Phenomenology of top-quark pair production at the LHC: studies with DiffTop

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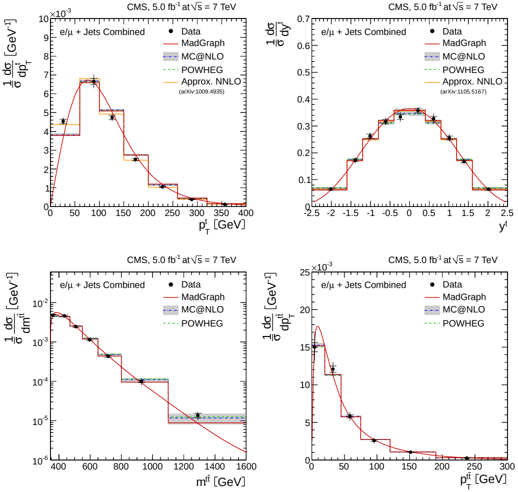
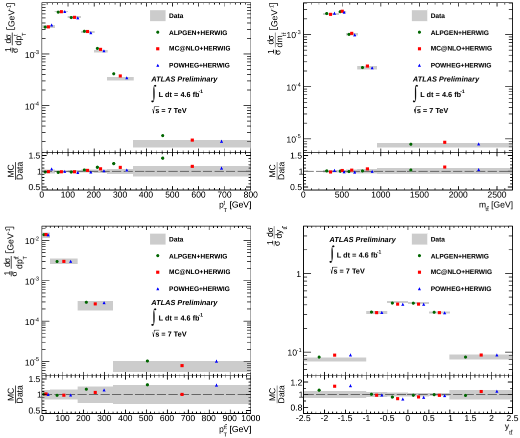
Outline and motivations

- Top-quark pair production at the LHC is crucial for many phenomenological applications/investigations:
  -Physics beyond the SM ($\Rightarrow$ distortions/bumps in distributions like $M_{t\bar{t}}$),
  -extent of QCD factorization,
  -PDFs determination in QCD analyses,
  -Correlation between α_s, top-quark mass m_t, and the gluon.

- New data available: the CMS and ATLAS collaborations published measurements of differential cross sections for $t\bar{t}$ pair production as a function of different observables of interest, with unprecedented accuracy:



The CMS Collaboration EPJC 2013, $\int Ldt = 5.0[\mathrm{fb}]^{-1}$, $\sqrt{S} = 7$ TeV,
TOP-12-028 $\rightarrow \int Ldt \approx 12[\mathrm{fb}]^{-1}$, $\sqrt{S} = 8$ TeV (more in Ivan Asin's talk)



The ATLAS Collaboration ATLAS-CONF-2013-099, lepton+jets, $\int Ldt = 4.6[\text{fb}]^{-1}$, $\sqrt{S} = 7$ TeV

We want to exploit the full potential of these new (and forthcoming) data

- We need tools incorporating the current state-of-the-art of QCD calculations.

- Some of them are already on the market, for some others work is still in progress (these calculations are very challenging)

  In the meanwhile...

- Here we present a tool **DiffTop** for calculating $t\bar{t}$ differential cross sections in 1PI kinematic at approximate NNLO $\mathcal{O}(\alpha_s^4)$.

Recent progress

NLO exact computations available since many years:

- Nason, Dawson, Ellis (1988); Beenakker, Kuijif, Van Neerven, Smith (1989); Meng, Schuler, Smith, Van Neerven (1990); Beenakker, Van Neerven, Schuler, Smith (1991); Mangano, Nason, Rodolfi (1992).

The NNLO $O(\alpha_s^4)$ full QCD calculation for the $t\bar{t}$ total cross section has been accomplished recently

- Czakon, Fiedler, Mitov (2013); Czakon, Mitov (2012), (2013); Baernreuther, Czakon, Mitov (2012)
- Top++ Czakon, Mitov (2011); Hathor Aliev, Lacker, Langenfeld, Moch, Uwer, Wiedermann (2011)

Exact NLO tools available

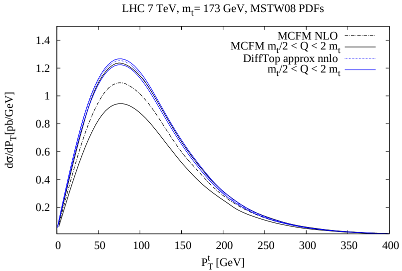
- MCFM Campbell, Ellis, Williams; MadGraph5 Alwall, Maltoni, et al.; MC@NLO Frixione, Stoeckli, Torrielli, Webber, White; POWHEG Alioli, Hamilton, Nason, Oleari, Re.

