tT cross-section at NNLO

Alexander Mitov
Theory Division, CERN

Based, in order of appearance, on:

- ✓ Baernreuther, Czakon, Mitov arXiv:1204.5201
- ✓ Czakon, Mitov arXiv:1207.0236
- ✓ Czakon, Mitov arXiv:1210.6832
- ✓ Czakon, Fiedler, Mitov arXiv:1303.6254

Also starring:

- ✓ Top++: Czakon, Mitov arXiv:1112.5675

The total tT x-section is now known exactly at NNLO:
no approximations or omissions of any kind

References: papers on previous slide

- Does that imply we are done?
- In a way yes (there is nothing more to do for the total x-section)
- In this talk I'll address 3 points:

  - The NNLO result, and its practical implications (QCD and bSM).

    Much more in Juan Rojo's talk

  - How to use our results in your everyday work

    (hint: easier than "*configure, make, make install*"; just type "*make*")

  - What/when to expect in the future and how to plan for it.

NNLO phenomenology at the Tevatron:

P. Bärnreuther et al arXiv:1204.5201

Czakon, Fiedler, Mitov '13

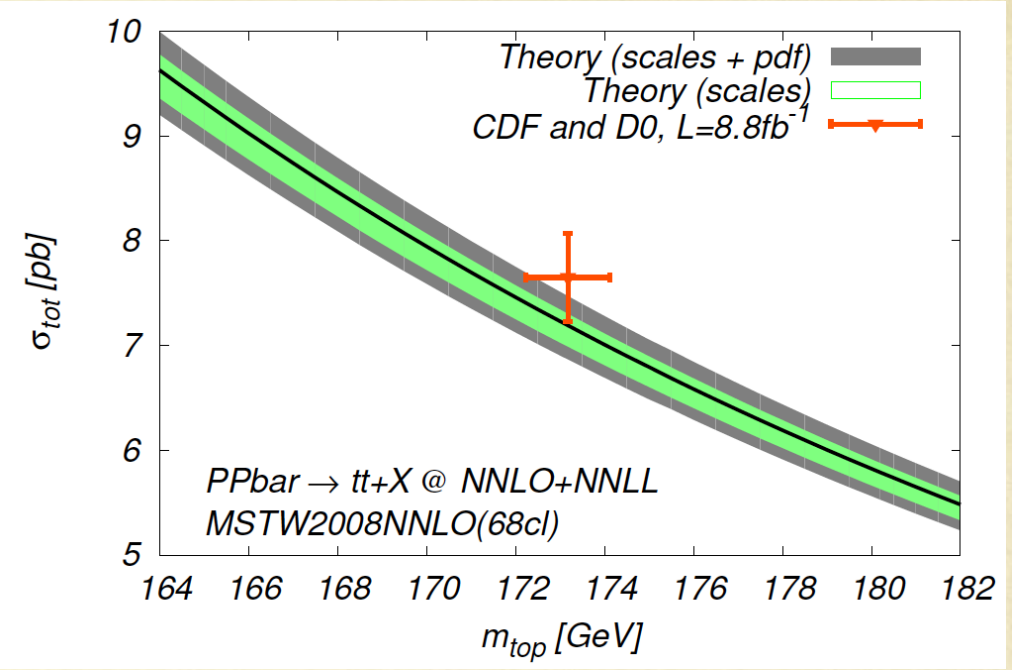
- ✓ Independent F/R scales
- ✓ MSTW2008NNLO
- ✓ mt=173.3

Best prediction at NNLO+NNLL

Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$^{+0.110(1.5\%)}_{-0.200(2.8\%)}$	$^{+0.169(2.4\%)}_{-0.122(1.7\%)}$
LHC 7 TeV	172.0	$^{+4.4(2.6\%)}_{-5.8(3.4\%)}$	$^{+4.7(2.7\%)}_{-4.8(2.8\%)}$
LHC 8 TeV	245.8	$^{+6.2(2.5\%)}_{-8.4(3.4\%)}$	$^{+6.2(2.5\%)}_{-6.4(2.6\%)}$
LHC 14 TeV	953.6	$^{+22.7(2.4\%)}_{-33.9(3.6\%)}$	$^{+16.2(1.7\%)}_{-17.8(1.9\%)}$

Pure NNLO

Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	$^{+0.259(3.7\%)}_{-0.374(5.3\%)}$	$^{+0.169(2.4\%)}_{-0.121(1.7\%)}$
LHC 7 TeV	167.0	$^{+6.7(4.0\%)}_{-10.7(6.4\%)}$	$^{+4.6(2.8\%)}_{-4.7(2.8\%)}$
LHC 8 TeV	239.1	$^{+9.2(3.9\%)}_{-14.8(6.2\%)}$	$^{+6.1(2.5\%)}_{-6.2(2.6\%)}$
LHC 14 TeV	933.0	$^{+31.8(3.4\%)}_{-51.0(5.5\%)}$	$^{+16.1(1.7\%)}_{-17.6(1.9\%)}$



- ✓ New NNLO gg corrections contribute little, ~ +1.3%, as anticipated.

