AUTOMATED CALCULATIONS FOR COLLIDERS

N. Giraudo, F. Herren

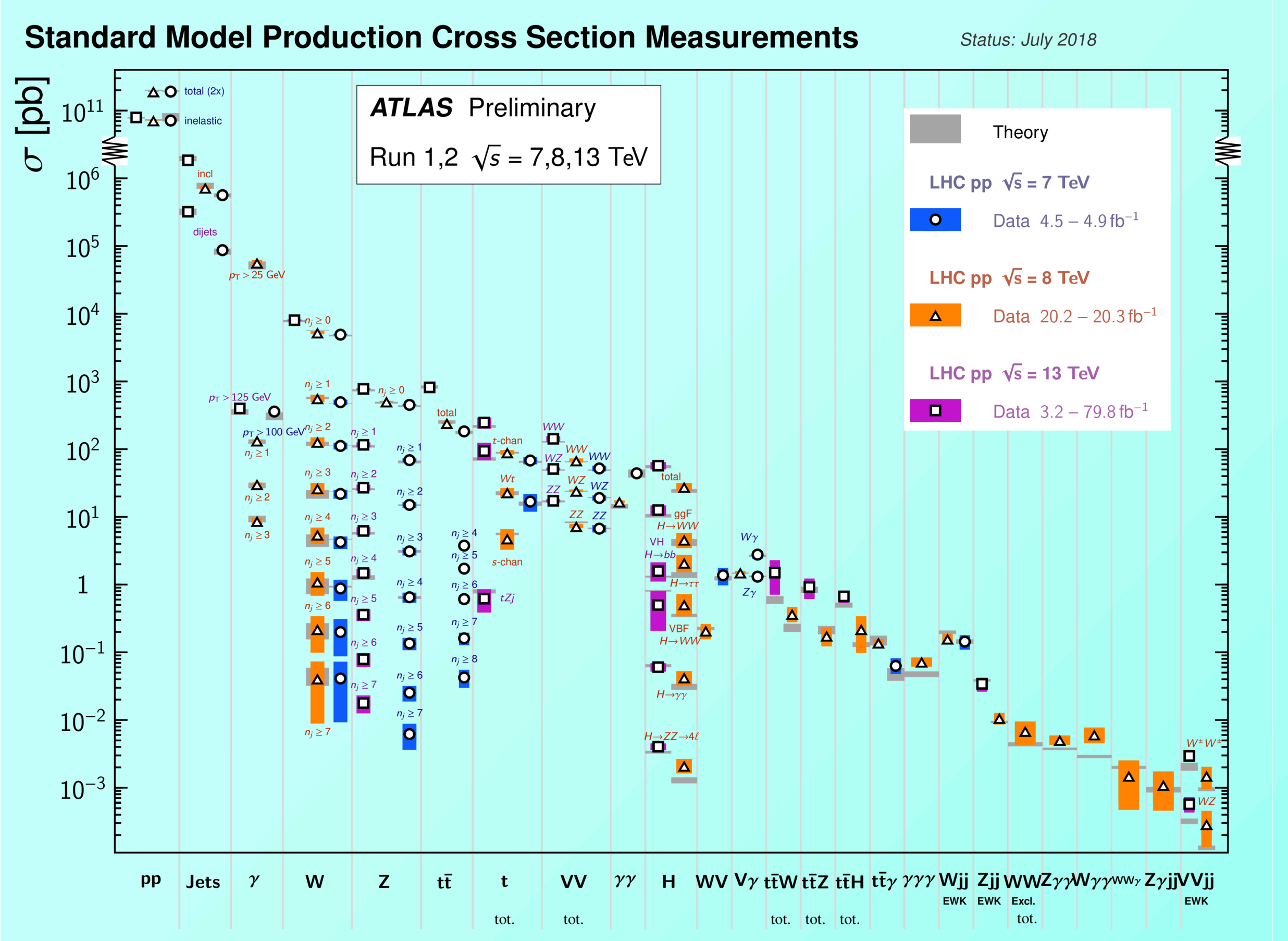
Universität ZürichUZH

Group of Stefano Pozzorini

WHY

$$\begin{aligned} L = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\Psi + h.c. \\ & - \bar{\Psi}_i y_{ij}\Psi_j\Phi + h.c. \\ & - |D_\mu\Phi| - V(\Phi) \end{aligned}$$

