Precise predictions for $t\bar{t}H(b\bar{b})$ backgrounds with Sherpa+OpenLoops

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based on

F. Cascioli, P. Maierhöfer and S.P.
PRL **108** (2012) 111601 [arXiv:1111.5206]

and

F. Cascioli, P. Maierhöfer, N. Moretti, S. P. and F. Siegert
arXiv:1309.5912

RADCOR 2013, Lumley Castle, 24 September 2013

$$\boxed{\text{Outline of the talk}}$$

(A) General remarks on OpenLoops

(B) NLO matching for $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ with massive b-quarks

NLO Revolution and Automation

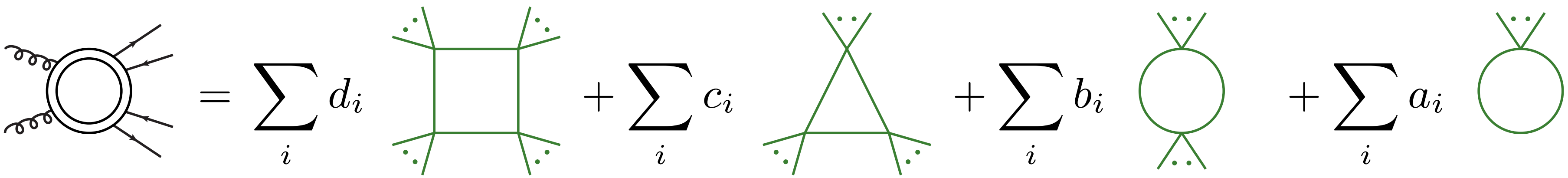
NLO calculations for $2 \to 4(5,6)$ processes at the LHC

- many recent results (2009-2013): $jjjj$, $\mathrm{W}+5j$, $\mathrm{Z}+4j$, $\mathrm{WW}jj$, $\mathrm{WZ}jj$, $\mathrm{W}\gamma\gamma j$, $\gamma\gamma jj$, $\mathrm{WWb\bar{b}}$, $\mathrm{b\bar{b}b\bar{b}}$, $\mathrm{t\bar{t}b\bar{b}}$, $\mathrm{t\bar{t}}jj$, $\mathrm{t\bar{t}t\bar{t}}$, $\mathrm{t\bar{t}H}j$, $\mathrm{H}jjj$,...
- *multi-particle* processes increasingly important at high energy and luminosity
  - $\Rightarrow$ more processes: especially interesting at the technical frontier
  - $\Rightarrow$ more “details”: matching, merging, NLO decays (t,W,Z), NLO EW,...

NLO automation (indispensable)

- many new NLO tools: `CutTools`, `Samurai`, `FormCalc`, `HELAC-NLO`, `MadLoop`, `GoSam`, `BlackHat`, `NGluon`, `Collier`, `Recola`
- lot of MC progress (matching and merging): `aMC@NLO`, `POWHEG`, `Sherpa`,...

OpenLoops+Sherpa

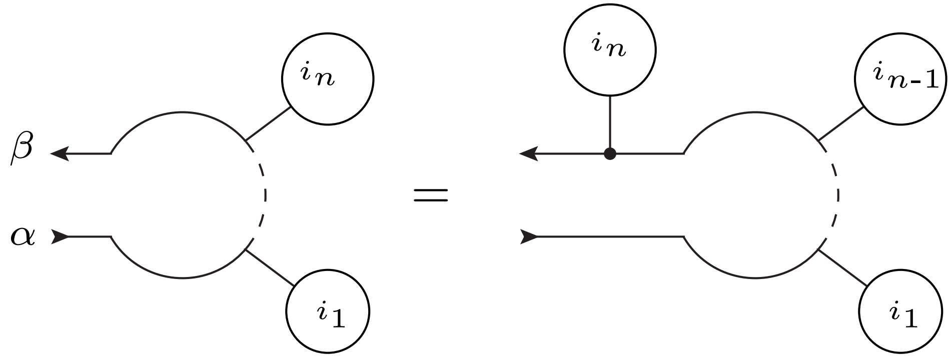


OpenLoops [Cascioli, Maierhöfer, S.P., PRL **108** (2012) 111601]

- fully automated loop-amplitude generator
- conceived to break **multi-particle** bottlenecks (fast, numerically stable, flexible)
- interfaced to `Collier` library [Denner, Dittmaier, Hofer] for tensor integrals (powerful!)
- NLO QCD for $2 \to 2, 3, 4$ SM processes

Sherpa2.0 [Hoeche, Hoeth, Krauss, Schoenherr, Schumann, Siegert, Zapp]

- fully automated interface to `OpenLoops`
- automated matching (MC@NLO) and merging of jet multiplicities (MEPS@NLO)

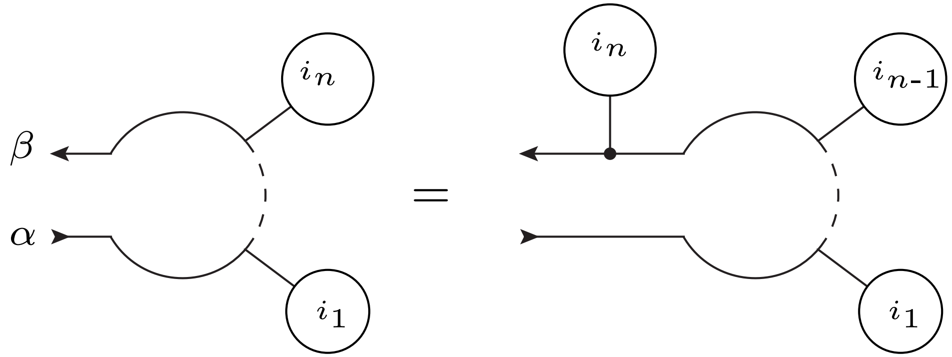


$\boxed{\text{OpenLoops recursion}}$

$$\sum_{r=0}^{n} \mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_n)\, q^{\mu_1}\ldots q^{\mu_r} \;=\; \left(Y^{\beta}_{\gamma\delta} + q^{\nu}\, Z^{\beta}_{\nu;\gamma\delta}\right) \sum_{r=0}^{n-1} \mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_{n-1})\, q^{\mu_1}\ldots q^{\mu_r}$$

Cut-open loops can be built by recursively merging tree-like objects

- can recycle conventional tree generators (Helac, Madgraph, ...)
- but efficient formulation requires loop-momentum *functional* dependence!

