NLO+PS Simulations for Top Physics with OpenLoops

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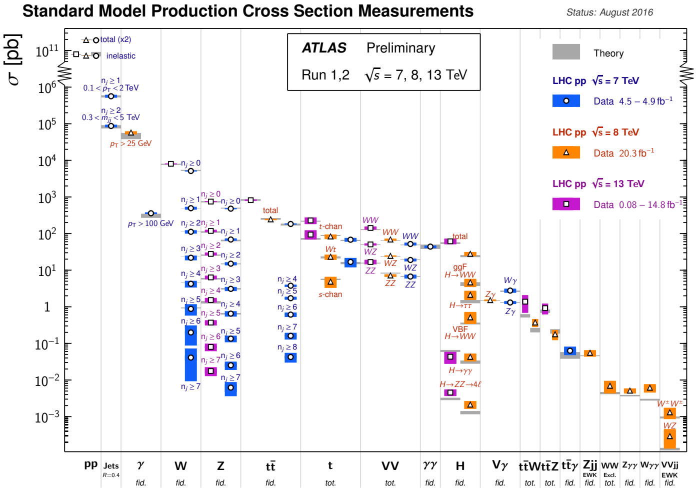
Outline

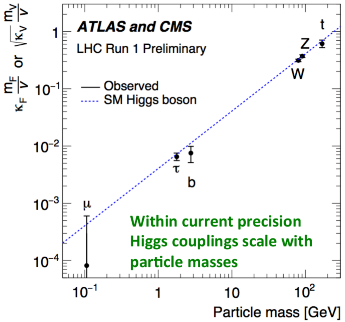
1. Introduction
2. The OpenLoops algorithm
3. NLO and NLO+PS
4. NLO+PS predictions for $pp \to t\bar{t}b\bar{b}$
5. NLO+PS predictions for $pp \to W^+W^-b\bar{b}$

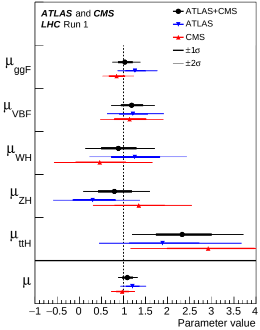
Success of LHC at Run 1+2



Data–theory consistency from milli-barn to femto-barn range

Success of the Standard Model





At present level of energy and precision

- SM promoted to realistic description of EW symmetry breaking
- M_H measurement turned the SM into a fully predictive theory

At higher precision and energy

- still lot of room to falsify the SM or verify it with more stringent tests (e.g. in $t\bar{t}H$)

Indirect BSM searches

EW precision tests at LHC [Farina et al, 1609.08157]

- Status of BSM searches suggests unexpected validity of SM up to

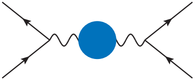
$$\Lambda_{\mathrm{BSM}} > 1\,\mathrm{TeV}$$

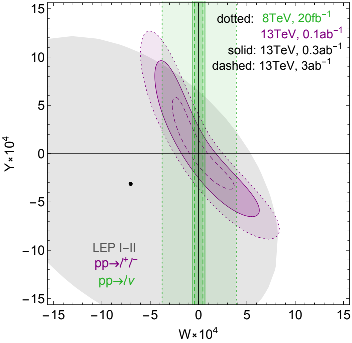
- For dimension-6 EFT operators that interfere with SM

$$\mathrm{BSM/SM} \sim E^2/\Lambda^2_{\mathrm{BSM}}$$

$\Rightarrow$ 10% precision at 1 TeV $\equiv$ 0.1% at LEP

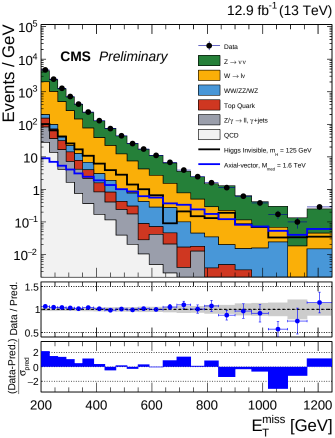
- High-mass DY measurements at LHC can improve on LEP bounds

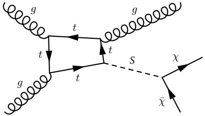




bounds on oblique parameters S, T, W, Y assuming 5% TH+EXP systematics

Direct BSM searches





- no large excesses/sharp bumps

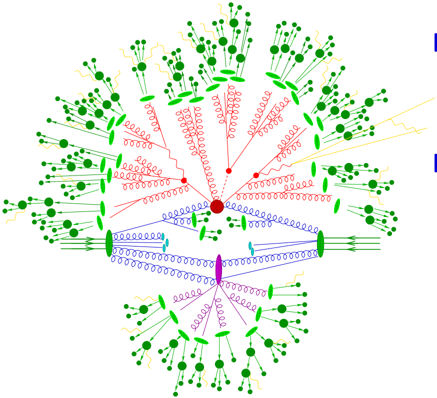
$\Rightarrow$ look for small or borad excesses $\sim$ SM-like signatures with large backgrounds

TH precision for SM backgrounds

- crucial for sensitivity of many searches
- needed for widest possible spectrum of signatures from EW to TeV scale
- including complex final states

Theoretical simulations of LHC collisions

$$\mathrm{d}\sigma \;=\; \mathrm{d}\sigma_{\mathrm{LO}} + \alpha_S\,\mathrm{d}\sigma_{\mathrm{NLO}} + \alpha_{\mathrm{EW}}\,\mathrm{d}\sigma^{\mathrm{EW}}_{\mathrm{NLO}} + \alpha_S^2\,\mathrm{d}\sigma_{\mathrm{NNLO}} \;+\; \ldots$$



High-energy scattering

- NLO QCD+EW and NNLO "revolutions"

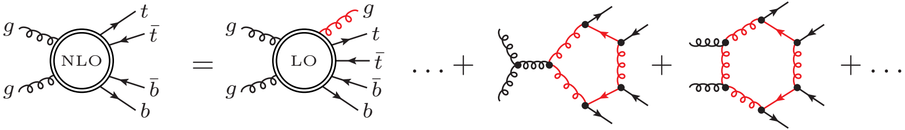
Parton-shower MC simulations

- matching to (N)NLO matrix elements
- multijet merging at NLO

More and more general and widely applicable algorithms

NLO revolution (last 10 years)

Multi-particle NLO calculations for $2 \to 4, 5, 6$ LHC processes



1-loop bottleneck:
$\mathcal{O}\left(10^3\right)$ diagrams $\Rightarrow$ gigantic algebraic expressions

Virtual 1-loop corrections

- complexity grows much faster than factorially with $N_{\text{particles}}$

$\Rightarrow$ various new methods: tensor reduction, on-shell method, OPP, ...

$\Rightarrow$ automated 1-loop generators (`CutTools`, `BlackHat`, `Collier`, `GoSam`, `HELAC 1-loop`, `MadLoop`, `NGluon`, `OpenLoops`, `Recola`, `Samurai`, ...)

Full NLO QCD automation (only limited by flexibility and efficiency of methods)

- automated NLO Monte Carlo frameworks (`Sherpa`, `Madgraph5_aMC@NLO`, `Munich`, `Powheg`, `Herwig`, `Whizard`, ...)

$\Rightarrow$ **vast range of multi-particle NLO predictions** ($pp \to 5j$, $W + 5j$, $Z + 4j$, $H + 3j$, $WW + 3j$, $WZjj$, $\gamma\gamma + 3j$, $W\gamma\gamma j$, $WWb\bar{b}$, $WWb\bar{b}H$, $WWb\bar{b}j$, $b\bar{b}b\bar{b}$, $t\bar{t}b\bar{b}$, $t\bar{t} + 3j$, $t\bar{t}t\bar{t}$, ...)

Outline

OpenLoops generator

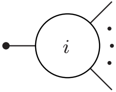
- fully automated generation of tree and loop amplitudes for NLO (with UV/IR CTs)
- conceived to break **multi-particle** bottlenecks (fast, stable, flexible)
- NLO QCD+EW for $2 \to 2, 3, 4\,(5)$ SM processes

Hybrid "tree–loop" algorithmic approach

- constructs process-dependent 1-loop ingredients with hybrid "tree–loop" approach
- numerical recursion based on diagrammatic building blocks

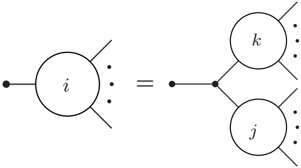
Tree recursion

Colour-stripped tree diagrams are built numerically in terms of sub-trees

$w^{\beta}(i) =$ 

$\beta \leftrightarrow$ off-shell line spin

and recursively merged by attaching vertices and propagators



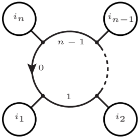
$$w^{\beta}(i) = \frac{X^{\beta}_{\gamma\delta}(i,j,k)}{p_i^2 - m_i^2}\, w^{\gamma}(j)\, w^{\delta}(k)$$

(sub-tree = individual topology with off-shell line $\neq$ off-shell current)

Completely generic and automatic

- **flexible** (only $\mathcal{L}_{\text{int}}$ dependent)
- **fast** (many diagrams share *common sub-trees*)
- **efficient colour bookkeeping** (colour factorisation and algebraic reduction)

