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Operation and Physics Potential of Tevatron Run 2

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Abstract.

Run 2 at the Fermilab Tevatron collider is now starting up. This article reviews the current performance of the upgraded CDF and DØ detectors, and outlines the physics goals and prospects for this run.

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Fig. 1. The CDF (left) and DØ (right) detectors being prepared for Run 2.

The Tevatron Collider

The Tevatron collider at Fermi National Accelerator Laboratory in Illinois is the world's highest energy accelerator, colliding protons and antiprotons at a centre of mass energy of almost 2 TeV. The collider was commissioned in the late 1980's with a first run in 1988-89 (CDF only). Run 1 with both the CDF and DØ detectors took place between 1992 and 1996, with an energy of 1.8 TeV, 6×6 proton and antiproton bunches (3.5 μs between crossings) and luminosities of order 10^{31} cm^{-2} s^{-1}. About 120 pb^{-1} per experiment was accumulated in Run 1. Between 1996 and 2001, major upgrades were undertaken both to the detectors and to the accelerator complex. Notably, a new 150 GeV synchrotron, the Main Injector, was constructed to replace the old Main Ring as the injector to the Tevatron. With this new machine in operation, Run 2 began in 2001. The first phase, Run 2a, has seen the energy raised to 1.96 TeV, 36×36 proton and antiproton buches (396 ns between crossings) and will have luminosities up to 2×10^{32} cm^{-2} s^{-1}. This will be followed by a short (6 month) shutdown to install upgraded silicon detectors. The second phase, Run 2b, will continue until it becomes uncompetitive with the LHC; in this period, the number of bunches will be increased to roughly 100×100

(132 ns between crossings) and the luminosity will rise to 5 × 10^{32} cm^{-2} s^{-1}. The total integrated luminosity foreseen for Run 2 is 15 fb^{-1}. To set the scale for these luminosities, recall that the top quark production cross section is roughly 6 pb, while those for the Higgs and Supersymmetry processes of interest in Run 2 are typically a few hundred femtobarns.

Like any hadron collider, the Tevatron is a broad-band quark and gluon collider. Even if we consider only "hard" parton-parton collisions, the subprocess centre-of-mass energies range from ~1 GeV all the way up to ~ 1 TeV. The huge increase in integrated luminosity from Run 1 to Run 2 means that we will increase our reach for discovery physics at the highest mass scales, but it also means that formerly rare processes will become precision physics or even backgrounds to tomorrow's discoveries — the *W* and *Z* bosons and the top quark being obvious examples. The luminosity gain will also yield huge statistics for precise measurements at lower mass scales, such as *b*-physics and QCD.

Detector Performance

The two large collider detectors CDF and DØ, shown in Fig. 1, were both substantially upgraded for Run 2. In this section I present some first results to illustrate how the new systems are performing.

