Resonant Top Quarks at Hadron Colliders

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and

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Outline

Why tops?

Heaviest member of the Standard Model and millions produced at LHC:

- top parameters/properties important in precision checks of SM
- tops contribute to backgrounds to other processes of interest, e.g. $h \to W^+W^-$
- sensitive to many BSM scenarios

Why off-shell tops ?

- mis-estimation of contribution of tops to backgrounds, when e.g. on-shell assumption made
- tagging top quarks
- template fitting (e.g. for measuring m_t): on-shell & stable assumptions often made (at the matrix element level).

Are systematics related to ignoring offshellness of top (and all this entails) understood and controlled?

This talk

The focus in this talk: production and decay of tops

- a method that allows for the inclusion of off-shell effects
- comparison between methods for treating production and decay of tops

Discussion will be at the parton/hard-scattering level, i.e. no parton-shower or hadronization effects.

Stable top not discussed, despite the huge progress at both NLO ($t\bar{t}+X$) and NNLO ($t\bar{t}$).

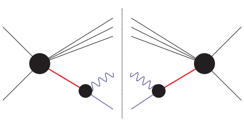
Heavy Unstable Particles: on-shell / NWA $p_X^2 = M_X^2$

Decay the unstable particle via the NWA

✓Pros:

- include corrections to production & decay
- good approx. for many obsevables

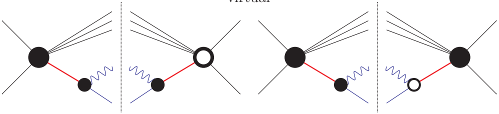
Born



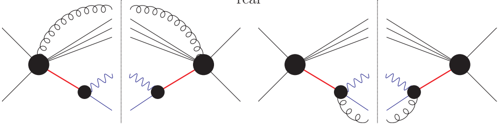
☹Not included:

- non-factorizable corrections
- off-shell/finite-width effects in NLO amplitudes
- non-resonant effects

virtual



real



$t\bar{t}$: [Bernreuther et al. '01, '04 ; Melnikov Schulze '09 ; Campbell, Ellis '12]

single-top: [Campbell et al. '04; Cao et al. '09, '10]

Heavy Unstable Particles: on-shell / NWA $p_X^2 = M_X^2$

NWA:

$$\frac{1}{(p_X^2 - m_X^2)^2 + m_X^2 \Gamma_X^2} \to \frac{\pi}{m_X \Gamma_X} \delta(p_X^2 - m_X^2) + \mathcal{O}(\Gamma_X / m_X)$$

For processes involving top quarks, this is $\sim 1\%$

For the inclusive production of an unstable particle, non-factorizable corrections are parametrically suppressed $\mathcal{O}(\Gamma_X / M_X)$

[theorems of: Fadin, Khoze, Martin '94 ; Melnikov,Yakovlev '94]

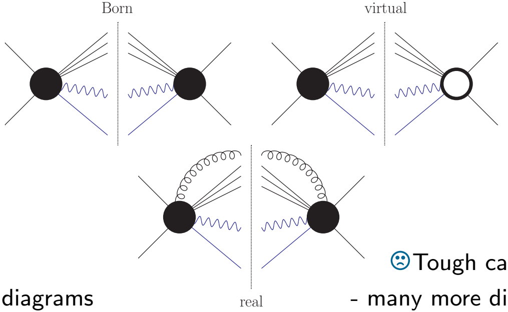
Is this still the case for more exclusive observables (e.g. $M(W^+, J_b)$) and at the fully differential level?

More generally, one would like to understand at the differential level:

- what changes in the resonant contributions when the on-shell assumption is relaxed?
- where do non-resonant/background contributions play important roles?

Heavy Unstable Particles: off-shell / CMS $p_X^2 \neq M_X^2$

Much more than just the resonant contributions included in the NWA



✓ Included:

- background diagrams
- non-factorizable corrections
- resonant/non-resonant interferences
- off-shell/finite-width effects in NLO amplitudes
- valid in all regions of phase-space

☹ Tough calculation:

- many more diagrams
- many multi-point loop diagrams with complex masses

Heavy Unstable Particles: off-shell / CMS $p_X^2 \neq M_X^2$

Finite-width in propagator arises from the resummation of a particular class of higher-order correction.

