$t\bar{t}$+jets and $t\bar{t}V$+jets in SHERPA+OPENLOOPS

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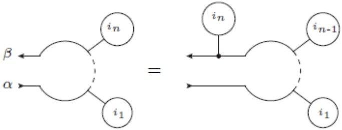
Outline

1. (N)NLO QCD+NLO EW automation with OpenLoops
2. S-MC@NLO matching for $t\bar{t}b\bar{b}$ in 4F scheme
3. MEPS@NLO merging for $t\bar{t}+0,1,2$ jets
4. MEPS@NLO merging for $t\bar{t}W+0,1$ jets

OpenLoops I

1-loop amplitudes with OpenLoops [Cascioli, Maierhöfer, S.P. '12]

- automated & fast generation of NLO QCD MEs for any $2 \to 4\,(5)$ SM process
- numerical recursion for "loop-momentum dependent" trees



- high speed at runtime with tensor reduction (Collier, [Denner, Dittmaier, Hofer]) and/or OPP reduction (CutTools, [Ossola, Papadopoulos, Pittau])

Complete NLO automation through interface with Monte Carlo Tools

- Sherpa2.1 [Höche, Höth, Krauss, Schönherr, Schumann, Siegert, Zapp]

  ⇒ S–MC@NLO matching to Sherpa shower and MEPS@NLO multi-jet merging
- Munich [S. Kallweit]

  ⇒ very fast parton level MC for NLO and NNLO (q_{T} subtraction)

OpenLoops II

Several challenging NLO, S–MC@NLO, MEPS@NLO and NNLO studies thanks to automation & speed (Higgs, Top and EW phenomenology)

- NLO for $pp \to W^+W^-b\bar{b}$ with $m_b > 0$, [Cascioli, Kallweit, Maierhöfer, S. P., arXiv:1312.0546]
- S–MC@NLO $pp \to t\bar{t}b\bar{b}$ with $m_b > 0$, [Cascioli, Maierhöfer, Moretti, S. P. , Siegert, arXiv:1309.5912]
- MEPS@NLO for $\ell\ell\nu\nu$+0,1 jets, [Cascioli, Höche, Krauss, Maierhöfer, S. P. , Siegert, arXiv:1309.0500]
- NLO merging for $pp \to HH$+0,1 jets, [Maierhöfer, Papaefstathiou, arXiv:1401.0007]
- MEPS@NLO for $t\bar{t}$+0,1,2 jets, [Höche, Krauss, Maierhöfer, S. P. , Schönherr, Siegert arXiv:1402.6293]
- MEPS@NLO for WWW+0,1 jets, [Höche, Krauss, S. P. , Schönherr, Thompson arXiv:1403.7516]
- NNLO for $pp \to \gamma Z$ production, [Grazzini, Kallweit, Rathlev, Torre, arXiv:1309.7000]
- NNLO for $q\bar{q} \to t\bar{t}$ production, [Abelof, Gehrmann–de Ridder, Maierhöfer, S.P. , arXiv:1404.6493]
- NNLO for $pp \to ZZ$ production, [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, S.P. , Rathlev, Tancredi, Weihs, arXiv:1405.2219]
- NNLO for $pp \to W^+W^-$ production, [Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, S.P. , Rathlev, Tancredi arXiv:1408.5243]
- **NEW:** NLO QCD+EW for $pp \to W + 1, 2, 3$ jets, [Kallweit, Lindert, Maierhöfer, S.P. , Schönherr arXiv:1412.5157]

Public Release I

OpenLoops 1.0 [Cascioli, Lindert, Maierhöfer, S.P.]

- publicly available at `openloops.hepforge.org` since Sept '14
- all NLO QCD amplitude building blocks
- download and installation easy

Interfaces to public MC tools

- automated built-in interfaces in SHERPA2.1 and HERWIG++
- BLHA or OPENLOOPS native interface for other MCs (tested with POWHEGBOX)

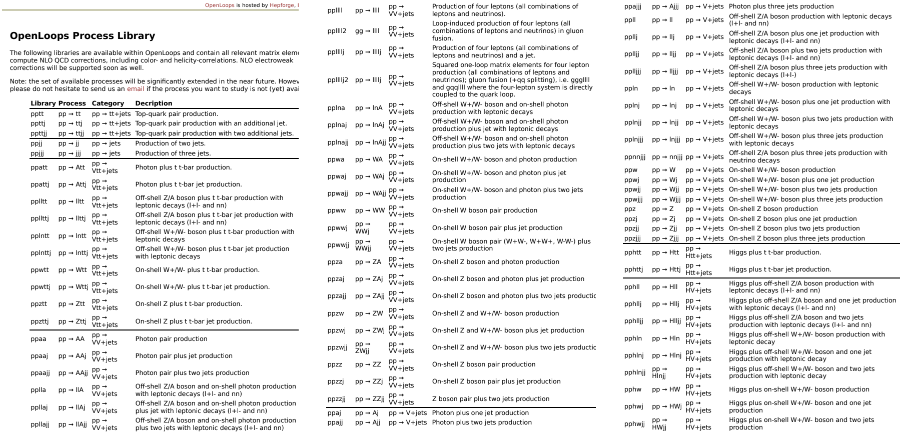
Process library

- pre-generated code for more than 100 processes (more coming)
- automated download+installation of desired process libraries, e.g.

  ```
  $ scons auto=ppwtt,ppwttj
  ```

OpenLoops process library

`http://openloops.hepforge.org/process_library.php`



OpenLoops is hosted by Hepforge, I

OpenLoops Process Library

The following libraries are available within OpenLoops and contain all relevant matrix elem compute NLO QCD corrections, including color- and helicity-correlations. NLO electroweak corrections will be supported soon as well.

Note: the set of available processes will be significantly extended in the near future. Howev please do not hesitate to send us an email if the process you want to study is not (yet) avai

