ETH Institute for Particle Physics

Higgs results from CMS

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Zürich Phenomenology Workshop
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Contents

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Status of the experiment

Highlights from the Higgs analyses:

- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^{(*)}$
- $H \rightarrow W^{+}W^{-}$
- $H \rightarrow b\bar{b}$
- $H \rightarrow \tau^{+}\tau^{-}$

Properties measurements

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

CMS - Compact Muon Solenoid

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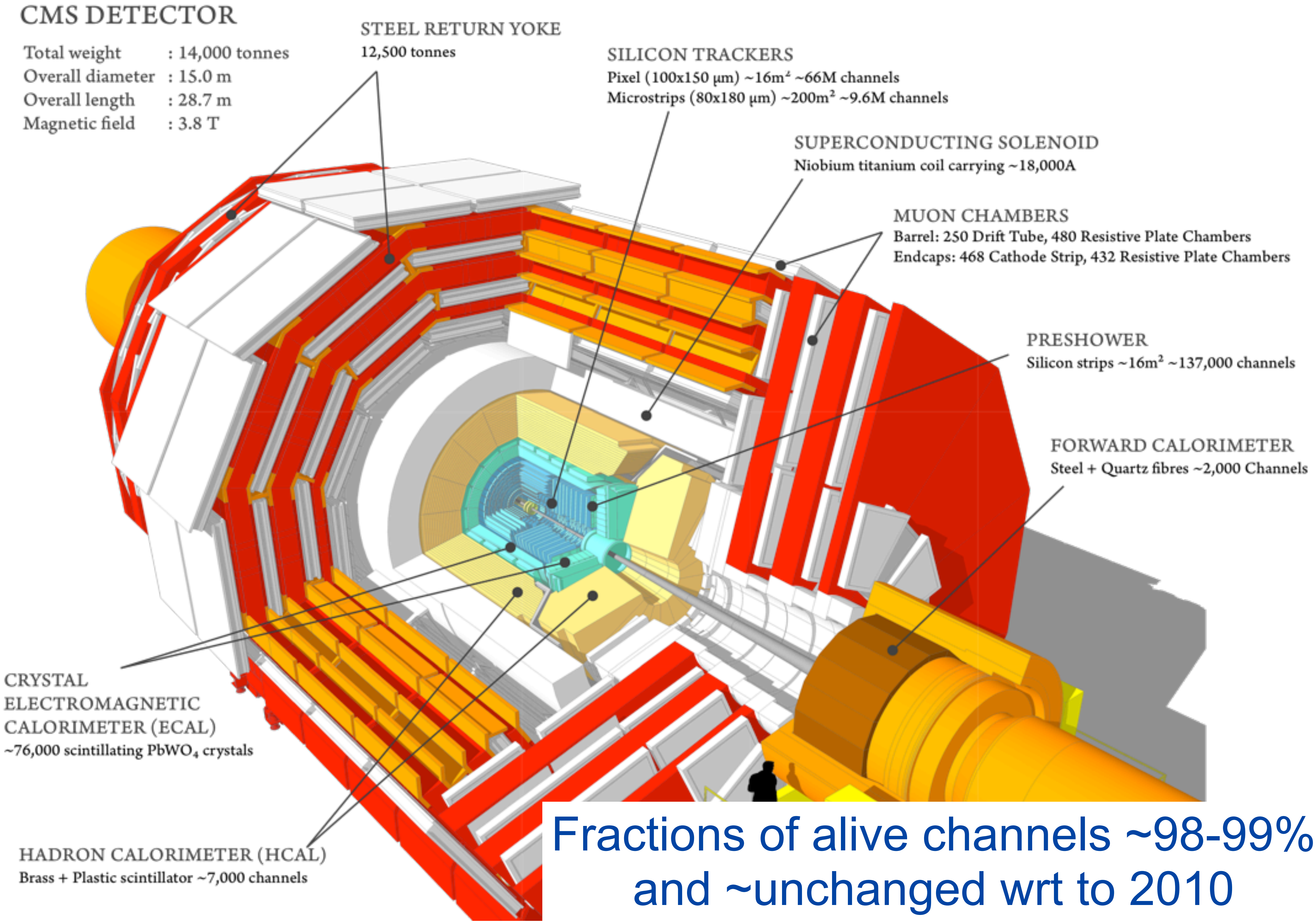

Fractions of alive channels ~98-99% and ~unchanged wrt to 2010

Dataset

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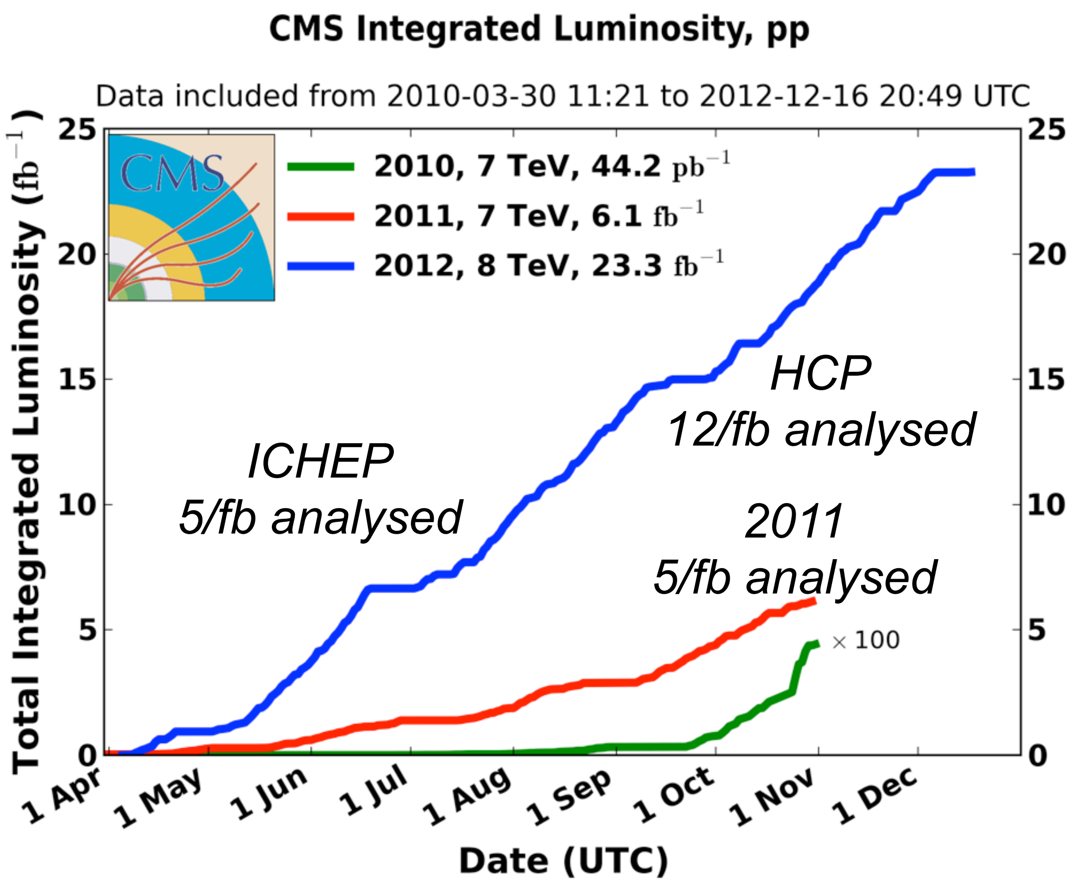
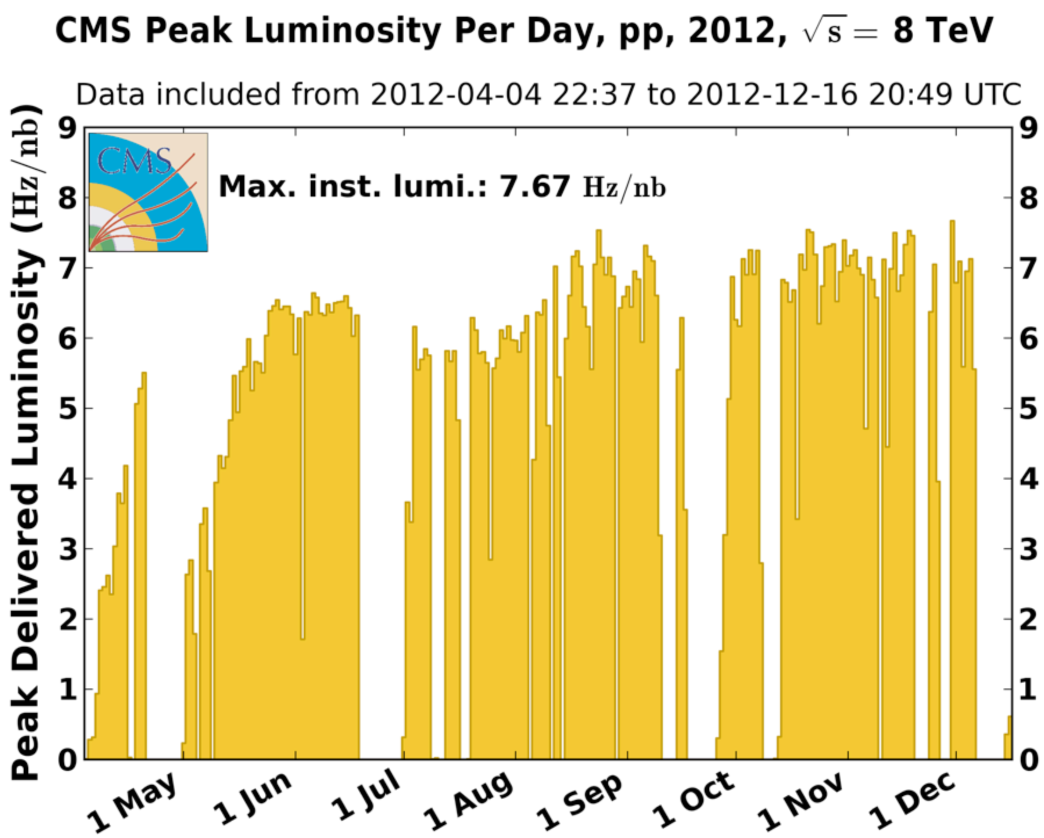
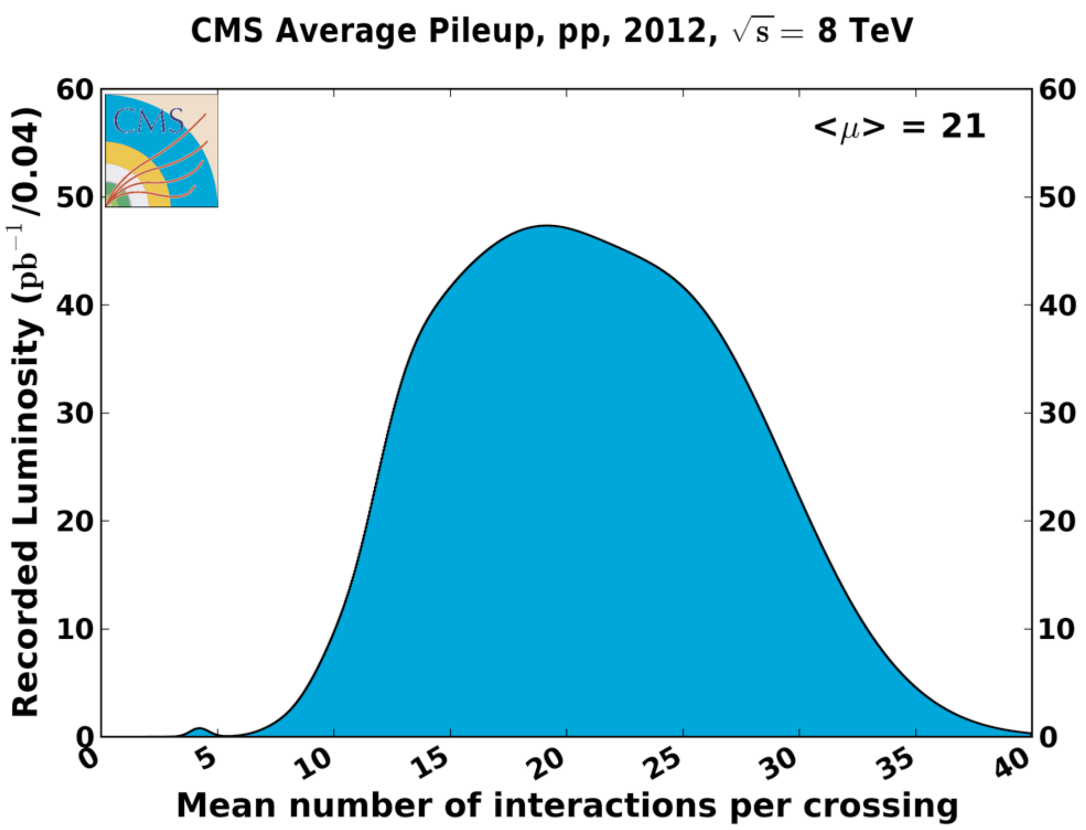




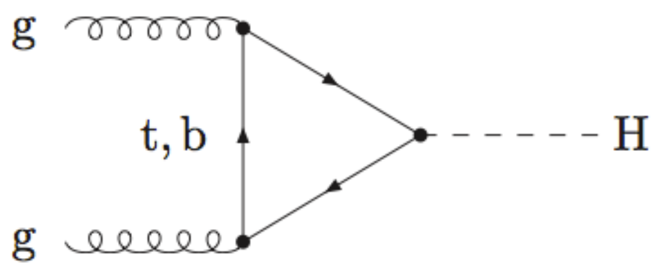


The LHC is performing extremely well !

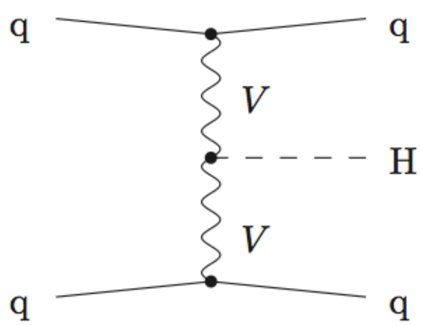
CMS data taking efficiency ~94%

Higgs Production

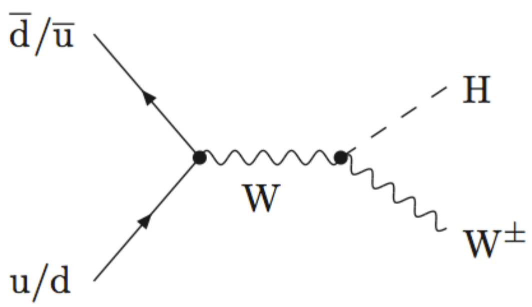
gluon fusion



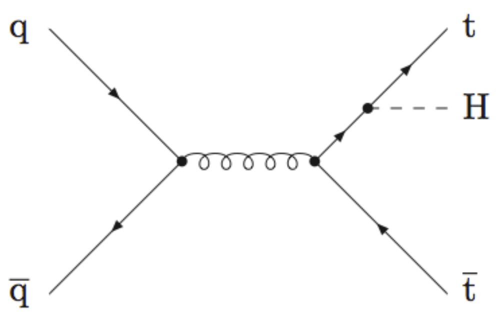
vector boson fusion

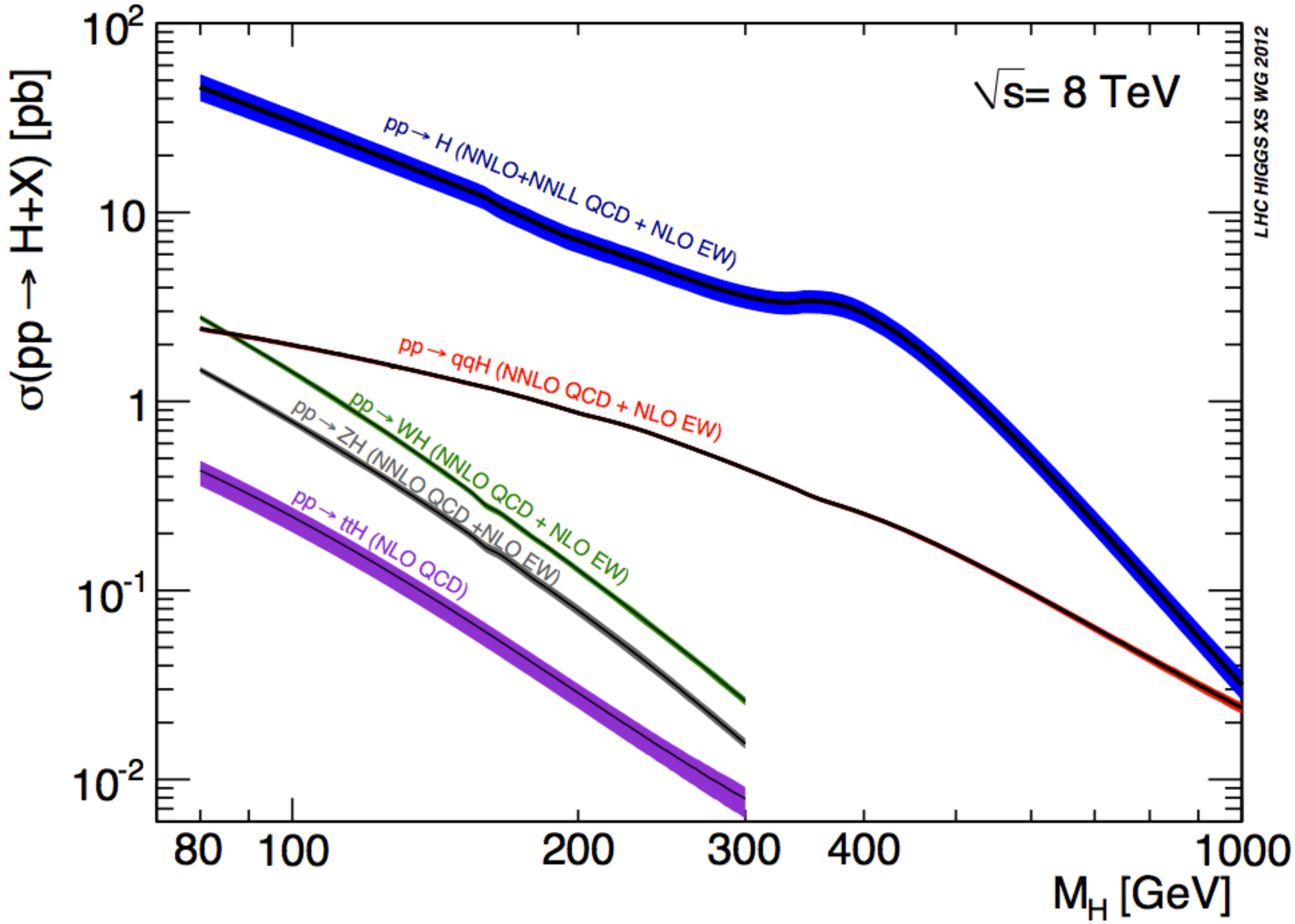


associate production

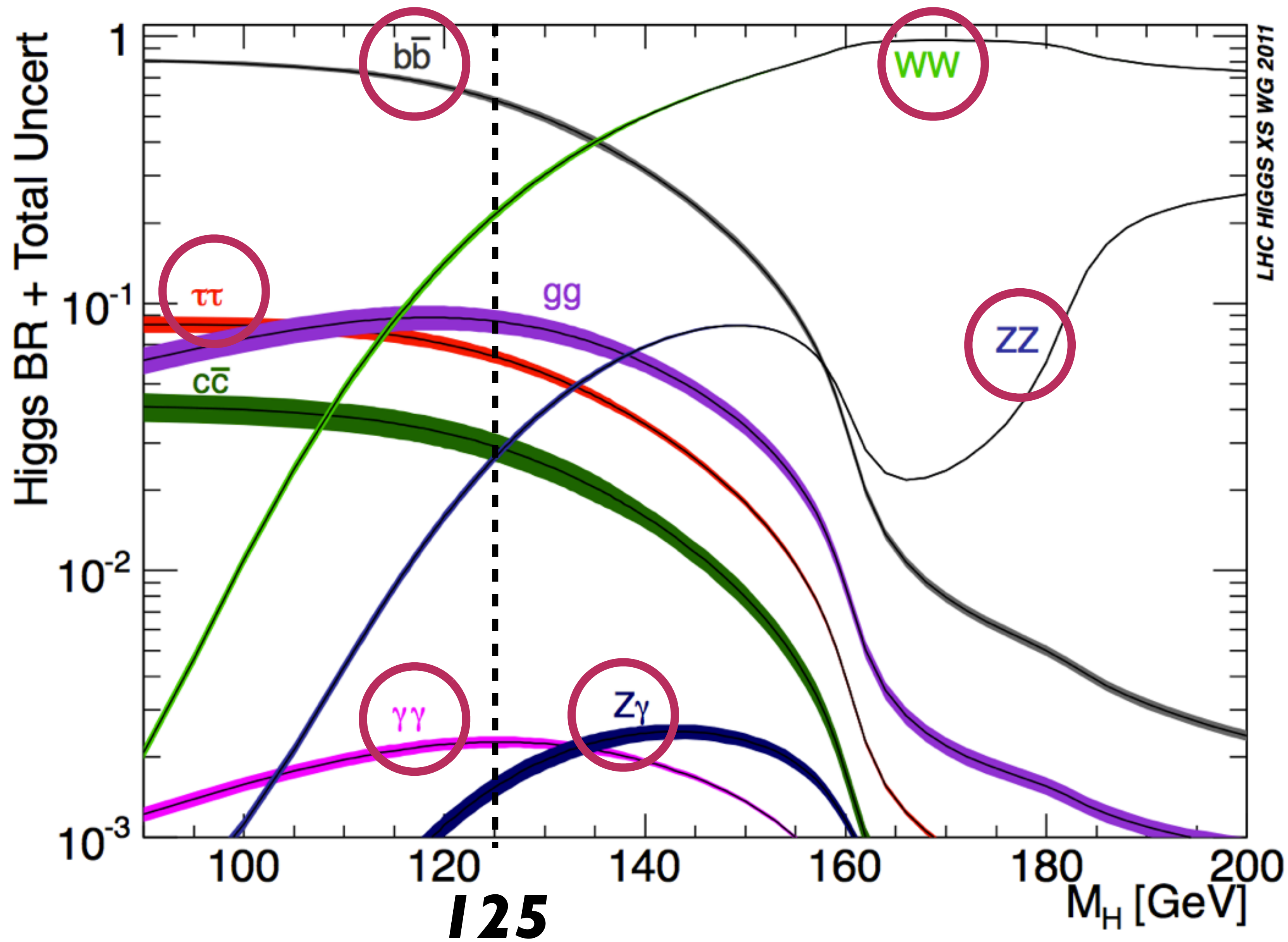


ttH





Higgs Decay


Higgs BR + Total Uncert
1
10^{-1}
10^{-2}
10^{-3}
100
120
140
160
180
200
M_H [GeV]
125
$b\bar{b}$
WW
ττ
gg
$c\bar{c}$
ZZ
γγ
Zγ
LHC HIGGS XS WG 2011

Main Higgs Analyses

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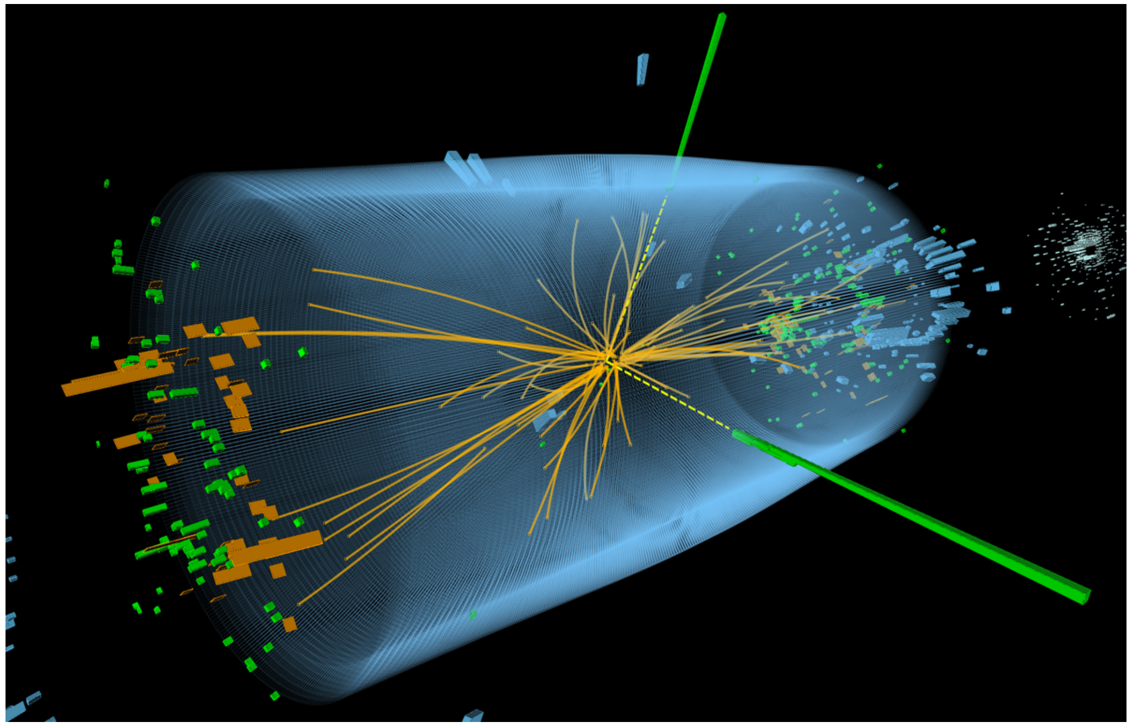
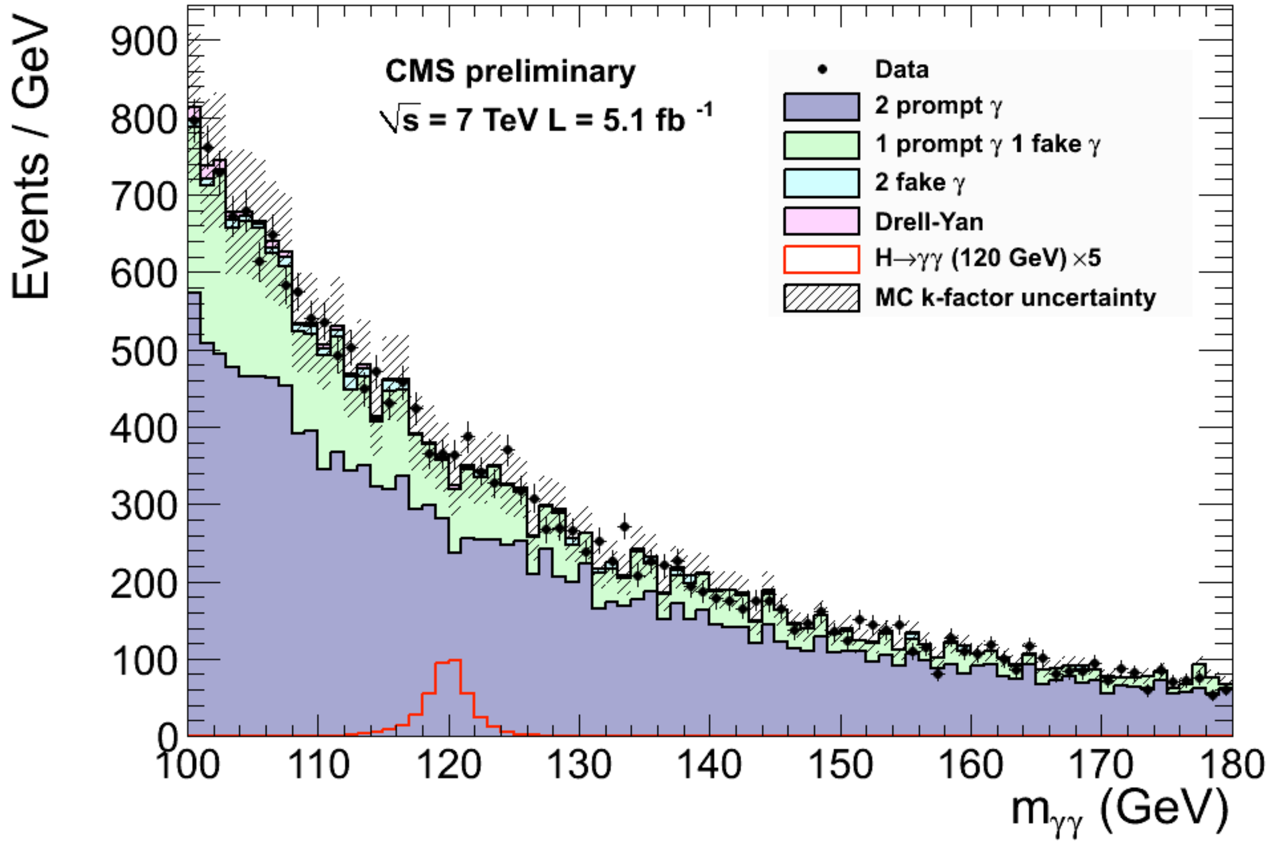
	mass range [GeV]	mass resolution	Data [fb^{-1}] @7TeV + @8TeV	untagged	VBF-tag	VH-tag	ttH-tag
$H \rightarrow \gamma\gamma$	110-150	1-2%	5+5	✓	✓		
$H \rightarrow Z\ Z^{(*)}$	110-1000	1-2%	5+12	✓			
$H \rightarrow b\bar{b}$	110-135	10%	5+12			✓	✓
$H \rightarrow \tau^+\tau^-$	110-145	15%	5+12	✓	✓	✓	
$H \rightarrow W^+W^-$	110-600	20%	5+12	✓	✓	✓	

Blinding procedures were applied to all channels

H → γγ: highlights





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

Fully reconstructed mass peak:
- Find the right vertex (BDT)
  - ~6cm beam-spot z-spread
- Photon Energy regression

Large QCD (γγ, γj, jj) backgrounds

Photon identification BDT:
- distinguish photons from jets faking photons

Di-Photon BDT categorization:
- S/B and mass resolution
- optimized on expected limit

Signal extraction:
- mass fit on di-photon categories

Cross check analyses:
- Cut in Categories
- Fit the background from sidebands

H → γγ: energy calibrations

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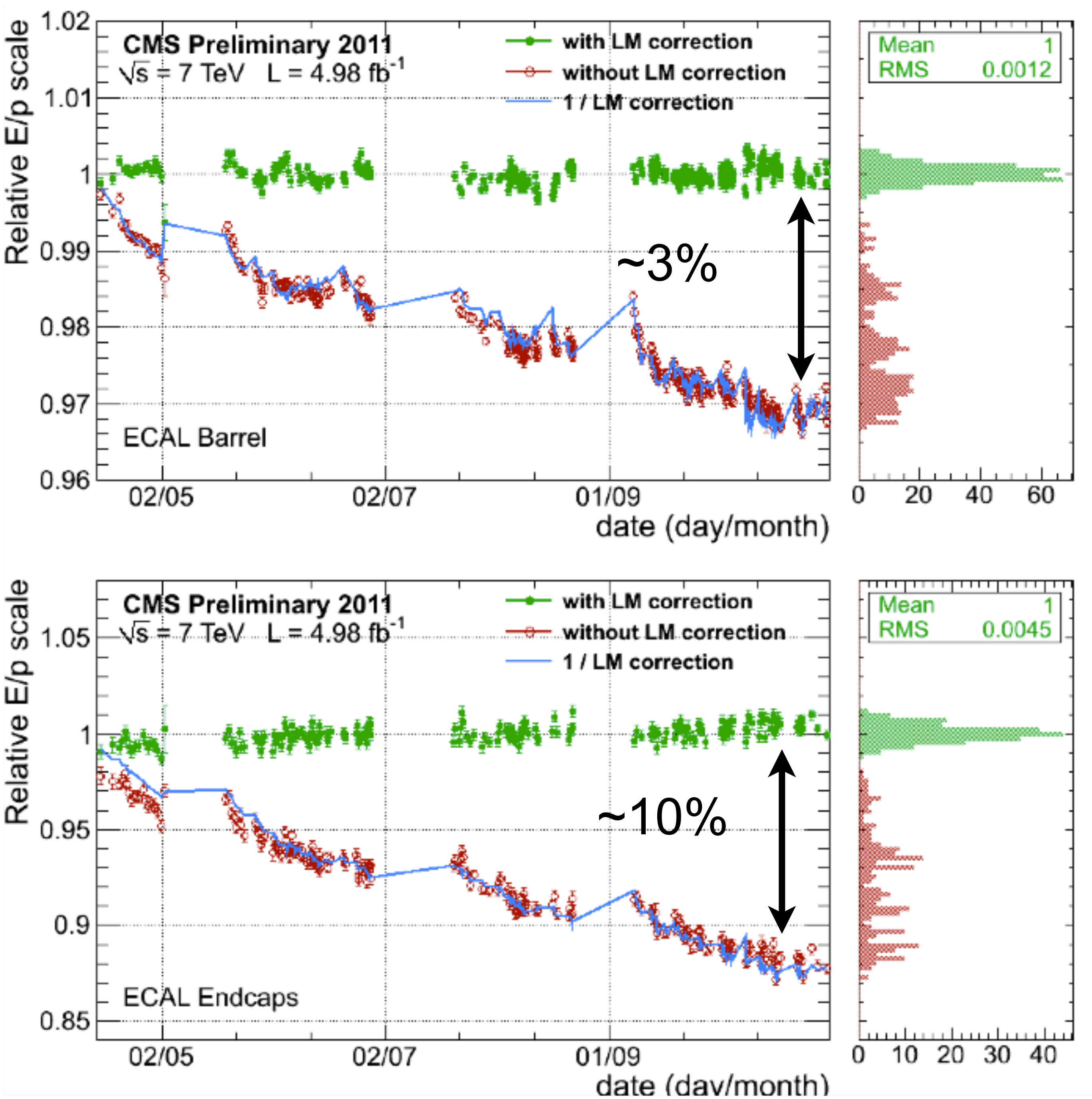

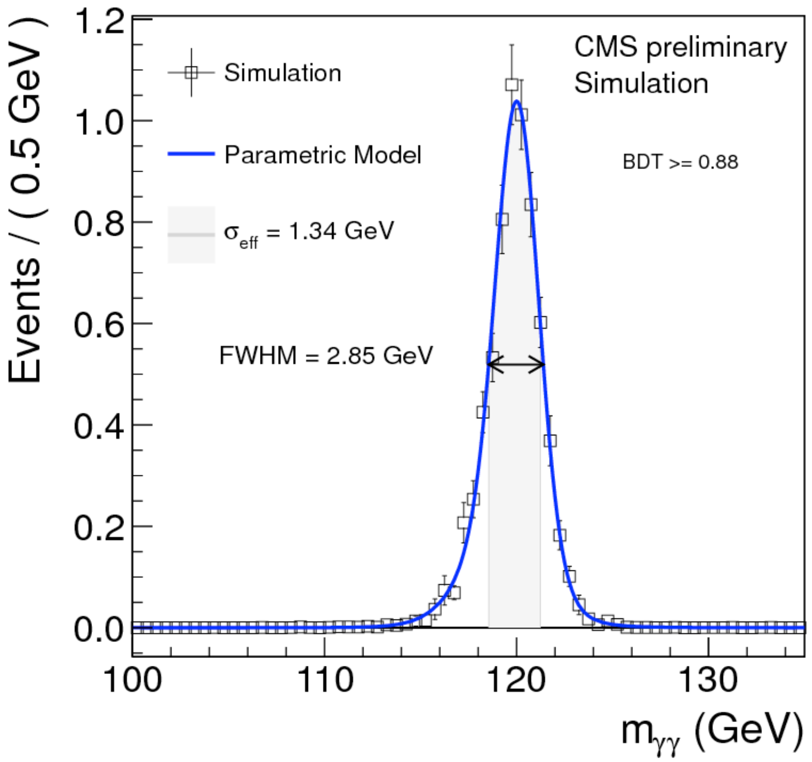

Energy calibrations:
- ECAL crystals transparency loss
- Inter-calibrations (for uniformity)
- Energy regression

Calibration stable with time

Mass resolution order of 1-2%

$H \rightarrow \gamma\gamma$: events classifications

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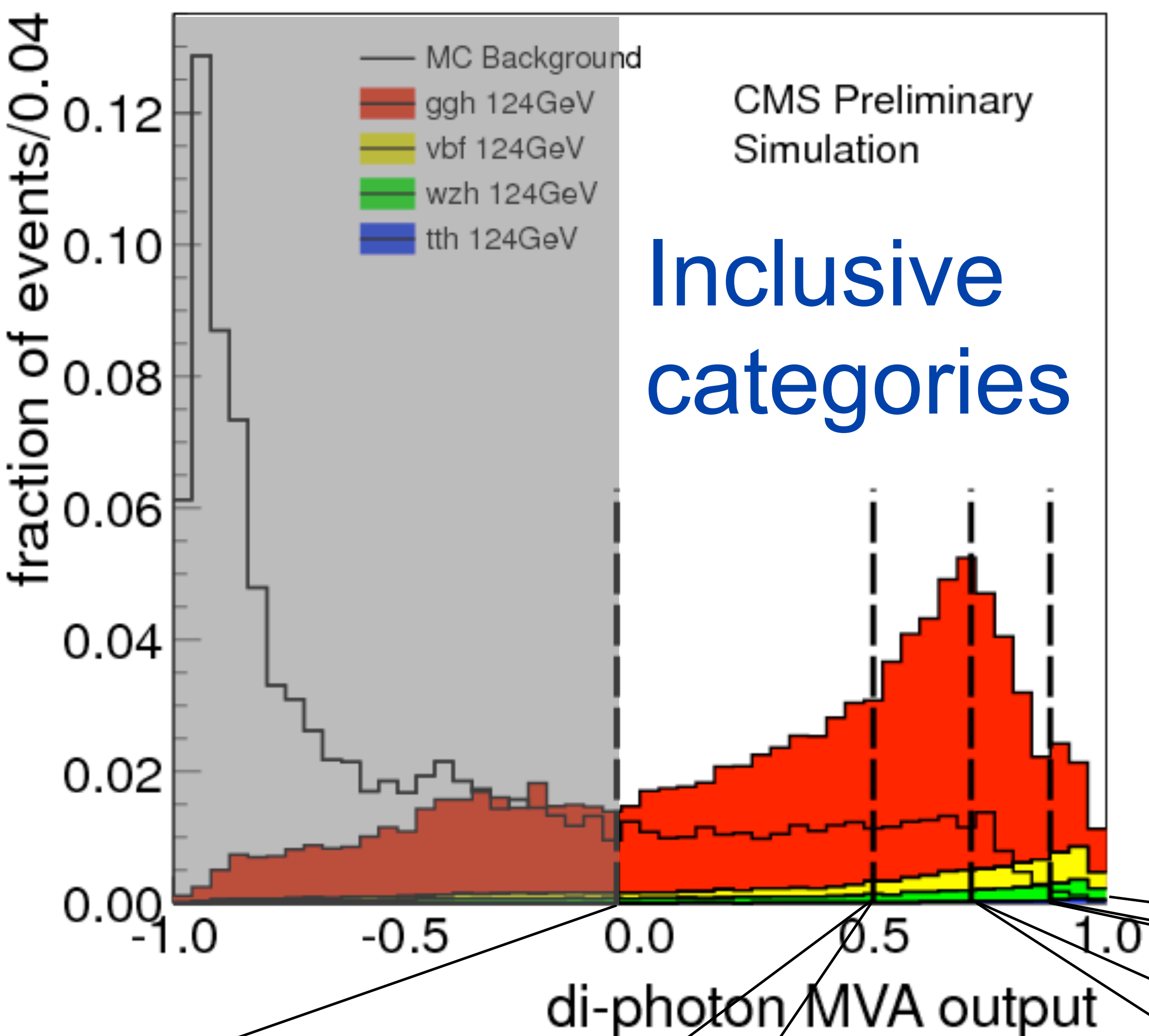
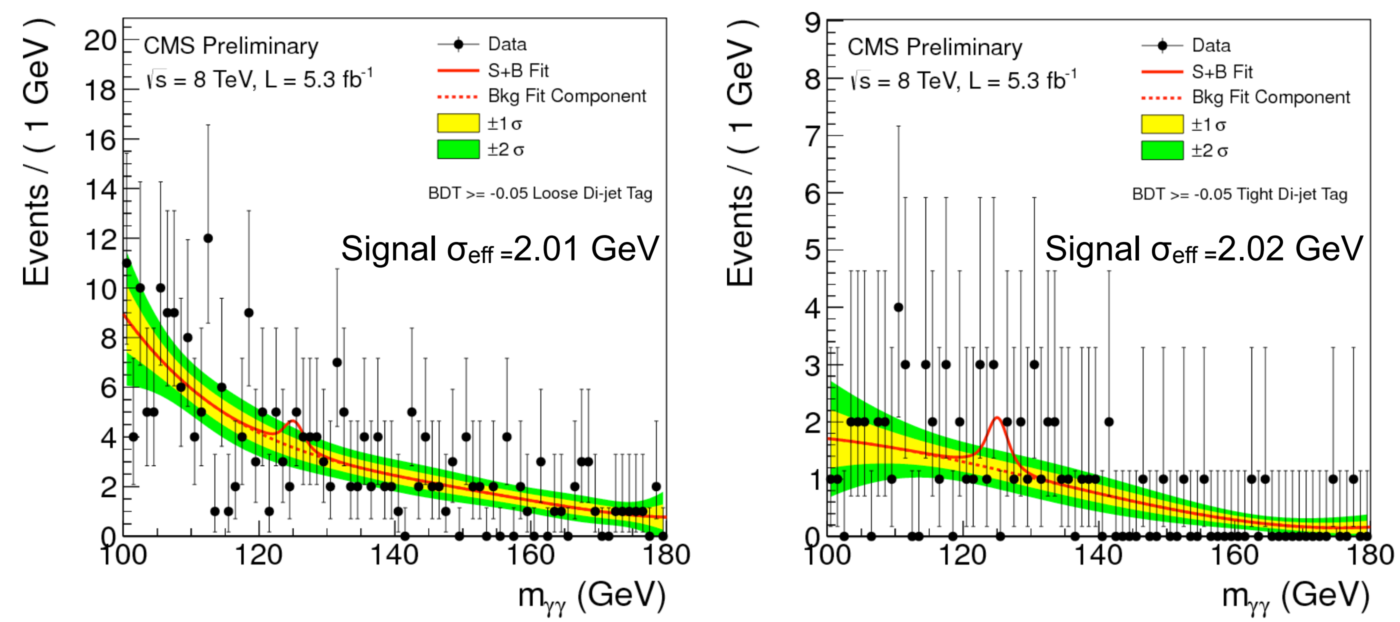
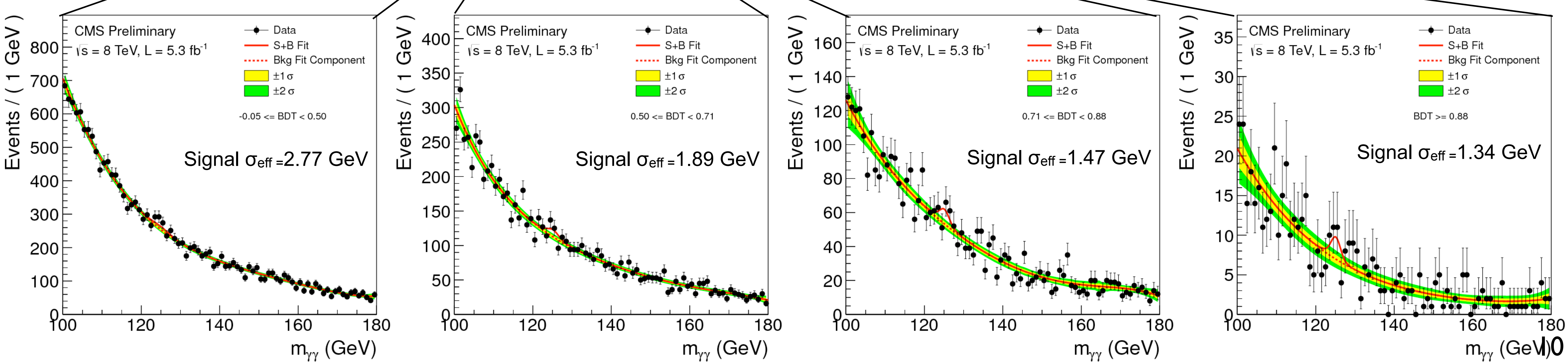


