Cross sections for $t\bar{t}H$ production with the top quark $\overline{\text{MS}}$ mass [arXiv:2111.12505]

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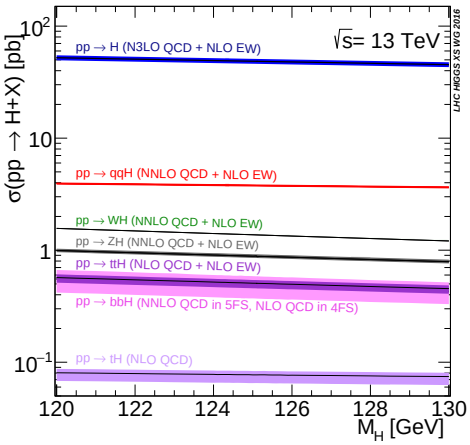
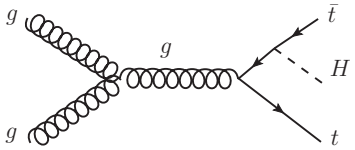
Motivation

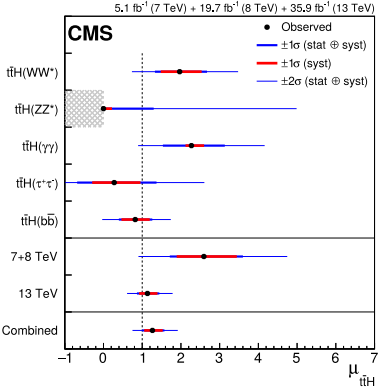


- **Higgs field** (SM):
  - Self-consistency of the Standard Model
  - Boson masses from interaction with the Higgs field
  - Main production mode at LHC: **gg→H**
- Spin-0 particle observed in 2012 by ATLAS and CMS
- **Fermions masses**:
  - Yukawa coupling: $y_f \propto m_f$
  - Studies are required to confirm SM-like nature of $m_H \approx 125$ GeV
- top-Higgs Yukawa coupling largest in SM ($\mathcal{O}(1)$)
- **BUT** gg→H only indirect study of couplings

Associated Top Quark Pair and Higgs boson production ($t\bar{t}H$)

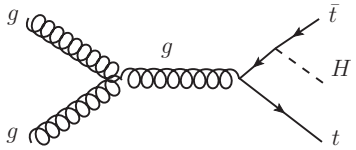


- **Associated $t\bar{t}$ and Higgs boson production** ($t\bar{t}H$)
  - **Direct probe** of top-Higgs Yukawa coupling
  - **Observation of $t\bar{t}H$ production** by ATLAS and CMS in 2018
  - In agreement with SM prediction
- **Measurement precision depends on:**
  - $t\bar{t}H$ signal modeling
  - Background composition/comprehension



[CMS, Phys.Rev.Lett. 120 (2018)]

Associated Top Quark Pair and Higgs boson production ($t\bar{t}H$)



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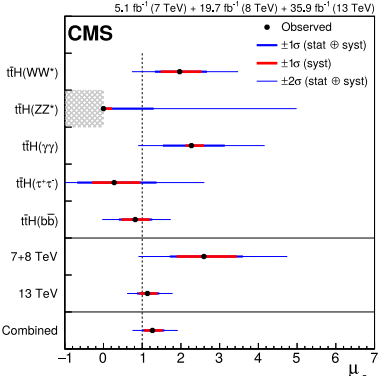
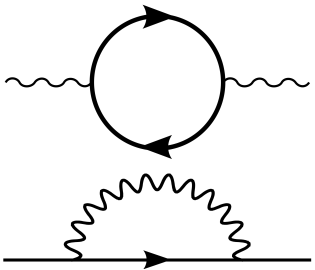


[CMS, Phys.Rev.Lett. 120 (2018)]

- **Motivation for studies:**
  Improvement of scale uncertainties, study of systematic effects!

