$t\bar{t}$ SM cross section

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November 29, 2016

CKM 2016, TIFR Mumbai

Outline

- Motivation
- NNLO total inclusive top pair production
- NNLO differential distributions
- Dynamical scales
- Summary

Top quark

- Top quark is the heaviest elementary particle presently known
- Only quark that decays before hadronisation and hence gives direct access to its properties. In SM, 99.8 % of $t \to W\ b$ and $W \to \ell\ \nu$ or $W \to q\ \bar{q}$
- Due to its large mass, it plays a crucial role in electroweak loop corrections, providing indirect constraints on the mass of the Higgs boson
- m_t together with m_h and α_s, are the main contributors of uncertainty in predicting the scale of SM vacuum stability breakdown
- Preferred decay mode of massive object in BSM models

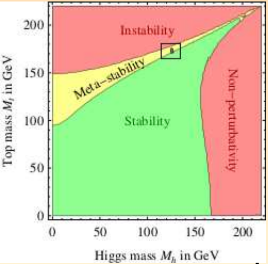
• Precise theoretical prediction and experimental measurement of top pair production is important step towards studying:
◦ top related parameters ◦ strong coupling constant ◦ directly constraint on gluon PDF at large x
• NNLO QCD predictions for ◦ total inclusive cross section and ◦ differential distribution for top pair production at hadron colliders are now known for stable top
• Searches for new physics are crucially dependent on how well we understand the SM and the collider environment of the LHC itself

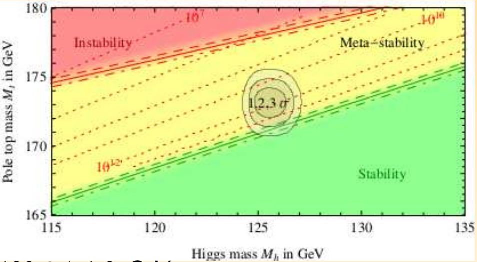
Implications on EW vacuum

- Condition of absolute stability of EW vacuum, $\lambda(M_P) \geq 0$ when SM extrapolated upto M_P puts lower bound (NNLO) on

$$m_h \text{ [GeV]} > 129.4 + 1.4 \left(\frac{m_t \text{ [GeV]} - 173.1}{0.7} \right) - 0.5 \left(\frac{\alpha_s(m_Z) - 0.1184}{0.0007} \right) \pm 1.0 GeV$$

Two-loop QCD and Yukawa corrections to the relation between the Higgs quartic coupling λ and the Higgs mass m_h





$$M_h > 129.4 \pm 1.8 \ GeV$$

- EW vacuum is stable or not up to the largest possible high-energy scale, relies on a precise determination of m_h, m_t and α_s

Degrassi, Vita et. al. JHEP08(2012)098

Bezrukov, Kalmykov, Kniehl, Shaposhnikov JHEP10(2012)140

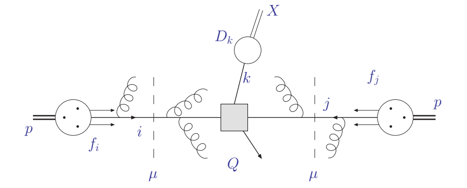
Factorisation of the hard scattering process

• Perturbative evaluation of the factorisation formula is based on a power series expansion in $\alpha_s(\mu)$

• An inclusive hard scattering process at the LHC

$$P(p_1) \ + \ P(p_2) \rightarrow \ t\bar{t}(Q, \{\cdots\}) \ + \ X$$

• At short distances, asymptotic freedom in QCD guarantees that, the partons in hadron are almost free, and are sampled essentially one at a time in hard collisions— QCD improved parton model



• Hadronic cross section for production of $t\bar{t}$ factorises, into a convolution of $\hat{\sigma}^{ij\rightarrow t\bar{t}}(x_1p_1, x_2p_2; \alpha_s, \mu_F, \mu_R)$ and $f_{i/P}(x_1, \alpha_s, \mu_F)$

$$\sigma(p_1, p_2) = \sum_{ij} \int_0^1 \int_0^1 dx_1 \ dx_2 \ f_{i/P}(x_1) \ f_{j/P}(x_2) \ \hat{\sigma}^{ij}(x_1, x_2) + \mathcal{O}(\Lambda/Q)$$

i, j are partons carrying a fraction $x_{1,2}$ of the proton momentum

Scale dependence of strong coupling $\alpha_s(\mu)$

- QCD has only one free parameter: $\alpha_s(\mu) = g_s^2/4\pi$ $\qquad a_s \equiv \alpha_s/4\pi$
- β function controls the evolution of $\alpha_s(\mu)$, known to 4-loops in $\overline{\mathrm{MS}}$ scheme

$$\frac{\partial a_s}{\partial \ln \mu^2} = \beta(a_s) = -\beta_0 a_s^2 - \beta_1 a_s^3 - \beta_2 a_s^4 - \beta_3 a_s^5 + \mathcal{O}(a_s^6)$$

