Top quark pair cross-section

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Content of the talk

- Precision applications at the LHC: what do we learn about SM and bSM?
- Top quark mass: the hot topic of the last year or so.
- New results: resolving the A_{FB} puzzle.
- Outlook

Precision phenomenological applications

In a nutshell:

- ✓ Top physics firmly in the precision stage
- ✓ Total x-section investigation shows what's possible
- ✓ High expectations about forthcoming NNLO differential results

Prediction at NNLO+ resummation (NNLL)

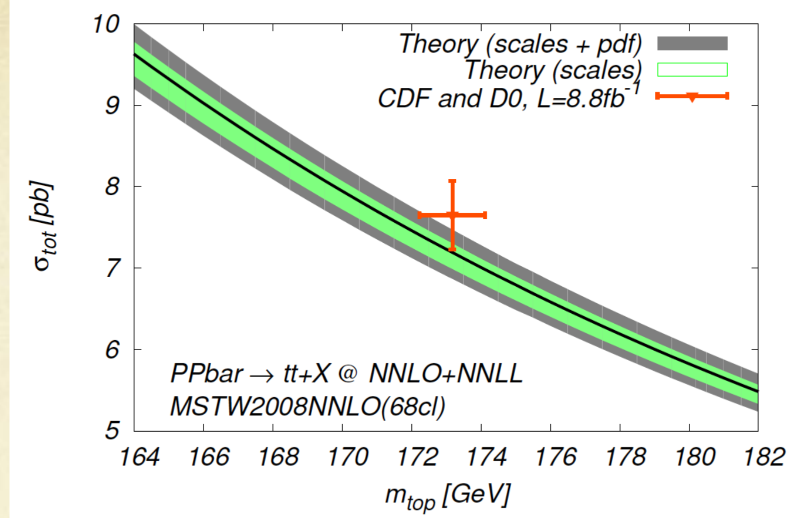
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$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

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

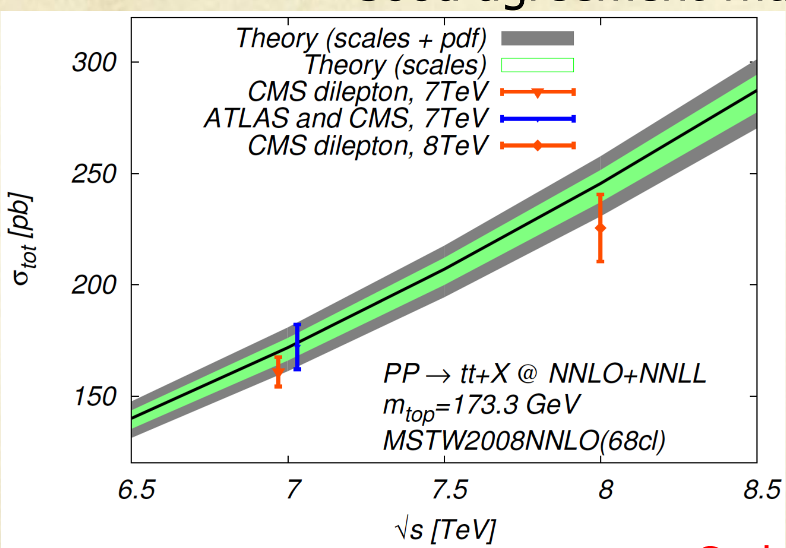
Czakon, Fiedler, Mitov '13

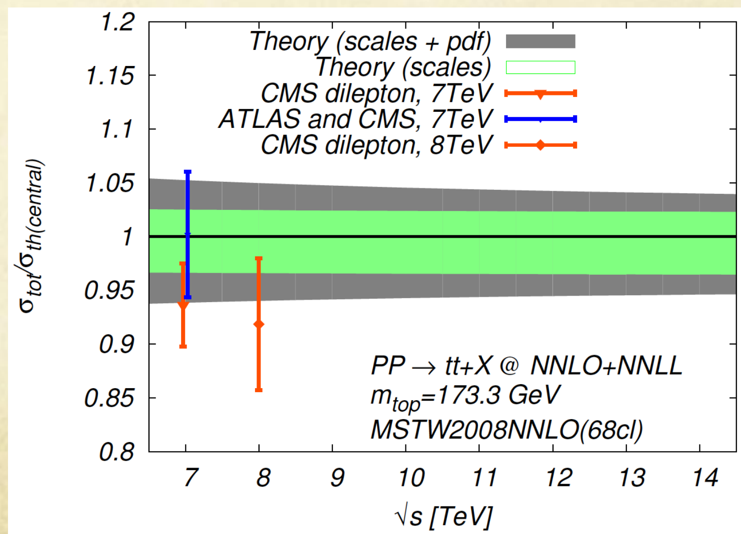
Good agreement with Tevatron measurements



