New generators (including future developments on EW corrections to top) for the HL-LHC

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My (limited) implementation of the title

A selection of very recent (or ongoing) MC developments and results that will play an important role for top physics at the HL-LHC (but also well before)...

...focussed on perturbative MC aspects (NLO QCD and EW) and with emphasis on recent OpenLoops developments

Outline

1. HL-LHC and MC tools
   - MC requirements for HL-LHC
   - NLO automation
2. EW corrections
   - Features of EW corrections
   - NLO EW for $pp \to t\bar{t}$
   - NLO EW automation
3. Recent MC progress at NLO QCD in top physics
   - $t\bar{t}+$ jets
   - $WWb\bar{b}$

HL-LHC

High-luminosity LHC (2025-2035)

- 14 TeV collisions with 150 times more luminosity than Run1 ($3000\,\mathrm{fb}^{-1}$)

⇒ enhanced energy reach, sensitivity to rare processes, precision

⇒ requires precise MC simulations with reliable uncertainty estimates

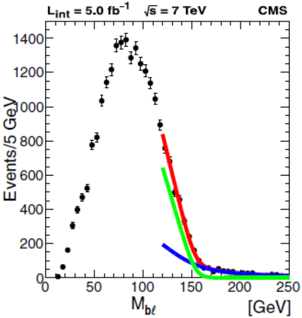
In the following: examples of top-related analyses with

- strong sensitivity improvements at HL-LHC
- serious MC challenges

Top mass measurements

CMS endpoint method [EPJ C 73 (2013)]

- m_t from fit of kinematic endpoints in $m_{\ell b}$, $\mu_{b\bar{b}}$, $\mu_{\ell\ell}$
- 2 GeV accuracy with 5 fb^{-1}



HL-LHC projections [Snowmass Top WG 2013]

Luminosity	$5fb^{-1}$	$100fb^{-1}$	$300fb^{-1}$	$3000fb^{-1}$
Δm_t^{syst} [GeV]	1.8	1.0	0.7	0.5
Δm_t^{stat} [GeV]	0.90	0.10	0.05	0.02
Total	**2.0**	**1.0**	**0.7**	**0.5**

MC requirements

- percent level shape precision close to (on-shell) endpoints

$\Rightarrow$ (N)NLO QCD $t\bar{t}$ production$\times$decay with off-shell effects

Precise measurements of top couplings

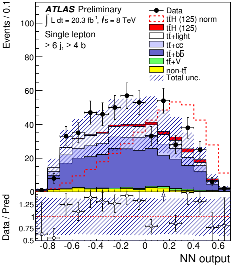
Measurements of $t\bar{t}V$ couplings [Snowmass 2013]

- factor 4 potential improvement from HL upgrade

$t\bar{t}H$ measurement with 3'000 fb^{-1} [Snowmass 2013]

$\gamma\gamma$	4ℓ	$\ell\nu\ell\nu$	$\tau\tau$	bb	$\mu\mu$	$\ell\ell\gamma$	$t\bar{t}H$ events
4.2 K	0.2 K	18 K	115 K	1.1 M	0.4 K	0.2 K	1.8 M

- projected σ_{ttH} accuracy $\sim 10\%(15\%)$ at 3000 (300) fb^{-1}
- potential λ_{ttH} accuracy $\sim 5\%$

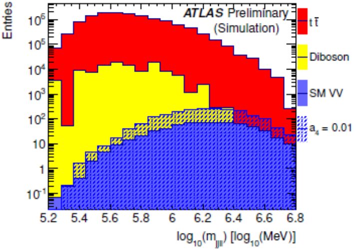


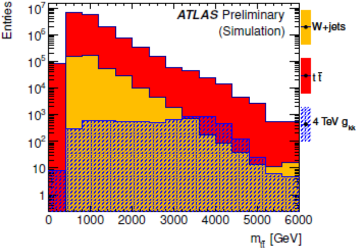
Requires MC precision in multi-particle final states

- for $t\bar{t}+H/W/Z/\gamma$ and $t\bar{t}+$ jets including c- and b-jets
- modeling of QCD emissions and shape uncertainties crucial

Leptons+jets+MET searches at TeV frontier

Many sensitivity improvements at 3000 (300) fb^{-1} [ATL-PHYS-PUB-2012-001]





$1.5\,(6.5)\,\%$ sensitivity to anomalous quartic couplings in WW scattering

exclusion up to 6.7 (4.3) TeV for $g_{\mathrm{KK}} \to t\bar{t}$ resonances

Huge top backgrounds require

- precise shapes for $m_{t\bar{t}}$, H_{T}, p_{T},... in multi-TeV regime
- precise modelling of $t\bar{t}+$ multi-jets and off-shell $t\bar{t}$ regime (e.g. for kinematic top veto)

MC requirements

Full exploitation of HL-LHC potential requires

- better than 10% accuracy for fully exclusive top final states

Perturbative precision

- NLO QCD for $2 \to 4(5)$
- NLO EW for $2 \to 3(4)$
- NNLO QCD for $2 \to 2(3)$

Other MC requirements

- top production$\times$decay with off-shell effects
- (N)NLO matching and merging
- higher CPU efficiency

On the wave of the (N)NLO revolution triggered by the advent of the LHC these goals are already partially achieved (this talk) and likely to be widely achieved in 10 years (talk at top2024?).

NLO multi-particle revolution and automation

- various new 1-loop techniques
- many $2 \to 4(5,6)$ processes at NLO QCD: $5j$, $W+5j$, $Z+4j$, $H+3j$, $WWjj$, $WZjj$, $\gamma\gamma+3j$, $b\bar{b}b\bar{b}$, $W\gamma\gamma j$, $WWb\bar{b}$, $t\bar{t}b\bar{b}$, $t\bar{t}jj$, $t\bar{t}t\bar{t}$, $t\bar{t}\gamma\gamma$, ...
- various new 1-loop tools: CutTools, Samurai, Helac-NLO, MadLoop, GoSam, BlackHat, Ninja, NJet, OpenLoops, Collier, Recola

Full automation of NLO and Monte Carlo tools

- IR subtraction, integration, NLO matching and multi-jet merging,...
- tools: Madgraph/aMC@NLO, Powheg/Powhel, Sherpa, Herwig, Pythia

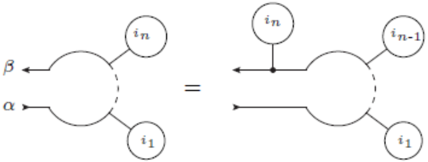
Great potential to promote NLO to standard TH accuracy at LHC

- wide range of NLO simulations possible
- further efficiency improvements crucial for challenging processes
- understanding of underlying physics and TH uncertainties can be non-trivial

Most results in this talk based on OpenLoops [Cascioli, Maierhöfer, S.P. '12]

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

- NLO QCD amplitudes for any $2 \to 4\,(5)$ SM process
- **since September '14 publicly available at** `openloops.hepforge.org`
- fast and generic numerical recursion for "loop-momentum dependent" trees



Complete NLO automation through interface with Monte Carlo Tools

- Sherpa2.1 [Hoeche, Hoeth, Krauss, Schoenherr, Schumann, Siegert, Zapp]
  - ⇒ S–MC@NLO matching to SHERPA shower and MEPS@NLO multi-jet merging
- parton-level Monte Carlo by S. Kallweit
  - ⇒ very fast integration for NLO and NNLO (q_{T} subtraction)
- BLHA interfaces to Herwig's MatchBox and other MC tools

Recent results with OpenLoops (Higgs and Top 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]

Several challenging NLO, S–MC@NLO, MEPS@NLO and NNLO studies
thanks to high automation, flexibility and CPU performance

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EW Sudakov logarithms I

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

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

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

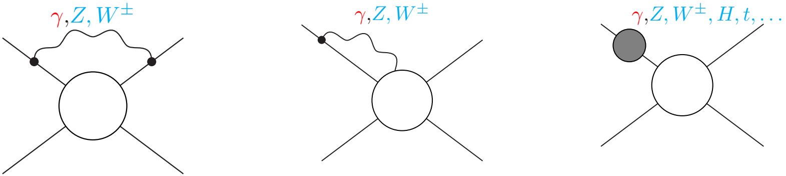
EW Sudakov logs at HL-LHC

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

$\Rightarrow$ 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

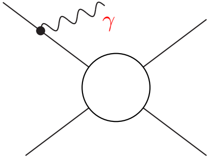
$$\delta^{1-\mathrm{loop}}_{\mathrm{LL+NLL}} = \frac{\alpha}{4\pi} \sum_{k=1}^{n} \left\{ \frac{1}{2} \sum_{l \neq k} \sum_{a=\gamma, Z, W^{\pm}} I^{a}(k) I^{\bar{a}}(l) \ln^2 \frac{s_{kl}}{M^2} + \gamma^{\mathrm{ew}}(k) \ln \frac{s}{M^2} \right\}$$

- 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

EW Sudakov logarithms III

Real photon emission

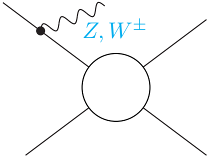
- mandatory since soft/collinear γ unresolved
- cancels QED singularities



Real Z, W emission [Ciafaloni,...]

- not mandatory since Z, W always *resolved* (in principle)
- even for inclusive case: only partial $\ln(\hat{s}/M_W)$ cancellation

$\leftrightarrow$ free SU(2) charges, collinear IS logs, kinematic $M_{Z,W}$ effects



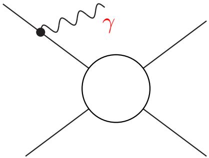
W, Z emissions in practice

- free from singularities $\Rightarrow$ trivial LO implementation as separate processes with extra W/Z (different physics!)
- typically modest $\ln(\hat{s}/M_W)$ cancellation (strongly process/observable dependent)

Other physically/technically nontrivial NLO EW features I

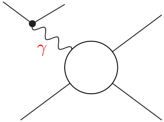
Cancellation of FS Photon singularities

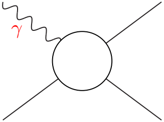
- requires IR subtraction method [Catani,Dittmaier,Seymour, Trocsanyi; Frixione, Kunszt, Signer]
- QED–QCD IR interplay requires nontrivial definition of unresolved photons (e.g. $q \to q\gamma$ fragmentation)
- leptons can receive significant corrections

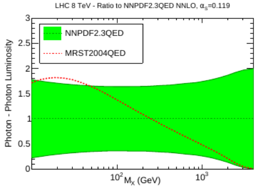


Cancellation of IS Photon singularities

- requires QED factorisation and PDF evolution [MRST2004, NNPDF2.3]
- γ-induced processes $\Rightarrow$ possible TeV scale enhancements (large uncertainty)



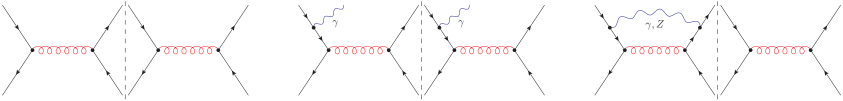




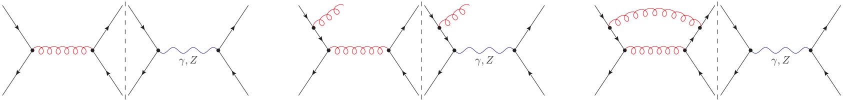
Other physically/technically nontrivial NLO EW features II

Nontrivial bookkeeping of interference effects 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



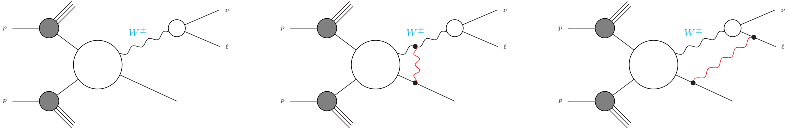
In practice above naive splitting inconsistent

- only complete $\mathcal{O}\left(\alpha_S^n\alpha^m\right)$ contribution makes sense (IR finite)
- note that $\mathcal{O}\left(\alpha\right)$ corrections can involve emissions of photons and QCD-partons

Other physically/technically nontrivial NLO EW features III

Treatment of unstable particles (e.g. $t \to Wb$ or $W \to \nu\ell$ resonances)

- $W \to \nu\ell$ trivial at NLO QCD (no corrections)
- but receives nontrivial NLO EW corrections to production×resonance×decay



Option A: complex mass scheme [Denner, Dittmaier]

- exact NLO description
- much higher complexity (one extra leg per $1 \to 2$ decay; non-factorisable corrections, IR singularities in resonance region)

Option B: narrow-width approximation (production×decay)

- $\mathcal{O}(1\%)$ uncertainty
- much simpler but requires exact helicity correlations at NLO

Outline

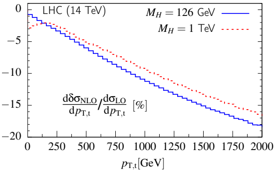
Existing NLO EW results for $t\bar{t}$ I

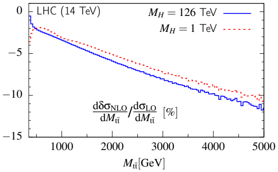
Existing NLO EW results for top (1994–2013)[Beenakker, Bernreuther, Denner, Hollik Kollar, Kühn, Moretti, Nolten, Pagani, Ross, Scharf, Si, Uwer, Wackeroth]

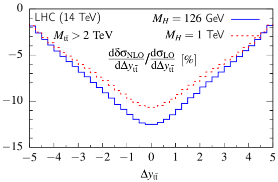
- thorough results only for $t\bar{t}$, while $t\bar{t}+V$, $t\bar{t}+$jets, . . . unknown

NLO weak corrections to $pp \to t\bar{t}$ at 14 TeV [Kühn,Scharf,Uwer '13]

- $\mathcal{O}(\alpha)$ correction of -2% to $\sigma_{t\bar{t}}$ and Sudakov behaviour at high p_T
- different $M_{t\bar{t}}$ behaviour and non-trivial $\Delta y_{t\bar{t}}$ dependence (t-channel peak)
- "only" -12% correction at 1 TeV $\leftrightarrow$ small EW charges in $gg/q\bar{q} \to t\bar{t}$



