大型强子对撞机上的希格思粒子
A SM Higgs or Something Else?

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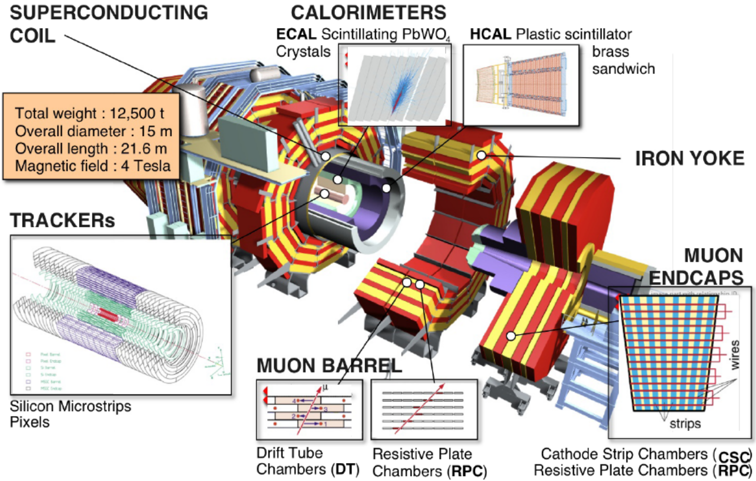
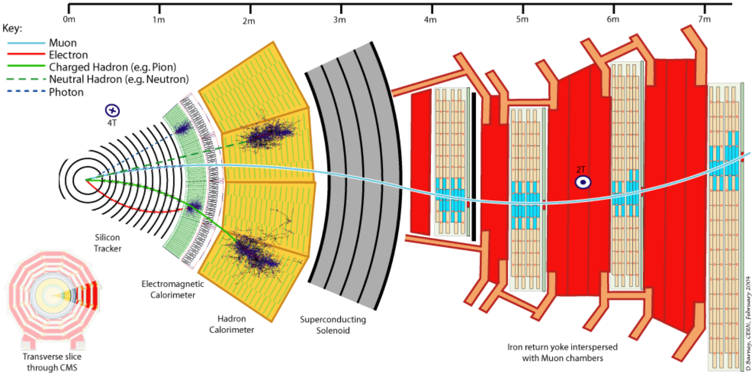

SUPERCONDUCTING COIL
CALORIMETERS
ECAL Scintillating PbWO4 Crystals
HCAL Plastic scintillator brass sandwich
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
IRON YOKE
TRACKERs
Silicon Microstrips
Pixels
MUON ENDCAPS
wires
strips
MUON BARREL
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)



- $\tau_{\rm QCD} \sim 10^{-25}$ s$(\Lambda_{\rm QCD}$ 100 MeV$)$
- $c\tau_{B^\pm} \sim 500$ μm$(\tau \sim 10^{-12}$ s$)$
- $c\tau_{\tau^\pm} \sim 80$ μm$(\tau \sim 10^{-13}$ s$)$: $\tau^+ \to \pi^+ \bar{\nu}_\tau$ isolated pion.
- $c\tau_{\mu^\pm} \sim 600$ m$(\tau \sim 10^{-6}$ s$)$

LHC is a QCD machine!

Digging signal out of QCD: 1 out of 10^8

- high p_T object of $p_T > 120$ GeV: large mass difference
- large missing transverse energy: $\not\!\!E_T > 100$ GeV: DM and right kinematics
- isolated hard leptons (electron or muon) or photon: $e^{\pm}, \mu^{\pm}, \gamma$: isolation is the key
- jet with displaced vertex: b-tagging: b is from gluon splitting third generation new physics

However, what we see may not be what we think we have seen.

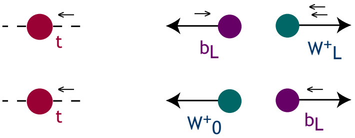
- jet/lepton energy measurement
- $\pi^0 \to \gamma\gamma$: boosted pion may look like photon
- $D_s^\pm$ being faked as $B^\pm$ 10%.
- π^+ being faked as μ^+.
- μ^+ from B semi-leptonic decay.
- τ identification
- ..... A lot of more faking

We should appreciate the tremendous effort put in by our experimental colleagues!

Heaviest known particle t: m_t breaks electroweak gauge symmetry.

