TECHNISCHE UNIVERSITÄT DRESDEN

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Sherpa+OpenLoops for tt+jets and tt+HF as backgrounds for ttH(H$\rightarrow$bb)

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LHC Higgs XS, ttH subgroup, 10 Nov 2014

- last week: suffering from strong background contaminations, no control regions
- reducible: $t\bar{t}jj$ or $t\bar{t}c\bar{c}$ with misidentified jets
- irreducible: $t\bar{t}b\bar{b}$ continuum

Overview of modern MCs for $t\bar{t}(+\mathrm{HF})$

- NLO+PS matched $pp \to t\bar{t}$
  Powheg, (a)MC@NLO, ...
  - ☹ $t\bar{t}jj$ at shower accuracy
  - ☹ inclusive for (massless) $t\bar{t} + \mathrm{HF}$, but only at shower accuracy
- ME+PS@LO $pp \to t\bar{t} + 0j, 1j, 2j, \ldots$
  Sherpa, Alpgen/MadGraph+Herwig/Pythia, ...
  - ☹ $t\bar{t}jj$ at leading order accuracy
  - ☹ inclusive for (massless) $t\bar{t} + \mathrm{HF}$, but below jet cuts only shower accuracy
- ME+PS@NLO $pp \to t\bar{t} + 0j, 1j, 2j, \ldots$
  Sherpa+OpenLoops, aMC@NLO(?)
  - ☺ NLO accuracy for $t\bar{t}jj$
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- NLO+PS matched $pp \to t\bar{t} + b\bar{b}$
  PowHel, Sherpa+OpenLoops
  - ☺ inclusive for $t\bar{t} + \mathrm{HF}$ at NLO accuracy
  - ☹ not inclusive for $t\bar{t} + \mathrm{jets}$
  - ☹ large logs at m_b threshold not taken into account in 4F scheme

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Theoretical challenges for $t\bar{t}b\bar{b}$ calculations

- many coloured particles in $pp \to t\bar{t}b\bar{b}$, $t\bar{t}jj$ or $t\bar{t}c\bar{c}$
  - $\to$ large QCD corrections/uncertainties
  - $\to$ complicated higher-order calculations
- several mass scales

Massive & matched calculation

Cascioli, Maierhöfer, Moretti, Pozzorini, FS (2013)

- NLO QCD calculation using automated tools in common framework:
  - SHERPA — Gleisberg, Höche, Krauss, Schönherr, Schumann, Winter, FS (2008)
    tree-level matrix elements, dipole subtraction, parton shower matching
  - OPENLOOPS — Cascioli, Maierhöfer, Pozzorini (2011)
    virtual corrections
  - COLLIER — Denner, Dittmaier, Hofer (in prep.)
    tensor integral reduction
- full b-quark mass dependence in 4-flavour-scheme
- matching to SHERPA's parton shower (S-MC@NLO) — Höche, Krauss, Schönherr, FS (2011)

$\leadsto$ unexpected new contribution

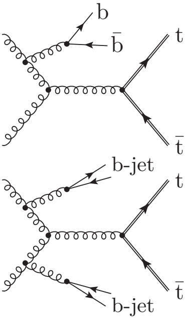
Simulation setup

- 4-flavour-scheme with finite b-mass and corresponding MSTW2008 PDFs + α_s
- top quarks treated as stable particles
  but LO decays could be included automatically with spin correlations
- renormalisation scale

$$\mu_R^4 \sim \prod_{i=t,\bar{t},b,\bar{b}} E_{\mathrm{T},i}$$

- factorisation and resummation scale

$$\mu_F \sim \mu_Q \sim \frac{1}{2}(E_{\mathrm{T},t} + E_{\mathrm{T},\bar{t}})$$



Analysis

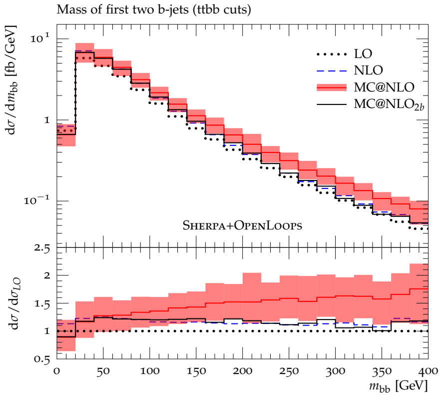
- jet reconstruction using anti-k_t with $R = 0.4$
- "(idealised) experimental" b-tagging:
  b-jet = jet with at least one b-quark constituent
  $\to$ allows for quasi-collinear $b\bar{b}$-pairs
- require ≥ 2 b-jets with $p_\perp > 25\,\mathrm{GeV}$ and $|\eta| < 2.5$
- Higgs signal region selection: $m_{bb} > 100\,\mathrm{GeV}$

