

Going beyond the Standard Model of Elementary Particle Physics

Saurabh D. Rindani

PRL, Ahmedabad

Symposium on Recent Trends in High Energy Physics

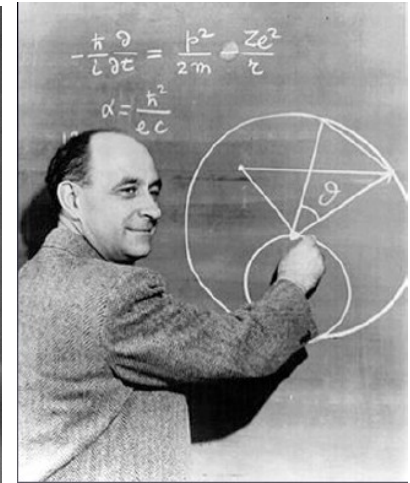
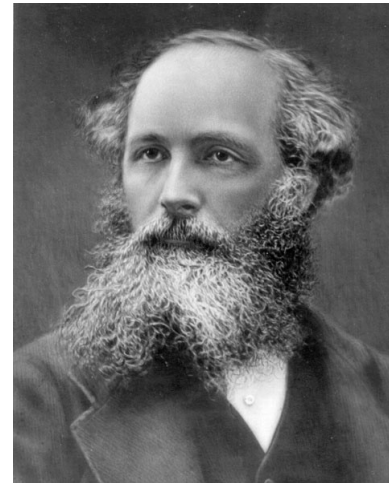
November 19, 2011

*77th Annual Meeting of the Indian Academy of Sciences
PRL Ahmedabad*



Fundamental Interactions

- *Electromagnetic* +
- *Weak* \Rightarrow
- **Electroweak**
- + *Strong* \Rightarrow
- **Standard Model**
- *Gravitational*

