Title: Rescuing the Standard Model in the case the Higgs Boson is not found

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Abstract: A plethora of Higgsless models have been proposed and we are in the peculiar situation where Fermilab & LHC results will be extremely interesting whether or not the Higgs boson is found. I present here a model where one of the sacred assumption of quantum field theory (renormalizability) is dropped. A precise prescription for the removal of the divergences guarantees both unitarity and predictivity. Interestingly the model is consistent if the Power counting criterion is enforced in a weak form (Weak Power Counting). Among the novel features one notices an extra parameter (the ratio M_W/M_Z) but also a consistent accommodation of the Majorana neutrino mass.

Perimeter Institut, May 14, 2010

Rescuing the Standard Model without a Higgs

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scue Step 1: a Mass for the Vector Mesons

G:

$$m_\gamma < 10^{-18} eV/c^2$$

ll...

oreticians cannot live without an invertible kinetic term
cessity of a gauge fixing), gauge invariance (unitarity),
ality, etc.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + \frac{m_\gamma^2}{2}(A_\mu - \partial_\mu\phi)^2 + \frac{b^2}{2\alpha} + b\partial^\mu A_\mu + Matter$$

Stückelberg mass. Nice invariance (except gauge fixing)

$$A_\mu \to A_\mu + \partial_\mu\omega, \qquad \phi \to \phi + \omega, \qquad \psi \to e^{i\omega}\psi$$

ntent:

- mass for Yang-Mills (Stückelberg)
- mass for Fermions
- flash over Nonlinear Sigma Model
- undamental requirements (locality, symmetry proper-ies)
- ction → effective action
- ow to perform Feynman calculus
- eveloper tools
- $U(2) \otimes U(1)$ old and new parameters
- lajorana

/lass for Yang-Mills: from Higgs....

rt with the usual Higgs field (textbook)

$$\Psi = \begin{pmatrix} i\phi_1 + \phi_2 \\ \phi_0 - i\phi_3 \end{pmatrix}$$

d double the term so that we can introduce

$$\Omega = \begin{pmatrix} \phi_0 + i\phi_3 & i\phi_1 + \phi_2 \\ i\phi_1 - \phi_2 & \phi_0 - i\phi_3 \end{pmatrix} = \phi_0 + i\tau_j\phi_j$$

$$\int d^4x |(\partial_\mu - i\frac{\tau_a}{2}A_{a\mu})\Psi|^2 = \int d^4x \frac{1}{4} Tr\{|\partial_\mu\Omega - iA_\mu\Omega|^2\}.$$

onlinear realization:

$$\Omega^\dagger = \Omega^{-1} \Longrightarrow \phi_0 = \sqrt{1 - \vec{\phi}^2}$$

Stückelberg Mass . It is a spontaneous breakdown of
metry, but not with the usual pattern.

$$\int d^4x \frac{M^2}{4} Tr\{(A_\mu - i\Omega\partial_\mu\Omega^\dagger)^2\}.$$

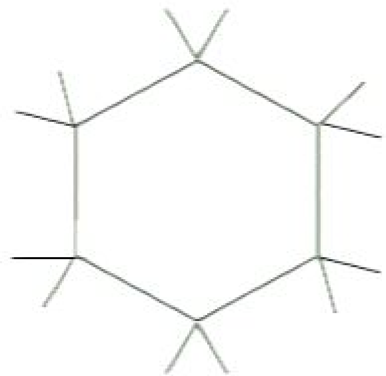
is is gauge invariant, since the new field ($F_{a\mu} = 2(\phi_0\partial_\mu\phi_a -$
$\phi_a + \epsilon_{abc}\partial_\mu\phi_b\phi_c)$)

$$F_\mu \equiv i\Omega\partial_\mu\Omega^\dagger \to UF_\mu U^\dagger + iU\partial_\mu U^\dagger$$

the same transformation property as the A_μ!

magic is in the constraint $\phi_0 = \sqrt{1 - \vec{\phi}^2}$.

