Phenomenology 2: Higgs Searches

Tilman Plehn

MPI für Physik & University of Edinburgh

RAL School, Oxford, 9/2007

Outline

Standard–Model Higgs sector: 1

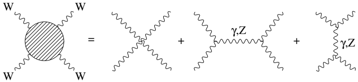
Theory of W, Z bosons

– start with $SU(2)$ gauge theory [like QED with massless W, Z]

– include measured masses $\mathcal{L} \sim -m_{W,Z} A_\mu A^\mu$

$\Rightarrow$ not gauge invariant, not renormalizable, so not pretty, but try...

Unitarity and Higgs scalar



– test theory in $WW \to WW$ scattering
$\to \mathcal{A} \propto G_F E^2$ like Fermi's theory, not unitary above 1.2 TeV [barely LHC energy]
$\to$ postulate additional scalar Higgs boson to conserve unitarity
$\to$ fixed coupling $g_{WWH} \propto m_W$

– add fermions and test $WW \to f\bar{f}$
$\to$ fixed coupling $g_{ffH} \propto m_f/m_W$

– test new theory in $WW \to WWH$
$\to$ fixed coupling $g_{HHH} \propto m_H^2/m_W$

– final test: $WW \to HHH$
$\to$ fixed coupling $g_{HHHH} \propto m_H^2/m_W^2$

$\Rightarrow$ Higgs couplings non-negotiable

Standard–Model Higgs sector: 2

Higgs potential

- remember Lagrangian invariant under $SU(2) \times U(1)$
- break symmetry through vacuum: SU(2) doublet with vev
- minimize Higgs potential $\Phi = (0, (v+H)/2)$ [$v = 246$ GeV known from W, Z masses]

⇒ first attempt: renormalizable Higgs potential [does all we want]

$$\mathcal{L}_\text{Higgs} = |D_\mu \Phi|^2 - V$$
$$V = \lambda \left(|\Phi|^2 - \frac{v^2}{2} \right)^2 = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4 + \text{const}$$

- not the whole story with new scale Λ [Standard Model as effective theory]

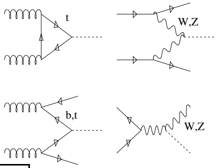
$$V = \sum_{n=0} \frac{\lambda_n}{\Lambda^{2n}} \left(|\Phi|^2 - \frac{v^2}{2} \right)^{2+n}$$

⇒ gauge–invariant dimension-6 Higgs operators $\mathcal{L}'_\text{Higgs} = \sum f_i/\Lambda^2 \, \mathcal{O}_i$

$$\mathcal{O}_\text{kin} = \frac{1}{2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi)$$
$$\mathcal{O}_\text{pot} = -\frac{1}{3} (\Phi^\dagger \Phi)^3$$

⇒ Higgs self couplings reflecting Higgs potential

Higgs production and decay: 1

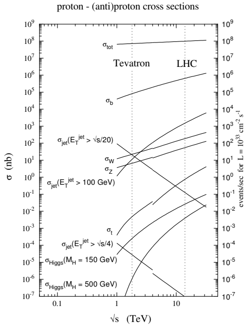


Design Higgs searches for LHC

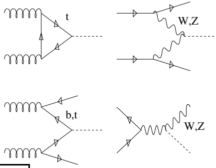
- (a) unitarity limit: $m_H < 1$ TeV
  (b) electroweak precision tests: $m_H \lesssim 250$ GeV
- production and decay of light Higgs

$gg \to H$ $qq \to qqH$ $gg \to t\bar{t}H$ $q\bar{q}' \to WH$	$\leftrightarrow$	signal $\times$ trigger backgrounds systematics $S/\sqrt{B}$ vs. S/B mass resolution...	$\leftrightarrow$	$H \to b\bar{b}$ $H \to WW$ $H \to \tau^+_{\ell h}\tau^-_{\ell}$ $H \to \gamma\gamma$ $H \to \mu\mu$...

Backgrounds



Higgs production and decay: 1



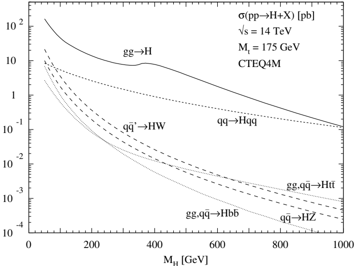
Design Higgs searches for LHC

– (a) unitarity limit: $m_H < 1$ TeV
(b) electroweak precision tests: $m_H \lesssim 250$ GeV

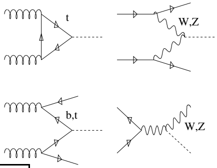
– production and decay of light Higgs

$gg \to H$ $qq \to qqH$ $gg \to t\bar{t}H$ $q\bar{q}' \to WH$	$\leftrightarrow$	signal $\times$ trigger backgrounds systematics $S/\sqrt{B}$ vs. S/B mass resolution...	$\leftrightarrow$	$H \to b\bar{b}$ $H \to WW$ $H \to \tau^+_{\ell h}\tau^-_\ell$ $H \to \gamma\gamma$ $H \to \mu\mu$...

