The MSR scheme for HATHOR & single-top updates

New features introduced to xFitter reactions

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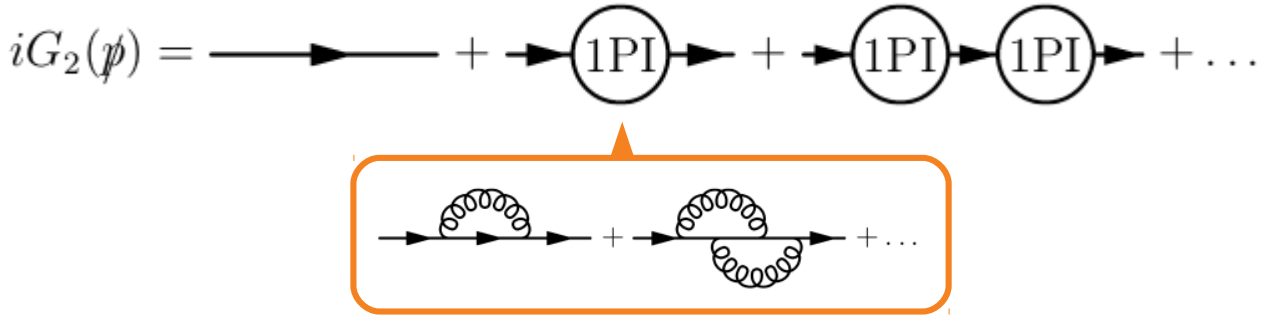
xFitter workshop, March 2022

The renormalization of the top quark mass

- A precise understanding of quark masses is important for a precise understanding of the standard model



- However, quarks are not observed as free particles, and their masses are defined formally via renormalization. E.g. two common options:
  - **The pole scheme** (pQCD equivalent of the on-shell mass of a free particle)
  - **The $\overline{\mathrm{MS}}$ scheme** (theoretical advantages)
- Although theoretically well-defined masses can be extracted from cross sections, there are long-standing discussions e.g. on how to interpret / calibrate the Monte Carlo mass parameter
  - The **MSR** mass has stirred interest in the theory and experimental communities

The MSR and $\overline{\mathrm{MS}}$ schemes

- The pole and $\overline{\mathrm{MS}}$ masses are related by

$$m_{\mathrm{t}}^{\mathrm{pole}} = \overline{m}_{\mathrm{t}}(\mu_m)\left(1 + \sum_{n=1} \frac{\alpha_S(\mu_m)^n}{\pi^n} d_n(\mu_m)\right)$$

- The MSR mass introduces a mass renormalization scale R and approaches the pole mass for $R \to 0$, and the $\overline{\mathrm{MS}}$ mass for $R \to \overline{m}_{\mathrm{t}}(\overline{m}_{\mathrm{t}})$

$$m_{\mathrm{t}}^{\mathrm{pole}} = m_{\mathrm{t}}^{\mathrm{MSR}} + R\sum_{n=1} \frac{\alpha_S(R)^n}{\pi^n} d_n^{\mathrm{MSR}}(R)$$

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Two ways to define the MSR mass lead to different decoupling coefficients

- Integrating the top quark out for scales below $\overline{m}_{\text{t}}$
  - *Natural MSR* (**MSRn**)
- Rewriting $\alpha_S^{(5+1)}$ in terms of $\alpha_S^{(5)}$
  - *Practical MSR* (**MSRp**)

