Theoretical advances in EW/Higgs/Top physics at the LHC

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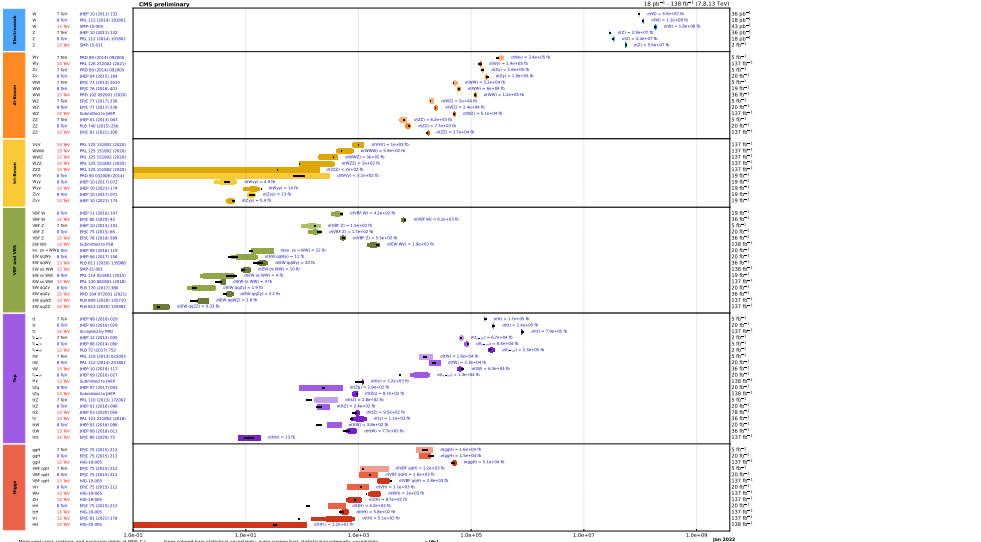


- Triumph of the Standard Model ...

- Huge theoretical effort backing up this endeavour
  → impossible to cover all theory progress on EW, Higgs, and top physics!

Disclaimer

⚠ Only selected topics will be presented
→ illustration of current theoretical/phenomenological status

- To get an overview:
  Les Houches wishlist [Huss, Huston, Jones, MP; 2207.02122]
  → State of the art on th. side at fixed order
  → 848 references
  → to be updated this year

process	known	desired
$pp \to V$	$\mathrm{N^3LO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}} + \mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{N^2LO_{EW}}$
$pp \to VV'$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ $+ \mathrm{NLO_{QCD}}$ (gg channel)	$\mathrm{NLO_{QCD}}$ (gg channel, w/ massive loops) $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to V + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	hadronic decays
$pp \to V + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (QCD component) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	$\mathrm{NNLO_{QCD}}$
$pp \to V + b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to VV' + 1j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to VV' + 2j$	$\mathrm{NLO_{QCD}}$ (QCD component) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^+W^+ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to W^+W^- + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to ZZ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to VV'V^*$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^{\pm}W^+W^-$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to \gamma\gamma$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma\gamma + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ $+ \mathrm{NLO_{QCD}}$ (gg channel)	
$pp \to \gamma\gamma\gamma$	$\mathrm{NNLO_{QCD}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$

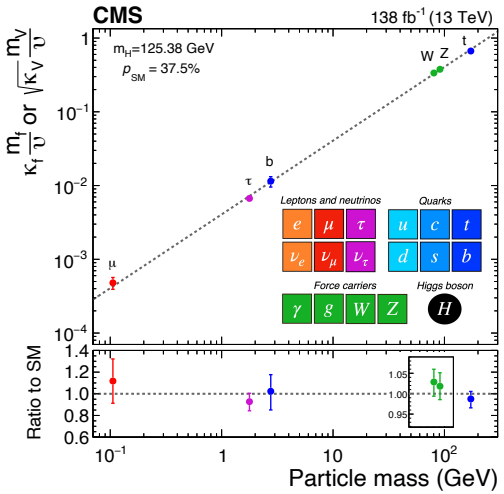
- Triumph of the Standard Model ... which culminated with

Discovery of the Higgs boson

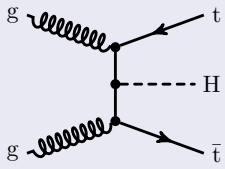
→ Great interest in measuring properties of the Higgs boson ...
(reflected in this presentation)

