Timescale of the LHC

we are here:  
$L = 140 \text{ fb}^{-1}$

where we are going:  
$L = 3000 \text{ fb}^{-1}$

Experimental uncertainties will dramatically decrease in the future. Often reaching $O(1\%)$. 

B SM certainly not ‘around the corner’

Mgluino > 2 TeV
Msquark > 0.7-2 TeV
Mstop > 400 GeV ...

Z’ > 4.5 TeV
W’ > 5 TeV
Mleptoquark > 1 TeV ...

*Only a selection of the available mass limits or new states or
generics is shown. Many of the limits are based on
graphical models, c.t. res. for the assumptions made.
Remarkable data vs. theory agreement in SM+Higgs measurements

**Precision tests of the SM at the quantum level**
Differential SM measurements
The need for precision in tails

**Diboson**

**Dark Matter**

**ATLAS**

\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

**Events / bin**

<table>
<thead>
<tr>
<th>( p_T^{\text{lead}} ) [GeV]</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta q_2 ) = 0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta \lambda' ) = 0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \lambda^2 = 0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta \lambda' = 0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \lambda^3 = 0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( pp \to WW \)

- In case new physics is heavy: expect small deviations in tails of distributions

→ good control on theory necessary!

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

**Events / GeV**

<table>
<thead>
<tr>
<th>( E_T^{\text{miss}} ) [GeV]</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1100</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Z \rightarrow \ell \ell ) + jets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( W(\ell \nu) + \text{jets}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Z \rightarrow \ell \ell ) + jets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( t \bar{t} + \text{single top}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diboson</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>multijets + ncb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( m(\ell, \ell') \approx (500, 495) \text{ GeV}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( m_{\text{total}} + m_{\text{miss}} \approx (400, 1000) \text{ GeV}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( n \rightarrow 4, M_{\text{miss}} \approx 400 \text{ GeV}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Missing-ET**

- Dark Matter particles produced at the LHC leave the detectors unobserved:
  signature missing transverse energy
- large irreducible SM backgrounds

→ good control on theory necessary!

**Figure 11**

Events / bin

\( p_T^{\text{lead}} [\text{GeV}] \)

**Table**

<table>
<thead>
<tr>
<th>AATLAS</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta q_2 = 0.6 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta \lambda' = 0.2 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \lambda^2 = 0.2 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta \lambda' = 0.2 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \lambda^3 = 0.2 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 12**

Events / GeV

\( E_T^{\text{miss}} [\text{GeV}] \)

Data 2015+2016

- Standard Model
- \( Z(\ell \ell) + \text{jets} \)
- \( W(\ell \nu) + \text{jets} \)
- \( Z(\ell \ell) + \text{jets} \)
- \( t \bar{t} + \text{single top} \)
- Diboson
- multijets + ncb
- \( m(\ell, \ell') \approx (500, 495) \text{ GeV} \)
- \( m_{\text{total}} + m_{\text{miss}} \approx (400, 1000) \text{ GeV} \)
- ADD, \( n \rightarrow 4, M_{\text{miss}} \approx 400 \text{ GeV} \)
LHC precision physics: a gateway to new physics

Direct searches

Z’ / W’
SUSY
Leptoquarks
Dark Matter
.....

= Resonances
MET+X
Long-lived particles
...

Indirect searches

Higgs couplings/properties
M_{top}
RGE running
M_W
aTGCs / aQGCs
**Direct searches** for new physics: taming overwhelming SM backgrounds

Thanks to state-of-the-art theory predictions + uncertainties for SM backgrounds

Thanks to state-of-the-art theory predictions + uncertainties for SM backgrounds

[Ref. 'JML, et.al., '17]

few percent!

