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Prospects for precision physics at the LHC: what to expect in a 15 years?

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Introduction

High-energy physics is build around a simple concept: hadron colliders in general and the LHC in particular are discovery machines. Discoveries at hadron collliders are followed by dedicated precision studies at lepton colliders.

Discovery of the Higgs boson and the current discussion of lepton Higgs factories is the case in point.

This concept may require some adjustments because

1) thanks to many theoretical and experimental developments, precision (or semi-precision) physics at the LHC is becoming a reality;

2) discoveries of new particles at the LHC may or may not happen; studies of small(ish) differences between data and the Standard Model theory may become a necessity at the LHC.

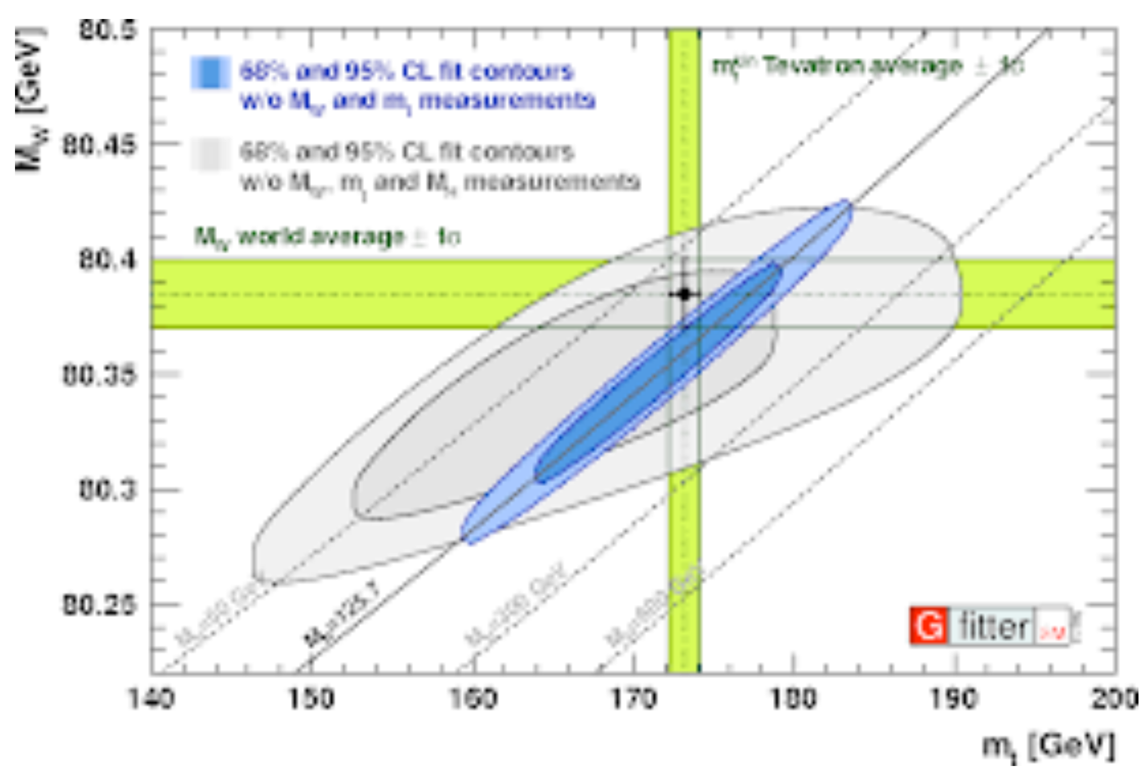
3) it is not clear if and when future lepton collider(s) will be built.

In this respect, it is natural to ask how far one can get with precision physics at the LHC and what will it take to get there?

Introduction

But what is ``precision physics”?   There is  ``traditional” sense in which this notion is used: precision electroweak. The idea is to measure over-constrained set of many EW parameters of the SM and then use these measurements to test the consistency of the SM.

This type of physics -- even with relatively optimistic projections -- is probably not competitive at the LHC.   Indeed, with 3000/fb, one can perhaps improve the measurement of the W-mass to about 5 MeV (this assumes that the error associated with PDFs is, essentially, eliminated). Together with improved Higgs mass measurement, this is probably the only significant improvement in our knowledge of traditional electroweak parameters that the LHC can deliver.

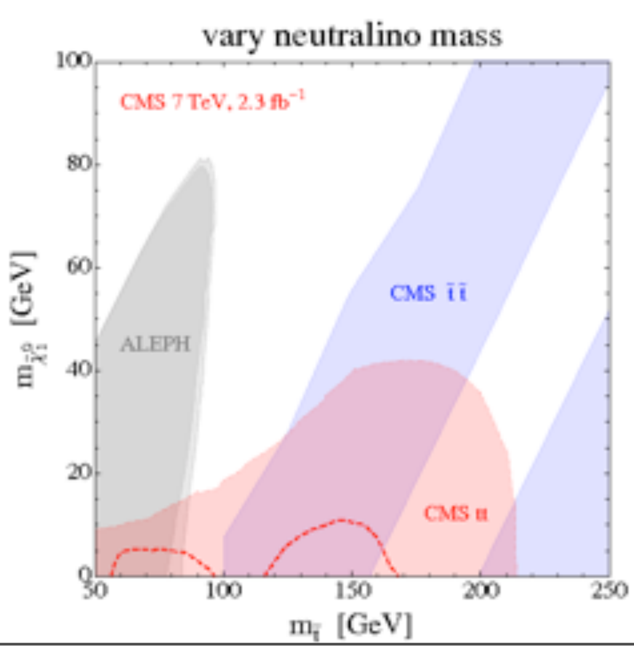


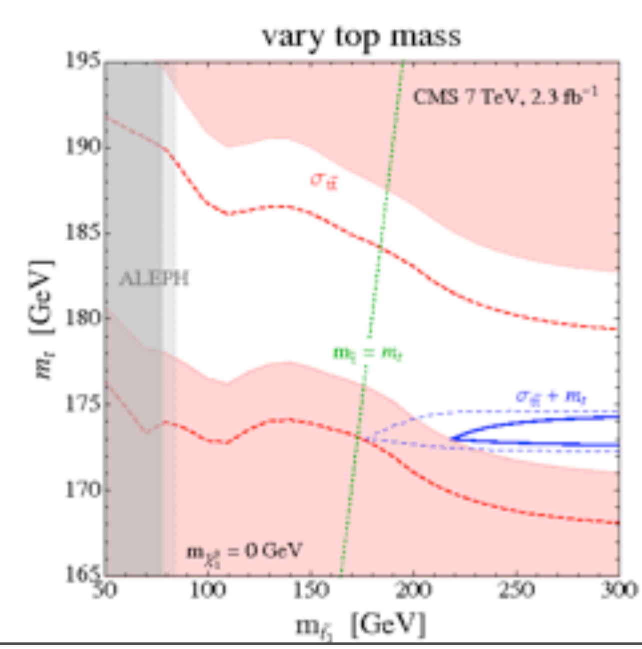
Introduction

Another type of precision physics that the LHC can contribute to is the "discovery" one. A prominent example of this type are improved measurements of the Higgs couplings and the ensuing opportunity to discriminate between different models of EWSB. A less prominent example is the exclusion of "stealthy stops" scenario that utilizes the recent NNLO QCD computation of top pair production cross-section.