Large m_t couples to symmetry breaking sector (“Goldstone” , longitudinal polarized W) strongly.

$m_b/m_t \to 0$: “massless” b is left-handed polarized.



$$\mathcal{M} \sim \frac{g}{\sqrt{2}} \cos\frac{\chi}{2}$$

$$\mathcal{M} \sim \sin\frac{\chi}{2}$$

Longitudinal W polarization: $\epsilon_0 \sim k_\mu/m_W$

$$\epsilon_0^* \bar{u}_{bL} \gamma_\mu u_t \simeq \frac{m_t}{m_W} \bar{u}_{bL} u_t$$

$$f_0 = \frac{\Gamma(t \to bW_0^+)}{\Gamma(t \to bW_0^+) + \Gamma(t \to bW_+^+) + \Gamma(t \to bW_-^+)} \simeq 70\%$$

$f_- \simeq 30\%, f_+ \simeq 0$

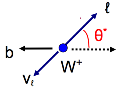
Confirmed by D0 and CDF and also CMS...

W polarization (2.2 fb^{-1})

CMS-PAS TOP-11-020

Feb'12

Anomalous contributions to the tWb vertex change the probabilities of the W helicity states

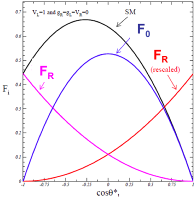


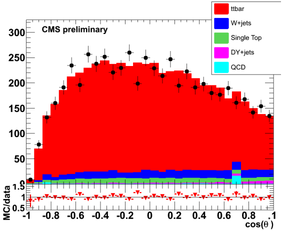
Angle between charged lepton and top direction in W rest frame

- In SM: 3 possible W helicity states:

F_0 (longitudinal) ~ 0.70, F_L (left) ~ 0.30, F_R (right) ~ 0

- Measure sensitive variable, cos(θ*), in **muon+jets** channel:
  - 1 isolated high-p_T μ, ≥ 4 jets, ≥ 1 b-tag
  - Kinematic fit to reconstruct ttbar system





- Helicity fractions extracted from maximum likelihood fit:

$$F_0 = 0.567 \pm 0.074(\text{stat.}) \pm 0.047(\text{syst.})$$
$$F_L = 0.393 \pm 0.045(\text{stat.}) \pm 0.029(\text{syst.})$$
$$F_R = 0.040 \pm 0.035(\text{stat.}) \pm 0.044(\text{syst.})$$

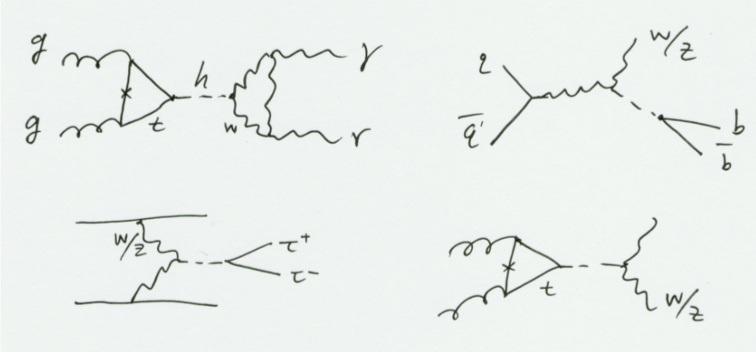
- Good agreement with SM
- Similar precision as previous measurements (Tevatron, ATLAS)

M. Aldaya 22 XXVI Rencontres de la Vallee d'Aoste, 01.03.12

Great! but what does it tell us? Only EWSB occurs but not how EWSB take place......

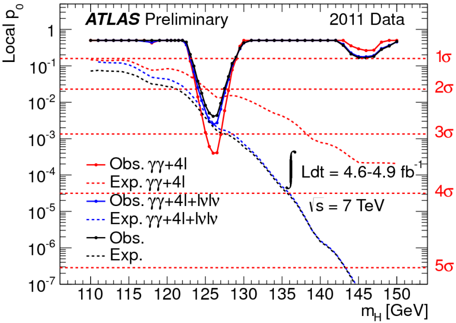
Hints from perturbative unitarity

- $W_L W_L \to W_L W_L$ scattering: $4\pi M_W/g \sim 1$ TeV
- $f\bar{f} \to W_L W_L$ scattering: $16\pi/\sqrt{2}\sqrt{3}G_F M_f \sim 4$ TeV



- Higgs couples to both weak gauge bosons $W^{\pm}$, Z and the SM fermions.
- $gg \to h$ and $h \to \gamma\gamma$ is sensitive to new physics indirectly just like flavor physics (INDIRECTLY).