- 4-loops β function, for $N_c = 3$

$$\beta_0 = 11 - \tfrac{2}{3} N_f \qquad \beta_1 = 102 - \tfrac{38}{3} N_f \qquad \beta_2 = \tfrac{2857}{2} - \tfrac{5033}{18} N_f + \tfrac{325}{54} N_f^2$$

$$\beta_3 = \left(\tfrac{149753}{6} + 3564\zeta_3\right) - \left(\tfrac{1078361}{162} + \tfrac{6503}{27}\zeta_3\right) N_f + \left(\tfrac{50065}{162} + \tfrac{6472}{81}\zeta_3\right) N_f^2 + \tfrac{1093}{729} N_f^3$$

Ritbergen, Vermaseren, Larin Phys. Lett. B400 (1997) 379
Czakon, Nucl. Phys. B710 (2005) 485

- Strong coupling g_s of QCD is characterized by two important features:
  - asymptotic freedom $\quad g_s \to 0 \quad$ UV
  - confinement $\quad g_s \to \infty \quad$ IR

- These properties are strongly dependent on N_f and N_c

Evolution of PDFs

• $f_i(x, \mu^2)$ are not calculable in pQCD, but its scale dependence is perturbatively controlled

• Universality allows for the determination of PDFs in global fits to experimental data

• Independence of any physical observable on scale μ gives rise to evolution equation for PDFs, which is a system of coupled integro-differential equations corresponding to different possible parton splittings

$$\frac{d}{d\ln\mu^2}\begin{pmatrix} f_{q_i}(x,\mu^2) \\ f_g(x,\mu^2) \end{pmatrix} = \frac{\alpha_s}{2\pi}\sum_j \int_x^1 \frac{dz}{z} \begin{pmatrix} P_{q_i q_j}(z,\alpha_s) & P_{q_i g}(z,\alpha_s) \\ P_{g q_j}(z,\alpha_s) & P_{gg}(z,\alpha_s) \end{pmatrix} \begin{pmatrix} f_{q_j}(\frac{x}{z},\mu^2) \\ f_g(\frac{x}{z},\mu^2) \end{pmatrix}$$

• Splitting functions P_{ij} are universal quantities, calculable in pQCD to an order in α_s

$$P_{ij}(z,\alpha_s) \quad = \quad P_{ij}^{(0)} + \alpha_s P_{ij}^{(1)} + \alpha_s^2 P_{ij}^{(2)} + \cdots$$

• Calculational tools, necessary for a consistent NNLO pQCD treatment of Tevatron & LHC hard scattering cross sections, available since 2004

Moch, Vermaseren, Vogt hep-ph/0403192,0404111

Theoretical Uncertainties

• In the high energy limit $m \ll Q$, we can set $m \to 0$, as it is much smaller than the relevant scale Q

• As a result if the x-section diverges due to collinear singularities, we need to define collinear safe observable, like jets, or introduce PDF/ fragmentation functions that can absorb the collinear singularities which are universal

- Absorbing the divergences into redefinitions:

Renormalisability	UV	$\alpha_s \to \alpha_s(\mu_R^2)$	β-function evolution
Factorisation	IR	$f_i(x) \to f_i(x, \mu_F^2)$	DGLAP evolution

Factorisation and Renormalisation scale

- μ_F: Factorisation scale separates short distance and long distance physics

- For $t\bar{t}$ production we set the scale to the relevant hard scale:
  - Total x-section, the only scale available is m_t
  - Differential distributions better choices *viz.* $m_T = \sqrt{p_T^2 + m_t^2}, \cdots$

- μ_R: Renormalisation scale is the scale at which the strong coupling constant is evaluated

- μ_F and μ_R are varied around a judiciously chosen default scale called the central scale, natural choice $\mu_F = \mu_R = Q \equiv m_t$

Estimate Theoretical Uncertainties

• To estimate the theoretical uncertainties, it is usual to vary either μ_R or μ_F about a central value Q: $1/2 < \xi < 2$

Together	Independently	Inversely
$\mu_F,\ \mu_R = \xi\ Q$	$\mu_R = Q;\ \mu_F = \xi\ Q$ $\mu_F = Q;\ \mu_R = \xi\ Q$	$\mu_R = \xi\ \ Q;\ \mu_F = \xi^{-1}\ Q$

• On physical grounds these scales have to be of the same order as Q, but their value can not be unambiguously fixed

$$f_{a/h_1}(x_1, \mu_F^2)\ f_{b/h_2}(x_2, \mu_F^2) \quad \hat{\sigma}_{ab}(x_1 p_1, x_2 p_2; Q, \{\ldots\}; \mu_R, \mu_F; \alpha_s(\mu_R))$$

$$\mu_F = Q \quad \downarrow \quad \mu_R = Q$$

$$f_{a/h_1}(x_1, Q^2)\ f_{b/h_2}(x_2, Q^2) \ \ \hat{\sigma}_{ab}(x_1 p_1, x_2 p_2; Q, \{\ldots\}; \alpha_s(Q))$$