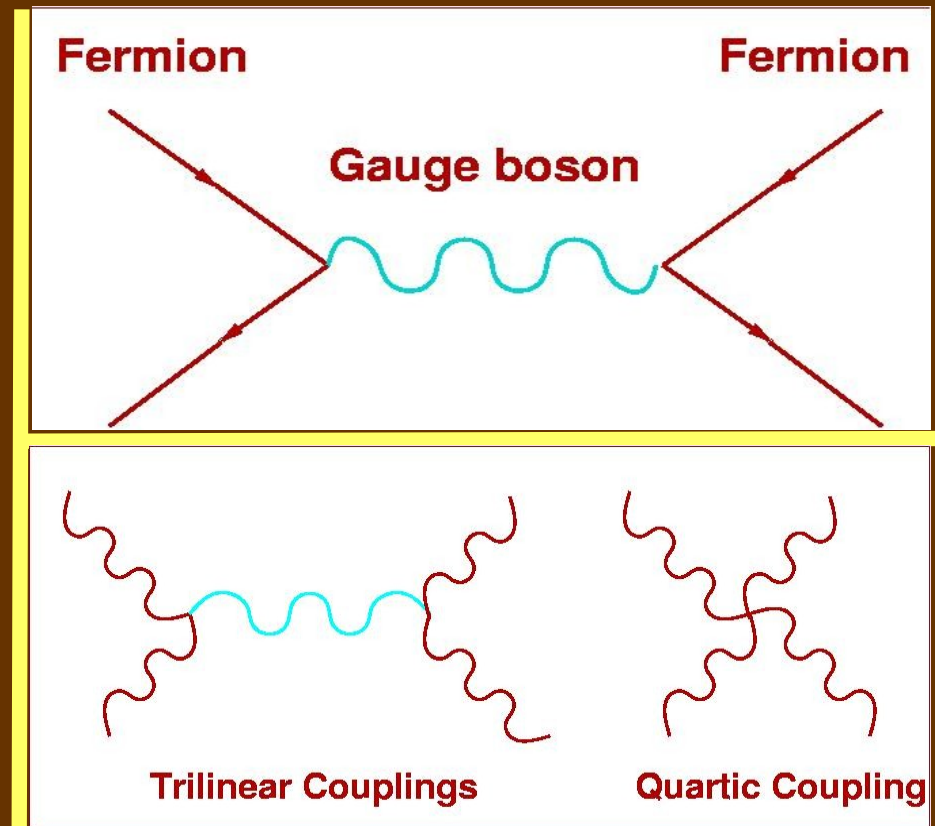


Standard Model of Strong, Weak and Electromagnetic Interactions

- Local gauge invariance
- Group $SU(3) \times SU(2) \times U(1)$
 Strong Interactions: $SU(3)_C$
 Electroweak: $SU(2)_L \times U(1)$
- Spontaneously broken to residual symmetry

$$SU(3)_C \times U(1)_{\text{e.m.}}$$

(Colour & electric charge)



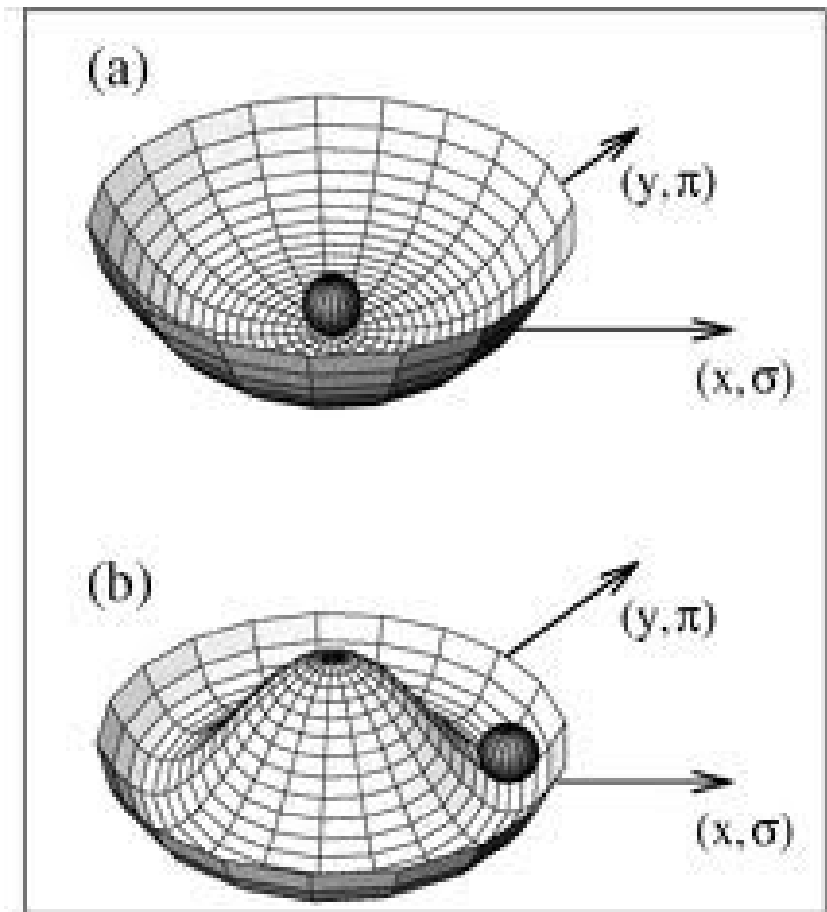
Contents of the Standard Model

Three Generations of Matter (Fermions)

	I	II	III	
mass →	3 MeV	1.24 GeV	172.5 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	u up	c charm	t top	γ photon
Quarks	6 MeV	95 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	d down	s strange	b bottom	g gluon
Leptons	< 2 eV	< 0.19 MeV	< 18.2 MeV	90.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z^0 weak force
	0.511 MeV	106 MeV	1.78 GeV	80.4 GeV
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e electron	μ muon	τ tau	W^\pm weak force
				Bosons (Forces)

Electroweak Symmetry Breaking and generation of mass

- $SU(2) \times U(1)$ symmetry requires 4 massless spin-1 particles
- Only photon is known to be massless
- Symmetry broken to $U(1)$ spontaneously
- Generates masses for fermions



