Higgs Physics, New Physics and a tiny bit of Statistics

Philip Bechtle

24th February 2011

1. On the way to the Terascale
   - The Search for the System behind Matter
2. Higgs Physics
   - Theory
   - Limits
   - Discovery and Measurements?
3. Other New Physics?
   - SUSY: The missing link at the Terascale?
   - One Possibility to Measure Features of SUSY
   - Other New Physics than SUSY

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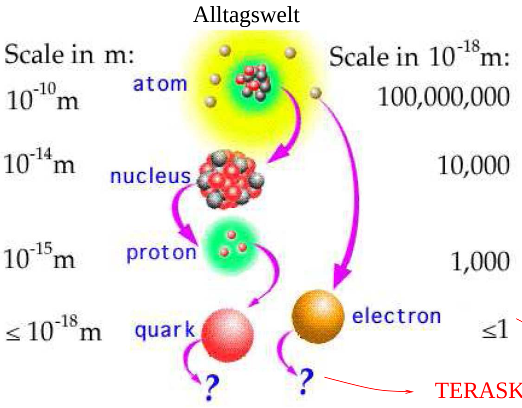
The Search for the Fundamental Buildung Blocks

Rutherford
Geiger Marsden
1909

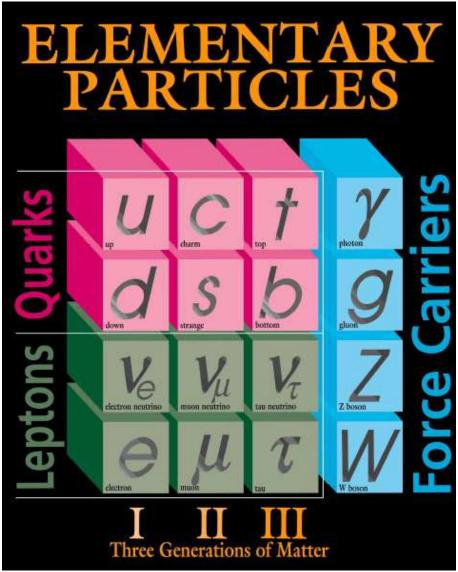
HERA
LEP
Tevatron
LHC
2009/2010



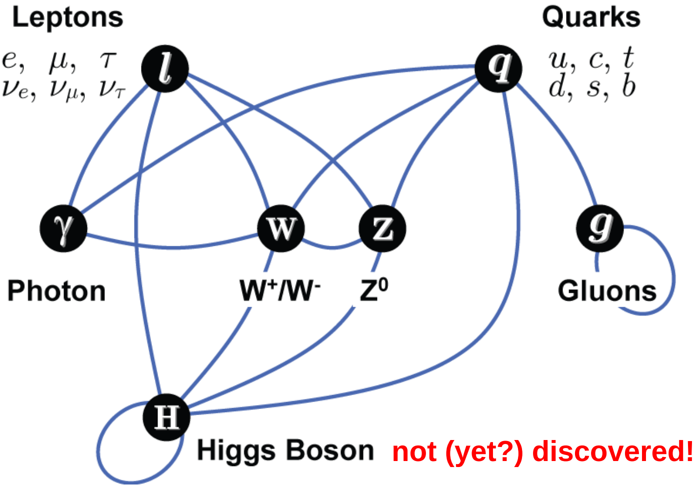
TERASKALA

A new era with the LHC, almost exactly 100 years after the first look into the atom

You know them very well by now ...



. . . but this is a better picture of the SM particles:



Why we know we missed something fundamental

- Experimentally known: The SM is incomplete!

It it isn't dark, it doesn't matter

- We do not experimentally know any particle or field which could explain dark matter or dark energy

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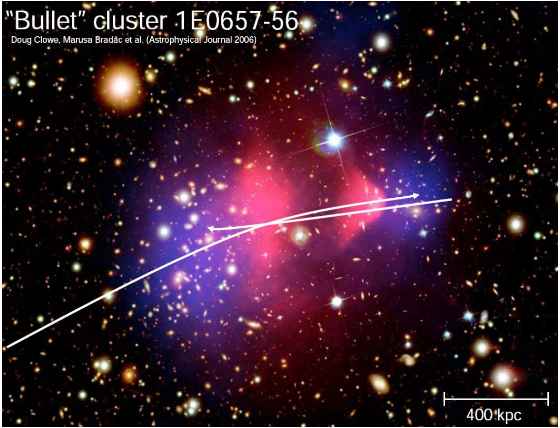

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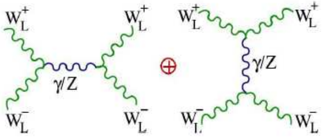
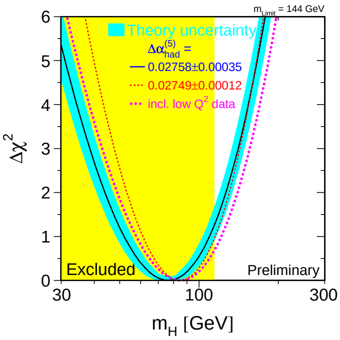
Why is the electromagnetic force of this tiny magnet so much stronger than all the gravity of the whole planet?

Why there must be New Physics at the Terascale

- We expect new physics at the Terascale $\approx 1\,\mathrm{TeV}$
- For theoretical reasons:
  - Without the Higgs: SM WW scattering violates unitarity at $\sqrt{s} \approx 1\,\mathrm{TeV}$
  - Very severe fine-tuning problem between m_h and m_{GUT}: Need new physics below $\approx 1\,\mathrm{TeV}$
- For experimental reasons:
  - Blue-band-plot shows that something like the Higgs must be there! Otherwise, all precision data would be wrong by orders of magnitude!
  - Dark matter





Teilchenphysik ist auch Philosophie

Nicht von Beginn an enthüllten die Götter uns Sterblichen alles;
Aber im Laufe der Zeit finden wir, suchend, das Bess're.
Diese Vermutung ist wohl, ich denke, der Wahrheit recht ähnlich.
Sichere Wahrheit erkannte kein Mensch und wird keiner erkennen
Über die Götter und alle die Dinge, von denen ich spreche,
Selbst wenn es einem einst glückt, die vollkommene Wahrheit zu künden,
Wissen kann er es nie: Es ist alles durchwebt von Vermutung.

Xenophanes von Kolophon, ca. 500 v.u.Z.

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Gauge Transformations

- Global Gauge Invariance:
  Require that $\mathcal{L}$ (i.e. the equation of motion) is invariant under the transformation:

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  Require that $\mathcal{L}$ is invariant under local transformations:
  $$\psi(x) \rightarrow e^{i\alpha(x)}\psi(x)$$
  This principle is the foundation of the SM

Introduction: QED

QED is a local abelian $U(1)$ gauge symmetry

Using our knowledge about the Lagrangian, we construct the Lagrangian which gives us the equation of motion of the Dirac equation ($(i\partial_\mu\gamma^\mu - m)\psi = 0$):

$$\mathcal{L}_{\text{free}} = \bar{\psi}(i\not{\partial} - m)\psi$$

using $\not{\partial} = \partial_\mu\gamma^\mu$.
Make the theory gauge invariant under local $U(1)$ transformations:

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What is the transformation behaviour of the free Lagrangian?

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That's not invariant!

But luckily it's also not QED ...

Introduction: QED

In order to save QED under the transformation $U(x) = e^{-1\alpha(x)}$, add a gauge field obeying:

$$A_\mu(x) \to U^{-1} A_\mu U + \frac{1}{q} U^{-1} \partial_\mu U = A_\mu(x) - \frac{1}{q} \partial_\mu \alpha(x)$$

A miracle has occured: we introduced not only a gauge field, but also a charge q. Also, we would have needed the photon A_μ anyway...

Now modify the derivative:

$$\partial_\mu \to \partial_\mu + iqA_\mu(x) = D_\mu$$

Let's write $\mathcal{L}$ again with all possible Lorentz and gauge invariant terms:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(i\partial\!\!\!/ - m)\psi - q\bar{\psi} A\!\!\!/ \psi$$

using

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

Introduction: QED

Let's check the transformational behaviour under local U(1) again:

$$\mathcal{L} \to \mathcal{L}' = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \bar{\psi}'(i\partial\!\!\!/ - m)\psi' - q\bar{\psi}'A\!\!\!/'\psi'$$

$$= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\partial\!\!\!/ - m)\psi - \bar{\psi}\gamma_\mu\psi(\partial^\mu\alpha(x)) - q\bar{\psi}\gamma_\mu\psi A^\mu + \bar{\psi}\gamma_\mu\psi(\partial^\mu\alpha(x))$$

$$= \mathcal{L}$$

with

$$F'_{\mu\nu} = \partial_\mu(A_\nu - \frac{1}{q}\partial_\nu\alpha(x)) - \partial_\nu(A_\mu - \frac{1}{q}\partial_\nu\alpha(x))$$

$$= F_{\mu\nu} - \partial_\mu\frac{1}{q}\partial_\nu\alpha(x) + \partial_\nu\frac{1}{q}\partial_\mu\alpha(x) = F_{\mu\nu}$$

QED including a gauge field is invariant under local U(1)!