Renormalization and the Running of Theory Parameters

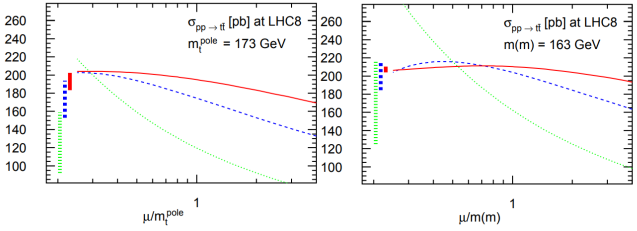
- Couplings and fermion masses are fundamental parameters of the SM
- Calculations of cross-sections:
  - Quantum corrections from vacuum polarization and self-energy
  - Divergent contributions
- **Renormalization**: Infinities subtracted at energy scale μ_R
- **Running:** Measurable quantities depend on scale $\alpha_S(\mu_R), m_q(\mu_R)$
  - Renormalization Group Equations describe energy dependence
- Definition depends on **renormalization scheme**



Motivation: $t\bar{t}H$ Production with Top Quark $\overline{\text{MS}}$ Mass

$$\frac{i}{\not{p} - m_0 - \delta m}$$

- **Pole Mass**
  - Used in state-of-the-art simulations
  - Quarks as asymptotic states
  - Intrinsic uncertainty of the order of Λ_{QCD}
- **$\overline{\text{MS}}$ Mass** (running mass)
  - Energy dependence of mass ($m_q(\mu_R)$)
  - **Improved convergence** and **smaller scale dependences** compared to pole mass shown for $t\bar{t}$ production



[Dowling, Moch, Eur.Phys.J.C 74 (2014)]

$\Rightarrow$ **$t\bar{t}H$ Production with $\overline{\text{MS}}$ mass studied for the first time!**

Calculation of Differential Cross-Sections in $\overline{\text{MS}}$ Scheme

- **Goal**: Calculate $\sigma\left(m\left(\mu_R\right)\right)$ given $\sigma\left(m_{\text{t}}^{\text{pole}}\right)$
- Using relationship: $m_{\text{t}}^{\text{pole}} = m(\mu_R)\left(1 + \frac{\alpha_S}{\pi} d_1 + ...\right)$
- Expanding in α_S

Resulting Cross-Sections in $\overline{\text{MS}}$ Scheme

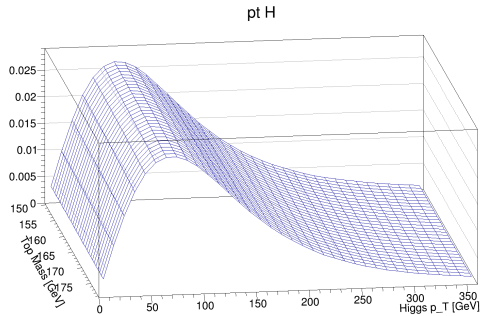
$$\frac{d\sigma\left(m\left(\mu_R\right)\right)}{dX} = \left(\frac{\alpha_s}{\pi}\right)^2 \frac{d\sigma^{(0)}\left(m\left(\mu_R\right)\right)}{dX} + \left(\frac{\alpha_s}{\pi}\right)^3 \frac{d\sigma^{(1)}\left(m\left(\mu_R\right)\right)}{dX} + \left(\frac{\alpha_s}{\pi}\right)^3 d_1 m\left(\mu_R\right) \frac{d}{dm_{\text{t}}} \left(\frac{d\sigma^{(0)}\left(m_{\text{t}}\right)}{dX}\right)\Bigg|_{m_{\text{t}}=m(\mu_R)} + O\left(\alpha_s^2\right)$$

- **Resulting Cross-Section** is independent of production process

Mass derivative needs to be calculated!

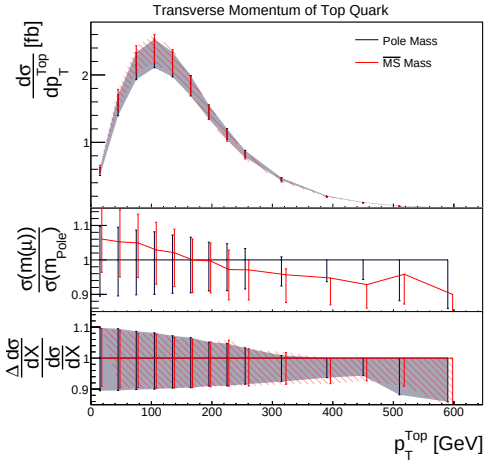
Calculation of Leading Order Mass Derivative