2 di-jet categories: (VBF)



Fit background from data (polynomials)



H → γγ: results

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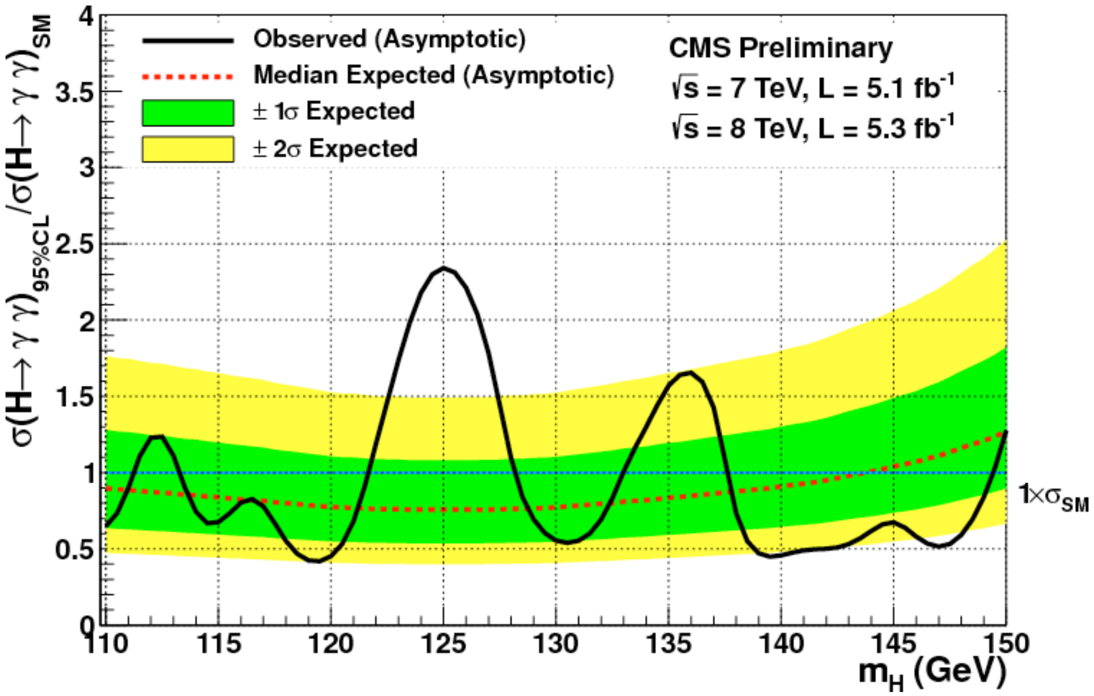

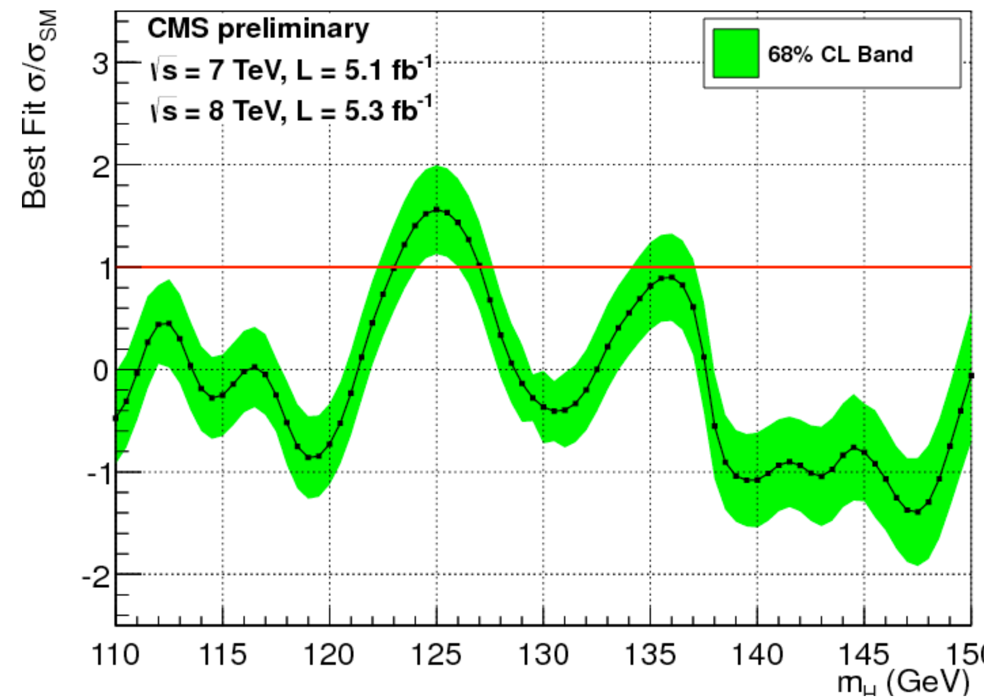

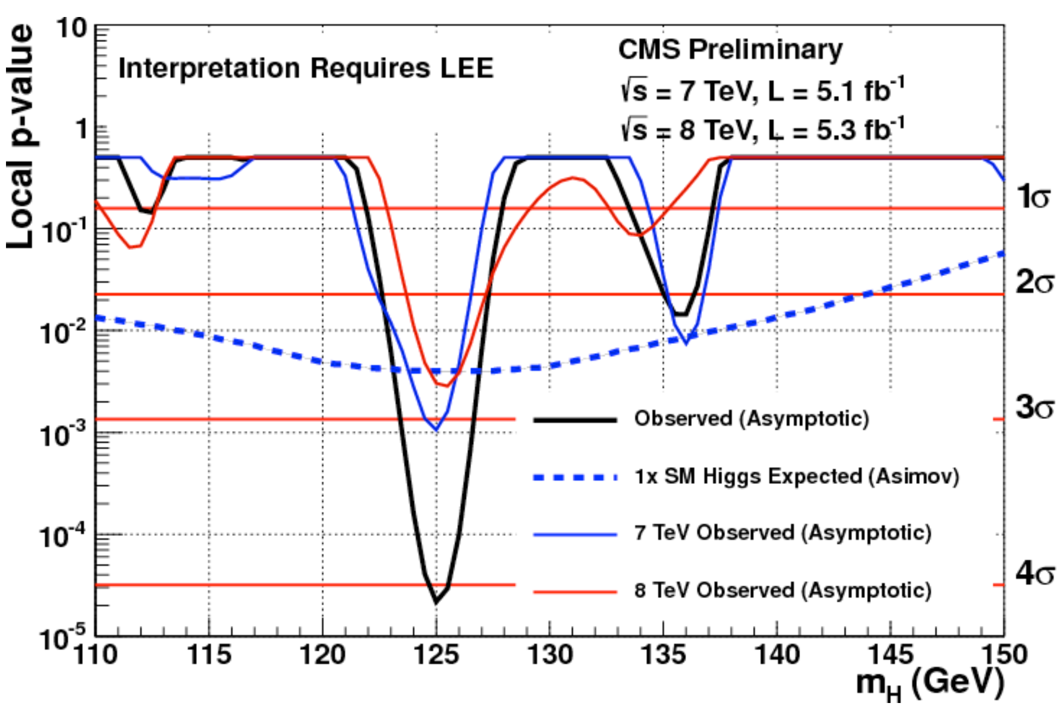

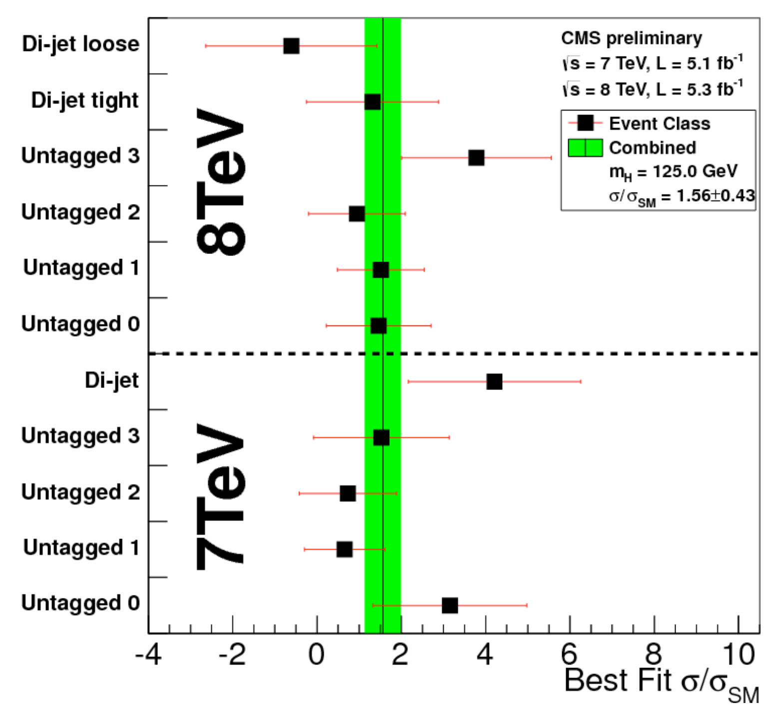

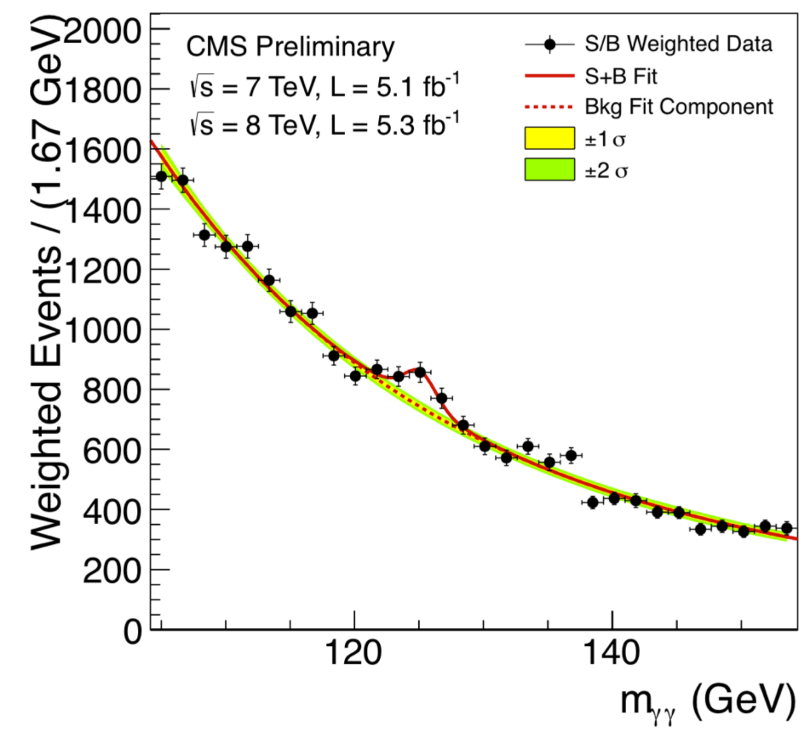

At 125 GeV: local significance 4.1σ
best fit signal strength 1.56 ± 0.43

$H \rightarrow ZZ^{(*)}$: highlights

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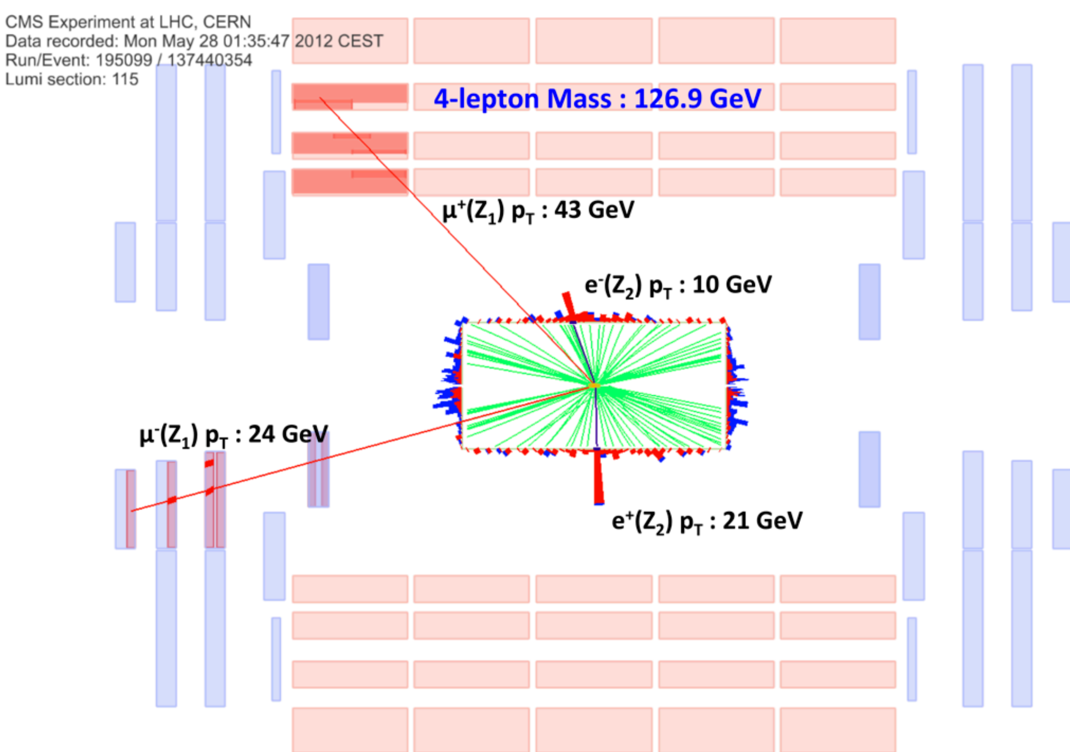
$H \rightarrow 4l$ $H \rightarrow 2l2\tau$ $H \rightarrow 2l2\nu$



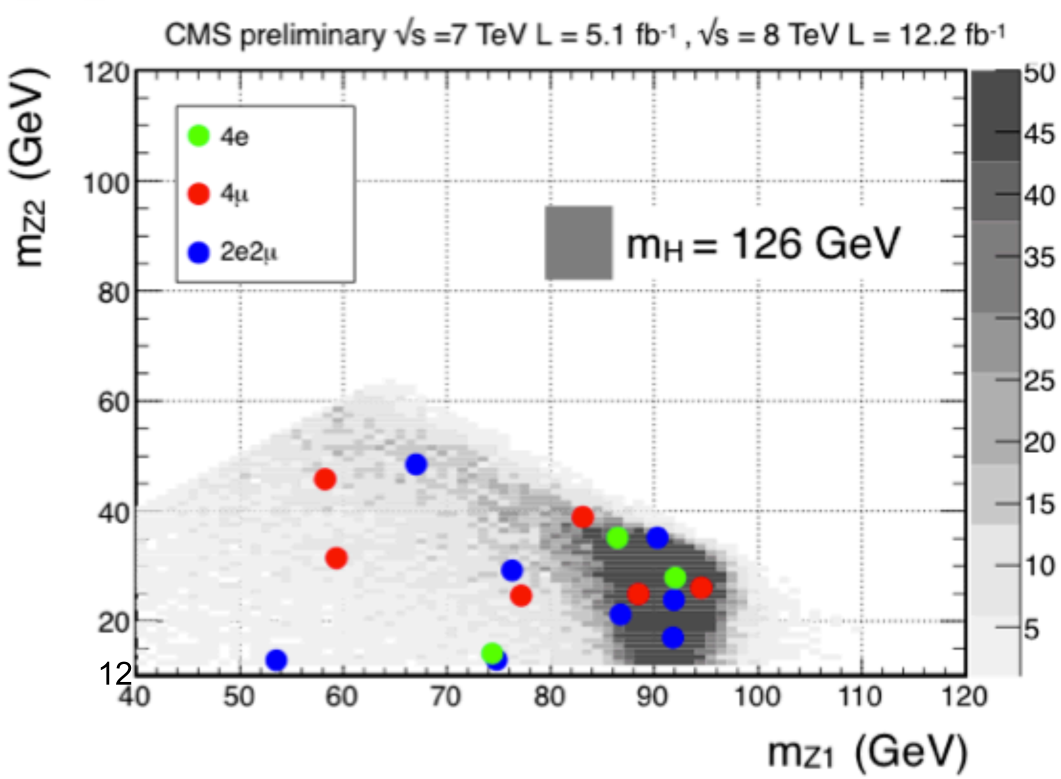
Golden channel: S/B~ 2:1

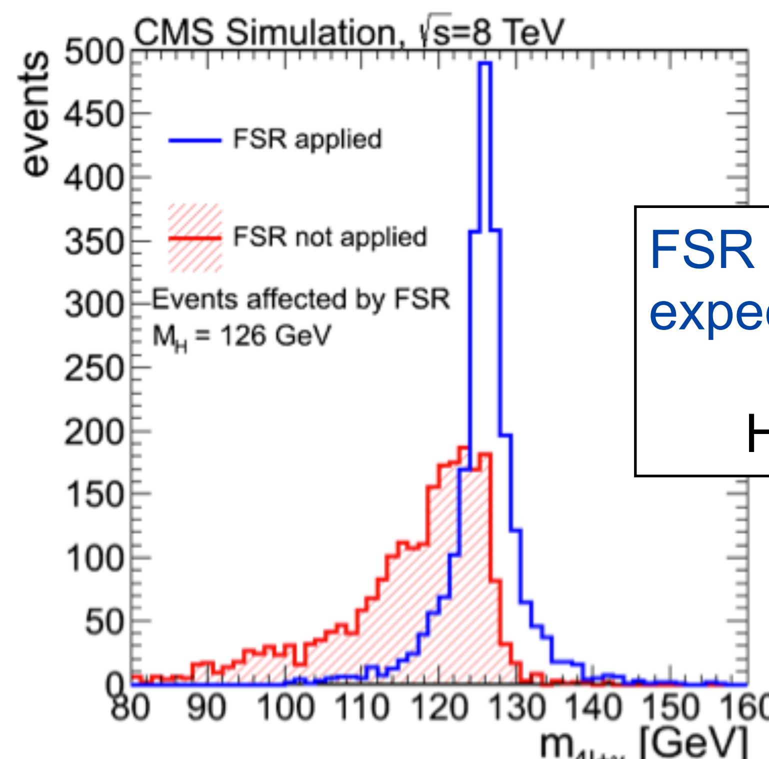
Fully reconstructed mass peak

Event selection:
4 isolated leptons from the same vertex
Lowest $p_T(\mu)$>5 GeV, $p_T(e)$>7 GeV

Mass(4l) resolution is ~1-2%

Backgrounds:
Non-resonant ZZ: MC (NLO with MCFM)
Reducible (Z+X, tt, Zbb) → data (<< ZZ)
all ~ flat around 125 GeV





FSR recovery expected gain:
3%, 2%, 1%
H → 4μ, 2e2μ, 4e

$H \rightarrow ZZ^{(*)}$: results

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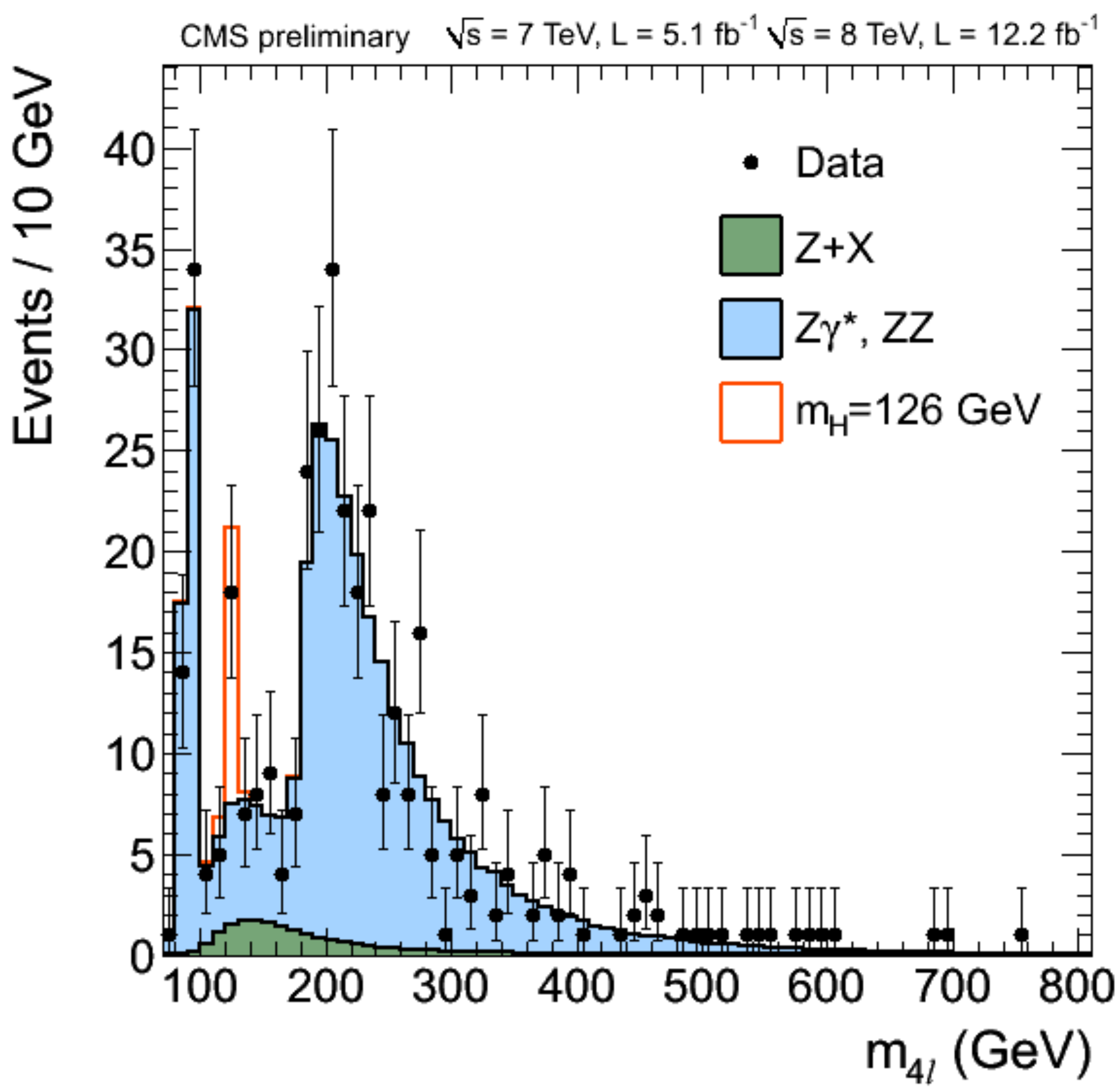

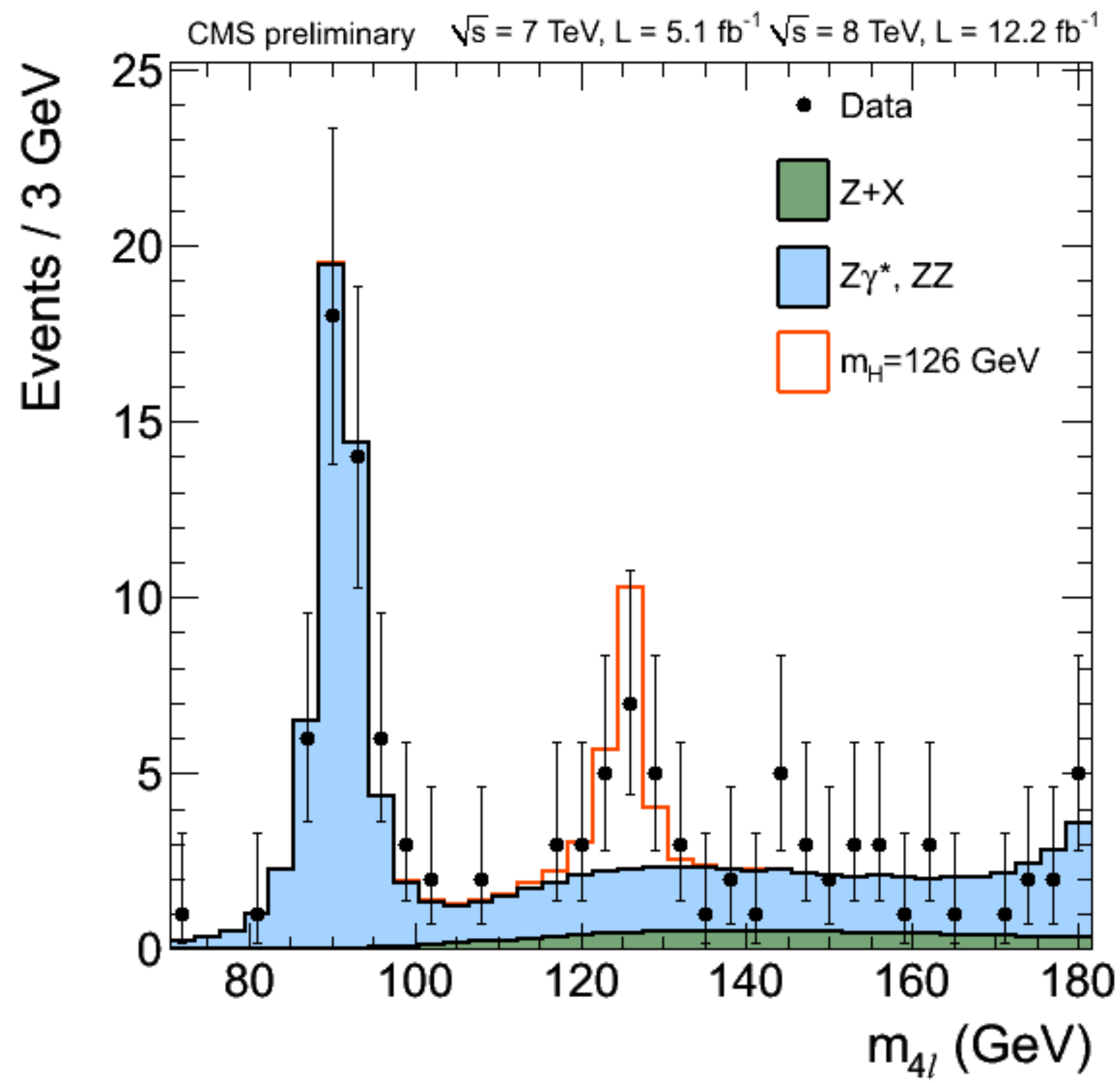

Expected events: background 6.5

signal 12.5

Observed events 17

$H\rightarrow ZZ^{(*)}$: Kinematic Discriminant

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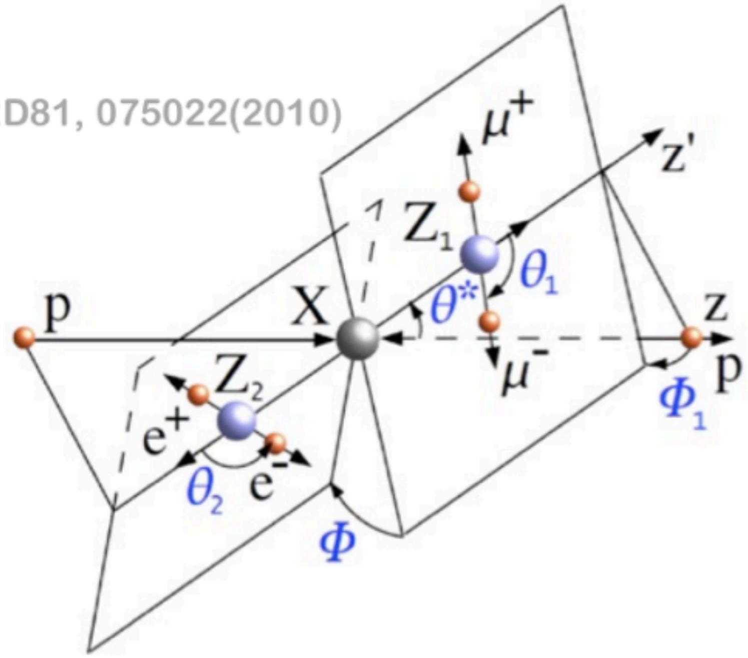
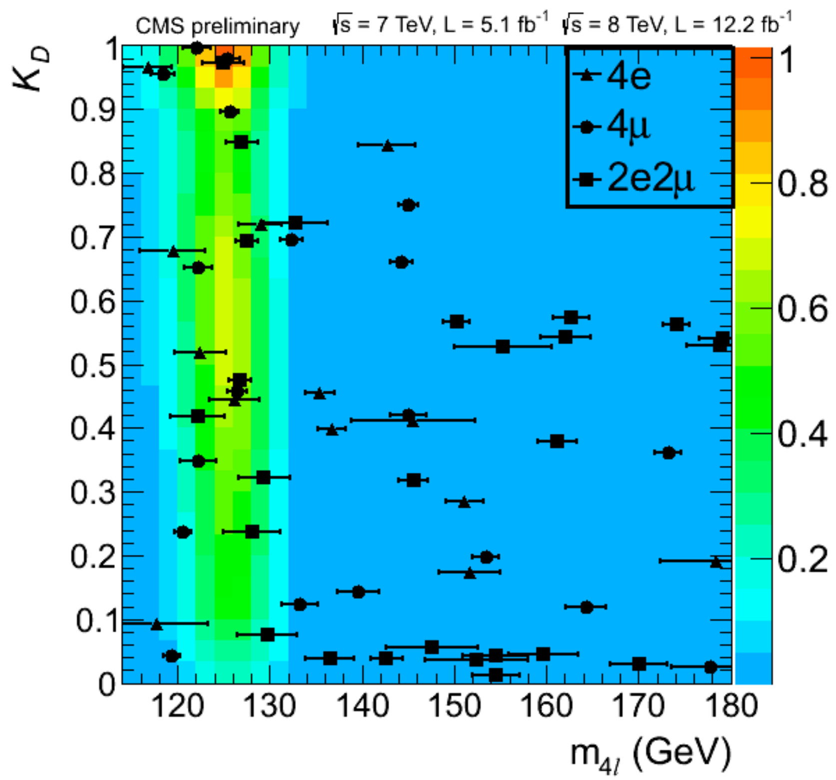
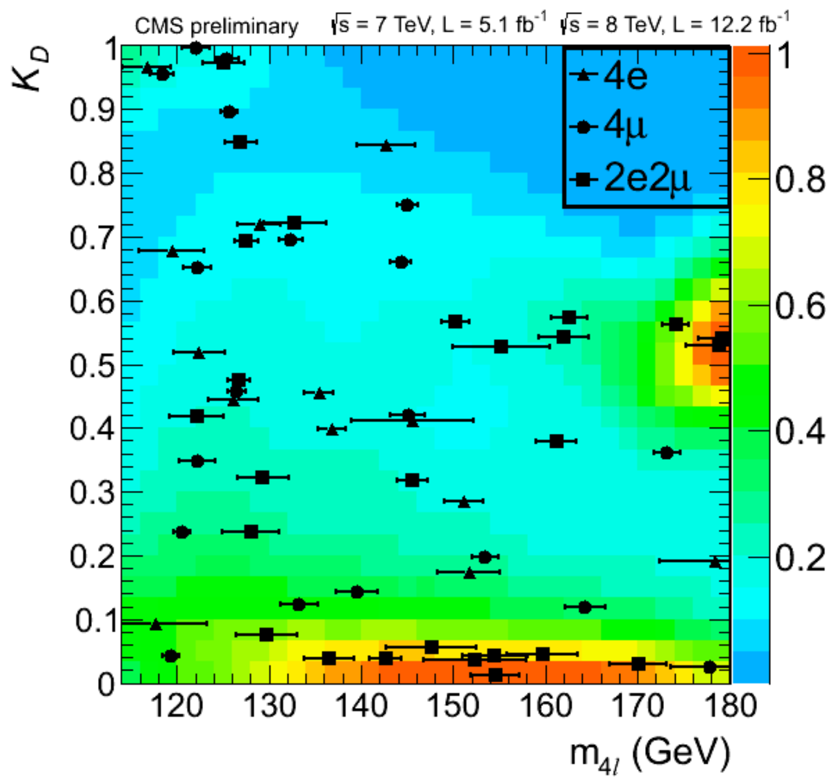


$$KD = \frac{\mathcal{P}_{\rm sig}}{\mathcal{P}_{\rm sig}+\mathcal{P}_{\rm bkg}} = \left[1+\frac{\mathcal{P}_{\rm bkg}(m_1,m_2,\vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm sig}(m_1,m_2,\vec{\Omega}|m_{4\ell})}\right]^{-1}$$

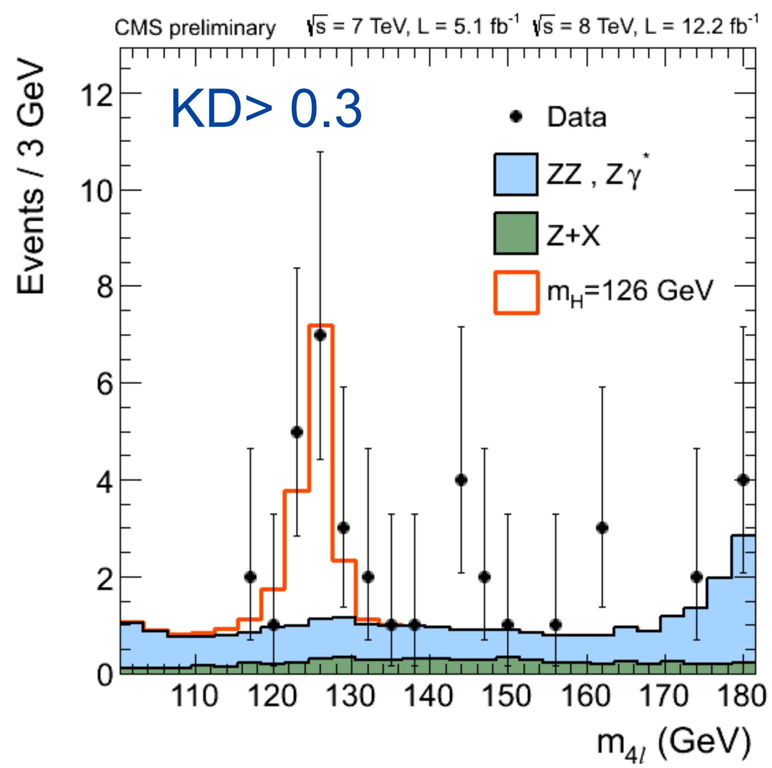
$$\vec{\Omega} = \{\theta^*, \Phi_1, \theta_1, \theta_2, \Phi\}$$



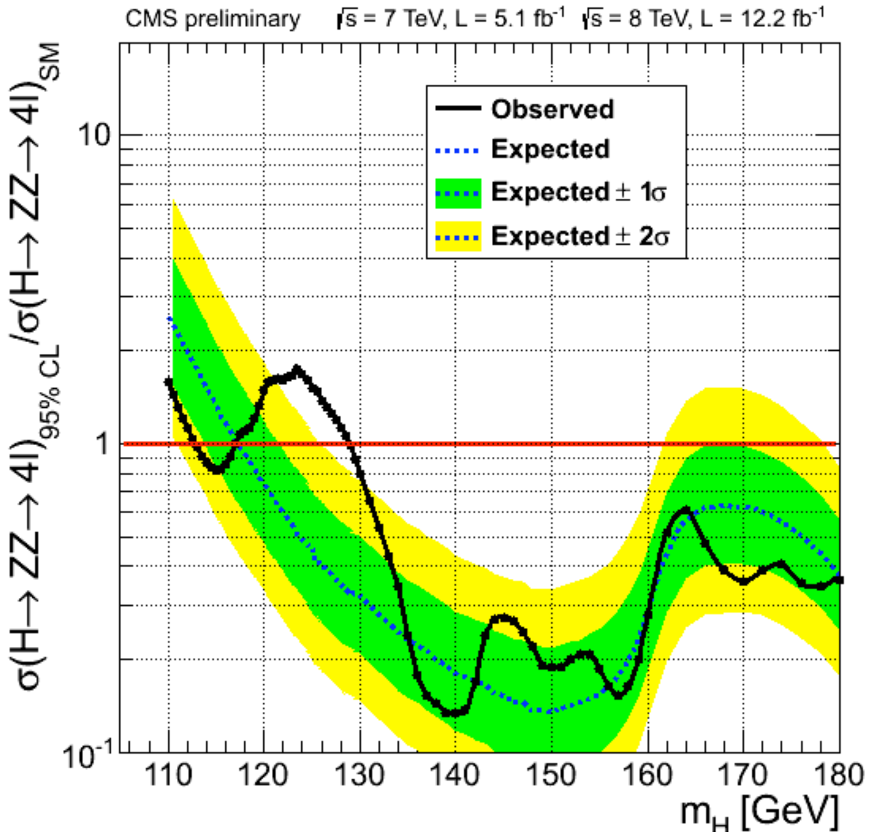
Signal expectation at 126 GeV

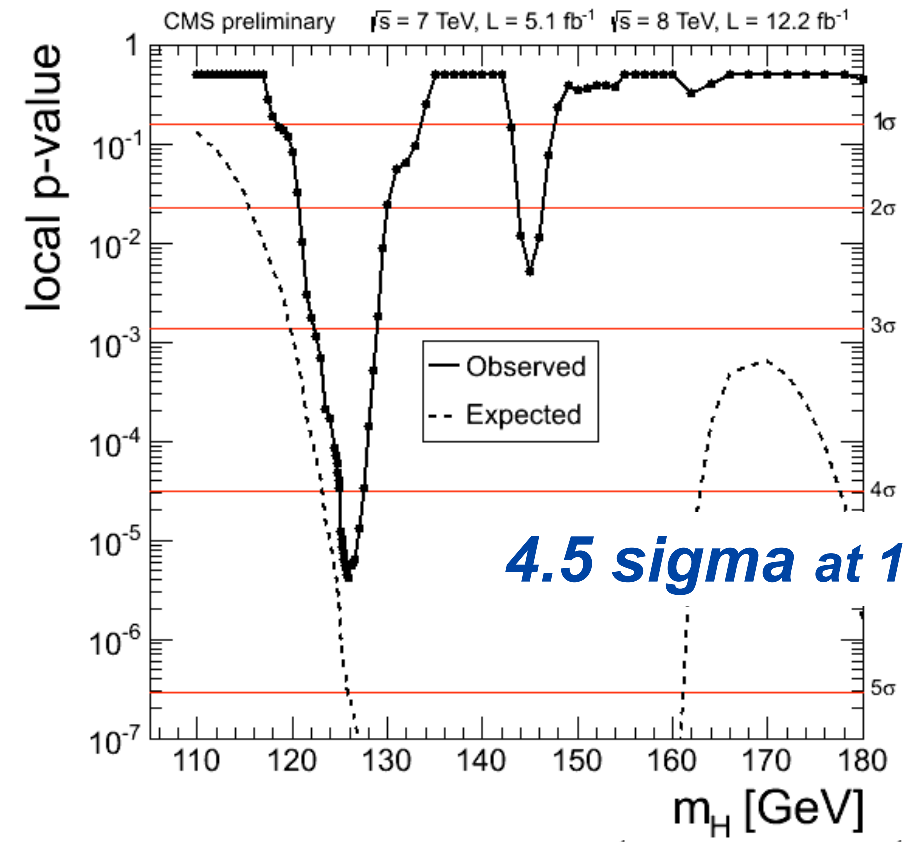


Background expectation

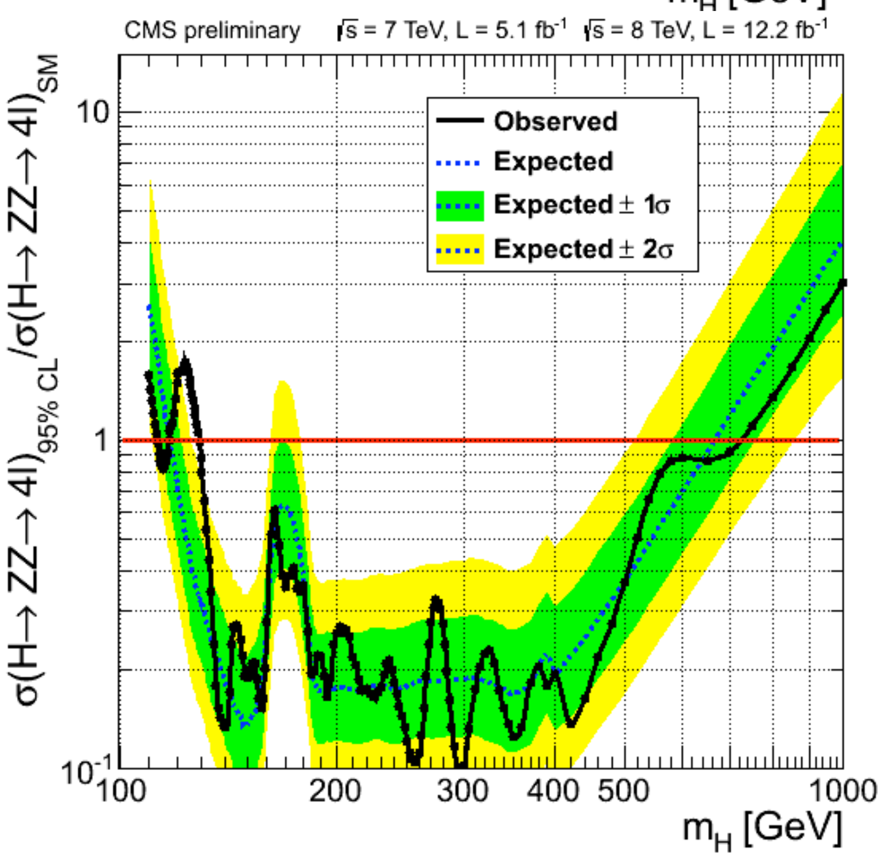


H→ZZ(*): results



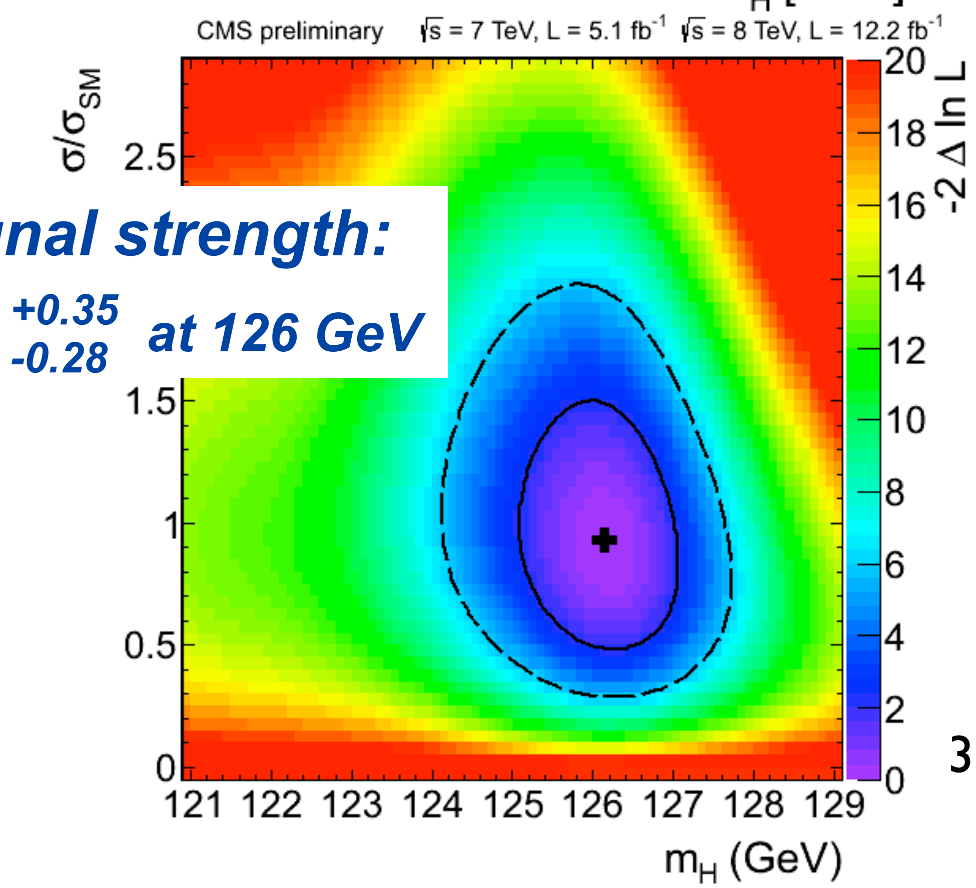


4.5 sigma at 126 GeV



Signal strength:

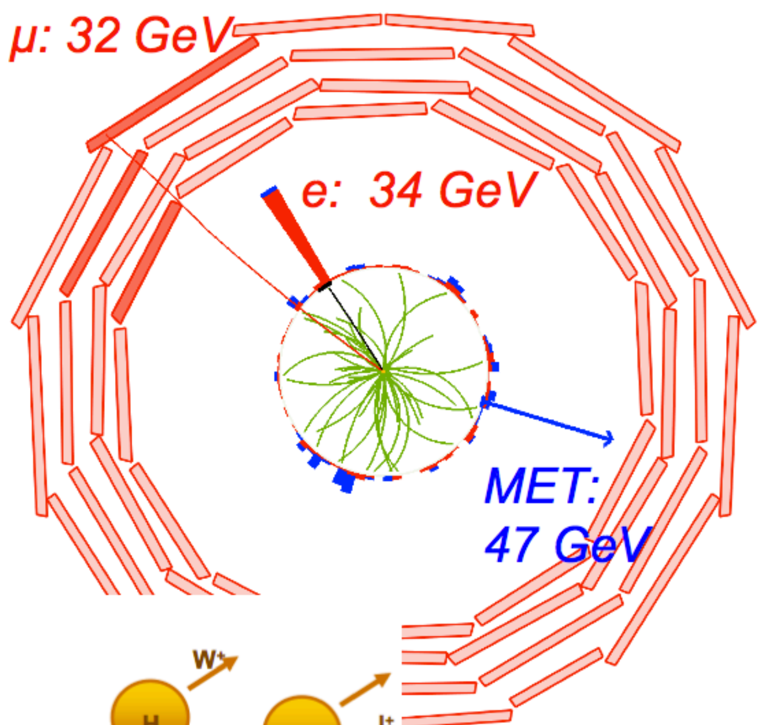
$0.8^{+0.35}_{-0.28}$ at 126 GeV

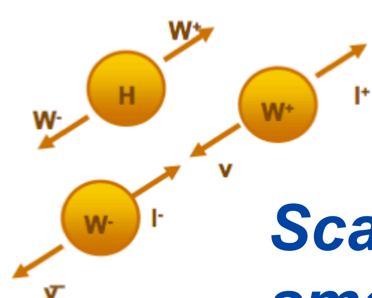


3D fit (μ, m, σ_m)

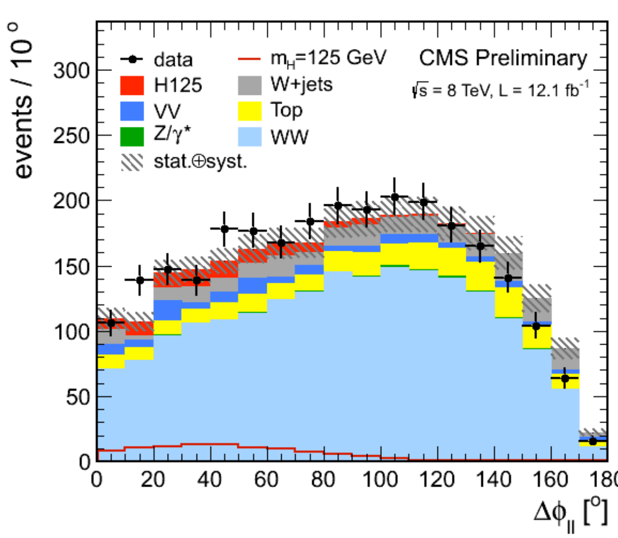
$H \to W^+W^-$ analysis highlights

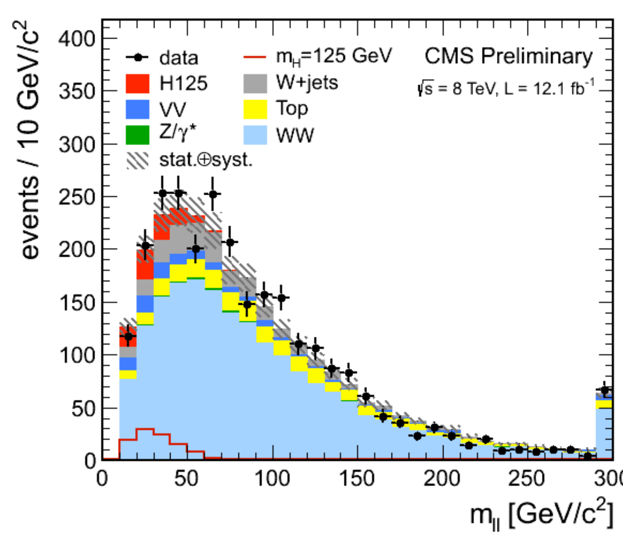
WW→2l2ν   WW→2l2q   (W)H→(W)WW





Scalar Higgs:
small $\Delta\varphi_{ll}$ and m_{ll}





No mass peak

Event Selection:
$p_T(l_1)$ >20 GeV, $p_T(l_2)$ >10 GeV
p_T(jets) > 30 GeV
$\not{E}_T$ > 45 GeV

Discriminating variables: m_{ll} and m_T

Categorization to optimize sensitivity

	0-jets	1-jets	2-jets
Different Flavor	2D	2D	cut&count
Same Flavor	cut&count	cut&count	cut&count

Dominant backgrounds:
- 0-j: WW
- 1-j, 2-j: top
- SF: Drell-Yan

Constrain backgrounds in control regions and use MC to extrapolate them to the signal region

H→W⁺W⁻: 2D shape analysis

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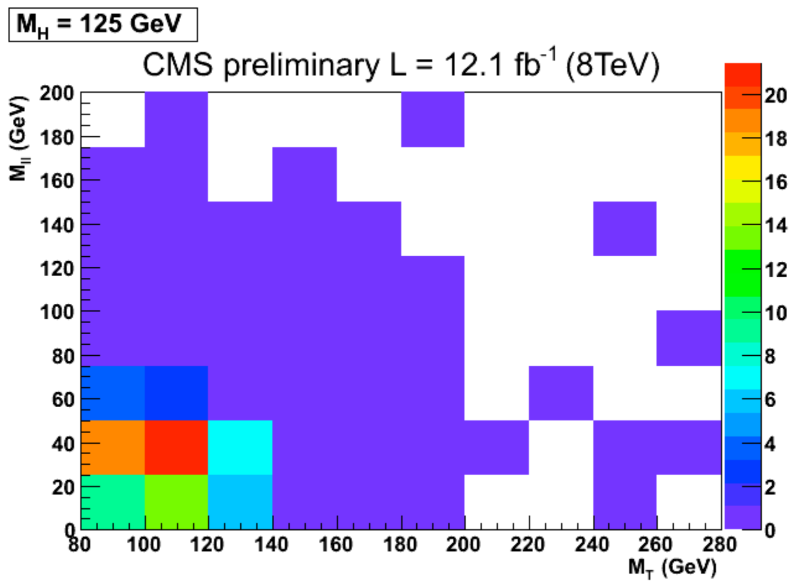
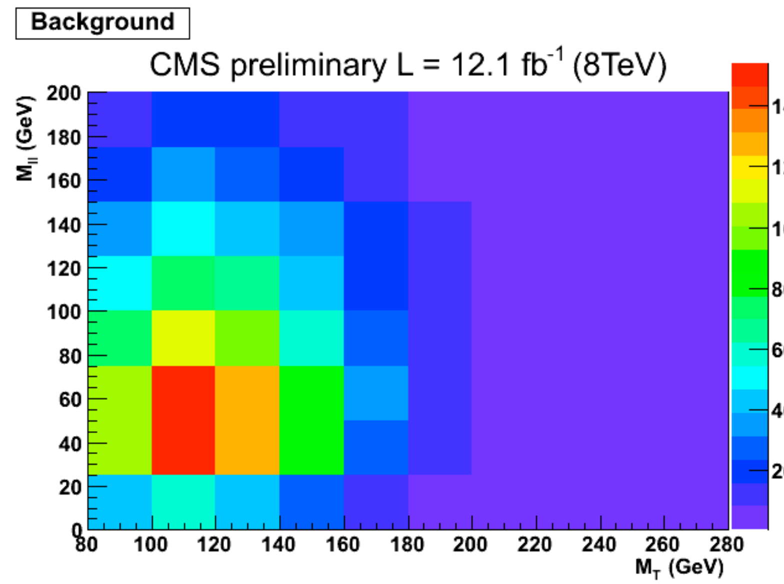
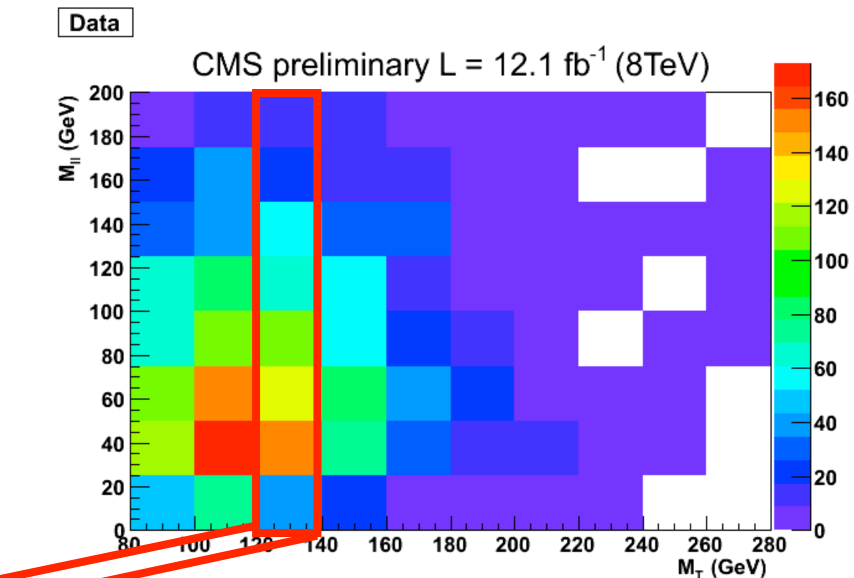
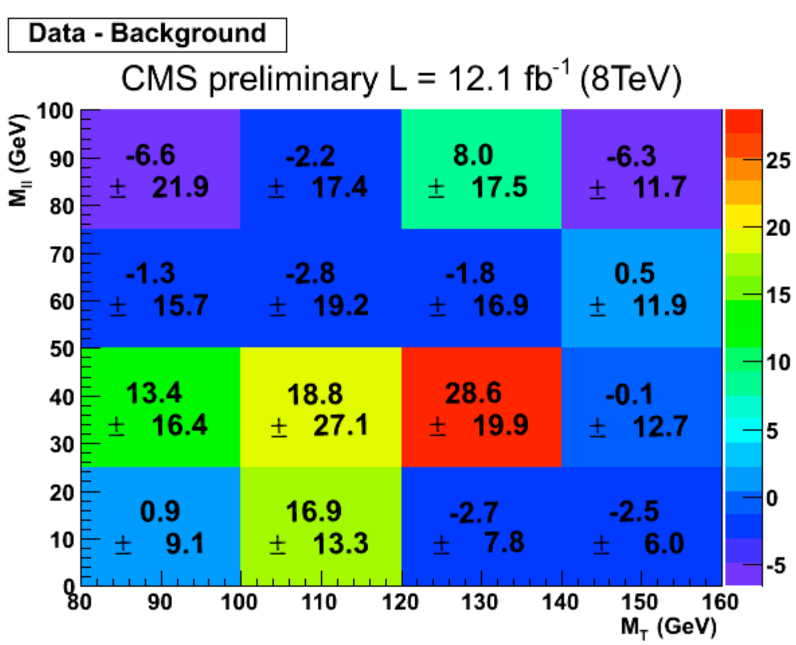
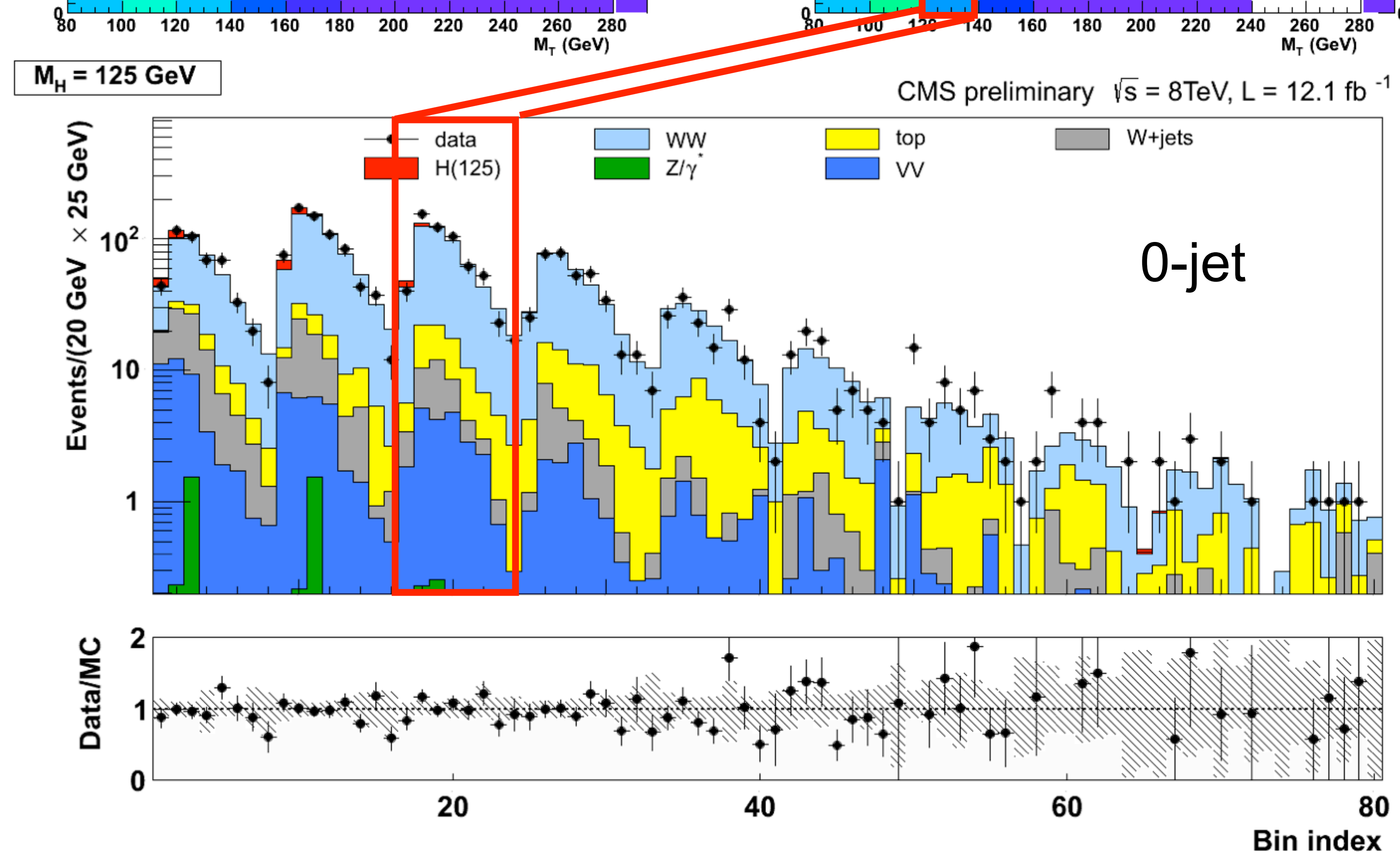
2D binned fit to increase sensitivity











$H \rightarrow W^+W^-$: Cut and Count xcheck

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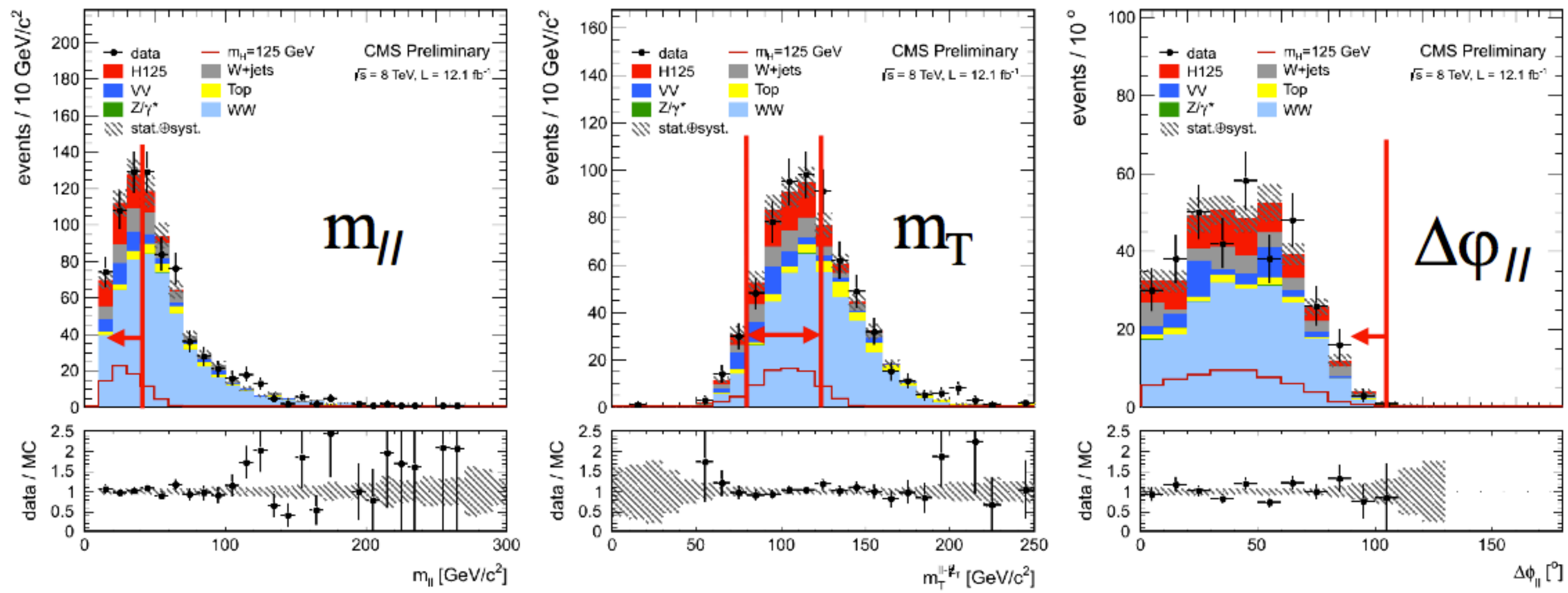
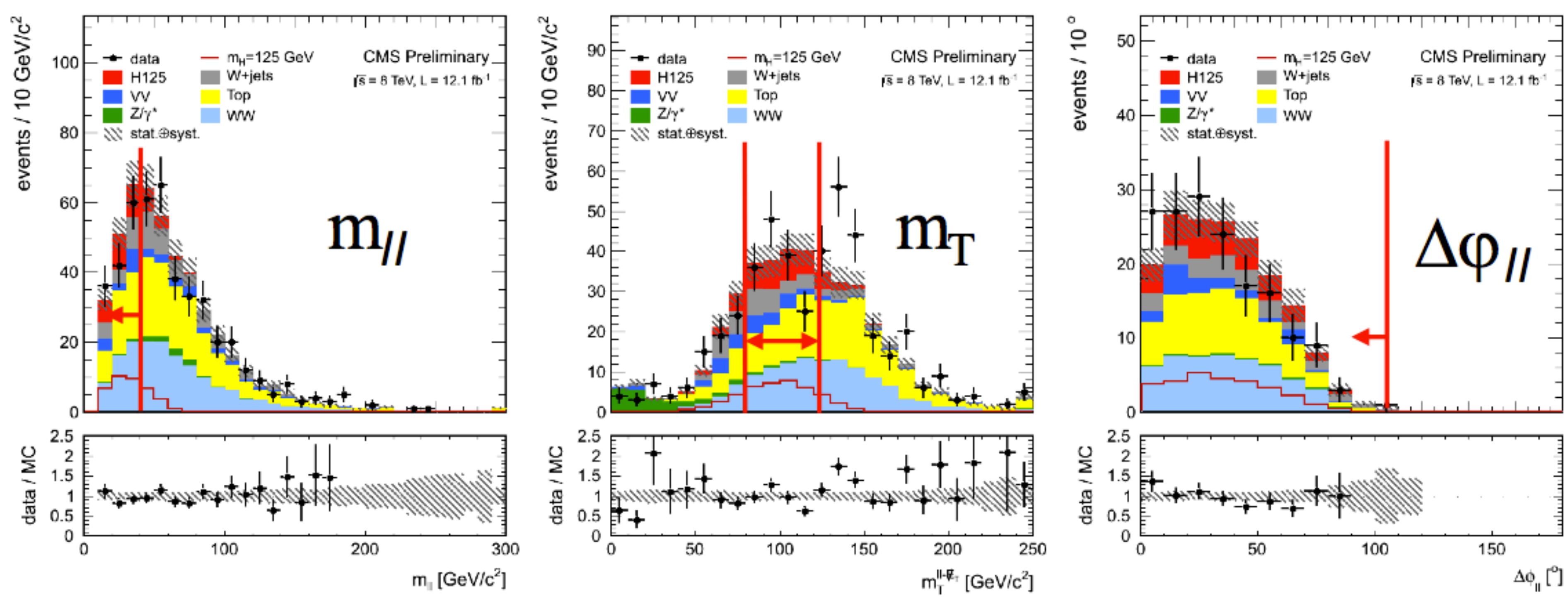
0-jet

Results:
Signal 58±12
BKG 291±27
DAT 349



1-jet

Results:
Signal 27±8
BKG 134±13
DAT 160



$H \rightarrow W^+W^-$: results

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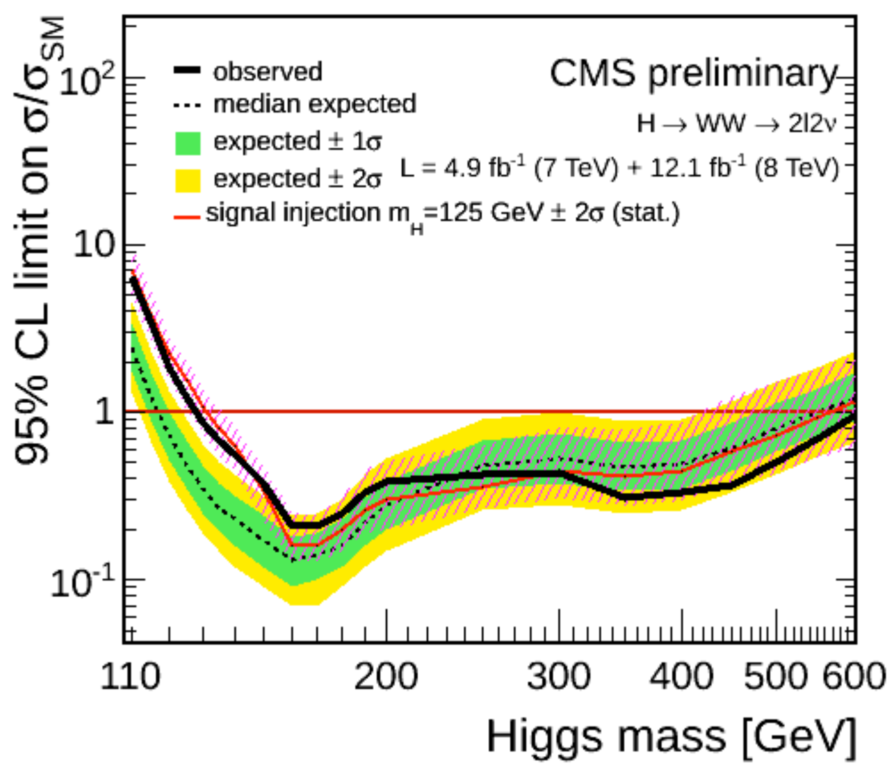
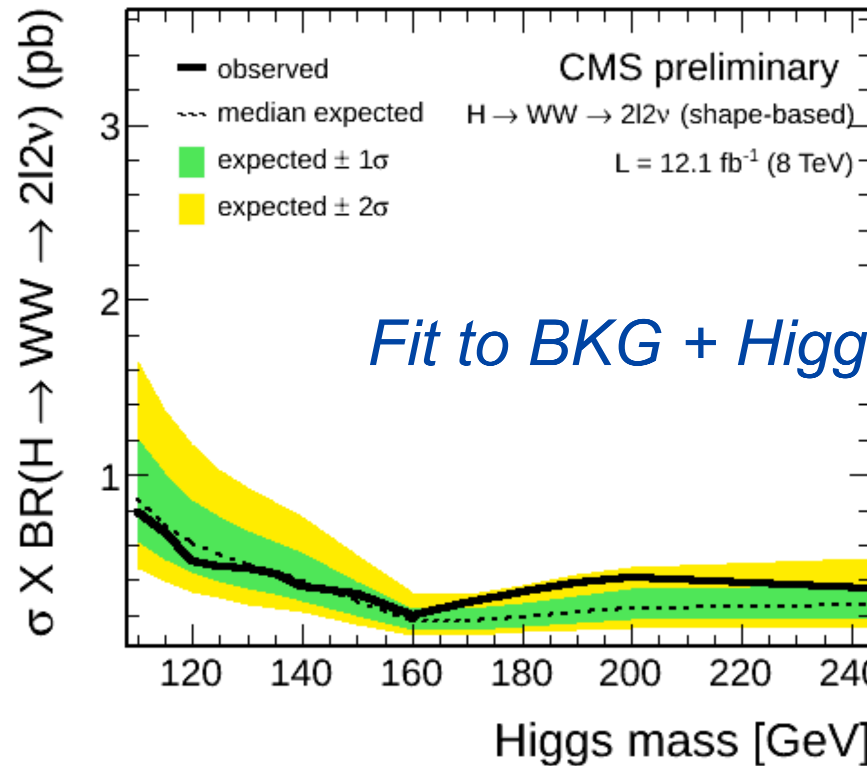
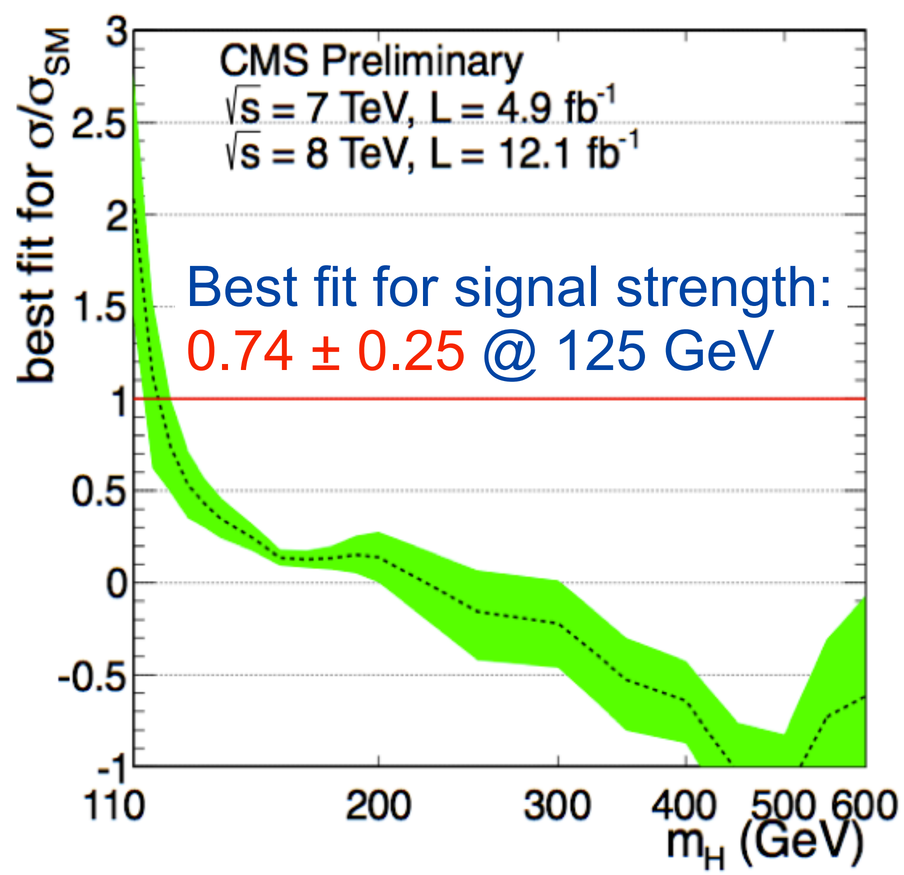
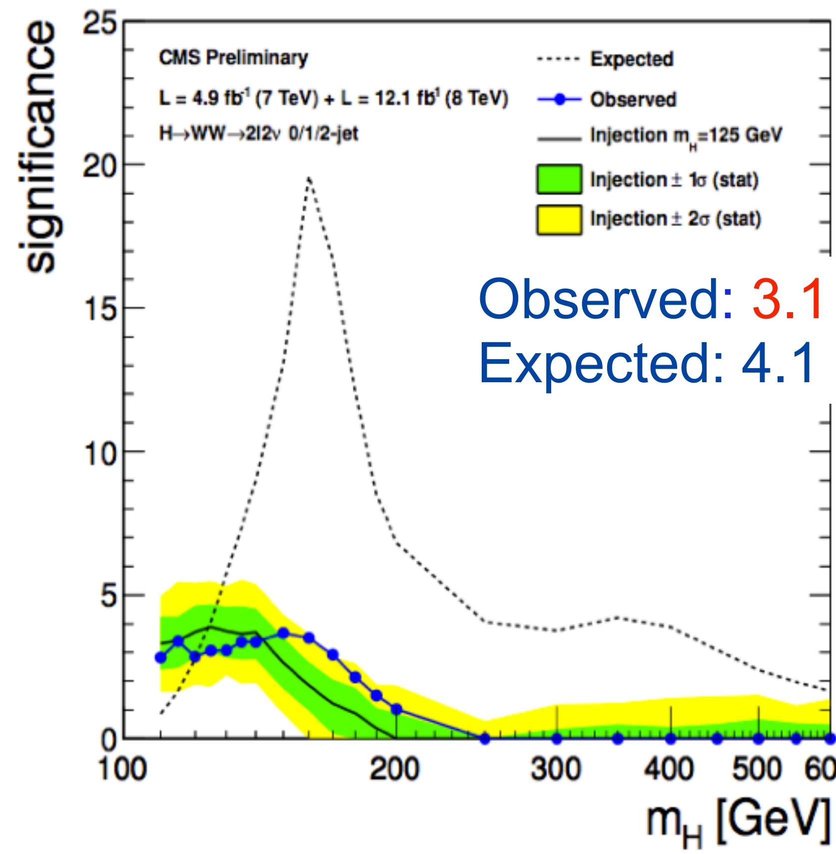




Fit to BKG + Higgs(125)



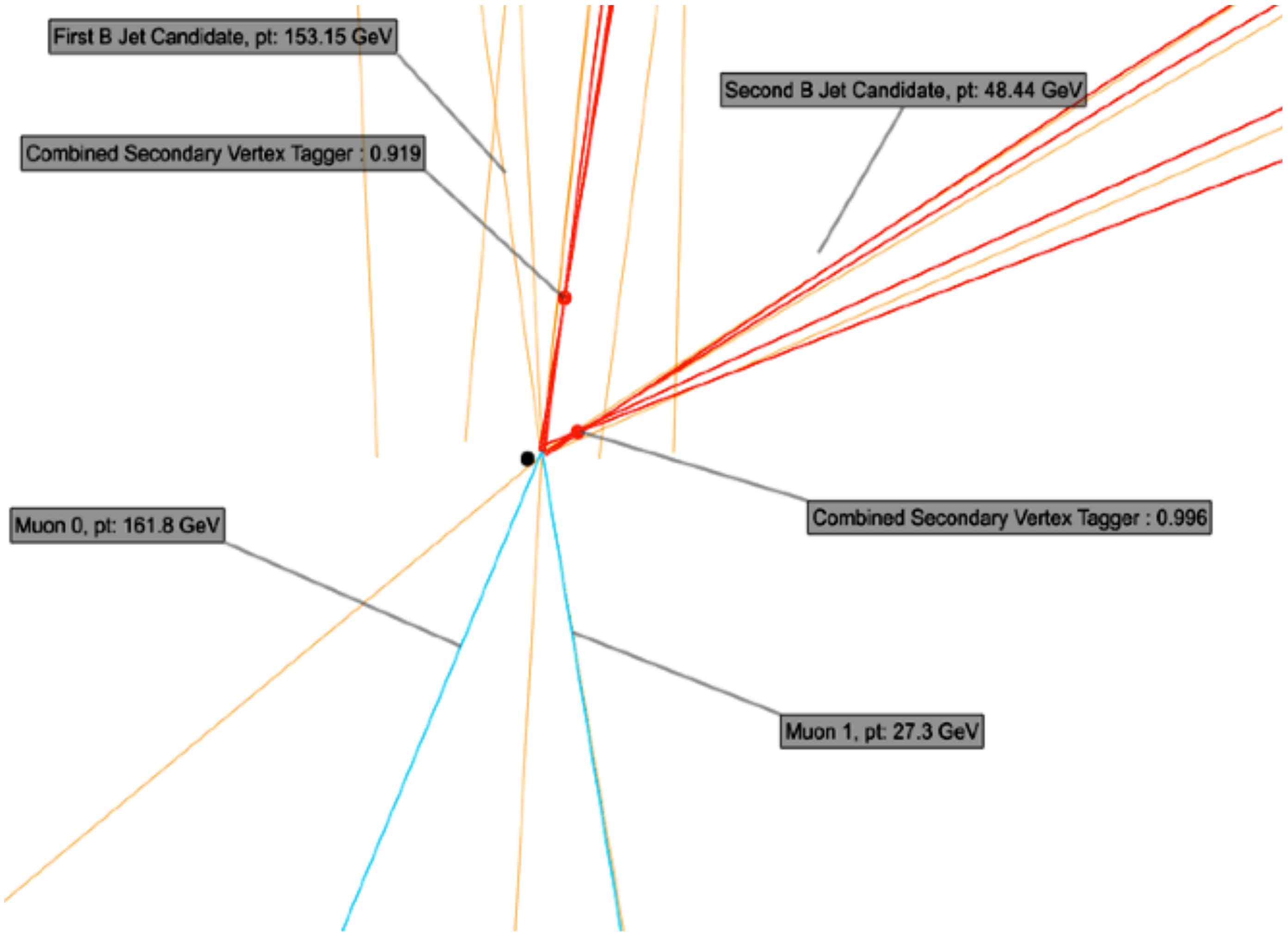
Best fit for signal strength:
0.74 ± 0.25 @ 125 GeV

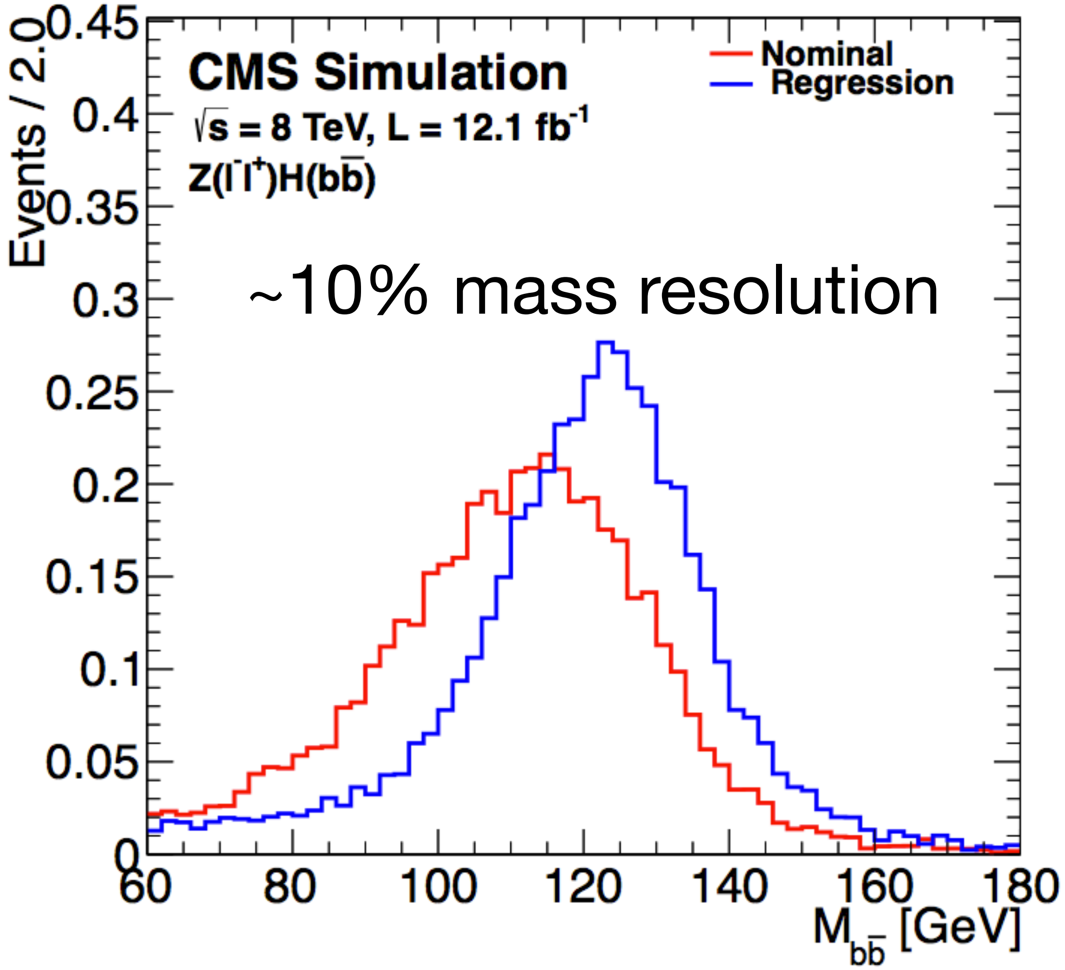


Observed: 3.1 σ
Expected: 4.1 σ @ 125 GeV

$H \to b\bar{b}$: analysis highlights

5 channels: Z(ℓℓ)H(bb), Z(νν)H(bb), W(ℓν)H(bb) ℓ = e,μ





Signature:

Back to back boosted VH with ≥ 2 b-tagged jets

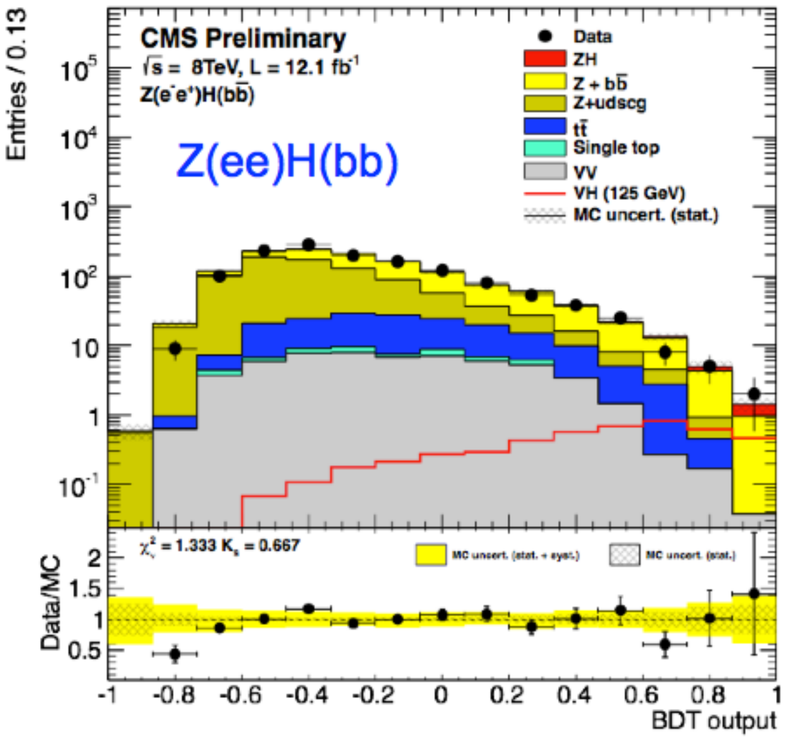
Main backgrounds: V+jets, tt

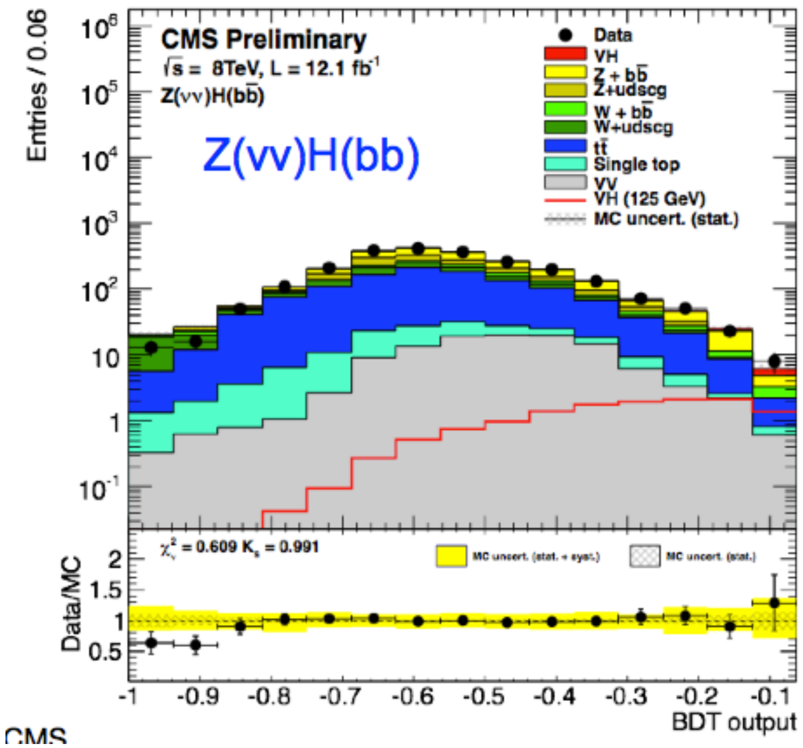
13 Categories: 5 channels x low/high boost + high pT W(ℓν) Z(νν) looser 2nd b-tag

