Particle Physics: The Standard Model

Dirk Zerwas

LAL
zerwas@lal.in2p3.fr

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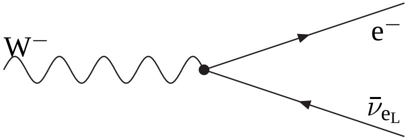
- Study properties of the $W^{\pm}$ boson
- Study properties of the Z° boson
- Study properties of the t quark
- Theory$+$Experiment to “discover” the Higgs boson



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

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

$$|\mathcal{M}|^2 = \sum{}' \epsilon^\mu \bar{u}(\mathbf{k})(-i \frac{e}{\sqrt{2}\sin\theta_W} \gamma_\mu \frac{1-\gamma_5}{2}) v(\mathbf{k}') \epsilon^{\nu\star} v^\dagger(\mathbf{k}')(\frac{1-\gamma_5}{2}) \gamma_\nu{}^\dagger i \frac{e}{\sqrt{2}\sin\theta_W} \gamma^{0\dagger} u(\mathbf{k})$$

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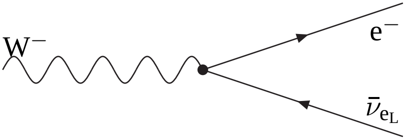

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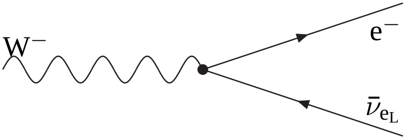

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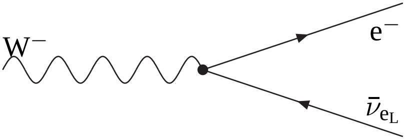

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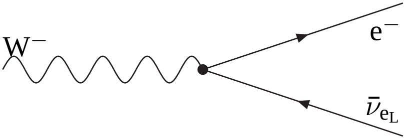

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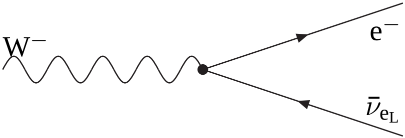

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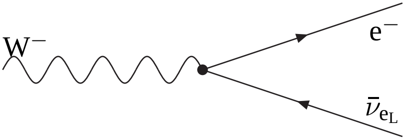

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- common factors and $\bar{v}$
- initial state Spin average and polarisation vector relationship
- Spinor relationship
- $Tr(0...3\gamma\gamma_5) = 0$

$$|\mathcal{M}|^2 = \frac{e^2}{2\sin^2\theta_W} \sum{}' \epsilon^\mu \epsilon^{\nu\star} \bar{u}(\mathbf{k})\gamma_\mu \frac{1-\gamma_5}{2} v(\mathbf{k}') v^\dagger(\mathbf{k}') \frac{1-\gamma_5}{2} \gamma^0 \gamma_\nu u(\mathbf{k})$$

$$= \frac{e^2}{8\sin^2\theta_W} \sum{}' \epsilon^\mu \epsilon^{\nu\star} \bar{u}(\mathbf{k})\gamma_\mu (1-\gamma_5) v(\mathbf{k}') \bar{v}(\mathbf{k}') (1+\gamma_5)\gamma_\nu u(\mathbf{k})$$

$$= \frac{e^2}{3\cdot 8\sin^2\theta_W} \sum(-g^{\mu\nu}) \bar{u}(\mathbf{k})\gamma_\mu (1-\gamma_5) v(\mathbf{k}') \bar{v}(\mathbf{k}') (1+\gamma_5)\gamma_\nu u(\mathbf{k})$$

$$= \frac{-e^2}{24\sin^2\theta_W} Tr(\not{\mathbf{k}}\gamma_\mu (1-\gamma_5) \not{\mathbf{k}}' (1+\gamma_5)\gamma^\mu)$$

$$= \frac{-e^2}{24\sin^2\theta_W} [Tr(\not{\mathbf{k}}\gamma_\mu \not{\mathbf{k}}'\gamma^\mu) - Tr(\not{\mathbf{k}}\gamma_\mu\gamma_5 \not{\mathbf{k}}'\gamma_5\gamma^\mu)]$$

