Higgs Physics

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Before we start

Please

- I can only show a small fraction of all the incredibly interesting searches going on
- Whether ATLAS or CMS is shown is typically purely accidential
- Please ask questions anytime whenever you have one
- Interrupt if I'm too fast, or
- Speed me up if I'm telling you stuff which has been told several times before
- Maybe, you'll hear about some crazy stuff which is not completely explained in this lecture. In this case: Ask questions anytime! ;-)
- Let's have as much interesting discussion as possible!

Motivation – March 2012

- We live in truly exciting times
- The LHC is a huge success
- Recent results could mean that the Higgs boson might be discovered soon
- The end of the reign of the SM is eagerly avaited
- You have the chance to witness and actively contribute to a new era of revolution in particle physics

Motivation – March 2014

- We live in truly exciting times
- The LHC is a huge success
- Recent results show that there is a *SM-like* Higgs boson
- The end of the reign of the SM is still eagerly avaited
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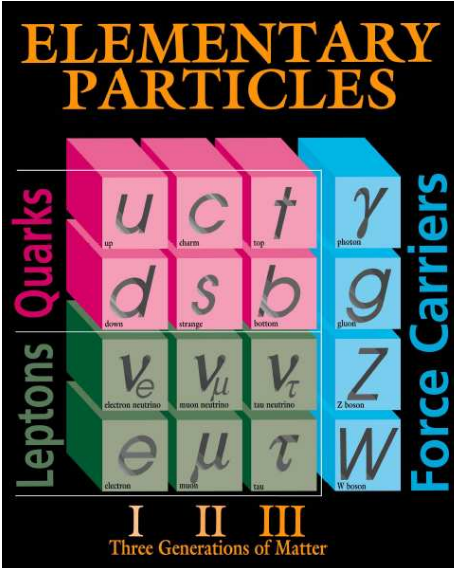
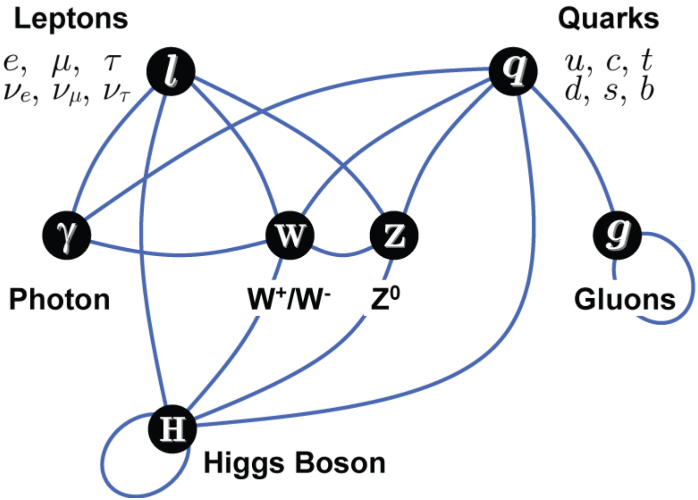
Our Current Picture of Elementary Particles



The Standard Model of Elementary Particles



„Dass ich erkenne, was die Welt im Innersten zusammenhält"

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Particle Physics is Philosophy

Not from the beginning the gods disclosed everything to us,
but in the course of time we find, searching, a better knowledge.
These things have seemed to me to resemble the truth.
There never was nor will be a person who has certain knowledge
about the gods and about all the things I speak of.
Even if he should chance to say the complete truth,
yet he himself can not know that it is so.

XENOPHANES OF KOLOPHON, ca. 500 b.c.

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

$$\begin{aligned} -m\bar{e}e &= -m\bar{e}\left(\frac{1}{2}(1-\gamma^5) + \frac{1}{2}(1+\gamma^5)\right) e \\ &= -m(\bar{e}_R e_L + \bar{e}_L e_R) \end{aligned}$$

  But only e_L and not e_R is transforming under $SU(2)$!

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$$= -m(\bar{e}_R e_L + \bar{e}_L e_R)$$

But only e_L and not e_R is transforming under $SU(2)$!

We have a beautiful theory of massless particles!

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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.

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

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

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

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

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

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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):

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

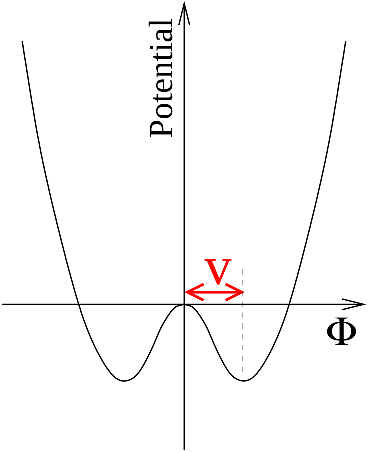
where

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

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

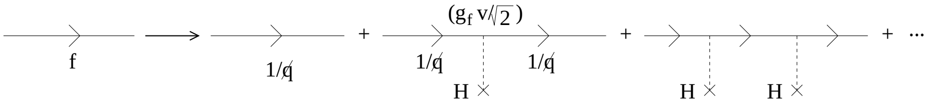
- The Higgs has been introduced to give mass to the gauge bosons, but it offers an elegant way to introduce masses of the fermions, too.

- There is a self-interaction among the gauge bosons in the $-\frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu}$ 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

The Higgs Mechanism, the easy way

Dynamic generation of mass:

- Spontaneous symmetry breaking: Higgs field is always present
- Massless fermion interaction with the non-vanishing background field:



- Geometric sum yields massive propagator:

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

- Effective mass of the fermion
- Similar process for gauge bosons

The Higgs Boson

The Higgs Boson

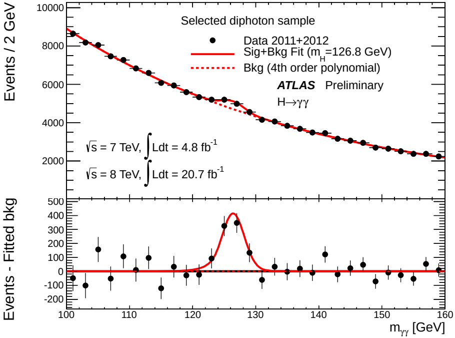
The Higgs boson fullfills
(at least!) 3 wishes at once!

The Higgs Boson

- The SM is the most complete theory of fundamental particles and interaction that we ever had
- But without the Higgs:
- *WW* scattering crosses the unitarity bound at $\sqrt{s} \approx 850\,\mathrm{GeV}$
- $\mathrm{SU}_L(2) \times \mathrm{U}_Y(1)$ does not allow masses for the gauge bosons and the fermions
- The Higgs allows to make the photon massless and uncoupled to the neutrinos at the same time

The Puzzle of Electroweak Symmetry Breaking

- Higgs-like particle at $m_h \approx 125$ GeV!
- A whole new window of experimental and theoretical possibilities opens!



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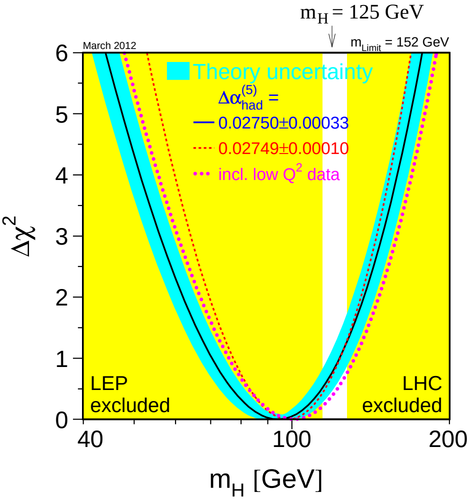

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- Why is that so important?
  - Up to 2011, we directly studied only half of the EW SM Lagrangian!

$$\mathcal{L}_{EW}^{SM} = -\frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu} - -\frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$
$$+\bar{L}\gamma^\mu \left(i\partial_\mu - \frac{1}{2} g \tau_a W^a_\mu - \frac{1}{2} g' Y B_\mu \right) L$$
$$+\bar{R}\gamma^\mu \left(i\partial_\mu - -\frac{1}{2} g' Y B_\mu \right) R$$

Studied since 1974 in many great experiments

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$$
\begin{aligned}
\mathcal{L}_{EW}^{SM} = & -\frac{1}{4} W_{\mu\nu}^a W_a^{\mu\nu} - -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\
& + \bar{L}\gamma^\mu \left(i\partial_\mu - \frac{1}{2} g \tau_a W_\mu^a - \frac{1}{2} g' Y B_\mu \right) L \\
& + \bar{R}\gamma^\mu \left(i\partial_\mu - -\frac{1}{2} g' Y B_\mu \right) R \\
& - \left| \left(i\partial_\mu - \frac{1}{2} g \tau_a W_\mu^a - \frac{1}{2} g' Y B_\mu \right) \Phi \right|^2 \\
& + \mu^2 |\Phi|^2 - \lambda |\Phi|^4 \\
& - (\sqrt{2}\lambda_d \bar{L} \Phi R + \sqrt{2}\lambda_u \bar{L} \Phi_c R + h.c.)
\end{aligned}
$$

Only began to explore this part at ATLAS and CMS in 2011

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- But is the SM really correctly describing EWSB? Need very precise model independent confirmation
- Why is that so important?
  - Up to 2011, we directly studied only half of the EW SM Lagrangian!
  - The masses of the particles shape our universe!

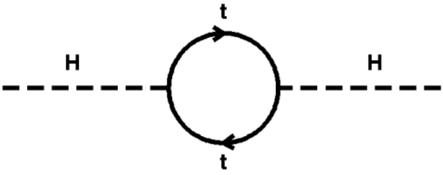
e.g. Bohr radius of the Hydrogen:

$$a_0 = \frac{\hbar}{m_e c \alpha}$$

No atoms without fundamental mass!
At least not as we know them . . .

Supersymmetry

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



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

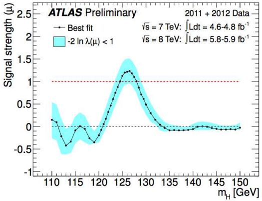
in the presence of gravity:

natural

$$m_h = \Lambda = M_{Planck} \approx 10^{19}\,\mathrm{GeV}$$

Finetuning at M_{Planck}:

- If the new particle is the Higgs: $m_h \approx 126$ GeV



$$m_{h,obs}^2 = m_{h,bare}^2 + (\mathrm{fine-tuned\ difference\ of\ couplings} \approx M_{Planck}^{-2}) \times M_{Planck}^2$$

Supersymmetry

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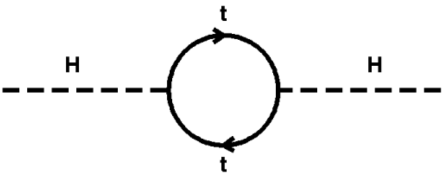

only SM: $m_h^2 \sim \Lambda^2$

SUSY: $m_h \sim m \ln M_{SUSY}^2 / \mu^2$

- If the new particle is the Higgs: $m_h \approx 126$ 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

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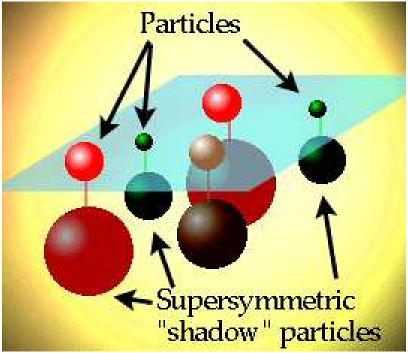


In any case: $m_{Hlike} < 1\,\mathrm{TeV}$
$m_{SUSY} \leq \mathcal{O}(\mathrm{TeV})$
$\Rightarrow$ Terascala

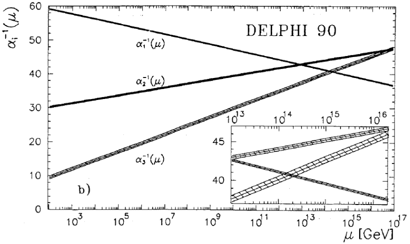
- If the new particle is the Higgs: $m_h \approx 126$ GeV
- To prevent quadratic divergencies: Introduce shadow world: One SUSY partner for each SM d.o.f.
- Nice addition for free: If R-parity conserved, automatically the Lightest SUSY Particle (LSP) is a stable DM candidate
- But: Where are all those states?
- SUSY breaking introduces a lot of additional parameters Understand model: Measure parameters!

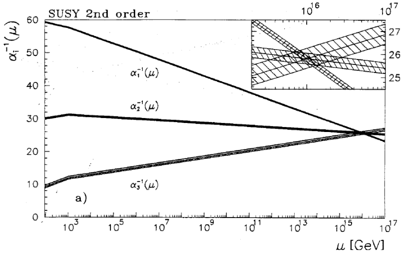
Why try (trust?) SUSY?

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 $\sin^2 \theta_W$:

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

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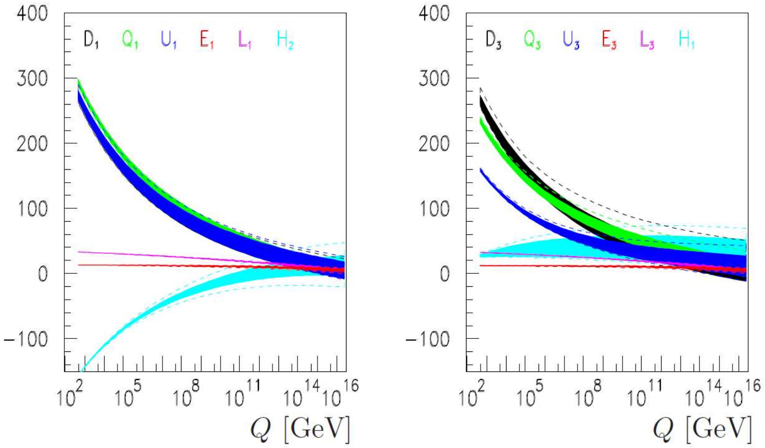
Explaining the Higgs Potential

- Naturally include $V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$ through RGE running for large m_t



- Example from arXiv:hep-ph/0511006v2

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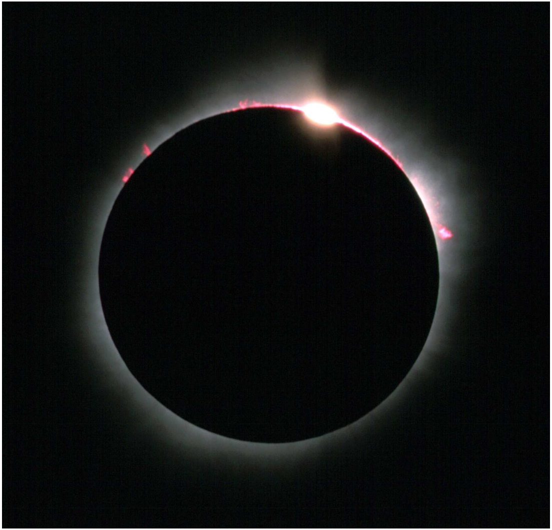
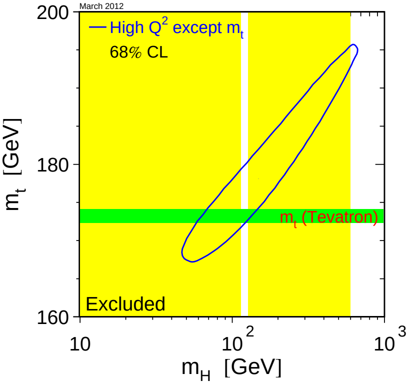
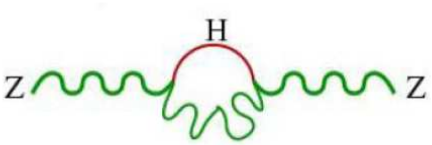
A Warning: Apparent Finetuning



Putting it all Together

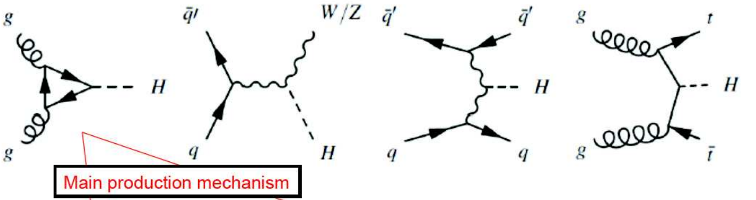
- Perform a global fit to all measurements to get the most precise indirect measurement of m_h:

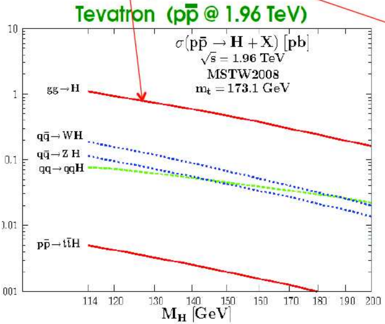


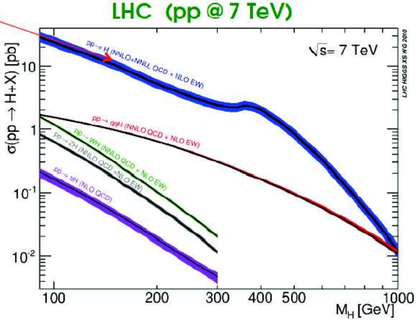


- From the fit:
  $m_h < 155\,\mathrm{GeV}$ @ 95 % CL
- What's the yellow bar?

