# Higgs to gamma gamma at CMS

## ICHEP 2014 Valencia


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On Behalf of the CMS Collaboration

# Overview

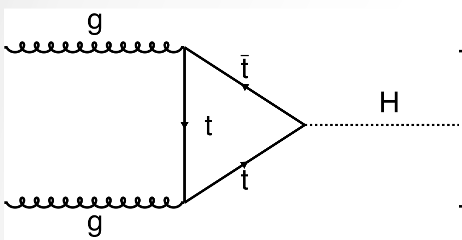
- *NEW* **result** with Full LHC Run1 Dataset (5.1fb$^{-1}$ at 7 TeV + 19.7fb$^{-1}$ at 8 TeV)
  - http://arxiv.org/pdf/1407.0558.pdf
- Analysis strategy is similar to previous preliminary result (Moriond 13) but with many improvements:
  - Final set of calibrations
  - MC now includes time dependent description (better simulation of out-of-time pileup)
  - Analysis chain completely re-optimised
  - Exclusive mode tagging expanded to include *ALL* production modes
  - New method for modelling the background
  - Considerable effort has gone into studying the energy scale uncertainties
    - Systematic uncertainty on the mass reduced by a factor of 3

| **Change** | **Improved energy resolution (new calibration+ new regression)** | **New event selection (re-training + re-categorisation)** | **Background modelling** |
|---|---|---|---|
| Improvement in expected sensitivity over published PAS (Moriond 2013) | ~9% | ~9% | ~7% |

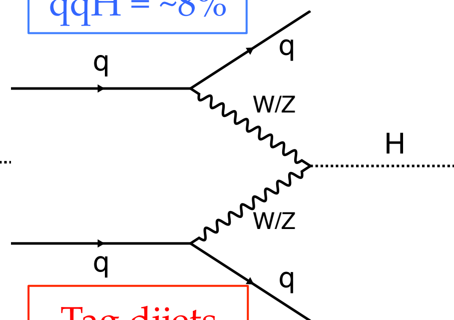
# Introduction

- Small peaking signal on large QCD falling background
  - Signal:

ggH = ~88%

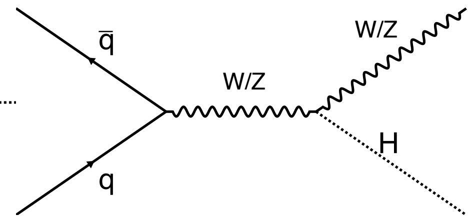



qqH = ~8%



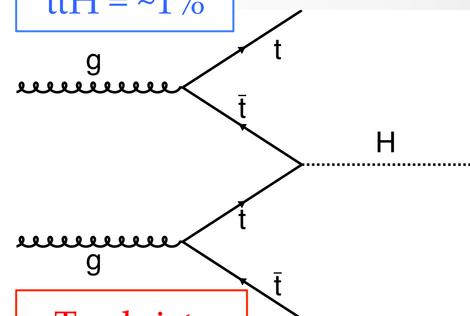

Tag dijets

VH = ~3%




Tag leptons/MET

ttH = ~1%



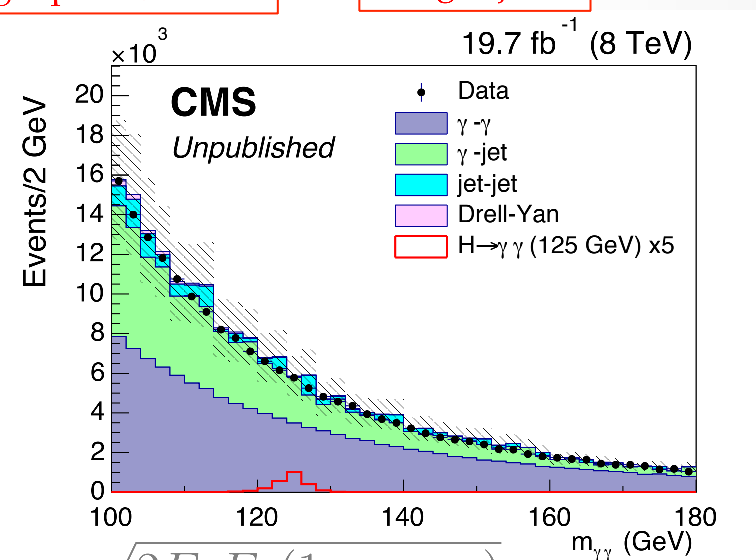

Tag b-jets

  - Background:

γγ = ~70%

γ+jet = ~30%

jet-jet = <1%

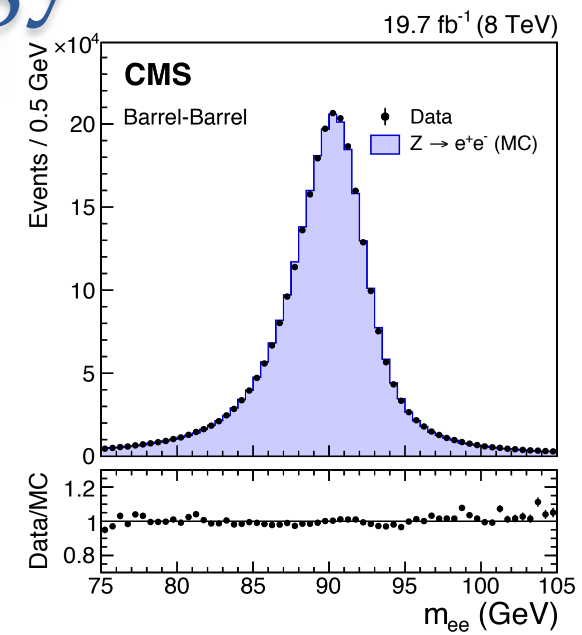



- Low BR ~0.2%
  - With 5.1fb$^{-1}$ at 7 TeV, 19.7fb$^{-1}$ at 8 TeV
  - For SM Higgs at $m_H$=125 GeV
  - CMS can expect around ½ million Higgs'
  - Of which ~1000 decay into two photons ($\alpha\varepsilon$=0.5)
- Clean final state
- Can reconstruct mass with good precision: $m_{\gamma\gamma} = \sqrt{2E_1E_2(1-cos\alpha)}$

# Analysis Strategy

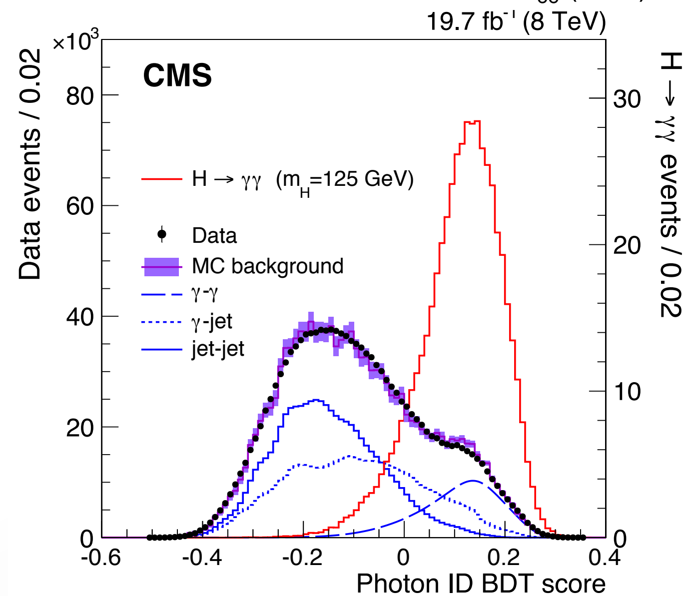


1. Photon Energy
   - Build superclusters from energy deposits in the ECAL
     - Algorithms are identical for electrons and photons
     - Use $Z \rightarrow e^+e^-$ to compute efficiencies and correct **scale and resolution** of photon energies
   - Use multivariate likelihood regression to correct photon energy
     - Also provides per photon energy resolution estimate




2. Vertex Location
   - Use BDT to select vertex and estimate, per-event, the correct vertex probability
     - Correct vertex assignment ~80% (for <PU>=20)

3. Photon Identification
   - Use a BDT to reject photon fakes (mainly $\pi^0$)
   - Uses shower shape and isolation variables to discriminate
   - Provides estimate of the per-photon quality



# Analysis Strategy II

Analysis Strategy
Event Tag Summary
Background Model
Systematics
Results
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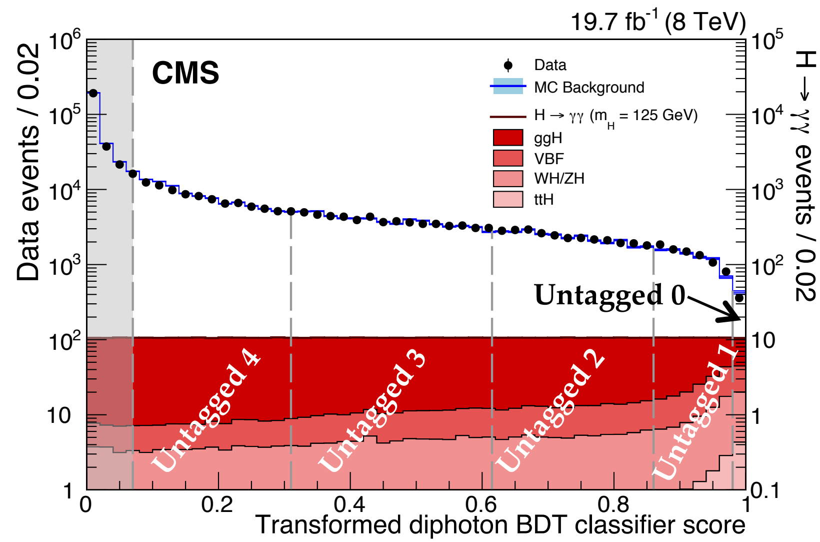
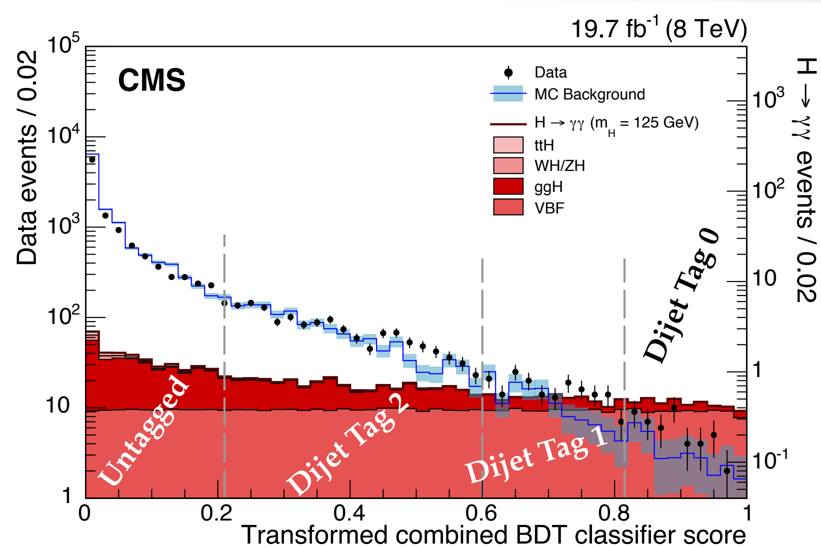
4. Diphoton BDT
   - Collapse all event information into one discriminating variable
     - Kinematics, resolution, photon quality
   - Use output to define a lower cut and a set of analysis categories
     - Cut and category boundaries are optimized for maximum sensitivity

5. Dijet BDT
   - Use dijet variables to pick out VBF-like topology
   - Use output to define a set of dijet categories
     - Optimized for VBF signal strength alone

6. Exclusive mode tags
   - Event topologies consistent with WH/ZH production
     - leptons, MET and jets consistent with W or Z
   - Event topologies consistent with ttH production
     - b-jets, leptons and MET consistent with tt pairs)

- In total there are 25 analysis categories (11 in 2011, 14 in 2012)



# Category Population

- Signal model is sum of Gaussians (as previously).
  - $\sigma_m$ in best categories = 1 GeV
- Background model on next slide

Acceptance × efficiency:
- Approx. 50%
- Same at 7 and 8 TeV

Analysis Strategy

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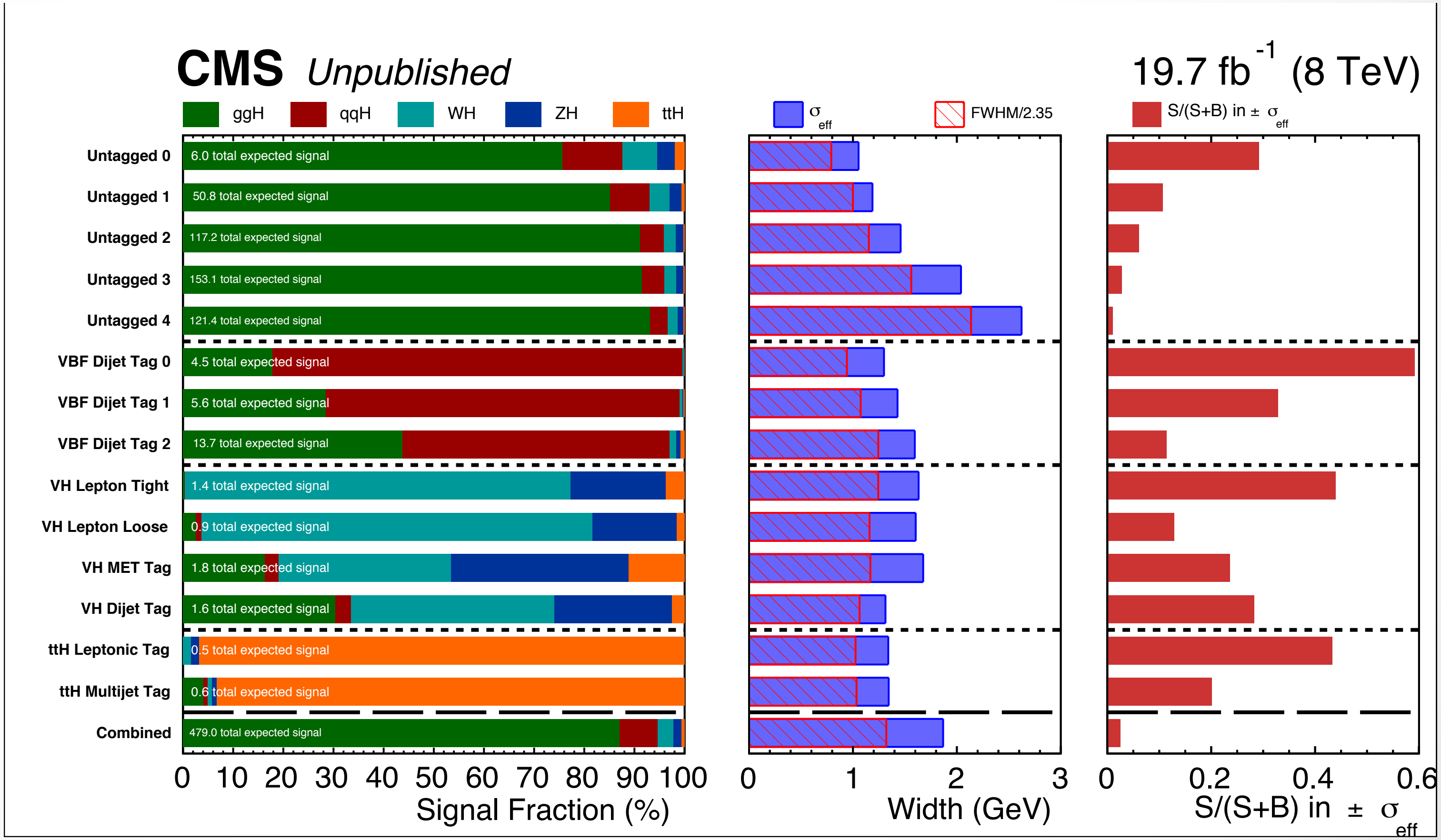


# Background model

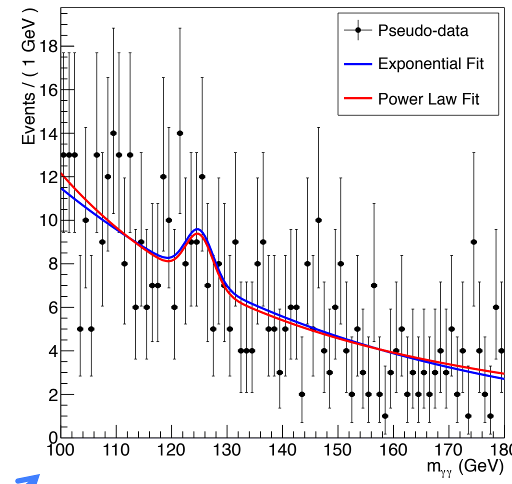
**PLOTS ARE DEMONSTRATIVE ONLY**

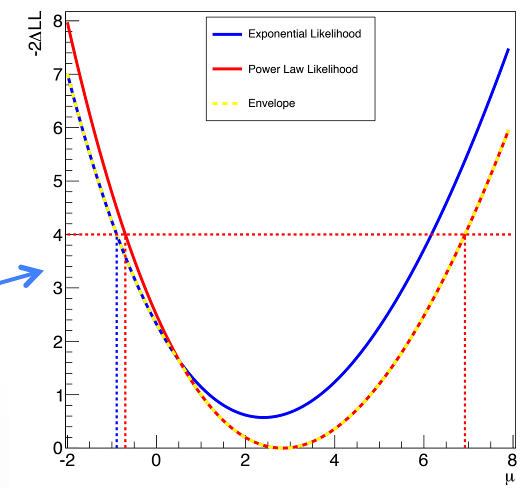
Analysis Strategy → Event Tag Summary → **Background Model** → Systematics → Results → Compatibility → Properties

- Employ a new strategy for modelling the background
- Background shape is *a priori* unknown
- The concept is to "profile" over several different function choices (i.e. all are considered in the fit)
- Allow the data to select the one which fits the best
- Subsequent "*envelope*" around NLL curve of different choices means uncertainty will take into account model assumption
- Correct likelihood for functions with different numbers of parameters

**Toy example**

- 1 category, 2 function choices, $e^{-px}$ and $x^{-p}$
- Profile "envelope" gives best fit with $x^{-p}$
- 2 sigma error is enlarged by the envelope
- In principle envelope method will increase uncertainty because of different function choices



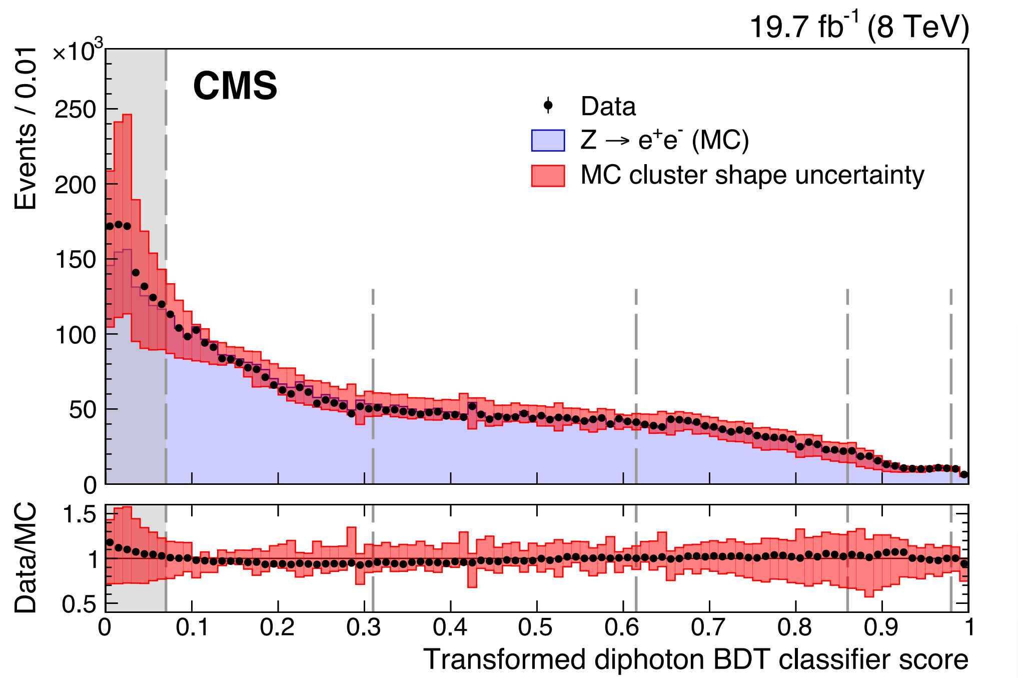



# Systematic Uncertainties

- Analysis Strategy
- Event Tag Summary
- Background Model
- Systematics
- Results
- Compatibility
- Properties

- Those which affect the signal yield

| Uncertainty | Effect |
|---|---|
| Theory | ± 0.11 |
| Energy scale and resolution corrections | ± 0.02 |
| Diphoton BDT mismodeling | ± 0.06 |
| Other experimental | ± 0.04 |



# Systematic Uncertainties II



- Those which affect the mass

**Mass scale**

**Object**

1.
$m_Z$ scale
**electrons**
Per photon scale and resolution correction uncertainties
(± 0.05 GeV)

Use boosted Zs

2.
$m_H$ scale
**electrons**
Non-linearity uncertainty
(± 0.10 GeV)

Use MC

3.
$m_H$ scale
**photons**
Electron – photon differences uncertainty
(± 0.10 GeV)

electrons

photons

# Results

Analysis Strategy

Event Tag Summary

Background Model

Systematics

Results

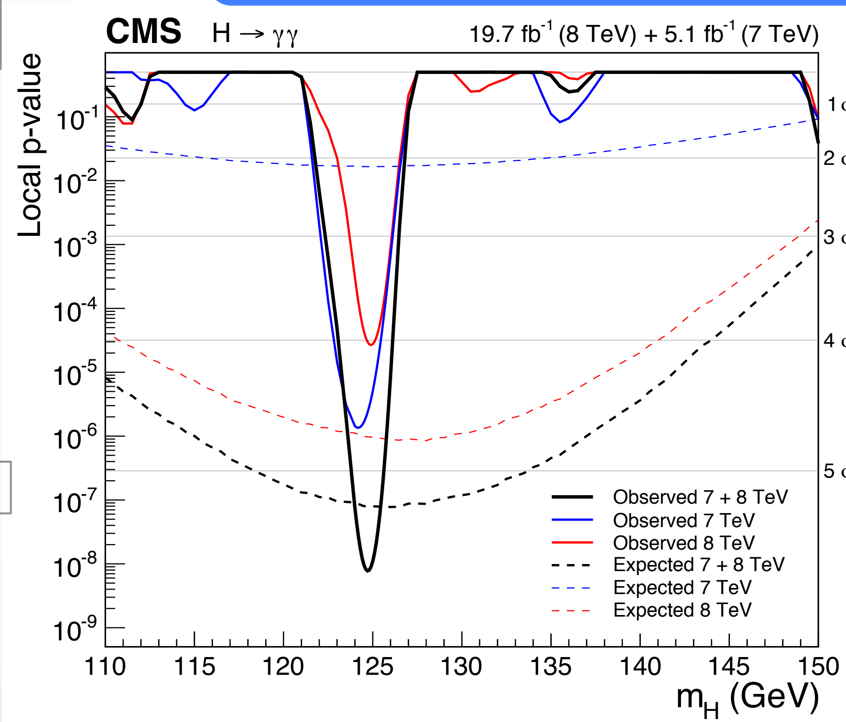
Compatibility

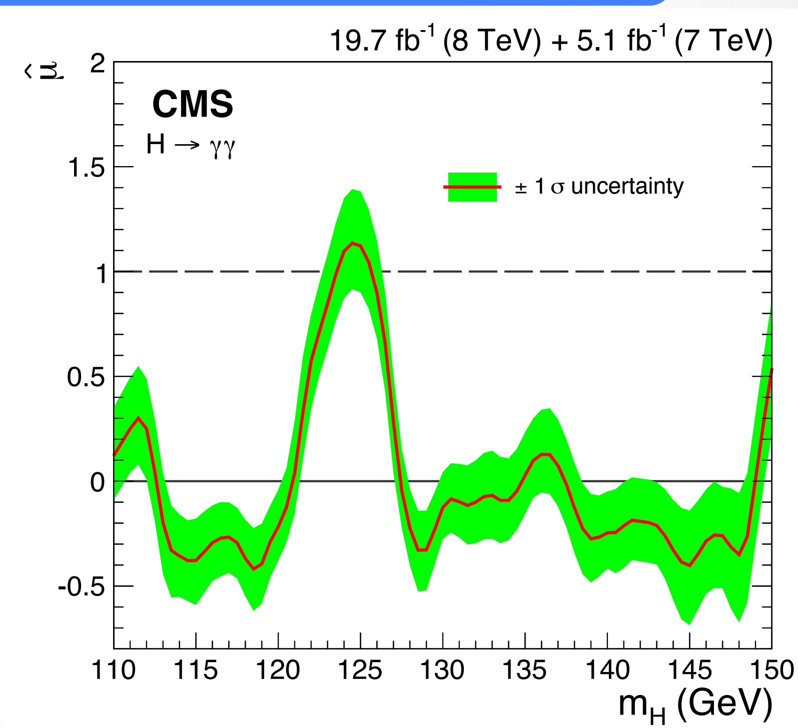
Properties

**Signal Strength:**

| Dataset | Significance (obs) | $\sigma/\sigma_{SM}$ | $m_H$ (GeV) |
|---|---|---|---|
| 7 TeV | 4.7σ | $2.22^{+0.62}_{-0.55}$ | 124.2 |
| 8 TeV | 4.0σ | $0.90^{+0.26}_{-0.23}$ | 124.9 |
| **7 + 8 TeV** | **5.7σ** | $\mathbf{1.14^{+0.26}_{-0.23}}$ | **124.7** |

$$\sigma/\sigma_{SM} = 1.14^{+0.26}_{-0.23}\left[\,{}^{+0.21}_{-0.21}(\text{stat.})\,{}^{+0.09}_{-0.05}(\text{syst.})\,{}^{+0.13}_{-0.09}(\text{th.})\right]$$



# Results II

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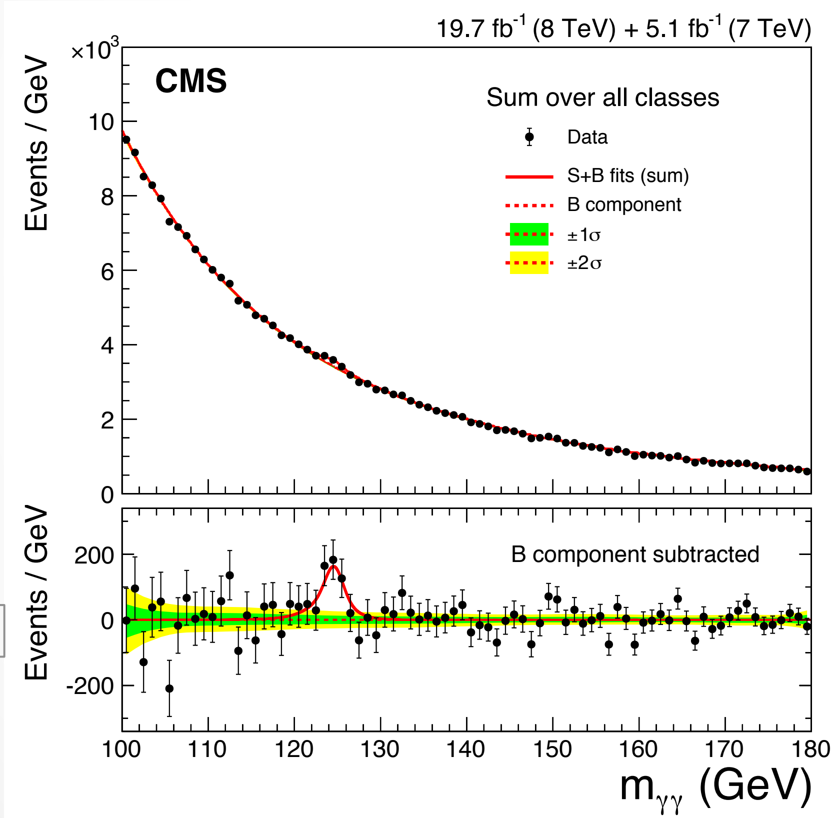
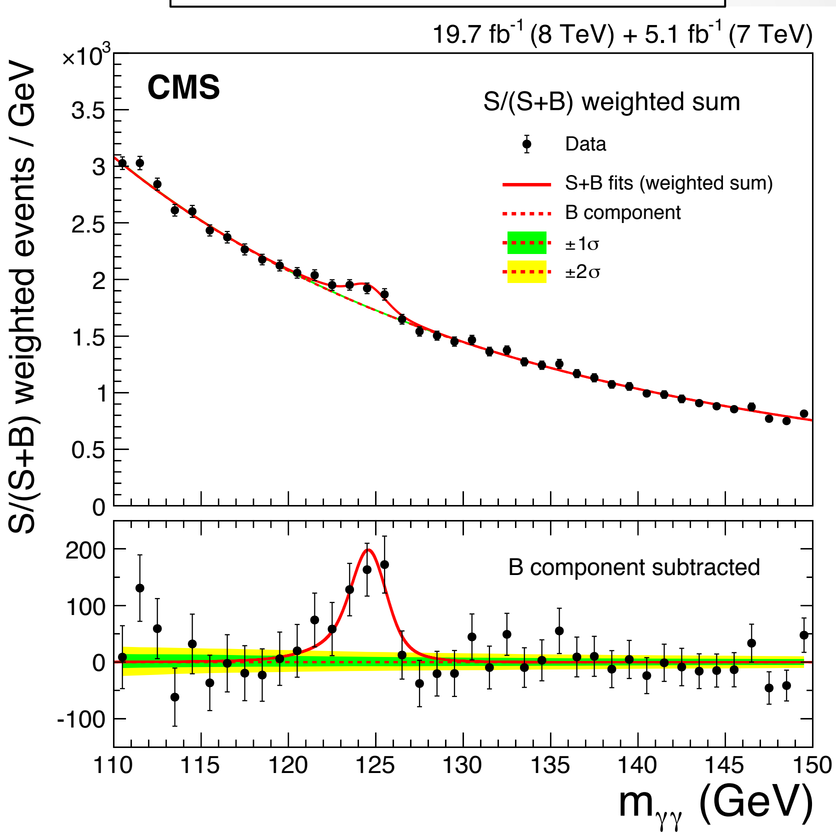
Inclusive sum of all events chosen




