Discoveries Ahead

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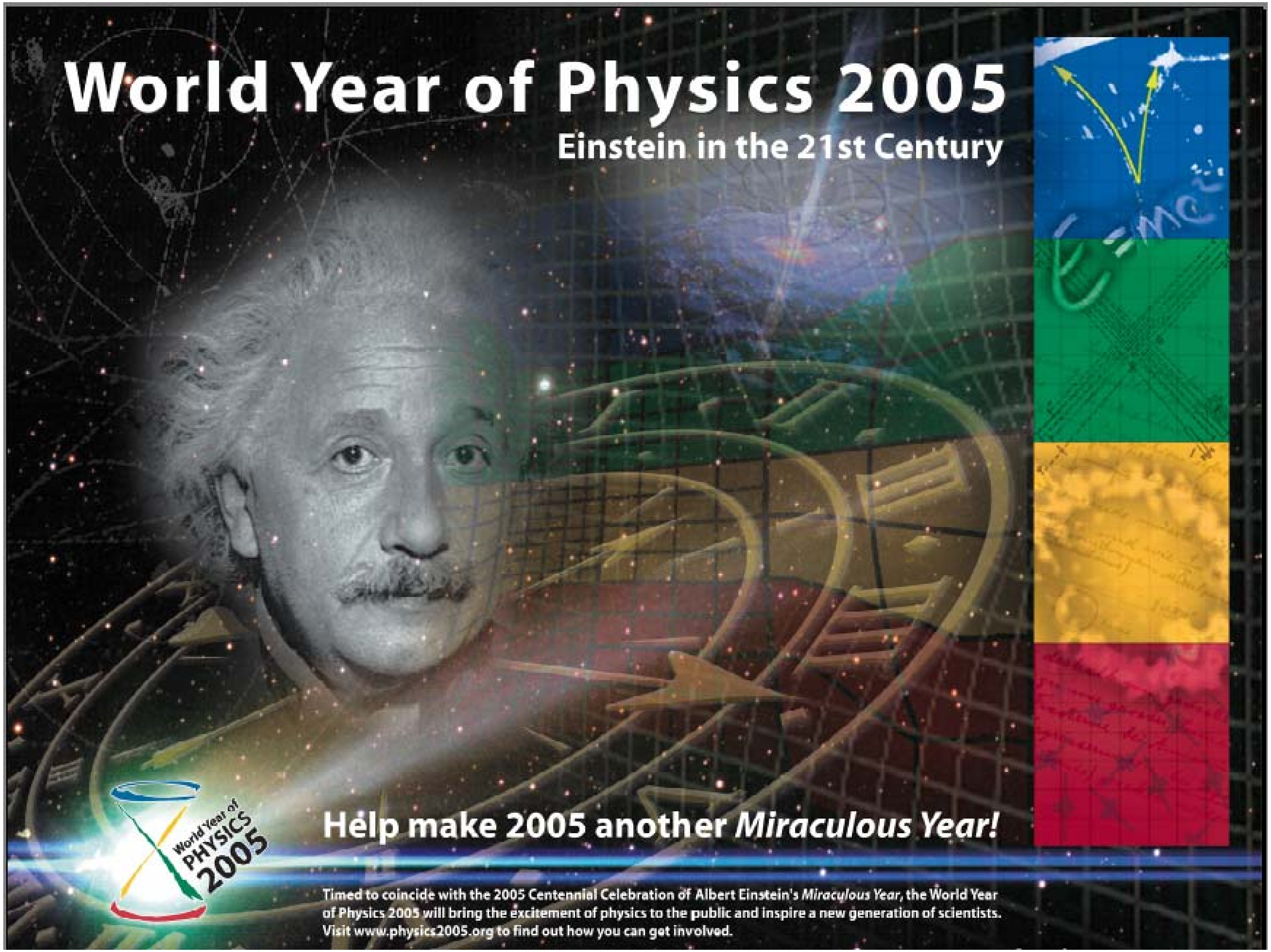
TeV4LHC@BNL

February 3, 2005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Einstein in the 21st Century
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Einstein in 1905

- Relativity
  - Deduced from Maxwell's Eqs.
  - Dispensed with the ether
- Photon
  - Explained photoelectric effect
  - Harbinger of Quantum Field Theory

QED

- Ampere, Faraday, Maxwell, …

$$\partial_\mu F^{\mu\nu} = J^\nu \qquad\qquad F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

- Dirac, Born, Jordan, Heisenberg, Pauli, …

$$L = -\tfrac{1}{4} F^{\mu\nu} F_{\mu\nu} + i\overline{\psi} \not{D} \psi - m\overline{\psi}\psi$$

Yang-Mills gauge theory

Conservation of Isotopic Spin and Isotopic Gauge Invariance*

C. N. Yang † and R. L. Mills
Brookhaven National Laboratory, Upton, New York
(Received June 28, 1954)

It is pointed out that the usual principle of invariance under isotopic spin rotation is not consistant with the concept of localized fields. The possibility is explored of having invariance under local isotopic spin rotations. This leads to formulating a principle of isotopic gauge invariance and the existence of a **b** field which has the same relation to the isotopic spin that the electromagnetic field has to the electric charge. The **b** field satisfies nonlinear differential equations. The quanta of the **b** field are particles with spin unity, isotopic spin unity, and electric charge $\pm e$ or zero.

INTRODUCTION

THE conservation of isotopic spin is a much discussed concept in recent years. Historically an isotopic spin parameter was first introduced by Heisenberg[1] in 1932 to describe the two charge states (namely neutron and proton) of a nucleon. The idea that the neutron and proton correspond to two states of the same particle was suggested at that time by the fact that their masses are nearly equal, and that the light stable even nuclei contain equal numbers of them. Then in 1937 Breit, Condon, and Present pointed out the approximate equality of $p-p$ and $n-p$ interactions in the ^1S state.[2] It seemed natural to assume that this equality holds also in the other states available to both the $n-p$ and $p-p$ systems. Under such an assumption one arrives at the concept of a total isotopic spin[3] which is conserved in nucleon-nucleon interactions. Experi-

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† On leave of absence from the Institute for Advanced Study, Princeton, New Jersey.
[1] W. Heisenberg, Z. Physik **77**, 1 (1932).
[2] Breit, Condon, and Present, Phys. Rev. **50**, 825 (1936). J. Schwinger pointed out that the small difference may be attributed to magnetic interactions [Phys. Rev. **78**, 135 (1950)].
[3] The total isotopic spin **T** was first introduced by E. Wigner, Phys. Rev. **51**, 106 (1937); B. Cassen and E. U. Condon, Phys. Rev. **50**, 846 (1936).

QCD

- Gross, Wilczek, Politzer, …
  - Scaling in DIS ➡ Asymptotic freedom

$$L = -\tfrac{1}{4} G^{A\mu\nu} G^{A}_{\mu\nu} + i\overline{\psi} \not{D} \psi - m\overline{\psi}\psi$$

where $$G^{A}_{\mu\nu} = \partial_\mu A^{A}_{\nu} - \partial_\nu A^{A}_{\mu} - g_S f^{ABC} A^{B}_{\mu} A^{C}_{\nu}$$

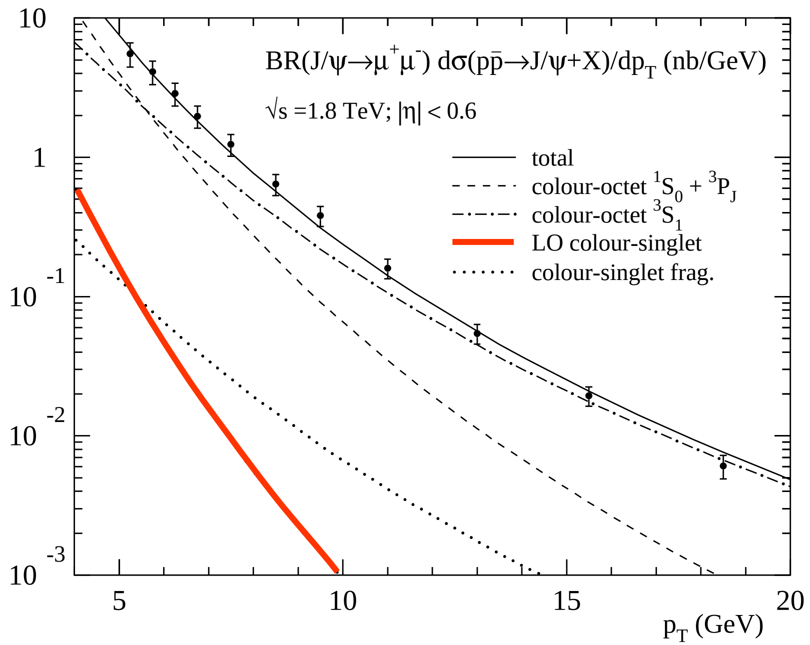
Why do we study QCD?