cue Step 2: a Mass for the Fermions



e F^2 (from the vector mesons mass term) contains ver-
es like

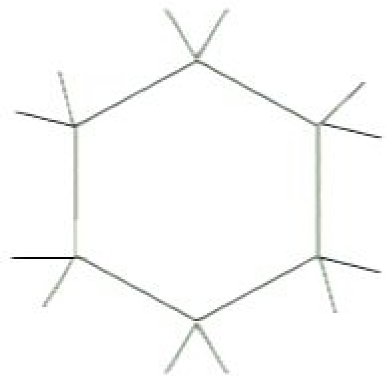
$$\frac{1}{1-\vec{\phi}^2}\phi_a\partial_\mu\phi_a\phi_b\partial^\mu\phi_b = \phi_a\partial_\mu\phi_a\phi_b\partial^\mu\phi_b(1+\vec{\phi}^2+\cdots).$$

e theory is nonrenormalizable .

the same token ($\phi_0 = \sqrt{1-\vec{\phi}^2}$) we can give a mass to
nions. A typical mass term is (here with CKM)

$$M_i V^\dagger_{ij} \bar{\psi}_{iR} \frac{1+\tau_3}{2} \begin{pmatrix} \phi_0 + i\phi_3 & i\phi_1 + \phi_2 \\ i\phi_1 - \phi_2 & \phi_0 - i\phi_3 \end{pmatrix}^\dagger \psi_{jL} + h.c. \; .$$

; we pay a high price due to the new interaction terms
the Goldstone boson fields.



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vare, you are leaving the textbook area.

nlinear sigma model.

st of the problems come from the nonlinear sigma model,

from the action

$$^{(D-4)}\frac{v^2}{8}\int d^D x F_{a\mu} F_a^\mu \sim \Lambda^{(D-4)} \int d^D x \frac{v^2}{2}(\partial^\mu \phi_b \partial_\mu \phi_b + \partial^\mu \phi_0 \partial_\mu \phi_0)$$

$$\Lambda^{(D-4)} \int d^D x \frac{v^2}{2}(\partial^\mu \phi_b \partial_\mu \phi_b + \frac{1}{1-\vec{\phi}^2} \phi_a \partial_\mu \phi_a \phi_b \partial^\mu \phi_b).$$

regularize this theory has been considered impossible.

never say never. Consider the path integral and in

ticular the measure over ϕ

$$\int \prod_x d\phi_0(x) d\phi_1(x) d\phi_2(x) d\phi_3(x) \delta(\phi_0^2 + \vec{\phi}^2 - 1)\ e^{iS+iS_{\text{SOURCES}}}$$

e measure is invariant under *chiral* (better: *left multiplica-*) $SU(2)$ transformations ($\Omega \to U(\omega)\Omega$). For small ω

$$\delta\phi_0 = -\frac{\omega_a(x)}{2}\phi_a$$
$$\delta\phi_a = \frac{\omega_a(x)}{2}\phi_0 + \frac{\omega_c(x)}{2}\epsilon_{abc}\phi_b.$$

one considers the transformations as a change of variables the path integral, an identity for the path integral functional is obtained . Then....

TION → EFFECTIVE ACTION

hy? Because the radiative corrections break the global
ral symmetry of the action! The cause is the nontrivial
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analogy: Hamiltonian → Free Energy in Statistical Me-
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ernal Sources

s standard: in order to get the Green functions one needs ernal sources

$$S_{\text{SOURCES}} = \int d^D x (J_{a\mu} F_a^\mu + K_0 \phi_0 + K_j \phi_j).$$

e physical operators are F_a^μ, ϕ_0, while ϕ_j are just param- rs.

nmary: (i) find the algebra of operators closed under lo- left multiplication transformations by starting from the sical action, (ii) associate to every composite operator external classical source (for subtraction strategy), (iii) te the Local Functional Equation (LFE) which follows n the invariance of the path integral measure.

