Off-Shell Effects for Top Quark Production at Hadron Colliders

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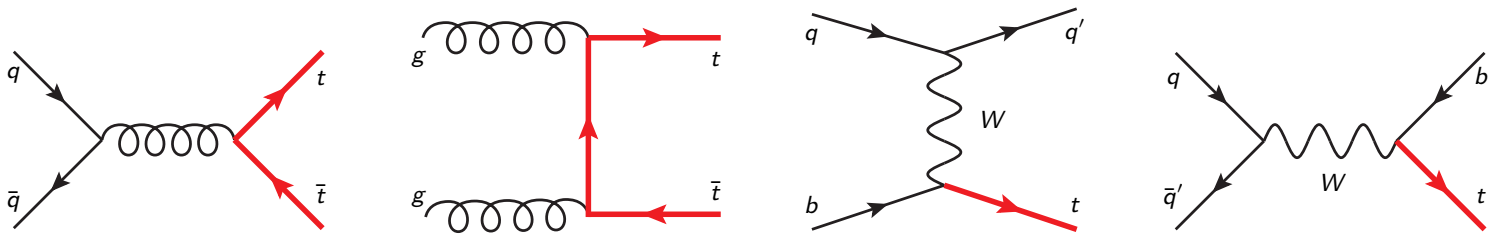
*In collaboration with Adrian Signer (IPPP), Paul Mellor (IPPP) and Pietro Falgari (Utrecht)

Outline

Motivation



- Abundance of Top-Quarks produced at the Tevatron and LHC

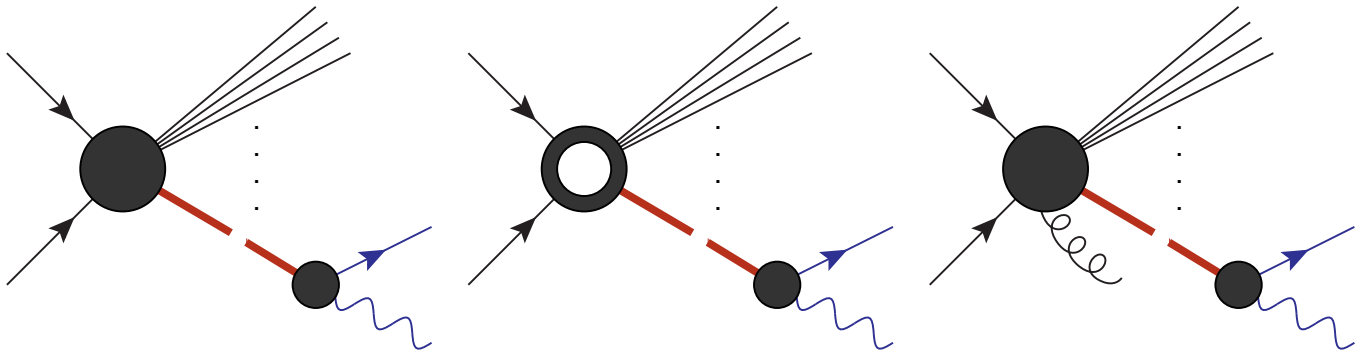
  $\rightarrow$ opportunity for precision top-studies in next few years

- Top-Quarks considered to be sensitive to New Physics at the EWSB scale
- Important background to Higgs decays (e.g. $H \rightarrow WW$) and New Physics signals (e.g. cascade decays in SUSY)
- Mass measurement (constrains SM Higgs mass, BSM parameters)

- $\Gamma_t \gg \Lambda_{\mathrm{QCD}} \rightarrow$ tops decay (to W and b) before hadronizing

  $\rightarrow$ treat top as unstable for best description: theory challenge

On-Shell; NWA; $p_t^2 = M_t^2$



- decay of tops included via (improved) Narrow Width Approximation

✓ spin correlations included, cuts on final states possible

✗ no non-factorizable corrections / off-shell effects

OK, for inclusive observables (σ etc) as effects of non-factorizable corrections are small, $\mathcal{O}(\frac{\Gamma_t}{M_t})$ for these [V. S. Fadin et. al. '94][K. Melnikov, O. I. Yakovlev '94]

Need off-shell effects for accuracy of $\delta M_t \lesssim \Gamma_t$

Single Top: [J.M. Campbell et al. '04, '05][Q. H. Hao et al. '05, '10]
$t\bar{t}$: [W. Bernreuther et. al. '01 & '04],[K. Melnikov, M. Schulze '09]
$\hookrightarrow$ "LO_{on}" to "NLO_{on}": corrections to $\sigma_{\text{incl}} \sim$ 30-40%

