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Prospects for Precision measurements at the Large Hadron Collider

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Abstract. The Large Hadron Collider with its two general-purpose proton-proton experiments Atlas and CMS provides ample opportunities for precision measurements of Standard Model parameters. Ultimate precisions of 15 MeV for the W boson mass and better than 1 GeV for the top mass are expected. Sensitivities to triple gauge couplings will improve by orders of magnitude. Novel areas like single top production and high-mass Drell-Yan lepton pairs will be open to exploration.

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1 Introduction

The Large Hadron Collider currently under construction at CERN is often perceived primarily as a discovery facility. Indeed, colliding protons at a center-of-mass energy of 14TeV with a design luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ will undoubtedly allow searches for a wide range of new phenomena. However, the facility will also lend itself to precision measurements of Standard Model parameters. This is particularly, yet not uniquely, true for the initial low luminosity phase.

Even in the low luminosity phase, each LHC experiment will collect $10\text{fb}^{-1}/\text{yr}$, which is comparable to the total integrated luminosity at Tevatron Run 2. Furthermore, as the center-of-mass energy is up by almost an order of magnitude, LHC has the advantage of high production cross-sections for key processes, expected production rates are shown in table 1. The leading-order implication of

Process	σ (pb)	N (s^{-1})	N (yr^{-1})
$W \to e\nu$	1.5×10^4	15	$\sim 10^8$
$Z \to e^+e^-$	1.5×10^3	1.5	$\sim 10^7$
$t\bar{t}$	800	0.8	$\sim 10^7$

Table 1. Examples of LHC production rates at $10^{33}\ \text{cm}^{-2}\text{s}^{-1}$

the vast event samples is that virtually all precision measurements will be systematics limited. Secondly, the large event samples available for calibration and controls will in turn reduce systematics. Finally, being able to apply hard cuts yields well-understood signal samples, again reducing systematics.

When commissioned, the Atlas and CMS detectors will constitute powerful systems for precision physics. Perhaps the hardest challenge in terms of detector systematics will be to understand the lepton energy/momentum scale with the accuracy required for the W mass measurements. Atlas has concluded [1] that a scale precision of 0.02% is possible, eventually using $Z \to \ell\ell$ for calibration. A 1% precision on the jet energy scale should be possible using transverse energy balance in $Z/\gamma+jet$ events. The jet energy scale in hadronic top decays can be fixed in-situ using the W boson mass constraint. Knowing the absolute luminosity is of course important for all measurements involving cross-section. Combining information from LHC itself with forward detectors and measurements of the W and Z rates, the goal is to achieve better than 5% precision.

2 *W* mass measurement

In the Standard Model the masses of the W boson, the top quark and the Higgs boson are related through radiative corrections:

$$\begin{aligned} M_W^2 &= \frac{\pi\alpha}{\sqrt{2}G_\mathrm{F}\sin^2\theta_w(1-\Delta r)} \qquad (1)\\ \Delta r &\sim m_t^2, \\ \Delta r &\sim \log M_H. \end{aligned}$$

This relation currently constrains the Higgs mass; assuming the Higgs boson is discovered at LHC, equation 1 will be used as a test of the Standard Model. Following LEP2 and Tevatron Run 1, $M_W = 80.451 \pm 0.033$ is still in a certain sense a poorly known precision parameter of the Standard Model. In order for M_W and m_t to have equal weights in a χ^2-test of equation 1, their precisions should be related by $\Delta M_W \simeq 0.7 \times 10^{-2}\Delta m_t$. Thus, a precision of $\Delta M_W = 15\,\mathrm{MeV}$ is needed to match a top mass measurement to $\Delta m_t = 2\,\mathrm{GeV}$.

