An EFT approach to finite-width effects

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High precision fundamental constants at the TeV scale

18th March 2014, MITP, Mainz

*Work with:

Pietro Falgari and Adrian Signer (PSI), arXiv:1303.5299

(see also Falgari, Gianuzzi, Mellor, Signer: 1007.0893, 1102.5267)

Offshell tops, finite Γ_t and m_t

- theory: m_t definition requires at least NLO
- many experimental extractions of m_t rely on creation of templates via parton-shower (PS) Monte-Carlos (MC), for observables intrinsically sensitive to offshellness of tops
- NLO hard matrix elements in MCs only available for onshell tops and only corrections to production

  (decay corrections, production-decay interferences not included)

  (PS used to decay tops at LO, often with a Breit-Wigner smearing)
- what are systematics introduced in m_t-extraction by not including off-shell top quarks at hard matrix-element level at NLO?
- study begins at parton-level ...

Huge recent progress at NLO

Narrow-width approximation (NWA): $p_t^2 = m_t^2$

$$\frac{1}{(p_t^2 - m_t^2)^2 + m_t^2\Gamma_t^2} \to \frac{\pi}{m_t\Gamma_t}\delta(p_t^2 - m_t^2) + \mathcal{O}(\Gamma_t/m_t)$$

$t\bar{t}$ production & decays: [Bernreuther, Brandenburg, Si, Uwer '04] , [Melnikov, Schulze '09] [Bernreuther, Si '10] , [Campbell, Ellis '12]

Single-top with decays: [Campbell, Ellis, Tramontano '04, '12] [Heim, Cao, Schweinhorst, Yuan '10, '11]

Complex-mass scheme (CMS) [Denner, Dittmaier, Roth, Wieders '05] : $p_t^2 \neq m_t^2$

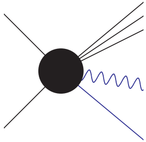
$$m_{t,0} = \mu_t + \delta m_t, \qquad \mu_t^2 = m_t^2 - i m_t\Gamma_t$$

$W^+W^-b\bar{b}$: [Denner, Dittmaier, Kallweit, Pozzorini '10,'12]
[Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '10]
[Heinrich, Maier, Nisius, Schlenk, Winter '13]
[Frederix '13] [Cascioli, Kallweit, Maierhöfer, Pozzorini '13]

W^+bj (t-channel): [AP, Frederix, Frixione, Hirschi, Maltoni '13]

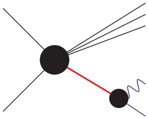
Outline

EFT approach



Application: mass scheme

Conclusions



Power-counting and Expansion

Focus on resonant region: $p_t^2 \sim m_t^2$

Why does it make sense to apply ET ideas here?

There are hard (m_t) and soft (Γ_t) scales naturally present. Use these à la EFT:

- m_t: characteristic scale of production/decay subprocesses (short-range, hard gluons)
- Γ_t: characteristic scale of production/decay interferences and connections (long-range, soft gluons)

$$\Gamma_t \ll m_t \quad \rightarrow \quad \text{expand full amplitude in } \frac{\Gamma_t}{m_t} \ll 1$$

When top is resonant: $$\frac{\Delta_t}{m_t^2} := \frac{p_t^2 - \mu_t^2}{m_t^2} \sim \frac{\Gamma_t m_t}{m_t^2} = \frac{\Gamma_t}{m_t}$$

Expansion in $\frac{\Gamma_t}{m_t}$ $\leftrightarrow$ expansion in top virtuality

Power-counting and Expansion

Combine perturbative expansion in α_s and α_w with an expansion in Δ_t

[pole expansion: Aeppli et. al. '94]

[& its systematization: Chapovsky et. al. '01 ; Beneke et. al. '04]

Introduce power-counting: $\frac{\Delta_t}{m_t^2} \sim \alpha_\mathrm{w} \sim \alpha_s^2 \sim \delta \ll 1$ $\quad (\Gamma_t \sim \alpha_\mathrm{w} m_t)$

→ Expand to NLO in δ: corrections of $\delta^{1/2}$ to the LO term in expansion.