- It's interesting
  - Interplay between perturbative and non-perturbative physics

J/ψ production

Run I

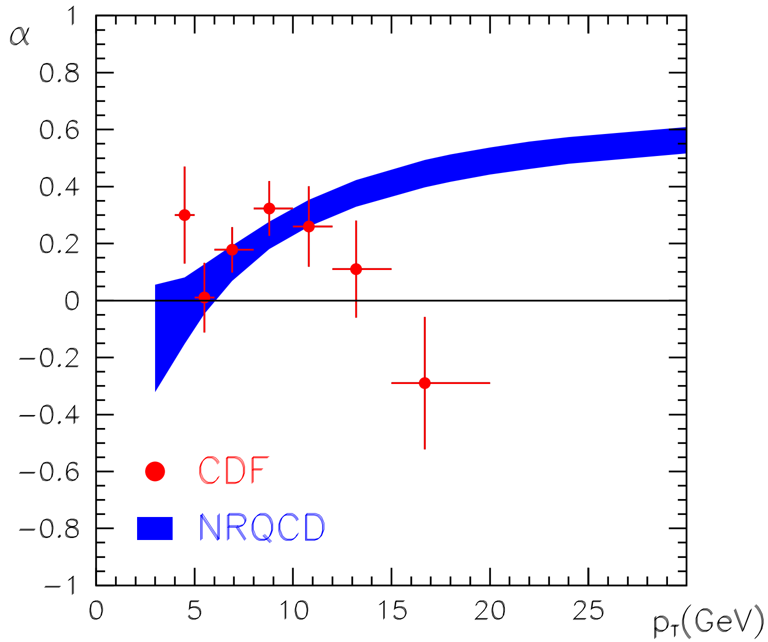
p_T spectrum



CDF, PRL 79, 578 (1997)

M. Kramer, hep-ph/0106120

polarization

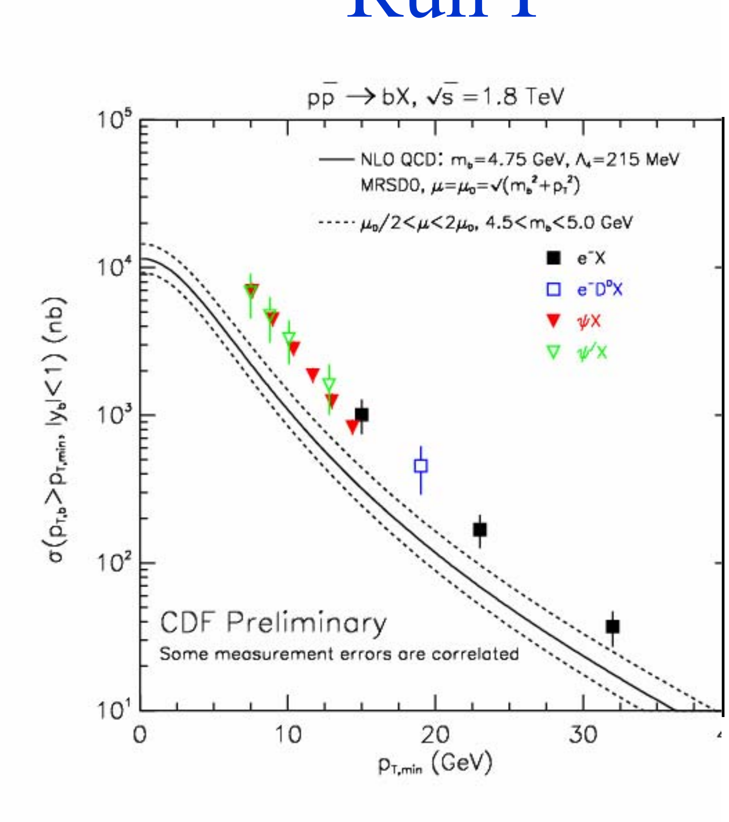


CDF, hep-ex/0004027

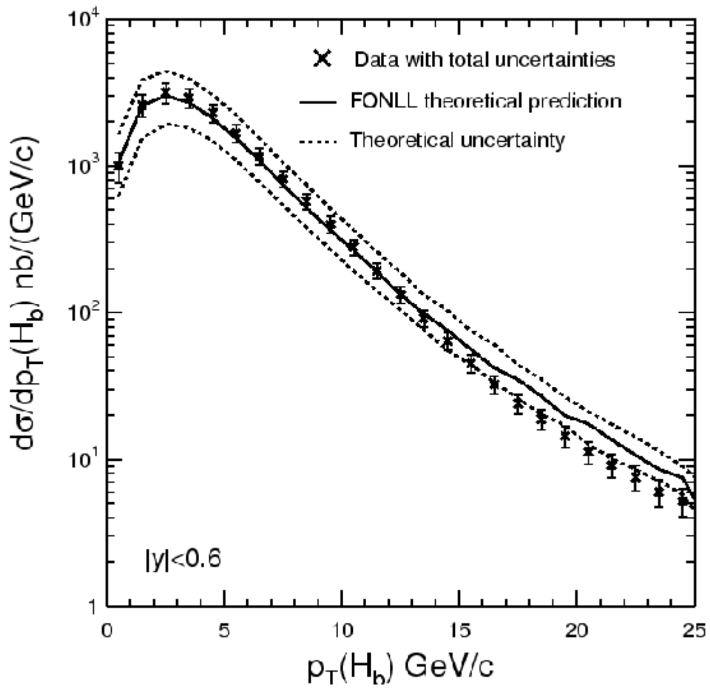
Braaten, Kniehl, Lee, hep-ph/9911436

b production

Run I



Run II

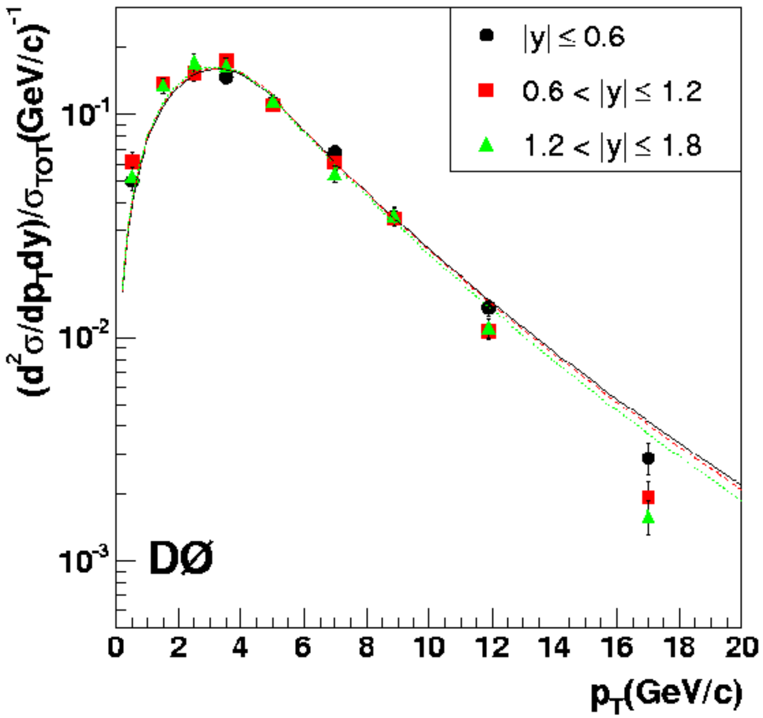


CDF, hep-ex/0412071

Cacciari, Frixione, Mangano, Nason, Ridolfi, hep-ph/0312132

Υ production

Run II



D0, ICHEP 04

Berger, Qiu, Wang, hep-ph/0404158

Weak Interaction

- Also a Yang-Mills gauge theory
  - Chiral
  - Spontaneously broken

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland

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Aachen [a]–Annecy (LAPP) [b]–Birmingham [c]–CERN [d]–Helsinki [e]–Queen Mary College, London [f]–Paris (Coll. de France) [g]–Riverside [h]–Rome [i]–Rutherford Appleton Lab. [j]–Saclay (CEN) [k]–Vienna [l] Collaboration

Received 23 January 1983

We report the results of two searches made on data recorded at the CERN SPS Proton–Antiproton Collider: one for isolated large-E_T electrons, the other for large-E_T neutrinos using the technique of missing transverse energy. Both searches converge to the same events, which have the signature of a two-body decay of a particle of mass ~80 GeV/c^2. The topology as well as the number of events fits well the hypothesis that they are produced by the process $\bar{p} + p \to W^{\pm} + X$, with $W^{\pm} \to e^{\pm} + \nu$; where $W^{\pm}$ is the Intermediate Vector Boson postulated by the unified theory of weak and electromagnetic interactions.