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

Good agreement with LHC measurements

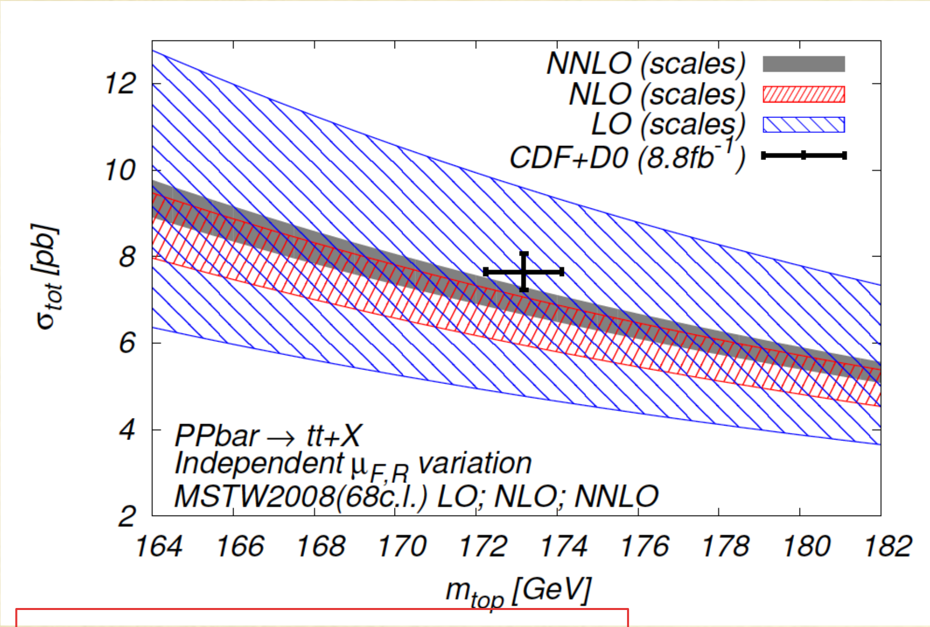




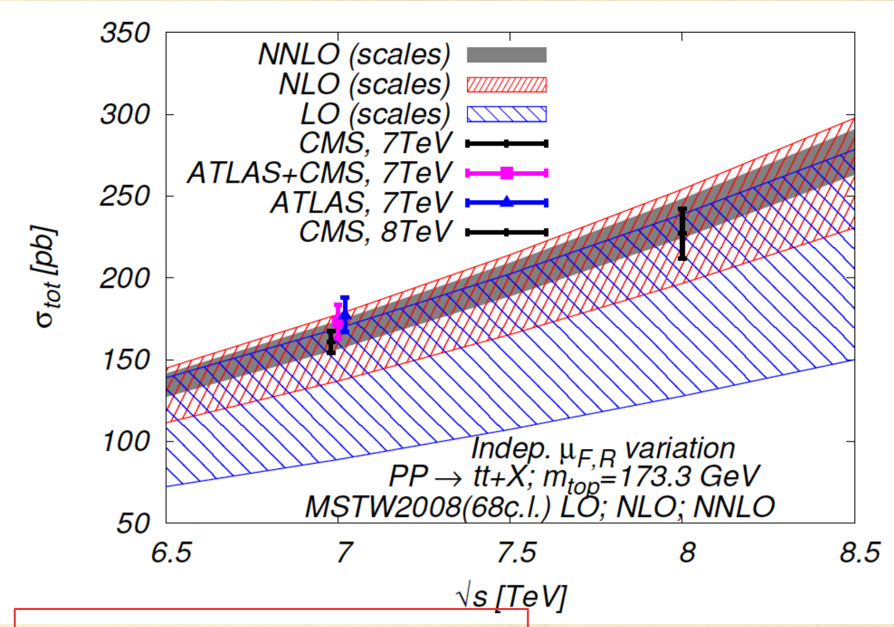
Czakon, Fiedler, Mitov '13

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.

For more detailed comparison, including soft-gluon resummation, see arXiv 1305.3892

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

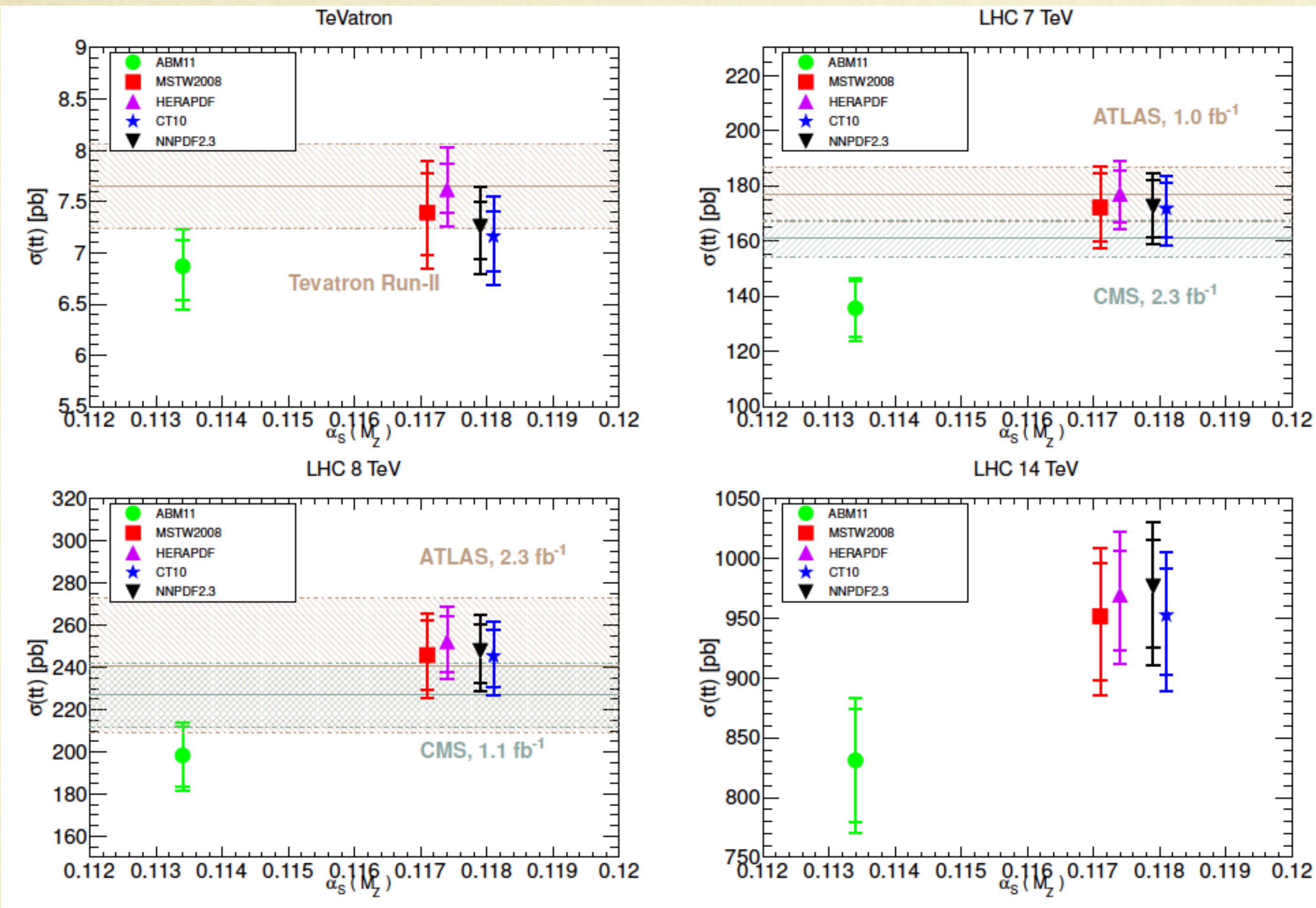
Application to PDF's

Czakon, Mangano, Mitov, Rojo '13

How existing pdf sets fare when compared to existing data?