- Top physics
  - → $pp \to t\bar{t}H$
  - → $pp \to t\bar{t}W$

Higgs coupling



- Yukawa coupling proportional to mass
- Higgs-top, largest coupling
  $\rightarrow$ $t\bar{t}H$ most sensitive at the LHC



$pp \to t\bar{t}H$

State of the art

- NLO QCD+EW with off-shell effects for top quarks [multileg computation $(2 \to 7)$]

  [Denner, Feger; 1506.07448][Denner, Lang, MP, Uccirati; 1612.07138]

- Resummation [on-shell tops]

  [Kulesza, Motyka, Stebel, Theeuwes; 1509.02780, 1704.03363], [Broggio, Ferroglia, Pecjak, Signer; 1510.01914], [Broggio, Ferroglia, Pecjak, Yang; 1611.00049]

- Matching with parton shower [on-shell tops]

  [Garzelli, Kardos, Papadopoulos, Trocsanyi; 1108.0387], [Hartanto, Jager, Reina, Wackeroth; 1501.04498]

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Next frontier

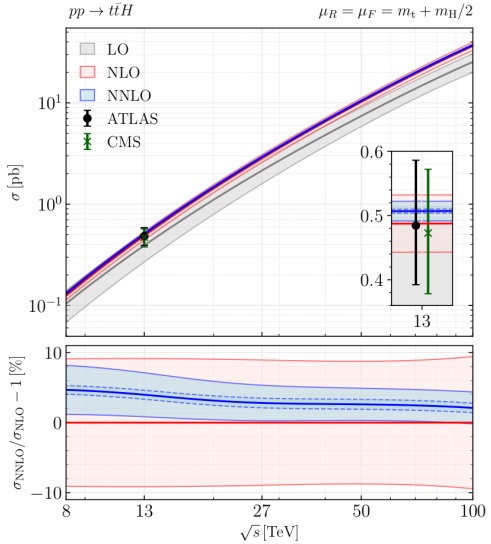
- NNLO QCD for on-shell top

  $\to$ Cross-section calculation (approximate) [Catani et al.; 2210.07846]

  $\to$ Two-loop contribution [Agarwal et al.; 2402.03301], [Wang, Xia, Yang, Ye; 2402.00431],

  [Buccioni, Kreer, Liu, Tancredi; 2312.10015], [Febres Cordero et al.; 2312.08131]

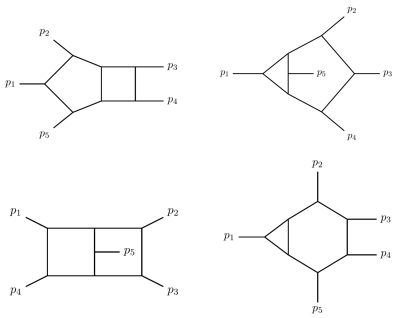
Cross-section at approximate NNLO QCD [Catani et al.; 2210.07846]

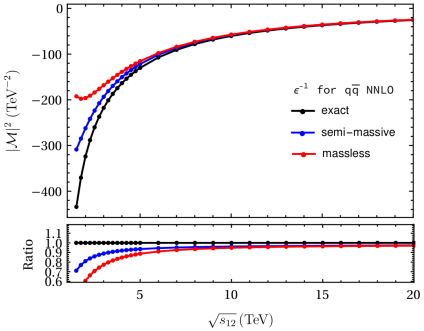


- Full computation apart from finite two-loop contribution
  - $\to \delta_{\mathrm{NNLO}} = \delta_{\mathrm{RR}} + \delta_{\mathrm{RV}} + \tilde{\delta}_{\mathrm{VV}}$
  - $\to$ use of soft Higgs approximation (valid for $p_{\mathrm{H}} \ll$ scales)
  - $\to$ good for inclusive numbers
  - $\to$ approximation good below 1%
- Moderate corrections: +4% at 13 TeV and +2% at 100 TeV

Two-loop contribution - [Wang, Xia, Yang, Ye; 2402.00431]

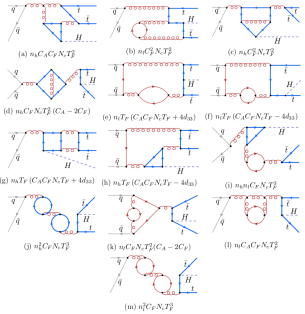
- Requires computation of 5-point two-loop amplitudes with 3 external masses and two different scales
  → most challenging to date
- Both $q\bar{q}$ and gg channels
  → revert to approximation valid for $s_{ij} \gg m_t^2$ i.e. in boosted topologies