Library	Process	Category	Decription
pptt	pp → tt	pp → tt+jets	Top-quark pair production.
ppttj	pp → ttj	pp → tt+jets	Top-quark pair production with an additional jet.
ppttjj	pp → ttjj	pp → tt+jets	Top-quark pair production with two additional jets.
ppjj	pp → jj	pp → jets	Production of two jets.
ppjjj	pp → jjj	pp → jets	Production of three jets.
ppatt	pp → Att	pp → Vtt+jets	Photon plus t t-bar production.
ppattj	pp → Attj	pp → Vtt+jets	Photon plus t t-bar jet production.
pplltt	pp → lltt	pp → Vtt+jets	Off-shell Z/A boson plus t t-bar production with leptonic decays (l+l- and nn)
pplltj	pp → llttj	pp → Vtt+jets	Off-shell Z/A boson plus t t-bar jet production with leptonic decays (l+l- and nn)
pplntt	pp → lntt	pp → Vtt+jets	Off-shell W+/W- boson plus t t-bar production with leptonic decays
pplnttj	pp → lnttj	pp → Vtt+jets	Off-shell W+/W- boson plus t t-bar jet production with leptonic decays
ppwtt	pp → Wtt	pp → Vtt+jets	On-shell W+/W- plus t t-bar production.
ppwttj	pp → Wttj	pp → Vtt+jets	On-shell W+/W- plus t t-bar jet production.
ppztt	pp → Ztt	pp → Vtt+jets	On-shell Z plus t t-bar production.
ppzttj	pp → Zttj	pp → Vtt+jets	On-shell Z plus t t-bar jet production.
ppaa	pp → AA	pp → VV+jets	Photon pair production
ppaaj	pp → AAj	pp → VV+jets	Photon pair plus jet production
ppaajj	pp → AAjj	pp → VV+jets	Photon pair plus two jets production
pplla	pp → llA	pp → VV+jets	Off-shell Z/A boson and on-shell photon production with leptonic decays (l+l- and nn)
pplaj	pp → llAj	pp → VV+jets	Off-shell Z/A boson and on-shell photon production plus jet with leptonic decays (l+l- and nn)
ppllajj	pp → llAjj	pp → VV+jets	Off-shell Z/A boson and on-shell photon production plus two jets with leptonic decays (l+l- and nn)
ppllll	pp → llll	pp → VV+jets	Production of four leptons (all combinations of leptons and neutrinos).
ppllll2	gg → llll	pp → VV+jets	Loop-induced production of four leptons (all combinations of leptons and neutrinos) in gluon fusion.
pplllj	pp → llllj	pp → VV+jets	Production of four leptons (all combinations of leptons and neutrinos) and a jet.
ppllllj2	pp → llllj	pp → VV+jets	Squared one-loop matrix elements for four lepton production (all combinations of leptons and neutrinos); gluon fusion (+qq splitting), i.e. gggllll and gqqllll where the four-lepton system is directly coupled to the quark loop.
pplna	pp → lnA	pp → VV+jets	Off-shell W+/W- boson and on-shell photon production with leptonic decays
pplnaj	pp → lnAj	pp → VV+jets	Off-shell W+/W- boson and on-shell photon production plus jet with leptonic decays
pplnajj	pp → lnAjj	pp → VV+jets	Off-shell W+/W- boson and on-shell photon production plus two jets with leptonic decays
ppwa	pp → WA	pp → VV+jets	On-shell W+/W- boson and photon production
ppwaj	pp → WAj	pp → VV+jets	On-shell W+/W- boson and photon plus jet production
ppwajj	pp → WAjj	pp → VV+jets	On-shell W+/W- boson and photon plus two jets production
ppww	pp → WW	pp → VV+jets	On-shell W boson pair production
ppwwj	pp → WWj	pp → VV+jets	On-shell W boson pair plus jet production
ppwwjj	pp → WWjj	pp → VV+jets	On-shell W boson pair (W+W-, W+W+, W-W-) plus two jets production
ppza	pp → ZA	pp → VV+jets	On-shell Z boson and photon production
ppzaj	pp → ZAj	pp → VV+jets	On-shell Z boson and photon plus jet production
ppzajj	pp → ZAjj	pp → VV+jets	On-shell Z boson and photon plus two jets productic
ppzw	pp → ZW	pp → VV+jets	On-shell Z and W+/W- boson production
ppzwj	pp → ZWj	pp → VV+jets	On-shell Z and W+/W- boson plus jet production
ppzwjj	pp → ZWjj	pp → VV+jets	On-shell Z and W+/W- boson plus two jets productic
ppzz	pp → ZZ	pp → VV+jets	On-shell Z boson pair production
ppzzj	pp → ZZj	pp → VV+jets	On-shell Z boson pair plus jet production
ppzzjj	pp → ZZjj	pp → VV+jets	Z boson pair plus two jets production
ppaj	pp → Aj	pp → V+jets	Photon plus one jet production
ppajj	pp → Ajj	pp → V+jets	Photon plus two jets production
ppajjj	pp → Ajjj	pp → V+jets	Photon plus three jets production
ppll	pp → ll	pp → V+jets	Off-shell Z/A boson production with leptonic decays (l+l- and nn)
ppllj	pp → llj	pp → V+jets	Off-shell Z/A boson plus one jet production with leptonic decays (l+l- and nn)
pplljj	pp → lljj	pp → V+jets	Off-shell Z/A boson plus two jets production with leptonic decays (l+l- and nn)
pplljjj	pp → lljjj	pp → V+jets	Off-shell Z/A boson plus three jets production with leptonic decays (l+l-)
ppln	pp → ln	pp → V+jets	Off-shell W+/W- boson production with leptonic decays
pplnj	pp → lnj	pp → V+jets	Off-shell W+/W- boson plus one jet production with leptonic decays
pplnjj	pp → lnjj	pp → V+jets	Off-shell W+/W- boson plus two jets production with leptonic decays
pplnjjj	pp → lnjjj	pp → V+jets	Off-shell W+/W- boson plus three jets production with leptonic decays
ppnnjjj	pp → nnjjj	pp → V+jets	Off-shell Z/A boson plus three jets production with neutrino decays
ppw	pp → W	pp → V+jets	On-shell W+/W- boson production
ppwj	pp → Wj	pp → V+jets	On-shell W+/W- boson plus one jet production
ppwjj	pp → Wjj	pp → V+jets	On-shell W+/W- boson plus two jets production
ppwjjj	pp → Wjjj	pp → V+jets	On-shell W+/W- boson plus three jets production
ppz	pp → Z	pp → V+jets	On-shell Z boson production
ppzj	pp → Zj	pp → V+jets	On-shell Z boson plus one jet production
ppzjj	pp → Zjj	pp → V+jets	On-shell Z boson plus two jets production
ppzjjj	pp → Zjjj	pp → V+jets	On-shell Z boson plus three jets production
pphtt	pp → Htt	pp → Htt+jets	Higgs plus t t-bar production.
pphttj	pp → Httj	pp → Htt+jets	Higgs plus t t-bar jet production.
pphll	pp → Hll	pp → HV+jets	Higgs plus off-shell Z/A boson production with leptonic decays (l+l- and nn)
pphllj	pp → Hllj	pp → HV+jets	Higgs plus off-shell Z/A boson and one jet production with leptonic decays (l+l- and nn)
pphlljj	pp → Hlljj	pp → HV+jets	Higgs plus off-shell Z/A boson and two jets production with leptonic decays (l+l- and nn)
pphln	pp → Hln	pp → HV+jets	Higgs plus off-shell W+/W- boson production with leptonic decay
pphlnj	pp → Hlnj	pp → HV+jets	Higgs plus off-shell W+/W- boson and one jet production with leptonic decay
pphlnjj	pp → Hlnjj	pp → HV+jets	Higgs plus off-shell W+/W- boson and two jets production with leptonic decay
pphw	pp → HW	pp → HV+jets	Higgs plus on-shell W+/W- boson production
pphwj	pp → HWj	pp → HV+jets	Higgs plus on-shell W+/W- boson and one jet production
pphwjj	pp → HWjj	pp → HV+jets	Higgs plus on-shell W+/W- boson and two jets production

includes $t\bar{t}b\bar{b}$, $t\bar{t}+$jets, $t\bar{t}V+$jets, $t\bar{t}H+$jets,. . .