al Functional Equation

e result of the procedure is the following equation

$$\cdots^{\mu}\frac{\delta\Gamma}{\delta J_a^{\mu}}+\epsilon_{abc}J_c^{\mu}\frac{\delta\Gamma}{\delta J_b^{\mu}}+\frac{\Lambda^{D-4}}{2}\phi_a K_0+\frac{1}{2\Lambda^{D-4}}\frac{\delta\Gamma}{\delta K_0}\frac{\delta\Gamma}{\delta\phi_a}+\frac{1}{2}\epsilon_{abc}\phi_c\frac{\delta\Gamma}{\delta\phi_b}=0.$$

the tree approximation

$$\cdots = S + S_{SOURCES} = \Lambda^{D-4}\int d^Dx\ (\frac{v^2}{8}\{F_{a\mu}-J_{a\mu}\}^2+K_0\phi_0).$$

s the scale parameter for the dimensional regularization.

e perturbative expansion is done by using the boundary

dition

$$\frac{1}{\Lambda^{D-4}}\frac{\delta\Gamma}{\delta K_0}\Big|_{\text{field \&sources=0}}=1.$$

he Spontaneous Breakdown of Symmetry).

rarchy

en LFE naturally induces a strong hierarchy structure ong the 1PI irreducible amplitudes: all amplitudes in- ving the $\vec{\phi}$ fields (descendant) are known in terms of the plitudes involving only the (ancestor) sources $\vec{J}_\mu, K_0$. For ance, if we differentiate the LFE with respect to $J^\nu_{a'}(y)$ get

$$-2\partial^\mu \frac{\delta^2\Gamma}{\delta J^\mu_a(x)\delta J^\nu_{a'}(y)} + \frac{\delta^2\Gamma}{\delta\phi_a(x)\delta J^\nu_{a'}(y)} = 0.$$

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w many ancestor divergent amplitudes? The degree of divergence of a graph G for an ancestor amplitude is bounded (n_L number of loops)

$$\delta(G) \leq n_L(D-2) + 2 - N_F - 2N_{K_0}. \quad (1)$$

r instance at $n_L = 1$ the only ancestor divergent (independent) amplitudes are $(J-J)$, $(J-J-J)$, $(J-J-J-J)$, $-J-J)$, (K_0-K_0). The one-loop divergences of graphs ere the descendant field appears ($\vec{\phi}$) are expressible all in ms of the ancestor divergences.

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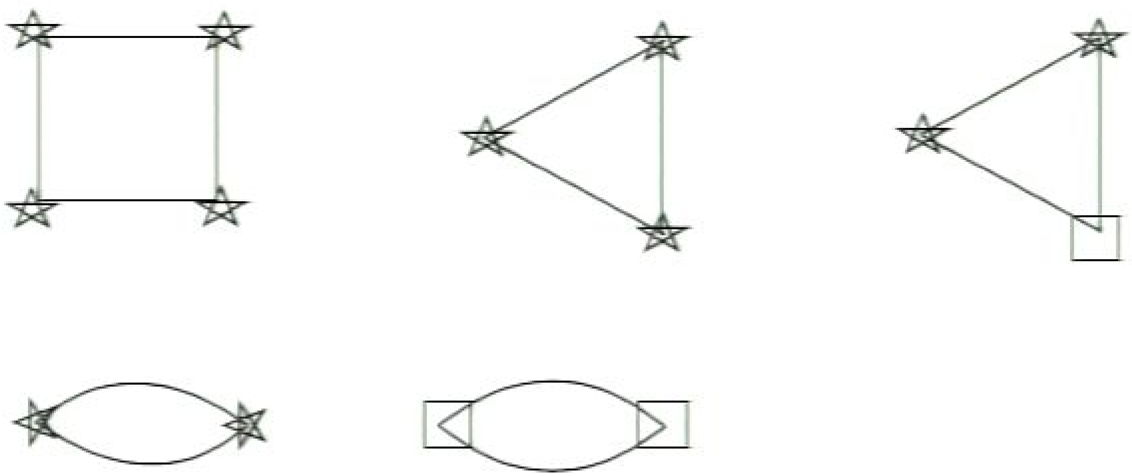

