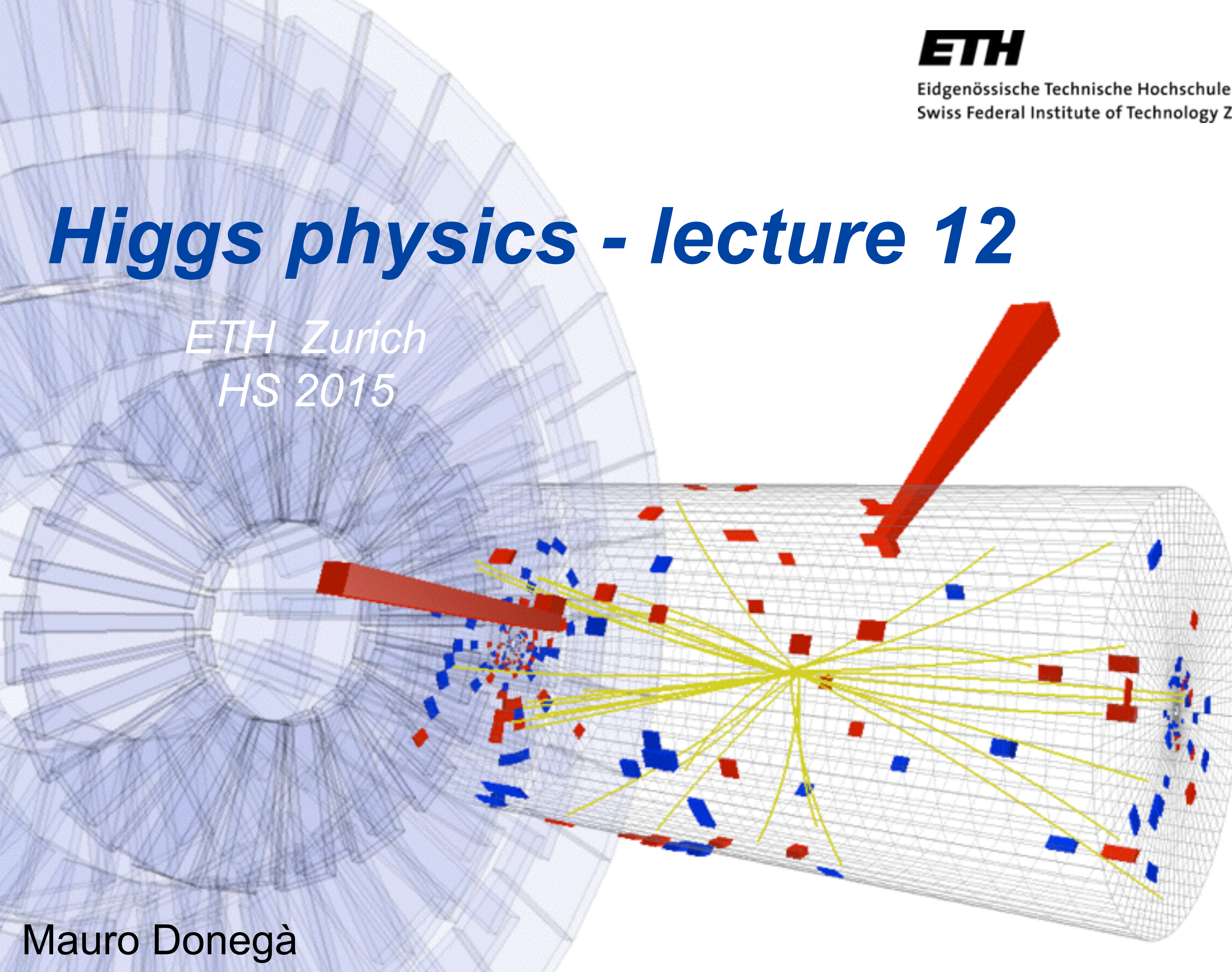
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Higgs physics - lecture 12

ETH Zurich
HS 2015



Mauro Donegà

Outline

Lectures

1
- Introduction
- Accelerators
- Detectors
- EW constraints

2
- Search at LEP1 / LEP 2
- Statistics: likelihood and hypothesis testing

3
- Searches at TeVatron
  - Channels overview
  - Neural Networks
  - Results

4
- Boosted Decision Trees
- Statistics at the LHC

5
- LHC
  - Dissect one analysis $H \to \gamma\gamma$
  - Channels overview
  - Higgs properties

6
- Extras
  - Differential distributions
  - Off shell
  - Beyond Standard Model
  - pseudo-observables / EFT

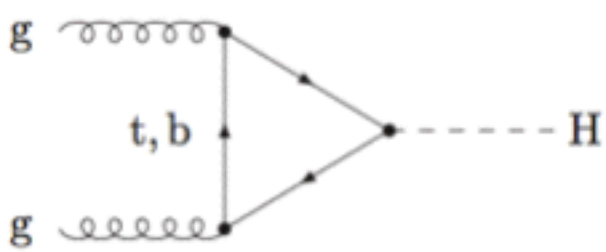
Exercises

- W mass
- CLs
- Hbb TeVatron
- SciKit MVA
- Toy CVCF

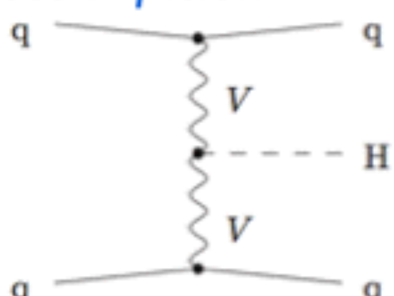
LHC Channels overview

Production modes: recap

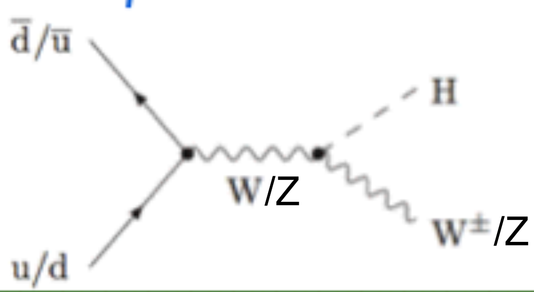
gluon fusion



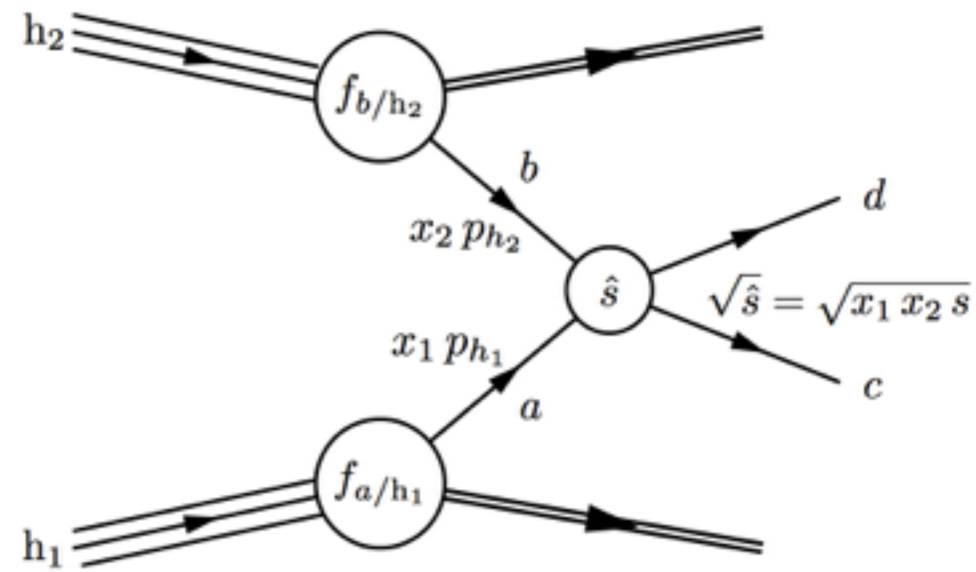
vector boson fusion



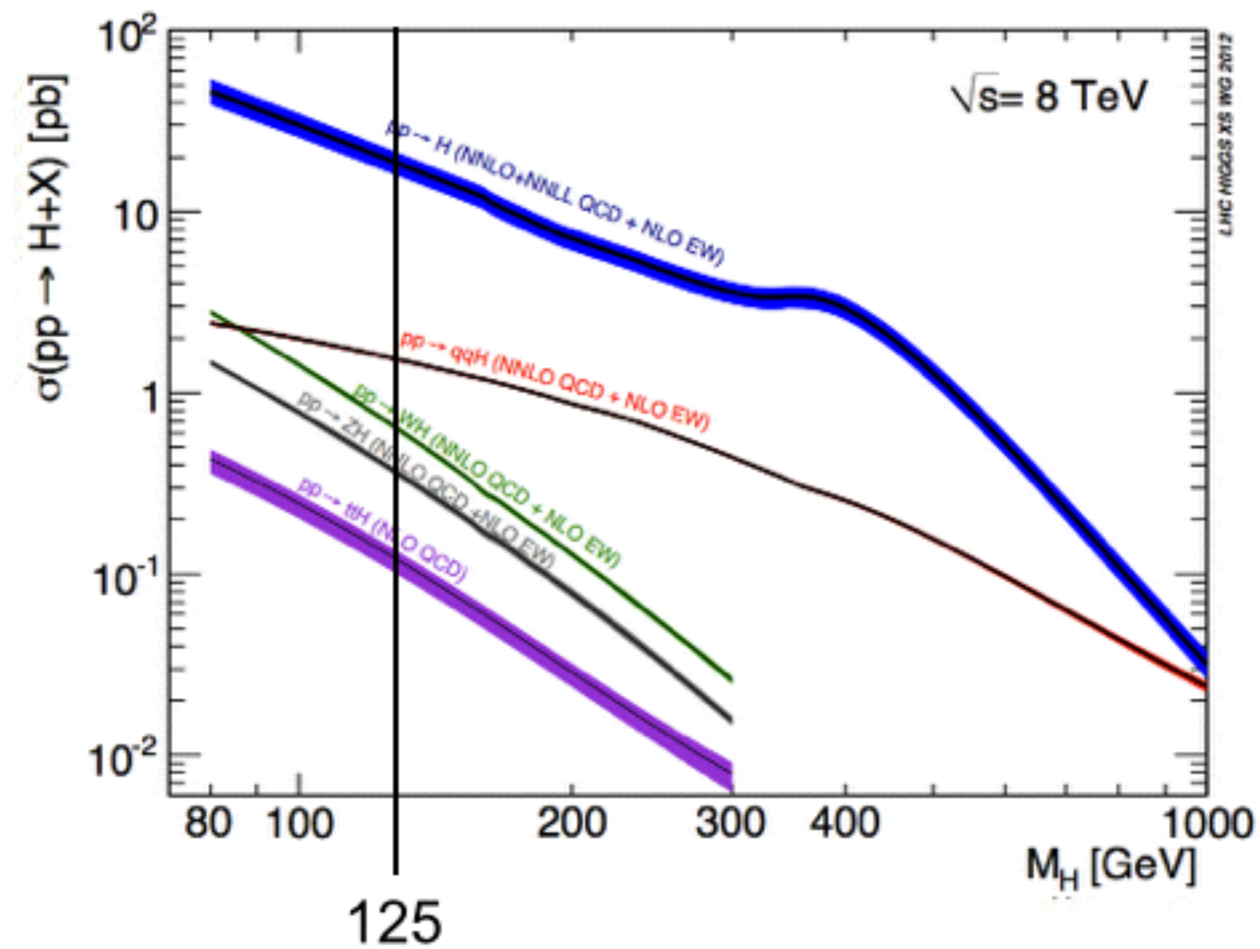
associated production



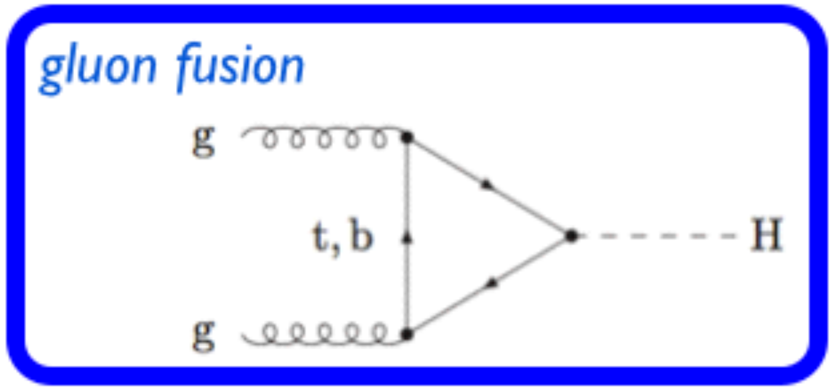
tt̄H

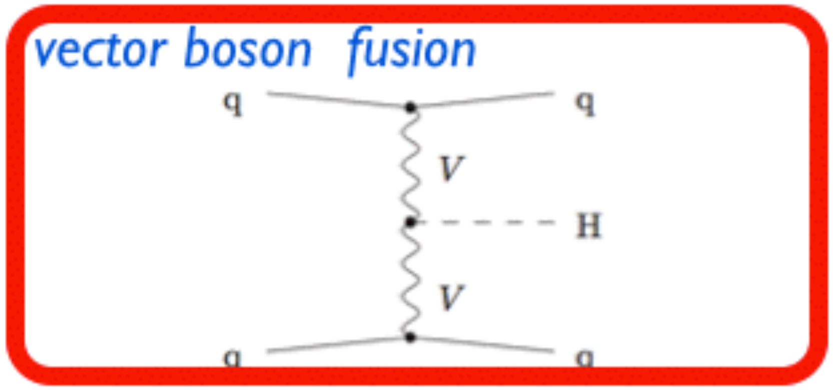


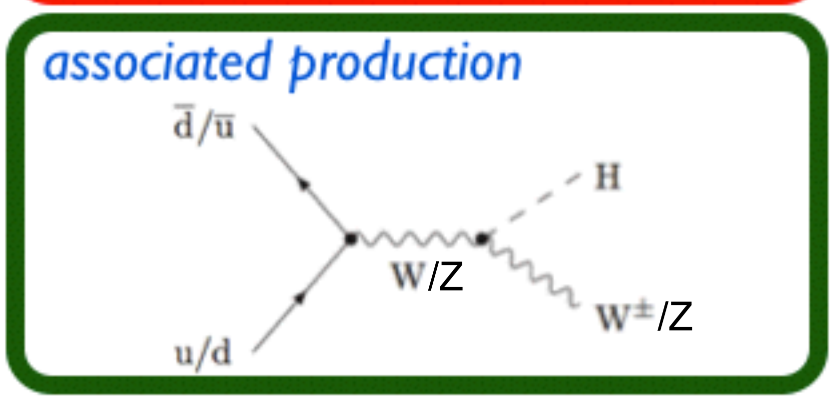
$$d\sigma(h_1 h_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_{a/h_1}(x_1, Q^2) f_{b/h_2}(x_2, Q^2) d\hat{\sigma}^{ab\to cd}(Q^2)$$

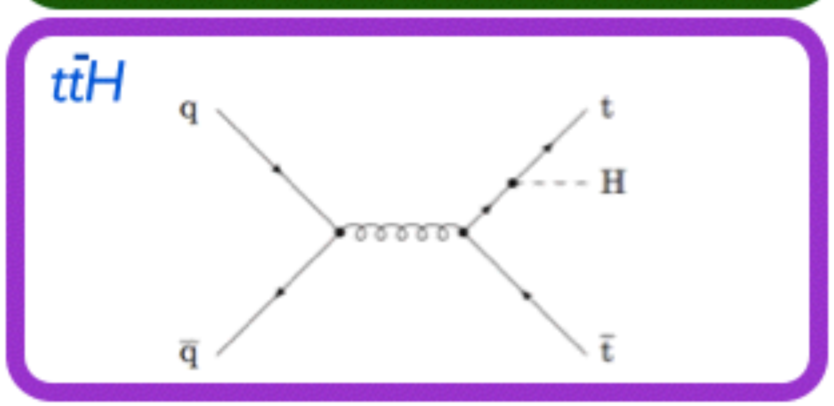


Production modes: signatures









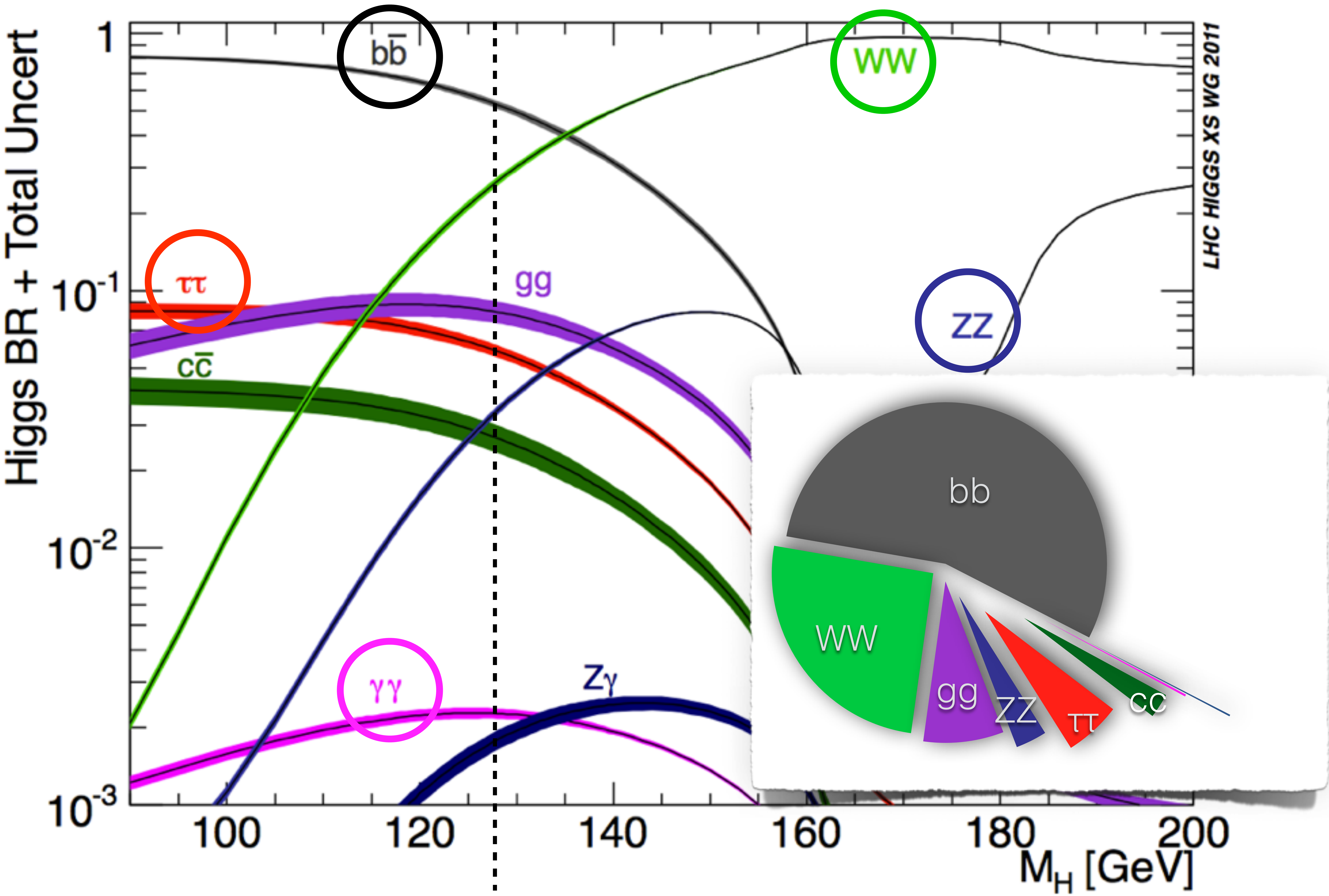
ggF:
- largest cross section
- no extra jet activity

VBF:
- harder pT spectrum
- two high eta jets (large rapidity gap no colorflow)

VH:
- tag on the presence of the W/Z
- pT spectrum similar to VBF

ttH:
- busy environment influence the isolation
- tag on the tops (high pT leptons, b-jets, #jets)

Decay modes: recap



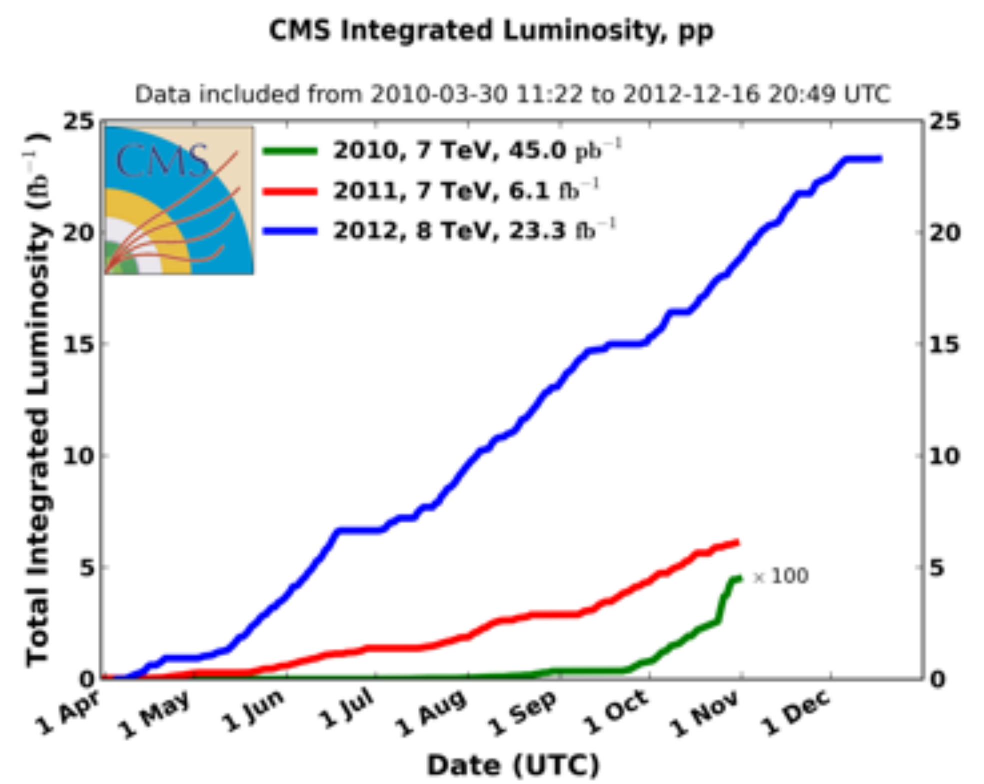
Luminosity delivered at the LHC

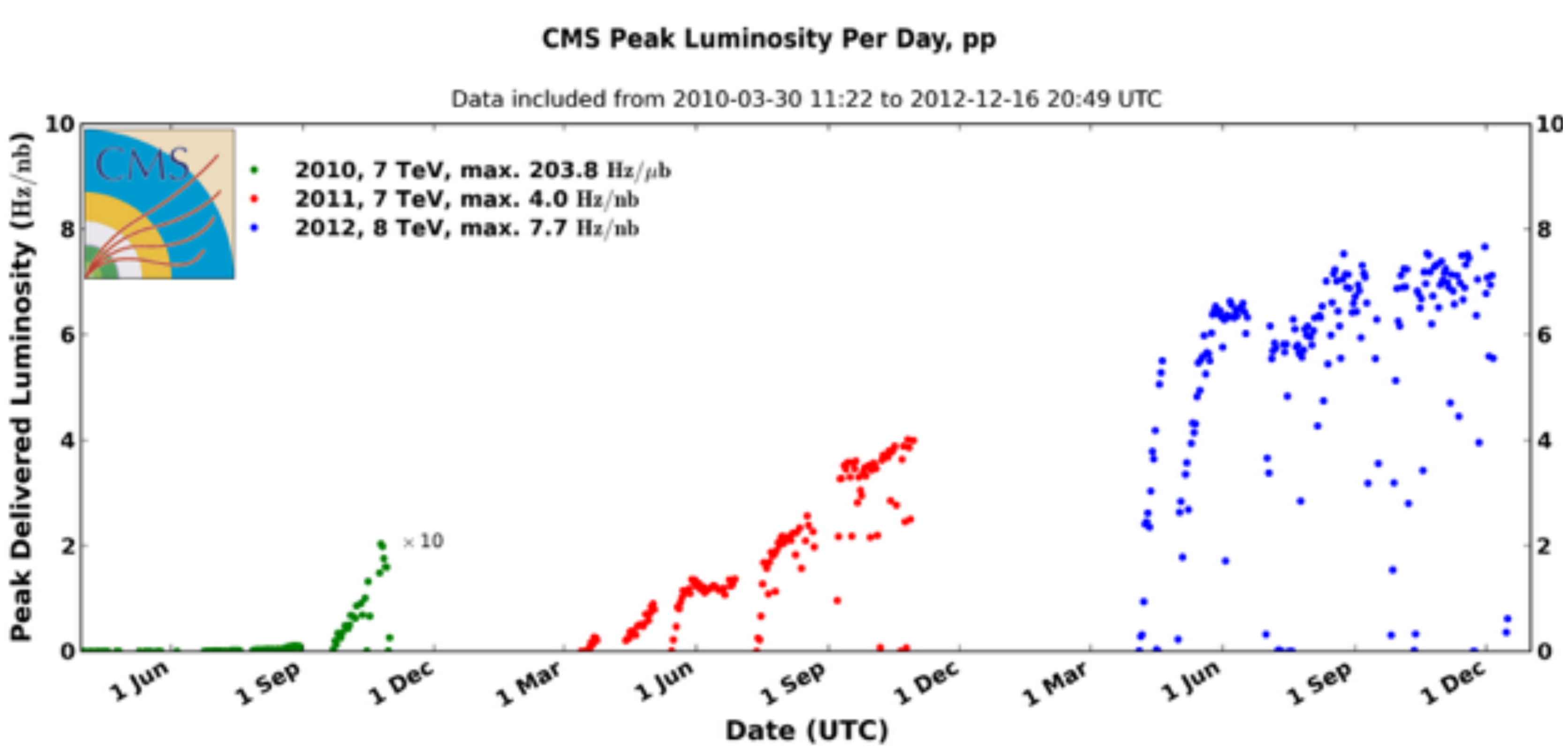
Instantaneous luminosity: o(10^{11}) protons/bunch

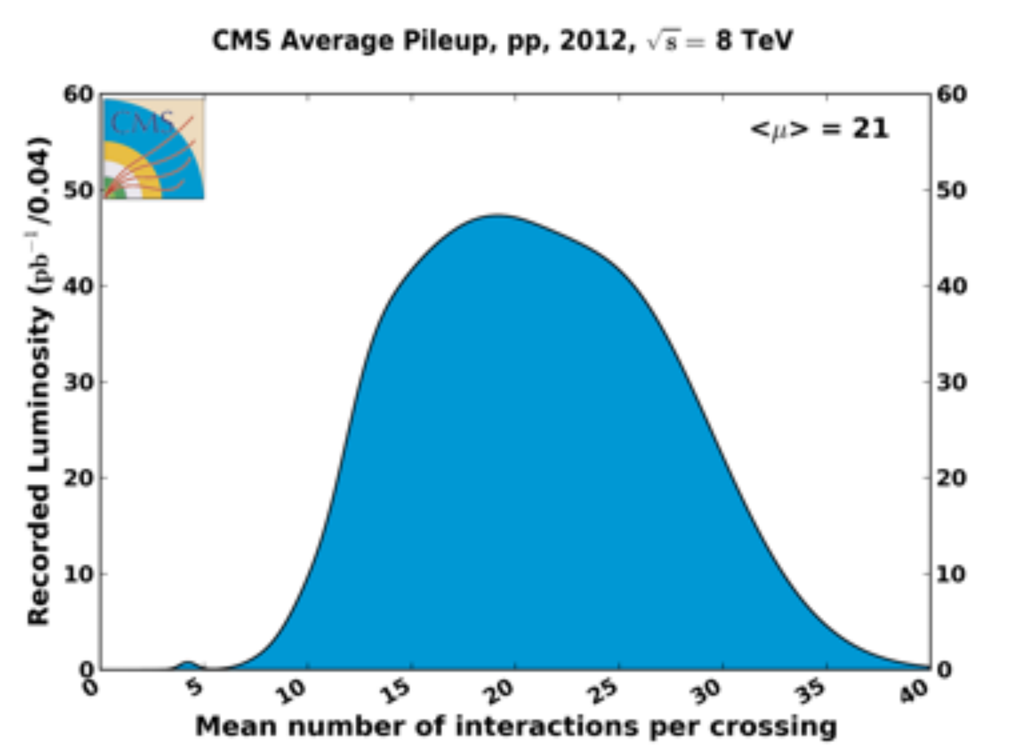
- $3.5\ 10^{33}$ /cm^{2}s @ 7 TeV
- $7.7\ 10^{33}$ /cm^{2}s @ 8 TeV

Useful conversion: 10^{33}/cm^{2}s = 1 /nb s. This way, given a cross section, it's trivial to get the number of events. (How many top / Higgs are produced per second ?)