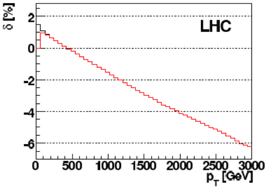




Existing NLO EW results for $t\bar{t}$ II

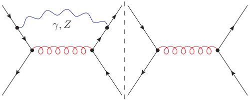
NLO QED corrections [Kollar,Hollik]

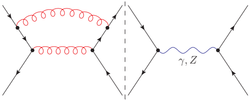
- $+1\%$ to $\sigma_{t\bar{t}}$ (dominated by γg channel)
- -4% at p_{T}=2 TeV (augments Sudakov weak correction)



EW corrections to charge asymmetry

- $\sim 25\%$ enhancement of $A_{\mathrm{FB}}^{t\bar{t}}$ at Tevatron [Hollik, Pagani] and similar effect at LHC [Bernreuther, Si]
- dominated by QED correction to $q\bar{q} \to t\bar{t}$ asymmetry $R_{QED} = Q_t Q_q \frac{36}{5} \frac{\alpha}{\alpha_S}$



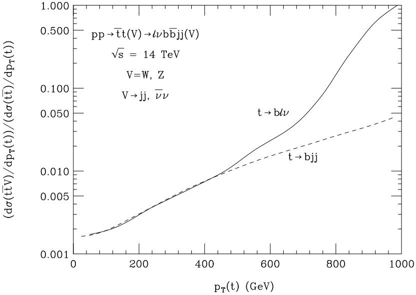


⇒ **QED effects can exceed weak ones and should always be included**

Existing NLO EW results for $t\bar{t}$ III

Real Z, W emission [Baur '06]

- impact of $t\bar{t}V(\to jj, \nu\bar{\nu})$ wrt $t\bar{t}$ in presence of $t\bar{t}$ cuts
- grows with p_{T} and at 1 TeV reaches +5% (+100%) for semi-leptonic (hadronic) top



"Fake" 100% effect illustrates strong cut-dependence of real Z, W emission

- due to boosted $t\bar{t}$ suppression from $\Delta R > 0.4$ separation cut between b, j, ℓ
- worthwhile to reinspect (also +5%) using boosted top taggers

Outline

NLO EW automation

Motivation

- NLO EW for $t\bar{t}+V$, $t\bar{t}+$jets, ...
- automated interface within MC frameworks

Technical tasks (tour de force)

- QED emission and subtraction of IR singularities, NLO matching
- bookkeeping of EW–QCD interferences
- 1-loops corrections + rational terms + complete EW renormalisation

  $\Rightarrow$ higher complexity wrt QCD (all SM particles in the loops)

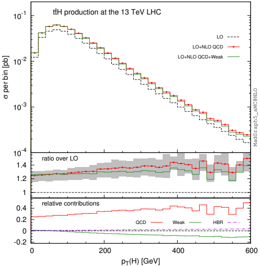
Ongoing/advanced implementations (diagrammatic/off-shell approaches)

- RECOLA $\Rightarrow \ell^+\ell^- jj$ NLO EW [Denner,Hofer,Scharf,Uccirati '13]
- MG5/aMC@NLO $\Rightarrow t\bar{t}H$ NLO weak [Frixione,Hirschi,Pagani,Shao,Zaro '14]
- OPENLOOPS $\Rightarrow$ coming soon [Kallweit,Lindert,Maierhöfer,S.P,Schönherr]

QCD+EW corrections to $t\bar{t}H$

Weak corrections

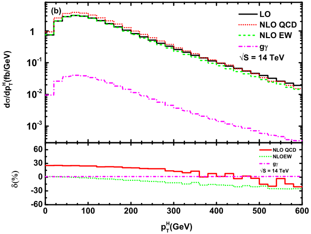
[Frixione,Hirschi,Pagani,Shao,Zaro '14]



- stable tops, no γ-emission
- from +1% (inclusive) to -10%
- real Z, W, H emission (HBR) cancels $1/3$ of virtual

Full EW corrections

[Yu,Wen–Gan,Ren–You,Chong,Lei '14]



- γ bremsstrahlung and γ-induced $(\sim 1\%)$ contribution
- top decays in NWA

Important for $t\bar{t}H$ precision in highly boosted regime

NLO EW automation in OpenLoops

NLO EW completely automated in OpenLoops

- OpenLoops [Lindert,Maierhöfer,S.P.] +Sherpa [Schönherr] and in-house MC [Kallweit]
- validation well advanced (based on 2 fully independent in-house generators)

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

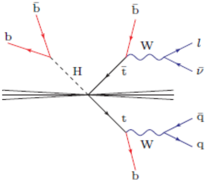
$t\bar{t}+0,1,2$ j	$n_{\text{loop diag}}$ QCD	EW	t_{compile} [s] QCD	EW	size [MB] QCD	EW	t_{run} [ms/point] QCD	EW
$d\bar{d}\to t\bar{t}$	11	33	2.1	3.5	0.1	0.2	0.27	0.69
$gg\to t\bar{t}$	44	70	3.6	3.7	0.2	0.3	1.6	2.8
$d\bar{d}\to t\bar{t}g$	114	360	3.5	5.9	0.4	0.9	4.8	13
$gg\to t\bar{t}g$	585	660	8.2	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!

Outline

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



$t\bar{t}H$ analyses at the LHC

- $t\bar{t}H(b\bar{b})$ originally considered best discovery channel for light Higgs
- $b\bar{b}b\bar{b}\ell\nu jj$ combinatorics hampers $H \to b\bar{b}$ reconstruction $\Rightarrow$ huge QCD backgrounds

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

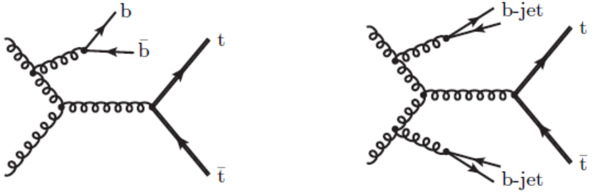
- $t\bar{t}b\bar{b}$ [Bredenstein, Denner, Dittmaier, S. P. '09/'10; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09];
- $t\bar{t}jj$ [Bevilacqua, Czakon, Papadopoulos, Worek '10/'11]

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 (quite important for exp. analyses!) requires $t\bar{t}g$+PS, i.e. $t\bar{t}+ \leq 2$ 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	$ttbb$	$ttbb\,(m_{bb} > 100)$
$\sigma_{\mathrm{LO}}[\mathrm{fb}]$	$2644^{+71\%+14\%}_{-38\%-11\%}$	$463.3^{+66\%+15\%}_{-36\%-12\%}$	$123.4^{+63\%+17\%}_{-35\%-13\%}$
$\sigma_{\mathrm{NLO}}[\mathrm{fb}]$	$3296^{+34\%+5.6\%}_{-25\%-4.2\%}$	$560^{+29\%+5.4\%}_{-24\%-4.8\%}$	$141.8^{+26\%+6.5\%}_{-22\%-4.6\%}$
$\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$	1.25	1.21	1.15
$\sigma_{\mathrm{MC@NLO}}[\mathrm{fb}]$	$3313^{+32\%+3.9\%}_{-25\%-2.9\%}$	$600^{+24\%+2.0\%}_{-22\%-2.1\%}$	$181^{+20\%+8.1\%}_{-20\%-6.0\%}$
$\sigma_{\mathrm{MC@NLO}}/\sigma_{\mathrm{NLO}}$	1.01	1.07	1.28