Muon System

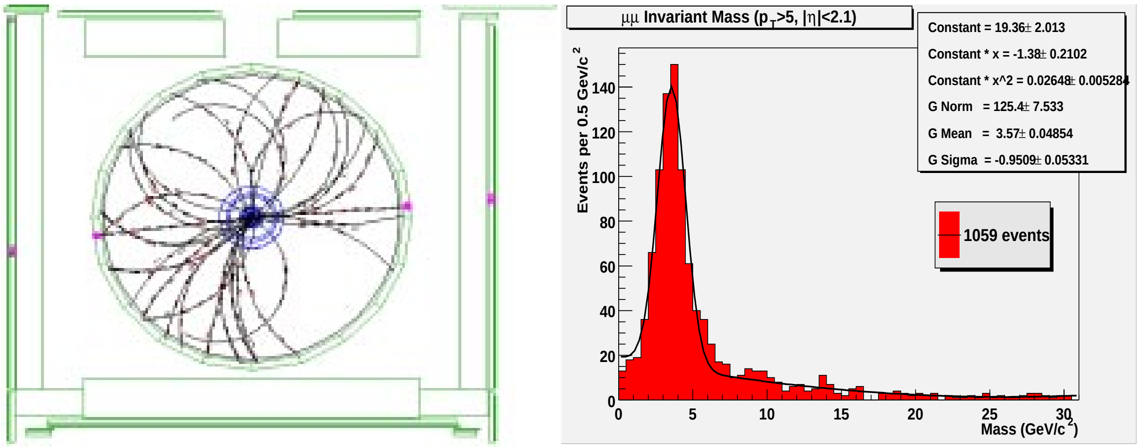

Fig. 2. (Left) *Z* →μμ candidate from CDF. The muons are the straight tracks at 3 o'clock 9 o'clock that point to hits in the muon chambers. The dimuon mass is 88 GeV. (Right) *J/ψ*→μμ signal from DØ using muons reconstructed in the forward direction.

DØ completely rebuilt its forward muon coverage for Run 2 and separated the triggering function (using scintillator tiles from IHEP, Protvino) from the precision tracking (using mini-drift tubes from JINR, Dubna). These systems, and also the upgraded central region triggers, are working very well. The CDF muon system has also been substantially upgraded to improve its hermeticity, and the forward part completely replaced. A $Z \to \mu^+\mu^-$ candidate event from CDF, and a $J/\psi \to \mu^+\mu^-$ signal from DØ, are shown in Fig.2.

Calorimetry

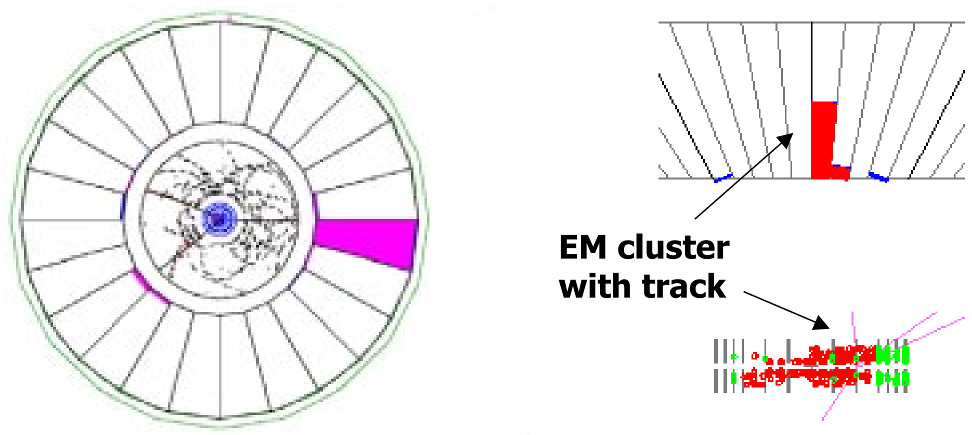

Fig. 3. $W \to e\nu$ candidates in CDF (left) and DØ (right).

CDF has upgraded its calorimetry in the forward direction, with new scintillating tile-fibre end plug calorimeters. DØ continues to use its outstanding uranium liquid argon calorimeter, but with all-new electronics. Calorimetry in both experiments is working well, as evidenced by clear signals for vector bosons decaying to electrons (Fig 3 and 4), for jets, and for photon+jet events. The $Z \to e^+e^-$ and γ+jet samples are of particular importance because of their role in calibrating the EM and the jet energy scales, respectively.

