QCD e fisica di precisione a LHC

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As of today

- As predicted in the SM, a new Yukawa force has been discovered, the first ever seen* not mediated by a gauge vector.

- Its mediator behaves a lot like the SM scalar: H-universality of the couplings

- No significant discrepancy with respect to the SM predictions

*fundamental, ie with elementary mediators.
As of today

- As predicted in the SM, a new Yukawa force has been discovered, the first ever seen* not mediated by a gauge vector.
- Its mediator behaves a lot like the SM scalar: H-universality of the couplings
- No significant discrepancy with the SM predictions
- No convincing sign of resonant new physics found so far
<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell, \gamma$</th>
<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>$\mathcal{L} dt$ [fb$^{-1}$]</th>
<th>Limit</th>
<th>Reference</th>
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<tbody>
<tr>
<td>ADD $G_{XX} \rightarrow g/q$</td>
<td>–</td>
<td>$\geq 1$</td>
<td>Yes</td>
<td>20.3</td>
<td>5.25 TeV</td>
<td>502.01518</td>
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<td>ADD non-resonant $\ell$</td>
<td>$2e, \mu$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>4.7 TeV</td>
<td>1407.2410</td>
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<tr>
<td>ADD $Q_{BH} \rightarrow t\bar{t}$</td>
<td>$1e, \mu$</td>
<td>1</td>
<td>–</td>
<td>20.3</td>
<td>5.2 TeV</td>
<td>1311.2006</td>
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<td>ADD $Q_{BH}$</td>
<td>$2\gamma$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>5.2 TeV</td>
<td>1407.1376</td>
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<tr>
<td>ADD BH high $\Sigma_{F}$</td>
<td>$2\mu$ (SS)</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>4.7 TeV</td>
<td>1308.4075</td>
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<tr>
<td>ADD BH high $\Sigma_{PT}$</td>
<td>$\geq 1e, \mu$</td>
<td>2</td>
<td>–</td>
<td>20.3</td>
<td>5.8 TeV</td>
<td>1456.4254</td>
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<tr>
<td>ADD BH high multijet</td>
<td>$2e, \gamma$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>5.8 TeV</td>
<td>1503.09986</td>
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<tr>
<td>RS1 $G_{XX} \rightarrow t\bar{t}$</td>
<td>$2e, \gamma$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>2.66 TeV</td>
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<tr>
<td>RS1 $G_{XX} \rightarrow gg$</td>
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<td>–</td>
<td>–</td>
<td>20.3</td>
<td>2.55 TeV</td>
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<tr>
<td>Bulk RS $G_{XX} \rightarrow ZZ \rightarrow q\bar{q}f\bar{f}$</td>
<td>$2e, \mu$</td>
<td>$2(\ell^+ J)$</td>
<td>20.3</td>
<td>4.66 TeV</td>
<td>1409.6190</td>
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<tr>
<td>Bulk RS $G_{XX} \rightarrow WW \rightarrow q\bar{q}f\bar{f}$</td>
<td>$1e, \mu$</td>
<td>2</td>
<td>$\ell^+ J$</td>
<td>20.3</td>
<td>4.66 TeV</td>
<td>1503.04677</td>
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<tr>
<td>Bulk RS $G_{XX} \rightarrow H^0 \rightarrow bb\bb$</td>
<td>$4b$</td>
<td>–</td>
<td>–</td>
<td>1506.00265</td>
<td></td>
<td></td>
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<tr>
<td>Bulk RS $G_{XX} \rightarrow tt$</td>
<td>$1e, \mu$</td>
<td>$\geq 1b, \geq 1/2$</td>
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<td>20.3</td>
<td>2.2 TeV</td>
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<td>2UED / RPP</td>
<td>$2e, \mu$ (SS)</td>
<td>$\geq 1b, \geq 1$</td>
<td>Yes</td>
<td>20.3</td>
<td>960 GeV</td>
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<td>SSM $Z \rightarrow \ell^+ \ell^-$</td>
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<td>–</td>
<td>20.3</td>
<td>2.8 TeV</td>
<td>1405.4123</td>
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<tr>
<td>SSM $Z \rightarrow \ell^+ \ell^-$</td>
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<td>–</td>
<td>–</td>
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<tr>
<td>SSM $W \rightarrow \ell^+ \ell^-$</td>
<td>$2e, \mu$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>3.24 TeV</td>
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<td>EGM $W \rightarrow \ell^+ \ell^-$</td>
<td>$2e, \mu$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>1.82 TeV</td>
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<tr>
<td>EGM $W \rightarrow \ell^+ \ell^-$</td>
<td>$2e, \mu$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>1.82 TeV</td>
<td>1409.1910</td>
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<tr>