- → corrections of $\mathcal{O}(\delta^{1/2})$: keep
- → corrections of $\mathcal{O}(\delta^{1})$: safely drop
- → corrections of $\mathcal{O}(\delta^{0})$: leading → resum (leads to width)
- → Dyson-resum resonant propagators

✓ expansion in δ is gauge invariant and systematically improvable

[Chapovsky et. al. '01 ; Beneke et. al. '04]

Expansion: how?

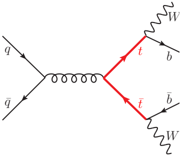
- loops: expansion done using method of regions [Beneke, Smirnov '98]

  $\rightarrow$ expand loop integrands in hard, $k^{\mu}_{\text{loop}} \sim m_t$ & soft $k^{\mu}_{\text{loop}} \sim m_t\delta$ regions

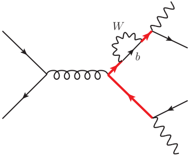
- reals: split up matrix elements in a manner consistent with method of regions used for loops (& use FKS/Catani-Seymour subtraction to treat IR-divergent regions)

Expansion example: what to resum in the propagator

(drop factors of m_t for ease)



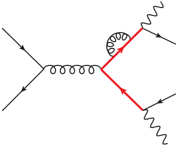
$\sim \alpha_s \alpha_w \frac{1}{\Delta_t \Delta_{\bar{t}}} \sim \frac{1}{\delta^{1/2}}$



$\mathcal{A}_{\text{hard}}^{\text{EW self-energy (W)}} \sim \delta^{-1/2}$ → leading: resum

→ Γ_t^{LO}

$\mathcal{A}_{\text{soft}}^{\text{EW self-energy (W)}} \to 0$



$\mathcal{A}_{\text{QCD,hard}}^{\text{self-energy}} \sim \delta^{-1}$ → super-leading!?!

↓

on-shell renormalization (or similar) makes this leading/subleading

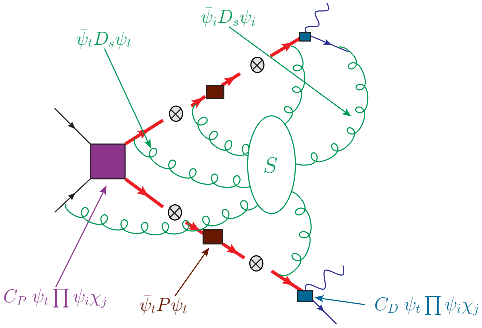
$\mathcal{A}_{\text{QCD,soft}}^{\text{self-energy}} \sim 1$

↙

include perturbatively

Expansion → EFT structure

Matrix element organization ≃ Wilson coefficients × operators
& dynamical degrees of freedom



Operators: production, propagation & decay of heavy tops

Dynamical dof: soft gluons

EFT structure: comments

- obtain an EFT-like organisation of amplitudes without formal multi-step matching procedure
- don't have a framework to resum potentially large logs (of Γ_t/m_t)
- are fully exclusive (& 'realistic' final states: jets, leptons)
- Key physical cut: $120 < M(W, J_b) < 200$ GeV

  (to preserve validity of power-counting)

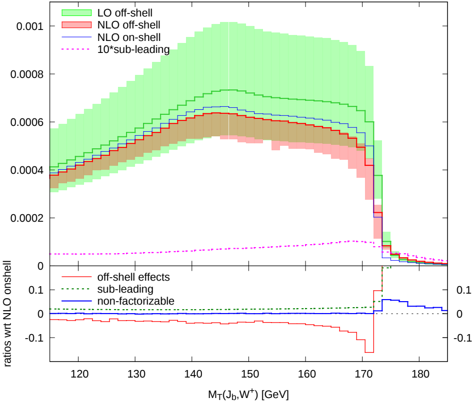
Can write differential cross-section as:

$$d\sigma^{NLO} = d\sigma^{P} + d\sigma^{D,\,t} + d\sigma^{D,\,\bar{t}} + d\sigma^{\text{non-fact.}} + d\sigma^{\text{prop}}$$

