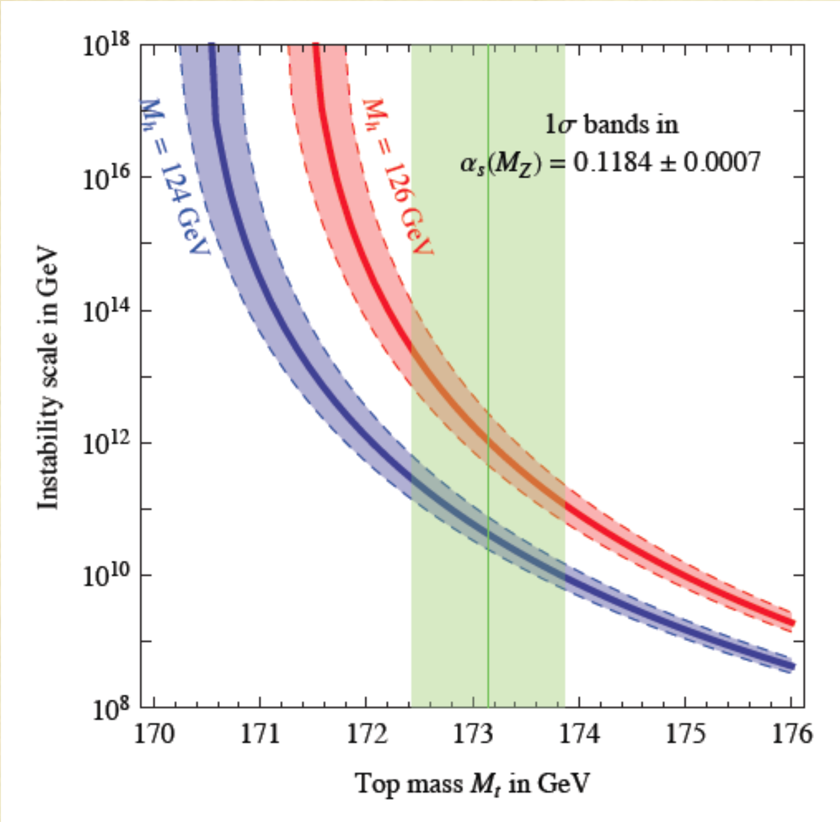
Vacuum stability condition: $$V_{\rm eff} = -\frac{m^2}{2}h^2 + \frac{\lambda}{4}h^4 + \Delta V$$

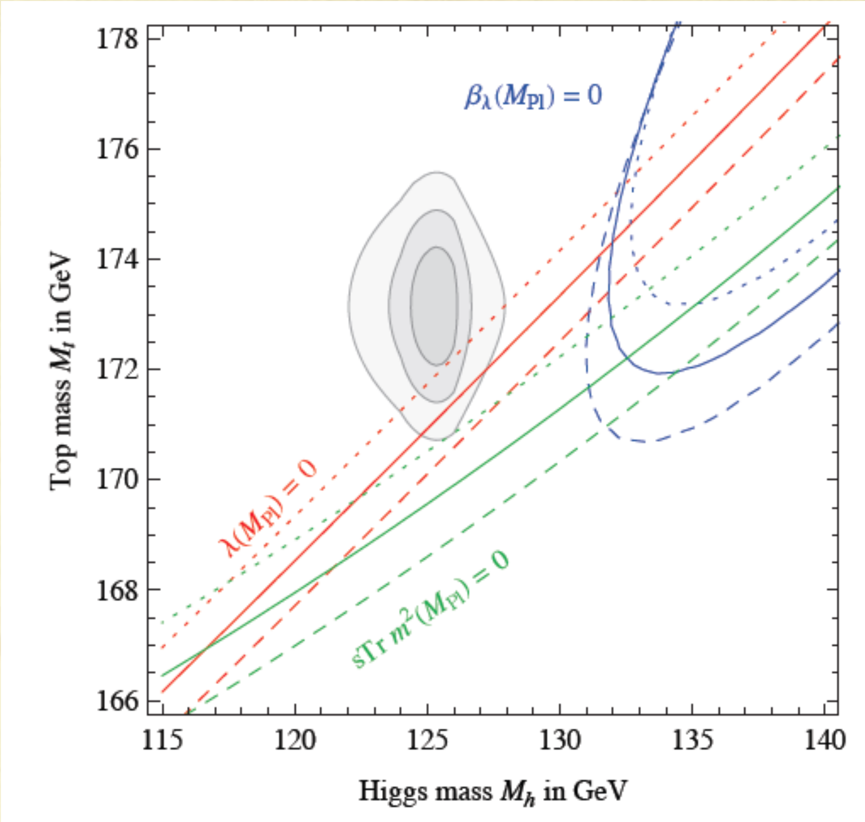
Quantum corrections (included)



Higgs mass and vacuum stability in the Standard Model at NNLO

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





Possible implication:

For the right values of the SM parameters (and we are right there)
SM might survive the Desert.

✓ Currently a big push for better understanding of the top mass. Precision is crucial here…

See, for example: Juste et al arXiv:1310.0799 ; Moch et al arXiv:1405.4781

Precision in particle physics

Precision in the LHC era

✓ The essence of the problem is to quantify the equation

Experiment – Standard Model = Discovery

Precision = confidence!

Within perturbation theory

- LO (leading order) = crude estimate of the result
- NLO (next to leading order) = better estimate of the result
  crude estimate of uncertainty
- NNLO = for the first time quantify the uncertainty

Three precision observables have been identified for the LHC:

"The three pillars":

✓ Higgs Production
✓ Drell-Yan
✓ Top Quark Production

NLO vs NNLO

- NLO calculations are the workhorse of LHC physic. They are:
  - Versatile
  - Flexible
  - Not always as accurate as we might want.
- Great value of NLO calculations: automation!!