Most conservative theory uncertainty:

Scales + pdf + as + mtop



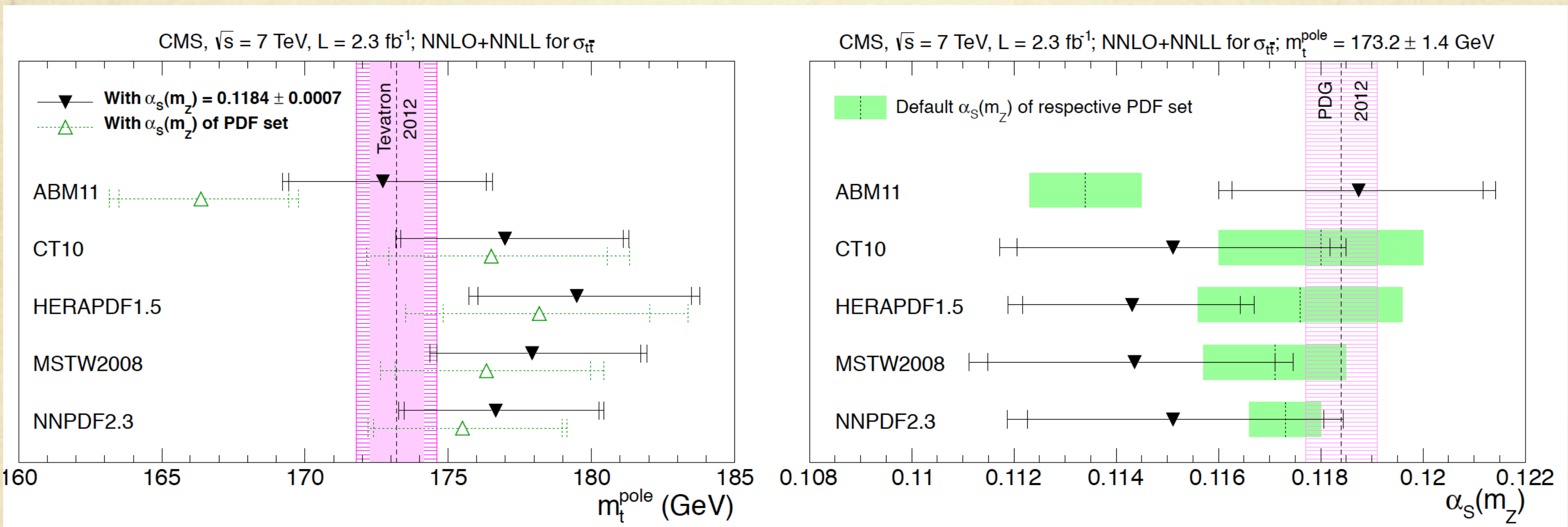
Excellent agreement between almost all pdf sets

$alpha_S$ and m_{TOP} extraction from top data (CMS)

How existing pdf sets fare when compared to existing data?

Excellent agreement between almost all pdf sets

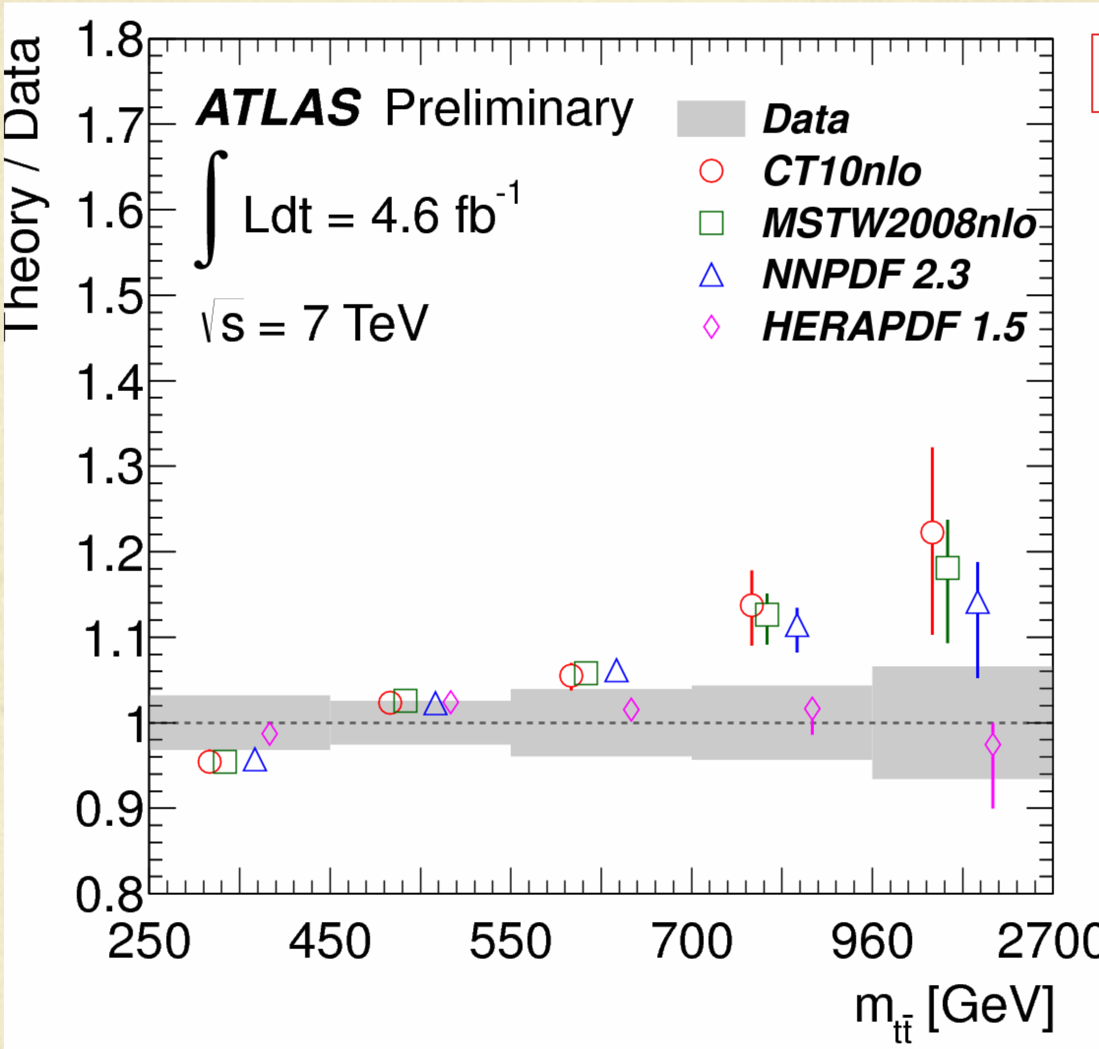
S. Naumann-Emme (CMS) Arxiv:1402.0709



- Results are consistent with world averages, although slight tendency can be seen.
- ABM11 returns value of $alpha_S$ that is incompatible with their assumed value.

Application to PDF's

How existing pdf sets fare when compared to existing data?



1407.0371

Doesn't look perfect at the differential level (which itself is NLO). Do we have a problem here?