<PU> ~ 10 @ 7 TeV
~ 20 @ 8 TeV

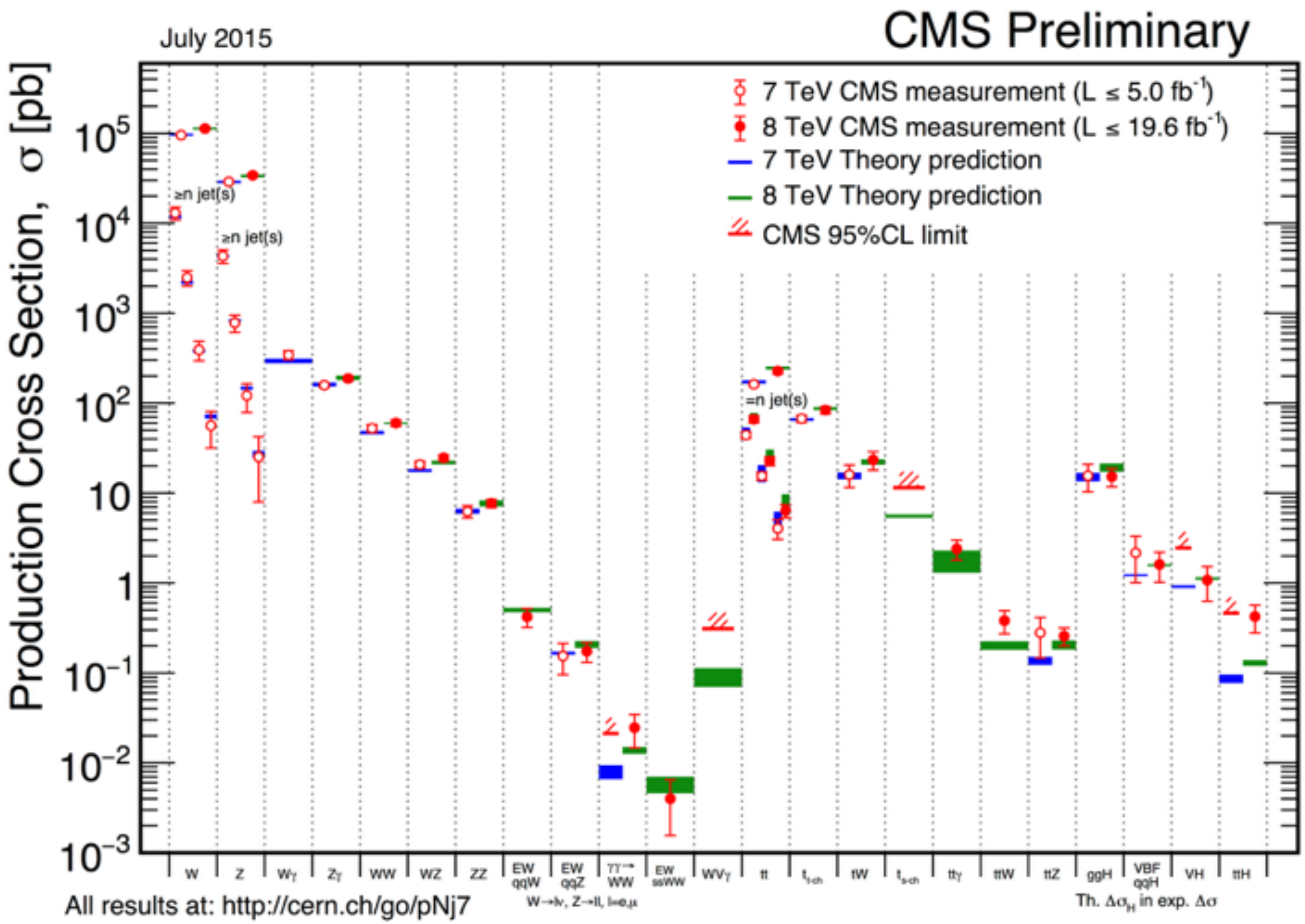






Before going to searches…

“rediscover” the SM and make sure your prediction are correct.



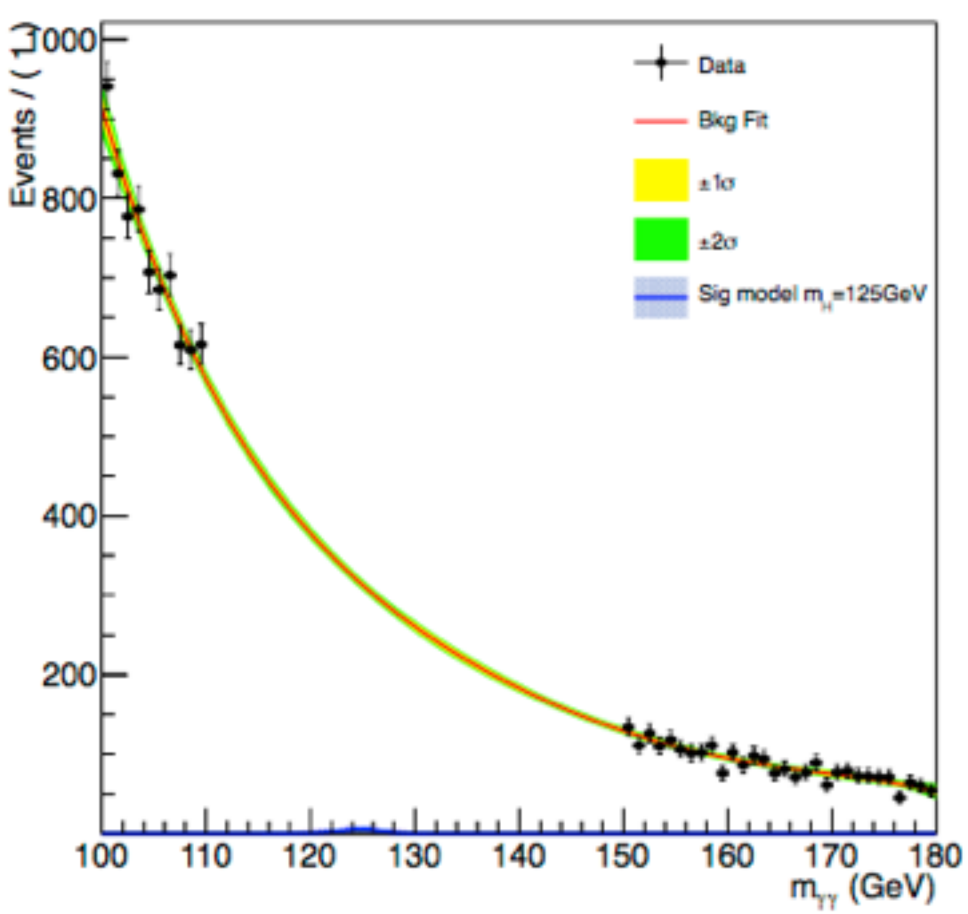
The NNLO revolution: all production cross section are computed at NNLO in α_S NLO in α

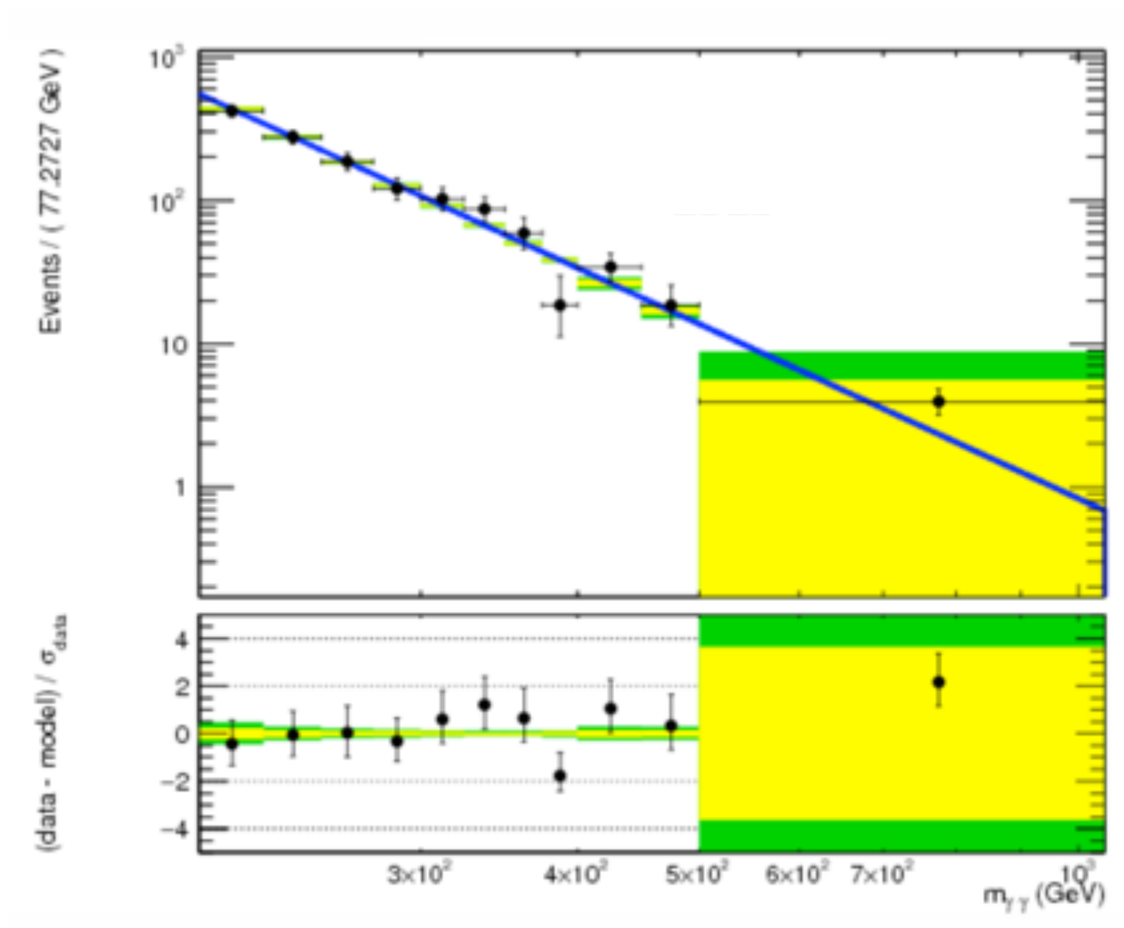
(but the ttH NLO at α_S)

Blinded analysis

Rule #0: NEVER use data to optimise your selection criteria!

All searched at the LHC are “blind”:
- define a signal region, sidebands/control/background regions
- use signal model as described by MC
- data in the sidebands: can be looked in any variable (even the discriminating/search one)
- data in the signal region of the discriminating variable(s) cannot be looked at
- data in the signal region can be used in fits, blinding the data





Reminder: basic analysis steps

1- Select the events online:
trigger (typically as loose as you can manage the detector readout rate)

2- Offline event selection:
reduce the dataset to increase the purity of in terms of signal candidates

3- Categorise the events to maximise the analysis sensitivity
(large S/B, better signal resolution…)

4- Signal extraction / Statistical inference
estimate the amount of background in each class (cut and count / fit)
parameters estimation / hypothesis testing

NB: There is more than one way to analyse the data !
The techniques shown here corresponds to the final Run1 published results

For convenience I will mostly show CMS results on the individual channels

Bosonic decays

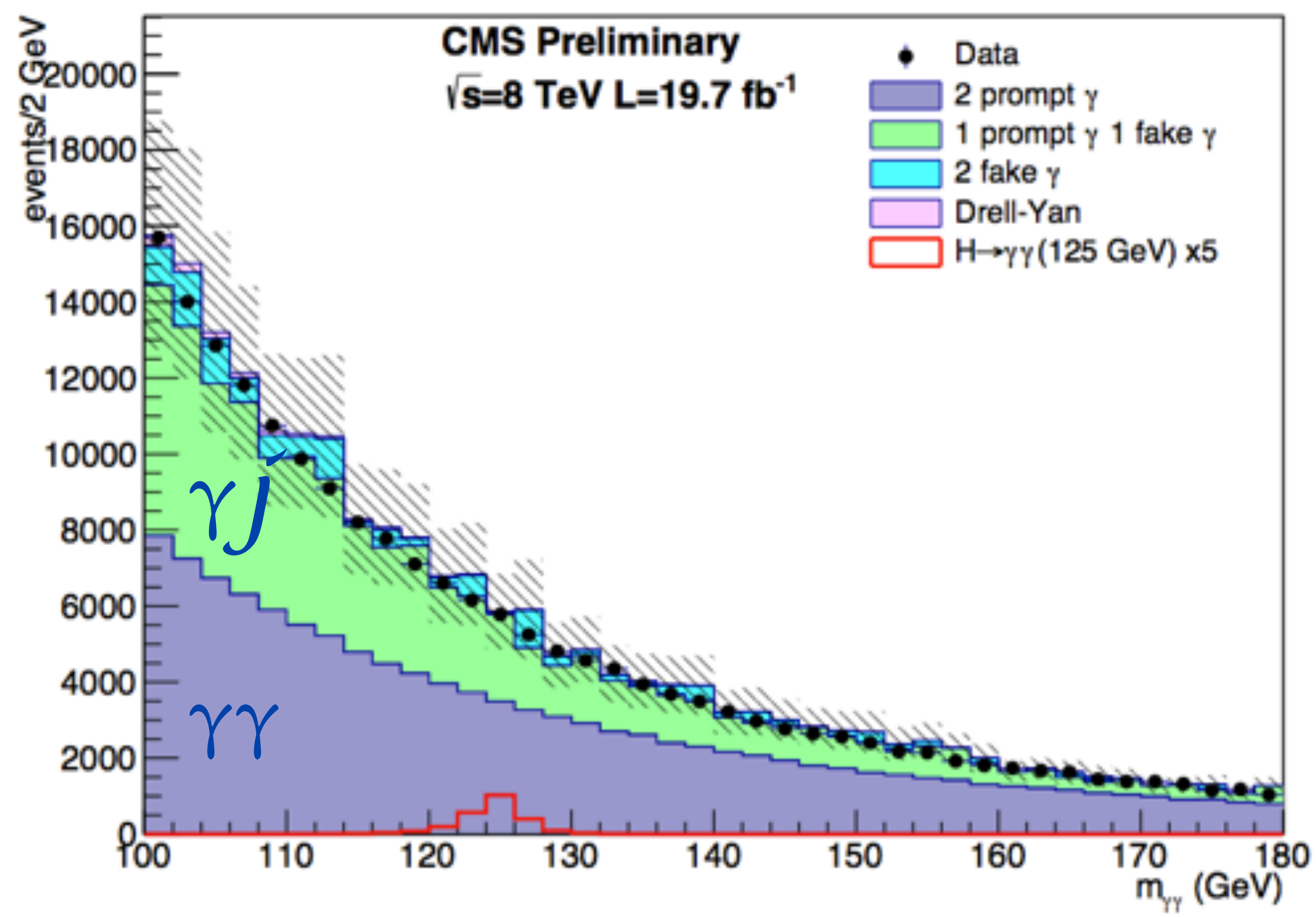
Dissect one analysis: H→$\gamma\gamma$

Golden channel !
Narrow resonance on a large steeply falling background

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\alpha)}$$

Analysis steps:

- select high pT isolated $\gamma\gamma$
- get the correct vertex
- get the best energy resolutions (see mass)
- photon Identification (gamma/jet)
- events classification
- model the background
- extract the signal
- measure properties



$H \rightarrow \gamma\gamma$ diphoton vertex

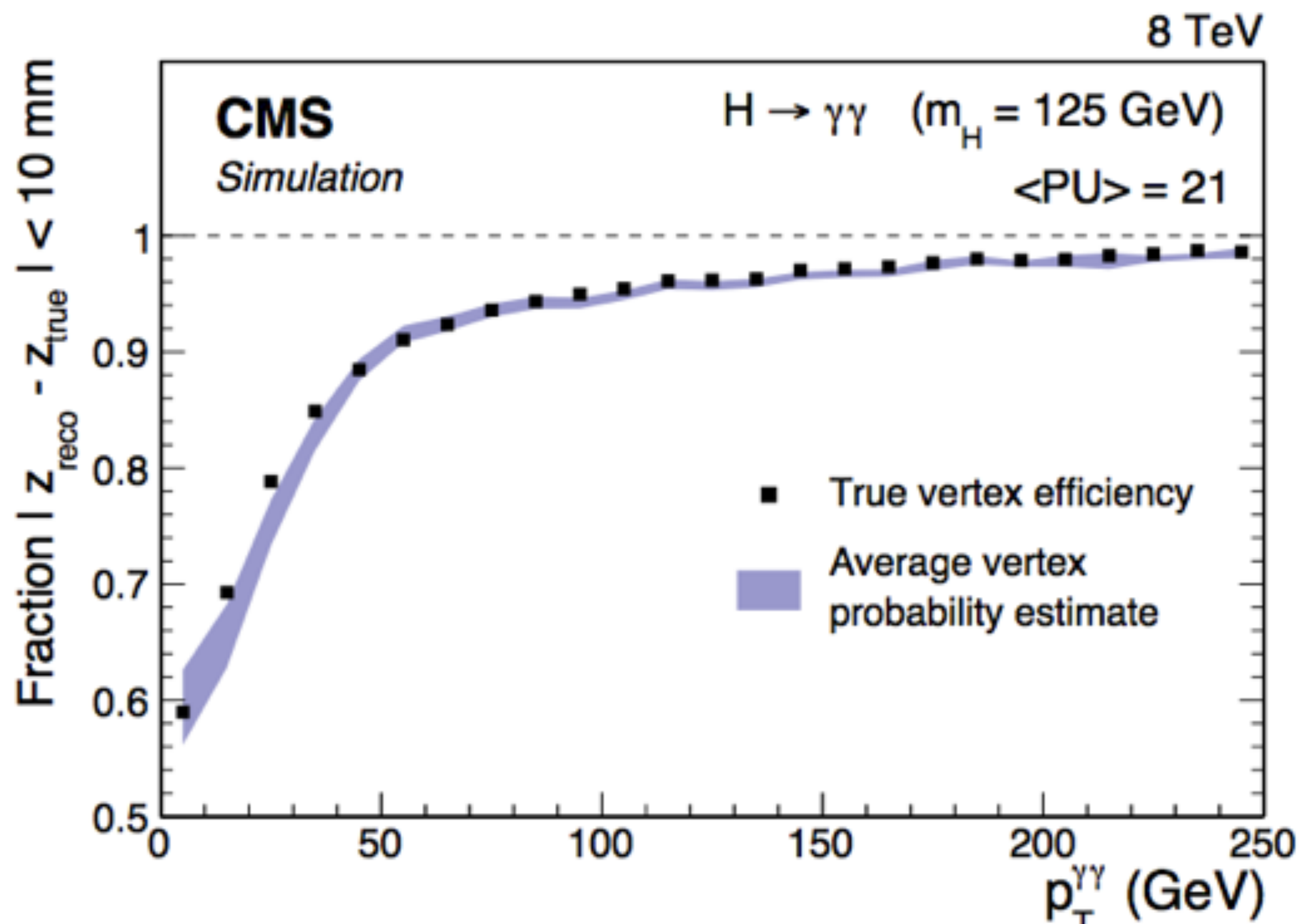
Diphoton vertex: no ionisation from the two photons in the tracker.
Use transverse quantities to train a BDT classifier to select the right vertex

$$m_{\gamma\gamma} = \sqrt{2E_1 E_2 (1 - \cos\alpha)}$$

$\sum \vec{p}_T^{\,2}$

$-\sum(\vec{p}_T \cdot \frac{\vec{p}_T^{\gamma\gamma}}{|\vec{p}_T^{\gamma\gamma}|})$, and

$(|\sum \vec{p}_T| - |\vec{p}_T^{\gamma\gamma}|)/(|\sum \vec{p}_T| + |\vec{p}_T^{\gamma\gamma}|)$.



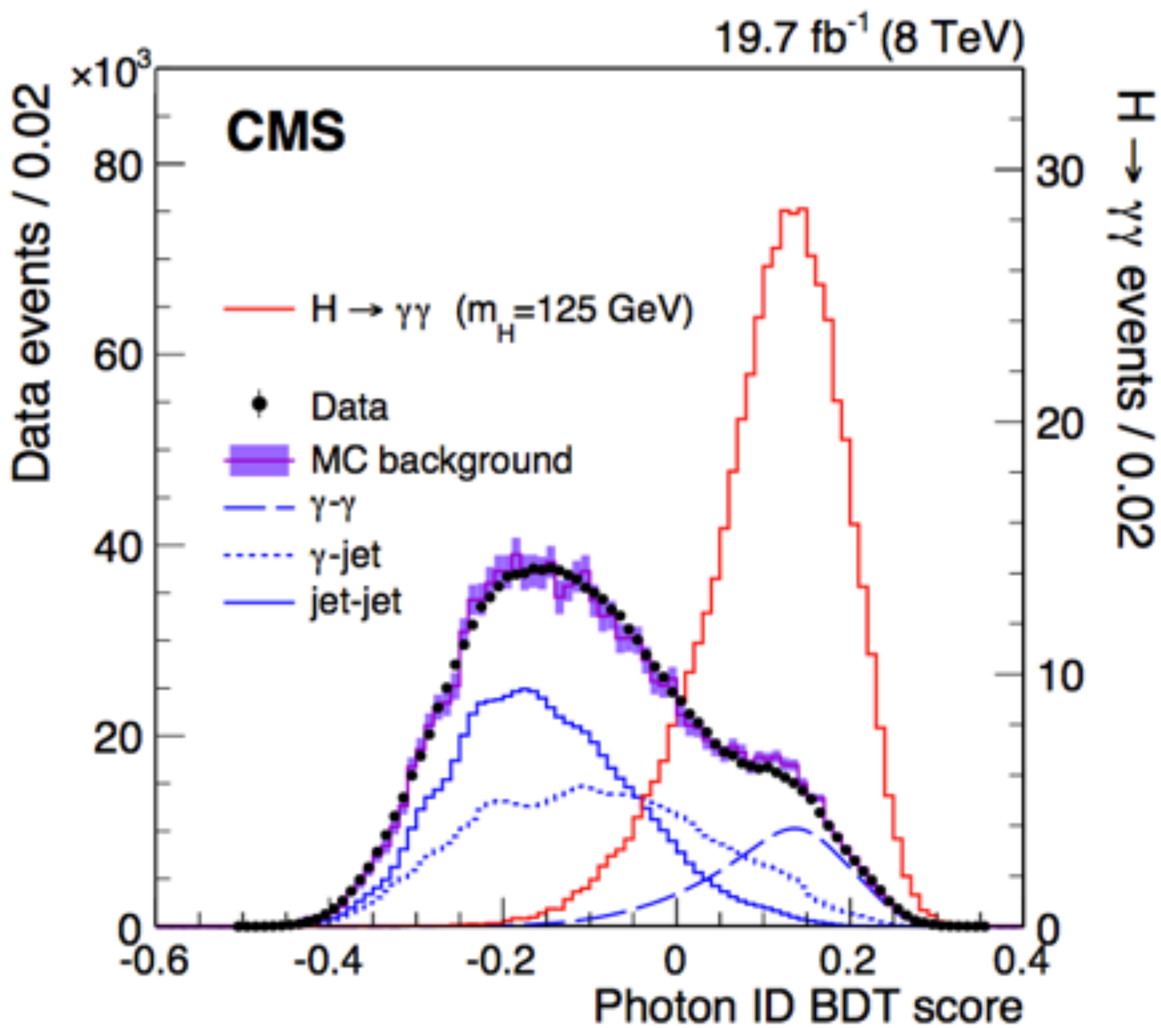
If you get the vertex close to <1cm to the true one, the effect of the wrong vertex is subdominant w.r.t. to the energy resolution on the mass resolution

A second BDT is trained to get the per-event vertex probability (together with the per event energy resolution gives the per-event mass resolution). Inputs = vtx BDT output, total reconstructed #vtx in the event, pTgg, distance from truth of the first 3 vertices, number of conversions

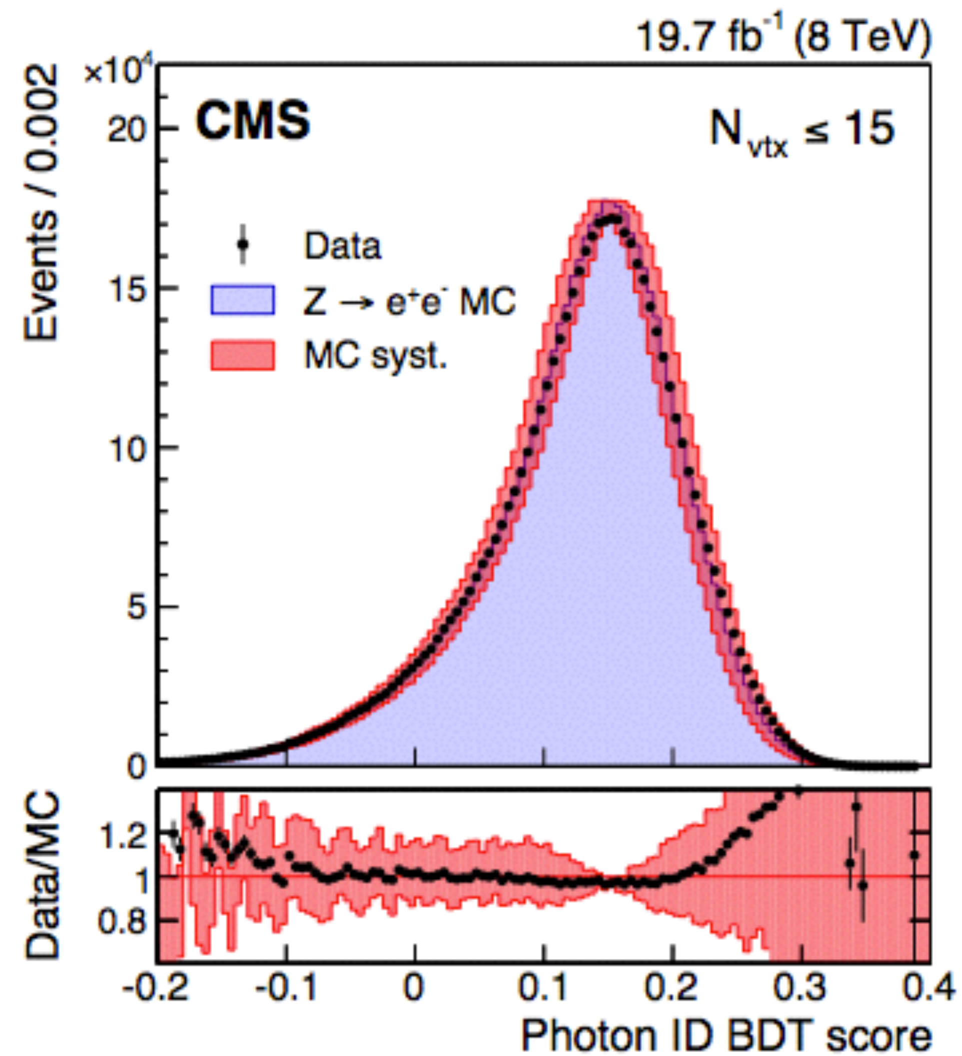
$H \to \gamma\gamma$ photon identification

A jet where the pT fluctuates to a single neutral hadron can fake a photon

Photon identification using a BDT:
(use shower shapes, isolation, rho, eta, E)



Validation on $Z \to ee$ events



Hairy problem: MVA systematics

$H\to\gamma\gamma$ event classification

Select events in a region $100 < m_{\gamma\gamma} < 180$

$p_T(\gamma_1) > m_{\gamma\gamma}/3$; $p_T(\gamma_1) > m_{\gamma\gamma}/4$ (don't want to feed any mass information to the classifier !)

photonID > -0.2 (99% efficient , remove 1/4 of the bkg)

Start by selecting the events tagging specific production mechanisms:

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

Diphoton classifier

Train a BDT on MC to separate Hgg candidates from QCD background processes:

- background: mix of all background mechanisms
- signal: before discovery we didn't know the mass of the Higgs boson !

  but for each mass we could build a very precise model:

  train at one given mass (e.g. 123 GeV) and make the BDT blind to the mass

We don't want to discover a bump at the signal mass used for training !