NLO calculations: a sample of full(*) automation

	Process	Syntax	Cross section (pb)			
Single Higgs production			LO 13 TeV		NLO 13 TeV	
g.1	$pp \to H$ (HEFT)	`p p > h`	$1.593 \pm 0.003 \cdot 10^{1}$	$^{+34.8\%}_{-26.0\%}$ $^{+1.2\%}_{-1.7\%}$	$3.261 \pm 0.010 \cdot 10^{1}$	$^{+20.2\%}_{-17.9\%}$ $^{+1.1\%}_{-1.6\%}$
g.2	$pp \to Hj$ (HEFT)	`p p > h j`	$8.367 \pm 0.003 \cdot 10^{0}$	$^{+39.4\%}_{-26.4\%}$ $^{+1.2\%}_{-1.4\%}$	$1.422 \pm 0.006 \cdot 10^{1}$	$^{+18.5\%}_{-16.6\%}$ $^{+1.1\%}_{-1.4\%}$
g.3	$pp \to Hjj$ (HEFT)	`p p > h j j`	$3.020 \pm 0.002 \cdot 10^{0}$	$^{+59.1\%}_{-34.7\%}$ $^{+1.4\%}_{-1.7\%}$	$5.124 \pm 0.020 \cdot 10^{0}$	$^{+20.7\%}_{-21.0\%}$ $^{+1.3\%}_{-1.5\%}$
g.4	$pp \to Hjj$ (VBF)	`p p > h j j $$ w+ w- z`	$1.987 \pm 0.002 \cdot 10^{0}$	$^{+1.7\%}_{-2.0\%}$ $^{+1.9\%}_{-1.4\%}$	$1.900 \pm 0.006 \cdot 10^{0}$	$^{+0.8\%}_{-0.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.5	$pp \to Hjjj$ (VBF)	`p p > h j j j $$ w+ w- z`	$2.824 \pm 0.005 \cdot 10^{-1}$	$^{+15.7\%}_{-12.7\%}$ $^{+1.5\%}_{-1.0\%}$	$3.085 \pm 0.010 \cdot 10^{-1}$	$^{+2.0\%}_{-3.0\%}$ $^{+1.5\%}_{-1.1\%}$
g.6	$pp \to HW^{\pm}$	`p p > h wpm`	$1.195 \pm 0.002 \cdot 10^{0}$	$^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.5\%}$	$1.419 \pm 0.005 \cdot 10^{0}$	$^{+2.1\%}_{-2.6\%}$ $^{+1.9\%}_{-1.4\%}$
g.7	$pp \to HW^{\pm}j$	`p p > h wpm j`	$4.018 \pm 0.003 \cdot 10^{-1}$	$^{+10.7\%}_{-9.3\%}$ $^{+1.2\%}_{-0.9\%}$	$4.842 \pm 0.017 \cdot 10^{-1}$	$^{+3.6\%}_{-3.7\%}$ $^{+1.2\%}_{-1.0\%}$
g.8*	$pp \to HW^{\pm}jj$	`p p > h wpm j j`	$1.198 \pm 0.016 \cdot 10^{-1}$	$^{+26.1\%}_{-19.4\%}$ $^{+0.8\%}_{-0.6\%}$	$1.574 \pm 0.014 \cdot 10^{-1}$	$^{+5.0\%}_{-6.5\%}$ $^{+0.9\%}_{-0.6\%}$
g.9	$pp \to HZ$	`p p > h z`	$6.468 \pm 0.008 \cdot 10^{-1}$	$^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.4\%}$	$7.674 \pm 0.027 \cdot 10^{-1}$	$^{+2.0\%}_{-2.5\%}$ $^{+1.9\%}_{-1.4\%}$
g.10	$pp \to HZj$	`p p > h z j`	$2.225 \pm 0.001 \cdot 10^{-1}$	$^{+10.6\%}_{-9.2\%}$ $^{+1.1\%}_{-0.8\%}$	$2.667 \pm 0.010 \cdot 10^{-1}$	$^{+3.5\%}_{-3.6\%}$ $^{+1.1\%}_{-0.9\%}$
g.11*	$pp \to HZjj$	`p p > h z j j`	$7.262 \pm 0.012 \cdot 10^{-2}$	$^{+26.2\%}_{-19.4\%}$ $^{+0.7\%}_{-0.6\%}$	$8.753 \pm 0.037 \cdot 10^{-2}$	$^{+4.8\%}_{-6.3\%}$ $^{+0.7\%}_{-0.6\%}$
g.12*	$pp \to HW^{+}W^{-}$ (4f)	`p p > h w+ w-`	$8.325 \pm 0.139 \cdot 10^{-3}$	$^{+0.0\%}_{-0.3\%}$ $^{+2.0\%}_{-1.6\%}$	$1.065 \pm 0.003 \cdot 10^{-2}$	$^{+2.5\%}_{-1.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.13*	$pp \to HW^{\pm}\gamma$	`p p > h wpm a`	$2.518 \pm 0.006 \cdot 10^{-3}$	$^{+0.7\%}_{-1.4\%}$ $^{+1.9\%}_{-1.5\%}$	$3.309 \pm 0.011 \cdot 10^{-3}$	$^{+2.7\%}_{-2.0\%}$ $^{+1.7\%}_{-1.4\%}$
g.14*	$pp \to HZW^{\pm}$	`p p > h z wpm`	$3.763 \pm 0.007 \cdot 10^{-3}$	$^{+1.1\%}_{-1.5\%}$ $^{+2.0\%}_{-1.6\%}$	$5.292 \pm 0.015 \cdot 10^{-3}$	$^{+3.9\%}_{-3.1\%}$ $^{+1.8\%}_{-1.4\%}$
g.15*	$pp \to HZZ$	`p p > h z z`	$2.093 \pm 0.003 \cdot 10^{-3}$	$^{+0.1\%}_{-0.6\%}$ $^{+1.9\%}_{-1.5\%}$	$2.538 \pm 0.007 \cdot 10^{-3}$	$^{+1.9\%}_{-1.4\%}$ $^{+2.0\%}_{-1.5\%}$
g.16	$pp \to Ht\bar{t}$	`p p > h t t~`	$3.579 \pm 0.003 \cdot 10^{-1}$	$^{+30.0\%}_{-21.5\%}$ $^{+1.7\%}_{-2.0\%}$	$4.608 \pm 0.016 \cdot 10^{-1}$	$^{+5.7\%}_{-9.0\%}$ $^{+2.0\%}_{-2.3\%}$
g.17	$pp \to Htj$	`p p > h tt j`	$4.994 \pm 0.005 \cdot 10^{-2}$	$^{+2.4\%}_{-4.2\%}$ $^{+1.2\%}_{-1.3\%}$	$6.328 \pm 0.022 \cdot 10^{-2}$	$^{+2.9\%}_{-1.8\%}$ $^{+1.5\%}_{-1.6\%}$
g.18	$pp \to Hb\bar{b}$ (4f)	`p p > h b b~`	$4.983 \pm 0.002 \cdot 10^{-1}$	$^{+28.1\%}_{-21.0\%}$ $^{+1.5\%}_{-1.8\%}$	$6.085 \pm 0.026 \cdot 10^{-1}$	$^{+7.3\%}_{-9.6\%}$ $^{+1.6\%}_{-2.0\%}$
g.19	$pp \to Ht\bar{t}j$	`p p > h t t~ j`	$2.674 \pm 0.041 \cdot 10^{-1}$	$^{+45.6\%}_{-29.2\%}$ $^{+2.6\%}_{-2.9\%}$	$3.244 \pm 0.025 \cdot 10^{-1}$	$^{+3.5\%}_{-8.7\%}$ $^{+2.5\%}_{-2.9\%}$
g.20*	$pp \to Hb\bar{b}j$ (4f)	`p p > h b b~ j`	$7.367 \pm 0.002 \cdot 10^{-2}$	$^{+45.6\%}_{-29.1\%}$ $^{+1.8\%}_{-2.1\%}$	$9.034 \pm 0.032 \cdot 10^{-2}$	$^{+7.9\%}_{-11.0\%}$ $^{+1.8\%}_{-2.2\%}$