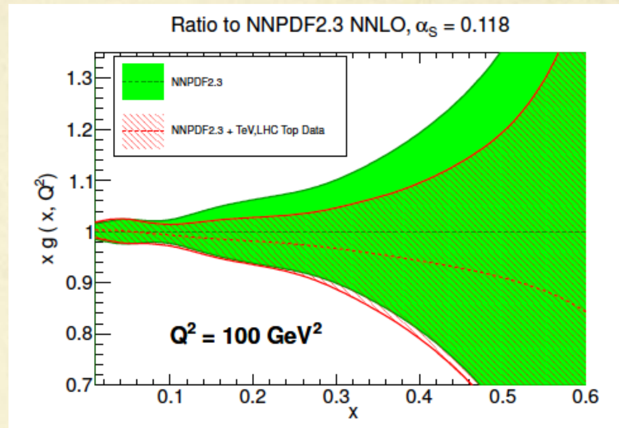
Application to PDF's

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

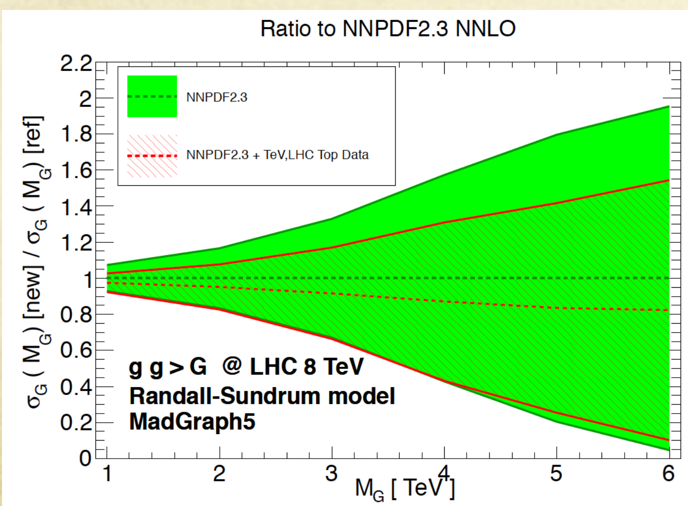
✓ implications to many processes at the LHC: Higgs and bSM production at large masses

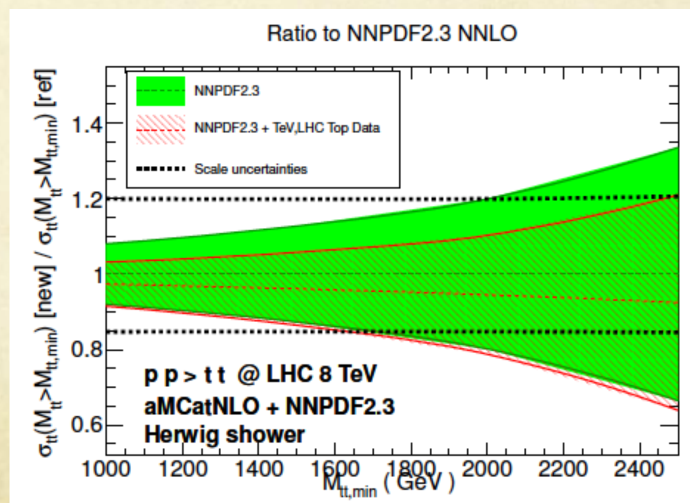
One can use the 5 available (Tevatron/LHC) data-points to improve gluon pdf

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



… and PDF uncertainty due to "old" vs. "new" gluon pdf: Czakon, Mangano, Mitov, Rojo '13





Application to bSM searches: stealthy stop

✓ Scenario: stop → top + missing energy

✓ m_stop small: just above the top mass.

✓ 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. <u>Assumptions</u>:

✓ Same experimental signature as pure tops

✓ the measured x-section is a sum of top + stop

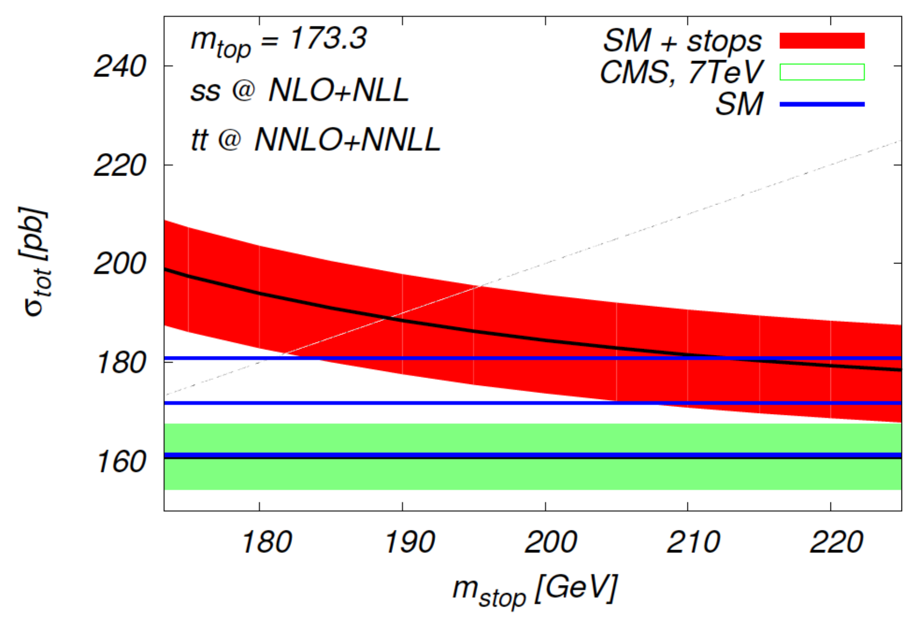
✓ Use precise predictions for stop production @ NLO+NLL

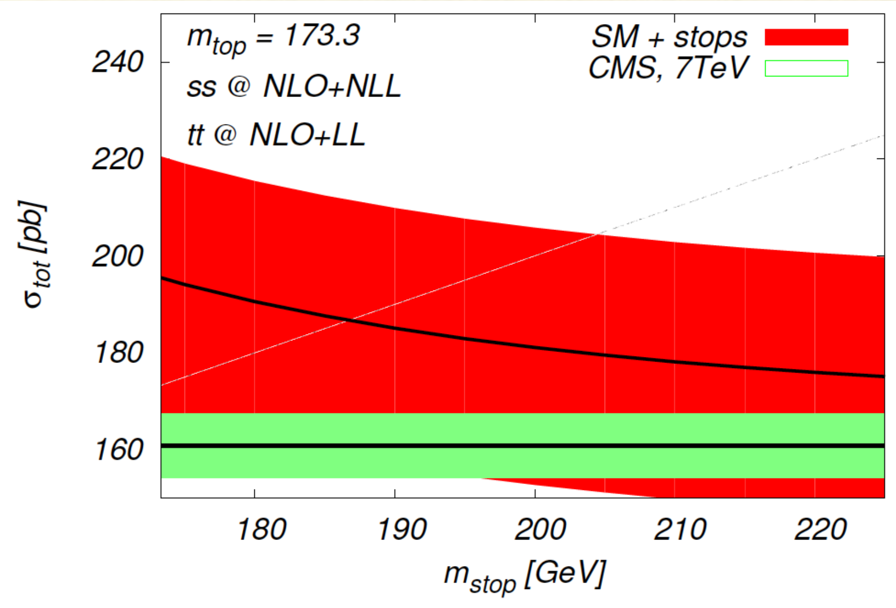
Krämer, Kulesza, van der Leeuw, Mangano, Padhi, Plehn, Portell `12