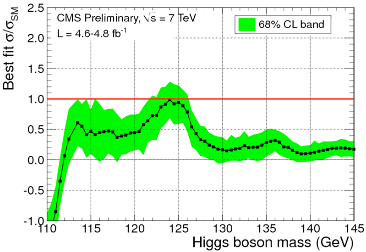
Excess in individual channels



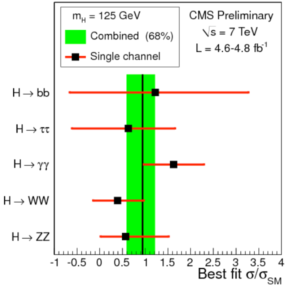
- Excess is mainly observed in two high-resolution channels:
  $\Rightarrow$ $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4\ell$ combined: 3.4σ local significance.
- No such excess (yet?) in $H \to WW^{(*)} \to \ell\nu\ell\nu$, $H \to \tau\tau$, $H \to b\bar{b}$.
  $\Rightarrow$ All channels combined: 2.5σ local significance.

Fitted signal strength σ/σ_{SM}

NEW



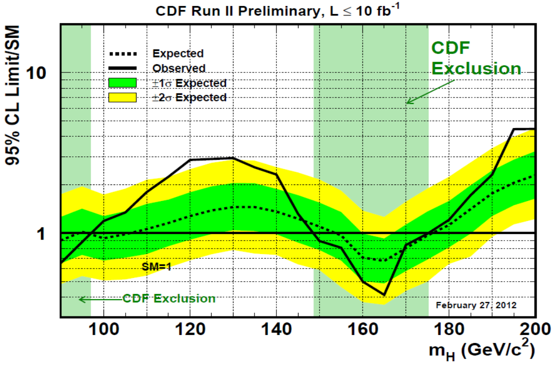
Comparison of channels for M_H=125 GeV



- The fitted σ of the excess near 125 GeV is consistent with the SM scalar boson expectation
- At low mass several channels show some excess
  - At 125 GeV all sensitive channels show an excess consistent with signal expectations
- More data are needed to investigate this excess

The CDF Combined Higgs Search

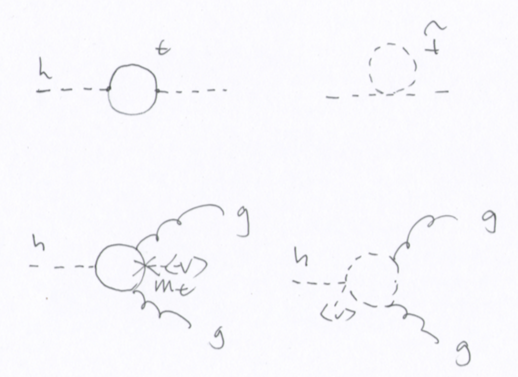
- Exclude 147-175 GeV
- Broad excess observed. Largest excess: 120 GeV
- Global p-value (LLE=4) = 2.1 sigma



SM Higgs?

- If LHC findings are consistent with SM prediction.
- More important! If Tevatron sees the SM prediction.
- Still needs direct measurement of Yukawa couplings for instance $gg \to t\bar{t}h$ with $h \to \tau^+\tau^-$.

A SUSY example



125 GeV Higgs is non-trivial in CMSSM: Large A-term or Heavy $\tilde{t}$

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

$$t = \log\frac{M_{\rm SUSY}^2}{m_t^2}; \tilde{X}_t = \frac{2\tilde{A}_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{\tilde{A}_t^2}{12M_{\rm SUSY}^2}\right); \tilde{A}_t = A_t - \mu\cot\beta$$

Dimension-one Squark-Higgs coupling
(calculation must be done in Mass eigenstates.)

$$\mathcal{M}_{\tilde{q}}^2 = \begin{pmatrix} m_{\tilde{q}_L}^2 + m_q^2 + D_L^q & m_q \tilde{A}_q \\ m_q \tilde{A}_q & m_{\tilde{q}_R}^2 + m_q^2 + D_R^q \end{pmatrix}$$