MadGraph5_aMC@NLO: sample from 172 processes

Courtesy of M. Grazzini

*) within reason and some limits …

NLO calculations: full(*) automation

- NLO calculations have become so advanced and almost fully automated that, really, there is no excuse to use LO in serious analyses!

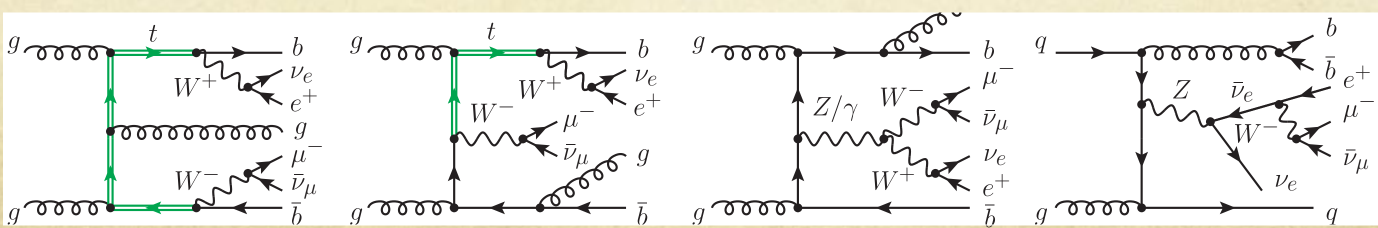
- I would mention the aMC@NLO collaboration which has taken the approach of full automation + shower following the extremely successful MC@NLO approach.

- NLO automation allows not only QCD but any SM process. In principle these are contained now in the aMC@NLO.
- Similar developments from the Sherpa+OpenLoops collaboration (see arXiv:1412.5157)

- The number of high-quality works I can't cover here is enormous. Let me only mention few:
  - Denner/Dittmaier et al
  - The Helac collaboration
  - GOSAM project
  - Njet library
  - BlackHat Collaboration
  - MCFM

- Among the most impressive results ever achieved at NLO is the monstrous tt+jet calculation with full off-shell effects and top decay:

Bevilacqua, Hartanto, Kraus, Worek 1509.09242



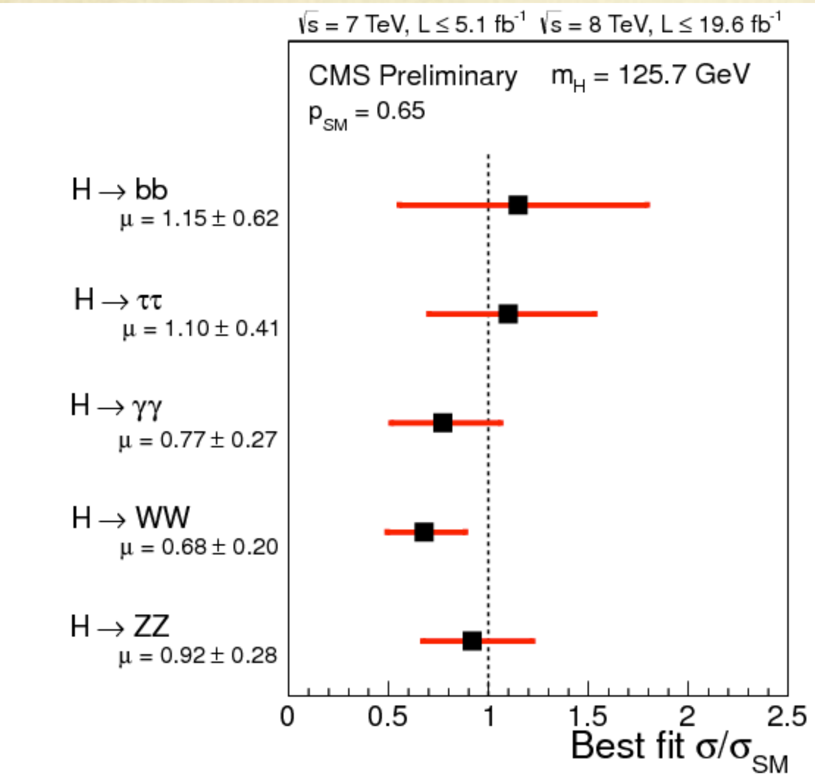
NLO vs NNLO

- NNLO, where possible, will ultimately define the reach of the LHC.
- The kind of questions to be addressed at NNLO (or N^3LO) are:
    - Detailed answers about the Higgs boson (in fact, requires even N^3LO)
    - Self consistency of the SM at the level of few percent.
    - Extract parameters with high precision (m_W, m_{top}, Higgs, …)
    - Search for non-SM couplings
    - Say as much as possible about the nature of Dark Matter candidates.
      If no candidate is found in direct searches, powerful exclusion limits might be very valuable hints about how to think about this very real problem.

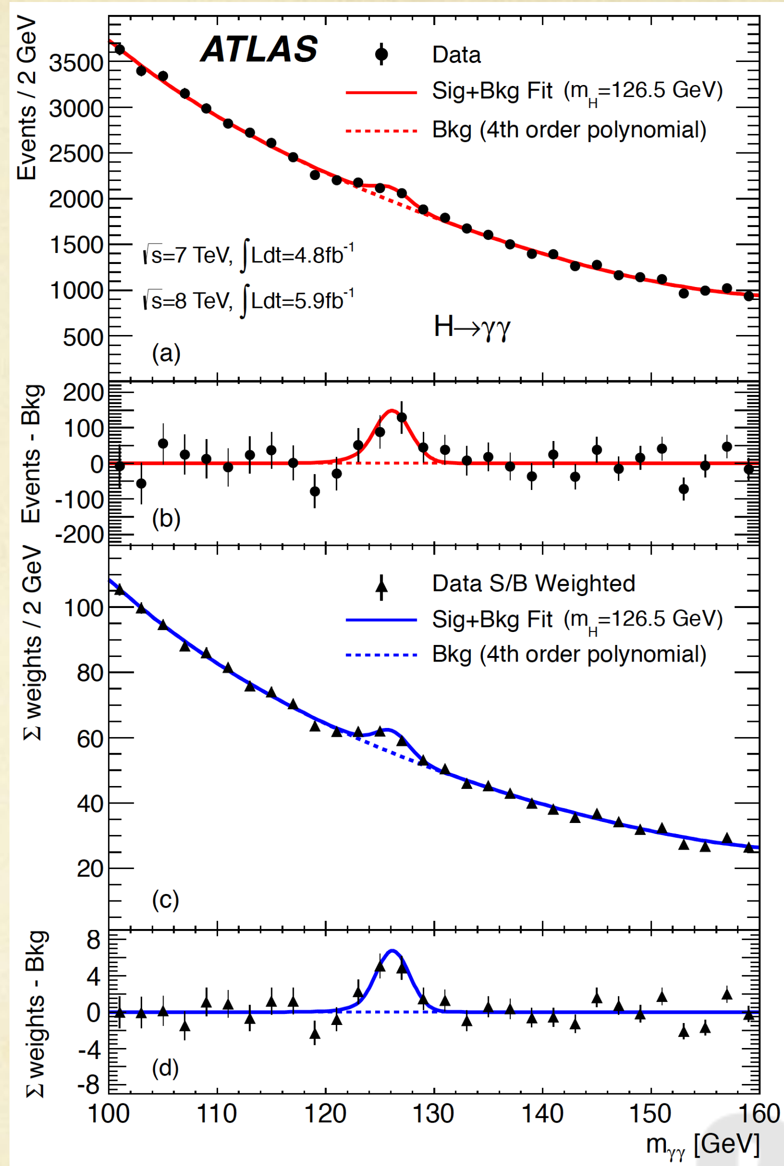
Higgs production

The actual Higgs observation!

