

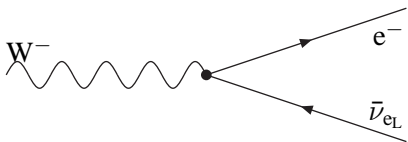
Particle Physics: The Standard Model

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May 24, 2012

- Study properties of the W^\pm boson
- Study properties of the Z^0 boson
- Study properties of the t quark
- Theory+Experiment to “discover” the Higgs boson



- W^- polarization vector
- electron final state
- anti-neutrino final state
- EW vertex
- $\gamma^{0\dagger} = \gamma^0$ and $\gamma_\nu^\dagger = \gamma^0 \gamma_\nu \gamma^0$

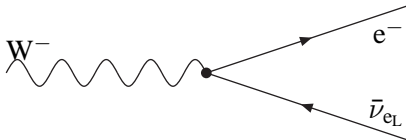
$$T_{fi} = \epsilon^\mu \bar{u}(\mathbf{k}) \left(-i \frac{e}{\sqrt{2} \sin \theta_W} \gamma_\mu \frac{1-\gamma_5}{2} \right) v(\mathbf{k}')$$

$$|\mathcal{M}|^2 = \sum' \epsilon^\mu \bar{u}(\mathbf{k}) \left(-i \frac{e}{\sqrt{2} \sin \theta_W} \gamma_\mu \frac{1-\gamma_5}{2} \right) v(\mathbf{k}')$$

$$\epsilon^{\nu*} v^\dagger(\mathbf{k}') \left(\frac{1-\gamma_5}{2} \right) \gamma_\nu^\dagger i \frac{e}{\sqrt{2} \sin \theta_W} \gamma^{0\dagger} u(\mathbf{k})$$

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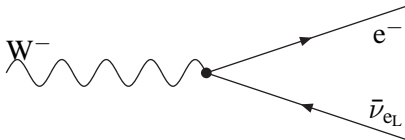
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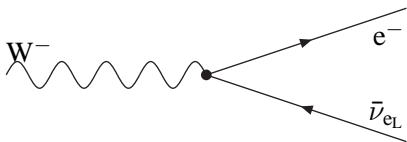
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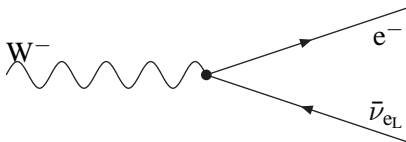
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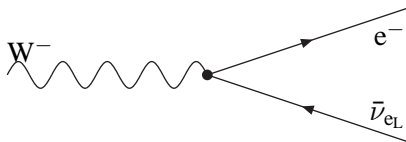
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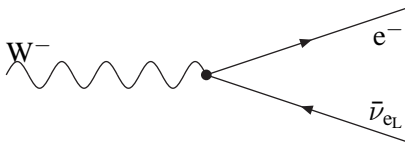


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- common factors and \bar{v}
- initial state Spin average and polarisation vector relationship
- Spinor relationship
- $Tr(0\dots3\gamma\gamma_5) = 0$

$$\begin{aligned} |\mathcal{M}|^2 &= \frac{e^2}{2 \sin^2 \theta_W} \sum' \epsilon^\mu \epsilon^{\nu*} \bar{u}(\mathbf{k}) \gamma_\mu \frac{1-\gamma_5}{2} v(\mathbf{k}') v^\dagger(\mathbf{k}') \frac{1-\gamma_5}{2} \gamma^0 \gamma_\nu u(\mathbf{k}) \\ &= \frac{e^2}{8 \sin^2 \theta_W} \sum' \epsilon^\mu \epsilon^{\nu*} \bar{u}(\mathbf{k}) \gamma_\mu (1 - \gamma_5) v(\mathbf{k}') \bar{v}(\mathbf{k}') (1 + \gamma_5) \gamma_\nu u(\mathbf{k}) \\ &= \frac{e^2}{3.8 \sin^2 \theta_W} \sum (-g^{\mu\nu}) \bar{u}(\mathbf{k}) \gamma_\mu (1 - \gamma_5) v(\mathbf{k}') \bar{v}(\mathbf{k}') (1 + \gamma_5) \gamma_\nu u(\mathbf{k}) \\ &= \frac{-e^2}{24 \sin^2 \theta_W} Tr(\not{k} \gamma_\mu (1 - \gamma_5) \not{k}' (1 + \gamma_5) \gamma^\mu) \\ &= \frac{-e^2}{24 \sin^2 \theta_W} [Tr(\not{k} \gamma_\mu \not{k}' \gamma^\mu) - Tr(\not{k} \gamma_\mu \gamma_5 \not{k}' \gamma_5 \gamma^\mu)] \\ &= \frac{-e^2}{24 \sin^2 \theta_W} [Tr(\not{k} \gamma_\mu \not{k}' \gamma^\mu) + Tr(\not{k} \gamma_\mu \not{k}' \gamma^\mu)] \end{aligned}$$