Theory precision is key to harness full potential of LHC data!
Determine V+jets backgrounds: the DM case

- global fit of $Z(\rightarrow l\bar{l})$+jets, $W(\rightarrow l\nu\bar{\nu})$+jets and $\gamma$+jets measurements
  - to determine $Z(\rightarrow \nu\bar{\nu})$+jet
  - and the visible channels at high-pT

- hardly any systematics (just QED dressing)
- very precise at low pT
- but: limited statistics at large pT
- fairly large data samples at large pT
- systematics from transfer factors: ratios of V+jets processes
Pure QCD uncertainties

\[ \frac{d}{dx} \sigma_{QCD}^{(V)} = \frac{d}{dx} \sigma_{LO}^{QCD} + \frac{d}{dx} \sigma_{NLO}^{QCD} + \frac{d}{dx} \sigma_{NNLO}^{QCD} \]

this is a ‘good’ scale for V+jets
- at large pTV: HT’/2 \approx pTV
- modest higher-order corrections
- sufficient convergence

scale uncertainties due to 7-pt variations:
- O(20%) uncertainties at LO
- O(10%) uncertainties at NLO
- O(5%) uncertainties at NNLO

with minor shape variations

How to correlate these uncertainties across processes?
Pure EW uncertainties

EW corrections become sizeable at large $p_{T,V}$: $-30\%$ @ 1 TeV

Origin: virtual EW Sudakov logarithms

$\gamma, Z, W^\pm$

$\sim$

$\Rightarrow$ increases with energy
$\Rightarrow$ large effect in the tails kinematic distributions (up to $O(1)$ at the TeV scale)

How to estimate corresponding pure EW uncertainties of relative $O(\alpha^2)$?
Precise predictions for $V$+jet DM backgrounds

work in collaboration with:

- Combination of state-of-the-art predictions: (N)NLO QCD+(N)NLO EW in order to match (future) experimental sensitivities (1-10% accuracy in the few hundred GeV-TeV range)

\[
\frac{d}{dx} \frac{d}{dy} \sigma^{(V)}(\bar{x}_{\text{MC}}, \bar{x}_{\text{TH}}) := \frac{d}{dx} \frac{d}{dy} \sigma^{(V)}(\bar{x}_{\text{MC}}) \left[ \frac{d}{dx} \sigma^{(V)}(\bar{x}_{\text{TH}}) \right] \left[ \frac{dx}{dx} \sigma^{(V)}_{\text{MC}}(\bar{x}_{\text{MC}}) \right]
\]

one-dimensional reweighting of MC samples in \( x = p_T^{(V)} \)

with \( \frac{d}{dx} \sigma^{(V)}_{\text{TH}} = \frac{d}{dx} \sigma^{(V)}_{\text{QCD}} + \frac{d}{dx} \sigma^{(V)}_{\text{mix}} + \frac{d}{dx} \Delta \sigma^{(V)}_{\text{EW}} + \frac{d}{dx} \sigma^{(V)}_{\gamma-\text{ind.}} \)

- Robust uncertainty estimates including
  1. Pure QCD uncertainties
  2. Pure EW uncertainties
  3. Mixed QCD-EW uncertainties
  4. PDF, $\gamma$-induced uncertainties . . .
- Prescription for correlation of these uncertainties
  - within a process (between low-pT and high-pT)
  - across processes
Combined uncertainties on V+jets ratios

\[ \frac{d\sigma}{dN} \text{LOQCD} \]

\[ \delta_{Z/W} = 1-3\% \text{ for } p_T < 1 \text{ TeV} \]
\[ \delta_{Z/Y} = 3-5\% \text{ for } p_T < 1 \text{ TeV} \]

[Figure: Predictions at NLO QCD]
Experimental closure tests
CMS monojet searches

35.9 fb⁻¹ (13 TeV)

Black ratio from data and statistical uncertainties / Red from MC
Grey band includes theoretical uncertainties
dashed lines -> what the uncertainties would have been without the work of the theory community

[Zeynep Demiragli, DM@LHC 2018]
The Zoo of DM+X searches

ISR

Mono-jet

Mono-\gamma/V

Loop-induced

Higgs-Strahlung

VBF

HF-associated

and many more....
The Zoo of DM+X searches: backgrounds

**ISR**

Mono-jet

\[ \bar{q} \rightarrow q + \text{jets} + \chi \]

**V+jets**

**Mono-Higgs-Strahlung**

\[ \bar{q} \rightarrow q + V + \chi \]

**V+jets & ttbar**

**VBF**

\[ \bar{q} \rightarrow q + W^+ \rightarrow Z + \chi \]

\[ \bar{q} \rightarrow q + W^- \rightarrow Z + \chi \]