Use this principle to construct the SM

QFD: $SU(2)_L \times U(1)_Y$ Leptonic Sector

We choose the SU$(2)_L$ doublett

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L = \frac{1}{2}(1-\gamma^5)\begin{pmatrix} \nu \\ e \end{pmatrix}, \quad \begin{matrix} I_3 = +\frac{1}{2},\ Q = 0,\ Y = -1 \\ I_3 = -\frac{1}{2},\ Q = -1,\ Y = -1 \end{matrix}$$

and the singlett

$$R = e_R = \frac{1}{2}(1+\gamma^5)e,\ \ I_3 = 0,\ Q = -1,\ Y = -2$$

which transform SU$(2)_L$ according to

$$L \to L' = e^{i\alpha^a \frac{\tau_a}{2}} L, \quad R \to R' = R$$

and under U$(1)_Y$ according to

$$L \to L' = e^{i\beta^a \frac{Y}{2}} L, \quad R \to R' = e^{i\beta^a \frac{Y}{2}} R$$

QFD: $SU(2)_L \times U(1)_Y$ Leptonic Sector

Now we construct the gauge fields W^a_μ for $\mathrm{SU}(2)_L$ analogously to $SU(3)_C$ before and B_μ of $\mathrm{U}(1)_Y$ analously to the QED before. We get the covariant derivative

$$D_\mu = \partial_\mu + ig\frac{\tau_a}{2}W^a_\mu + ig'\frac{Y}{2}B_\mu.$$

Using this, we can construct the first part of the QFD Lagrangian

$$\mathcal{L}^1_{\mathrm{QFD}} = -\frac{1}{4}W^a_{\mu\nu}W^{\mu\nu}_a - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + i\overline{L}\not{D}L + i\overline{R}\not{D}R,$$

with

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g\epsilon^a{}_{bc}W^b_\mu W^c_\nu$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu.$$

QFD: $SU(2)_L \times U(1)_Y$ Masses

- Mass of the gauge bosons
  Now we would like to add gauge boson masses:
  $$\frac{1}{2} M^2 B^\mu B_\mu$$
  However, this is not invariant under $SU(2)$:
  $$\rightarrow \frac{1}{2} M^2 (B^\mu - \frac{1}{g'} \partial^\mu \alpha(x))(B_\mu - \frac{1}{g'} \partial_\mu \alpha(x))$$

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- Mass of the fermions
  $$-m\bar{e}e = -m\bar{e}\left(\frac{1}{2}(1-\gamma^5) + \frac{1}{2}(1+\gamma^5)\right)e$$
  $$= -m(\bar{e}_R e_L + \bar{e}_L e_R)$$
  But only e_L and not e_R is transforming under $SU(2)$!

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We have a beautiful theory of massless particles!

QFD: $SU(2)_L \times U(1)_Y$ EWSB

In order to allow masses for the gauge bosons, we introduce the Higgs doublett into the theory:

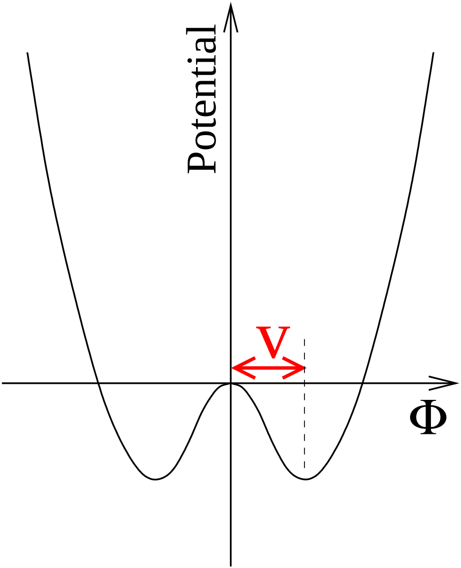
$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \; Y = +1 \quad \text{which is gauged like} \quad \Phi = e^{i\frac{\sigma_a \alpha^a}{2v}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \eta \end{pmatrix}$$

We obtain $v = \sqrt{-\mu^2/\lambda}$ as vacuum expectation value of the field in the potential

$$V(\Phi) = \frac{\mu^2}{2}\Phi^+\Phi + \frac{\lambda}{4}(\Phi^+\Phi)^2$$

with $\lambda > 0$ and $\mu^2 < 0$, such that there is spontaneous symmetry breaking (the ground state does not obey the symmetries of the theory). ϕ^+ has to be gauged to 0 in order to render the charge operator $Q = I_3 + \frac{Y}{2}$ unbroken. Otherwise the photon acquires mass.

Higgs Potential



QFD: $SU(2)_L \times U(1)_Y$ EWSB

Using the global $SU(2)_L$ gauge transformation from before

$$L \to L' = e^{-i\frac{\sigma^a \alpha_a}{2v}} L \Rightarrow \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \eta \end{pmatrix}$$

we obtain the following expression for the mass sector of the QFD:

$$\mathcal{L}^2_{\mathrm{QFD}} = -\sqrt{2} f (\overline{L} \Phi R + \overline{R} \Phi^+ L) + |D_\mu \Phi|^2 - V(\Phi)$$

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From where do we get the fermion masses?

$$-\sqrt{2} f(\overline{L} \Phi R + \overline{R} \Phi^+ L)$$

acts as a mass term with the Yukawa coupling parameter f determining the mass of the fermion.

QFD: $SU(2)_L \times U(1)_Y$ EWSB

The gauge boson masses are coming from

$$|D_\mu \Phi|^2 = \frac{1}{8} g^2 v^2 (W^a_{\mu\nu})^2 + \frac{1}{8} g'^2 v^2 B_\mu B^\mu - \frac{1}{4} g g' v^2 B^\mu W^3_\mu$$

using

$$(W^1_\mu)^2 + (W^2_\mu)^2 = (W^1_\mu + iW^2_\mu)(W^1_\mu - iW^2_\mu) = 2W^+_\mu W^-_\mu$$

introducing the charged currents. That yields

$$\frac{1}{4} g^2 v^2 W^+_\mu W^-_\mu + \frac{1}{8} v^2 (B^\mu, W^3_\mu) \begin{pmatrix} g'^2 & -gg' \\ -gg' & g^2 \end{pmatrix} \begin{pmatrix} B^\mu \\ W^{3\mu} \end{pmatrix}$$

We have the mass term on the $W^\pm$ already. Let's diagonalize the mass matrix of the hypercharge field B_μ and the third component of the $SU(2)_L$ gauge field W^3_μ:

$$\begin{pmatrix} A_\mu \\ Z^0_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^\mu \\ W^{3\mu} \end{pmatrix}$$

Now another miracle has occured: The photon field A_μ drops out of EWSB!

QFD: $SU(2)_L \times U(1)_Y$ EWSB

we have now introduced the Weinberg angle

$$\sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

From the diagonalization of the mass matrix for W^3_μ and B_μ

$$A_\mu = \frac{1}{\sqrt{g^2 + g'^2}}(g' W^3_\mu + g B_\mu), \quad m^2_A = 0$$

$$Z^0_\mu = \frac{1}{\sqrt{g^2 + g'^2}}(g W^3_\mu - g' B_\mu), \quad m^2_{Z^0} = \frac{(g^2 + g'^2)v^2}{4}$$

QFD: $SU(2)_L \times U(1)_Y$ EWSB

We also obtain the charged current and its coupling to the W^+_μ as

$$\frac{g}{2\sqrt{2}}(\bar{\nu}_L \gamma^\mu e_L W^+_\mu + h.c.)$$

In addition, as the first tested firm prediction of this theory, the neutral currents have been introduced ('74 November revolution: Gargamelle):

$$\frac{\sqrt{g^2+g'^2}}{4}\,(\overline{L}\gamma^\mu \tau_3 L - 2\frac{g'^2}{g^2+g'^2}\bar{e}\gamma^\mu e)Z^0_\mu, \qquad \frac{gg'}{\sqrt{g^2+g'^2}}\,\bar{e}\gamma^\mu e\, A_\mu$$

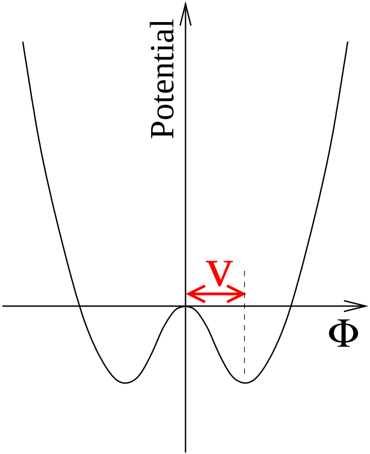
where

$$q_e = \frac{gg'}{\sqrt{g^2+g'^2}}$$

is the electromagnetic charge and $e = e_L + e_R$

This formalism has to be written for all three lepton families $\ell = e, \mu, \tau$.