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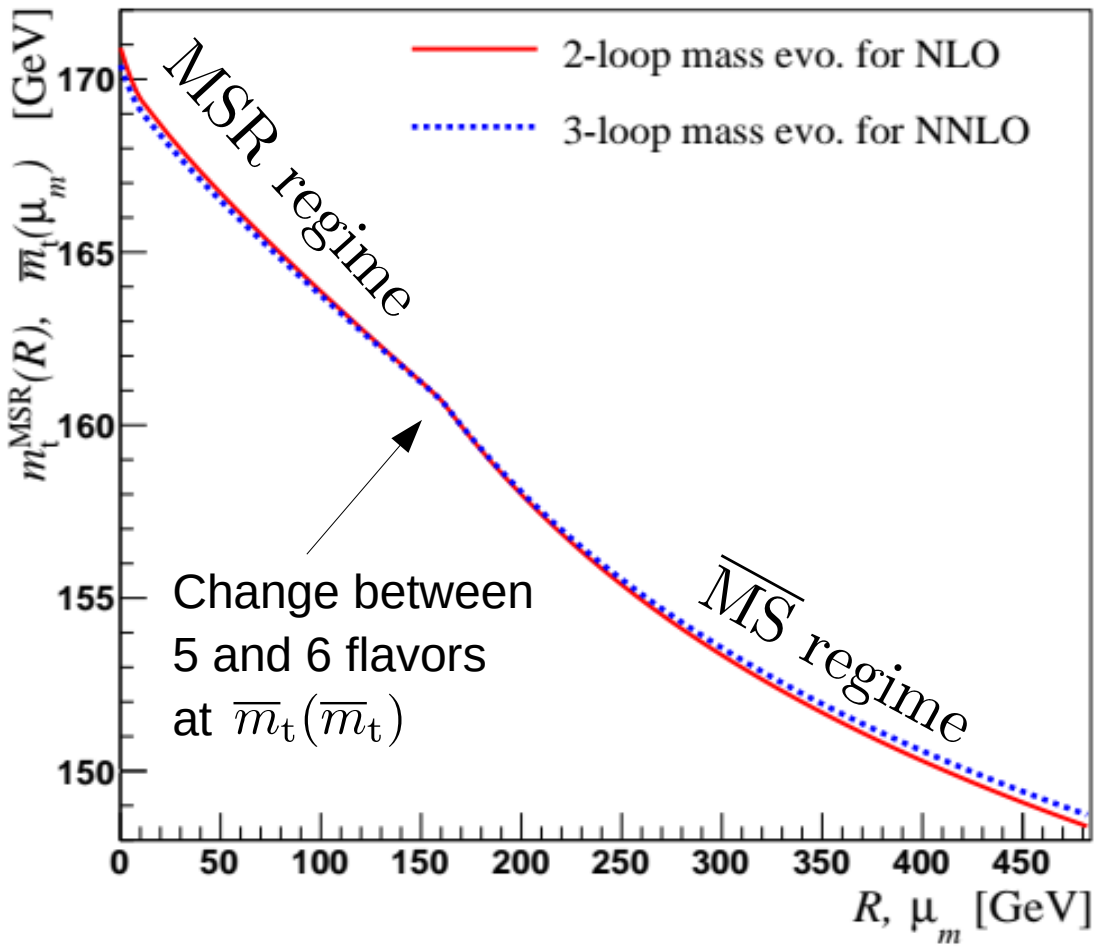
Running

- The MSR mass is mostly expected to be applied at mass scales below the $\overline{\rm MS}$ mass

