Top-quark Pair Production in a Running Mass Scheme

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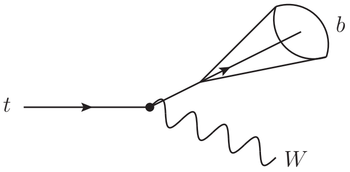
Top-Quark

The top-quark is unique in the sense that it is very massive and short lived.

This short lifetime gives access to properties as if it was a “free” quark.

Its production and decay can be treated perturbatively.



Top Mass

The ability to kinematically reconstruct the event allows for very precise measurements of the mass.

There is a recent combined Tevatron LHC analysis which gives

$$m_t = 173.34 \pm 0.76 \text{GeV}$$ [arXiv:1403.4427]

The most precise single measurement is given by D0

$$m_t = 174.98 \pm 0.76 \text{GeV}$$ [arXiv:1405.1756]

Which Mass?

Mass in the Standard Model is a free parameter (not an observable).

In particular, the choice of renormalization scheme can affect the measured mass.

The direct measurements of the top-mass usually assume that it is the pole mass.

Which Mass?

The problem is partially that the pole mass is not a well defined physical quantity for a quark.

The pole mass suffers from a renormalon ambiguity which limits the accuracy to

$\Lambda_{QCD} \sim 200\text{MeV}$. I.Bigi, et *al.* [Phys.Rev., D50, 2234]

In addition, all direct measurements rely on matching with Monte Carlo (MC) simulations.

Short-Distance Mass

Instead of the pole mass, it is possible to define running mass schemes that are more well defined.

So called short-distance schemes can then be related to the pole mass via a perturbative relation.

$$m_{pole} = m_{SD}(\mu_R)\left(1 + \frac{\alpha_s(\mu_R)}{\pi}d_1 + \left(\frac{\alpha_s(\mu_R)}{\pi}\right)^2 d_2 + \dots\right)$$

Why use a running mass scheme?

Analogy with $e^+e^- \to t\bar{t}$

Hoang and Stewart relate elements of the factorization theorem to inputs in MC event generators.

They show that what is actually measured is similar to a jet mass

$$M^{\mathrm{peak}} = m_{SD} + \Gamma_t(\alpha_S + \alpha_S^2 + \ldots) + \frac{Q\Lambda_{QCD}}{m_{SD}}$$

Hoang, Stewart [Nucl.Phys.Proc.Suppl. 185 220]

Hoang et *al* [Phys.Rev.Lett. 101 151602]

Monte Carlo Mass

This jet or MC mass is then identified with the mass in the so-called MSR scheme at low scales.

From this identity, it is possible to estimate the order of magnitude of the error in pole mass.

$$m_{pole} = m_{MC} + Q_o[\alpha_S(Q_o)c_1 + ...]$$

A. Hoang

With Q_o arguably $\mathcal{O}(1\text{GeV})$ and $\alpha_S, c_1 \sim \mathcal{O}(1)$ this gives an uncertainty of about 1GeV.

Other Observables

A recent paper by CMS uses a description of the endpoints of various kinematic distributions to extract a mass for the top.

$$m_t = 173.9 \pm 0.9(\mathrm{stat.})^{+1.6}_{-2.0}(\mathrm{syst.})\mathrm{GeV}$$ CMS [arXiv:1304.5783].

This method does not depend as strongly on MC matching.

Compare Perturbative Quantities

Recently it was proposed to use the differential distribution

$$\mathcal{R}(m_{pole}, \rho) = \frac{1}{\sigma_{t\bar{t}+1jet}} \frac{d\sigma_{t\bar{t}+1jet}}{d\rho}(m_{pole}, \rho)$$

with

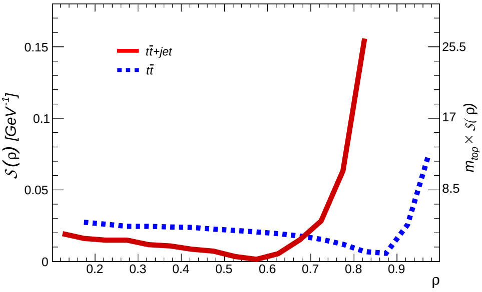
$$\rho = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}.$$

S. Alioli et *al.* [Eur.Phys.J., C73, 2438]

This benefits from a having a well defined mass.

It was argued that it could be competitive in precision.