Since this operation mixes up orders in perturbation theory, if it is not done with care, gauge-invariance can be broken (even at LO).

The complex-mass scheme (CMS) [Denner, Dittmaier, Roth, Wieders '05] is a generalization of the on-shell renormalization scheme:

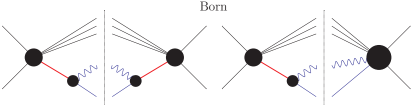
$$m_{t,0} = \mu_t + \delta m_t, \qquad \mu_t^2 = m_t^2 - i m_t \Gamma_t$$

→ δm_t fixed so μ_t^2 corresponds to complex pole of propagator
→ complex masses introduced consistently at the level of the Lagrangian.

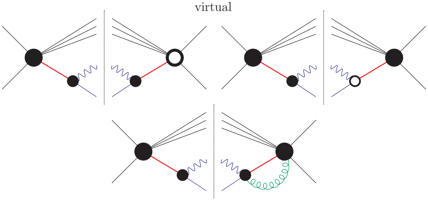
$W^+ b W^- \bar{b}$: [Denner, Dittmaier, Kallweit, Pozzorini '10 & '12]
[Bevilacqua,Czakon,van Hameren,Papadopoulos '10]

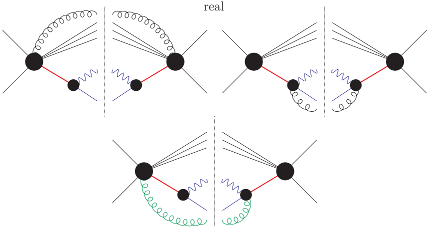
$W^+ bj$: [Pittau '96 (s-ch, final-state non-factorizable corrections)]
[Frederix,Frixione,Hirschi,Maltoni,AP - to appear (t-ch)]

Heavy Unstable Particles: resonant / ET $p_X^2 \sim M_X^2$



systematically pick out leading contributions in this region





✓ Pros:

- dominant offshell/width effects
- non-factorizable corrections
- relevant non-resonant effects kept
- easy to pick out relative importance of different top contributions

☹ Disadvantages:

- not valid over full phase-space
- not a computation of the full process

Single-top: [Falgari,Mellor,Signer '10; Falgari,Gianuzzi,Mellor,Signer '11]
$t\bar{t}$: [Falgari, AP, Signer '13 ($q\bar{q}$ channel)]

Scales in Processes with Tops

Top production and decay processes separated in space/time by $\sim 1/\Gamma_t$

Large(ish) $\Gamma_t \Rightarrow$ production/decay connections can only really happen when emitted gluons induce long-range interactions

$\Rightarrow$ dominant contributions from interconnections come from regions where gluons are soft, $p_g \sim \Gamma_t$

(Hard gluons $p_g \sim m_t$ induce short range interactions)

Idea: pick out dominant/relevant contributions

$\rightarrow$ use the widely separated physical scales present to simplify calculation

$\Gamma_t \ll m_t \quad \rightarrow \quad$ 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

Effective Theory (ET) expansion: summary

Combine standard expansion in α_s and $\alpha_{\rm w}$ with an expansion in Δ_t

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

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

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

→ 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 $\mathcal{O}(\delta^{-1})$: leading → resum (leads to width)
- → *only* Dyson-resum resonant propagators

✓ expansion in δ is gauge invariant and systematically improvable

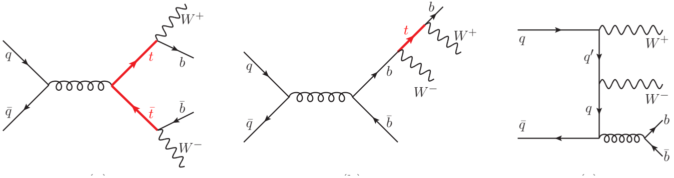
[A.P. Chapovsky et. al. '01 ; M. Beneke et. al. '04]

In resonant region, δ-expansion re-arranges full perturbation theory.