Higgs Production Mechanisms at Hadron Colliders







This part: Some content thanks to A. Juste

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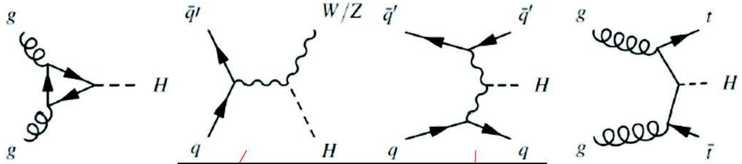
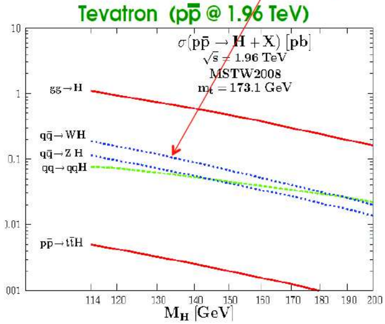
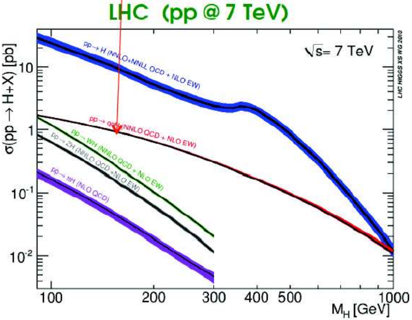


Next most important production mechanism





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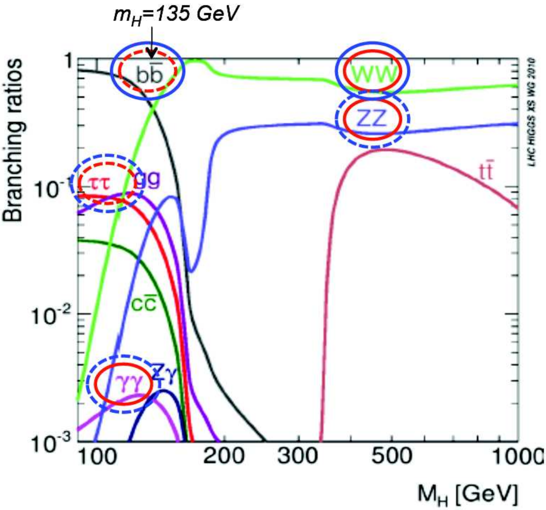
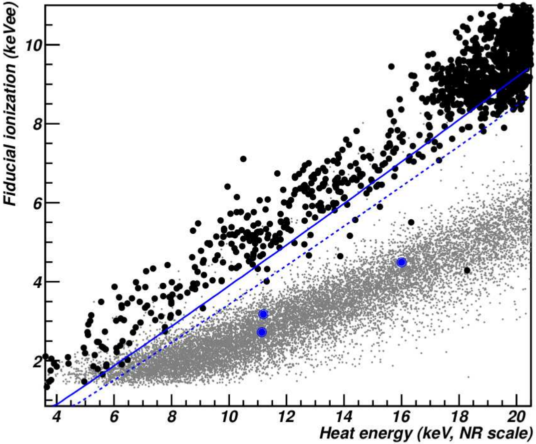
Higgs Decays



- Blue: Tevatron
- Red: LHC
- $b\bar{b}$ final state cannot be effectively triggered and tagged at the LHC

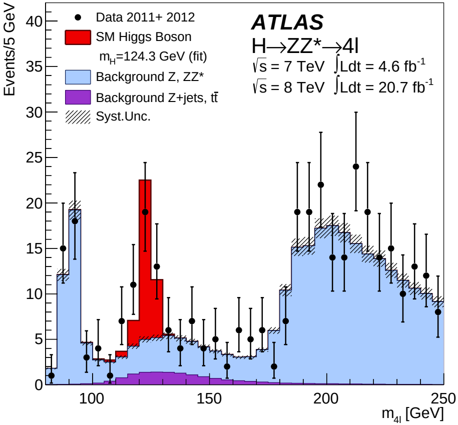
The Task

- Statistics can be used for very many purposes
- I guess here we are most concerned about
  - Finding or excluding a signal
  - Determining uncertainties



The Task

- Statistics can be used for very many purposes
- I guess here we are most concerned about
  - Finding or excluding a signal
  - Determining uncertainties



The Definition of the Probability

- For most of the talk: Define Probability P of X as

$$P(X) = N(X)/N \quad \text{for} \quad N \rightarrow \infty$$

  Examples: coins, dice, cards

- For continuous x extend to Probability Density

$$P(x\,\text{to}\,x + \mathrm{d}x) = p(x)\mathrm{d}x$$

  $p(x)$ is the *probability density function (pdf)*

- Examples:
  - Measuring continuous quantities ($p(x)$ often Gaussian, Poisson, ...)
  - Counting rates
  - Physical Quantities: Parton momentum fractions (proton pdfs) ...
- Alternative: Define Probability $P(X)$ as “degree of belief that X is true”

The Likelihood

- Probability distribution of random variable x often depends on some parameter a
- Joint function $p(x, a)$:
  - Considered as $p(x)|a$ this is the pdf.
  - Normalised: $\int p(x)\mathrm{d}x = 1$
  - Considered as $p(a)|x$ this is the Likelihood $L(a)$ (or $\mathcal{L}(a)$)
  - Not "likelihood of a" but "likelihood that a would give x"
  - Not normalised. Indeed, must never be integrated.
- This is going to be one of the central concepts/quantities for the rest of the talk
- If we want to know a parameter a, we are looking for the point where the likelihood that a would predict the data x is maximized
- If we want to test a Hypothesis H_0 against another one (H_1), we want to compare their likelihoods
- If we want to know what a cannot be, we want to know where $\mathcal{L}(a)|x$ is small

Frequentist Reasoning

It's pretty simple, I think:

- Probability of an event is the relative frequency of its occurrence

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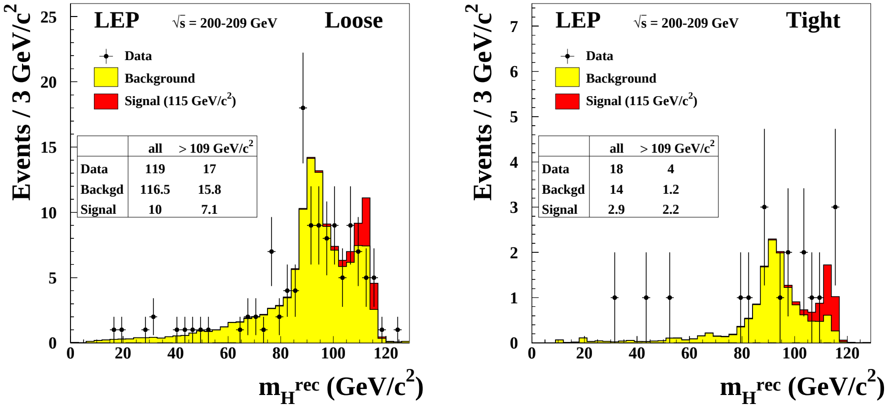
- Since the universe can't be repeated (we don't know how to simulate its genesis before the big bang, therefore the parameters of the Universe are not random variables): there exists no probability density in theory/parameter space
- Therefore, the only statements we can make are:
  If theory H is true (which we will *never* know), then the probability of the observed outcome D of our experiment $P(D|H)$ is...

Frequentist Reasoning: Examples for interpeting physics results

- Can't say
  "m_t has a 68% probability of lying between 171 and 175 GeV"
- Have to say "The statement 'm_t lies between 171 and 175 GeV' has a 68% probability of being true"
- Be aware:
  - In this context, a certain value of m_t has no probability. It is either true or false.
  - But the interval $[171, 175]$ depends on the data and does fluctuate. If you repeat the experiment, you will get different intervals each time, and 68% of them should cover the invariant true value.
- if you always say a value lies within its error bars, you will be right 68% of the time
- Say "m_t lies between 171 and 175 GeV" with 68% Confidence. Or 169 to 177 with 95% confidence.
- That is the Confidence Level CL

Do we see a Higgs mass peak? Use LEP for simplcity

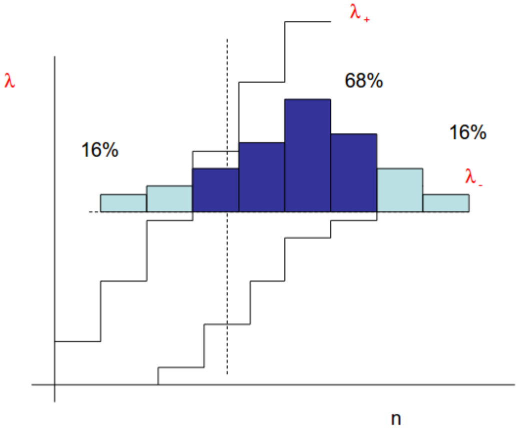
- Are there many of these candidates?



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

The Neyman Interval

- Let's neglect systematics for the time being . . .
- Use Poisson-Distribution $p(n; \lambda) = e^{-\lambda}\lambda^n/n!$
- For any true λ the probability that $(n|\lambda)$ is within the belt is 68% (or more) by construction
- For any n, $[\lambda_-, \lambda_+]$ covers the true λ at 68% confidence
- Only integrated over n, not over λ!

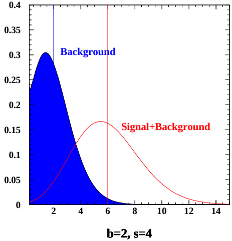


Technique technically works for every CL, and single or double sided

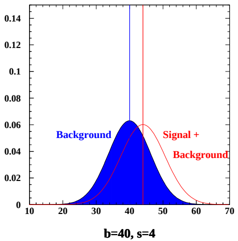
Getting the most out of the availale events?

- If hypothesis exists with $d \approx s+b$ on a significant level: Higgs found
- If not: Calculate, how improbable d is under a certain hypothesis s: $\rightarrow$ 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 . . .

Avoiding a big problem?

- Observe $d = 5$ events. Expected background b of 0.9 events
  Data d = signal s + background b
- Say with 68% confidence: $[2.84, 8.38]$ covers $s + b$
- So say with 68% confidence: $[1.94, 7.48]$ covers s

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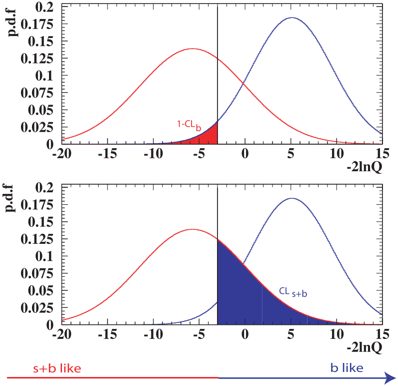
  While it is mathematically correct, it makes no sense physically
- We know that the background happens to have a downward fluctuation. How can we incorporate that knowledge?

We assume *here* that the background is calculated correctly
Deal with systematics later using nuisance parameters

A simple choice of a better test statistics Q

- 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
  $Q = \prod_i P_{d_i}(s_i + b_i)/P_{d_i}(b_i)$
- 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:
$\mathrm{CL}_s = \mathrm{CL}_{s+b}/\mathrm{CL}_b$

The Likelihood Ratio: Neyman-Pearson-Lemma

- We are performing a hypothesis test between two hypotheses H_0: $\theta = \theta_0$ and H_1: $\theta = \theta_1$
- the likelihood-ratio test which rejects H_0 in favour of H_1 when the test statistics

$$Q(d) = \frac{L(d|\theta_0)}{L(d|\theta_1)} \leq \eta$$

with

$$P(Q(d) \leq \eta \mid H_0) = \alpha$$

is the most powerful test of size α

- What does that mean? And what are H_0 and H_1?

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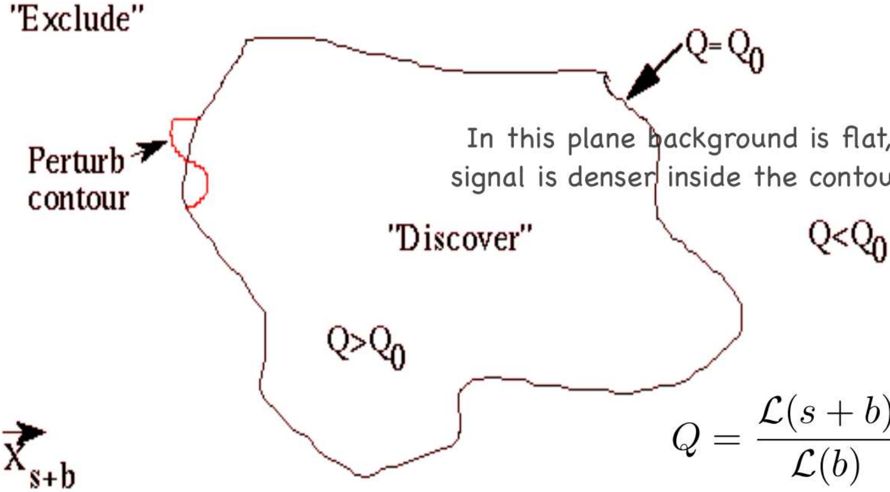
  is the most powerful test of size α
- What does that mean? And what are H_0 and H_1?
- We want α ("Type I" error) very small
- We want the power

$$P(\text{reject } H_0 | H_0 \text{ is false}) = \beta$$

  to be as large as possible. $1 - \beta$ is the "Type II" error.

The Likelihood Ratio: Neyman-Pearson-Lemma



In this plane background is flat, signal is denser inside the contour

$$Q = \frac{\mathcal{L}(s+b)}{\mathcal{L}(b)}$$

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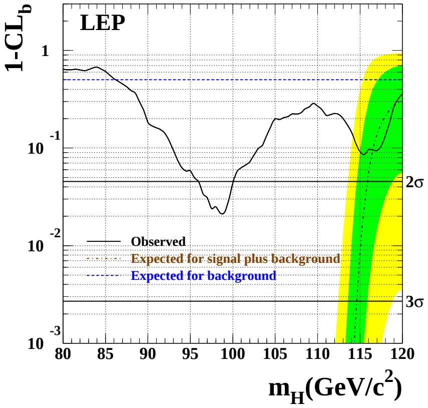
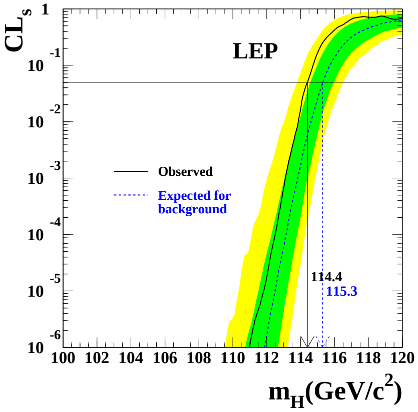
Is there a Significant Excess?