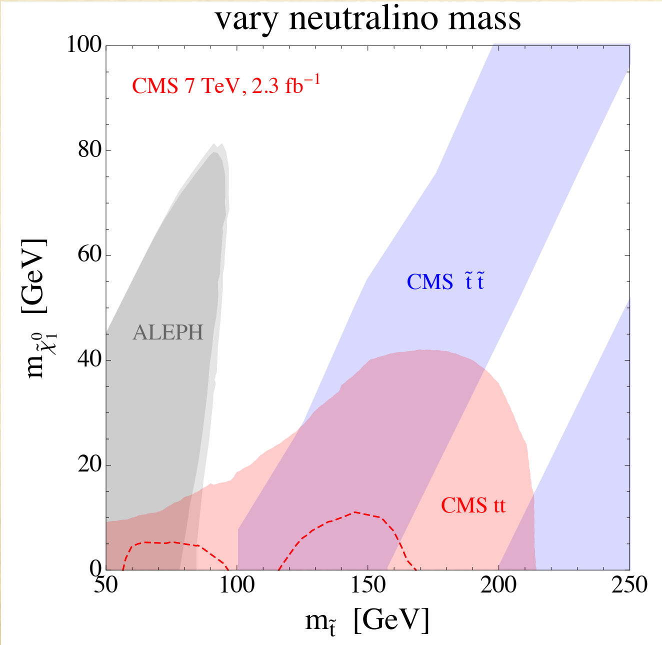
✓ Total theory uncertainty: add SM and SUSY ones in quadrature.

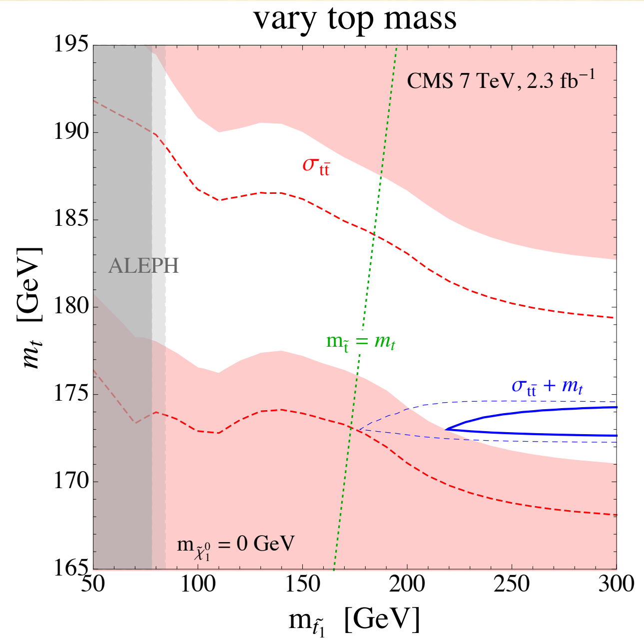
Applications to the bSM searches: stealth stop

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









- Approach is orthogonal to previously used ones
- Improved NNLO accuracy makes all the difference
- Non-trivial exclusion limits possible

Summary on top pair production

- ✓ Some developments in the last year
- ✓ Soft-gluon resummation and approximate NNLO results. Notable works:
  - ➢ On Transverse-momentum resummation at NLO+NNLL

    Catani, Grazzini, Torre '14
  - ➢ Approximate NNLO for tt with decay to leptons

    Broggio, Papanastasiou, Signer '14
  - ➢ Discrepancies in top P_T among showers; due to modeling of momentum reshuffling in the shower. Formally NNLO effect; NNLO might be able to resolve

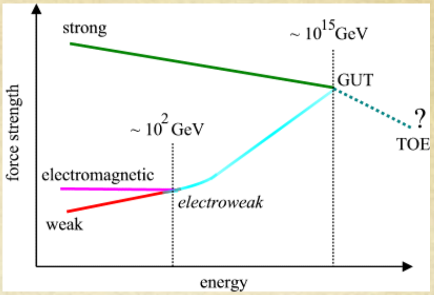
    Nason (TopWG May 2014)
- ✓ Main new developments expected: differential tt production at NNLO
- ✓ Interesting problem awaiting resolution: the top P_T spectrum
- ✓ Above expected imminently (<u>see end of this talk</u>)
- ✓ Will allow for more detailed re-analysis of all examples I presented so far.
- ✓ Dedicated workshop in 2.5 weeks (prior to Top2014 – see Top2014 website). Hope to have a white paper that will serve as a roadmap for LHC Run 2

Where is the New Physics?