Higgs Mechanism

- Spontaneous symmetry breaking needs a field to be non-zero everywhere
- To break SU(2) (three-dimensional rotations) at least 4 fields needed
- Excitations of one field: Massive spin-0 particle

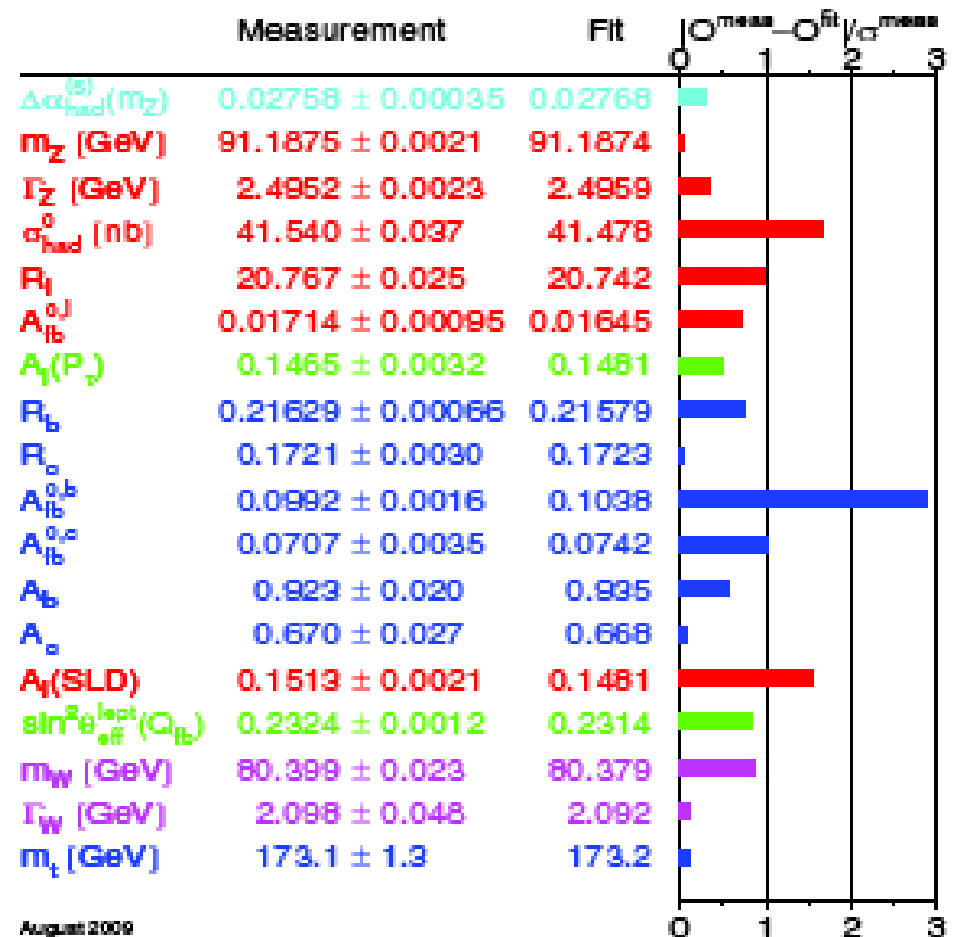
“The Higgs boson”

(Brout, Englert, Guralnik, Hagen, Higgs, Kibble)

