PhD Defense

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PhD Defense, 2017

Outline

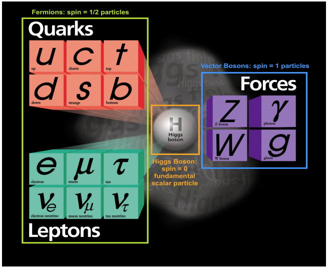
Where we stand

- 5 years at The University of Iowa as PhD Student
  - Test Beams at Fermilab and CERN
- 3 years at CERN working on Compact Muon Solenoid Experiment
  - CMS 2015 Achievement Award
  - HCAL Operations Deputy Coordinator
  - HCAL DQM Group Lead.
- Received CERN IT Fellowship to work as Big Data Engineer.

Outline

Introduction: Standard Model

- Standard Model - Quantum Field Theory
- Incorporates Electromagnetic, Weak, Strong forces
- Force Carriers (Bosons) and matter constituents (Fermions)
- Bosons: gluons, vector bosons.
- Fermions: 6 quarks and 6 leptons.



Remark

- What is Higgs Boson and where does it fit into SM?!
- Why searching Higgs Boson decaying into 2 muons?!

Introduction: Standard Model U(1)

- Start with a Lagrangian for a free fermion:

$$\mathcal{L} = \bar{\psi} i \gamma^{\mu} \partial_{\mu} \psi - m \bar{\psi} \psi \tag{1}$$

- 2 types of transformations:

$$Global: \quad \psi \rightarrow e^{i\theta} \psi \tag{2a}$$

$$Local: \quad \psi \rightarrow e^{i\theta(x)} \psi \tag{2b}$$

- Local Transformation does not hold $\rightarrow$ introduce a vector field A^{μ}:

$$A^{\mu} \rightarrow A^{\mu} - \frac{1}{q} \partial^{\mu} \theta(x) \tag{3a}$$

$$D^{\mu} = \partial^{\mu} + iqA^{\mu} \tag{3b}$$

- We obtain the Quantum Electrodynamics Lagrangian (almost):

$$\mathcal{L} = \bar{\psi} i \gamma^{\mu} D_{\mu} \psi - m \bar{\psi} \psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + m_A^2 A^{\mu} A_{\mu} \tag{4}$$

- For $m_A^2 A^{\mu} A_{\mu}$ is not local gauge invariant $\rightarrow$ $m_A = 0$
- $m\bar{\psi}\psi$ is U(1) local gauge invariant

Introduction: Standard Model - SU(2) and SU(2)$_L$

- Consider 2 fermionic fields and define a doublet:

$$\Psi = (\psi_1, \psi_2) \tag{5}$$

- Require a free Lagrangian to be invariant under Transformations:

$$Global: \quad \Psi \to e^{i\boldsymbol{\theta}\cdot\boldsymbol{\sigma}}\Psi \tag{6a}$$

$$Local: \quad \Psi \to e^{i\boldsymbol{\theta}(\mathbf{x})\cdot\boldsymbol{\sigma}}\Psi \tag{6b}$$

- Will introduce 3 new massless vector fields.
- Define Chiral Projections for a Dirac-field (4-component):

$$\psi_L = \frac{1}{2}(1-\gamma^5)\psi \tag{7a}$$

$$\psi_R = \frac{1}{2}(1+\gamma^5)\psi \tag{7b}$$

$$m\bar{\psi}\psi = m\bar{\psi}_L\psi_R + m\bar{\psi}_R\psi_L \tag{7c}$$

- Standard Model Electroweak theory imposes gauge invariance only for left-handed fermions! $\to$ SU(2)$_L$

Introduction: Standard Model - Problems and Solutions

- $SU(2)_L \times U(1) \rightarrow$ 3 Massless Vector fields - contrary to observation
- ψ_L transforms according to $SU(2)_L \times U(1)$, ψ_R according to $U(1) \rightarrow$ Fermions are massless - contrary to observation

Remark

Solution: Higgs Mechanism - a new field living in $SU(2)_L \times U(1)$ and a particular choice of the potential term. Upon Spontaneous Symmetry Breaking - masses for gauge bosons are generated!

Quote

S. Coleman: "In general, there is no reason why an invariance of the Hamiltonian of a quantum-mechanical system should also be an invariance of the ground state of the system."

Introduction: Standard Model - Higgs Mechanism

- Adding an SU(2) doublet field - 4 degrees of freedom:

$$\Phi = \begin{bmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{bmatrix} \tag{8}$$

- With a Potential Term:

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2 \tag{9a}$$

$$\mu^2 < 0 \tag{9b}$$

- With a Lagrangian:

$$\mathcal{L} = \bar{\Psi} i \gamma^\mu D_\mu \Psi + (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2 \tag{10a}$$

- With a Yukawa coupling to fermions

$$m\bar{\psi}\psi \rightarrow y[\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \bar{\phi} \psi_L] \tag{11a}$$

$$\rightarrow y[[\bar{\psi}_1, \bar{\psi}_2]_L \begin{bmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{bmatrix} \psi_R + \bar{\psi}_R \left[\phi_1^\dagger - i\phi_2^\dagger, \phi_3^\dagger - i\phi_4^\dagger\right] \begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix}_L] \tag{11b}$$

Introduction: Higgs Mechanism

- Perturb the, Φ-field, SU(2) $\times$ U(1) doublet around the minimum:

$$\Phi = \begin{bmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{bmatrix} \rightarrow \begin{bmatrix} \phi_1 + i\phi_2 \\ H + \nu + i\phi_4 \end{bmatrix}, \nu = \sqrt{-\frac{\mu^2}{\lambda}} \tag{12}$$

- Expand Lagrangian and select the Unitary Gauge
- ϕ_1, ϕ_2, ϕ_3 components will be absorbed (upon choosing the Unitary Gauge) into mass terms for 3 vector bosons by expanding the kinetic term:

$$\mathcal{L}_{kinetic} = (D^{\mu}\Phi)^{\dagger} D_{\mu}\Phi \tag{13a}$$

- Fermion mass and Coupling to Higgs Field will come from:

$$m\bar{\psi}\psi \rightarrow y[\bar{\psi}_L\phi\psi_R + \bar{\psi}_R\bar{\phi}\psi_L] \tag{14a}$$

$$\rightarrow y[\left[\bar{\psi}_1, \bar{\psi}_2\right]_L \begin{bmatrix} 0 \\ H + \nu \end{bmatrix} \psi_R + \bar{\psi}_R \left[0, H + \nu\right] \begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix}_L] \tag{14b}$$

$$\rightarrow y\sqrt{-\frac{\mu^2}{2\lambda}}\bar{\psi}_{Dirac}\psi_{Dirac} + \frac{y}{\sqrt{2}}H\bar{\psi}_{Dirac}\psi_{Dirac} \tag{14c}$$

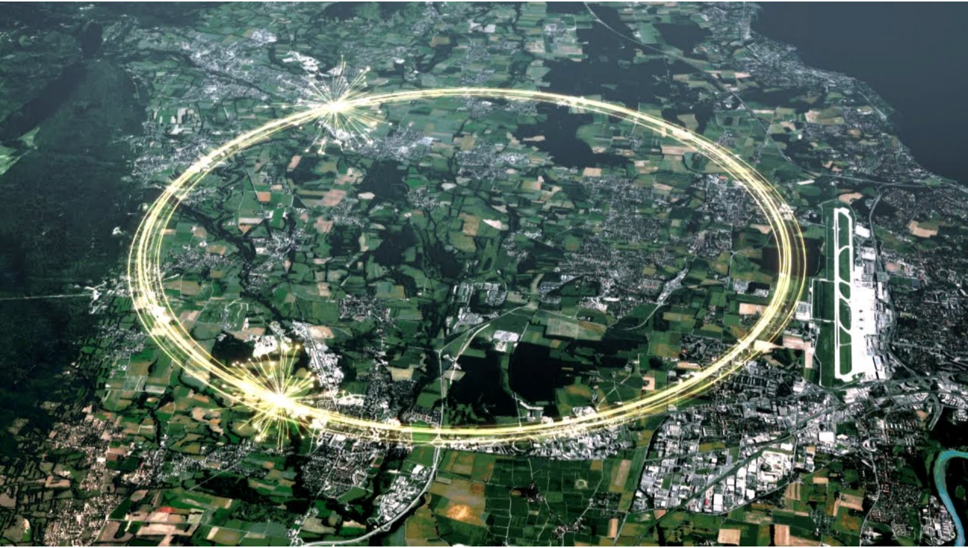
Introduction: Summary

- Original phenomenological Lagrangian possesses local gauge invariance!
- Spontaneous Symmetry Breaking, by definition, is the change of the ground state to another ground state under certain transformation - local $SU(2)_L \times U(1)$ for SM!
- Real Higgs Field!
- Mass for the fermions:

$$y\sqrt{-\frac{\mu^2}{2\lambda}}\bar{\psi}_{Dirac}\psi_{Dirac} \rightarrow m = \frac{y\nu}{\sqrt{2}} \tag{15a}$$

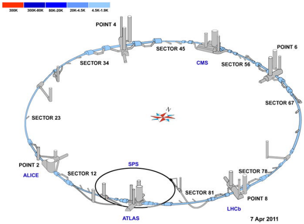
- Yukawa Coupling of Higgs to Fermions
- At 125 GeV Higgs boson mass, Branching Fraction is 0.00022

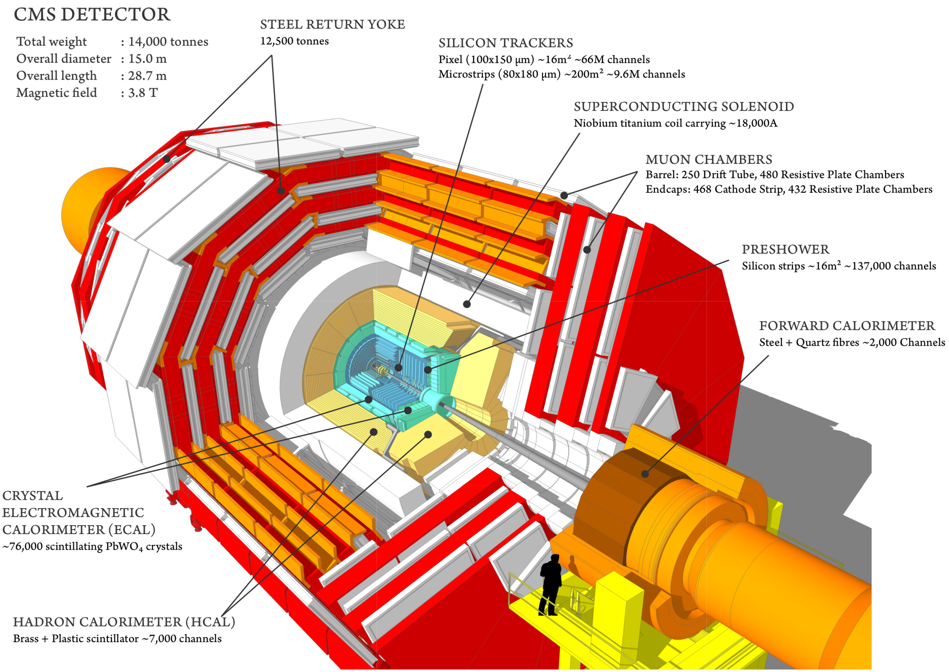
$$\mathcal{B}(H \rightarrow \mu\mu) = \frac{\Gamma(H \rightarrow \mu\mu)}{\sum \Gamma(H \rightarrow \dots)} \tag{16a}$$

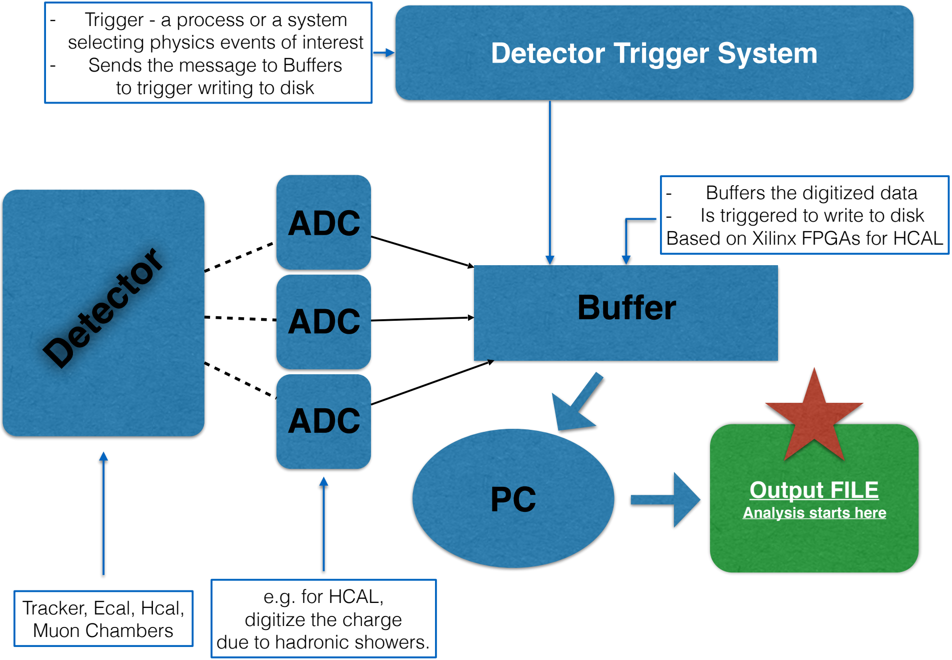


Large Hadron Collider

- LHC - Accelerating Complex
- Accelerates/Collides pp, Pb-p, Pb-Pb
- Current maximum momentum per beam is 6.5TeV/c ($\sqrt{s} = 13\,TeV$) for proton beam
- “Data Factory” one of its kind
    - Even without recording collisions

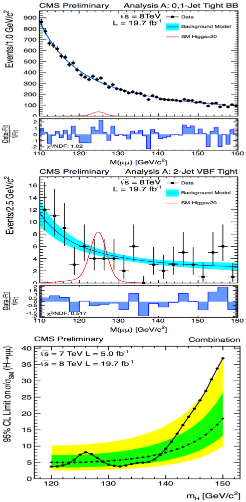



CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels


- Trigger - a process or a system selecting physics events of interest
- Sends the message to Buffers to trigger writing to disk
Detector Trigger System
Detector
ADC
ADC
ADC
Buffer
- Buffers the digitized data
- Is triggered to write to disk
Based on Xilinx FPGAs for HCAL
PC
Output FILE
Analysis starts here
Tracker, Ecal, Hcal, Muon Chambers
e.g. for HCAL, digitize the charge due to hadronic showers.

SM Higgs Search at CMS in Run I

- Run I proton-proton collsions at $\sqrt{s} = 7TeV(L = 5fb^{-1})$ and $\sqrt{s} = 8TeV(L = 19.7fb^{-1})$
- CMS made observations of Higgs Boson
  - $H \to \gamma\gamma$
  - $H \to ZZ \to 4l$
  - $H \to \tau\tau$
  - no observation for $H \to \mu\mu$
- 1.1σ excess in significance for mass $125GeV$ was observed - compatible with statistical fluctuation
- 95% Confidence Level (CL) exclusion limits were set on $125GeV$ Higgs Production Cross-Section.
  - for $7TeV \to \sigma = 12.8 \times SM$(Exp.) and $\sigma = 19.0 \times SM$(Obs.)
  - for $8TeV \to \sigma = 5.6 \times SM$(Exp.) and $\sigma = 6.9 \times SM$(Obs.)



Problem Statement

Remark

The primary objective of this work is to investigate the $\mu^+\mu^-$ Higgs decay mode with 35.9 fb$^-$1 of data collected in proton-proton collisions at $\sqrt{s} = 13$ TeV by Compact Muon Solenoid (CMS) Experiment during the second operational phase of LHC (2016)

Analysis Workflow

- Collect the data!
- Data Preprocesssing/Skimming
  - Apply basic selection criteria (e.g. at least 2 muons in event)
  - Reduce the amount of data by orders of magnitude.
- Event Selections
  - Apply muon corrections
  - Apply various selections
  - Choose objects of interest
  - Compare Data with MC simulations and establish the validity of simulated models.
    - If matches - good, does not - why?! Other models. . . ?
- Event Categorization
  - Grouping events by #jets, $p_t^{\mu\mu}$, BDT score, . . .
- Compute Systematics
- Statistical Analysis
  - Build Signal/Background Models
  - Extract the 95% CL Exclusion Limits

Datasets and Configuration: General

- Data
  - Use 36.9 fb^{-1} of data collected over 2016
  - SingleMuon Primary Dataset
- Monte Carlo
  - Higgs Signal
    - VBF, ggFuson, $W^{+/-}$H, Zh production processes
  - Backgrounds
    - Drell-Yan + Jets
    - $t\bar{t}$ + Jets
    - ...
  - PileUp reweighting for 69.2 mb

Datasets and Configuration: Data

Table: Datasets for proton-proton collisions recorded at $\sqrt{s} = 13$ TeV by CMS at LHC in 2016.

Datasets	Int. Luminosity (fb^{-1})
/SingleMuon/Run2016B-03Feb2017_ver2-v2/MINIAOD	5.788
/SingleMuon/Run2016C-03Feb2017-v1/MINIAOD	2.573
/SingleMuon/Run2016D-03Feb2017-v1/MINIAOD	4.248
/SingleMuon/Run2016E-03Feb2017-v1/MINIAOD	4.009
/SingleMuon/Run2016F-03Feb2017-v1/MINIAOD	3.102
/SingleMuon/Run2016G-03Feb2017-v1/MINIAOD	7.540
/SingleMuon/Run2016H-03Feb2017_ver2(3)-v1/MINIAOD	8.606

Datasets and Configuration: SM Higgs Signal

Table: Standard Model 125 GeV Higgs Boson Signal Datasets for 13 TeV. Dataset names for 120/130 GeV are omitted for brevity. Moriond 2017 conditions are used (omitted the conditions specification for brevity).

Datasets	σ (pb)
/GluGlu_HToMuMu_M125_13TeV_powheg_pythia8	48.58
/VBF_HToMuMu_M125_13TeV_powheg_pythia8	3.782
/WMinusH_HToMuMu_M125_13TeV_powheg_pythia8	0.5331
/WPlusH_HToMuMu_M125_13TeV_powheg_pythia8	0.851
/ZH_HToMuMu_M125_13TeV_powheg_pythia8	0.8839

Datasets and Configuration: Backgrounds

Table: Background Datasets. Moriond 2017 conditions have been used (omitted the conditions specification for brevity).

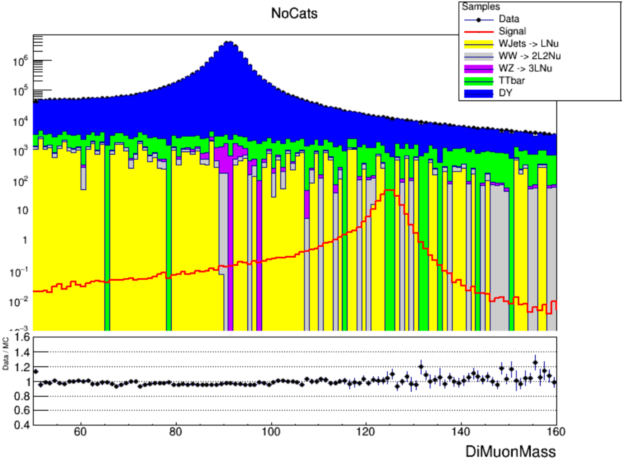
Dataset	σ (pb)
/DYJetsToLL_M-50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	5765
/ST_tW_top_5f_NoFullyHadronicDecays_13TeV-powheg_TuneCUETP8M1	35.85
/TTJets_DiLept_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	85.656
/WJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	61526.7
/WWTo2L2Nu_13TeV-powheg-herwigpp	10.481
/WZTo3LNu_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	4.712

Event Selections

- Primary Vertex
  - at least 1 Primary Vertex with
  - $|zPV| < 24$ - shift along the beam axis w.r.t. nominal CMS center
  - $ndf > 4$ - degrees of freedom
- HLT - HLT_IsoMu24 or HLT_IsoTkMu24 to fire
  - Event must have at least 1 μ with $p_t \geq 24GeV$
- Jets
  - $p_t > 30$ GeV && $|\eta| < 4.7$ && $\Delta R_\mu < 0.4$
- Muons
  - 2 oppositely charged muons
  - Each Muon
    - Rochester Muon Corrections
    - Medium Muon Id
    - $p_t > 10$ GeV && $|\eta| < 2.4$ && $I^{PF}_{rel} < 0.25$
  - At least 1 muon to match HLT
    - $p_t > 26$ GeV && $|\eta| < 2.4$ && $\Delta R_{HLT} < 0.1$
- Passed basic event selections - identify this as the TopCategory - combination of all.

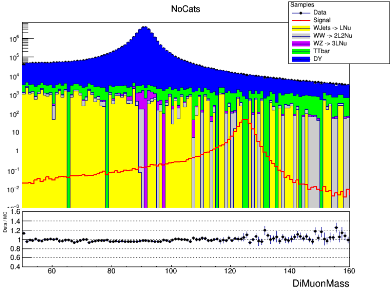
Top Category: Mass Distribution

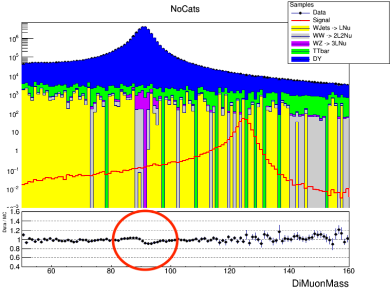
Dimuon Mass ($m_{\mu\mu}$) distribution with Rochester Muon Corrections:



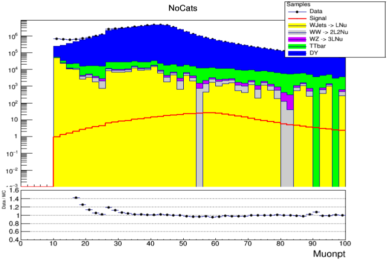
Top Category: Corrected vs Uncorrected

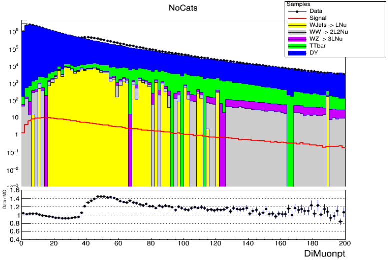
Corrected (Rochester) vs Uncorrected:

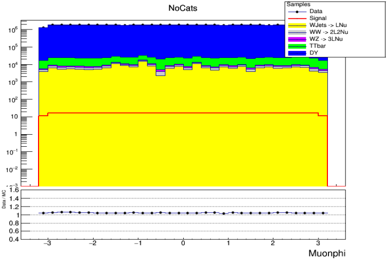


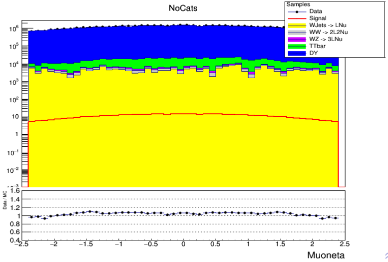


Top Category: Kinematic Distributions









Event Categorization

- Grouping events using certain crteria
- 2 different procedures
- Baseline Categorization is based on Run I categorization selections
- Greedy Categorization: 2-step procedure
  - Binary Classification: Engineer a new feature, BDT score, using Boostead Decision Tree (BDT)
  - Greedy Event Grouping: Use 2 features (max(η_{μ_1}, η_{μ_2}) and BDT score) to split events into different categories.

Event Categorization: Baseline

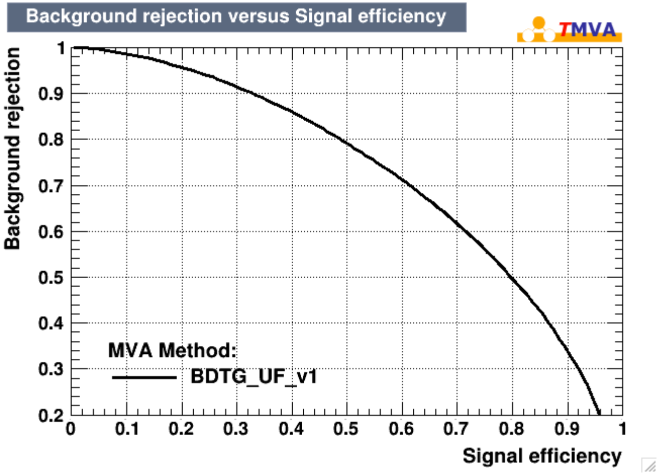
- Require only $m_{\mu\mu}$ in $[110, 160]$
- 2Jet Category
  - # Jets $>= 2$
  - $p_t^{j_1} > 40$ GeV && $p_t^{j_2} > 30$ GeV && $p_t^{MET} < 40$ GeV
    - if not satisfied, go to 01Jet Category part
    - passed, then if $m_{jj} > 650$ GeV && $|d\eta| > 3.5 \rightarrow$ VBFTIght Category
    - else if $m_{dijet} > 250$ GeV && $p_t^{\mu\mu} > 50$ GeV $\rightarrow$ ggFTight Category
    - else $\rightarrow$ ggFLoose Category
- 01Jet Category
  - # Jets $<= 1$
  - if $p_t^{\mu\mu} \geq 25$ GeV $\rightarrow$ 01JetsTight $\rightarrow$ Geometry Categorization
  - else $\rightarrow$ 01JetsLoose $\rightarrow$ Geometry Categorization

Event Categorization: Greedy Step1 - Binary Classification

- Require only $m_{\mu\mu}$ in $[110, 160]$ GeV mass range
- Train a Boosted Decision Tree to perform a binary classification: signal / background.
- Training / Cross-Validation / Testing using half of Signal and all of Background events
- BDT Features are various event and kinematic variables: $p_t^{\mu\mu}$, $\eta_{\mu\mu}$, # jets, ...
  - No mass dependence among the BDT features!
- BDT score (continuous value [-1, 1]) is preserved - do not actually select the ”turning point” (for binary classification).

Event Categorization: Greedy Step1 - BDT ROC

BDT Receiver Operating Curve:



Event Categorization: Greedy Step2 - Event Splitting

Define a Significance, S_c, for a histogram:

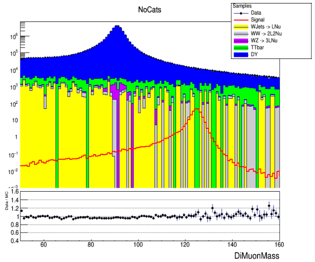
$$S_c^2 = \sum_{c,i} N_{c,i}^{S2} / N_{c,i}^{B} \qquad (17)$$

Use 2 features: $\max(\eta_{\mu_1}, \eta_{\mu_2})$ and BDT score
Define a Gain, G, of a split:

$$G = S_{left}^2 + S_{right}^2 - S_{node}^2 \qquad (18)$$

- For a given histogram, greedily scan through the features
- Pick the split that maximizes Gain
- Proceed recursively.