P. Bärnreuther et al arXiv:1204.5201

- ✓ Very week dependence on unknown parameters (sub 1%) A, etc.
- ✓ ~ 50% scales reduction compared to the NLO+NNLL analysis of

Cacciari, Czakon, Mangano, Mitov, Nason '11

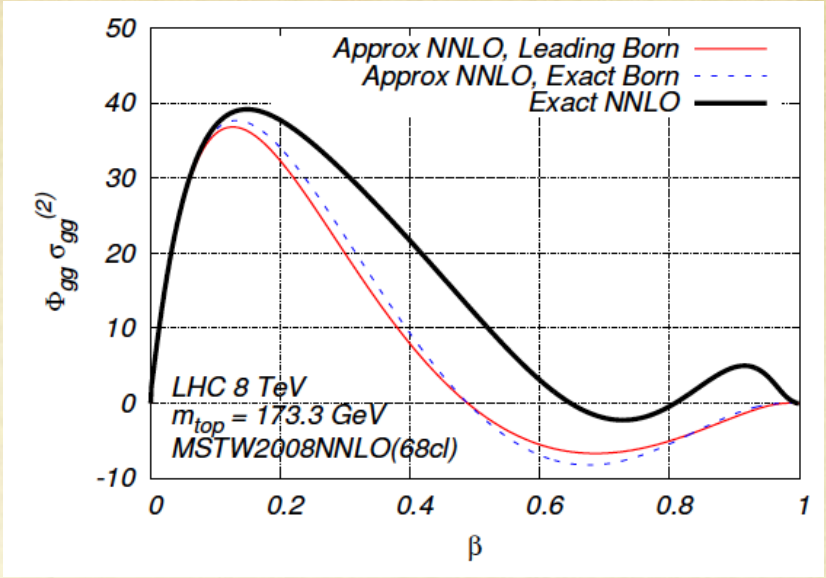
$$6.722\ ^{+0.238\,(3.5\%)}_{-0.410\,(6.1\%)}\ [\text{scales}]\ ^{+0.160\,(2.4\%)}_{-0.115\,(1.7\%)}\ [\text{PDF}]$$

Resumed (approximate NNLO)

NNLO phenomenology at the LHC:

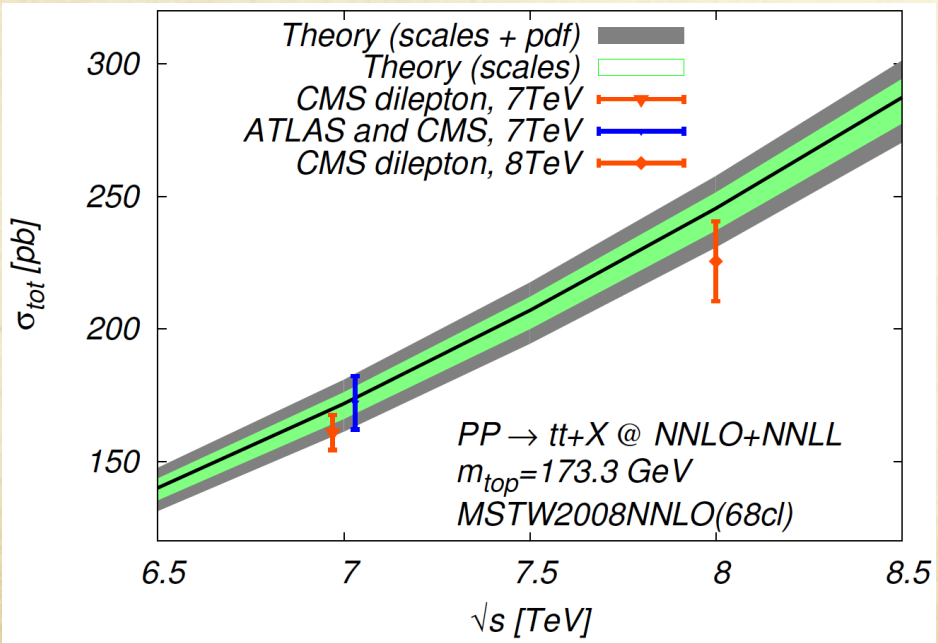
Czakon, Fiedler, Mitov '13

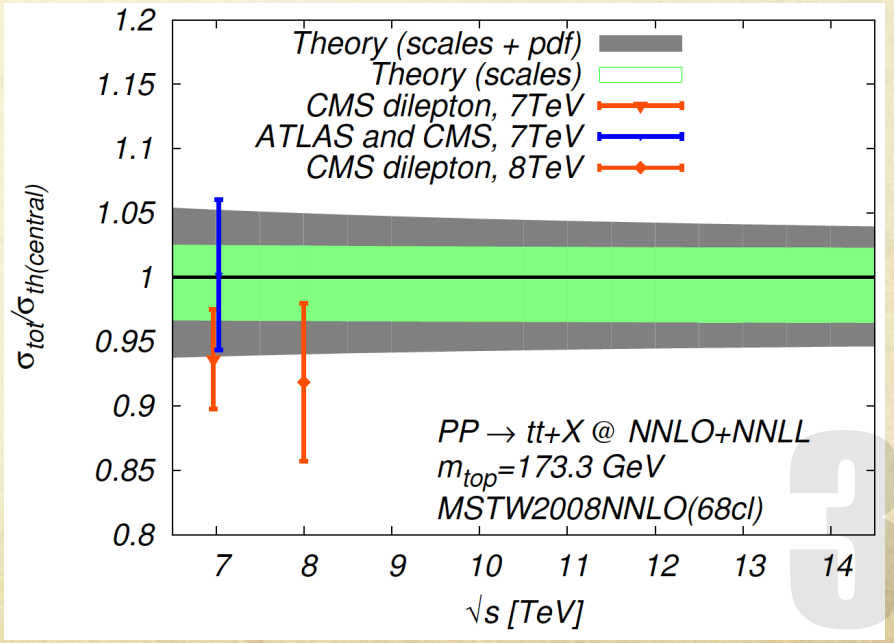
- ✓ New NNLO corrections from gg-reaction are large: as large as the ones due to the Coulomb-threshold approximation
- ✓ At most 6% scale +pdf uncertainty
- ✓ Good agreement with LHC measurements