• Theoretical uncertainty as a result of truncation, can ONLY be reduced by actually computing more terms in perturbation theory

• In the absence of direct evidence of any news physics one need to look for deviations in precision measurements

• Important for new physics searches & backgrounds to have better control over the theoretical uncertainties

Partonic cross section

- Partonic cross sections are perturbatively calculable order by order in α_s

$$\hat{\sigma}^{i\,j\to t\bar{t}}(\alpha_s,\mu_F,\mu_R) = \alpha_s(\mu_R)^2\Big\{\hat{\sigma}^{LO} + \frac{\alpha_s}{2\pi}\hat{\sigma}^{NLO}(\mu_F,\mu_R) + \left(\frac{\alpha_s}{2\pi}\right)^2\hat{\sigma}^{NNLO}(\mu_F,\mu_R) + \mathcal{O}(\alpha_s^3)\Big\}$$

- full NNLO

$$d\hat{\sigma}^{NNLO} = d\hat{\sigma}^{VV} + d\hat{\sigma}^{RV} + d\hat{\sigma}^{RR} \qquad \mathcal{O}(\alpha_s^4)$$

- NNLO cross sections beyond the known threshold expansions was essential and the missing ingredients involved

  ◦ double-real ◦ real-virtual

• LO	$i\,j \to t\bar{t}$	$ij \equiv q\bar{q};\, gg$	$\mathcal{O}(\alpha_s^2)$
• NLO	$i\,j \to t\bar{t} + X_1$	$ij \equiv q\bar{q};\, gg;\, q(\bar{q})g$	$\mathcal{O}(\alpha_s^3)$
• NNLO	$i\,j \to t\bar{t} + X_2$	$ij \equiv qq'(\bar{q}');\, gg;\, q(\bar{q})g$	$\mathcal{O}(\alpha_s^4)$

X_1 **one** additional parton X_2 **two** additional parton

- New channels open up, as one goes higher up in the perturbative order
- Important development is the development of sector-improved residue subtraction scheme (STRIPPER) to handle the NNLO computations.

Czakon (2010); (2011); Czakon, Heymes (2015)

Partonic cross sections $t\bar{t} + X$ to NNLO

- NLO $\mathcal{O}(\alpha_s^3)$
  - $|i\ j \to (n+1)|^2$
  - $i\ j \to n$ (LO) $\times$ $i\ j \to n$ (1-loop amplitude)

Nason, Dawson, Ellis 1988
Beenakker, Kuijf, van Neerven, Smith 1989
Czakon, Mitov 2010

- NNLO $\mathcal{O}(\alpha_s^4)$
  - $|i\ j \to (n+2)|^2$ (RR)
  - $i\ j \to (n+1)$ (NLO) $\times$ 1-loop amplitudes (RV)
  - n-parton (LO) $\times$ 2-loop amplitudes (VV)
  - $|$n-parton 1-loop$|^2$ (VV)

- quark initiated:
  - $q\bar{q} \to t\bar{t}X_2$ Bärnreuther, Czakon, Mitov 2012
  - $qq \to t\bar{t}X_2$, ◦ $qq' \to t\bar{t}X_2$, ◦ $q\bar{q}' \to t\bar{t}X_2$ Czakon, Mitov 2012
- quark-gluon initiated:
  - $q(\bar{q})\ g \to t\bar{t}X_2$ Czakon, Mitov 2013
- gluon initiated:
  - $gg \to t\bar{t}X_2$ Czakon, Fiedler, Mitov 2013

- First NNLO computation with two colored partons and massive fermions at a hadron collider which is exact and complete

Total inclusive top pair production

- $$\sigma_{\rm tot} = \sum_{i,j} \int_0^{\beta_{\rm max}} d\beta \;\; \Phi_{ij}(\beta, \mu_F^2) \;\; \hat{\sigma}_{ij}(\alpha_s(\mu_R^2), \beta, m^2, \mu_F^2, \mu_R^2)$$

$$\beta_{\rm max} \equiv \sqrt{1 - 4m^2/S} \qquad \beta = \sqrt{1-\rho} \qquad \rho \equiv 4m^2/s \qquad 0 < \rho < 1$$

$$\begin{array}{llll} \beta \to 0 & \text{Threshold limit} & \rho \to 1 & 4m^2 \approx s \text{ (soft radiation)} \\ \beta \to 1 & \text{High energy limit} & \rho \to 0 & 4m^2 \ll s \text{ (massless limit)} \end{array}$$

m: top quark mass, a scheme dependent quantity. Usually the pole mass

- Partonic flux

$$\Phi_{ij}(\beta, \mu_F^2) = \frac{2\beta}{1-\beta^2} \; \mathcal{L}_{ij}\left(\frac{1-\beta_{\rm max}^2}{1-\beta^2}, \mu_F^2\right)$$