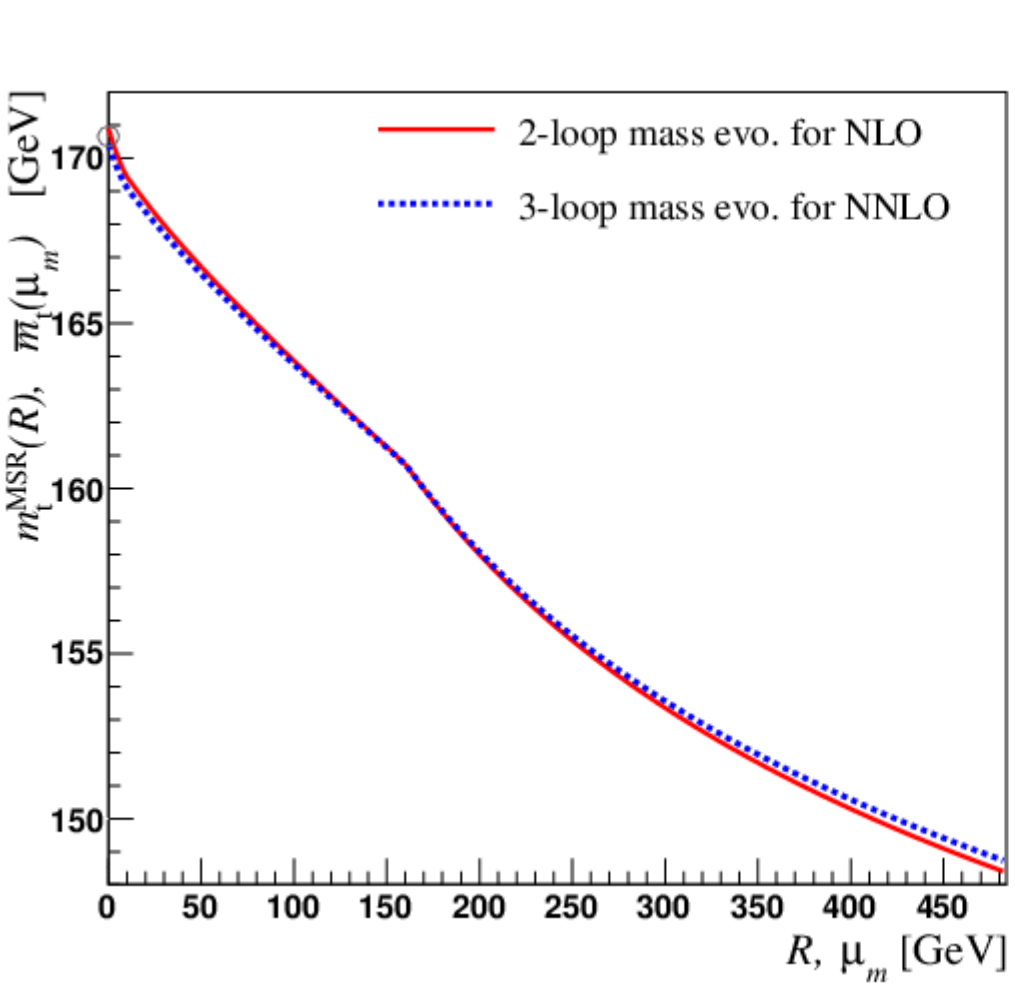


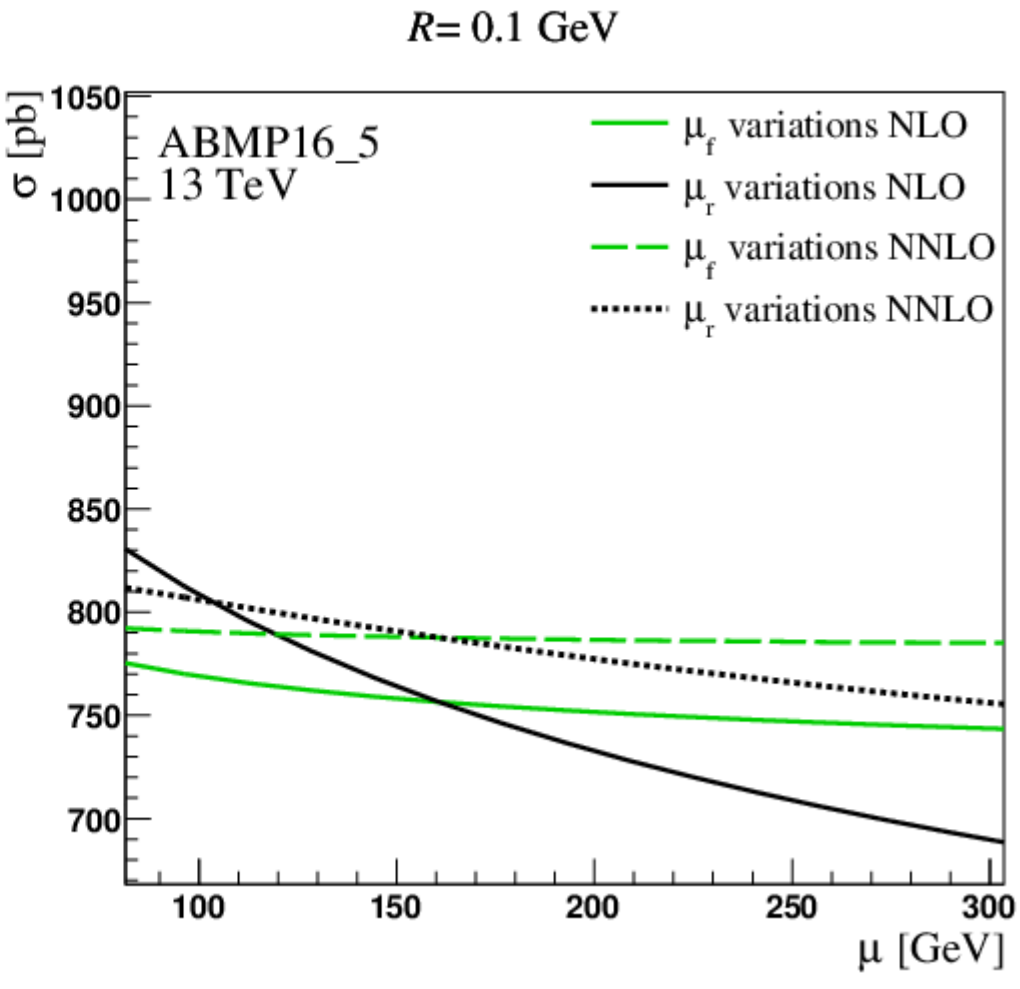
Features of the HathorMSR reaction

- Computes inclusive $\mathrm{t\bar{t}}X$ production cross sections up to NNLO
- Both the MSRp and MSRn schemes are implemented into HathorMSR
  (in addition to the pole and $\overline{\mathrm{MS}}$ implementations that already exist in default HATHOR)
- m_t can be given directly as the MSR mass, or as the $\overline{\mathrm{MS}}$ mass which is then matched to MSR and evolved to R
  - In the latter case, MSR evolution is chosen for $R < \overline{m}_\mathrm{t}(\overline{m}_\mathrm{t})$ and $\overline{\mathrm{MS}}$ for $R = \mu_m > \overline{m}_\mathrm{t}(\overline{m}_\mathrm{t})$ and the final MSR mass value is written into `output/ReactionHathorMSR.log`
- In both the MSR and $\overline{\mathrm{MS}}$ regimes, the mass scale is kept distinct from the renormalization and factorization scales

The running in the MSRn scheme