- ✓ Independent F/R scales
- ✓ MSTW2008NNLO
- ✓ mt=173.3

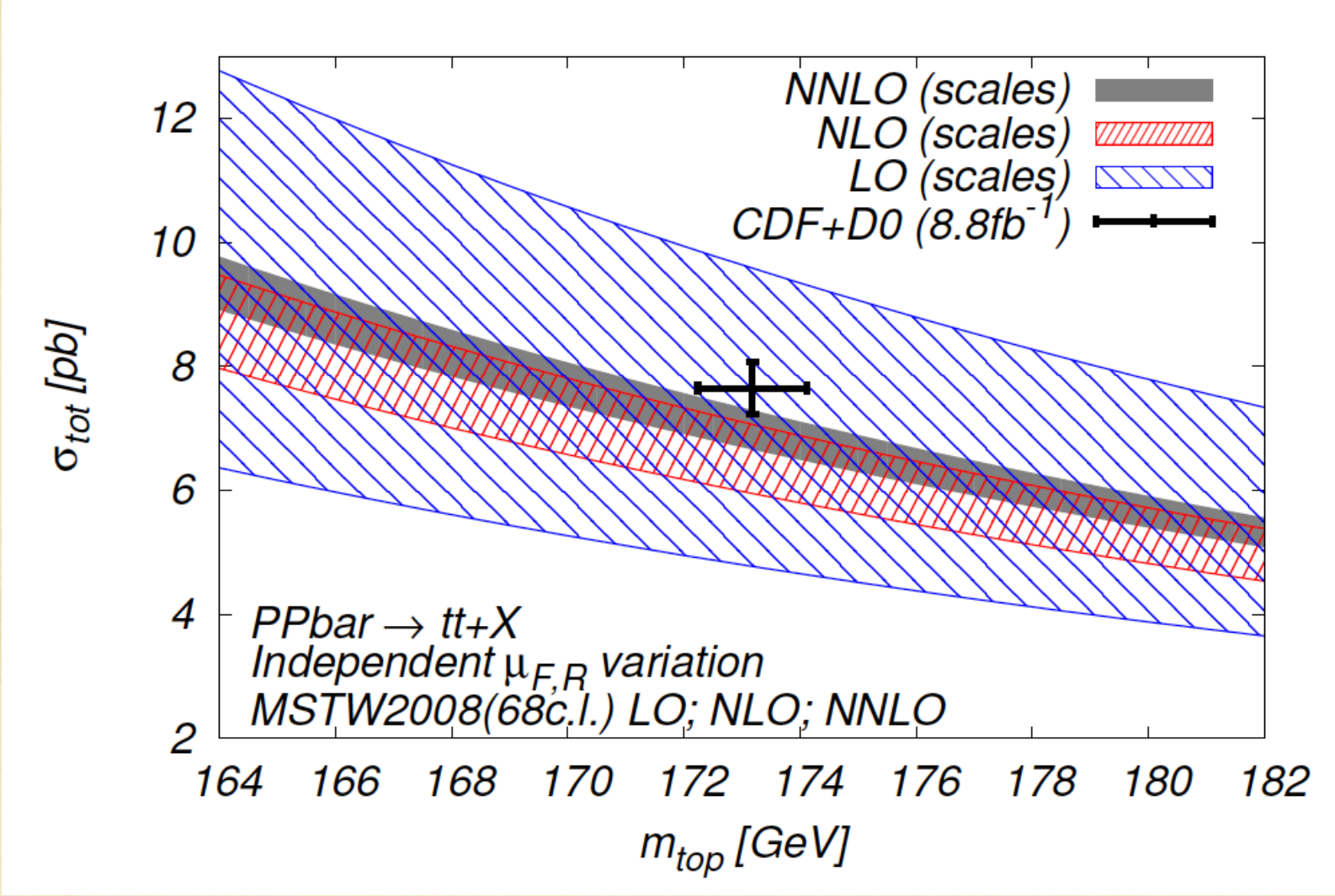
Best prediction at NNLO+NNLL





Good perturbative convergence: scale variation @ Tevatron

✓ Independent F/R scales

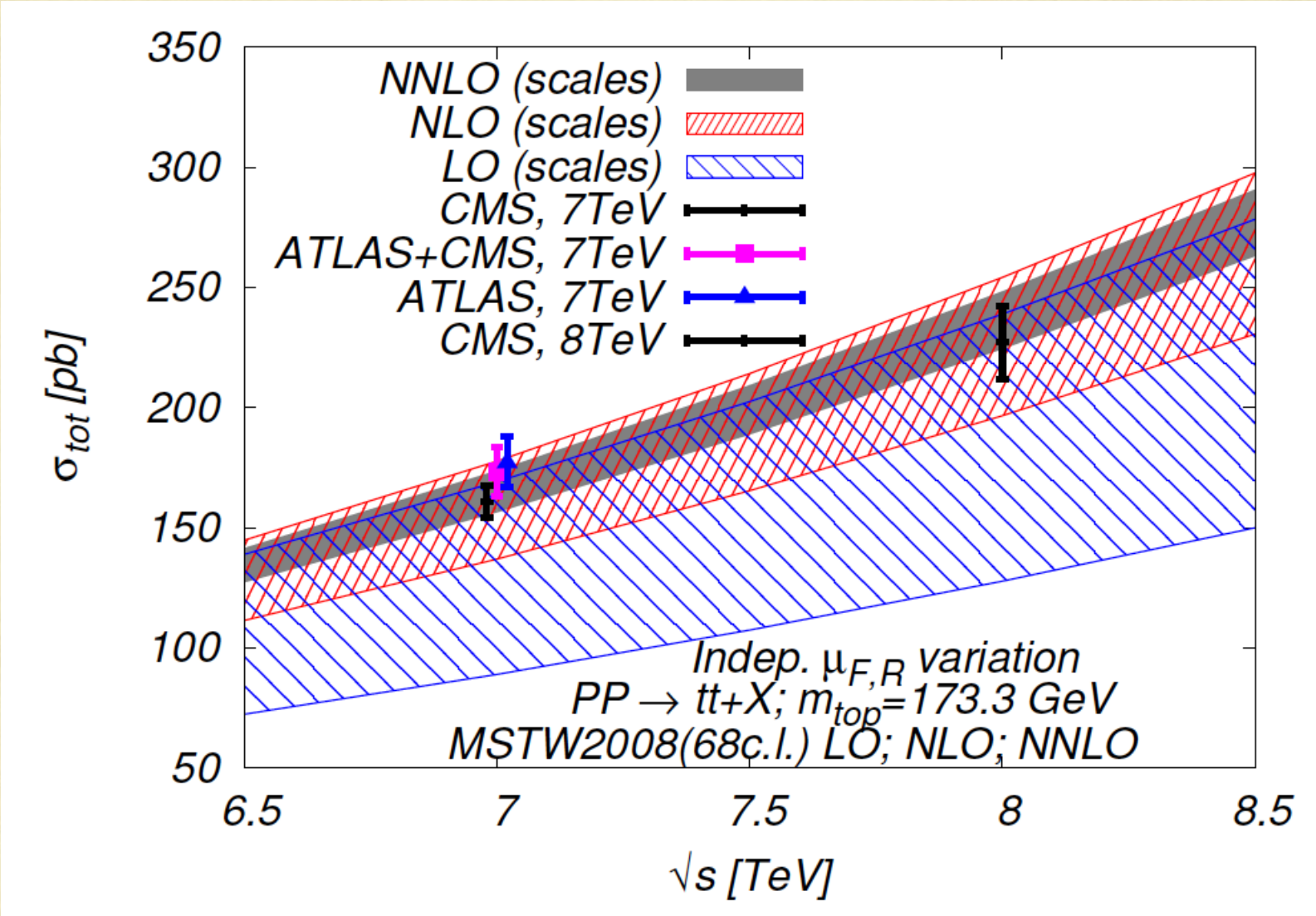


✓ Good overlap of various orders (LO, NLO, NNLO).

✓ Suggests our (restricted) independent scale variation is good

Good perturbative convergence: scale variation @ LHC

- ✓ Independent F/R scales
- ✓ mt=173.3



- ✓ Good overlap of various orders (LO, NLO, NNLO).
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LHC: general features at NNLO+NNLL

Czakon, Fiedler, Mitov '13

Czakon, Mangano, Mitov, Rojo '13

- ✓ We have reached a point of saturation: uncertainties due to
