Theory meets experiment at the LHC

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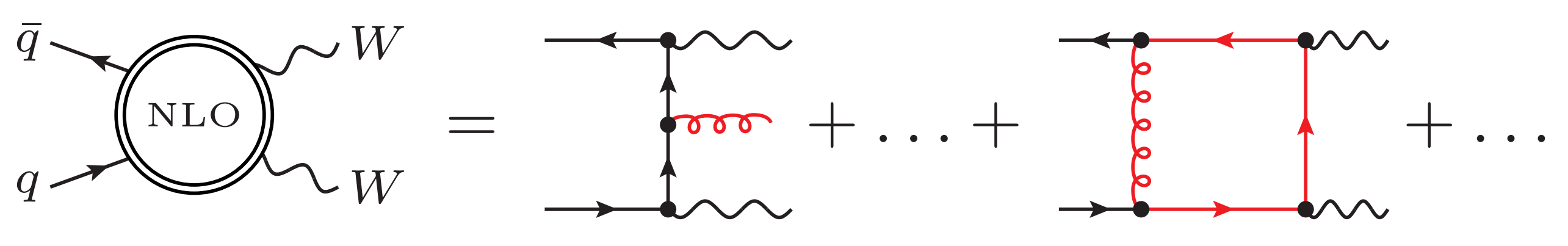
Motivation

Colliding protons at the TeV energy scale, the Large Hadron collider (LHC) probes fundamental particles and their interactions with a resolution that corresponds to **one billionth of the size of an atom**. After the discovery of the **Higgs boson** in 2012, the LHC will run for another two decades. The goal of this huge campaign of measurements is to find first evidence for the existence of **physics Beyond the Standard Model** of particle physics (BSM).

BSM signals turned out to be more elusive than originally expected, and, so far, **LHC data are well consistent with the Standard Model** (SM). In this context, possible BSM phenomena are likely to emerge in the form of **small anomalies** in precision observables or in the high-energy tails of distributions. Thus **precise theoretical predictions** based on the SM are becoming an increasingly important ingredient of the physics program of the LHC.

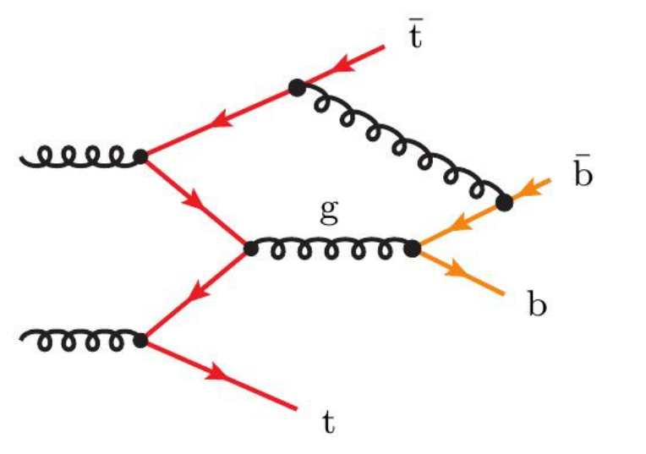
Higher-order calculations

Theoretical calculation are based on perturbation theory, and their **complexity grows extremely fast** with the perturbative order and the number of scattering particles.



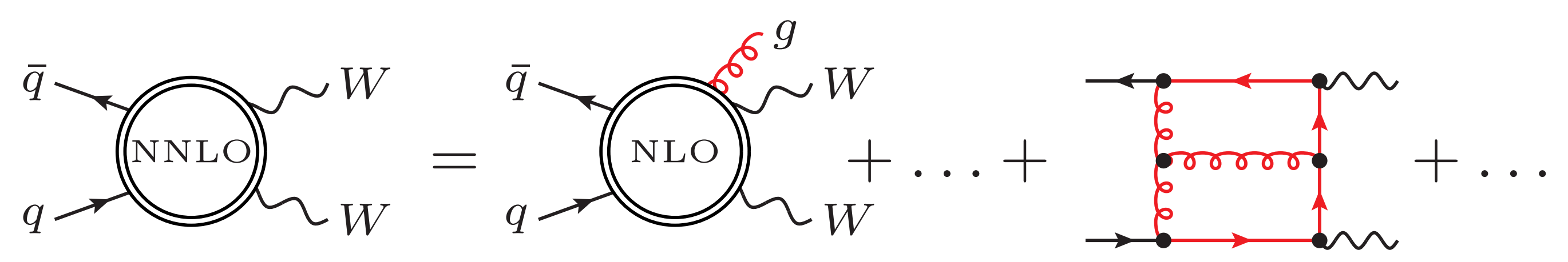
Scattering processes at the **next-to-leading order (NLO)** involve Feynman diagrams with one additional real or virtual particle, and NLO calculations are mandatory for a realistic prediction.

