(Getting ready for) precision physics at hadron colliders

Marco Zaro, LPTHE - UPMC Paris VI

FFP2014, Marseille
May 15th, 2014
Why do we need precision?
1) Discoveries at hadron colliders
I) Discoveries at hadron colliders

Peak

$$H \rightarrow \gamma \gamma$$

EASY

Background directly measured from data.
Theory needed only for parameter extraction.
1) Discoveries at hadron colliders

**Peak**

\[ H \rightarrow \gamma \gamma \]

**Shape**

\[ P P \rightarrow Z H \rightarrow \ell\ell + \text{inv.} \]

**EASY**

Background directly measured from data.
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**HARD**

Background **SHAPE** needed.
Flexible MC for both signal and background validated and tuned to data
I) Discoveries at hadron colliders

**Peak**

\[ H \rightarrow \gamma \gamma \]

**Shape**

\[ P P \rightarrow Z \ H \rightarrow \ell \ell + \text{inv.} \]

**Rate**

\[ P P \rightarrow H \rightarrow W^+ W^- \]

---

**EASY**

Background directly measured from data. Theory needed only for parameter extraction.

**HARD**

Background SHAPE needed. Flexible MC for both signal and background validated and tuned to data.

**VERY HARD**

Relies on prediction for both shape and normalization. Complicated interplay of best simulations and data.
New physics?

• No NP has been discovered yet
• Either there is no NP, or it is hiding very well
• If it is there, it will be a ‘Hard’ or ‘very Hard’ discovery
• Need for accurate predictions for signal and background
2) Measurement of parameters

- E.g.: Extracting the top mass from leptonic observables
- Start with pseudo-data with $m_t^{pd}=174.3$ GeV
- Use theoretical predictions with different accuracy

<table>
<thead>
<tr>
<th>TH. ACC.</th>
<th>$m_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLO+PS+MS</td>
<td>$174.48^{+0.73}_{-0.77}[5.0]$</td>
</tr>
<tr>
<td>LO+PS+MS</td>
<td>$175.98^{+0.63}_{-0.69}[16.9]$</td>
</tr>
<tr>
<td>NLO+PS</td>
<td>$175.43^{+0.74}_{-0.80}[29.2]$</td>
</tr>
<tr>
<td>LO+PS</td>
<td>$187.90^{+0.6}_{-0.6}[428.3]$</td>
</tr>
<tr>
<td>fNLO</td>
<td>$174.41^{+0.72}_{-0.73}[96.6]$</td>
</tr>
<tr>
<td>fLO</td>
<td>$197.31^{+0.42}_{-0.35}[2496.1]$</td>
</tr>
</tbody>
</table>

- Large differences appear in the reco $m_t$, due to different TH accuracies
- Better TH simulations improve central value and reliability of uncertainties

Frixione, Mitov arXiv:1407.2763
LHCPheNoNet
How to compute a cross-section

\[ \sum_{a,b} \int d\xi_1 d\xi_2 d\Phi_{FS} f_a(x_1, \mu_F) f_b(x_2, \mu_F) \hat{\sigma}_{ab} \rightarrow X (\hat{s}, \mu_F, \mu_R) \]

- Phase-space integral
- Parton density functions
- Parton-level cross section

Marco Zaro, 15-07-2014
Perturbation theory at work

\[ \hat{\sigma}_{ab \rightarrow X} \left( \hat{S}, \mu_F, \mu_R \right) \quad \text{Parton-level cross section} \]

- The parton-level cross section can be computed as a series in perturbation theory, using the coupling constant as an expansion parameter:

\[
\hat{\sigma} = \sigma^{\text{Born}} \left( 1 + \frac{\alpha_s}{2\pi} \sigma^{(1)} + \left( \frac{\alpha_s}{2\pi} \right)^2 \sigma^{(2)} + \left( \frac{\alpha_s}{2\pi} \right)^3 \sigma^{(3)} + \ldots \right)
\]
Perturbation theory at work

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**Diagrams:**
- LO predictions
- NLO corrections
- NNLO corrections
Perturbation theory at work

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Parton-level cross section

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\]

LO predictions

NLO corrections

NNLO corrections

NNNLO corrections

\[ \cdots \]

Marco Zaro, 15-07-2014
Perturbation theory at work
Perturbation theory at work

The inclusion of higher order improves the reliability of the computation
Perturbation theory at work

The inclusion of higher order improves the reliability of the computation

- Residual uncertainties decrease
The inclusion of higher order improves the reliability of the computation.

- Residual uncertainties decrease.