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 &= \frac{e^2}{8 \sin^2 \theta_W} \sum' \epsilon^\mu \epsilon^{\nu*} \bar{u}(\mathbf{k}) \gamma_\mu (1 - \gamma_5) v(\mathbf{k}') \bar{v}(\mathbf{k}') (1 + \gamma_5) \gamma_\nu u(\mathbf{k}) \\
 &= \frac{e^2}{3.8 \sin^2 \theta_W} \sum (-g^{\mu\nu}) \bar{u}(\mathbf{k}) \gamma_\mu (1 - \gamma_5) v(\mathbf{k}') \bar{v}(\mathbf{k}') (1 + \gamma_5) \gamma_\nu u(\mathbf{k}) \\
 &= \frac{-e^2}{24 \sin^2 \theta_W} Tr(\not{k} \gamma_\mu (1 - \gamma_5) \not{k}' (1 + \gamma_5) \gamma^\mu) \\
 &= \frac{-e^2}{24 \sin^2 \theta_W} [Tr(\not{k} \gamma_\mu \not{k}' \gamma^\mu) - Tr(\not{k} \gamma_\mu \gamma_5 \not{k}' \gamma_5 \gamma^\mu)] \\
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- $Tr(\gamma_\mu \gamma_\nu \gamma_\rho \gamma_\sigma) = 4(g_{\mu\nu}g_{\rho\sigma} + g_{\mu\sigma}g_{\nu\rho} - g_{\mu\rho}g_{\nu\sigma})$
- $m_{W^\pm}^2 = s = (\mathbf{k} + \mathbf{k}')^2 = \mathbf{k}^2 + \mathbf{k}'^2 + 2\mathbf{k}\mathbf{k}' \approx 2\mathbf{k}\mathbf{k}'$
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$$\begin{aligned} |\mathcal{M}|^2 &= \frac{-e^2}{12 \sin^2 \theta_W} [Tr(\mathbf{k} \gamma_\mu \mathbf{k}' \gamma^\mu)] \\ &= \frac{-e^2}{3 \sin^2 \theta_W} k^\mu k'^\rho g^{\nu\sigma} (g_{\mu\nu}g_{\rho\sigma} + g_{\mu\sigma}g_{\nu\rho} - g_{\mu\rho}g_{\nu\sigma}) \\ &= \frac{-e^2}{3 \sin^2 \theta_W} (\mathbf{k} \cdot \mathbf{k}' + \mathbf{k} \cdot \mathbf{k}' - \mathbf{k} \cdot \mathbf{k}' \cdot 4) \\ &= \frac{2e^2}{3 \sin^2 \theta_W} \mathbf{k} \cdot \mathbf{k}' \\ &= \frac{e^2}{3 \sin^2 \theta_W} m_{W^\pm}^2 \end{aligned}$$

$$d\Gamma_{e\bar{\nu}_e L} = \frac{1}{64\pi^2} \frac{|\mathcal{M}|^2}{\sqrt{s}} d\Omega$$

