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STANDARD MODEL CONSTRAINTS FROM THE LHC*

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With our current knowledge limited by the absence of physics data, I review our expectations from standard processes measurements at the LHC. Focusing on charged and neutral current processes, I illustrate how their measurement will constrain our uncertainties on discovery physics, and give some arguments about our precision goal for the W mass measurement. Detailed analysis reveals that there is no reason to believe we can not measure this fundamental parameter to about 5 MeV. This sets a natural goal of about 500 MeV for the top mass; to decide whether this is realistic requires further investigation.

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1. Introduction

The LHC promises many discoveries, in final states of various complexity. Extra dimensions can show up as resonant or non-resonant excitations, in simple two-body processes; new gauge bosons can appear through high-mass resonances in two-lepton or diboson production; Higgs bosons or supersymmetry often display final states with many leptons and/or jets. Except for a few rare cases, the New Physics signal will manifest itself above a substantial background from standard processes; those must be modeled precisely if any claim of a discovery is to be defended.

After a first round of comparisons between data and simulation, the most obvious discrepancies will become apparent. These will most certainly appear in the domain of strong interactions, such as the description of soft QCD (minimum bias and underlying event, accurate today to roughly 50% [1]), or jet cross-sections. This will become the main focus of the first publications of the LHC experiments, and will allow to constrain non-perturbative parameters (controlling *e.g.* soft track multiplicities), to clarify the interplay between parton shower models and hard matrix elements (describing

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jet multiplicities), and to improve our knowledge of the gluon density in the proton, at high momentum fraction ($x \sim 10^{-1}$, affecting the high-E_T jet spectrum).

Meanwhile, the first W's and Z's will be observed. After a long period of accumulation, the ultimate statistics (10^7–10^8 events) will allow the measurements of all distributions (rapidity, transverse momentum, invariant mass) to almost arbitrary precision. The transverse momentum distributions will again give access to non-perturbative QCD parameters ($p_\mathrm{T} \sim$ GeV), and test higher order QCD predictions ($p_\mathrm{T} \gg$ GeV), while the rapidity distributions provide a powerful handle on the parton densities at low momentum fraction ($x \sim 10^{-3}$). Besides, the very precise knowledge of the Z boson mass [2] gives the possibility to use this particle as a probe of the detector parameters (energy and momentum scale and resolution).

Ultimately, fundamental parameters of the electroweak interaction should be accessible with high precision. The expected statistical precision on these quantities is appealing (one expects $\delta m_W(\mathrm{stat}) \sim 1$ MeV, $\delta m_t(\mathrm{stat}) \sim 0.1$ GeV), but the final result depends on how well the theoretical and experimental environment is modeled. This again illustrates the importance of the measurements mentioned above.

I will try to expand on this subject in the following. After a brief review of the simplest high-mass processes, I will describe the impact of W and Z measurements in more detail. In the light of what can be achieved on their cross-sections and distributions, I will review the LHC potential for the measurement of m_W, and the consequences for m_t.

2. Pair-production cross-sections

The traditional and most obvious probes of new physics signals at hadron colliders are the mass spectra of pair-produced particles. For instance, new massive states will be produced through high-mass parton–parton fusion, and partly decay to pairs of jets, leptons, or photons. Measuring the production rates of such signals requires good knowledge of our uncertainty on the standard model predictions for these final states.

Uncertainties on dijet and dilepton production have been studied in [3]. As illustrated in Fig. 1, current structure functions sets [4] induce a precision of about 50% on the high-mass ends of the dijet spectra, and 10% on the high-mass dilepton cross-section. In addition, the cross-sections have a residual dependence on the renormalization and factorization scales (∼5% in the case of lepton pair-production).

In the case of dijets, this is enough to hide, for example, the effect of non-resonant cross-section distortions arising from extra-dimensions, when the compactification scale is above 6 TeV [3]. One can expect similar results for dilepton production.