\( \sigma (pp \rightarrow H + X) \ [\text{pb}] \)

\( M_H \ [\text{GeV}] \)

\( \sqrt{s} = 14 \ \text{TeV} \)

From R. Harlander talk at HiggsHunting 2012
Perturbation theory at work

The inclusion of higher order improves the reliability of the computation

- Residual uncertainties decrease
- Better TH/EXP agreement, less need of fine-tuning
Perturbation theory at work

The inclusion of higher order improves the reliability of the computation:

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Higgs production via VBF (+1j) at the 13 TeV LHC:
$M_H = 125$ GeV, NLO + PS

Ratio over H+3j HW6 (H+2j not resc.)
Ratio over H+2j HW6 (PY8 x0.75)
Perturbation theory at work

The inclusion of higher order improves the reliability of the computation

- Residual uncertainties decrease
- Better TH/EXP agreement, less need of fine-tuning
- The computational complexity grows exponentially
Perturbation theory at work

The inclusion of higher order improves the reliability of the computation

- Residual uncertainties decrease
- Better TH/EXP agreement, less need of fine-tuning
- The computational complexity grows exponentially
- Several progress has been done, in particular in the very last years
- NLO mandatory for LHC analyses
NNNLO

- Progresses towards the first computation of key LHC processes at $N^3\text{LO}$
- $N^3\text{LO}$ for precision physics (e.g. Drell-Yan) or when corrections can be large (Higgs)
- No complete result available yet, approaches based on resummation

Ball, Bonvini, Forte, Marzani, Ridolfi, arXiv:1404.3204 & 1305.3590

Ahmed, Mandal, Rana, Ravindran, arXiv:1404.6504

Anastasiou, Duhr, Dulat, Mistlberger, arXiv:1302.4379
  + Herzog, arXiv:1311.1425
  + Furlan, Gehrmann, arXiv:1403.4616
NNLO
NNLO

• NNLO well-established techniques available
  (I won’t list them here, sorry!)
• 2→2 processes at reach
NNLO

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NNLO

- NNLO well-established techniques available (I won’t list them here, sorry!)
- $2 \rightarrow 2$ processes at reach

---

**Figure 1:**


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**NNLO**

- **NNLO** well-established techniques available (I won’t list them here, sorry!)
- 2→2 processes at reach

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**Figure 1:**

- **ZZ:** Cascioli et al. arXiv:1405.2219
- **Top pair:** Czakon et al. arXiv:1303.6254

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**TABLE II:** Pure NNLO theoretical predictions for various colliders and c.m. energies.

<table>
<thead>
<tr>
<th>Collider</th>
<th>NNLO/LO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron 1.8 TeV</td>
<td>NLO</td>
</tr>
<tr>
<td>LHC 7 TeV</td>
<td>NLO</td>
</tr>
<tr>
<td>LHC 8 TeV</td>
<td>NLO</td>
</tr>
<tr>
<td>LHC 14 TeV</td>
<td>NLO</td>
</tr>
</tbody>
</table>

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**CONCLUSIONS AND OUTLOOK**

- To assess the numerical impact from soft gluon re-
- Theoretical prediction at full NNLO+NNLL is very high.
- Next we compare our predictions with the most precise measurements at Tevatron prediction of Ref. [12] by about 4%
- Increasing the Tevatron prediction of Ref. [12] by about 4%
- In Table 1 we report the LO, NLO and NNLO cross sections and scale uncertainties, evaluated separately, (Tevatron, LHC7, LHC8, LHC14).
- The LHC and ATLAS experimental results at NNLO well-established techniques available.
NNLO

- NNLO well-established techniques available
  (I won’t list them here, sorry!)
- $2\rightarrow2$ processes at reach

And much more…

- top pair: Czakon et al. arXiv:1303.6254
- HH: de Florian et al. arXiv:1309.6594
- $\gamma\gamma$: Catani et al. arXiv:1110.2375

Marco Zaro, 15-07-2014
NNLO

• NNLO well-established techniques available (I won’t list them here, sorry!)
• $2 \rightarrow 2$ processes at reach
• Each new process implies a HUGE effort
e.g. $t\bar{t}$:
• 04/2012: $q\bar{q}$ initiated channel (Berneuther, Czakon, Mitov, arXiv:1204.5201)
• 10/2012: $qg$ initiated channel (Czakon, Mitov, arXiv:1210.6832)
• 03/2013: full calculation (Czakon, Mitov, arXiv:1303.6254)
NLO