Total cross sections

	ttb	ttbb	ttbb$(m_{bb} > 100)$
σ_{LO}[fb]	$2644^{+71\%\,+14\%}_{-38\%\,-11\%}$	$463.3^{+66\%\,+15\%}_{-36\%\,-12\%}$	$123.4^{+63\%\,+17\%}_{-35\%\,-13\%}$
σ_{NLO}[fb]	$3296^{+34\%\,+5.6\%}_{-25\%\,-4.2\%}$	$560^{+29\%\,+5.4\%}_{-24\%\,-4.8\%}$	$141.8^{+26\%\,+6.5\%}_{-22\%\,-4.6\%}$
$\sigma_{\text{NLO}}/\sigma_{\text{LO}}$	1.25	1.21	1.15
$\sigma_{\text{S-MC@NLO}}$[fb]	$3313^{+32\%\,+3.9\%}_{-25\%\,-2.9\%}$	$600^{+24\%\,+2.0\%}_{-22\%\,-2.1\%}$	$181.0^{+20\%\,+8.1\%}_{-20\%\,-6.0\%}$
$\sigma_{\text{S-MC@NLO}}/\sigma_{\text{NLO}}$	1.01	1.07	1.28
$\sigma^{2b}_{\text{S-MC@NLO}}$[fb]	3299	552	146
$\sigma^{2b}_{\text{S-MC@NLO}}/\sigma_{\text{NLO}}$	1.00	0.99	1.03

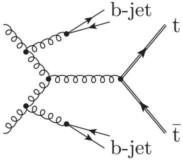
- uncertainty estimates from μ_R and $\mu_F \oplus \mu_Q$ variations
- large enhancement of S-MC@NLO prediction in $m_{bb} > 100$ GeV region!

A closer look at high m_{bb}

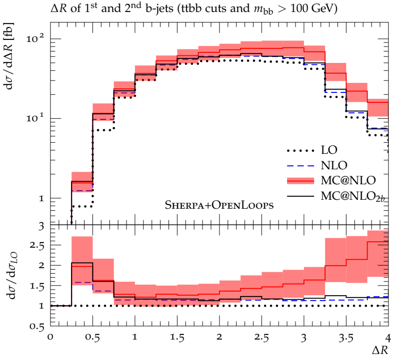


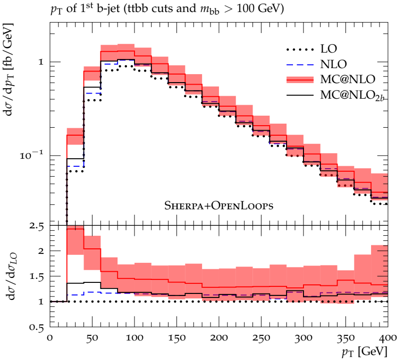
- clear enhancement of S-MC@NLO prediction at high m_{bb}
- caused by double quasi-collinear $g \to b\bar{b}$ splitting

  (technical test: absent if $g \to b\bar{b}$ switched off in PS $\rightsquigarrow$ black line)

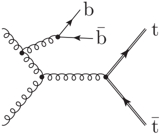


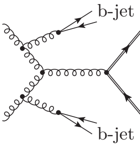
- contribution very relevant for Higgs search region $m_{bb} > 100$ GeV exceeds Higgs signal? ☹
- can only be simulated at this accuracy due to massive and PS matched calculation!





- topology of enhancement:
  back-to-back b-jets with smallest $p_\perp$ to reach $m_{bb} > 100$ GeV
  $\Rightarrow$ completely consistent with expectation from double splitting picture





Reducible backgrounds from $t\bar{t}$+jets

ME+PS@NLO $pp \to t\bar{t}$+jets

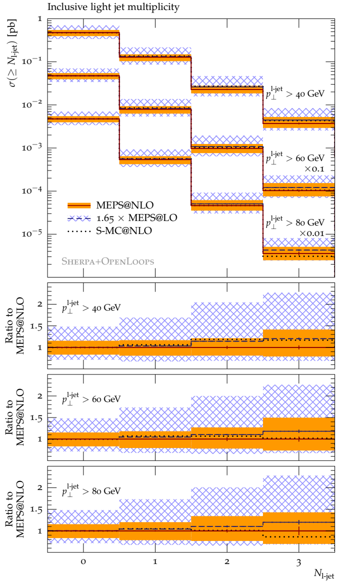
Höche, Krauss Maierhöfer, Pozzorini, Schönherr, FS (2014)

Simulation setup:

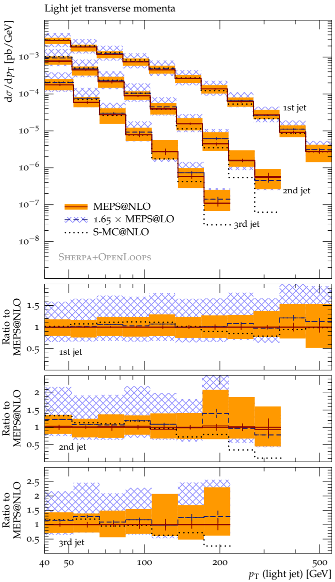
- $pp \to t\bar{t} + 0j, 1j, 2j$@NLO $+ 3j$@LO
- 5-flavour scheme with massless b-quarks in ME, massive b-quarks in PS evolution
- dileptonic decays
- uncertainty assessment from quadrature sum of:
  - envelope of all μ_R, μ_F factor-2-variations
  - μ_Q variation by factor $\sqrt{2}$
  - merging scale variation from $Q_{\text{cut}} = 20 \ldots 40$ GeV
  - varying parton shower kinematics (recoil schemes)

