Search for a new light ($m_H < 125 GeV$) Higgs boson particle decaying into two photons within the CMS detector and interpretation

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IP2I PhD day

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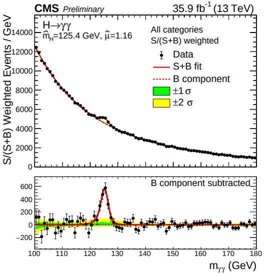
I) Motivations for a search of a new low-mass Higgs boson

II) Photon reconstruction in CMS

III) Low-mass $h \to \gamma\gamma$ analysis in CMS

IV) Phenomenology with new low-mass Higgs bosons

New Particle discovered in 2012, is this the Standard Model (SM) Higgs boson ?



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SM issues

Even if this particle is the SM Higgs boson, it does not solve the SM issues:

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

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

- **Experimentally:**
  - Little 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 go into low masses.

- **Theoretically** with BSM containing multiple scalar particles, the m_H=125 GeV particle may not be the lightest one:

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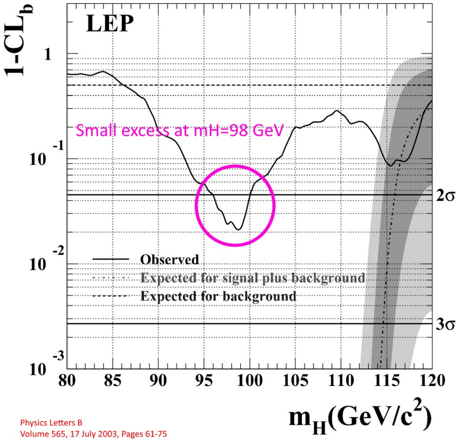

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- **Theoretically** with BSM containing multiple scalar particles, the m_H=125 GeV particle may not be the lightest one:
  - 1 Higgs Doublet in SM but there can be 2 (or more) Higgs Doublet in BSM (2HDM).
  - Next-to-Minimal Supersymmetry Model with 7 Higgs boson like particles.
  - Composite Higgs models where the Higgs boson appears as a strongly coupled condensate (as in QCD).

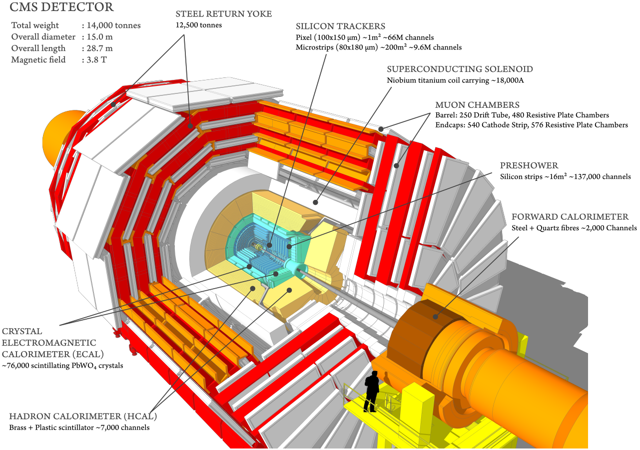
Photon reconstruction in CMS

The Large Hadron Collider at CERN

CERN offical website home.cern

- LHC is the biggest particle accelerator ever built
- protons are accelerated up to 6.5 TeV for a center of mass energy of 13 TeV for proton-proton collisions
- collisions take place in 1 of the 4 LHC detectors
- ALICE, ATLAS, **CMS** and LHCb

The CMS detector

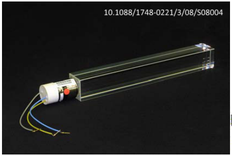


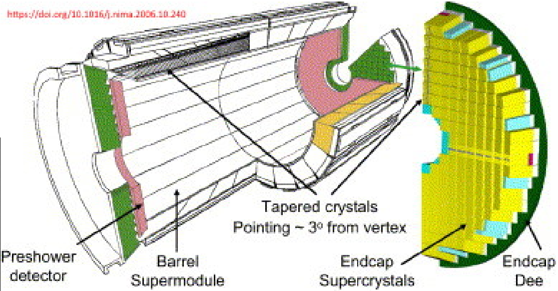
CMS offical website cms.cern

- charged particle trajectories are curved due to presence of high intensity magnetic field
- passing particles that can interact within the detector leads to energy deposits
- energy deposits are converted into analogue signals
- complex methods are used to reconstructed particle proprieties and identification $\Longrightarrow$ this is our data !

CMS uses a trigger system reducing the flow of recorded data.
Producing simulations to compare to our data.

The ECAL was built to stop electrons and photons and to obtain information on these particles (**very important for photon reconstruction**)
$\Longrightarrow$ composed of $\sim$ 76000 $PbWO_4$ scintillator crystals

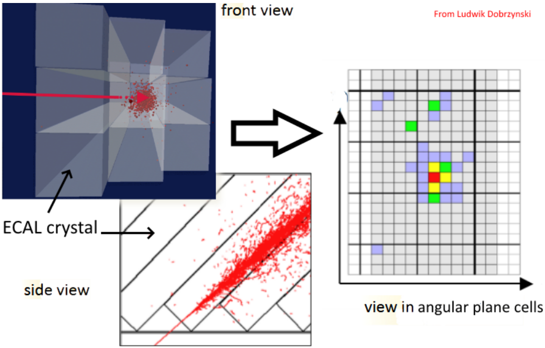




Particle in the ECAL $\Longrightarrow$ electromagnetic interaction with crystals $\Longrightarrow$ crystal electron receive energy $\Longrightarrow$ emission of photons to go back to fundamental state $\Longrightarrow$ emitted photon energy is measured thanks to photo-detectors.

Intensity from ECAL crystals tracks back information on particles interacting within ECAL.