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W^\pm partial widths

$$\begin{aligned} \Gamma_{e\bar{\nu}_{eL}} &= \frac{1}{16\pi} \frac{e^2}{3 \sin^2 \theta_W} m_{W^\pm} \\ \frac{e^2}{\sin^2 \theta_W} &= 8 \frac{G}{\sqrt{2}} m_{W^\pm}^2 \\ \Gamma_{e\bar{\nu}_{eL}} &= G \frac{1}{6\pi\sqrt{2}} m_{W^\pm}^3 \\ \Gamma_{\bar{u}d} &= G \frac{1}{6\pi\sqrt{2}} m_{W^\pm}^3 \cdot 3 \cdot |V_{ud}|^2 \\ &\quad \left(1 + \frac{\alpha_S(m_{W^\pm}^2)}{\pi}\right) \end{aligned}$$

To include the radiative corrections means inclusive:

$$\Gamma_{\bar{u}d} = \Gamma_{\bar{u}d}(g)$$

Branching ratios

$$\begin{aligned} \Gamma &= \Gamma_{e\nu_{eL}} + \Gamma_{\mu\nu_{\mu L}} + \Gamma_{\tau\nu_{\tau L}} \\ &\quad \Gamma_{ud} + \Gamma_{cs} \\ &\approx (3 + 2 \cdot 3) \Gamma_{e\nu} \\ \mathcal{B}(l\nu) &\approx 30\% \end{aligned}$$

- $t\bar{b}$ final state excluded by mass $180\text{GeV} \gg 80\text{GeV}$
- V_{ij} for $i \neq j$ excluded
 $V_{ij} \ll 1$

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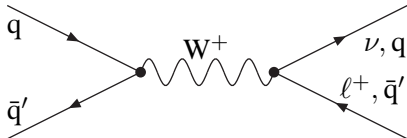
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Branching ratios

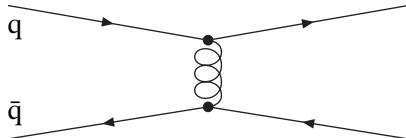
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Hadron colliders



- leptons or jets
- each vertex G_F
- LHC: sea \bar{q}
- LHC NLO: gluon (splitting)
- $\sqrt{\hat{s}} = m_W^\pm$
- $\sqrt{x_1 \cdot x_2} \cdot \sqrt{s} = m_W^\pm$
- $\sqrt{s} \approx 3 \cdot 2m_W^\pm$ (gluon 50%)



- no leptons :)
- each vertex g_S
- jet-jet mass only difference to signal
- LHC: 10^4 lepton-jet rejection

The discovery machine

- SPPS transformed to SP \bar{P} S
- $\sqrt{s} \approx 600$ GeV
- stochastic cooling

TeVatron

- $p\bar{p}$
- $\sqrt{s} \leq 1.96$ TeV
- ≈ 10 fb $^{-1}$
- fb cross sections measureable

LHC

- pp
- $\sqrt{s} \leq 14$ TeV
- luminosity of anti-protons
- gluon PDFs dominate
- QCD cross sections increase more rapidly than the signal
- 2011: 7 TeV ≈ 5 fb $^{-1}$
- 2012: 8 TeV
- 2014: 14 TeV-X

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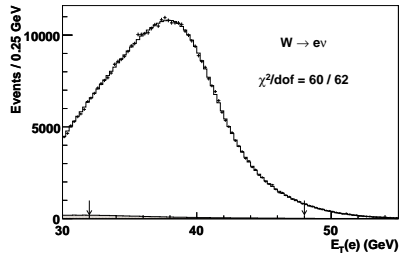
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Transverse Energy

$$E_T \leq \frac{m_W^\pm}{2}$$

- **Problem Solving**
- 2-body decay
- particles massless
- maximal energy half of the mother mass



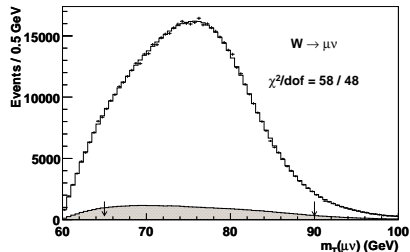
Experimental issues

- finite width
- final state radiation
- detector effects
- ISR

Transverse Mass

$$m_T = m(\sqrt{E_T}, \mathbf{p}_\ell)$$

- $\sqrt{E_T}$ negative sum of activity
- ignore longitudinal component
- maximal mass is m_W^\pm
- less sensitive to NLO