Production rates [[luminosity 30-300 fb^{-1}]]



Higgs production and decay: 1



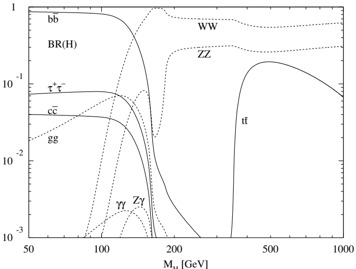
Design Higgs searches for LHC

– (a) unitarity limit: $m_H < 1$ TeV
  (b) electroweak precision tests: $m_H \lesssim 250$ GeV

– production and decay of light Higgs

$gg \to H$ $qq \to qqH$ $gg \to t\bar{t}H$ $q\bar{q}' \to WH$	$\leftrightarrow$	signal $\times$ trigger backgrounds systematics $S/\sqrt{B}$ vs. S/B mass resolution...	$\leftrightarrow$	$H \to b\bar{b}$ $H \to WW$ $H \to \tau^+_{\ell h}\tau^-_\ell$ $H \to \gamma\gamma$ $H \to \mu\mu$...

Branching fractions [up to 10^6 events]



Higgs production and decay: 2

Gluon fusion

– heavy quark loop: ggH coupling

– effective operator $\mathcal{L} \sim g_{ggH}\, H\, G^{\mu\nu}\, G_{\mu\nu}/\Lambda$

– without any approximation [just compute top loop]

$$\frac{g_{ggH}}{\Lambda} \sim \frac{y_t^2 \alpha_s}{4\pi M_H^3} \left[1 + (1-\tau) f(\tau)\right]$$

$$\text{with} \quad \tau = \frac{4 m_t^2}{M_H^2} \quad \text{and} \quad f(\tau) = \begin{cases} \left[\sin^{-1}\sqrt{1/\tau}\right]^2 & \tau > 1 \\ -\frac{1}{4}\left[\log\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \end{cases}$$

$\Rightarrow$ all we need to compute $gg \to H$ at Tevaton/LHC

Effective couplings

– compute heavy–top limit: $g_{ggH}/\Lambda \sim y_t^2 \alpha_s / m_t^3 = \alpha_s / m_t$

– attach more gluons: $gggH, ggggH$ [QCD gauge invariance]

– attach more Higgs bosons [low–energy theorems]

link leading g_{ggH^n} to gluon self energy: $F\, T_{\mu\nu}$

$$F_{(n+1)H} = m_t^2 \partial (F_{nH}/m_t)/\partial m_t \qquad \text{or} \qquad F_{ggH} = -F_{ggHH} = F_{ggHHH} = \frac{2}{3} + \mathcal{O}(m_H^2/m_t^2)$$

Higgs production and decay: 3

Some numbers behind it

– gluon-fusion production and $H \to ZZ \to 4\mu$ no-brainer

[‘golden channel’ above 140 GeV, mass resolution excellent]

– $H \to WW$ only slightly harder, but no mass peak

[above 150 GeV, angular correlation, off-shell still not clear]

– 6 million light Higgses in gluon fusion: $gg \to H \to \gamma\gamma$

[mass resolution $\Delta m_H / m_H \sim \Gamma / \sqrt{S} < 0.5\%$]

– backgrounds smaller in WW fusion: $qq \to qqH \to qqWW$

[works off-shell down to $m_H < 120$ GeV]

– light Higgs: $qq \to qqH \to qq\tau\tau$ [my favorite; will discuss later]

– more challenging channels:

$gg \to t\bar{t}H \to t\bar{t}b\bar{b}$ [also later]
$gg \to t\bar{t}H \to t\bar{t}WW$ [likely to work]
$gg \to t\bar{t}H \to t\bar{t}\tau\tau$ [yet unclear]
$q\bar{q}' \to WH \to Wb\bar{b}$ [killer QCD backgrounds]
$qq \to qqH \to qqb\bar{b}$ [no ATLAS trigger]
$qq \to qqH \to qq\mu\mu$ [maybe later]

$\Rightarrow$ Very cool, just $H \to b\bar{b}$ a sad story...

Higgs production and decay: 3

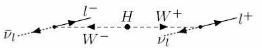
Some numbers behind it

– gluon-fusion production and $H \to ZZ \to 4\mu$ no-brainer

['golden channel' above 140 GeV, mass resolution excellent]

– $H \to WW$ only slightly harder, but no mass peak

[above 150 GeV, angular correlation, off-shell still not clear]



– 6 million light Higgses in gluon fusion: $gg \to H \to \gamma\gamma$

[mass resolution $\Delta m_H / m_H \sim \Gamma/\sqrt{S} < 0.5\%$]

– backgrounds smaller in WW fusion: $qq \to qqH \to qqWW$

[works off-shell down to $m_H < 120$ GeV]

– light Higgs: $qq \to qqH \to qq\tau\tau$ [my favorite; will discuss later]

– more challenging channels:

$gg \to t\bar{t}H \to t\bar{t}b\bar{b}$ [also later]
$gg \to t\bar{t}H \to t\bar{t}WW$ [likely to work]
$gg \to t\bar{t}H \to t\bar{t}\tau\tau$ [yet unclear]
$q\bar{q}' \to WH \to Wb\bar{b}$ [killer QCD backgrounds]
$qq \to qqH \to qqb\bar{b}$ [no ATLAS trigger]
$qq \to qqH \to qq\mu\mu$ [maybe later]

$\Rightarrow$ Very cool, just $H \to b\bar{b}$ a sad story...