MSTW2008 NLO(LO) 4F PDFs

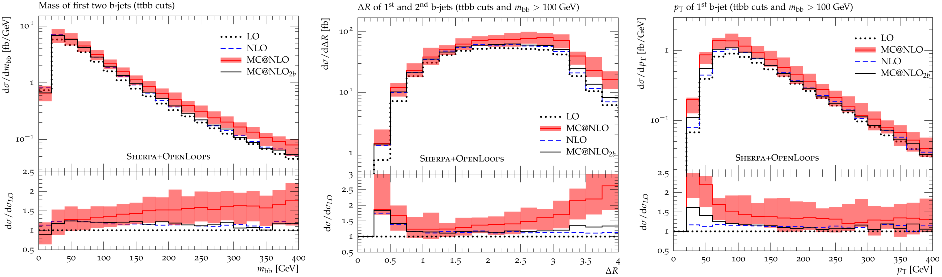
Good perturbative stability but unexpected MC@NLO enhancement

- 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 ($\sim$30%) in Higgs-signal region ($m_{b\bar{b}} > 100$ 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}



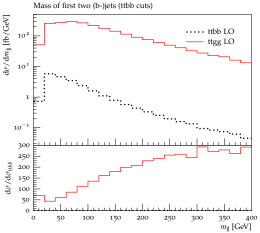
Characteristic kinematic features

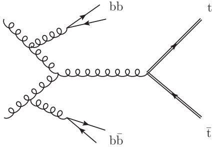
- **MC@NLO enhancement at large $m_{b_1 b_2}$, $\Delta R_{b_1 b_2} \sim \pi$, and small $p_{\mathrm{T},b}$**
- reaches 25–30% at $m_{b_1 b_2} \sim 125\,\mathrm{GeV}$, which exceeds $t\bar{t}H(b\bar{b})$ signal!
- disappears almost completely in MC@NLO$_{2b}$ where $g \to b\bar{b}$ splittings are switched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

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!)

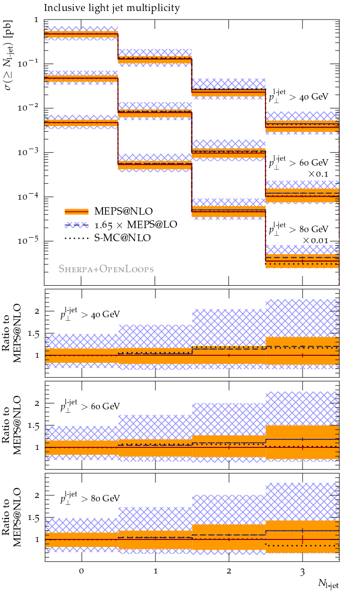
Why NLO merging?

- inclusive $t\bar{t}$ NLO+PS simulations lose NLO (LO) accuracy for $t\bar{t} + 1(2, 3\dots)$ jet
- NLO merging combines $t\bar{t} + n$-jet NLO+PS simulations with $n = 0, 1, 2\dots$ w.o. double counting ⇒ NLO accuracy for $0, 1, 2\dots$ jets and log accuracy of PS

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

- $0, 1, 2, \dots$ jet regions separated via k_{T}-type jet algorithm (merging scale Q_{cut}) and filled with $t\bar{t} + 0, 1, 2$ jet S–MC@NLO simulations
- intra-jet regions filled by (matched) PS emissions and inter-jet regions filled by MEs
- 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 ⇒ 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

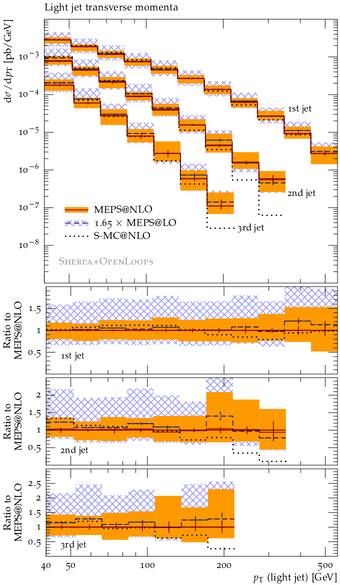
Reduction of μ_R, μ_F, μ_Q variations

$N_{\text{light-jet}} \geq$	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 $t\bar{t}$
- $1.65\times$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

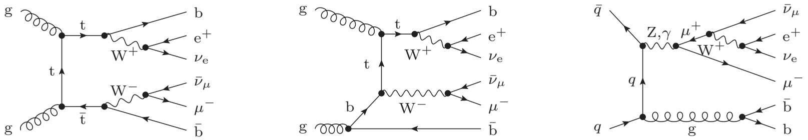
- MEPS@NLO provides NLO accuracy for $t\bar{t} + 0, 1, 2$ jets
- will now permit to study lot of interesting things (more exclusive observables/correlations, heavy-flavour jets,. . .)

Outline

1. HL-LHC and MC tools
   - MC requirements for HL-LHC
   - NLO automation
2. EW corrections
   - Features of EW corrections
   - NLO EW for $pp \to t\bar{t}$
   - NLO EW automation
3. Recent MC progress at NLO QCD in top physics
   - $t\bar{t}+$ jets
   - $WWb\bar{b}$

Treatments of Top production and decay at NLO I

Representative doubly- ($t\bar{t}$ like) singly- (tW like) and non-resonant (WW like) trees

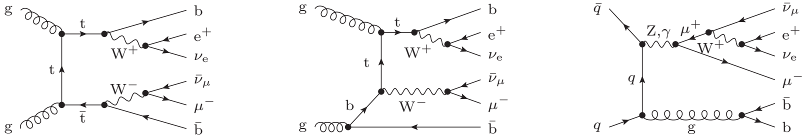


$W^+W^-b\bar{b}$ in 5F scheme [Denner, Dittmaier, Kallweit, S.P. '10; Bevilacqua et al. '10; Heinrich et al. '13; Kardos et al. '14]

- full set of diagrams (including $\sim 10^3$ loop diagrams) with $\mu_t^2 = m_t^2 - \mathrm{i}\Gamma_t m_t$
- finite Γ_t effects involve off-shell, single- and non-resonant contributions with interferences ("quantum overlap" of $t\bar{t}$, Wt, WW "processes"!)
- small $\mathcal{O}(\Gamma_t/m_t)$ effects wrt NWA for inclusive $t\bar{t}$ observables
- $m_b = 0$ approx. requires two hard b-jets ($g \to b\bar{b}$ collinear singularities)