OBSERVATION OF SINGLE ISOLATED ELECTRONS OF HIGH TRANSVERSE MOMENTUM IN EVENTS WITH MISSING TRANSVERSE ENERGY AT THE CERN $\bar{p}p$ COLLIDER

The UA2 Collaboration

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Received 15 February 1983

We report the results of a search for single isolated electrons of high transverse momentum at the CERN $\bar{p}p$ collider. Above 15 GeV/c, four events are found having large missing transverse energy along a direction opposite in azimuth to that of the high-p_T electron. Both the configuration of the events and their number are consistent with the expectations from the process $\bar{p} + p \to W^{\pm}$ + anything, with $W \to e + \nu$, where $W^{\pm}$ is the charged Intermediate Vector Boson postulated by the unified electroweak theory.

Why do we study QCD?

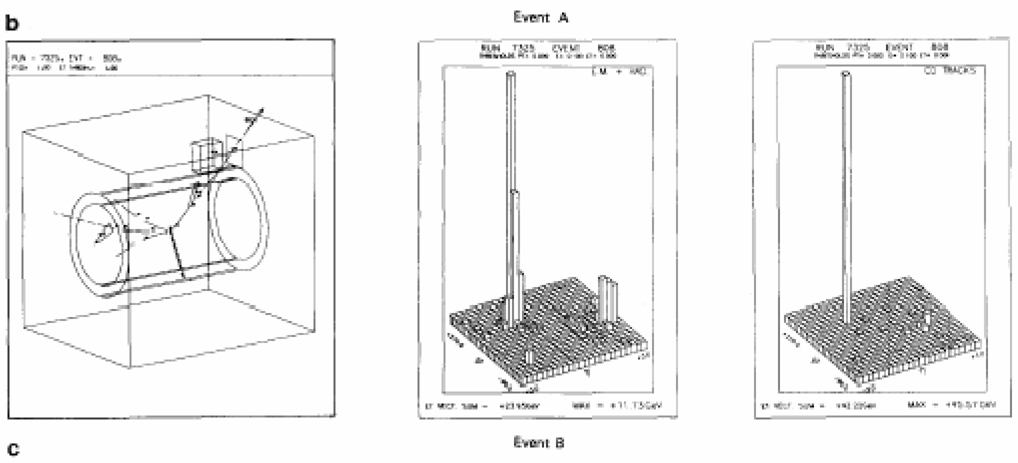
- It’s interesting
  - Interplay between perturbative and non-perturbative physics
- It’s not interesting
  - Background to other physics that we would like to study

Monojets

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON (S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.

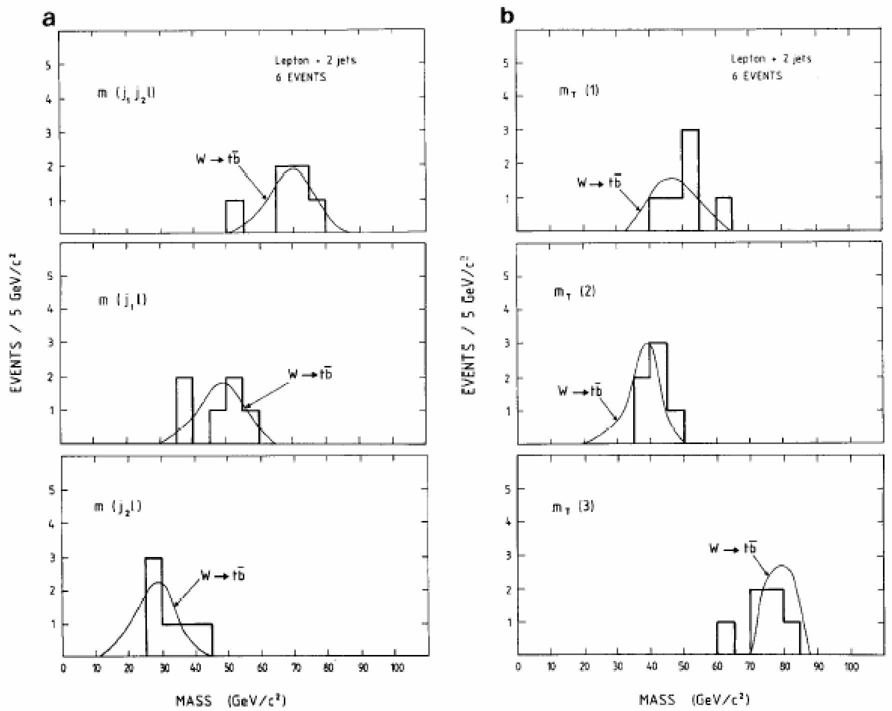


$W \to t\bar{b}$

ASSOCIATED PRODUCTION OF AN ISOLATED, LARGE-TRANSVERSE-MOMENTUM LEPTON (ELECTRON OR MUON), AND TWO JETS AT THE CERN $p\bar{p}$ COLLIDER

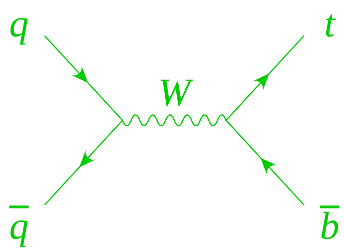
UA1 Collaboration, CERN, Geneva, Switzerland

A clear signal is observed for the production of an isolated large-transverse-momentum lepton in association with two or three centrally produced jets. The two-jet events cluster around the $W^{\pm}$ mass, indicating a novel decay of the Intermediate Vector Boson. The rate and features of these events are not consistent with expectations of known quark decays (charm, bottom). They are, however, in agreement with the process $W \to t\bar{b}$ followed by $t \to b\ell\nu$, where t is the sixth quark (top) of the weak Cabibbo current. If this is indeed so, the bounds on the mass of the top quark are 30 GeV/c^2 < m_t < 50 GeV/c^2.