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&= \frac{e^2}{8\sin^2\theta_W}\sum{}' \epsilon^\mu\epsilon^{\nu\star}\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\cdot 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) \\
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- $Tr(\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma) = 4(g_{\mu\nu}g_{\rho\sigma} + g_{\mu\sigma}g_{\nu\rho} - g_{\mu\rho}g_{\nu\sigma})$
- $m^2_{W^\pm} = s = (\mathbf{k}+\mathbf{k}')^2 = \mathbf{k}^2 + \mathbf{k}'^2 + 2\mathbf{k}\mathbf{k}' \approx 2\mathbf{k}\mathbf{k}'$
- ME isotropical (as should be for unpolarized decay!

$$|\mathcal{M}|^2 = \frac{-e^2}{12\sin^2\theta_W}[Tr(\not{\mathbf{k}}\gamma_\mu\not{\mathbf{k}}'\gamma^\mu)]$$
$$= \frac{-e^2}{3\sin^2\theta_W}k^\mu k'^\rho g^{\nu\sigma}(g_{\mu\nu}g_{\rho\sigma} + g_{\mu\sigma}g_{\nu\rho} - g_{\mu\rho}g_{\nu\sigma})$$
$$= \frac{-e^2}{3\sin^2\theta_W}(\mathbf{k}\cdot\mathbf{k}' + \mathbf{k}\cdot\mathbf{k}' - \mathbf{k}\cdot\mathbf{k}'\cdot 4)$$
$$= \frac{2e^2}{3\sin^2\theta_W}\mathbf{k}\cdot\mathbf{k}'$$
$$= \frac{e^2}{3\sin^2\theta_W}m^2_{W^\pm}$$

$$d\Gamma_{e\bar{\nu}_{e_L}} = \frac{1}{64\pi^2}\frac{|\mathcal{M}|^2}{\sqrt{s}}d\Omega$$
$$\Gamma_{e\bar{\nu}_{e_L}} = \frac{1}{64\pi^2}\frac{1}{m_{W^\pm}}\frac{e^2}{3\sin^2\theta_W}m^2_{W^\pm}4\pi$$

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$$
\begin{aligned}
|\mathcal{M}|^2 &= \frac{-e^2}{12\sin^2\theta_W}[Tr(\not{\mathbf{k}}\gamma_\mu \not{\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) \\
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$\mathrm{W}^\pm$ partial widths

$$\Gamma_{e\bar{\nu}_{e_L}} = \frac{1}{16\pi}\frac{e^2}{3\sin^2\theta_W} m_{\mathrm{W}^\pm}$$

$$\frac{e^2}{\sin^2\theta_W} = 8\frac{G}{\sqrt{2}} m^2_{\mathrm{W}^\pm}$$

$$\Gamma_{e\bar{\nu}_{e_L}} = G\frac{1}{6\pi\sqrt{2}} m^3_{\mathrm{W}^\pm}$$

$$\Gamma_{\bar{u}d} = G\frac{1}{6\pi\sqrt{2}} m^3_{\mathrm{W}^\pm} 3\cdot|V_{ud}|^2 \left(1+\frac{\alpha_S(m^2_{\mathrm{W}^\pm})}{\pi}\right)$$

To include the radiative corrections means inclusive: $\Gamma_{\bar{u}d} = \Gamma_{\bar{u}d(g)}$

Branching ratios

$$\Gamma = \Gamma_{e\nu_{e_L}} + \Gamma_{\mu\nu_{\mu_L}} + \Gamma_{\tau\nu_{\tau_L}} + \Gamma_{ud} + \Gamma_{cs} \approx (3+2\cdot 3)\Gamma_{e\nu}$$

$$\mathcal{B}(\ell\nu) \approx 30\%$$

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

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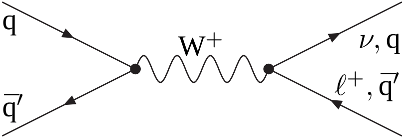
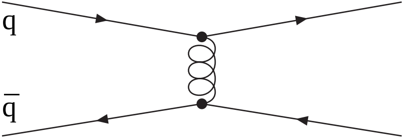
Hadron colliders





- 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
- $\approx 10\text{fb}^{-1}$
- 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: 7TeV $\approx 5\text{fb}^{-1}$
- 2012: 8TeV $\approx 25\text{fb}^{-1}$
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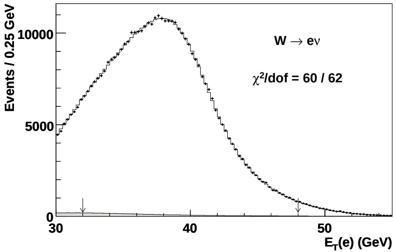
Transverse Energy