While exact NLO calculations for $t\bar{t}$ total and differential cross sections have been implemented into publicly available Monte Carlo numerical codes,

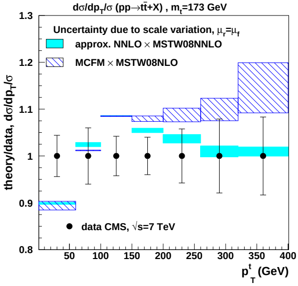
full NNLO calculations for the $t\bar{t}$ production cross section at differential level are not yet available.

NLO predictions are not accurate enough to describe the data:

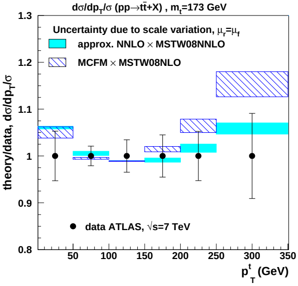
- perturbative corrections are large,
- systematic uncertainties associated to various scales entering the calculation are important.



LHC 7 TeV, m_t= 173 GeV, MSTW08 PDFs
MCFM NLO
MCFM $m_t/2 < Q < 2\ m_t$
DiffTop approx nnlo
$m_t/2 < Q < 2\ m_t$
$d\sigma/dP_T$[pb/GeV]
P_T^t [GeV]



$d\sigma/dp_T/\sigma$ ($pp \to t\bar{t}+X$) , m_t=173 GeV
Uncertainty due to scale variation, $\mu_r=\mu_f$
approx. NNLO × MSTW08NNLO
MCFM × MSTW08NLO
data CMS, √s=7 TeV
theory/data, $d\sigma/dp_T/\sigma$
p_T^t (GeV)



$d\sigma/dp_T/\sigma$ ($pp \to t\bar{t}+X$) , m_t=173 GeV
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data ATLAS, √s=7 TeV
theory/data, $d\sigma/dp_T/\sigma$
p_T^t (GeV)

QCD threshold resummation: instruments to re-factorize the cross section in certain kinematic limits ⇒ approx. predictions

Sterman (1986)

Approx. NNLO including threshold resummation

- Kidonakis, Sterman (1997); Laenen, Oderda, Sterman (1998)
- Kidonakis (2001); Kidonakis, Laenen, Moch, Vogt (2001)
- Czakon, Mitov, Sterman, (2009); Kidonakis (2010); Moch, Uwer, Vogt (2012); Cacciari, Czakon, Mangano, Mitov, Nason (2012)
- Beneke, Falgari, Klein, Piclum, Schwinn, Ubiali, Yan, (2012) (TOPIXS total inclusive Xsec.)

Progress in Soft Collinear Effective Theory (SCET)

- Ahrens, Ferroglia, Neubert, Pecjak, Yang (2010), (2011), (2012)

Development of tools for phenomenology: DiffTop

Public NLO/NNLO codes (in particular for differential cross section computations) are important for the experimental groups and for QCD analyses to determine PDFs

PROSA: Proton Structure Analyses in Hadronic Collisions
https://prosa.desy.de
activity 2013 - 2014 on DESY side

DiffTop: a Mellin-space resummation computer code for computing total and differential cross section for heavy-flavor production at hadron colliders at approx. NNLO within threshold resummation

Implementation based on the calculation by Kidonakis, Moch, Laenen, Vogt (2001).

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

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

where is k any additional radiation, and $s_4 = p_2' - m^2 \to 0$ momentum at the threshold.

In the pair-invariant mass kinematics (PIM)

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

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

What's in the box ?

The factorized differential cross section is written as

$$S^2 \frac{d^2\sigma(S, T_1, U_1)}{dT_1\ dU_1} = \sum_{i,j=q,\bar{q},g} \int_{x_1^-}^{1} \frac{dx_1}{x_1} \int_{x_2^-}^{1} \frac{dx_2}{x_2} f_{i/H_1}(x_1, \mu_F^2) f_{j/H_2}(x_2, \mu_F^2)$$
$$\times \omega_{ij}(s, t_1, u_1, m_t^2, \mu_F^2, \alpha_s(\mu_R^2)) + \mathcal{O}(\Lambda^2/m_t^2)\,,$$

$$\omega_{ij}(s_4, s, t_1, u_1) = \omega_{ij}^{(0)} + \tfrac{\alpha_s}{\pi}\omega_{ij}^{(1)} + \left(\tfrac{\alpha_s}{\pi}\right)^2 \omega_{ij}^{(2)} + \cdots$$

where $\omega_{ij}^{(2)}$ at parton level in 1PI is

$$\omega_{ij}^{(2)} = s^2 \frac{\hat{\sigma}_{ij}^{(2)}}{du_1 dt_1}\Bigg|_{1PI} = F_{ij}^{Born} \frac{\alpha_s^2(\mu_R^2)}{\pi^2} \left\{ D_{ij}^{(3)} \left[\frac{ln^3(s_4/m_t^2)}{s_4}\right]_+ \right.$$
$$\left. + D_{ij}^{(2)} \left[\frac{ln^2(s_4/m_t^2)}{s_4}\right]_+ + D_{ij}^{(1)} \left[\frac{ln(s_4/m_t^2)}{s_4}\right]_+ + D_{ij}^{(0)} \left[\frac{1}{s_4}\right]_+ + R_{ij}^{(2)}\delta(s_4) \right\}.$$

The contribution of the 2-loop soft-anomalous dimension (Kidonakis (2010)) is also included which formally is beyond the NNLL accuracy.

What is it good for?

Top-quark pair production at LHC probes high-x gluon and the differential cross section is strongly correlated at $x \approx 0.1$:

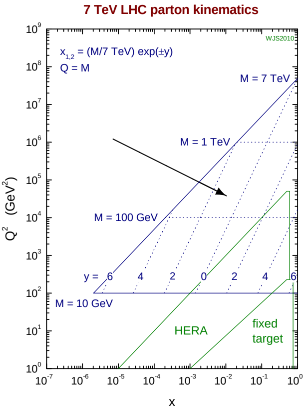
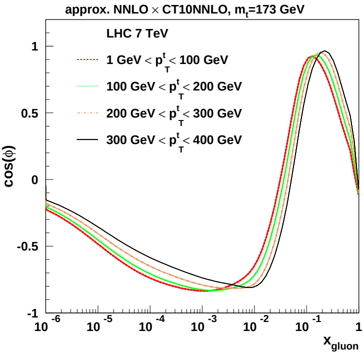


Figure by J. Stirling



Here we choose MSTW08 and CT10 as representative. ABM11, HERA1.5 and NNPDF2.3 show a similar behavior.

What is it good for?

Top-quark pair production at LHC probes high-x gluon ($x \approx 0.1$): but there is a strong correlation between $g(x)$, α_s and the top-quark mass m_t that we want to pin down

- 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 PLB (2014))

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

DiffTop has been succesfully interfaced to fastNLO.

This is important for applications in PDF fits, because NNLO computations are generally CPU time consuming.

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

beyond the NLO one has double log contributions

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

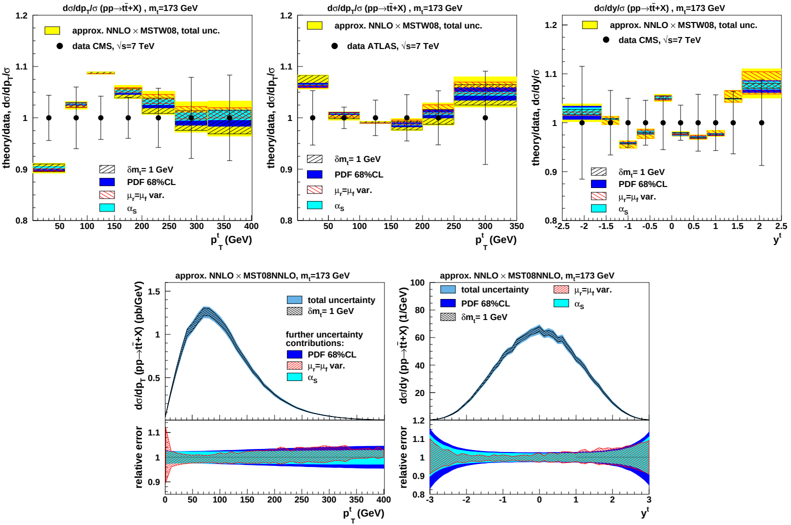
♠**DiffTop is now included into HERAFitter for PDF analyses**

Work is in progress on numerics and fastNLO grids generation to make all publicly available soon.

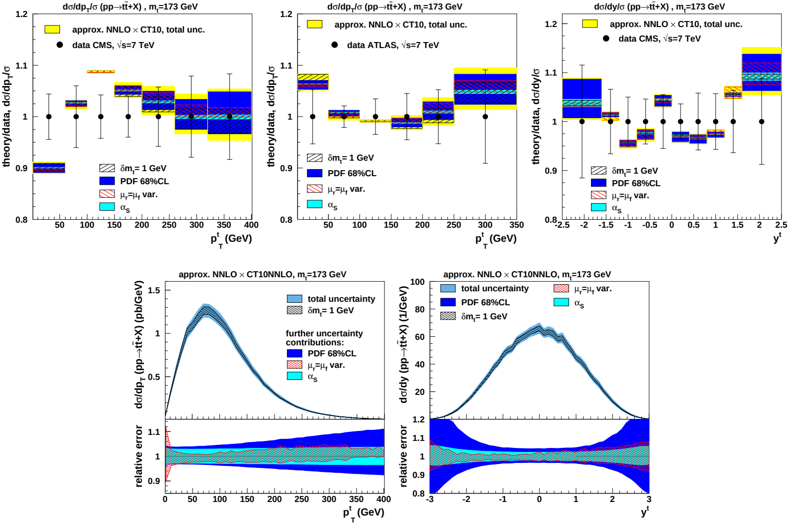
DiffTop Results

In what follows:

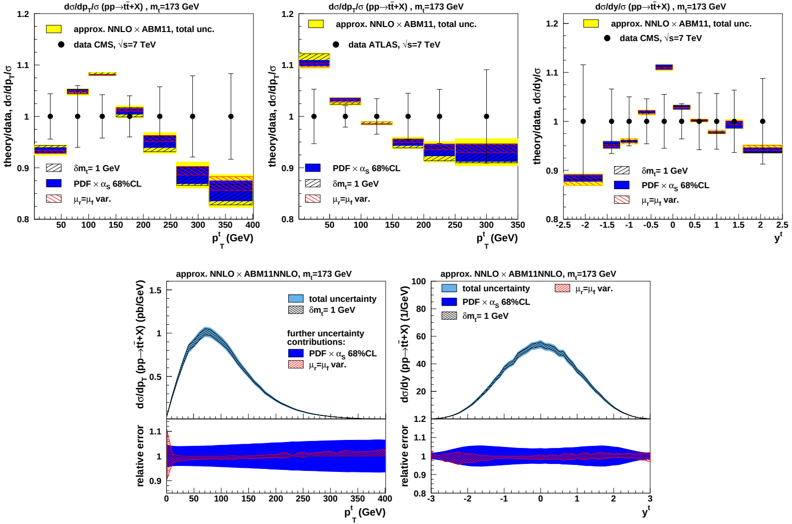
- PDF unc. are computed by following the prescription given by each PDF group at 68% CL ;
- The uncertainty associated to $\alpha_s(M_Z)$ is given by the central value as given by each PDF group $\pm\Delta\alpha_s(M_Z) = 0.001$;
- Scale unc. is obtained by variations $m_t/2 \leq \mu_R = \mu_F \leq 2m_t$;
- Uncertanty associated to the top-quark mass is estimated by using $m_t = 173$ GeV (Pole mass) $\pm\Delta m_t = 1$ GeV.



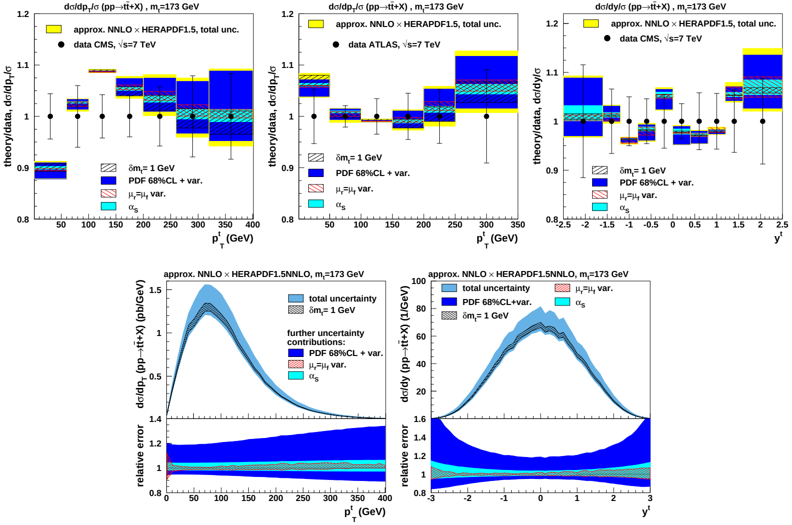
Uncertainties for the top p_T^t and y^t distribution obtained by using DiffTop with MSTW08NNLO PDFs. PDF and $\alpha_s(M_Z)$ errors are evaluated at the 68% CL.