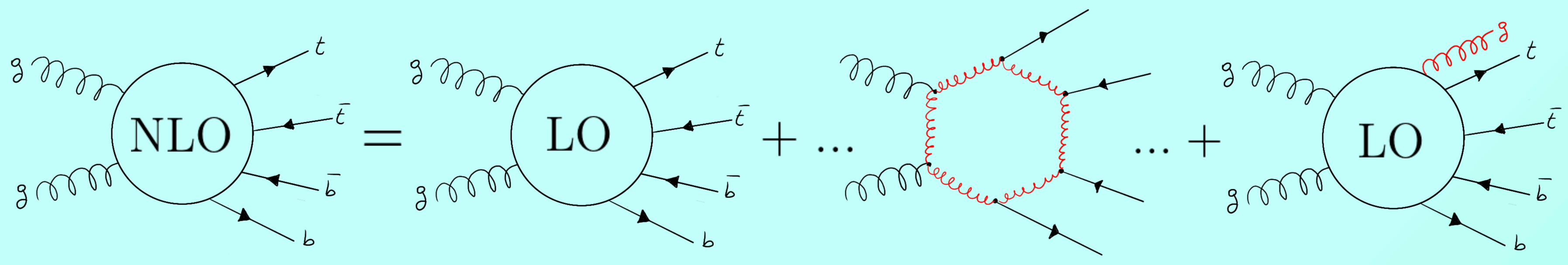
The main goal of the LHC is to test the Standard Model of Particle Physics (SM) and search for new physics up to the TeV energy scale.
To this end, the LHC experiments are collecting data for a **vast range of scattering processes**, where different combinations of quarks, gluons, photons, charged leptons, neutrinos and Higgs bosons are produced.
To test the SM, such data need to be compared against **precise theoretical predictions** based on the Standard Model Lagrangian.



WHAT

In perturbative quantum field theory, scattering processes can be described through Feynman diagrams. At leading order only tree diagrams contribute, while the higher orders also involve **loop diagrams**, which require the calculation of nontrivial loop integrals. Already at the next-to-leading order (NLO), the number of required loop diagrams and their **complexity grow extremely fast** with the number of scattering particles. This challenge has triggered the development of new techniques and **automated tools for NLO calculations.**

1-loop diagrams for pp$\to t\bar{t}+Nj$	$N=0$	1	2	3
$gg\to t\bar{t}+Ng$	47	630	9438	152070
$u\bar{u}\to t\bar{t}+Ng$	12	122	1608	23835
$u\bar{u}\to t\bar{t}u\bar{u}+(N-2)g$	–	–	506	6642
$u\bar{u}\to t\bar{t}d\bar{d}+(N-2)g$	–	–	252	3321



LO and NLO virtual and real ingredients of $pp\to t\bar{t}b\bar{b}$

OpenLoops is a fully automated public tool for one-loop calculations, which was developed within our group.
It is based on a **process-independent algorithm**, where all one-loop diagrams are constructed through the recursive multiplication of loop vertices and loop propagators.
All needed loop integrals are reduced to a small set of standard integrals that are known in analytic form.
The OpenLoops algorithm depends only on the Feynman rules of the SM and can be applied to any scattering processes.