QFD: $SU(2)_L \times U(1)_Y$ Properties of the Higgs



- The heavier the particle, the stronger the Higgs coupling to it (or the other way around!)
- The position of the minimum of the potential

$$V(\Phi) = \frac{\mu^2}{2}\Phi^+\Phi + \frac{\lambda}{4}(\Phi^+\Phi)^2$$

is known: Compare

$$\frac{g}{2\sqrt{2}}\bar{\nu}_L \gamma^\mu e_L W^+_\mu$$

with $V - A$ theory: $\mathcal{L}_{eff}^{V-A} \sim -\frac{G_F}{2} \ldots$

$$\left(\frac{g}{2\sqrt{2}}\right)^2 \frac{1}{M_W^2} = \frac{G_F}{2} \Rightarrow v = 246\,\mathrm{GeV}$$

QFD: $SU(2)_L \times U(1)_Y$ Remarks

There are a few non-trivial observations about EWSB in the SM:

- It is not trivial that the photon field A_μ fullfills

$$m_A = 0$$

$$q_e \bar{e} \gamma^\mu e A_\mu$$

(i.e. no coupling to the neutrino and the same coupling to the left and right fields) at the same time!

- All three elements of

$$\frac{M_W}{M_Z} = \cos\theta_W$$

can be measured independently $\Rightarrow$ precision tests

- The Higgs has been introduced to give mass to the gauge bosons, but it offers an elegant way to introduce masses of the fermions, too.
- There is a self-interaction among the gauge bosons in the $-\frac{1}{4} W^a_{\mu\nu} W^{\mu\nu}_a$ term. This just pops out of the theory, it was not constructed as the gauge boson fermion interactions. Does Nature obey the SM also in this unforeseen field? $\Rightarrow$ precision tests

Self Interaction of Gauge Bosons

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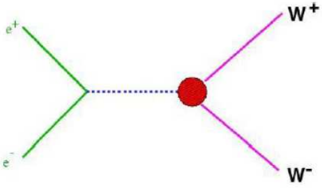
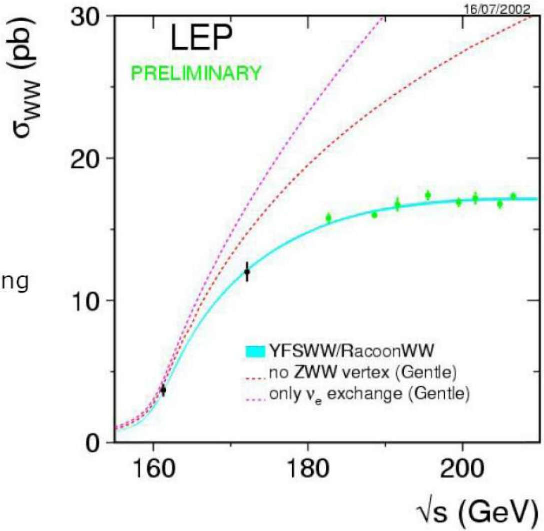
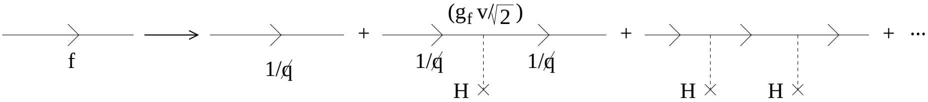




Graphical Representation of how Mass is Created

The Higgs mechanism is like a boring cocktail party:

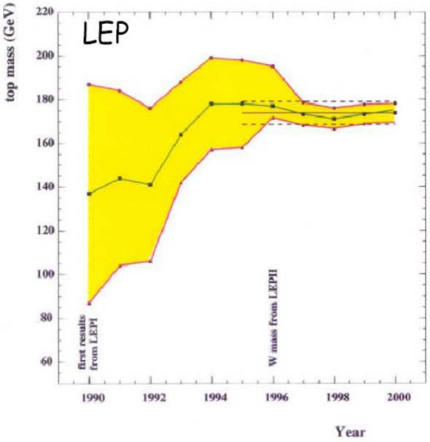
„famousness“ g_f of a particle determines its mass:

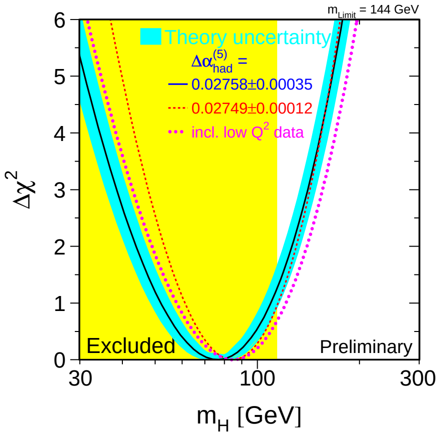


$$\frac{1}{\not q} + \frac{1}{\not q}\left(\frac{g_f v}{\sqrt{2}}\right)\frac{1}{\not q} + \cdots = \frac{1}{\not q}\sum_{n=0}^{\infty}\left[\left(\frac{g_f v}{\sqrt{2}}\right)\frac{1}{\not q}\right]^n = \frac{1}{\not q - \left(\frac{g_f v}{\sqrt{2}}\right)}$$

Precision Tests of Loop Corrections

e^+e^- machines can see effects of virtual particles





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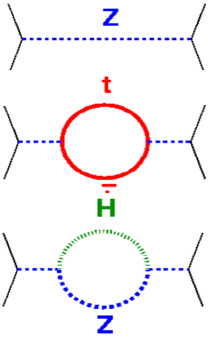
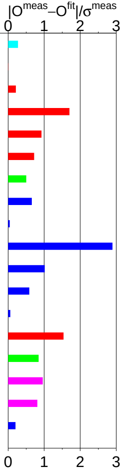
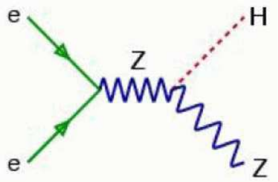


	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

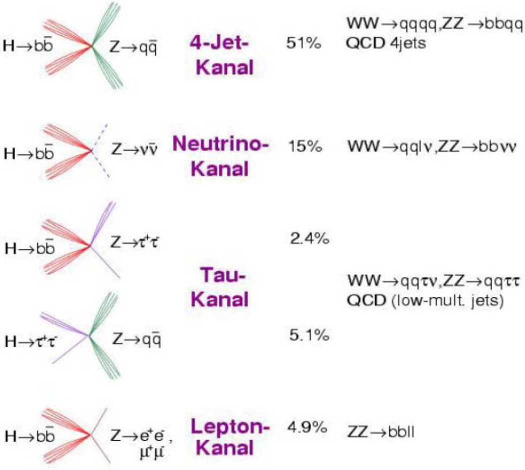


$$M_Z^2 = M_Z^{2\,0th\ order}\left(1+\mathcal{O}(m_t^2)+\mathcal{O}(\ln m_h^2)+\cdots\right)$$

Hunting for the Higgs: Signatures

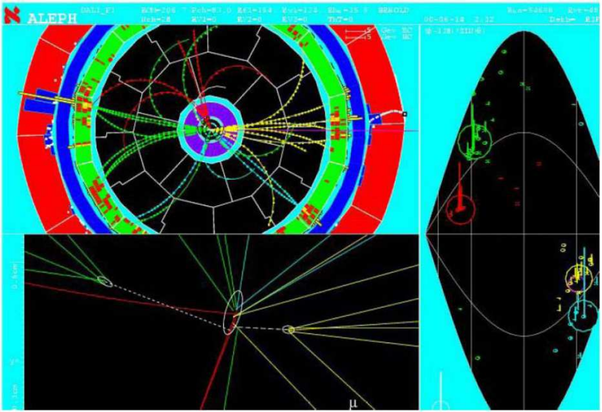


- The different Higgs decays and the different Z desays together define the signatures:
- For $m_h < 115\,\mathrm{GeV}$: More than 80 % of all decays
- Typcal selection efficiencies: 50 %



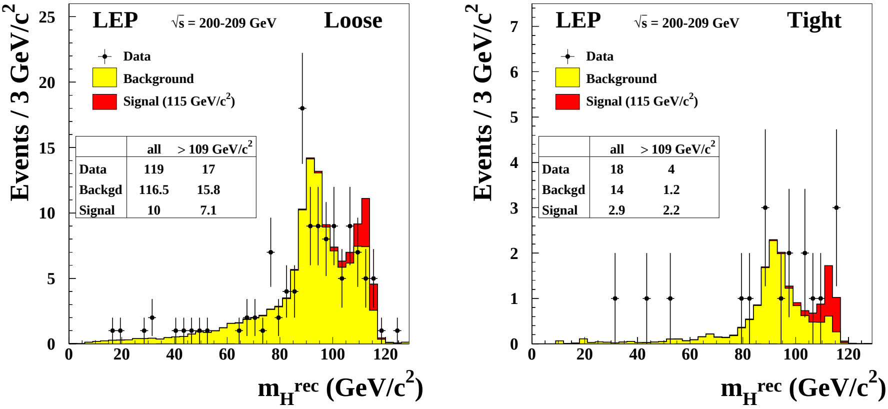
A Higgs Candidate

- A nice Higgs candidate from ALEPH ($m_h = 115\,\mathrm{GeV}$):



Do we see a Higgs mass peak?