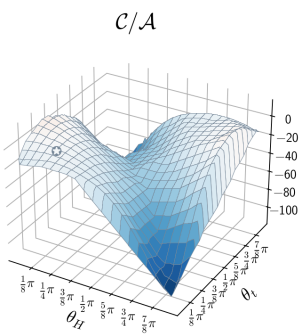




Two-loop contribution - [Agarwal et al.; 2402.03301]

- N_f part (i.e. with closed fermion loops) of the qq channel
  - $\rightarrow$ exact numerical result
  - $\rightarrow$ proof of concept for full computation
- $\sim$ minutes for a given phase-space point
  - $\rightarrow$ interpolation grids needed to compute cross section





$pp \to t\bar{t}W$

Motivation

- Background to ttH
- Interesting in its own right / typical BSM signature
- Some tension with data
  - $\to$ direct measurements [ATLAS; 1901.03584], [CMS; 1711.02547]
  - $\to$ as ttH background [ATLAS; ATLAS-CONF-2019-045], [CMS; CMS-PAS-HIG-17-004]

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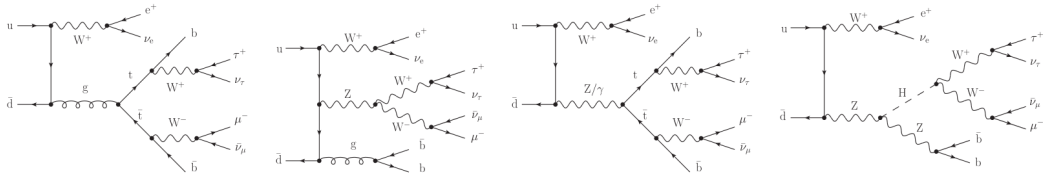
State of the art

- Approximate NNLO QCD for on-shell [Buonocore et al.; 2306.16311] (similar computation as before)
- Full NLO QCD + EW for on-shell [Frederix, Pagani, Zaro; 1711.02116]
- NLO QCD for off-shell [Bevilacqua et al.; 2012.01363, 2005. 09427], [Denner, Pelliccioli; 2007.12089]
- Full NLO QCD + EW for off-shell [Denner, Pelliccioli; 2102.03246]
- Approximate N3LO [on-shell]: [Kidonakis, Foster; 2312.00861]

$pp \to t\bar{t}W$ [Denner, Pelliccioli; 2102.03246]

→ Several amplitudes for one signature!



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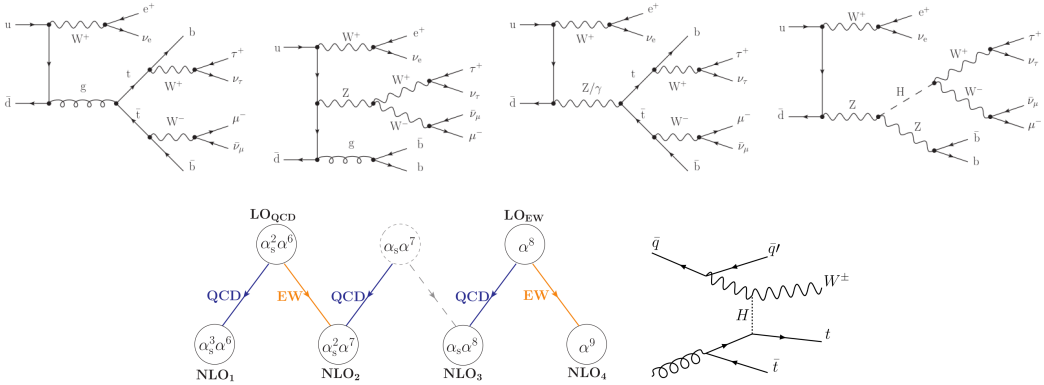
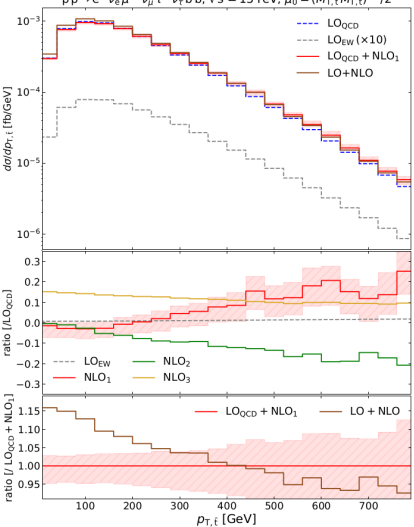
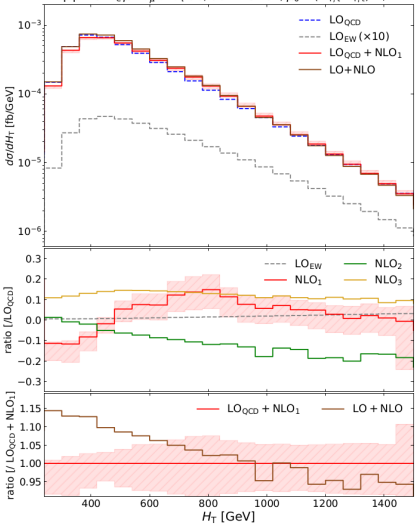