**HF-associated**

b+\[ V+b-jets \& V+jets \]

t+M\[ V+jets \& ttbar \]

tt+\[ ttbar \& V+jets \]

**Loop-induced**

**Mono-γ/V**

\[ \bar{q} \rightarrow q + VV \]

\[ \bar{q} \rightarrow q + VV \]

\[ q \rightarrow V + \gamma \text{ or } VV \]

**V+jets & Vγ / VV**

**V+jets & Vγ / VV**

**V+jets & Vγ / VV**
The Zoo of DM+X searches: backgrounds

- **ISR**
- **Higgs-Strahlung**
- **VBF**
- **HF-associated**

**Mono-jet**
- V+jets - \(\tilde{\chi}\)
- V+jets & ttbar
- V+jets & VBF-V

**Mono-\(\gamma\)/V**
- V+jets & V\(\gamma\) / VV
- V+jet & VBF-V

**Loop-induced**
- ...work in progress... stay tuned!
Indirect searches for new physics: disentangling very small effects

Look for BSM effects in small deviations from SM predictions:
→ Higgs processes natural place to look at
→ very good control on theory necessary!

→ Theory precision opens the door to new analysis strategies!
Precision goals for indirect searches

Imagine to have new physics at heavy scale $\Lambda$

Typical modification to observable w.r.t. SM predictions

Precision requirements for sensitivity on new physics

In the bulk:

$Q \gtrsim 500 - 1000$ GeV

$\rightarrow \sim 1\%$

In the tails:

$\rightarrow 10\%-20\%$

$\rightarrow$ requires state of the hard higher-order QCD+EW simulations
The fabulous four

$\Delta_{TH} \sim 5\%$

N3LO QCD + NLO EW

$\Delta_{TH} \sim 1-2\%$

NNLO QCD + NLO EW

$\Delta_{TH} \sim <0.5\%$

N3LO QCD + NLO EW

$\Delta_{TH} \sim 5\%$

NLO QCD + NLO EW
HV(+jet) at NLO+PS QCD+EW

[Granata, JML, Oleari, Pozzorini; '17]

- HV with H→bb allows to constrain Hbb coupling
- only feasible in boosted regime pT,V > 150-200 GeV
- in this regime impact of large (negative) virtual EW Sudakov corrections
- possible distortions of Z line-shape due to QED radiation

\[ \gamma, Z, W^\pm \]

\begin{align*}
\frac{d\sigma}{dp_T^H} &= 10^{-5} \text{ pb/GeV} \\
\frac{d\sigma}{dM^{e+e-}} &= 10^{-7} \text{ pb/GeV} \\
\frac{d\sigma}{dQ^2} &= 10^{-8} \text{ pb/GeV} \\
\end{align*}

\begin{itemize}
  \item pT of Higgs
    \begin{itemize}
      \item NLO EW: -10(-20)% > 200(800) GeV
      \item MiNLO ensures NLO QCD and NLO EW accuracy in the whole phase-space
    \end{itemize}
  \item Mll
    \begin{itemize}
      \item large QED effects due to radiative tail…
      \item …reliably modelled by QED-PS
      \item matching at NLO EW has to be resonance-aware
    \end{itemize}
\end{itemize}

one of the main bottlenecks in NLO EW + PS matching in MC tools

(as provided by POWHEG-BOX-RES) [Jezo & Nason; '15]
Top-mass

reconstruction using analytical distributions derived from simulated samples

precise value of top mass crucial for stability of EW vacuum

kinematic measurements strongly rely on MC modelling!
these are based on on-shell tt production @ NLO + LO decays
what about NLO in decay and off-shell effects?

Figure 5: Evolution of $\lambda$ top matching and top measurement uncertainties for $M_t = 173.39$ GeV.

