QCD at LHC: theoretical developments

(mostly within the last 1 year)

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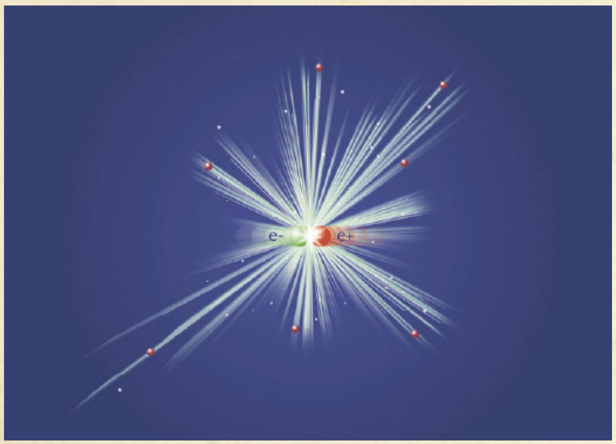
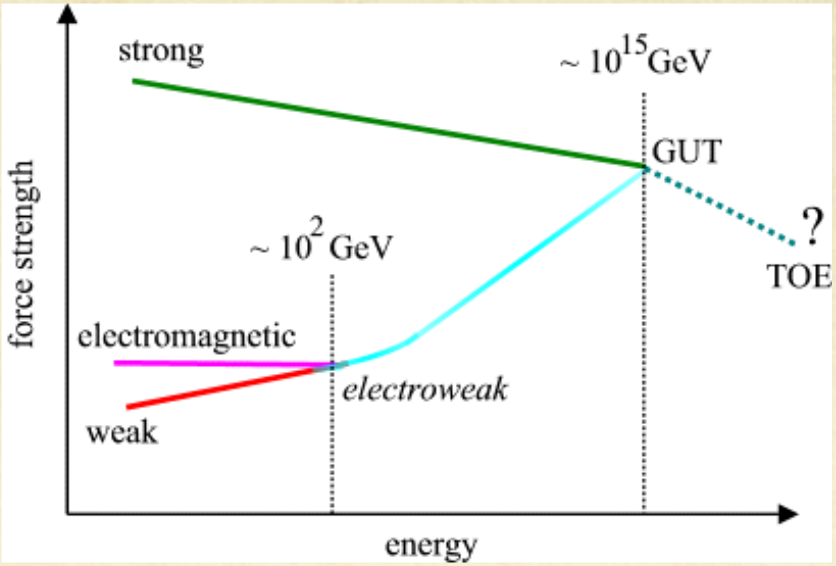
Particle physics is driven by the belief that:



… 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?

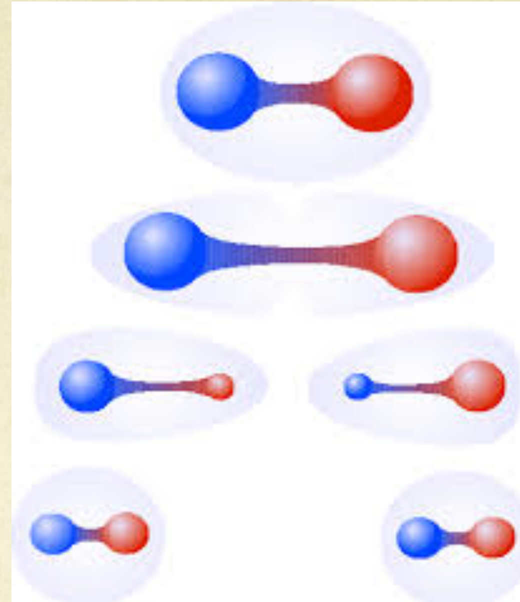
Is it merely a desert?

Or an oasis?

Or perhaps a jungle?

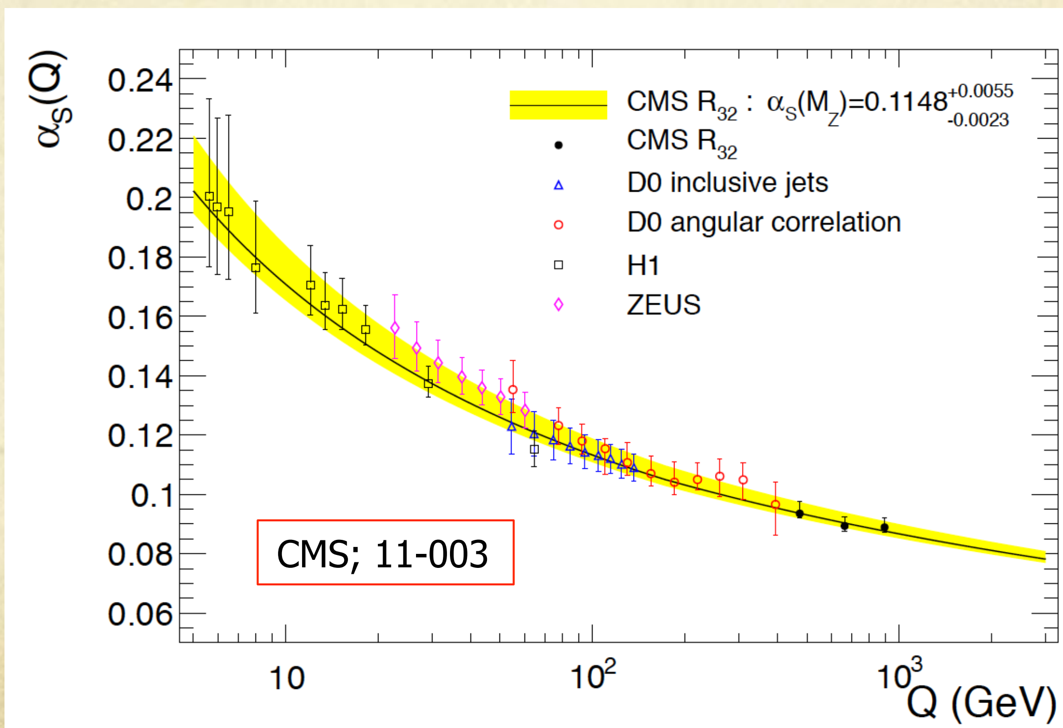
There are several important problems that are in the realm of particle physics:

Ex: Confinement:



- ✓ An outstanding problem.
- ✓ Yet we know how to go around it and keep making progress.

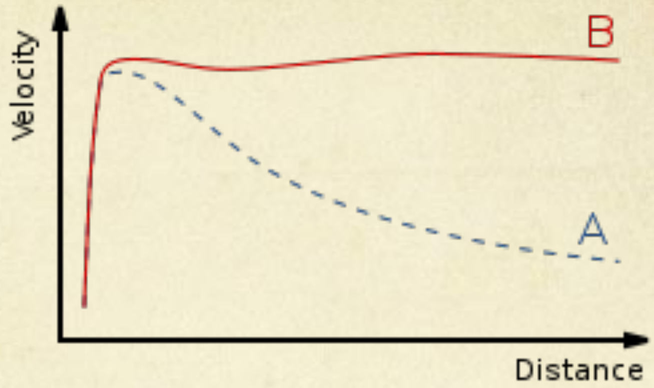
Proof: The LHC



The Dark Matter Problem

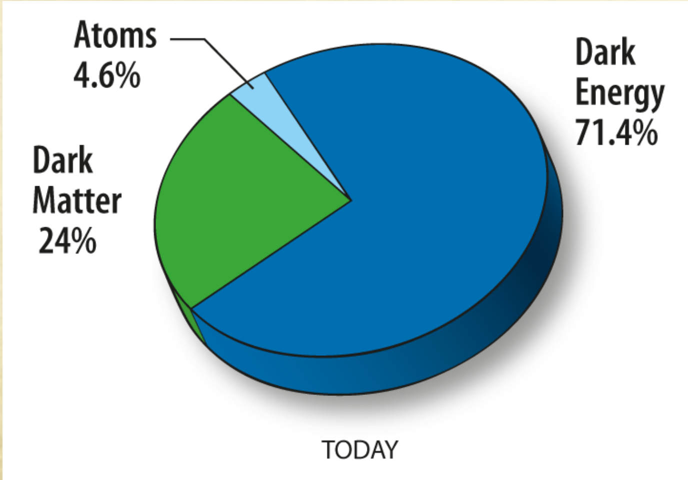
Fritz Zwicky '1933

The famous galactic rotation curves problem:



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

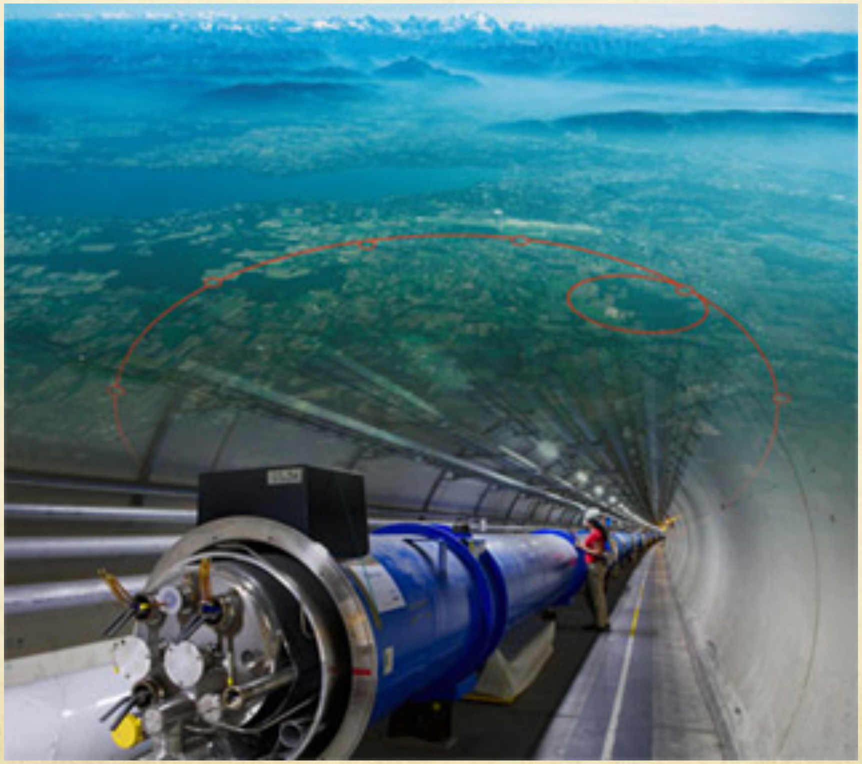
- ✓ (more subtle) If there is a jungle of particles in the desert, then such new physics offers Dark Matter candidates.

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

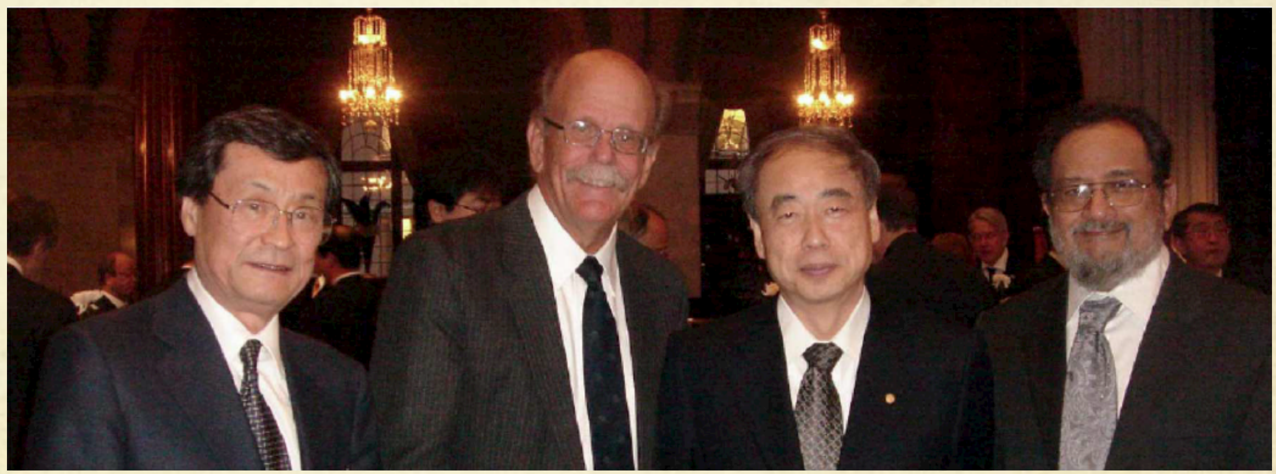
The modern physics at particle accelerators



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

Discovered Higgs boson:

… established the CKM paradigm:



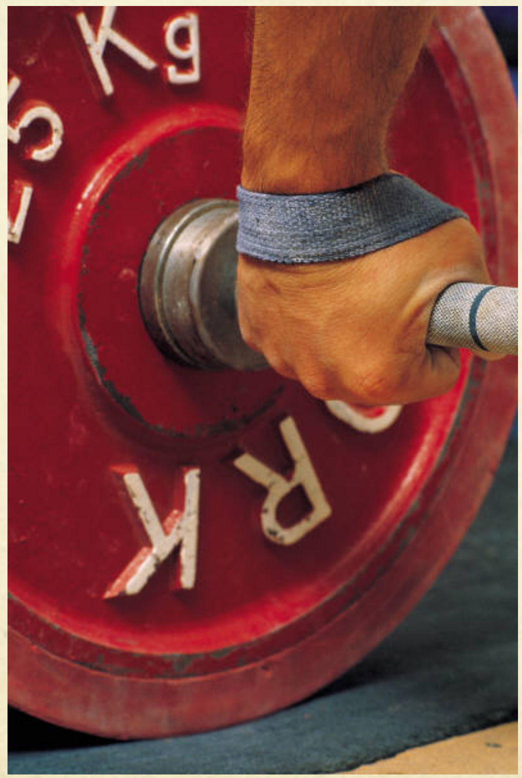
40 years of tireless scrutiny: no deviation from the SM so far

- The apparent success of the SM can hardly by overstated.
- Yet, there is much more to do!

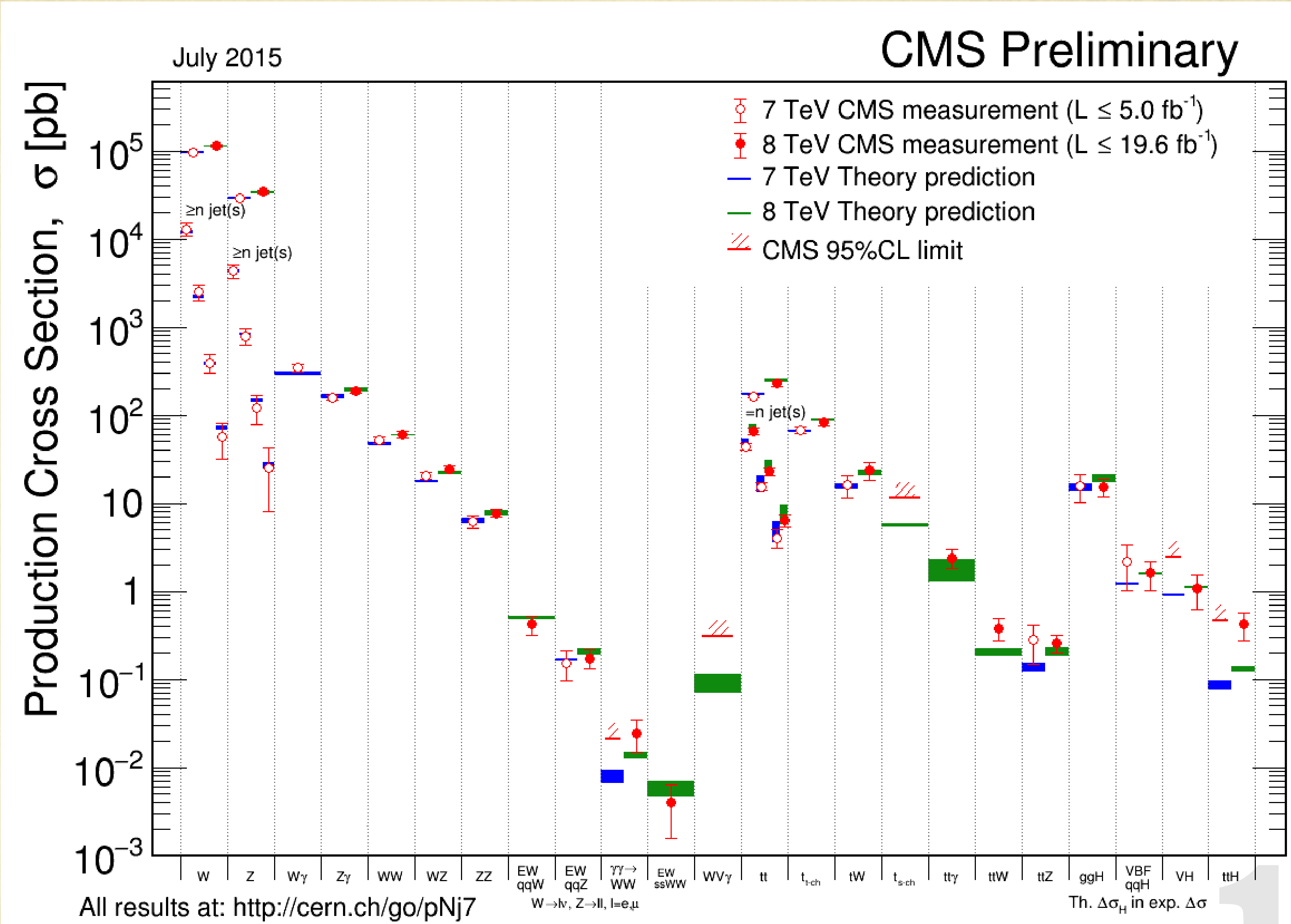
The role of QCD at Colliders (LHC)

