Shopping list for Run II

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Abstract

The upgraded Tevatron collider and DØ detector provide a superb instrument to study a broad range of exciting physics. The purpose of this "brain storm" is to make up my own mind on just what it is that I wish to study in Run II. In the last of five independent Sections I make the case for muon triggers that do not use Fiber Tracker information, and for weekly reversals of the DØ magnetic fields.

Contents

1 Shopping list for Run II

We assume an integrated luminosity of 2 fb^{-1} at 2 TeV center of mass energy. This Section is mostly from a talk by Meenakshi Narain.[1] See also [2].

- Measure top quark mass to $\approx \pm 3$ GeV.
- Measure W mass to $\approx \pm 40$ MeV (comparable with LEP-II). Method: m_T distribution. Other methods: electron p_T spectrum, ratio of Z transverse mass to W transverse mass, and electron p spectrum.

- From mass of t and W constrain mass of Higgs to $\approx \pm 60\%$.
- Measure top quark cross section to $\approx \pm 8\%$. In comparison, theoretical predictions have a spread of $\approx \pm 15\%$.
- Single top production ($q\bar{q} \to t\bar{b}$) measures V_{tb} to $\approx \pm 14\%$[1]. (My guesstimate however is that we will need 10 fb^{-1}.)
- Measure $B(t \to Wb)/B(t \to Xb)$ and set a limit to the mass of H^+.
- Measure $t\bar{t}$ invariant mass and set limit to mass of top-color Z' to $\approx$ 800 GeV.
- Check expectation of top decay's: $W_{long}/W_{left} = 0.5 m_t^2/m_W^2$.
- Measure $B(t \to Wb)/B(t \to Wq)$ and obtain V_{tb} to $\approx$ 2%. This measurement will further constrain the existence of a fourth family of quarks and leptons.
- Top quark rare decays to measure V_{ts} and V_{td}.
- Measure W width Γ_W to $\approx \pm 0.030$ GeV by indirect method, and to $\approx \pm 0.020$ GeV by direct method.
- Check couplings $WW\gamma$ and WWZ. Set limits to anomalous couplings a factor 3 to 5 better than in Run I.
- Check couplings $ZZ\gamma$ and $Z\gamma\gamma$ and set limits to anomalous couplings a factor 10 to 100 better than in Run I.
- Measure W asymmetry and constrain structure functions.
- Measure Z asymmetry and obtain $\sin^2(\theta)$ to $\approx \pm 0.001$ (compared to LEP's ± 0.0016).
- Check that $qq \to W\gamma$ is zero at $\cos(\theta^*) = \pm 1/3$.
- Measure the W and Z differencial cross sections $\times$ leptonic branching fractions.
- Higgs search (either Standard Model h or SUSY h_0). LEP has set the limit $m_h > 113.5$ at 95% confidence level (CL).[3] Higgs mass $m_h < 130$ GeV is a window of opportunity for the Tevatron because the LHC has a large $t\bar{t}$ background. DØ with 2 fb^{-1} can set a 95% CL limit up to 120 GeV, and a 3-sigma observation up to 100 GeV[4]. DØ with 3.5 fb^{-1} can set a 95% CL limit up to 130 GeV. DØ with 8 fb^{-1} can

establish a 3-sigma observation up to 130 GeV[4]. Combining DØ and CDF measurements with 10 fb^{-1} each can set a 95% confidence limit up to 182 GeV[5]. The global Standard Model fit to electroweak data yields $m_h = 67^{+60}_{-88}$ GeV, or $m_h < 188$ GeV at 95% confidence. So there is really a good chance to discover Higgs with 10 fb^{-1} of data. The most promising channels for $m_H < 130$ GeV are:

$$q\bar{q} \to W^* \to hW \to b\bar{b}l\nu_l,$$

$$q\bar{q} \to Z^* \to hZ \to b\bar{b}l^+l^-.$$

- Measure $\sin(2\beta)$ in channel $B_d^0 \to J/\psi K_s$ to $\approx \pm 0.16$.

- Search for B_s mixing. Set limit up to $x_s \equiv \Delta m_s/\Gamma_s \approx 20$ at 95% CL. Some channels are $B_s \to D_s l\nu$, $B_s \to D_s + \pi$'s. Fits to precision electroweak measurements and direct searches obtain $15 < x_s < 30$ at 95% CL. DØ with a reach of $x_s \approx 20$ is not competitive with CDF which has a reach of $x_s \approx 60$ due to their time-of-flight separation of K/π.