- No prediction for mass
- Not yet seen, though the search is on

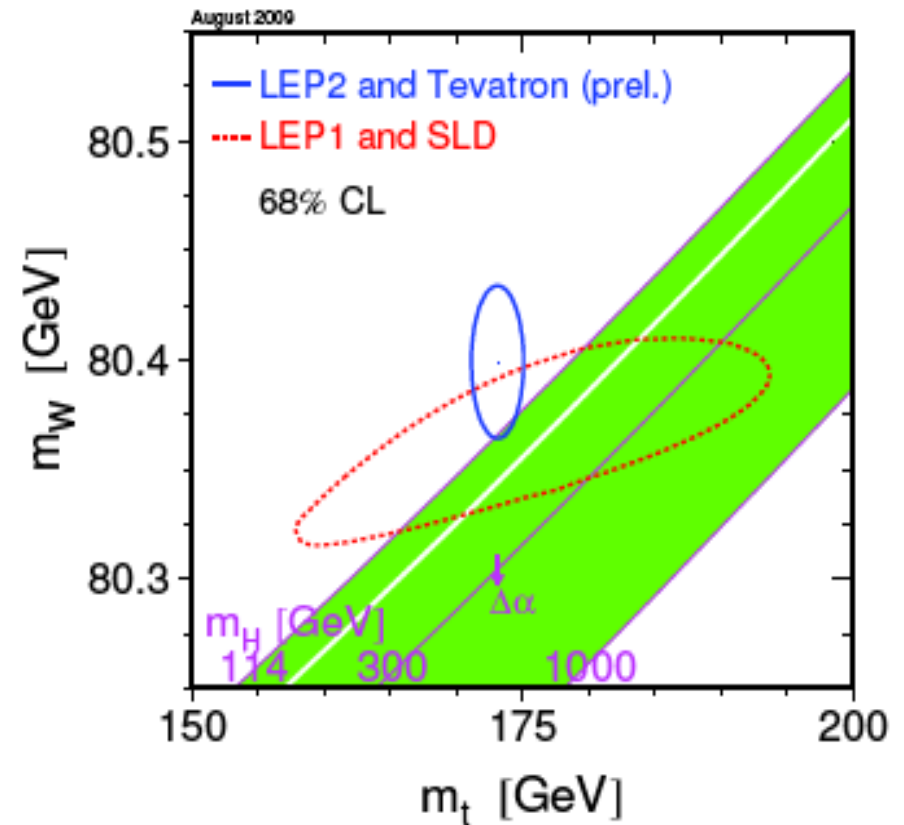
Precision Tests of the Standard Model

- Detailed measurements at the Large Electron Positron (LEP) collider at CERN in the 90's
- Centre-of-mass energy tuned to the Z resonance – “Z factory”
- Later, c.m. energy was increased to around 200 GeV
- Also measurements at Stanford Linear Collider (SLC)



Precision Tests of the Standard Model

- Further tests at Tevatron in Fermilab (shut down 2011)
- Proton-proton collider: centre-of-mass energy 1.8 TeV
- Discovered the top quark
- Precise measurement of masses of t , W