Sum weighted by sensitivity

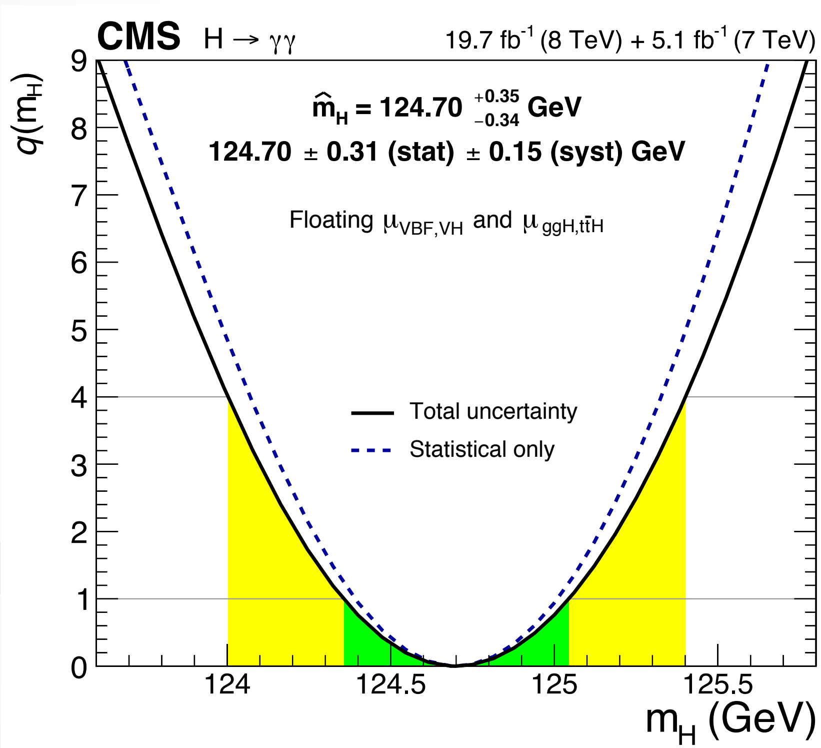


# Results III



## Mass measurement:

- For 1D mass scan relative signal strength to fermions and bosons is floated



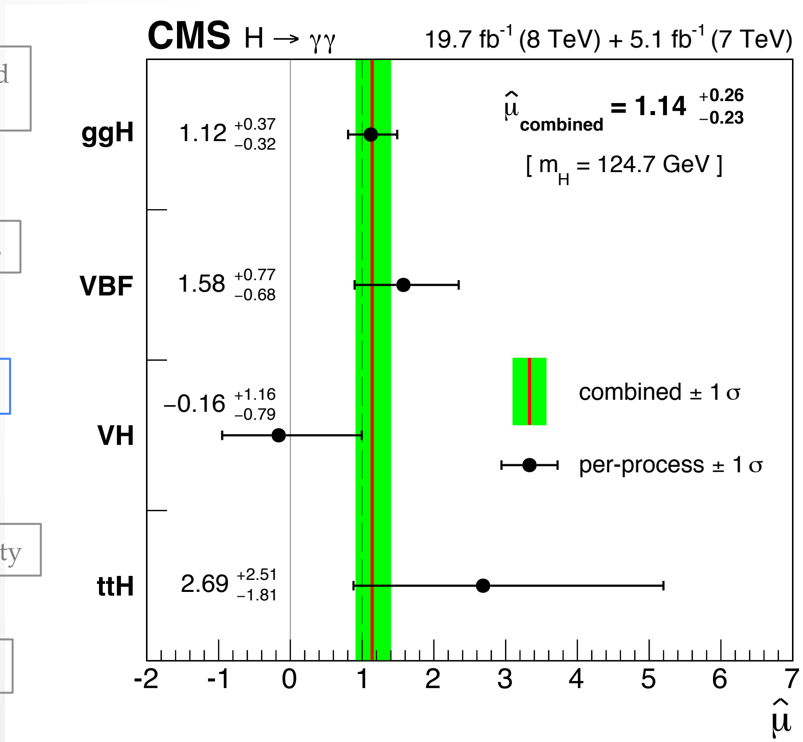

| Uncertainty | Details | Effect (GeV) |
|---|---|---|
| Energy scale calibration and resolution | • Uncertainty on the correction applied<br>• Use ET dependent corrections<br>• Also model stochastic and constant terms in resolution | ± 0.05 |
| Non-linearity in scale extrapolation from $m_Z$ to $m_H$ | • Imperfect modelling in MC of differences between showers from $Z \rightarrow ee$ at $m_Z$ scale and $H \rightarrow \gamma\gamma$ at $m_H$ scale<br>• $E_T$ dependent scale corrections reduce this | ± 0.10 |
| Electron – photon differences not modelled in MC | • Tracker material mis-modelling (inflate tracker material)<br>• Variation in scintillation light peak between electrons and photons<br>• Imperfect EM shower simulation in Geant4<br>• Imperfections in OOT-PU description | ± 0.10 |
| Other | | ± 0.04 |

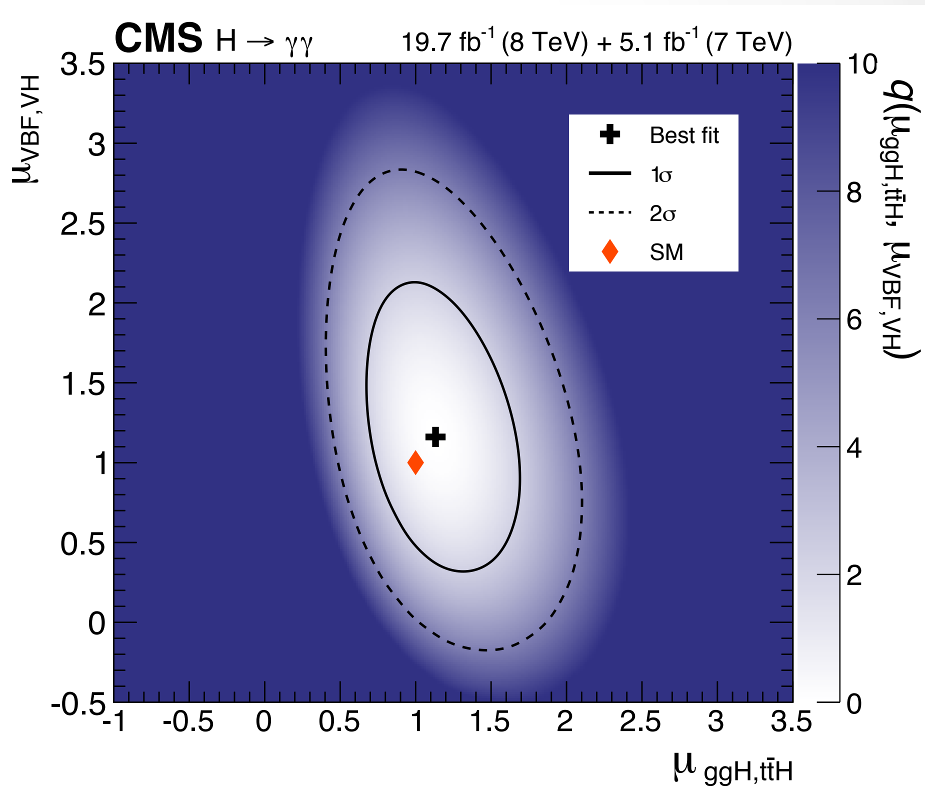
# Results IV



Signal strength by production type:

$$\mu_{ggH+ttH} = 1.13^{+0.37}_{-0.32}$$
$$\mu_{qqH+VH} = 1.16^{+0.58}_{-0.60}$$



# Compatibility

Analysis Strategy
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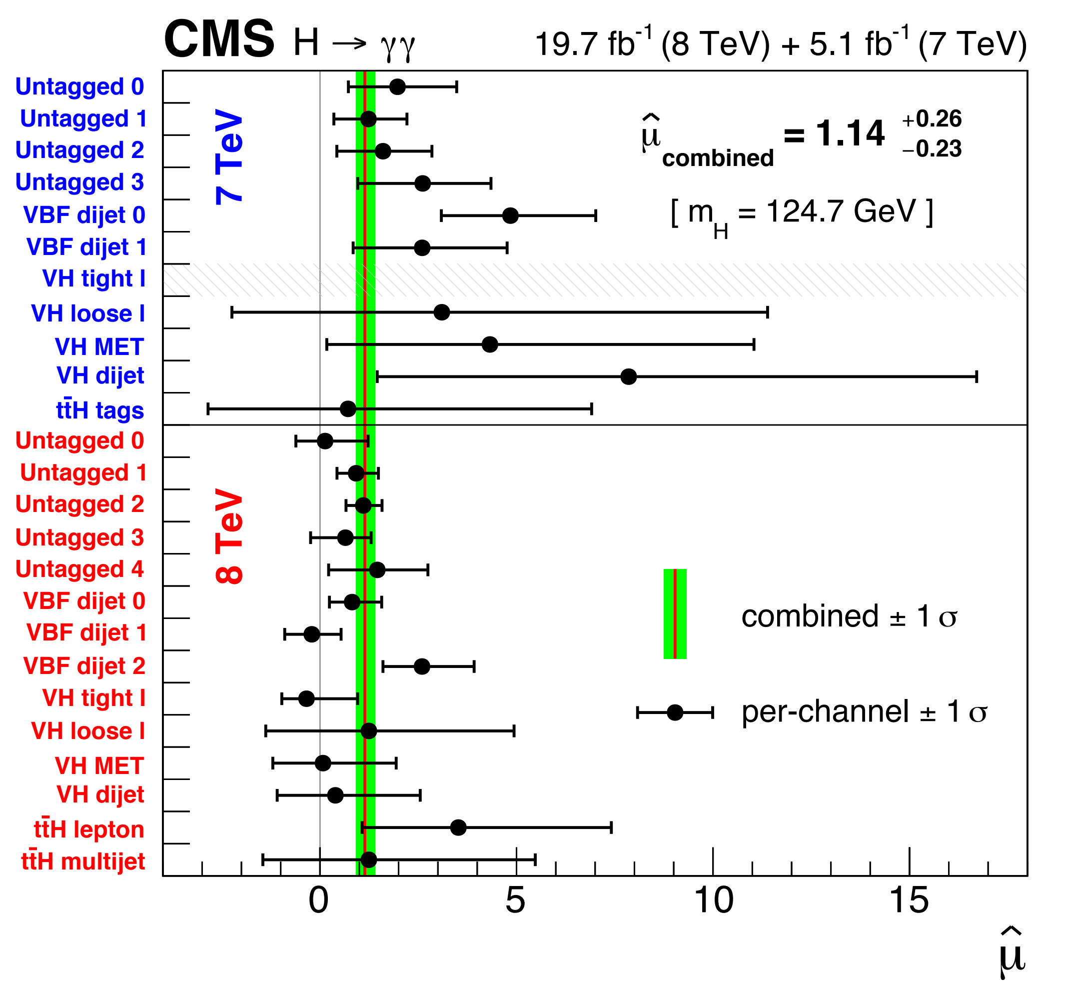
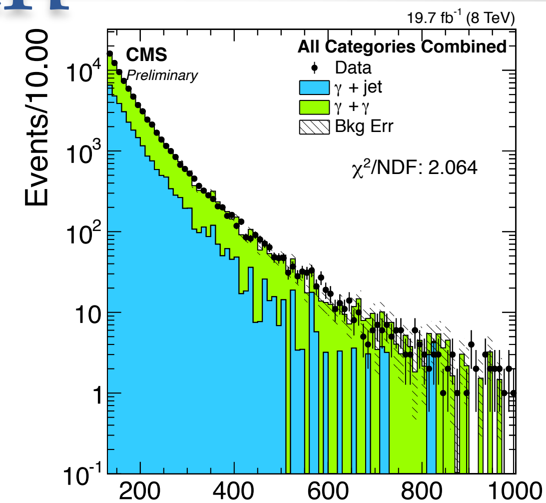
- 3 alternative analyses:
  - Check validity of MVA selection, categorisation, background model and VBF selection
  - All compatible at < 1σ level
- Compatibility with preliminary result
  - using jackknife techniques to estimate correlations <2σ
- Compatibility between 7 TeV and 8 TeV datasets
  - at the level of 2σ
- Compatibility across categories shown on right

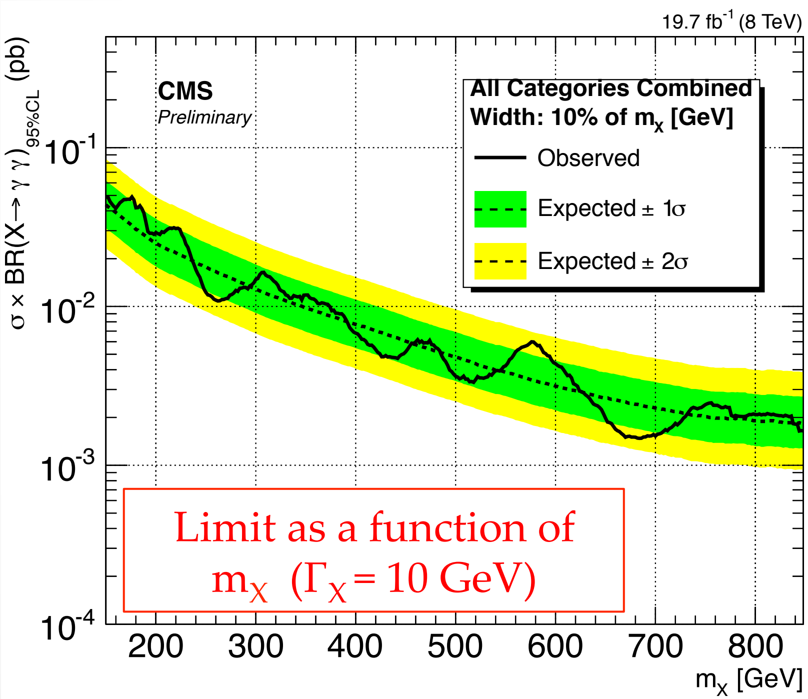


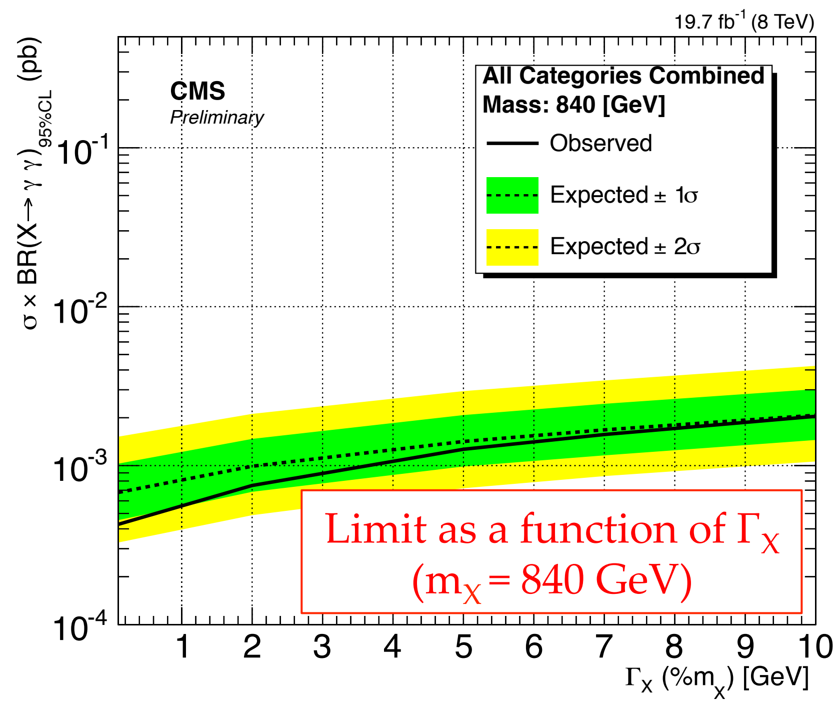
# High mass search

Analysis Strategy → Event Tag Summary → Background Model → Systematics → Results → Compatibility → Properties

- https://cds.cern.ch/record/1714076?ln=en
- Simplified cut-based selection
- Signal model is double Crystal-Ball convoluted with Breit-Wigner
  - Such that the signal width and mean scale appropriately with $m_H$
- Limits on $\sigma_{xs}$•BR produced as a function of $m_X$ and $\Gamma_X$



# Summary

- Reported CMS analysis in search for SM $H \rightarrow \gamma\gamma$
  - Data consists of $5.1 fb^{-1}$ at 7 TeV and $19.7 fb^{-1}$ at 8 TeV
  - Split events into categories to increase overall sensitivity AND sensitivity to specific couplings
- Best fit signal strength:

$$\sigma/\sigma_{SM} = 1.14^{+0.26}_{-0.23} \left[ {}^{+0.21}_{-0.21}(\mathrm{stat})^{+0.13}_{-0.09}(\mathrm{theory})^{+0.09}_{-0.05}(\mathrm{syst}) \right]$$

- Best fit mass of the observed boson is:

$$m_H = 124.70^{+0.35}_{-0.34} \left[ 0.31\ (\mathrm{stat}) \pm 0.15\ (\mathrm{syst}) \right]\ \mathrm{GeV}$$

- Fermionic and bosonic production signal strengths observed as:

$$\mu_{ggH+ttH} = 1.13^{+0.37}_{-0.32}$$
$$\mu_{qqH+VH} = 1.16^{+0.58}_{-0.60}$$

- Upper limit at 95% CL on the natural width is found at 2.4 GeV

Standalone observation of 5.7σ
Properties seem very consistent with a SM Higgs around 125 GeV

# Back Up

…

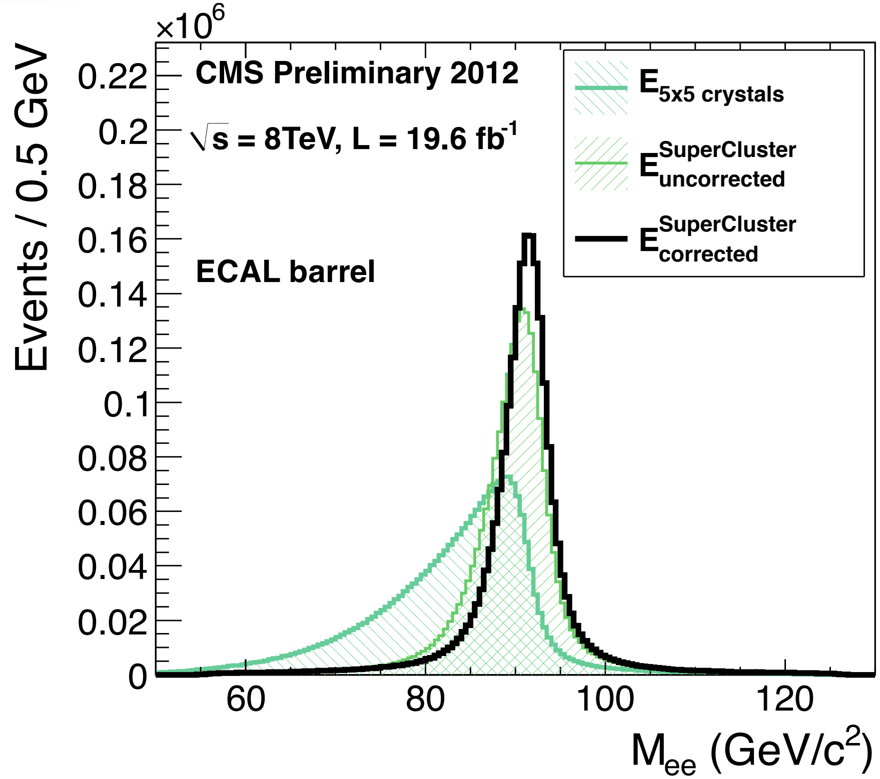
# Back Up (Photon energy)

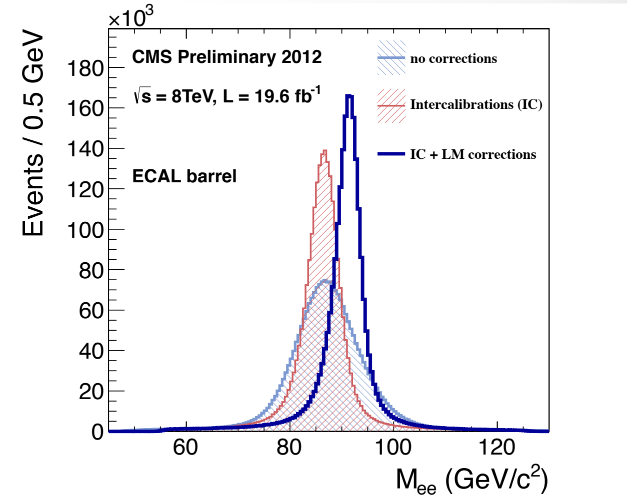
…

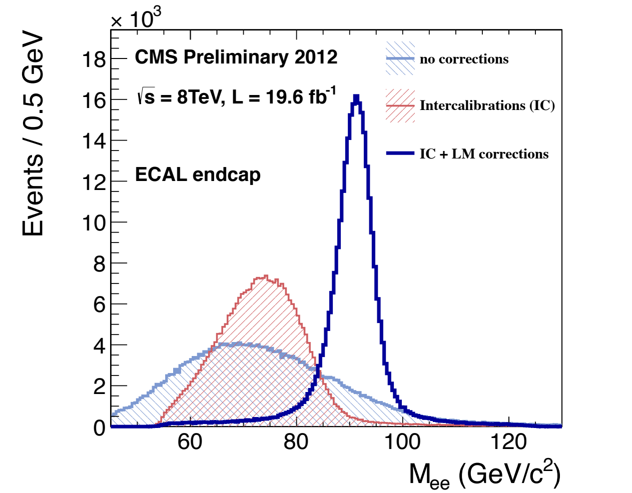
# Channel inter-calibration

Data samples
Photon energy
Photon ID
Vertex ID
Event tagging
Statistical Analysis
Results

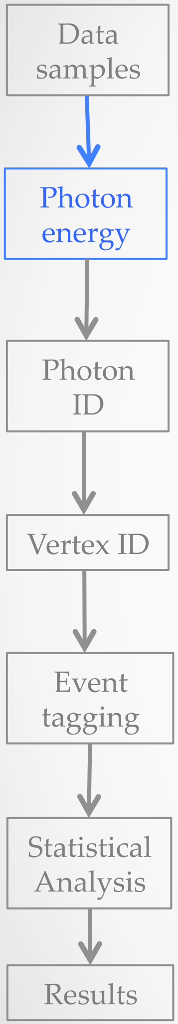
- The uniformity and time stability of the single channel response affects the resolution
- Derive individual corrections *in situ* by equalising the response to diphoton resonaces ($\eta$,$\pi^0$)
  - Cross check using $\phi$ invariance of energy flow
  - And E/p ratio for electrons



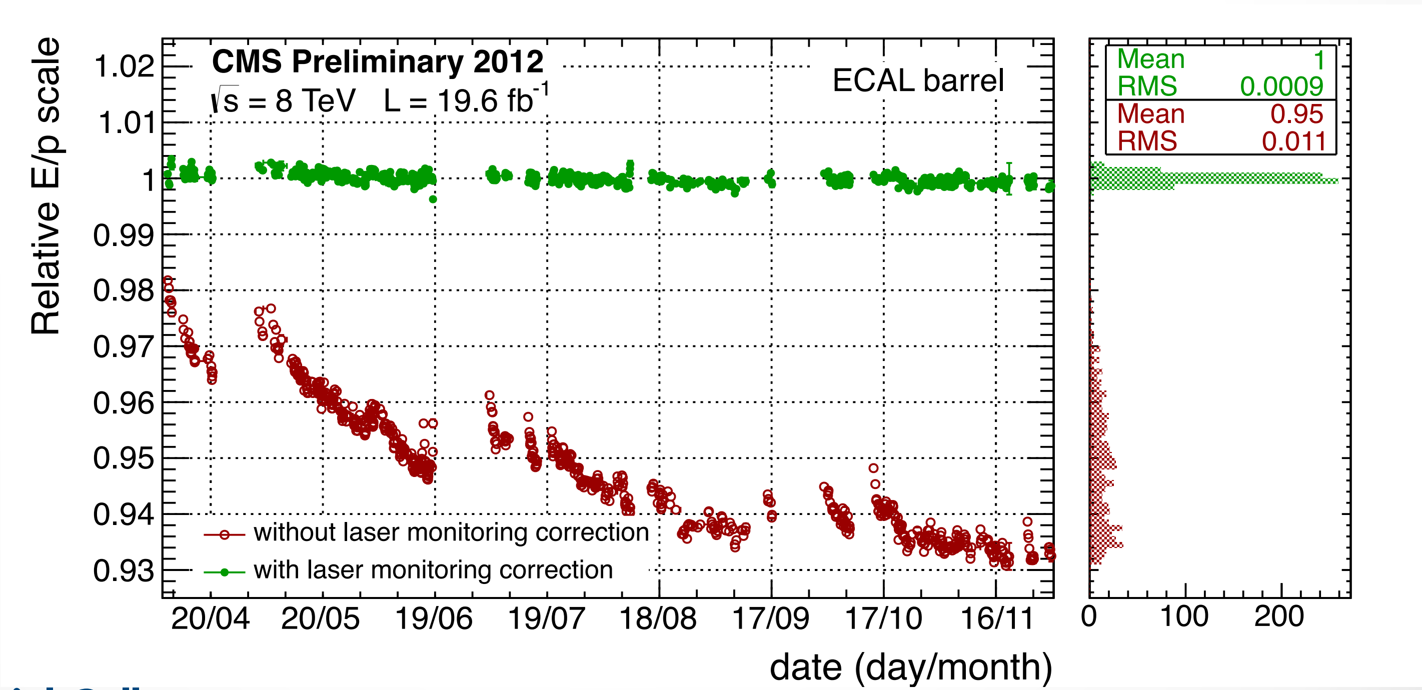



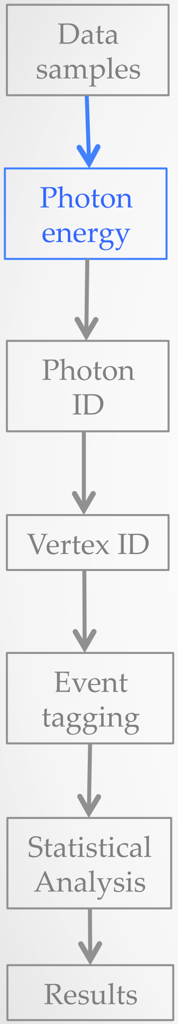
# ECAL Calibrations




- Monitor crystal transparency using blue (and green) laser light
  - Construct time dependent set of corrections to give a flat response over time
- Derive inter channel calibration constants
  - The uniformity of the single channel response affects the resolution
  - Individual corrections by equalising the response to diphoton resonances ($\eta$,$\pi^0$, E/p and $\phi$-symmetry
  - Zee events also used for eta and absolute scale
- Thanks to ECAL DPG for their work in calibration and simulation



