Top quark production at the LHC: differetial cross section and phenomenology with DiffTop

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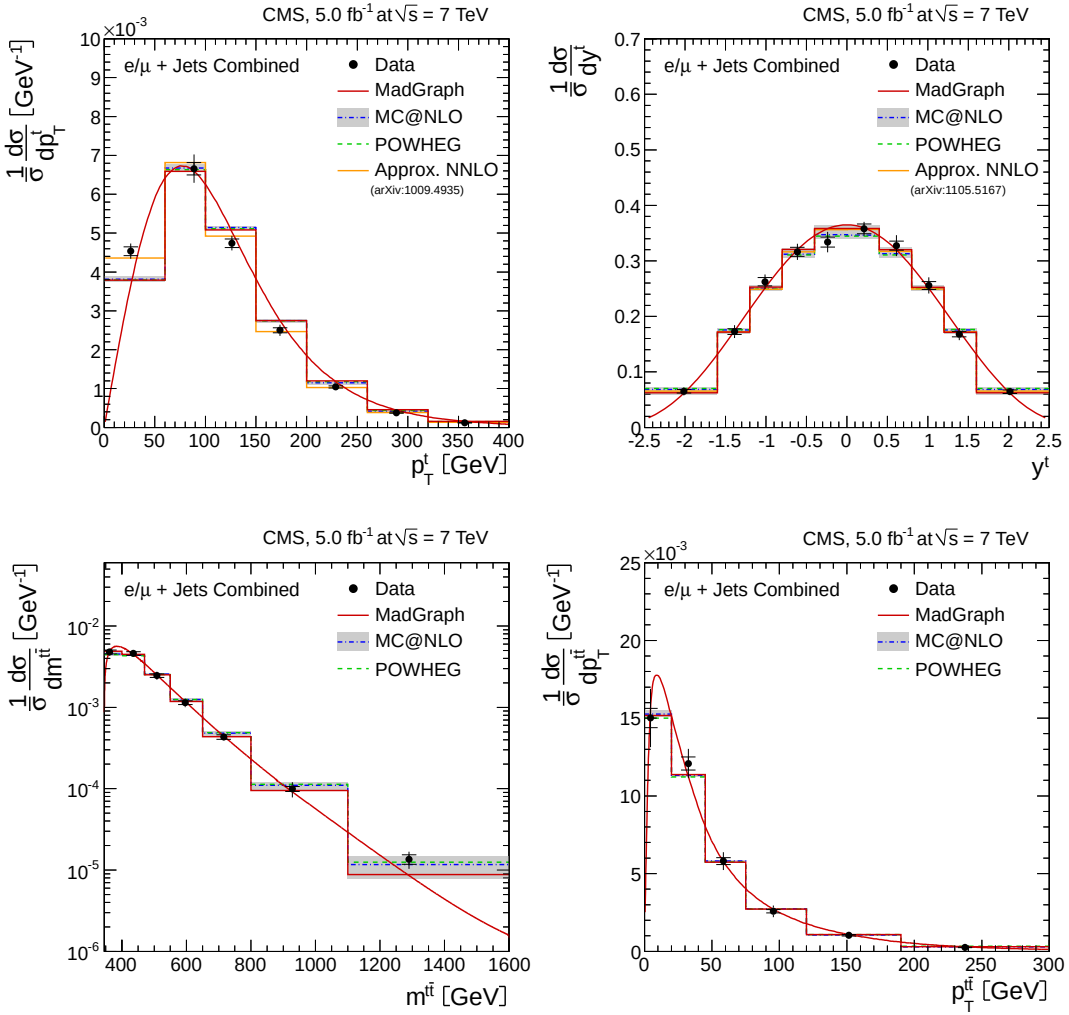
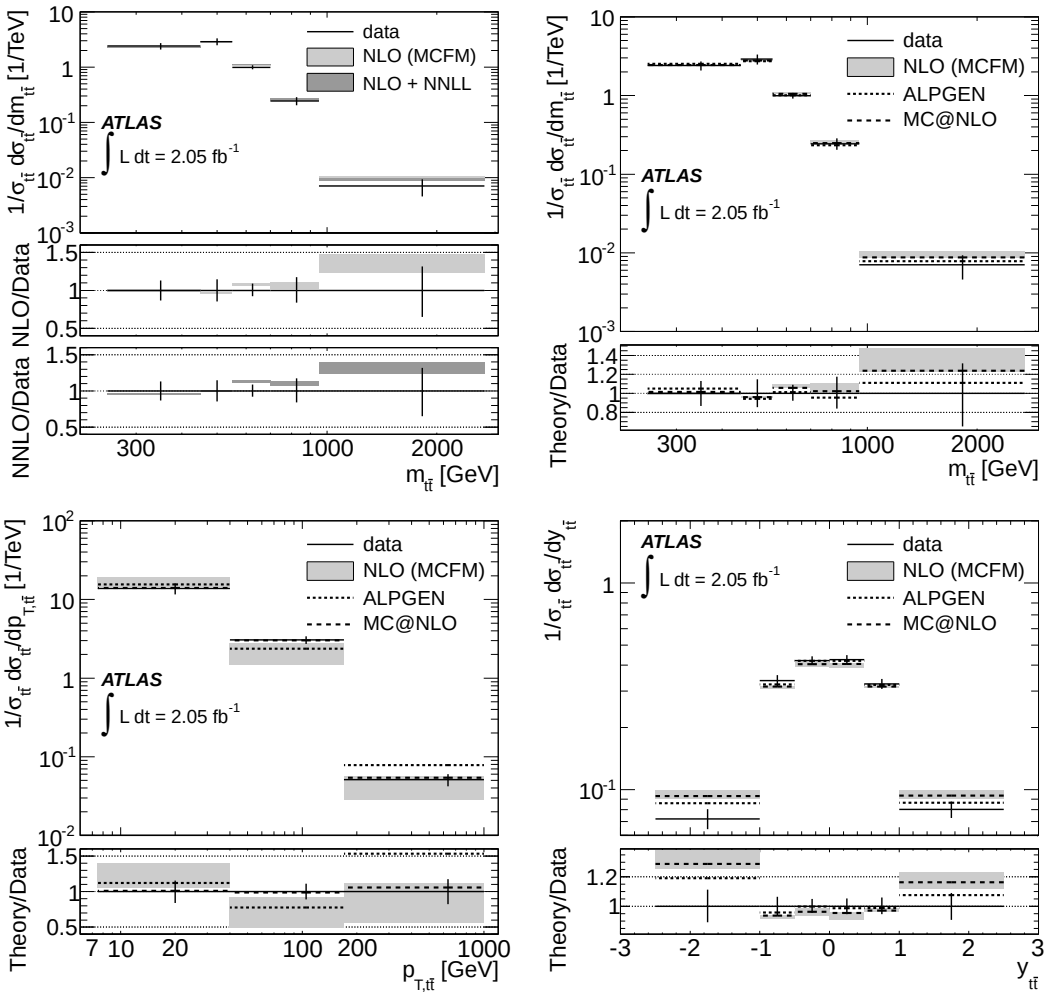
Motivations