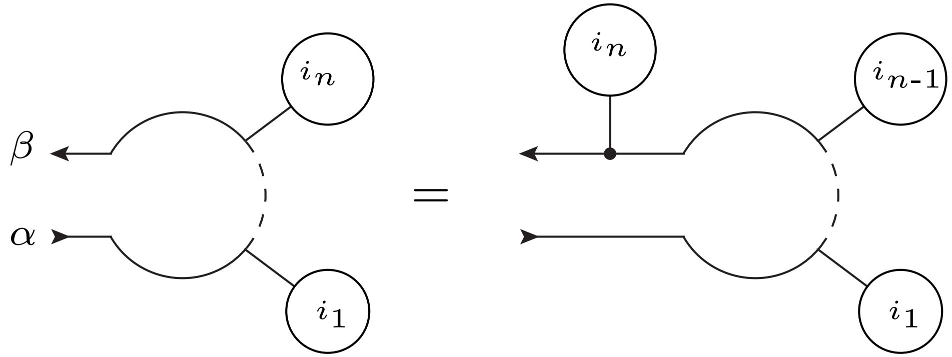


OpenLoops recursion

$$\sum_{r=0}^{n} \mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_n)\; q^{\mu_1}\ldots q^{\mu_r} \;=\; \left(Y^{\beta}_{\gamma\delta} + q^{\nu}\; Z^{\beta}_{\nu;\gamma\delta}\right)\; \sum_{r=0}^{n-1} \mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_{n-1})\; q^{\mu_1}\ldots q^{\mu_r}$$

Handles building blocks as *polynomials* in the loop momentum q

- recursive *numerical* construction of (symmetrised) polynomial coefficients
- universal kernels dictated by Feynman rules ⇒ automated and flexible
- inspired by Dyson-Schwinger formulation [van Hameren '09] but diagrammatic



OpenLoops recursion

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Works with two alternative reductions

(A) **Tensor-integral reduction** [Denner/Dittmaier '05] **avoids instabilities** (Gram-determinant expansions)

(B) **OPP reduction** [Ossola, Papadopolous, Pittau '07] is based on numerical evaluations at multiple q-values: **huge speed-up exploiting** $\mathcal{N}_{\mu_1\ldots\mu_r}(\mathcal{I}_n)$!

Technical performance wrt (fast) computer-algebraic approach

- event faster
- 2–3 orders-of-magnitude improvements in code-generation time and compactness

more details in talk by P. Maierhöfer

$\boxed{\text{First Pheno applications of Sherpa+OpenLoops}}$

(A) NLO merging of $ll\nu\nu$+jets production talk by P. Maierhöfer

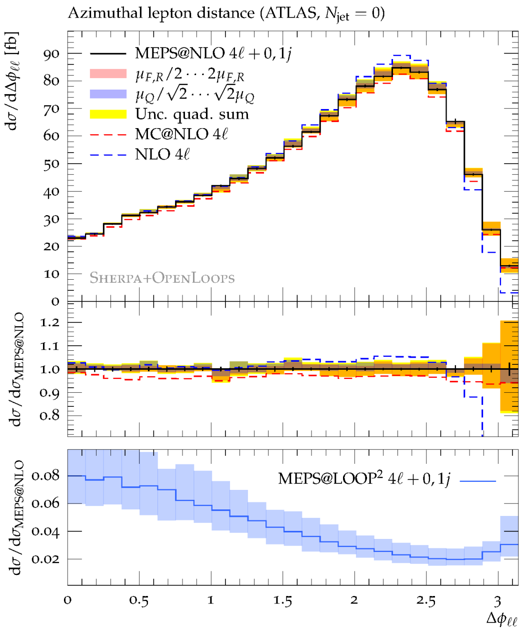
(B) NLO $\mathrm{W^+W^-b\bar{b}}$ production with $m_\mathrm{b} > 0$ talk by S. Kallweit

(C) MC@NLO $\mathrm{t\bar{t}b\bar{b}}$ production with $m_\mathrm{b} > 0$ this talk

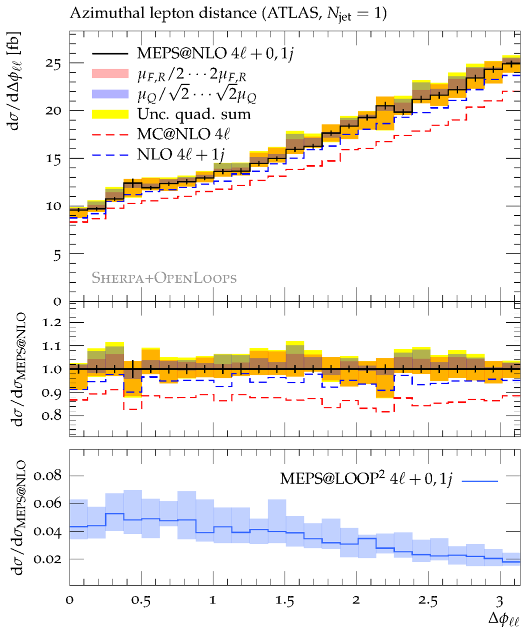
(A) NLO merging of $ll\nu\nu+$ jets production

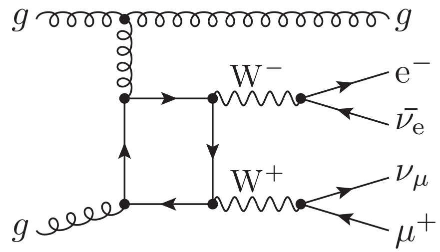
talk by P. Maierhöfer

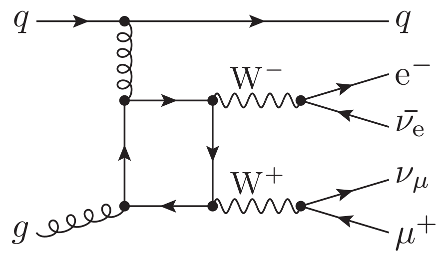
0-jet bin



1-jet bin







Irreducible background to ATLAS/CMS $\mathrm{H} \to \mathrm{WW}^*$ analysis

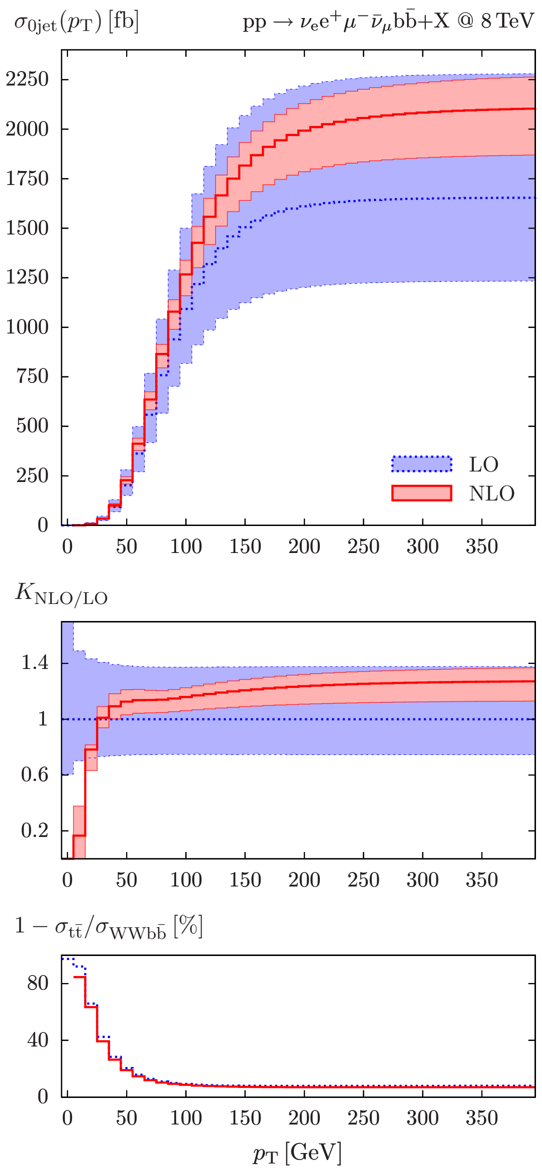
- NLO merged predictions for 0- and 1-jet bins
- merging of squared quark-loop contributions $gg \to ll\nu\nu + 0, 1$ jets including quark channels