# Energy regression

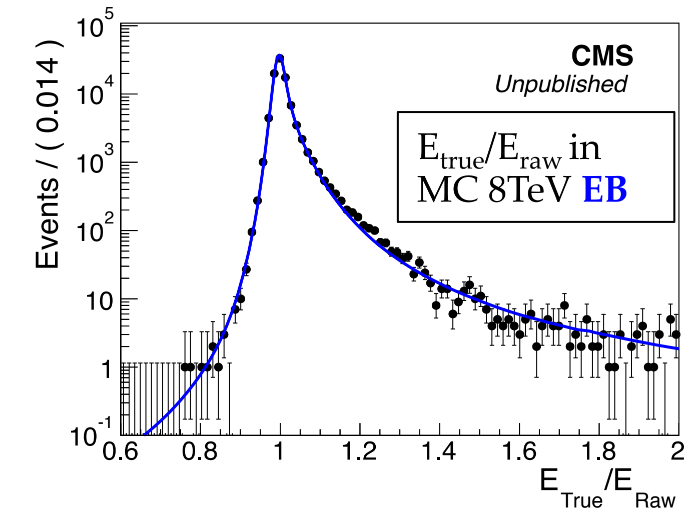



- Use the raw supercluster energy and several other input variables
  - to model shower shape, position etc. (label inputs as $\vec{x}$)
  - Correct for local containment of showers and bremsstrahlung losses etc.
- Now use specialised BDT (not TMVA) to predict full probability distribution for $E_{true}/E_{raw}$
  - Distribution is given by a double CB which has six free params ($\mu$, $\sigma$, $\alpha_L$, $\alpha_R$, $n_L$, $n_R$ )
  - "Regress" the non-parametric dependence of each of these variables on the BDT input variables whilst minimising the likelihood,

$$-\ln\mathcal{L} = -\sum_{MCphotons} \ln p(E_{true}/E_{raw}|\mu(\vec{x}), \sigma(\vec{x}), \alpha_L(\vec{x}), \alpha_R(\vec{x}), n_L(\vec{x}), n_R(\vec{x}))$$

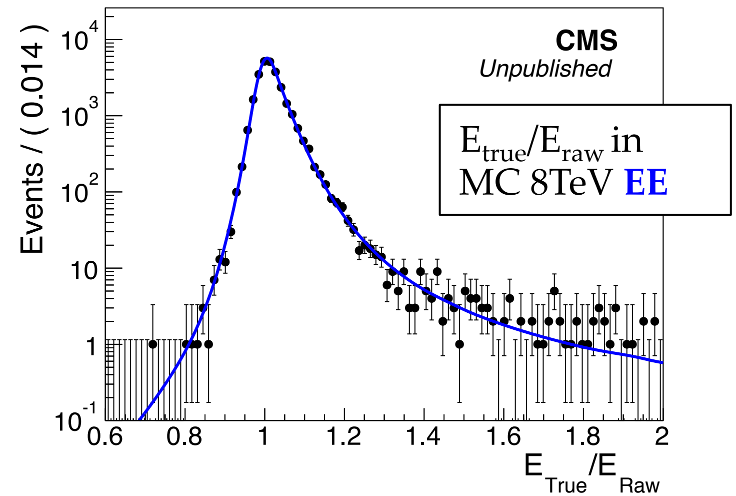
Best estimate for the true energy:

$$E(\vec{x}, E_{raw}) = \mu(\vec{x})E_{raw}$$




Per photon energy resolution:

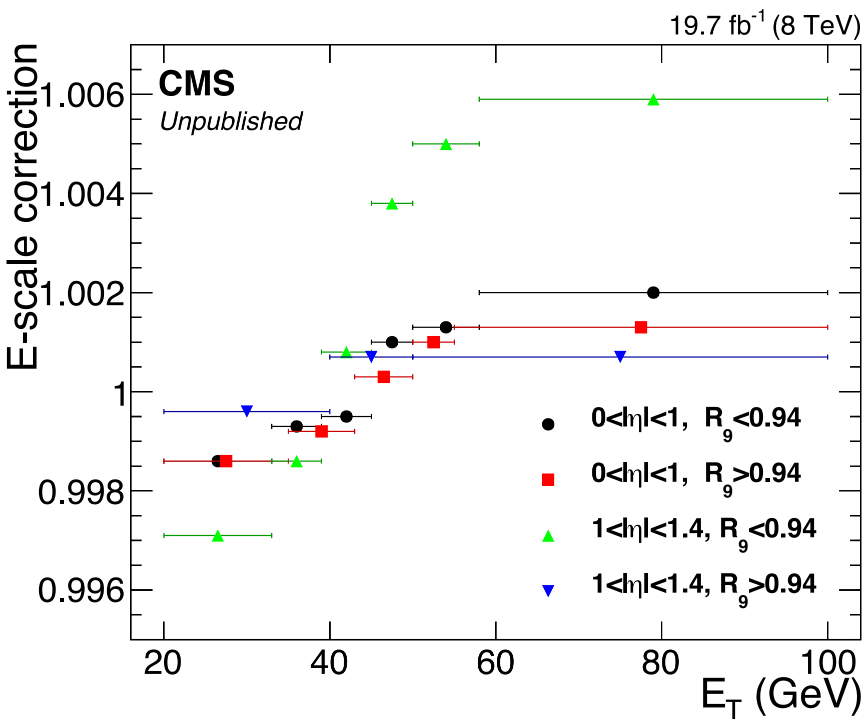
$$\frac{\sigma_E(\vec{x}, E_{raw})}{E(\vec{x}, E_{raw})} = \frac{\sigma(\vec{x})}{\mu(\vec{x})}$$



# Energy scale and smearing

Data samples → **Photon energy** → Photon ID → Vertex ID → Event tagging → Statistical Analysis → Results

- Apply residual scale corrections to the data and subsequent smearings to the MC
- resolve differences between data and MC from Z→ee decay (when electrons are reconstructed as photons)
- Employ a new multistep procedure
  - Split data and MC into 59 run ranges, 4 η bins and 2 $R_9$ bins
  - Fit Z line shape and find scale correction from data→MC in run×|η| bins
  - Simultaneously fit scale with a Gaussian smearing term for MC in |η|×$R_9$
    - In the barrel (for 8 TeV) the smearing term has an energy dependence by parameterisation through: $b/\sqrt{E_T} + c$
  - Then have a further residual scale correction in $E_T$×|η|×$R_9$



Data samples

Photon energy

Photon ID

Vertex ID

Event tagging

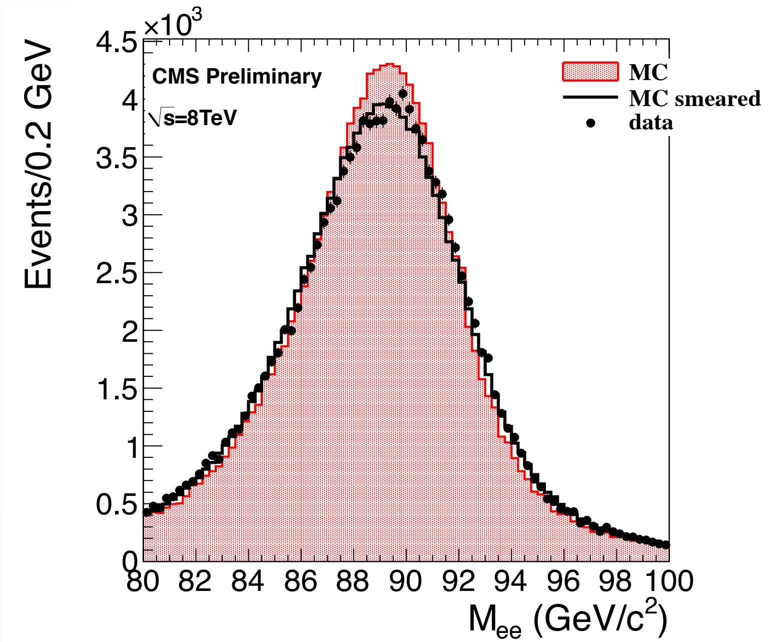
Statistical Analysis

Results

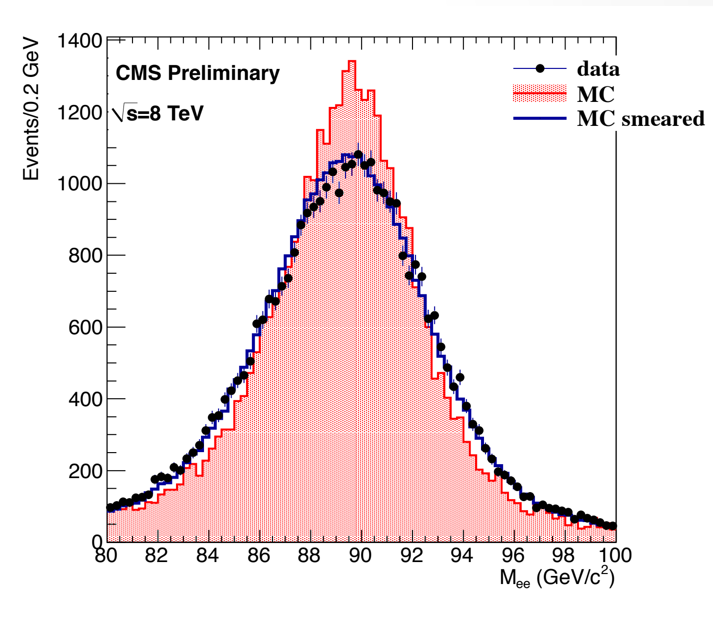
# Energy scale and smearing II

- These corrections all have a corresponding uncertainty which enters the analysis as a systematic uncertainty

Barrel




Endcap



# Back Up (Photon ID)

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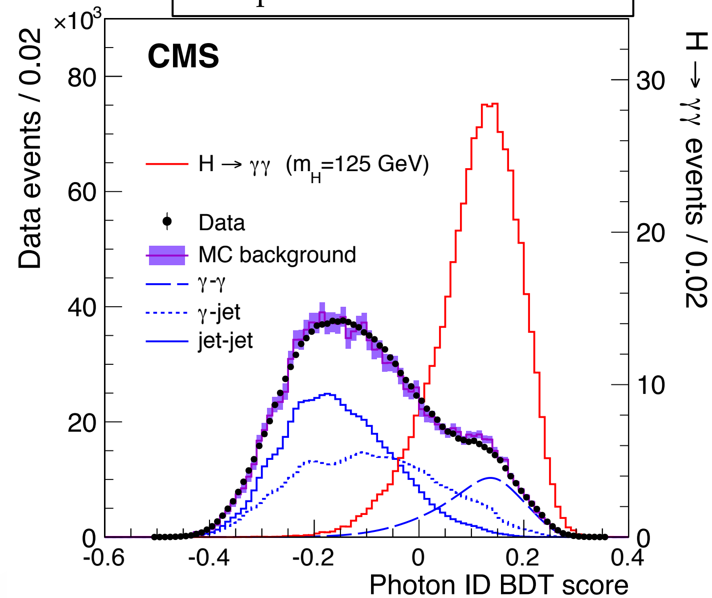
# Photon ID BDT

Data samples → Photon energy → **Photon ID** → Vertex ID → Event tagging → Statistical Analysis → Results

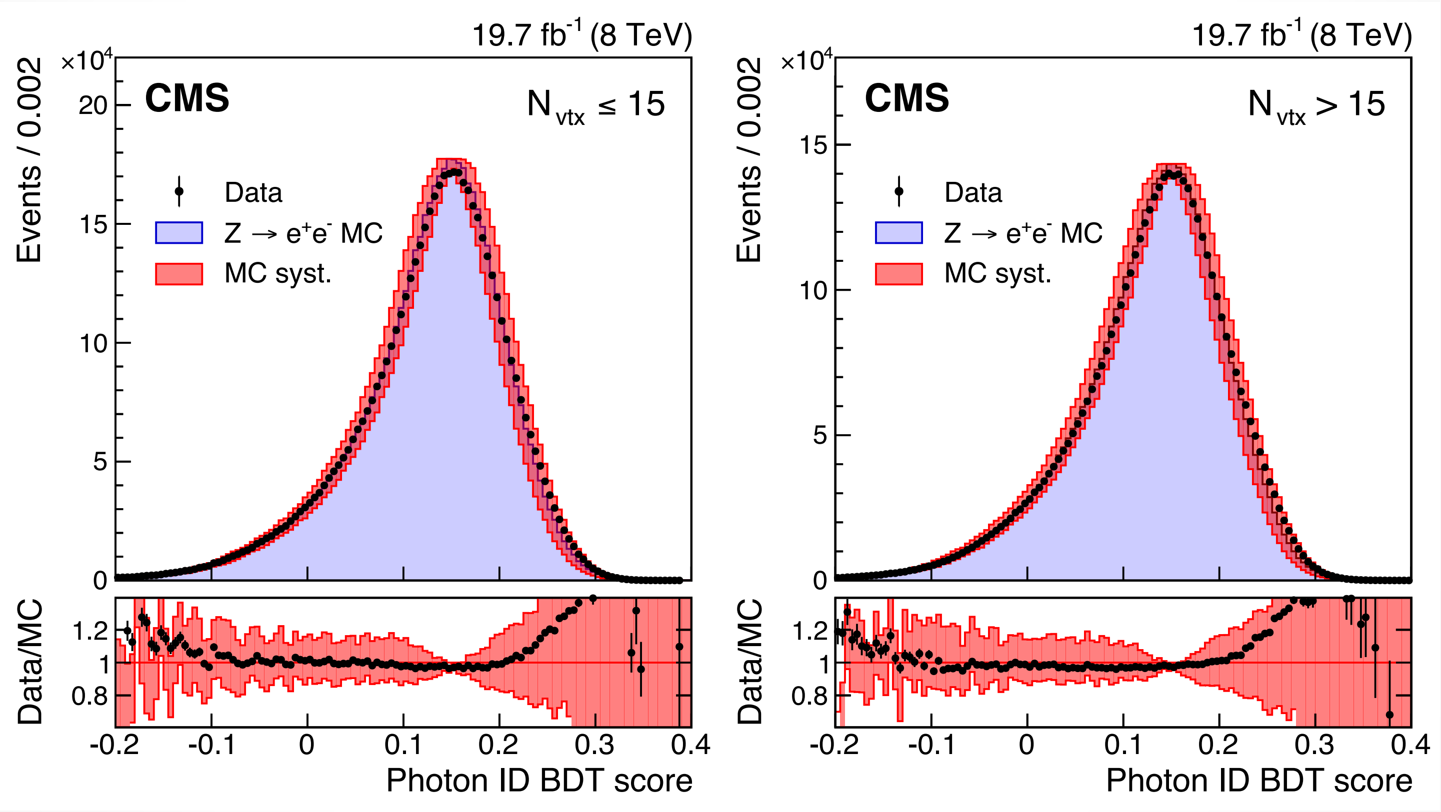
- Use loose pre-selection to pick two photons
- Train identification BDT to reject from *fakes* ($\eta,\pi^0$)
  - shower shape variables
  - isolation sums (based on PF algorithms)
  - $\rho$ (median energy density), $\eta$ and $E_{raw}$
- Remove any $p_T$ dependence
- Use BDT output variable as input to diphoton BDT
- Still can cut out considerable amount of background by defining a loose lower cut (of -0.2) which is 99% signal efficient
- Separate trainings for EB/EE (7/8 TeV)
- Validated with Z→ee and also Z→μμγ
- Systematic uncertainty applied to cover any data/MC discrepancies ±0.01

Data and signal MC passing pre-selection at 8TeV



# Photon ID BDT II

- Photon ID output (including systematic band) for Z→ee events



# Back Up (Vertex ID)

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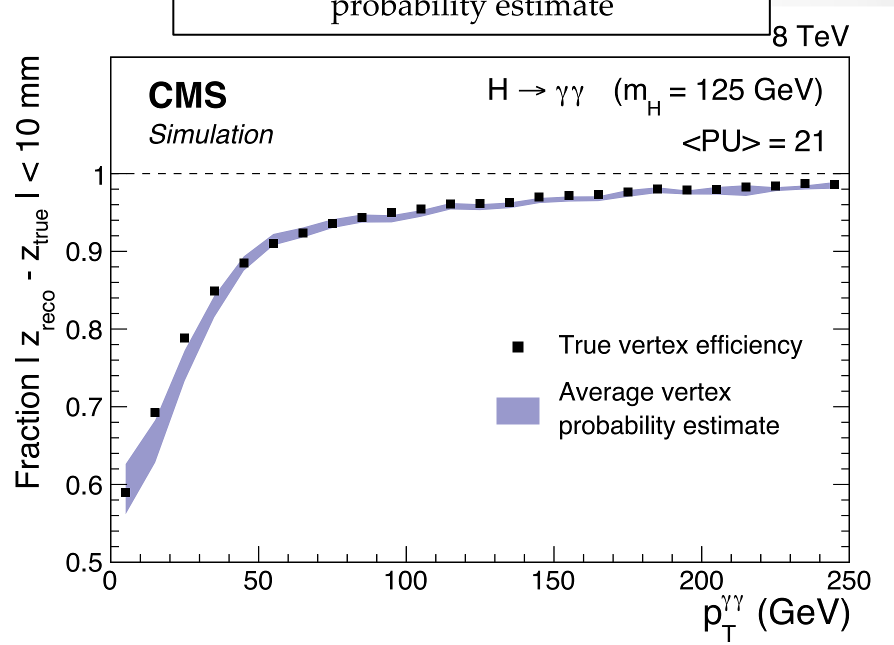
# Vertex ID

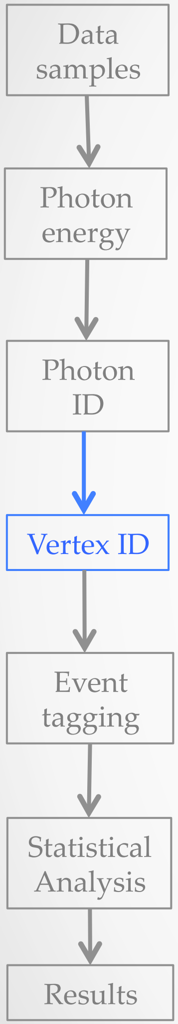


- Resolution on opening angle has negligible effect if selected vertex is within 10mm of true position
- Use a BDT to select vertex.
- Input variables designed to consider:
  - hardness of interactions
  - recoil and asymmetry between the diphoton system and other tracks from the vertex
  - conversion information
- Test performance in Z→μμ events (remove mu tracks and re-reco vertices) and also γ+jet events
- Construct BDT to complement resolution estimate whose output definition will map correct vertex efficiency (probability)
- Exploit this information later when estimating the per event resolution

Hgg MC simulation closure test.
Comparison of true vertex efficiency to probability estimate



# Vertex ID BDT

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  - hardness of interactions
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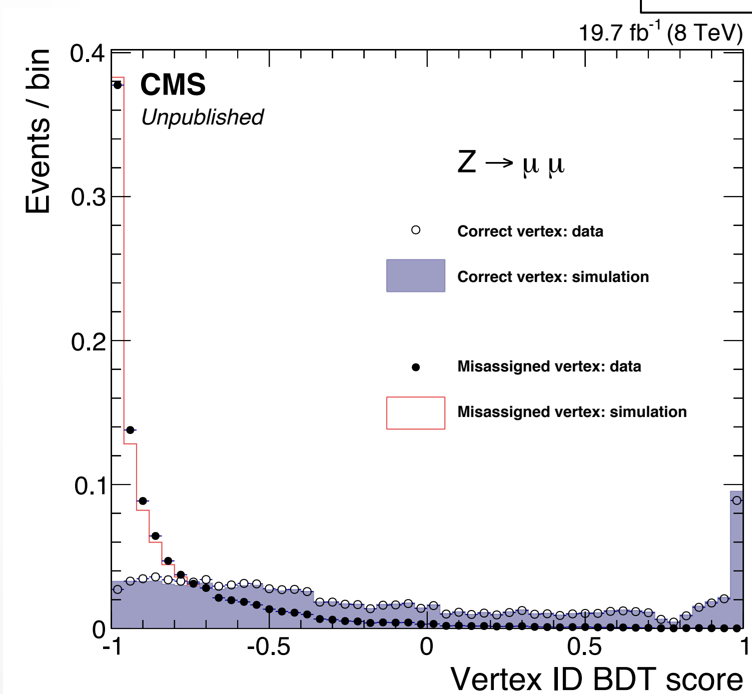
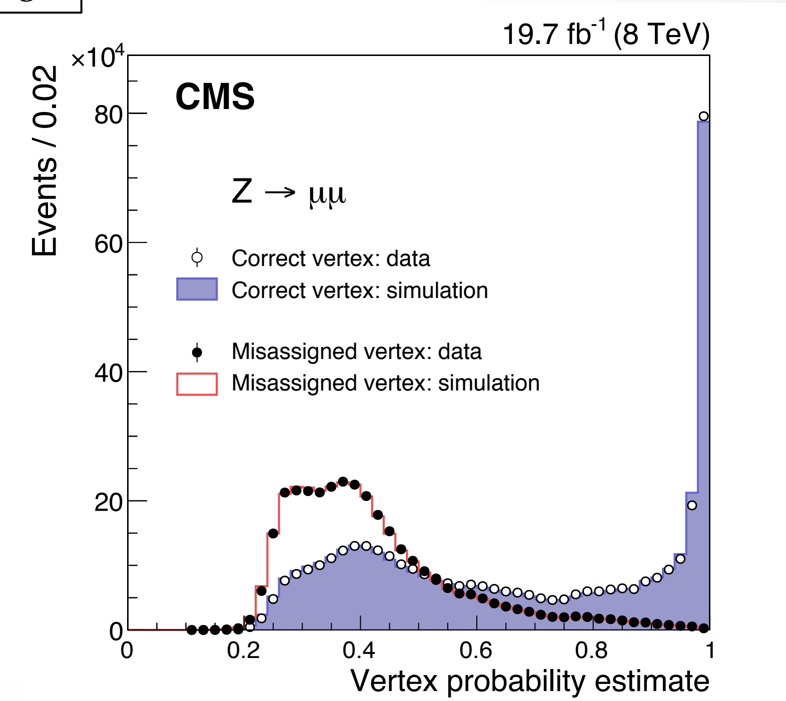
  - conversion information
- Performance in Z→μμ events (remove mu tracks and re-reco vertices)

8TeV training



# Back Up (Diphoton BDT)

…

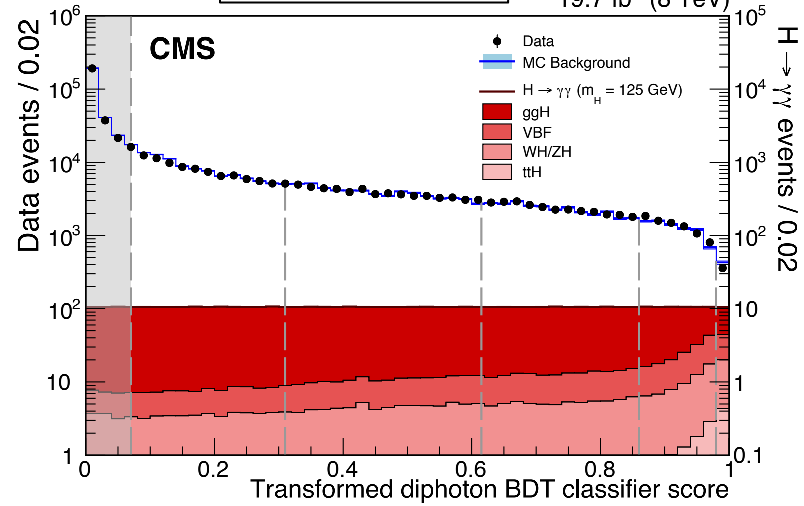
# Diphoton BDT

Data samples → Photon energy → Photon ID → Vertex ID → **Event tagging** → Statistical Analysis → Results

- Event classifier which collapses event information into one discriminant
- Assigns a high score to events with:
  - signal like kinematics (mainly high $p_T^{\gamma\gamma}$)
  - good diphoton mass resolution (i.e. good photon resolution and high vertex probability)
  - high photon quality
- The discriminant is independent of mass
- Place a cut on classifier value to cut out background
- Categorise events using bins in the classifier value
- Use this as input to a further BDT which focuses on dijet selection

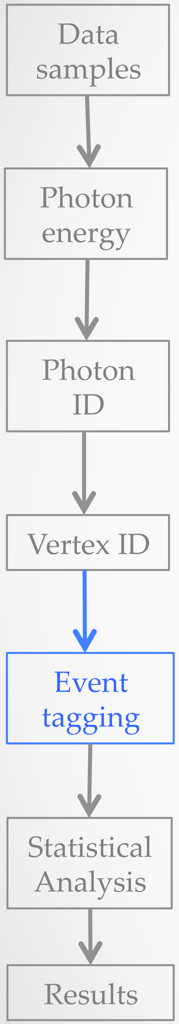
Diphoton BDT output transformed to flat in total signal

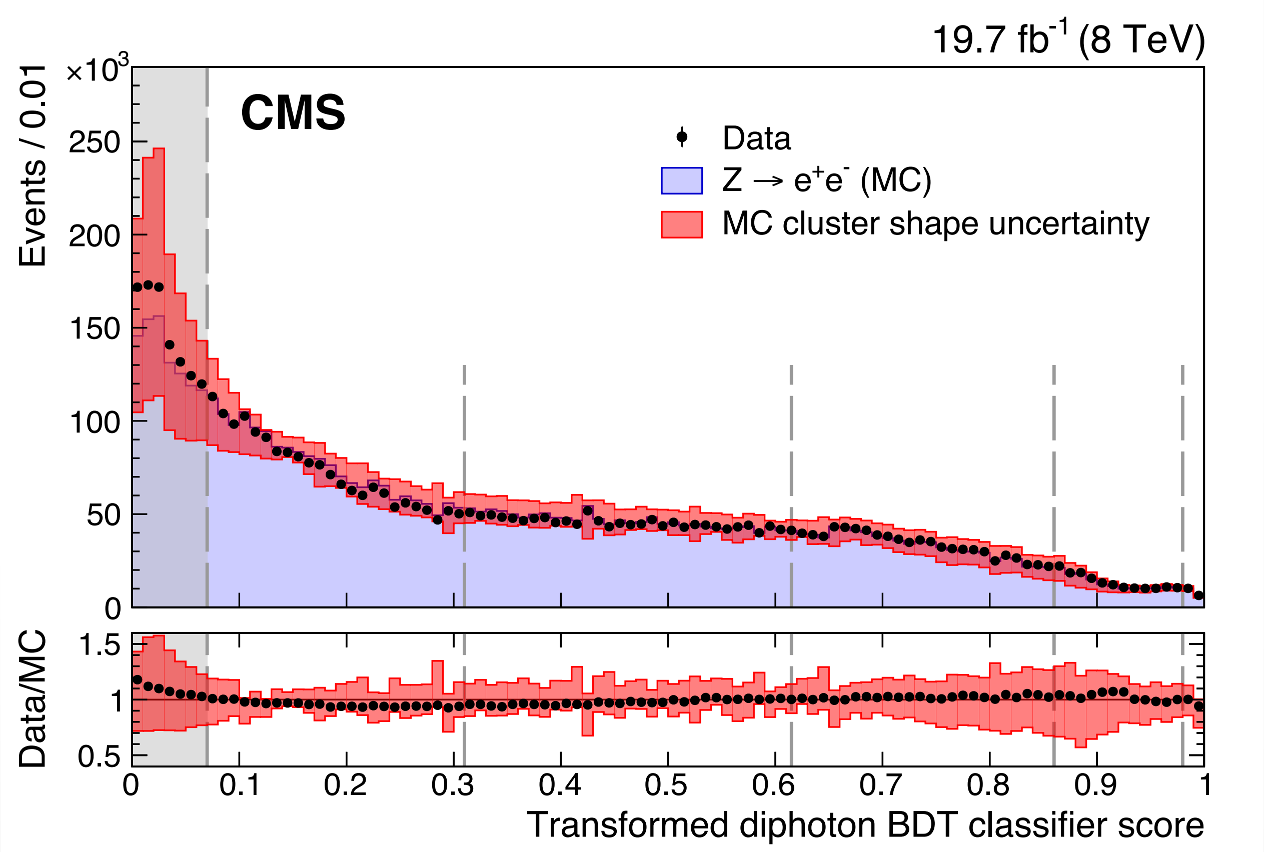
MC 8 TeV



# Diphoton BDT II

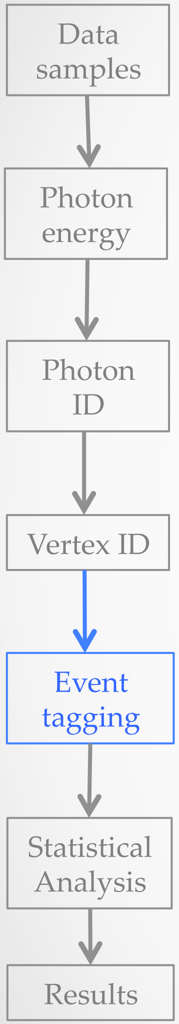
- Classifier output is validated with Z→ee
- Apply systematics for components which can distort shape of output enough to effect categorisation
  - photon ID quality
  - energy resolution estimate



# Back Up (Exclusive Tags)

# Event Tag Summary




| Label | No. of classes 8 GeV | 7 GeV | Main requirements |
|---|---|---|---|
| $t\bar{t}$H lepton tag | 1 | $\star$ | $p_T^\gamma(1) > m_{\gamma\gamma}/2$<br>1 b-tagged jet + 1 electron or muon |
| VH tight $\ell$ tag | 1 | 1 | $p_T^\gamma(1) > 3 \cdot m_{\gamma\gamma}/8$<br>e or $\mu$, $p_T > 20\,\text{GeV}$, and $E\!\!\!/_T > 45\,\text{GeV}$ OR<br>2e or 2$\mu$, $p_T > 10\,\text{GeV}$; $70 < m_{\ell\ell} < 110\,\text{GeV}$ |
| VH loose $\ell$ tag | 1 | 1 | $p_T^\gamma(1) > 3 \cdot m_{\gamma\gamma}/8$<br>e or $\mu$, $p_T > 20\,\text{GeV}$ |
| VBF dijet tag 0-2 | 3 | 2 | $p_T^\gamma(1) > m_{\gamma\gamma}/2$<br>2 jets; dijet and combined diphoton-dijet BDTs used |
| VH $E\!\!\!/_T$ tag | 1 | 1 | $p_T^\gamma(1) > 3 \cdot m_{\gamma\gamma}/8$<br>$E\!\!\!/_T > 70\,\text{GeV}$ |
| $t\bar{t}$H multijet tag | 1 | $\star$ | $p_T^\gamma(1) > m_{\gamma\gamma}/2$<br>1 b-tagged jet + 4 more jets |
| VH dijet tag | 1 | 1 | $p_T^\gamma(1) > 3 \cdot m_{\gamma\gamma}/8$<br>jet pair, $p_T > 40\,\text{GeV}$ and $60 < m_{jj} < 120\,\text{GeV}$ |
| Untagged 0-4 | 5 | 4 | The remaining events,<br>classified using diphoton BDT |

$\star$ For the 7 TeV dataset, events in the $t\bar{t}$H lepton tag and multijet tag classes are selected first, and combined to form a single event class.