- Partonic luminosity

$$\mathcal{L}_{ij}(x, \mu_F^2) = x\,(f_i \otimes f_j)\,(x, \mu_F^2) = x \int_0^1 dy \int_0^1 dz\, \delta(x - yz) f_i(y, \mu_F^2) f_j(z, \mu_F^2)\,.$$

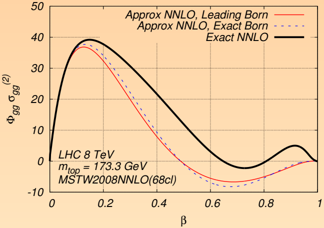
- Partonic cross section upto NNLO ($\mu_F = \mu_R = \mu$)

$$\hat{\sigma}_{ij} = \frac{\alpha_s^2}{m^2}\left\{\sigma_{ij}^{(0)} + \alpha_s\left[\sigma_{ij}^{(1)} + L\,\sigma_{ij}^{(1,1)}\right] + \alpha_s^2\left[\sigma_{ij}^{(2)} + L\,\sigma_{ij}^{(2,1)} + L^2\sigma_{ij}^{(2,2)}\right]\right\}$$

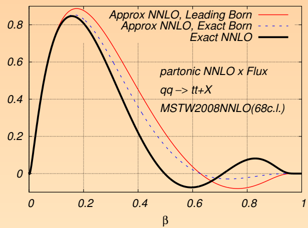
$$L = \ln(\mu^2/m^2)$$

Partonic cross section × flux

• gg



• $q\bar{q}$



• Exact NNLO (black), in comparison with approximate NNLO (blues, red); approximates the exact result close to the threshold

• Outside of the threshold region, they do not agree, difference in between is pure NNLO, which the threshold resummation could not predict

• Integrating over β, one gets the contribution to total cross section and the exact gg contribution is a factor of 2 larger then the approximate results, in the $q\bar{q}$ case the ration is smaller

$q\bar{q}$: Bärnreuther, Czakon, Mitov 2012
gg: Czakon, Fiedler, Mitov 2013

Relative contribution of partonic sub channels

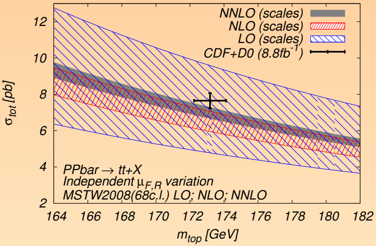
- Tevatron and LHC collider energies to NNLO+NNLL

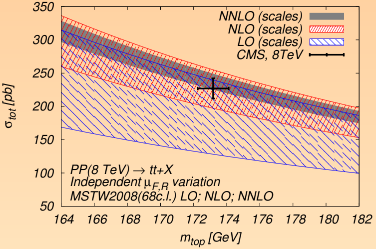
	Tevatron	LHC@7 TeV	LHC@8 TeV	LHC@14 TeV
gg	15.4%	84.8%	86.2%	90.2%
$qg + \bar{q}g$	-1.7%	-1.6%	-1.1%	0.5%
qq	86.3%	16.8%	14.9%	9.3%

Czakon, Mangano, Mitov, Rojo 2013

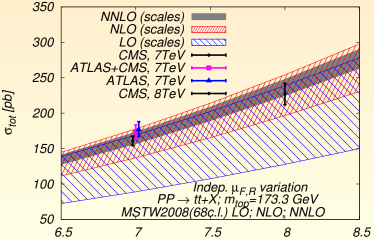
- Top-quark pair production, sensitive to gluon (LHC)/quark (Tevatron) and can be consistently included in a NNLO PDF fit without any approximations

Scale variation Fixed Order NNLO

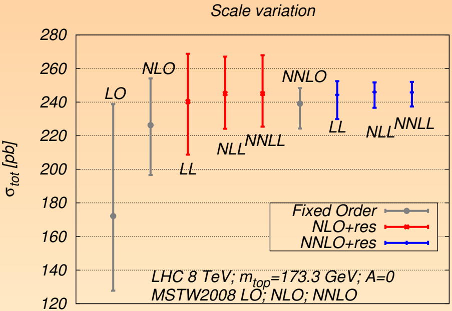




- Perturbative expansion well convergent
- Scale variation of NNLO $\subset$ NLO $\subset$ LO implies the scale variation approximates the missing higher order terms well
- PDF sets used, match the accuracy of the Fixed order



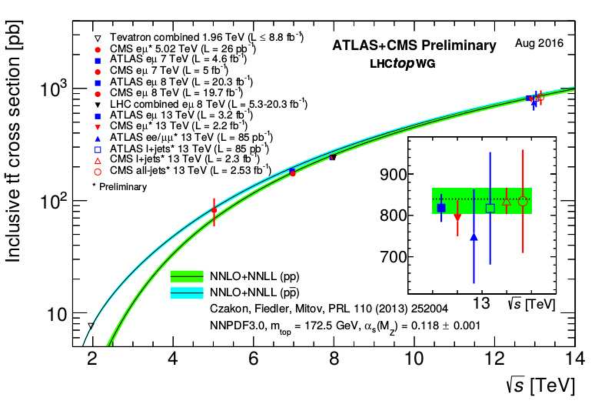
Soft-gluon resummation



- Scale dependence for various Fixed Order and Logarithmic accuracy
- Impact of soft-gluon resummation on the size of the scale dependence and the theoretical central value
- PDF sets match the accuracy of the Fixed order
- Perturbative convergence preserved after the inclusion of soft-gluon resummation
- Inclusion of resummation with logarithmic accuracy decreases the scale dependence