- QCD is everywhere (we collide hadrons, we measure hadrons; strong coupling is largest in SM)
- How QCD helps:
  - Increases the accuracy of SM predictions for signals that we care about
    - Higgs
    - PDF's and α_s
    - Vector bosons
    - Jets
    - Top quarks (incl. results on top quark mass)
  - QCD and BSM searches
- For the QCD aficionados (and, yes, there are many of them)
  - LO is long dead, live NLO! (despite the fact that I'll focus on NNLO)
  - Parton showers, resummation and all that

Lifting the accuracy of SM predictions



Here is the big picture

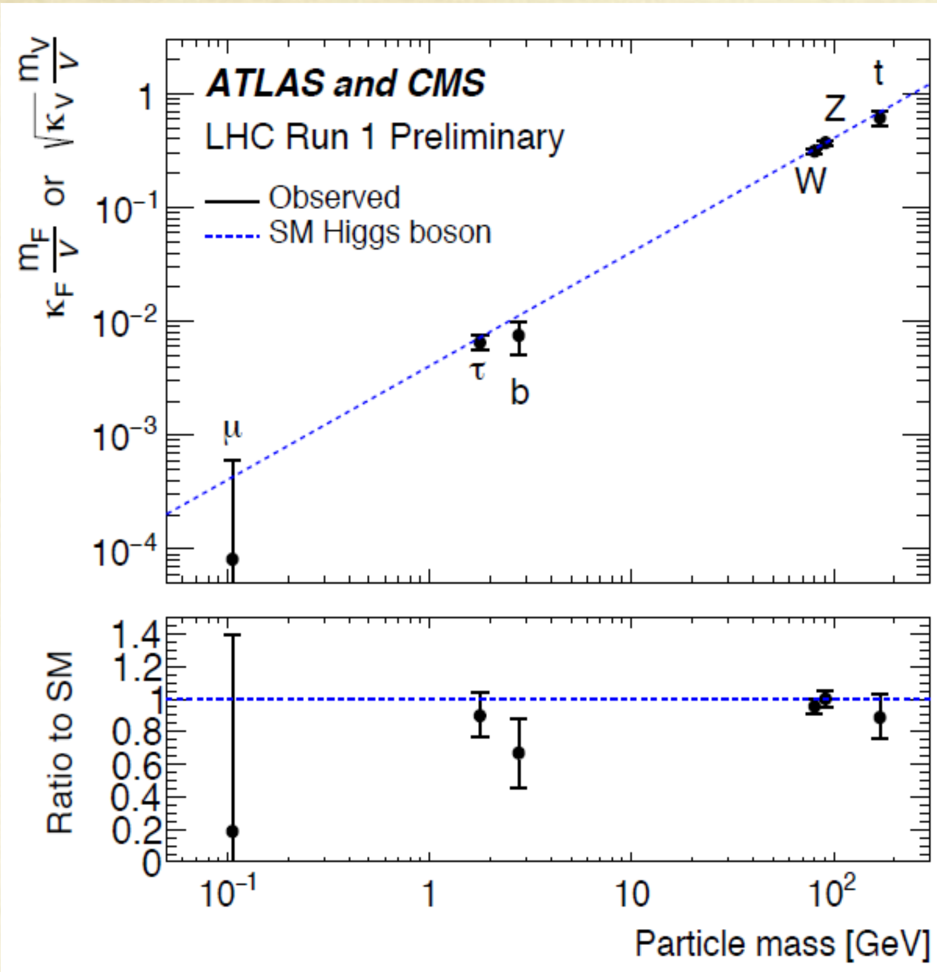


- LHC Run I: impressively broad agreement with SM!

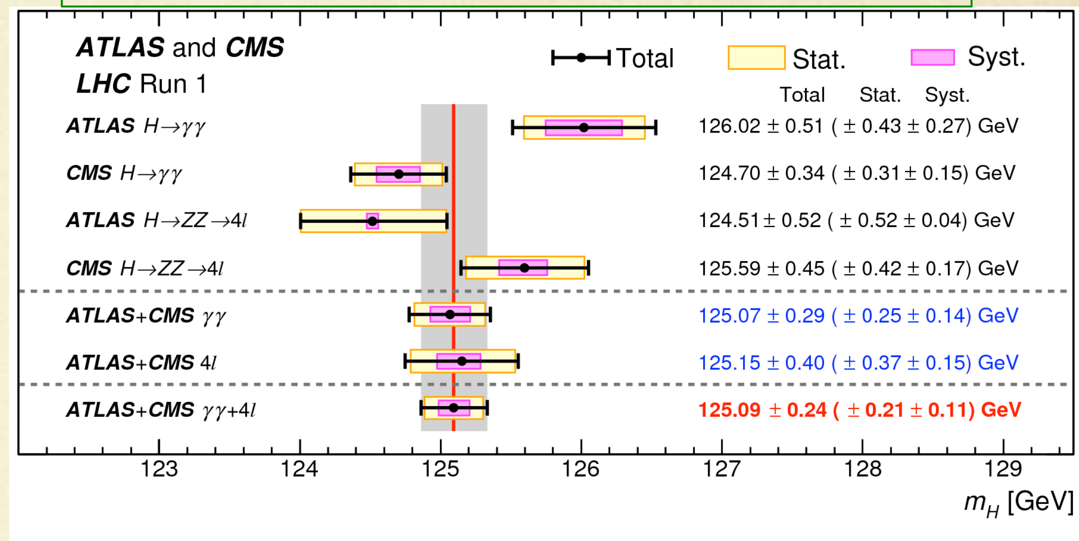
Higgs

- LHC Run I discovered the Higgs and established it is SM-like

Higgs couplings, assuming SM:



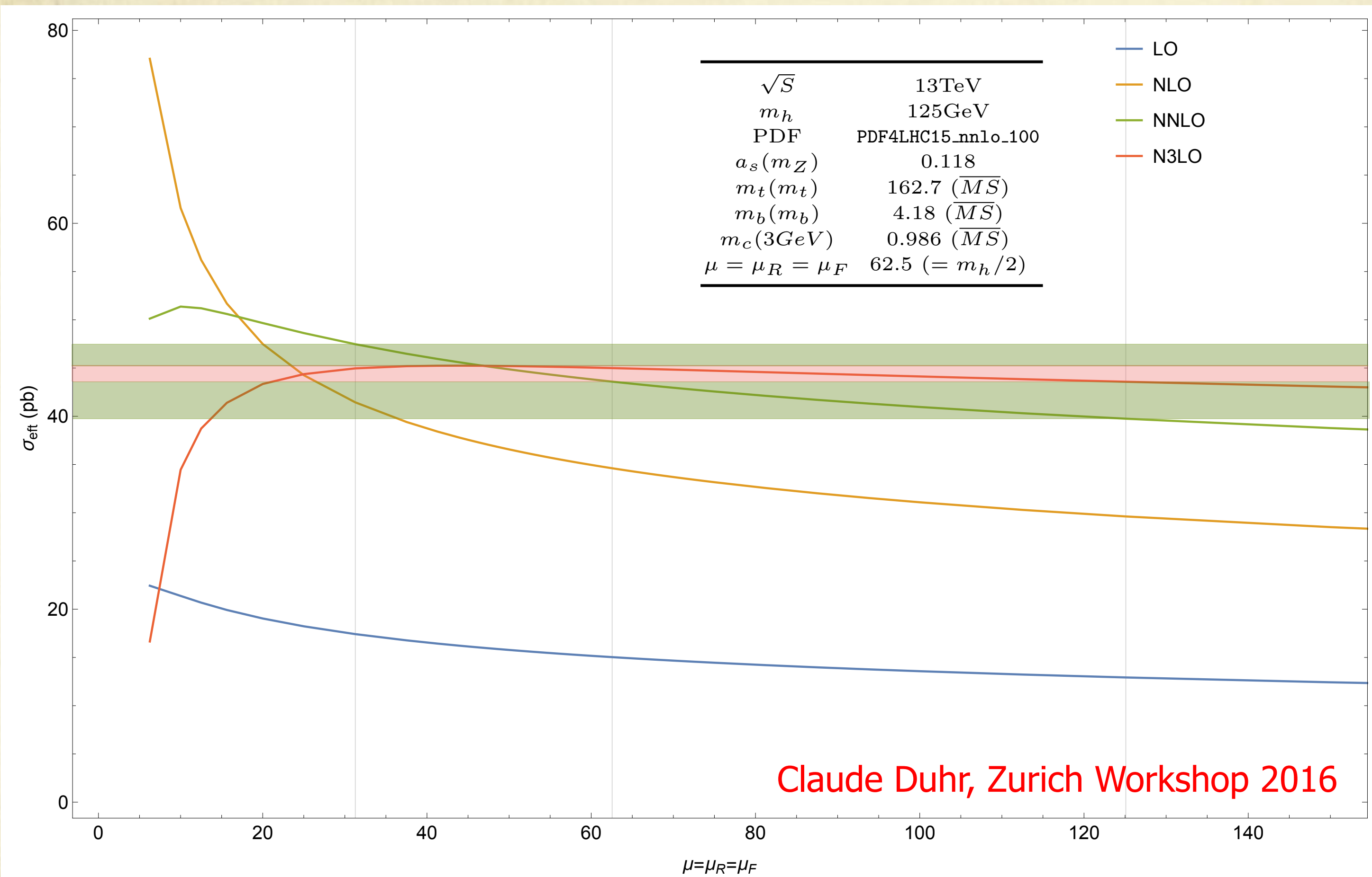
Higgs mass measurements (2 channels):



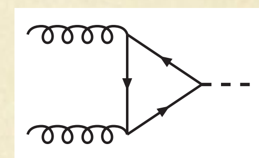
Higgs

- 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

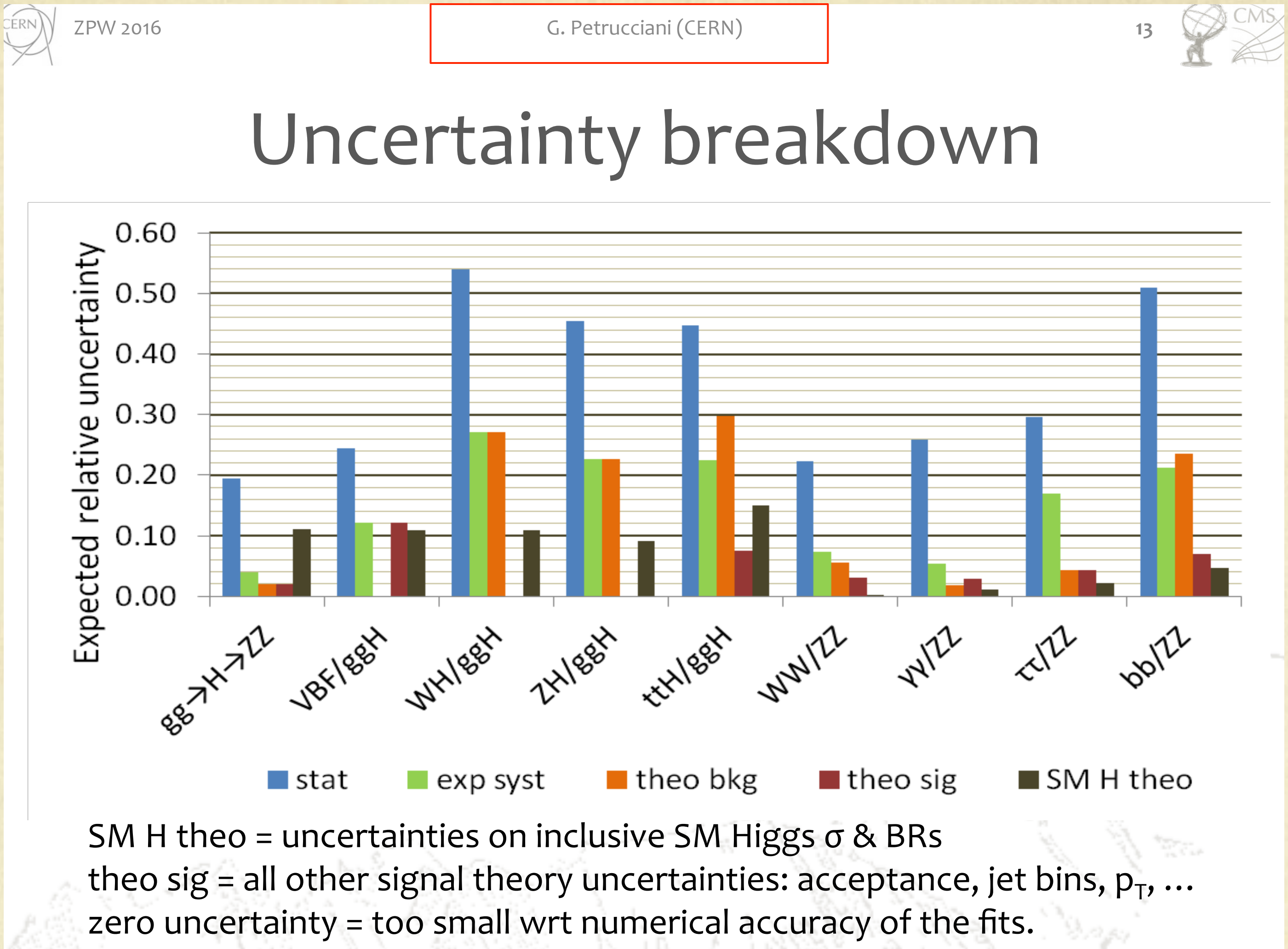
- Total cross-section at N^{3}LO:

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
	±1.86%	±2.60%	$^{+0.2}_{-2.3}$ %	±0.25%	±1.15%	±1.00%	±0.70%	±1.00%

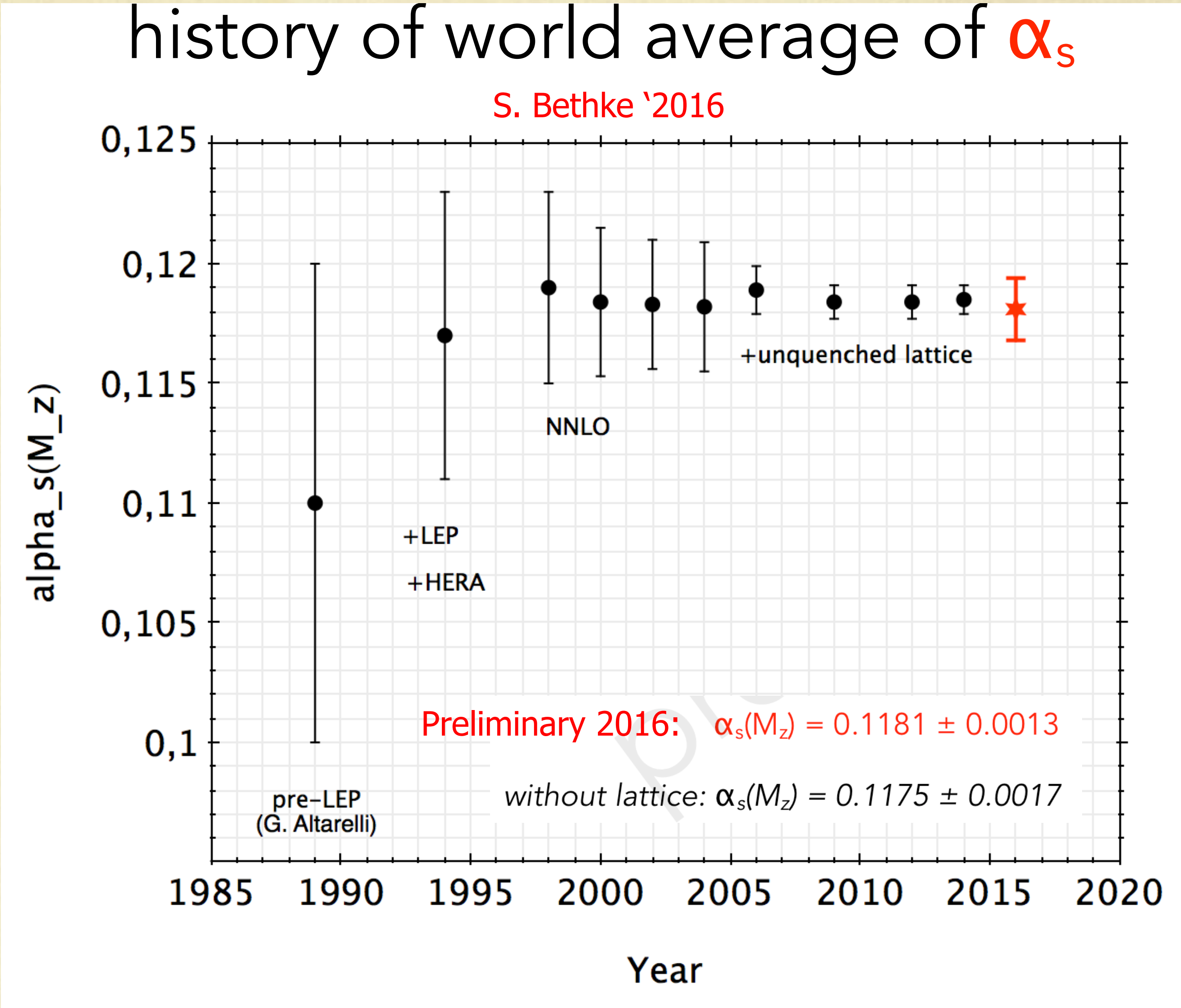
- Uses NNLO pdf; no N^{3}LO pdf's available (likely 1% effect) See also Forte et al '14
- EW corrections exact at NLO; at mixed QCD-EW included in an EFT approach (gauge bosons integrated out into Wilson coefficients)
- Quark masses (m_t m_b) included exactly at NLO. NNLO desirable
- Threshold resummation 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)