# Event Tag Summary



Preselection → Photon ID MVA → Diphoton BDT

| | | |
|---|---|---|
| ttH lepton tag | 1 cat * | At least 1 b-tagged jet +1 lepton |
| VH tight lepton | 1 cat | 2 same flavour leptons consistent with Z OR 1 lepton and MET consistent with W |
| VH loose lepton | 1 cat | One lepton |
| VBF dijet tag | 3 (2) cats | 2 jets. Categorised with combined dijet-diphoton BDT |
| VH MET tag | 1 cat | MET > 70 GeV |
| ttH multijet tag | 1 cat * | At least 1 b-tagged jet + 4 more jets |
| VH dijet tag | 1 cat | Jet pair consistent with W or Z |
| Untagged | 5 (4) cats | Remainder classified with diphoton BDT |

- * ttH categories are merged at 7 TeV
- category numbers in brackets are where different for 7 TeV

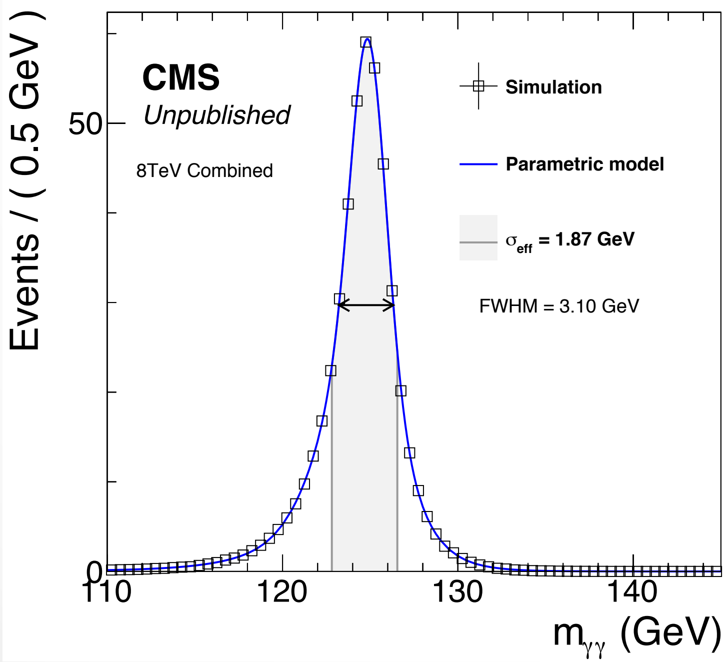
# Back Up (Signal Model)

# Signal Model

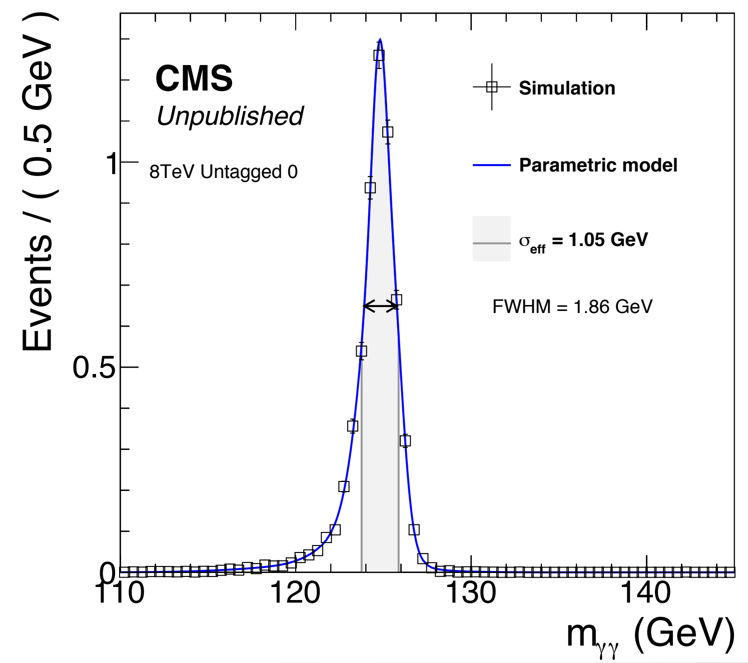
Data samples → Photon energy → Photon ID → Vertex ID → Event tagging → **Statistical Analysis** → Results

- Use a sum of Gaussians to fit the signal shape in MC
  - position and resolution of the shape can vary according to nuisance parameters
- Fit each signal process (ggH, VBF, WH, ZH, ttH) and each event category separately
- Acceptance × efficiency:
  - 7 TeV at $m_H = 125$ GeV: **A×ε = 49%**
  - 8 TeV at $m_H = 125$ GeV: **A×ε = 49%**

Summed signal model @ 8 TeV



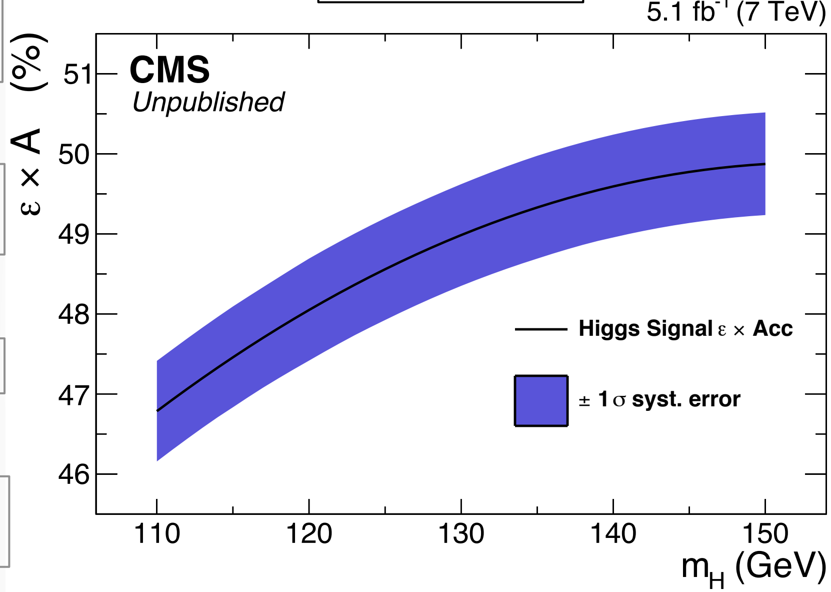

Signal model in cat 0 @ 8 TeV



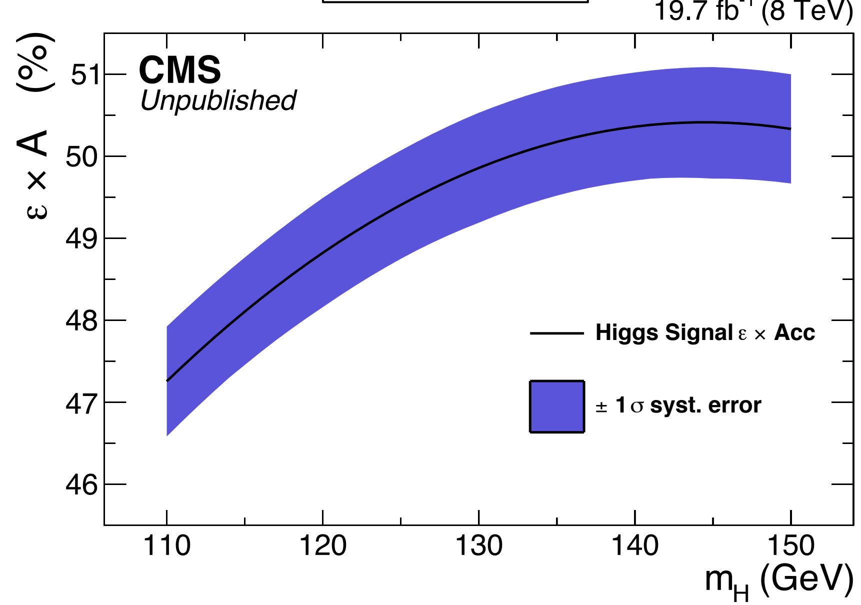
# Efficiency x acceptance of selection

Data samples
Photon energy
Photon ID
Vertex ID
Event tagging
Statistical Analysis
Results

A×ε @ 7 TeV




A×ε @ 8 TeV




At $m_H$=125 GeV:

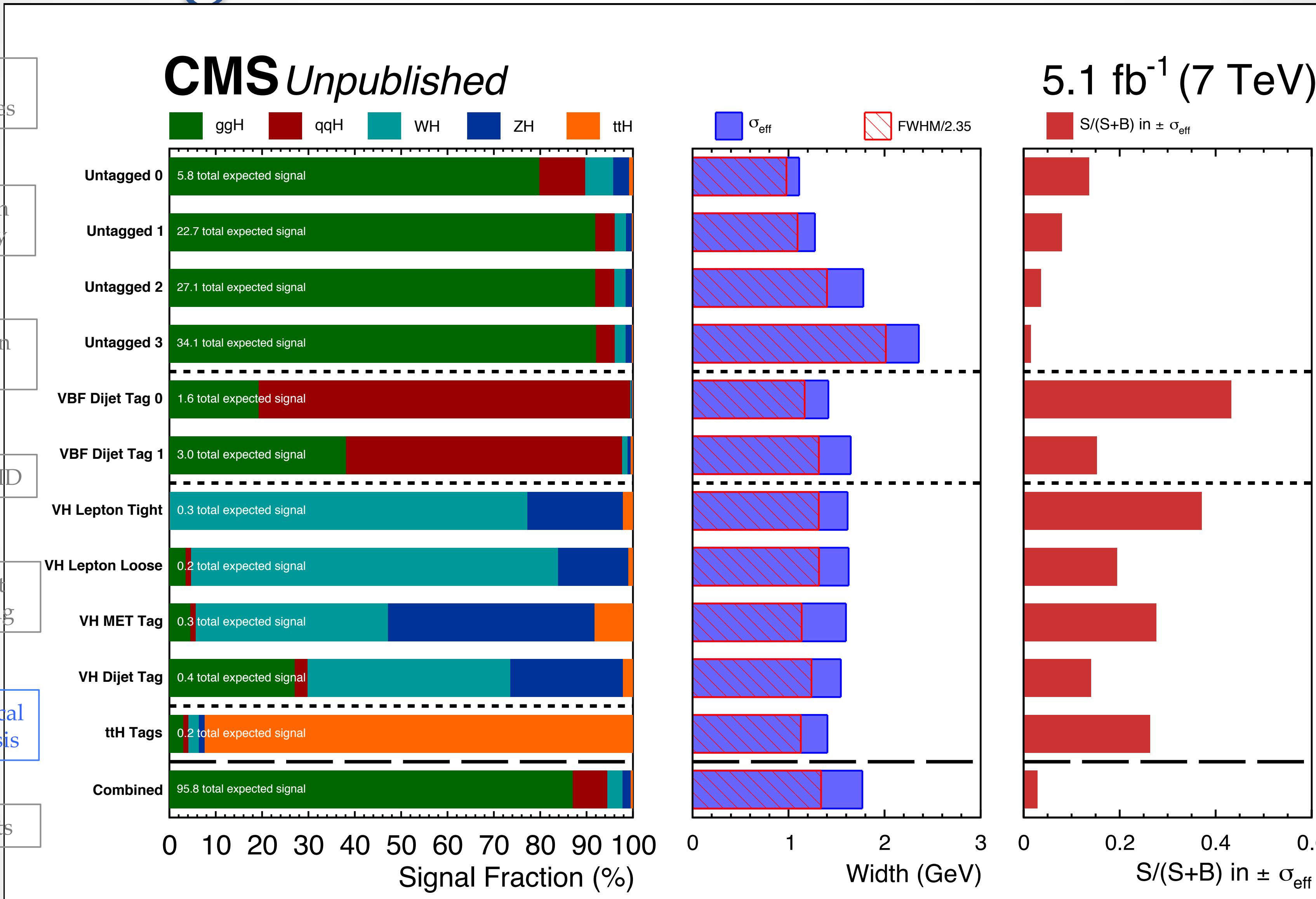
A×ε = 48.6%

At $m_H$=125 GeV:

A×ε = 49.3%

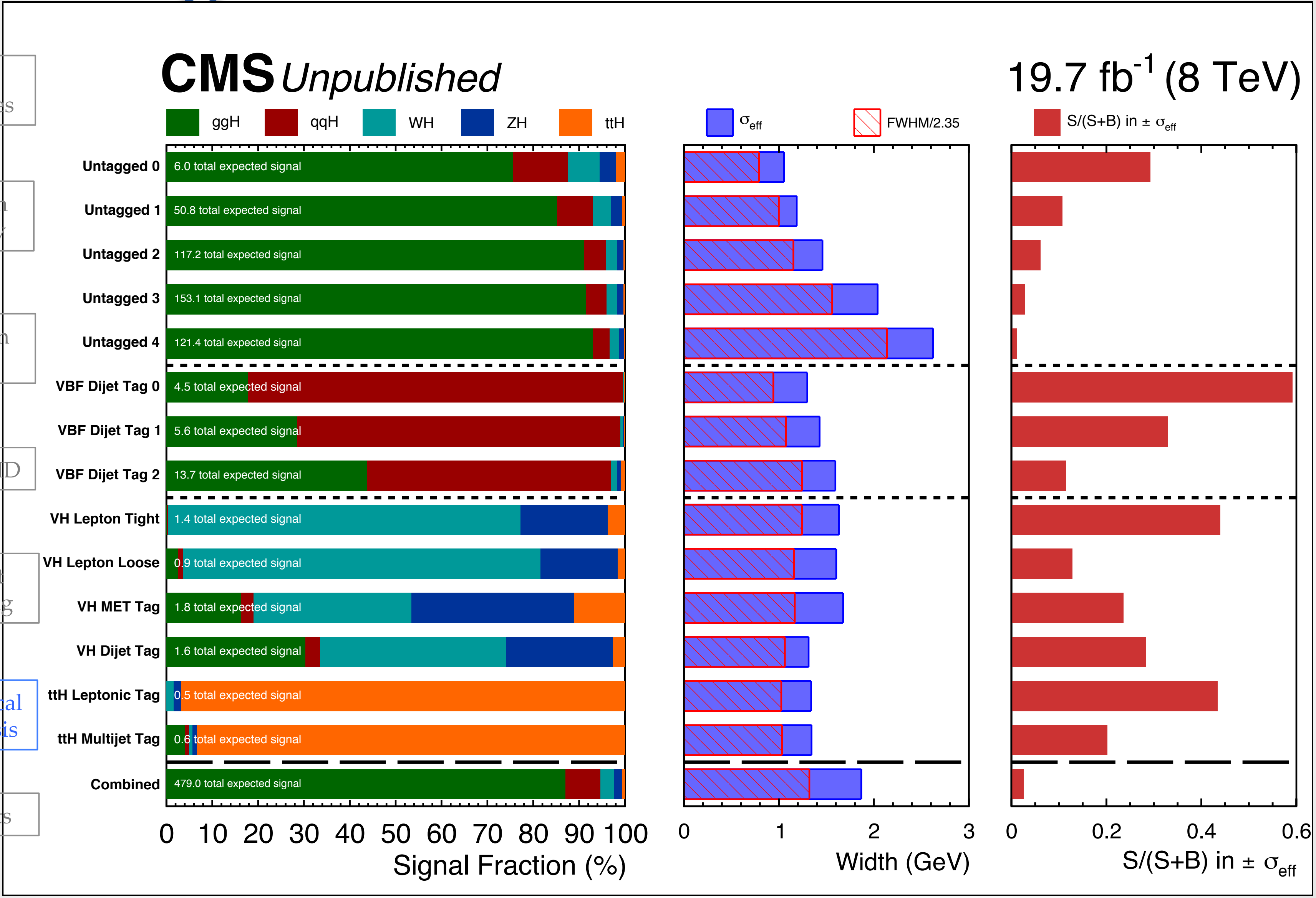
# Signal breakdown at 7 TeV

Data samples
Photon energy
Photon ID
Vertex ID
Event tagging
Statistical Analysis
Results

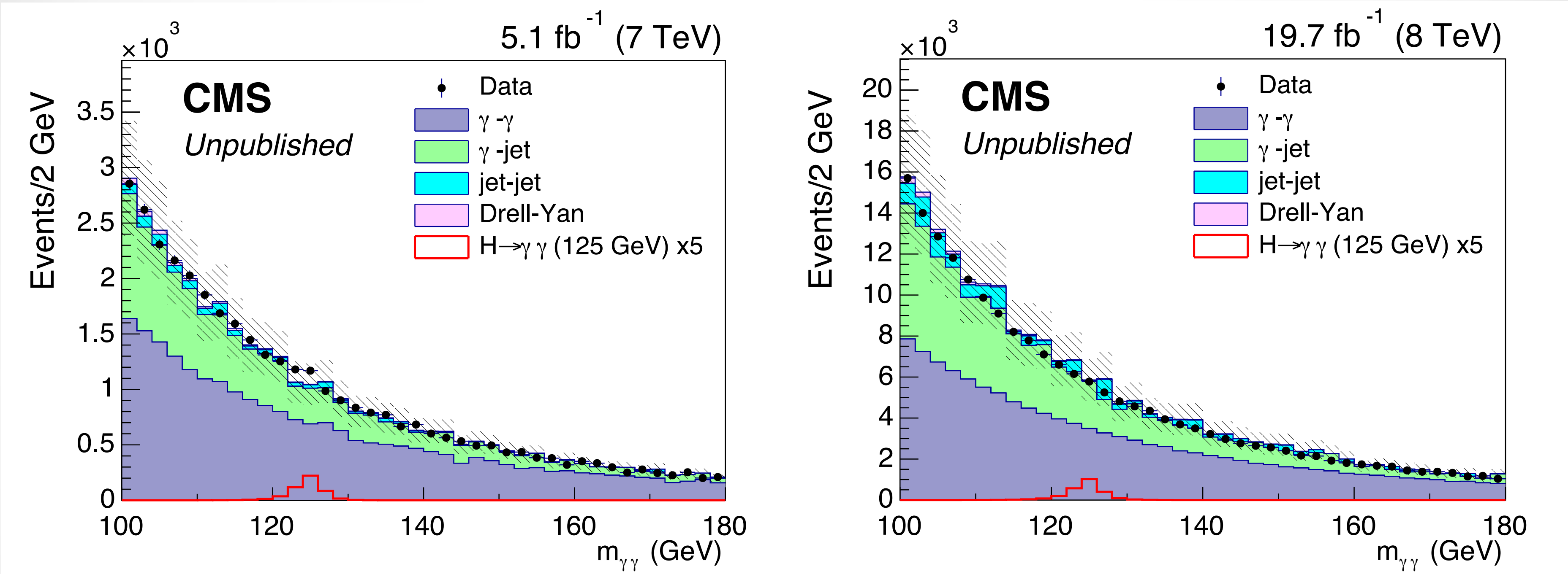


# Signal breakdown at 8 TeV

Data samples → Photon energy → Photon ID → Vertex ID → Event tagging → Statistical Analysis → Results



