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

Marco Guzzi, Katerina Lipka and Sven-Olaf Moch

DESY Hamburg

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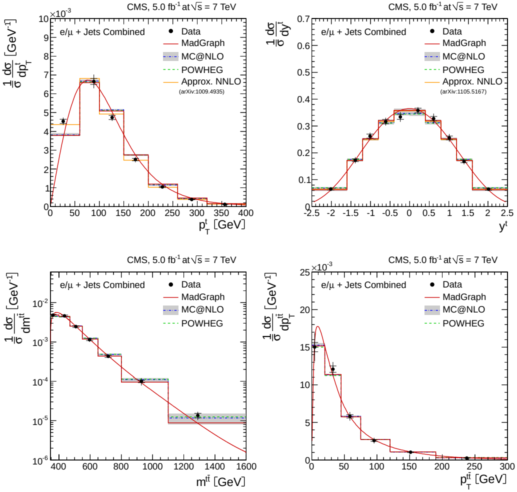
Outline and motivations

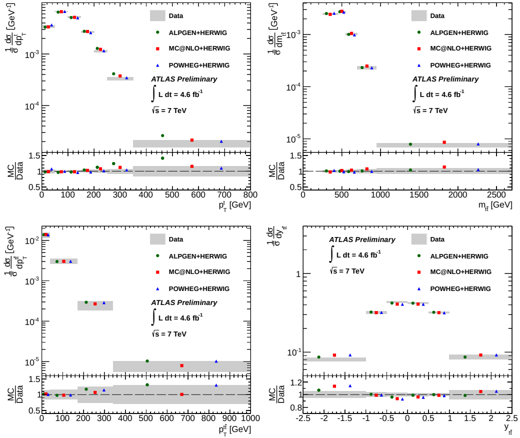
- Top-quark pair production at the LHC is crucial for many phenomenological applications/investigations:
  -Physics beyond the SM ($\Rightarrow$ distortions/bumps in distributions like $M_{t\bar{t}}$),
  -extent of QCD factorization,
  -PDFs determination in QCD analyses,
  -Correlation between α_s, 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, $\int Ldt = 5.0[\text{fb}]^{-1}$, $\sqrt{S} = 7$ TeV,

TOP-12-028 $\rightarrow \int Ldt \approx 12[\text{fb}]^{-1}$, $\sqrt{S} = 8$ TeV



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.

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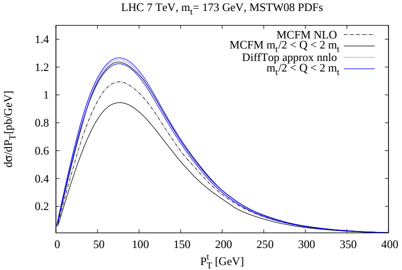

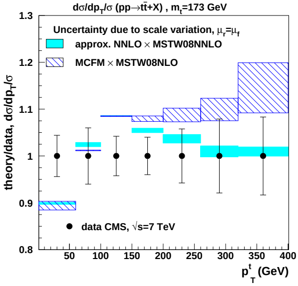

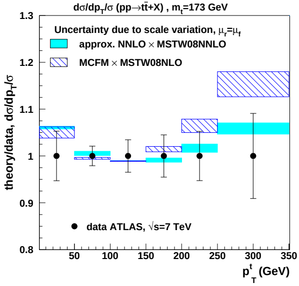

QCD threshold resummation: instruments to re-factorize the cross section in certain kinematic limits ⇒ approx. predictions

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

Based on/cross checked against the computation 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

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

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)

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

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

What's in the box ?

The factorized differential cross section is written as

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

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

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

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

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 $x \approx 0.1$:

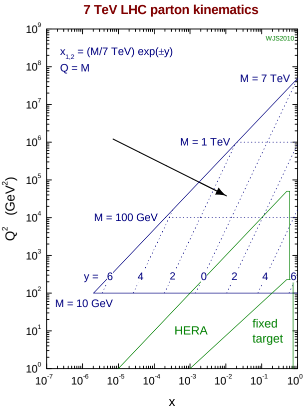

Figure by J. Stirling

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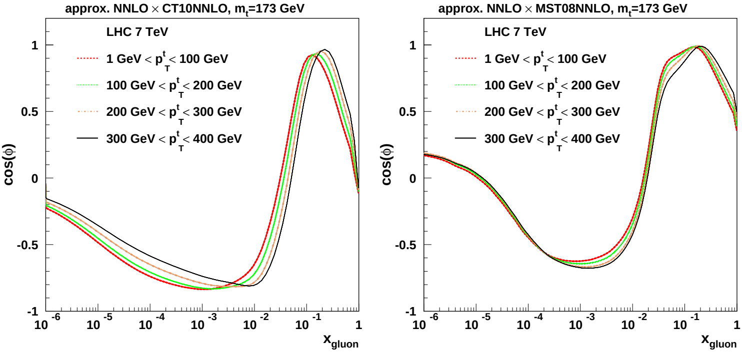

Here we choose MSTW08 and CT10 as representative. ABM11, HERA1.5 and NNPDF2.3 show a similar behavior (see also).