- Subleading corrections (NLO_3) observed to be larg for on-shell

  [Frederix, Pagani, Zaro; 1711.02116], [Dror, Farina, Salvioni, Serra; 1511.03674]



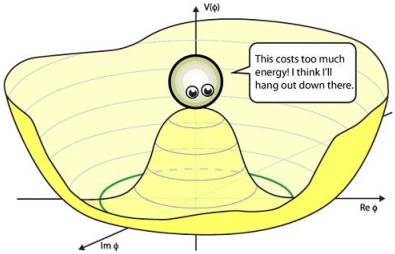


- Non-trivial interplay between various contributions

- Higgs physics
  → di-Higgs

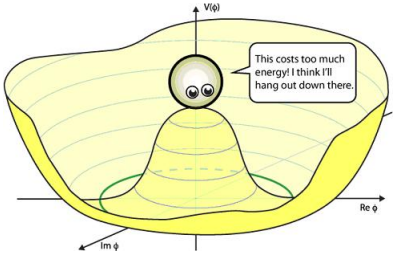
More readings on recent Higgs results/calculations:

- [Jakobs, Zanderighi; 2311.10346]
- [Jones; LHEP 2023 (2023) 442]



Motivations

- Higgs potential: $V(H) = \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$ $\quad [\lambda = m_H^2/(2v^2) \sim 0.13]$
  $\rightarrow$ test of the EWSB mechanism
- Di-Higgs production: direct probe of λ!
  $\rightarrow$ Next target for SM physics at High-Luminosity LHC!



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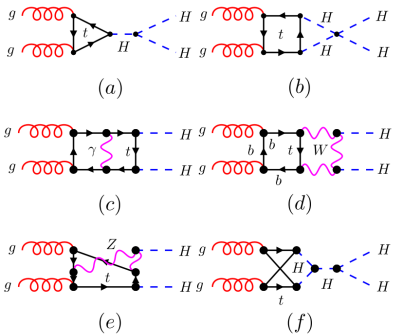
State of the art

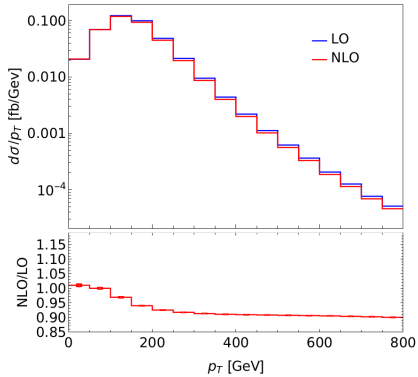
- N3LO QCD in some approximations
  $\rightarrow$ full references by Kay Schönwald @ last LHC Higgs WG meeting [clickable link]

NLO EW to pp $\to$ HH

- Loop induced process
  $\to$ LO is one-loop
  $\to$ NLO is two-loop for the virtual part
- No real QED correction (Furry's theorem)
  $\to$ Weak radiation (W,Z) not needed for IR finiteness and rejected experimentally
- NLO EW is "only" the two-loop virtual contribution
- Exact calculation: [Bi et al.; 2311.16963]
  Large m_t-limit: [Davies, Schönwald, Steinhauser, Zhang; 2308.01355]



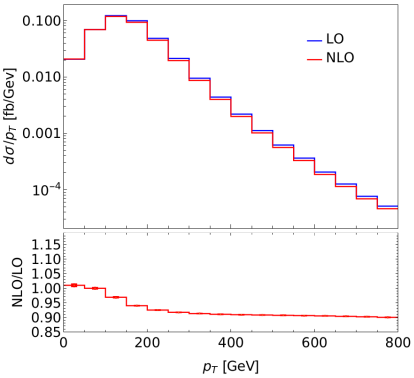
NLO EW to pp $\rightarrow$ HH [Bi et al.; 2311.16963]