- Rare B decays, their expected DØ and CDF Run II branching fraction limits at 90% CL[6], current limits at 90% CL[7], and the corresponding SM prediction[6]:

Decay	Run II limit	Current limit	SM prediction
$B^+ \to \mu^+\mu^- K^+$	$2 \cdot 10^{-7}$	$5.2 \cdot 10^{-6}$	$(2-5) \cdot 10^{-7}$
$B_d^0 \to \mu^+\mu^- K^{*0}$	$4 \cdot 10^{-7}$	$4.0 \cdot 10^{-6}$	$(2-5) \cdot 10^{-6}$
$B_d^0 \to \mu^+\mu^-$	$1 \cdot 10^{-8}$	$6.8 \cdot 10^{-7}$	$(0.6-1.9) \cdot 10^{-10}$
$B_s^0 \to \mu^+\mu^-$	$4 \cdot 10^{-8}$	$2.0 \cdot 10^{-6}$	$(1.5-15) \cdot 10^{-9}$
$B_s^0 \to \pi^+\pi^-$			
$B_s^0 \to J/\psi\phi$			

- B_c mesons and baryons: masses and lifetimes.

- Λ_c, Λ_b and Ξ_b: masses and lifetimes.

- Search for squark and gluino to ≈ 300 GeV. Signature: missing E_T plus jets.

- Search for chargino and neutralinos to ≈ 210 GeV. Signature: trileptons plus missing E_T.

- Search for stop to ≈ 150 GeV.

- Search for W' to ≈ 1200 GeV.
- Search for Z' to ≈ 1000 GeV.
- Search for leptoquarks (scalar and vector of first or second generation) to ≈ 300 GeV.
- Search for axigluons to ≈ 1250 GeV.
- Search for excited quarks to ≈ 1050 GeV.
- Search for color octet technirho to ≈ 900 GeV.
- Search for E_6 diquarks to ≈ 700 GeV.
- Search for gaugino to ≈ 90 GeV.
- QCD: parton distributions.
- QCD: Drell-Yan γ, W and Z production. Constrain structure functions and compositness. Clean studies that do not depend on hadronization.
- QCD: measurement of α_s with W/Z + jets.
- Diffraction, semi-diffraction, elastic scattering(?), Pomeron structure, rapidity gaps.
- Search for fourth generation quark b'.
- Around 1997 James Bjorken presented at Fermilab interesting ideas on rapidity gaps and the break up of color strings into quark-antiquark pairs so that jets should come out in "sheets".
- Quasi model independent searches for new physics with tools such as Sherlok, Sleuth and Quaero. Very important as theorists might have missed the point entirely.
- Measure the dimuon charge asymmetry due to asymmetric mixing and decay of $B_d^0 \leftrightarrow \bar{B}_d^0$ to $\approx \pm 0.4\%$ (a factor ≈ 10 improvement over current limits). Complement the time-independent measurement with time-dependent studies (using the fact that the muons originate from secondary vertices).
- Color coherence.

And much, much more... Do our triggers miss any of these channels?

2 What's wrong with the Standard Model?

I remember, some ten years ago in a talk at Fermilab, James Bjorken saying: "There is not a shred of evidence against the Standard Model. We do not know whether to rejoice or dispare." In fact, the Standard Model of quarks and leptons is wildly successful over 20 orders of magnitude in energy, from tiny corrections to the Lamb shift of order 10^{-9} eV, to the energy scale probed by the gigantic collider experiments that discovered the top quark at 174 GeV. So then, why do we want to extend such a successful model? First, we need extensions to the Standard Model if only to test this model and set limits to "new" physics. Secondly, there may already be "shreds" of evidence beyond the Standard Model:

- At least two types of neutrinos appear to have mass and oscillate[8];
- The dark matter that dominates the universe is not composed of quarks and leptons; and
- The Standard Model apparently can not account for baryogenesis.

Thirdly, the symmetries of the "Periodic Table of Quarks and Leptons" beg for a deeper understanding. Let us recall that the "Periodic Table of the Elements" was understood with the Bohr model of the atom, and the "Periodic Tables of Mesons and Baryons" were understood with the quarks of Gell-Mann and Zweig. What is the "Periodic Table of Quarks and Leptons" telling us?

