MC for $t\bar{t}H$ and SM backgrounds

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Higgs Couplings 2015
Lumley Castle, 13 October 2015

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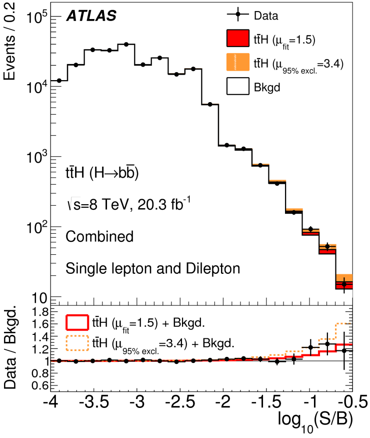
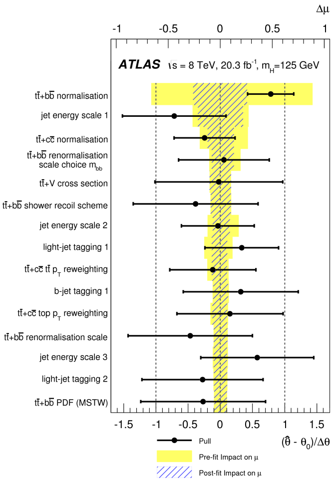
Large backgrounds in $t\bar{t}H$ searches

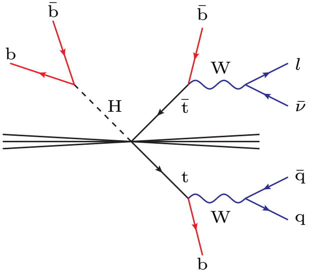
Dominant $t\bar{t}H(b\bar{b})$ channel suffers from heavy $t\bar{t}$+jets contamination

- $\sim 3'000\ t\bar{t}H$ events but only 3–4$\times\sigma_{\mathrm{SM}}$ exclusion at Run1
- main bottleneck is the background theory uncertainty





Theory priorities in $t\bar{t}H$ searches



Key priority is precision for backgrounds

- various multi-particle processes: $t\bar{t}+$jets, $t\bar{t}V+$jets, $t\bar{t}\gamma\gamma$, $VV+$jets
- NLO automation crucial but $2 \to 4$ CPU intensive

NLO matching & merging crucial

- *various* new methods (FxFx, MEPS@NLO, MINLO, UNLOPS,...)
- *various* automated tools support NLO precision for signal and most backgrounds: MG5_aMC@NLO, Sherpa+OpenLoops/GoSam, Powheg/Powhel

Theory uncertainty estimates nontrivial

- still limited experience in NLO matching+merging framework
- sophisticated analyses (profile likelihood, MEM, background reweighting, ...)

Recent progress in theory precision [slide by M. Zaro]

- $t\bar{t}H$
  - NLO QCD corrections (30% @ RunII)
    Beenakker et al. hep-ph/0107081 & hep-ph/0211352
    Dawson et al. hep-ph/0211438 & hep-ph/0305087
  - Matching to PS
    aMC@NLO: Frederix et al. arXiv:1104.5613
    Powhel: Garzelli et al. arXiv:1108.0387
    2015! Powheg Box: Hartanto et al. arXiv:1501.04498
  - NLO QCD corrections to $b\bar{b}\ell^+\ell^-\nu\bar{\nu}H$
    2015! Denner et al. arXiv:1506.07448
  - Weak and Electro-Weak corrections (1.5% @ RunII)
    2015! Frixione et al. arXiv:1407.0823 & arXiv:1504.03446
    Zhang et al. arXiv:1407.1110
  - Soft gluon resummation (2-6% @ RunII)
    2015! Kulesza et al. arXiv:1509.02780
- tH
  - NLO QCD corrections
    (5FS) Farina et al. arXiv:1211.3737
    (5FS) Campbell et al. arXiv:1302.3856
  - Matching to PS
    2015! (4FS and 5FS) Demartin et al. arXiv:1504.00611
    tHW see poster by F. Demartin

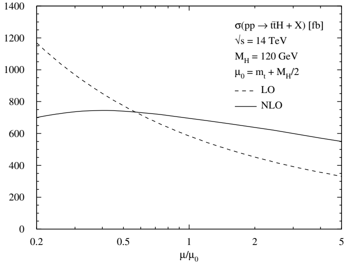
Marco Zaro, 17-09-2015 4

- $t\bar{t}b\bar{b}$
  - NLO QCD corrections
    Bredenstein et al. arXiv:0905.0110 & arXiv:1001.4006
    Bevilacqua et al. arXiv:0907.4723
  - Matching to PS
    Kardos et al. 1303.6201
    Cascioli et al. 1309.5912
- $t\bar{t}V$
  - NLO QCD corrections
    $t\bar{t}\gamma$ Melnikov et al. arXiv:1102.1967
    $t\bar{t}W, t\bar{t}\gamma^*/Z, t\bar{t}\gamma$ Hirschi et al. arXiv:1103.0621
    $t\bar{t}Z$ Lazopoulos et al. arXiv:0804.2220
    $t\bar{t}Z$ Kardos et al. arXiv:1111.0610
    $t\bar{t}W$ Campbell et al. arXiv:1204.5678
  - Matching to PS
    $t\bar{t}Z$ Garzelli et al. arXiv:1111.1444
    $t\bar{t}W, t\bar{t}Z$ Garzelli et al. arXiv:1208.2665
  - Electro-Weak corrections
    2015! $t\bar{t}W, t\bar{t}Z$ (and $t\bar{t}H$) Frixione et al. arXiv:1504.03446
- $t\bar{t}VV$
  - NLO QCD corrections + PS
    $t\bar{t}\gamma\gamma$ Kardos et al. arXiv:1408.0278
    2015! all $t\bar{t}VV$ Maltoni et al. arXiv:1507.05640
    2015! $t\bar{t}\gamma\gamma$ van Deurzen et al. arXiv:1509.02077

Outline

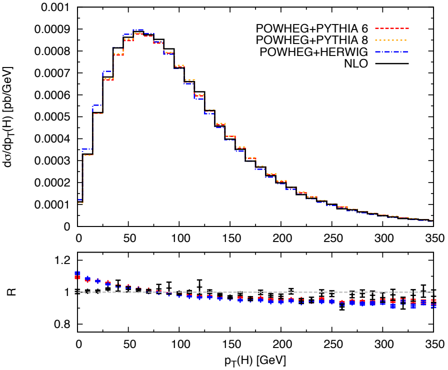
1. $t\bar{t}H$ Signal
2. Backgrounds for $H \to b\bar{b}$
3. Backgrounds for $H \to WW, ZZ, \tau\tau \to$ multi-leptons
4. Backgrounds for $H \to \gamma\gamma$

NLO tools for $t\bar{t}H$



$\sigma_{t\bar{t}H}$ **at NLO** [Beenakker et al '01; Reina, Dawson '01]

- moderate uncertainty (9% scale, 8% PDF+α_S)
- sufficient for mid-term future

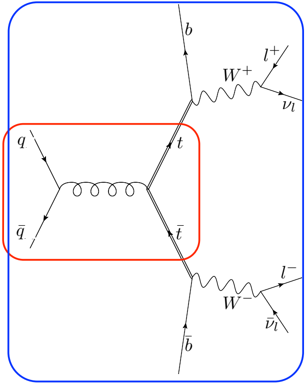


Publicly available NLO+PS tools

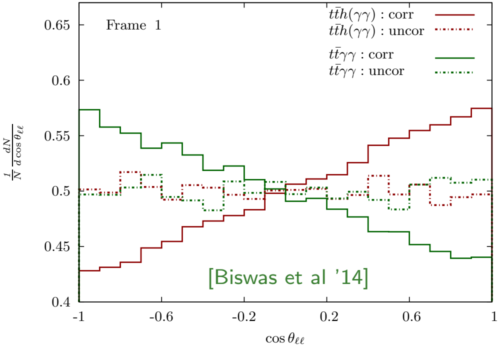
- MG5_aMC@NLO [Frederix et al. '15]
- Powhel [Garzelli at al. '11] and Powheg Box [Jaeger et al. '15]
- Sherpa+OpenLoops or GoSam

$\lesssim 10\%$ uncertainty for inclusive observables (more if sensitive to jet radiation)

Spin-correlated Top decays



Mandatory for signal and all backgrounds



NLO+PS level automation in POWHEG, MG5_aMC@NLO and SHERPA

- via full production×decay LO MEs for $t\bar{t}H$(+j) assuming same 1-loop correlations
- only (NLO production)×(LO decay) accuracy

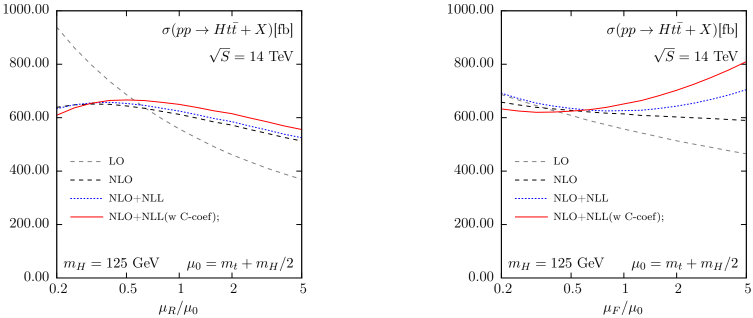
Soft-gluon NLL resummation for $\sigma_{t\bar{t}H}$ [Kulesza et al. '15]

Resummation of threshold logarithms of $\beta = \sqrt{1-(2m_t+m_H)^2/\hat{s}}$

- optimal for $m_H + 2m_t \to \sqrt{s}$
- logs are β^4-suppressed by $t\bar{t}H$ phase space $\Rightarrow$ no realistic estimate of full NNLO

Matched prediction: $\sigma^{t\bar{t}H}_{\text{NLO+NLL}} = 650^{+7.9\%}_{-5.7\%}$ $(\sigma^{t\bar{t}H}_{\text{NLO}} = 613^{+6.2\%}_{-9.4\%})$

- moderate +7% correction and modest reduction of scale uncertainty
- dominant effects from $\mathcal{O}(\alpha_S)$ matching coefficient $C^{(1)}$ (formally NNLL)



Soft-gluon NNLL resummation for $\mathrm{d}\sigma/\mathrm{d}\Phi_{t\bar{t}H}$ [Broggio et al. '15]

SCET PIM resummation formalism

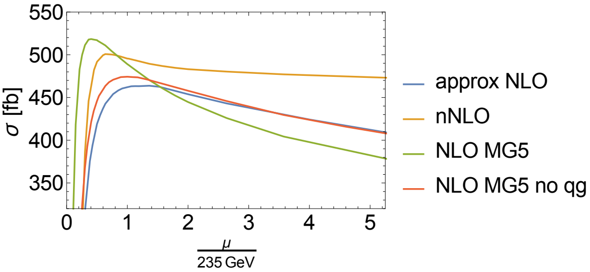
- resums threshold-type logarithms of $1 - z = 1 - M^2_{t\bar{t}H}/\hat{s}$
- valid for $M_{t\bar{t}H} > 2m_t + m_H$ and optimal for $M^2_{t\bar{t}H} \to s$

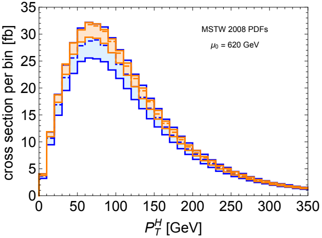
$\Rightarrow$ applicable to differential distributions

nNLO approx. from truncated NLO+NNLL

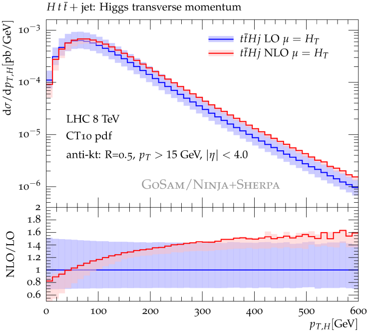
$\mu_0 = m_t + m_H/2 = 235$ GeV

- $\mu = 2.64\,\mu_0 \;\Rightarrow\;$ +8% nNLO correction & 5% uncertainty (scale+subleading logs)
- standard scale $\mu = \mu_0 \;\Rightarrow\;$ smaller nNLO correction





NLO QCD corrections to $t\bar{t}H + 1$ jet



Parton-level NLO with SHERPA+GOSAM [Deurzen et al, '13]

- more reliable prediction *and* uncertainty for extra jet activity
- room for significant effects in the hard region (depending on μ)
- NNLO contributions of hard type

Applicable to $t\bar{t}H$ analysis through $t\bar{t}H + 0, 1$ jets NLO merging (automated)

- MEPS@NLO merging [Höche et al. '12] in SHERPA+OPENLOOPS/GOSAM
- FxFx merging [Frederix, Frixione '12] in MG5_AMC@NLO

$\Rightarrow$ impact on $\sigma_{t\bar{t}H}$ and $t\bar{t}H$ searches?

$t\bar{t}H$ (and $t\bar{t}V$) at NLO QCD+EW [Frixione et al. '14–15; Zhang et al. '14]

Emerging NLO QCD+EW automation

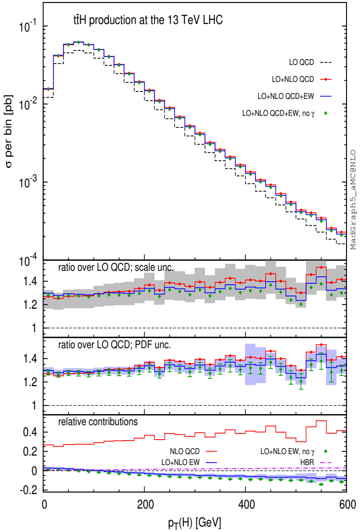
- RECOLA [1411.0916], OPENLOOPS [1412.5157], MG5_AMC [1504.03446], GOSAM [1507.08579]
- applicable to $t\bar{t}H$ signal *and* backgrounds (matching/merging automation ongoing)
- large NLO EW effects at $p_T \gg M_W$

NLO EW corrections to $t\bar{t}H$ and $t\bar{t}V$

- NLO correction to $m_t = \lambda_t v/\sqrt{2}$ relation
- impact below QCD scale+PDF uncertainties and more significant for backgrounds

$t\bar{t}H$: -1% for $\sigma_{\rm tot}$ (-8% at $p_T > 200$ GeV)

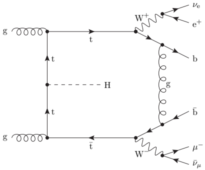
$t\bar{t}W$: -8% for $\sigma_{\rm tot}$ (-12% at $p_T > 200$ GeV)

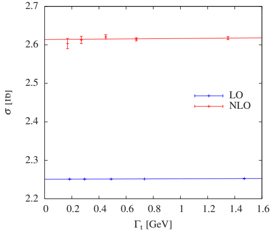


$pp \to t\bar{t}H \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H$ at NLO QCD [Denner and Feger '15]

Challenging $2 \to 5$ NLO calculation

- heptagons, complex mass scheme for top resonances
- RECOLA+COLLIER [Denner, Dittmaier, Hofer, Uccirati]





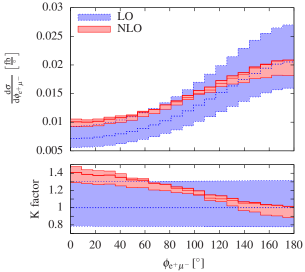
Results for total cross section with $t\bar{t}$-type cuts

- excellent agreement with NWA $(\Gamma_t \to 0)$ as for $t\bar{t}$
- bigger off-shell effects from $pp \to tWH$ if one b unresolved (would require $m_b > 0$)

Distributions with $\mu_{\rm dyn} = (E_{T,t}E_{T,\bar{t}}E_{T,H})^{1/3}$

- nontrivial NLO shape corrections
- due to NLO corrections to production *and* decay?

$\Rightarrow$ cf. (NLO production)$\times$(LO+PS decay) in MC



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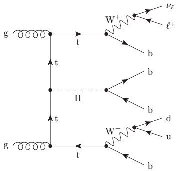
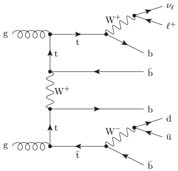
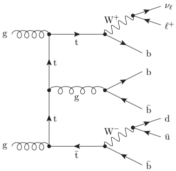
$2 \to 8$ simulation of $t\bar{t}H(b\bar{b})$ signal and irred. backg. I



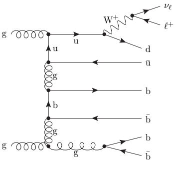
$\mathcal{O}\left(\alpha_S^1\right)$



$\mathcal{O}\left(\alpha_S^1\right)$



$\mathcal{O}\left(\alpha_S^2\right)$

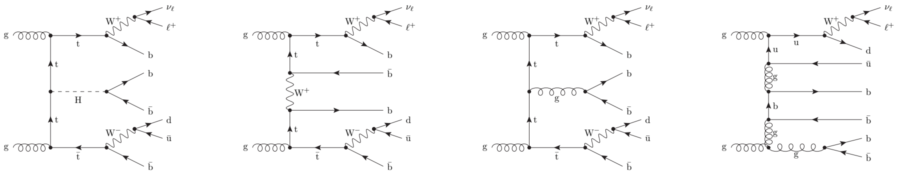


$\mathcal{O}\left(\alpha_S^3\right)$

$pp \to \ell\nu + 2j + 4b$ **at LO** [Denner, Feger, Scharf, 1412.5290]

- 48 partonic channels and up to 78'000 diagrams/channel at LO
- MEs of order α_S^0, α_S^1, α_S^2, α_S^3 with interferences and non-resonant effects

$2 \to 8$ simulation of $t\bar{t}H(b\bar{b})$ signal and irred. backg. II



$\mathcal{O}\left(\alpha_S^1\right)$ $\mathcal{O}\left(\alpha_S^1\right)$ $\mathcal{O}\left(\alpha_S^2\right)$ $\mathcal{O}\left(\alpha_S^3\right)$

$\mathcal{O}\left(\alpha_S\right)$ EW contributions to $t\bar{t}b\bar{b}$

- $t\bar{t}H$ (70%), $t\bar{t}Z$ ($\sim 10\%$), $t\bar{t}\gamma^*$ ($\sim 10\%$), and t-channel W-exchange ($\sim 10\%$)

Interference between $\mathcal{O}\left(\alpha_S^2\right)$ QCD and $\mathcal{O}\left(\alpha_S\right)$ EW contributions to $t\bar{t}b\bar{b}$

- -8% wrt $t\bar{t}b\bar{b}$ QCD, mostly from t-channel W-exchange (tiny $t\bar{t}H$ interference)

Off-shell contributions with ≤ 1 top resonance (new qg and qq' channels)

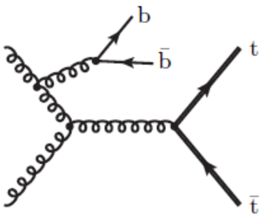
- $+12\%$ wrt $t\bar{t}b\bar{b}$ QCD (might be attributed to Wbb+jets?)

Non-standard background contributions of order 10–50% $\sigma_{t\bar{t}H}$

Irreducible $t\bar{t}b\bar{b}$ QCD background at NLO

NLO $t\bar{t}b\bar{b}$ [Bredenstein et al '09/'10; Bevilacqua et al '09];

- $t\bar{t}b\bar{b}$ dominates $t\bar{t}H(b\bar{b})$ systematics
- NLO reduces uncertainty from 80% to 20–30%



NLO+PS $t\bar{t}b\bar{b}$ 5F scheme ($m_b = 0$) with POWHEL [Garzelli et al '13/'14]

- $t\bar{t}b\bar{b}$ **NLO MEs cannot describe collinear $g \to b\bar{b}$ splittings**

$\Rightarrow$ *inclusive* $t\bar{t}$+b-jets simulation requires parton shower in collinear $b\bar{b}$ region

$\Rightarrow$ **NLO merging $t\bar{t} + 0, 1, 2$ jets** (see later)

NLO+PS $t\bar{t}b\bar{b}$ 4F scheme ($m_b > 0$) with SHERPA+OPENLOOPS [Cascioli et al '13]

- $t\bar{t}b\bar{b}$ **NLO MEs cover full b-quark phase space**

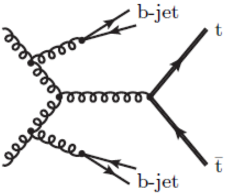
$\Rightarrow$ inclusive NLO accurate $t\bar{t}$+b-jets simulation possible

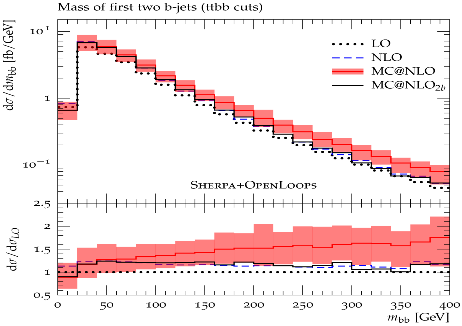
S–MC@NLO $t\bar{t}b\bar{b}$ 4F scheme [Cascioli et al '13]

Good perturbative stability but unexpected MC@NLO enhancement

	ttb	$ttbb$	$ttbb\,(m_{bb} > 100)$
$\sigma_{\rm LO}$[fb]	$2644^{+71\%+14\%}_{-38\%-11\%}$	$463.3^{+66\%+15\%}_{-36\%-12\%}$	$123.4^{+63\%+17\%}_{-35\%-13\%}$
$\sigma_{\rm NLO}$[fb]	$3296^{+34\%+5.6\%}_{-25\%-4.2\%}$	$560^{+29\%+5.4\%}_{-24\%-4.8\%}$	$141.8^{+26\%+6.5\%}_{-22\%-4.6\%}$
$\sigma_{\rm NLO}/\sigma_{\rm LO}$	1.25	1.21	1.15
$\sigma_{\rm MC@NLO}$[fb]	$3313^{+32\%+3.9\%}_{-25\%-2.9\%}$	$600^{+24\%+2.0\%}_{-22\%-2.1\%}$	$181^{+20\%+8.1\%}_{-20\%-6.0\%}$
$\sigma_{\rm MC@NLO}/\sigma_{\rm NLO}$	1.01	1.07	1.28

Large enhancement (∼30%) in Higgs region from double $g \to b\bar{b}$ splittings





matching, shower and 4F/5F systematics remain to be understood!