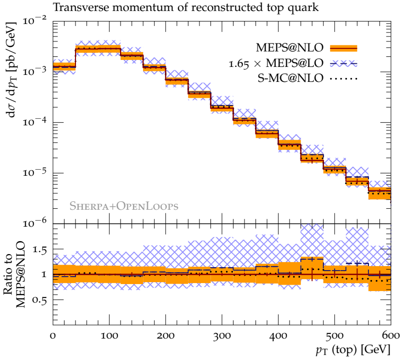
Analysis setup:

- anti-k_t jets with $R = 0.4$
- exactly one b- and one $\bar{b}$-jet with $p_\perp > 25$ Gev, $|\eta| < 2.5$



Results from $t\bar{t}$+jets ME+PS@NLO





- uncertainties reduced in particular in $+0, 1, 2$-jet bins
- $\Rightarrow$ improvements at high $p_\perp^{\text{top}}$
- high $p_\perp^{\text{jet2}}$ suffers from statistics and influence of $t\bar{t} + 3j$ configurations

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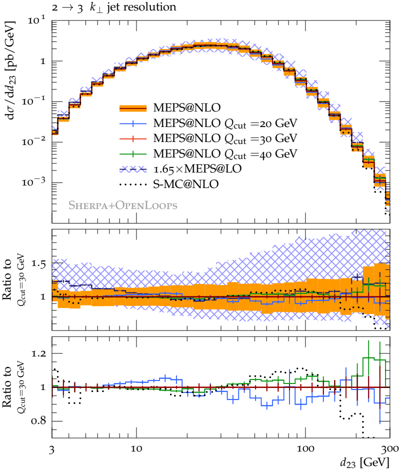
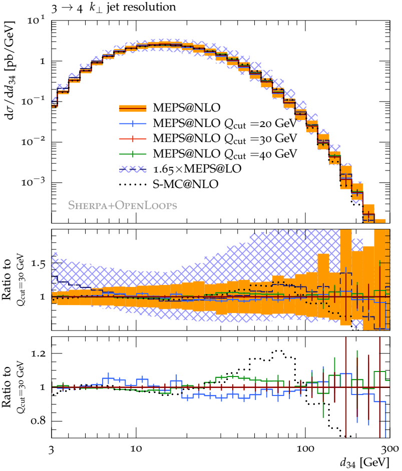
Merging scale uncertainties

- assessment of merging-induced uncertainties in addition to perturbative uncertainties
- variation of merging scale: $Q_{\text{cut}} = 20 \ldots 30 \ldots 40\,\text{GeV}$
- most sensitive observables: k_t splitting scales for $2 \to 3$ and $3 \to 4$ splitting (including the two b-quarks from top decays)





What about $pp \to t\bar{t}c\bar{c}$?

- generalise from $pp \to t\bar{t}b\bar{b}$ simulation? (technically trivial)
- not advisable(?): inclusive 3-flavour calculation does not resum logarithms close to the m_c thresholds, which should be more relevant than for m_b (where we found rather negligible effects)

Future with ME+PS@NLO

- future ME+PS@NLO samples will "allow for a consistent treatment of bb/cc"?
- yes and no: dedicated $tt + \mathrm{HF}$ still has the advantage of the inclusive massive NLO ME prediction even below 2-bjet cuts (e.g. "ttB" with merged bjets)
- MC authors have to work for consistent combination (overlap removal)

Shower dominance even in ME+PS-merged samples

- shower dominance not surprising if merging scale is at 40 GeV and jets defined at 15 or 25 GeV
- more realistic cross check possibly with merging scale below analysis cut

Summary

- $t\bar{t}H$ measurements depend on precise Monte-Carlo predictions for background modelling

- Main background to $pp \to t\bar{t}H[\to b\bar{b}]$ from NLO+PS matched $pp \to t\bar{t}b\bar{b}$ calculation with massive b-quarks
- Surprising: large contribution from double collinear configurations in Higgs region

Outlook

- Consistent combination of $t\bar{t}H[\to b\bar{b}]$ backgrounds
  - inclusive, massive S-MC@NLO prediction for $t\bar{t}b\bar{b}$
  - ME+PS@NLO prediction for $t\bar{t} + 0, 1, 2j$
- Predictions for $t\bar{t}c\bar{c}$: included in $t\bar{t}$+jets or dedicated (3F?) $t\bar{t}c\bar{c}$ needs more studies