Soft Gluon Resummation for the Associated Single Top and Higgs Production at the LHC

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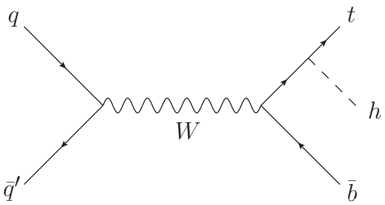
Graduiertenkolleg 2149 Research Training Group

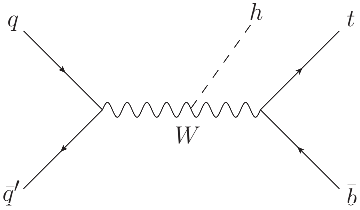
- Beyond-the-Standard Model (BSM) physics search
  - Precision calculations ⇒ find deviations between theoretical predictions and experimental data
  - Higgs and top quark processes are of particular interest: direct access to Yukawa coupling
- $pp \to Htj$: very small cross section, $g_{hWW}/g_{ht\bar{t}}$, very **sensitive** to new physics, currently being measured together with $t\bar{t}H$
  [ATLAS Collaboration PRL.125.061802 (2015)] *[CMS Collaboration PRD.99.092005 (2019)]*

GOAL: extend the precision of theoretical predictions beyond the known NLO accuracy by resumming soft-gluon corrections to all-orders for the Htj production

FIRST STEP: s-channel (ca. 35% NLO QCD corrections)

- Tree-level Feynman diagrams in s-channel $pp \to Htj$





$$\sigma_{pp\to Htj}(\{m^2\}) = \sum_{i,k} \int \mathrm{d}x_1 \int \mathrm{d}x_2 \quad \underbrace{f_i(x_1,\mu_F^2) \quad f_k(x_2,\mu_F^2)}_{\text{parton distribution functions (PDFs)}}$$

$$\times \underbrace{\hat{\sigma}_{ik\to Htj}(x_1, x_2, \alpha_s(\mu_R^2), \{m^2\}, \mu_F^2)}_{\text{partonic cross section}}$$

- Higher order contributions to σ
  - Next-to-leading order (NLO) known *[Demartin, Maltoni, Mawatari, Zaro (2015)]*
  - NLO QCD+EW corrections for all combined channels *[Pagani, Tsinikos, Vryonidou (2020)]*
  - Full NNLO for Htj not available
    - aNNLO t-channel recently calculated *[Forslund, Kidonakis (2020, 2021)]*
  - Soft gluon corrections: well-defined class of higher-order corrections, can be resummed to all orders (achieved for $t\bar{t}H$) *[Kulesza, Motyka, Schwartländer, Stebel, Theeuwes (2020)] [Broggio, Ferroglia, Frederix, Pagani, Pecjak, Tsinikos (2019)]*

- Improving theoretical precision: adding contributions from soft gluon emission
  - Gluons emitted from coloured particles
  - Close to production threshold, only soft gluons
  - Logarithmic form with logarithms becoming large as threshold is approached
  - Depending on the observable, various measures of softness w ($\sim$ distance to threshold) are used

$$w = 1 - z = 1 - Q^2/s \quad \text{(Invariant Mass Threshold)} \quad \rightarrow \quad \left[\frac{\ln(1-z)}{1-z}\right]_+$$

- Soft Gluon Resummation

$$\sigma \sim 1 + \alpha_s \left(L + 1\right) + \alpha_s^2 \left(L^3 + L^2 + L + 1\right) + \ldots$$

  - Large logs (L) can invalidate predictive power of perturbative series in α_s
  - Systematic treatment to all orders: resummation
  - Relies on: $|\mathcal{M}|^2$ and Phase Space factorization $\rightarrow$ Mellin space

$$\int_0^1 \mathrm{d}z\, z^{N-1}\, f(z) = \{\mathcal{M} f\}(N) \equiv f_N \equiv \tilde{f}_N$$