• NLO evolution:
  • e.g. \( pp \rightarrow W^+ n \) jets

\[
\begin{align*}
\text{year} & \quad 1978 \quad 1989 \quad 2002 \quad 2009 \quad 2010 \quad 2013 \\
\text{\#virt diag} & \quad 2 \quad 43 \quad 416 \quad 4489 \quad 57026 \quad \ldots \\
\text{\( u\bar{d} \rightarrow W^+ \) ng} & \quad 43 \quad 416 \quad 4489 \quad 57026 \quad \ldots
\end{align*}
\]
NLO

• NLO evolution:
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<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>Altarelli, Ellis, Martinelli</td>
<td>Arnold, Ellis, Reno</td>
<td>Campbell, Ellis</td>
<td>BlackHat+Sherpa</td>
<td>Ellis, Melnikov, zanderighi</td>
<td>BlackHat+Sherpa</td>
</tr>
<tr>
<td>NLO revolution!</td>
<td>2009</td>
<td>2010</td>
<td>2013</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( n = )</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>( #\text{virt diag} )</td>
<td>2</td>
<td>43</td>
<td>416</td>
<td>4489</td>
<td>57026</td>
<td>...</td>
</tr>
<tr>
<td>( \bar{u}d \rightarrow W^+ n g )</td>
<td></td>
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</table>
NLO revolution

- Amazing development of computational techniques to tackle any process at NLO
  - Local subtraction
  - Computation of loop MEs
    - Tensor reduction
    - Generalized unitarity
    - Integrand reduction

Frixione, Kunszt, Signer, hep-ph/9512328
Catani, Seymour, hep-ph/9605323

Passarino, Veltman, 1979
Denner, Dittmaier, hep-ph/509141

Binoth, Guillet, Heinrich, Pilon, Reiter, arXiv:0810.0992

Ellis, Giele, Kunszt, arXiv:0708.2398
+ Melnikov, arXiv:0806.3467

Bern, Dixon, Dunbar, Kosower, hep-ph/9403226 + …
Ossola, Papadopoulos, Pittau, hep-ph/0609007

Del Aguila, Pittau, hep-ph/0404120

Mastrolo, Ossola, Reiter, Tramontano, arXiv:1006.0710
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  - Computation of loop MEs
  - Tensor reduction
  - Generalized unitarity
  - Integrand reduction

**MadGraph5_aMC@NLO**

fully automatic and public code available (since 2012)!

Alwall, Frederix, Frixione, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Hirschi, MZ
arXiv:1405.0301
Accurate and realistic
Accurate and realistic

- The parton-level picture is good for theorists, not much for experimentalists
- Realistic (i.e. hadron level) predictions are needed in order to compare with experiments
- Need to match parton-level computation with a parton shower
  - Trivial at LO
  - Non-trivial, but understood at NLO (automated & publicly available)
  - General proof of concept at NNLO
  - NNLO+PS predictions available for Higgs production and DY
- PS matching also cures ill-defined observables in perturbation theory

MC@NLO: Frixione, Webber, hep-ph/0204244
POWHEG: Nason, hep-ph/0409146
Alwall, Frederix, Frixione, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Hirschi, MZ arXiv:1405.0301
Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi, arXiv:1311.0286
Hamilton, Nason, Re, Zanderighi arXiv:1309.0017
Karlberg, Re, Zanderighi arXiv:1407.2940
Hoeche, Li, Prestel arXiv:1407.3773
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Advantages of automation