$t\bar{t}$+ jets background and merging at NLO

NLO $t\bar{t} + 2$ jets [Bevilacqua, Czakon, Papadopoulos, Worek '10/'11]

- reduces uncertainty from 80% to 15%

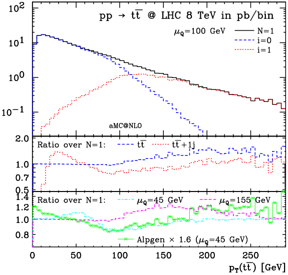
NLO merging (FxFx, MEPS@NLO, UNLOPS, . . .)

0-jet	NLO+PS $t\bar{t}$
1-jet	NLO+PS $t\bar{t} + 1$ j
. . .	. . .
$\geq n$ jets	NLO+PS $t\bar{t} + n$ j

- NLO and log accuracy for $0, 1, \ldots n$ jets
- separated via k_{T}-algo at merging scale Q_{cut}
- smooth PS–MEs transition $\leftrightarrow$ MEs with PS-like scale and Sudakov FFs

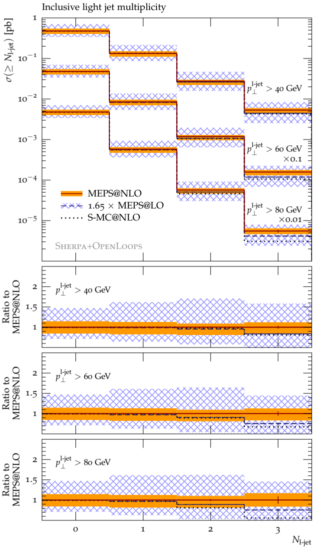
NLO merging for $t\bar{t} + 0, 1$ jets

- FxFx with MADGRAPH5/AMC@NLO [Frederix, Frixione '12]
- MEPS@NLO with SHERPA+GOSAM [Höche et al '13]



MEPS@NLO for $t\bar{t} + 0, 1, 2$ jets (SHERPA+OPENLOOPS)

[Höche, Krauss, Maierhöfer, S. P. , Schönherr, Siegert '14]



Consistency with LO merging and NLO+PS

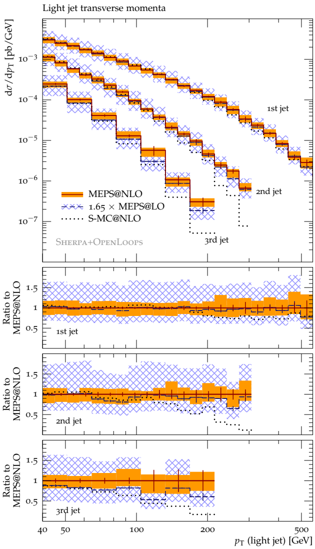
- decent (10–20%) mutual agreement

Reduction of μ_R, μ_F, μ_Q variations

$N_{\text{light-jet}} \geq$	0	1	2
LO	48%	65%	80%
NLO	17%	18%	19%

MEPS@NLO for $t\bar{t} + 0, 1, 2$ jets (SHERPA+OPENLOOPS) II

[Höche, Krauss, Maierhöfer, S. P. , Schönherr, Siegert '14]



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LO	48%	65%	80%
NLO	17%	18%	19%

Differential distributions

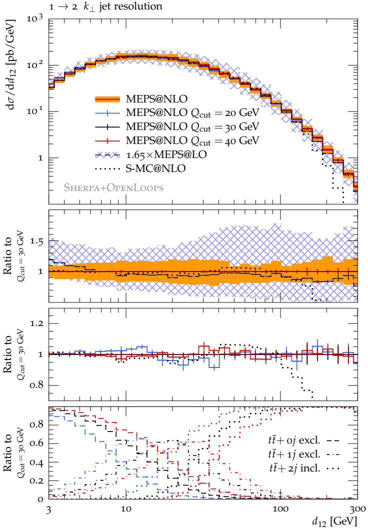
- similarly mild scale dependence
- small shape corrections

Next steps

- improve CPU performance
- consistent combination with $t\bar{t}b\bar{b}$

MEPS@NLO for $t\bar{t} + 0, 1, 2$ jets (Sherpa+OpenLoops) III

[Höche, Krauss, Maierhöfer, S. P. , Schönherr, Siegert '14]



Small merging scale choice

- $Q_{\mathrm{cut}} = 30\,\mathrm{GeV}$ such that exp. resolved jets are described by MEs

Merging scale uncertainty

- $Q_{\mathrm{cut}} = 30 \pm 10\,\mathrm{GeV}$

$\Rightarrow$ $\ll 10\%$ dependence

does not spoil $t\bar{t} + 0, 1, 2$ jets NLO precision

Scale dependencies in NLO matching and merging

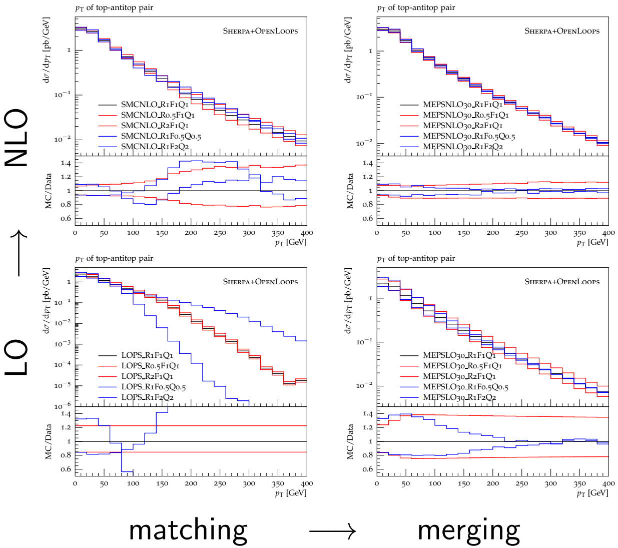
Scale variations

- basis for definition of *intrinsic* theory precision of (N)NLO Monte Carlo
- quantitative and realistic uncertainty estimate is a key advantage of (N)NLO MC wrt (tuned) LO MC