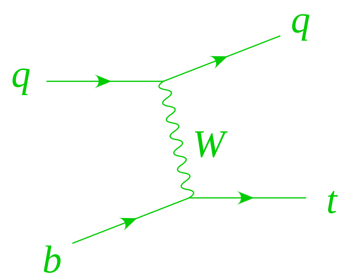


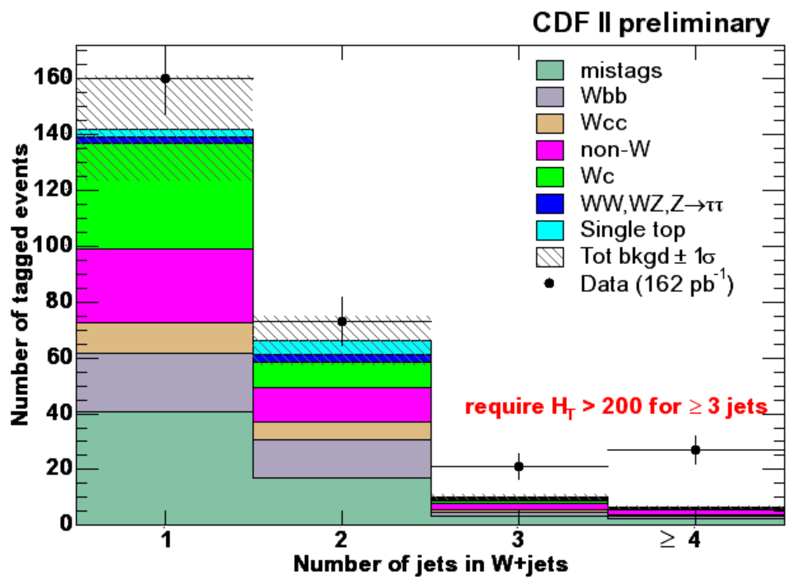
Single top

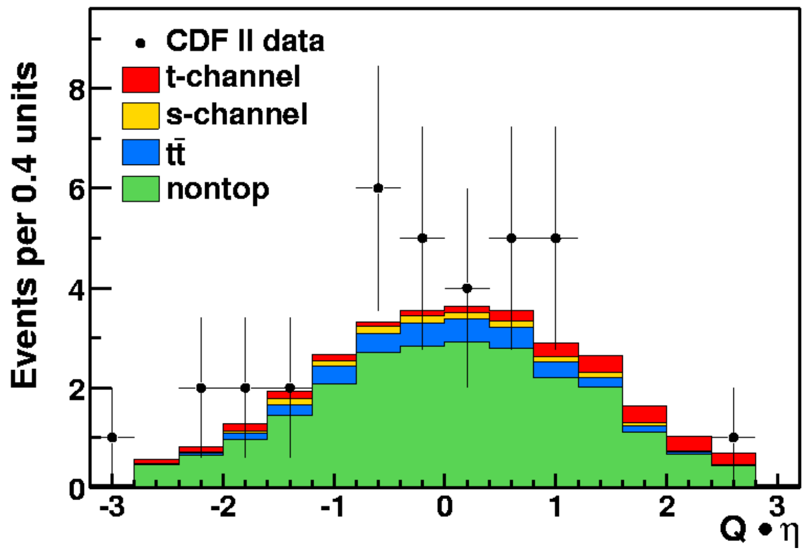
s-channel



t-channel







CDF, hep-ex/0410058

Standard Model

	SU(3)	SU(2)	$U(1)_Y$
$Q_L^i = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix}$	3	2	1/6
$u_R^i = u_R, c_R, t_R$	3	1	2/3
$d_R^i = d_R, s_R, b_R$	3	1	-1/3
$L_L^i = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}, \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	1	2	-1/2
$e_R^i = e_R, \mu_R, \tau_R$	1	1	-1
$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	1	2	1/2

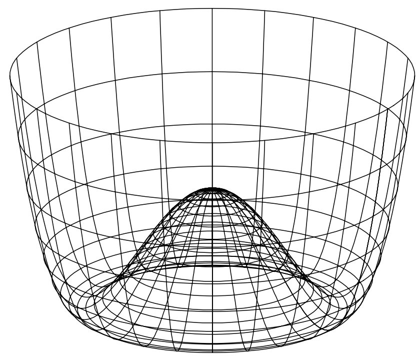
Standard Model

$$L = -\tfrac{1}{4} F^{\mu\nu} F_{\mu\nu} - \tfrac{1}{4} G^{A\mu\nu} G^{A}_{\mu\nu} - \tfrac{1}{4} W^{A\mu\nu} W^{A}_{\mu\nu}$$ Gauge

$$+ i\overline{Q}{}^{i}_{L} \not{D} Q^{i}_{L} + i\overline{u}{}^{i}_{R} \not{D} u^{i}_{R} + i\overline{d}{}^{i}_{R} \not{D} d^{i}_{R} + i\overline{L}{}^{i}_{L} \not{D} L^{i}_{L} + i\overline{e}{}^{i}_{R} \not{D} e^{i}_{R}$$ Matter

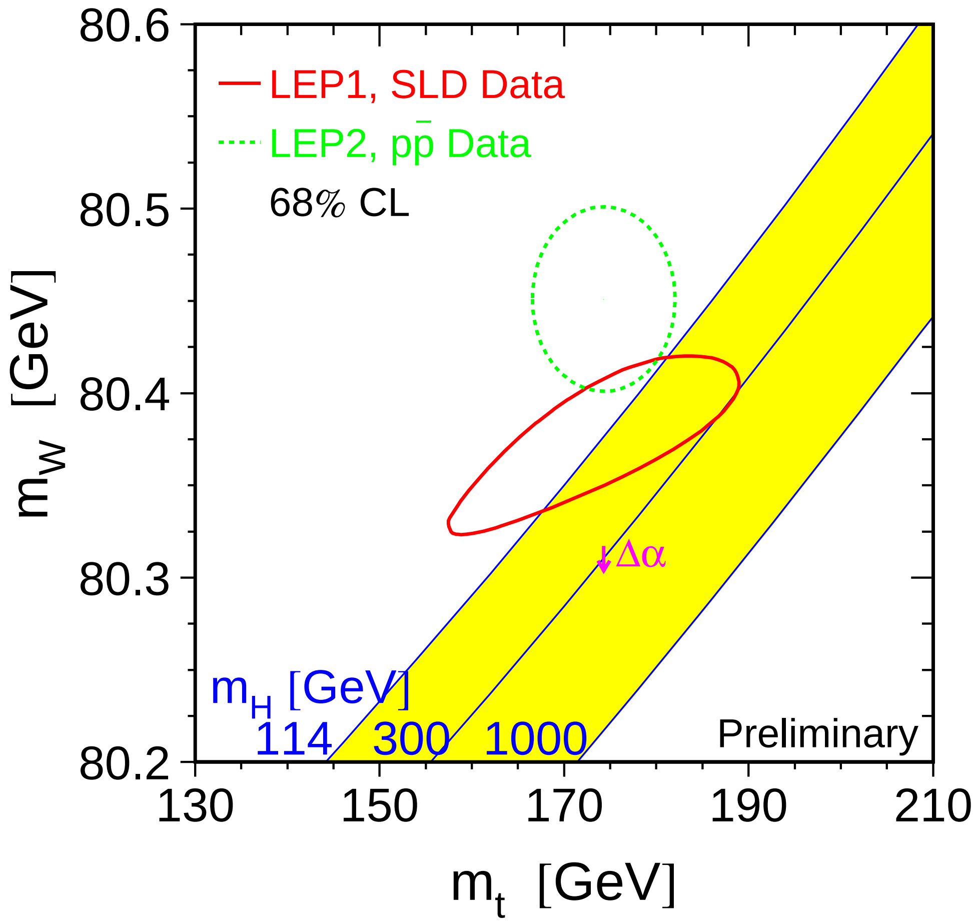
$$-\Gamma^{ij}_{u} \overline{Q}{}^{i}_{L} \varepsilon \phi^{*} u^{j}_{R} - \Gamma^{ij}_{d} \overline{Q}{}^{i}_{L} \phi d^{j}_{R} - \Gamma^{ij}_{e} \overline{L}{}^{i}_{L} \phi e^{j}_{R} + h.c.$$ Yukawa

$$+ \left(D^{\mu}\phi\right)^{\dagger} D_{\mu}\phi + \mu^{2} \phi^{\dagger}\phi - \lambda\left(\phi^{\dagger}\phi\right)^{2}$$ Higgs