  - ✓ scales (i.e. missing yet-higher order corrections) ~ 3%
  - ✓ pdf (at 68%cl) ~ 2-3%
  - ✓ alpha$_S$ (parametric) ~ 1.5%
  - ✓ m_{top} (parametric) ~ 3%

→ All are of similar size!

- ✓ Soft gluon resummation makes a difference: scale uncertainty 5% → 3%

- ✓ The total uncertainty tends to decrease when increasing the LHC energy

Precision applications

Much more in Juan Rojo's talk

bSM searches: stealthy stop

- ✓ Scenario: 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

- ✓ The idea: use the top 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

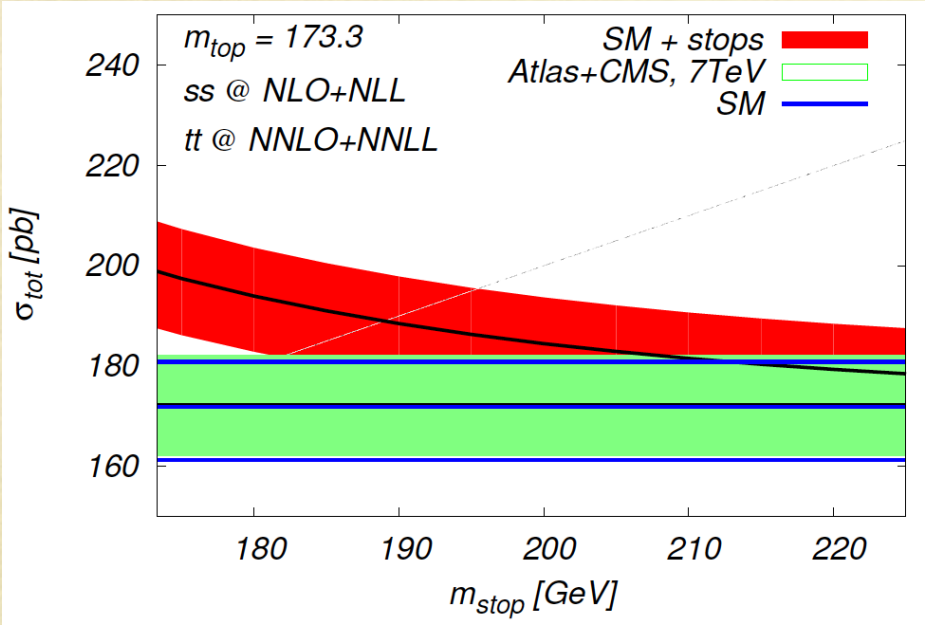
Krämer, Kulesza, van der Leeuw, Mangano, Padhi, Plehn, Portell `12