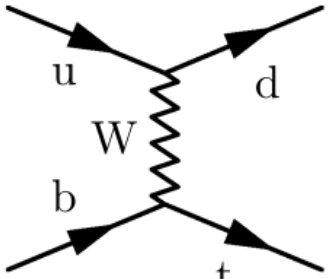
Independent μ_f, μ_r variations at different R



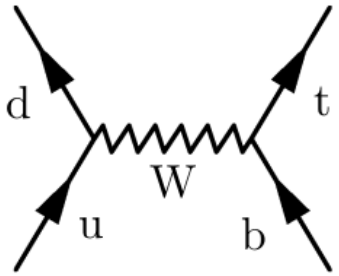


Updates to the HATHOR single top reaction

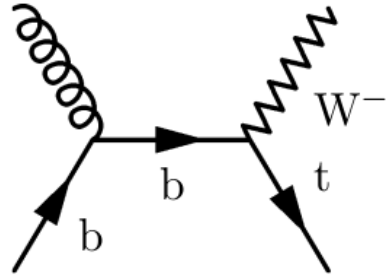
- Single top production is conventionally divided into three types of processes:



(a) t-channel



(b) s-channel



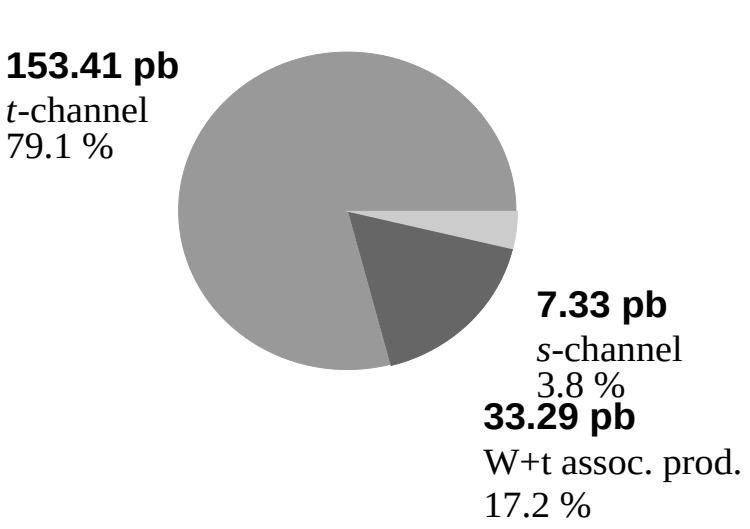
(c) W+t

- NNLO calculations are not yet publicly available for all processes, and not included in standard HATHOR 2.0
- The implementation of pole and $\overline{\mathrm{MS}}$ cross section computations is performed up to NLO
  - However, NNLO terms are included in the reaction interface
    - ➔ Easy to enable if a future HATHOR release includes NNLO, or if the user gets NNLO tables from theorists
- Any combination of the three processes can be included in the cross section calculation
- The CKM matrix and other EW parameters are read from `constants.yaml`