- Top quark production at the LHC: crucial in the near future phenomenology!
- $t\bar{t}$ pairs are copiously produced in PP reactions at the LHC, $\Longrightarrow$ inflow of precise measurements of top-quark production cross section with unprecedented accuracy
- Precise measurements of differential cross section for $t\bar{t}$ pair production as a function of different observables are available from ATLAS and CMS.



The CMS Collaboration Eur.Phys.J. C73 (2013) 2339, $\int Ldt = 5.0[\text{fb}]^{-1}$, $\sqrt{S} = 7$ TeV



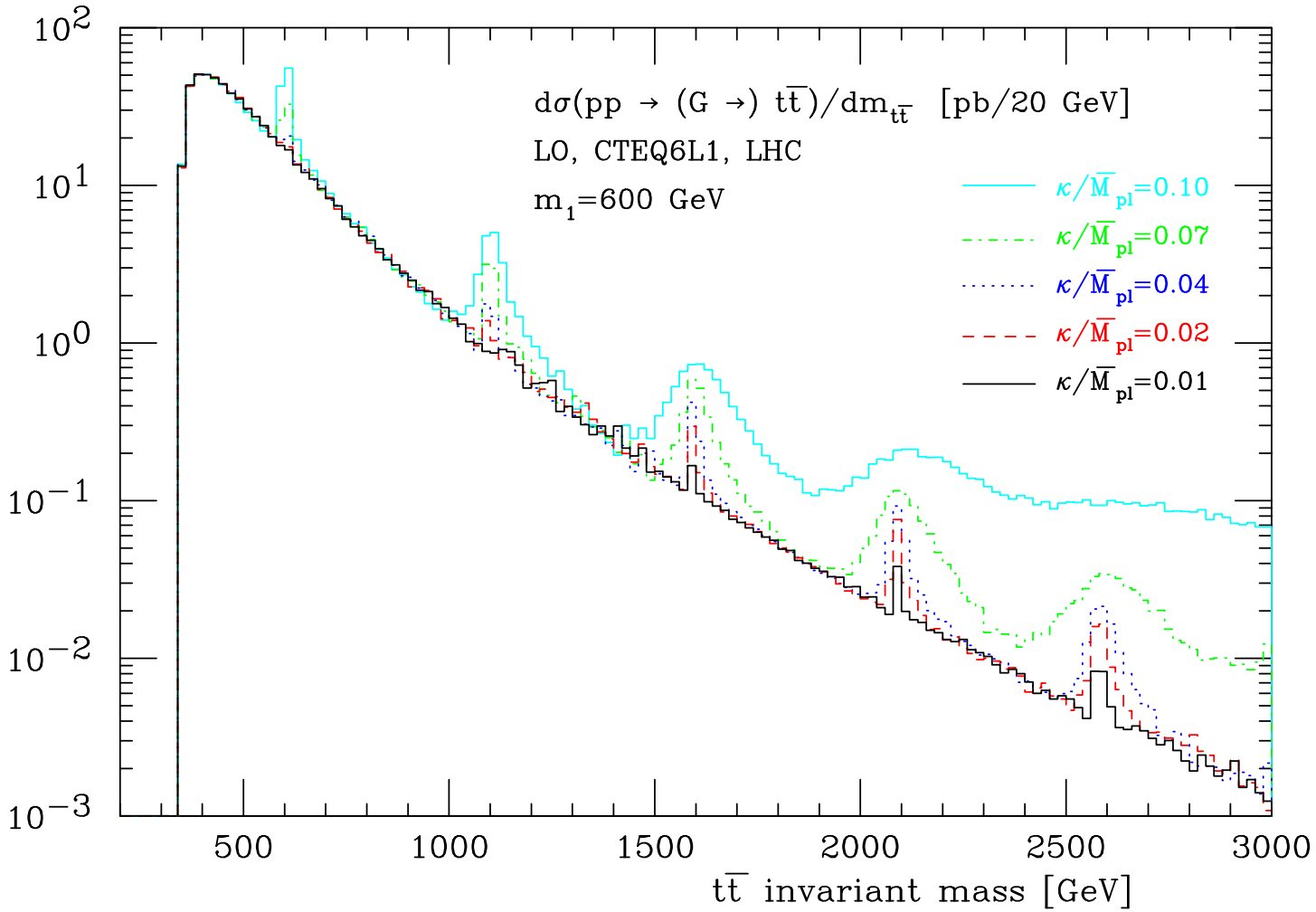
The ATLAS Collaboration Eur.Phys.J.C73 (2013) 2261,
$\int Ldt = 2.05[\text{fb}]^{-1}$, $\sqrt{S} = 7$ TeV