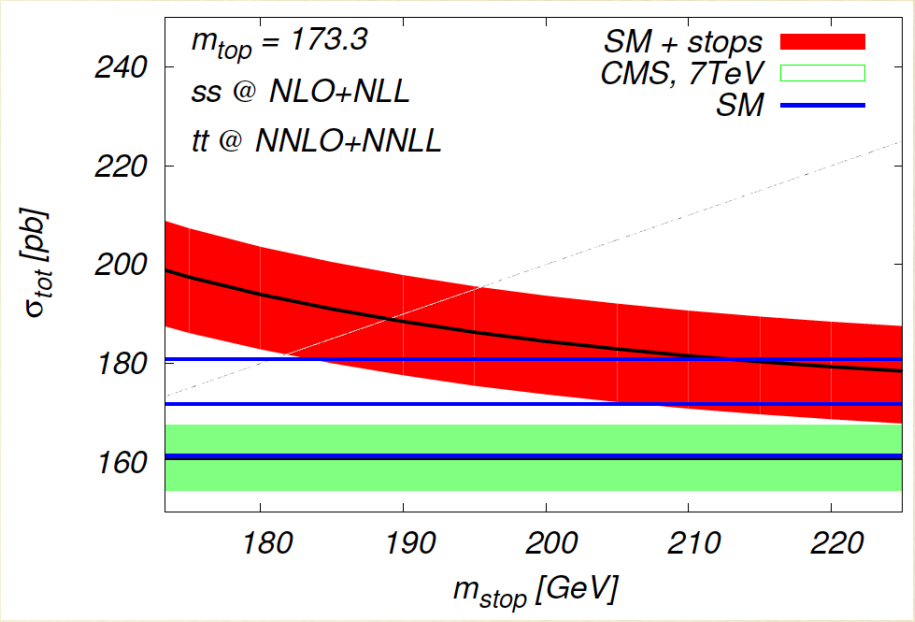
  - ✓ Total theory uncertainty: add SM and SUSY ones in quadrature.

Applications to the bSM searches: stealth stop

✓ Predictions

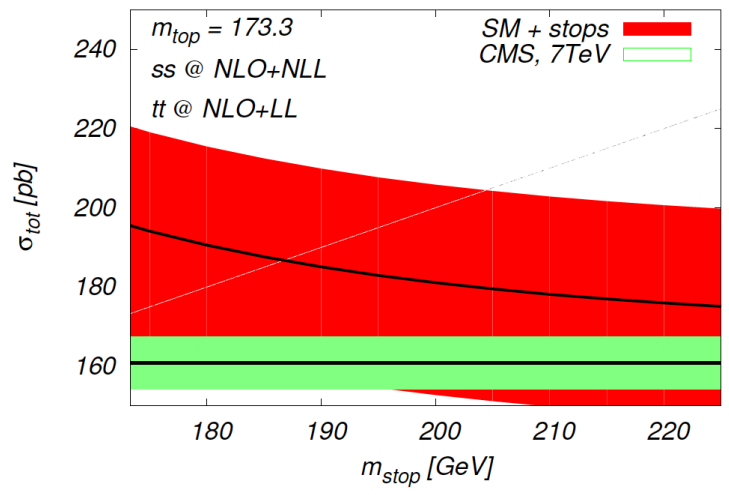
Preliminary





Wonder why limits were not imposed before?

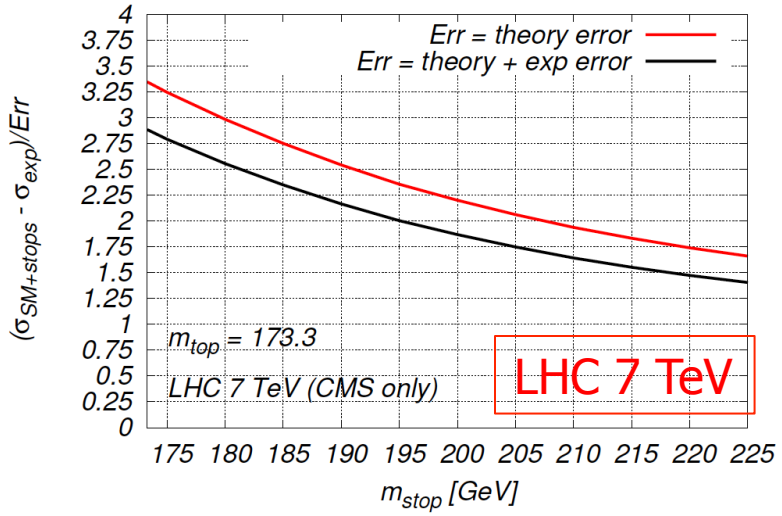
Here is the result with "NLO+shower" accuracy :