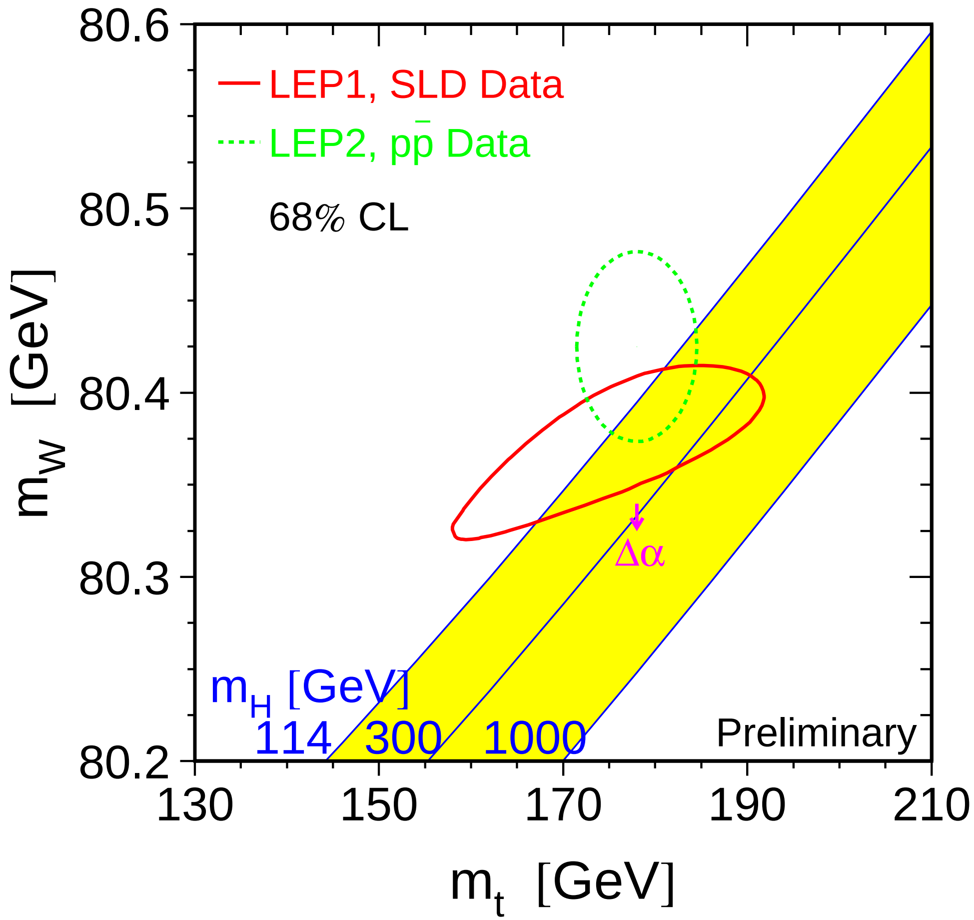
$$\langle \phi \rangle = v$$

Winter 2002



LEP1, SLD Data
LEP2, pp̄ Data
68% CL
80.6
80.5
80.4
80.3
80.2
m_W [GeV]
Δα
m_H [GeV]
114
300
1000
Preliminary
130
150
170
190
210
m_t [GeV]

Summer 2004



80.6
80.5
80.4
80.3
80.2
LEP1, SLD Data
LEP2, pp̄ Data
68% CL
Δα
m_H [GeV]
114
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Preliminary
130
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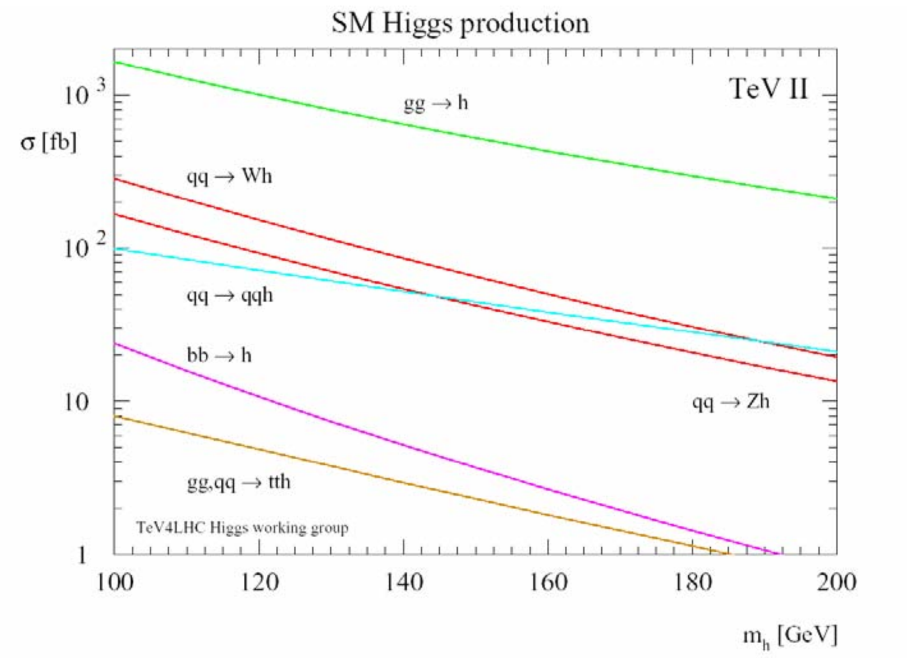
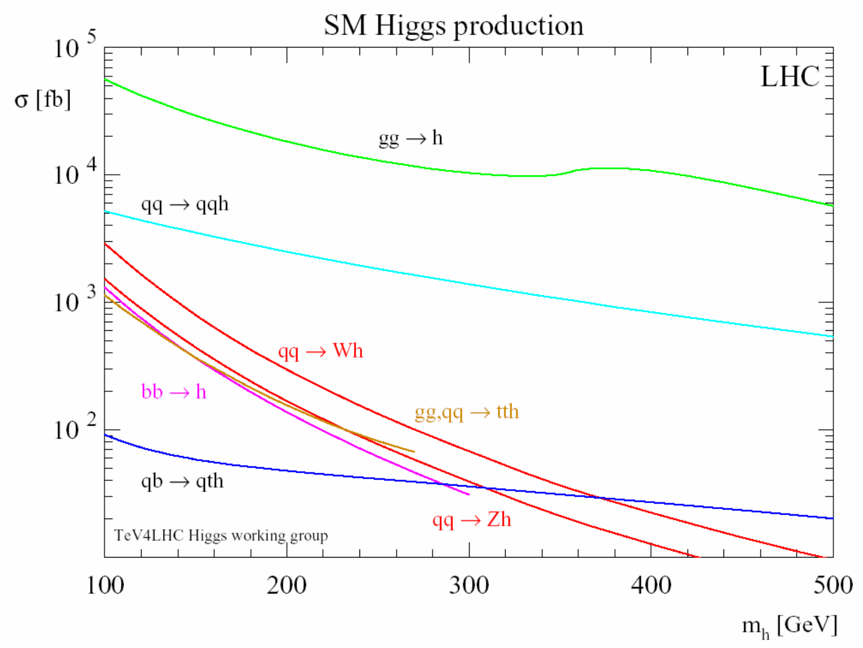
170
190
210
m_t [GeV]
m_W [GeV]