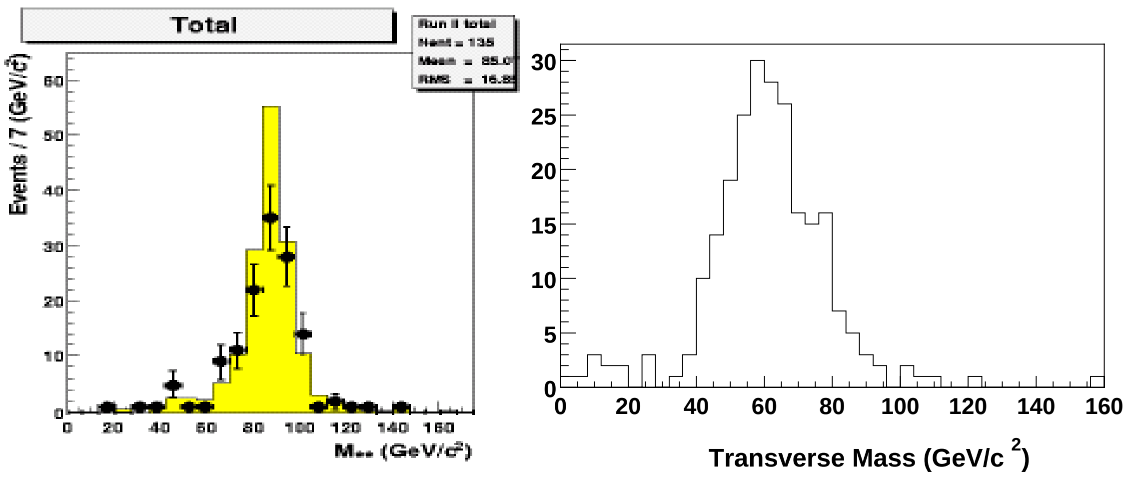

Fig. 4. (left) $Z \to ee$ signal from Run 2 data and from Monte Carlo in CDF; (right) $W \to e\nu$ transverse mass from Run 2 data in DØ.

Central Tracking

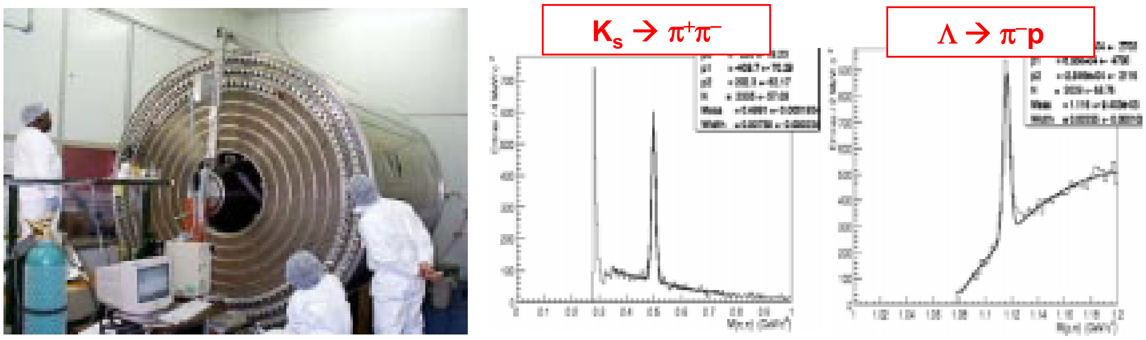

Fig. 5. CDF COT chamber and reconstructed K and Λ signals.

Both experiments are entering Run 2 with new central tracking systems. In the case of CDF, an entirely new Central Outer Tracker (COT) drift chamber has been constructed. It uses 30,000 sense wires in 96 wire planes (8 superlayers) half axial and half small angle stereo. A hit resolution of 200 µm has already been achieved (compared with a goal of 180 µm) and clear signals for $K_S \to \pi\pi$ and $\Lambda \to \pi p$ are seen (Fig. 5).

DØ uses a scintillating fibre tracker with 77,000 fibres in 8 layers, read out with solid state VLPC light sensors. The front end electronics for this detector was not installed until October 2001, but photopeaks and tracks have been seen and indications are that the performance will be very good.

Fig. 6. (left) one of three CDF barrel sections under construction; (right) south half of the DØ silicon detector completed.