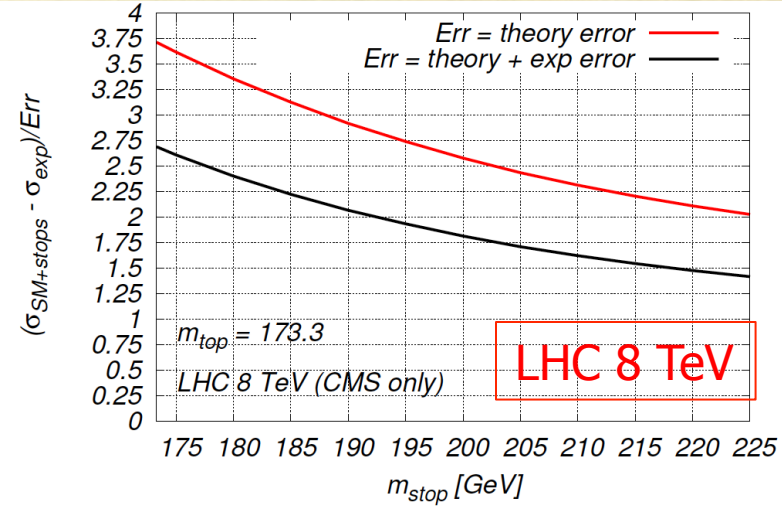


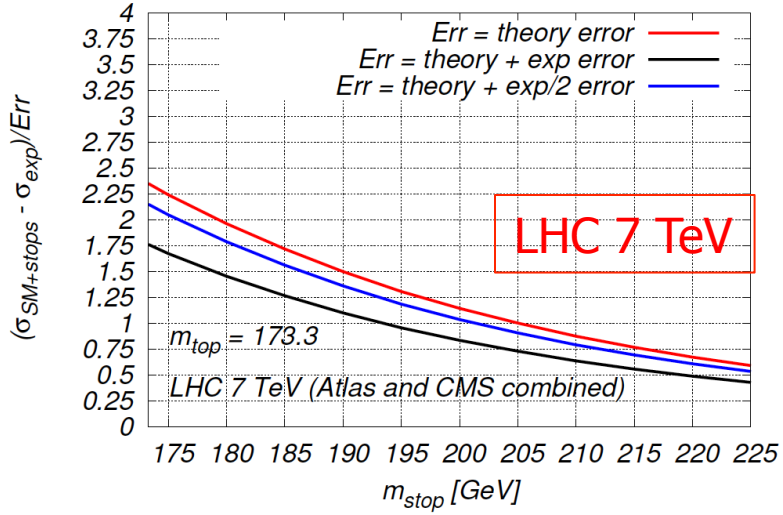
Improved NNLO accuracy makes all the difference

Applications to bSM searches: stealth stop

✓ How strong exclusions can be placed? Preliminary







CMS data allows 2 sigma exclusion for

m_stop < 195 GeV

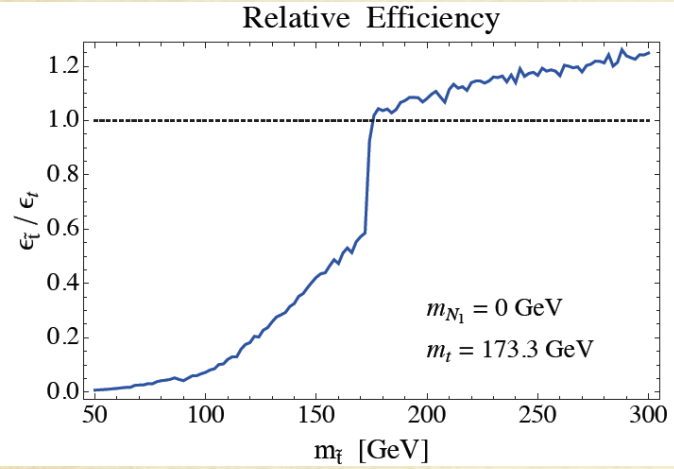
CMS and Atlas combined data (same as SM) allows 2 sigma exclusion for

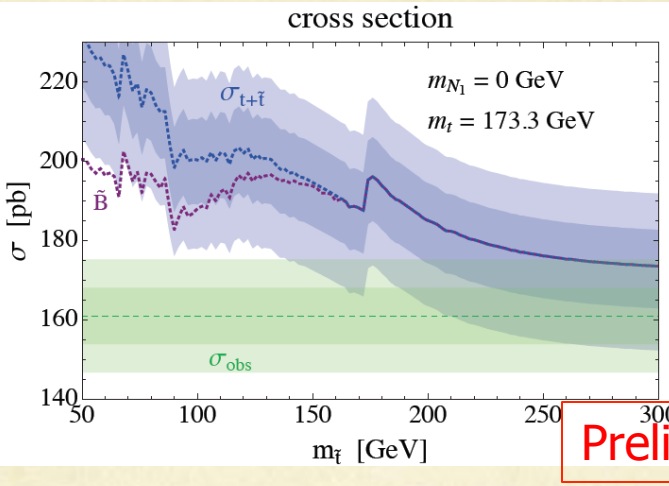
m_stop < 177 GeV
(if combined exp error reduced by ½)

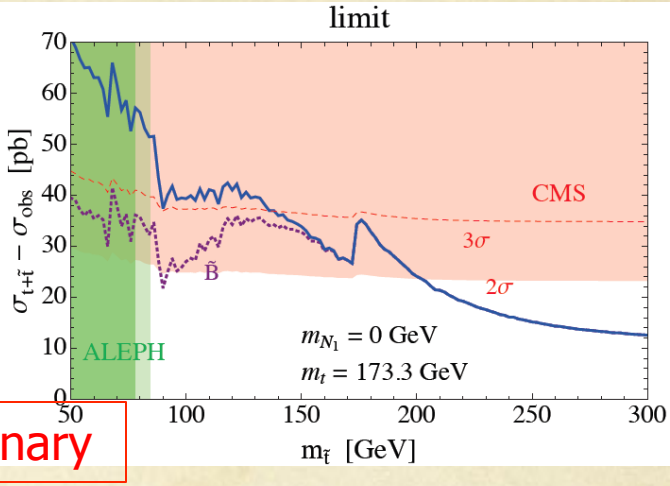
Clearly, theory permits exclusion; looking forward to future data improvements!