Colour-stripped loop diagrams



$$= \int \frac{\mathrm{d}^D q\, \mathcal{N}(\mathcal{I}_n; q)}{D_0 D_1 \dots D_{n-1}} = \sum_{r=0}^{R} \mathcal{N}_{\mu_1 \dots \mu_r}(\mathcal{I}_n) \underbrace{\int \frac{\mathrm{d}^D q\, q^{\mu_1} \dots q^{\mu_r}}{D_0 D_1 \dots D_{n-1}}}_{\text{tensor integral}}$$

`OpenLoops` computes *symmetrised $\mathcal{N}_{\mu_1 \dots \mu_r}(\mathcal{I}_n)$ coefficients*

tensor-rank	R	0	1	2	3	4	5	6	7
# coeff. per diagram	$\binom{R+4}{4}$	1	5	15	35	70	126	210	310

$\underbrace{70 \quad 126 \quad 210}_{\text{6 particles}}$

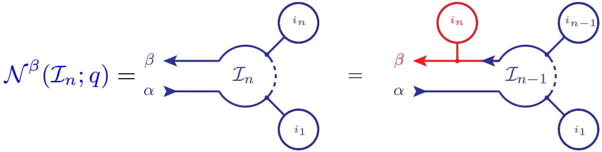
and applies **two alternative** methods for the **reduction to scalar integrals:**

(A) **Tensor-integral reduction** [Denner/Dittmaier '05]

(B) **OPP reduction** [Ossola, Papadopolous, Pittau '07] based on numerical evaluation of $\mathcal{N}(\mathcal{I}_n; q) = \sum \mathcal{N}_{\mu_1 \dots \mu_r}(\mathcal{I}_n)\, q^{\mu_1} \dots q^{\mu_r}$ at multiple q-values (**strong speed-up!**)

OpenLoops recursion [Cascioli, Maierhöfer, S.P '11]

Cut-open loops can be built by recursively attaching external sub-trees



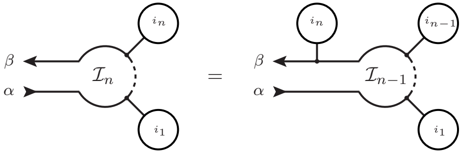
Handle building blocks of recursion as *polynomials* in the loop momentum q

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

and construct polynomial coefficients with "open loops recursion"

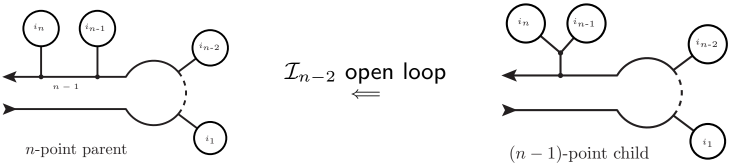
$$\mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_n) = \left[Y^{\beta}_{\gamma\delta}\,\mathcal{N}^{\gamma}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_{n-1}) + Z^{\beta}_{\mu_1;\gamma\delta}\,\mathcal{N}^{\gamma}_{\mu_2\ldots\mu_r;\alpha}(\mathcal{I}_{n-1})\right]\; w^{\delta}(i_n)$$

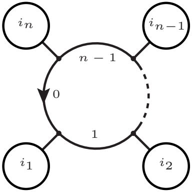
Key features



High flexibility and efficiency

- tree-like recursion with $\mathcal{L}$ **dependent kernels** $\Rightarrow$ fully automated and general
- complete **loop-momentum information** $\Rightarrow$ high reduction speed
- **parent-child relations** $\Rightarrow$ efficient recursion



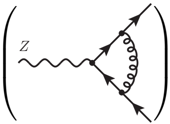


$$= \sum_{r=0}^{R} \underbrace{\mathcal{N}_{\mu_1\ldots\mu_r}(\mathcal{I}_n)}_{\text{in } D=4} \int \frac{\mathrm{d}^D q \; q^{\mu_1}\ldots q^{\mu_r}}{D_0 D_1 \ldots D_{n-1}}$$

Extra rational terms from $3 < \mu_1,\ldots,\mu_r \leq D-1$ coefficient components

$$R_2 = \sum_{\mu_1\ldots\mu_r=0}^{D-1} \mathcal{N}_{\mu_1\ldots\mu_r}\Big|_{D=4-2\varepsilon} T_{\mathrm{UV}}^{\mu_1\ldots\mu_r} \;-\; \sum_{\mu_1\ldots\mu_r=0}^{3} \mathcal{N}_{\mu_1\ldots\mu_r}\Big|_{D=4} T_{\mathrm{UV}}^{\mu_1\ldots\mu_r}$$

From catalogue of 2-, 3- and 4-point 1PI diagrams (depends only on model)



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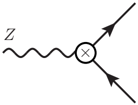


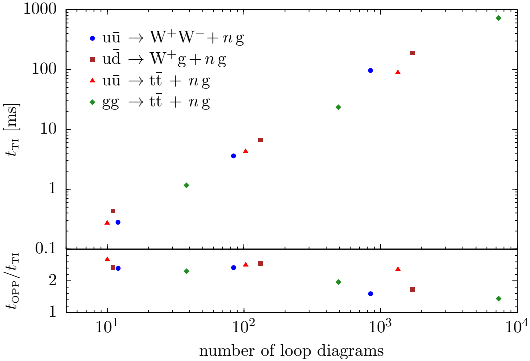
$$= -\frac{g_s^2}{16\pi^2}\frac{N_c^2-1}{2N_c}\gamma^\mu\left(g_{\mathrm{V}}^Z - g_{\mathrm{A}}^Z\gamma_5\right) \qquad \text{etc.}$$

[Draggiotis, Garzelli, Malamos, Papadopoulos, Pittau '09–'11; Shao, Zhang, Chao '11]

OpenLoops performance for $2 \to 2, 3, 4$ processes

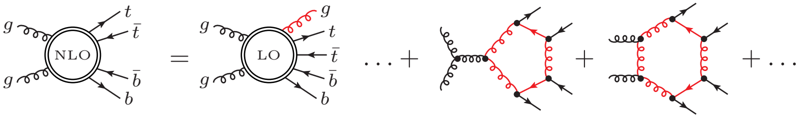
Orders of magnitude improvements for multi-particle amplitudes

- $\mathcal{O}(10^2\text{–}10^3)$ in code generation (code size and time for generation+compilation)
- $\mathcal{O}\left(10^2\right)$ in speed of amplitudes (wrt original OPP automation)



$\Rightarrow$ **large scale applicability to multi-particle processes**

OpenLoops 1.3 [Cascioli, Lindert, Maierhöfer, S.P.]



Automated generator of NLO QCD+EW matrix elements ($>$ 30K lines of code)

- public library with more than 100 LHC processes at `openloops.hepforge.org`
- Collier [Denner, Dittmaier, Hofer '16] or CutTools [Ossola, Papadopolous, Pittau '05] for reduction

Interface to multi-purpose Monte Carlo programs

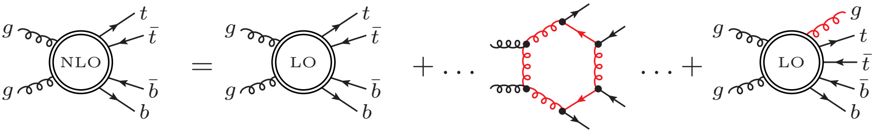
- Munich [Kallweit]
- Sherpa [Höche, Krauss, Schönherr, Siegert et al.]
- Powheg [Nason, Oleari et al.]
- Whizard [Kilian, Ohl, Reuter et al.]
- Herwig [Gieseke, Plätzer et al.]
- Geneva [Alioli, Bauer, Tackmann et al.]

Applications (entirely or largely automated)

- NLO QCD and NLO+PS for any $2 \to 2, 3, 4$ SM processes at LHC and ILC
- NLO EW for any $2 \to 2, 3, 4$ SM processes [Kallweit,Lindert,Maierhöfer,S. P.,Schönherr]
- NNLO QCD for $pp \to V, VV$ with Matrix [Grazzini, Kallweit, Rathlev, Wiesemann]

Outline

Structure of NLO Calculations



Born, virtual and real $2 \to n$ contributions ($|\mathcal{M}|^2$, flux factor and PDFs implicit)

$$\sigma_n^{\mathrm{NLO}} = \int \mathrm{d}\Phi_n \left[\mathcal{B}(\Phi_n) + \mathcal{V}(\Phi_n)\right] + \int \mathrm{d}\Phi_{n+1} \mathcal{R}(\Phi_{n+1})$$

Dipole subtraction method [Catani, Seymour '96 + Dittmaier '00 + Trocsanyi '02]

- factorisation and universality of sof/collinear (IR) singularities

$$\mathcal{R}(\Phi_{n+1}) \longrightarrow \mathcal{B}(\Phi_n) \otimes \mathcal{S}(\Phi_1) \qquad \mathcal{I} = \int \mathrm{d}\Phi_1 \mathcal{S}(\Phi_1) \quad \text{analytically}$$