Higgs couplings



- Theory errors are subdominant at present but in some cases are close contenders

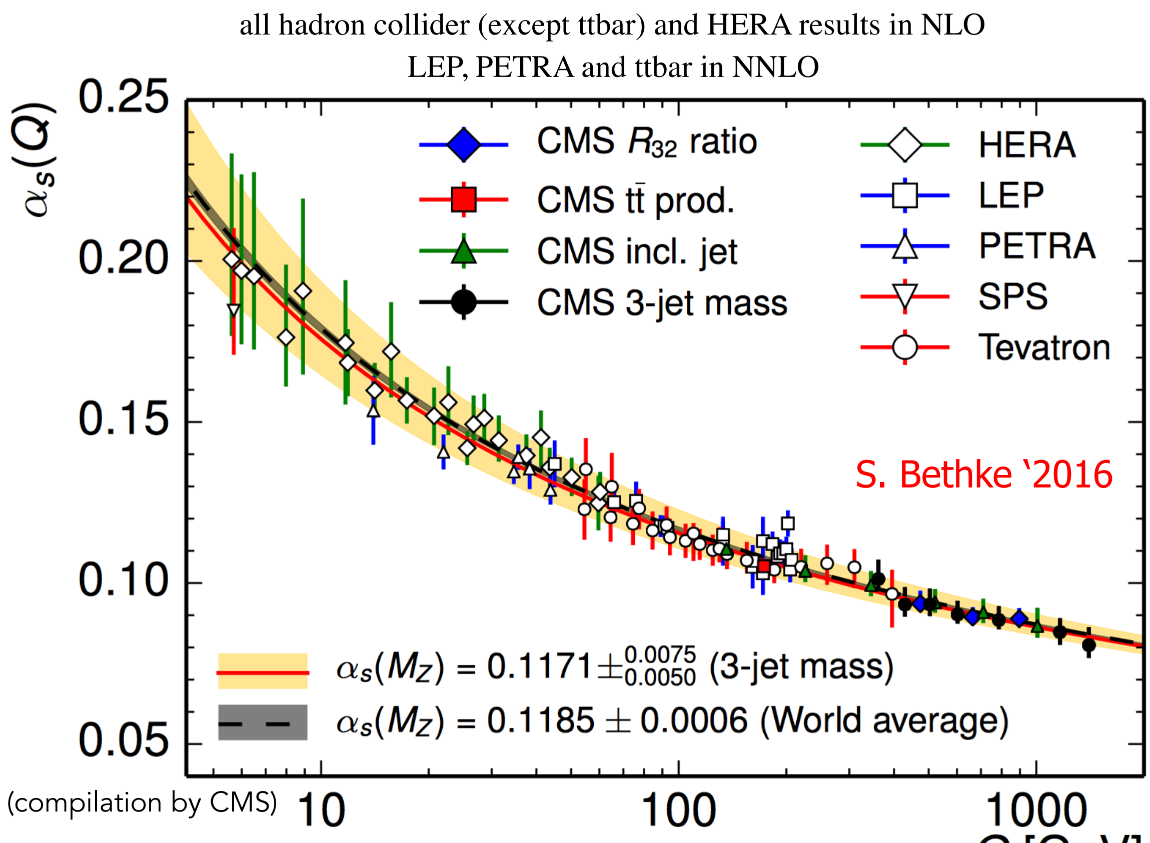
Strong coupling α_S



- What happened?
  - Jump in the error from lattice.
  - Inclusion of ttbar measurement which is in downward fluctuation.

Strong coupling α_S

α_s results from hadron collider data



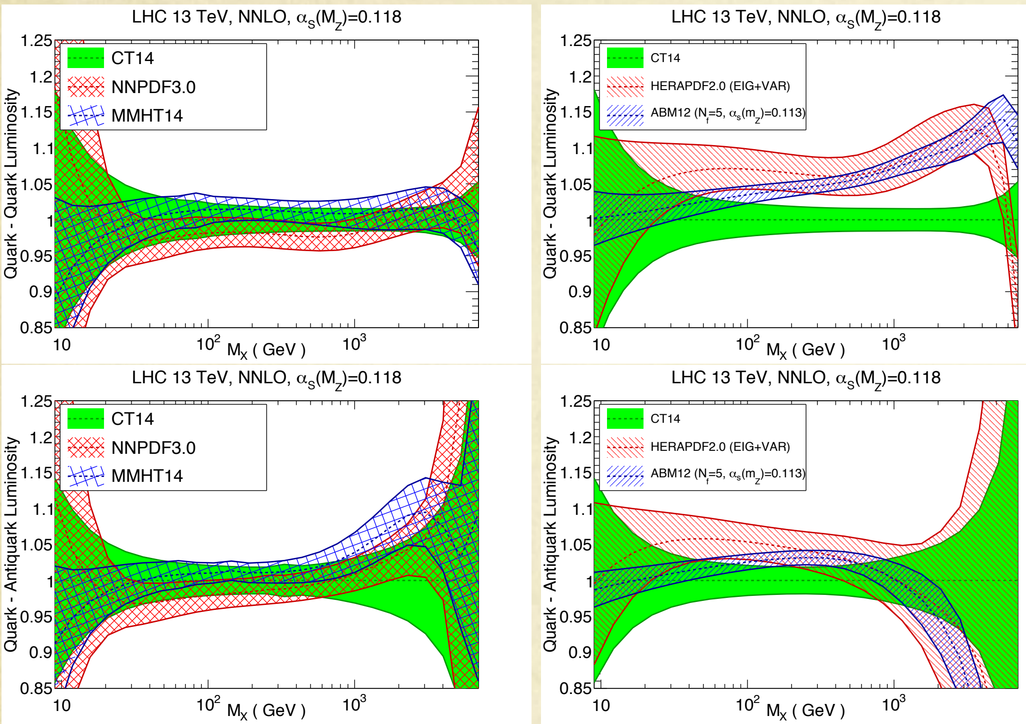
not shown: ATLAS incl. jet: $\alpha_s(M_Z)$= 0.115 ± 0.009
ATLAS TEEC: $\alpha_s(M_Z)$= 0.1173 + 0.0066 - 0.0028
ATLAS ATEEC: $\alpha_s(M_Z)$= 0.1195 + 0.0065 - 0.0028

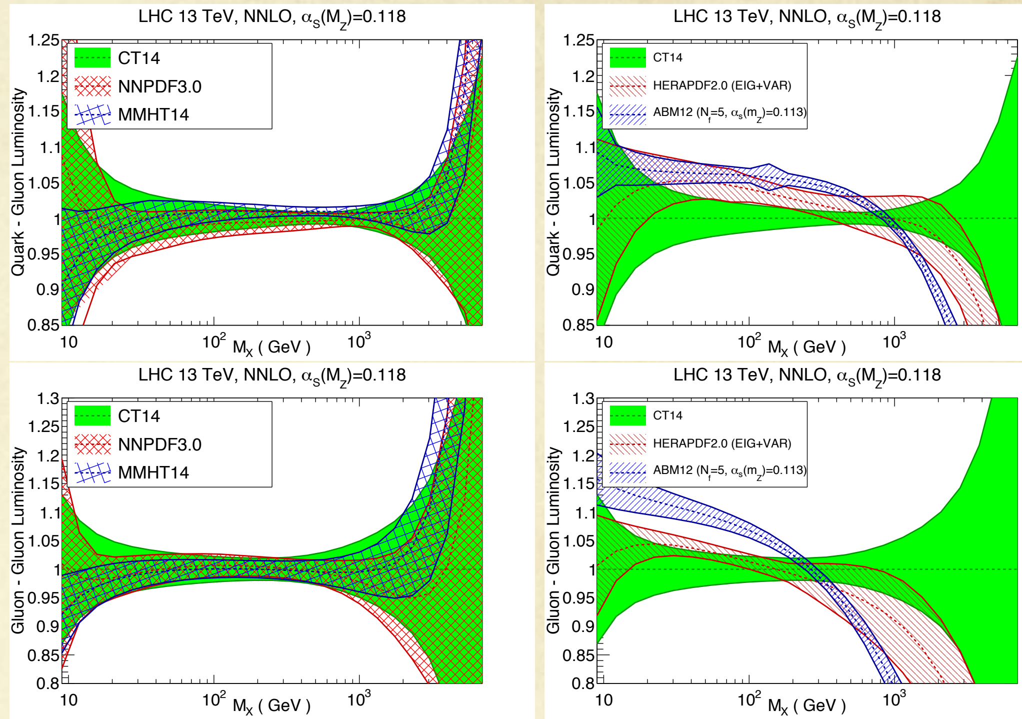
LHC and Tevatron results average to: $\alpha_s(M_Z)$= 0.1172 ± 0.0059

- LHC data provides good access to α_S, albeit with larger error.
- Allows unprecedented access to running of α_S at high scales (TeV) from, for example, jets and ttbar.

Parton distribution functions

- New generation of global PDF sets available: CT14, NNPDF3.0 and MMHT14.





- They are compatible with the PDF4LHC recommendation and their fluxes are rather similar.
- Some other sets differ (see above).
- Essential improvements are expected once LHC top differential calculations (NNLO now available) as well as jet calculations (NNLO to appear soon) are included.

Parton distribution functions

- New combination set: PDF4LHC15:

See arXiv:1510.03865

  - Provides both MC and Hessian sets with varying number of members

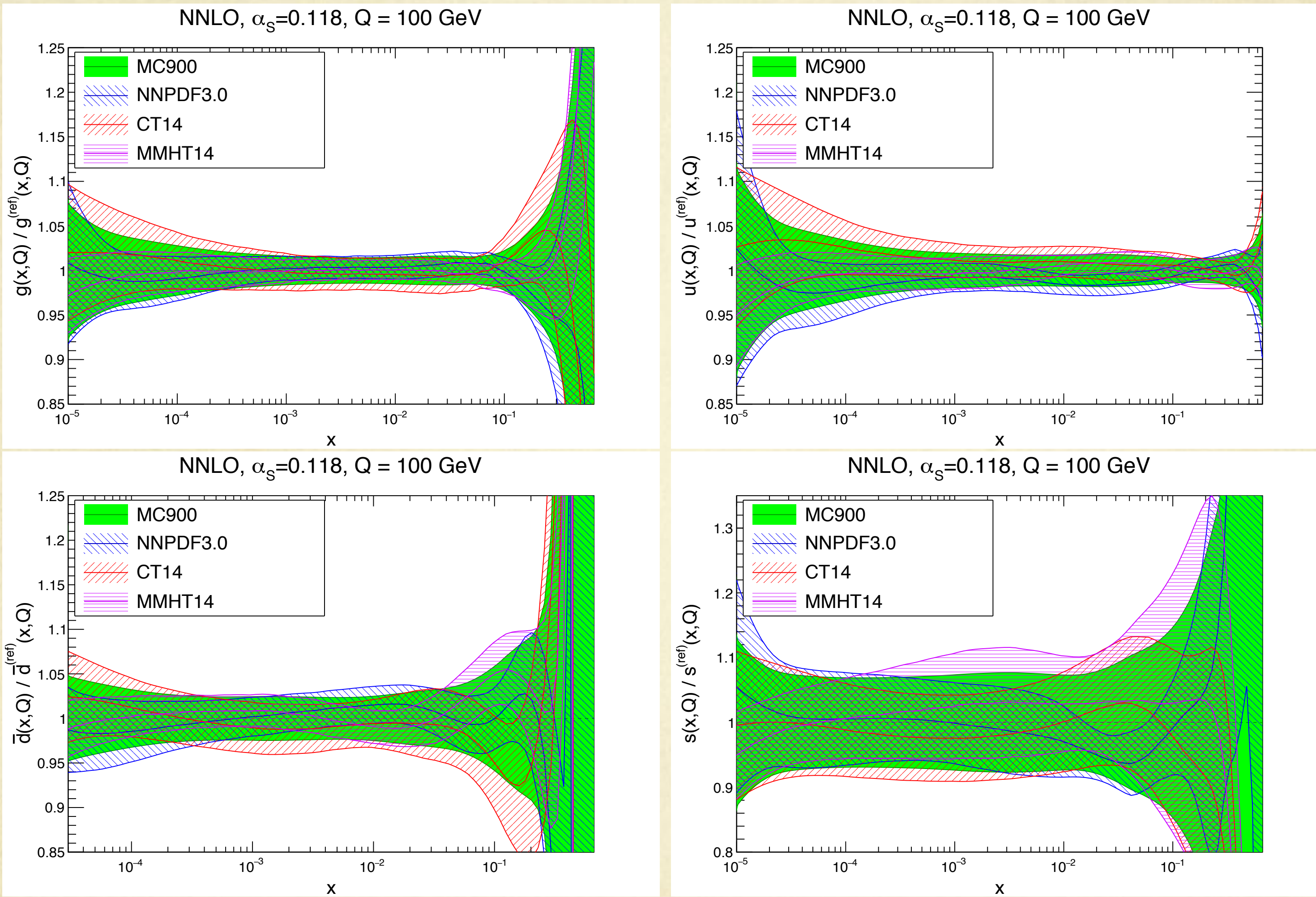


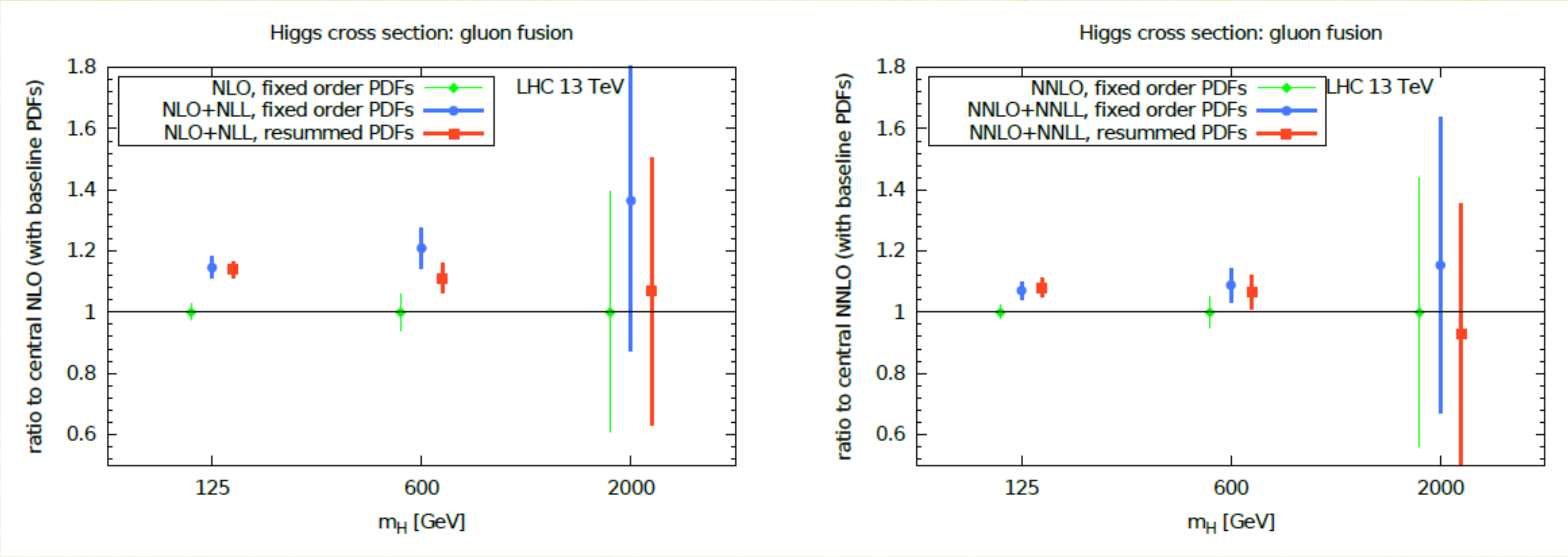
Figure 8: Comparison of the MC900 PDFs with the sets that enter the combination: CT14, MMHT14 and NNPDF3.0 at NNLO. We show the gluon and the up, anti-down and strange quarks at $Q = 100$ GeV. Results are normalized to the central value of MC900.