CMS '13



ATLAS '12

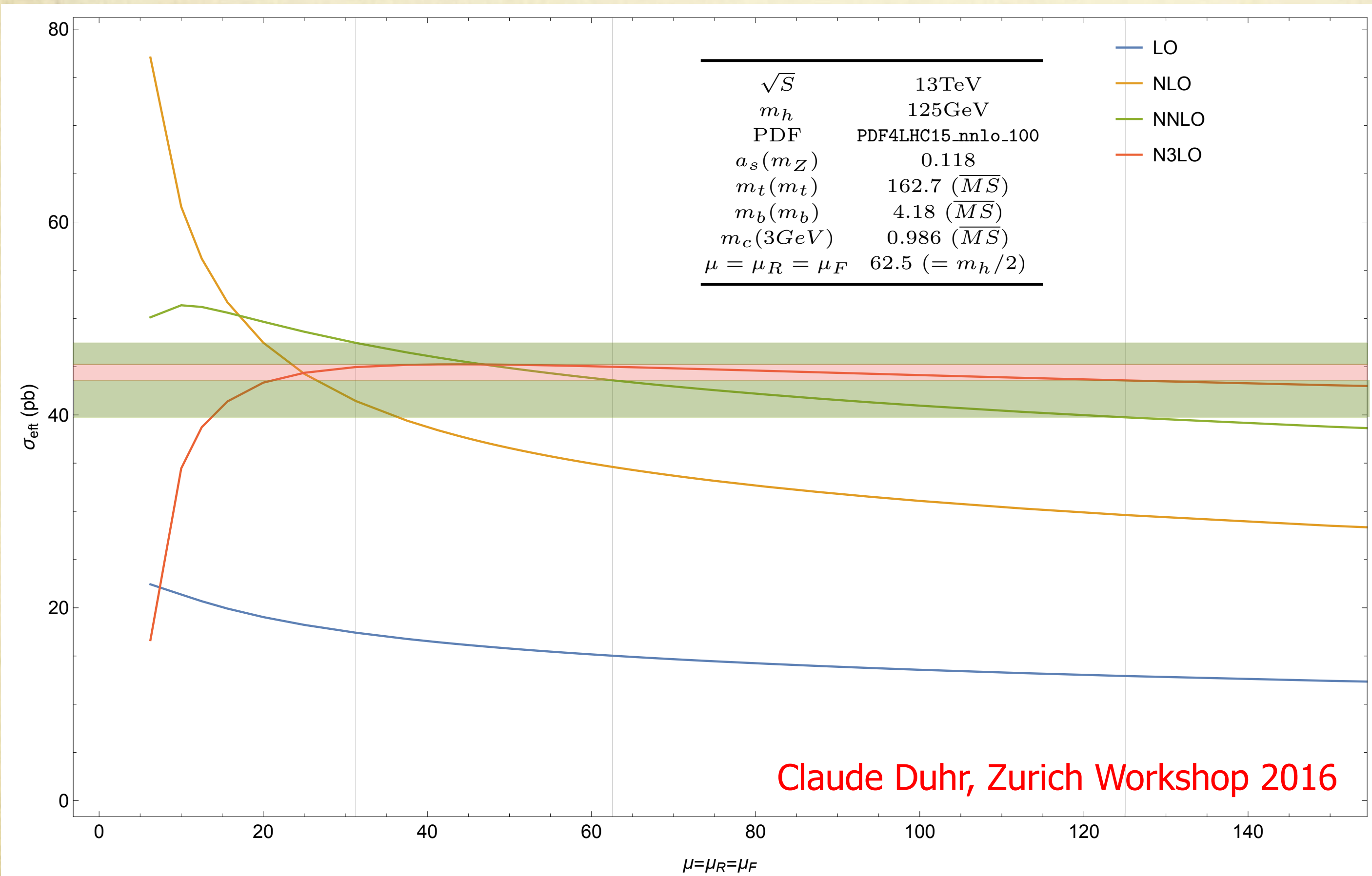


Precision in theory and experiment is key in ID-ing. Work ongoing. Need to go beyond NNLO?

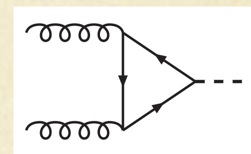
Higgs at N^3LO

- We want to know as much as possible about the Higgs. This means precise SM predictions to compare with experiment.
- Most pressing question: the uncertainty of the total cross-section
- It necessitated the calculation of the N^3LO correction (a first for hadron colliders!)

Anastasiou, Dulat, Duhr, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger '15



Total cross-section in the large m_t limit



Higgs at N^3LO

- Total cross-section at N^3LO:

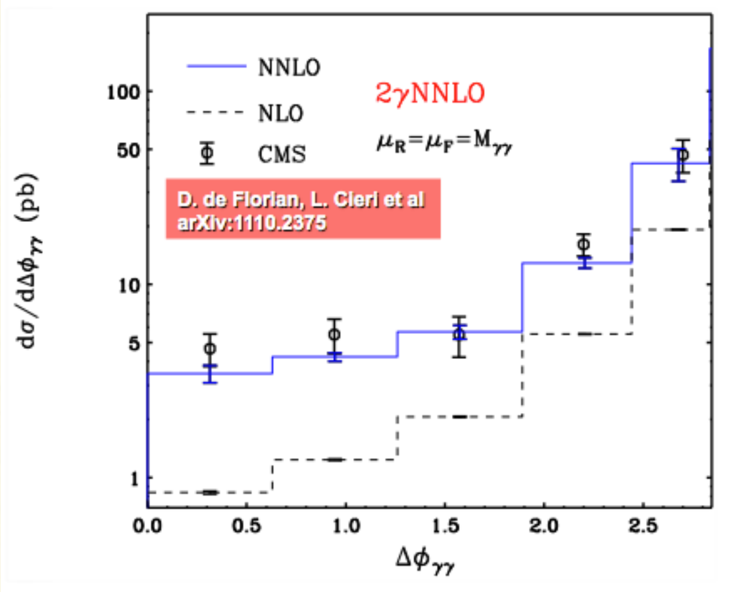
Claude Duhr, Zurich Workshop 2016

σ[pb]	δ_{PDF}	δ_{α_s}	δ_{scale}	δ_{trunc}	$\delta_{\text{PDF-TH}}$	δ_{EW}	δ_{tb}	δ_{1/m_t}
48.48	± 0.90pb	± 1.26pb	$^{+0.09}_{-1.11}$ pb	± 0.12	± 0.56	± 0.48	± 0.34	± 0.48
	$\pm 1.86\%$	$\pm 2.60\%$	$^{+0.2}_{-2.3}\%$	$\pm 0.25\%$	$\pm 1.15\%$	$\pm 1.00\%$	$\pm 0.70\%$	$\pm 1.00\%$

- Uses NNLO pdf; no N^3LO pdf's available (likely 1% effect) See also Forte et al '14
- EW corrections exact at NLO; at mixed QCD-EW included in an EFT approach (gauge bosons integrated out into Wilson coefficients)
- Quark masses (m_t m_b) included exactly at NLO. NNLO desirable
- Threshold resummation likely not pressing issue anymore.
- Basically, at N3LO the Higgs cross-sections starts to look just like the NNLO cross-sections of 2-to-2 processes (top-pair, for example)

Vector boson pair production at NNLO

Following the idea of Catani and Grazzini '07, the availability of 2-loop amplitudes makes it possible to compute NNLO corrections to processes with non-strongly interacting final states.