Both CDF and DØ have constructed new silicon detectors for vertexing and tracking close to the collision point (Fig. 6). The CDF detector contains 7 layers (8 for $1<|\eta|<2$) in a barrel geometry, with double sided small angle and 90° stereo. There are 722,000 channels. The DØ detector contains only 4 barrel layers but uses disks to extend the tracking up to $|\eta|=2.5$. It uses single and double sided silicon with small angle and 90° stereo, and contains 790,000 channels. Both detectors use versions of the SVX readout chip.

The detectors are working well. Figure 7 shows the reconstructed distribution of track impact parameters in CDF. The SVT trigger can cut on this online for heavy-flavour triggering, as shown. The figure also shows reconstructed K_S and J/ψ signals seen in DØ using silicon standalone tracking.

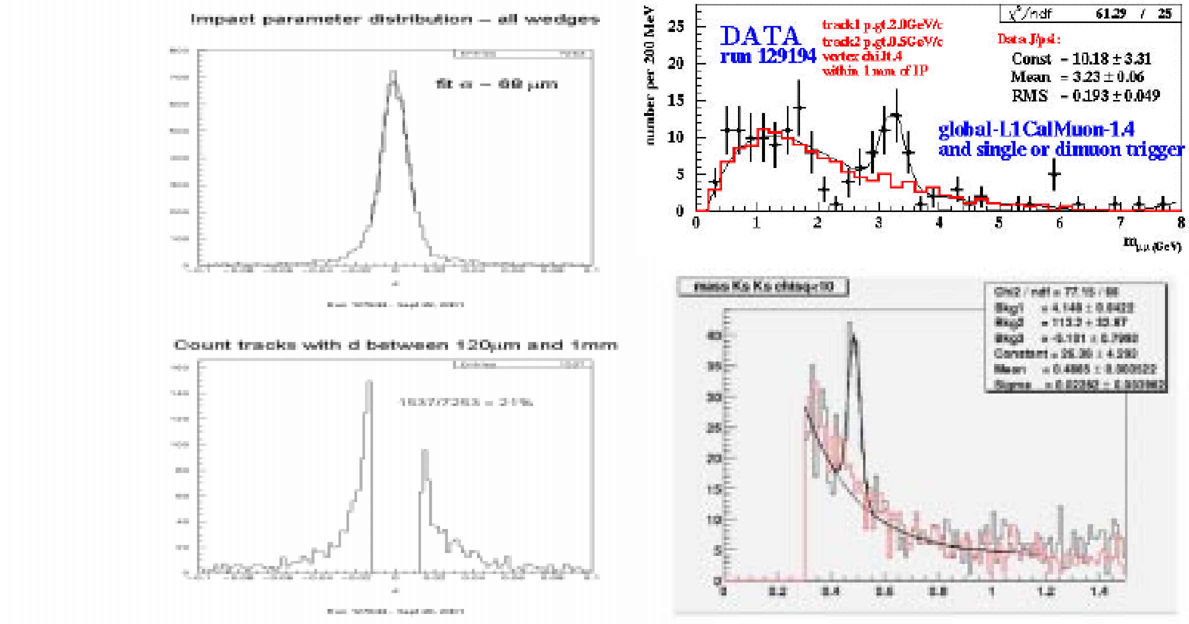

Fig. 7. Silicon detector performance. (left) CDF silicon vertex trigger: impact parameter before and after selection of triggered events. (right) reconstructed K_S and J/ψ signals seen in DØ using silicon standalone tracking.

The Tevatron Physics Programme

There are two major thrusts to the physics programme of Run 2:

- Direct searches for new physics (*i.e.* beyond the currently known Standard Model particles and forces, thus including the Higgs sector)
- Precise measurements of the known quanta of the Standard Model, in order to find indirect hints of (or place constraints on) new particles and forces.