Electrons/photons are reconstructed from (but not only !) the energy deposited in the ECAL.



1. Crystals are clustered together if $E_{crystal} > E_{lim}$. Seeds are identified.
2. Clusters are further gathered into' superclusters' in a 'mustache' geometric area from the seeds to account for conversions, bremsstrahlung scattering, etc.
3. Electron trajectories are reconstructed from hits in the pixel detector compatible with a supercluster position. For the photon, a dedicated algorithm is used to take care of conversion.
4. Additional selection criteria are used for particle reconstruction and to separate electrons from photons.

The energy of a reconstructed photon is the sum of the energy in the associated supercluster **crystals** i:

$$\boxed{E_\gamma = G_\gamma \times F_\gamma \times \sum_i^{supercluster} LC_i \times IC_i \times A_i}$$

Photon Energy reconstruction

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Per crystal term:

A_i: reconstructed pulse from the crystal electronic readout

IC_i: inter-calibration of the crystals to make the energy response uniform in space

LC_i: laser monitoring correction term to account for t-dependency of crystal transparency

Global term:

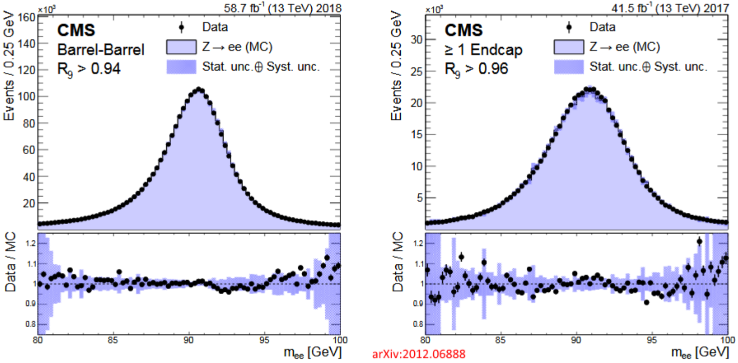
F_γ: energy correction term to account for materiel budget, gaps between crystals, etc

G_γ: energy scale term

G_γ Photon Energy corrections: scale and smearing

G_γ term is applied to data (scale) and to simulation (smearing) to account for data/simu discrepancy due to imperfect reconstruction of the ECAL in simulation.

$\Longrightarrow$ Data are **corrected** and simulation are **degraded**

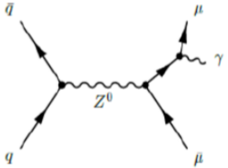


G_γ is obtained comparing mass distribution from $Z \to ee$ events.

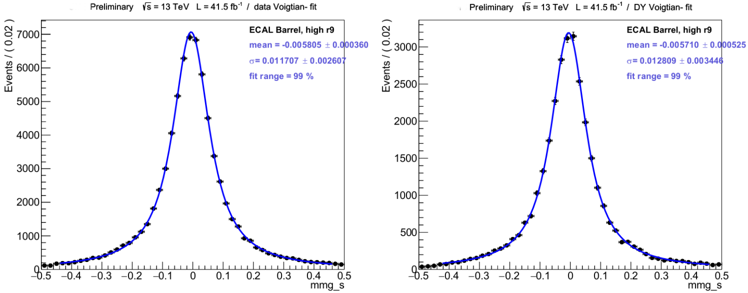
Scale and smearing obtained with electrons $\Longrightarrow$ need to be validated for photons

Using γ from $Z \to \mu\mu\gamma$ FSR

- $\Delta R(\mu, \gamma) < 0.8$
- $M_{\mu\mu\gamma} \in [60{,}120]$ GeV
- $M_{\mu\mu} + M_{\mu\mu\gamma} < 180$ GeV



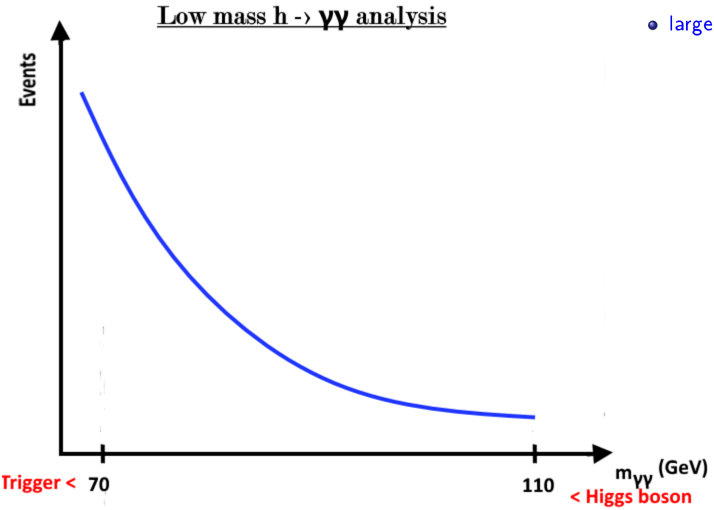
Scale unbiased estimator extracted from fits with Voigtian function and dedicated systematic uncertainties.



Data/simulation difference is < 0.1 % !

Low-mass $h \to \gamma\gamma$ analysis in CMS

Search for a SM-like signal bump in a large falling background.
Diphoton canal: 2 γ with high energy, **clean signature** and **good mass resolution**.
Analysis close to the SM H $\rightarrow \gamma\gamma$ analysis but with additional difficulties.