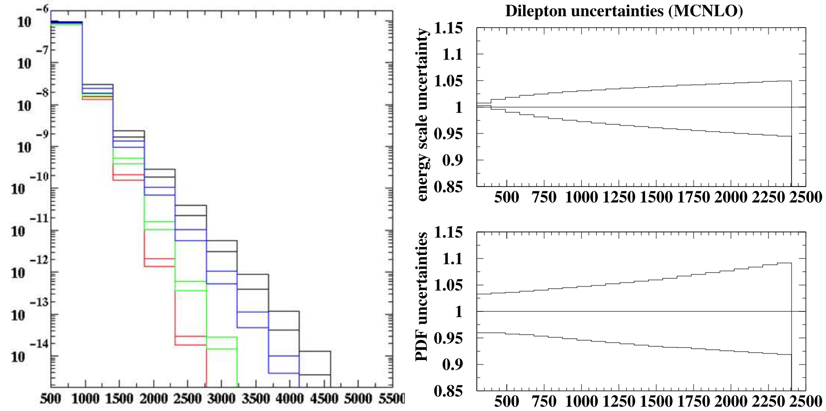

Fig. 1. Left: dijet cross-section uncertainty bands in the Standard Model (upper pair of curves), and in the presence of extra dimensions of compactification scale 6, 4 and 2 TeV (pairs from top to bottom). Right: dilepton production uncertainty bands, arising from the NLO scale dependence (top), and from structure functions (bottom).

We show below how the analysis Z production, among other measurements, will allow to improve the situation. As it appears, the measurements of total rates will quickly be limited by the effects that we precisely need to constrain. However, the distributions contain much more information than the total rates, and will allow to increase our understanding.

W and Z total cross-section measurements have recently been reviewed, for example, in [5]. The selections, relying on either one reconstructed lepton and the presence of missing transverse energy, or two reconstructed leptons, pose no particular problems and are almost free of background. The angular acceptance for identified leptons is typically $|\eta_l| < 2.5$ for the central LHC detectors. Fig. 2 shows two distributions exploited in the analysis of W and Z events.

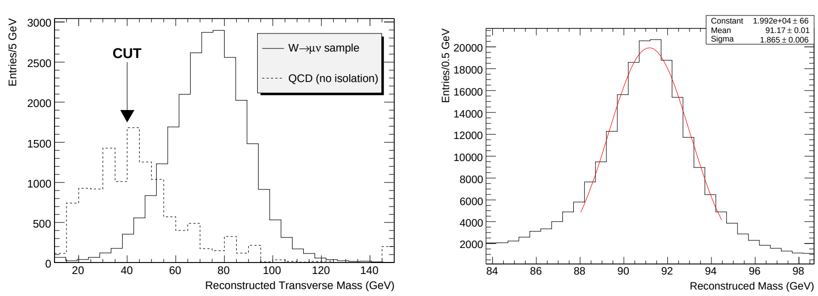

Fig. 2. Right: reconstructed transverse mass for W events, and background from QCD. Left: invariant mass of lepton pairs, in Z events.

The results of [5] are summarized in Table I. The counting rates of these processes are such that the direct statistical uncertainty will be well below 1% within one year of running, but other uncertainties, in particular related to the theoretical description of the process (high-order corrections, structure functions), dominate. These affect the distributions of variables which are used to select the signal (*e.g.* the lepton transverse p_{T} distribution); this translates into an uncertainty on the signal acceptance, hence on the total cross-section.

TABLE I

Main sources of systematic uncertainty on W and Z cross-section measurements, as estimated in [5]. See text for more discussion.

$\delta\sigma_Z$	Source	$\delta\sigma_W$	Source
1%	Tracker eff.	1.3%	Missing transverse energy
		1.0%	Trigger efficency
1.1%	Total exp.	2.2%	Total exp.
2.0%	Theory	2.5%	Theory

So total cross-section measurements do not constrain the theory; the effects that hinder high-mass predictions are also affecting this measurement. The acceptance uncertainties (*i.e.* not knowing how many events are outside the $y(W,Z)$, $p_{\mathrm{T}}(W,Z)$, $p_{\mathrm{T}}(l)$ windows we select) need to be improved.