The Standard Model is a renormalizable theory that may be valid all the way up to the Planck energy scale where gravity between elementary particles becomes comparable with the other interactions (provided that the Higgs mass m_h turns up in the range 130 to 180 GeV[5, 7, 9]). Is there a "desert" from the electroweak energy scale of ≈ 100 GeV all the way up to the Planck scale of $\approx 10^{19}$ GeV? Perhaps not. The Standard Model has three gauge couplings g_1, g_2 and g_3 corresponding to each of the symmetry groups $U(1)_Y$, $SU(2)_L$ and $SU(3)_c$ of the model. These couplings "run" with energy and become approximately equal at $\approx 10^{15}$ GeV. This "coincidence" may indicate that a new "Grand Unified Theory" (GUT) sets in at this energy scale. Examples are $SU(5)$, $SU(4) \times SU(2)_L \times SU(2)_R$, $SO(10)$ and E_6, that spontaneously brake down, in one or more steps, to the Standard Model symmetry $U(1)_Y \times SU(2)_L \times SU(3)_c$, and finally to $U(1)_{em} \times SU(3)_c$ where $U(1)_{em}$ is the symmetry of Quantum Electrodynamics. The points in favor of a GUT are:

- The three running coupling constants could become unified at the GUT energy scale (at least two energies of vacuum symmetry breaking are required, one at about 10^{16} GeV and one between 10^2 and 10^{15} GeV).

- Below the GUT scale the running couplings g_1 and g_2 determine the "Weinberg angle" that "mixes" $SU(2)_L$ and $U(1)_Y$ at low energies: $\tan(\theta_W) = g_1/g_2$.

- The GUT with no $U(1)$ factor would explain the discrete values of the Y quantum numbers corresponding to $U(1)_Y$ which are otherwise arbitrary.

- The GUT would guarantee the cancellation of divergences called "anomalies".

- Many GUT's contain massive neutrinos that could explain the solar and atmospheric neutrino "problems".

- GUT's have new sources of CP violation needed to explain baryogenesis.

- The smallness of lepton number violation can be traced to the large mass scale M_{GUT} in non-supersymmetric GUT's.[10]

If GUT unification occurs, then quarks can decay into leptons and the proton becomes unstable. Perhaps one day we will detect proton decay. The non-observation of proton decay to this date has already ruled out $SU(5)$. My favorite non-supersymmetric GUT is $SO(10) \to SU(3)_c \times U(1)_{B-L} \times SU(2)_L \times SU(2)_R$ at $\approx 10^{16}$ GeV $\to SU(3)_c \times SU(2)_L \times U(1)_Y \times ...$ at $\approx 10^{10}$ GeV $\to SU(3)_c \times U(1)_{em}$ at $\approx 10^2$ GeV. This GUT may be in agreement with observations (except for a dark matter candidate).[10, 11] The group $SO(10)$ includes $SU(5)$ (since a complex 5 vector can be mapped to a real 10 vector) and also includes the Pati-Salam group $SU(4) \times SU(2)_L \times SU(2)_R$. Massive neutrinos could provide some of the dark matter of the universe: the sum of their masses would be $46 \times \Omega_\nu$ eV. This mass corresponds to "hot dark matter". Models of galaxy formation require mostly "cold dark matter". So $SO(10)$ may have a problem with dark matter. Unfortunately GUT's seem to have no experimental consequences at present day colliders unless the last stage of symmetry breaking happens to occur below a few TeV.

Is there a "desert" from the electroweak energy scale of $\approx 10^2$ GeV up to the GUT scale at $\approx 10^{15}$ eV? Perhaps not. Suppose that "new" physics sets in at an energy scale Λ. Then all low-energy couplings and fermion masses are logarithmically sensitive to Λ[5]. In contrast the Higgs mass squared is **quadratically** sensitive to Λ:

$$m_h^2 = 2\lambda v_F^2 + c \cdot g_2^2 \Lambda^2. \tag{1}$$

$v_F \approx 246$ GeV is the vacuum expectation value of the Higgs field Φ, $\lambda[\Phi^\dagger\Phi - \frac{1}{2}v_F^2]^2$ is the Higgs field potential, c is a constant presumably of order 1, and $g_2 = e/\sin(\theta_W) = \sqrt{4\pi/(137 \cdot 0.23)} = 0.63$. If Λ is much larger than m_h, then the two terms on the right hand side of (1) nearly cancel which is "unnatural". Furthermore this near cancellation must be redone at every order of the perturbation expansion. "This kind of fine-tuning is really unacceptable, so one is invited to look for some protective symmetry to guarantee that the hierarchy $v_F << M_P$ is stable."[9] So, according to this argument, the "natural" energy scale for new physics is of order $\Lambda \approx 1$ TeV, and so there is plenty of new physics to be discovered at the Tevatron and the Large Hadron Collider (LHC). I do not find this fine tuning argument to be entirely compelling. After all the "bare" λ is not observable, and the required fine tuning at every order in perturbation theory is the same as the renormalization of the electron mass in Quantum Electrodynamics, only here the divergences are quadratic instead of logarithmic. There is really no fine tuning problem with the Standard Model itself. It is only when the Standard Model is extended to a GUT with scale Λ that fine tuning of the GUT is required to obtain Higgs masses $\ll \Lambda$. The scale Λ of new physics required to have a given level of fine tuning for a given m_h can be found in [12]. For example if we allow 1% (10%) fine tuning, and the Higgs mass is found to be $m_h = 140$ GeV, then $\Lambda \approx 10$ TeV (2 TeV). It is interesting to note that for each Λ it is possible to choose one specific m_h for which there is no fine tuning! For example, for $\Lambda = 100$ TeV there is no fine tuning if $m_h = 160$ GeV.[12] So two experimentally acceptable solutions with no fine tuning are the Standard Model plus right handed neutrinos and Dirac masses and no GUT; or a GUT with a special m_h. I emphasize that the Standard Model is renormalizable, so that once everything is expressed in terms of observables (instead of bare masses, charges and couplings) all calculations are finite. In other words the "hierarchy problem" is just that: a problem, not a terminal disease.