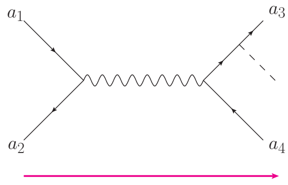
- Resummed Logarithms: $\alpha_s^{n} \left[\frac{\ln^{k}(1-z)}{1-z}\right]_+$, $k \leq 2n - 1$

- Resummed partonic cross section for $pp \to Htj$

$$\begin{aligned}\hat{\tilde{\sigma}}^{(\mathrm{NLL})}_{ij\to tHk} &= \mathrm{Tr}\left[\mathbf{H}_{ij\to tHk}\,\mathbf{S}_{ij\to tHk}\right]\Delta_i\,\Delta_j\,\mathcal{J}_k \\ &= \mathrm{Tr}\left[\mathbf{H}_{ij\to tHk}\,\bar{\mathbf{U}}_{ij\to tHk}\,\tilde{\mathbf{S}}_{ij\to tHk}\,\mathbf{U}_{ij\to tHk}\right]\Delta_i\,\Delta_j\,\mathcal{J}_k\end{aligned}$$

with

$$\mathbf{U}_{ij\to tHk}(N, Q^2, \mu_F^2, \mu_R^2) = \mathrm{P}\,\exp\left[\int_{\mu}^{Q/\tilde{N}} \frac{dq}{q}\,\mathbf{\Gamma}_{ij\to tHk}\left(\alpha_s(q^2)\right)\right]$$



Natural choice: s-channel colour basis

$$c_1^{\text{s-ch}} = \delta_{a_1 a_2}\delta_{a_3 a_4}$$
$$c_2^{\text{s-ch}} = T^c_{a_2 a_1} T^c_{a_3 a_4} = $$
$$= \frac{1}{2}\left(\delta_{a_1 a_3}\delta_{a_2 a_4} - \frac{1}{N_c}\delta_{a_1 a_2}\delta_{a_3 a_4}\right)$$

$$\text{Orthogonal} \Rightarrow \tilde{\mathbf{S}}^{(0)} = \begin{pmatrix} |c_1^{\text{s-ch}}|^2 & 0 \\ 0 & |c_2^{\text{s-ch}}|^2 \end{pmatrix} = \begin{pmatrix} N_c^2 & 0 \\ 0 & \frac{N_c^2-1}{4} \end{pmatrix}$$

$$\mathcal{M} = \mathcal{M}'\delta_{a_1 a_2}\delta_{a_3 a_4} = \mathcal{M}' c_1^{\text{s-ch}} \Rightarrow \mathbf{H}^{(0)} = \begin{pmatrix} |\mathcal{M}'|^2 & 0 \\ 0 & 0 \end{pmatrix}$$

- One-loop Soft Anomalous Dimension $\mathbf{\Gamma}^{(1)}_{q\bar{q}'\to tHk}$ checked with [Forslund, Kidonakis (2020)]

$$\mathbf{\Gamma}_{q\bar{q}'\to tHk}(\alpha_s) = \left(\frac{\alpha_s}{\pi}\right)\mathbf{\Gamma}^{(1)}_{q\bar{q}'\to tHk} + \left(\frac{\alpha_s}{\pi}\right)^2 \mathbf{\Gamma}^{(2)}_{q\bar{q}'\to tHk} + \ldots$$