<td>EGM $W \rightarrow \ell^+ \ell^-$</td>
<td>$2e, \mu$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>1.82 TeV</td>
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<tr>
<td>HVT $W \rightarrow W' \rightarrow t\bar{b}$</td>
<td>$2e, \mu$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>1.47 TeV</td>
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<tr>
<td>LRS$W_{L} \rightarrow tb$</td>
<td>$1e, \mu, 2b, 0-1$</td>
<td>Yes</td>
<td>20.3</td>
<td>1.92 TeV</td>
<td>1410.4103</td>
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<td>LRS$W_{R} \rightarrow tb$</td>
<td>$1e, \mu, 2b, 0-1$</td>
<td>Yes</td>
<td>20.3</td>
<td>1.92 TeV</td>
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<td>DM operator (Dirac)</td>
<td>$0e, \mu, 1 \geq 1$</td>
<td>Yes</td>
<td>20.3</td>
<td>974 GeV</td>
<td>1504.03567</td>
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<tr>
<td>DM operator (Dirac)</td>
<td>$0e, \mu, 1 \geq 1$</td>
<td>Yes</td>
<td>20.3</td>
<td>974 GeV</td>
<td>1504.03567</td>
<td></td>
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<tr>
<td>Scalar LQ 1st gen</td>
<td>$2e, \mu$</td>
<td>$\geq 2$</td>
<td>Yes</td>
<td>20.3</td>
<td>1.05 TeV</td>
<td>1502.01518</td>
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<td>Scalar LQ 2nd gen</td>
<td>$2e, \mu$</td>
<td>$\geq 2$</td>
<td>Yes</td>
<td>20.3</td>
<td>1.05 TeV</td>
<td>1309.6017</td>
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<tr>
<td>Scalar LQ 3rd gen</td>
<td>$2e, \mu$</td>
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<td>Yes</td>
<td>20.3</td>
<td>1.05 TeV</td>
<td>1504.04605</td>
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<tr>
<td>VLQ $TT \rightarrow Ht + X$</td>
<td>$1e, \mu$</td>
<td>$\geq 2b, \geq 3$</td>
<td>Yes</td>
<td>20.3</td>
<td>640 GeV</td>
<td>1505.04524</td>
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<td>VLQ $YY \rightarrow Wb + X$</td>
<td>$1e, \mu$</td>
<td>$\geq 2b, \geq 3$</td>
<td>Yes</td>
<td>20.3</td>
<td>T (Tb) doublet</td>
<td>1508.04936</td>
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<td>VLQ $BB \rightarrow HB + X$</td>
<td>$1e, \mu$</td>
<td>$\geq 2b, \geq 3$</td>
<td>Yes</td>
<td>20.3</td>
<td>770 GeV</td>
<td>1505.04306</td>
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<tr>
<td>VLQ $BB \rightarrow Zb + X$</td>
<td>$3e, \mu$</td>
<td>$\geq 2b, \geq 3$</td>
<td>Yes</td>
<td>20.3</td>
<td>735 GeV</td>
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<td>$T_{3/2} \rightarrow Wt$</td>
<td>$1e, \mu$</td>
<td>$\geq 2b, \geq 3$</td>
<td>Yes</td>
<td>20.3</td>
<td>840 GeV</td>
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<td>Excited quark $g' \rightarrow q\gamma$</td>
<td>$1 \gamma$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>3.5 TeV</td>
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<td>Excited quark $g' \rightarrow qg$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>4.09 TeV</td>
<td>1407.1376</td>
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<tr>
<td>Excited quark $b' \rightarrow Wt$</td>
<td>$1 \gamma$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>4.09 TeV</td>
<td>1301.5183</td>
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<tr>
<td>Excited lepton $\nu' \rightarrow \ell\nu, \gamma\nu$</td>
<td>$3e, \mu$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>1.6 TeV</td>
<td>1411.2921</td>
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<td>LSTC $\gamma \gamma \rightarrow WW$</td>
<td>$1e, \mu, 1 \gamma$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>870 GeV</td>
<td>1407.8150</td>
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<td>LSTC $\gamma \gamma \rightarrow WW$</td>
<td>$2e, \mu$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>870 GeV</td>
<td>1506.06020</td>
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<tr>
<td>Higgs triplet $H_{t}^{+} \rightarrow \ell\gamma$</td>
<td>$2e, \mu$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>2.0 TeV</td>
<td>1412.0237</td>
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<td>Higgs triplet $H_{t}^{+} \rightarrow \ell\gamma$</td>
<td>$3e, \mu$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>4.09 TeV</td>
<td>1410.4521</td>
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<td>Monopole (non-res prod)</td>
<td>$3e, \mu$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>557 GeV</td>
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<td>Multi-charged particles</td>
<td>$4e, \mu$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>785 GeV</td>
<td>1504.04188</td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown.*
Goals of the SM LHC programme