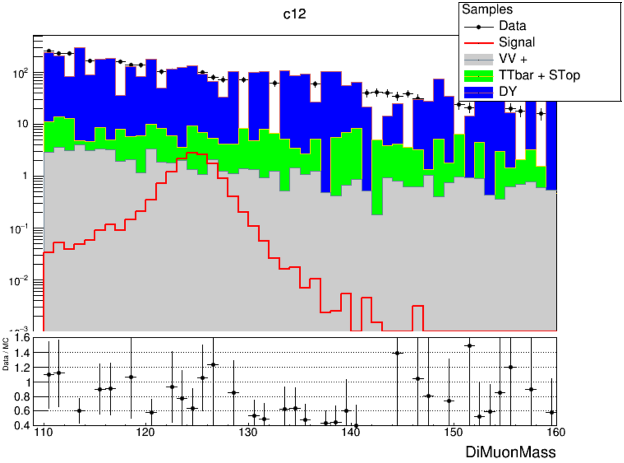
Top Category Mass Distribution:



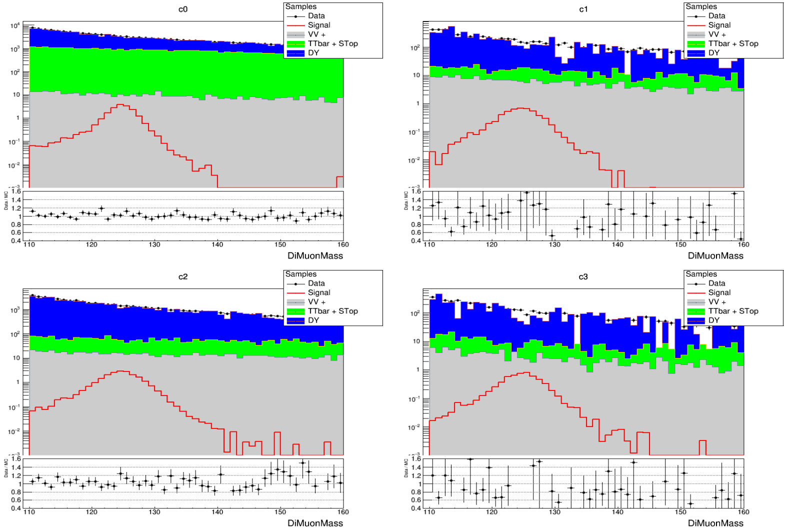
The result is 13 categories (15 for Baseline) that are obtained via a greedy procedure!

Event Categorization: Greedy - Mass Distributions

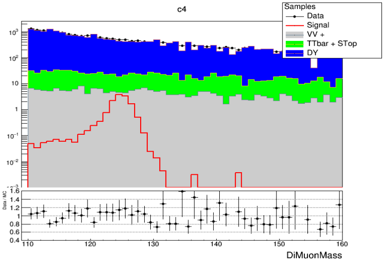
Most Sensitive Category ”c12”:

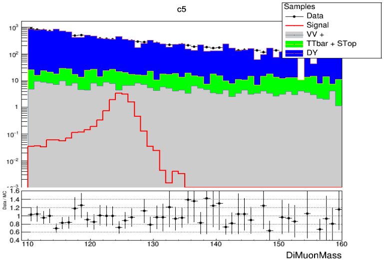


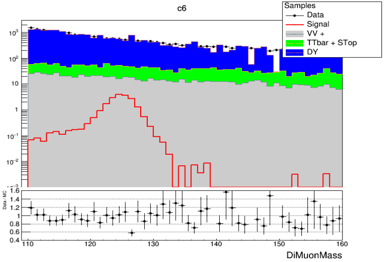
Event Categorization: Greedy - Mass Distributions

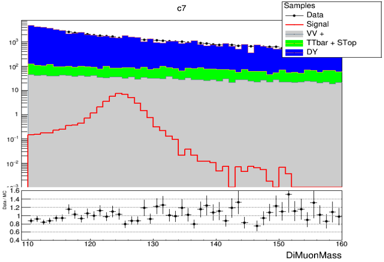


Event Categorization: Greedy - Mass Distributions

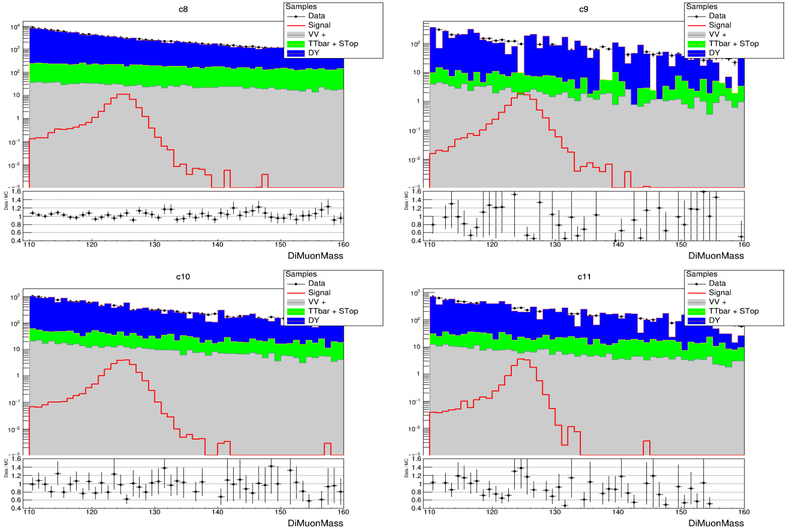








Event Categorization: Greedy - Mass Distributions



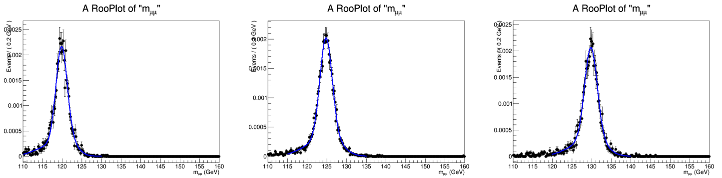
Signal Model: Basics

- Triple Gaussian PDF:

$$S(x, m_H, \theta) = f_1\mathcal{N}_1(x, \mu_1, \sigma_1) + (1 - f_1)\left(f_2\mathcal{N}_2(x, \mu_2, \sigma_2) + (1 - f_2)\mathcal{N}_3(x, \mu_3, \sigma_3)\right) \tag{19}$$

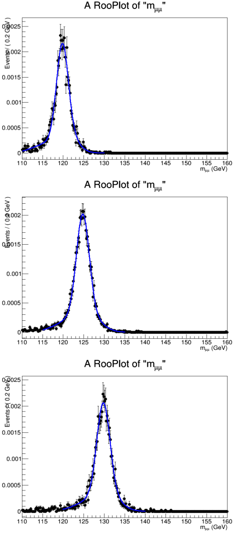
- Each production process treated separately
- MC mass distributions are fitted and all model parameters are fixed
- Total Signal Normalization, the SM yield, is fixed:

$$\text{Yield} = \mathcal{L}\,\sigma(pp \to H)\,\mathcal{B}(H \to \mu\mu)\,\varepsilon A \tag{20}$$

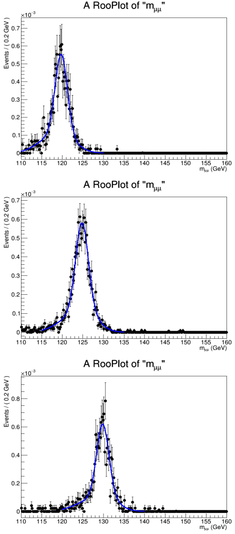


Signal Model: Examples

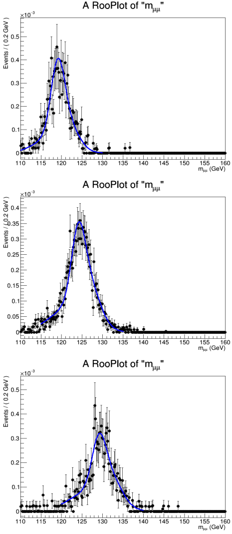
Category "c0" Gluon Fusion



Category "c0" Vector Boson Fusion

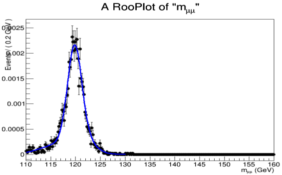


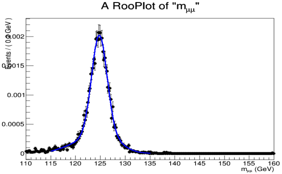
Category "c1" Gluon Fusion Fusion

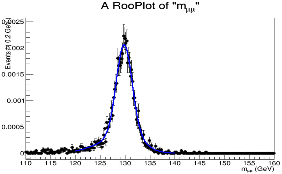


Signal Model: Mass Interpolation

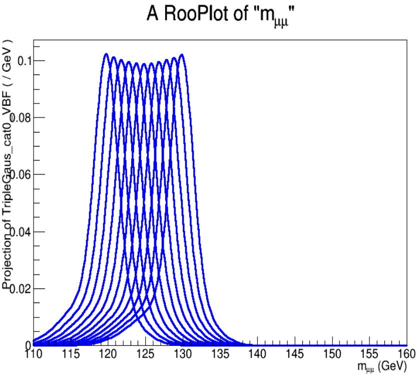
Category "c0" Gluon Fusion







- The search is performed in the mass range [120, 130] GeV.
- 3 mass points used for parameter interpolation: 120, 125, 130 GeV
- Parameters of individual models are fitted and then interpolated in between as function of the Higgs mass.