- Mass derivative is estimated **numerically**
  - **Advantage**: Independent of the physics process
  - **Disadvantage**: Computationally demanding
- Produce 2D differential cross-sections
- Derivative approximated with simulations of $\Delta m_t = 0.5$ GeV
- **Setup**:
  - $m_t^{\text{pole}} = 172.5$ GeV, $m_t(m_t) = 163.2$ GeV, $m_H = 125$ GeV
  - LO $\Delta\sigma = 0.1\%$
  - MMHT2014, $\alpha_S(m_Z) = 0.118$



Differential $t\bar{t}H$ Production Cross-Sections

- Comparisons: pole mass and $\overline{\text{MS}}$ mass schemes
- **Renormalization Scale Uncertainty**: Variation $\mu_R = \{\frac{1}{2}, 2\}$
- **Upper ratio**: Shape comparisons
  - Entries normalized to the cross-section in the pole mass scheme
- **Lower ratio**: Relative uncertainty comparisons
  - Uncertainty $\frac{\Delta d\sigma}{dX}$ normalized to the corresponding cross-section $\frac{d\sigma}{dX}$



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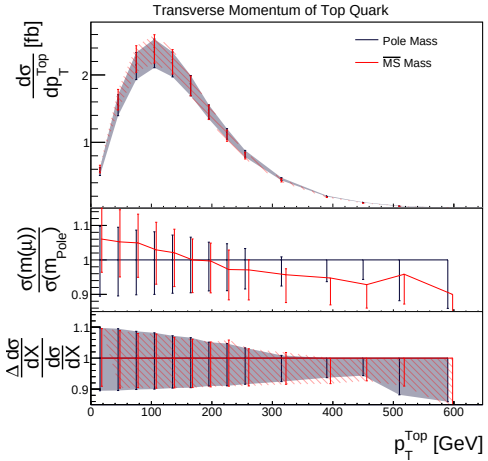
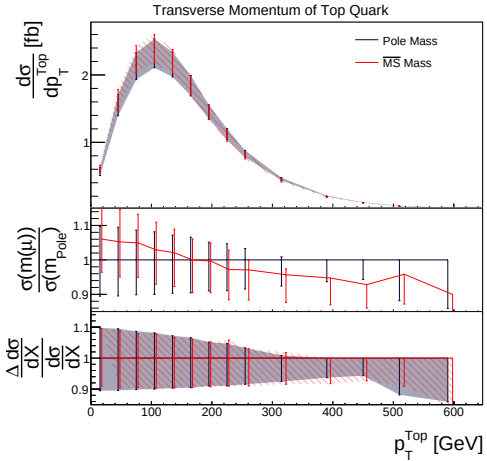
- **Distributions studied**:
  - p_T, y of top quarks and Higgs boson
  - Invariant masses: $M_{t\bar{t}}$, $M_{t\bar{t}H}$



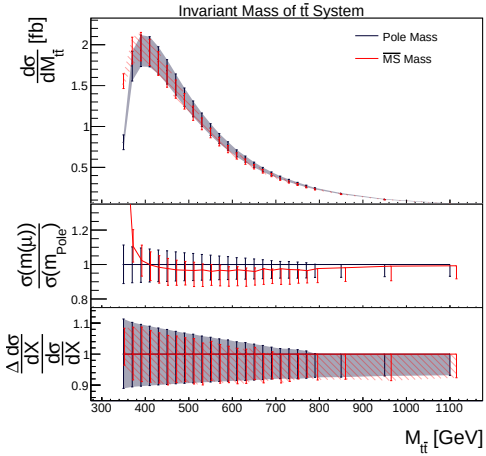
Differential $t\bar{t}H$ Production Cross-Sections

- **Transverse momentum (p_T) of the top quarks**
  - Shape difference (slope) covered by scale uncertainties
  - $\overline{\text{MS}}$ scheme: shifted to lower p_T values, peak more pronounced
  - Negligible uncertainty reduction in low p_T bins
- Similar conclusions for rapidity of top quarks!