1. Precise determination of the fundamental parameters of the dim=4 SM lagrangian, such as masses ($m_h$, $m_W$, $m_t$), and couplings:
   - SM measurements of fundamental parameters provide information to be fed to the whole HEP community.
   - Range of validity of the SM

2. Search and quantification of deviations from the SM (New Physics).
Search for New Physics at the LHC

Two main strategies for searching new physics

**Search for new states**

**Search for new interactions**

“Peak” or more complicated structures searches. Need for **descriptive MC** for discovery = Discovery is data driven. Later need precision for characterisation.

Deviations are expected to be small. Intrinsically a precision measurement. Needs for **predictive MC** and accurate predictions for SM and EFT.
BSM goals of the SM LHC programme

Two main strategies for searching new physics

Search for new states

SUSY, EXOTICS, BSM HIGGS

Search for new interactions

SM

The matter content of SM has been experimentally verified and evidence for light states is not present. SM measurements can always be seen as searches for deviations from the dim=4 SM Lagrangian predictions.

\[ \mathcal{L}^{(6)}_{SM} = \mathcal{L}^{(4)}_{SM} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i + \ldots \]

BSM goal of the SM LHC program:

determination of the couplings of the SM lagrangian at DIM=6
Dim=6 SM Lagrangian

Based on all the symmetries of the SM

New physics is heavier than the resonance itself: $\Lambda >> M_X$

QCD and EW renormalizable (order by order in $1/\Lambda$)

Number of extra couplings reduced by symmetries and dimensional analysis

Extends the reach of searches for NP beyond the collider energy.

Valid only up to the scale $\Lambda$
BSM in SM dijets measurements

\[ \mathcal{L}_{NP} = \frac{1}{2\Lambda^2} (c_1 O_1 + c_2 O_2) \]

\[ O_1 = \delta_{ij} \delta_{kl} \left( \sum_{c=1}^{3} \bar{q}_L c_i \gamma_\mu q_L c_j \sum_{d=1}^{3} \bar{q}_L d_k \gamma^\mu q_L d_l \right), \]

\[ O_2 = \sum_{i,j,k,l} T^a_{ij} T^a_{kl} \left( \sum_{c=1}^{3} \bar{q}_L c_i \gamma_\mu q_L c_j \sum_{d=1}^{3} \bar{q}_L d_k \gamma^\mu q_L d_l \right), \]

\[ [\text{Gao et al, 2011}] \]

Calculation at NLO accuracy in the EFT. Both operators switched on because of mixing. Comparison with SM at NLO consistent.

Many other 4F operators possible, flavour structure to be constrained, NLO+PS. Other observables with quark-gluon tagging.
Master formula for the LHC

\[ \sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \rightarrow X} (x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}) \]

Accurate predictions for observables in hadronic collisions depend on the knowledge of both parton distribution functions and partonic x sections.
PDFs

Non-perturbative information that is fitted from a wealth of experimental data

• The pdf is parametrised at a given low scale in terms of an analytic or NN function and momentum sum rules are imposed.

