Latest theory developments for top pair production, generators and showering

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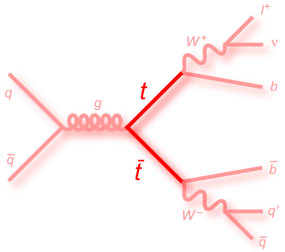
plan of the talk

1. total & differential cross sections
   - fixed-order
   - resummation and approximate higher-orders
2. event generators
   - top-decays, offshellness and interference effects
   - $t\bar{t} + X$ and NLO+PS merging
3. conclusions



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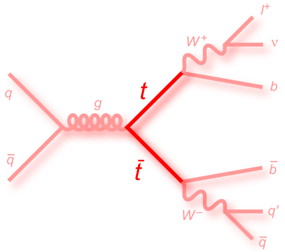


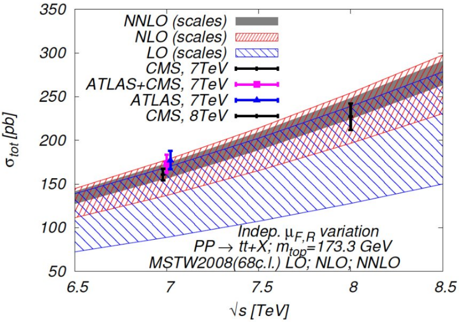
- e^+e^- not discussed
- electroweak corrections and more on $t\bar{t} + X$ as well as on differential distributions on Thursday
- surely I've missed something - apologies for omissions

1. total & differential cross sections

total & differential cross sections

- At fixed order, state of the art is NNLO [Baernreuther,Czakon,Fiedler,Heymes,Mitov '12-]

[talk by Heymes on Thursday]



- good perturbative convergence

figure from M. Czakon

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[talk by Heymes on Thursday]

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$	$+16.2(1.7\%)$ $-17.8(1.9\%)$

- good perturbative convergence
- matching to NNLL resummation improves (scale) uncertainty: $5\% \to 3\%$

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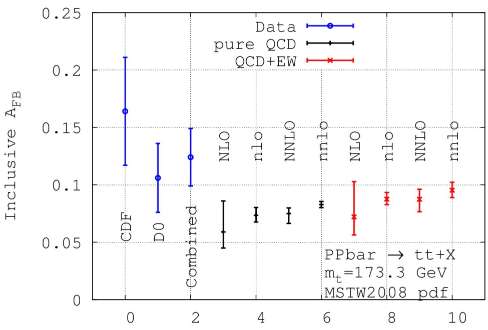

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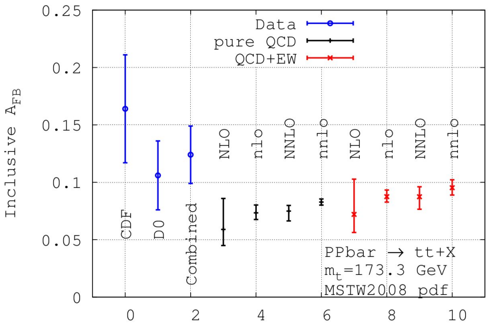

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Other groups working on NNLO corrections: [Abelof,Gehrmann-De Ridder, et al], [Catani,Grazzini, et al]

- recent progress on q_T-subtraction for colored final state:
  - small-$p_{T,t\bar{t}}$ structure now known
  - fully differential NLO reproduced, steps towards NNLO

[Bonciani,Catani,Grazzini,Sargsyan,Torre '14-'15]

total & differential cross sections

☞ higher-order log-ennhanced terms can be computed, and resummed

- match with fixed order (or use them to guess unknown next order)
- argument of log $\leftrightarrow$ distance wrt LO kinematics

$\beta = \sqrt{1 - 4m^2/\hat{s}}$ PIM $[(1-z) = 1 - M^2_{t\bar{t}}/\hat{s}]$ 1PI $[s_4/m^2, s_4 = (p_{\bar{t}} + p_X)^2 - m^2]$

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fully inclusive

- NNLL threshold logs: $\alpha_S^n \log^m \beta$ [Czakon,Mitov,Sterman],[Beneke,Falgari,Schwinn, et al],[Cacciari et al]
- public codes:
  TOP++ [NNLO+soft], TOPiXS [NNLO+soft+Coulomb], HATHOR [NNLO]
- approximate N^{3}LO (soft & high-energy logs) [Muselli,Bonvini, et al '15]