Background Model

- Data-driven approach - providing actual mathematical functions as pdf candidates
- 2 types of models: **Physics-motivated** and **Order-dependent**
- **Order-dependent** - various polynomial-like series
- Background is left completely floating - all parameters of the model are floating!
- Employ an envelope method - build a set of functions and use them simultaneously for the fitting procedure.
- Envelope method $\rightarrow$ simplify the bias estimation

Background Model

- Physics-motivated functional forms:

$$\textit{ExpPolynomial: } B(x) = e^{a_1 x + a_2 x^2} \tag{21}$$

$$\textit{BWZ: } B(x) = \frac{e^{ax}\sigma_z}{(x-\mu_z)^2 + (\frac{\sigma_z}{2})^2} \tag{22}$$

$$\textit{BWZRedux: } B(x) = \frac{e^{a_2 x + a_3 x^2}}{(x-\mu_z)^{a_1} + (\frac{2.5}{2})^{a_1}} \tag{23}$$

$$\textit{BWZGamma: } B(x) = f\frac{e^{ax}\sigma_z}{(x-\mu_z)^2 + (\frac{\sigma_z}{2})^2} + (1-f)\frac{e^{ax}}{x^2} \tag{24}$$

Background Model

- Various order-dependent functional forms:
- Order is selected by using F-Test (Fisher Test) procedure

$$\textit{Bernsteins: } B(x) = \sum_{i=0}^{n} \alpha_i [\binom{n}{i} x^i (1-x)^{n-i}] \tag{25}$$

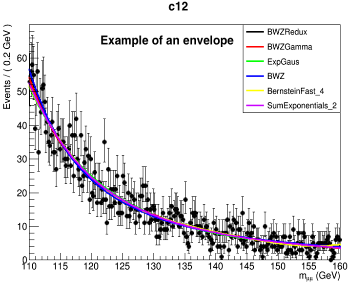
$$\textit{SumExponentials: } B(x) = \sum_{i=1}^{n} \beta_i e^{\alpha_i x} \tag{26}$$

$$\textit{SumPowers: } B(x) = \sum_{i=1}^{n} \beta_i x^{\alpha_i} \tag{27}$$

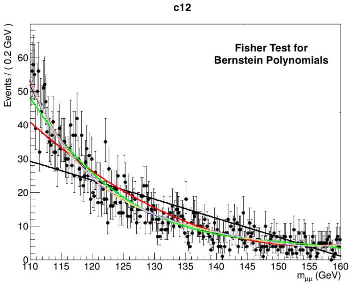
$$\textit{LaurentSeries: } B(x) = \sum_{i} \alpha_i x^i \tag{28}$$

Background Model: Examples

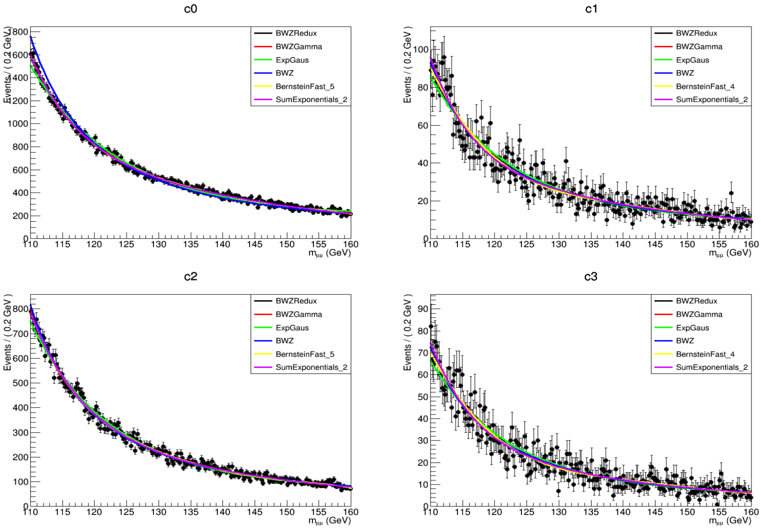
Example of an envelope of background functions for **c12**



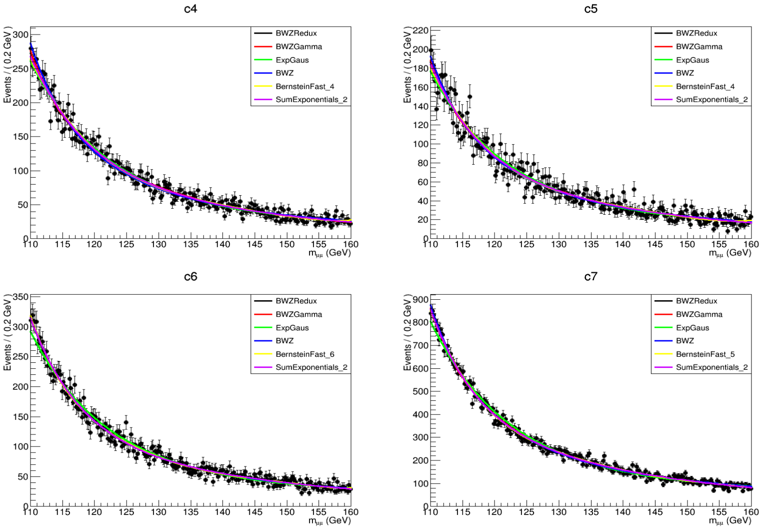
Example of the Fisher Test for Bernstein Polynomials for **c12**



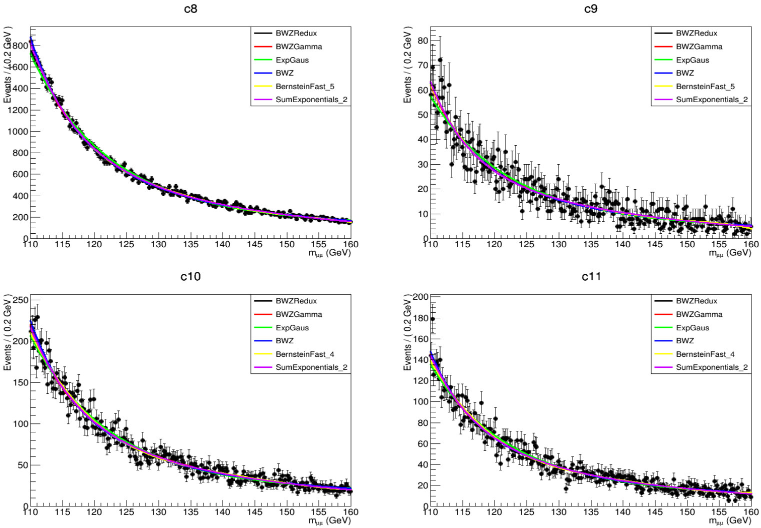
Background Model: c0 - c3



Background Model: c4 - c7



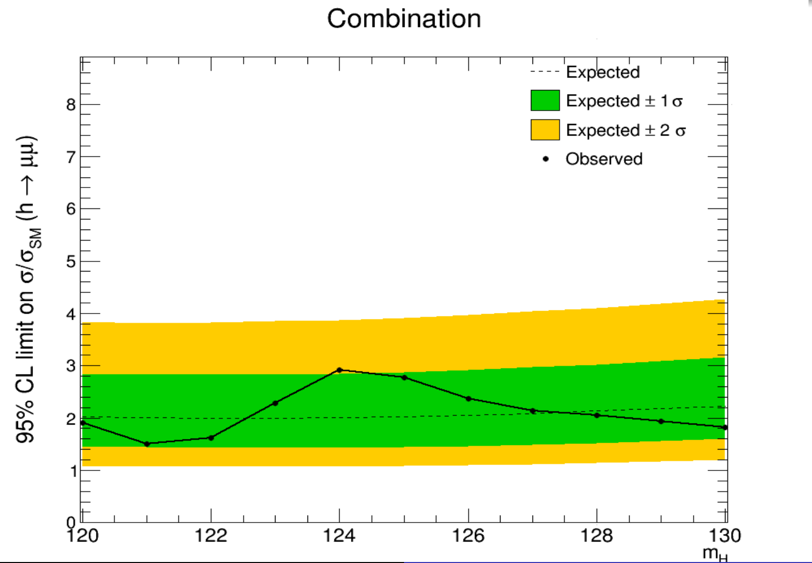
Background Model: c8 - c11

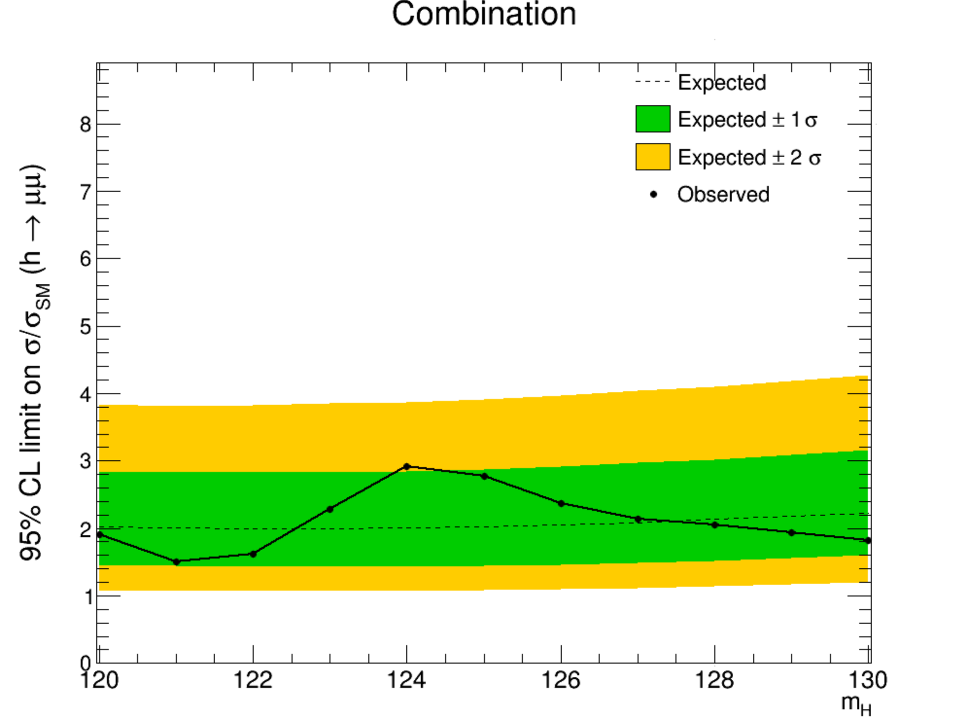


Systematic Uncertainties

- Signal Shape Uncertainty
  - Muon Scale: 5%
  - Muon Resolution: up to 10%
  - Nuisances to modify the shape of the signal model are added
- Category Migration
  - Jets Energy Scale: up to 6%
  - Jets Energy Resolution: 1 - 2%
  - Pile-Up: 1 - 2%
  - ...
- Rate Uncertainties
  - Branching Ratio $\mathcal{B}(H \to \mu\mu)$ - 1.7%
  - Higgs boson Production Cross-sections 5 - 10%
- Integrated Luminosity: 2.6%
- All of the systematics, except for shape, are incorporated as multiplicative nuisances that allow the overall normalization of the signal to vary within certain bounds