$\rightarrow$ real/virtual IR pole cancellation occurs separately within each contribution, and order by order in δ

- ET approach shown to agree very well with complex-mass scheme result in region of validity for single-top [AP, Frederix, Frixione, Hirschi, Maltoni '13]

Transverse Mass, M_T



- off-shell effects small, except at edge of distribution (exceed 10%)
- non-factorizable corrections zero everywhere except beyond edge (small)
- single-resonant contributions grow beyond the sharp edge

Propagator renormalisation

$(D_{r,t} = p_t^2 - m_{r,t}^2)$

$$\text{prop}_t = i\frac{\not{p}_t + m_{r,t}}{D_{r,t}} + A_{\rm QCD}(m_{r,t})\left[\frac{2im_{r,t}^2(\not{p}_t + m_{r,t})}{D_{r,t}^2} + \frac{im_{r,t}}{D_{r,t}} - \frac{i(\not{p}_t + m_{r,t})}{D_{r,t}}\right]$$

$$+\frac{\delta m_{r,t}}{m_{r,t}}\left[\frac{2im_{r,t}^2(\not{p}_t + m_{r,t})}{D_{r,t}^2} + \frac{im_{r,t}}{D_{r,t}}\right]$$

Pole-mass scheme:

$$\frac{\delta m_t}{m_t} = -A_{\rm QCD}(m_t)$$

$$\text{prop}_t \to i\frac{\not{p}_t + m_t}{D_t}\left(1 - A_{\rm QCD}(m_t)\right)$$

PS-mass

- so far, the pole-mass, m_t, has been used
- pole-mass suffers from renormalon ambiguities [Bigi et al. '94, Beneke, Braun '94, Smith, Willenbrock '97, ...]
- other mass-schemes can be used, so long as they do not spoil the EFT counting $m_{r,t}^2 - \mu_t^2 \sim \delta$

  (e.g. $\overline{\text{MS}}$ is a bad scheme in this case, $m_{\overline{\text{MS}},t}^2 - m_t^2 \sim \mathcal{O}(\alpha_s) \sim \delta^{1/2}$).
- Masses consistent with EFT counting: threshold masses [Bigi et al. '94, Beneke '98, Hoang, Teubner '99, Pineda '01 ...] , jet masses [Flemming, Hoang, Mantry, Stewart '08]

Potential-subtracted mass [Beneke '98] :

$$m_t = m_{t,\text{PS}} + \mu_{\text{PS}} \left[\frac{\alpha_s}{2\pi} d_1^{\text{PS}} + \left(\frac{\alpha_s}{2\pi} \right)^2 d_2^{\text{PS}} \right] + \mathcal{O}(\alpha_s^3)$$

Power-counting: $d_{1,2}^{\text{PS}} \sim 1$, $\mu_{\text{PS}} \sim \alpha_s m_t \sim \delta^{1/2}$

Propagator renormalisation

$(D_{r,t} = p_t^2 - m_{r,t}^2)$

$$\text{prop}_t = i\frac{\not{p}_t + m_{r,t}}{D_{r,t}} + A_{\text{QCD}}(m_{r,t})\left[\frac{2im_{r,t}^2(\not{p}_t + m_{r,t})}{D_{r,t}^2} + \frac{im_{r,t}}{D_{r,t}} - \frac{i(\not{p}_t + m_{r,t})}{D_{r,t}}\right]$$

$$+\frac{\delta m_{r,t}}{m_{r,t}}\left[\frac{2im_{r,t}^2(\not{p}_t + m_{r,t})}{D_{r,t}^2} + \frac{im_{r,t}}{D_{r,t}}\right]$$