Parton distribution functions

- Sets with EW corrections available (NNPDF2.3): makes possible the consistent calculation of mixed EW-QCD corrections up to NNLO in QCD.

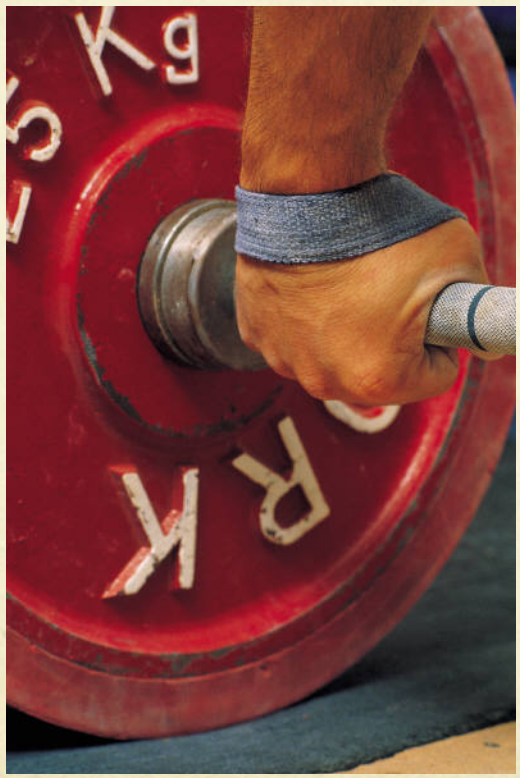
- Soft-gluon resummation's effect on pdf studied (NNPDF3.0) in NNLO with DIS, DY and top data

See arXiv:arXiv:1507.01006



- For the SM Higgs, what matters is the resummation in the Higgs partonic cross-section; resummation in PDF is insignificant.

From Higgs, to Higgs + jets, to Higgs decays (VV+jets)



Higgs + 1 jet at NNLO

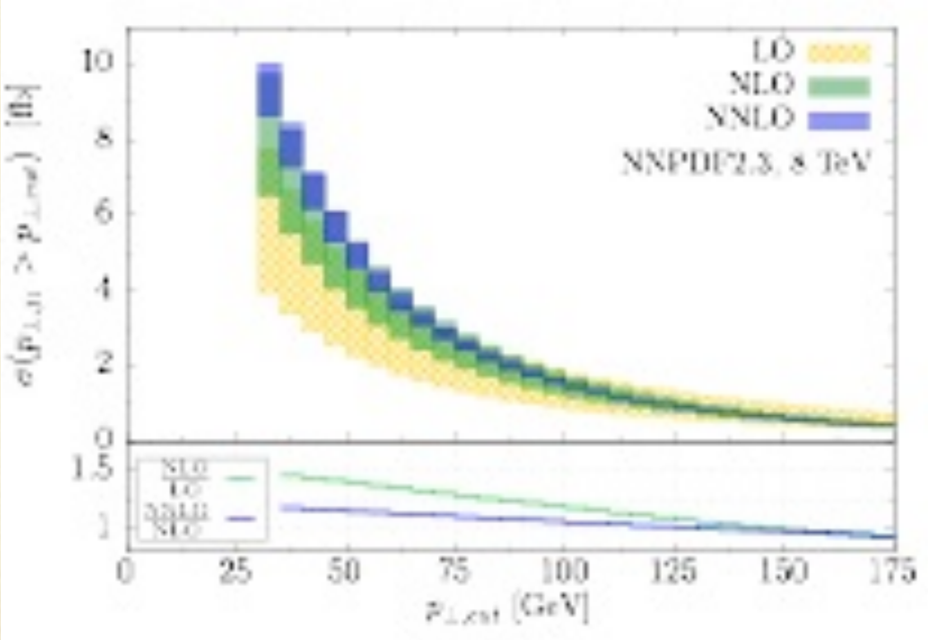
- Studied extensively by several groups (large m_t limit)

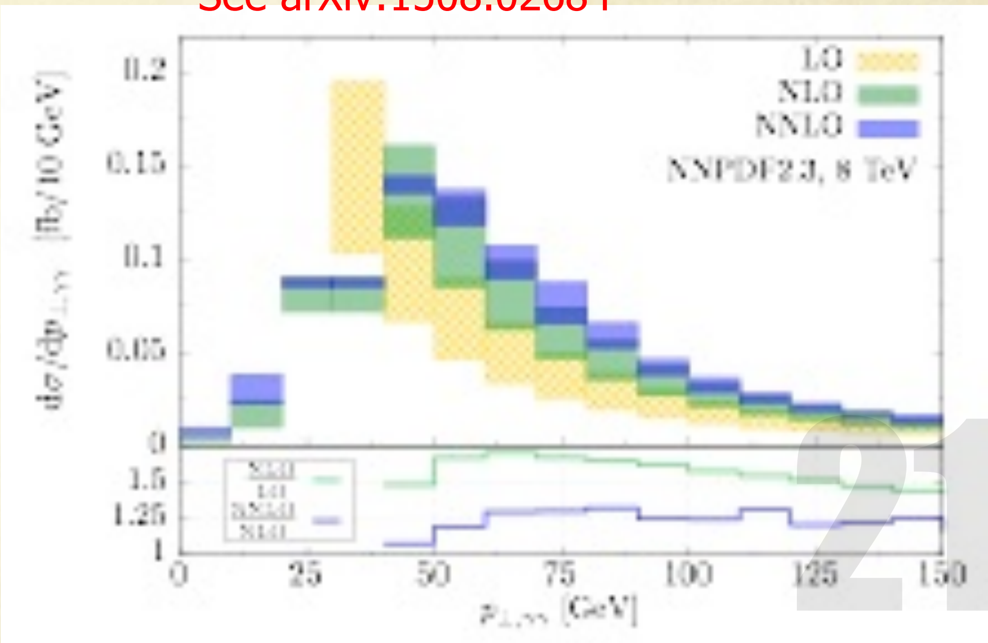
Boughezal, Caola, Melnikov, Petriello, Schulze '13
Chen, Gehrmann, Jaquier, Glover '14
Boughezal, Focke, Giele, Liu, Petriello '15
Caola, Melnikov, Schulze '15

- Moreover the Higgs boson has been decayed:
  - H+j → γγ+j
  - H+j→WW +j→e$\mu\nu\nu$+j

- Such calculations allow for precise predictions that directly match the experimental setup (and are thus very useful)

See arXiv:1508.02684





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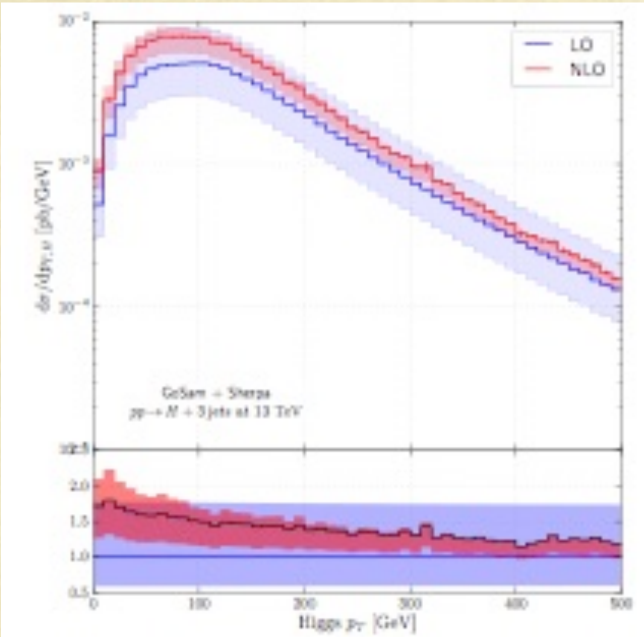
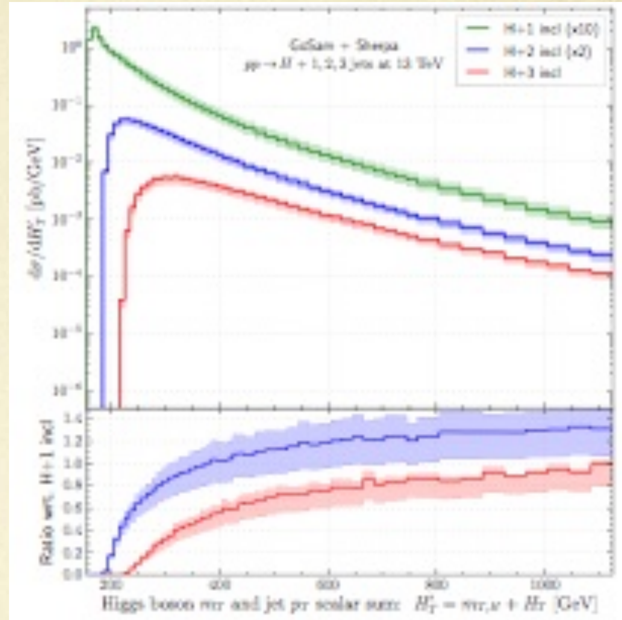
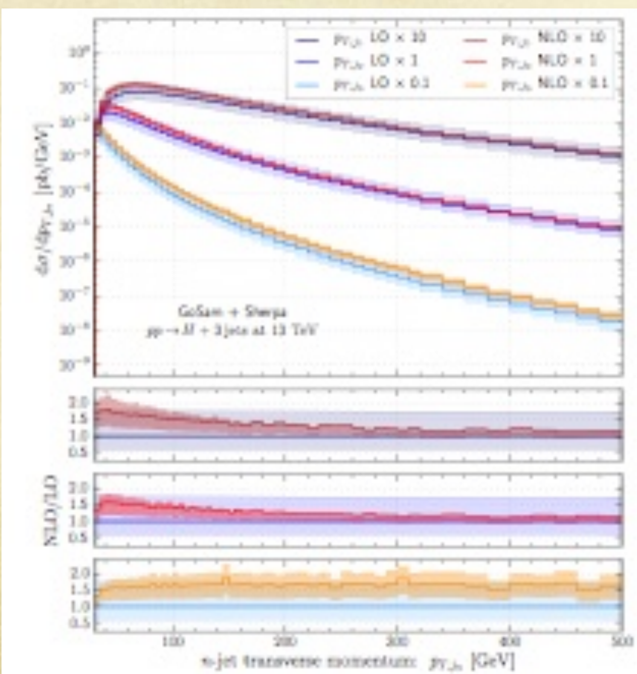
Higgs + up to 3 jets at NLO

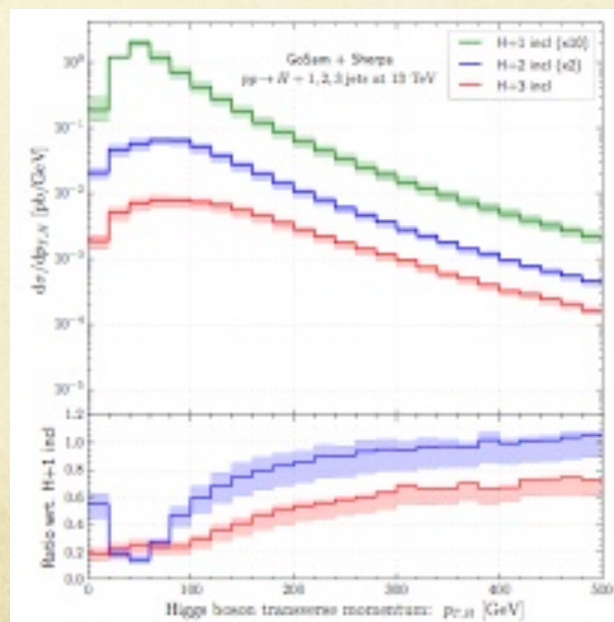
Cullen et al (GOSAM) 1307.4737

- Very significant NLO corrections. Great reduction in theoretical uncertainty









From 1506.01016

VV (vector boson pair) production at NNLO

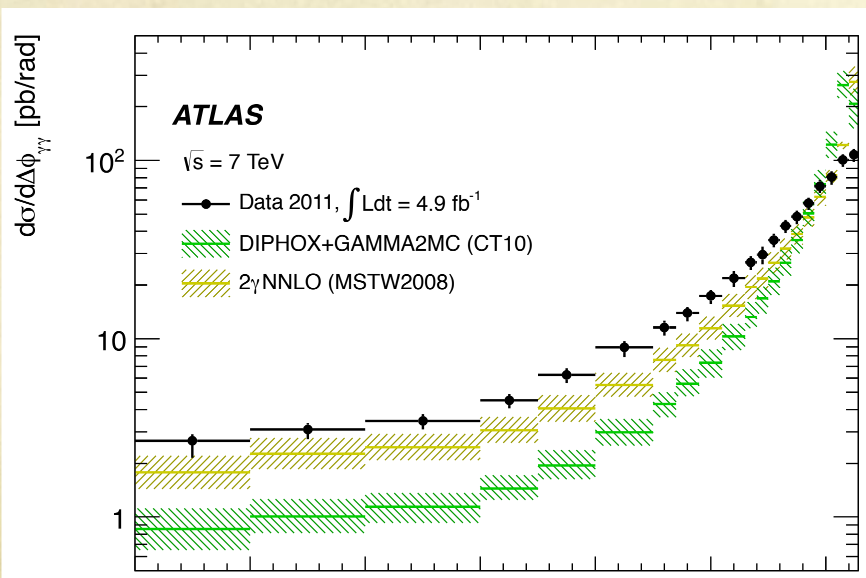
- Vector boson pair production is motivated:
  - an alternative to/decay of Higgs boson
  - in its own right

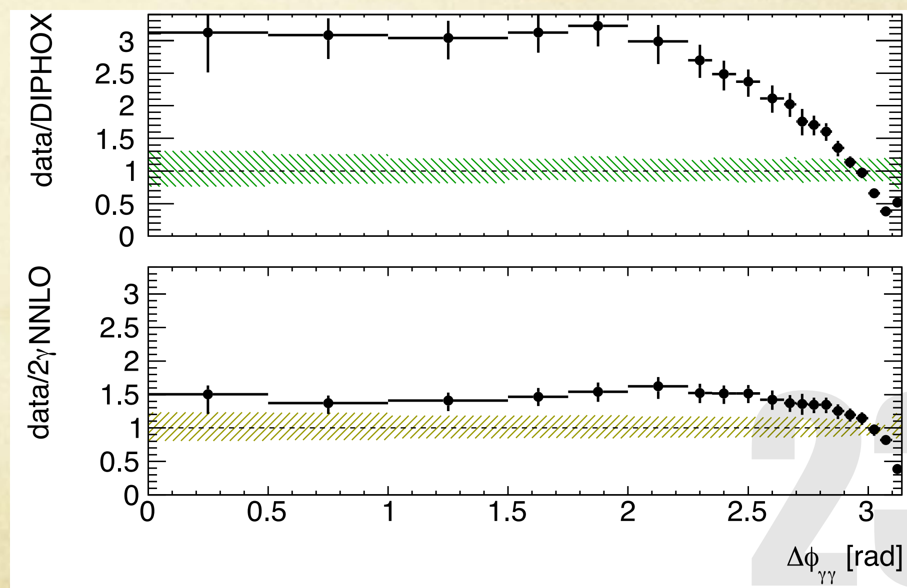
- Thus all precision requirements for Higgs production are directly translated into VV.

- Tremendous progress has been achieved so far: since VV is a colorless final state, one can compute NNLO QCD corrections with effectively NLO methods   Catani, Grazzini '07

- By now all relevant combinations of pairs of W,Z and γ are known to NNLO

- These were some of the early 2-to-2 NNLO calculations and showed surprisingly large NNLO corrections that were essential for finding agreement with data! (especially γγ).