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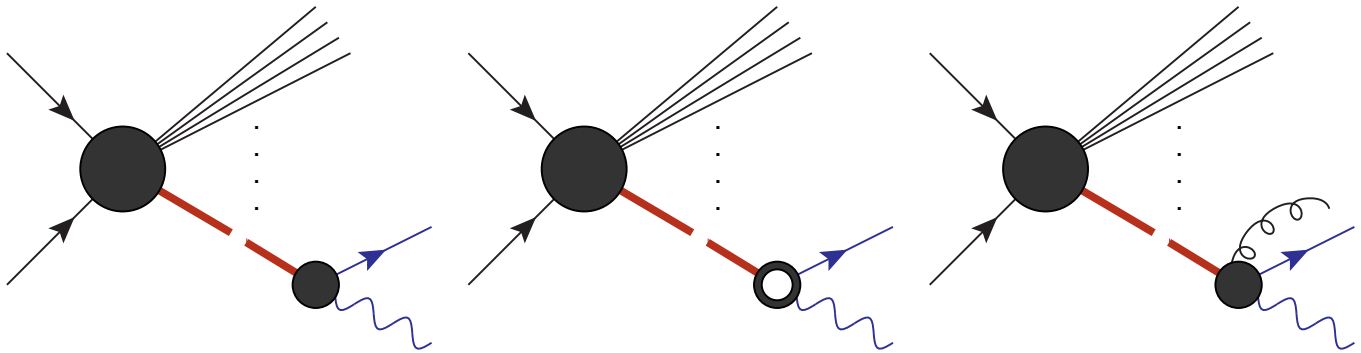

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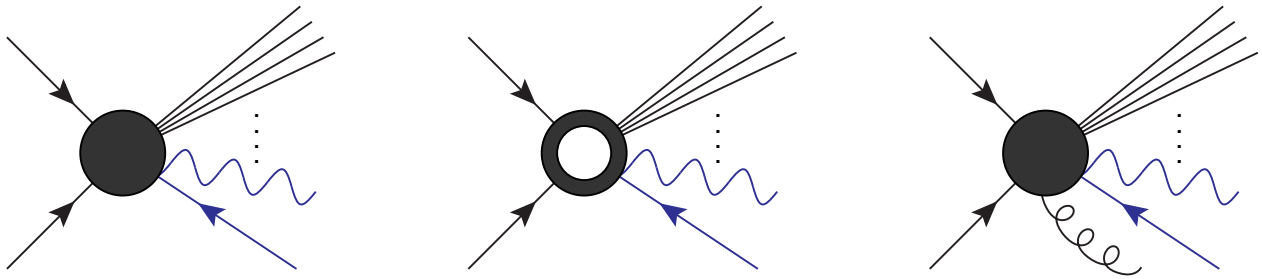
Off-Shell; $p_t^2 \neq M_t^2$



- non-factorizable corrections included
- all background diagrams included

✓ off-shell effects

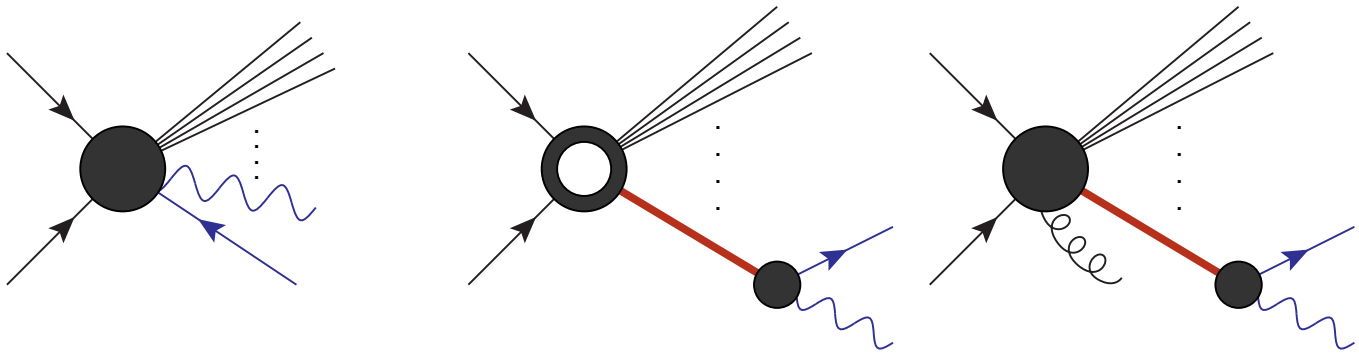
✓ spin-correlations and cuts on final states

