Phenomenology at collider experiments [Part 3: The Higgs boson]

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Outline

Reminder: The Higgs mechanism

Masses and gauge invariance

- SM contains gauge and matter fields: spin-1 bosons and spin-$\frac{1}{2}$ fermions
- Massless fields guarantee good features:
  - Gauge invariance under $SU(2)_L \otimes U(1)_Y$
  - Renormalizability of theory
- Could introduce mass terms "by hand":

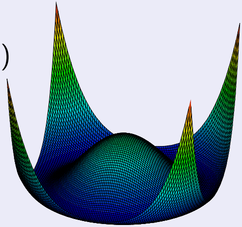
$$\mathcal{L}_m \propto m_A^2 A^\mu A_\mu + m_f(\bar{\Psi}_R \Psi_L + \bar{\Psi}_L \Psi_R)$$

- Violates gauge invariance, since
  - $A^\mu \longrightarrow A^\mu + \frac{1}{g}\partial^\mu\theta$, therefore $A^\mu A_\mu$ yields terms $\propto \theta$ after gauge trafo.
  - Ψ_L and Ψ_R transform differently under $SU(2)_L$ (Ψ_R is singlet = neutral), therefore terms $\propto \theta$ do not cancel.
- This is bad: We love the local gauge principle!

Reminder: The Higgs mechanism

Generating mass from the vacuum expectation value

- Add complex doublet under $SU(2)_L$ (4 d.o.f.), couple it gauge-invariantly with the vectors: $\mathcal{L}_{\Phi A} = (D^\mu\Phi)(D_\mu\Phi)$
- Add interaction term with fermions: $\mathcal{L}_{\Phi\Psi} = g_f\bar{\Psi}_L\Phi\Psi_R + \mathrm{h.c.}$ (need Φ for down-type fermions and $i\sigma_2\Phi^*$ for up-types)
- Add potential with non-trivial structure (infinite number of equivalent minima needed)
- Pick one minimum and expand around it:
  - One radial and three circular modes
  - Circular modes "gauged away" $\longrightarrow$ "eaten" by bosons
  - vev (energy of minimum) $\longrightarrow$ masses



Reminder: The Higgs mechanism

Fixing the parameters

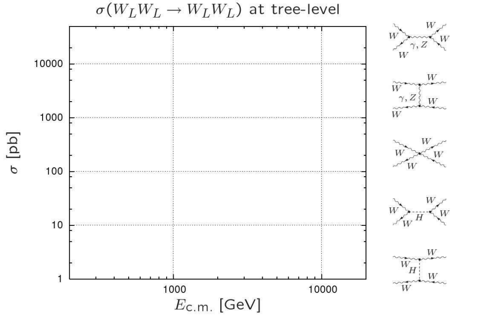
- From the structure above:

$$\begin{array}{lclcl} (D_\mu\Phi)^2 & \longrightarrow & \frac{g^2v^2}{4} W_\mu W^\mu & \longrightarrow & M_W^2 = \frac{g^2v^2}{4} \\ g_f\bar{\Psi}_L\Phi\Psi_R & \longrightarrow & g_f\frac{v}{\sqrt{2}}\bar{\Psi}_L\Phi\Psi_R & \longrightarrow & m_f = \frac{g_f v}{\sqrt{2}} \\ \lambda(|\Phi|^2 - v^2/2)^2 & \longrightarrow & \lambda v^2 H^2 & \longrightarrow & M_H^2 = 2\lambda v^2 \end{array}$$

- Fixed relation between mass and coupling to (surviving) Higgs scalar.
- Therefore, to verify EWSB:
  - find H
  - check it's a scalar
  - verify coupling $\propto$ mass
  - measure potential through self-interactions

Reminder: The Higgs mechanism

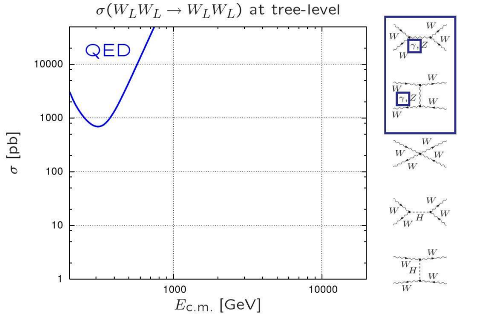
Restoring unitarity of $WW \to WW$-scattering



(from O.Brein)

Reminder: The Higgs mechanism

Restoring unitarity of $WW \to WW$-scattering



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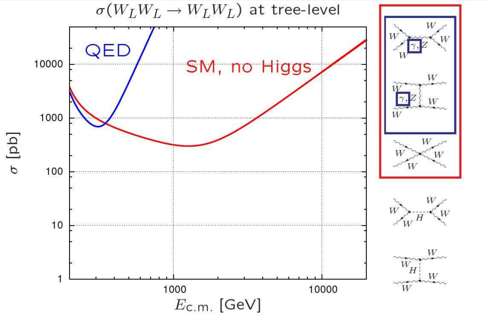

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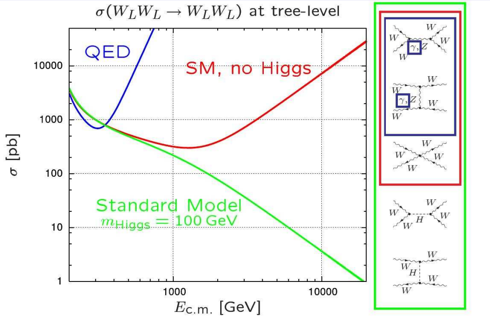
Reminder: The Higgs mechanism

Restoring unitarity of $WW \to WW$-scattering

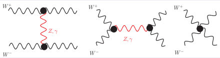


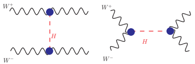
(from O.Brein)

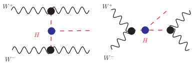
Reminder: The Higgs mechanism

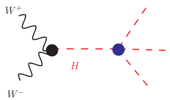
(Fixing the parameters)'

- Consider $W^+W^- \to W^+W^-$
- Without H: violates unitarity at ≈ 1 TeV.
- Therefore: Must add H with $g_{WWH} \propto m_W$.
- Repeat for $WW \to ZZ \longrightarrow g_{ZZH} \propto m_Z$.
- Repeat for $WW \to f\bar{f} \longrightarrow g_{f\bar{f}H} \propto m_f$.
- Test in $WW \to WWH \longrightarrow g_{HHH} \propto m_H^2/m_W$.
- Test in $WW \to HHH \longrightarrow g_{HHHH} \propto m_H^2/m_W^2$.
- Once it is there, the functional dependence of the Higgs boson couplings is fixed by the unitarity requirement of the theory.