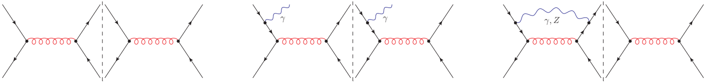
NLO QCD+EW automation in OpenLoops I

NLO QCD+EW completely automated [arXiv:1412.5157]

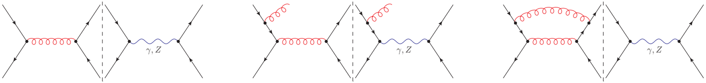
- OPENLOOPS [Lindert,Maierhöfer,S.P.] + MUNICH [Kallweit] and SHERPA [Schönherr]
- any $\mathcal{O}\left(\alpha_S^n \alpha^m\right)$ NLO contribution in the SM

Nontrivial bookkeeping of QCD–EW interferences e.g. in $q\bar{q} \to q\bar{q}$ at $\mathcal{O}\left(\alpha_S^2 \alpha\right)$

- EW corrections × QCD Born



- QCD corrections × EW Born



Other subtleties beyond trivial extension of QCD automation

- interplay of QED+QCD singularities in phton/jet definition
- resonances and weak decay

NLO QCD+EW automation in OpenLoops II

Technical performance of 1-loop EW for $t\bar{t}+$ jets

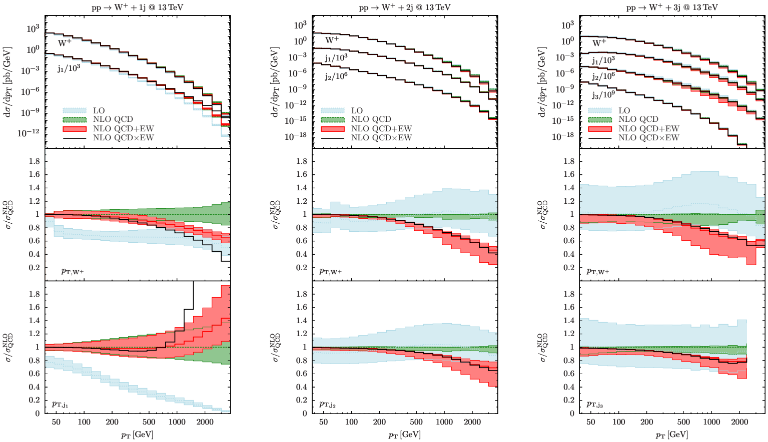
- code size, compilation&runtime reflect moderate increase of complexity wrt QCD
- 1-loop EW similarly fast as highly competitive 1-loop QCD timings up to $t\bar{t}+2$ jets

	$n_{\text{loop diag}}$		t_{compile} [s]		size [MB]		t_{run} [ms/point]	
$t\bar{t}+0,1,2$ j	QCD	EW	QCD	EW	QCD	EW	QCD	EW
$d\bar{d}\to t\bar{t}$	11	33	2.1	3.5	0.1	0.2	0.27	0.69
$gg\to t\bar{t}$	44	70	3.6	3.7	0.2	0.3	1.6	2.8
$d\bar{d}\to t\bar{t}g$	114	360	3.5	5.9	0.4	0.9	4.8	13
$gg\to t\bar{t}g$	585	660	8.2	8.8	1.4	1.6	40	56
$d\bar{d}\to t\bar{t}u\bar{u}$	236	1274	5.3	16	0.8	2.8	12	48
$d\bar{d}\to t\bar{t}d\bar{d}$	472	2140	9.5	56	1.4	1.4	30	99
$d\bar{d}\to t\bar{t}gg$	1507	4487	20	47	3.5	8.2	133	327
$gg\to t\bar{t}gg$	8739	7614	105	79	18	16	1458	1557

Timings on `i7-3770K` with gcc 4.8 –O0 dynamic and unpolarised $t\bar{t}$ (significantly faster with decays!)

Opens the door to multi-leg NLO EW computations!

NLO QCD+EW predictions for $W + 1, 2, 3$ jets [Kallweit, Lindert, Maierhöfer, S.P. , Schönherr, arXiv:1412.5157]



EW corrections ~50% in multi-TeV range, nontrivial dependence on N_{jets} and interplay with NLO QCD

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3. MEPS@NLO merging for $t\bar{t} + 0, 1, 2\,$jets

4. MEPS@NLO merging for $t\bar{t}W + 0, 1\,$jets

$t\bar{t}b\bar{b}$ and $t\bar{t}+$ jets as $t\bar{t}H$ backgrounds

$t\bar{t}H(b\bar{b})$ analyses at the LHC

- systematics dominated by TH uncertainty of $t\bar{t}b\bar{b}$ and $t\bar{t}+$ multijet backgrounds

NLO reduces $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ uncertainties from 80% to 15–30%

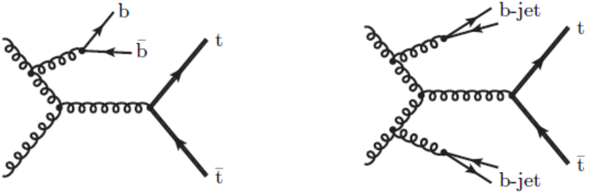
- $t\bar{t}b\bar{b}$ [Bredenstein, Denner, Dittmaier, S. P. '09/'10; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09];
- $t\bar{t}jj$ [Bevilacqua, Czakon, Papadopoulos, Worek '10/'11]

ATLAS/CMS analyses require matching to parton showers

- $t\bar{t}b\bar{b}$ **5FNS** (PowhegBox+HELAC-NLO) [Garzelli, Kardos, Trocsanyi '13/'14]
- $t\bar{t}b\bar{b}$ **4FNS** (Sherpa+OpenLoops) [Cascioli, Maierhoefer, Moretti, S. P., Siegert '13]
- $t\bar{t}+0,1,2$ jets (Sherpa+OpenLoops) [Höche, Krauss, Maierhoefer, S. P., Schönherr, Siegert '14]

S–MC@NLO $t\bar{t}b\bar{b}$ 4F [Cascioli, Maierhöfer, Moretti, S. P. , Siegert '13]

Why NLO matching for $t\bar{t}b\bar{b}$ production in 4F scheme



5F scheme ($m_b = 0$): $t\bar{t}b\bar{b}$ MEs cannot describe collinear $g \to b\bar{b}$ splittings

⇒ *inclusive* $t\bar{t}$+b-jets simulation (important for exp. analyses!) requires $t\bar{t}+ \leq 2$ jets NLO merging [Höche, Krauss, Maierhöfer, S. P. , Schönherr, Siegert '14]

4F scheme ($m_b > 0$): $t\bar{t}b\bar{b}$ MEs cover full b-quark phase space

⇒ MC@NLO $t\bar{t}b\bar{b}$ sufficient for inclusive $t\bar{t}$+b-jets simulation

- access to **new $t\bar{t} + 2$b-jets production mechanism** wrt 5F scheme: double collinear $g \to b\bar{b}$ splittings (surprisingly important impact on $t\bar{t}H(b\bar{b})$ analysis!)

S–MC@NLO $t\bar{t}b\bar{b}$ 4F II

NLO Corrections and Uncertainties for ttb and $ttbb$ Cross Sections

Analyses with $N_b \geq 1$ (ttb) and $N_b \geq 2$ ($ttbb$) QCD b-jets ($p_\mathrm{T} > 25\,\mathrm{GeV}$, $|\eta| < 2.5$)

	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]	$3296^{+34\%\,+5.6\%}_{-25\%\,-4.2\%}$	$560^{+29\%\,+5.4\%}_{-24\%\,-4.8\%}$	$141.8^{+26\%\,+6.5\%}_{-22\%\,-4.6\%}$
$\sigma_\mathrm{NLO}/\sigma_\mathrm{LO}$	1.25	1.21	1.15
$\sigma_\mathrm{MC@NLO}$[fb]	$3313^{+32\%\,+3.9\%}_{-25\%\,-2.9\%}$	$600^{+24\%\,+2.0\%}_{-22\%\,-2.1\%}$	$181^{+20\%\,+8.1\%}_{-20\%\,-6.0\%}$
$\sigma_\mathrm{MC@NLO}/\sigma_\mathrm{NLO}$	1.01	1.07	1.28