→ provides an intuitive picture of the structure of corrections

ET expansion: Born

Power-counting for tree-level diagrams:



$\sim \alpha_s \alpha_w A^{(1,1)}_{(-2)}$ | $\sim \alpha_s \alpha_w A^{(1,1)}_{(-1)}$ | $\sim \alpha_s \alpha_w A^{(1,1)}_{(0)}$

$\sim \alpha_s \alpha_w \frac{1}{\Delta_t \, \Delta_{\bar{t}}}$ | $\sim \alpha_s \alpha_w \frac{1}{\Delta_t}$ | $\sim \alpha_s \alpha_w$

$\sim \delta^{1/2}\delta/\delta^2 = \delta^{-1/2}$ | $\sim \delta^{1/2}\delta/\delta = \delta^{1/2}$ | $\sim \delta^{1/2}\delta = \delta^{3/2}$

Note: δ-scalings here are how the *leading* contributions of an expansion of these diagrams would scale.

ET expansion: Born

Colour summed/averaged tree-level matrix element for full process can be written as:

$$\mathcal{M}_{\text{full}}^{\text{tree}} = \frac{C_F}{2N_c}\alpha_s^2\alpha_{\text{w}}^2 \left[\left| A_{(-2)}^{(1,1)} \right|^2 + 2\text{Re}\left\{ A_{(-2)}^{(1,1)} A_{(-1)}^{(1,1)\,*} \right\} + \ldots \right]$$

$$+ \alpha_{\text{w}}^2 \left[\left| A_{(-2)}^{(0,2)} \right|^2 + \ldots \right]$$

$$= \sim \delta^{-1} + \sim \delta^0 + \ldots$$

Ellipses indicate terms of $\mathcal{O}(\delta)$ and higher.

ET expansion: higher orders

To consistently go to higher orders in the δ expansion must include higher orders in standard coupling expansions.

Think about α_s-corrections to leading double resonant contributions

loop corrections $\sim A^{(2,1)}_{(-2)}$

$$\mathcal{M}^{\text{Virt}} \sim \alpha_s^3 \alpha_{\text{w}}^2 2\text{Re}\left\{ A^{(2,1)}_{(-2)} A^{(1,1)\,*}_{(-2)} \right\} \sim \delta^{-\frac{1}{2}}$$

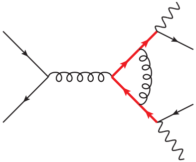
real emission corrections $\sim A^{(3/2,1)}_{(-2)}$

$$\mathcal{M}^{\text{Real}} \sim \alpha_s^3 \alpha_{\text{w}}^2 \left| A^{(\frac{3}{2},1)}_{(-2)} \right| \sim \delta^{-\frac{1}{2}}$$

Here the aim is to compute the next-to-leading term in the δ expansion, i.e. we want to keep all contributions scaling as $\delta^{-1/2}$ in the matrix element $\rightarrow$ 'NLO'.

ET expansion: loop example

Method of regions [M. Beneke, V. A. Smirnov '98] used to extract pieces of loop diagrams we must keep.



$$= \alpha_s^2 \, \alpha_{\rm w} \ldots \frac{1}{\Delta_t \, \Delta_{\bar t}} \int [dk] \, \frac{\gamma^\mu \, (\not{p}_t - \not{k} + m_t) \, \gamma_\rho \, (\not{p}_{\bar t} + \not{k} - m_t) \, \gamma_\mu}{k^2 \, ((p_t - k)^2 - m_t^2) \, ((p_{\bar t} + k)^2 - m_t^2)} \ \ldots$$

Start from full amplitudes and expand in relevant regions...

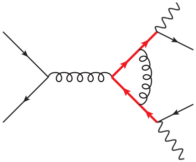
For the case at hand we must expand regions where virtual gluon is:

- hard, $k_0 \sim \vec{k} \sim m_t$
- soft, $k_0 \sim \vec{k} \sim m_t \delta$

Drop factors of m_t to ease discussion.