The idea is that stops that are degenerate in mass with top quarks and that decay to top quarks with very little missing energy are kinematically indistinguishable from tops (apart from spin correlations). However, they increase the "top" cross-section. If we know the top cross section sufficiently precise, we can detect the excess !

Thanks to a recent computation of top pair production cross section through NNLO QCD, the uncertainty on the cross-section is reduced to just O(4) percent; this improvement is necessary and sufficient for providing informative constraints on stop pair production cross-section.





$$\sigma_{\tilde{t}\tilde{t}} \sim 0.14\ \sigma_{tt}$$

$$m_{\tilde{t}} = m_t$$

$$\sigma_{\tilde{t}\tilde{t}} \sim \sqrt{\delta\sigma^2_{tt,\rm exp} + \delta\sigma^2_{tt,\rm th}}$$

Czakon, Mitov, Papucci, Rudermann, Weiler

Introduction

Thinking about the future, I believe that this type of ``discovery precision physics" is what we should be aiming at. Interestingly, it matches very well the ``broad-band" nature of the LHC, that enables exploration of many interesting processes and kinematic regimes at once and, for this reason, makes it natural to study correlations between different ``signals".

However, this is challenging to do with high precision because both theoretical and experimental environments are non-trivial:

a) theoretical: relatively large coupling constant; multi-scale problems, event selection criteria, multi-particle final states;

b) experimental: backgrounds, energy scales, tagging efficiencies, acceptances, isolation, multiple interactions etc.

Nevertheless, If high(er) precision can be achieved uniformly -- beyond a well-known set of topologically simple processes -- this will be very interesting since large number of ``(in)consistency checks" can be envisioned and performed.

The framework

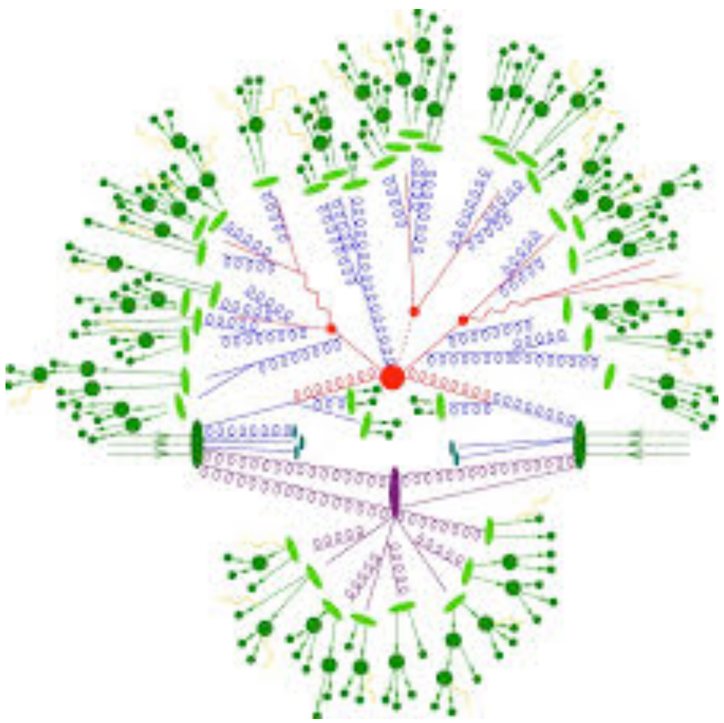
To talk about precision physics at the LHC, we need to use theoretical framework that is based on first principles. Such framework is provided by perturbative QCD.

Within perturbative QCD, the cross-section for a hard process is written as

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f_i(x_1) f_j(x_2) \mathrm{d}\sigma_{ij}(x_1, x_2) F_J \left(1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)\right)$$

It is important to keep in mind that perturbative QCD is not a model but an approximation, derivable from correct QFT, whose validity is determined by an interplay of a few parameters. Perturbative QCD can be a ``poor approximation" but it can not be a ``wrong model".

In its region of validity, pQCD predictions for hard scattering processes are systematically improvable provided that parton distribution functions, partonic cross-sections, and the input parameters (strong coupling constant, quark masses) are known with matching precision.



However, to map pQCD factorization formula onto ``experimental reality" (detector response), parton shower event generators are needed. Ultimately, this limits the precision that is achievable at the LHC and introduces some degree of model-dependence.

The framework

Improvements in precision physics at the LHC require progress with:

1) calculations of partonic cross-sections;

2) determination of the strong coupling constant, parton distributions and other input parameters;

3) better understanding the role of Monte Carlo event generators;

4) refinements of experimental practices to make them compatible with precision physics;

Of course it is impossible to say to what extent our understanding of the LHC physics will change at the time-scale of fifteen years, but some improvements are definitely guaranteed. I will now talk about these topics in some detail.

Methodological developments in pQFT: successes and challenges

Ingredients of perturbative QFT

Perturbative predictions for collider physics require calculation of scattering amplitudes with increasing number of loops and final state particles.

Integration over momenta of final state particles -- being subject to experimental constraints -- is also needed and is non-trivial because of infra-red and collinear divergencies.

Advances in pQFT -- as applied to collider physics -- are determined by our ability to

a) better compute loop integrals and scattering amplitudes;

b) design practical ways to integrate (extract singularities from) higher-multiplicity processes over unresolved phase-spaces, to enforce the Kinoshita-Lee-Nauenberg cancellation in a process-independent way.

Both of these topics are well-appreciated since mid 90's; first systematic studies of both were done in the context of NLO QCD computations. Recently, they went through a phase of a rapid development, opening up a way for new exciting applications.

pQFT: loop integrals

Perturbative predictions require multi-loop computations. The recent progress in this field is related to a number of technological improvements that include:

1) wide-spread use of the spinor-helicity methods;

2) novel techniques for multi-leg one-loop computations (unitarity, OPP, Openloops, optimization of the Passarino-Veltman procedure);

3) development of the efficient methods for the reduction of Feynman integrals to master integrals using integration-by-parts and Laporta algorithm (e.g. FIRE, REDUZE);

4) efficient use of differential equations for the computation of master integrals (canonical basis);

5) better understanding of mathematical structures behind the multi-loop computations and related improvements in our ability to calculate Feynman integrals (symbols, GPLs, etc.);

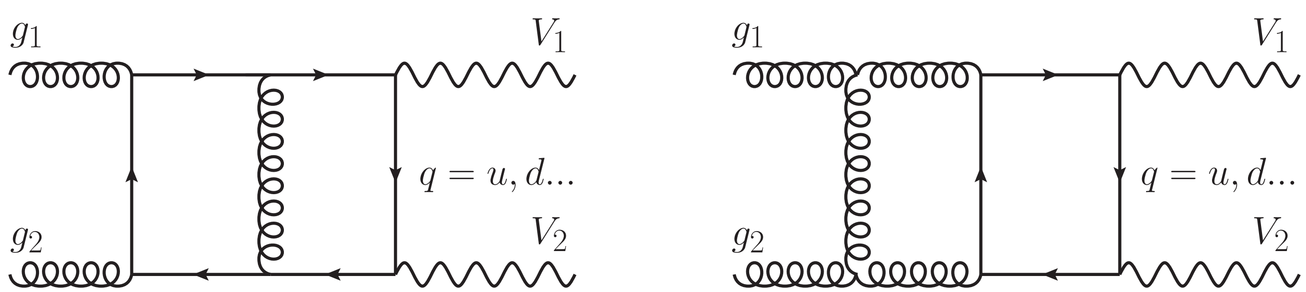
These developments lead to a very impressive progress in one-, two- and three-loop computations and the ultimate potential of these developments is clearly not yet exhausted.