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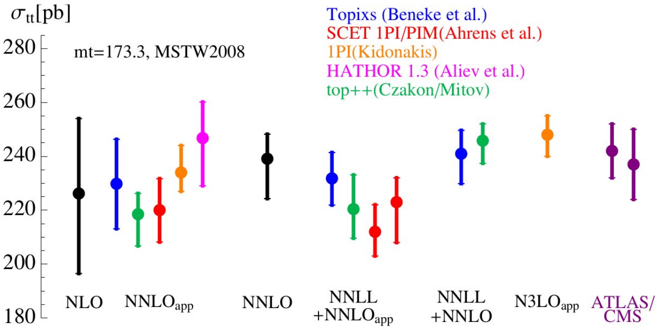
differential

- 1PI and PIM NNLL threshold (NLO matched) [Ahrens,Ferroglia,Neubert,Pecjak,Yang]
- being extended also to boosted top regime [talk by Pecjak on Thursday]
- 1PI and PIM approximate NNLO, with decays at NLO [Broggio,Papanastasiou,Signer, '14]
- 1PI approximate NNLO public code: DiffTOP [Guzzi,Lipka,Moch, '14]
- 1PI approximate N^{3}LO [Kidonakis, '15]

fixed order + resummation

- how do they compare?

figure from C. Schwinn



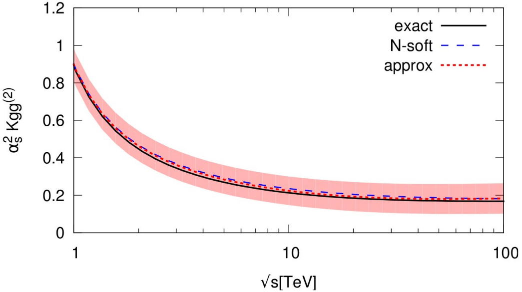
- information from exact NNLO clearly relevant

approximate N^{3}LO

- combine soft and high-energy resummation [Muselli,Bonvini,Forte,Marzani,Ridolfi '15]

in Mellin space: $C_{\text{approx}}(N) = C_{\text{soft}}(N) + C_{\text{h.e.}}(N)$

K-factors relative to LO (gg-only)



- check approximation at NNLO

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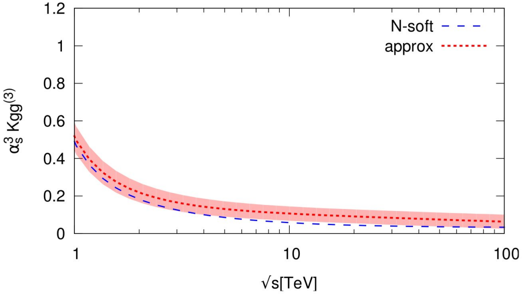

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K-factors relative to LO (gg-only)

		$\alpha_s(m^2)K_{gg}^{(1)}$	$\alpha_s^2(m^2)K_{gg}^{(2)}$	$\alpha_s^3(m^2)K_{gg}^{(3)}$
13 TeV	exact	0.555	0.199	
	approx	0.569 ± 0.125	0.209 ± 0.077	0.083 ± 0.036
	N-soft	0.619	0.221	0.040

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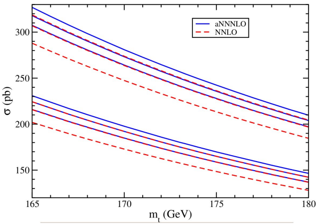
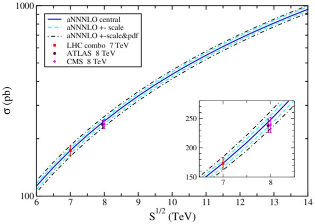
- approximate N^{3}LO results expanding 1PI threshold logs [Kidonakis, '14-'15]



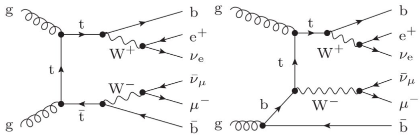


fully-differential pair-production with decays

- state of the art: $pp \to W^+(\ell\nu)W^-(\ell\nu)b\bar{b}$
  - QCD NLO in prod and decay, narrow-width approximation [Bernreuther et al],[Melnikov,Schulze],[Campbell,Ellis]
  - fully exclusive NLO, massless b-quarks [Denner et al],[Bevilacqua et al],[Heinrich et al]
  - fully exclusive NLO, massive b-quarks [Frederix '13],[Cascioli,Kallweit, et al '13]

★ important spinoff: $t\bar{t}$ vs. tW:

the inclusion of decays, with massive b-quarks, allows also an unambiguos definition of $t\bar{t}$ vs. tW:



- " $t\bar{t}$ " $\to WWbb$: 2 resolved b-jets
- " Wt " $\to WWb$: at least one resolved b-jet
- arbitary cuts on the other objects

