# Hot topics in top physics

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# Top physics in a nutshell (for the people outside of top physics)

What makes the top quark worth paying attention to?

- ✓ The only quark in SM that was studied in limited statistics in the past
  - ✓ LHC offers unlimited opportunity to study top quarks (a first!)

- ✓ The top quark is pops up virtually in any New Physics

- ✓ Unique among all the quarks: decays (mostly) free from confining effects.
  - ✓ One can probe the SM Lagrangian directly.

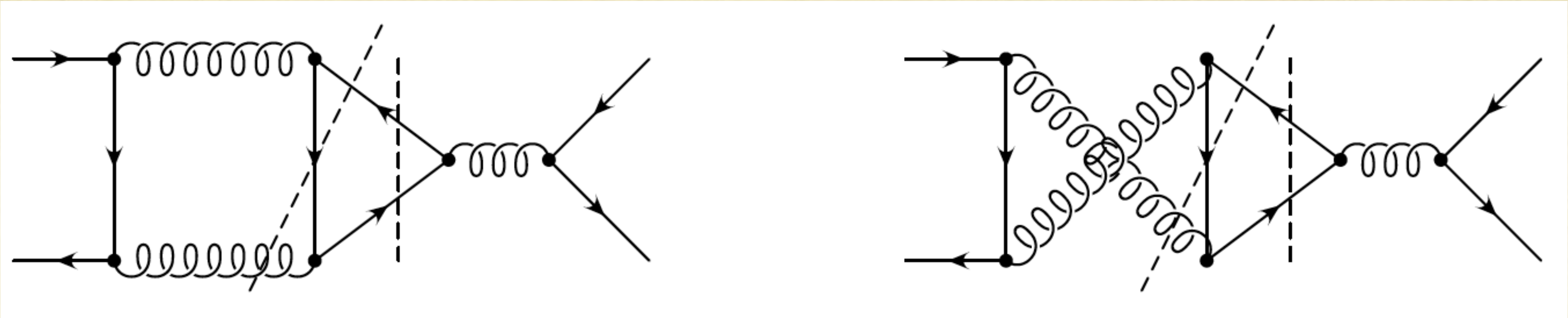
In the rest of this talk:

- ✓ Review few facts about A_FB
- ✓ Few words about m_top
- ✓ A bit about NLO calculations
- ✓ NNLO calculations (new)

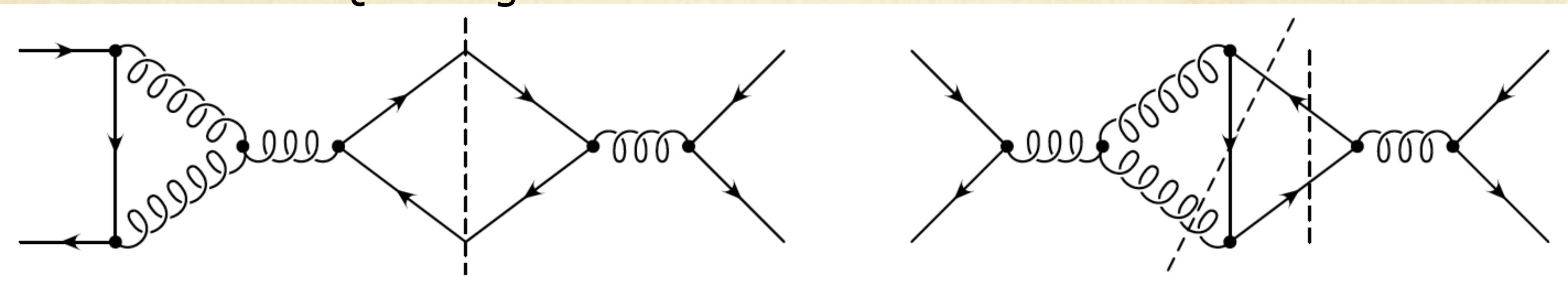
The t-tbar charge (a.k.a. forward-backward $A_{FB}$) asymmetry

QCD diagrams that generate asymmetry:

Kuhn, Rodrigo '98



… and some QCD diagrams that do not:



- ✓ A_FB due to combining 2 effects: charge-conjugation; asymm. pdf in the proton
- ✓ For ttbar: charge asymmetry starts from NLO
- ✓ Asymmetry appears when sufficiently large number of fermions (real or virtual) are present.
- ✓ The asymmetry is QED like.
- ✓ It does not need massive fermions.
- ✓ It is the twin effect of the perturbative strange (or c- or b-) asymmetry in the proton!

## What is known about $A_{FB}$ ?

✓ The largest known contribution to $A_{FB}$ is due to NLO QCD, i.e. $\sim(\alpha_S)^3$.

Kuhn, Rodrigo '98

✓ Higher order soft effects probed. No new effects appear (beyond Kuhn & Rodrigo).

Almeida, Sterman, Wogelsang '08
Ahrens, Ferroglia, Neubert, Pecjak, Yang ` 11
Manohar, Trott '12
Skands, Webber, Winter '12

✓ F.O. EW effects checked. Not as small as one might naively expect. Can't explain it.

Hollik, Pagani '11

✓ BLM scales setting does the job? Claimed near agreement with the measurements.

Brodsky, Wu '12

✓ Final state interactions? Small.

Mitov, Sterman '12
Rosner '12

✓ Higher order hard QCD corrections? Not yet known. Expect soon-ish.

Top mass measurement

## Why we care about $M_{top}$?

- $M_{top}$ is a fundamental parameter of SM
- Currently $M_{top}$ is not a limiting factor in collider physics
- **However, the fate of the Universe might depend on 1 GeV in $M_{top}$!**