In order to further illustrate the dependence of the vacuum stability problem on the top mass and the importance of the issues related to the top pole mass as an input parameter we show the evolution of $\lambda$ also for the PDG value extracted from cross section measurements of the top pole mass (5.1) and the corresponding uncertainties in Fig. 7. The conclusion for vacuum stability remains the same as in our previous works [10, 11, 13–15]. It looks as if $\lambda$ becomes negative at around $\log_{10}(\mu)$ (GeV) $\sim 9.6$ or $\log_{10}(\mu)$ (GeV) $\sim 8.7$ in Fig. 7) rendering the Standard Model extendable to scales above, but a definitive answer is pending on a more precise extraction of $y_t(\mu_0)$ from experimental data. It is worth noting,
top-pair production and decay

reconstruction using analytical distributions derived from simulated samples

CMS Dilepton, 19.7 fb^{-1} (8 TeV)

Data/MC

Events / 10 GeV

m_{\text{AMWT}} \ [GeV]

mtop = 172.82 \pm 0.19 \ (\text{stat}) \pm 1.22 \ (\text{syst}) \ GeV

- kinematic measurements strongly rely on MC modelling!
- these are based on on-shell tt production @ NLO + LO decays
- what about NLO in decay and off-shell effects?

In a traditional off-shell NLO+PS calculation: subtraction, matching and PS do not see/preserve intermediate resonances

⇒ NLO: efficiency problem
⇒ NLO+PS: distortion of important kinematic shapes!
top-pair production and decay

reconstruction using analytical distributions derived from simulated samples

CMS Dilepton, 19.7 fb\(^{-1}\) (8 TeV)

Data/MC

Events / 10 GeV

m_{t\bar{t}}^{AMW} [GeV]

top = 172.82 \pm 0.19 (stat) \pm 1.22 (syst) GeV

• kinematic measurements strongly rely on MC modelling!
• these are based on on-shell tt production @ NLO + LO decays
• what about NLO in decay and off-shell effects?

In a traditional off-shell NLO+PS calculation: subtraction, matching and PS do not see/preserve intermediate resonances

⇒ NLO: efficiency problem
⇒ NLO+PS: distortion of important kinematic shapes!
Reconstructed top-quark mass at NLO+PS

Different level of precision in top decays:

- Significant shape distortions around resonance with respect to on-shell $t\bar{t}$ calculation
- Very relevant for top mass determination
  - Average $m_{W_{J\beta}}$ roughly 500 MeV smaller in on-shell $t\bar{t}$ (in ±30 GeV around mtop)
- Very good agreement (mostly <5%) level between $b\bar{b}4\ell$ and $t\bar{t} \otimes$ decay
  - Average $m_{W_{J\beta}}$ roughly 100 MeV smaller in $tt$ decay (in ±30 GeV around mtop)

Note: Mtop measurements using this new off-shell modelling under way!
Interplay between top-pair and Wt single-top production

**4FS**

- unified treatment of top-pair and Wt including **interference**
- Wt enhanced in phase-space regions where one b becomes unresolved/vetoed
- requires off-shell WWbb calculation (with massive b's)

**5FS**

- NLO corrections to Wt swamped by LO tt+decay
- requires ad-hoc subtraction prescription: DRI, DRII, DSI, DSII
- NLO+PS for Wt available in MC@NLO [Frixione, et. al; '08], POWHEG [Re; '11] and Madgraph_aMC@NLO [Demartin et. al; '16]
Interplay between top-pair and Wt single-top production

\[ m_{b\ell}^{\text{minimax}} = \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\} \]

• sizeable tt-Wt interference expected for large \( m_{b\ell}^{\text{minimax}} \)
• very good data vs. off-shell 4FS agreement
• DR vs. DS yields conservative uncertainty estimate

Work in progress:
extension to semi-leptonic/hadronic top decays
Theoretical Predictions for the LHC

Different problems require different methods:

- LO
- LO+PS
- LO multi-jet merging
- NLO
- NLO+PS
- NLO+NNLL
- NLO multi-jet merging
- NNLO
- NNLO+PS
- NNLO+N3LL
- N3LO
Theoretical Predictions for the LHC

Different problems require different methods:

- Experimental reality
- \( LO \) → \( LO+PS \)
- \( LO \) multi-jet merging
- \( NLO \) → \( NLO+PS \)
- \( NLO+NNLL \)
- \( NLO \) multi-jet merging
- \( NNLO \) → \( NNLO+PS \)
- \( NNLO+N3LL \)
- \( N3LO \)
Theoretical Predictions for the LHC

Different problems require different methods:

- **LO**
- **LO multi-jet merging**
- **NLO**
- **NLO+PS**
- **NLO multi-jet merging**
- **NLO+NNLL**
- **NNLO**
- **NNLO+PS**
- **NNLO+N3LL**
- **N3LO**
Conclusions

- There is no clear scale/signature for new physics effects:
  Let's explore the unknown leaving no stone unturned!