• They are evolved through the DGLAP equations:

$$Q^2 \frac{\partial f_a(x, Q^2)}{\partial Q^2} = \int_x^1 \frac{dz}{z} P_{ab}(\alpha_S(Q^2), z) f_b(x/z, Q^2)$$

$$P_{ab}(\alpha_S, z) = \frac{\alpha_s}{2\pi} P_{ab}^{(0)}(z) + \left(\frac{\alpha_s}{2\pi}\right)^2 P_{ab}^{(1)}(z) + \left(\frac{\alpha_s}{2\pi}\right)^3 P_{ab}^{(2)}(z) + \ldots$$

PDFs

Global fits: recent progress in methodology and data sets:

- NNPDF3.0 1410.8849
- MMHTCT14 1412.3989
- CT14 1506.07443

<table>
<thead>
<tr>
<th></th>
<th>NNPDF3.0</th>
<th>MMHT14</th>
<th>CT14</th>
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<td>NO. OF FITTED PDFS</td>
<td>7</td>
<td>7</td>
<td>6</td>
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<td>PARAMETRIZATION</td>
<td>NEURAL NETS</td>
<td>$x^a (1 - x)^b \times$ CHEBYSCHEV</td>
<td>$x^a (1 - x)^b \times$ BERNSTEIN</td>
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<td>FREE PARAMETERS</td>
<td>259</td>
<td>37</td>
<td>30-35</td>
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<td>REPLICA</td>
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<td>TOLERANCE</td>
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<td>X</td>
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<td>CLOSURE TEST</td>
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<td>EIGENVECTORS</td>
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<tr>
<td>REWEIGHTING</td>
<td></td>
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</tbody>
</table>

Other non-global sets: HeraPDF, ABM14, GJR
2012
LHC 8 TeV - Ratio to NNPDF2.3 NNLO - $\alpha_s = 0.118$

Quark-Quark Luminosity

2015
Quark-Quark, luminosity

Gluon-Gluon
LHC 8 TeV - Ratio to NNPDF2.3 NNLO - $\alpha_s = 0.118$

Gluon-Gluon Luminosity

~3%
Perturbative expansion

\[ \hat{\sigma}_{ab \rightarrow X}(\hat{\mathcal{S}}, \mu_F, \mu_R) \] 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

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

- Including higher corrections improves predictions and reduces theoretical uncertainties: improvement in accuracy and precision.
Perturbative expansion

• Leading order (LO) calculations typically give only the order of magnitude of cross sections and distributions
  - the scale of $\alpha_s$ is not defined
  - jets partons: jet structure starts to appear only beyond LO
  - Born topology might not be leading at the LHC

• To obtain reliable predictions at least NLO is needed

• NNLO allows to quantify uncertainties

Furthermore:

• Resummation of the large logarithmic terms at phase space boundaries
• NLO ElectroWeak corrections ($\alpha_s^2 = \alpha_W$)
• Fully exclusive predictions available in terms of event simulation that can be used in experimental analysis
Predictions in QCD: before the LHC

pp→ n particles

accuracy [loops]

- Ⅲ 2
- Ⅱ 1
- Ⅰ 0

complexity [n]

- fully inclusive
- parton-level
- fully exclusive
Predictive MC (simplified) progress

- Merging and matching: ME+PS NLO+PS
- New Loop techniques
- Automatic NLO
- BSM
- Merging at NLO
- BSM at NLO+PS
- NNLO+PS
- First (LO) industrial revolution
- Second (NLO) industrial revolution
- Third (NNLO) industrial revolution?
NLO Basics

NLO contributions have three parts

\[ \sigma^{\text{NLO}} = \int_m d^{(d)} \sigma^V + \int_{m+1} d^{(d)} \sigma^R + \int_m d^{(4)} \sigma^B \]

Virtual part \hspace{1cm} Real emission part \hspace{1cm} Born

- Loops have been for long the bottleneck of NLO computations
- Virtuals and Reals are each divergent and subtraction scheme need to be used (Dipoles, FKS, Antenna’s)
- A lot of work is necessary for each computation

The cost of a new prediction at NLO used to exceed 100k\(\text{€}\).
New Loop techniques

For the calculation of one-loop matrix elements, several methods have been established and public tools released:

• Generalized Unitarity (ex. BlackHat, Rocket,...)
  [Bern, Dixon, Dunbar, Kosower, hep-ph/9403226 + ....; Ellis, Giele, Kunszt 0708.2398, +Melnikov 0806.3467]

• Integrand Reduction (ex. CutTools, Samurai)