# Invariant mass in MC

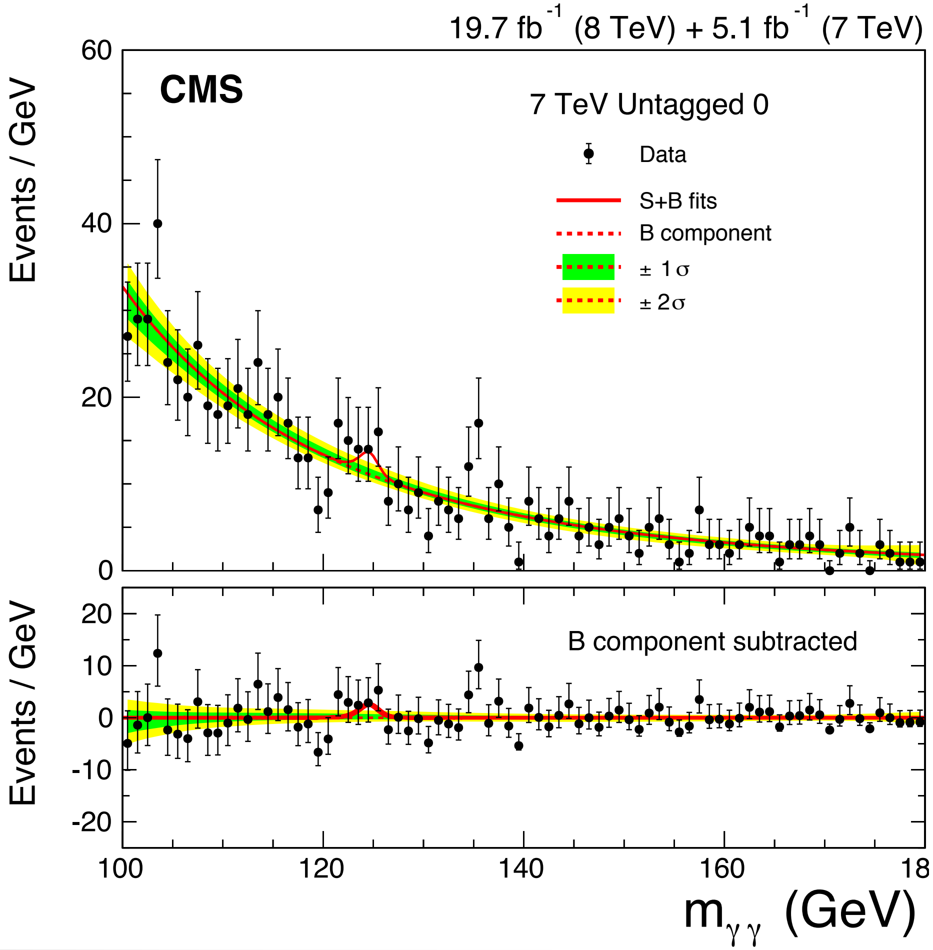


# Back Up (Background)

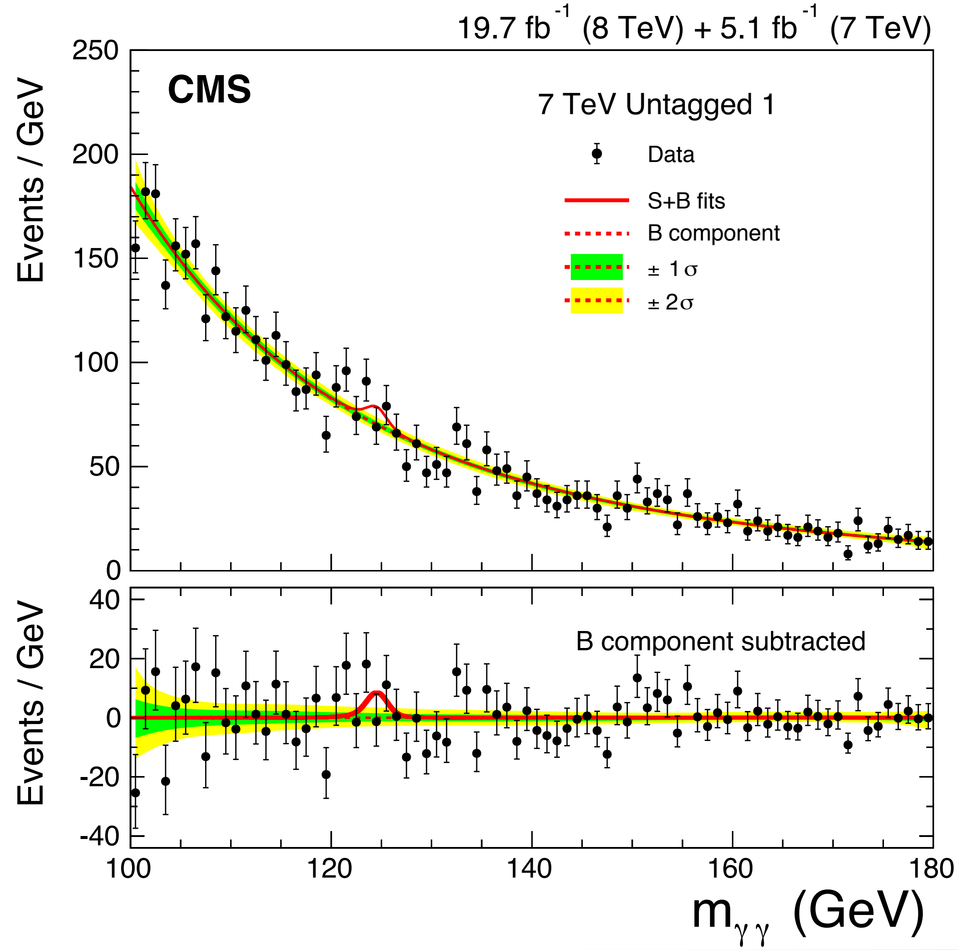
…

# Invariant mass by category 7 TeV I

7 TeV Untagged 0

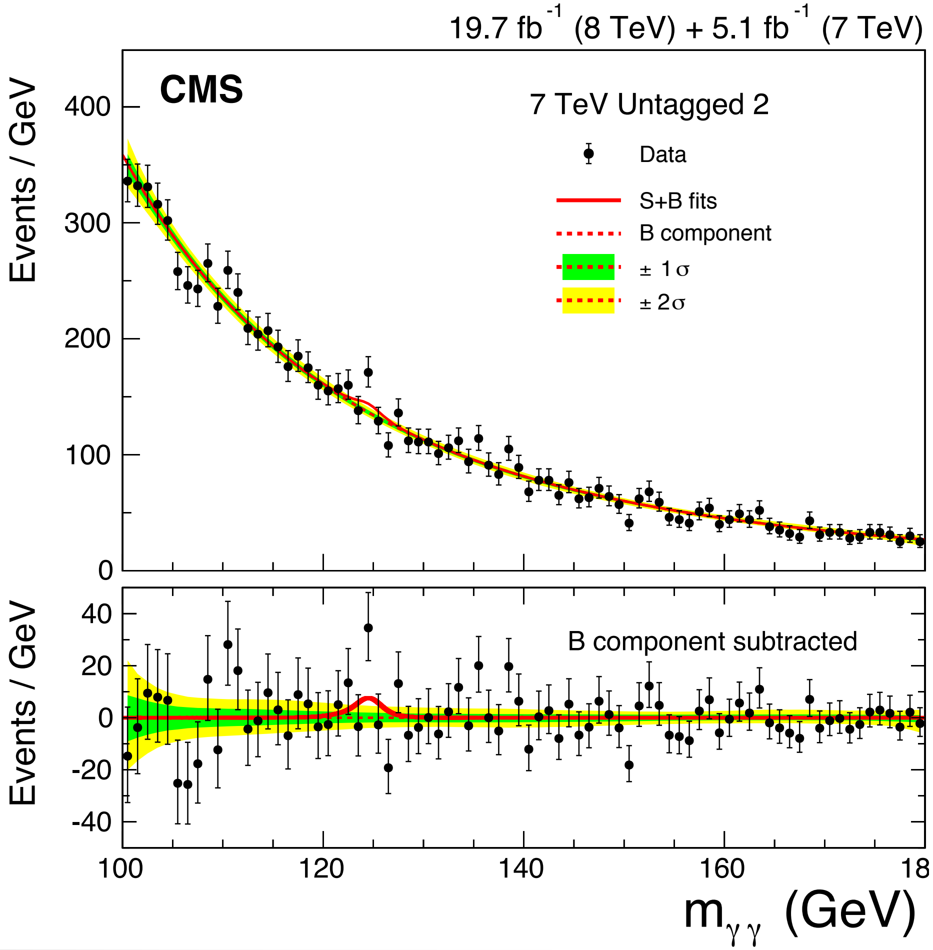



7 TeV Untagged 1

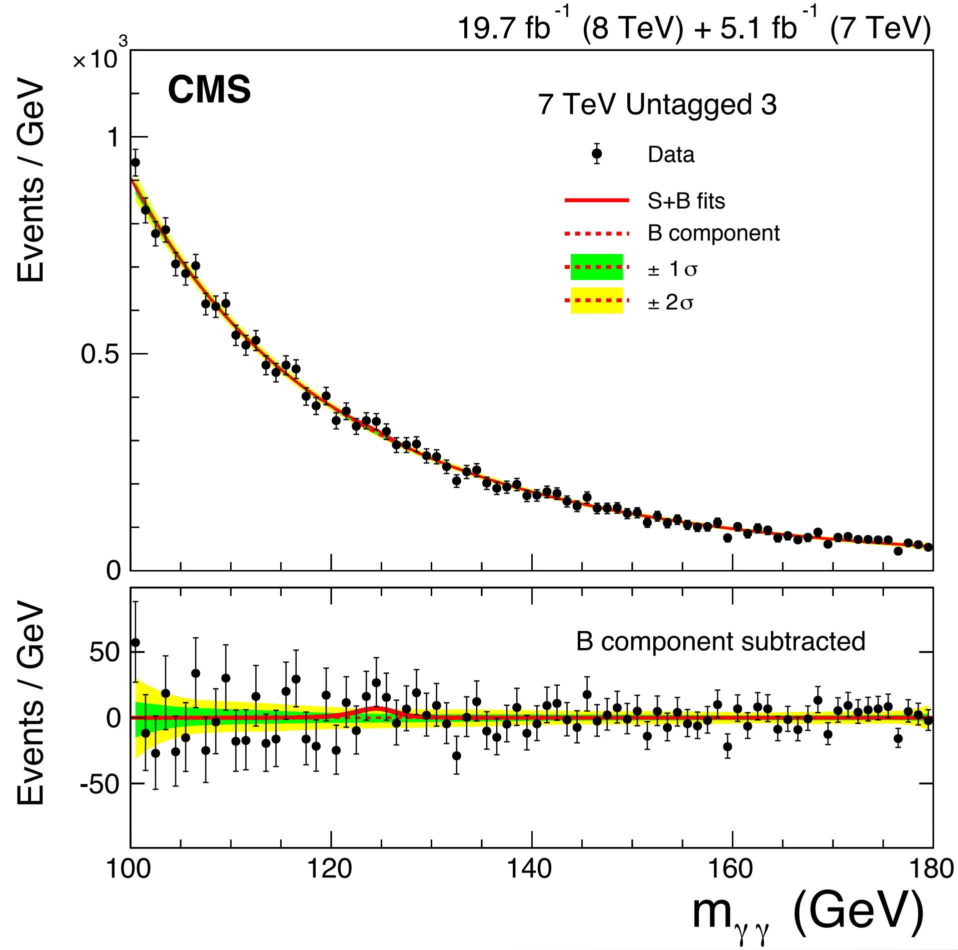


# Invariant mass by category 7 TeV II

7 TeV Untagged 2

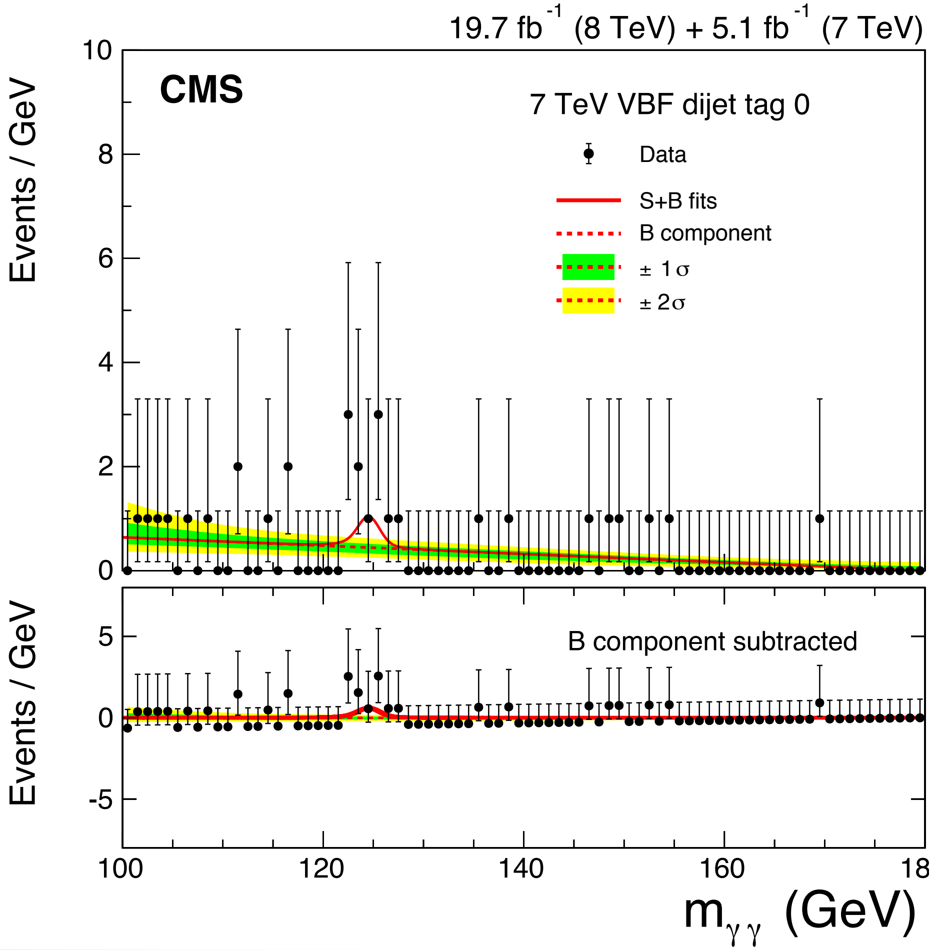



7 TeV Untagged 3

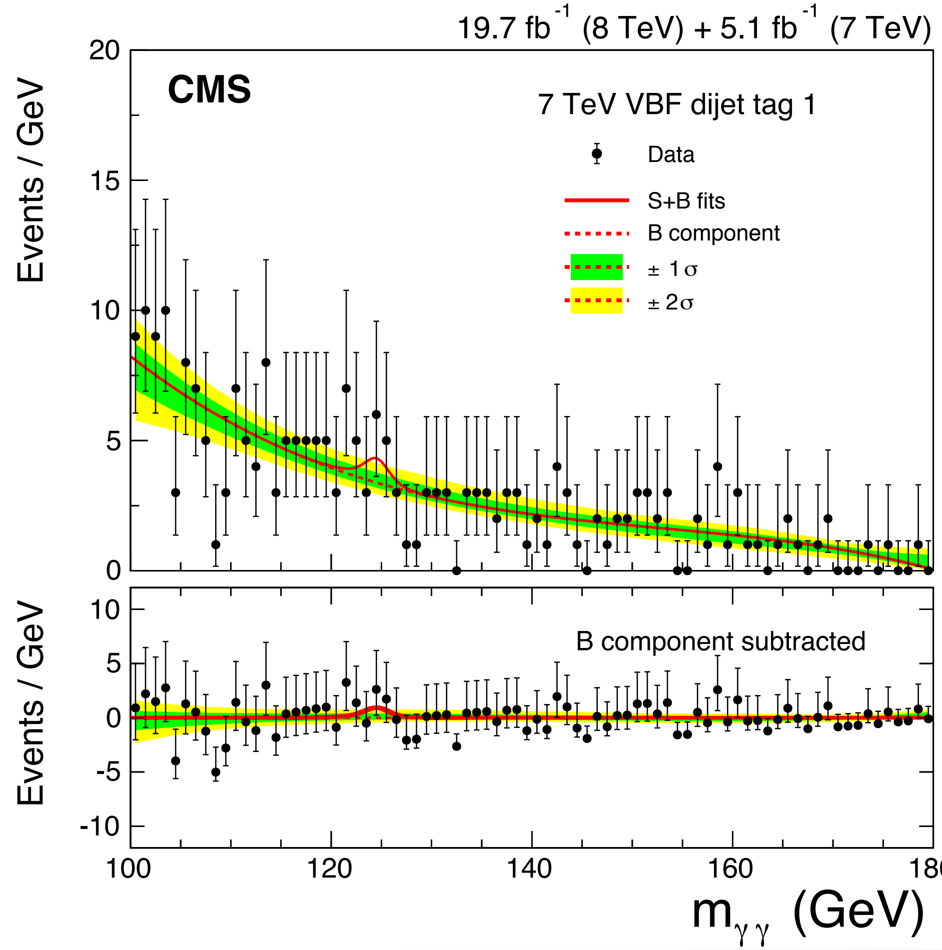


# Invariant mass by category 7 TeV III

7 TeV VBF dijet tag 0

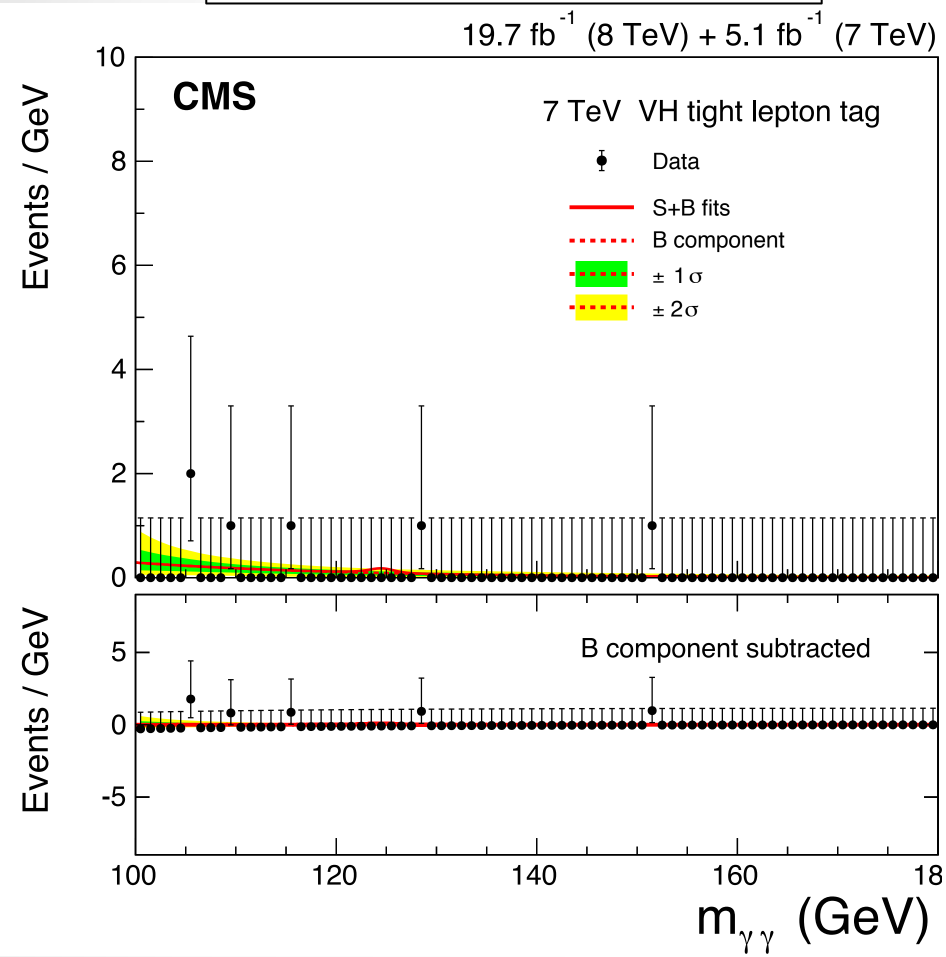



7 TeV VBF dijet tag 1

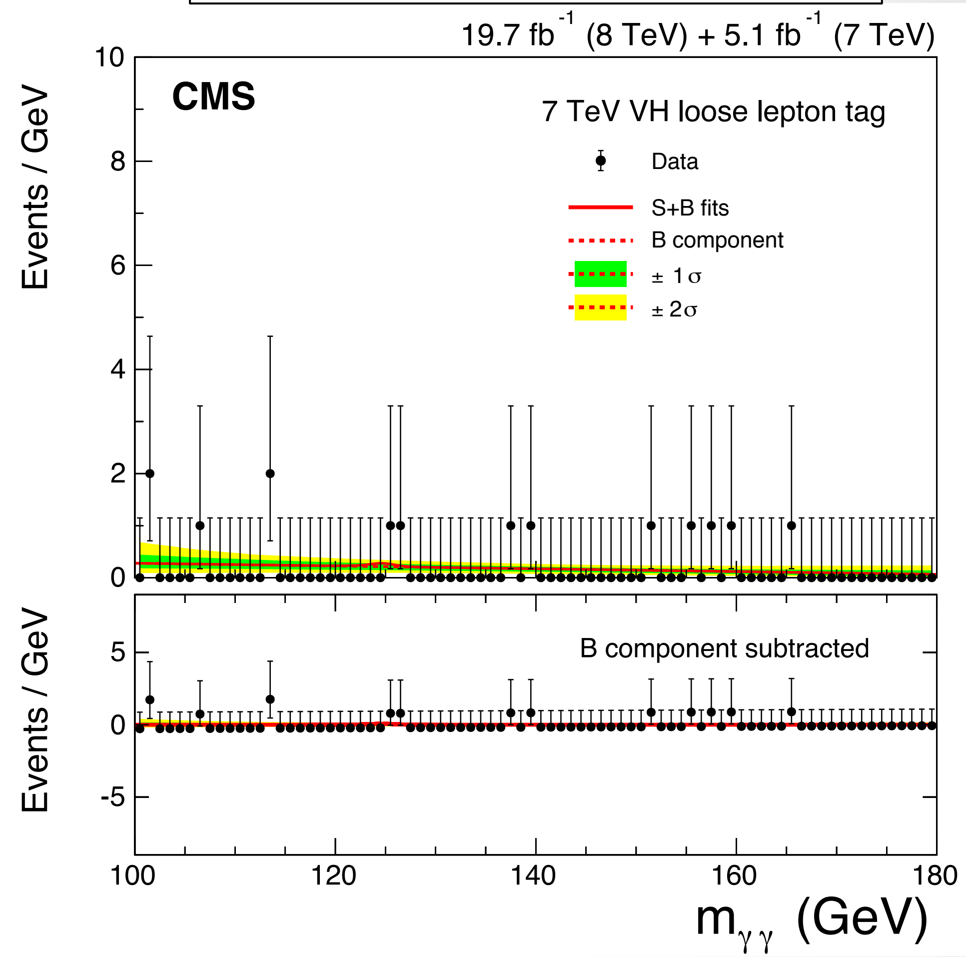


# Invariant mass by category 7 TeV IV

7 TeV VH tight lepton tag

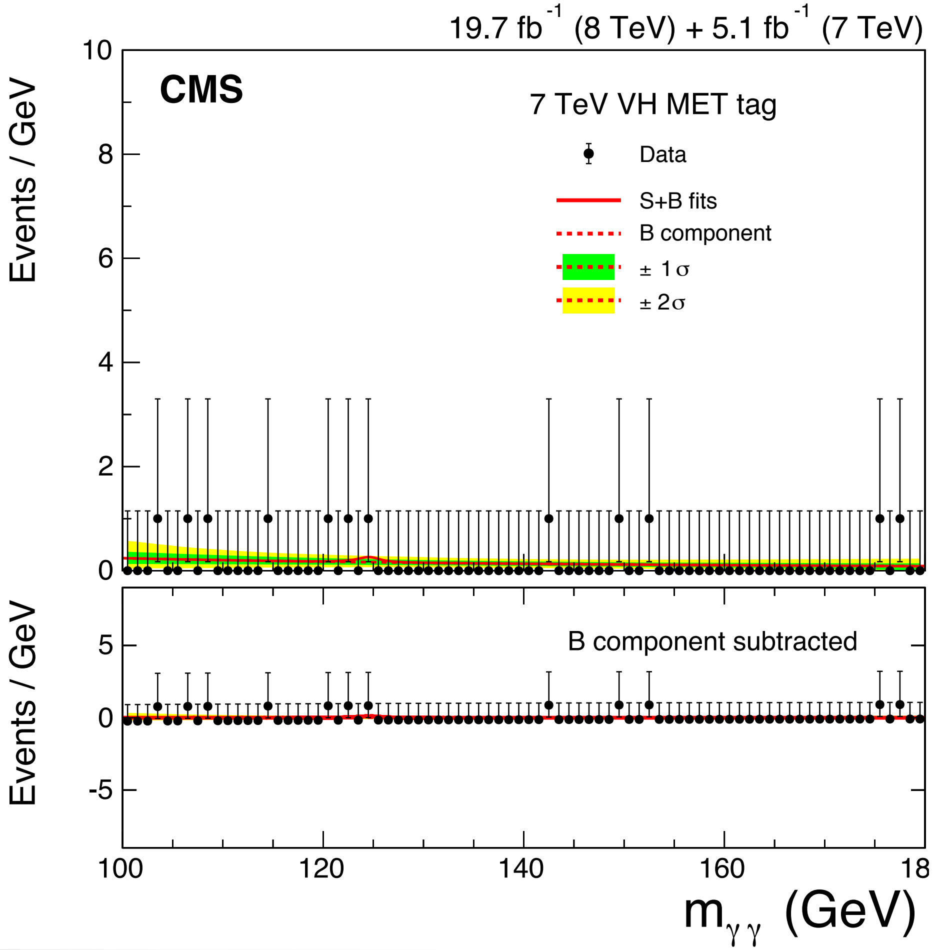



7 TeV VH loose lepton tag

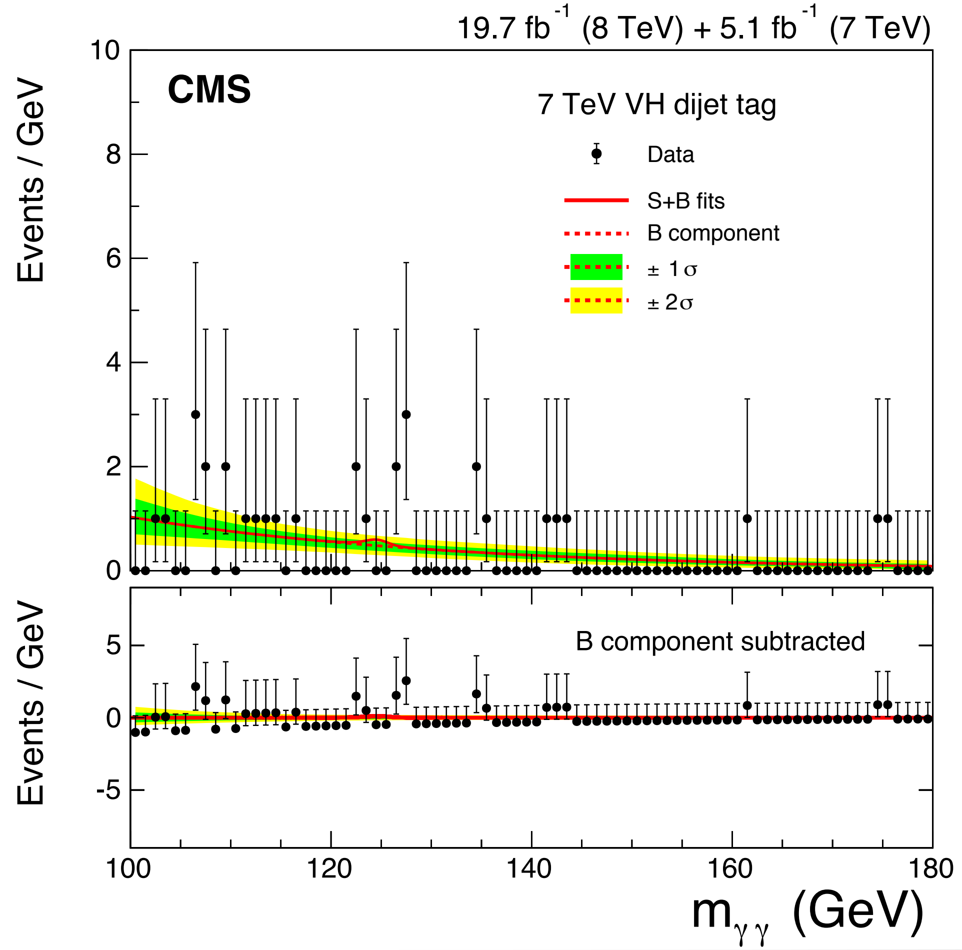


# Invariant mass by category 7 TeV V

7 TeV VH MET tag

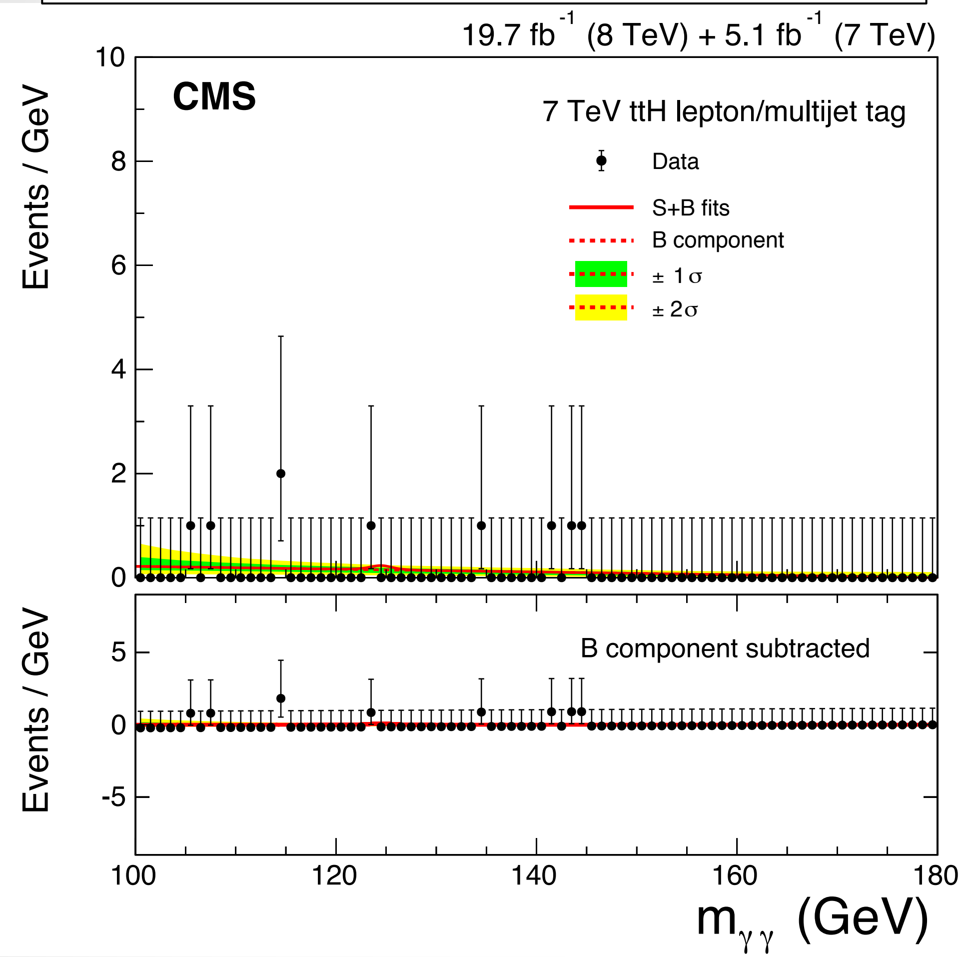



7 TeV VH dijet tag



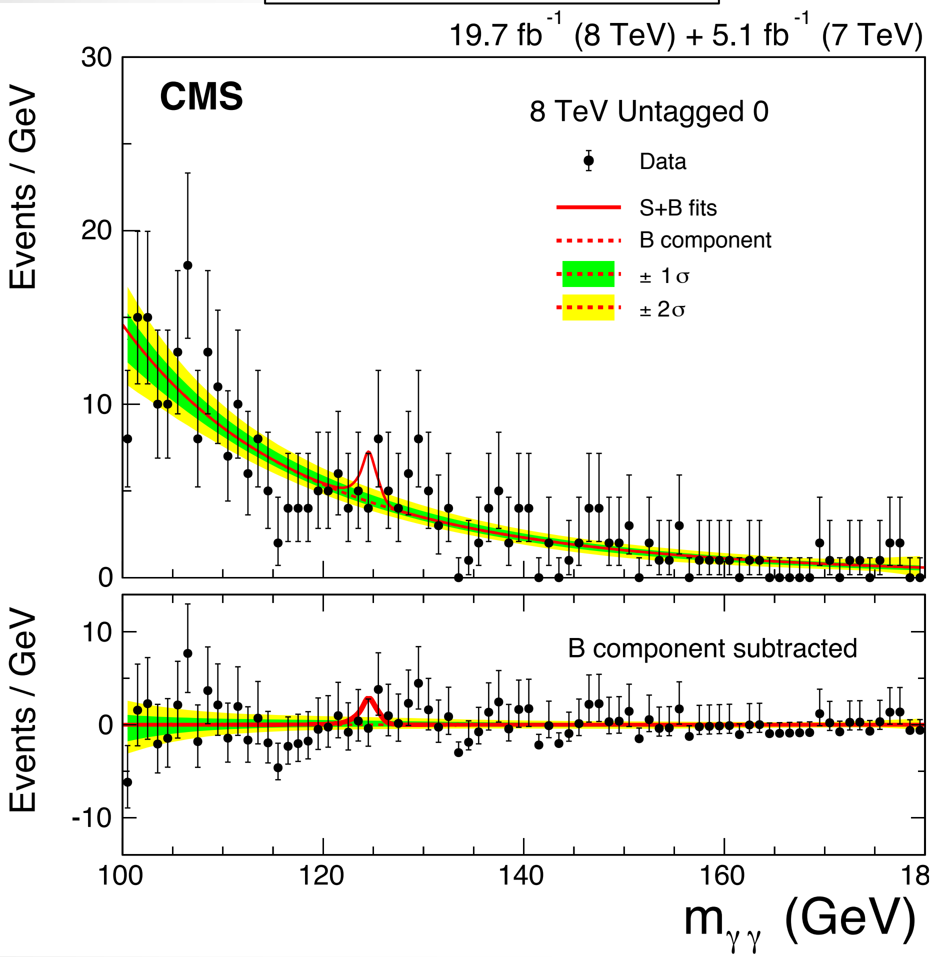
# Invariant mass by category 7 TeV VI

7 TeV ttH tight lepton/multijet tag

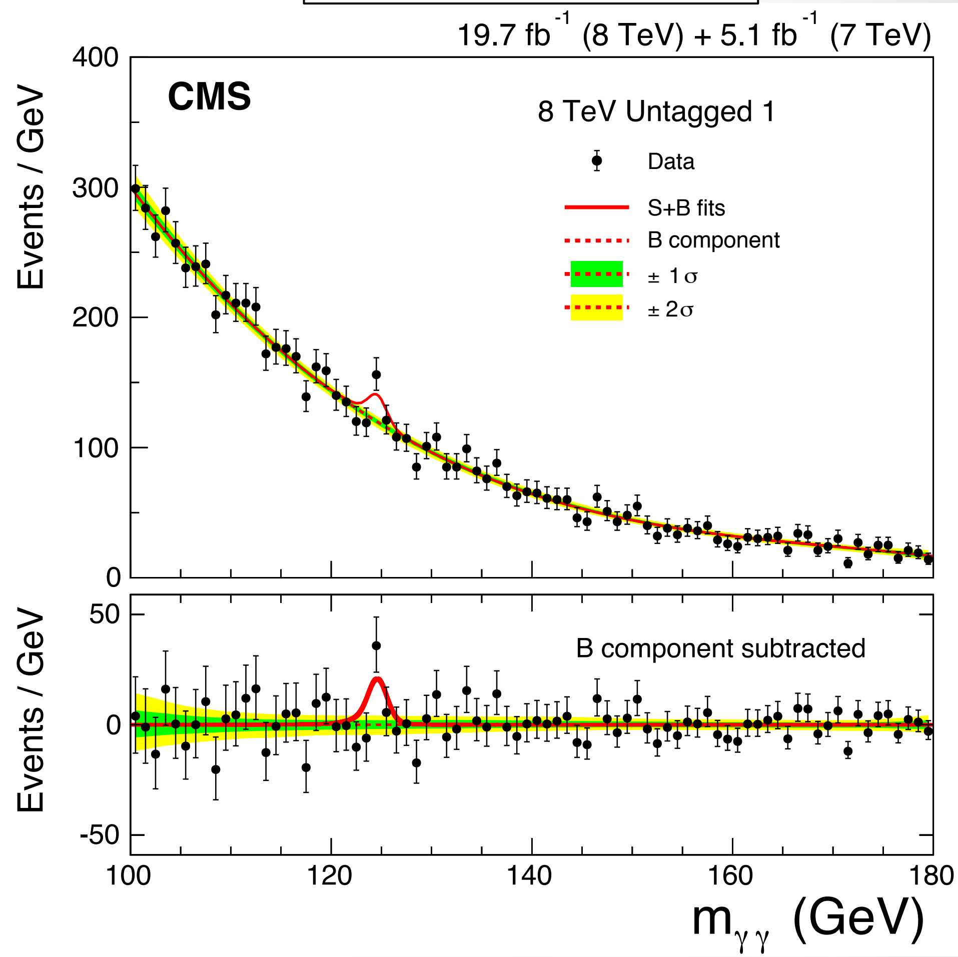


# Invariant mass by category 8 TeV I

8 TeV Untagged 0

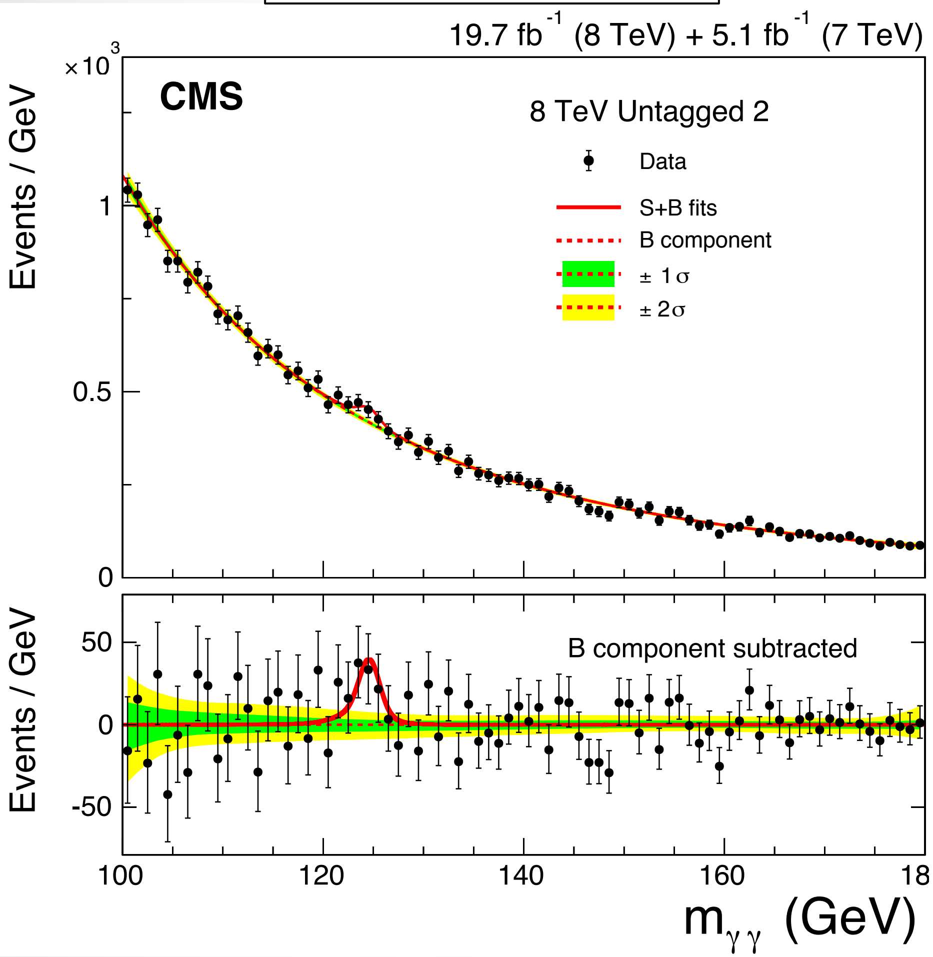



8 TeV Untagged 1

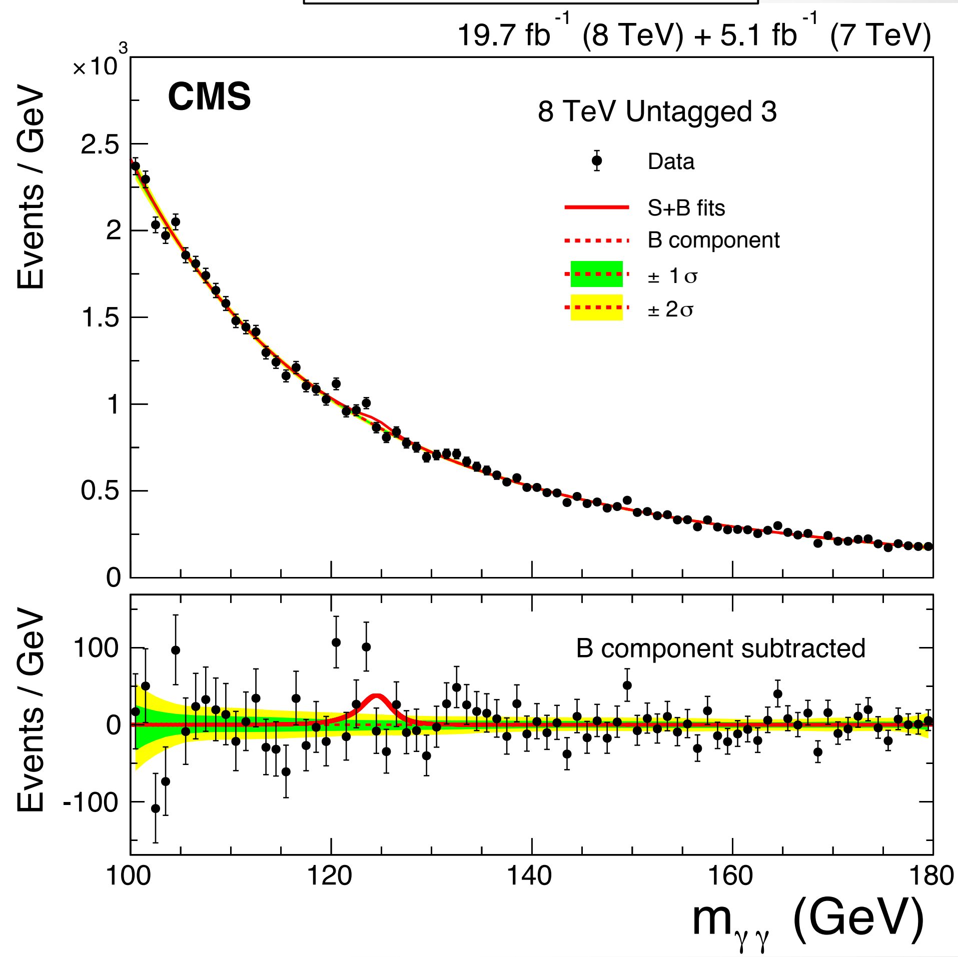


# Invariant mass by category 8 TeV II

8 TeV Untagged 2

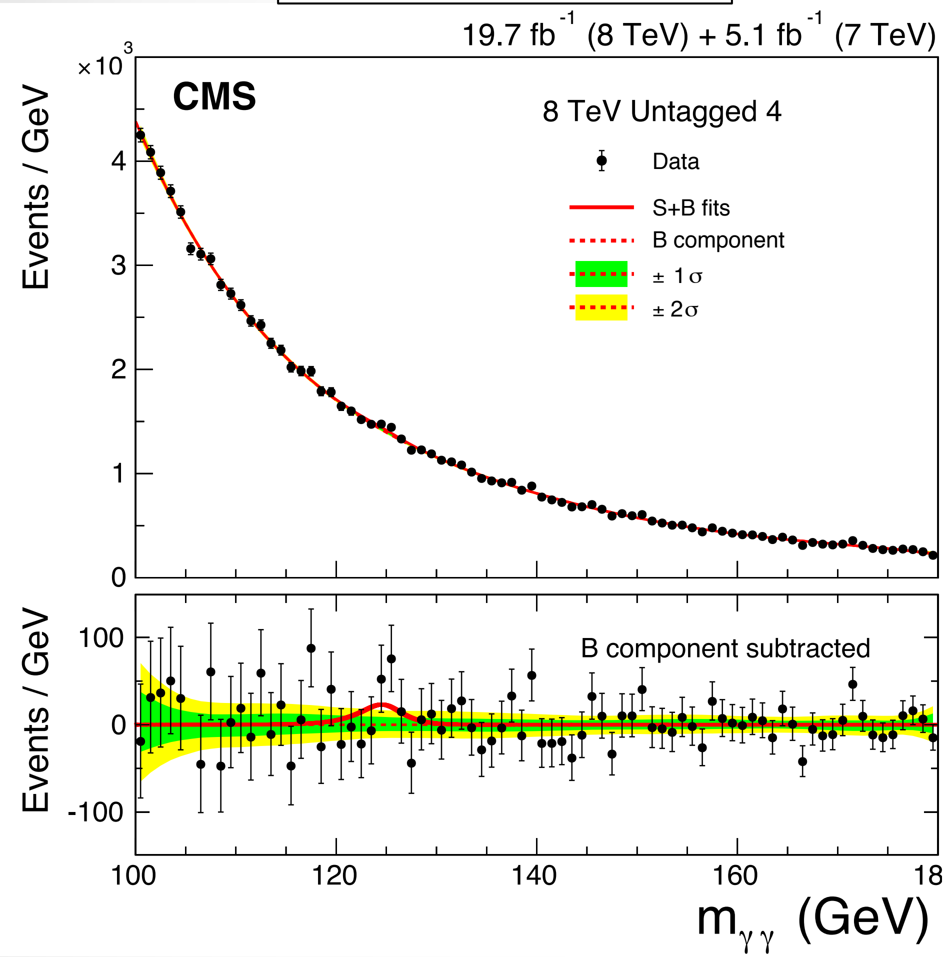



8 TeV Untagged 3

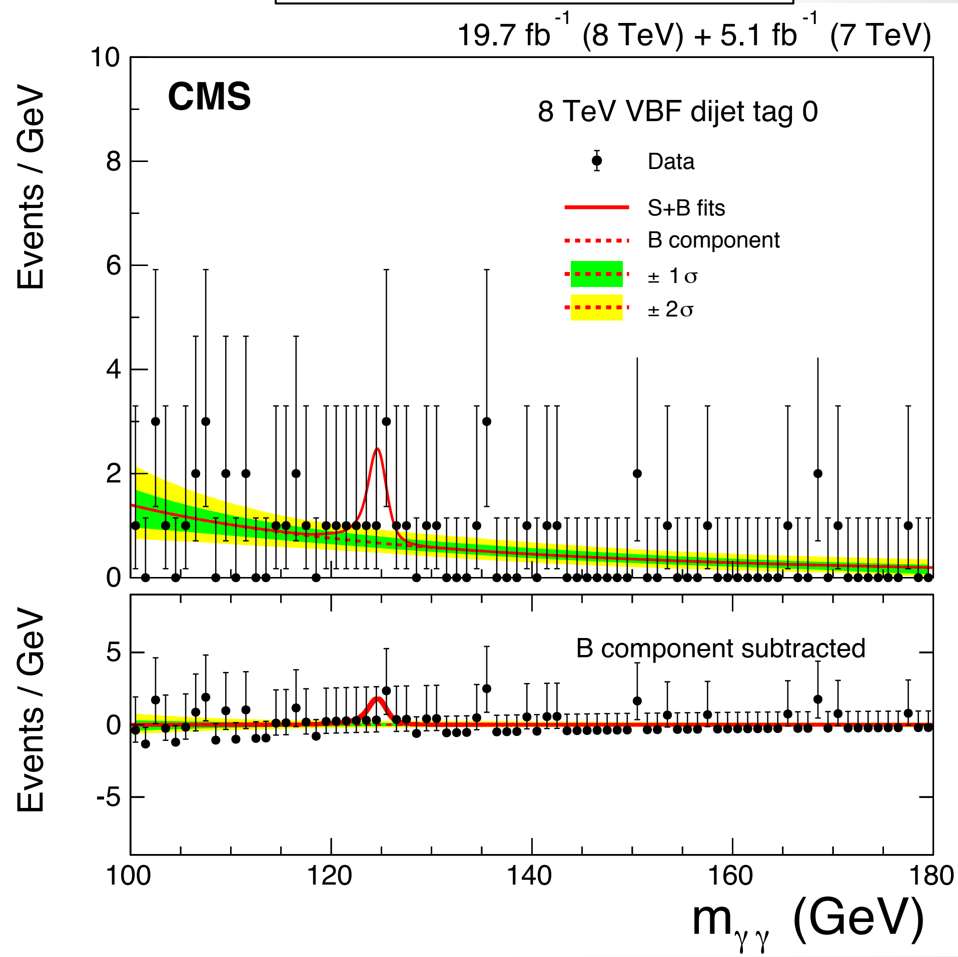


# Invariant mass by category 8 TeV III

8 TeV Untagged 4



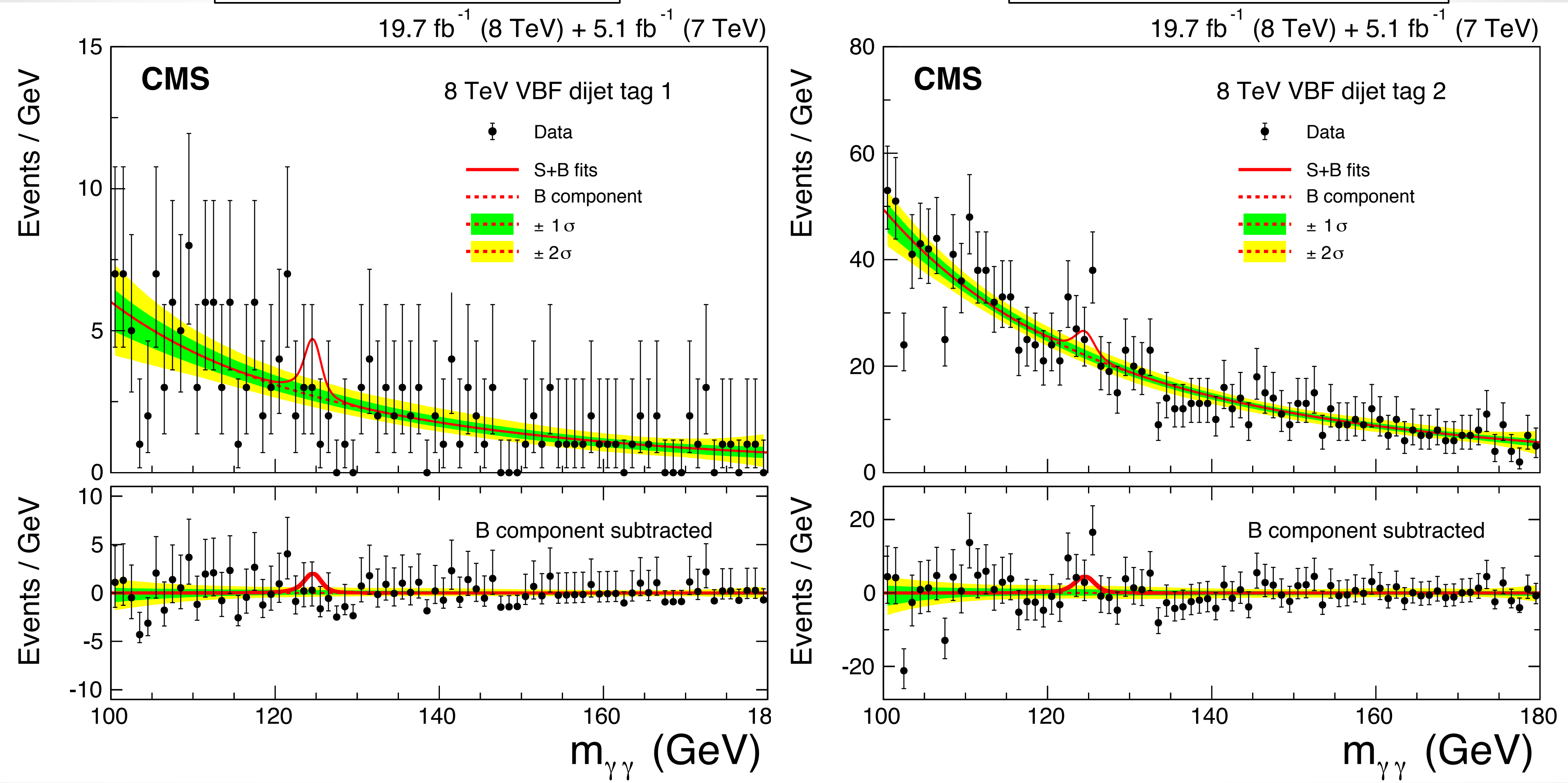

8 TeV VBF dijet tag 0



# Invariant mass by category 8 TeV IV

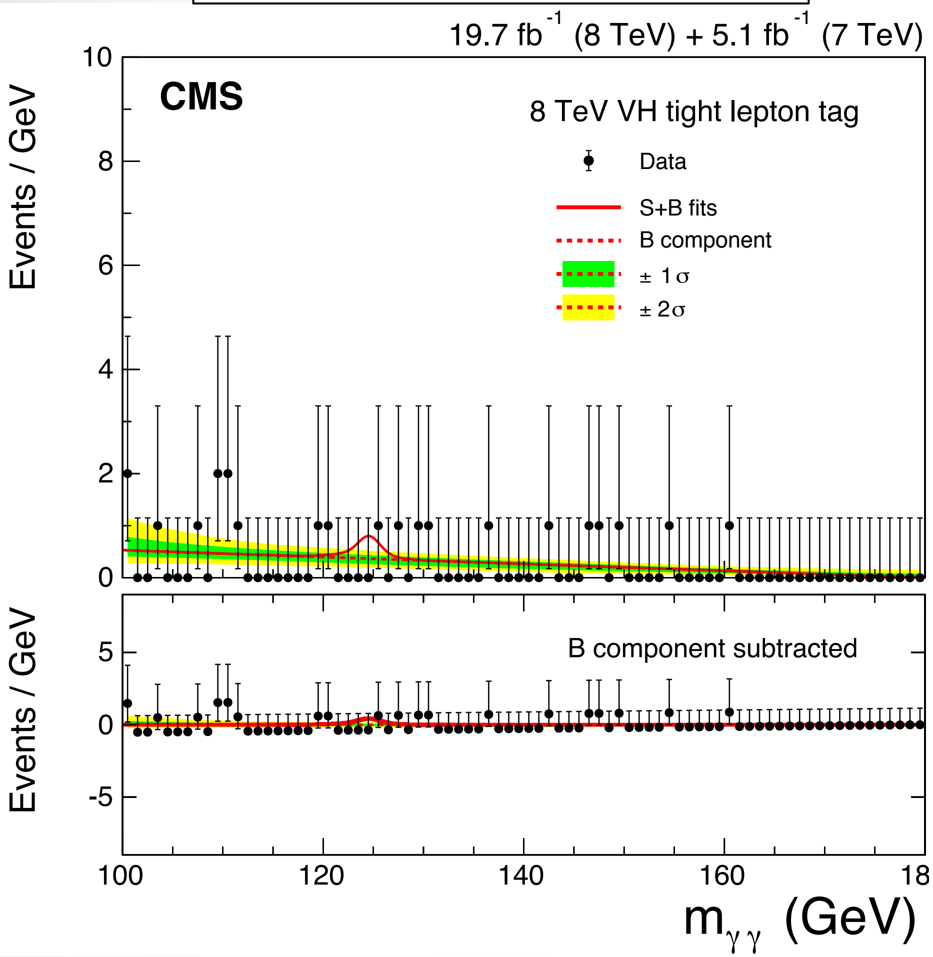
8 TeV VBF dijet tag 1

8 TeV VBF dijet tag 2

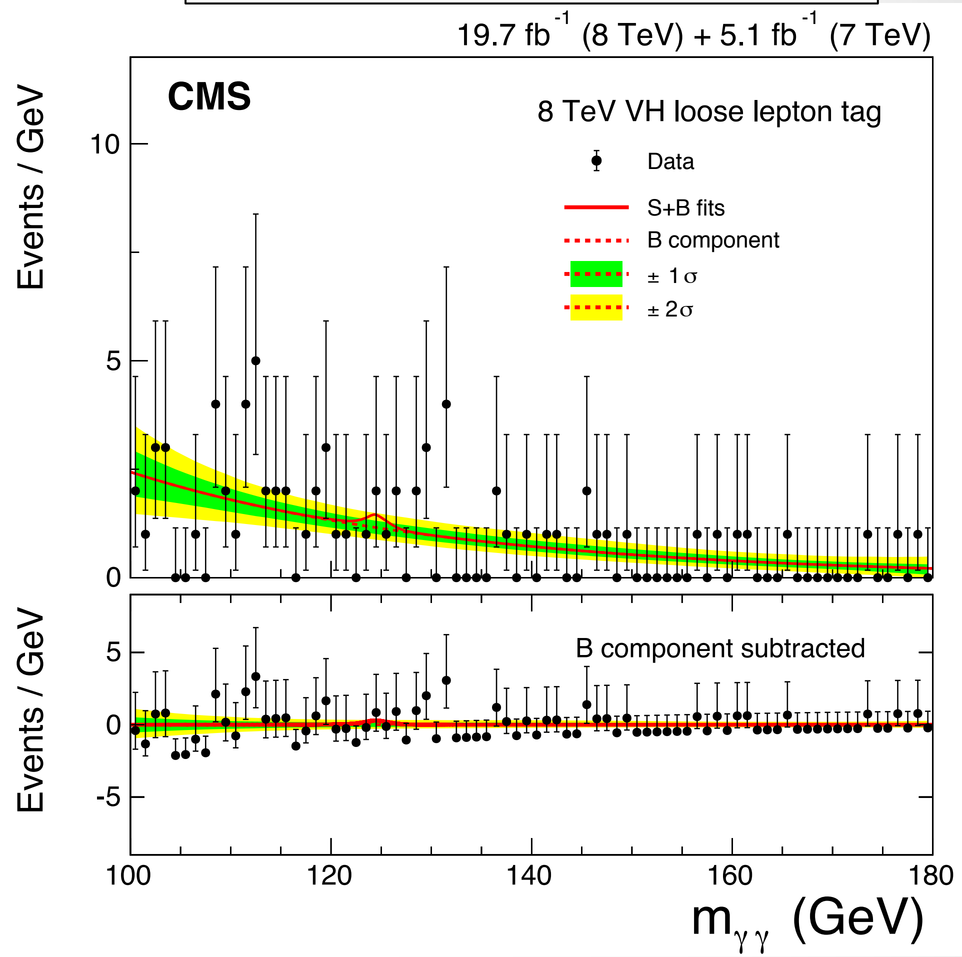


# Invariant mass by category 8 TeV V

8 TeV VH tight lepton tag

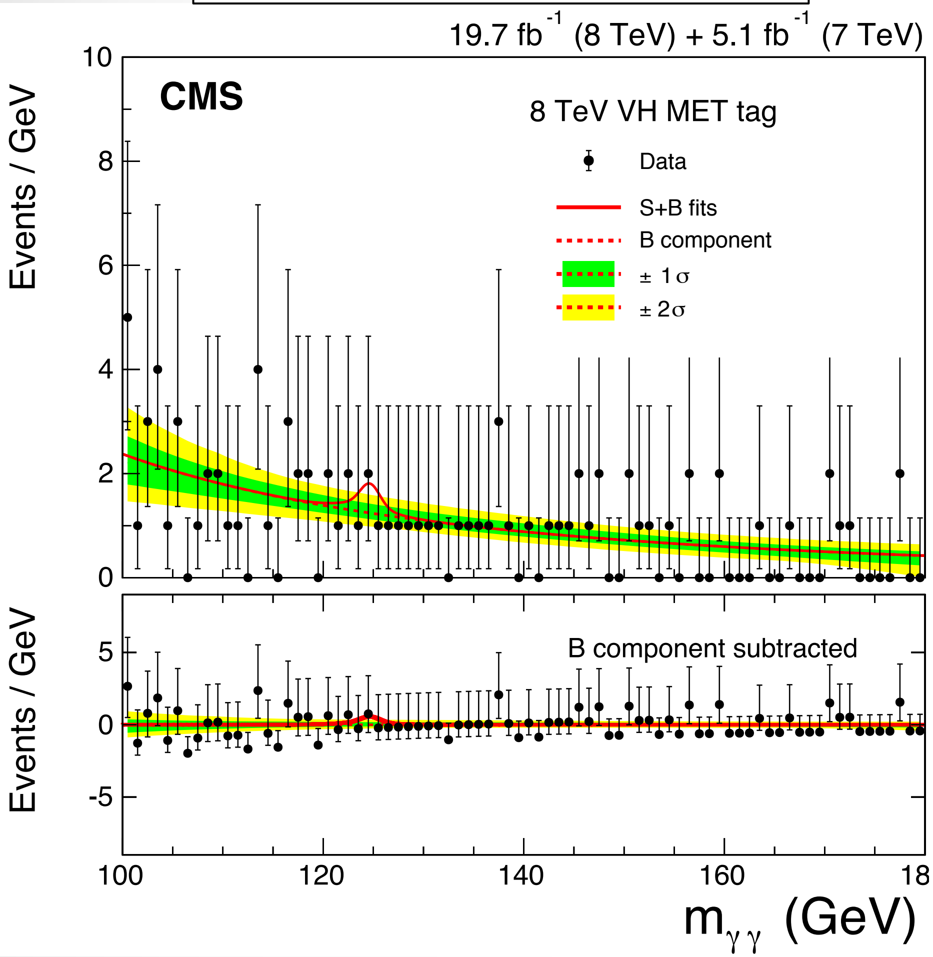



8 TeV VH loose lepton tag

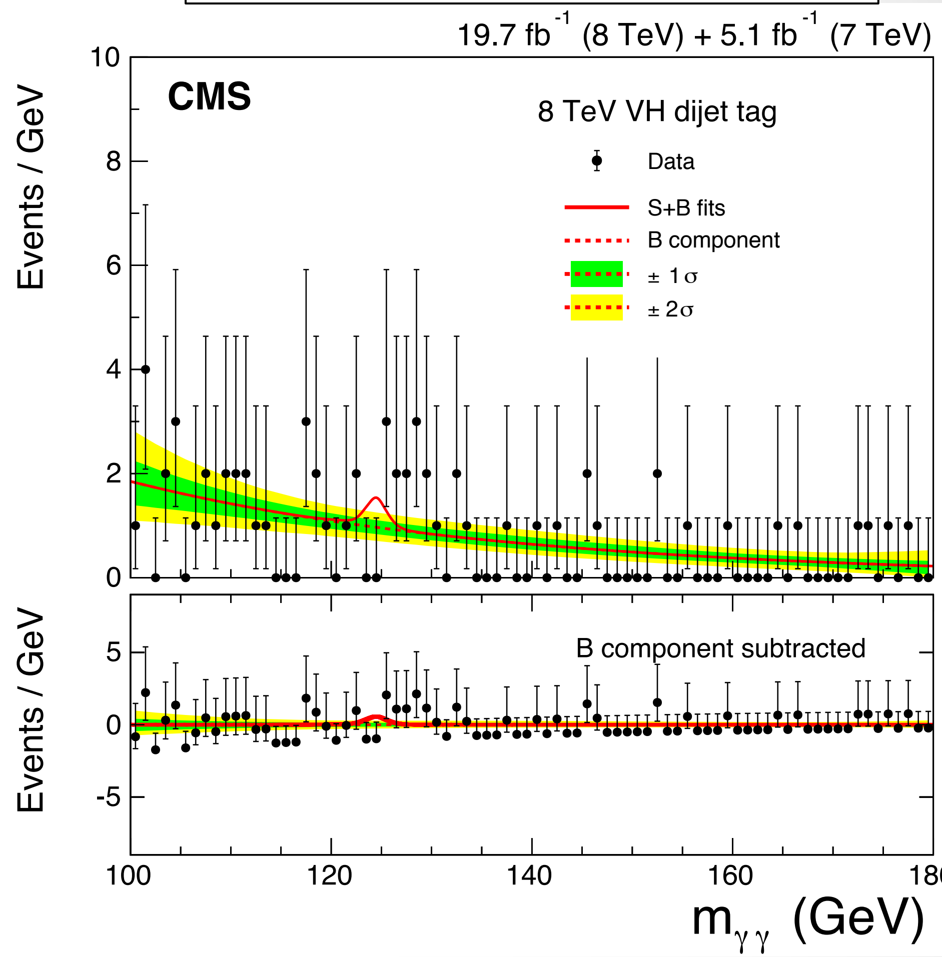


# Invariant mass by category 8 TeV VI

8 TeV VH MET tag

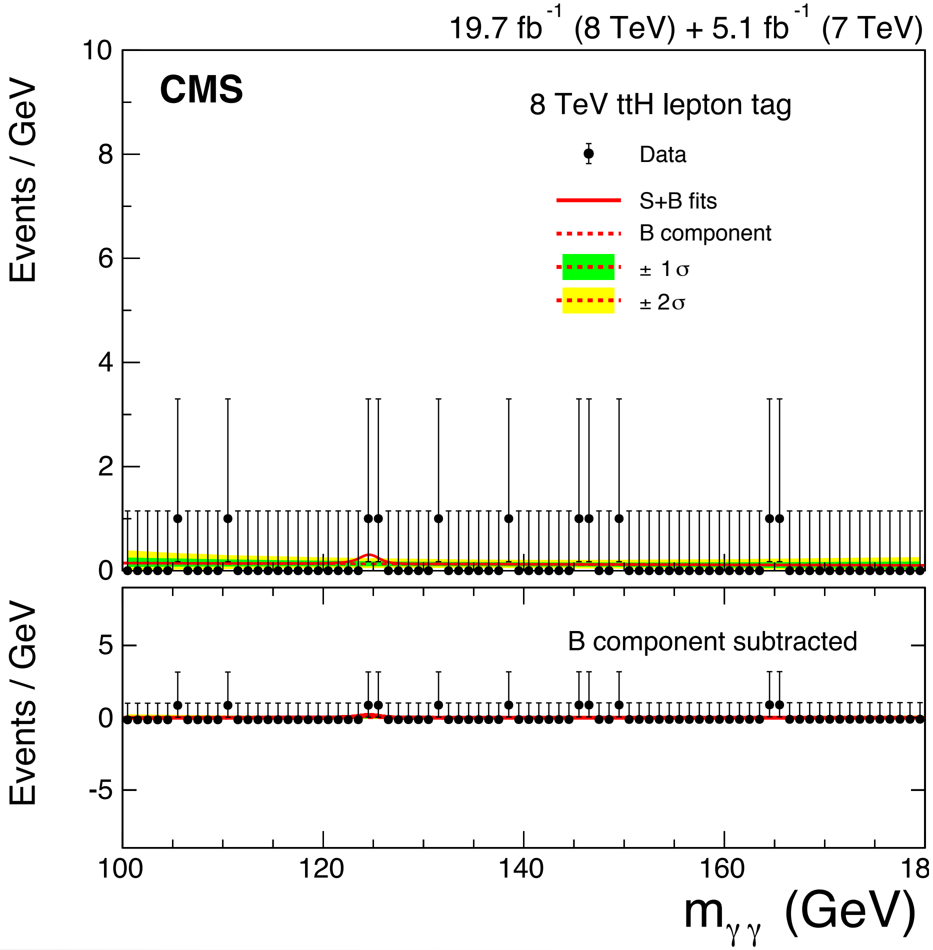



8 TeV VH dijet tag

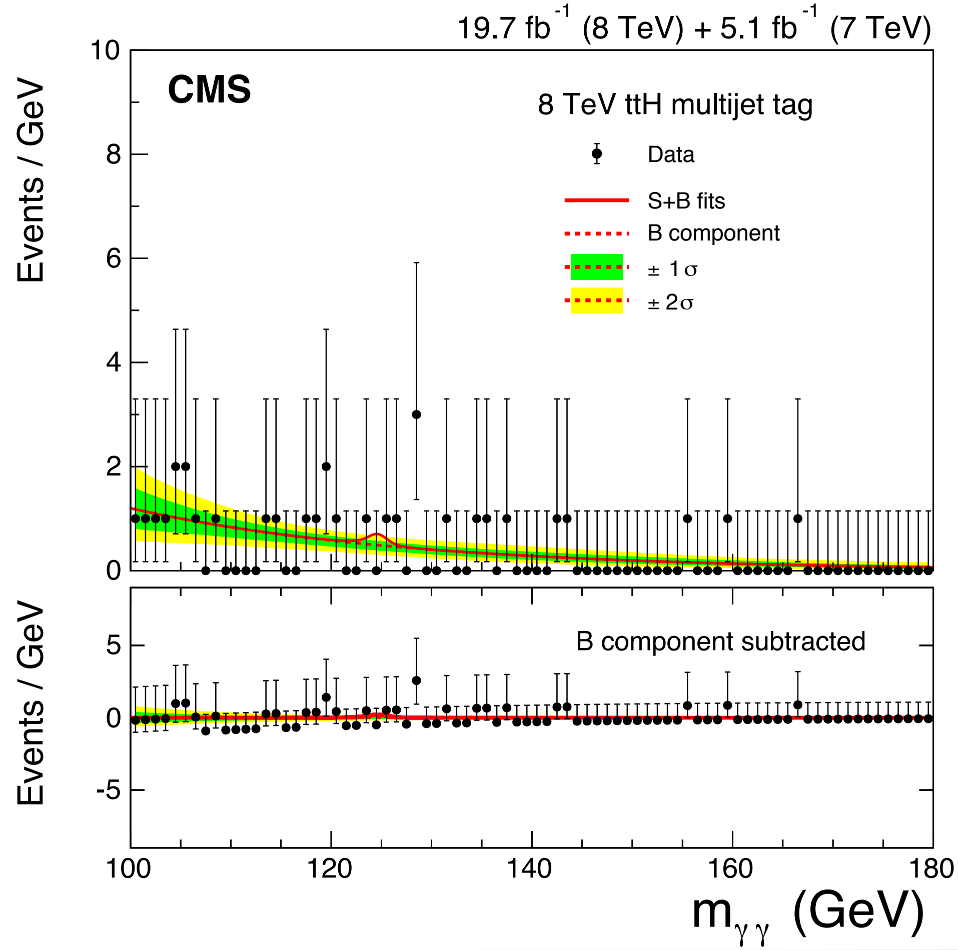


# Invariant mass by category 8 TeV VII

8 TeV ttH lepton tag




8 TeV ttH multijet tag

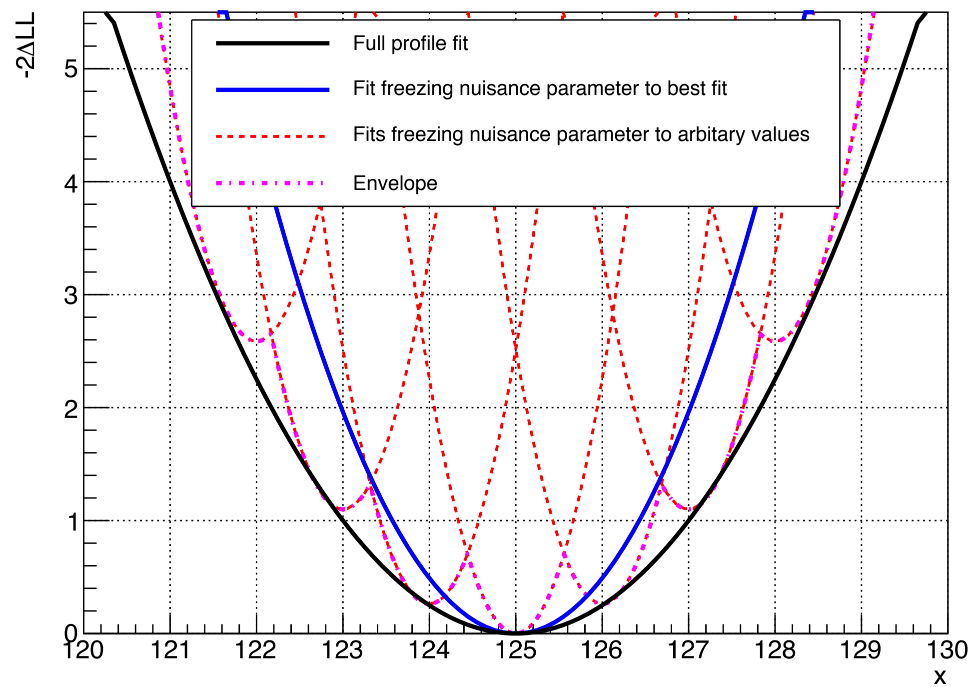


# Envelope method



- Imagine a simple case with one POI, x, and one nuisance parameter, $\theta$
  - Black line – standard likelihood scan of x profiling $\theta$
  - Blue line – standard likelihood scan of x freezing $\theta$ (stat only)
  - Red lines – standard likelihood scans of freezing $\theta$ to different values
  - Pink line – Envelope around this

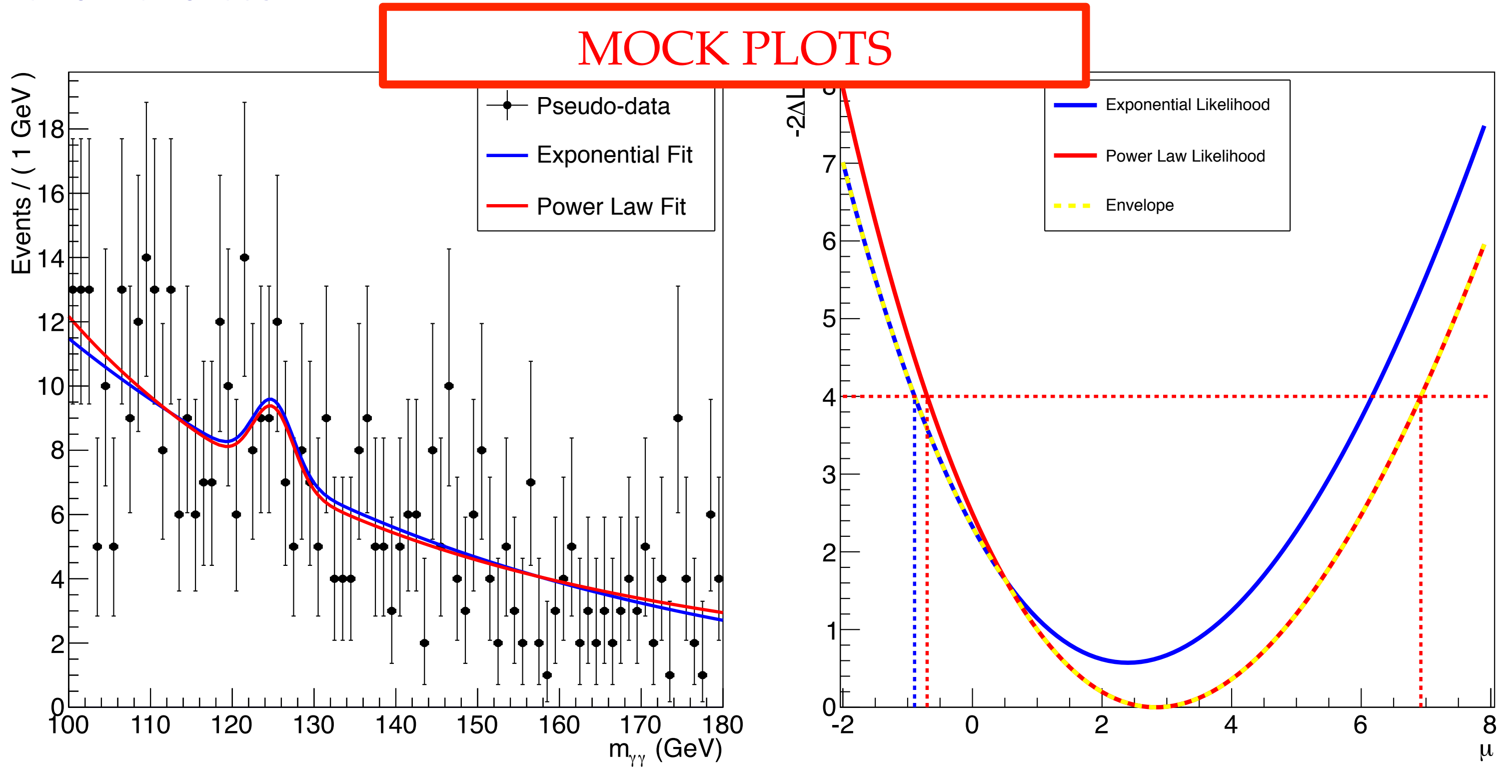
- If you sample enough of the infinite $\theta$ phase-space eventually you can reproduce the black curve with the pink "envelope"



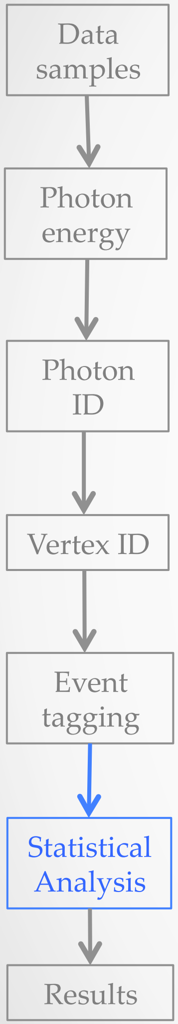
# Envelope method II

Data samples → Photon energy → Photon ID → Vertex ID → Event tagging → **Statistical Analysis** → Results

- For a toy example
  - one category
  - two function choices, $e^{-px}$ and $x^{-p}$, both with 1 free param
- Profile "envelope" gives best fit with $x^{-p}$
- 2 sigma error is enlarged by the envelope
- In principle envelope method will increase uncertainty because of different function choices

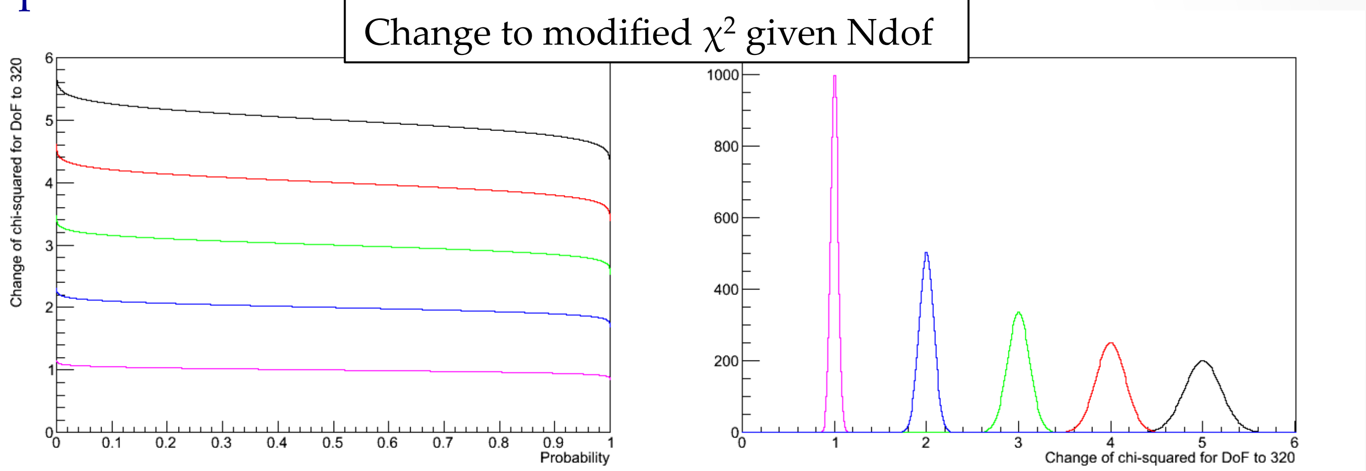


# Envelope method III




- This is simple enough when different functions have the same number of free params
- However when comparing to functions of the same type with different numbers of free params
  - Function with more free parameters will give lower negative likelihood
- Consequently correct this by converting -2NLL = $\chi^2$ into equivalent $\chi^2$ with 0 free parameters

Change to modified $\chi^2$ given Ndof

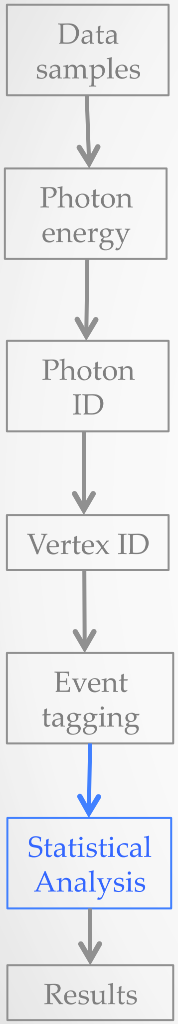



- Can see this results gives an average correction to -2NLL of 1 per degree of freedom
- Our likelihood is redefined as:

$$2NLL = \min\{-2\ln\mathcal{L}_i + N_i\}_i$$

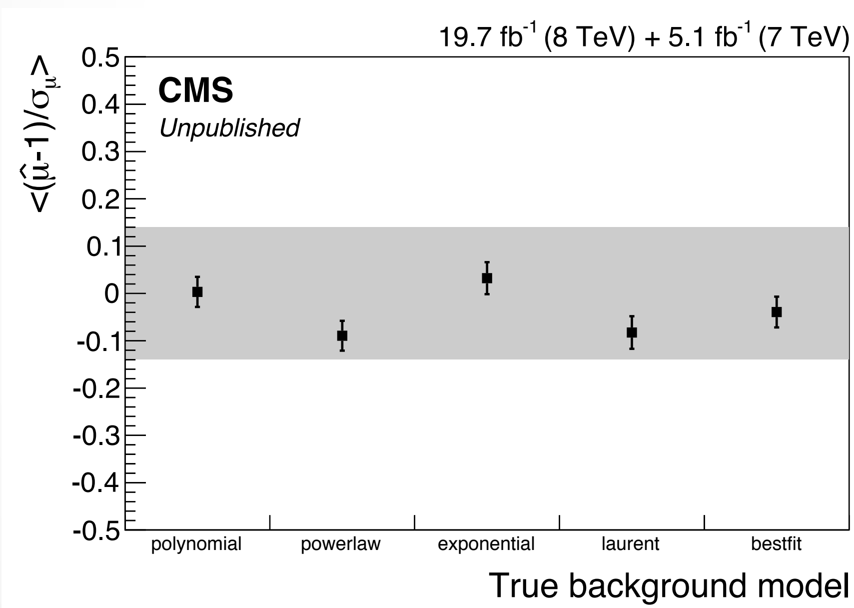
*i* labels a discrete number of functions each with $N_i$ free parameters

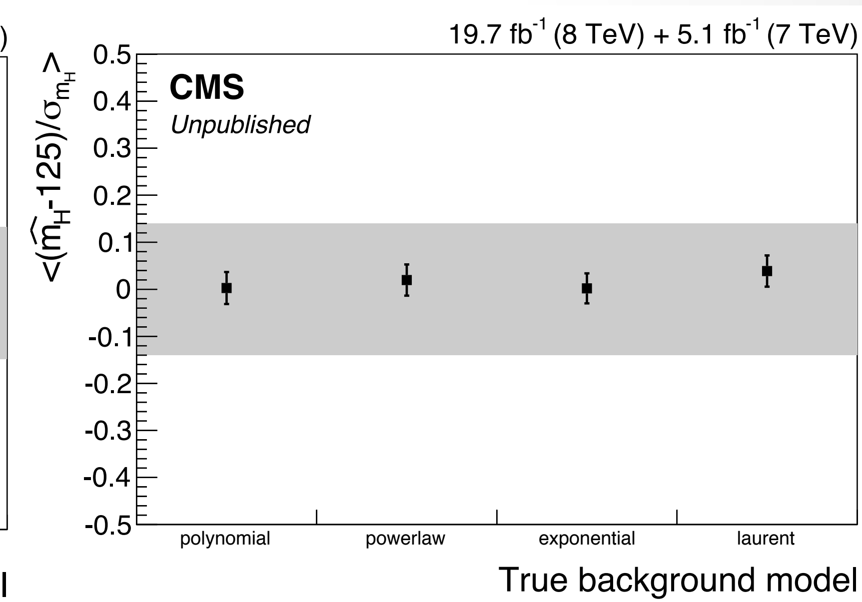
# Envelope method IV



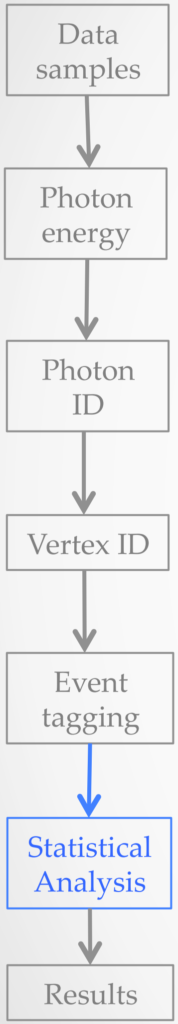

- Previous background strategy was to use high (ish) order Bernstein polynomials
  - increase order until pull mean < 14% of pull sigma from bias studies
  - add more degrees of freedom in the fit so that statistical uncertainty swamps the systematic
- Profiling over several function choices
  - Best fit functions typically have fewer free parameters
  - Systematic error (from function choice) is handled by the method
  - Overall sensitivity of envelope method is better than polynomial method

Overall signal strength and mass bias for different background scenarios



# Choosing envelope functions



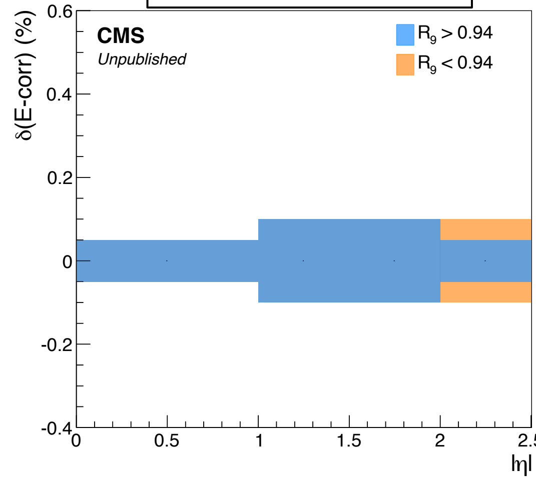

- In principle would like to sample the “infinite” phase space of all possible functions
