Search for Higgs boson at CMS

Roberta Volpe

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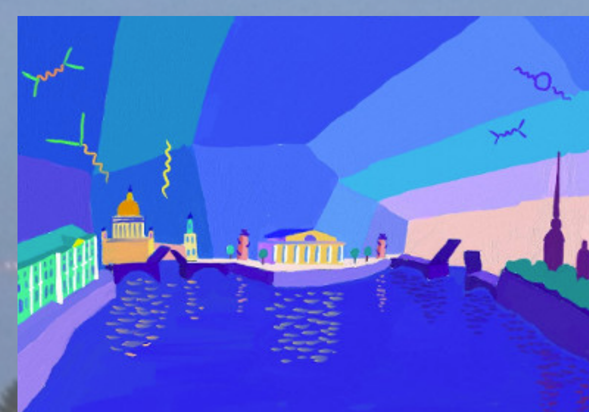
for the CMS Collaboration



QFTHEP 2013

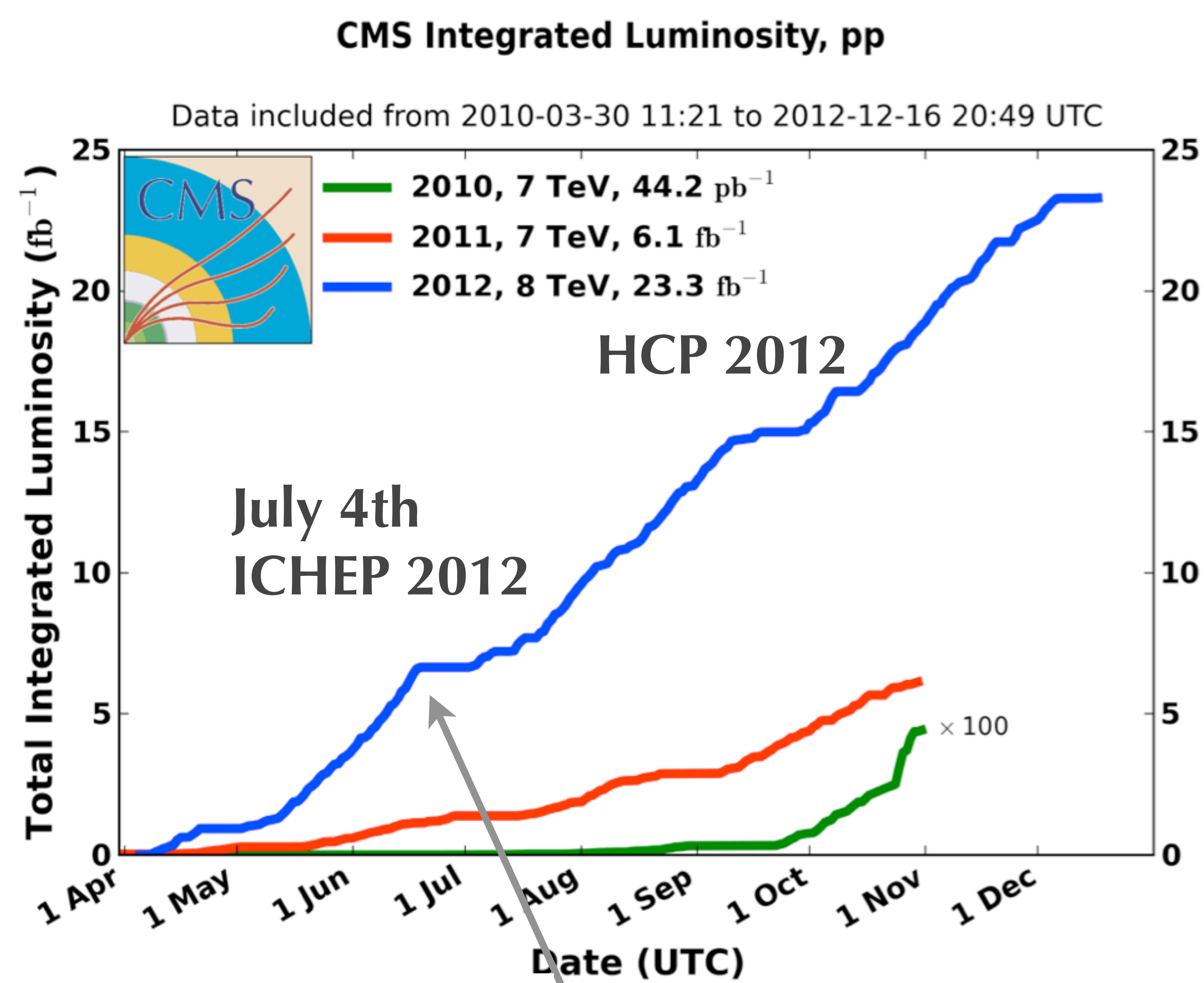
June 23-30, Repino, Russia

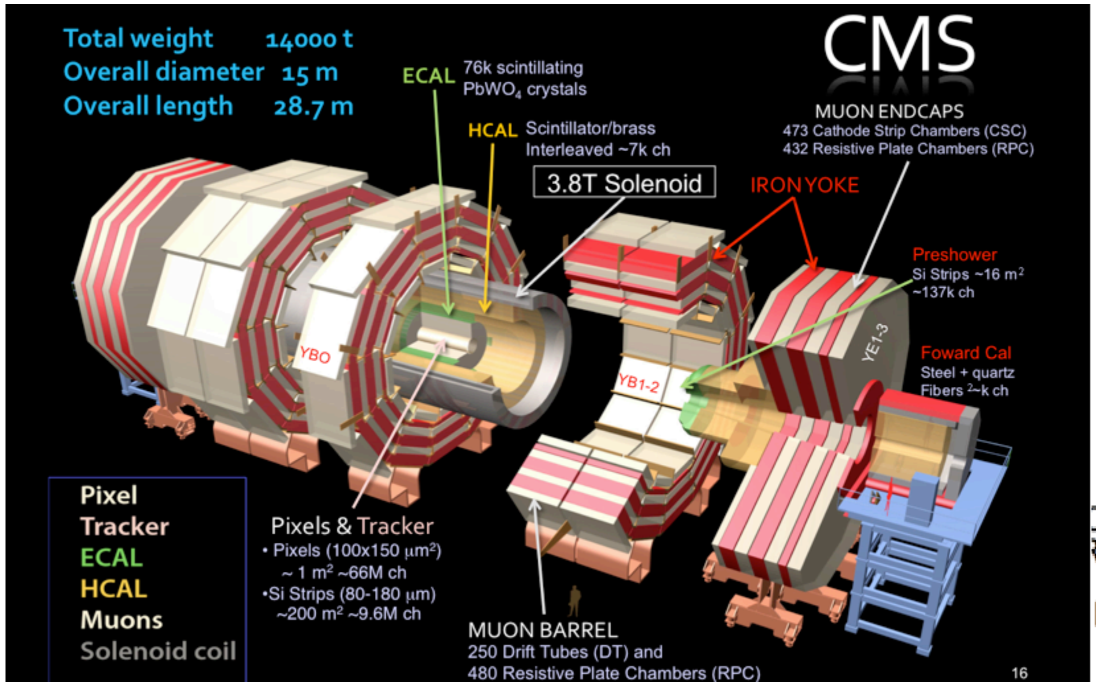
Outline

- The ingredients needed to find and study the Higgs
- Analyses included in the latest combination:
  - $H \to \gamma\gamma$
  - $H \to ZZ$
  - $H \to WW$
  - $H \to \tau\tau$
  - $H \to bb$
- Properties of the new particle with the combination results
- Short look at new Higgs analyses (published for LHCP and LP)

What has been needed

- Performance of LHC
- CMS detector
- Data recording
- Physics Object reconstruction

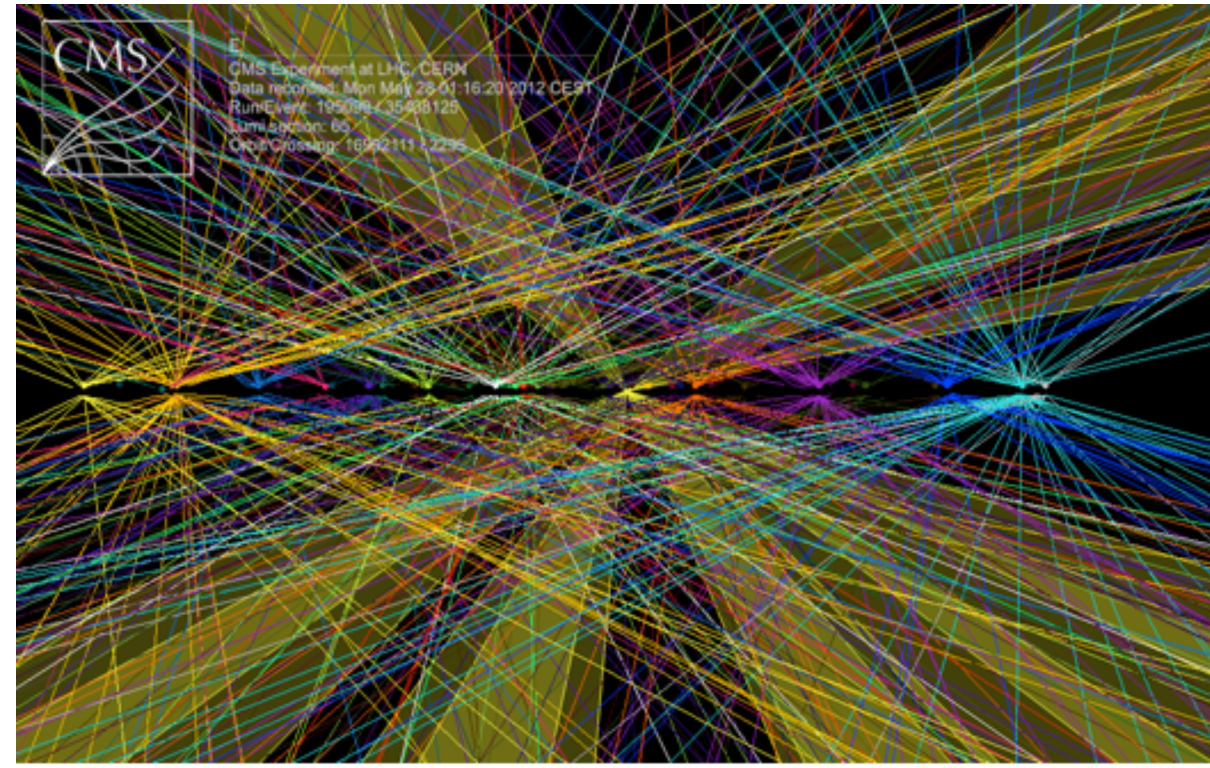




Higgs(-like) boson observation

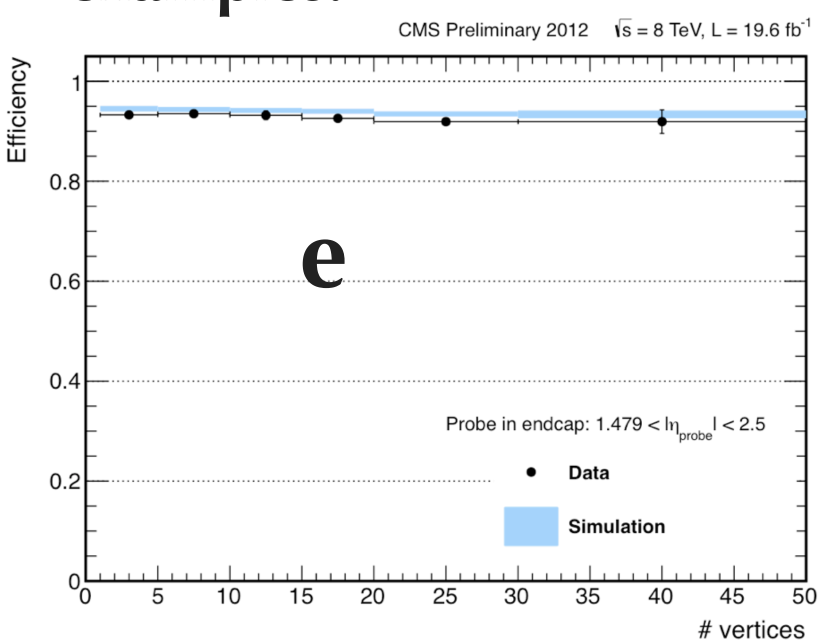
What has been needed

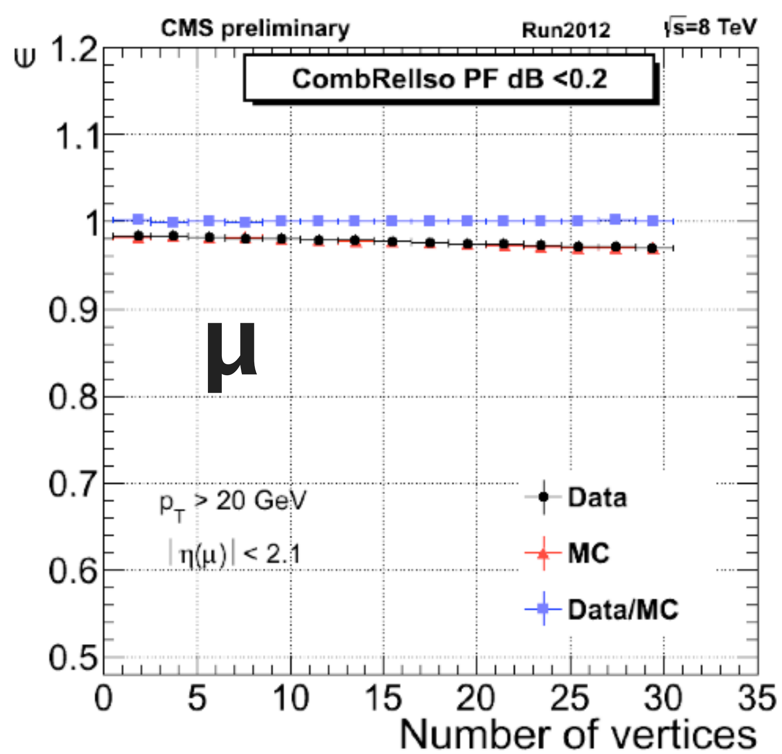
- Performance of LHC
- CMS detector
- Data recording
- Physics Object reconstruction
  - understand the PU

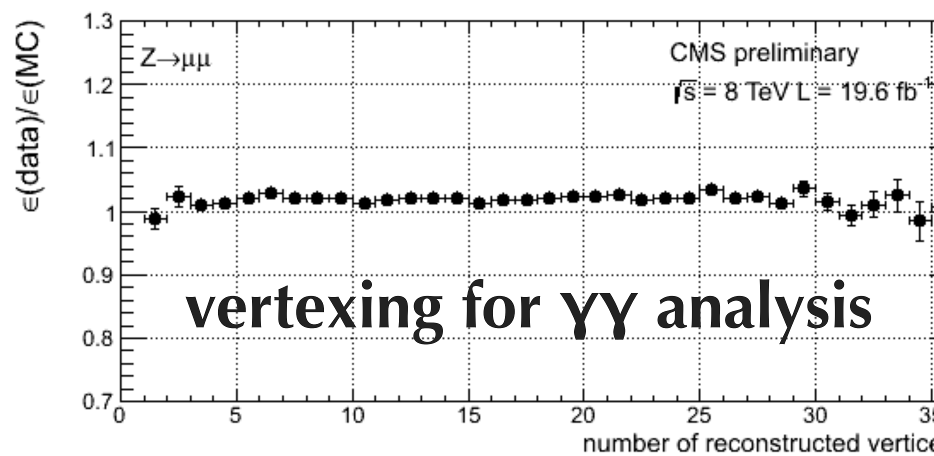


- Standard Model measurements

examples:







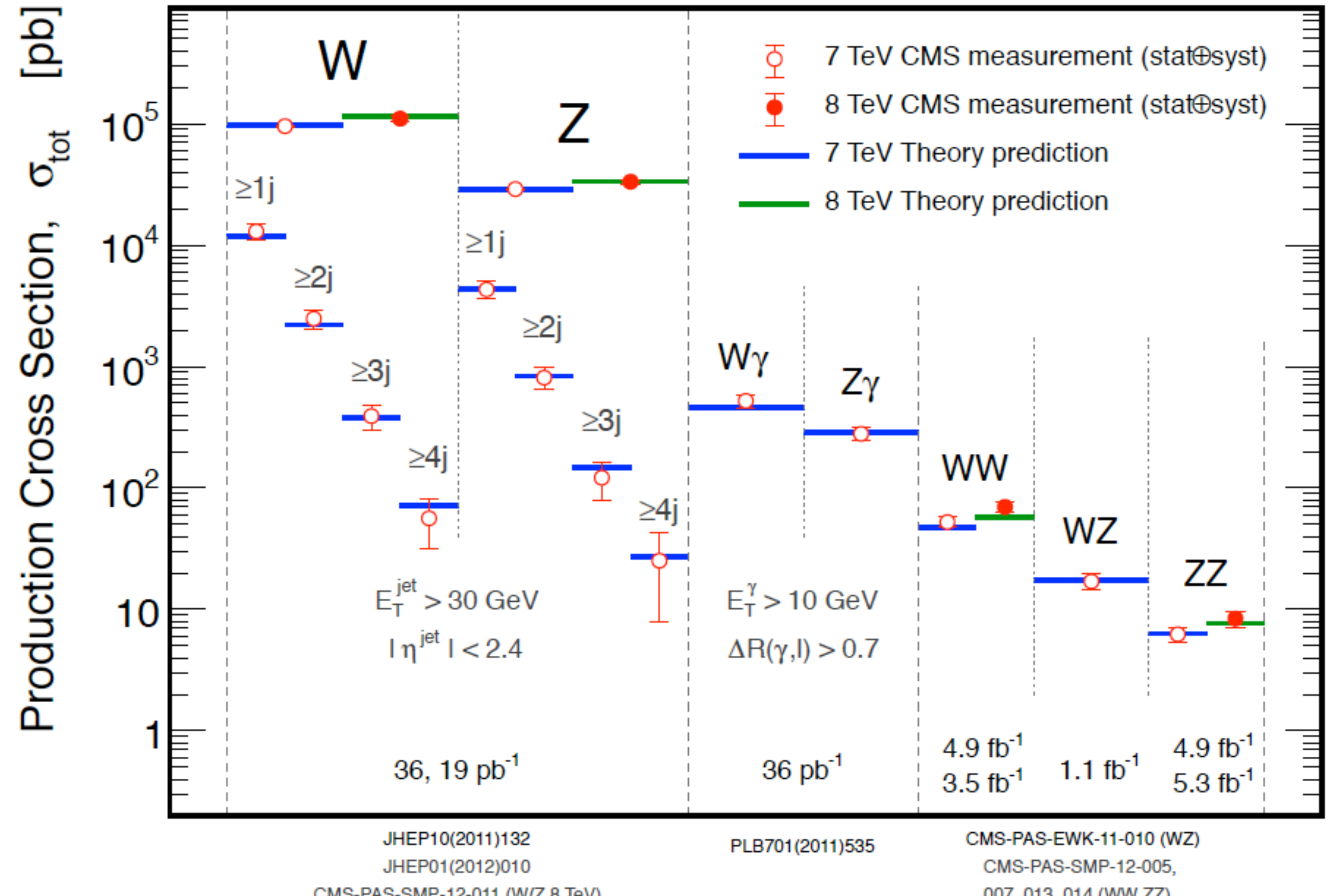
the performance is made as stable as possible as a function of the number of vertices

SM measurements

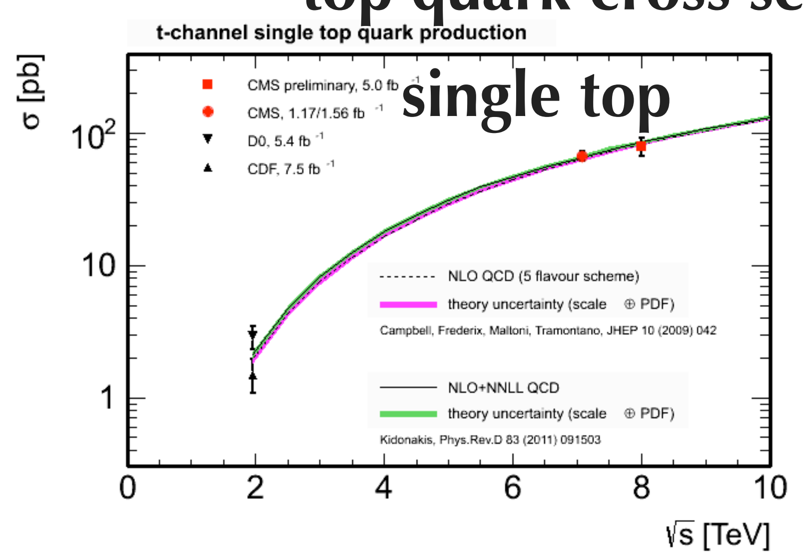
- Performance of LHC
- CMS detector
- Data recording
- Physics Object reconstruction
  - understand the PU
- Standard Model measurements
  - understand the background

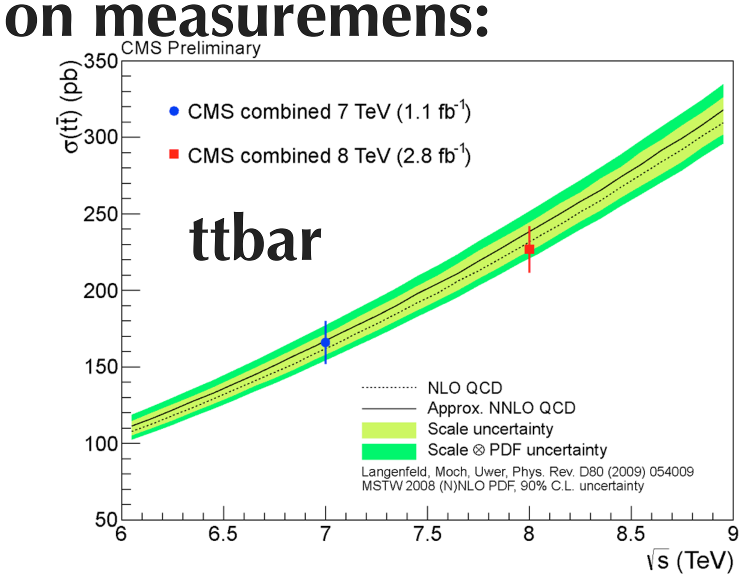
Higgs(-like) boson observation

EW cross section measurements



top quark cross section measuremens:





SM measurements

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Higgs(-like) boson observation

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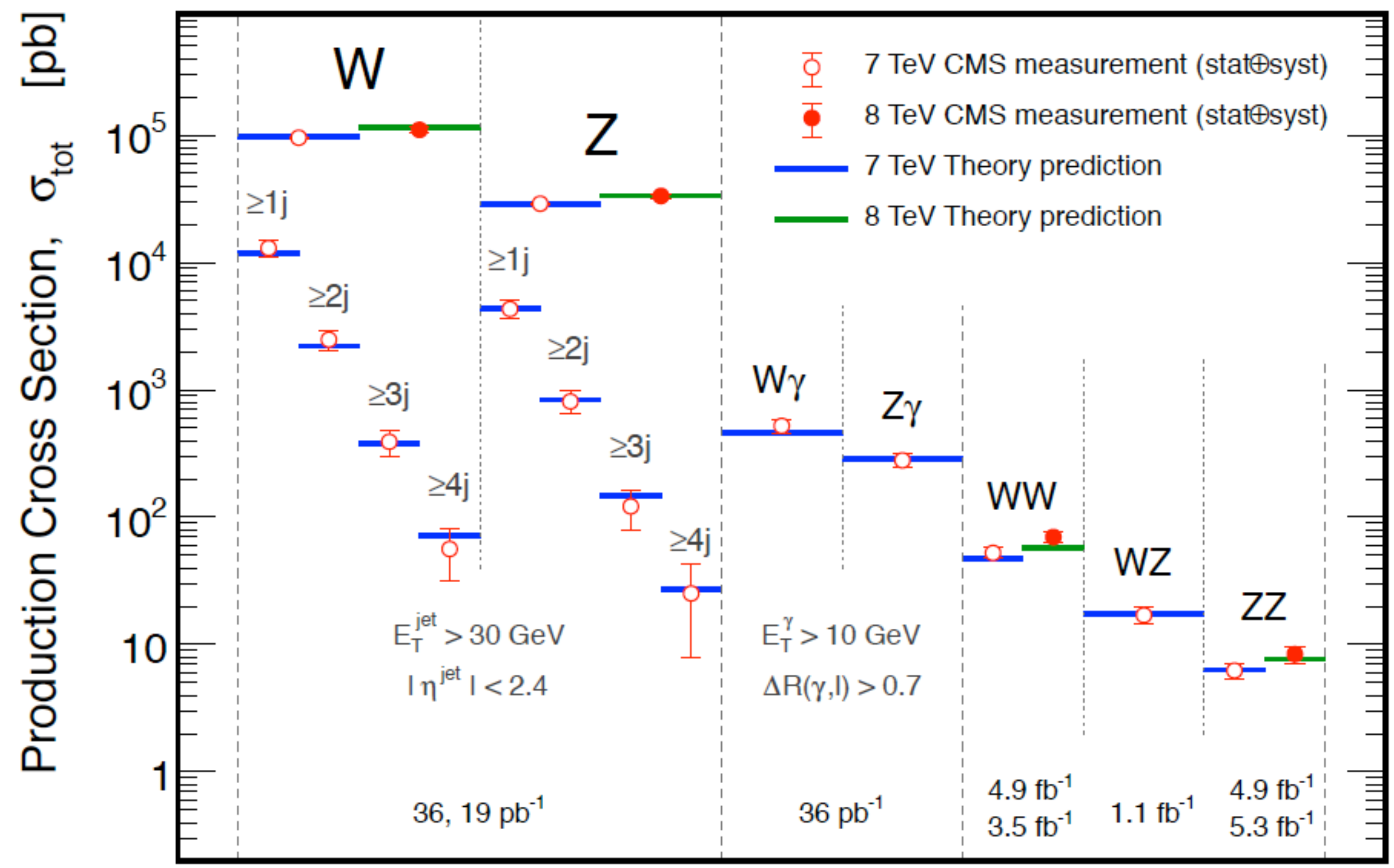
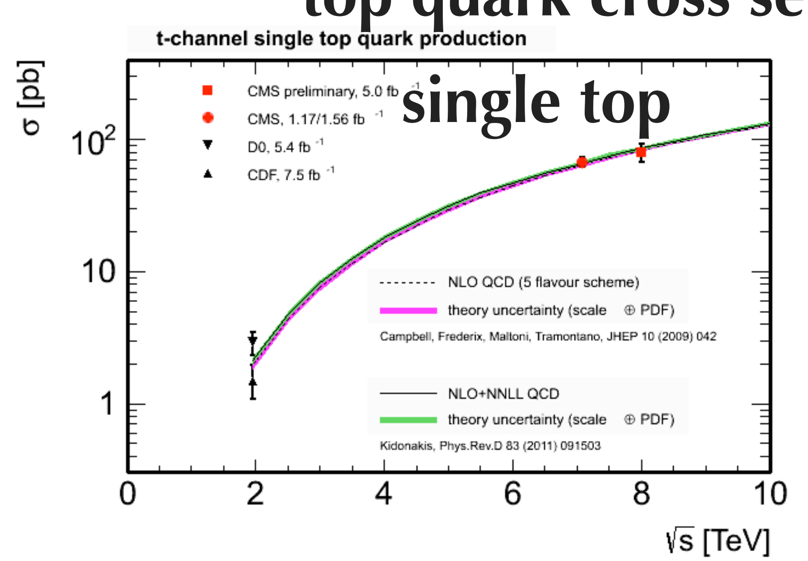
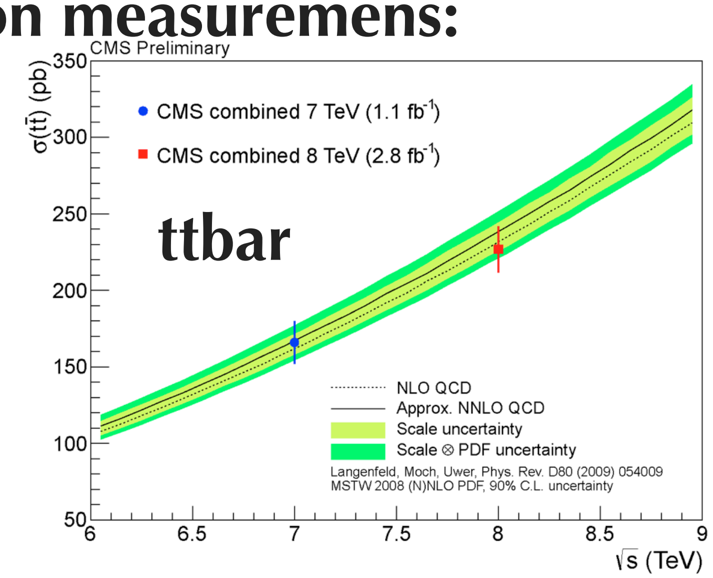


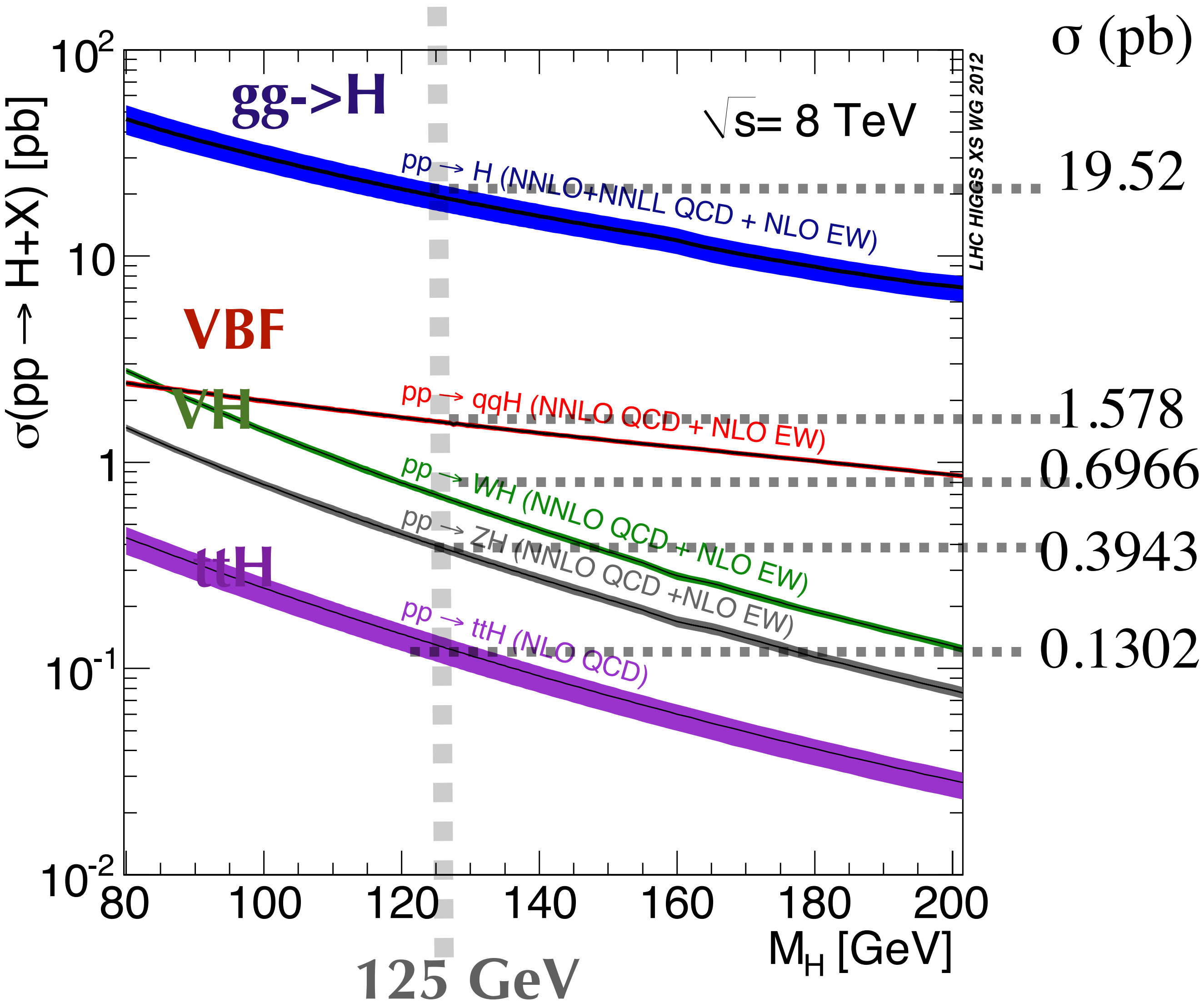
JHEP10(2011)132
JHEP01(2012)010
CMS-PAS-SMP-12-011 (W/Z 8 TeV)
PLB701(2011)535
CMS-PAS-EWK-11-010 (WZ)
CMS-PAS-SMP-12-005, 007, 013, 014 (WW ZZ)

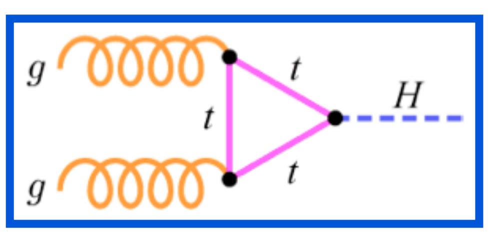
top quark cross section measuremens:

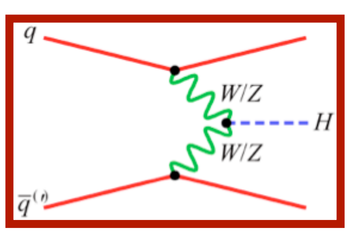


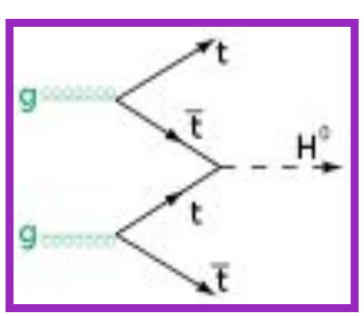


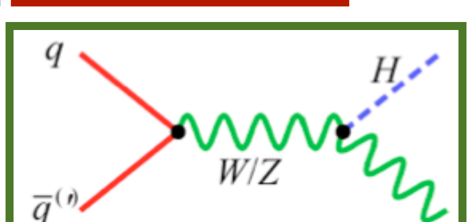
Higgs production modes and decays





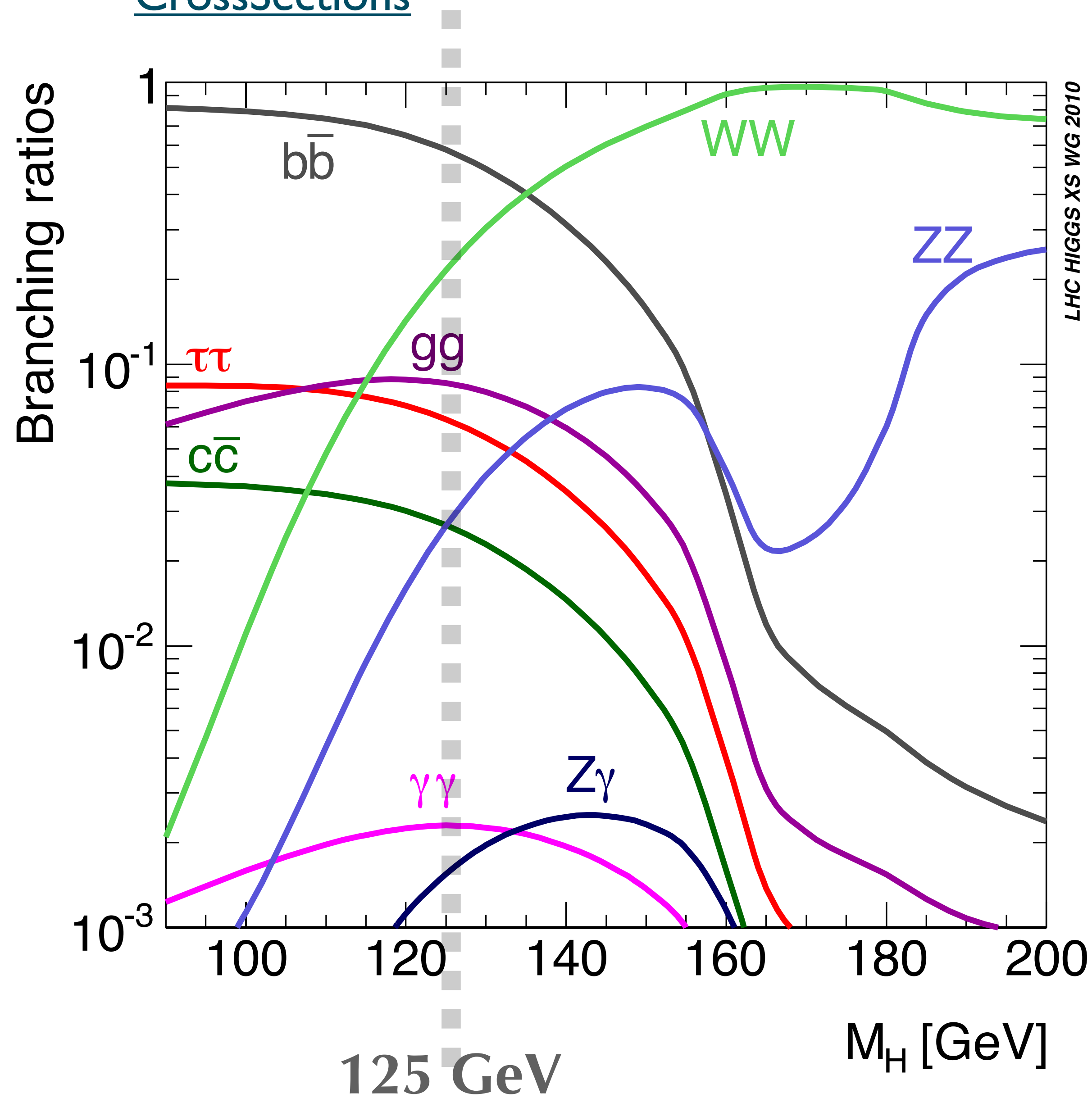






LHC Higgs Cross Section WG
See yellow reports:
YR1: Inclusive cross sections
YR2: Differential cross sections
YR3: Properties (to appear)

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections



CMS publications of SM Higgs analyses

H→γγ	CMS-PAS-HIG-13-001
H→ZZ→4l	CMS-PAS-HIG-13-002
H→WW→2l 2ν, 0/1 jet	CMS-PAS-HIG-13-003
H→WW→2l 2ν, VBF tag	CMS-PAS-HIG-12-042
H→WW→2l 2ν, WH tag	CMS-PAS-HIG-13-009
H→ττ, inclusive and VBF	CMS-PAS-HIG-13-004
H→ττ, WH and ZH tag	CMS-PAS-HIG-12-053
H→bb, VH tag	CMS-PAS-HIG-12-044
H→bb, ttH tag	arXiv:1303.0763, JHEP

Combination CMS-PAS-HIG-13-005

H→Zγ	CMS-PAS-HIG-13-006
ttH H→γγ	CMS-PAS-HIG-13-015
H→ZZ→2l 2ν	CMS-PAS-HIG-13-014
H→WW→lνqq′	CMS-PAS-HIG-13-008
H→bb, VBF tag	CMS-PAS-HIG-13-011
H→bb, VH tag	CMS-PAS-HIG-13-012

VH, H→WW→lνlν, V→qq′	CMS-PAS-HIG-13-017
H→γγ properties	CMS-PAS-HIG-13-016

NEW
(shown at LHCP2013)

VERY NEW!
(shown for the first time last Monday at LP2013)

Statistical treatment of data

Each analysis as well as the combination uses:

ATL-PHYS-PUB/CMS NOTE 2011.11,2011/005,(2011)

modified frequentist approach: CL_S
Systematic uncertainties: frequentist paradigm
Asymptotic formulae

agreement with ATLAS in summer 2011

Test Statistic: ***Profile likelihood ratio***

$$q_0 = -2\ln\frac{\mathcal{L}(\text{obs}\,|\,b,\,\hat{\theta}_0)}{\mathcal{L}(\text{obs}\,|\,\hat{\mu}\cdot s + b,\,\hat{\theta})}$$

p-value

$$p_0 = \mathrm{P}(q_0 \geq q_0^{obs}\,|\,\mathrm{b})$$

local significance Z

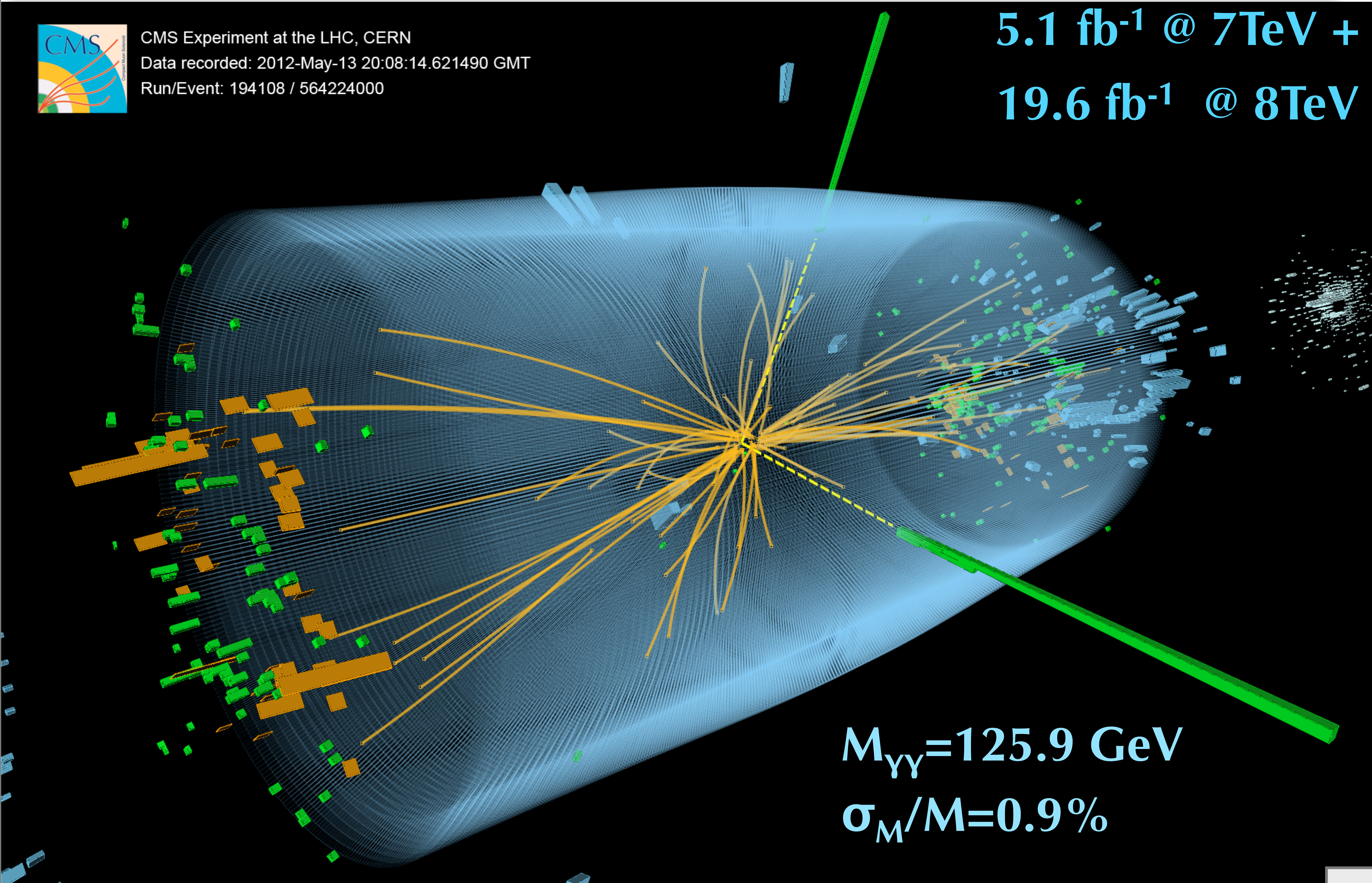
$$p_0 = \int_Z^{+\infty} \frac{1}{\sqrt{2\pi}} \exp(-x^2/2)\,\mathrm{d}x$$

signal parameter a:

$$q(a) = -2\ln\frac{\mathcal{L}(\text{obs}\,|\,s(a)+b,\,\hat{\theta}_a)}{\mathcal{L}(\text{obs}\,|\,s(\hat{a})+b,\,\hat{\theta})}$$

$$\mathcal{L}(\text{obs}\,|\,s(\hat{a})+b,\,\hat{\theta}) = \mathcal{L}_{\max}$$

H→γγ



5.1 fb^{-1} @ 7TeV +

19.6 fb^{-1} @ 8TeV

$M_{\gamma\gamma}$=125.9 GeV

σ_M/M=0.9%

H→γγ

search for a peak over a smoothly falling bkg shape in $m_{\gamma\gamma}$ distribution

main ingredients:

- **good invariant mass resolution**
- **photon identification, photon pair selection, event categorization**

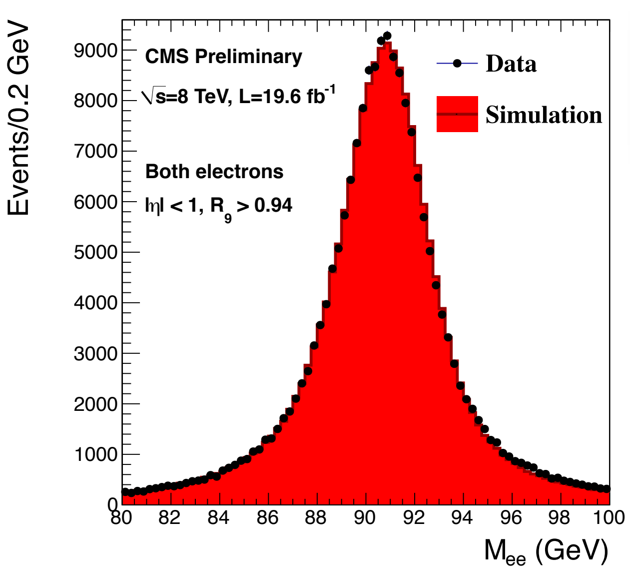
MVA Mass Factorized Analysis
(better expected expected UL of 15%)
baseline analysis

Cut based
cross-check

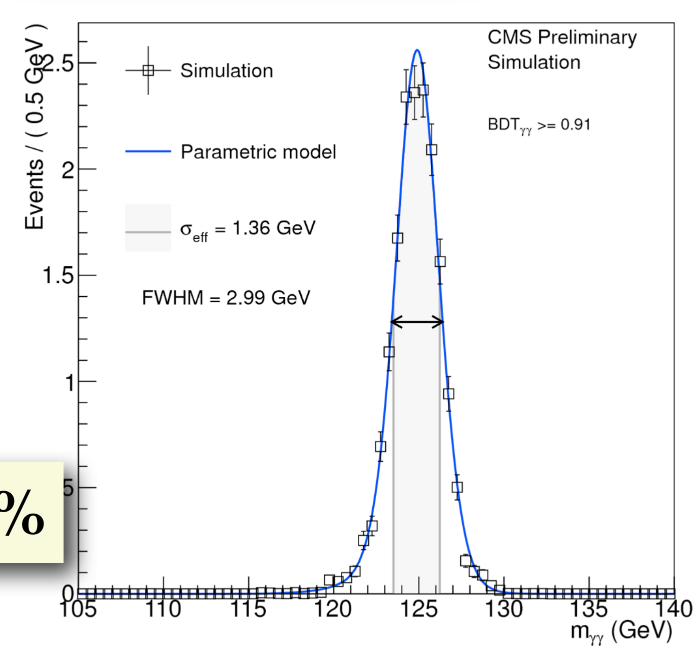
$$m^2_{\gamma_1,\gamma_2} = 2E_{\gamma_1}E_{\gamma_2}(1 - cos\theta)$$

Good photon energy resolution

Efficient vertex finding algorithm

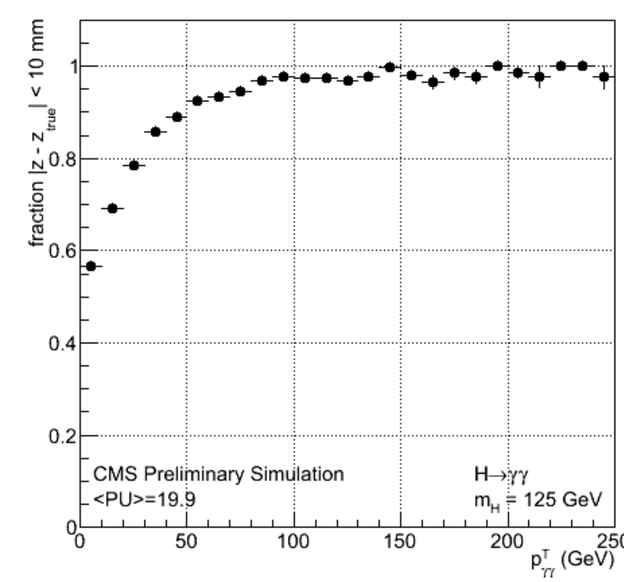


excellent data/MC agreement

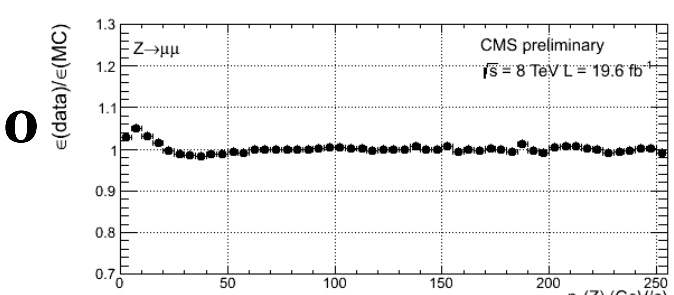


$\sigma_m/m \sim 1$ %

MC signal efficiency



Data/MC ratio using Z→μμ



MVA diphoton selection

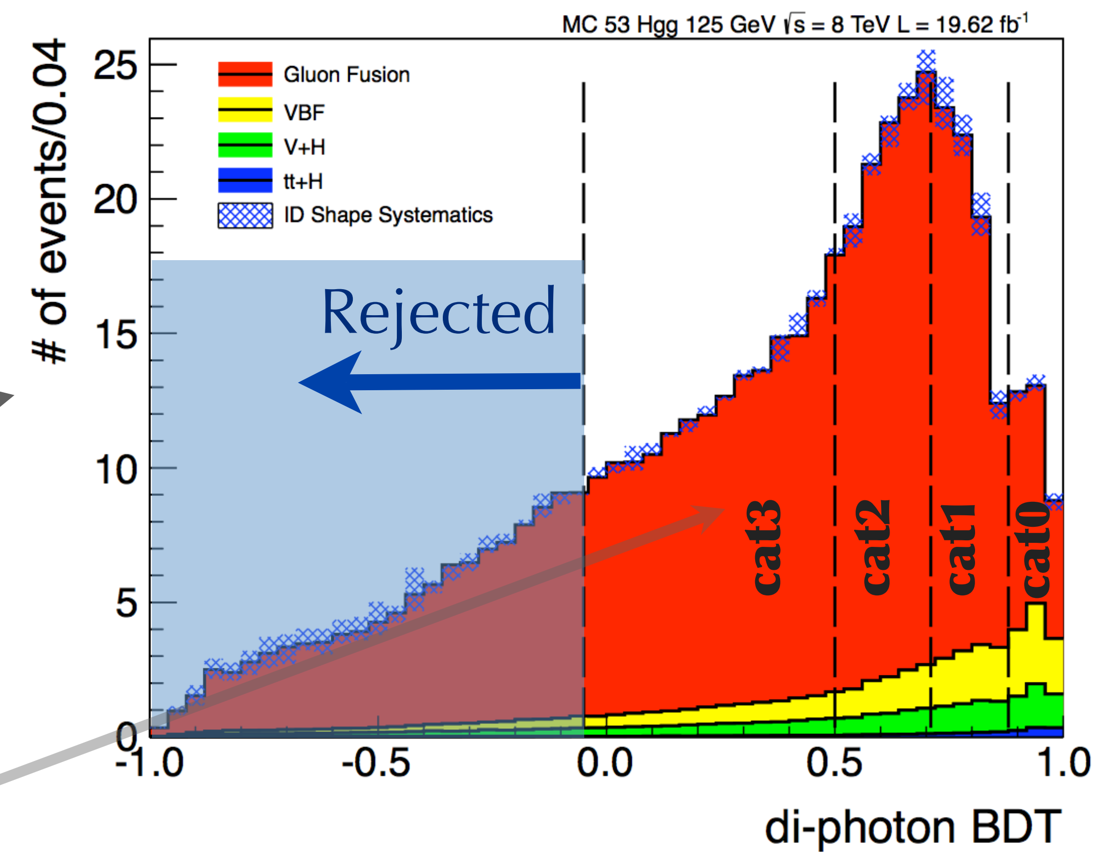
H→γγ

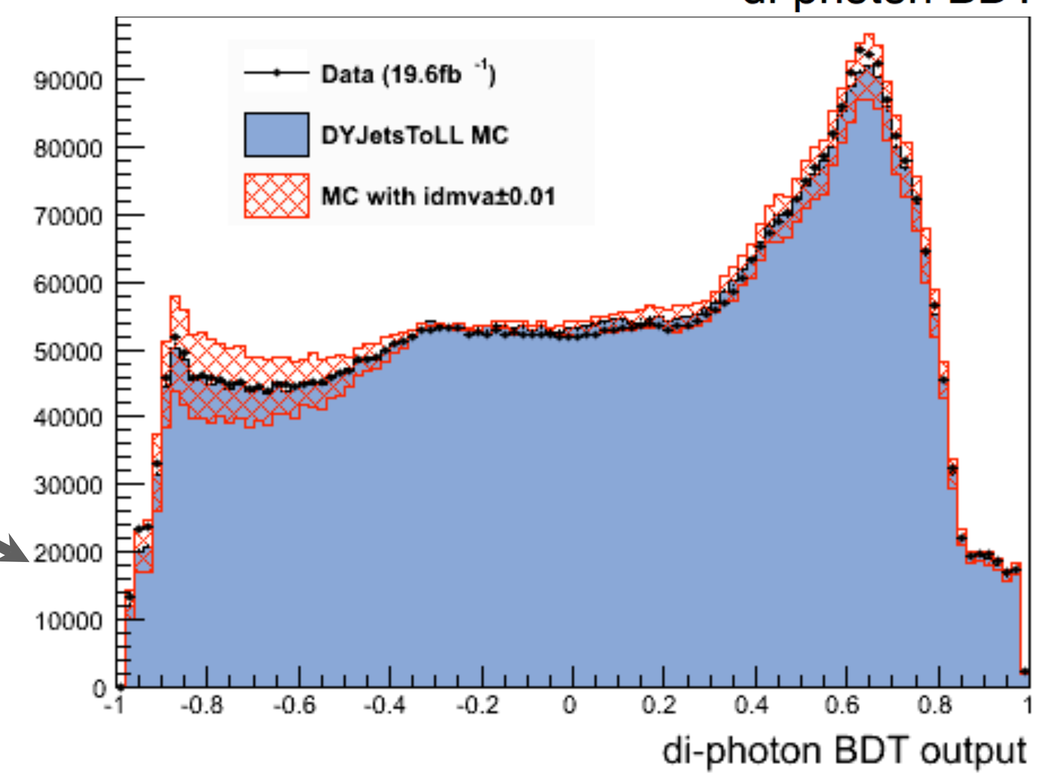
HIG-13-001

- photon selection:
  - photon pt cuts scaled with $m_{\gamma\gamma}$
  - single photon ID BDT: photon/jet discriminator

    (trained on simulated jet+γ events)

    input: shower shape and isolation
- choose the ID photon pair with highest sum E_T
- **diphoton selection: A single discriminant (BDT) trained on MC signal and background using**
  - photon kinematics
  - photon ID MVA score
  - di-photon mass resolution
- ***4 untagged categories are defined on the output of the di-photon BDT***
  - Validation of the MVA inputs (photonID, energy resolution) done on Z→ee and Z→μμγ
- **Output of the MVA validated using Z→ee**