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 More details in D. Britzger's talk)

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 will be included into HERAFitter for PDF analyses

Work is in progress on code clean-up 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.

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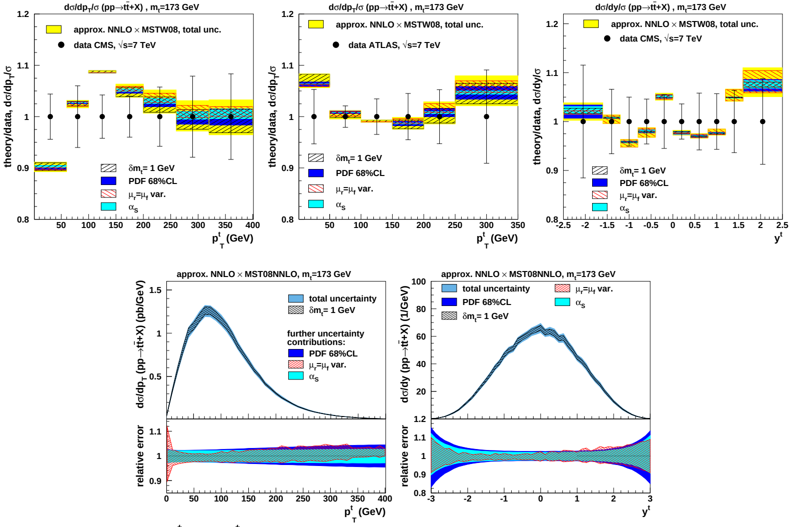

Uncertainties for the top p_T^t and y^t distribution obtained by using DiffTop with MSTW08NNLO PDFs. PDF and $\alpha_s(M_Z)$ errors are evaluated at the 68% CL.

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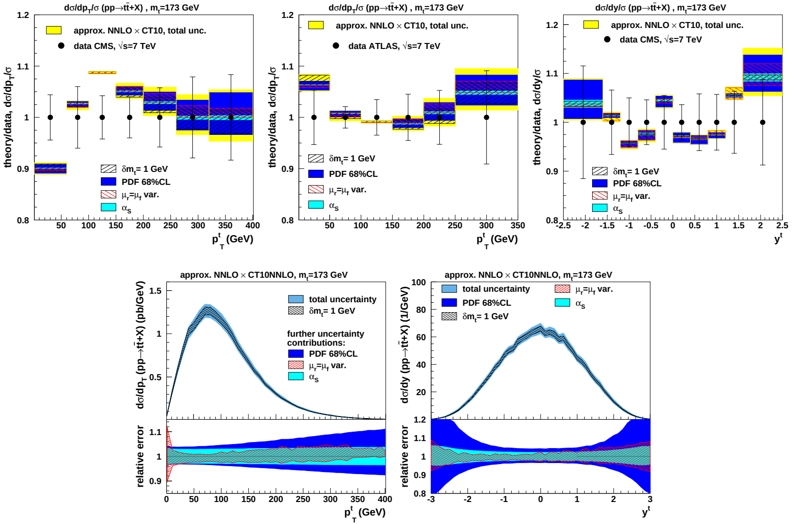

As in the previous slide but with CT10 NNLO PDFs. PDF and $\alpha_s(M_Z)$ errors are evaluated at the 68% CL.

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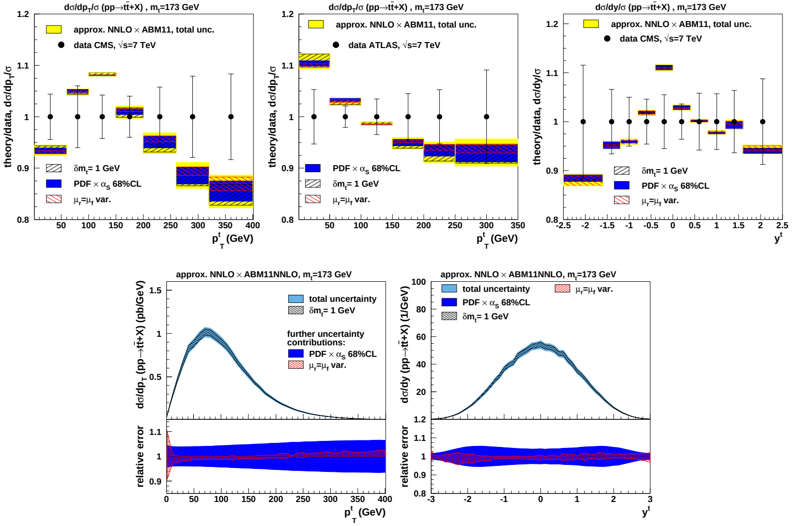

As in the previous slide but with ABM11 NNLO PDFs. Here the uncertainty on $\alpha_s(M_Z)$ is already part of the total PDF uncertainty.