- NLO formula suitable for numerical integration

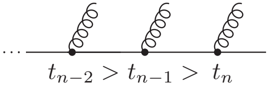
$$\sigma_n^{\mathrm{NLO}} = \int \mathrm{d}\Phi_n \left[\mathcal{B}(\Phi_n) + \mathcal{V}(\Phi_n) + \mathcal{B}(\Phi_n) \otimes \mathcal{I}\right] + \int \mathrm{d}\Phi_{n+1} \left[\mathcal{R}(\Phi_{n+1}) - \mathcal{B}(\Phi_n) \otimes \mathcal{S}(\Phi_1)\right]$$

Parton Showers in a Nutshell I

Idea: High-energy n-parton final state $\Rightarrow$ realistic multi-parton/hadron event

Factorisation of ordered emissions ($t = k_{\mathrm{T}}$)

$$\mathrm{d}\sigma_{n+1} \simeq \mathrm{d}\sigma_n \frac{\alpha_s}{2\pi} \frac{\mathrm{d}t_{n+1}}{t_{n+1}} \, \mathrm{d}z \, \mathrm{d}\phi P(z,\phi)$$

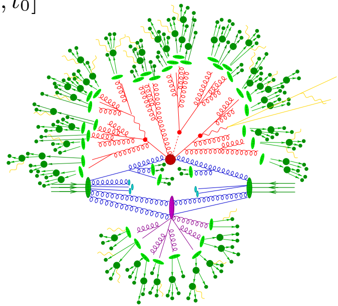


Sudakov FF evolution = no-emission probability in $[t, t_0]$

$$\frac{\mathrm{d}\Delta(t_0,t)}{\mathrm{d}\ln t} = \Delta(t_0,t) \frac{\alpha_s}{2\pi} \int \mathrm{d}z \, \mathrm{d}\phi P(z,\phi)$$

Resummation of large logarithms at small t

$$\Delta(t_0,t) = \exp\left\{ -\frac{\alpha_s}{2\pi} \int_t^{t_0} \frac{\mathrm{d}\tau}{\tau} \int \mathrm{d}z \, \mathrm{d}\phi P(z,\phi) \right\}$$



Parton Showers in a Nutshell II

First emission master formula

$$\sigma_n^{\mathrm{LO+PS}} = \int \mathrm{d}\Phi_n \mathcal{B}(\Phi_n) \Big\{ \underbrace{\Delta(\mu_Q^2, t_{\mathrm{IR}})}_{\text{no emission above } t_{\mathrm{IR}}} + \int_{t_{\mathrm{IR}}}^{\mu_Q^2} \frac{\alpha_s}{2\pi} \underbrace{\frac{\mathrm{d}t_1}{t_1} \int \mathrm{d}z\, \mathrm{d}\phi P(z,\phi)}_{\text{emission at } t_1} \underbrace{\Delta(\mu_Q^2, t_1)}_{\text{no emission above } t_1} \Big\}$$

Full shower evolution and unitarity

- iterated emissions $\mu_Q > t_1 > \cdots > t_n > \cdots > t_{\mathrm{IR}} \quad \Rightarrow \quad n \leq n_{\mathrm{partons}} < \infty$
- from resummation scale $\mu_Q \sim \hat{s}$ down to $t_{\mathrm{IR}} \sim 1\,\mathrm{GeV} \quad \Rightarrow$ hadronisation
- $\{\dots\} \equiv 1 \quad \Rightarrow$ inclusive LO cross section and uncertainty unchanged
- $\frac{\mathrm{d}t_n}{t_n}\Delta(t_{n-1}, t_n)$ regular at $t_n \to 0$

$\Rightarrow$ resummation of soft/collinear logs (in distributions at $p_{\mathrm{T}} \to 0$, etc.)

Sherpa Formulation of MC@NLO Matching I

Matching NLO calculations to PS with MC@NLO [Frixione, Webber '02]

- NLO accuracy + shower resummation w.o. double counting of 1$^{\text{st}}$ emission
- achieved by using shower kernels as NLO subtraction terms

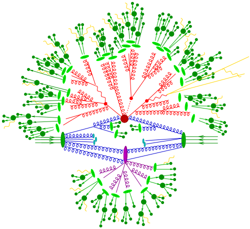
Sherpa shower ideally suited: splitting kernels = dipole subtraction terms!

$$\frac{\alpha_s}{2\pi}\,\frac{\mathrm{d}t}{t}\,\mathrm{d}z\,\mathrm{d}\phi P(z,\phi) \longrightarrow \theta(\mu_Q - t)\mathcal{S}(\Phi_1)\mathrm{d}\Phi_1 \qquad\qquad t = t(\Phi_1)$$

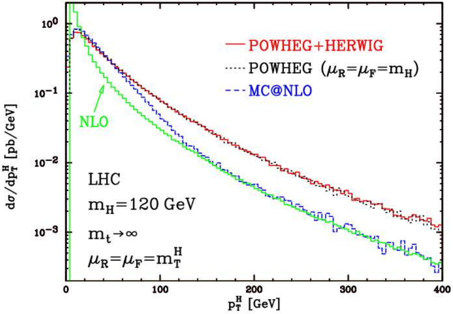
Sherpa's MC@NLO master formula [Höche, Krauss, Schönherr, Siegert '11]

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

- 1st emission shared by shower and $\mathcal{R}(\Phi_{n+1})$ ME
- NLO accuracy modulo $\mathcal{O}(\alpha_s^2)$ modifications
- continued with standard shower below t_1



Sherpa Formulation of MC@NLO Matching II



Accuracy of NLO+PS simulation

- NLO for observables with n jets
- LO for observables with $n+1$ jets
- PS for observables with $> n+1$ jets

Features of 1st MC@NLO emission

- $\mathcal{R}(\Phi_{n+1})$ ME dominates at high p_T
- $(\mathcal{B}+\mathcal{V}+\mathcal{I})\times$PS dominates at small p_T

$\Rightarrow$ regularises IR singularity of ME

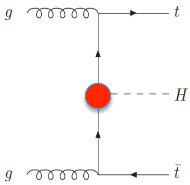
Uncertainties of $\mathcal{O}\left(\alpha_S^2\right)$

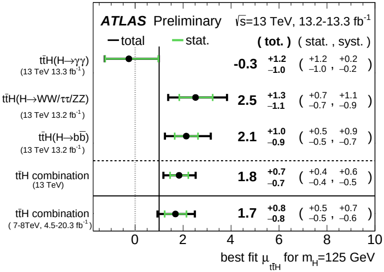
- standard μ_R, μ_F scale uncertainties
- nontrivial and potentially large effects dependent on resummation scale, matching method (MC@NLO vs POWHEG), parton shower, . . . (see later)

Outline

$t\bar{t}H$ at Run2

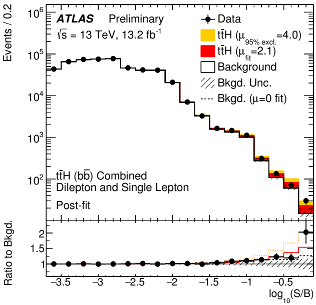
Measurement of λ_t $\Rightarrow$ test of m_t origin





Experimental status at 13 TeV

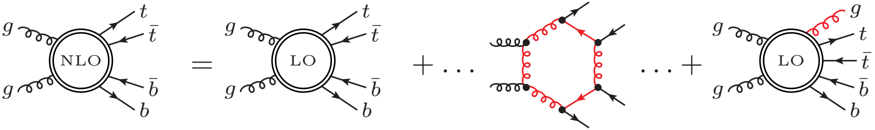
- 3.8 times higher $\sigma_{t\bar{t}H}$ wrt 8 TeV
- $\mu_{t\bar{t}H} \sim 2$ like in Run 1 but consistent with SM
- $H \to b\bar{b}$ and $H \to$ multi-leptons dominated by systematics (large backgrounds)



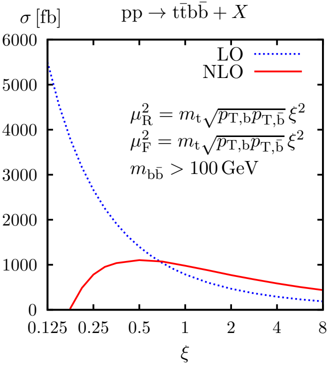
Theory priority: precision for backgrounds

- nontrivial processes: $t\bar{t}+$jets, $t\bar{t}V+$jets

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



$pp \to t\bar{t}b\bar{b}$ **at NLO** [Bredenstein, Denner, Dittmaier, S.P. '09–'10; Bevilacqua et al. '10]



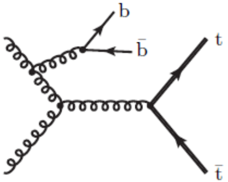
- $t\bar{t}b\bar{b}$ dominates $t\bar{t}H(b\bar{b})$ systematics
- $\sim 80\%$ LO uncertainty from $\sigma_{t\bar{t}b\bar{b}} \propto \alpha_S^4(\mu_R)$
- reduced to 20–30% at NLO
- NLO+PS mandatory for EXP analysis

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

Key features of $pp \to t\bar{t}b\bar{b}$

- 6 external coloured partons
- 34 LO diagrams, multiple scales from 5 to 500 GeV
- dominated by topologies with $g \to b\bar{b}$ splittings

$\Rightarrow$ collinear regions and m_b effects important



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 $t\bar{t}g$ ME+PS $\Rightarrow t\bar{t} + 0, 1, 2$ jets NLO merging

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**

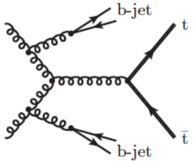
$\Rightarrow$ **NLO accuracy for any inclusive $t\bar{t}$+b-jet observable with ≥ 1 b-jets!**

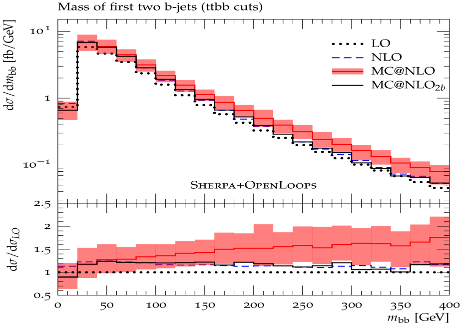
S–MC@NLO $t\bar{t}b\bar{b}$ at 8 TeV in 4F scheme [Cascioli et al '13]

Convergence of 4F scheme but unexpected MC@NLO enhancement

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

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





One $g \to b\bar{b}$ splitting from PS

⇒ TH uncertainties related to matching, shower and 4F/5F schemes crucial!