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

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



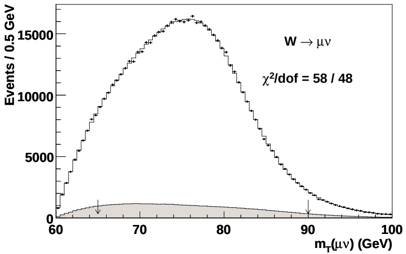
Experimental issues

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

Transverse Mass

$$m_T = m(\not{E}_T, \mathbf{p}_\ell)$$

- $\not{E}_T$ negative sum of activity
- ignore longitudinal component
- maximal mass is $m_W^{\pm}$
- less sensitive to NLO

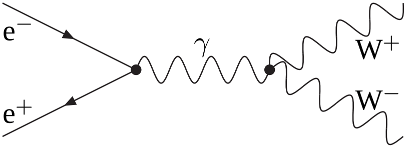


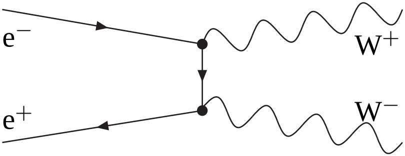
Experimental Results

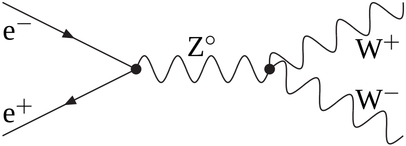
CDF	80.413	$\pm$	0.048 GeV
D0	80.401	$\pm$	0.043 GeV

Lepton Colliders

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

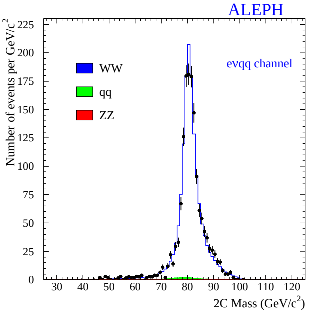






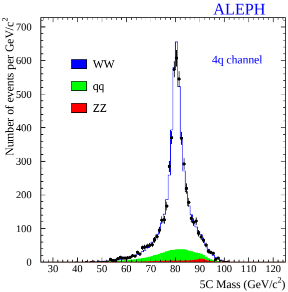
Signatures

- $W^+W^- \to q\bar{q}q\bar{q}$ 50%
- $W^+W^- \to \ell\nu q\bar{q}$ 40%
- $W^+W^- \to \ell\nu\ell\nu$ 10%
- 90% useful with $\nu = \not{E}$



Semi-leptonic

- low background
- use separately leptonic decay and hadronic decay



Fully hadronic

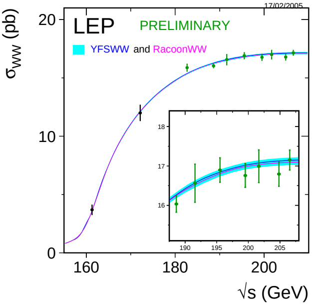
- QCD background
- jet reconstruction and calibration
- Color reconnection (jet algo)

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

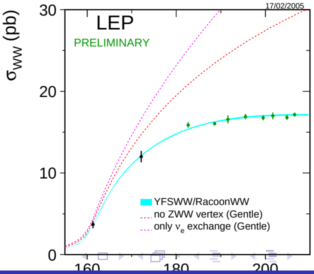
WW Cross section

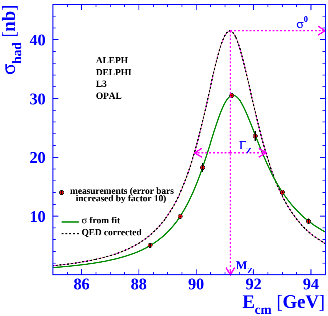
- threshold scan sensitive to W mass
- width washes out threshold