Treatments of Top production and decay at NLO II

Representative doubly- ($t\bar{t}$ like) singly- (tW like) and non-resonant (WW like) trees



$W^+W^-b\bar{b}$ in 4F scheme ($m_b > 0$) [Frederix'13; Cascioli,Kallweit,Maieröfer,S.P. '13]

- important for top-backgrounds in 0- and 1-jet bins (e.g. in $H \to WW$)
- first consistent $t\bar{t}$ and Wt combination with interference at LO and NLO
- avoids separation of $Wt \to WWb$ from $t\bar{t} \to WWbb$ in 5F scheme (unstable and ill-defined due to $t\bar{t}$ contamination at NLO)

$W^+W^-b\bar{b}$ background to $H \to WW$ in 1-jet bin [Frederix '13]

4F simulation with MADGRAPH5/aMC@NLO

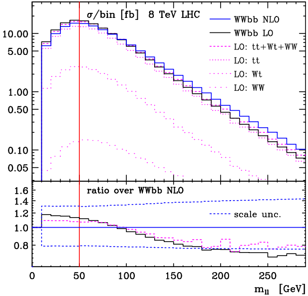
- 1-jet bin of ATLAS $H \to WW$ ATLAS analysis
- large top background with $\mathcal{O}(20\%)$ Wt component

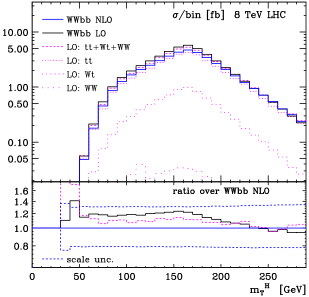
NLO effects (depend $\mu_0 = H_\mathrm{T}/2$)

- moderate correction around -20% but important shape distortion in $m_{\ell\ell}$ (less in m_T^{WW})
- large scale uncertainty (25%) attributed to veto against 2nd jet

Interference at LO

- moderate positive $t\bar{t}/Wt$ interference





Unified $t\bar{t} + tW$ NLO description I [Cascioli, Maierhöfer,Kallweit, S.P. '13]

4F NLO $W^+W^-b\bar{b}$ simulation with OpenLoops

- 0,1,2 jet bins
- detailed study of "$t\bar{t}$–Wt interplay"

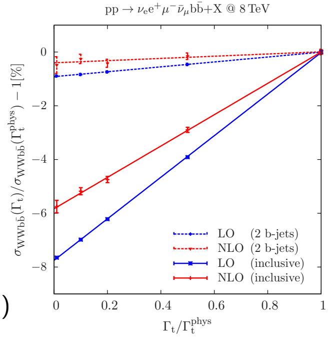
Ill-defined $t\bar{t}/Wt$ separation (5F) ⇒ gauge-inv $t\bar{t}$/non-$t\bar{t}$ separation (4F)

Numerical NWA ⇒ on-shell $t\bar{t}$ production×decay

$$\mathrm{d}\sigma_{t\bar{t}} = \lim_{\Gamma_t \to 0} \left(\frac{\Gamma_t}{\Gamma_t^{\mathrm{phys}}}\right)^2 \mathrm{d}\sigma_{W^+W^-b\bar{b}}(\Gamma_t)$$

Finite-top-width (FtW) remainder of $\mathcal{O}(\Gamma_t/m_t)$

- dominated by Wt but contains also off-shell $t\bar{t}$, interferences, non-factorisable corrections, ...
- from sub-percent for 2 b-jet final states to 6–8% effect in inclusive case (and more for 0/1-jet bins!)



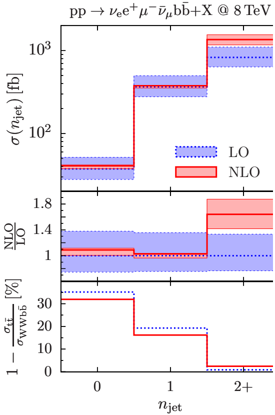
Unified $t\bar{t} + tW$ NLO description II [Cascioli, Maierhöfer,Kallweit, S.P. '13]

$W^+W^-b\bar{b}$ cross section in jet bins

- most interesting application of $m_b > 0$

NLO and FtW effects in jet bins

- 40% inclusive NLO correction driven by 2-jet bin, with very stable 0/1-jet bins
- only $\lesssim$ 10% NLO uncertainty in all bins
- **FtW contribution** bin-dependent (2% to 30%) and **strongly enhanced in 0/1-jet bins**!



NLO(LO) 4F NNPDFS, $p_{T,j} = 30\,\text{GeV}$

Nontrivial interplay of NLO and off-shell/single-top effects

NLO+PS for $W^+W^-b\bar{b}$ (conceptual and technical issues)

Need of NLO+PS matching

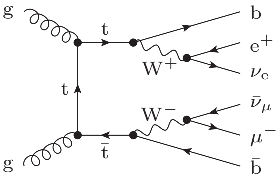
- NLO precision in the context of fully exclusive simulations for experimental analysis
- describes higher-order resummation effects in the shower aproximation and, possibly, related uncertainties (both should be small!)

NLO+PS matching for a process with intermediate resonances

- matrix elements provide NLO accurate description of "Breit-Wigner" top-distributions (with off-shell effects,. . .)
- crucial for precision observables sensitive to shape of top resonance (kinematic m_t measurements!), edges of on-shell $t\bar{t}$ phase space, single-top Wt contributions, . . .

Nontrivial conceptual and technical (open) issue

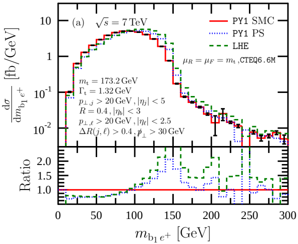
- recoil of standard shower emissions off $W^+W^-b\bar{b}$ final states induce arbitrary kinematic distortions of m_{Wb}
- potentially very strong distortions of Breit-Wigner shape (formally of order $\alpha_S^2 m_t/\Gamma_t \sim 1$!)
- requires yet unknown technique for matching PS to off-shell resonances at NLO



NLO+PS $W^+W^-b\bar{b}$ with POWHEL [Garzelli,Kardos,Trocsanyi '14]

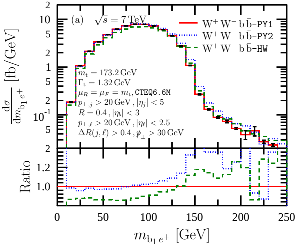
Employed matching (standard POWHEL)

- does not address potential order $\alpha_S^2 m_t/\Gamma_t$ inconsistencies in top-resonance shape
- can provide insights into potential pathologic features: large shower effects in observables that are sensitive to M_{Wb}



Distribution in $m_{\ell b}$

- mass measurement thanks to $m_{\ell b}^2 \leq m_t^2 - m_W^2$ endpoint sensitive to m_t (and off-shell effects)
- requires very precise shape prediction
- **upper plot**: severe distortions from shower (blue) and hadronisation (red) after 1st matched emission (green)
- **lower plot**: sizable shape distortions depending on PYTHIA (or HERWIG) version



Open question: physical or fake $\mathcal{O}(\alpha_S^2 m_t/\Gamma_t)$ effect?

