Pair Production Theory

Top at Twenty

Something

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What a journey!

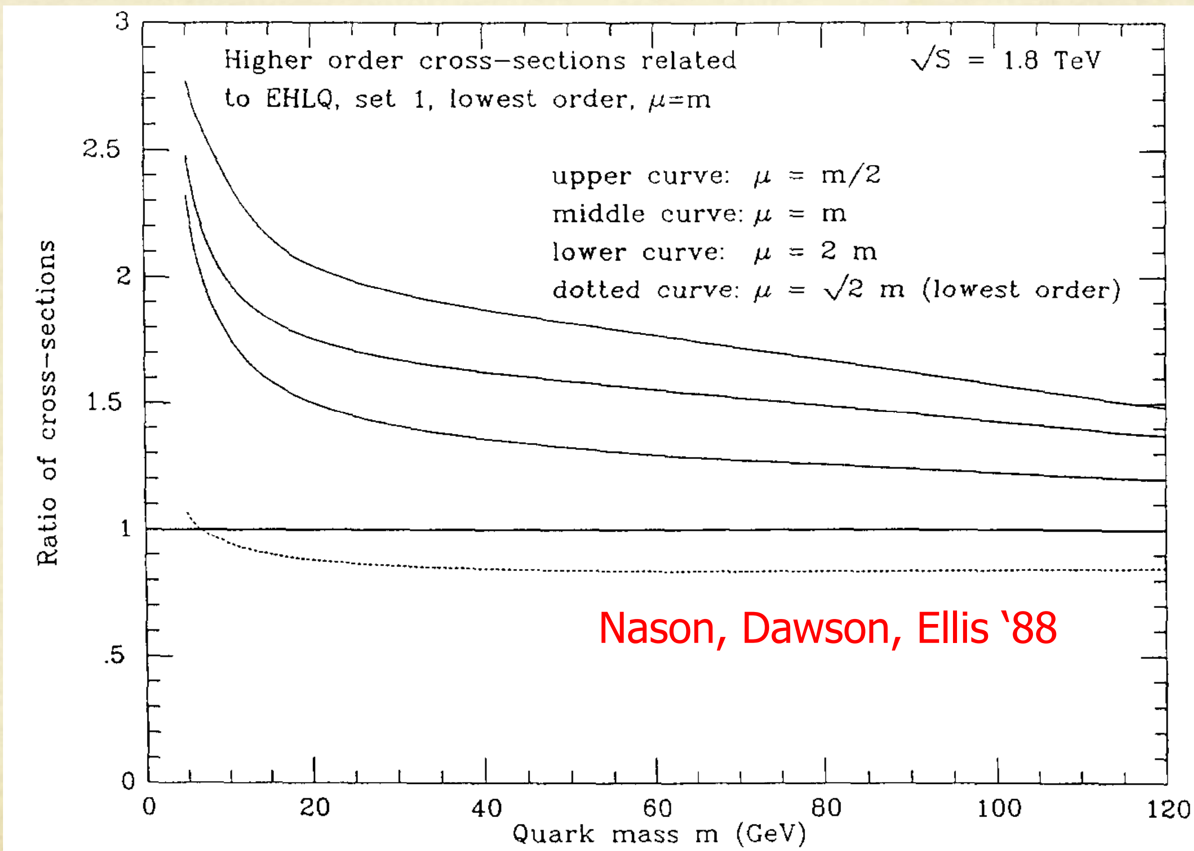
✓ Let's recall the (not-so-humble) beginning!

✓ Around the time of the top discovery (~'95) top pair theory was already very sophisticated:

- Well-established NLO QCD corrections:
  - Inclusive cross-section
  - One-particle inclusive differential cross-section
  - Fully differential tT production at NLO QCD

Nason, Dawson, Ellis '88
Beenakker, Smith, van Neerven '89

Mangano, Nason, Ridolphi '92



✓ Around the time of the top discovery (~'95) top pair theory was already very sophisticated:

- Some EW corrections were known, too.

Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth `93

- Another crucial and unique property of the top quark was understood:

Fadin, Khoze '87-90
Strassler, Peskin '90
Orr '91

  - If $M_{top} > M_W$ the top quark would decay very fast:
  - t-> b+W and $\Gamma_{top} << M_{top}$.

➔ Therefore no toponium or top-flavoured bound states can exist!

➔ Furthermore, in the limit $M_{top} >> M_W$, top production and decay would decouple from each other and both would be perturbative.

➔ Thus studying stable tops was a very adequate approach then (and still is today; only recently we went beyond that; more later).

✓ We've come a long way since top discovery. Two driving factors:

- Experiment:
  - With the top discovery we learned that, for sure, M_{top} >> 40 GeV ☺
  - Subsequent progress was driven by D0 and CDF, especially during RunII.
  - Nowadays ATLAS and CMS have increased the pace, although certain observables are still dominated by Tevatron measurements (for example A_{FB}, M_{top}).

- Theory:

- We always want better theory and top pair production is the best playground since it offers all complications (i.e. toys) a theorist may wish for:
  - Strongly interacting colored particle
  - Decaying resonance
  - Multiple colored particles at Born level so non-trivial color algebra
  - A combination of massless and massive partons at Born level

- NLO corrections seemed large.

All of the above injected strong motivation in going farther and doing things better.
This long, winding and very productive story is the subject of the rest of this talk.

The rise of soft-gluon resummation

✓ Fixed Order calculations can be an expensive business.

✓ Indeed going beyond NLO QCD in the 90's simply wasn't an option: as it turned out, the NLO calculations exhausted the "budget" for doing higher order calculations for the next 25 years!

✓ During the second half of 1990's a different kind of approach appeared: soft gluon resummation. It became prominent once:

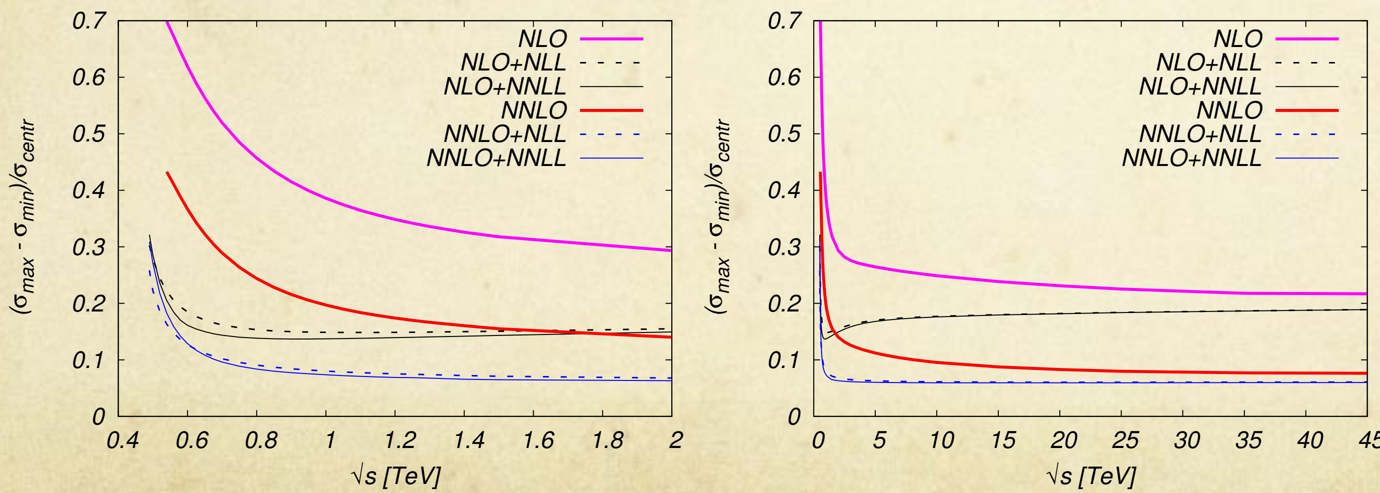
- NLL soft gluon resummation was developed,
- Some kinks in the earlier attempts for resummation were ironed out.