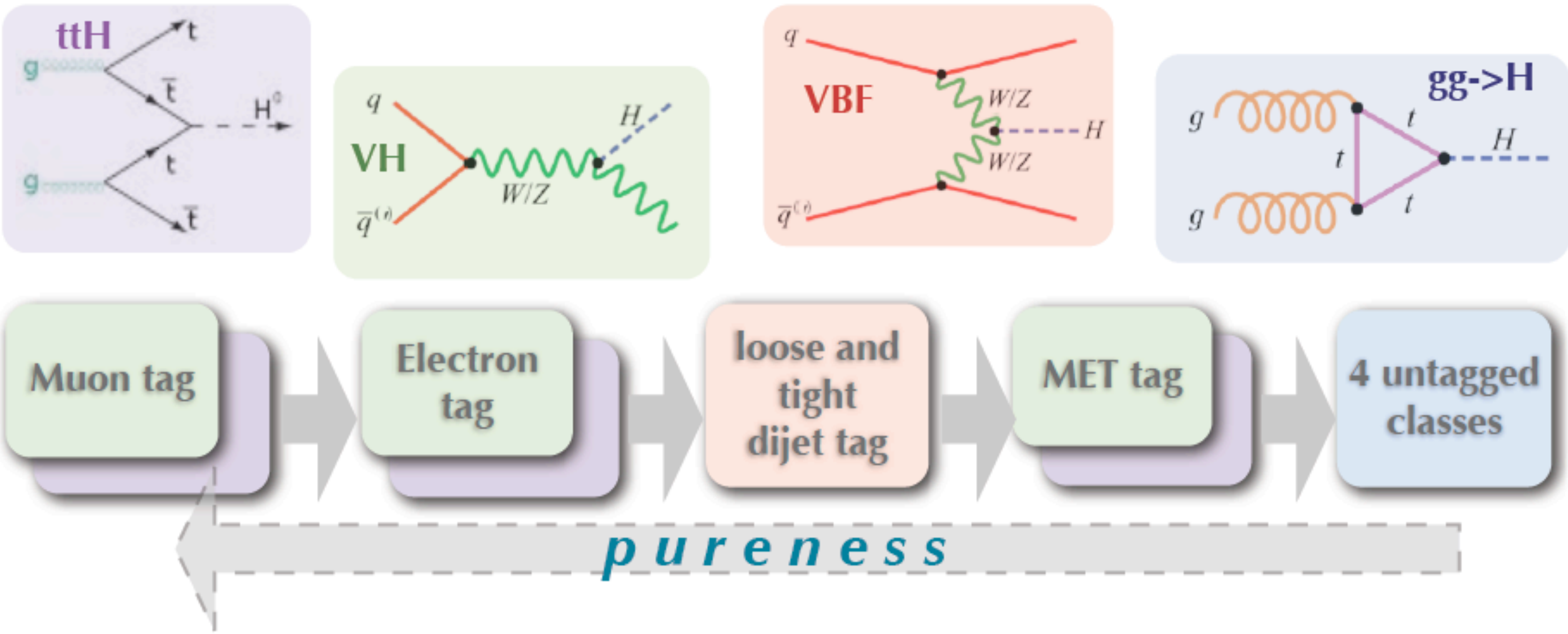


cut: diphoton BDT > -0.05

Event Classification

H→γγ

HIG-13-001



pureness

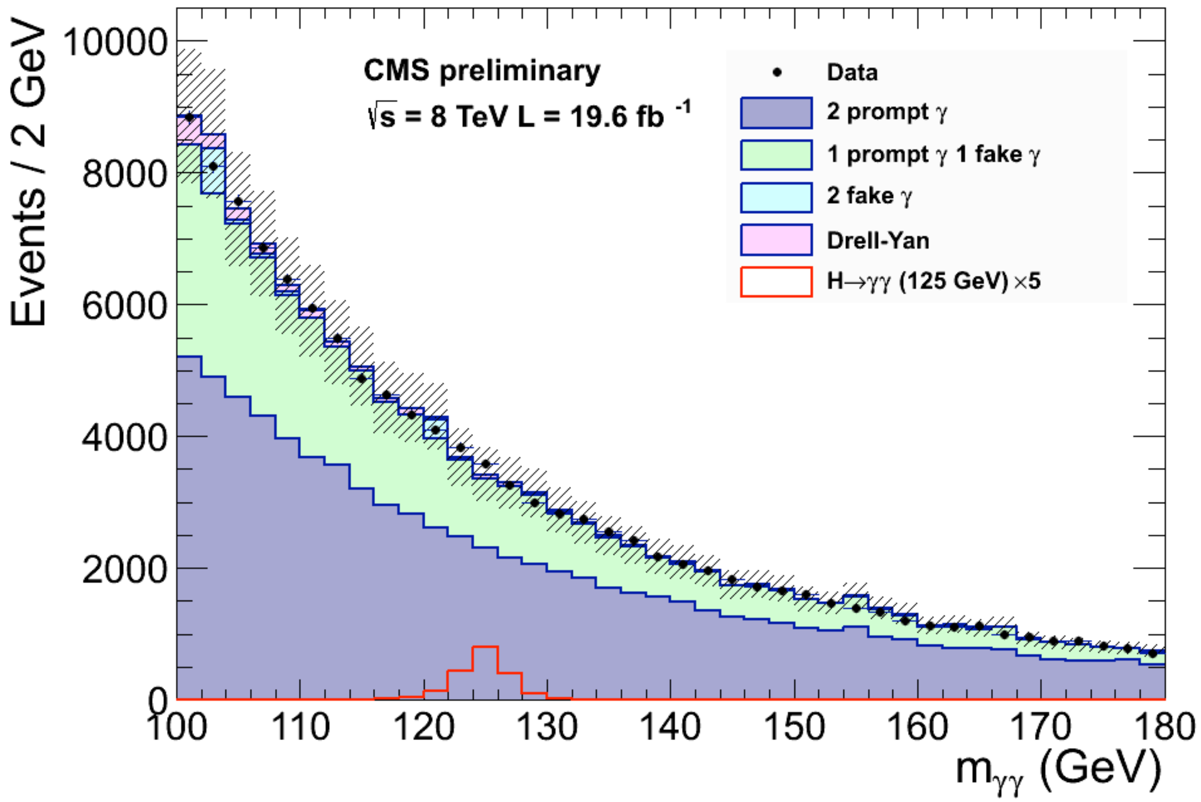
	gg->H contamination	sensitivity	differences between cut based and MVA
Muon tag (pt(μ)>20 GeV)	negligible	-	no difference
Electron tag (pt(e)>20 GeV)	negligible	-	
Di-Jet tight tag	20%	+	MVA analysis uses a dijet BDT-based selection (validated using Z+jets events)
Di-Jet loose tag	50%	+	
MET tag (MET>70 GeV)	20%	-	no difference
untagged 0,1,2,3		+	different categorization

Background composition and estimation

H→γγ

HIG-13-001

Background composition



in [100,150] GeV
72% of the selected data is constituted of irreducible bkg (2 prompt photons)

MC not used in the bkg estimation

Background modeling

- fit to the data mass spectrum in [100,180] GeV range
- several fitting function tested
- choice of the functional form and number of degrees of freedom performed with possible bias study

from 3^{th} to 5^{th} order polynomial

(possible bias < 0.2 x stat unc.)

another analysis, MVA mass sideband analysis, with different background modeling, has been performed and gives similar results

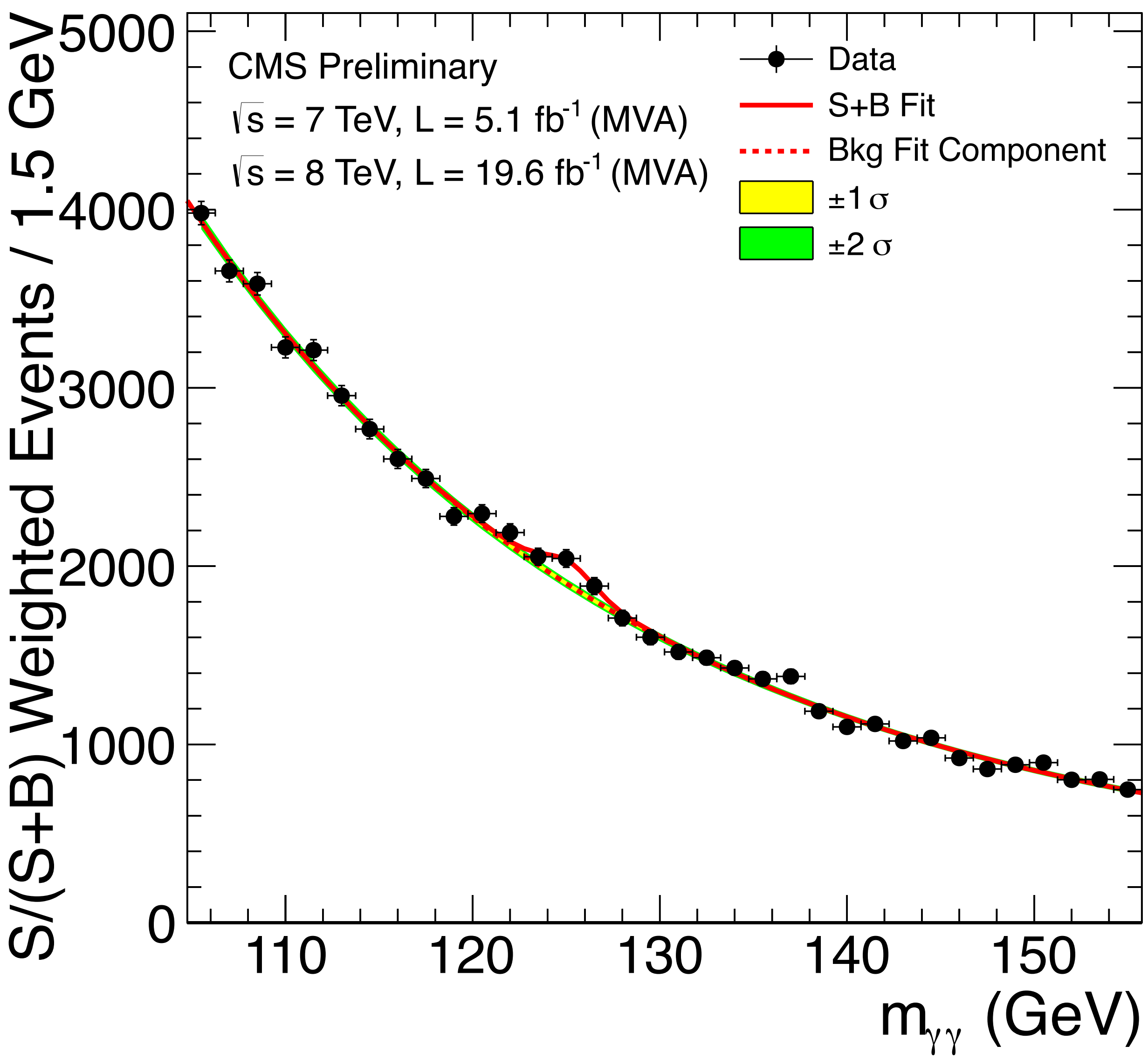
(see old publication **HIG-12-001** *for a description of such analysis)*

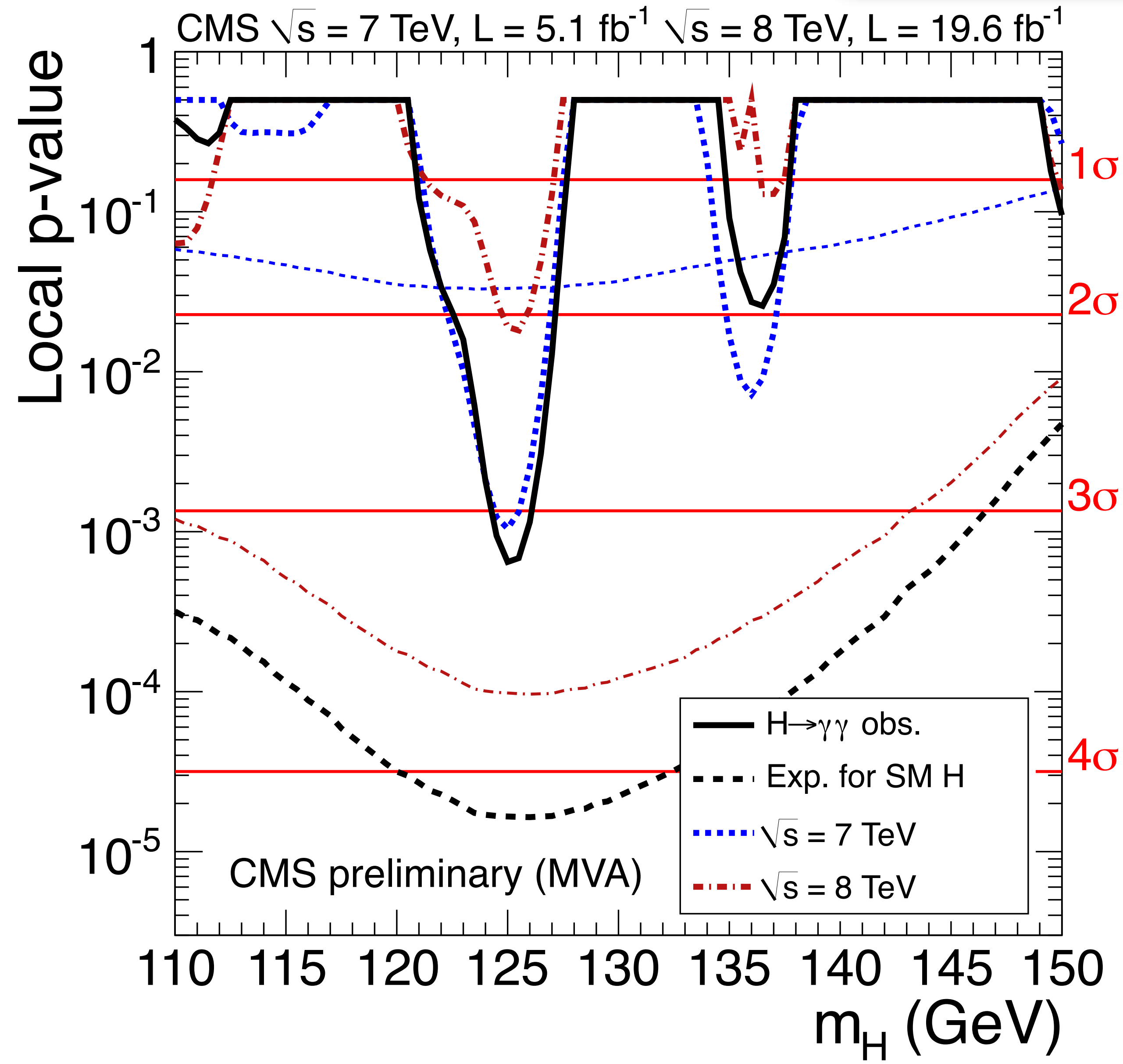
γγ results

H→γγ

HIG-13-001

MVA mass-factorized





each event weighted by the S/(S+B) value of its category

Local significance:

3.2 σ at 125.0 GeV

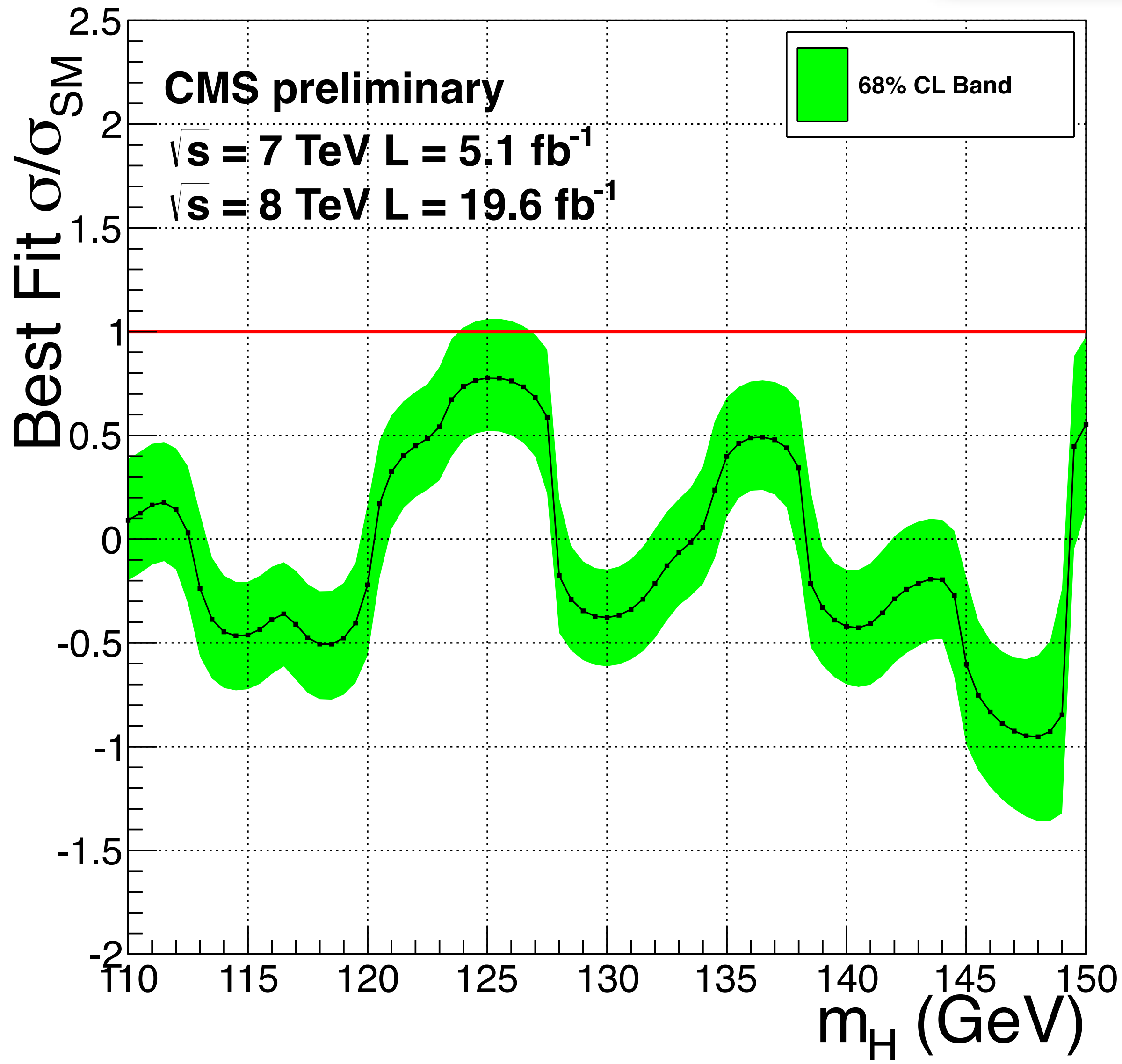
Expected significance:

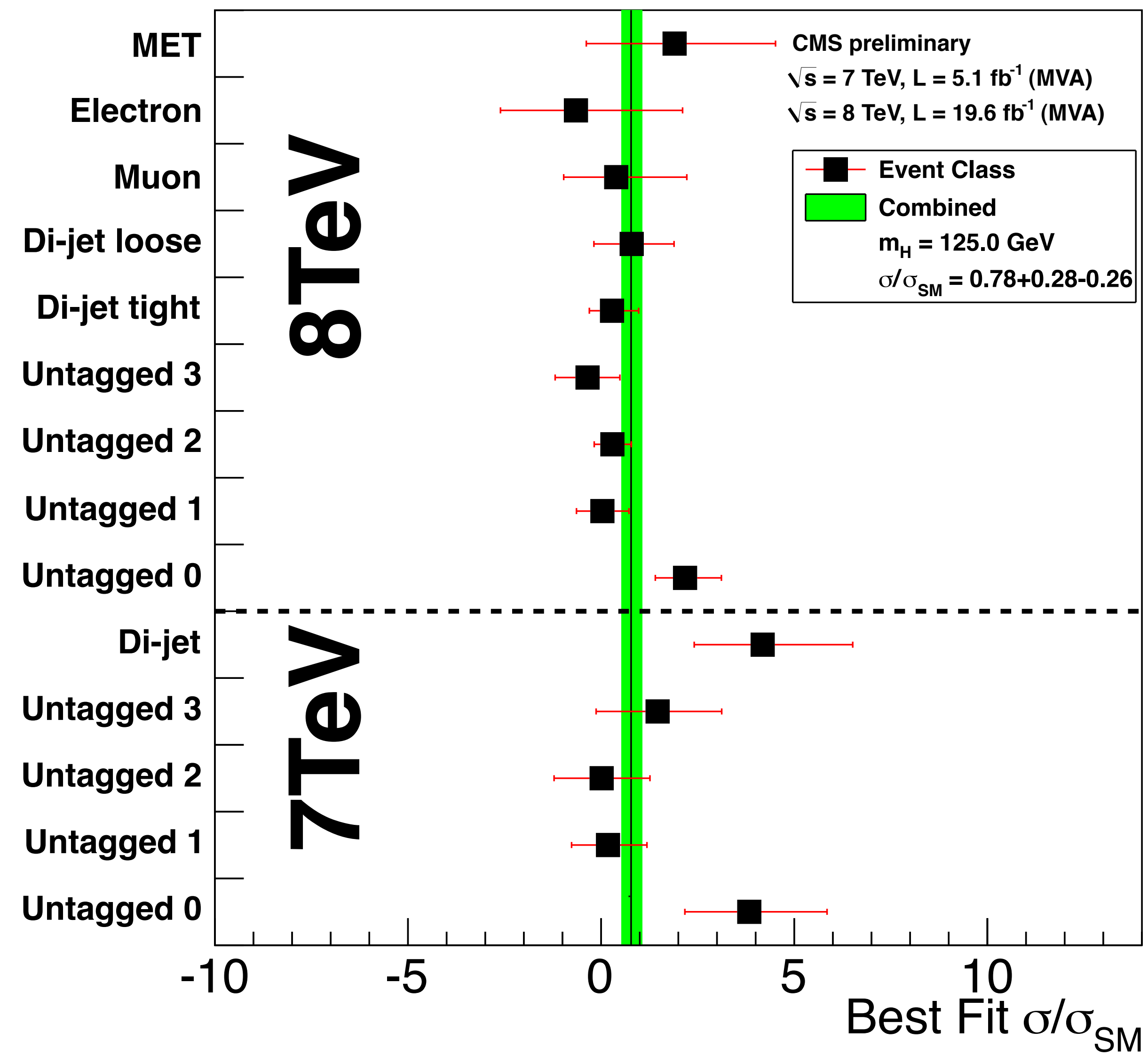
4.2 σ at 125.0 GeV

H→γγ

HIG-13-001

MVA mass-factorized





Fitted signal strength:

$\sigma/\sigma_{SM} = 0.78^{+0.28}_{-0.26}$

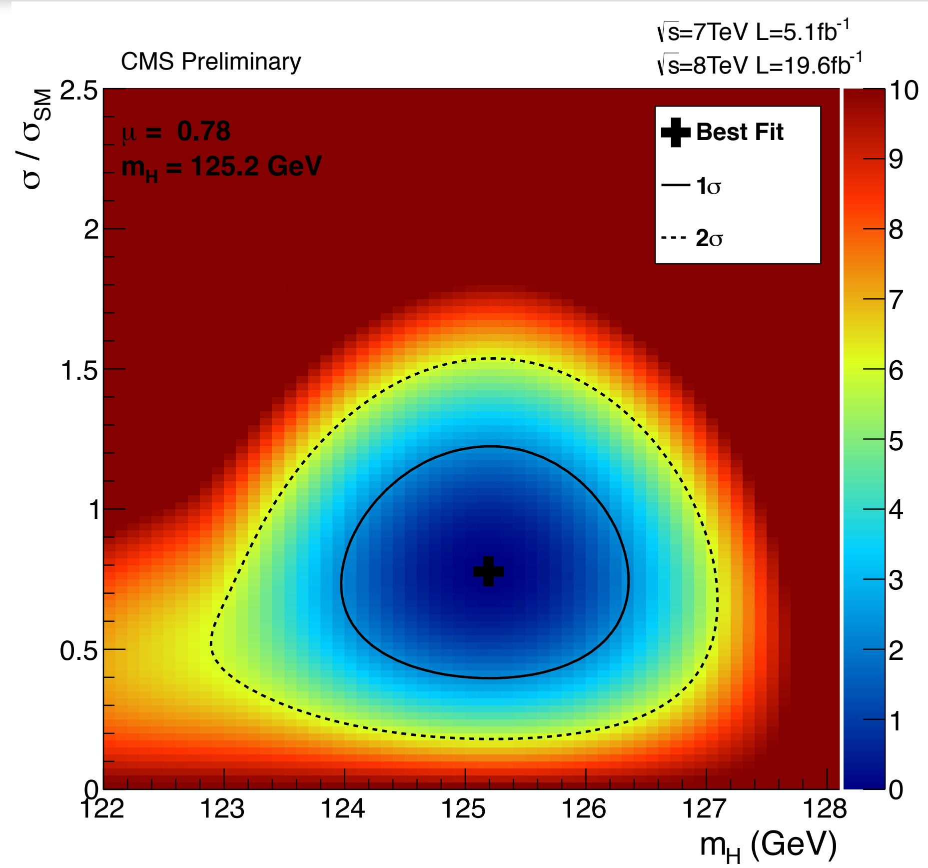
consistent with cut based result:

$\sigma/\sigma_{SM} = 1.11^{+0.32}_{-0.30}$

γγ mass and $\mu_V \mu_F$

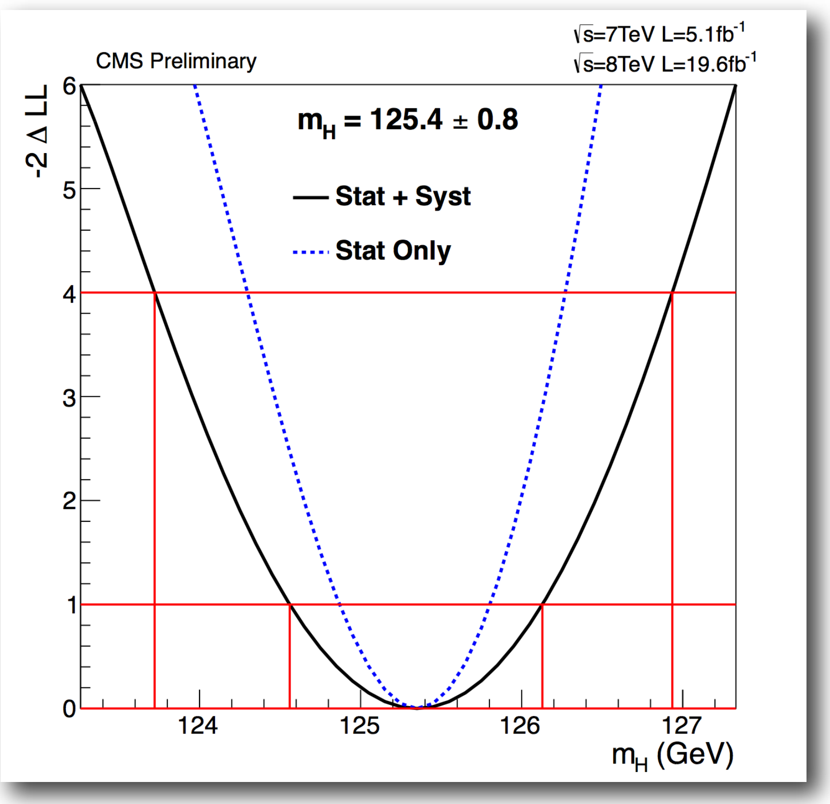
H→γγ

HIG-13-001

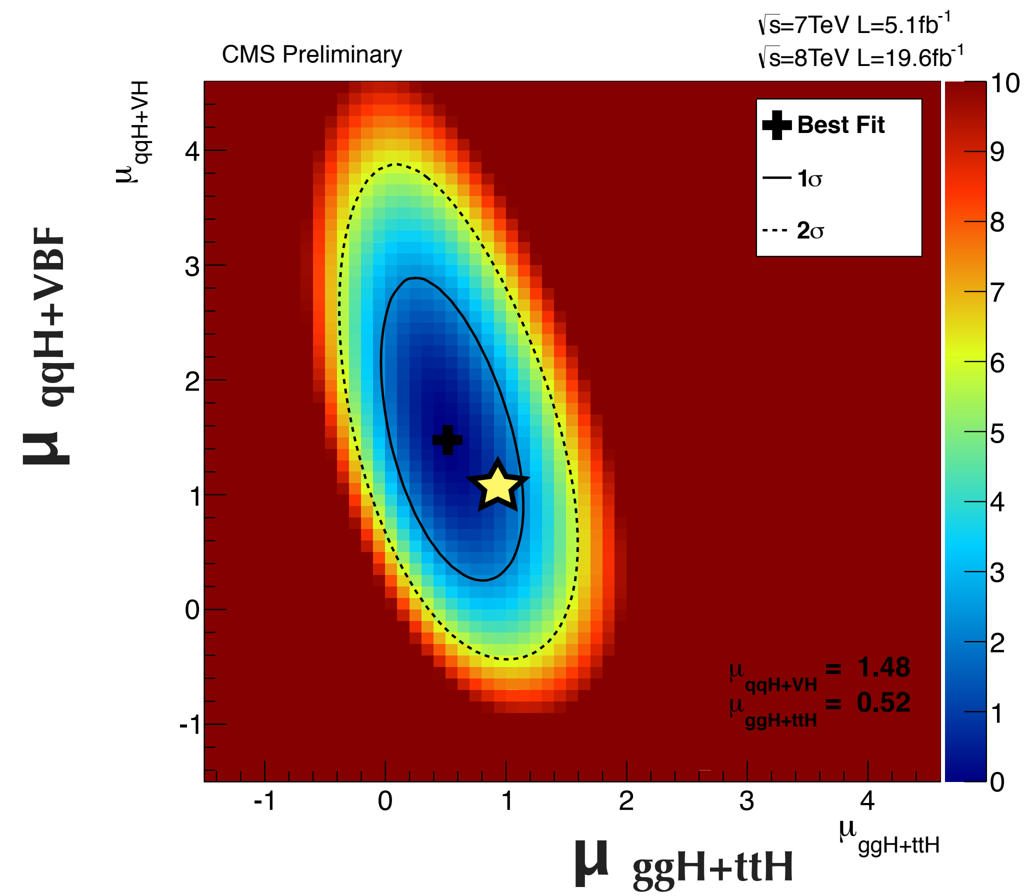


$M_H = 125.4 \pm 0.5(\text{stat.}) \pm 0.6(\text{syst.})$ GeV

The systematic uncertainty is dominated by the overall photon energy scale uncertainty (0.47%)



$\mu_V \mu_F$ are found to be consistent well within 1 sigma with SM



$\mu_{qqH+VBF} = 1.48$

$\mu_{ggH+ttH} = 0.52$

ZZ Introduction

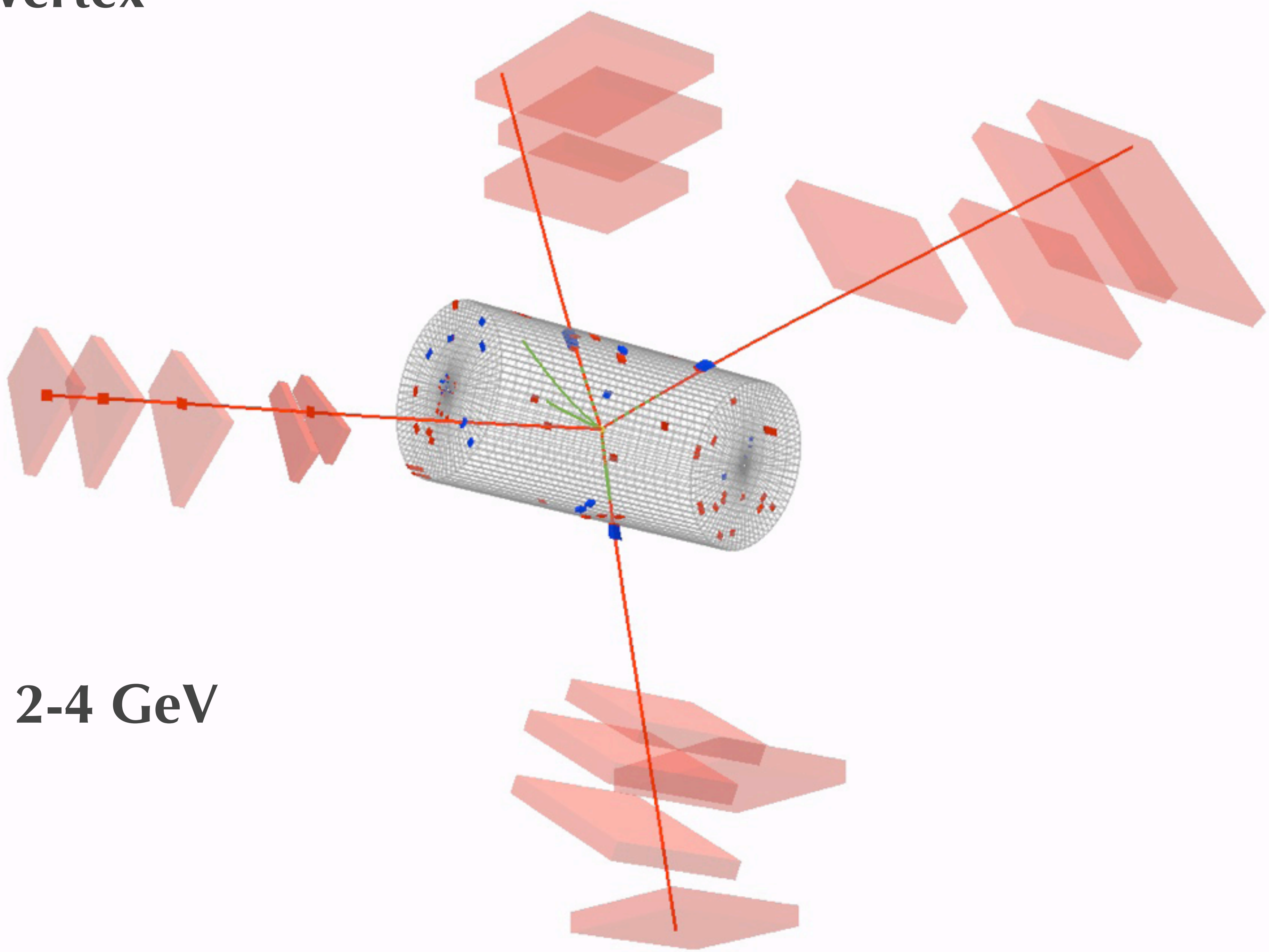
H→ZZ

HIG-13-002

- 4 isolated high pT leptons
  - from the same vertex
  - from Z decays

- low background, the most is irreducible non resonant ZZ

- high resolution: 2-4 GeV



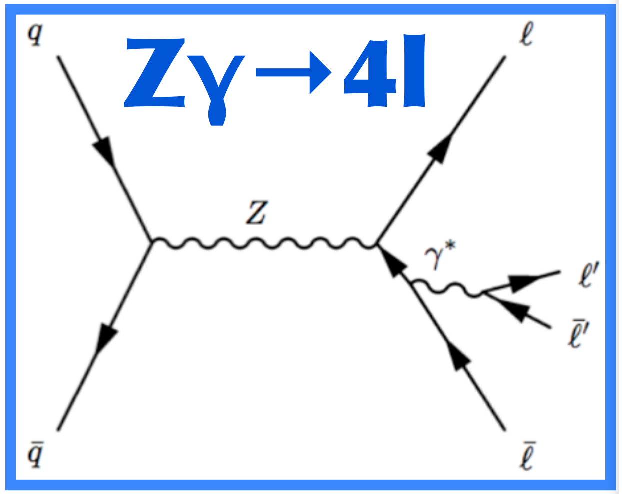
Background composition

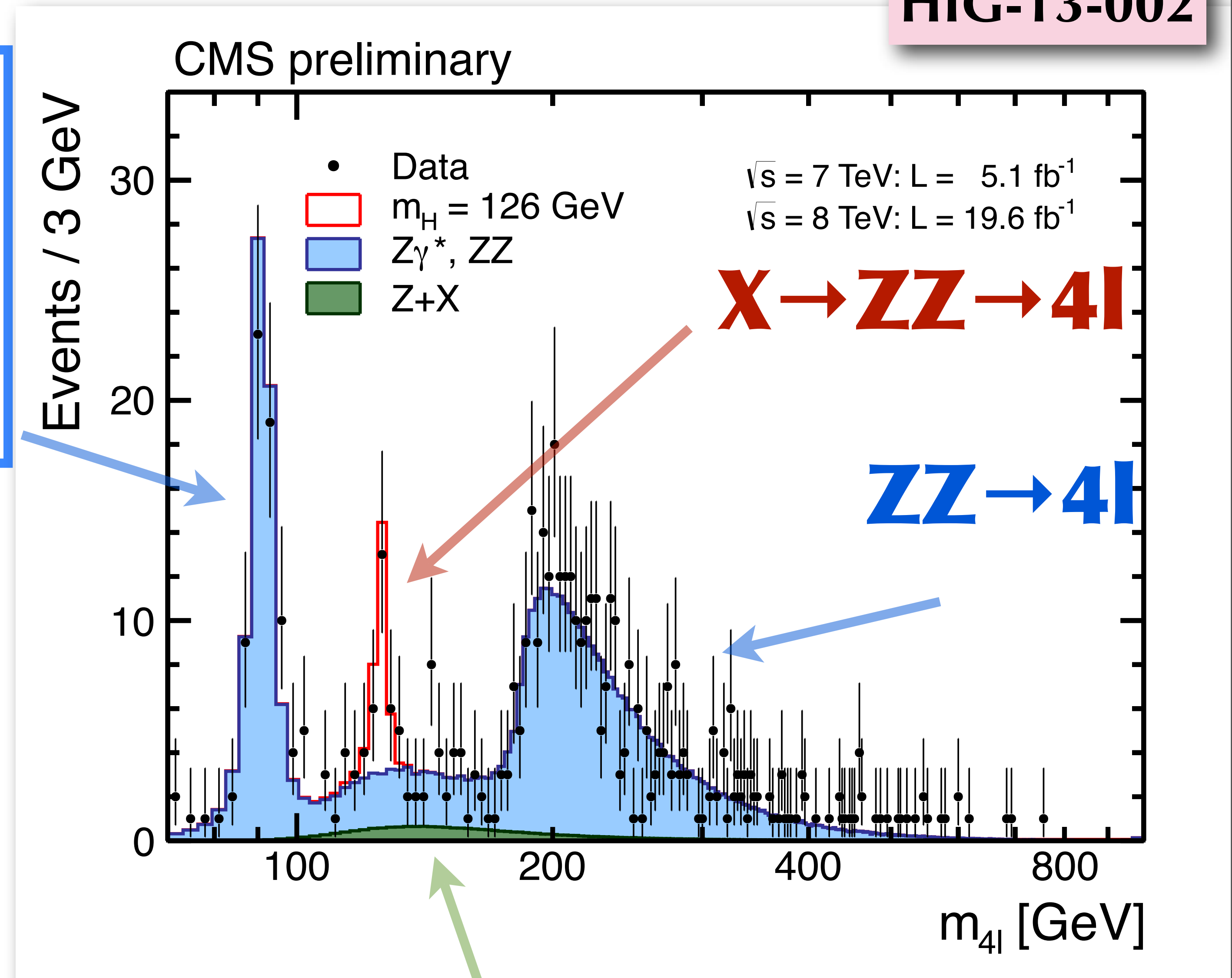
H→ZZ

HIG-13-002

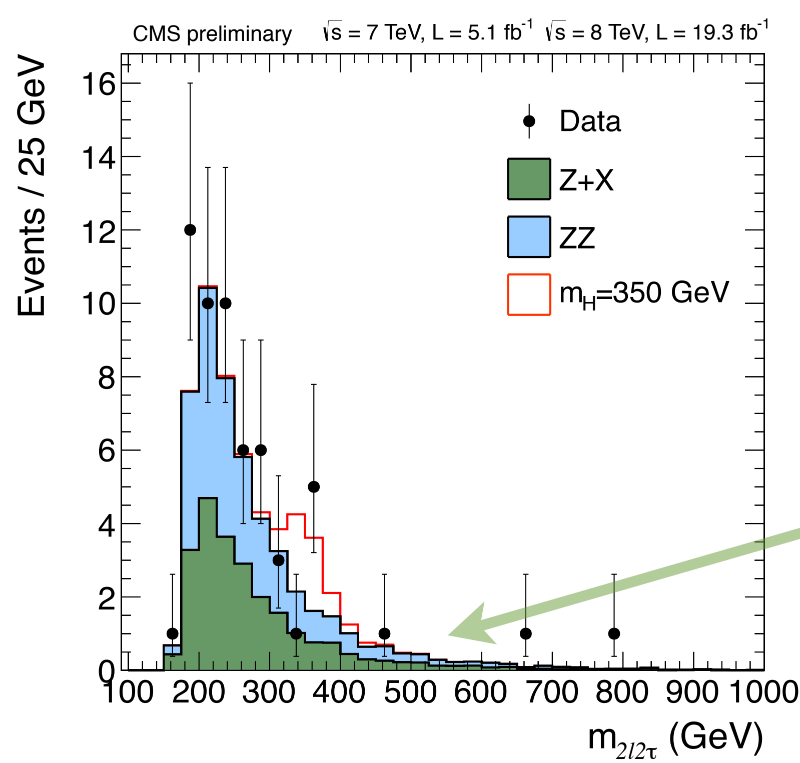
4l with l= e,μ

(the most sensitive channels, I will focus on this in the following)





2l2τ



reducible background

(estimated from data)

K_D discriminant

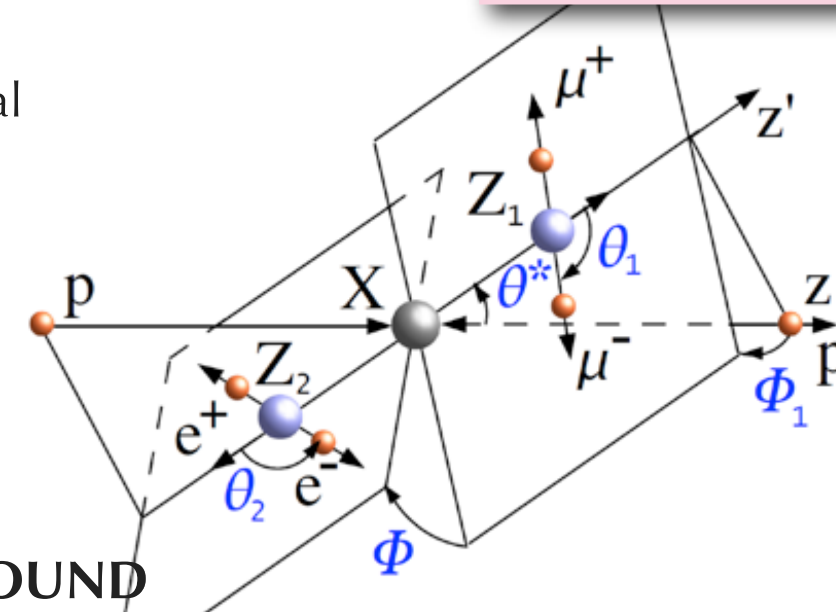
H→ZZ

HIG-13-002

~25 events in signal region, not enough full angular analysis

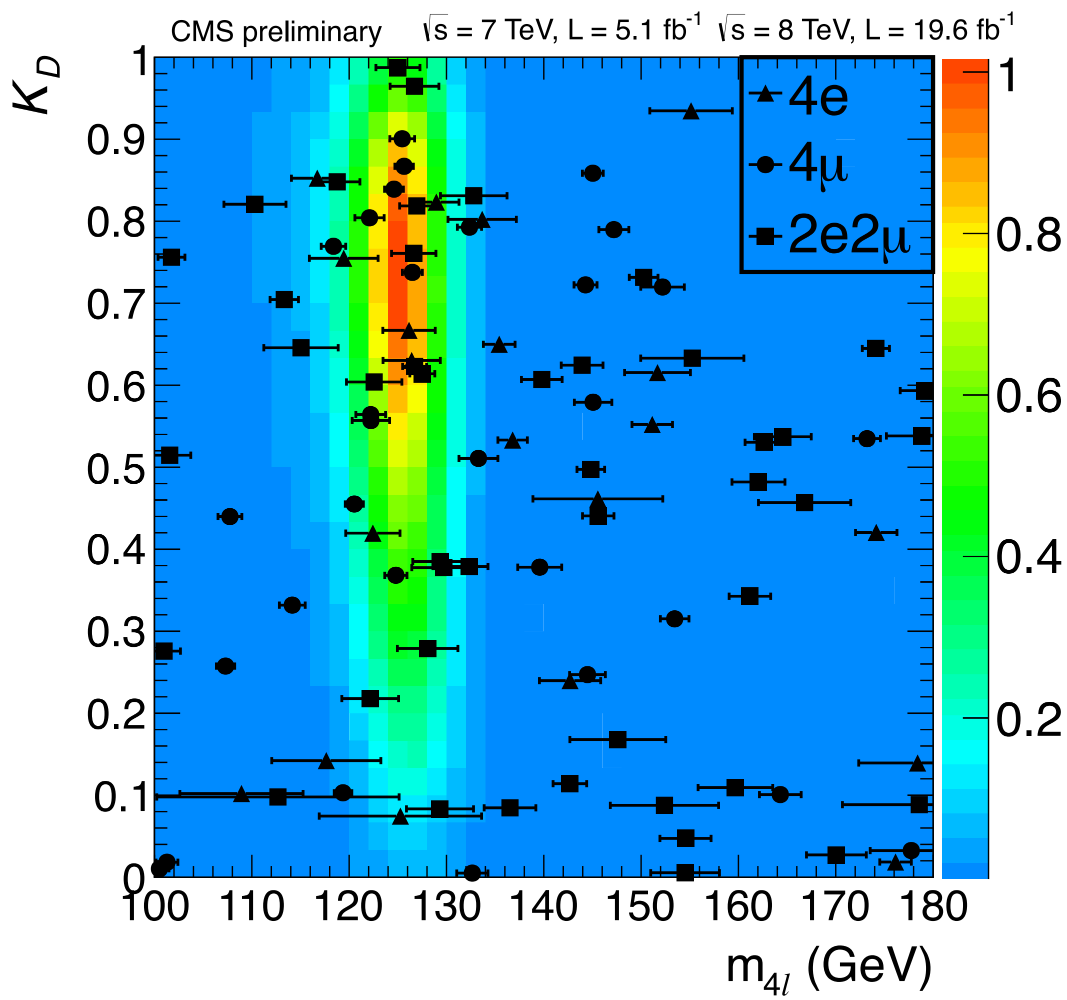
Construct a likelihood ratio discriminator based on kinematical quantities

Matrix **E**lement **L**ikelihood **A**nalysis:
uses kinematic inputs to build a kinematic discriminant (**KD**) for signal to background discrimination using
{m1,m2,θ1,θ2,θ*,Φ,Φ1}

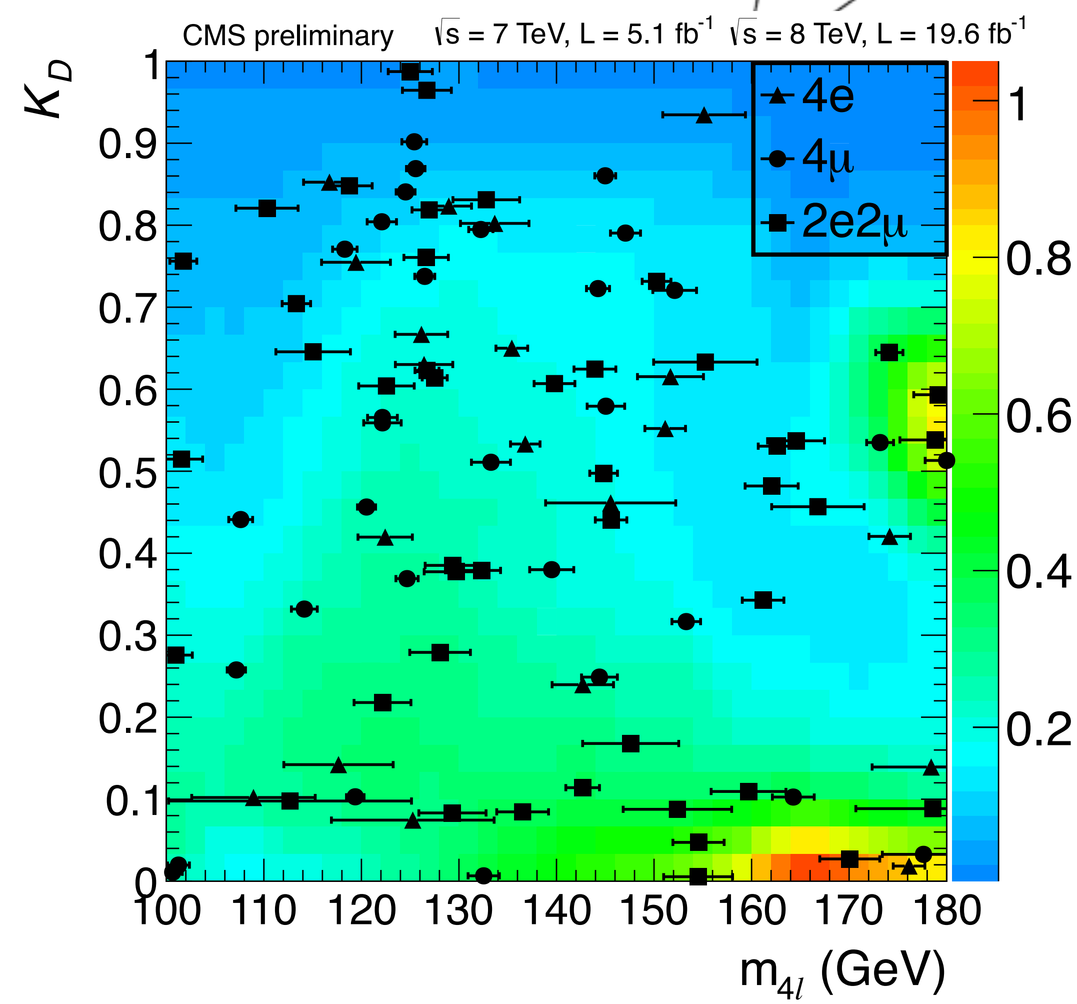


$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

SIGNAL



BACKGROUND



Event Categorization

H→ZZ

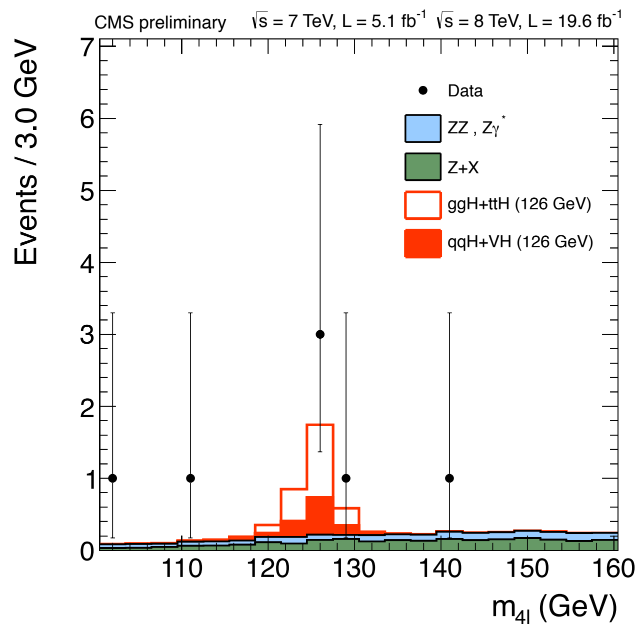
HIG-13-002

Split events by **number of jets** and use different variables to separate contributions

cut on

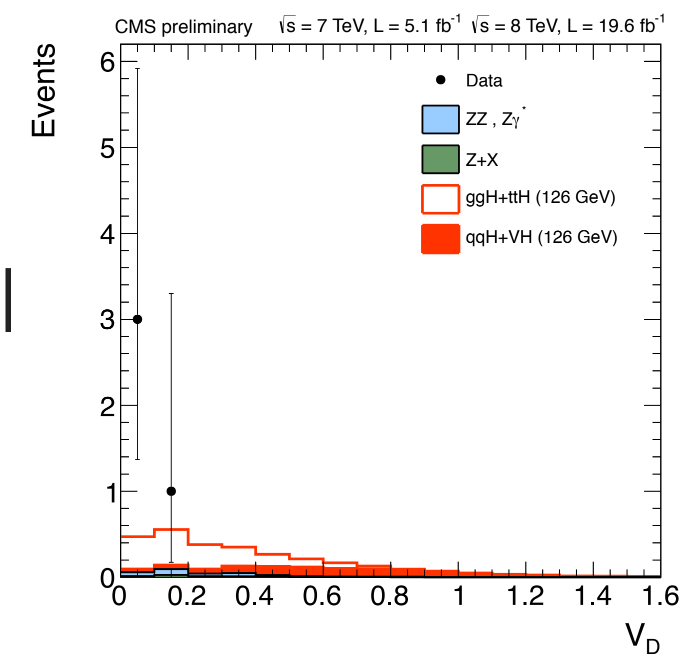
121.5 < m_{4l} <130.5 GeV

≥ 2 jets:
"VBF-tagged"

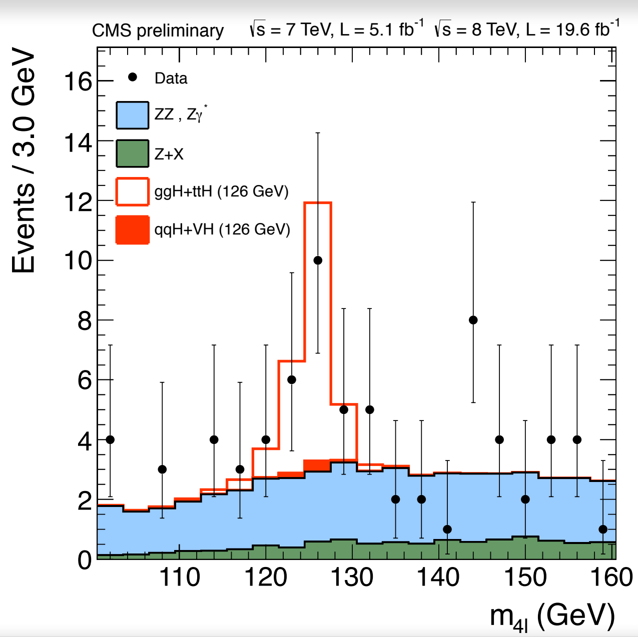


use a discriminant V_D, based on m_{JJ} and $|\Delta\eta_{JJ}|$

$P(m_{4l})xP(K_D)x(V_D)$

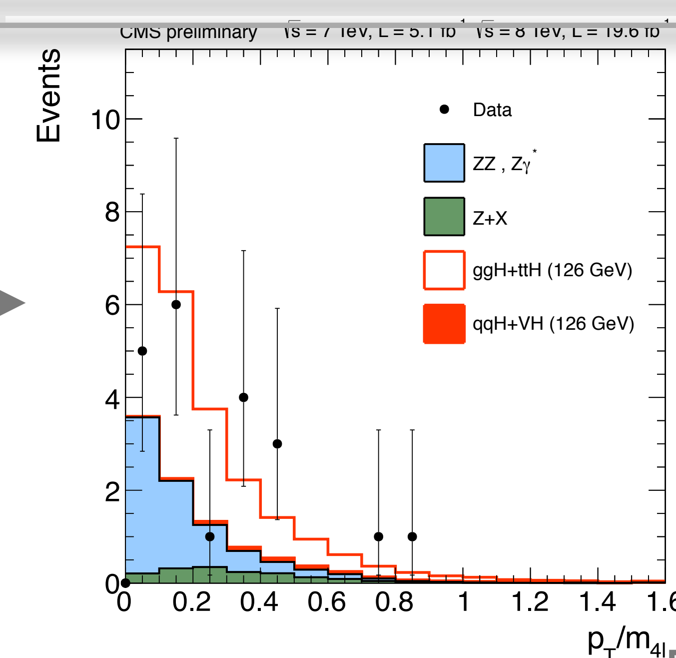


0/1 jets:
NOT-"VBF-tagged"