Higgs production and decay: 3

Some numbers behind it

– gluon-fusion production and $H \to ZZ \to 4\mu$ no-brainer

['golden channel' above 140 GeV, mass resolution excellent]

– $H \to WW$ only slightly harder, but no mass peak

[above 150 GeV, angular correlation, off-shell still not clear]

– 6 million light Higgses in gluon fusion: $gg \to H \to \gamma\gamma$

[mass resolution $\Delta m_H/m_H \sim \Gamma/\sqrt{S} < 0.5\%$]

– backgrounds smaller in WW fusion: $qq \to qqH \to qqWW$

[works off-shell down to $m_H < 120$ GeV]

– light Higgs: $qq \to qqH \to qq\tau\tau$ [my favorite; will discuss later]

– more challenging channels:

$gg \to t\bar{t}H \to t\bar{t}b\bar{b}$ [also later]

$gg \to t\bar{t}H \to t\bar{t}WW$ [likely to work]

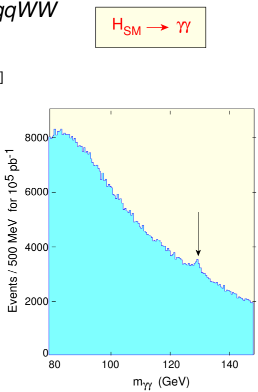
$gg \to t\bar{t}H \to t\bar{t}\tau\tau$ [yet unclear]

$q\bar{q}' \to WH \to Wb\bar{b}$ [killer QCD backgrounds]

$qq \to qqH \to qqb\bar{b}$ [no ATLAS trigger]

$qq \to qqH \to qq\mu\mu$ [maybe later]

$\Rightarrow$ Very cool, just $H \to b\bar{b}$ a sad story...



Higgs production and decay: 3

Some numbers behind it

– gluon-fusion production and $H \to ZZ \to 4\mu$ no-brainer

['golden channel' above 140 GeV, mass resolution excellent]

– $H \to WW$ only slightly harder, but no mass peak

[above 150 GeV, angular correlation, off-shell still not clear]

– 6 million light Higgses in gluon fusion: $gg \to H \to \gamma\gamma$

[mass resolution $\Delta m_H / m_H \sim \Gamma / \sqrt{S} < 0.5\%$]

– backgrounds smaller in WW fusion: $qq \to qqH \to qqWW$

[works off-shell down to $m_H < 120$ GeV]

– light Higgs: $qq \to qqH \to qq\tau\tau$ [my favorite; will discuss later]

– more challenging channels:

$gg \to t\bar{t}H \to t\bar{t}b\bar{b}$ [also later]

$gg \to t\bar{t}H \to t\bar{t}WW$ [likely to work]

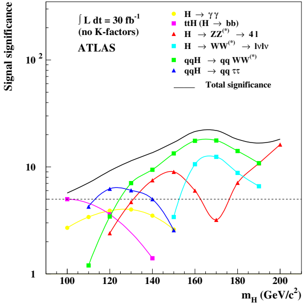
$gg \to t\bar{t}H \to t\bar{t}\tau\tau$ [yet unclear]

$q\bar{q}' \to WH \to Wb\bar{b}$ [killer QCD backgrounds]

$qq \to qqH \to qqb\bar{b}$ [no ATLAS trigger]

$qq \to qqH \to qq\mu\mu$ [maybe later]

$\Rightarrow$ Very cool, just $H \to b\bar{b}$ a sad story...



Weak boson fusion: 1

two hard, isolated leptons
missing transverse momentum
two forward tagging jets
90 GeV$<\ m_{\tau\tau}^{\text{coll}}\ <$160 GeV

Signal: $pp \to qqH,\ H \to \tau\tau \to e^{\pm}\mu^{\mp}4\nu$

– $\tau \to \ell\bar{\nu}_\ell\nu_\tau$ not reconstructable

– τ from Higgs decay strongly boosted

[lepton ($\vec{k}$) and τ ($\vec{p}$) approximately collinear: momentum fraction x]

$\Rightarrow$ solve eqs: $\vec{k}_{T,1}/x_1 + \vec{k}_{T,2}/x_2 = \vec{p}_{T,1} + \vec{p}_{T,2} = \vec{k}_{T,1} + \vec{k}_{T,2} + \vec{p}_T^{\,\text{miss}}$

$\Rightarrow$ solve for x_1, x_2 and obtain $m_{\tau\tau}^{\text{coll}} \sim 2(k_1 \cdot k_2)/(x_1 x_2)$

$\Rightarrow$ mass measurement $\Delta m_H/m_H \sim 15\text{ GeV}/\sqrt{S} \sim 5\text{ GeV}$