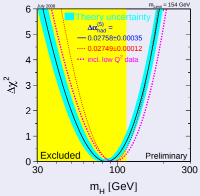


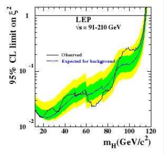


Tayloring search channels

Limits on m_H

- Unitarity: < 1 TeV.
- EW precision tests: < 250 GeV.
- LEP searches: > 114 GeV.





(from LEPEWWG)

Basic considerations

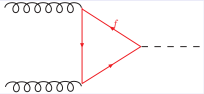
- Signal rates defined by triggers: you won't measure what you don't see.
- Significance: $S/\sqrt{B}$ vs. S/B.
- Important: Control systematics. Avoid embarassment.
- Mass resolution for m_H and decay products: may help to suppress backgrounds
- Any topological help?

Tayloring search channels

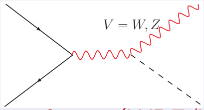
Higgs production processes at hadron colliders

Common feature: Couple to heavy objects (top, W, Z)

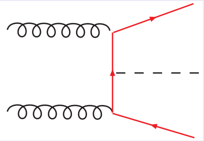
Gluon fusion:



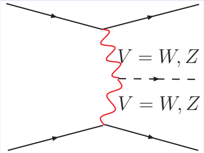
Higgs-Strahlung:



Quark-associated:

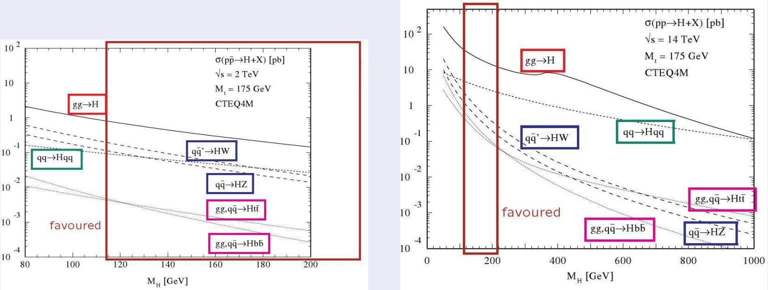


Weak boson fusion (WBF/VBF):



Tayloring search channels

Higgs production cross sections at hadron colliders



(from M.Spira, hep-ph/9810289)

Tayloring search channels

Higgs decays

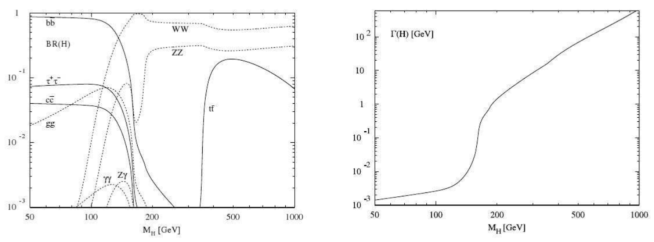
- Individual decay channels:

decay mode	width Γ
$H \to f\bar{f}$	$\frac{G_F M_H}{8\pi\sqrt{2}} \cdot 2m_f^2 N_c \left(1 - \frac{4m_f^2}{m_H^2}\right)^{\frac{3}{2}}$
$H \to W^+W^-$	$\frac{G_F M_H}{8\pi\sqrt{2}} \cdot m_H^2 \left(1 - \frac{4m_W^2}{m_H^2} + \frac{12m_W^4}{m_H^4}\right)\left(1 - \frac{4m_W^2}{m_H^2}\right)^{\frac{1}{2}}$
$H \to ZZ$	$\frac{G_F M_H}{8\pi\sqrt{2}} \cdot m_H^2 \frac{m_W^2}{2m_Z^2} \left(1 - \frac{4m_Z^2}{m_H^2} + \frac{12m_Z^4}{m_H^4}\right)\left(1 - \frac{4m_Z^2}{m_H^2}\right)^{\frac{1}{2}}$
$H \to \gamma\gamma$	$\frac{G_F M_H}{8\pi\sqrt{2}} \cdot m_H^2 \left(\frac{\alpha}{4\pi}\right)^2 \cdot \left(\frac{4}{3} N_c Q_t^2\right)^2$ $(2m_t > m_H)$
$H \to gg$	$\frac{G_F M_H}{8\pi\sqrt{2}} \cdot m_H^2 \left(\frac{\alpha_s}{4\pi}\right)^2 \cdot \left(\frac{2}{3}\right)^2$ $(2m_t > m_H)$
$H \to VV^*$	more complicated, but important for $m_H \lesssim 2m_V$

- $m_H < 2m_W$: Higgs boson quite narrow, $\Gamma_H = \mathcal{O}(\mathrm{MeV})$.
- $m_H > 2m_W$: H becomes obese, $\Gamma_H(m_H = 1\mathrm{TeV}) \approx 0.5$ TeV.
- At large m_H: decay into VV dominant, $\Gamma_{H\to WW} : \Gamma_{H\to ZZ} \approx 2:1$.

Tayloring search channels

Higgs decays



(from V.Buescher & K.Jakobs, Int. J. Mod. Phys. A **20** (2005) 2523)

Tayloring search channels

Some typical channels (mostly @ Tevatron)

- $gg \to H \to W^+W^- \to \ell\ell' + \not{E}_\perp$: "golden plated"
  No mass peak, but background partially killed with $\angle_{\ell\ell'}$ etc..
- $q\bar{q} \to ZH \to \ell\ell b\bar{b}$: only limits on σ
  Key ingredient: b-tagging efficiencies, mass resolution for jets to suppress QCD backgrounds.
- $q\bar{q}' \to WH \to \ell\nu b\bar{b}$: like above.
- $q\bar{q}' \to WH \to \not{E}_\perp + b\bar{b}$: only limits on σ
  combination of the two above, with $Z \to \nu\nu$
- $q\bar{q}' \to W^\pm H \to W^\pm W^+ W^-$: only limits on σ
  same sign leptons, other W goes hadronically (xsec!).

Tayloring search channels

Some typical channels (mostly @ LHC)

- $gg \to H \to ZZ \to 4\mu, 2e2\mu$: "Golden plated" for $m_H > 140$ GeV.
  Key ingredients: Mass peak from excellent mass resolution (leptons).
- $gg \to H \to W^+W^- \to \ell\ell' + \not{E}_\perp$: nearly as good as ZZ
  but no mass peak. Background killed with $\angle_{\ell\ell'}$ etc..
  Very similar to Tevatron analysis with huge stats.
- $gg \to H \to \gamma\gamma$: Good for small $m_H \lesssim 120$ GeV.
  Key ingredient: mass resolution for γ's & veto on π^0's.
- $WBF \to H \to \tau\tau$: Popular mode
  Key ingredient: QCD-backgrounds killed with rapidity gap
- $WBF \to H \to WW$: ditto.
- $WBF \to H \to b\bar{b}$: in principle ditto
  but: Hard to trigger, pure QCD-like objects (jets)

Tayloring search channels

Difficult channels (mostly @ LHC)

- top-associated production and $H \to b\bar{b}$: xsec okay, but difficult. Potential show-stopper: backgrounds from $t\bar{t}$+jets W+jets, etc., many jets to be reconstructed, combinatorics from $t\bar{t}$-reco ....
- top-associated production and $H \to \gamma\gamma$: xsec small, difficult.
- top-associated production and $H \to \tau\tau$: xsec okay, but difficult. Potential show-stopper: backgrounds from $t\bar{t}+Z$, W, Z+jets, etc., many jets to be reconstructed, combinatoric backgrounds from t-reco, find the τ's (only 1/3 into leptons) ....
- Higgs decays into μ: small BR, could be useful for SUSY.

Remarks on resonance production

Simple "rule of the thump" to calculate xsec

- Consider processes like $gg \to H \to ZZ$ etc.: resonant production.
- If width small: can cut internal resonant propagator.
- Two-body decay $R \to ab$: $\Gamma_{ab} = \frac{|\langle ab|R\rangle|^2}{16\pi m_R}$
- Resonance production in $cd \to R$: $\sigma_{cd} = \frac{2\pi|\langle R|cd\rangle|^2}{m_R^2} \frac{m_R\Gamma_R}{\pi[(s-m_R^2)^2+\Gamma_R^2 m_R^2]}$
- Use peak at $s = m_R^2$ (will yield a δ function)
- Therefore $\sigma_{ab\to R\to cd} = \frac{32\pi}{m_R^2}\mathrm{BR}(R \to ab)\mathrm{BR}(R \to cd)$
- If width not so small: include Breit-Wigner.
- At hadron colliders: Need to integrate over Bjorken-x.

Search channel: $gg \to H \to WW \to \ell\ell'\nu\nu$ @ Tevatron

Short intro

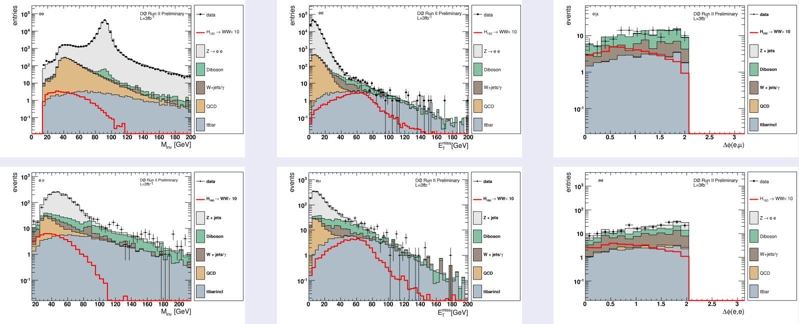
(from D0 Note-5757Conf)

- Consider ee, $e\mu$, and $\mu\mu$ final states, each with 2 neutrinos
- Use m_H in steps of 5 GeV, from 115 to 200 GeV.
- Backgrounds: direct WW, WZ, ZZ, $t\bar{t}$, DY, QCD, W+jets
- Main cuts (acceptance and background suppression):
  - lepton isolation etc., $|\eta_{e,\mu} < 3, 2$.
  - $p_\perp^{e,\mu} > 15, 10$ GeV, $\not{E}_\perp > 20$ GeV (anti-DY)
  - some protection against wrong E
  - $M_{\ell\ell} > 15$ GeV
  - $\Delta\phi_{\ell\ell'} < 2 \ldots 2.5$ (channel-dep.): most background like back-to-back, H likes small.
- Neural network, trained with $\mathcal{O}(15)$ observables (some shown below)
- Similar analysis for CDF, public page
- Up-to data analysis: 3 fb^{-1}.

Search channel: $gg \to H \to WW \to \ell\ell'\nu\nu$ @ Tevatron

Distributions for signals and backgrounds

(from D0 Note-5757Conf)

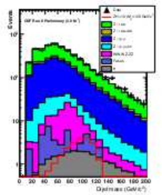
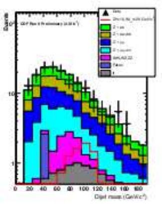
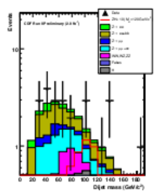


Search channel: $q\bar{q}' \to ZH \to \ell\bar{\ell}b\bar{b}$ @ Tevatron

Distributions for signals and backgrounds

(from CDF public homepage, also D0-Note 5570/Conf)

- Use $\ell = e$, μ, major backgrounds: Z+jets, ZZ, WZ, WW, $t\bar{t}$.
- Signal- or background-like? ME method (CDF, 2 fb^{-1}).
- Relevant observable: $m_{b\bar{b}}$, need b-tagging to kill jj-pairs and similar

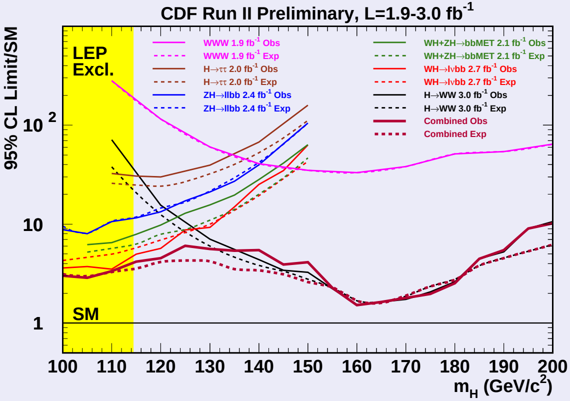




- Finally bound: $\sigma_{\rm signal} \leq 15 \cdot \sigma_{H({\rm SM})}$ at 95% C.L..
- Similar analysis with more data and NN (CDF& D0).

