LHC Precision Phenomenology with OpenLoops

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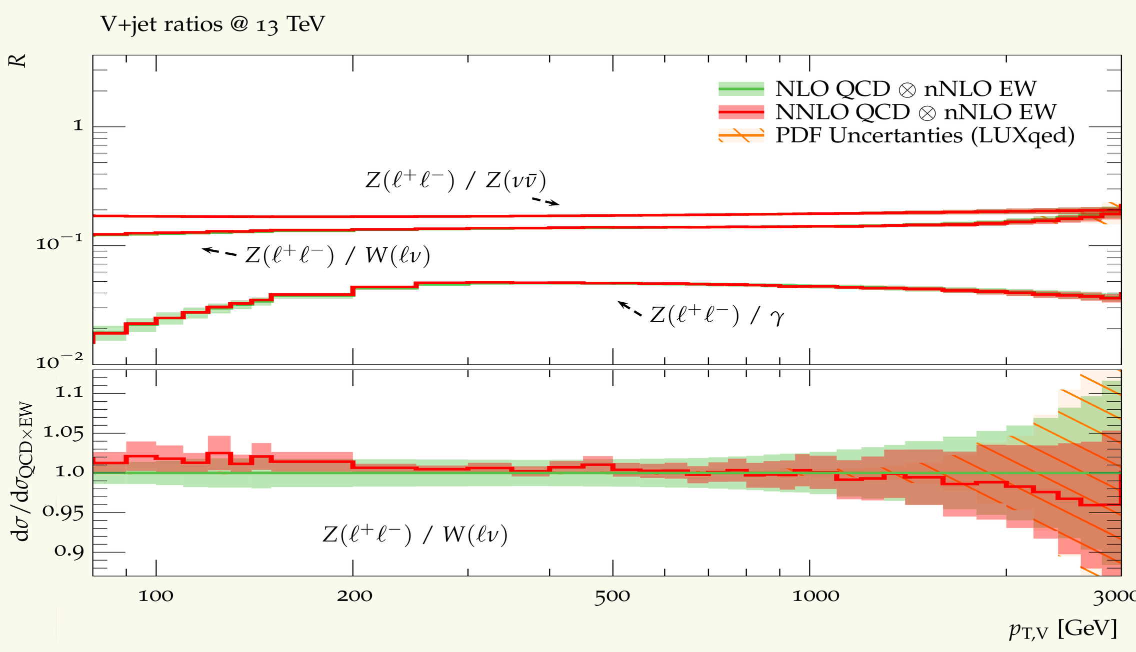
The Large Hadron Collider (LHC) is probing fundamental interactions at ever increasing energy and sensitivity.

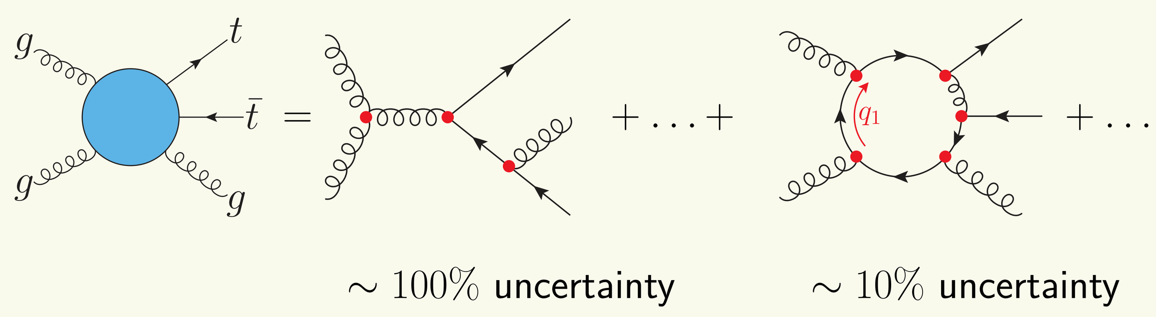
Signals of physics Beyond the Standard Model (BSM) turned out to be more elusive than originally expected and are likely to show up as small anomalies.