An example of "new" physics that could set in at the energy scale of ≈ 1 TeV and protect the hierarchy $v_F \ll M_P$ is "low-energy" or "weak-scale" supersymmetry (SUSY)[13]. In SUSY the quadratic dependencies on Λ cancel between fermions and bosons, leaving only logarithmic dependencies. Equation (1) becomes replaced by

$$m_h^2 = 2\lambda v_F^2 + \alpha(\tilde{m}_W^2 - m_W^2) \cdot \ln(\Lambda/v_F). \tag{2}$$

"So, as long as the masses of the SUSY partners (denoted by a tilde) are themselves not split away by much more than v_F, radiative corrections will not destabilize the hierarchy $v_F << M_P$."[9] So, according to this line of thought, there is "plenty of new physics to be discovered, since all particles have superpartners of mass $\tilde{m} \approx m + O(v_F)$."[9]

Points in favor of SUSY are:

- If SUSY sets in below about 1 TeV it could be valid all the way up to the Planck scale without the scalar masses becoming "unnatural", thus solving the "hierarchy problem".

- If SUSY sets in at Λ_{SUSY} between 0.1 and 1 TeV the three running couplings meet at a single GUT scale of $\approx 10^{16}$ GeV. (This can also be arranged for non-SUSY GUT's with more than one symmetry breaking scale such as $SO(10)$, or with additional Higgs doublets.)

- SUSY with R-parity conservation provides a lightest supersymmetric particle that is stable and weakly interacting. This particle might be the dark matter that dominates the universe. The best candidate is the neutralino, a superposition of the photino, Z-ino and higgsino. Assume that particles of cold dark matter are equal to (or have equal abundance as) their antiparticles, and assume that they annihilate with electro-weak strength. Then the observed density of dark matter in the universe is obtained if the particles have $m_{dm} \approx 100$ GeV[7] which is quite remarkable!

- Fits to electroweak data favor a light Higgs as predicted by SUSY. If the Higgs boson turns out to be heavy (say $m_h > 150$ GeV) then "SUSY at the weak scale" is in trouble. This will be a crucial test of the model. Also the cross section and decay of the Higgs distinguishes the Standard Model from SUSY.

- There is even hope of extending SUSY to include gravity (by promoting the global SUSY symmetry to a local symmetry).

- We hope that SUSY predicts approximately zero cosmological constant because the positive contribution from bosons cancels the negative contribution from fermions. (The Hubble plot for supernovas together with the observations by Boomerang and Maxima appear to require $\Omega_\Lambda \approx 0.7$, small but non-zero.)

A problem with supersymmetric extensions of the Standard Model, is that there are low dimensional lepton-number violating terms that must be suppressed in some way, presumably by imposing appropriate symmetries.[10]

Non supersymmetric GUT's do not have this problem as long as M_{GUT} is sufficiently large. Another so-called μ-problem (having to do with the cross-coupling between the two Higgs doublets in the superpotential) "endangers the whole idea of weak-scale supersymmetry".[10]

Let us emphasize that supersymmetry tames the renormalization of m_h^2 (from quadratic to logarithmic); it does not tame observable predictions of the Standard Model (which are finite) and neither does it explain why $m_h << M_P$ in the first place. And the price to pay is huge: we must include all the supersymmetric partners of the Standard Model particles for which we have no evidence whatsoever; we have to replace the 19 or so arbitrary parameters of the Standard Model with 124 to 315 parameters of **minimum SUSY** depending on the details of the model[13]; and solve a host of problems[14]. A theory with so many independent parameters can predict anything, which is akin to predicting nothing. The nice thing about supersymmetry, whether right or wrong, is that it provides lots and lots of channels with well defined signatures to search.