✗ complicated/difficult calculation

Single Top (s-channel): [R. Pittau '96]
$t\bar{t}$: [A. Denner et. al. '10][Bevilacqua at. al. '10]

$\hookrightarrow$ "NLO_{on}" to "NLO_{off}": corrections to $\sigma_{\text{incl}} \sim$ 1-2% (expected)

Resonant; $p_t^2 \sim M_t^2$



- non-factorizable corrections included
- (relevant) background diagrams included

✓ off-shell effects included

✓ spin-correlations and cuts on final states

✓ simpler calculation

✗ not valid outside resonant region $p_t^2 \sim M_t^2$

Single Top: [P. Falgari et al. '10, '11]
$t\bar{t}$: [P. Falgari, A.P., A. Signer - In Progress]

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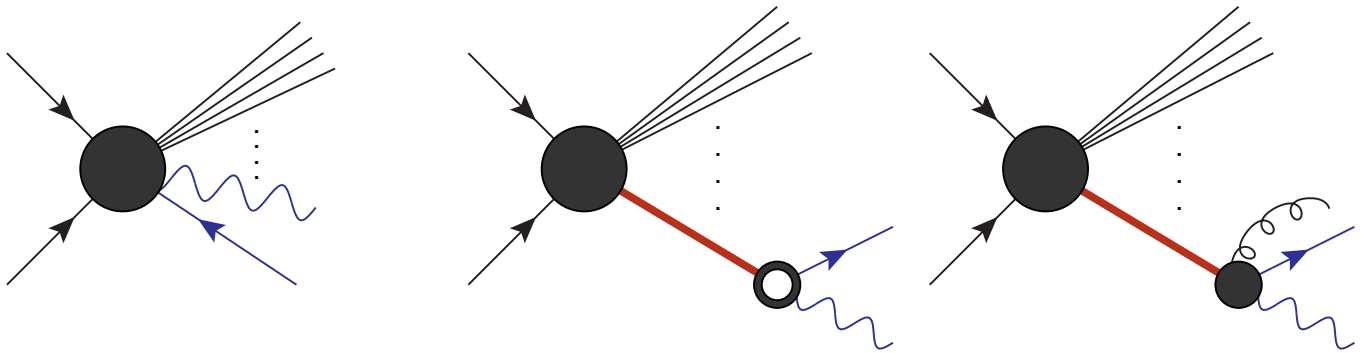

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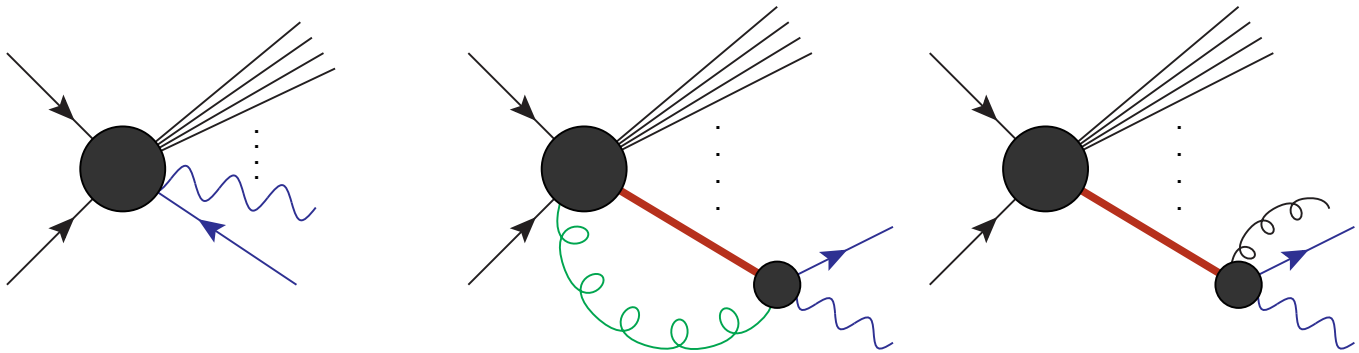

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Scales in Processes with Tops