Standard Model Higgs

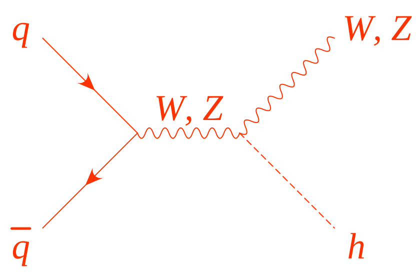
Tevatron

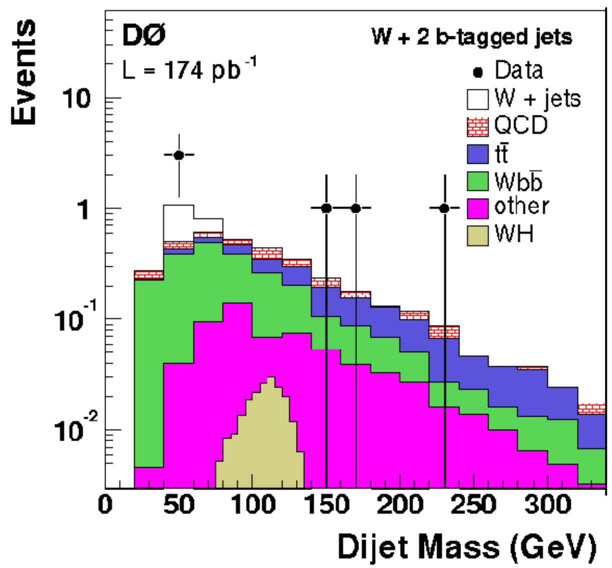


LHC



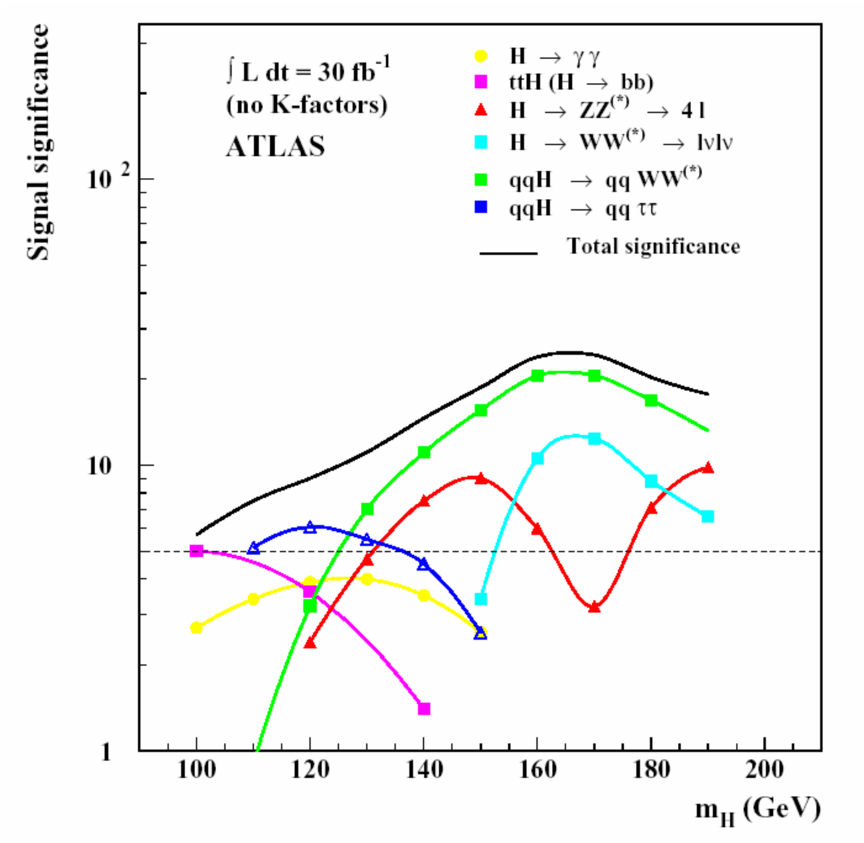
Higgs at the Tevatron





D0, hep-ex/0410062

Higgs at the LHC



Beyond the SM

- Neutrino mass

Grand Unified Theories and Proton Decay*

SLAC-PUB-2544
June 1980
(T/E)

Paul Langacker

Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94305
and
University of Pennsylvania
Dept. of Physics, Philadelphia, PA 19104

6.1.3. Neutrino Masses and B-L.

In this section I will describe neutrino masses, especially in the SU_5, SO_{10}, and E_6 models. It will be seen that the neutrino masses are closely associated with parity and with the B-L quantum number [6.20,3.67], (which plays a role similar to that of lepton number in the $SU_2 \times U_1$ model). Except for the SU_5 model, the neutrinos will generally be massive. The mechanisms that have been proposed to keep the ordinary (SU_2 doublet) neutrinos light usually require extremely large Majorana and/or Dirac mass terms for the other (SU_2 singlet) neutrinos. The physical masses of the ordinary neutrinos are usually estimated to be in the 10^{-5} - 10^{2} eV range.

Standard Model

$$L = -\tfrac{1}{4} F^{\mu\nu} F_{\mu\nu} - \tfrac{1}{4} G^{A\mu\nu} G^{A}_{\mu\nu} - \tfrac{1}{4} W^{A\mu\nu} W^{A}_{\mu\nu} \quad \text{Gauge}$$

$$+ i\overline{Q}^{i}_{L} \not{D} Q^{i}_{L} + i\overline{u}^{i}_{R} \not{D} u^{i}_{R} + i\overline{d}^{i}_{R} \not{D} d^{i}_{R} + i\overline{L}^{i}_{L} \not{D} L^{i}_{L} + i\overline{e}^{i}_{R} \not{D} e^{i}_{R} \quad \text{Matter}$$

$$- \Gamma^{ij}_{u} \overline{Q}^{i}_{L} \varepsilon \phi^{*} u^{j}_{R} - \Gamma^{ij}_{d} \overline{Q}^{i}_{L} \phi d^{j}_{R} - \Gamma^{ij}_{e} \overline{L}^{i}_{L} \phi e^{j}_{R} + h.c. \quad \text{Yukawa}$$

$$+ \left(D^{\mu}\phi\right)^{\dagger} D_{\mu}\phi + \mu^{2} \phi^{\dagger}\phi - \lambda\left(\phi^{\dagger}\phi\right)^{2} \quad \text{Higgs}$$

$$m_{\nu} = 0$$

Standard Model

$$L = -\tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} - \tfrac{1}{4}G^{A\mu\nu}G^{A}_{\mu\nu} - \tfrac{1}{4}W^{A\mu\nu}W^{A}_{\mu\nu}$$ Gauge

$$+i\overline{Q}^{i}_{L}\not{D}Q^{i}_{L} + i\overline{u}^{i}_{R}\not{D}u^{i}_{R} + i\overline{d}^{i}_{R}\not{D}d^{i}_{R} + i\overline{L}^{i}_{L}\not{D}L^{i}_{L} + i\overline{e}^{i}_{R}\not{D}e^{i}_{R}$$ Matter

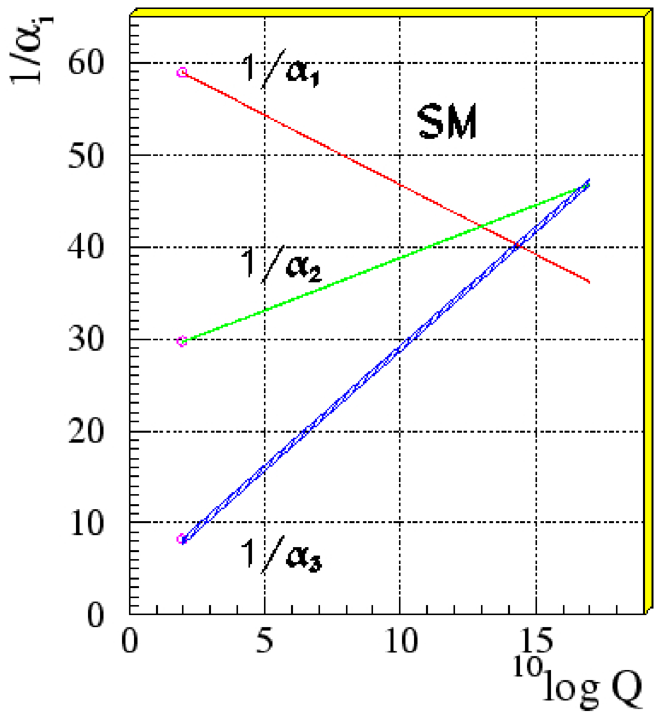
$$-\Gamma^{ij}_{u}\overline{Q}^{i}_{L}\varepsilon\phi^{*}u^{j}_{R} - \Gamma^{ij}_{d}\overline{Q}^{i}_{L}\phi d^{j}_{R} - \Gamma^{ij}_{e}\overline{L}^{i}_{L}\phi e^{j}_{R} + h.c.$$ Yukawa

$$+\left(D^{\mu}\phi\right)^{\dagger}D_{\mu}\phi + \mu^{2}\phi^{\dagger}\phi - \lambda\left(\phi^{\dagger}\phi\right)^{2}$$ Higgs