MSTW2008 NLO(LO) 4F PDFs

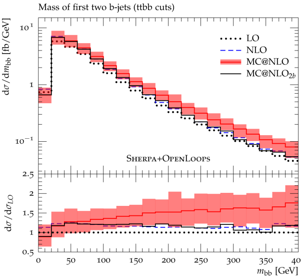
Good perturbative stability but unexpected MC@NLO enhancement

- K-factors moderate and rather independent of selection (including ttb!)
- 25–30% NLO and MC@NLO uncertainties mainly from μ_R (1^st) variation, only 5% from μ_F, μ_Q (2^nd) variations
- MC@NLO/NLO difference is negligible(moderate) in standard ttb($ttbb$) selections but large enhancement (∼30%) in Higgs-signal region ($m_{b\bar{b}} > 100\,\mathrm{GeV}$)

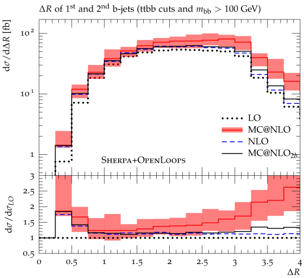
S–MC@NLO $t\bar{t}b\bar{b}$ 4F III

MC@NLO effects in Distributions ($t\bar{t}b\bar{b}$ Selection)

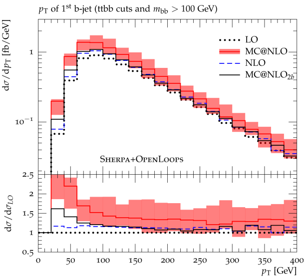
$m_{b_1 b_2}$



$\Delta R_{b_1 b_2}$



p_{T,b_1}



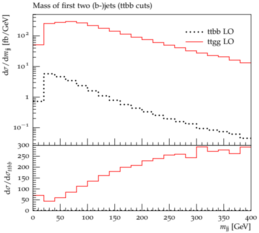
Characteristic kinematic features

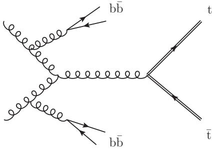
- **MC@NLO enhancement at large $m_{b_1 b_2}$, $\Delta R_{b_1 b_2} \sim \pi$, and small $p_{\mathrm{T},b}$**
- reaches 25–30% at $m_{b_1 b_2} \sim 125\,\mathrm{GeV}$, which exceeds $t\bar{t}H(b\bar{b})$ signal!
- disappears almost completely in MC@NLO$_{2b}$ where $g \to b\bar{b}$ splittings are switched off in the parton shower (double $g \to b\bar{b}$ splittings "smoking gun")

S–MC@NLO $t\bar{t}b\bar{b}$ 4F IV

Double $g \to b\bar{b}$ Splitting Contributions consistent with MC enhancement

- $t\bar{t}gg/t\bar{t}b\bar{b}$ ratio grows at same rate of MC@NLO excess
- emission of back-to-back small-p_{T} gluons enhanced by soft-collinear singularity





Don't fit into conventional hard-scattering $t\bar{t}b\bar{b}$ picture

- present also in $t\bar{t}$+jets LO merged samples
- but large effect in hard $t\bar{t}H(b\bar{b})$ signal region unexpected

Implications for theory systematics in $t\bar{t}$+HF

- understanding PS and matching systematics crucial (both for 4F $t\bar{t}b\bar{b}$ or 5F $t\bar{t}$+jets)
- in $t\bar{t}H(b\bar{b})$ signal region 4F $t\bar{t}b\bar{b}$ MC@NLO provides first $g \to b\bar{b}$ splitting at NLO

Public $t\bar{t}b\bar{b}$ samples

S-MC@NLO $t\bar{t}b\bar{b}$ in 4F scheme

- public samples at `http://www.physik.uzh.ch/data/ttHsim/TTBBV1/`
- setup of arXiv:1309.5912 apart from CT10 4F PDFs and dileptonic $t\bar{t}$ decays
- generated with mid statistics for studies of $t\bar{t}b\bar{b}$ theory systematics in ATLAS/CMS at 8 TeV
- HEP-MC weighted events, fully showered+UE+hadronisation
- can be generated with publicly available tools: SHERPA 2.1 and OPENLOOPS 1.0

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MEPS@NLO $t\bar{t} + 0, 1, 2$ jets [Höche, Krauss, Maierhöfer, S. P. , Schönherr, Siegert '14]

Fixed-order $t\bar{t}jj$ NLO [Bevilacqua, Czakon, Papadopoulos, Worek '10/'11]

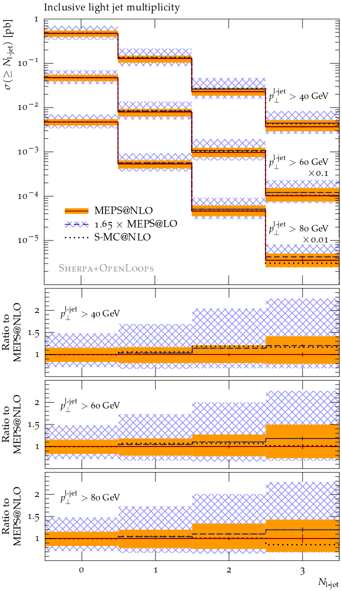
- very challenging (more than 7'000 $gg \to t\bar{t}gg$ loop diagrams)
- theory uncertainty reduced from 80% to 15%
- matching to PS crucial for $t\bar{t}H(b\bar{b})$ background (and many other searches!)

MEPS@NLO merging [Höche, Krauss, Schönherr, Siegert '12]

0-jet	S-MC@NLO $t\bar{t}$
1-jet	S-MC@NLO $t\bar{t}j$
$\geq$2 jets	S-MC@NLO $t\bar{t}jj$

- provides NLO accuracy for $0, 1, 2 \ldots$ jets and log accuracy of PS
- jet regions separated at merging scale Q_{cut} via k_{T}-type jet algorithm
- smooth PS–MEs transition ensured by supplementing MEs with PS-like CKKW scale and (subtracted) Sudakov FFs
- nodal scales of relevant pseudo-shower histories by inverting parton shower $\Rightarrow$ optimal merging (small Q_{cut} dependence) in SHERPA

MEPS@NLO $t\bar{t} + 0, 1, 2$ jets II



Jet-bin cross sections ($p_T > 40, 60, 80$ GeV)

- S-MC@NLO $t\bar{t}$
- 1.65×MEPS@LO $t\bar{t} + 0, 1, 2$ jets (LO merging)
- MEPS@NLO $t\bar{t} + 0, 1, 2$ jets (NLO merging)

Decent (10–20%) mutual agreement

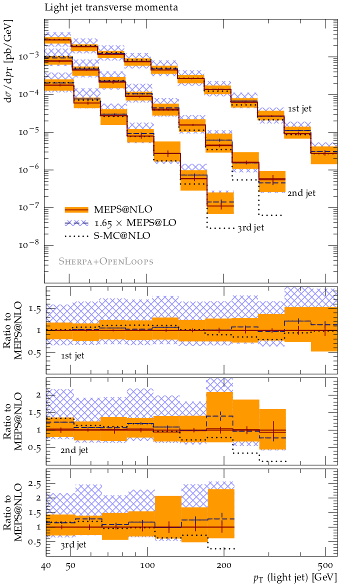
Reduction of μ_R, μ_F, μ_Q variations

$N_{\text{light-jet}} \geq$	0	1	2
LO	48%	65%	80%
NLO	17%	20%	20–30%

Merging scale choice and dependence

- Q_{cut} below jet-p_T threshold and above Sudakov peak ⇒ for NLO accurate multi-jet bins avoiding problematic $\ln(Q_{\text{cut}})$
- $Q_{\text{cut}} = 30 \pm 10$ GeV and $\ll 10\%$ dependence

MEPS@NLO $t\bar{t} + 0, 1, 2$ jets III



p_T spectra of first 3 jets ($p_T > 40$ GeV)

- S-MC@NLO $t\bar{t}$
- 1.65×MEPS@LO $t\bar{t} + 0, 1, 2$ jets (LO merging)
- MEPS@NLO $t\bar{t} + 0, 1, 2$ jets (NLO merging)

Mutual agreement (apart from tails of $2^{\text{nd}}/3^{\text{rd}}$ jet)

Reduction of scale dependence

- similarly strong as for corresponding jet bins apart from hard tails (still dirty due to stat fluctuations)

Take home message

- MEPS@NLO provides NLO accuracy for $t\bar{t} + 0, 1, 2$ jets
- will now permit to study lot of interesting things (more exclusive observables/correlations, heavy-flavour jets,. . .)