New measurements at $\sqrt{S} = 8$ TeV from CMS and ATLAS will make things more exciting!

A lot work to do on the phenomenological side

- crucial to test Standard Model (SM) properties: $m_t \approx m_H \rightarrow$ glimpse of the Higgs sector!
- ongoing efforts for precise determination of m_t
- investigation of the correlation $\alpha_s(M_Z)$, m_t, and *PDFs*
- QCD factorization
- A new realm of precision calculations
- scrutiny of related Physics Beyond the Standard Model (PBSM)

Physics Beyond the SM: is there any?



from F. Maltoni and R. Frederix, JHEP 0901 (2009) 047

We need precise theoretical predictions beyond NLO QCD!

..Reduction of theoretical systematic uncertainties associated to variation of scales in the calculation (although this is not the end of the story...)

A lot of work has been done in the past years on soft-gluon resummation

Remarkable progress recently on fixed order NNLO calculations

Recent progress

The NNLO exact calculation for the $t\bar{t}$ total cross section is now complete up to $O(\alpha_s^4)$

- Czakon, Fiedler, Mitov (2013); Czakon, Mitov (2012), (2013); Baernreuther, Czakon, Mitov (2012)

Exact NLO tools available

- MCFM Campbell, Ellis, Williams; MadGraph5 Alwall, Maltoni, et al.; MC@NLO Frixione, Stoeckli, Torrielli, Webber, White; POWHEG Alioli, Hamilton, Nason, Oleari, Re.

Calculations including threshold resummation

- Czakon, Mitov, Sterman, (2009); Kidonakis (2010); Moch, Uwer, Vogt (2012); Cacciari, Czakon, Mangano, Mitov, Nason (2012)

Progress in Soft Collinear Effective Theory (SCET)

- Ahrens, Ferroglia, Neubert, Pecjak, Yang, (2011)

Tools for phenomenology are needed:

Open source NLO/NNLO codes (in particular for differential cross section computations) are important for the experimental groups and PDF fitters:

usable packages for data analyses and phenomenological applications are needed!

Approx. NNLO calculation including NNLL threshold resummation (**DiffTop**: a Mellin-space resummation computer code)

Calculation based-on/cross-checked against the results of N.Kidonakis, S.-O.Moch, E.Laenen and R.Vogt PRD (2001).

Contributions from soft anomalous dimensions at $\mathcal{O}(\alpha_s^2)$ (heavy-quark) included. Kidonakis (2010).

Some known facts about resummation and kinematics...

Remnants of long-distance dynamics in a hard scattering function can be large in regions of phase space near partonic threshold and dominate higher order corrections: $\rightarrow$ logarithmic corrections.

Threshold resummation organizes double-logarithmic corrections to all orders, thereby extending the predictive power of QCD to these phase space regions. G. Sterman (1987); S. Catani and L. Trentadue (1989); H. Contopanagos, E. Laenen, and G. Sterman (1997); Kidonakis and Sterman (1997).

The kinematics of inclusive heavy-quark hadroproduction depend on which final state momenta are reconstructed.
In threshold resummation, a kinematic choice manifests itself at next-to-leading-logarithmic level.

Resummation in single-particle inclusive (1PI) and pair-invariant mass kinematics (PIM)

Near the threshold, heavy-quark hadroproduction in 1PI kinematics is dominated by the partonic subprocesses

$$i(k_1) + j(k_2) \to Q(p_1) + X[\bar{Q}](p_2') \qquad p_2' = \bar{p}_2 + k \tag{1}$$

where is k any additional radiation, and
$s_4 = p_2' - m^2 = s + t_1 + u_1$ measures the inelasticity of the parton reaction. $k \to 0$ when approaching the threshold.
In the pair-inclusive kinematics (PIM)

$$i(k_1) + j(k_2) \to Q\bar{Q}(p') + X'(k) \tag{2}$$

$X'(k) = 0$ the reaction is at the threshold $p'^2 = M^2$.