Kidonakis, Sterman '95
Bonciani, Catani, Mangano, Nason, Trentadue '96-98
Kidonakis, Laenen, Moch, R. Vogt '01

✓ Soft-gluon resummation is still very much alive today because it is:

- Beautiful, tantalizing, controversial.

✓ It is easy to demonstrate that, in principle, soft-gluon resummation works as intended:



- Note the failing FO result close to threshold
- And the much more stable resumed result there…

Cacciari et al '11

✓ The relevance of soft-gluon resummation for most "typical" observables is a separate question.

- ✓ In the last 5 years or so, resummation was extended to NNLL (the developments were not always smooth, but eventually we got there). Many groups contributed to this extensive enterprise:

Kidonakis
Moch, Uwer
Almeida, Sterman, Vogelsang
Ahrens, Ferroglia, Neubert, Pecjak, Yang
Beneke, Falgari, Schwinn
Cacciari, Czakon, Mitov, Mangano, Nason
Becher, Neubert
Broggio, Papanastasiou, Signer

- ✓ Soft gluon resummation, makes partial prediction for NNLO (and beyond). Its quality as a substitute for NNLO is debatable. Some prominent applications:
  - Total cross-section
  - Differential cross-section
  - Top AFB

- ✓ Even without direct phenomenology, soft gluon resummation provides certain inputs that are very useful (and were used) in complete NNLO calculations:
  - Subtracting the divergences of two-loop amplitudes
  - Fixed order calculations close to threshold.

NLO corrections to tT + X (associated tT production)

✓ The main effort in top pair production during the 2000's went in the direction of many legs.

✓ First, the associated production ttH was computed (very important phenomenologically)

Beenakker, Dittmaier, Kramer, Plumper, Spira, Zerwas '01
Dawson, Jackson, Orr, Reina, Wackeroth '02

✓ A lesson from those calculations was that doing NLO calculations this way was hitting a hard wall [more on this later]

✓ In parallel, the modern workhorses of experimental analyses were conceived:

- MCFM — Campbell, Ellis
- MC@NLO — Frixione, Webber
- POWHEG — Nason

✓ They allow, among others:

- ➢ working simultaneously with a number of processes (vital for estimating complex backgrounds in BSM searches – *and top is always a background*)
- ➢ interfacing NLO calculations with Parton Showers (mc@nlo/powheg)

✓ The newest development in this direction is the aMC@NLO library:

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro '14

- Interface any(*) NLO process with the parton shower of choice.
- All is fully automated; no deep understanding/profound computational skills are required from the user in order to answer the pheno questions he/she has!

(*) Up to some reasonable multiplicity and with some reasonable simplifications

- ✓ But much more has happened in the last several years! 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 calculations of ttbar + (1jet, 2 jets, bb, gamma, etc) were completed:

Dittmaier, Uwer, Weinzierl '07
Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09-'11
Bredenstein, Denner, Dittmaier, Pozzorini '10
Melnikov, Scharf, Schulze '10-'12

- ✓ NLO production + NLO top decay in narrow width approximation.

Melnikov, Schulze '09
Bernreuther, Si '10
Campbell, Ellis '12

- ✓ Finally, fully off-shell NLO production and decay, including interference effects. In some calculations the b-quark mass is taken to be zero, while in others the b-quark mass is retained.

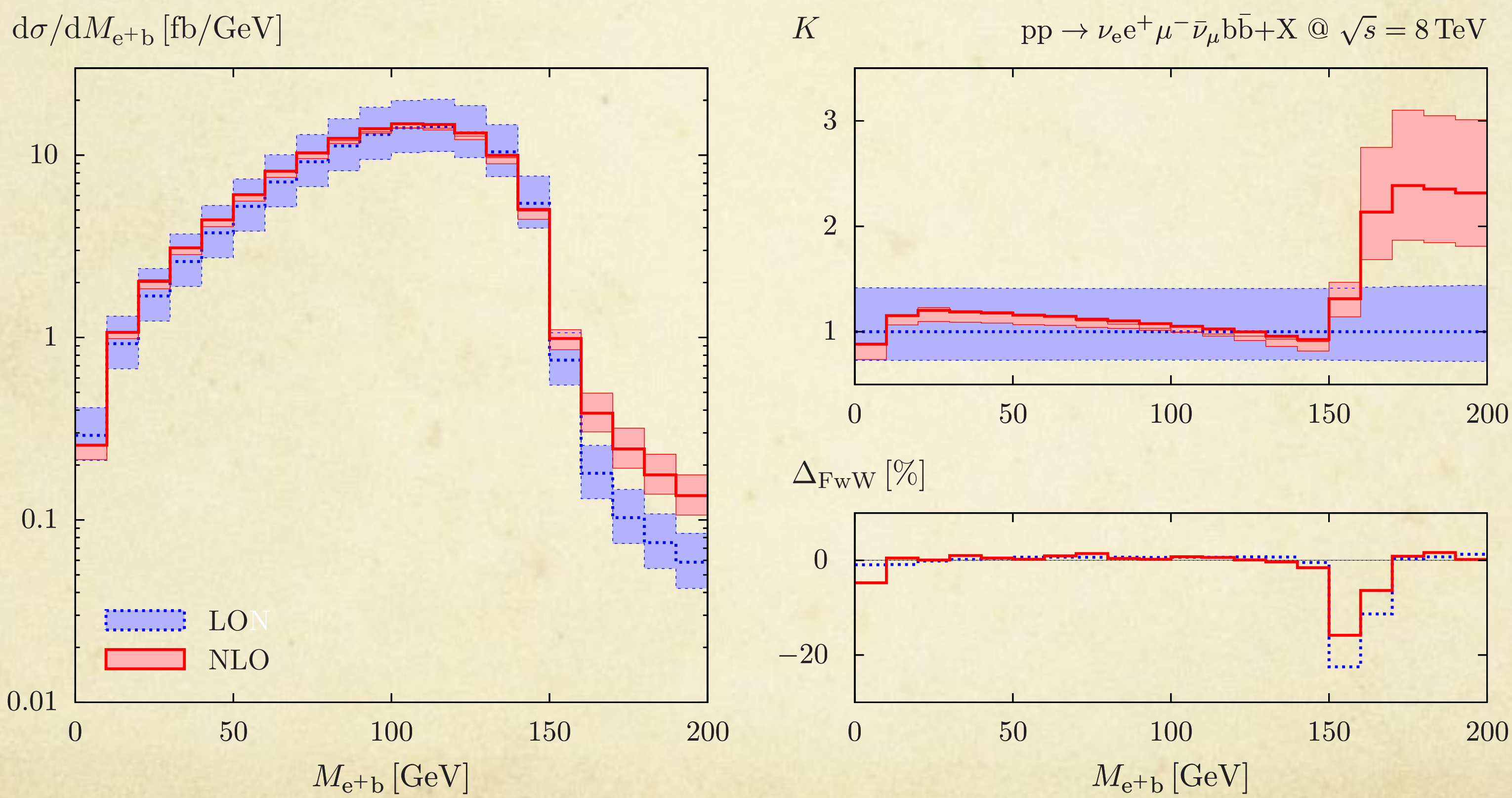
Denner, S. Dittmaier, S. Kallweit, and S. Pozzorini '10
Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '10
Heinrich, Maier, Nisius, Schlenk, Winter '13
Frederix '13
Cascioli, Kallweit, Maierhfer, Pozzorini '13

- ✓ Full NLO production + decay matched to parton showers, through POWHEG:
  - ➢ For the full off-shell case — Garzelli, Kardos, Papadopoulos, Trócsányi `11
  - ➢ In the NWA — Campbell, Ellis, Nason, Re '14

For the first time full control over Γ_{top} effects. The circle closes in 20+ years: off-shell effects were estimated small

Pittau '96
Macesanu '01

and now, finally, they are verified directly. Indeed, the NWA works well in the bulk (say for inclusive x-sections), but fails close to kinematic boundaries. These can be important in some measurements (like top mass extraction from the kinematic endpoint).



arXiv:1207.5018v2

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EW corrections to tT production

✓ EW corrections to top pair production at hadron colliders have long history:

Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth `93
Kao, Ladinsky, Yuan '97
Bernreuther, Fuecker, Si '06
Kuehn, Scharf, Uwer '06 –'13
Hollik, Kollar '07

✓ The effect on the total x-section is small (1%) and likely negligible even with NNLO QCD

✓ But effects on tails could be much larger: 10% or more in the TeV range.