Scale dependences in $t\bar{t} + 0, 1$ jets

Scale choices and variations in MEPS

- basis for definition of *intrinsic* precision of NLO Monte Carlo (precision is meaningless w.o. solid concept of uncertainty)
- matching (μ_Q) and merging (Q_{cut}) involve two technical scales; no widely accepted prescription for their choice and variation (Q_{cut} debate)

Pedagogical exercise [Simulations by N. Moretti]

- study impact of individual scale variations for simple case of $t\bar{t} + 0, 1$ jets

μ_R	$\{0.5, 1, 2\} \times m_t$	renormalisation
μ_F	$\{0.5, 1, 2\} \times m_t$	factorisation
μ_Q	$\{0.5, 1, 2\} \times m_t$	resummation (shower starting scale)
Q_{cut}	$5, 10, 20, 30, 40\,\mathrm{GeV}$	merging

(8 TeV, MSTW20008nlo 5F, anti-k_T R=0.4 $p_{\mathrm{T},j} > 25\ \mathrm{GeV}$, $|\eta_j| < 2.5$)

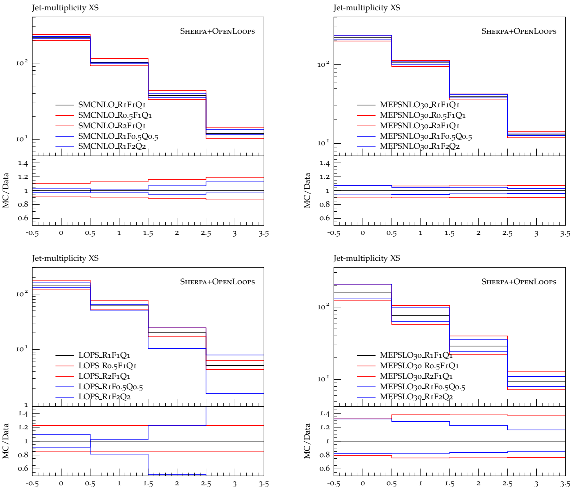
- following results not thoroughly validated, mainly for illustration of LO → NLO and PS → ME+PS improvements
- 128×3 CPU hours for MEPS@NLO $t\bar{t} + 0, 1$ jets (w.o. variations)

Inclusive jet multiplicity

NLO

↑

LO



matching $\longrightarrow$ merging

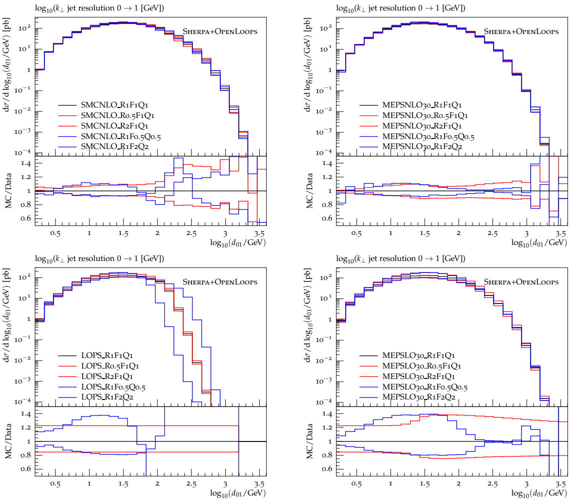
μ_R dependence

- 20–30% at LO $\Rightarrow$ 10% at NLO

$\mu_Q = \mu_F$ dependence

- strongly reduced (for $N_j \geq 1$) by merging and by NLO

First-jet emission scale (jet-k_{T} resolution)



NLO

↑

LO

matching ⟶ merging

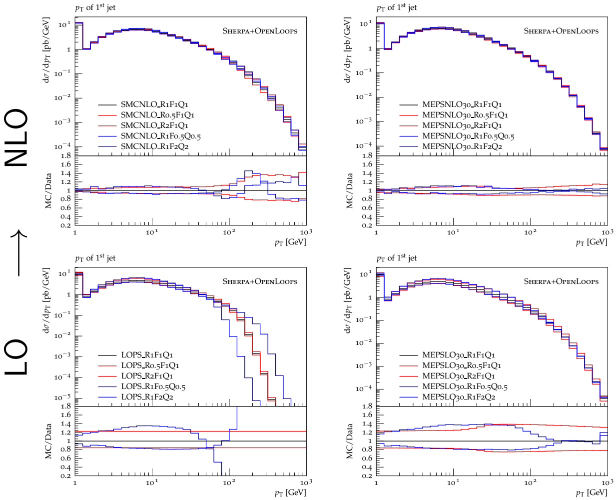
μ_R dependence

- NLO accuracy in MEPS@NLO tail
- NLO+PS uncert. underestimated for mid–low p_{T} (hidden)

$\mu_Q = \mu_F$ dependence

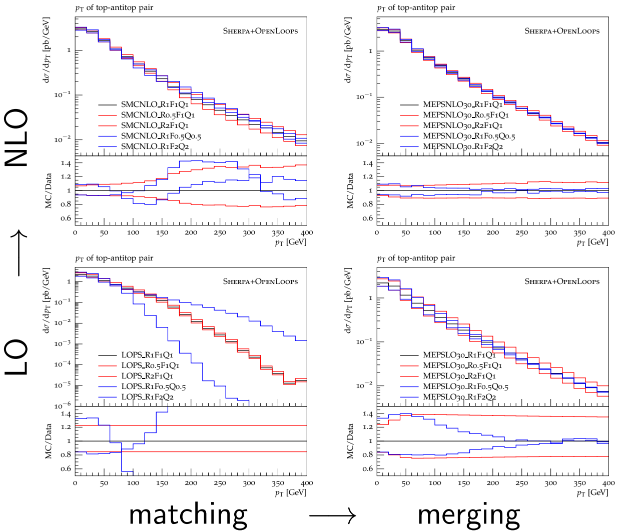
- merging and NLO strongly improve tail

1^{st} jet p_T (analogous to k_T resolution)



matching ⟶ merging

Top-pair p_{T} (similar effects "amplified" by linear scale)



Bottom line

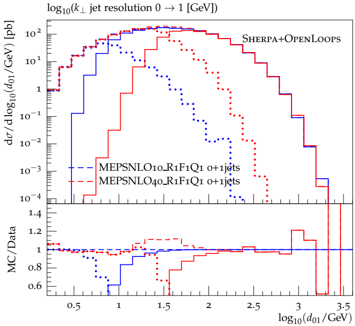
- 10% MEPS@NLO accuracy over whole spectrum

Merging scale variations in MEPS@NLO $t\bar{t} + 0, 1$ jets I

Merging scale

$k_\mathrm{T} < Q_\mathrm{cut}$ 0-jet S-MC@NLO
$k_\mathrm{T} > Q_\mathrm{cut}$ 1-jet S-MC@NLO

$Q_\mathrm{cut} = 10, 40\,\mathrm{GeV}$



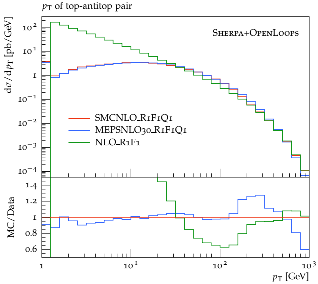
Technical scale: how to choose and vary it?