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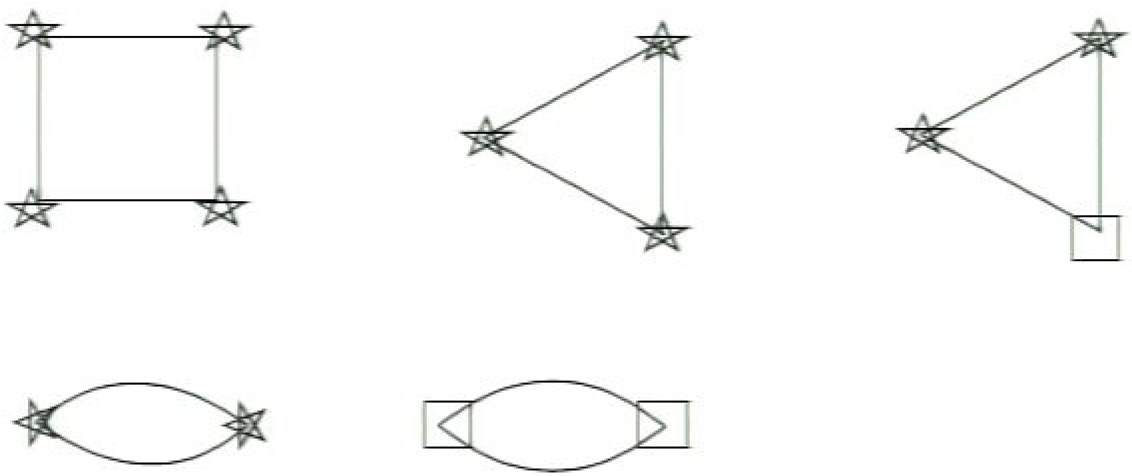

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e Electroweak Model

e required invariance of the path integral measure is (2)$_L$ local left, $U(1)_R$ local right. For instance

$$\Omega \to U(\vec{\omega}(x))\Omega V(\alpha(x))^{\dagger}$$

reover BRST invariance is required for physical unitarity ncellation of Faddeev-Popov ghosts, Goldstone bosons l spin zero components of the vector fields.). Thus we two equations

AVNOV-TAYLOR identity (for unitarity)

CAL FUNCTIONAL EQUATION (for hierarchy, WPC, traction of divergences and finally model construction) ally

e obtains the same interaction pattern for gauge and mat-
fields as in the Standard Model, with some changes.
Replace the Higgs field according to

$$\phi_0 \to \sqrt{1 - \vec{\phi}^2}$$

An extra mass-like term appears for the intermediate
tor mesons. Consequently $\frac{M_W}{M_Z}$ (Weinberg's angle) be-
nes a free parameter (work in progress: in GUT models
parameter is not anymore free).
nman rules in 0903.0281 [hep-th] by D. Bettinelli, R.F.
A. Quadri (analytic calculation of the W and Z mass
-loop corrections).

onus

ile in the Standard Model a Majorana mass for the neu-
o is forbidden by renormalization, in our model (non-
ar realization of the gauge group) it is not. Use the
ached field $\nu = (1+\tau_3)\Omega^\dagger\psi_L$, then the mass-like term is

$$m\bar{\nu}_c\nu + h.c.$$

$$\Omega = \sqrt{1-\vec{\phi}^2} + i\tau_j\phi_j.$$

ses the check of WPC. The term is allowed!

se and hideous accusations by the well-known enemies of
people's revolution

our job's referees

usations

he whole theory cannot be true. Hopefully this is not he case. We do honestly our best to avoid mistakes.

Ve do not follow algebraic renormalization. Of course

ur scheme is based on dimensional regularization. We o not consider this a flaw: if one finds a way to contruct a consistent theory, this should be acceptable from physical point of view

Ve do not have a renormalization group invariance. Yes nd no: a derivative respect to Λ yields a very complicated quation. Work still in progress

is not a physical parameter. The masses replace the rder parameter.

'he model must have problems with unitarity. This is a
ough issue.

More about Unitarity (the High Energy Problem)

Glance to the Nonlinear Sigma Model

e forward $\pi\pi$ elastic scattering amplitude behaves like

$$T^{(n)} \sim (\frac{s}{v^2})^{(n+1)} \tag{2}$$

= number of loops, $s =$ (center of mass energy)^2). Thus expect that the theory is phenomenologically relevant y for

$$s < v^2. \tag{3}$$

yond this constraint one needs some new tool (lattice ulations?). Conclusion: the theory is unitary in the set parameters where it makes sense.