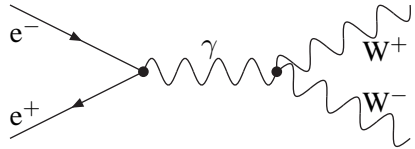
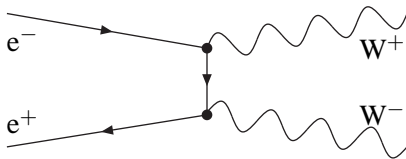


Experimental Results

CDF	80.413	\pm	0.048 GeV
D0	80.401	\pm	0.043 GeV

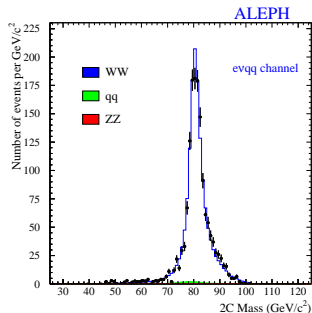
Lepton Colliders

- CM system is lab system
- $\sqrt{\hat{s}} = \sqrt{s}$ (modulo ISR)
- initial state charge zero
- pair production



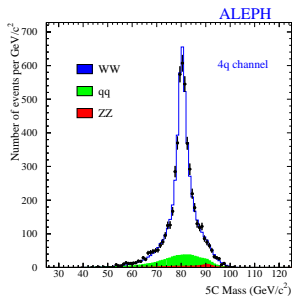
Signatures

- $W^+W^- \rightarrow q\bar{q}q\bar{q}$ 50%
- $W^+W^- \rightarrow l\nu q\bar{q}$ 40%
- $W^+W^- \rightarrow l\nu l\nu$ 10%
- 90% useful with $\nu = \cancel{E}$



Semi-leptonic

- low background
- use separately leptonic decay and hadronic decay



Fully hadronic

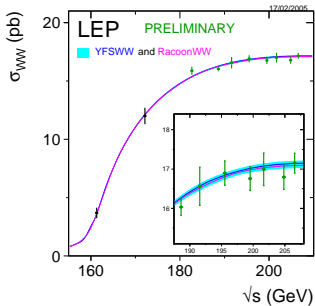
- QCD background
- jet reconstruction and calibration
- Color reconnection (jet algo)

Experimental Results

ALEPH	80.440	\pm	0.051 GeV
DELPHI	80.336	\pm	0.067 GeV
L3	80.270	\pm	0.055 GeV
OPAL	80.415	\pm	0.052 GeV
PDG	80.399	\pm	0.023 GeV

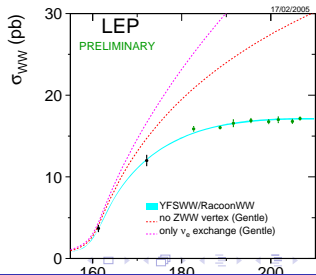
WW Cross section

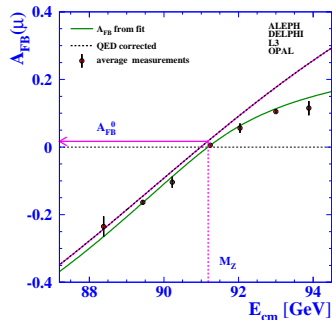
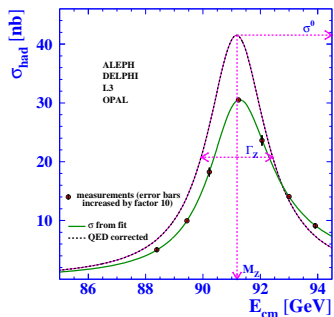
- threshold scan sensitive to W mass
- width washes out threshold



WW Interpretation

- 1 t channel alone: insufficient
- 2 adding γW^+W^- still insufficient
- 3 **unitarity not proven**