Summary and Outlook

High momentum in multi-leg NLO MC developments

- fast NLO QCD multi-leg amplitudes with OpenLoops (now public)
- NLO+PS and NLO-merging with OpenLoops+Sherpa
- NLO EW automation around the corner

Precise and realistic MC simulations for multi-particle final states

- $t\bar{t} + 0, 1, 2$ jets including b-jets
- $WWb\bar{b}$ (conceptual NLO matching issues)
- $m_b > 0 \Rightarrow t\bar{t}$–$tW$ interference, double $g \to b\bar{b}$ splittings in $t\bar{t}b\bar{b}$

Outlook

- new NLO multi-leg MC precision highly relevant for HL-LHC
- exploit it as much (and soon) as possible in (S and B) simulations at LHC
- higher precision (NLO EW, NNLO+PS,. . .) is likely to emerge well before HL-LHC

Backup slides

S–MC@NLO $t\bar{t}b\bar{b}$ 4F II

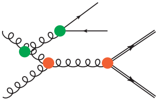
Sherpa's MC@NLO formula [Frixione,Webber '02; Höche,Krauss,Schönherr,Siegert '11]

$$\sigma_n = \int \mathrm{d}\Phi_n \left[\mathcal{B}(\Phi_n) + \mathcal{V}(\Phi_n) + \mathcal{B}(\Phi_n) \otimes \mathcal{I}\right] \left\{\Delta(\mu_Q^2, t_{\mathrm{IR}}) + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1 \mathcal{S}(\Phi_1)\, \Delta(\mu_Q^2, t)\right\}$$
$$+ \quad \int \mathrm{d}\Phi_{n+1} \left[\mathcal{R}(\Phi_{n+1}) - \mathcal{B}(\Phi_n) \otimes \mathcal{S}(\Phi_1)\right]$$

- 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

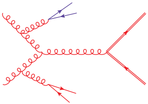


$$\mu_R^4 = E_{\mathrm{T},t} E_{\mathrm{T},\bar{t}} E_{\mathrm{T},b} E_{\mathrm{T},\bar{b}} \;\Rightarrow\; \alpha_S^4(\mu_R^2) = \alpha_S(E_{\mathrm{T},t}^2)\alpha_S(E_{\mathrm{T},\bar{t}}^2)\alpha_S(E_{\mathrm{T},b}^2)\alpha_S(E_{\mathrm{T},\bar{b}}^2)$$

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

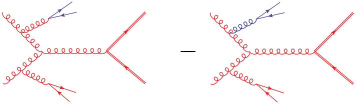
Accuracy of "Double Splittings" in MC@NLO $ttbb$ Simulation

Naive picture



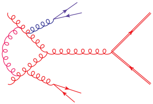
real-emission $t\bar{t}b\bar{b}g$ MEs plus $g \to b\bar{b}$ shower splitting
$\Rightarrow$ only LO+PS accuracy as in usual LO merging

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}

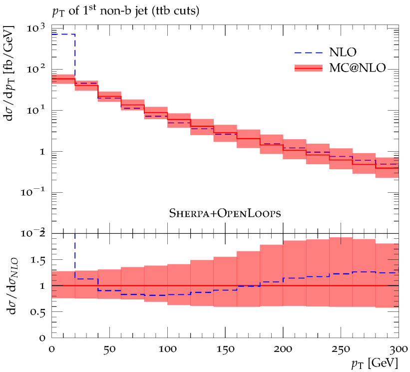


$t\bar{t}b\bar{b}$ MEs plus PS gluon and $g \to b\bar{b}$ emissions

- 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 $t\bar{t}b\bar{b}$...

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

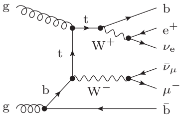
NLO matching and merging for $t\bar{t}+$ jets

- 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 $1/\mu^2_{\text{core}} = 1/\hat{s} + 1/(m_t^2 - \hat{t}) + 1/(m_t^2 - \hat{u})$

Dynamic scale for $W^+W^-b\bar{b}$ I [Cascioli, Maierhöfer,Kallweit, S.P. '13]



Idea: $\mu_R \sim m_t$ for $g \to b\bar{b}$ splittings might generate corrections up to $\alpha_S(m_b)/\alpha_S(m_t) \sim 2$ in Wt contribution

Appropriate scales for $t\bar{t}$ and Wt production (see CKKW and AP evolution)

$$\mu^2_{t\bar{t}} = E_{\mathrm{T},t}E_{\mathrm{T},\bar{t}} \qquad \mu^2_{tW^-} = E_{\mathrm{T},t}E_{\mathrm{T},\bar{b}} \qquad \Rightarrow \qquad \alpha^2_S(\mu^2_{tW^-}) \simeq \alpha_S(E^2_{\mathrm{T},t})\alpha_S(E^2_{\mathrm{T},\bar{b}})$$

Global "interpolating scale"

$$\mu^2_{WWbb} = \mu_{W^+b}\,\mu_{W^-\bar{b}} \quad \text{with} \quad \mu_{Wb} = P_b(p_{\mathrm{W,b}})\,E_{\mathrm{T},b} + P_t(p_{\mathrm{W,b}})\,E_{\mathrm{T},t}$$

$g \to b\bar{b}$ and $t \to Wb$ **probabilities dictated by** respective **singularity structures**

$$\frac{P_b}{P_t} \propto \frac{\chi_b}{\chi_t} \qquad \text{with} \qquad \chi_b = \frac{m_t^2}{E^2_{\mathrm{T},b}}, \quad \chi_t = \frac{m_t^4}{[(p_W+p_b)^2 - m_t^2]^2 + \Gamma_t^2 m_t^2},$$

and free constants fixed by **natural normalisation conditions**

$$P_b + P_t \quad = \quad 1, \qquad \text{and} \qquad \int \mathrm{d}\sigma^{\mathrm{FtW}}_{W^+W^-b\bar{b}} = \int \mathrm{d}\Phi\,[1 - P_t(\Phi)P_{\bar{t}}(\Phi)]\,\frac{\mathrm{d}\sigma_{W^+W^-b\bar{b}}}{\mathrm{d}\Phi}$$

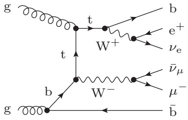
Consistency of $t\bar{t}$ vs tW Probability Densities Check normalisation identity for more exclusive/differential observables

$$\int \mathrm{d}\sigma^{\mathrm{FtW}}_{W^+W^-b\bar{b}} = \int \mathrm{d}\Phi \left[1 - P_t(\Phi)P_{\bar{t}}(\Phi)\right] \frac{\mathrm{d}\sigma_{W^+W^-b\bar{b}}}{\mathrm{d}\Phi}$$