- Use the right tool for the problem.

- Precision is key for both direct and indirect searches.

- Let's push the precision frontier!
BACKUP
With the discovery of the Higgs the SM is ‘complete’
The motivation for BSM searches are as compelling as ever

EW vacuum stability
Dark Matter
GUT unification
Neutrino masses
Hierarchy problem

\[ m_h^2 = (m_H^0)^2 + \frac{3A_t^2v^2}{8\pi^2} (m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2) \]
intrinsic V: MEPS@NLO QCD+EW$_{\text{virt}}$

- Bases on Sherpa’s standard MEPS@NLO
- Stable NLO QCD+EW predictions in all of the phase-space…
- …including Parton-Shower effects.
- Can directly be used by the experimental collaborations

\[ p_{T,V} : \text{MEPS@NLO QCD+EW} \]

in agreement with QCD$\times$EW (fixed-order)

\[ p_{T,j1} : \]
- merging ensures stable results (dijet topology at LO)
- compensation between negative Sudakov and LO mix

### Automation of NLO EW

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Process</th>
<th>Refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>MoCaNLO+Recola</td>
<td>$pp \rightarrow ll + 2 \text{jets}$, $pp \rightarrow e^+e^-\mu^+\mu^- / \mu^+\mu^- \mu^+\mu^- / e^+\nu_e\nu_\mu$</td>
<td>[1411.0916] [1601.07787] [1611.05338] [1607.05571] [1611.02951] [1708.00268] [1612.07138]</td>
</tr>
<tr>
<td></td>
<td>$pp \rightarrow e^+\nu_e\nu_\mu$ $\mu^+\nu_\mu$ $bb (tt)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$pp \rightarrow e^+\nu_e\nu_\mu$ + 2 jets (VBS)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$pp \rightarrow e^+\nu_e\nu_\mu$ $bbH (ttH)$</td>
<td></td>
</tr>
<tr>
<td>Sherpa/Munich+OpenLoops</td>
<td>$pp \rightarrow W+1,2,3 \text{jets}$</td>
<td>[1412.5156] [1511.08692] [1705.00598] [1706.03522]</td>
</tr>
<tr>
<td>POWHEG+OpenLoops</td>
<td>$pp \rightarrow ll/\nu\nu + 0, 1, 2 \text{jets} (V+jets)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$pp \rightarrow ll\nu\nu$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$pp \rightarrow llH/ll\nu H + 0,1 \text{jet} (HV)$</td>
<td></td>
</tr>
<tr>
<td>MadGraph_aMC@NLO+MadLoop</td>
<td>$pp \rightarrow tt+H/Z/W$</td>
<td>[1504.03446]</td>
</tr>
<tr>
<td></td>
<td>$pp \rightarrow tt$</td>
<td>[1606.01915] [1705.04105]</td>
</tr>
<tr>
<td></td>
<td>$pp \rightarrow 2 \text{jets}$</td>
<td>[1612.06548]</td>
</tr>
<tr>
<td>MadDipole+GoSam</td>
<td>$pp \rightarrow W+2 \text{jets}$</td>
<td>[1507.08579]</td>
</tr>
<tr>
<td>Sherpa+GoSam</td>
<td>$pp \rightarrow \gamma\gamma + 0,1,2 \text{jets}$</td>
<td>[1706.09022]</td>
</tr>
</tbody>
</table>

- many NLO QCD+EW calculations for **multi-particle processes** are becoming available
- NLO QCD+EW matching and merging with parton showers is under way (approximations available)
- Given the achieved automation: **attention is shifting towards detailed phenomenological applications**
off-shell vector-boson pair production: \( WW-\text{DF} \)