ET expansion: loop example - hard

In hard region, virtual gluon momentum scales as $k_0 \sim \vec{k} \sim 1$.



$\sim \delta \,.\, \delta \,.\, \frac{1}{\delta \,.\, \delta} \,.\, 1 \,.\, \frac{1}{1 \,.\, 1 \,.\, 1} \;\sim 1 \;\rightarrow$ keep!

$$= \alpha_s^2\, \alpha_w \ldots \frac{1}{\Delta_t\, \Delta_{\bar{t}}} \int [dk]\, \frac{\gamma^\mu\, (\not{p}_t - \not{k} + m_t)\, \gamma_\rho\, (\not{p}_{\bar{t}} + \not{k} - m_t)\, \gamma_\mu}{k^2\, \left((p_t - k)^2 - m_t^2\right) \left((p_{\bar{t}} + k)^2 - m_t^2\right)} \;\ldots$$

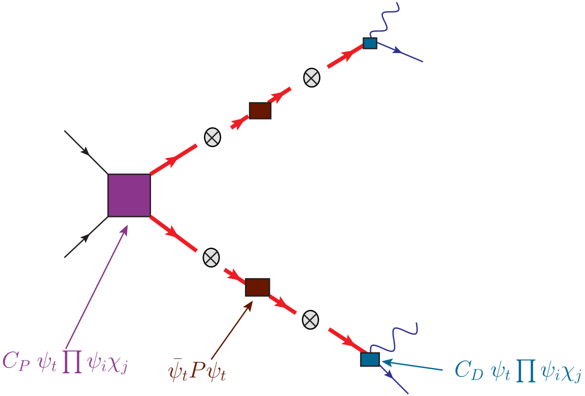
$$\text{hard: } (p_t - k)^2 - m_t^2 = k^2 - 2k.p_t + D_t \;\rightarrow\; k^2 - 2k.p_t .$$

$(D_t = p_t^2 - m_t^2 \sim \delta)$

$$\rightarrow \alpha_s^2\, \alpha_w \ldots \frac{1}{\Delta_t\, \Delta_{\bar{t}}} \int [dk]\, \frac{\gamma^\mu\, (\not{p}_t - \not{k} + m_t)\, \gamma_\rho\, (\not{p}_{\bar{t}} + \not{k} - m_t)\, \gamma_\mu}{k^2\, (k^2 - 2k.p_t)\, (k^2 + 2k.p_{\bar{t}})} \;\ldots$$

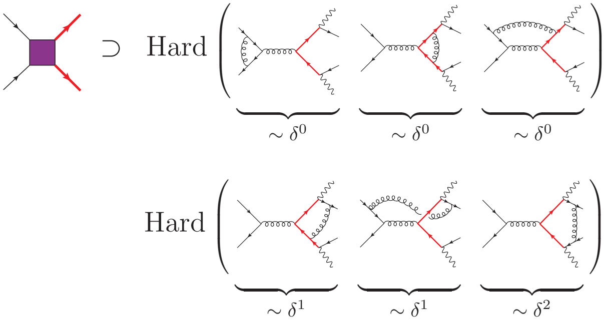
ET structure: hard corrections / wilson coefficients

"Hard" corrections: contained in matching coefficients multiplying production, propagation, decay operators



ET structure: hard corrections / wilson coefficients

Example: $t\bar{t}$ production operator:



$\rightarrow$ subleading

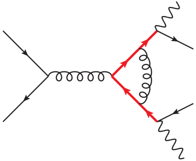
Expansion in δ of matrix elements, requires the expansion of the external momenta around $p_{t,\bar{t}}^2 = \mu_t^2 = m_t^2 + \mathcal{O}(\delta)$

$\leftrightarrow$ analogous to formal effective theory, where matching performed 'on-shell'

Project off-shell momenta onto on-shell configurations to evaluate matrix elements.

