

Beyond the narrow-width limit for off-shell and boosted differential top quark decays

FAKT Workshop 2024

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with

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February 22, 2024



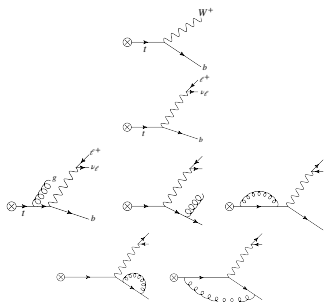
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Particles and Interactions



Motivation

- The top quark is a **sensitive probe** of searches of physics beyond the Standard Model (m_t measurements [CMS collaboration, Eur.Phys. J.C. 83 (2023) 7, 560]).
- We are investigating the **decay of boosted top quarks**.
- Common approaches in FOPT:
 - **Narrow-width (NW) limit:** Factorisation of top production and decay, top on-shell limit, state-of-the-art: NNLO QCD [Catani, S. et al., JHEP 07, 100 (2019)].
 - **Off-shell fixed-order:** includes finite life-time effects, non-resonant and non-factorisable corrections, state-of-the-art: NLO QCD.
- Our approach: Combine factorisation property of NW-limit with full off-shell calculation (expansion in m_t^2/Q^2).
 - **Factorised approach** for **boosted** top quarks, allows for gauge-invariant description of off-shell effects within effective field theory framework of **soft-collinear effective theory (SCET)**.
 - Account for **resummed QCD corrections** for differential top decay observables.
 - **Universal** form of off-shell top decay and collinear gluon radiative effects.



Soft-collinear effective theory (SCET)

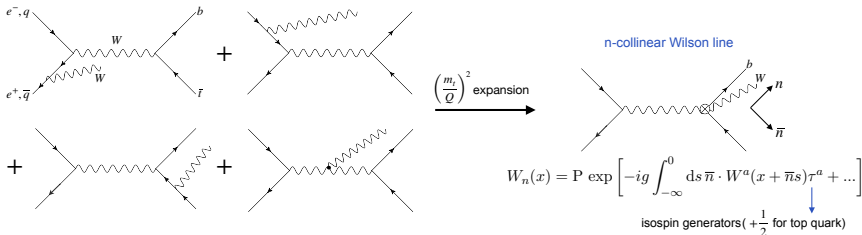
- SCET: describe long-distance physics given by emission of soft and collinear particles, e.g.
 - Decay of heavy particle in its rest frame into light particles
 - Production of energetic top decay jet in boosted top production

- Power-counting:

$$p^\mu = \frac{\bar{n}^\mu}{2} \underbrace{n \cdot p}_{p^+} + \frac{n^\mu}{2} \underbrace{\bar{n} \cdot p}_{p^-} + \underbrace{p_\perp^\mu}_{\vec{p}_\perp} \equiv (p^+, p^-, \vec{p}_\perp)$$

collinear modes: $p_n^\mu \approx Q(\lambda^2, 1, \lambda)$ hard modes: $p_h^\mu \approx Q(1, 1, 1)$
 $p_{\bar{n}}^\mu \approx Q(1, \lambda^2, \lambda)$ soft modes: $p_s^\mu \approx Q(\lambda^2, \lambda^2, \lambda^2)$

- Wilson line (example for $(e^+e^-, q\bar{q}) \rightarrow bW^+\bar{t}$):



Soft-collinear effective theory (SCET)

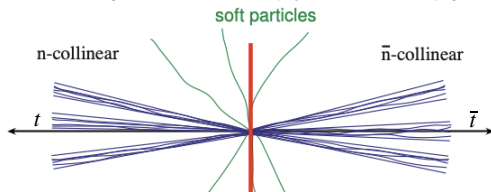
- Application of the SCET framework to boosted top jet production in $e^+e^- \rightarrow t\bar{t}$, valid for CM energies $Q \gg m_t$.
- Important application of the SCET framework to boosted top jet production: determine **factorisation theorems** of the hard interaction, the soft and collinear sectors:

$$\frac{d^2\sigma}{dM_{t\bar{t}}^2 M_{t\bar{t}}^2} \approx \sigma_0 H_Q(Q, \mu) \int dl^+ dl^- J_n(s_t - Ql^+, \mu) J_{\bar{n}}(s_{\bar{t}} - Ql^-, \mu) S(l^+, l^-, \mu),$$

allows to resum logs of $\frac{m_t^2}{Q^2}, \frac{\Gamma_t}{m_t}$

with $s_{t,\bar{t}} = M_{t,\bar{t}}^2 - m_t^2$.

- It allows one to **separate** the dynamics of the **top jet**, the anti-top jet and **soft emissions**.



- Approach also applicable for $p\bar{p} \rightarrow t\bar{t}$.