- until very recently, top quarks treated as stable in NLO+PS event generators: decay products generated a-posteriori, retaining tree-level angular correlations

[method by Frixione,Laenen,Motylinski,Webber, now also automated in MadSpin]

2. tools & MC generators

status and recent developments

Two most important developments in the last couple of years:

1. (towards) fully-consistent NLO+PS simulation of $WWbb$, with exact decays at NLO and offshellness effects

   - improvement on m_t measure likely to come from combination of different strategies: total x-section, $t\bar{t}$ + jet, leptonic spectra, $b\ell$ endpoint,... [talk by Corcella on Wednesday]

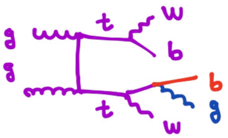


figure from R. Franceschini

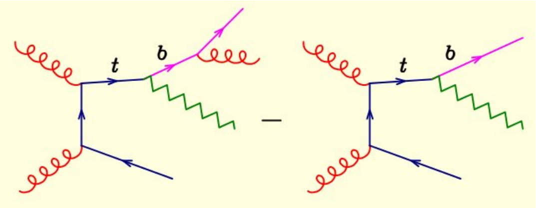
   - some techniques rely on looking into the kinematics of visible particles from top-decay
   - important that simulations are as accurate as possible, and associated uncertainties are quantified

2. simulation of $t\bar{t} + X$ and NLO+PS multijet merging

   - backgrounds to “all” BSM direct searches
   - relevant to indirectly probe BSM effects, *e.g.* Higgs couplings and $t\bar{t}H$

$WWbb$ at NLO+PS

- to understand the origin of issues, let's first consider NLO (no shower):
  - when computing $WWb\bar{b}$ at NLO, current subtraction schemes (FKS, CS) don't preserve top virtuality between real emission terms and their counterterms



  - when bgW is on-shell, the counterterm goes off-shell:
    - top virtuality displaced by amount m_{bg}^2/E_b
    - subtraction works until $m_{bg}^2/E_b \approx \Gamma_t$
    - in the strict narrow-width limit, IR cancellation spoiled
  - the above statement means that approaching the zero-width limit from an off-shell computation should fail. However, the top-quark width is "not so small", and indeed NLO computations for $WWbb$ were completed succesfully, both in 5- and 4-flavour scheme

$WWbb$ at NLO+PS

- at NLO+PS, things get more serious:

$$d\sigma = d\Phi_{\mathrm{rad}} \bar{B}(\Phi_B) \frac{R(\Phi_B, \Phi_{\mathrm{rad}})}{B(\Phi_B)} \exp\left[- \int \frac{R(\Phi_B, \Phi_{\mathrm{rad}})}{B(\Phi_B)} d\Phi_{\mathrm{rad}} \right]$$

- because virtuality is not preserved, $\bar{B}/B$ is suppressed or ennhanced, if $(\Phi_B, \Phi_{\mathrm{rad}})$ or Φ_B are off-shell, respectively.
- these effects don't mutually compensate, because if Φ_B is off-shell, the Sudakov factor always yield large suppression (the converse is true only if m_{bg}^2 is small).
- expect distorsion of b-jet mass when $m^2/E \approx \Gamma_t$, *i.e.* $m_j \simeq 8$ GeV
- a `POWHEG` implementation for the full $WWb\bar{b}$ computation exists [Garzelli,Kardos,Trocsanyi '14]. It'll be interesting to investigate further.

- In the meanwhile, `POWHEG-BOX` was improved: now it can deal with radiation in resonance decays, in the zero-width limit, in a fully general way. First step towards exact $WWb\bar{b}$ at NLO+PS...

towards $WWbb$ at NLO+PS

[Campbell,Ellis,Nason,ER '14]

In a nutshell:

- in narrow-width limit, NLO corrections in production and decay decouple [✓]
  - real corrections can be separated between production and decay (for each resonance)
  - similar for virtual corrections
- if radiation comes from resonance, Φ_B constructed in the resonance frame, so that top-virtuality is preserved [✓]
- finite-width effects included approximately, by rescaling with exact LO matrix elements
  - generic (offshell) phase-space + projection onto on-shell zero-width phase-space
  - reweighting using LO exact results (finite width, non-double-resonant diagrams,...)
- "multiplicative `POWHEG`": keep multiple emissions before showering
  - by default `POWHEG` is additive: keeps only the hardest emission.
  - for heavy-pair production and decay, emissions from decay are rarely the hardest. Hence, with default `POWHEG`, they would be dealt with by the shower.
  - keep hard radiation and the emissions from all decaying resonances, then merge them into a single radiation phase space with several radiated partons, up to one for each resonance.