$\Rightarrow$ 1–2% theory uncertainty for data-driven WW determination

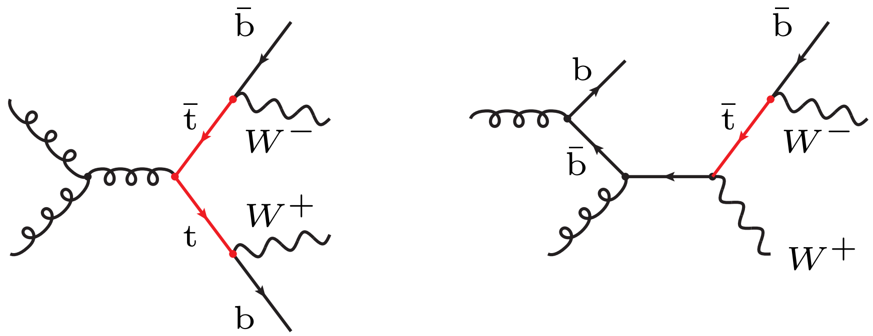
(B) NLO $W^+W^-b\bar{b}$ production with $m_b > 0$

talk by S. Kallweit

$$\sigma_{WWbb}(p_T < p_T^{veto})$$



$t\bar{t}$ and tW interference

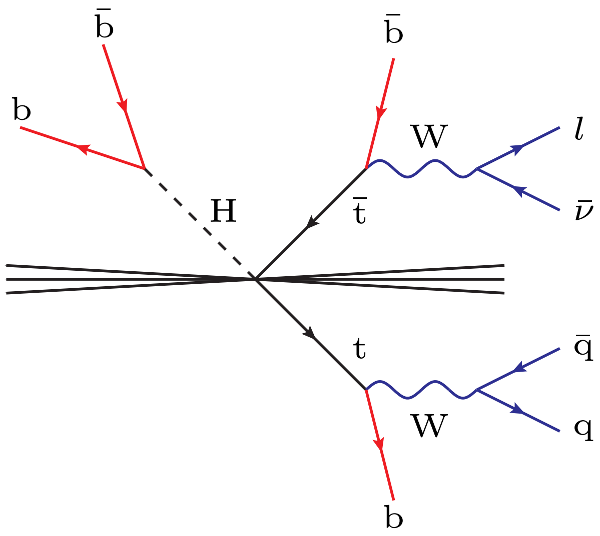


Full b-quark phase space thanks to $m_b > 0$

- can study top-background to $H \to WW$ in 0- and 1-jet bins
- consistent $t\bar{t}$ and Wt combination with interference at NLO
- interesting interplay of large NLO and off-shell effects in presence of jet veto!

(C) MC@NLO $\mathrm{t\bar{t}b\bar{b}}$ production with $m_{\mathrm{b}} > 0$ this talk

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



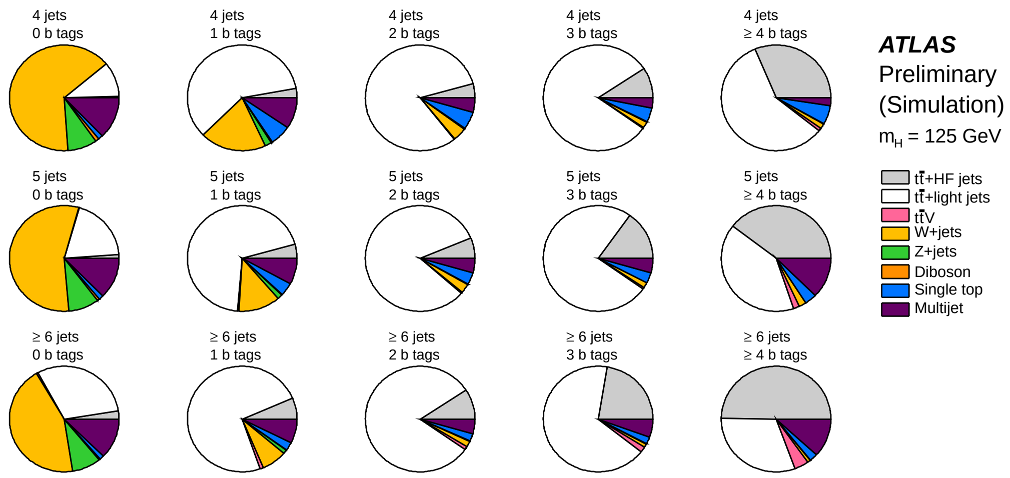
- complicated $b\bar{b}b\bar{b}\ell\nu jj$ final state hampers $H \to b\bar{b}$ peak reconstruction
- huge background contamination ($S/B \sim 10\%$)
- $5.8(5.2) \times \sigma^{\mathrm{SM}}_{t\bar{t}H}$ excluded at 95% CL with $5 + 5(20)\mathrm{fb}^{-1}$

  (CMS HIG-12-035, CMS PAS HIG-13-019)

No significant improvement with statistics: dominated by 50% theory uncertainty attributed to (LO MC) $t\bar{t}b\bar{b}$ background

$t\bar{t}+$ light-, c- and b-jets backgrounds

Sophisticated data-driven background determination



ATLAS-CONF-2012-135

- data binned according to (N_j, N_b)
- fit to MC using BDT
- decent $t\bar{t}$+jets measurement
- poor $t\bar{t}b\bar{b}$ separation from signal

Likely to improve with matrix element methods, boosted jets, . . .
but $t\bar{t}H(b\bar{b})$ interpretation will require robust theoretical background uncertainties for:

- extrapolations across different N_j and N_b multiplicities
- shapes

Existing NLO results

NLO(+PS) predictions for $\mathrm{t\bar{t}} + 1$-jet

- $\mathrm{t\bar{t}} + 1$ jet at NLO [Dittmaier, Uwer, Weinzierl '07/'09; Melnikov, Schulze '10]
- $\mathrm{t\bar{t}} + 1$ jet PowHeg matching [Alioli, Moch, Uwer '12]
- $\mathrm{t\bar{t}} + \leq 1$ jets MEPS@NLO merging [Hoeche, Huang, Luisoni, Schoenherr, Winter '13]

NLO predictions for $\mathrm{t\bar{t}} + 2$-jets

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

Towards NLO+PS for $\mathrm{t\bar{t}} + 2$ b-jets

- PowHeg matching (first emission) for $\mathrm{t\bar{t}b\bar{b}}$ with massless b-quarks based on `HELAC-NLO`+ `PowHegBox` [Kardos, Trocsanyi '13]
- MC@NLO matching for $\mathrm{t\bar{t}b\bar{b}}$ with massive b-quarks [Cascioli, Maierhoefer, Moretti, S. P., Siegert '13]