✓ So far EW corrections have not been really considered in analyses, likely because of the lack of generic tools for their calculation. This is about to change with the addition of EW corrections to the aMC@NLO library. This will allow for:
- More flexibility
- Combining EW corrections with NNLO QCD.

✓ EW+NNLO QCD will, ideally, become the standard for LHC Run II.

✓ One place where EW correction became prominent was the top A_{FB} where EW corrections account for 25% of the leading term.

Hollik, Pagani '11
Bernreuther, Si '12

Clearly EW effects can be relevant and need to be considered systematically in future analyses

NNLO QCD corrections to tT production

Status

- ✓ Total inclusive cross-section known fully

  P. Bernreuther, Czakon, Fiedler, Mitov '12-'13

- ✓ First differential distributions have been computed for the Tevatron.

  Czakon, Fiedler, Mitov '14 and to appear

- ✓ Methods are based on the subtraction scheme STRIPPER

  Czakon '10

- ✓ Alternative approaches are possible

- ✓ Work in progress based on antennae subtractions.

  Abelof, Gehrmann-De Ridder, Maierhofer, Pozzorini '14

- ✓ As a proof of principle the calculation of qq->tt (NF parts done). Very encouraging result although not yet pheno-relevant.

  Abelof, Gehrmann-De Ridder '14

- ✓ Alternative approach based on top pair PT resummation

  Zhu, Li, Li, Shao, Yang '13
  Catani, Grazzini, Torre '14

- ✓ Currently at NNLL and NLO; the remaining tasks for NNLO are not that formidable.

Prediction at NNLO+ resummation (NNLL)

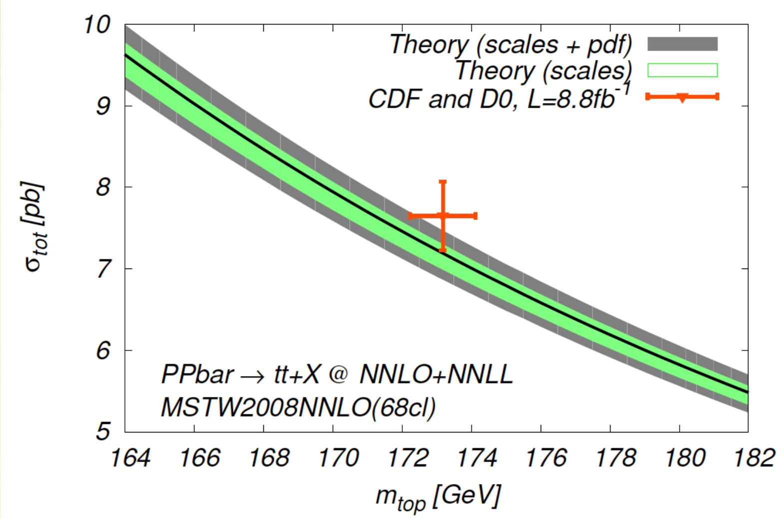
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$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

Pure NNLO

Collider	σ_{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	$+31.8(3.4\%)$ $-51.0(5.5\%)$	$+16.1(1.7\%)$ $-17.6(1.9\%)$

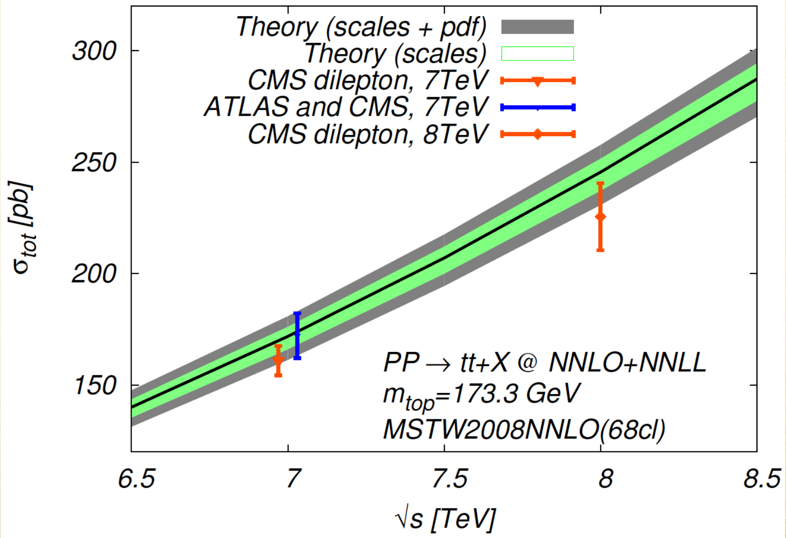
Czakon, Fiedler, Mitov '13

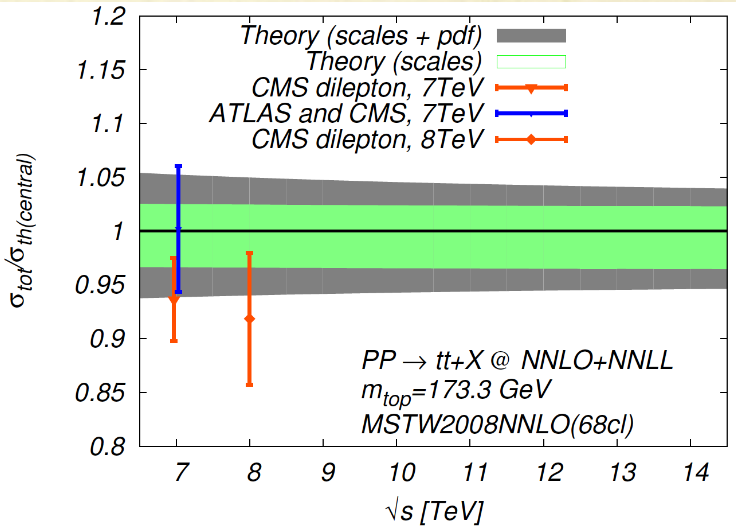
Good agreement with Tevatron measurements