## Cosmological implications:

- Higgs Inflation: Higgs = inflaton

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

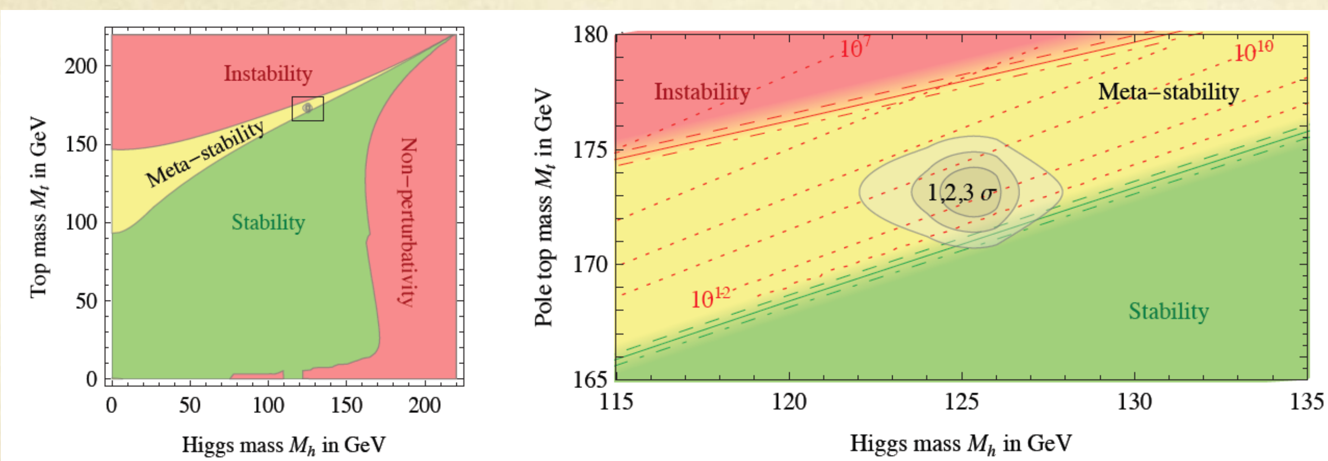
$$\mathcal{L}_h = -|\partial H|^2 + \mu^2 H^\dagger H - \lambda (H^\dagger H)^2 + \xi H^\dagger H \mathcal{R}$$

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

Strong dependence on the top mass!

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

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




Instability scale Λ in GeV: $\delta M_{top}$ is the dominant uncertainty!

**Issues with top mass determination:**

More in the talk by Peter Uwer, later today

Astounding experimental precision, both from Tevatron and LHC:

$$M_{top} = 173.2 \pm 0.9 \text{ GeV}$$

arXiv:1107.5255

? What is measured, $M_{top}$ or top “pseudo mass”?

? How is the top “pseudo mass” related to $M_{top}$?

➢ Past usage of LO MC’s should prompt us to think about:

✓ Higher order effects (needed for proper mass definition)

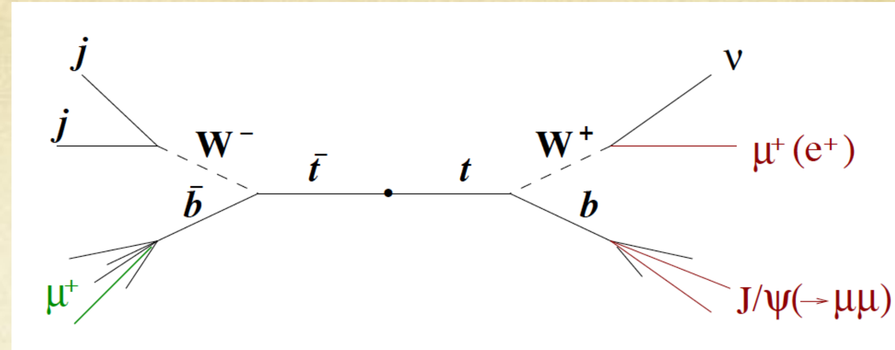
✓ Attempt measurements as little sensitive as possible to modeling of hadronic radiation

- ✓ Dilepton channel without top reconstruction (very clean)
- ✓ This would be fantastic, given the NLO with complete off-shell top production and decay

Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek ’10
Denner, Dittmaier, Kallweit, Pozzorini `10 – ‘12

# Theoretical approaches for $M_{top}$ determination

✓ $M_{top}$ from J/Ψ final states.

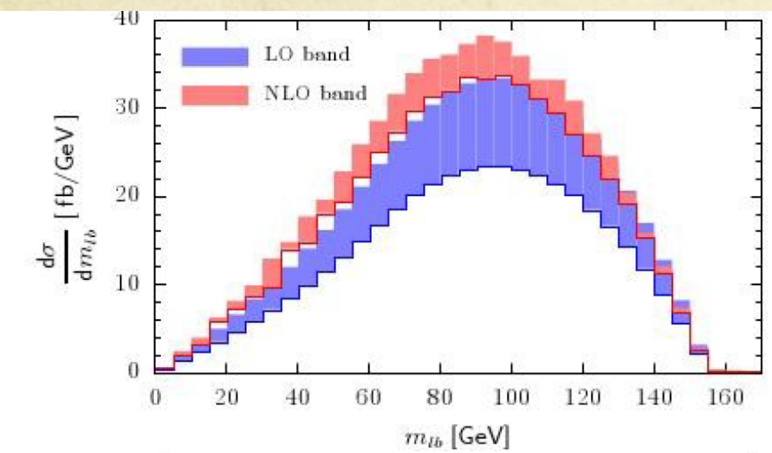


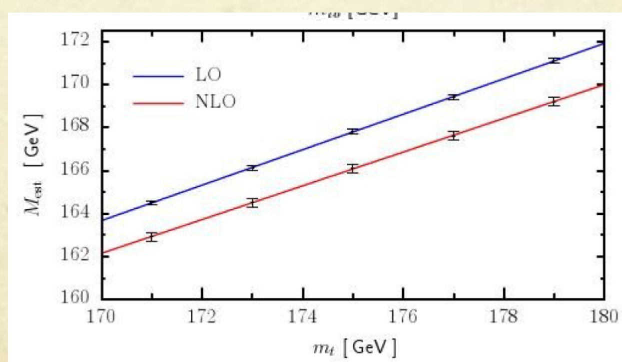

Kharchilava '99
Chierici, Dierlamm CMS NOTE 2006/058

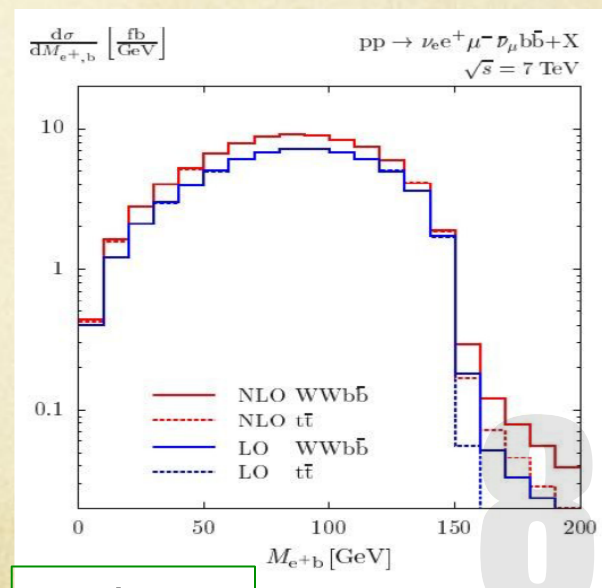
A very different method.