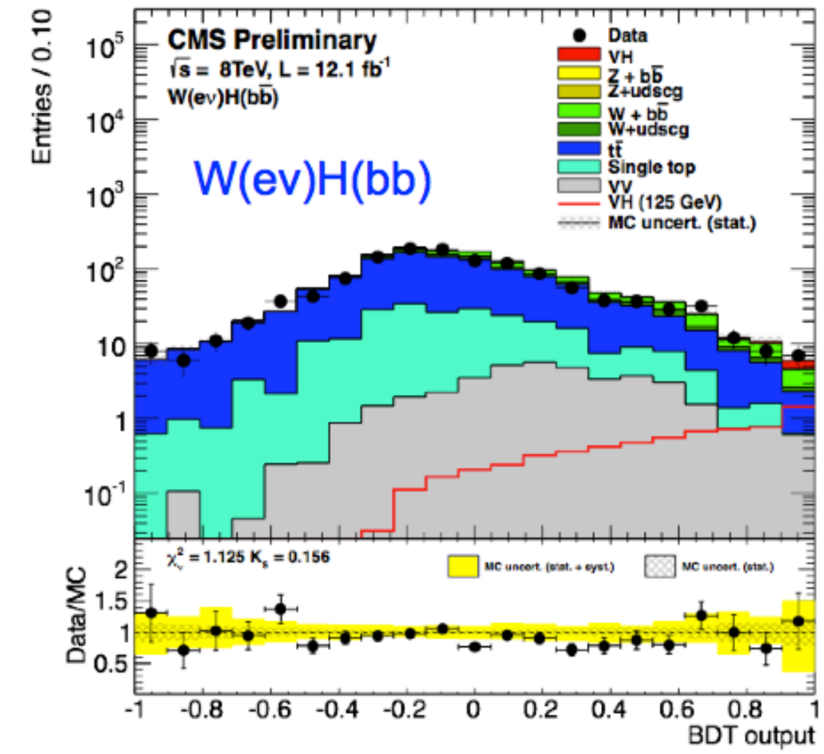
BDT shape analysis wrt BDT Cut and Count +20% sensitivity

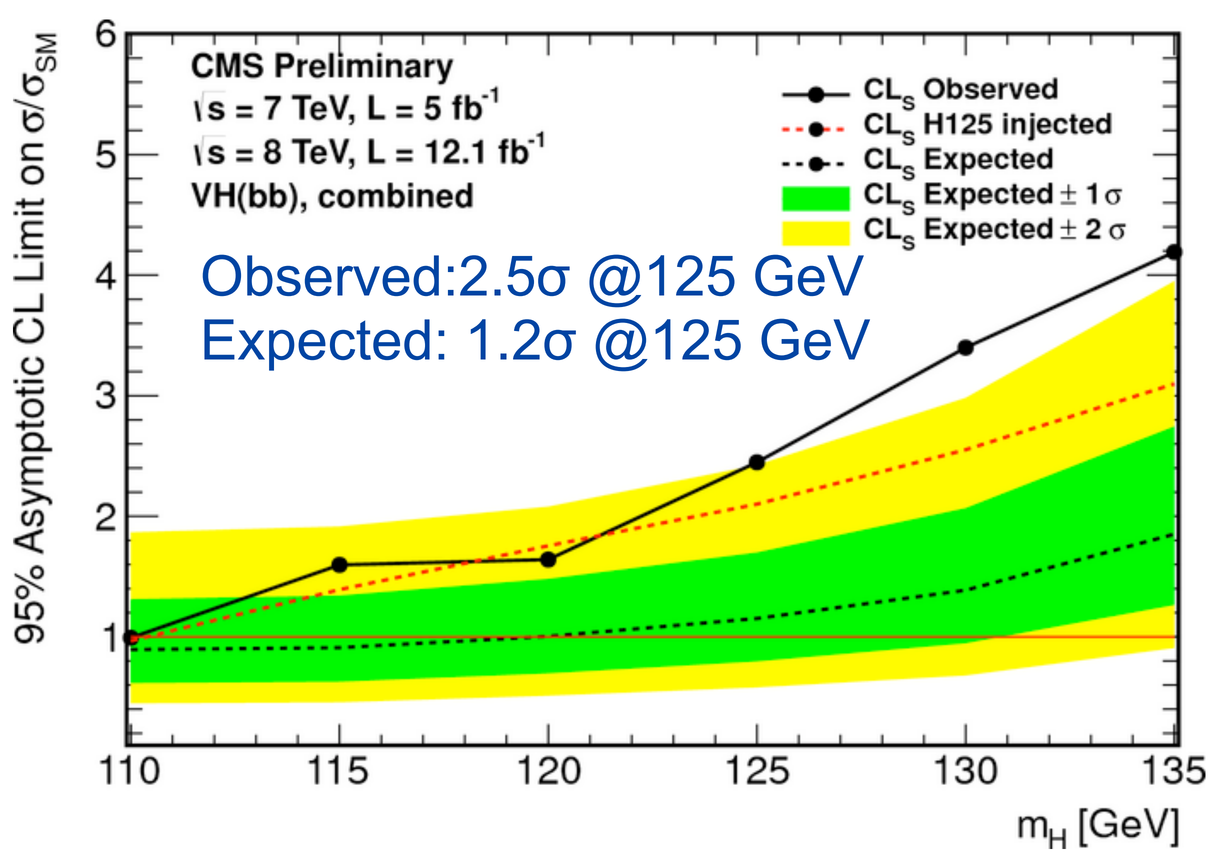
Energy regression 15% better resolution → 10-20% gain in sensitivity

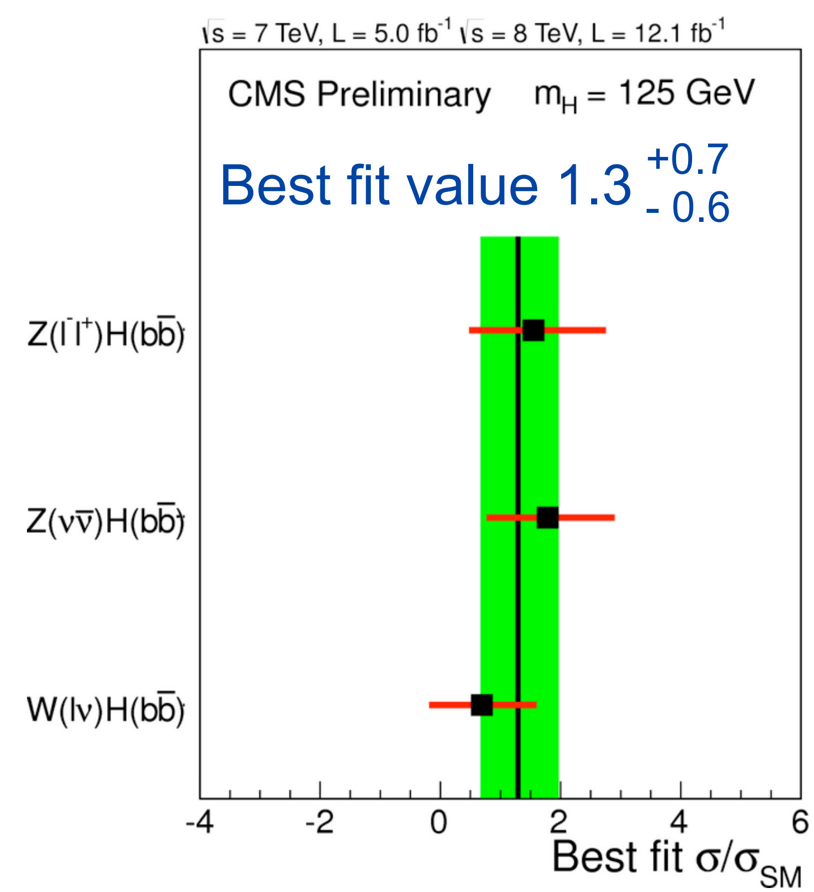
$H \to b\bar{b}$: BDT shape analysis results





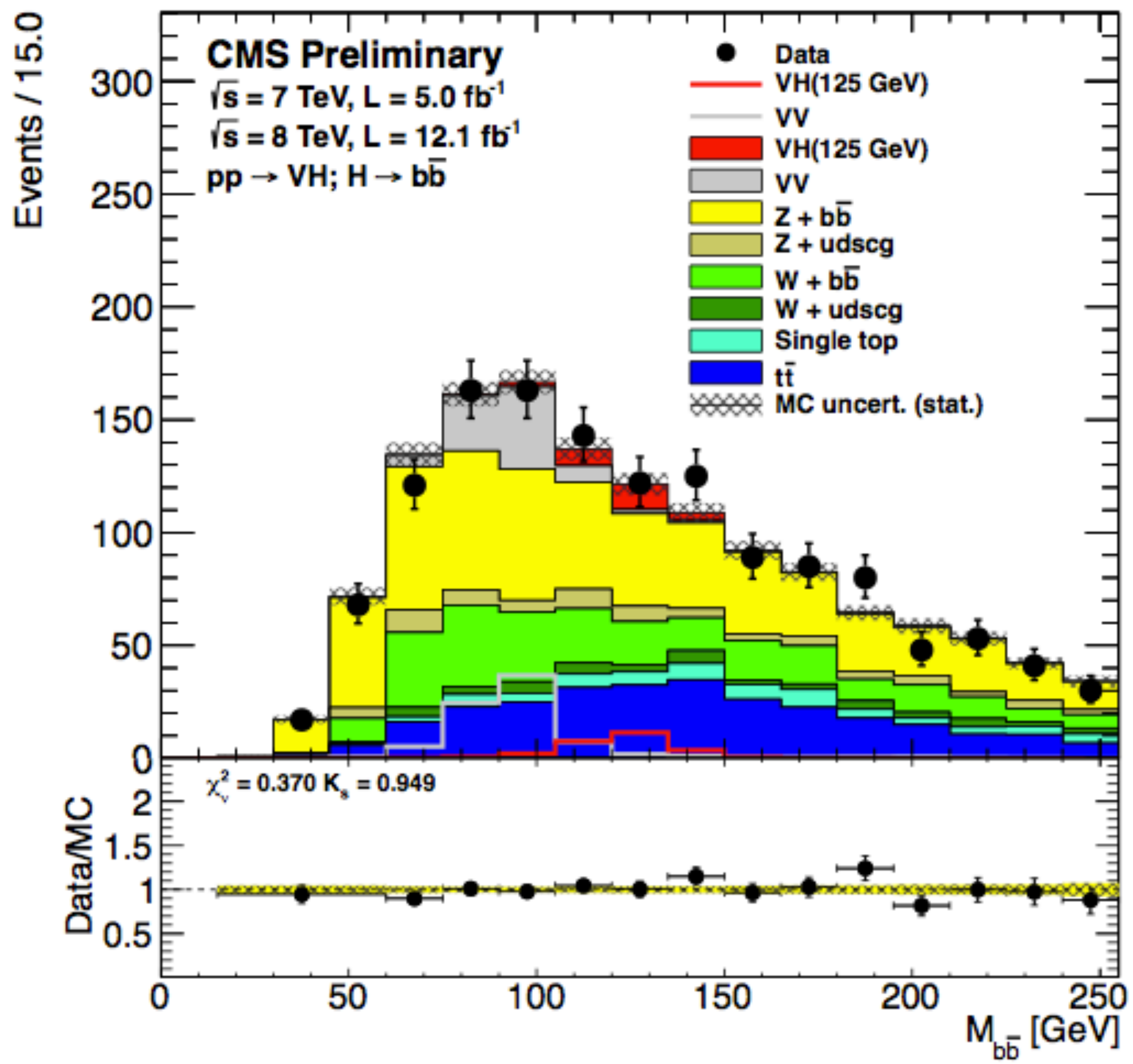


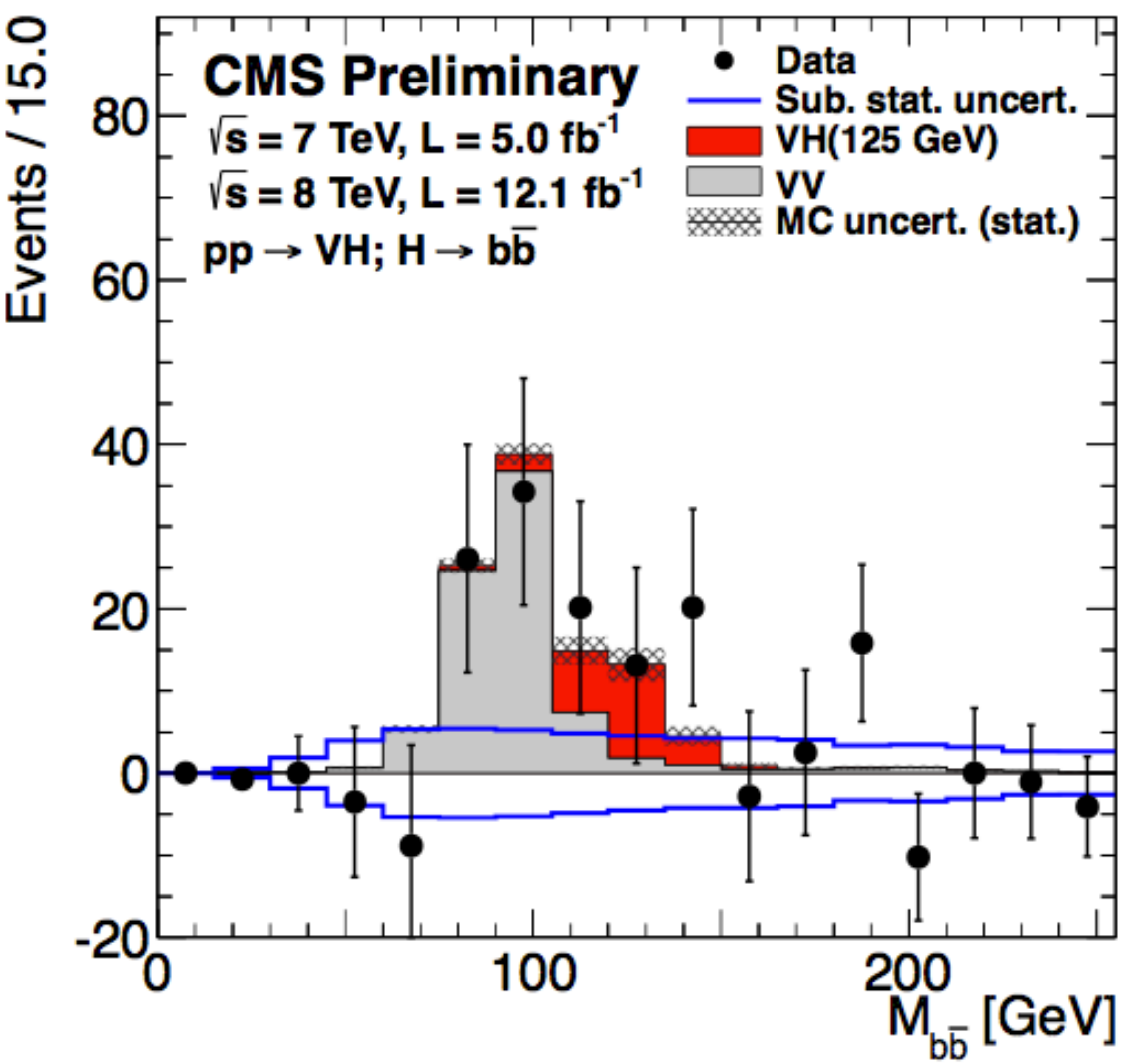




$H \to b\bar{b}$: results

Selection re-optimized for a counting experiment





$H \to \tau^+\tau^-$: analysis highlights

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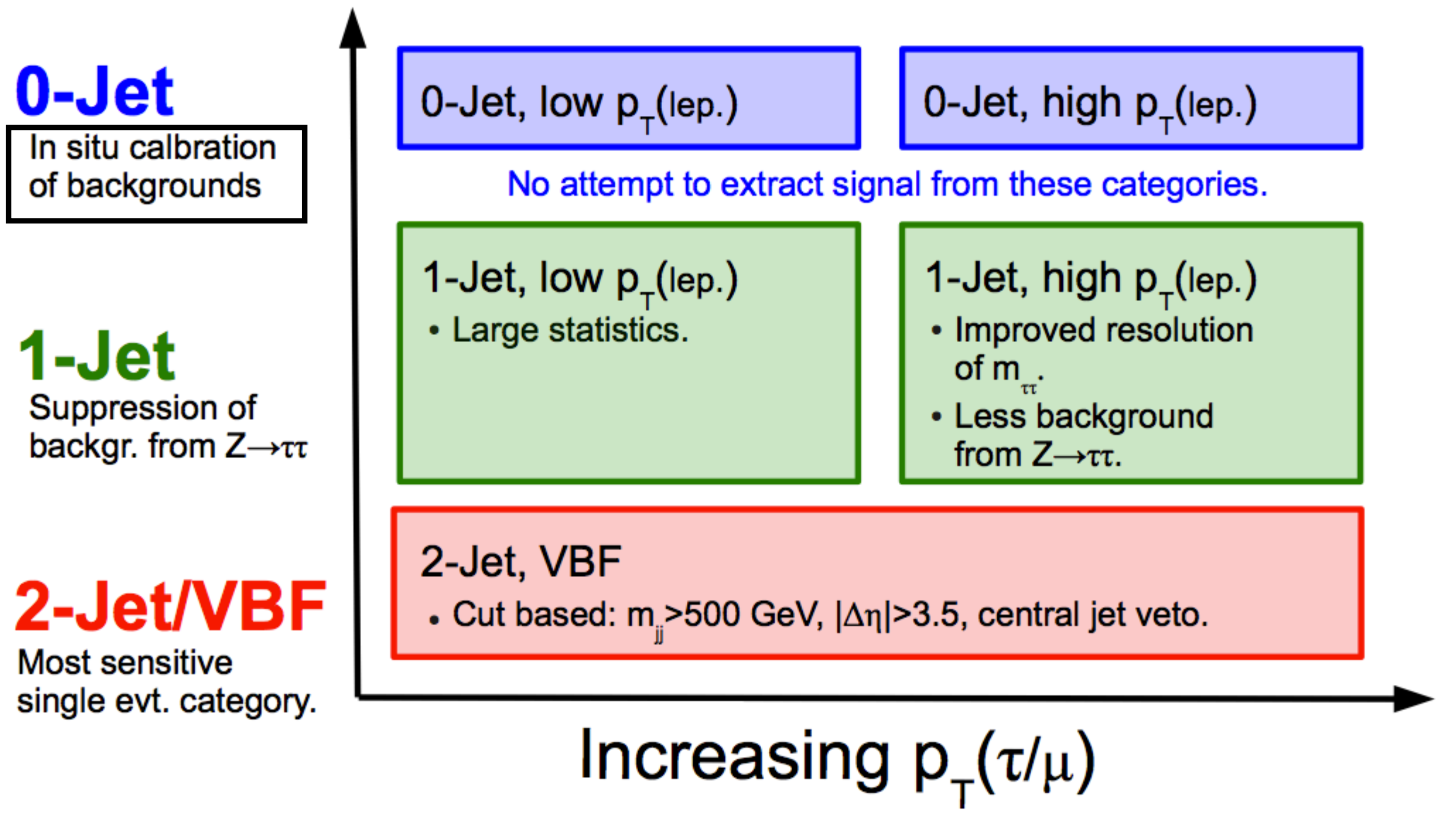
$H \to \tau\tau \to \mu\mu$; $H \to \tau\tau \to e\mu$; $H \to \tau\tau \to \mu$+had.; $H \to \tau\tau \to e$+had.; $H \to \tau\tau \to$ had.+had.

Associate production: $WH \to e\mu\tau_h$, $WH \to \mu\mu\tau_h$ ($WH \to l\tau\tau$)
$ZH \to ee\tau\tau$, $ZH \to \mu\mu\tau\tau$ ($\tau \to e$, μ, had.) ($ZH \to ll\tau\tau$).

Particle flow reconstruction
Likelihood fit $m_{\tau\tau}$ to the leptons four-vectors and MET on an event by event basis.
Mass resolution ~10-20%

Main backgrounds: $Z \to \tau^+\tau^-$; QCD; $Z \to ee$

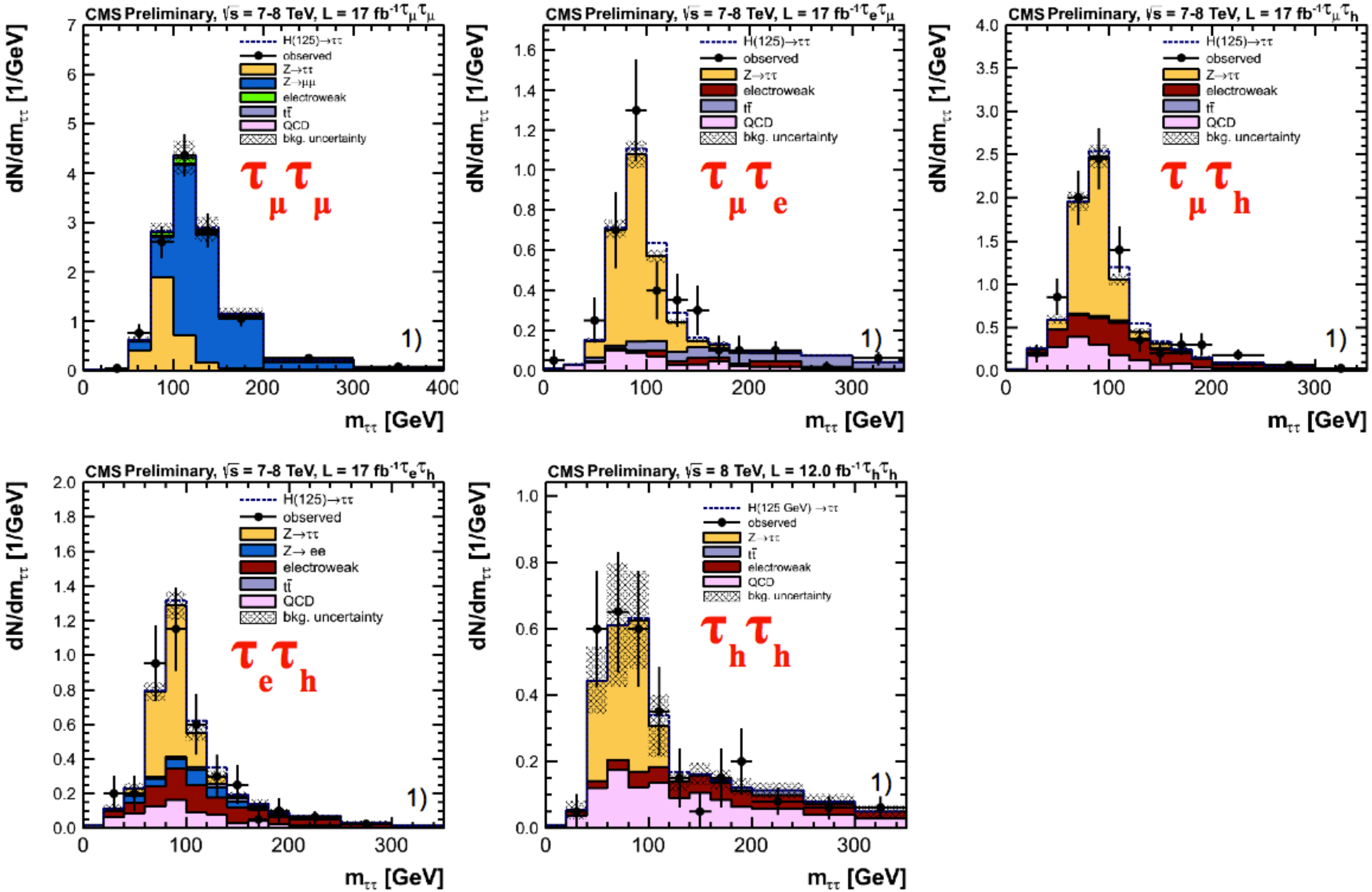
Categorization



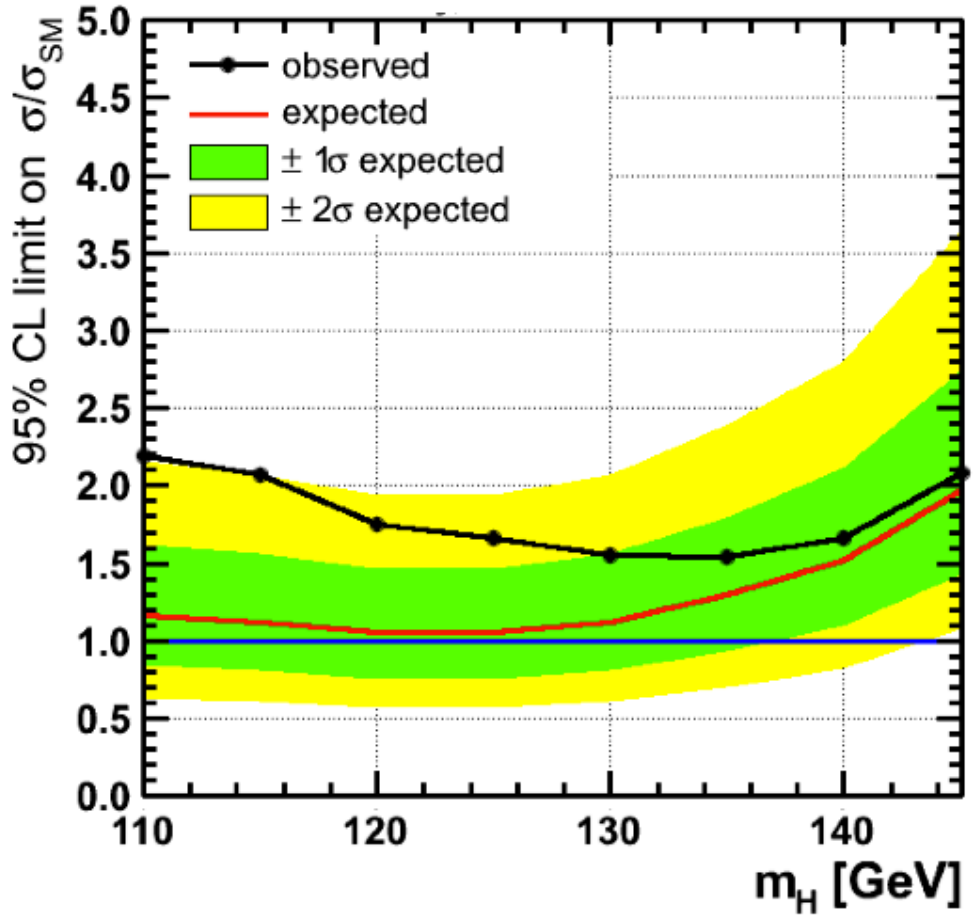
R.Wolf at HCP

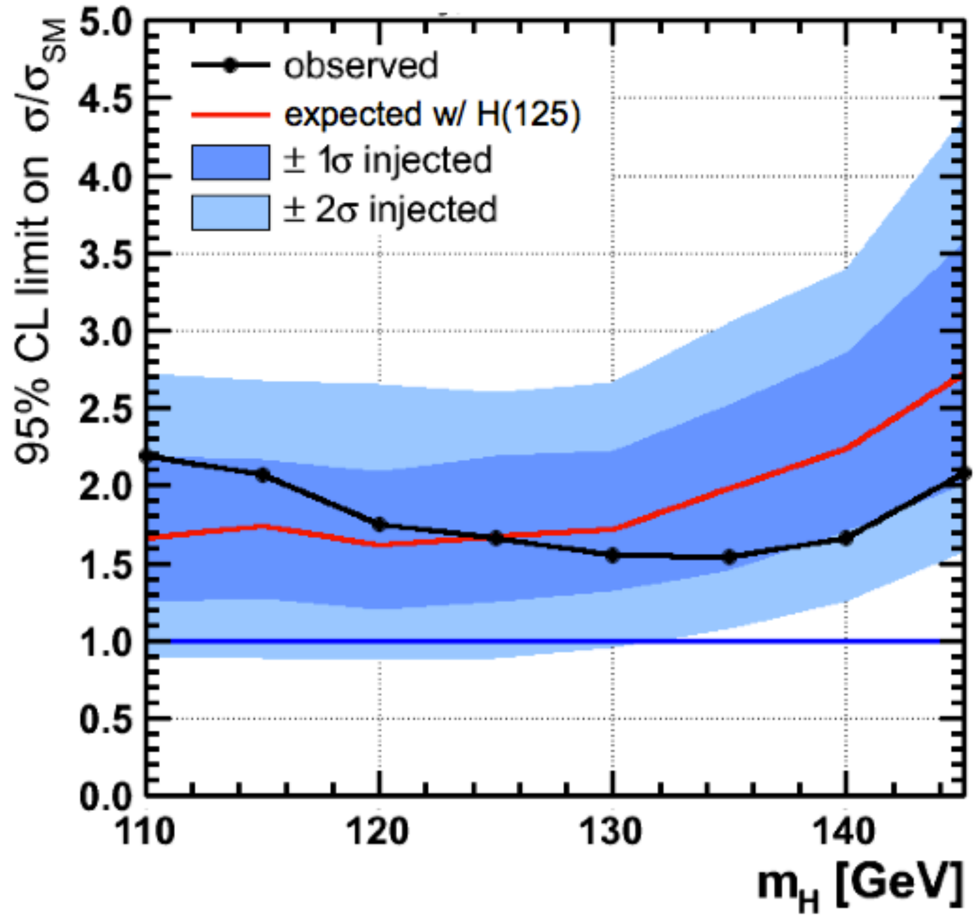
$H \to \tau^+\tau^-$: 2-jet category

Binned maximum likelihood fit on the 5 cats simultaneously



$H\to\tau^+\tau^-$: results





Expected (@125 GeV)=1.05
Observed(@125 GeV)=1.66

Compatibility with signal injection

H→Zγ

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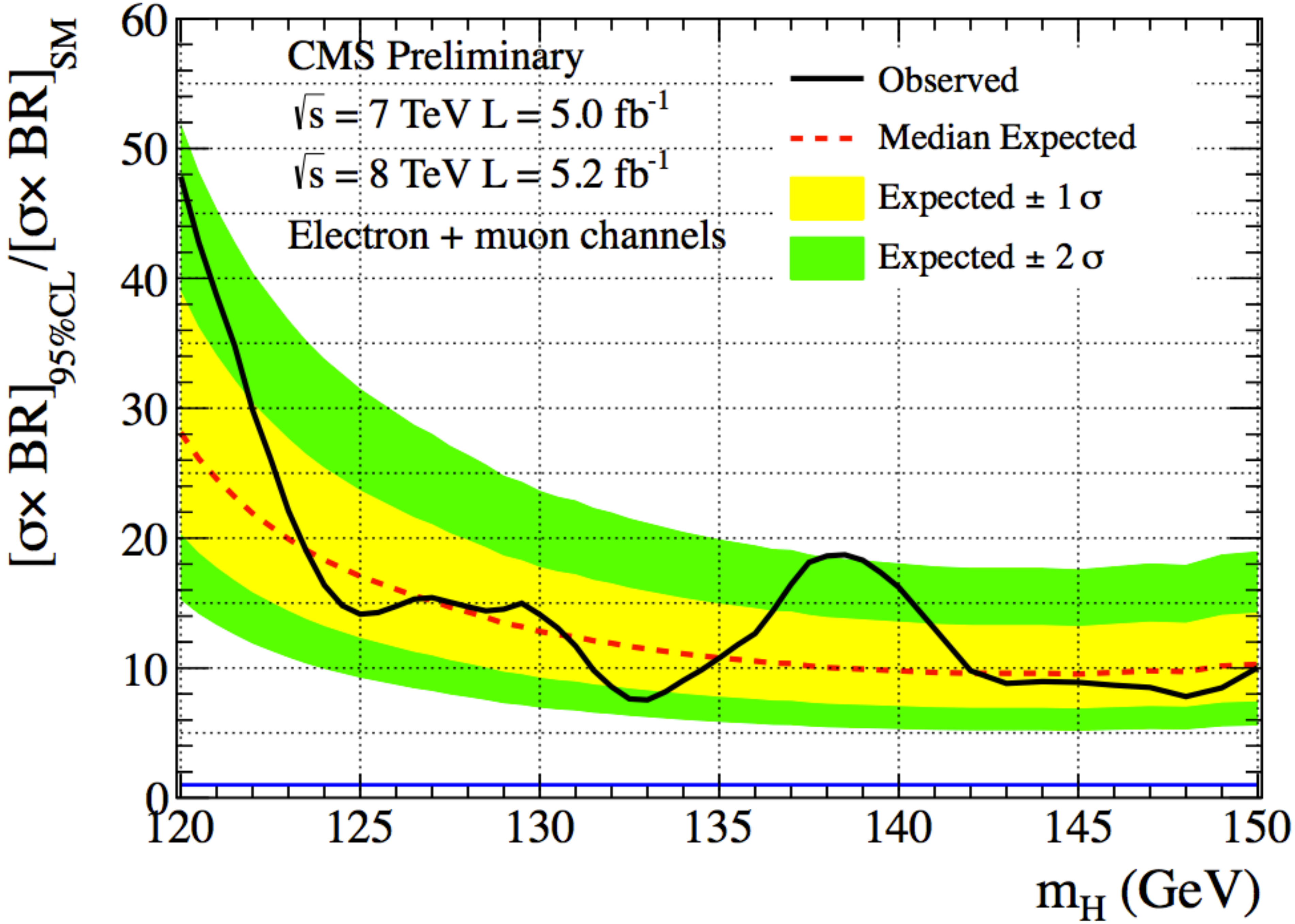

Other channels used in the combination

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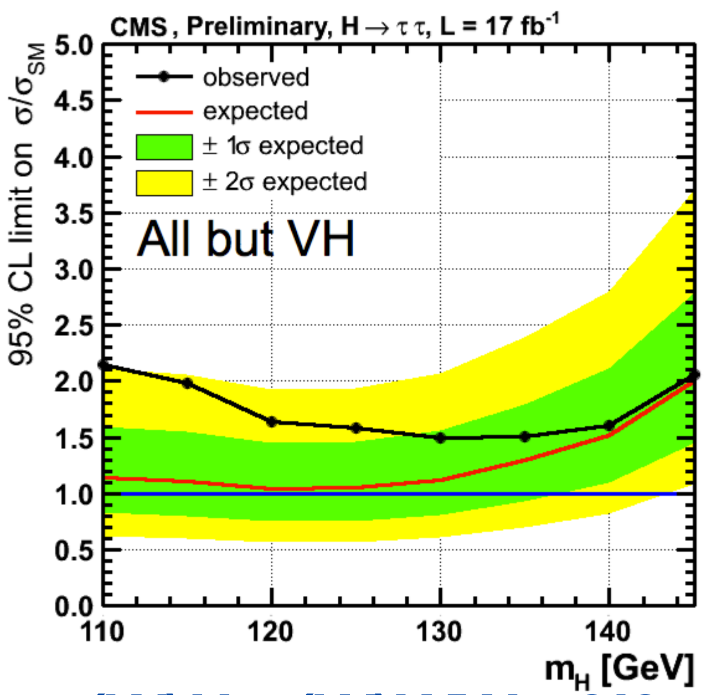
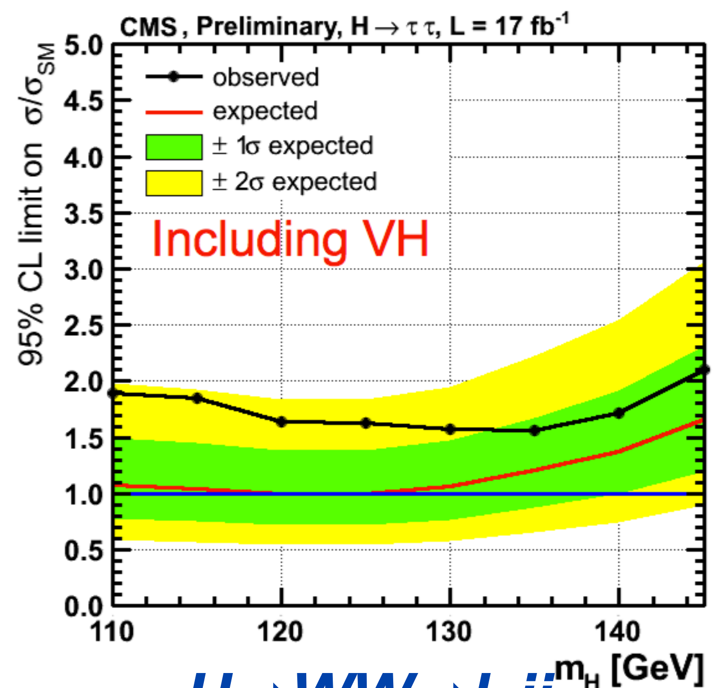
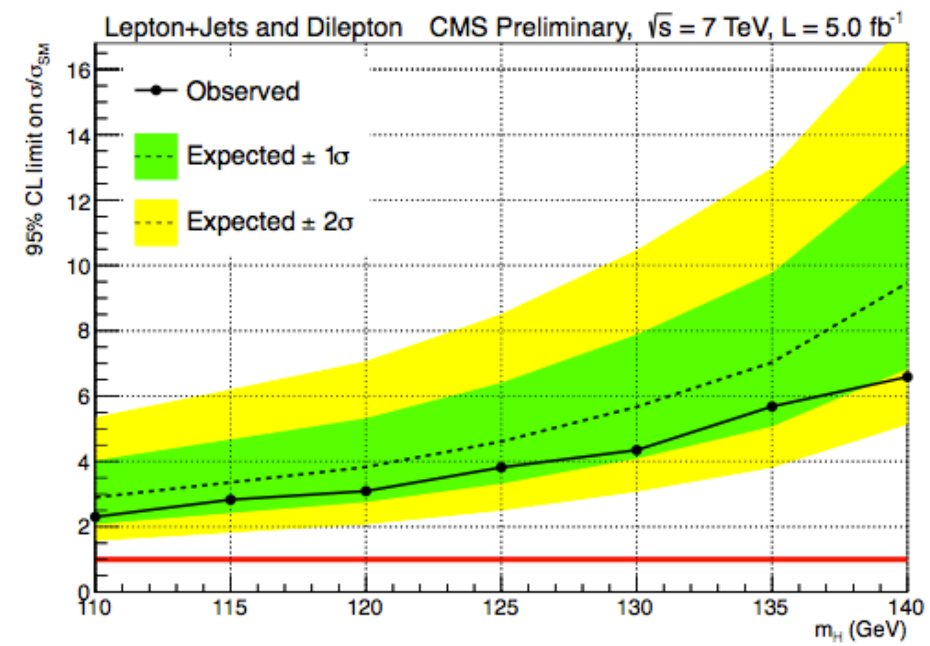
(V)H→τ⁺τ⁻