$$\begin{aligned}
\mathbf{\Gamma}^{(1)}_{11,q\bar{q}'\to tHk} &= C_F\left(\log\frac{s_{tk}-m_t^2}{m_t\sqrt{s}} - \frac{1}{2}\right)\\
\mathbf{\Gamma}^{(1)}_{12,q\bar{q}'\to tHk} &= \frac{C_F}{2N_c}\log\frac{\tilde{t}_{qt}\tilde{t}_{\bar{q}'k}}{\tilde{t}_{\bar{q}'t}\tilde{t}_{qk}}\\
\mathbf{\Gamma}^{(1)}_{21,q\bar{q}'\to tHk} &= \log\frac{\tilde{t}_{qt}\tilde{t}_{\bar{q}'k}}{\tilde{t}_{\bar{q}'t}\tilde{t}_{qk}}\\
\mathbf{\Gamma}^{(1)}_{22,q\bar{q}'\to tHk} &= C_F\left(\log\frac{s_{tk}-m_t^2}{m_t\sqrt{s}} - \frac{1}{2}\right) + \frac{4C_F-N_c}{2}\log\frac{\tilde{t}_{qt}\tilde{t}_{\bar{q}'k}}{\tilde{t}_{\bar{q}'t}\tilde{t}_{qk}} + \frac{N_c}{2}\log\frac{\tilde{t}_{qk}\tilde{t}_{\bar{q}'t}}{s(s_{tk}-m_t^2)}
\end{aligned}$$

with $s = (p_a+p_b)^2$, $s_{ij} = (p_i+p_j)^2$, $\tilde{t}_{ij} = (p_i-p_j)^2 - m_j^2$.

- We take exponential functions at NLL accuracy
- **H** and $\tilde{\mathbf{S}}$ up to $\mathcal{O}(\alpha_s)$

$$\mathbf{H}(\mu_R, \mu_F) = \mathbf{H}^{(0)} + \frac{\alpha_s(\mu_R)}{\pi}\mathbf{H}^{(1)}(\mu_R, \mu_F)$$

$$\tilde{\mathbf{S}}(1) = \tilde{\mathbf{S}}^{(0)}\left(\mathbf{1} + \frac{\alpha_s(\mu_R)}{\pi}\tilde{\mathbf{S}}^{(1)}(1)\right)$$

- Resulting in NLLwC accuracy (NLL' in SCET notation)

$$\mathbf{H}\,\tilde{\mathbf{S}} = \mathbf{H}^{(0)}\,\tilde{\mathbf{S}}^{(0)}\left(\mathbf{1} + \frac{\alpha_s}{\pi}\mathbf{C}^{(1)}\right)$$

Invariant mass threshold:

- Massless jet at threshold ($p_j^2 = 0$):

  $1 - z = 1 - \frac{(p_H+p_t)^2+2p_j\cdot(p_H+p_t)}{\hat{s}}$

  In $\mathcal{J}_k$: double and single log at $\mathcal{O}(\alpha_s)$

  Outgoing collinear contribution in $\mathbf{C}^{(1)}$: subleading terms in N

- Massive jet at threshold:

  $1 - z = 1 - \frac{Q^2}{\hat{s}}$, with $Q^2 = (p_H + p_t + p_j)^2$

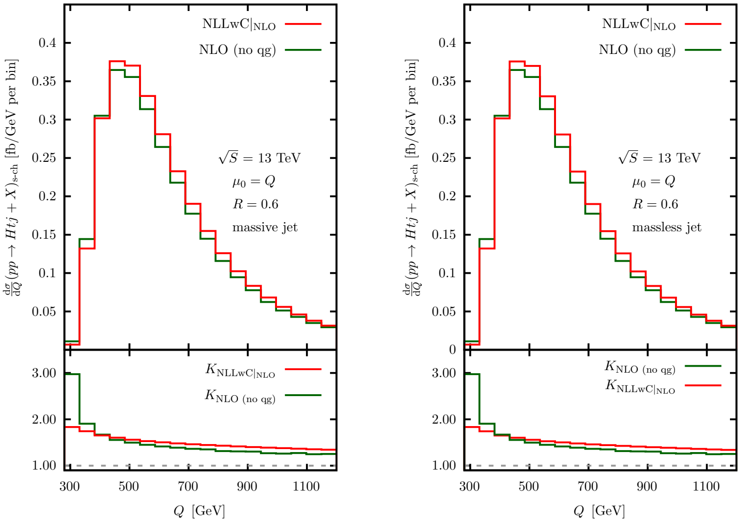
  In $\mathcal{J}_k$: single log at $\mathcal{O}(\alpha_s)$

