Phenomenology

Gavin P. Salam

LPTHE, Universities of Paris VI and VII and CNRS

BUSSTEPP
Ambleside, August 2005

Phenomenology

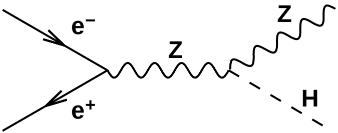
Lecture 2
(Searching for the Higgs)

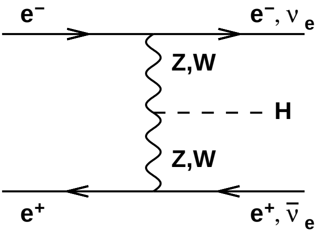
High-energy colliders

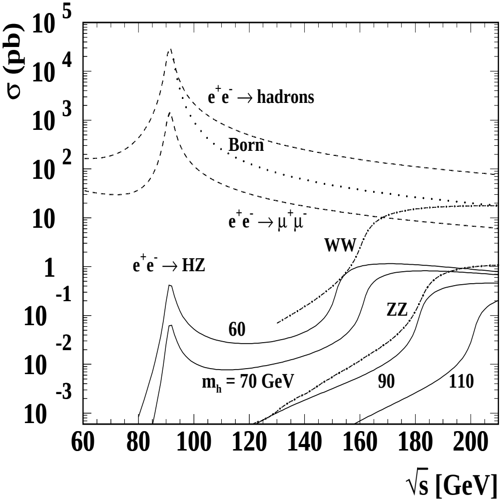
Collider	Process	max $\sqrt{s}$	experiments	status
SLC	e^+e^-	100 GeV	SLD	closed 1998
LEP	e^+e^-	208 GeV	Aleph, Delphi, L3, Opal	closed 2000
HERA	$e^\pm p$	330 GeV	H1, ZEUS (& Hermes)	running
Tevatron	$p\bar{p}$	1.96 TeV	CDF, DØ	running
LHC	pp	14 TeV	Atlas, CMS, LHCb, Alice	starts 2007

Higgs production at LEP

Production channels, *e.g.*







Higgs decay modes

Easily calculate widths (for tree-level decays, *cf.* question sheet)

$$\Gamma(H \to f\bar{f}) = \frac{C\, G_F\, m_f^2 M_H}{4\pi\sqrt{2}} \left(1 - \frac{4m_f^2}{M_H^2}\right)^{\frac{3}{2}}$$

$C = N_c = 3$ for quarks, $C = 1$ for leptons. Proportional to m_f^2 because $Hf\bar{f}$ vertex contains m_f.

$$\Gamma(H \to W^+W^-) = \frac{G_F M_H^3}{8\pi\sqrt{2}} \left(1 - \frac{4M_W^2}{M_H^2}\right)^{\frac{1}{2}} \left(1 - \frac{4M_W^2}{M_H^2} + 12\frac{M_W^4}{M_H^4}\right)$$

$$\Gamma(H \to ZZ) = \frac{G_F M_H^3 M_W^2}{16\pi\sqrt{2} M_Z^2} \left(1 - \frac{4M_Z^2}{M_H^2}\right)^{\frac{1}{2}} \left(1 - \frac{4M_Z^2}{M_H^2} + 12\frac{M_Z^4}{M_H^4}\right)$$

Widths grow as M_H^3: strong coupling of longitudinal modes at large M_H.

Higgs decay modes

Easily calculate widths (for tree-level decays, *cf.* question sheet)

$$\Gamma(H \to f\bar{f}) = \frac{C\, G_F\, m_f^2 M_H}{4\pi\sqrt{2}} \left(1 - \frac{4m_f^2}{M_H^2}\right)^{\frac{3}{2}}$$

$C = N_c = 3$ for quarks, $C = 1$ for leptons. Proportional to m_f^2 because $Hf\bar{f}$ vertex contains m_f.

$$\Gamma(H \to W^+W^-) = \frac{G_F M_H^3}{8\pi\sqrt{2}} \left(1 - \frac{4M_W^2}{M_H^2}\right)^{\frac{1}{2}} \left(1 - \frac{4M_W^2}{M_H^2} + 12\frac{M_W^4}{M_H^4}\right)$$

$$\Gamma(H \to ZZ) = \frac{G_F M_H^3 M_W^2}{16\pi\sqrt{2} M_Z^2} \left(1 - \frac{4M_Z^2}{M_H^2}\right)^{\frac{1}{2}} \left(1 - \frac{4M_Z^2}{M_H^2} + 12\frac{M_Z^4}{M_H^4}\right)$$

Widths grow as M_H^3: strong coupling of longitudinal modes at large M_H.

Higgs decay modes

Easily calculate widths (for tree-level decays, *cf.* question sheet)

$$\Gamma(H \to f\bar{f}) = \frac{C\, G_F\, m_f^2 M_H}{4\pi\sqrt{2}} \left(1 - \frac{4m_f^2}{M_H^2}\right)^{\frac{3}{2}}$$

$C = N_c = 3$ for quarks, $C = 1$ for leptons. Proportional to m_f^2 because $Hf\bar{f}$ vertex contains m_f.

$$\Gamma(H \to W^+W^-) = \frac{G_F M_H^3}{8\pi\sqrt{2}} \left(1 - \frac{4M_W^2}{M_H^2}\right)^{\frac{1}{2}} \left(1 - \frac{4M_W^2}{M_H^2} + 12\frac{M_W^4}{M_H^4}\right)$$

$$\Gamma(H \to ZZ) = \frac{G_F M_H^3 M_W^2}{16\pi\sqrt{2}M_Z^2} \left(1 - \frac{4M_Z^2}{M_H^2}\right)^{\frac{1}{2}} \left(1 - \frac{4M_Z^2}{M_H^2} + 12\frac{M_Z^4}{M_H^4}\right)$$

Widths grow as M_H^3: strong coupling of longitudinal modes at large M_H.

Higgs decay modes

Easily calculate widths (for tree-level decays, *cf.* question sheet)

$$\Gamma(H \to f\bar{f}) = \frac{C\, G_F\, m_f^2 M_H}{4\pi\sqrt{2}} \left(1 - \frac{4m_f^2}{M_H^2}\right)^{\frac{3}{2}}$$

$C = N_c = 3$ for quarks, $C = 1$ for leptons. Proportional to m_f^2 because $Hf\bar{f}$ vertex contains m_f.

$$\Gamma(H \to W^+W^-) = \frac{G_F M_H^3}{8\pi\sqrt{2}} \left(1 - \frac{4M_W^2}{M_H^2}\right)^{\frac{1}{2}} \left(1 - \frac{4M_W^2}{M_H^2} + 12\frac{M_W^4}{M_H^4}\right)$$

$$\Gamma(H \to ZZ) = \frac{G_F M_H^3 M_W^2}{16\pi\sqrt{2}M_Z^2} \left(1 - \frac{4M_Z^2}{M_H^2}\right)^{\frac{1}{2}} \left(1 - \frac{4M_Z^2}{M_H^2} + 12\frac{M_Z^4}{M_H^4}\right)$$

Widths grow as M_H^3: strong coupling of longitudinal modes at large M_H.

Higgs decay modes

Easily calculate widths (for tree-level decays, *cf.* question sheet)

$$\Gamma(H \to f\bar{f}) = \frac{C\, G_F\, m_f^2 M_H}{4\pi\sqrt{2}} \left(1 - \frac{4m_f^2}{M_H^2}\right)^{\frac{3}{2}}$$

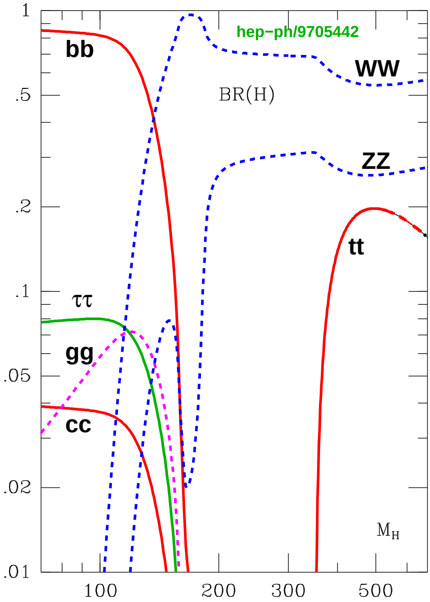
$C = N_c = 3$ for quarks, $C = 1$ for leptons. Proportional to m_f^2 because $Hf\bar{f}$ vertex contains m_f.

$$\Gamma(H \to W^+W^-) = \frac{G_F M_H^3}{8\pi\sqrt{2}} \left(1 - \frac{4M_W^2}{M_H^2}\right)^{\frac{1}{2}} \left(1 - \frac{4M_W^2}{M_H^2} + 12\frac{M_W^4}{M_H^4}\right)$$

$$\Gamma(H \to ZZ) = \frac{G_F M_H^3 M_W^2}{16\pi\sqrt{2} M_Z^2} \left(1 - \frac{4M_Z^2}{M_H^2}\right)^{\frac{1}{2}} \left(1 - \frac{4M_Z^2}{M_H^2} + 12\frac{M_Z^4}{M_H^4}\right)$$

Widths grow as M_H^3: strong coupling of longitudinal modes at large M_H.