- $(1 - CL_b)$ 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:

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

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Developments since LEP: Profile Likelihood

- Already at LEP: The important thing is to split the the statistics in bins with high s_i/b_i and low s_i/b_i
- New: Introduce signal strength scaling parameter μ
- Assume you measure d_i and try to explain it with $\mu s_i + b_i$ as assumed expectation values
- In addition, measure m_k background bins and try to explain with $u_k(\vec{\theta})$ as expectation value

$$L(\mu, \boldsymbol{\theta}) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \quad \prod_{k=1}^{M} \frac{u_k^{m_k}}{m_k!} e^{-u_k}$$

- Significance test is based on profile likelihood test statistics:

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

maximizes L for specified μ

maximize L

See how this is similar to a fit?

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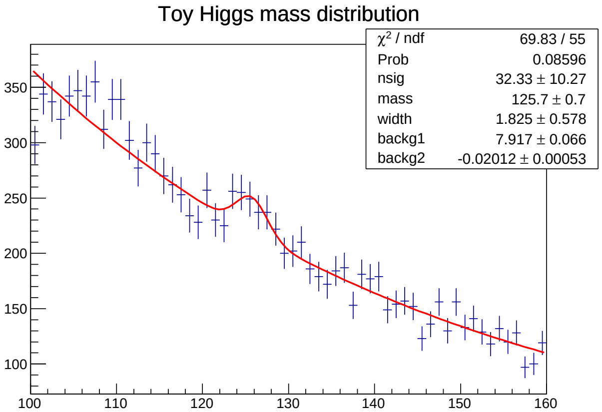
The Profile Likelihood Technique in a fit

- In a fit to measurements $\vec{x}$, you vary the parameters $\vec{a}$ and either maximize the Likelihood $\ln \mathcal{L}(\vec{x};\vec{a})$ (or minimize the χ^2)
- In special cases:

$$-2\ln\mathcal{L} = \chi^2 = (\vec{x} - \vec{\bar{x}}(\vec{a}))^T C^{-1} (\vec{x} - \vec{\bar{x}}(\vec{a}))$$



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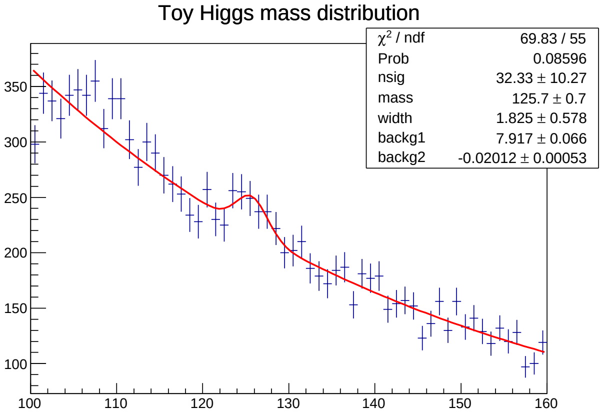
- In special cases: (and no correlations)

$$-2\ln\mathcal{L} = \chi^2 = \sum_i \frac{(x_i - \bar{x}_i(\vec{a}))^2}{\sigma_i^2}$$



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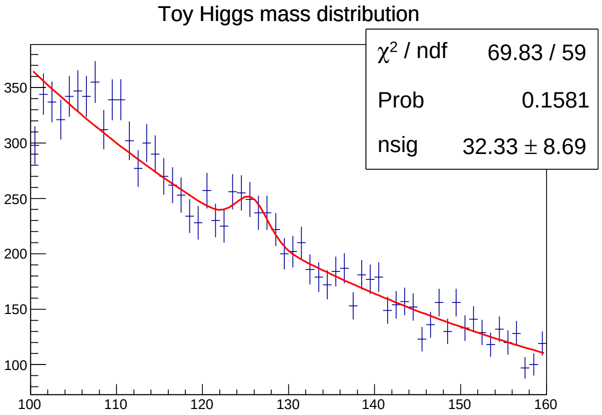
- In the above fit, the uncertainty on the number of signal events seems to be larger than the poisson uncertainty $\sqrt{N}$. Why?

The Profile Likelihood Technique in a fit

- In the above fit, the uncertainty on the number of signal events seems to be larger than the poisson uncertainty $\sqrt{N}$. Why?
- Obviously that is because there is an uncertainty on the background model. Let's fix everything apart from NSig:



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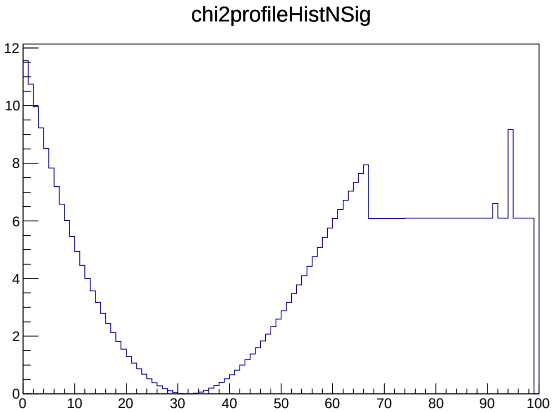
- So what does “profiling” mean?
- Study how the χ^2 (or more precisely $-2\ln\mathcal{L}$) behaves if one parameter of interest is varied and if all other nuisance parameters are varied such that they give the lowest possible $-2\ln\mathcal{L}$ for each given parameter of interest



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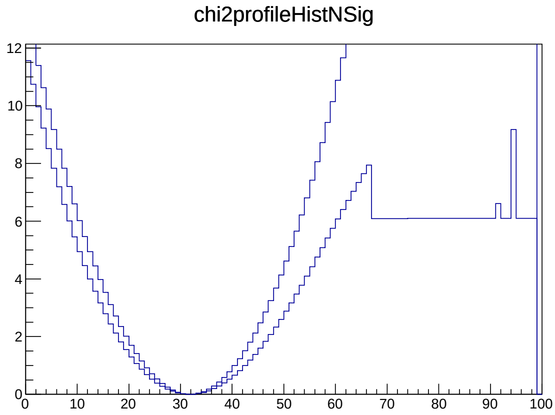

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$$-2\ln\lambda(\mu) = -2\ln\mathcal{L}(d;\mu,\hat{\hat{\vec{\theta}}}) + 2\ln\mathcal{L}(d;\hat{\mu},\hat{\vec{\theta}})$$

- that looks mightily familiar to the fit. There, we plotted

$$-2\Delta\ln\mathcal{L} \approx \Delta\chi^2 = \chi^2(\mu) - \chi^2_{min}$$

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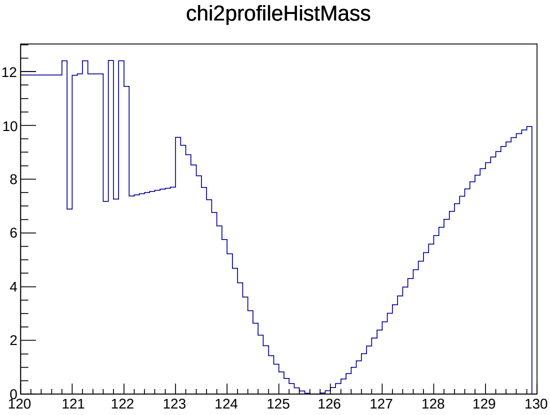
- The choice of $\lambda(\mu)$ is optimal (Neyman-Pearson) for distinguishing the hypothesis μ from what is observed ($\hat{\mu}$). I.e. it is optimal for excluding ranges of μ.
- Example: If we exclude $\mu = 0$: Exclude that there is no Higgs
- If we exclude $\mu = 1$: Exclude that there is a SM Higgs

The Profile Likelihood Technique in a fit

- We can do this with every parameter ... here it's the mass:



The Profile Likelihood Technique in a fit

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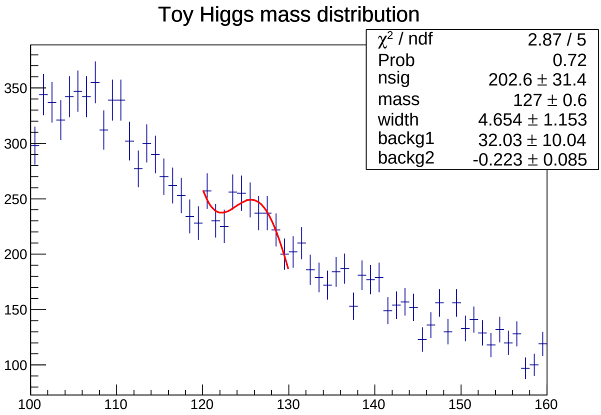
- In addition, it can be (depends on the experimental situation) an elegant way of determining the background in the first place:



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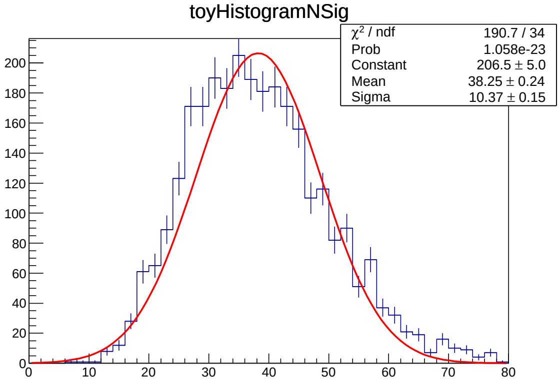

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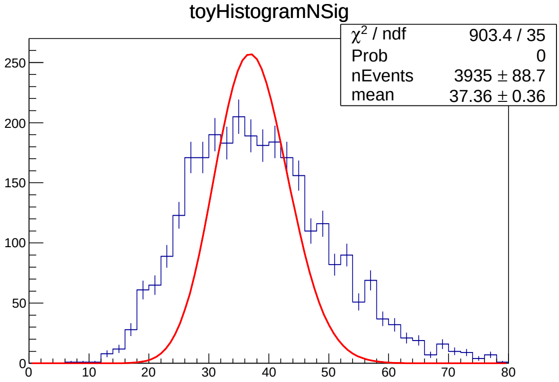


Developments since LEP

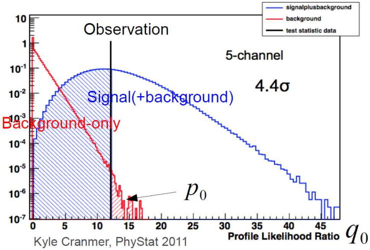
	Test statistic	Test statistic	Nuisance parameters	Pseudo-experiments
LEP	$-2\ln\frac{L(\mu,\tilde{\theta})}{L(0,\tilde{\theta})}$	Simple LR	Fixed by MC	Nuisance parameters randomized about MC
Tevatron	$-2\ln\frac{L(\mu,\hat{\hat{\theta}})}{L(0,\hat{\theta})}$	Ratio of profiled likelihoods	Extracted from priors	Nuisance parameters randomized from priors
LHC	$-2\ln\frac{L(\mu,\hat{\hat{\theta}})}{L(\hat{\mu},\hat{\theta})}$	Profile likelihood ratio	Profiled (fit to data)	New nuisance parameters fitted for each pseudo-exp.

Limits at the LHC: Setting the CL

- Try to reject the background hypothesis based on q_0, independent of s_i

$$q_0 = \begin{cases} -2\ln\lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

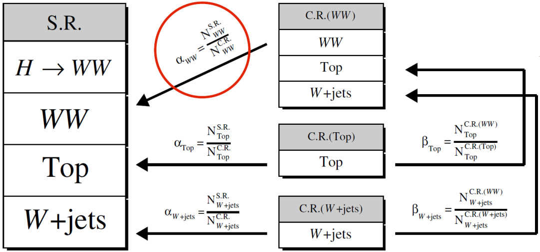
- E.g. could get the following: if p_0 small, reject SM! Found new physics! But it doesn't tell us whether we found the SM Higgs. We might have found something else!
- To get a hint whether a new observation could be the SM Higgs, $\hat{\mu}$ must be compatible with 1

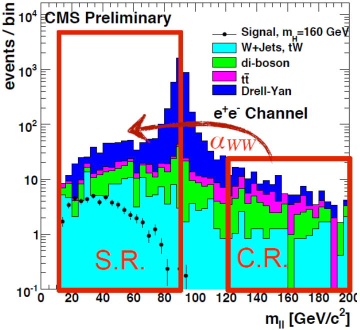


Kyle Cranmer, PhyStat 2011

Limits at the LHC: How to control θ

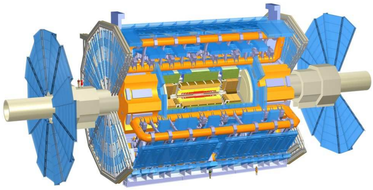
- The big thing since LEP: Ged rid of partly bayesian techniques by fitting the systematic uncertainties to the data during limit setting at each toy MC





The ATLAS Experiment

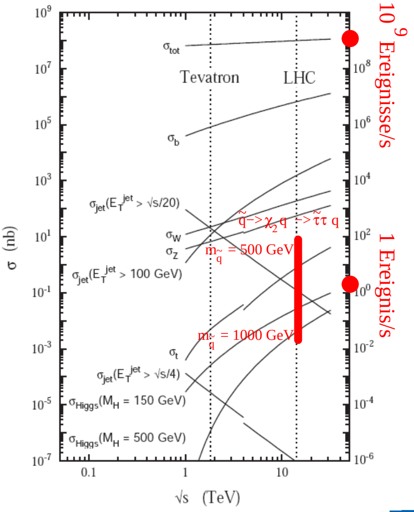
- ATLAS and CMS: First direct experimental access to the Terascale



Diameter	25 m
Length	46 m
Weight	7000 t

≈ 100 Million readout channels

≈ 3000 km cables



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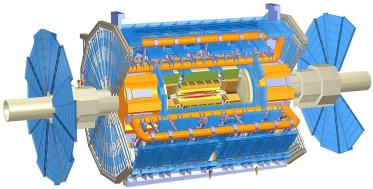
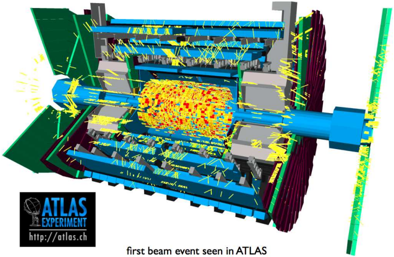
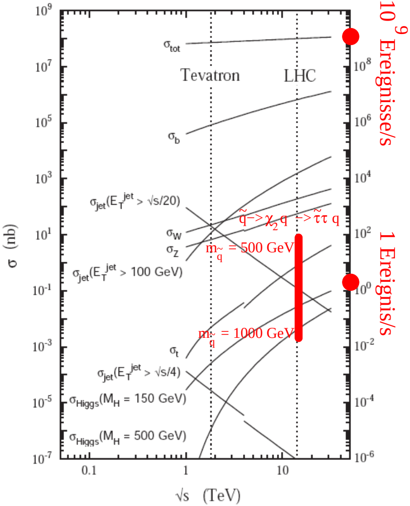
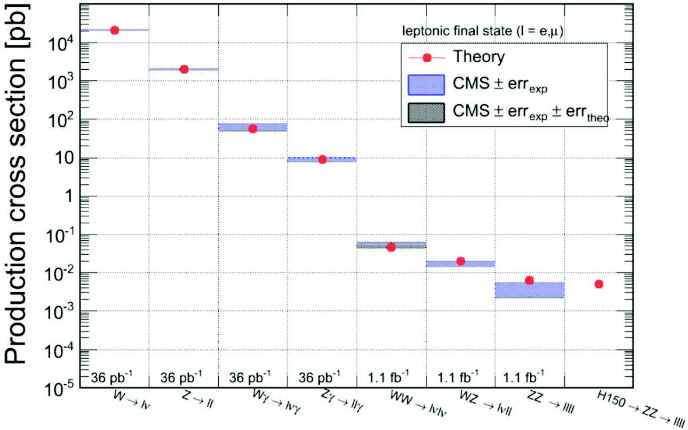




first beam event seen in ATLAS

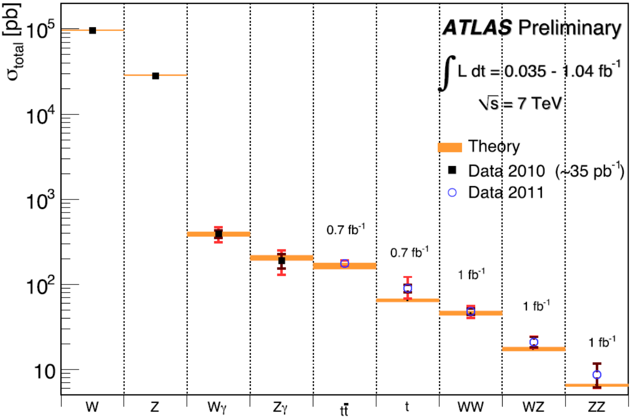


Very quick summary of CMS and ATLAS



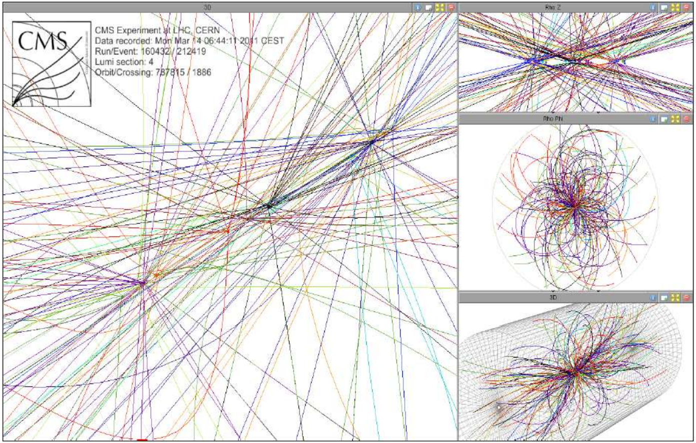
In this section some content from A. Korytov

Very quick summary of CMS and ATLAS



In this section some content from A. Korytov

Impressive Luminosity at LHC

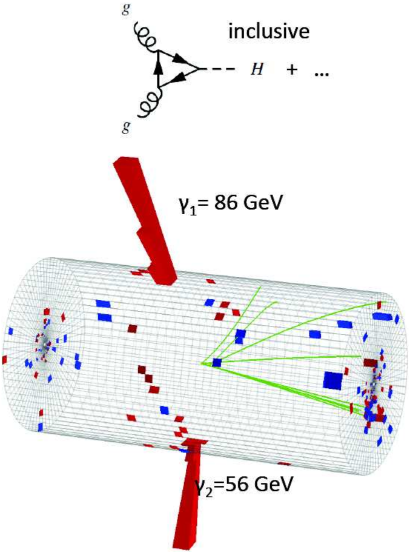


On average, 2011 data have 6 pile-up events per BX

Event shown above has 13 reconstructed vertices

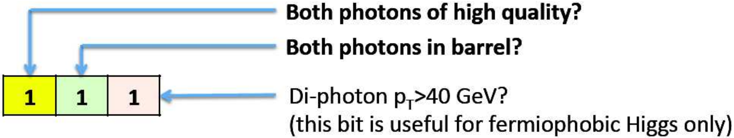
Around $int\mathcal{L} = 3\,\mathrm{fb}^{-1}$ per experiment on tape, $\mathcal{L}^{peak} 5 \times 10^{33}$

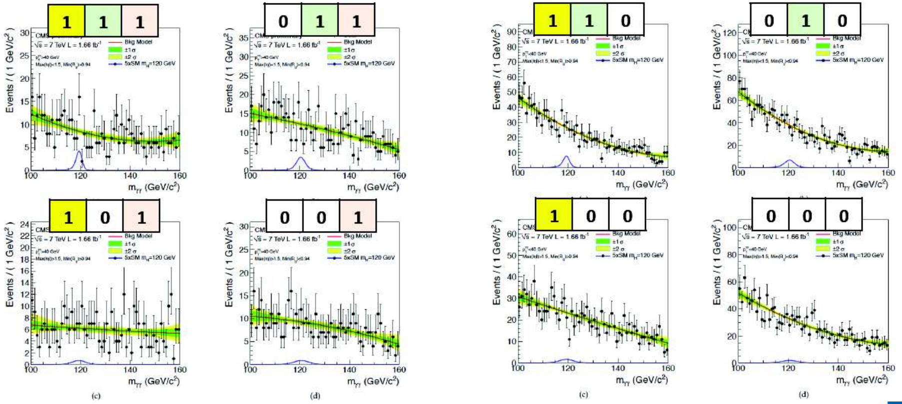
The most sensitive search at very low masses



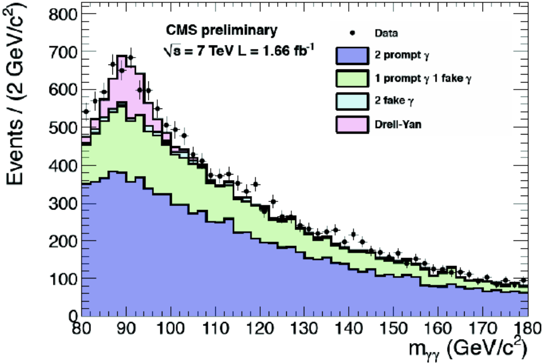
- Inclusive production
- Two isolated photons
- Best $\Delta m \approx 1\%$
- Entirely data-driven analysis, use sidebands
- Background from real 'SM' di-photons and from fakes (e or π with missing tracks)

Different classes for $h \to \gamma\gamma$



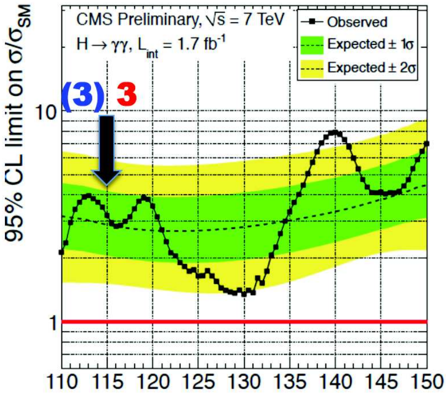


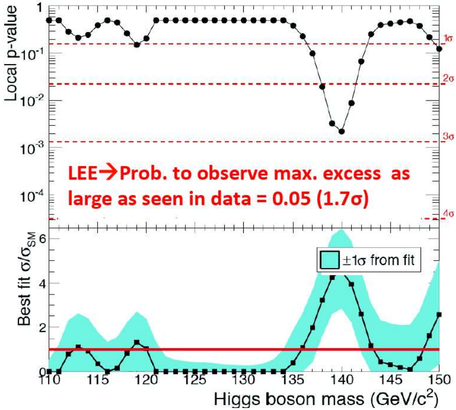
$h \to \gamma\gamma$ Results



- MC just for illustration, not used
- Very good statistics already acquired
- Some interesting spikes . . . but can we have so many Higgses?

$h \to \gamma\gamma$ Results

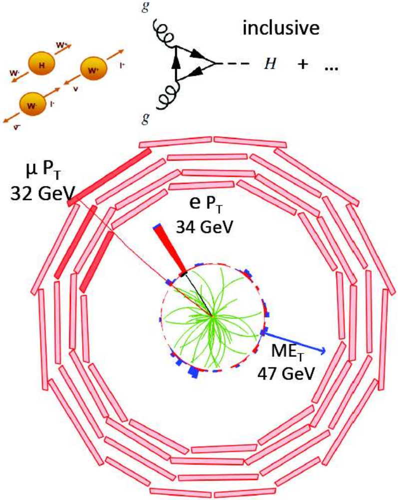




vspace*-3mm

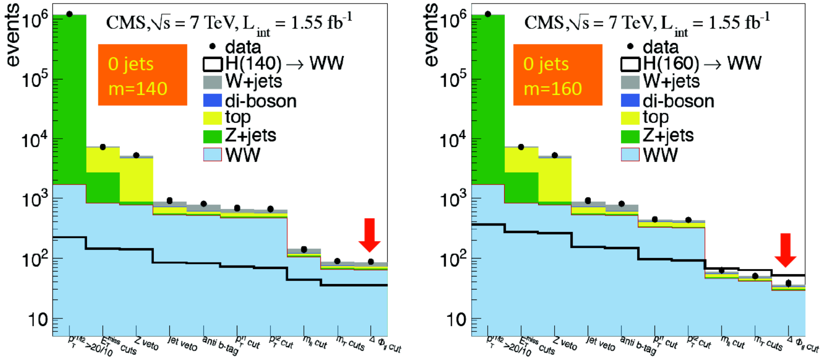
- Set limit around 3 times the SM cross section times BR
- Two small spikes at 113 and 120 compatible with Higgs and no Higgs
- Spike at 140 much too big for SM Higgs!
- Beware of the Look Elsewhere Effect!

Very wide sensitivity: $h \to WW \to \ell\nu\bar{\ell}\bar{\nu}$



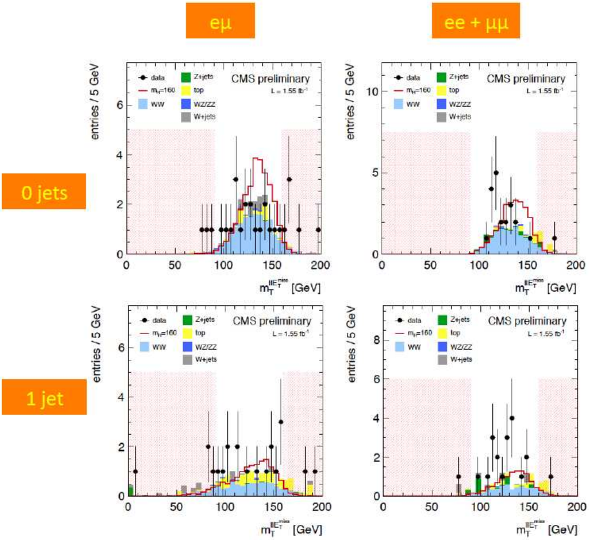
- Covers big region in m_h
- mass resolution only $\Delta m \approx 20\%$
- Trigger on two isolated leptons
- Require E_T^{miss}, small $\Delta\phi$, small $m_l l$
- Use transverse mass $m_T = \sqrt{(2p_T^{\ell\ell} E_T^{miss}(1 - \cos\theta))}$
- Split up in different regions accoring to $n$jets, lepton flavour, due to different backgrounds
- Backgrounds: $t\bar{t}$, W+jets, WZ, WW, Drell-Yan

$h \to WW$ Properties

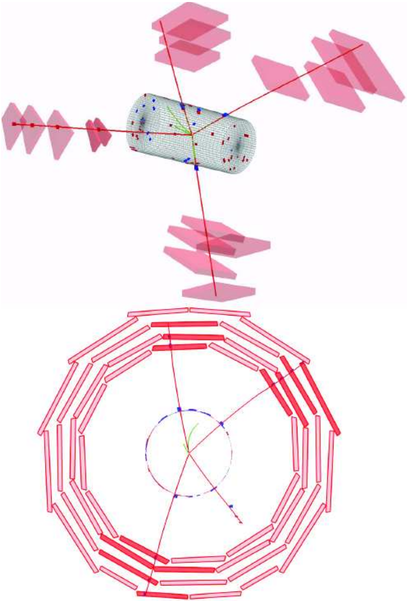


- Remarkable agreement cut by cut
- Would have seen a 160 GeV SM Higgs since long!

$h \to WW$ Properties

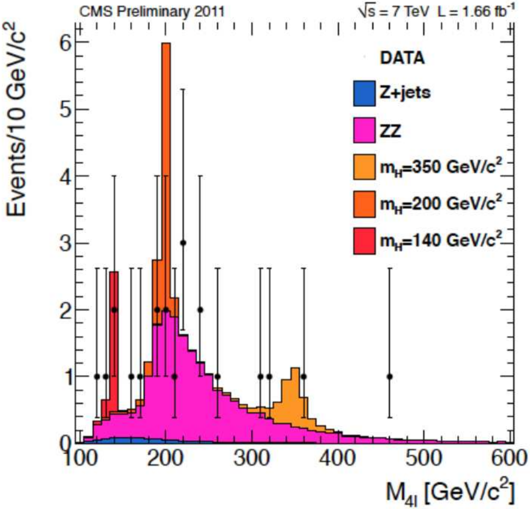


Very good mass res.: $h \to ZZ \to 4\ell$



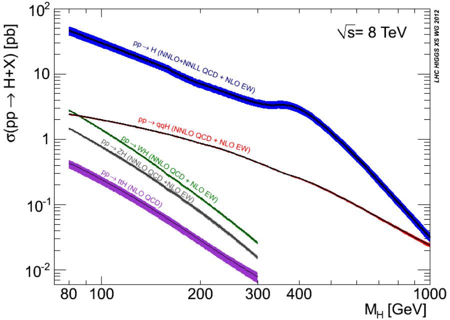
- Inclusive Producton
- 4 isolated leptons $4e, 4\mu, 2e2\mu$
- no impact parameter
- final discriminant: $m_{4\ell}$
- $\Delta m \approx 1\%$
- ZZ and $t\bar{t}, Z$+jets backgrounds
- Also look at $2\ell 2\nu$

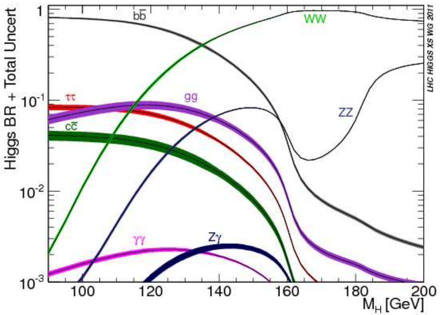
Very good data/bkg agreement in $h \to ZZ \to 4\ell$



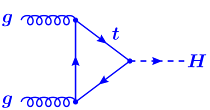
- 21 obs, 21.2 expected
- Note: Low background and very good Δm: Very single candidate will make big impact on limit/discovery!
- Therefore, observed limits still strongly changing with each update

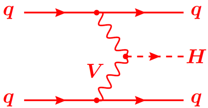
General Features of Higgs Production

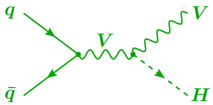


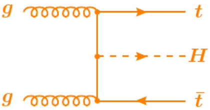


- One new particle, often a clearly reconstructable resonance
- Production mode not easy to isolate, but Higgs decays can be disentangled very clearly
- Nature couldn't have been more kind than putting $m_H \approx 125\,\mathrm{GeV}$!

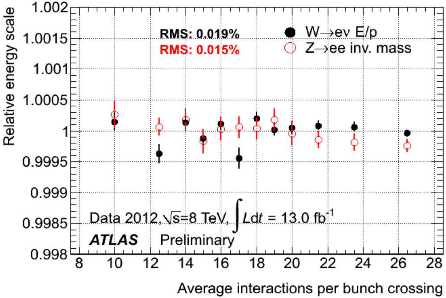


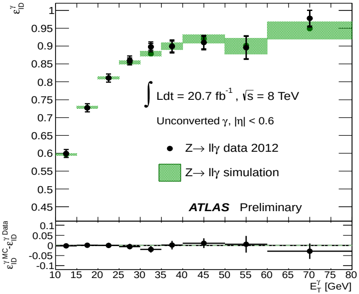




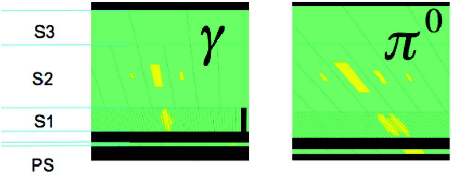


Controlling Higgs Searches



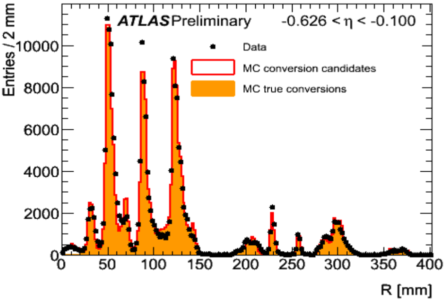


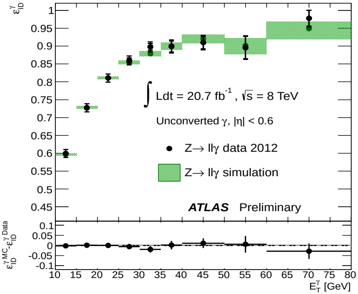
- Shower shape γ ID
- ϵ_γ from $Z \to \ell\ell\gamma$, $Z \to e^+e^-$
- EM scale from $Z \to e^+e^-$
- Energy scale known to 0.3 % – 0.45 %



- $ZZ \to 4\ell$, $\gamma\gamma$ seem straightforward, but a lot of challenging details!
- Fermionic final states still very challenging due to high backgrounds and coarser mass resolution

Controlling Higgs Searches





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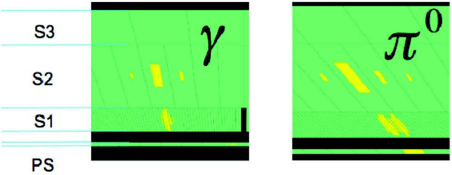
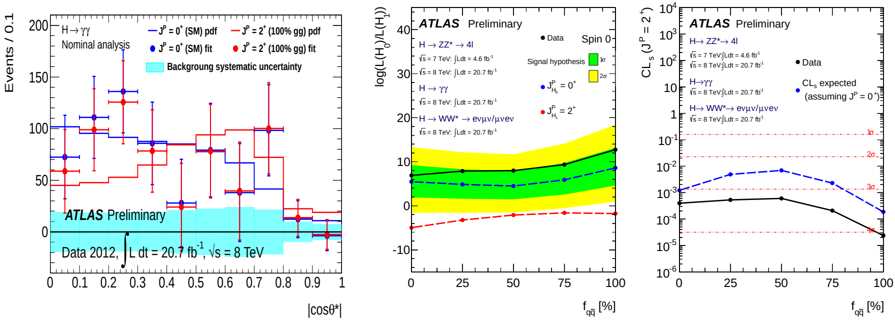


- $ZZ \to 4\ell$, $\gamma\gamma$ seem straightforward, but a lot of challenging details!
- Fermionic final states still very challenging due to high backgrounds and coarser mass resolution

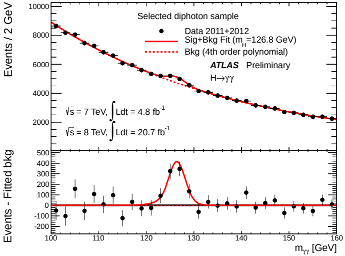
Is the New Particle actually a $J^P = 0^+$ Boson?



- Example of observable from $H \to \gamma\gamma$. Look at $|\cos\theta^*|$, decay angle distribution in the Collins-Soper frame
- Exclude $J^P = 2^+$ at $> 99.9\,\%$ CL independent of $q\bar{q}$ fraction in the production of the $J = 2$ particle
- Exclude $J^P = 0^-$ at $99.6\,\%$ CL based on $H \to ZZ^{(*)} \to 4\ell$
- Assume $J^P = 0^+$ hypothesis for all following measurements

ATLAS-CONF-2013-040, ATLAS-CONF-2013-029, ATLAS-CONF-2013-031, ATLAS-CONF-2013-013

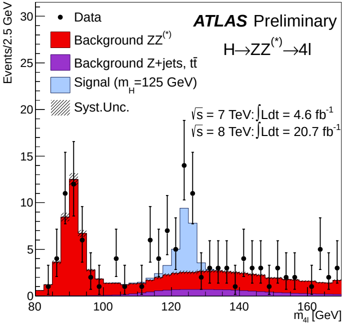
Higgs Peaks in $H \to ZZ$ and $H \to \gamma\gamma$



$$\mu_{\gamma\gamma} = 1.65 \pm 0.24(\mathrm{stat}) \pm 0.21(\mathrm{syst})$$

$$m_{H_{\gamma\gamma}} = 126.8 \pm 0.2(\mathrm{stat}) \pm 0.7(\mathrm{syst})$$

local $p_0 < 10^{-13}$ ($> 7\,\sigma$)



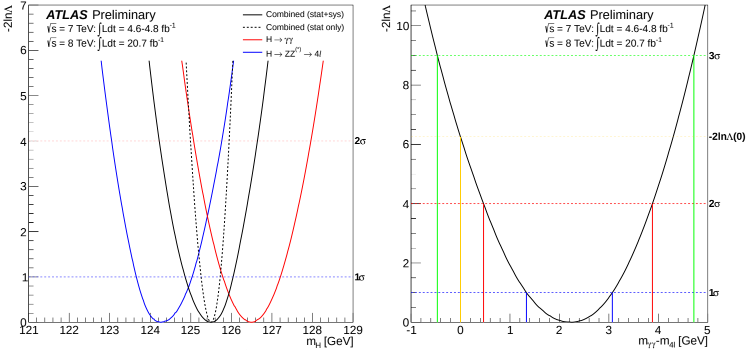
$$\mu_{ZZ\to 4\ell} = 1.7 \pm 0.5(\mathrm{stat}+\mathrm{syst})$$

$$m_{H_{ZZ\to 4\ell}} = 124.3 \pm 0.6(\mathrm{stat}) \pm 0.4(\mathrm{syst})$$

local $p_0 < 10^{-10}$ ($> 6\,\sigma$)

ATLAS-CONF-2013-012, ATLAS-CONF-2013-013

Mass Consistency in the ZZ and $\gamma\gamma$ Channels



- Measure mass using Profile Likelihood Ratio
$$\Lambda(m_H) = \mathcal{L}(m_H, \hat{\hat{\theta}})/\mathcal{L}(\hat{m}_H, \hat{\theta})$$
put all systematics and parametric uncertainties in θ ($\mu_{4l}, \mu_{\gamma\gamma}$,theo,exp.syst.)
- $m_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(syst)$ GeV
- Use $m_H, \Delta m_H$ for parametrization and flat E scale profile:
$$\mathcal{P}(\Delta m_H = 0) = 8\,\%$$

ATLAS-CONF-2013-014

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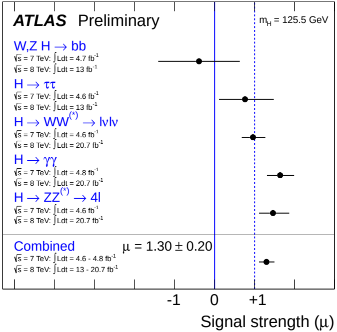
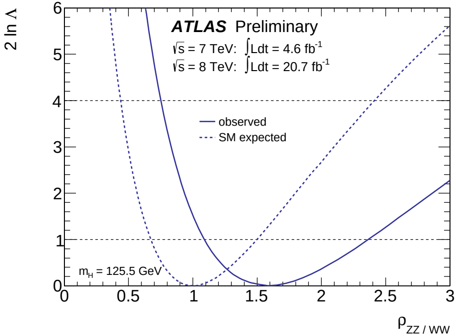
Higgs Coupling Measurements: Z vs. W





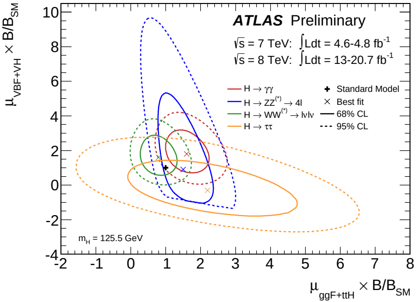
- Overview over the coupling measurements: Fermionic channels not yet very significant, bosonic channels a bit high, but consistent with SM
- $\mu = 1.30 \pm 0.13(stat) \pm 0.14(syst)$, $\mathcal{P}(\mu_i = 1) = 8\,\%$
- Fundamental prediction of QFD (Custodial Symmetry):

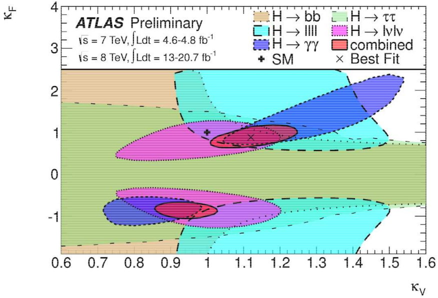
$$\rho_{ZZ/WW} = \frac{\mathcal{B}(H \to ZZ)}{\mathcal{B}(H \to WW)} \times \frac{\mathcal{B}_{SM}(H \to WW)}{\mathcal{B}_{SM}(H \to ZZ)} = 1$$

$$\text{exp.result} : \rho_{ZZ/WW} = 1.6^{+0.8}_{-0.5}$$

ATLAS-CONF-2013-034

Higgs Coupling Measurements: f vs. V (I)





- Separate vector boson couplings from fermion couplings, assuming NWA
- Sensitivity to both even within $H \to WW, ZZ, \gamma\gamma$:
  Direct couplings HZZ, HWW and in loops Htt

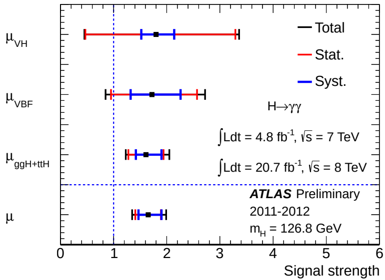
$$\mu_{\gamma\gamma} \propto \sigma(gg \to H)\mathcal{B}(H \to \gamma\gamma) = (\sigma_{SM}(gg \to H)\kappa_g^2)(\mathcal{B}_{SM}(H \to \gamma\gamma)\kappa_\gamma^2)/\kappa_{\Gamma_H}^2(\kappa_g, \kappa_\gamma)$$

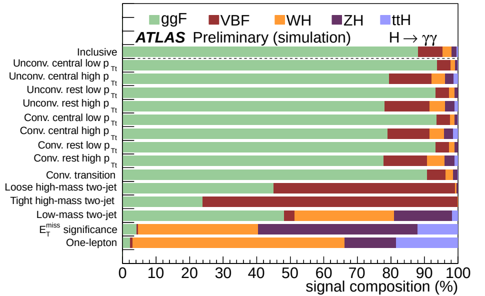
$$\mu_{\gamma\gamma} \propto \sigma(gg \to H)\mathcal{B}(H \to \gamma\gamma) = (\sigma_{SM}(gg \to H)\kappa_F^2)(\mathcal{B}_{SM}(H \to \gamma\gamma)f(\kappa_F, \kappa_V))/\kappa_{\Gamma_H}^2(\kappa_F, \kappa_V)$$

- or $\mu_{VBF+VH}/\mu_{ggH+t\bar{t}H}$ with the same final state each, incl. all final states
- $\mathcal{P}(\mu_{VBF}/\mu_{ggH+t\bar{t}H} = 0) = 0.09\,\%\,(3.1\sigma)$ Evidence for VBF!

ATLAS-CONF-2013-034

Higgs Coupling Measurements: f vs. V (II)





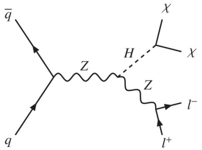
- This works even when only using $H \to \gamma\gamma$
- MVA based selection of events with 2 (forward) jets
- VBF purity 74 % (initial SM $\sigma_{gg\to H} = 19.5\,\mathrm{pb}^{-1}/\sigma_{VBF} = 1.6\,\mathrm{pb}^{-1}$)
- VH enriched samples using
  E_{Tmiss} significance, inclusive lepton, $W, Z \to jj$ mass
- Then vary μ_{ggH}, μ_{VBF} and μ_{VH} individually in

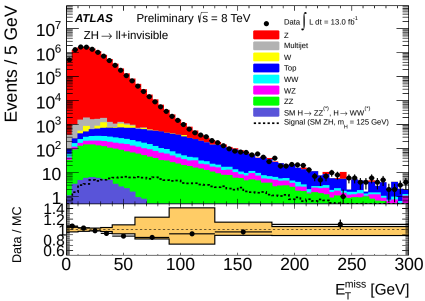
$$\Lambda(\mu_{ggH}, \mu_{VBF}, \mu_{VH}) = \frac{\mathcal{L}(\mu_{ggH}, \mu_{VBF}, \mu_{VH}, \hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu}_{ggH}, \hat{\mu}_{VBF}, \hat{\mu}_{VH}, \hat{\theta})}$$

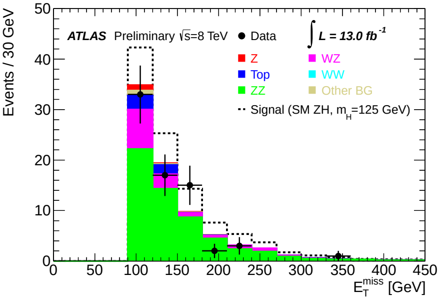
ATLAS-CONF-2013-012

Searching for Invisible Higgs Decays in $ZH \to \ell\ell\,\mathrm{inv}$

- Extremely important, since total width of the Higgs cannot be directly measured at the LHC for narrow $\Gamma_H < \mathcal{O}(0.5)$ GeV
- Select events with
  - 2 SFOS leptons $p_T > 20$ GeV
  - overlap $\Delta\phi(E_{Tmiss}, \vec{p}_{Tmiss}) < 0.2$, large $\Delta\phi(\vec{p}_Z, E_{Tmiss}) > 2.6$
  - $|p_T^{\ell\ell} - E_{Tmiss}|/p_T^{\ell\ell} < 0.2$

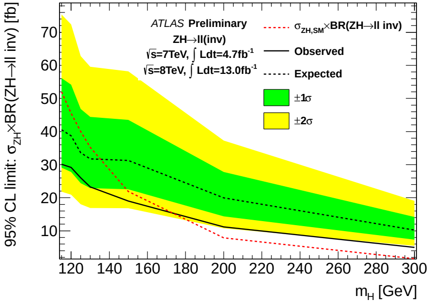


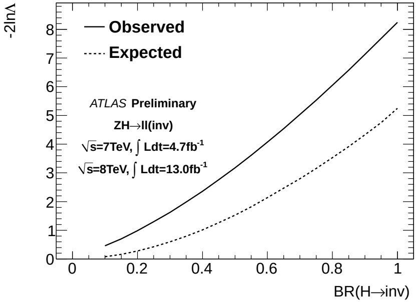




ATLAS-CONF-2013-011

Searching for Invisible Higgs Decays in $ZH \to \ell\ell\,\mathrm{inv}$

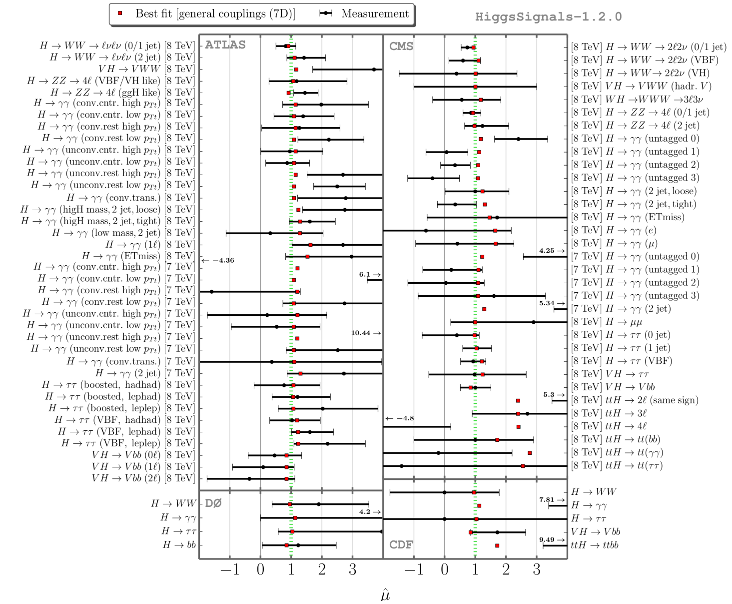




- No significant deviation from the SM found
- At SM production strength: $\mathcal{B}(H \to inv.) < 0.65(0.84)\,@\,95\,\%\,\mathrm{CL}$
- For $m_H = 125.5\,\mathrm{GeV}$: Result also presented in terms of PL ratio $-2\ln\Lambda \approx \chi^2$. Fully model independent! Can directly be used in a (global) fit

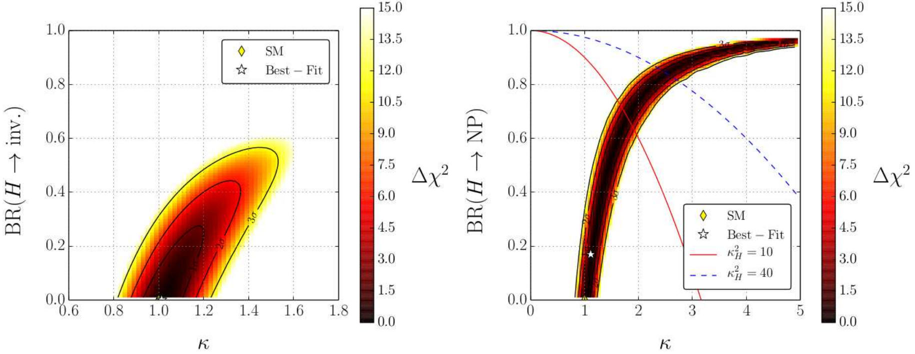
Does anything show a clear hint for New Physics?

from arxiv:1403:1582



So do we already know its the SM Higgs?

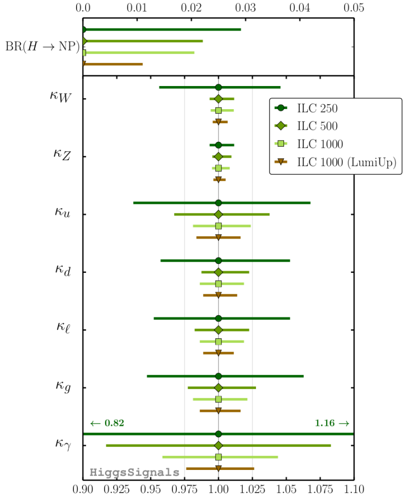
from arxiv:1403:1582

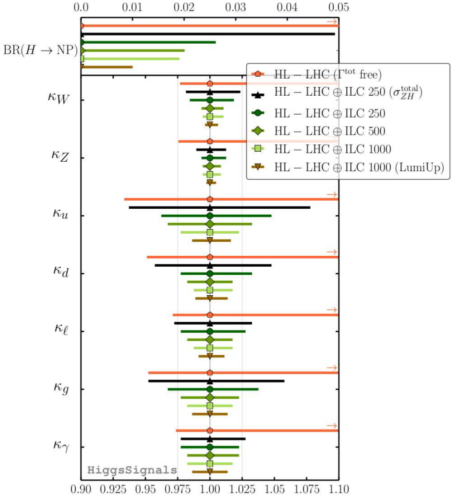


$\kappa^2_{H,\text{limit}} = 40\ (10) \quad \rightarrow \quad \kappa \leq 2.51\ (1.78)$ and $\mathcal{B}(h \rightarrow \mathrm{NP}) \leq 84\%\ (68\%)$

So do we already know its the SM Higgs?

from arxiv:1403:1582





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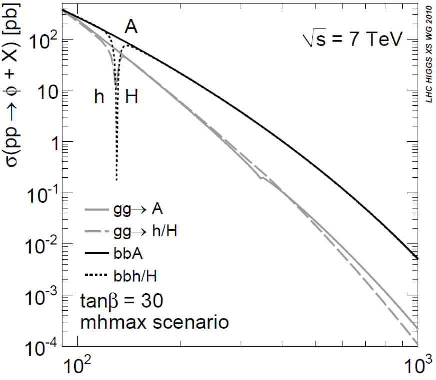
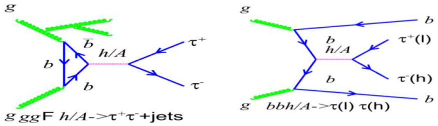
The most important Channel for BSM Higgs

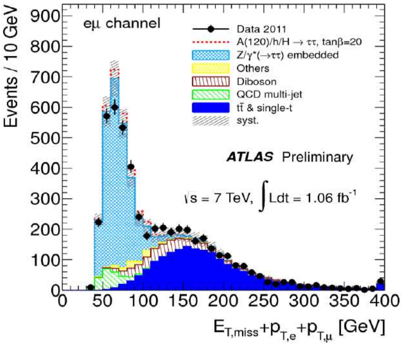
- Let's just accept for the time being that e.g. in SUSY we have extended Higgs sectors, e.g. $h, A, H, H^{\pm}$
- E.g. in SUSY: High $\tan\beta = v_2/v_1$ means much increased couplingof A to down type fermions (b, τ)
- can have significantly increased $\sigma \times BR$

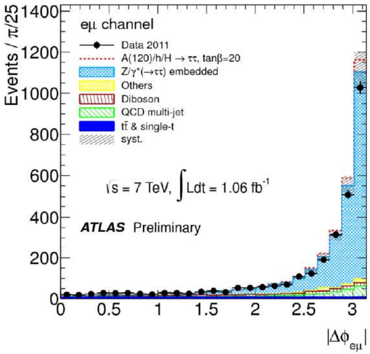




Some content in this section from M. Schumacher

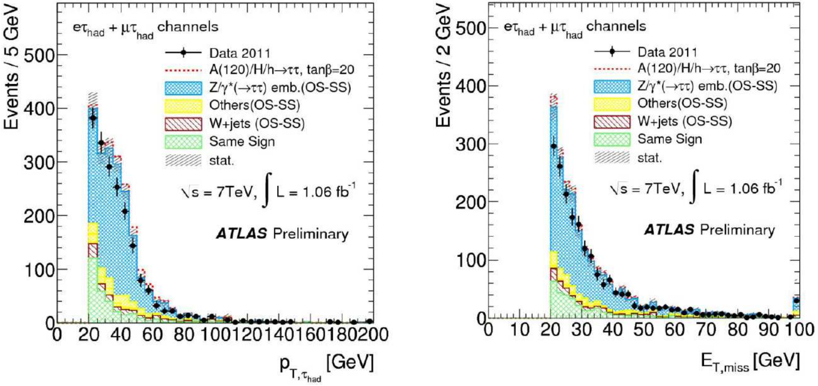
$\phi \to \tau^+\tau^- \to e\mu$





- Lots of background in all searches
- Trigger on leptons, Good Lepton ID crucial
- final discriminant: $m_{\tau\tau}^{eff} = p_{\tau^+} + p_{\tau^-} + p_{miss}$

$\phi \to \tau^+\tau^- \to \ell had$



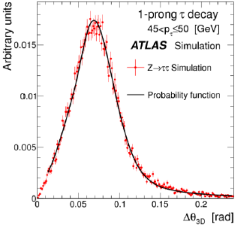
- Lots of background in all searches. Trigger on one lepton
- τ_{had} performance: $\epsilon \approx 60\%$ for jet rejection of 20
- Cut against $W \to \tau\nu, \ell\nu$ using m_T

The Missing Mass Calculator

- 7 unknowns: leptonic τ decay: four momentum of di-neutrino system
  hadronic τ decay: three momentum of single neutrinos

- 4 constraints: MET from neutrinos (x,y component)
  m(vis,ν) = m_τ (τ^+,τ^--decays)

$$E_x^{\rm miss} = p_{\rm miss_1}\sin\theta_{\rm miss_1}\cos\phi_{\rm miss_1} + p_{\rm miss_2}\sin\theta_{\rm miss_2}\cos\phi_{\rm miss_2},$$
$$E_y^{\rm miss} = p_{\rm miss_1}\sin\theta_{\rm miss_1}\sin\phi_{\rm miss_1} + p_{\rm miss_2}\sin\theta_{\rm miss_2}\sin\phi_{\rm miss_2},$$
$$m_\tau^2 = m_{\rm miss_1}^2 + m_{\rm vis_1}^2 + 2\sqrt{p_{\rm vis_1}^2 + m_{\rm vis_1}^2}\sqrt{p_{\rm miss_1}^2 + m_{\rm miss_1}^2}, \quad -2p_{\rm vis_1}p_{\rm miss_1}\cos\Delta\theta_{\rm vm_1},$$
$$m_\tau^2 = m_{\rm vis_2}^2 + 2\sqrt{p_{\rm vis_2}^2 + m_{\rm vis_2}^2}\cdot p_{\rm miss_2}, \quad -2p_{\rm vis_2}p_{\rm miss_2}\cos\Delta\theta_{\rm vm_2}$$



- assume 3 kinematics values ($\phi_{\rm miss,1(2)}$, $m_{\rm miss}$) and solve system → τ 4-vectors
  scan 3(+2)-dim parameter space and weight each solution according to consistency with τ decay kinematics (+consisteny with MET resolution)

- performance: resolution ~17% efficiency of algorithm >98%

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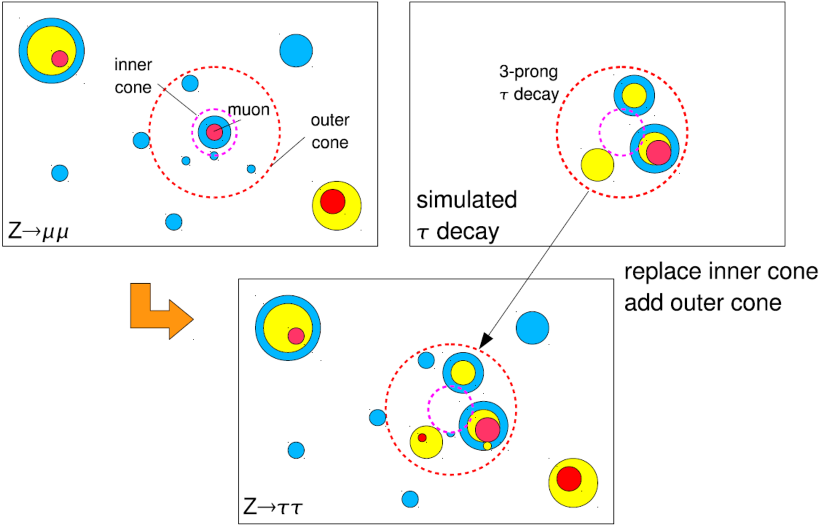
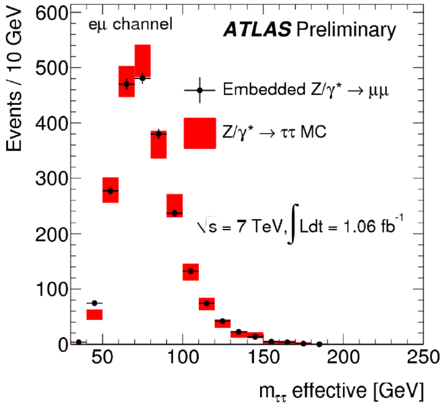
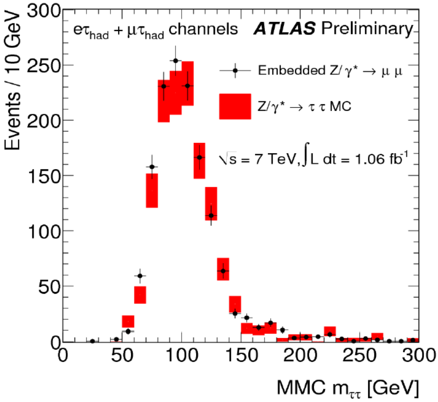
Checking the Simulation: Embedding

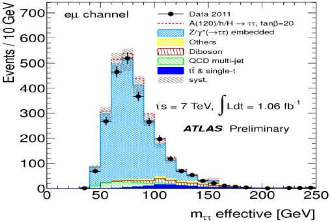


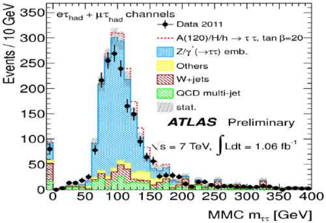
Checking the Simulation: Embedding

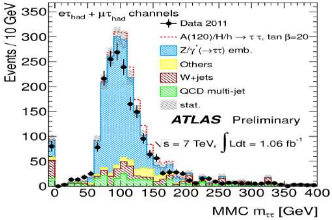




The Result in terms of Histograms



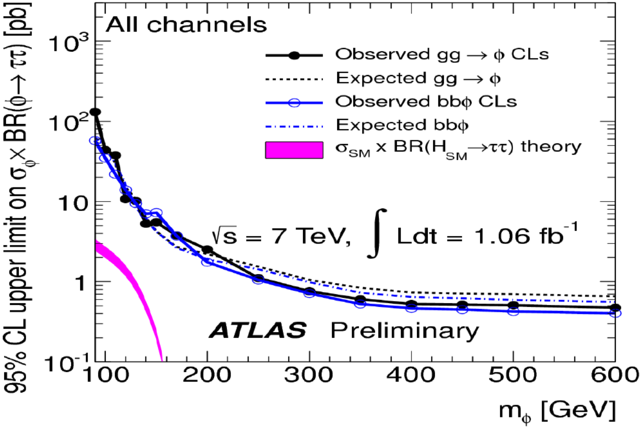




Final state	Est. BG	Data
e μ	2600 ± 200	2472
l τ_{had}	2100 ± 400	1913
τ_{had} τ_{had}	233 +44-28	245
Sum	4900 ± 600	4630

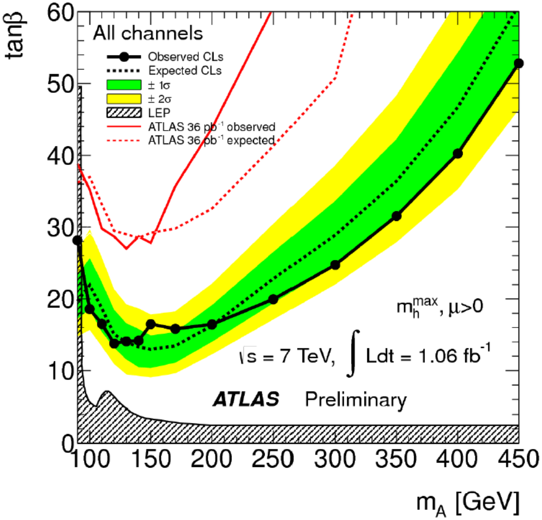
stat. and sys. uncertainty

The Result in terms of Model Independent Limits



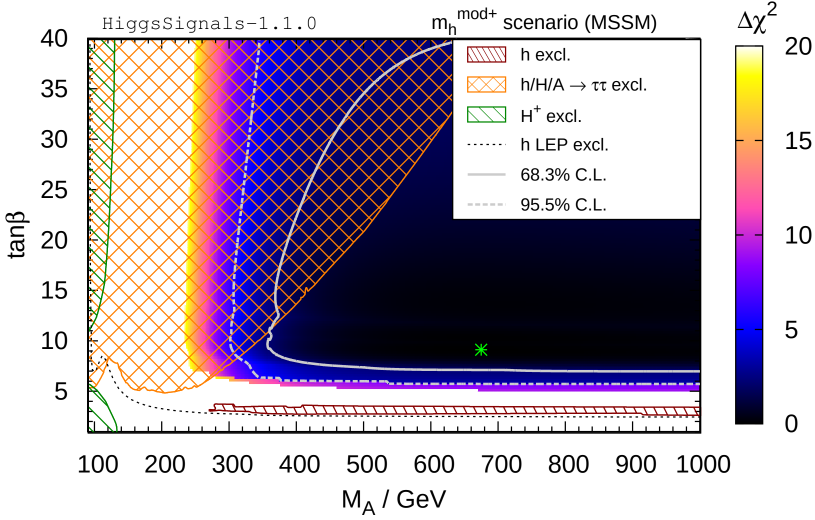
- Slight difference in production modes $gg \to \phi X$ and $gg \to b\bar{b}X \to b\bar{b}\phi X$
- Due to different efficiencies and mass resolutions

The Result in terms of the MSSM



Example: MSSM benchmark $m_h^{\mathrm{mod+}}$ scenario

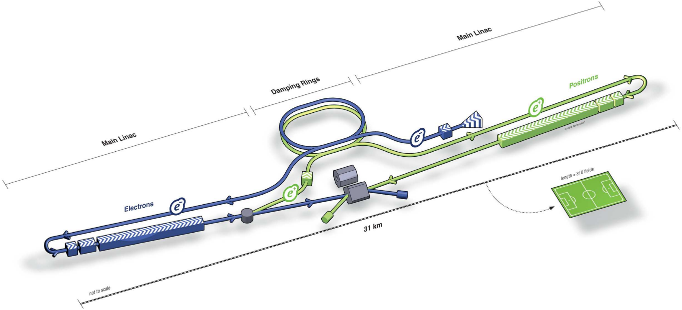
Carena, Heinemeyer, Stål, Wagner, Weiglein '13, [arXiv:1302.7033]



(+ HiggsBounds LEP χ^2 extension)

$\chi^2/\mathrm{ndf} = 70.6/66$

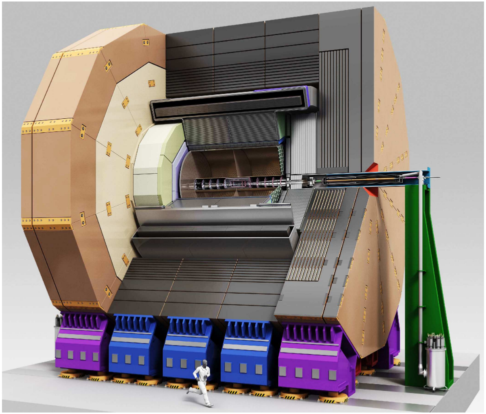
The ILC Machine



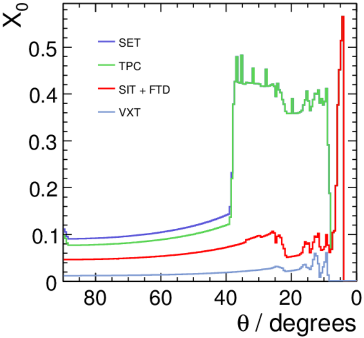
The ILC is the most advanced future e^+e^- collider proposal

- Polarized $e^+(30\%)e^-(80\%)$
- Superconducting RF technology
- High luminosity from $\sqrt{s} = 250$ GeV to 500 GeV, expandabe to 1 TeV
- About 31 km site length
- Proven technology
- Facilities and tests (final focus, damping rings, positron polarization, RF) exist or under construction (XFEL)
- Industrialization underway

The Detector Concepts ILD and SiD



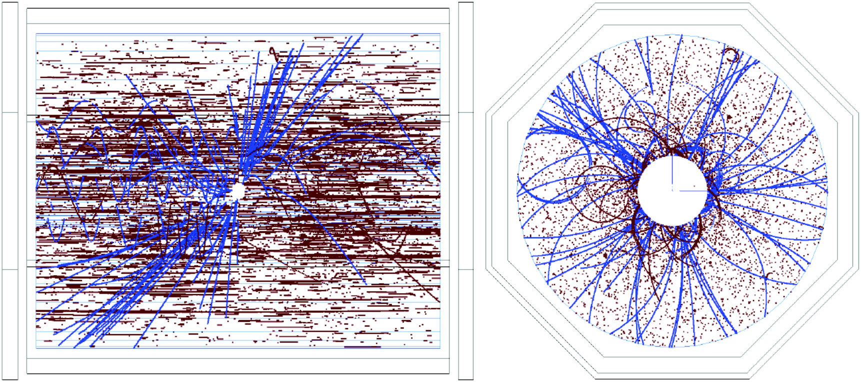
ILD



ILD tracking material budget (incl. cabling, cooling, support)

- ILD and SiD concepts optimized for the particle flow concept – imaging calorimetry, coil outside HCAL, large B field (3.5 – 5 T)
- Detailed engineering and R&D going on for every component – lots of test beam activity to test components and verify full sim
- Detector baseline Documents (DBD) going to be public soon

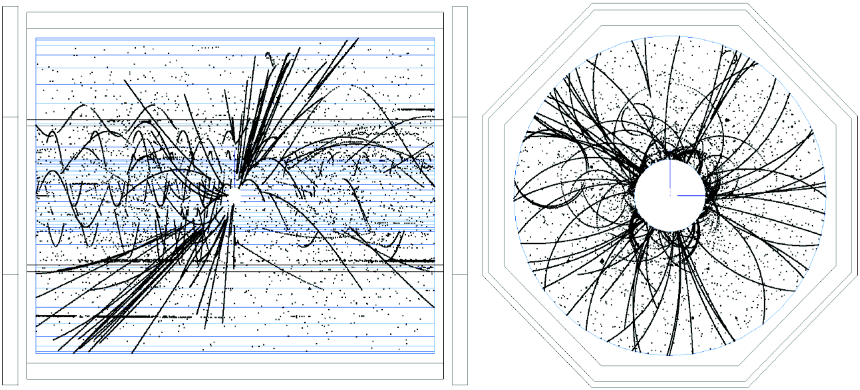
Taking Backgrounds fully into account



$t\bar{t}$ event with 150 BX background overlayed

- Never had such advanced and controlled full simulation for a new project at such an early state!
- Need high $B > 3.5$ T to control beam backgrounds

Taking Backgrounds fully into account



same event after microcurler removal algorithm

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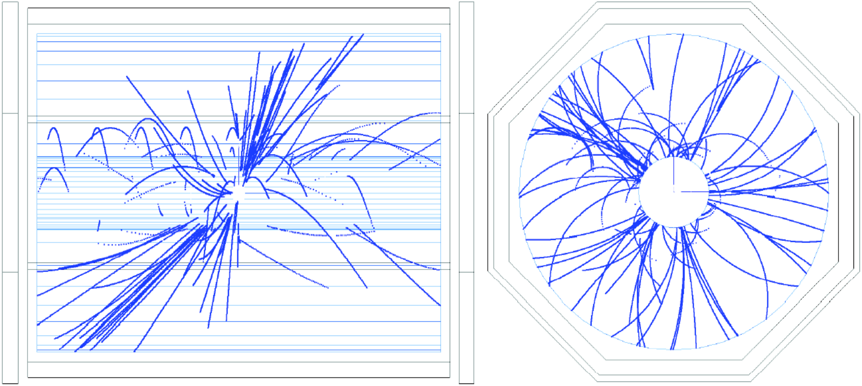
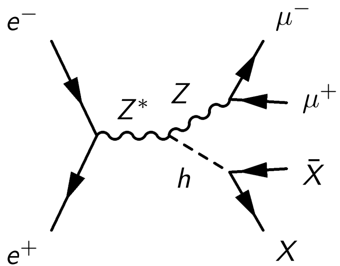
Taking Backgrounds fully into account

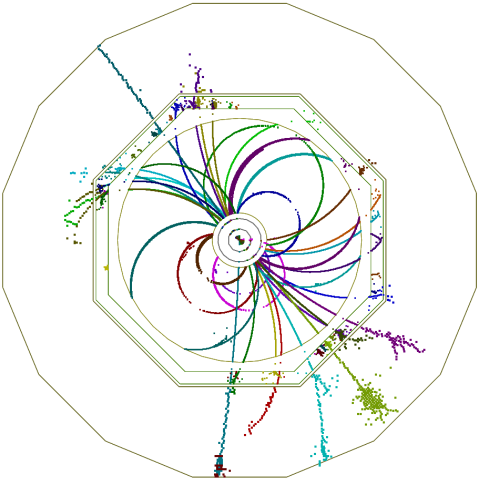


result from track finding (hits attached to tracks) clean event

- Never had such advanced and controlled full simulation for a new project at such an early state!
- Need high $B > 3.5$ T to control beam backgrounds

Observe the Higgs without looking at it





- Reconstruct the Higgs mass from the recoiling Z:

$$s = m_h^2 + m_Z^2 + 2((\sqrt{s}, \vec{0}) - p_Z)p_Z \quad \rightarrow \quad m_h = \sqrt{s + m_Z^2 - 2E_Z\sqrt{s}}$$

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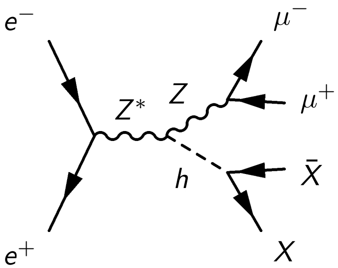

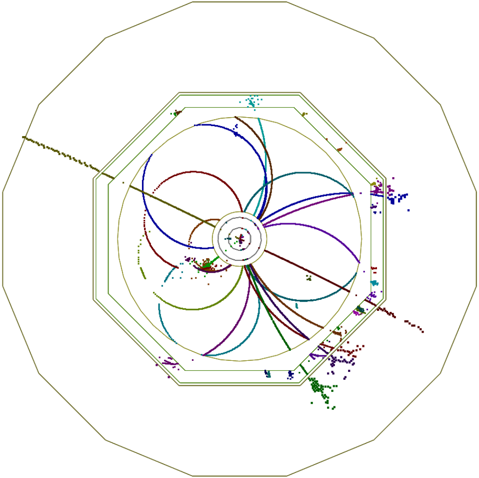

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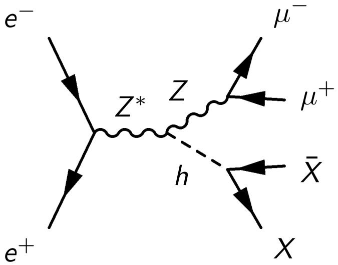

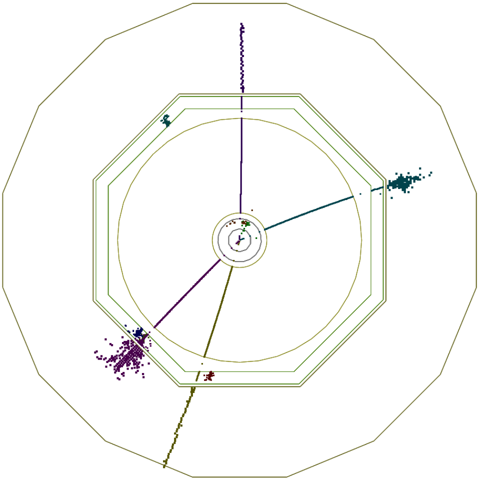

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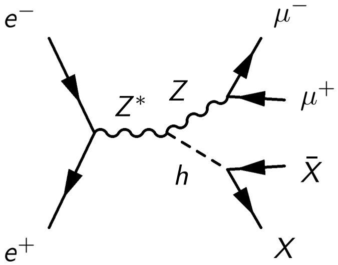

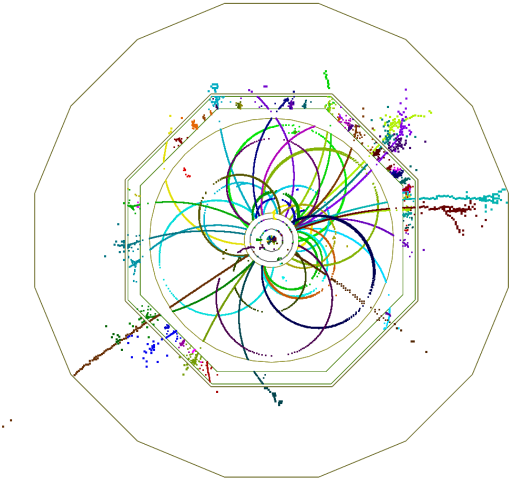

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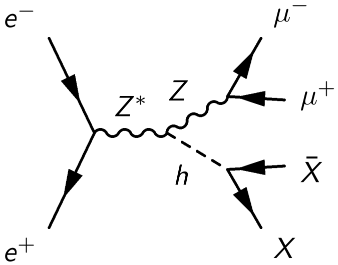

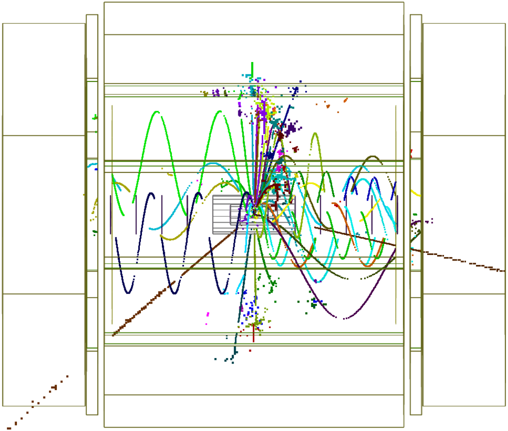

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Why we know that we missed something

- Experimental Knowledge: The SM is incomplete!

- In the SM, there are no particles with the correct properties for Dark Matter


© supermagnete.de

Why is the electromagnetic force of the tiny magnet stronger than the gravity of all the earth combined?

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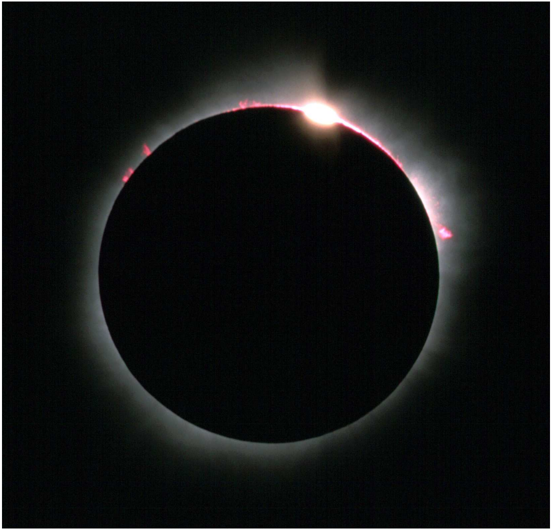
A warning: Order without fundamental reason



Backup Slides

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 ($(i\partial_\mu\gamma^\mu - m)\psi = 0$):

$$\mathcal{L}_{\text{free}} = \bar{\psi}(i\partial\!\!\!/ - m)\psi$$

using $\partial\!\!\!/ = \partial_\mu\gamma^\mu$.
Make the theory gauge invariant under local $U(1)$ transformations:

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

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

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

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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 $\mathrm{SU}(2)_L$ doublett

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

and the singlett

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

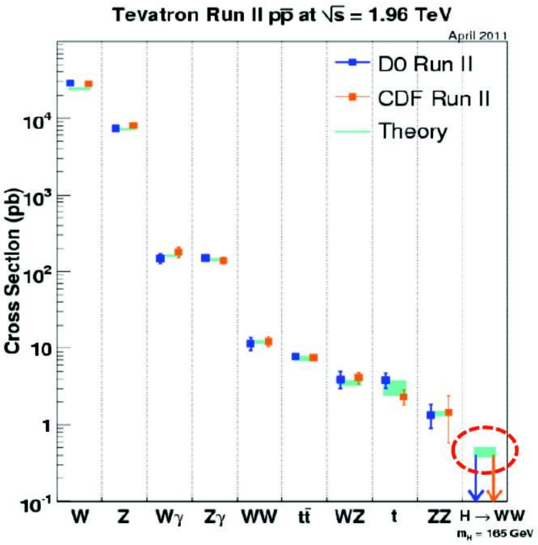
which transform $\mathrm{SU}(2)_L$ according to

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

and under $\mathrm{U}(1)_Y$ according to

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

Success over almost the full SM range



- Tremendous Success of the SM
- Tremendous success of the experiments
- Just one last piece missing for the completion of the SM

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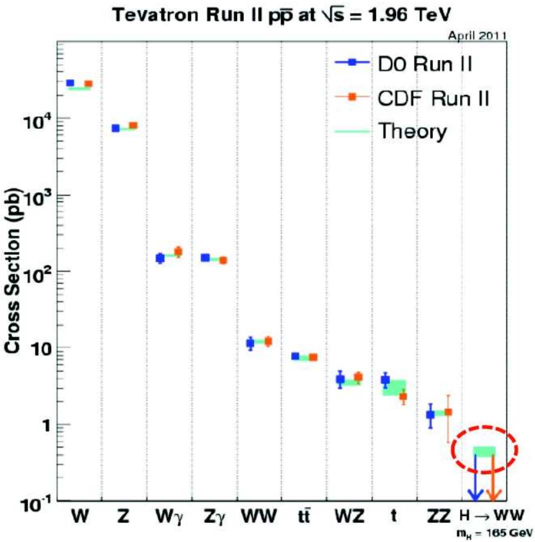
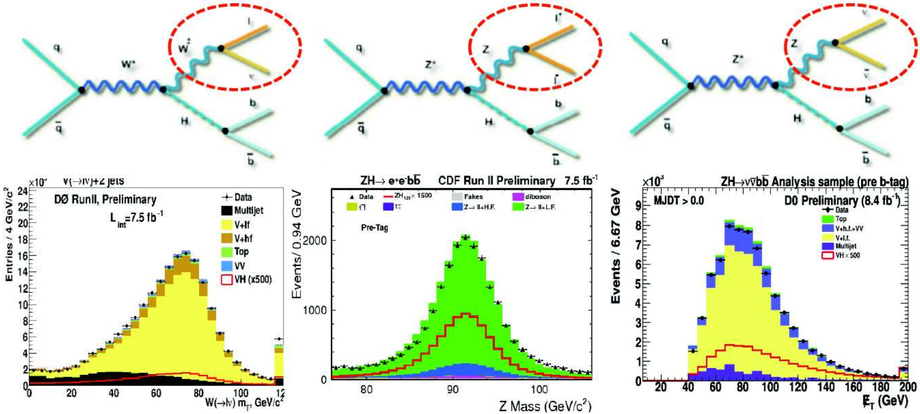


- Tremendous Success of the SM
- Tremendous success of the experiments
- Just one last piece missing for the completion of the SM
- It would look so perfect, let;s hope we find something else instead!

Most important Channel: $h \to b\bar{b}$

- Associated production with W or Z allows to trigger on high-p_T lepton from leptonic gauge boson decays
- Also E_T^{miss} from $W \to \ell\nu$ or $Z \to \nu\bar{\nu}$



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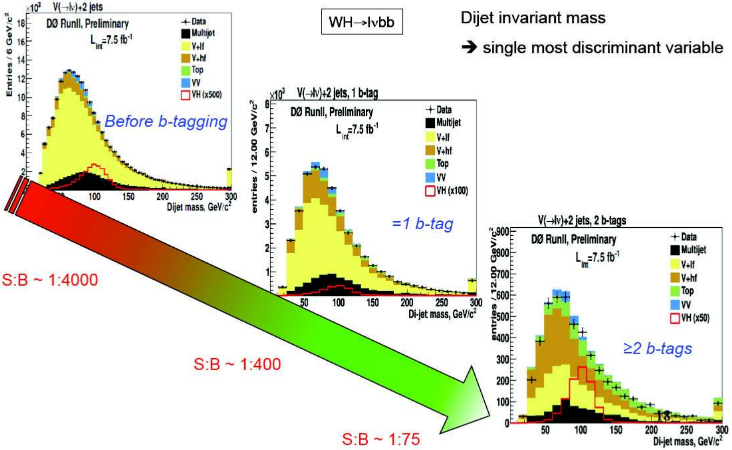
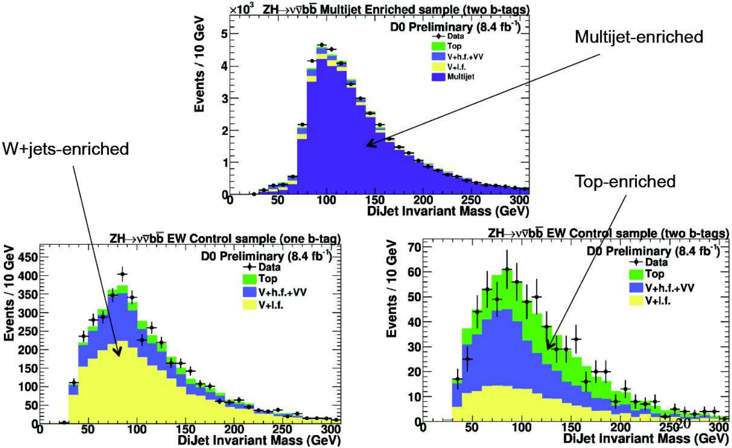


Dijet invariant mass

➔ single most discriminant variable

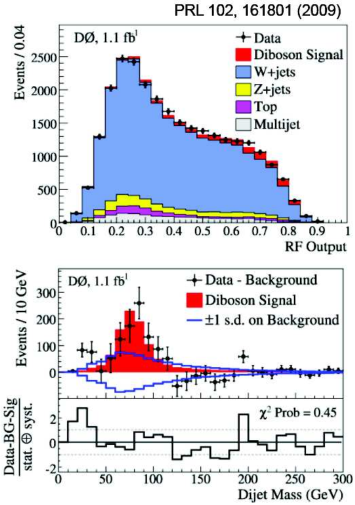
$h \to b\bar{b}$ Control Regions

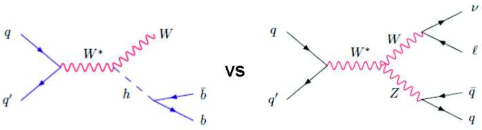


Searching for a similar process

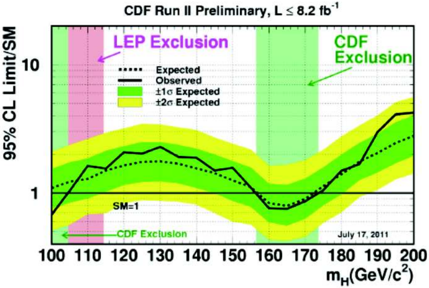
WW/WZ→lνjj

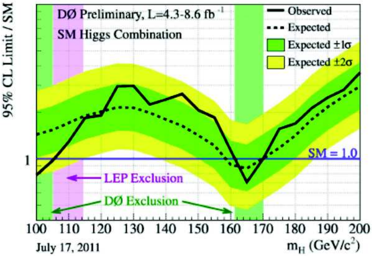
- Background to WH→lνbb.
- Small signal in large W+jets background
- Requires same optimizations/techniques as for the Higgs searches:
  - Exploit dijet mass distribution.
  - Use multivariate techniques.
  - Constrain systematic uncertainties using side-band regions in data.





Now let's look at the Tevatron Limits





At m_H = 115 GeV:

Exp. limit: 1.49 x SM
Obs. limit: 1.55 x SM

At m_H = 165 GeV:

Exp. limit: 0.79 x SM
Obs. limit: 0.75 x SM

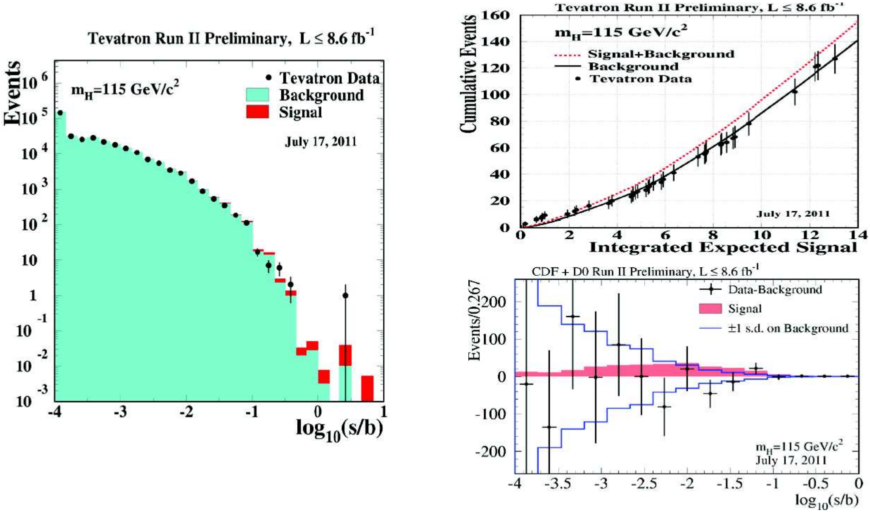
At m_H = 115 GeV:

Exp. limit: 1.90x SM
Obs. limit: 1.83 x SM

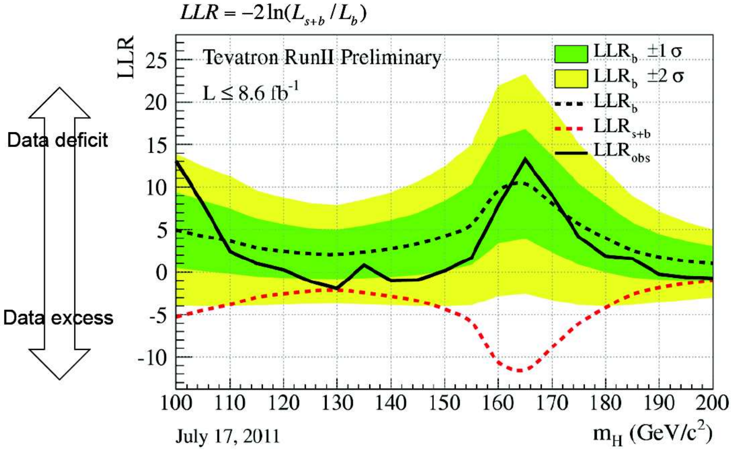
At m_H = 165 GeV:

Exp. limit: 0.87 x SM
Obs. limit: 0.71 x SM

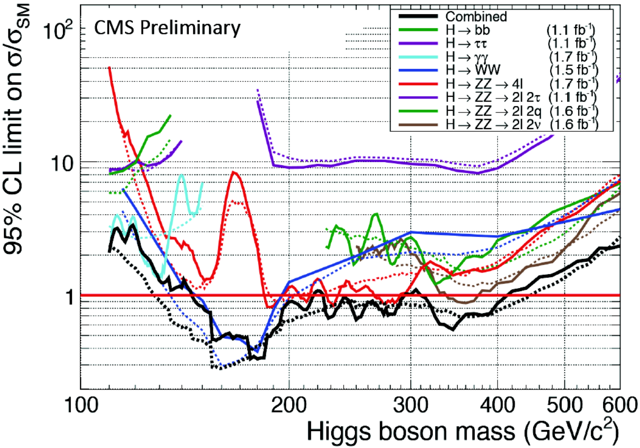
Visualizing the Tevatron Limits



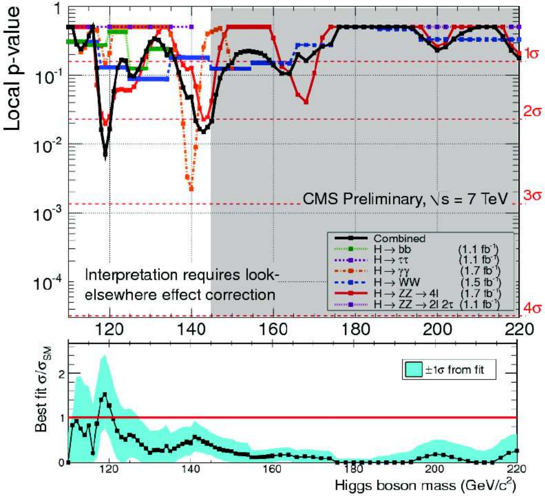
Visualizing the Tevatron Limits



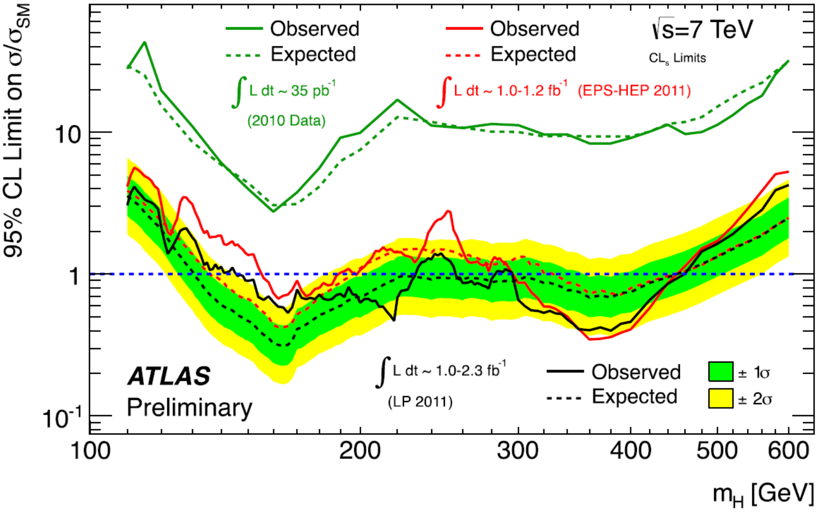
Interplay of the Searches in the SM



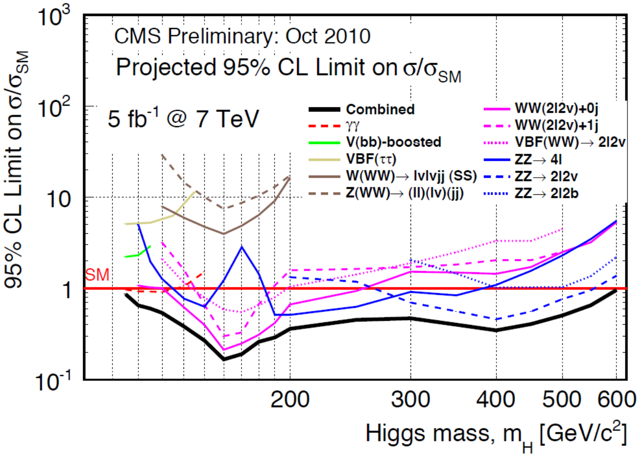
CMS and ATLAS SM Combinations



CMS and ATLAS SM Combinations

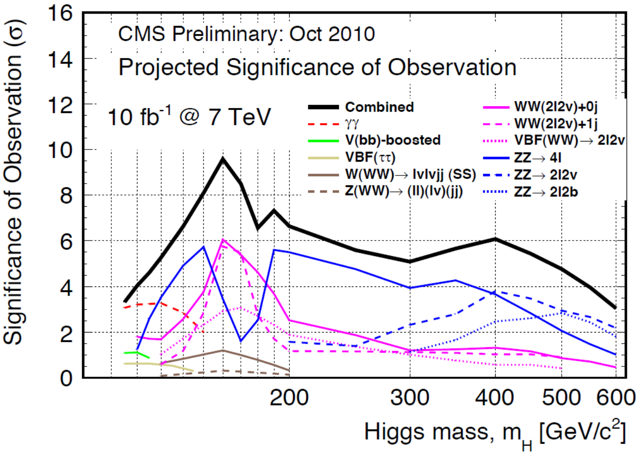


CMS Projections for 2011/12



- Could cover the full SM range in 2012
- At least in a LHC combination . . .

CMS Projections for 2011/12



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