• Tensor Reduction (ex. Golem, GoSam, MadLoop)
  [Passarino, Veltman, 1979; Denner, Dittmaier, hep-ph/0509141, Binoth, Guillet, Heinrivh, Pilon, Reiter 0810.0092]
The NLO Guinness World Records

\[ p\ p \rightarrow W + 5 \text{ jets} \]

\[
\begin{align*}
\sigma(W + N_{\text{jet}} \text{ jets}) & [\text{pb}] \\
\int L dt = 36 \text{ pb}^{-1} & \text{anti-}\kappa, R=0.4 \\
p_{T}^{\text{jet}} > 30 \text{ GeV, } |y_{\text{jet}}| < 4.4 \\
\text{Number of jets} & \\
N_{\text{jet}} & \\
\text{Inclusive Jet Multiplicity} \\
\end{align*}
\]

[Bern et al., 1304.1253]

\[ p\ p \rightarrow 5 \text{ jets} \]

\[
\text{Theory/Data} \\
\text{Inclusive Jet Multiplicity, } N_{\text{jet}} \\
\text{Theory / data} \\
\text{Inclusive Jet Multiplicity} \\
\]

[Badger et al. 1309.6585]
NLO+PS matching

Parton Shower Monte Carlo provide a simulation of all the stages of the hadronic collision: merge QCD matrix element + shower in the soft collinear approximation + hadronization model.

The **MC@NLO** and **POWHEG** methods allow to combine NLO calculations with existing shower/hadronisation programs such as PYTHIA8, HERWIG++, SHERPA....

POWHEG and MC@NLO implementations have same formal accuracy but differ in the amount of radiation that is exponentiated.

The MC@NLO method has been extended to deal with samples of different jet multiplicity (merging) keeping NLO accuracy (FxFx in MG5aMC, ME@NLOPS in SHERPA).

The POWHEG method has been extended via the MINLO technique to obtain inclusive samples without merging scales.
Automation of NLO+PS

- **MadGraph5_aMC@NLO** Alwall, Frederix, Frixione, FM, Mattelaer, Shao, Stelzer, Torrielli, Zaro et al, 0908.4272, 1103.062, 1104.5613, 1110.4738, 1110.5502, 1304.7927, 1305.7088, 1306.6464, 1311.1829, 1401.7340, 1405.0301, 1407.5089, 1409.5301, 1504.00611, 1507.05640, 1507.02549, 1508.05327…

  Fully automatic framework, where all the elements of a NLO+PS computation in the SM and (BSM) are automatically generated.

- **POWHEG-BOX** and applications: Alioli, Nason, Oleari, Re et al, 1002.2581, 1009.2450, 1009.5594, 1012.3380, 1102.4846, 1105.4488, 1107.5051, 1108.0909, 1310.4491, 1306.2442, 1311.1365, 1402.4001:

  Framework which allows to promote a standard NLO calculation into a MC at NLO generator. Very popular choice. More than ~30 processes implemented. Similar in spirit to MCFM.

- **SHERPA** Hoeche et al, 1008.5399, 1009.1127, 1111.1220, 1402.6293, 1403.7516

  Flexible framework having both MC@NLO and POWHEG methods based on CS dipoles, needs virtuals. Fully automatic except for virtuals which are taken from BlackHAT, OpenLoops, GoSam..
NLO+PS Automation

For example, the level of automation in MadGraph5_aMC@NLO is as follows:

```
./bin/mg5_aMC
> generate p p > t t~ W+ W- [QCD]
> output ttww
> launch
```

Uncertainties from scale variation and pdfs are automatically computed (at no extra cost) and associated to each of the unweighted events (=any distribution will have the corresponding uncertainty band). Short-distance events ready to be “dressed” by PS and hadronisation.

Virtually unlimited set of LHC processes available at NLO

[Alwall, et al. 1505.0301]
NLO+PS Automation

The same level of automation is being achieved for BSM:

[Degrande, Fuks, Hirschi,Proudom, Shao, 1412.5589, 1509.XXXX]

```
./bin/mg5_aMC
> import model SUSYQCD
> generate p p > t1 t1~ [QCD]
> output StopPair
> launch
```

```
./bin/mg5_aMC
> import model SUSYQCD
> generate p p > gl gl [QCD]
> output GluinoPair
> launch
```
The same level of automation is being achieved for EFT’s:

```
./bin/mg5_aMC
> import model TopEFT
> generate p p > t t~, NP=1 [QCD]
> output Chromott
> launch
```

```
./bin/mg5_aMC
> import model HC
> generate p p > X0 j j [QCD]
> output VBFdim6
> launch
```