Tuned comparison of NLO+PS $t\bar{t}b\bar{b}$ simulations at 13 TeV

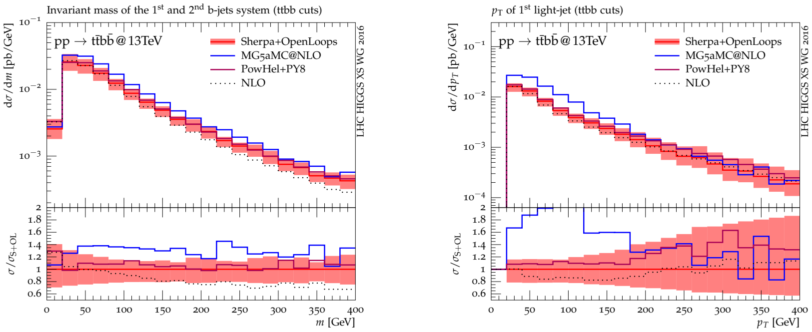
Different NLO+PS methods, showers, and m_b treatments

Tool	Matching	Shower	$m_b\,[\mathrm{GeV}]$	gencuts
SHERPA2.1+OPENLOOPS	SMC@NLO	Sherpa 2.1	4.75 (4F)	no
MG5_AMC@NLO	MC@NLO	Pythia 8.2	4.75 (4F)	no
POWHEL	Powheg	Pythia 8.2	0 (5F)	$p_{T,b} > 4.75\,\mathrm{GeV}$ $\frac{m_{bb}}{2} > 4.75\,\mathrm{GeV}$

Detailed setup

- HXSWG's Yellow Report 4 [arXiv:1610.07922]
- https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ProposalTtbb

$t\bar{t}b\bar{b}$ distributions with $\geq 2b$-jets



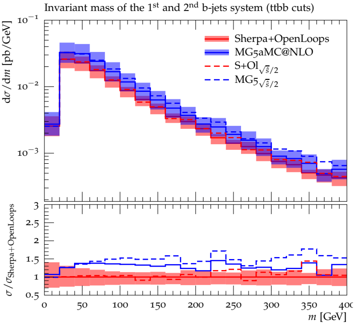
S-MC@NLO vs PowHel+PY8

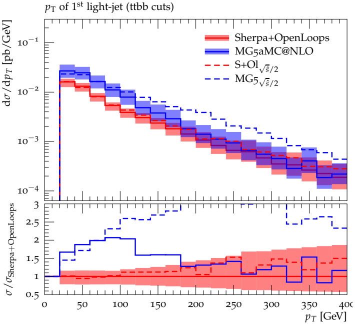
- well consistent also in observables that receive significant shower corrections
- confirmation of "double-splitting effects" (see e.g. m_{bb})

S-MC@NLO vs MG5aMC@NLO

- 40% enhancement of $t\bar{t}+2$b XS & sizable differences in NLO radiation pattern
- related to strong sensitivity to resummation scale (shower starting scale) in MG5 ...

Dependence on resummation scale μ_Q





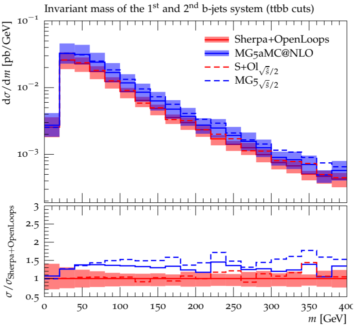
Nominal MG5_aMC and Sherpa+OpenLoops predictions in YR4

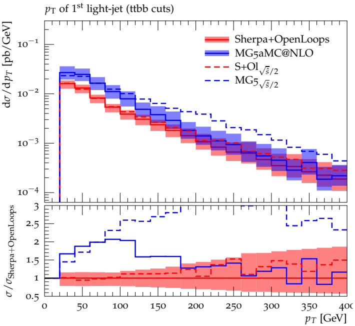
- MG5_aMC supports only $\mu_Q = f(\xi)\sqrt{\hat{s}}$ $\Rightarrow$ smearing function restricted to $0.1 < f(\xi) < 0.25$ to mimic recommended $\mu_Q = H_T/2$ implemented in Sherpa

New: μ_Q variations enhance the discrepancy

- $\mu_Q = \sqrt{\hat{s}}/2$ in Sherpa to mimic MG5_aMC default choice $0.1 < f(\xi) < 1$
- strong μ_Q-sensitivity of MG5_aMC $\Rightarrow$ much more pronounced deviations

Dependence on resummation scale μ_Q





General aspects and relevance of the problem

- understanding of c- and b-jet production via $g \to Q\bar{Q}$ splittings
- how to describe multi-scale process $(M_{tt} \sim 100 M_b)$ in NLO+PS framework (MC@NLO) with single scale μ_Q for 1st emission?
- relevant for various BSM searches and $Hc\bar{c}$ and $Hb\bar{b}$ production

$\Rightarrow$ **motivates $pp \to t\bar{t} + 3$ jets at NLO!**

$t\bar{t} + 3$ jets at NLO [Moretti, Höche, S.P., Maierhöfer, Siegert, ArXiv:1607.06934]

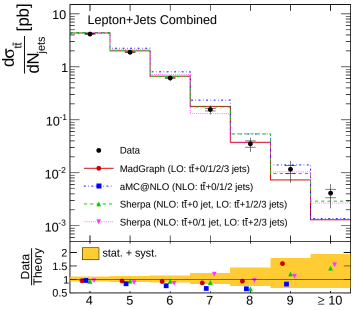
Technical challenge with Sherpa+OpenLoops

- fully coloured $2 \to 5$ process with heavy quarks and $\mathcal{O}\left(10^5\right)$ one-loop diagrams

partonic channel \ N	0	1	2	3
$gg \to t\bar{t} + N\,g$	47	630	9'438	152'070
$u\bar{u} \to t\bar{t} + N\,g$	12	122	1'608	23'835
$u\bar{u} \to t\bar{t}u\bar{u} + (N-2)\,g$	–	–	506	6'642
$u\bar{u} \to t\bar{t}d\bar{d} + (N-2)\,g$	–	–	252	3'321

Motivations for $t\bar{t}$+multijet precision

- omnipresent multijet+MET background
- benchmark for perturbative QCD and tools

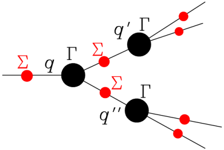


MINLO approach for multi-scale processes [Hamilton et al. '12]

Idea: NLO+NLL resummation via "shower-inspired" (CKKW) scale setting

(1) Interpretation of $t\bar{t}+N$ jet events throught k_T-jet clustering

- $t\bar{t}+M$ jet core process with $0 \leq M < N$ and $\mu_{\text{core}} = H_T/2$
- $N-M$ ordered jet emissions at $q_1 < q_2 < \ldots q_{\tilde{N}} < \mu_{\text{core}}$



(2) CKKW scale choice + Sudakov FFs for ext & int lines

$$[\alpha_S(\mu_R)]^{N+2} = [\alpha_S(\mu_{\text{core}})]^{2+M} \prod_{i=1}^{\tilde{N}} \alpha_S(q_i),$$

$$\Delta_a(q_{\min}, q_i) \quad \text{and} \quad \Sigma(q_k, q_l) = \frac{\Delta_a(q_{\min}, q_l)}{\Delta_a(q_{\min}, q_k)}$$

(3) Matching to NLO calculations

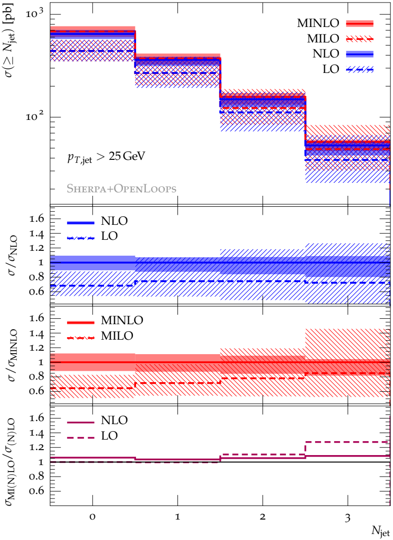
- $\mathcal{O}(\alpha_S)$ amputation of Sudakov FFs