- Very sensitive to b-fragmentation (non-perturbative).
- Non-traditional, but it could be applied with confidence.
- Precision of $\delta M_{top} \leq 1$ GeV is feasible with this method. Full theoretical control.
- Fully differential NLO QCD description available for this method:

Biswas, Melnikov, Schulze '10
Denner, Dittmaier, Kallweit, Pozzorini `10-`12




For b-jets

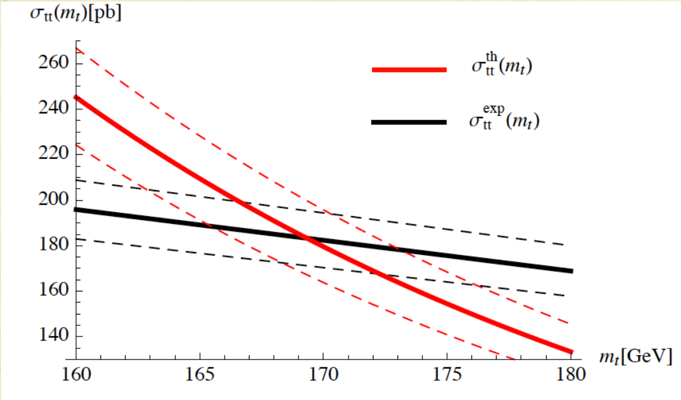
# Theoretical approaches for $M_{top}$ determination

✓ Extract $M_{top}$ from the top cross-section.

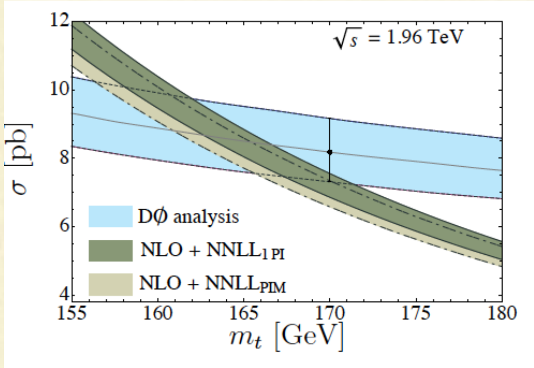
✓ Theoretically very good control.

✓ Extraction not as sensitive to $M_{top}$ : $(\delta M_{top}/M_{top}) = \pm 3\%$.

✓ A good independent cross-check. So far well consistent with direct measurements.




Beneke, Falgari, Klein, Schwinn `11




Ahrens, Ferroglia, Neubert, Pecjak, Yang `11

Best extraction: $m_t = (169.8^{+4.9}_{-4.7})\,\mathrm{GeV}$

Similar extractions from:

Langenfeld, Moch, Uwer `09
Ahrens, Ferroglia, Neubert, Pecjak, Yang `11

✓ Proposed idea: extract MSbar mass; not pole mass

Langenfeld, Moch, Uwer `09

✓ Makes little difference

Ahrens, Ferroglia, Neubert, Pecjak, Yang `11

NLO: *the new LO*

Advances in NLO technology made possible calculations unthinkable just few years ago

Bern, Dixon, Dunbar, Kosower `94
Britto, Cachazo, Feng `04
Ossola, Papadopoulos, Pittau `07
Giele, Kunszt, Melnikov `08

- ✓ Fully differential calculation of ttbar + up to 2 jets
- ✓ NLO production + NLO top decay
- ✓ NLO production and decay, including interference effects (in semi-leptonic decays)
  For the first time full control over $\Gamma_{top}$ effects. Recall top mass determination!

Dittmaier, P. Uwer, S. Weinzierl ’07
Bevilacqua, Czakon, van Hameren, Papadopoulos, Pittau, Worek ’08 -`11
Bredenstein, Denner, Dittmaier, Kallweit, Pozzorini `09 -`12
Melnikov, Scharf, Schulze `09 - `11
Campbell, Ellis `12

- ✓ Matched to parton showers; POWHEG, PowHel.

Frixione, Nason, Ridolfi `07
Garzelli, Kardos, Papadopoulos, Trócsányi `11
Alioli, Moch, Uwer `11

- ✓ Switching gears: aMC@NLO

http://amcatnlo.web.cern.ch/amcatnlo/

NLO lessons:

- (Any) top-related observable can now be computed at NLO.
- Top decays can be included
- How to take advantage of this fact? LO not justified when there is NLO.
- Top mass applications.

NNLO: the new wave in top physics

Much progress made towards tT @ NNLO in the last year

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

- Published qQ → tt +X

  Bärnreuther, Czakon, Mitov `12

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

  Czakon, Mitov `12

- Published gq

  Czakon, Mitov `12

- The only remaining reaction gg computed; to appear soon.

  Czakon, Fiedler, Mitov (to appear)

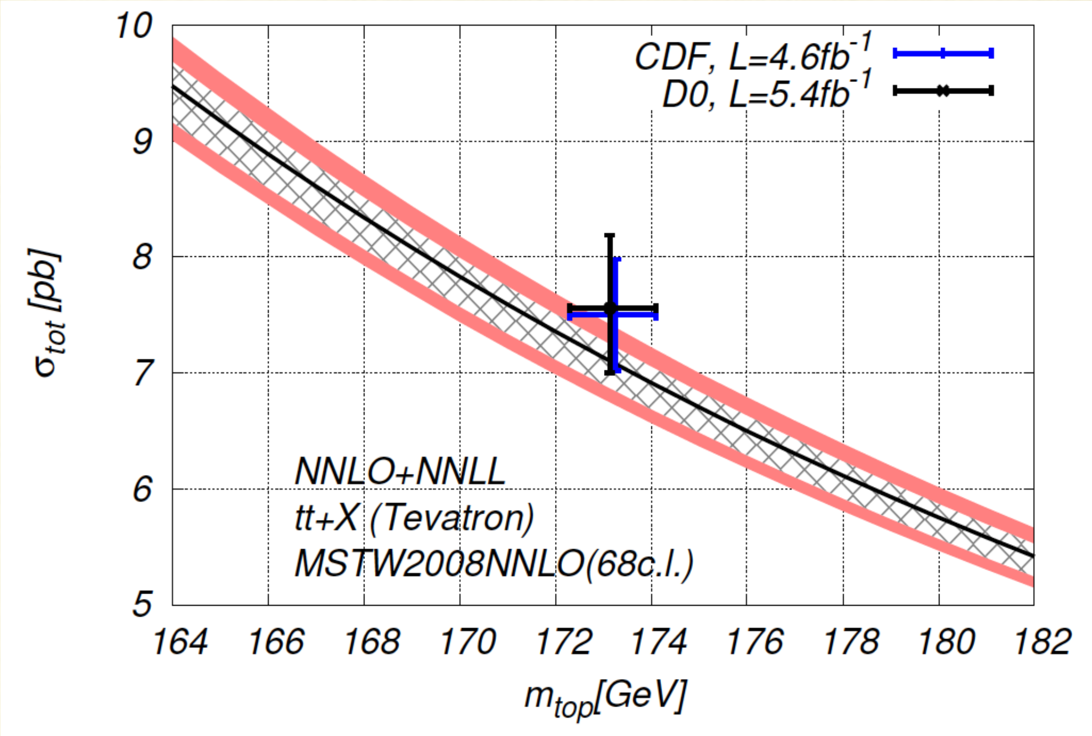
Now the top pair total x-section is known exactly at NNLO in QCD