It is thus important to analyze the shapes ($d\sigma/dy$, $d\sigma/dp_{\mathrm{T}}$). Although their cross-section is much smaller than the W cross-section, Z events are more powerful than W events in this respect, since they are fully measured. Since the Z decay is well known, the acceptance uncertainty on differential cross-sections is very small. Fig. 2 illustrate this, in the case of the Z rapidity and mass distributions. The left plot shows two extreme predictions of the Z rapidity distribution, reflecting the current structure function uncertainties, and example pseudo-data whose error bars represent the expected precision with 10 fb^{-1}. The precision is about 4% today, and will improve to 0.2%.

The right plot shows the Z mass distribution, with curves (representing various theoretical assumptions) and dots (pseudo-data as above). The tails of the mass distribution are most sensitive to structure function effects, and will allow a factor ~ 5 improvement of the relevant parton distributions.

It is also important to enlarge the selected signal phase space as much as possible. As said above, lepton selections are usually limited to $|\eta_l| < 2.5$, which effectively limits the Z boson acceptance to $|y_Z| < 2.5$. The full Z phase space actually extends to $|y_Z| \sim 5$, meaning that this can only constrain the theory within 50% of the Z rapidity domain.

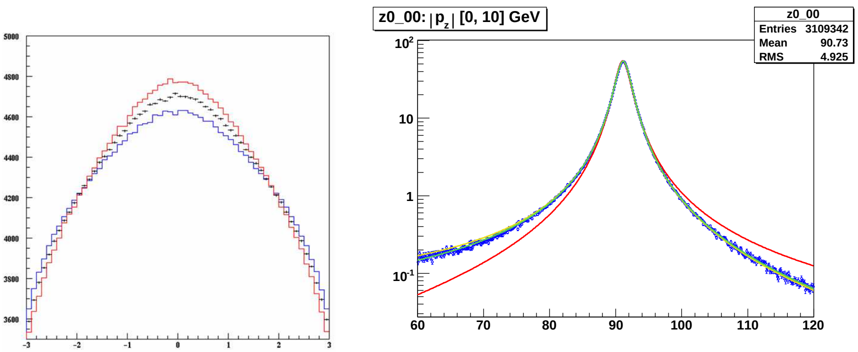

Fig. 3. Left: two extreme predictions of the Z rapidity distribution (histograms), and example pseudo-data (dots) corresponding to $10\,\mathrm{fb}^{-1}$. Right: the dilepton mass distributions, as seen in data (histogram), and according to various models. The symmetric curve is a pure Breit–Wigner, the first tilted curve includes final state radiation effects, and the second tilted curve includes structure function effects.

In the case of electrons, it is possible to extend the selections up to $|\eta_e| \sim 5$, using the good coverage of the LHC calorimeters. Electrons and hadrons are still well separated in the forward calorimeters, as illustrated on Fig. 4, left. High rapidity electrons are outside the tracking acceptance, and hence will have no charge measurement; the calorimeter granularity and resolution is also less performant in this region; however, the combination of one central and one forward electron still allows enough background rejection to extract a useful Z signal [6]. In this way, the accessible rapidity domain increases to $|y_Z| < 4$, *i.e.* 80% of the full domain (*cf.* Fig. 4, right). Simultaneously, the signal acceptance increases from $\sim 50\%$ to $\sim 65\%$.