  - practically this is impossible
- Instead choose from four classes which we expect can reasonably cover the phase-space
  - power law sum
  - exponential sum
  - laurent series
  - Bernstein polynomials
- Lowest order selected by loose G.O.F test
- Highest order selected by loose variant of the fTest

# Back Up (Systematics)

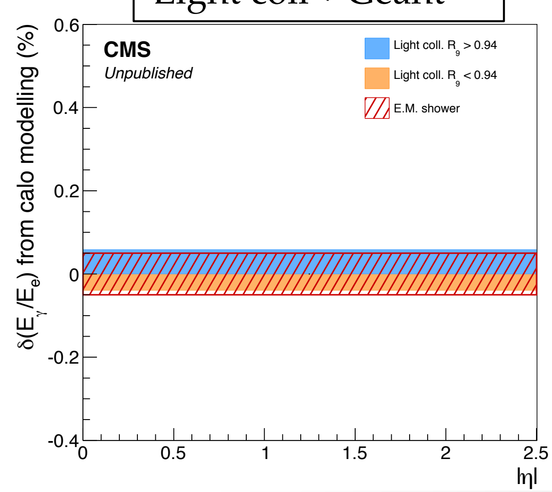
# Mass uncertainties summary II

- Photon energy scale corrections
- 8 uncertainties
  - 2x$\eta$, 2x$R_9$ (for 7 and 8 TeV)
  - partial correlation across years
  - contributes 0.05 GeV to total mass error
- Z line shape
- 1 uncertainty
  - 1 x Z mass uncertainty (0.01%)
  - Effect of 10 MeV uncertainty on Z mass
  - contributes 0.01 GeV to total mass error
- Residual non-linearity in scale
- 2 uncertainties
  - 1 x 7 and 8 TeV
  - partial correlation across years
  - contributes 0.10 GeV to total mass error
- e/$\gamma$ differences in MC
- 3 uncertainties
  - 1 x Material (contributes 0.07 GeV)
  - 1 x FNUF (contributes 0.02 GeV)
  - 1 x Geant 4 (contributes 0.06 GeV)
  - fully correlated across years
  - contributes 0.10 GeV to total mass error

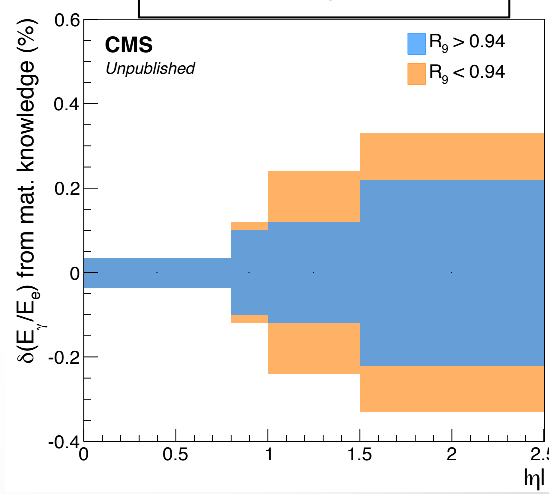
Scale corrections




Light coll + Geant




Material




**Other contributions studied with negligible effect**
- Gain switch (<2% of events at higher gain)
- Residual OOT-PU mismodelling

# Energy scale correction uncertainties

Data samples → Photon energy → Photon ID → Vertex ID → Event tagging → Statistical Analysis → Results

- These uncertainties arise from corrections to the photon energy scale from Z→ee studies
  - It is the uncertainty on the correction applied
  - Sources:
    - R9 reweight to $H\rightarrow\gamma\gamma$ photon distribution
    - Changing electron selection
    - Method (studied with toys)
    - Changing $m_{ee}$ fit range
  - Propagated from per-photon level to the diphoton invariant mass shape

| | Barrel | | Endcap | |
|---|---|---|---|---|
| | $\lvert\eta\rvert<1$ [%] | $1<\lvert\eta\rvert<1.4$ [%] | $1.4<\lvert\eta\rvert<2$ [%] | $2<\lvert\eta\rvert<2.5$ [%] |
| $R_9 > 0.94$ | 0.05 | 0.10 | 0.10 | 0.05 |
| $R_9 < 0.94$ | 0.05 | 0.05 | 0.10 | 0.10 |

  - Correlates energy scale across analysis categories

# Difference between e's and $\gamma$'s

Data samples
Photon energy
Photon ID
Vertex ID
Event tagging
Statistical Analysis
Results

