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

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with

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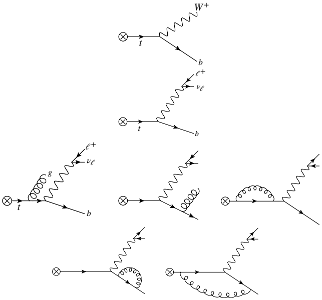
Motivation

- 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)

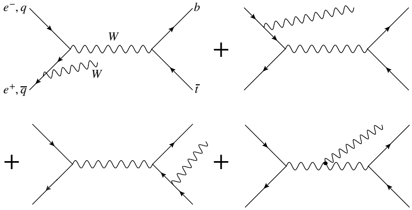
- SCET: describe long-distance physics given by emission of soft and collinear particles, e.g.
  - Decay of heavy particle in its rest frame into light particles
  - Production of energetic top decay jet in boosted top production
- Power-counting:

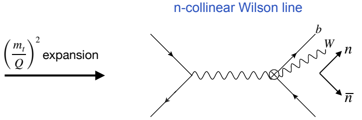
$$p^\mu = \frac{\bar{n}^\mu}{2}\underbrace{n \cdot p}_{p^+} + \frac{n^\mu}{2}\underbrace{\bar{n} \cdot p}_{p^-} + \underbrace{p_\perp^\mu}_{\vec{p}_\perp} \equiv (p^+, p^-, \vec{p}_\perp)$$

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





$$W_n(x) = \mathrm{P}\ \exp\left[-ig\int_{-\infty}^{0} \mathrm{d}s\, \bar{n}\cdot W^a(x+\bar{n}s)\tau^a + ...\right]$$

isospin generators ($+\frac{1}{2}$ for top quark)

Soft-collinear effective theory (SCET)

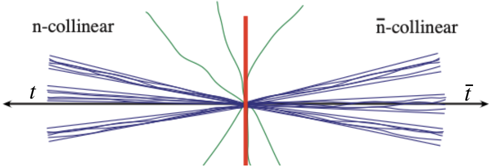
- Application of the SCET framework to boosted top jet production in $e^+e^- \to t\bar{t}$, valid for CM energies $Q \gg m_t$.
- Important application of the SCET framework to boosted top jet production: determine factorisation theorems of the hard interaction, the soft and collinear sectors:

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

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 $p\bar{p} \to t\bar{t}$.

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

chirality conserving

symbolic final/initial states

$$J_n^{\mathrm{LL/RR}}(p^2) = \frac{1}{N_c\,(\bar{n}\cdot p)} \sum_X (2\pi)^3\,\delta^{(4)}(p - P_X)\,\mathrm{Tr}\Big[\,\langle 0|\,\frac{\bar{\not{n}}}{4}\,\chi_n^{\mathrm{L/R}}(0)\,|X\rangle\,\langle X|\,\overline{\chi_n^{\mathrm{L/R}}}(0)\,|0\rangle\,\Big]$$

n-collinear

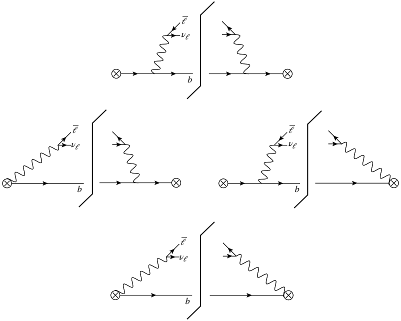
top momentum

jet fields $\chi_n^{\mathrm{L/R}} = W_n^\dagger P_{\mathrm{L/R}}\xi_n$

electro-weak+QCD n-collinear Wilson line

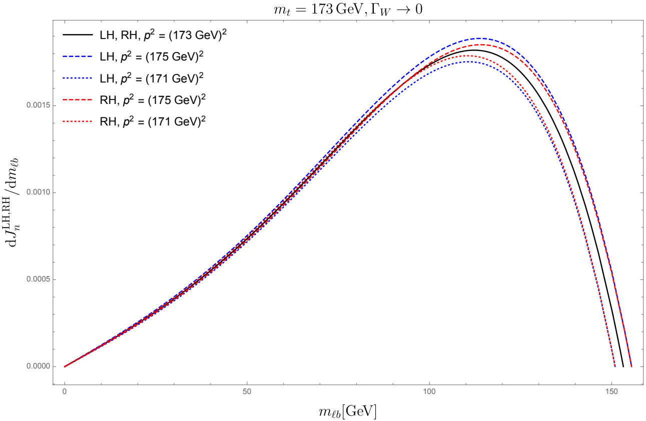
Emergence of universal, gauge-invariant jet function:

- 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.