Dividing all variables with dimensions by the invariant mass of the candidate ($m_{\gamma\gamma}$) we hide the mass to the BDT (and it cannot learn it indirectly because of the incomplete information on the kinematics of the event)

Energy γ_1 / $m_{\gamma\gamma}$
Energy γ_2 / $m_{\gamma\gamma}$
η (γ_1)
η (γ_2)
cos ($\Delta\phi_{\gamma\gamma}$)
Photon ID (γ_1)
Photon ID (γ_2)
σ_m / $m_{\gamma\gamma}$

…

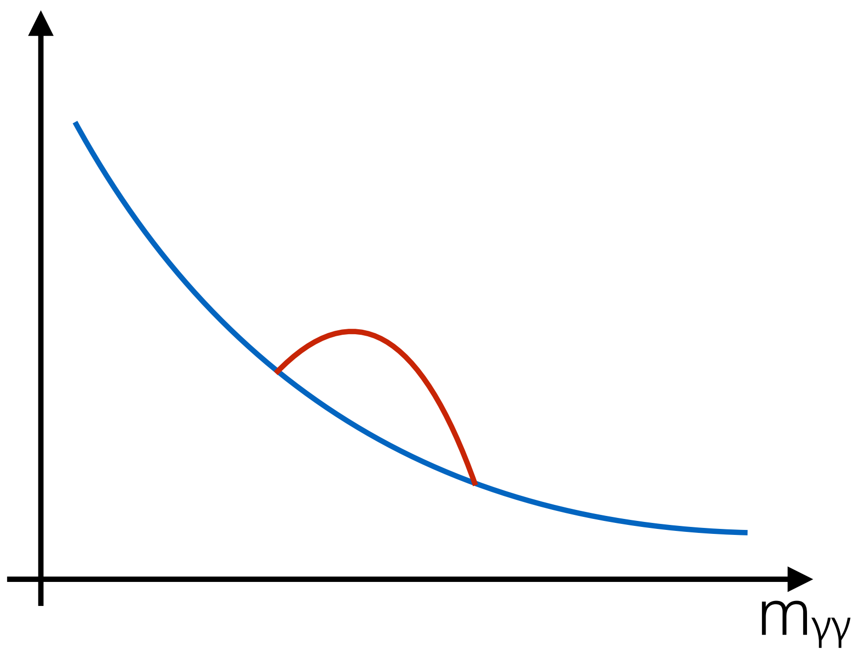
Signal like candidates in general have:

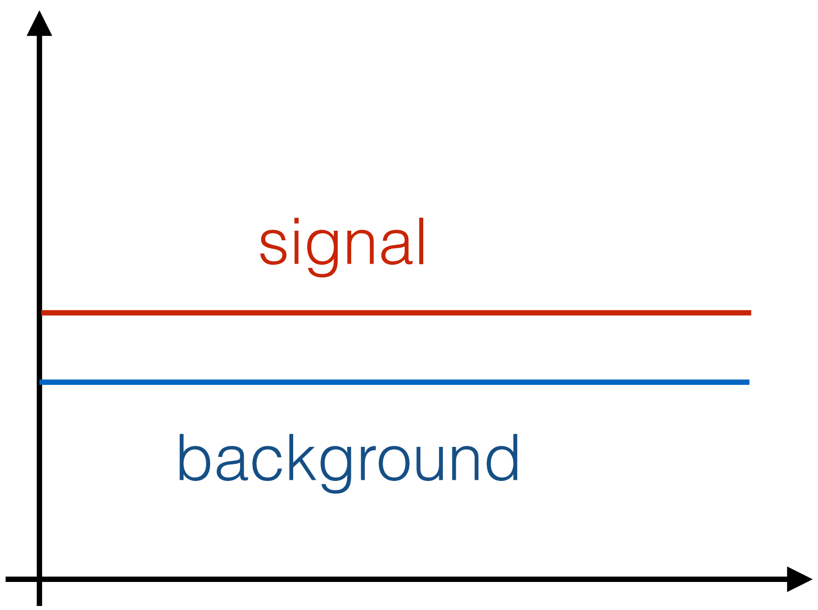
- higher photon energy
- more centrally produced
- better identified photons
- better mass resolution

Use BDTs in cascade: exe input energy regression, photon classifier, etc…

Diphoton classifier

Making the BDT mass blind…





…also means losing the important handle on the resolution information.
To bring the resolution back we apply a signal weight:

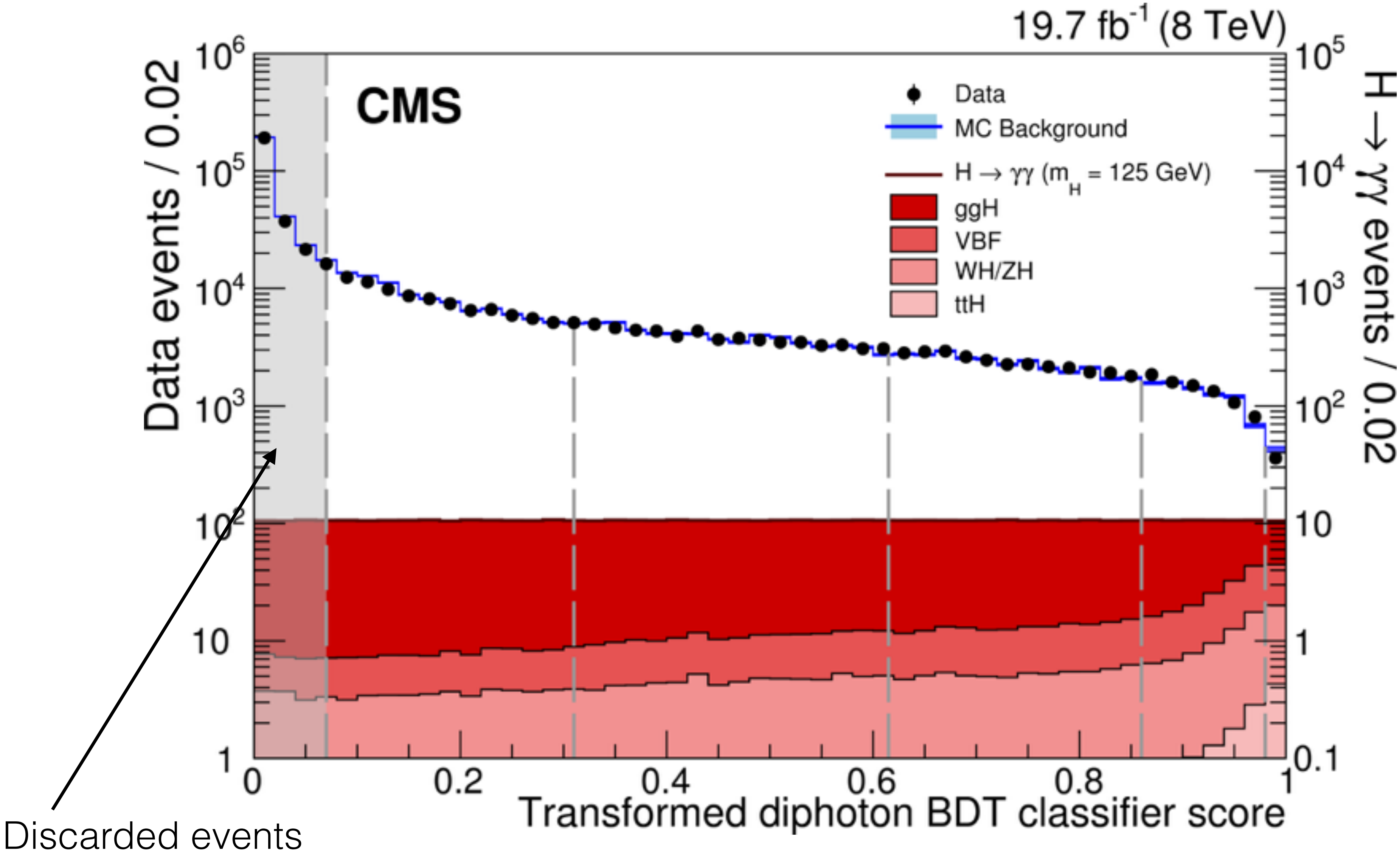
$$\text{Weight} = 1 / \left(\sigma_m / m_{\gamma\gamma} \right)$$ the better the resolution the larger the weight

In reality we don't know precisely the vertex (we get it from another BDT)
and so we build a more complex weight that takes this into account:

$$\text{Weight} = p^{vtx} / \left(\sigma^{\text{right vertex}}{}_m / m_{\gamma\gamma} \right) + (1 - p^{vtx}) / \left(\sigma^{\text{wrong vertex}}{}_m / m_{\gamma\gamma} \right)$$

BDT output

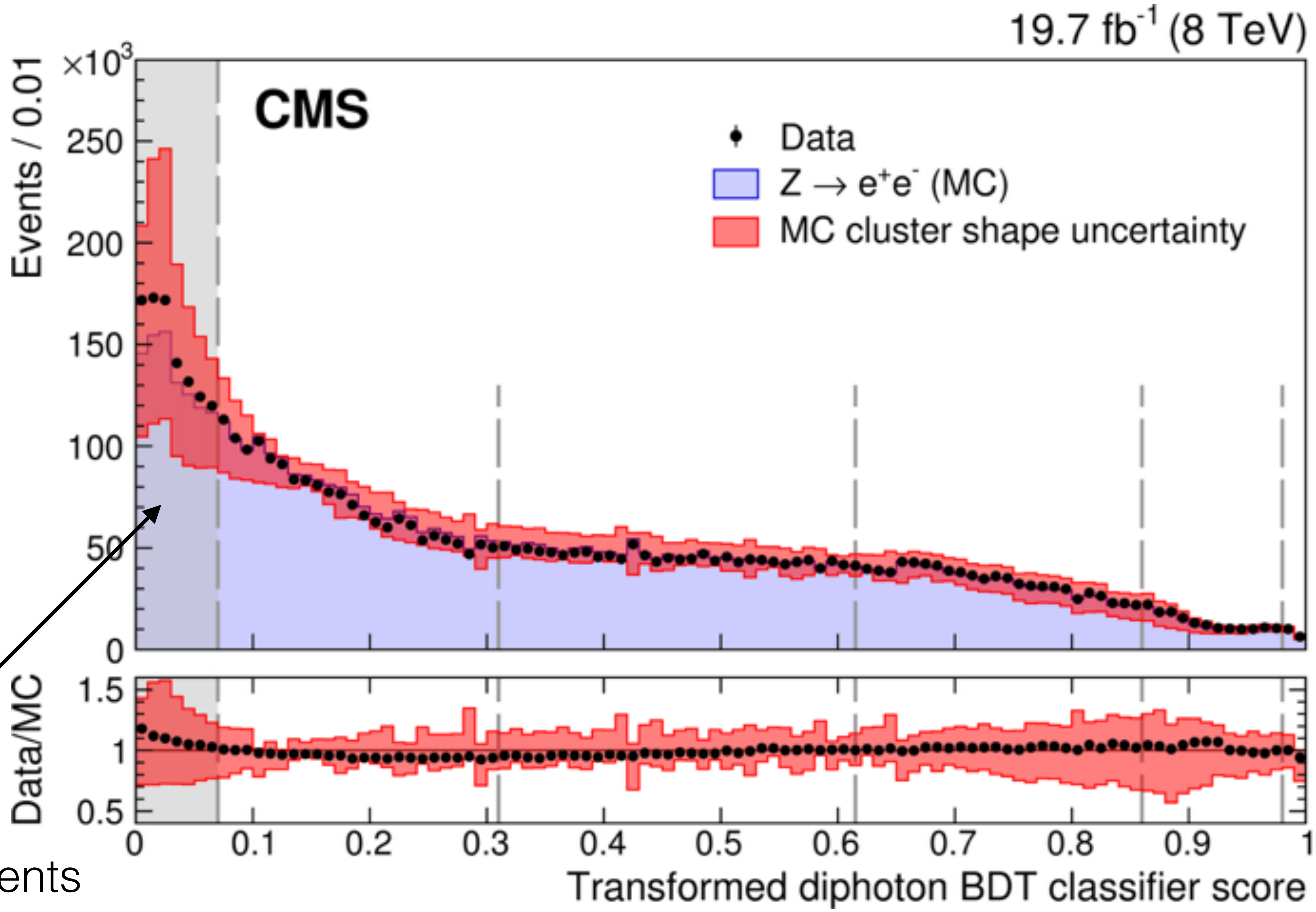
Number of classes (5) and boundaries chosen to optimize the S/B.
(discard events in the lowest score bin)



Transformed such that the sum of the signal components is flat

Validation

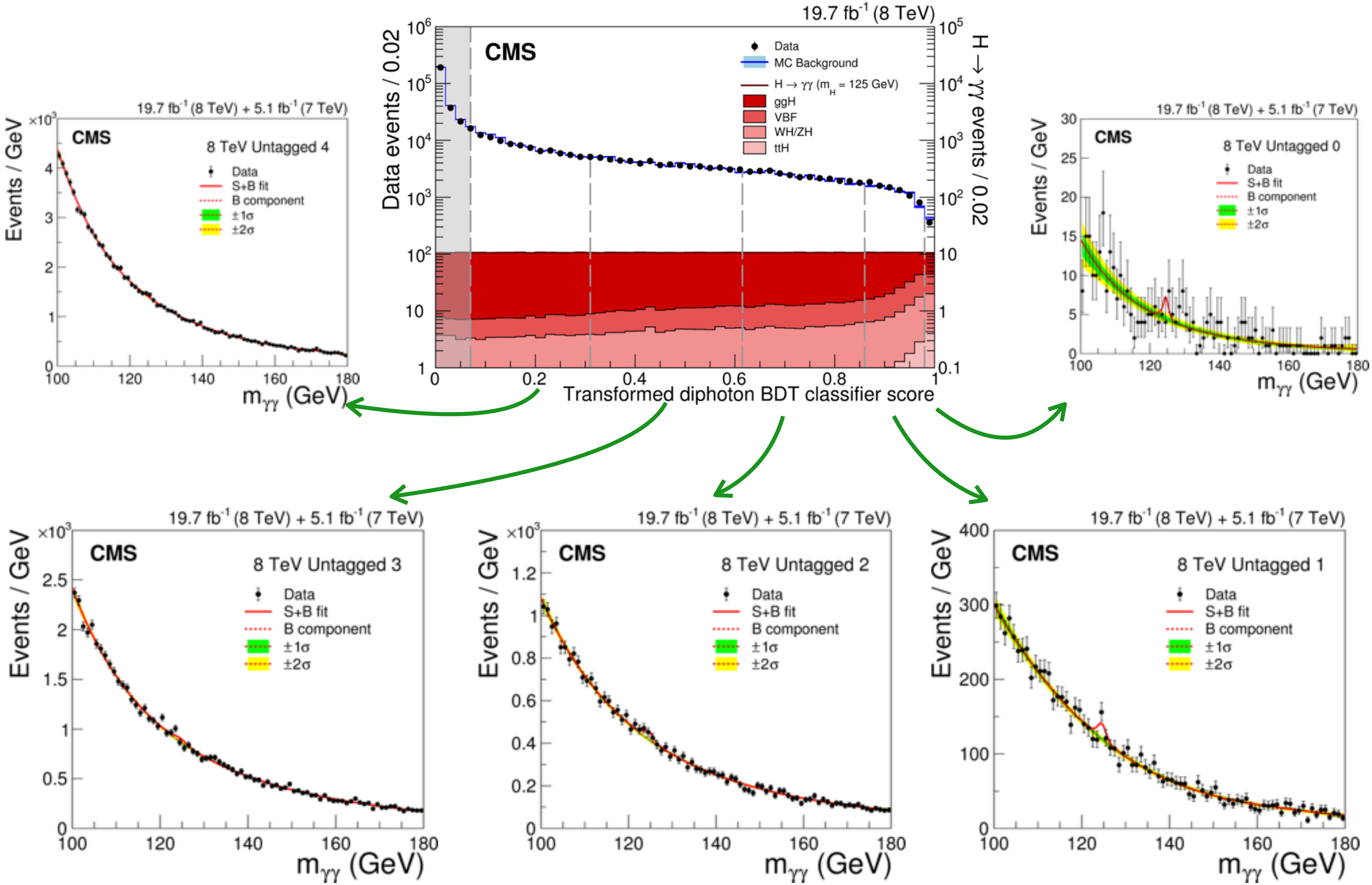
Validation on standard candle Z→ee events reconstructed as photons: check that input variables and their correlations in the MC is sufficiently accurate



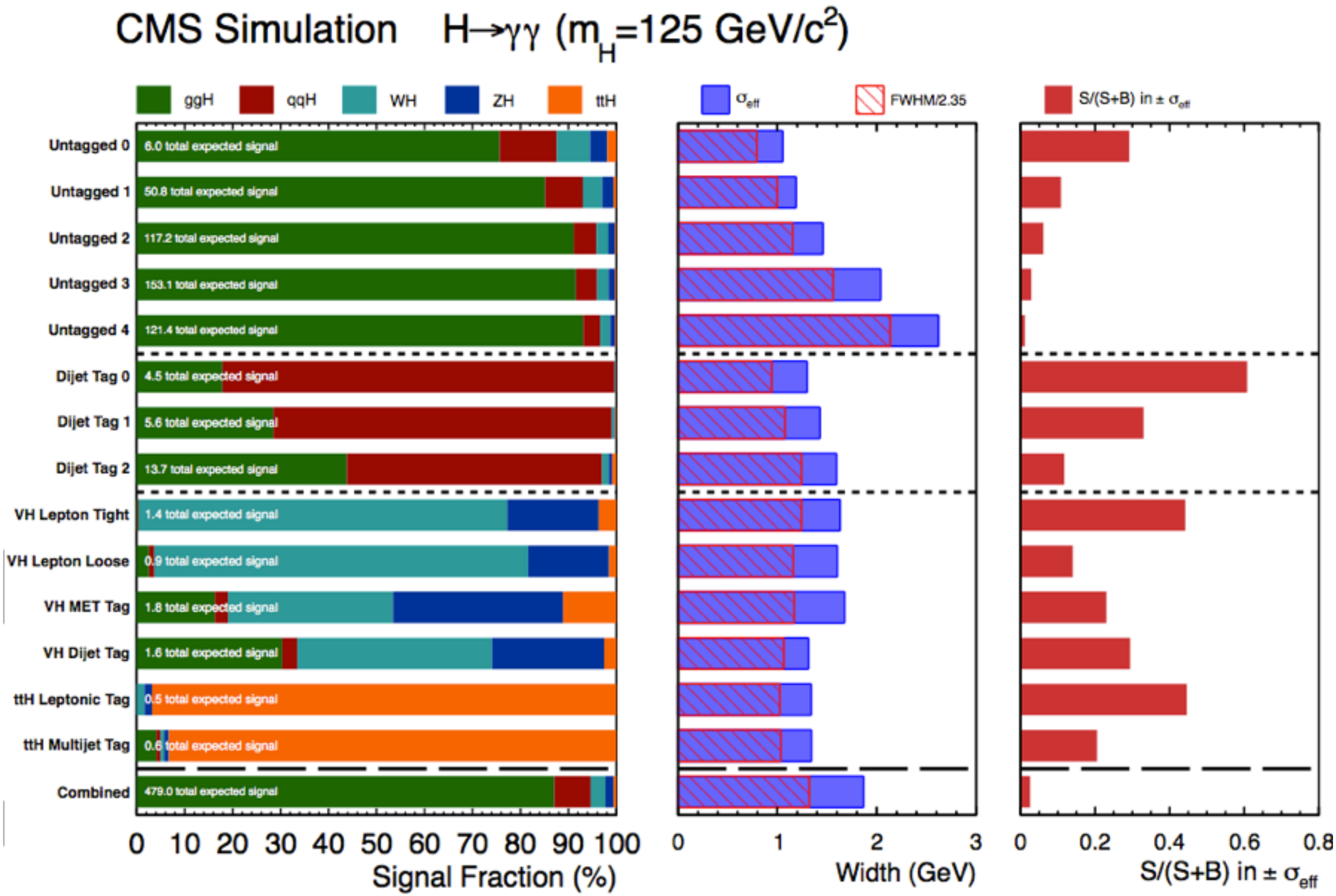
Discarded events

Systematic uncertainty band obtained propagating the photon identification uncertainty and the energy resolution uncertainty

Mass fit

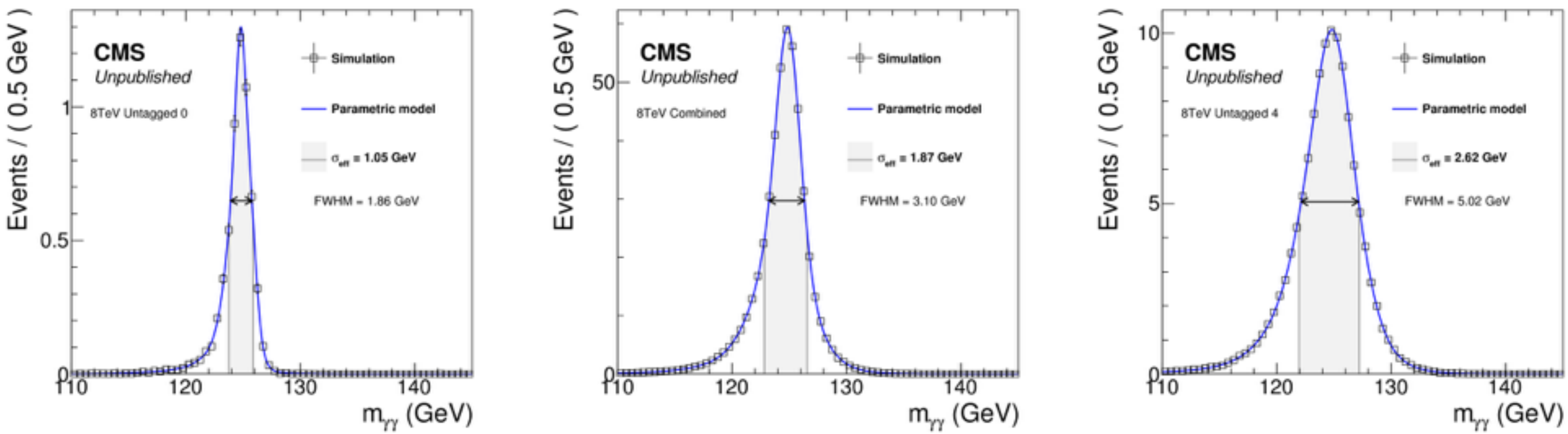

19.7 fb^{-1} (8 TeV)
CMS
Data
MC Background
H → γγ (m_H = 125 GeV)
ggH
VBF
WH/ZH
ttH
Data events / 0.02
H → γγ events / 0.02
Transformed diphoton BDT classifier score
19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
8 TeV Untagged 4
8 TeV Untagged 3
8 TeV Untagged 2
8 TeV Untagged 1
8 TeV Untagged 0
S+B fit
B component
±1σ
±2σ
Events / GeV
$m_{\gamma\gamma}$ (GeV)

H→γγ signal composition



H→γγ signal/background model

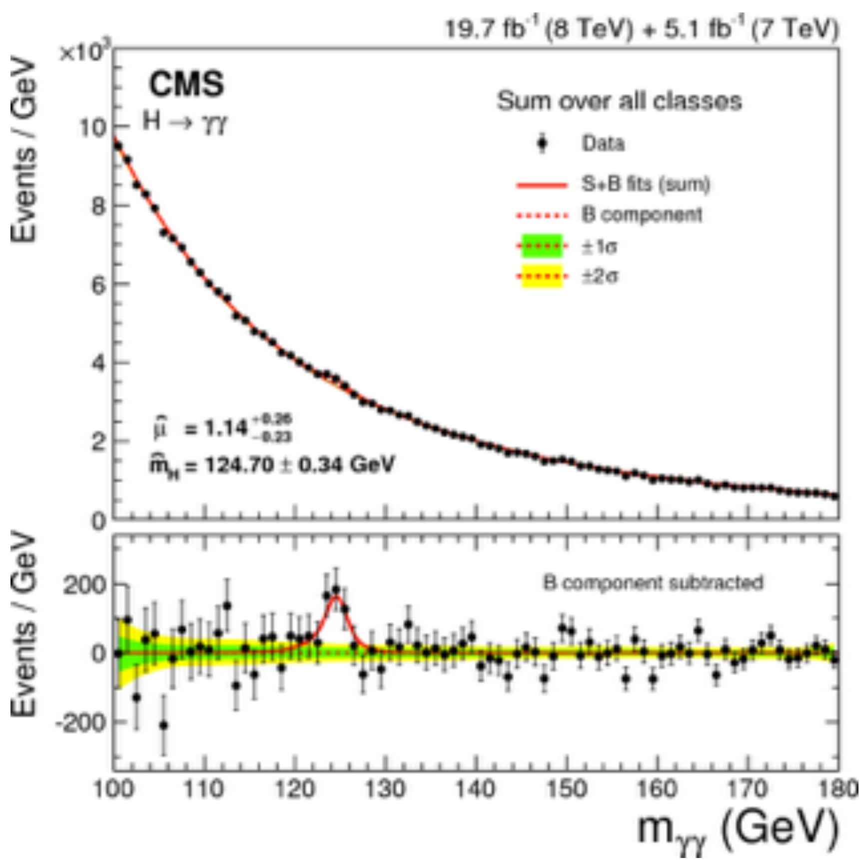
For each category produce a signal model taking into account the proportion of different production mechanisms right/wrong vertex assignments (model = sum of gaussians)

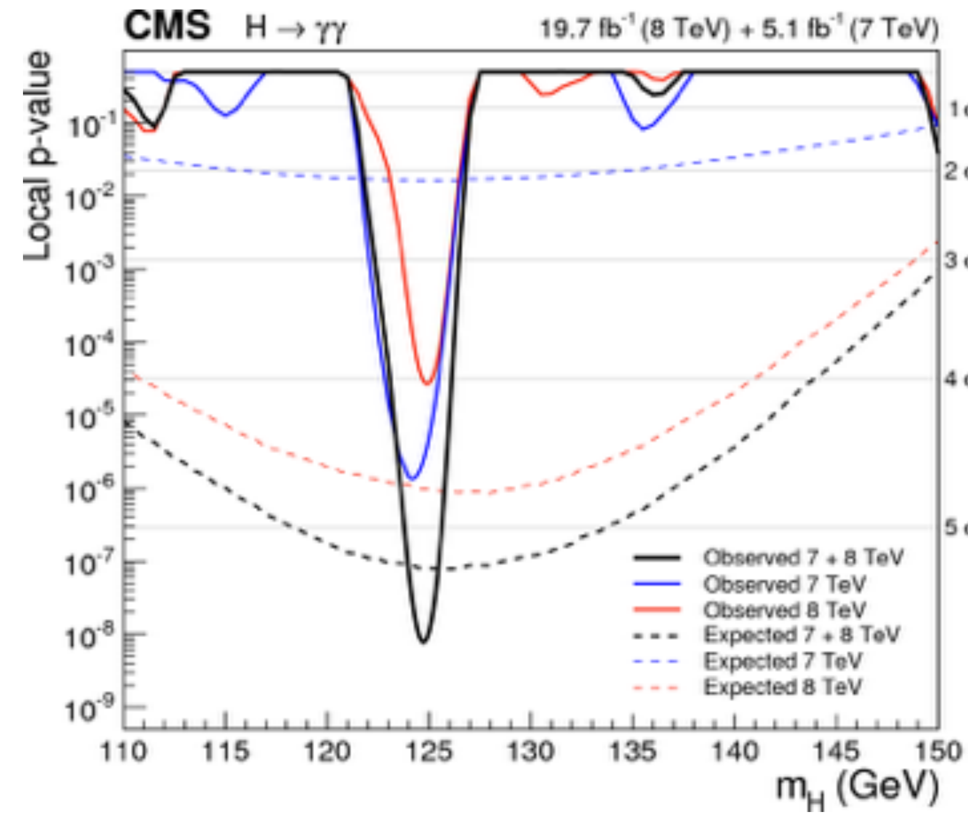


Background: MC description not accurate (QCD modelling + **modelling of fakes photons**)
CMS: discrete profiling method;
the systematics uncertainty on the bkg goes into the statistical error