W_L elastic scattering

e attention has been focused on this process for differ- reasons. At high energy $(s, t >> M_W^2)$ some anomalous avior is expected for the longitudinal polarization. The a is to entangle the presence of the Higgs boson to the uirement of unitarity. The calculations often make use he so called Equivalence Theorem.

itarity: It is better to stress the conceptual difference
ween the Optical Theorem for the S-matrix

$$S = \mathbb{I} - iT, \quad S^{\dagger}S = \mathbb{I}, \quad \Longrightarrow ImT_{ii} \sim \sigma_{iT}. \tag{4}$$

l Perturbative Unitarity gives ($k > 0$)

$$0 = \sum_{j=0}^{k} S^{(j)\dagger} S^{(k-j)}. \tag{5}$$

ere

$$S = \sum_{k=0}^{\infty} S^{(k)}, \quad S^{(0)} = \mathbb{I}. \tag{6}$$

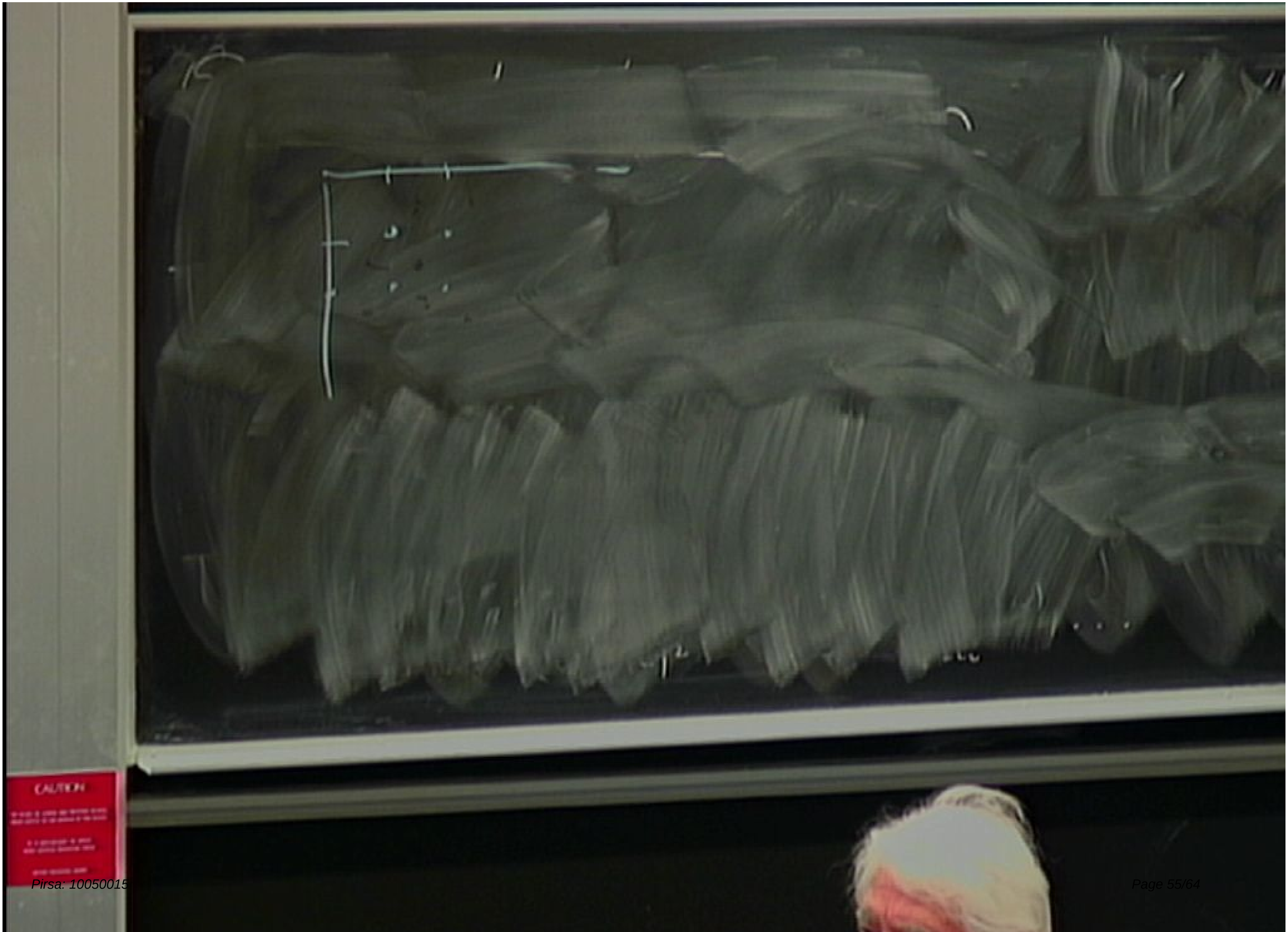
any finite order calculation $S_{in} = \sum_{j=0}^{k} S_{in}^{(j)}$