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

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

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

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

Effective Theory Expansion

Combine standard expansion in α_s and α_{ew} with an expansion in Δ_t

(Generalisation of Pole Expansion [A. Aeppli et. al. '94]
[A.P. Chapovsky et. al. '01] [M. Beneke et. al. '04])

Introduce scalings $\Delta_t \sim \alpha_{ew} \sim \alpha_s^2 \sim \delta$ $(\Gamma_t \sim \alpha_{ew} M_t)$

$\rightarrow$ expand full amplitude in δ

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

✓ expansion in δ is strictly gauge invariant and systematically improvable

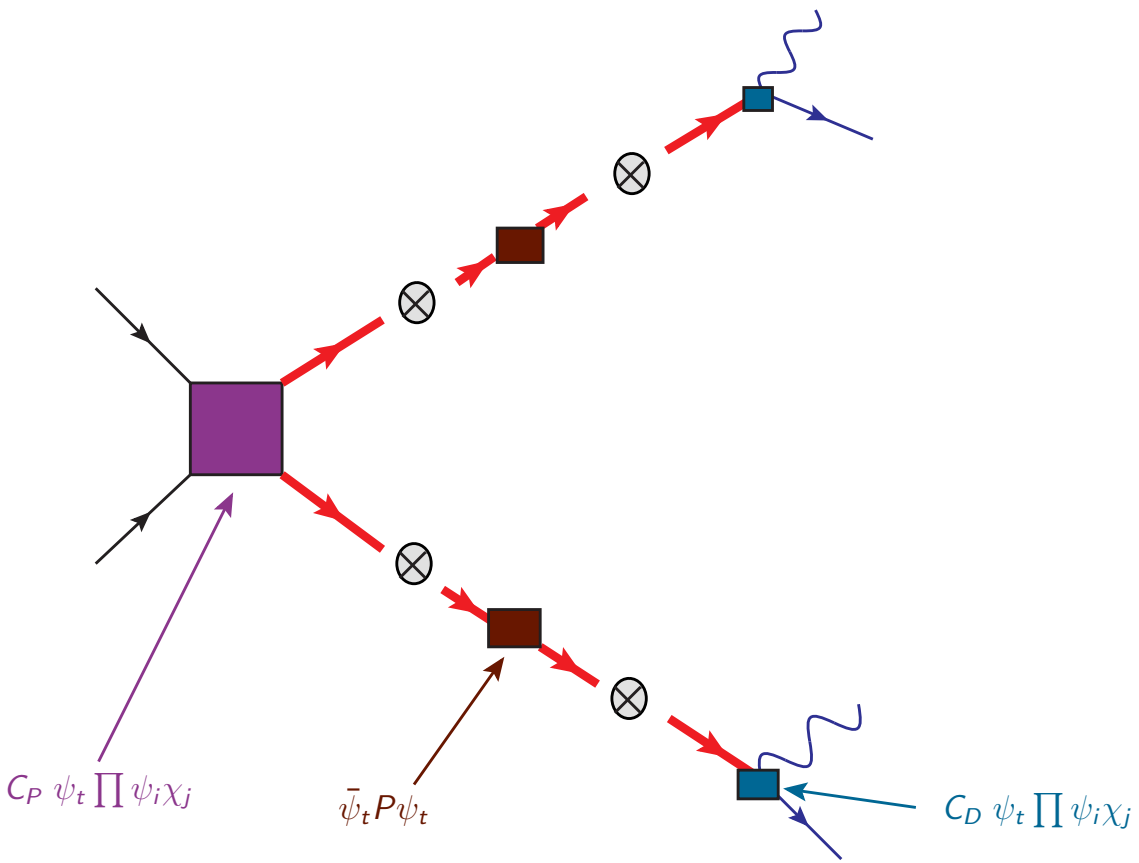
Born: expansion arranges (parts of) diagrams into double/single/non-resonant pieces

Virtual: use Method of Regions [M. Beneke, V. A. Smirnov '98]

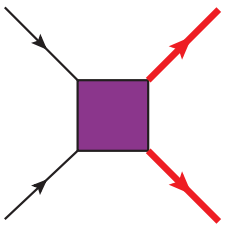
- expand integrands in 'hard' and 'soft' regions
  - $\rightarrow$ Hard contributions to production/decay connections: sub-leading in δ
  - $\rightarrow$ Soft contributions to production/decay connections: keep!