ATLAS: gets the functional forms fitting on MC, then throws toys and look for one function that fit them all
Systematics uncertainty as the maximum bias the largest absolute signal component fitted anywhere in [110-150] GeV with the background samples above

H→γγ results

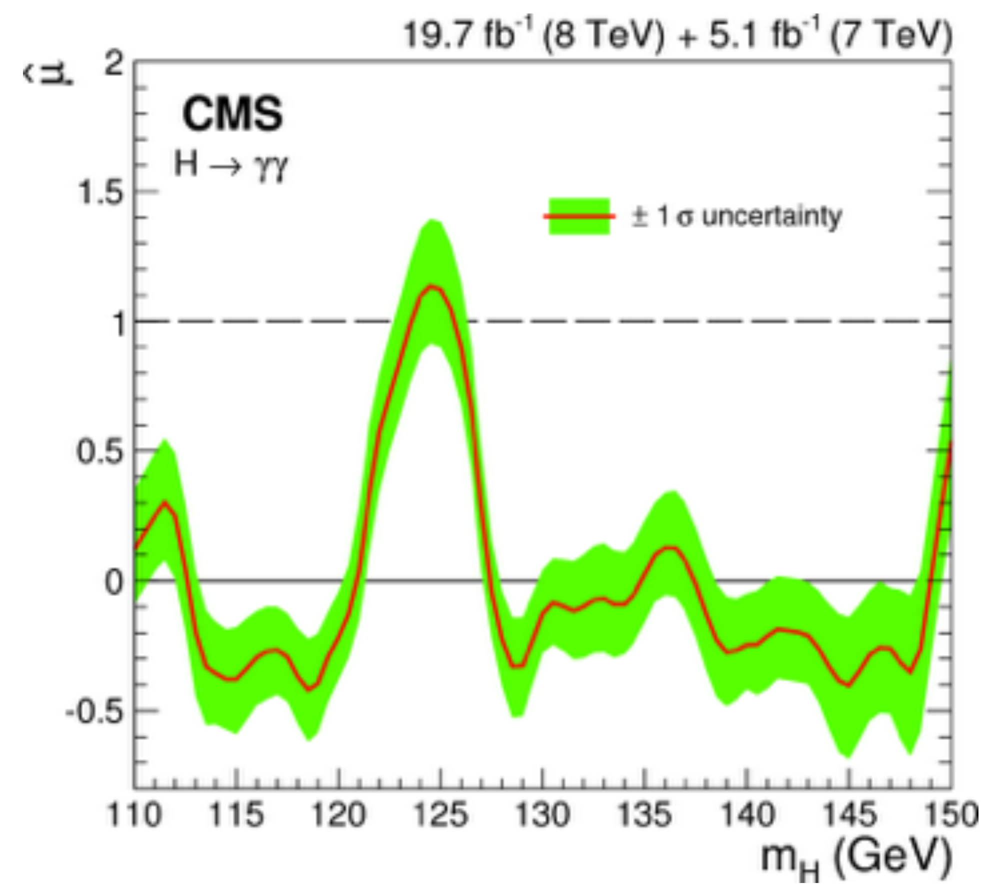




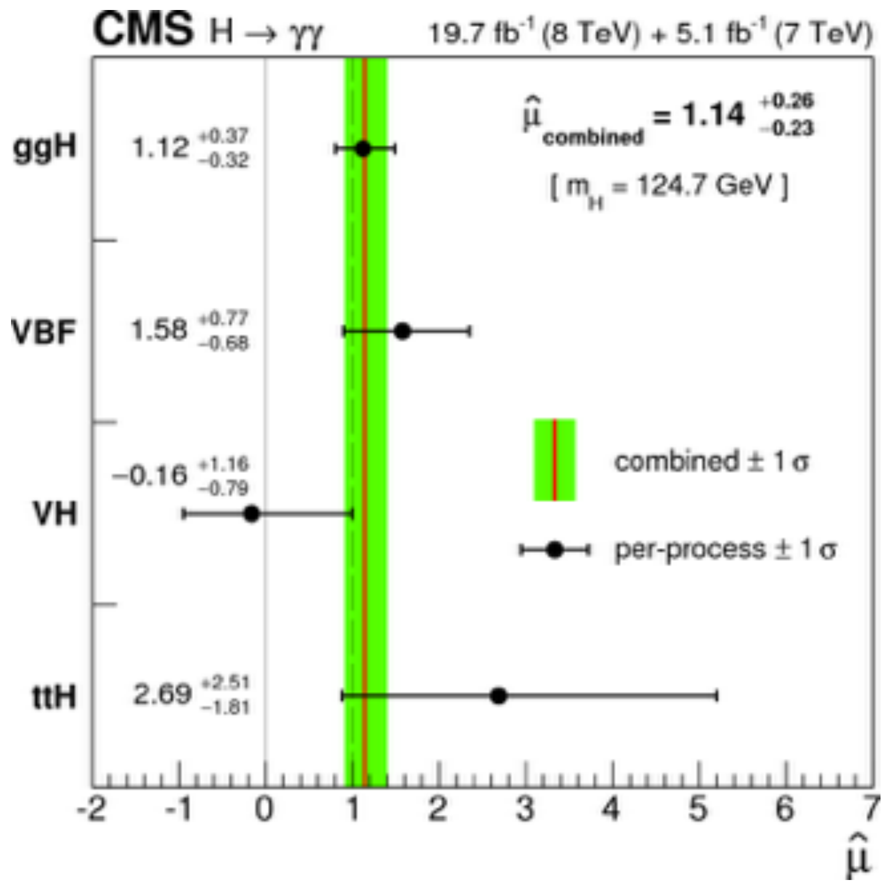
Significance @ 124.7 GeV
Expected 5.2 σ
Observed 5.7 σ

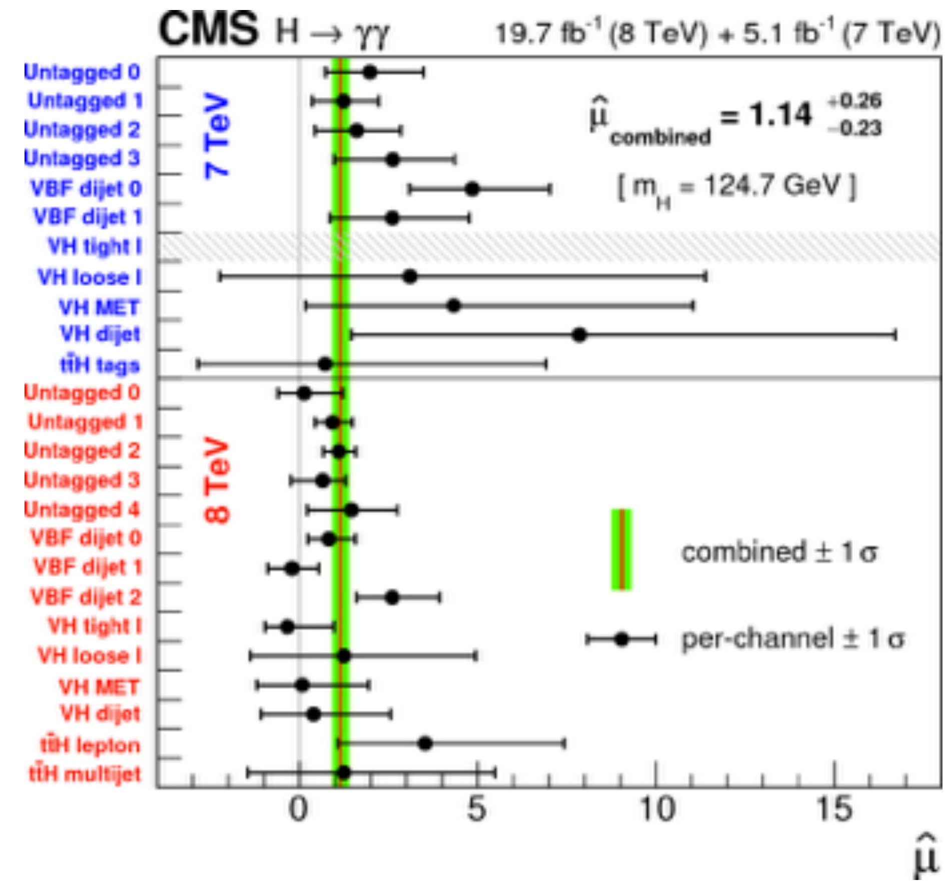
$$\hat{\mu} = 1.14^{+0.26}_{-0.23}$$

$$1.14 \pm 0.21\,(\text{stat})\ ^{+0.09}_{-0.05}\,(\text{syst})\ ^{+0.13}_{-0.09}\,(\text{theo})$$



H→γγ results





Source of uncertainty	Uncertainty in $\hat{\mu}$
Production cross sect. and branching frac.	0.11
Shower shape modelling	0.06
Energy scale and resolution	0.02
Other	0.04
All syst. uncert. in the signal model	0.13
Statistical	0.21
Total	0.25

$H \to ZZ$

Golden channel: 4 leptons = 4μ, 2e2μ, 4e

Clear signature:

4 leptons from the decay of the 2 Z-bosons: fully reconstructed
high mass resolution: ~1-2 % σ_m/m
low background (ZZ, Z+jets, tt)

Main issue:

small number of events ⇒ need to keep very high efficiencies

push lepton reconstruction to the limits: pT(e) > 5 GeV, pT(μ) > 7 GeV

Lepton selection:

color neutral Z ⇒ no jet activity around the candidate lepton ⇒ select isolated leptons (correct isolation for pileup)

Obtain data/MC scale factors (this ration is then applied to simulations to match data) from standard candles:
$Z \to ll$, $J/\psi \to ll$, $Y \to ll$

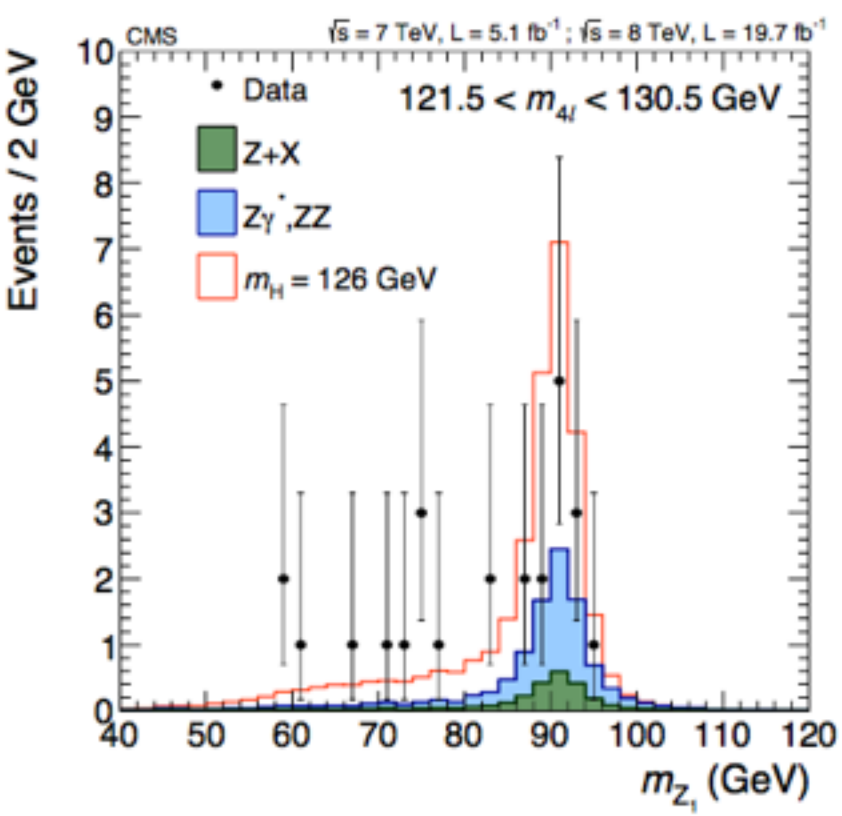
Brehmsstralung recovery to improve momentum resolution:
design an algorithm on MC to add to the lepton selected nearby photons

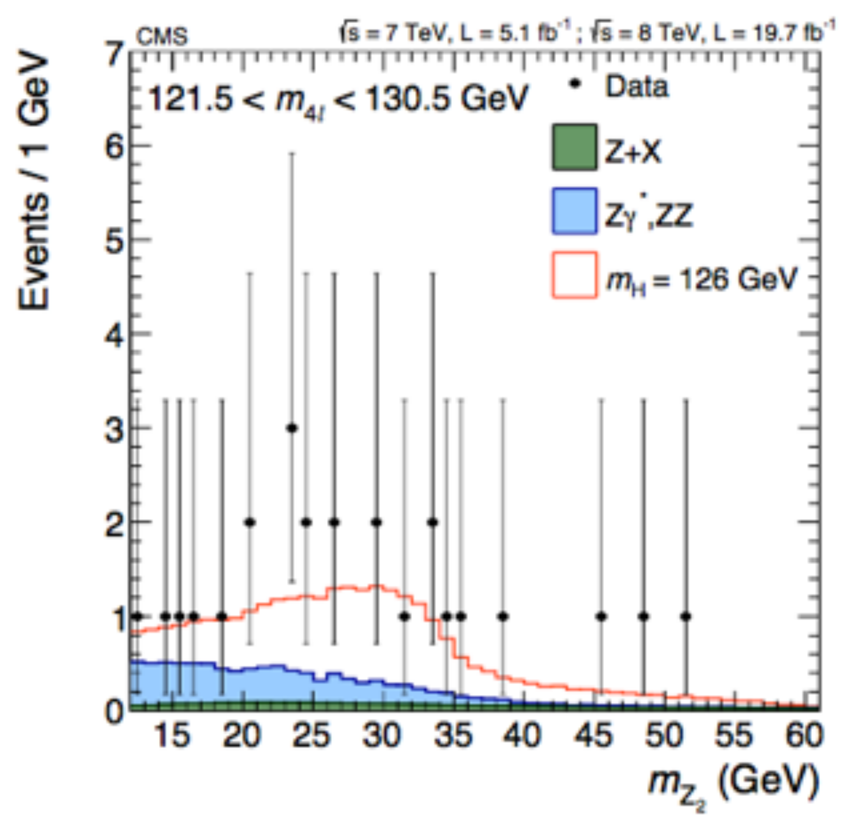
H→ZZ selection

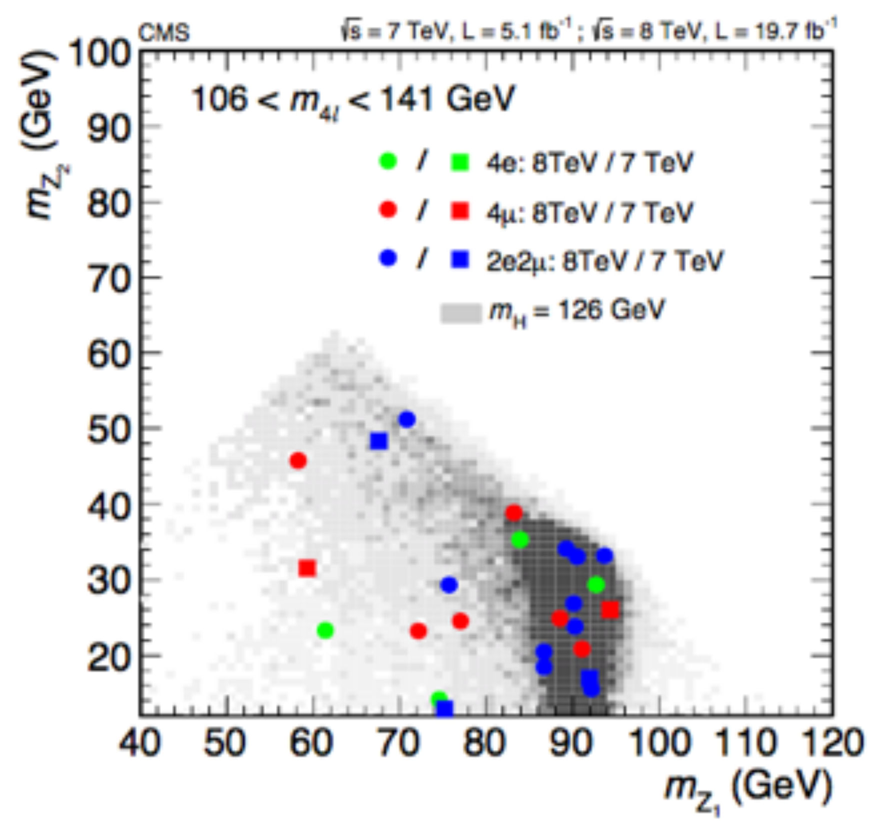
Event selection:

2 x 2 opposite sign same flavour leptons (call Z_1 the closest to a Z on shell, Z_2 the other)
m4l > 100 GeV (search window)

ε x acceptance ~ 62%, 43%, 40% for 4μ, 2e2μ, 4e
σ_m/m ~ 1%, 1.5%, 2% for 4μ, 2e2μ, 4e







H→ZZ MELA

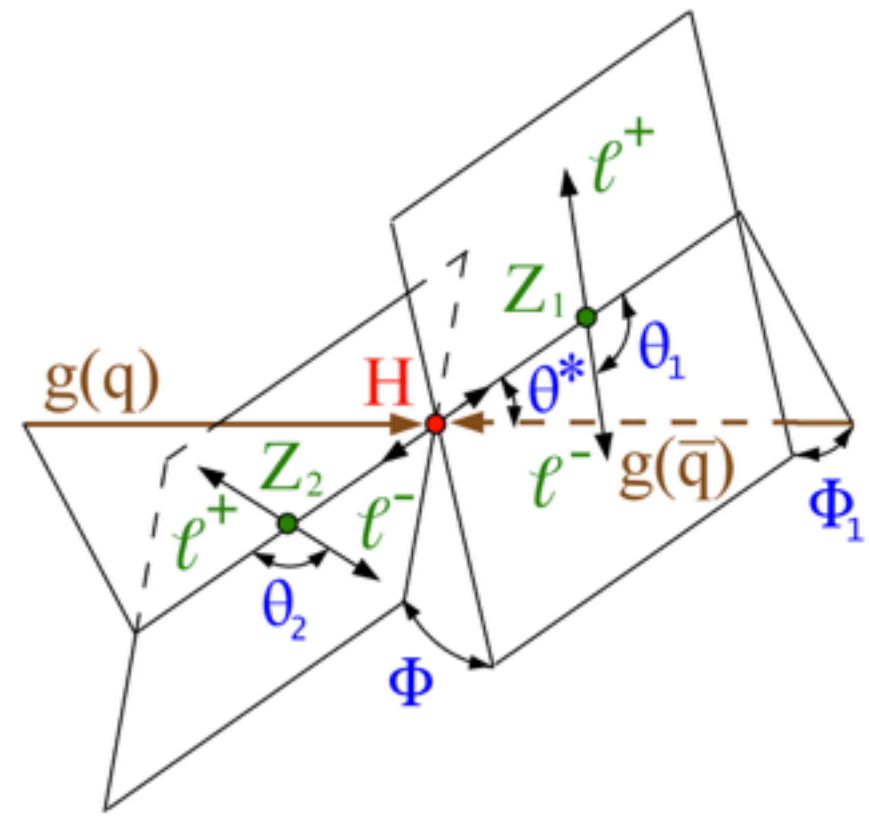
Classify events to increase the analysis sensitivity:

Split events using a linear discriminant "D_{jet}" (on $\Delta\eta_{jj}$ and m_{jj}) to maximize the separation

0/1 jet (gluon fusion) vs. dijet (VBF signature)

(obtain ~30% fraction of VBF instead of the initial ~1%: still 1.5 evt expected in Run1)

Analysis takes advantage of the full kinematics of the event: 5 angles + m_{4l} + m_{Z1} + m_{Z2}



Build pdf using matrix elements (MELA):

$$\mathcal{P}_{\rm bkg} = \mathcal{P}^{\rm kin}_{\rm bkg}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm bkg}(m_{4\ell}),$$
$$\mathcal{P}_{J^P} = \mathcal{P}^{\rm kin}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm sig}(m_{4\ell}|m_{\rm H}),$$

Signal = 0+

bkg = SM ZZ

and from these build kinematic discriminants

$$\mathcal{D}^{\rm kin}_{\rm bkg} = \frac{\mathcal{P}^{\rm kin}_{0^+}}{\mathcal{P}^{\rm kin}_{0^+} + \mathcal{P}^{\rm kin}_{\rm bkg}} = \left[1 + \frac{\mathcal{P}^{\rm kin}_{\rm bkg}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\rm kin}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

For an introduction to ME methods see Bianchini @ http://indico.cern.ch/event/395374/other-view?view=standard

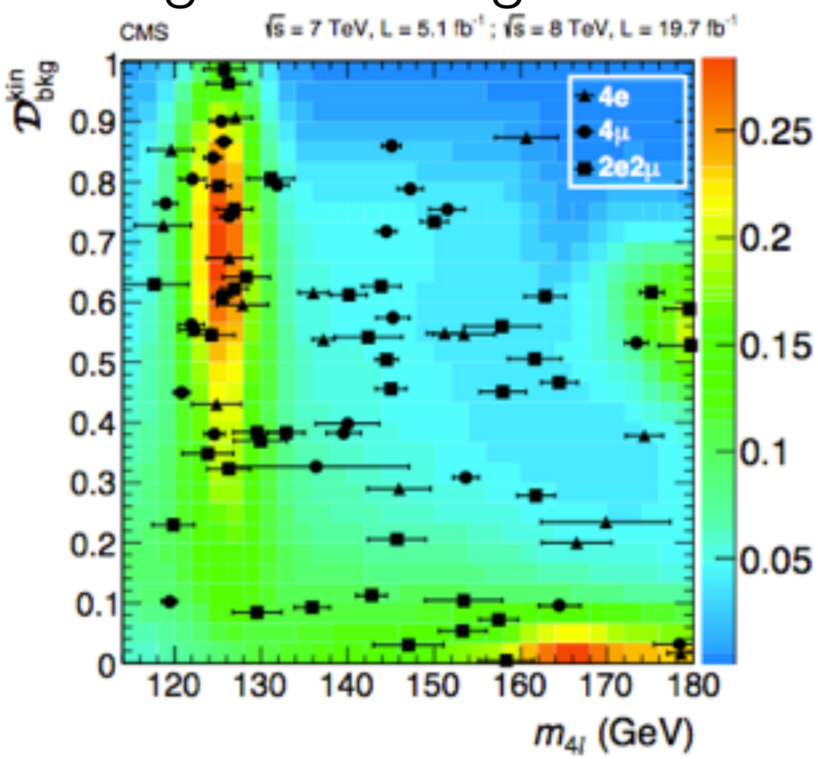
H→ZZ 2D discriminant

$$\mathcal{D}^{\rm kin}_{\rm bkg} = \frac{\mathcal{P}^{\rm kin}_{0^+}}{\mathcal{P}^{\rm kin}_{0^+}+\mathcal{P}^{\rm kin}_{\rm bkg}} = \left[1+\frac{\mathcal{P}^{\rm kin}_{\rm bkg}(m_{Z_1},m_{Z_2},\vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\rm kin}_{0^+}(m_{Z_1},m_{Z_2},\vec{\Omega}|m_{4\ell})}\right]^{-1}$$

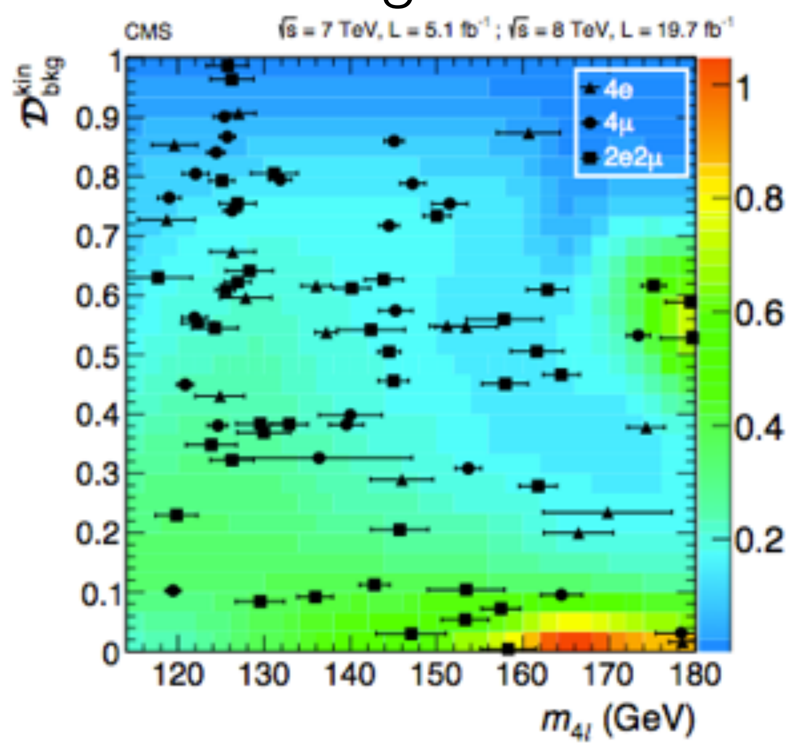
Written like this the discriminant is factorized from m_{4l} which can be used as a second discriminating variable

Discriminate signal from background in the 2D plane: (D^{kin}, m_{4l})