PS-mass scheme:

$$\frac{\delta m_{\text{PS},t}}{m_{\text{PS},t}} = -A_{\text{QCD}}(m_{\text{PS},t}) + \frac{\mu_{\text{PS}}}{m_{\text{PS},t}}\left[\frac{\alpha_s}{2\pi}d_1^{\text{PS}} + \left(\frac{\alpha_s}{2\pi}\right)^2 d_2^{\text{PS}} + \ldots\right]$$

$$\text{prop}_t = i\frac{\not{p}_t + m_{\text{PS},t}}{D_{\text{PS},t}}\left(1 - A_{\text{QCD}}(m_{\text{PS},t})\right)$$

$$+ i\frac{\not{p}_t + m_{\text{PS},t}}{D_{\text{PS},t}}\left(\frac{\alpha_s}{\pi}\frac{\mu_{\text{PS}}m_{\text{PS},t}d_1^{\text{PS}}}{D_{\text{PS},t}} + \frac{\alpha_s^2}{2\pi^2}\frac{\mu_{\text{PS}}m_{\text{PS},t}d_2^{\text{PS}}}{D_{\text{PS},t}}\right)$$

~ 1 (resum) $\qquad \sim \delta^{1/2}$

Propagator renormalisation

$(D_{r,t} = p_t^2 - m_{r,t}^2)$

$$\text{prop}_t = i\frac{\not{p}_t + m_{r,t}}{D_{r,t}} + A_{\text{QCD}}(m_{r,t})\left[\frac{2im_{r,t}^2(\not{p}_t + m_{r,t})}{D_{r,t}^2} + \frac{im_{r,t}}{D_{r,t}} - \frac{i(\not{p}_t + m_{r,t})}{D_{r,t}}\right]$$

$$+\frac{\delta m_{r,t}}{m_{r,t}}\left[\frac{2im_{r,t}^2(\not{p}_t + m_{r,t})}{D_{r,t}^2} + \frac{im_{r,t}}{D_{r,t}}\right]$$

PS-mass scheme:

$$\frac{\delta m_{\text{PS},t}}{m_{\text{PS},t}} = -A_{\text{QCD}}(m_{\text{PS},t}) + \frac{\mu_{\text{PS}}}{m_{\text{PS},t}}\left[\frac{\alpha_s}{2\pi}d_1^{\text{PS}} + \left(\frac{\alpha_s}{2\pi}\right)^2 d_2^{\text{PS}} + \dots\right]$$

$$\text{prop}_t \to i\frac{\not{p}_t + m_{\text{PS},t}}{D_{\text{PS},t} - \frac{\alpha_s}{\pi}\mu_{\text{PS}}\, m_{\text{PS},t}\, d_1^{\text{PS}}}\left(1 - A_{\text{QCD}}(m_{\text{PS},t}) + \frac{\alpha_s^2}{2\pi^2}\frac{\mu_{\text{PS}}\, m_{\text{PS},t}\, d_2^{\text{PS}}}{D_{\text{PS},t} - \frac{\alpha_s}{\pi}\mu_{\text{PS}}\, m_{\text{PS},t}\, d_1^{\text{PS}}}\right)$$

Toy Mass-scheme study ($q\bar{q}$ channel only)

- compare m_t-extraction at NLO for $\mu_{\text{PS}} \in \{0, 10, 20\}$ GeV
  ($\mu_{\text{PS}} \sim \alpha_s m_t$, so reasonable to do so)
- NLO: includes corrections to prod & decay, propagator, non-factorizable
- measurement: $M(W^+, J_b)$ distribution in pole scheme, $m_t = 172.9$ GeV
- extract mass in each scheme by adjusting value such that predicted $M(W^+, J_b)$ optimally agrees with measurement
- convert extracted $m_{\text{PS},t}(\mu_{\text{PS}})$ to $m_{\overline{\text{MS}},t}$ & m_t using $\mathcal{O}(\alpha_s^3)$ conversion
  [Melnikov, Ritbergen '00] (error in conversion $\leq$ 100 MeV)