Resonant $t\bar{t}$: Effective Theory Structure

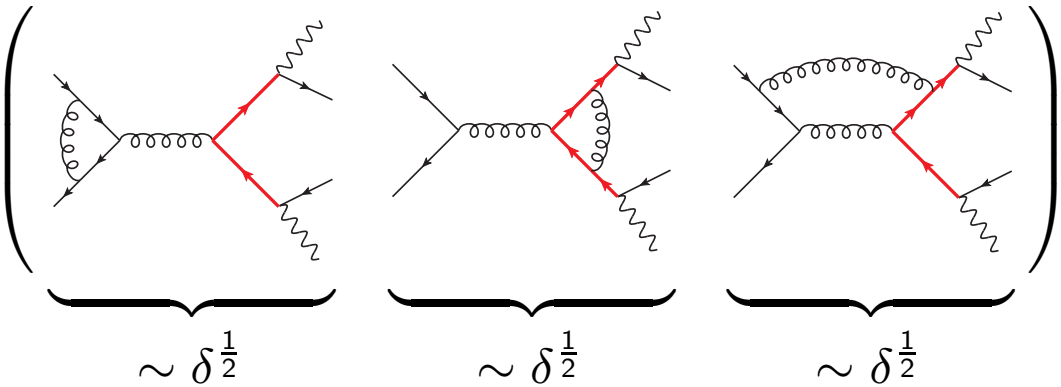
"Hard" corrections: contained in matching coefficients multiplying production, propagation, decay operators