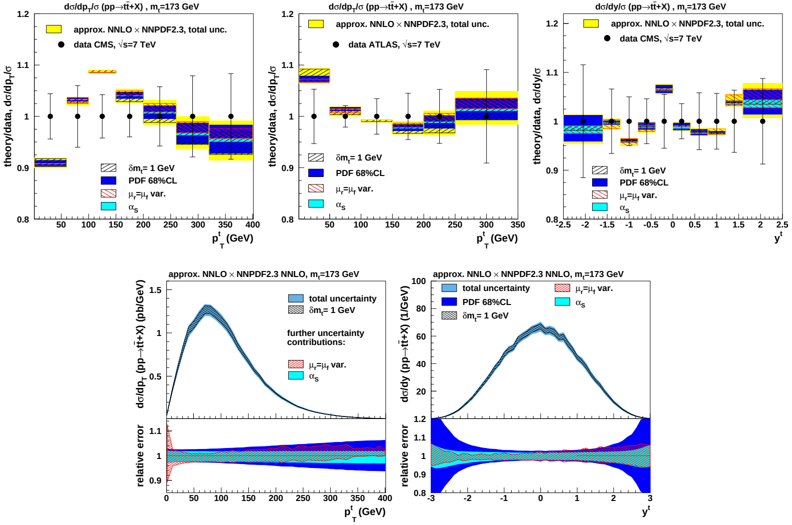
As in the previous slide but with CT10 NNLO PDFs. PDF and $\alpha_s(M_Z)$ errors are evaluated at the 68% CL.



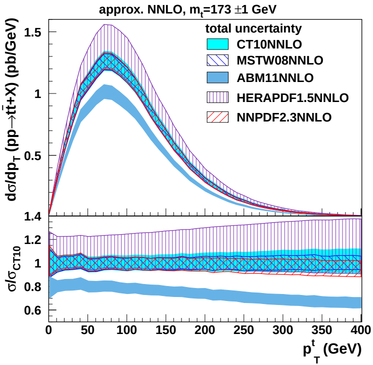
As in the previous slide but with ABM11 NNLO PDFs. Here the uncertainty on $\alpha_s(M_Z)$ is already part of the total PDF uncertainty.



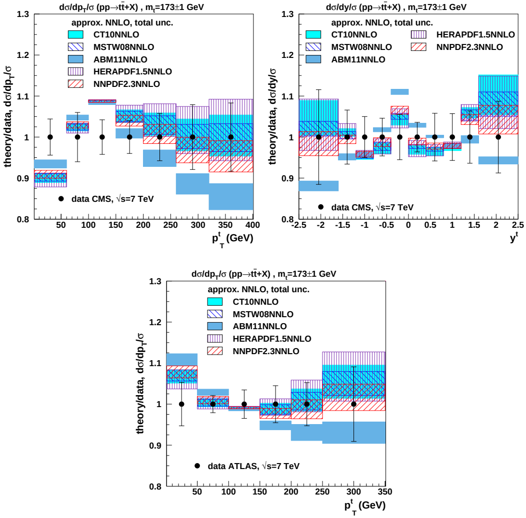
As in the previous slide but with HERA1.5 NNLO PDFs.



As in the previous slide but with NNPDF2.3 NNLO PDFs.



PDF uncertainties $\sqrt{S} = 7$ TeV p_T^t and y^t distributions: comparison between all PDF sets (bands are total unc.).



PDF uncertainties $\sqrt{S} = 7$ TeV p_T^t and y^t distributions: ratio to the LHC measurements (bands are total unc.).

Conclusions

- We have shown phenomenological results relevant for hadron colliders obtained by using DiffTop.
- DiffTop code and relative FastNLO tables will be released for a public use.
- Precise data for the diff. Xsec. will constrain the gluon at large-x once included in PDF fits.
- More data is needed: absolute differential cross section data will bring more information.
- DiffTop will be continuosly updated on the theory side: a new branch for the PIM kinematic is currently under development.
- Looking forward to see all this machinery at work in fits of PDFs.

BACKUP

Quality check:

NLO Exact Calculation vs approx NLO