Czakon, Fiedler, Mitov, Rojo 2013

Total $t\bar{t}$ cross section LHC & Tevatron



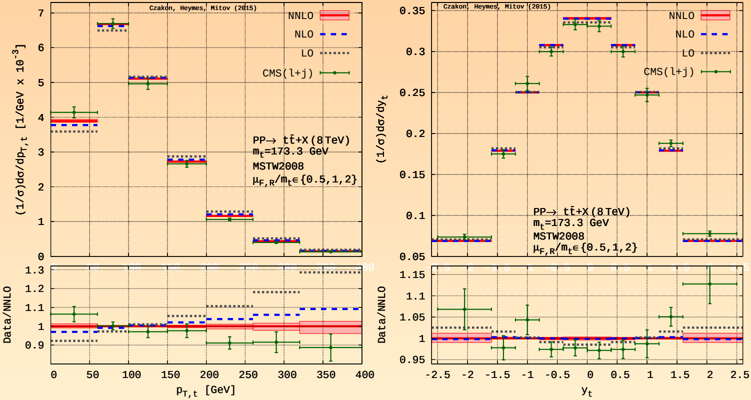
- As a function of $\sqrt{s}$ compared to NNLO QCD + NNLL resummation
- Theory band reflects uncertainties due to • renormalisation μ_R and factorisation scale μ_F, • PDFs and • strong coupling $\alpha_s(\mu_R^2)$
- Input $m_t = 172.5$ GeV

LHC*top*WG

Differential top-quark pair production

Normalised $t\bar{t}$ distributions p_T^t, y_t to NNLO

- Distributions at LO, NLO and NNLO compared to CMS data

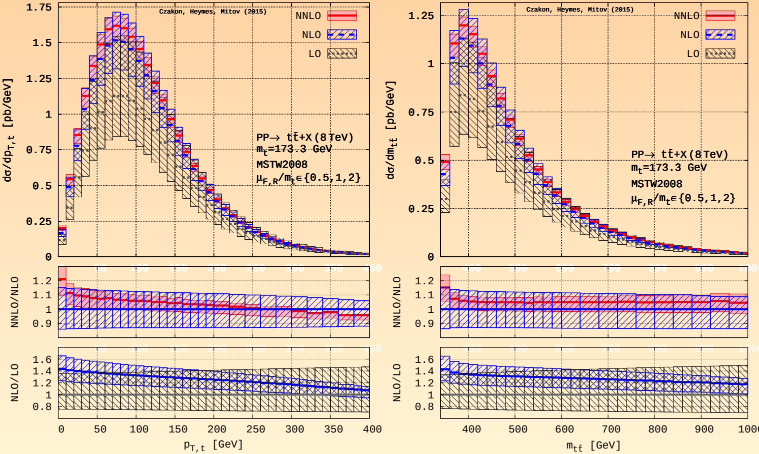


- Scale variation only shown for the NNLO corrections
- Calculation reproduces σ_{tot} for each value of μ_R, μ_R
- Verified cancellation of infrared singularities in each histogram bin
- Inclusion of NNLO corrections in the p_T^t distribution brings SM predictions closer to CMS data in all bins
- Kinematics-independent scales with the central value $\mu_R = \mu_F = m_t$ used

Czakon, Heymes, Mitov 2016

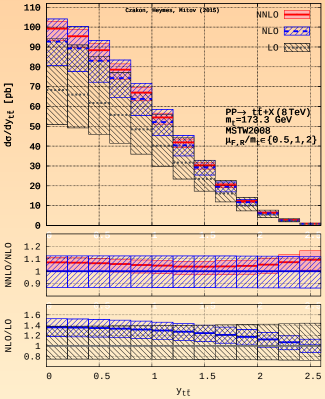
p_T^t and $m_{t\bar{t}}$ distribution to NNLO

- Scale variation for each perturbative order, with NLO, NNLO K-factors



- Consistent reduction in scale variation with successive perturbative order and NNLO corrections are contained within the NLO error band
- Result includes all partonic channels contribution to NNLO and does not resort to leading color approximation