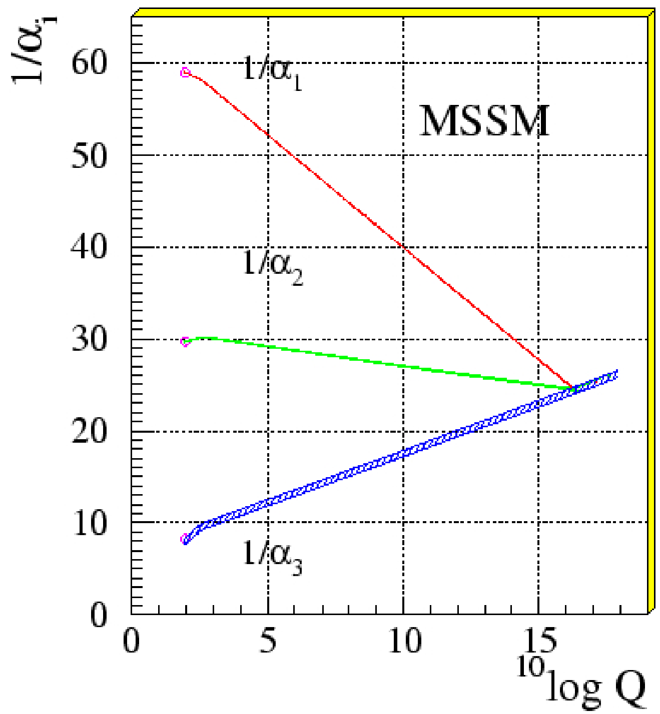
$$+\frac{c^{ij}}{M}\left(L^{i}_{L}\phi\right)\left(L^{j}_{L}\phi\right) + h.c.$$ Neutrino mass

$$m_{\nu} \approx \frac{v^{2}}{M} \quad \Rightarrow \quad M \approx 10^{14} - 10^{16}\ \text{GeV}$$

SU(5) Grand Unification



ϕ



ϕ_1, ϕ_2

From strings to SUSY

Dual Theory for Free Fermions

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A wave equation for free fermions is proposed based on the structure of the dual theory for bosons. Its formal properties preserve the role played by the Virasoro algebra. Additional Ward-like identities, compatible with the equation, are shown to exist. Its solutions lie on linear trajectories. In particular, the parent is shown to be doubly degenerate, but these solutions lie on different sheets of the cut j plane.

INTRODUCTION

In spite of its obvious theoretical appeal, the dual model[1] has been denied full acceptance (credibility) because of its failure to include fermions. In this paper we present an extension of the model to encompass half-integer-spin states by making use of a structure evident in the dual theory of free bosons.[2] Namely, we found that the following view of duality led to no contradiction with existing results: Each "free" boson appearing in the theory is a state of a complex system. Its structure can be parametrized in terms of an internal motion which is periodic in an internal time coordinate so that each observable of the system is the average over a cycle of the internal motion of suitably generalized operators. In this way, operators appearing in the description of point particles in conventional theories must be thought of as averages over some internal motion when applied to a hadronic system. The system then becomes a point particle in the limit of the internal the (already known) free-boson theory. The free hadronic system is described in terms of an internal motion generated by the Nambu[3] Hamiltonian

$$H_B=\tfrac{1}{2}\sum_{n=0}^{\infty}\left[p^{(n)}\cdot p^{(n)}+\omega_n^2 q^{(n)}\cdot q^{(n)}\right], \qquad (1.1)$$

with

$$\omega_{n+1}-\omega_n=\omega\,,\quad n=0,1,2,\ldots \qquad (1.2)$$

and the normal-mode coordinates are four-vector operators satisfying the usual commutation relations

$$\begin{aligned}&[q_\alpha^{(n)},q_\beta^{(m)}]=[p_\alpha^{(n)},p_\beta^{(m)}]=0\,,\\&[q_\alpha^{(m)},p_\beta^{(n)}]=-ig_{\alpha\beta}\delta^{m,n}\,,\quad m,n=0,1,\ldots\end{aligned} \qquad (1.3)$$

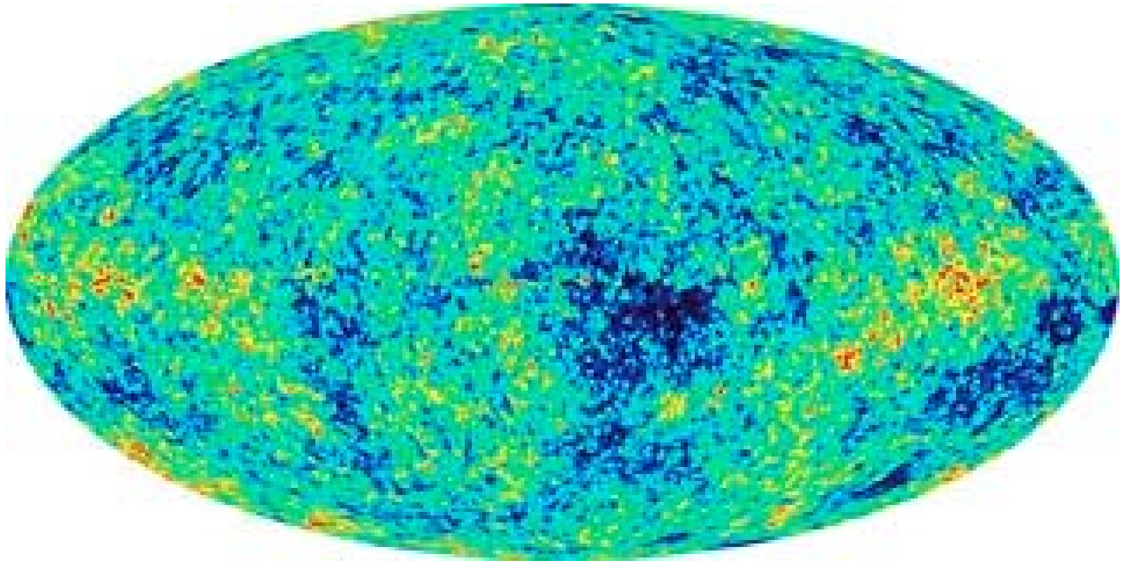
where we use $g_{\alpha\beta}=(1,-1,-1,-1)$ for the Lorentz metric. The internal system carries a total momentum

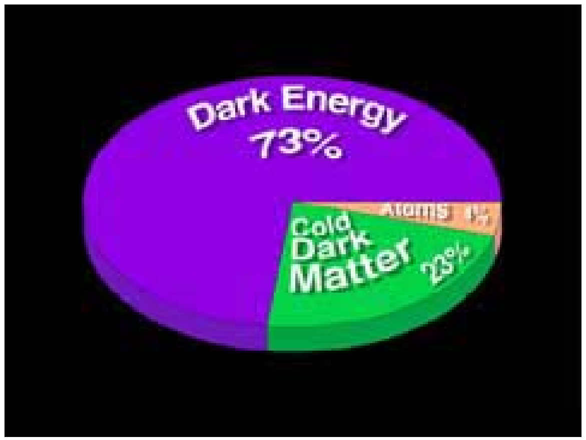
$$P_\mu=\sum_{n=0}^{\infty}p_\mu^{(n)} \qquad (1.4)$$