Atlas has studied [2] the classical method for measuring M_W at hadron colliders. Leptonically decaying W bosons are selected requiring one isolated lepton, significant missing transverse energy and minimal hadronic activity. The W mass is extracted from the transverse mass

$$m_\mathrm{T} = \sqrt{2p_\mathrm{T}^\ell p_\mathrm{T}^\nu(1-\cos\Delta\phi)}. \qquad (2)$$

Here, the neutron transverse momentum p_T^ν is reconstructed using the transverse momenta of the lepton and hadronic recoil $\mathbf{u}$, see figure 1. A negligible statistical error of $\sigma_{M_W}^{\mathrm{stat}} < 2\,\mathrm{MeV}$ can be reached after only one year running at low luminosity, collecting $10\,\mathrm{fb}^{-1}$, and the experimental precision will be determined by systematics. Table 2 shows a comparison of systematic errors at CDF Run 1B [3] with projections for one LHC experiments. Note that several contributions to the systematics scale down with increased statistics, others are expected to be constrained by LHC measurements. The lepton scale uncertainty is dominating the systematics and, as already mentioned, will probably be the most challenging to control. Combining both leptonic channels from the two experiments, a combined precision of 15 MeV should be possible albeit challenging.

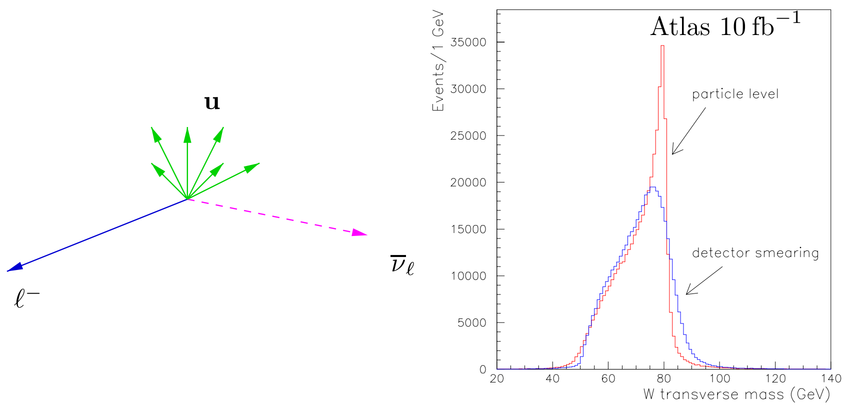

Fig. 1. W mass measurement. Left panel: Transverse view of leptonic W decay. Right panel: Transverse mass distribution, without and with detector smearing.

Source of systematic error	ΔM_W CDF Run IB 84 pb^{-1} e-channel	ΔM_W Atlas 10 fb^{-1} ℓ-channel	
Lepton scale	75 MeV	15 MeV	
Lepton resolution	25 MeV	5 MeV	Known to $< 1.5\%$
p_T^W	15 MeV	5 MeV	Constrain with p_T^Z
Recoil	37 MeV	5 MeV	Constrain with Z data
PDFs	15 MeV	< 10 MeV	Constrained at LHC
Γ_W	(10 MeV)	7 MeV	$\Delta\Gamma_W = 30$ MeV from Run II
Radiative decays	20 MeV	< 10 MeV	Theoretical calculations
Total	92 MeV	< 25 MeV	Per lepton species, per experiment

Table 2. Systematic errors of W mass measurements at CDF Tevatron Run 1B compared to the expectations for the Atlas experiment at LHC. Similar performance is expected from CMS.

Alternative methods for measuring M_W do exist and will be used for cross checks. One possibility is to compare the transverse mass distributions of W and Z boson decays. Being effectively a measurement of M_W/M_Z, important systematics cancel but for the price of a factor 10 loss of statistics. Another option is to abandon the transverse mass and study the transverse momentum distribution of the lepton. As this method does not depend on hadronic recoil reconstruction, it avoids the associated systematics and could even be used at high luminosity. However, the measurement is highly sensitive to assumptions on the W boson transverse momentum spectrum, and would require improved theoretical understanding.

3 Triple gauge couplings

General charged TGCs are customarily parameterized assuming Lorentz and electro-magnetic gauge invariance, and C and P conservation, yielding five independent parameters: λ_V, κ_V, g_1^Z ($V = Z, \gamma$). Likewise, neutral TGCs are parameterized under the assumptions of Lorentz and electro-magnetic gauge invariance, and Bose symmetry. This gives eight parameters h_i^V ($i = 1 \ldots 4$) for the $Z\gamma\gamma/ZZ\gamma$ vertex, and four parameters f_i^V ($i = 4, 5$) for the $ZZ\gamma/ZZZ$ vertex. The only triple gauge couplings present in the Standard Model are λ_Z and λ_γ. As naively adding anomalous couplings to the Standard Model generally violates unitarity, the parameterization has to include form factors with a scale parameter Λ_{FF}, interpreted as the scale of new physics. Running at a center of mass energy almost an order of magnitude above the Tevatron, the LHC experiments will push the exploration limits from about 2 TeV to 10 TeV.