$$\sum |\sum_{j=0}^{k} S_{in}^{(j)}|^2 = \sum_{n} \sum_{l=0}^{k} \sum_{j=0}^{k} S_{in}^{(j)*} S_{in}^{(l-j)} + \sum_{n} \sum_{l=k+1}^{2k} \sum_{j=0}^{k} S_{in}^{(j+l)*} S_{in}^{(l-j)}$$

$$1 + \sum_{n} \sum_{l=k+1}^{2k} \sum_{j=l-k}^{k} S_{in}^{(j)*} S_{in}^{(l-j)}$$

ere is always a violation of the Optical Theorem of order $+1)$.

e Optical Theorem has a meaning only if an operative nition of <u>forward</u> scattering exists. If long range inter-ions are present, then forward amplitude is an elusive ect. Only eq. (5) has a meaning.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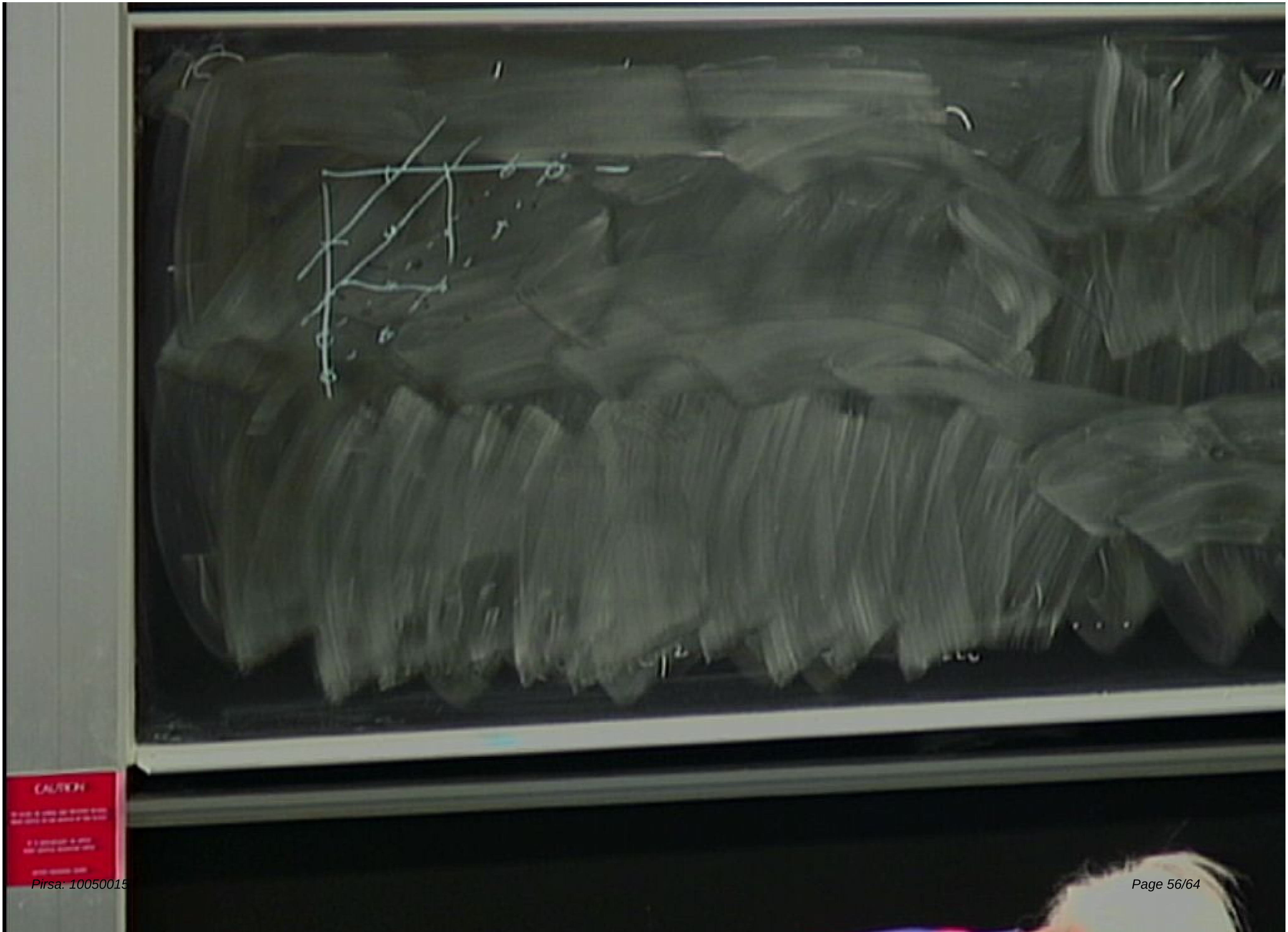
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any finite order calculation $S_{in} = \sum_{j=0}^{k} S_{in}^{(j)}$