Higgs decays cont.



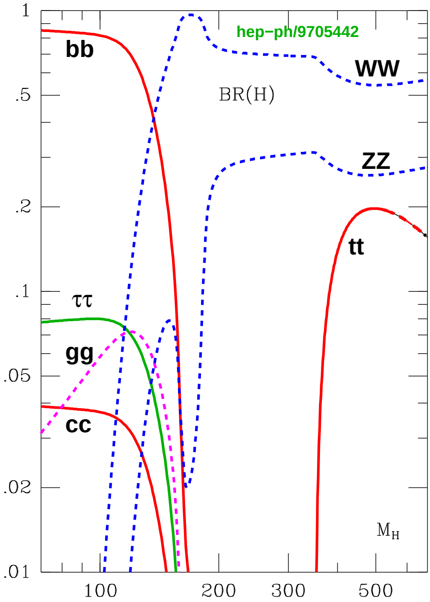
$BR(H \to X) = \Gamma(H \to X)/\Gamma_{\text{tot}}$

Most features can be understood based on previous page's formulae:

- b is strongest decay channel at low masses (width $\sim m_f^2$).
- rapid dominance of W, Z at higher masses (width $\sim M_H^3$ v. $\sim M_H$ for $f\bar{f}$) once they're kinematically allowed.

NB: Not just tree-level decays, *e.g.* $H \to gg$ and $H \to \gamma\gamma$:

Higgs decays cont.



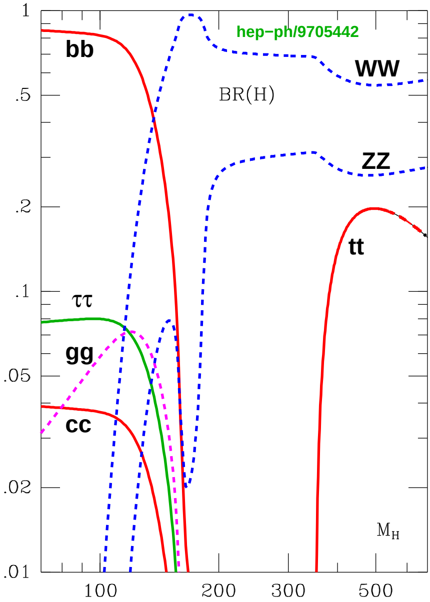
$BR(H \to X) = \Gamma(H \to X)/\Gamma_{tot}$

Most features can be understood based on previous page's formulae:

- b is strongest decay channel at low masses (width $\sim m_f^2$).
- rapid dominance of W, Z at higher masses (width $\sim M_H^3$ v. $\sim M_H$ for $f\bar{f}$) once they're kinematically allowed.

NB: Not just tree-level decays, *e.g.* $H \to gg$ and $H \to \gamma\gamma$:

Higgs decays cont.

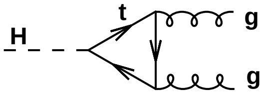


$BR(H \to X) = \Gamma(H \to X)/\Gamma_{\text{tot}}$

Most features can be understood based on previous page's formulae:

- b is strongest decay channel at low masses (width $\sim m_f^2$).
- rapid dominance of W, Z at higher masses (width $\sim M_H^3$ v. $\sim M_H$ for $f\bar{f}$) once they're kinematically allowed.

NB: Not just tree-level decays, *e.g.* $H \to gg$ and $H \to \gamma\gamma$:



Comment on τ versus charm?

Beware: plots like those of previous page often contain subtleties. . .

Expect

$$\frac{\Gamma(H \to c\bar{c})}{\Gamma(H \to \tau^+\tau^-)} \simeq \frac{N_c m_c^2}{m_\tau^2} \simeq 2 \text{ (for } m_c = 1.5 \text{ GeV, } m_\tau = 1.8 \text{ GeV)}$$

But actual ratio ~ 0.5. Why?

Masses are not constants. Like coupling 'constants', they run with scale (*i.e.* have anomalous dimensions). QCD gives significant running effects for quark masses

$$Q^2 \frac{\partial m}{\partial Q^2} = -\gamma_m(\alpha_s) m(Q^2)\,, \qquad \gamma_m = \frac{\alpha_s}{\pi} + \mathcal{O}\left(\alpha_s^2\right)\,.$$

In expression for Higgs width use $m_q(M_H^2)$. Since $\partial m/\partial Q^2 < 0$ this reduces $\Gamma(H \to c\bar{c})$. ➥question on problem sheet.

[NB: ∃ also other higher-order effects, but generally more modest]

Comment on τ versus charm?

Beware: plots like those of previous page often contain subtleties. . .

Expect

$$\frac{\Gamma(H \to c\bar{c})}{\Gamma(H \to \tau^+\tau^-)} \simeq \frac{N_c m_c^2}{m_\tau^2} \simeq 2 \text{ (for } m_c = 1.5 \text{ GeV, } m_\tau = 1.8 \text{ GeV)}$$

But actual ratio ~ 0.5. Why?

Masses are not constants. Like coupling 'constants', they run with scale (*i.e.* have anomalous dimensions). QCD gives significant running effects for quark masses

$$Q^2 \frac{\partial m}{\partial Q^2} = -\gamma_m(\alpha_s) m(Q^2)\,, \qquad \gamma_m = \frac{\alpha_s}{\pi} + \mathcal{O}\left(\alpha_s^2\right)\,.$$

In expression for Higgs width use $m_q(M_H^2)$. Since $\partial m / \partial Q^2 < 0$ this reduces $\Gamma(H \to c\bar{c})$. ➥question on problem sheet.

[NB: $\exists$ also other higher-order effects, but generally more modest]

Comment on τ versus charm?

Beware: plots like those of previous page often contain subtleties...

Expect

$$\frac{\Gamma(H \to c\bar{c})}{\Gamma(H \to \tau^+\tau^-)} \simeq \frac{N_c m_c^2}{m_\tau^2} \simeq 2 \text{ (for } m_c = 1.5 \text{ GeV, } m_\tau = 1.8 \text{ GeV)}$$

But actual ratio ~ 0.5. Why?

Masses are not constants. Like coupling 'constants', they run with scale (*i.e.* have anomalous dimensions). QCD gives significant running effects for quark masses

$$Q^2 \frac{\partial m}{\partial Q^2} = -\gamma_m(\alpha_s) m(Q^2) \,, \qquad \gamma_m = \frac{\alpha_s}{\pi} + \mathcal{O}\left(\alpha_s^2\right) \,.$$

In expression for Higgs width use $m_q(M_H^2)$. Since $\partial m / \partial Q^2 < 0$ this reduces $\Gamma(H \to c\bar{c})$. ➥question on problem sheet.

[NB: ∃ also other higher-order effects, but generally more modest]

Comment on τ versus charm?

Beware: plots like those of previous page often contain subtleties...

Expect

$$\frac{\Gamma(H \to c\bar{c})}{\Gamma(H \to \tau^+\tau^-)} \simeq \frac{N_c m_c^2}{m_\tau^2} \simeq 2 \text{ (for } m_c = 1.5 \text{ GeV, } m_\tau = 1.8 \text{ GeV)}$$

But actual ratio ~ 0.5. Why?

Masses are not constants. Like coupling 'constants', they run with scale (*i.e.* have anomalous dimensions). QCD gives significant running effects for quark masses

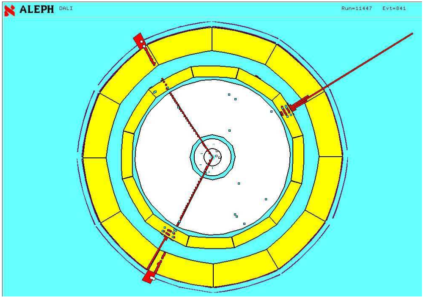
$$Q^2 \frac{\partial m}{\partial Q^2} = -\gamma_m(\alpha_s) m(Q^2)\,, \qquad \gamma_m = \frac{\alpha_s}{\pi} + \mathcal{O}\left(\alpha_s^2\right)\,.$$

In expression for Higgs width use $m_q(M_H^2)$. Since $\partial m / \partial Q^2 < 0$ this reduces $\Gamma(H \to c\bar{c})$.