use p_T/m_{4l}

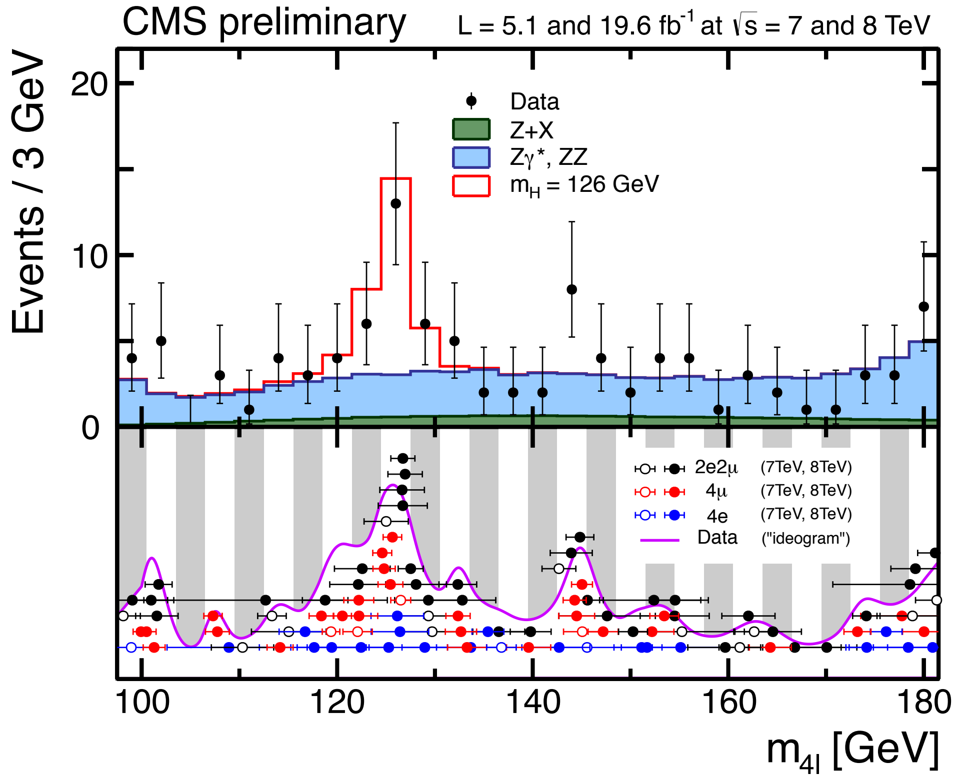
$P(m_{4l})xP(K_D)xP(p_T/m_{4l})$

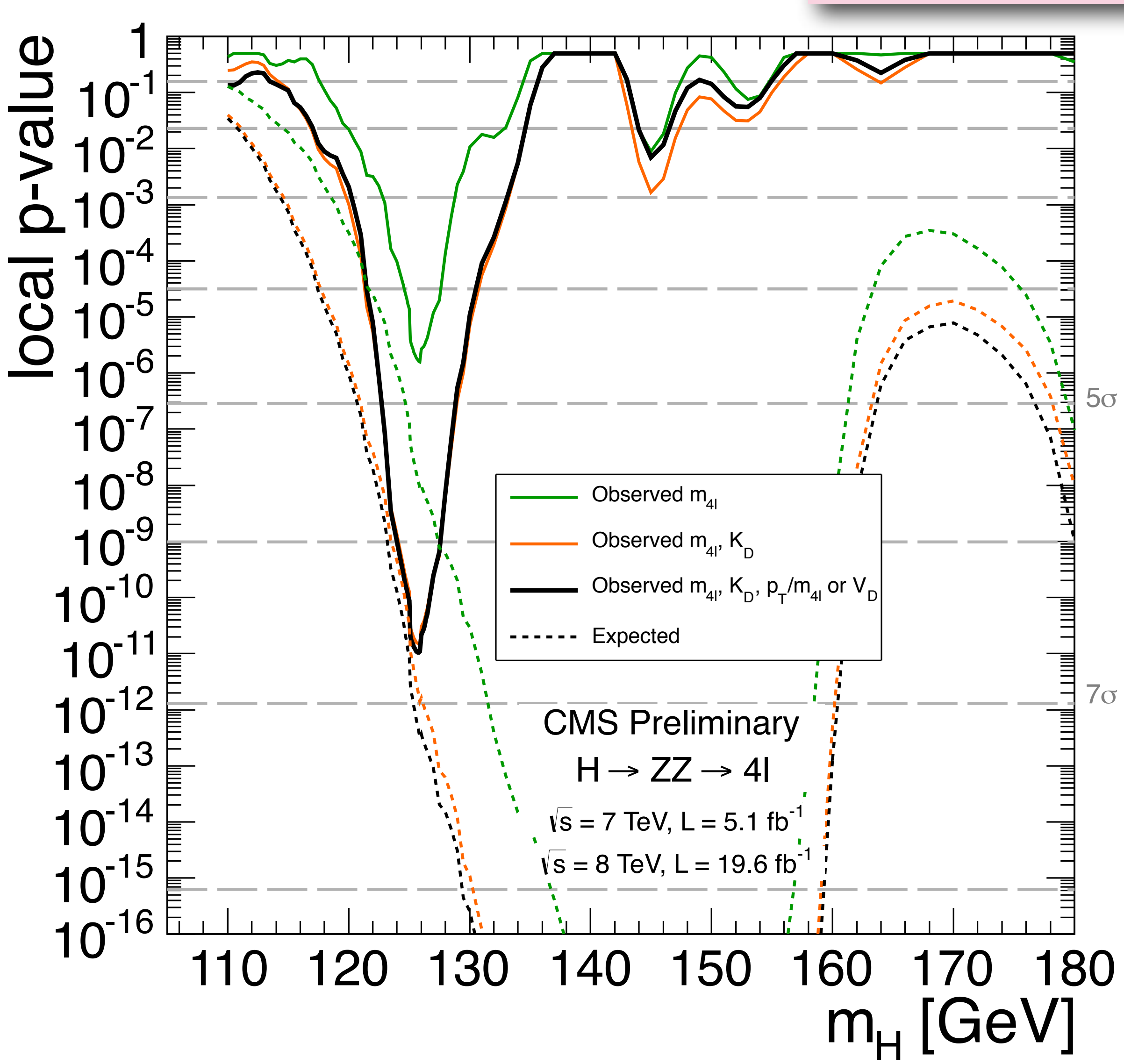


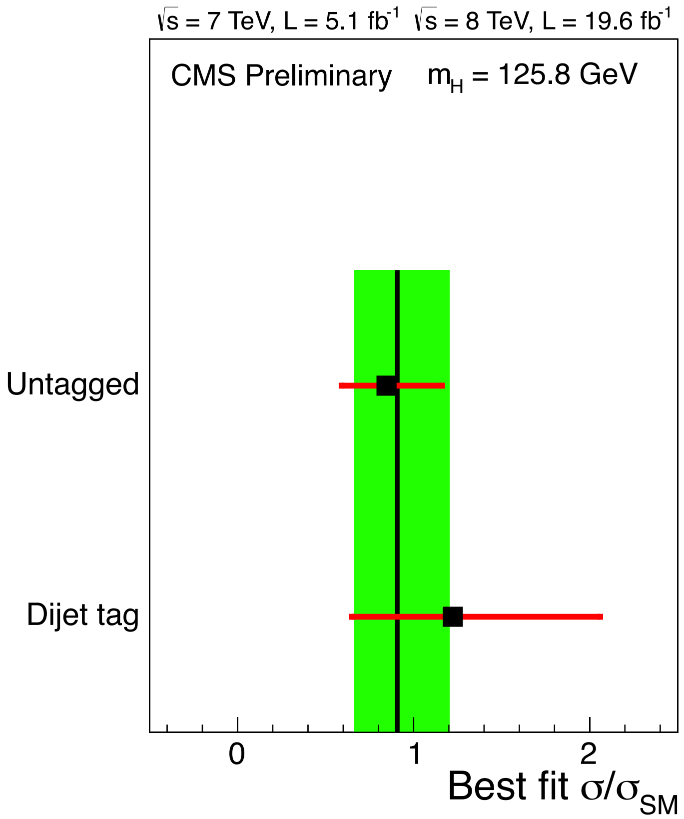
Results

H→ZZ

HIG-13-002







$\mu = 0.85^{+0.32}_{-0.26}$

$\mu = 1.22^{+0.84}_{-0.57}$

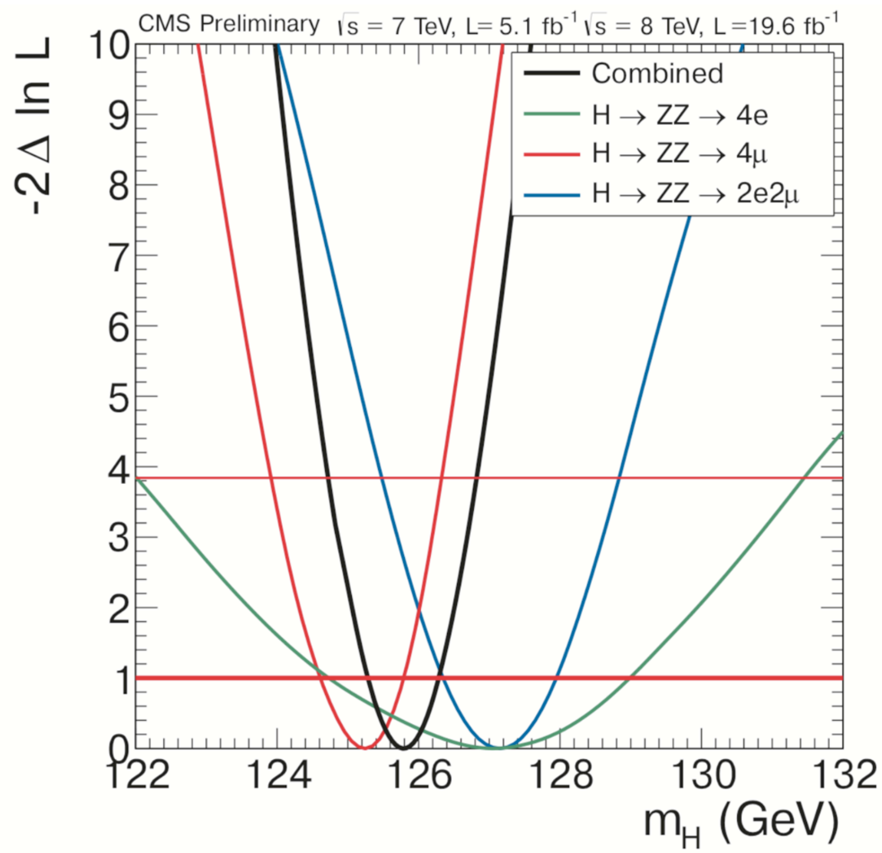
p-value:
Expected: 7.1σ
Observed: 6.7σ

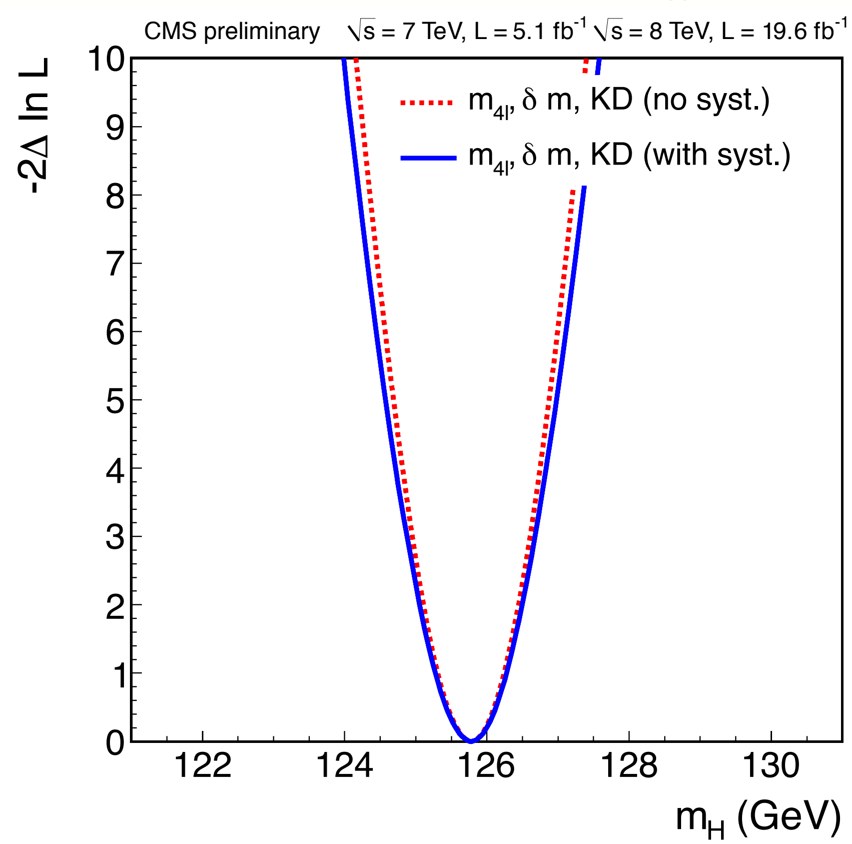
$\mu = 0.92^{+0.30}_{-0.24}$

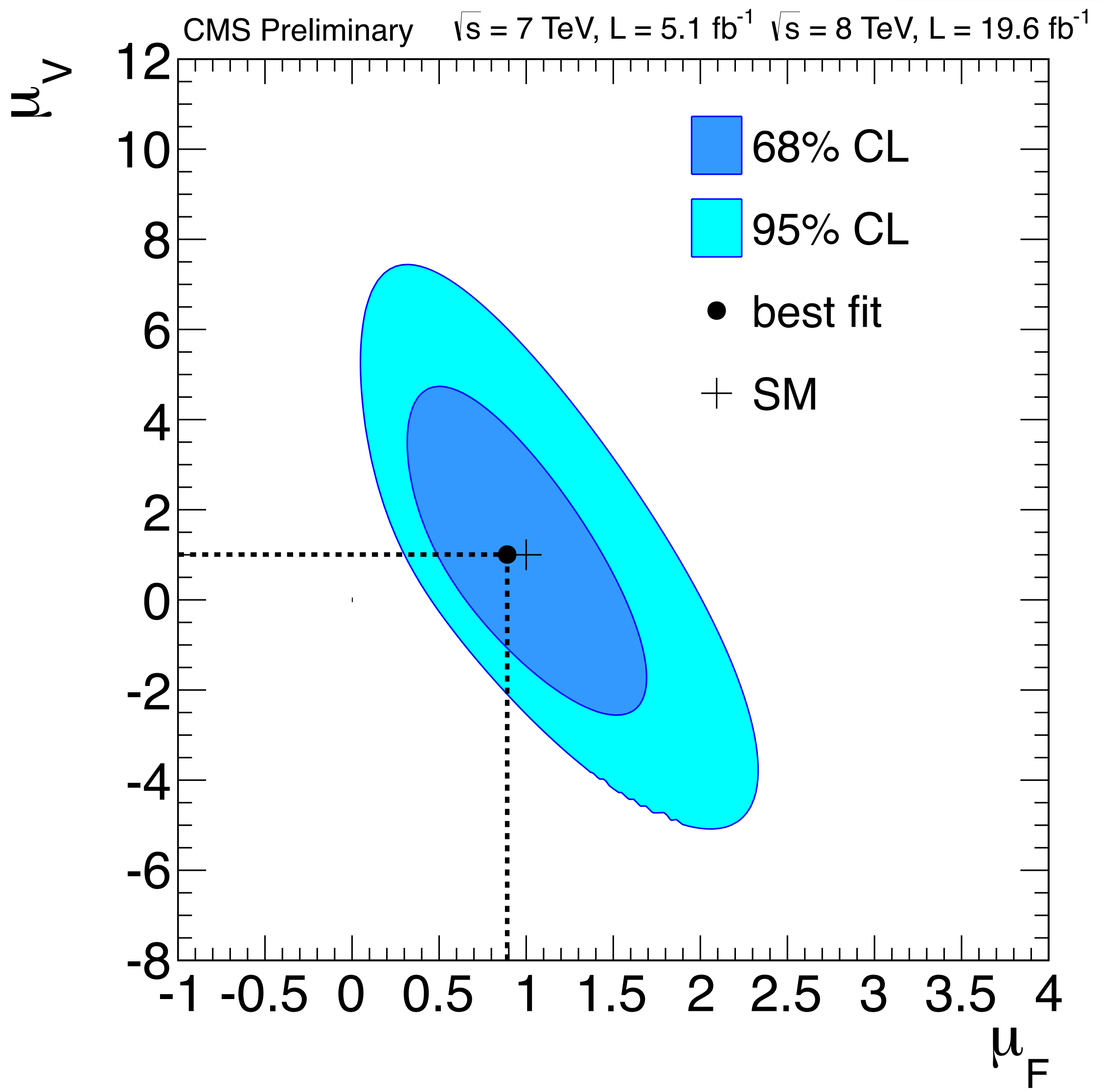
Properties: mass and couplings

H→ZZ

HIG-13-002







$$\mu_V\ (qqH,\ ZH,\ WH) = 1.0^{+2.4}_{-2.3}$$

$$\mu_F\ (gg \to H,\ t\bar{t}H) = 0.9^{+0.5}_{-0.4}$$

M_H= 125.8 ± 0.5(stat) ± 0.2(syst) GeV

Properties: J^P

H→ZZ

HIG-13-002

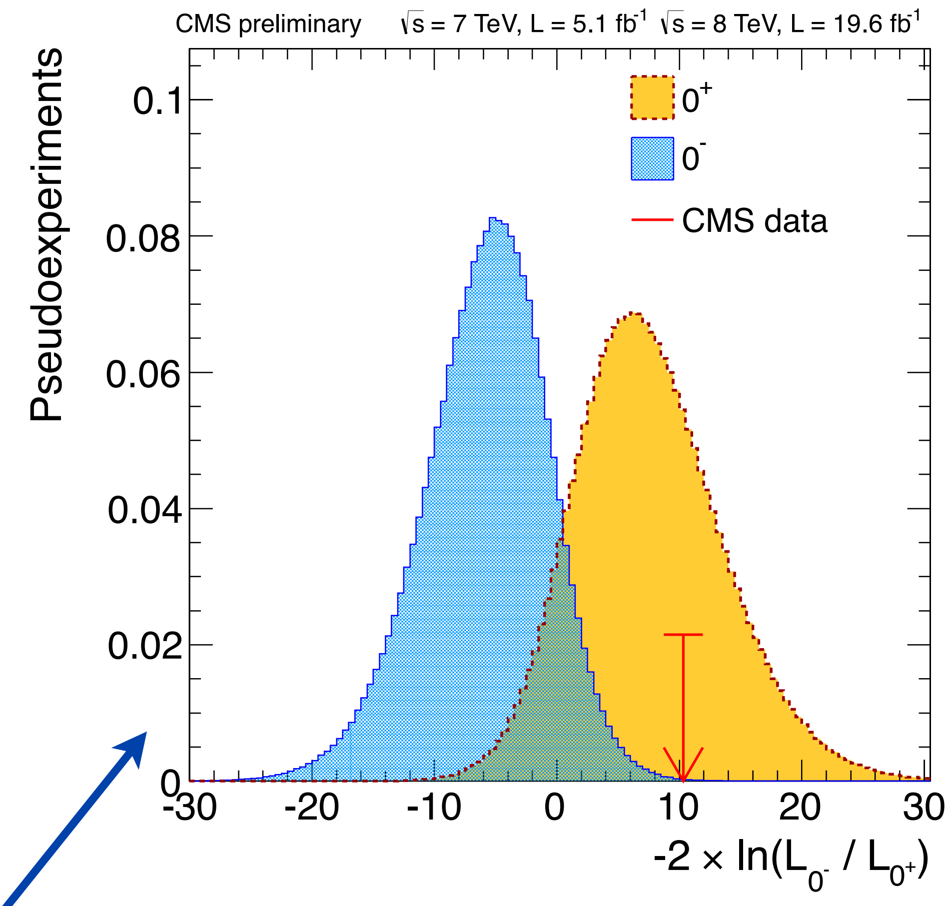
the kinematic of the new particle decaying to ZZ is sensible to its spin and other properties

fully reconstructed final state

- **use a kinematic discriminant**
- **probability ratio between 2 signal hypotheses**

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

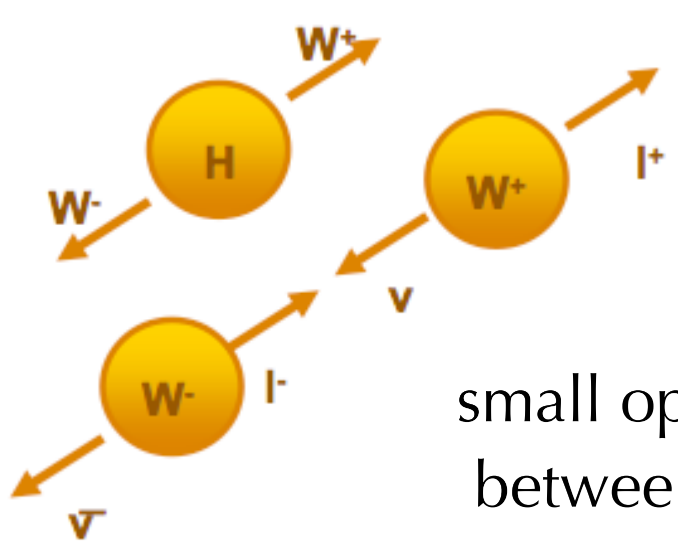
example 0^+ vs 0^-



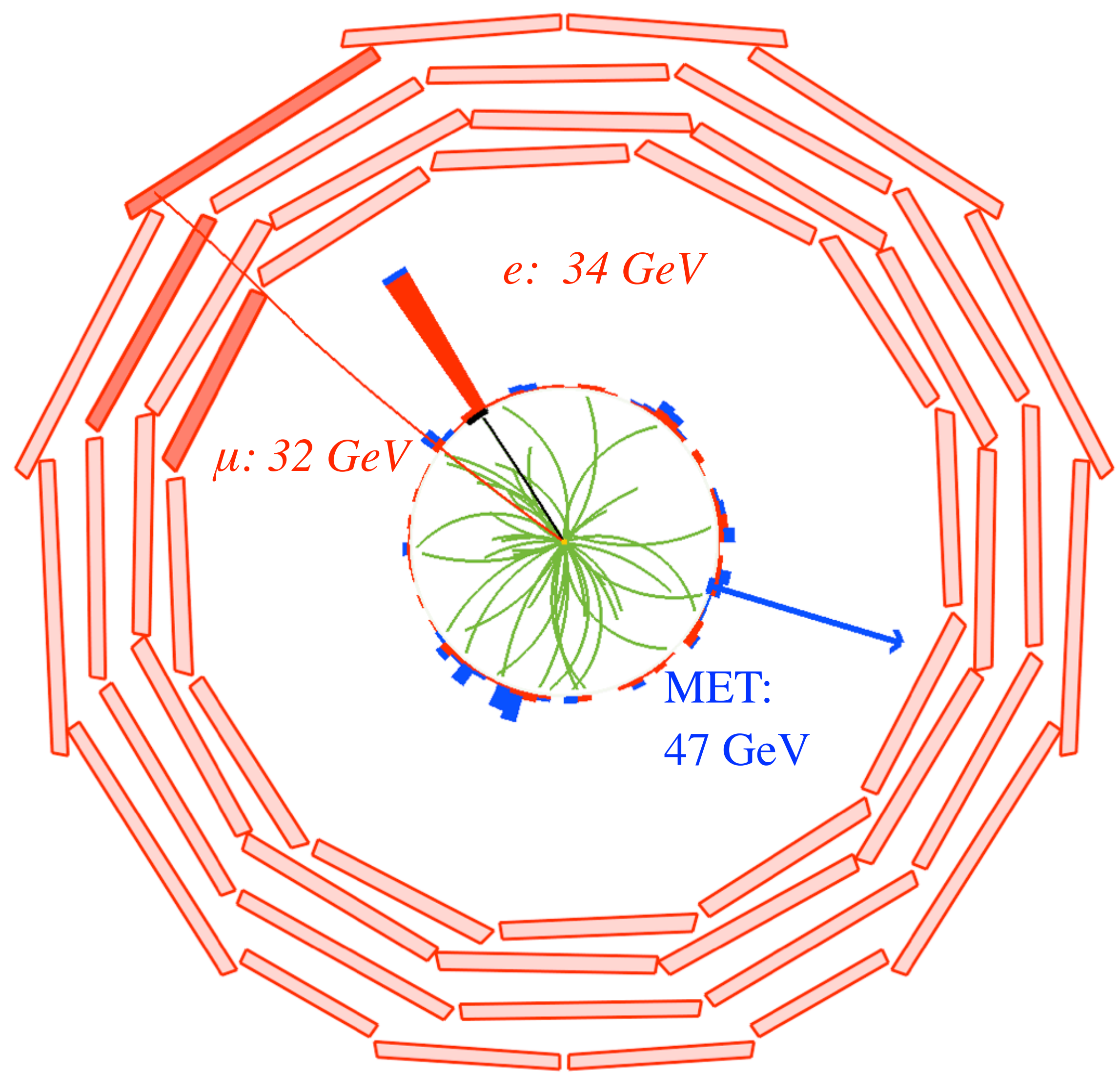
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2_{mgg}^+	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2_{mq\bar{q}}^+$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	>4.0σ	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	>4.0σ	<0.1%

WW Introduction

- ➡2 opposite charged leptons (leptons only e, μ)
- ➡2 neutrinos → missing transverse energy (MET)
- No Higgs mass peak
- Basically a counting analysis
- Selection optimization for each mass point



small opening angle between leptons



Analysis on the full data set for WW+0 jets and +1 jets categories
(The W+2jets (VBF) channel is in progress)

Selection, bkg estimation

H→WW

After the only WW selection

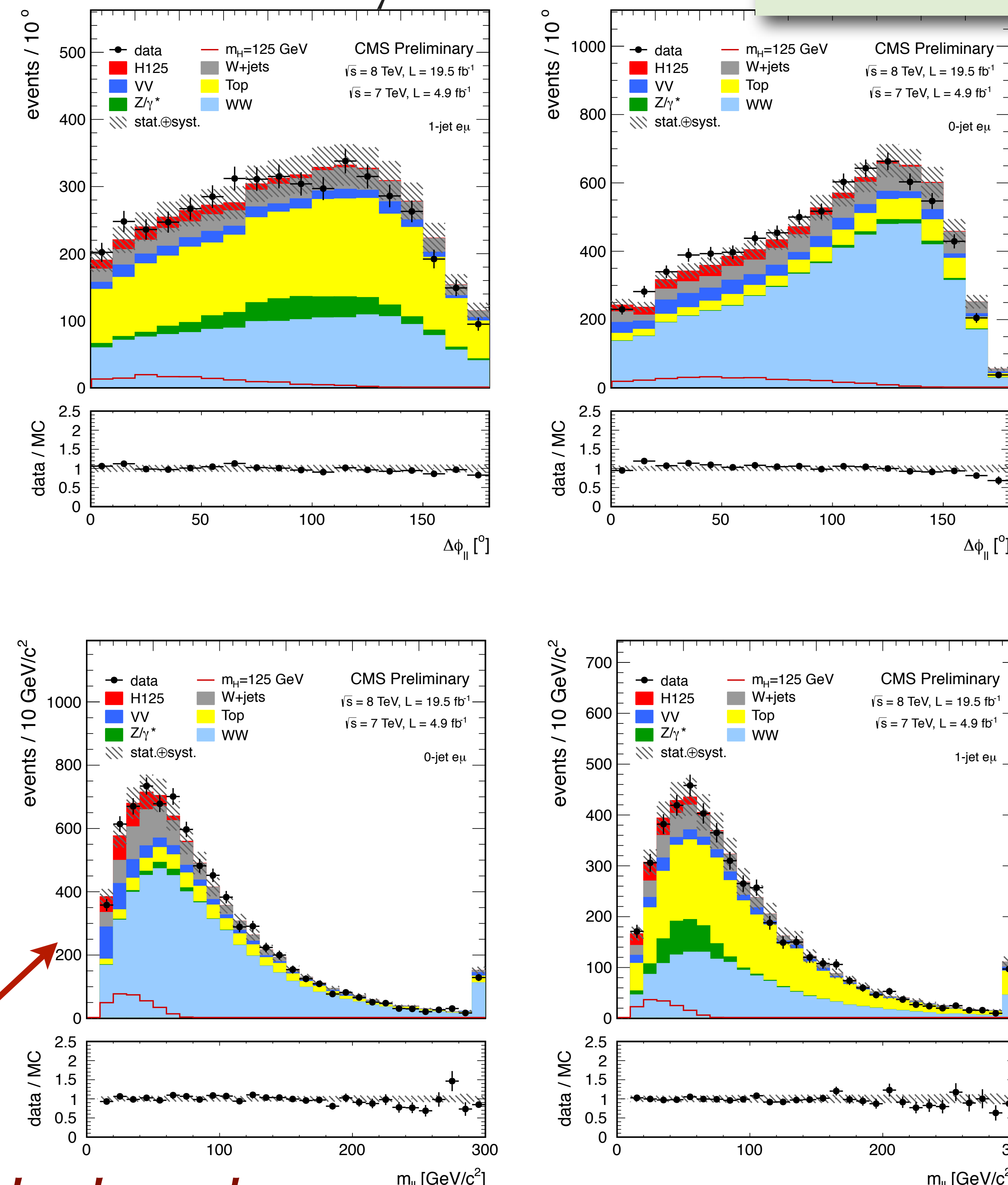
HIG-13-003

same flavor channels:

cut based analysis

selection on the variables:

m_{H}	$p_{\mathrm{T}}^{\ell,\max}$	$p_{\mathrm{T}}^{\ell,\min}$	$m_{\ell\ell}$	$\Delta\phi_{\ell\ell}$	m_{T}



different flavor channels:

bi-dimensional analysis

m_{ll} and m_T

Analysis challenge

Understand backgrounds:

WW, W+jets, top, DY

Determined from control regions

excess of events over the bkg observed

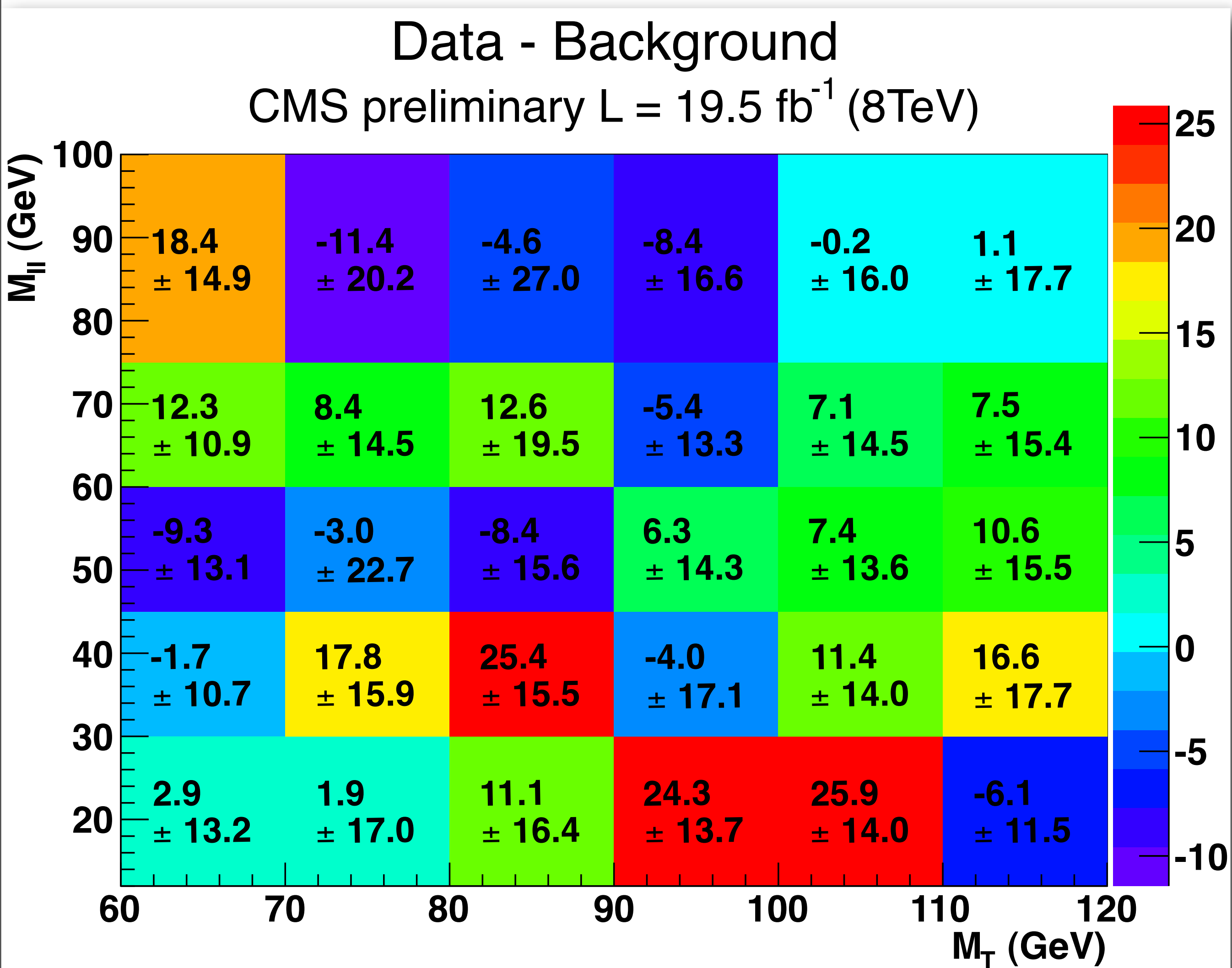
Different flavor 2-D analysis

H→WW

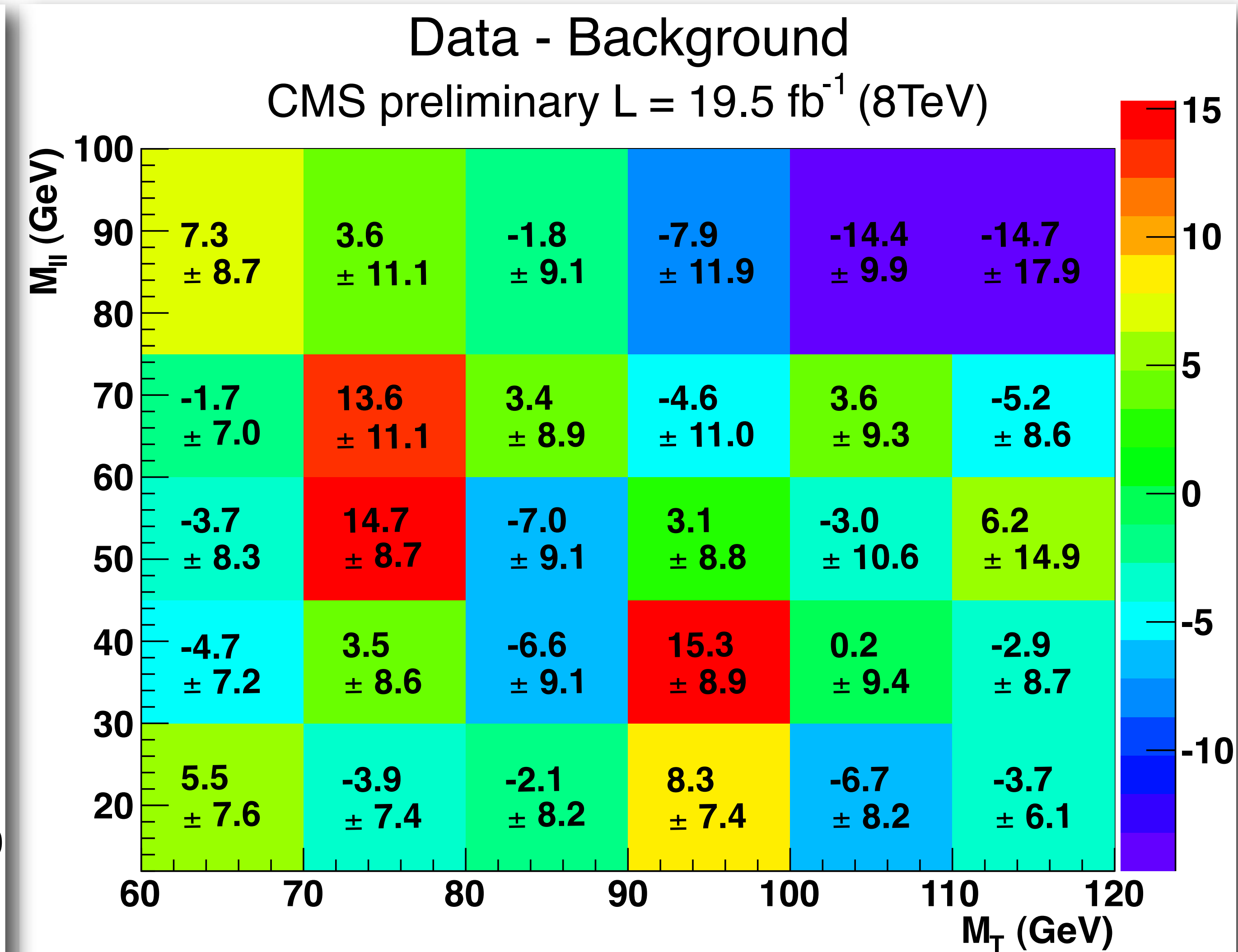
HIG-13-003

m_{ll} VS m_T

0 Jet-bin



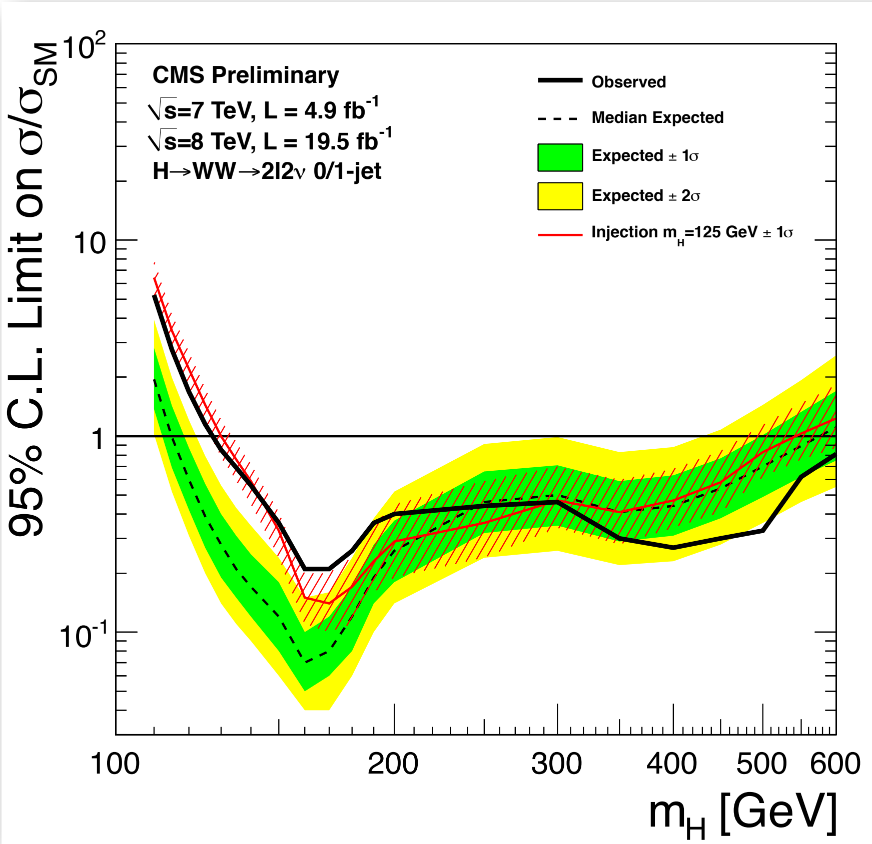
1 Jet-bin



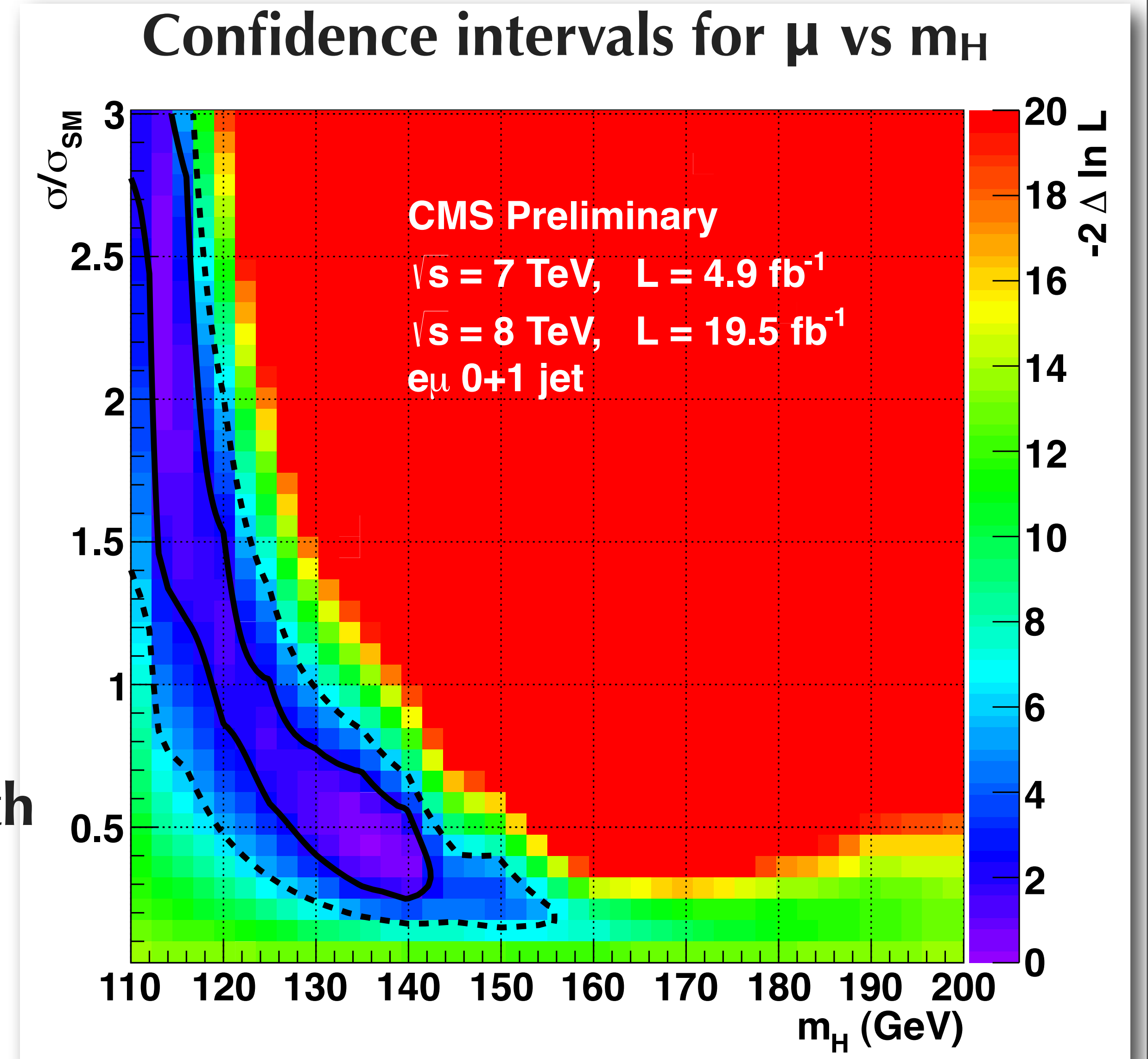
Results

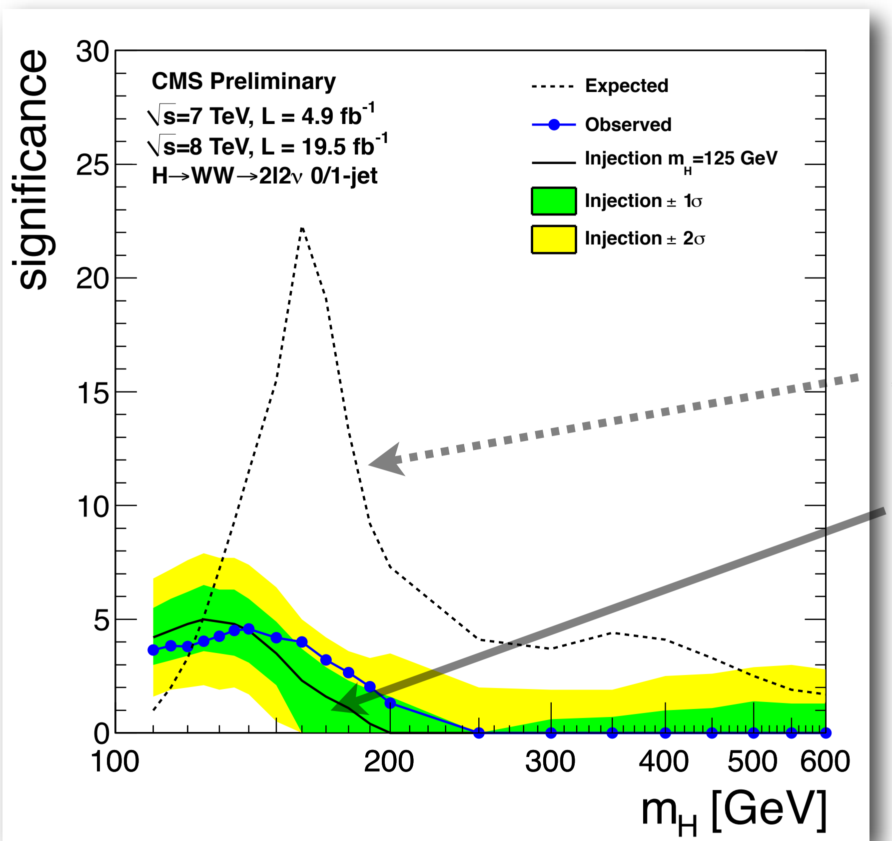
H→WW

HIG-13-003



Exclusion at 95% in the mass range 128-600 GeV
Large excess in the low mass region





expected significance:

- for a Higgs of that mass
- for a Higgs with m_H=125 GeV

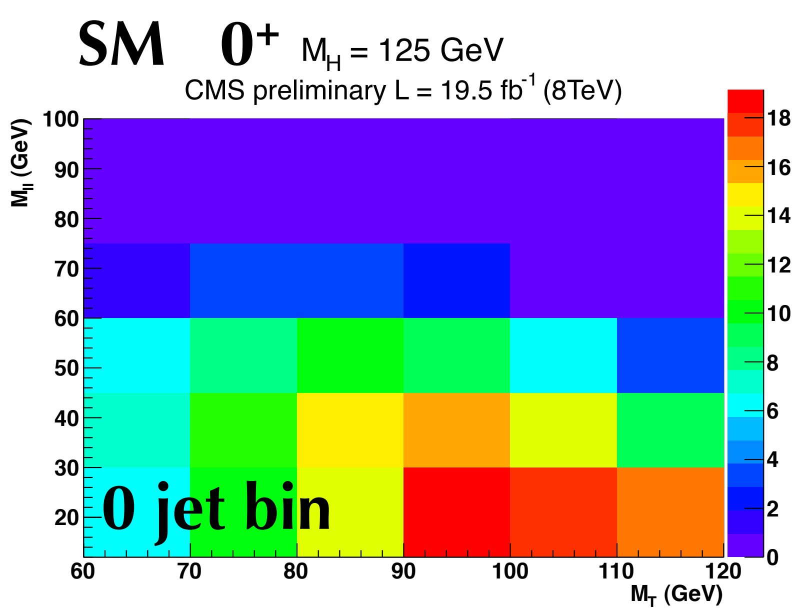
Properties: study of J^P

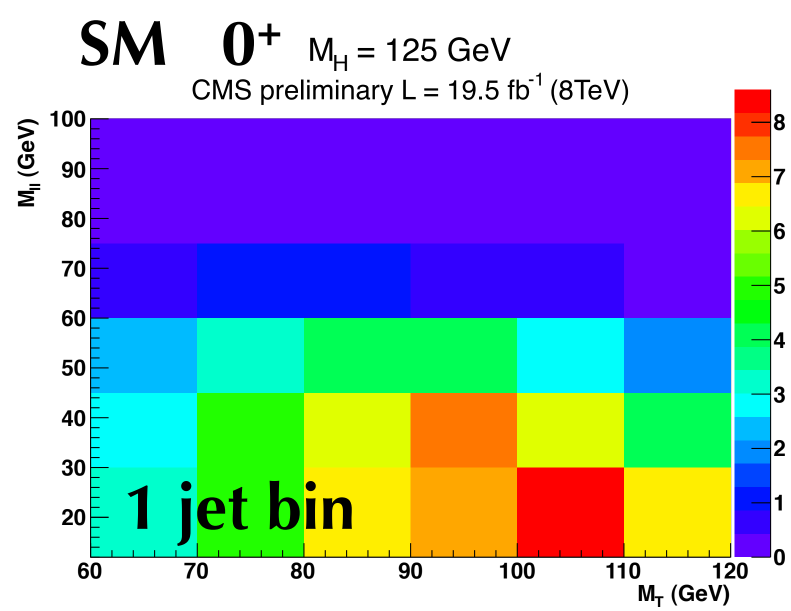
H→WW

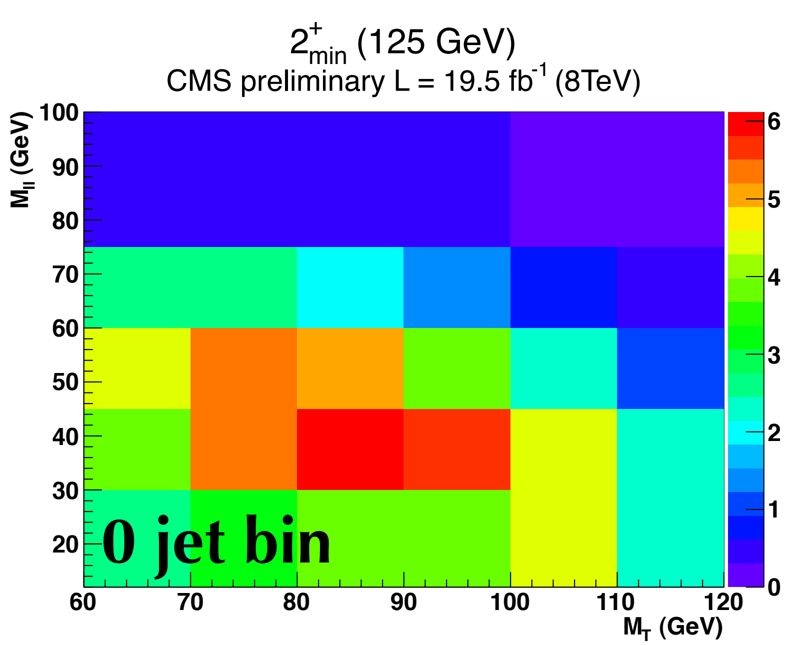
HIG-13-003

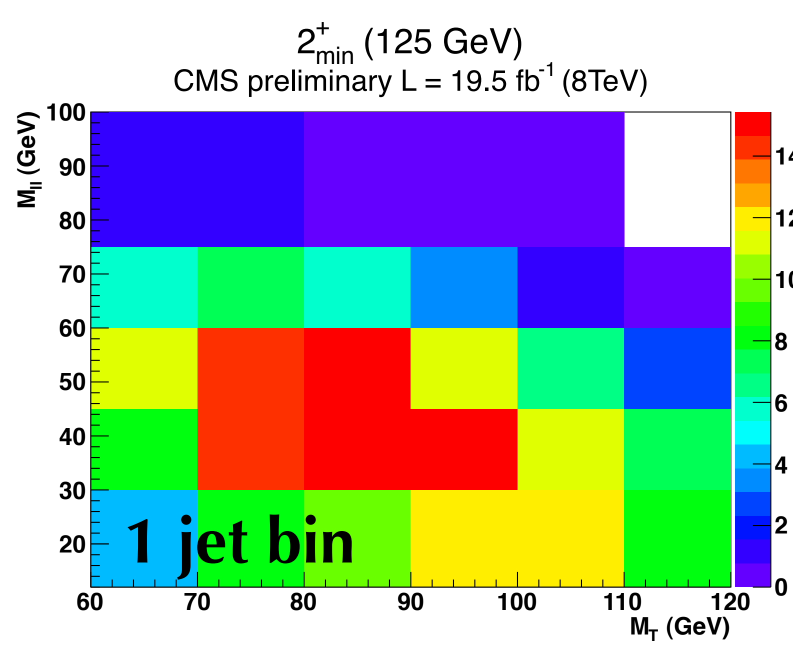
performed only with the different flavor channels

sensitivity to distinguish SM and spin-2 resonance with minimal couplings to bosons





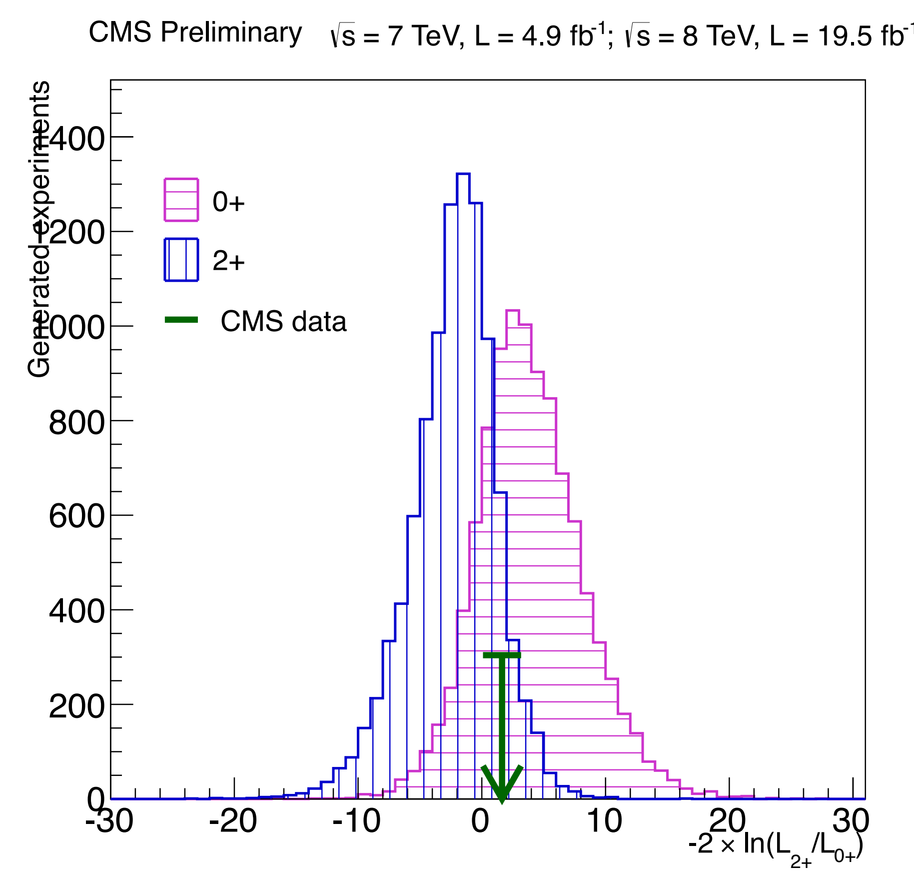




with signal strength from fit to data:

0.76 for 0^+

0.83 for $2^+{}_m$



2^+m is disfavored with CLs of 14%

WH, with H→WW

H→WW

HIG-13-009

3 high pt leptons (e, μ)

divide in categories:

- Opposite Sign Same Flavor **(OSSF)**
- Same Sign Same Flavor **(SSSF)**

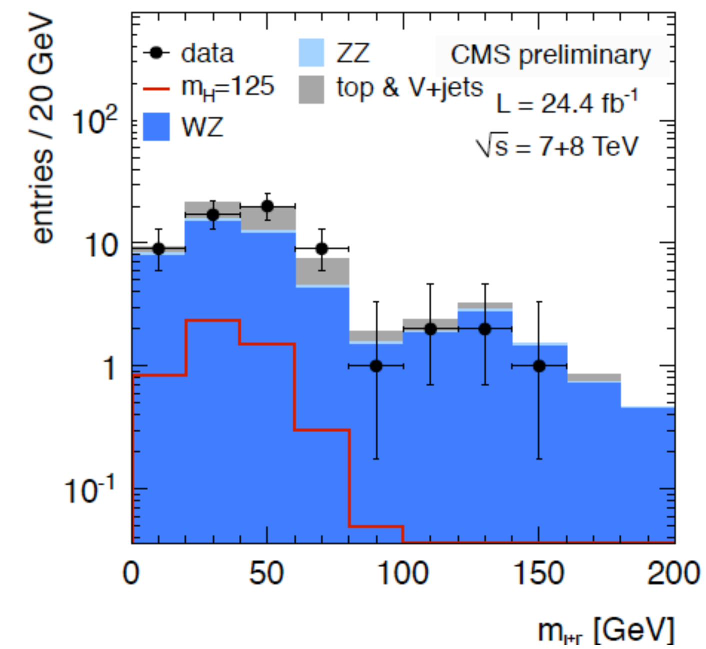
main background contributions

$WZ \rightarrow 3\ell\nu$

$Z + \gamma$

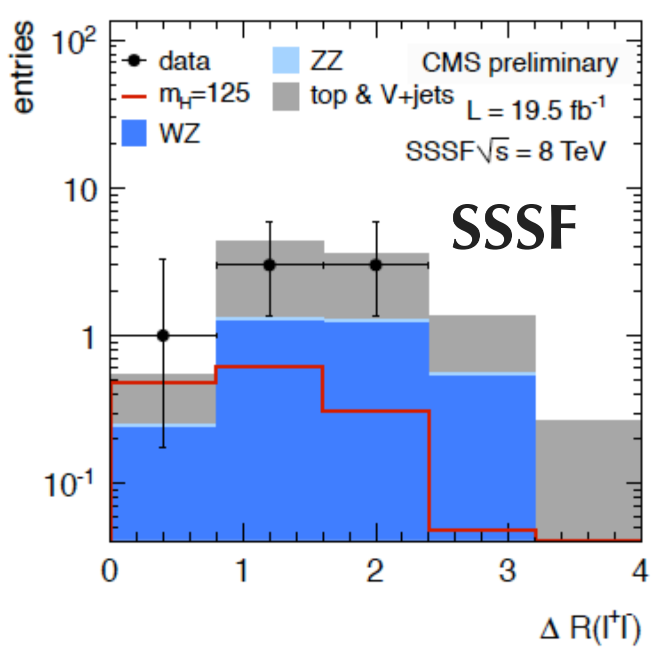
$ZZ \rightarrow 4\ell$

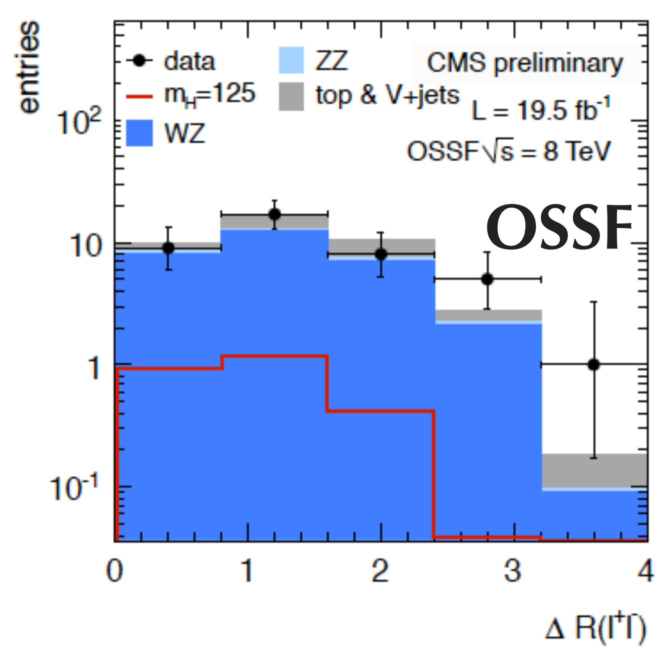
tribosons

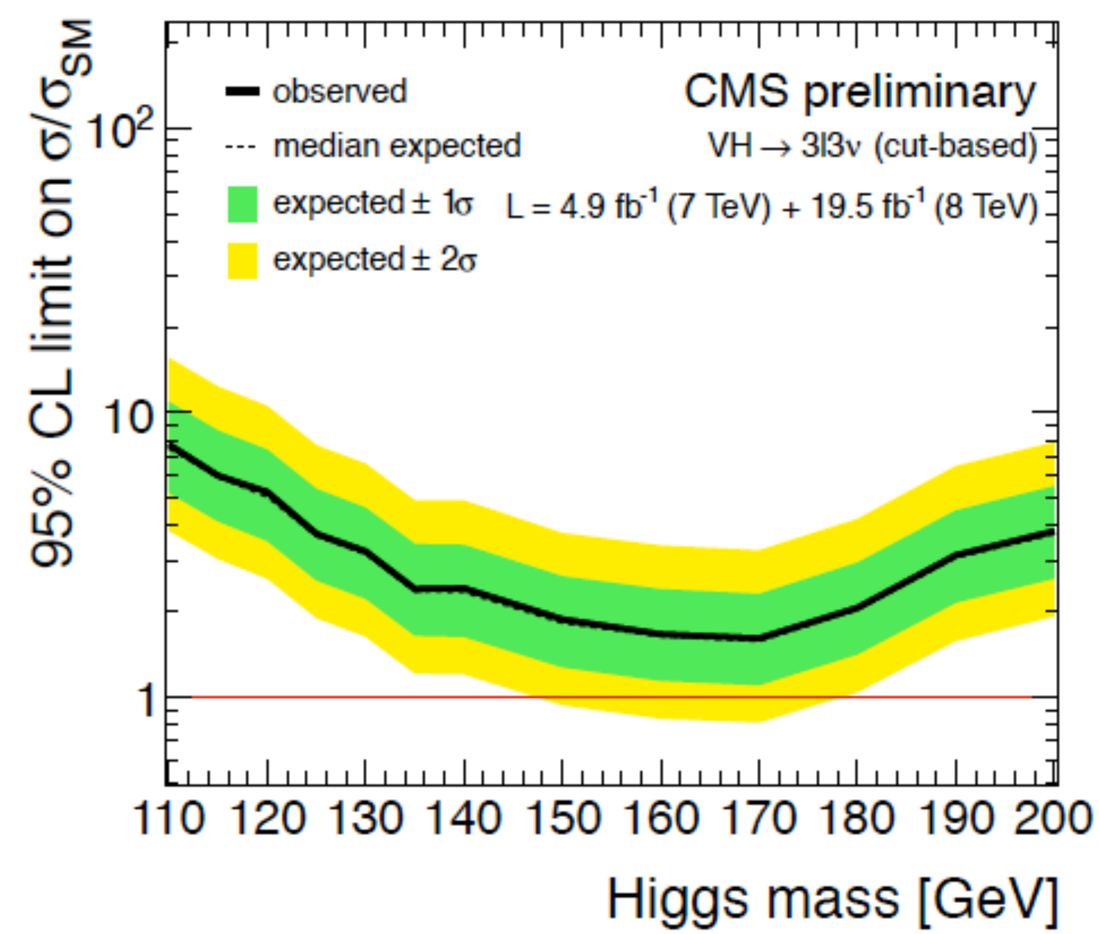


good data/MC agreement

$\Delta R_{\ell^+\ell^-}$ **is used as discriminant**







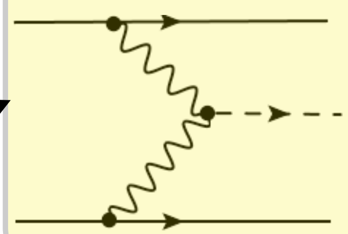
H→ττ

HIG-13-004

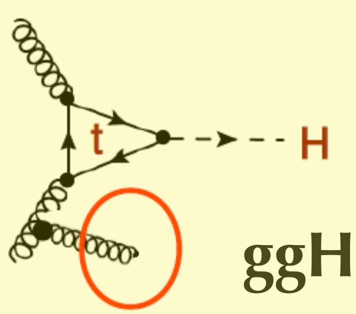
each lepton flavor channel is splitted in