MINLO automation in Sherpa and application to $t\bar{t}$+multi-jets [1607.06934]

- comparison vs hard scale $\mu = H_T/2$ [Blackhat+Sherpa] (good for V+multijets)

$\Rightarrow$ better picture of scale uncertainty wrt naive factor-2 variations

$t\bar{t} + 0, 1, 2, 3$ jet cross sections at 13 TeV



Setup

- stable tops and anti-k_T jets
- $R = 0.4$, $p_{T,j} > 25$ GeV, $|\eta_j| < 2/5$
- Ntuples allow decays & showering

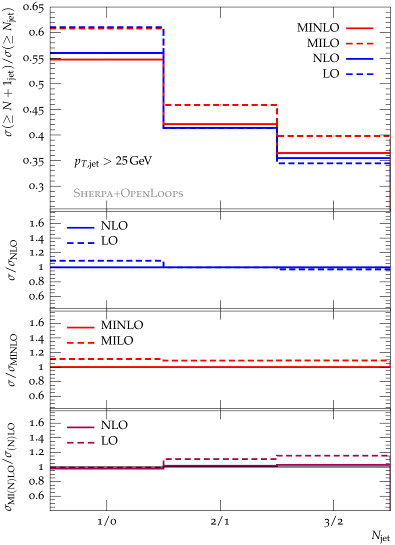
Plotted predictions and ratios

- LO/NLO at $\mu = H_T/2$
- MILO/MINLO
- MINLO/NLO

NLO corrections and uncertainties

- MINLO convergence better at large N_{jets} (also for larger $p_{T,j}$)
- $\sim$10% factor-2 variations in (MI)NLO
- 4–8% MINLO/NLO agreement!

Multijet scaling: $\sigma(t\bar{t} + n\,\text{jets})/\sigma(t\bar{t} + n - 1\,\text{jets})$



Motivation

- insights into multi-jet emission pattern
- cancellations of TH and EXP uncertainties

No clear scaling for $t\bar{t} + 0, 1, 2, 3$ jets

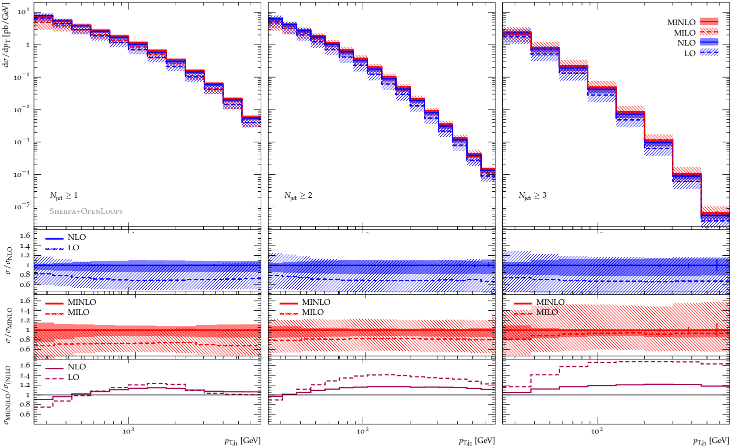
- similar to V+jets (scaling onset beyond 3 jets)
- related to delayed opening of qg and qq channels

Perturbative convergence

- NLO/LO and MINLO/MILO corrections of order 10%
- MINLO/NLO agreement of order 1%

$\Rightarrow$ benchmarks for precision tests!

n-th jet p_T for $pp \to t\bar{t} + n$ jets with $n = 1, 2, 3$



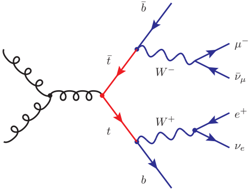
- **large NLO/LO but excellent MINLO convergence** at large N_{jets} and p_T
- In general: very good MINLO/NLO agreement and factor-2 scale variations consistent with TH uncertainty $\lesssim 10\%$

Outline

$W^+W^-b\bar{b}$ production at NLO [Cascioli,Kallweit,Maieröfer,S.P. '13]

Vast $t\bar{t}$ physics program at LHC (~ 900 pb at 14 TeV)

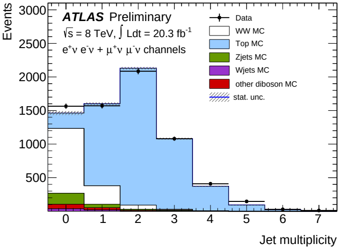
- precision SM tests and measurements (m_t, PDFs)
- leading background to leptons + jets + missing E_T discovery signatures (top partners, $H \to W^+W^-$, ...)
- $\sim$30 years of precision calculations: NLO+NNLL QCD, NLO EW, NNLO QCD (mostly $t\bar{t}$ production...)



Full description of $t\bar{t}$ prod$\times$decay

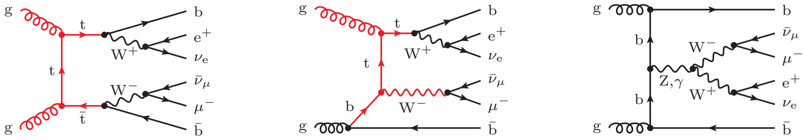
- decay kinematics crucial for any experimental measurement (cuts, m_t measurements,...)
- especially for jet veto

  (e.g. in $H \to WW$ analysis!)



$pp \to WWb\bar{b}$ at NLO QCD

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



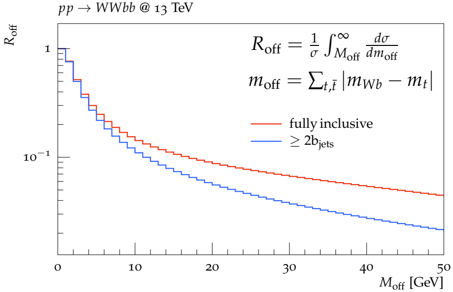
On-shell $t\bar{t}$ production×decay in NWA [Bernreuther et al. '04; Melnikov, Schulze '09]

$$\lim_{\Gamma_t \to 0} \left|\frac{1}{p_t^2 - m_t^2 + \mathrm{i}\Gamma_t m_t}\right|^2 = \frac{\pi}{\Gamma_t m_t}\delta(p_t^2 - m_t^2) \quad \Rightarrow$$ life much simpler beyond LO

Full calculations of $pp \to W^+W^-b\bar{b}$ [Denner et al. '10; Bevilacqua et al. '10; Heinrich et al. '13; Cascioli et al '13; Frederix'13] **and $WWb\bar{b}j$** [Bevilacqua et al,'15–'16]

- $t\bar{t}$ production *and* decays at NLO with off-shell effects
- $t\bar{t} + Wt$ and non-resonant channels with interferences
- also 0- and 1-jet bins with $m_b > 0$ [Cascioli,Kallweit,Maierhöfer,S.P. '13; Frederix'13]

Finite-width corrections wrt NWA



10% of $\sigma_{t\bar{t}}$ with off-shellness > 10 GeV

- deviations from NWA can be significant, depending on the observable

Finite-width effects

- *inclusive* $t\bar{t}$ observables (2 b-jets) receive only order $\Gamma_t/m_t \simeq \alpha \simeq 10^{-2}$ corrections
- sizable effects in 0- and 1-jet bins

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

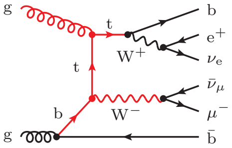
- first $t\bar{t}$+tW NLO predictions for $n_{\text{jet}} = 0, 1$
- crucial for suppression of $t\bar{t}$ backgrounds

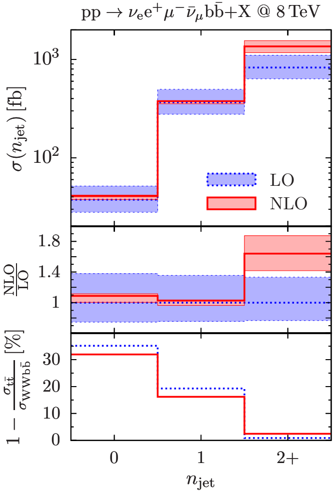
Excellent convergence for $n_{\text{jet}} = 0, 1$

- small NLO correction and reduction of scale uncertainty from 40% to less than 10%

$\mathcal{O}(\Gamma_t/m_t)$ effects (driven by Wt production)

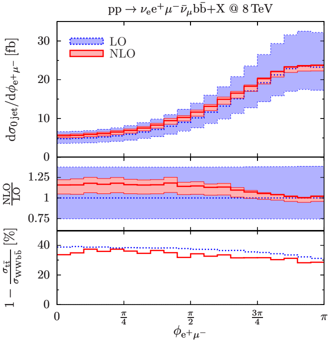
- **strong enhancement in 0/1-jet bins!** (up to 30%)