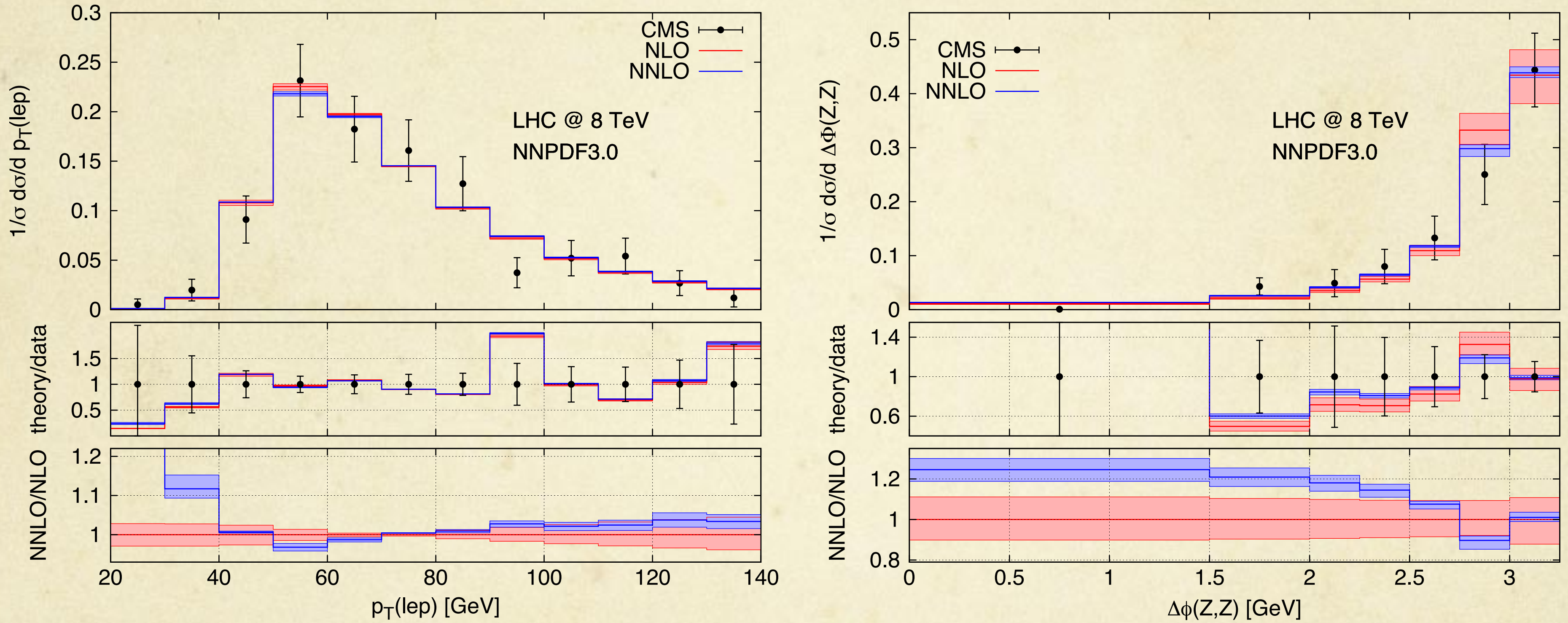


Catani, Cieri, de Florian, Ferreraeta, Grazzini '11

ZZ production with Z decay

Kallweit, Rathlev, Grazzini '15

- Improved Δφ distribution
- Data cannot discriminate the lepton PT yet but the NNLO K-factor has significant shape.



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ZZ production with Z decay

- Fiducial cross-section:

Kallweit, Rathlev, Grazzini '15

Channel	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	$\sigma_{\rm NNLO}$ (fb)	$\sigma_{\rm exp}$ (fb)
$e^+e^-e^+e^-$	$3.547(1)^{+2.9\%}_{-3.9\%}$	$5.047(1)^{+2.8\%}_{-2.3\%}$	$5.79(2)^{+3.4\%}_{-2.6\%}$	$4.6^{+0.8}_{-0.7}(\text{stat})^{+0.4}_{-0.4}(\text{syst.})^{+0.1}_{-0.1}(\text{lumi.})$
$\mu^+\mu^-\mu^+\mu^-$				$5.0^{+0.6}_{-0.5}(\text{stat})^{+0.2}_{-0.2}(\text{syst.})^{+0.2}_{-0.2}(\text{lumi.})$
$e^+e^-\mu^+\mu^-$	$6.950(1)^{+2.9\%}_{-3.9\%}$	$9.864(2)^{+2.8\%}_{-2.3\%}$	$11.31(2)^{+3.2\%}_{-2.5\%}$	$11.1^{+1.0}_{-0.9}(\text{stat})^{+0.5}_{-0.5}(\text{syst.})^{+0.3}_{-0.3}(\text{lumi.})$

8 TeV

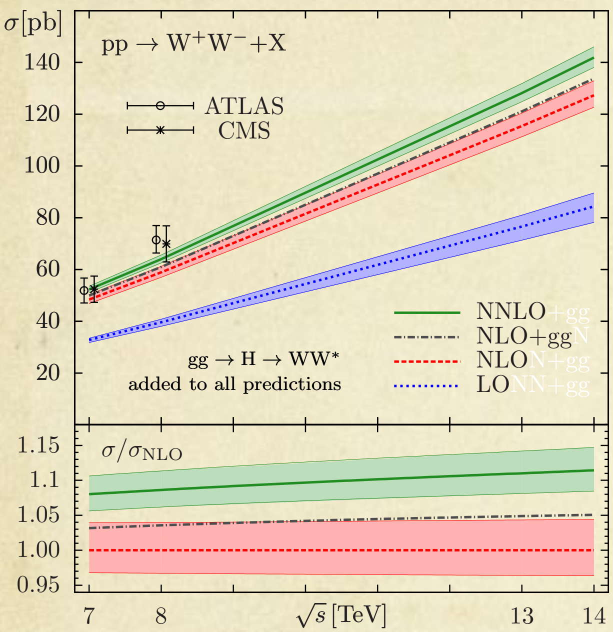
- Curiously, the NNLO corrections significantly improve agreement with ATLAS but the same flavor channels seems to go away from data …
- However experimental errors are large but this will change at 13 TeV

Channel	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	$\sigma_{\rm NNLO}$ (fb)	$\sigma_{\rm exp}$ (fb)
$e^+e^-e^+e^-$	$5.007(1)^{+4\%}_{-5\%}$	$6.157(1)^{+2\%}_{-2\%}$	$7.14(2)^{+2\%}_{-2\%}$	$8.4^{+2.4}_{-2.0}(\text{stat})^{+0.4}_{-0.2}(\text{syst.})^{+0.5}_{-0.3}(\text{lumi.})$
$\mu^+\mu^-\mu^+\mu^-$				$6.8^{+1.8}_{-1.5}(\text{stat})^{+0.3}_{-0.3}(\text{syst.})^{+0.4}_{-0.3}(\text{lumi.})$
$e^+e^-\mu^+\mu^-$	$9.906(1)^{+4\%}_{-5\%}$	$12.171(2)^{+2\%}_{-2\%}$	$14.19(2)^{+2\%}_{-2\%}$	$14.7^{+2.9}_{-2.5}(\text{stat})^{+0.6}_{-0.4}(\text{syst.})^{+0.9}_{-0.6}(\text{lumi.})$

13 TeV

WW production at NNLO

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



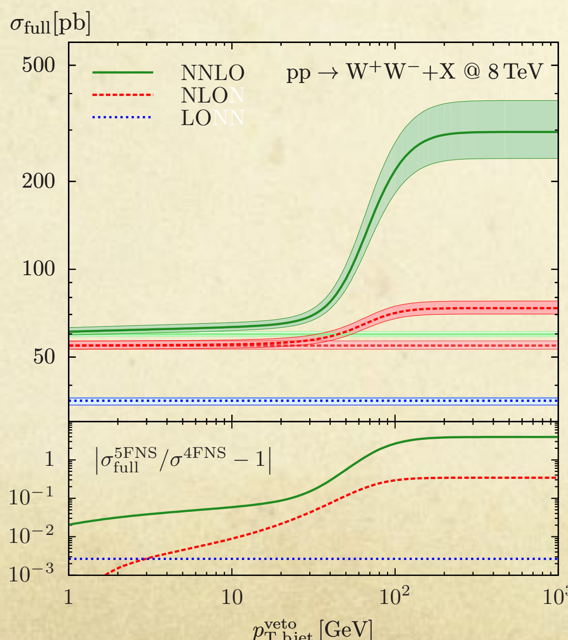
Gehrmann, Grazzini, Kallweit et al ‘14

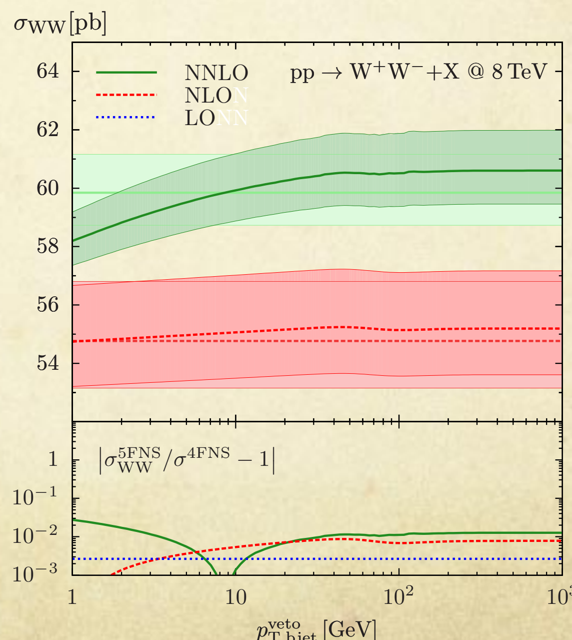
- NNLO correction similar in size to H→ WW*

$\frac{\sqrt{s}}{\mathrm{TeV}}$	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

V+jet production at NNLO

- Vector boson production is the absolute classics (think Drell-Yan) at hadron collider
- Served as the discovery mode for W and Z bosons in 1983 at SPS
- First NNLO corrections to Drell-Yan were computed 25 years ago

Hamberg, van Neerven, Matsuura ’91
Harlander, Kilgore ‘02

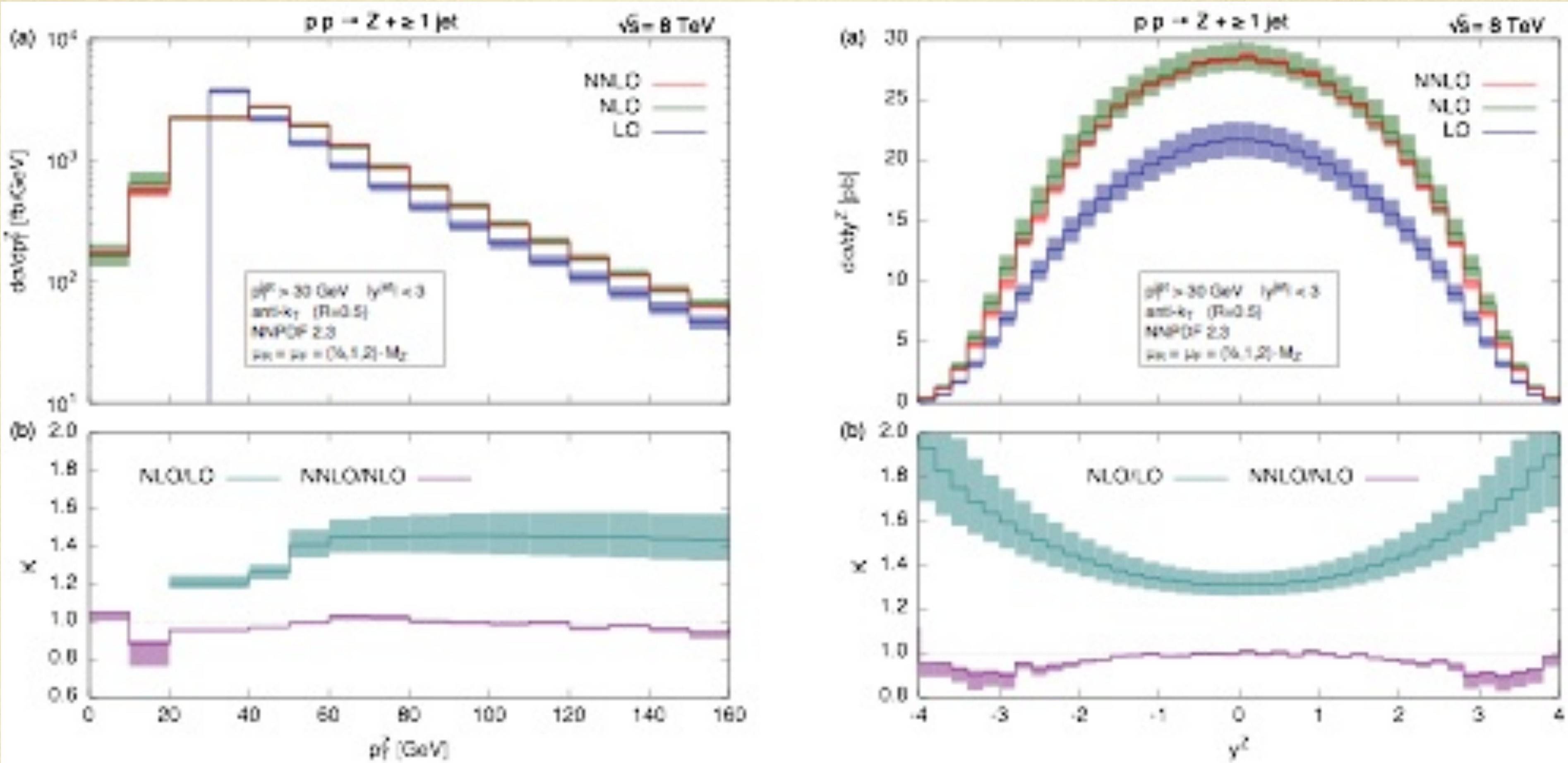
- And differential vector boson production around 10 years ago

Anastasiou, Dixon, Melnikov, Petriello ‘03

- V+jet calculation needed in order to have full NNLO accuracy for the V P_T spectrum
- Recall: precision requirements in vector boson production is very high: it is at the-% level and was even proposed as a luminosity monitor for LHC.

Z+jet production at NNLO

Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan ’15
Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello ‘15

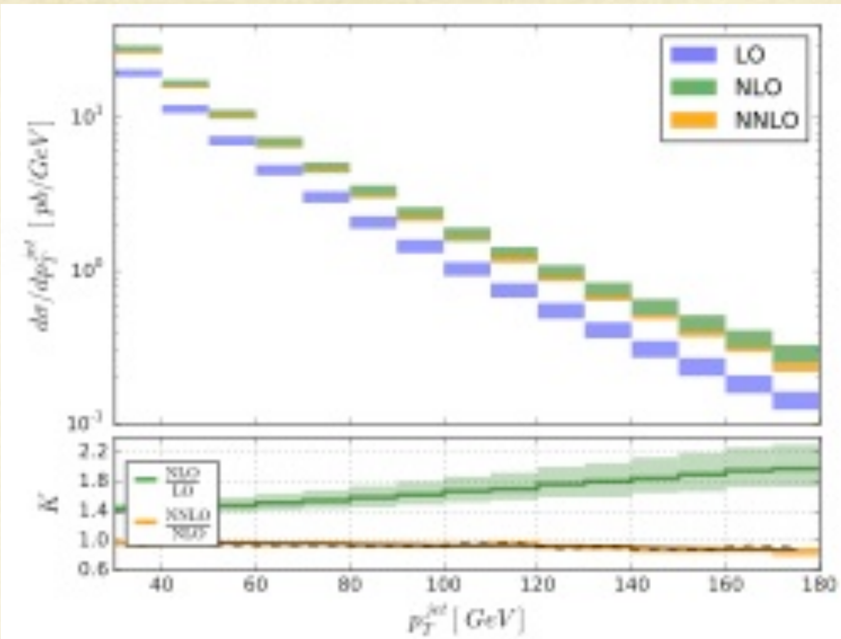


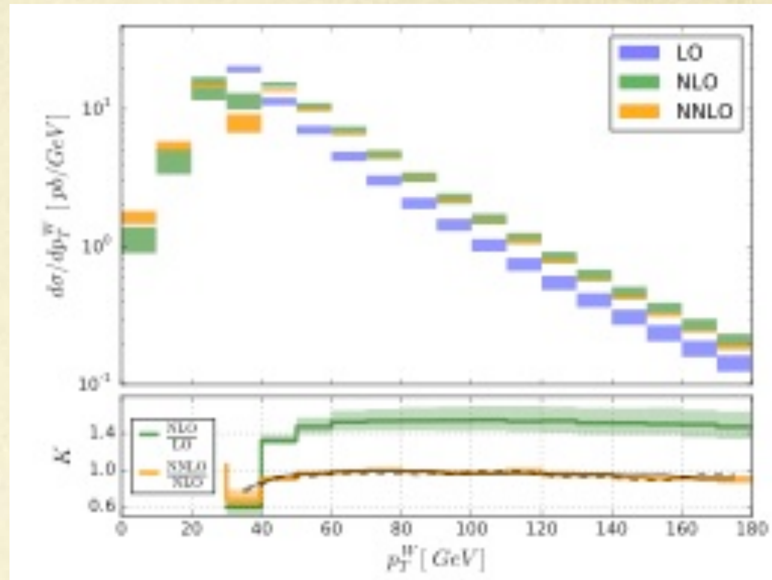
- As expected, impressive impact on the PT distribution of Z-boson
- Notice the very high perturbative stability of the fiducial cross-section:

$$\sigma_{LO} = 103.6^{+7.7}_{-7.5} \ \text{pb} \,,$$
$$\sigma_{NLO} = 144.4^{+9.0}_{-7.2} \ \text{pb} \,,$$
$$\sigma_{NNLO} = 140.3^{+0.0}_{-1.4} \ \text{pb}$$