NLO multiparticle and NNLO

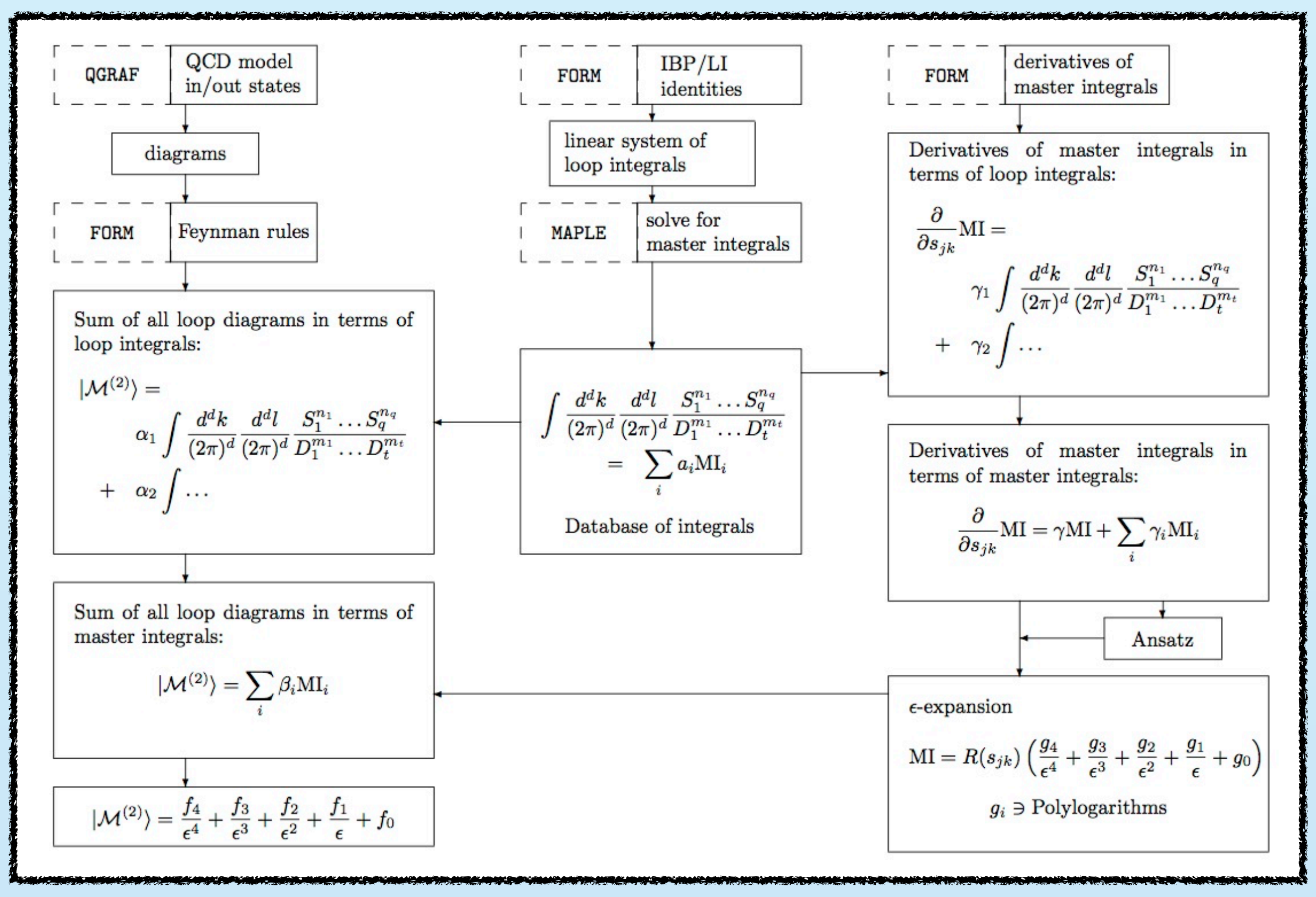


Thanks to recent new methods, nowadays we can perform NLO calculations for a wide spectrum of **multi-particle processes** in a **highly automated** way.