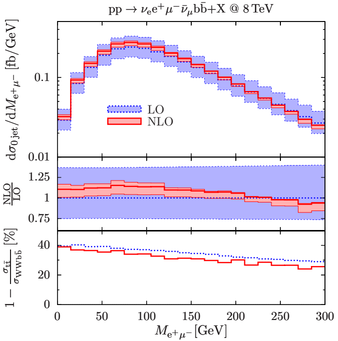




NLO(LO) 4F NNPDFSs, $p_{T,j} = 30\,\text{GeV}$

Top background to 0-jet bin of $H \to W^+W^-$ analysis



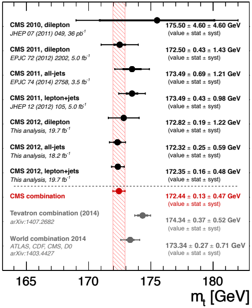


NLO distributions in key variables for $H \to W^+W^-$ measurement

- better than 10% accuracy and stable shape
- $\mathcal{O}(\Gamma_t/M_t)$ contributions around 25–40%

$WWb\bar{b}$ at NLO crucial for precision $H \to W^+W^-$ physics

Precision m_t determination



Direct and indirect m_t determinations

- $\Delta m_t^{(\mathrm{exp})} \sim 0.5\,\mathrm{GeV}$ but spread around 2 GeV
- EW precision fit ($m_t = 177 \pm 2.1$ GeV) 1.6σ above world average

Kinematic m_t^{pole} determinations

- excellent experimental systematics
- require accurate theory understanding of

  $m_t^{\overline{\mathrm{MS}}} \quad \leftrightarrow \quad m_t^{\mathrm{pole}} \quad \leftrightarrow \quad$ observables

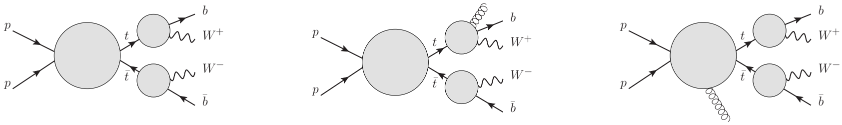
Non-perturbative (renormalon) ambiguity in $m_t^{\overline{\mathrm{MS}}} \leftrightarrow m_t^{\mathrm{pole}}$

- intrinsic $\mathcal{O}(\Lambda_{\mathrm{QCD}})$ ambiguity of pole mass much smaller than previously expected: $\Delta m_t^{\mathrm{pole}} \sim 70$ MeV [Beneke et al, 1605.03609]

Monte Carlo simulations with higher-order $pp \to WWb\bar{b}$ matrix elements

- well defined m_t^{pole} input (no MC mass!)
- systematic precision improvements in $m_t^{\mathrm{pole}} \leftrightarrow$ observables

NLO+PS matching for $pp \to W^+W^-b\bar{b}$



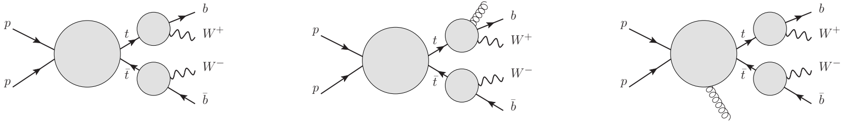
Motivation for NLO+PS matching

- NLO accuracy + QCD radiation at particle level crucial for precision measurements based on shape of top resonance and related observables

Nontrivial theoretical issues

- recoil of *standard* shower emissions off $W^+W^-b\bar{b}$ final states shifts M_{Wb} inducing unphysical distortions of Breit-Wigner shape
- problem starts at LO+PS and affect also $\Gamma_t \to 0$ limit: smearing of $\delta(p_t^2 - m_t^2)$

NLO+PS matching for $pp \to W^+W^-b\bar{b}$



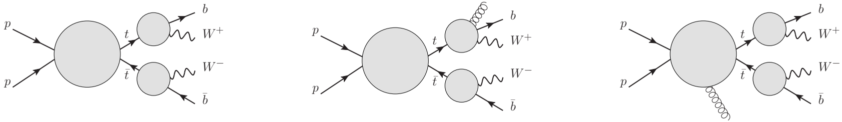
MC@NLO master formula [Höche, Krauss, Schönherr, Siegert '11]

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

- formal NLO accuracy $\Leftrightarrow$ cancellations between $\mathcal{S}$ and $\mathcal{I}$ terms up to $\mathcal{O}\left(\alpha_S^2\right)$
- involve kinematic mappings for IR factorisation and shower

$$\mathcal{R}(\Phi_{n+1}) \to \mathcal{B}(\Phi_n) \otimes \mathcal{S}(\Phi_1)$$

NLO+PS matching for $pp \to W^+W^-b\bar{b}$



Mismatch between resonances in Φ_{n+1} and Φ_n phase space

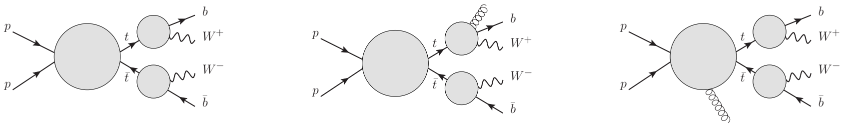
$$\frac{m_t^4}{\left[M_{Wb}^2(\Phi_n)-m_t^2\right]^2+\Gamma_t^2 m_t^2}-\left.\frac{m_t^4}{\left[M_{Wb}^2(\Phi_{n+1})-m_t^2\right]^2+\Gamma_t^2 m_t^2}\right|_{M_{Wb}(\Phi_{n+1})=m_t}$$

$$=\frac{m_t^4}{\left[M_{Wb}^2(\Phi_n)-m_t^2\right]^2+\Gamma_t^2 m_t^2}-\frac{m_t^2}{\Gamma^2} \;=\; -\frac{m_t^2}{\Gamma_t^2}\,\frac{\left[M_{Wb}^2(\Phi_n)-m_t^2\right]^2}{\left[M_{Wb}^2(\Phi_n)-m_t^2\right]^2+\Gamma_t^2 m_t^2}$$

- cancels only in soft/collinear limits, where $M_{Wb}(\Phi_n) \to M_{Wb}(\Phi_{n+1})$

$\Rightarrow$ unphysical $\mathcal{O}\left(\alpha_S^2 \frac{m_t^2}{\Gamma_t^2}\right) = \mathcal{O}(1)$ distortions of top line shape in resonance region

Resonance aware Powheg matching [Jezo and Nason, 1509.09071]



Idea: avoid unphysical $\mathcal{O}\left(\alpha_S^2 \frac{m_t^2}{\Gamma_t^2}\right)$ effects based on $\Gamma_t \to 0$ limit

(A) all-order factorisation of top production$\times$decay

$\Rightarrow$ assign radiation to top production or decays consistently with $\Gamma_t \to 0$ limit

(B) top on-shellness

$\Rightarrow$ modify NLO+PS mappings and subtraction terms such as to preserve resonance virtualities (M_{Wb} or M_{Wbg} depending on "resonance history")

see analogous approach in MC@NLO [Frederix et al, 1603.01178]

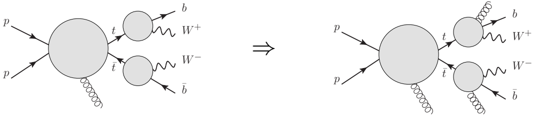
$pp \to b\bar{b} + 4\ell$ resonance aware NLO+PS generator

[Jezo, Lindert, Nason, Oleari, S.P., 1607.04538] http://powhegbox.mib.infn.it

based on POWHEG+OPENLOOPS

Precision improvements wrt standard $t\bar{t}$ NLO+PS generators

- full $pp \to t\bar{t} + Wt \to b\bar{b} + 4\ell$ process with $t\bar{t}$–tW interference
- well defined $M_t^{(\mathrm{OS})}$ with quantum corrections to top propagators
- applicable to observables with unresolved b quarks (jet vetoes) thanks to $m_b > 0$
- NLO+PS top production *and* decay with multi-radiation scheme [Campbell, Ellis, Nason, Re '15]

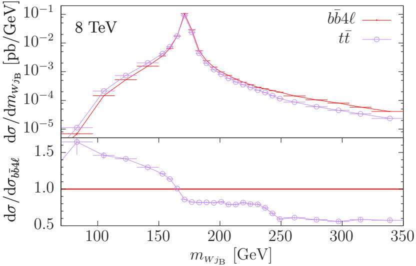


$pp \to b\bar{b}4\ell$ vs traditional Powheg $t\bar{t}$ generator I

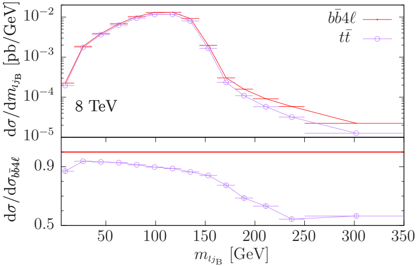
$b\bar{b}4\ell$: NLO+PS $pp \to e^+\mu^-\nu_e\bar{\nu}_\mu b\bar{b}$ [Jezo et al, 1607.04538]

$t\bar{t}$: NLO+PS $pp \to t\bar{t}$ with LO+PS decays (hvq) [Frixione, Nason, Ridolfi, '07]

Reconstructed top mass



b-jet–lepton mass

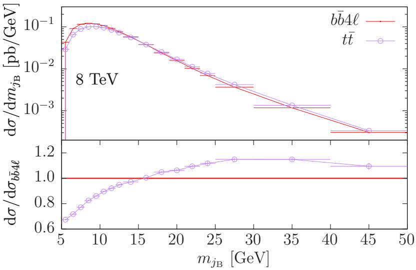


Significant effects for m_t determination

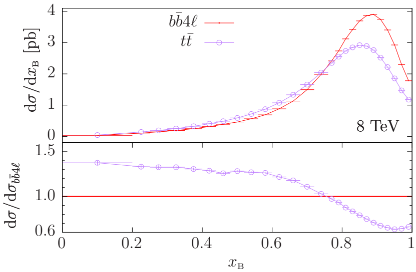
- asymmetric shape distortion around the resonance
- average M_{Wj_B} roughly 0.5 GeV higher (within ± 30 GeV around m_t) in $b\bar{b}4\ell$
- 20–30% effects around the $M_{\ell j_B}$ edge

$pp \to b\bar{b}4\ell$ vs traditional Powheg $t\bar{t}$ generator II

b-jet mass



B-hadron fragmentation function



Significant effects in b-jet properties

- narrower b-jets and harder B-fragmentation
- due to reduced radiation from b-quarks in $b\bar{b}4\ell$ generator

calls for detailed studies of realistic LHC observables

Summary and Conclusions

Automated tools (NLO QCD+EW, NLO+PS, NNLO,...)