Precise predictions based on the Standard Model (SM) are thus becoming increasingly important in order to increase the sensitivity to BSM phenomena.

For example, recent calculations carried out at UZH make it possible to achieve percent precision in the $Z(\nu\bar{\nu})$+jet background to mono-jet searches, thereby boosting the sensitivity to dark matter signals at the LHC.



Precise scattering cross sections require higher-order calculations in perturbation theory. At next-to-leading order (NLO) Feynman diagrams with one additional real or virtual parton occur.



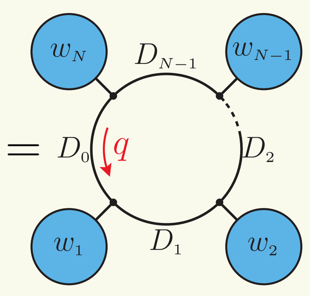
The NLO complexity grows extremely fast with the number of scattering particles, and modern approaches like OpenLoops opened the door to multi-particle NLO calculations.

The OpenLoops Method

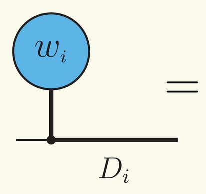
OpenLoops is a generic algorithm for the efficient numerical computation of tree and one-loop amplitudes. Applicable to arbitrary processes in the SM and beyond. It has been used extensively for precision phenomenology.

One-loop diagram: integral in $D = 4$

$$\int \mathrm{d}^D q \frac{S_1(q)\cdots S_N(q)}{D_0(q)\cdots D_{N-1}(q)} =$$



Numerator factorised into segments



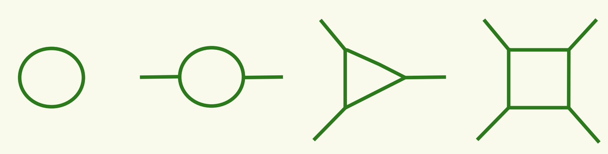
$$S_i(q) = \ldots = \mathcal{Z}_{i,\mu}\, q^\mu + \mathcal{Y}_i$$

Construction via recursive dressing

$$S_1(q)\cdots S_N(q) = \mathcal{N}_{\mu_1\ldots\mu_N} q^{\mu_1}\cdots q^{\mu_N}$$

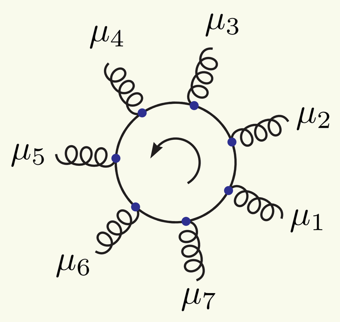
A-posteriori reduction to scalar integrals