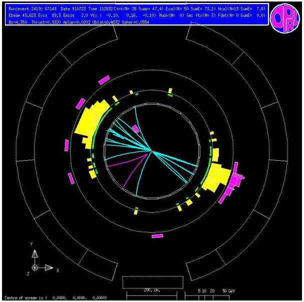
➥question on problem sheet.

[NB: ∃ also other higher-order effects, but generally more modest]

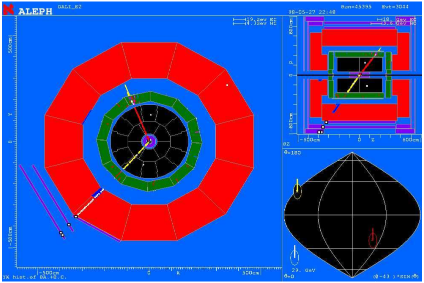
What can experiments detect?



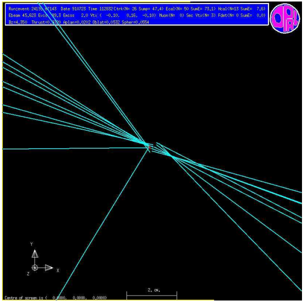
$e^+e^- \to \mu^+\mu^-\gamma\gamma$



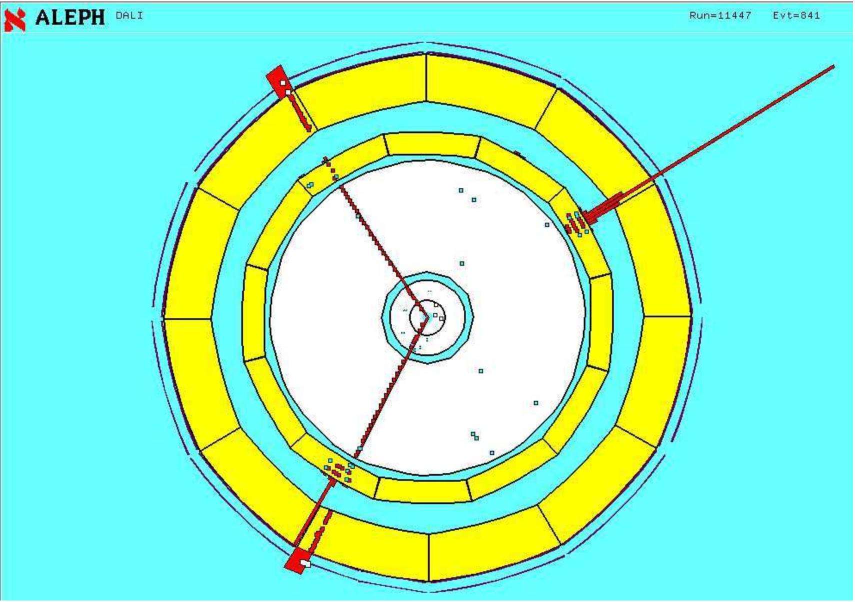
$e^+e^- \to q\bar{q}$



$e^+e^- \to e\mu\nu_e\nu_\mu$

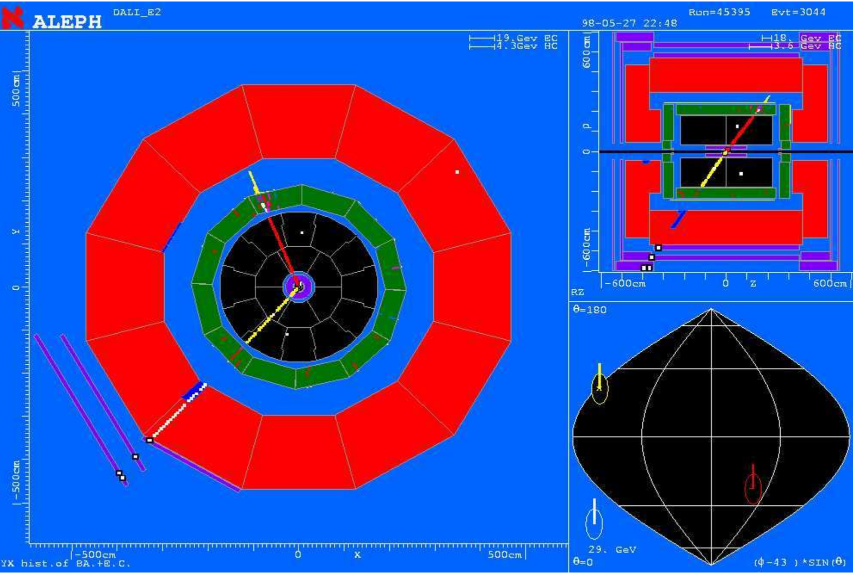


$e^+e^- \to b\bar{b}$ (secondary vertex)



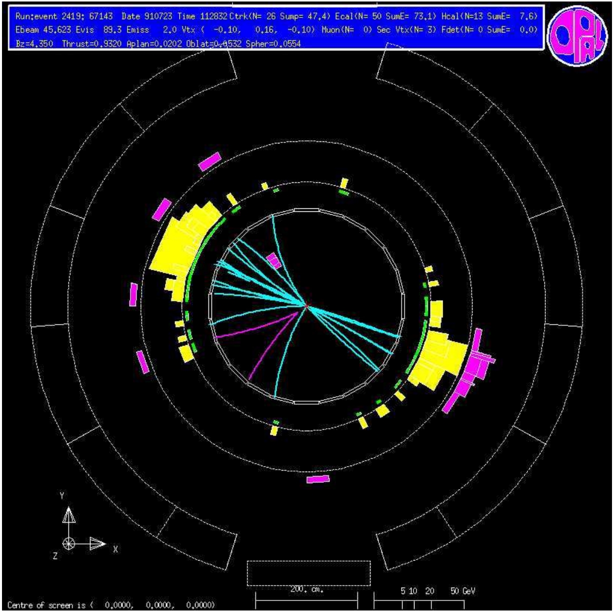
$$e^+e^- \to \mu^+\mu^-\gamma\gamma$$

e^-

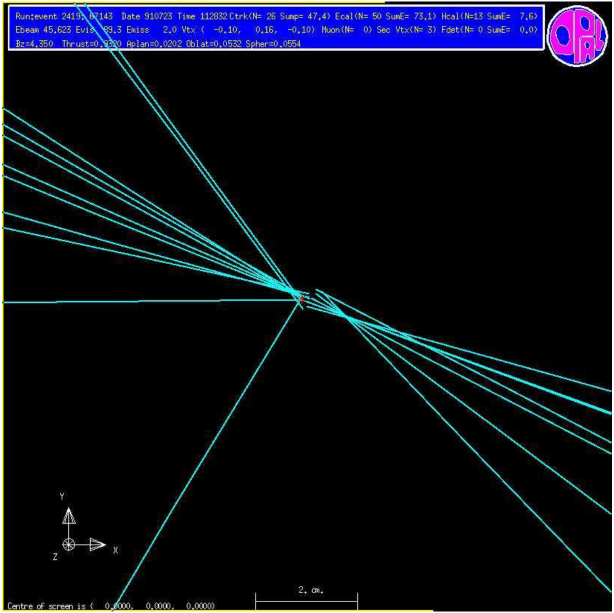


$$e^+e^- \longrightarrow e\mu\nu_e\nu_\mu$$

e^-



$$e^+e^- \longrightarrow q\bar{q}$$



$e^+e^- \rightarrow b\bar{b}$ (secondary vertex)

LEP Higgs search

Searches in various channels ($e^+e^- \to HZ$)

- $H \to b\bar{b}$, $Z \to q\bar{q}$
- $H \to b\bar{b}$, $Z \to \nu\bar{\nu}$
- $H \to b\bar{b}$, $Z \to \ell^+\ell^-$
- $H \to \tau^+\tau^-$, $Z \to q\bar{q}$

Must reduce backgrounds *e.g.*

- $ee \to Z \to b\bar{b}gg$. Call the jets 1,2,3,4, require $M_{34} \simeq M_Z$
- $ee \to Z(\to b\bar{b})Z(\to q\bar{q})$. Require $M_{34} \simeq M_Z$ and $M_{12} \neq M_Z$

Example event (from Aleph):

Centre-of-mass energy	206.7 GeV
NN value	0.996
b-tag probabilities	0.99 0.99 0.14 0.01
HZ hypothesis	$M_H = 112.4$ GeV $M_Z = 93.3$ GeV
ZZ hypothesis	$M_Z = 102$ GeV $M_Z = 91.7$ GeV

LEP Higgs search

Searches in various channels ($e^+e^- \to HZ$)