Standard Model Higgs

For any given Higgs mass, the production cross section and decays of the SM Higgs are all calculable. The inclusive cross section at 2 TeV is surprisingly high, about 1 pb for $m_H \sim 120$ GeV. Unfortunately, for masses below about 140 GeV, the dominant Higgs decay mode is $H \to bb$ which is swamped by background. At higher masses, one can use inclusive production followed by $H \to WW$ decays. The best bet below 140 GeV appears to be associated production of H plus a W or Z. The leptonic decays of the W/Z help provide the trigger and the needed background rejection. The cross section is about a factor of five lower, and one must additionally pay the price of the leptonic branching ratios of the W/Z.

As an example[1], for m_H = 115 GeV, 2fb^{-1} per experiment would be sufficient to exclude a Higgs at 95% by combining the $WH \to \ell\nu bb$ and $ZH \to (\ell\ell/\nu\nu)bb$ modes and using both CDF and DØ data. For a 3 (or 5) standard deviation effect, one would need about 5 fb^{-1} (15 fb^{-1}) per experiment respectively. The luminosities required are large because the signal to background ratio is quite low (1:5 in the WH channel). The dominant backgrounds are QCD production of a W or Z together with two b-jets, and single and pair production of top quarks.

If we do see a Higgs signal, we will want to test whether it is really a SM Higgs by measuring the production cross section and searching for other decays such as $H \to \tau\tau$ (the Standard Model branching ratio at 115 GeV is ~ 9%), $H \to WW$ (~ 8% at 115 GeV), and $H \to \gamma\gamma$ (which should not be detectable at the Tevatron for a SM Higgs).

Combining the $H \to bb$ searches with $H \to WW$ at higher masses, one obtains the familiar Higgs reach plot shown in Fig.8[1]. It is interesting to compare the range of sensitivity with the probability distribution for the Higgs (estimated using all the existing measurements) by Erler[2]. Clearly, the mass range we can probe is an interesting one. We cannot guarantee success, but the possibility is enticing.

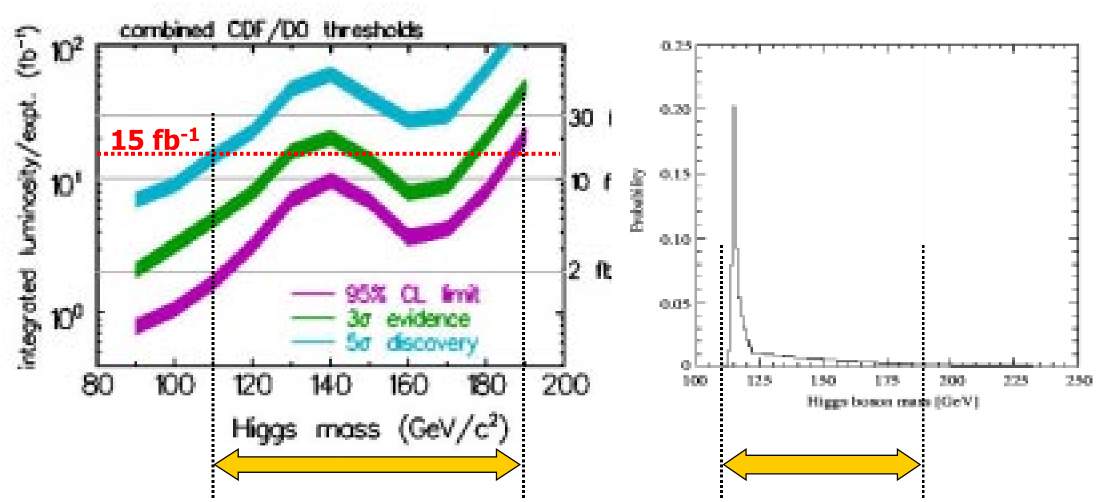

Fig. 8. (left) Tevatron reach plot for Standard Model Higgs searches[1]; (right) probability density as a function of mass for the Standard Model Higgs, from Erler[2]. The arrows are intended to highlight the region 110-190 GeV.