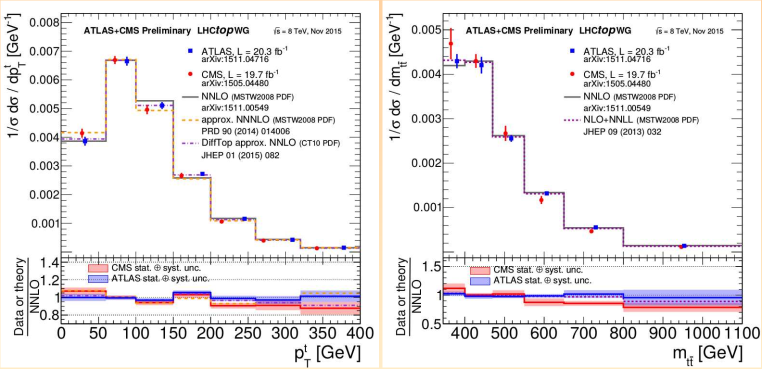
$y_{t\bar{t}}$ distribution to NNLO



• In this computation a fixed scale has been used to perform checks with existing NNLO calculation

• For differential distributions it is appropriate to use dynamical scales, say top quark transverse mass $m_T = \sqrt{p_T^2 + m_t^2}$, which would deviate from fixed scale at large p_T

Normalised p_T^t and $m_{t\bar{t}}$ distribution to NNLO



• CMS and ATLAS results are compared to NNLO and approximate NNLO calculations. The shaded bands show the total uncertainty on the data measurements in each bin. The lower panel shows the ratio of the data measurements and the approximate NNLO calculations to the full NNLO calculation

LHC*top*WG

Dynamical scales

- Functional form of default central scale μ_0 is a prerequisite to scale variation. Possible options

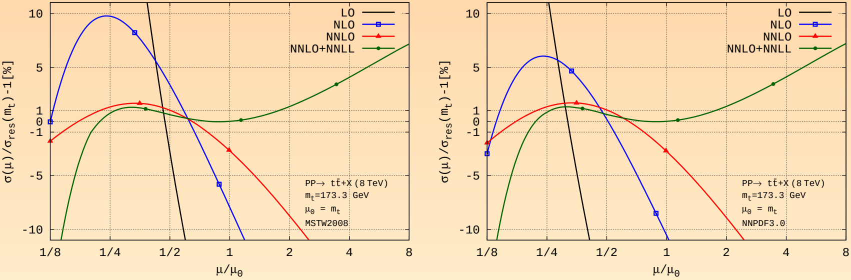
$$
\begin{aligned}
\mu_0 &\sim m_t \\
\mu_0 &\sim m_T = \sqrt{m_t^2 + p_T^2} \\
\mu_0 &\sim H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} \\
\mu_0 &\sim H_T' = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} + \sum_i p_{T,i} \\
\mu_0 &\sim E_T = \sqrt{\sqrt{m_t^2 + p_{T,t}^2}\sqrt{m_t^2 + p_{T,\bar{t}}^2}} \\
\mu_0 &\sim H_{T,\mathrm{int}} = \sqrt{(m_t/2)^2 + p_{T,t}^2} + \sqrt{(m_t/2)^2 + p_{T,\bar{t}}^2} \\
\mu_0 &\sim m_{t\bar{t}}
\end{aligned}
$$

- Note the proportionality constant also need to be fixed

Czakon, Heymes, Mitov 2016

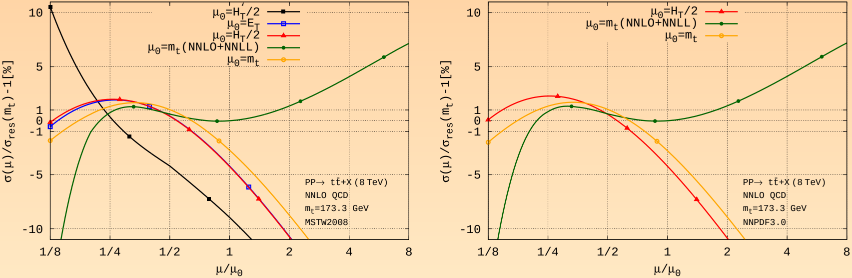
Total cross section

- Fixed scale $\mu_F = \mu_R = m_t$ for LO, NLO, NNLO and NNLO+NNLL. Plots normalised to NNLO+NNLL cross section evaluated with corresponding PDF sets at scale $\mu_0 = m_t$



- Scale at which perturbative convergence is maximised is slightly above $m_t/2$, significantly lower than the std choice $\mu_0 = m_t$
- Numerical agreement between the fixed order result evaluated at a lower scale and the usual resumed result is significant
- Difference between the two PDF sets decreases fast with higher order and almost negligible at NNLO and NNLO+NNLL
- For both inclusive top-pair and Higgs production x-section exhibit faster perturbative convergence at scales lower than usual, m_t and $m_h/2$