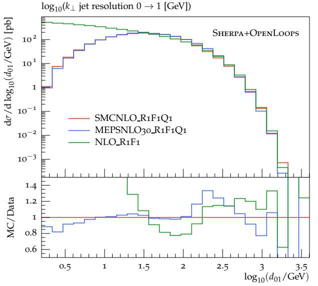
- NLO accuracy for measured jets highly desirable $\Rightarrow Q_\mathrm{cut}$ below experimental jet threshold (?)
- to avoid dependence on exp analysis Q_cut should be just set as small as possible

Questions

- smallest "possible" value of Q_cut?
- natural (physical) reference scale?

Merging scale variations in MEPS@NLO $t\bar{t} + 0, 1$ jets II





Sudakov suppression

- Sudakov FF in MEPS $\Rightarrow$ exponential suppression of IR singularity
- Q_{cut} can be taken small (in principle)

Formal NLO accuracy [Hamilton, Nason, Oleari, Zanderighi '12]

- inclusive NLO accuracy lost if Q_{cut} approaches Sudakov peak (formal argument)
- shower/MEs subleading-log mismatch
- integrating down to Sudakov region $\alpha_S \log^2(k_T^2/Q^2) \sim 1$ yields $\alpha_S^{1.5}$ uncertainty

Quantitative analysis

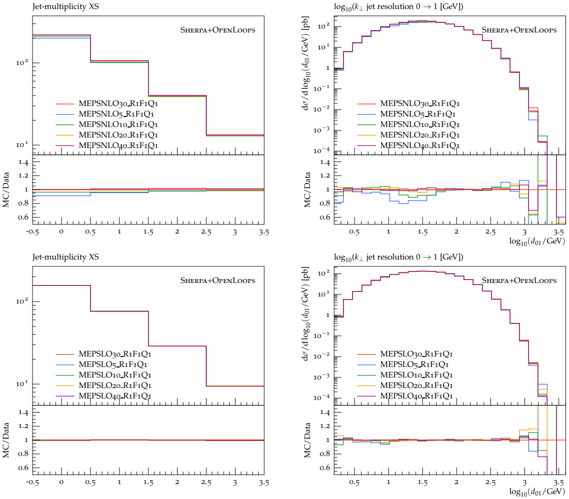
- vary Q_{cut} across Sudakov peak to estimate maximal impact of shower/MEs mismatch
- take Q_{cut} close to the peak while avoiding Q_{cut} variations $>$ NLO scale variations.

Merging scale variations in MEPS@NLO $t\bar{t} + 0, 1$ jets III

NLO

$\uparrow$

LO



N_{jets}

1st jet k_{T}

Q_{cut} scan through Sudakov region

- 5,10,20,30,40 GeV

MEPS@LO

- tiny variations

MEPS@NLO

- less than 10% local dependence with $Q_{\text{cut}} \geq 10\,\text{GeV}$
- $10\,\text{GeV}$ "possible"
- full $g \to b\bar{b}$ phase space covered with MEs!

Outline

1. (N)NLO QCD+NLO EW automation with OpenLoops
2. S-MC@NLO matching for $t\bar{t}b\bar{b}$ in 4F scheme
3. MEPS@NLO merging for $t\bar{t}+0,1,2$ jets
4. MEPS@NLO merging for $t\bar{t}W+0,1$ jets

Scale studies in $t\bar{t}W$+jets

General considerations

- complexity not dramatic and very similar to ttH+0,1j (between ttj and ttjj)
- different QCD radiation pattern wrt ttH+jets (no gg channel)

Pedagogical exercise [Simulations by N. Moretti]

- scale variation studies for $t\bar{t}W + 0, 1$ jets

μ_R	$\{0.5, 1, 2\} \times (m_t + M_W/2)$	renormalisation
μ_F	$\{0.5, 1, 2\} \times (m_t + M_W/2)$	factorisation
μ_Q	$\{0.5, 1, 2\} \times (m_t + M_W/2)$	resummation (shower starting scale)
Q_{cut}	$20, 30, 40\,\text{GeV}$	merging

(8 TeV, MSTW20008nlo 5F, anti-k_T R=0.4 $p_{T,j} > 25\,\text{GeV}$, $|\eta_j| < 2.5$)

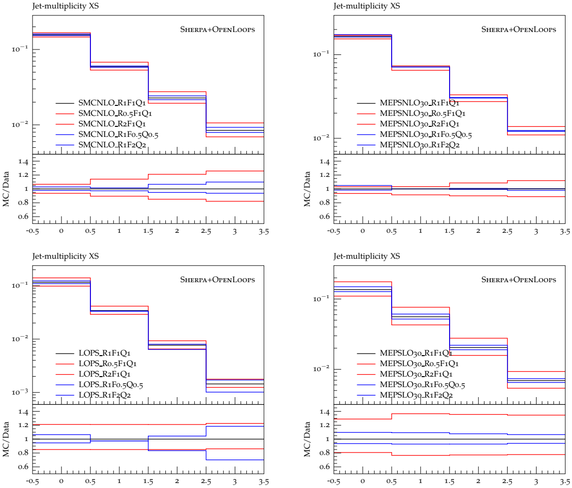
- following results not thoroughly validated, mainly for illustration of LO → NLO and PS → ME+PS improvements
- following plots with 128×2 CPU hours for MEPS@NLO $t\bar{t}W + 0, 1$ jets (w.o. variations)

Inclusive jet multiplicity

NLO

↑

LO



matching $\longrightarrow$ merging

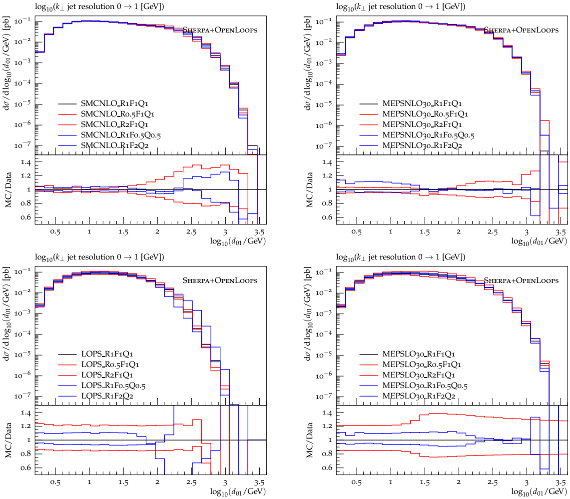
μ_R dependence

- 20–30% at LO
  $\Rightarrow$ 10% at NLO

$\mu_Q = \mu_F$ dependence

- reduced by merging and NLO (for $N_j \geq 1$)

First-jet emission scale (jet-k_T resolution)