or

injecting new life into the top mass determination problem

Interesting connection between M_{top} and physics at the Planck scale

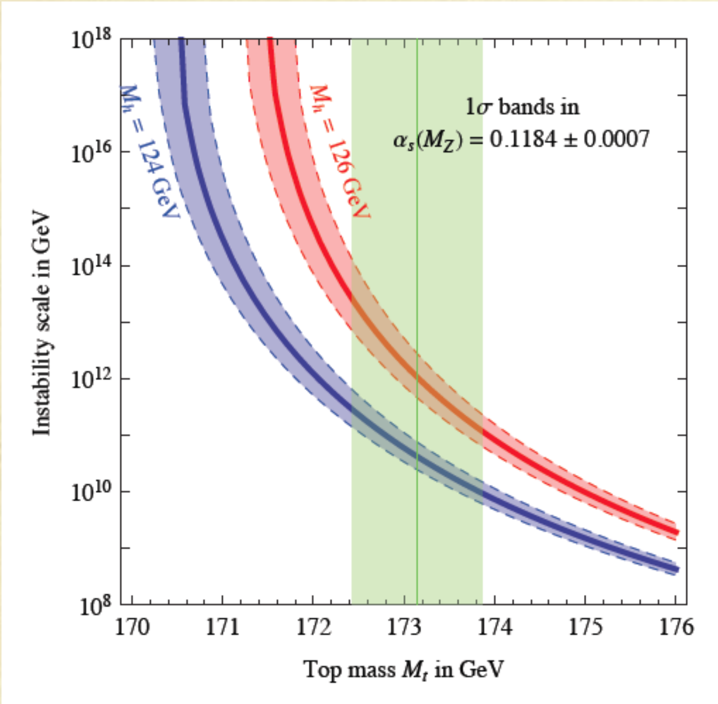


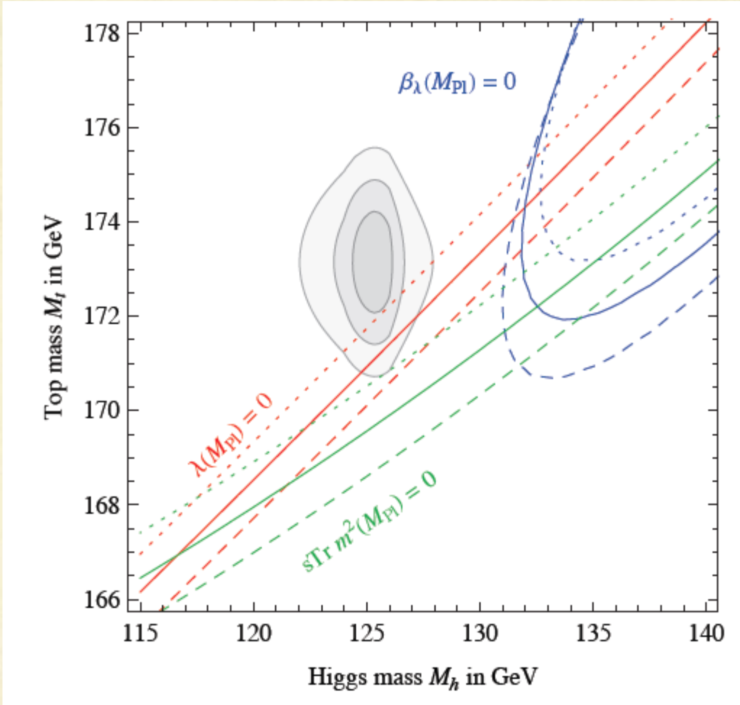
- Higgs inflation

Bezrukov, Shaposhnikov ’07-’08

- Vacuum stability in the Standard Model and beyond

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





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

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

Top quark mass: some thoughts

- ✓ The apparent sensitivity to m_{top} requires convincing m_{top} determination
- ✓ What do I mean by convincing?
  - ✓ m_{top} is not an observable; cannot be measured directly.
  - ✓ It is extracted indirectly, through the sensitivity of observables to m_{top}

$$\sigma^{\rm exp}(\{Q\}) = \sigma^{\rm th}(m_t, \{Q\})$$

  - ✓ The implication: the "determined" value of m_{top} is as sensitive to theoretical modeling as it is to the measurement itself
- ✓ A worry: can there be an additional systematic O(1 GeV) shift in m_{top} ?
- ✓ The measured mass is close to the pole mass (it decays …)
- ✓ Lots of activity (past and ongoing). Reviews:

Juste, Mantry, Mitov, Penin, Skands, Varnes, Vos, Wimpenny '13
Moch, Weinzierl, Alekhin, Blümlein2, de la Cruz, Dittmaier, Dowling et al '14

Why maybe all is not well with current M_{top} extractions

$$m_t = 173.34 \pm 0.76\,\mathrm{GeV} \quad \text{[World Average]}$$
$$m_t = 172.04 \pm 0.77\,\mathrm{GeV} \quad \text{[CMS Collaboration]}$$
$$m_t = 174.98 \pm 0.76\,\mathrm{GeV} \quad \text{[D0 Collaboration]}\,.$$

All 3 results are very precise. But not very compatible.

✓ There are many precise methods on the market
✓ However, it is not clear how well they control theory errors

✓ Recommendation: minimize theory biases.
They cannot be removed even with a perfect measurement!

Frixione, Mitov '14

✓ Our suggestion: use many leptonic observables and combine them
✓ From this distribution, with zero exp error, we can extract m_{top} with error of 0.85 GeV
✓ Reasonable sized error for reliable extraction
✓ In reality it is more complicated (backgrounds!)

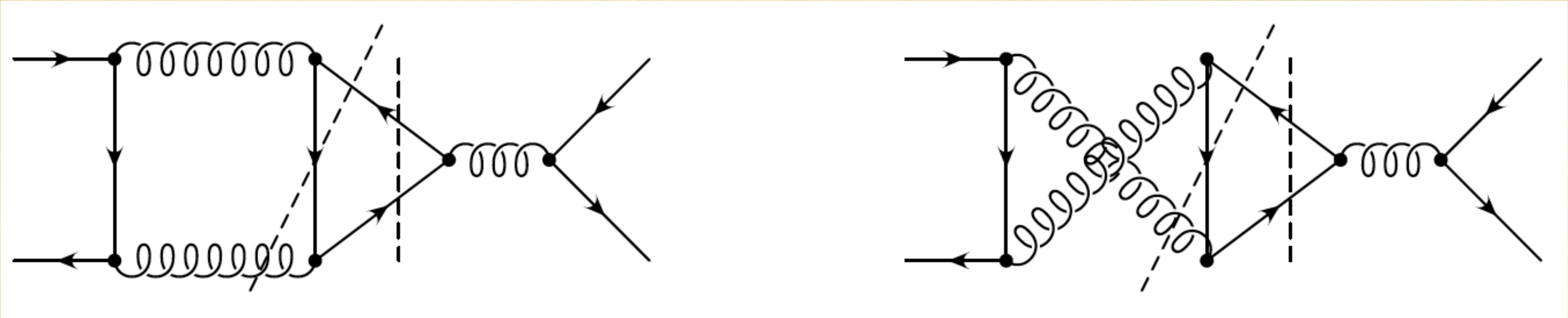
The main message is that theory errors could be systematically underestimated

New and very preliminary!