ET expansion: loop example - soft

In soft region, virtual gluon momentum scales as $k_0 \sim \vec{k} \sim \delta$.



$$\sim \delta \,.\, \delta \,.\, \frac{1}{\delta \,.\, \delta} \,.\, \delta^4 \,.\, \frac{1}{\delta^2 \,.\, \delta \,.\, \delta} \;\sim 1 \;\rightarrow\; \text{keep!}$$

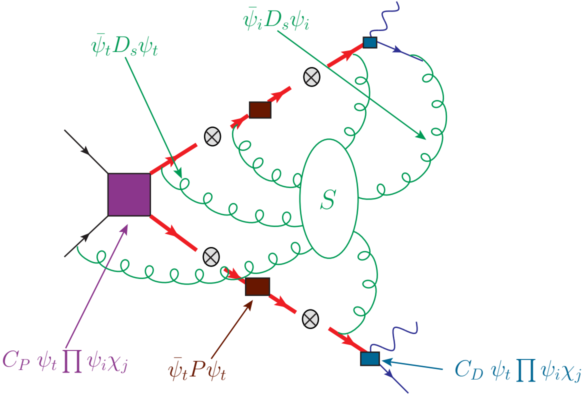
$$= \alpha_s^2\, \alpha_{\rm w} \ldots \frac{1}{\Delta_t\, \Delta_{\bar{t}}} \int [dk]\, \frac{\gamma^\mu\, (\not{p}_t - \not{k} + m_t)\, \gamma_\rho\, (\not{p}_{\bar{t}} + \not{k} - m_t)\, \gamma_\mu}{k^2\, \left((p_t - k)^2 - m_t^2\right) \left((p_{\bar{t}} + k)^2 - m_t^2\right)} \ldots$$

$$\text{soft: } (p_t - k)^2 - m_t^2 = k^2 - 2k.p_t + D_t \;\rightarrow\; -2k.p_t + \Delta_t.$$

$$\rightarrow \alpha_s^2\, \alpha_{\rm w} \ldots \frac{1}{\Delta_t\, \Delta_{\bar{t}}} \int [dk]\, \frac{\gamma^\mu\, (\not{p}_t + m_t)\, \gamma_\rho\, (\not{p}_{\bar{t}} - m_t)\, \gamma_\mu}{k^2\, (-2k.p_t + \Delta_t)\, (2k.p_{\bar{t}} + \Delta_{\bar{t}})} \ldots$$

ET structure: soft corrections / dynamical d.o.f.

"Soft" corrections: dynamical degrees of freedom left in theory after hard (high virtuality) modes integrated out.



→ separation of contributions which live at different scales μ_h and μ_s

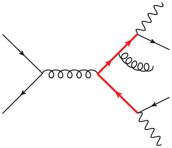
Real contributions

Want to study exclusive observables, so must include real emission diagrams

→ do this in a way consistent with Method of Regions used for loops

However, harder to identify what the correct expansion parameter is.

Consider a gluon emitted (with momentum k) off a top quark line:



In resonant region possibilities are:

- $p_t^2 \sim m_t^2$
- $(p_t + k)^2 \sim m_t^2$
- both

Real contributions

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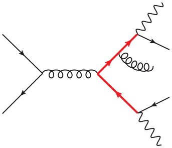


In resonant region possibilities are:

- $p_t^2 \sim m_t^2$ $\rightarrow \delta \sim (p_t^2 - m_t^2)$?
- $(p_t + k)^2 \sim m_t^2$ $\rightarrow \delta \sim ((p_t + k)^2 - m_t^2)$?
- both

Real contributions

Previously, what we had to do was modify standard subtraction method:

$$d\sigma^{NLO} = \left(d\sigma^{V} + \int_1 d\sigma^{R,c.t.} \right) + \int_1 (d\sigma^{R} - d\sigma^{R,c.t.})$$

by

$$d\sigma^{NLO} \simeq \left(d\sigma^{V}_{\text{exp}} + \int_1 d\sigma^{R,c.t.}_{\text{exp}} \right) + \int_1 (d\sigma^{R} - d\sigma^{R,c.t.})$$

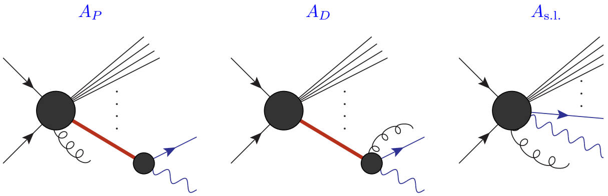
Add back something different from what you subtract - but difference suppressed in δ ... unsatisfactory however.