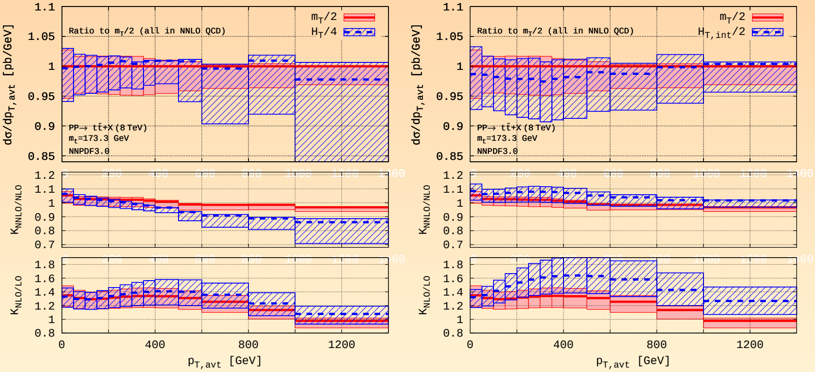
Comparison of different dynamic scales at NNLO



- Predictions are rather stable w.r.t choice of PDF sets at this level of perturbation theory
- Typical scale μ_0 used in past studies reduced by a factor 2 is a better option
- Such functional forms of μ_0 leads to faster perturbative convergence, small to moderate scale error and NNLO total x-section not too different from NNLO+NNLL $\sigma_{tot}(m_t)$

Average t, $\bar{t}$, p_T differential x-section at NNLO

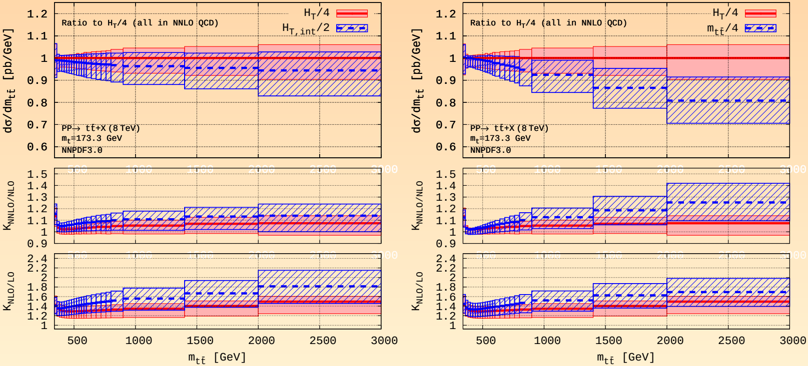
• Ratio of $\mu_0 = H_T/4$; $H_{T,int}/2$; m_T; $m_{t\bar{t}}/4$ w.r.t default scale $m_T/2$. Bands describe scale variation



• Scale $m_T/2$ leads to K-factors close to unity— best fits requirement for fastest perturbative convergence in the full kinematical range
• Scale $m_T/2$ has smallest scale variation

Comparison $m_{t\bar{t}}$ differential x-section at NNLO

- Ratio of $\mu_0 = H_{T,int}/2$; $H_T/2$; $m_{t\bar{t}}/4$; $m_{t\bar{t}}/2$ w.r.t default scale $H_T/4$



- Dynamical scale $\mu_0 = H_T/4$ best fits the requirement for fastest perturbative convergence
- Note $m_{t\bar{t}}$ based scale lead to poor perturbative convergence

Dynamical scales for top-pair production at LHC

- Scale based on the principle of fastest perturbative convergence
- Require the scale be such that the K-factor at NLO and NNLO introduces the smallest K-factor across the full kinematical range
- $\mu_0 = m_T/2$ for p_T distribution
- $\mu_0 = H_T/4$ for all other distribution

Phenomenological implications of NNLO computation

Allow to undertake accurate phenomenological analysis of LHC data

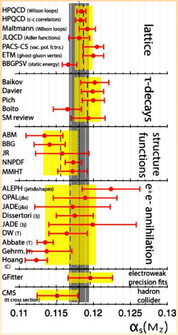
• Extract NNLO PDFs from LHC data

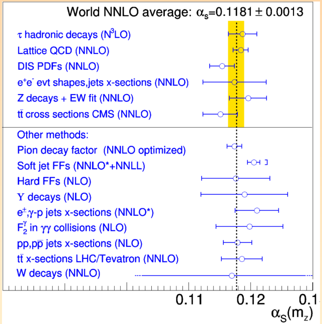
• Improved determination of top-quark mass

• Validation of different implementation of higher order effect in MC event generators

• Direct measurement of the running of α_s at high scales

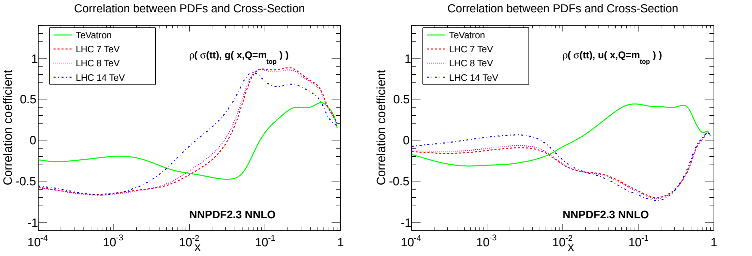
- Of all fundamental constants in nature α_s is the least precisely known
- $\delta G/G \approx 10^{-5}$ • $\delta G_F/G_F \approx 10^{-8}$ • $\delta\alpha/\alpha \approx 10^{-10}$