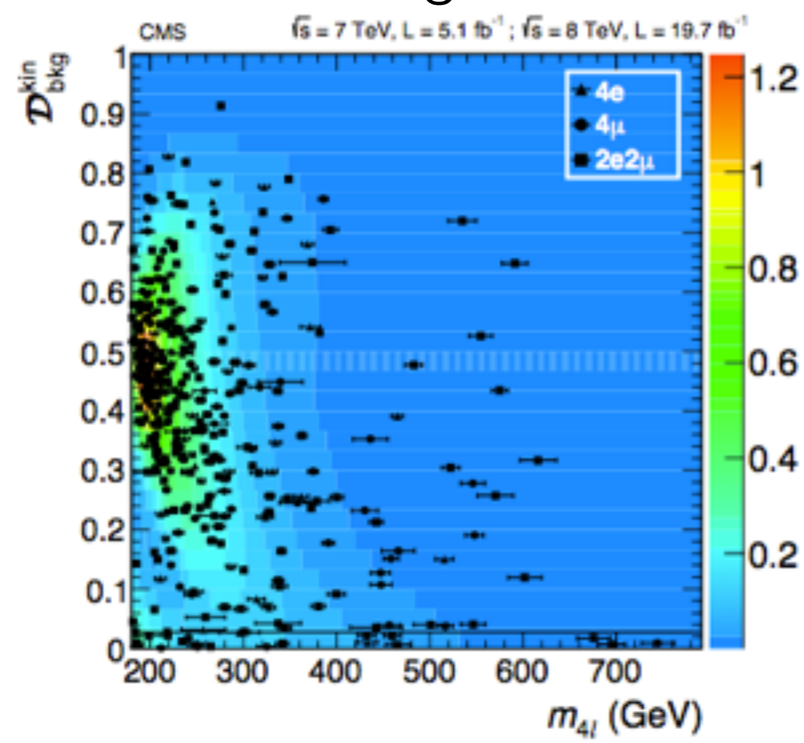
signal+ background



background



background

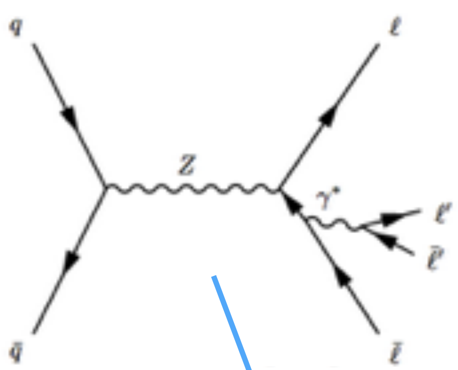


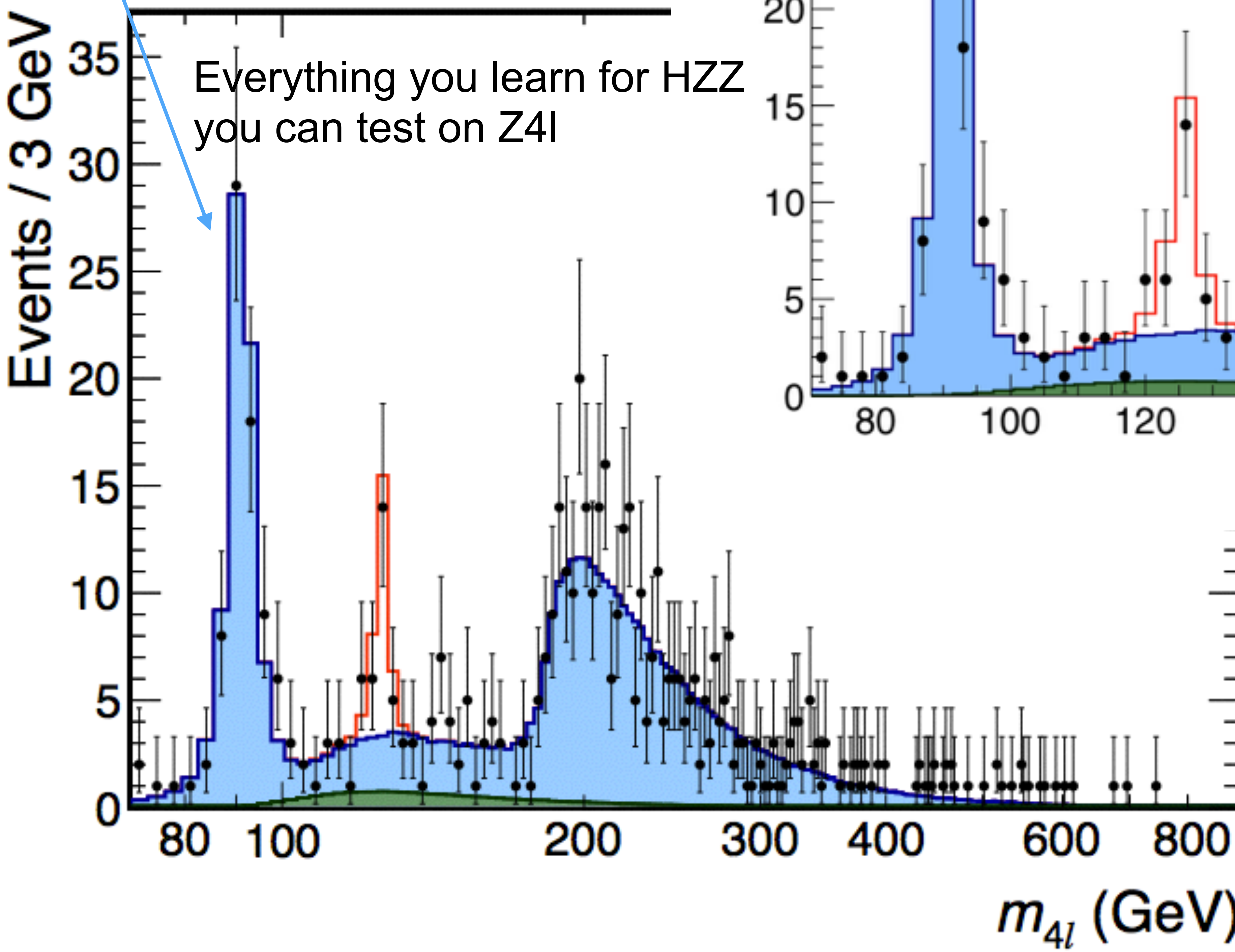
Finally using also pT_{4l} we can define:

$$\mathcal{L}^{\mu,0/1\text{-jet}}_{3D}(m_{4\ell},\mathcal{D}^{\rm kin}_{\rm bkg},p_{\rm T}^{4\ell}) \text{ and } \mathcal{L}^{\mu,\text{dijet}}_{3D}(m_{4\ell},\mathcal{D}^{\rm kin}_{\rm bkg},\mathcal{D}_{\rm jet})$$

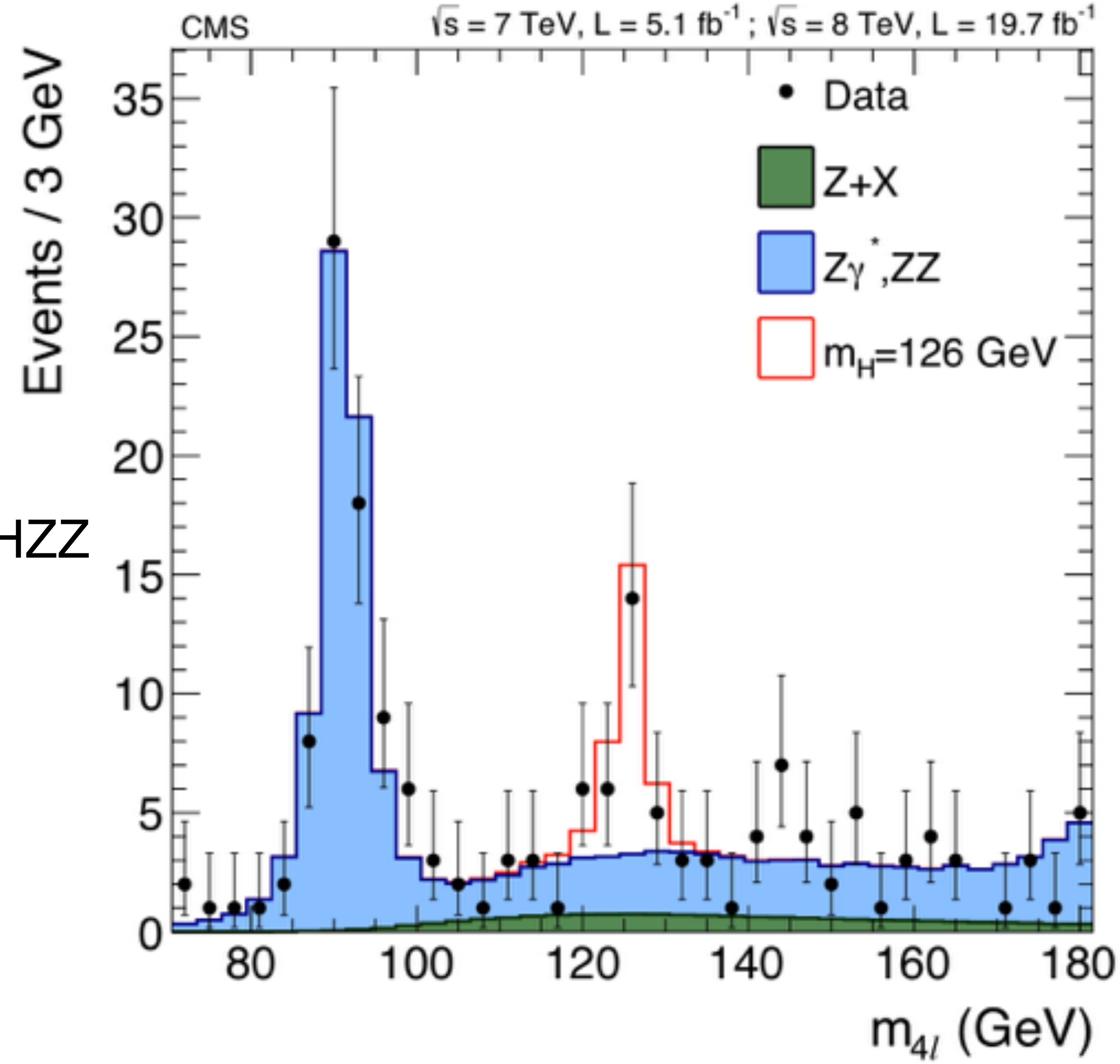
to fit the 5 signal components (ggH, VBF, ZH, WH, ttH) and bkg (qq→ZZ, gg→ZZ, Z+X)

H→ZZ

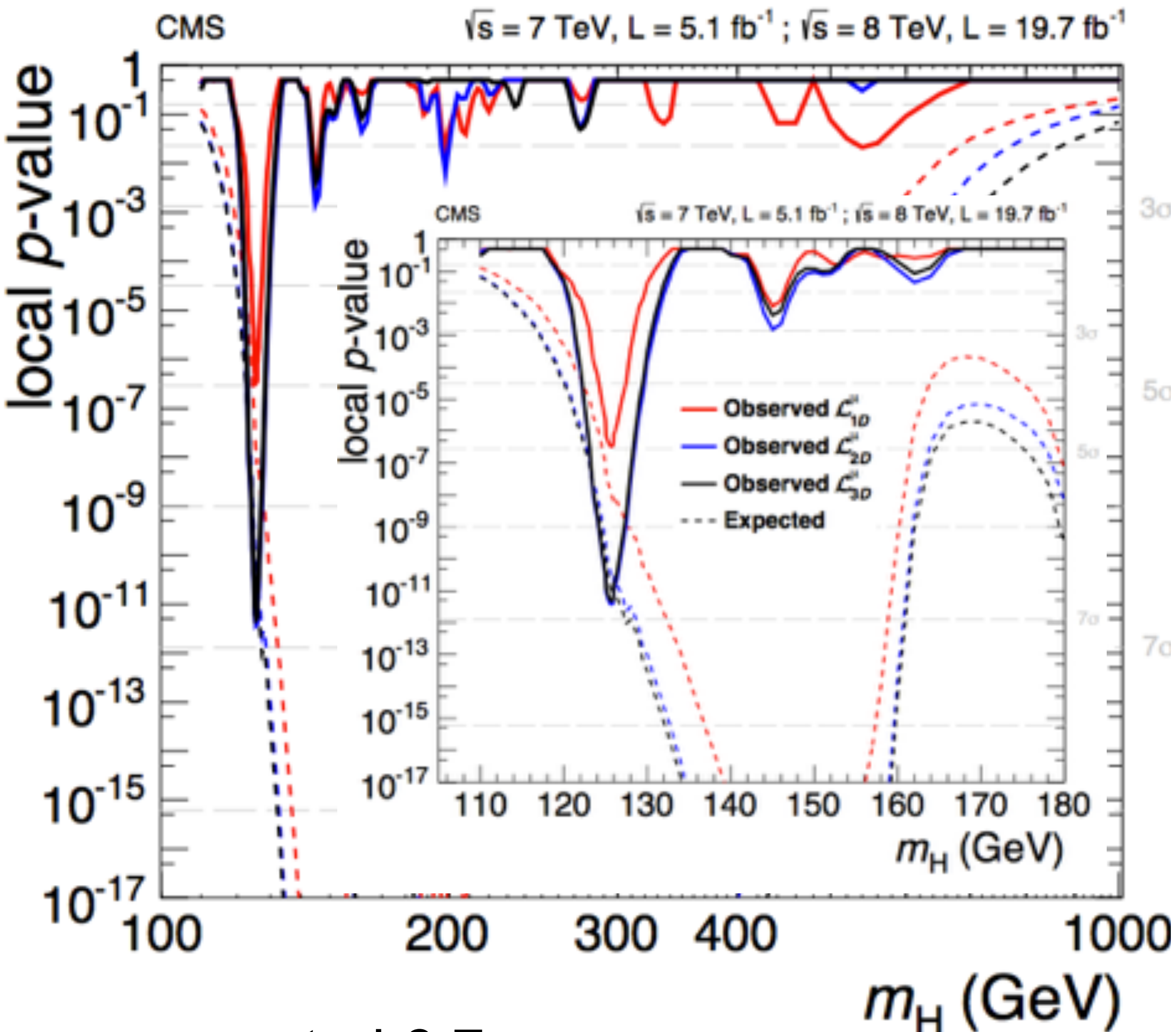


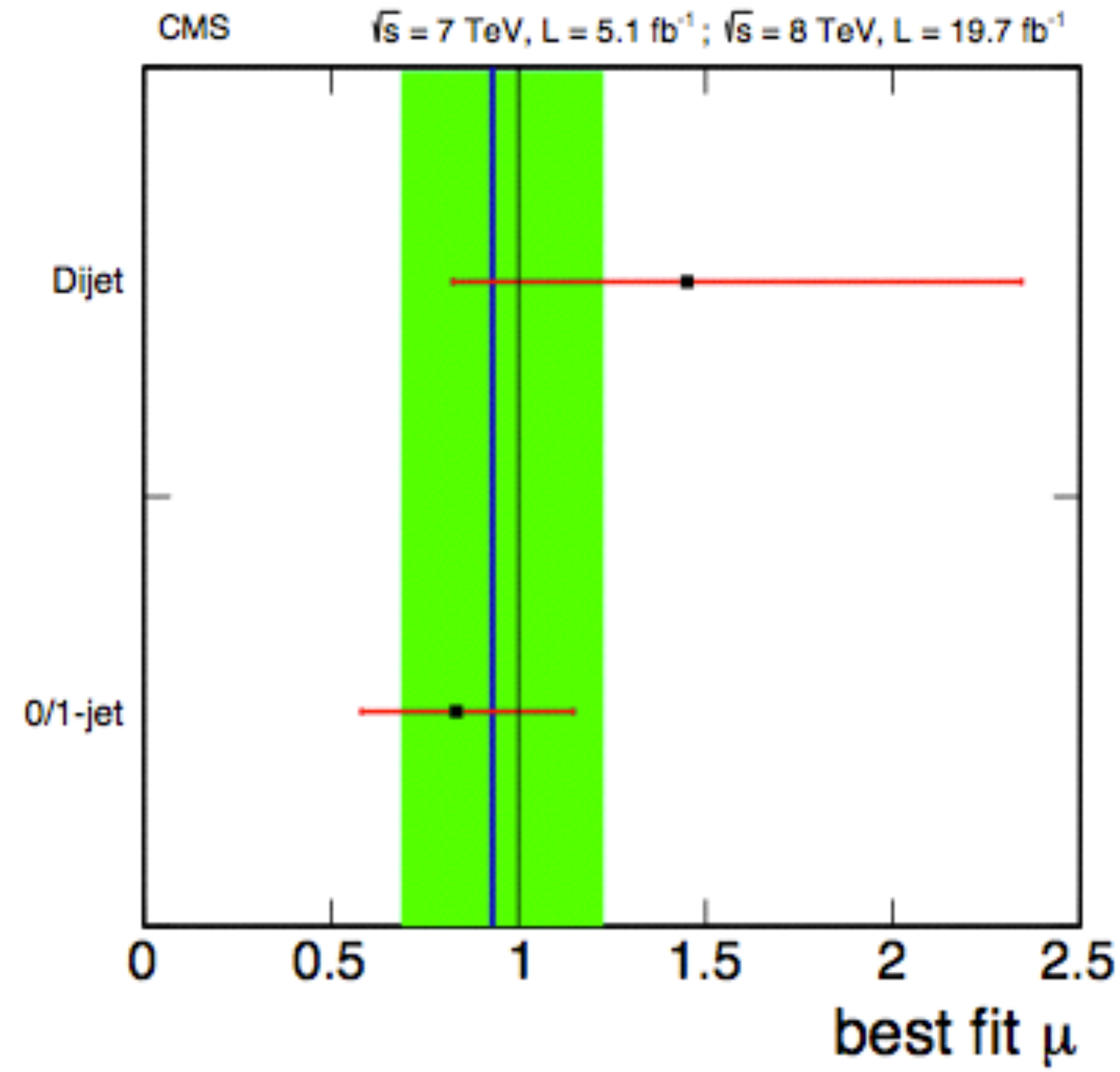


Everything you learn for HZZ you can test on Z4l



H→ZZ results





expected 6.7 σ
observed 6.8 σ @ 125.6 GeV

$$\mu = \sigma/\sigma_{SM} = 0.93^{+0.26}_{-0.23}\,(\text{stat.})^{+0.13}_{-0.09}\,(\text{syst.})$$

@ 125.6 GeV

H→WW

Largest bosonic BR(H→WW→2l2ν) = 0.0106
Expect ~5000 events before selection

Signature: 2 isolated leptons + missing transverse energy
Main issue: not full reconstructed final state ⇒ σ_m/m ~20%

Categories to increase sensitivity: (2μ, eμ, 2e) x (0 or 1 jet)
defined to better control the backgrounds:
non resonant SM WW
single Z production (mostly for same flavour)
tt (mostly for the 1 jet category)

Categories to increase sensitivity: (2μ, eμ, 2e) x (2 jets)
to study qqH (VBF)
WH (W→qq)

Categories to increase sensitivity: (2μ, eμ, 2e) x (3 lepton)
to study WWW (all decaying leptonic)
ZWW (Z and one W decaying leptonic, one hadronic)

H→WW selection

Selection:

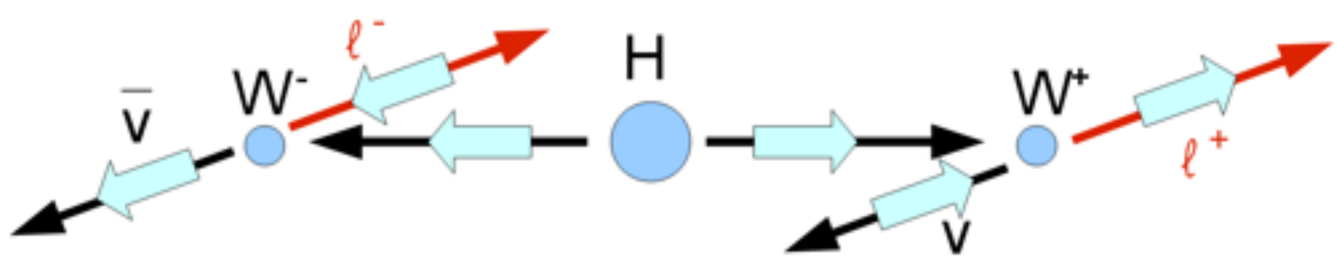
2 oppositely charged isolated leptons
(e/mu min pT > 20/10 GeV)
Missing Transverse Energy from neutrinos (>20GeV)
jets pT > 30 GeV (veto b-jets)
m_{ll} > 12 GeV
pT_{ll} > 30 GeV
mT > 30 GeV where $m_T^2 = 2p_T^{\ell\ell} E_T^{\text{miss}} (1 - \cos\Delta\phi(\ell\ell, \vec{E}_T^{\text{miss}}))$

To suppress Z→ττ use MET projection: $\vec{E}_T^{miss} \cdot \vec{p}_{lep}$

In tau decays the MET tends to be aligned to the tau momentum, for W is more back to back

To reduce tt background vet b-tagged jets

Use the same spin trick already seen at TeVatron

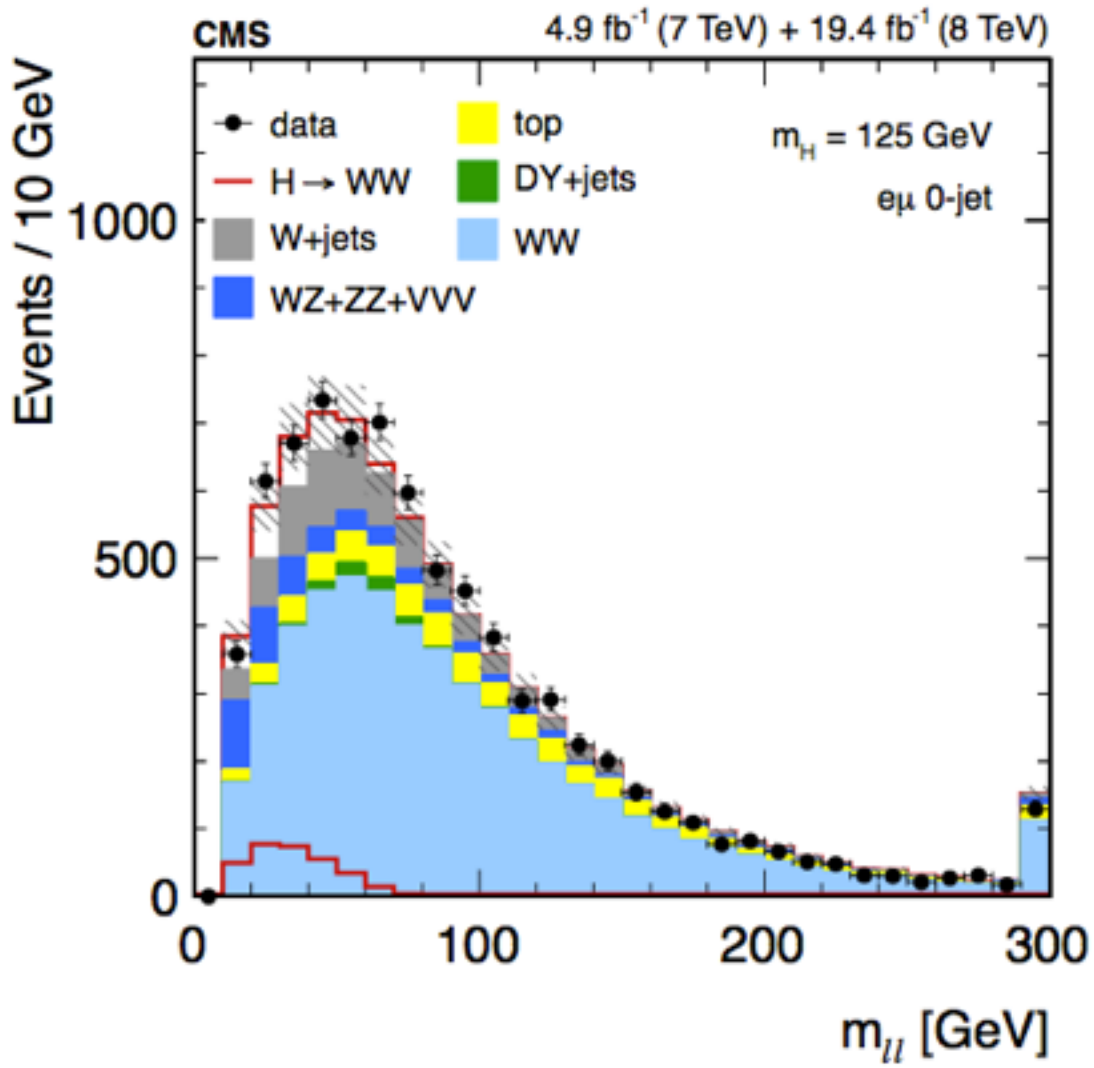


m_{ll} and $\Delta\phi_{l+l-} \rightarrow 0$

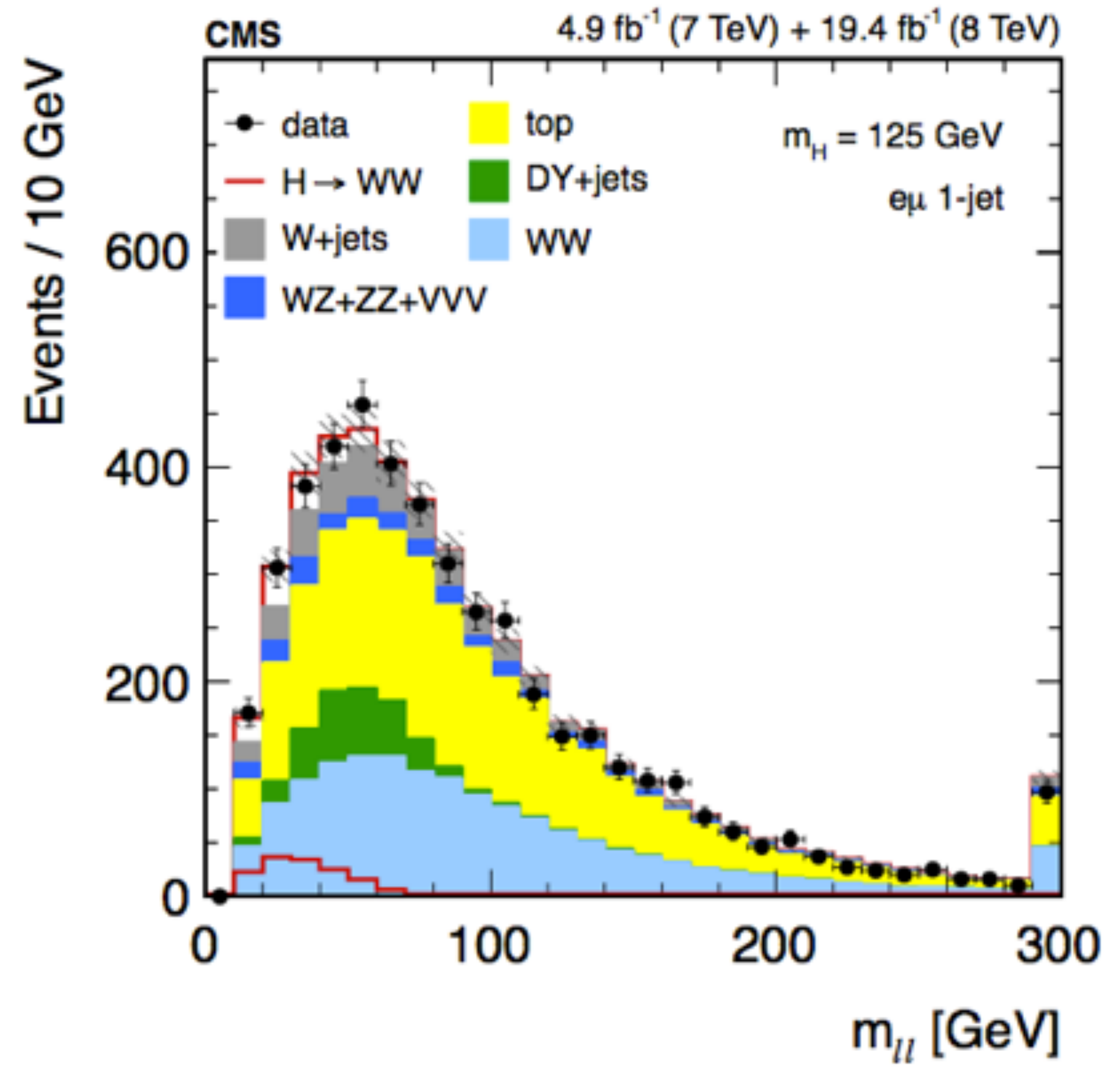
H→WW selection

Distribution of mll for the most sensitive channel eμ:

0 - jets



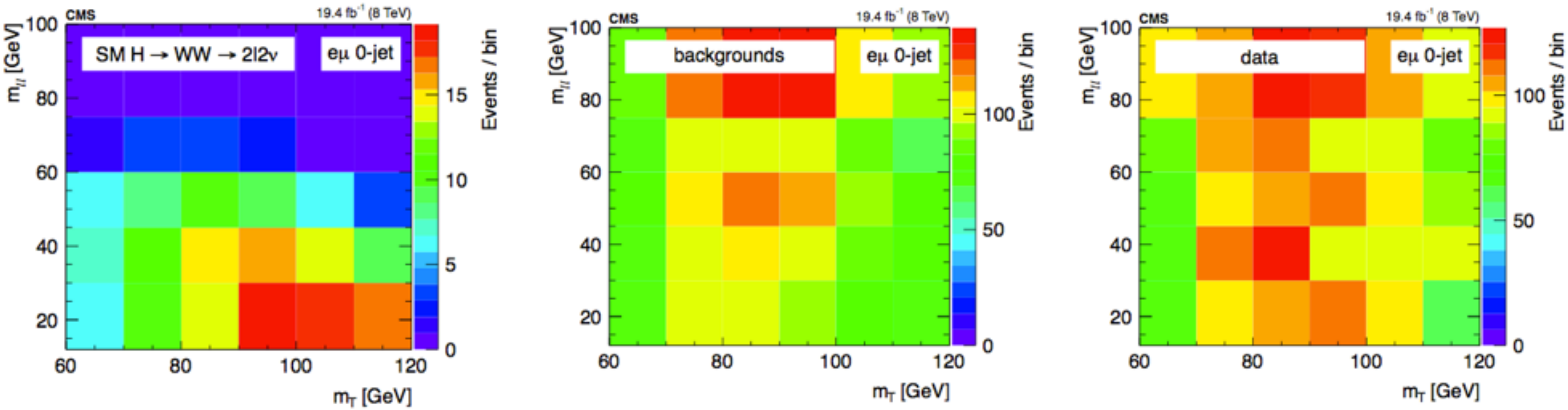
1 - jets

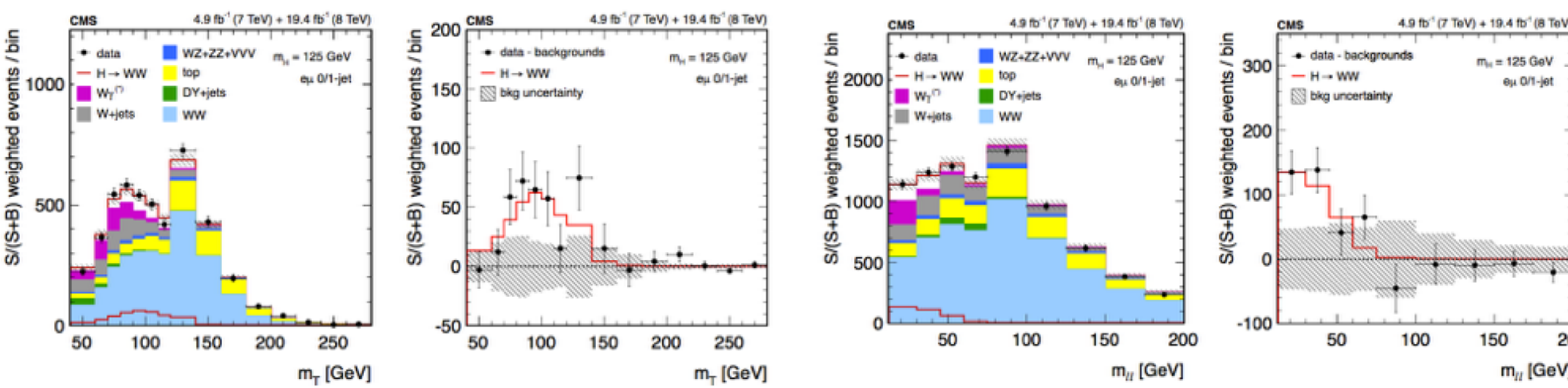


H→WW 0/1 jet bins

Signal extraction from a 2D template fit on (m_{ll}, m_T)

exe 0 jet bin



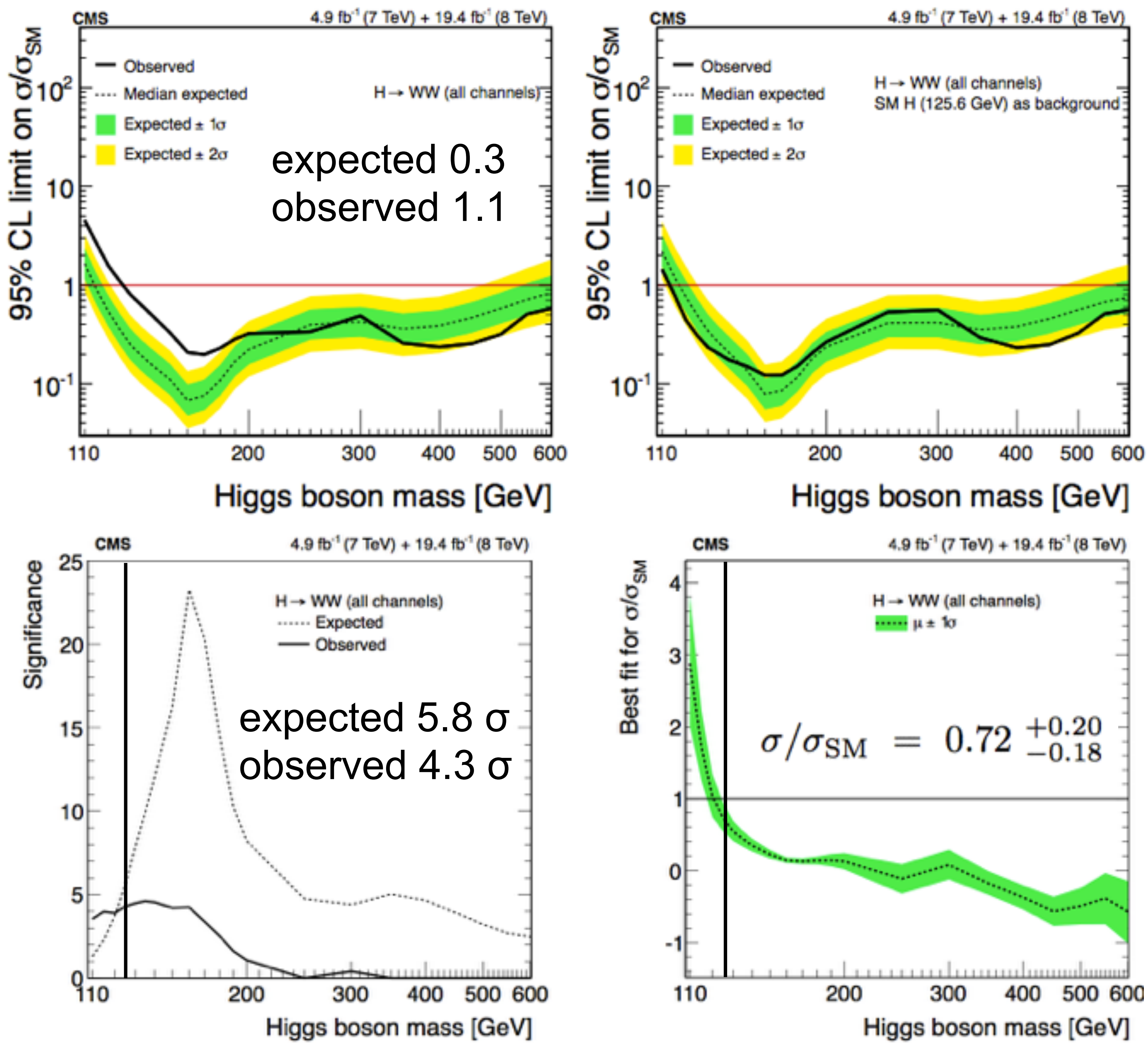


significance: expected 5.2 σ
observed 4.0 σ

$\hat{\mu}$ = 0.76 ± 0.21

H→WW results

@ 125.6 GeV

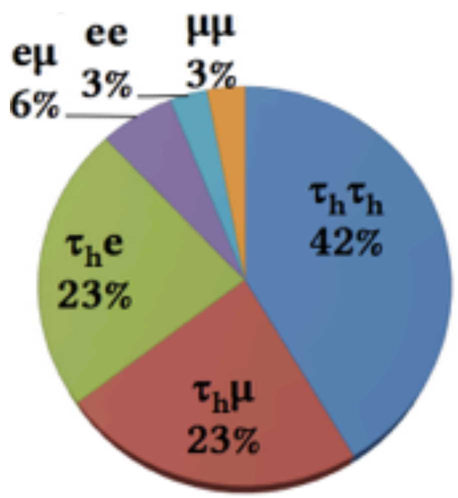


Fermionic decays

$H \to \tau\tau$

Tau : $m_\tau \sim 1.77$ GeV ; $c\tau \sim 87$ μm

Look for all 6 decays:



Main decay modes:	BR
$\tau \to h^- h^+ h^- \nu_\tau$	9.8 %
$\tau \to a_1^- \nu_\tau \to \pi\, \nu_\tau\, 2\pi^0$	9.3%
$\tau \to \rho\, \nu_\tau \to \pi^-\, \nu_\tau\, \pi^0$	25.5%
$\tau \to \pi^- \nu_\tau$	10.8%
$\tau \to e^- \nu_e \nu_\tau$	17.8%
$\tau \to \mu^- \nu_\mu \nu_\tau$	17.4%

BR($H \to \tau\tau$) ~ 6.4% vs BR($H \to bb$) ~ 57.7%
but its sensitivity is higher because it is cleaner:

- high pT leptons
- largest background is $Z \to \tau\tau$ instead of the overwhelming QCD

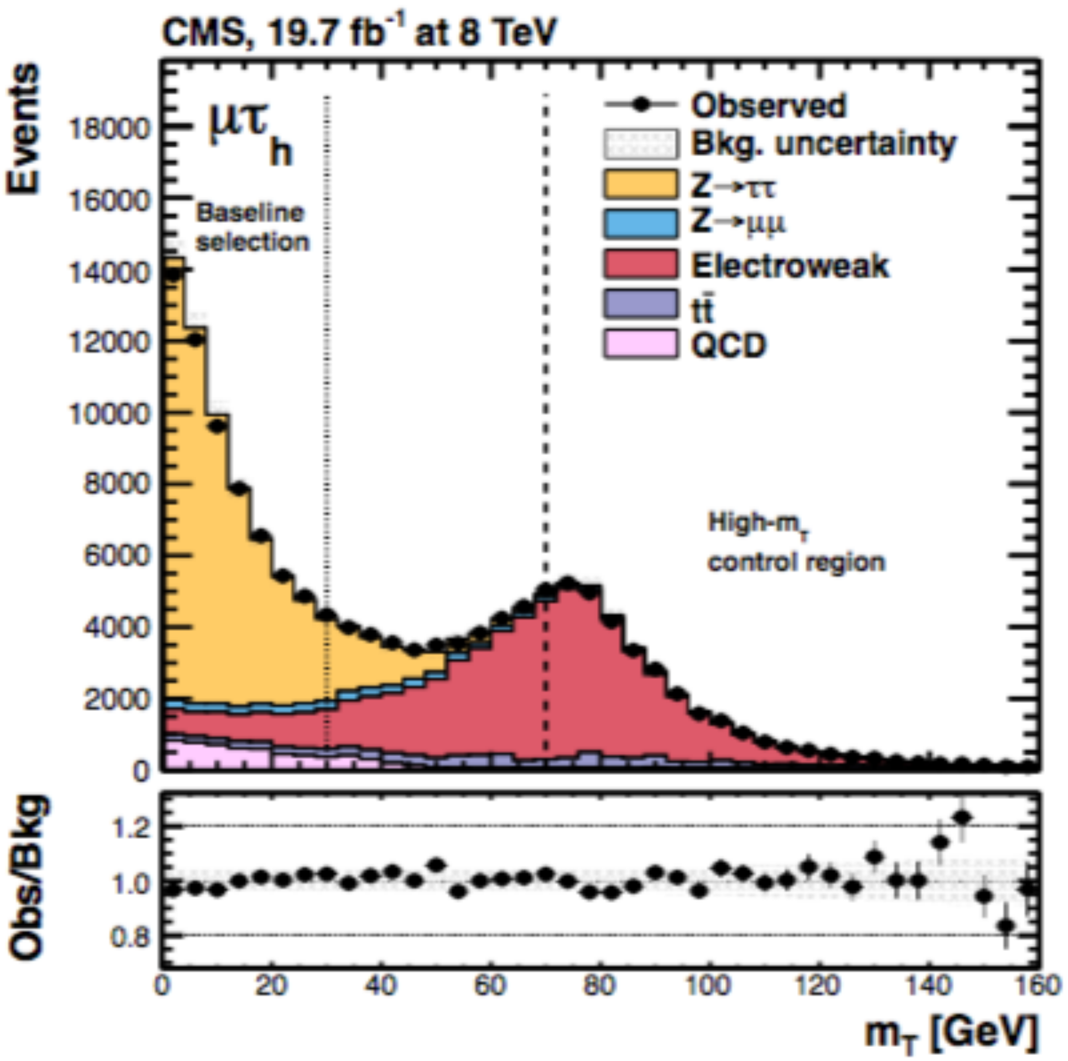
Need a very good control of the Z line shape: use $Z \to \mu\mu$ embedding technique:
(basically take $Z \to \mu\mu$ in data, replace the two muons with taus (lepton universality);
you get the correct kinematics and high statistics pure sample of $Z \to \tau\tau$)

$H \rightarrow \tau\tau$ backgrounds

Expected ~30000 $H \rightarrow \tau\tau$ decays in the 8 TeV dataset before reconstruction/selection

Typical selection cuts on leptons and τ_h : pT > 20 - 40 GeV

In $e\tau_h$ and $\mu\tau_h$ to reduce the W+jet (Electroweak) background a cut on m_T is applied



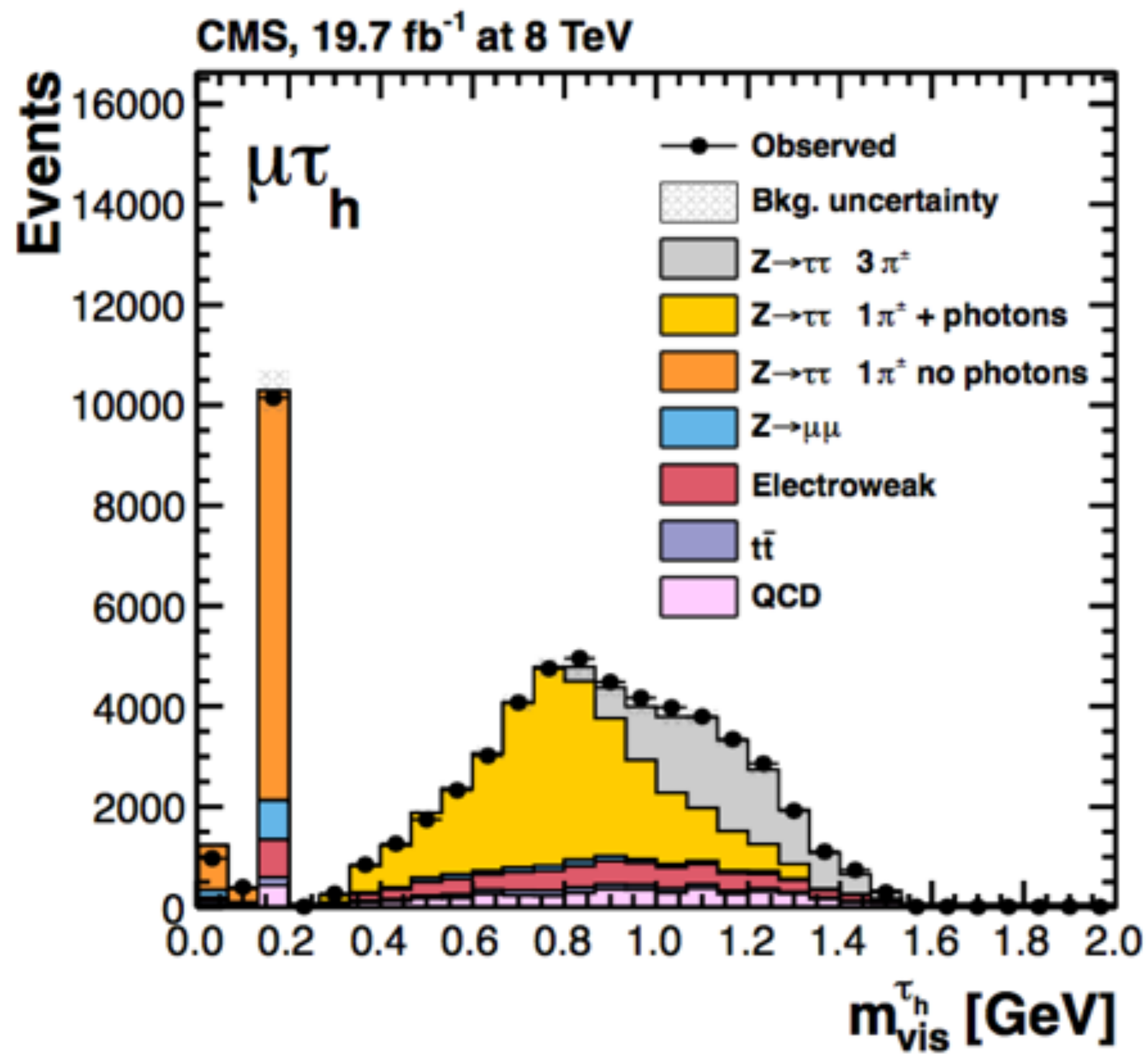
W+ jets high m_T (neutrino from real W)
$Z \rightarrow \tau\tau$ low m_T (neutrino from $\tau\tau$)

Finally in eμ the largest background is tt: reduced using a BDT classifier

H→ττ invariant mass

Discriminating variable: invariant mass of the ττ system, but you have 2ν in the final state

Simple approach: ignore the presence of the neutrinos and compute the visible mass m_{vis}



Good Data/MC agreement means both
good daata/MC in τ reco efficiency and E calibrations

H→ττ invariant mass

"collinear approximation": neutrino emission coincide with the tau direction

$$E_{T,x}^{\text{miss}} = p_{\tau_1}^{\nu} \cdot \sin\vartheta_{\tau_1} \cos\varphi_{\tau_1} + p_{\tau_2}^{\nu} \cdot \sin\vartheta_{\tau_2} \cos\varphi_{\tau_2}$$
$$E_{T,y}^{\text{miss}} = p_{\tau_1}^{\nu} \cdot \sin\vartheta_{\tau_1} \sin\varphi_{\tau_1} + p_{\tau_2}^{\nu} \cdot \sin\vartheta_{\tau_2} \sin\varphi_{\tau_2}$$

$$p_{\tau_1}^{\nu} = \frac{E_{T,x}^{\text{miss}} \cdot \sin\varphi_{\tau_2} - E_{T,y}^{\text{miss}} \cdot \cos\varphi_{\tau_2}}{\sin\vartheta_{\tau_1} \sin(\varphi_{\tau_1} - \varphi_{\tau_2})} \qquad p_{\tau_2}^{\nu} = -\frac{E_{T,x}^{\text{miss}} \cdot \sin\varphi_{\tau_1} - E_{T,y}^{\text{miss}} \cdot \cos\varphi_{\tau_1}}{\sin\vartheta_{\tau_2} \sin(\varphi_{\tau_1} - \varphi_{\tau_2})}$$

and $m_{\tau\tau}$ can be calculated as

$$m_{\tau\tau} = \frac{m_{\text{vis}}}{\sqrt{x_{\tau_1} x_{\tau_2}}}, \qquad x_{\tau_i} = \frac{p_{\tau_i}^{\text{vis}}}{p_{\tau_i}^{\text{vis}} + p_{\tau_i}^{\nu}}$$

The collinear approximation works better when the taus are highly boosted.
The system of eq. is degenerate when the taus are back to back

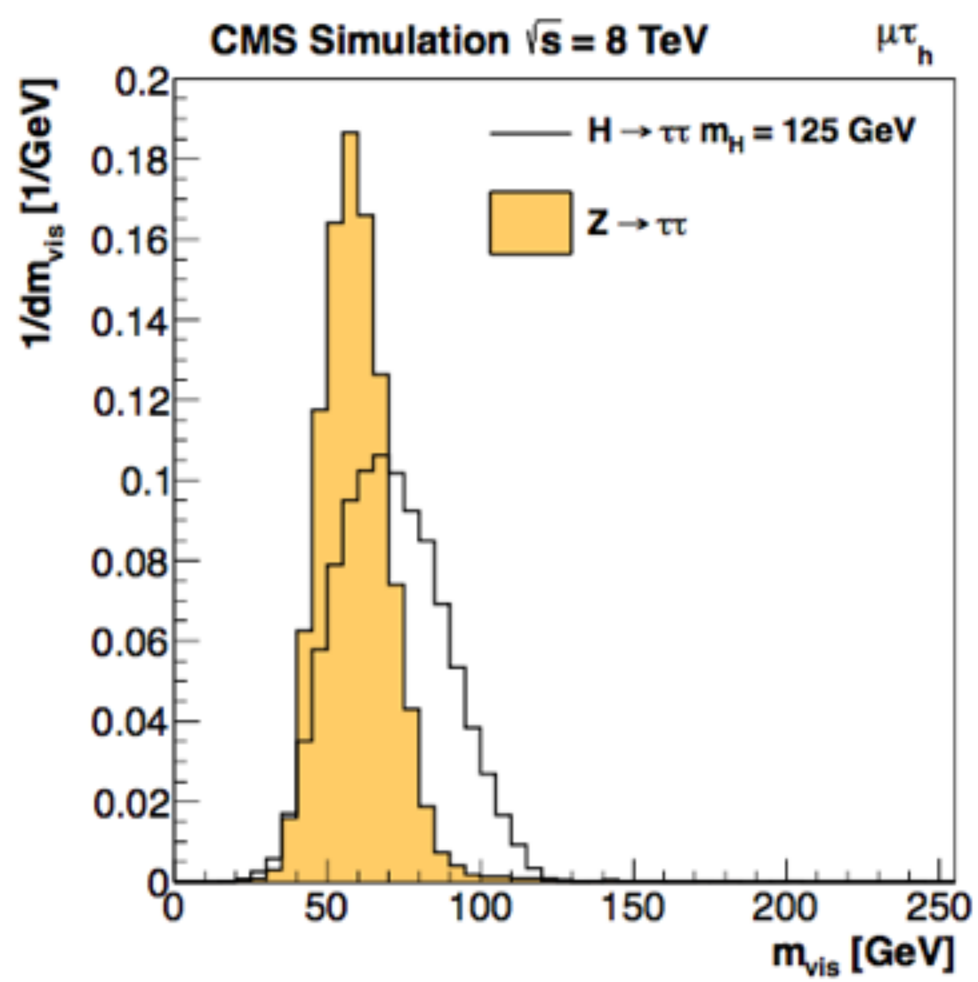
H→ττ invariant mass

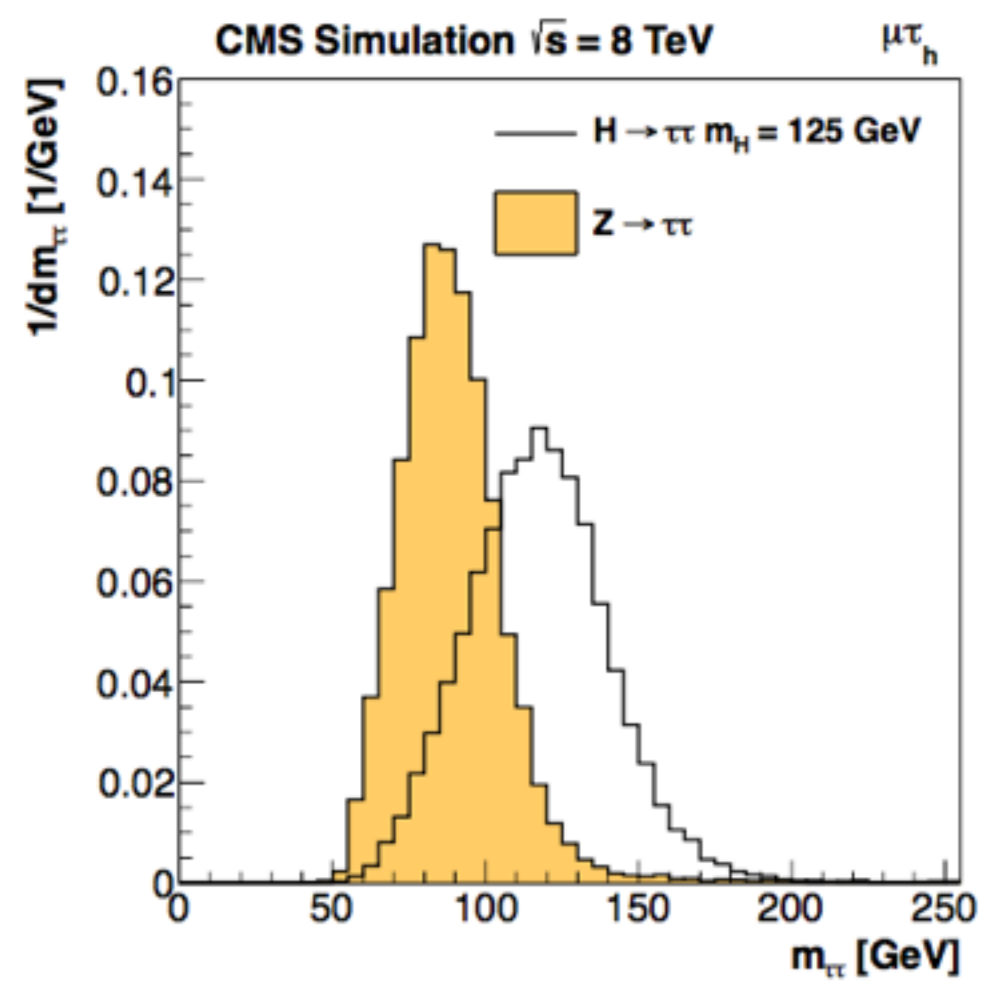
Final choice was to use a likelihood fit to get the neutrino momenta:

$$\mathcal{L}_\nu(E_x^{\text{miss}}, E_y^{\text{miss}}) = \frac{1}{2\pi\sqrt{|V|}} \exp\left[-\frac{1}{2}\begin{pmatrix} E_x^{\text{miss}} - \sum p_x^\nu \\ E_y^{\text{miss}} - \sum p_y^\nu \end{pmatrix}^T V^{-1} \begin{pmatrix} E_x^{\text{miss}} - \sum p_x^\nu \\ E_y^{\text{miss}} - \sum p_y^\nu \end{pmatrix}\right]$$

V is the covariance matrix of the MET

Resolution: ~10 /15 / 20 % for $\tau_h\tau_h$ / $l\tau_h$ / ll





H→ττ categories

Categories:

0j,1j (ggF), 2j (VBF)