- $H \to b\bar{b}$, $Z \to q\bar{q}$
- $H \to b\bar{b}$, $Z \to \nu\bar{\nu}$
- $H \to b\bar{b}$, $Z \to \ell^+\ell^-$
- $H \to \tau^+\tau^-$, $Z \to q\bar{q}$

Must reduce backgrounds *e.g.*

- $ee \to Z \to b\bar{b}gg$. Call the jets 1,2,3,4, require $M_{34} \simeq M_Z$
- $ee \to Z(\to b\bar{b})Z(\to q\bar{q})$. Require $M_{34} \simeq M_Z$ and $M_{12} \neq M_Z$

Example event (from Aleph):

Centre-of-mass energy	206.7 GeV
NN value	0.996
b-tag probabilities	0.99 0.99 0.14 0.01
HZ hypothesis	$M_H = 112.4$ GeV $M_Z = 93.3$ GeV
ZZ hypothesis	$M_Z = 102$ GeV $M_Z = 91.7$ GeV

LEP Higgs search

Searches in various channels ($e^+e^- \to HZ$)

- $H \to b\bar{b},\ Z \to q\bar{q}$
- $H \to b\bar{b},\ Z \to \nu\bar{\nu}$
- $H \to b\bar{b},\ Z \to \ell^+\ell^-$
- $H \to \tau^+\tau^-,\ Z \to q\bar{q}$

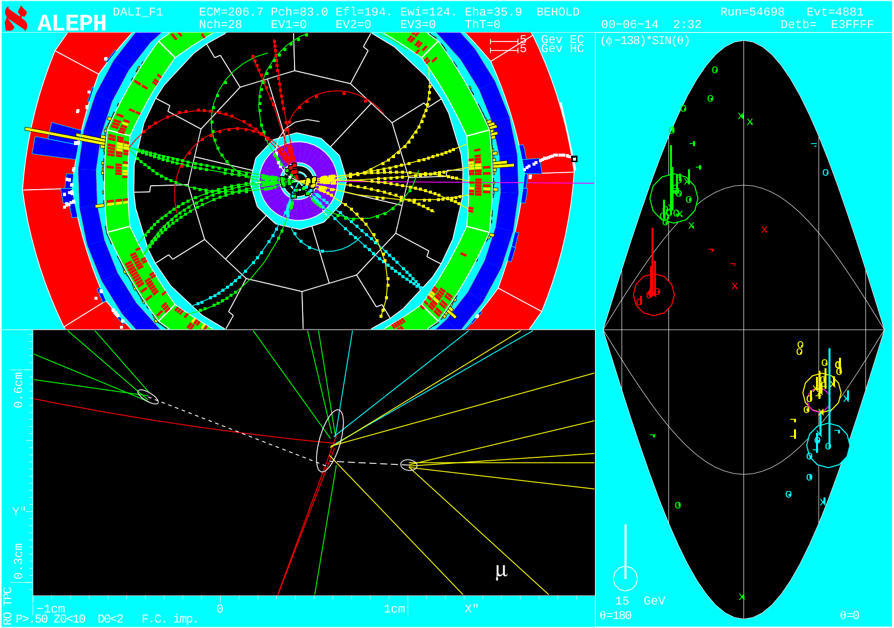
Must reduce backgrounds *e.g.*

- $ee \to Z \to b\bar{b}gg$. Call the jets 1,2,3,4, require $M_{34} \simeq M_Z$
- $ee \to Z(\to b\bar{b})Z(\to q\bar{q})$. Require $M_{34} \simeq M_Z$ and $M_{12} \neq M_Z$

Example event (from Aleph):

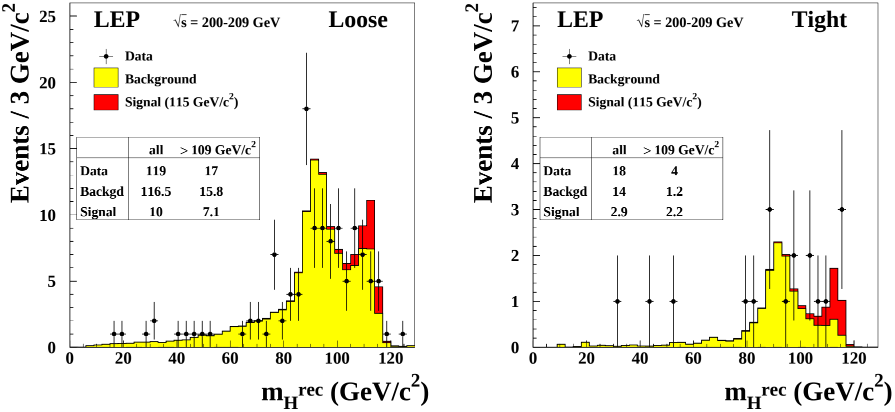
Centre-of-mass energy	206.7 GeV
NN value	0.996
b-tag probabilities	0.99 0.99 0.14 0.01
HZ hypothesis	$M_H = 112.4$ GeV $M_Z = 93.3$ GeV
ZZ hypothesis	$M_Z = 102$ GeV $M_Z = 91.7$ GeV

Example Higgs candidate



Made on 29-Aug-2000 17:06:54 by DREVERMANN with DALI_F1.
Filename: DC054698_004881_000829_1706.PS_H_CAND

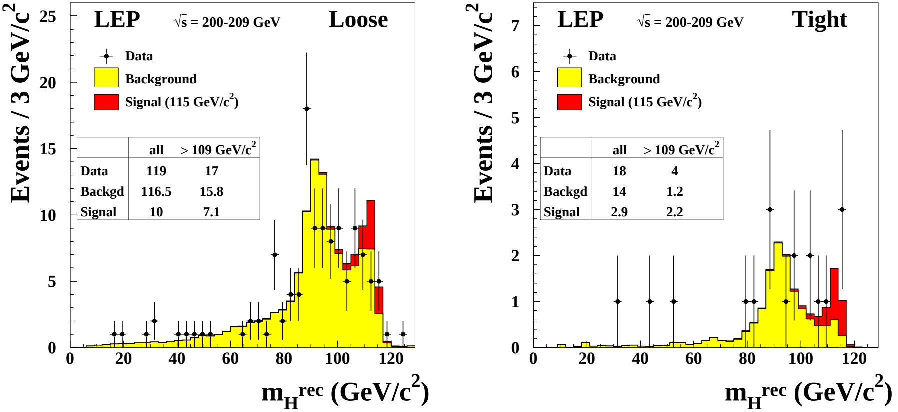
Data v. expected signal & background



LEP Higgs WG conclusions:

statistical analysis: signal at 1.7 standard dev., corresponding to $M_H \simeq 116$ GeV

Data v. expected signal & background



LEP Higgs WG conclusions:

statistical analysis: signal at 1.7 standard dev., corresponding to $M_H \simeq 116$ GeV

LEP limit

- LEP's highest (sustained) energy was $\sqrt{s} \simeq 206$ GeV.
- Threshold: $\sqrt{s} \gtrsim M_Z + M_H$, so $M_{H,max} \simeq \sqrt{s} - M_Z = 115$ GeV
- Higgs signal at ~ 115 GeV, *i.e.* right at kinematic limit. Possible because there is *only one* reaction at a time: takes all energy and is 'clean'.
- So why not increase $\sqrt{s}$? Synchrotron energy loss too large:

$$E_{loss} \sim \frac{E_{beam}^4}{R} \frac{1}{m_e^4}, \qquad (\sim 2.5 \text{ GeV per turn})$$

- Next generation e^+e^- collider will be *linear*. Not before ~ 2015.
- For now have *hadron colliders* (at same energy, synchrotron energy loss $(m_e/m_p)^4 \sim 10^{-13}$ smaller).

LEP limit

- LEP's highest (sustained) energy was $\sqrt{s} \simeq 206$ GeV.
- Threshold: $\sqrt{s} \gtrsim M_Z + M_H$, so $M_{H,max} \simeq \sqrt{s} - M_Z = 115$ GeV
- Higgs signal at ~ 115 GeV, *i.e.* right at kinematic limit. Possible because there is *only one* reaction at a time: takes all energy and is 'clean'.
- So why not increase $\sqrt{s}$? Synchrotron energy loss too large:

$$E_{loss} \sim \frac{E_{beam}^4}{R}\frac{1}{m_e^4}, \qquad (\sim 2.5 \text{ GeV per turn})$$

- Next generation e^+e^- collider will be *linear*. Not before ~ 2015.
- For now have *hadron colliders* (at same energy, synchrotron energy loss $(m_e/m_p)^4 \sim 10^{-13}$ smaller).