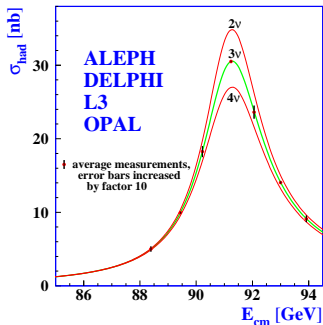


Experimental Issues

- measure beam energy precisely
- measure efficiency precisely

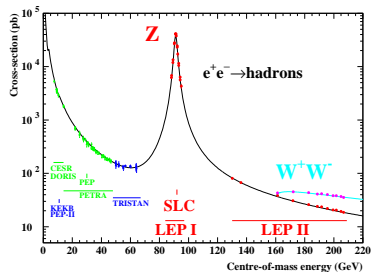
Predictions/Measurements

- Radiative corrections important
- Interference zero on peak



Results

- 3 generations
- $91.1875 \pm 0.0021 \text{ GeV}$
- $2.4952 \pm 0.0023 \text{ GeV}$



Results

Impressive agreement over

- decades in time
- different machines
- different energies

Forward/backward asymmetry

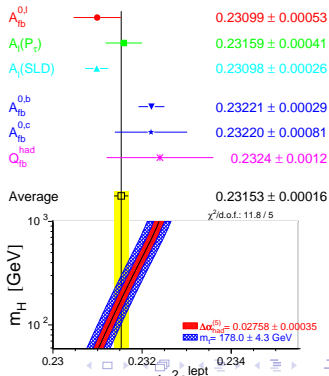
$$A_{FB}(f) = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta}{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta + \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta}$$

Measurements

- A_{FB} is a measurement of $\sin^2 \theta_W$
- leptons easy
- hadrons hard
- leptons with polarization

Open question

Do leptons behave differently than hadrons?

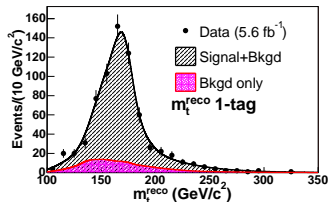
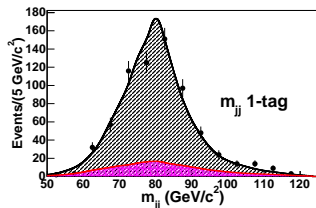


Experimental issues

- jet reconstruction
- jet calibration
- b tagging
- W mass constraint
- all final states used

Experimental result

PDG $172.9 \pm 0.6 \pm 0.9$ GeV



Perturbativity and Unitarity

- unitarity of WW scattering (see WW)
- width smaller than mass
- upper limit on Higgs boson mass

Triviality

RGE solution Quartic coupling (only Higgs sector for large λ):

$$\lambda(Q^2) = \lambda(v^2) \left[1 - \frac{3}{4\pi^2} \lambda(v^2) \log \frac{Q^2}{v^2} \right]^{-1}$$

- $Q \gg v \rightarrow \lambda = \infty$ Landau pole
- $Q = 0 \rightarrow \lambda = 0$ (trivial)
- ϕ^4 must be trivial if valid at all scales
- navigate between the poles

Perturbativity and Unitarity

- unitarity of WW scattering (see WW)
- width smaller than mass
- upper limit on Higgs boson mass

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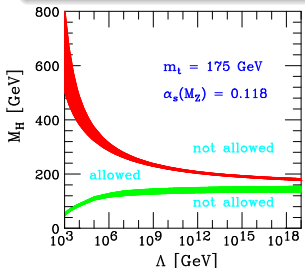
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Stability

RGE solution including fermions (small λ):

$$\lambda(Q^2) = \lambda(v^2) \frac{1}{16\pi^2} \left[+\frac{3}{16} \left(-12 \frac{m_t^4}{v^4} + 2g_2^4 + (g_2^2 + g_1^2)^2 \right) \right] \log \frac{Q^2}{v^2}$$