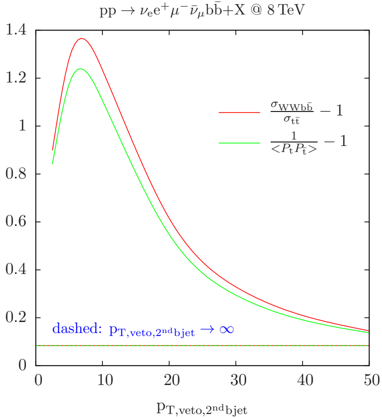
to verify if observed finite-top-width effects (computed via $\Gamma_t \to 0$) are consistent with (pseudo)probability densities

Test dependence wrt veto on 2nd b-jet

- single-top Wt contribution strongly enhanced when $p_{\mathrm{T,veto}} \to 0$



- enhancement fairly well described by $P_t(\Phi)$,$P_b(\Phi)$ probability densisties



$\sigma_{W^+W^-b\bar{b}}$ in Jet Bins I [Cascioli, Maierhöfer,Kallweit, S.P. '13]

Generic-Jet Bins: complete cross section and finite-top-width (FtW) effects

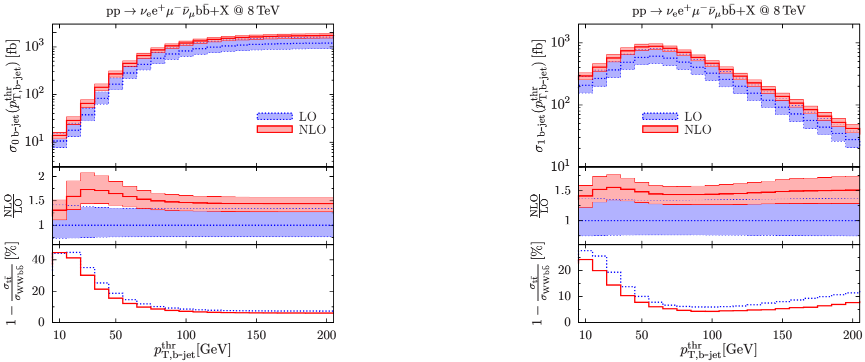
	μ_0	σ[fb]	σ_0[fb]	σ_1[fb]	σ_{2+}[fb]
LO	μ_{WWbb}	$1232^{+34\%}_{-24\%}$	$37^{+38\%}_{-25\%}$	$367^{+36\%}_{-24\%}$	$828^{+33\%}_{-23\%}$
NLO	μ_{WWbb}	$1777^{+10\%}_{-12\%}$	$41^{+3\%}_{-8\%}$	$377^{+1\%}_{-6\%}$	$1359^{+14\%}_{-14\%}$
K	μ_{WWbb}	1.44	1.09	1.03	1.64
LO	m_t	$1317^{+35\%}_{-24\%}$	$35^{+37\%}_{-25\%}$	$373^{+36\%}_{-24\%}$	$909^{+35\%}_{-24\%}$
NLO	m_t	$1817^{+8\%}_{-11\%}$	$40^{+4\%}_{-8\%}$	$372^{+1\%}_{-8\%}$	$1405^{+13\%}_{-13\%}$
K	m_t	1.38	1.14	1.00	1.55
	μ_0	$\sigma^{\rm FtW}$[fb]	$\sigma_0^{\rm FtW}$[fb]	$\sigma_1^{\rm FtW}$[fb]	$\sigma_{2+}^{\rm FtW}$[fb]
LO	μ_{WWbb}	$91^{+41\%}_{-27\%}$	$13^{+42\%}_{-27\%}$	$71^{+40\%}_{-27\%}$	$7^{+45\%}_{-29\%}$
NLO	μ_{WWbb}	$107^{+6\%}_{-11\%}$	$13^{+1\%}_{-7\%}$	$61^{+2\%}_{-16\%}$	$33^{+51\%}_{-31\%}$
K	μ_{WWbb}	1.18	0.99	0.86	4.70
LO	m_t	$63^{+36\%}_{-25\%}$	$8^{+36\%}_{-25\%}$	$49^{+36\%}_{-24\%}$	$6^{+46\%}_{-29\%}$
NLO	m_t	$100^{+17\%}_{-16\%}$	$13^{+14\%}_{-14\%}$	$65^{+9\%}_{-12\%}$	$23^{+42\%}_{-28\%}$
K	m_t	1.58	1.47	1.32	3.89

$\sigma_{W^+W^-b\bar{b}}$ in Jet Bins II [Cascioli, Maierhöfer,Kallweit, S.P. '13]

b-Jet Bins: complete cross section and finite-top-width (FtW) effects

	μ_0	σ[fb]	σ_0[fb]	σ_1[fb]	σ_{2+}[fb]
LO	μ_{WWbb}	$1232^{+34\%}_{-24\%}$	$37^{+38\%}_{-25\%}$	$367^{+36\%}_{-24\%}$	$828^{+33\%}_{-23\%}$
NLO	μ_{WWbb}	$1777^{+10\%}_{-12\%}$	$65^{+20\%}_{-17\%}$	$571^{+14\%}_{-14\%}$	$1140^{+7\%}_{-10\%}$
K	μ_{WWbb}	1.44	1.73	1.56	1.38
LO	m_t	$1317^{+35\%}_{-24\%}$	$35^{+37\%}_{-25\%}$	$373^{+36\%}_{-24\%}$	$909^{+35\%}_{-24\%}$
NLO	m_t	$1817^{+8\%}_{-11\%}$	$63^{+20\%}_{-17\%}$	$584^{+14\%}_{-14\%}$	$1170^{+5\%}_{-9\%}$
K	m_t	1.38	1.80	1.56	1.29
	μ_0	σ^{FtW}[fb]	σ_0^{FtW}[fb]	σ_1^{FtW}[fb]	$\sigma_{2+}^{\mathrm{FtW}}$[fb]
LO	μ_{WWbb}	$91^{+41\%}_{-27\%}$	$13^{+42\%}_{-27\%}$	$71^{+40\%}_{-27\%}$	$7^{+45\%}_{-29\%}$
NLO	μ_{WWbb}	$107^{+6\%}_{-11\%}$	$20^{+18\%}_{-17\%}$	$82^{+4\%}_{-10\%}$	$5^{+2\%}_{-10\%}$
K	μ_{WWbb}	1.18	1.49	1.16	0.77
LO	m_t	$63^{+36\%}_{-25\%}$	$8^{+36\%}_{-25\%}$	$49^{+36\%}_{-24\%}$	$6^{+46\%}_{-29\%}$
NLO	m_t	$100^{+17\%}_{-16\%}$	$16^{+22\%}_{-18\%}$	$77^{+16\%}_{-15\%}$	$6^{+12\%}_{-16\%}$
K	m_t	1.58	1.89	1.58	1.10

$\sigma_{W^+W^-b\bar{b}}$ b-jet veto [Cascioli, Maierhöfer,Kallweit, S.P. '13]



- NLO radiation doesn't change b-jet multiplicity ⇒ rather stable K-factor and uncertainties
- single-top and off-shell effects still enhanced at small b-jet p_T

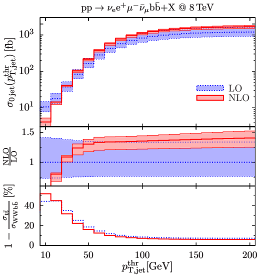
In general: nontrivial interplay of NLO and off-shell/single-top effects