LEP limit

- LEP's highest (sustained) energy was $\sqrt{s} \simeq 206$ GeV.
- Threshold: $\sqrt{s} \gtrsim M_Z + M_H$, so $M_{H,max} \simeq \sqrt{s} - M_Z = 115$ GeV
- Higgs signal at ~ 115 GeV, *i.e.* right at kinematic limit. Possible because there is *only one* reaction at a time: takes all energy and is 'clean'.
- So why not increase $\sqrt{s}$? Synchrotron energy loss too large:

$$E_{loss} \sim \frac{E_{beam}^4}{R} \frac{1}{m_e^4}, \qquad (\sim 2.5 \text{ GeV per turn})$$

- Next generation e^+e^- collider will be *linear*. Not before ~ 2015.
- For now have *hadron colliders* (at same energy, synchrotron energy loss $(m_e/m_p)^4 \sim 10^{-13}$ smaller).

LEP limit

- LEP's highest (sustained) energy was $\sqrt{s} \simeq 206$ GeV.
- Threshold: $\sqrt{s} \gtrsim M_Z + M_H$, so $M_{H,max} \simeq \sqrt{s} - M_Z = 115$ GeV
- Higgs signal at ~ 115 GeV, *i.e.* right at kinematic limit. Possible because there is *only one* reaction at a time: takes all energy and is 'clean'.
- So why not increase $\sqrt{s}$? Synchrotron energy loss too large:

$$E_{loss} \sim \frac{E_{beam}^4}{R}\frac{1}{m_e^4}, \qquad (\sim 2.5 \text{ GeV per turn})$$

- Next generation e^+e^- collider will be *linear*. Not before ~ 2015.
- For now have *hadron colliders* (at same energy, synchrotron energy loss $(m_e/m_p)^4 \sim 10^{-13}$ smaller).

LEP limit

- LEP's highest (sustained) energy was $\sqrt{s} \simeq 206$ GeV.
- Threshold: $\sqrt{s} \gtrsim M_Z + M_H$, so $M_{H,max} \simeq \sqrt{s} - M_Z = 115$ GeV
- Higgs signal at ~ 115 GeV, *i.e.* right at kinematic limit. Possible because there is *only one* reaction at a time: takes all energy and is 'clean'.
- So why not increase $\sqrt{s}$? Synchrotron energy loss too large:

$$E_{loss} \sim \frac{E_{beam}^4}{R} \frac{1}{m_e^4}\,, \qquad (\sim 2.5 \text{ GeV per turn})$$

- Next generation e^+e^- collider will be *linear.* Not before ~ 2015.
- For now have *hadron colliders* (at same energy, synchrotron energy loss $(m_e/m_p)^4 \sim 10^{-13}$ smaller).

LEP limit

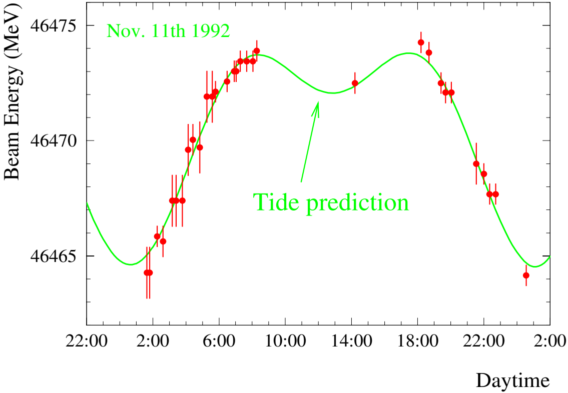
- LEP's highest (sustained) energy was $\sqrt{s} \simeq 206$ GeV.
- Threshold: $\sqrt{s} \gtrsim M_Z + M_H$, so $M_{H,max} \simeq \sqrt{s} - M_Z = 115$ GeV
- Higgs signal at ~ 115 GeV, *i.e.* right at kinematic limit. Possible because there is *only one* reaction at a time: takes all energy and is 'clean'.
- So why not increase $\sqrt{s}$? Synchrotron energy loss too large:

$$E_{loss} \sim \frac{E_{beam}^4}{R} \frac{1}{m_e^4}, \qquad (\sim 2.5 \text{ GeV per turn})$$

- Next generation e^+e^- collider will be *linear.* Not before ~ 2015.
- For now have *hadron colliders* (at same energy, synchrotron energy loss $(m_e/m_p)^4 \sim 10^{-13}$ smaller).

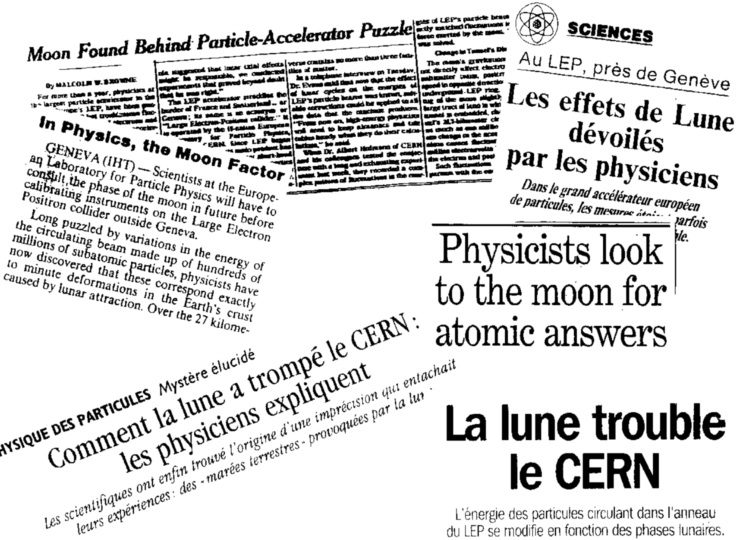
Moonrise over LEP

Fall of 1992 : The historic tide experiment !



The total strain is 4 x 10^{-8} (ΔC = 1 mm)

Success in the Press !



Moon Found Behind Particle-Accelerator Puzzle

By MALCOLM W. BROWNE

In Physics, the Moon Factor

GENEVA (IHT) — Scientists at the European Laboratory for Particle Physics will have to consult the phase of the moon in future before calibrating instruments on the Large Electron Positron collider outside Geneva.

Long puzzled by variations in the energy of the circulating beam made up of hundreds of millions of subatomic particles, physicists have now discovered that these correspond exactly to minute deformations in the Earth's crust caused by lunar attraction. Over the 27 kilome-

SCIENCES

Au LEP, près de Genève

Les effets de Lune dévoilés par les physiciens

Dans le grand accélérateur européen de particules, les mesures ...

Physicists look to the moon for atomic answers

PHYSIQUE DES PARTICULES Mystère élucidé

Comment la lune a trompé le CERN : les physiciens expliquent

Les scientifiques ont enfin trouvé l'origine d'une imprécision qui entachait leurs expériences : des « marées terrestres » provoquées par la lune

La lune trouble le CERN

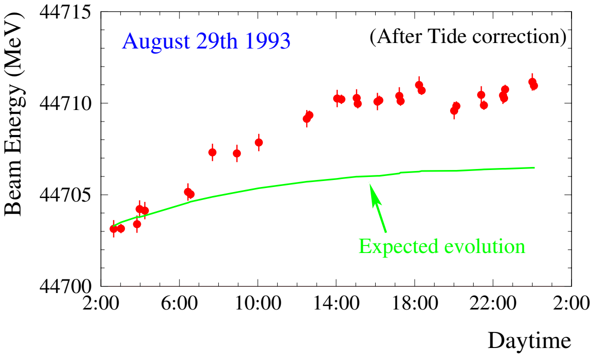
L'énergie des particules circulant dans l'anneau du LEP se modifie en fonction des phases lunaires.

The Crack in the Model

Spring of 1994 : the beam energy model seemed to explain all observed sources of energy fluctuations...

EXCEPT :

An unexplained energy increase of 5 MeV was observed in ONE experiment.



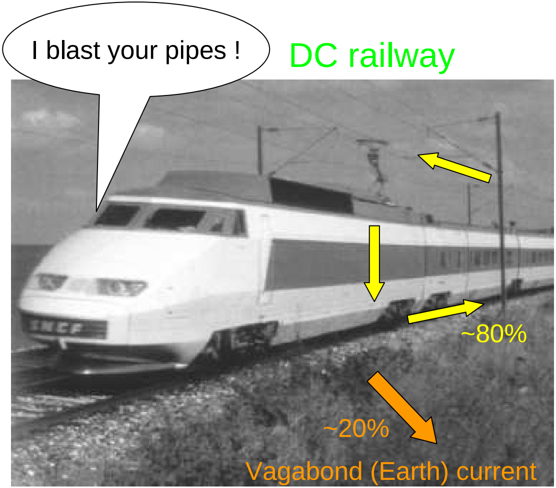
It will remain unexplained for two years…

Pipebusters

The explanation was given by the Swiss electricity company EOS...