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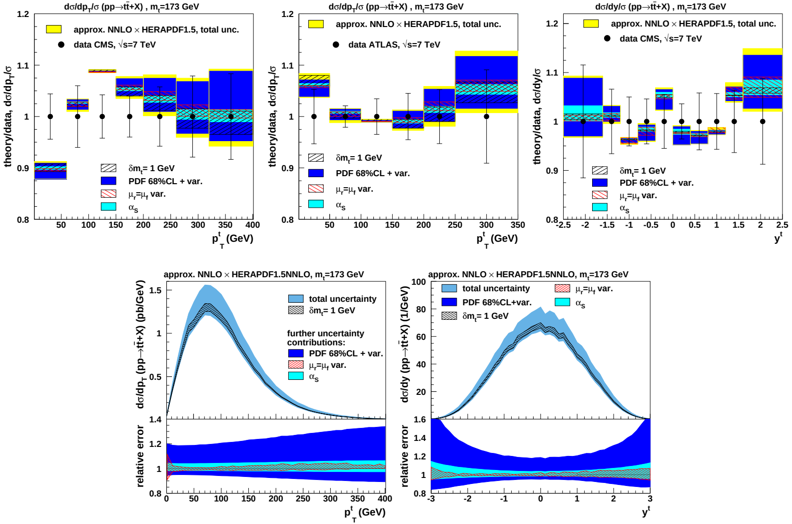

As in the previous slide but with HERA1.5 NNLO PDFs.

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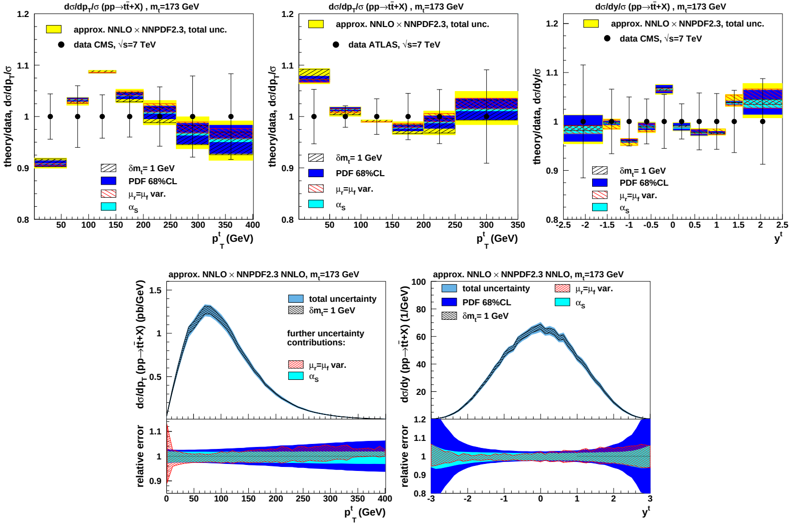

As in the previous slide but with NNPDF2.3 NNLO PDFs.

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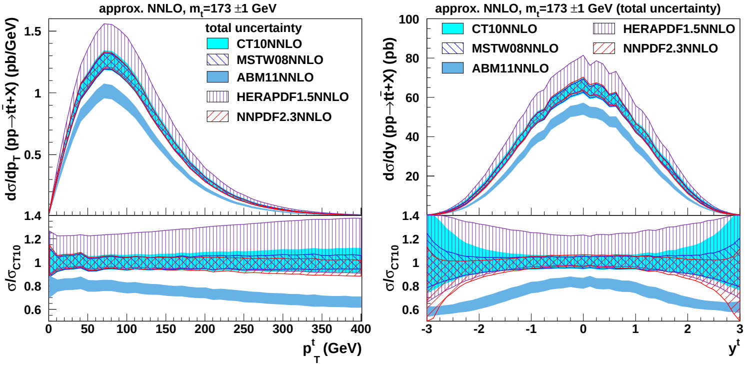
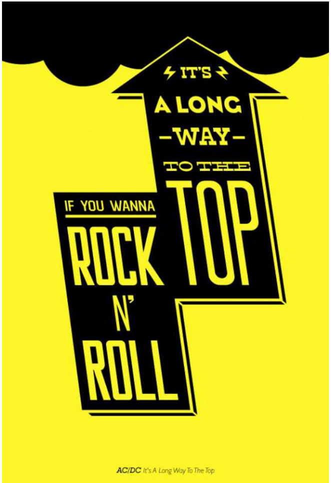


PDF uncertainties $\sqrt{S} = 7$ TeV p_T^t and y^t distributions: comparison between all PDF sets.

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.
- The precision of the current data for the diff. Xsec. is not enough to put severe constraints on the large-x gluon.
- 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.

Last year in Marseille at DIS2013



Yes, but now are ready to Roll!!

BACKUP

Quality check:

NLO Exact Calculation vs approx NLO