NLO

↑

LO

matching ⟶ merging

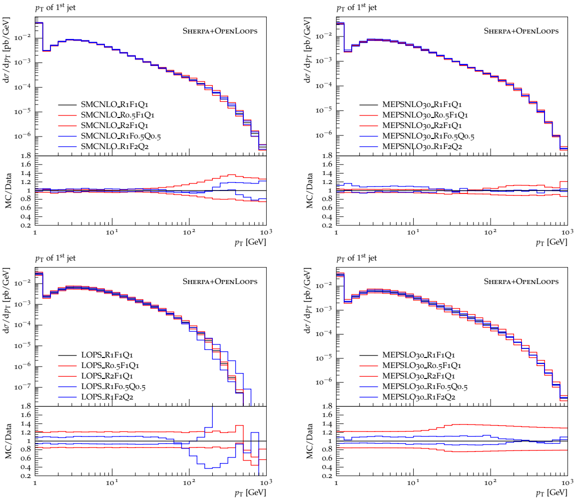
μ_R dependence

- NLO accuracy in MEPS@NLO tail
- NLO+PS uncert. underestimated for mid–low p_T

$\mu_Q = \mu_F$ dependence

- merging and NLO strongly improve tail

p_{T} **of** $t\bar{t}W$ **sysmtem** (similar effects "amplified" by linear scale)



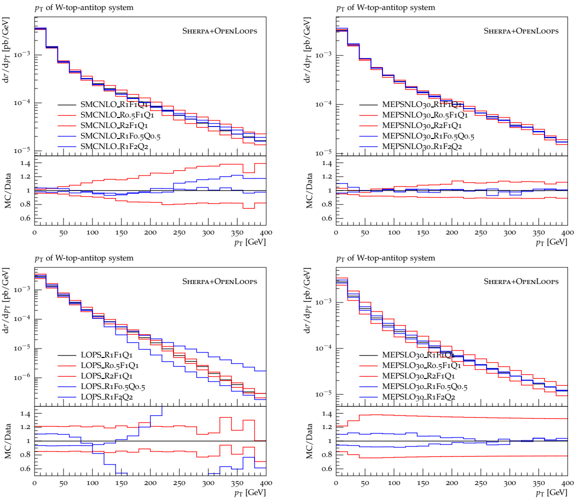
NLO

↑

LO

matching ⟶ merging

p_T of $t\bar{t}W$ system



NLO

↑

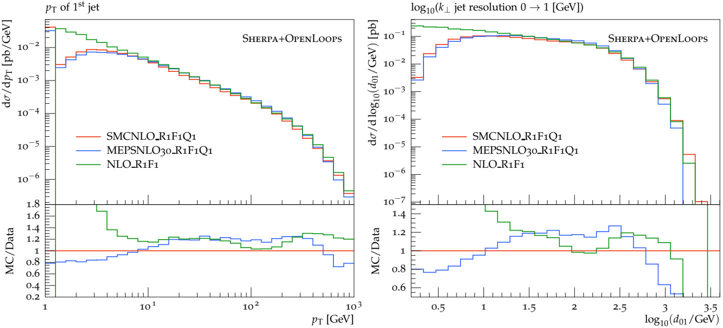
LO

matching ⟶ merging

Bottom line

- 10% MEPS@NLO accuracy over whole spectrum

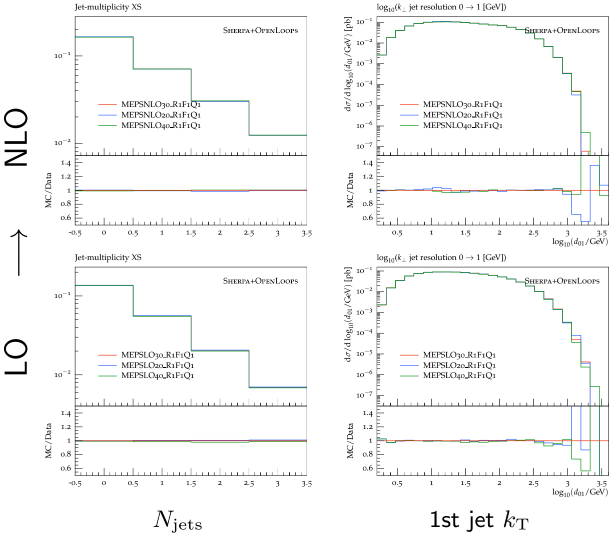
Sudakov peak



Sudakov behaviour ($q\bar{q}$ dominated!)

- less intense QCD radiation
- lower Sudakov peak
- less pronounced logs and Q_{cut} issues

Merging scale dependence



Q_{cut} scan above Sudakov region

- 20,30,40 GeV

MEPS@LO & NLO

- tiny variations
- can safely use $Q_{\mathrm{cut}} \gtrsim 20\,\mathrm{GeV}$

Summary and Outlook

Many recent (N)NLO developments with OpenLoops

- fast multi-leg amplitudes with OPENLOOPS (now public!)
- S-MC@NLO and NLO-merging with OPENLOOPS+SHERPA
- NLO EW automation with OPENLOOPS+SHERPA and MUNICH
- OPENLOOPS+MUNICH used in NNLO QCD calculations

$t\bar{t} + X +$ jets with OpenLoops+Sherpa

- $t\bar{t}b\bar{b}$ with S-MC@NLO and $m_b > 0 \Rightarrow$ inclusive $t\bar{t} + b$-jets sample
- $t\bar{t} + 0, 1, 2j$ with MEPS@NLO
- $t\bar{t}W + 0, 1j$ (and $t\bar{t}H + 0, 1j$) much simpler that $t\bar{t} + 0, 1, 2j$

Some todo items

- independent checks and uncertainty estimate for $g \to b\bar{b}$ splitting in $t\bar{t}b\bar{b}$
- combination of $t\bar{t}b\bar{b}$ 4F and $t\bar{t}+$ jets 5F
- solid and widely accepted prescriptions for scale choices and variations
- etc, etc

Backup slides

S–MC@NLO $t\bar{t}b\bar{b}$ 4F II

Sherpa's MC@NLO formula [Frixione,Webber '02; Höche,Krauss,Schönherr,Siegert '11]

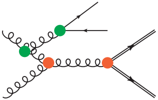
$$\sigma_n = \int \mathrm{d}\Phi_n \Big[\mathcal{B}(\Phi_n) + \mathcal{V}(\Phi_n) + \mathcal{B}(\Phi_n) \otimes \mathcal{I}\Big] \Big\{\Delta(\mu_Q^2, t_{\mathrm{IR}}) + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1 \mathcal{S}(\Phi_1)\, \Delta(\mu_Q^2, t)\Big\}$$

$$+ \quad \int \mathrm{d}\Phi_{n+1} \Big[\mathcal{R}(\Phi_{n+1}) - \mathcal{B}(\Phi_n) \otimes \mathcal{S}(\Phi_1)\Big]$$

- shower resummation effectively acts starting from $\mathcal{O}(\alpha_s^2)$, and iterated emissions yield fully realistic events
- inclusive observables with n $(n+1)$ particles preserve NLO (LO) accuracy

Scale choice crucial due to $\alpha_S^4(\mu^2)$ dependence (80% LO variation)

- widely separated scales $m_b \leq Q_{ij} \lesssim m_{t\bar{t}b\bar{b}}$ can generate huge logs
- CKKW inspired scale adapts to b-jet p_{T} and guarantees good pert. convergence