- applicable to $2 \to 2, 3, 4, 5, \ldots$ SM process

Irreducible $t\bar{t}b\bar{b}$ background to $t\bar{t}H(b\bar{b})$

- 2009–2013: NLO and NLO+PS $\Rightarrow$ sizable PS & $t\bar{t}+$ multijet uncertainties
- 2016: first $t\bar{t} + 3$ jet calculation (and still lot of work to do)

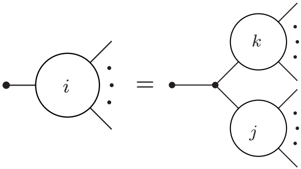
Off-shell $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ production at NLO QCD

- 2010–2013: NLO production & decays, off-shell effects, $t\bar{t} + Wt$, ...
- 2016: NLO+PS resonance-aware generator $\Rightarrow$ $\Delta m_t \sim 0.5\,\mathrm{GeV}$?

Automation opens the door to "new territory"

- wide range of applicability and many benefits for physics sensitivity of LHC
- entering new territory (e.g. multi-particle/multi-scale processes) we often face increasing physics complexity and new challenging problems
- more and more important with increasing precision of LHC measurements

Backup slides



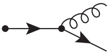
$$w^{\beta}(i) = \frac{X^{\beta}_{\gamma\delta}(i,j,k)}{p_i^2 - m_i^2}\, w^{\gamma}(j)\, w^{\delta}(k)$$

sub-tree $=$ individual topology with off-shell line $\neq$ off-shell current

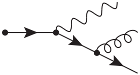
Example

$w_\alpha(1) \quad =$  $= \bar{u}_\alpha(p_1,\lambda_1)$

$w_\mu(2) =$  $= \epsilon^*_\mu(p_2,\lambda_2)$

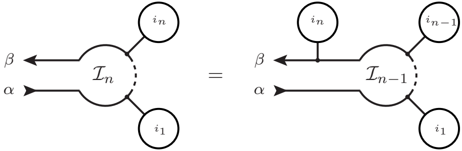
$w_\beta(12) \quad =$  $= \dfrac{g_s\, [(\not{p}_{12} + m)\gamma^\mu]_{\alpha\beta}}{p_{12}^2 - m^2}\, w_\alpha(1)\, w_\mu(2)$

$w_\nu(3) =$  $= \epsilon^*_\nu(p_3,\lambda_3)$

$w_\gamma(123) \quad =$  $= \dfrac{e\, [(\not{p}_{123} + m)\gamma^\nu(1-\gamma_5)]_{\beta\gamma}}{2\sqrt{2} s_{\mathrm{w}} (p_{123}^2 - m^2)}\, w_\beta(12)\, w_\nu(3)$ etc.

Recursion terminates when full set of diagram can be obtained via sub-diagram merging

One-loop amplitudes with conventional tree generators



$$\boxed{\text{Tree generators for "usual" OPP-input } \mathcal{N}(\mathcal{I}_n; q)}$$

Cut-open loops can be built by recursively attaching external sub-trees

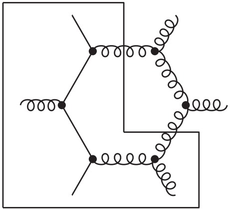
$$\mathcal{N}^{\beta}_{\alpha}(\mathcal{I}_n; q) = X^{\beta}_{\gamma\delta}(\mathcal{I}_n, i_n, \mathcal{I}_{n-1})\, \mathcal{N}^{\gamma}_{\alpha}(\mathcal{I}_{n-1}; q)\; w^{\delta}(i_n)$$

like in **conventional tree generators**

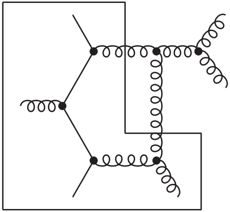
- one-loop automation in `Helac-NLO` (off-shell recursion) and `MadLoop` (diagrams)
- CPU expensive OPP reduction (multiple-q evaluations) since *tree algorithms conceived for fixed momenta*

Nature of loop amplitudes requires loop-momentum *functional* dependence!

Example of parent-child recursion



6-point parent

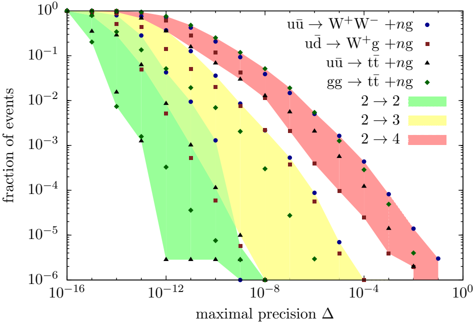


5-point child

Complicated diagrams require only “last missing piece” (always works in QCD!)

Numerical stability with tensor reduction in double precision

Stability Δ in samples of 10^6 points ($\sqrt{\hat{s}} = 1\,\mathrm{TeV}$, $p_\mathrm{T} > 50\,\mathrm{GeV}$, $\Delta R_{ij} > 0.5$)



Average number of correct digits

- 11-15

Cross section accuracy

- depends on tails
- stability issues grow with n_part

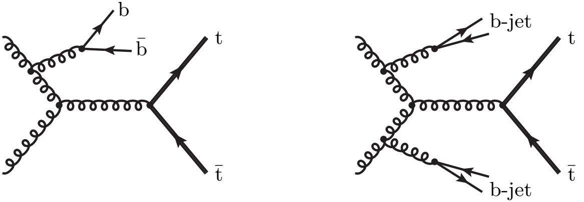
$2 \to 4$ processes very stable

- $\lesssim 0.01\%$ prob. that $\Delta_S < 10^{-3}$
- thanks to Gram-determinant expansions in `Collier`!

Real-life NLO applications

- $\mathcal{O}(10^{-4})$ unstable points in most challenging $2 \to 4$ calculations considered so far
- automatically monitored and repaired on the flight in quad precision

Why NLO Matching for $t\bar{t}b\bar{b}$ Production in 4F (and not 5F) Scheme



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

$\Rightarrow$ *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]

see talk by F. Krauss

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

$\Rightarrow$ 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!)

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

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

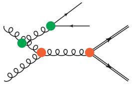
- shower resummation effectively acts starting from $\mathcal{O}(\alpha_s^2)$, and iterated emissions yield fully realistic events
- inclusive observables with n $(n+1)$ particles preserve NLO (LO) accuracy

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

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

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



$$\mu_{\mathrm{R}}^4 = E_{\mathrm{T,t}} E_{\mathrm{T,\bar{t}}} E_{\mathrm{T,b}} E_{\mathrm{T,\bar{b}}} \quad \Rightarrow \quad \alpha_S^4(\mu_{\mathrm{R}}^2) = \alpha_S(E_{\mathrm{T,t}}^2)\alpha_S(E_{\mathrm{T,\bar{t}}}^2)\alpha_S(E_{\mathrm{T,b}}^2)\alpha_S(E_{\mathrm{T,\bar{b}}}^2)$$

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

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

- reduces uncertainty from 80% to 15%
- experiments need inclusive particle-level simulation with $t\bar{t}+0,1,2$ jets at NLO

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

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

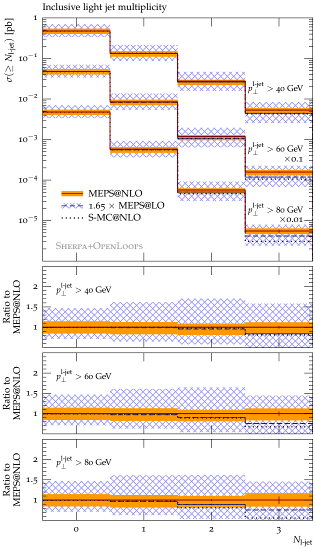
[see also FxFx, UNLOPS, GENEVA, MINLO]

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

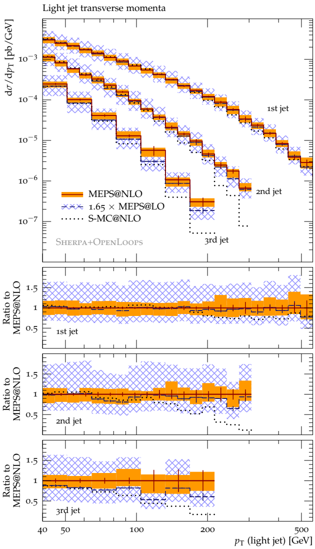
Reduction of μ_R, μ_F, μ_Q variations

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

More realistic uncertainties when multijet emission described by matrix elements instead of parton shower!