- *Better use of time:* spend time developing new ideas, not debugging codes
- *Reliability:* test building blocks, then results are correct by definition
- *Democracy:* automatic tools can be used as black boxes. No need for the user to know the underlying details, just to provide inputs (choose process and parameters)
<table>
<thead>
<tr>
<th>Vector-boson pair +jets</th>
<th>Process</th>
<th>Syntax</th>
<th>LO 13 TeV</th>
<th>NLO 13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>b.1 pp → W+V− (4f)</td>
<td>pp &gt; νν</td>
<td>7.355 ± 0.005 · 10^2</td>
<td>3.730 ± 0.001 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.2 pp → ZZ</td>
<td>pp &gt; Z Z</td>
<td>1.097 ± 0.002 · 10^2</td>
<td>1.415 ± 0.005 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.3 pp → ZZ</td>
<td>pp &gt; Z Z</td>
<td>2.777 ± 0.003 · 10^2</td>
<td>4.877 ± 0.001 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.4 pp → γγ</td>
<td>pp &gt; γ γ</td>
<td>2.510 ± 0.002 · 10^2</td>
<td>6.593 ± 0.001 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.5 pp → Z j</td>
<td>pp &gt; Z j</td>
<td>2.523 ± 0.002 · 10^2</td>
<td>3.695 ± 0.001 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.6 pp → W j</td>
<td>pp &gt; W j</td>
<td>2.954 ± 0.005 · 10^2</td>
<td>7.124 ± 0.002 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.7 pp → W+V− j (4f)</td>
<td>pp &gt; νν j</td>
<td>2.865 ± 0.003 · 10^2</td>
<td>3.703 ± 0.001 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.8 pp → ZZ j</td>
<td>pp &gt; Z Z j</td>
<td>3.662 ± 0.005 · 10^2</td>
<td>4.830 ± 0.001 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.9 pp → ZWW</td>
<td>pp &gt; Z W</td>
<td>1.605 ± 0.005 · 10^2</td>
<td>2.086 ± 0.007 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.10 pp → γγ j</td>
<td>pp &gt; γ γ j</td>
<td>1.022 ± 0.005 · 10^2</td>
<td>2.292 ± 0.010 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.11* pp → Zjj</td>
<td>pp &gt; Z j j</td>
<td>8.310 ± 0.017 · 10^2</td>
<td>1.220 ± 0.005 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.12* pp → Wjj</td>
<td>pp &gt; W j j</td>
<td>2.546 ± 0.010 · 10^2</td>
<td>3.713 ± 0.015 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.13 pp → W+V−jj (4f)</td>
<td>pp &gt; νν jj</td>
<td>1.484 ± 0.006 · 10^3</td>
<td>2.251 ± 0.011 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.14 pp → W+V− j j</td>
<td>pp &gt; νν jj</td>
<td>6.752 ± 0.007 · 10^2</td>
<td>1.003 ± 0.003 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.15 pp → W+V− j j (4f)</td>
<td>pp &gt; νν jj</td>
<td>1.144 ± 0.002 · 10^2</td>
<td>1.396 ± 0.005 · 10^2</td>
<td></td>
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<tr>
<td>b.16 pp → Zjj</td>
<td>pp &gt; Z jj</td>
<td>1.344 ± 0.002 · 10^2</td>
<td>1.706 ± 0.011 · 10^2</td>
<td></td>
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<tr>
<td>b.17 pp → Zjj</td>
<td>pp &gt; Z jj</td>
<td>8.038 ± 0.009 · 10^2</td>
<td>9.139 ± 0.010 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.18 pp → γγjj</td>
<td>pp &gt; γ γ jj</td>
<td>5.377 ± 0.002 · 10^2</td>
<td>7.501 ± 0.003 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.19* pp → Zjj jj</td>
<td>pp &gt; Z j j</td>
<td>3.260 ± 0.009 · 10^2</td>
<td>4.242 ± 0.016 · 10^2</td>
<td></td>
</tr>
<tr>
<td>b.20* pp → Wjj jj</td>
<td>pp &gt; W j j</td>
<td>1.233 ± 0.002 · 10^2</td>
<td>1.448 ± 0.005 · 10^2</td>
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<tr>
<td>c.1 pp → W+V− W+V− (4f)</td>
<td>pp &gt; νν</td>
<td>1.307 ± 0.003 · 10^3</td>
<td>2.109 ± 0.006 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.2 pp → ZZZ</td>
<td>pp &gt; Z Z Z</td>
<td>9.658 ± 0.005 · 10^2</td>
<td>3.855 ± 0.009 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.3 pp → ZZZ</td>
<td>pp &gt; Z Z Z</td>
<td>2.996 ± 0.016 · 10^2</td>
<td>5.550 ± 0.020 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.4 pp → ZZ</td>
<td>pp &gt; Z Z</td>
<td>1.085 ± 0.002 · 10^2</td>
<td>1.417 ± 0.005 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.5 pp → W+V− j j (4f)</td>
<td>pp &gt; νν jj</td>
<td>1.427 ± 0.011 · 10^3</td>
<td>2.581 ± 0.008 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.6 pp → γγW</td>
<td>pp &gt; γ γ W</td>
<td>2.681 ± 0.007 · 10^2</td>
<td>8.251 ± 0.032 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.7 pp → ZZ</td>
<td>pp &gt; Z Z</td>
<td>4.994 ± 0.011 · 10^2</td>
<td>1.117 ± 0.004 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.8 pp → ZZ</td>
<td>pp &gt; Z Z</td>
<td>2.320 ± 0.005 · 10^2</td>
<td>3.118 ± 0.012 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.9 pp → γγZ</td>
<td>pp &gt; γ γ Z</td>
<td>3.078 ± 0.007 · 10^2</td>
<td>4.634 ± 0.020 · 10^2</td>
<td></td>
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<td>c.10 pp → γγγ</td>
<td>pp &gt; γ γ γ</td>
<td>1.369 ± 0.003 · 10^3</td>
<td>4.446 ± 0.012 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.11 pp → W+V− W+V− j j</td>
<td>pp &gt; νν jj</td>
<td>9.167 ± 0.010 · 10^2</td>
<td>1.197 ± 0.004 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.12* pp → W+V− W+V− j j</td>
<td>pp &gt; νν jj</td>
<td>8.340 ± 0.010 · 10^2</td>
<td>1.066 ± 0.003 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.13* pp → W+V− W+V− j j</td>
<td>pp &gt; νν jj</td>
<td>2.410 ± 0.010 · 10^2</td>
<td>6.346 ± 0.025 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.14* pp → W+V− W+V− j j</td>
<td>pp &gt; νν jj</td>
<td>4.823 ± 0.011 · 10^2</td>
<td>1.233 ± 0.004 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.15* pp → W+V− W+V− j j</td>
<td>pp &gt; νν jj</td>
<td>1.182 ± 0.004 · 10^2</td>
<td>5.807 ± 0.023 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.16* pp → W+V− W+V− j j</td>
<td>pp &gt; νν jj</td>
<td>4.107 ± 0.015 · 10^2</td>
<td>7.764 ± 0.025 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.17* pp → ZZZ</td>
<td>pp &gt; Z Z Z</td>
<td>5.833 ± 0.023 · 10^2</td>
<td>3.827 ± 0.006 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.18* pp → ZZZ</td>
<td>pp &gt; Z Z Z</td>
<td>9.995 ± 0.013 · 10^2</td>
<td>1.371 ± 0.005 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.19* pp → γγZ</td>
<td>pp &gt; γ γ Z</td>
<td>1.372 ± 0.003 · 10^3</td>
<td>2.051 ± 0.011 · 10^2</td>
<td></td>
</tr>
<tr>
<td>c.20* pp → γγZ</td>
<td>pp &gt; γ γ Z</td>
<td>1.372 ± 0.003 · 10^3</td>
<td>2.051 ± 0.011 · 10^2</td>
<td></td>
</tr>
</tbody>
</table>
Application: Rare processes at the LHC