Applications to bSM searches: stealth stop

Currently refining the analysis (with Czakon, Papucci, Ruderman, Weiler)

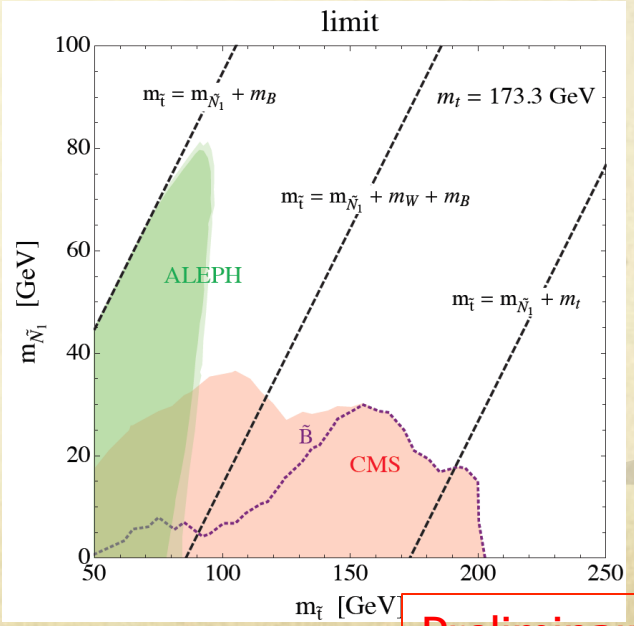






Preliminary

For the 7 TeV CMS dilepton (cut- and-count) measurement



Preliminary

How to get and use all these results?

- Available fits of m_{top} dependence:

Czakon, Fiedler, Mitov: arXiv:1303.6254

$$\sigma(m) = \sigma(m_{ref}) \left(\frac{m_{ref}}{m}\right)^4 \times \left(1 + a_1 \frac{m - m_{ref}}{m_{ref}} + a_2 \left(\frac{m - m_{ref}}{m_{ref}}\right)^2\right)$$

$m_{ref} = 173.3$ GeV		$\sigma(m_{ref})$ [pb]	a_1	a_2
Tevatron	Central	7.1642	−1.46191	0.945791
	Scales +	7.27388	−1.46574	0.957037
	Scales −	6.96423	−1.4528	0.921248
	PDFs +	7.33358	−1.4439	0.930127
	PDFs −	7.04268	−1.4702	0.936027
LHC 7 TeV	Central	172.025	−1.24243	0.890776
	Scales +	176.474	−1.24799	0.903768
	Scales −	166.193	−1.22516	0.858273
	PDFs +	176.732	−1.22501	0.861216
	PDFs −	167.227	−1.2586	0.918304
LHC 8 TeV	Central	245.794	−1.1125	0.70778
	Scales +	252.034	−1.11826	0.719951
	Scales −	237.375	−1.09562	0.677798
	PDFs +	251.968	−1.09584	0.682769
	PDFs −	239.441	−1.12779	0.731019

- … together with many other results (incl. all NNLO pdf sets):

Czakon, Mangano, Mitov, Rojo '13

How to get and use all these results? Use Top++

- Program for computing the total top-pair cross-section

Top++ (2.0) Czakon, Mitov '11 (just submitted to CPC)

This program contains all results, from the people who derived them + resummation

☺ You will not get a better deal!

For comparison, here is what's inside Hathor 1.4 (beyond NLO):

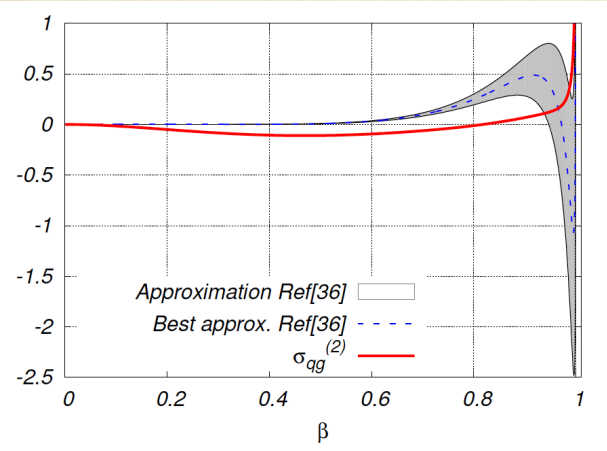
- ✓ Expansion of the x-section to approximate NNLO
  Derived by: Beneke, Czakon, Falgari, Mitov, Schwinn `09
- ✓ qQ,qq,qq',qQ',qg
  Computed by: Bärnreuther, Czakon, Fiedler, Mitov '12-'13
- ✓ NO gg (yet). Computed, available in Top++
- ✓ No resummation (available in Top++). Important effect at NNLO.