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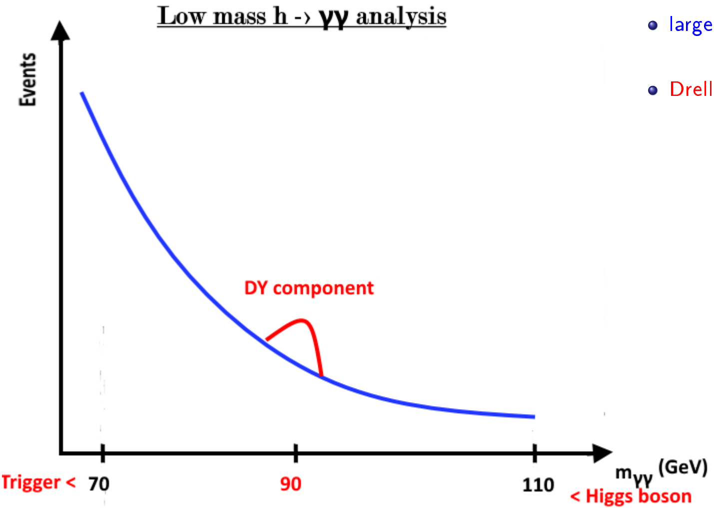

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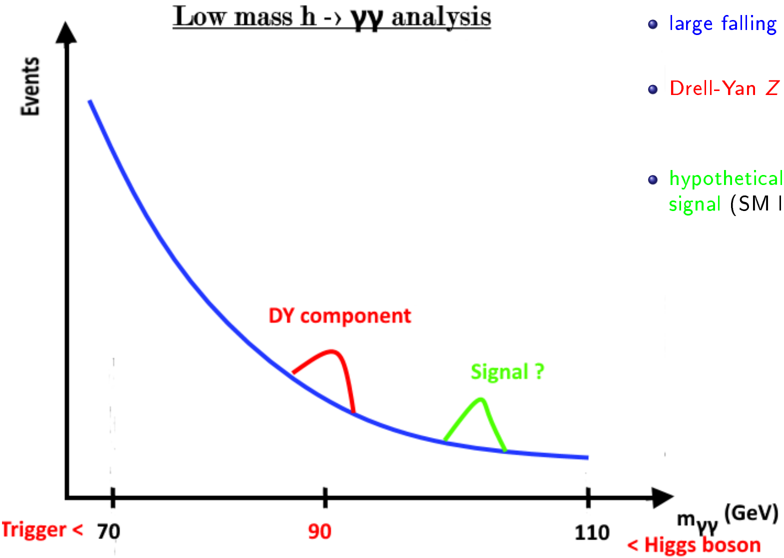

- large falling background $\gamma\gamma$
- Drell-Yan $Z \rightarrow ee$ relic events
- hypothetical presence of a signal (SM like Higgs)

Analysis Plan for $h \to \gamma\gamma$ analysis

1) Reconstructed photon events are required to pass through dedicated trigger and preselection

2) Use of a Boosted Decision Tree (BDT), a maching learning tool used to discriminate between variables, to distinguish prompt photons from others

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4) Other BDT are trained to distinguish VBF like events $\Longrightarrow$ **VBF classification**

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5) Signal ($h \to \gamma\gamma$) Parametrization

6) Background ($\gamma\gamma$, γ+jet, etc) Parametrization

7) Systematic uncertainties determination

8) Final results using statistical combinations

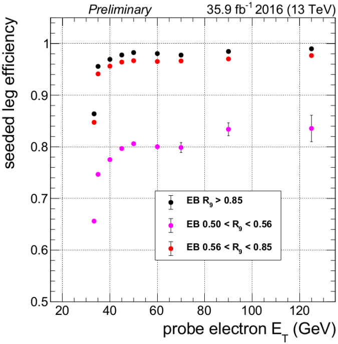
From the reconstructed photon events:

Trigger

* flow of data is too big to be registered $\Longrightarrow$ use a trigger system to reduce bandwidth from $\sim$ 20 MHz to $\sim$ 1 kHz

* New dedicated trigger paths have been developped for the specific low mass case

* Efficiencies are measured on data (from $Z \to ee$ events) and applied to signal simulation



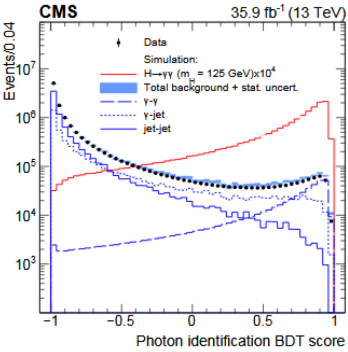
Preselection

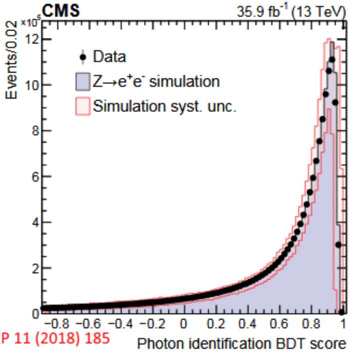
Reconstructed photon candidates will be asked to satisfy some additional low-mass optimized criteria to mimic trigger constraints:

- Analysis mass range 65 GeV$<m_{\gamma\gamma}<$120 GeV
- Pixel Seed Electron Veto
- Showershape and isolation cuts

Photon identification

* A BDT to determine prompt photons using variables related to isolation and energy
* Trained for low-mass using γ+jets simulations
* Loose cut applied on the output to get rid off non prompt photon (meson decay, jets, etc)
* Validated with $Z \to ee$ and $Z \to \mu\mu\gamma$ data and simulations