Atlas has studied the possibility of measuring anomalous charged TGCs using the WZ and $W\gamma$ final states [4]. Neutral TGCs have been studied by CMS in the $Z\gamma$ final state [2], and by ATLAS in the ZZ final state [5]. The expected sensitivities are summarized in table 3. Comparing to existing LEP2 results [6] and to expectations for Tevatron Run 2 [7], the LHC improvements range from one to several orders of magnitude.

4 Drell-Yan production of lepton pairs

Drell-Yan produced lepton pairs have a distinct experimental signature and are accessible at LHC even at high luminosity. The cross section and forward-backward asymmetry are both functions of the invariant mass and the rapidity which are experimentally well-defined observables. An integrated luminosity of $100\,\mathrm{fb}^{-1}$ at LHC will provide about 100 million events at the Z pole, and tens of thousand events with invariant mass above 400 GeV. The cross section is sensitive to any new physics that might show up in the s-channel: New resonances, contact terms, R-parity violating SUSY etc. Figure 2 compares the expected number of lepton pair events at Tevatron Run 2 and LHC.

Unlike e^+e^- and $p\overline{p}$ facilities, a proton-proton collider does not have a naturally defined forward direction for A_{FB} measurements. However, as the incoming *anti-quark* must be a sea-quark whose PDF peaks at low x, the incoming *quark* is

	LEP2	Run 2	LHC 100 fb^{-1}
λ_γ	$[-0.089, +0.020]$	–	$[-0.0031, +0.0030]$
λ_Z	–	–	$[-0.0060, +0.0061]$
$\Delta\kappa_\gamma$	$[-0.13, +0.13]$	–	$[-0.060, +0.062]$
$\Delta\kappa_Z$	–	–	$[-0.11, 0.13]$
Δg_1^Z	$[-0.074, 0.028]$	–	$[-0.0073, +0.0096]$
h_3^Z	$[-0.20, +0.07]$	–	0.0007
h_4^Z	$[-0.05, +0.12]$	–	2×10^{-6}
f_4^γ	$[-0.17, +0.19]$	0.163	0.00073
f_4^Z	$[-0.31, +0.28]$	0.159	0.00062
f_5^γ	$[-0.36, +0.40]$	$[-0.179, +0.170]$	0.00074
f_5^Z	$[-0.36, +0.39]$	$[-0.184, +0.162]$	0.00062

Table 3. LHC sensitivities to anomalous TGCs compared to LEP2 results and Tevatron Run 2 expectations

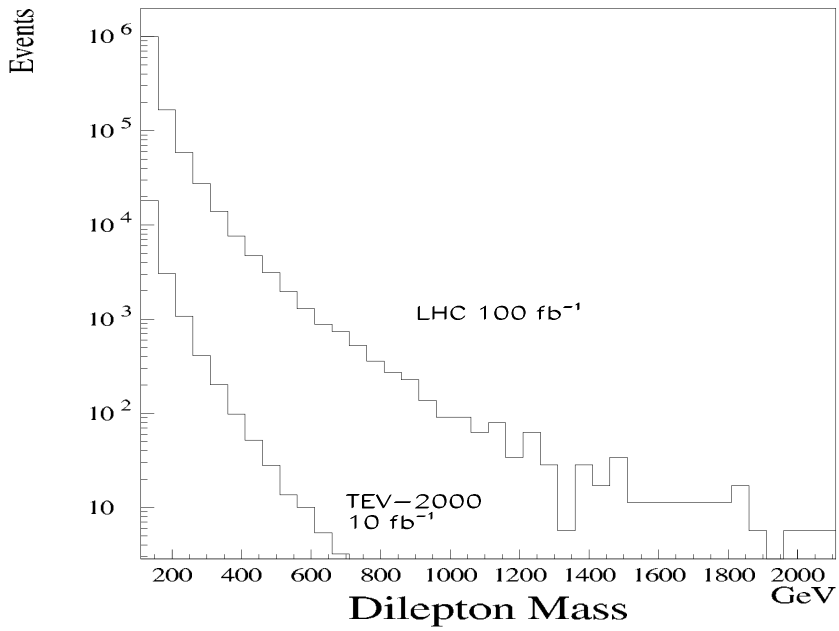

Fig. 2. Drell-Yan lepton pair cross sections at Tevatron and LHC

most likely the one carrying the highest longitudinal momentum. Consequently, the forward direction can be tagged event by event according to the sign of the lepton pair rapidity. Due to the statistical nature of the direction tag, the asymmetry vanishes in central events and increases with increasing rapidity.