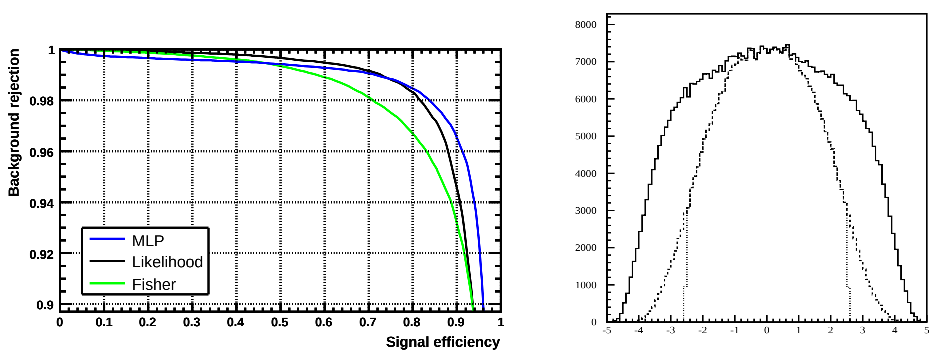

Fig. 4. Left: performance of electron identification in the ATLAS forward calorimeter [6]. Right: Z rapidity acceptance when both electrons have $|\eta| < 2.5$ (inner histogram); when one electron has $|\eta| < 2.5$, and the other has $|\eta| < 5$ (intermediate histogram); and the full distribution (outer histogram).

How does this link to high-mass dilepton events? A central heavy object ($M \sim 2$–$3\,\mathrm{TeV}$) has $x \sim M/\sqrt{s}\,e^0 \sim 0.2$. Similar values of x are probed if $M \sim M_Z$, but $y_Z \sim 3.5$; indeed $x \sim M/\sqrt{s}\,e^{3.5} \sim 0.2$.

Improvement on the theoretical description thus comes from confronting distributions in data and theory, within the analyzed (y, p_{T}, M) domain; and this domain should be as large as possible. This then allows better extrapolation outside measured region, notably towards high masses.

3. Electroweak measurements: the W boson mass

At hadron colliders, the W boson mass measurement proceeds through the analysis of the W transverse mass distribution, or through its decay lepton p_{T} distribution. Both distributions exhibit a steep edge (the so-called Jacobian peak), sensitive to the W mass. At the LHC, the statistical precision of this measurement will be $\sim 1\,\mathrm{MeV}$. The procedure is illustrated in Fig. 5. Throughout this section, we will discuss only the analysis of the lepton p_{T} spectrum.

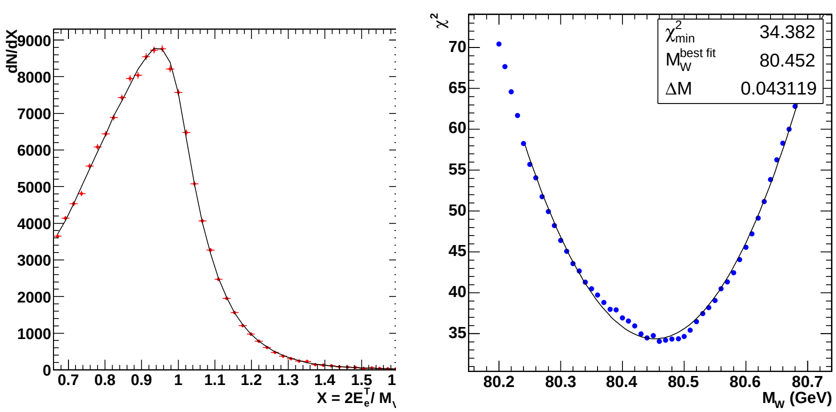

Fig. 5. Left: an example lepton p_{T} distribution. The falling edge at $p_{\mathrm{T}} \sim m_W/2$ reflects the W boson mass. Right: χ^2 graph resulting from the comparison of the distribution on the right with a series of "template" distributions of the same variable, obtained by varying the W mass.

Past studies [7] estimate that the systematical uncertainty will ultimately be about 15–20 MeV: imperfect theoretical modeling of the distributions would prevent to establish a precise relationship between those and the W boson mass; in addition, the detector scale would need to be controlled with a precision of $\sim 10^{-5}$ in order to match the statistical precision. Recently, an evaluation of systematics has be performed in [8], focusing on the first $1\,\mathrm{fb}^{-1}$. A summary of the main systematic uncertainties is given in Table II.