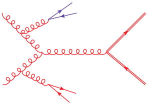


$$\mu_R^4 = E_{\mathrm{T},t} E_{\mathrm{T},\bar{t}} E_{\mathrm{T},b} E_{\mathrm{T},\bar{b}} \;\Rightarrow\; \alpha_S^4(\mu_R^2) = \alpha_S(E^2_{\mathrm{T},t})\alpha_S(E^2_{\mathrm{T},\bar{t}})\alpha_S(E^2_{\mathrm{T},b})\alpha_S(E^2_{\mathrm{T},\bar{b}})$$

S–MC@NLO $t\bar{t}b\bar{b}$ 4F VI [Cascioli, Maierhöfer, Moretti, S. P. , Siegert '13]

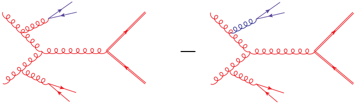
Accuracy of "Double Splittings" in MC@NLO $ttbb$ Simulation

Naive picture



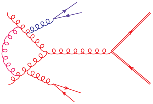
real-emission $t\bar{t}b\bar{b}g$ MEs plus $g \to b\bar{b}$ shower splitting
⇒ only LO+PS accuracy as in usual LO merging

Correct MC@NLO picture: interplay of three different contributions



$t\bar{t}b\bar{b}g$ MEs plus PS $g \to b\bar{b}$ emission

- LO $t\bar{t}b\bar{b}g$ uncertainty ∼100% at large p_T
- largely cancelled by PS-matching at small p_T



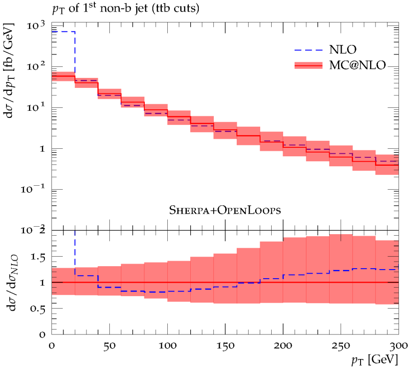
$t\bar{t}b\bar{b}$ MEs plus PS gluon and $g \to b\bar{b}$ emissions

- dominates at small p_T
- NLO $t\bar{t}b\bar{b}$ accuracy ∼25–30%

Well reflected in scale uncertainty of 1^{st} light-jet emission on top of $t\bar{t}b\bar{b}$. . .

S–MC@NLO $t\bar{t}b\bar{b}$ 4F VII [Cascioli, Maierhöfer, Moretti, S. P. , Siegert '13]

ttb analysis ($N_b \geq 1$): 1^{st} light-jet p_{T} distribution (responsible for double splittings)



MC@NLO vs NLO

- Sudakov damping of NLO IR singularity at $p_{\text{T}} \to 0$
- 25% NLO excess in the hard tail (probably due to dynamic μ_Q, multi-jet final state, unresolved b-quark)

MC@NLO scale uncertainty

- LO-like uncertainty (∼100%) in the tail irrelevant for $t\bar{t}H(b\bar{b})$
- NLO-like accuracy (∼30%) up to $70\,\text{GeV}$

⇒ NLO-like accuracy in the region relevant for $t\bar{t}H(b\bar{b})$

MEPS@NLO $t\bar{t} + 0, 1, 2$ jets II

NLO matching and merging for $t\bar{t}+$ jets

- NLO+PS $t\bar{t} + 1$ jet (with PowhegBox) [Alioni, Moch, Uwer '12]
- FxFx $t\bar{t} + 0, 1$ jets (with Madgraph5/aMC@NLO) [Frederix, Frixione '12]
- MEPS@NLO $t\bar{t} + 0, 1$ jets (with Sherpa+GoSam) [Höche, Huang, Luisoni, Schönherr, Winter '13]
- MEPS@NLO $t\bar{t} + 0, 1, 2$ jets (with Sherpa+OpenLoops) [Höche, Krauss, Maierhöfer, S. P. , Schönherr, Siegert '14]

Setup of MEPS@NLO $t\bar{t} + 0, 1, 2$ jets simulation

- 7 TeV LHC with 5F MSTW2008 NLO PDFs
- LO+PS top decays including spin correlations
- standard dileptonic $t\bar{t}$ cuts, $R = 0.4$ anti-k_{T} jets
- central scale $1/\mu^2_{\mathrm{core}} = 1/\hat{s} + 1/(m_t^2 - \hat{t}) + 1/(m_t^2 - \hat{u})$

EW Sudakov logarithms I

Virtual EW corrections strongly enhanced by $\ln(\hat{s}/M_W^2)$ at $\hat{s}$ ∼1 TeV

$\mathcal{O}(10\%)$ corrections at **1-loop**

$$\left(\frac{\delta\sigma_1}{\sigma_0}\right)_{\mathrm{LL}} \simeq -\frac{\alpha}{\pi s_{\mathrm{w}}^2}\log^2\frac{s}{M_W^2} \simeq -26.4\%$$

$$\left(\frac{\delta\sigma_1}{\sigma_0}\right)_{\mathrm{NLL}} \simeq +\frac{3\alpha}{\pi s_{\mathrm{w}}^2}\log\frac{s}{M_W^2} \simeq +15.6\%$$

$\mathcal{O}(1\%)$ corrections at **2-loops**

$$\left(\frac{\delta\sigma_2}{\sigma_0}\right)_{\mathrm{LL}} \simeq +\frac{\alpha^2}{2\pi^2 s_{\mathrm{w}}^4}\log^4\frac{s}{M_W^2} \simeq 3.5\%$$

$$\left(\frac{\delta\sigma_2}{\sigma_0}\right)_{\mathrm{NLL}} \simeq -\frac{3\alpha^2}{\pi^2 s_{\mathrm{w}}^4}\log^3\frac{s}{M_W^2} \simeq -4.1\%$$

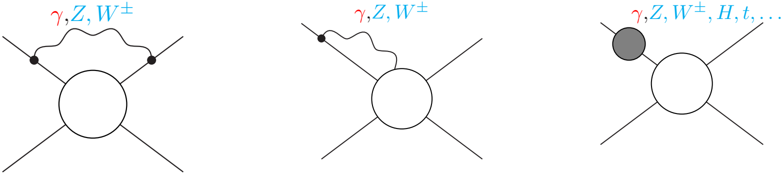
EW Sudakov logs at HL-LHC

- large negative effects in tails of energy-dependent observables $p_{\mathrm{T}}, M_{\mathrm{inv}}, \ldots$ ⇒ can hide BSM excesses
- size strongly depends on process and kinematic details

⇒ strong motivation for full NLO EW predictions (+ higher-order logarithms)

EW Sudakov logarithms II

Originate from soft/collinear *virtual* EW bosons coupling to on-shell legs



Universality and factorisation [Denner,S.P. '01] similarly as in QCD

$$\delta^{1-\mathrm{loop}}_{\mathrm{LL+NLL}} = \frac{\alpha}{4\pi} \sum_{k=1}^{n} \left\{ \frac{1}{2} \sum_{l \neq k} \sum_{a=\gamma,Z,W^\pm} I^{a}(k) I^{\bar{a}}(l) \ln^2 \frac{s_{kl}}{M^2} + \gamma^{\mathrm{ew}}(k) \ln \frac{s}{M^2} \right\}$$

- process-independent and simple structure
- tedious implementation (ALPGEN [Chiesa et al. '13]) due to nontrivial $SU(2) \times U(1)$ features (P-violation, mixing, soft SU(2) correlations, Goldstone modes, ...)
- 2-loop extension and resummation partially available