The possibility of extracting the electoweak mixing angle $sin^2\theta_{\rm eff}^{\rm lept}(M_Z^2)$ from lepton pair forward-backward asymmetry at LHC has been studied by Atlas [8]. Utilizing moderate electron identification capabilities in the very forward region $|\eta| = 2.5 - 4.9$, it is possible to measure $sin^2\theta_{\rm eff}^{\rm lept}$ with a statistical error of 1.4×10^{-4}. Extracting the parameter with such a precision would require a factor 10 improved understanding of parton distribution functions. Such knowledge might become available from future measurements at HERA, the Tevatron Run 2, and LHC itself. Alternatively, forward-backward asymmetry measurements could be combined with the electroweak mixing angle measurements from LEP to further constrain PDFs.

5 Top quark mass measurements

The CDF and D0 experiments have measured the mass of the heaviest quark to $m_t = 174.3 \pm 5.1$ [9][10]. At Run 2 the precision is expected to improve to $2-3$ GeV. The prospects for further improved measurements at LHC have been studied using a variety of approaches, see [11][12] as well as [13][14]. The precision again turns out to be limited by systematic errors.

For tagging purposes, top mass analyses at LHC require one top quark to decay semileptonically while the other is allowed to decay hadronically. The basic event topology is shown in figure 3. Reconstructing the invariant mass

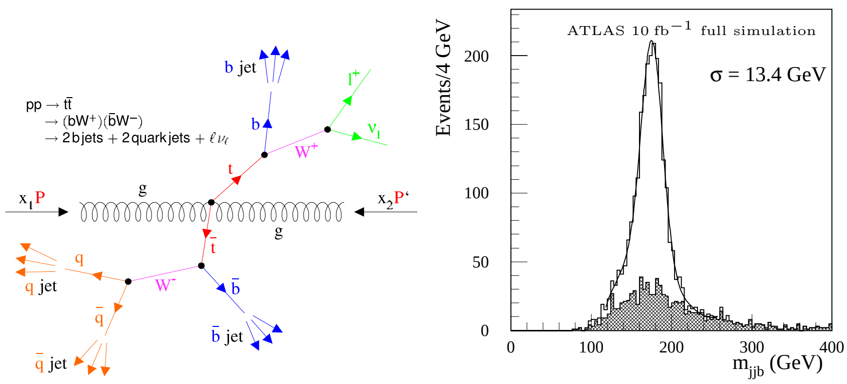

Fig. 3. Lepton plus jets $t\bar{t}$ decays. Left panel: Event topology. Right panel: Signal and combinatorial background distribution.

of the hadronic top using the reconstructed bjj system and assuming a 1% jet calibration, the resulting top mass precision of $\simeq 2$ GeV turns out to be limited by the uncertainty of final state radiation.

Several ways of reducing the impact of FSR have been explored. One promising approach is to reconstruct also the semileptonically decaying top and do a constrained kinematic fit using $m_{jj} = M_W = m_{\ell\nu}$ and $m_{jjb} = m_{\ell\nu b}$. Arguing that events with excessive final state radiation or energy lost to b-decay neutrinos will give a bad fit, the reconstructed top mass is studied as a function of the χ^2 of the fit, see figure 4, left panel. Using $M^{\rm fit}(\chi^2 = 0)$ as the estimator, a precision of 1 GeV can be reached. The residual systematic errors are dominated by the uncertainty on the b-jet calibration.

Another option is to select $t\bar{t}$ events with a high transverse momentum and then reconstruct the hadronically decaying top using a single large calorimeter cone. This method requires an algorithm to subtract the underlying event contribution. As can be seen from the right panel of figure 4, a recalibration procedure is needed to get back the simulated top mass. The recalibration together with the fact that Atlas has a non-compensating calorimeter limits the accuracy to 2.3 GeV.