Example: Production Operator

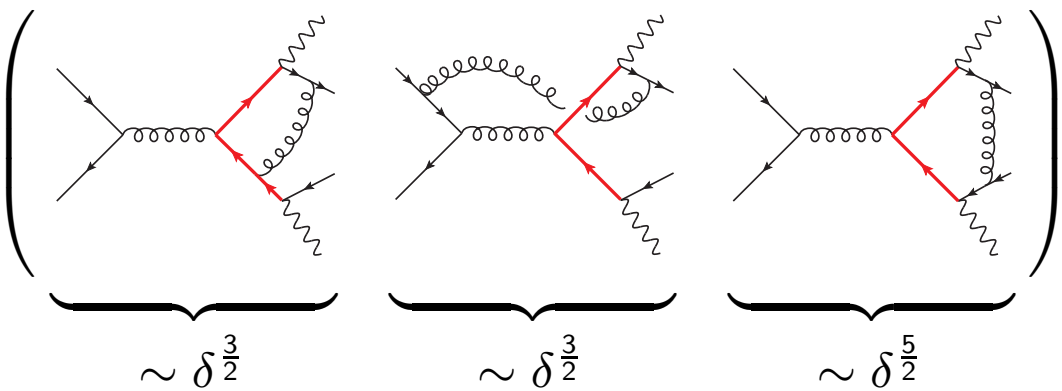


$\supset$ Hard



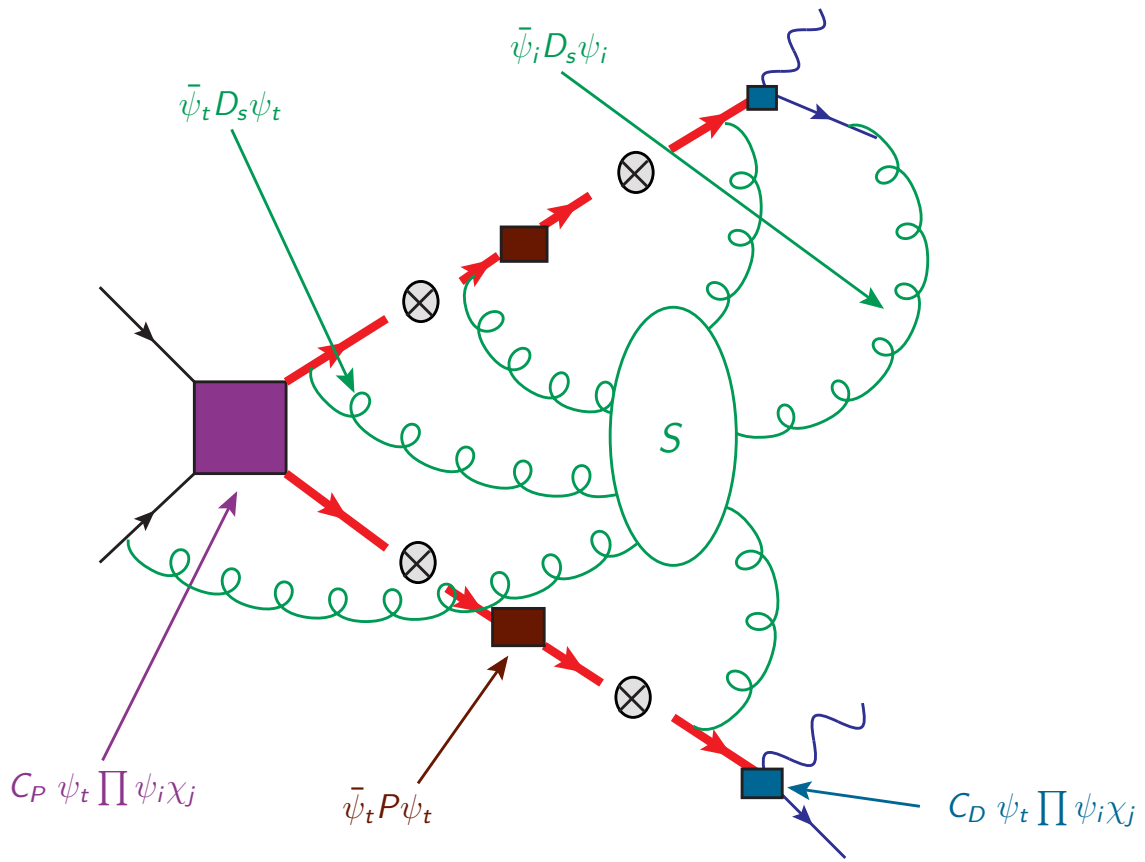
whereas

Hard



Resonant $t\bar{t}$: Effective Theory Structure

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



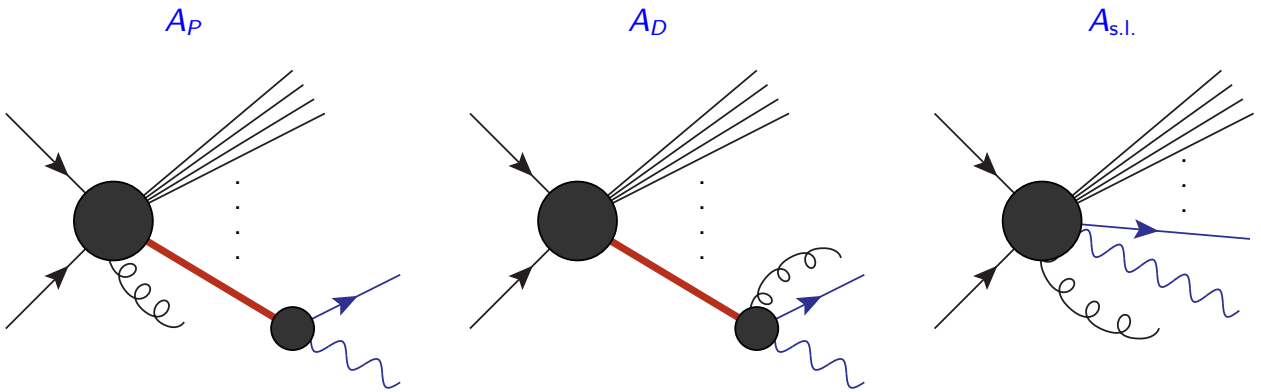
$\rightarrow$ separation of contributions which live at different scales μ_h and μ_s

Real Corrections

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

$\rightarrow$ do this in a way consistent with Method of Regions used for loops

Split $A_{\text{full}}^{\text{real}}$ into:



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

Pole cancellation works as expected (and desired):

$\int d\Phi_g \, |A_{P/D}|^2$ 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.

t-Channel Single Top: 7 TeV LHC

Process: $pp \to J_b\, J_l\, e^+ \not{E}_T + X$

- two independent parton-level monte carlos (FKS & CS subtractions)
- allow (in principle) arbitrary cuts on final state jets/leptons, e.g.