Compare Perturbative Quantities



It was found that the sensitivity to the top mass could become quite large.

$$\left|\frac{\Delta\mathcal{R}}{\mathcal{R}}\right| \approx \left(m_{pole} \times S(\rho)\right) \left|\frac{\Delta m_{pole}}{m_{pole}}\right|$$

Compare Perturbative Quantities

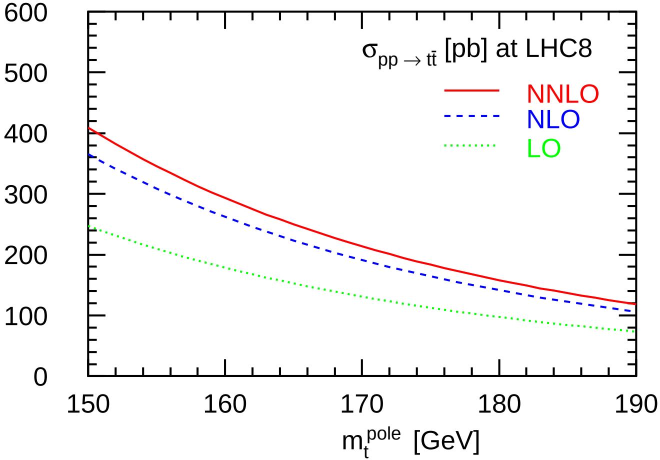
Another option is to compare the production cross-section with the predicted quantity from calculations.

This provides a result that is well defined

$$m_{pole} = 171.2 \pm 2.4\text{GeV}$$ Alekhin, Blümlein, Moch [Phys.Rev.D89 054028]

This agrees well with direct measurements but has larger errors.

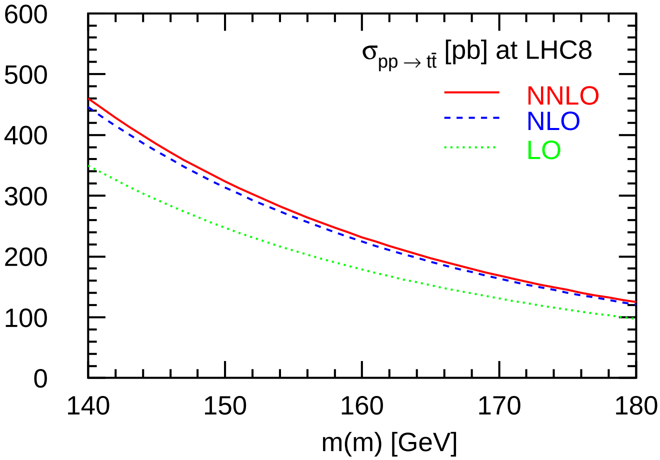
Total Cross-Section



M.D. and S.Moch [arXiv:1305.6422]

The NNLO corrections represent a 12% increase in the cross-section.

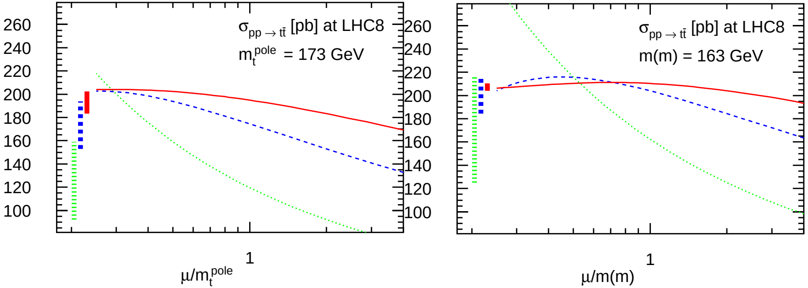
Total Cross-Section



M.D. and S.Moch [arXiv:1305.6422]

The NNLO corrections represent a 3% increase in the cross-section.

Scale Dependence



M.D. and S.Moch [arXiv:1305.6422]

Differential Cross-Sections

Differential cross-sections are now being measured at the LHC.

CMS [Eur.Phys.J., C73 2339]

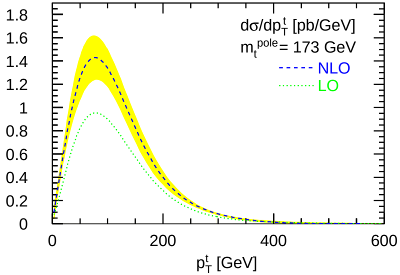
ATLAS [Eur.Phys.J., C73 2261]

The same improvements hold when moving from the pole mass to $\overline{\mathrm{MS}}$ scheme.