$$\sum |\sum_{j=0}^{k} S_{in}^{(j)}|^2 = \sum_{n} \sum_{l=0}^{k} \sum_{j=0}^{k} S_{in}^{(j)*} S_{in}^{(l-j)} + \sum_{n} \sum_{l=k+1}^{2k} \sum_{j=0}^{k} S_{in}^{(j+l)*} S_{in}^{(l-j)}$$

$$1 + \sum_{n} \sum_{l=k+1}^{2k} \sum_{j=l-k}^{k} S_{in}^{(j)*} S_{in}^{(l-j)}$$

ere is always a violation of the Optical Theorem of order $+1)$.

e Optical Theorem has a meaning only if an operative nition of forward scattering exists. If long range inter-ions are present, then forward amplitude is an elusive ect. Only eq. (5) has a meaning.

perimental side

might think of some experimental proof/disproof of the
del.

'it of the precision data at low and medium energy ($s \sim$
M_W^2).

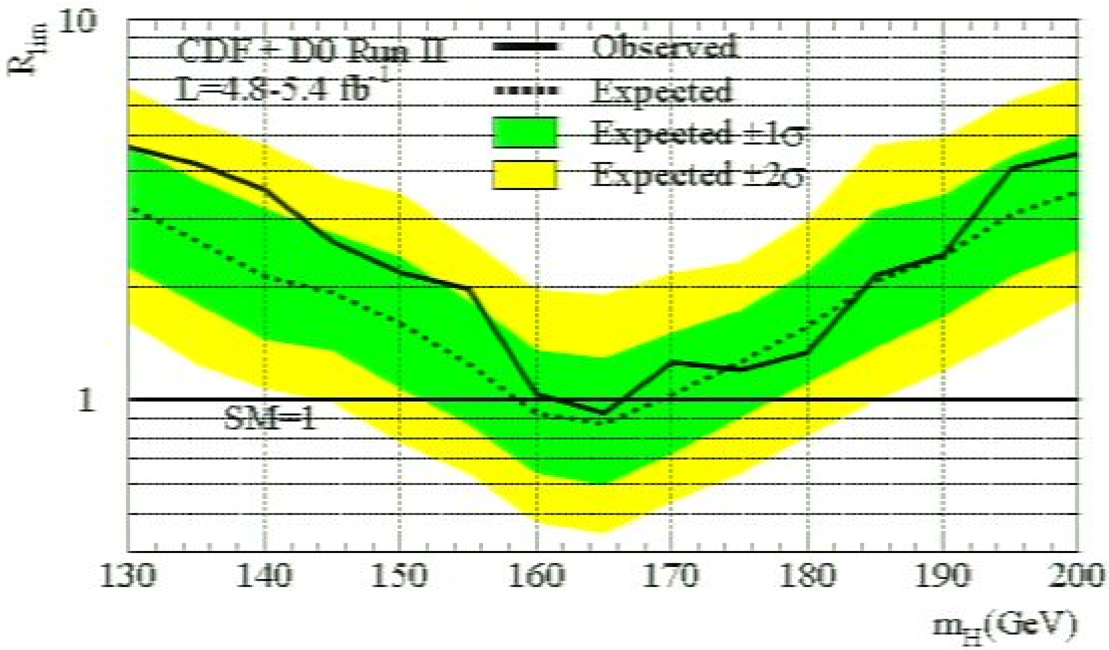
'it of the data at LHC energy.