Four scale variations

- standard prescription for renormalisation (μ_R) and factorisation (μ_F) scales
- no widely accepted prescription for resummation (μ_Q) and merging (Q_{cut}) scales

Benefits of NLO matching and merging (top-pair p_T in $t\bar{t} + 0, 1$ jets)



$\mu_R = \xi\, m_t$

- renorm. scale

$\mu_Q = \mu_F = \xi\, m_t$

- factorisation scale
- resummation scale

NLO merging

- 10% accuracy over whole spectrum!

Choice and variation of merging scale $Q_{\rm cut}$?!

Virtue of small $Q_{\rm cut}$

- NLO accuracy over whole $p_{\rm T}$ spectrum of experimentally resolved jets

Formal problem at (very) small $Q_{\rm cut}$ [Hamilton, Nason, Oleari, Zanderighi '12]

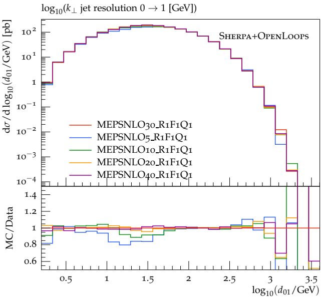
- when $Q_{\rm cut}$ approaches Sudakov peak, i.e. $\alpha_S \log^2(Q_{\rm cut}/Q_{\rm hard}) \sim 1$

$\Rightarrow$ uncontrolled $\mathcal{O}\left(\alpha_S^{1.5}\right)$ subleading logs can spoil NLO precision

$\Rightarrow$ Optimal $Q_{\rm cut}$ choice? Uncertainty?

Quantitative estimate (conservative)

- consider jet-$k_{\rm T}$ dist $\Rightarrow$ max $Q_{\rm cut}$ sensitivity
- push $Q_{\rm cut}$ down to Sudakov region
- take *local* $Q_{\rm cut}$ dependence as uncertainty estimate
- stop before you exceed NLO scale dependence



Example: MEPS@LO for $t\bar{t} + 0, 1$ jets

- $Q_{\rm cut} = 40 \ldots 5$ GeV $\Rightarrow$ less than 10% uncertainty for $Q_{\rm cut} \geq 10\,\text{GeV}$

Outline

1. $t\bar{t}H$ Signal
2. Backgrounds for $H \to b\bar{b}$
3. Backgrounds for $H \to WW, ZZ, \tau\tau \to$ multi-leptons
4. Backgrounds for $H \to \gamma\gamma$

Most relevant Backgrounds to $t\bar{t}H(H \to VV)$

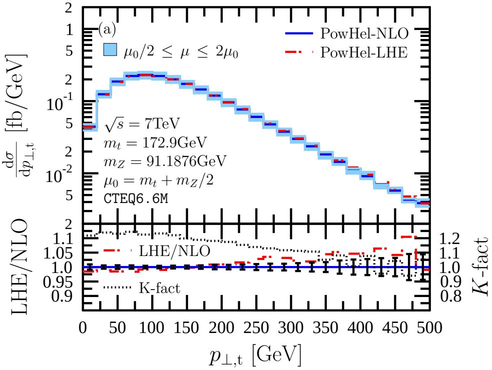
$t\bar{t} + W/Z/\gamma^*$+extra jets

- MC systematics dominated by $t\bar{t}W + 0, 1, 2\,\text{jets}$
- same signature as $t\bar{t}H(H \to WW \to \ell\nu jj)$!
- $t\bar{t} + Z/\gamma(\to \ell^+\ell^-)$ requires off-shell effects down to small $m_{\ell\ell}$

VV+jets

- mainly $WZ \to 3\ell$ but also $ZZ \to 4\ell$
- requires inclusive sample with NLO precision up to 2 jets
- HF jets crucial (genuine $VVb\bar{b}$ component and light-jet mistags)

NLO+PS $t\bar{t}+W^{\pm}/Z$ with POWHEG/POWHEL [Garzelli et al '12]



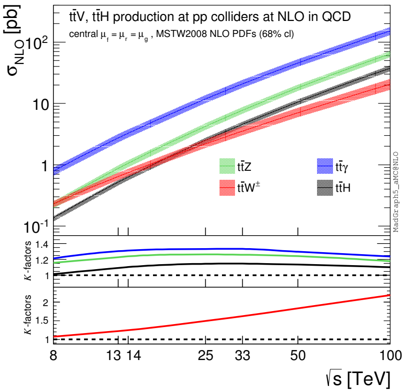
Moderate NLO+PS corrections

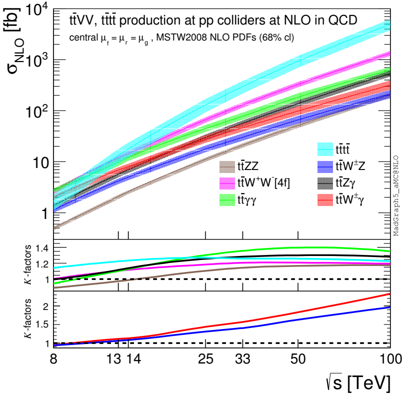
- $K = 1.1$–1.35 and mild uncertainties (10% scale, 8% PDFs)
- top decays in NWA (uncorrelated)
- $t\bar{t}V + 2$ jets from PS