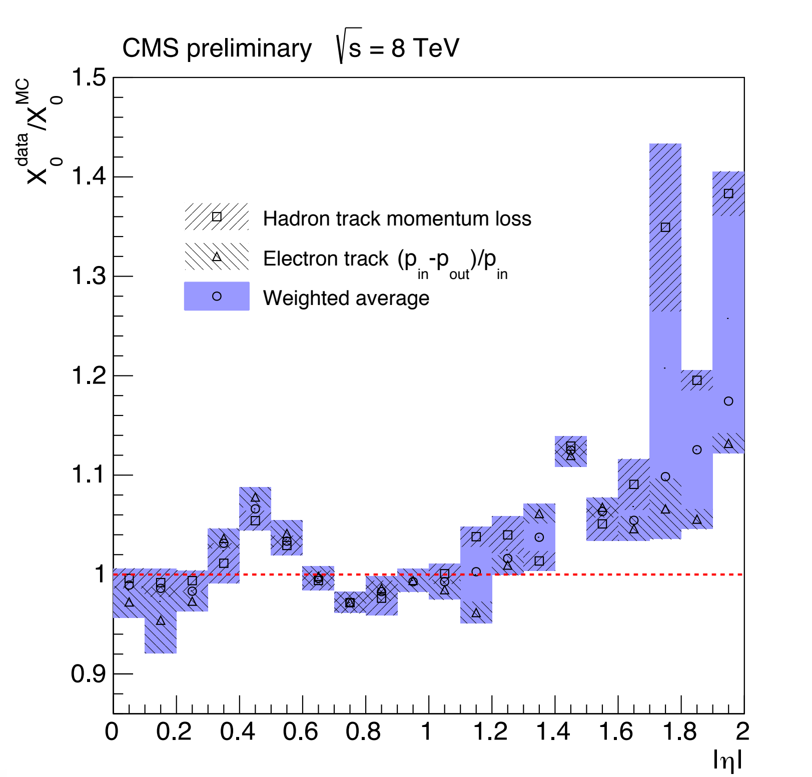
- There are residual further uncertainties because the detector responds differently to electrons and photons
- Extrapolation factors above are derived from data/MC differences
  - the absolute difference in detector response between e's and $\gamma$'s is not what is important (these are clearly different)
  - the difference in modelling of electrons and photons from data to MC is important
- Additional uncertainties:
  - imperfect description of material in the tracker in MC (Material)
  - variation in scintillation light peak between e's and $\gamma$'s (FNUF / LightColl)
  - imperfect EM shower simulation in Geant4 (Geant4)
  - remaining imperfections in OOT-PU (found to have a negligible effect)

# Tracker material description

Data samples → Photon energy → Photon ID → Vertex ID → Event tagging → **Statistical Analysis** → Results

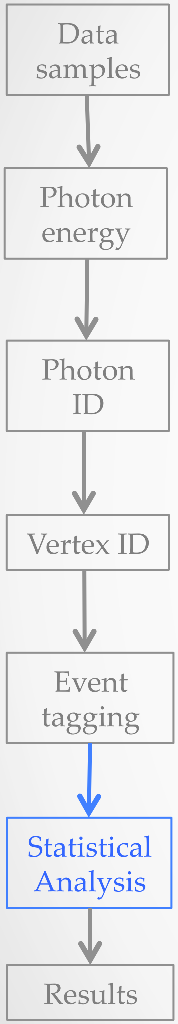
- Results of the tracker material group suggest ~5% missing material in the MC for $|\eta| < 1$ and ~10 % for $|\eta|>1$)
- To assess the systematic from material modelling we have studied extra geometries were the tracker material is increased by 10% for $|\eta| < 1$ and 20% for $|\eta|>1$
  - $m_H = 90$ to disentangle from extrapolation studies
- The effect between electrons and photons of having the extra material is quantified with:

$$\frac{< E_{rec}/E_{gen} >_{\mathrm{new},\gamma} - < E_{rec}/E_{gen} >_{\mathrm{new},e}}{< E_{rec}/E_{gen} >_{\mathrm{std},\gamma} - < E_{rec}/E_{gen} >_{\mathrm{std},e}}$$




- The effect ranges from 0.03% to 0.3%

# Tracker material description II




- Sources:
  - Variation of Gaussian fit range
  - electron / photon id selection
- Propagated from per-photon level to the diphoton invariant mass shape

| Photon category | E-scale Uncertainty [%] |
|---|---|
| Central EB ($\|\eta\| < 0.8$) low $R_9$ | 0.035 |
| Central EB ($\|\eta\| < 0.8$) high $R_9$ | 0.033 |
| Intermediate EB ($0.8\ \|\eta\| < 1.0$) low $R_9$ | 0.058 |
| Intermediate EB ($0.8\ \|< \|\eta\| < 1.0$) high $R_9$ | 0.12 |
| Outer EB ($1.0 < \|\eta\| < 1.44$) low $R_9$ | 0.22 |
| Outer EB ($1.0 < \|\eta\| < 1.44$) high $R_9$ | 0.34 |
| EE ($\|\eta\| > 1.56$) low $R_9$ | 0.22 |
| EE ($\|\eta\| > 1.56$) high $R_9$ | 0.34 |

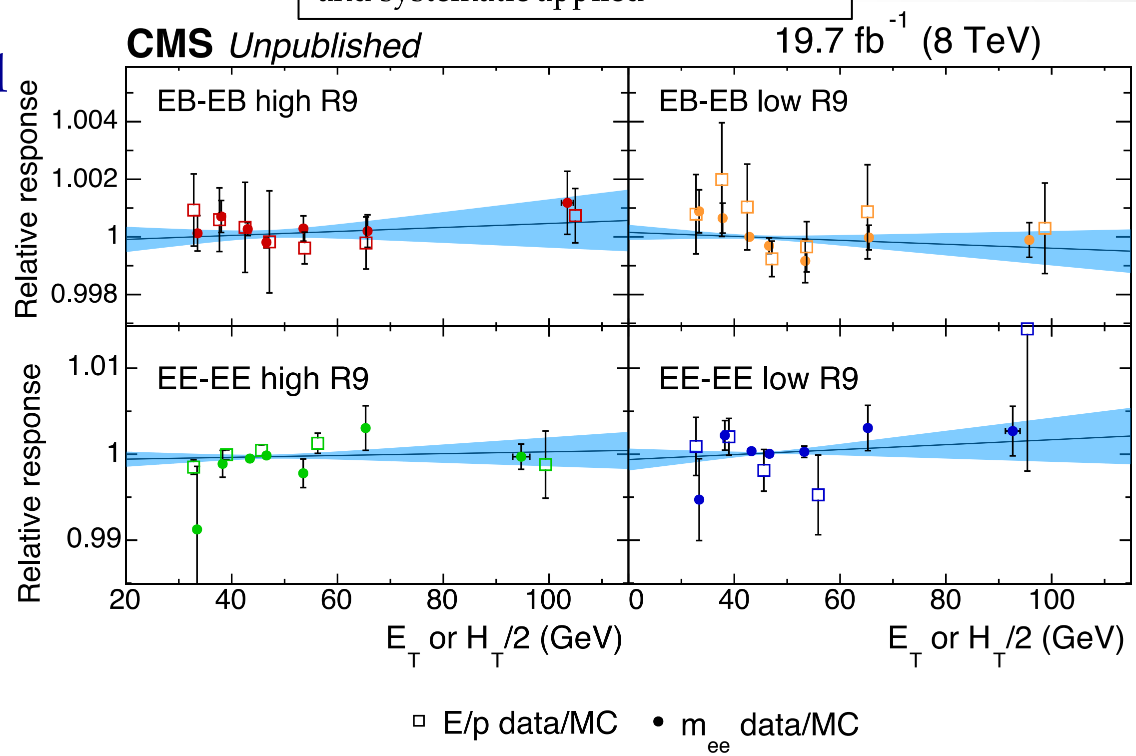
- Correlates energy scale across analysis categories

# Extrapolation from $m_Z$ to $m_H$

Data samples → Photon energy → Photon ID → Vertex ID → Event tagging → Statistical Analysis → Results

- Imperfect modelling in MC of differences between showers from $Z \rightarrow ee$ at the $m_Z$ scale and $H \rightarrow \gamma\gamma$ at the $m_H$ scale
- Uncertainty on the residual differential non-linearity
- Check $Z \rightarrow e^+e^-$ peak position in bins of $H_T = E_T^1 + E_T^2$ and also E/p
- All measured contributions are found well covered by quoted uncertainties
- Linearity assumption checked using parabola
- Additional effects checked
  - validity of the linear extrapolation
  - effect of the gain switch

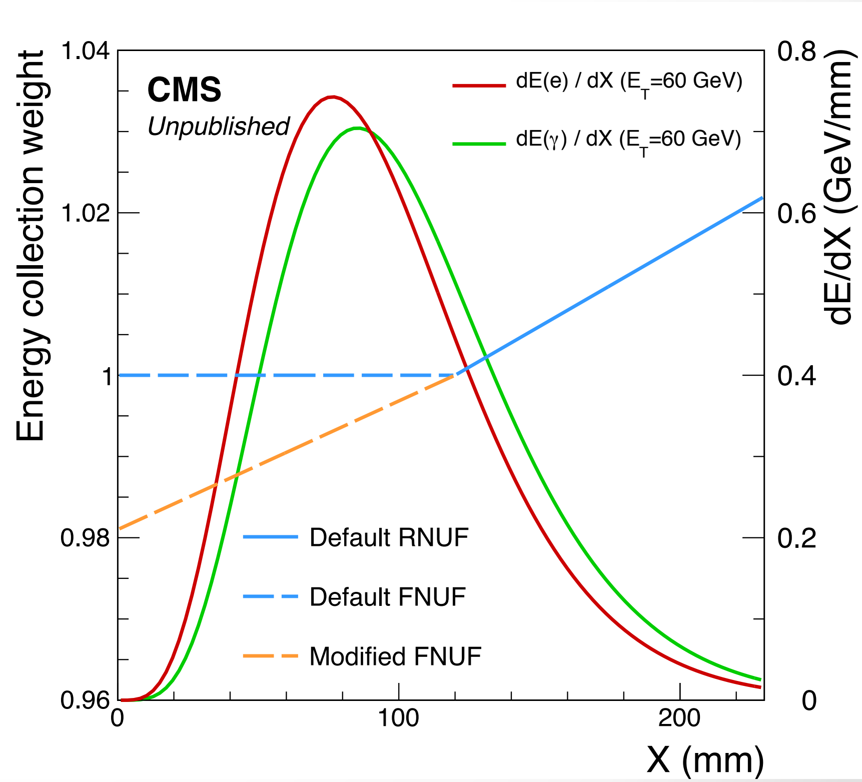
Non-linearity in scale extrapolation and systematic applied



# FNUF / Light Collection

Data samples → Photon energy → Photon ID → Vertex ID → Event tagging → **Statistical Analysis** → Results

- Unconverted photons on average penetrate crystal one radiation length further than electrons
  - simulation includes this non-uniformity for the rear of the crystal
  - does not include it for the front of the crystal
  - this has been measured in the laboratory
  - the effect on the energy scale is found to be at most 0.05% (anti-correlated between converted and un-converted photons)
  - Additional effect due to radiation damage has also been studied
    - smaller than current uncertainty



# Geant 4

Data samples → Photon energy → Photon ID → Vertex ID → Event tagging → **Statistical Analysis** → Results

- Our standard simulation in Geant4 misses a “precise physics” custom fragment which has:
    - more accurate $\gamma$ conversion cross section above 100 GeV
    - more accurate $e^{-}$ bremsstrahlung model below 1 GeV
- We produced some private samples for this study and compute the double ratio:

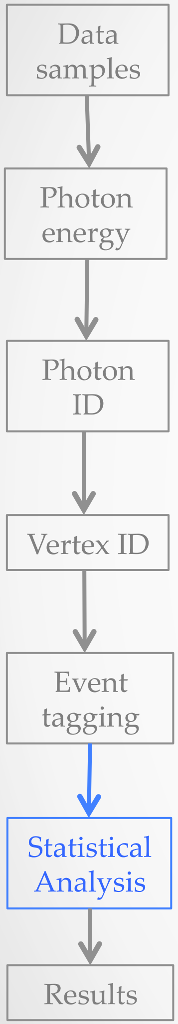
$$\frac{E^{\gamma}_{\mathrm{stdG4}}/E^{e}_{\mathrm{stdG4}}}{E^{\gamma}_{\mathrm{modG4}}/E^{e}_{\mathrm{modG4}}}$$

- A 0.05% uncertainty is added to account for this effect

# Back Up (Alternative Analyses)…

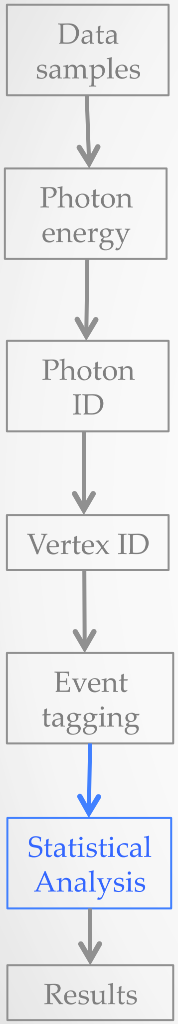
Cut based analysis
Sideband MVA analysis
2D VBF analysis

# Alternative Analyses



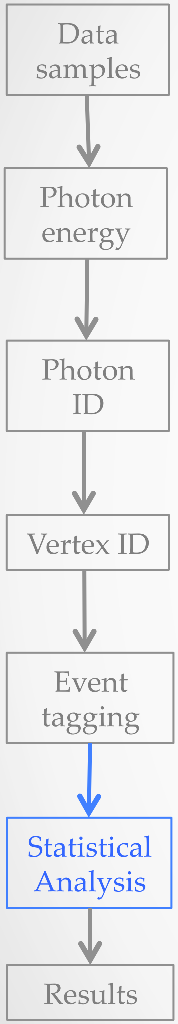

- Cut-based:
  - Photon selection is done in a cut based way
  - No MVAs used in selection or VBF category definitions
  - Categorise events according to $\eta$, $R_9$, $p_T^{\gamma\gamma}/m_{\gamma\gamma}$
  - Cross check of photon selection, event selection and categorisation
- Sideband MVA
  - Categorisation done in 2D of diphoton BDT output and $\Delta m/m$
  - Background extracted from sidebands
  - Cross check of categorisation and background model
- 2D VBF
  - Fits two dimension of $m_{\gamma\gamma}$ and $m_{jj}$ (harder for VBF signal than background)
  - Categorise using mass resolution variable (no diphoton or dijet BDTs)
  - Cross check of VBF selection and extraction of VBF signal
- Cross checked in 2 frameworks
  - high level of synchronisation in selection, tagging
  - high level of agreement in statistical analysis and final results

# Cut-Based analysis

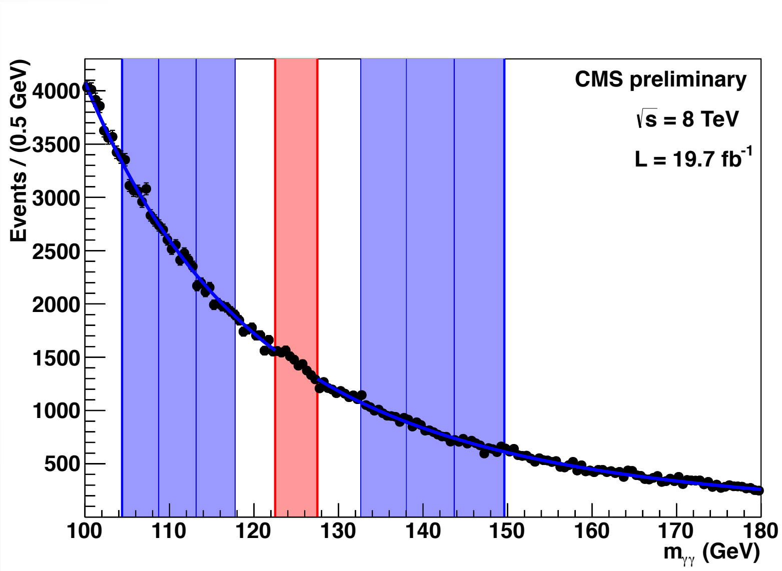


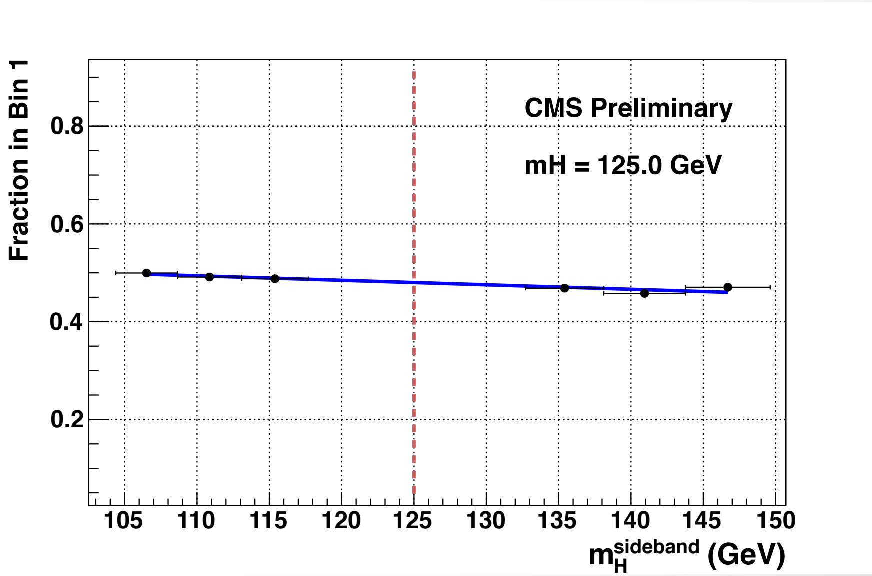

- Photons are selected using "cuts in categories" (CiC) selection
  - No photon ID MVA
  - No diphoton BDT MVA
- VBF selection is purely cut based (2 categories)
  - No dijet kinematics BDT
  - No combined dijet-diphoton BDT
- VH and ttH cuts are identical
  - however lower BDT cut is removed
- Inclusive events are categorised according to 8 bins
  - Both photons EB
  - Both photons R9>0.94
  - Both photons $p_T^{\gamma\gamma}/m_{\gamma\gamma} > 40/125$
- Signal and background models identical to baseline
- Systematics identical to baseline
  - apart from one or two MVA specific
- Sensitivity is 10-20% less than baseline

# Sideband MVA analysis




- Selection and exclusive mode categorisation identical to baseline
- Inclusive categorisation and background determination done differently
  - Categorise on expected S/B in 2D
  - Extract background from simultaneous fit to sidebands

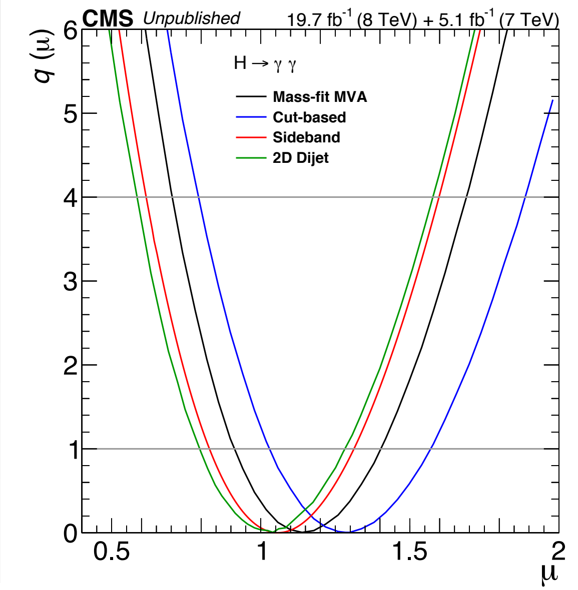


# 2D VBF Analysis

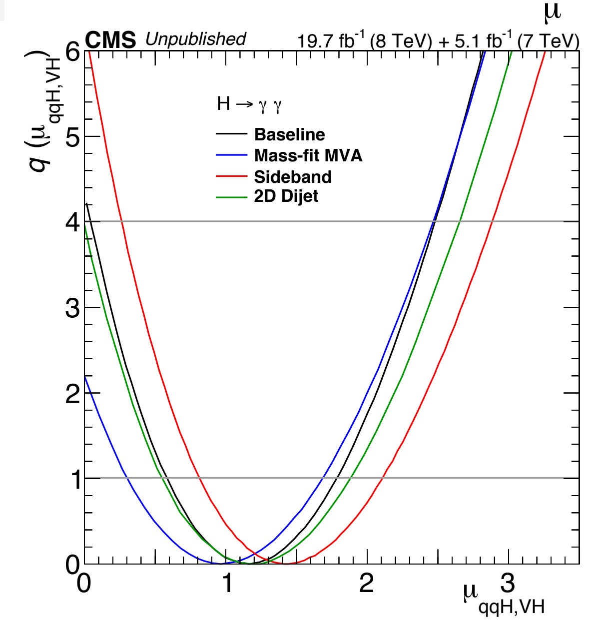
- Selection same as MVA analysis
- Categorise on mass resolution
- Fit in 2 dimensions of $m_{\gamma\gamma}$ and $m_{jj}$

# Comparison between analyses




$\boxed{\mu}$

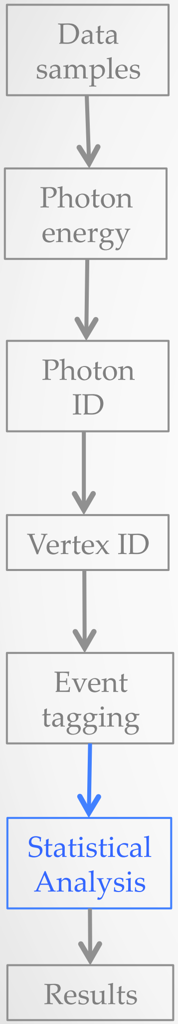
| Systematic | Value | Error |
|---|---|---|
| Baseline (obs) | 1.14 | +0.26 -0.23 |
| Cut-based (obs) | 1.29 | +0.29 -0.26 |
| Sideband (obs) | 1.06 | +0.26 -0.23 |
| 2D Dijet (obs) | 1.04 | +0.25 -0.25 |




$\boxed{\mu_{VBF+VH}}$

| Systematic | Value | Error |
|---|---|---|
| Baseline (obs) | 1.16 | +0.63 -0.58 |
| Cut-based (obs) | 0.96 | +0.73 -0.66 |
| Sideband (obs) | 1.43 | +0.69 -0.61 |
| 2D Dijet (obs) | 1.19 | +0.70 -0.63 |

# Background model cross check




- Still produce results with previous background model procedure
  - use Bernstein polynomials and find order from results of bias study

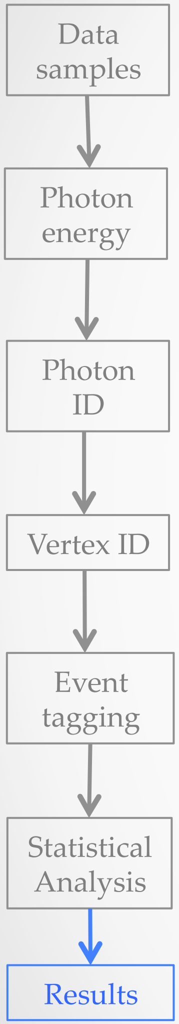
# Spin Analysis

Data samples → Photon energy → Photon ID → Vertex ID → Event tagging → Statistical Analysis → Results

- Use CiC photon selection (less model dependent)
- No exclusive mode tagging
- Categorise events on simply
  - $2 \times \eta$, $2 \times R_9$ (for resolution)
  - $5 \times |\cos(\theta^*)|$ (decay angle in Collins-Soper frame)
- Test different signal model hypotheses:
  - Spin 0 – 0+ SM
  - Spin 2 – 2m+ graviton (gg)
  - Spin 2 – 2m+ graviton (qq)

  Relative yield adjusted by $f_{qq}$
- Also extract SM signal strength in bins of $|\cos(\theta^*)|$
  - compare to Asimov expectation for different spin models

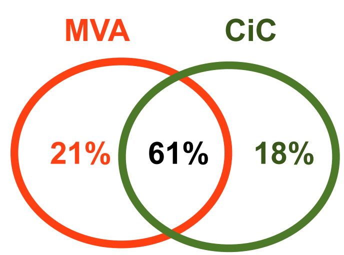
# Jack-knife comparison



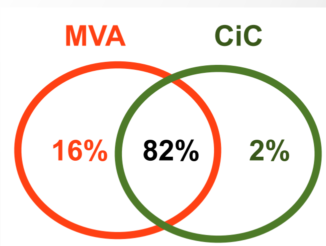

- Jack-knife provides estimate of expected width, $\sigma(\delta\mu)$, between two correlated analyses using sub-samples of each dataset
  - Used Bernstein polynomial background model for speed

| Analysis 1 | Analysis 2 | $\sigma(\delta\mu)$ | $\delta\mu$ (obs) | Linear correlation |
|---|---|---|---|---|
| Legacy MVA 8 TeV | Legacy CiC 8 TeV | 0.20 | 0.19 | 74% |
| Legacy MVA 7 TeV | Legacy CiC 7 TeV | 0.42 | 0.17 | 72% |
| Legacy MVA 8 TeV | Moriond MVA 8 TeV | 0.21 | 0.22 | 71% |
| Legacy CiC 8 TeV | Moriond CiC 8 TeV | 0.21 | 0.03 | 76% |
| Legacy MVA (envelope) 8 TeV | Legacy MVA (Bernsteins) 8 TeV | 0.22 | 0.35 | - |

CiC – MVA Overlap (Legacy **Data** 8 TeV)



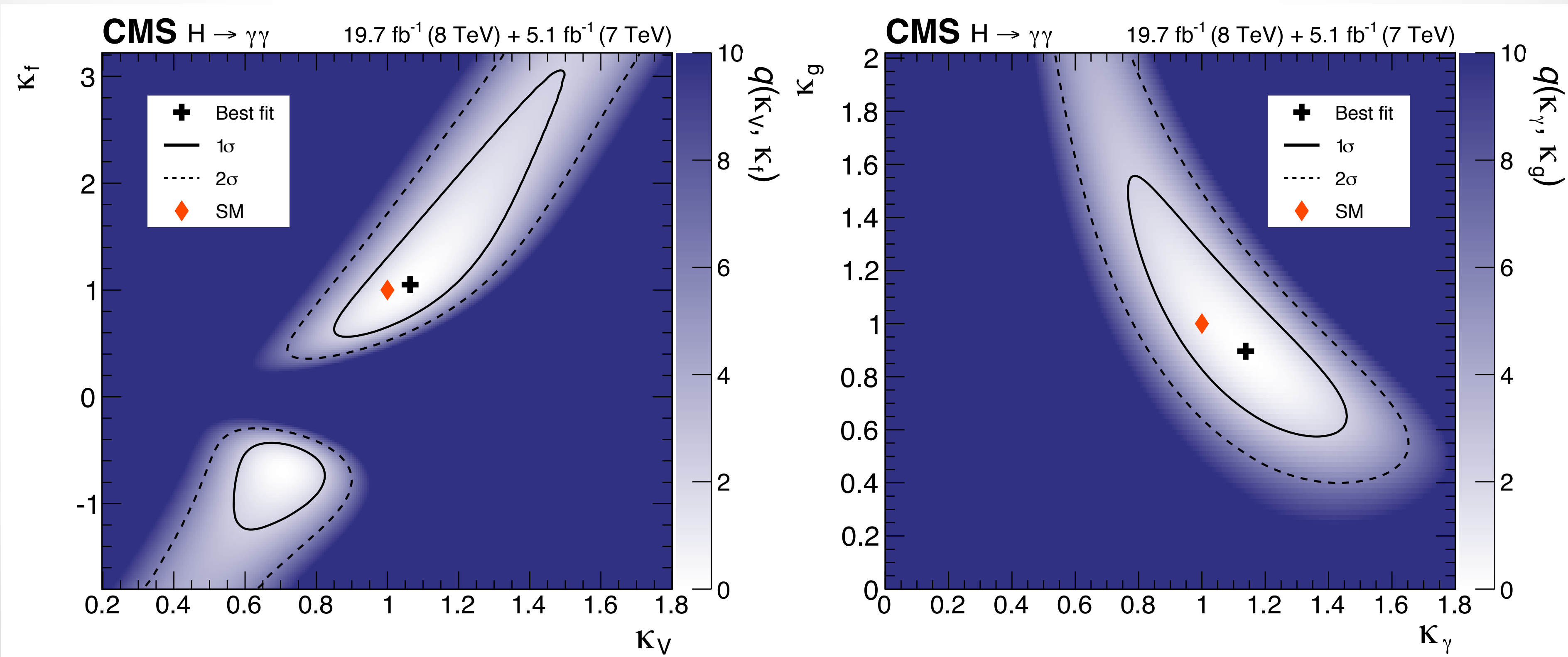

CiC – MVA Overlap (Legacy **Signal** 8 TeV)



# Back Up (Results)

...

# Couplings Fits



# Compatibility between years

- Compatibility between 7 and 8 TeV is ~2.2σ
- When evaluated at a common best fit mass ~1.9σ
- Considerable part of the difference comes from very high signal strength in VBF cat 0 at 7 TeV
    - removing this category from the fit brings compatibility to ~1.5σ

Inv mass in just 7 TeV dijet tag cat 0