Figure adapted from Fleming, S., Hoang, A. H., Mantry, S. & Stewart, I. W. Jets from massive unstable particles: Top-mass determination. *Physical Review D* **77** (2008)

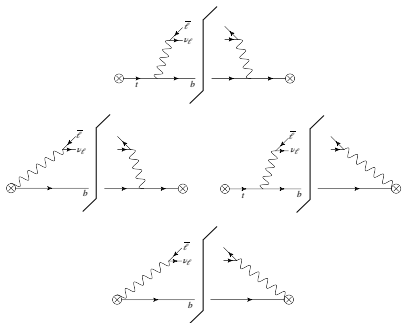
Electro-weak top jet function

$$\begin{aligned}
 & \text{chirality conserving} \downarrow \\
 & J_n^{\text{LL/RR}}(p^2) = \frac{1}{N_c (\bar{n} \cdot p)} \sum_X (2\pi)^3 \delta^{(4)}(p - P_X) \text{Tr} \left[\langle 0 | \frac{\not{\bar{n}}}{4} \chi_n^{\text{L/R}}(0) | X \rangle \langle X | \overline{\chi_n^{\text{L/R}}}(0) | 0 \rangle \right] \\
 & \begin{array}{l} \nearrow \text{n-collinear} \\ \uparrow \text{top momentum} \end{array}
 \end{aligned}$$

symbolic final/initial states
 \uparrow jet fields $\chi_n^{\text{L/R}} = W_n^\dagger P_{\text{L/R}} \xi_n$
 \downarrow electro-weak+QCD n-collinear Wilson line

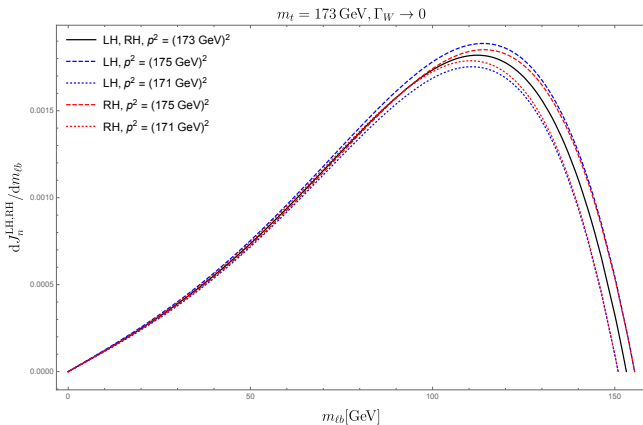
Emergence of **universal, gauge-invariant jet function**:

- Generalisation to off-shell top quark in a gauge-invariant way.
- Can be combined with top spin density matrix formalism (\rightarrow spin correlations).
- Possible application: Top spin measurements for off-shell top decay.



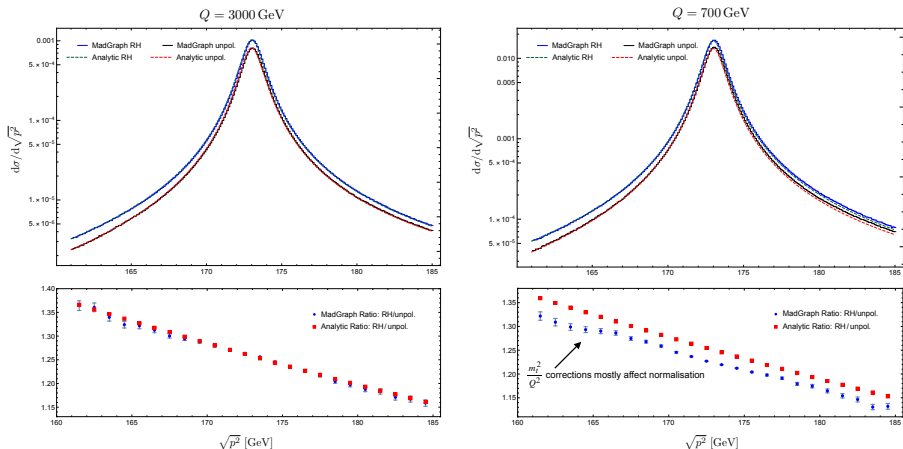
Differential electro-weak top jet functions

- Analysed the impact of **varying the off-shellness** of the top quark in comparison to the narrow width (on-shell top) limit.
- The NW limit assumes a **factorisation of the production** of the unstable particle in the on-shell approximation and the subsequent **on-shell decay**.



Comparison to MadGraph

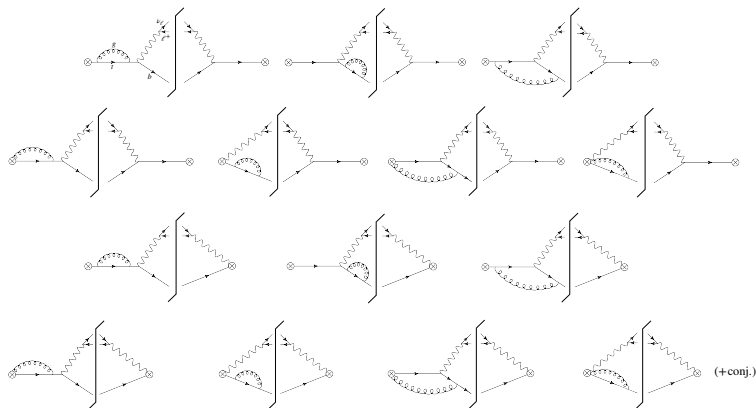
Compare our result to common fixed-order approach given by MadGraph[†] for $e^+e^- \rightarrow bW^+\bar{t}$ with $p^2 = (p_b + p_w)^2$:



[†] Alwall, J., Frederix, R., Frixione, S., Hirschi, V., Maltoni, F., Mattelaer, O., Shao, H.-S., Stelzer, T., Torrielli, P. & Zaro, M. The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. *Journal of High Energy Physics* 2014 (2014)

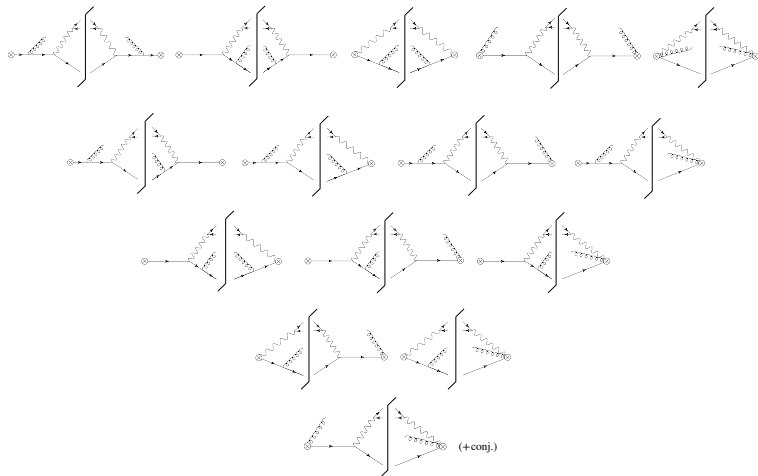
Electro-weak top jet functions with QCD corrections

- Include **NLO QCD corrections**: Virtual exchange



Electro-weak top jet functions with QCD corrections

- Include **NLO QCD corrections**: Real emission



Electro-weak top jet functions with QCD corrections

- Include **NLO QCD corrections** (virtual exchange and real emission).
- The **high multiplicity** of particles in the **final state** requires a **numerical (subtraction) approach** (Monte-Carlo simulation for PS integration).
- Before numerical methods can be used, IR divergences have to be analytically cancelled between real and virtual contributions.

→ “**Subtraction methods**”

- Using a suitable **momentum-mapping** ($p_b, q_w, q_g \rightarrow \tilde{p}_b, \tilde{q}_w$) one systematically isolates the (leading) singularities of the real emission matrix element.

$$\begin{aligned} d\phi_{n+1} |\mathcal{M}_{n+1}^R|^2 + d\phi_n |\mathcal{M}_n^V|^2 &= \left[d\phi_{n+1} (|\mathcal{M}_{n+1}^R|^2 - |\mathcal{M}_{\text{LO}}^c|^2 \mathcal{V}) \right] \\ &+ \left[d\phi_n |\mathcal{M}_n^V|^2 + d\phi_n |\mathcal{M}_{\text{LO}}^c|^2 d\phi_1 \mathcal{V} \right] . \end{aligned}$$

Conclusion & Outlook

- For **boosted top quarks** we combine the **factorisation property** of the NW limit and the **full off-shell approach** using an expansion in m_t^2/Q^2 , taking into account both **QCD and electro-weak effects** in gauge-invariant way.
- Include **finite life-time effects** for the **top quark** → go beyond the NW limit for top quark (up to leading order in m_t^2/Q^2), can be combined with spin-density matrix formalism (spin-correlations).
- Our calculation is fully analytical at LO QCD, numerical subtraction method at NLO QCD → **development of flexible Monte-Carlo simulation**.
- Current objective: Determine **suitable subtraction terms** for the real emission contributions.

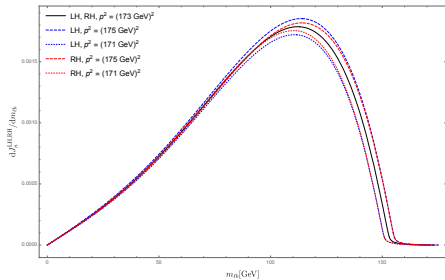
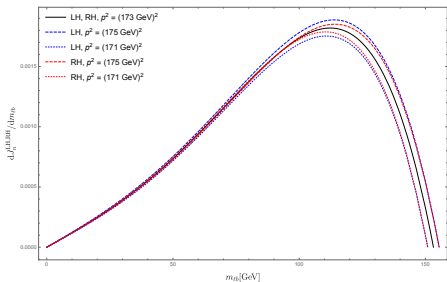
Thank you for your attention!

Central references

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Back-up

Comparison between NW-limit and full off-shell treatment for W -boson in $m_{\ell b}$:



Back-up

Comparison between NW-limit and full off-shell treatment for W -boson in E_ℓ :