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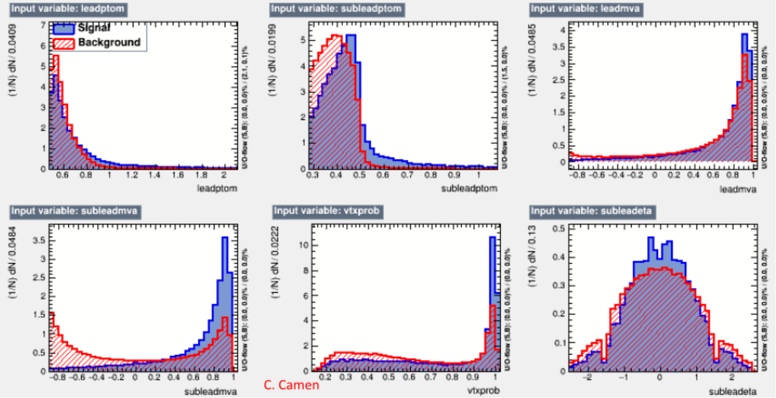
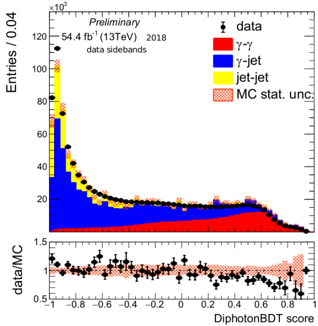
Diphoton-BDT

- To gain sensitivity, events are classified according to their similarity with diphoton background/ $h \to \gamma\gamma$ signal
- Using a multivariate event classifier, the diphoton-BDT, to discriminate between events
- Discriminating is done using mostly kinematic diphoton variables and the output of photonID BDT
- Training is done using signal $h \to \gamma\gamma$ and 2 γ, jet-jet, jet-γ background simulations



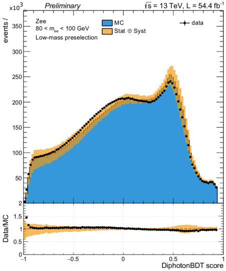
Diphoton-BDT score

* Diphoton-BDT is applied on data
* The output of diphoton-BDT is a score between -1 and 1
* Signal close to 1 / Background close -1



Diphoton-BDT Validation

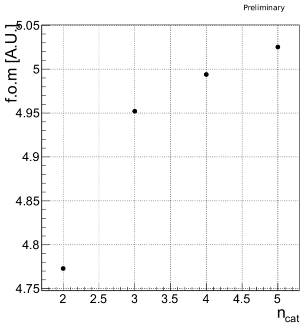
* trained and tested on simu but need validation on data !
* validation of input/output variables wrt data sidebands and simu
* data/MC of the diphotonBDT input and output variables distribution with $Z \to ee$ events and dedicated systematics

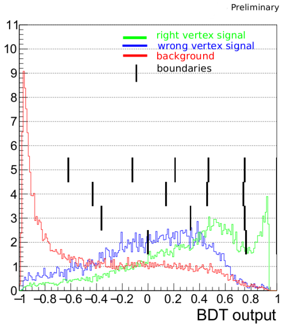


Untagged Classification

Events are classified into untagged classes according to their diphoton-BDT output score to gain sensitivity

- Simple model using simulated events where class boundaries are adjusted minimizing p-value
- Enforcing a **minimal width** value for classes to have enough events in each especially for background modelling.
- No significant difference of f.o.m between 3, 4 and 5 classes.
- We choose n_{cat} =3 with boundaries [1.000, 0.753, 0.334, -0.364]



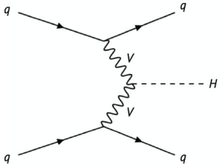


Data events with diphoton-BDT < -0.364 are **rejected**.
The most signal-like are in class within diphoton-BDT ∈ [0.753,1.0].

VBF Class

Additional Vector-Boson Fusion production mode class is present:

- Higher sensitivity in some BSM
- 2 forward jets + 2 γ in the final state
- Dedicated events selection and cuts



VBF dedicated BDTs:

* 2 BDTs to discriminate VBF like events from others
* Use kinematic variables and diphoton-BDT output score
* Trained on VBF $h \rightarrow \gamma\gamma$ simulation for signal

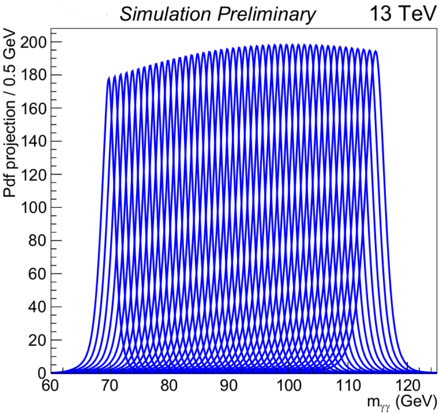
VBF classification:

* Same as untagged but only 1 class
* Need enough VBF events
* Requirement is VBF BDT score > 0.8 to go in the VBF class, else events go into untagged

Signal parametrization

Signal: Events corresponding to $h \to \gamma\gamma$
Needed to know the form of the bump we are looking for.

* Using SM like $H \to \gamma\gamma$ Monte-Carlo simulation samples by steps of 5 GeV from 70 to 110 GeV
* Fit by a sum of Gaussian for each production modes, classification and choice of vertex
* Then interpolate together to have a signal model for each mass point
* Final mass resolution is < 1.8 % for all classes



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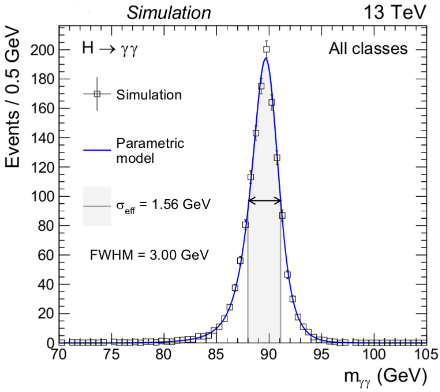
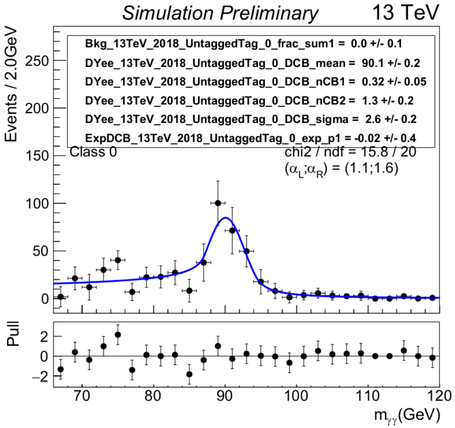