No approximations of any kind

NNLO phenomenology at the Tevatron:

P. Bärnreuther et al arXiv:1204.5201

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




$$\sigma_{\rm tot}^{\rm res} = 7.067\ {}^{+0.143\,(2.0\%)}_{-0.232\,(3.3\%)}\ [\text{scales}]\ {}^{+0.186\,(2.6\%)}_{-0.122\,(1.7\%)}\ [\text{pdf}]$$

Best prediction at NNLO+NNLL

- ✓ New NNLO gg corrections contribute little, ~ +1.3%, as anticipated.
  Czakon, Fiedler, Mitov (to appear)
- ✓ 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

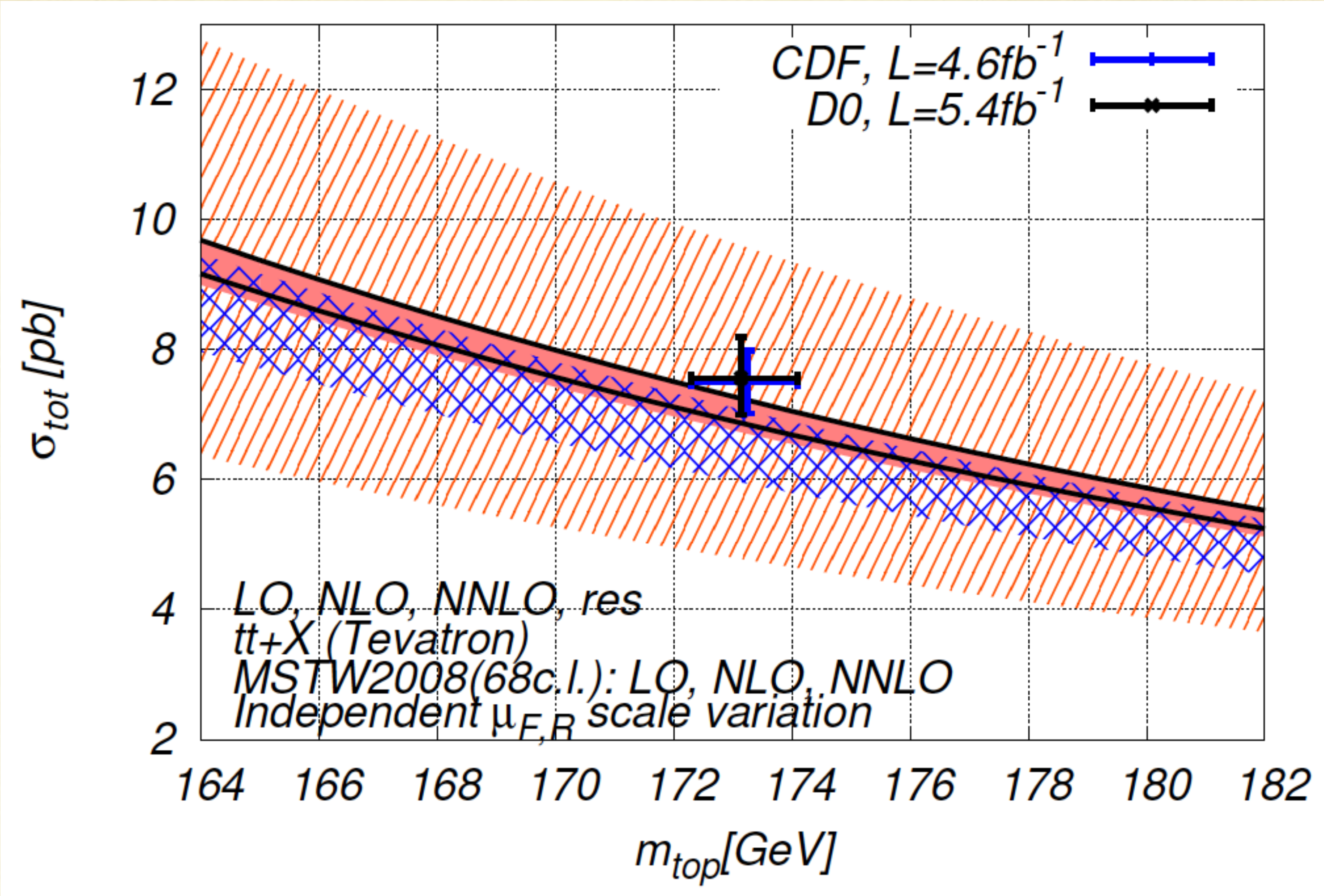
$$6.722\ {}^{+0.238\,(3.5\%)}_{-0.410\,(6.1\%)}\ [\text{scales}]\ {}^{+0.160\,(2.4\%)}_{-0.115\,(1.7\%)}\ [\text{PDF}]$$

Resumed (approximate NNLO)

Good perturbative convergence:

✓ Independent F/R scales
✓ mt=173.3

P. Bärnreuther et al arXiv:1204.5201




✓ Good overlap of various orders (LO, NLO, NNLO).
✓ Suggests our (restricted) independent scale variation is good

NNLO phenomenology at the LHC:

Czakon, Fiedler, Mitov (to appear)