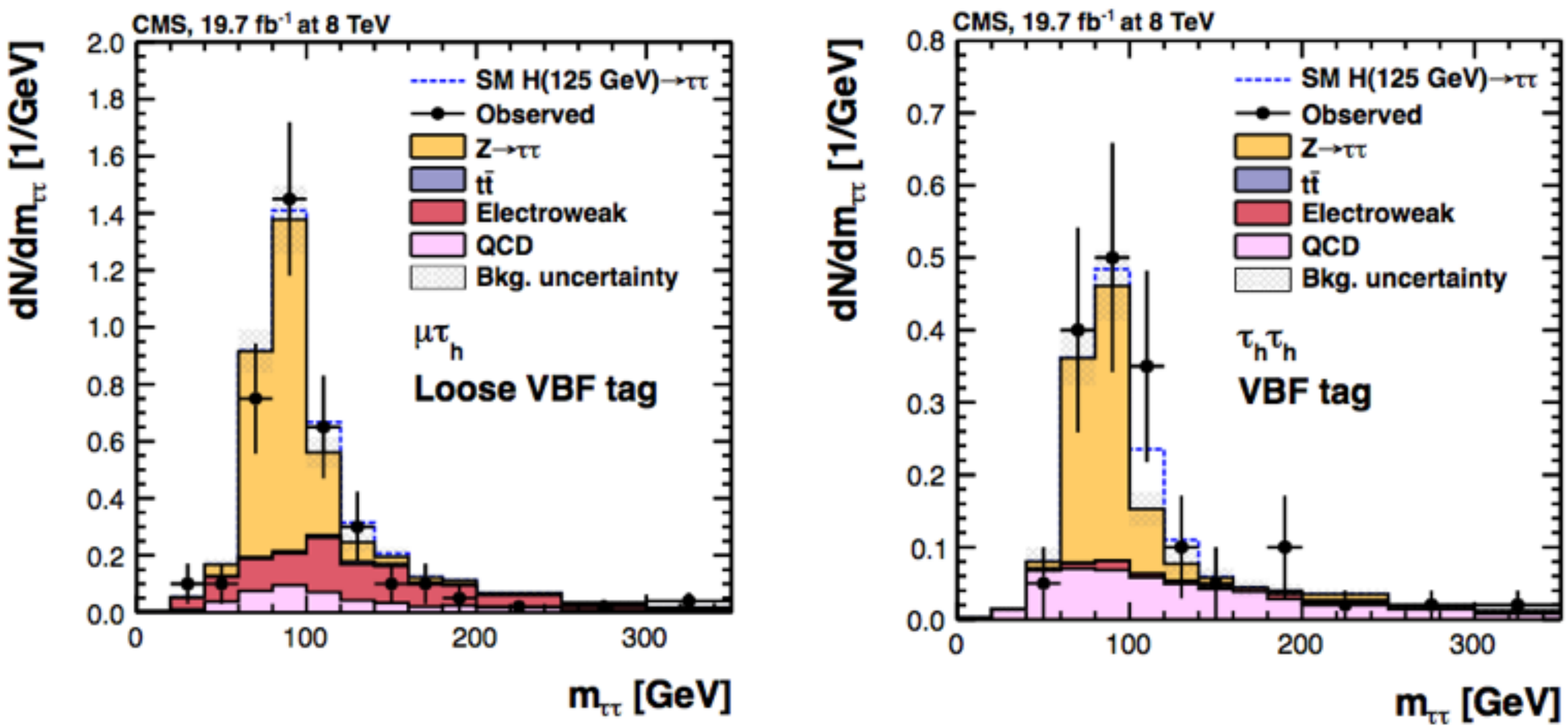
l+ττ ll+ττ (WH, ZH)

and further lepton p_T, $p_T(\tau\tau)$ and jet properties

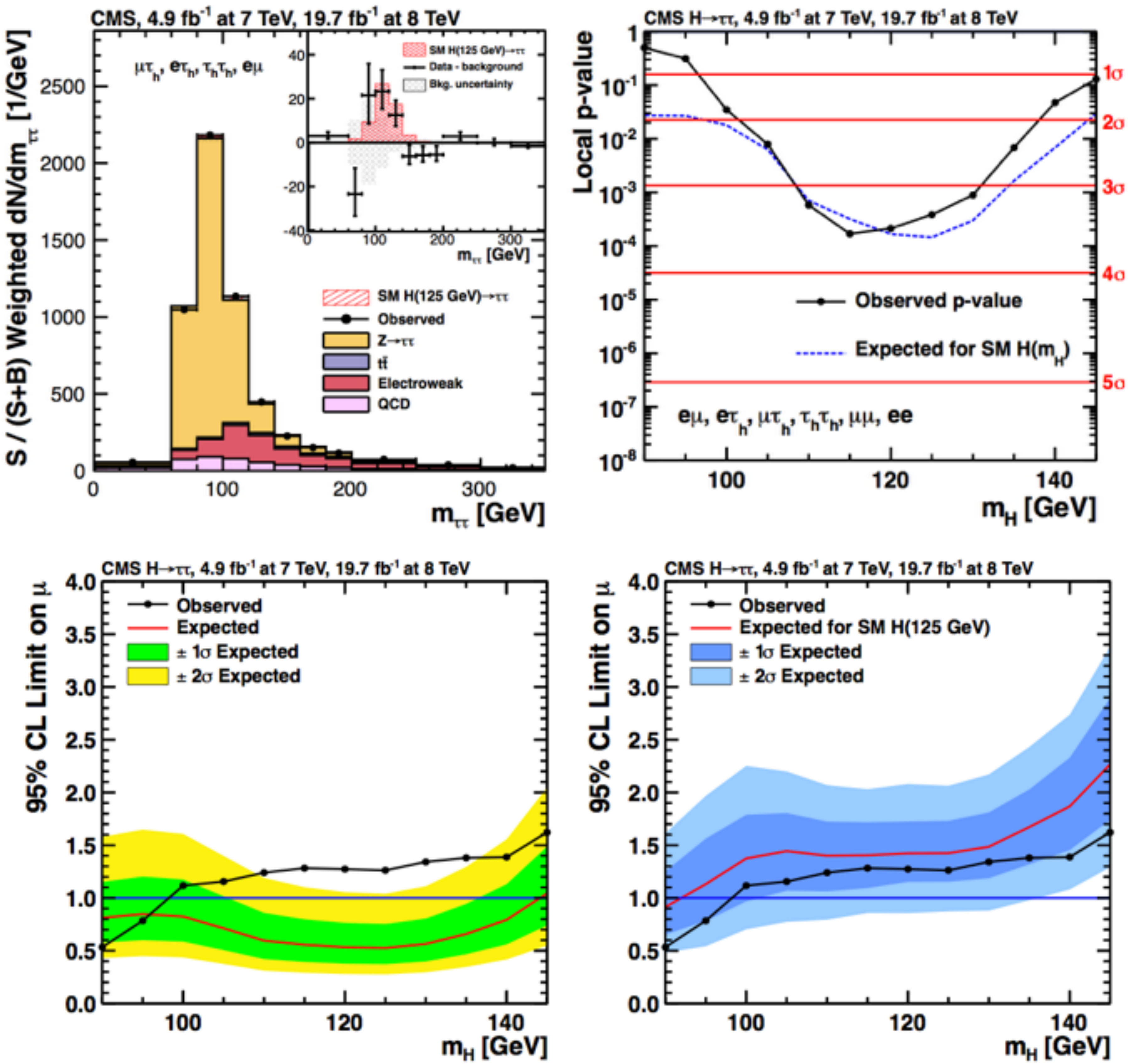
Total 27 categories.

The VBF channel has 2100 events before reco/selection: in the dijet category the signal fraction is ~80%

Largest S/B VBF categories:



H→ττ results



Significance > 3 sigma ; Best fit μ = 0.78 ± 0.27

$H\to bb$

b is the heaviest quark accessible

Largest BR (~57.7%) ~ 250 10^3 events before reco/selection

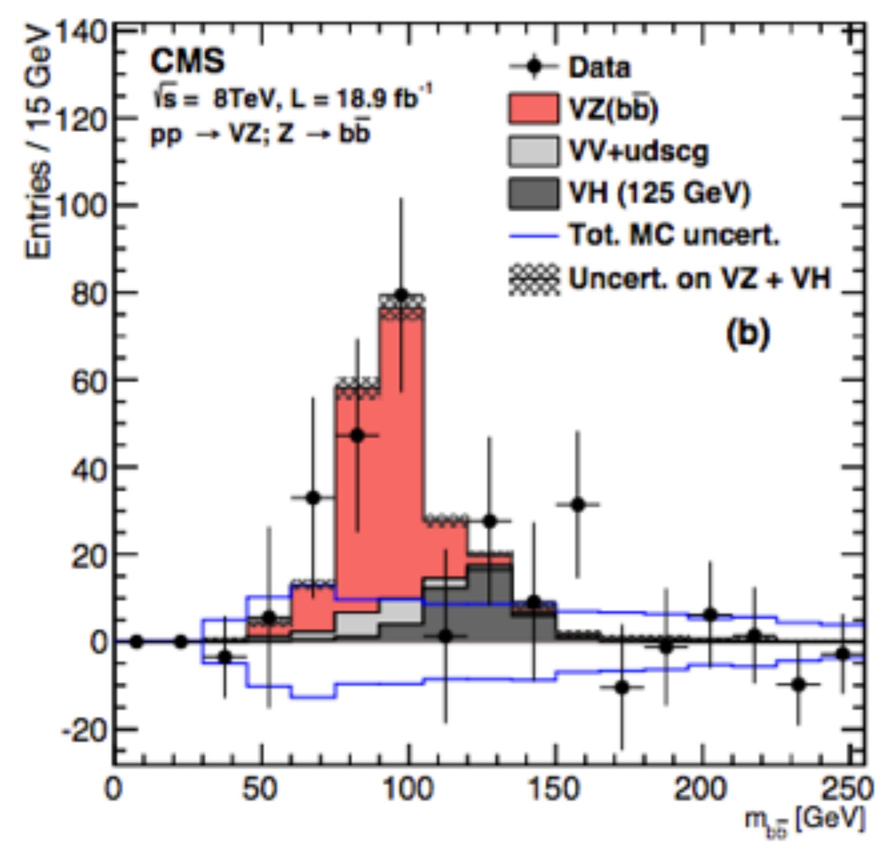
Can't look for it in ggF too much background (10^7 times larger)

Idea: look for boosted VH production (>100GeV):
multijet bkg reduced + better mass resolution

Cut 95% of the initial signal to gain sensitivity: down to ~12000 events

With this choice the main background QCD is replaced with a more manageable EW:
Z+bb, W+bb, VV, tt

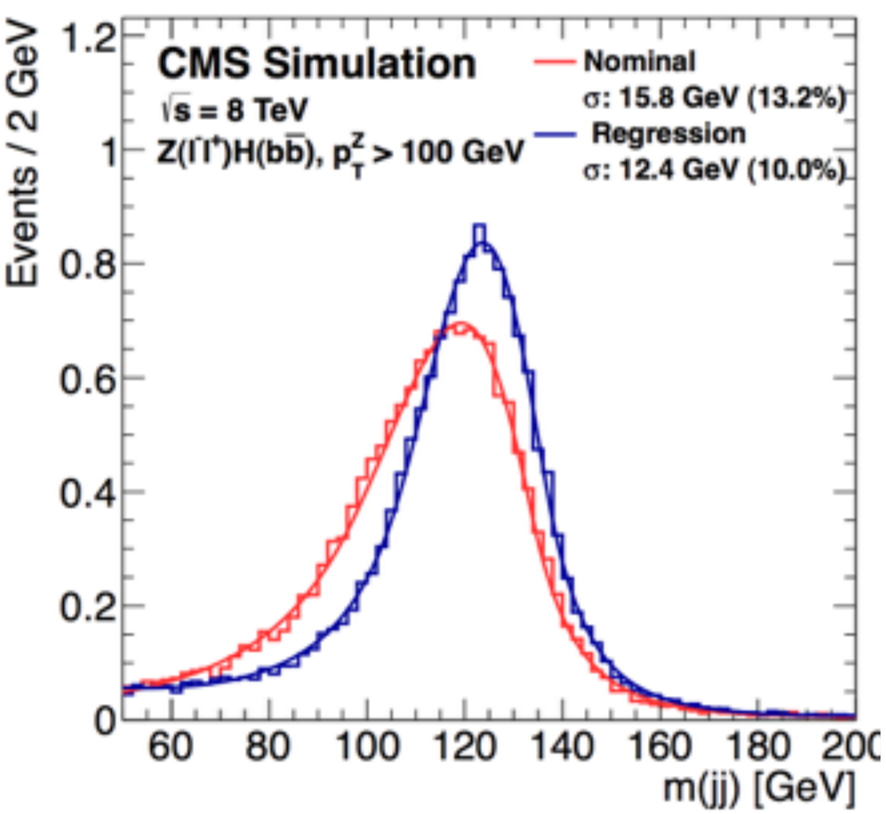
Key point of the analysis: everything can be tested on WZ and ZZ SM processes.
As a by product is was possible to extract a $Z\to bb$ signal at 7σ

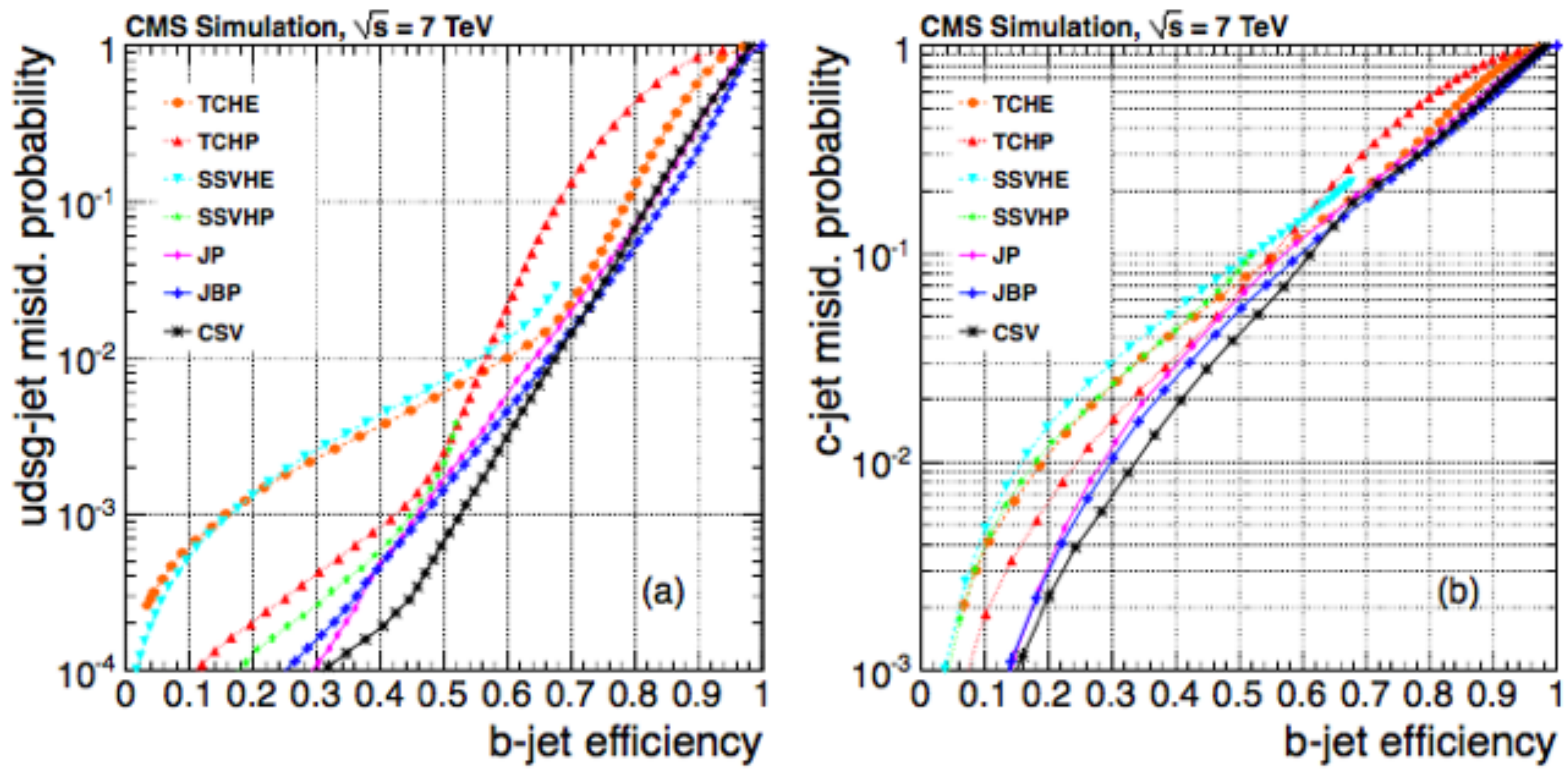


H→bb main tools

Energy regression

b-tagging





Mass resolution ~ 10%

CSV (Combined Secondary Vertex)
likelihood based on:
- tracks impact parameters
- secondary vertices

H→bb categories

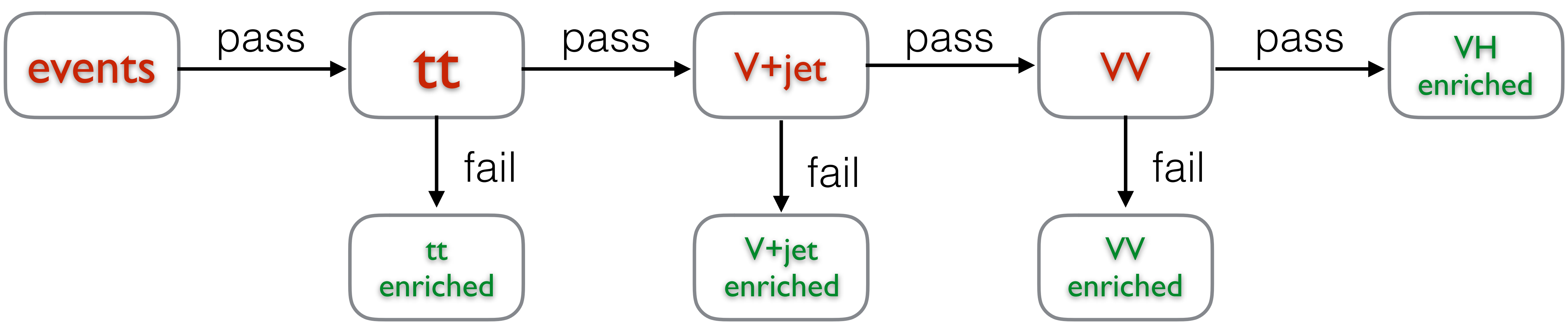
6 Final states: W(τν)H, W(μν)H, W(eν)H, Z(ee)H, Z(μμ)H, Z(νν)H

Z(νν)H no leptons (need to work with MET) larger BR ~50% larger that ee+μμ

14 boosted categories:

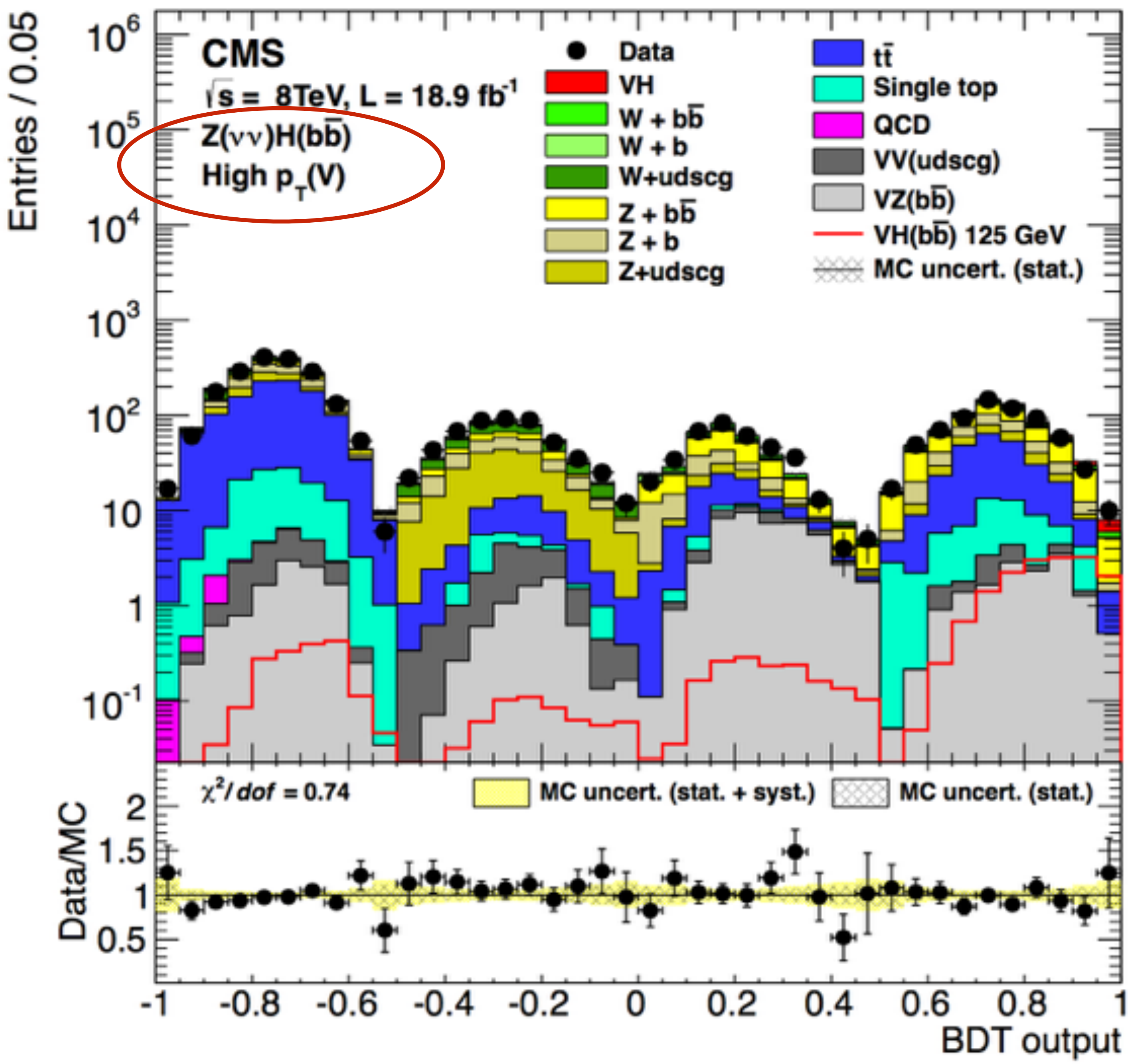
	Boost categories		
	Low	Medium	High
$W(\tau\nu)$	–	–	$120\,\mathrm{GeV} < p_T(V)$
$W(\mu\nu)$	$100 < p_T(V) < 130\,\mathrm{GeV}$	$130 < p_T(V) < 180\,\mathrm{GeV}$	$180\,\mathrm{GeV} < p_T(V)$
$W(e\nu)$	$100 < p_T(V) < 130\,\mathrm{GeV}$	$130 < p_T(V) < 180\,\mathrm{GeV}$	$180\,\mathrm{GeV} < p_T(V)$
$Z(\mu\mu)$	$50 < p_T(V) < 100\,\mathrm{GeV}$	–	$100\,\mathrm{GeV} < p_T(V)$
$Z(ee)$	$50 < p_T(V) < 100\,\mathrm{GeV}$	–	$100\,\mathrm{GeV} < p_T(V)$
$Z(\nu\nu)$	$100 < E_T^{\mathrm{miss}} < 130\,\mathrm{GeV}$	$130 < E_T^{\mathrm{miss}} < 170\,\mathrm{GeV}$	$170\,\mathrm{GeV} < E_T^{\mathrm{miss}}$