pQFT: loop integrals and amplitudes

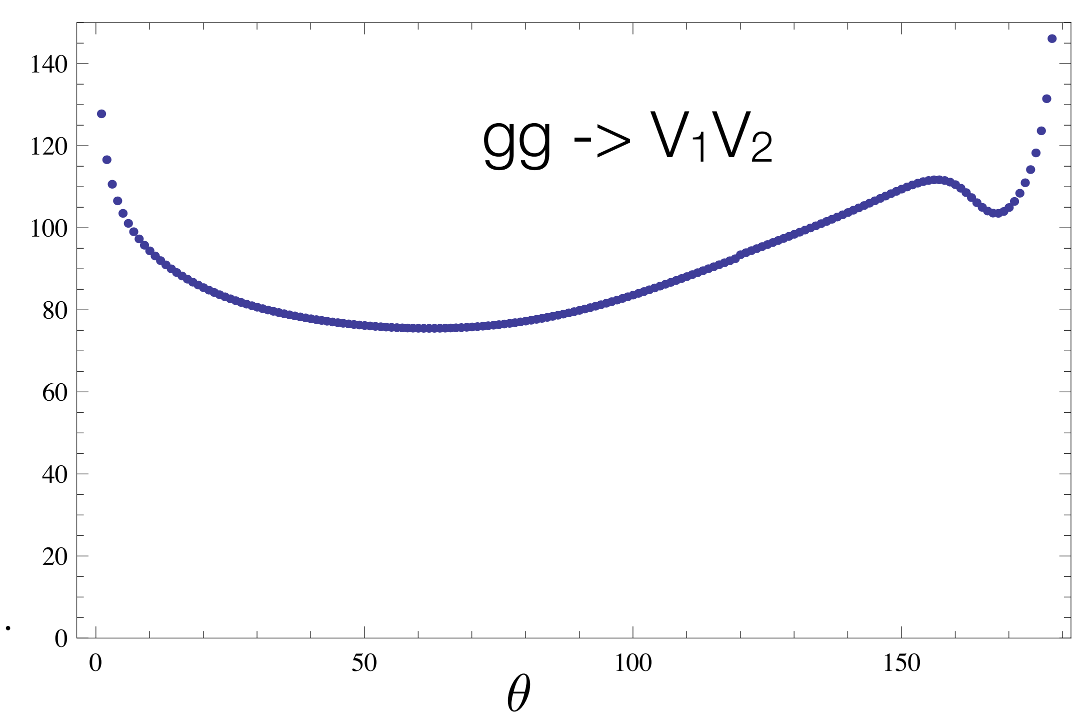
We have now results for many new one- and two-loop amplitudes and master integrals that were considered to be out of reach even recently. What did we learn from this endeavor? Roughly speaking, two things:

a) In cases with relatively small number of kinematic scales, modern analytic computations do a superb job (stable, easy-to-handle results);

b) In cases with larger number of kinematic scales (e.g. analytic computations of scattering amplitudes for qq -> V_1 V_2 and gg -> V_1 V_2 processes -- a three-scale 2->2 problem), we begin to experience; i) limitations of diagrammatic approaches at two loops; ii) difficulties with reductions and iii) appearance of large (O(100 MB)) analytic expressions.



$$
\begin{aligned}
\mathcal{A}_{3L4L}^{\lambda_1\lambda_2} = \mathcal{N}_{\lambda_1\lambda_2}\Big\{ & \Big(F_1^{\lambda_1\lambda_2}\langle 15\rangle[61] + F_2^{\lambda_1\lambda_2}\langle 25\rangle[62]\Big)\langle 17\rangle[81] \\
& + \Big(F_3^{\lambda_1\lambda_2}\langle 15\rangle[61] + F_4^{\lambda_1\lambda_2}\langle 25\rangle[62]\Big)\langle 27\rangle[82] + 2F_5^{\lambda_1\lambda_2}\langle 57\rangle[86] \\
& + \frac{1}{2}\Big(F_6^{\lambda_1\lambda_2}\langle 15\rangle[61] + F_7^{\lambda_1\lambda_2}\langle 25\rangle[62]\Big)\Big(\langle 12\rangle\langle 78\rangle[81][82] + \langle 17\rangle\langle 27\rangle[21][87]\Big) \\
& - \frac{1}{2}\Big(F_8^{\lambda_1\lambda_2}\langle 17\rangle[81] + F_9^{\lambda_1\lambda_2}\langle 27\rangle[82]\Big)\Big(\langle 12\rangle\langle 56\rangle[61][62] + \langle 15\rangle\langle 25\rangle[21][65]\Big)\Big\}.
\end{aligned}
$$



pQFT: loop integrals and amplitudes

In addition, although calculation of two-loop amplitudes is, by now, a mature business, there are still cases where difficulties can be anticipated. For example

1) calculation of amplitudes (at two-loops and beyond) often starts with their parametrization in terms of invariant form factors. This is relatively straightforward to do but the complexity grows rapidly when the number of external particles (and their spins) grows.

2) parameterizations are challenging in case when odd number of axial currents is involved. So far, in all two-loop amplitudes the vector-axial contribution was argued away... but there are cases where this won't happen (c.f. different internal masses).

3) numerical stability issues in computations of complex two-loop amplitudes will be similar and perhaps even more severe than what we have seen at one loop.

4) calculations of two-loop integrals for processes with internal masses is challenging since in some cases differential equations can't be brought to a canonical form and the resulting integrals are not Goncharov polylogarithms.

5) numerical calculations of loop integrals (Fiesta, SecDec) in physical (Minkowski) kinematics are problematic.

pQFT: loop integrals and amplitudes

One-loop calculations are used both as a way to improve precision in the description of complex multi-leg processes and as an important ingredient for multi-loop computations.

In the latter case, one-loop amplitudes require extrapolation to kinematic regions where at least one of the final state partons is not resolved. This is a challenging regime since absolute majority of one-loop methods was not designed for these cases.

From the current experience, we know that optimized analytic expressions for moderately complex one-loop amplitudes (0 -> H+4 partons, 0-> Z + 4 partons) are well-suited for such computations.

We also know that numerical methods (e.g. OPENLoops), supplemented with a switch to quadrupole precision in unresolved regions, seem to work fine for a variety of processes (pp -> WW, ZZ, Zgamma, certain contributions to pp-> tt etc.)

It is quite possible that both of these approaches will start being problematic for higher-multiplicity processes since analytic results for one-loop amplitudes are not known and numerical techniques may not be precise enough. But this remains to be seen.

pQFT: integration over unresolved phase-spaces

Development of subtraction schemes for NNLO computations was an important topic of the past decade; as the result of these efforts, we now have several options (antenna, improved sector-decomposition, q_t , jettiness etc.) in our disposal. They are NNLO generalizations of the famous NLO algorithms, such as Catani-Seymour and FKS subtraction schemes, and the phase-space slicing.

The NNLO algorithms are implemented in computer codes for a number of processes including production of top pairs, di-jets, Higgs+jet, V+jet, single top, WW, ZZ etc. They work in practice.