One way to constrain the scale Λ of "new" physics is to measure the Higgs mass. If m_h if found to be above 180 GeV then the Higgs self-coupling blows up at a scale Λ below the Planck scale. If m_h is found to be less than 130 GeV then the Higgs potential develops a second minimum again requiring "new" physics below the Planck scale. The value of Λ at which the Standard Model breaks down if m_h is outside the range of 130 to 180 GeV is given in [5]. The present experimental bounds of $113.5 GeV < m_h <$ 188 GeV at 95% confidence imply that the Standard Model does not require "new" physics below 100 TeV[5].

Nucleon decay can probe extremely high energies: up to 10^{15} GeV in non-supersymmetric GUT's, or up to 10^{24} GeV in SUSY.[15] So the current bound on nucleon decay is already putting constraints on physics at the Planck scale!

To summarize: The Standard Model is a renormalizable theory and may be valid all the way up to the Planck scale. In spite of 30 years of studies of Grand Unified Theories *et. al.* we have no clearly preferred one, and no compelling argument that guarantees that there is new physics around the corner. We clearly need experimental guidance and perhaps a new principle in relation to the generation of mass. GUT's, not the Standard Model, have a "hierarchy problem" which is just that: a problem, not a terminal disease. In fact there is a particular value of m_h which has no fine tuning. The Standard Model is in agreement with observations over 20 decades in energy with only one breaking of the vacuum symmetry. What is the chance that in the next decade of energy new physics will show itself? My guesstimate is this: for the three couplings g_1, g_2 and g_3 to come together we need (at least) one vacuum symmetry breaking between $\approx 10^2$ and $\approx 10^{15}$ GeV before the GUT symmetry breaking at about $\approx 10^{16}$ GeV; the "probability" that this intermediate symmetry breaking happens to occur between 10^2 and 10^3 GeV is about $\approx (3-2)/(15-2)$ or 10%.

So our hopes for Run II are the discovery of the Higgs particle (tho 10 fb^{-1} might be required), the measurement of B_s^0 mixing (tho CDF will beat us), the discovery of single top production, the observation of CP violation in the channel $B_d^0 \rightarrow J/\psi K_s$, and further constrain the Standard Model in many channels. The measurement of the Higgs mass and its production cross section $\times$ branching fraction will narrow the options for new physics. The direct discovery of new physics at DØ would be, in my view, **unexpected** gravy, and all the more fantastic if we should be so lucky.

So this discussion leaves us with the baffling mysteries of masses and the nature of vacuum; families, CKM matrix, CP violation and baryogenesis; dark matter, the cosmological constant and inflation. In the next Section we discuss new physics to search.

3 Extensions of the Standard Model

The quantization of gravity drives the search for a Theory of Everything. But, does gravity need to be quantized? Is the gravitational interaction classical or quantum? Perhaps nature never answered that question[16]. In this Section, instead of descending from a Theory of Everything hoping to understand the mysteries of the Standard Model and beyond, we will take the view that Nature may have surprises on the way so that we need experimental guidance to advance. Let us consider extensions of the Standard Model "one step at a time". First we list renormalizable extensions:

- Add three right handed neutrinos, give neutrinos a Dirac mass and introduce a CKM-like matrix for leptons in exact analogy to quarks. Then we have the mystery: Why are neutrinos much lighter than quarks and leptons? (And, once we introduce right handed neutrinos with no gauge couplings, then, for consistency, we should add Majorana mass terms for them!) Unfortunately this extension of the Standard Model has no experimental consequences at colliders.

- Add Majorana mass terms for the left-handed neutrinos (this violates lepton number conservation), and optionally introduce right-handed neutrinos and give them a Majorana and/or Dirac mass.[9] Then the see-saw mechanism could explain the small masses of neutrinos. The testable prediction is that the neutrino masses would be proportional to the squares of the corresponding lepton or quark masses. The see-saw mechanism requires new physics in the range 10^{11} GeV to 10^{15} GeV. Unfortunately this extension of the Standard Model has no experimental consequences at colliders, and "are unlikely to give much information on the nature of the physics which gives rise to the Fermi scale v_F."[9]

- Add a second complex Higgs doublet. Higgs doublets can be added to the Standard Model without upsetting the Z/W mass ratio; higher dimensional representations upset this ratio. Adding a second complex doublet to the Standard Model results in three neutral Higgs (h_0, H_0 and A_0) and two charged Higgs (H^+ and H^-), instead of the single neutral Higgs h of the Standard Model. DØ will be able to set limits on, or discover, these Higgs. Limits from B meson mixing and decay, competitive with the collider limits, can be found in [17].