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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Reduction of μ_R, μ_F, μ_Q variations

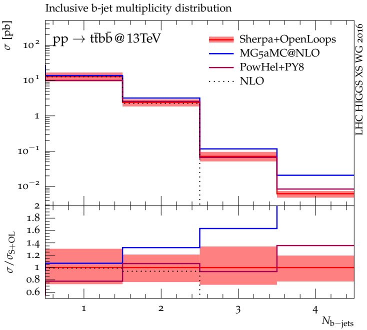
$N_{\text{light-jet}} \geq$	0	1	2
LO	48%	65%	80%
NLO	17%	18%	19%

Differential distributions

- similarly mild scale dependence
- small shape corrections

⇒ **Precision for omnipresent $t\bar{t}$ +multijet background**

Inclusive $t\bar{t} + b$-jet multiplicity distribution



- S-MC@NLO (Sherpa+OpenLoops) with $\mu_{R,F}$ variations
- MG5_aMC@NLO+PY8 w.o. variations
- Powhel+PY8 w.o. variations

NLO vs NLO+PS

- decent agreement in NLO accurate bins with ≥ 1 and ≥ 2 b-jets

S-MC@NLO vs PowHel+PY8

- good overall agreement in spite of differences in matching method, parton shower, N_f-scheme and ad-hoc cuts in Powhel

S-MC@NLO vs MG5aMC@NLO

- good agreement only for $\geq 1\, b$-jets despite similar matching method and same N_f

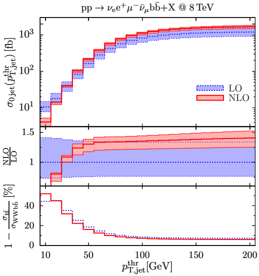
Jet-Veto and Binning Effects

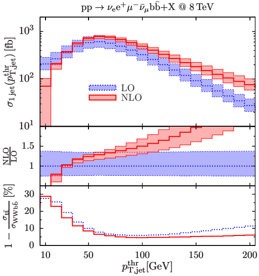
0-jet bin vs p_{T}-veto

- 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 ($K \sim 1$)

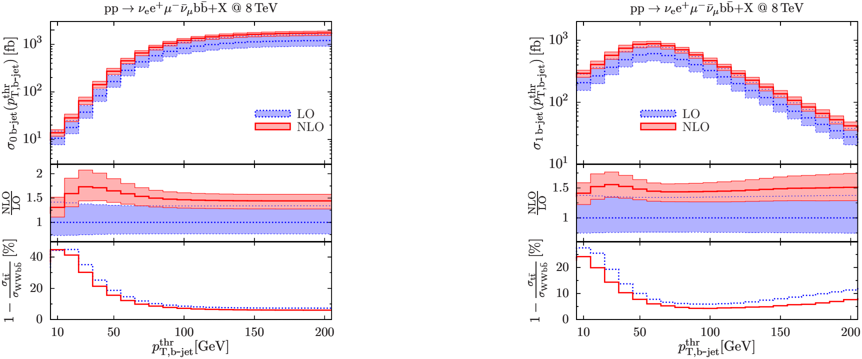
1-jet bin vs p_{T} threshold

- 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 $W^+W^-b\bar{b}$





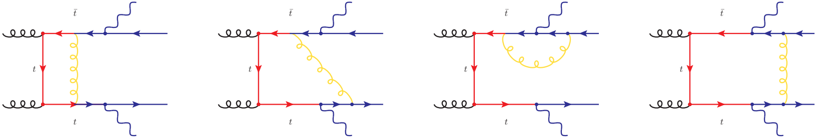
$WWbb$ cross section in b-jet bins [Cascioli, Maierhöfer,Kallweit, S.P. '13



- 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

Examples of factorisable and non-factorisable 1-loop diagrams

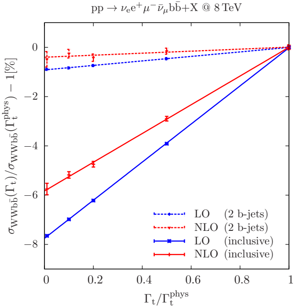


Separation of narrow- and finite-top-width parts

- via numerical $\Gamma_t \to 0$ extrapolation

$$\lim_{\xi_t \to 0} \mathrm{d}\sigma_{W^+W^-b\bar{b}}(\xi_t\Gamma_t) = \xi_t^{-2}\left[\mathrm{d}\sigma_{t\bar{t}} + \xi_t\, \mathrm{d}\sigma_{\mathrm{FtW}}\right]$$

$\Rightarrow$ permille-level convergence demonstrates nontrivial cancellation of soft-gluon $\ln(\Gamma_t/m_t)$ singularities



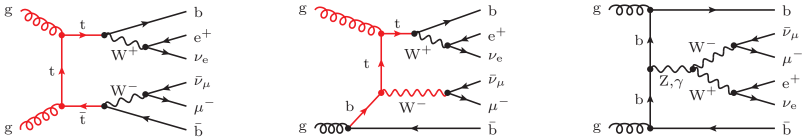
$\sigma_{t\bar{t}} =$ on-shell $t\bar{t}$ production$\times$decay

$\sigma_{\mathrm{FtW}} = \mathcal{O}(\Gamma_t/m_t)$ effects dominated by Wt + interference + off-shell $t\bar{t}$ +...

$=$ 6–8% of $\sigma_{\mathrm{inclusive}}$ (cf. sub-percent effect with $t\bar{t}$ cuts!)

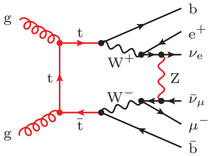
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ at NLO EW [Denner and Pellen '16]

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



Exact $2 \to 6$ NLO EW calculation

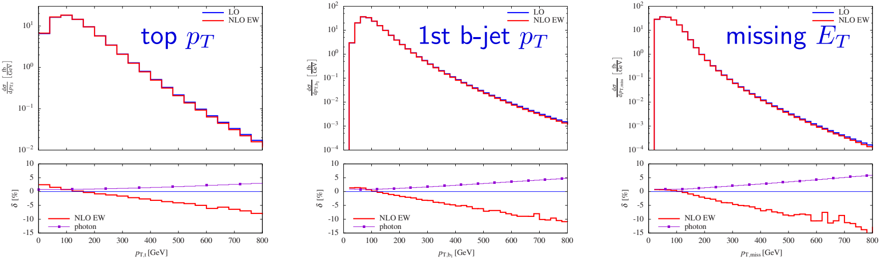
- fully differential 6-particle final state
- NLO EW top decays
- off-shell $t\bar{t} + Wt$ + non-resonant contributions



Applicable only with $t\bar{t}$ type cuts ($m_b = 0 \Rightarrow$ no unresolved b-quarks)

- 2 b-jets ($p_T > 25$ GeV, $|\eta| < 2.5$)
- 2 charged leptons ($p_T > 20$ GeV, $|\eta| < 2.5$) and missing $E_T > 20$ GeV

NLO EW corrections and γg contributions [Denner and Pellen '16]



NLO EW corrections

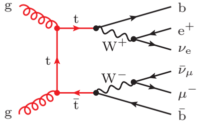
- up to -10-15% at $p_T \sim 800\,$GeV
- qualitatively consistent with [Pagani et al '16] for reconstructed top p_T

γ-induced contributions (γg at LO and γq at NLO EW included)

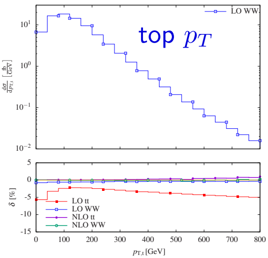
- 5–6% at $p_T \sim 800\,$GeV
- smaller wrt [Pagani et al '16] due to fixed $\mu_F = m_t$

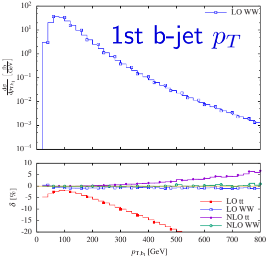
Exact $pp \to b\bar{b} + 4\ell$ vs double-pole approximation

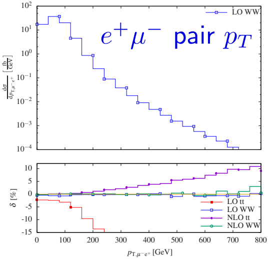
Double-pole approximation (similar to $t\bar{t}$ MC generators!)



- on-shell $t\bar{t} \to b\bar{b} + 4\ell$ matrix elements
- approx. off-shell effects via $1/[(p^2 - m_t^2)^2 + \Gamma_t^2 m_t^2]$ distributions







Genuine off-shell and Wt effects (see deviations wrt LO $t\bar{t}$)

- $+3\%$ for σ_{tot} and $+5\%$ in tail of reconstructed top p_T
- beyond 20–30% in p_T-tails of individual top-decay products

$\Rightarrow$ **NLO EW and $\mathcal{O}(\Gamma_t/m_t)$ effects mandatory for precision at high p_T**