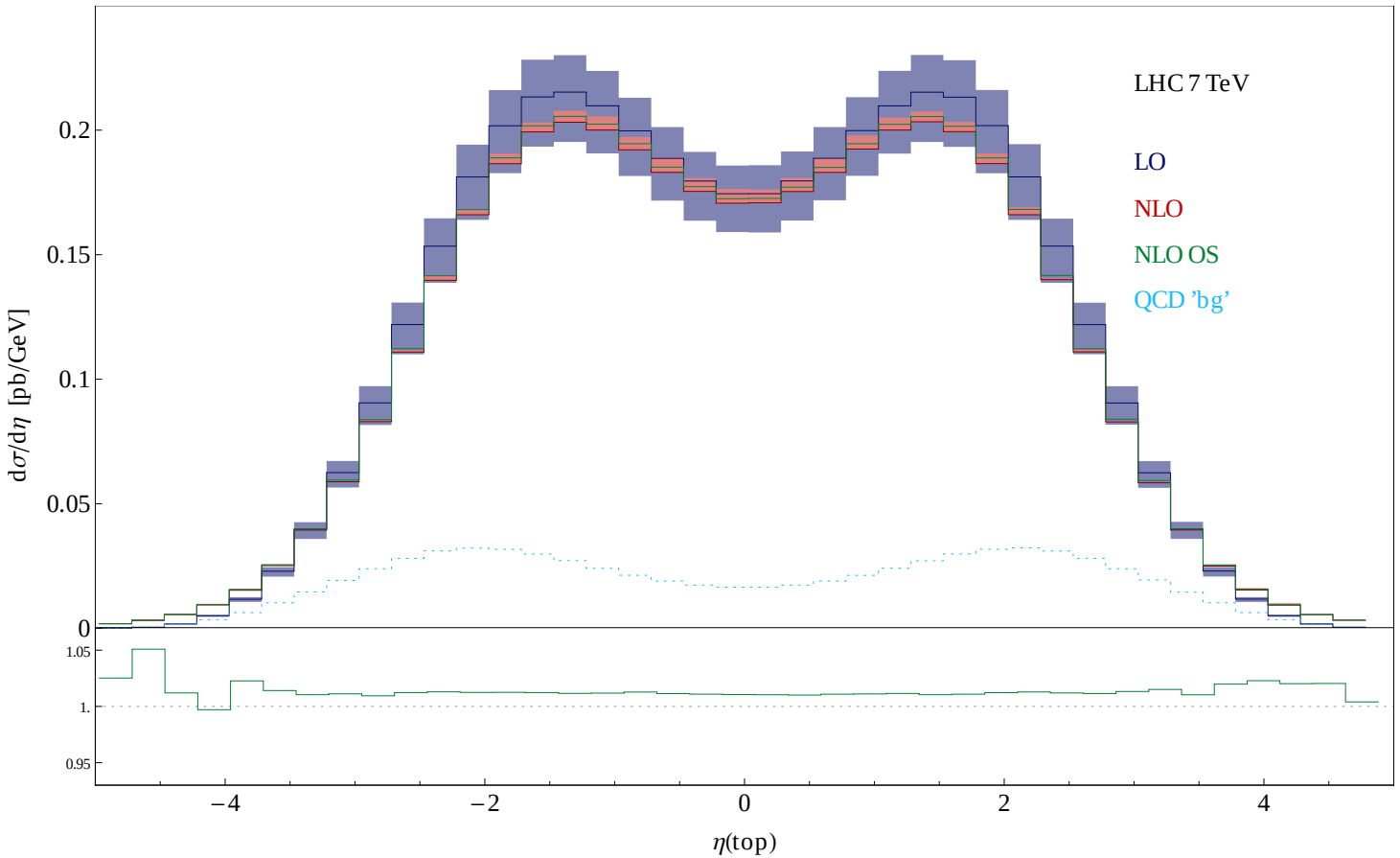
$p_T(J_b) > 20$ GeV	$\not{E}_T > 20$ GeV
$p_T(\text{hardest}J_l) > 20$ GeV	$\eta(J_b) < 2.5$
$p_T(e) > 20$ GeV	$\eta(\text{hardest}J_l) < 2.0$
$120 < m_{\text{inv}} < 200$ GeV	$\eta(e) < 2.5$

Cross-Section Results:

	ET	**NWA**
LO [fb]	1137.0(2)	1152.3(1)
NLO [fb]	1086.5(2)	1098.5(2)