[Franzosi and Zhang. 1503.08841]

[101 Congresso Nazionale della Società Italiana di Fisica]

[Mawatari, Zaro, FM: 1311.1829]
The NNLO era

NNLO calculations important at least for the following cases:

1) Benchmark processes measured with high precision
   - e+e- → 3 jets ✓
   - pp → W, Z ✓
   - pp → 2 jets partial
   - pp → t tbar ✓

2) Processes with large NLO corrections (eg, new channels)
   - pp → H (EFT) ✓
   - pp → H+jet (EFT) ✓
   - pp → HH (EFT) ✓

3) Important/Irreducible backgrounds for Higgs or NP searches
   - pp → t tbar ✓
   - pp → VV’ (W,γ,Z) ✓
   - pp → W/Z j ✓

In addition it is essential to provide codes that are able to deal with final state selections (at the parton level) so that fiducial cross sections and distributions can be directly compared with data.
Ingredients of NNLO calculations

Double virtual contribution with \( n \) resolved partons

Real-virtual contribution with 1 unresolved parton

Double-real contribution with 2 unresolved partons

Each of the three contributions is divergent, yet the sum is finite (KLN theorem). How to deal with IR singularities?
NNLO methods

There are two main approaches available in the literature:

1. Organise the calculation from scratch so as to cancel all the singularities
   - sector decomposition
   - antenna subtraction
   - “colourful” subtraction
   - joint use of subtraction and sector decomposition
   - qT subtraction
   - “N-jettiness” method
   - “Born projection” method for VBF

   ...and then of course the (sometimes extremely hard) two-loop amplitudes!

   G. Somogyi, Z. Trocsanyi, V. Del Duca (2005, 2007)
   M. Czakon (2010, 2011)
   R. Boughezal, K. Melnikov, F. Petriello (2011)

   S. Catani, M. Grazzini (2007)
   F. Tackmann et al. (2015)
V+jet at NNLO

Small NNLO effect and significant reduction of scale uncertainties. First application of new “N-jettiness” method: relatively flat NNLO correction.

Similar effects for Z+jet: antenna subtraction (large Nc approximation for the dominant channels)
H+jet

From a global fit the coupling of the higgs to the top is poorly determined: the loop could still be dominated by np.

[Grojean et al., 2013][Banfi et al. 2014]  [Buschmann, et al. 2014]

\[ O_{Hy} = H^\dagger H (H \bar{Q}_L) t_R \]
\[ O_{HG} = \frac{1}{2} H^\dagger HG_{\mu\nu}G_\mu^\dagger G_\nu^\dagger \]

EFT at NLO predictions available, yet SM NLO predictions are needed to control accuracy and precision. NLO prediction for H+1jet with top loops not yet available.
H+jet at NNLO (in the EFT)

NNLO calculation carried out with three independent methods (antenna subtraction, subtraction+sector, N-jettiness)


Quantitative effect smaller than previously anticipated from gg only: at the 20% level (μ=m_H)
VBF at NNLO

Vector boson fusion (VBF) is an important production channel for the Higgs boson: distinctive signature with little hadronic activity in the central rapidity region.

Fully inclusive NNLO corrections known since quite some time [P.Bolzoni, F.M, S.Moch, M.Zaro (2010)] in the structure function approach: O(1%) effect.

Fully exclusive NNLO computation recently completed (still neglecting color exchanges between quark lines) [M.Cacciari, F.Dreyer, A.Karlberg, G.Salam, G.Zanderighi (2015)]

NNLO corrections make $p_T$ spectra softer larger impact when VBF cuts are applied

<table>
<thead>
<tr>
<th></th>
<th>$\sigma^{(\text{no cuts})}$ [pb]</th>
<th>$\sigma^{(\text{VBF cuts})}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO</td>
<td>$4.032^{+0.057}_{-0.069}$</td>
<td>$0.957^{+0.066}_{-0.059}$</td>
</tr>
<tr>
<td>NLO</td>
<td>$3.929^{+0.024}_{-0.029}$</td>
<td>$0.876^{+0.008}_{-0.018}$</td>
</tr>
<tr>
<td>NNLO</td>
<td>$3.888^{+0.016}_{-0.012}$</td>
<td>$0.826^{+0.013}_{-0.014}$</td>
</tr>
</tbody>
</table>
Monumental MILESTONE in perturbative QCD:

[Bärnreuther, Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Fiedler, Mitov 2013]

- Two loop hard matching coefficient extracted and included
- Very weak dependence on unknown parameters (sub 1%): gg NNLO, A, etc.
- ~50% scales reduction compared to the NLO+NNLL analysis

\[ \text{\ttbar cross section at NNLO} \]
\( \bar{t}t \) cross section at NNLO

Having a NNLO prediction opens the door to new possibilities.