Drell-Yan component

Drell-Yan contribution to the background: 'double-fake' events with 2 e misidentified as γ passing the analysis selection

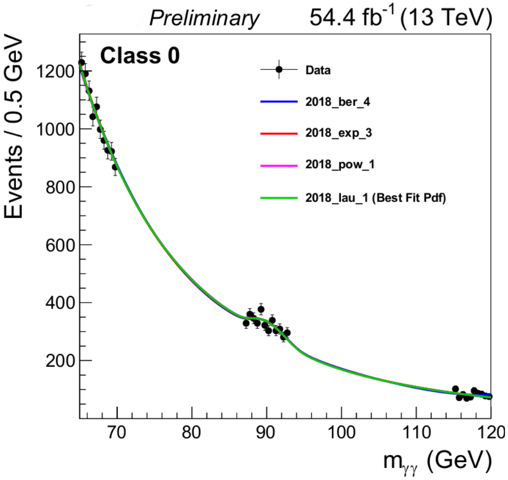
- contribution fitted by a double-sided Crystal Ball (DCB)+ exp function on each class
- fit performed on DY simulated $Z \to ee$ events for each class to obtain the function initial parameters
- dedicated systematics to account for data/MC differences



Background: Events giving 2 γ, jet-jet, jet-γ, ee, ... which do not come from a Higgs like particle.

Continuum Background

* Fit on **data** by a sum of functions (power, exp, Laurent and Bernstein) whose order is determined by a F-test for each class



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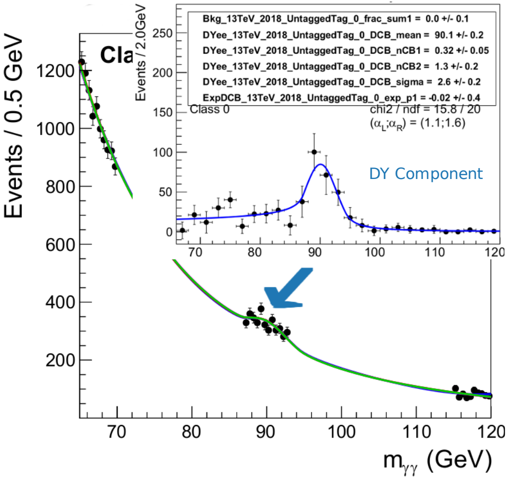
Drell-Yan component

* Relic $Z \to ee$ events 'double fakes' (e seen as γ)
* Modelled by a DCB+exp fitted on Monte-Carlo events

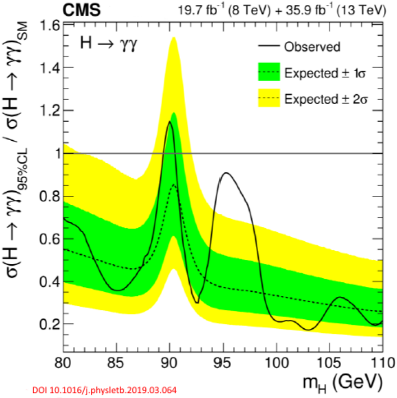
Final Background

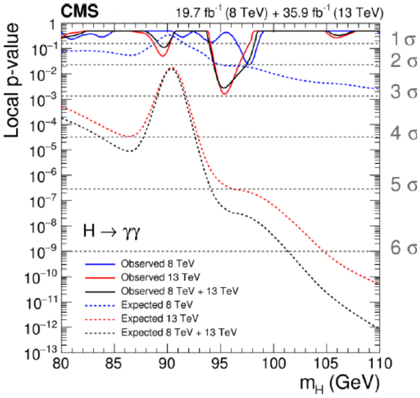
* Add the double crystal ball with a floating normalization to the continuum background.
* Systematic unc. to cover the choice of function



Previous Results

Previous results published: DOI 10.1016/j.physletb.2019.03.064
Limits on $\sigma \times BR(h \to \gamma\gamma)$ in absence of signal ('Expected') and with the real data ('Observed') for the Run I (8 TeV) and the Run II (13 TeV) 2016 data.
No significant excess observed wrt what is expected in absence of signal.





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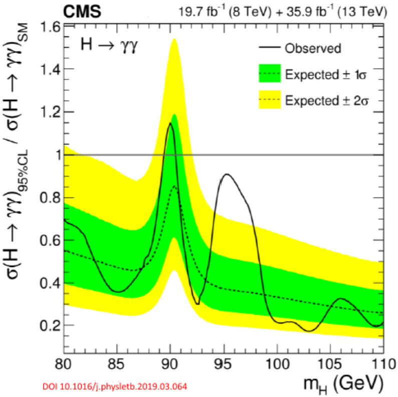