Beyond the SM

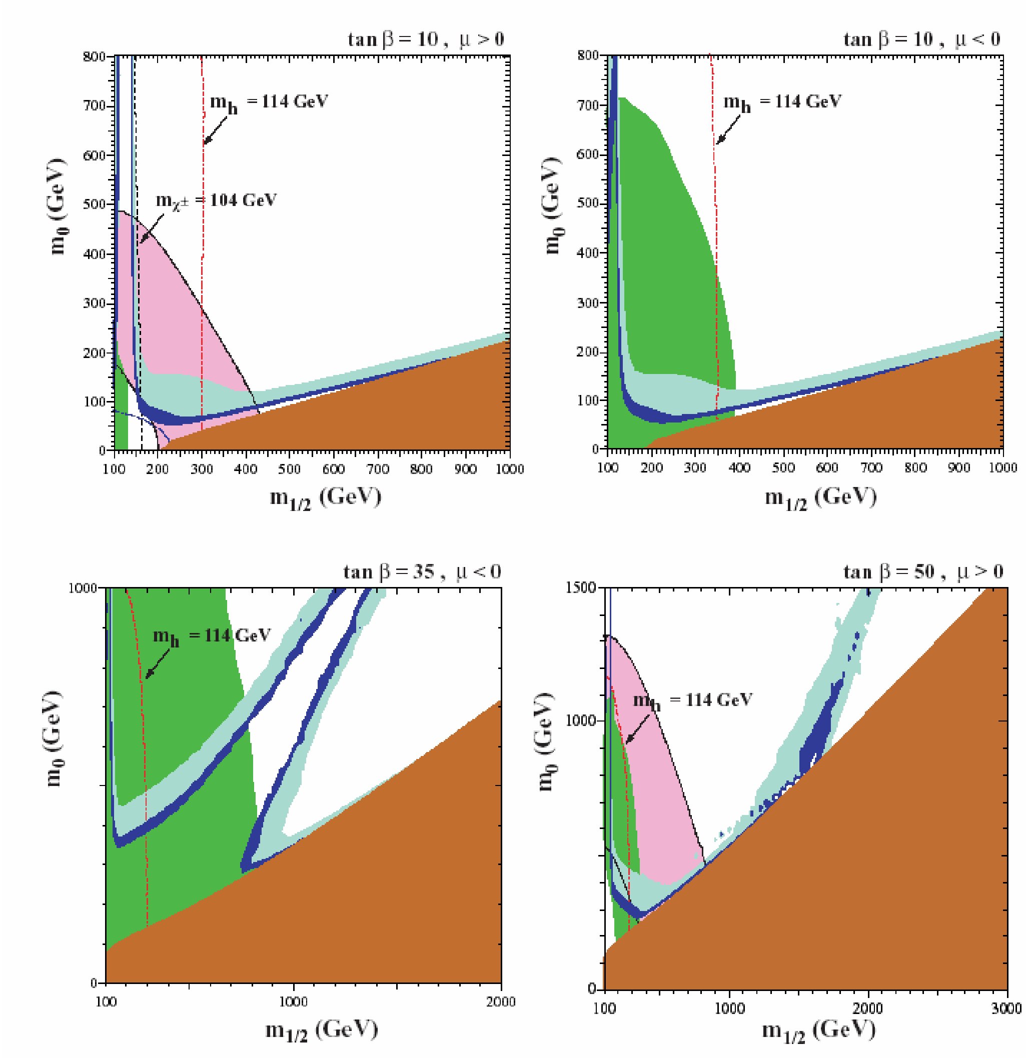
- Neutrino mass
- Dark matter

WMAP





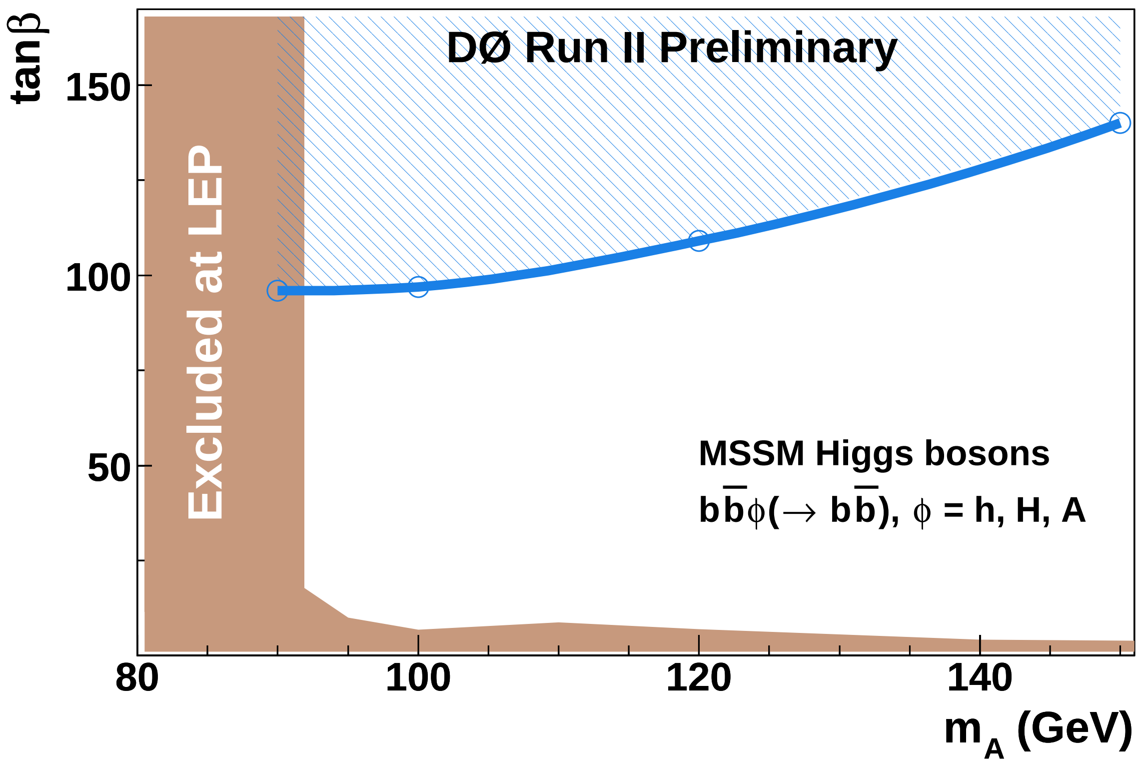
Neutralino dark matter



$$\chi^0\chi^0 \to A^0 \to f\bar{f}$$

Ellis, Olive, Santoso, Spanos, hep-ph/0303043

$b\bar{b}h$



tanβ
150
100
50
80
100
120
140
m_A (GeV)
Excluded at LEP
DØ Run II Preliminary
MSSM Higgs bosons
$b\bar{b}\phi(\rightarrow b\bar{b})$, ϕ = h, H, A

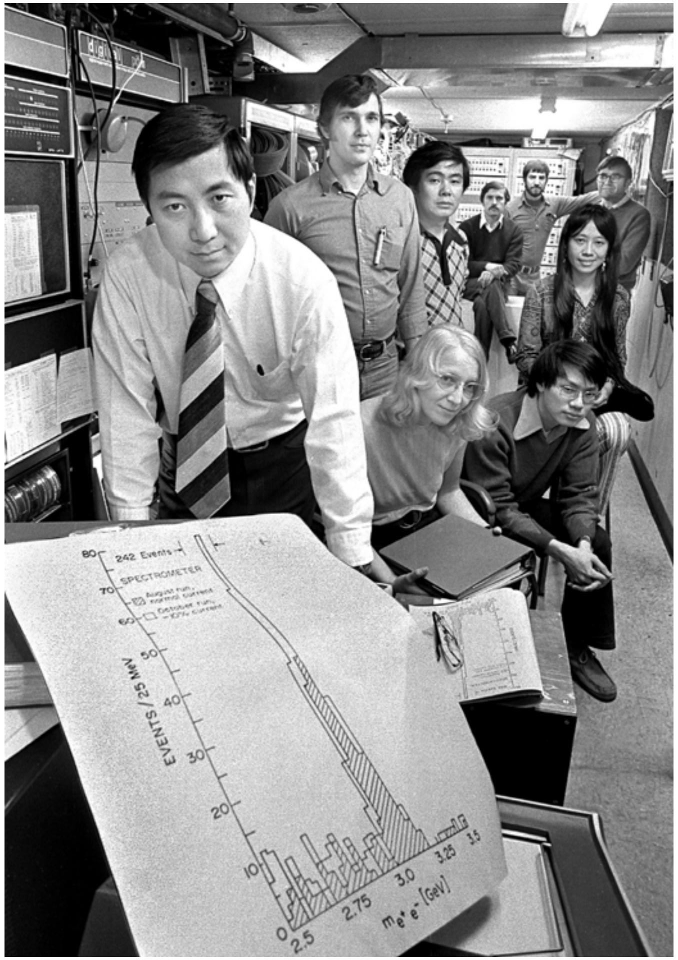
Beyond the SM

- Neutrino mass — $+\frac{c^{ij}}{M}\left(L_L^i\phi\right)\left(L_L^j\phi\right)+h.c.$
- Dark matter — $\chi^0\chi^0 \to A^0 \to f\bar{f}$
- Dark energy — $\langle\phi\rangle = v$
- CKM, MNS
- CP violation

$$-\Gamma_u^{ij}\overline{Q}_L^i\varepsilon\phi^* u_R^j - \Gamma_d^{ij}\overline{Q}_L^i\phi d_R^j - \Gamma_e^{ij}\overline{L}_L^i\phi e_R^j + h.c.$$

- Grand Unification — ϕ_1, ϕ_2
- Inflation — Inflaton
- …

November Revolution



Conclusion

We are making history at the Tevatron and the LHC, and we are laying the path to the next revolution