W+jet production at NNLO

Boughezal, Focke, Liu, Petriello '15





- Impact of NNLO corrections is significant, just as for Z+jet:

$p_T^{jet} > 30$ GeV, $\lvert\eta_{jet}\rvert < 2.4$	
Leading order:	533^{+39}_{-38} pb
Next-to-leading order:	797^{+63}_{-49} pb
Next-to-next-to-leading order:	787^{+0}_{-8} pb

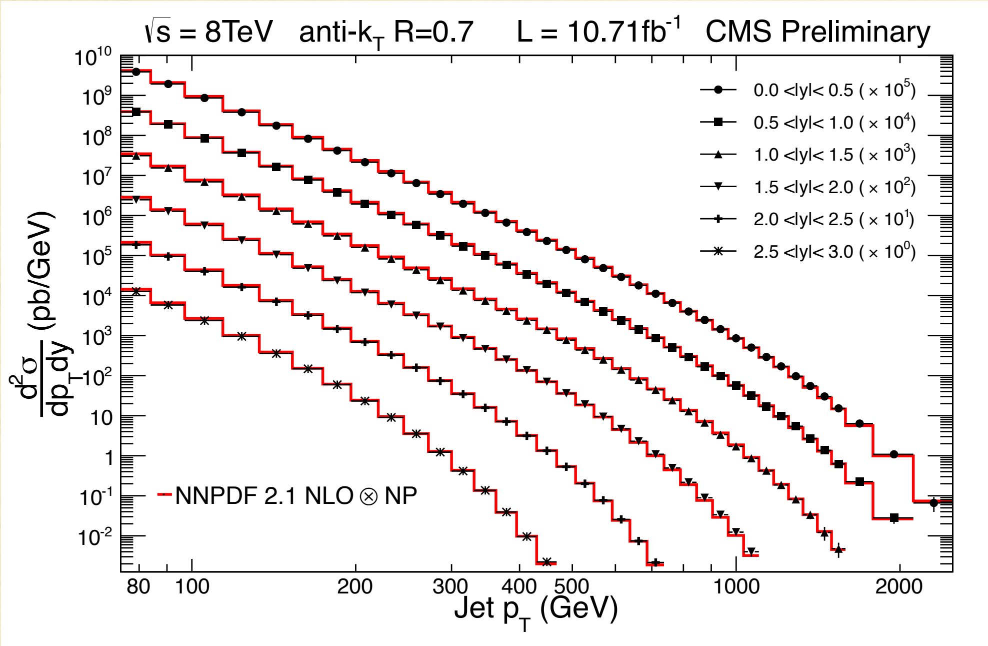
- Fiducial cross-section at 1% level !

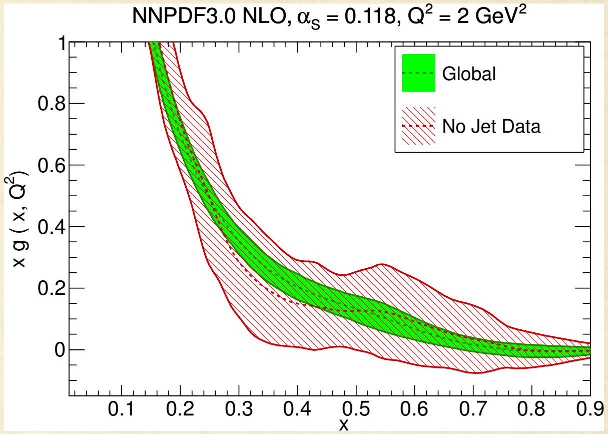
Pure QCD beasts: dijets and top-pair production

Dijet production towards NNLO

- If there is one thing at hadron colliders – that's a lot of jets!

- Measured over a large energy range and over many orders of magnitude
- Overall NLO QCD (+EW) agrees with data.





(Jets are essential in PDF's)

- What we really need is high-precision comparison, in order to:
  - Search for BSM physics decaying to jets
  - Provide input to SM: measurement of α_S and extraction of PDF's (including or not jet data in pdf's has been one of the most debated subjects in pdf community)

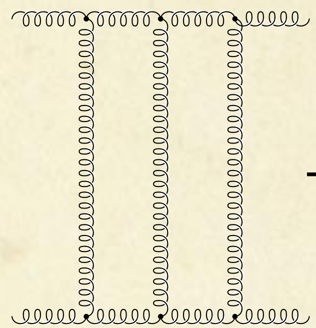
Dijet production towards NNLO

- The expectation is that NNLO QCD (supplemented with EW corrections) will be able to Dittmaier, Huss, Speckner '12 significantly increase the theoretical precision.

- Expectation is based on several partial NNLO contributions (gg-> gg, qqbar-> gg)

A number of papers up to 2014:
Curie, Gehrmann-De Ridder, Gehrmann, Glover, Pires

+ Ongoing Work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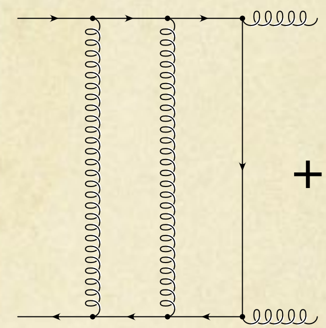
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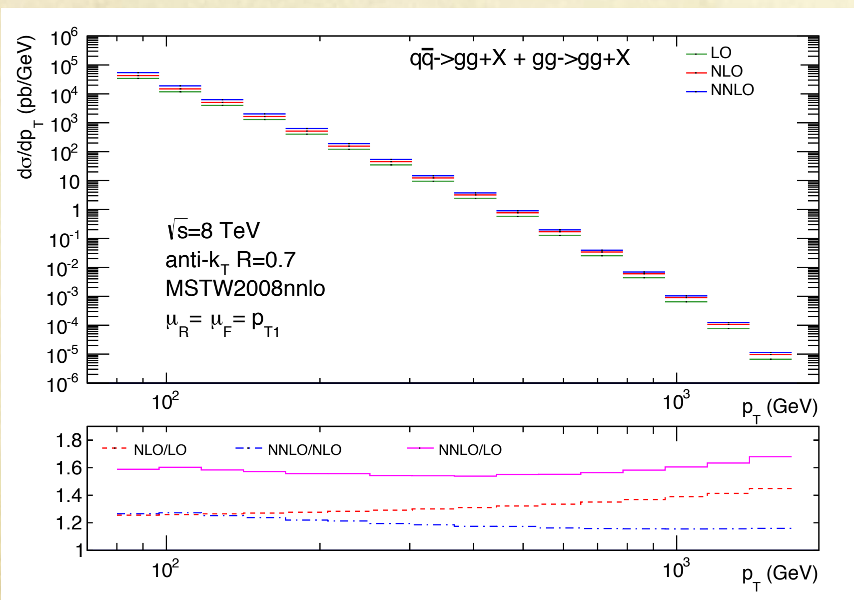
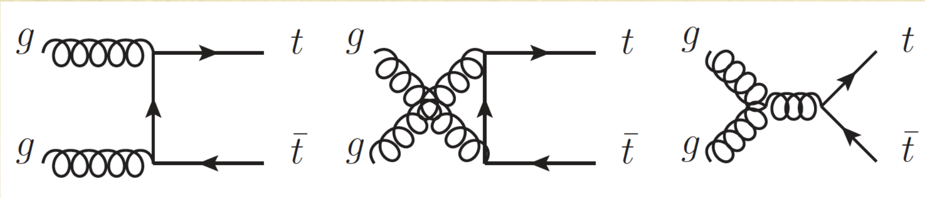
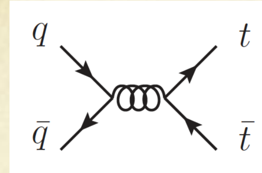
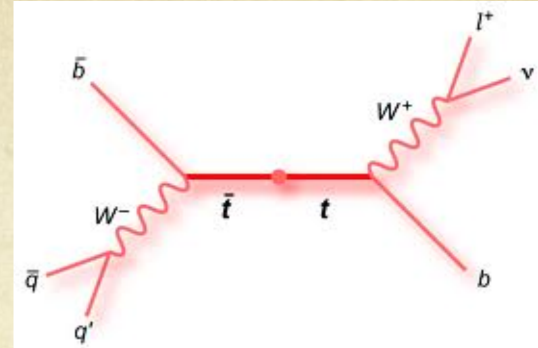


Looking forward to the complete result!

Top-pair production at NNLO



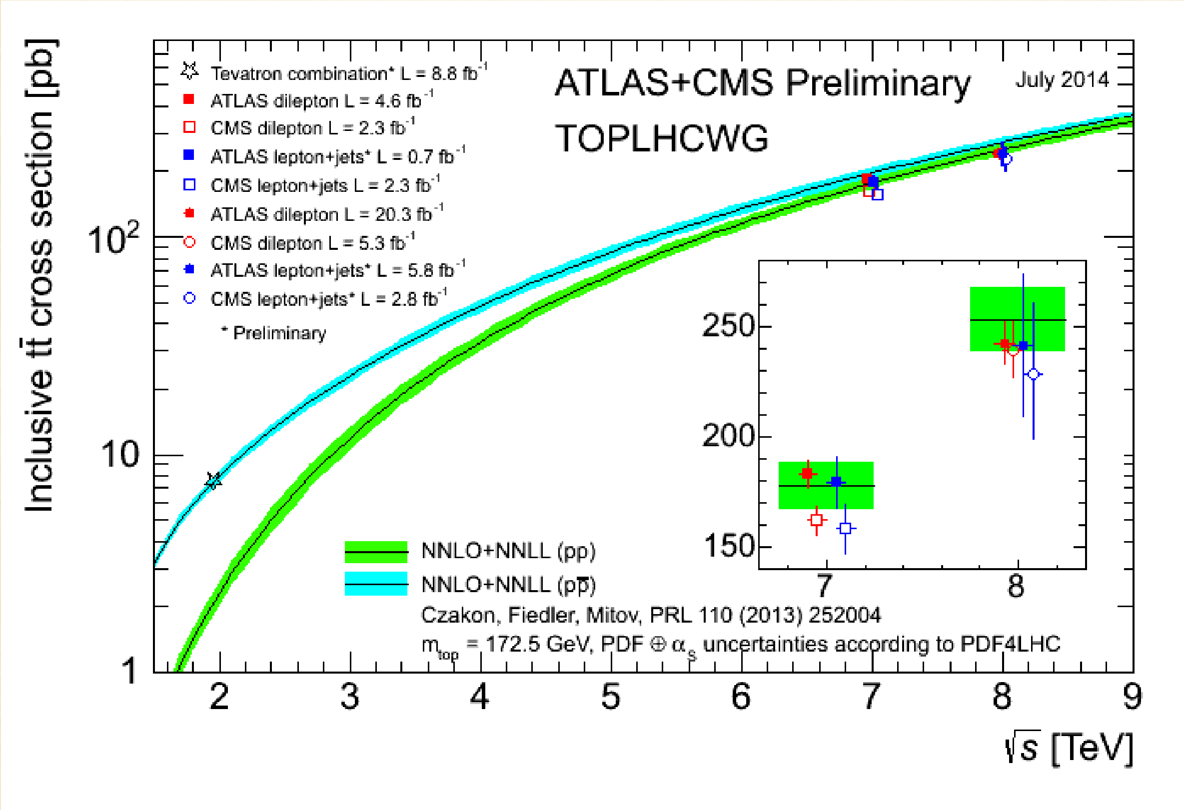




- LHC: the top factory
  - Top discovered at the Tevatron but statistics there was very limited (~1k events)
  - LHC gets the chance to produce lots of top events (>100k events recorded at Run I)
  - LHC Run 2 cross-section larger by a factor of 4.
  - The LHC should, for the first time, study the top 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).

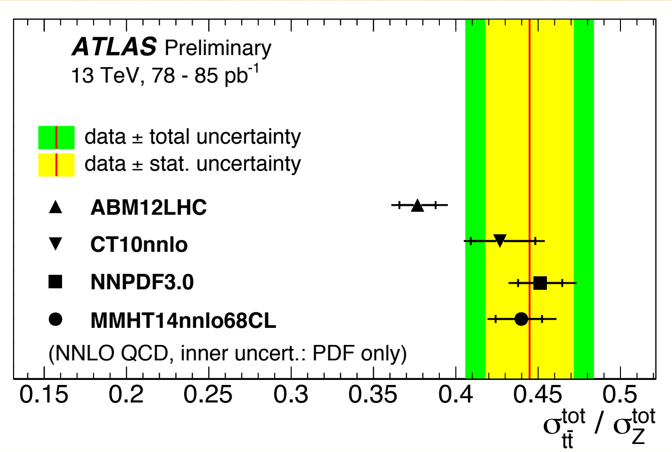
Top-pair production at NNLO

- 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.



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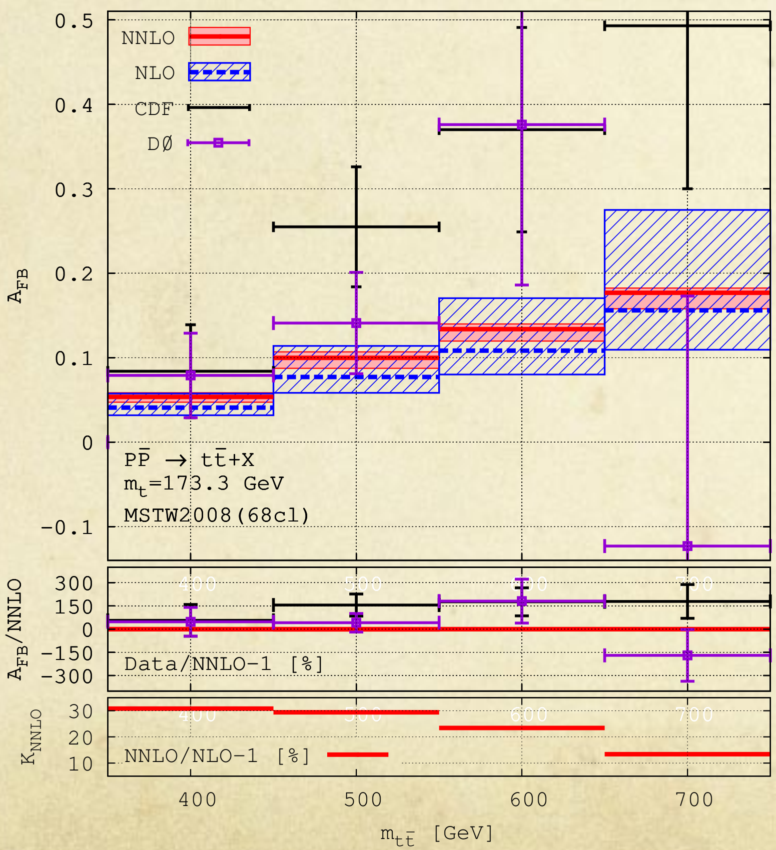
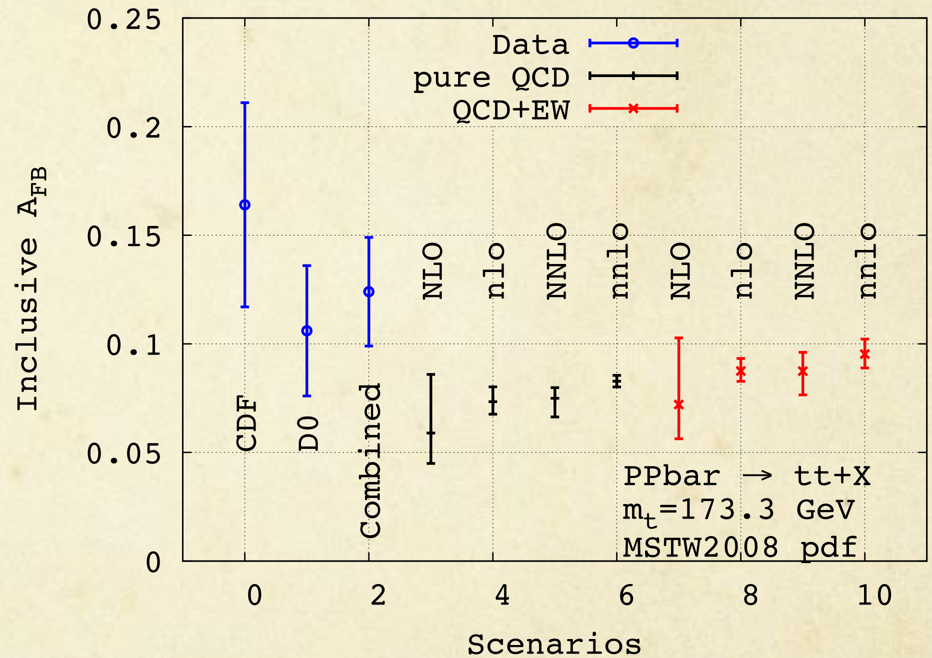
Top-pair production at NNLO

- A lot of recent activity: Czakon, Heymes, Fiedler, Mitov '15
  - fully differential NNLO QCD production for stable top quarks at the Tevatron and LHC
  - This can easily be combined with EW corrections (will be important for TeV scales)
  - No top decay implemented at NNLO. Understood in principle. This is for the future.