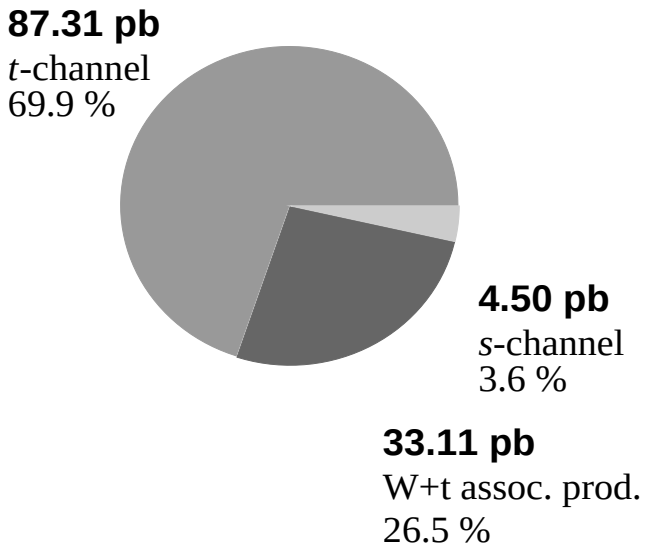
Updates to the HATHOR single top reaction

- Illustration of the processes' contributions to cross sections in the $\overline{\text{MS}}$ scheme at NLO, using ABMP16_5_nlo:

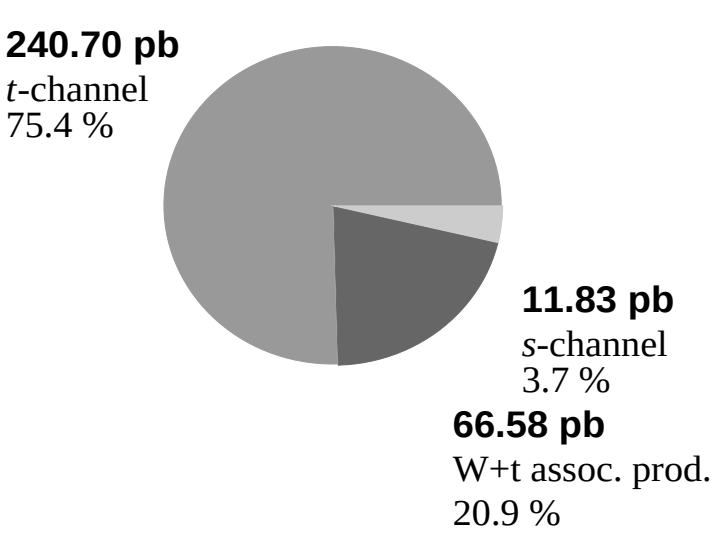
Single t, pp, $\sqrt{s}$=13 TeV



Single $\bar{t}$, pp, $\sqrt{s}$=13 TeV



Both, pp, $\sqrt{s}$=13 TeV



Summary of the HathorMSR and HathorSingleTop reactions

- The reaction interfaces contain the numerical calculations for translating the results obtained from a standard version of HATHOR 2.0 into running mass schemes.
- No changes are required to the HATHOR installed in xFitter dependencies
- For $\mathrm{t\bar{t}}X$ production, HathorMSR can be used with the pole, $\overline{\mathrm{MS}}$, MSRn and MSRp masses
- For single top production, the current implementation includes the pole and $\overline{\mathrm{MS}}$ masses
  - The implementation can be extended rather straightforwardly to MSR (or other schemes) in the future

Thanks for your attention!

Bonus: $t\bar{t}X$ production in MCFM

- An implementation of the MSR schemes to MCFM v 6.8 is currently well underway
- The code is in the validation phase
- This will enable computing single-differential cross sections

As a first check, both programs produce consistent inclusive cross sections