- Are there many of these candidates?

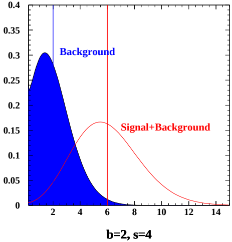


- How significant is the small excess? Need advanced statistical analysis

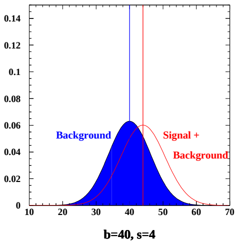
How to Calculate the Sensitivity?

- If hypothesis exists with d $\approx$ s+b on a significant level: Higgs found
- If not: Calculate, how improbable a certain hypothesis s is $\rightarrow$ exclusion
- First example: Add all s, b, d of all channels (Counting Experiment)
- If s$\neq$0 only in one channel: this degrades sensitivity

Poisson-distributions for s=4,b=2



Poisson-distributions for s=4,b=40

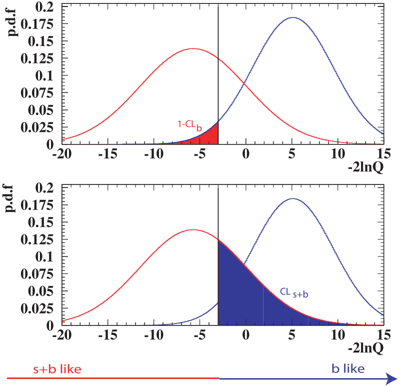


Not the most sensitive method . . . Instead: Define test statistics

$$-2\ln Q = -2\ln\frac{P_d(s+b)}{P_d(b)} = -2\sum_i s_i + 2\sum_i d_i \ln\left(1+\frac{s_i}{b_i}\right)$$

How to Calculate the Sensitivity?

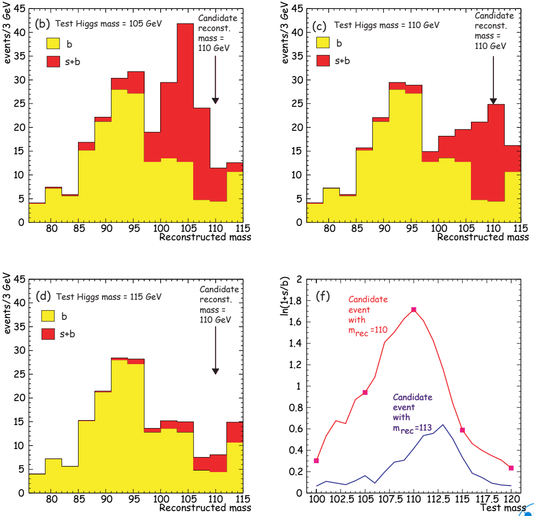
- For optimal sensitivity, do just not add the total channel contents
  but use the information of full (mass) distributions
- Define the test statistics Q as a likelihood ratio $P_d(s+b)/P_d(b)$
- Define $1-\mathrm{CL}_b$: Probability of a b-experiment to give a less background like result than the observed one
- Define CL_{s+b}: Probability of a s+b-experiment to give a more background like result than the observed one



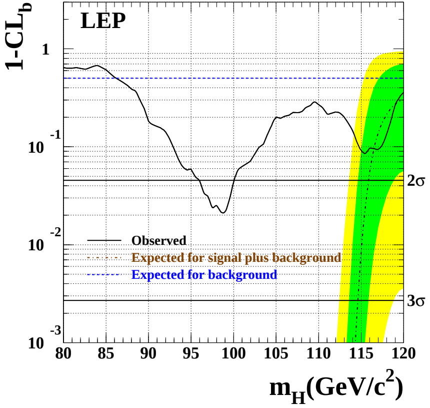
Conservative limit:
$\mathrm{CL}_s = \mathrm{CL}_{s+b}/\mathrm{CL}_b$

How to Calculate the Sensitivity?

- Don't know m_{H_1}, m_{H_2}, $\sigma_{H_iZ}, \ldots$ a priori
- Finite Detector Resolution $\rightarrow$ $m_{\rm rec} \neq m_{\rm H}$
- $\Rightarrow$ Test result of all searches under different hypotheses of m_{H_1}, m_{H_2}, $\sigma_{H_iZ}, \ldots$

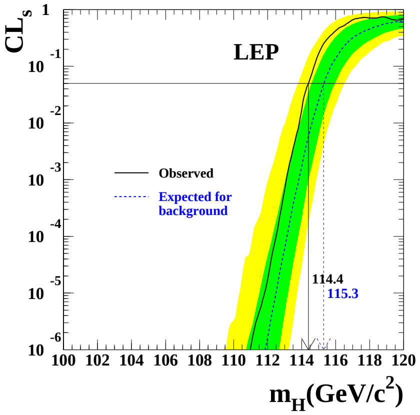


Is there a Significant Excess?



- $(1 - CL_b)$ is a measure of the 'background-likeness' of an experiment. If $(1 - CL_b)$ is e.g. 5 %, then the probability of this outcome to be caused by a fluctuation of the background is 5 %
- No excess above 3σ
- Be aware of the 'look-elsewhere' effect!

No Significant Excess: What's the Limit?

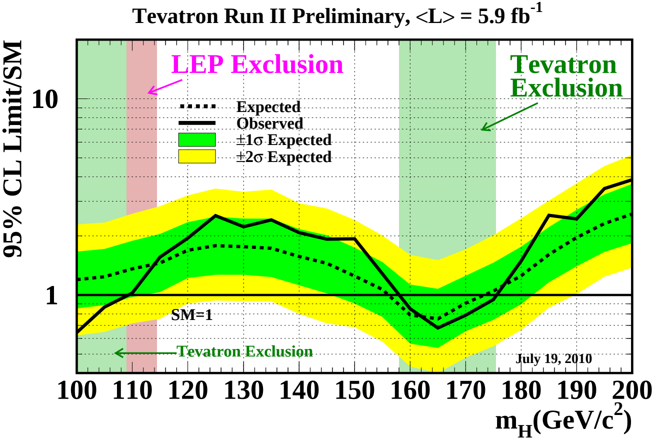


- CL_s is a measure of how signal-like the outcome of an experiment is. If CL_s is small, it is very unlikely that there is a signal. Hence, a 95 % CL corresponds to $CL_s = 0.05$
- Final word from LEP on the SM Higgs:

$$m_h > 114.4\,\mathrm{GeV}$$

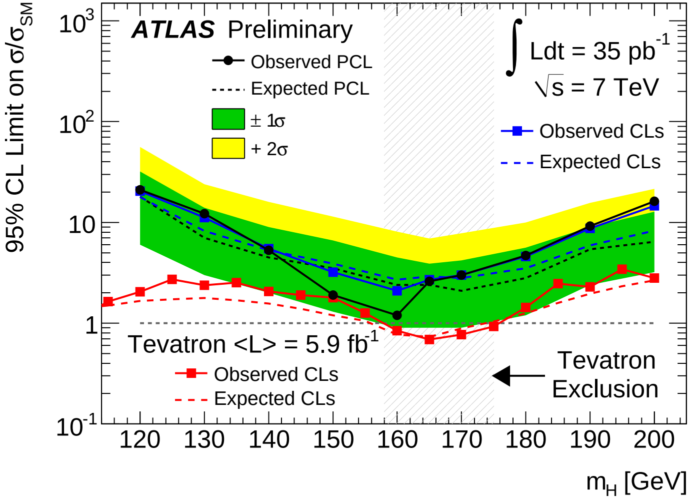
Current Situation

Tevatron:

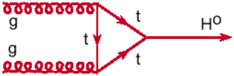


Current Situation

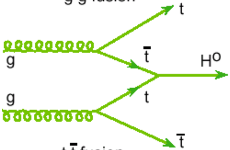
LHC e.g.:



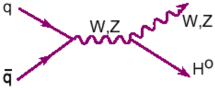
Higgs Production and Decay at the LHC



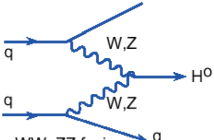
g g fusion



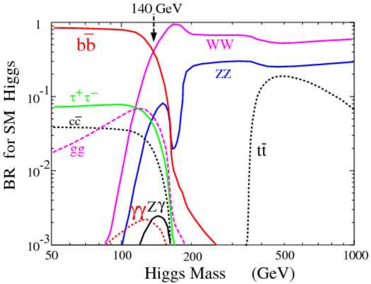
t t̄ fusion

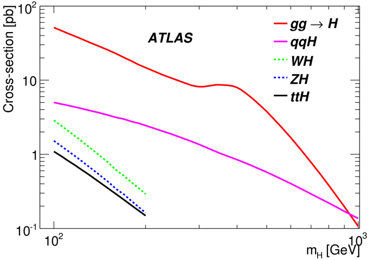


W, Z bremsstrahlung

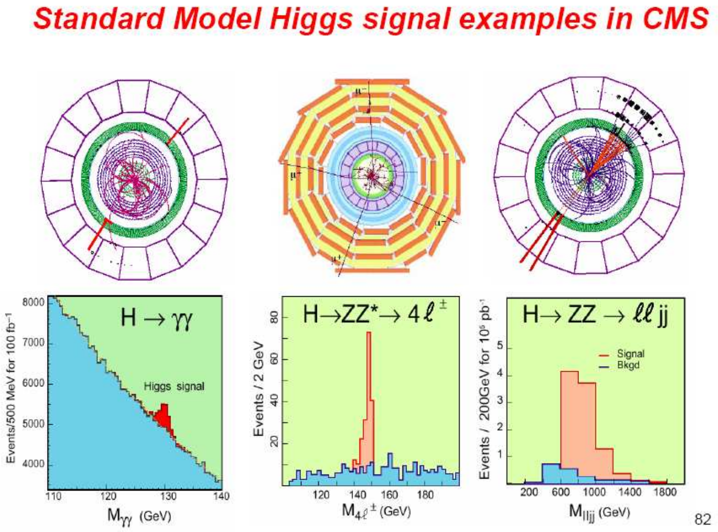


WW, ZZ fusion



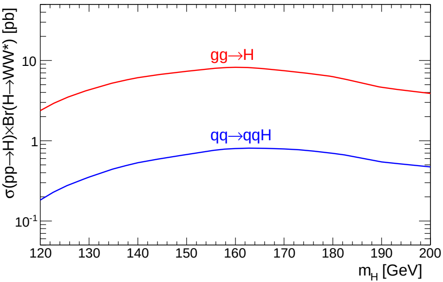


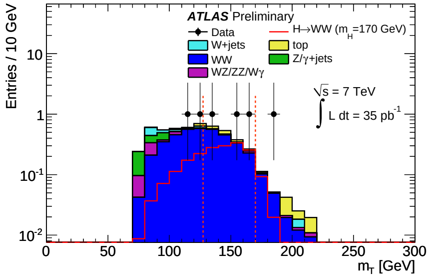
Promising Search Channels at the LHC



Search for $h \to WW^* \to \ell\nu\ell\nu$

Productin dominated by gluon fusion





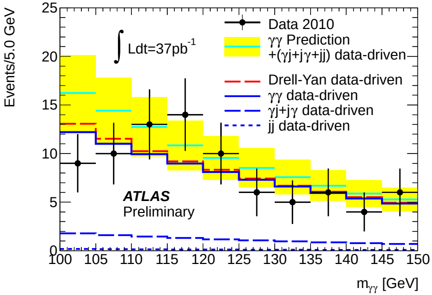
Look at

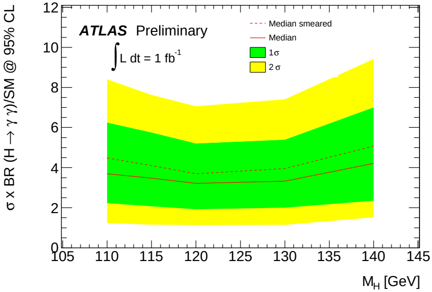
$$m_T^2 = (E_T^{\ell\ell} + E_T^{miss})^2 - (\vec{p}_T^{\ell\ell} + \vec{p}_T^{miss})^2$$

Unfortunately, no significant excess found yet, but exclusion at $1.2 \times SM$ (see slide 38)

Search for $h \to \gamma\gamma$

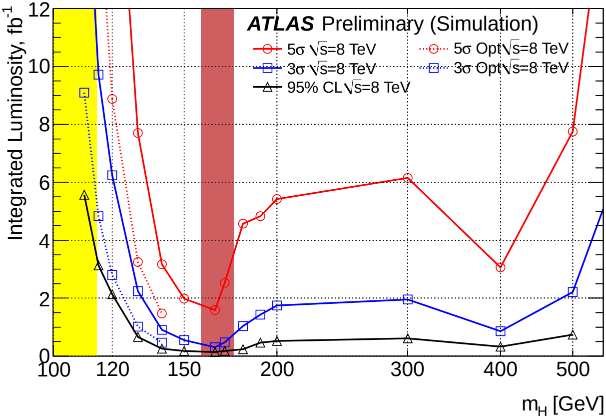
Tiny and very insignificant peak above the data driven BG estimation can be seen, if desperately wanted:





Even at $\mathcal{L}^{int} = 1\,\mathrm{fb}^{-1}$: No sensitivity to SM Higgs expected

Current Expectations



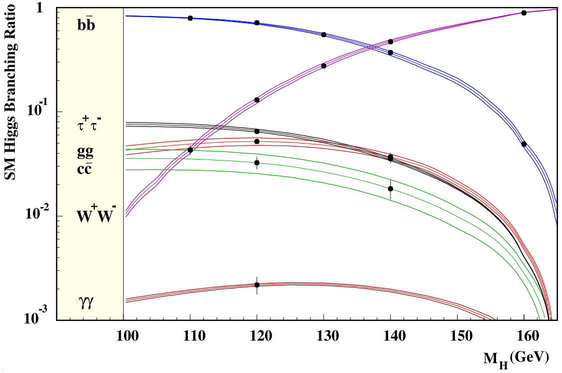
Combination of

$$H \to \gamma\gamma,\ H \to ZZ^{(*)} \to 4\ell/2\ell\nu/2\ell 2b,\ H \to WW^{(*)},\ H \to b\bar{b},\ H \to \tau^+\tau^-$$

Very challenging at very low masses

Precision Tests of the Higgs Mechanism

Once absolute Higgs cross-section can be measured at a LC:
Make an absolute and precise measurement of the coupling g_f of each particle to the Higgs:

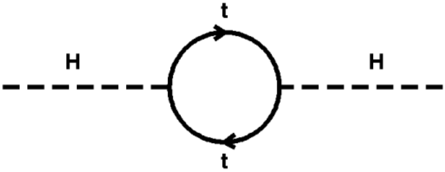


and make a detailed comparison with the SM

1. On the way to the Terascale
   - The Search for the System behind Matter
2. Higgs Physics
   - Theory
   - Limits
   - Discovery and Measurements?
3. Other New Physics?
   - SUSY: The missing link at the Terascale?
   - One Possibility to Measure Features of SUSY
   - Other New Physics than SUSY

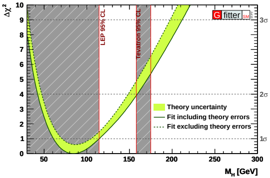
Supersymmetry

- Even if we find the Higgs, we still have a problem . . .



$$\Delta m_h \sim \Lambda^2$$
natural $m_h = M^2_{Planck}$
Finetuning:

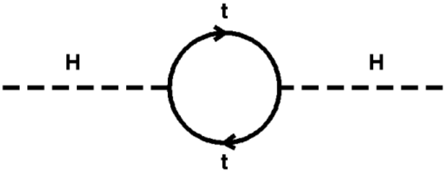
- From indirect measurements: $m_h < 140$ GeV



$$m_{h,obs} = \underbrace{10^{2\cdot 19}\,\mathrm{GeV}}_{\text{nat. mass}} - \underbrace{(1-\epsilon)10^{2\cdot 19}\,\mathrm{GeV}}_{Renormalisation} \approx 100\,\mathrm{GeV}$$

Supersymmetry

- Even if we find the Higgs, we still have a problem . . .



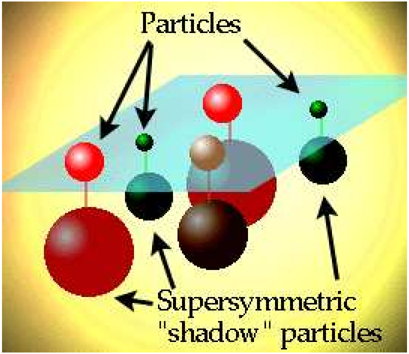
$$\Delta m_h \sim \Lambda^2$$

$$\Delta m_h \sim \ln \Lambda$$

- From indirect measurements:
  $m_h < 140$ GeV
- To prevent quadratic divergencies:
  Introduce shadow world:
  One SUSY partner for each SM d.o.f.
- Nice addition for free: If R-parity conserved, automatically the Lightest SUSY Particle (LSP) is a stable DM candidate
- But: Where are all those states?

Supersymmetry

- Even if we find the Higgs, we still have a problem . . .