- eμ
- μμ
- $\mu\tau_h$
- $e\tau_h$
- $\tau_h\tau_h$

VBF

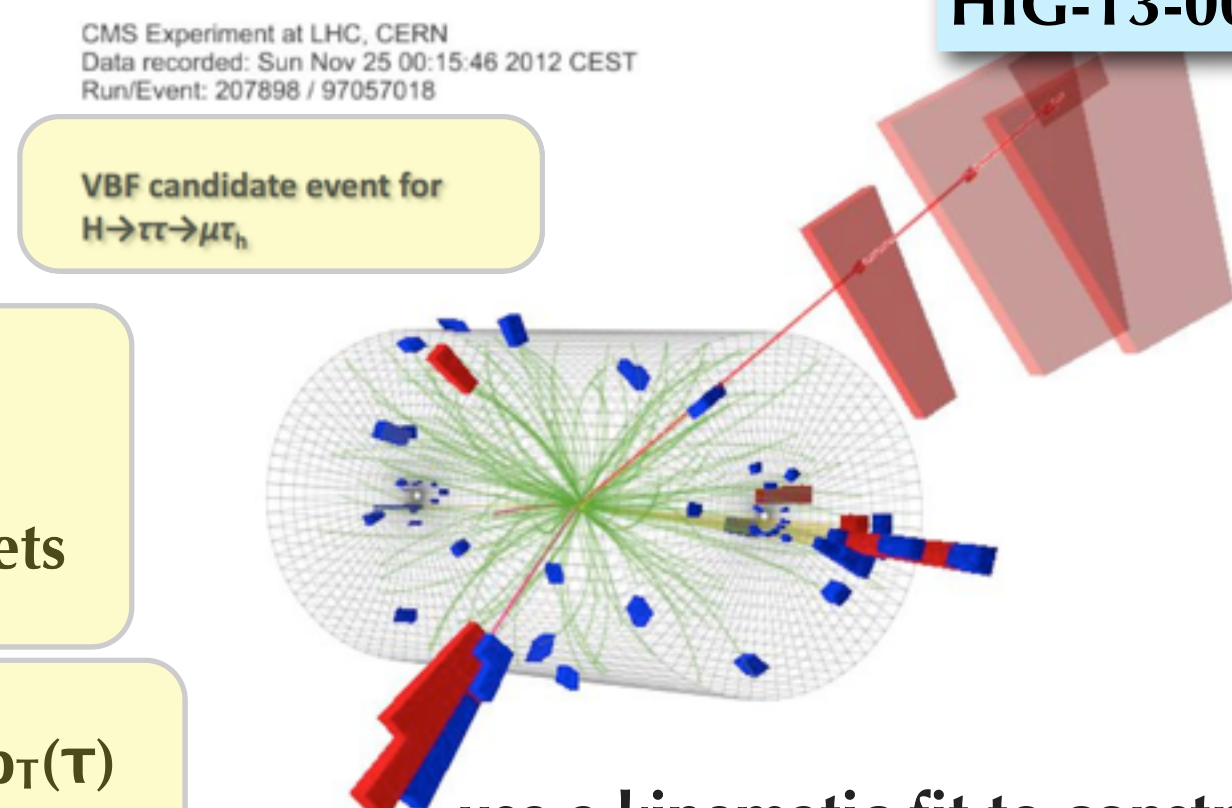


1 forward and 1 background jets



ggH with a high p_T jet

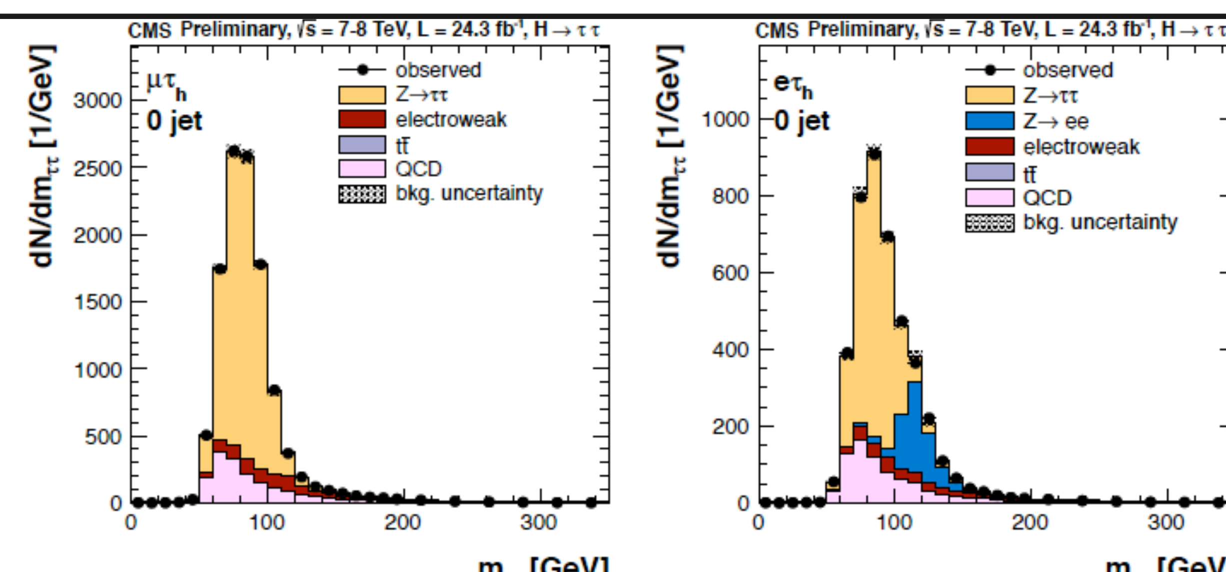
- high $p_T(\tau)$
- low $p_T(\tau)$



use a kinematic fit to construct the $m_{\tau\tau}$ from the *visible $m_{\tau\tau}$*

invariant mass of all the decay product of the taus: e,μ,π,γγ

the 0 jet category is used to constraint the background →



H→ττ, background estimation

H→ττ

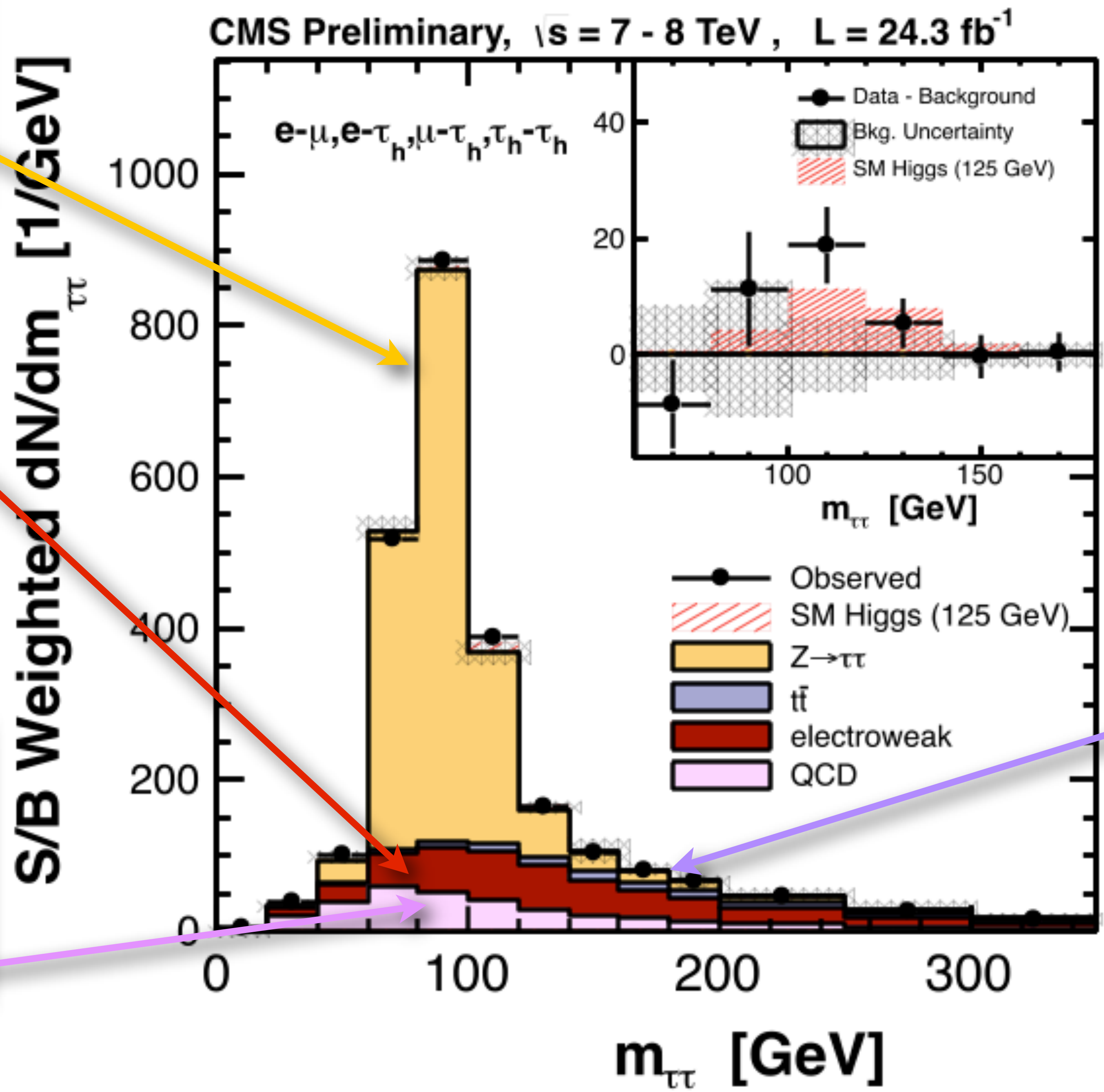
HIG-13-004

Combine the sensitive categories of all channels with a S/B weight

Z→ττ
Normalization from Z→μμ data
(Syst: 5%)

EW
Shape from simulation
Normalization from control region
Syst: 10-20%

QCD
SS data, corrected for SS/OS ratio
Syst: 10%

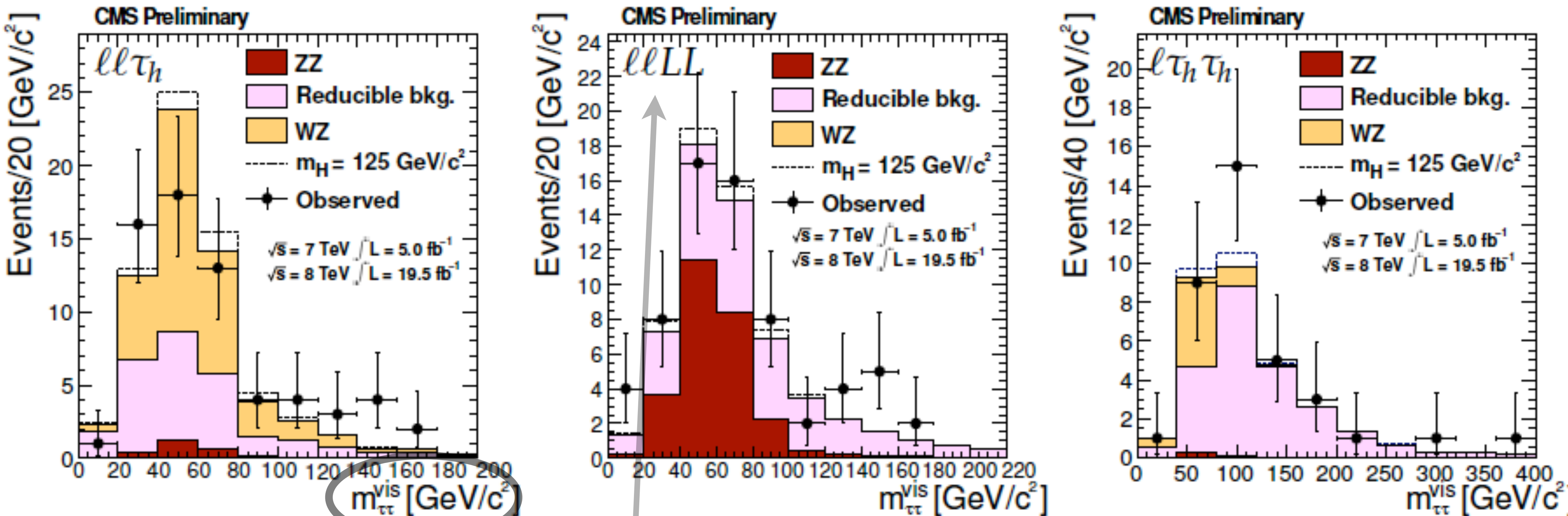


ttbar
(important for eμ channel)
simulation rescaled to yield from control sample
Syst: 10%

VH, with H→ττ

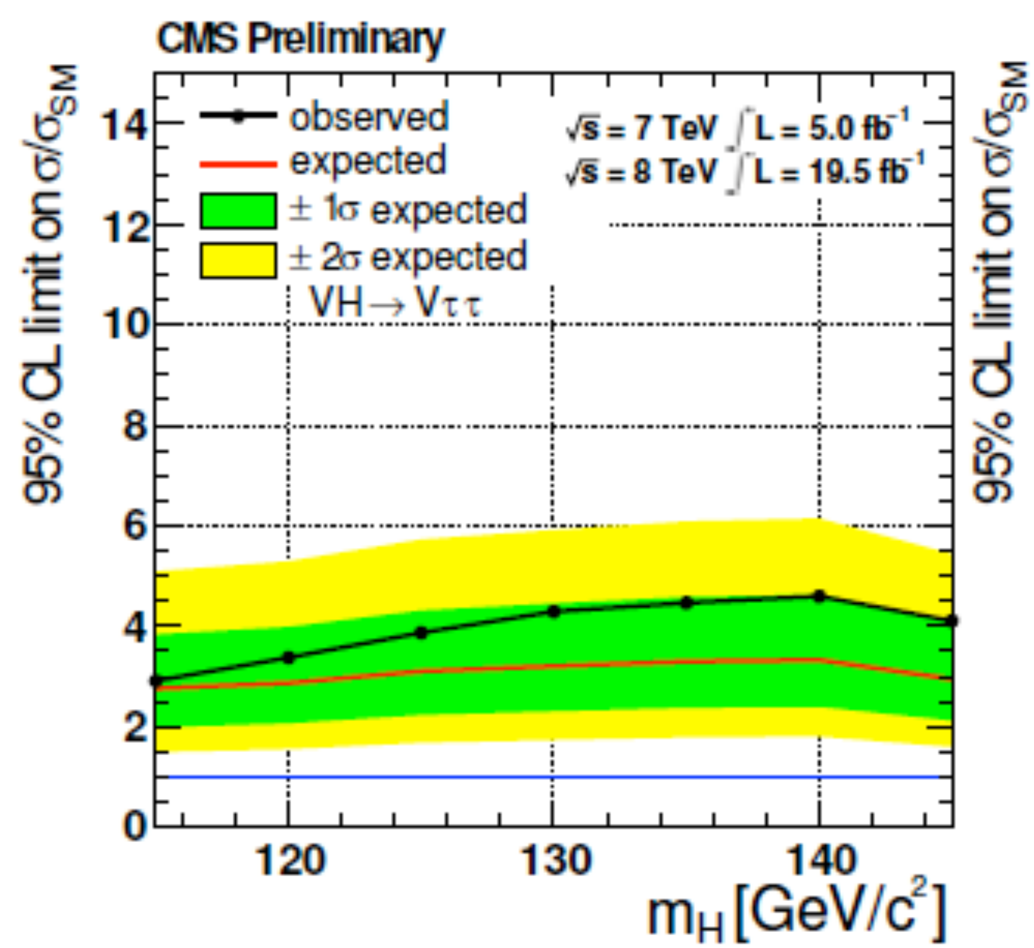
H→ττ

HIG-12-053



visible $m_{\tau\tau}$:
invariant mass of all the decay product of the taus: e,μ,π,γγ

L: e,μ ,τ_h



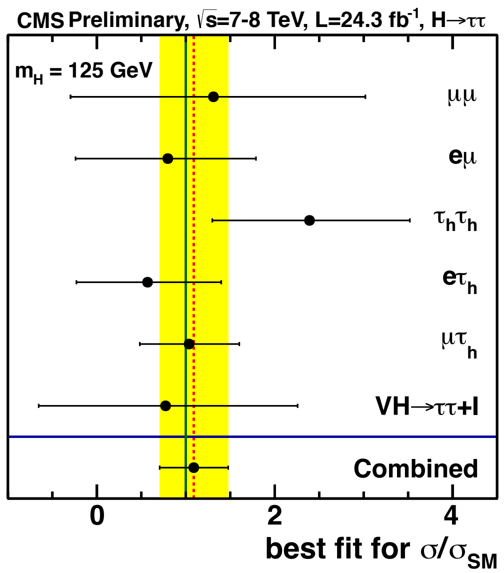
<u>main systematics:</u>
PDF
non-prompt bkg estimation
WZ and ZZ cross section

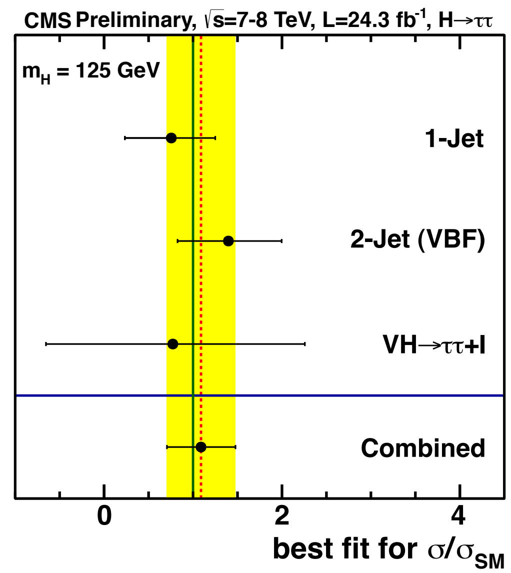
Results

H→ττ

HIG-13-004

Compatibility test with SM Higgs production

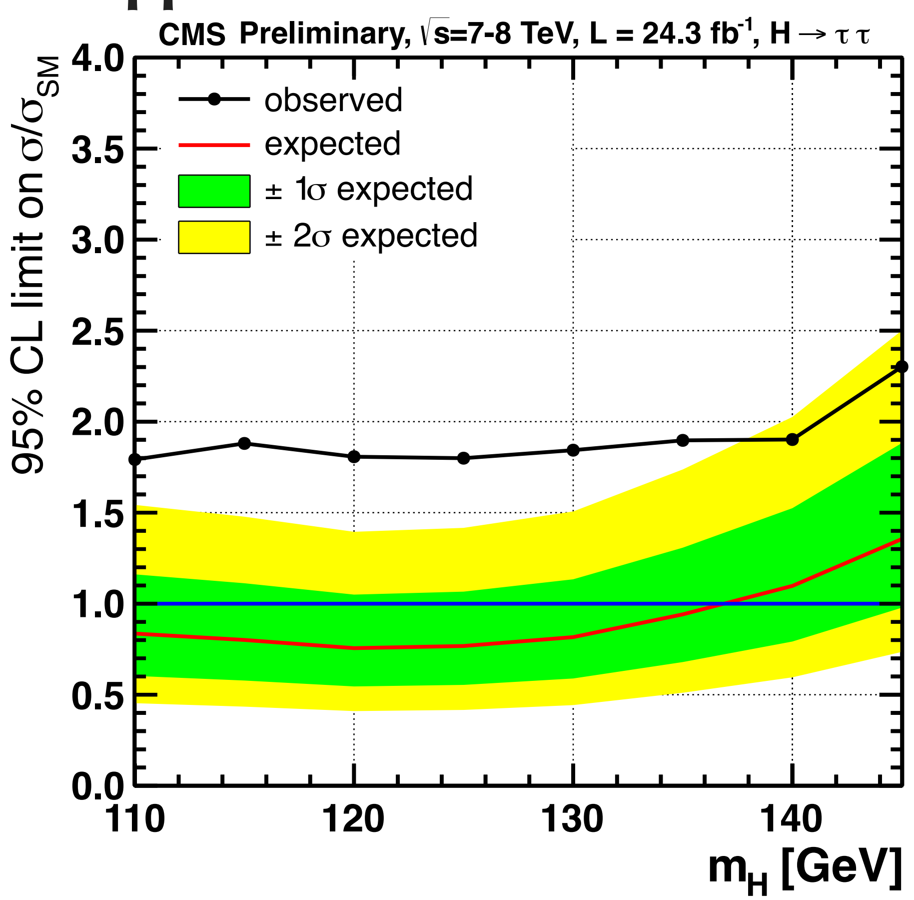




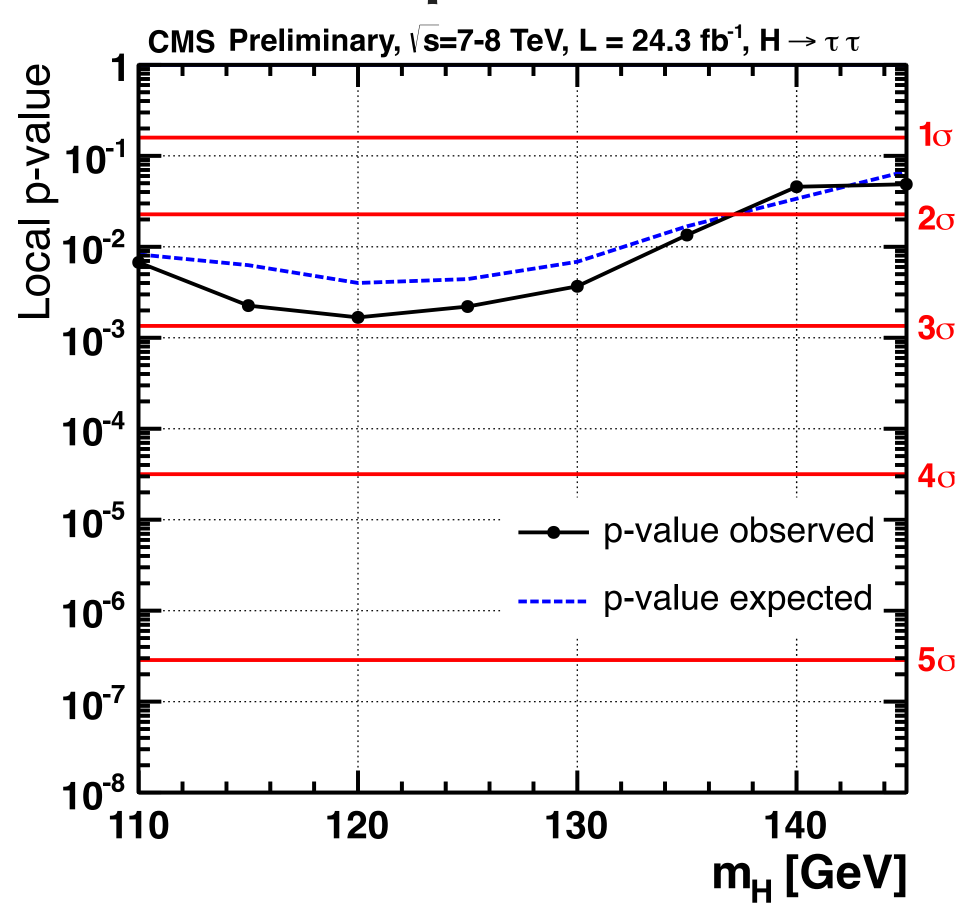
$$\hat{\mu} = 1.1 \pm 0.4$$

combination also with WWW HIG-12-053

Upper limit



Local p-value

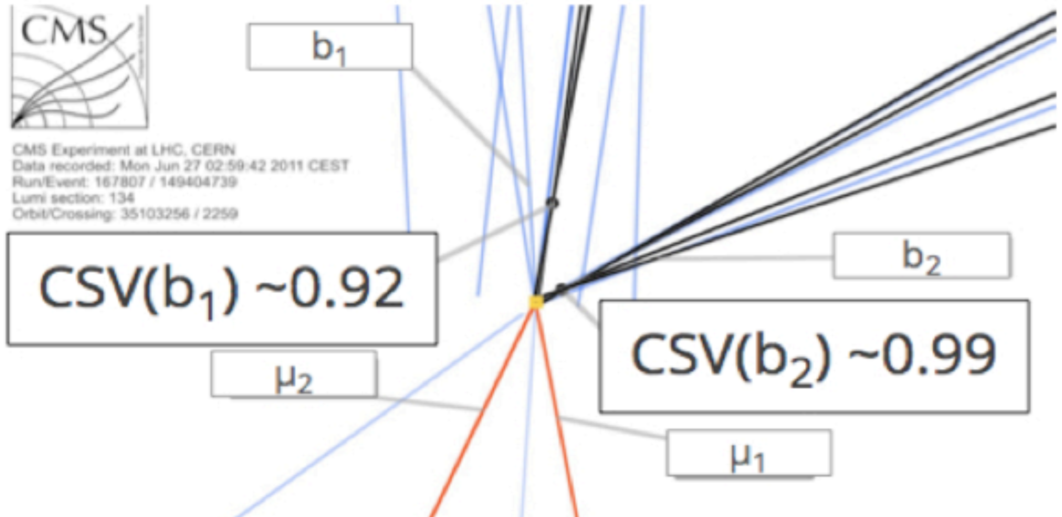


VH, with H→bb

H→bb

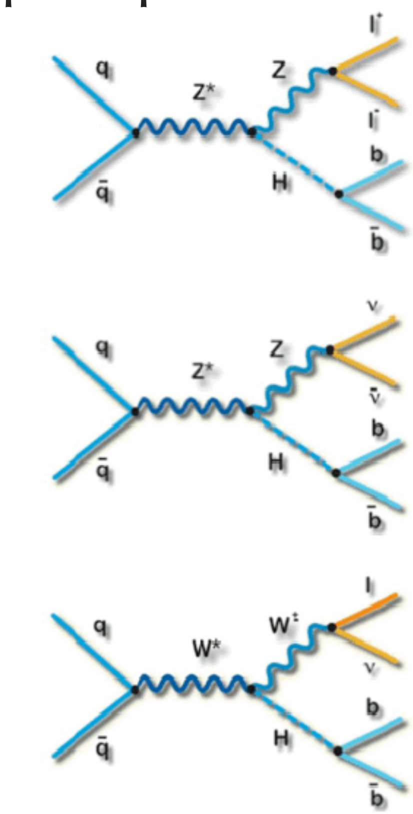
HIG-12-044

CSV: likelihood discriminant based on track impact parameters and secondary vertices



MVA regression to estimate the pT(b-jets)
MVA to separate signal from background, the output is used in the limit settings

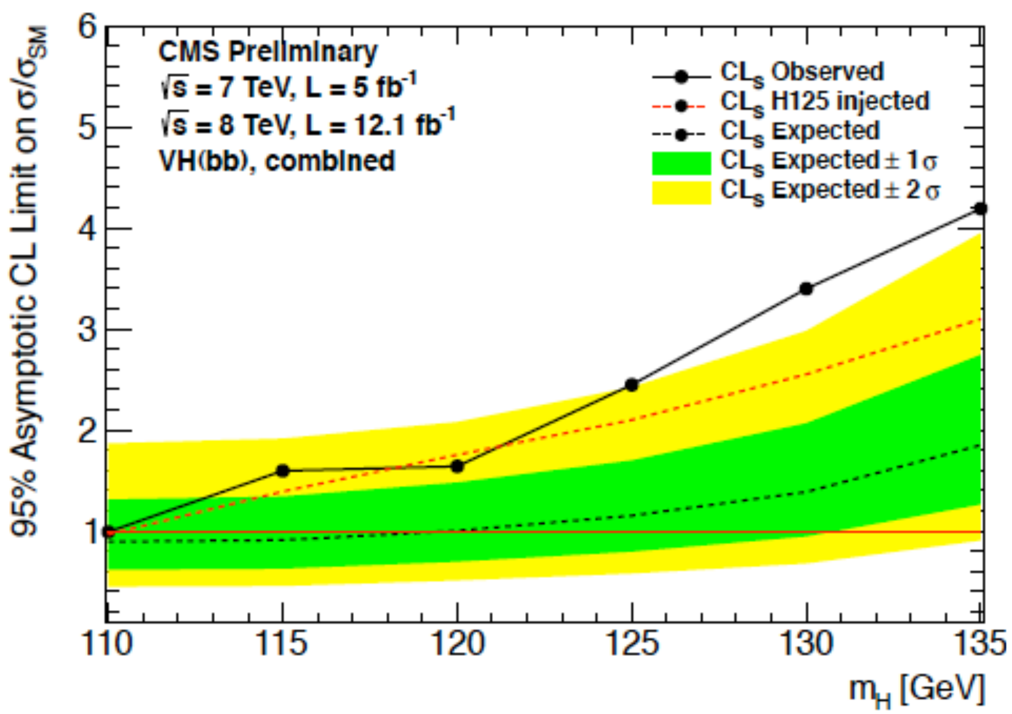
VH

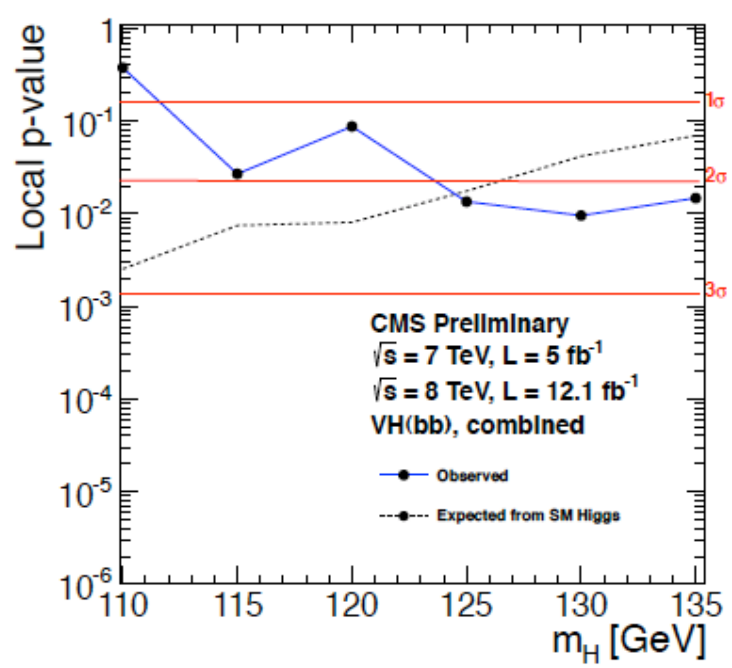


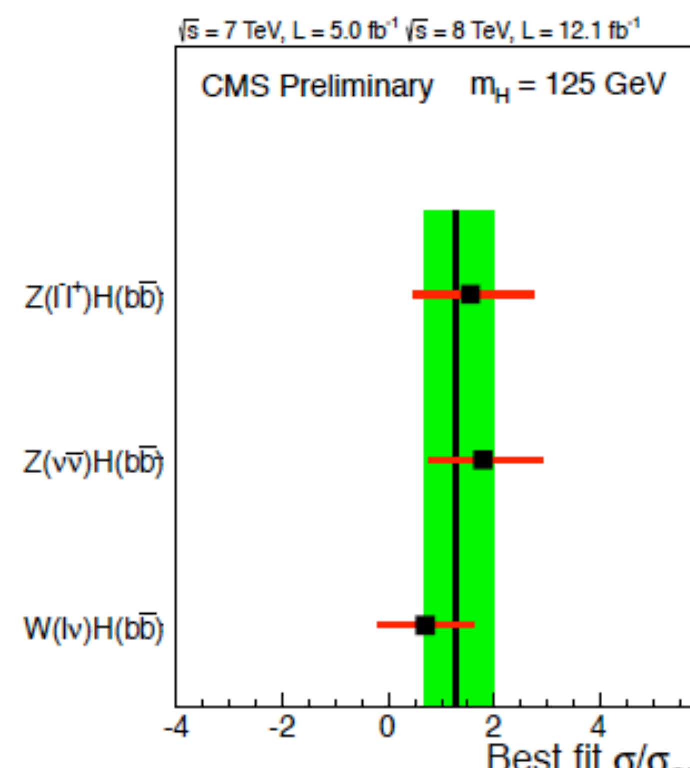
2 leptons

large MET → tight btag / loose btag

medium MET → tight btag / loose btag



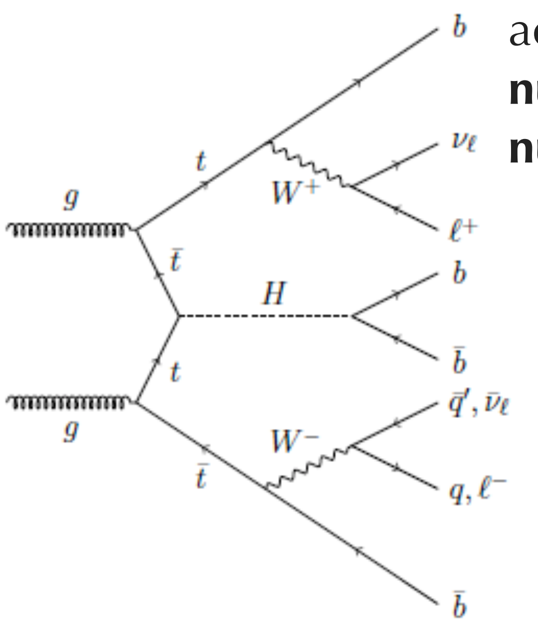




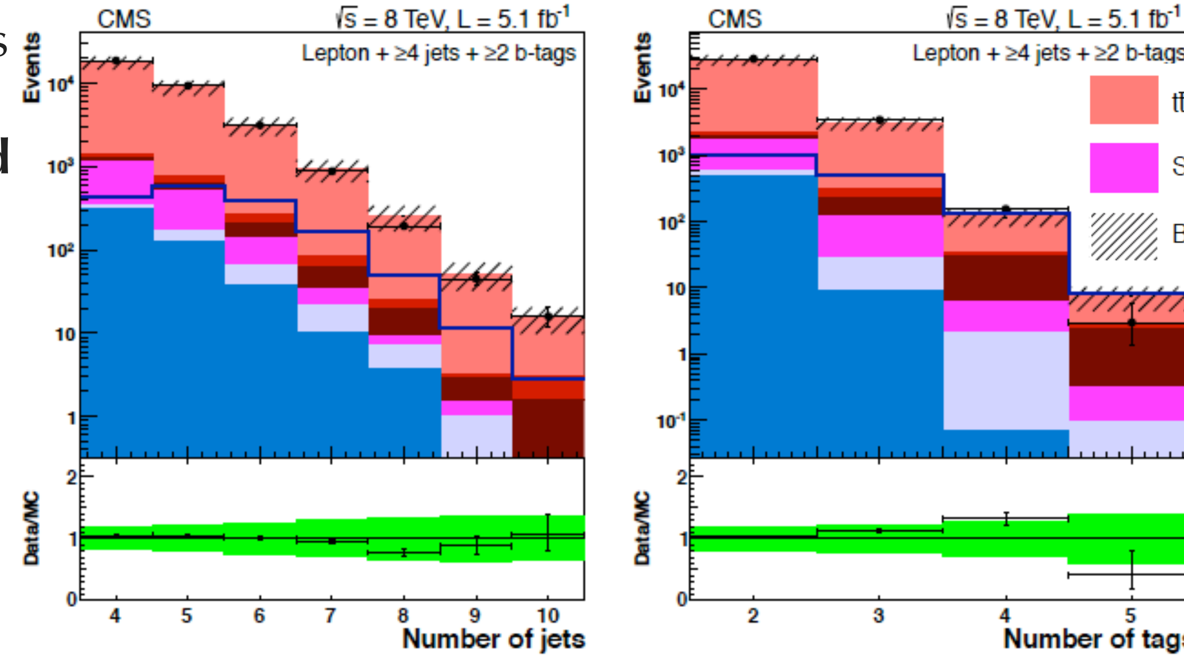
ttH, with H→bb

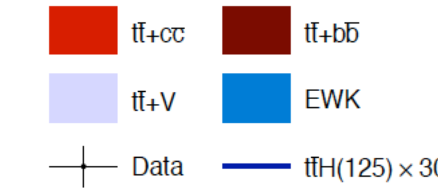
H→bb

arXiv:1303.0763



different categories according to the **number of jets and number of tags**

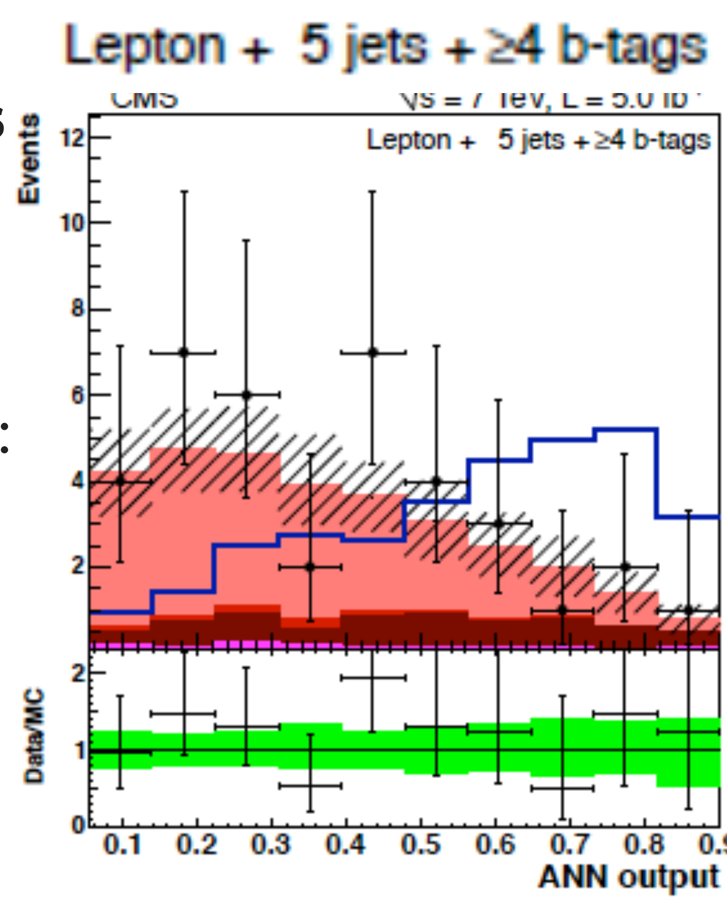




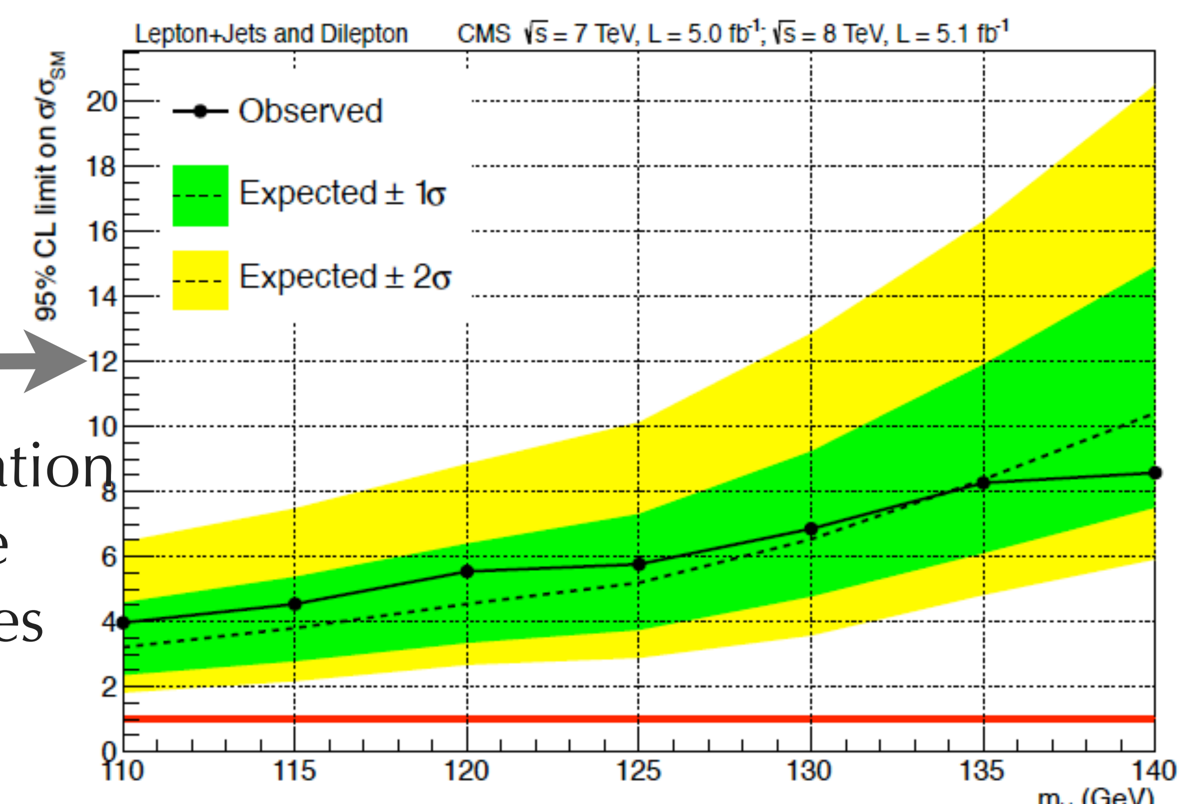
signal has large number of jets and tag

different ANNs for each category

example:



combination of all the categories



Combination

combination

HIG-13-005

high resolution channels

H decay	Prod. tag	Analyses: Exclusive final states	No. of channels	m_H resolution	Lumi (fb^{-1}) 7 TeV	Lumi (fb^{-1}) 8 TeV
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4 + 4	1-2%	5.1	19.6
	VBF-tag	$\gamma\gamma + (jj)_{VBF}$ (two dijet classes for 8 TeV)	1 + 2	<1.5%	5.1	19.6
	VH-tag	$\gamma\gamma + (e, \mu, MET)$	3	<1.5%		19.6
$ZZ \to 4\ell$	$N_{jet} < 2$ $N_{jet} \geq 2$	4e, 4μ, $2e2\mu$	3 + 3 3 + 3	1-2%	5.1	19.6
$WW \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) × (0 or 1 jets)	4 + 4	20%	4.9	19.5
	VBF-tag	$\ell\nu\ell\nu + (jj)_{VBF}$ (DF or SF dileptons for 8 TeV)	1 + 2	20%	4.9	12.1
	WH-tag	$3\ell3\nu$ (same-sign SF and otherwise)	2 + 2		4.9	19.5
$\tau\tau$	0/1-jet	$(e\tau_h, \mu\tau_h, e\mu, \mu\mu) \times$ (low or high p_T^{τ})	16 + 16	15%	4.9	19.6
	1-jet	$\tau_h\tau_h$	1 + 1			
	VBF-tag	$(e\tau_h, \mu\tau_h, e\mu, \mu\mu, \tau_h\tau_h) + (jj)_{VBF}$	5 + 5			
	ZH-tag	$(ee, \mu\mu) \times (\tau_h\tau_h, e\tau_h, \mu\tau_h, e\mu)$	8 + 8		5.0	19.5
	WH-tag	$\tau_h\mu\mu, \tau_h e\mu, e\tau_h\tau_h, \mu\tau_h\tau_h$	4 + 4			
bb	VH-tag	$(\nu\nu, ee, \mu\mu, e\nu, \mu\nu$ with 2 b-jets) × (low or high $p_T(V)$ or loose b-tag)	10 + 13	10%	5.0	12.1
	ttH-tag	(ℓ with 4, 5 or ≥6 jets) × (3 or ≥4 b-tags); (ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or ≥3 b-tagged jets)	6 + 6 3 + 3		5.0	5.1

Decay mode	Expected (σ)	Observed (σ)
ZZ	7.1	6.7
$\gamma\gamma$	3.9	3.2
WW	5.3	3.9
bb	2.2	2.0
$\tau\tau$	2.6	2.8

mass measurement and compatibility tests for several properties

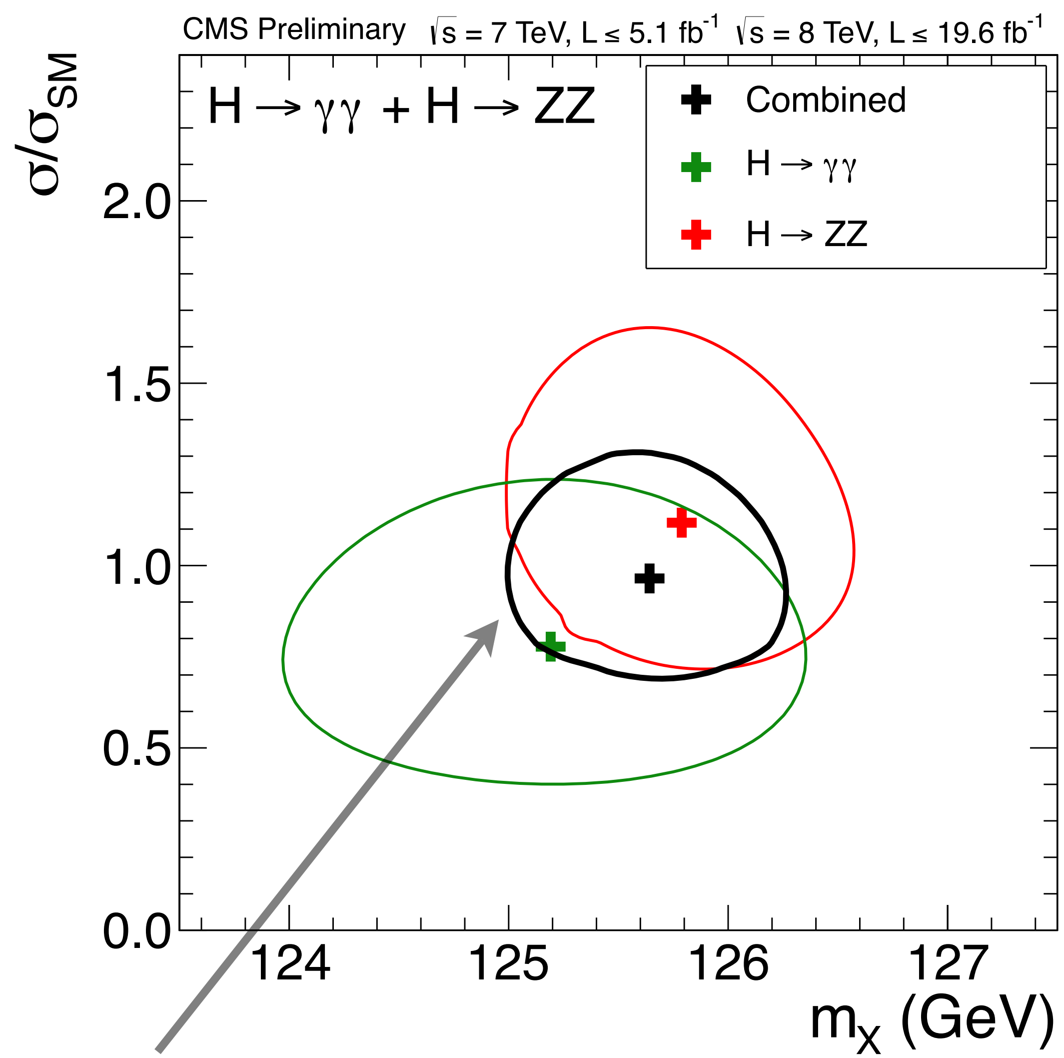
mass meas. with: γγ and ZZ

combination

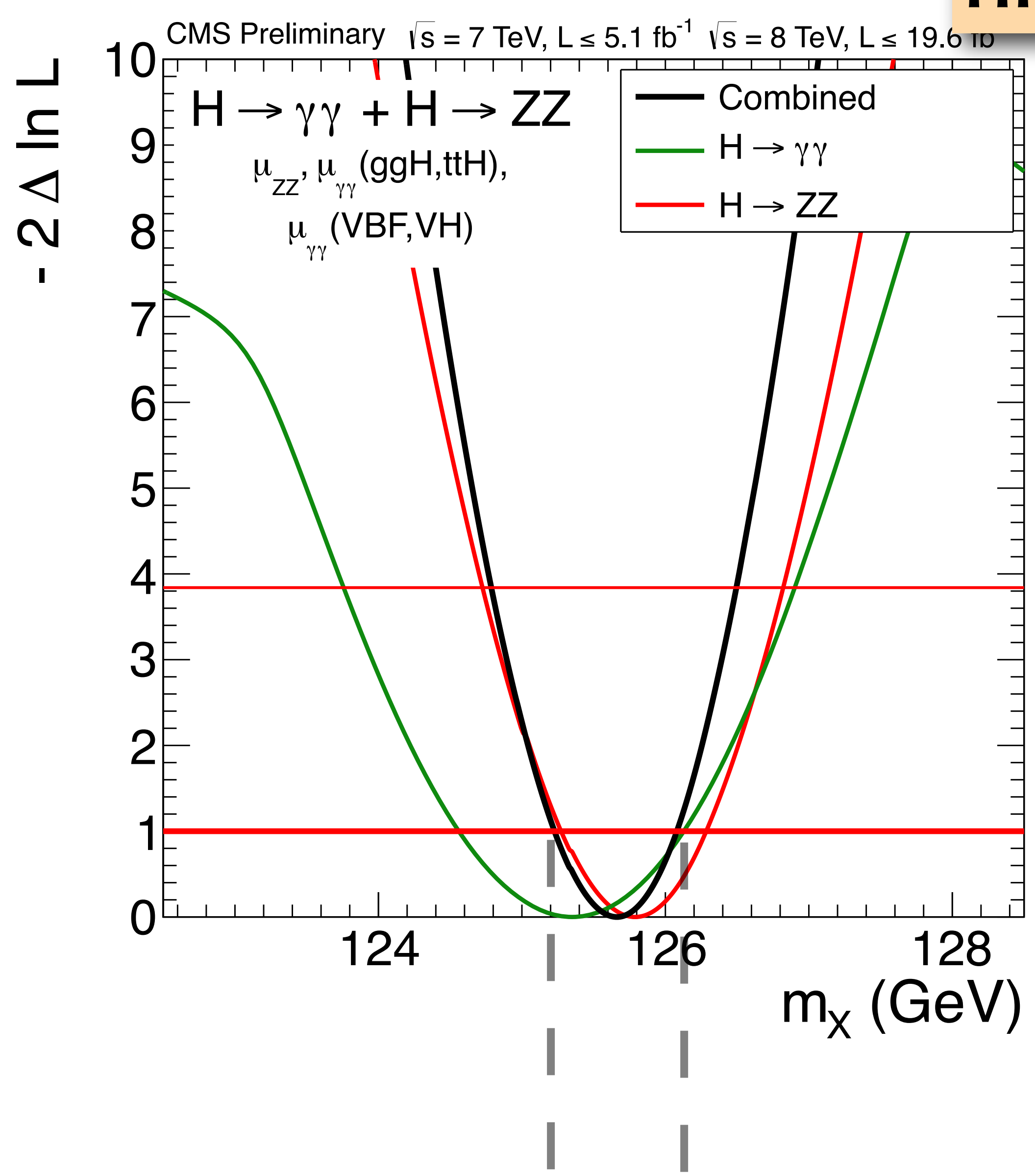
HIG-13-005

use the high resolution channel to measure the mass

- relative signal strength between γγ and ZZ constrained to the SM value
- Overall signal strength as free parameter



68% CL contour



m_X = 125.7± 0.4 GeV

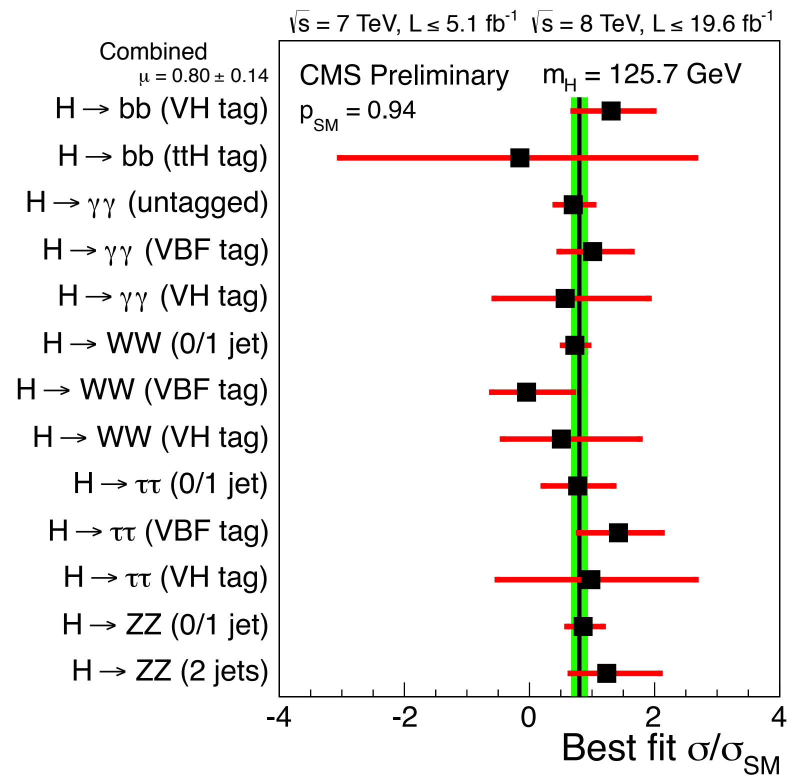
by scanning the test statistics the statistical uncertainty is evaluated to be 0.3

m_X = 125.7± 0.3 (stat) ± 0.3 (syst) GeV

Signal strength

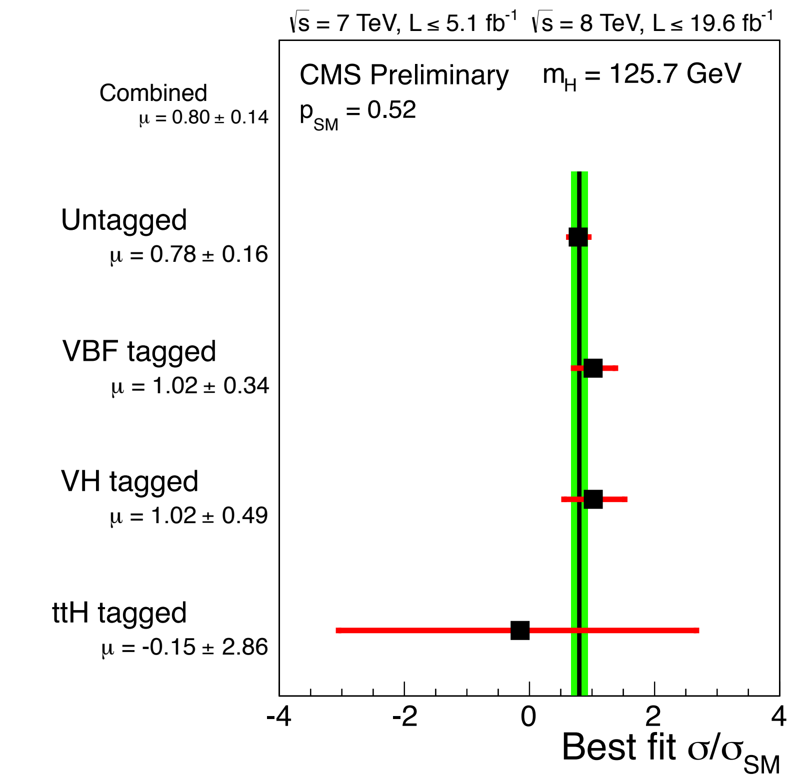
combination

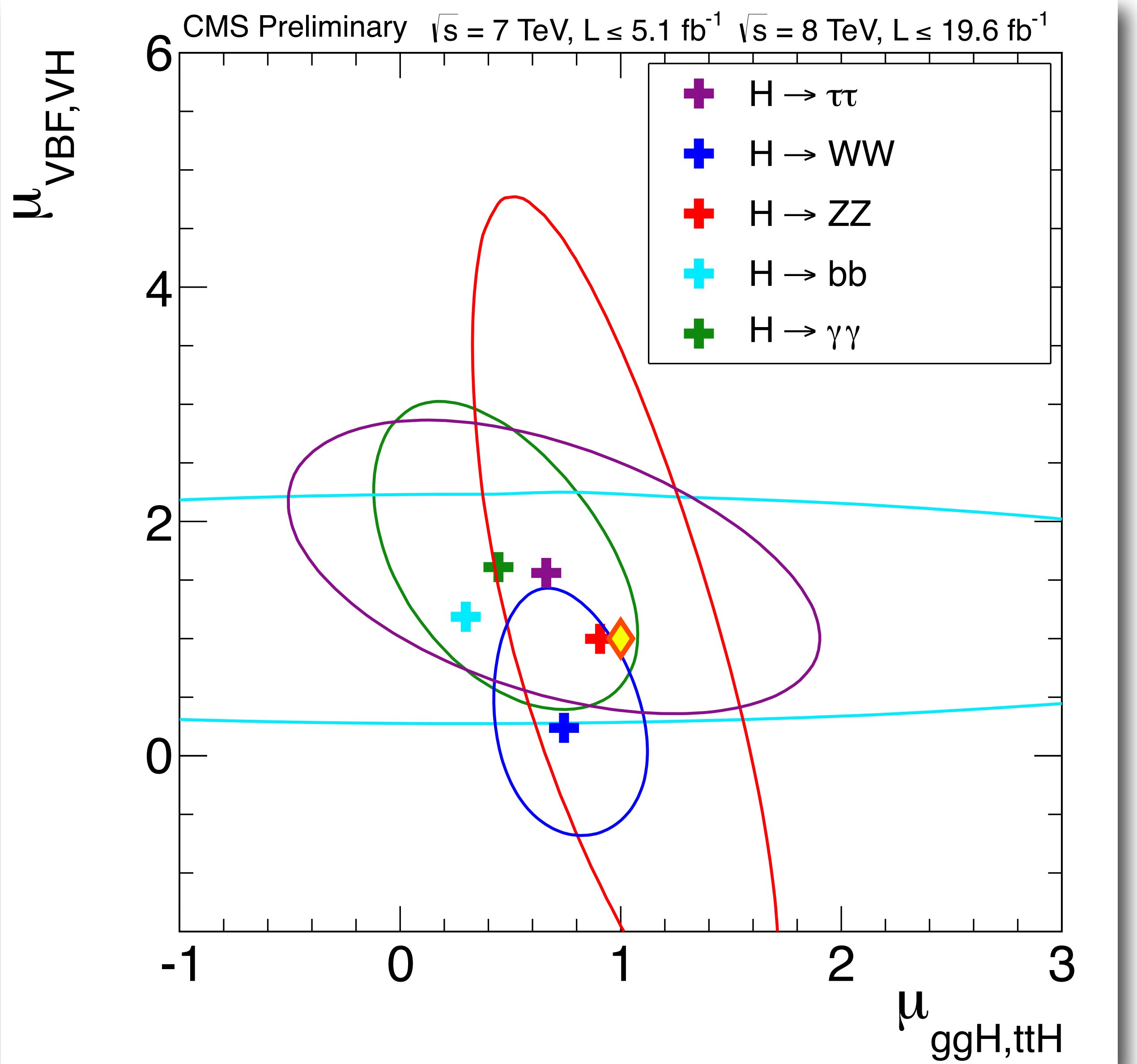
HIG-13-005



at m_X = 125.7 GeV

μ = 0.80 ± 0.14





Couplings

combination

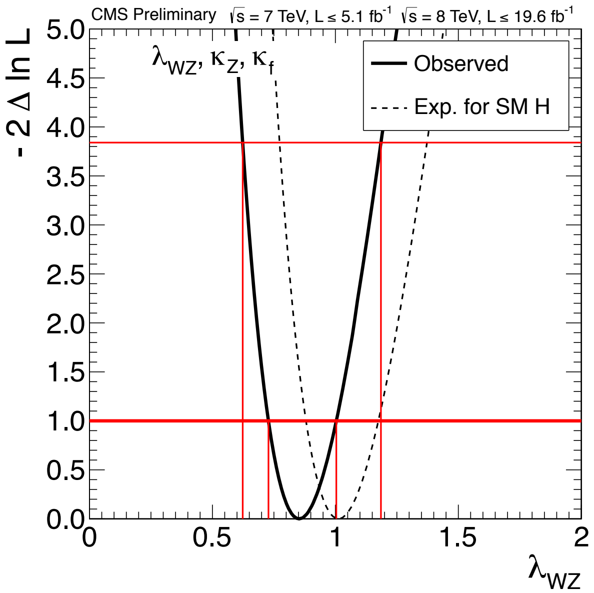
HIG-13-005

$$(\sigma \cdot \mathrm{BR})\,(x \to \mathrm{H} \to ff) = \frac{\sigma_x \cdot \Gamma_{ff}}{\Gamma_{\mathrm{tot}}}$$