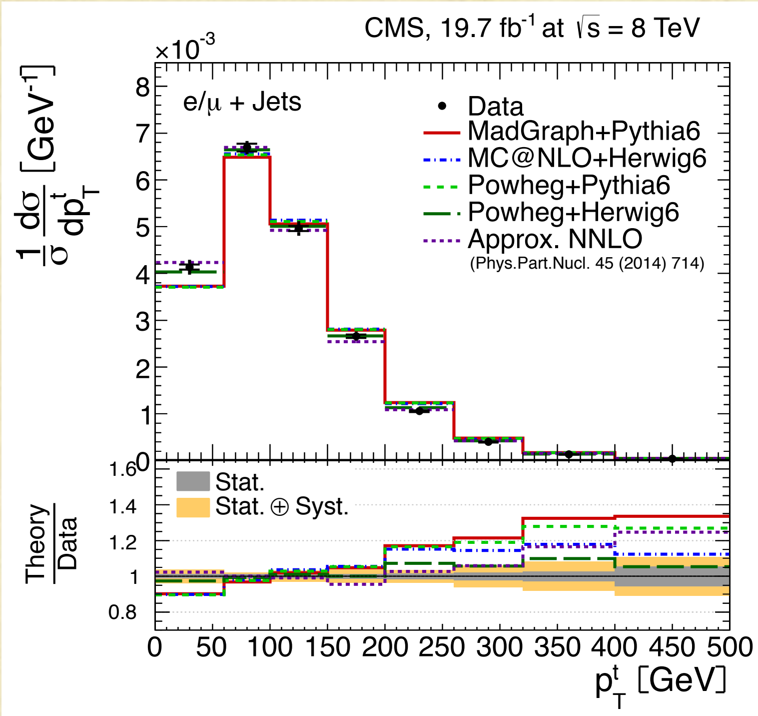


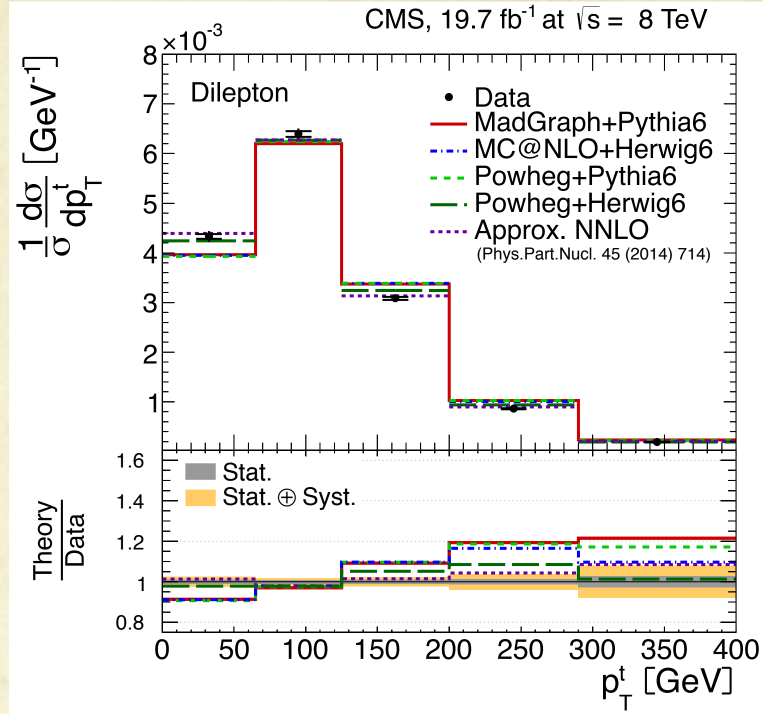


NNLO QCD crucial for making sense of the top forward-backward asymmetry

Top-pair production at NNLO

- Differential distributions at the LHC: important in the context of the "top P_T discrepancy"





- Several qualifications:
  - Lepton- and jet-based observable appear to be fine.
  - Top quark-level ones – no so much.
  - But tops are not measured; they are "inferred" from data using MC's.
  - Therefore, any discrepancy between SM top quark predictions and 'measurements' are testing how well current MC's describe top production.
  - Implications are very broad and go much beyond top physics: Higgs, BSM.

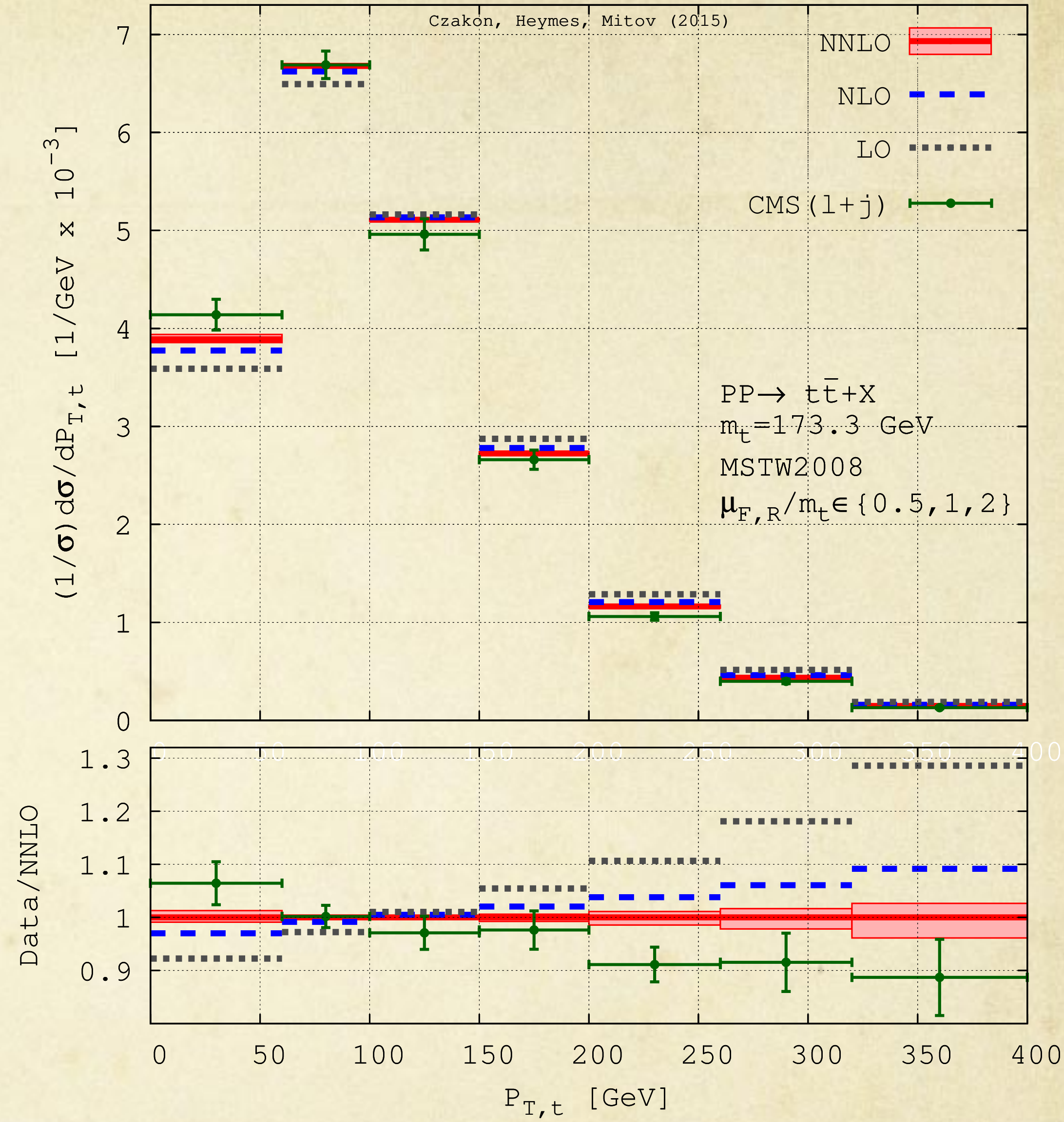
Top-pair production at NNLO: P_T spectrum

✓ NNLO QCD corrections systematically improve the agreement with CMS data.

✓ Agreement with ATLAS (not shown) even better.

✓ NNLO does what one normally expects:

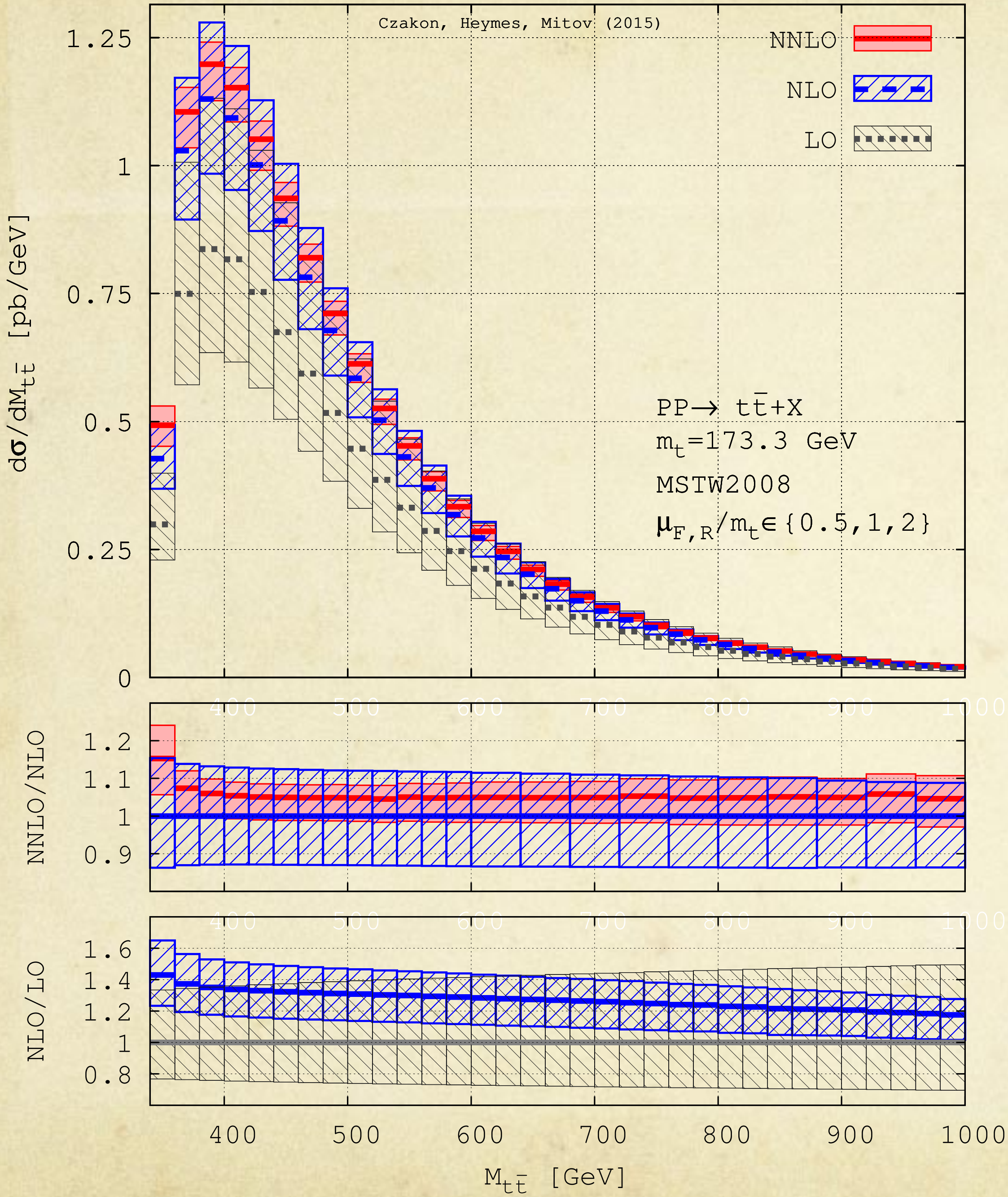
- Convergence
- Decrease of scale error
- Pdf error not included



- Approximate results within the antenna approach have also appeared

Abelof, Gehrmann-De Ridder, Majer `15

Top-pair production at NNLO: M_{tt} spectrum



✓ The quality of the calculation is high:

✓ Fine binning

✓ NNLO does what one normally expects:

- Convergence
- Decrease of scale error
- Pdf error not included
- Threshold effects can be seen
- Note the extreme stability of the shape: no change from NLO to NNLO (0.5% or so)
- An opportunity for searches?

Top-pair production at NNLO: PDF dependence

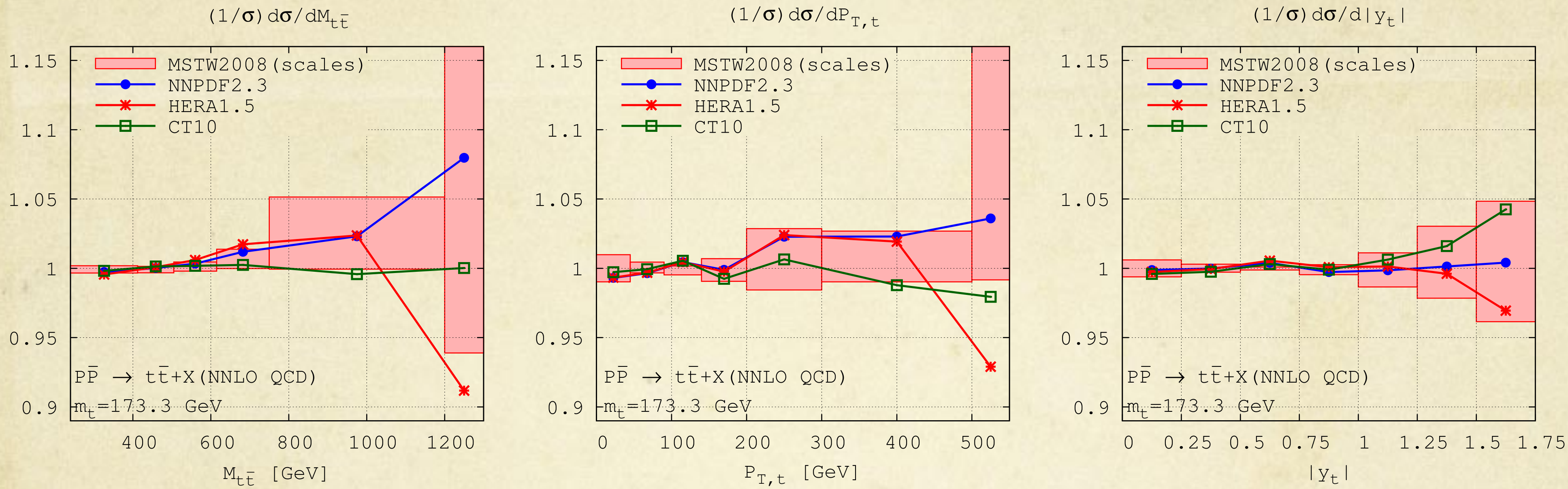


Figure 11. As in fig. 10 but for the normalised to unity distributions.

