Heavy signatures at the LHC:
NLO corrections to off-shell ttW production

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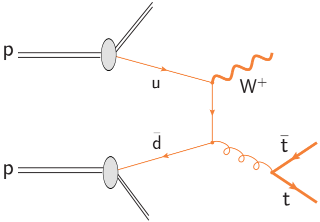
In collaboration with Ansgar Denner.

Based on JHEP 11 (2020) 069 [2007.12089] and EPJC 81 (2021) 4, 354 [2102.03246].

What are we talking about?



Hard scattering: on-shell, leading-order (LO) in perturbation theory.
Fully automated in Monte Carlo codes. But tops and W's are unstable ...

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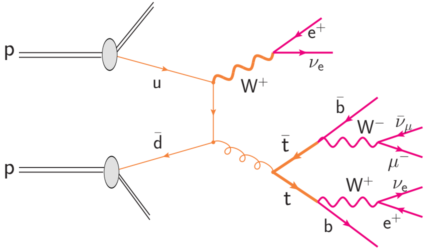

Hard scattering: off-shell, leading-order (LO) in perturbation theory.
Automated in Monte Carlo codes, but LO is not accurate enough ...

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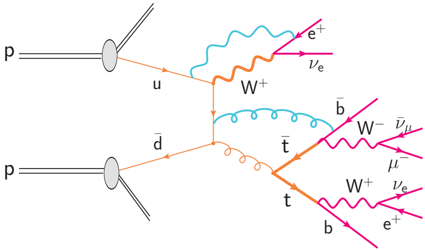

Hard scattering: radiative corrections, (next)^k-to-leading order (N^{k}LO, perturbative)
NLO automated (challenges in numerical integration), but not what is measured ...

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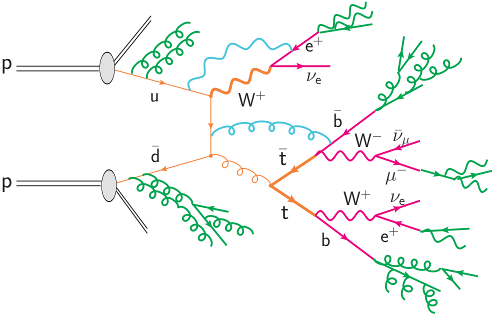

Parton shower: approximated resummation of higher orders
Automated, much closer to what is measured . . .

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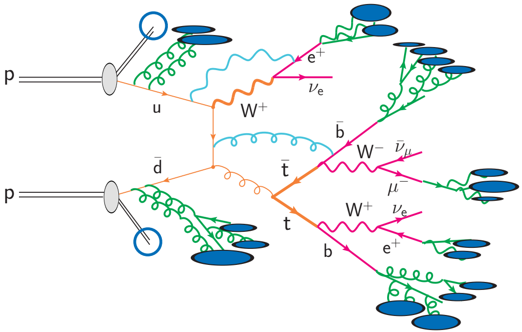
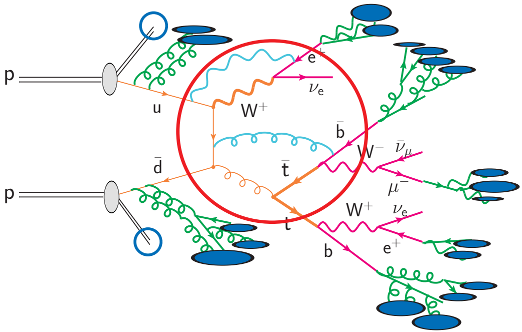


Hadronization & multi-parton scattering (non-perturbative)
Automated, this is what experimentalists measure.

What we do?

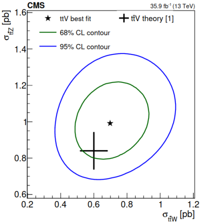


Hard scattering, radiative corrections to the off-shell process (NLO EW + QCD).
Hard numerical integration, a lot of contributions, but interesting phenomenology!

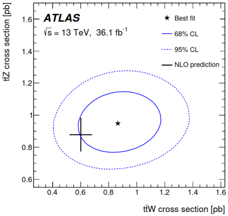
$t\bar{t}W^{\pm}$ at the LHC, one of the heaviest signatures, an optimal process for studying

- $t\bar{t}V$ coupling in or beyond the SM, new-physics effects (EFT, SUSY, ...)
- charge asymmetries [Maltoni et al. 1406.3262, Bevilacqua et al. 2012.01363]
- important background to $t\bar{t}H$ [Maltoni et al. 1507.05640]

Measured with Run-2 dataset [ATLAS 1609.01599 & 1901.03584, CMS 1711.02547].



[CMS 1711.02547]



[ATLAS 1901.03584]

Tension between data and SM predictions, both direct and $t\bar{t}H$ measurements (excess of $t\bar{t}W$ events over SM)

$\rightarrow$ improved theory modeling required

Perturbative orders

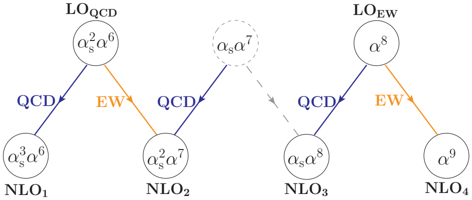
LHC process:

$\mathrm{p\,p} \to \mathrm{b\,\bar{b}\,e^+}\nu_\mathrm{e}\,\mu^-\bar{\nu}_\mu\,\tau^+\nu_\tau\ + X$

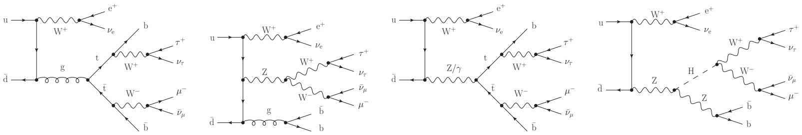
at NLO accuracy

$\to$ several contributions.