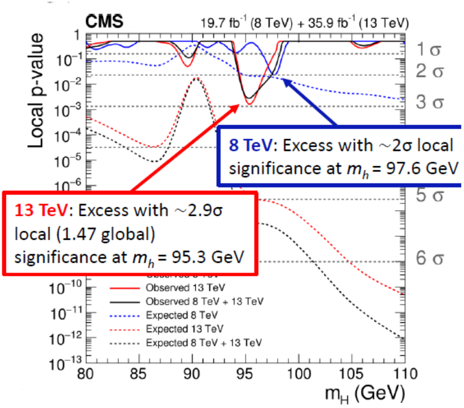

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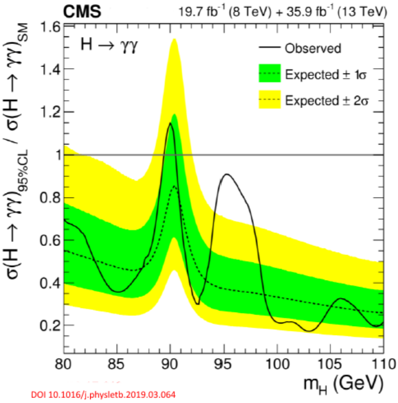
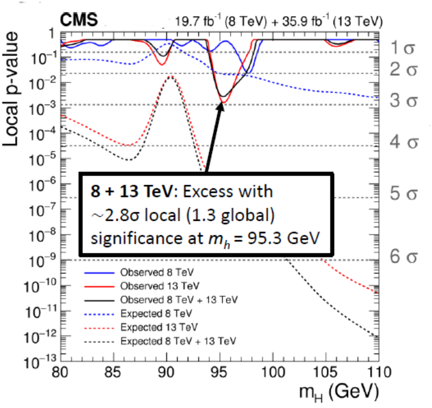
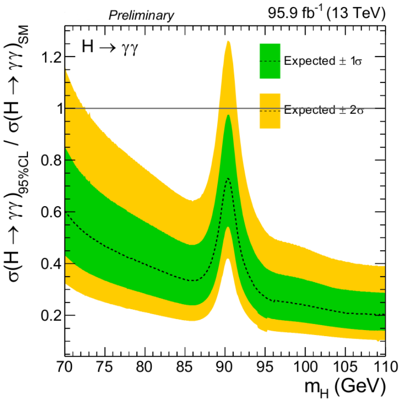
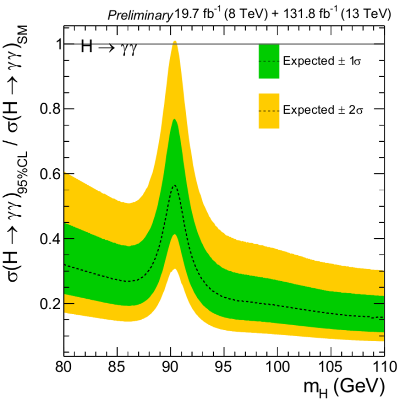




New Results

Limits on $\sigma \times BR(h \rightarrow \gamma\gamma)$ in absence of signal ('Expected') for 2017 and 2018 data combined (left) and combined with 2012+2016 for full Run I and II combination (right).





Full combination improves limits by $\sim$ 50 % !

Work in progress. Actually reviewed by the collaboration: Expect the 'Observed' results soon !

Phenomenology with new low-mass Higgs bosons

Les Houches 2019 Physics at TeV Colliders work (arXiv:2002.12220): SM Higgs decay to Z and a new pseudoscalar a. Focusing $Z \rightarrow \mu\mu$ and $a \rightarrow \gamma\gamma$, $a \rightarrow \mu^+\mu^-$, $a \rightarrow \tau^+\tau^-$ with on-shell decays (m_a<34 GeV).
Model widely motivated but interpreted in term of axion-like particle.

$a \rightarrow \gamma\gamma$

Clean final state with two photons but depends on $\Delta R(\gamma, \gamma)$:

- if $\Delta R(\gamma, \gamma) \lesssim 0.1$ ($m_a < 1$ GeV) $\Longrightarrow$ only 1 reconstructed γ. Reinterpretation with existing literature for $H \rightarrow Z\gamma$.
- else signal and background are simulated through detector level (MadGraph, Pythia and Delphes)

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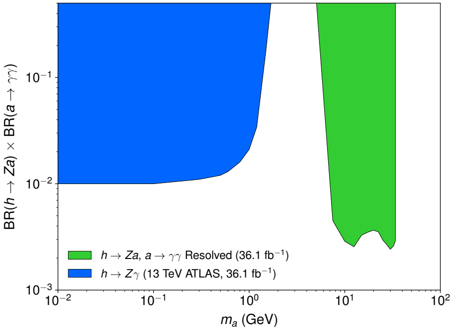
- if $\Delta R(\gamma,\gamma) \lesssim 0.1$ ($m_a < 1$ GeV) $\Longrightarrow$ only 1 reconstructed γ. Reinterpretation with existing literature for $H \to Z\gamma$ (ATLAS)
- else signal and background are simulated through detector level (MadGraph, Pythia and Delphes)

Background: mainly $pp \to \mu\mu\gamma\gamma$ and $pp \to \mu\mu jj$
Signal: H $\to Za$, $a \to \gamma\gamma$ with $m_a \in [5{,}34]$ GeV
Events selection:

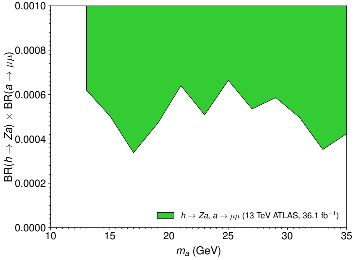
* 2 isolated γ with $p_T^\gamma > 10$ GeV and $|\eta_\gamma| < 2.5$, and two oppositely charged μ with $p_T^\mu > 10$ GeV and $|\eta_\mu| < 2.4$.
* $m_{\mu\mu} \in [75,\ 105]$ GeV and $m_{\mu\mu\gamma\gamma} \in [115,\ 135]$ GeV.
* $m_{\gamma\gamma} + p_T^{\gamma\gamma} < m_h/2$ to suppress reducible $Z+$ jets SM background



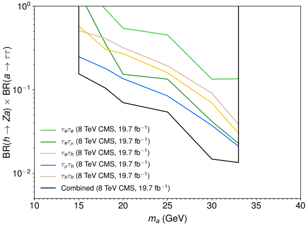
$a \to \mu^+\mu^-$

Already CMS and Atlas papers targeting the final state $(H \to ZZ_D \to 4l) \Longrightarrow$ reinterpretation possible. Try to mimic the analysis cuts at parton level:

- Two pairs of same-flavour (SF), opposite-sign (OS) leptons, ℓ_i.
- $p_T(\ell_1, \ell_2, \ell_3) > 20,\ 15,\ 10$ GeV.
- $\Delta R(\ell, \ell^{'}) > 0.1\,(0.2)$ for SF (OF).
- 115 GeV $< m_{4\ell} <$ 130 GeV.
- $m_{i,j} >$ 5 GeV.
- cuts on m$_{ij}$



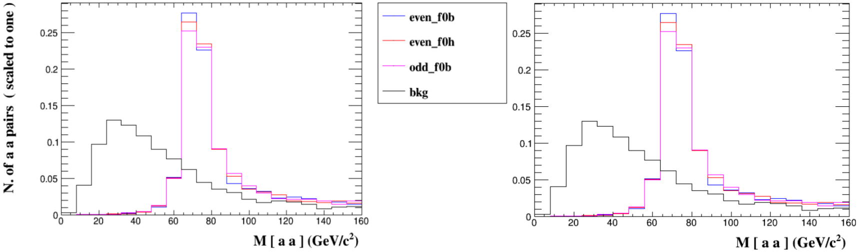
$a \to \tau^+\tau^-$



Les Houches 2019 Physics at TeV Colliders work (arXiv:2002.12220): Extra Scalar Boson Searches at the LHC through Vector Boson Fusion.

VBF production of pseudoscalar ϕ going into 2 γ.
CP-even might be a radion (High Dimension Models), CP-odd scalar might a p-NGB (Composite Higgs Models).

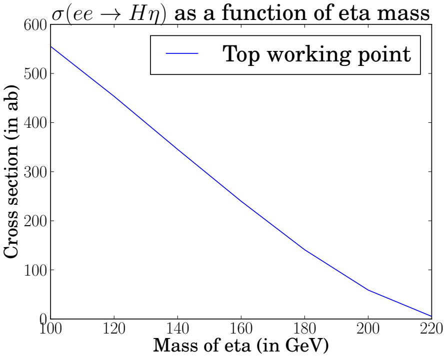
Reconstruction to detector level (Delphes) seems to show possibility to isolate signal from background but not CP-even from CP-odd symmetry.



Works in progress with G. Cacciapaglia, K. Sridhar and N. Manglani:
Composite Higgs model based on SU(4)/Sp(4) with 2 p-NGBs, one of which can be considered the SM Higgs, the other is a pseudoscalar η. For $m_\eta < 2m_W$, the only decay is $\eta \to Z\gamma$.

FCC-ee

Futur Circular Collider with a COM energy up to 350 GeV with clean experimental conditions.
Study $e^+e^- \to \gamma^* \to H\eta$ events.



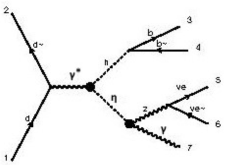
XS is too small even with optimistic setup... Solution: try photon fusion production mode ? (in progress)

Works in progress with G. Cacciapaglia, K. Sridhar and N. Manglani.

HL-LHC

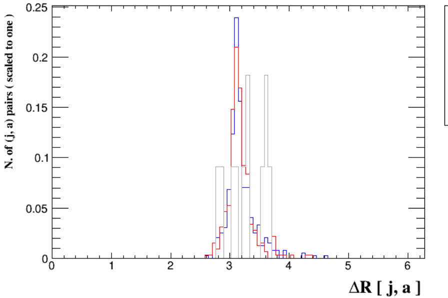
Study $pp \to \gamma^* \to H\eta$ events.

- Signal m_η>90 GeV, $\eta \to Z\gamma$, $H \to bb$, Z to invisible
- Background irreducible $pp \to b\bar{b}\nu_l\bar{\nu}_l$ and $Z \to ZH$



Reconstruction with Pythia and FastJet:

* 1 fat jet with $m_j \in$ [115,135] GeV with 2 b-like subjets ($p_T < 15$ GeV)
* $p_{T,j}$ >160 GeV and $\Delta R(b,b)$<0.7
* $\Delta R(\gamma, inv)$<0.6
* ...



Signal vs background optimization and cuts are still under discussion.

Conclusion

- A search for a new Higgs particle highly motivated by both theory and experiment as been presented

- New presented results provide a very significant improvement in term of sensitivity

- Contribution to the reconstruction and validation of photon within CMS to be included in a upcoming paper

- Main contributor of low-mass $h \to \gamma\gamma$ analysis which is nearly finished, final observed results are expected very soon $\Longrightarrow$ Stay tuned !

- Contribution in a few phenomenology studies with additional Higgs boson, some are still ongoing

Thanks for your attention !

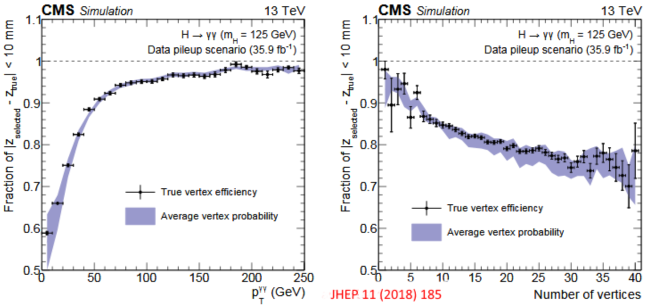
Backup

Vertex assignment

* In case of converted photons can be difficult to find to get info on the photon direction and on the diphoton vertex
* use BDT with input variables related to photon tracks and recoil to distinguish diphoton primary vertex from others
* Validated using $Z \to \mu\mu$ events