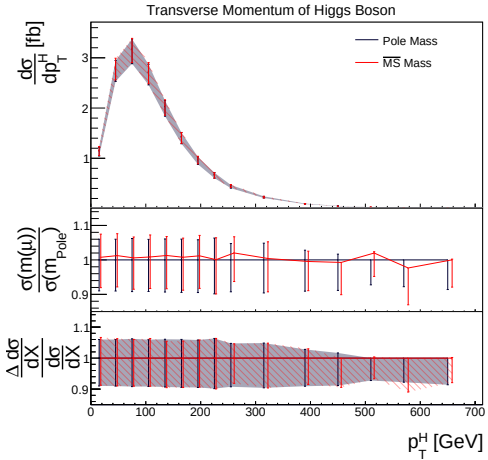
Differential $t\bar{t}H$ Production Cross-Sections

- **Invariant mass of the top quarks ($M_{t\bar{t}}$)**
  - Shape difference in low $M_{t\bar{t}}$ region
  - Scale uncertainty reduction 1-2% in $M_{t\bar{t}} < 800$ GeV
- Smaller differences for large $M_{t\bar{t}}$ values



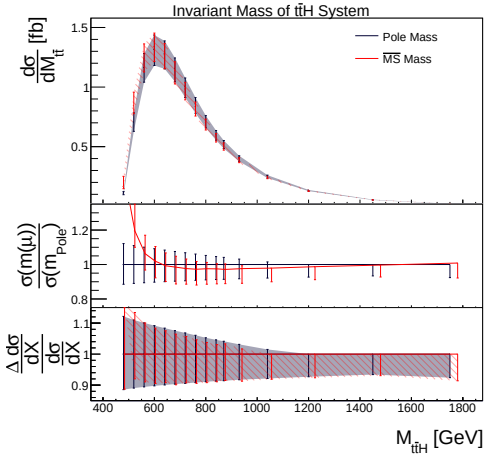
Differential $t\bar{t}H$ Production Cross-Sections

- **Transverse momentum (p_T) of the Higgs boson**
  - Similar shape across wide range of p_T
  - Similar scale uncertainties
- Behavior of the Higgs boson barely influenced by the QCD running of the top quark
- Similar conclusions for rapidity of Higgs boson!



Differential $t\bar{t}H$ Production Cross-Sections

- **Invariant Mass of $t\bar{t}H$ System**
  - Significant shape differences in low $M_{t\bar{t}H}$ region
  - Uncertainty reduction in $600\ \text{GeV} < M_{t\bar{t}H} < 1200\ \text{GeV}$
  - **Near threshold: Uncertainty in $\overline{\text{MS}}$ scheme increased!**
- $\overline{\text{MS}}$ mass defined in perturbative theory
  $\Rightarrow$ **known disadvantages close to the threshold!**



Summary

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- **First study** of $t\bar{t}H$ production with the top quark running mass in $\overline{\text{MS}}$ scheme
  - Numerical calculation of the Born-level mass derivative
  - Scale uncertainties slightly reduced top quark distributions
  - Behavior of the Higgs boson in $t\bar{t}H$ production is barely influenced by the QCD running of the top quark mass
  - Largest impact on $M_{t\bar{t}H}$, and $M_{t\bar{t}}$
- Paper available at **[arXiv:2111.12505]**

Outlook

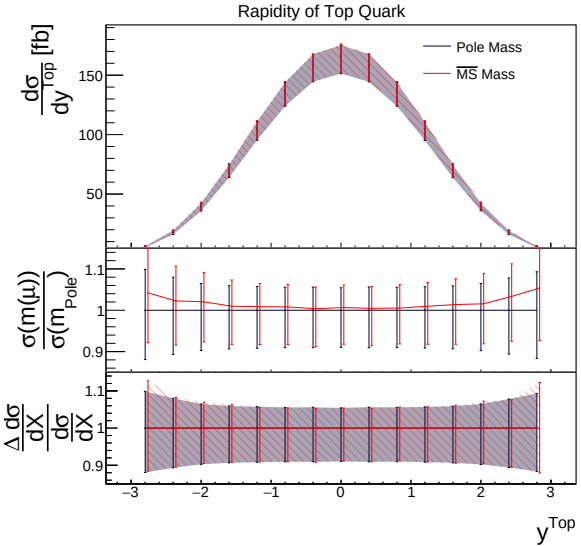
- Study of electroweak running of the top quark mass
- Shortcomings at threshold $\rightarrow$ use low-scale short-distance masses (MSR)
- Analytical Born-level derivative
- Calculation of $t\bar{t}$+X cross-sections in $\overline{\text{MS}}$ scheme can be done in the same framework!

Thank you very much for your attention!

Backup

BACKUP

Rapidity of the Top Quarks



Rapidity of the Higgs Boson