For ambiguous contributions use of the identity:

$$\frac{1}{(p_t^2 - m_t^2)\left((p_t + k)^2 - m_t^2\right)} = \frac{1}{2p_t \cdot k} \left[\frac{1}{(p_t^2 - m_t^2)} - \frac{1}{\left((p_t + k)^2 - m_t^2\right)} \right],$$

which helps make the separation.

Separation of real contributions



$A_P \sim \frac{1}{\Delta_t}$ and approximates full real amplitude when $(p_W + p_b)^2 \sim m_t^2$

$A_D \sim \frac{1}{\Delta_{tg}}$ and approximates full real amplitude when $(p_W + p_b + p_g)^2 \sim m_t^2$

$\longrightarrow A_P + A_D + A_{\text{s.l.}}$ approximates full amplitude always

$\int d\Phi_g \, |A_{P/D}|^2$ results in $\frac{1}{\epsilon^2}$ and $\frac{1}{\epsilon}$ poles $\rightarrow$ cancelled by hard virtual pieces.

$\int d\Phi_g \, 2\,\text{Re}\left(A_P \, [A_D]^*\right)$ results in a standard $\frac{1}{\epsilon}$ soft-pole

$\rightarrow$ cancelled by $\frac{1}{\epsilon}$-pole of the soft virtual contribution.

Separation of contributions

We note that the non-factorizable term

$$2\text{Re}\left(A_P\left[A_D\right]^*\right) \sim \frac{1}{\Delta_t \Delta_{tg}}$$

which gives a sizeable contribution *only* if both Δ_t and Δ_{tg} are resonant, i.e. when the emitted gluon is soft

→ confirms that, as for virtual correction, the non-factorizable real corrections are encoded by soft radiation.

Can now write:

$$d\sigma^{NLO} = d\sigma^{P} + d\sigma^{D,\,t} + d\sigma^{D,\,\bar{t}} + d\sigma^{\text{NF}}$$

and study each of these contributions separately in a consistent manner.

→ in particular, can evaluate soft corrections at their 'natural' scale, $\mu_s \simeq m_t \delta$.

Some comments

- dependence on projection used
  (however, difference between different projections is at an order higher than order which we aim for)
- pair-production near threshold: expansion in δ no longer captures the relavant physics (coulomb interactions $\rightarrow$ would have to match to a different expansion). ☹
- with ET method we study $t\bar{t}$ above threshold
  $\rightarrow$ can be done via a physical cut on final states.

Resonant $t\bar{t}$ production: process definition

Collider : 1.96 TeV Tevatron

W-decays to leptons via NWA

Use MSTW2008NLO PDF set, with $\alpha_s(M_Z) = 0.12018$,

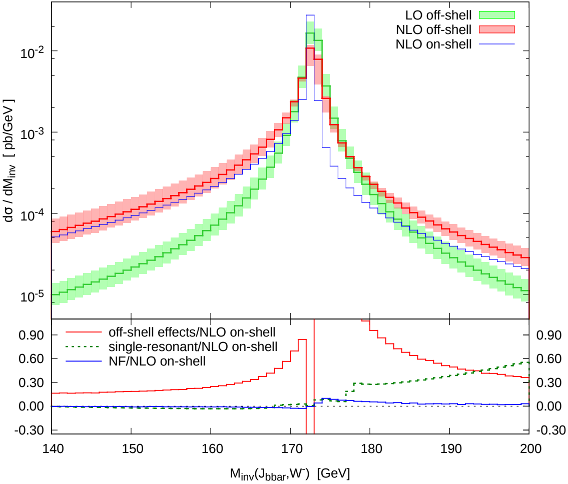
$$m_t^{\text{pole}} = 172.9 \text{ GeV} \qquad M_W = 80.4 \text{ GeV}$$
$$\Gamma_t = 1.366 \text{ GeV} \qquad \Gamma_W = 2.140 \text{ GeV}$$
$$\mu_F = \mu_R = m_t \qquad \mu_s = m_t\delta,\ \delta = 0.02$$