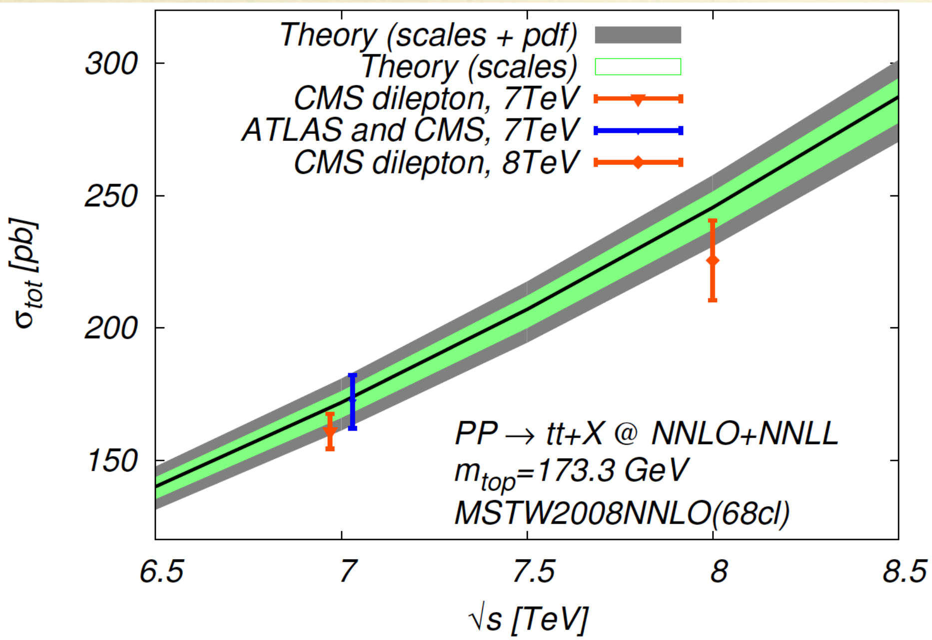
- ✓ New NNLO corrections from gg-reaction are large:
  as large as the ones due to the Coulomb-threshold approximation

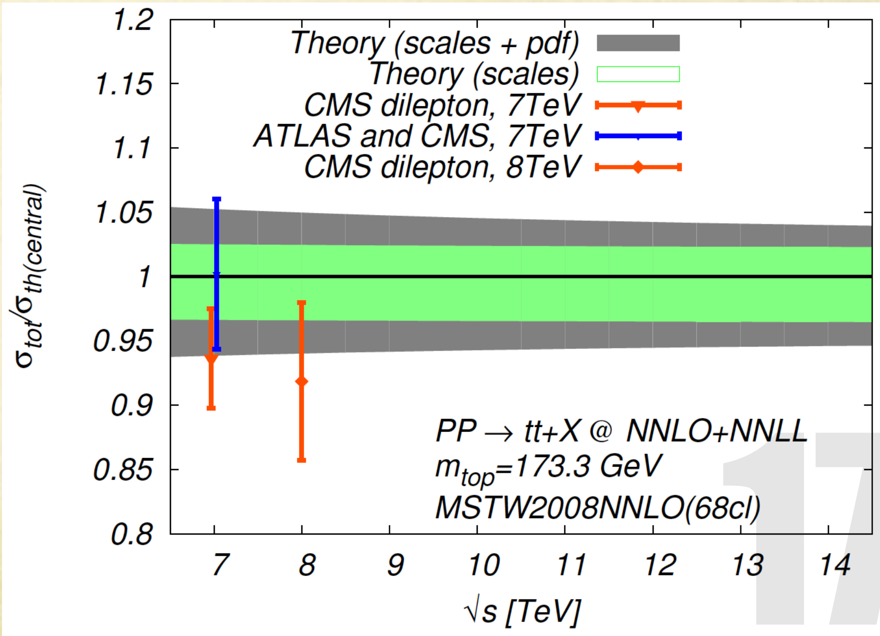
- ✓ At most 6% scale +pdf uncertainty

- ✓ Good agreement with LHC measurements

Best prediction at NNLO+NNLL (preliminary)

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



LHC: general features at NNLO+NNLL (preliminary)

Czakon, Fiedler, Mitov (to appear)

Czakon, Mangano, Mitov, Rojo (to appear)

- ✓ 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!

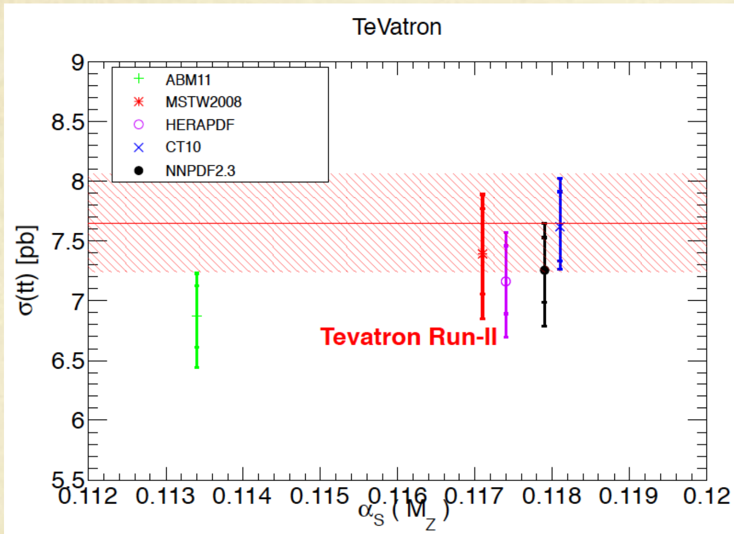
- ✓ Soft gluon resummation makes a difference: scale uncertainty 5% → 3%

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

# Application to PDF's

Czakon, Mangano, Mitov, Rojo (to appear)

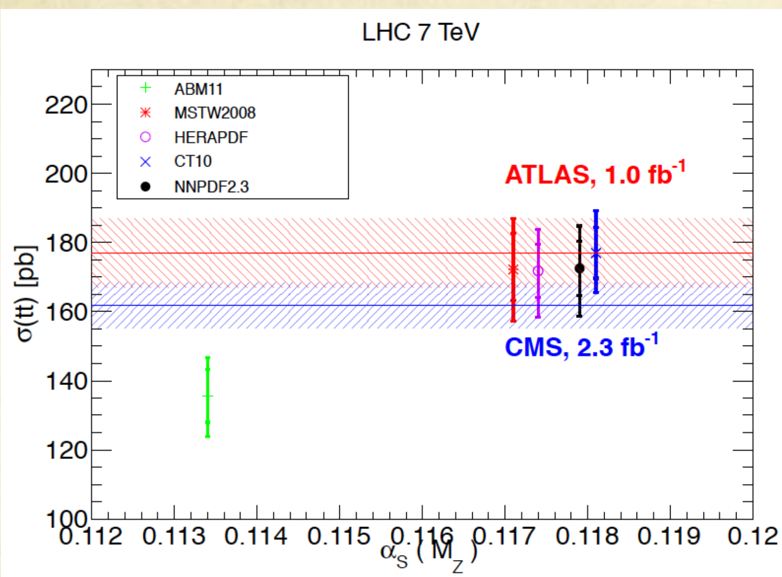
How existing pdf sets fare when compared to existing data?