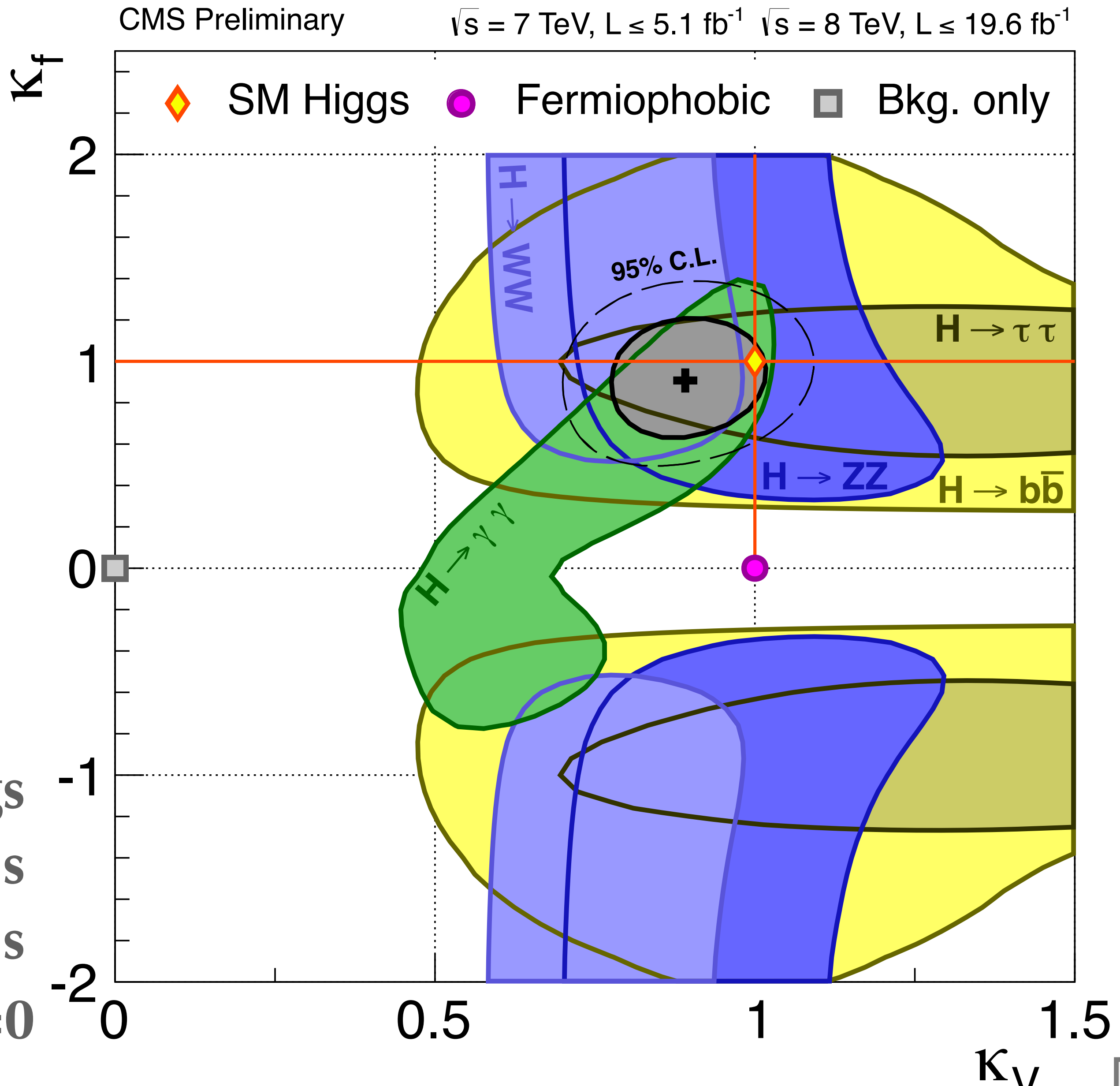
$$\Gamma_{\mathrm{tot}} = \sum \Gamma_{ii} + \Gamma_{\mathrm{BSM}}$$

Mass is fixed to 125.7 GeV

- Test of custodial symmetry $\lambda_{WZ} = \kappa_W / \kappa_Z$



in the following tests, we assume $\lambda_{WZ} = 1$



- Test of couplings to fermions and bosons

assumptions: $\Gamma_{\mathrm{BSM}} = 0$

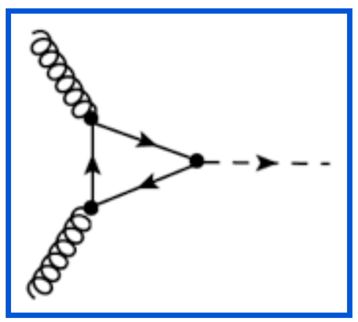
BSM particles and coupling to fermions

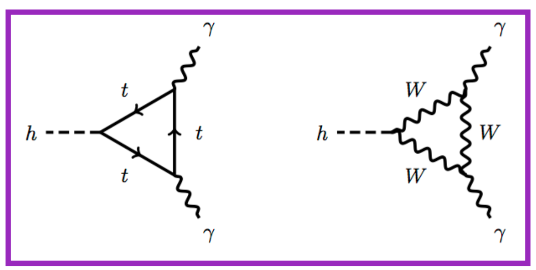
combination

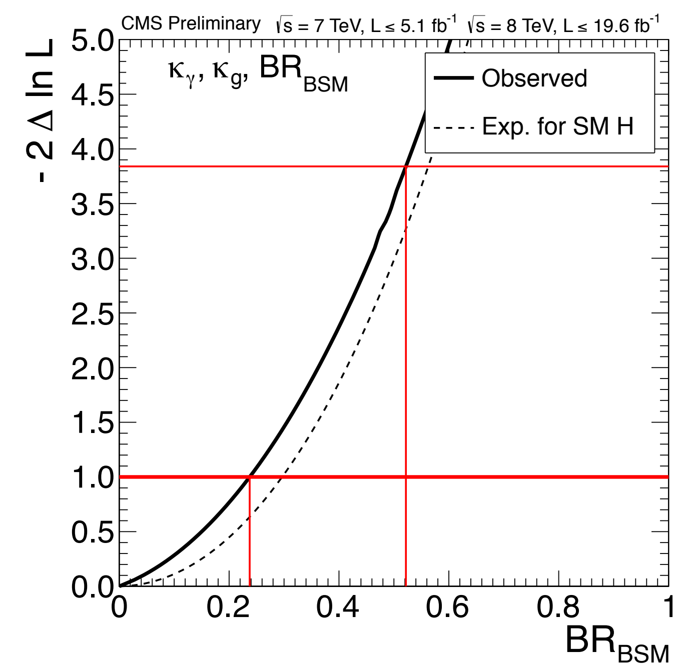
HIG-13-005

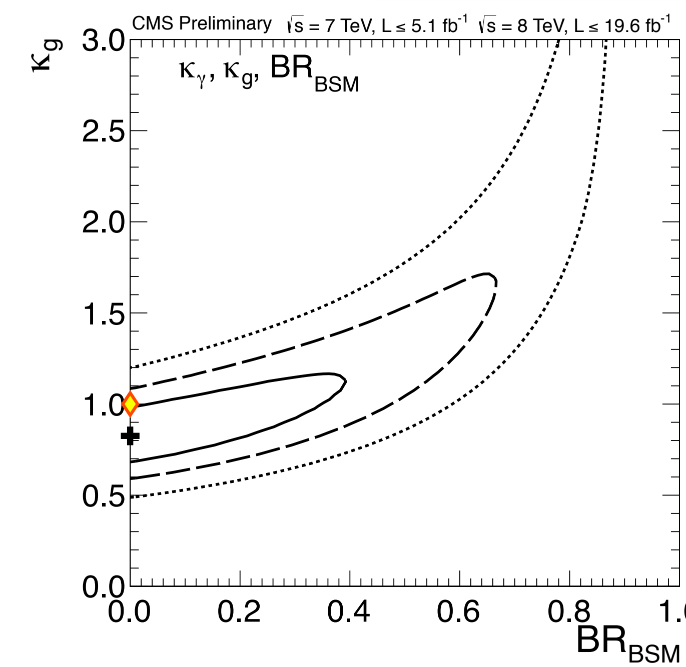
presence of BSM particles

$H \to \gamma\gamma$ decay and **$gg \to H$** production are sensitive to the presence to new particles which couple with H









$$(\kappa_\gamma, \kappa_g) = (0.97, 0.83)$$

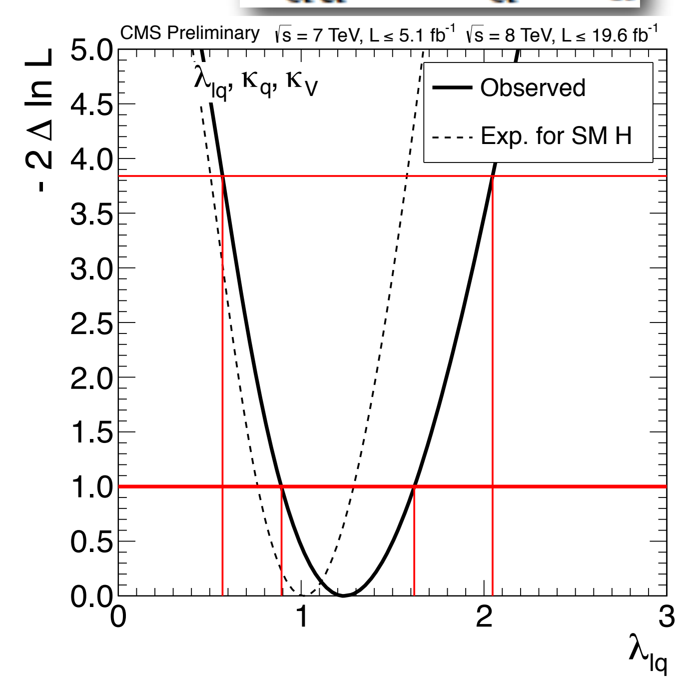
test for asymmetries in the couplings to fermions

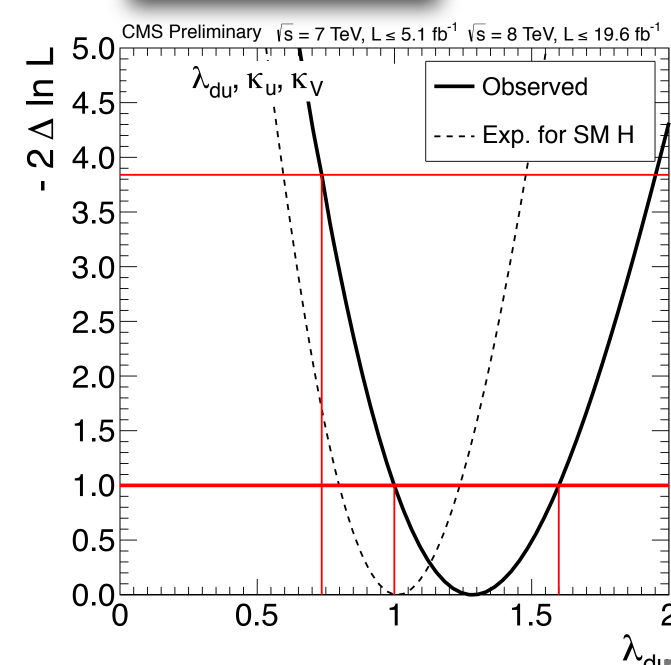
$$\lambda_{du} = \kappa_d / \kappa_u$$

$$\lambda_{\ell q} = \kappa_\ell / \kappa_q$$

in models with 2 Higgs doublets (2HDM)

the coupling of the neutral boson to fermions can be different w.r.t. the Yukawa couplings in the SM



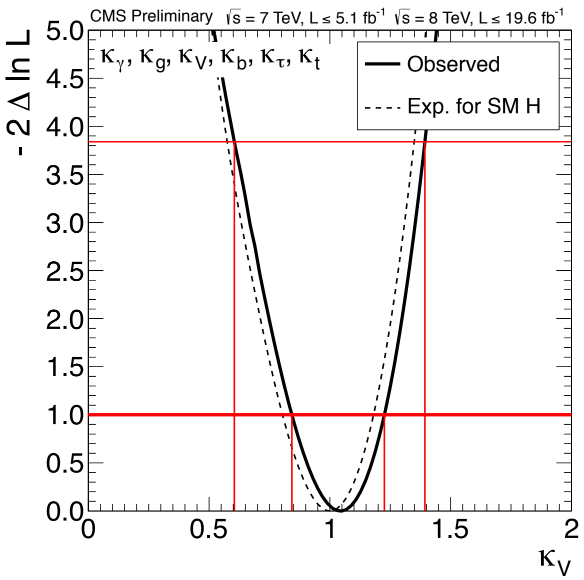


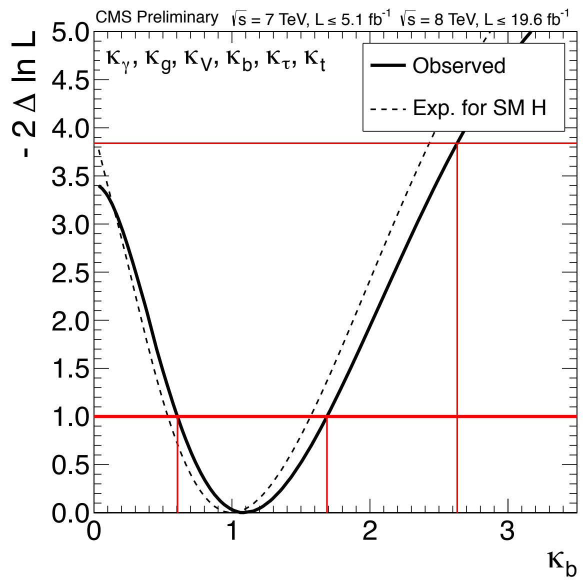
Independent couplings

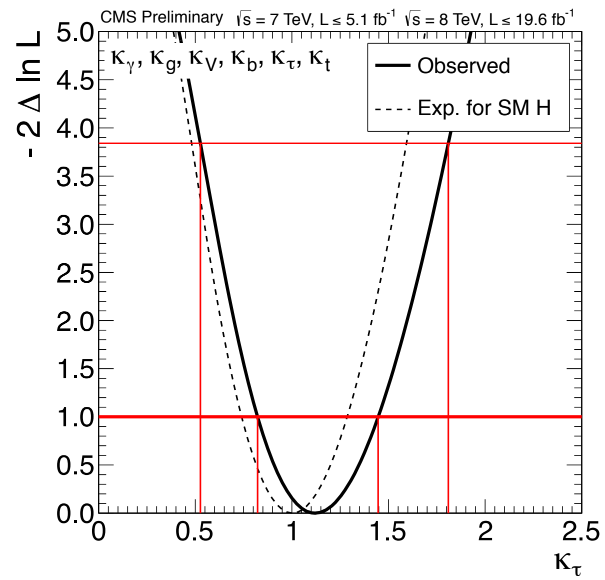
combination

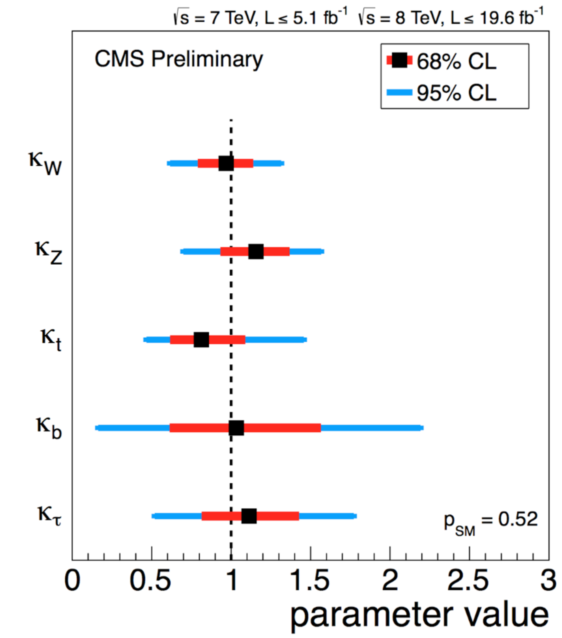
HIG-13-005

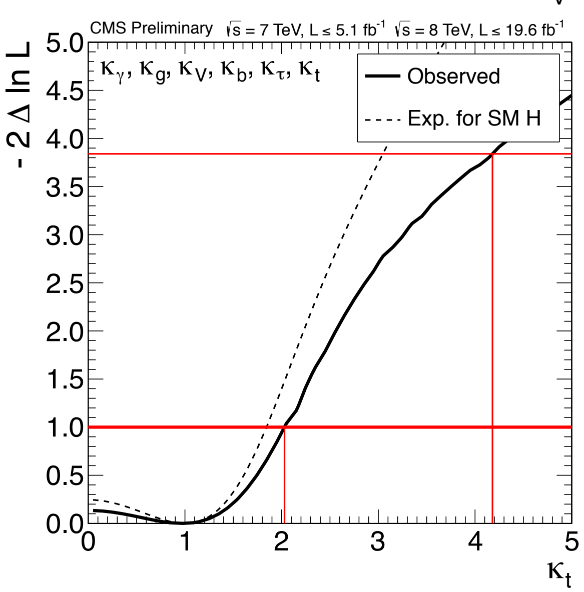
- test of model with 6 independent couplings assuming $\Gamma_{BSM} = 0$

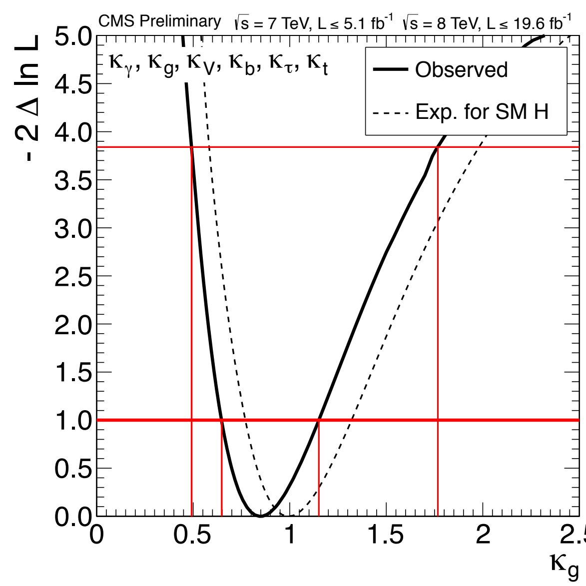


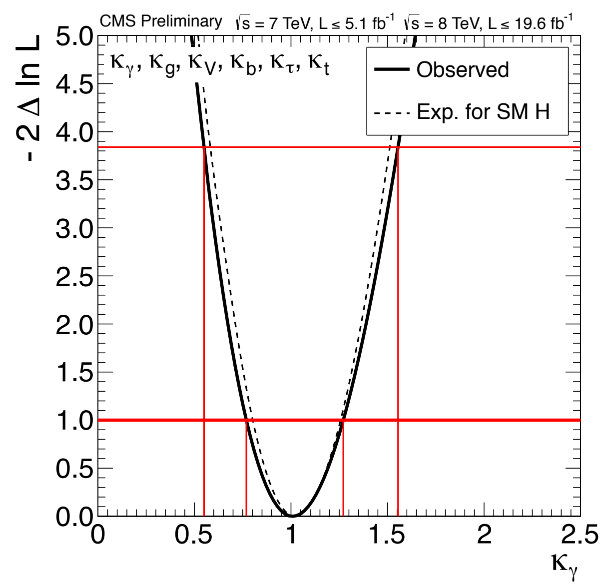


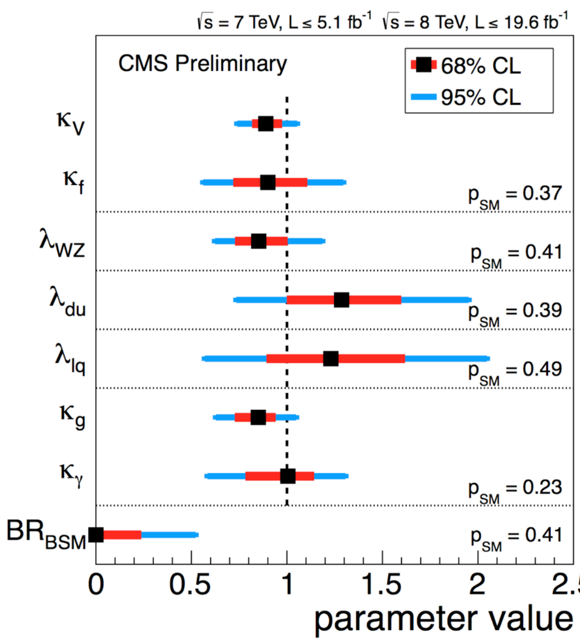




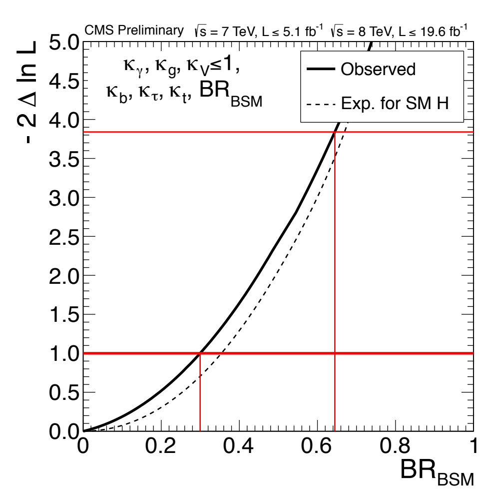








- constraints on Γ_{BSM} assuming $\kappa_V \leq 1$



everything is compatible with the SM

Spin: combination of ZZ and WW

$J^P = 0^+$ and $2^+_{\rm m}(gg)$ signal hypotheses

$$q = -2\ln(\mathcal{L}_{2^+_{\rm m}(gg)+{\rm bkg.}} / \mathcal{L}_{0^+ + {\rm bkg.}})$$

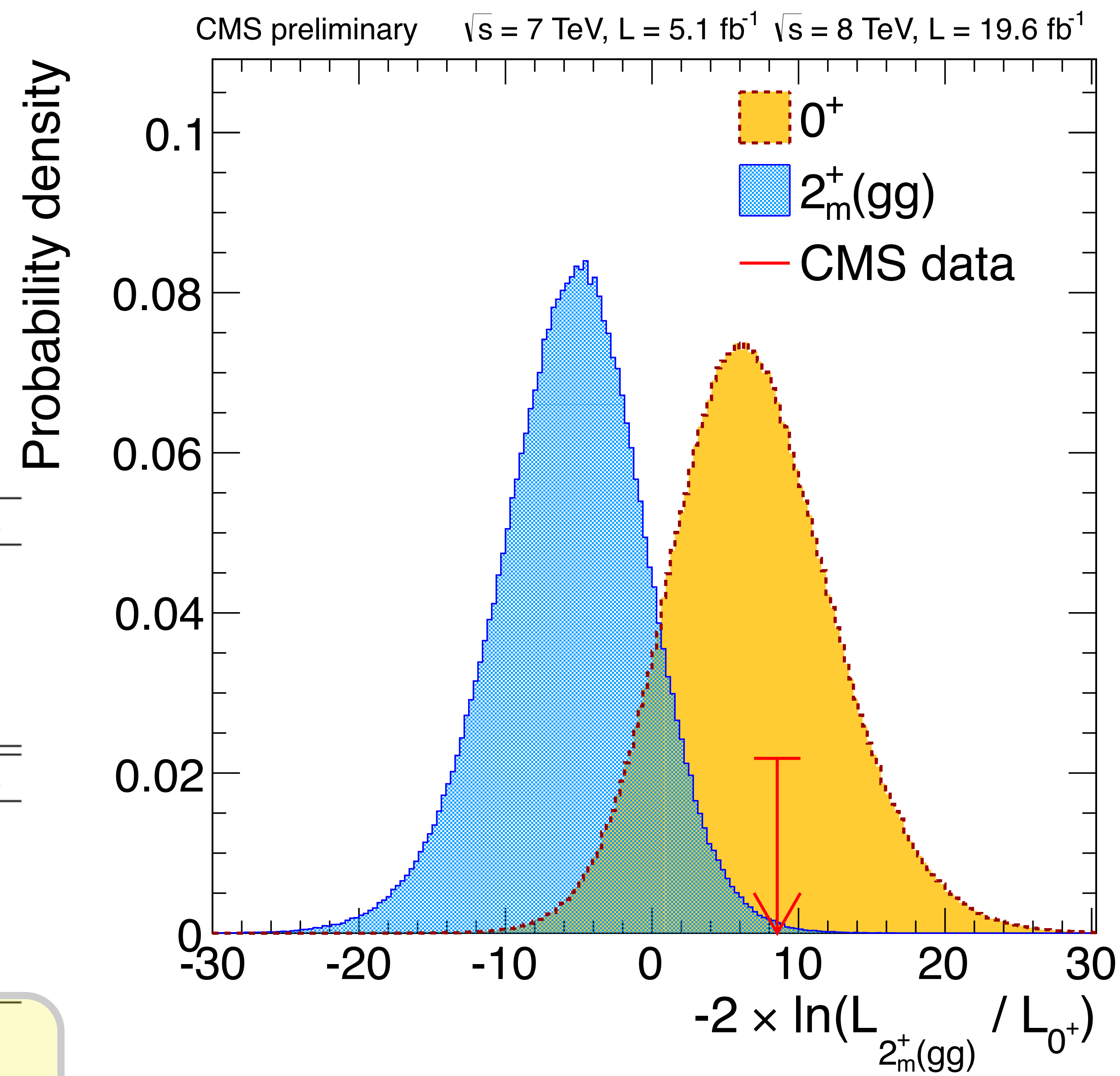
$$CL_s^{obs.} = P(q \geq q^{obs.} \mid 2^+_{\rm m}(gg)) / P(q \geq q^{obs.} \mid 0^+)$$

$$CL_s^{exp.} = P(q \geq q^{exp.}_{0^+} \mid 2^+_{\rm m}(gg)) / 0.5$$

test performed with:

- **SM signal strength**
- **measured signal strength**

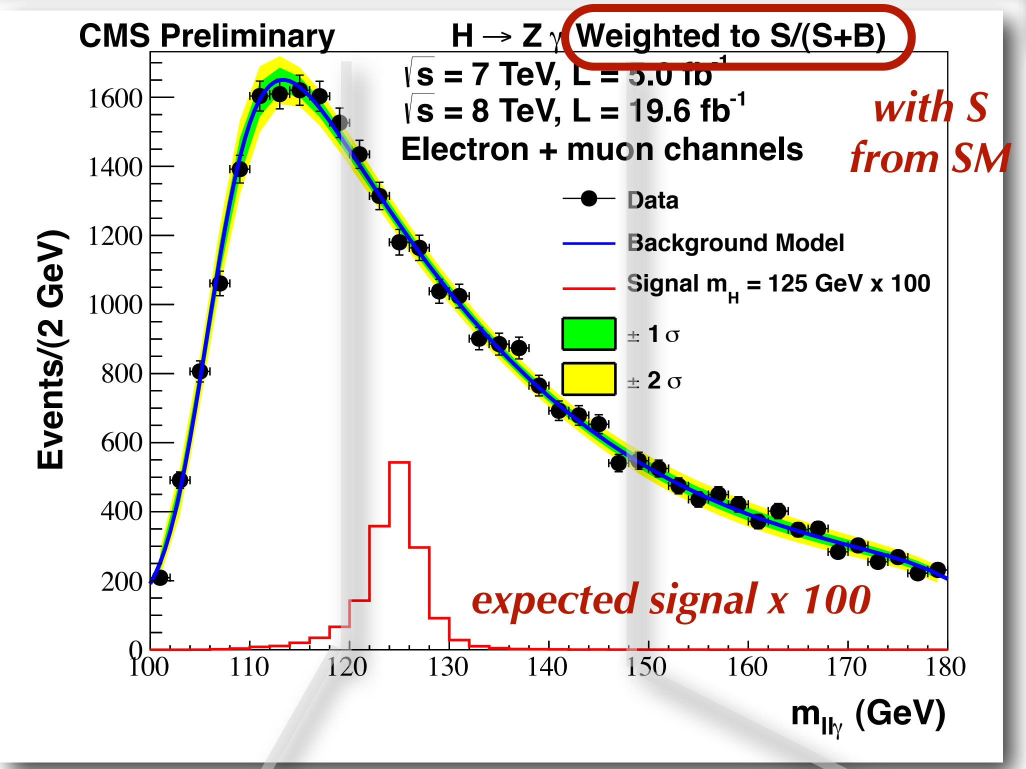
Pre-fit model ($\mu_i = 1$)	$ZZ \to 4\ell$	$WW \to \ell\nu\ell\nu$	Combined
Separation	81.6%	87.1%	92.4%
$P(q \leq q^{exp.}_{2^+_{\rm m}(gg)} \mid 0^+)$	1.8σ	1.9σ	2.6σ
$P(q \geq q^{exp.}_{0^+} \mid 2^+_{\rm m}(gg))$	1.8σ	2.5σ	3.0σ
$1 - CL_s^{exp.}$	93.2%	98.6%	99.8%
Post-fit model (μ_i profiled)	$ZZ \to 4\ell$	$WW \to \ell\nu\ell\nu$	Combined
Separation	80.7%	80.9%	88.8%
$P(q \leq q^{exp.}_{2^+_{\rm m}(gg)} \mid 0^+)$	1.6σ	1.6σ	2.3σ
$P(q \geq q^{exp.}_{0^+} \mid 2^+_{\rm m}(gg))$	1.8σ	1.7σ	2.5σ
$1 - CL_s^{exp.}$	93.1%	91.9%	98.8%
$P(q \leq q^{obs.} \mid 0^+)$	-0.90σ	0.44σ	-0.34σ
$P(q \geq q^{obs.} \mid 2^+_{\rm m}(gg))$	2.81σ	1.32σ	2.84σ
$1 - CL_s^{obs.}$	98.6%	86.0%	99.4%

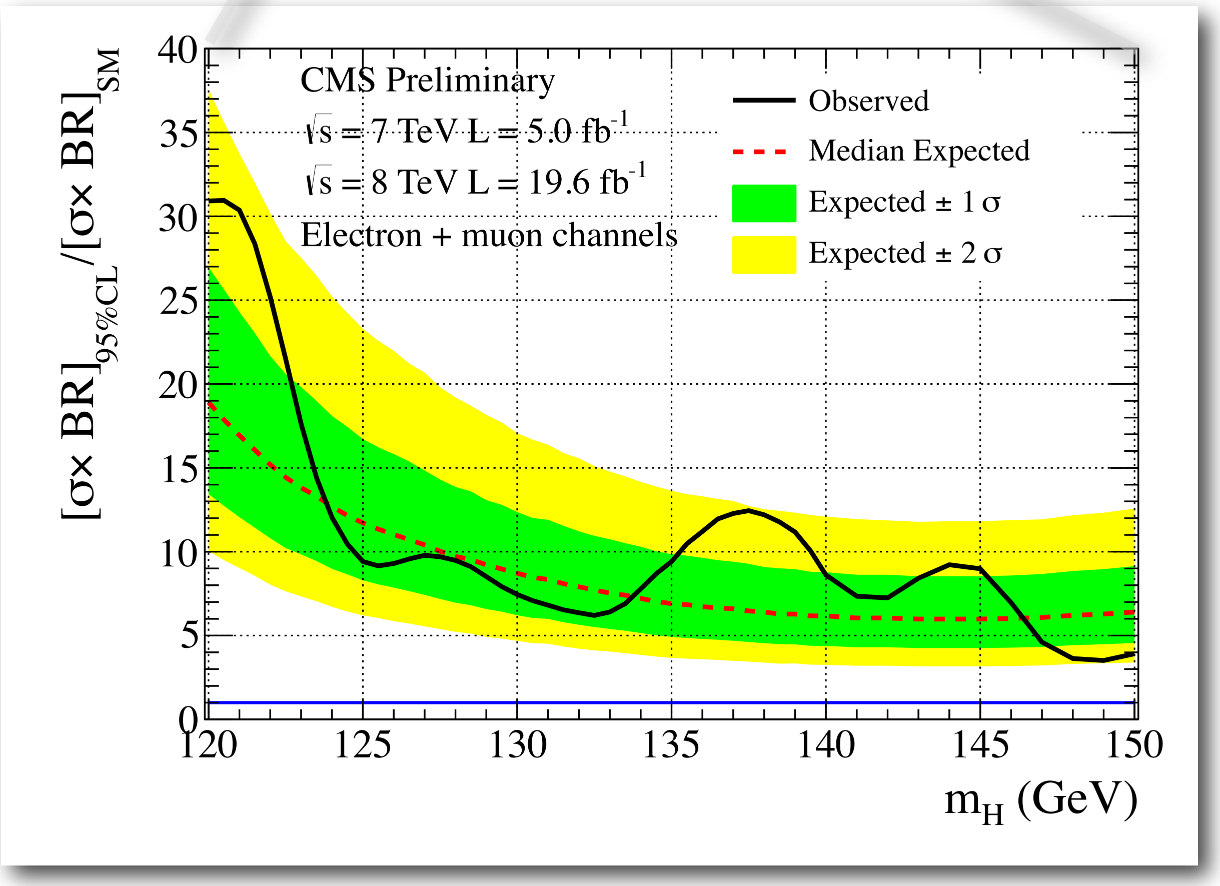


$2^+_{\rm m}(gg)$ **is disfavored by the data with a CL_s= 0.60%**

H→Zγ

For some models the BR(H→Zγ) and BR (H→γγ) are not correlated, so a combined analysis of the two decay modes can give information on new physics





main systematics (apart the theo sys):

- event class migration
- signal scale and resolution

		at m_H=125 GeV
expected	6÷19 × SM	12 × SM
observed	3÷31 × SM	9 × SM

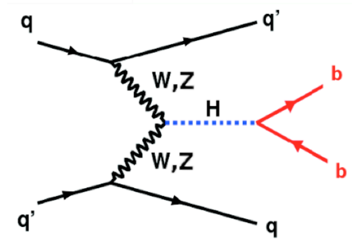
VBF and VH production, with H→bb

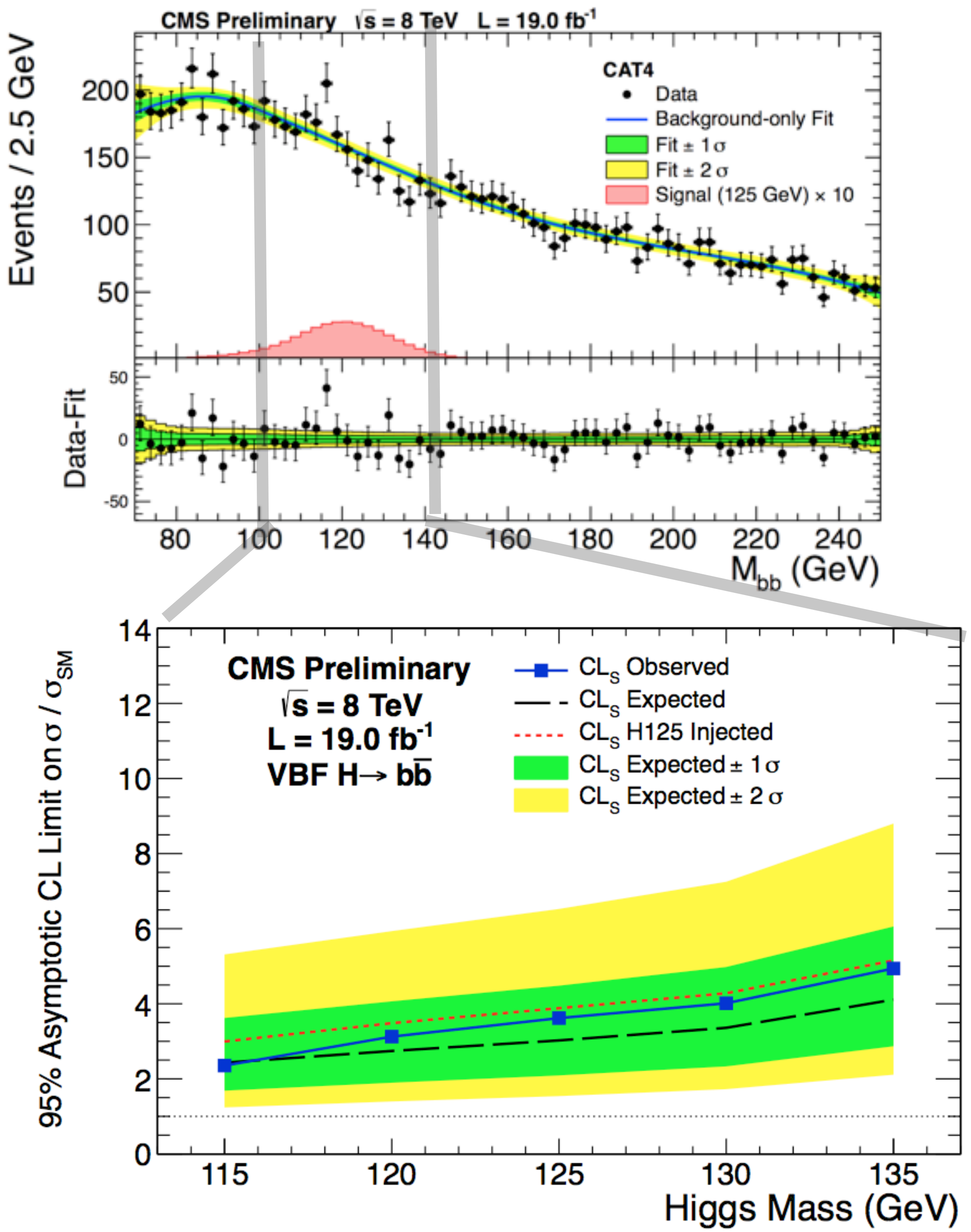
NEW

H→bb

HIG-13-011

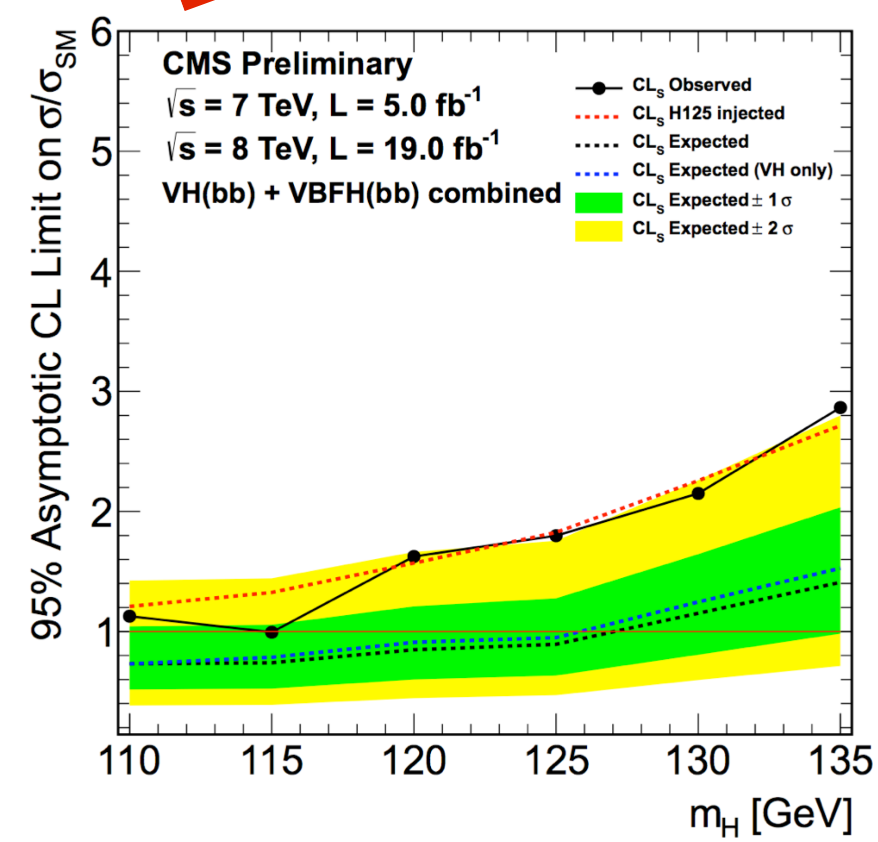
VBF

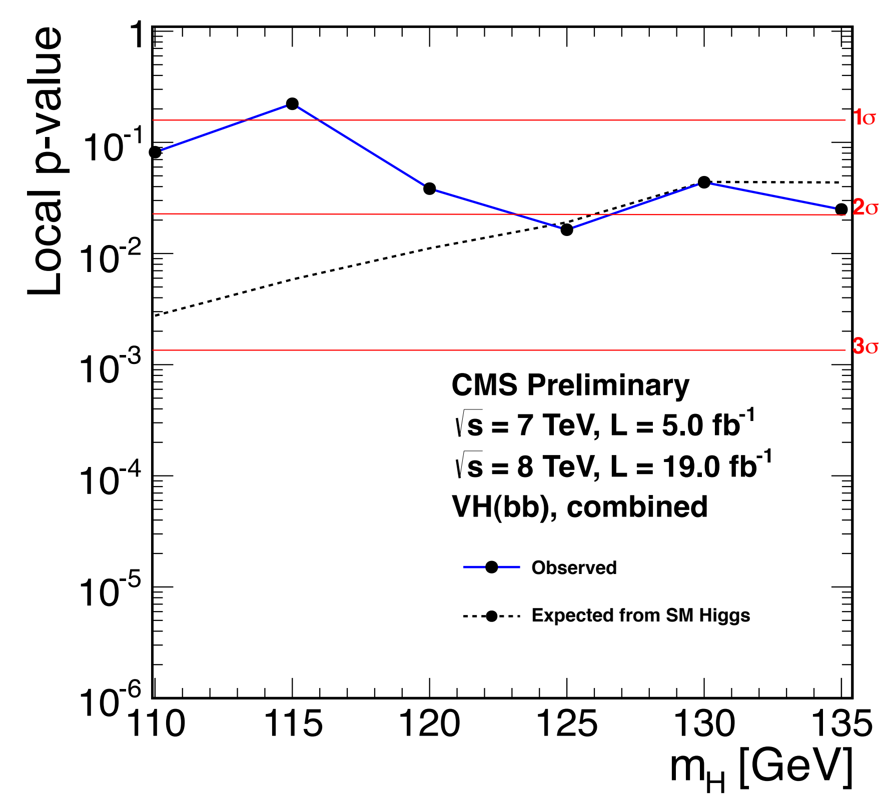




HIG-13-012

VH

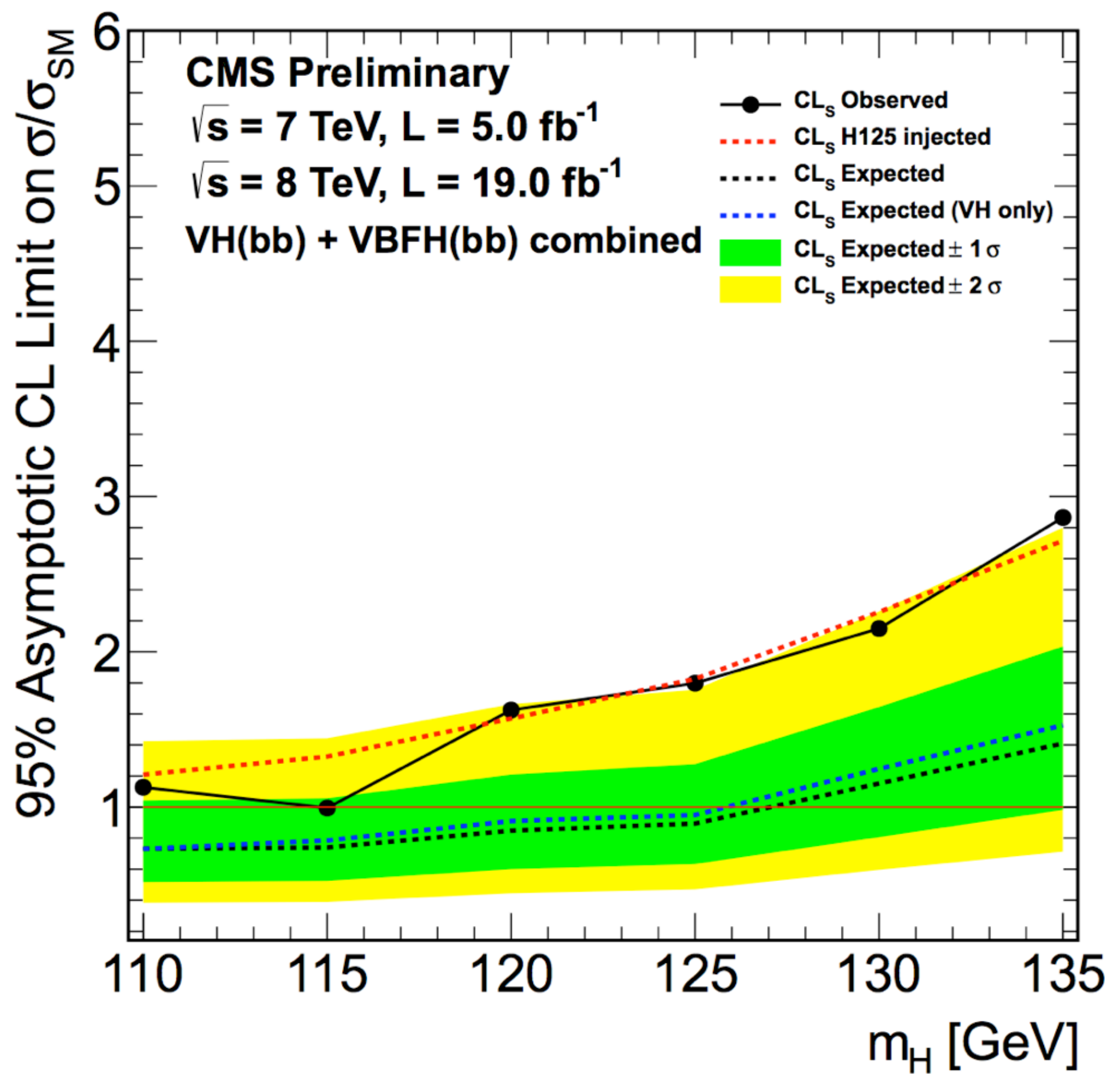


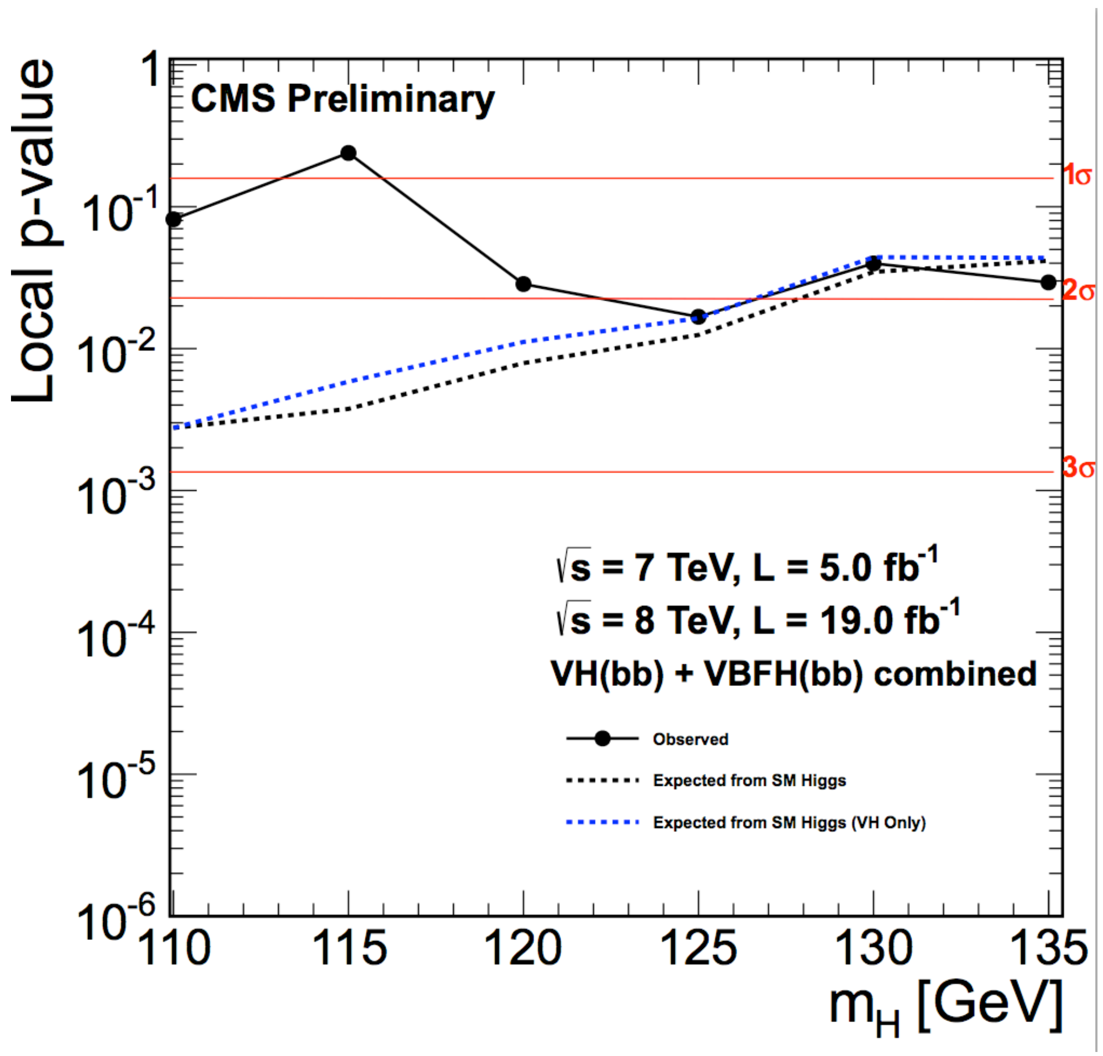


Combination of VH and VBF

VERY NEW!

H→bb





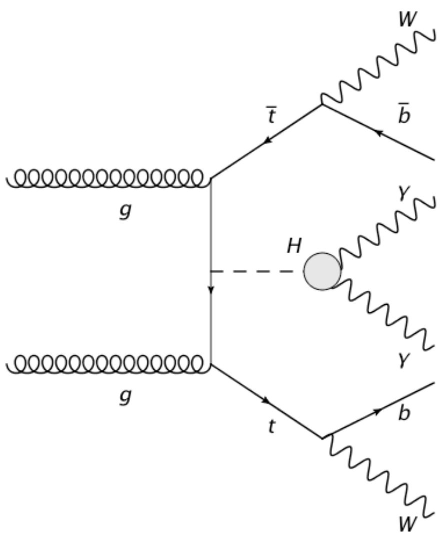
95% CL limit observed (expected) at 125 GeV: 1.79 (0.89)
Significance observed (expected) at 125 GeV : 2.1σ (2.2σ)
Signal strength at 125 GeV: μ= 0.97±0.48

ttH with H→γγ

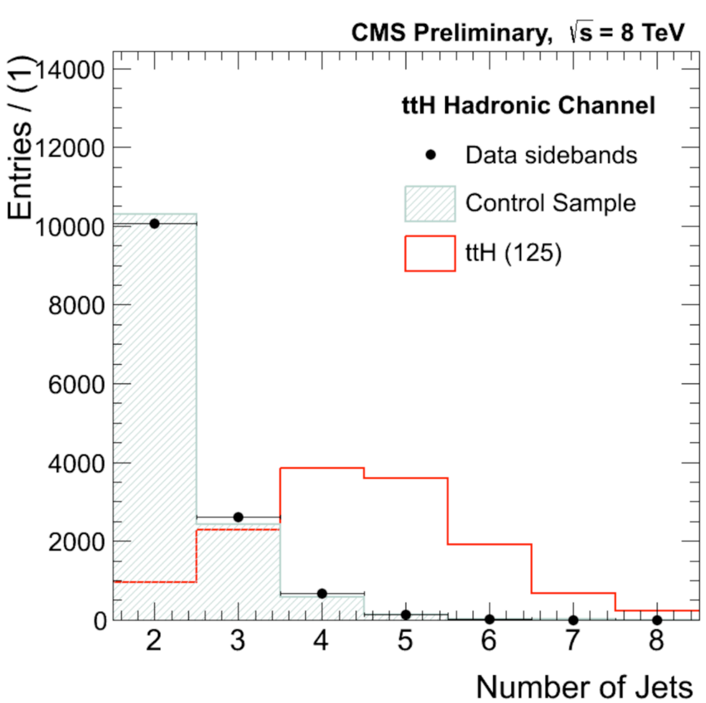
NEW

H→γγ

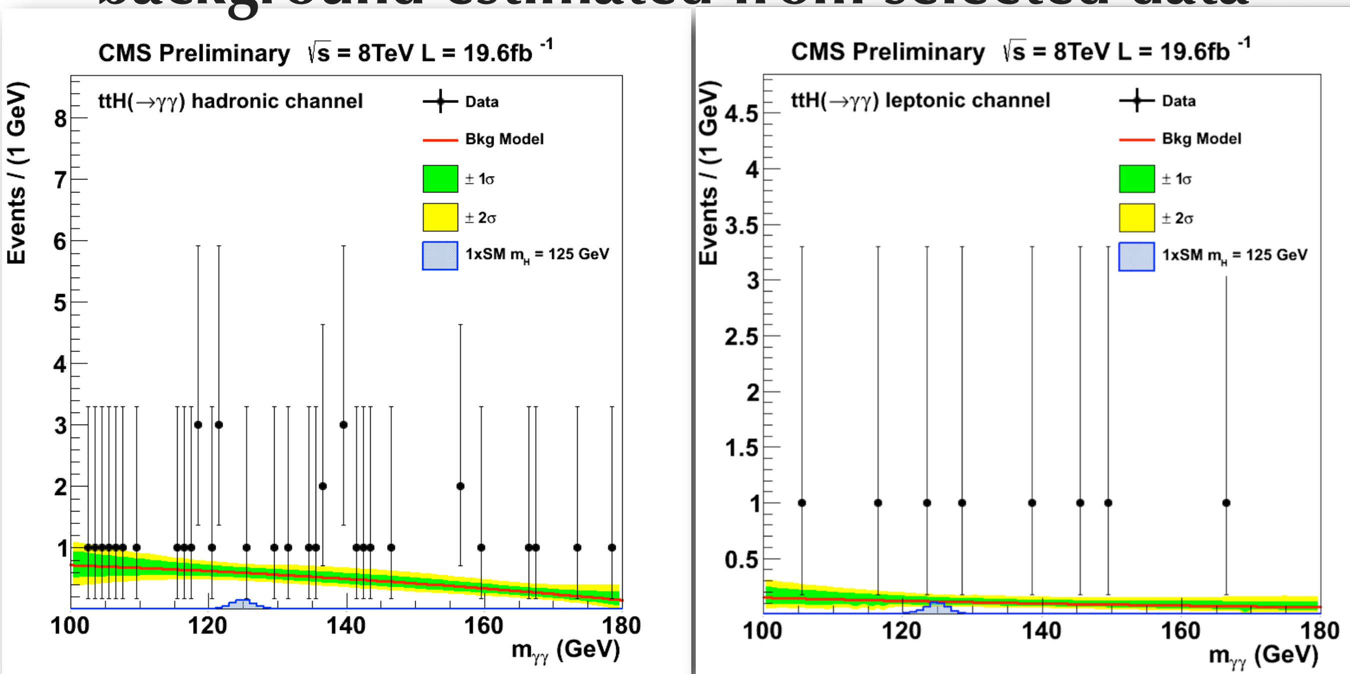
HIG-13-015



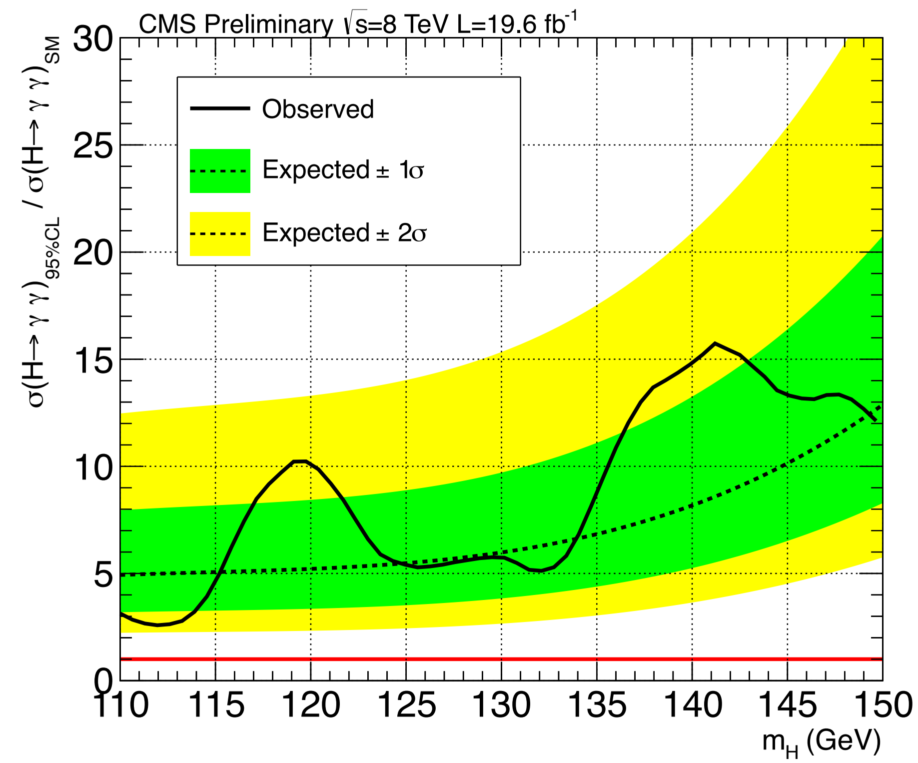
understanding
the bkg by using
a control sample



background estimated from selected data



**combine
semileptonic
and fully hadronic
ttbar decays**

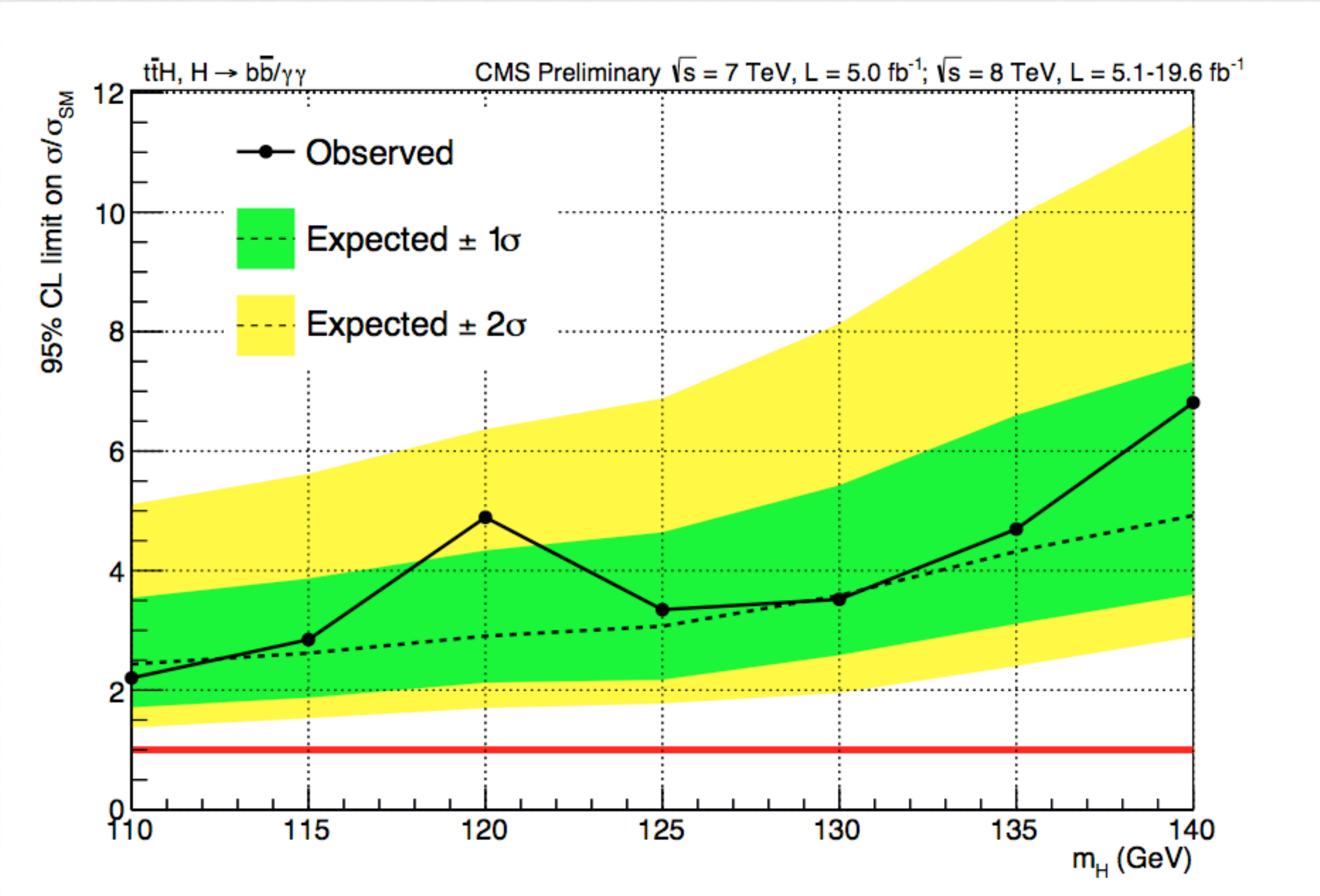


ttH, combination of H→bb and H→γγ

H→γγ

H→bb

very NEW



Higgs Mass	Observed	Expected Median	Expected 68% C.L. Range	Expected 95% C.L. Range
110 GeV/c^2	2.2	2.4	[1.7,3.5]	[1.4,5.1]
115 GeV/c^2	2.8	2.6	[1.9,3.9]	[1.5,5.6]
120 GeV/c^2	4.9	2.9	[2.1,4.3]	[1.7,6.4]
125 GeV/c^2	3.3	3.1	[2.2,4.6]	[1.8,6.9]
130 GeV/c^2	3.5	3.6	[2.6,5.4]	[2.0,8.1]
135 GeV/c^2	4.7	4.3	[3.1,6.6]	[2.4,9.9]
140 GeV/c^2	6.8	4.9	[3.6,7.5]	[2.9,11.5]

Spin with H→γγ

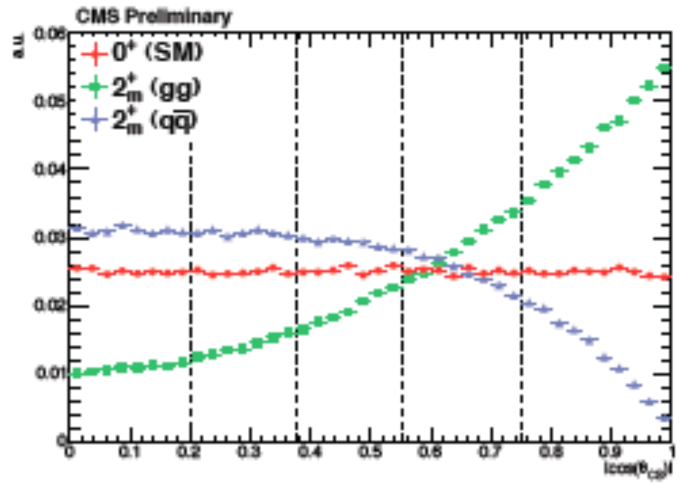
H→γγ

VERY NEW!