In any case: $m_{Hlike} < 1\,\mathrm{TeV}$
$m_{SUSY} \leq \mathcal{O}(\mathrm{TeV})$
$\Rightarrow$ Terascala

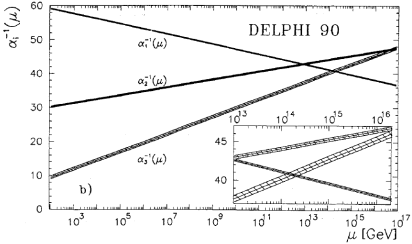
- From indirect measurements: $m_h < 140$ GeV
- To prevent quadratic divergencies: Introduce shadow world: One SUSY partner for each SM d.o.f.
- Nice addition for free: If R-parity conserved, automatically the Lightest SUSY Particle (LSP) is a stable DM candidate
- But: Where are all those states?
- SUSY breaking introduces a lot of additional parameters
  Understand model: Measure parameters!

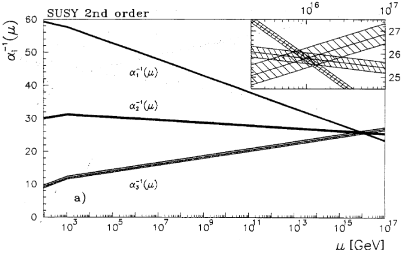
Why try (trust?) SUSY?

Wim de Boer *et al.* (1991):

It was shown that the evolution of the coupling constants within the minimal Standard Model with one Higgs doublet does not lead to Grand Unification, but if one adds five additional Higgs doublets, unification can be obtained at a scale below $2 \cdot 10^{14}$ GeV. However, such a low scale is excluded by the limits on the proton lifetime.

On the contrary, the minimal supersymmetric extension of the Standard Model leads to unification at a scale of $10^{16.0 \pm 0.3}$ GeV. Such a large unification scale is compatible with the present limits on the proton lifetime of about 10^{32} years. Note that the Planck mass (10^{19} GeV) is well above the unification scale of 10^{16} GeV, so presumably quantum gravity does not influence our results.

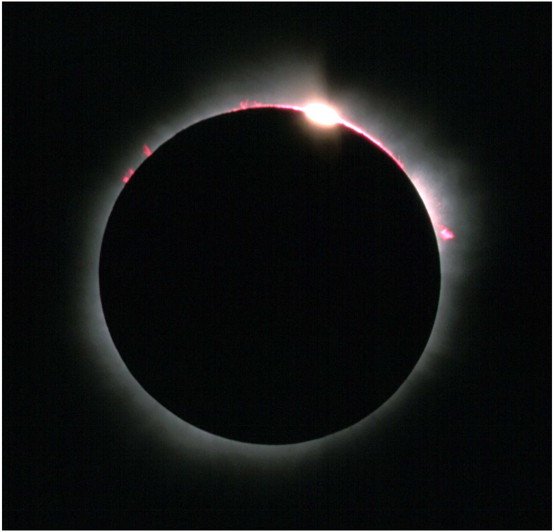




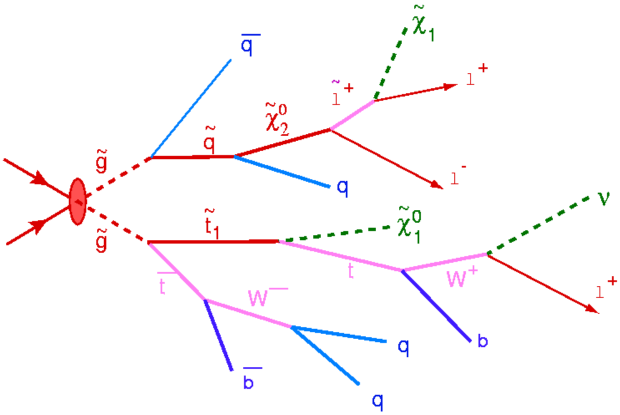
„Prediction" of $\sin^2 \theta_W$:

$$\sin^2 \theta_W^{SUSY} = 0.2335(17), \qquad \sin^2 \theta_W^{exp} = 0.2315(02)$$

A Warning: Apparent Finetuning



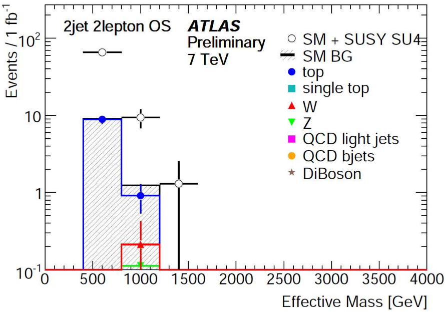
What do we hope to find?



Need everything: MET, Jets, B-Jets, elektrons, myons, taus

The possible discovery of Physics at the Terascale

- inclusive spectra: probably fastest way to discover SUSY-like physics
- Challenging because very good detector understanding with relatively little data needed (ca. $\mathcal{L} \approx 1\,\mathrm{fb}^{-1}$)



$$M_{eff} = \sum_i p_{T,i} + E_{Tmiss}$$

ATLAS MC $1\,\mathrm{fb}^{-1}$ @ $7\,\mathrm{TeV}$

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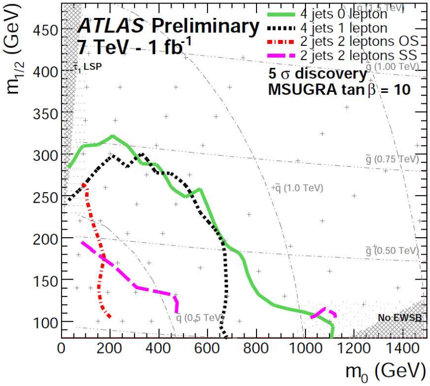
- Is it really SUSY? Or something else?
- Which particles, which masses, which decay chains?
- Quantum numbers, couplings?



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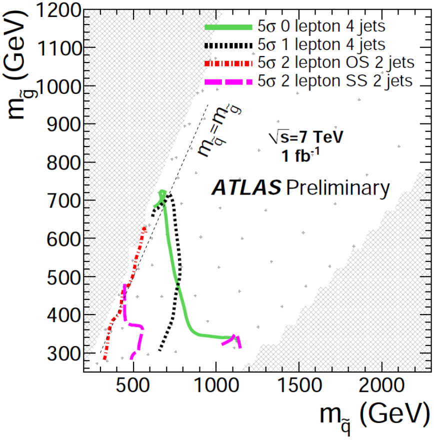

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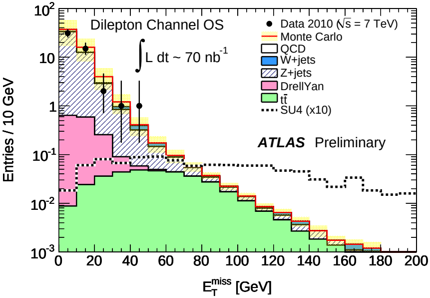

ATLAS data @ $7\,\mathrm{TeV}$ only 70 nb!

The possible discovery of Physics at the Terascale

- inclusive spectra: probably fastest way to discover SUSY-like physics
- Challenging because very good detector understanding with relatively little data needed (ca. $\mathcal{L} \approx 1\,\mathrm{fb}^{-1}$)
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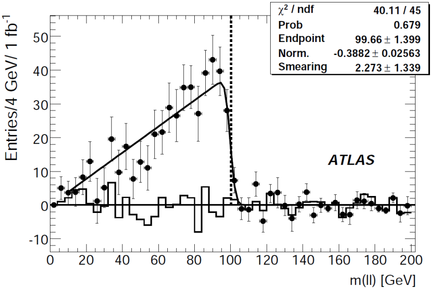
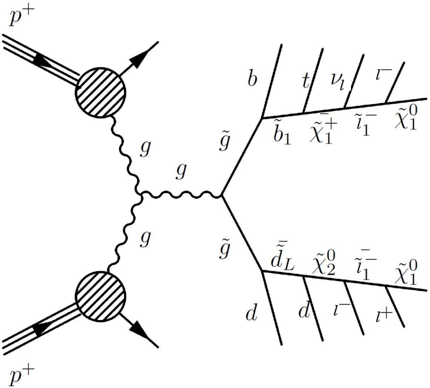


ATLAS MC $1\,\mathrm{fb}^{-1}$ @ $14\,\mathrm{TeV}$

kinematic edges

$\Rightarrow$ mass information

Typical SUSY Process in the Expected Region

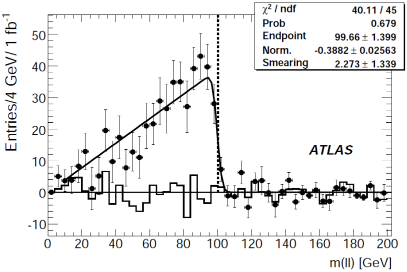


- Cannot detect LSP
- Only SM-particles visible:
  - Leptons (3)
  - Jets (at least 4)
  - missing transverse momentum
- Observable: Inavriant mass $m^2_{\ell^+\ell^-}(m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1}, m^2_{\tilde{\chi}^0_1})$

- Cannot reconstruct any sparticle mass directly
- Observable $m^2_{\ell\ell}$ depends on sparticle masses $(m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1}, m^2_{\tilde{\chi}^0_1})$
- Combinatoric background from second decay chain

Measurement of the invariant $\ell\ell$ mass

ATLAS 14TeV MC, update in progress!