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

Good agreement with LHC measurements

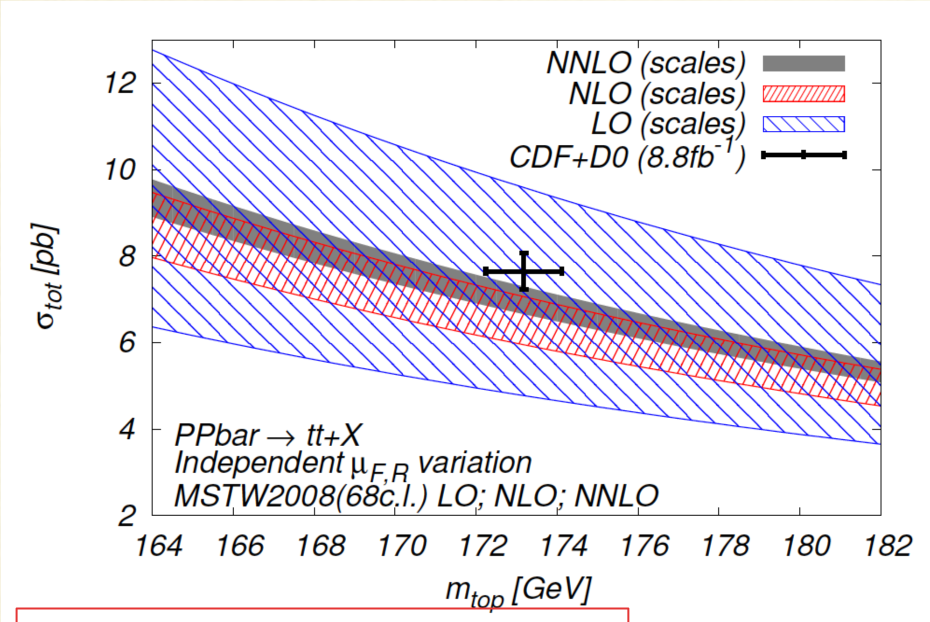




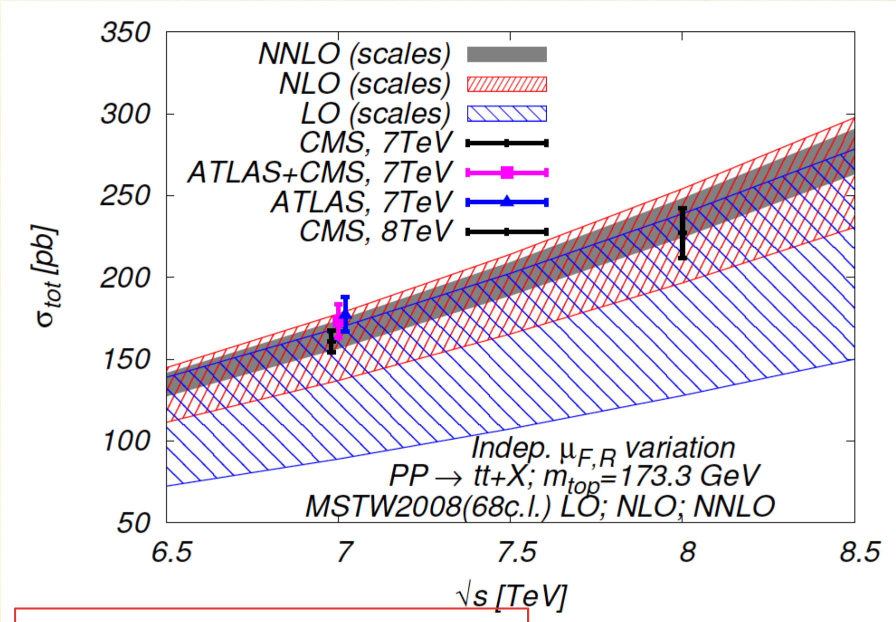
Good perturbative convergence

✓ …

✓ Independent F/R scales variation



Scale variation @ Tevatron



Scale variation @ LHC

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

✓ Suggests the (restricted) independent scale variation is a good estimate of missing higher order terms!

This is very important: good control over the perturbative corrections justifies less-conservative overall error estimate, i.e. more predictive theory.

LHC: general features at NNLO+NNLL

Czakon, Fiedler, Mitov '13

Czakon, Mangano, Mitov, Rojo '13

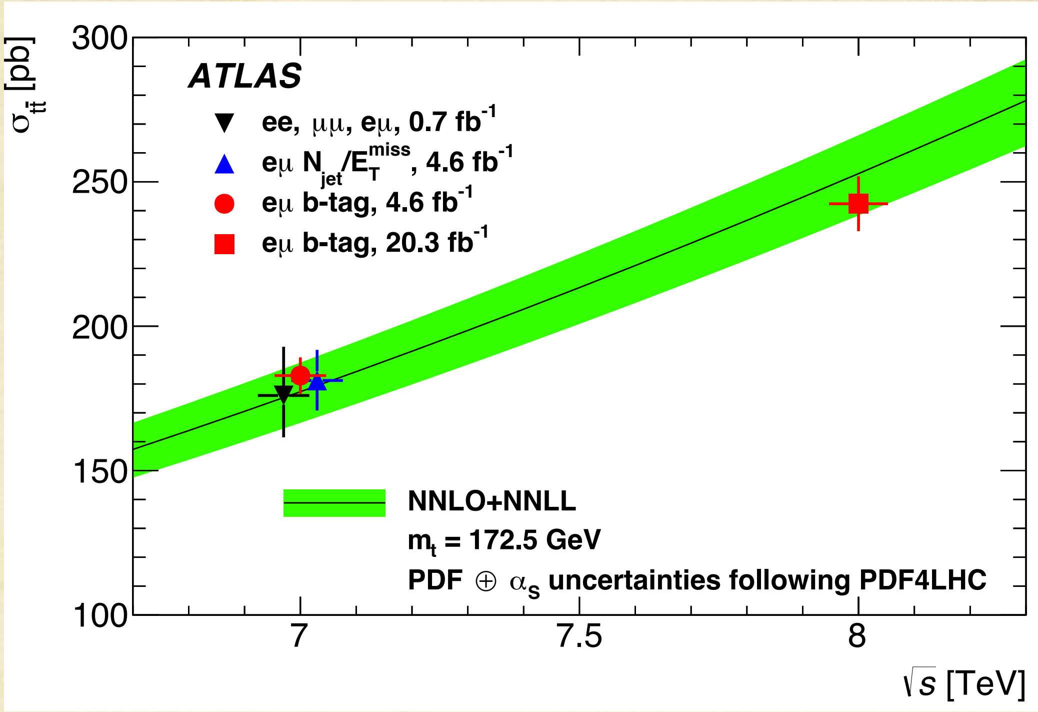
✓ We have reached a point of saturation: uncertainties due to

- ✓ 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%

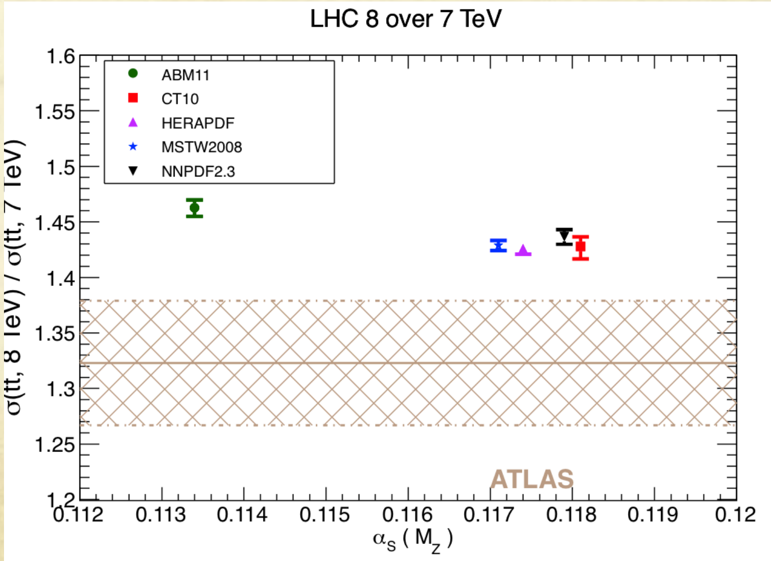
✓ The cross-section agrees well:



ATLAS 1406.5375v2

✓ But the 8TeV/7TeV ratio not so much:

Note: theory errors dramatically cancel in the ratio!



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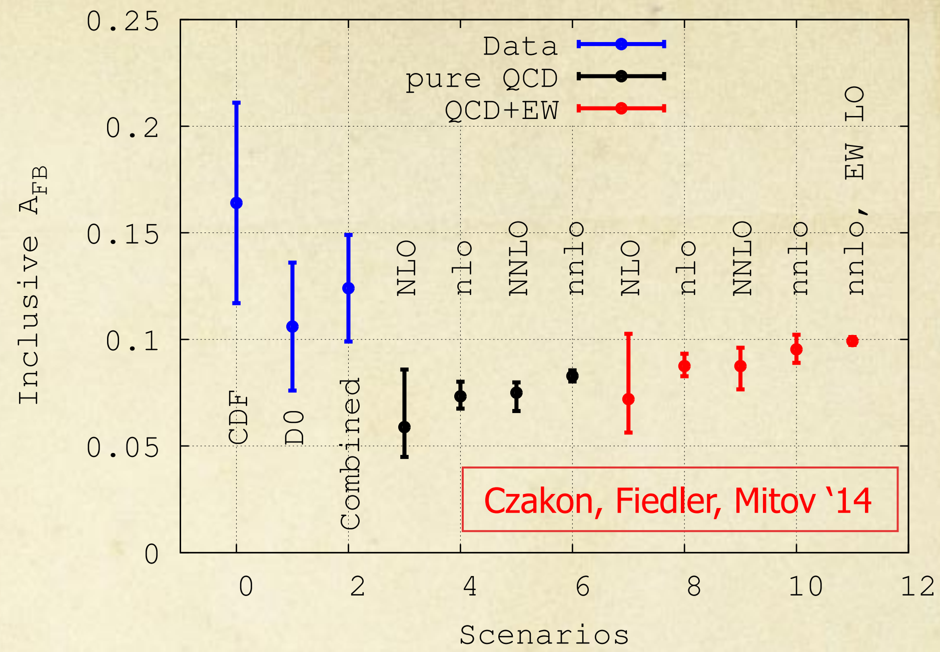
Results for inclusive A_{FB}