- Add a fourth family of quarks and leptons. First, all members of the family must have masses greater than 45 GeV to not upset the observed width of the Z. Secondly, fits to precision electroweak data rule out a fourth family at 97% CL even if the fourth family neutrino mass is "very heavy"[7]. Direct searches imply $m_b' > 199$ GeV[7]. DØ may raise this direct search limit.

- Add new gauge bosons W' and/or Z'. This can be done once the Higgs sector has been enlarged. A right-handed $W_R^\pm$, Z_R corresponding to a $SU(2)_R$ symmetry is particularly welcome for left-right symmetric models. From the $K_L - K_S$ mass splitting, $m_W' > 1.6$ TeV. From supernovae, $m_W' > 16$ TeV. From direct searches in the channel $W' \to jj$, $m_W' > 680$ GeV (set by DØ).[7] Limits on various models of Z' range from $m_Z' > 294$ to 898 GeV, see [7]. GUT's such as $SO(10)$ and E_6 contain an extra $U(1)$ and therefore predict a Z'.

- Consider a $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ left-right symmetric extension with a Higgs biodoublet. This model has $m_W' > 16$ GeV as explained above.

- Vector and scalar leptoquarks appear in many extensions of the Standard Model.

- Add higher dimensional Higgs representations. Their vacuum expectation values must be less than a few percent of 246 GeV in order to not upset the Z/W mass ratio.

- The Higgs particle may be composite: Technicolor.
- Add SUSY extensions to the Standard Model.
- Axions. No experimental consequence at colliders.

Now consider non-renormalizable extensions of the Standard Model valid in the low energy limit ($\ll \Lambda$) of a non-specified renormalizable theory:

- Quark and lepton compositeness. To the lagrangian add four-fermion contact terms.[7] Limits can be set to the compositeness scales Λ_{LL}, Λ_{RR}, Λ_{VV}, Λ_{AA}, etc.
- Excited quarks and leptons. If particles are composite there will appear excited states.
- Higgs compositness described by a contact interaction.
- Gauge boson compositness.

Note that none of the extensions of the Standard Model discussed above shed any light on the three families of quarks and leptons nor on the CKM matrix that links them! Note that many of these extensions of the Standard Model introduce new sources of CP violation.

4 Crazy ideas

The preceding discussion covers some "more-of-the-same" extensions of the Standard Model. The Standard Model is based on principles: locality, Lorentz invariance, local (gauge) symmetries that determine the interactions, and spontaneous symmetry breaking that generates the masses in a renormalizable way. In my view, this last principle and the whole concept of vacuum and mass is mysterious. Perhaps totally different ideas are needed. I will list a few, not because I give them any weight, but just for amusement and to set the stage. (Readers in a hurry should skip this Section.)

- Tachyons. Consider the following classical toy model of an electron: a rotating sphere with uniform surface charge, with radius r, "mechanical mass" M, charge e, and angular velocity ω. Try to satisfy the four measured properties of the electron: charge, mass, magnetic dipole moment and angular momentum (including the energy and angular momentum of the electromagnetic field). You will soon find that this model is all wrong since the equatorial velocity turns out to be larger than c[18]. Then consider this model for the electron: a tachyon (call it "telectron") with charge e and imaginary mass M rotating in a circle with velocity greater than c. In analogy with Bohr's hydrogen atom, let the circumference $2\pi r = \lambda/2$ where $\lambda = h/p$. Then $L = r \cdot p = \hbar/2$. There is no proton to keep the telectron on its circular orbit: the telectron attracts itself! As the tachyon goes around the circle it emits photons that it later re-absorbs.[18] It is possible to obtain the correct acceleration of this "electron" in an external electric field, the precession in a magnetic field, the acceleration in a non-homogeneous magnetic field, and the Stern-Gerlach experiment[19]. The Standard Model expanded around the symmetric vacuum, and extensions of the Standard Model, contain tachyons. Can these tachyons condense into bound states due to their self-interactions? Perhaps variations on these ideas will turn out to be fruitful if the predicted excited states are observed.

- Massless particles. Electromagnetic waves propagate at the velocity c with the dispersion relation

$$\frac{\omega^2}{c^2} - k_x^2 - k_y^2 - k_z^2 = 0$$

corresponding to zero mass. Let the wave propagate down a waveguide (along z) with transverse dimensions a and b. Then $k_x = \pm 2\pi/\lambda_x = \pm\pi/a$ and $k_y = \pm\pi/b$ for the $(1,1)$ mode. The dispersion relation becomes

$$\frac{\omega^2}{c^2} - k_z^2 = \left[\frac{m \cdot c}{\hbar}\right]^2$$

with

$$m = \frac{h}{2c}\sqrt{\frac{1}{a^2} + \frac{1}{b^2}}$$

So the photons have acquired mass! And the transverse dimension of the wave is comparable to its Compton wavelength h/mc. If a perturbation is set up the wave acquires a trembling motion ("zitterbewegung") with disturbances propagating back and fourth at the speed of light (as is familiar from the study of the Dirac or Klein-Gordon equations).