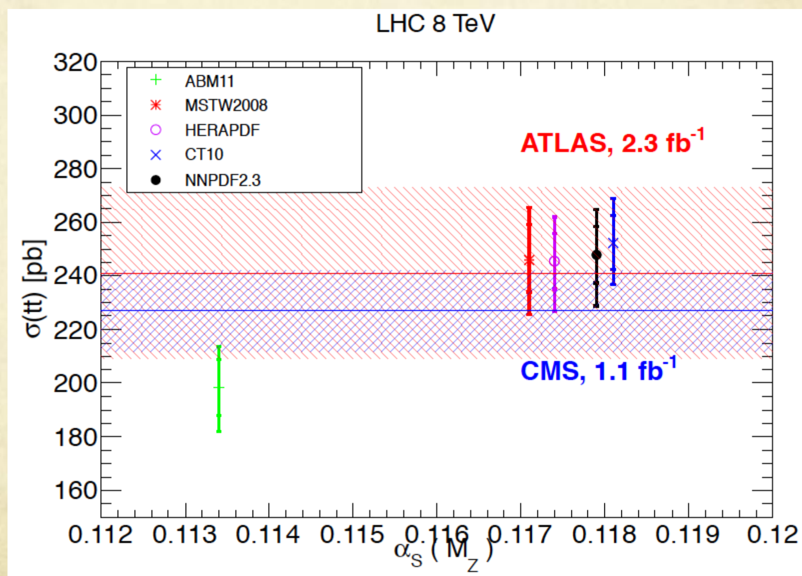



Most conservative theory uncertainty:

Scales + pdf + as + mtop

Excellent agreement between almost all pdf sets




Preliminary

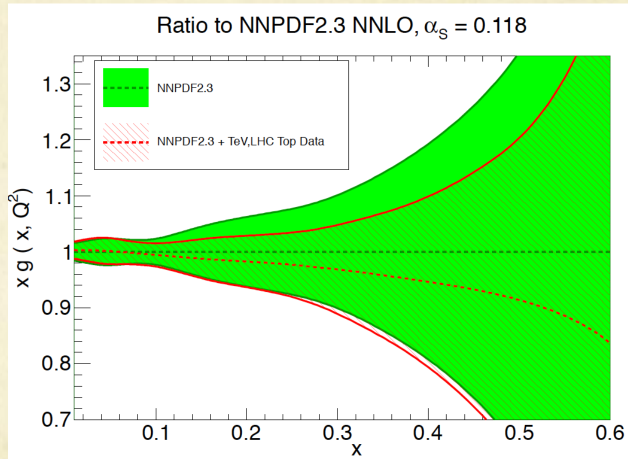
# Application to PDF's

✓ tT offers for the first time a direct NNLO handle to the gluon pdf (at hadron colliders)

✓ implications to many processes at the LHC: Higgs and bSM production at large masses

One can use the 5 available (Tevatron/LHC) data-points to improve gluon pdf

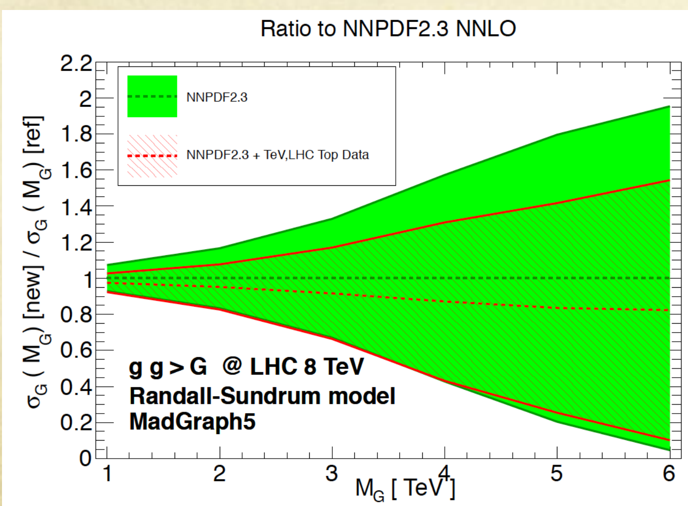
"Old" and "new" gluon pdf at large x:

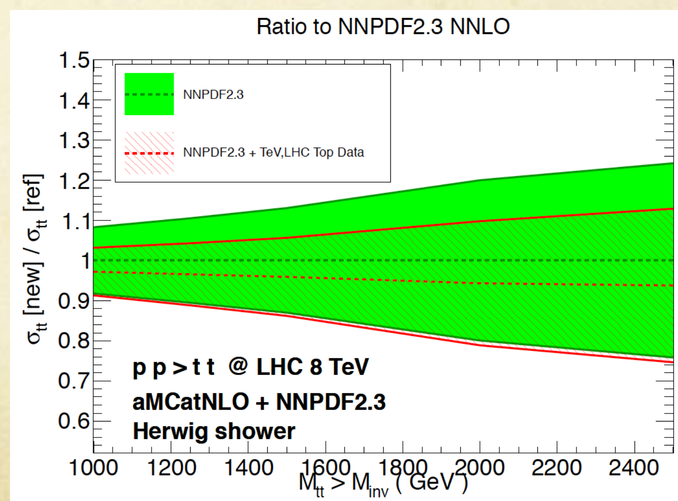



Preliminary

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

Czakon, Mangano, Mitov, Rojo (to appear)