Supersymmetry

The attractiveness of the theory notwithstanding, all direct searches for supersymmetry have proved negative so far. "Naturalness" arguments suggest we should expect to see something soon or we are likely on the wrong track. At hadron colliders, squarks and gluinos are the most copiously produced superpartners. If R-parity is conserved, there is a missing transverse energy signature from escaping neutralinos. The search region is typically $E_T^{miss} > 75$ GeV or so, and additional jets and/or leptons are required. The Run 1 searches excluded squarks below about 250 GeV and gluinos below about 200 GeV (in an mSUGRA framework). With 2 fb^{-1}, similar analyses will be sensitive to gluinos up to 400 GeV[3]. Beyond this, squark and gluino production starts to run into kinematic limits because of falling parton distributions. Chargino/neutralino searches will then become increasingly important (up till now they were not competitive with LEP, but they gain greatly from increased luminosity). The "golden" final state with three leptons has extremely small standard model backgrounds. The Run 2 reach in chargino mass (Fig. 9) extends to about 180 GeV (150 GeV for large tanβ). Searches for stop and sbottom are also of interest, because these are often the lightest squarks. Final states involve heavy flavour tags plus jets and E_T^{miss}. The sensitivity in Run 2 will be about 200 GeV for both stop and sbottom.

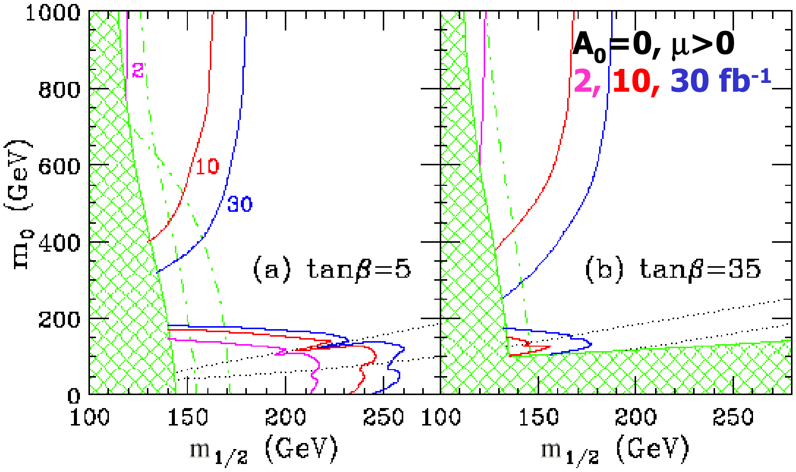

Fig. 9. Range of sensitivity in mSUGRA parameter space for chargino/neutralino searches in Run 2 with 2, 10 and 30 fb^{-1} per experiment[3].

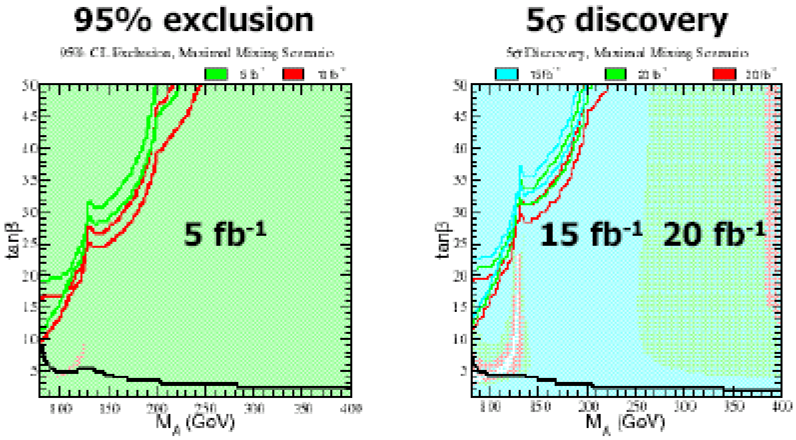

Fig. 10. Colored areas show regions in the m_A-tanβ plane of the SUSY Higgs sector that can be excluded with 5 fb^{-1} (left) and discovered with 15 or 20 fb^{-1} (right) , assuming maximal stop mixing and sparticle masses = 1 TeV. Luminosity is per experiment and CDF and DØ are assumed to be combined[1].