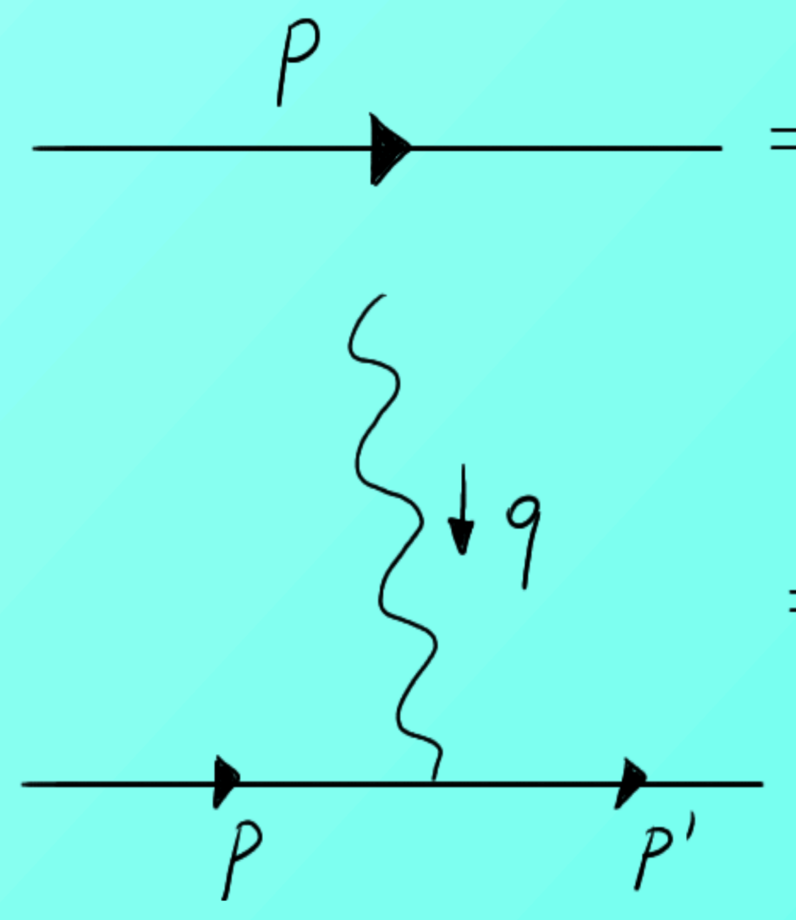
NOW

$$\sum_\Gamma\sum_r N_{\mu_1,\ldots,\mu_r}\int\frac{q^{\mu_1}\ldots q^{\mu_r}}{D_0(q)\ldots D_{N-1}(q)}$$

Numerical Coefficients

Analytic Integration

OpenLoops is interfaced to some of the main Monte Carlo generators (Sherpa, Powheg) that are used for the **analysis of LHC data**.
Moreover, within the theory community, OpenLoops is widely used to obtain nontrivial one-loop amplitudes that are needed in the context of Next-to-next-to-leading order (NNLO) calculations.