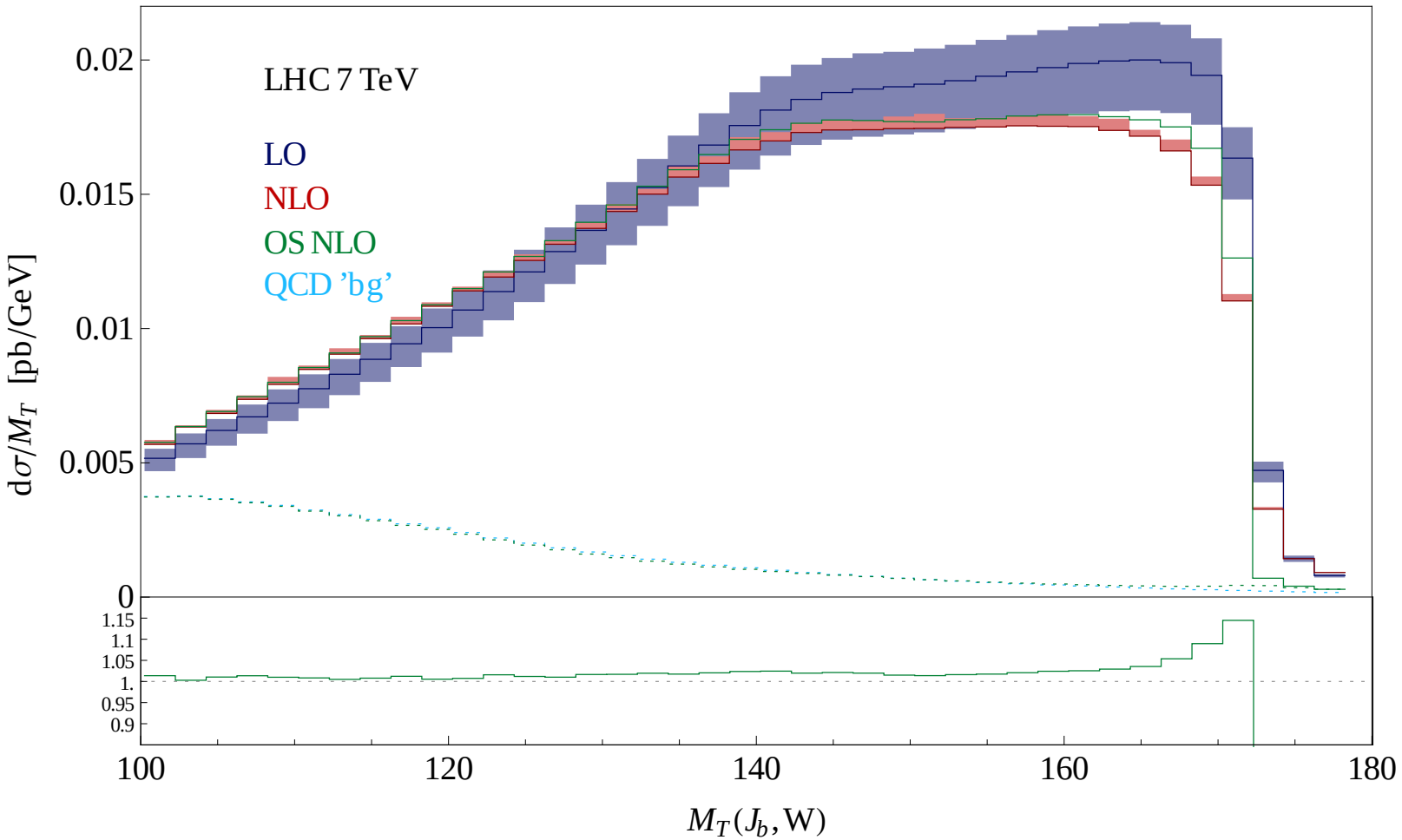
As expected, 1-2% difference between $NLO_{\text{on-shell}}$ & $NLO_{\text{off-shell; ET}}$

Example distribution: η(top)



Off-shell effects small

Example distribution: M_T(top)



Off-shell effects important (near M_t)

Conclusions / Outlook

- Off-Shell effects important to control for precision top studies

  Single Top: $\hookrightarrow$ small contributions for inclusive observables
  $\hookrightarrow$ noticeable effects near edges of (some) distributions

- ET inspired way to tackle this problem in resonant region

  $\rightarrow$ reduction in complexity of calculation

  $\rightarrow$ gauge invariant split of contributions into factorizable / non-factorizable

  $\rightarrow$ split of contributions naturally living at hard (μ_h) & soft (μ_s) scales

To do list:

- full study of off-shell effects in $t\bar{t}$ production (pending)
- include anomalous decays of tops, hadronic decays of W's
- progress towards resummation of $\log\left(\frac{\mu_s}{\mu_h}\right)$ for exclusive observables

Thanks for listening!