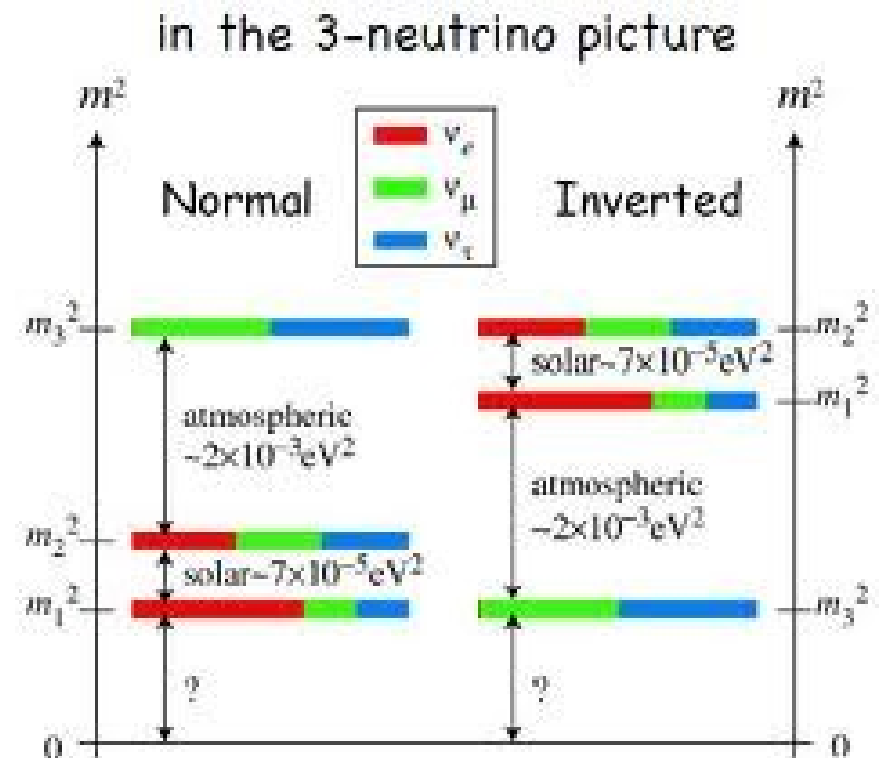


Do we need to go beyond SM?

- Good agreement with current electroweak data
- Yet, SM has unsatisfactory features: No proper understanding of:
 1. The size of fermion masses – ***non-zero*** and ***small*** neutrino masses.
 2. Matter-antimatter asymmetry – baryogenesis and CP violation
 3. Dark matter, dark energy
 3. Electroweak symmetry breaking: the **Higgs mechanism**

Neutrino masses and mixing

- Neutrinos massless in SM
- Observations show at least two neutrinos massive
- All masses less than eV
- Masses obey hierarchy
- $\Delta m_{\text{atm}}^2 \approx 2 \times 10^{-3} \text{ eV}^2$
- $\Delta m_{\text{solar}}^2 \approx 7 \times 10^{-5} \text{ eV}^2$



Neutrino masses and mixing

Theoretical approaches:

- See-saw mechanism
- Flavour symmetry
- Supersymmetry

New Features:

- Additional fermions
- Additional scalar fields

A few of our papers:

A.S. Joshipura, K.M. Patel (2010, 2011)

S. Patra, A. Sarkar, U. Sarkar (2010)

S. Goswami, S. Khan (2010)

A.S. Joshipura, B.P. Kodrani, K.M. Patel (2009)

J.R. Bhatt, U. Sarkar (2008)

N. Sahu, U. Sarkar (2007)

U. Sarkar, S.K. Singh (2006)

A.S. Joshipura, S. Mohanty (2004)

A.S. Joshipura, S.D. Rindani. (2003)

A.S. Joshipura, R.D. Vaidya, S.K. Vempati (2002)

Gauge symmetry breaking

Naturalness problem:

Higgs cannot be naturally light because of higher-order corrections

Possible solutions:

- Bosonic partners for all fermions (and vice versa), with equal coupling constants [Supersymmetry]
- Fermion condensates generate symmetry breaking, not elementary spin-0 fields [Technicolor]

Multi-Higgs Scenarios

- SM has only one Higgs boson
- A simple extension (“two-Higgs-doublet model”) has **5** Higgs bosons
- Three neutral: h, H, A
- Two charged: H^+, H^-
- Required by supersymmetry
- Possibly for baryogenesis
- New mechanisms for CP violation
- May provide new insights for B physics (A.S. Joshipura, B.P. Kodrani)

Experimental Tests

Direct Tests

- Direct observation of new particles
- Unstable particles seen through decay into light particles
- Detectors tuned to expected outcome

Indirect Tests

- Observations made only on known particles
- New physics effects occur in intermediate virtual states (*“loop effects”*)
- Detailed analysis of kinematics needed

Polarization of the top quark

- Top quark has spin $\frac{1}{2}$
- Mass of about 172 GeV ensures rapid decay into $b + W^-$

$$\tau \approx 5 \times 10^{-25} \text{ s}$$

- “Hadronization” scale:

$$\Lambda \approx 3 \times 10^{-24} \text{ s}$$

- Top spin information is retained in the decay products

Polarization of the top quark

- Top quark copiously pair-produced at LHC
- Main production mechanism:
$$\text{gluon} + \text{gluon} \rightarrow \text{top} + \text{antitop}$$
- Strong interaction process, conserves parity
No top-quark polarization !
- Any polarization observed would be signal of physics beyond the SM

How can polarization be measured?