	NLO		
μ_{PS}	m_{ext}	$m_{\overline{\text{MS}},t}$	m_t
0	172.9	162.2	172.9
10	172.2	162.4	173.3
20	171.5	162.5	173.4

$\Rightarrow$ m_t ($m_{\overline{\text{MS}},t}$)-extraction has ambiguity of 400-500 (200-300) MeV at NLO

Conclusions & Outlook

Conclusions:

- EFT-like expansion of full amplitudes in resonant region
- offshell and non-factorizable corrections are generally small, ...
- but are sizeable for observables sensitive to top invariant mass
- computation allows exploration of additional (suitable) mass-schemes

  $\rightarrow$ toy study: 400-500 MeV ambiguity in extraction of pole mass

  $\rightarrow$ toy study: 200-300 MeV ambiguity in extraction of $\overline{\text{MS}}$ mass

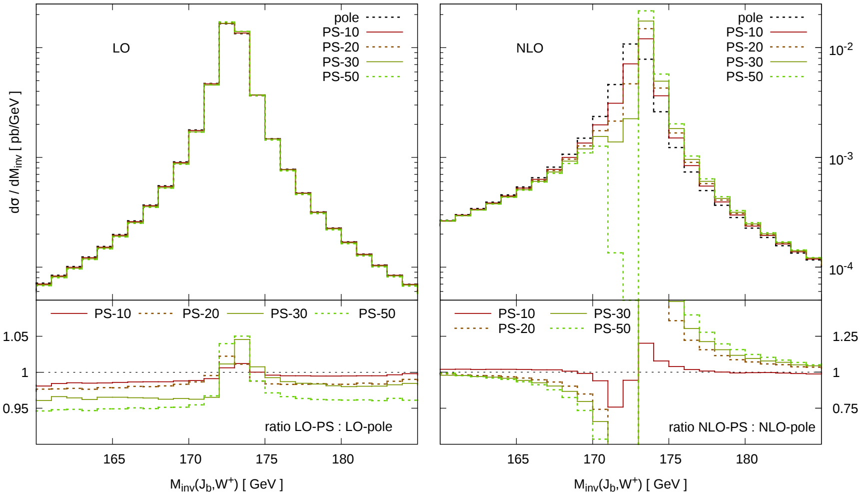
  (obviously a realistic study must include many other effects, e.g. color-reconnections.)

- part of the way to quantifying the mistake we make if we blindly interpret the extracted mass as the pole-mass.

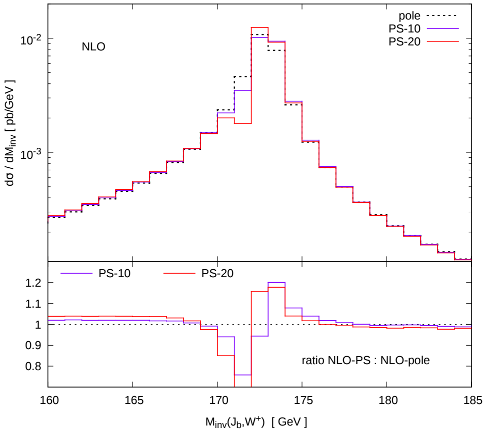
Thanks for listening
and thank you for the opportunity to attend this MITP workshop!

Backup slides

- fix m_t, vary $\mu_{\text{PS}} \in [0, 50]$ GeV



- vary $m_{\mathrm{PS},t}(\mu_{\mathrm{PS}})$ for $\mu_{\mathrm{PS}} \in [0, 20]$ to obtain optimal agreement with $m_t = 172.9$ GeV 'data.'



ET approach works

- t-channel single-top: ET vs complex-mass scheme vs NWA, all NLO