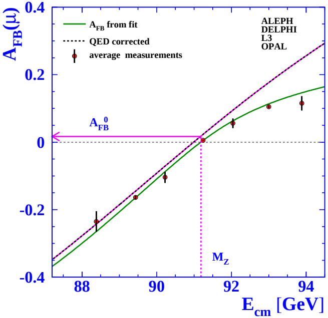


WW Interpretation

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





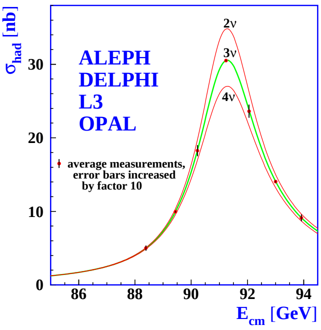


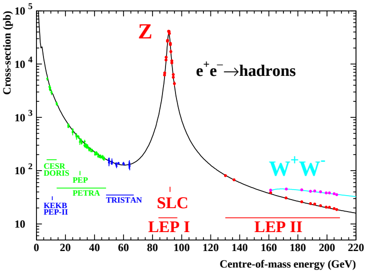
Experimental Issues

- measure beam energy precisely
- measure efficiency precisely

Predictions/Measurements

- Radiative corrections important
- Interference zero on peak





Results

- 3 generations
- 91.1875 ± 0.0021GeV
- 2.4952 ± 0.0023 GeV

Results

Impressive agreement over

- decades in time
- different machines
- different energies

Forward/backward asymmetry

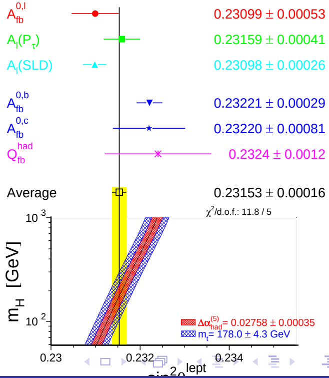
$$A_{FB}(f) = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta}{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta + \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta}$$

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?

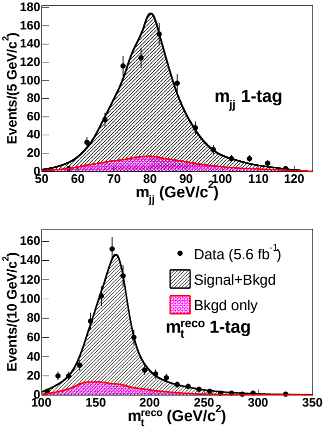


Experimental issues

- 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):

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

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

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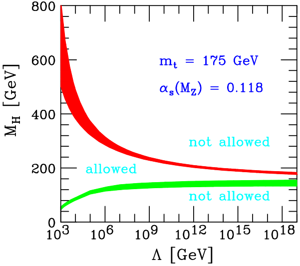
Stability

RGE solution including fermions (small λ):

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

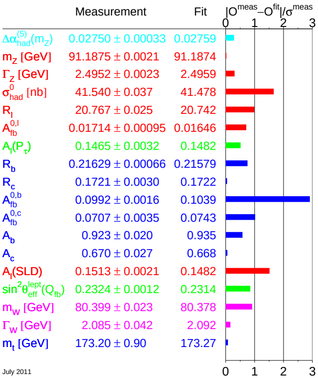
- λ small $\rightarrow$ top yukawa can turn $\lambda < 0$
- Higgs potential unbounded

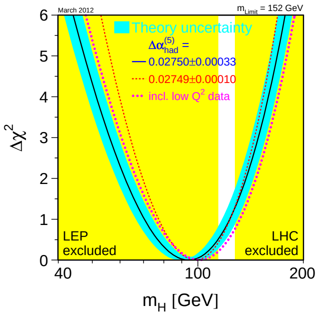


Consequences

Λ: cut-off scale for new physics

- $m_H \leq 700$ GeV
- window for SM valid up to GUT scale at 125GeV





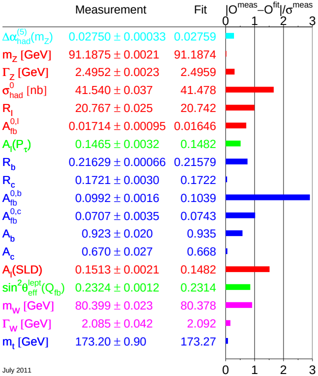
EW measurements

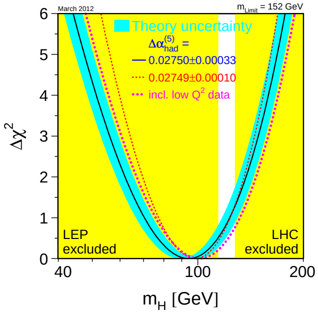
- internally compatible
- largest deviation: asymmetry

Indirect Higgs Search

logarithmic dependence on Higgs boson mass:

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





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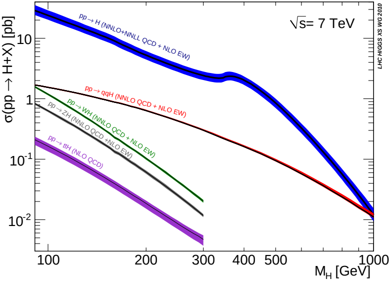
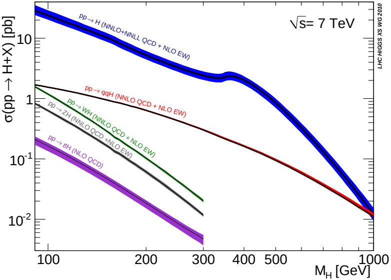


Higgs boson production

- 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 $\sim \mathrm{mb} = 10^{-3}\mathrm{b}$
- signal $\sim \mathrm{pb} = 10^{-12}\mathrm{b}$
- pile-up



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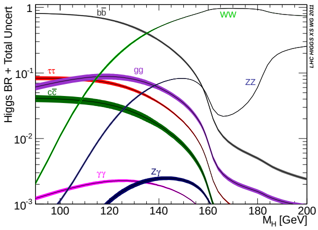
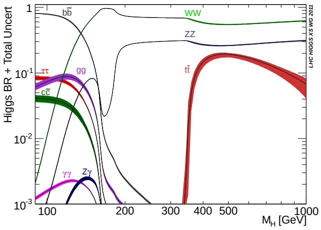


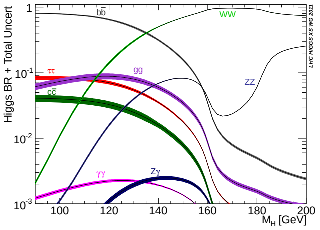


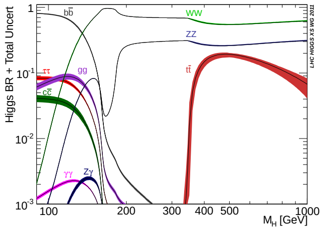
Low mass Higgs boson

- 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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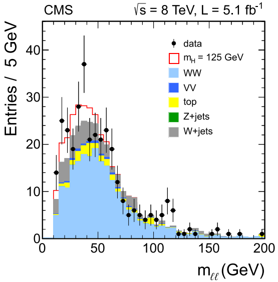
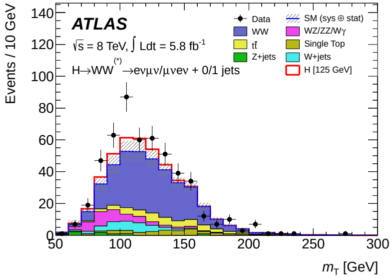
Higgs to WW*

- WW EW production
- no mass peak



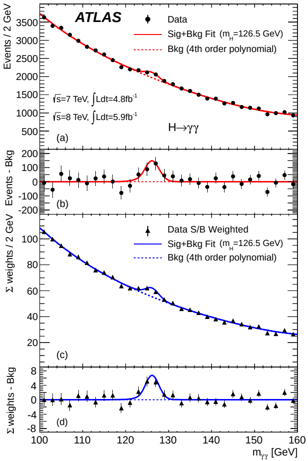


Using the spin correlation

- Higgs Spin-0
- W opposite
- charged leptons emitted in the same direction

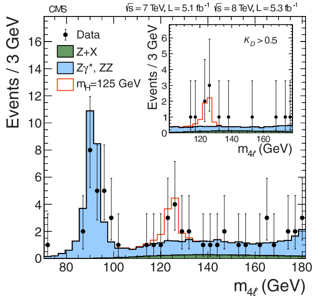
Higgs to $\gamma\gamma$

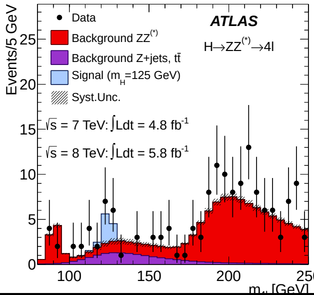
- Rare decay (via triangle) as γ is massless 10^{-3}
- SM background from continuum di-photon production (EM couplings)
- excellent mass resolution necessary