Approx. NNLO+NNLL differential cross section at parton level in 1PI, here $s_4 = \hat{s} + \hat{t}_1 + \hat{u}_1$

$$s^2 \frac{\hat{\sigma}_{ij}^{(2)}}{du_1 dt_1}|_{1PI} = F_{ij}^{Born} \frac{\alpha_s^2(\mu_R^2)}{\pi^2} \left\{ D_{ij}^{(3)} \left[\frac{ln^3(s_4/m_t^2)}{s_4} \right]_+ \right.$$

$$\left. + D_{ij}^{(2)} \left[\frac{ln^2(s_4/m_t^2)}{s_4} \right]_+ + D_{ij}^{(1)} \left[\frac{ln(s_4/m_t^2)}{s_4} \right]_+ + D_{ij}^{(0)} \left[\frac{1}{s_4} \right]_+ + R_{ij}\delta(s_4) \right\}.$$

$$\alpha_s^n \left[\frac{\ln^m(s_4/m_t^2)}{s_4} \right]_+ \qquad m = 0, \cdots, 2n-1, \tag{3}$$

Recent progress in Soft Collinear Effective Theory, where one apdopts a different approach to compute the soft function and resums slightly different logs

$$\alpha_s^n \left[\frac{1}{s_4} \ln^m \left(\frac{s_4}{\sqrt{s_4 + m_t^2}} \right) \right]_+ . \tag{4}$$

These kind of corrections can be numerically important. Detailed analysis by Ahrens, Ferroglia, Neubert, Pecjak, Yang, (2011), (2012). Differences between the two formalisms in Kidonakis and Pecjak (2012); Sterman et al (2013,2014).

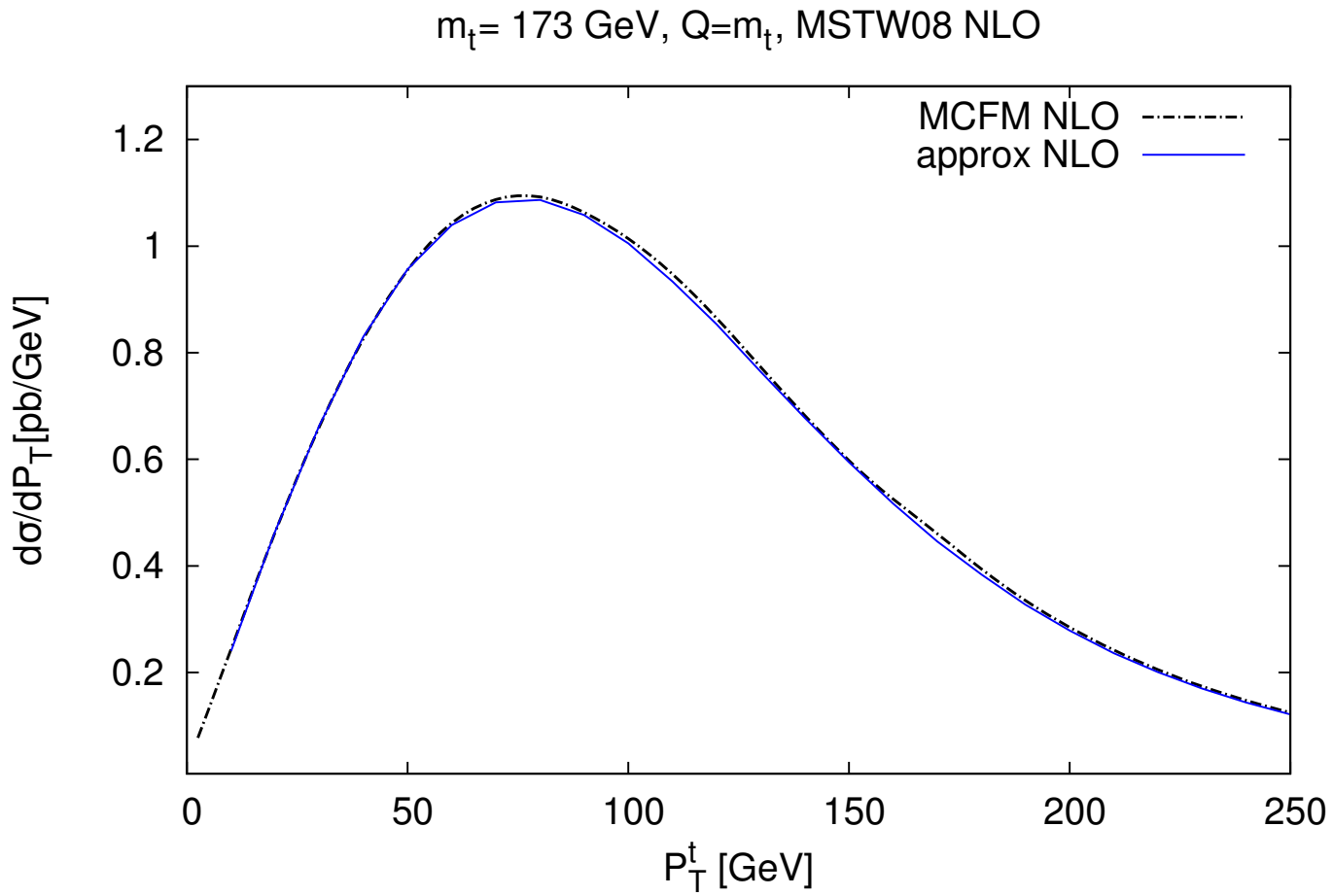
What is it good for?

- precise measurements of $t\bar{t}$ differential cross section available
- theory @ NLO and approx NNLO sizeable K-factors (perturbative level)
- correlations between $\alpha_s(M_Z)$, m_t and the gluon(x) $\Rightarrow$ simultaneous determination $\Rightarrow$ global fit predictions!
  attempt in this direction done by using state-of-the-art $\sigma_{t\bar{t}}^{NNLO+NNLL}$ and Bayesian PDF reweighting. Czakon, Mangano, Mitov, Rojo (2013)
- Tools development (work in collaboration with K. Lipka, CMS DESY Hamburg, and S.-O. Moch Univ. Hamburg):
  - flexible OPEN SOURCE code for theoretical/experimental analyses
  - possibility of manipulating inputs: $(PP, P\bar{P})$, m_t, μ_F, μ_R, α_s evol., lhapdf interface, perturbative order, logarithmic approximation etc..