# Application to bSM searches: stealthy stop

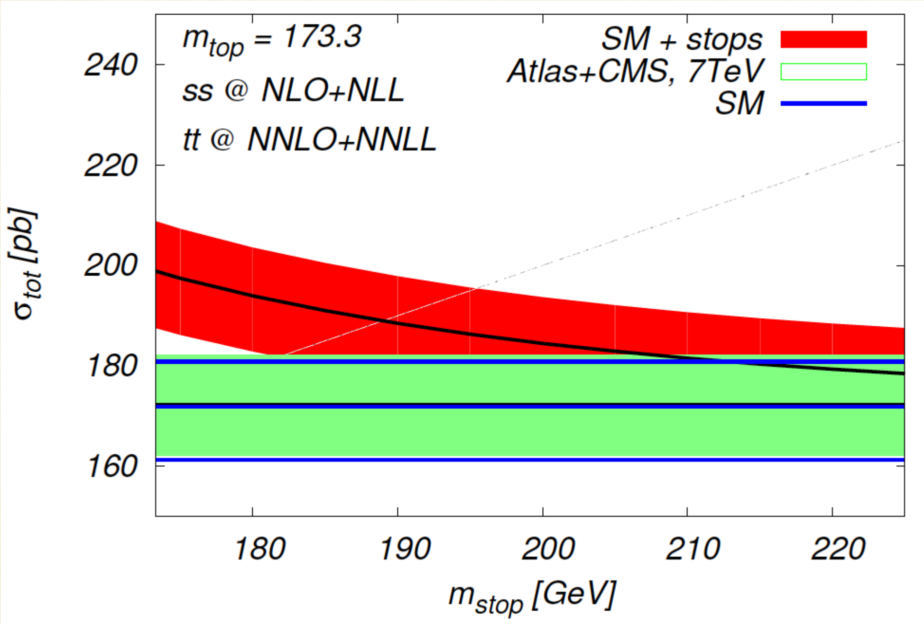
- ✓ SUSY scenario of broad interest: stop → top + missing energy
  - ✓ m_stop small: just above the top mass.
  - ✓ Stop mass < 225 GeV is allowed by current data
  - ✓ Usual wisdom: the stop signal hides in the top background

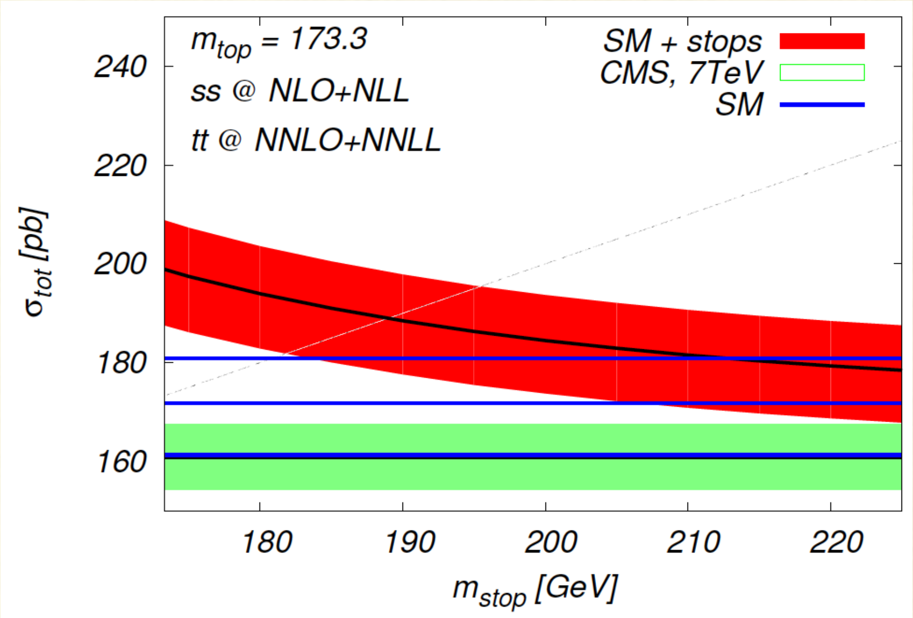
- ✓ The idea: use the top x-section to derive a bound on the stop mass. Assumptions:
  - ✓ Same experimental signature as pure tops
  - ✓ the measured x-section is a sum of top + stop
  - ✓ Use precise predictions for stop production @ NLO+NLL

    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

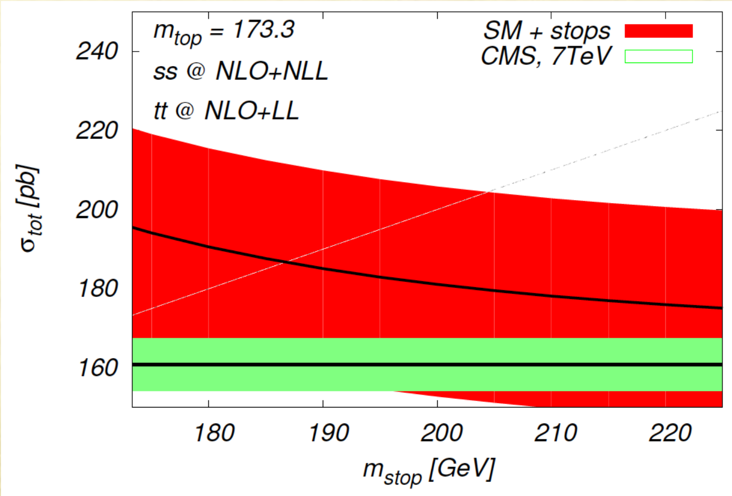
✓ Predictions   Preliminary




Wonder why limits were not imposed before?