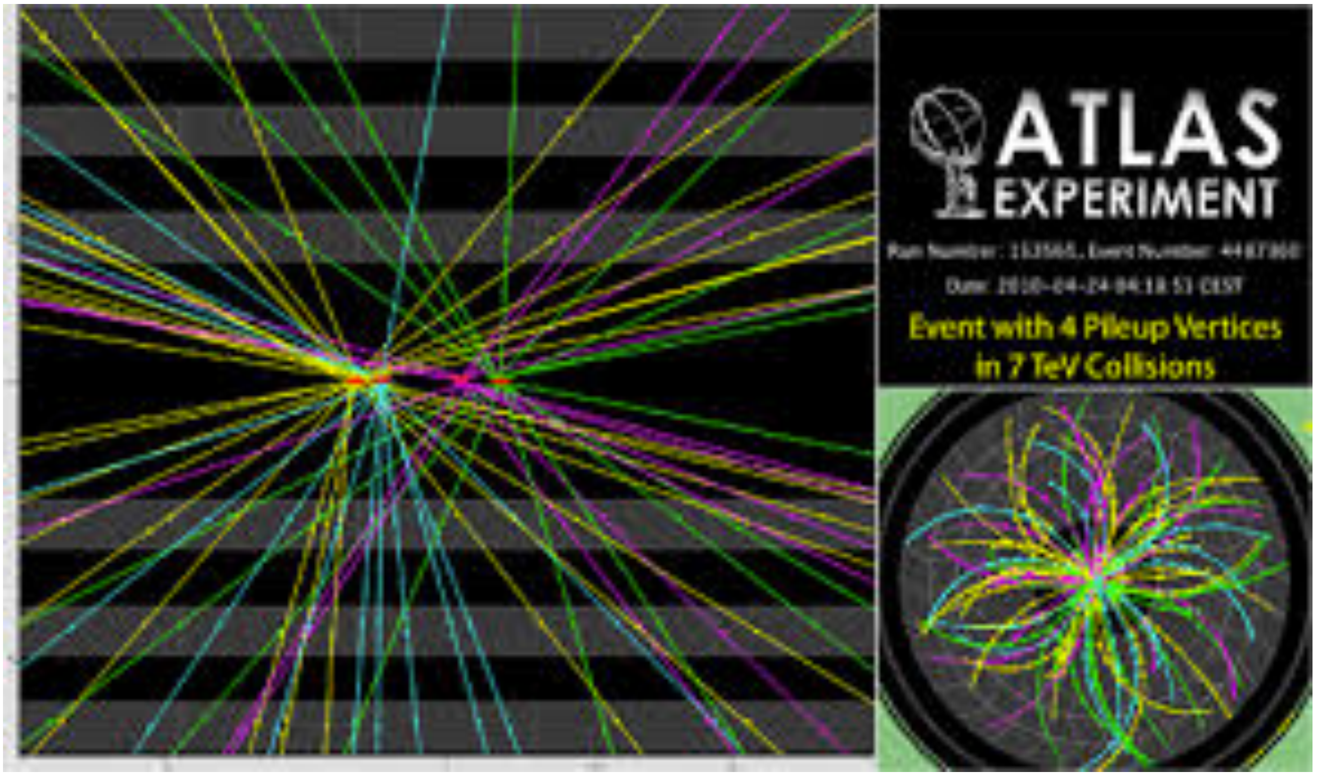
The important feature of these (subtraction) methods is that they rely on factorization of scattering amplitudes in infra-red and collinear limits and, therefore, can be applied to processes of arbitrary high multiplicity (for now, as a matter of principle).

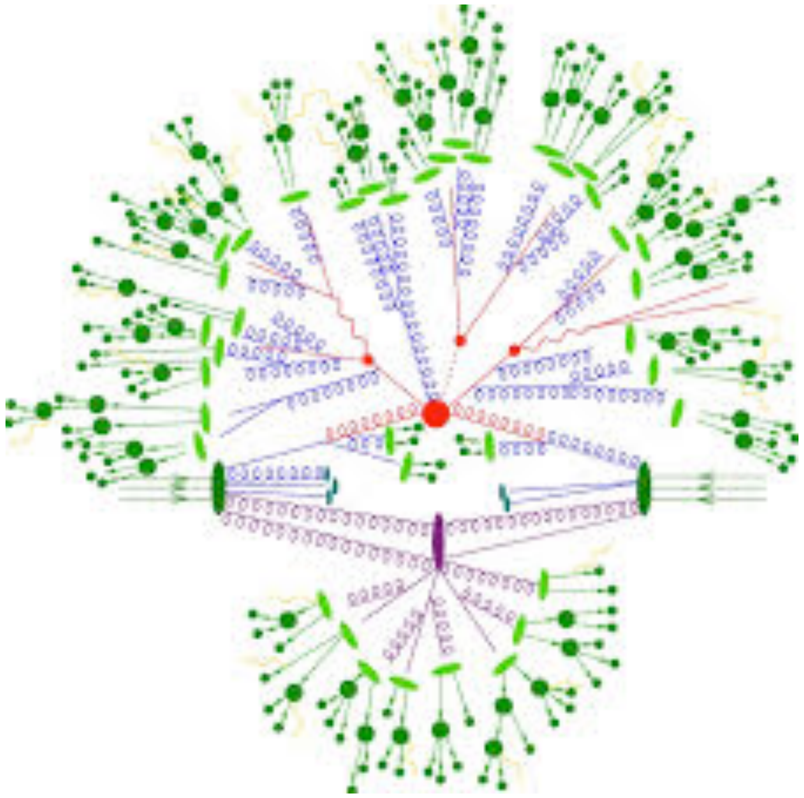
More efforts will go into improving these algorithms (both technically and conceptually) but there is no doubt at this point that NNLO calculations for broad classes of higher-multiplicity processes are becoming important and rapidly expanding part of the LHC phenomenology.

Phenomenological realities

Obviously, even if we are able to perfectly compute scattering processes in perturbation theory, we have to face a problem of connecting these results to reality. Making this connection is not easy. Most likely, this will be a limiting factor for high-precision physics at the LHC.

$$\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 \; f(x_1) f(x_2) \; \sigma(x_1 x_2 s)$$





Where are we now ?

For many important processes current theoretical uncertainties are comparable to experimental ones; experimental systematic is dominated by energy scales, deficiencies of background and signal simulation, detector effects etc. Removing theory-related sources of systematics and PDF errors -- will be more important than further increase in perturbative precision for ``simple" LHC processes.

Process	Experimental systematic	Theory error (not pdf)
Drell-Yan	~1%	~2% (NNLO)
Higgs	~10%	~2% (NNNLO)
Higgs+jet	~10%	~7% (NNLO)
W+jet	~10%	~2% (NNLO)
top pair	~4%	~4% (NNLO)
top pair + jet	~14%	~10% (NLO)
WW, ZZ	~8%	~3% (NNLO)
V+2 jets	~10%	5%(NLO)
single top	~10%	~1% ($NNLO_{factorizable}$)

Issues

Several potential issues that were not relevant at the level of O(10%) precision are becoming important once we pass this point; they include

1) collinear factorization violations;

2) uncertainties related to input parameters (strong coupling, PDFs);

3) the role of parton showers;

4) experimental practices;

It appears therefore that further improvements in phenomenology require a coherent effort of theorists and experimentalists, to address a broad spectrum of non-trivial topics.

We will discuss some of these points in turn.

Violations of collinear factorization

Computations within pQCD framework are based on the concept of collinear factorization.