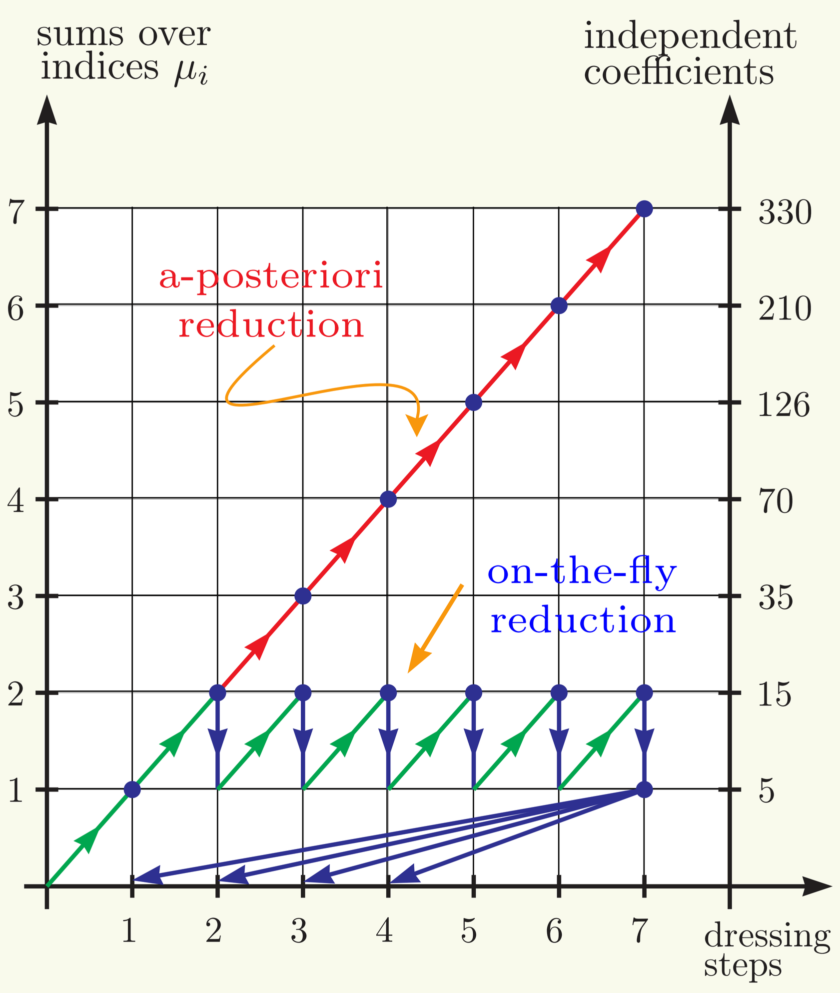
$$\int \mathrm{d}^D q \frac{q^{\mu_1}\cdots q^{\mu_N}}{D_0(q)\cdots D_{N-1}(q)} =$$



The on-the-fly method in OpenLoops2

The complexity of $\mathcal{N}_{\mu_1\ldots\mu_N}$ grows fast for multi-particle processes.





On-The-Fly reduction

$$q^\mu q^\nu = \sum_k (A_k^{\mu\nu} + B_{k,\alpha}^{\mu\nu} q^\alpha) D_k(q)$$

$D_k(q)$ can be cancelled against loop denominators at each dressing step.

Numerators construction and tensor reduction combined in a single algorithm.

First algorithm of its kind

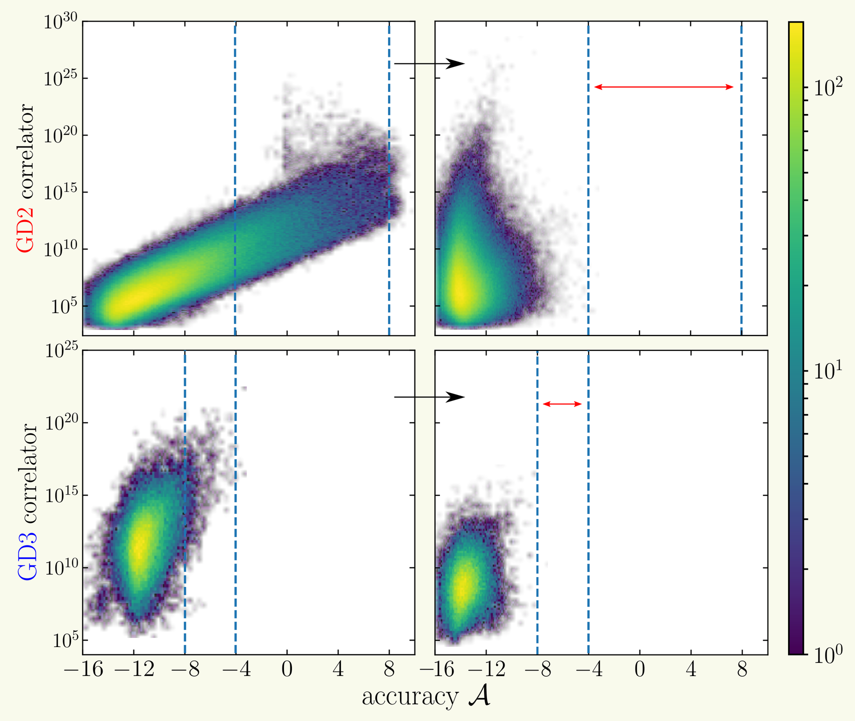
- Drastic reduction of complexity keeping rank ≤ 2 throughout
- Fully general and automated for QCD and EW corrections
- Applicable to any process in renormalisable theories