High precision requires **next-to-next-to-leading order (NNLO)** calculations, which involve two real or virtual extra particles



Computer algebra



QGRAF | QCD model in/out states

diagrams

FORM | Feynman rules

Sum of all loop diagrams in terms of loop integrals:

$$|\mathcal{M}^{(2)}\rangle = \alpha_1 \int \frac{d^dk}{(2\pi)^d}\frac{d^dl}{(2\pi)^d}\frac{S_1^{n_1}\dots S_q^{n_q}}{D_1^{m_1}\dots D_t^{m_t}} + \alpha_2 \int \dots$$

Sum of all loop diagrams in terms of master integrals:

$$|\mathcal{M}^{(2)}\rangle = \sum_i \beta_i \mathrm{MI}_i$$

$$|\mathcal{M}^{(2)}\rangle = \frac{f_4}{\epsilon^4} + \frac{f_3}{\epsilon^3} + \frac{f_2}{\epsilon^2} + \frac{f_1}{\epsilon} + f_0$$

FORM | IBP/LI identities

linear system of loop integrals

MAPLE | solve for master integrals

$$\int \frac{d^dk}{(2\pi)^d}\frac{d^dl}{(2\pi)^d}\frac{S_1^{n_1}\dots S_q^{n_q}}{D_1^{m_1}\dots D_t^{m_t}} = \sum_i a_i \mathrm{MI}_i$$

Database of integrals

FORM | derivatives of master integrals

Derivatives of master integrals in terms of loop integrals:

$$\frac{\partial}{\partial s_{jk}}\mathrm{MI} = \gamma_1 \int \frac{d^dk}{(2\pi)^d}\frac{d^dl}{(2\pi)^d}\frac{S_1^{n_1}\dots S_q^{n_q}}{D_1^{m_1}\dots D_t^{m_t}} + \gamma_2 \int \dots$$

Derivatives of master integrals in terms of master integrals:

$$\frac{\partial}{\partial s_{jk}}\mathrm{MI} = \gamma \mathrm{MI} + \sum_i \gamma_i \mathrm{MI}_i$$

Ansatz

ϵ-expansion

$$\mathrm{MI} = R(s_{jk})\left(\frac{g_4}{\epsilon^4} + \frac{g_3}{\epsilon^3} + \frac{g_2}{\epsilon^2} + \frac{g_1}{\epsilon} + g_0\right)$$

$g_i \ni$ Polylogarithms

Loop corrections to scattering amplitudes are the key ingredient to higher order calculations. Their analytic computation requires extensive use of **computer algebra**. Calculations are implemented into computer algebra programmes such as FORM, Mathematica or Maple, and specialized packages for applications in particle theory are developed.

Numerical implementation

LHC experiments measure final state particles only in a limited phase space range

A theoretical calculation must be **fully differential** so as to allow the computation of **fiducial cross sections and distributions**