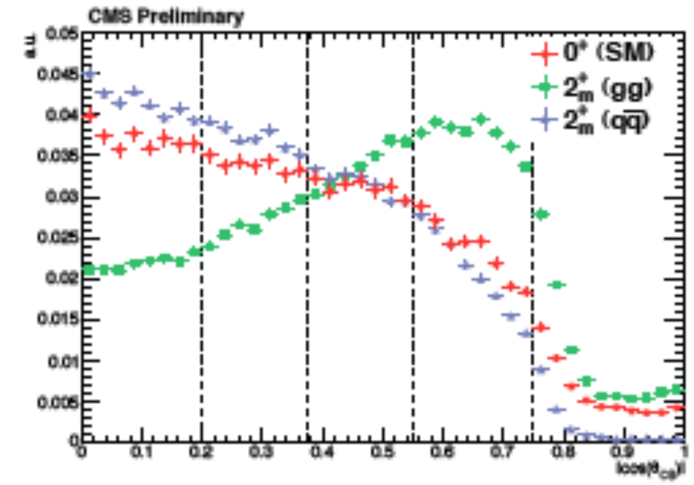
HIG-13-016

$$\cos(\theta^*_{CS}) = 2 \times \frac{E_2 p_{z1} - E_1 p_{z2}}{m_{\gamma\gamma}\sqrt{m^2_{\gamma\gamma} + p^2_{T\gamma\gamma}}}$$

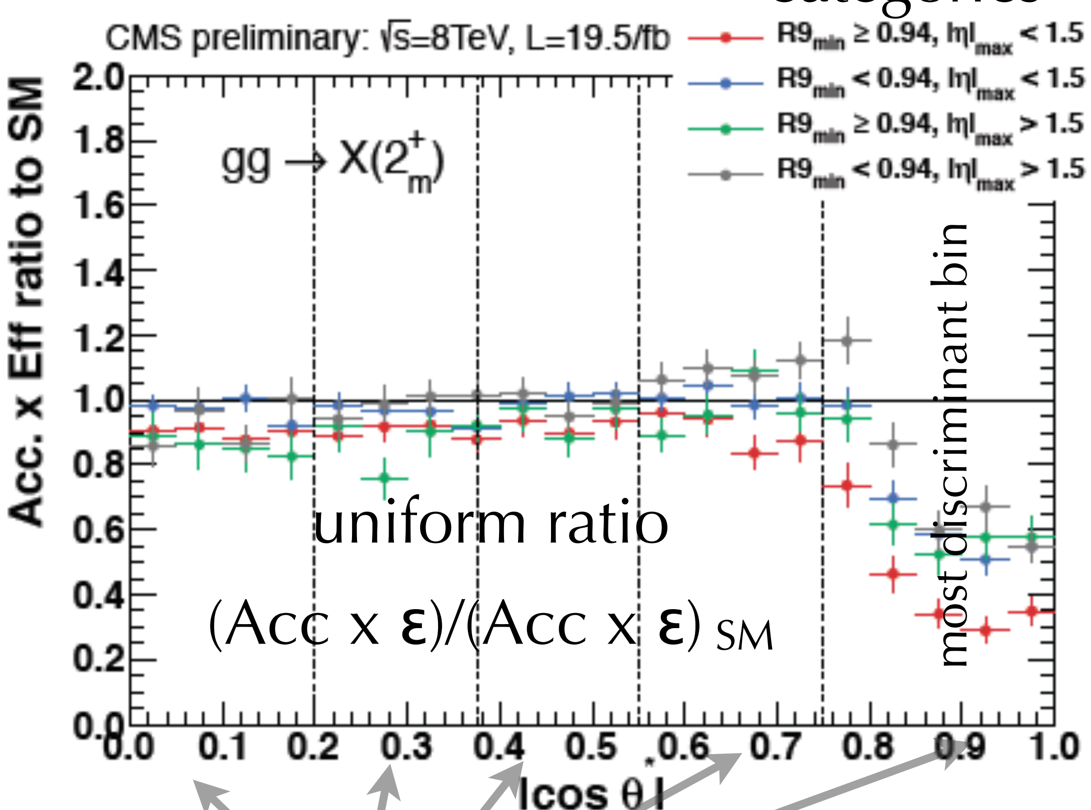
before cuts



after cuts



categories



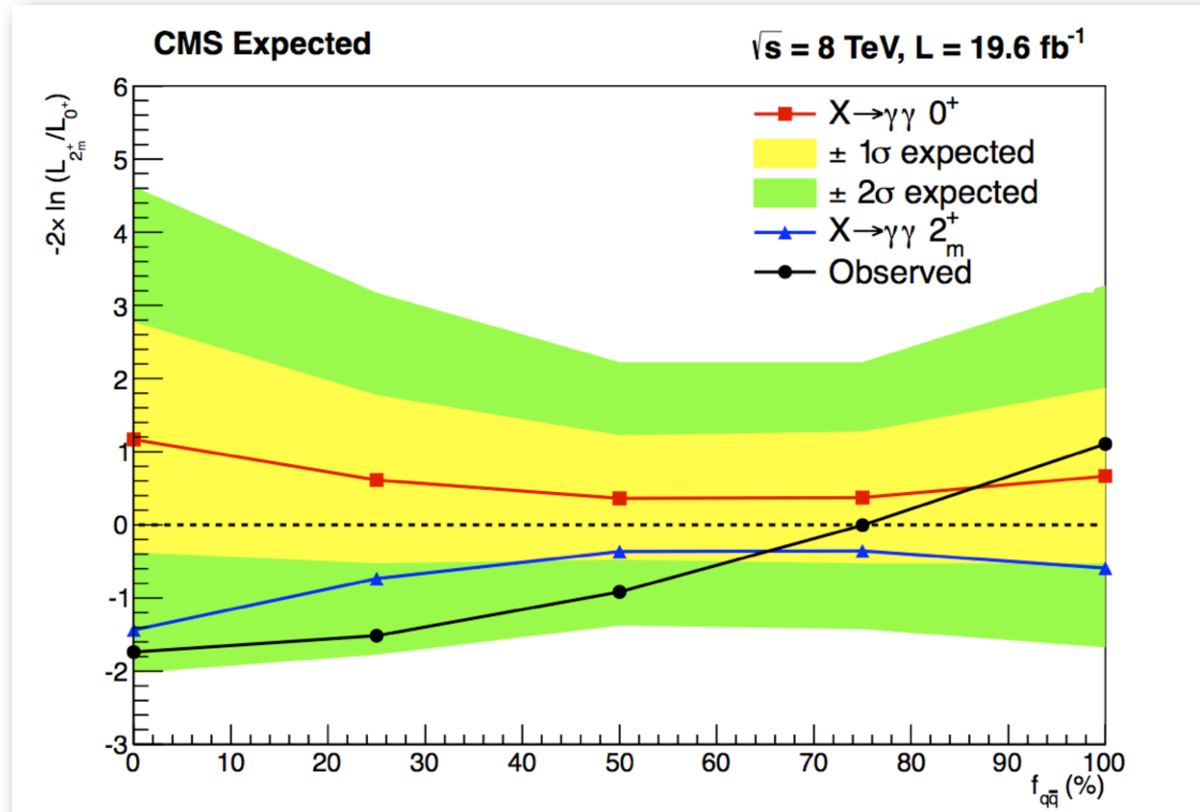
uniform ratio

(Acc x ε)/(Acc x ε) SM

most discriminant bin

4 x **5** categories

Barrel-endcap and converted/unconverted



The present γγ data does not have the power for a significant hypothesis test

Reinterpretation of H→γγ results

VERY NEW!

H→γγ

HIG-13-016

2HDM

high resolution of γγ

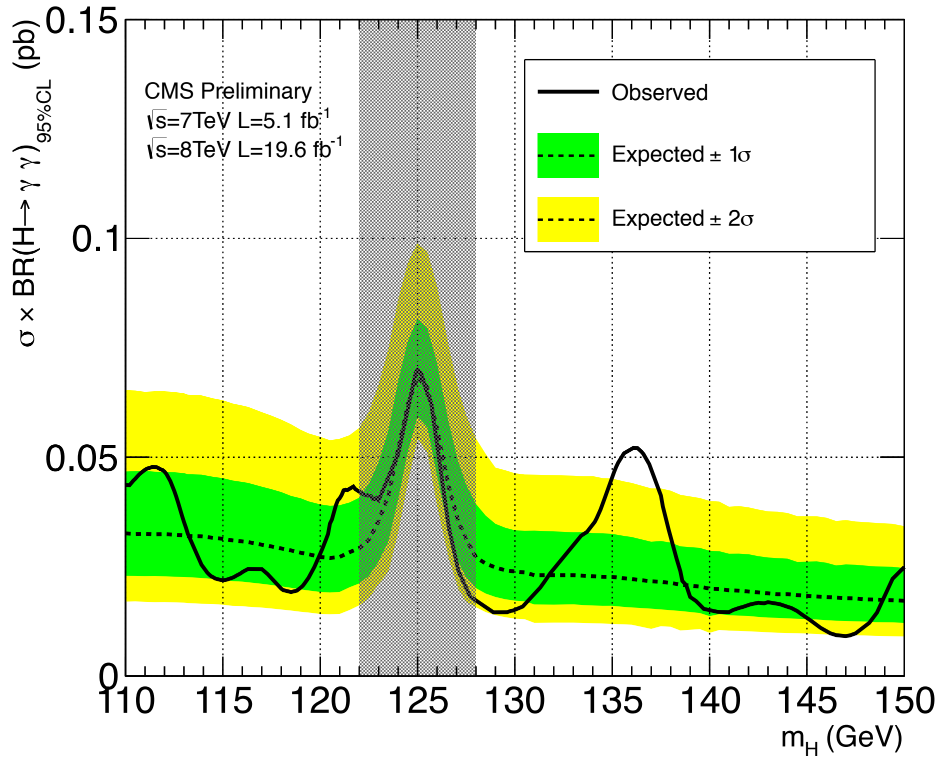
search for 2 near-degenerate states

$$m_{H2} = m_H + \Delta m$$

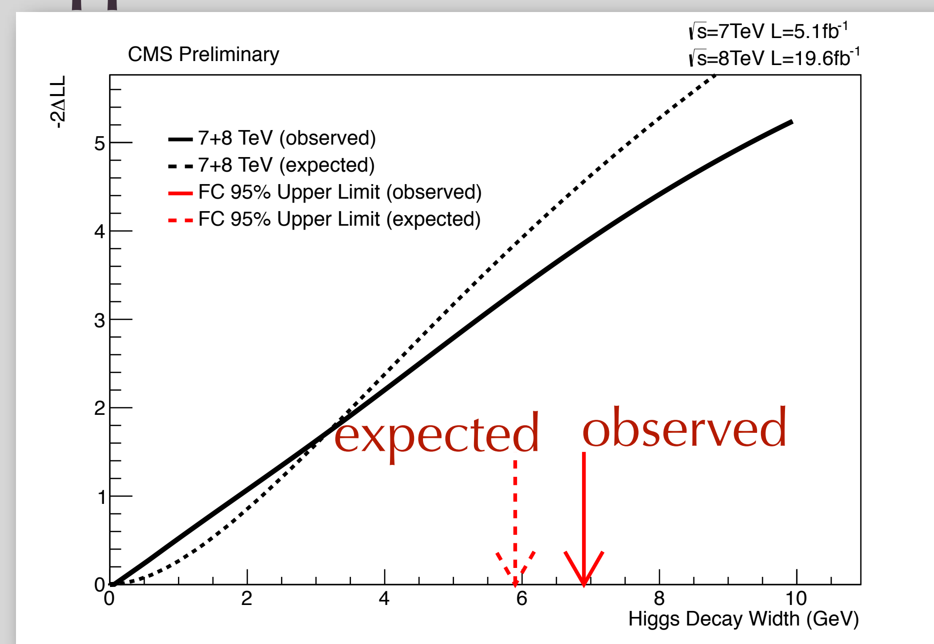
relative strength of the 2 signals:
x: fraction of the signal in the lower state
rx, r(1-x)

mH and r are profiled

125 GeV state is considered as a background

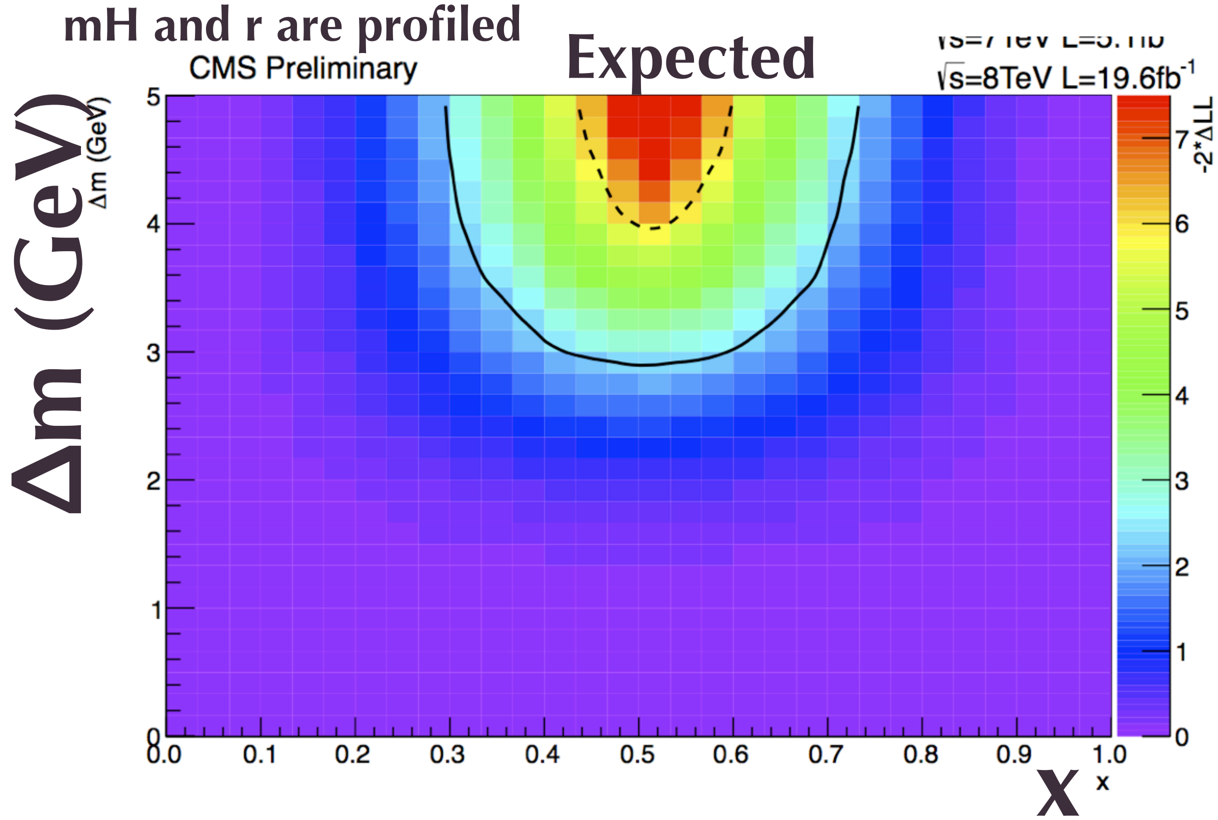


Upper limit to the natural width

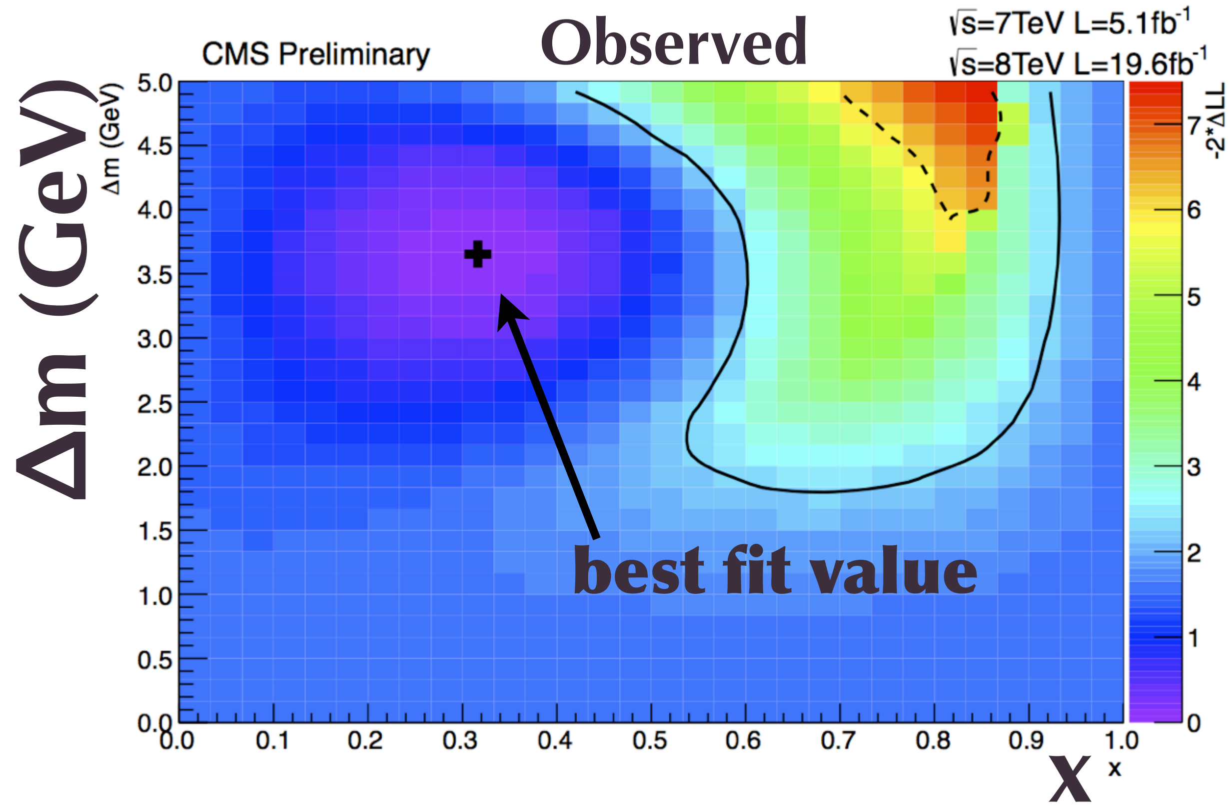


width < **5.9** **6.9** 95% CL

Expected



Observed

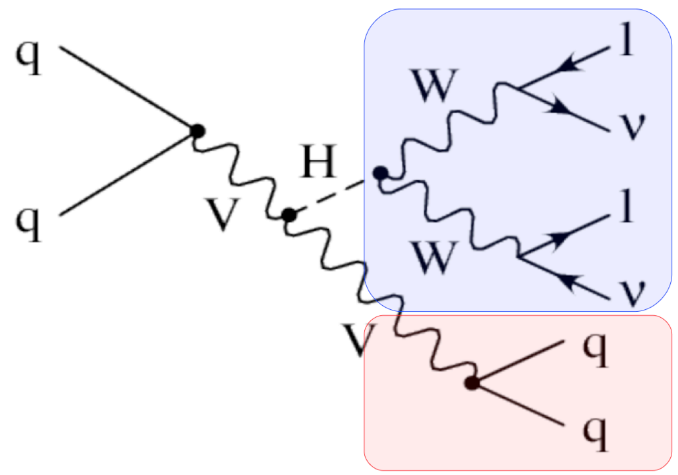


VH,H→WW, V→qq′

NEW

H→WW

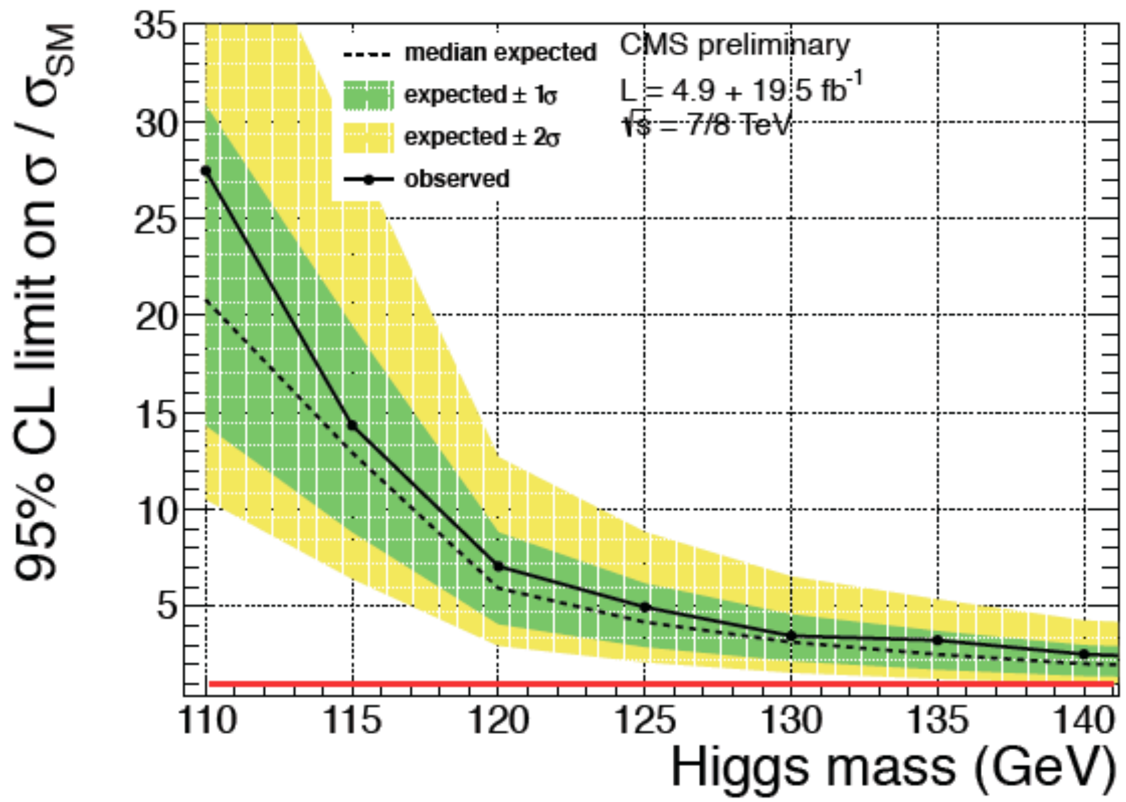
HIG-13-017

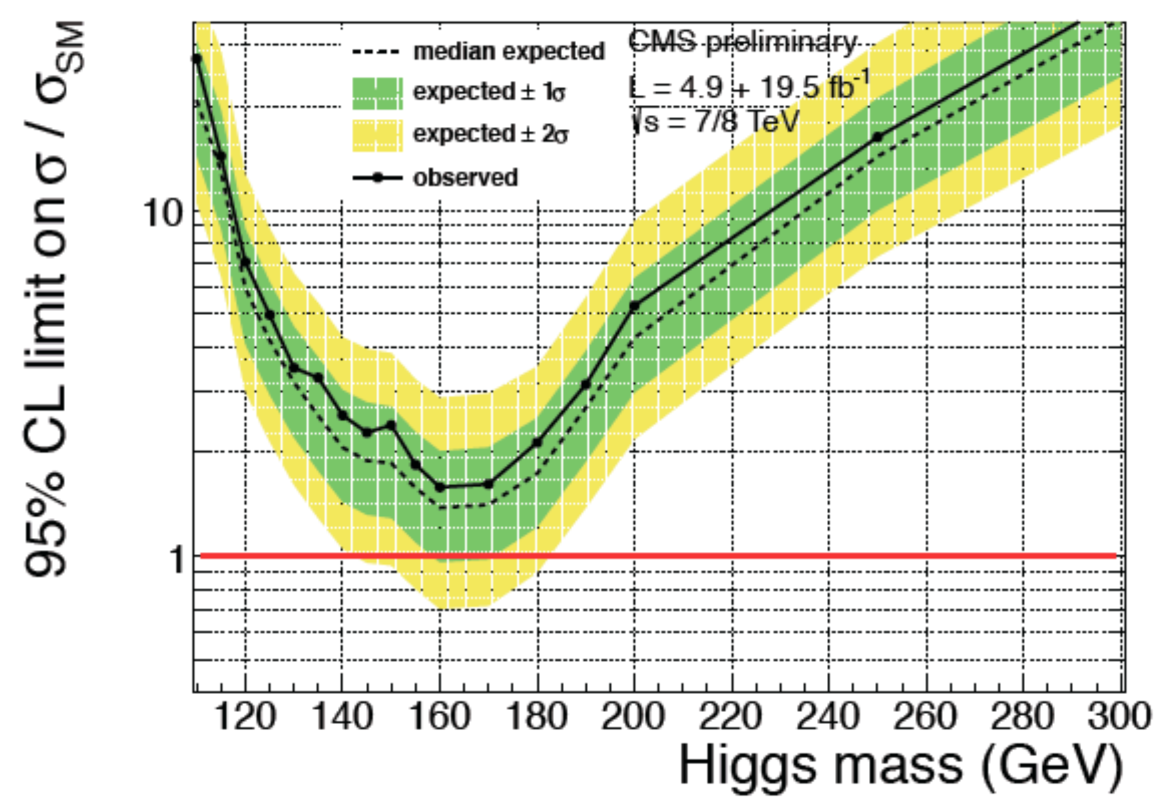


- WW analysis lepton cuts
- 2 jets:
  - |jet η|<2.5
  - 65<Mjj<105 GeV
  - Δηjj<1.5

7 TeV: cut and count

8 TeV: shape analysis





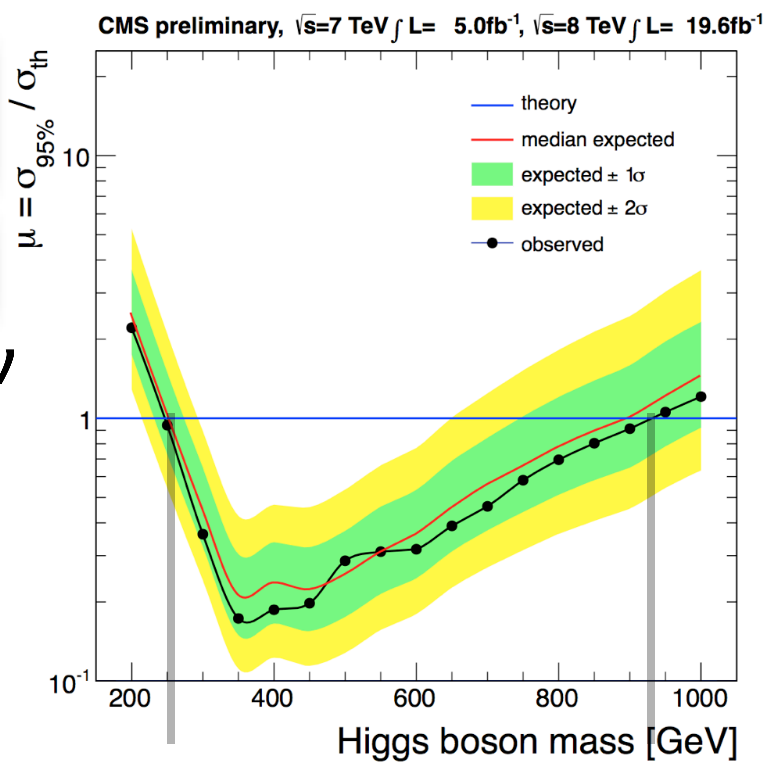
Searches for high mass Higgs

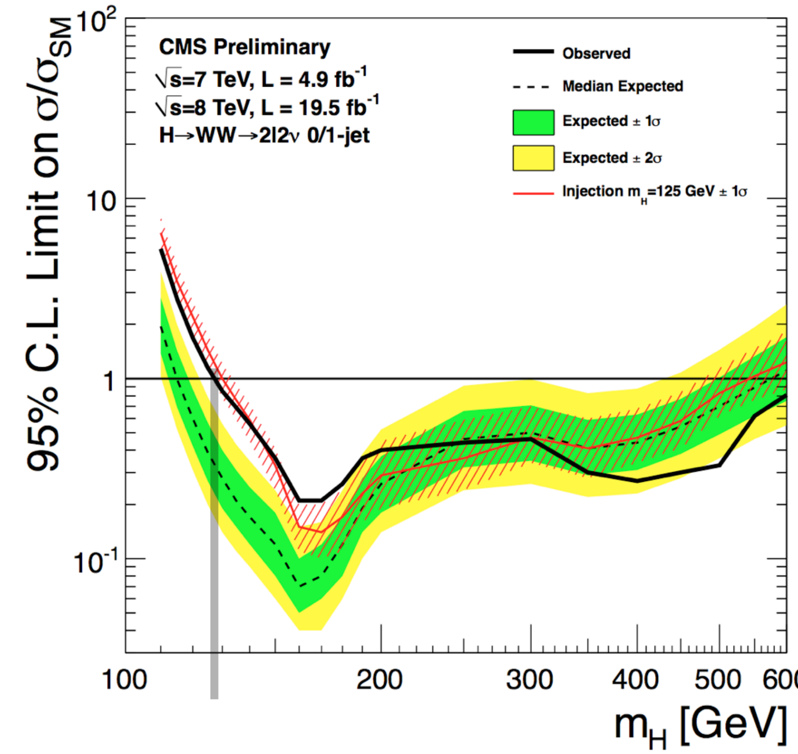
H→ZZ

HIG-13-014

H→ZZ→2l2ν

VERY NEW!





H→WW

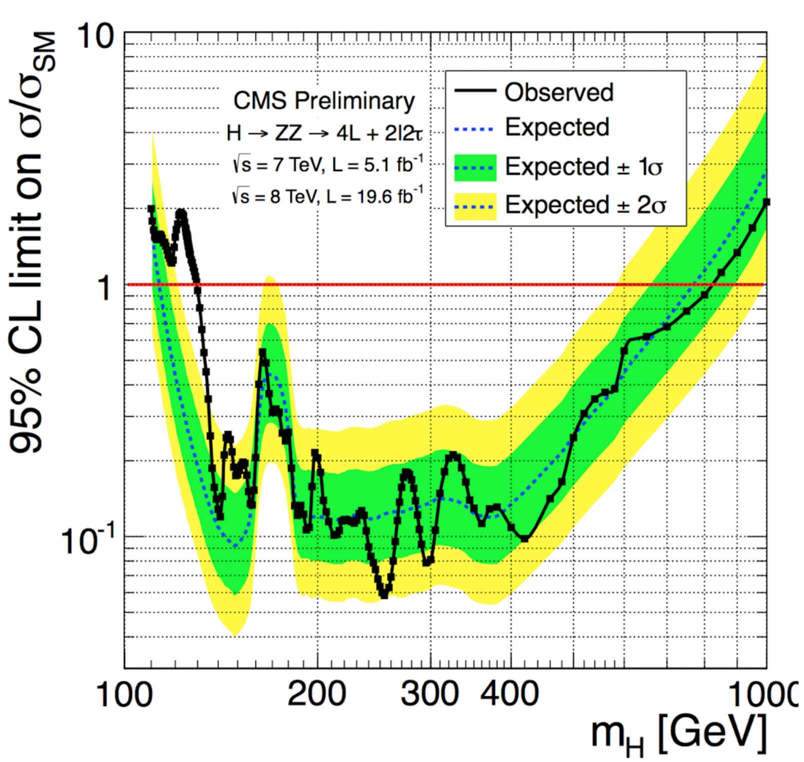
HIG-13-003

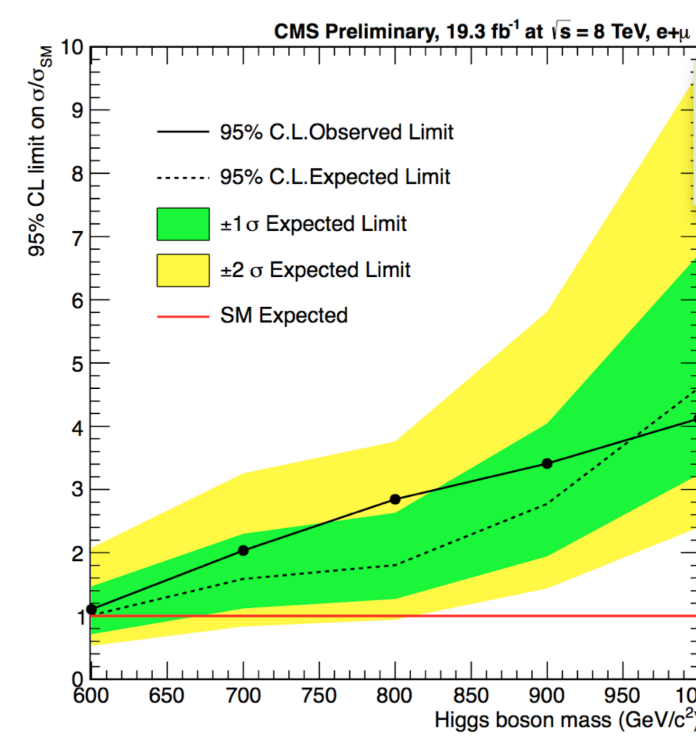
VH H→WW→2l2ν

H→ZZ

HIG-13-002

H→ZZ→4l





H→WW

HIG-13-008

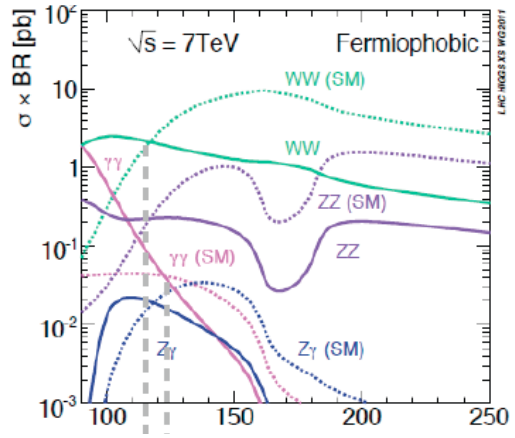
WW→lνqq′

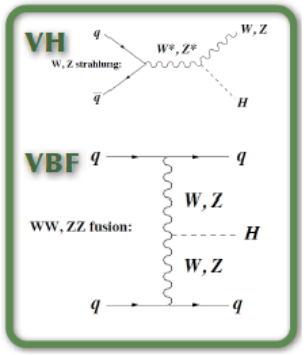
NEW

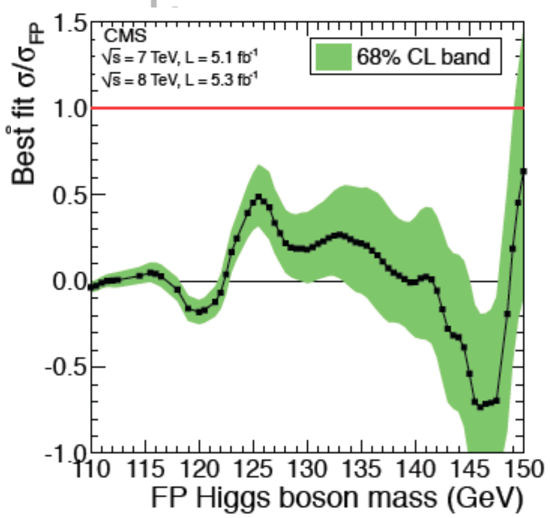
no other SM-like Higgs, with SM couplings with mass <~ 1 TeV

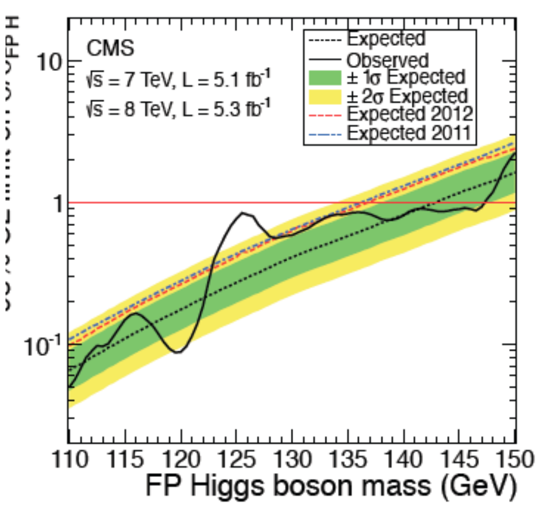
BSM Higgs ?

Fermiophobic Higgs







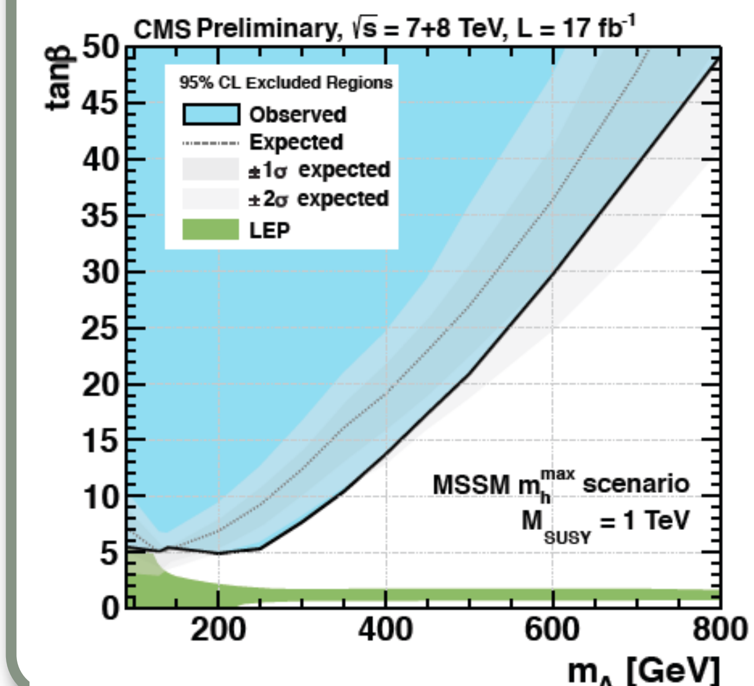


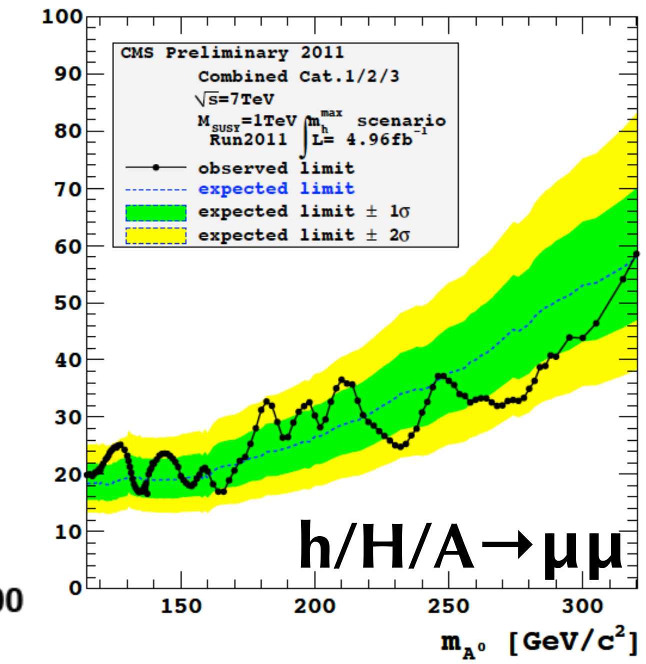
MSSM

1 Standard Model like Higgs: **h** with CP=+1

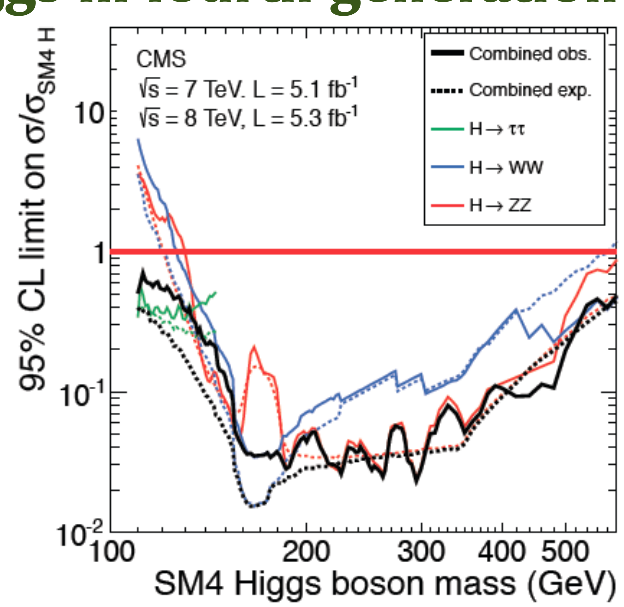
2 neutral Higgs: **A** with CP=-1 and **H** with CP=1

2 charged Higgs: **H^+** and **H^-**





Higgs in fourth generation models:



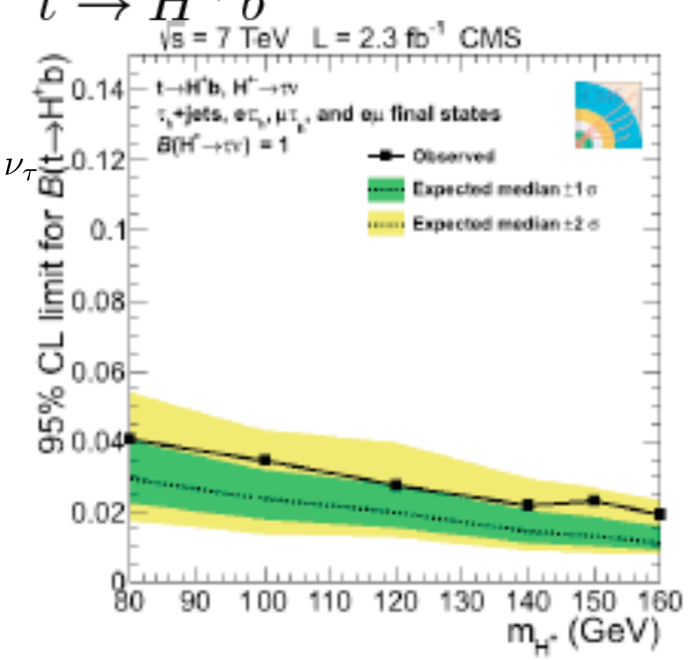
light charged Higgs

$m_{H^+} < m_t - m_b$ ⟹ $t \to H^+ b$

for $\tan\beta > 5$
H^+ preferentially decays as $H^+ \to \tau^+\nu_\tau$

analysis strategy:

Look for an enhancement of taus w.r.t. other leptons in the final state, in top pair events



BSM Higgs ?

NEW

H→WW

H→ZZ

model with a singlet scalar where a heavy boson couples with the 125 GeV state

h: SM Higgs with m~125 GeV, with coupling C

h′: new EW singlet state, with coupling C′

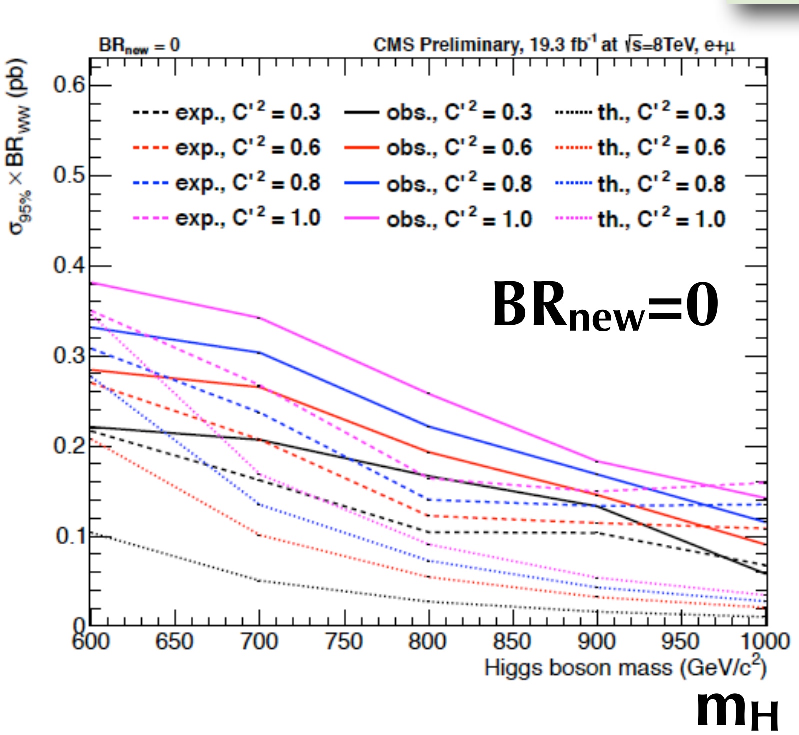
unitariety ⇒$C^2+C'^2=1$

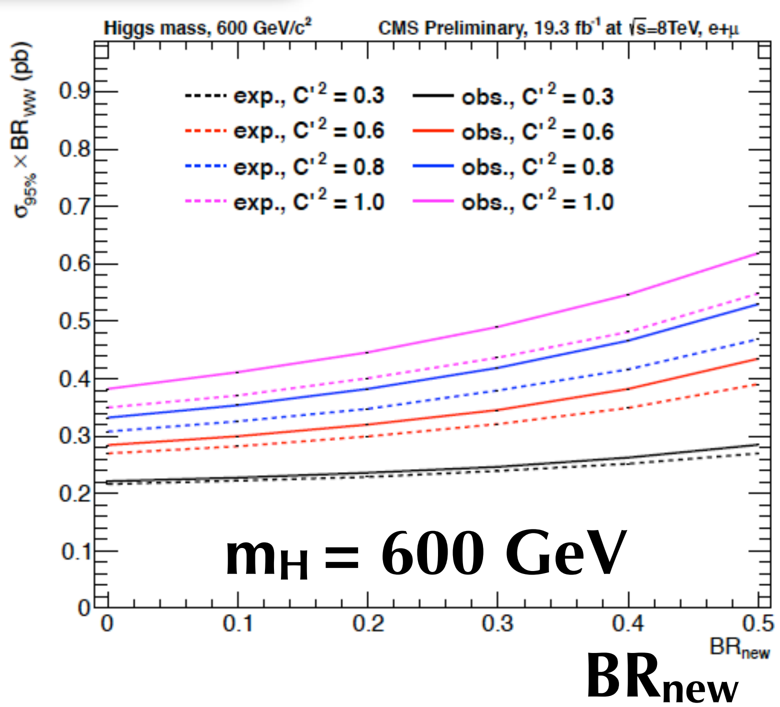
$$\mu' = C'^2(1-\mathcal{BR}_{\text{new}})$$

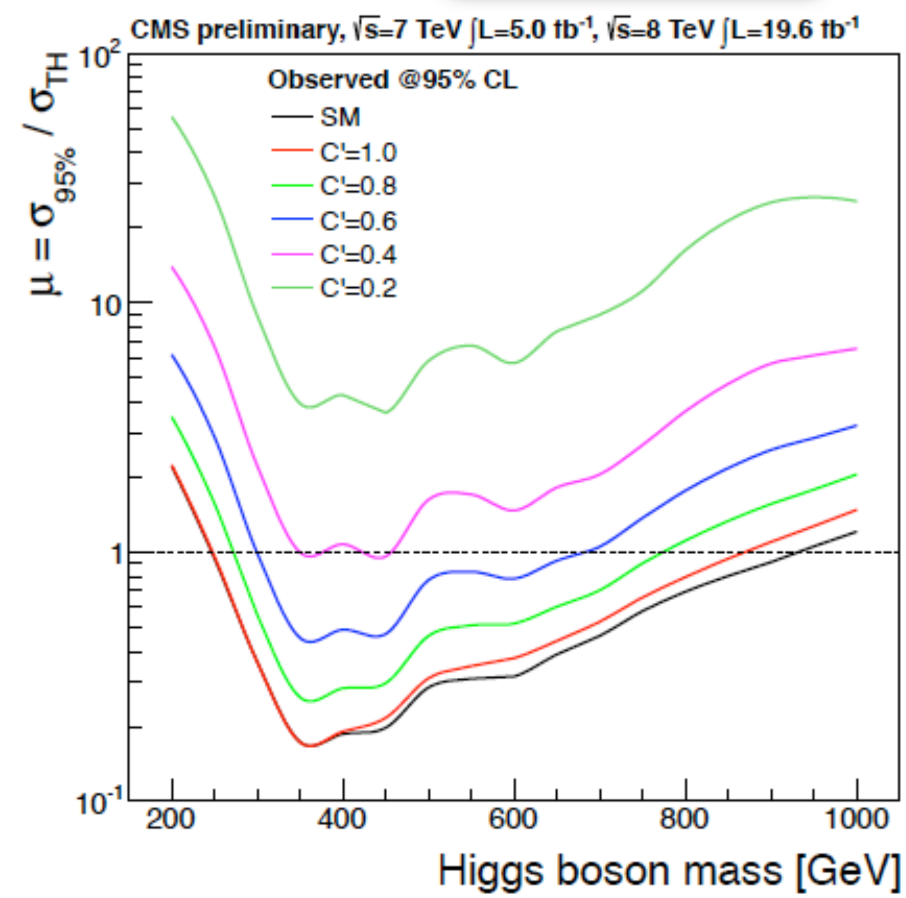
$$\Gamma' = \Gamma_{\text{SM}} \times \frac{C'^2}{(1-\mathcal{BR}_{\text{new}})}$$

ZZ→llνν **HIG-13-014**

WW→lνqq′ **HIG-13-008**

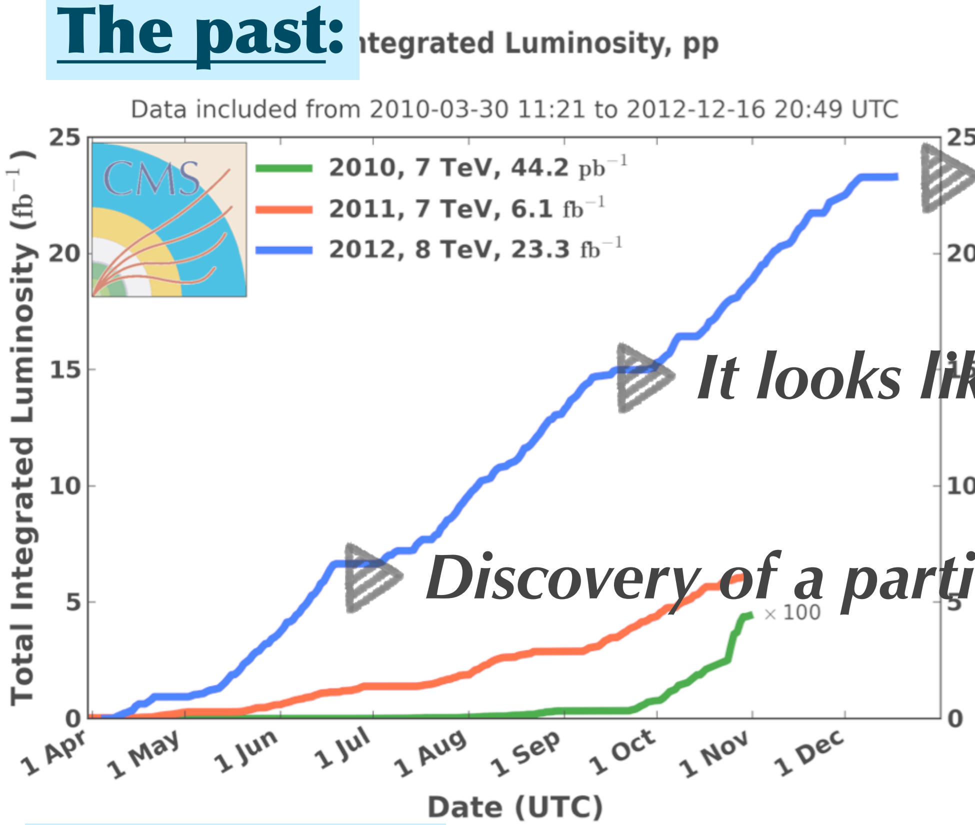






Conclusions

The past:



full phase-1 dataset, properties studied, it is a "Higgs"

It looks like a Higgs-like particle

Discovery of a particle with m~ 125 GeV (decays to bosons)

March 14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New results indicate that particle discovered at CERN is a Higgs boson

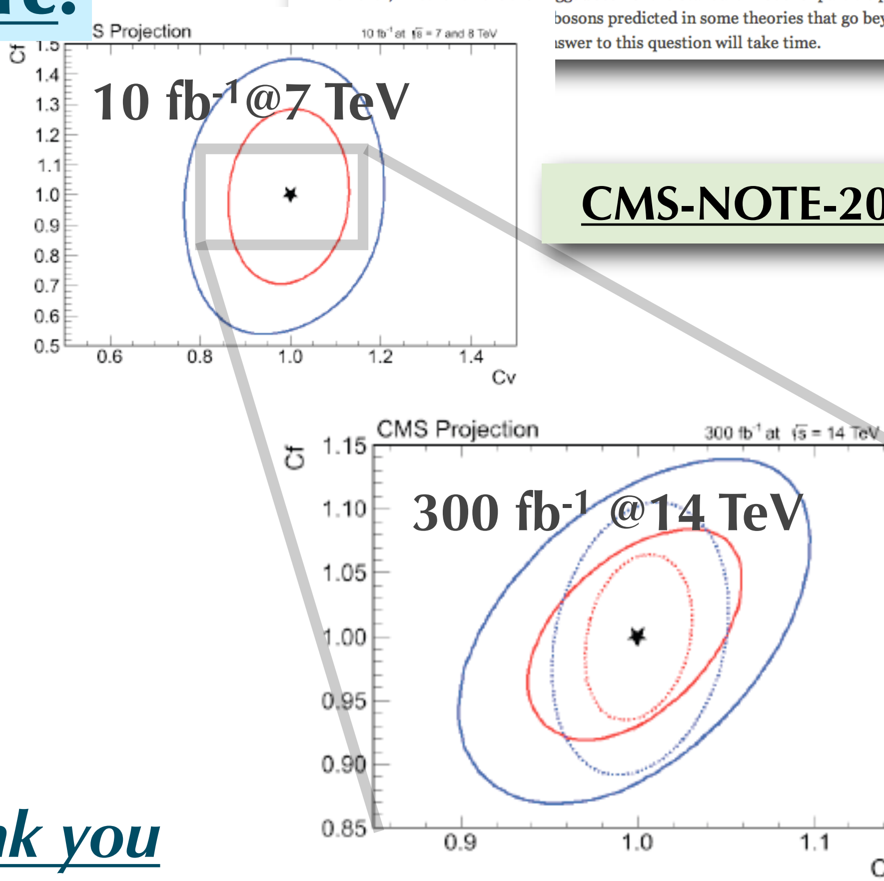
14 Mar 2013

Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN[1]'s Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery announcement in July, they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or ... bosons predicted in some theories that go beyond the ... swer to this question will take time.