Other examples: massless photons acquire mass when they interact with a plasma such as the ionosphere; electrons change their mass when they interact with the periodic potential of the silicon crystal.

Perhaps "bare" quarks, leptons and gauge bosons are massless. However they can not travel freely because they couple to vacuum. The resulting motion may resemble propagation down a waveguide or propagation in a plasma. The coupling to vacuum is scalar so each reflection on the "waveguide" wall conserves angular momentum but not linear momentum (and a left-handed Weyl spinor becomes a right-handed Weyl spinor). Such non-conservation of linear momentum by an amount $\delta p_x = 2\hbar k_x = h/a$ is allowed over a distance $\approx a$ (by the uncertainty relation) so all is well. Perhaps something of this sort is the Higgs mechanism.

- The propagator of a massive particle is equivalent to the propagation of a massless particle with zero, one, two,... intermediate interactions with the Higgs vacuum expectation value: summing up the corresponding geometric series results in the propagator of a massive particle.

- Extra dimensions. Take the dispersion relation of a massless graviton to be

$$\frac{\omega^2}{c^2} - k_x^2 - k_y^2 - k_z^2 - k_w^2 = 0$$

with w an extra dimension that is "curled up" so that it is periodic with period a. Then $k_w = 2\pi/\lambda = 2\pi/a$ for the lowest mode, and the particle acquires mass h/ac. Higher Kaluza-Klein modes exist. The excitation of a Kaluza-Klein mode apears experimentally as a non-conservation of energy-momentum, *i.e.* as missing E_T and imbalance of momentum due to gravitons escaping into the extra dimensions. We can set limits to the first Kaluza-Klein excitation of gravitons at DØ, and of Standard Model particles at LHC.[20]

In GUT's we expect gravity to become important at energy scales $M_P \approx 10^{19}$ GeV. Is there some way to have the gravitational coupling become comparable to the gauge couplings already at the electro-weak scale $\approx 10^3$ GeV? This would solve the "hierarchy" problem. A scheme to realize this miracle is to assume that our $3+1$ space-time is embeded in a higher dimensional space in which only gravitons are free to roam. The higher dimensions are assumed to be compactified. If there are δ extra dimensions, then the radius of the compactified dimensions is $R \approx M_D^{-1-2/\delta} M_P^{2/\delta}$ with $M_D \approx 10^3$ GeV.

A review of these and other ideas, and references to the literature can be found in [20]. A most beautiful article on current ideas on extra dimensions is [21] with experimental consequences accessible to colliders. None of these ideas has yet been extended to a full theory including the Standard Model.

- Suppose there is only one fundamental fermion family, and excitations of the Higgs field produce additional families of fermions[22].

There are many ideas on extensions of, or alternatives to, the Higgs mechanism. Unfortunately some are not renormalizable so that they introduce a cut-off Λ, or introduce new interactions, or do not provide new predictions, and in general are more complex than the Higgs mechanism they are designed to replace. Nevertheless, the Higgs sector may turn out to be surprizing and perhaps an entirely new principle will be needed.

5 A channel that interests me

In general, extensions of the Standard Model have new sources of CP violation as required by baryogenesis.[23] In the Standard Model, CP violation (or the branching fraction to CP-violating final states) is suppressed by small mixing angles in the CKM-matrix. So the measurement of CP violation is a good probe to search new physics.[23] At DØ the particle that can best be triggered on and separated from background is the muon. The **cleanest imaginable** channel to probe CP violation is $\mu\mu X$ where the two muons have the same sign. Very few processes have this signature. In contrast, many processes contribute to the channel μX so that any CP-violating asymmetry is greatly diluted. Therefore single muon events are useful to study systematic errors.