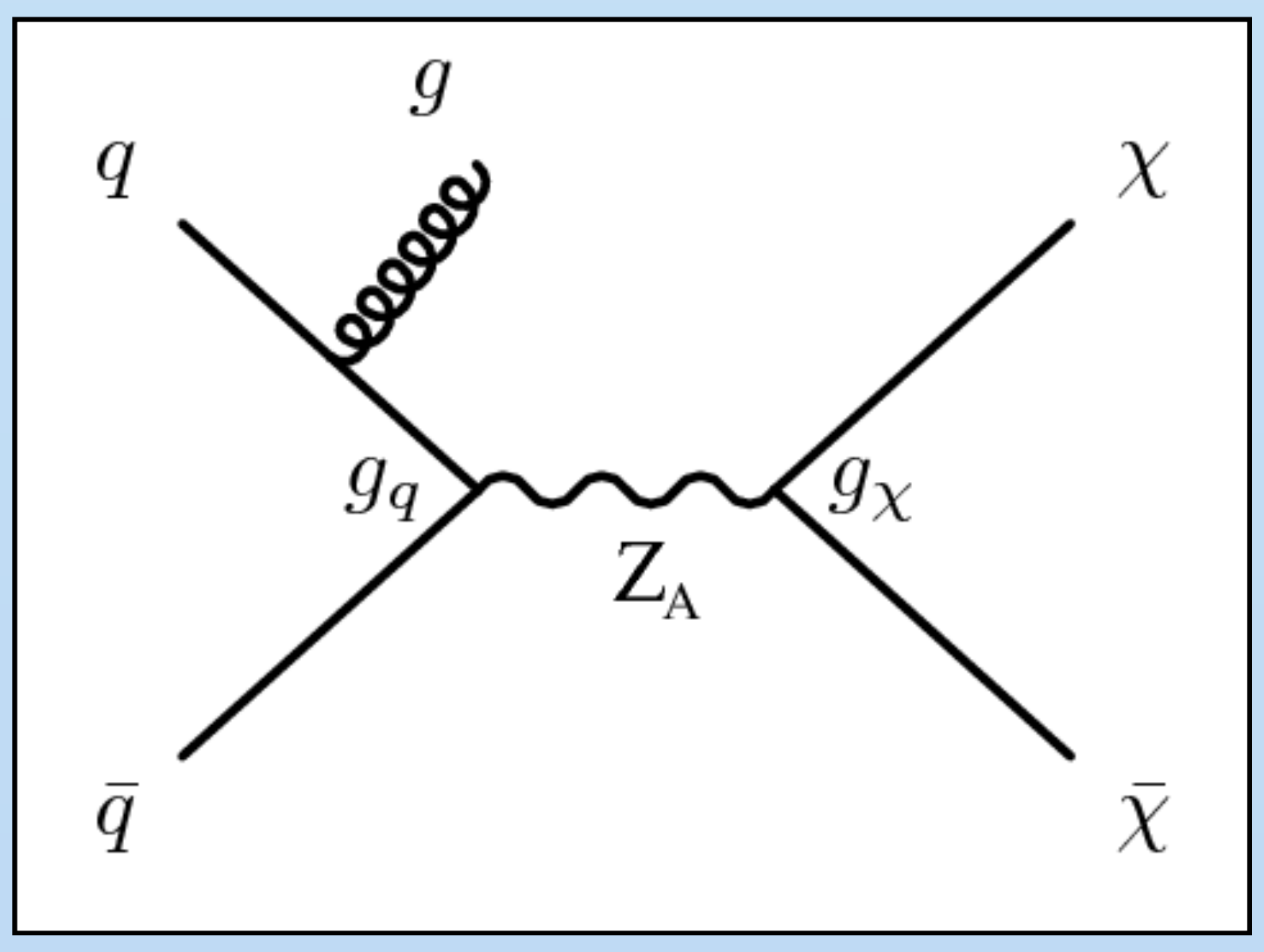
The computation of **fiducial cross sections and distributions** at the NNLO requires the combination of virtual and real contributions that are separately affected by **infrared singularities**. Only the sum of all the contributions is finite, and methods to achieve this cancellation have to be developed and **numerically implemented**.

The q_T subtraction method is one of these:

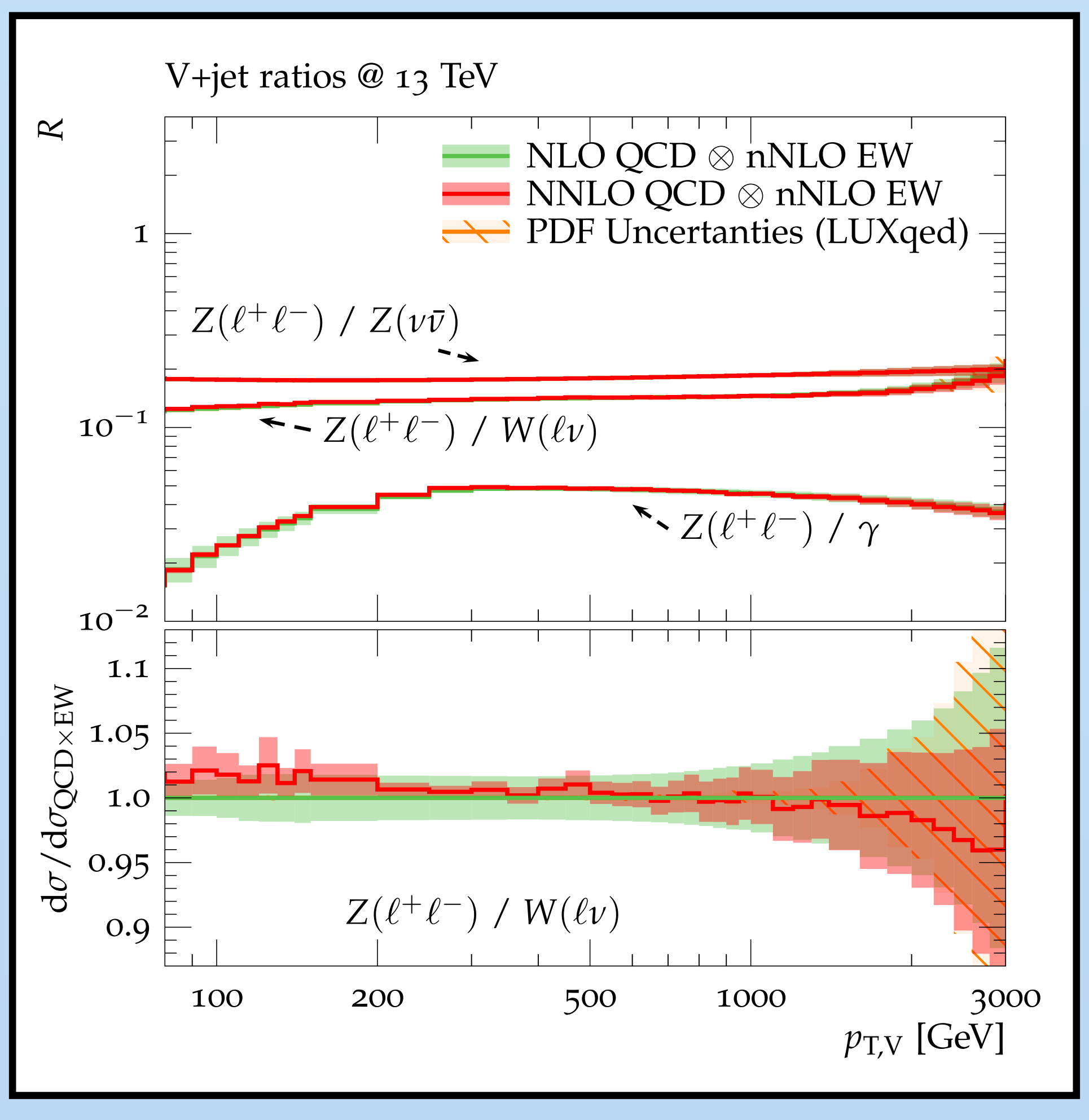
$$d\sigma^{F}_{(N)NLO} = \mathcal{H}^{F}_{(N)NLO} \otimes d\sigma^{F}_{LO} + \left[d\sigma^{F+jet}_{(N)LO} - d\sigma^{CT}_{(N)NLO}\right]$$

Dark matter searches

Mono-jet signatures with large missing energy are powerful probes of dark matter at the LHC. Such dark-matter searches require a precise control of the **Z+jet background with invisible Z-decays**, which is achieved by a theory driven extrapolation of W+jet and photon+jet data to Z+jet.



The most recent calculations have reduced theory uncertainties to the percent level, opening the door to **strong sensitivity improvements in mono-jet searches.**



Vector boson pair production

The recent series of **NNLO calculations for all di-boson processes** is a crucial step forward for the full exploitation of the physics potential of LHC data, both for **Standard Model tests** and in **exotic searches** with di-boson backgrounds.