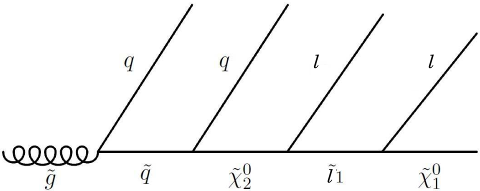


$$
\begin{array}{llrl}
m_0 & = & 100 & \text{GeV} \\
m_{12} & = & 300 & \text{GeV} \\
A_0 & = & -300 & \text{GeV} \\
\tan\beta & = & 6 &
\end{array}
$$

- Select events with E_{Tmiss}, hard jets and at least 2 ℓ
- Sharp edge in the $m_{\ell\ell}$ spektrum smeared due to finite resolution
  $\Rightarrow$ E.g. calibrate inflection point to edge
- Use data itself to subtract background:
  $OS - SS$ or $OSSF - QSDF$

More Mass Edges

- One observables $m^2_{\ell\ell}$ epends on 3 sparticle masses $(m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1}, m^2_{\tilde{\chi}^0_1})$

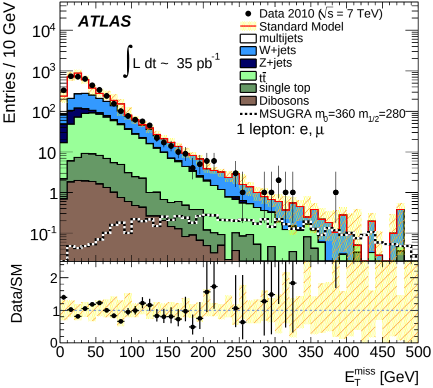


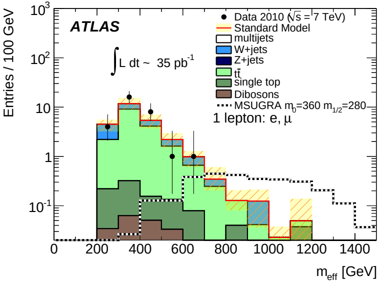
Mass edges:
$m^2_{\ell^+\ell^-}(m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1}, m^2_{\tilde{\chi}^0_1})$
$m^2_{q\ell^+\ell^-}(m^2_{\tilde{q}}, m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1}, m^2_{\tilde{\chi}^0_1})$
$m^2_{q\ell_{near}}(m^2_{\tilde{q}}, m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1})$
$m^2_{q\ell_{far}}(m^2_{\tilde{q}}, m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1}, m^2_{\tilde{\chi}^0_1})$
$m^2_{q\ell_{low}} = min[(m^2_{q\ell_{near}}), (m^2_{q\ell_{far}})]$
$m^2_{q\ell_{high}} = max[(m^2_{q\ell_{near}}), (m^2_{q\ell_{far}})]$

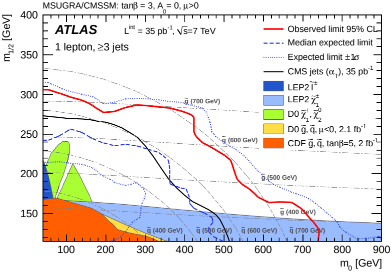
- e.g. by adding a reconstructed jet:
  - **1** additional sparticle mass
  - But **3** additional observables!
- ℓ_{near} and ℓ_{far} cannot be resolved $\rightarrow$
  - $q\ell_{high}$ and $q\ell_{low}$ edges
- Di-leptonic final states: $\rightarrow$ **4**(5) observables and **4** sparticle masses $\rightarrow$ distinct solution(s)

Examples for the current situation

Search for at least 3 hard jets, isolated leptons and E_T^{miss}

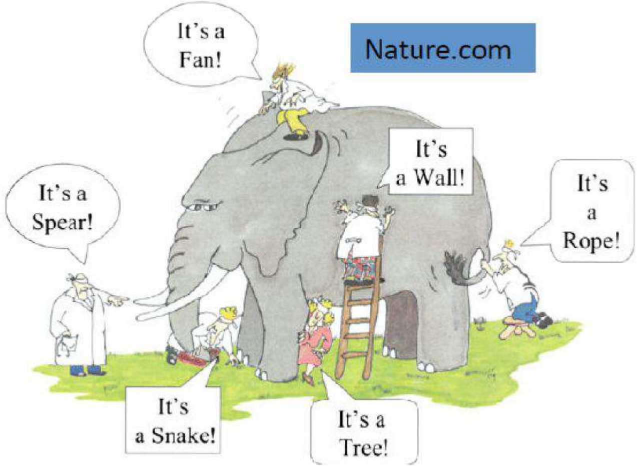






Look at $M_{eff} = \sum_i p_{T,i} + E_{Tmiss}$

How to figure out what we might see?



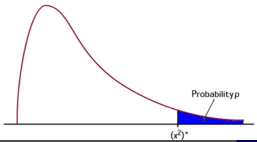
thanks to I. Fleck

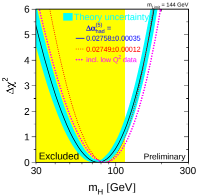
Statistical Evaluation of Agreement

- Assume a set of N measurements O_i with uncertainties σ_i
- Assume theory with N predictions $T_i(P_j)$ and M parameters P_j
- The statistically most sensitive quantity (derived from max. Likelihood thechnique) for approximately gaussian errors σ_i is

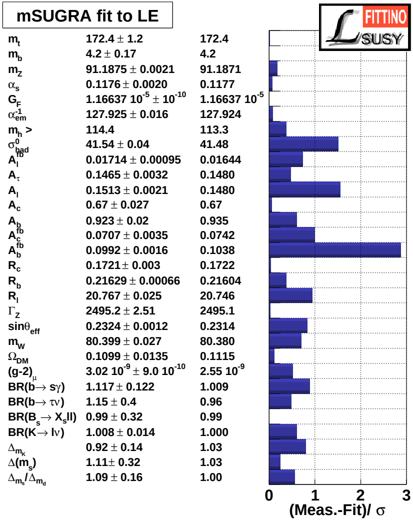
$$\chi^2 = \sum_{i=0}^{i<N} \frac{(O_i - T_i(P_j))^2}{\sigma_i^2}$$

- Vary P_j until χ^2 is minimal: Best fit point P_j^{opt}
- Derive two important quantities:
  - Does the theory describe the data? Given by $\mathcal{P}_{\chi^2}(\chi^2_{min}, ndf)$
  - How wide can I vary the parameters P_j (with respect to P_j^{opt}) without loosing agreement too much?





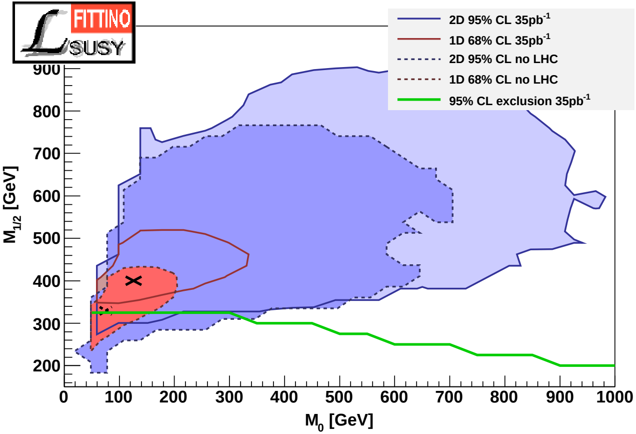
Experimental Status of SUSY



- Fit SM+mSUGRA to measured observables
- $\chi^2 = 20.6$ at 23 d.o.f. $\Rightarrow$ $\mathcal{P}$-Value $= 60.5\,\%$
- Best fit for sign$\mu = +1$ und

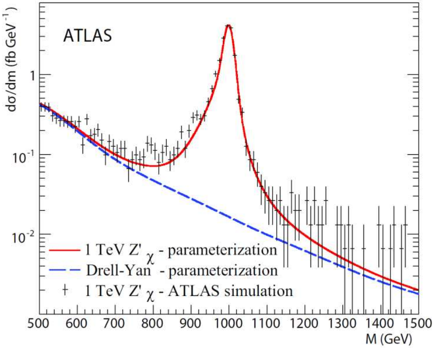
Parameter	Value and Uncertainty
$\tan\beta$	13.2 ± 7.2
M_{12}	331.5 ± 86.6
M_0	$76.2^{+79.8}_{-29.2}$
A_0	383.1 ± 647.0
α_s	0.1177 ± 0.0020
α_{em}	127.924 ± 0.014
m_Z	91.1871 ± 0.0020
m_t	172.4 ± 1.1
G_F	$1.16637 \cdot 10^{-5} \pm 1 \cdot 10^{-10}$

How does this compare to the current limits?