$\to$ embeds $\mathrm{t\bar{t}W^+}$ resonant structure



Leading order (LO): many contributions, but feasible.
Included all off-shell effects (no production $\times$ decay approx.).

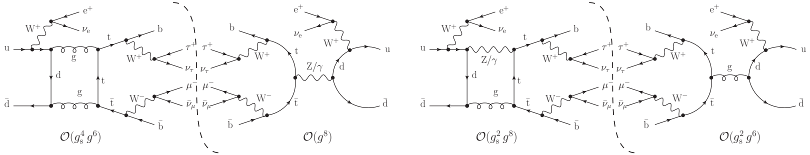


Next-to-leading order is more involved: we computed NLO_1, NLO_2 and NLO_3.

Next-to-leading order

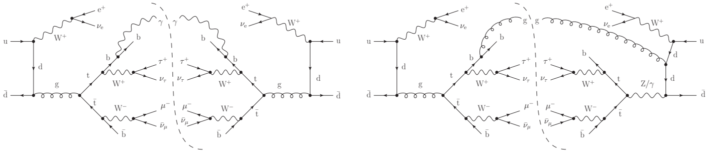
Only the sum of real and virtual corrections is free of infrared singularities.

Virtual corrections (NLO_2):



Difficult loop-integral to be reduced and evaluated numerically.

Real corrections (NLO_2):



High-multiplicity final state, to be integrated with multi-channel Monte Carlo.

Combining NLO EW and QCD: integrated cross-sections

Realistic setup [Denner GP 2102.03246]: rare process ($\approx$ 35 events in LHC Run 2)!

	$\mu_0 = H_T/3$	
order	σ (fb)	ratio (/$\mathrm{LO_{QCD}}$)
$\mathrm{LO_{QCD}}$ ($\alpha_s^2\alpha^6$)	$0.2218(1)^{+25.3\%}_{-18.8\%}$	1
$\mathrm{LO_{EW}}$ (α^8)	$0.002164(1)^{+3.7\%}_{-3.6\%}$	0.010
$\mathrm{NLO_1}$ ($\alpha_s^3\alpha^6$)	0.0147(6)	0.066
$\mathrm{NLO_2}$ ($\alpha_s^2\alpha^7$)	−0.0122(3)	−0.055
$\mathrm{NLO_3}$ ($\alpha_s\alpha^8$)	0.0293(1)	0.131
$\mathrm{LO_{QCD}+NLO_1}$	$0.2365(6)^{+2.9\%}_{-6.0\%}$	1.066
$\mathrm{LO_{QCD}+NLO_2}$	$0.2094(3)^{+25.0\%}_{-18.7\%}$	0.945
$\mathrm{LO_{EW}+NLO_3}$	$0.03142(4)^{+22.2\%}_{-16.8\%}$	0.141
LO+NLO	$0.2554(7)^{+4.0\%}_{-6.5\%}$	1.151

- $\mathrm{NLO_1}$ corrections amount at 7%, but strongly depend on choice of renormalization (and factorization) scale
- $\mathrm{NLO_2}$ corrections are negative (−6%, as usual for NLO EW) and scale-indep.
- $\mathrm{NLO_3}$ corrections are 10 times larger than its LO (13% of $\mathrm{LO_{QCD}}$) and larger than $\mathrm{NLO_2}$: power counting of perturbative couplings can be misleading!
- theory-uncertainties (scale) dominated by $\mathrm{NLO_1}$: from 25% (LO) to 5% (NLO)

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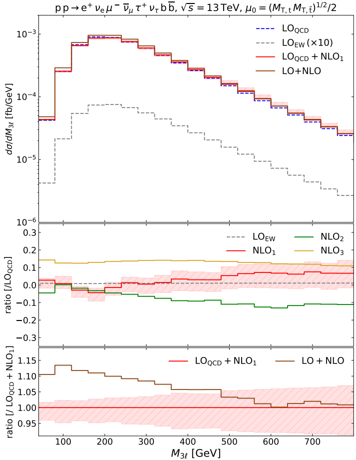
Combining NLO EW and QCD: distributions

Total cross-sections are not the end of the story: NLO corrections distort the shape of differential cross-sections. FIgure: invariant mass of the three-charged-lepton system.



Conclusions

Perturbative description of LHC processes is only the first step towards realistic theory predictions.

NLO QCD and EW corrections feature several challenges when dealing with

1. high-multiplicity final states,
2. complicated resonant structures,
3. off-shell effects (non-resonant contributions, spin-correlations).

$t\bar{t}W^{\pm}$ is a heavy and rare signature that is interesting both to probe the Standard Model and to search for new-physics.

We have computed the NLO QCD and EW corrections in the fully-leptonic decay channel, including all off-shell effects both at LO and at NLO.

NLO QCD is not enough: essential to provide use NLO predictions for $t\bar{t}W^{\pm}$.

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