Combined searches @ Tevatron

Collected results from CDF

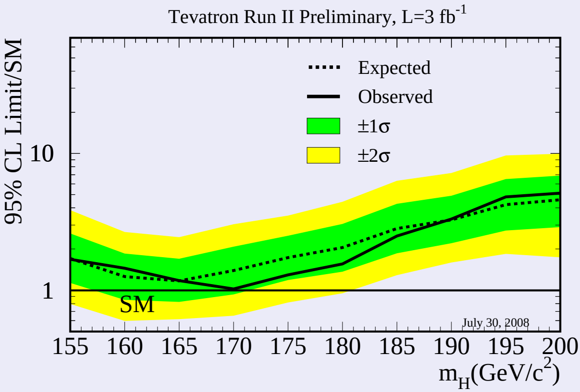
(from CDF Note-9282)



Combined searches @ Tevatron

Results from Tevatron, 2008

(from D0 Note-5754Conf/and CDF)



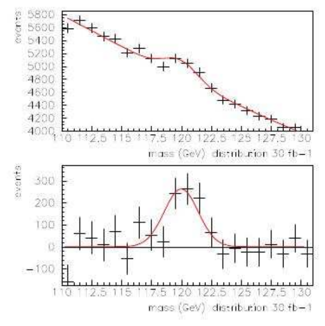
Prospects for Higgs boson searches @ LHC

(from ATLAS-Note Pub-2007-013)

Search channel: $gg \to H \to \gamma\gamma$

- Characteristic: Bump on a smooth background $\longrightarrow$ side-band subtraction
- Tricky issue: Mass resolution of $\gamma\gamma$

  (converted γ's, $j(\pi^0) \to \gamma$ conversions, γ direction)
- $\delta m_{\gamma\gamma} \approx 1.5$ GeV.
- $S/\sqrt{B}(30\text{fb}^{-1}) \approx 6$ for $m_H \in [120, 140]$ GeV

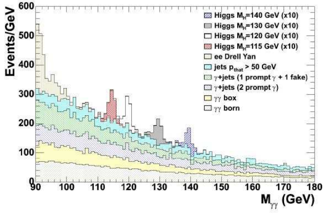


Prospects for Higgs boson searches @ LHC

(from CMS-Note Pub-2006-112)

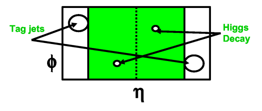
Search channel: $gg \longrightarrow H \longrightarrow \gamma\gamma$

- Characteristic: Bump on a smooth background $\longrightarrow$ side-band subtraction
- Main obstacles: converted γ's, $j(\pi^0) \to \gamma$ conversions, γ direction
- After hard work: $\delta m_{\gamma\gamma} \approx 1.5$ GeV.
- $S/\sqrt{B}(30\text{fb}^{-1}) \approx 6$ for $m_H \in [120,\, 140]$ GeV



Characteristics

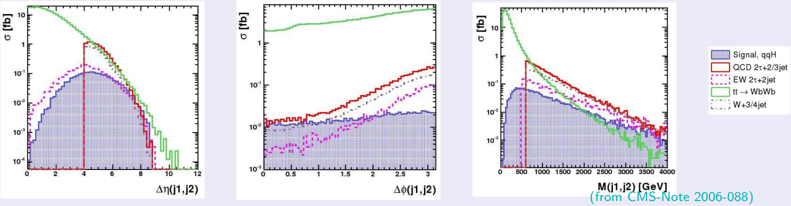
- At LO: No colour exchange between protons
  Tag-jets tend to be forward, at low $p_\perp \approx m_H/2$,
  colour connected with "adjacent" proton remnants
  $\longrightarrow$ hadronic activity mostly forward
  (between tag jet and proton rump)
  $\longrightarrow$ no hadronic activity at center
  $\longrightarrow$ rapidity gap for signal



- Rapidity gap filled by Higgs boson and its decay products
- Typical backgrounds: $W, Z+$jets, $t\bar{t}$, W, Z-pairs, QCD
  all of them typically have colour exchange between protons
  $\longrightarrow$ no rapidity gap for background

Weak boson fusion processes: Behaviour of the tag jets

Example: WBF, $H \to \tau\tau$

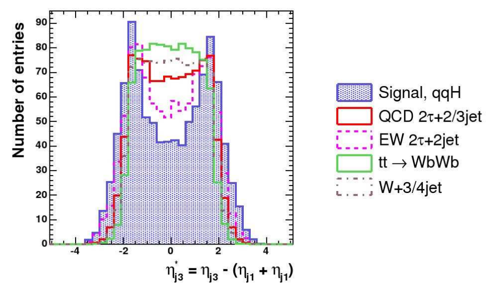


(from CMS-Note 2006-088)

Weak boson fusion processes: Rapidity gap

Example: WBF, $H \to \tau\tau$

- Many backgrounds with 3rd jet - typically quite central, i.e. between the hardest two (tag) jets
- Quantify by "Zeppenfeld"-variable: $\eta_3^* = \eta_3 - \frac{\eta_1+\eta_2}{2}$



(from CMS-Note 2006-088)

WBF, $H \to \tau\tau \to \ell j \not{E}_\perp$

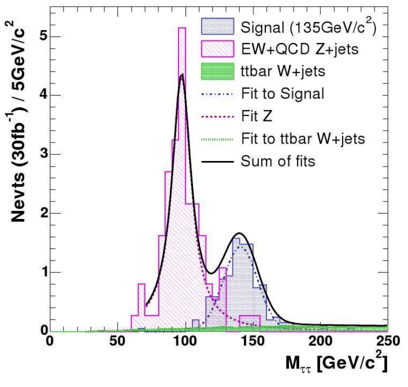
Results

Selection	Cumulative Cross Section [fb] (% from previous step)									
	signal samples: qqH, $H \to \tau\tau \to lj$				background samples					
					QCD 2τ+2/3jet		EW	$t\bar{t} \to$ WbWb	W+3/4jet ($W \to \mu\nu$)	
	M_H=115	M_H=125	M_H=135	M_H=145	2τ+2jet	2τ+3jet	2τ+2jet	($W \to l\nu$)	W+3jet	W+4jet
production σ	4.65$\times 10^3$	4.30$\times 10^3$	3.98$\times 10^3$	3.70$\times 10^3$	-	-	-	86$\times 10^3$	-	-
$\times$BR($H \to \tau\tau \to lj$)	157.3 (3.4)	112.9 (2.9)	82.38 (2.1)	45.37 (1.2)	-	-	-	-	-	-
preselection	-	-	-	-	468.7	1147.	299.0	-	4558.	9888.
L1	81.81 (52.0)	60.76 (53.8)	46.50 (56.5)	26.36 (58.1)	132.6 (28.3)	411.3 (35.9)	179.8 (60.1)	71.39$\times 10^3$ (83.0)	2815. (61.8)	6371. (64.4)
L1 + HLT	41.46 (50.7)	31.39 (51.7)	24.60 (52.9)	14.19 (53.8)	52.53 (39.6)	148.7 (36.2)	58.81 (32.7)	55.43$\times 10^3$ (77.6)	2138. (76.0)	4472. (70.2)
Lepton ID	39.46 (95.2)	29.95 (95.4)	23.34 (94.9)	13.46 (94.9)	49.44 (94.1)	138.0 (92.8)	50.67 (86.2)	54.08$\times 10^3$ (97.6)	2119. (99.1)	4430. (99.1)
Lepton p_T	39.12 (99.1)	29.71 (99.2)	23.16 (99.3)	13.34 (99.1)	49.17 (99.4)	136.4 (98.9)	49.13 (97.0)	53.54$\times 10^3$ (99.0)	2118. (99.9))	4425. (99.9)
τ-jet ID	12.70 (32.5)	10.36 (34.9)	8.276 (35.7)	4.888 (36.7)	10.60 (21.6)	29.04 (21.3)	10.49 (21.3)	5056. (9.4)	(0.07)*	(0.31)*
τ-jet E_T	9.014 (71.0)	7.564 (73.0)	6.422 (77.6)	3.858 (78.9)	6.092 (57.5)	18.16 (62.5)	7.360 (70.2)	3215. (63.6)	-	-
valid mass	6.113 (67.8)	5.042 (66.7)	4.462 (69.5)	2.649 (68.7)	3.866 (63.5)	10.62 (58.5)	4.232 (57.5)	848.6 (26.4)	(25.0)	(13.3)
VBF ID (η, E_T)	2.718 (44.4)	2.192 (43.5)	1.949 (43.7)	1.081 (40.8)	1.679 (43.4)	7.462 (70.3)	2.944 (69.6)	222.9 (26.3)	(68.5)**	(52.1)**
VBF: $\Delta\eta_{jj}$	1.498 (55.1)	1.231 (56.1)	1.104 (56.6)	0.588 (54.4)	1.230 (73.3)	4.417 (59.2)	1.012 (34.4)	13.11 (5.9)	-	-
VBF: $\Delta\phi_{jj}$	1.174 (78.4)	0.928 (75.4)	0.806 (73.0)	0.427 (72.5)	0.723 (58.7)	2.481 (56.2)	0.460 (45.5)	9.380 (71.6)	(16.3)	(30.4)
VBF: M_{jj}	0.771 (65.7)	0.634 (68.4)	0.545 (67.7)	0.283 (66.4)	0.312 (43.2)	1.353 (54.5)	0.391 (85.0)	2.738 (29.2)	(50.8)	(65.6)
$M_T(l,\not{E}_T)$	0.620 (80.4)	0.476 (75.1)	0.423 (77.6)	0.207 (73.1)	0.254 (81.3)	1.128 (83.3)	0.322 (82.4)	0.942 (34.4)	(34.3)	(30.2)
CJV	0.503 (81.2)	0.382 (80.1)	0.344 (81.3)	0.175 (84.6)	0.254 (100.)	0.301 (26.7)	0.230 (71.4)	0.224 (23.8)	(80.1)	(21.7)
Events at 30 fb^{-1}	15.1	11.4	10.3	5.3	16.6		6.9	6.7	1.5 ($W \to l\nu$)	

(from CMS-Note 2006-088)

WBF, $H \to \tau\tau \to \ell j \not{E}_\perp$

Results: m_H and significance



M_H [GeV]	115	125	135	145
N_S (30fb^{-1})	10.47	7.79	7.94	3.63
N_B (30fb^{-1})	3.70	2.21	1.84	1.42
S_{cP} at 30fb^{-1} (no uncertainty)	4.04	3.71	3.98	2.19
S_{cP} at 30fb^{-1} (σ_B = 7.8%)	3.97	3.67	3.94	2.18
S_{cP} at 60fb^{-1} (σ_B = 5.9%)	5.67	5.26	5.64	3.19

(from CMS-Note 2006-088)

A new idea: Higgs-Strahlung @ LHC

(from J.M.Butterworth et al., Phys. Rev. Lett. **100** (2008) 242001)

Basic idea

- ZH and WH production not really considered up to now
- Obstacle: if produced at low mass
  - Good fraction of $\sigma_{\rm prod}$ out of acceptance
  - Decay products often with too low $p_\perp$
- Typically: Huge backgrounds (e.g. $t\bar{t}$ at same scales)
- So: Why not try to produce at large $p_\perp$, back-to-back?
  ($p_\perp > 200$ GeV, $\sigma_{ZH,\rm boosted} \approx 0.05 \times \sigma_{ZH,\rm tot}$)
- Large boosts: decay products in relatively small cones
- Kills also backgrounds such as tops:
  Impossible to have $b\bar{b}$ with large boost in one direction and $W \to \ell\nu$ in other direction without having massive QCD radiation
- Added benefit: For $Z \to \nu\nu$ massive $\not{E}_\perp$.