Results, recent developments, updates...

DiffTop quality check:

NLO Exact Calculation vs approx NLO



Beenakker, Kujif, Smith, Van Neerven, 1989, Dawson, Ellis, Nason, 1988-89

Recent developments

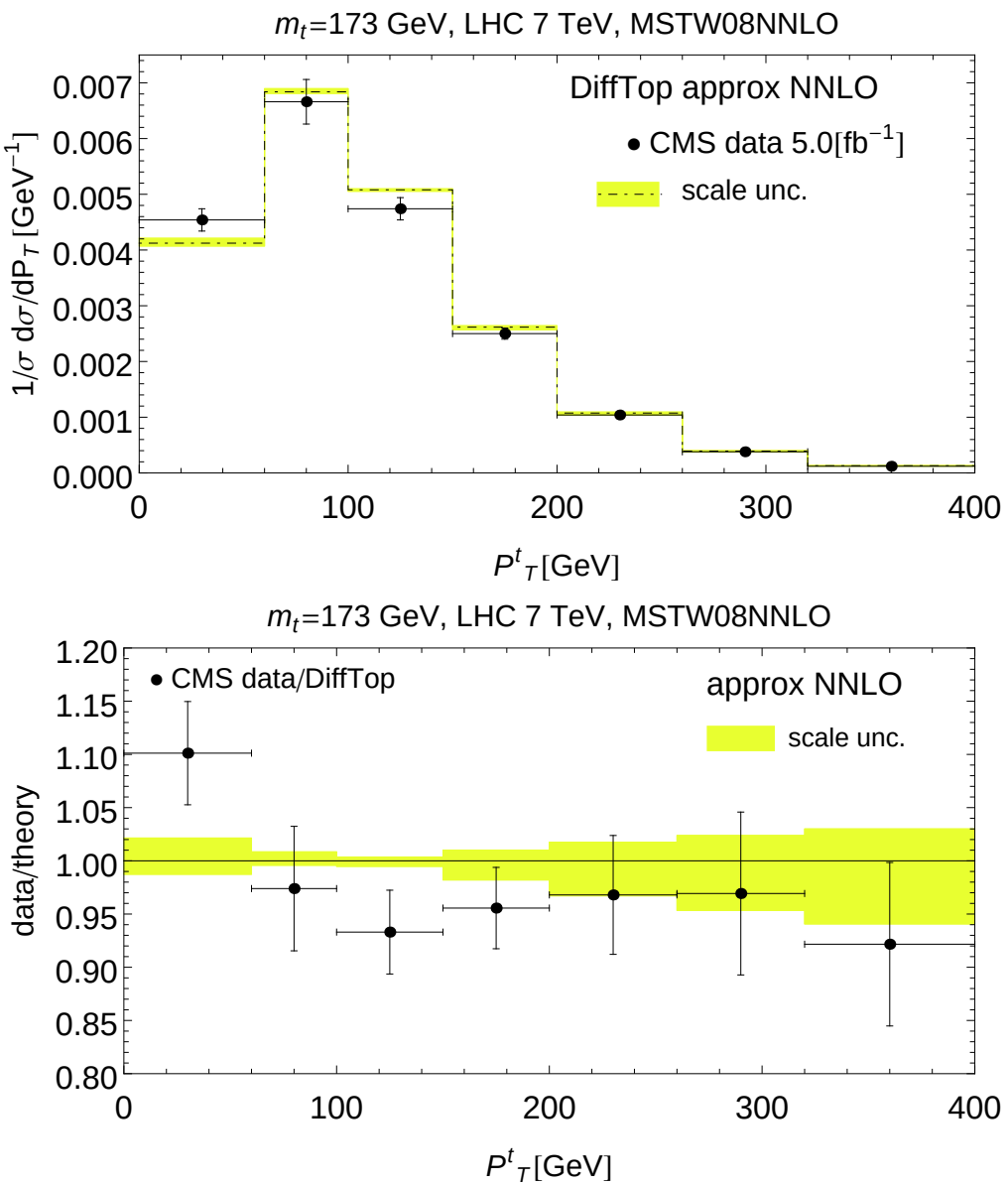
- the code is finalized
- few tests on speed CPU time and accuracy
- At the moment: writing the paper...

Total cross section comparison (MSTW08 NNLO PDFs) for $m_t = 173.3$ GeV. Errors are scale uncertainties.