Weak boson fusion: 1

two hard, isolated leptons
missing transverse momentum
two forward tagging jets
90 GeV$<$ $m_{\tau\tau}^{\rm coll}$ $<$160 GeV

Signal: $pp \to qqH, \; H \to \tau\tau \to e^\pm \mu^\mp 4\nu$

– $\tau \to \ell \bar{\nu}_\ell \nu_\tau$ not reconstructable

– τ from Higgs decay strongly boosted

[lepton ($\vec{k}$) and τ ($\vec{p}$) approximately collinear: momentum fraction x]

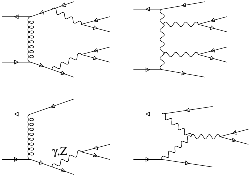
$\Rightarrow$ solve eqs: $\vec{k}_{T,1}/x_1 + \vec{k}_{T,2}/x_2 = \vec{p}_{T,1} + \vec{p}_{T,2} = \vec{k}_{T,1} + \vec{k}_{T,2} + \vec{p}_T^{\rm miss}$

$\Rightarrow$ solve for x_1, x_2 and obtain $m_{\tau\tau}^{\rm coll} \sim 2(k_1 \cdot k_2)/(x_1 x_2)$

$\Rightarrow$ mass measurement $\Delta m_H/m_H \sim 15 \text{ GeV}/\sqrt{S} \sim 5$ GeV

After acceptance cuts

2.2 fb	signal $pp \to H_{\rm SM} + jj$ [m_H = 120 GeV]
1230 fb	$pp \to t\bar{t} + jets$ [tagging jet either $t \to bW$ or additional jet]
1050 fb	$pp \to b\bar{b} + jj$ [with $b \to \ell\nu c$]
4.9 fb	$pp \to W^+W^- + jj$ (QCD) [with $W \to \ell\nu$]
3.3 fb	$pp \to W^+W^- + jj$ (EW)
57 fb	$pp \to \tau\tau + jj$ (QCD)
2.3 fb	$pp \to \tau\tau + jj$ (EW)
	$pp \to H_{\rm SM} + jj \to W^+W^- + jj$



Weak boson fusion: 1

two hard, isolated leptons
missing transverse momentum
two forward tagging jets
90 GeV< $m_{\tau\tau}^{\rm coll}$ <160 GeV

Signal: $pp \to qqH,\ H \to \tau\tau \to e^\pm\mu^\mp 4\nu$

– $\tau \to \ell\bar{\nu}_\ell\nu_\tau$ not reconstructable

– τ from Higgs decay strongly boosted

[lepton ($\vec{k}$) and τ ($\vec{p}$) approximately collinear: momentum fraction x]

$\Rightarrow$ solve eqs: $\vec{k}_{T,1}/x_1 + \vec{k}_{T,2}/x_2 = \vec{p}_{T,1} + \vec{p}_{T,2} = \vec{k}_{T,1} + \vec{k}_{T,2} + \vec{p}_T^{\rm miss}$

$\Rightarrow$ solve for x_1, x_2 and obtain $m_{\tau\tau}^{\rm coll} \sim 2(k_1 \cdot k_2)/(x_1 x_2)$

$\Rightarrow$ mass measurement $\Delta m_H/m_H \sim 15$ GeV$/\sqrt{S} \sim 5$ GeV

Background suppression cuts

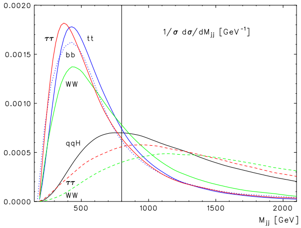
– veto central $p_{T_b} > 20$ GeV [$t\bar{t}$+jets down to 72 fb]

– $p_T^{\rm miss} > 30$ GeV [soft $b\bar{b}jj$ gone]

– $m_{jj} > 800$ GeV [anti-QCD: gluons with low m_{jj}]

– non-τ rejection [anti-W]

$\Rightarrow$ S/B up to 1/1 for $m_H = 120 \pm 10$ GeV



Weak boson fusion: 1

two hard, isolated leptons
missing transverse momentum
two forward tagging jets
90 GeV< $m_{\tau\tau}^{\text{coll}}$ <160 GeV

Signal: $pp \to qqH, \; H \to \tau\tau \to e^{\pm}\mu^{\mp}4\nu$

- $\tau \to \ell\bar{\nu}_\ell\nu_\tau$ not reconstructable
- τ from Higgs decay strongly boosted

  [lepton ($\vec{k}$) and τ ($\vec{p}$) approximately collinear: momentum fraction x]

$\Rightarrow$ solve eqs: $\vec{k}_{T,1}/x_1 + \vec{k}_{T,2}/x_2 = \vec{p}_{T,1} + \vec{p}_{T,2} = \vec{k}_{T,1} + \vec{k}_{T,2} + \vec{p}_T^{\text{miss}}$

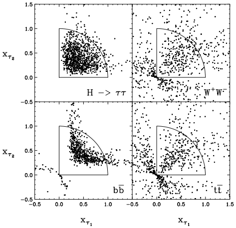
$\Rightarrow$ solve for x_1, x_2 and obtain $m_{\tau\tau}^{\text{coll}} \sim 2(k_1 \cdot k_2)/(x_1 x_2)$