Vagabond currents from trains and subways

Source of electrical noise and corrosion (first discussed in …1898 !)



TGV for Paris

November 1995 : Measurements of

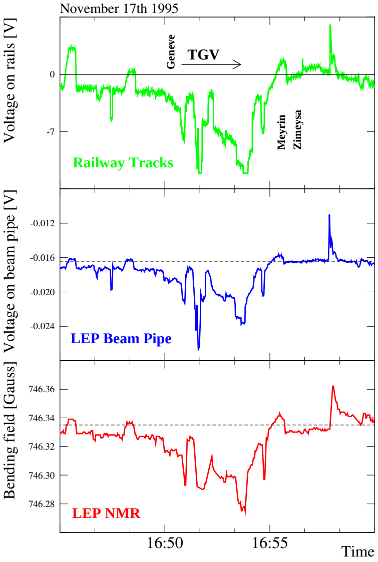
- The current on the railway tracks
- The current on the vacuum chamber
- The dipole field in a magnet

correlate perfectly !

Because energy calibrations were usually performed :

- At the end of fills (saturation)
- During nights (no trains !)

we “missed” the trains for many years !

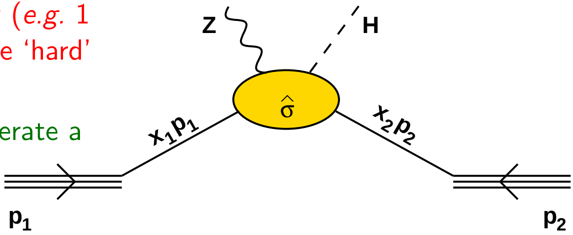


Basics of hadronic collisions

Protons are *composite objects.*

- Only a fraction of energy (*e.g.* 1 of 3 quarks) goes into the 'hard' collision

  ➥need higher $\sqrt{s}$ to generate a given process



$$\sigma = \int dx_1 f_{q/p}(x_1,\mu^2) \int dx_2 f_{\bar{q}/\bar{p}}(x_2,\mu^2)\,\hat{\sigma}(x_1p_1,x_2p_2,\mu^2)\,, \quad \hat{s} = x_1x_2s$$

- Momentum fractions x_1 and x_2 are different in each collision

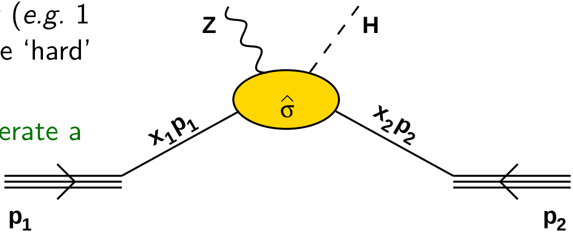
  ➥C.O.M. frame not easily identifiable (ambiguous kinematic reconstruction)

Basics of hadronic collisions

Protons are *composite objects.*

- Only a fraction of energy (*e.g.* 1 of 3 quarks) goes into the 'hard' collision

  ➥need higher $\sqrt{s}$ to generate a given process



$$\sigma = \int dx_1 f_{q/p}(x_1,\mu^2) \int dx_2 f_{\bar{q}/\bar{p}}(x_2,\mu^2)\, \hat{\sigma}(x_1 p_1, x_2 p_2, \mu^2)\,, \quad \hat{s} = x_1 x_2 s$$

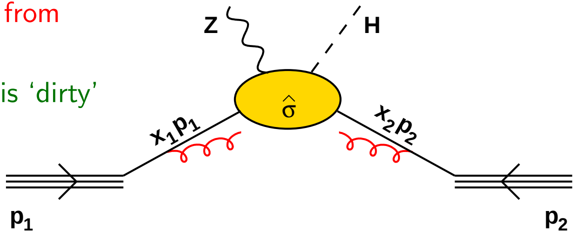
- Momentum fractions x_1 and x_2 are different in each collision

  ➥C.O.M. frame not easily identifiable (ambiguous kinematic reconstruction)

Basics of hadronic collisions (cont.)

- There is QCD radiation from initial-state partons

  ➥collision environment is 'dirty'



- 'remnants' from protons fragment & can also interact
  ➥collision environment is even dirtier

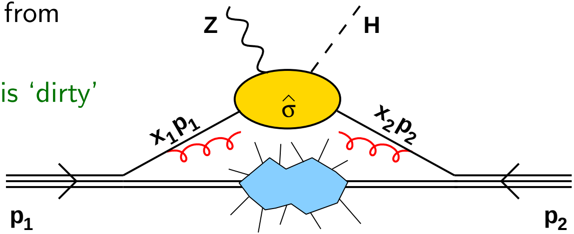
- quarks and gluons interact via QCD (strong); Higgs & some other 'new' physics, via EW (weak).

  ➥Backgrounds (from QCD) are enhanced relative to (some) signals of new physics

Basics of hadronic collisions (cont.)

- There is QCD radiation from initial-state partons

  ➥collision environment is 'dirty'



- 'remnants' from protons fragment & can also interact

  ➥collision environment is even dirtier

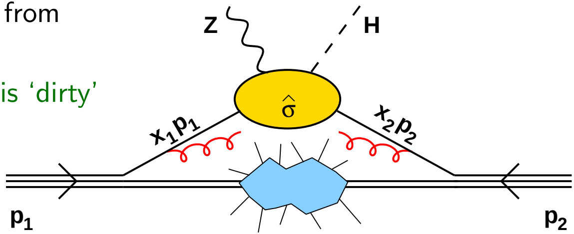
- quarks and gluons interact via QCD (strong); Higgs & some other 'new' physics, via EW (weak).

  ➥Backgrounds (from QCD) are enhanced relative to (some) signals of new physics

Basics of hadronic collisions (cont.)

- There is QCD radiation from initial-state partons

  ➥collision environment is 'dirty'



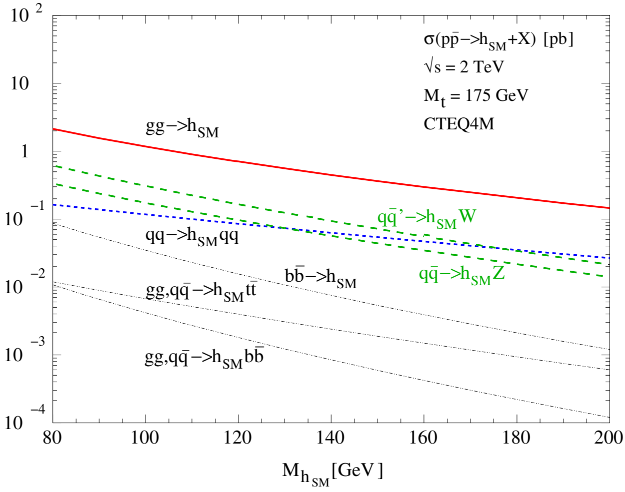
- 'remnants' from protons fragment & can also interact
  ➥collision environment is even dirtier

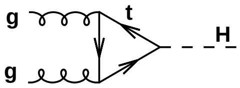
- quarks and gluons interact via QCD (strong); Higgs & some other 'new' physics, via EW (weak).

  ➥Backgrounds (from QCD) are enhanced relative to (some) signals of new physics

Example: Tevatron Higgs search

Largest production channel: $gg \to H$, with decay $H \to b\bar{b}$ (for $M_H \lesssim 135$ GeV).



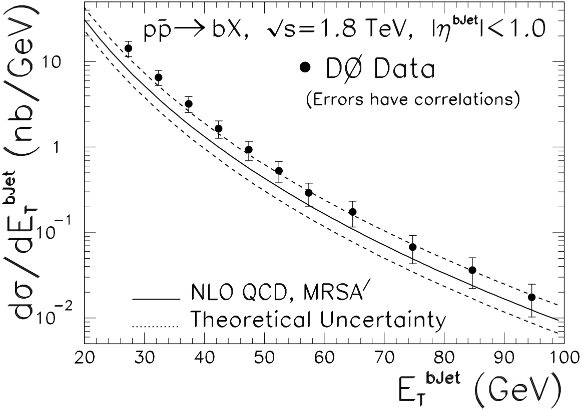


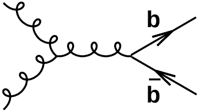
For 115 GeV Higgs, production cross section is ~ 1 pb.

[1 barn (b) $= 10^{-28}$ m^2]

[1 mb $\simeq 2.56$ GeV$^{-2}(\hbar c)^2$]

$b\bar{b}$ background





$m_{b\bar{b}} \simeq 115$ GeV $\equiv$ $E_T \simeq 50$ GeV

Cross section ~ 1 nb

Background is $\sim 10^3\times$ signal.