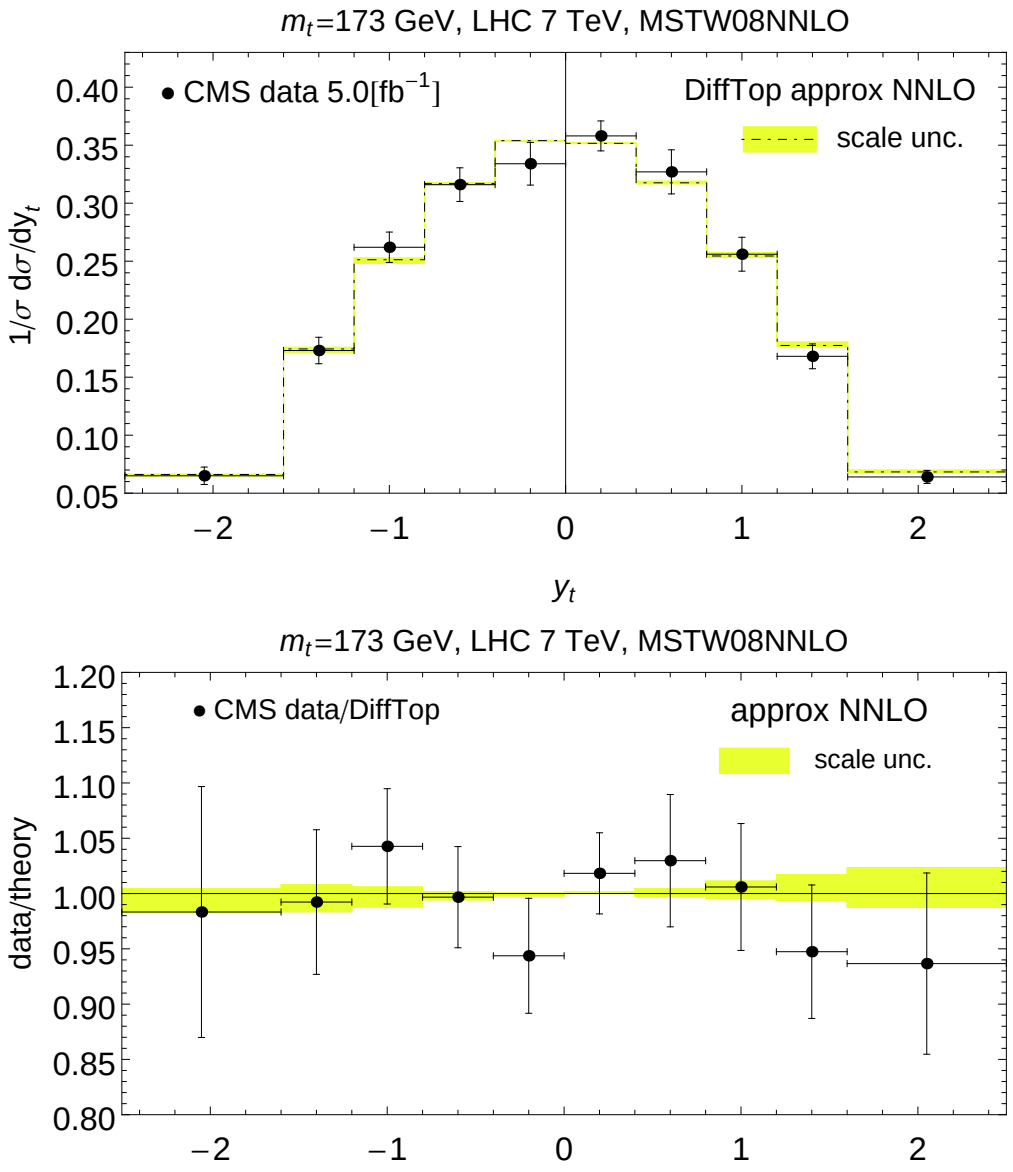
$\sigma_{DiffTop} = 177[pb]^{+5}_{-11}$ (approx NNLO)

$\sigma_{Top++} = 172[pb]^{+4}_{-11}$ (Full NNLO)

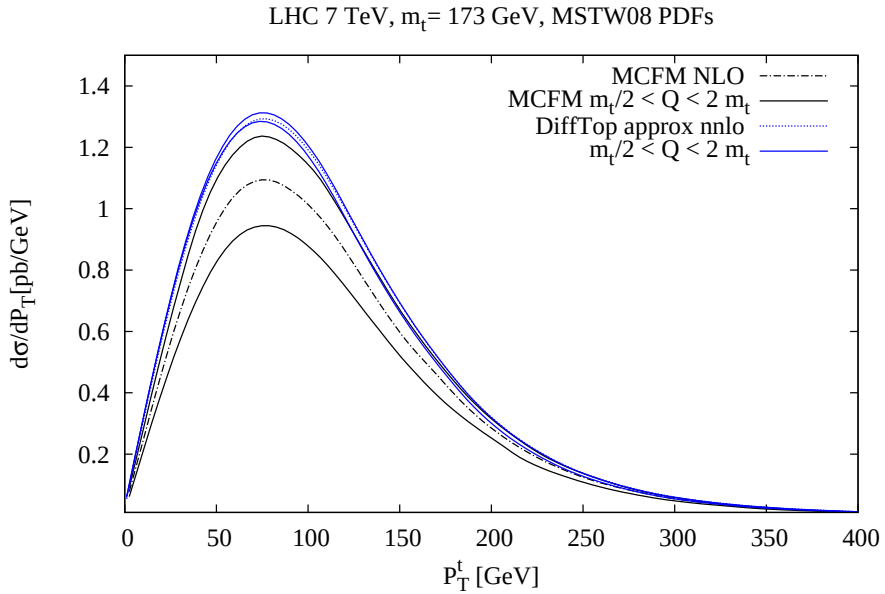
Recent results: the P_T distribution.