$\Rightarrow$ mass measurement $\Delta m_H/m_H \sim 15\text{ GeV}/\sqrt{S} \sim 5$ GeV

Background suppression cuts

- veto central $p_{T_b} > 20$ GeV [$t\bar{t}$+jets down to 72 fb]
- $p_T^{\text{miss}} > 30$ GeV [soft $b\bar{b}jj$ gone]
- $m_{jj} > 800$ GeV [anti-QCD: gluons with low m_{jj}]
- non-τ rejection [anti-W]

$\Rightarrow$ S/B up to 1/1 for $m_H = 120 \pm 10$ GeV



Weak boson fusion: 2

Anti-QCD: central mini-jet veto

– additional jet emission cross section large (e.g. $t\bar{t}, t\bar{t}j, t\bar{t}jj$)

$$\sigma_2 \lesssim \sigma_3 \equiv \int_{p_T^{\text{min}}}^{\infty} d\sigma_3 \qquad \text{for} \quad p_T^{\text{min}} \sim 10\,\text{GeV (WBF)}, \quad p_T^{\text{min}} \sim 40\,\text{GeV (QCD)}$$

– veto $p_{T_j} > 20$ GeV and $\eta_j^{\text{min}} < \eta_j < \eta_j^{\text{max}}$ to suppress QCD

– probability like Sudakov: additional jet with p_{jet} [initial state radiation, $p_T^{\text{min}} = 20$ GeV]

$$p_{\text{jet}} = \frac{\sigma_3^{\text{reg}}}{\sigma_2^{\text{reg}}} = \frac{\sigma_{n+1}^{\text{reg}}}{\sigma_n^{\text{reg}}} \qquad f(n; p_{\text{jet}}) = \frac{p_{\text{jet}}^n\, e^{-p_{\text{jet}}}}{n!} \qquad f(n \neq 0; p_{\text{jet}}) = 1 - e^{-p_{\text{jet}}}$$

veto probabilities 0.88 (signal) and 0.85...0.24 (backgrounds)

⇒ S/B=2.8/1 for $m_H = 120 \pm 10$ GeV

Both $\tau\tau$ channels with safe margins [Standard Model with 60fb^{-1}]

M_H[GeV]	100	110	120	130	140	150
$\epsilon \cdot \sigma_{sig}$ (fb)	0.62	0.58	0.50	0.37	0.23	0.11
S	37.4	35.0	30.0	22.3	13.7	6.5
B	67.5	27.0	10.8	6.7	5.7	5.3
S/B	0.6	1.3	2.8	3.3	2.4	1.2
σ_{Gauss} (dual leptonic)	4.2	5.7	6.9	6.2	4.4	2.3
σ_{Gauss} (lepton-hadron)		5.7	7.4	6.3	4.7	2.6

Weak boson fusion: 2

Anti-QCD: central mini-jet veto

– additional jet emission cross section large (e.g. $t\bar{t}, t\bar{t}j, t\bar{t}jj$)

$$\sigma_2 \lesssim \sigma_3 \equiv \int_{p_T^{\rm min}}^{\infty} d\sigma_3 \qquad \text{for} \quad p_T^{\rm min} \sim 10\,\text{GeV (WBF)} \quad p_T^{\rm min} \sim 40\,\text{GeV (QCD)}$$

– veto $p_{T_j} > 20$ GeV and $\eta_j^{\rm min} < \eta_j < \eta_j^{\rm max}$ to suppress QCD

– probability like Sudakov: additional jet with $p_{\rm jet}$ [initial state radiation, $p_T^{\rm min} = 20$ GeV]

$$p_{\rm jet} = \frac{\sigma_3^{\rm reg}}{\sigma_2^{\rm reg}} = \frac{\sigma_{n+1}^{\rm reg}}{\sigma_n^{\rm reg}} \qquad f(n;p_{\rm jet}) = \frac{p_{\rm jet}^n\, e^{-p_{\rm jet}}}{n!} \qquad f(n \neq 0; p_{\rm jet}) = 1 - e^{-p_{\rm jet}}$$

veto probabilities 0.88 (signal) and 0.85...0.24 (backgrounds)

⇒ S/B=2.8/1 for $m_H = 120 \pm 10$ GeV

General features of WBF production

– cross section $10 \cdots 3$ pb for $m_H < 200$ GeV

⇒ $(H \to \gamma\gamma)$@50 fb^{-1} for $m_H = 110 \cdots 145$ GeV [$\gamma\gamma$ mass resolution]

$(H \to \tau\tau)$@60 fb^{-1} for $m_H = 100 \cdots 140$ GeV [lepton-hadron and dual lepton]

$(H \to WW)$@5 fb^{-1} for $m_H = 140 \cdots 200$ GeV

even invisible higgs decay observable!

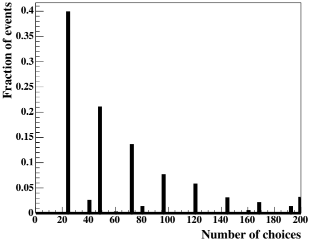
Top–Higgs production

Decay $H \to b\bar{b}$ for a light Higgs?