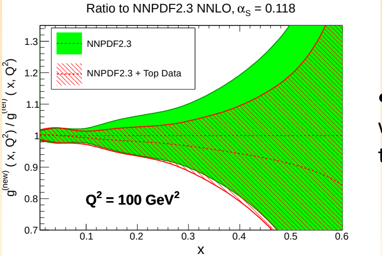




- Obtained from extractions based on (at least) full NNLO QCD predictions
- Top-pair x-sec (NNLO+NNLL)— first hadronic collider measurements that constraint $\alpha_s(m_z) = 0.1151 \pm 0.0028$ (CMS 7 TeV). If combined with Tevatron the value increases to 0.1186 ± 0.0033 (closer to world average).
- Precise determination of α_s is essential to reduce theoretical uncertainties for any high-precision pQCD observables that depends on higher powers of α_s

Top quark data and PDF fits





- Comparison of default fit v/s fits with inclusion of Tevatron and LHC top quark data

- Gluon in the large x range, where the gluon PDFs uncertainties are large can be constrained by top cross section at the LHC
- NNPDF 3.0 and MMHT14 have included $t\bar{t}$ total cross section data

Czakon, Mangano, Mitov, Rojo 2013

Constraints on large-x gluon NNLO differential distributions

• Study the impact on the large-x gluon of top-quark pair differential distributions measured by ATLAS and CMS at $\sqrt{S} = 8$ TeV.

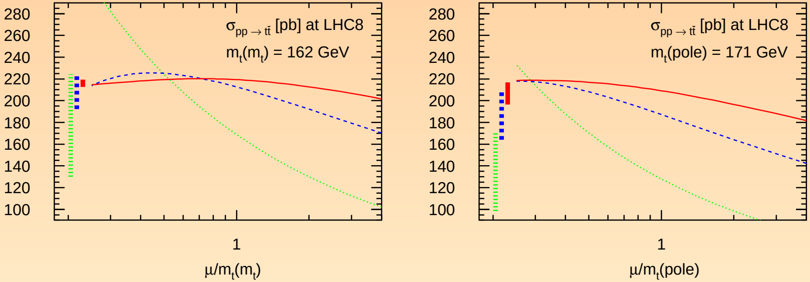
• Analysis, performed in the NNPDF3.0 framework at NNLO accuracy, allows to identify the optimal combination of LHC top-quark pair measurements that maximize the constraints on the gluon, as well as to assess the compatibility between ATLAS and CMS data.

Czakon, Hartland, Mitov, Nocera, Rojo— 1611.08609

Top quark mass

• Quark mass are fundamental parameters of the QCD Lagrangian but not directly observable due to confinement
• Quark mass that appear in theory predictions are subject to definitions of a renormalisation scheme once higher order quantum corrections are included
• In many QCD applications the pole mass is conventional scheme of choice. Defined at each finite order of perturbation theory as the location of single pole in the two-point correlation function— pole mass scheme
• Due to confinement, quark do not appear as free particle in asymptotic states in the S-matrix. Pole mass acquire non-perturbative corrections, leading to intrinsic uncertainty in the definition of m_t^{pole} of the order of Λ_{QCD}
• Alternative definition based on $\overline{MS}$ scheme which realises the concept of a running $m_t(\mu)$ at a scale μ (short-distance mass M_t^{MSR}). The short distance mass can be related to the MC mass extracted from experiment. M_t^{MC} is related to M_t^{MSR} which in turn can be related to m_t^{pole}

$\overline{MS}$ v/s pole mass @ LO, NLO and NNLO (ABM12 PDF)



- Scale dependence for the $t\bar{t}$ total cross section for a top-quark mass $m_t(m_t) = 162$ GeV in the $\overline{MS}$ scheme (left) and $m_t(\mathrm{pole}) = 171$ GeV in the on-shell scheme (right) with the choice $\mu = \mu_R = \mu_F$.
- Scale variation in the range $\mu/m_t(\mathrm{pole}) \in [1/2, 2]$ and $\mu/m_t(m_t) \in [1/2, 2]$ indicated by vertical bars
- Improved convergence as the higher order corrections are successively added
- Small theoretical uncertainty form scale variation

Summary

• Driven by the vast number of top quark pairs produced at the LHC, top physics is entering into a high precision phase

• New generation of high precision calculations have appeared, NNLO+NNLL total inclusive top-pair production and NNLO differential distribution

• These developments will allow one to undertake number of high caliber phenomenological studies at the LHC:
◦ Direct measurement of running α_s at high scales
◦ Extraction of NNLO PDF from LHC data. Improved determination of poorly known large-x gluon PDFs.
◦ Total cross-section data is already included in several PDF determinations but differential distributions are not
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◦ Translates into more accurate predictions of BSM heavy particles and high mass tail of the top pair invariant mass distribution
◦ Improved determination of top-quark mass