$\Rightarrow$ crucial for 80% (LO) to 20% (NLO) reduction of scale uncertainty in exp. analysis

5F vs 4F scheme for $t\bar{t}b\bar{b}$ production

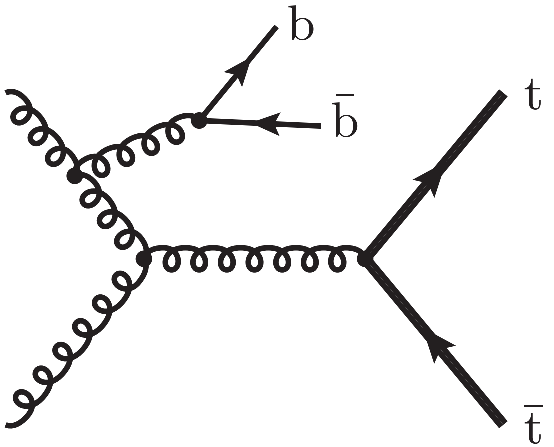
	5F scheme	4F scheme
b-quark mass	$m_b = 0$	$m_b > 0$
b-quark FSR	resummed via PS $g \to b\bar{b}$	idem (with $m_b > 0$)
b-quark ISR	resummed via PDF+PS (backward) evolution	from PDF gluons via fixed-order $g \to b\bar{b}$
$\ln(\mu_R/m_b)$ in α_S^4	resummed	at one loop
ttb final states	not possible at parton level (collinear b-quarks sing.)	possible (collinear sing. regulated by m_b)
collimated $b\bar{b}$ pairs	requires $t\bar{t}$+g MEs + $g \to b\bar{b}$ PS splittings	possible in NLO $t\bar{t}b\bar{b}$

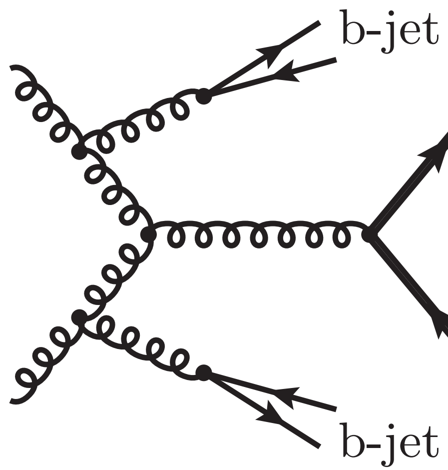
Needed parton-level ingredients for complete $t\bar{t}$+b-jets simulation

- 4F scheme permits to cover full b-quark PS $\Rightarrow$ MC@NLO $t\bar{t}b\bar{b}$ simulation provides complete description
- 5F scheme requires mix of showered $t\bar{t}$+jets *and* $t\bar{t}b\bar{b}$ NLO MEs

Matching NLO $t\bar{t}b\bar{b}$ to PS in 4F scheme gives access to new $t\bar{t} + 2$b-jets production mechanisms

- double (rather) collinear $g \to b\bar{b}$ splittings
- (surprisingly) important impact on $t\bar{t}H(b\bar{b})$ analysis
- first splitting NLO accurate in 4F scheme (only PS splittings in 5F scheme)





Sherpa formulation of MC@NLO matching [Höche, Krauss, Schönherr, Siegert '11]

Modified NLO formula (first emission)

$$\langle\mathcal{O}\rangle = \int \mathrm{d}\Phi_B \Big[B(\Phi_B) + V(\Phi_B) + I(\Phi_B)\Big] U(t_0, \mu_Q^2)$$
$$+ \int \mathrm{d}\Phi_R \Big[R(\Phi_R) - \sum_{ijk} D_{ijk}(\Phi_R)\theta(\mu_Q^2 - t)\Big] \mathcal{O}(\Phi_R).$$

Integrated subtraction terms

$$I(\Phi_B) = \sum_{ijk} \int \mathrm{d}\Phi_{R|B} D_{ijk}(\Phi_R)\theta(\mu_Q^2 - t),$$

First emission of CS diple shower ($\Phi_B \to \Phi_R$ inverse mapping)

$$U(t_0, \mu_Q^2) = \Delta(t_0, \mu_Q^2)\mathcal{O}(\Phi_B) + \sum_{ijk} \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_{R|B} \frac{D_{ijk}(\Phi_R)}{B(\Phi_B)} \Delta(t, \mu_Q^2)\mathcal{O}(\Phi_R),$$

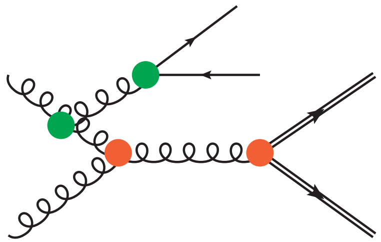
Resummation scale μ_Q (parton-shower starting scale) restricts shower to meaningful region and its variations provide systematic shower-uncertainty estimates

Choice of μ_{R}, μ_{F} and μ_Q

Scale choice in $\alpha_S^4(\mu^2)$ is crucial

- widely separated scales $m_{\mathrm{b}} \leq Q_{ij} \lesssim m_{\mathrm{t\bar{t}b\bar{b}}}$ can generate huge logs

Dynamical "BDDP" scale [Bredenstein, Denner, Dittmaier, S. P. '10] guarantees good convergence by adapting to b-jet p_{T}



$$\alpha_S^4(\mu_{\mathrm{BDDP}}^2) = \alpha_S^4\left(m_t\sqrt{p_{\mathrm{T},b1}p_{\mathrm{T},b2}}\right) \simeq \alpha_S^2(m_t^2)\alpha_S(p_{\mathrm{T},b1}^2)\alpha_S(p_{\mathrm{T},b2}^2)$$

Natural generalisation (for $p_{\mathrm{T}} \to 0$ region)

$$\mu_{\mathrm{R}}^4 = \prod_{i=\mathrm{t},\bar{\mathrm{t}},\mathrm{b},\bar{\mathrm{b}}} E_{\mathrm{T},i} = \prod_{i=\mathrm{t},\bar{\mathrm{t}},\mathrm{b},\bar{\mathrm{b}}} \sqrt{m_i^2 + p_{\mathrm{T},i}^2}$$

Factorisation and Resummation scales (available phase space for QCD emission)

$$\mu_{\mathrm{F}} = \mu_Q = \frac{1}{2}(E_{\mathrm{T,t}} + E_{\mathrm{T},\bar{\mathrm{t}}})$$

ttb and $ttbb$ analyses

Top decays

- spin-correlated top decays fully automated (at LO) in Sherpa
- stable top quarks in order to focus on the b-jets arising from QCD dynamics, which are more subtle (dynamical scale choices, 4F/5F scheme issues, $g \to b\bar{b}$ splittings)

b-jet counting

- any jet containing one *or more* b-quarks is considered a b-jet (possible only with $m_{\mathrm{b}} > 0$)
- we classify events according to the number N_{b} of QCD b-jets with

$$p_{\mathrm{T}} > 25\,\mathrm{GeV}, \qquad |\eta_b| < 2.5$$

- we perform a ttb ($N_{\mathrm{b}} \geq 1$) and a $ttbb$ ($N_{\mathrm{b}} \geq 2$) analysis, plus an extra $\mathrm{t\bar{t}b\bar{b}}$ analysis in the signal region $m_{\mathrm{bb}} > 100\,\mathrm{GeV}$.