– what about the 90% of Higgses decaying to $b\bar{b}$?
– gluon-fusion: killed by QCD background
– WBF fusion: no trigger, killed by QCD backgrounds
– WH production: killed by low rate and NLO background
– $\sigma(t\bar{t}H) \sim 100$ fb

$t\bar{t}H$, $H \to b\bar{b}$ for a light Higgs [Atlas study, CMS-TDR even worse]

– trigger: one $t \to bW^+ \to b\ell^+\nu$
– reconstruction and rate: one $t \to bW^+ \to bjj$
– continuum background $t\bar{t}b\bar{b}$, $t\bar{t}jj$ [weighted by b-tag]
– reconstruct m_H in $pp \to 4b_{tag}\ 2j\ \ell\nu$
⇒ higher lumi means poorer b-tag, no-win
⇒ likely to be ‘challenging’



Top–Higgs production

Decay $H \to b\bar{b}$ for a light Higgs?

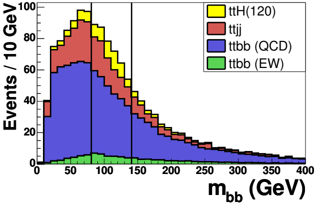
- what about the 90% of Higgses decaying to $b\bar{b}$?
- gluon-fusion: killed by QCD background
- WBF fusion: no trigger, killed by QCD backgrounds
- WH production: killed by low rate and NLO background
- $\sigma(t\bar{t}H) \sim 100$ fb

$t\bar{t}H$, $H \to b\bar{b}$ for a light Higgs [Atlas study, CMS-TDR even worse]

- trigger: one $t \to bW^+ \to b\ell^+\nu$
- reconstruction and rate: one $t \to bW^+ \to bjj$
- continuum background $t\bar{t}b\bar{b}$, $t\bar{t}jj$ [weighted by b-tag]
- reconstruct m_H in $pp \to 4b_{tag}\ 2j\ \ell\nu$

⇒ higher lumi means poorer b-tag, no-win

⇒ likely to be ‘challenging’



Top–Higgs production

Decay $H \to b\bar{b}$ for a light Higgs?

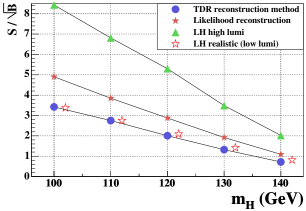
- what about the 90% of Higgses decaying to $b\bar{b}$?
- gluon-fusion: killed by QCD background
- WBF fusion: no trigger, killed by QCD backgrounds
- WH production: killed by low rate and NLO background
- $\sigma(t\bar{t}H) \sim 100$ fb

$t\bar{t}H$, $H \to b\bar{b}$ for a light Higgs [Atlas study, CMS-TDR even worse]

- trigger: one $t \to bW^+ \to b\ell^+\nu$
- reconstruction and rate: one $t \to bW^+ \to bjj$
- continuum background $t\bar{t}b\bar{b}$, $t\bar{t}jj$ [weighted by b-tag]
- reconstruct m_H in $pp \to 4b_{tag}\ 2j\ \ell\nu$

⇒ higher lumi means poorer b-tag, no-win

⇒ likely to be ‘challenging’



Higgs couplings

Coupling extraction at the LHC

– motivation: e.g. little Higgs axions vs. radion vs. Higgs?

– measurements: $gg : H \to ZZ, WW, \gamma\gamma$
$VV : H \to ZZ, WW, \gamma\gamma, \tau\tau$
$t\bar{t}H : H \to WW, b\bar{b}$...

$\to$ light Higgs: 8 good $\sigma \cdot BR$ plus $H \to b\bar{b}$

– extract: couplings to $W, Z, t, b, \tau, g, \gamma$, invisible

$\to$ most complete: 8 parameters [plus Higgs mass]

– trick: cancel uncertainties

$(WBF : H \to WW)/(WBF : H \to \tau\tau)$
$(WBF : H \to WW)/(gg : H \to WW)$...

– goals: Higgs vs. scalars? SM vs MSSM? doublet vs. general Higgs?

$\Rightarrow$ unwanted assumption: $g_{WWH} \leftrightarrow g_{ZZH}$ via SU(2)
unwanted assumption: $g_{bbH} \leftrightarrow g_{\tau\tau H}$ via down-type Yukawa

Higgs couplings

Coupling extraction at the LHC

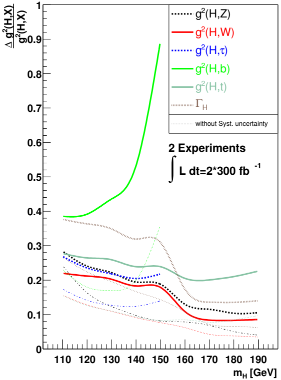
– motivation: e.g. little Higgs axions vs. radion vs. Higgs?