Cuts: $k_\perp$-algorithm, $R_{\text{jet}} = 0.7$

$$p_T(J_b),\ p_T(J_{\bar{b}}) > 15 \text{ GeV}$$
$$p_T(l^+),\ p_T(l^-) > 15 \text{ GeV} \qquad \not{E}_T > 20 \text{ GeV}$$
$$140 < M(W^+, J_b) < 200 \text{ GeV} \qquad 140 < M(W^-, J_{\bar{b}}) < 200 \text{ GeV}$$
$$M_{t\bar{t}} > 350 \text{ GeV}$$

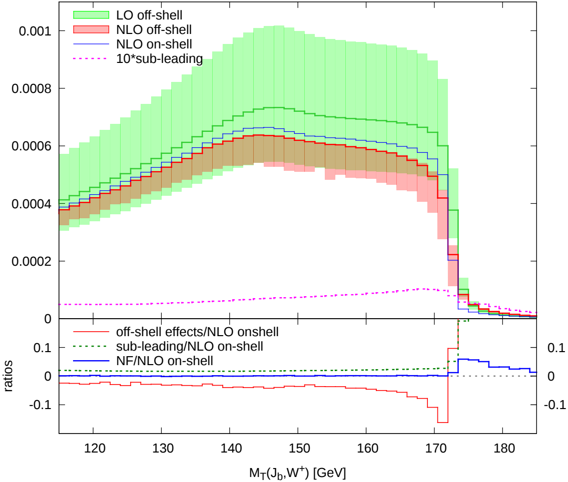
Note: $M_{t\bar{t}} = M_{t\bar{t}}^{\text{rec.}} = M((W^+, J_b), (W^-, J_{\bar{b}}))$

Resonant $t\bar{t}$ production: invariant mass



- off-shell effects large near peak
- pure non-factorizable corrections small
- sub-leading terms in δ grow away from peak

Resonant $t\bar{t}$ production: transverse mass



- below kinematic edge, off-shell effects $\sim$ 1-2%
- near and beyond the edge off-shell effects important
- non-factorizable terms insignificant, except perhaps near the edge

t-channel EW $W^+ b\, j$ production

Study t-channel EW $W^+ J_b J_{\text{light}}$ production in the 5-flavour scheme, using CMS, i.e. t-channel single-top with off-shell effects

[Frederix,Frixione,Hirschi,Maltoni,AP - to appear]

- in the framework of aMC@NLO [Frederix,Frixione,Hirschi,Maltoni,Pittau,Torrielli]
- CMS recently implemented in aMC@NLO

[Buarque Franzozi,Hirschi,Mattelaer - to appear]

Comparison is made at NLO to:

- NWA (as implemented in MCFM [Campbell,Ellis,Tramontano '04]) and
- ET [Falgari,Mellor,Signer '10] (strict 'NLO' in δ)

t-channel EW $W^+ b j$ production

Collider : 8 TeV LHC

Use MSTW2008NLO PDF set, with $\alpha_s(M_Z) = 0.12018$,

$m_t^{\text{pole}} = 173.2$ GeV $\quad M_W = 80.398$ GeV $\quad M_Z = 80.398$ GeV