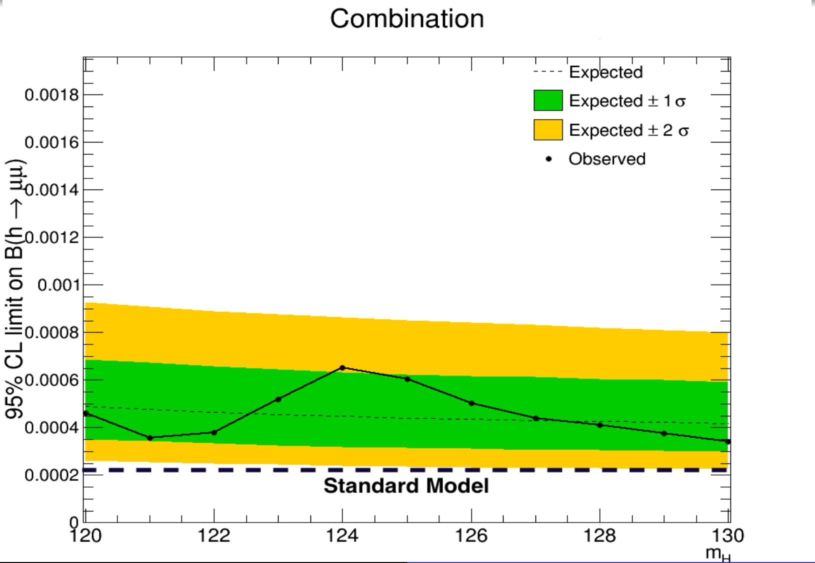
Results: 95% CL Exclusion Limits on Signal Strength μ

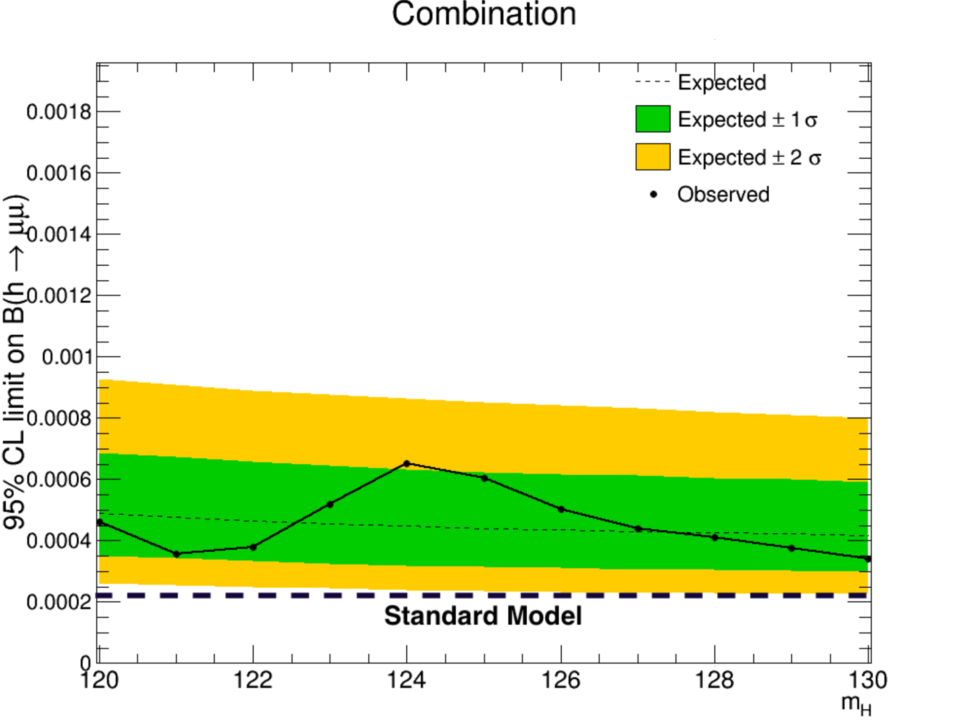




Combination
95% CL limit on σ/σ_SM (h → μμ)
m_H
Expected
Expected ± 1 σ
Expected ± 2 σ
Observed
0
1
2
3
4
5
6
7
8
120
122
124
126
128
130

Results: 95% CL Exclusion Limits on Branching Fraction $\mathcal{B} \to \mu\mu$





Combination
Expected
Expected ± 1 σ
Expected ± 2 σ
Observed
95% CL limit on B(h → μμ)
Standard Model
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
120
122
124
126
128
130
m_H

Conclusions: 95% CL Limits on σ/σ_{SM}

m_h [GeV]	Expected Limits					Observed limit
	-2σ	-1σ	median	1σ	2σ	
120	1.08	1.44	2.02	2.84	3.84	1.90
121	1.07	1.44	2.01	2.83	3.82	1.50
122	1.07	1.43	1.99	2.83	3.82	1.63
123	1.07	1.43	1.99	2.83	3.85	2.28
124	1.07	1.43	2.01	2.84	3.87	2.92
125	1.08	1.44	2.02	2.87	3.91	2.77
126	1.10	1.47	2.05	2.91	3.97	2.37
127	1.12	1.49	2.09	2.98	4.04	2.13
128	1.15	1.52	2.13	3.03	4.09	2.06
129	1.17	1.56	2.18	3.09	4.18	1.94
130	1.20	1.60	2.23	3.16	4.27	1.82

Conclusions

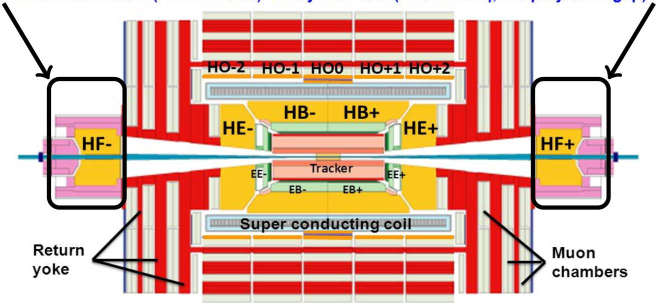
- A search for the Standard Model Higgs Boson decaying to 2 muons has been performed.
- No significant excess of events was observed
- For the 125 GeV Higgs Boson, the observed (expected) limit on μ is 2.77 ($2.02^{+0.85}_{-0.58}$) $\times$ SM for 13 TeV
- The observed / expected difference corresponds to $\approx 1\sigma$ around 125 GeV.
- For Run I, the combined observed (expected) limit for the 7 and 8 TeV data was found to be 7.4 ($6.5^{+2.8}_{-1.9}$) $\times$SM.
- With 95% CL we exclude the Branching Fraction ($\mathcal{B} \rightarrow \mu\mu$) above $\approx$ 0.0006.

Outline

Hadron Forward

CMS Calorimeter

CMS Calorimeter (ECAL+HCAL) - Very hermetic (>10λ in all η, no projective gap)

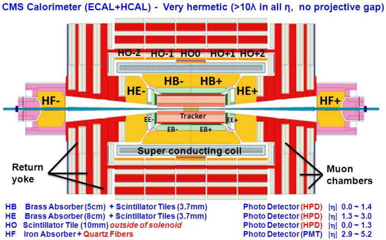


HB	Brass Absorber (5cm) + Scintillator Tiles (3.7mm)	Photo Detector (HPD)	$\lvert\eta\rvert$	0.0 ~ 1.4
HE	Brass Absorber (8cm) + Scintillator Tiles (3.7mm)	Photo Detector (HPD)	$\lvert\eta\rvert$	1.3 ~ 3.0
HO	Scintillator Tile (10mm) *outside of solenoid*	Photo Detector (HPD)	$\lvert\eta\rvert$	0.0 ~ 1.3
HF	Iron Absorber + Quartz Fibers	Photo Detector (PMT)	$\lvert\eta\rvert$	2.9 ~ 5.2

Description of Hadron Forward

- 165 cm Steel $\rightarrow 10\lambda_I$ Hadron Calorimeter.
  - Acts as Electromagnetic as well, as there is no ECAL in front.
- Covers large pseudorapidity range, $3 \leq |\eta| \leq 5$
- Active Medium: Quartz Fibers - Radiation Hard
- Light, generated via Cherenkov Radiation from showering particles, captured with fibers and read out with PMTs.
- 2 types of fibers per tower: Long and Short
  - Long $\rightarrow$ catches Electromagnetic component
  - Short (22cm shorter) $\rightarrow$ catches only Hadronically developed showers.