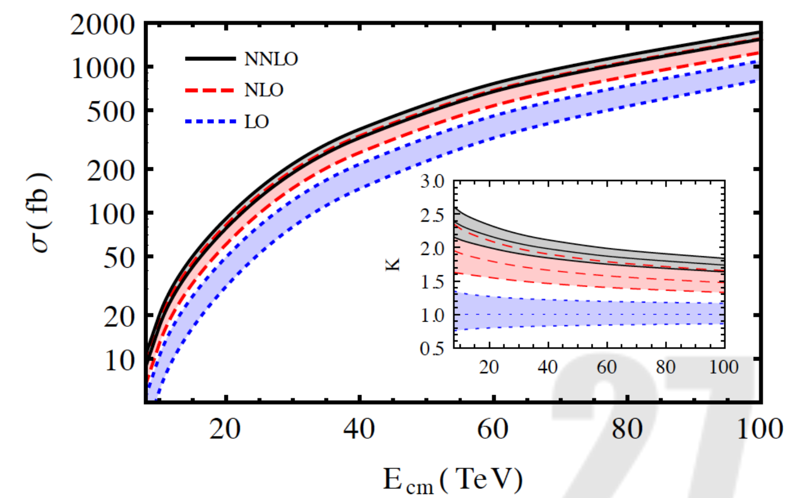


- First example: di-photon production. Spectacular example of the need of higher order corrections!

- Very recently:

Z(→ l^+l^-) + γ @ NNLO
HH @ NNLO

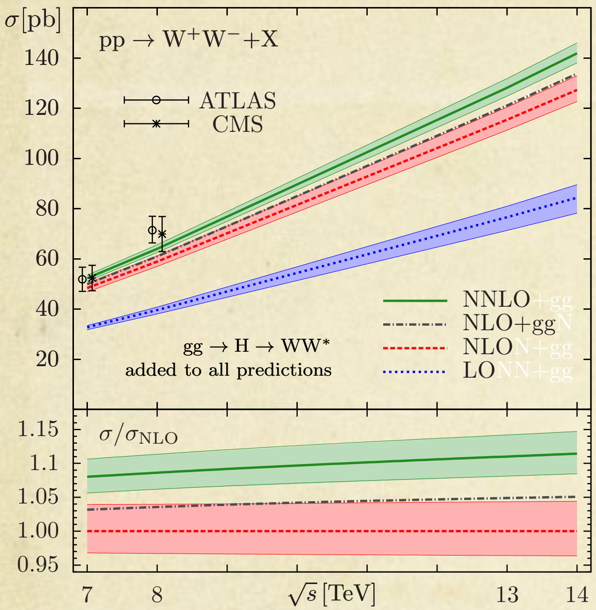
Grazzini, Kallweit, Rathlev, Torre '13
de Florian, Mazzitelli '13



The delayed perturbative convergence we know from Higgs can also be seen in HH

WW production at NNLO

- Essential for understanding EWSB physics
- NNLO correction reduces tension with ATLAS; agrees with CMS



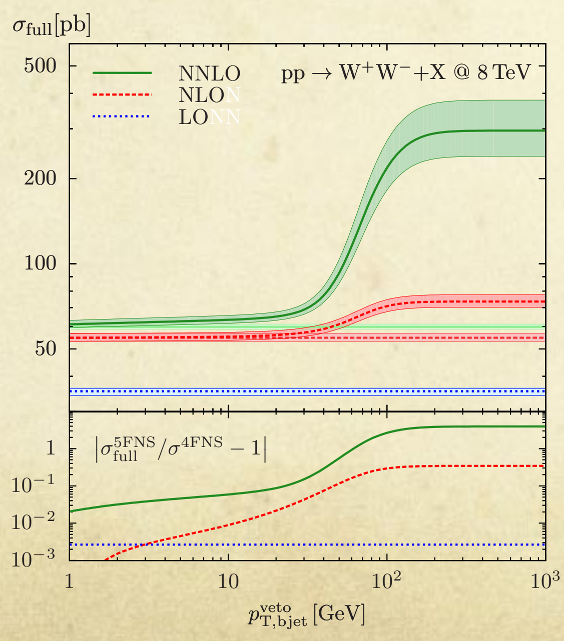
Gehrmann, Grazzini, Kallweit et al '14

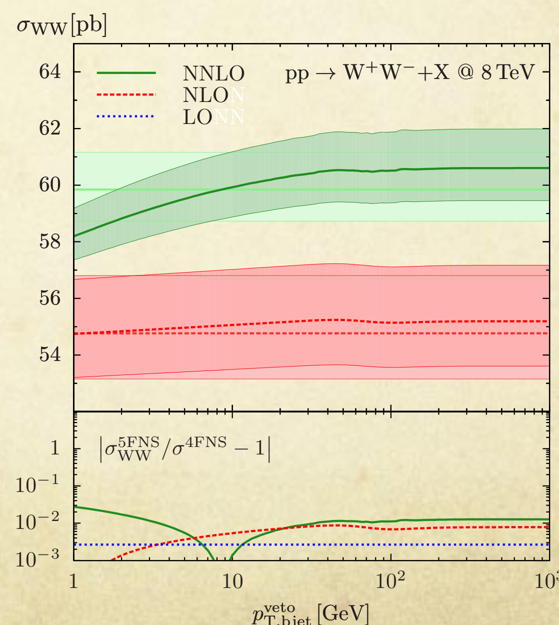
- NNLO correction similar in size to H→ WW*