NLO corrections to *ttb* and *ttbb* cross sections

	ttb	ttbb	ttbb($m_{\mathrm{bb}} > 100$)
σ_{LO}[fb]	$2547^{+71\%+14\%}_{-37\%-11\%}$	$463.9^{+66\%+15\%}_{-36\%-12\%}$	$123.7^{+62\%+17\%}_{-35\%-13\%}$
σ_{NLO}[fb]	$3192^{+33\%+4.6\%}_{-25\%-4.9\%}$	$557^{+28\%+5.6\%}_{-24\%-4.0\%}$	$141^{+25\%+8.6\%}_{-22\%-3.8\%}$
$\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$	1.25	1.20	1.14

Good perturbative convergence (also for *ttb*)

- K-factors and uncertainties rather independent of selection
- +20% correction from b-quark contribution to α_{S} running in 4F scheme ($K \simeq 1$ in 5F scheme)
- 20–30% residual uncertainty dominated by μ_{R} variations

M@NLO corrections wrt NLO in *ttb* and *ttbb* cross sections

	ttb	ttbb	ttbb$(m_{\mathrm{bb}} > 100)$
$\sigma_{\mathrm{MC@NLO}}[\mathrm{fb}]$	$3223^{+33\%+4.3\%}_{-25\%-2.5\%}$	$607^{+25\%+2.2\%}_{-22\%-2.8\%}$	$186^{+21\%+5.4\%}_{-20\%-4.7\%}$
$\sigma_{\mathrm{MC@NLO}}/\sigma_{\mathrm{NLO}}$	1.01	1.09	1.32
$\sigma^{\mathrm{2b}}_{\mathrm{MC@NLO}}[\mathrm{fb}]$	3176	539	145
$\sigma^{\mathrm{2b}}_{\mathrm{MC@NLO}}/\sigma_{\mathrm{NLO}}$	0.99	0.97	1.03

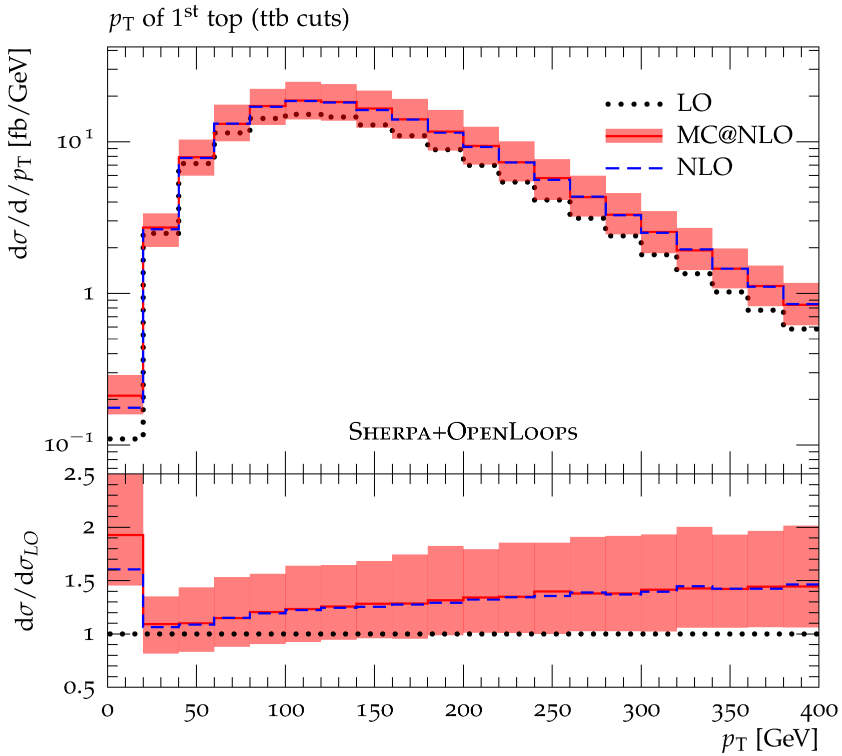
Nontrivial MC@NLO effects

- negligible(moderate) MC@NLO/NLO differences with standard *ttb*(*ttbb*) selections
- large MC@NLO effect ($\sim 30\%$) in Higgs-signal region of *ttbb*
- disappears in $\mathrm{MC@NLO}_{\mathrm{2b}}$, where $\mathrm{g} \to \mathrm{b\bar{b}}$ PS splittings are switched off! (see more details in distributions)
- μ_{R}, μ_{F} and μ_{Q} uncertainties similar as for NLO

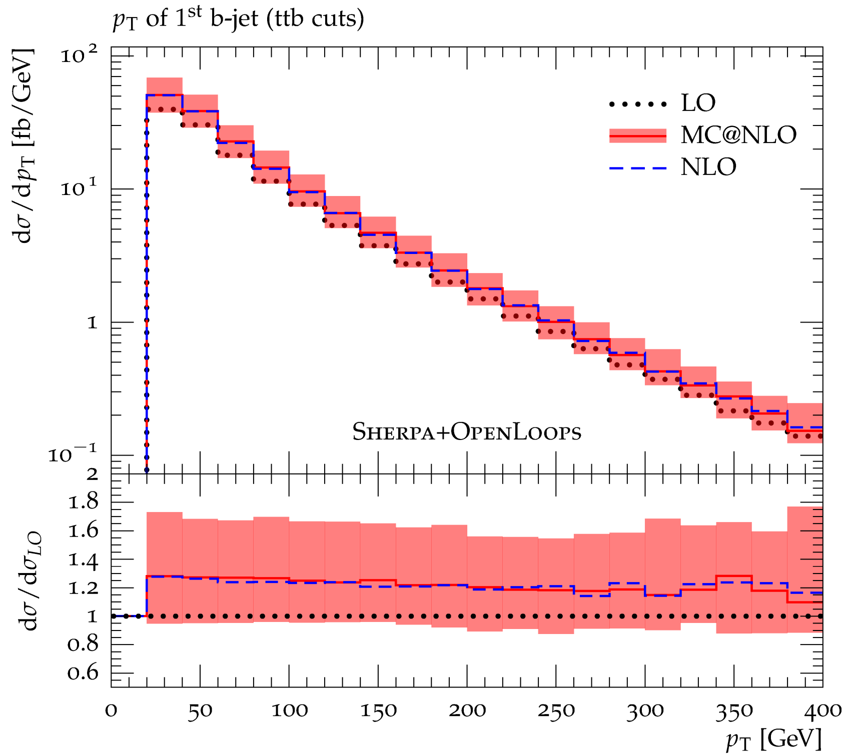
ttb final states with $N_b \geq 1$ QCD b-jets