CMS Calorimeter

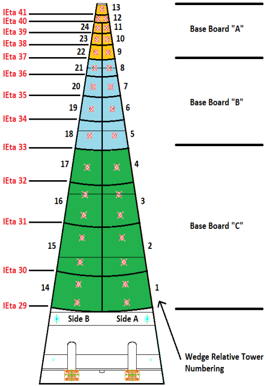


Description of Sourcing

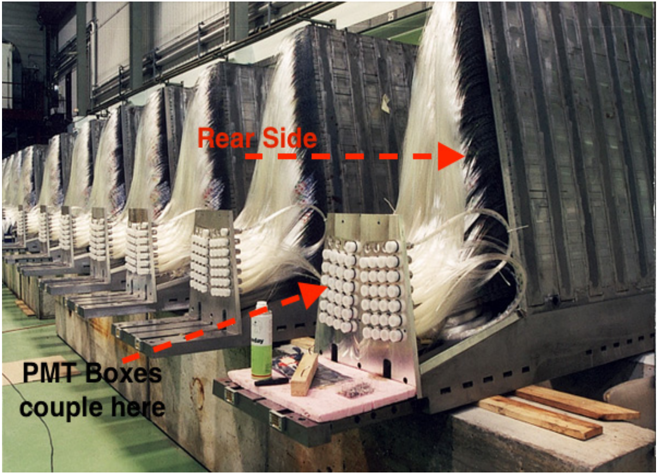
Why Sourcing

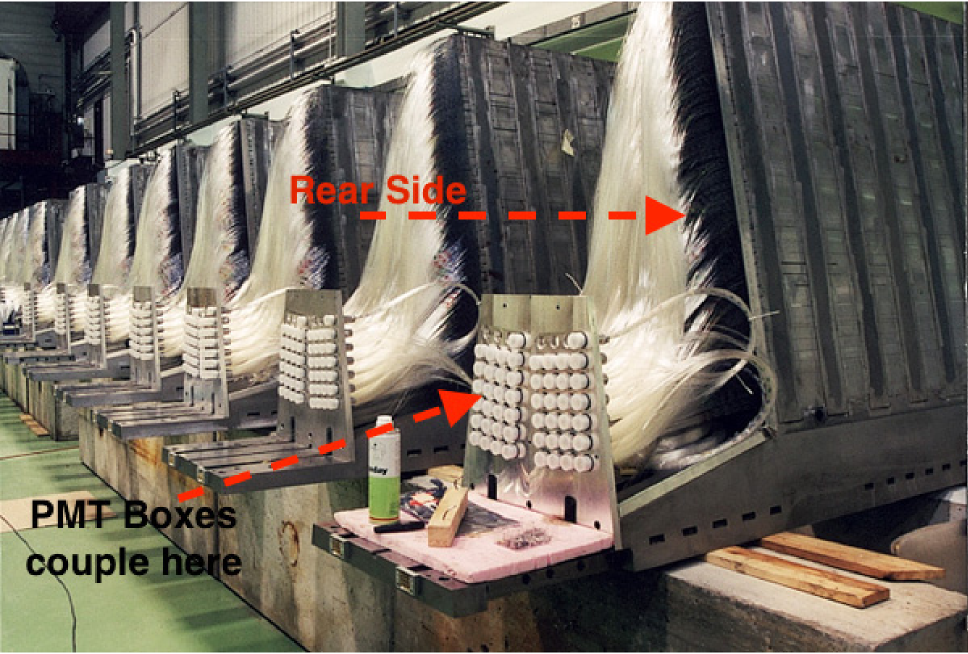
Given that our system is located 100m underground, and weighs like a tank, our options are limited.

- To establish Absolute Energy Scale (up to 10%)
- Co-60 γ-source
- 3 sourcing campaigns
  - HFM 2013 - old HF PMTs
  - HFM/P 2014 - new PMTs
- Every Tower is sourced separately (7-8 mins per tube) $\rightarrow 24 \times 36 \times 7 \rightarrow$ 4days per mode
- Asynchronous data-taking mode (w.r.t. the source)
- 2 data-taking modes
  - 1TS with OV1
  - 2TS with OV2



HF Wedges




Rear Side
PMT Boxes
couple here

Problem statement

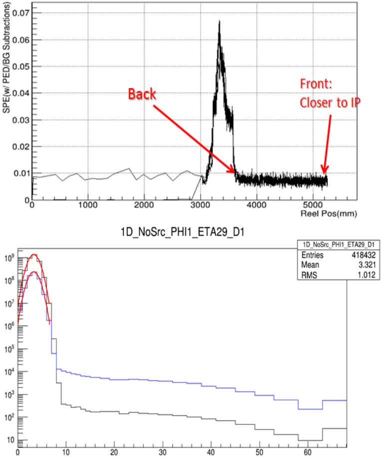
- During Long Shutdown of LHC, new PhotoMultiplier Tubes have been installed on HF.
- General: Transfer the Hadron Forward Energy Calibration used in Run I to be used with new Hardware in Run II.
- Step 1: Extract HF Energy Deposition from the Source using Run I calibration and old PMTs.
- Step 2: Derive the Calibration Coefficients for Run II. Provide Systematics Evaluation. Apply Corrections.

General Description of the Analysis

- Both steps 1&2 proceed in parallel at first - processing all of the data: various modes and voltages.
- Signal Reconstruction - obtain amount of charge collected from the source
- Resolve Issues during the actual sourcing: Channel or Tube swaps, ...
- For step 1: obtain the energy deposition of the source
- For step 2: Use step1 results to compute the calibration coefficient.
- Evaluate the systematics
- Apply correction for the Magnetic Field.

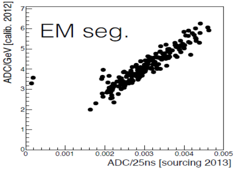
Signal Reconstruction

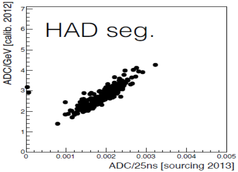
- Signal is reconstructed within $[Back + 300mm; Front - 300mm]$
- Add up all the RAW Charge Histograms
    - For Signal - channels in a tower that contains the source
    - For Background - channels outside of the tower being sourced. Geometric Isolation is applied
- Compute the Charge (Source Signal) for every channel
- Correct the charge by the geometry containment factor



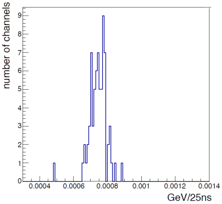
Signal Reconstruction

- The Source Signal (Charge) has been computed
- Extract the Run I Calibration Coefficients
  - Outlier channels have been excluded from further analysis
  - Only channels for $i\eta < 35$ considered (to minimize the raddam effects for higher $i\eta$ towers)
- Energy Deposition is computed separately for H and EM channels.

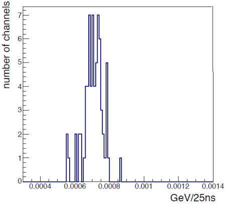




EM



HAD



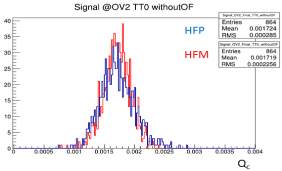
$$\langle E\rangle_c = \langle Q\rangle_c^{Geom} \times CC_c^{Run\ I}$$

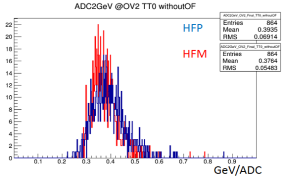
Signal Reconstruction

$$\langle Q\rangle_c^{Geom,OV2} = \frac{\langle Q\rangle_c^{Geom}}{nTS} \times \frac{GAIN^{OV2}}{GAIN^{OV1,OV1+100}}$$

$$CC_c^{RunII} = \tau \times \frac{\langle E\rangle^{2013}}{\langle Q\rangle_c^{Geom,OV2}}$$

- The Source Signal (Charge) has been computed
- Signal is then further tweaked by applying PMT gain ratios and integration window correction.
- Finally Calibration Coefficient is computed.
  - Correct for the source radioactivity drop between sourcing campaigns.





Issues observed during Sourcing

Remark

During the Sourcing Campaigns, a few problems were observed, which, on one hand, made the process more complicated, on the other, it showed the extreme usefullness of the sourcing as the baseline detector validation after reassembly.

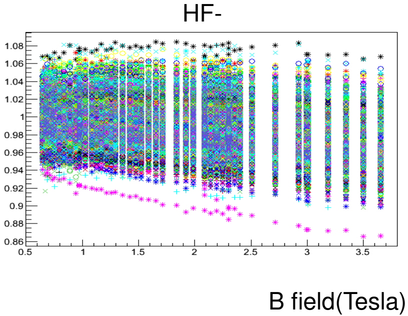
- Channel Swaps - Cables on the QIE side were not connected as expected.
  - No other data-taking mode is able to resolve this problem!
- Source Tube Swaps.
- Source Driver Error - source didn't penetrate the tube or stopped in between.

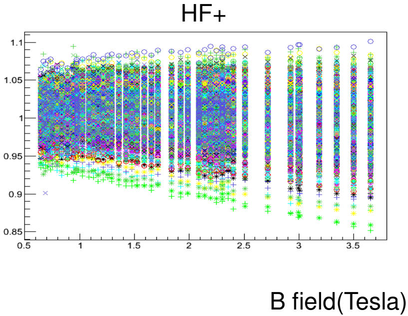
Systematic Uncertainties

- 1TS vs 2TS - since data-taking has been performed for the whole detector using different integration windows we can estimate the difference
- Transversal Uniformity Tubes A&B - certain towers have 2 source tubes, therefore they were sourced twice and the difference can be estimated.
- Overflow - can estimate the lower bound only, but number of events in the tail is $< 1\%$ w.r.t. total
- Longitudinal Uniformity - can use parts of the source path within the tower to estimate the difference in the signal along the path.
- Results have been cross-checked via 2 completely analyses.

Remark

During the commissioning period, before proton-proton collisions, dependency of the PMT response on the magnetic field was evaluated. Calibration Coefficients are then further corrected.