No stretch between indirect expectations and direct observations yet
Stretch would show if no discovery at around $\mathcal{L}^{int} = 7\,\mathrm{fb}^{-1}$

Finally: Other New Phyics



- GUT theories (new, larger gauge groups SO(10) etc.) or extra dimensions tend to predict new bosons
- They mix with SM gauge bosons
- Similar interactions (but different mass and couplings) than Z^0 and $W^\pm$
- No public results from CMS or ATLAS yet . . .

Summary

- From precision experiments (LEP, SLC, W-mass at Tevatron, etc.) we know that somethig new has to be around the corner
- From theory (unitarity bound) we know: Whatever it is, it has to be below 1 TeV:

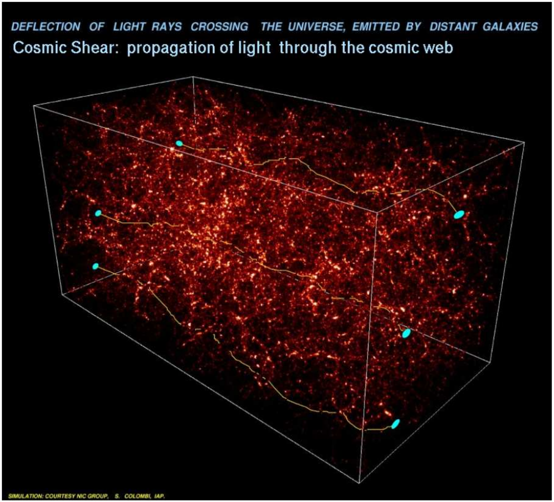
New physics below or at the Terascale

- For the first time, we are directly probing the Terascale at ATLAS and CMS
- New physics below or at the Teracale could be
  - Just the SM Higgs (leaves many questions open! Dark Matter!)
  - A (or several) Higgs and something else (typical for SUSY)
  - New strong interactions, new dimensions, many other things up to now unthought of!

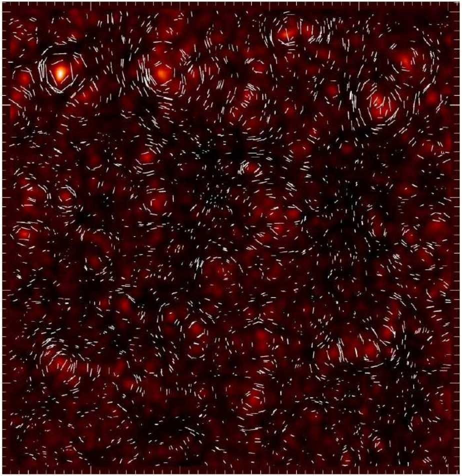
Very interesting times ahead for you!

Backup Slides

Weak Lensing



Weak Lensing



Prerequisites: γ_μ, ∂^μ and the $\dagger$

The notation is a little bit confusing sometimes, so let's try to sort things a little bit:

Fermions are represented by 4-dimensional spinors:

$$\psi(p) = \sqrt{p_0 + m} \begin{pmatrix} \chi_s \\ \frac{\vec{\sigma}\vec{p}}{p_0+m}\chi_s \end{pmatrix}, \quad \chi_{1/2} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \chi_{-1/2} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

The 4×4 γ matrices are acting on the 4 dimensions of ythe spinors.

An index (γ_μ, A_μ or $F_{\mu\nu}$) always denotes a 4-dimensional Lorentz vector. This 4-dimensional space is independent of the 4-dimensional spinor space.

∂^μ denotes a partial derivative for x^0, x^1, x^2, x^3 respecively.

Einstein convention:

4-vector: x^μ

scalar: $x^\mu y_\mu$

matrix: $x^\mu y^\nu$

Prerequisites: γ_μ, ∂^μ and the $\dagger$

Dirac matrices (each matrix acting on a 4-dim spinor):

$$\gamma^0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}, \gamma^1 = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix}$$

$$\gamma^2 = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{pmatrix}, \gamma^3 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

$$\gamma^5 := i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

Hermitean adjoint: $\psi^\dagger$: $a_{ij} = a^*_{ji}$, Dirac adjoint: $\bar{\psi} = \psi^\dagger\gamma^0$

The Lagrangian

Require that the action S remains invariant under small changes of the fiends ϕ:

$$\frac{\delta\mathcal{S}}{\delta\varphi_i} = 0$$

S is determined by the Lagrangian (classically: $\mathcal{L} = T - V$)

$$\mathcal{S}[\varphi_i] = \int \mathcal{L}[\varphi_i(s)]\,\mathrm{d}^n s,$$

where s_α denotes the parameters of the system.

The equations of motion of the system can then be derived from the Euler-Lagrange equation:

$$\partial_\mu\left(\frac{\partial\mathcal{L}}{\partial(\partial_\mu\varphi)}\right) - \frac{\partial\mathcal{L}}{\partial\varphi} = 0$$

The Lagrangian

Classical Example in three-dimensional space:

$$L(\vec{x}, \dot{\vec{x}}) = \frac{1}{2}\, m\, \dot{\vec{x}}^2 - V(\vec{x}).$$

Then, the Euler-Lagrange equation is:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}_i}\right) - \frac{\partial L}{\partial x_i} = 0$$

with $i = 1, 2, 3$. The derivation yields:

$$\frac{\partial L}{\partial x_i} = -\frac{\partial V}{\partial x_i}$$

$$\frac{\partial L}{\partial \dot{x}_i} = \frac{\partial}{\partial \dot{x}_i}\left(\frac{1}{2}\, m\, \dot{\vec{x}}^2\right) = \frac{1}{2}\, m\, \frac{\partial}{\partial \dot{x}_i}\left(\dot{x}_i\, \dot{x}_i\right) = m\, \dot{x}_i$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}_i}\right) = m\, \ddot{x}_i$$

From the Euler-Lagrange-equation we get the equation of motion:

Some Mathematics: $SU(2)$

For the special unitary group $SU(2)$, the generators are proportional to the Pauli matrices:

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

The generators of the group are $\tau_i = \frac{1}{2}\sigma_i$. The Pauli matrices obey

$$\begin{aligned} [\sigma_i, \sigma_j] &= 2i\,\varepsilon_{ijk}\,\sigma_k \\ \{\sigma_i, \sigma_j\} &= 2\delta_{ij} \cdot I \end{aligned}$$

Example for an $SU(2)$ transformation:

$$\psi(x) \to e^{i\tau_i\alpha^i(x)}\psi(x)$$

$SU(2)$ and $SU(3)$ are not abelian, i.e. the generators of the group do not commute.

Some Mathematics: $SU(3)$

The analog of the Pauli matrices for $SU(3)$ are the Gell-Mann matrices:

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

The generators of $SU(3)$ are defined as T by the relation

$$T_a = \frac{\lambda_a}{2}.$$

Some Mathematics: $SU(3)$

The generators T obey the relations

$$[T_a, T_b] = i \sum_{c=1}^{8} f_{abc} T_c$$

where f is called structure constant and has a value given by

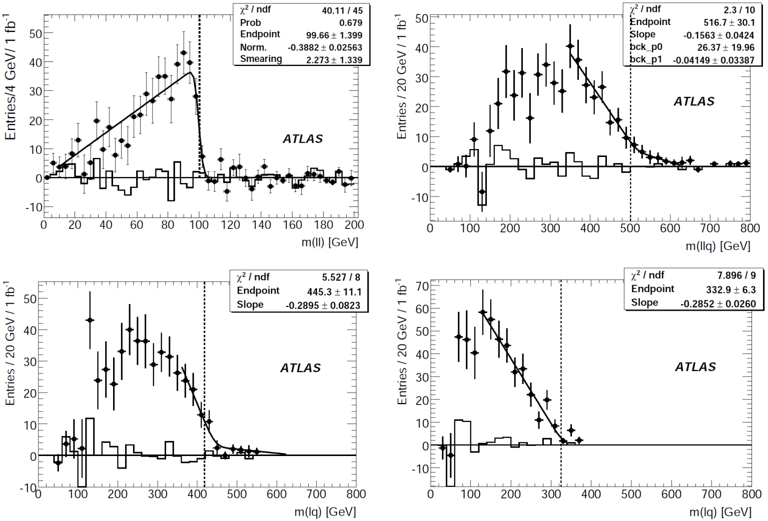
$$f^{123} = 1$$

$$f^{147} = f^{165} = f^{246} = f^{257} = f^{345} = f^{376} = \frac{1}{2}$$

$$f^{458} = f^{678} = \frac{\sqrt{3}}{2}$$

$$\mathrm{tr}(T_a) = 0$$

Expected mass spectra



ATLAS 14TeV 1 fb^{-1}, updates at 7TeV in progress!