- In the rest frame of the top quark, measure the angular distribution of the product

$$N(\Theta) \propto 1 + \alpha \cos(\Theta)$$

- α : Depends on final state (+1 for electron)
- Θ : Angle between spin and direction of decay particle
- Look for angular distribution of electron (muon) in



Measurement in the lab. frame

- Difficult to reconstruct the rest frame of the top
- Some particles undetected (neutrinos) or charge measurement not possible (jets)

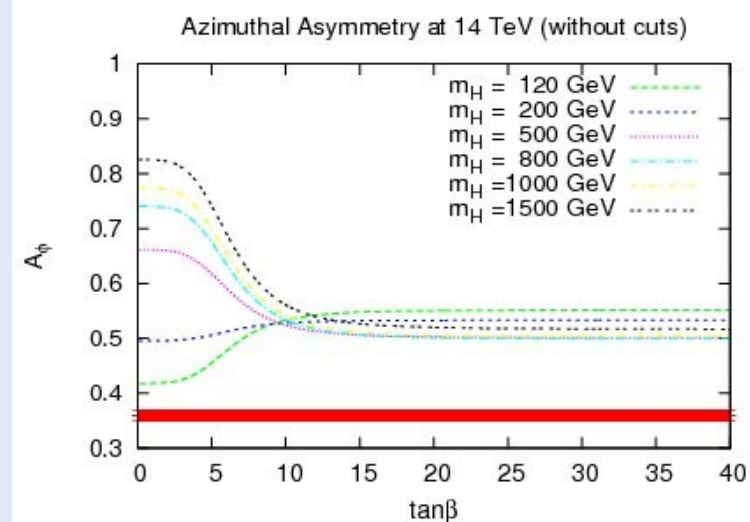
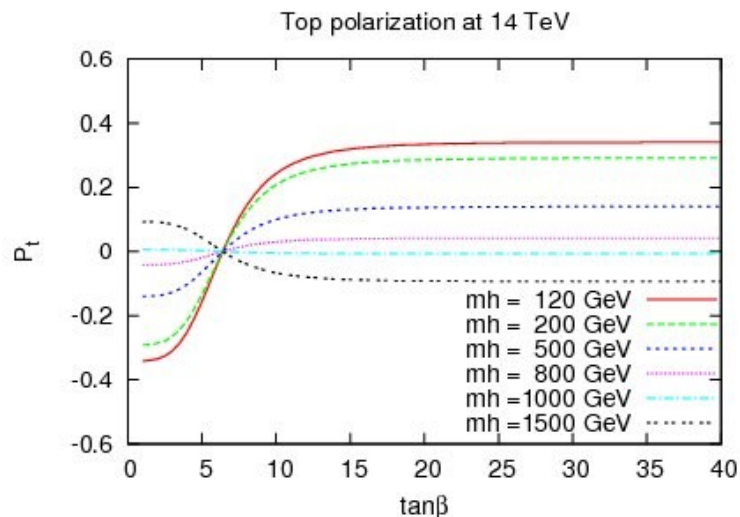
We recommend:

Look at azimuthal distribution of electron (muon) in



R.M. Godbole, K. Rao, SDR, R.K. Singh, JHEP (2010); K. Huitu, S.K. Rai, K. Rao, SDR, P. Sharma, JHEP (2011); P. Sharma, SDR, JHEP (2011)

Single-top production at LHC



Single-top production accompanied by
charged Higgs in 2HDM

K. Huitu, S.K. Rai, K. Rao, SDR, P. Sharma, JHEP (2011)

Hint of new physics?