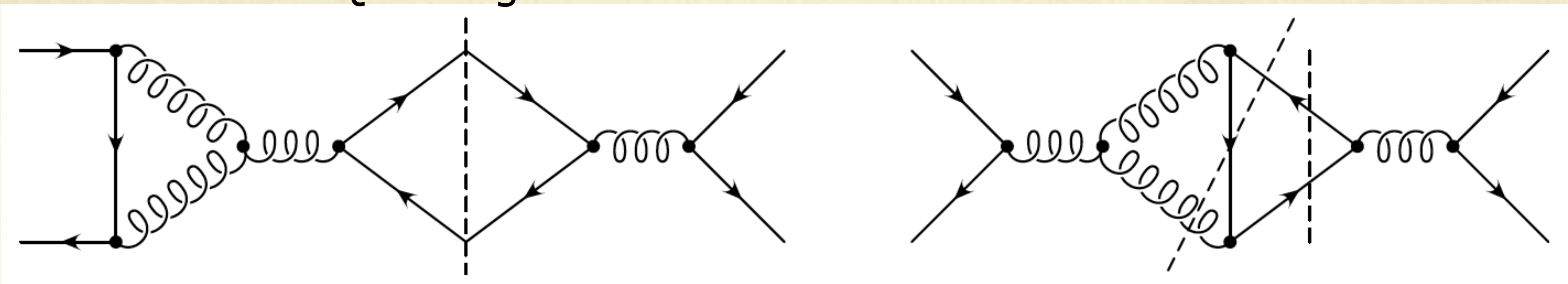
Resolving the A_{FB} puzzle

QCD diagrams that generate asymmetry:

Kuhn, Rodrigo '98



… and some QCD diagrams that do not:

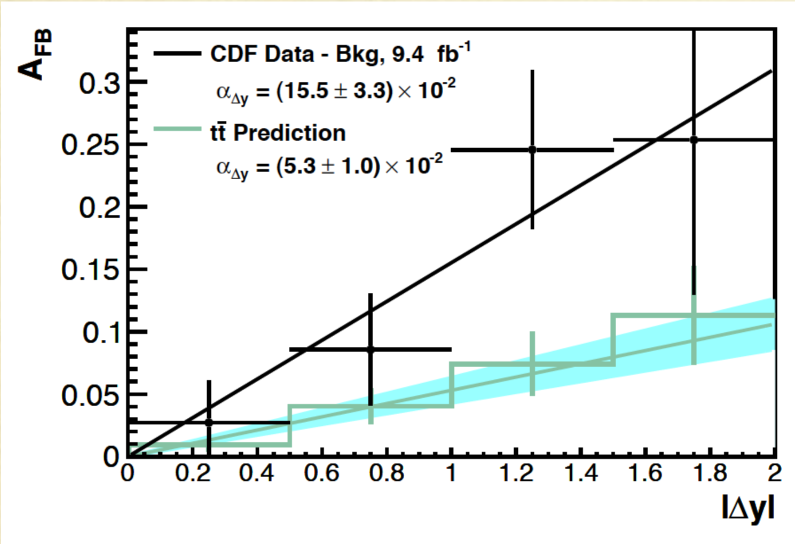


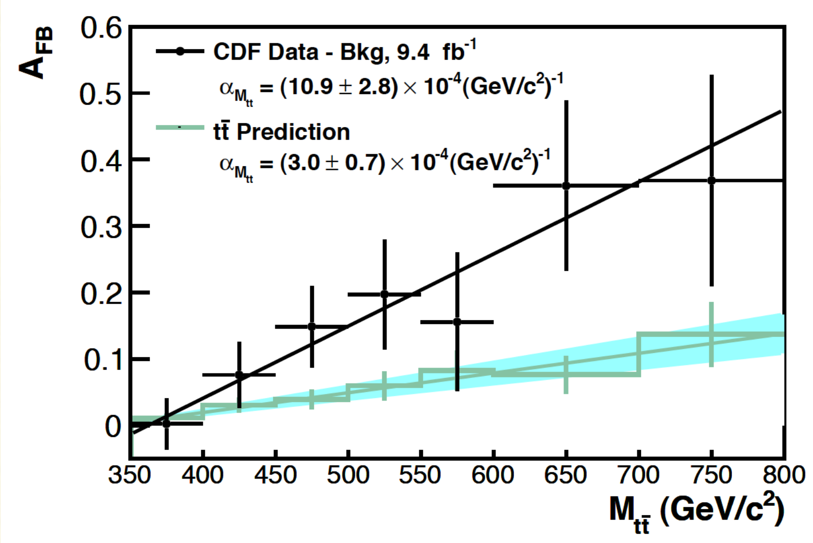
- ✓ For ttbar: charge asymmetry starts from NLO
- ✓ For ttbar + jet: starts already from LO
- ✓ Asymmetry appears when sufficiently large number of fermions (real or virtual) are present.
- ✓ The asymmetry is QED like.
- ✓ It does not need massive fermions.
- ✓ It is the twin effect of the perturbative strange (or c- or b-) asymmetry in the proton!

Definition of the asymmetry:

$$A_{\mathrm{FB}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

… and the CDF measurement versus (known) SM:





Discrepancy ≤ 3σ

✓ New D0 measurement (2014): it is much lower than CDF and in good agreement with SM

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. ~25% effect: not as small as one might naively expect!

Hollik, Pagani '11
Bernreuther, Si '12

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

Brodsky, Wu '12

✓ Higher order hard QCD corrections? Next slide.

✓ Final state non-factorizable interactions? Unlikely.

Mitov, Sterman '12
Rosner '12

NNLO QCD corrections to A_{FB}

Czakon, Fiedler, Mitov, to appear

New and very preliminary!

✓ Computed AFB following the definition and binning of CDF '12

- Inclusive
- $|\Delta y|$
- M_{tt}
- $P_{T,tt}$

$$\mathrm{A_{FB}} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\,, \quad \text{where} \quad \sigma^\pm \equiv \int \theta(\pm\Delta y)\, d\sigma$$

✓ The EW corrections to inclusive A_{FB} included (from Bernreuther, Si '12)