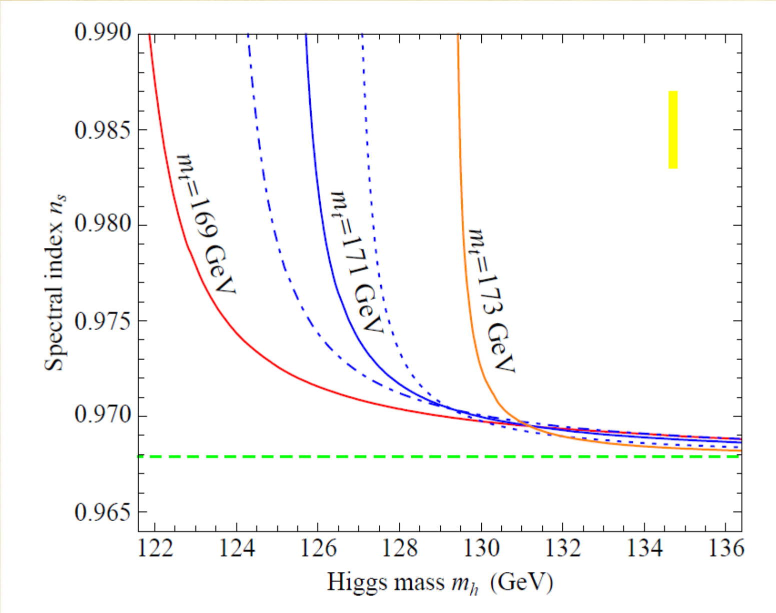
✓ Normalized distributions show very small sensitivity to PDF's

✓ Good news for m_{top} extractions from differential distributions.

Top quark mass

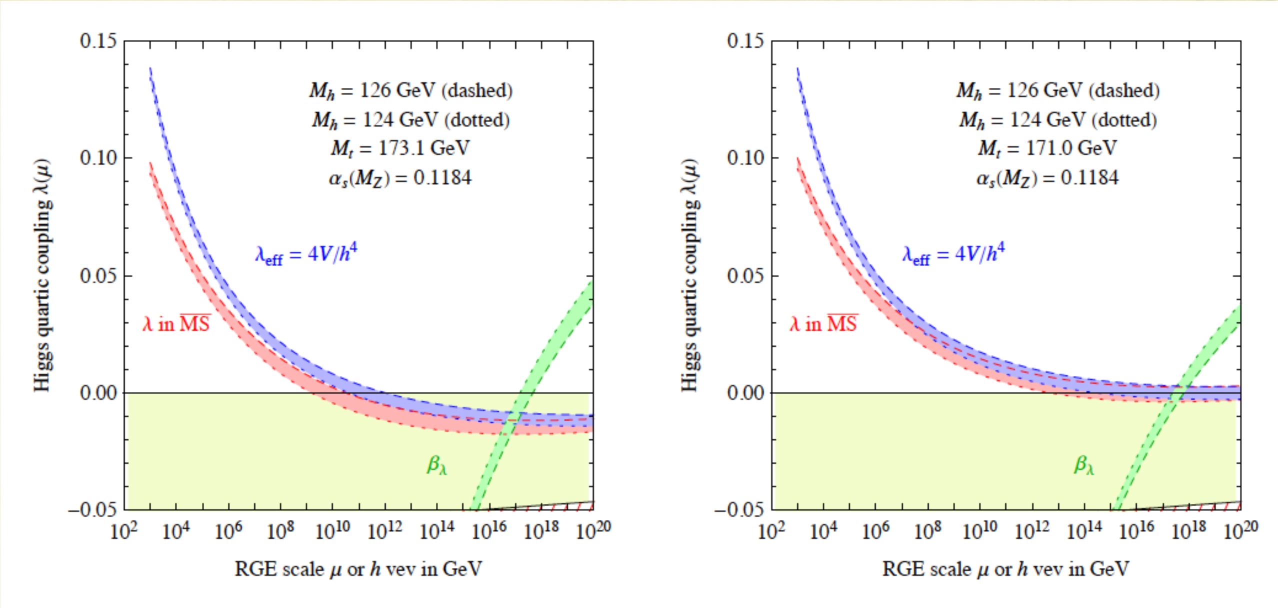
- Not only is the top mass a fundamental SM parameter. It plays outsize role in extending the SM from current collider energies to GUT energies:

Higgs inflation:



De Simone, Hertzbergy, Wilczek 0812.4946

SM vacuum stability:



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

- The implications to BSM physics are well known.
- The notable fact is that 1 GeV change in the top mass completely alters the predictions.

- So, how well do we know the top mass anyway?

Top quark mass

- Look at the spread across current measurements:
  - m_t = 173.34 ± 0.76 GeV [World Average]
  - m_t = 172.04 ± 0.77 GeV [CMS Collaboration]
  - m_t = 174.98 ± 0.76 GeV [D0 Collaboration]
- Comparable uncertainties; rather different central values!
  - Spread likely due to different theory systematics! Many methods proposed (recent reviews)

    Juste et al arXiv:1310.0799

    Moch et al arXiv:1405.4781
- I would single out leptonic observables since they are cleaner and, supposedly, under better theory control

  Kawabata, Shimizu, Sumino, Yokoya '11-`14

  Frixione, Mitov '14
- Another important issue: how well can we determine the top mass at LHC?
  - Current m_t error of O(1GeV) could in principle go down even below O(100MeV). Therefore, pole mass calculations for the LHC are fine.
- Finally, what is the ultimate precision on m_t one might expect?
- 50-100MeV from a threshold scan at a linear e^+e^- collider.
- N^3LO corrections recently completed

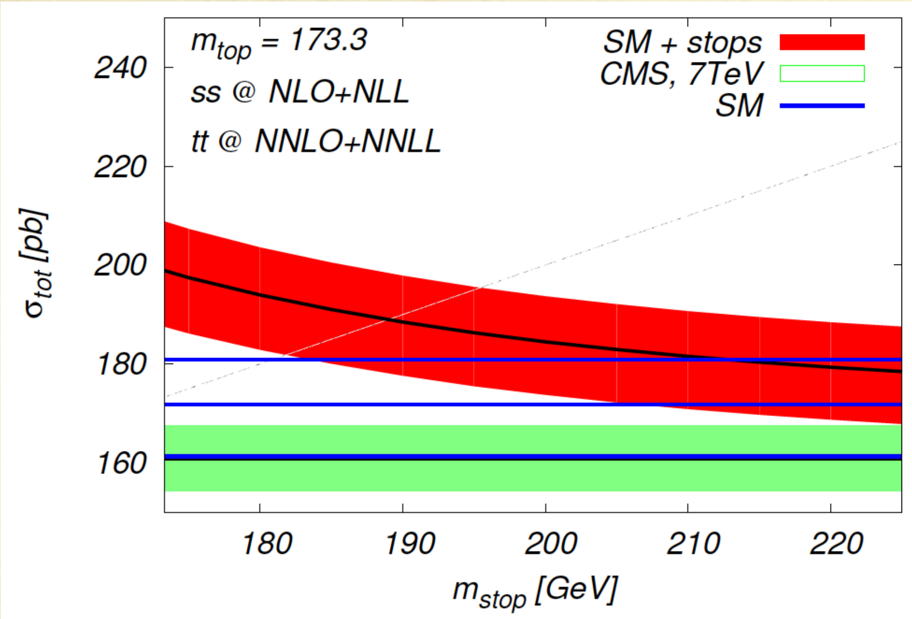
Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser `15

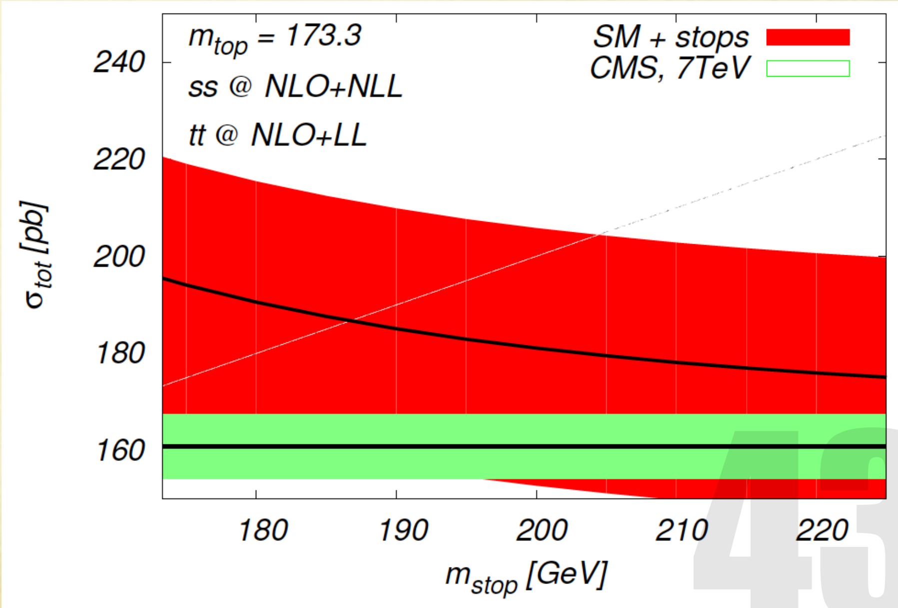
QCD and BSM

Few thoughts on BSM and QCD

- Not only is QCD important for BSM, but BSM plays great role in developing QCD applications!
- AFB: it was a whole saga. But, it was the discrepancy and the interest in it that prompted many very deep QCD developments. Whatever the outcome, we do understand QCD/SM much better now.
- Stop searches (especially stealth stop). Can only be done with high-precision in the SM predictions. Again, this example points at the big picture of possibilities!

Czakon, Mitov, Papucci, Ruderman, Weiler '14
ATLAS '14 (1406.5375)



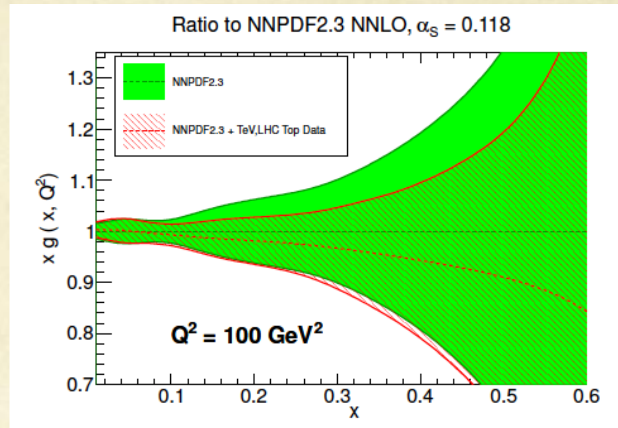


Few thoughts on BSM and QCD

✓ Improved gluon pdf (from LHC measurements of NNLO top and dijets) has implications to many processes at the LHC.

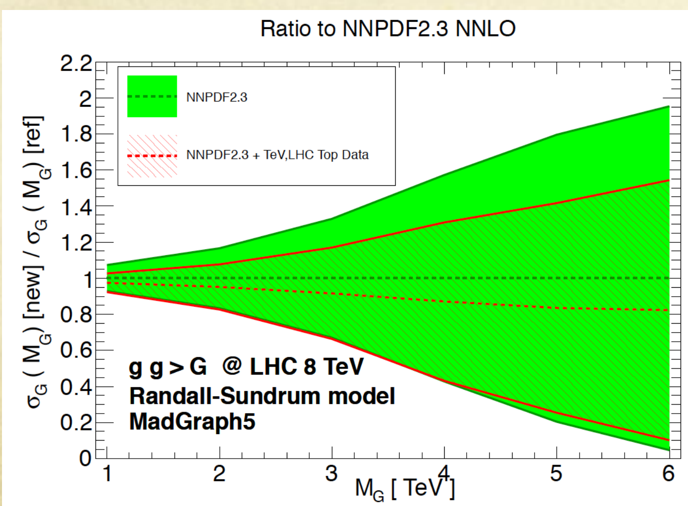
- ➢ Example: bSM production at large masses

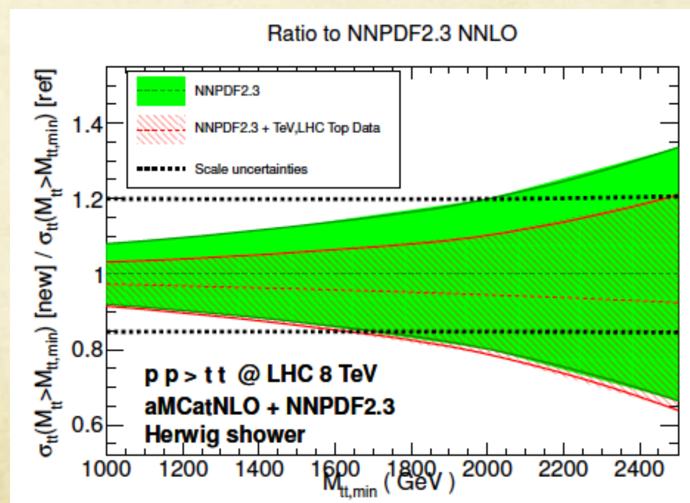
"Old" (i.e. usual) and
"new" (including inclusive NNLO top data)
gluon pdf at large x:



… and implied PDF uncertainty due to "old" vs. "new" gluon pdf:

Czakon, Mangano, Mitov, Rojo '13





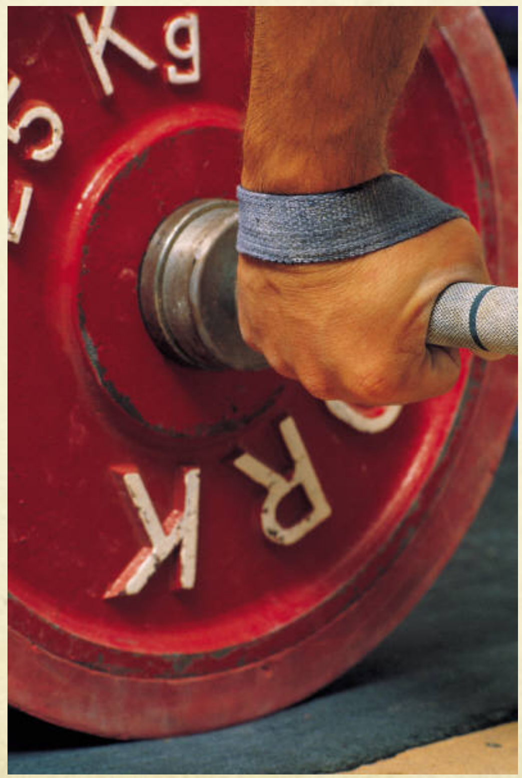
Few thoughts on BSM and QCD

- Diboson excess:
  - Understanding better how to search for bumps
  - Tails of distributions (we are searching for bumps on a smooth background; fine but wat is its slope?)
  - Jets and their structure

- Current diphoton excess:
  - It is a clean signal, which is great. But:
    - If it is an extra Higgs, it should decay to tops
    - Why hasn't it been seen in the Mtt spectrum?
    - One needs detailed estimate of effects; likely we are talking about O(5%) effect.
    - With large bins and current errors (even NNLO that just appeared) this is a small effect.
    - One has to devise new strategies for such searches, and this excess (real or not) is an excellent motivation. Work underway.

For QCD aficionados:

NLO automation, parton showers



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	$pp \to HZ j$	`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*	$pp \to HZ jj$	`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!

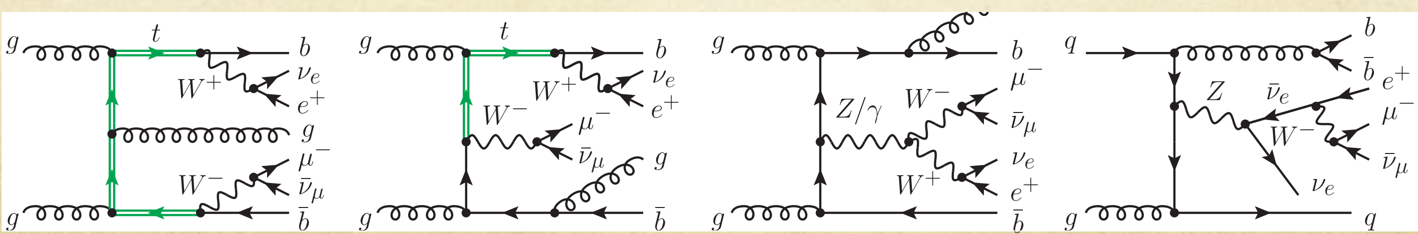
- I would mention the aMC@NLO collaboration which has taken the approach of full automation + shower following the extremely successful MC@NLO approach.

- 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



Summary

Summary

- QCD is the workhorse of LHC physics
- Great recent developments allow for unprecedented accuracy and flexibility:
  - NLO calculations are mature and used everywhere
  - NLO is now fully included in "event generators" like MC@NLO, POWHEG, Sherpa.
  - NNLO is now actively developed and very soon all major 2-to-2 processes (which I discussed here) will be completed.
  - For newest results: stay tuned to the Moriond presentations during next 2 weeks.
- What about the future?
  - Improved accuracies in all interesting processes. Match/beat experimental precision.
  - Ultimately, we want to help answer the question: is there New Physics in the TeV range?
  - People are also thinking about the far future:
    - Future e^+e^- collider of some sort (ILC, CLIC, etc)
    - A future 100 TeV hadron collider (i,.e. much bigger future LHC)