- *NLO, NNLO* : exact numerator and denominator
- *nlo, nnlo* : expanded in powers of a_S



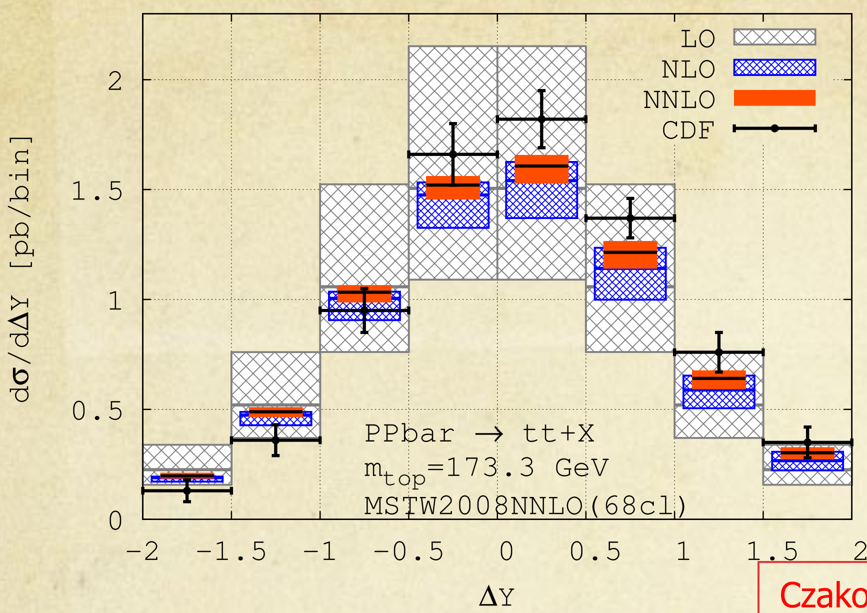
✓ Large QCD corrections: NNLO ~ 27% of NLO (recall EW is 25% of NLO).

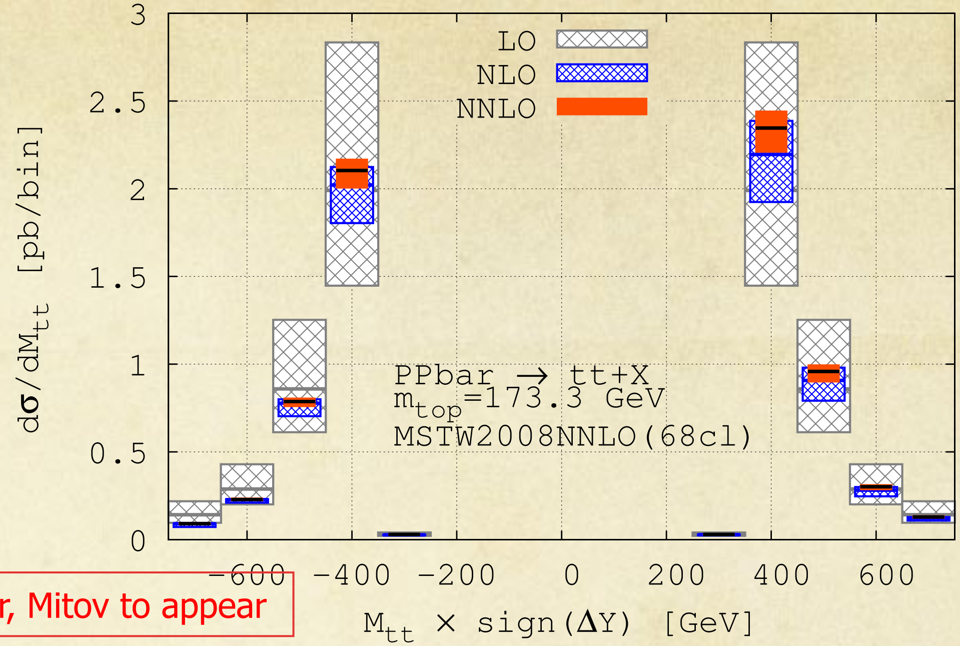
➔ This was not expected, given soft-gluon resummation suggests negligible correction.

✓ Adding all corrections A_{FB} ~ 10%.

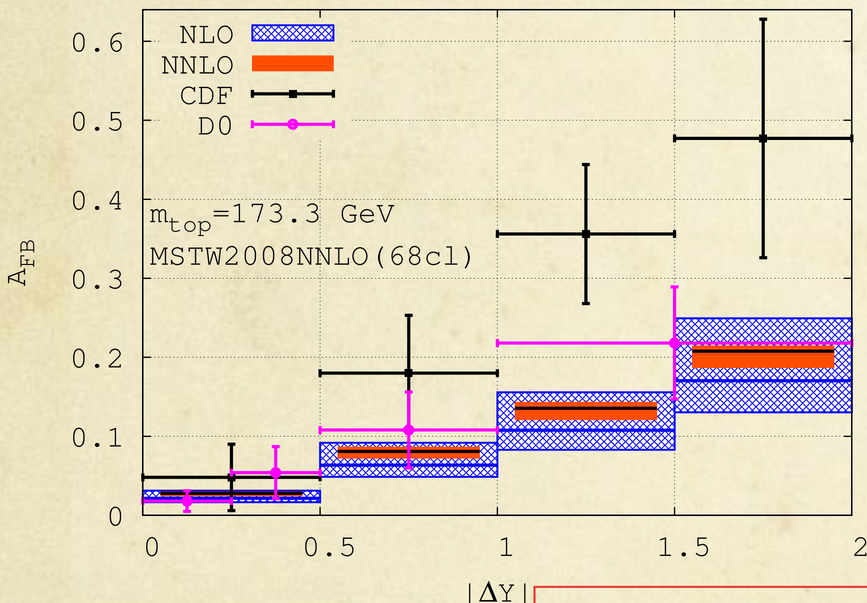
- ✓ Agrees with D0 and CDF/D0 naive combination
- ✓ Less than 1.5σ below CDF

✓ We observe good perturbative convergence (based on errors from scale variation)