TABLE II

The main sources of systematic uncertainty in the m_W analysis, as estimated in [7]. See text for more discussion.

Uncertainty (m_W)	Source
25 MeV	Structure function uncertainty (current)
15 MeV	Lepton energy scale and linearity
10 MeV	QCD higher orders
5 MeV	Lepton resolution
5 MeV	Background description

Let us first discuss the main source according to Table II, namely structure function uncertainties. The number quoted in Table II is extracted from [8], where the CTEQ6 structure functions have been used (see also Fig. 6, left). It is possible to estimate how this uncertainty will evolve with LHC data, without performing a formal QCD fit to simulated pseudo-data. As can be seen on Fig. 6, right, there is almost full correlation between the W and Z distributions. This feature is observed with other structure function sets as well [4], and is explained by the fact that the W and Z are produced by partons of very similar x, Q^2 values. Using this correlation in combination with the result of the previous section, namely that the Z rapidity shape precision will be improved by a factor ~ 20, the extrapolated PDF uncertainty should be around $\sim 1\,\text{MeV}$.

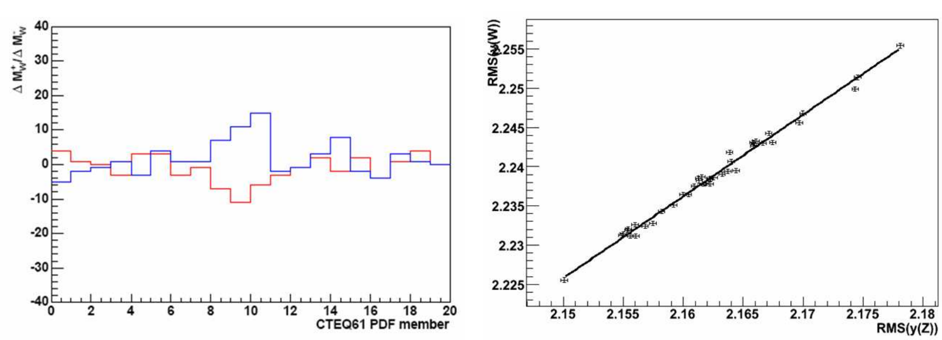

Fig. 6. Left: bias on m_W induced by a $\pm 1\sigma$ variation of each of the 20 parameters defining the CTEQ6 PDF's. Right: correlation between the W and Z rapidity distributions, when varying the proton structure functions within uncertainties. A similar correlation is observed for the W and Z p_{T} distributions.

The most difficult experimental source of uncertainty is considered to be the detector scale and resolution uncertainty. It is often stated that although the Z peak provides a very precise handle (the peak position can be determined with almost arbitrary precision, and the Z mass itself is known with a precision of 2 MeV; the width of the distribution reflects the detector resolution in addition to the natural Z width), the extrapolation to W events relies on excellent control of the linearity. Indeed, Z decay leptons typically have $p_{\mathrm{T}} \sim 45\,\mathrm{GeV}$, whereas W decay leptons have $p_{\mathrm{T}} \sim 40\,\mathrm{GeV}$.

One can improve on this argument once one remembers that Z decay leptons actually cover a wide range of energy. It is thus possible to measure the scale as a function of energy, *i.e.* control the linearity. This was done in [9], and is illustrated in Fig. 7. Furthermore, it is always possible to arrange the analysis (using cuts) such that the selected W leptons cover a p_{T} range included in the Z lepton p_{T} range, so that there is no extrapolation involved in propagating the energy scale uncertainty. Performing the scale analysis on the equivalent of $10\,\mathrm{fb}^{-1}$ of pseudo-data, and propagating the residual scale and resolution uncertainties to m_W, yields an uncertainty of 3 MeV on m_W.