Top-quark and b-jet distributions in the ttb analysis ($N_b \geq 1$)

$p_{\mathrm{T,t_1}}$



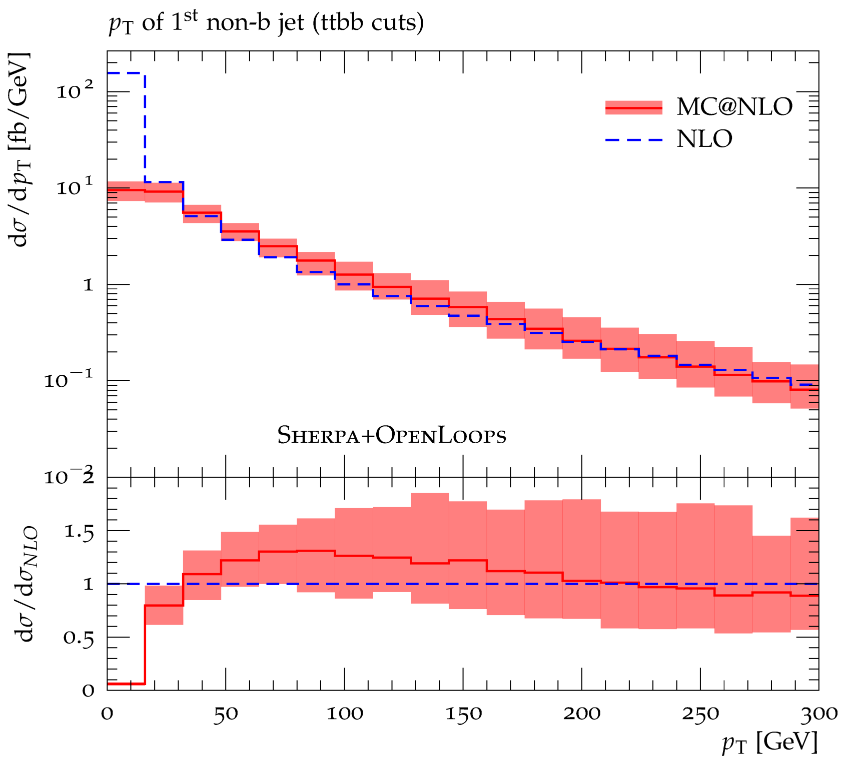
$p_{\mathrm{T,b_1}}$



- significant NLO shape correction to p_{T} of 1^{st} top
- excellent MC@NLO vs NLO agreement (suggesting reliable prediction within 4F scheme)

$ttbb$ final states with $N_b \geq 2$ QCD b-jets

First ligh-jet p_T distribution in the $ttbb$ analysis ($N_b \geq 2$)

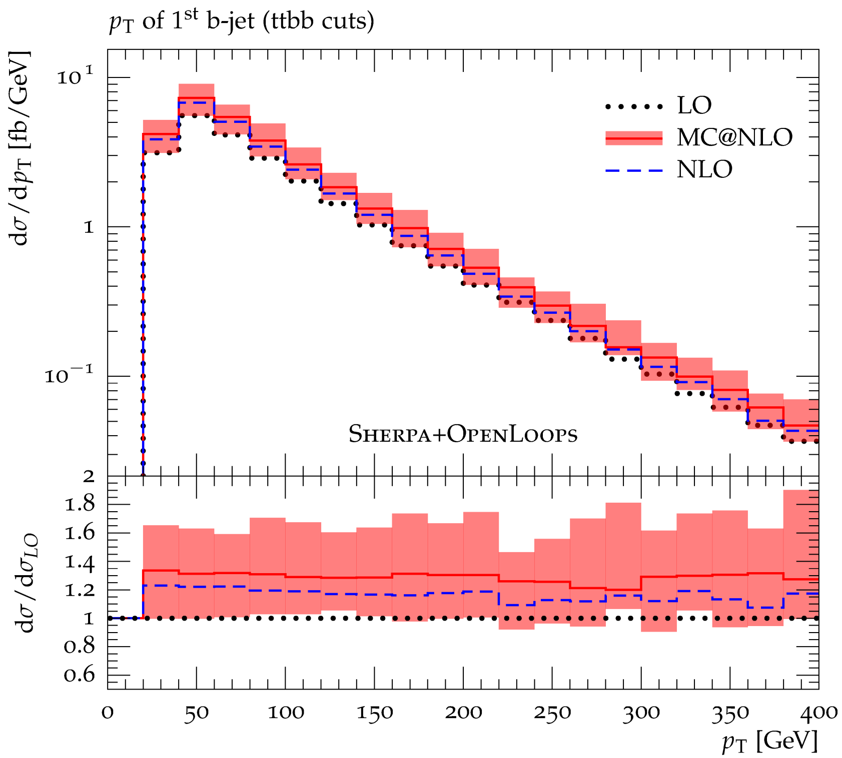


Consistent NLO+PS matching

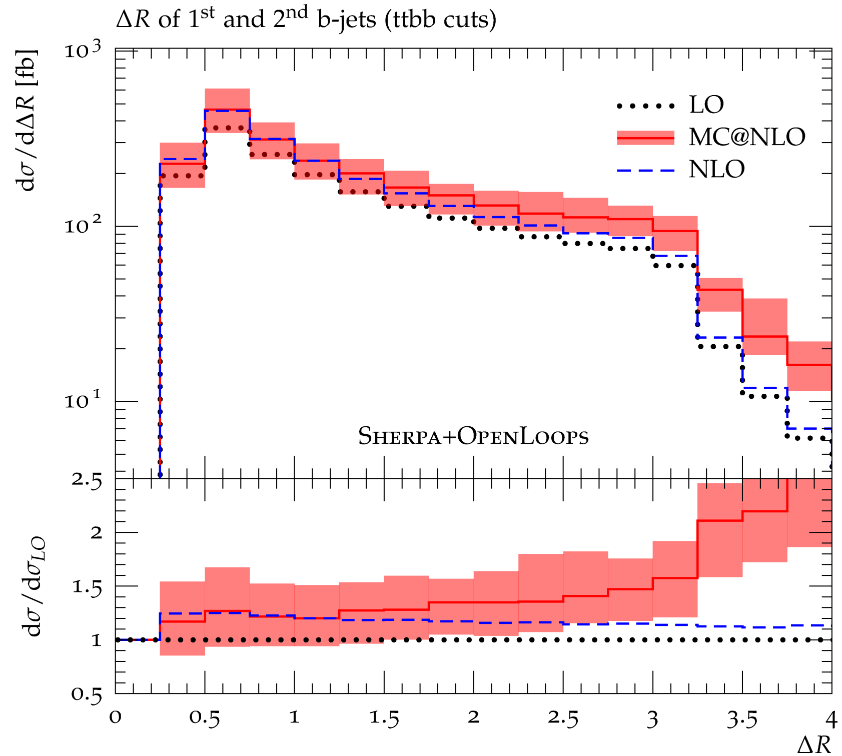
- MC@NLO vs NLO in good (5%) agreement in the tail
- Sudakov damping of NLO IR singularity $p_\mathrm{T} \to 0$
- significant Sudakov effects already at 50 GeV $\leftrightarrow$ intense multi-jet radiation
- MC@NLO correction of 30% at intermediate p_T is a order α_S^2 effect (depends on μ_R, μ_Q)

b-jet distributions in the *ttbb* analysis ($N_b \geq 2$)