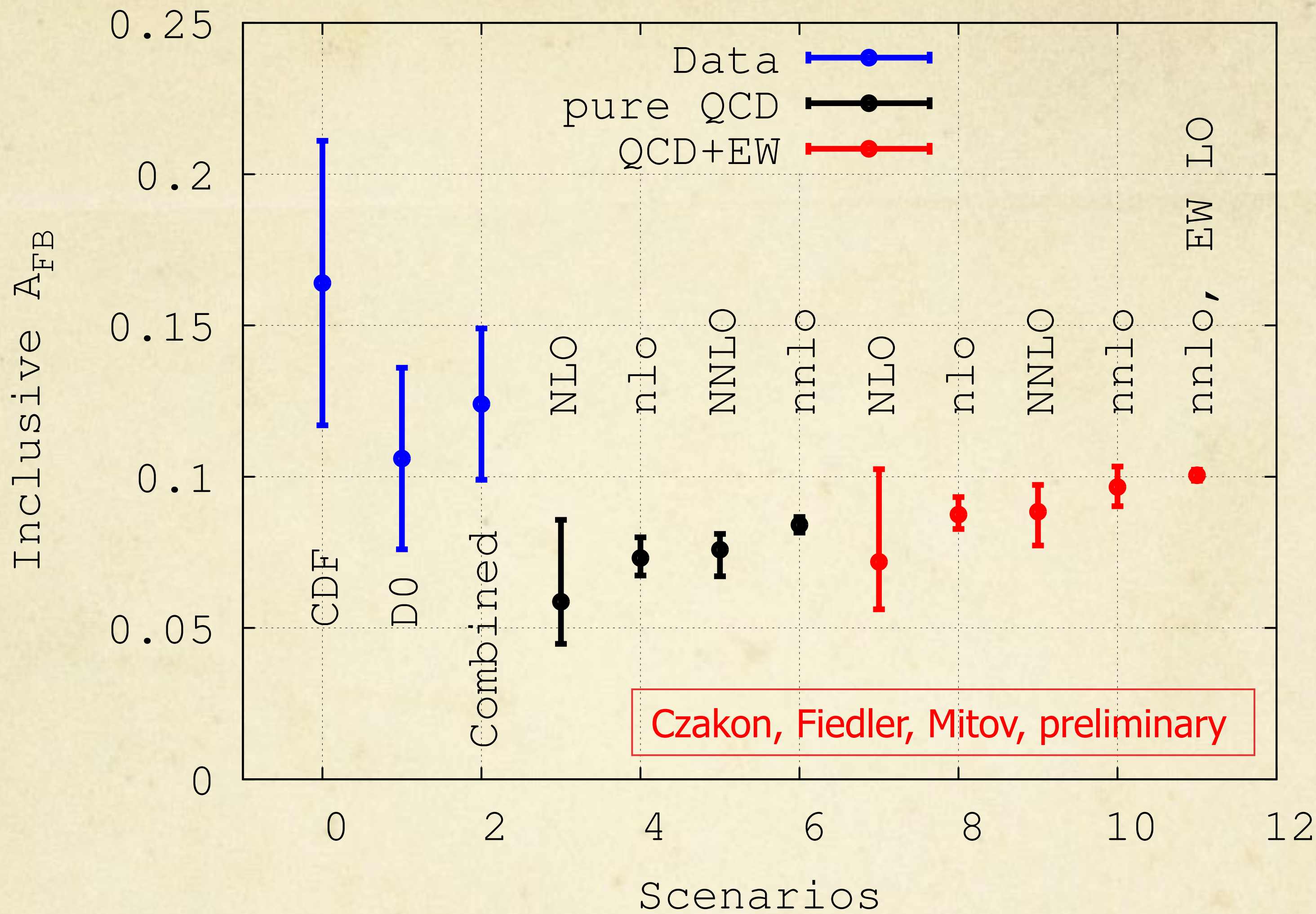
$$\begin{aligned}\mathrm{A_{FB}} &\equiv \frac{N_{ew} + \alpha_S^3 N_3 + \kappa\alpha_S^4 N_4}{\alpha_S^2 D_2 + \alpha_S^3 D_3 + \kappa\alpha_S^4 D_4} \\ &= \alpha_S \frac{N_3}{D_2} + \kappa\alpha_S^2 \left(\frac{N_4}{D_2} - \frac{N_3}{D_2}\frac{D_3}{D_2}\right) + \mathcal{O}(\alpha_S^3) \\ &+ \frac{N_{ew}}{\alpha_S^2 D_2}\left(1 - \kappa\frac{\alpha_S D_3}{D_2}\right).\end{aligned}$$

Two alternative expansions

✓ All checks passed:

- Pole cancellation (each bin, each scale)
- Total x-section for generic μ_F and μ_R

Preliminary results



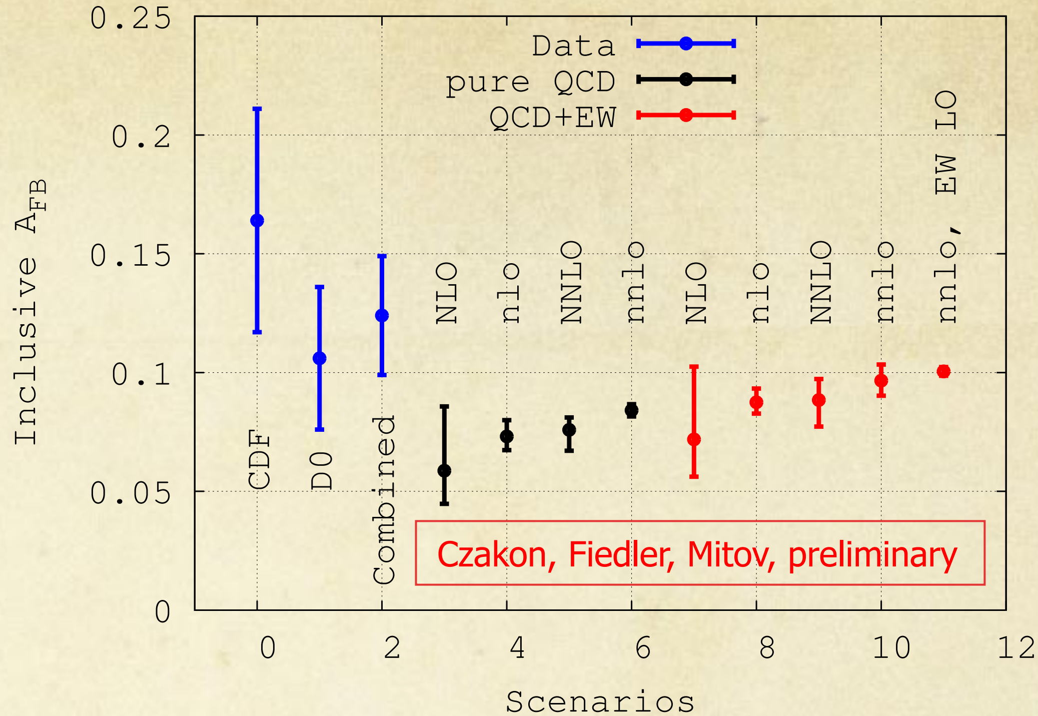
Errors due to scale variation only

How to read the above plot:

- *NLO, NNLO* : exact numerator and denominator (see previous slide)
- *nlo, nnlo* : expanded in powers of a_s

Preliminary results

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



✓ We find large QCD corrections: NLO ~ 30% of LO (recall EW is 25% of LO).

➔ 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 consider this as *agreement* between SM and experiment.

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

✓ Expanded results (both *nlo* and *nnlo*) seem to have accidentally small scale variation

Summary and Conclusions

- Top physics is in precision phase
- Total x-section for tT production now known in full NNLO
- Fully differential top production to appear soon. This will become standard for LHC run 2.
- 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.

New results

- Presented preliminary new results for NLO QCD corrections to A_{FB}
- Large corrections found. (NLO ~ 30% LO)
- QCD + EW corrections bring A_{FB} ~ 10%, in agreement with D0 and near-agreement with CDF
- Full differential results for Tevatron/LHC expected soon (accumulating events…).