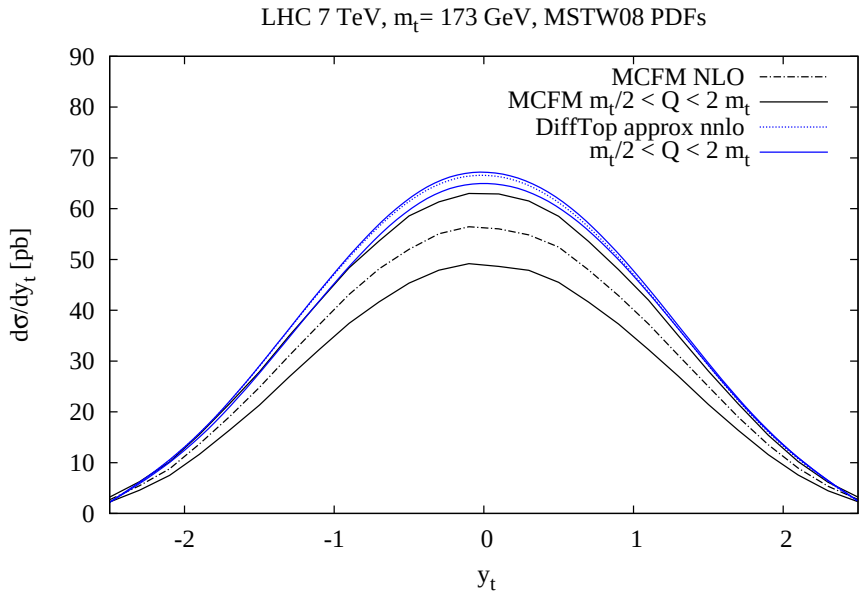


Recent results: the rapidity distribution.