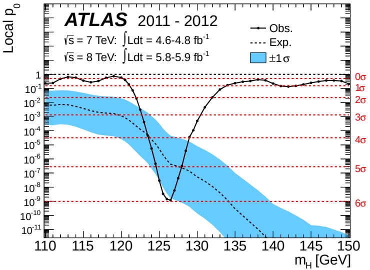


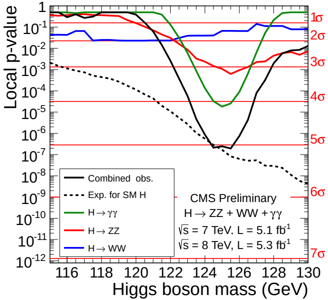
Higgs to ZZ*

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









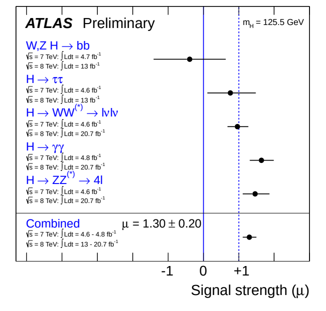
A new resonance

- discovery convention: 5σ
- independent discovery in two experiments

A success of particle physics

- discovery 50 years after the prediction

Signal Strengths ATLAS (Moriond 2013)



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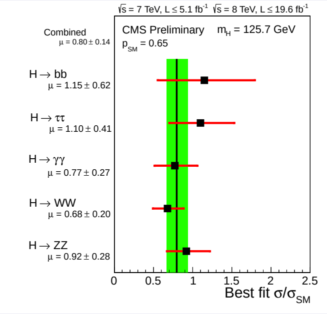
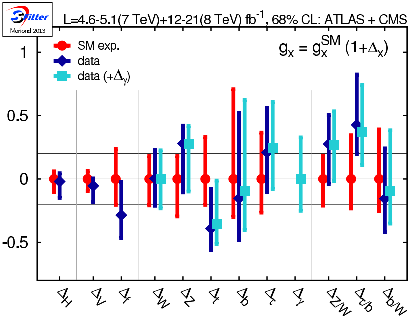
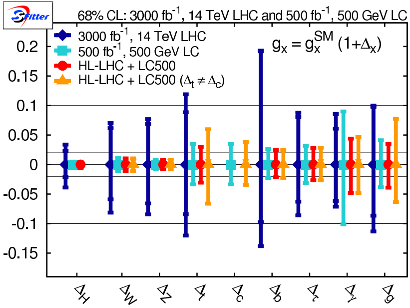




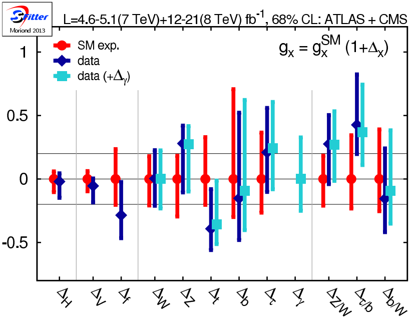


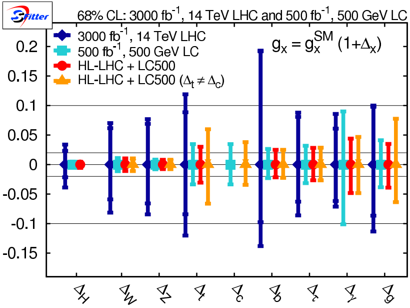
Higgs couplings

- global sensitivity 15%
- smallest errors for gauge boson couplings

Higgs couplings future

- luminosity $3000 fb^{-1}$
- global sensitivity 5%
- precision of the order 10-20%





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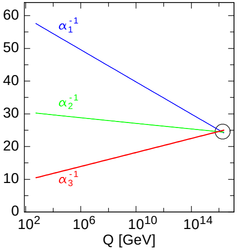
Gauge couplings

- 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
- unification g_1, g_2, g_3 at 10^{16}GeV
- light < 140GeV Higgs boson
- stabilizes the Higgs boson mass
- dark matter candidate

Experimental evidence

- half discovered?
- or nada?

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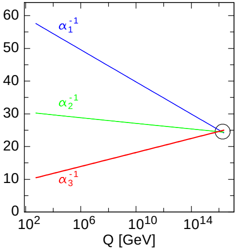

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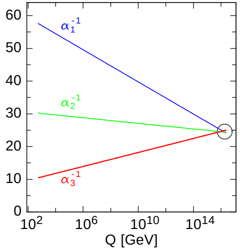

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Future

- The Standard Model is alive and kicking
- The Higgs boson be discovered:
  - What are the couplings of the Higgs boson?
  - What is the self-coupling of the Higgs boson?
  - Is it a Spin-0 particle?
- Neutrinos
  - Mixing in the leptonic sector
  - Is the Neutrino Majorana or DIRAC?
- Are 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?