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

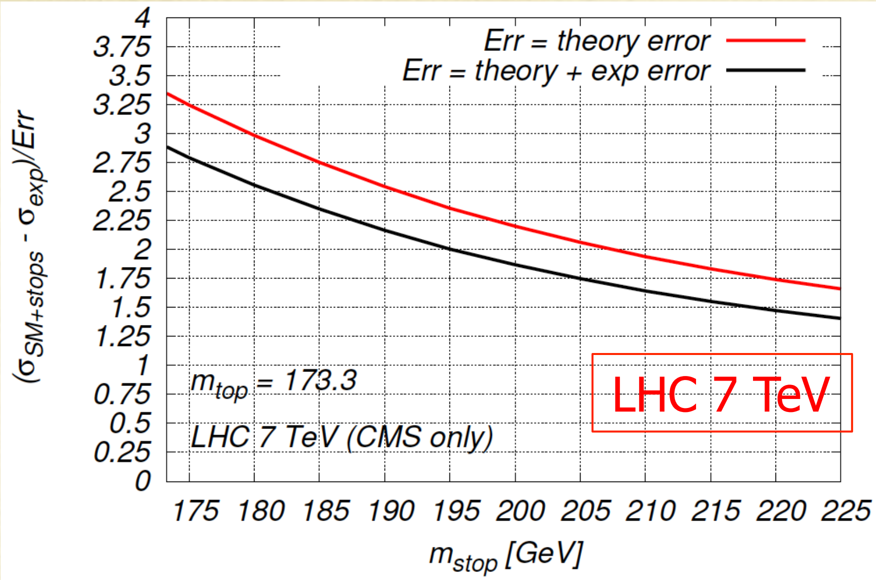


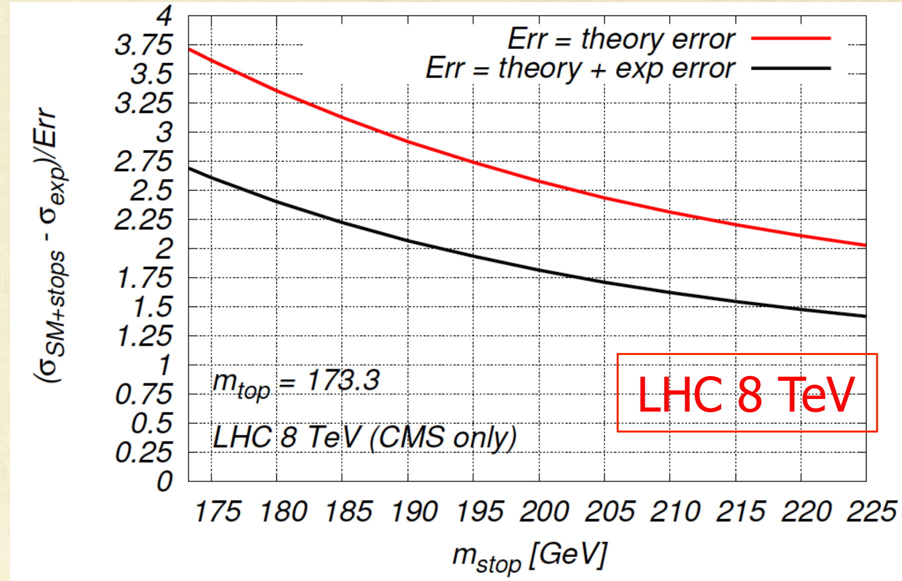

Improved NNLO accuracy makes all the difference

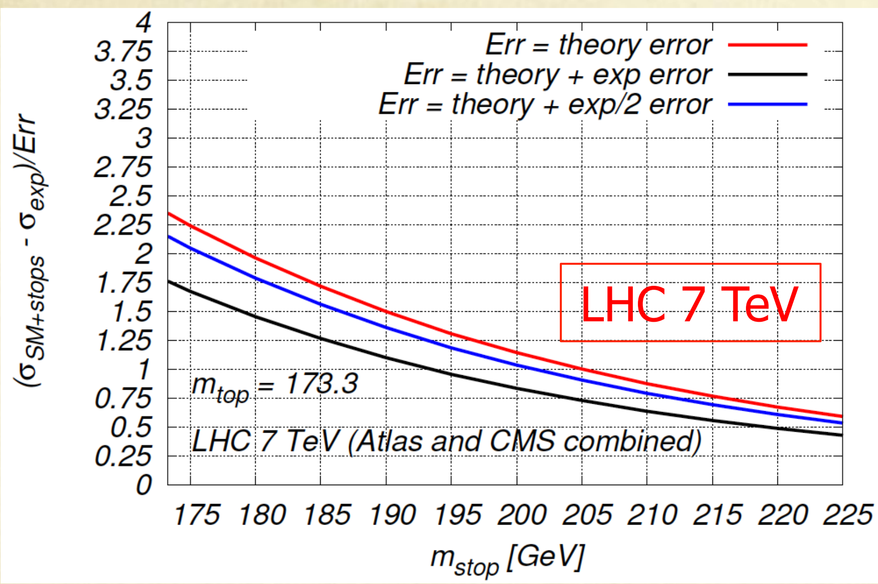
# Applications to bSM searches: stealth stop

✓ 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!

# Summary and Conclusions

- ✓ Shift of paradigm in top physics: statistics not an issue any more!
  - ✓ Few percent measurements already available
- ✓ Dramatic changes in top theory, too:
  - ✓ Percent level precision for total x-section now fully known in NNLO QCD
  - ✓ Fully differential kinematics (for now at NLO), with top decay and off-shell effects.

Such unprecedented precision has to be exploited!

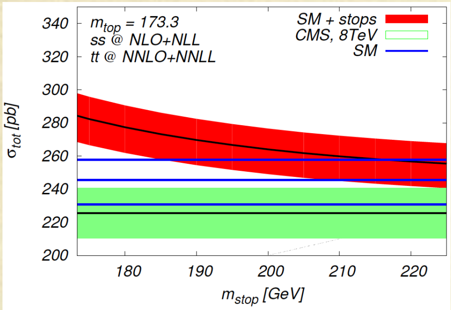
- ✓ PDF's get new handle; increased precision propagates everywhere (esp. high-mass)
- ✓ New Physics Searches
- ✓ Precision parameter measurements (alpha_S, M_top, etc)
- ✓ And a wish list: even more precise measurements at 7 and 8 TeV!

# Applications to the bSM searches: stealth stop

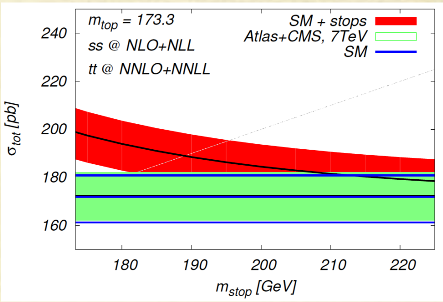
Czakon, Mitov (in preparation)

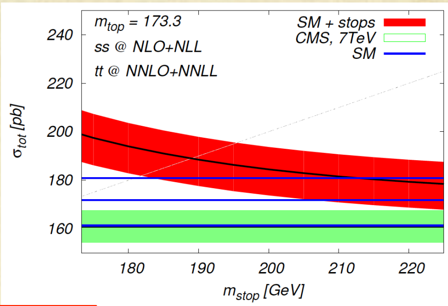
✓ How strong exclusions can be placed?

Preliminary




LHC 8 TeV




LHC 7 TeV

**Backup slide**