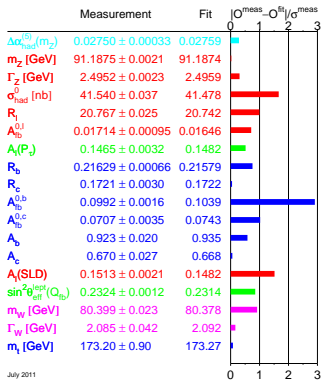
- λ small \rightarrow top yukawa can turn $\lambda < 0$
- Higgs potential unbounded



Consequences

Λ : cut-off scale for new physics

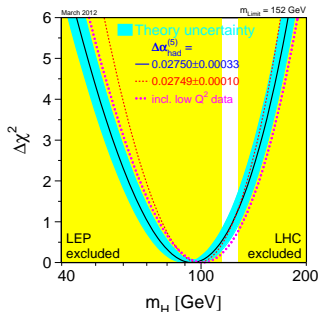
- $m_H \leq 700 \text{ GeV}$
- window for SM valid up to GUT scale



July 2011

EW measurements

- internally compatible
- largest deviation: asymmetry



Indirect Higgs Search

logarithmic dependence on Higgs boson mass:

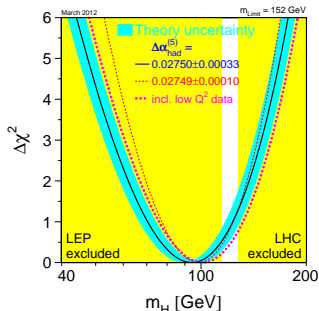
$$m_H = 94_{-24}^{+29} \text{ GeV}$$

	Measurement	Fit	$ \sigma_{\text{meas}} - \sigma_{\text{fit}} / \sigma_{\text{meas}}$
	$\Delta\alpha_{\text{had}}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
	m_Z [GeV]	91.1875 ± 0.0021	91.1874
	Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
	σ_{had}^0 [nb]	41.540 ± 0.037	41.478
	R_b	20.767 ± 0.025	20.742
	$A_{\text{fb}}^{0,l}$	0.01714 ± 0.00095	0.01646
	$A_1(P_\tau)$	0.1465 ± 0.0032	0.1482
	R_b	0.21629 ± 0.00066	0.21579
	R_c	0.1721 ± 0.0030	0.1722
	$A_{\text{fb}}^{0,b}$	0.0992 ± 0.0016	0.1039
	$A_{\text{fb}}^{0,c}$	0.0707 ± 0.0035	0.0743
	A_b	0.923 ± 0.020	0.935
	A_c	0.670 ± 0.027	0.668
	$A_1(\text{SLD})$	0.1513 ± 0.0021	0.1482
	$\sin^2\theta_{\text{eff}}^{\text{lep}}(Q_{\text{fb}})$	0.2324 ± 0.0012	0.2314
	m_W [GeV]	80.399 ± 0.023	80.378
	Γ_W [GeV]	2.085 ± 0.042	2.092
	m_t [GeV]	173.20 ± 0.90	173.27

July 2011

EW measurements

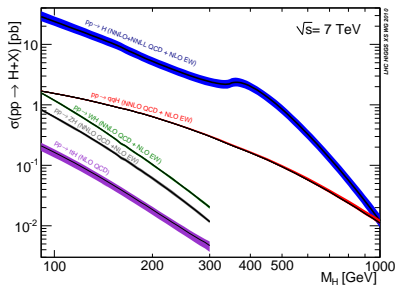
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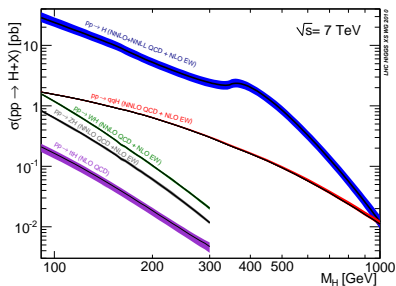


Higgs boson production

- gluon fusion (NLO > 2)
- VBF ($\mathcal{O}(20\%)$)
- associated production
- radiation off heavy quark

Experimental issues

- huge QCD background for jets
- mass information?
- mass resolution?
- total cross section
 $\sim \text{mb} = 10^{-3}\text{b}$
- signal $\sim \text{pb} = 10^{-12}\text{b}$
- pile-up