Scale dependence in the unnormalized differential cross sections

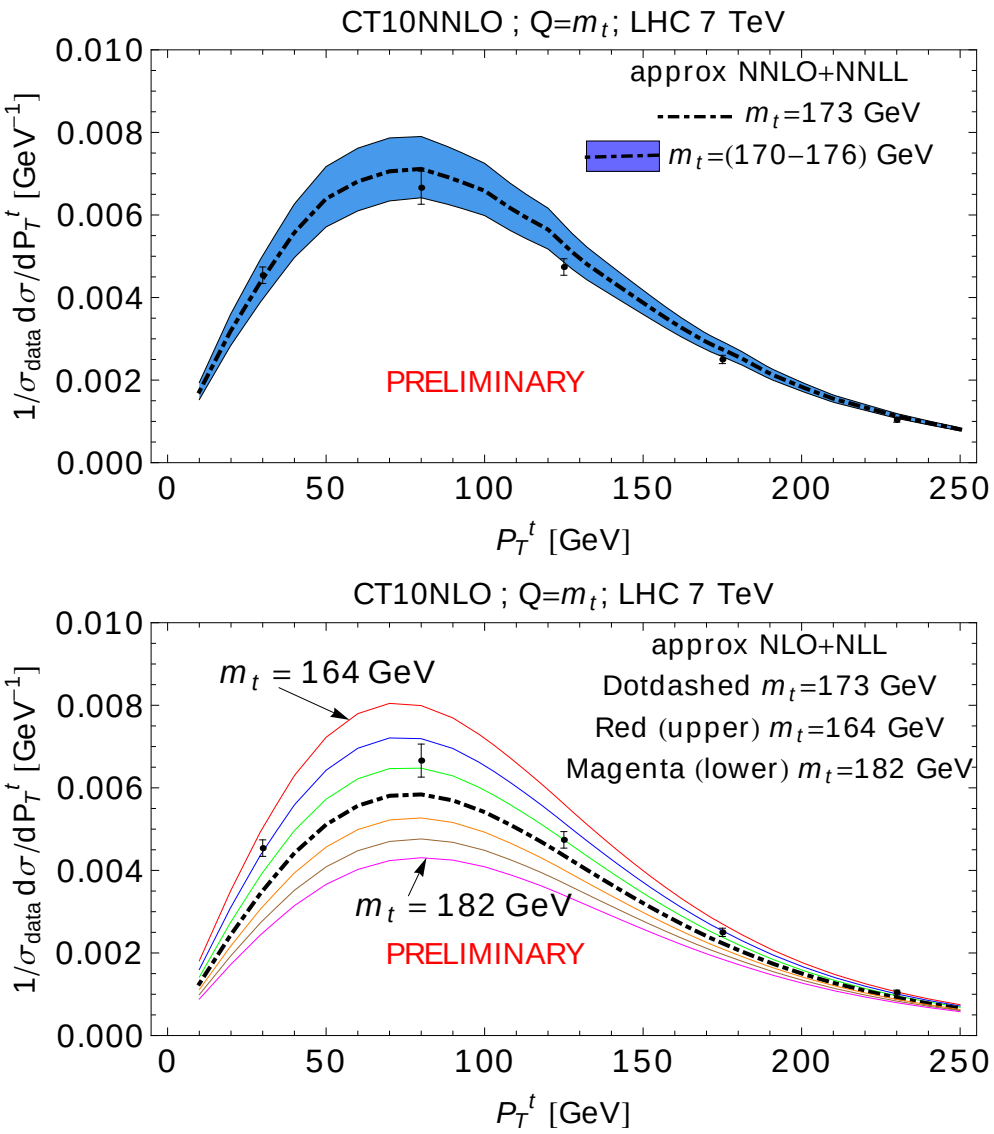




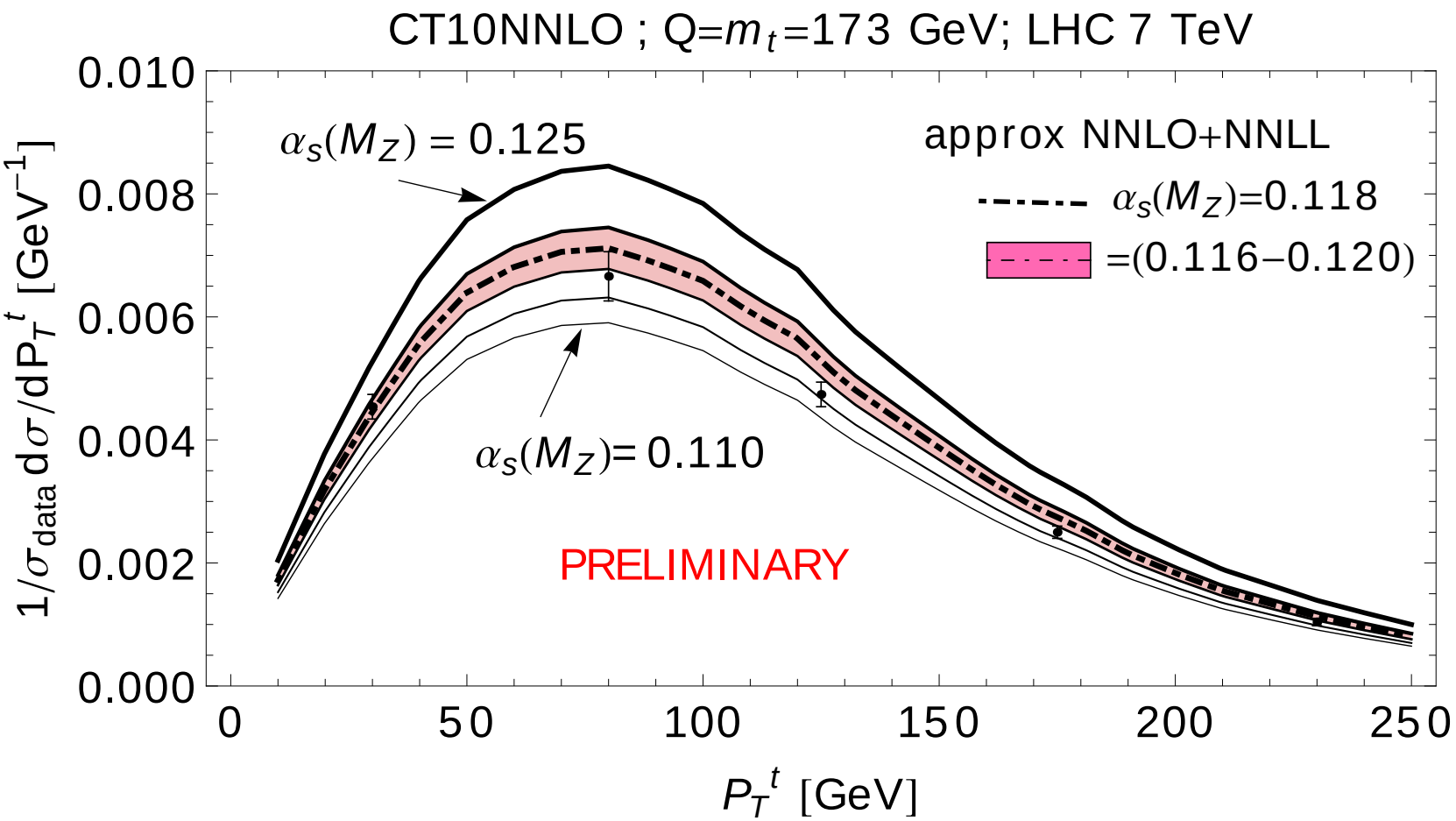
Top-pair production at LHC probes high-x gluon: but there is a strong correlation between $g(x)$, α_s and the top-quark mass m_t

- Precise measurements of the total and differential cross section of $t\bar{t}$ pair production provide us with a double handle on these quantities
- Precise measurements of the absolute differential cross section constrain the gluon PDF
- The shape of the differential cross section is modified by m_t and α_s (very sensitive)
- extraction of m_t will benefit from the interplay between these two measurements. (recent CMS paper 1307.1907)

Dependence on m_t



$\alpha_s(M_Z)$ dependence within CT10NNLO PDFs



Interface to *fast*NLO(In collaboration with D. Britzger)

The current version of the code has been modified for interfacing it to fastNLO. It required full rearrangement of all scale dependent contributions. This is important for future applications in PDF fits, because the code is CPU time consuming.

$$c_{i,n}(\mu_R, \mu_F) = c^0_{i,n} + \log(\mu_R) c^R_{i,n} + \log(\mu_F) c^F_{i,n} + ...$$

beyond the NLO one has double log contributions

$$.. + \log^2(\mu_F) c^{(2,F)}_{i,n} + \log^2(\mu_R) c^{(2,R)}_{i,n} + \log(\mu_F)\log(\mu_R) c^{(2,R\ F)}_{i,n}$$

Recent: DiffTop has been successfully interfaced to FastNLO!
DiffTop will be included into HERAFitter

Conclusions - Plans

- ongoing progress on development of tools for top-quark phenomenology
- $M_{t\bar{t}}, cos\theta$ distribution in DiffTop: forthcoming
- Implementation of $m_t(m_t)$ running mass
- Implementation into HERAFitter
- Possibility of investigating the charge asymmetries.
- Comparisons data-theory for differential observables are in progress.
- Precise top-quark pair production measurements will play a key role in global analyses of PDFs.
- valuable tool for physics BSM analyses.

BACKUP