The present:

- The mass of the new particle is measured to be: (125.7±0.4) GeV
- Several compatibility tests performed on properties, *no discrepancy to SM observed*
- First sign of decays to fermions, ττ and bb
- Keeping on looking for deviation from SM, by using the phase-1 dataset with new analyses, and plan strategies to be ready to use the next LHC run dataset

The future:



CMS-NOTE-2012-006

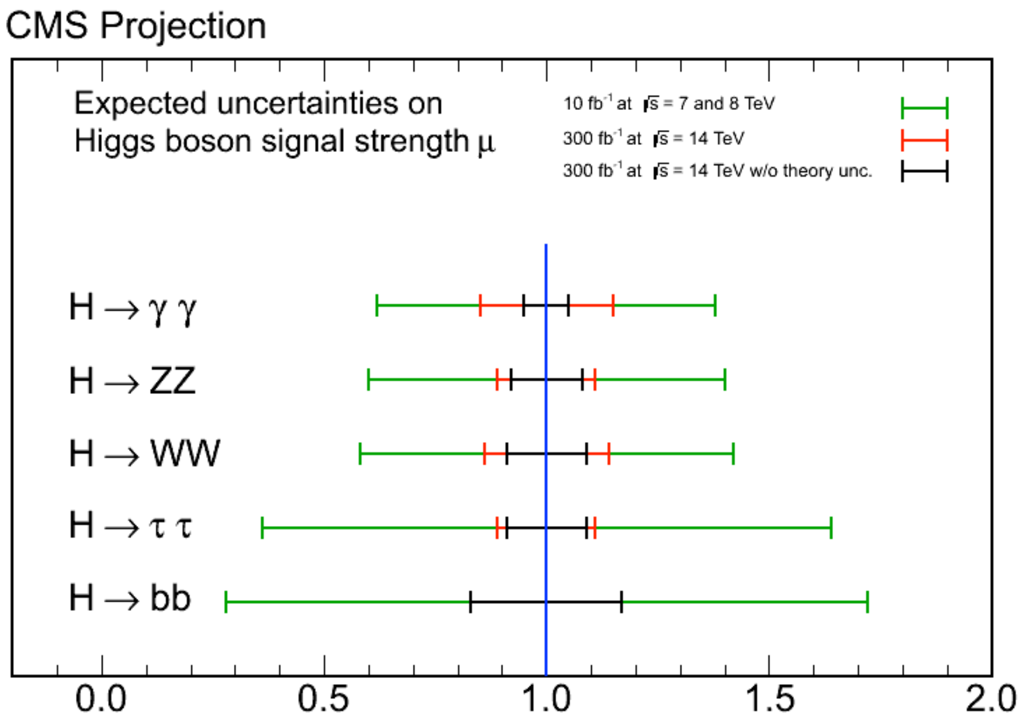
Thank you

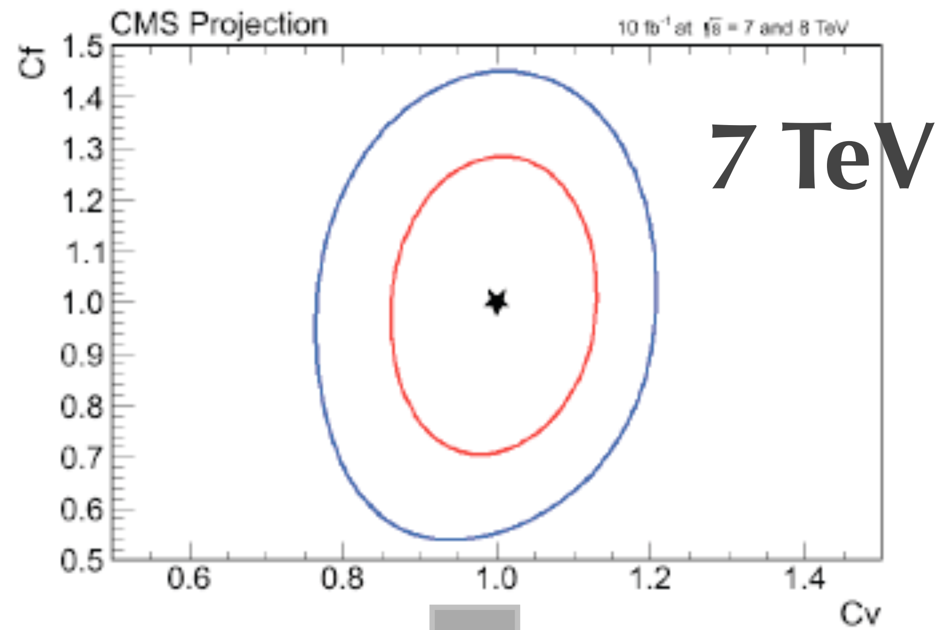
Back Up

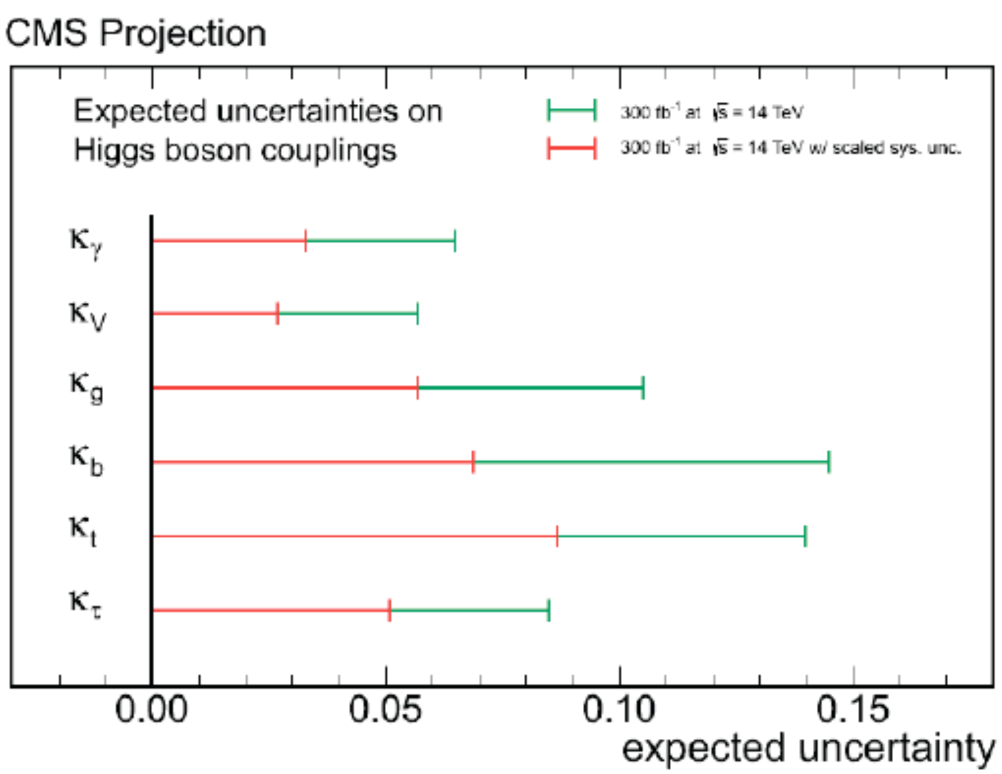
Projections at 14 TeV

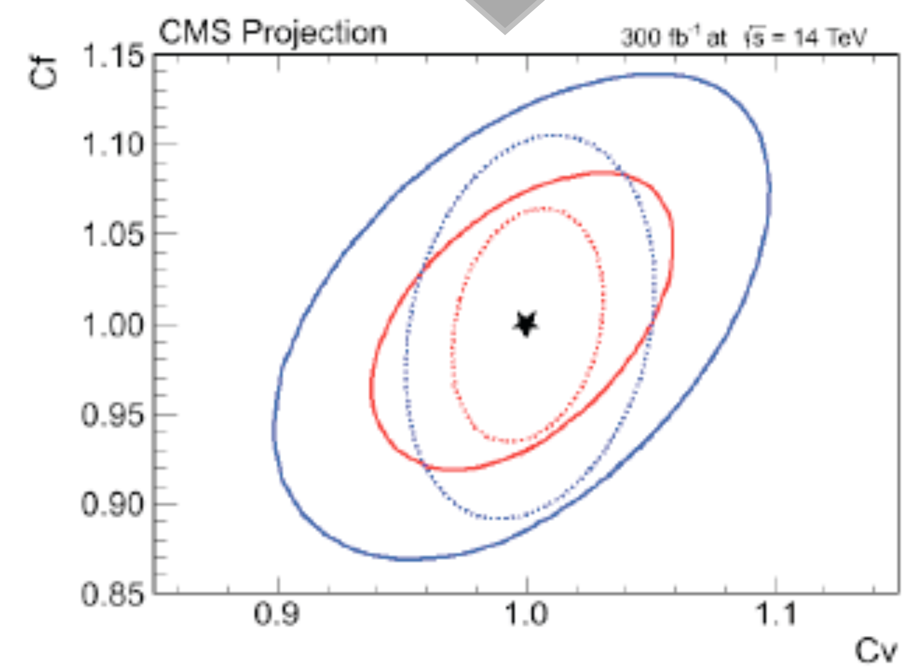
CMS-NOTE-2012-006

CMS submission to the European Strategy Group









ECAL performance

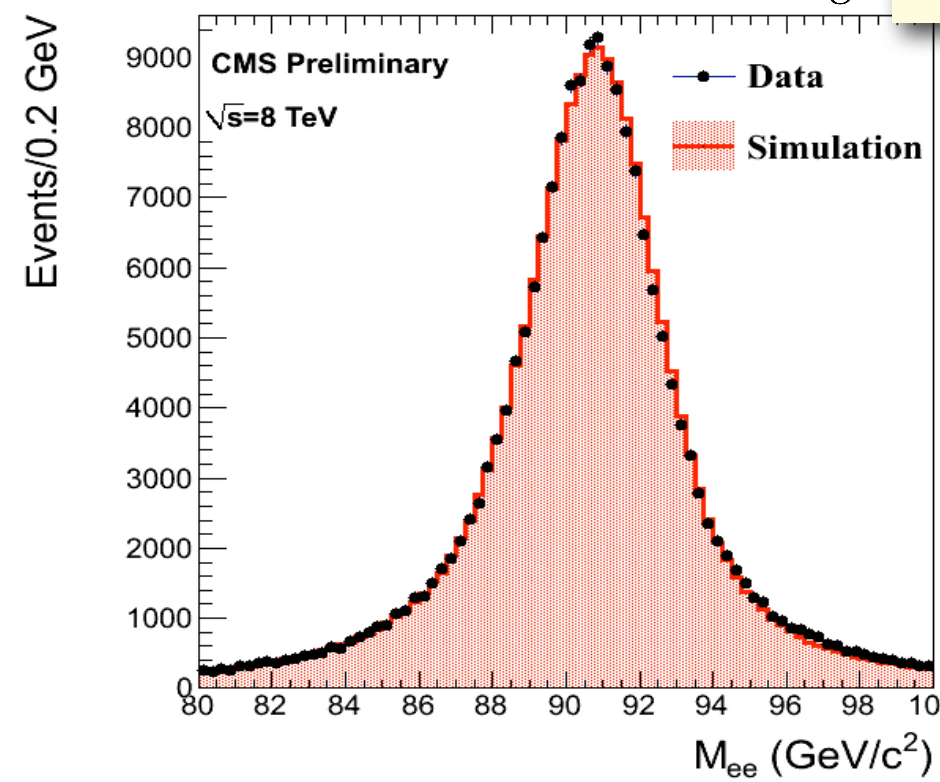
H→γγ

HIG-13-001

$$m^2_{\gamma_1,\gamma_2} = 2E_{\gamma_1}E_{\gamma_2}(1 - cos\theta)$$

Good photon energy resolution

Both electrons in ECAL Barrel with low bremsstrahlung

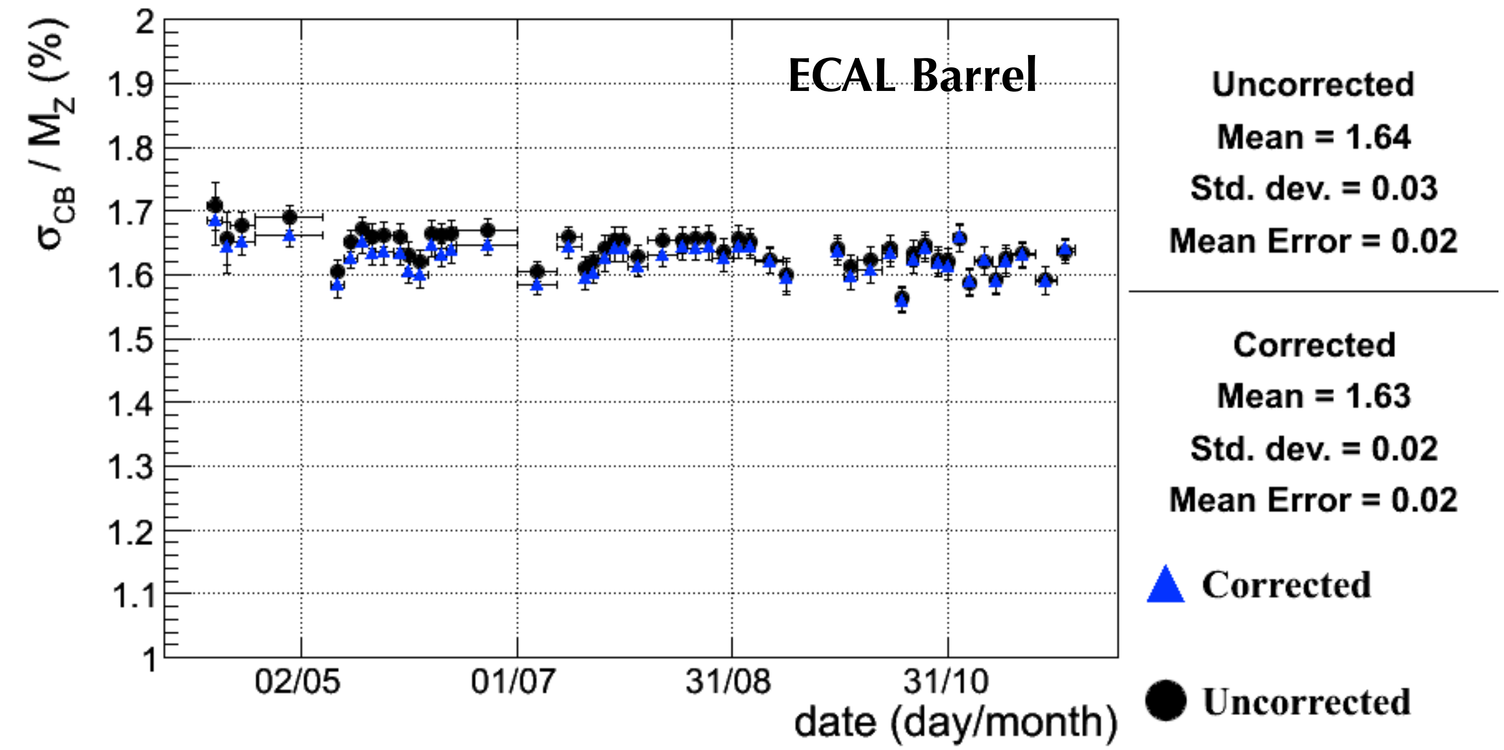


Z→ee mass resolution better than 1.2% for electrons with low bremsstrahlung in the barrel.

Z→ee lineshape: good agreement between data/MC

Stable performance already using promptly reconstructed data

Z mass resolution as a function of time after application of analysis level corrections



Vertex finding

H→γγ

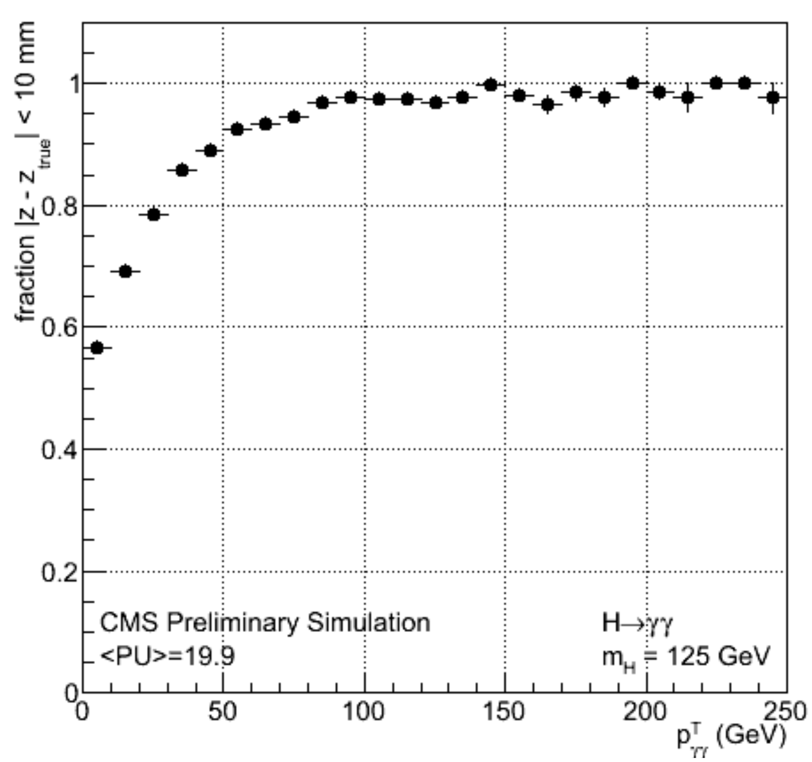
HIG-13-001

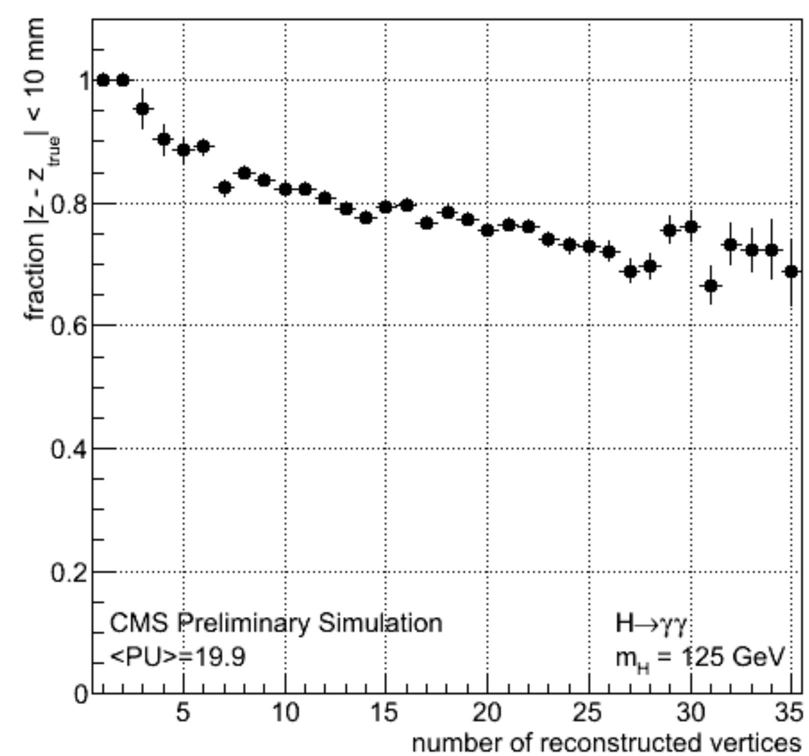
$$m^2_{\gamma_1,\gamma_2} = 2E_{\gamma_1}E_{\gamma_2}(1-cos\theta)$$

Efficient vertex finding algorithm

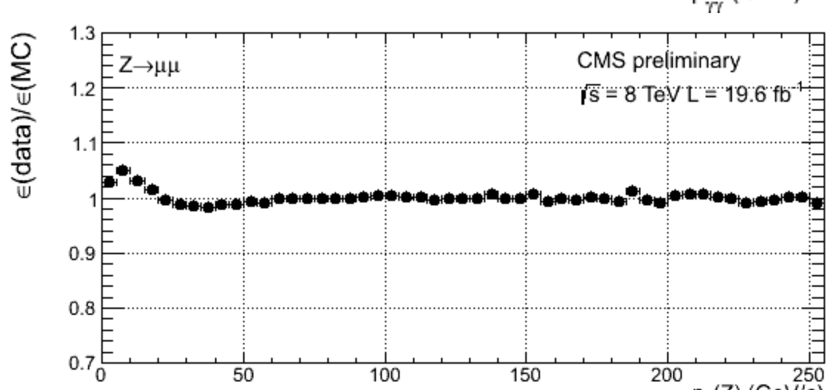
- Higgs production vertex is selected using a Boosted Decision Tree (BDT)
- Inputs: Σp_T^2 of vertex tracks, vertex recoil wrt diphoton system, pointing from converted photons
- ***An additional BDT is used to estimate the vertex probability in the MVA analysis.***
- Control samples: Z→μμ for unconverted photons, γ+jets for converted photons

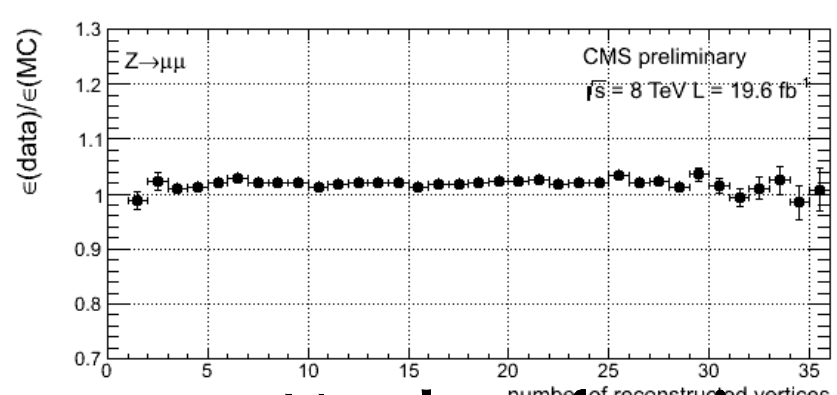
MC signal efficiency





Data/MC ratio using Z→μμ





$p_T(\gamma\gamma)$ **Number of vertices**

Cut based diphoton selection

H→γγ

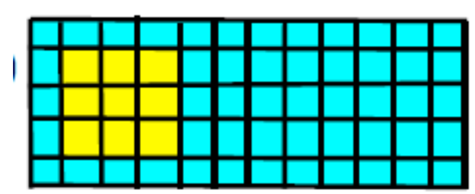
Cut based

HIG-13-001

- **photon pt cuts scaled with $m_{\gamma\gamma}$**
- **cut-based photon identification**
  - Photon identification data/MC efficiency scale factors computed from Z→ee and Z→μμγ.
- **choose the ID photon pair with highest sum E_T**
- **4 categories are defined according to the photon characteristics**
  - Barrel-endcap and converted/unconverted from shower shape
  - Different mass resolution and S/B among the 4 categories

converted photons discriminated by

$$R_9 = \Sigma E(3\times3)/E_{SC}$$



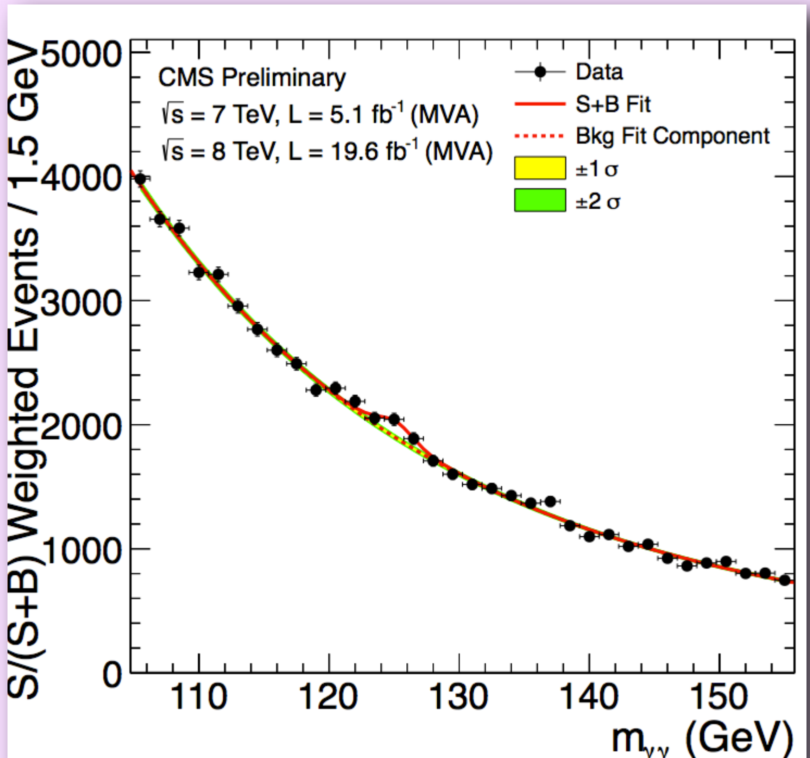
Cat 0	Both photons in barrel	Both photons $R_9 > 0.94$
Cat 1	Both photons in barrel	At least one photon with $R_9 < 0.94$
Cat 2	At least one photon in endcaps	Both photons $R_9 > 0.94$
Cat 3	At least one photon in endcaps	At least one photon with $R_9 < 0.94$

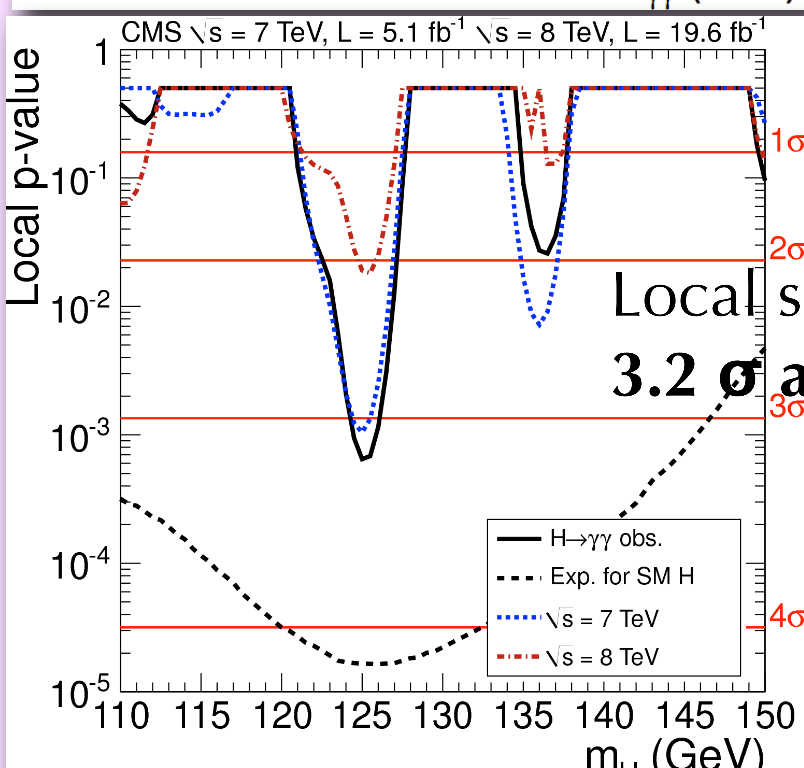
MVA MFA VS Cut based

H→γγ

HIG-13-001

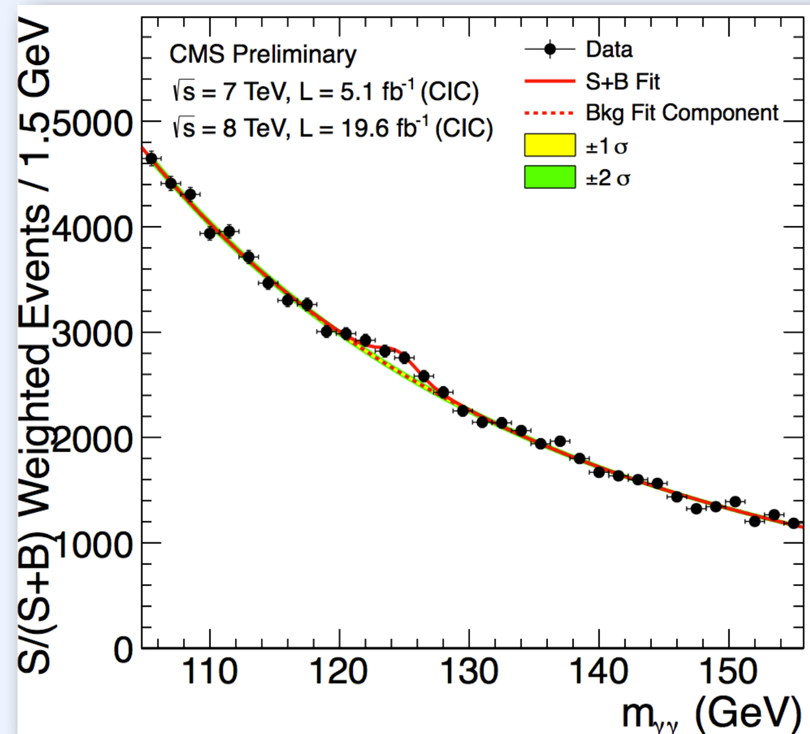
MVA mass-factorized

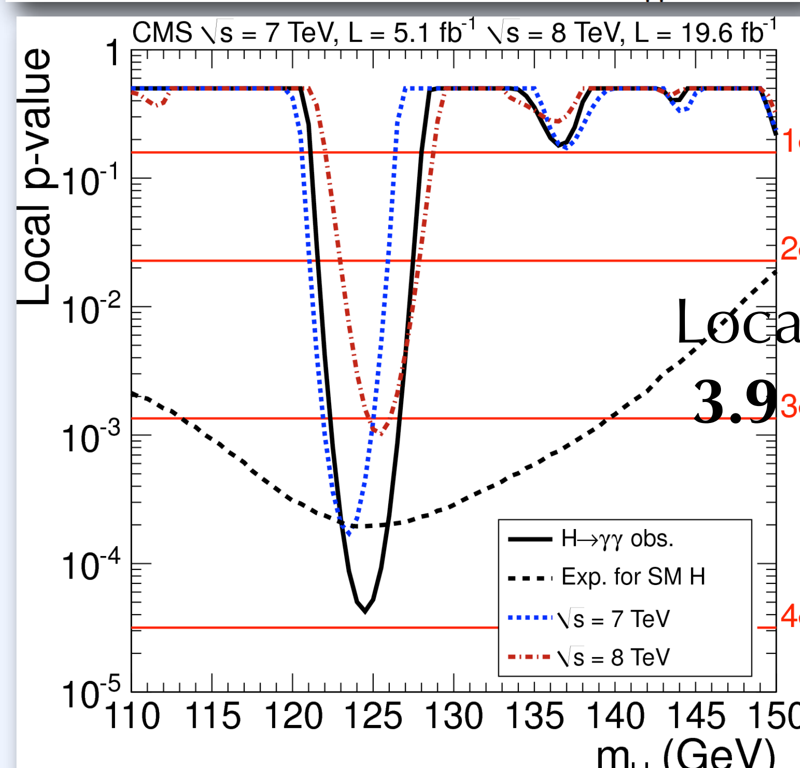




Local significance:
3.2 σ at 125.0 GeV

Cut-based





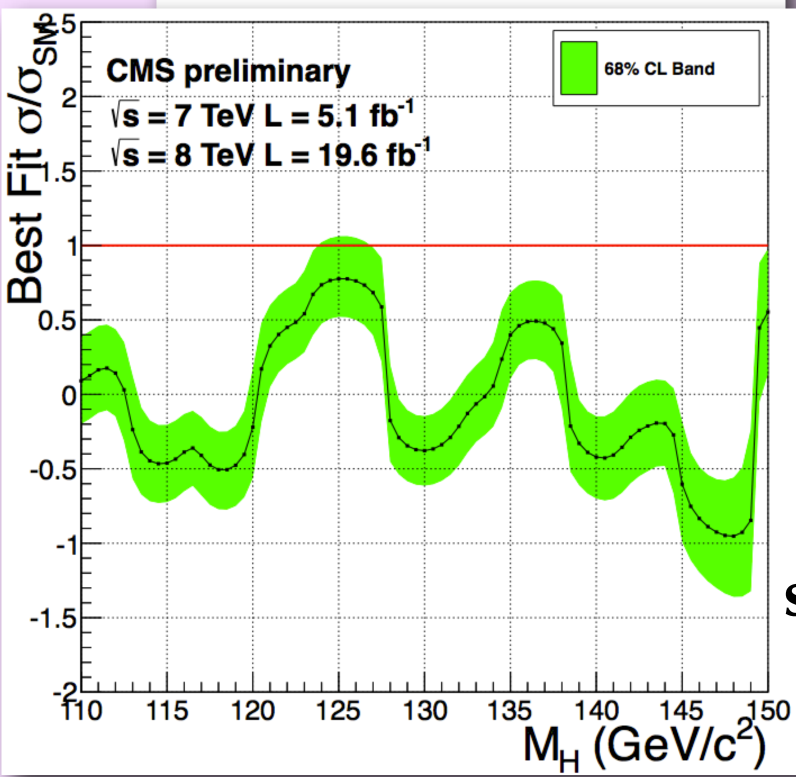
Local significance:
3.9 σ at 124.5 GeV

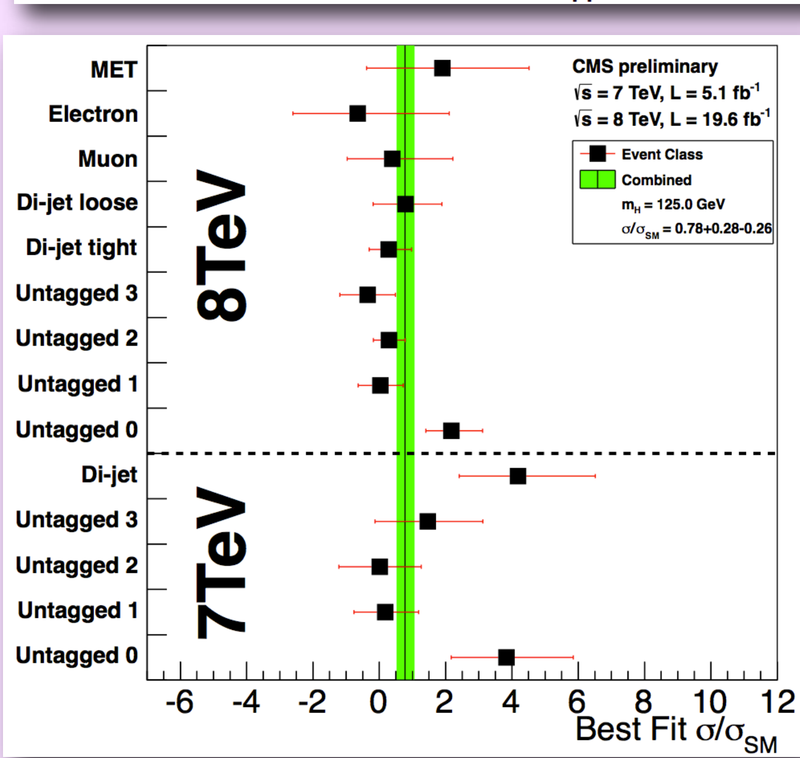
Results: fitted signal strenght

H→γγ

HIG-13-001

MVA mass-factorized

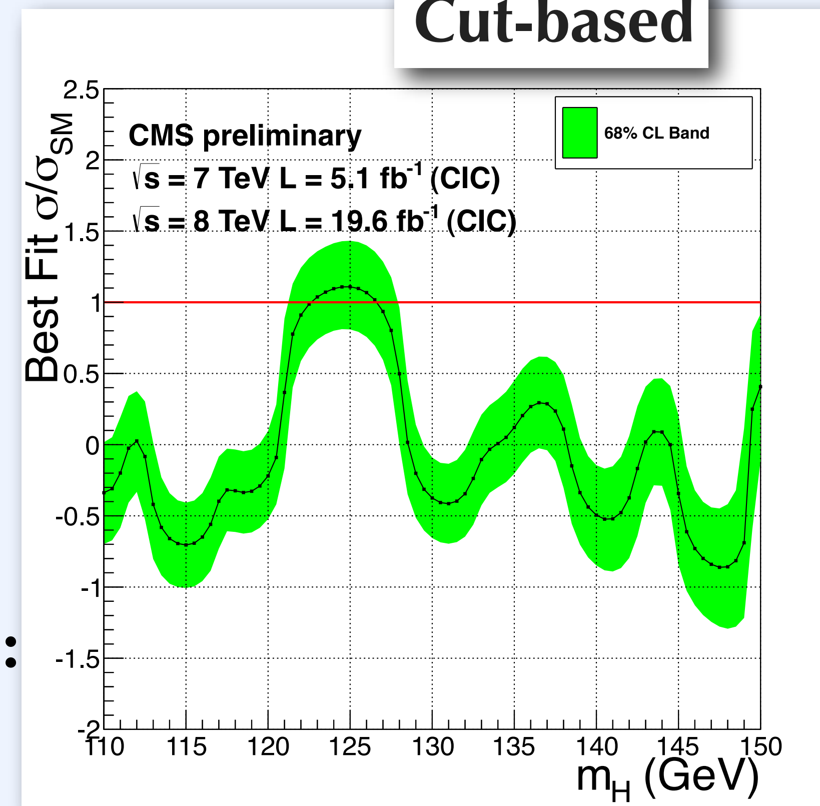


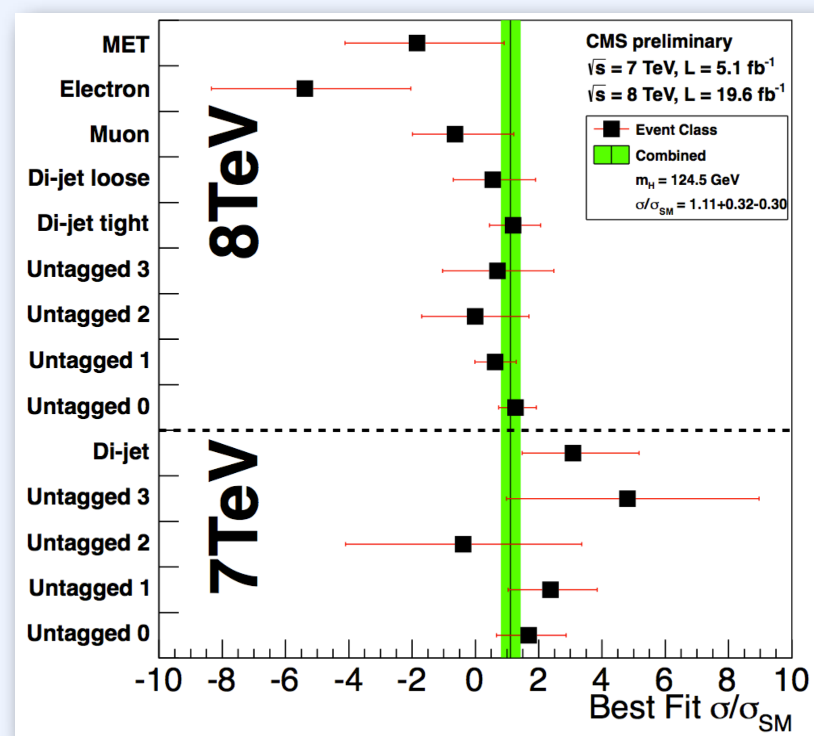


Fitted signal strength:

0.78±0.27 (MVA)

Cut-based





Fitted signal strength:

1.11±0.31 (Cut-based)

compatibility between the two analyses

how much the MVA and Cut Based results are compatible?

the two results are correlated because of common events, we need to take into account the correlation

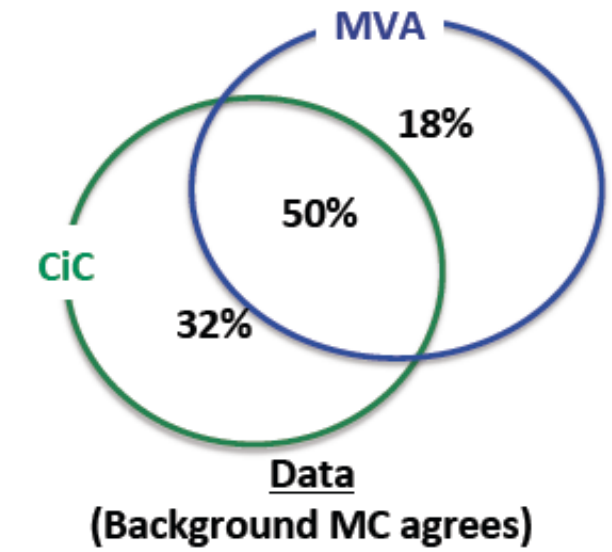
- We estimate the correlation between the two analyses using the resampling jackknife technique

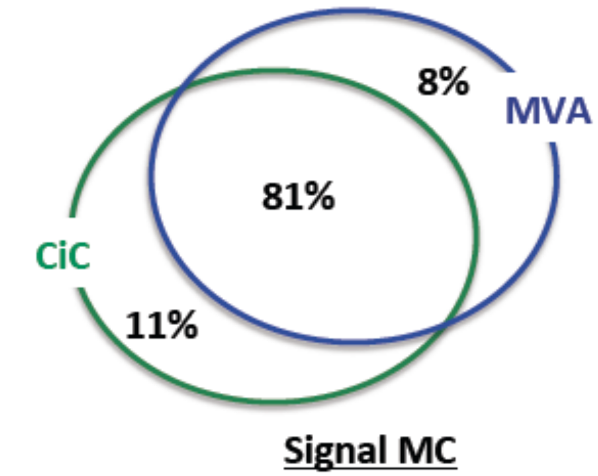
  (Quenouille M (1949), Tukey JW (1958))

- The correlation coefficient between the two measurements is found to be **r=0.76**

	Compatibility (including correlation)
MVA vs CUT BASED in full dataset	1.5 σ
MVA vs CUT BASED only in 2012 dataset	1.8 σ

within 2 σ



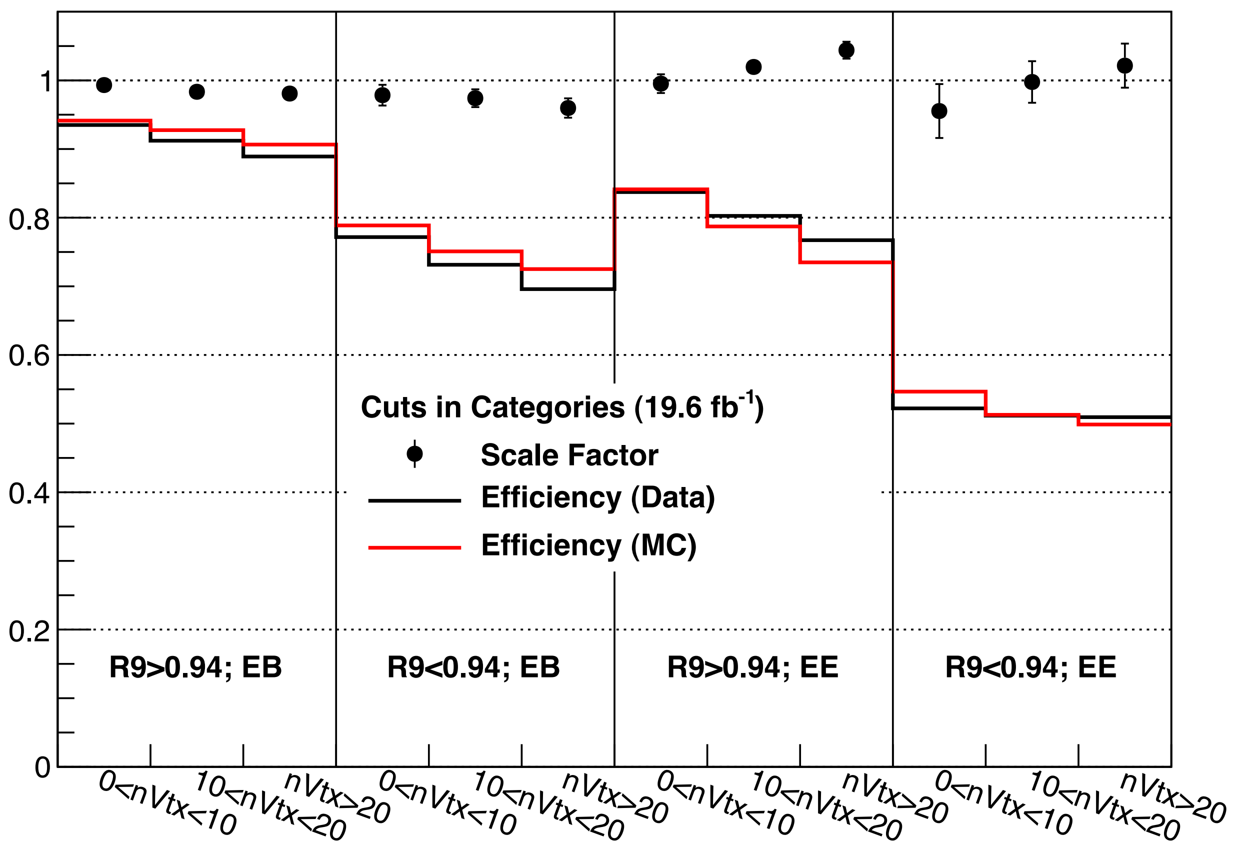


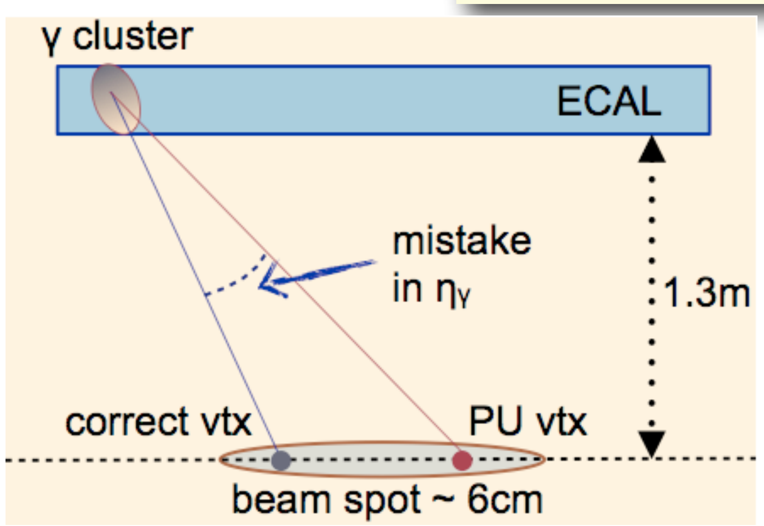
- **A large number of tests have been performed. No source of systematic error was found. Differences appear to be of a statistical nature.**