Couplings normalized by $2M_Z^2(\sqrt{2}G_F)^{1/2}$

$$\begin{aligned} g_{h\tilde{q}_1\tilde{q}_1} &= -\cos 2\beta \left[I_q^3 \cos^2\theta_{\tilde{q}} - e_q \sin^2\theta_W \cos 2\theta_{\tilde{q}}\right] - \frac{m_q^2}{M_Z^2} + \frac{1}{2}\sin 2\theta_{\tilde{q}} \frac{m_q \tilde{A}_q}{M_Z^2} \\ g_{h\tilde{q}_2\tilde{q}_2} &= -\cos 2\beta \left[I_q^3 \sin^2\theta_{\tilde{q}} - e_q \sin^2\theta_W \cos 2\theta_{\tilde{q}}\right] - \frac{m_q^2}{M_Z^2} - \frac{1}{2}\sin 2\theta_{\tilde{q}} \frac{m_q \tilde{A}_q}{M_Z^2} \end{aligned}$$

To enhance $\gamma\gamma$ will need additional contribution like stau $\tilde{\tau}$.

A more exotic example

SM Fermion masses break electroweak symmetry BUT....

$$\bar{\psi}_L \not{D} \psi_L + \bar{\psi}_R \not{D} \psi_R$$

Chiral symmetries

$$U(3)_Q \otimes U(3)_u \otimes U(3)_d \otimes U(3)_\ell \otimes U(3)_e$$

must be broken in order to generate SM fermion masses

$$m_\psi \bar{\psi}_L \psi_R \ .$$

In the minimal Higgs boson model (known as “Standard Model”), chiral symmetries are broken by the Yukawa coupling y:

$$y_u \bar{u}_R Q H \ : y \to 0 \longrightarrow \text{restore Chiral symmetry}$$

Masses

- gauge boson mass : gauge symmetry breaking effect
  Longitudinal polarization of W boson
- fermion mass: chiral symmetry breaking

$$\bar{\psi}_L \not{D} \psi_L + \bar{\psi}_R \not{D} \psi_R$$

$$\bar{\psi}_L \psi_R$$

$$\Delta m_e = m_e \left[1 + \frac{\alpha}{4\pi} \ln\left(\frac{\Lambda}{m_e}\right) + ... \right]$$

  Another example: $M_{1/2}$ in SUSY, R-symmetry breaking effect.
- scalar mass: no symmetry breaking.
- non-zero SM fermion masses $\longrightarrow W/Z$ masses
- non-zero W/Z masses $\not\longrightarrow$ SM fermion masses

Models of EWSB are severely constrained.

- Precision electroweak S,T...
  New $SU(2)$ doublets
  Custodial $SU(2)_{L+R}$
- SM fermion mass generation and flavor violation
  ETC scale is low for large m_t but ETC sectors couple to everything, light quarks, leptons....

Minimal Flavor Violation

$$-y^U_{ij}\bar{u}_{Ri}Q_jH - y^d_{ij}\bar{d}_{Ri}Q_jH^\dagger + H.c.$$

Q_j transforms as $\mathbf{3_Q}$ Under $U(3)_Q$

$$M^U = \sum_\alpha y^U_\alpha \langle H_\alpha \rangle, M^D = \sum_\beta y^D_\beta \langle H_\beta \rangle^\dagger$$

$y^{U,D}$ be diagonal in the same basis where $M^{U,D}$ are diagonal.

- $\alpha = \beta$, Only one doublet breaks $U(3)_Q \otimes U(3)_u \otimes U(3)_d$
- $\alpha \neq \beta$, One for M^U, one for M^D: Type-II 2HDM

Assumption

- SM fermions masses are still due to one doublet.
- Weak gauge boson masses are due to one fermiophobic sector as well as the one responsible for the SM fermion masses.
  How to achieve fermiophobic?
  - SM symmetry: non $SU(2)_L$ doublet, break custodial symmetry?
  - New symmetry: strong dynamics, bosonic Techni-Color model

Electroweak Chiral Lagrangian in Bosonic Techni-Color

Π : isotriplet of techni-pions with decay constant f

$$\Sigma = \exp(2i\Pi/f), \quad \Pi = \begin{pmatrix} \pi^0/2 & \pi^+/\sqrt{2} \\ \pi^-/\sqrt{2} & -\pi^0/2 \end{pmatrix},$$