Current projects:

- Extension to two loops
- Application to phenomenology studies of many-particle processes
- Numerical stability in challenging kinematical regions

Numerical instabilities

Any reduction algorithm is plagued by severe numerical instabilities, particulary challenging for NLO multi-particle and NNLO real-virtual calculations.



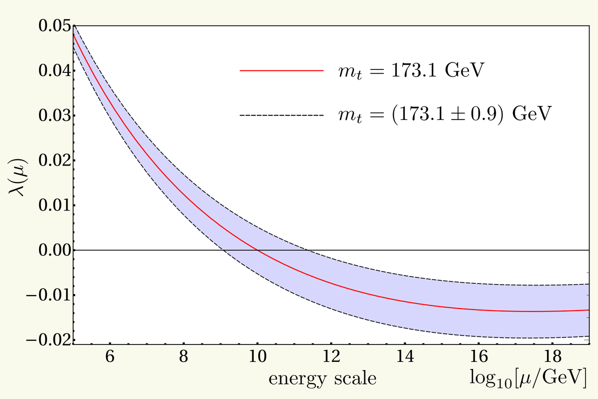
Results can be off by orders of magnitude in regions with small Gram determinants.

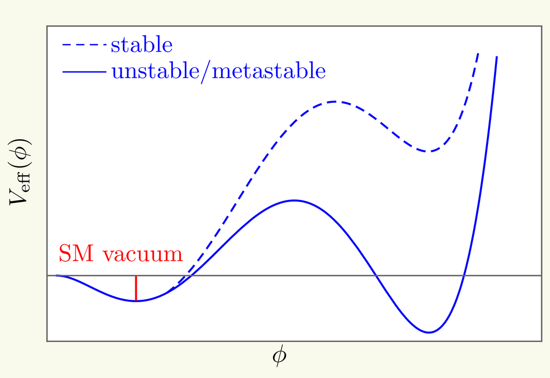
Stability in OpenLoops2

Analytical any-order expansions, reshuffling of propagators and hybrid precision yield unprecedented numerical stability. Crucial for future multiparticle NNLO calculations.

Precision in the Top-Higgs Sector

Top-Higgs interactions play a critical role for the internal consistency of the SM. This provides strong motivation for BSM searches in the Top-Higgs sector and for precise measurements of the Top mass and Top-Higgs coupling.