$\frac{\sqrt{s}}{\rm TeV}$	σ_{LO}	σ_{NLO}	σ_{NNLO}	$\sigma_{gg\to H\to WW^*}$
7	$29.52^{+1.6\%}_{-2.5\%}$	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}_{-1.8\%}$	$3.25^{+7.1\%}_{-7.8\%}$
8	$35.50^{+2.4\%}_{-3.5\%}$	$54.77^{+3.7\%}_{-2.9\%}$	$59.84^{+2.2\%}_{-1.9\%}$	$4.14^{+7.2\%}_{-7.8\%}$
13	$67.16^{+5.5\%}_{-6.7\%}$	$106.0^{+4.1\%}_{-3.2\%}$	$118.7^{+2.5\%}_{-2.2\%}$	$9.44^{+7.4\%}_{-7.9\%}$
14	$73.74^{+5.9\%}_{-7.2\%}$	$116.7^{+4.1\%}_{-3.3\%}$	$131.3^{+2.6\%}_{-2.2\%}$	$10.64^{+7.5\%}_{-8.0\%}$

- Hard to separate WW from top-pair production;
- b-jets essential in this:

Top included





Top not included

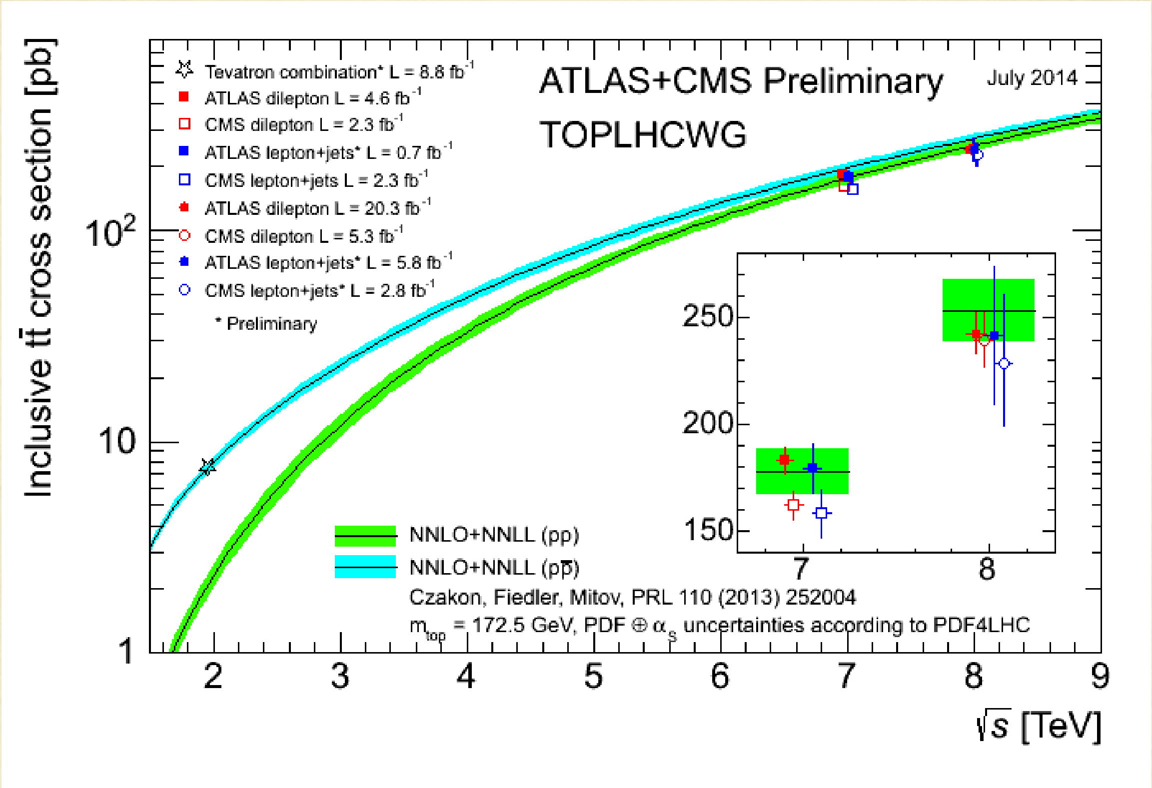
Top-pair production at NNLO

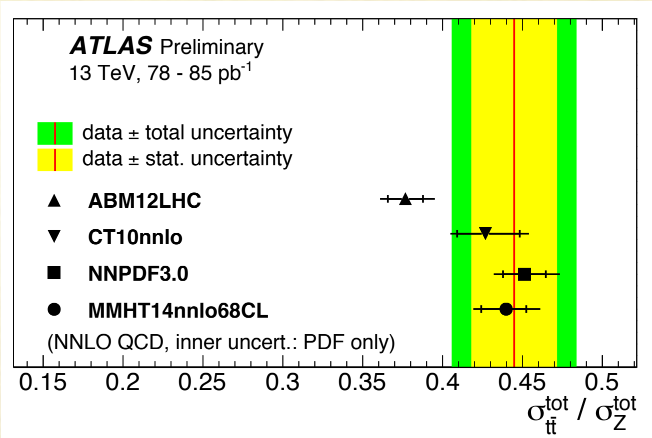
- LHC: the top factory
  - Top discovered at the Tevatron but statistics there was very limited (~1k events)
  - LHC gets the chance to produce lots of top events (>100k events recorded at Run I)
  - LHC Run 2 cross-section larger by a factor of 4.
  - The LHC should, for the first time, study the top completely, all its couplings and parameters.
- Top is (most) important background for most BSM searches.
- Interesting anomalies (top forward-backward asymmetry at the Tevatron)
- Important for SM Higgs
- So far the only NNLO input for gluon pdf from hadron colliders
- Measurement of α_S . Top mass is a major input when extending SM towards GUT scales

  (think vacuum stability, Higgs inflation).