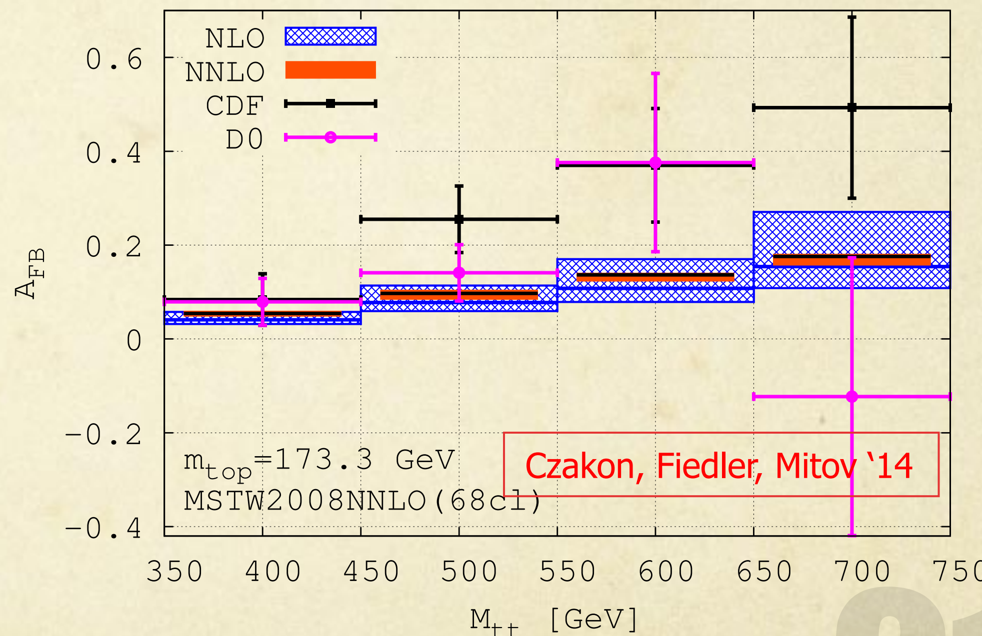




Czakon, Fiedler, Mitov to appear



Czakon, Fiedler, Mitov '14



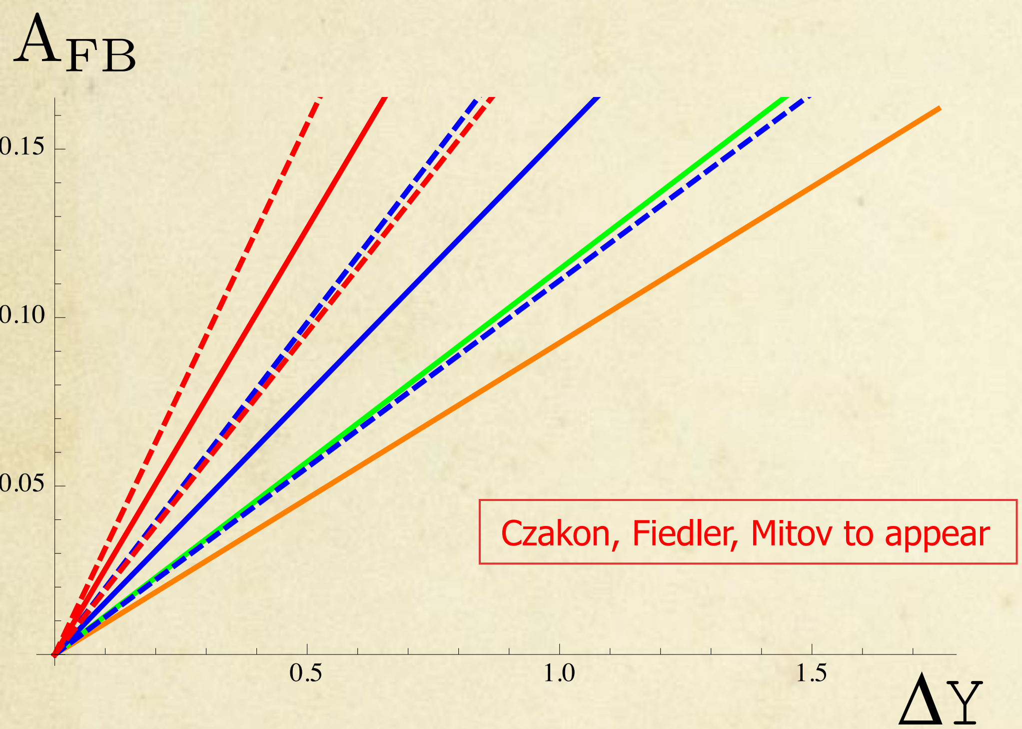
Czakon, Fiedler, Mitov '14

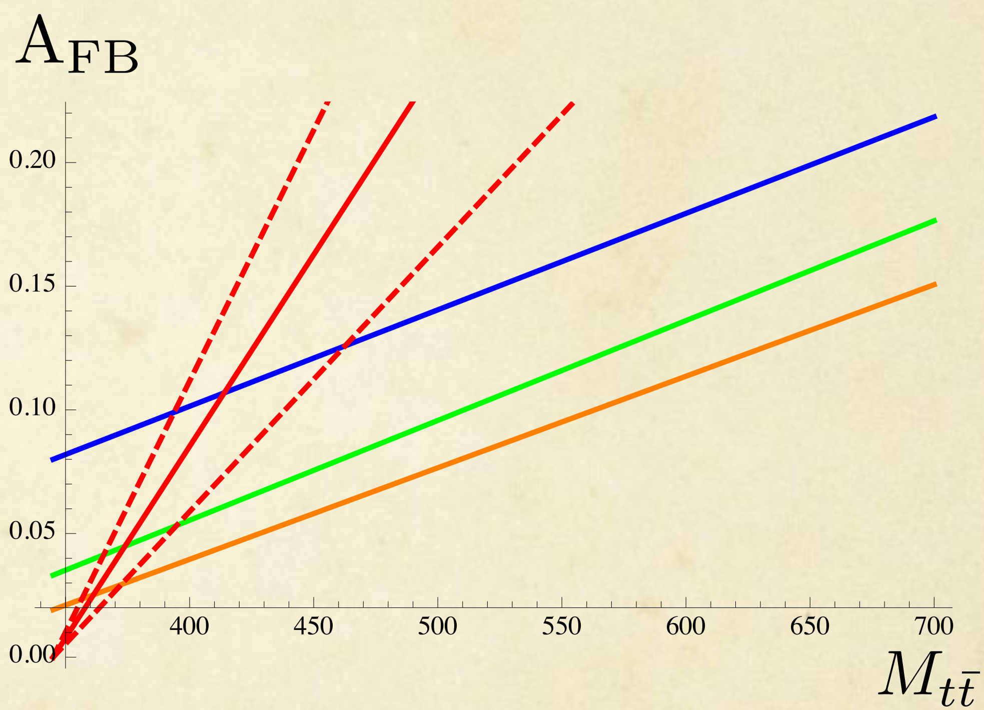
FIG. 2: The $|\Delta y|$ differential distribution (top) and asymmetry (bottom) in pure QCD at LO (grey), NLO (blue) and NNLO (orange) versus CDF [2] and D0 [1] data. Error bands are from scale variation only. For improved readability some bins are plotted slightly narrower. The highest bins contain overflow events.

FIG. 3: As in fig. 2 but for the $M_{t\bar{t}}$ differential asymmetry. Both lowest and highest bins contain overflow events.

The slope of A_{FB}

- It was noted previously that the differential asymmetry is close to a straight line
- For the rapidity dependence it is clear it is actually slightly curved at both NLO and NNLO
- For M_{tt} at NNLO is very close to a straight line – unlike NLO





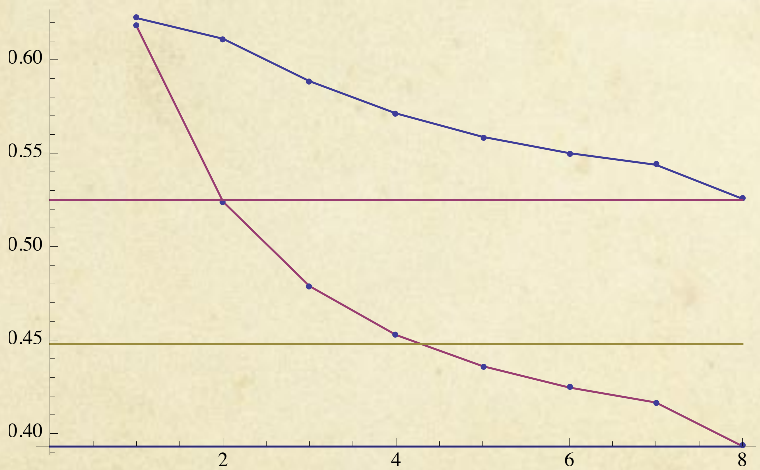
- CDF (dashes – errors)
- D0 (dashes – errors)
- NNLO QCD
- NLO QCD

- Agreement with D0 within errors even without EW corrections (D0 error not shown)