The channel of interest is

$$p\bar{p} \to B_d^0 \bar{B}_d^0 X$$

with

$$B_d^0 \to \mu^+ X$$

and

$$\bar{B}_d^0 \to B_d^0 \to \mu^+ X$$

and CP conjugate. Due to "indirect CP violation (or CP violation in the mixing)", *i.e.* to complex effects in $B^0 \leftrightarrow \bar{B}^0$ mixing and decay, the dimuon charge asymmetry

$$A \equiv \frac{N_{++} - N_{--}}{N_{++} + N_{--}} = Im\left\{\frac{\Gamma_{12}}{M_{12}}\right\} = -4\frac{Re(\epsilon)}{1+|\epsilon|^2} \tag{3}$$

in the B_d^0 channel is predicted in the Standard Model to be of order $-(2-5)\cdot 10^{-4}$[23] (or as large as $1.9 \cdot 10^{-3}$ when the mixing angles vary over their allowed range[24]) when quarks are assumed to be free (*i.e.* in the approximation of quark-hadron duality); or, considering the effects of hadronization, in the range from approximately $\pm 0.1\%$ to $\pm 1\%$ (with a sign that is difficult to determine)[25], or up to $\approx 1-3\%$ (depending on the magnitude of V_{ub}) and positive[26]. The uncertainty in the predictions originate in a sum of terms with opposite signs coupled with the uncertainties due to hadronization. A detailed discussion of these issues can be found in [25, 26]. In summary, we do not have a reliable Standard Model prediction.

In Run I of DØ, with about 70 pb^{-1} of data, we were able to measure the asymmetry A with a statistical error $\pm 1.9\%$ and a systematic error $^{+0.8}_{-0.5}\%$.[27] (Let me mention that these errors were 4 times smaller than those of the competition at the time.[27]) Extrapolating to Run II with 2 fb^{-1} we can expect a total error $\approx \pm 0.4\%$ from the time-independent analysis. This estimate is conservative: it does not include the increased η coverage of the muon system, nor the improved trigger due to the new muon scintillators. Systematic errors may turn out to be the limiting factor. The two muons originate from two different secondary vertices. Therefore time-dependent asymmetry studies of B^0 events are possible (and should be competitive with the time-independent measurement).[7, 28] So in Run II we will be sensitive to new physics[24] and perhaps even to the Standard Model[26].

New physics may change the mixing matrix element M_{12} which involves the high momentum loops of the box diagrams. It is less probable that new physics will change Γ_{12} because this decay matrix element involves on-shell particles and therefore depends on low momenta propagators. Extensions of the Standard Model that introduce new phases to B_d^0 mixing are Multi-Higgs-Doublet models with no "Natural Flavor Conservation"; Supersymmetric models with "Effective SUSY", or with "R-Parity Violation"; Left-Right Symmetric models with $V_L \neq V_R$; 4th generation; and Z-mediated Flavor Changing Neutral Currents.[29] Extensions of the Standard Model that do not contribute new phases to B_d^0 mixing are: Multi-Higgs-Doublet models with "Natural Flavor Conservation"; Minimum Supersymmetric Model; Supersymmetric models with "Squark Alignment"; and Left-Right Symmetric models with $V_L = V_R$.[29]

Reference [24] concludes that "It is possible that the dilepton asymmetry could be one of the first indications of physics beyond the standard model". The results obtained in Run I[27] make this measurement all the more interesting. In comparison, the asymmetry measured by OPAL corresponds to $A_d = -0.8 \pm 2.8 \pm 1.2\%$ if CPT symmetry is assumed to hold, or $+2.4 \pm 4.0 \pm 2.4\%$ if CPT is not invoked.[7, 30] So the proposed measurement is certainly competitive: it can improve the current limit by a factor ≈ 10.

The major backgrounds to this measurement at DØ are cosmic rays that traverse the detector (and are reconstructed as two like-sign muons) and sequential decays $B \to D \to \mu$ which dilute the asymmetry. The upgrade of the DØ detector provides large enhancements to our ability to reject both these backgrounds. To tame systematic errors we have two independent muon systems (central "PDT" and forward "MDT"); an assortment of triggers, single muon events, weekly reversal of magnetic fields as in Run I (indispensable for this measurement), and the dielectron asymmetry (which however has a higher E_T threshold due to calorimeter resolution, and higher backgrounds). A unique advantage of the Tevatron is that the initial $p\bar{p}$ state is invariant under CP.

This study needs three dedicated triggers: Muons with as-low-as-possible p_T based on the **muon systems only** (no Central Fiber Tracker (CFT) information):

- Unprescaled for like-sign di-muons.
- Prescaled for opposite-sign di-muons, and
- Prescaled for single muons.

All three triggers must have exactly the same single muon cuts. Complementary triggers for additional studies of systematic errors are already used by other groups. A major concern with CFT triggers is that they introduce a ϕ-dependent fake charge asymmetry due to the beam offset that changes from store to store.

In summary, we must measure the dimuon charge asymmetry because we can push the current limit down by a factor ≈ 10 and reach interesting territory. An in-depth discussion of CP violation in the Standard Model and beyond is given in [23], and the details involved in the measurement of the dimuon charge asymmetry can be found in [27].

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