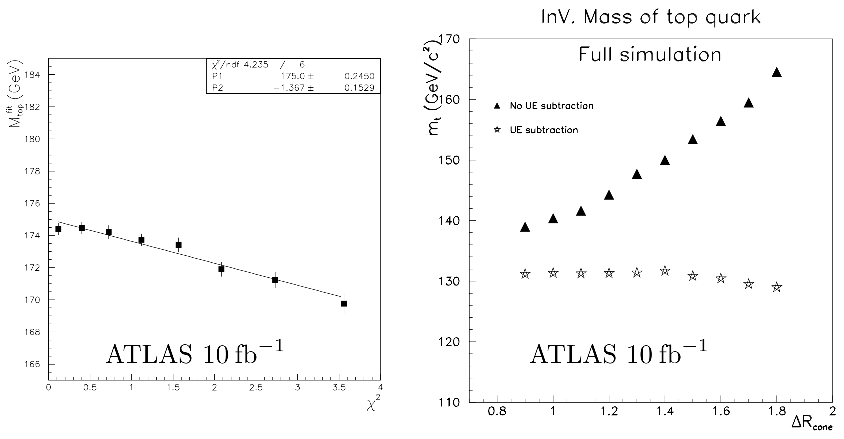

Fig. 4. Two approaches to reducing top mass systematics. Left panel: Reconstructed top mass as a function of χ^2 of constrained kinematic fit. Right panel: Top mass estimation using a single large calorimeter cone.

CMS has pioneered a method to measure the top mass using semileptonic top decays with a $J/\Psi(\mu\mu)$ in the final state [15]. The b-jet from the opposite top quark is required to contain yet another muon for tagging; the topology is illustrated in figure 5. Not depending on jet measurements, this method can also be used at high luminosity. Unfortunately, the branching suppression is severe, and an integrated luminosity of $500\,\text{fb}^{-1}$ is required to reach a statistical error of 0.9 GeV. The method has a significant dependence on the transverse momentum spectrum of the $t\bar{t}$, and would thus require careful tuning of simulations to data. The main source of systematics is expected to be the uncertainty on the b-fragmentation, amounting to 0.4 GeV.

Taking advantage of the complementary systematic errors of the above methods, an ultimate precision of $\Delta m_t \leq 1$ GeV should be possible at LHC.

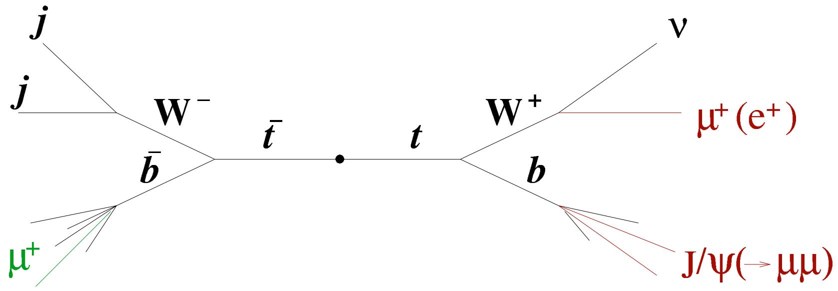

Fig. 5. Top mass measurement using the $\ell J/\psi$ final state.

6 Single top production

While single top production is not yet observed at the Tevatron [16][17], the production rate will be significant at LHC. The relevant cross sections are shown in table 4, to be compared to cross sections for $t\bar{t}$ and non-top backgrounds. The

Process	σ (pb)
Wg-fusion	244
Wt	60
W^*	10
$t\bar{t}$	830
$Wb\bar{b}$	300
$W+$jets	18000

Table 4. Single top production, signal and background cross sections

Standard Model has very specific predictions for electroweak single-top events: The top quarks will be produced fully left-polarized, and the branching fraction to longitudinally polarized W's is 69% with the remaining 31% left-polarized. Using $10\,\text{fb}^{-1}$ of data, measurements of either polarization with better than 2% resolution should be possible [18].

7 Conclusions

Assuming the challenges of systematic errors can be handled, the LHC experiments will provide valuable precision measurements of important Standard Model parameters.

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