Direct evidence of the Higgs boson existence.

e third case is of course a clear cut answer, although,
ng one of the author, I would feel curious to understand
y renormalized Higgs mechanism is realized and not a
d theory where the gauge group is represented nonlin-
ly. Recent results at Tevatron
p://tevnphwg.fnal.gov/results/SMHPubWinter2010/index.html

CDF Run II Preliminary	$\int \mathcal{L} = 4.8\ \mathrm{fb}^{-1}$		
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	196	$\pm$	32
DY	342	$\pm$	61
WW	605	$\pm$	65
WZ	54.8	$\pm$	7.5
ZZ	42.3	$\pm$	5.8
W+jets	278	$\pm$	70
$W\gamma$	191	$\pm$	27
Total Background	1710	$\pm$	140
$gg \to H$	22.3	$\pm$	4.8
WH	4.38	$\pm$	0.57
ZH	1.59	$\pm$	0.21
VBF	1.61	$\pm$	0.26
Total Signal	29.8	$\pm$	5.1
Data		1733	

High Mass



R_{lim}
10
1
CDF + D0 Run II
L=4.8-5.4 fb^{-1}
Observed
Expected
Expected ±1σ
Expected ±2σ
SM=1
130
140
150
160
170
180
190
200
m_H(GeV)

CDF Run II Preliminary	$\int \mathcal{L} = 4.8\ \mathrm{fb}^{-1}$		
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High Mass

ect and Indirect tests

e low energy test is lengthy and uncertain. We have luated the self-masses of the vector mesons. We have iost finished the one-loop corrections to G_μ. More work vaiting. Moreover the uncertainty on θ_W makes the fit icult. In the Standard Model $M_W \sim gv, G_F \sim v^{-2}, e =$ θ_W thus the fit encounters some rigidity.

e high energy is based on the gg- $q\bar{q}$-, WW- and ZZ-fusion. e Standard model and our model at the tree level differ y by the absence of the Higgs boson contribution in our e. Thus in this particular case it corresponds to the limit $\to \infty$. Probably a very difficult task to distinguish the models.

o PDG is ready to issue some *imprimatur*:

Higgs bosons are not discovered at the Tevatron or the
C, other studies might be able to test alternative theories
dynamical electroweak symmetry breaking which do not
olve a fundamental Higgs scalar (from the 2008 Review
Particle Physics: "Higgs Bosons: Theory and Searches
v.)" pag. 48).

$$\left(\Phi_c^{\dagger} (\partial^\mu - A^\mu + B) \phi \right)^{\dagger} \Phi_c^{\dagger} (\partial_\mu - A_\mu B) \Phi$$

$$\varphi_0 = \sqrt{1-\varphi^2} \sim 1 - \frac{\varphi^2}{2}$$

$$M \, \bar{\psi}_R \, \Omega \, \psi_L$$

$$\Omega \to \begin{pmatrix} \varphi_0 & \\ & \varphi \end{pmatrix}$$