We have computed this at NLO using

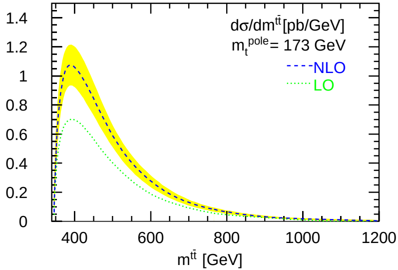
$$\frac{d\sigma(m(\mu_r))}{dX} = \left(\frac{\alpha_s}{\pi}\right)^2 \frac{d\sigma^{(0)}(m(\mu_r))}{dX} + \left(\frac{\alpha_s}{\pi}\right)^3 \left\{ \frac{d\sigma^{(1)}(m(\mu_r))}{dX} + d_1 m(\mu_r) \frac{d}{dm_t} \left(\frac{d\sigma^{(0)}(m_t)}{dX} \right)\Bigg|_{m_t = m(\mu_r)} \right\} + \mathcal{O}(\alpha_s^4) \,.$$

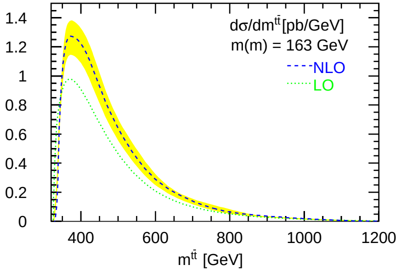
p_t Cross-section



M.D. and S.Moch [arXiv:1305.6422]

$m^{t\bar{t}}$ Cross-section





M.D. and S.Moch [arXiv:1305.6422]

$m^{t\bar{t}}$ Cross-section

Very close to threshold, the differential cross-section diverges.

This is due to the presence of a $\frac{1}{\sqrt{1-4\frac{m_t^2}{(m^{t\bar{t}})^2}}}$ in the derivative term.

This behaviour indicates a breakdown of fixed-order perturbation theory and bound-state effects need to be included.

MCFM

We have implemented this in MCFM for p_T, y, and $m_{t\bar{t}}$ differential cross-sections.

The change is implemented to NLO and uses analytic expressions except for computing the mass derivatives of the PDFs.

Will be provided as a plugin on the MCFM website.

We plan to provide the ability to choose different short distance schemes e.g. $\overline{\mathrm{MS}}$, PS, 1S.

MCFM

All integration is done with the virtual part, so no extra integrations are required.

Works by setting an additional flag in the `input.dat` file:
`msbar .true.`

Should be available in the next few weeks.

Summary

The top mass measured by experiments isn't necessarily the pole mass.

Work is being done to understand the difference between the MC mass and pole mass.

Similarly, perturbative observables are being looked at and give an unambiguous mass determination.

Using the $\overline{\mathrm{MS}}$ scheme improves convergence and scale dependence.

Outlook

We are working on implementing this in MCFM.

Higher order corrections, finite width effects and threshold resummation need to be included in differential cross-sections.

N.Kidonakis [Phys.Rev., D82, 114030]

V.Ahrens et *al.* [Phys.Lett., B687, 331]

A.Denner et *al.* [JHEP, 1210, 110]

The theoretical uncertainty is not as prevalent at an e^+e^- collider where approximations to the N^3LO corrections are known.

M.Beneke et *al.* [Phys.Lett., B668, 143]

A.Hoang [Phys.Rev., D69, 034009]

A.Penin and M.Steinhauser [Phys.Lett., B538, 335]

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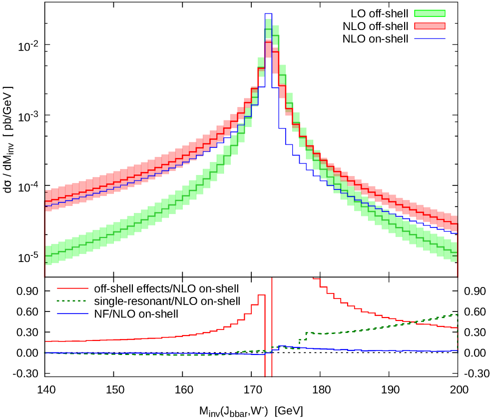
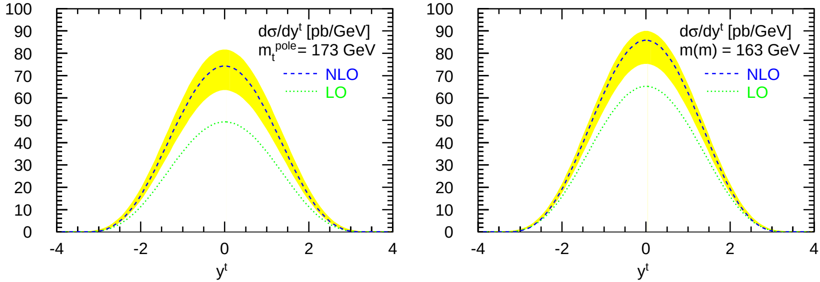
Finite Width

The top-quark is not a stable particle, which means that finite width effects should be taken into account.



P.Falgari, A.Papanastasiou, A.Signer [arXiv:1303.5299]

y Cross-section



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