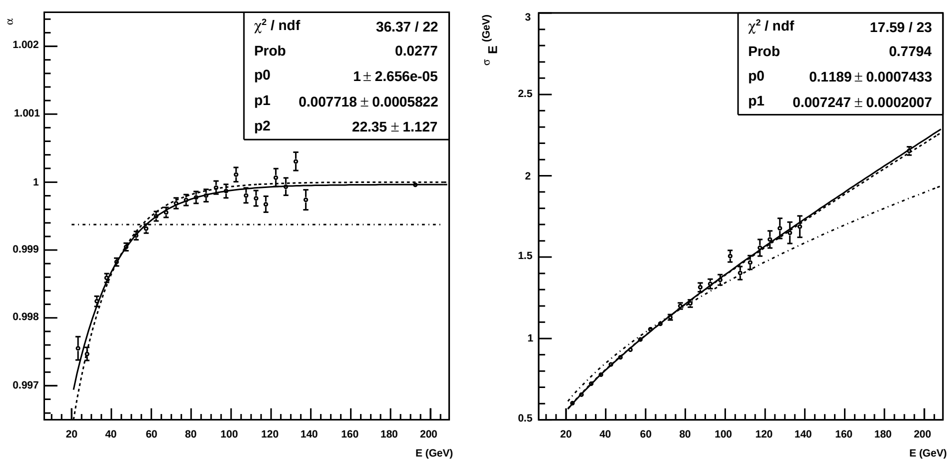

Fig. 7. Measurement of scale (left) and resolution (right) as a function of the lepton energy, in Z boson decays [9].

Let us also comment on the effect of unknown QCD higher orders. It is regularly claimed [10] that uncertainties in the W p_{T} distribution render the lepton p_{T} distribution too uncertain for an m_W application. The argument is once more that although these effects can be precisely measured using Z events, the extrapolation to W events is non-trivial, because of the non-negligible mass difference.

However, Drell–Yan events extend well below (and above) the Z peak. One can actually measure the dilepton p_{T} distribution over a dilepton mass interval spanning from 20–30 GeV up to a few hundred GeV; using this powerful lever arm, together with the very precise p_{T} measurement on the Z peak, allows to infer the $W\,p_{\mathrm{T}}$ distribution with high precision. This is illustrated in Fig. 8: using $10\,\mathrm{fb}^{-1}$, the p_{T} distribution on the Z peak can be known to 5 MeV. The precision in the W mass region is 7 MeV. A separate study of the relation between the $p_{\mathrm{T}}(W)$ and m_W biases tells us that $\delta m_W \sim 0.3\,\delta p_{\mathrm{T}}(W)$; hence, the resulting uncertainty on m_W is 2 MeV.

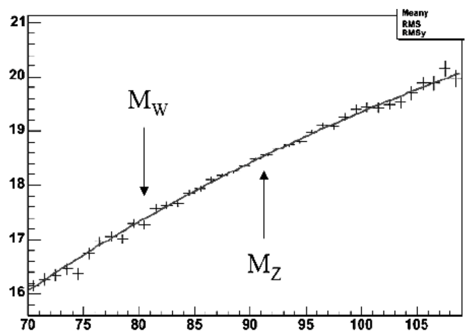

Fig. 8. Average value of $p_{\mathrm{T}}(ll)$, measured in Drell–Yan events, as a function of the lepton pair invariant mass. Both axes are labeled in GeV.

The impact of backgrounds has been studied in [8]. Given the excellent lepton identification capabilities of the LHC detectors, backgrounds from QCD are expected to be negligible. Hence, the main (and largely irreducible) backgrounds come from $W \to \tau$ events followed by leptonic τ decays, and from $Z \to ll$ events where one lepton is outside the acceptance. It is shown in [8] that the related uncertainty is equal, in MeV, to the background uncertainty in percents; the study then concludes that 5 MeV should be achievable, assuming that the background normalization can be known to 5%. Let us stress that this is indeed a conservative number, since the normalization of the $W \to \tau$ background is equal to that of the $W \to l$ signal[1], up to a well known $\tau \to l$ branching fraction; besides, the Z background will have been precisely measured beforehand, as discussed in the previous section.