NLO+PS predictions for $t\bar{t}V$ and $t\bar{t}VV$ [Maltoni et al. '15]

Thorough study with scale+PDF variations for all $V = W, Z, \gamma$

- moderate K-factors and shape corrections at 13–14 TeV
- small irreducible $t\bar{t}H(VV)$ backgrounds: 2 fb $\leq \sigma_{t\bar{t}VV} \leq 12$ fb





Backgrounds to $t\bar{t}H \to$ multileptons [Maltoni et al. '15]

Simulation of 2-, 3- and 4-lepton CMS searches at 13 TeV

$\sigma_{\rm NLO+PS}$ [fb]	2 same-sign leptons	3 leptons	4 leptons
$t\bar{t}H(H \to WW^*)$	$1.54^{+5.1\%\,+2.2\%}_{-9.0\%\,-2.6\%}$	$1.47^{+5.2\%\,+2.0\%}_{-9.0\%\,-2.4\%}$	$0.095^{+7.4\%\,+2.0\%}_{-9.7\%\,-2.4\%}$
$t\bar{t}H(H \to ZZ^*)$	$0.0437^{+5.5\%\,+2.3\%}_{-9.2\%\,-2.8\%}$	$0.119^{+6.3\%\,+2.1\%}_{-9.6\%\,-2.5\%}$	$0.0170^{+5.0\%\,+2.0\%}_{-8.5\%\,-2.4\%}$
$t\bar{t}H(H \to \tau^+\tau^-)$	$0.563^{+4.6\%\,+2.2\%}_{-8.8\%\,-2.7\%}$	$0.669^{+6.0\%\,+2.1\%}_{-9.4\%\,-2.6\%}$	$0.0494^{+7.1\%\,+2.1\%}_{-9.9\%\,-2.5\%}$
$t\bar{t}W^\pm$	$5.77^{+15.1\%\,+1.6\%}_{-12.7\%\,-1.2\%}$	$2.44^{+13.1\%\,+1.7\%}_{-11.6\%\,-1.4\%}$	-
$t\bar{t}Z/\gamma^*$ $(\to \ell^+\ell^-)$	$1.61^{+7.7\%\,+2.0\%}_{-10.5\%\,-2.5\%}$	$2.70^{+9.0\%\,+2.0\%}_{-11.2\%\,-2.5\%}$	$0.280^{+9.8\%\,+1.9\%}_{-11.0\%\,-2.3\%}$
$t\bar{t}W^+W^-$	$0.288^{+8.0\%\,+2.3\%}_{-11.1\%\,-2.6\%}$	$0.201^{+7.4\%\,+2.1\%}_{-10.7\%\,-2.3\%}$	$0.0116^{+6.9\%\,+2.2\%}_{-10.2\%\,-2.3\%}$
$t\bar{t}t\bar{t}$	$0.340^{+27.5\%\,+5.5\%}_{-25.8\%\,-6.4\%}$	$0.211^{+27.4\%\,+5.2\%}_{-25.6\%\,-6.1\%}$	$0.0110^{+27.0\%\,+5.0\%}_{-25.5\%\,-5.9\%}$
$t\bar{t}ZZ$	$0.0096^{+3.5\%\,+1.8\%}_{-8.4\%\,-1.8\%}$	$0.0050^{+3.7\%\,+1.8\%}_{-8.3\%\,-1.7\%}$	$0.00025^{+7.2\%\,+1.9\%}_{-9.6\%\,-1.8\%}$
$t\bar{t}W^\pm Z$	$0.0620^{+9.0\%\,+2.2\%}_{-10.2\%\,-1.6\%}$	$0.0279^{+9.2\%\,+2.3\%}_{-10.3\%\,-1.7\%}$	$0.00091^{+7.2\%\,+2.4\%}_{-9.2\%\,-1.7\%}$

- B/S up to 350% for $t\bar{t}V$ and only 15–25% for $t\bar{t}WW + t\bar{t}t\bar{t}$
- NLO precision (10–15%) seems sufficient apart from $t\bar{t}W$ (and $t\bar{t}W$+jets!)

Outline

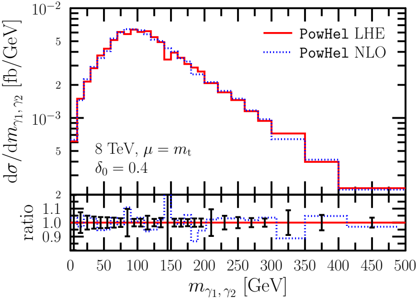
Backgrounds to $t\bar{t}H(\gamma\gamma)$ and MC predictions

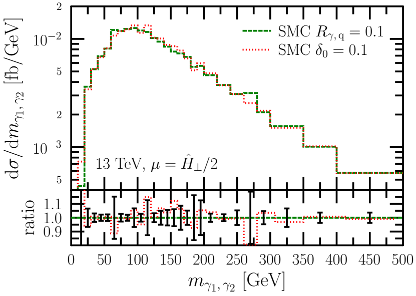
$\sigma_{t\bar{t}H(\gamma\gamma)} \sim 1.5\,\text{fb}$ **contaminated by mild backgrounds**

- $t\bar{t} + 1, 2\gamma$, single-top$+1, 2\gamma$, jets$+1, 2\gamma$
- H+jets with $H \to \gamma\gamma$ and HF jets

NLO+PS for $t\bar{t}\gamma$ and $t\bar{t}\gamma\gamma$ with POWHEL [Kardos, Trocsanyi '14]