– measurements: $gg : H \to ZZ, WW, \gamma\gamma$
$VV : H \to ZZ, WW, \gamma\gamma, \tau\tau$
$t\bar{t}H : H \to WW, b\bar{b}...$

$\to$ light Higgs: 8 good $\sigma \cdot BR$ plus $H \to b\bar{b}$

– extract: couplings to $W, Z, t, b, \tau, g, \gamma$, invisible

$\to$ most complete: 8 parameters [plus Higgs mass]



Include total width

– on–shell degeneracy: $\sigma\, BR \propto (g_p^2/\sqrt{\Gamma_H})\ (g_d^2/\sqrt{\Gamma_H})$

[from (WBF : $WW/\tau\tau$) measure $g_{WWH}/g_{\tau\tau H}$]

– additional constraint: $\sum \Gamma_i(g^2) < \Gamma_H \Rightarrow \Gamma_H|_{min}$

– $WW \to WW$ unitarity: $g_{WWH} \lesssim g_{WWH}^{SM} \Rightarrow \Gamma_H|_{max}$

$\Rightarrow$ couplings and width extraction great but hard

Higgs potential and self coupling

Higgs self coupling

– scalar with Yukawa couplings to fermions, so what?

– renormalizable SM potential: $\mu^2 = -\lambda v^2$ with $\lambda = m_H^2/(2v^2)$
and self couplings $\lambda_{3H}/\lambda_{4H} = v$

– MSSM: $\lambda_{3h}/\lambda_{4h} = v \sin(\beta+\alpha)/\cos 2\alpha$

– D6 operator: $\mu^2/v^2 = -\lambda_0 + 3\lambda_1 v^2/(4\Lambda^2)$ and $\lambda = \lambda_0 - 3\lambda_1 v^2/(2\Lambda^2)$.

Higgs pair production

– $HH \to 4W$: serious detector simulation needed, not hopeless

[use observable m_{vis} to determine λ_{HHH}, need NLO $\sigma(t\bar{t}j)$]

– $HH \to b\bar{b}\tau\tau$: miracle required

– $HH \to 4b$: several major miracles mandatory

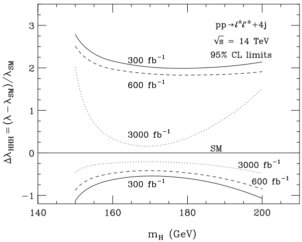
[ILC in better shape]

– $HH \to b\bar{b}\mu\mu$: small miracle would be helpful

[might come out of $\mu\mu$ mass resolution]

– $HH \to b\bar{b}\gamma\gamma$: some enhancement needed

$\Rightarrow$ serious challenge to detectors and machine

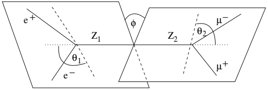


Spin and CP

Higgs Spin

– spin-1/2 not coupling to WW, gg; no production
– spin-1 not coupling to $\gamma\gamma$ on mass shell [Landau–Yang theorem for spin-1 bosons]
– threshold behavior in $H \to ZZ$ for $m_H \sim 155$ GeV
$\Rightarrow$ spin-0 fairly obvious

Scalar or pseudoscalar?



– pseudoscalar couplings $g_{HVV}/\Lambda \sim \epsilon^{\mu\nu\rho\sigma} p_\rho p'_\sigma \Lambda$
– decay–plane angle

$$\frac{d\sigma}{d\phi} \propto 1 + a\cos\phi + b\cos(2\phi) \qquad a_{-1} = 0 \quad b_{-1} = \frac{1}{4} \qquad a_{+1}(m_H) > \frac{1}{4}$$

$\Rightarrow$ easy with $H \to ZZ$

Spin and CP

Higgs Spin

- spin-1/2 not coupling to WW, gg; no production
- spin-1 not coupling to $\gamma\gamma$ on mass shell [Landau–Yang theorem for spin-1 bosons]
- threshold behavior in $H \to ZZ$ for $m_H \sim 155$ GeV

$\Rightarrow$ spin-0 fairly obvious

Scalar or pseudoscalar?

- pseudoscalar couplings $g_{HVV}/\Lambda \sim \epsilon^{\mu\nu\rho\sigma} p_\rho p'_\sigma \Lambda$
- decay–plane angle

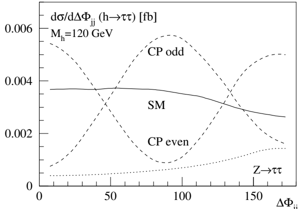
$$\frac{d\sigma}{d\phi} \propto 1 + a\cos\phi + b\cos(2\phi) \qquad a_{-1} = 0 \quad b_{-1} = \frac{1}{4} \qquad a_{+1}(m_H) > \frac{1}{4}$$

$\Rightarrow$ easy with $H \to ZZ$

Coupling structures

- same azimuthal angle between jets in WBF
- distinguish: $g_{\mu\nu}$, CP-even $T_{\mu\nu}$, CP-odd

$\Rightarrow$ independent of decay



Modern statistics

Statistics: Neyman–Pearson lemma

- assume correct hypothsis m_1: Higgs signal
  assume wrong hypothsis m_2: SM background
- likelihood ratio $p(d|m_1)/p(d|m_2)$ most powerful estimator

  [lowest probability to mistake right for fluctuation of wrong (type-II error)]
- probability of event $p(d|m) \sim |\mathcal{M}|^2$
- combined likelihood ratios of events $\rightarrow$ PS integral over likelihood ratio

$\Rightarrow$ Compute maximum statistical significance

Matrix element method

- compute likelihood of top events estimating $|\mathcal{M}|^2$
- maximize probability $p(d|\text{SM}, m_t)$ as function of m_t...