$p_{\mathrm{T,b_1}}$



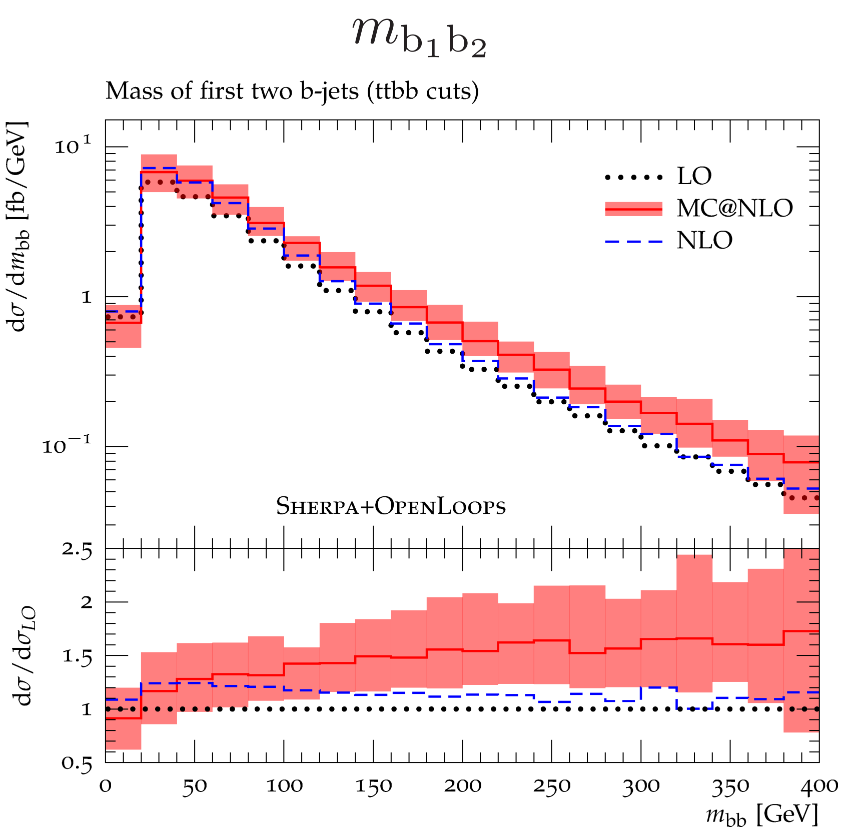
$\Delta R_{\mathrm{b_1 b_2}}$



Moderate MC@NLO excess wrt NLO

- rather independent of p_{T} of 1^{st} b-jet
- clearly enhanced at large $\Delta R_{\mathrm{b_1 b_2}}$ ...

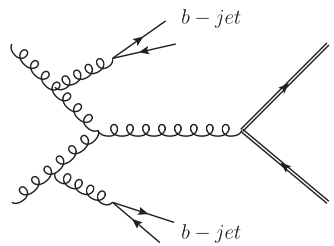
Invariant mass of first two b-jets in the *ttbb* analysis ($N_b \geq 2$)



MC@NLO excess grows with $m_{b_1 b_2}$

- reaching 30–40% at $\sim 125\,\mathrm{GeV}$
- largely exceeds $t\bar{t}H(b\bar{b})$ signal

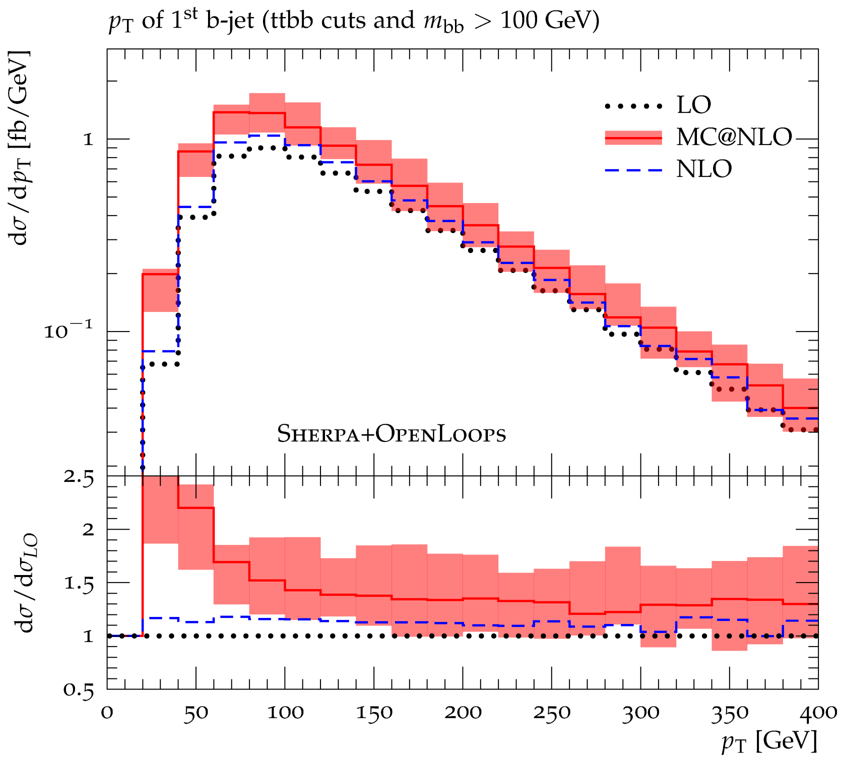
Consistent with double $g \to b\bar{b}$



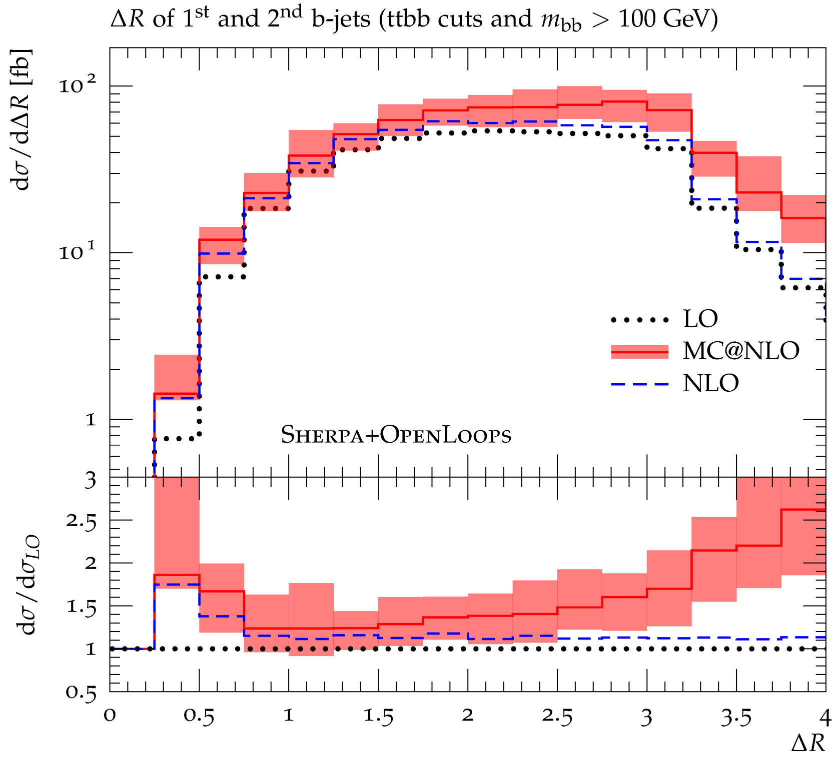
- collinear $g \to b\bar{b}$ probability does not decrease at large m_{gg}
- further distinctive kinematic features ...