Conclusions

- A brief description of the Calibration Procedure and Results have been provided
- Details on the study of systematics have been omitted.
- This project has been fully completed.

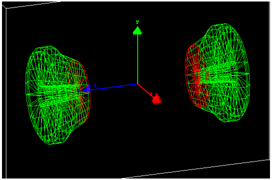
Remark

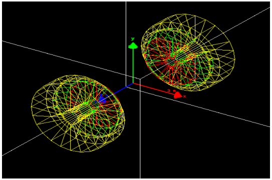
Calibration Coefficients derived in this project have been successfully used during Run II data-taking campaign!

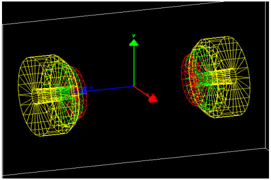
Outline

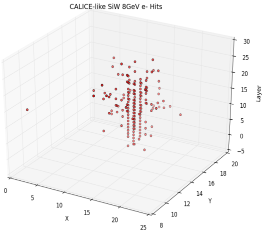
1. Search for Standard Model Higgs Boson decaying to 2 muons with CMS
2. Calibration of CMS Hadron Forward Calorimeter
3. Simulations of Modern Calorimeter Systems

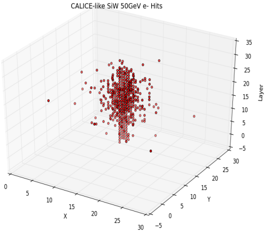
Geant4 based Systems

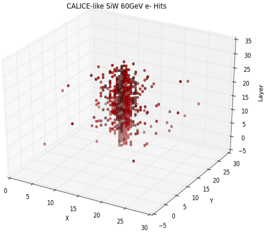








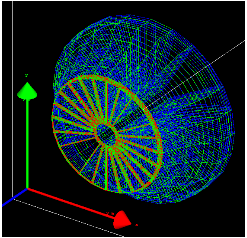




Geant4 based Systems

- Experimental High Energy Physics *revolves* around detecting particles, measuring deposited energy, identifying position, . . .
- Geant4 is the HEP library that provides such functionality:
  - Build and Visualize the Geometry of the System.
  - Define the properties of various materials
  - Specify the Physics of interest or invent your own.
  - Provides an engine to carry out the actual simulation of the experiment.
  - Allows one to define special regions (Sensitive Detectors) mapped to geometry and responsible for readout.
- Geant4 provides means to create “The Matrix” for Experimental HEP

Full scale custom built CMS Phase 2 Upgrade Endcap.



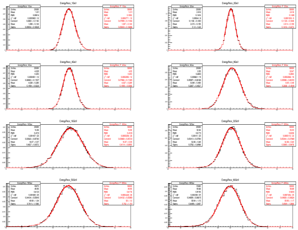
Problem Statement

- Simulate small size `Shashlik`. Calibrate and establish energy resolution properties
- Simulate small size `Hadron Endcap`. Calibrate and establish energy resolution properties.
- Simulate small size `CALICE-like SiW or High Granularity Calorimeter like system`. Calibrate and establish energy resolution properties for both: EM and Hadronic parts.
- Scale up both `Shashlik+HE and CALICE-like systems` to the proposed CMS Phase 2 dimensions and estimate the "Particle Gun" reconstruction efficiency.

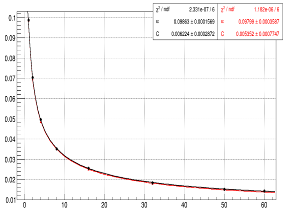
Shashlik

- $25 - 30X_0$ Electromagnetic Calorimeter with no Longitudinal Segmentation
- Alternating layers of W (tungsten) and LYSO plastic scintillator.
- Try both: Geant4 Scintillation mechanism and parametrized scintillation response.
- No simulation of photodetectors.
- Use e^- beam with 8 different energies.

Reconstructed Energy

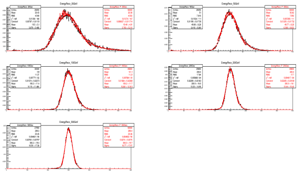


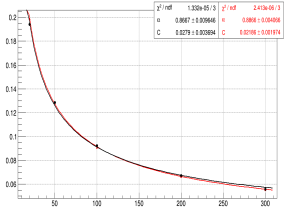
Energy Resolution



Hadron Endcap

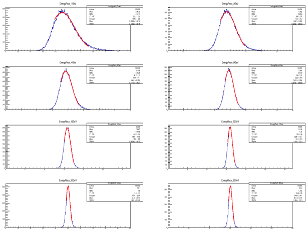
- approx. 10λ Hadronic Calorimeter
- Alternating layers of Brass and SCSN-81 plastic scintillator
- Both G4Scintillation and parametrized scintillation response simulated.
- No simulation of photodetectors
- Use π^- beam with 5 different energies.
- Results are consistent with `CMS NOTE 2008/010`

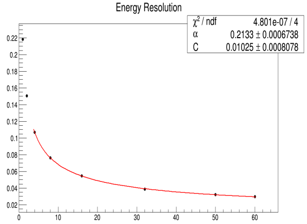




CALICE-like SiW/CMS High Granularity Calorimeter

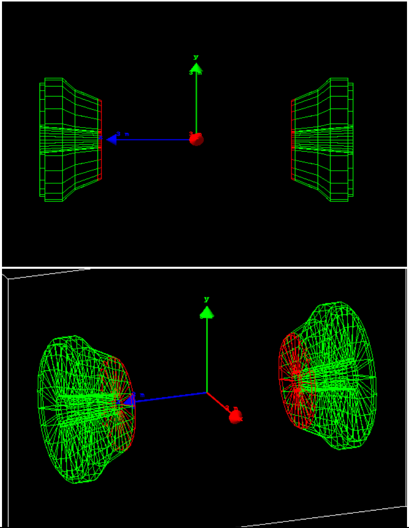
- $24X_0$ Electromagnetic Calorimeter with Longitudinal Segmentation
- Alternating layers of Lead (Pb)/Si/PCB(G10)
  - Tungsten (W) and Lead (Pb) were tried. W is used for CALICE-like and Pb was used for HGC.
  - `PCB` and `G10` are materials of the electronics boards that are "sandwiched in".
- 80e/hole pairs per 1um - a simple assumption on the number of electron-hole pairs generated by the traversing charged track in Si used.



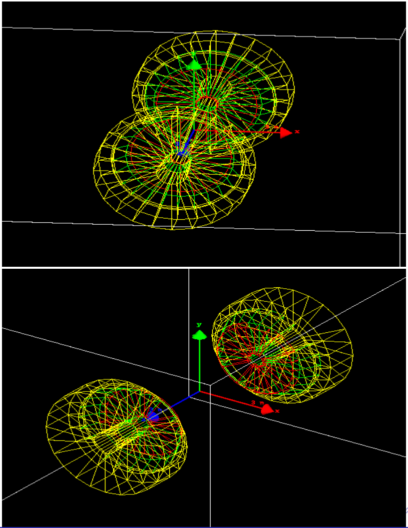


Full Scale CMS Phase 2 Options

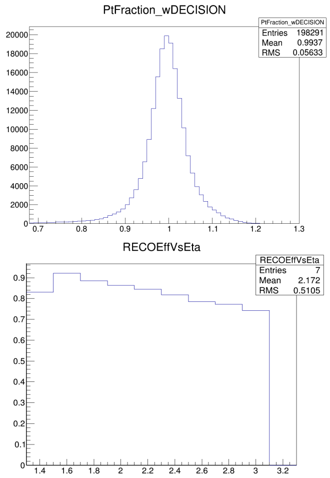
Shashlik



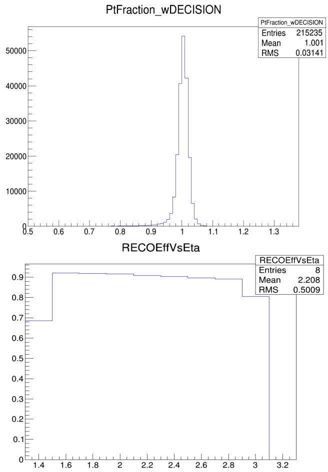
HGC



Full CMS scale Phase 2 with Particle Gun



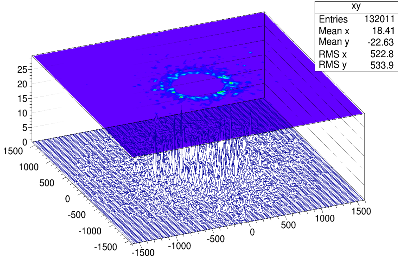
HGC. 3 $\times$ 3 clusterization RECO. Each layer is seeded individually

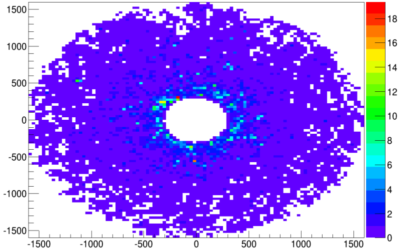


Shashlik/HE. 3 $\times$ 3 clusterization RECO.

Custom built full CMS scale Phase 2 with 140PU

- Added 140 Min Bias events for 1 VBF Higgs (to $\gamma\gamma$)
- Very time and memory consuming
- Event Displays: 3D and XY-plane projection





Summary

- Results for 3 projects have been presented!
- Search for SM-like Higgs Boson in proton-proton Collisions at $\sqrt{s} = 13 TeV$ with CMS Experiment.
- Calibration of Hadron Forward Calorimeter for LHC Run II.
- Modern Calorimeter Systems Simulations with Geant4.