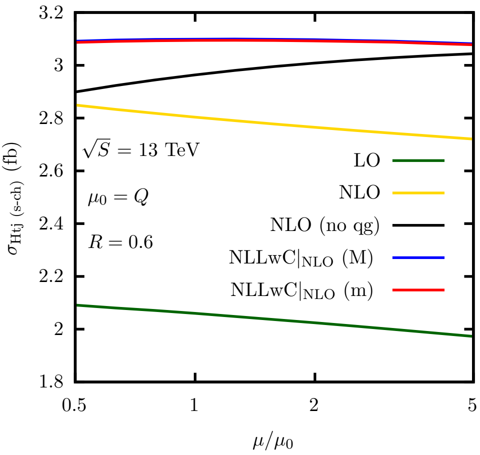
[Kidonakis, Oderda, Sterman (1998)]

- Matching to NLO cross section

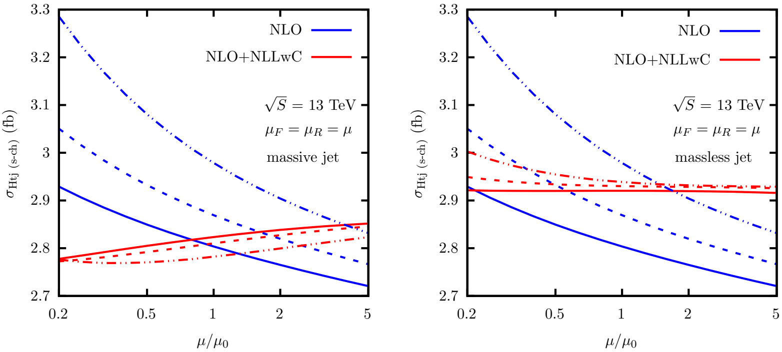
$$\sigma^{NLO+NLLwC}_{pp\to Htj} = \sigma^{NLO}_{pp\to Htj} + \sum_{i,k} \int \frac{\mathrm{d}N}{2\pi i} \rho_h^{-N} \tilde{f}_i(N+1,\mu_F^2) \tilde{f}_k(N+1,\mu_F^2) \times \underbrace{\left[\tilde{\sigma}^{NLLwC}_{ik\to Htj}(N) - \tilde{\sigma}^{NLLwC}_{ik\to Htj}(N)\Big|_{NLO} \right]}_{\text{avoid double counting with NLO!}}$$

- $q\bar{q}'$ channel at NLO+NLLwC
- qg channel at NLO


NLLwC|NLO
NLO (no qg)
$\sqrt{S}$ = 13 TeV
$\mu_0 = Q$
$R = 0.6$
massive jet
massless jet
$\frac{d\sigma}{dQ}(pp \to Htj + X)_{\text{s-ch}}$ [fb/GeV per bin]
$K_{\text{NLLwC}|\text{NLO}}$
$K_{\text{NLO (no qg)}}$
Q [GeV]
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
3.00
2.00
1.00
300
500
700
900
1100


3.2
3
2.8
2.6
2.4
2.2
2
1.8
0.5
1
2
5
$\sigma_{\mathrm{Htj\ (s\text{-}ch)}}$ (fb)
μ/μ_0
$\sqrt{S} = 13$ TeV
$\mu_0 = Q$
$R = 0.6$
LO
NLO
NLO (no qg)
NLLwC$|_{\mathrm{NLO}}$ (M)
NLLwC$|_{\mathrm{NLO}}$ (m)

Different central scale choices: Q: —, $H_T/2$: - - -, $H_T/6$:–··–



- Associated top and Higgs production very important for BSM searches: coupling $t\bar{t}H$
- Extending precision of theoretical calculations beyond NLO
- Effects of soft gluon emission at NLLwC
- Different jet treatment: massive and massless at threshold
- Reduced scale dependence NLO+NLLwC

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