b-jet distributions in the $ttbb$ analysis $(N_b \geq 2)$ with $m_{b_1b_2} > 100\,\mathrm{GeV}$

p_{T,b_1}



$\Delta R_{b_1b_2}$

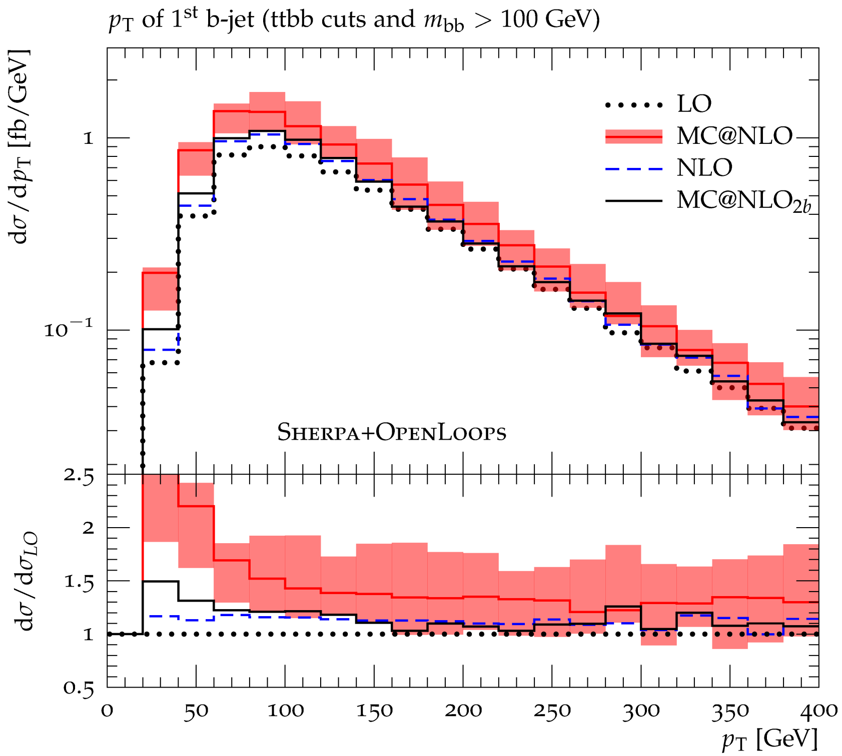


MC@NLO excess from back-to-back soft jets

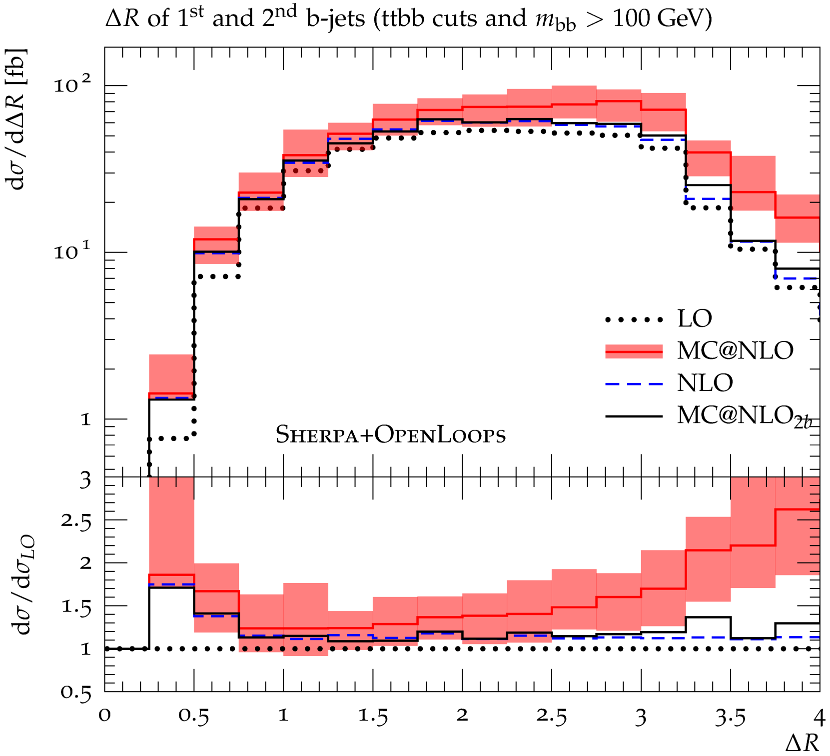
- $\Delta R \sim \pi$ and smallest possible p_T
- consistent with soft-collinear behaviour of parent gluon jets

b-jet distributions in the *ttbb* analysis ($N_b \geq 2$) with $m_{b_1 b_2} > 100\,\mathrm{GeV}$

p_{T,b_1}



$\Delta R_{b_1 b_2}$



Double $g \to b\bar{b}$ **splitting "smoking gun"**

- MC@NLO excess disappears when $g \to b\bar{b}$ PS splittings are switched off (MC@NLO$_{2b}$ agrees with NLO)
- additional evidence from various b-quark correlations

This changes the conventional $t\bar{t}b\bar{b}$ **hard-scattering picture ...**

Summary

NLO+PS predictions for $\mathrm{t\bar{t}b\bar{b}}$ production with $m_{\mathrm{b}} > 0$

- full b-quark phase space $\Rightarrow$ $\mathrm{t\bar{t}}+ \geq 1$ b-jets w.o. need of $\mathrm{t\bar{t}}$+jets MEs
- double $g \to b\bar{b}$ splittings important for $\mathrm{t\bar{t}H(b\bar{b})}$ analysis
  - NLO accuracy for first collinear $\mathrm{g} \to \mathrm{b\bar{b}}$ splitting
  - PS tuning important for second splitting

Sherpa+OpenLoops

- first real-life applications: $\mathrm{t\bar{t}b\bar{b}}$ and $\mathrm{W^+W^-b\bar{b}}$ (talk by S.Kallweit) with massive b-quarks; $\ell\ell\nu\nu$+jets (talk by P. Maierhöfer)
- demontrate feasibility of fully realistic simulations for nontrivial LHC analyses (multi-scale processes, off-shell particles, loop-induced processes, NLO matching and merging,. . .)