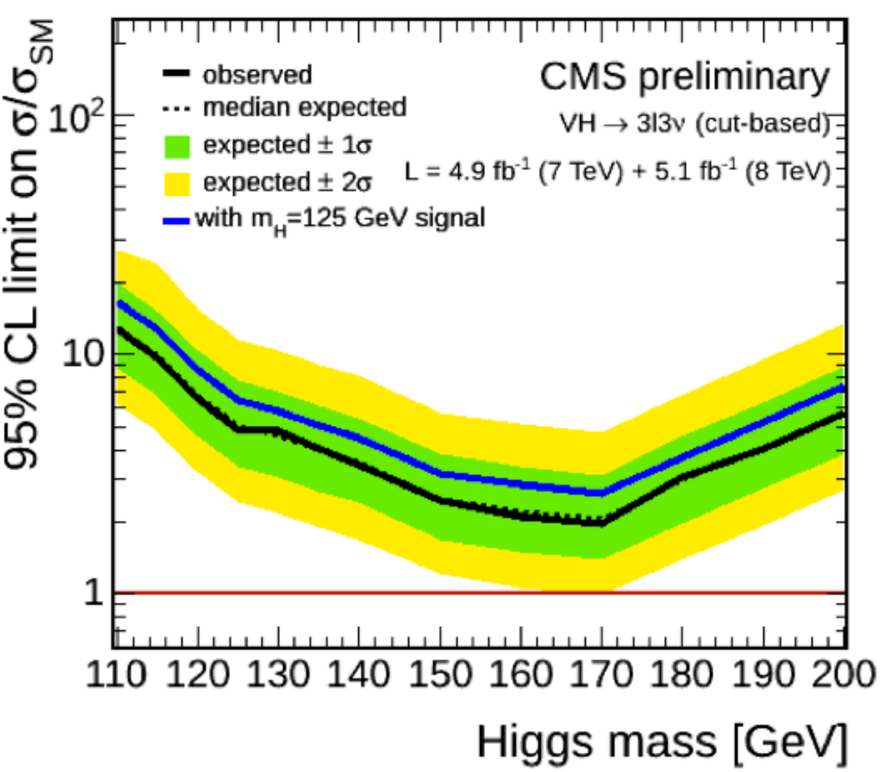




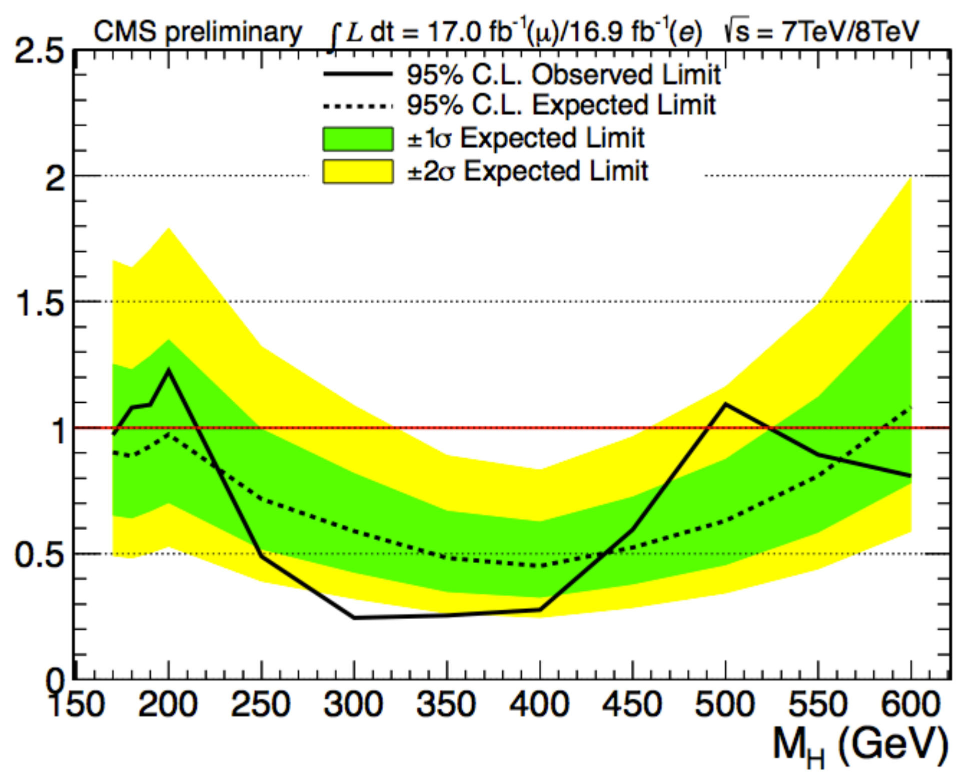
tt̄H→tt̄bb



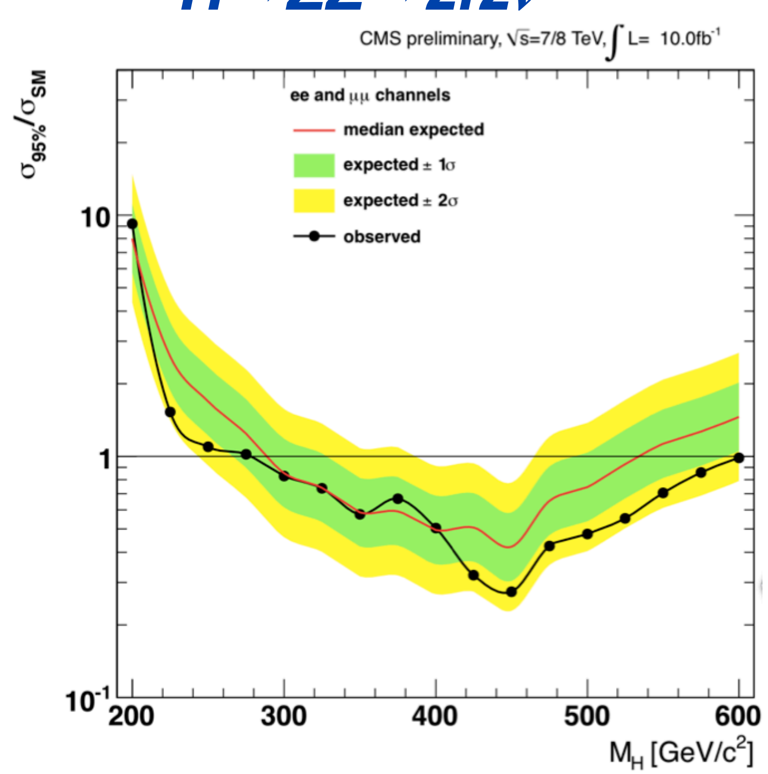
(W)H→(W)WW→3l3ν



H→WW→lνjj



H→ZZ→2l2ν



Analyses			No. of	m_{H} range	m_{H}	Lumi (fb^{-1})	
H decay	H prod	Exclusive final states	channels	(GeV)	resolution	7 TeV	8 TeV
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	110–150	1-2%	5.1	5.3
	VBF-tag	$\gamma\gamma + (jj)_{VBF}$ (low or high m_{jj} for 8 TeV)	1 or 2	110–150	1-2%	5.1	5.3
bb	VH-tag	($\nu\nu$, ee, $\mu\mu$, $e\nu$, $\mu\nu$ with 2 b-jets)$\times$ (low or high p_T^V or loose b-tag)	10 or 13	110–135	10%	5.0	12.1
	ttH-tag	(ℓ with 4,5,$\geq$6 jets) $\times$ (3,$\geq$4 b-tags); (ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-tagged jets)	9	110–140		5.0	-
$\mathrm{H} \to \tau\tau$	1-jet	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$)$\times$ (low or high p_T^τ) and $\tau_h\tau_h$	9	110–145	20%	4.9	12.1
	VBF-tag	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$) + $(jj)_{VBF}$	5	110–145	20%	4.9	12.1
	ZH-tag	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	110–160		5.0	-
	WH-tag	$\tau_h ee$, $\tau_h\mu\mu$, $\tau_h e\mu$	3	110–140		4.9	-
$\mathrm{WW} \to \ell\nu qq$	untagged	($e\nu$, $\mu\nu$)$\times$($(jj)_{\mathrm{W}}$ with 0 or 1 jets)	4	170–600		5.0	12.1
$\mathrm{WW} \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\times$ (0 or 1 jets)	4	110–600	20%	4.9	12.1
$\mathrm{WW} \to \ell\nu\ell\nu$	VBF-tag	$\ell\nu\ell\nu + (jj)_{VBF}$ (DF or SF dileptons for 8 TeV)	1 or 2	110–600	20%	4.9	12.1
$\mathrm{WW} \to \ell\nu\ell\nu$	WH-tag	$3\ell3\nu$	1	110–200		4.9	5.1
$\mathrm{ZZ} \to 4\ell$	inclusive	$4e$, 4μ, $2e2\mu$	3	110–1000	1-2%	5.0	12.2
$\mathrm{ZZ} \to 2\ell2\tau$	inclusive	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	180–1000	10-15%	5.0	12.2

Properties measurements

Exclusion limits

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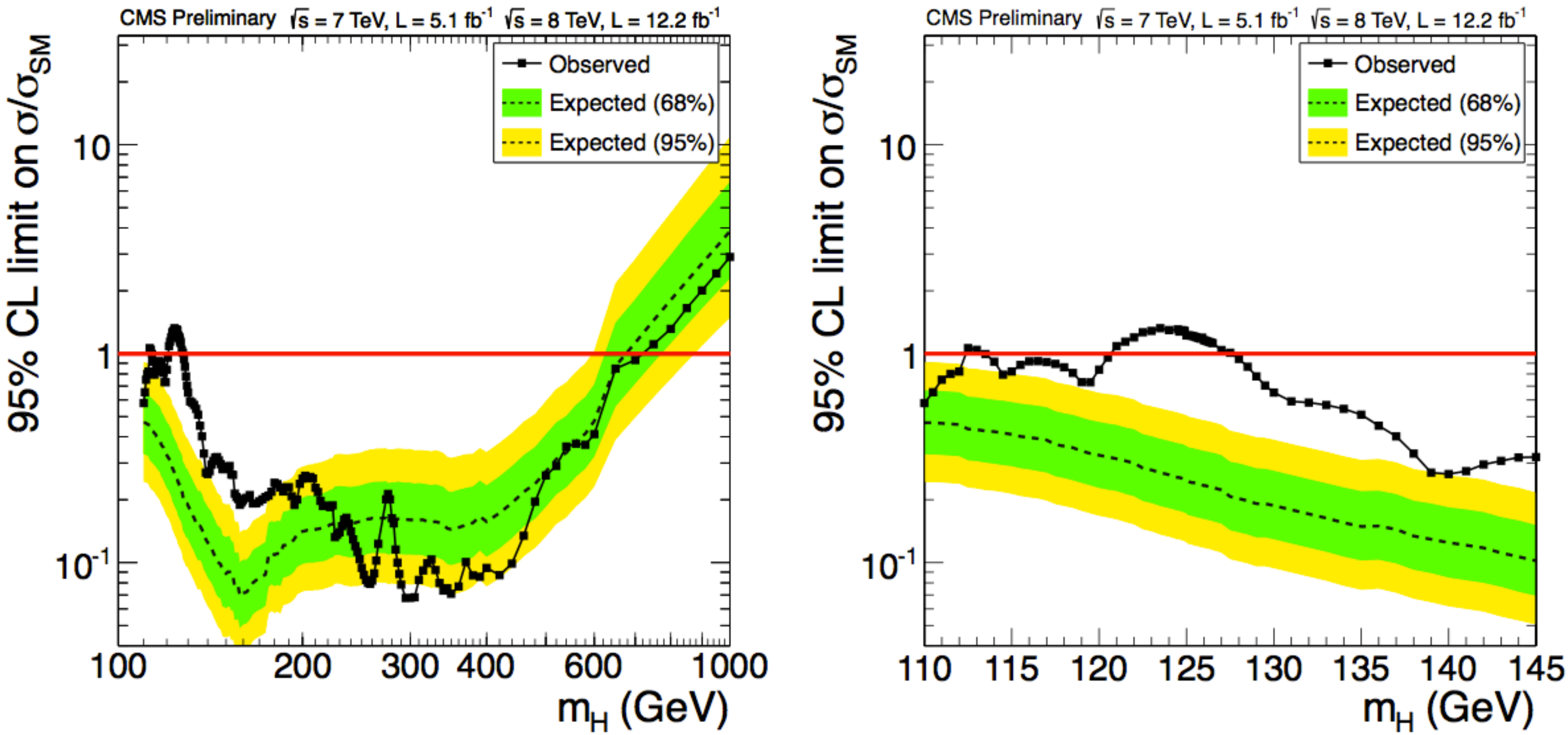
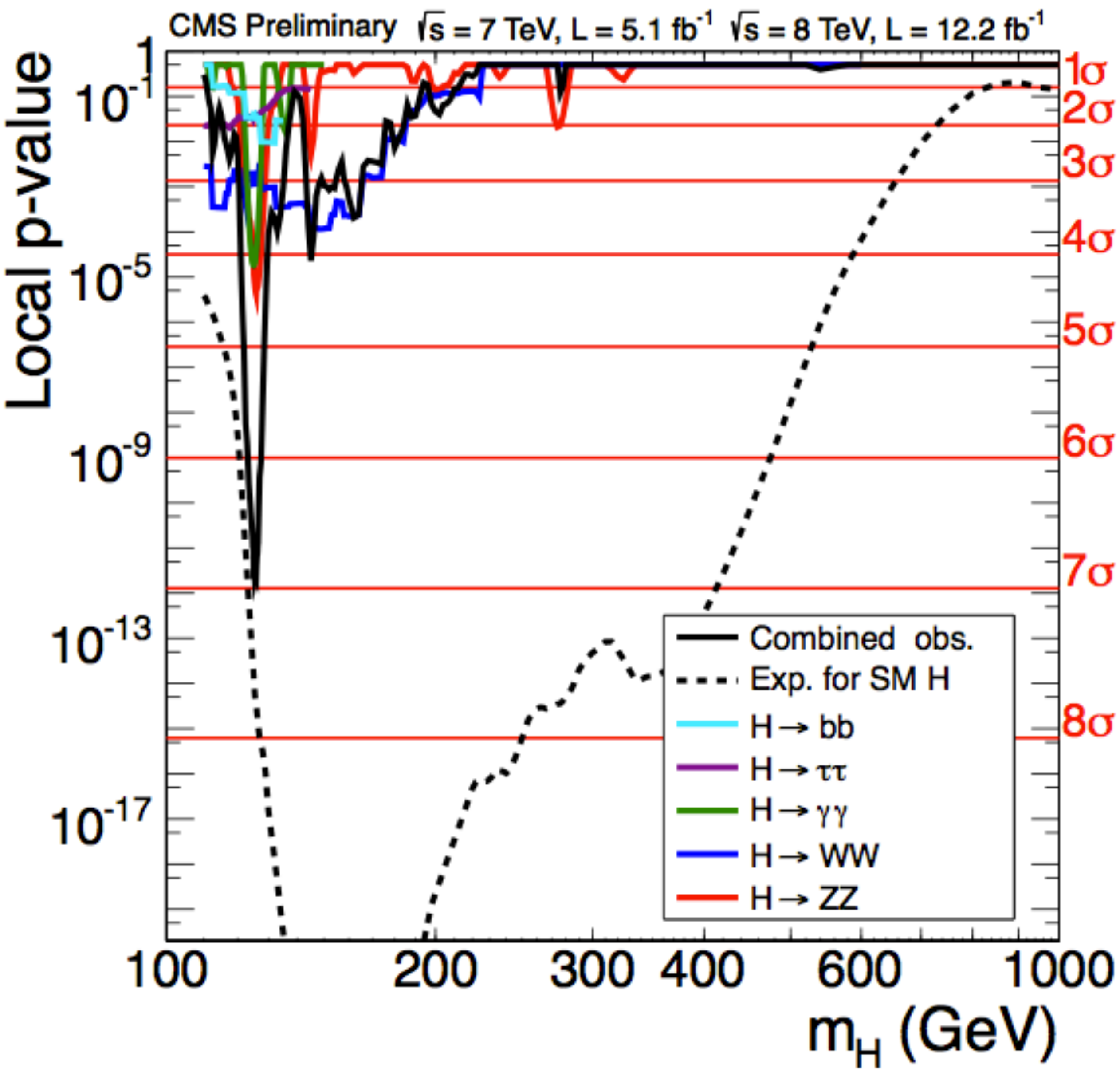
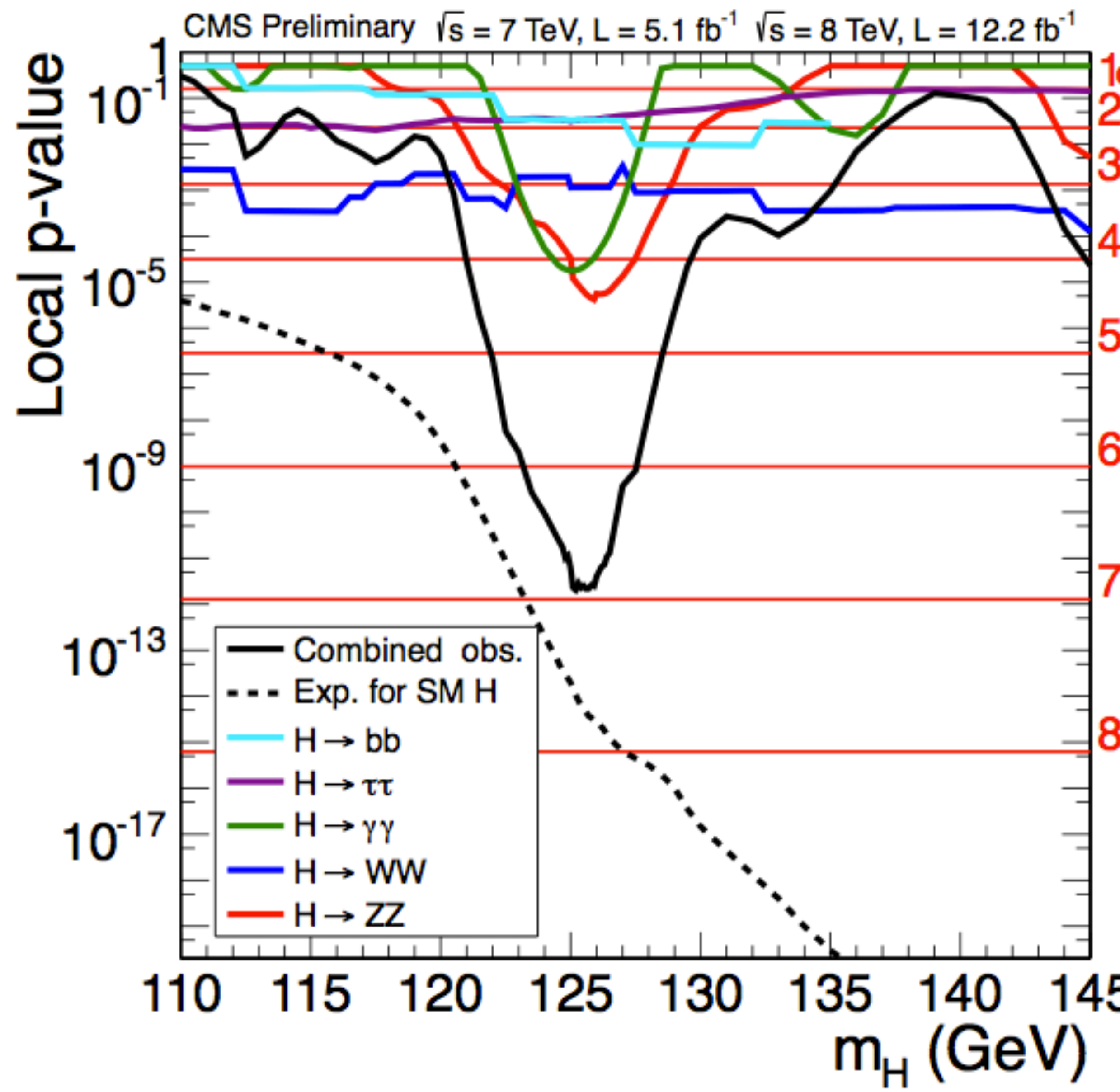


All the range up to 700 GeV is excluded but [120,130] GeV

p-values





Combined Significance = 6.9 σ

Best signal strength fit

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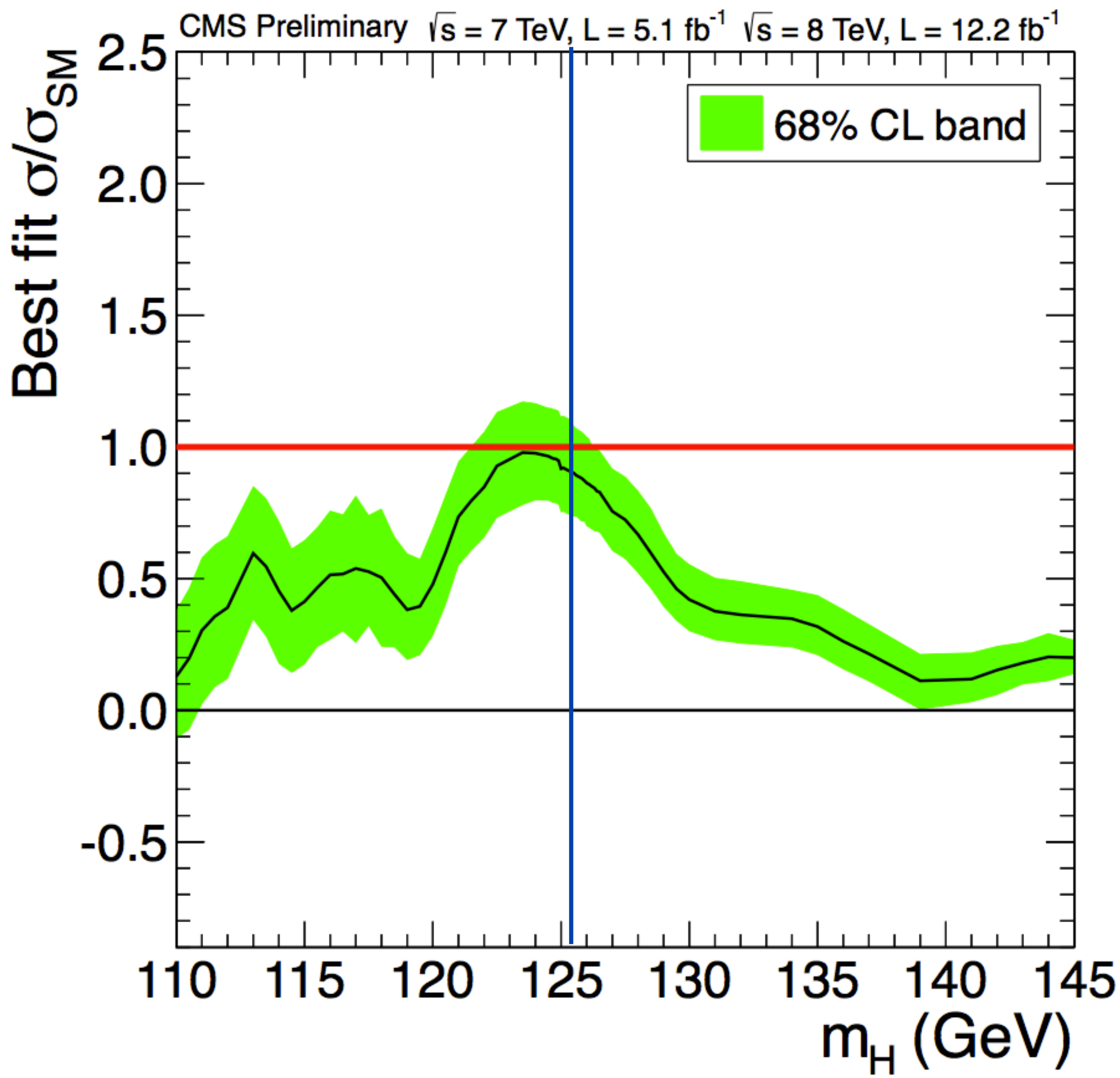
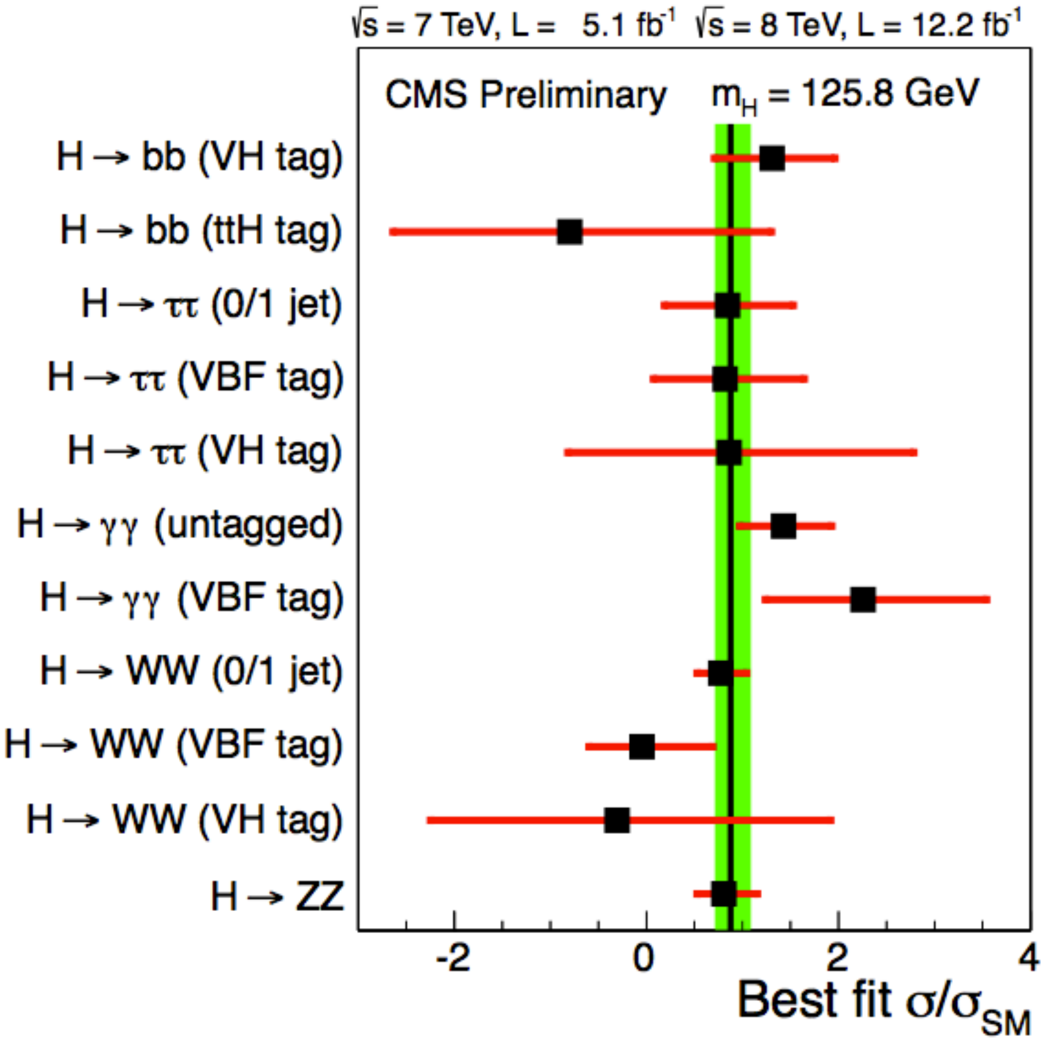


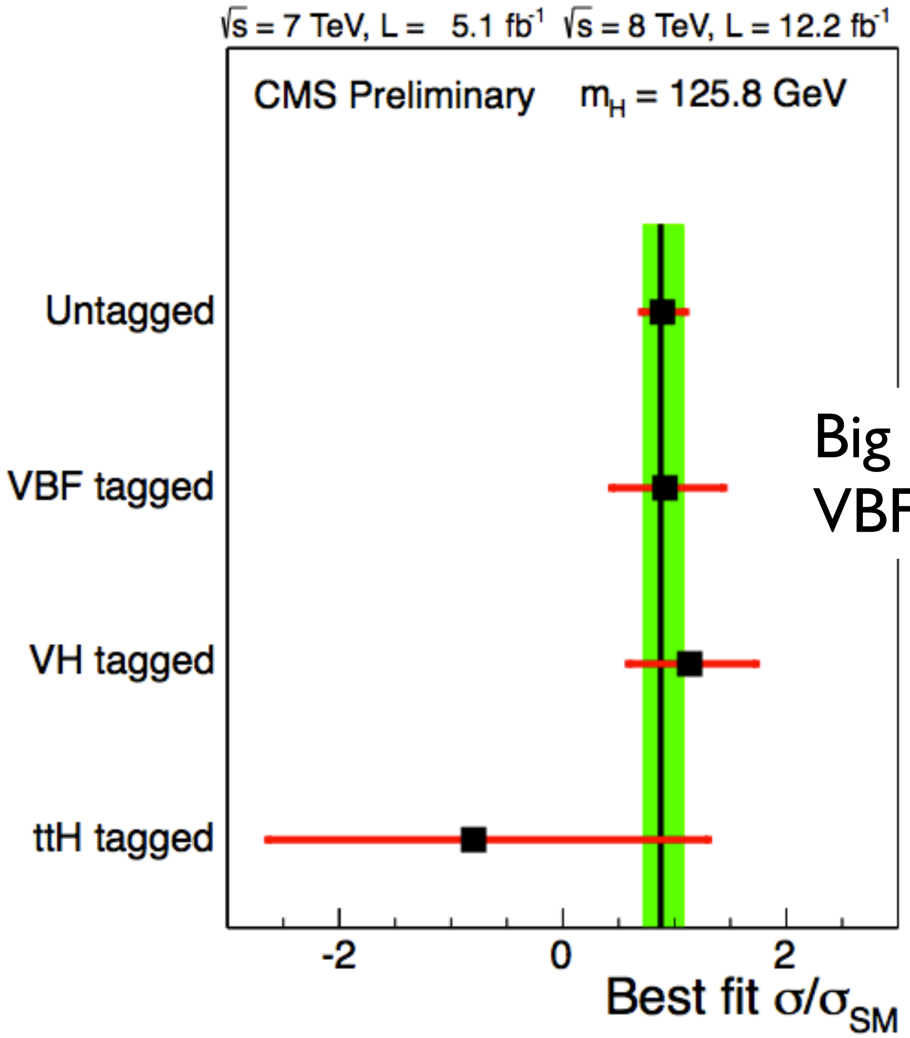
Best fit value at 125.8 GeV = 0.88 ±0.21

Channels compatibility

$$q_\mu = -2\ln\frac{L(data|\mu,\hat{\theta}_\mu)}{L(data|\hat{\mu},\hat{\theta}_\mu)} \quad \text{at} \quad \mu = 1$$

Sum of individual q_μ expected to behave asymptotically as a X^2 distribution





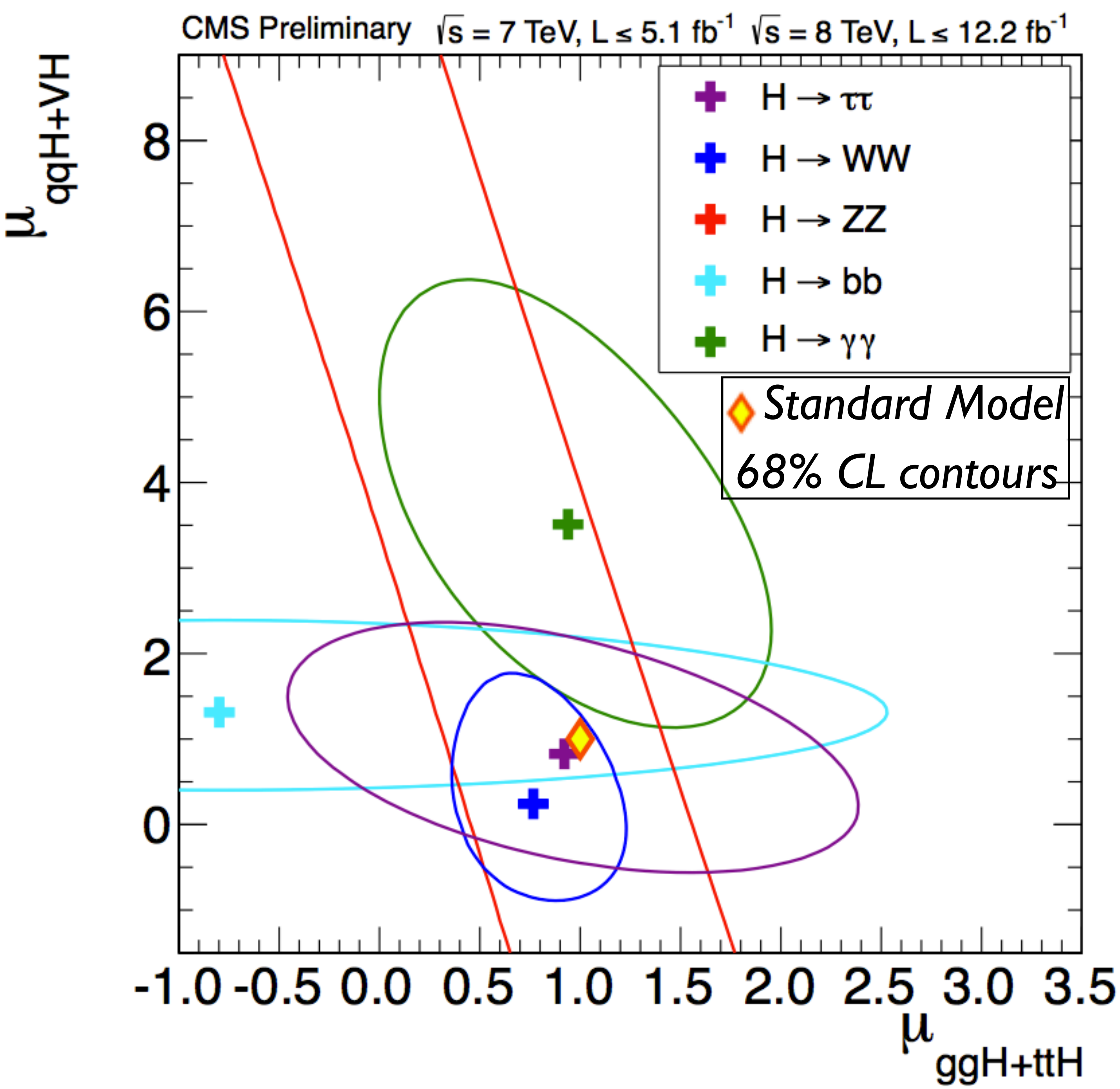
Big contaminations: VBF has ~20-50% gg

X^2/ndf = 8.7/11 (*p*-value = 0.65)

X^2/ndf = 1.3/4 (*p*-value = 0.86)

Production mechanisms

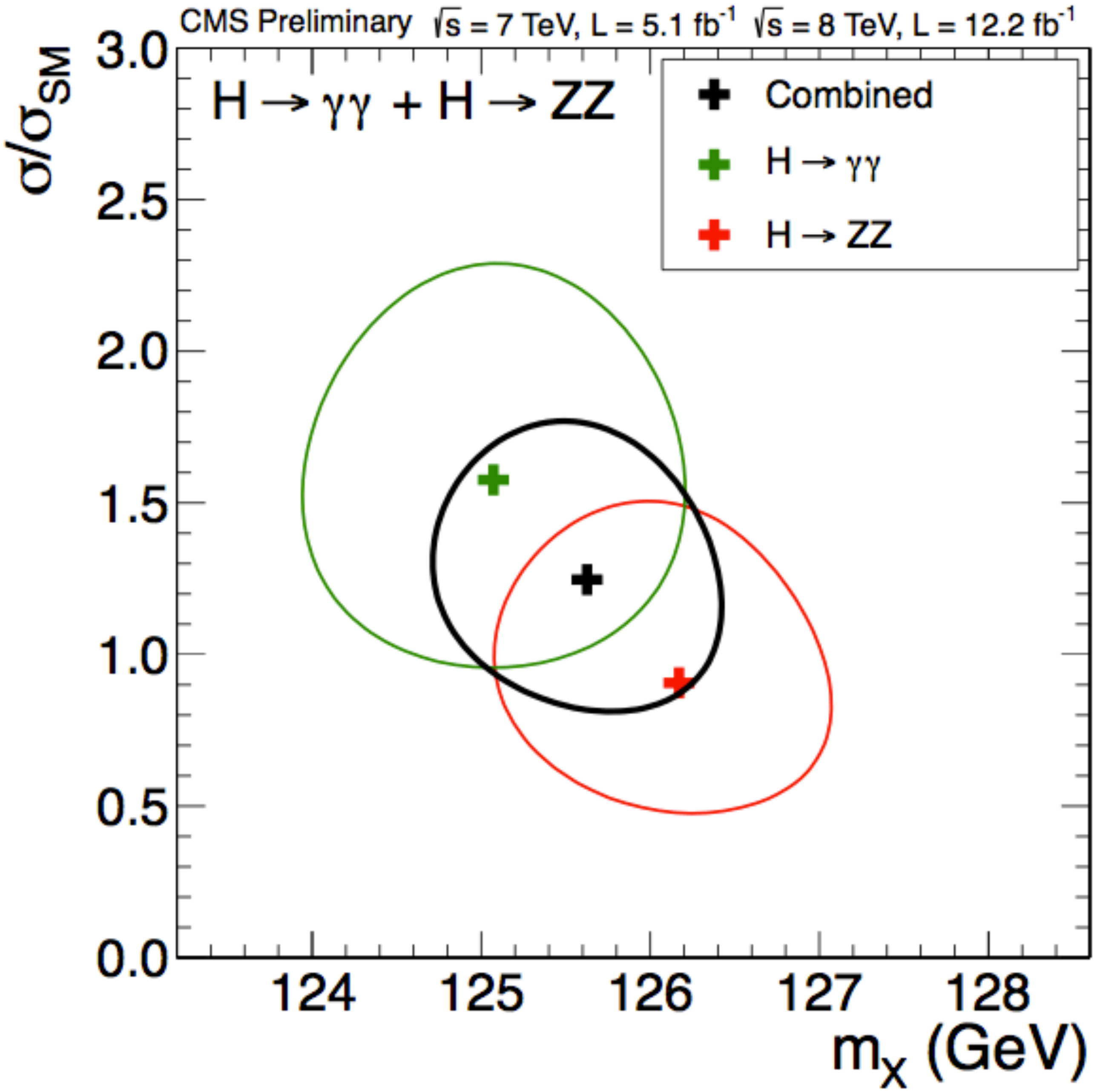
The four main production mechanisms are all related to a top-coupling (gg, ttH) or to vector boson (VBF, VH)



SM is within 95% CL of each channel

Mass measurement

Test statistics: $$q(m) = -2\ln\frac{L(obs|\mu s(m)+b,\hat{\hat{\theta}}_m)}{L(obs|\hat{\mu}s(m)+b,\hat{\theta})}$$



- *relative event yield fixed to the SM expectation*
- *overall signal strength free*

Mass measurement

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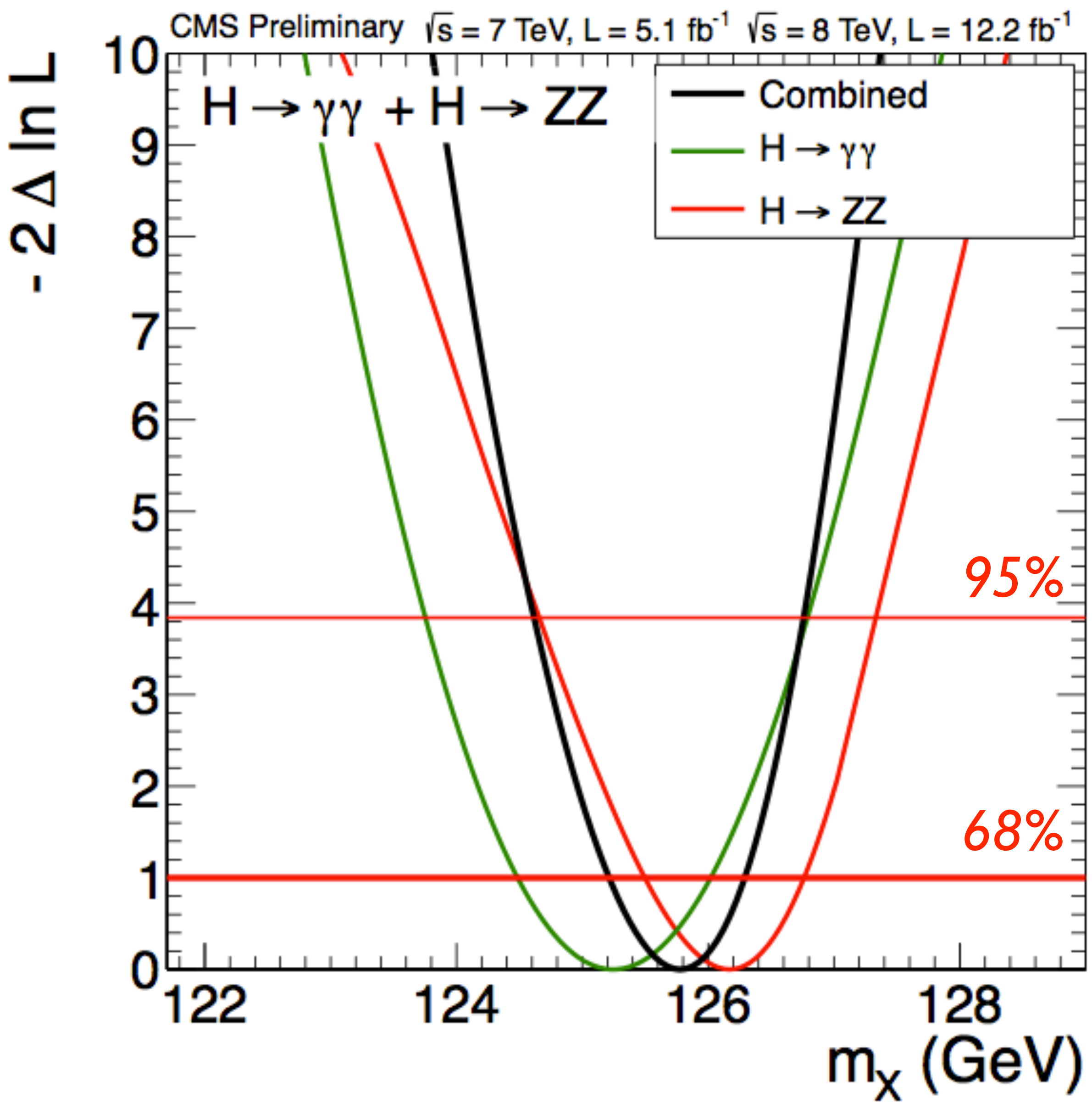

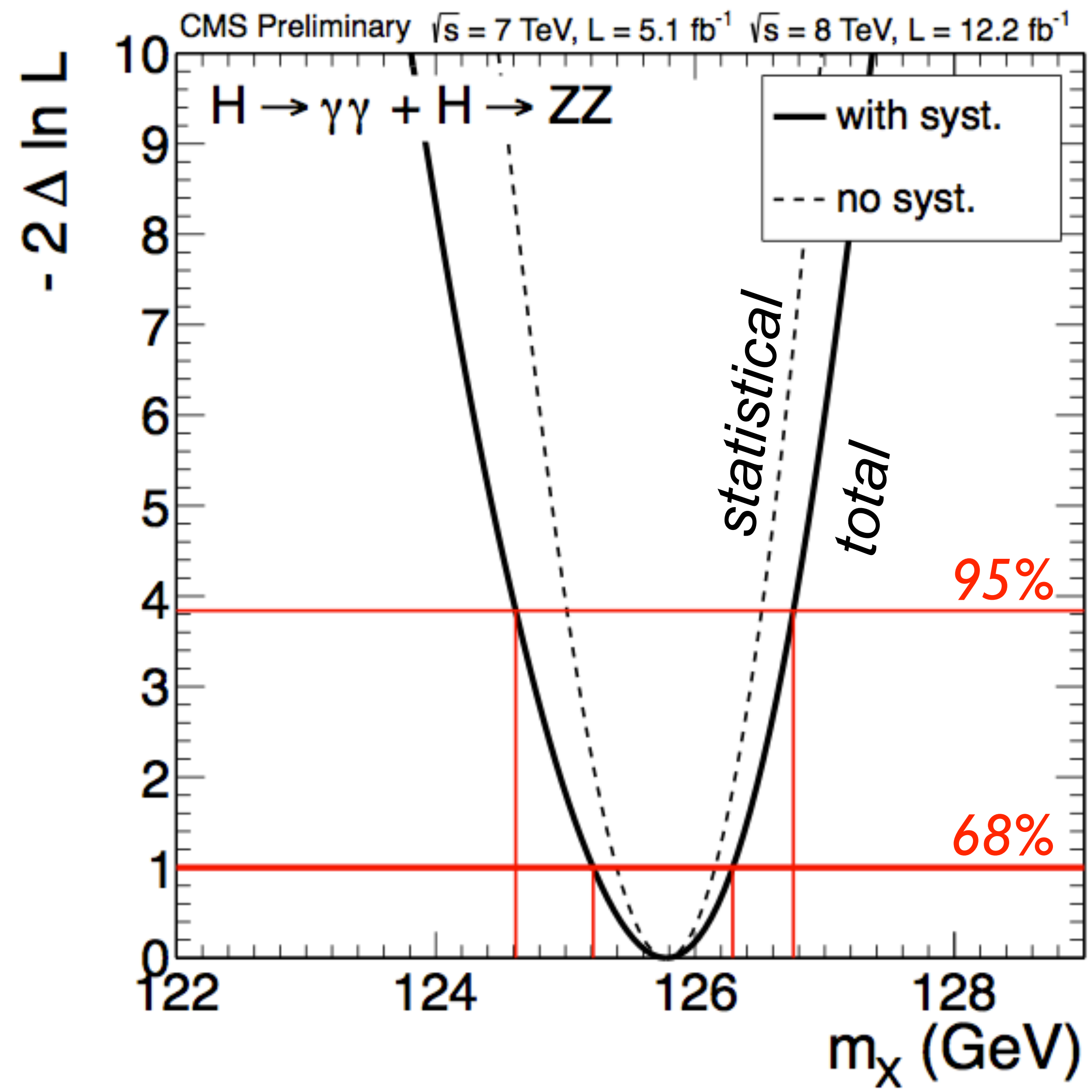

The three signal strength modifiers
($gg \to H \to \gamma\gamma$

$VBF + VH \to H \to \gamma\gamma$

$H \to ZZ$ *)*
are left free and profiled like all other nuisances

m = 125.8 ± 0.4 (stat) ± 0.4 (syst) GeV

All nuisance parameters set to their best-fit values define the statistical uncertainty.

The difference in quadrature wrt to the total gives the systematics.