Final step: 4 categories defined on BTD classifiers

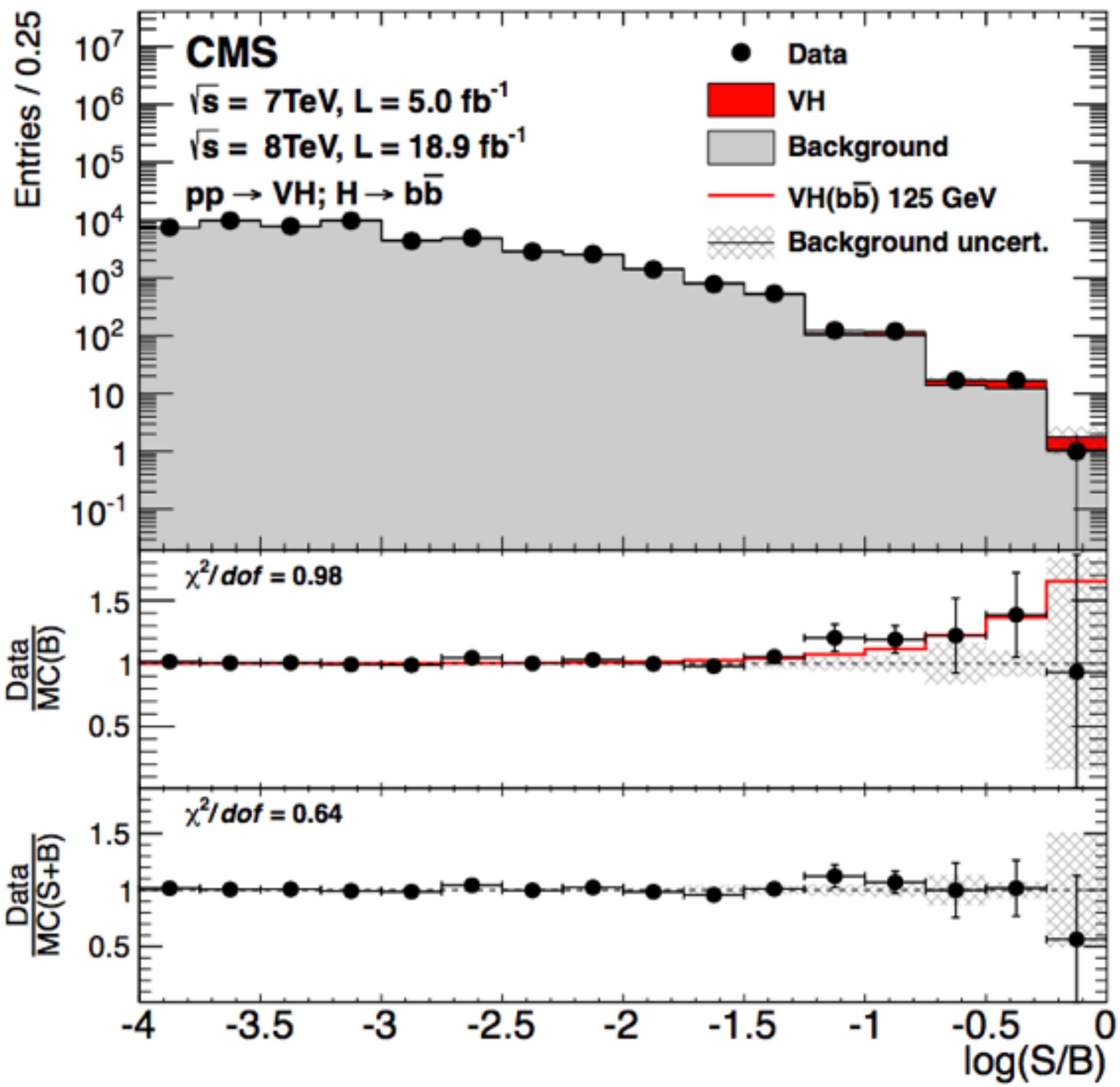


H→bb categories

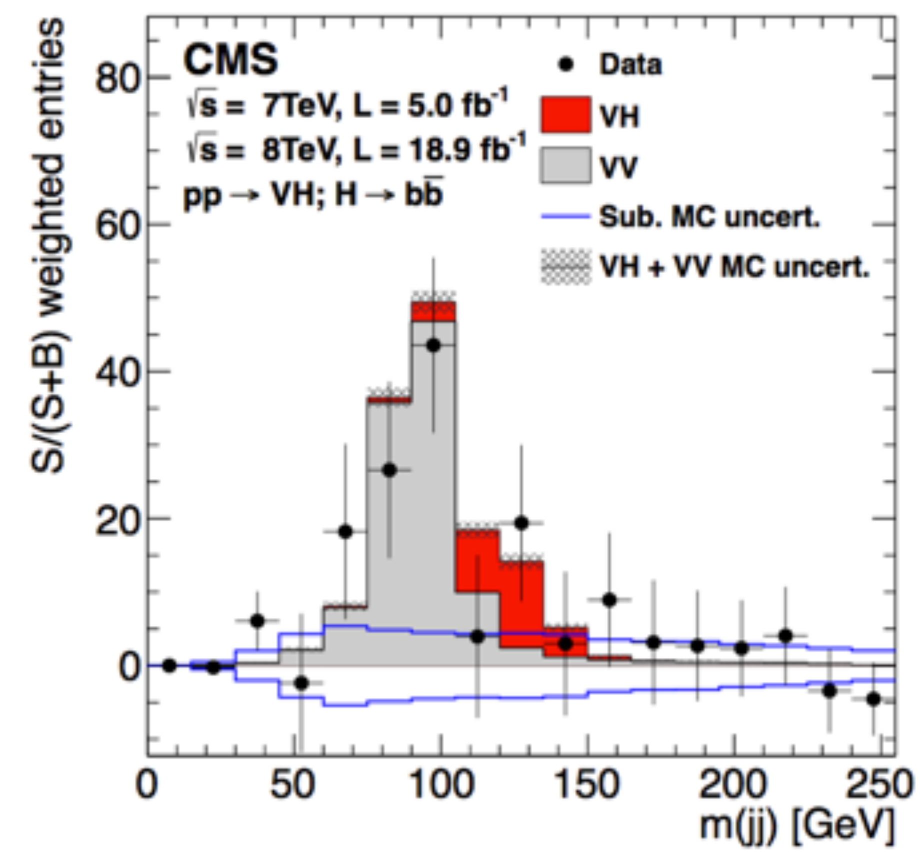
Example “post-fit” distribution



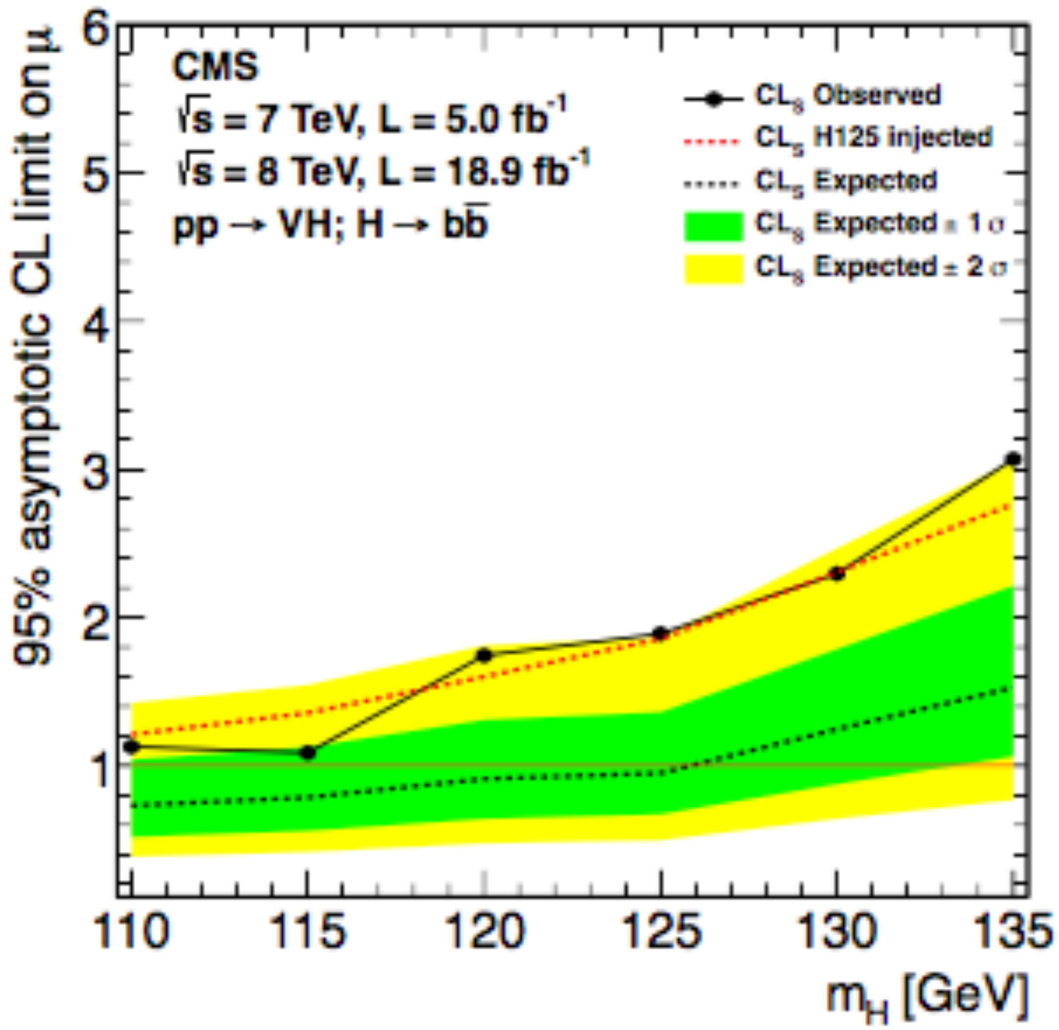
H→bb results

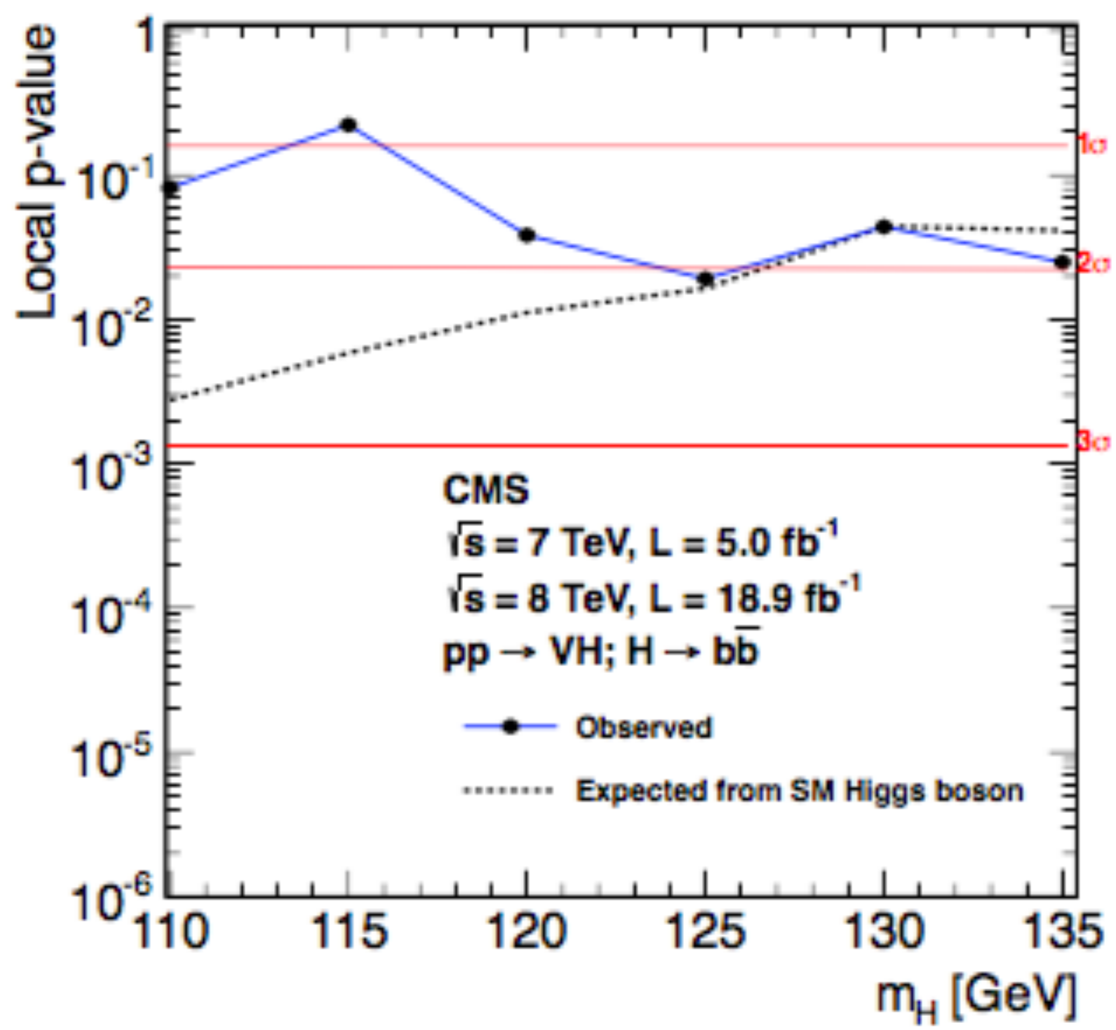


xcheck analysis



H→bb results

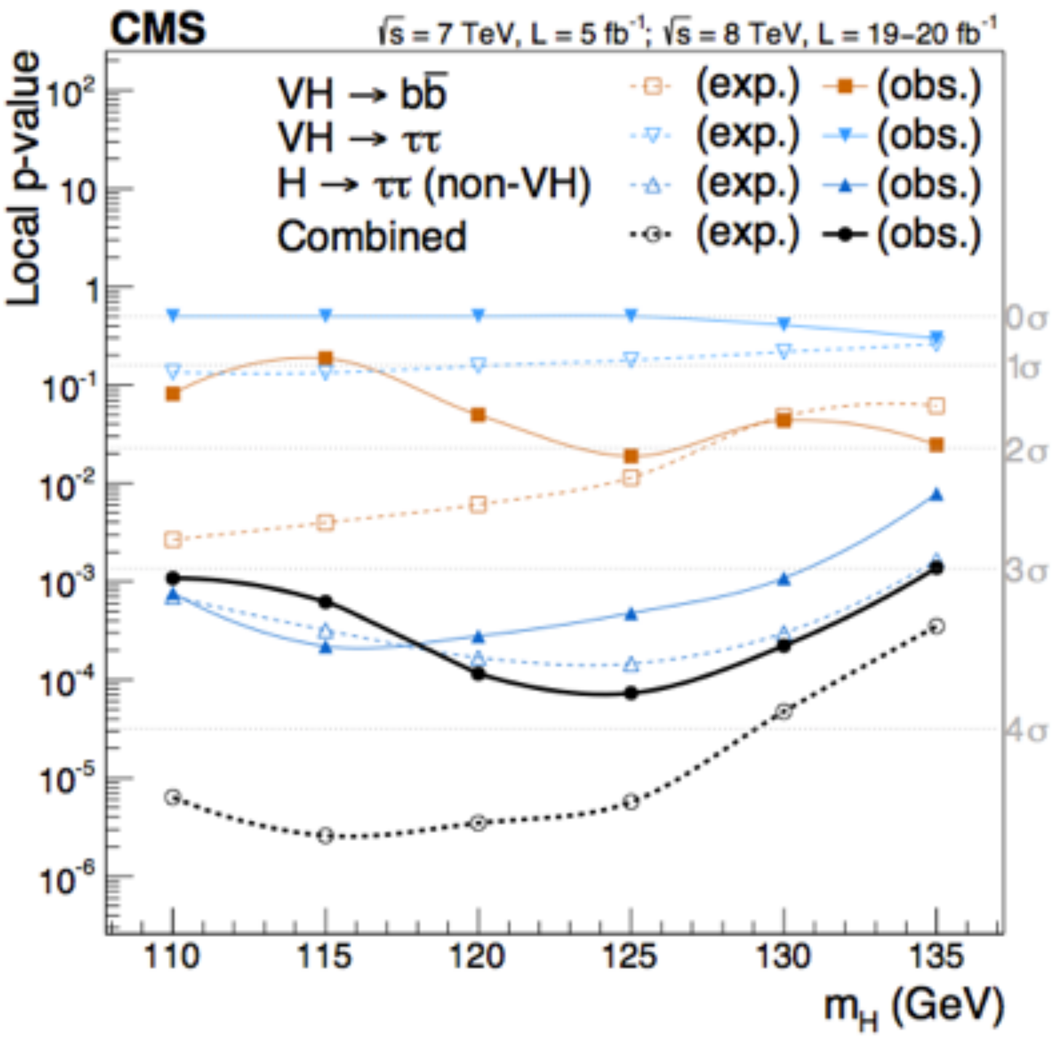


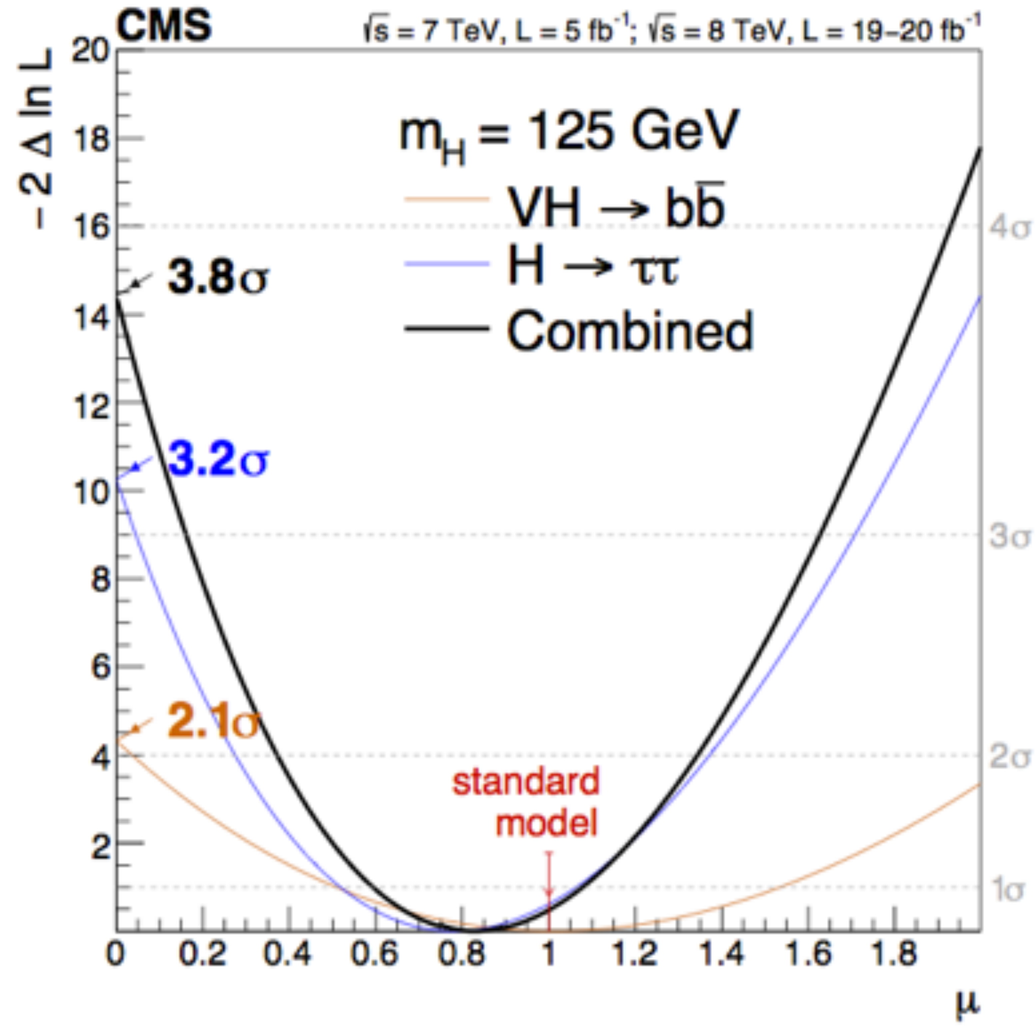


expected limit: 0.95
observed limit: 1.98

local significance @ 125 GeV

Higgs to fermion evidence

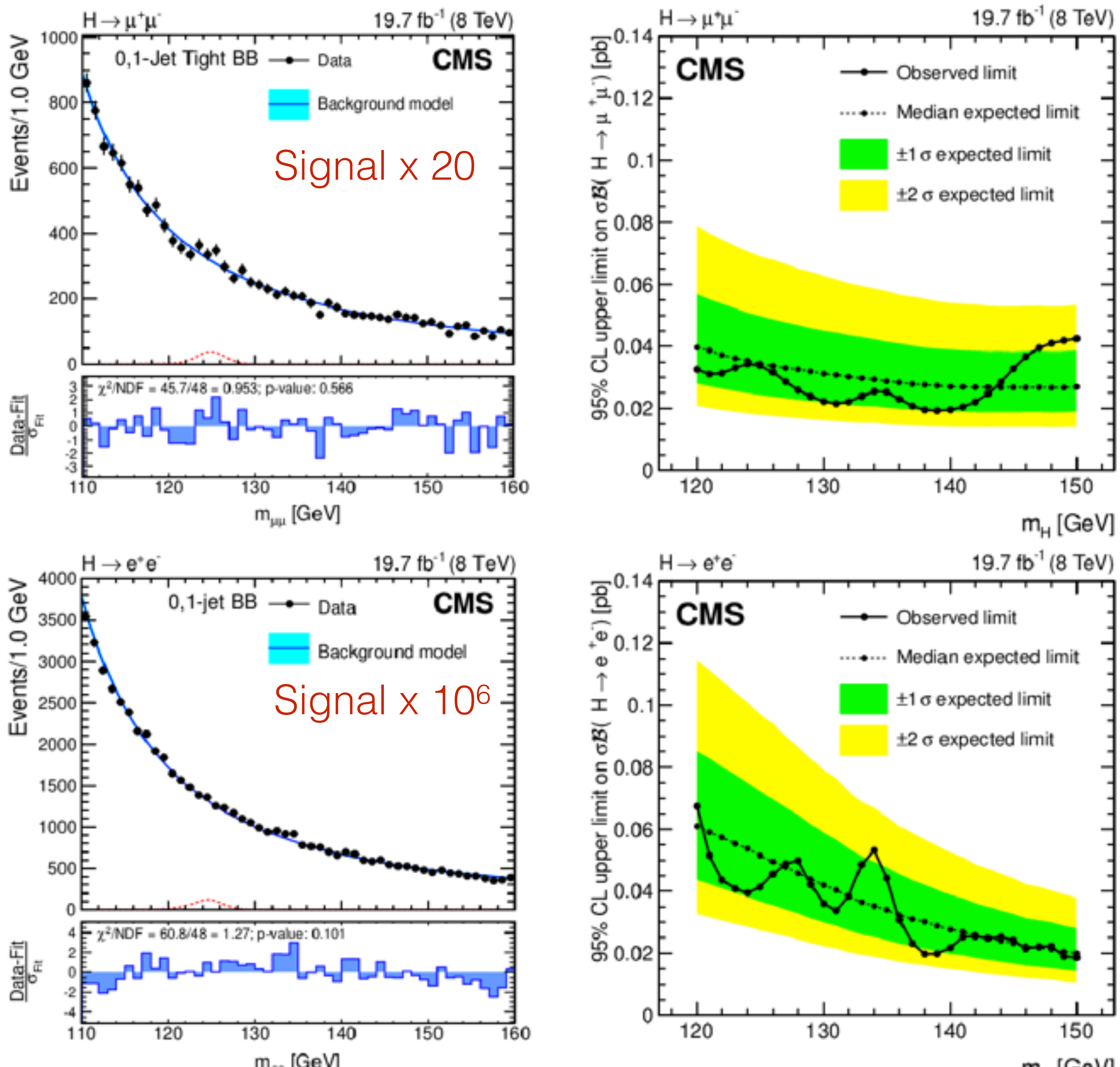




Channel (m_H = 125 GeV)	Significance (σ) Expected	Observed	Best-fit μ
VH → $b\bar{b}$	2.3	2.1	1.0 ± 0.5
H → $\tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24

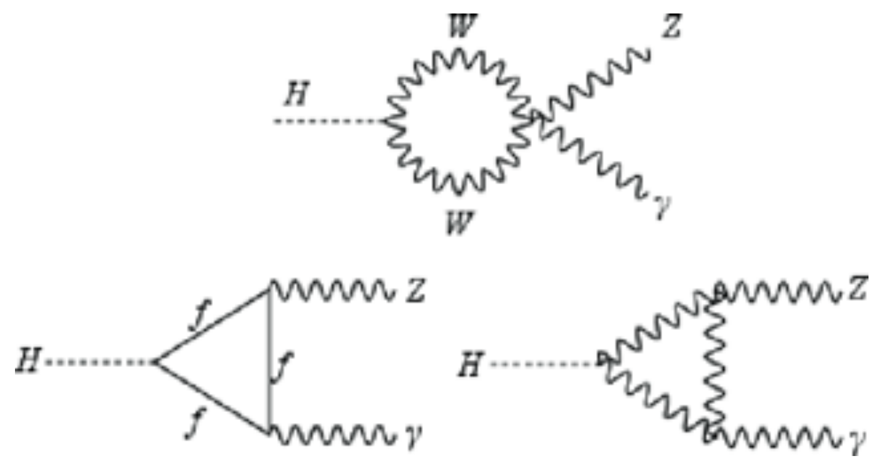
Other channels: flash

H→μμ H→ee

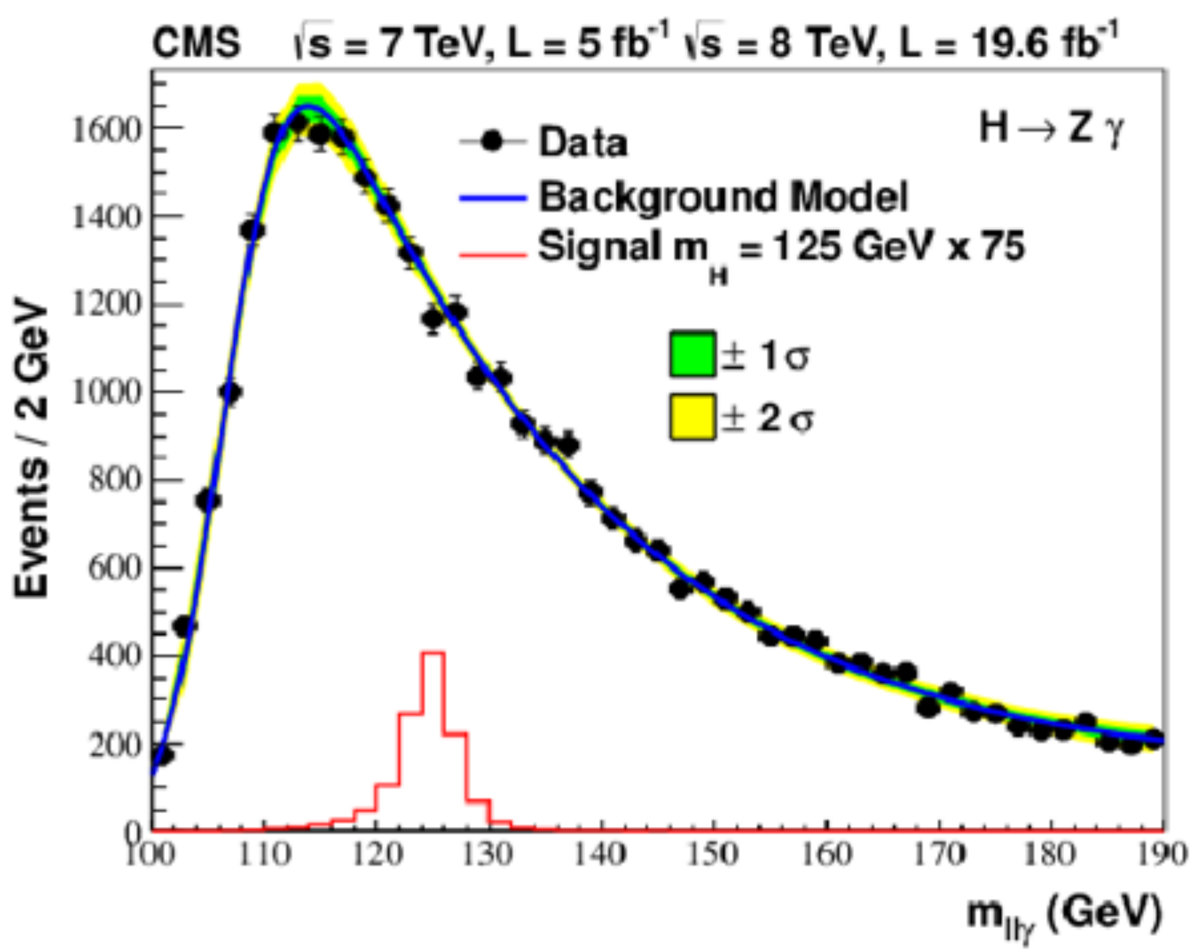


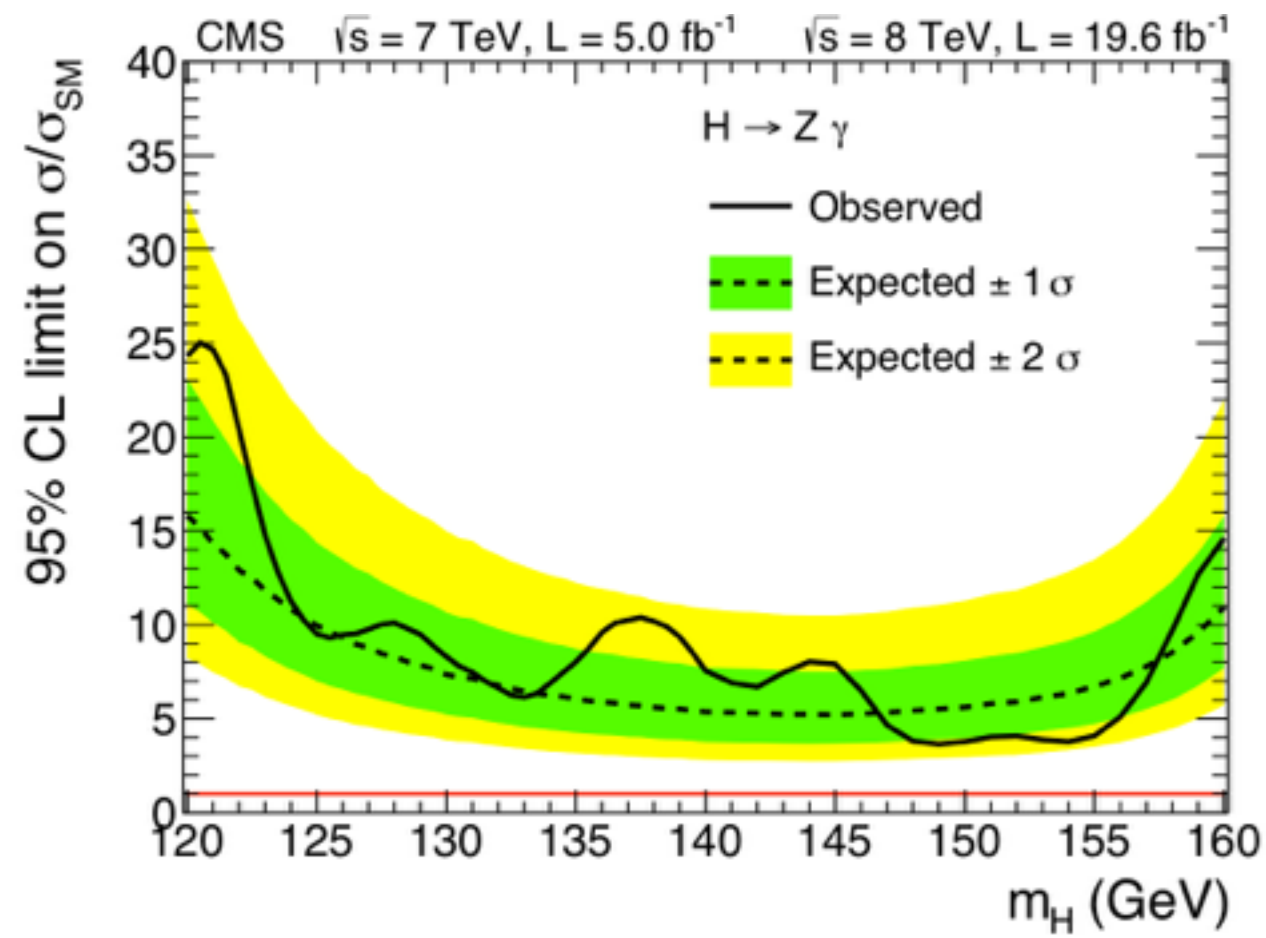
H → μ⁺μ⁻
19.7 fb⁻¹ (8 TeV)
0,1-Jet Tight BB
Data
Background model
CMS
Signal x 20
Events/1.0 GeV
χ²/NDF = 45.7/48 = 0.953; p-value: 0.566
m_μμ [GeV]
Observed limit
Median expected limit
±1 σ expected limit
±2 σ expected limit
95% CL upper limit on σB(H → μ⁺μ⁻) [pb]
m_H [GeV]
H → e⁺e⁻
0,1-jet BB
Signal x 10⁶
χ²/NDF = 60.8/48 = 1.27; p-value: 0.101
m_ee [GeV]
95% CL upper limit on σB(H → e⁺e⁻) [pb]

H→Zγ



fit $m_{Z\gamma}$





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