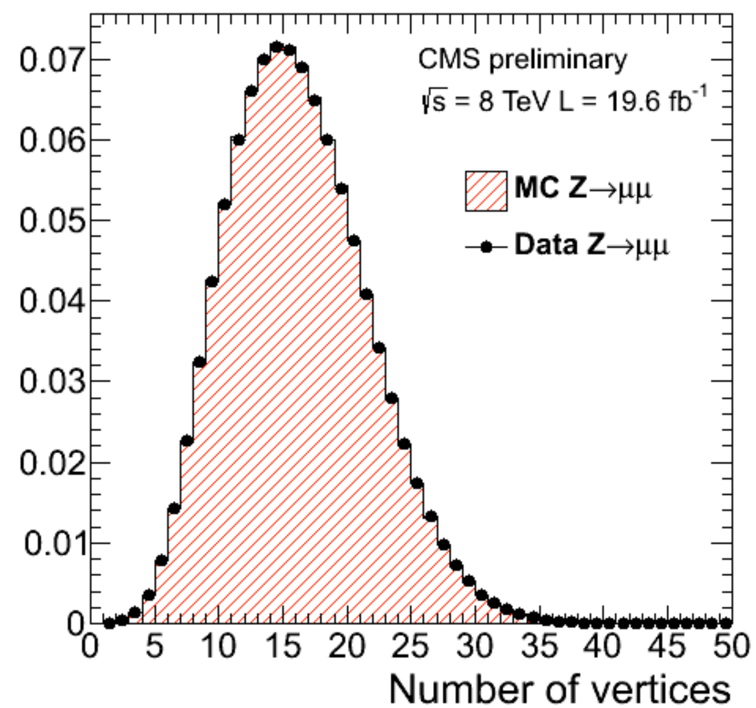
γγ cross checks

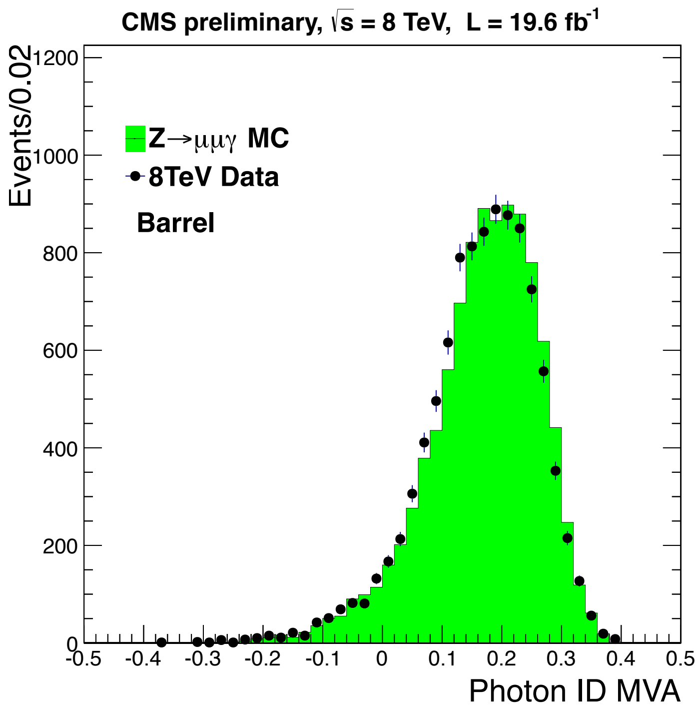
H→γγ

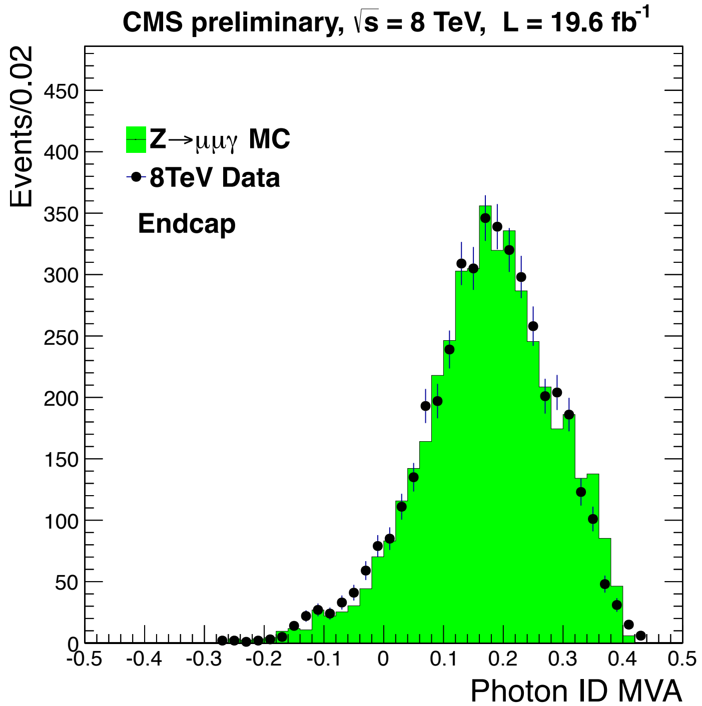
HIG-13-001







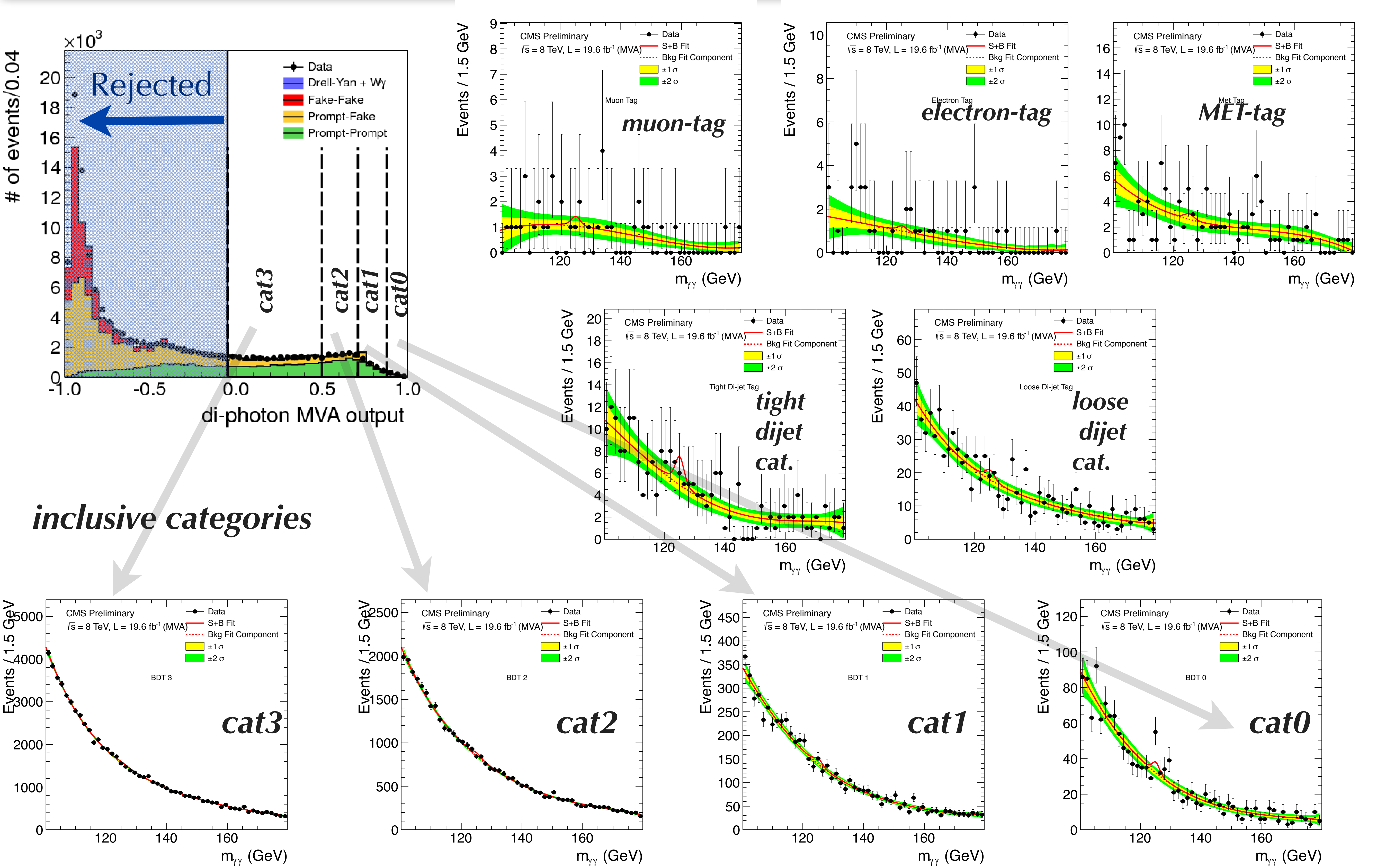




Mass spectrum for each category

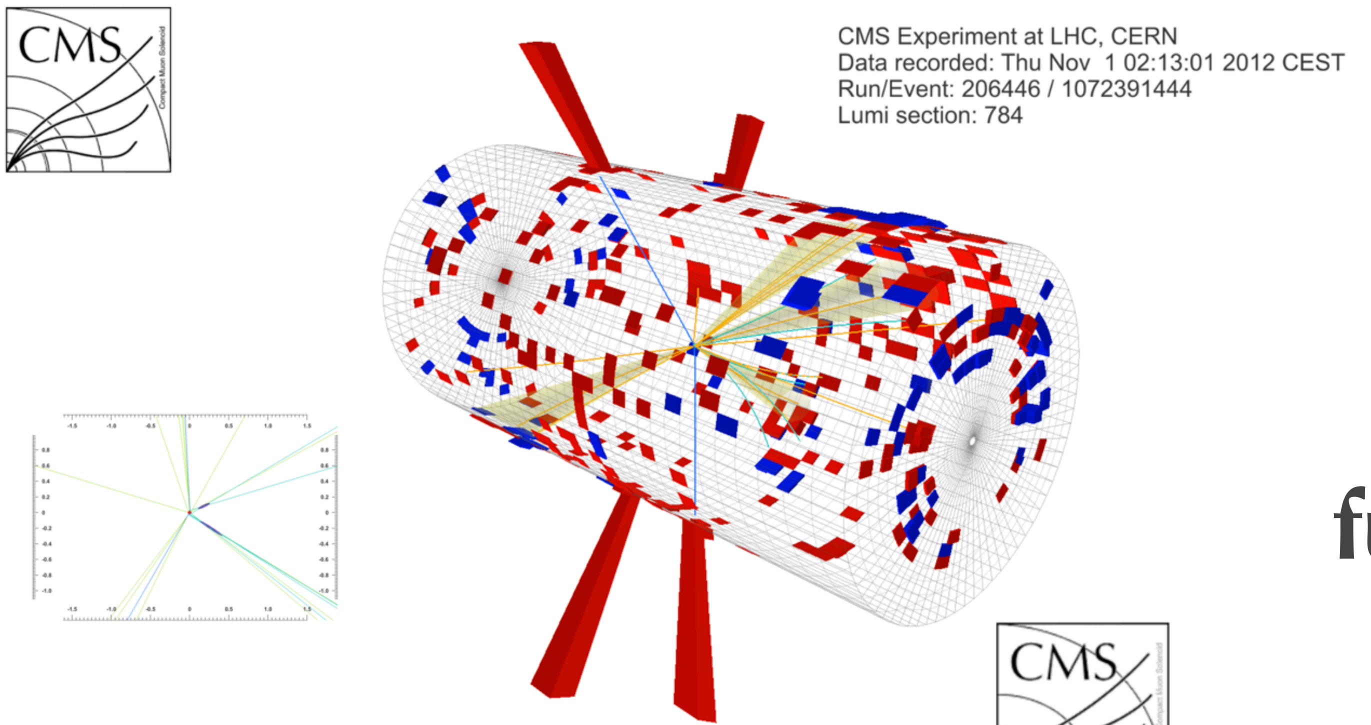
plots shown are for 8 TeV

Best fit with a floating signal strenght

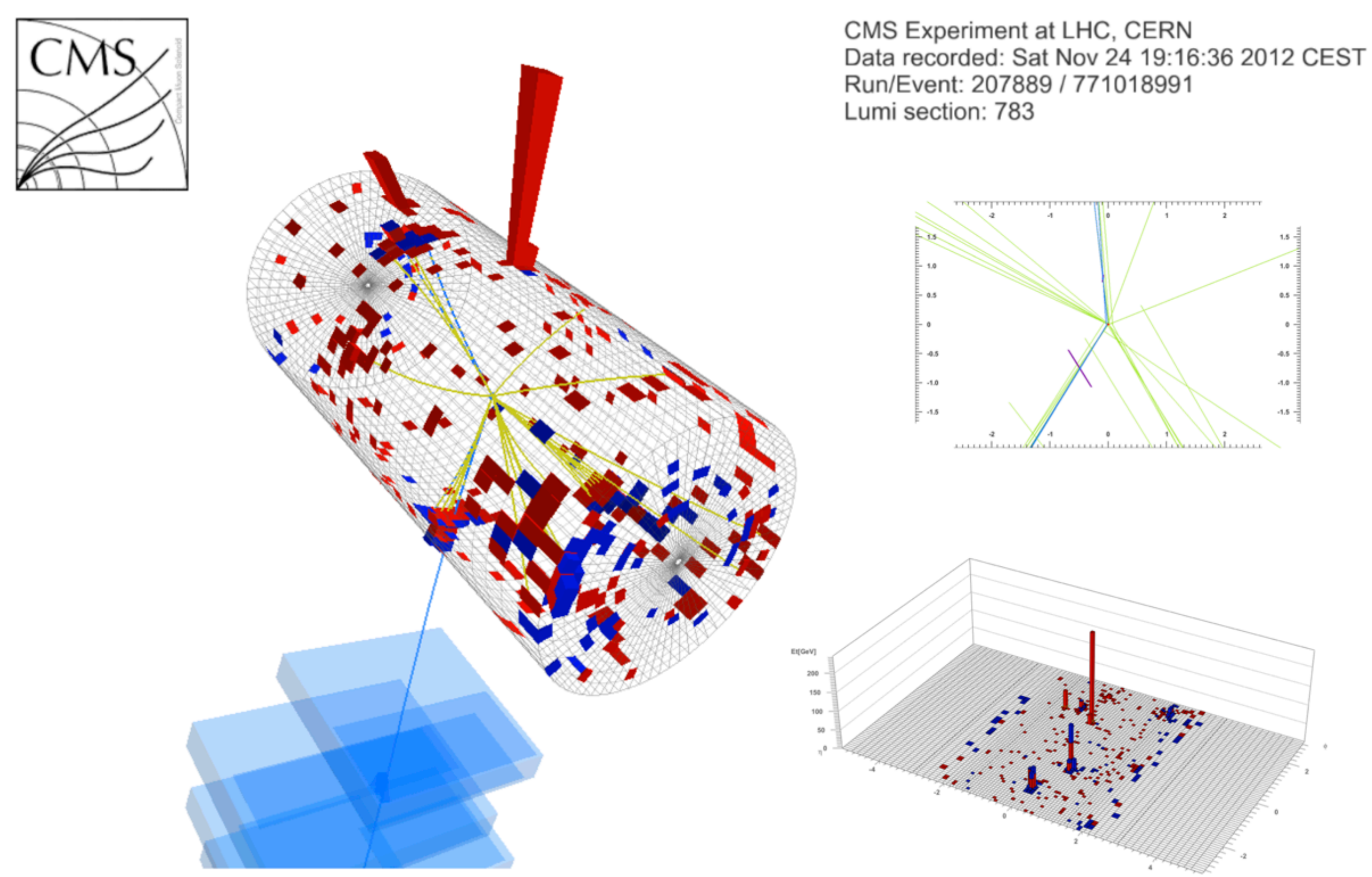


ttH, H→γγ

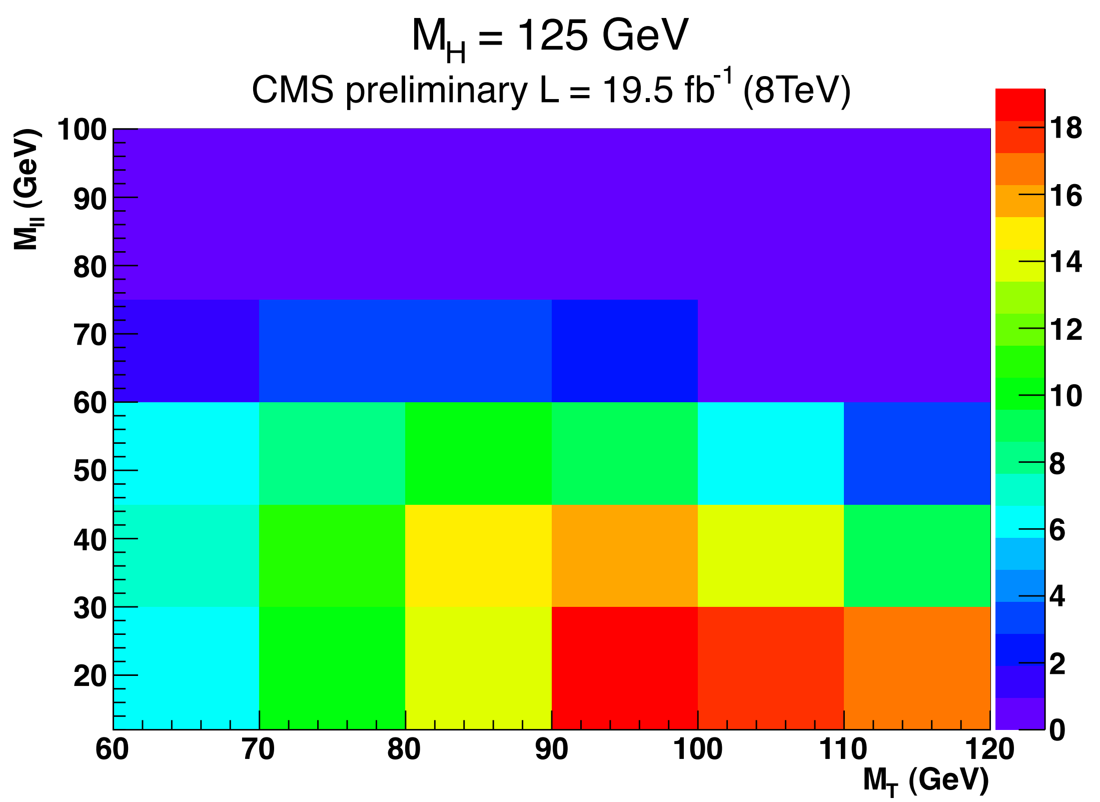
semi leptonic



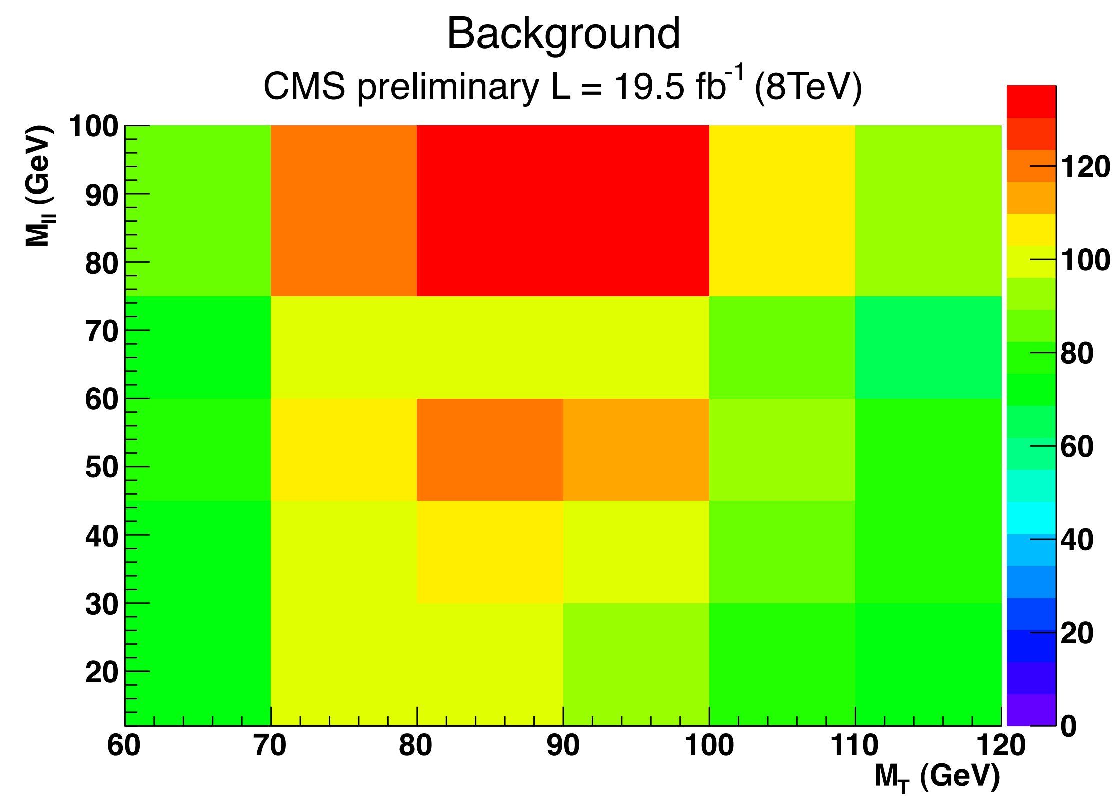
fully hadronic



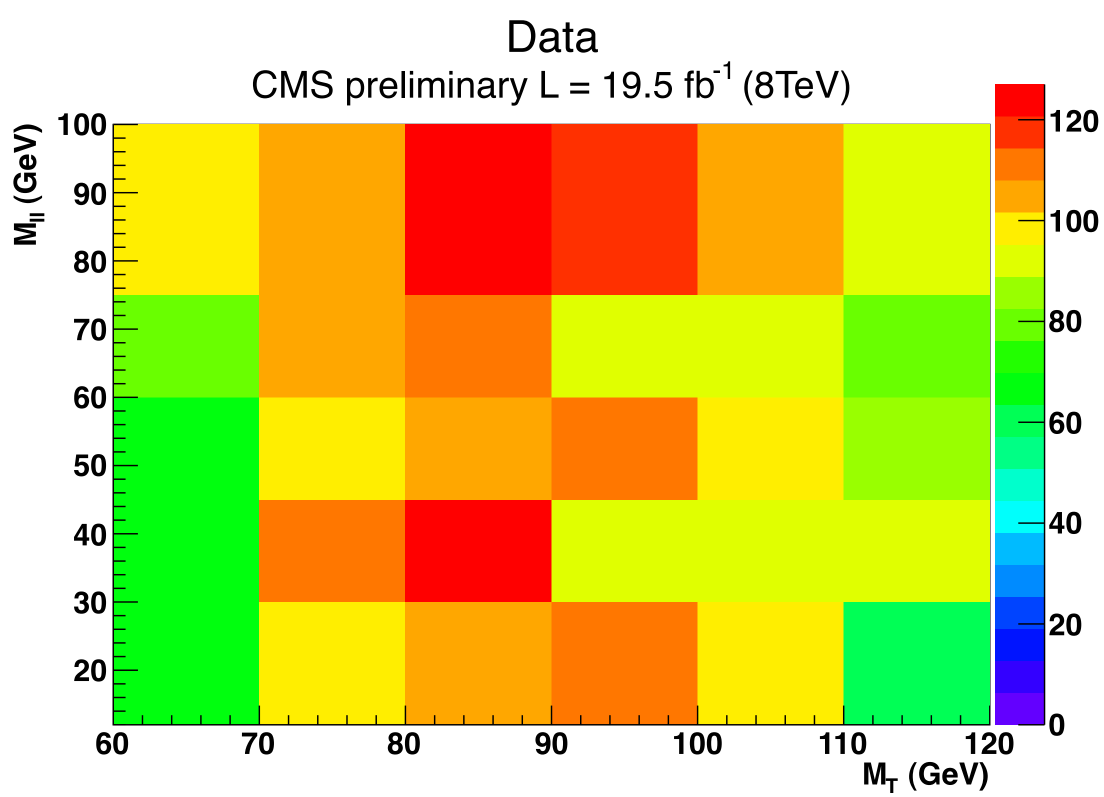
WW, 0 jet bin



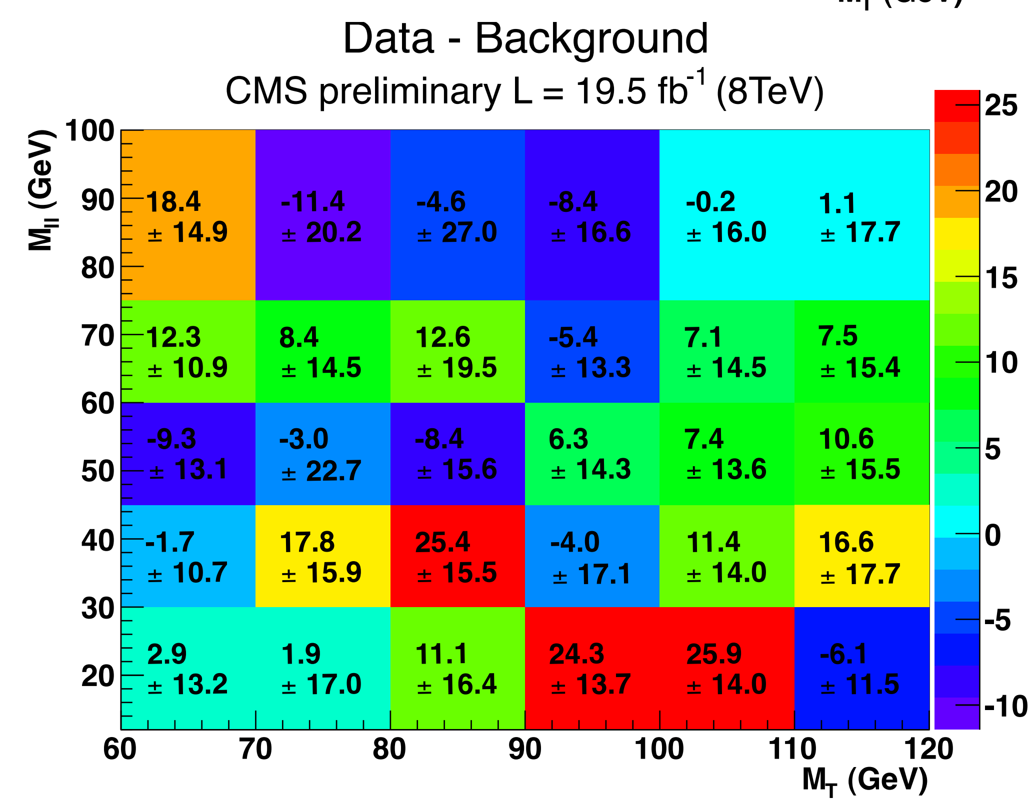
MH = 125 GeV
CMS preliminary L = 19.5 fb-1 (8TeV)
Mll (GeV)
MT (GeV)



Background
CMS preliminary L = 19.5 fb-1 (8TeV)
Mll (GeV)
MT (GeV)

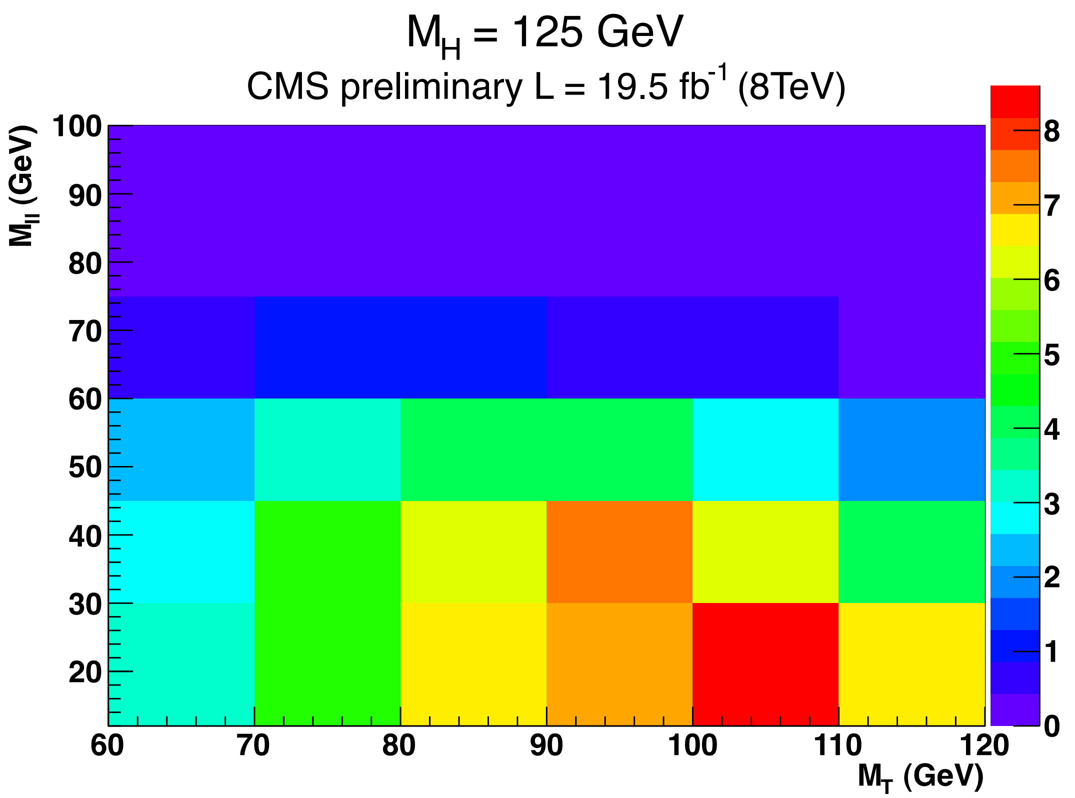


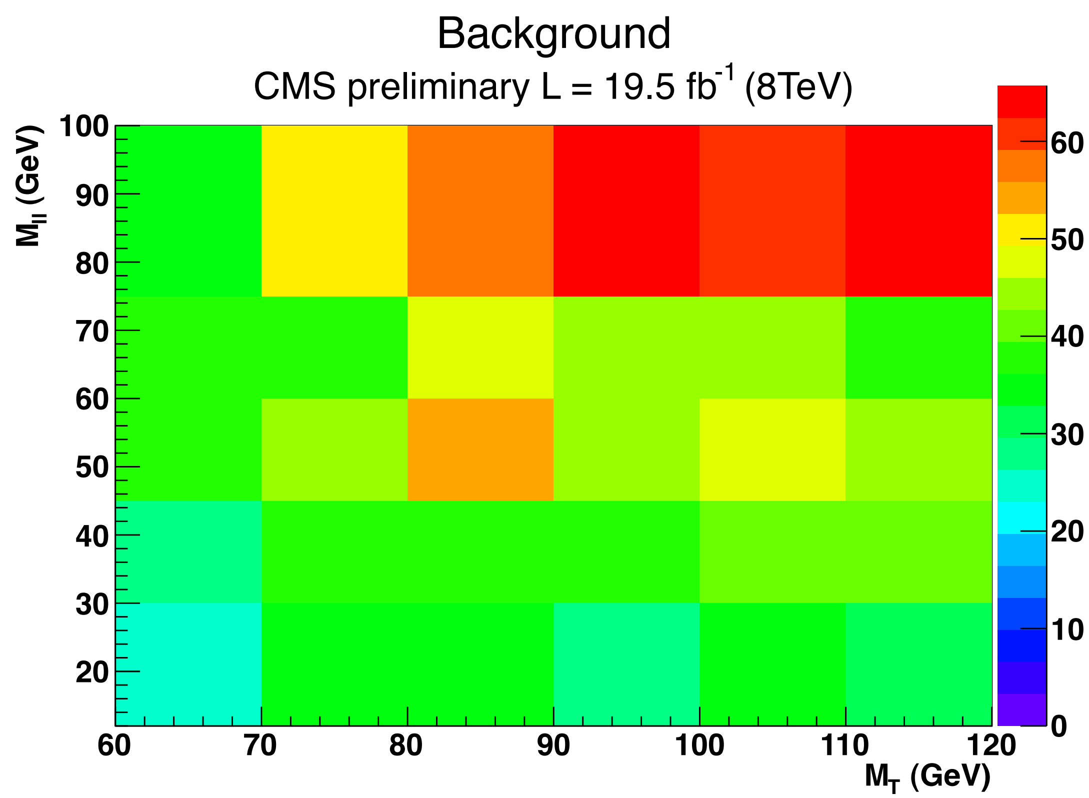
Data
CMS preliminary L = 19.5 fb-1 (8TeV)
Mll (GeV)
MT (GeV)

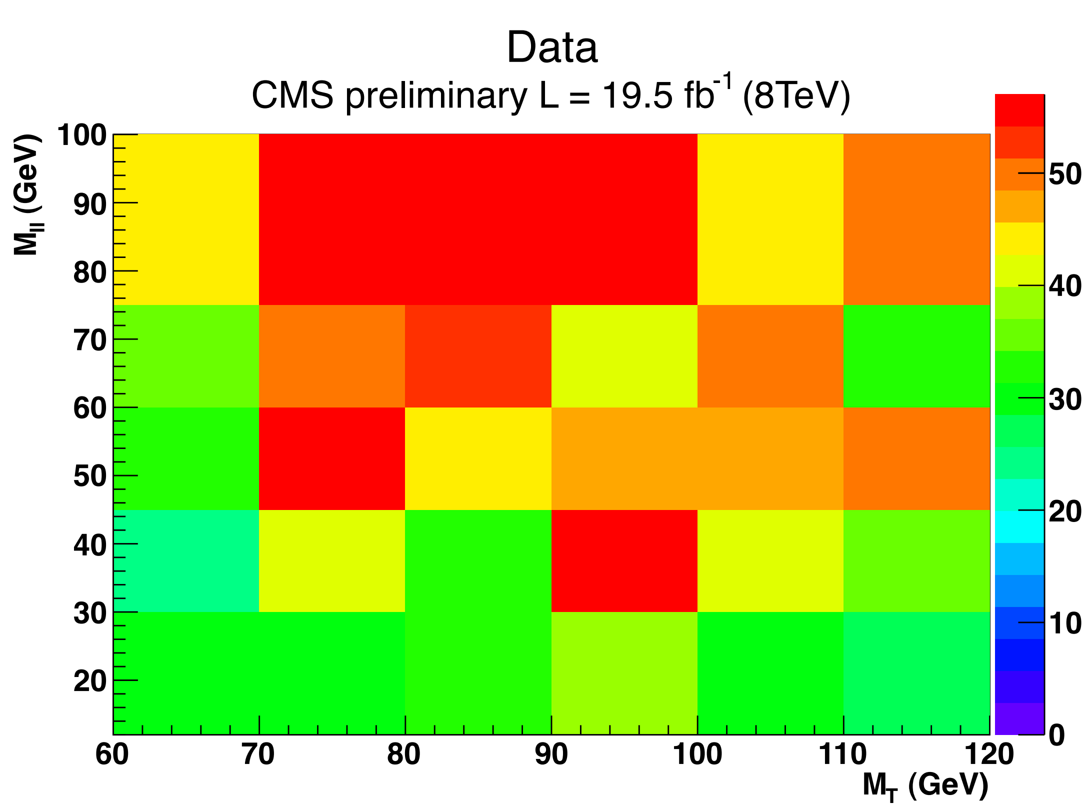


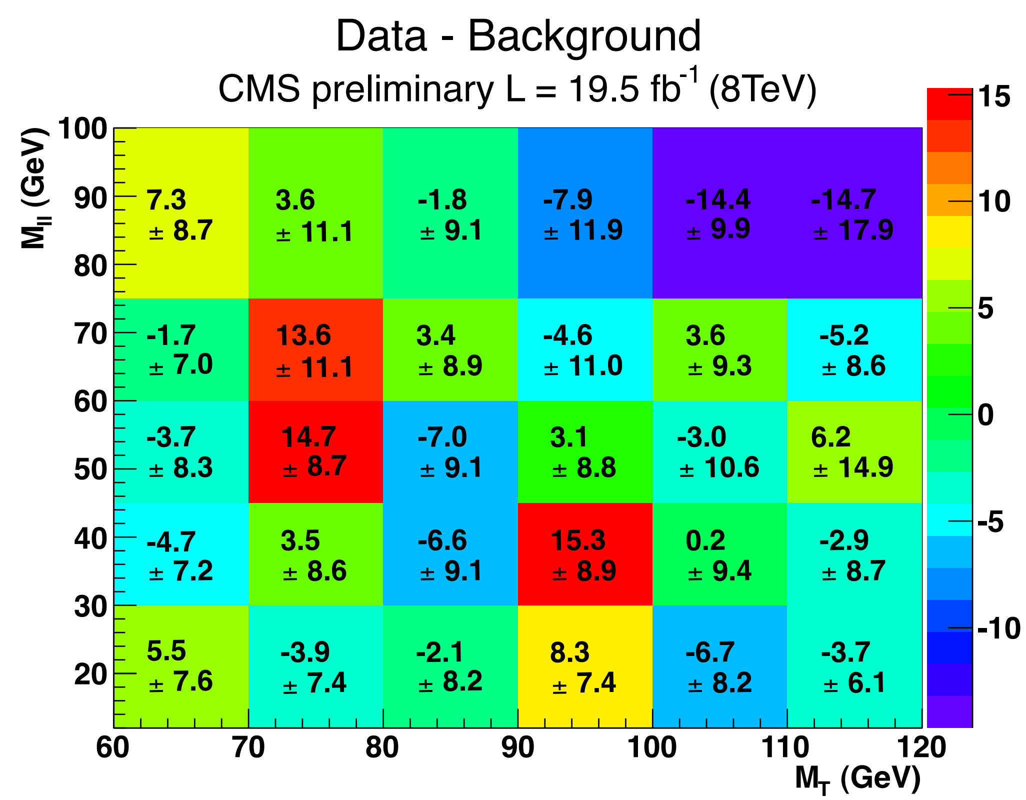
Data - Background
CMS preliminary L = 19.5 fb-1 (8TeV)
Mll (GeV)
MT (GeV)
18.4 ± 14.9
-11.4 ± 20.2
-4.6 ± 27.0
-8.4 ± 16.6
-0.2 ± 16.0
1.1 ± 17.7
12.3 ± 10.9
8.4 ± 14.5
12.6 ± 19.5
-5.4 ± 13.3
7.1 ± 14.5
7.5 ± 15.4
-9.3 ± 13.1
-3.0 ± 22.7
-8.4 ± 15.6
6.3 ± 14.3
7.4 ± 13.6
10.6 ± 15.5
-1.7 ± 10.7
17.8 ± 15.9
25.4 ± 15.5
-4.0 ± 17.1
11.4 ± 14.0
16.6 ± 17.7
2.9 ± 13.2
1.9 ± 17.0
11.1 ± 16.4
24.3 ± 13.7
25.9 ± 14.0
-6.1 ± 11.5

WW, 1 jet bin


M_H = 125 GeV
CMS preliminary L = 19.5 fb^-1 (8TeV)
M_ll (GeV)
M_T (GeV)


Background
CMS preliminary L = 19.5 fb^-1 (8TeV)
M_ll (GeV)
M_T (GeV)

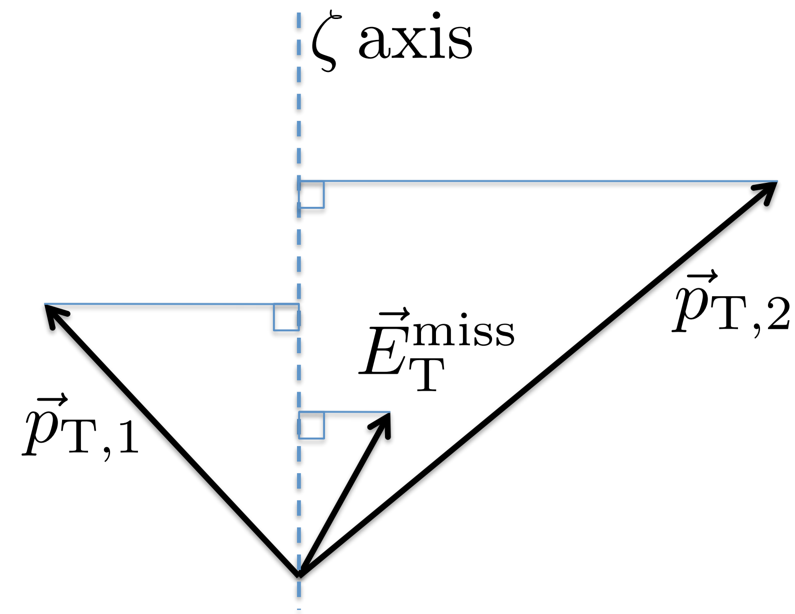

Data
CMS preliminary L = 19.5 fb^-1 (8TeV)
M_ll (GeV)
M_T (GeV)

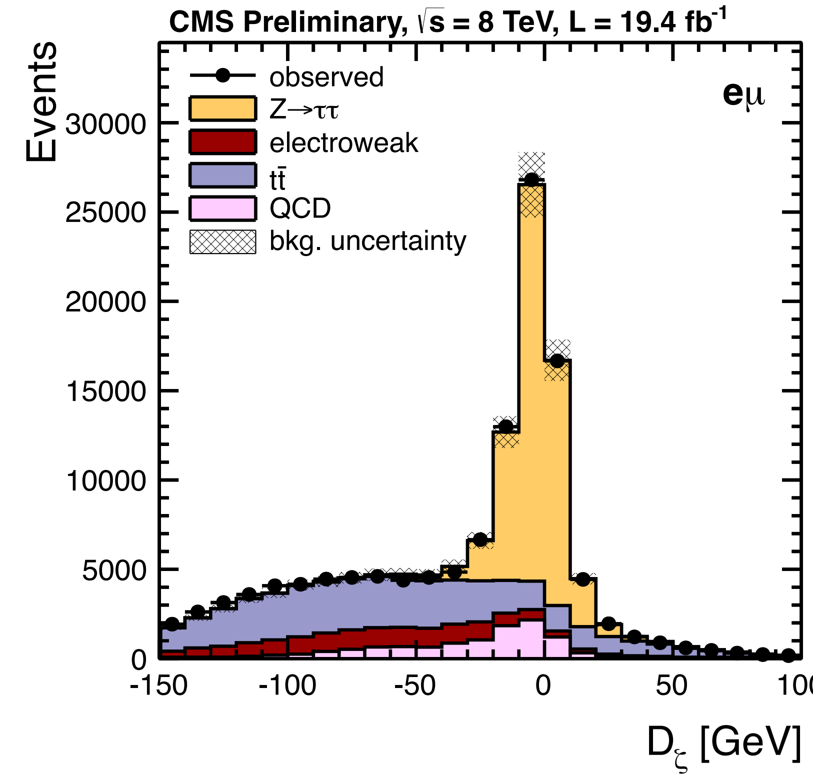

Data - Background
CMS preliminary L = 19.5 fb^-1 (8TeV)
M_ll (GeV)
M_T (GeV)
7.3 ± 8.7
3.6 ± 11.1
-1.8 ± 9.1
-7.9 ± 11.9
-14.4 ± 9.9
-14.7 ± 17.9
-1.7 ± 7.0
13.6 ± 11.1
3.4 ± 8.9
-4.6 ± 11.0
3.6 ± 9.3
-5.2 ± 8.6
-3.7 ± 8.3
14.7 ± 8.7
-7.0 ± 9.1
3.1 ± 8.8
-3.0 ± 10.6
6.2 ± 14.9
-4.7 ± 7.2
3.5 ± 8.6
-6.6 ± 9.1
15.3 ± 8.9
0.2 ± 9.4
-2.9 ± 8.7
5.5 ± 7.6
-3.9 ± 7.4
-2.1 ± 8.2
8.3 ± 7.4
-6.7 ± 8.2
-3.7 ± 6.1

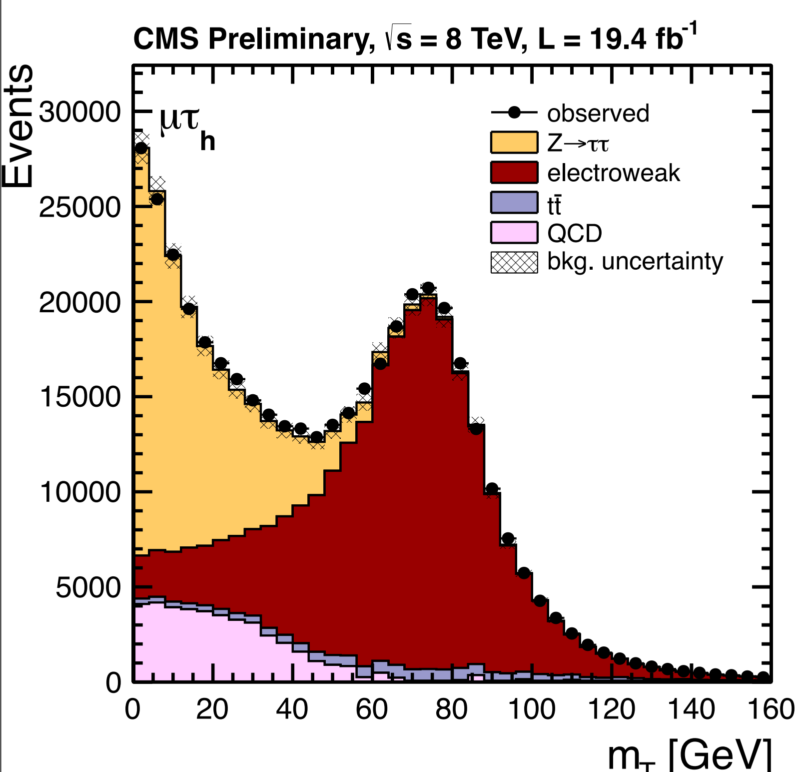
H→ττ, Selection

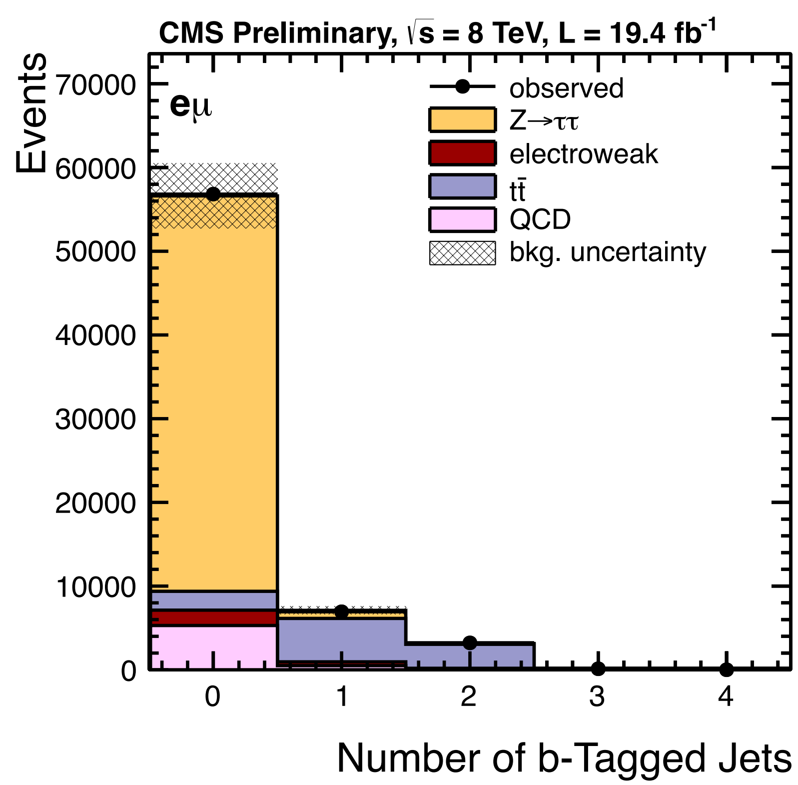
H→ττ

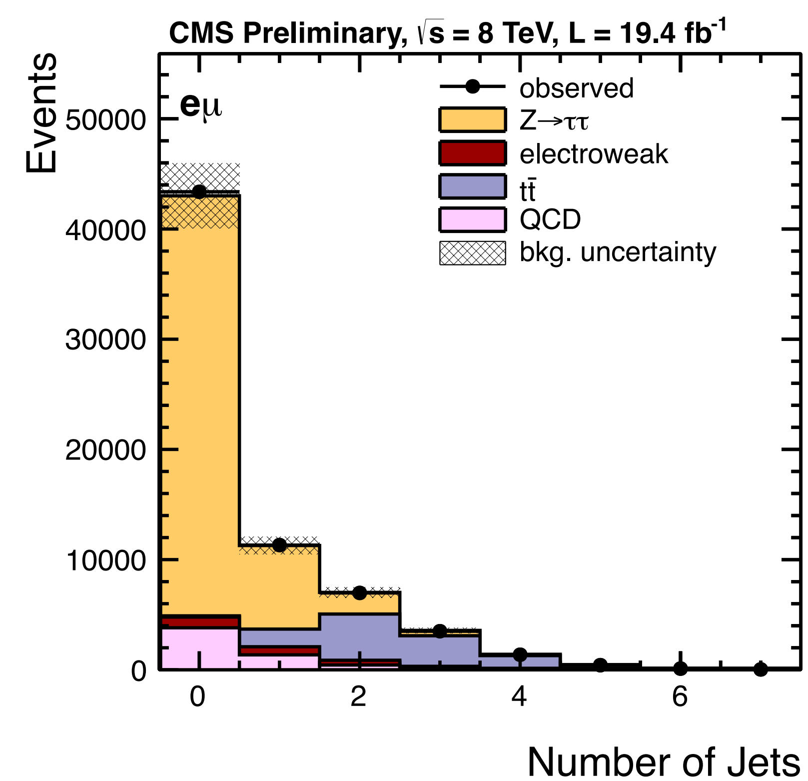
HIG-13-004



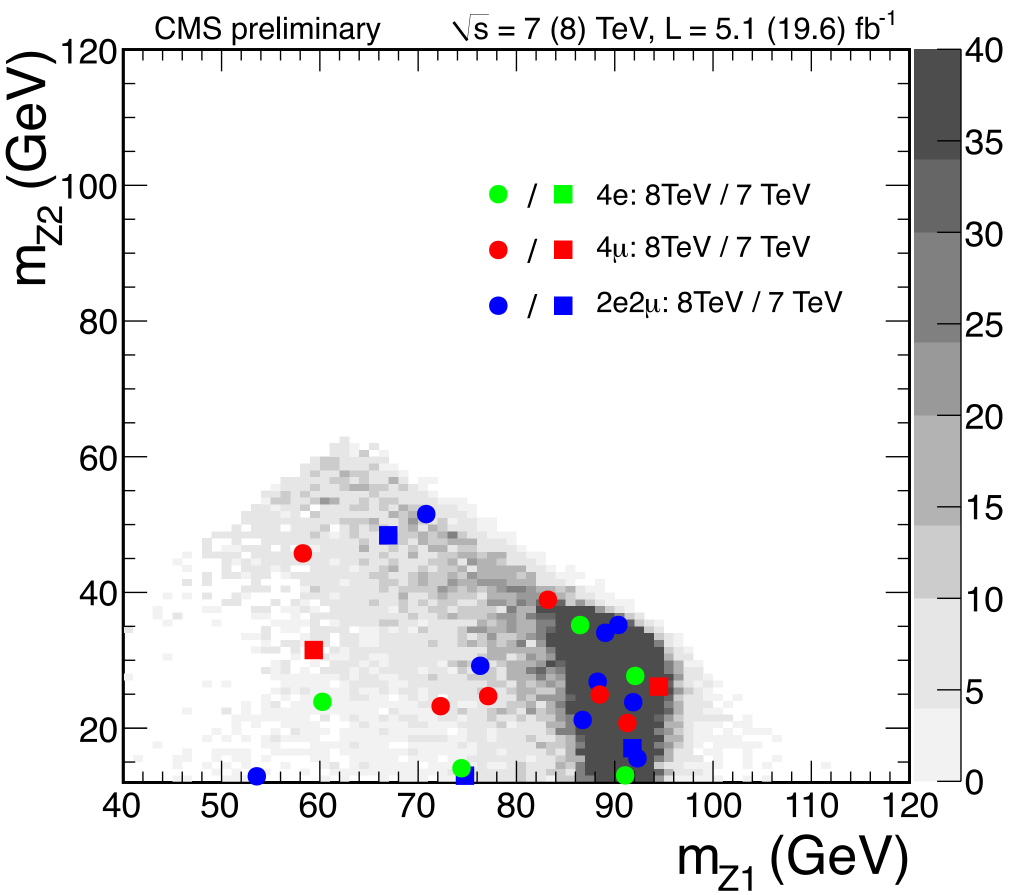


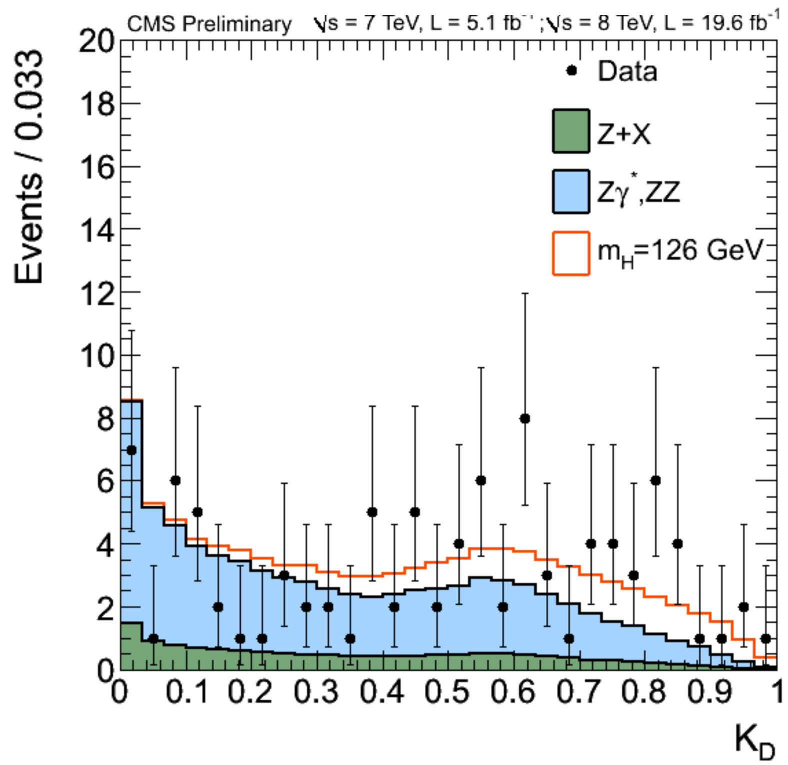


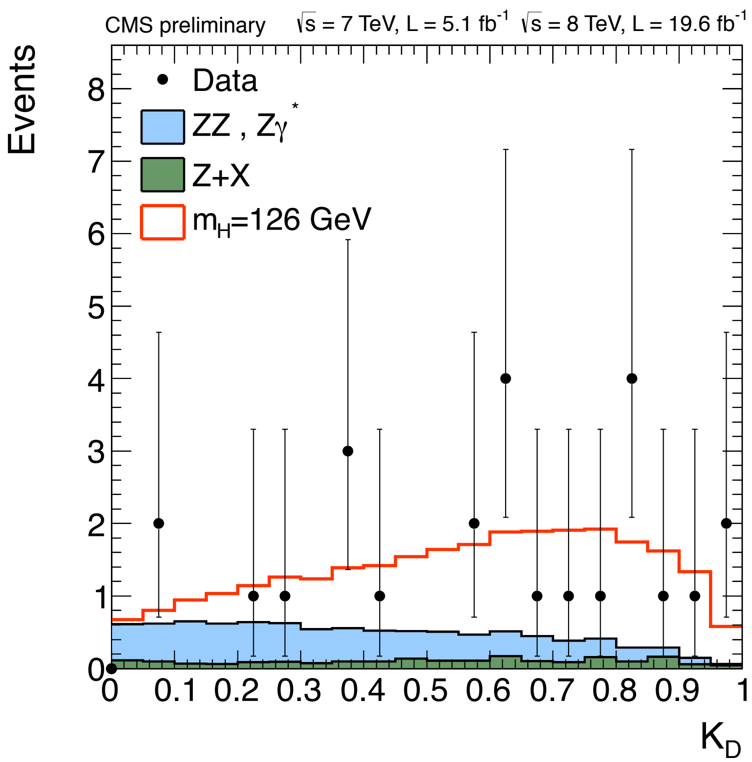




ZZ


CMS preliminary
√s = 7 (8) TeV, L = 5.1 (19.6) fb⁻¹
4e: 8TeV / 7 TeV
4μ: 8TeV / 7 TeV
2e2μ: 8TeV / 7 TeV
m_Z2 (GeV)
m_Z1 (GeV)


CMS Preliminary
√s = 7 TeV, L = 5.1 fb⁻¹ ; √s = 8 TeV, L = 19.6 fb⁻¹
Data
Z+X
Zγ*,ZZ
m_H=126 GeV
Events / 0.033
K_D

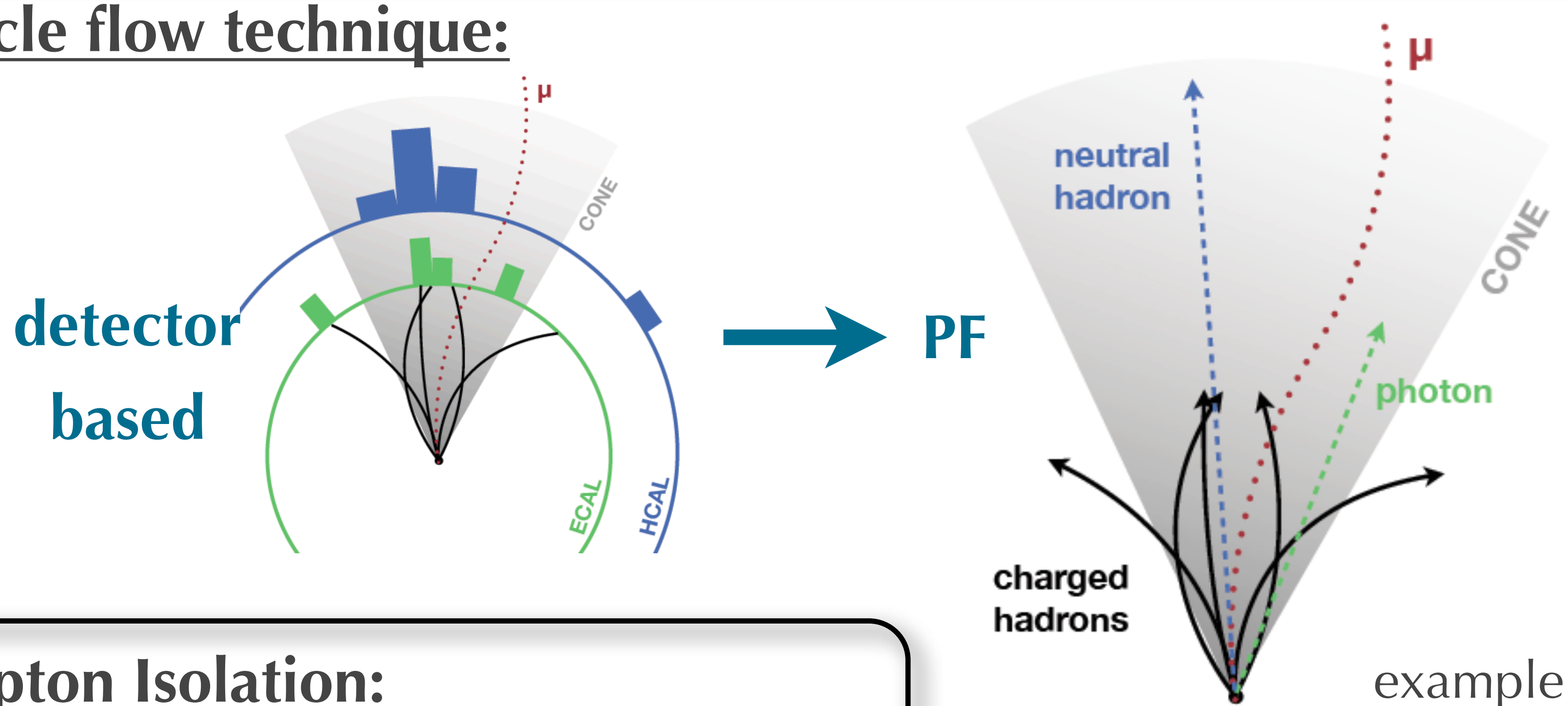

CMS preliminary
√s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 19.6 fb⁻¹
Data
ZZ , Zγ*
Z+X
m_H=126 GeV
Events
K_D

Object isolation

H→Zγ

HIG-13-006

Particle flow technique:



Pile Up correction applied to both leptons and photon PF isolation

Lepton Isolation:

cone ΔR<0.4

$$\frac{\sum p_T(PFcand) + \sum E_T(PFcand)}{p_T(lep)} < 0.4$$

with medium energy per unit area (ρ) subtracted

Photon isolation:

cone ΔR<0.3

Barrel, EndCap

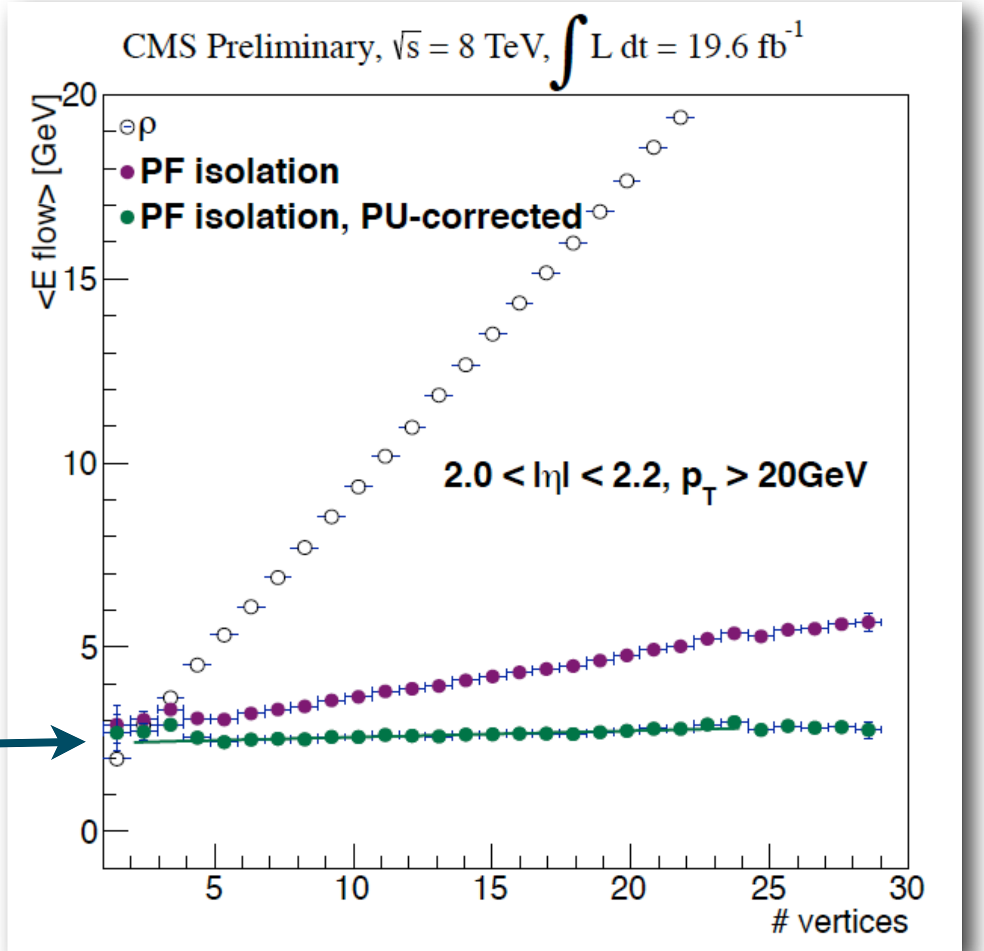
$$\sum p_T(ChHad) < 1.5, 1.2$$

$$\sum p_T(NeuHad) < 1, 1.5$$

$$\sum p_T(Photons) < 0.7, 1$$

isolation variables independent of nVtx

example for electrons:

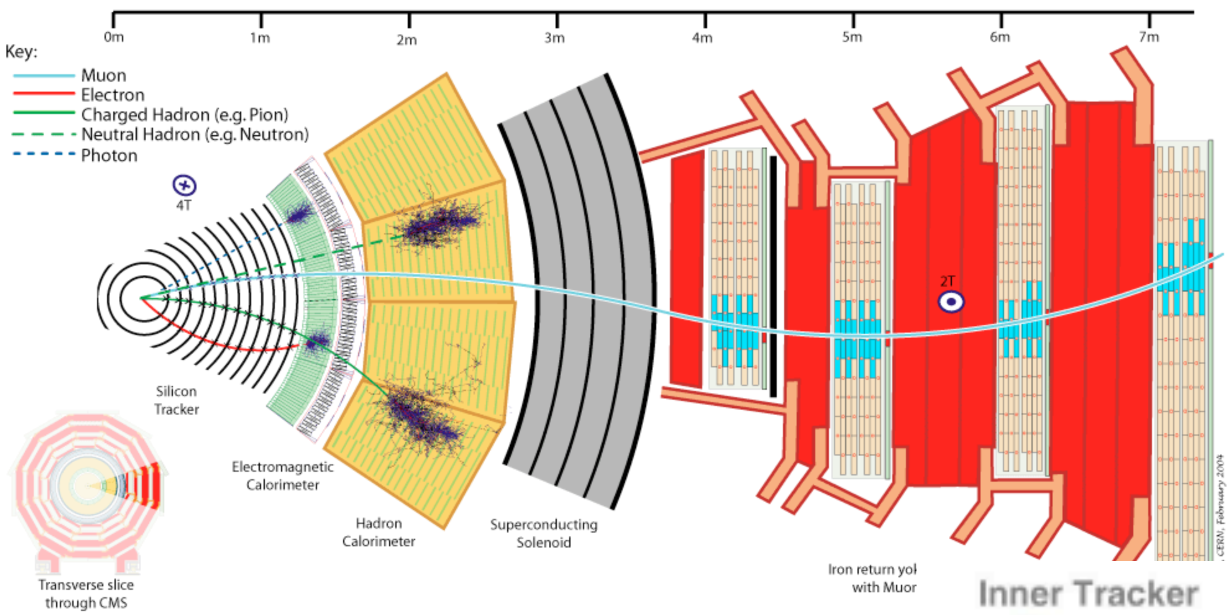


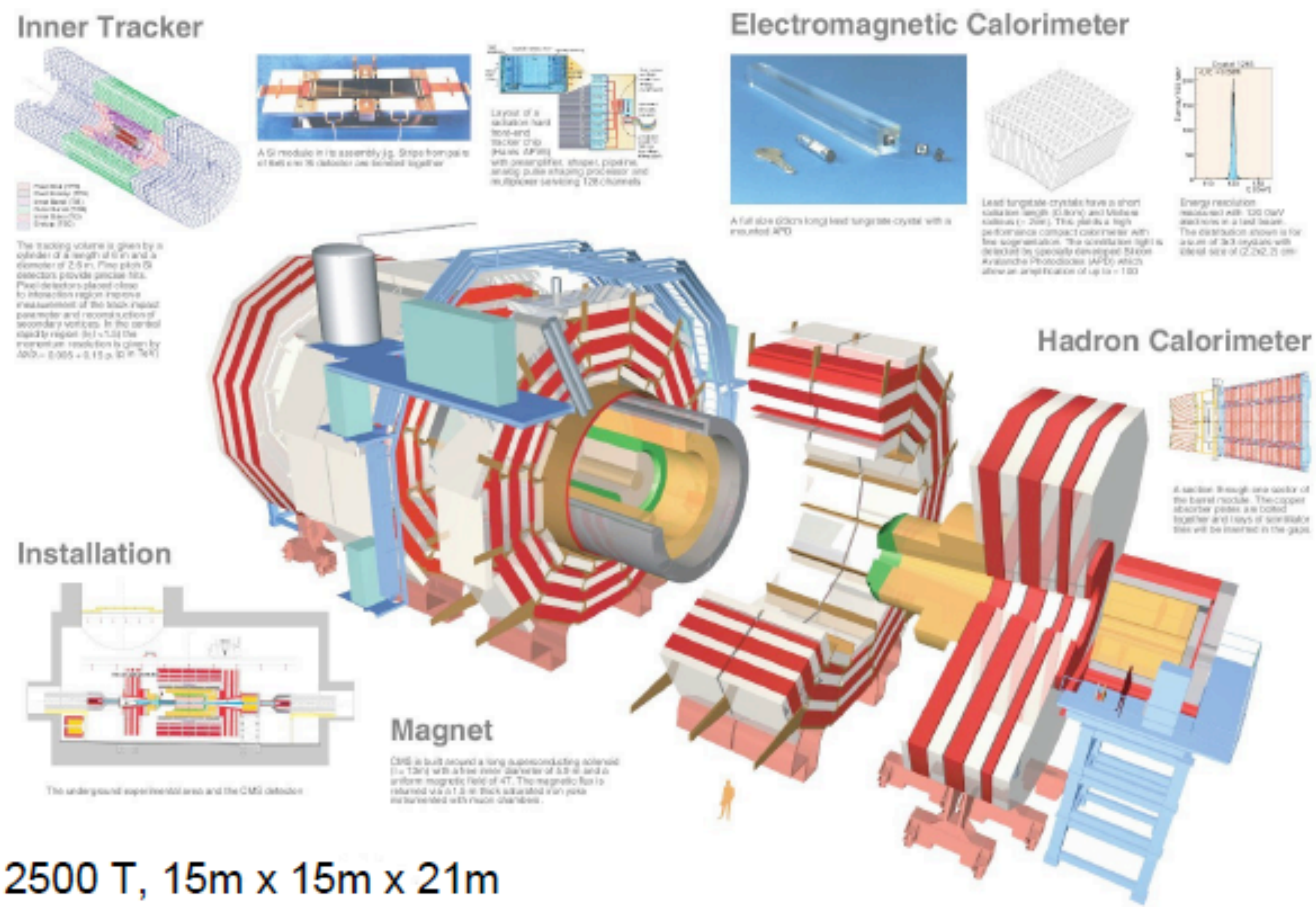
combination

combination

HIG-13-005

Model parameters	Assessed scaling factors (68% and 95% CL intervals)		
λ_{WZ}, κ_Z	λ_{WZ}	[0.75,1.13]	[0.60,1.40]
λ_{WZ}, κ_Z, κ_f	λ_{WZ}	[0.73,1.00]	[0.62,1.19]
κ_V, κ_f	κ_V	[0.81,0.97]	[0.73,1.05]
	κ_f	[0.71,1.11]	[0.55,1.31]
κ_γ, κ_g	κ_γ	[0.79,1.14]	[0.59,1.30]
	κ_g	[0.73,0.94]	[0.63,1.05]
$\mathcal{B}(H \to BSM)$, κ_γ, κ_g	$\mathcal{B}(H \to BSM)$	[0.00,0.24]	[0.00,0.52]
λ_{du}, κ_V, κ_u	λ_{du}	[1.00,1.60]	[0.74,1.95]
$\lambda_{\ell q}$, κ_V, κ_q	$\lambda_{\ell q}$	[0.89,1.62]	[0.57,2.05]
κ_V, κ_b, κ_τ, κ_t, κ_g, κ_γ	κ_V	[0.84,1.23]	[0.60,1.39]
	κ_b	[0.61,1.69]	[0.00,2.63]
	κ_τ	[0.82,1.45]	[0.53,1.81]
	κ_t	[0.00,2.03]	[0.00,4.20]
	κ_g	[0.65,1.15]	[0.49,1.77]
	κ_γ	[0.77,1.27]	[0.55,1.55]
as above + $\mathcal{B}(H \to BSM)$, but $\kappa_V \le 1$	$\mathcal{B}(H \to BSM)$	[0.00,0.30]	[0.00,0.64]





12500 T, 15m x 15m x 21m