Custodial symmetry

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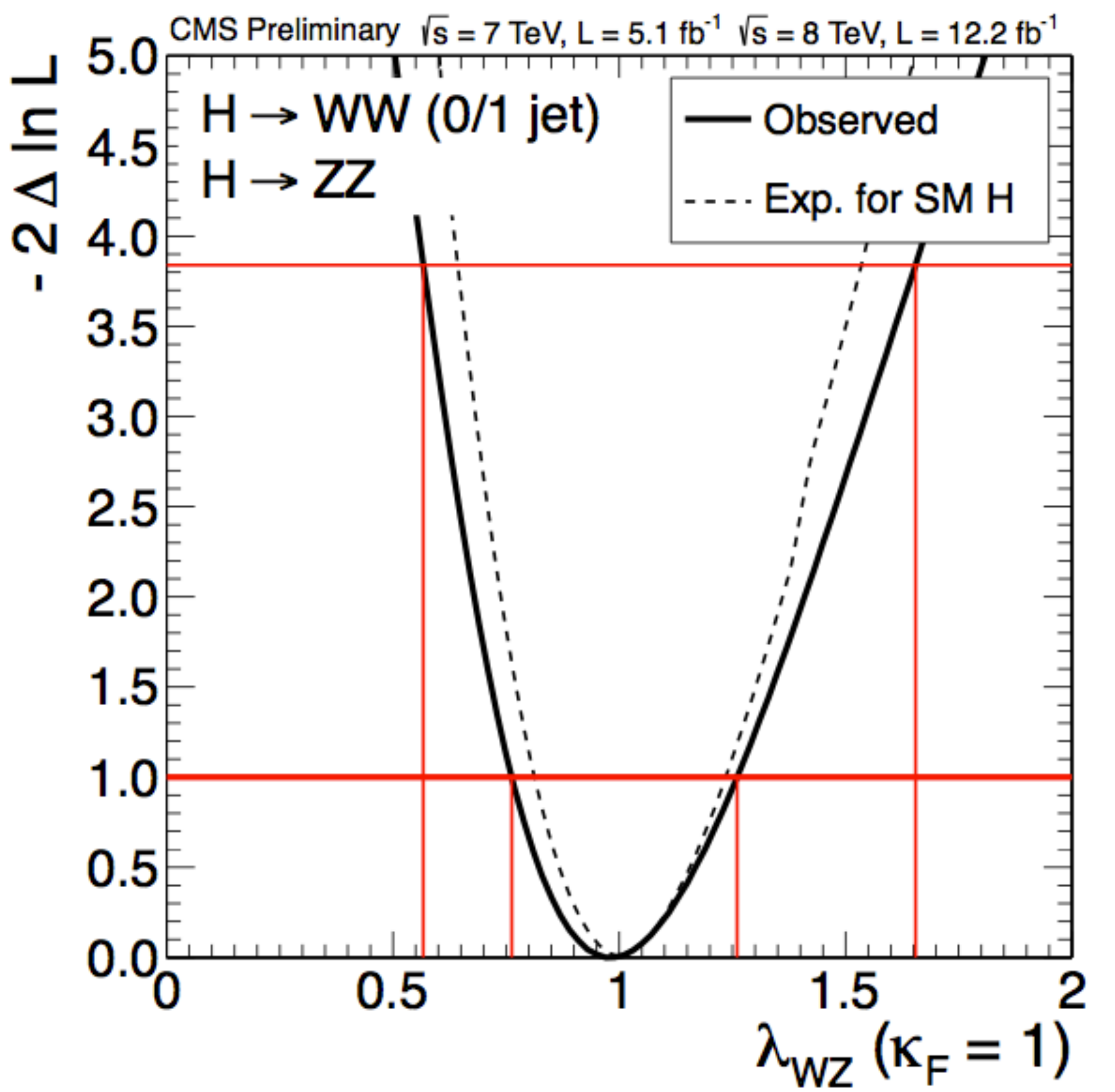
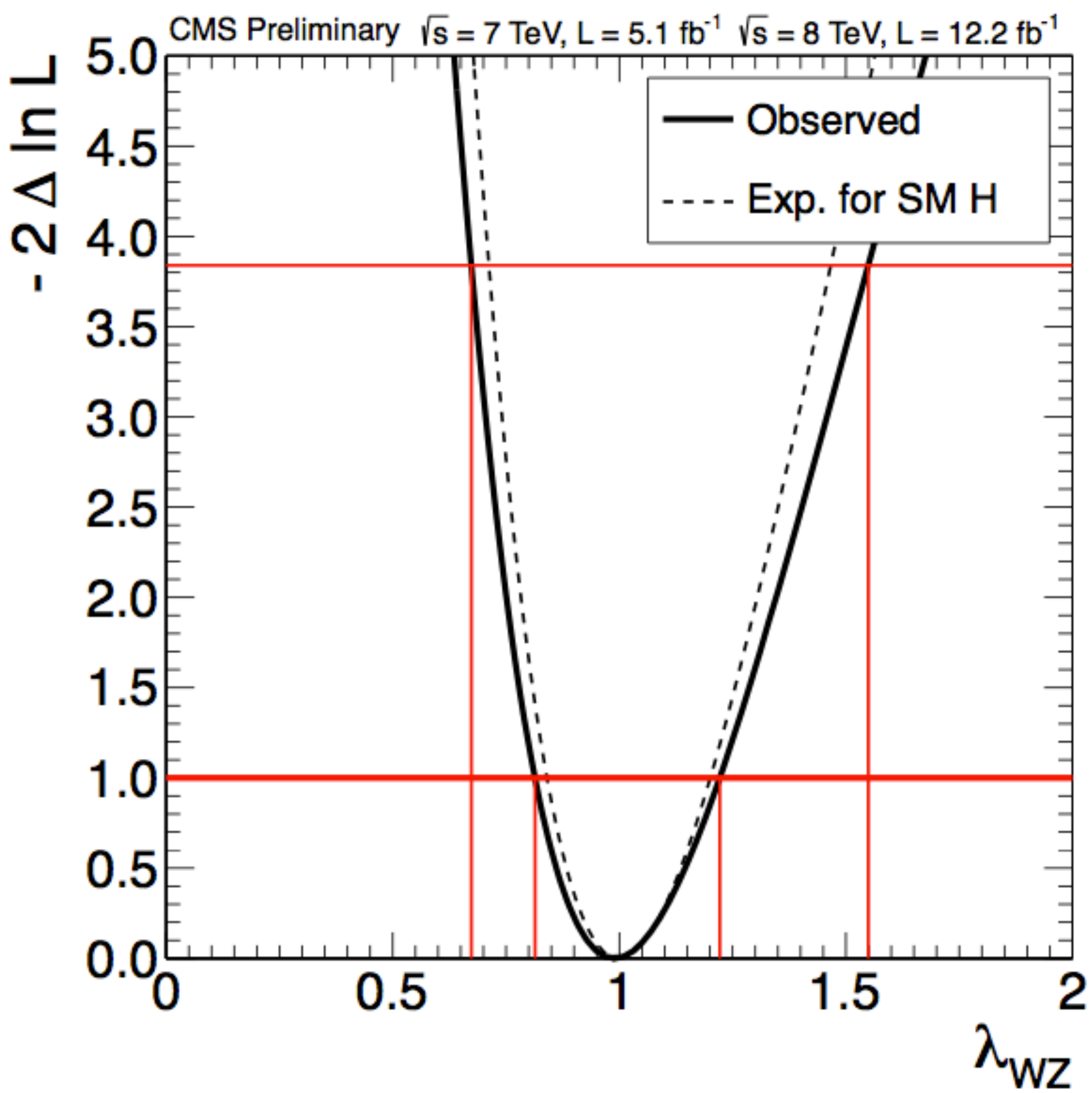
gg dominant production ⇒ $$\frac{pp \to H \to ZZ}{pp \to H \to WW} \propto \frac{\not{\Gamma}_{gg}\Gamma_{ZZ}}{\not{\Gamma}_{gg}\Gamma_{WW}}$$

Nearly model independent measurement of $\lambda_{WZ} = \kappa_W / \kappa_Z$



(SM coupling to fermions in gg loop)



To account for small unequal fractions of VBF use 2 parameters: scan λ_{WZ} and profile κ_Z

Using *all channels: scan* λ_{WZ} and profile κ_V κ_f (one κ_f for all fermions ⇒model dependent)

Higgs couplings

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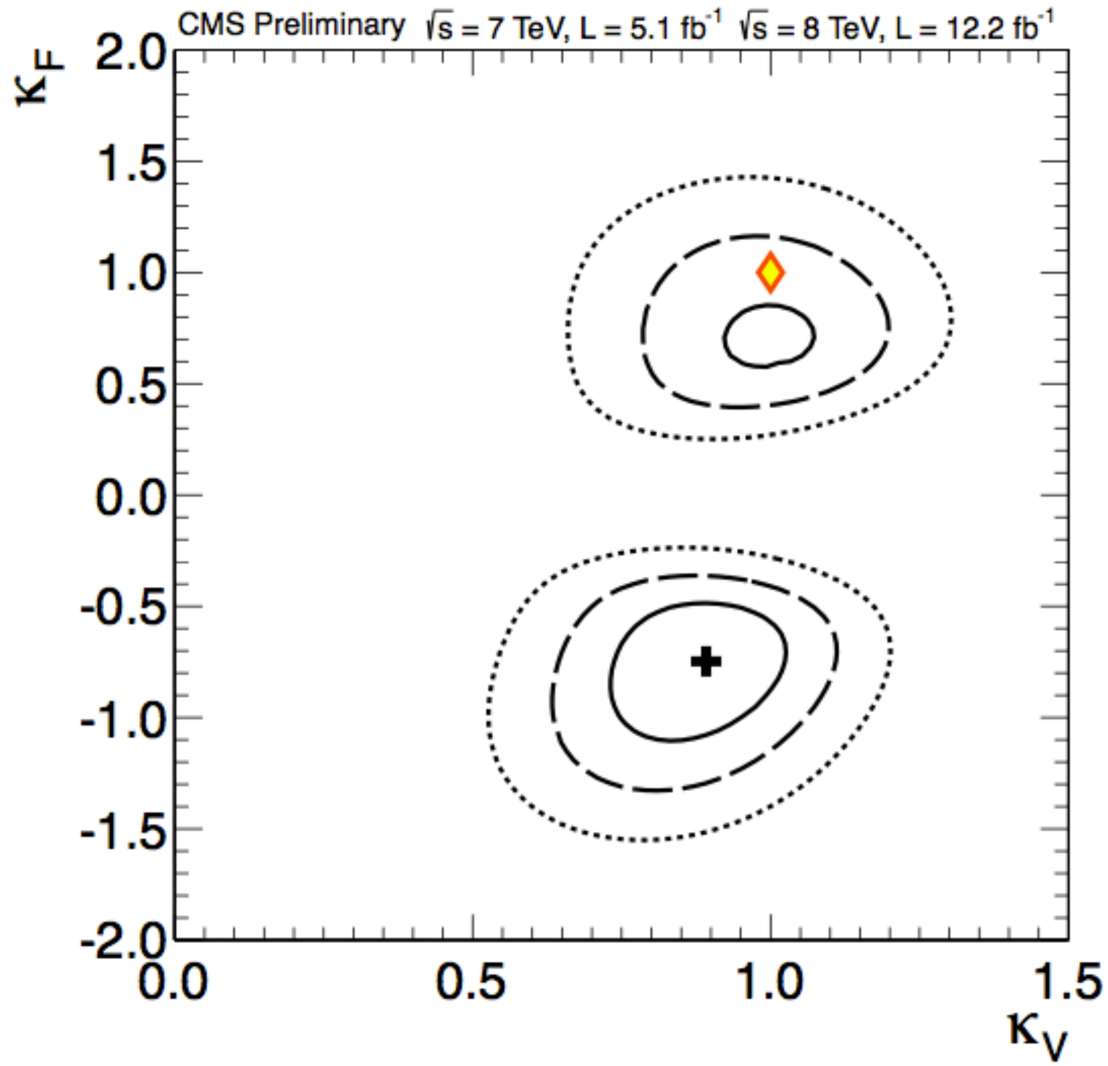
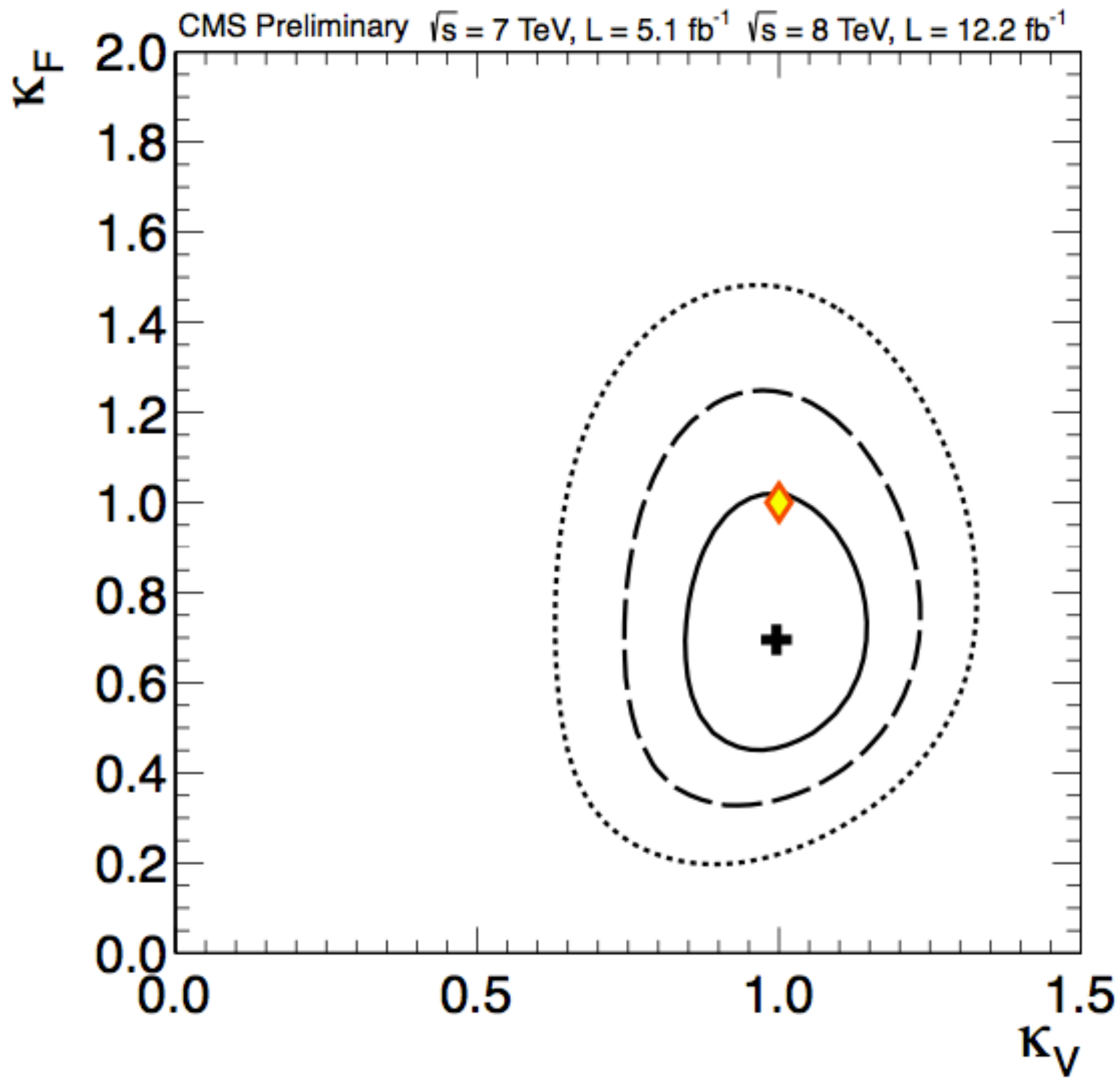
coupling = κ x coupling(SM)

At LO all partial widths ∝ κ_V^2 or κ_F^2

$\gamma\gamma$ *is the only sensitive to both W and top in the loop and to the relative sign in* $|\alpha\kappa_V + \beta\kappa_f|^2$





constraint to the positive quadrant

Higgs couplings

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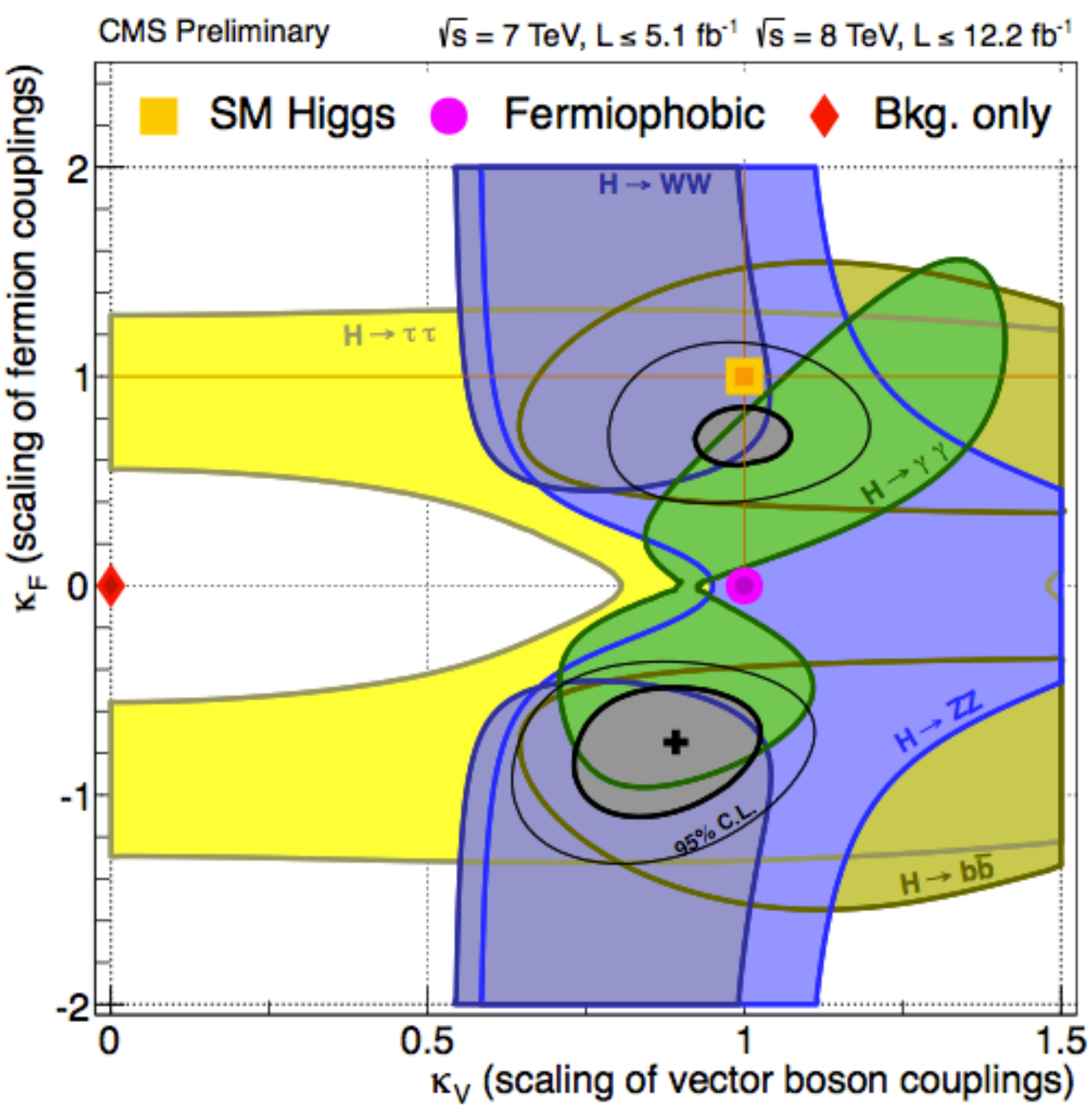
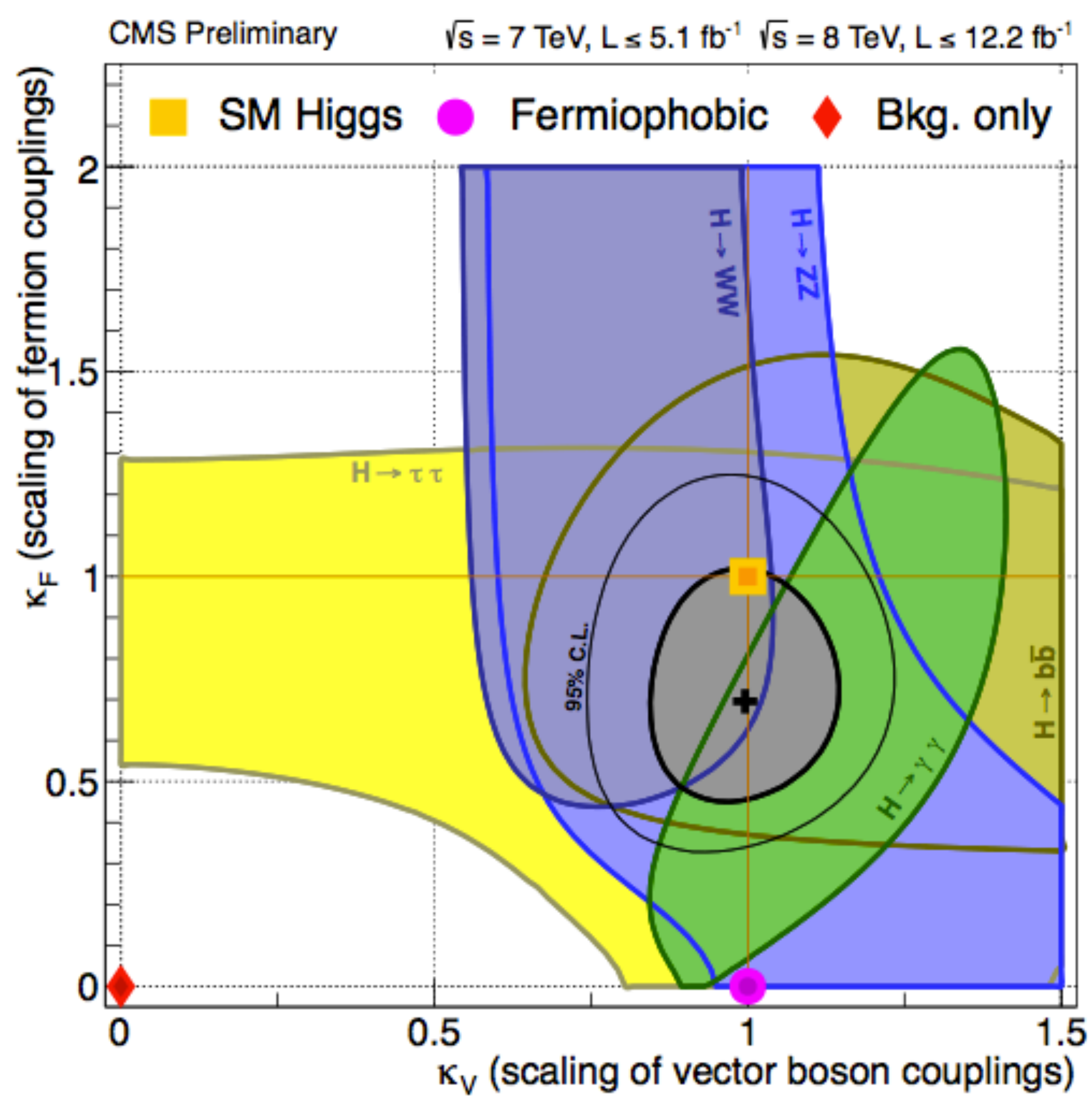
coupling = κ x coupling(SM)





Fermiophobic excluded at >4σ

Beyond the Standard Model

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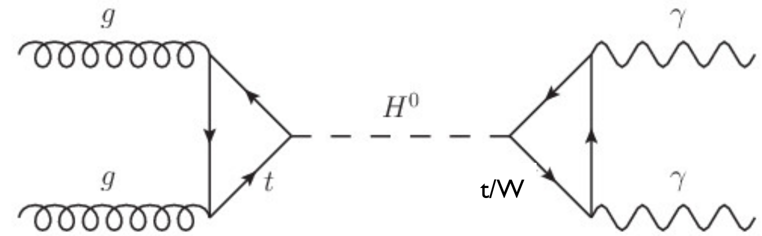
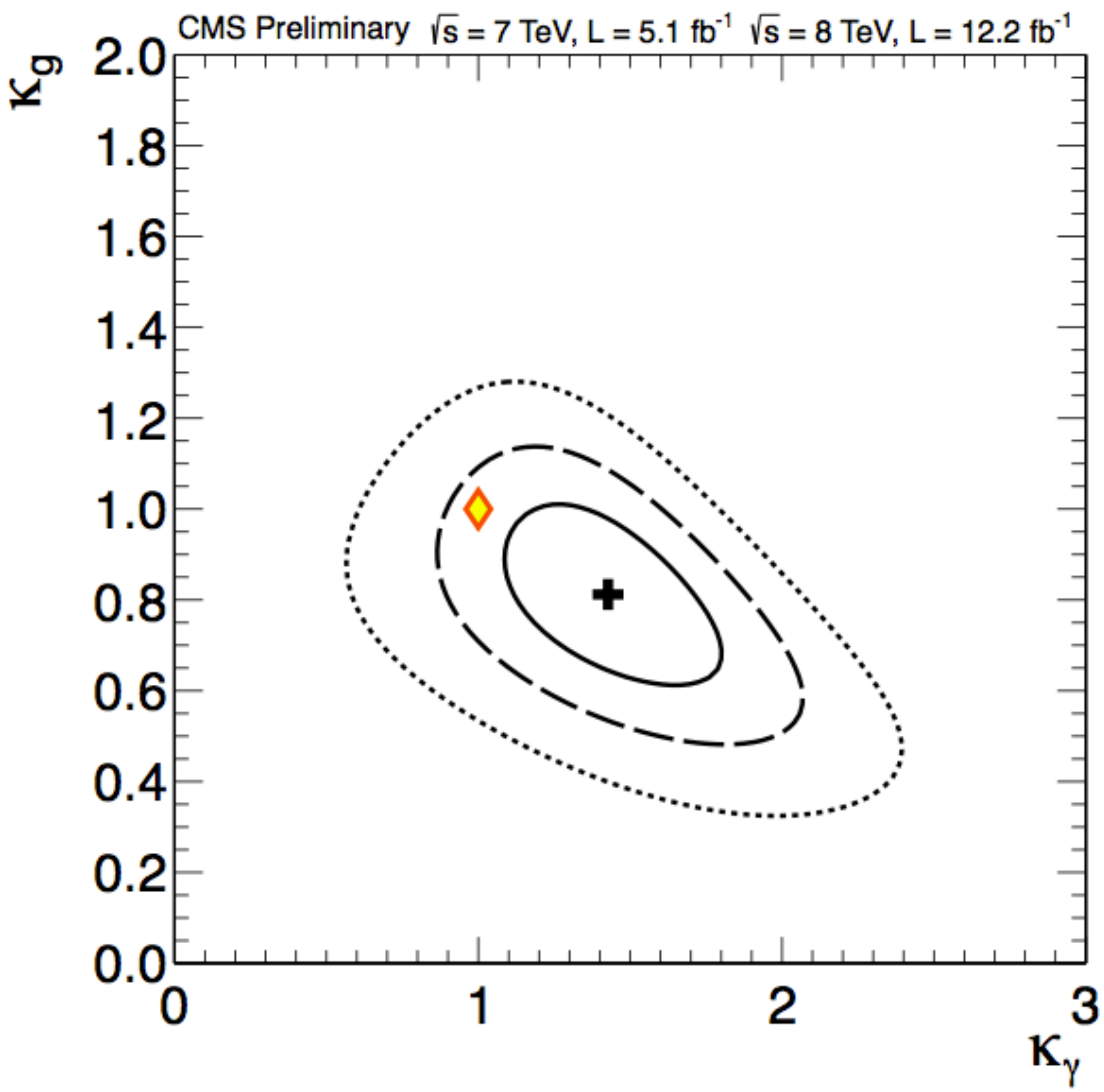
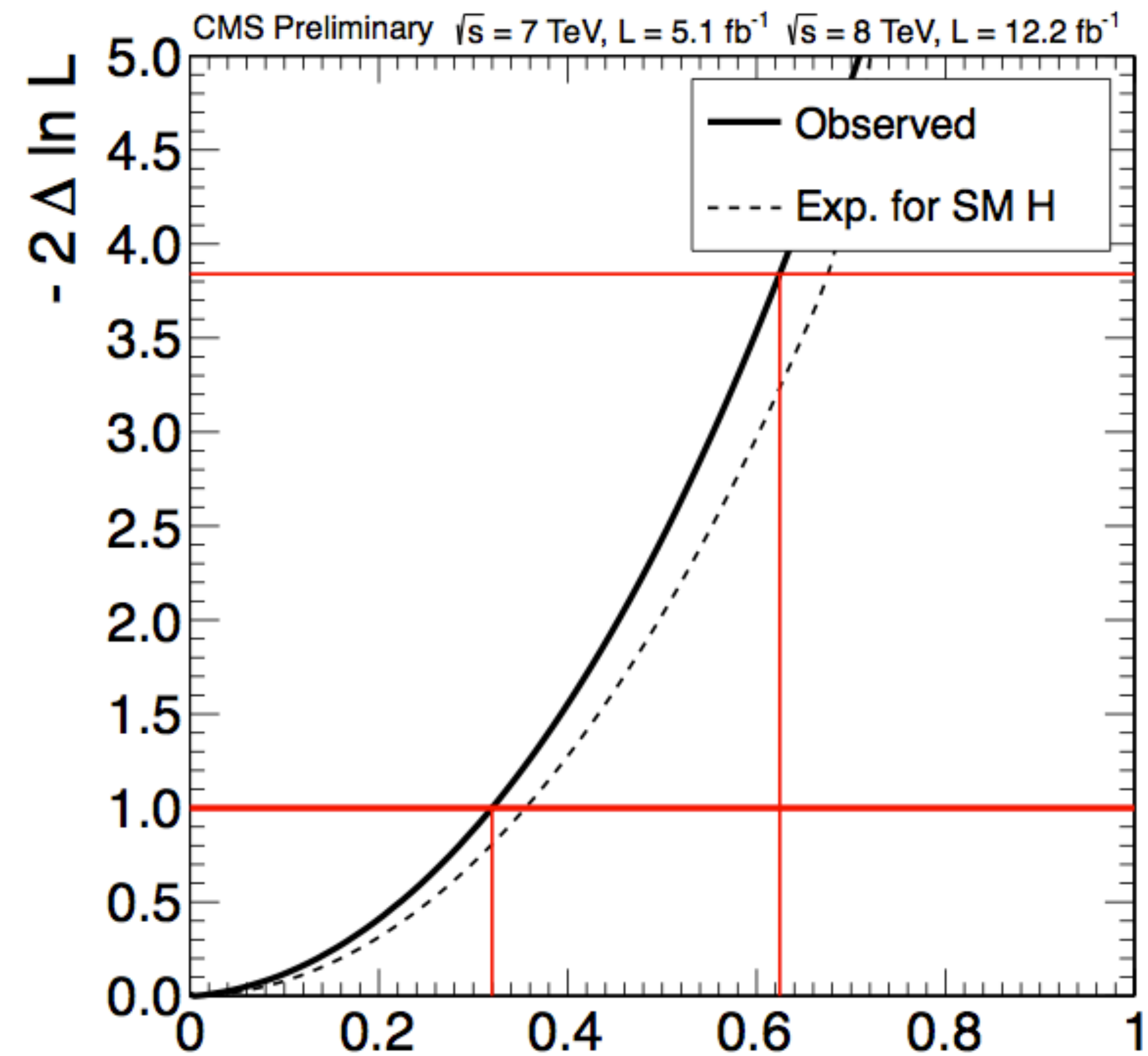
Test processes induced by loop diagrams





Set Γ_{BSM} =0



$$BR_{BSM} = \frac{\Gamma_{BSM}}{\Gamma_{tot}}$$

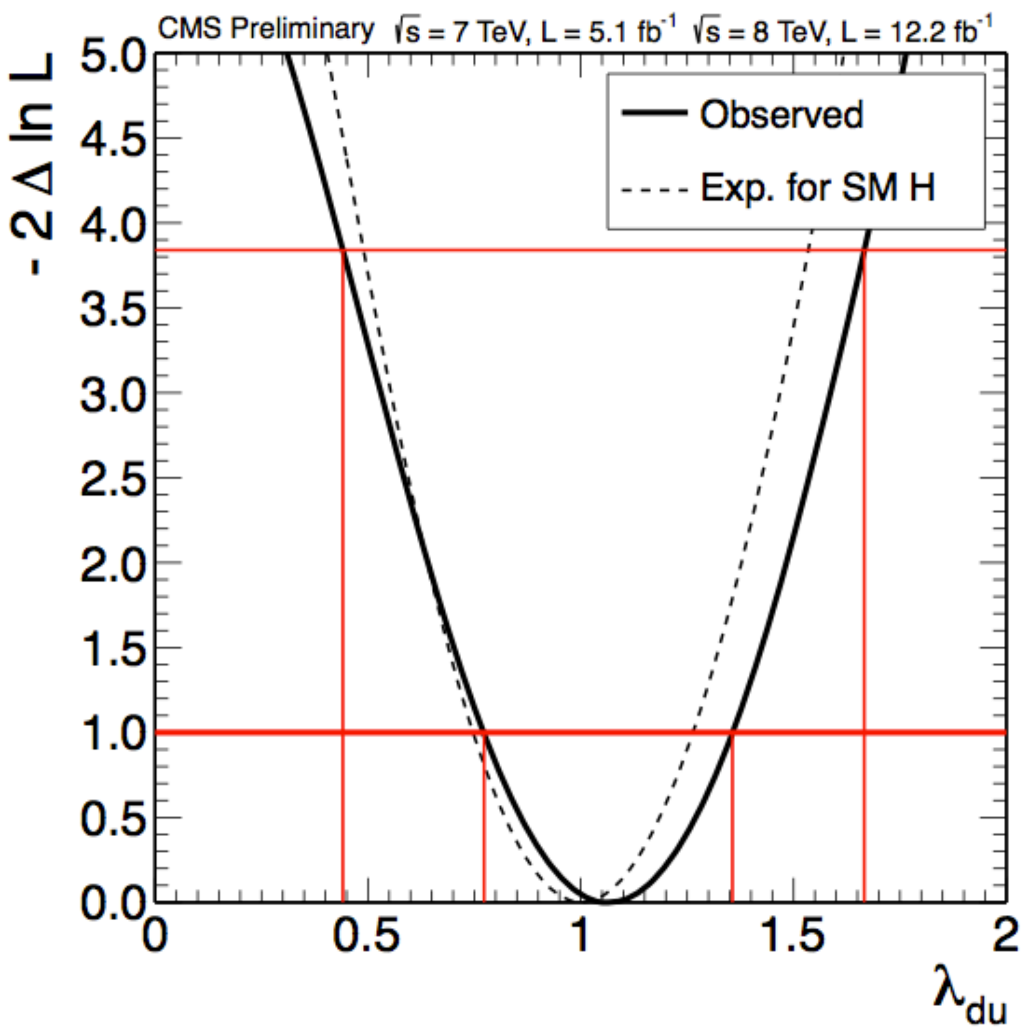
Scan BR_{BSM} and profile κ_V κ_f

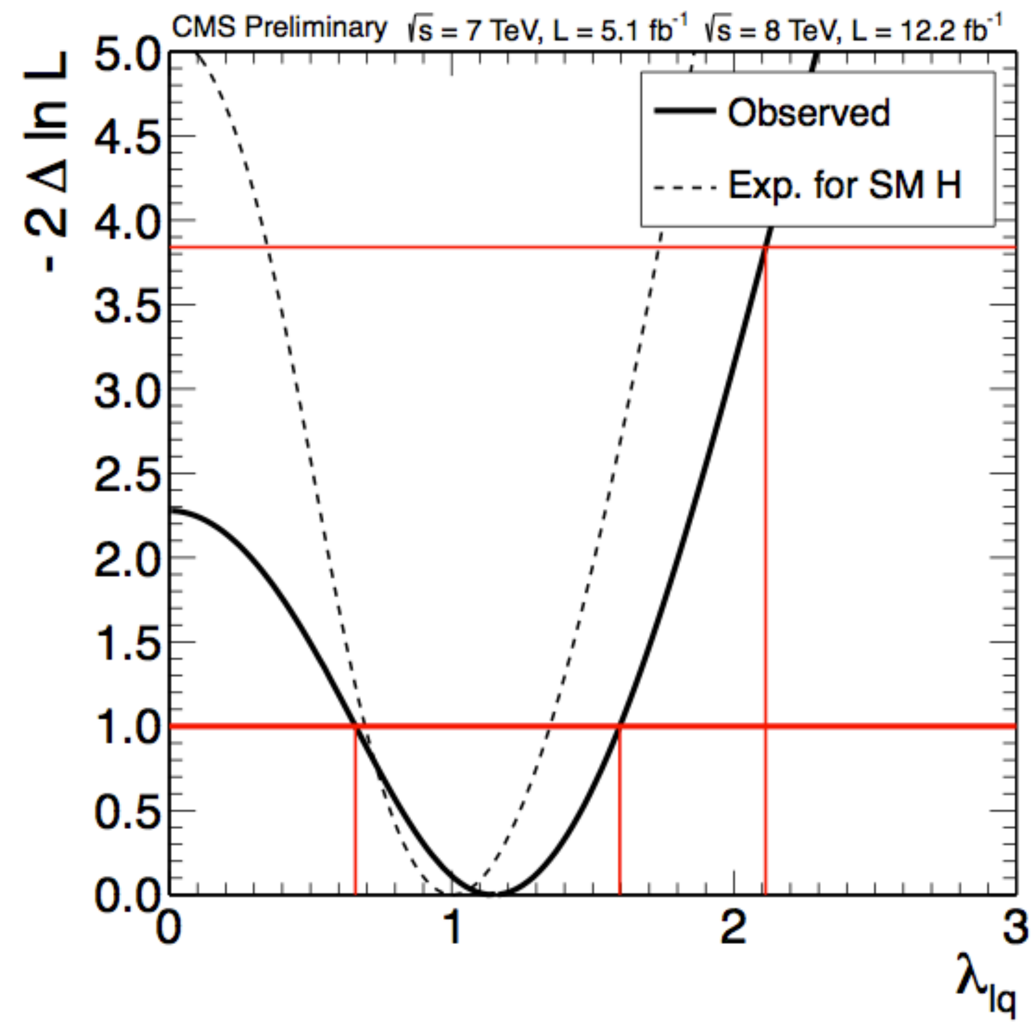
BR_{BSM} below 0.62 at 95% CL

Coupling to fermions

Test different ratios of the couplings to:

- up/down fermions $\lambda_{du}=\kappa_d/\kappa_u$
- lepton/quark $\lambda_{lq}=\kappa_l/\kappa_q$





Test 6 independent couplings

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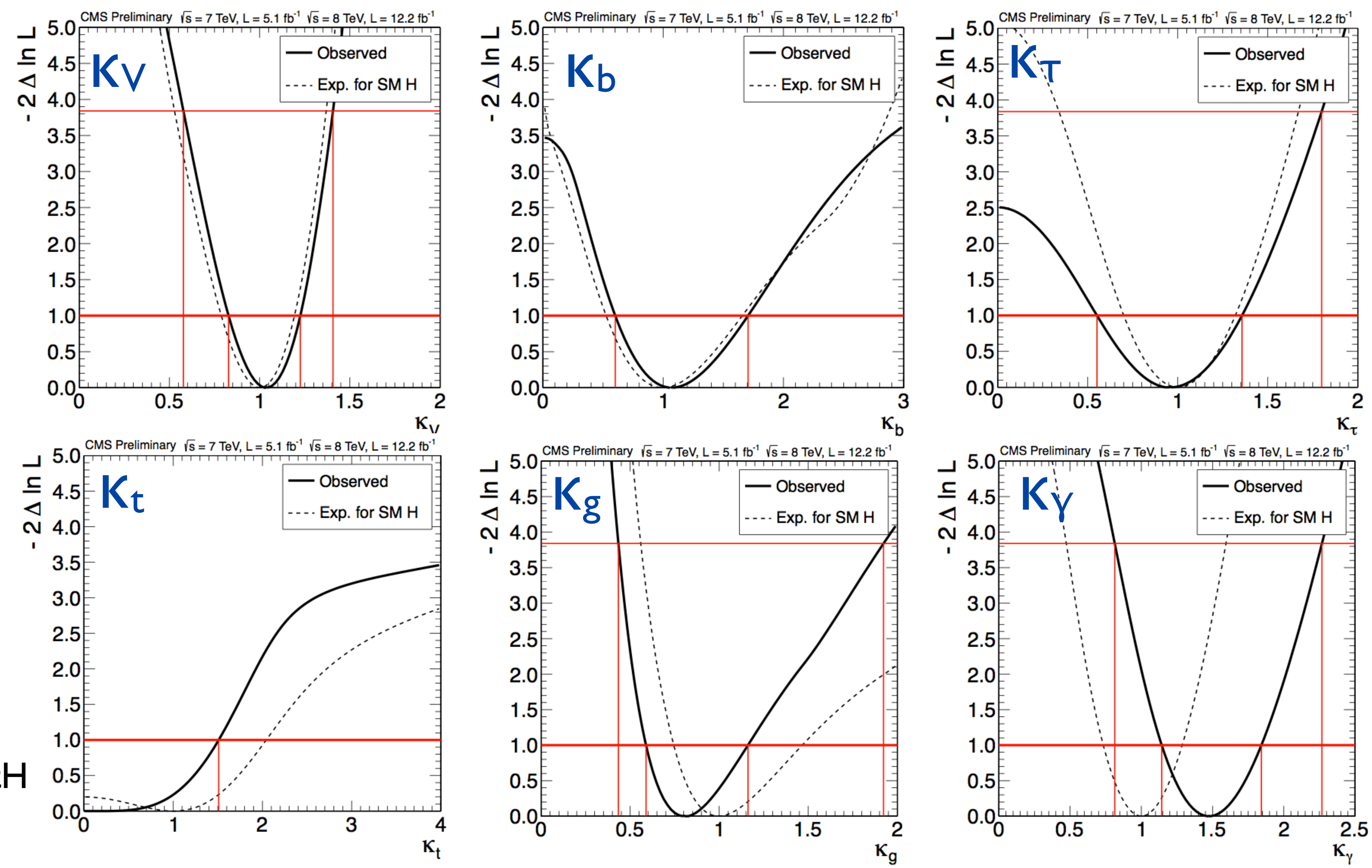
Coupling scaling factors:

κ_V for both W and Z

κ_t, κ_b, κ_τ also for 1st 2nd generations { u c t / d s b / ν_e ν_μ ν_τ / e μ τ }

κ_g, κ_γ

Fit one at the time and profile the others



low stat ttH

Spin/Parity measurement

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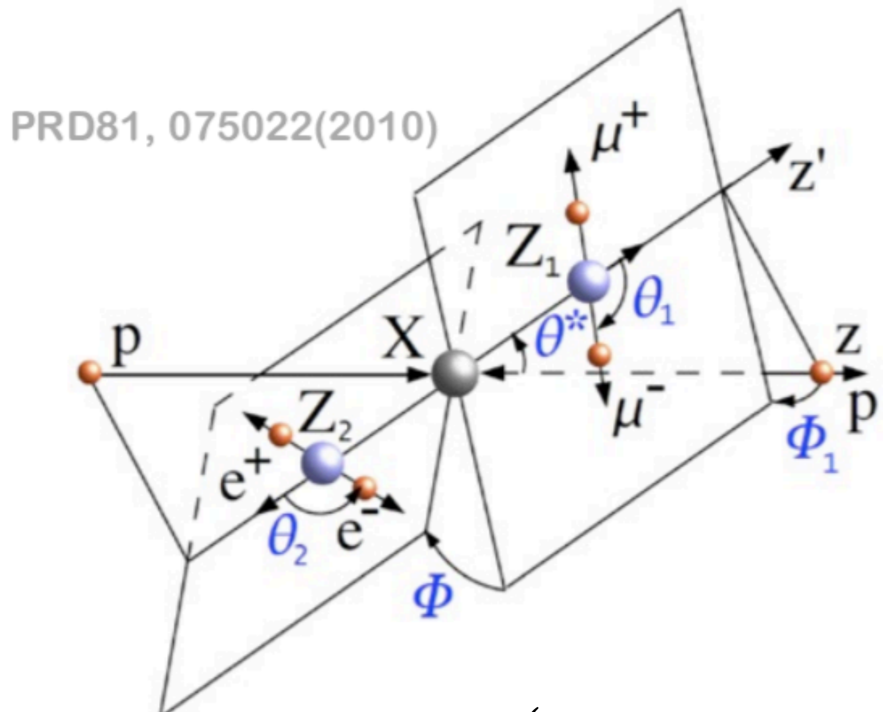
arXiv:1212.6639