A new idea: Higgs-Strahlung @ LHC

(from J.M.Butterworth et al., Phys. Rev. Lett. **100** (2008) 242001)

Key: Structure of boosted $H \longrightarrow b\bar{b}$

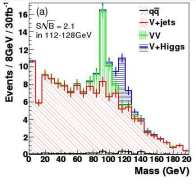
- Boosted H will produce a "fat" jet with two b's in it.
- Distance of the two b's in LEGO: $R_{b\bar{b}} \approx \frac{m_H}{p_\perp^H} \frac{1}{\sqrt{z(1-z)}}$
- For resolution use $k_\perp$-like algorithm
- The last two subjets must have b-tags, and there must not be a too large mass drop between them ($m_1 > \mu m_2$)

A new idea: Higgs-Strahlung @ LHC

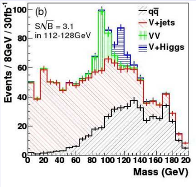
(from J.M.Butterworth et al., Phys. Rev. Lett. **100** (2008) 242001)

Results: Signal in four regions

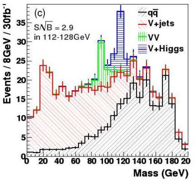
$ZH \rightarrow \ell\bar{\ell}b\bar{b}$



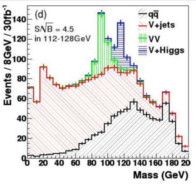
$ZH \rightarrow \nu\bar{\nu}b\bar{b}$



$WH \rightarrow \ell\bar{\nu}b\bar{b}$

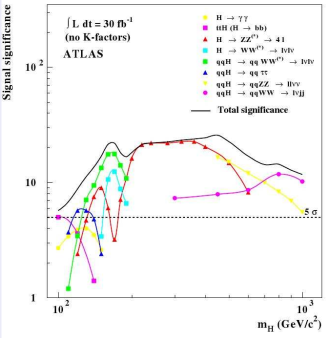


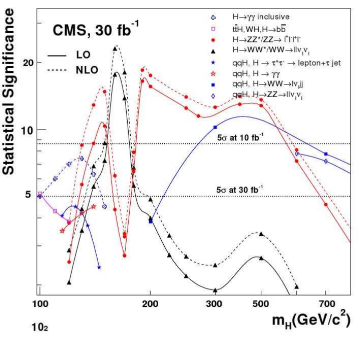
Combination



SM-Higgs boson searches at LHC: upshot

Sensitivities after 30 fb^{-1}





(from V.Buescher & K.Jakobs, Int. J. Mod. Phys. A **20** (2005) 2523)

Measuring the properties of the Higgs boson

Reminder: Why do we care?

- Okay, so we've found plenty of evidence for a "bump" in some distributions, i.e. a new particle.
- Is this enough to claim victory and for P.Higgs to book flights?
- Question: How do we know the bump is the Higgs boson?
  Answer: It must be the scalar responsible for mass generation!
  Therefore:
  1. Is it a scalar, i.e. spin-0 and even CP?
  2. Is the coupling to the other fields proportional to their mass?
  3. Is this an accident or the result of the potential/self-interactions?
- Answers to all three questions may not be available quickly.

Test 1: Spin and CP

Measuring the H-spin its decays: $H \longrightarrow ZZ$

(from S.Y.Choi et al., Phys. Lett. B **553** (2003) 61)

- Basic idea: polarizations of Z bosons correlated, must be visible.
- Check differential cross sections/distributions of Z-decay products.
- For scalar particles, all Z polarizations contribute:

$$\mathcal{M}_+ \sim \varepsilon_1 \cdot \varepsilon_2$$

  (including the longitudinal ones which are dominant for large m_H).
- For pseudoscalar particles, only the transverse polarisations contribute:

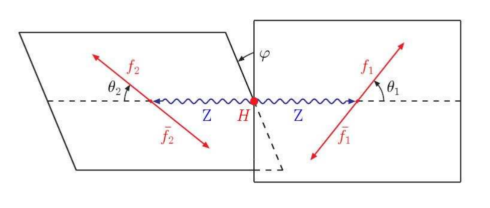
$$\mathcal{M}_- \sim \epsilon_{\mu\nu\rho\sigma} k_1^\mu k_2^\nu \varepsilon_1^\rho \varepsilon_1^\sigma \sim \vec{k}_1 \cdot (\vec{\varepsilon}_1 \times \vec{\varepsilon}_2)$$

- Will give rise to different distributions.

Test 1: Spin and CP

Measuring the H-spin its decays: $H \to ZZ$

(from S.Y.Choi et al., Phys. Lett. B **553** (2003) 61)



- Differential cross sections:

$$\frac{d\Gamma_H^{\pm}}{d\cos\theta_1 d\cos\theta_2} \sim A_\theta^{\pm}\sin^2\theta_1\sin^2\theta_2 + B_\theta^{\pm}(1+\cos^2\theta_1)(1+\cos^2\theta_2) + C_\theta^{\pm}\cos\theta_1\cos\theta_2$$

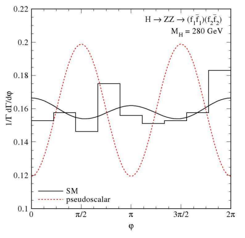
$$\frac{d\Gamma_H}{d\phi} \sim A_\phi^{\pm} + B_\phi^{\pm}\cos\phi + C_\phi^{\pm}\cos(2\phi)\,,$$

where $\{A, B, C\}^{\pm}_{\phi,\theta}$ depend on CP state ($\pm$) of the Higgs boson and on $Zf\bar{f}$ couplings and kinematics.