THE OHIO STATE UNIVERSITY

Final State Modes and Backgrounds

Signal Production and Final State:	Primary Background Processes:
$gg \rightarrow H \rightarrow b\bar{b}$	QCD Dijet Background…Huge
$p\bar{p} \rightarrow WH \rightarrow q\bar{q}'b\bar{b}$	QCD Jet Background/W+jets
$p\bar{p} \rightarrow WH \rightarrow \ell\nu b\bar{b}$	W+$b\bar{b}$/$c\bar{c}$, Single top, $t\bar{t}$
$p\bar{p} \rightarrow ZH \rightarrow q\bar{q}b\bar{b}$	QCD Jet Background/W+jets
$p\bar{p} \rightarrow ZH \rightarrow \ell^+\ell^- b\bar{b}$	W/Z+$b\bar{b}$/$c\bar{c}$, $t\bar{t}$ (Poor BR)
$p\bar{p} \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$	W/Z+$b\bar{b}$/$c\bar{c}$, $t\bar{t}$, QCD Jets

Essentials:

Lepton Acceptance, b-tagging eff/Acceptance, dijet Mass Resolution

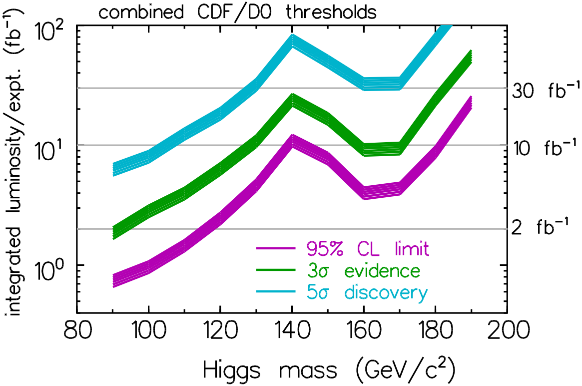
Event Rates/fb^{-1}

Rates determined from a combination of MC and data.

Missed Chg Lepton

	No Mass Window	Mass Window
WH Signal(115)	1.7	1.5
ZH Signal(115)	2.5	2.3
Total Signal	4.2	3.8
tt	8.8	2.2
t(W*)	3.3	0.7
t(Wg)	2.4	0.5
W/Z bb	22.3	3.3
WZ/ZZ	16.5	2.7
QCD	61.2	10.2
Total Bkg	114	19.6
$S/\sqrt{B}$	0.39	0.85
S/B	0.037	0.19

Tevatron Higgs search: prospects



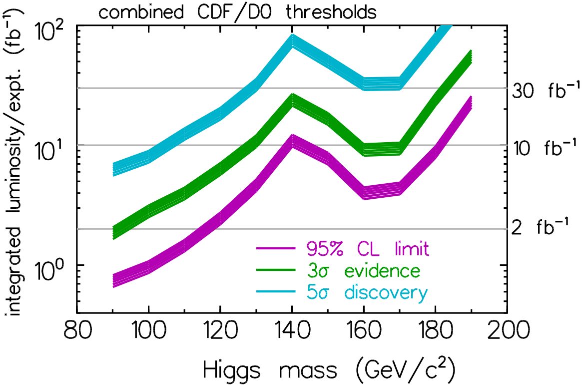
Express results of studies in terms of *luminosity* needed in order to see a Higgs signal, as function of M_H.

Dip at $\sim$ 160 GeV: $H \to W^+W^-$ (easier to identify, smaller backgrounds).

Currently Tevatron has $\gtrsim 1$ fb^{-1}.

For full details, see joint theoretical-experimental 'Report of the Tevatron Higgs working group', hep-ph/0010338. (For luminosity progress, see: http://www.fnal.gov/pub/now/tevlum.html)

Tevatron Higgs search: prospects



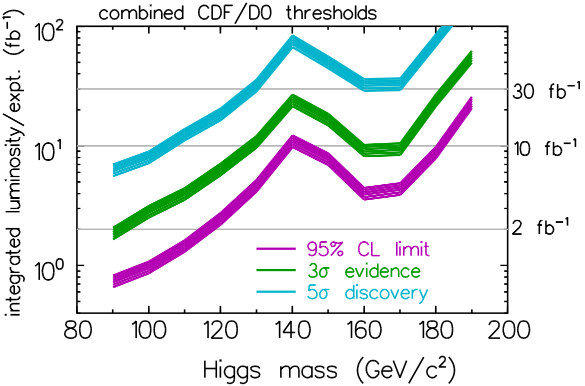
Express results of studies in terms of *luminosity* needed in order to see a Higgs signal, as function of M_H.

Dip at $\sim$ 160 GeV: $H \to W^+W^-$ (easier to identify, smaller backgrounds).

Currently Tevatron has $\gtrsim 1\ \text{fb}^{-1}$.

For full details, see joint theoretical-experimental 'Report of the Tevatron Higgs working group', hep-ph/0010338. (For luminosity progress, see: http://www.fnal.gov/pub/now/tevlum.html)

Tevatron Higgs search: prospects



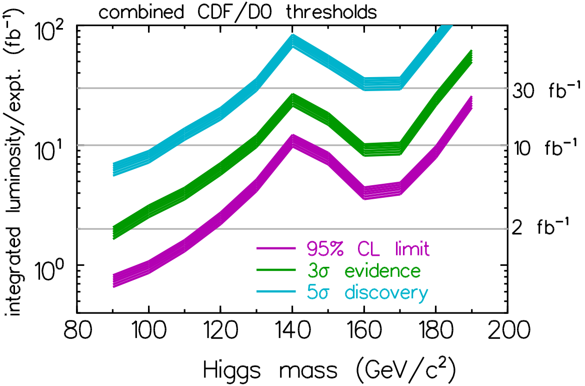
Express results of studies in terms of *luminosity* needed in order to see a Higgs signal, as function of M_H.

Dip at $\sim$ 160 GeV: $H \to W^+W^-$ (easier to identify, smaller backgrounds).

Currently Tevatron has $\gtrsim 1$ fb^{-1}.

For full details, see joint theoretical-experimental 'Report of the Tevatron Higgs working group', hep-ph/0010338. (For luminosity progress, see: http://www.fnal.gov/pub/now/tevlum.html)

Tevatron Higgs search: prospects



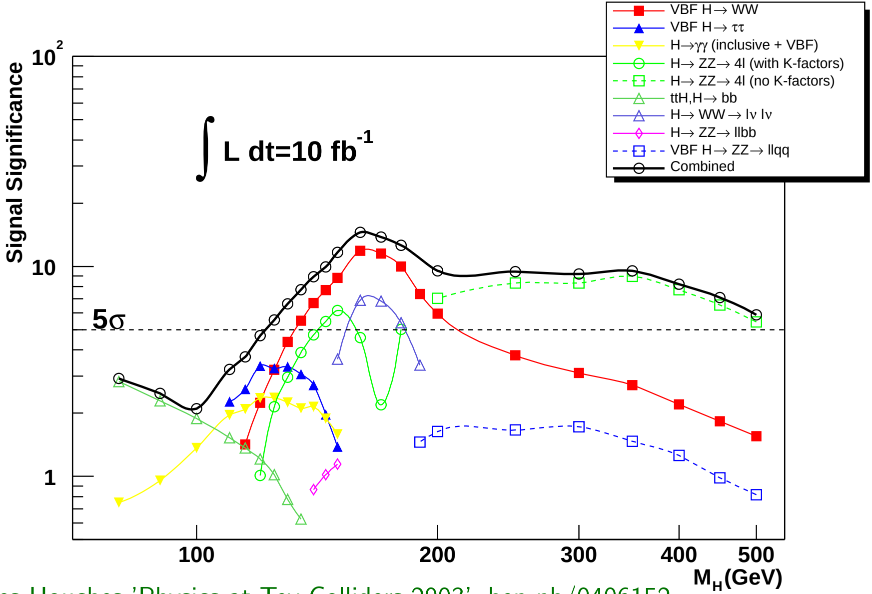
Express results of studies in terms of *luminosity* needed in order to see a Higgs signal, as function of M_H.

Dip at $\sim$ 160 GeV: $H \to W^+W^-$ (easier to identify, smaller backgrounds).

Currently Tevatron has $\gtrsim 1\ \text{fb}^{-1}$.

For full details, see joint theoretical-experimental 'Report of the Tevatron Higgs working group', hep-ph/0010338. (For luminosity progress, see: http://www.fnal.gov/pub/now/tevlum.html)

LHC Higgs search: prospects



Les Houches 'Physics at Tev Colliders 2003', hep-ph/0406152

Higgs is one of the main high-priority searches. Involves far more work than could possibly be done justice to in 1 lecture.

e.g. recent NNLO QCD calculations of $gg \to H$

Aim was to explain principles behind searches — these are similar regardless of what you're looking for.