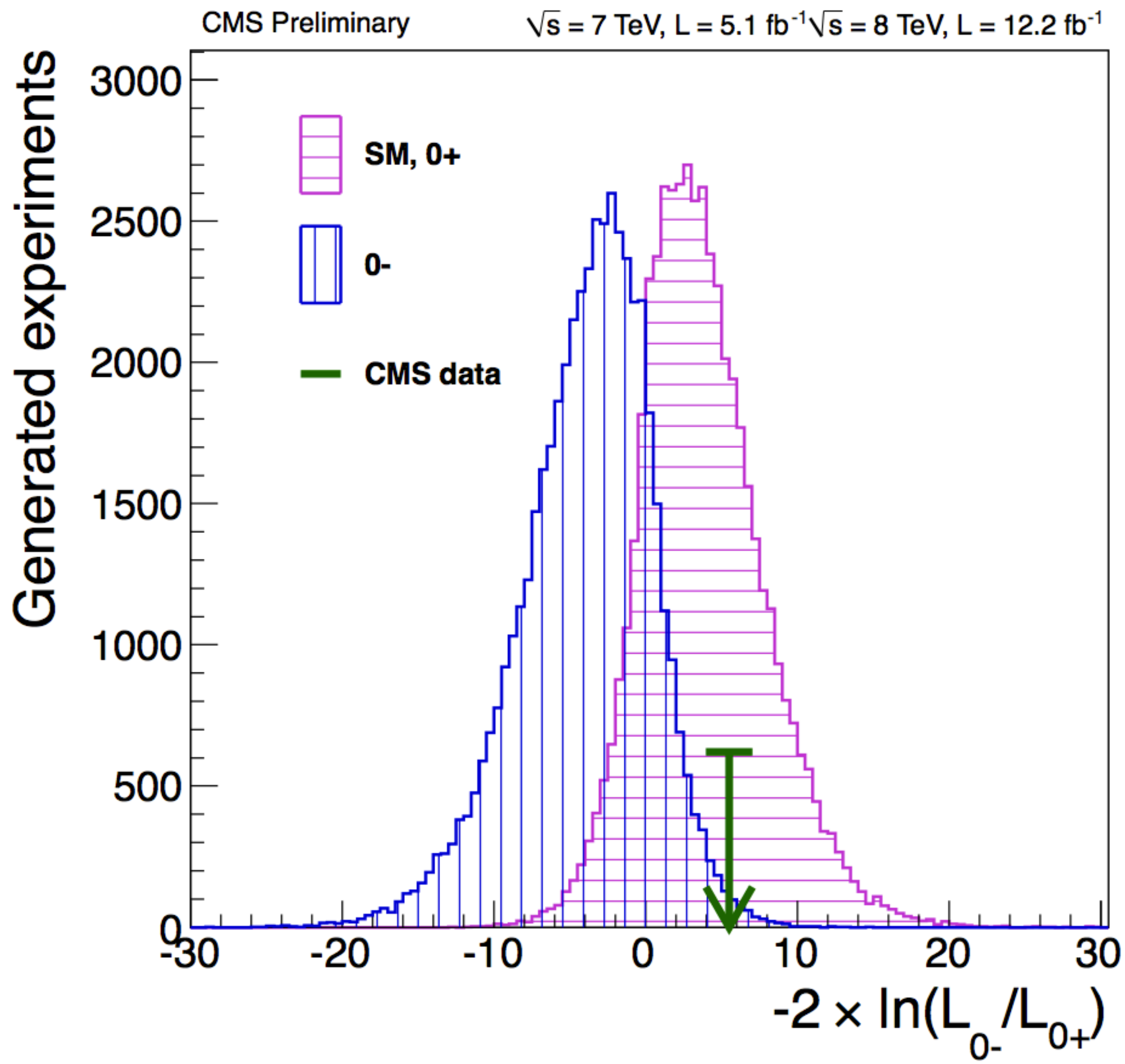
The boson decays to two photons ⇒ it has integer spin ≠1(Landau-Yang theorem)

Angular analysis of the H→ZZ



$$q = -2\ln\frac{L(0^- + bkg)}{L(0^+ + bkg)}$$

Expected separation: 1.93 σ
Observed:
0^- deviated at 2.45 σ,
0^+ (SM) compatible within 0.53 σ



Summary

The LHC and CMS are performing extremely well

All Higgs channels are under intense experimental scrutiny

No tensions with respect to SM predictions observed up to now

Backup Material

Planning the future

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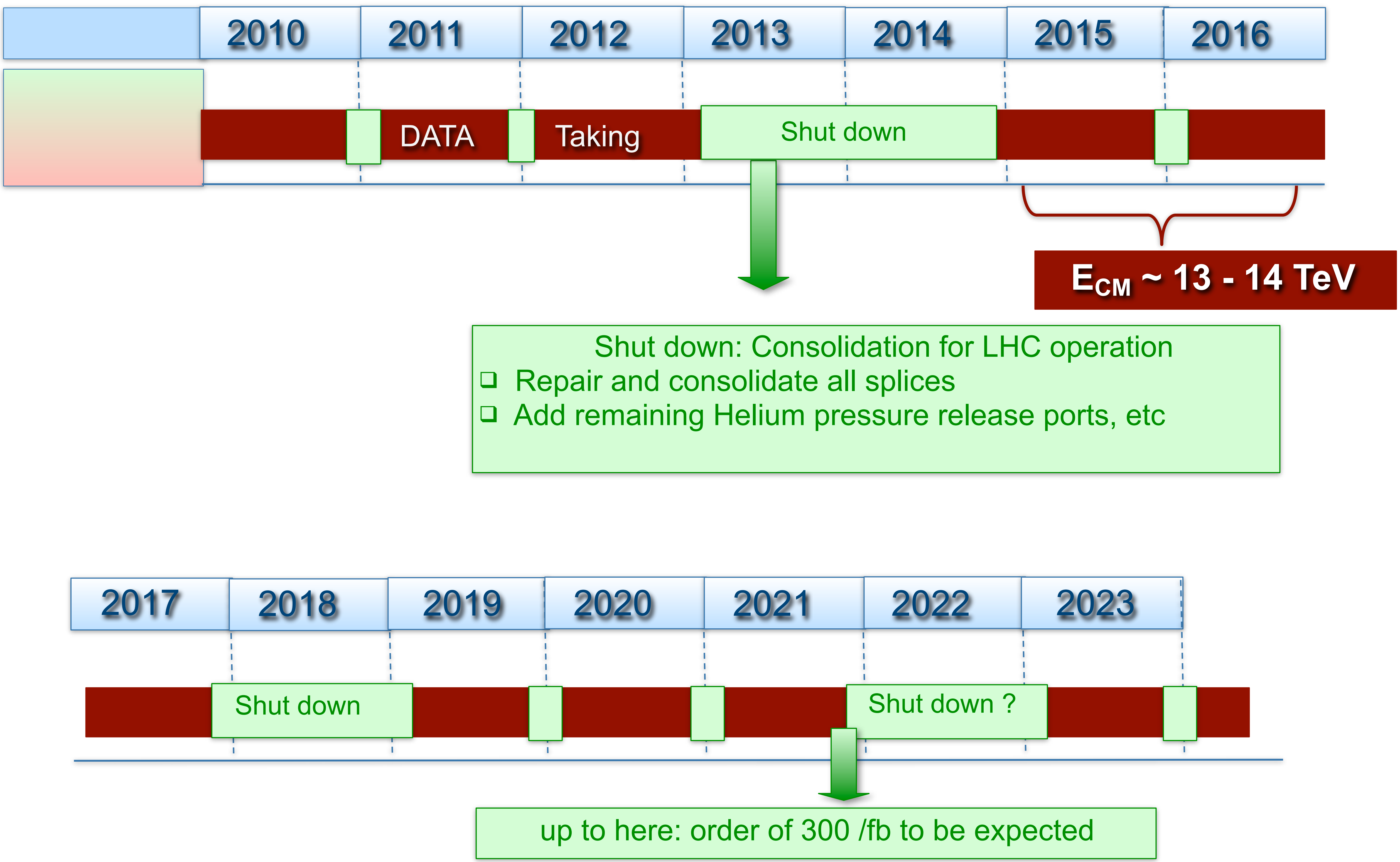

F. Pauss

Projections

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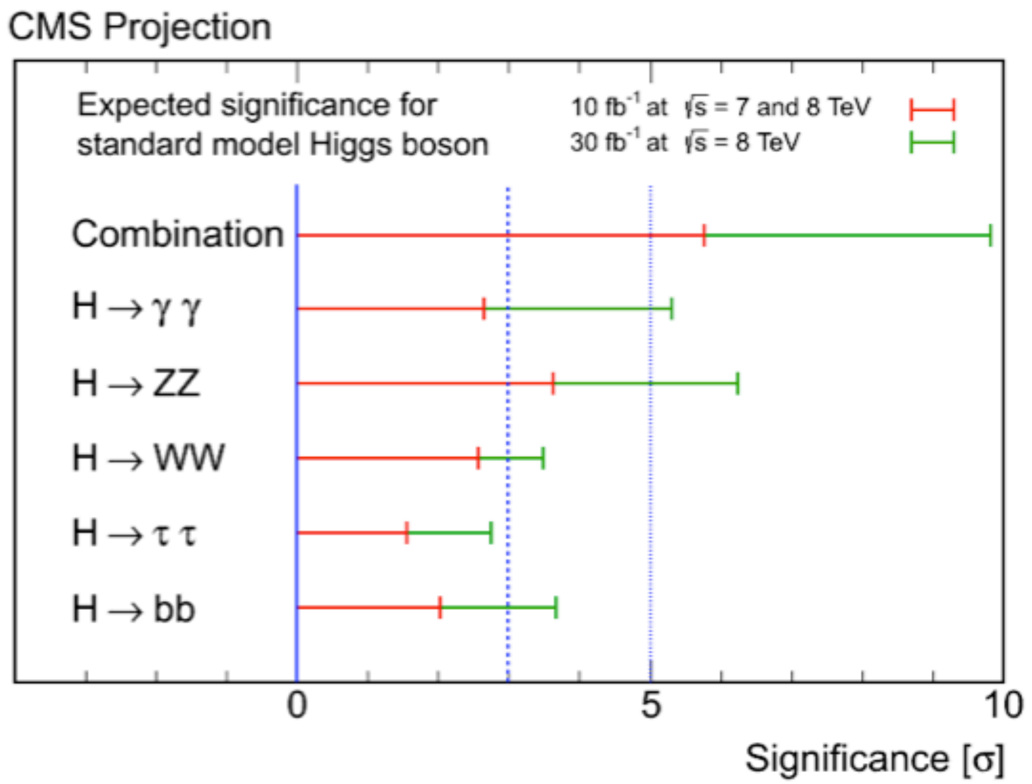
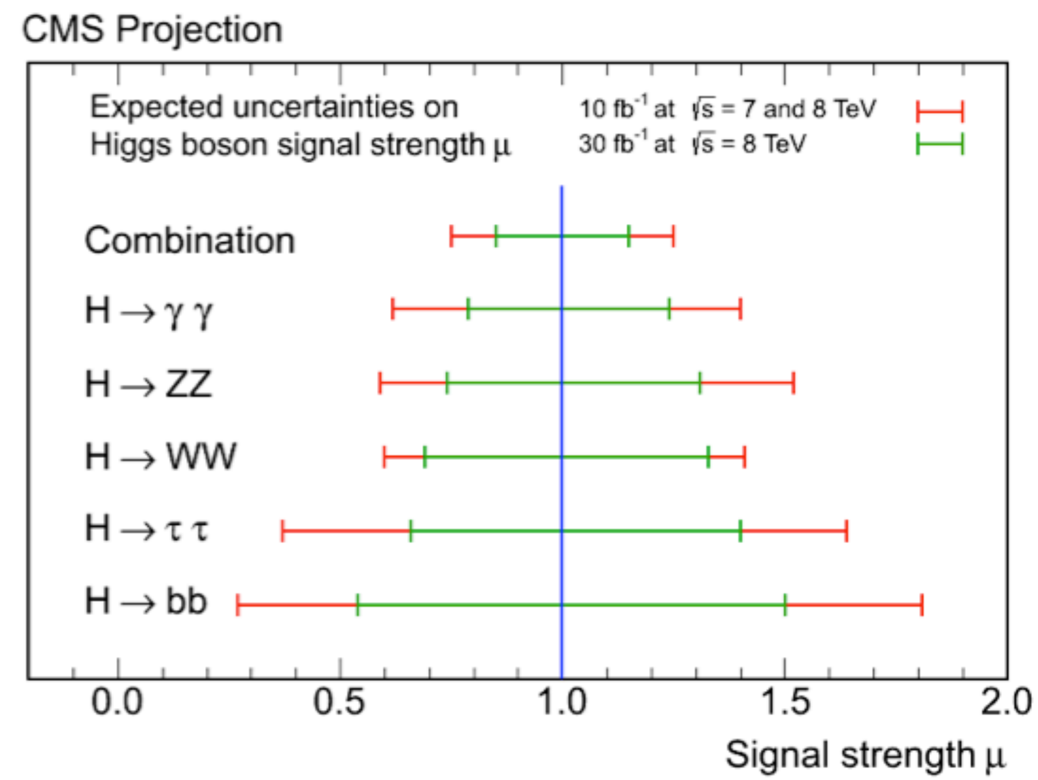
Dissertori @ ESPP2012 Krakow





5σ each in γγ and ZZ channels, **~3σ each** in WW, bb, tautau in reach

~15 % precision on total signal strength achievable **with 30/fb at 8 TeV**

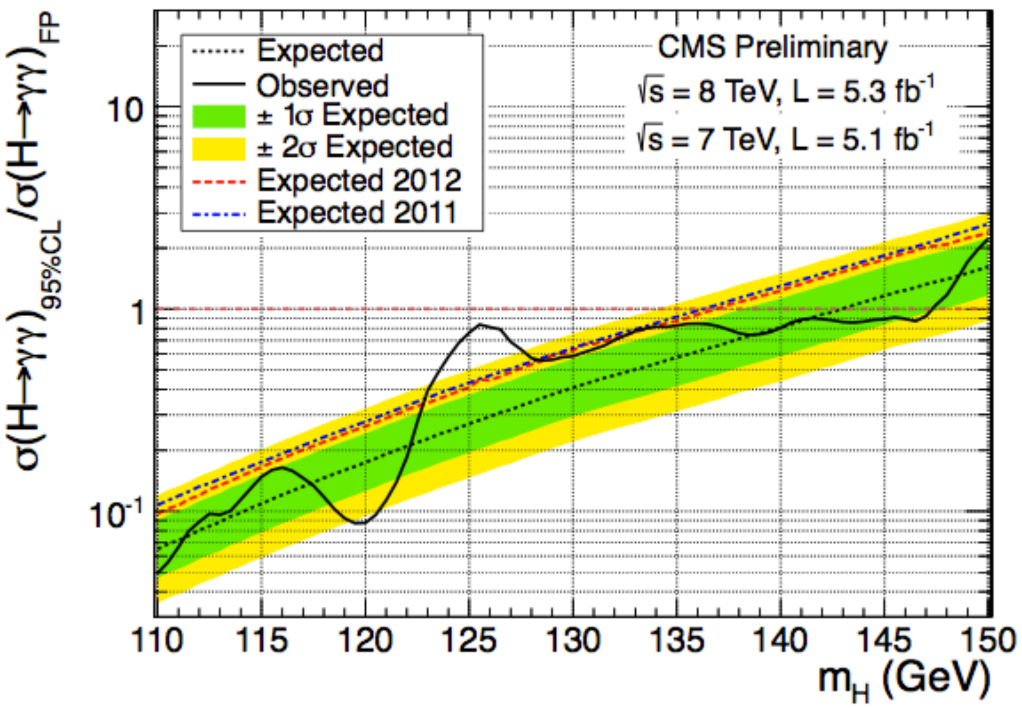
JP: by end of 8 TeV run, assuming a total of 35/fb per exp: **~4 σ separation of 0+ vs 0- and 0+ vs 2+**

scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$	combined
0_m^+ vs bkg	7.1	4.5	5.2	9.9
0_m^+ vs 0^-	4.1	1.1	0.0	4.2
0_m^+ vs 2_m^+	1.6	2.5	2.5	3.9

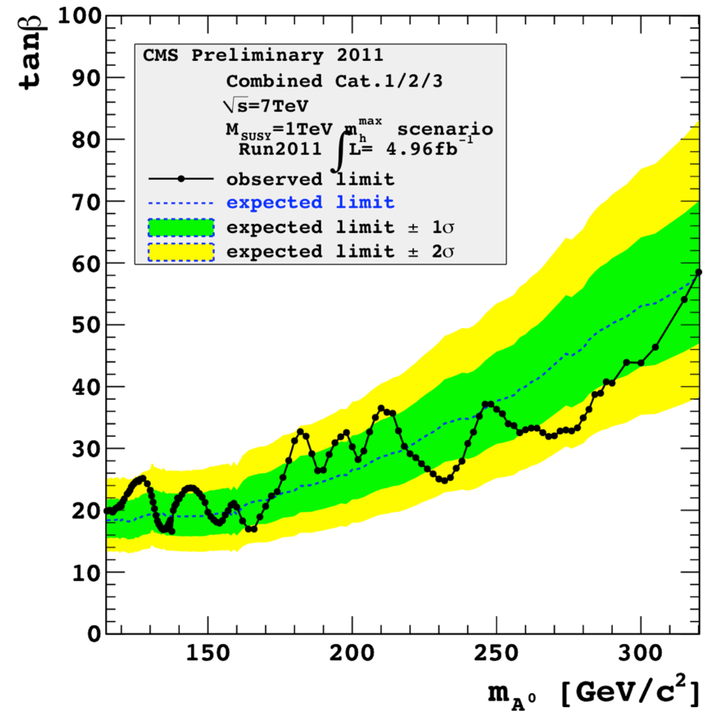
arXiv:1208.4018

BSM Higgs searches

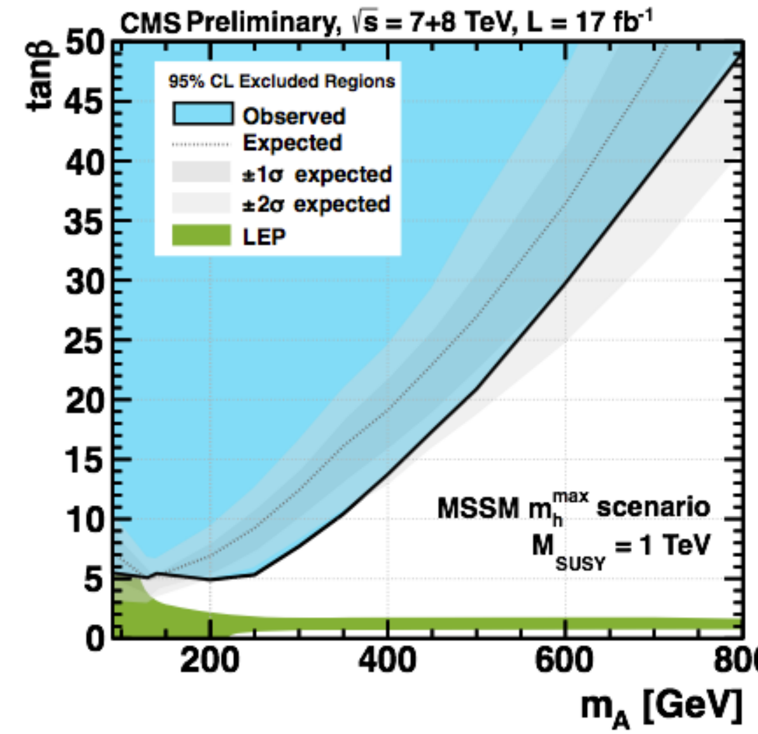
fermiophobic ***H* → *γγ***



Φ→μμ

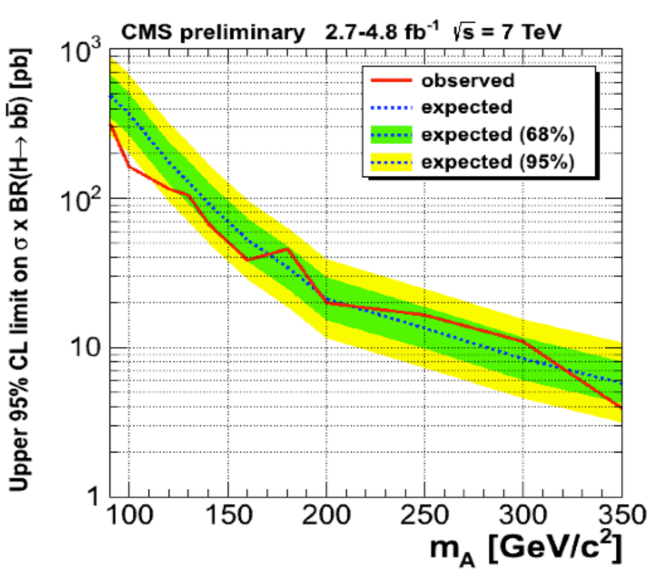


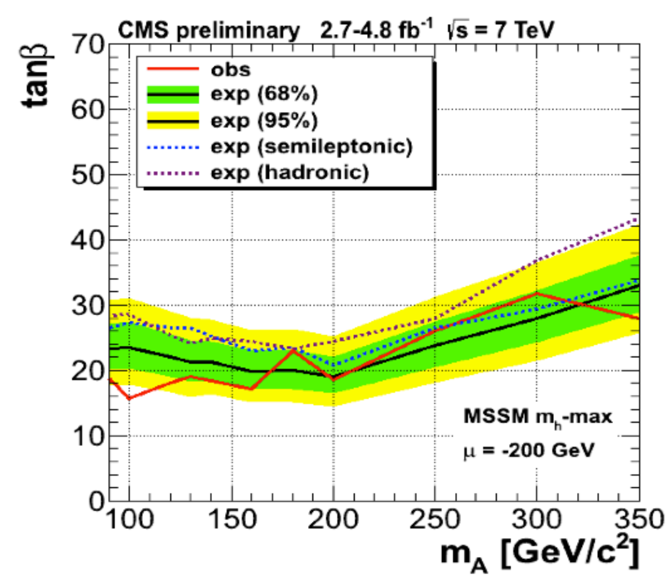
MSSM H→τ+τ-



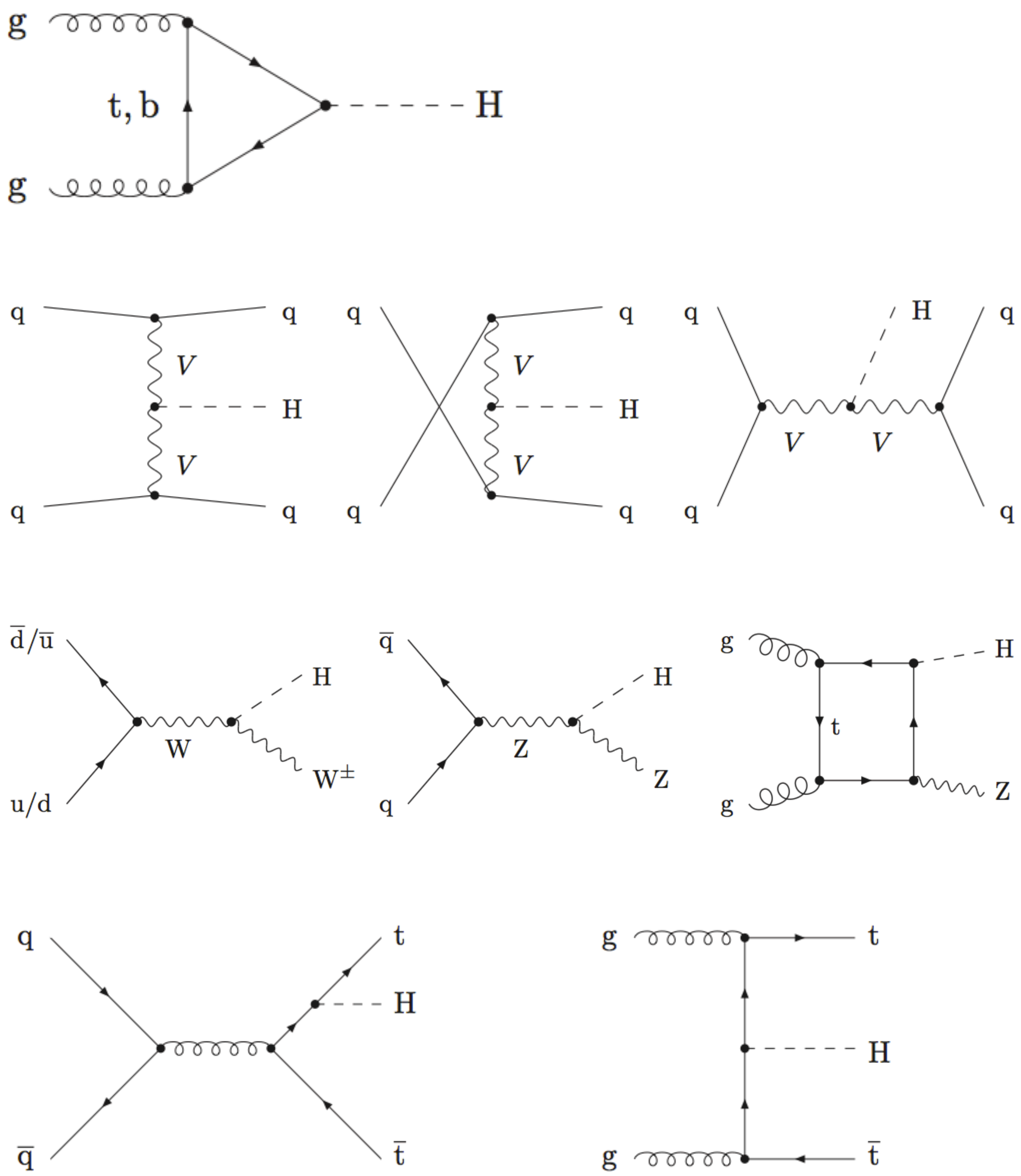
MSSM Φ→*b̄b*

- Set upper limits at the 95% CL on σ(pp→bΦ)×BR(Φ→bb).
- Exclude large tanβ region at the 95% CL in the MSSM parameter space (m_h-max scenario)





Higgs production diagrams



Higgs production x decay

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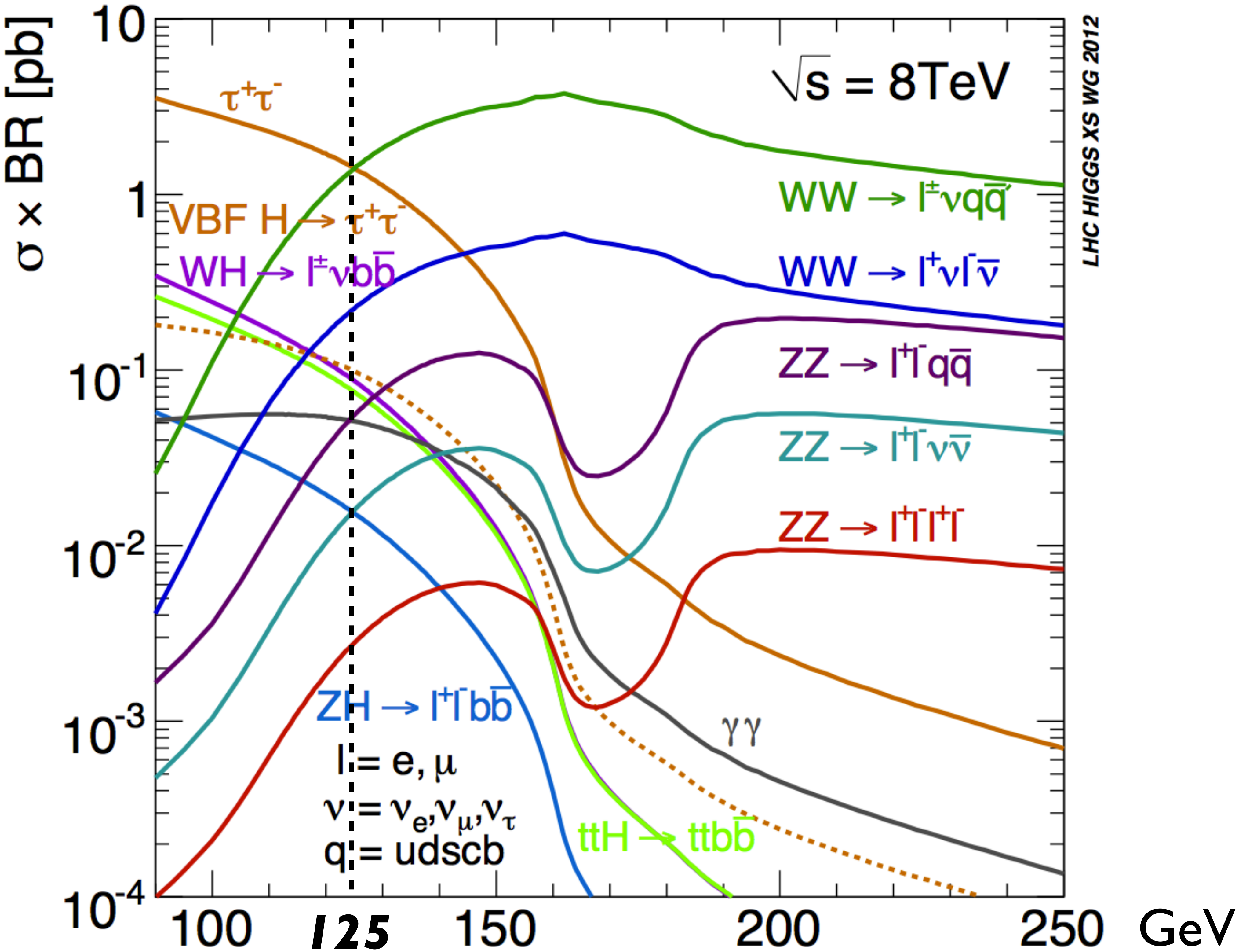

Higgs Signal generators

POWHEG Monte Carlo + PYTHIA for showering and hadronization

Cross sections normalized to LHC Higgs xsection working group
(NNLO+NNLL for gg, NNLO for VBF and VH processes)

$H \rightarrow \gamma\gamma$: systematics

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Sources of systematic uncertainty		**Uncertainty**	
Per photon		Barrel	Endcap
Photon selection efficiency		0.8%	2.2%
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.22%, 0.60%	0.90%, 0.34%
	$R_9 < 0.94$ (low η, high η)	0.24%, 0.59%	0.30%, 0.52%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.19%, 0.71%	0.88%, 0.19%
	$R_9 < 0.94$ (low η, high η)	0.13%, 0.51%	0.18%, 0.28%
Photon identification BDT	(Effect of up to 4.3% event class migration.)	$\pm$0.01 (shape shift)	
Photon energy resolution BDT	(Effect of up to 8.1% event class migration.)	$\pm$10% (shape scaling)	
Per event			
Integrated luminosity		4.4%	
Vertex finding efficiency		0.2%	
Trigger efficiency	One or both photons $R_9 < 0.94$ in endcap	0.4%	
	Other events	0.1%	
Dijet selection			
Dijet-tagging efficiency	VBF process	10%	
	Gluon-gluon fusion process	50%	
	(Effect of up to 15% event migration among dijet classes.)		
Production cross sections		Scale	PDF
Gluon-gluon fusion		+12.5% -8.2%	+7.9% -7.7%
Vector boson fusion		+0.5% -0.3%	+2.7% -2.1%
Associated production with W/Z		1.8%	4.2%
Associated production with $t\bar{t}$		+3.6% -9.5%	8.5%
Scale and PDF uncertainties	(Effect of up to 12.5% event class migration.)	(y, p_T)-differential	

H→ZZ: systematics

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- trigger (1.5%)
- combined lepton reconstruction, identification and isolation efficiencies = 1.2% to 3.8% in the 4μ channel
  and from 5.5% to 11% in 4e channel
- τh identification and isolation is 6%
- τh energy scale (3%)
- momentum calibration 0.1% for muons
- energy-momentum electrons 0.4% (1%) in the barrel (endcaps)
- energy resolution uncertainties is 20%
- limited statistical precision in the reducible background control regions 50%
- reducible background estimate for the 2τ final state ~ 30%.
- all reducible and instrumental background sources are derived from control regions, and the comparison
  of data with the background expectation in the signal region is independent of the uncertainty on the
  LHC integrated luminosity of the data sample. This uncertainty (2.2% at 7 TeV, 4.4% at 8 TeV)
- systematic uncertainties on the Higgs boson cross section (17 – 20%) branching fraction (2%)

$H \rightarrow W^+W^-$: systematics

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- signal efficiency from pile-up is evaluated to be 1%.
- luminosity measurement is 4.4%
- theoretical ambiguities: jet bin migration + lepton acceptance 10% and 30%
- overall signal efficiency uncertainty is estimated to be about 20%
- background estimations in the $H \rightarrow W^+W^-$ signal region is about 15%, dominated by the statistical uncertainty on the observed number of events in the background-control regions.

$H\rightarrow\tau^{+}\tau^{-}$: systematics

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- normalization uncertainty:
  uncertainty in the total integrated luminosity, 2.2% in 7 TeV and 4.5% in 8 TeV data
  jet energy scale (2–5% depending on η and pT)
  background normalization (see note)
  Z boson production cross section (2.5%)
  lepton identification and isolation efficiency (1.0%),
  trigger efficiency (1.0%)
- tau-identification efficiency uncertainty 8%
- lepton identification and isolation efficiencies vs. pileup: 2%
- b-tagging efficiency ~ 5%
- b-mistag rate ~10%
- mass spectrum shape variations from energy scales:
  tau 3%
  muon 1%
  electron 1.5%
- MET scale (due to pile-up effects) varying the mass spectrum shape (see note)
- Theoretical uncertainties on the Higgs production cross section :12% gg 10% VBF

$H \to b\bar{b}$: systematics

Source	Range
Luminosity	2.2-4.4%
Lepton efficiency and trigger (per lepton)	3%
$Z(\nu\nu)H$ triggers	3%
Jet energy scale	2–3%
Jet energy resolution	3–6%
Missing transverse energy	3%
b-tagging	3–15%
Signal cross section (scale and PDF)	4%
Signal cross section (p_T boost, EWK/QCD)	5–10% / 10%
Signal Monte Carlo statistics	1-5%
Backgrounds (data estimate)	$\approx$ 10%
Single-top (simulation estimate)	15–30%
Dibosons (simulation estimate)	30%

$H \rightarrow \gamma\gamma$: flowchart

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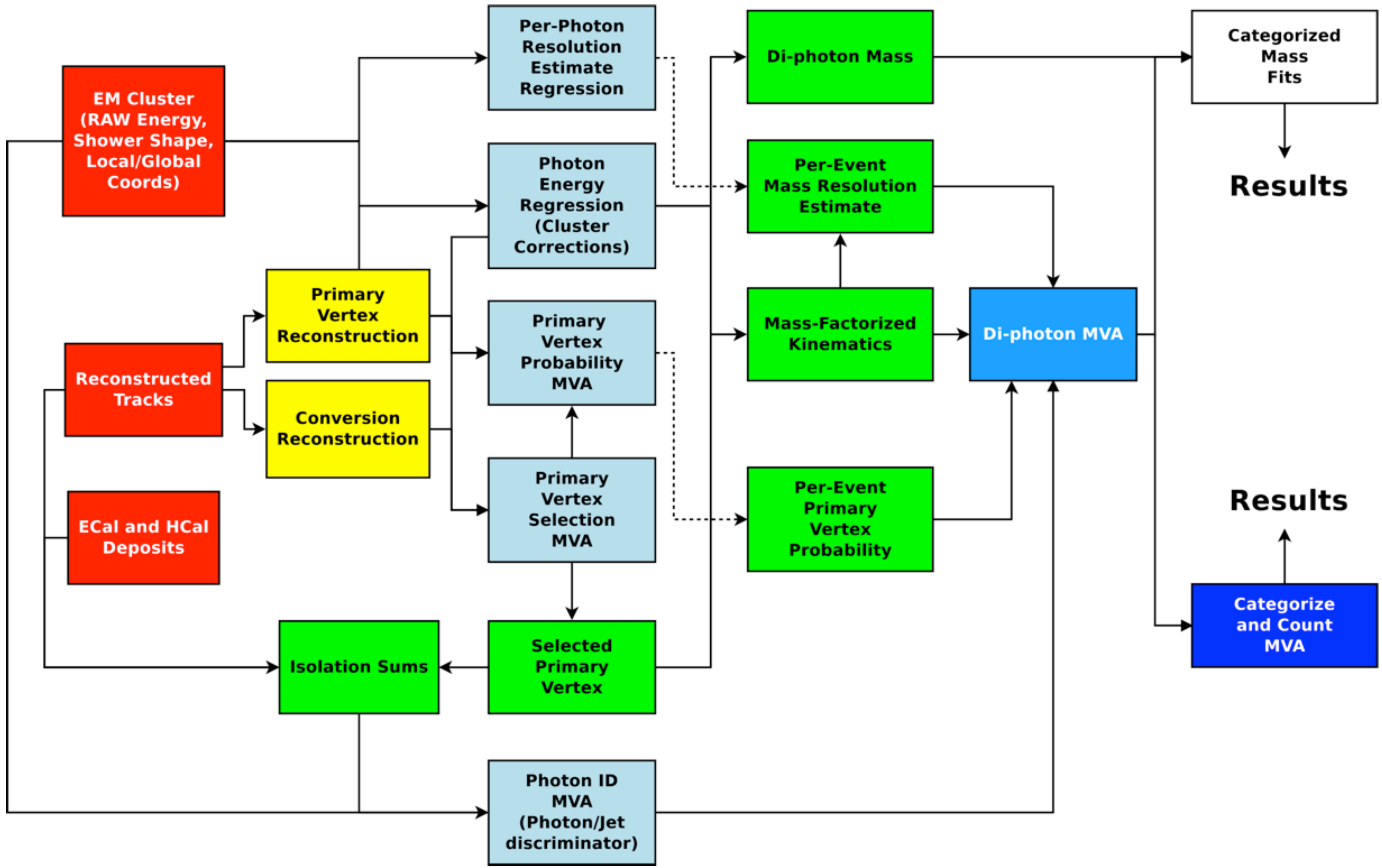

Radiation Hardness

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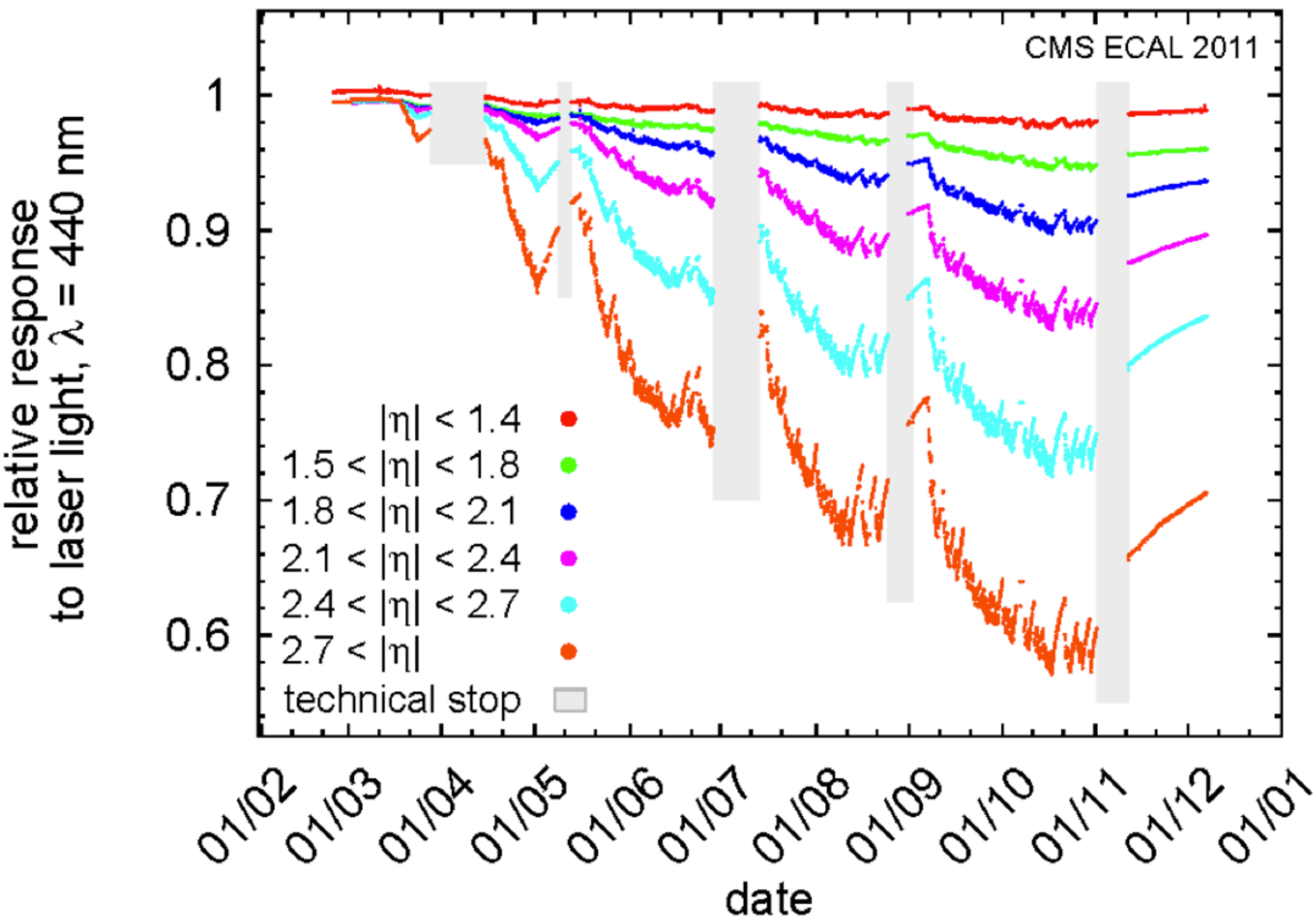

FSR recovery

FSR photon selection:

$|\eta_{\gamma}|$ 2.4

$p_{T\gamma}$ 2 GeV

ΔR 0.07 from a selected lepton candidate
OR
$p_{T\gamma}$ 4 GeV and be found isolated within 0.07 ΔR 0.5 from a selected lepton candidate.

R^{γ}_{ISO} 1

R^{γ}_{ISO}= [T(charged hadrons)+pT(photons)+pT(neutrals)] / $p_{T\gamma}$
in a cone of size $\Delta R = 0.3$ around the candidate photon direction.