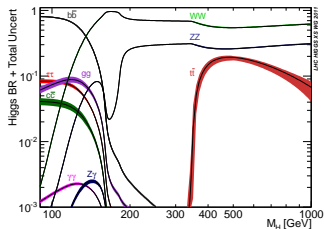
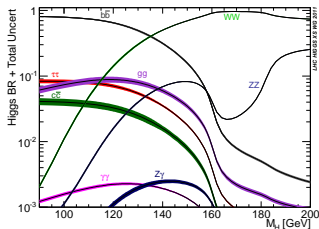


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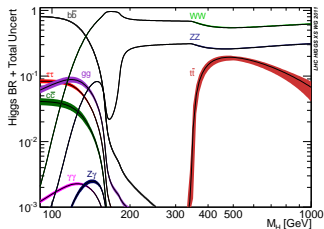
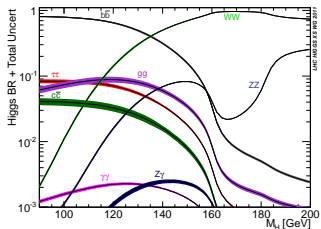


Low mass Higgs boson

- heaviest fermion dominates: b
- gauge boson pairs (one off-shell) kick in
- thresholds visible

High mass Higgs boson

- gauge bosons dominate
- top threshold 350 GeV
- \sqrt{s} dependence in gauge bosons

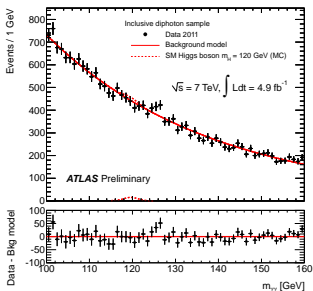
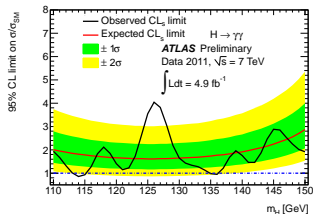
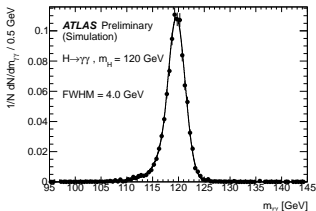


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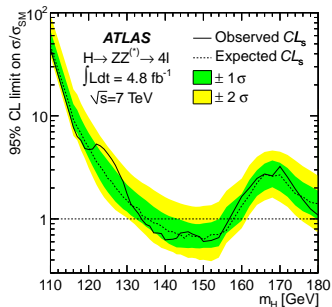
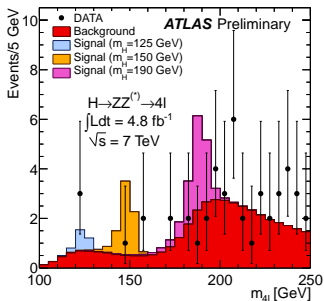
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Result

- more data than expected from background alone around 125GeV

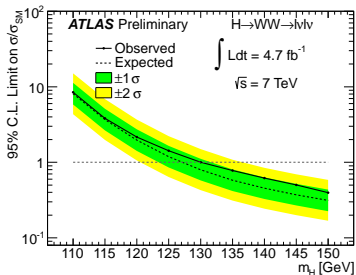
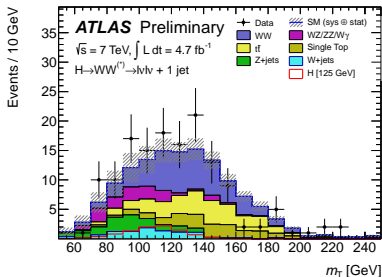


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- ZZ EW production
- mass resolution required
- e, μ : low \mathcal{B}