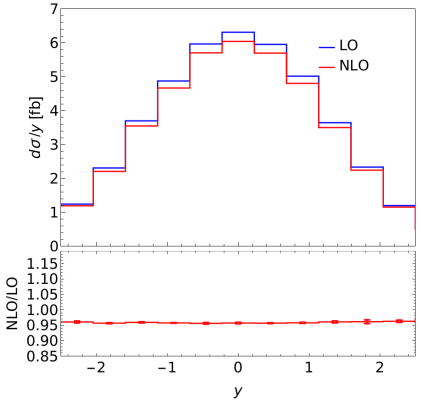


Typical behaviour for EW corrections at the LHC

- EW corrections larger in high-energy limit (Sudakov logarithms)

NLO EW to pp $\longrightarrow$ HH [Bi et al.; 2311.16963]





Typical behaviour for EW corrections at the LHC

- EW corrections larger in high-energy limit (Sudakov logarithms)
- Flat corrections for inclusive observables ($\sim$ per cent)

- Electroweak physics
  - → Triboson

Triboson

Motivation

- Quartic gauge coupling (like in VBS)
  $\rightarrow$ Another test of the EWSB mechanism and SM

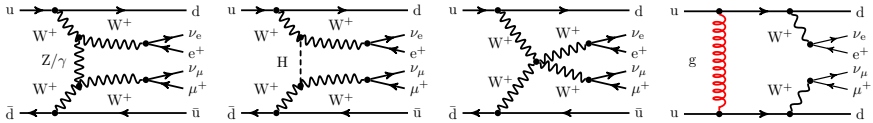
State of the art

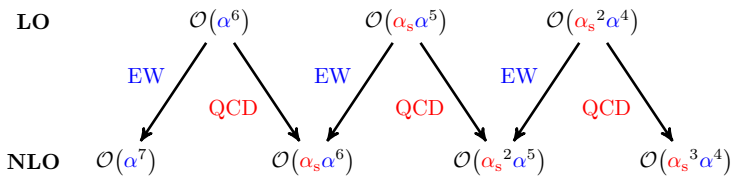
- NLO QCD + NLO EW for ON-shell for all processes (see [Huss, Huston, Jones, MP; 2207.02122])
- NLO QCD + NLO EW for OFF-shell for WWW
  [Schönherr; 1806.00307], [Dittmaier, Knippen, Schwan; 1912.04117]
- NLO QCD + NLO EW for OFF-shell for $V\gamma\gamma$ [Greiner, Schönherr; 1710.11514]
- NLO QCD + NLO EW for OFF-shell for WZγ [Cheng, Wackeroth; 2112.12052]

⚠ only leptonic decays considered

Triboson - [Denner, MP, Schönherr, Schumann; to appear]

Signature: W^+W^+jj ... golden channel for vector-boson scattering





→ Full NLO EW+QCD [Biedermann, Denner, MP; 1708.00268]

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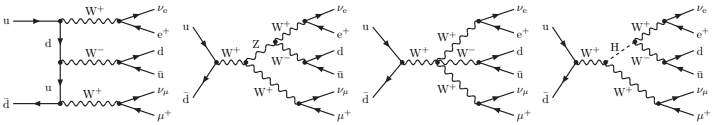
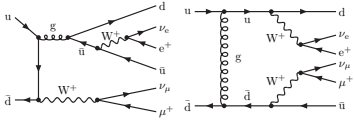
- **EW process**



- **QCD process**



→ Measurement by ATLAS [ATLAS; 2201.13045]

→ Investigation of EW corrections [Biedermann, Denner, MP; 1611.02951]

→ Full NLO QCD+EW + **PS corrections using** SHERPA

→ Typical phase space (inspired by [ATLAS; 2201.13045]):

$$
\begin{aligned}
p_{\mathrm{T},\ell^+} &> 20\,\mathrm{GeV} \quad \text{and} \quad |y_{\ell^+}| < 2.5 \\
p_{\mathrm{T,j}} &> 20\,\mathrm{GeV} \quad \text{and} \quad |y_{\mathrm{j}}| < 4.5 \\
m_{\mathrm{jj}} &< 160\,\mathrm{GeV} \quad \text{and} \quad |\Delta y_{\mathrm{jj}}| < 1.5
\end{aligned}
$$