- mild NLO uncertainty (14%) and MC effects for inclusive observables
- realistic IR-safe hard-photon isolation (without $q \to q\gamma$ fragmentation): loose Frixione isolation (generation cuts) + tighter cone isolation (analysis cuts)

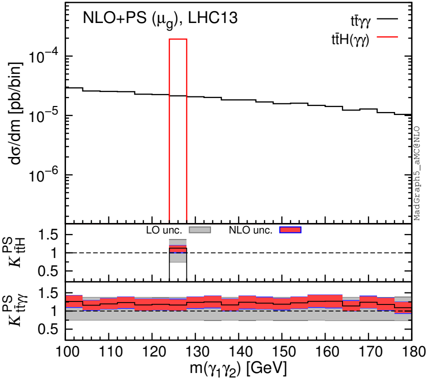




$t\bar{t}\gamma\gamma$ background in $t\bar{t}H(\gamma\gamma)$ searches [Maltoni et al. '15]

MC@NLO simulations of $t\bar{t}H(\gamma\gamma)$ and $t\bar{t}\gamma\gamma$ see also [van Deurzen at al. '15]

- CMS-like cuts for $t\bar{t}H(\gamma\gamma)$ search with one lepton
- Higgs peak fully reconstructed within $|m_{\gamma\gamma} - m_H| < 2$ GeV mass window



- 20 signal events/100 fb^{-1}
- $S/B_{\text{irred.}} \sim 10$
- NLO+PS for S and $B_{\text{irred.}}$ well under control: $\lesssim 10\%$ uncertainty

$\Rightarrow$ MC better than side-band approach for background?

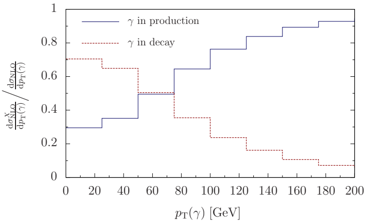
What about reducible backgrounds (fake photons, leptons,. . .)?

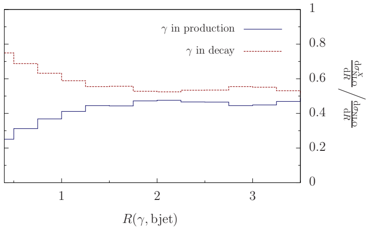
Subtleties in $t\bar{t}$+multi-γ production

Radiative top decays (not included in recent NLO MC studies)

- two photons can arise from $t\bar{t} + 0, 1, 2\,\gamma$ production plus $2, 1, 0\ \gamma$s from top decays
- photons with $M_{b\ell\nu\gamma} < m_t$ mainly from top-decay products (light leptons/quarks)

NLO study of $t\bar{t} + 0, 1\,\gamma$ with $t \to b\ell^+\nu + 0, 1\,\gamma$ [Melnikov, Schulze '11]



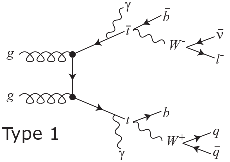


- photons from top decays dominate up to $p_T(\gamma) \lesssim 60\,\text{GeV}$ (smooth isolation, $R_{\gamma i} > 0.4$)

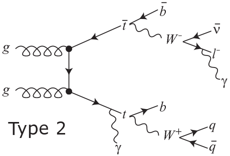
$t\bar{t}H(\gamma\gamma)$ searches require $t\bar{t} + X$ background with $n_\gamma = 1, 2$

- radiative top decays can be generated with QED parton shower
- $t\bar{t} + 0, 1, 2\,\gamma$ MEs need to be merged (to avoid double counting)

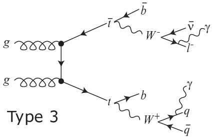
Relevance of radiative top decays for $t\bar{t}H(\gamma\gamma)$ searches



Type 1



Type 2



Type 3

LO Monte Carlo study [LH2005, hep-ph/0604120]

- inclusive $\sigma(\ell\nu jjb\bar{b}\gamma\gamma)$ dominated by Type 2+3
- # of events/100 fb^{-1} for $t\bar{t}H(\gamma\gamma)$ selection with stringent γ-hardness+isolation cuts and $|m_{\gamma\gamma} - m_H| < 1.5$ GeV

m_H [GeV]	120	130	140
$t\bar{t}H(\gamma\gamma)$	13.5	13.1	9.5
$t\bar{t}\gamma\gamma$ Type 1	0.38	0.48	0.53
$t\bar{t}\gamma\gamma$ Type 2	0.5	0.3	0.5
$t\bar{t}\gamma\gamma$ Type 3	0.5	<0.5	<0.5

$\Rightarrow$ radiative top decays still dominant

Implications on shapes and acceptance efficiencies deserve detailed NLO studies

Summary and Outlook

Theory precision for $t\bar{t}H$ and backgrounds

- crucial for measurements of $t\bar{t}H$ rate and coupling
- main priority: multi-particle backgrounds ($t\bar{t}$+jets, $t\bar{t}$+b-jets, $t\bar{t}V$+jets,...)

Recent theory progress

- powerful automated NLO MC tools
- lot of results for $t\bar{t}H$ signal (soft resummation, NLO EW, off-shell effects)
- all backgrounds available at NLO+PS level but not yet optimally understood

Sophisticated MC simulations and experimental analyses

- solid understanding of matching/merging/shower uncertainties non-trivial
- precision MC simulations in ATLAS/CMS require theory guidance

To follow/contribute to ongoing $t\bar{t}H$ HXSWG studies

⇒ `https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGTTH`

⇒ subscribe e-group mailing list `lhc-higgs-xsbr-tth`