$\Gamma_t^{\text{LO}} = 1.5017$ GeV $\quad \Gamma_Z = 2.4952$ GeV

$\mu = \mu_F = \mu_R = m_t/2 \quad V_{tb} = 1$

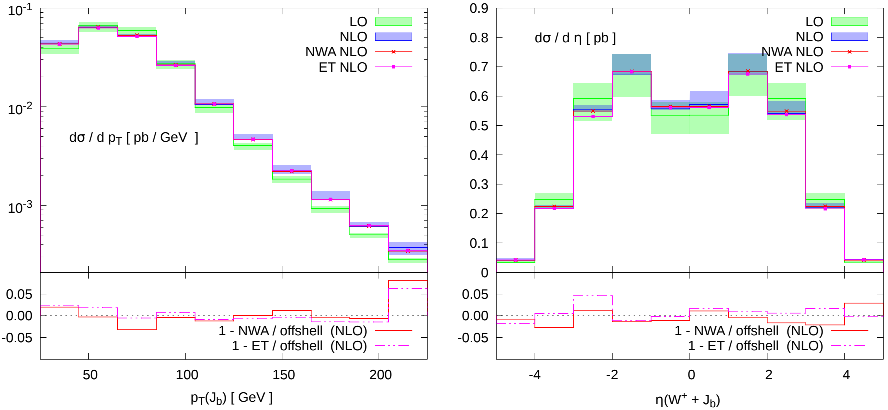
Cuts: $k_\perp$-algorithm, $R_{\text{jet}} = 0.5$

$p_T(J_b) > 25$ GeV $\quad p_T(J_{\text{light}}) > 25$ GeV

$\eta(J_b) < 4.5 \quad \eta(J_{\text{light}}) < 4.5$

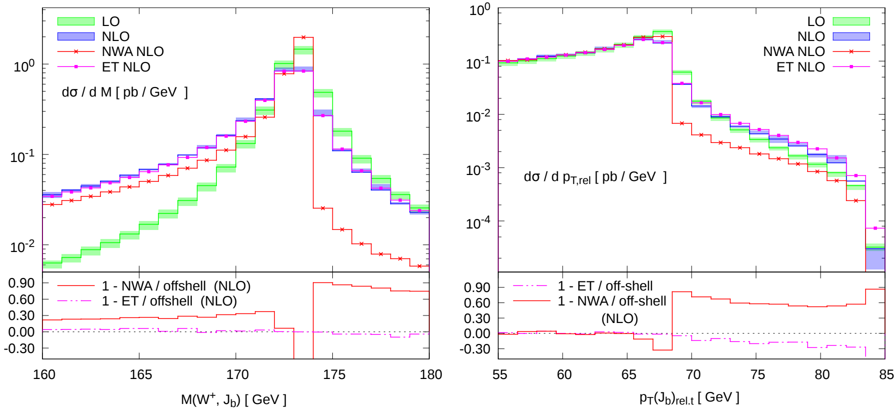
$140 < M(W^+, J_b) < 200$ GeV

t-channel EW $W^+ b j$ production: inclusive observables



Differences between NWA, ET and fully offshell (CMS) approaches are small.

t-channel EW $W^+ bj$ production: less inclusive observables



Significant differences in shapes of distributions between NWA and ET & CMS approaches.

In RHS plot, terms subleading in δ i.e. resonant/non-resonant interferences and subleading-Γ_t effects become noticeable, as expected.

Conclusions

- discussed an effective theory approach to unstable particle production
- expansion valid in the resonant region
- application to $t\bar{t}$ and single-top
- comparison to NWA and complex-mass scheme in single-top

  $\rightarrow$ very good agreement between CMS and ET in resonant region
  $\rightarrow$ differences between CMS and ET grow away from resonant region (as we expect)

- off-shell effects small in general (NWA a v. good approximation)
- ... but can be large for observables sensitive to $M(W^+, J_b)$
- resonant/non-resonant interferences increase in importance away from resonance
- expect larger differences if final-state cuts are such that non-resonant contributions are enhanced

Outlook and further work

In progress:

- $t\bar{t}$: gg & qg channels (no conceptual problems now, 'just' a matter of implementation)
- approximate NNLO in production (with A.Signer and A.Broggio) in fashion of [Ahrens,Ferroglia,Neubert,Pecjak & Yang] (...still early days)

Future:

- addition of PS to unstable single-top (?)

Thanks for listening
and thank you for the invitation to visit Freiburg!