The SUSY Higgs sector will be explored by combining the same searches used for the Standard Model Higgs with some additional possibilities. The latter includes associated production of (*h/H/A*)+*bb* giving signatures with four *b*-jets in the final state. At large tan β the cross sections can be very large (1 pb for tan β = 30 and m_h = 130 GeV). Regions of exclusion and discovery are shown in Fig.10. Clearly, almost all of the SUSY

Higgs parameter plane can be covered —and its exclusion would certainly be interesting.

TeV-scale gravity and extra dimensions

The observable effects of strong gravity in extra dimensions at the TeV scale can be direct and spectacular, such as the production of monojets recoiling against a graviton, or even production of black holes (which rapidly evaporate). At the Tevatron, it is more likely that we will be sensitive to virtual graviton effects and indeed, Run 1 data have already been used to set limits. In Run 2, scales of extra dimensions between 2 and 3 TeV can be probed (in the Arkani-Hamed/Dimopoulos/Dvali scheme) by searching for deviations from the expected e^+e^- and $\gamma\gamma$ spectrum at large invariant masses.

Model-independent searches

DØ has come up with a new approach to searching for new physics[4]. It will never be as sensitive to a particular model as a targeted search, but it is open to anything. The package, called *Sleuth*, searches for deviations from the Standard Model prediction and carries out the correct statistical calculation of their significance. DØ carried out a systematic study of 32 final states involving electrons, muons, photons, W's and Z's, jets and missing E_T in the Run 1 data. None of these final states had less than a 4% probability to agree with the SM prediction and overall the confidence level was 89%. *Sleuth* is really a way of characterising the scale of "unexpectedness" evident in the data. This approach will be extremely powerful in Run 2.

Standard Model Physics in Run 2

N. Lockyer describes the *b*-physics prospects at the Tevatron in a separate article in these proceedings. Some other highlights of the programme are outlined briefly here. In the area of QCD, we will study jets at high E_T, measure photon and b cross sections and try to resolve their disagreement with NLO predictions; use Tevatron jet data to constrain parton distributions, and study diffraction. The goals for top quark physics include the first observation of electroweak single top production, searches for rare decays as a window to new physics, and precise measurements of the top mass. Δm_t of 2–3 GeV should be achievable with 2fb^{-1} and 1–2 GeV with 15fb^{-1}[5]. The W mass can also be measured more precisely: Δm_W of 30 MeV should be achievable with 2fb^{-1} and 20 MeV with 15fb^{-1}[5]. Such measurements would provide a powerful indirect test of the Standard model that would complement the direct search for the Higgs: Fig.11 shows how the resulting situation might look.