How to get and use all these results? Use Top++

The only input in Hathor not computed by us is the HE approximation to the NNLO:

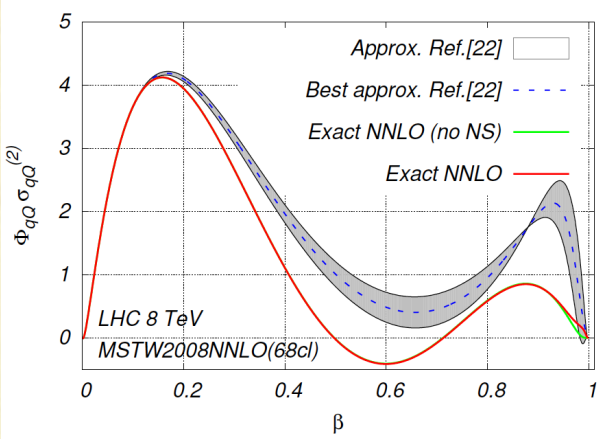
Moch, Uwer, Vogt `12

- Exact result now known, thus HE approximate obsolete
- HE is anyway not a good approximation to the NNLO x-section. Example:



qg-reaction O(1%)

HE approx: O(5%)



qQ-reaction

- As I said, Top++ contains all results, from the people who derived them + resummation

☺ You cannot get a better deal!

- And when you use our results, please, cite them! (see first slide)

Summary and Conclusions

- Total x-section for tT production now known in full NNLO
- Small scale uncertainty (2.2% Tevatron, 3% LHC). Similar to uncertainties from pdf, α_S, M_{top}
- Important phenomenology
  - Constrain and improve PDF's
  - Searches for new physics
  - Very high-precision test of SM (given exp is already at 5% !). Good agreement.

Future tasks

- The idea is to compute fully differential top production, including decays (in NWA), at NNLO
- This is complicated and will take time (beyond 2013)
- For 2013: compute $O(\alpha_S^4)$ corrections to A_{FB} and differential stable top production

As always: we are listening! Tell us what you need!

Backups

The path to NNLO: some relevant history of tT production

- It all started with the NLO calculation 25 years ago

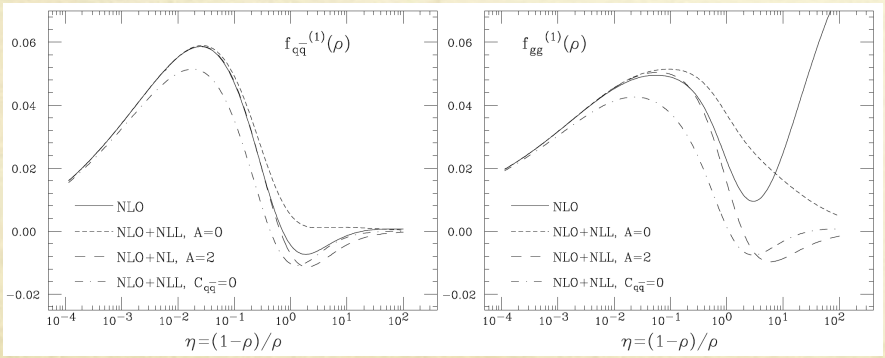
  Nason, Dawson, Ellis '88
  Beenakker et al '89
  Mangano, Nason, Ridolfi' 92

- NLL soft gluon resummation was the next big step:

  Catani, Mangano, Nason, Trentadue '96
  Kidonakis, Sterman '97
  Bonciani, Catani, Mangano, Nason `98

What did we learn from these papers? (back then)

- NLO corrections are very important
- Resummation matters
- Coulomb effects are ~1% effects (even at higher orders)
- Resummation, alone, does not approximate the NLO very well. The "A"-term



Bonciani, Catani, Mangano, Nason `98

At that point (late 1990's) the NLO+NLL precision was already saturated.
Nothing new (w/r to new higher order results) happened in the following 10 years…

The path to NNLO: some relevant history of tT production

- Around 2006 the first building blocks for the NNLO result appeared

  Czakon, Mitov, Moch '06
  Czakon '07

- … it would take till 2013 for all the rest be put together for a complete NNLO.

  - Working subtraction scheme (STRIPPER) — Czakon '10-'11
  - IR singularities for RV amplitude — Bierenbaum, Czakon, Mitov '11
  - 2-loop gg-tt amplitude — Bärnreuther, Czakon, Fiedler '13 (to appear)
  - Put all together and compute the results — Bärnreuther, Czakon, Fiedler, Mitov '12-'13

- Along the way soft gluon resummation at NNLL was developed

  Beneke, Falgari, Schwinn `08
  Czakon, Mitov, Sterman `08

- … which led to the approximate NNLO expression

  Beneke, Czakon, Falgari, Mitov, Schwinn `09

- … and large number of applications with varying mileage (reflecting the limited validity of the soft approximation for fixed order calculations).

  N.B.: it is useful close to threshold and that's where we use it.

Calculation of the total inclusive x-section tT @ NNLO during the last year

- Published qQ → tt +X

  Bärnreuther, Czakon, Mitov `12

- Published all fermionic reactions (qq,qq',qQ')

  Czakon, Mitov `12

- Published gq

  Czakon, Mitov `12

- Published gg

  Czakon, Fiedler, Mitov '13

Now the top pair total x-section is known exactly at NNLO in QCD

No approximations of any kind

- First hadron collider calculation at NNLO with more than 2 colored partons.
- First NNLO hadron collider calculation with massive fermions.