• Rare processes:
  multi Higgs, multi vector bosons, top pair+vector bosons…
• Very small cross-section (~1 fb or less) at 8 TeV
• Can provide very important informations about parameters (Higgs self coupling, tri- and quadri-linear vector coupling, …)
• Spectacular signatures (multi-jet/lepton/…), and background to NP
Application:
Rare processes at the LHC

Marco Zaro, 15-07-2014


I am grateful to S. Frixione, F. Maltoni, T. Gehrmann, and A. Papaefstathiou for helpful discussions.

Maximum center-of-mass energy, precision at the LHC •

Table 2: Production of multiple vector bosons at the LHC and at a 100 TeV FCC-hh. The rightmost column reports the differential cross sections.

\[ \sigma \text{(pp collisions at NLO in QCD)} \]
Application: Rare processes at the LHC

Rare processes at the LHC

Multiple Z production at pp colliders at NLO in QCD

$tW^+W^-$ production at 13 TeV LHC

$t\bar{t}V(V)$ production at

References

- S. Prestel and P. Torrielli, unpublished.
What about BSM?

• BSM signals typically simulated at LO (+PS, +merging)
  • LO is easier
  • NLO computations exist, but typically carried out on a process-by-process case
  • Bottleneck: NLO computations need extra model dependent Feynman rules (UV, $R_2$)
  • Extraction of extra Feynman rules typically is not worth the effort
• Automate the extraction of UV and $R_2$ terms
  • Achieved! (for renormalizable theories)
• Automatic NLO(+PS) predictions for BSM available!

DeGrande, arXiv:1406.3030
Conclusion

• Accurate predictions are strongly needed at the LHC, for both discoveries and parameter measurements
• Huge recent progresses
  • First approximate $N^3LO$ predictions for key processes
  • NNLO predictions for most of the $2\rightarrow 2$ processes
  • Automation of NLO computation, for SM and BSM, in a publicly available code
• Further directions: go beyond QCD
  • Automation of electro-weak corrections is on going

Actis, Denner, Hofer, Scharf, Uccirati, arXiv:1211.6316
Frixione, Hirschi, Pagani, Shao, MZ, arXiv:1407.0823
Yu, Wen-Zan, Ren-You, Chong, Lei, arXiv:1407.1110