Let us summarize this (too short) discussion. Although current theoretical knowledge prevents to anticipate a precise measurement of m_W, it is possible to estimate how this knowledge will evolve with the exploitation of the LHC data. The Z boson is an excellent probe of both detector per-

[1] This actually assumes lepton universality. Although absolute universality is not guaranteed, it has been measured to sufficient precision in earlier experiments [2].

formance and the theoretical environment. Updated estimates of the main m_W systematics are listed in Table III. With $10\,\mathrm{fb}^{-1}$ and one experiment, $\delta m_W \sim 6\,\mathrm{MeV}$ is possible. With more luminosity and combining the experimental results, a precision below 5 MeV looks achievable.

TABLE III

Updated estimates of the m_W systematic uncertainties.

δm_W (update)	Source (extrap.)	Tool or comments
$\sim 1\,\mathrm{MeV}$	PDF uncertainty	$d\sigma_Z/dy$, $d\sigma_Z/dM$
$\sim 3\,\mathrm{MeV}$	E, p scale & linearity	Z lepton spectra
$\sim 2\,\mathrm{MeV}$	QCD higher orders	$d\sigma_Z/dp_\mathrm{T}$
$< 1\,\mathrm{MeV}$	Lepton resolution	Z lepton spectra
$< 5\,\mathrm{MeV}$	Backgrounds	conservative estimate

4. Consequences: the top quark mass

Assuming a $\sim 5\,\mathrm{MeV}$ precision can be achieved on the W mass, electroweak fits to the Higgs boson mass provide a goal for the top-quark mass measurement. If both quantities are to contribute similarly to the Higgs boson mass indetermination, the uncertainty on m_t should not exceed $\sim 500\,\mathrm{MeV}$ [2].

The top quark mass measurement experiences a very similar situation. As explained in detail in [11], the analysis relies on $t\bar{t} \to (jjb)(l\nu b)$ decays (the (jj) system resulting from a W decay) and exploits the (jjb) invariant mass distribution. The foreseen measurement techniques are very sophisticated and will provide a statistical sensitivity of about 100 MeV, as one can expect from the mass peak illustrated in Fig. 9 (left). In contrast, the systematic uncertainties are expected to sum up to about 2 GeV.

The main listed contributions to these (*cf.* Table IV) are uncertainties on soft QCD (pile-up, underlying event properties), and the jet energy scales, similarly to the problem of the lepton scales in the m_W analysis. With the data, the soft QCD uncertainties will however become much smaller [14]; on the other hand, the constraint provided by the well-known W mass strongly limits the impact of the light jet scale uncertainty.

This leaves the b-jet scale uncertainty. A 2% uncertainty on this quantity induces a 1.2 GeV systematic uncertainty on the top quark mass, and dominates the measurement without further input. However, the b-jet scale can be assessed independently. This is illustrated in Fig. 9 (right), where an analysis of three-jet events containing a high-E_T leading jet reveals that the $Z \to b\bar{b}$ resonance is well observable above the QCD background [13].