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f_i(x_1) f_j(x_2) \mathrm{d}\sigma_{ij}(x_1,x_2) F_J \left(1 + \mathcal{O}(\Lambda_{\rm QCD}/Q)\right)$$

Collinear factorization is proven for a limited number of processes and/or observables, but it is used as a starting point to describe complicated kinematic distributions in multi-particle processes. It is important to clarify to what extent collinear factorization is valid for practical purposes at the LHC since, for phenomenological reasons, many processes are being studied at more and more detailed (differential) level. Unfortunately, very little is known about that.

Explicit examples of violations of factorization for space-like processes in perturbation theory (color coherence restricted by causality) exist;

Catani, de Florian, Rodrigo

Restricting phase-space for final state radiation (jet vetos) may lead to new non-perturbative, factorization-violation effects, caused by interaction with spectators. For typical values of jet vetoes, O(5%) corrections are conceivable.

Mitov, Sterman

Double parton scattering contributions are significant; their current treatment however is entirely phenomenological and probably will remain so for a long time (note, however, an attempt to treat DPS in QCD).

Manohar, Waalewijn

$$\sigma^{\rm DPS}(pp \to F_1 F_2) = \frac{\sigma(pp \to F_1)\sigma(pp \to F_2)}{\sigma_{\rm eff}}, \quad \sigma_{\rm eff} \sim 15~{\rm mb}$$

Input parameters: the strong coupling constant

It is fair to say that the strong coupling constant with the precision of about one percent is the limit of what can be achieved at the current facilities. Lattice results are nominally more precise but since they come from a single collaboration, independent confirmation of errors is essential.

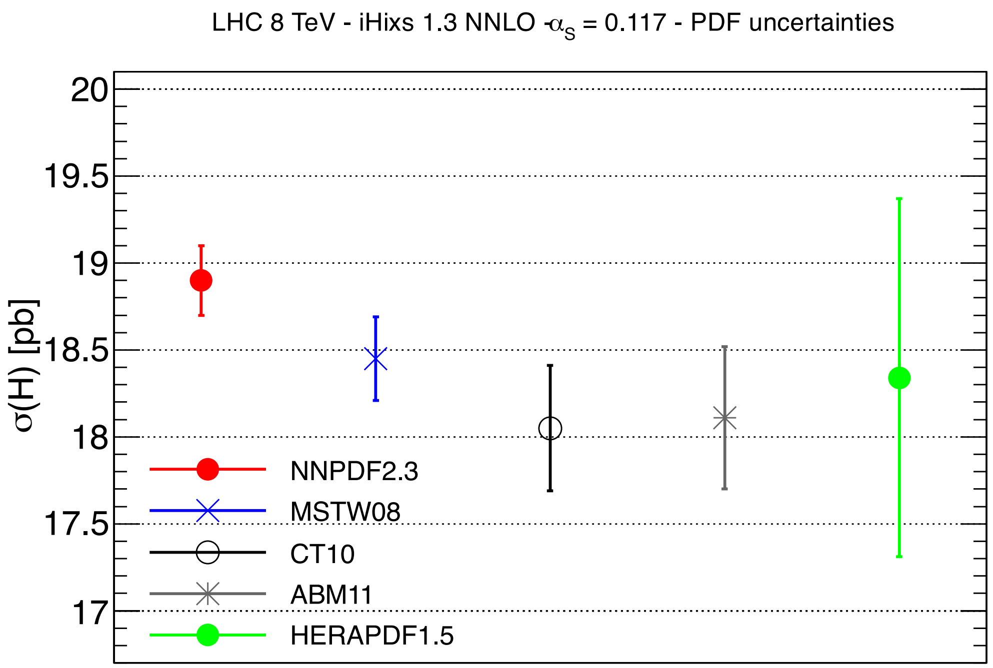
Method	Current relative precision	Future relative precision
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2-dep.)
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9, 29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, $\sim$ 10 yrs)
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, $\sim$ 10 yrs)
ep colliders	~ 1–2% (pdf fit dependent) [30, 31], (mostly theory, NNLO) [32, 33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17, 21, 34]	$< 1\%$ challenging (NNLO jets imminent [22])
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ ($\sim$ 5 yrs [38])

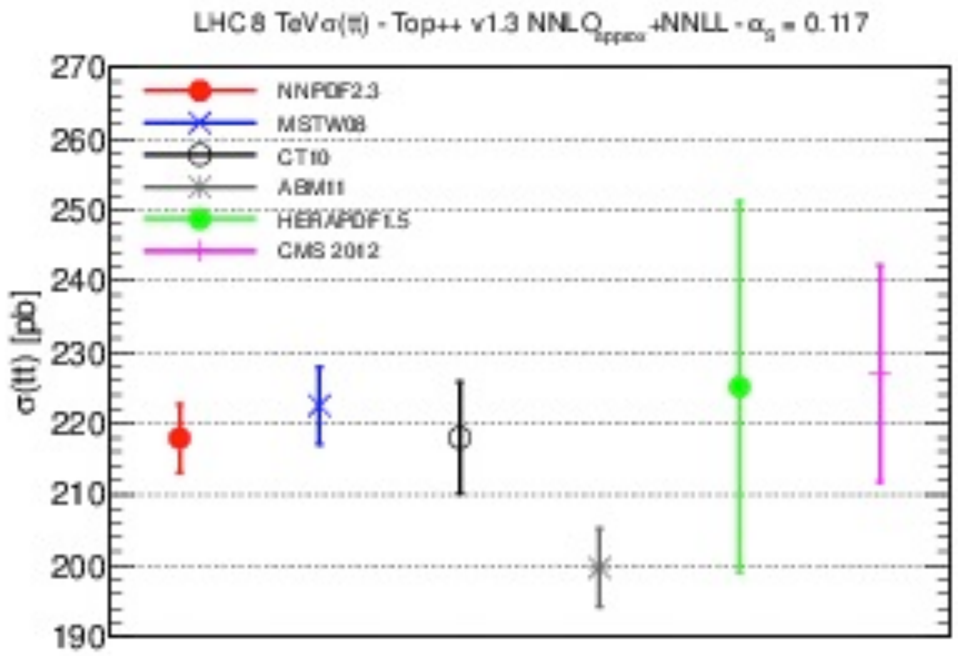
Table taken from the report of the Snowmass working group on QCD

Ultimate uncertainties in the strong coupling constant imply irreducible errors for basic cross-sections in the range of a few percent even if all other uncertainties are completely eliminated.

Input parameters: parton distribution functions

Knowledge of parton distribution functions is essential for any hadron collider process. Parton distributions are known well in some kinematic regions and poorly in some others (large x). Genuine NNLO PDF sets will eventually be constructed. Extension to N3LO sets? Consistent combination of QED and QCD effects in PDF extraction may be essential.





Improvements in PDF determination will come from the LHC where several interesting processes can be used for this purpose. By exactly how much our knowledge of PDFs can be improved in O(15) years is not clear; errors are dominated by systematics including our ability to describe hadron collisions with high precision (somewhat circular logic).

Note that if the majority of needed PDF data will come from the LHC using processes with matching values of Q^2, one probably does not need to know AP evolution kernels precisely, since the logarithms are small. Perhaps useful for emerging N3LO calculations.

Experimental methods / practices

An issue that one should worry about in connection with precision physics are experimental methods/practices and indiscriminate use of parton shower generators. While -- in many cases -- these are unavoidable aspects of hadron collider physics, we should recognize that they take us beyond controllable framework of collinear factorization in QCD and introduce model-dependent biases.