Consider the light stop window in a compressed spectrum, that mimicks the normal \( \bar{t}tbar \) production:

[Czakon, Mitov, Papucci, Ruderman, Weiler, 2014]
The asymmetry at NLO accuracy (from the NNLO total cross section calculation) is sizeably larger and much more precise than the LO result.
t\bar{t} at NNLO: differential distributions

The first differential distributions at NNLO for the p_T (top), y(top), m(ttbar):

[Czakon, Fiedler, Heymes, Mitov.; in preparation]

Good perturbative convergence. Improved precision.
\( \bar{t}t \) at NNLO: differential distributions

For the first time the issue of “a softer than NLO” \( p_T \) (top) has been seen in data can be studied. NNLO predictions seem to go in the direction of data.

[Czakon, Fiedler, Heymes, Mitov.; in preparation]
NNLO + PS

NLO matching well established, while NNLO matching still in its infancy

1) **NNLOPS**: use MINLO to obtain a NLO generator for both H and H+jet(s)  

2) **UN2LOPS**: use S-MC@NLO + UNLOPS + \(q_T\) slicing  
[N.Lavesson, L.Lonnblad (2008), S.Hoeche,Y.Li, S.Prestel (2014)]

Enforce correct NNLO normalisation by reweighing the inclusive rapidity distribution to the NNLO calculation

NNLO virtual corrections confined in the low \(p_T\) region while in the POWHEG-MINLO approach they are spread over the whole \(p_T\) region
The frontier: N3LO

[C.Anastasiou, C.Duhr, F.Dulat, F.Herzog, B.Mistlberger (2015)]

Full calculation for the gg → H completed through the evaluation of 30 terms in the soft-expansion: first ever complete calculation at N3LO in hadronic collisions.

Significant reduction of uncertainties from missing higher orders and PDF+αs

Scale dep. stabilizes around μ=m_H/2

N3LO effect +2.2% at μ=m_H/2

Corresponding new results for the Higgs cross section including mass effects at NLO and the other known corrections at 13 TeV expected soon.
The best predictions for Higgs production include threshold resummation effects.

Results of systematically including the resummation of the threshold logs points towards a stabilisation of the scale dependence.

Such a flat behaviour puts into question the reliability of very method that we use to evaluate the effects of unknown higher-order contributions through scale variation.
Predictions in QCD: before the LHC

$pp \rightarrow n$ particles

Accuracy [loops]

- Fully inclusive
- Parton-level
- Fully exclusive

Complexity [n]
Predictions in QCD for the LHC: status 2015

pp→ n particles

accuracy [loops]

<table>
<thead>
<tr>
<th>Complexity [n]</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully exclusive</td>
<td>red</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parton-level</td>
<td></td>
<td>yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fully exclusive and automatic</td>
<td>green</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

The graph illustrates the accuracy of predictions in QCD for the LHC, with different complexities and accuracies represented by colored dots.
Summary

• The LHC physics program demands predictions at an unprecedented level of accuracy and precision.

• Rapid and impressive progress in techniques in the last few years has lead to:
  - Full automation of the computation of NLO QCD corrections and their matching/merging with parton shower program: experimental grade predictions are now available for SM and BSM (resonant and in EFTs). Automatic NLO EW is being achieved now.
  - The new era of differential predictions at NNLO in QCD for a every-day increasing set of important SM processes $2 \rightarrow 2$, such as $H+\text{jet}$, $V+\text{jet}$, $VV$, $t\bar{t}$ production. In addition first exploration of NNLO+PS for $2 \rightarrow 1$ process has started.
  - Moving the frontier to N3LO.

• Main outcomes:
  - Progress in understanding of QCD and pp collisions at high $Q^2$
  - TH Ready for Run II LHC
Credits

A special thank to the italian TH QCD/MC at LHC community, currently working in Italy or abroad, great collaborators and precision passionates (rnd order):

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