- Identify how new particle or 'phenomenon' (e.g. BH) can be produced.
- Identify how it decays.

Higgs is one of the main high-priority searches. Involves far more work than could possibly be done justice to in 1 lecture.

e.g. recent NNLO QCD calculations of $gg \to H$

Aim was to explain principles behind searches — these are similar regardless of what you're looking for.

- Identify how new particle or 'phenomenon' (*e.g.* BH) can be produced.
- Identify how it decays.
- Choose production and decay channels so as to minimize backgrounds.

NB

Higgs is one of the main high-priority searches. Involves far more work than could possibly be done justice to in 1 lecture.

e.g. recent NNLO QCD calculations of $gg \to H$

Aim was to explain principles behind searches — these are similar regardless of what you're looking for.

- Identify how new particle or 'phenomenon' (*e.g.* BH) can be produced.
- Identify how it decays.
- Choose production and decay channels so as to minimize backgrounds.
- Exploit experimental detector capabilities in choice of channels.
- Very different strategies may be needed in e^+e^- v. hadronic colliders.

Don't forget that it isn't enough to discover it. Then you have to prove it really was what you were looking for in the first place. E.g. for Higgs

Higgs is one of the main high-priority searches. Involves far more work than could possibly be done justice to in 1 lecture.

e.g. recent NNLO QCD calculations of $gg \to H$

Aim was to explain principles behind searches — these are similar regardless of what you're looking for.

- Identify how new particle or 'phenomenon' (*e.g.* BH) can be produced.
- Identify how it decays.
- Choose production and decay channels so as to minimize backgrounds.
- Exploit experimental detector capabilities in choice of channels.
- Very different strategies may be needed in e^+e^- v. hadronic colliders.

Don't forget that it isn't enough to discover it. Then you have to prove it really was what you were looking for in the first place. E.g. for Higgs

NB

Higgs is one of the main high-priority searches. Involves far more work than could possibly be done justice to in 1 lecture.

e.g. recent NNLO QCD calculations of $gg \to H$

Aim was to explain principles behind searches — these are similar regardless of what you're looking for.

- Identify how new particle or 'phenomenon' (*e.g.* BH) can be produced.
- Identify how it decays.
- Choose production and decay channels so as to minimize backgrounds.
- Exploit experimental detector capabilities in choice of channels.
- Very different strategies may be needed in e^+e^- v. hadronic colliders.

Don't forget that it isn't enough to discover it. Then you have to prove it really was what you were looking for in the first place. E.g. for Higgs

NB

Higgs is one of the main high-priority searches. Involves far more work than could possibly be done justice to in 1 lecture.

e.g. recent NNLO QCD calculations of $gg \to H$

Aim was to explain principles behind searches — these are similar regardless of what you're looking for.

- Identify how new particle or 'phenomenon' (*e.g.* BH) can be produced.
- Identify how it decays.
- Choose production and decay channels so as to minimize backgrounds.
- Exploit experimental detector capabilities in choice of channels.
- Very different strategies may be needed in e^+e^- v. hadronic colliders.

Don't forget that it isn't enough to discover it. Then you have to prove it really was what you were looking for in the first place. E.g. for Higgs

- Yukawa couplings to fermions

Higgs is one of the main high-priority searches. Involves far more work than could possibly be done justice to in 1 lecture.

e.g. recent NNLO QCD calculations of $gg \to H$

Aim was to explain principles behind searches — these are similar regardless of what you're looking for.

- Identify how new particle or 'phenomenon' (*e.g.* BH) can be produced.
- Identify how it decays.
- Choose production and decay channels so as to minimize backgrounds.
- Exploit experimental detector capabilities in choice of channels.
- Very different strategies may be needed in e^+e^- v. hadronic colliders.

Don't forget that it isn't enough to discover it. Then you have to prove it really was what you were looking for in the first place. E.g. for Higgs

- Yukawa couplings to fermions.
- Couplings to other gauge bosons

Higgs is one of the main high-priority searches. Involves far more work than could possibly be done justice to in 1 lecture.

e.g. recent NNLO QCD calculations of $gg \to H$

Aim was to explain principles behind searches — these are similar regardless of what you're looking for.

- Identify how new particle or 'phenomenon' (*e.g.* BH) can be produced.
- Identify how it decays.
- Choose production and decay channels so as to minimize backgrounds.
- Exploit experimental detector capabilities in choice of channels.
- Very different strategies may be needed in e^+e^- v. hadronic colliders.

Don't forget that it isn't enough to discover it. Then you have to prove it really was what you were looking for in the first place. E.g. for Higgs

- Yukawa couplings to fermions.
- Couplings to other gauge bosons.
- Self-couplings (reconstruct potential).

NB

Higgs is one of the main high-priority searches. Involves far more work than could possibly be done justice to in 1 lecture.

e.g. recent NNLO QCD calculations of $gg \to H$

Aim was to explain principles behind searches — these are similar regardless of what you're looking for.

- Identify how new particle or 'phenomenon' (*e.g.* BH) can be produced.
- Identify how it decays.
- Choose production and decay channels so as to minimize backgrounds.
- Exploit experimental detector capabilities in choice of channels.
- Very different strategies may be needed in e^+e^- v. hadronic colliders.

Don't forget that it isn't enough to discover it. Then you have to prove it really was what you were looking for in the first place. E.g. for Higgs

- Yukawa couplings to fermions.
- Couplings to other gauge bosons.
- Self-couplings (reconstruct potential).

Higgs is one of the main high-priority searches. Involves far more work than could possibly be done justice to in 1 lecture.

e.g. recent NNLO QCD calculations of $gg \to H$

Aim was to explain principles behind searches — these are similar regardless of what you're looking for.

- Identify how new particle or 'phenomenon' (*e.g.* BH) can be produced.
- Identify how it decays.
- Choose production and decay channels so as to minimize backgrounds.
- Exploit experimental detector capabilities in choice of channels.
- Very different strategies may be needed in e^+e^- v. hadronic colliders.

Don't forget that it isn't enough to discover it. Then you have to prove it really was what you were looking for in the first place. E.g. for Higgs

- Yukawa couplings to fermions.
- Couplings to other gauge bosons.
- Self-couplings (reconstruct potential).

NB

Higgs is one of the main high-priority searches. Involves far more work than could possibly be done justice to in 1 lecture.

e.g. recent NNLO QCD calculations of $gg \to H$

Aim was to explain principles behind searches — these are similar regardless of what you're looking for.

- Identify how new particle or 'phenomenon' (*e.g.* BH) can be produced.
- Identify how it decays.
- Choose production and decay channels so as to minimize backgrounds.
- Exploit experimental detector capabilities in choice of channels.
- Very different strategies may be needed in e^+e^- v. hadronic colliders.

Don't forget that it isn't enough to discover it. Then you have to prove it really was what you were looking for in the first place. E.g. for Higgs

- Yukawa couplings to fermions.
- Couplings to other gauge bosons.
- Self-couplings (reconstruct potential).

Things swept under the carpet. . .

- We talked about quark production and discussed it perturbatively, but experiments see jets of (non-perturbative) hadrons. What's the relation? Are we justified in making the connection? Is it well-defined?
- We talk about hard interactions between partons from the proton. But proton is non-perturbative. To what extent are we allowed to do this?
- When you calculate them in detail many cross sections seem divergent. . . What's going on?

Subject of the remaining two lectures

Things swept under the carpet...

- We talked about quark production and discussed it perturbatively, but experiments see jets of (non-perturbative) hadrons. What's the relation? Are we justified in making the connection? Is it well-defined?
- We talk about hard interactions between partons from the proton. But proton is non-perturbative. To what extent are we allowed to do this?
- When you calculate them in detail many cross sections seem divergent... What's going on?

Subject of the remaining two lectures

Things swept under the carpet. . .

- We talked about quark production and discussed it perturbatively, but experiments see jets of (non-perturbative) hadrons. What's the relation? Are we justified in making the connection? Is it well-defined?
- We talk about hard interactions between partons from the proton. But proton is non-perturbative. To what extent are we allowed to do this?
- When you calculate them in detail many cross sections seem divergent. . . What's going on?

Subject of the remaining two lectures

Things swept under the carpet...

- We talked about quark production and discussed it perturbatively, but experiments see jets of (non-perturbative) hadrons. What's the relation? Are we justified in making the connection? Is it well-defined?
- We talk about hard interactions between partons from the proton. But proton is non-perturbative. To what extent are we allowed to do this?
- When you calculate them in detail many cross sections seem divergent. . . What's going on?

Subject of the remaining two lectures