Test 1: Spin and CP

Measuring the H-spin its decays: $H \longrightarrow ZZ$

(from S.Y.Choi et al., Phys. Lett. B **553** (2003) 61)



(after 300 fb^{-1})

- Difference between $\mathcal{M}_+$ and $\mathcal{M}_-$, persists for the "normality" towers $\longrightarrow$ can rule out 0^-, 1^+, 2^- etc..
- Can rule out odd spins (1^-): missing $A_\theta^+ = 0$ (Bose symmetry)
- Need other decays for even spins (2^+)

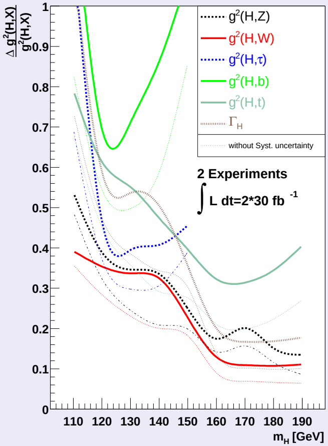
Test 2: Yukawa couplings

Strategy

- Yukawa couplings $\propto$ masses $\longrightarrow$ light particles $(u, d, \ldots)$ hopeless
- Typically: Extract couplings from total cross section measurements
- As we've seen before, this is often more than challenging: lumi/PDF uncertainties, systematics of the process itself, . . .
- Ratios might be better/more sensitive due to cancellations: but maybe not sensitive to new physics in Higgs sector

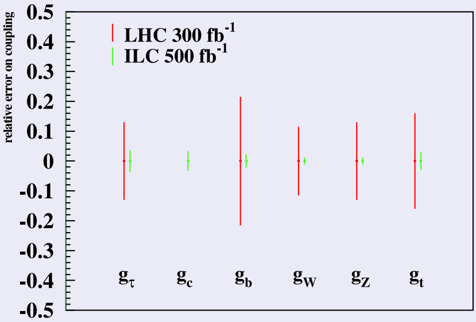
Test 2: Yukawa couplings

Some results



Test 2: Yukawa couplings

Projection: From LHC to ILC



Test 3: Higgs potential and self-interactions

Or: Why to build the ILC

- It does not seem as if the Higgs potential and the *HHH* self-interactions are accessible in the SM Higgs-sector at the LHC. Of course, this is different in the MSSM, if $m_{H^0} > 2m_{h^0}$ (resonant production of the heavy Higgs)
- It does seem, however, as if this is accessible in the SM Higgs-sector at the ILC, operating at 500 GeV c.m.-energy.

Cross sections for $e^+e^- \to \mu^+\mu^- + 4b$ [fb]

QCD	*HHH* on	*HHH* off
yes	$3.096(60)\cdot 10^{-2}$	$6.308(24)\cdot 10^{-3}$
no	$2.34(12)\cdot 10^{-2}$	$3.704(15)\cdot 10^{-3}$

(from T.Gleisberg et al.,

Eur. Phys. J. C **34** (2004) 173)

Non-minimal Higgs sectors

Motivation

- Adding one complex scalar doublet is a minimal version, why not more fields and a more involved theory?
- The SM Higgs-boson is under some stress from data (EW precision wants it lighter than 100 GeV, LEP bound wants it beyond 114 GeV).
- In many attractive models (SUSY, extra dimensions) the Higgs sector becomes larger - either enforced in order to make sure that all particles gain masses in a gauge invariant way (SUSY), or through replica of the original single doublet (ED).
- But: Need to be careful!
  Typically constraints from absence of FCNC at tree-level (charged Higgs should couple $\simeq V_{CKM}$, EW precision data ($\Delta\rho$, mass ratios of weak bosons should be respected) etc..

The simplest solution: THDM

Basic idea

- The idea behind the THDM is to add another Higgs doublet.
- There are various versions (types) to do that, respecting CP-invariance or adding CP-violation to the theory.
- Full Lagrangian introduces $\mathcal{O}(10)$ new parameters.
- Most interesting THDM-II: Interesting in its own right, but mostly because the SUSY-Higgs sector looks like a constrained THDM-II.
- SUSY-Higgs sector described by two new parameters:

  $$m_{A^0} \text{ and } \tan\beta.$$
- Indirect constraints from rare processes in K- and B-sector, EW precision data, cosmology.
- Will concentrate on it in the next few slides.

Non-minimal Higgs sectors: THDM/MSSM

Theory setup: upshot

- Two doublets with two vevs: $v_{1,2}$
$$v_1^2 + v_2^2 = v^2 \approx (246\mathrm{GeV})^2\,, \quad \tan\beta = v_2/v_1\,.$$
- H_1 doublet gives mass to the up-type fermions, H_2 for the down-types, both together are responsible for the gauge bosons.
- After EWSB and mixing to mass eigenstates:
5 fields (h^0, H^0, A^0, $H^\pm$) as linear combinations of original fields.
- Immediate consequence: VVH-couplings reduced w.r.t. the SM,
$\bar{f}fH$-coupling altered by $\tan\beta$: $\bar{d}dH$ enhanced, $\bar{u}uH$ reduced.
- Tree-level mass relations (big loop-corrections, esp. for m_{h^0}):
$$m_{H^\pm}^2 = m_{A^0}^2 + m_W^2\,, \quad m_{H^0}^2 + m_{h^0}^2 = m_{A_0}^2 + m_Z^2$$
- At tree-level, typically: $m_{h^0} < m_Z$! (after loops: $m_{h^0} < 140$ GeV)

MSSM Higgs searches

Searches for h^0

- Typical feature: decays to vector bosons less dominant.
- Relevant channels are: $h^0 \to \gamma\gamma$, $h^0 \to ZZ \to 4\ell$, $t\bar{t}h^0$ with $h^0 \to b\bar{b}$ and WBF with $h^0 \to \tau\bar{\tau}$.
- At small $\tan\beta$, searches very similar to the SM, gluon fusion $gg \to h^0$ a good process.
- At large $\tan\beta$, $gg \to h^0$ enhanced due to b-triangle, decays to τ's gain significance.
- With 100 fb^{-1} they cover nearly the full m_{A^0}-$\tan\beta$ plane in each experiment individually (with a hole around $m_{A^0} \in [90, 130]$ GeV)