Unified $t\bar{t} + tW$ NLO description [Cascioli, Maierhöfer,Kallweit, S.P. '13]

Jet-Veto and Binning Effects

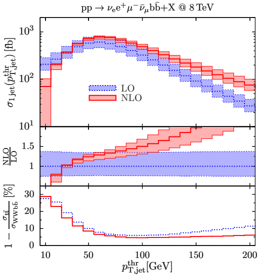
0-jet bin vs p_{T}-veto

- smooth inclusive limit at large p_{T} and very strong p_{T} sensitivity below $50\,\mathrm{GeV}$:
  - FtW effects increase up to 50%
  - K-factor falls very fast
- at low p_{T} IR singularity calls for NLO+PS matching
- typical veto $p_{\mathrm{T}} \sim 30\,\mathrm{GeV}$ yields 98% suppression and still decent NLO stability ($K \sim 1$)

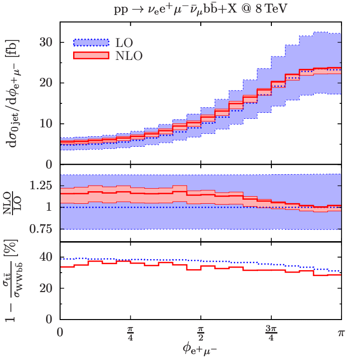


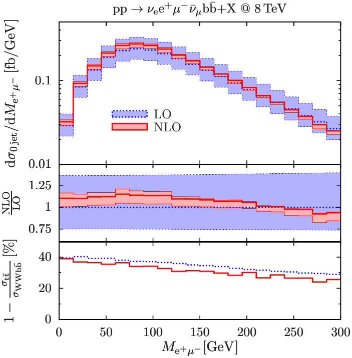
1-jet bin vs p_{T} threshold

- low p_{T} behaviour driven by veto on 2nd jet and analogous to 0-jet case
- high p_{T} region driven by 1st jet and NLO radiation dominates over b-jets from $W^+W^-b\bar{b}$



$t\bar{t}$ and Wt Background to $H \to W^+W^-$ in 0-Jet Bin





- $\Delta\phi_{e^+\mu^-}$ and $M_{e^+\mu^-}$ distributions feature 10% NLO uncertainty
- significant (although moderate) NLO shape distortions
- 30–40% FtW contributions (nontrivial $t\bar{t}/Wt$ mix)

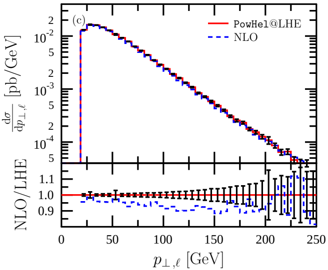
NLO+PS $W^+W^-b\bar{b}$ with POWHEL I [Garzelli,Kardos,Trocsanyi '14]

Simulation with POWHEGBOX+HELAC-NLO

- NLO+PS for $pp \to \ell^+\nu\ell^-\nu b\bar{b}$ for 7 TeV
- standard $t\bar{t}$ cuts with 2 b-jets + veto against non-b jets
- 5F scheme $(m_b = 0)$
- factor-2 variations around $\mu_0 = m_t$

Sanity check: NLO vs LHE (NLO+PS$_{\text{1st emission}}$)

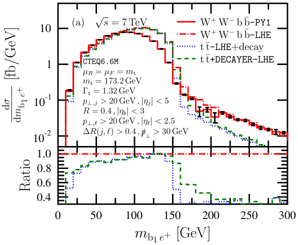
- **expected**: exact agreement for *inclusive* cross section and $\mathcal{O}(\alpha_S^2)$ distortions in distributions
- **observed**: 10% shape distortions
- probably a POWHEG-related side effect of large NLO shape corrections with $\mu = m_t$ (can be avoided using a dynamical scale)



NLO+PS $W^+W^-b\bar{b}$ with POWHEL II [Garzelli,Kardos,Trocsanyi '14]

Importance of off-shell effects and NLO corrections to decay

- assessed by comparing NLO+PS results (1st emission only) based on $W^+W^-b\bar{b}$ and on-shell $t\bar{t}$ with LO decays
- shape distortions at large $m_{\ell b}$ (off-shell effects) and small $m_{\ell b}$ (LO decays)



m_t from $m_{\ell b}$ distribution I [Heinrich, Winter et al '13]

$WWbb$ NLO simulation with GoSam+Sherpa

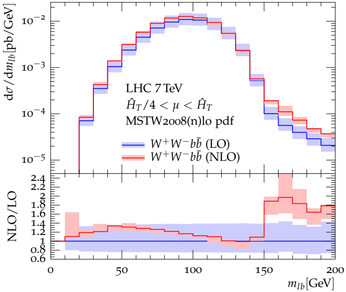
- 5F scheme ($m_b = 0$) and NWA for $W \to \ell\nu$
- includes NLO top decays, Wt contribution, ...

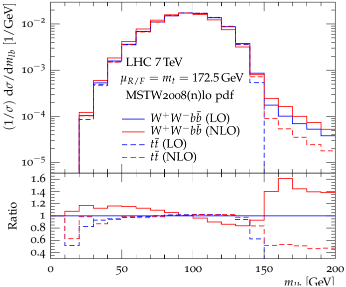
NLO effects and scale uncertainties

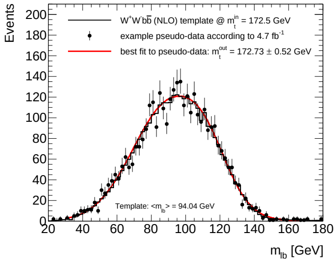
- 20% correction to LO shape ($\Delta m_t \sim 2\,\text{GeV}$)
- non-negligible scale uncertainty in NLO shape (factor-2 variations around $\mu_0 = H_\text{T}/2$)

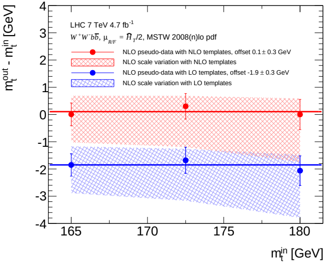
NLO $WWb\bar{b}$ vs NLO $t\bar{t}$ with LO decays

- NLO $WWb\bar{b}$ shape distortion disappears, most likely due to LO decays
- would be interesting to compare against LO+PS decays and to asses off-shell effects ...









m_t determination based on $WWb\bar{b}$ templates

(1) generate NLO pseudo-data with m_t^{in} and $0.5 \leq \mu/\mu_0 \leq 2$

(2) extract m_t^{out} by fitting to NLO templates with $\mu = \mu_0$ (and variable m_t)

(3) similar fit with LO templates

NLO effects and uncertainties

- neglecting NLO (and shower) corrections to m_ℓ underestimates m_t by 2 GeV
- NLO scale uncertainty $\Delta m_t \simeq 1\,\text{GeV}$!

Remains to be studied

- variation of kinematic μ_0 dependence
- NLO+PS for $WWb\bar{b}$ (nontrivial!)