Scalar doublet Φ:

$$\Phi = \begin{pmatrix} \overline{\phi^0} & \phi^+ \\ -\phi^- & \phi^0 \end{pmatrix}.$$

rewrite as

$$\Phi = \frac{\sigma + f'}{\sqrt{2}}\Sigma', \quad \Sigma' = \exp(2i\Pi'/f'),$$

The kinetic terms for the Φ and Σ fields are

$$\mathcal{L}_{KE} = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{f^2}{4}\mathrm{Tr}(D_\mu\Sigma^\dagger D^\mu\Sigma) + \frac{(\sigma+f')^2}{4}\mathrm{Tr}(D_\mu\Sigma'^\dagger D^\mu\Sigma'),$$

where the covariant derivative is given by

$$D^\mu\Sigma = \partial^\mu\Sigma - igW_a^\mu\frac{\tau^a}{2}\Sigma + ig'B^\mu\Sigma\frac{\tau^3}{2}.$$

For a specific linear combination of the pion fields:

$$\pi_a = \frac{f\,\Pi + f'\,\Pi'}{\sqrt{f^2+f'^2}}.$$

there exist quadratic terms that mix the gauge fields with derivatives. Such states are unphysical and can be gauged away. The physical state π_p then arises from the orthogonal linear combination,

$$\pi_p = \frac{-f'\,\Pi + f\,\Pi'}{\sqrt{f^2+f'^2}}.$$

$$m_W^2 = \frac{1}{4} g^2 v^2, \qquad m_Z^2 = \frac{1}{4}(g^2 + g'^2) v^2,$$

where v is the electroweak scale as $v \equiv \sqrt{f^2 + f'^2} = 246\ \mathrm{GeV}$.

$$\sin\theta = \frac{f'}{v}, \cos\theta = \frac{f}{v}\ .$$

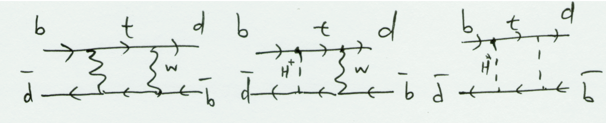
$$\mathcal{L}_{\sigma WZ} = 2\sin\theta \frac{m_W^2}{v} \sigma W^{+\mu} W_\mu^- + \sin\theta \frac{m_Z^2}{v} \sigma Z^\mu Z_\mu\ ,$$

$$\mathcal{L}_{\sigma \bar{f} f} = -\sum_{\text{fermions}} \frac{1}{\sin\theta} \frac{m_f}{v} \sigma \bar{f} f\ .$$

$$\mathcal{L}_{\pi_p^\pm} = -i\cot\theta \frac{m_{u_i}}{v} \pi_p^- \bar{d}_{iL} u_{iR} - i\cot\theta \frac{m_{d_j}}{v} \pi_p^+ \bar{u}_L^i V_{CKM}^{ij} d_R^j + h.c.$$

Enhanced Yukawa and Flavor Violation

$B_u \to \tau\nu_\tau$, $\mu \to e\gamma$ (Barr-Zee)
$B_d - \bar{B}_d$ mixing



$$\Delta M_{B_d} = \frac{G_F^2 m_t^2 f_{B_d}^2 \hat{B}_d M_B \mid V_{td}^* V_{tb} \mid^2 \eta_b}{24\pi^2} [I_{WW}(y^W) + I_{W\Pi}(y^W, y^\Pi, x) + I_{\Pi\Pi}(y^\Pi)],$$

where

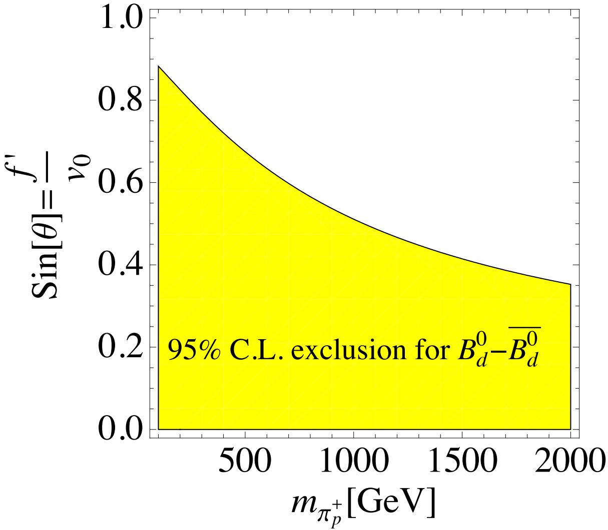
$$y_W = \frac{m_t^2}{m_W^2}, \quad y_\Pi = \frac{m_t^2}{m_{\pi_p^+}^2}, \quad x = \frac{m_{\pi_p^+}^2}{m_W^2},$$