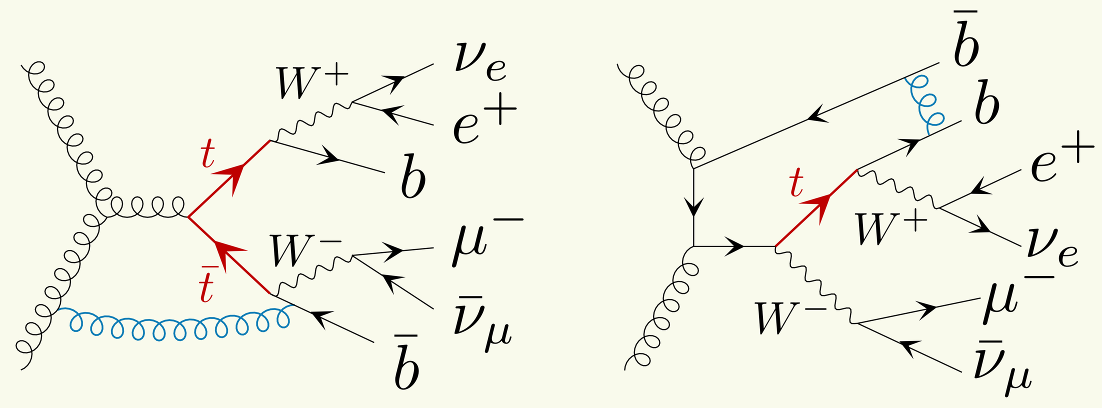


For large m_t, quantum corrections result in a SM Higgs self-coupling $\lambda(\mu) < 0$ at large scales $\mu \gtrsim 10^{10}$ GeV, rendering the SM vacuum metastable or unstable due to a second, global minimum in the effective Higgs potential $V_{\rm eff}(\phi)$ below the Planck scale.

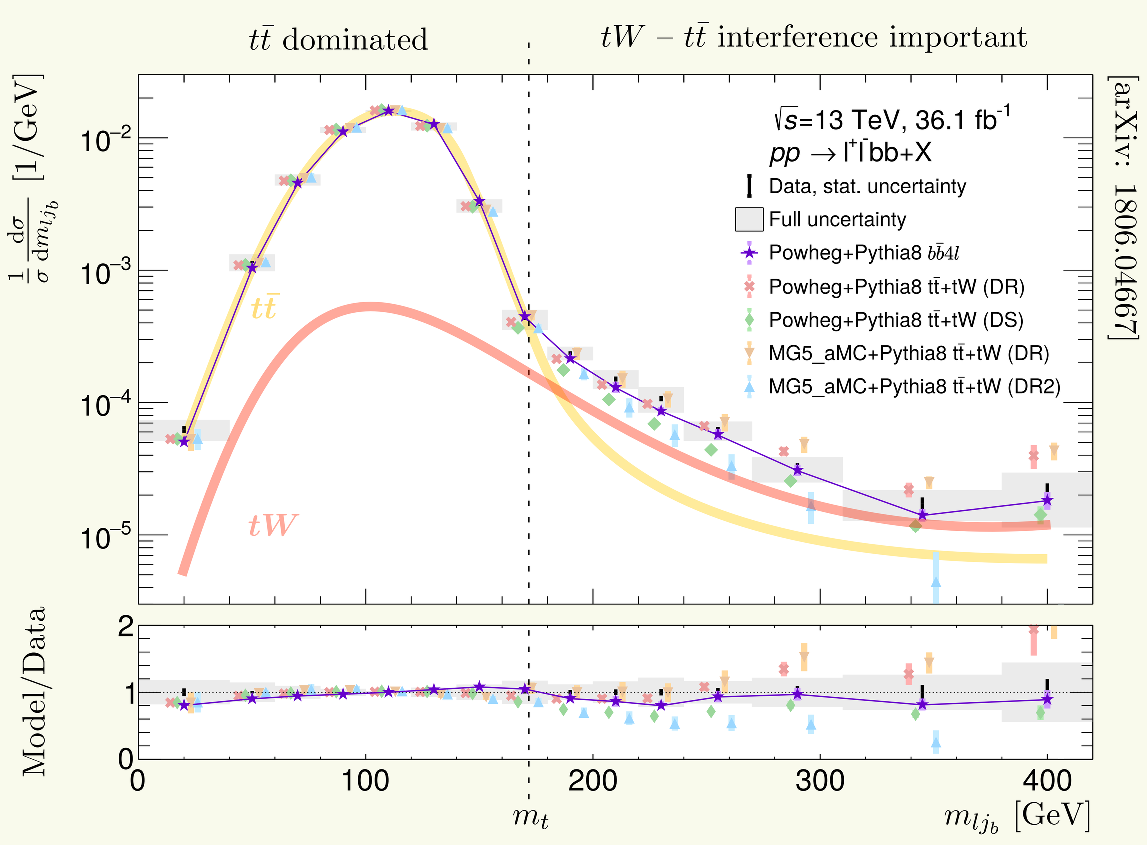
The measured m_t lies $\sim 1\%$ (2σ) away from the SM stability limit $m_t \approx 171$ GeV, and theoretical uncertainties are crucial for the interpretation of this result.