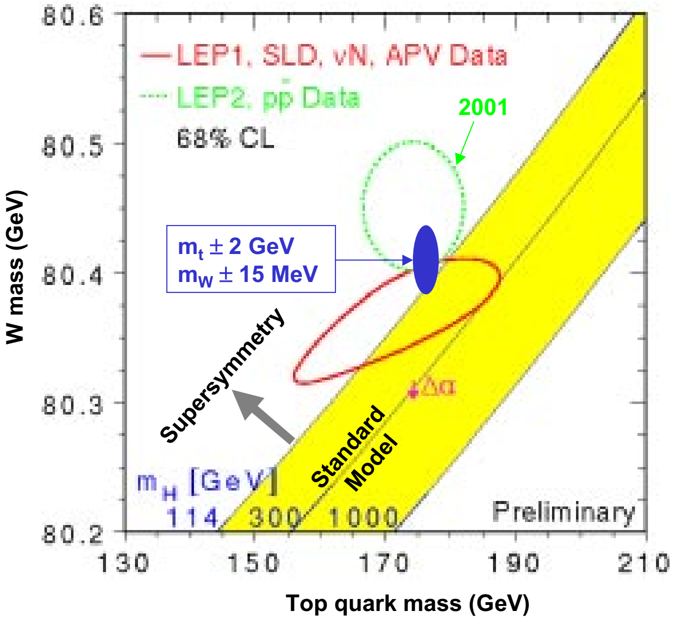

Fig. 11. Measured and predicted top mass and *W* mass plane from summer 2001[6], with hypothetical future measurements ($\Delta m_t = \pm 2$ GeV, $\Delta m_W = \pm 15$ MeV) overlaid.

Complementarity with LHC

The Physics goals of the Tevatron and the LHC are not very different, but the discovery reach of the LHC is hugely greater: for SM Higgs, for example, the Tevatron can probe up to perhaps 180 GeV compared to the LHC's 1 TeV, while for squarks and gluinos, the Tevatron's 400–500 GeV reach compares to 2 TeV at the LHC. What makes the Tevatron compelling is its timeliness, and the fact that both Higgs and SUSY "ought to be" light enough to be within its reach.

For Standard Model physics, systematics may dominate, and the LHC's advantage is less clear. If the Tevatron can determine the top mass at the 1 GeV level and the *W* mass to 15–20 MeV, I believe that the LHC will have a hard task to significantly improve on these measurements.

What are we doing now?

Run 2 officially started on March 1, 2001. First collisions were observed on April 3, and consistent running with 36 × 36 proton and antiproton bunches started in early June. Roughly 12 pb^{-1} has been delivered so far, and we are still commissioning both the detectors and the accelerator. Currently the Tevatron is in a six-week shutdown (October-November 2001): DØ is completing the installation of its fiber tracker electronics, and the trigger is being phased in, while CDF is addressing cooling problems in its outer silicon layers. The pause in data-taking has also allowed us to make a lot of progress in understanding our detectors and systems by reprocessing and reanalysing the data taken so far.

There are some lessons for the LHC community in this. Bringing a hadron collider and two major multipurpose detectors into operation is a complicated task and will probably take longer than you think. The balance between allowing the schedule to slip, or deciding to install partially instrumented detectors is a delicate one. Commissioning a detector is often painful, slow and frustrating, but for an experimentalist, it is also an immense amount of fun.

Currently, the Tevatron collider is delivering luminosities of $\sim 7 \times 10^{30}$ cm^{-2} s^{-1}. The goal for early 2002 is 4×10^{31} cm^{-2} $\text{s}^{-1}$with 200 $\text{pb}^{-1}$to be delivered by summer. Later in 2002, the luminosity should reach 8×10^{31} cm^{-2} $\text{s}^{-1}$and the Recycler Ring should be commissioned. The Recycler is a storage ring designed to accept the unused antiprotons at the end of a store and allow them to be cooled and reused, with a significant gain in luminosity.

Also, planning is well underway for the additional detector enhancements that will be needed to meet the goal of accumulating 15 fb^{-1} by the end of 2007. The major component of the upgrade, both for CDF and DØ, will be new silicon detectors to replace the present devices, which cannot survive the radiation dose. Technical design reports were submitted to the laboratory in October 2001, with the goal of having the detectors installed and running by mid-2005.

Conclusions

Run 2 has begun! The Tevatron programme in the next six years offers a real opportunity to significantly advance our understanding of the fundamental properties of the universe. It is an exciting, challenging programme that goes straight to the highest priorities of high energy physics worldwide. The accelerator and detectors are being commissioned and seem to be performing well. We anticipate first physics results in the summer of 2002.

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