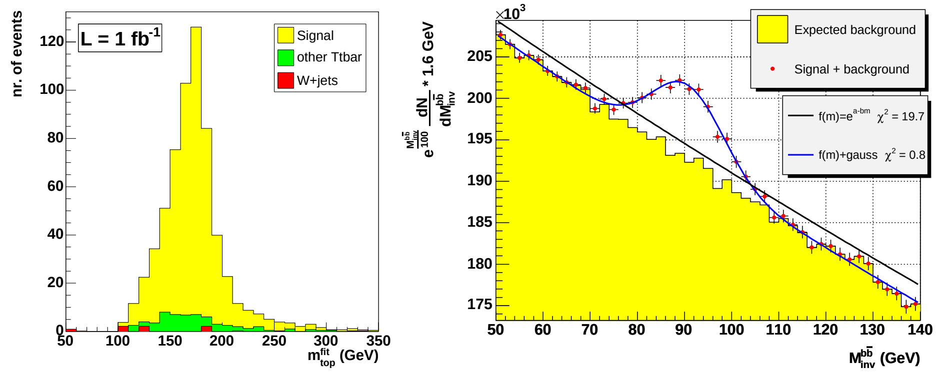

Fig. 9. Left: expected (jjb) mass distribution in semi-leptonic $t\bar{t}$ decays [12]. Right: $Z \to b\bar{b}$ resonance above the QCD background, in three-jet events [13].

TABLE IV

The main sources of systematic uncertainty in the m_t analysis, as estimated in [12]. See text for more discussion.

δm_t	Source
1.2 GeV	Pile-up
0.5 GeV	Underlying event
0.1 GeV	Jet energy scale (light)
1.2 GeV	Jet energy scale (heavy)
0.5 GeV	Sum of others
1.9 GeV	Total

Thanks to the large sidebands, the background can be precisely subtracted, and the precision on the peak position is better than 1%, with 30 fb^{-1}. This divides the b-jet scale uncertainty by a factor 2.

Besides, as is noted in [12], b-jets can also be calibrated relatively to light quark jets, for example by studying the $p_{\rm T}$ imbalance in $j + b$ events. Together with the absolute b-jet scale from Z decays, and the absolute light jet scale from top events themselves, this provides an over-constrained system.

Summarizing the above, we can expect that with enough data, uncertainties related to pile-up and the underlying event will become very small, and the b-jet scale will be known to better than 1%, with $30\,\text{fb}^{-1}$ of data. Re-evaluating Table IV, the systematic uncertainty to the top-mass measurement should be $\sim 800\,\text{MeV}$. Since this number corresponds to $30\,\text{fb}^{-1}$ and one experiment, one can conclude that the target of $\sim 500\,\text{MeV}$ should not be out of reach.

5. Conclusions

Firmly establishing discoveries needs well understood standard processes. It is crucial to move beyond "background control", and actually measure the cross-sections in as much detail as possible. Using the example of Z production, we saw that exploiting only the total production rate is soon limited by theory systematics, and hence does not bring much new understanding. On the contrary, the Z distributions (even ignoring their normalization) will enable us to significantly improve our knowledge of the strong interaction and the proton structure.

An improved study of the m_W potential reveals that the LHC experiments should aim at a measurement precision of $\delta m_W \sim 5\,\text{MeV}$. This follows again from the exploitation of all the distributions of the Z and its decay particles.

Given $\delta m_W \sim 5\,\text{MeV}$, a natural goal for the top quark mass is $\delta m_t \sim 500\,\text{MeV}$. The b-jet scale (usually considered the main systematic uncertainty) can be determined to sufficient precision at the LHC, provided the experiments can observe the $Z \to b\bar{b}$ resonance. However, at this level, the theoretical definition of the top quark mass poses additional problems that need to be addressed [15].

Achieving such results is obviously a long-term challenge to the experiments. However, the precision estimates above make it a worthwhile challenge to address. As a reward, the LHC will have an EW output that will allow the experiments to constrain the theory underlying its discoveries well beyond earlier prospects.

It is a pleasure to thank the many ATLAS and CMS collaborators who helped in gathering this material. I am particularly grateful to Sascha Mehlhase, Esben Klinkby, Troels Petersen, Nathalie Besson, Samir Ferrag, Juan Alcaraz, Martina Malberti, Iacopo Vivarelli, Jorgen d'Hondt, Sanjay Padhi. All figures included here that are not explicitly referenced have been presented by the above at recent ATLAS Collaboration meetings. Many thanks also the organizers for this week of stimulating discussions.

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