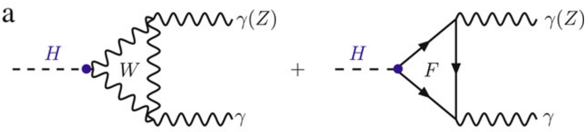
and

$$I_{WW} = 1 + \frac{9}{1-y^W} - \frac{6}{(1-y^W)^2} - \frac{6}{y^W}\left(\frac{y^W}{1-y^W}\right)^3 \ln y^W$$

$$I_{W\Pi} = \lambda_{tt}^2\, y^\Pi \left[\frac{(2x-8)\ln y^\Pi}{(1-x)(1-y^\Pi)^2} + \frac{6x \ln y^W}{(1-x)(1-y^W)^2} - \frac{8-2y^W}{(1-y^W)(1-y^\Pi)}\right]$$

$$I_{\Pi\Pi} = \lambda_{tt}^4\, y^\Pi \left[\frac{1+y^\Pi}{(1-y^\Pi)^2} + \frac{2y^\Pi \ln y^\Pi}{(1-y^\Pi)^3}\right].$$


1.0
0.8
0.6
0.4
0.2
0.0
500
1000
1500
2000
$m_{\pi_p^+}$[GeV]
$\mathrm{Sin}[\theta]=\frac{f'}{v_0}$
95% C.L. exclusion for $B_d^0-\overline{B_d^0}$



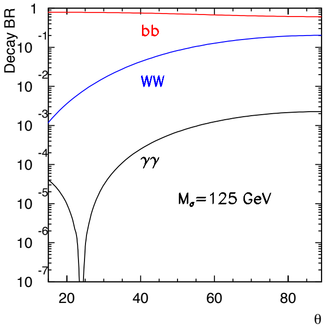
$$\Gamma(\sigma \to \gamma\gamma) = \frac{G_\mu \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 A_{1/2}^H(\tau_f)/\sin\theta + A_1^H(\tau_W)\sin\theta \right|^2$$

where

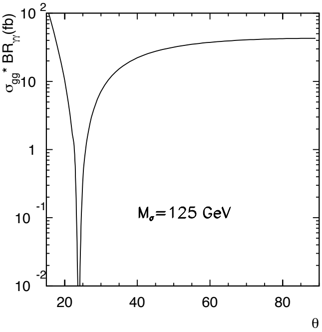
$$\begin{aligned} A_{1/2}^H(\tau) &= 2[\tau + (\tau - 1) f(\tau)]\tau^{-2} \\ A_1^H(\tau) &= -[2\tau^2 + 3\tau + 3(2\tau - 1) f(\tau)]\tau^{-2} \end{aligned} \qquad (1)$$

and the function $f(\tau)$ is defined as

$$f(\tau) = \begin{cases} \arcsin^2 \sqrt{\tau}; & \tau \leq 1 \\ -\frac{1}{4}\left[\log \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}}\right]^2; & \tau > 1 \end{cases}$$



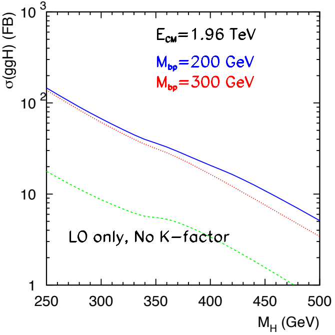
Decay BR
bb
WW
γγ
M_σ=125 GeV
θ



σ_gg * BR_γγ (fb)
M_σ=125 GeV
θ

A Fourth-Generation Example

- Enhancement of production by a factor of 9.



- Again, cancelation in $h \to \gamma\gamma$
- 4th generation neutrinos may significantly change the decay.

Not excluded yet!

谢谢!