Precise simulations for top production and decay

The precision of theoretical simulations is crucial for kinematic m_t measurements, and the $b\bar{b}4\ell$ generator—based on OpenLoops and the novel resonance-aware matching method—provides the first complete NLO simulation of top-pair production and decay.



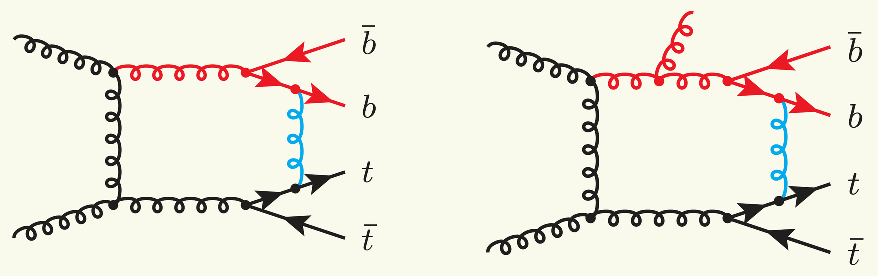
The $b\bar{b}4\ell$ generator includes $t\bar{t}$ and tW resonances as well as NLO radiation from top production and decays, accounting for all quantum interferences. Its predictions are supported by recent measurements of the $t\bar{t}$–tW interference.



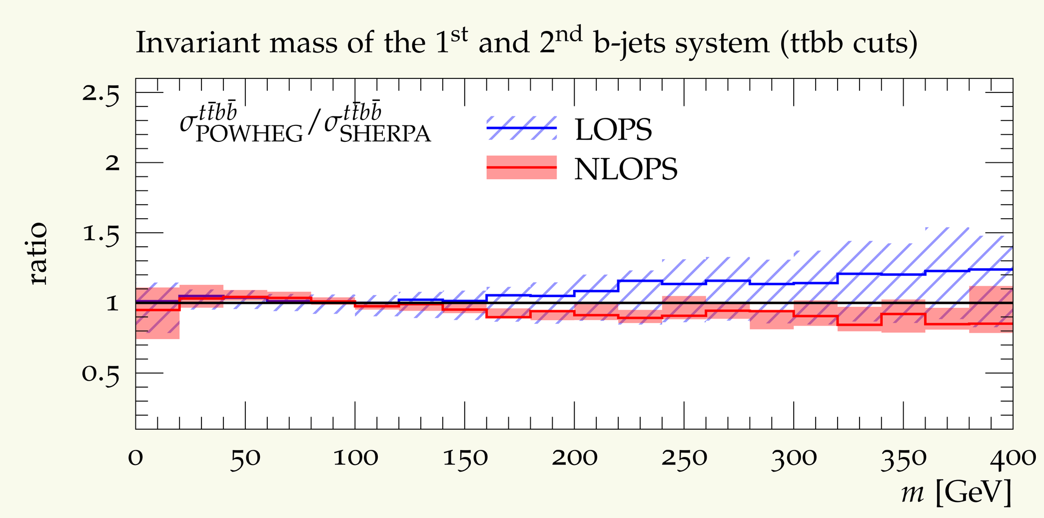
$t\bar{t}H$ production with $H \to b\bar{b}$

The recent discovery of $t\bar{t}H$ production at the LHC has opened the door to direct measurements of the Top-Higgs coupling.

To exploit the high statistics of the $H \to b\bar{b}$ channel, the shape of its irreducible $t\bar{t}b\bar{b}$ background needs to be controlled with percent precision.



NLO generators based on OpenLoops, Sherpa and Powheg are not far from this ambitious goal.



A further important step forward was provided by the recent NLO calculation of $t\bar{t}b\bar{b}$+jet production, carried out with OpenLoops2.