- Tevatron (proton-antiproton collider at Fermilab, USA) has evidence for FORWARD-BACKWARD asymmetry in top-antitop production

- All explanations involve parity violating couplings

E.g. A. Djouadi, G. Moreau, F. Richard, R.K. Singh, Phys. Rev.D. (2009), K.M. Patel, P. Sharma, JHEP (2011)

- They would lead to non-zero top polarization

- Can also be studied at LHC

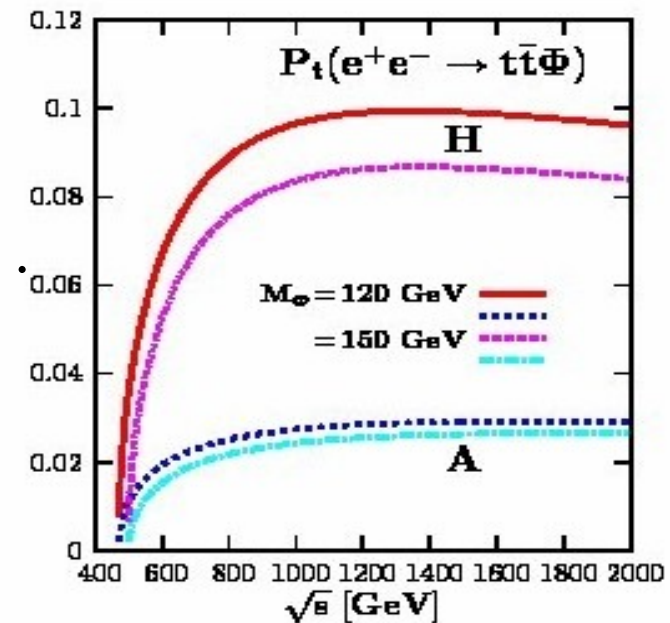
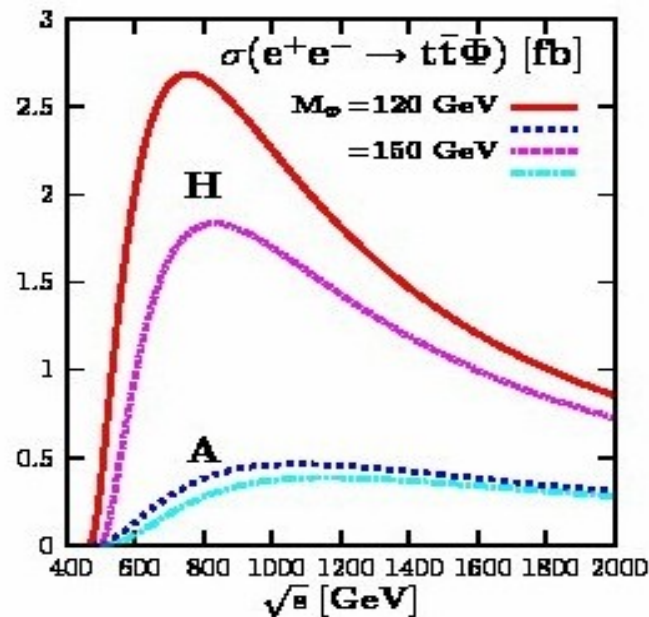
D. Choudhury, R.M. Godbole, SDR, P. Saha, Phys. Rev. D (2011)

CP Property of Higgs Bosons

- Multi-Higgs extensions of SM have several spin-0 particles
- Some of them have odd intrinsic CP parity
- In general, CP may not be conserved – new mechanisms for CP violation
- One important parameter: **Top-antitop-Higgs coupling** – can be studied in top-antitop-Higgs production in e^+e^- collisions

Study at e^+e^- collider

Distinction between CP-even and CP-odd Higgs



P.S. Bhupal Dev, A. Djouadi, R.M. Godbole, M.M. Muhlleitner, SDR,
Phys. Rev. Lett. (2008)

Summary

- Standard Model fares well in precision tests
- Many observational features not well understood
- Fermion masses and mixings better understood
extra features like symmetries
- Mechanism of symmetry breaking is under investigation
- Higgs not yet discovered – if found/not found, it will tell us more about symmetry breaking
- Hint of new physics? Top polarization can help