The origin of the difference w/r to approximate NNLO

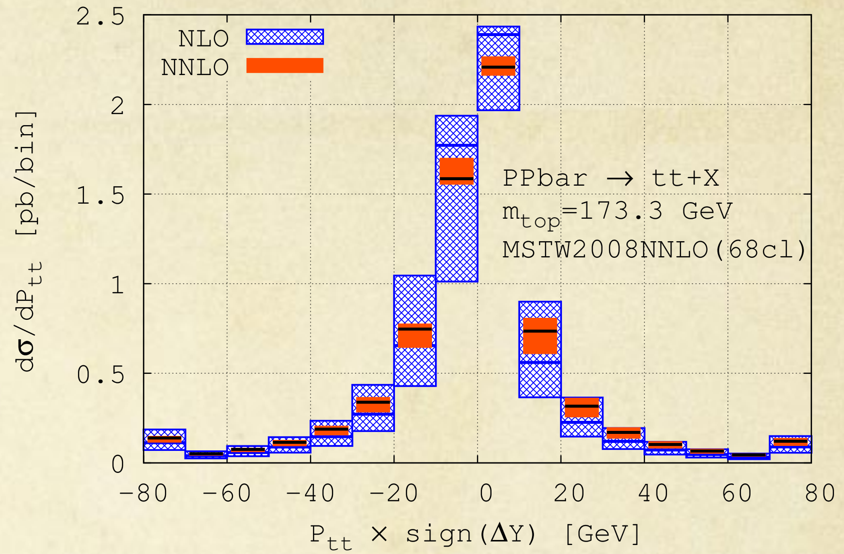
- It is better to look at the Cumulative differential asymmetry (i.e. the inclusive asymmetry with a cut on $P_{T,tt}$)
- Recall: the inclusive asymmetry is <u>not</u> an integral over the differential one …
- Soft gluon resummation "operates" near $P_{T,tt}$=0. The Cumulative asymmetry will illustrate how A_{FB} develops
- Cumulative $P_{T,tt}$ asymmetry:

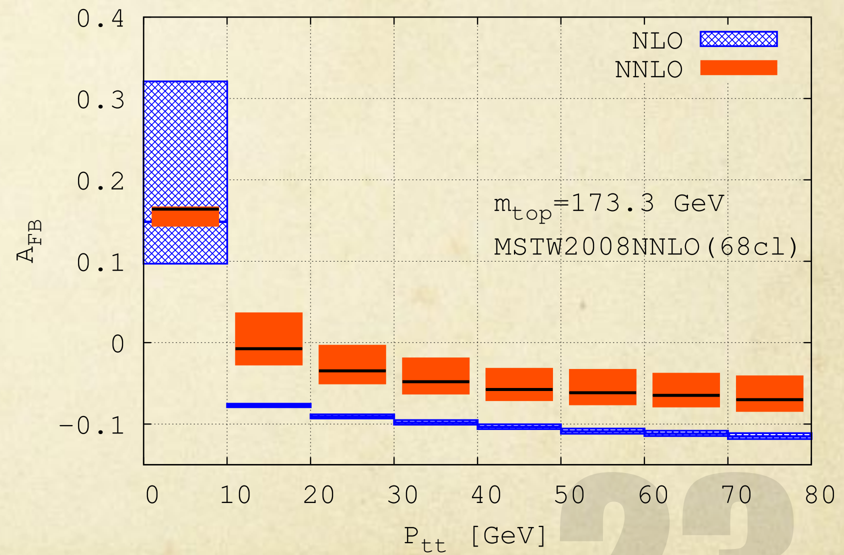
NNLO and NLO numerators



$P_{T,tt}$ bin

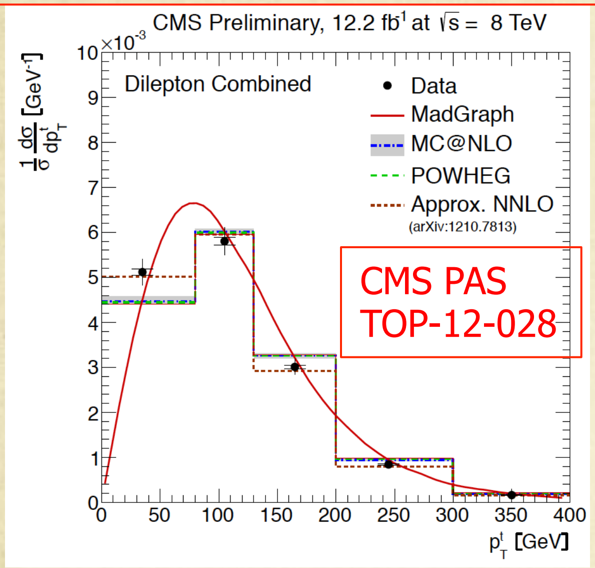
Czakon, Fiedler, Mitov to appear





✓ Differential distributions (known in approximate NNLO). Important in their own right and for getting NNLO PDF's right.

P_T spectrum of a top quark (inferred)

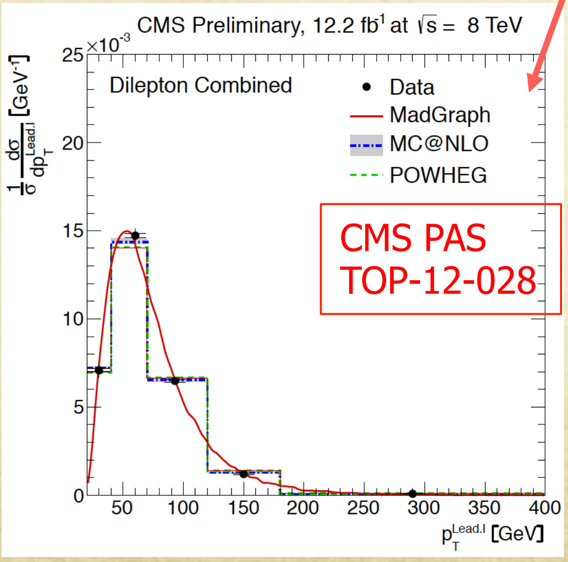


✓ It seems that approximate NNLO result (from resummation) Kidonakis `12 describes top quark distributions better than fully differential NLO calculations. MC@NLO, POWHEG

✓ However: diff. NLO calculations describe well the distributions of top-decay products (leptons in particular). Which is what's measured!

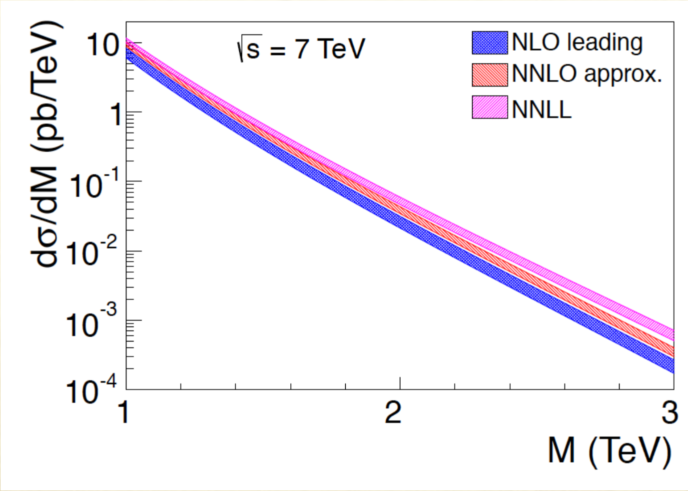
✓ Looking forward to the resolution of this in the near future …

P_T spectrum of the lepton in top quark decay (measured)



✓ In the very high energy region top production necessitates resummation of collinear logs. Recent work at NNLL:

Ferroglia, Pecjak, Yang '13



Notable difference between Various approximations

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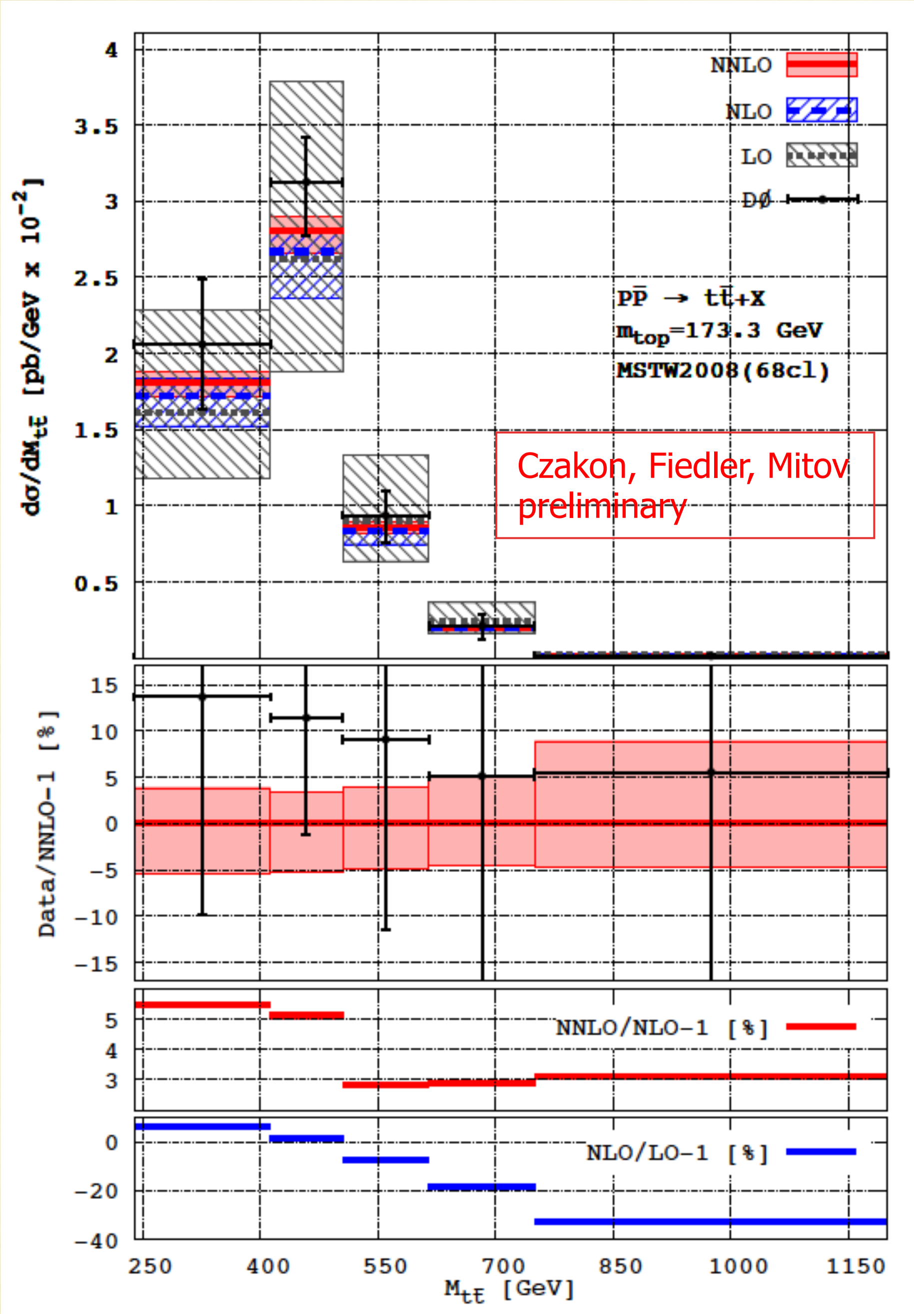
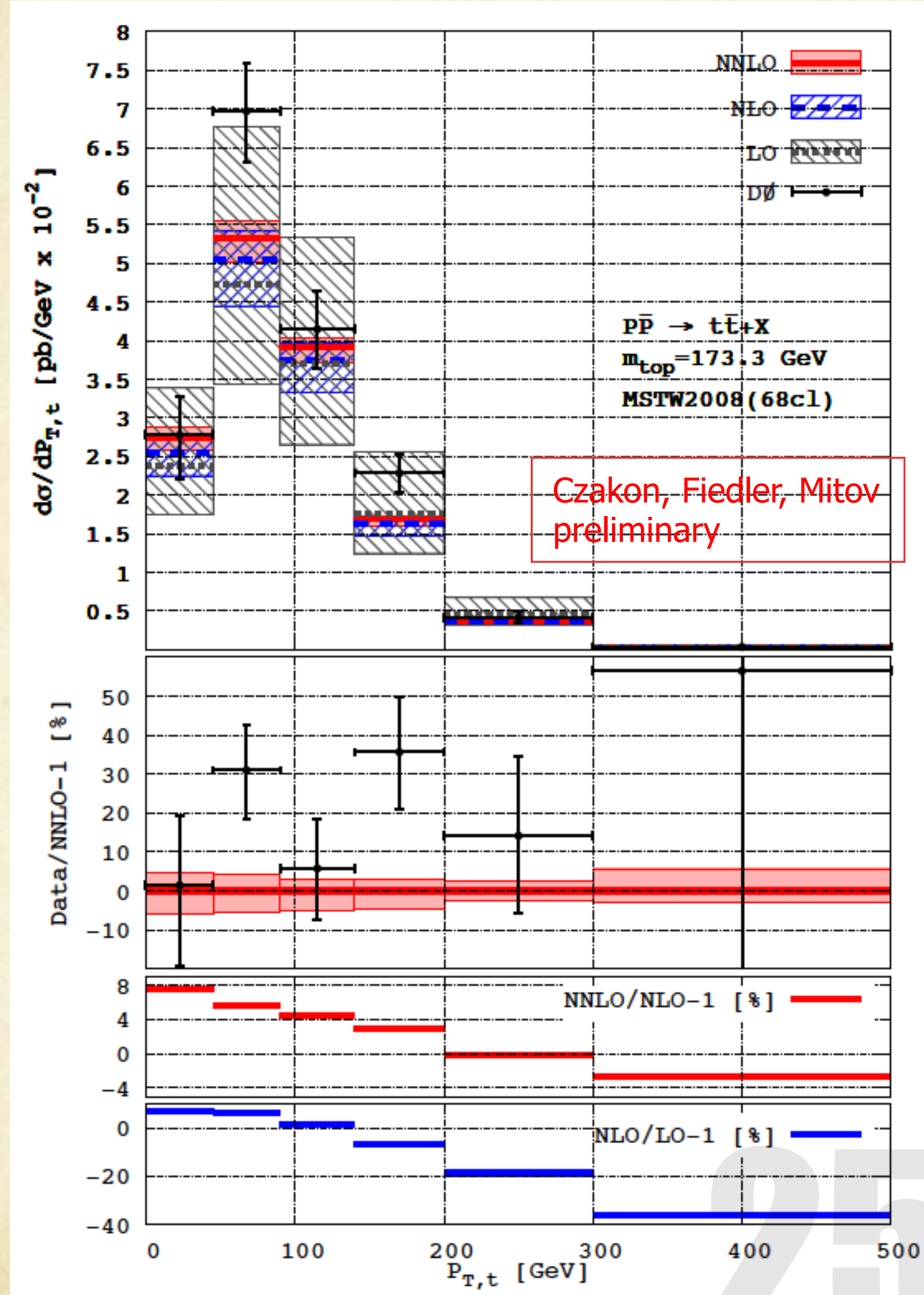
✓ New preliminary results for the Tevatron in full NNLO QCD (no approximations):





Expectations for future developments in ttbar production

&

list of current bottlenecks

- ✓ So far discussed past and current status. What about the future prospects?
  - ➢ Fully differential partonic MC for top pair production in NNLO QCD
  - ➢ Fully differential NNLO partonic MC with top decay in NWA. Top decay already known through NNLO:

    Gao, Li, Zhu '12
    Brucherseifer, Caola, Melnikov '13
  - ➢ The next big milestone is to shower NNLO top production.
    - Initially by using existing LL showers
    - Will add a momentum in the direction of extending showers to NLL and beyond
    - NNLO+PS is still a fairly new subject with first results for processes with simpler analytical structure (like H, Z).

      Hamilton, Nason, Re, Zanderighi '13
      Hoeche, Li, Prestel '14
      Karlberg, Re, Zanderighi '14
    - Extending showers to top production will require a general solution. Some activity:

      Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '13
- ✓ What about current bottlenecks?
  - ➢ NLO ttbar calculations are now extremely advanced.
  - ➢ At NNLO the clear bottleneck is the fast evaluation of one-loop amplitudes for RV corrections to inclusive ttbar.
  - ➢ Going farther into the future, if we want to have ttbar+jet etc also at NNLO we will need to develop ways of computing the required 2-loop amplitudes. This is a totally open problem at present.

Indeed, what a journey!