Currently, many experimental methods are designed to extract maximal information from (often) statistically limited measurements and include extrapolation of fiducial cross-sections, use of pseudo-observables (e.g. top pair production cross-section), loose reconstruction requirements and data-driven methods for background estimates.

Parton showers, on the other hand, are designed to describe hadronization, non-perturbative energy flows and exotic (e.g. double-parton) contributions to hard scattering. In the context of precision physics, we should remember that understanding of these physics is not based on first principles QCD.

Eventually, these features will limit the precision that can be achieved. For the precision physics program, it should be important to design observables that can be explored using simple and transparent experimental methods and that dependent minimally on the use of parton showers.

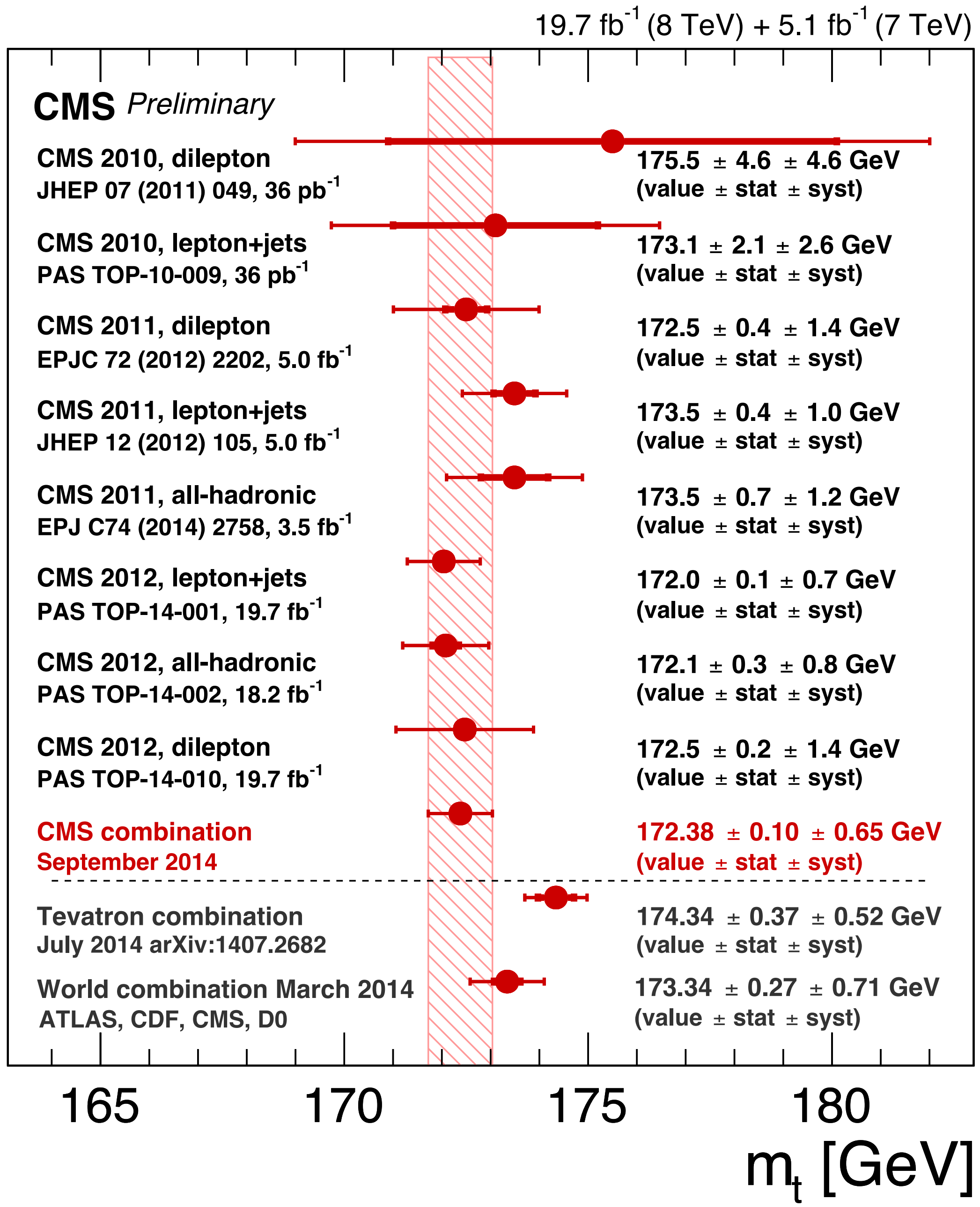
Experimental methods and practices: the top mass

As an example -- consider measurement of the top quark mass. The measured value (CMS combination) m_t = 172.38(0.1)(0.65) is extremely precise ! However, these results on the top mass are subject to never-ending discussions (is it the pole or the MSbar or the Monte Carlo mass).

The reason for these discussions: experimentalists want to obtain precise number as fast as possible. This is achieved by using multivariate techniques which increase the sensitivity to the mass parameter.

However, since not everything can be described by pQCD and since we do not understand where the sensitivity to m_t comes from, the discussion about the meaning of the extracted parameter m_t continues.

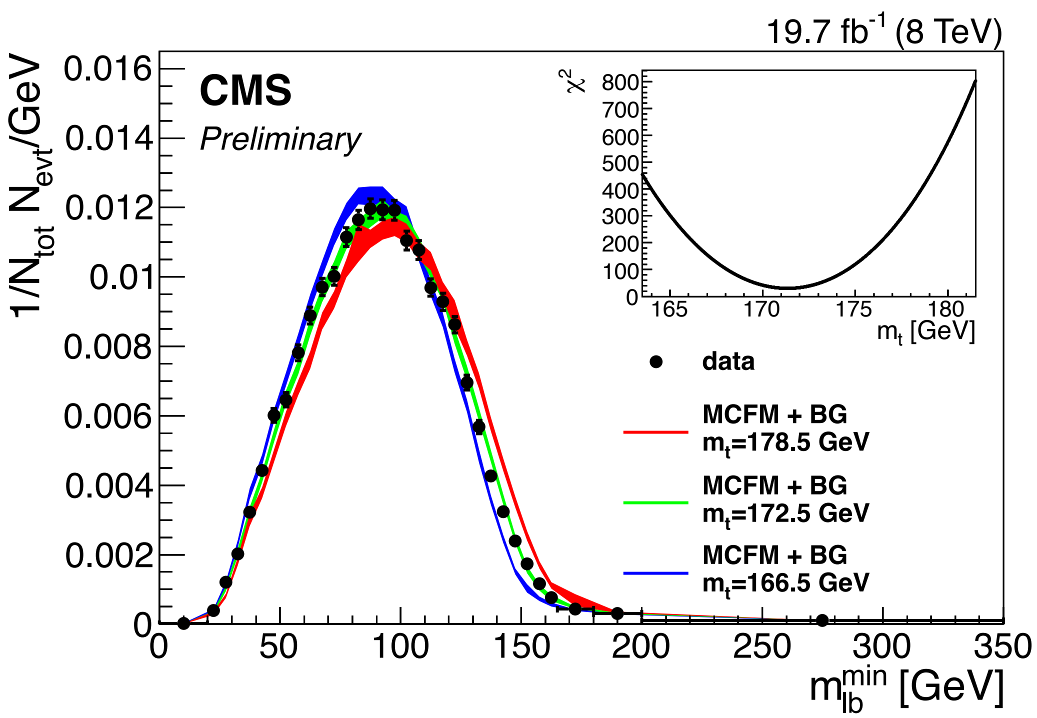
In my opinion, the best solution to this problem is to find kinematic distributions that (to a large extent) are computable in pQCD, so that the reliance on parton showers is limited. In case of the top quark mass measurement, a number of such distributions were suggested.