$$
40\,\mathrm{GeV} < m_{\ell^+\ell^+} < 400\,\mathrm{GeV}
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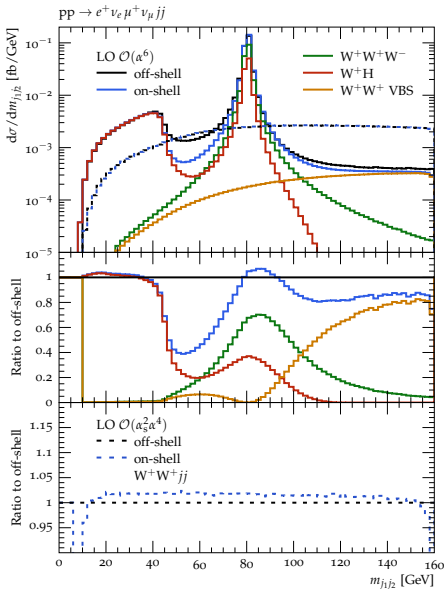
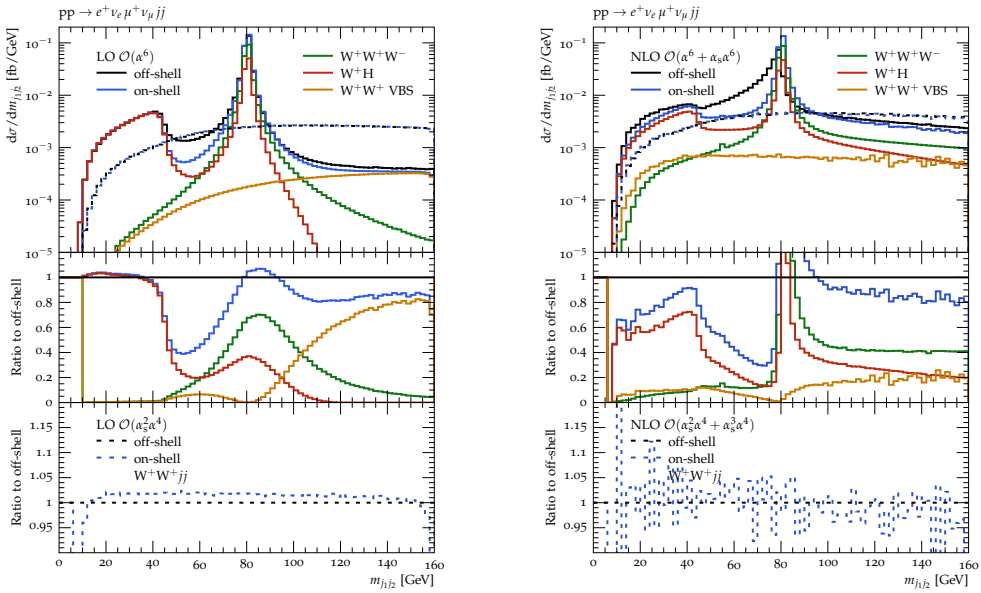
$\mathcal{O}(\alpha^6)$	off-shell	on-shell	on-shell subprocess			
Process	$\mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$	sum	$\mathrm{W}^+\mathrm{W}^+\mathrm{W}^-$	$\mathrm{W}^+\mathrm{H}$	$\mathrm{W}^+\mathrm{Z}$	$\mathrm{W}^+\mathrm{W}^+$ VBS
σ_{LO}[fb]	0.7917	0.7738	0.4207	0.3265	$5 \cdot 10^{-7}$	0.0266
$\sigma/\sigma_{\mathrm{LO}}^{\text{off-shell}}$[%]	100	97.7	53.1	41.2	$7 \cdot 10^{-5}$	3.3

⚠ Large contribution from WH! ⚠ **preliminary**



[Denner, MP, Schönherr, Schumann] ⚠ **preliminary**



[Denner, MP, Schönherr, Schumann] ⚠ **preliminary** → More complex picture with higher-orders

Summary

New computations and theory frontier:

- $pp \to t\bar{t}H$ [approximate NNLO QCD/two-loop virtual for $2 \to 3$ with masses]
- $pp \to t\bar{t}W$ [NLO QCD+EW for $2 \to 8$]
- $pp \to HH$ [two-loop EW]
- $pp \to WWW$ [NLO QCD+EW with PS for $2 \to 6$]

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  $\to$ Precision programme at the LHC
- Crucial interplay between theory and experiment
  $\to$ Big impact on physics results

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Thank you