**Motivation:**
- important BSM background: **2 OS-DF leptons + MET**
- dominant \( H \to WW \to 2l2\nu \) background
- Search for aTGC’s

[Kallweit, JML, Pozzorini, Schönherr; ’17]

\( \sigma \rightarrow \mu^- \nu \bar{\nu}_\mu \) final states only in the case of same lepton flavour

\( +40\% \) QCD corrections in the tail (Note: slight jet veto applied)

\( \text{LARGE negative EW corrections due to Sudakov behaviour: } -40\% @ 1 \text{ TeV} \)

\( \text{MET} \)
- at large MET>MW: W’s are forced off-shell
- jump in QCD corrections (extra jet unlocks back-to-back)
- relatively small EW corr.: -10\% @ 1 \text{ TeV}
- sizeable photon-induced contrib.: 10\% for MET > 200 GeV

\( p_T, l_1 \)

\( pp \to e^+ \mu^- \nu_\mu \bar{\nu}_\mu \)
QCD uncertainties

\[
\frac{d}{dx} \sigma^{(V)}_{N^{LO}}(x) \varepsilon_{QCD} = \left[ K^{(V)}_{N^{LO}}(x) + \sum_{i=1}^{3} \varepsilon_{QCD,i} \delta^{(i)} K^{(V)}_{N^{LO}}(x) \right] \times \frac{d}{dx} \sigma^{(V)}_{N^{LO}}(\mu_0).
\]

- correlated across processes
- correlated across pT bins

nuisance parameters:
interpreted as 1σ Gaussian

- symmetrized scale uncertainty

yields max shape distortion within scale variation band
(correlated)

(important for extrapolation from low-pT to high-pT)

Difference of (N)NLO corrections as process correlation uncertainty
Mixed QCD-EW uncertainties

Given QCD and EW corrections are sizeable, also mixed QCD-EW uncertainties of relative have to be considered.

Additive combination
\[ \sigma_{\text{QCD+EW}}^{\text{NLO}} = \sigma^{\text{LO}} + \delta\sigma_{\text{QCD}}^{\text{NLO}} + \delta\sigma_{\text{EW}}^{\text{NLO}} \]

Multiplicative combination
\[ \sigma_{\text{QCD}\times\text{EW}}^{\text{NLO}} = \sigma_{\text{QCD}}^{\text{NLO}} \left( 1 + \frac{\delta\sigma_{\text{EW}}^{\text{NLO}}}{\sigma^{\text{LO}}} \right) \]

(try to capture some contributions, e.g. EW Sudakov logs × soft QCD)

Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

\[ K_{\text{QCD} \otimes \text{EW}} - K_{\text{QCD} \otimes \text{EW}} \sim 10\% \text{ at } 1\text{ TeV} \]

Too conservative?

For dominant Sudakov EW logarithms factorization should be exact!
Mixed QCD-EW uncertainties

Consider real correction to $V+\text{jet}$

\[ \approx \text{NLO EW to } V+2\text{jets} \]

and we observe

\[ \left| \frac{d\sigma_{\text{NLO EW}}}{d\sigma_{\text{LO}}} \right|_{V+2\text{jet}} - \left| \frac{d\sigma_{\text{NLO EW}}}{d\sigma_{\text{LO}}} \right|_{V+1\text{jet}} \lesssim 1\% \]

strong support for

- factorization
- multiplicative QCD × EW combination

$pT_{j,2} > 30 \text{ GeV}$
Mixed QCD-EW uncertainties

Estimate of non-factorising contributions

\[ \delta K_{mix}^{(V)}(x, \mu) = \zeta^{(V)} \left[ K_{TH,\oplus}^{(V)}(x, \mu) - K_{TH,\oplus}^{(V)}(x, \mu) \right] \]

\[ \zeta^{Z} = 0.1, \quad \zeta^{W} = 0.2, \quad \zeta^{\gamma} = 0.4 \]

(tuned to cover above difference of EW K-factors)

N-jettiness cut ensures approx. constant ratio V+2jets/V+jet

\[ \tau_1 = \sum_k \min \left\{ \frac{2p_t \cdot q_k}{Q_t \sqrt{s}} \right\} \]