Vertex probability

* another related BDT used to estimate the proba to have found the correct vertex
* input variables include vertex assignment BDT output, number of vertices, transverse diphoton momentum, etc
* BDT trained on $H \to \gamma\gamma$ simulation



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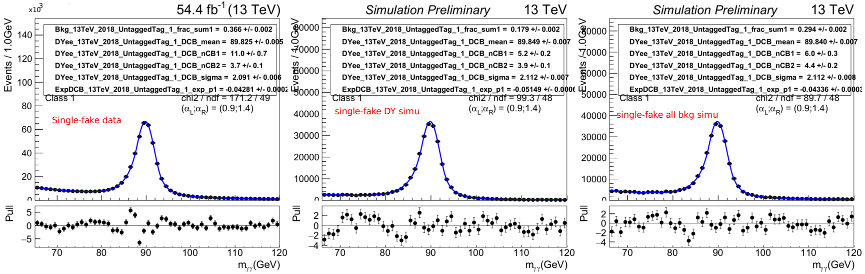
Main uncertainties:

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.

Systematic uncertainties: Drell-Yan component

- DY DCB+exp parameters determined on simulation and apply on data $\Longrightarrow$ need systematics to account for data/MC discrepancies
- Done comparing the differences on DCB mean and sigma between **single-fake** (1 fake γ) events in data and simulation (DY only and all background).
- $\Delta\mu_{data-MC_{All}} = \mid \mu_{data} - \mu_{sim_{All}} \mid$ if $> \sqrt{(\Delta\mu^{stat}_{data})^2 + (\Delta\mu^{stat}_{sim_{All}})^2}$ else non applicable

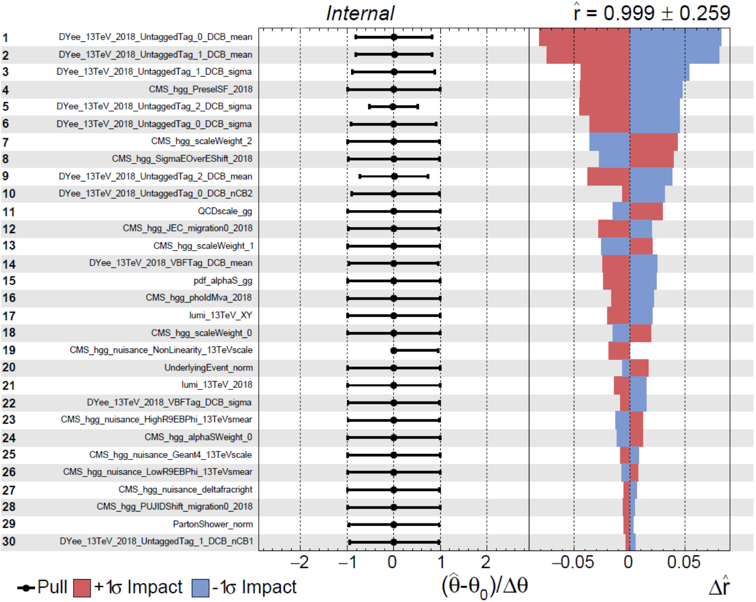
  Final uncert $\Delta\mu_{tot} = \sqrt{(\Delta\mu_{stat})^2 + (2\Delta\mu_{data-sim_{All}})^2 + (2\Delta\mu_{sim_{All}-MC_{DY}})^2}$



- Final syst. uncer. are between 1-3 $\times$ DCB+exp stat. uncert.

Systematic uncertainties

Impact of different systematics at m_h=93 GeV on a hypothetical signal



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

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

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

Supersymétrie (SUSY) : extension au MS, on rajoute à ce dernier une symétrie supplémentaire qui associe à chaque particule du MS un partenaire qui est appelé superparticule. Contexte théorique différent, on utilise par exemple des objets comme les superchamps et les superpotentiels.

Beaucoup de modèles de SUSY : le plus simple **Minimal Supersymmetric Model (MSSM)** mais difficilement avec les contraintes mesurées expérimentalement. $\Longrightarrow$ **Next-to Minimal Supersymmetric Model (NMSSM)**, ajout d'un superchamp scalaire complexe.

Le NMSSM prévoit de particules dont 7 particules de type bosons de Higgs : 2 bosons chargés $\mathrm{H}^{\pm}$, 2 pseudoscalaires neutres A_1 et A_2 et 3 scalaires neutres H_1, H_2 et H_3 avec $m_{H_1} < m_{H_2} < m_{H_3}$. Si l'on identifie H_2 ou H_3 avec le boson de Higgs détecté au LHC, ce modèle pourrait conjecturer un, ou deux, boson scalaires de plus faible masse.

Intérêts :

- une solution élégante au problème de la hiérarchie
- unification des couplages forts, faibles et électromagnétiques
- matière noire

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:

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

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

χ^2

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

Ajustement

1. Calculate χ^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 σ_i

Envelope method

F-test

Increase the nb 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 likelyhood function associated to the considered fit for a function of rank N.

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

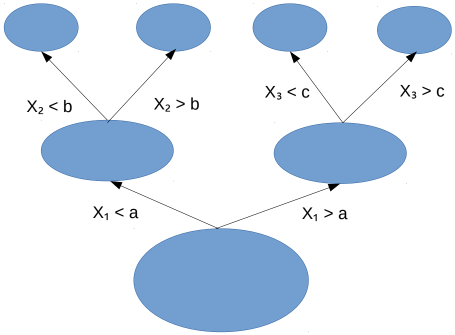
$$Lau_N(x) = \sum_{i=1}^{N} b_i x^{-4+\sum_{j=1}^{i}(-1)^j(j-1)};\ Pow_N(x) = \sum_{i=1}^{N} b_i x^{a_i} + dCB(x)$$

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.