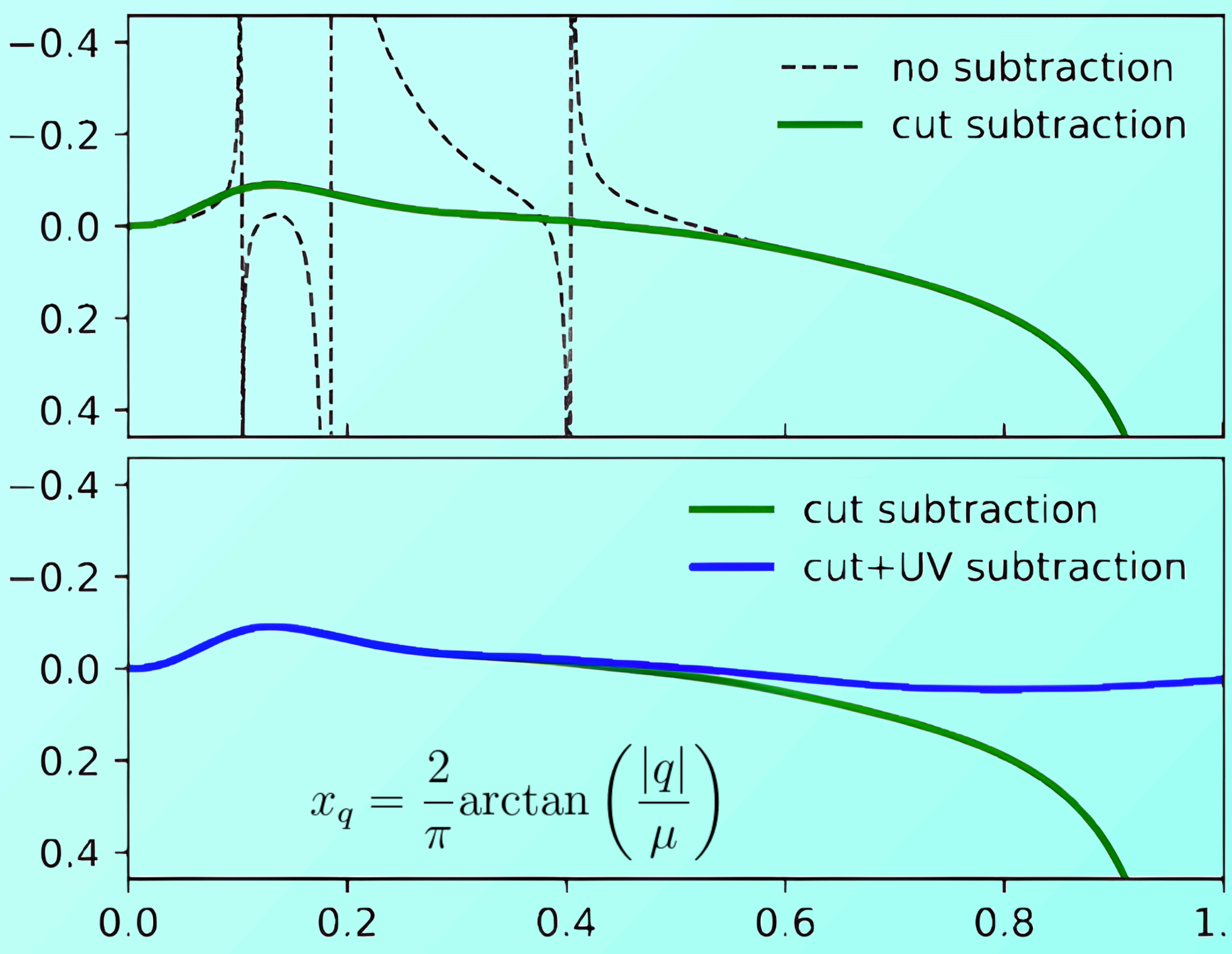


$$= \frac{i(\not{p}+m)}{p^2-m^2+i\epsilon}$$

$$= \frac{ie}{2m}(p+p')$$

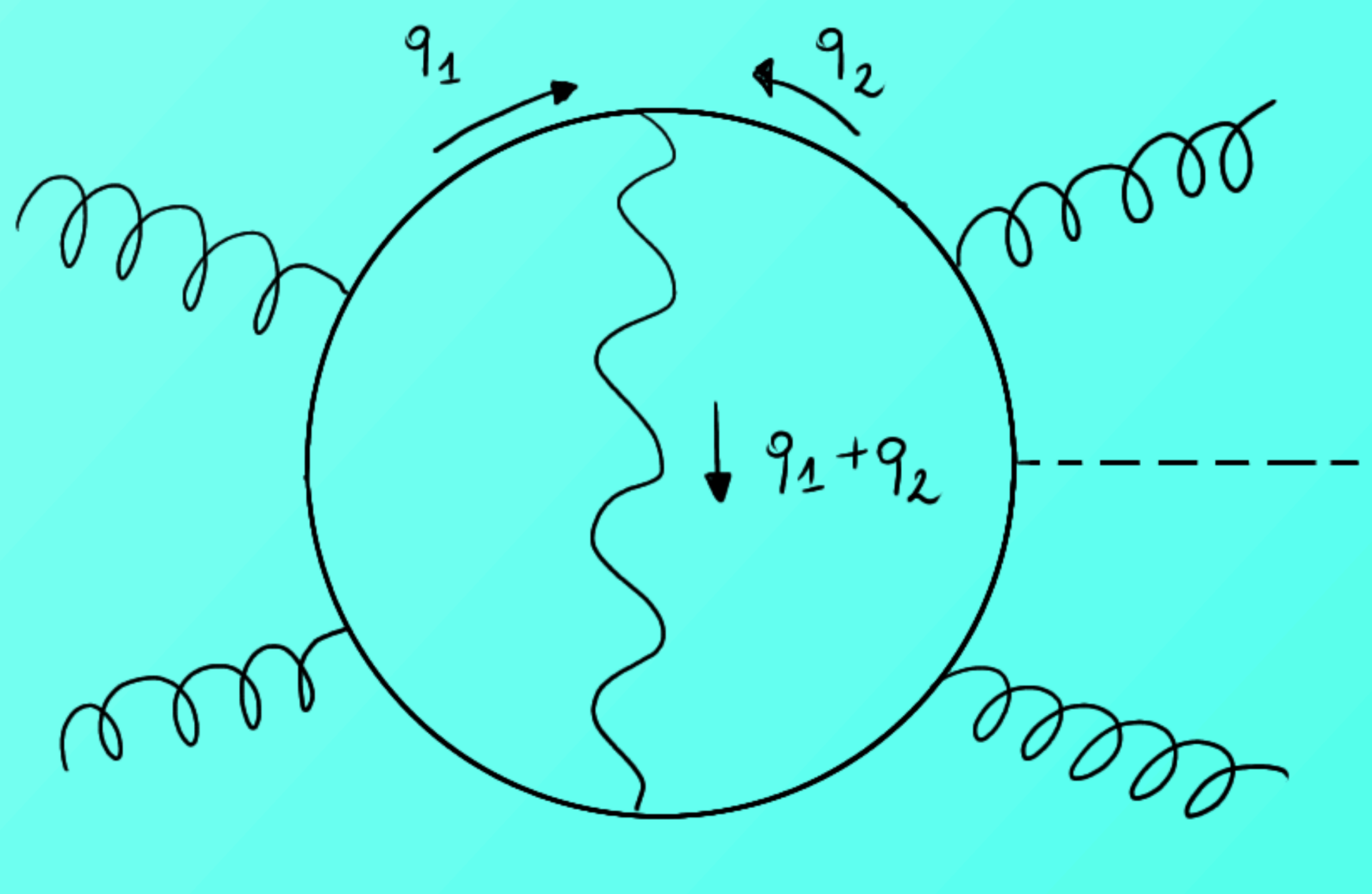
Feynman Rules for the propagation and interaction in QFT

NEXT



Local cancellation of threshold and UV one-loop singularities in loop-momentum space

In the recent past NNLO predictions became available for an increasing number of scattering processes.
However, the increasing precision of LHC data requires NNLO predictions for a number of highly nontrivial multiparticle processes that are still out of reach.
Moreover, for the most involved parts of NNLO calculations general and automated techniques are not available to date.
To address this challenge, our aim is to develop an **automated algorithm for NNLO** calculations based on OpenLoops.



The strategy is to construct two-loop amplitudes by doing one of the loop integrations with the existing OpenLoops technology, and the remaining loop integration numerically.
In this semi-numerical approach, the **cancellation of two-loop singularities** of UV and threshold kind requires local subtraction terms.
At the same time, the numerical treatment of the loop momentum can be exploited such as to achieve a direct cancellation of the infrared divergences due to virtual and real radiation. This will require a fully general understanding of the singularity structure of two-loop scattering amplitudes in our semi-numerical approach.

$$\sum_\Gamma\int d^4q_1\int d^4q_2\frac{N_\Gamma(q_1,q_2,\{p_i\})}{D_\Gamma(q_1,q_2,\{p_i\})}$$

Numerical Integration

Analytic Integration