Top-pair production at NNLO

- Impressive agreement for the total cross-section (level of 4-5%)

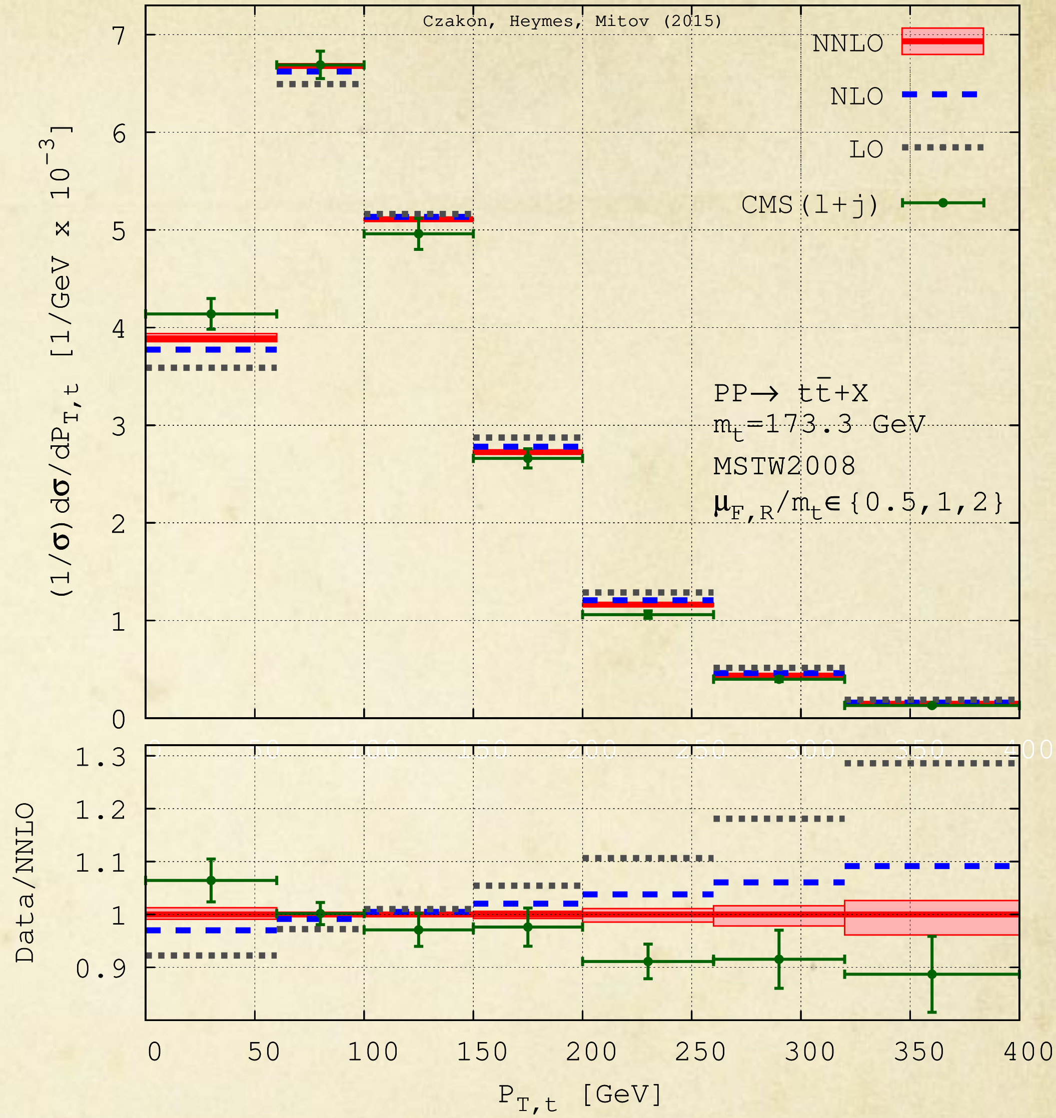




- ✓ Notable: after a month of data taking the largest error, by far, is the one due to luminosity!
- ✓ Cancels in the tt/Z ratio. Excellent agreement with NNLO SM.

Top-pair production at NNLO: P_T spectrum

- ✓ NNLO QCD corrections systematically improve the agreement with CMS data.
- ✓ Agreement with ATLAS (not shown) even better.
- ✓ NNLO does what one normally expects:
  - Convergence
  - Decrease of scale error
  - Pdf error not included



Next Lectures

- ✓ Learn to think as physicists: what matters and what doesn't
- ✓ Factorization for physical processes and non-perturbative contributions (PDF, etc)
- ✓ Perturbative loop computations
- ✓ Understanding how to tame Infra Red singularities
  - ➢ Unlike UV divergences we do not renormalize them away
  - ➢ One needs to rethink the concept of a final state: the final states we measure are mixture of basic states (in the sense of S-matrix elements)
  - ➢ This is a huge problem
- ✓ A lot of computing: all problems worth considering involve 10^3 - 10^6 Feynman diagrams
- ✓ Analytical and numerical methods used; How to evaluate integrals?
- ✓ (Efficient) evaluation of amplitudes
- ✓ What does it mean to evaluate an integral in terms of functions that themselves cannot be computed numerically
- ✓ Etc.