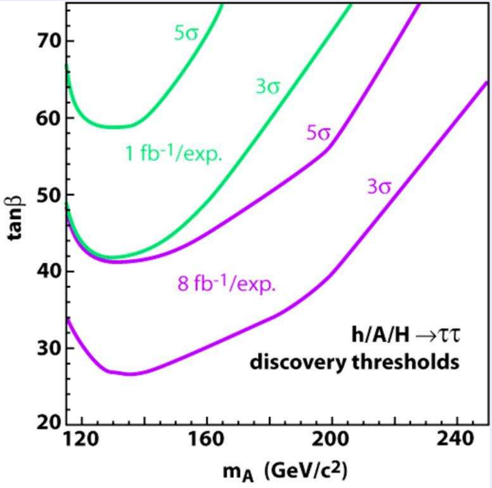
MSSM Higgs searches

Searches for H^0/A^0

- Typical feature: decays to vector bosons less dominant.
- At large $\tan\beta$, b-associated production is dominant, the final state $b\bar{b}\tau\bar{\tau}$ covers a good fraction of the parameters space.
  In addition, decays to $\mu\mu$ benefit from good mass resolution (this does not work for h^0 due to the Z nearby)
- At small $\tan\beta$, $A^0 \to Zh^0$ is a good candidate (Zhh absent in the SM): good for $m_{A^0} \in [200\mathrm{GeV}, 2m_t]$
  for $m_{A^0} > 2m_t$, both A^0 and H^0 decay predominantly into $t\bar{t}$
  $\longrightarrow$ look for resonances.

Neutral Higgs bosons at Tevatron

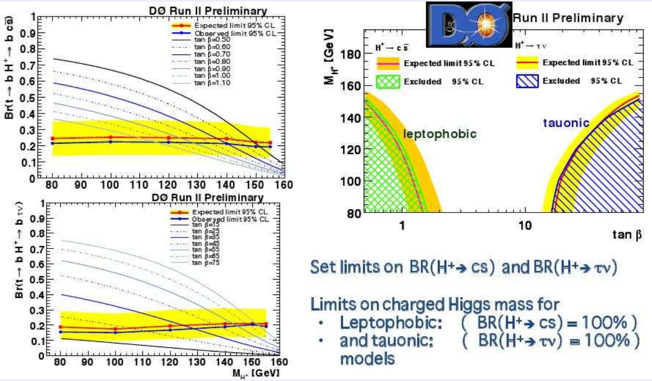
Discovery contours



MSSM Higgs searches

Searches for $H^{\pm}$

- Relevant production processes: $t \to H^+ b$ (small $m_{H^\pm}$), already being studied at the Tevatron:



MSSM Higgs searches

Searches for $H^{\pm}$

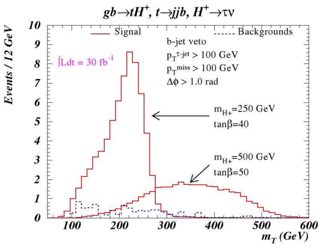
- Relevant processes $gg \to tbH^{\pm}$, pair production and $WH^{\pm}$-associated production (large $m_{H^{\pm}}$).
- Relevant decays: $H^{\pm} \to \tau\nu$, $H^{\pm} \to cs$, $H^{\pm} \to tb$, $H^{\pm} \to Wh^0$; at larger $\tan\beta$, $\tau\nu$ is a good candidate.
- Interesting case: $gb \to H^{\pm}t \to \tau^{\pm} + \not{E}_{\perp} + 2jb$, $\tau \to \nu +$ hadrons. Then transverse mass of τ-jet and $\not{E}_{\perp}$ is a good S-B discriminator: Yields a Jacobean peak at $m_{H^{\pm}}$.

MSSM Higgs searches

$gb \longrightarrow H^{\pm}t \longrightarrow \tau^{\pm} + \not{E}_{\perp} + 2jb$, $\tau \longrightarrow \nu +$ hadrons

- Tricks & cuts:
  - Only 3 high-$p_{\perp}$ jets, one b-tagged;
  - use hard hadron spectrum from $H^{\pm}$ (harder than W^{+})

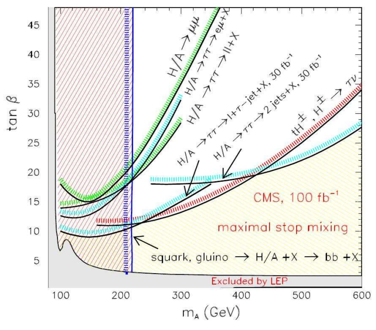
(cut on 80% of visible energy reduces $t\bar{t}$ by 300, signal to 10-20%)

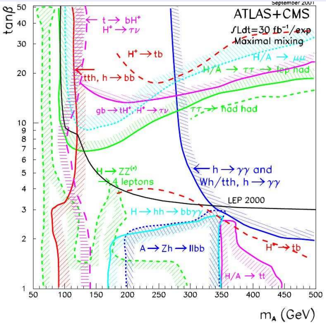


(from V.Buescher & K.Jakobs, Int. J. Mod. Phys. A **20** (2005) 2523)

MSSM-Higgs boson searches at LHC: upshot

Sensitivities in the m_A-tan β plane





(from V.Buescher & K.Jakobs, Int. J. Mod. Phys. A **20** (2005) 2523)

A more exotic solution: Adding extra singlets

Basic idea

- Add a further Higgs singlet ϕ (real or complex) + interactions with the SM Higgs-sector through $\mathcal{L} \propto (\Phi^\dagger\Phi)(\phi^*\phi)$.

  (Note: No renormalisable interactions with the SM gauge sector for ϕ.)

- Typical result: mixing of the scalar fields to mass eigenstates:
  - Complex ϕ, no further interactions ("phantom model"): H_1^0, H_2^0, massless A^0 (goldstone of broken $U(1)$), the latter with potentially large coupling to H_i^0.
  - Complex ϕ + additional $U(1)$: A^0 is eaten by Z'.
  - Real ϕ: H_1^0 and H_2^0
- Consequence: reduced couplings to SM fields - can make life hard.
- Perversion of the above: Many singlets $\longrightarrow$ can make H totally invisible due to huge width and small coupling to individual modes.