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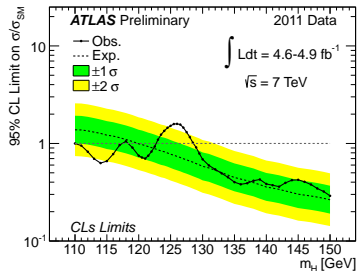
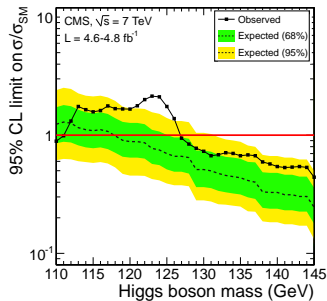
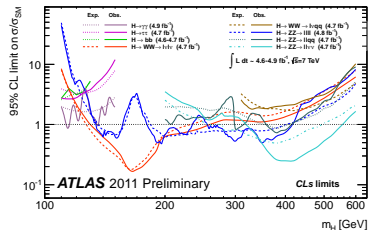


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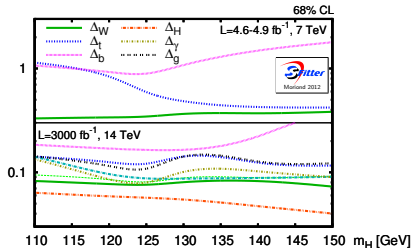
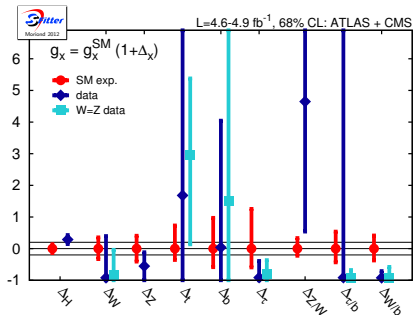
- WW EW production
- no mass peak
- use azimuthal correlation

Result

- compatible with background only at 1σ level



Higgs Summary
 after LEE: about $2\sigma \rightarrow$ more data is needed

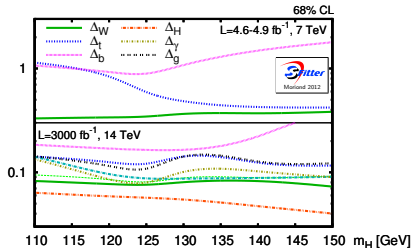
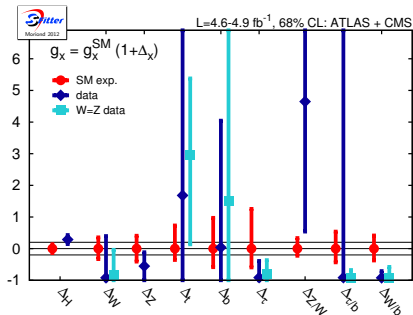


Higgs couplings

- global sensitivity 15%
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- luminosity 3000 fb^{-1}
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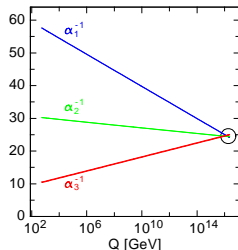
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- Planck scale (gravity) 10^{18}GeV
- unification of g_1, g_2, g_3 at 10^{16}GeV ?
- Standard Model: close miss

Supersymmetry

- fermionic degree of freedom has a bosonic counter part
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- light $< 140\text{GeV}$ Higgs boson
- stabilizes the Higgs boson mass
- dark matter candidate



Experimental evidence

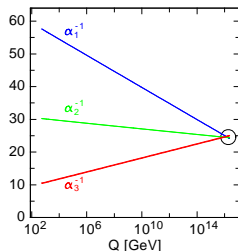
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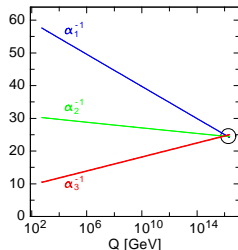
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Future

- The Standard Model is alive and kicking
- Will the Higgs boson be discovered?
 - What the couplings of the Higgs boson?
 - What is the self-coupling of the Higgs boson?
- Neutrinos
 - Mixing in the leptonic sector
 - Is the Neutrino Majorana or DIRAC?
- Is there new physics beyond the Standard Model?
 - Supersymmetry
 - Extra Dimensions
 - ...
- What happens up to the Planck scale at 10^{18}GeV ?
 - Desert from EW to GUT scale?
 - Unification of the 3 forces at the GUT scale?