Experimental methods / practices: the top mass

One example is the (recent) measurement of the top quark mass from m_{lb} distribution in di-lepton events. The result is 172.3(1.3) GeV. CMS explicitly checked that dependence on QCD effects in the production is (largely) absent.

Statistical error is 0.3 GeV. Largest systematic errors are top quark transverse momentum modelling, b-fragmentation, jet energy scale and the dependence on the choice of the renormalization and factorization scales. It is interesting that almost all of these sources of errors are within pQCD domain and, as such, are improvable. Removal of the renormalization/factorization scale uncertainty alone should lead to a reduction of the total systematic by 20-30 percent.



Note that, currently, decays of top quarks are taken at leading order and supplemented with a parton shower. This may be a very good approximation for practical purposes but it is not sufficient for a measurement that we would like to call a precision one. The good news is that it should be easy (possible ?) to remove this limitation: indeed, upgrades to describe top decays at NNLO are, in principle, straightforward and must be used in any analysis that aims at O(0.5 GeV) precision.

In summary: well-defined observable; analysis is improvable with already existing tools; full NNLO accuracy for the production and decay is definitely within reach.

Parton showers

Parton showers are workhorses for hadron collider physics. They are used to provide a link between partons that we employ to describe the hard scattering and hadrons that we measure in particle detectors.

From this point of view, parton showers are no different from any other ``detector simulation" tool that exists (e.g. GEANT) and its use in that context is unavoidable.

However, the problem with parton showers is that we also try to use them as a shortcut to perturbative QCD especially when real calculations get too complicated. It is this second point that was criticized on many occasions.

The overarching point of this critique is that very often when parton showers are used as a substitute for perturbative QCD, they are employed outside of their region of validity (perhaps one of the less-known examples, is the forward-backward top pair asymmetry that was generated by event generators to the surprise of their masters..).

From this perspective, progress in matching/merging of parton showers to fixed order computations is a very welcome development since it restricts uses of parton showers to regions of phase-spaces where they are valid. For this progress to be sustainable, progress in fixed order computations (LO, NLO and NNLO, eventually) is absolutely crucial.

It's hard to make predictions, especially about the future.

Wer Visionen hat, soll zum Arzt gehen.

Future

pQFT: back then, now and into the future

Although progress does not need to be continuous, it is useful to look back at what we knew 15-20 years ago (circa 2000) to imagine what will be possible to do in 15 years from now. The similarities are quite striking...

Back then

1) automated (or nearly automated) leading order calculations for arbitrary-multiplicity processes at colliders ;

2) NLO subtraction schemes just appeared;

3) early experience with high-multiplicity NLO (e+e- > 4 jets, pp -> V + 2j) etc.; emergence of NLO unitarity.

4) Drell-Yan total cross-section at NNLO .

5) applications of IBP's to NNLO 2->2 processes;

Now

1) automated (or nearly automated) NLO calculations for arbitrary multiplicity processes at colliders;

2) NNLO subtraction schemes just appeared;

3) early experience with higher-multiplicity NNLO (pp -> 2 jets, pp -> tt, pp->H+j) etc; glimpses of NNLO unitarity.

4) Higgs total cross-section at N3LO .

5) attempts to apply IBP's to NNLO 2->3 processes

pQFT: future

The ``linear" extrapolation is easy: in 15 -20 years, we should be able to perform NNLO QCD computations in an automated fashion for ``high"-multiplicity final states; we should get some experience with higher-multiplicity calculations at N3LO and first inclusive cross-sections at N4LO ... Electroweak corrections, masses etc.

It is hard to say how accurate these extrapolations will turn out to be. There is no doubt that ``standard" approaches to loop calculations (more efficient solutions of IBPs, differential equations, underlying mathematical structures for integrals) will keep being developed; they still have a lot of potential.

On the other hand, we should not discount dramatic changes that may grow out of the technological developments that are being quietly pursued currently:

1) generalization of unitarity ideas to two-loop computations; perhaps crucial if we want to pursue NNLO for higher-multiplcity processes;

2) work on efficient numerical calculations of master integrals and/or amplitudes ... perhaps important to deal with multi-scale problems (direct integration in momentum space, quasi-finite basis of integrals, numerical solution of diff. eqs.)

3) understanding the best framework for combining real and virtual corrections in higher orders of perturbation theory. What exactly is meant by ``best" isn't clear -- recall a NLO story: analytic computations -- mostly Catani-Seymour subtraction, automated computations -- renaissance of FKS...

pQFT: future

I believe that advances in perturbative computations -- in particularly advances that are applicable to complex final states -- will have most important consequences for all aspects of hadron collider physics.

In particular, higher-multiplicity fixed order computations, be it LO, NLO or NNLO, will play increasingly important role in interfaces to parton showers, through merging and matching. These developments -- extended to electroweak sector -- will allow for an easy ``inclusion" of (potentially large) electroweak radiative corrections to parton showers.

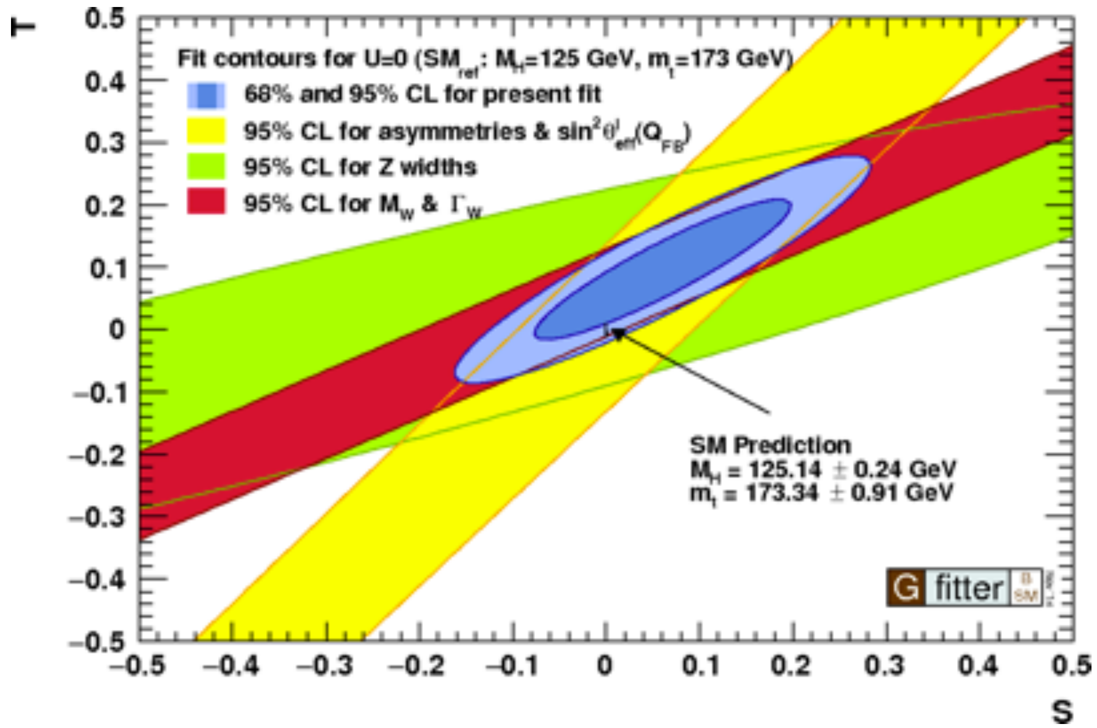
Further developments in resummations will lead to an improved first-principles description of semi-hard (transitional) regions for realistic processes/final states.