Modern statistics

Statistics: Neyman–Pearson lemma

– assume correct hypothsis m_1: Higgs signal
  assume wrong hypothsis m_2: SM background

– likelihood ratio $p(d|m_1)/p(d|m_2)$ most powerful estimator

  [lowest probability to mistake right for fluctuation of wrong (type-II error)]

– probability of event $p(d|m) \sim |\mathcal{M}|^2$

– combined likelihood ratios of events $\to$ PS integral over likelihood ratio

$\Rightarrow$ Compute maximum statistical significance

Maximum significance for LHC signals

– example: Poisson statistics $[p(n|s+b) = e^{-(s+b)} \, (s+b)^n / n!]$

$$q = \log \frac{p(n|s+b)}{p(n|b)} = -s + n \, \log \left(1 + \frac{s}{b} \right) \longrightarrow -\sum_j s_j + \sum_j n_j \, \log \left(1 + \frac{s_j}{b_j} \right)$$

– phase space integration of $s, b \to p(s,b) \sim |\mathcal{M}_{s,b}|^2$ [LEP–Higgs inspired]

$$q(\vec{r}) = -\sigma_s \mathcal{L} + \log \left(1 + \frac{|\mathcal{M}_s(\vec{r})|^2}{|\mathcal{M}_b(\vec{r})|^2} \right)$$

– probability distribution function via Fourier transform: $\rho_{s,b}(q)$

$\to$ compute $CL_b(q) = \int_q^\infty dq' \, \rho_b(q')$ [5σ is $CL_b = 2.85 \, 10^{-7}$]

Modern statistics

Statistics: Neyman–Pearson lemma

– assume correct hypothsis m_1: Higgs signal
  assume wrong hypothsis m_2: SM background

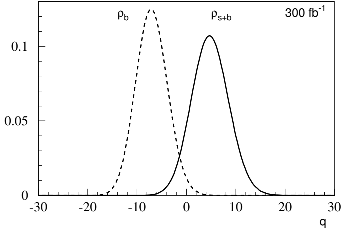
– likelihood ratio $p(d|m_1)/p(d|m_2)$ most powerful estimator

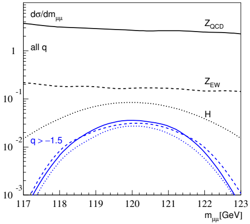
  [lowest probability to mistake right for fluctuation of wrong (type-II error)]

– probability of event $p(d|m) \sim |\mathcal{M}|^2$

– combined likelihood ratios of events → PS integral over likelihood ratio

⇒ Compute maximum statistical significance





Modern statistics

Statistics: Neyman–Pearson lemma

- assume correct hypothsis m_1: Higgs signal
  assume wrong hypothsis m_2: SM background
- likelihood ratio $p(d|m_1)/p(d|m_2)$ most powerful estimator

  [lowest probability to mistake right for fluctuation of wrong (type-II error)]
- probability of event $p(d|m) \sim |\mathcal{M}|^2$
- combined likelihood ratios of events $\rightarrow$ PS integral over likelihood ratio

$\Rightarrow$ Compute maximum statistical significance

Semi–realistic results

- irreducible & unsmeared

$$\sigma_{\rm tot} = \int dPS \, M_{PS} \, d\sigma_{PS} = \int d\vec{r} \, M(\vec{r}) \, d\sigma(\vec{r})$$

- smearing $\Delta m_{\mu\mu}^{\rm width} \ll \Delta m_{\mu\mu}^{\rm meas}$

$$\sigma_{\rm tot} = \int d\vec{r}_\perp dr_m^* \int_{-\infty}^{\infty} dr_m \, M(\vec{r}) \, d\sigma(\vec{r}) \, W(r_m, r_m^*)$$

- acceptance cuts to reduce phase space...

$\Rightarrow$ WBF $H \rightarrow \mu\mu$: 3.5σ in 300 fb^{-1}

$\Rightarrow$ Tool works, waiting for applications

Outlook

Standard-Model Higgs at the LHC

– we will find it in more than one channel for all m_H

– we will measure many properties more or less well:

set of couplings and width
self coupling (only λ_{HHH})
CP properties and *WWH* coupling structure
invisible decays
Higgs to muons (2nd generation Yukawa)
former stealth models...

– hardly anything still correct in Higgs chapter of Atlas TDR

$\Rightarrow$ for WBF we need to understand central jet veto [or give up and measure it]

$\Rightarrow$ for some measurements we need NLO backgrounds

$\Rightarrow$ it is a disgrace that we will miss $H \to b\bar{b}$

$\Rightarrow$ higher-dimensional operators mandatory [little done yet]