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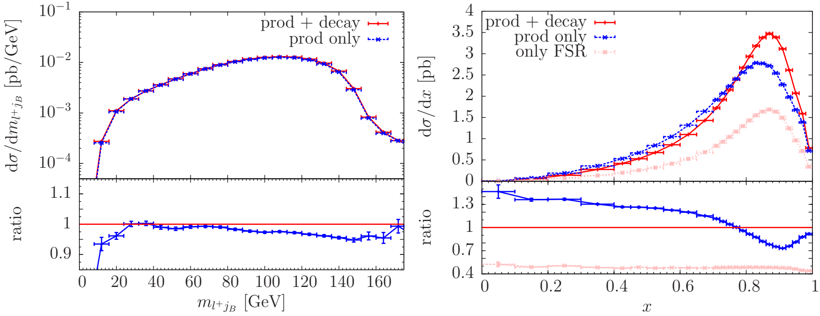
- Work is in progress to generalize this approach, in order to allow the inclusion of all diagrams, with no approximations. This required further changes in the POWHEG−BOX code; currently being tested in the t-channel single-top case [Jezo,Nason]

towards $WWbb$ at NLO+PS: results

[Campbell,Ellis,Nason,ER '14]

- code for NLO+PS in production and NLO+PS in decays is available, with approximate off-shellness effects



  - left: 5% effects on $m_{\ell j_b}$ end-point distribution.
  - right: fragmentation function ($x = E_B/E_{B,max}$)

- can be used as a tool to study, with a fully realistic simulation, recently proposed methods to extract m_t

NLO+PS for heavy pair + X

For this type of processes, NLO+PS has now become standard due to the high-level of automation reached in the QCD NLO community

- MadGraph5_aMC@NLO [Alwall,Frederix,Frixione,Hirschi,Maltoni,Mattelaer,Shao,Stelzer,Torrielli,Zaro]
  all relevant process involving a $t\bar{t}$ pair produced in association with extra light or heavy objects can now be simulated at NLO+PS accuracy, in a fully-automated way.
- Within the POWHEG method, several studies have been performed too, mostly with PowHel [Garzelli,Kardos,Trocsanyi]
  - $t\bar{t}+j$, $t\bar{t}b\bar{b}$, $t\bar{t}V$, $t\bar{t}H$ ...
- Progress also in Sherpa-MC@NLO [Hoeche,Krauss,Schoenherr,Siegert]
  - $t\bar{t}b\bar{b}$, $t\bar{t}+ \leq 2$ jets [using OpenLoops]
    easy to simulate other processes linking to 1-loop codes

NLO+PS merging

- significant fraction of interesting final states is accompanied by one (or more) jets
- sometime a single tool describing several jet multiplicities at the same time is needed
- CKKW-L and MLM-merging methods succesfully address this issue at LO:
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- challenge: extend these methods to NLO ("NLOPS multijet merging"):
  - from one single event sample, have 1-, 2-,...,n-jet observables at NLO

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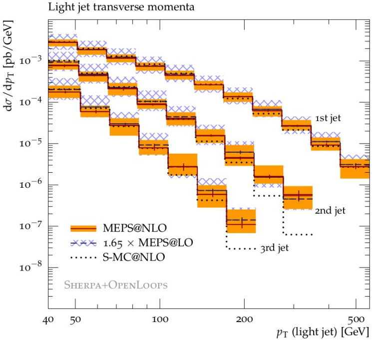
several proposals on the market. However so far only 2 of them have been applied to $t\bar{t}$ processes

- MEPS@NLO [Sherpa]
- FxFx [MadGraph5_aMC@NLO]
- RunII measurements of QCD activity in $t\bar{t}$ events will provide a great chance to test these tools



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   - total x-section known at NNLO.
   - residual uncertainties from pQCD $\leq 5\%$ (or even less if matching to resummation).
   - first NNLO differential results. As for A_{FB}, they will become the reference.

2. differential cross sections with decays
   - all well-known at NLO (including finite width effects and non-resonant diagrams).
   - shown issues for $WWb\bar{b}$ at NLO+PS, and first steps to fix them.
   - progresses here will probably be important to assess the potential of newly-proposed methods to measure the top mass.

3. $t\bar{t}$ production in association with jets or heavy particle
   - at 13 TeV, it will be very relevant (as a signal and as a background)
   - automation of QCD NLO computations now completed:
     it allows to simulate "everything" at NLO+PS
   - NLO+PS multijet-merging is the more important development in MC community in the last 2-3 years. Tools are available also for $t\bar{t}$: Run II offers the possibility to test them against data.

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