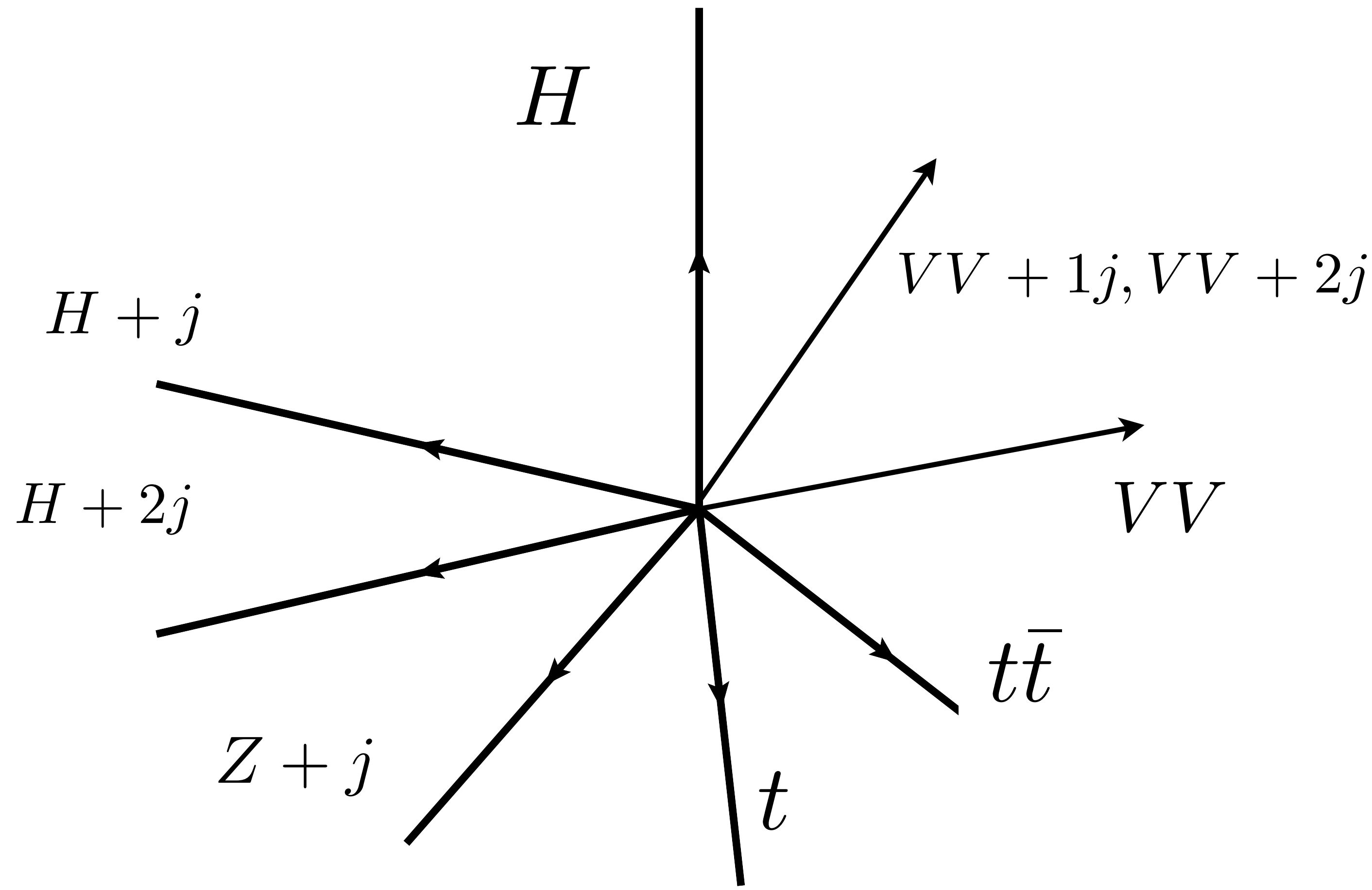
As the result, parton showers -- as we know them now -- will be only used to describe truly low-Q^2 physics. This will be a very welcome news as it will remove at least one of the potential obstacles for precision physics at the LHC.

Advances in perturbative computations should also open up new opportunities for the extraction of parton distribution functions, primarily from the LHC data (no non-perturbative effects at low scale, no significant evolution, ``modern" data sets used in fitting).

Future: precision physics at a hadron collider

Precision physics program should aim at facilitating discoveries at the LHC which means that the focus should be on improving precision for complex processes, across the board. This will allow us to extract maximal information from the multitude of LHC processes by watching for correlated BSM contributions to many of them.





Future: precision physics at a hadron collider

In many cases, theoretical progress is required to get to interesting physics. The advances are non-trivial but they don't look completely unreachable on the scale of O(5) years.

Process	Progress required	Comment
pp-> HH	2-loop massive (inside/ outside) integrals	Higgs self coupling
gg->VV*	2-loop massive (inside/ outside) integrals	``Higgs width", background
H+j	2-loop massive (inside/ outside) integrals	Test for new degrees of freedom in HGG vertex
diff. H@N^3LO	subtraction algorithms to one order higher	Higgs couplings
3 jets	two-loop masters; amplitude, subtractions	strong coupling constant, constraints on higher-dimensional operators
VV+2j	two-loop masters; amplitude, subtractions	weak boson fusion

Experimental practices

Experimental practices will change to compline with requirements of precision physics. They will not be driven by the need to increase statistics (which will anyhow be unlimited).

There will be

1) larger number of cut-and-count analyses that are easy to understand; more stringent event reconstruction and selection.

2) more measurements restricted to central regions of the detectors, where experimental systematics is minimized;

3) no extrapolations from fiducial volume to total cross-sections; fiducial volumes will be chosen to maximize applicability of perturbative QCD, even if this reduces the rates somewhat.

4) (almost) no data-driven backgrounds estimates;

5) more frequent use of advanced simulation programs based primarily on exact matrix elements; traditional parton showers will only be used to describe hadronization.

Conclusions

1) Theoretical methods that are currently being developed in pQCD will continue to contribute to phenomenology of hard scattering processes. Many developments lead to across-the-board impact. For many reasons, it is crucial to continue improving theory description of complex processes.

2) The most advanced perturbative computations available currently indicate that all (scale, strong coupling, PDF) sources of uncertainties are becoming comparable in size -- O(few) percent. Potential violations of collinear factorization may be similar. Systematic errors reported for the most advanced measurements are also in this ballpark. To improve on that, we need a coherent effort of theory and experimental communities, in addition to pushing the pQFT frontier.

3) Experimental measurements should rely on observables that are computable within perturbative QCD. They should be driven not by the desire to reach the most accurate result as fast as possible but by clarity.

4) Progress with precision physics at the LHC will not be driven by computing simple observables in even higher orders of PT but rather in extending NNLO computations to more and more complex processes.