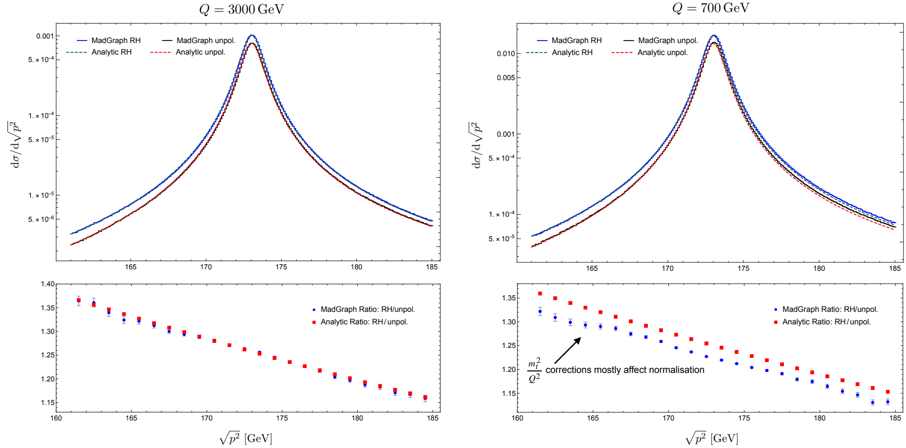
Differential electro-weak top jet functions

- 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

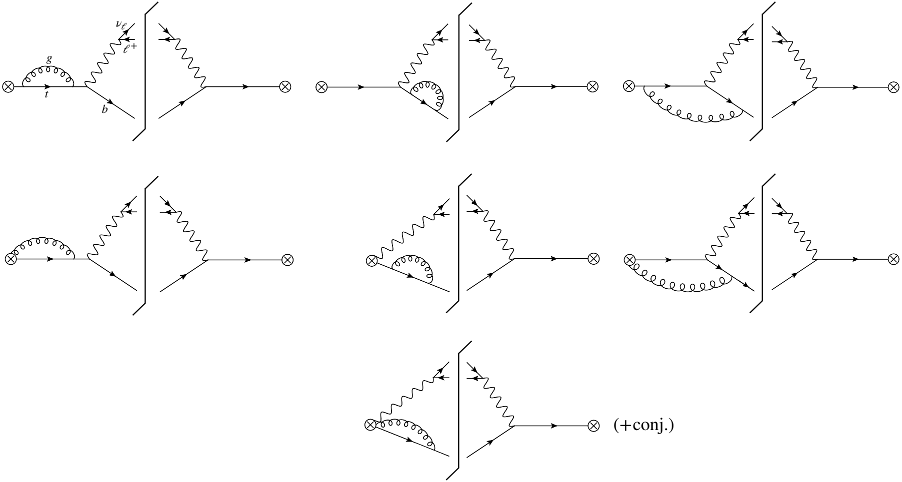
Compare our result to common fixed-order approach given by MadGraph† for $e^+e^- \to bW^+\bar{t}$ with $p^2 = (p_b + p_w)^2$:



† 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)

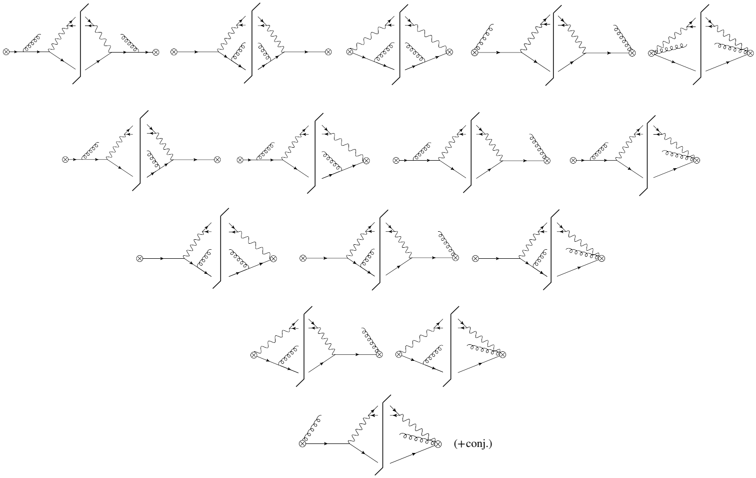
Electro-weak top jet functions with QCD corrections

- 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.

$\rightarrow$ "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.

$$\mathrm{d}\phi_{n+1}\,|\mathcal{M}^R_{n+1}|^2 + \mathrm{d}\phi_n\,|\mathcal{M}^V_n|^2 = \left[\mathrm{d}\phi_{n+1}\,(|\mathcal{M}^R_{n+1}|^2 - |\mathcal{M}^c_{\mathrm{LO}}|^2\mathcal{V})\right] + \left[\mathrm{d}\phi_n|\mathcal{M}^V_n|^2 + \mathrm{d}\phi_n|\mathcal{M}^c_{\mathrm{LO}}|^2\mathrm{d}\phi_1\mathcal{V}\right]\ .$$

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 $\rightarrow$ 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 $\rightarrow$ 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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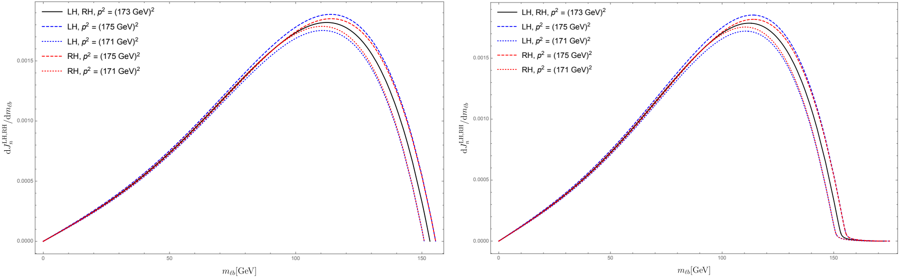
Back-up

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: