# Search for a standard model-like Higgs boson in the mass range between 70 and 110 GeV in the diphoton final state in proton-proton collisions at $\sqrt{s} = 8$ and 13 TeV in CMS

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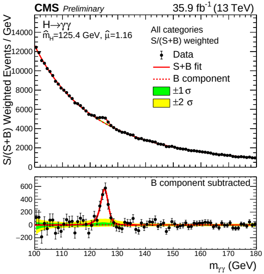
April 25, 2019

# Introduction

A new particle was discovered in 2012 at LHC by ATLAS and CMS collaborations. High probability of it to be the Standard Model (SM) Higgs boson but there is still place for Beyond Standard Model (BSM) possibilities.

Is the 2012 discovered scalar particle really the SM Higgs boson ?



## SM issues still not solved

- naturality problems
- no gravity
- no couplings unification
- what is dark matter/energy ?
- neutrinos masses
- asymmetry matter/antimatter

# Motivations

To solve those SM issues, a possibility is to search for low-mass ($< 125$ GeV) new scalar particles. This is motivated:

- **Experimentally:**
  - Small **excess** of events ($\sim 2\sigma$) wrt background (bkg) observed at LEP by 3 of the 4 experiments.
  - Search for SM Higgs boson at LHC does not explore low-mass region (lower bound was 110 GeV).
- **Theoretically** with BSM containing multiple scalar particles, the m=125 GeV particle might not be the lightest one:
  - 1 Higgs Doublet in SM but there can be 2 (or more) Higgs Doublets in BSM.
  - Next-to-Minimal Supersymmetry Model with 7 Higgs boson-like particles.
  - Composite Higgs models where the Higgs boson appears as a strongly coupled condensate (as in QCD).
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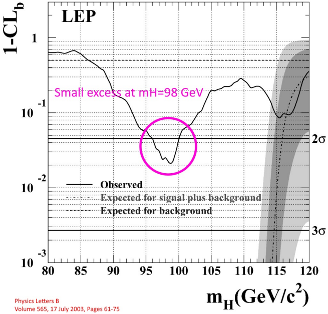

Physics Letters B
Volume 565, 17 July 2003, Pages 61-75

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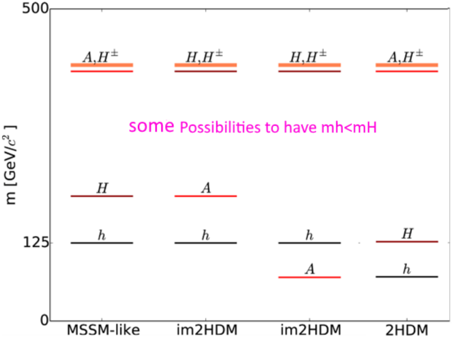

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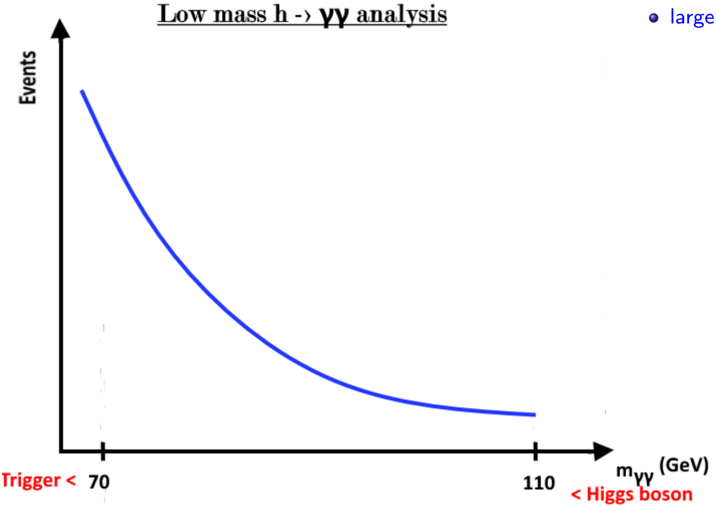
# Search strategy h$\rightarrow \gamma\gamma$

Diphoton canal presents 2 $\gamma$ with high energy and clean signature $\Longrightarrow$ good mass resolution.

Analysis close to the SM H $\rightarrow \gamma\gamma$ analysis (HIG-16-040 (JHEP 11 (2018) 185), HIG-18-029 + see next talk by Sijing Zhang) but with additional difficulties.



- large falling background

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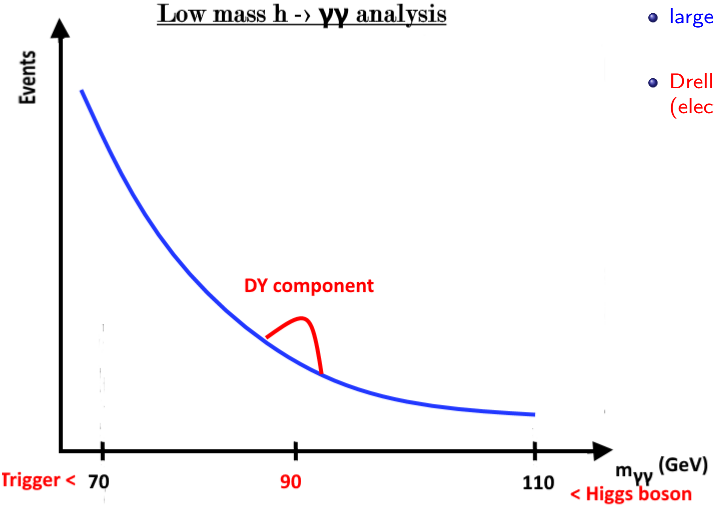

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- Drell-Yan $Z \rightarrow ee$ relic events (electrons faking photons)

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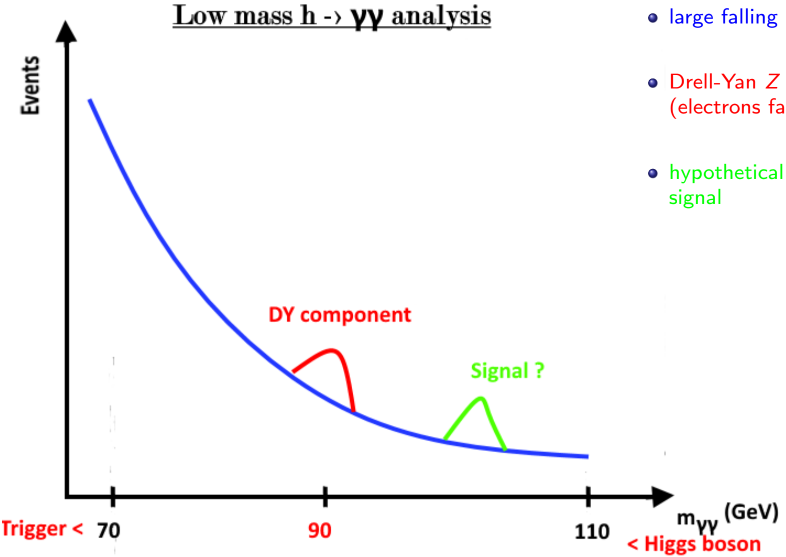


- large falling background
- Drell-Yan $Z \to ee$ relic events (electrons faking photons)
- hypothetical presence of a signal

# Event selection

## Detection

- p-p collisions at LHC in the CMS detector
- particles from collisions interact within the detector and leave energy
- energy is converted into electronic signal $\Longrightarrow$ this is our data !

## Trigger

- flow of data is too big to be registered $\Longrightarrow$ use a trigger system to reduce bandwidth
- trigger used has dedicated low-mass paths

## Preselection

- reconstructed photon candidates will be asked to satisfy some additional criteria
- low-mass optimized criteria
- need to satisfy an electron veto

# Photons

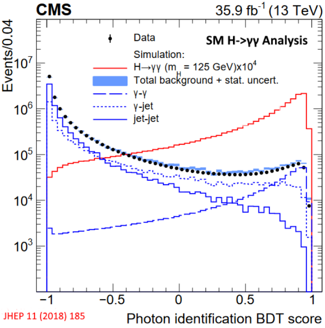
$$\boxed{m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta)}}$$

## Photon reconstruction

- reconstructed according to a clustering algorithm on the deposited energy in the electromagnetic calorimeter
- energy corrected mainly using a multivariable regression: a boosted decision tree (BDT)

## Photon identification

- another BDT to discriminate prompt photons from photons from light meson decays using variables related to isolation and shower shape
- loose cut applied on the output to get rid of a part of non prompt photon background



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# Vertex

$$\boxed{m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta)}}$$

## Vertex assignment

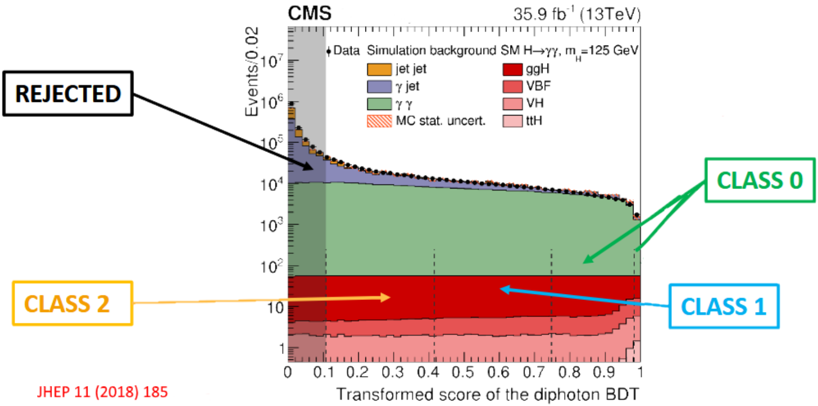
- correct vertex if within 1 cm of the estimated diphoton interaction point
- use BDT with input variables related to recoil tracks in the event

## Vertex probability

- another related BDT used to estimate the probability that the chosen vertex is the correct one

# Event classification

- To gain sensitivity, events are classified according to their similarity with $h \to \gamma\gamma$.
- Using a multivariate event classifier, the 'diphotonBDT', to distinguish events from the decay of a heavy object from standard model diphoton continuum with input variables such as photonID BDT output value, diphoton system kinematics,...
- A loose cut is applied for events that are too close to background.



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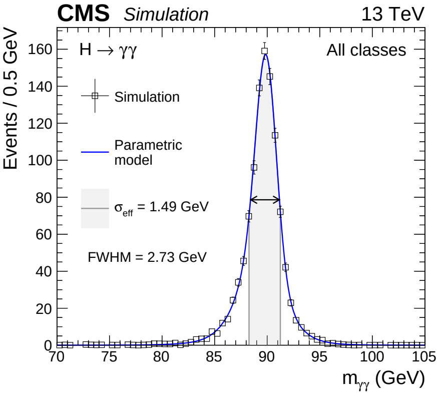
# Signal model

**Signal:** Events corresponding to $h \to \gamma\gamma$

## Signal parametrization

- Using SM-like $H \to \gamma\gamma$ Monte-Carlo simulation samples in steps of 10 GeV from 70 to 110 GeV.
- Fit by a sum of Gaussians for each production modes, classification and choice of vertex.
- Then interpolate together to have a signal model for each mass point.



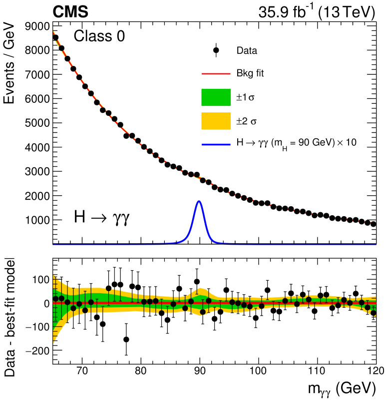
CMS-HIG-17-013// arXiv 1811.08459

# Background parametrization

**Background:** Events giving 2 $\gamma$, jet-jet, jet-$\gamma$, ee, ... which do not come from a Higgs-like particle.

## Continuum Background

- Envelope method: fit on data by a sum of functions (power, exp, Lauren and Bernstein) whose order is determined by an F-test, choice of function treated as a nuisance parameter.



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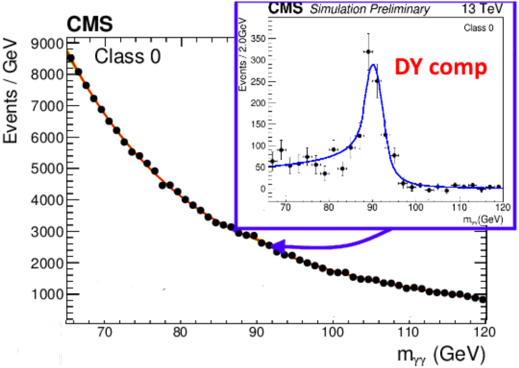
## Drell-Yan component

- Relic $Z \to ee$ events ('double fakes') passing through the analysis selection ($e$ seen as $\gamma$).
- Modelled by a double crystal ball function fitted on Monte-Carlo events.
- MC/data systematic uncertainties taken into account using single-fake events.

## Final Background

- Add the double crystal ball function with a floating normalization to the continuum background.



**CMS-HIG-17-013**

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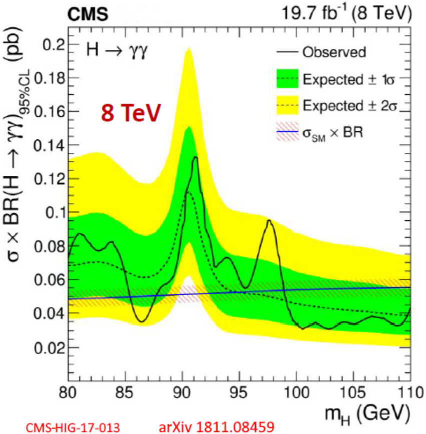
# Results Run I (2012) and Run II (2016)

- Results from CMS-HIG-17-013 (arXiv 1811:08459), accepted for publication in **Physics Letter B**.
- Expected and observed limit on $\sigma \times BR(h \to \gamma\gamma)$ for the Run I (8 TeV) 2012 data and the Run II (13 TeV) 2016 data.
- **No significant excess** ($> 3\sigma$) observed wrt expected number of background events, modest excess of 2.9 $\sigma$ at m=95.3 GeV at 13 TeV.



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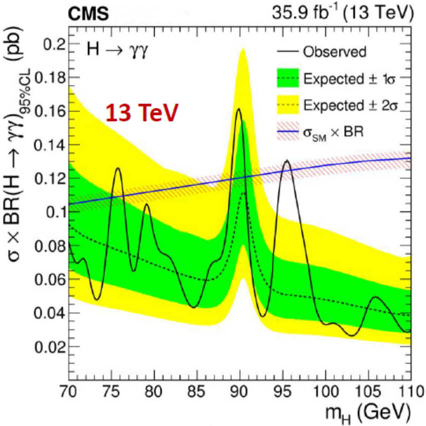

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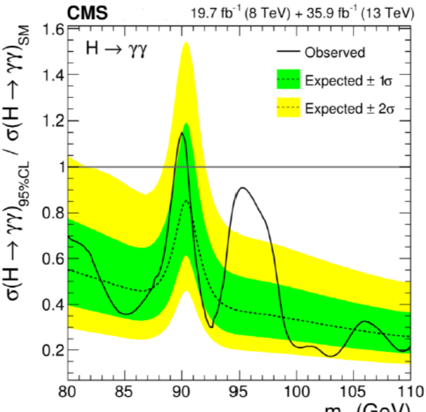
# Combined Results Run I and Run II (2012 + 2016)

- Limit on $\sigma \times BR(h \to \gamma\gamma)$ normalized to SM.
- Local excess of $2.8\sigma$ at $m_H = 95.3$ GeV but **no significant excess observed** wrt expected number of background events.



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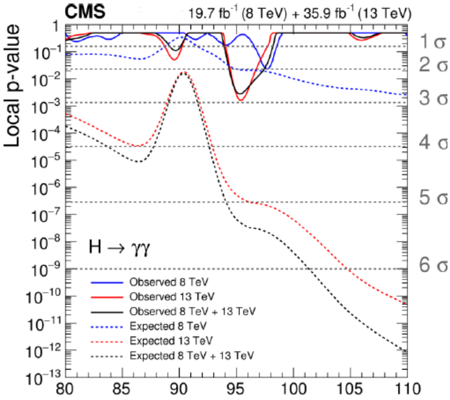

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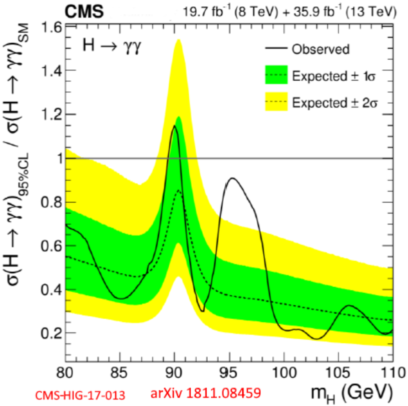

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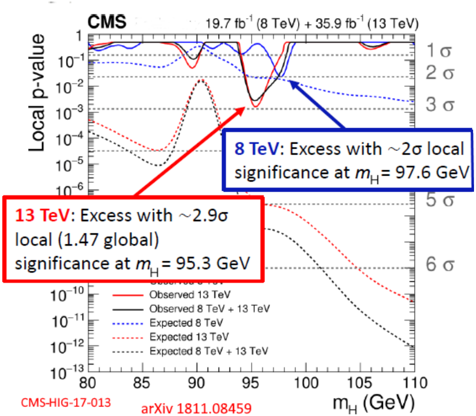

**8 TeV**: Excess with $\sim 2\sigma$ local significance at $m_H$= 97.6 GeV

**13 TeV**: Excess with $\sim 2.9\sigma$ local (1.47 global) significance at $m_H$ = 95.3 GeV

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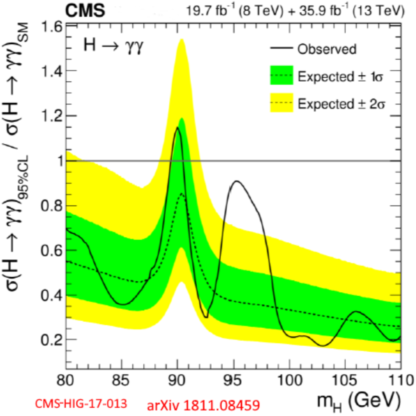

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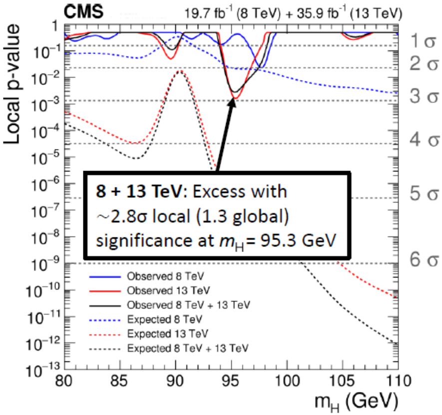


**8 + 13 TeV**: Excess with ~2.8σ local (1.3 global) significance at $m_H$ = 95.3 GeV

# Conclusion

- the search for a low-mass High boson is strongly motivated by several theories
- no significant ($> 3\sigma$) excess with respect to the expected number of background events is observed
- but modest excess has $\sim 2.8\ \sigma$ local ($1.3\ \sigma$ global) significance at $m_h = 95.3$ GeV (combining 8 and 13 TeV results); need more data to determine the origin of this excess
- look forward to our next results !

# Conclusion

Thanks for your attention

# Backup

# Systematics uncertainties

Main uncertainties:

1. By photon uncertainties coming from BDT.
2. By events uncertainties coming from class migration, luminosity, trigger system and vertex identification.
3. Theoretical uncertainties; mainly coming from "particle distribution functions", of the QCD scale and coupling constant.
4. Uncertainties on the DY component modelisation MC/data.

# Two Higgs Doublets Models

Simple extension of the MS.

Two doublets: $\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} = \begin{pmatrix} \eta_1 + i\eta_2 \\ \eta_3 + i\eta_4 \end{pmatrix}$ et $\Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix} = \begin{pmatrix} \eta_5 + i\eta_6 \\ \eta_7 + i\eta_8 \end{pmatrix}$

8 particles $\Longrightarrow$ 3 Goldstone bosons (2 charged) et 8-3=5 new physical bosons (2 charged).

**Usual potential :**

$$\begin{aligned} V = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right) + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1\right)^2 \\ & + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right) \left(\Phi_2^\dagger \Phi_2\right) \\ & + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right) \left(\Phi_2^\dagger \Phi_1\right) + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_1\right)^2\right] \end{aligned}$$

VEV are $\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}$ et $\langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$ minima conditions

$$\left.\frac{\partial V}{\partial \eta_i}\right|_{vide} \text{ pour } i = 1, .., 8$$

# Two Higgs Doublets Models

Particle mass after symmetry breaking for $i, j = 1, \ldots, 8$ :

$$M_{ij} = \frac{1}{2} \frac{\partial^2 V}{\partial \eta_i \partial \eta_j}\bigg|_{vide}$$

.

Then we got two scalar bosons with different mass $\Longrightarrow$ possibility for a low mass Higgs

**Interests:**

- relatively simple
- possible role in the matter/antimatter asymmetry
- Higgs Composite Models

# Supersymmetry Models

**Supersymétrie (SUSY) :** MS extension with an additional symmetry which associates a superpartner to each SM particle.

Lots of SUSY models: the simplest is **Minimal Supersymmetric Model (MSSM**) but not very compatible with experiments $\Longrightarrow$ **Next-to Minimal Supersymmetric Model (NMSSM)**, add a complex new scalar superfield.

NMSSM contains new particles, 7 of which are Higgs boson like: 2 charged bosons $\mathrm{H}^{\pm}$, 2 neutral pseudoscalar $\mathrm{A}_1$ et $\mathrm{A}_2$ and 3 scalars $\mathrm{H}_1$, $\mathrm{H}_2$ et $\mathrm{H}_3$ avec $m_{H_1} < m_{H_2} < m_{H_3}$. If $H_2$ or $H_3$ is identified as the detected Higgs particle, predicts 1 or 2 low mass new scalars.

**Motivations :**

- elegant solution to the hierarchy issue
- unification of strong, weak and em couplings
- dark matter

# Drell-Yan

Component of the type $q\bar{q} \to Z/\gamma \to l\bar{l}$.
$Z \to e^+e^-$ descriptions produces a decreasing of sensitivity around 90 GeV.
Adjust with a dCB with 7 parameters:

$$dCB(x) = N\times\begin{cases} \frac{1}{\sqrt{2\pi\sigma}}(\frac{n_L}{|\alpha_L|})^{n_L} exp(-|\alpha|^2/2)(\frac{n_L}{\alpha_L} - |\alpha_L| - \frac{x-\mu}{\sigma})^{-n_L} & \text{si } \frac{x-\mu}{\sigma} < -\alpha_L \\ \frac{1}{\sqrt{2\pi\sigma}}(\frac{n_R}{|\alpha_R|})^{n_R} exp(-|\alpha|^2/2)(\frac{n_R}{\alpha_R} - |\alpha_R| + \frac{x-\mu}{\sigma})^{-n_R} & \text{si } \frac{x-\mu}{\sigma} > \alpha_R \\ \frac{1}{\sqrt{2\pi\sigma}}(\frac{n_L}{|\alpha_L|})^{n_L} exp(-\frac{(x-\mu)^2}{2\sigma^2}) & \text{sinon.} \end{cases}$$

N is a normalization factor, $\mu$ et $\sigma$ mean and deviation of a Gaussian distribution, $\alpha_{R/L}$ and $n_{R/L}$ describe the queues.

# $\chi^2$ and fits

## $\chi^2$

Consider $N$ measured quantities $x_i$. We want to test the fit with a set $\mu_i$ of errors $\sigma_i$.
$\chi^2 = \sum_{i=1}^{N} \frac{(x_i - \mu_i)^2}{\sigma_i^2}$.
The fit is good if $\frac{\chi^2}{dof} \longrightarrow 1$

## Fit

1. Calculate $\chi^2$ for the set we want
2. Calculate $\chi^2_{ddl,0.05}$ given by $\int_{\chi^2_{ddl,0.05}}^{\infty} f(\chi^2) d\chi^2 = 0.05$
3. if $\chi^2 > \chi^2_{ddl,0.05}$ then 95 % of chance for the model to be valid
4. if $\chi^2 > \chi^2_{ddl,0.05}$ then model valid or problem with $\sigma_i$

# Envelope method

## F-test

Increase the order N of functions until the quality of the fit reaches a certain value.
Calculate $\chi^2_N = 2(LL_N - LL_{N+1})$, fit is fixed if $p(\chi^2 > \chi^2_N) < 0.05$
$LL_N$ is the logarithm min of the likelihood function associated to the considered fit for a function of rank N.

$$Exp_N(x) = \sum_{i=1}^{N} b_i \exp(a_i x);\ Ber_N(x) = \sum_{i=0}^{N} b_i \begin{pmatrix} N \\ \\ i \end{pmatrix} x^i (1-x)^{N-i};$$

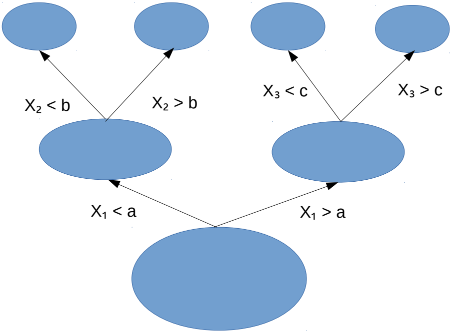
$$Lau_N(x) = \sum_{i=1}^{N} b_i x^{-4+\sum_{j=1}^{i}(-1)^j(j-1)};\ Pow_N(x) = \sum_{i=1}^{N} b_i x^{a_i} + dCB(x)$$

F-test to find N, then fit on data.
For the "best minimal fits", minimizing $-2LL_N + 0.5N_p$ with $N_p$ the nb of parameters.

# Boosted Decision Tree

Multivariate analysis tools which take into input discriminating variables and give a score as an output.
Events are sorted thanks to successive cuts.
Trained on MC simulations.

Figure: BDT



A tree is 'boosted' when weights are used, for each event, to correct the issue of statistic fluctuation.