$H \to W^+W^-$: at preselection

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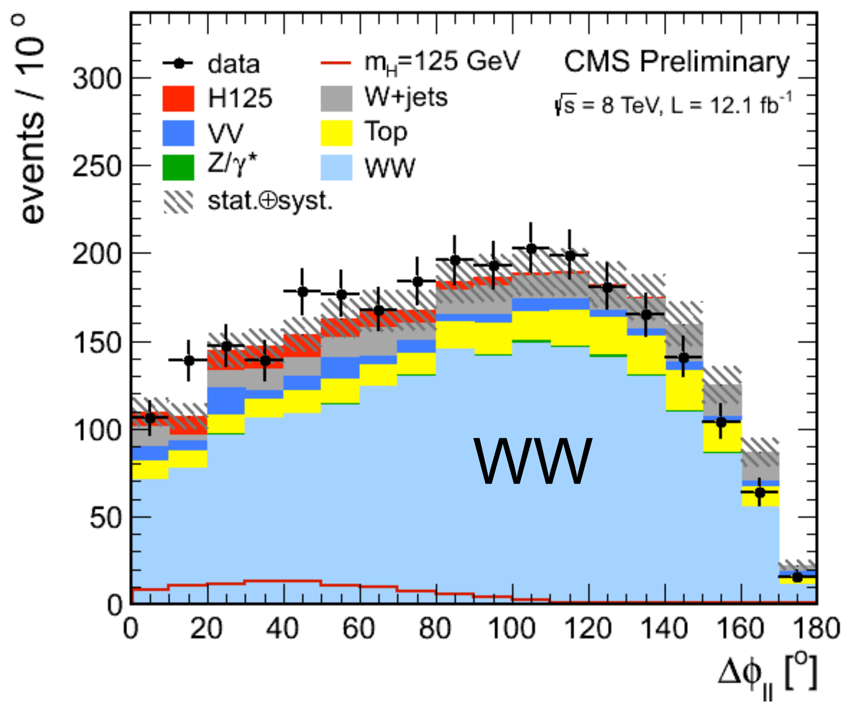
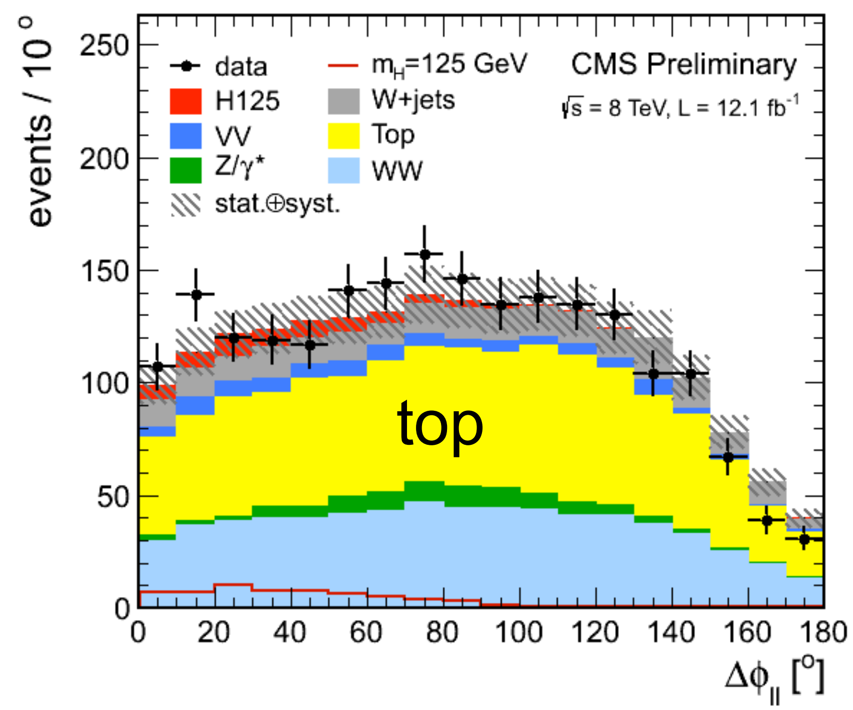
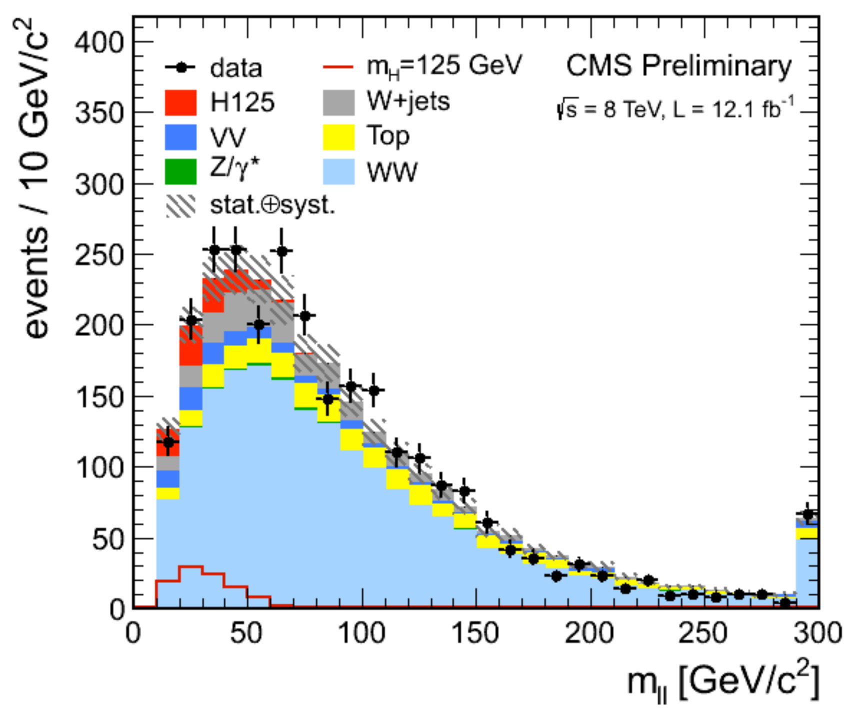
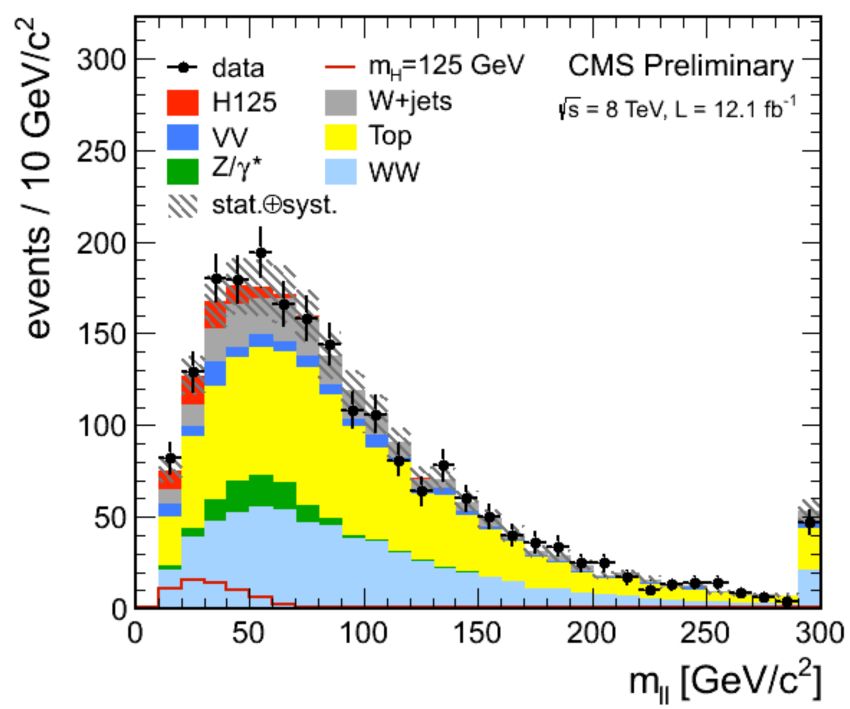
DF 0-jet



DF 1-jet







$H \rightarrow W^+W^-$: background estimations

Define a control region and extrapolate to the signal region

- **Top**: count $N_{top\text{-}tagged}$ events in data, apply $\varepsilon_{top\text{-}tagged}$ measured separately
- **W+Jets**: from a "tight-loose" (i.e., "real-fake") dilepton data control sample, apply ε_{loose} measured separately
- **Z+Jets**: estimate by measuring N_{events} in tight window around the Z pole from data, and extrapolating out using simulation
- **WW**: measure s from data with m_{ll} 100 GeV at preselection
  for cut-and-count,extrapolate to signal region using simulation;
  for M_H 200GeVand shape based categories, normalize simulations with data
- Other backgrounds from simulation,cross-checked with data

R. Walsh at HCP

$H \to W^+W^- \to 2l2\nu$

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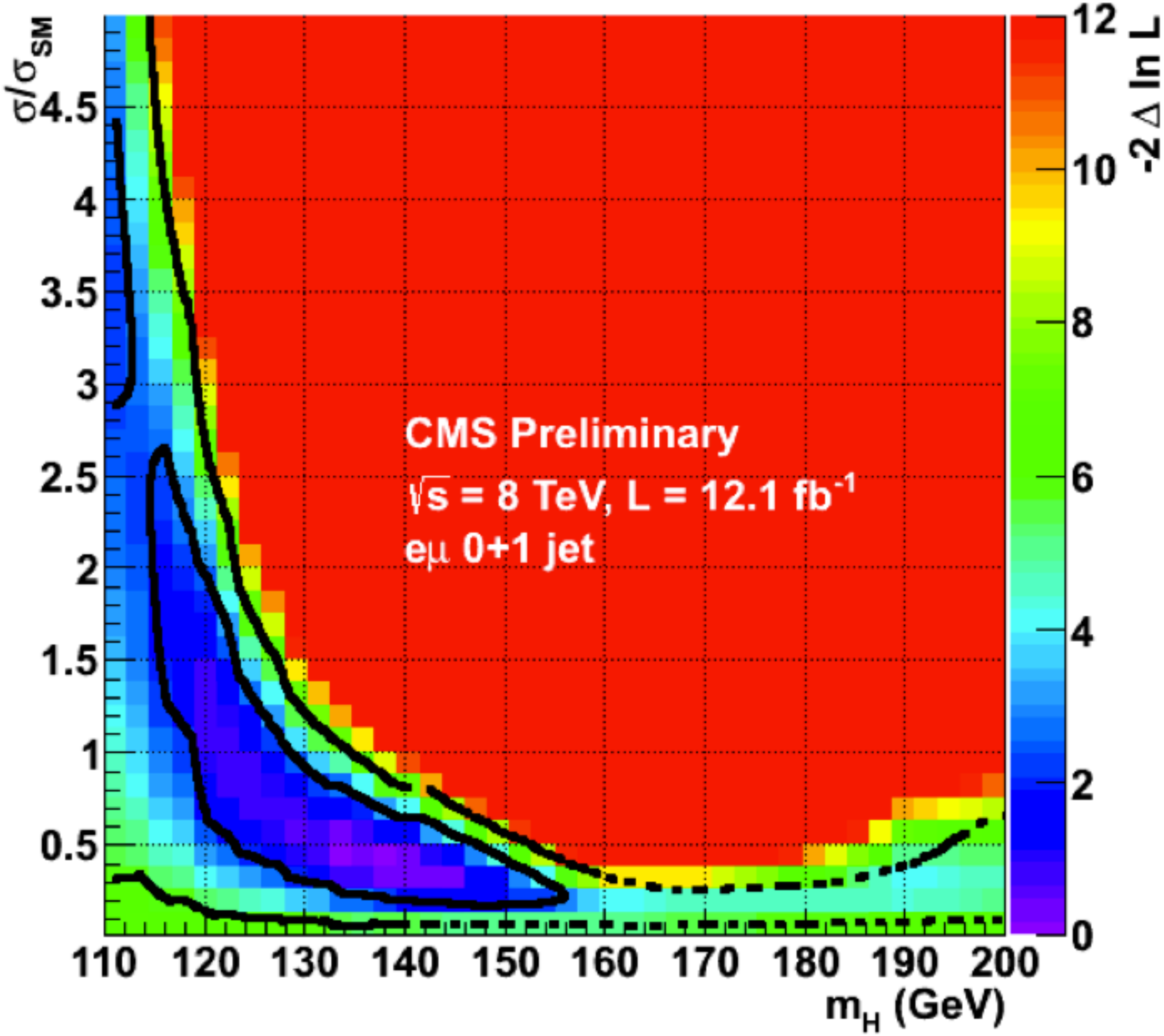

$H\rightarrow\tau^+\tau^-$: mass determination

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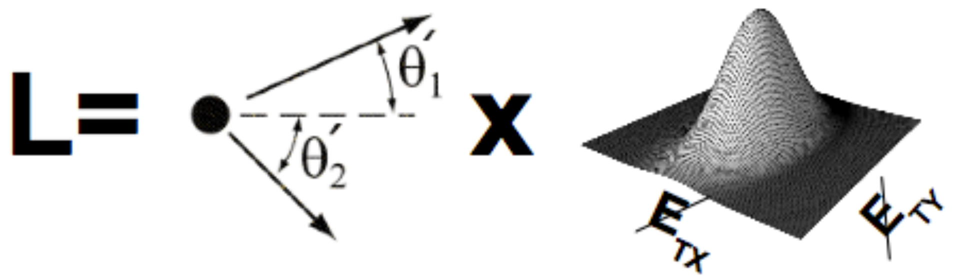
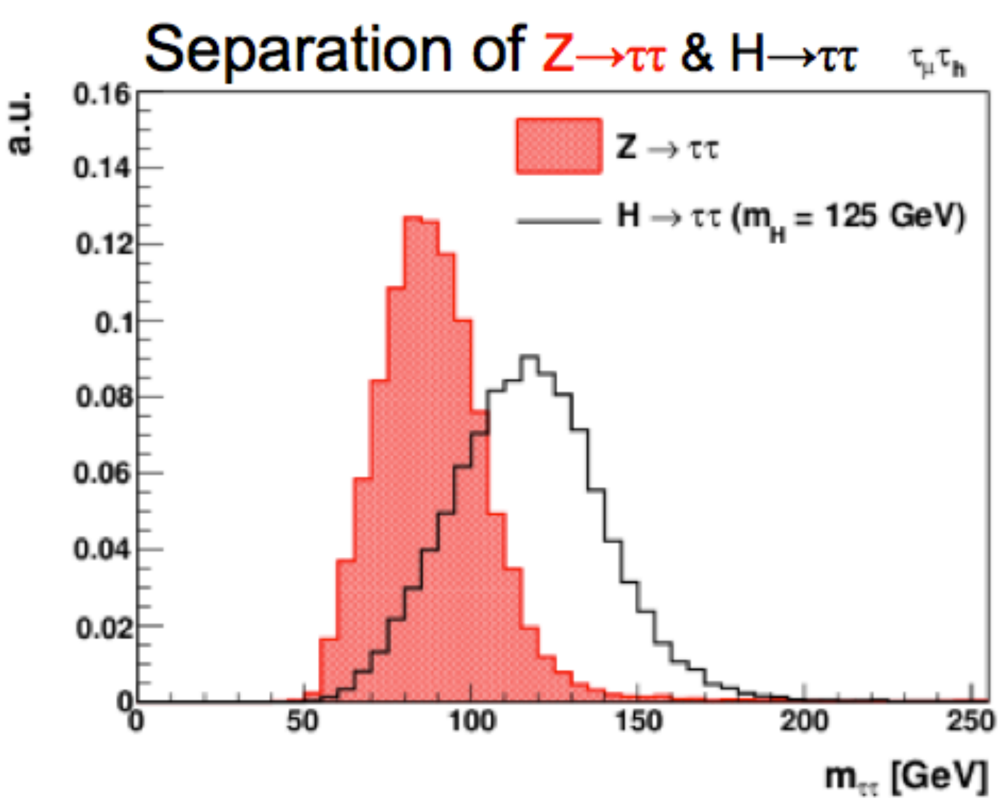
- Determine invariant mass of di-τ system with maximum likelihood method.



Phasespace of τ-decays

Expected $\not\!\!E_T$ Resolution

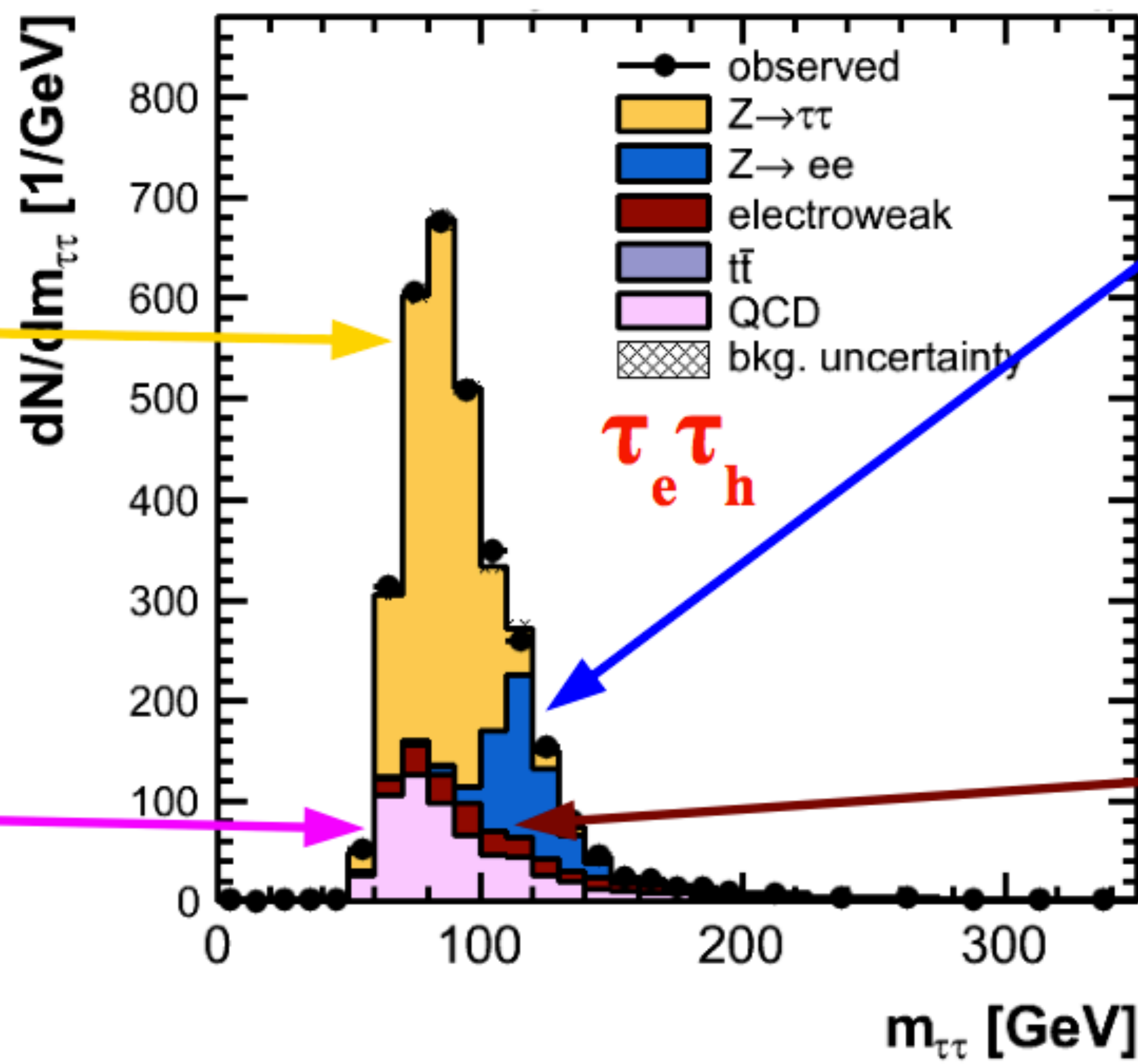
- Estimate for di-τ system, to be true for given value of $m_{\tau\tau}$.
- Inputs: four-vector information of visible leptons, x- and y- component of $\not\!\!E_T$ on event by event basis.
- Free parameters: φ, θ^*, ($m_{\upsilon\upsilon}$) per τ-lepton (4-6 parameters).
- Full integration of kernel. Scan of $m_{\tau\tau}$ from m_τ up to 2TeV.
- 15-20% resolution of the reconstructed $m_{\tau\tau}$ mass.



R. Wolf at HCP

$H \to \tau^+\tau^-$: backgrounds

$Z \to \tau\tau$:
- Embedding: in $Z \to \mu\mu$, replace μ by sim. τ decay.
- Normalized from $Z \to \mu\mu$ events.

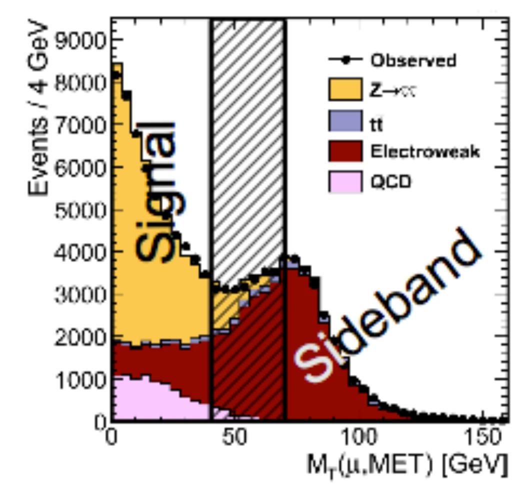


$Z \to ee(/\mu\mu)$:
- From simulation.
- Corrected for jet→τ, $e/\mu \to \tau$ fakerate.

QCD:
- Normalization & shape taken from LS/OS or fakerate.

Diboson/W+jets:
- From simulation.
- Normalization from sideband.

ttbar:
- From simulation.
- Normalization from sideband.



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Statistical tools

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Define the signal strength: $\mu = \sigma / \sigma_{SM}$

Define the ***LHC*** test statistics: $$q_\mu = -2 \ln \frac{\mathcal{L}(\text{obs} \,|\, \mu \cdot s + b, \hat{\theta}_\mu)}{\mathcal{L}(\text{obs} \,|\, \hat{\mu} \cdot s + b, \hat{\theta})}$$

(likelihood ratio)

All likelihood parameters in θ (nuisance). All “hat”- quantities with are fitted.

$$p_\mu = \int_{q_{\mu,\text{obs}}}^{\infty} f(q_\mu|\mu)\, dq_\mu$$

Scan μ until you find the highest value for which the p-value is not less than 0.05.
And at that point you claim a 95% CL upper limit on μ (i.e. if the signal exist it has a strength below a certain value).

Define the ***LHC*** confidence level as: $$\text{CL}_\text{s} = \frac{\text{P}(q_\mu \geq q_\mu^{\text{obs}} \,|\, \mu \cdot s + b)}{\text{P}(q_\mu \geq q_\mu^{\text{obs}} \,|\, b)} \leq \alpha$$

Test statistics for upper limits

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$$q_\mu = \begin{cases} -2\ln\lambda(\mu) & \hat{\mu} \le \mu \\ 0 & \hat{\mu} > \mu \end{cases} \qquad \text{where} \qquad \lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

I want to have a test with a high power on the alternative that the signal does not exist !

And in the same way the p-value is

$$p_\mu = \int_{q_{\mu,\mathrm{obs}}}^{\infty} f(q_\mu|\mu)\, dq_\mu$$

Then you carry on the test with different values of μ until you find the highest value for which the p-value is not less than 0.05. And at that point you claim a 95% CL upper limit on μ (i.e. if the signal exist it has a strength below a certain value).

Expected exclusion limits

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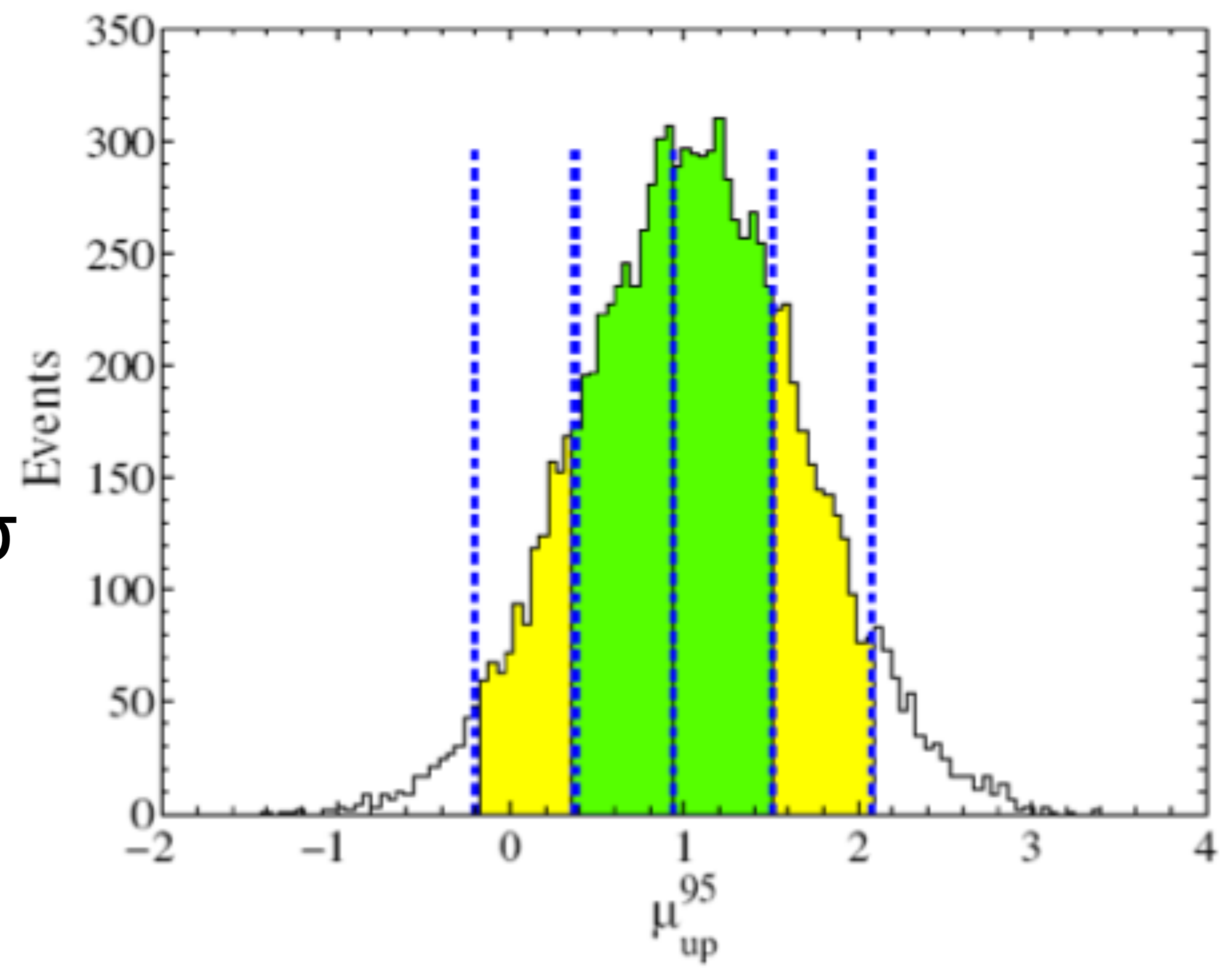
$\mu = \sigma/\sigma_{SM}$ and we want to set a limit μ_{up}. for each mass hp.

First you can ask yourself what is your sensitivity on a particular mass value. Generate an "ensemble of toy-experiments" under the background only hypothesis and calculate the upper μ_{up} limit for each toy (as in the previous slide).

The median of the distribution is where you expect μ_{up} to be if the background only hypothesis is true.

To take into account the statistical fluctuations you can quote the 1σ 2σ (often the distribution turns out to be ~gaussian, otherwise you have to go back to the definition of 68% 95% etc)



p-value

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The level of compatibility between data and a hypothesis H can be quantified in terms of p-value:

p-value = probability, under assumption of *H*, to observe data with equal or lesser compatibility with *H* than the data we got.

If you get a small p-value it means that the probability to obtain something even more off is very small, i.e. your hypothesis is not OK

$$p_0 = \int_{q_{0,\mathrm{obs}}}^{\infty} f(q_0|0)\, dq_0$$

Parametrization

arXiv:1209.0040

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$$\sigma \cdot BR(ii \to H \to ff) = \sigma_{SM} \cdot BR_{SM} \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}$$

$$N(xx \to \mathrm{H} \to yy) \sim \sigma(xx \to \mathrm{H}) \cdot \mathcal{B}(\mathrm{H} \to yy) \sim \frac{\Gamma_{xx}\Gamma_{yy}}{\Gamma_{\mathrm{tot}}}$$

$$\Gamma_{xx} = \Gamma_{WW}, \Gamma_{ZZ}, \Gamma_{tt}, \Gamma_{bb}, \Gamma_{\tau\tau}, \Gamma_{gg}, \Gamma_{\gamma\gamma}$$

through loops ⇒ sensitive to new Physics

$$\Gamma_{tot} = \Sigma\Gamma_i(SM) + \Gamma_{BSM}$$

independent to account for H decays to BSM

Higgs as probe for BSM

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$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 \ldots$$
$$- \left(m_W^2\, W_\mu W_\mu + \frac{1}{2}m_Z^2\, Z_\mu Z_\mu\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right)$$
$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi \frac{h}{v} + c_{2\psi}\frac{h^2}{v^2} + \ldots\right)$$
$$+ \frac{g^2}{16\pi^2}\left(c_{WW}\, W^+_{\mu\nu}W^-_{\mu\nu} + c_{ZZ}\, Z^2_{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma_{\mu\nu}\right)\frac{h}{v} + \ldots$$
$$+ \frac{g^2}{16\pi^2}\left[\gamma^2_{\mu\nu}\left(c_{\gamma\gamma}\frac{h}{v} + \ldots\right) + G^2_{\mu\nu}\left(c_{gg}\frac{h}{v} + c_{2gg}\frac{h^2}{v^2}\ldots\right)\right]$$
$$+ \frac{g^2}{16\pi^2}\left[\frac{c_{hhgg}}{\Lambda^2}G^2_{\mu\nu}\frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2}G_{\mu\rho}G_{\rho\nu}\frac{\partial_\mu h \partial_\nu h}{v^2} + \ldots\right]$$
$$+ \ldots$$

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

SM

$$a = b = c = d_3 = d_4 = 1$$
$$c_{2\psi} = c_{WW} = c_{ZZ} = c_{Z\gamma} = c_{\gamma\gamma} = \ldots = 0$$

Not enough data yet to constrain all parameters but we can already put some structure under test

Beyond the Standard Model

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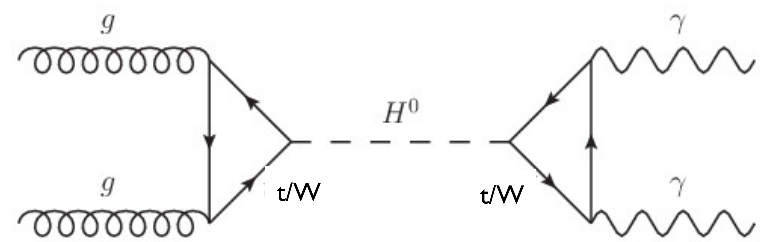
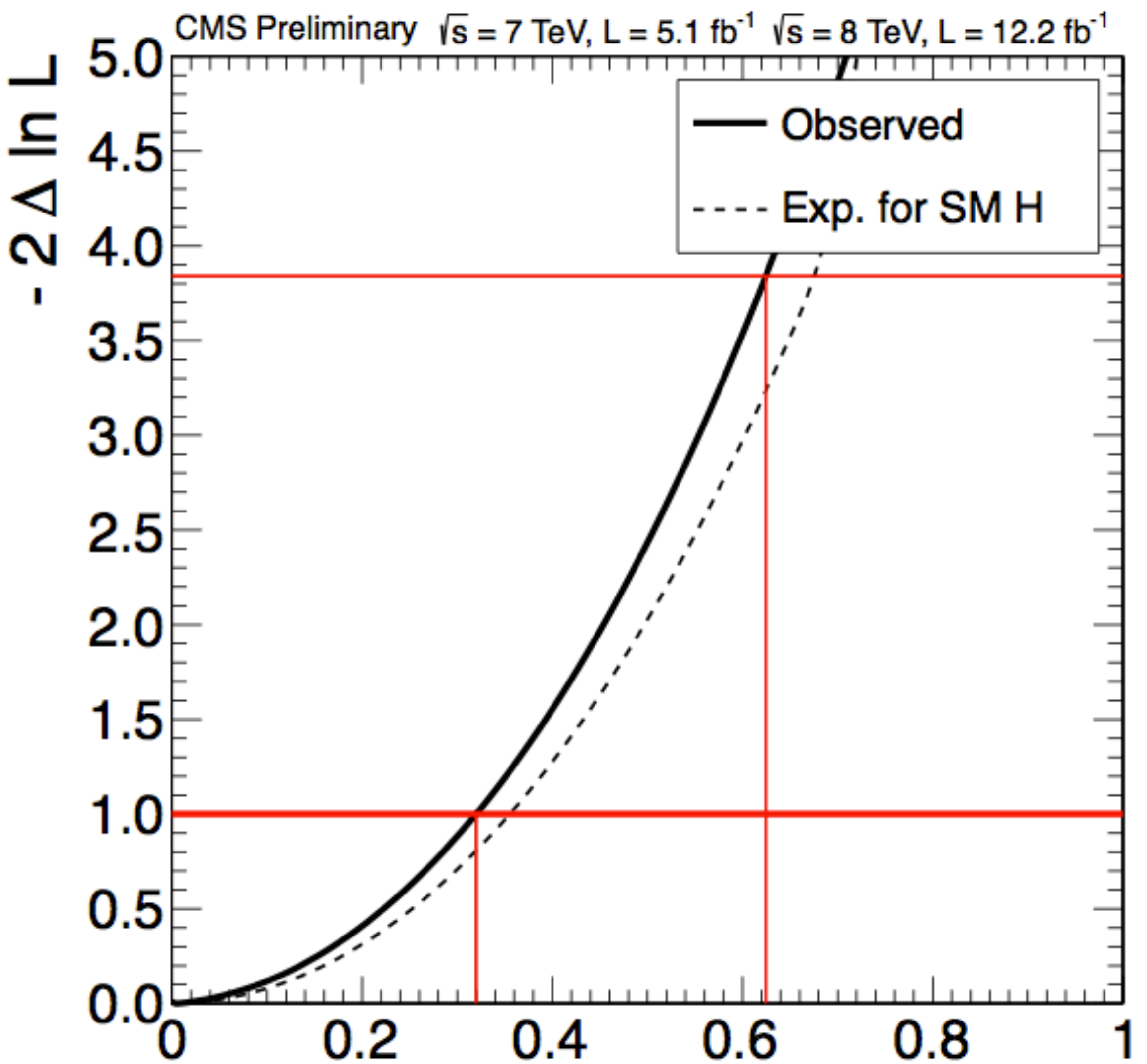
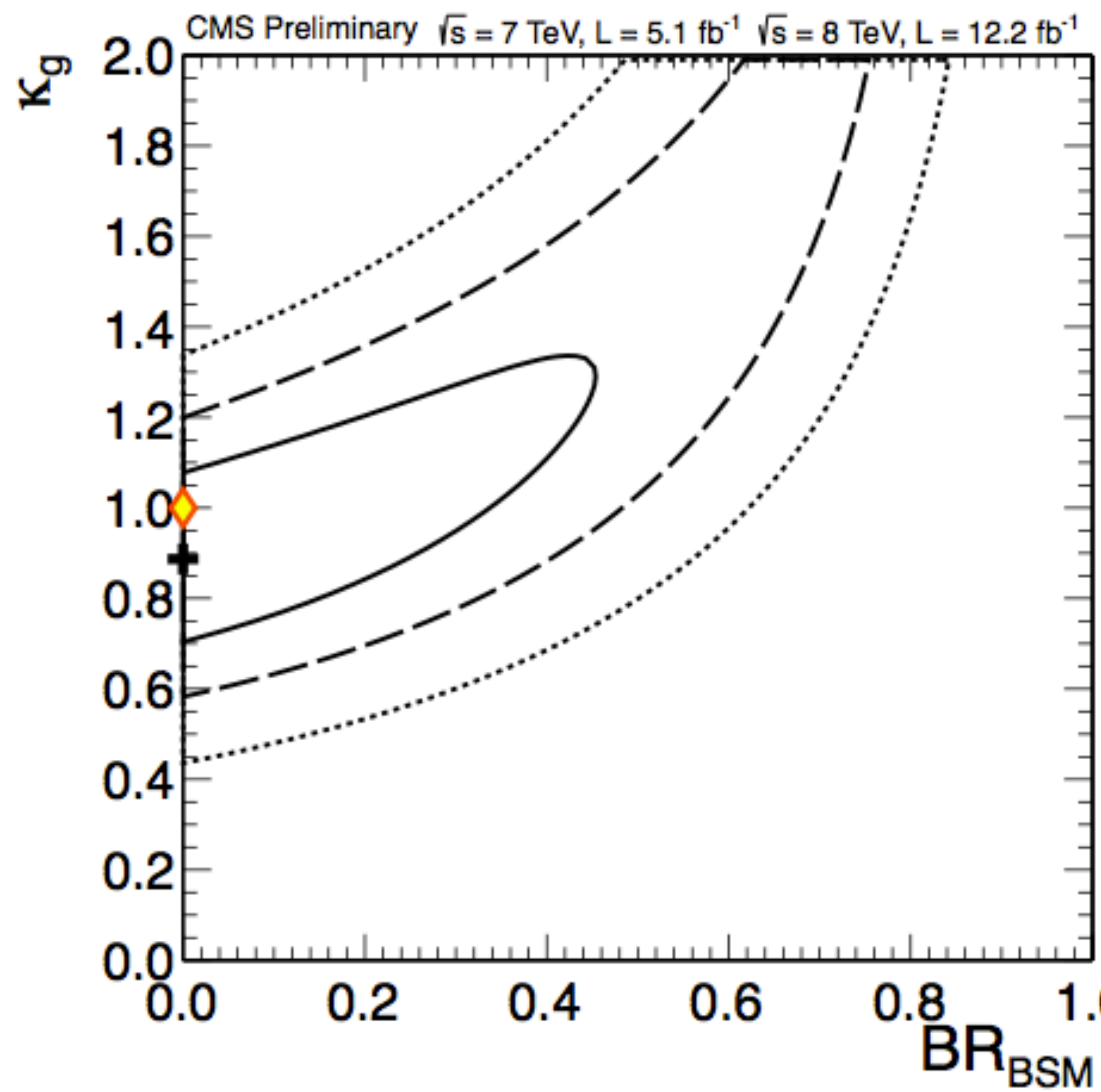
Test processes induced by loop diagrams







$$BR_{BSM} = \frac{\Gamma_{BSM}}{\Gamma_{tot}}$$

Scan BR_{BSM} and profile κ_V κ_f

BR_{BSM} below 0.62 at 95% CL

Higgs couplings: unitarity

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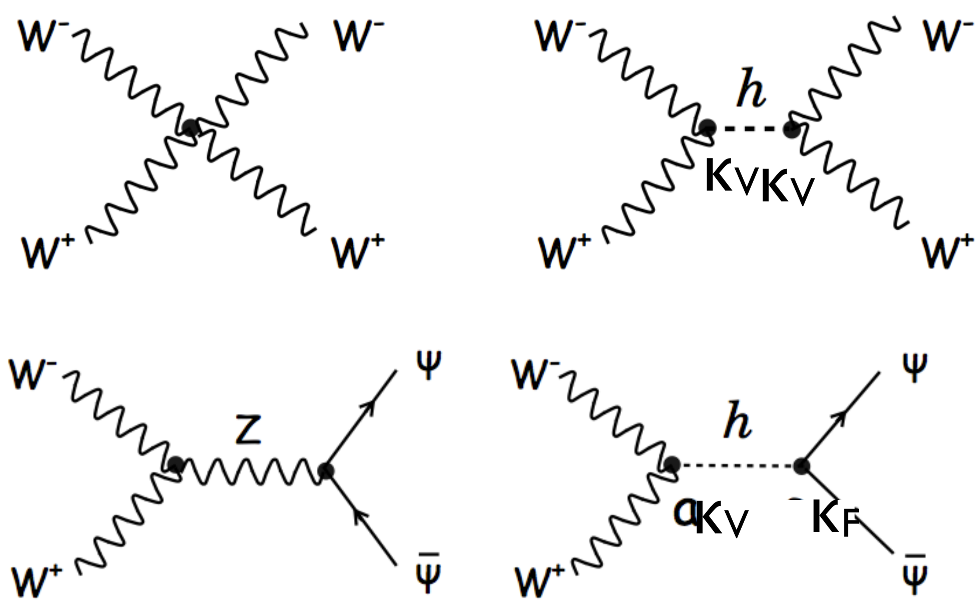
Partial width ∝ coupling² **coupling = κ x coupling(SM)**



$$A = \frac{1}{v^2}\left(s - \frac{\kappa_V^2 s^2}{s - m_h^2}\right)$$

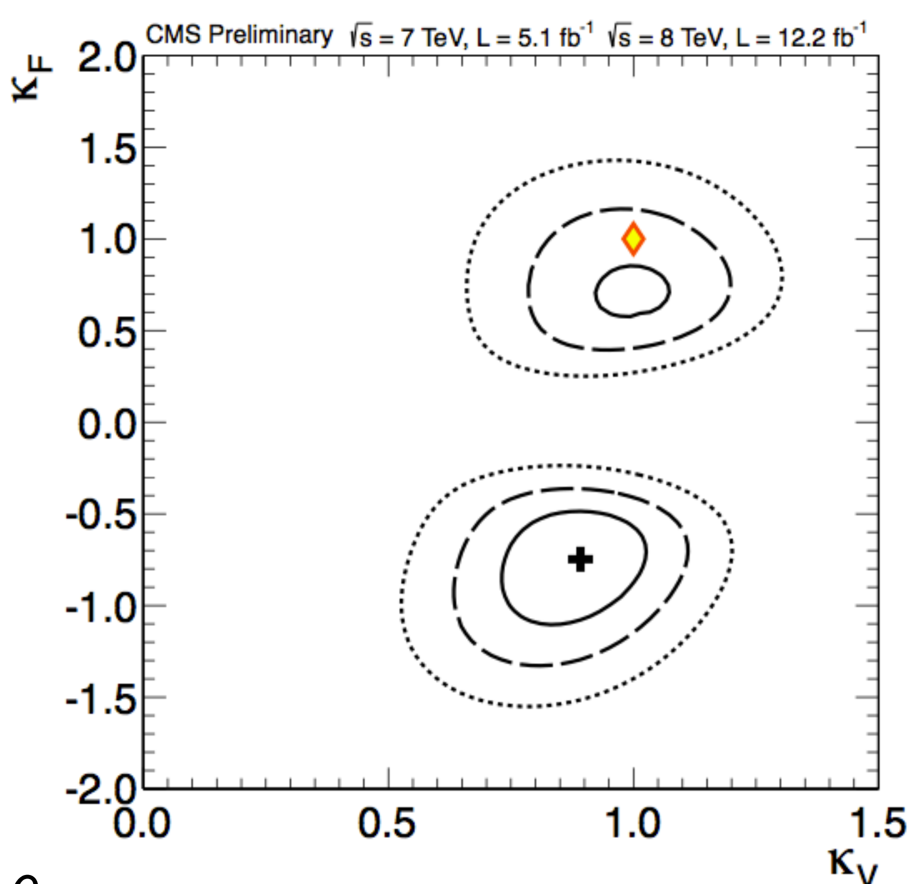
$$A = \frac{m_\psi \sqrt{s}}{v^2}\left(1 - \frac{\kappa_V \kappa_F s}{s - m_h^2}\right)$$

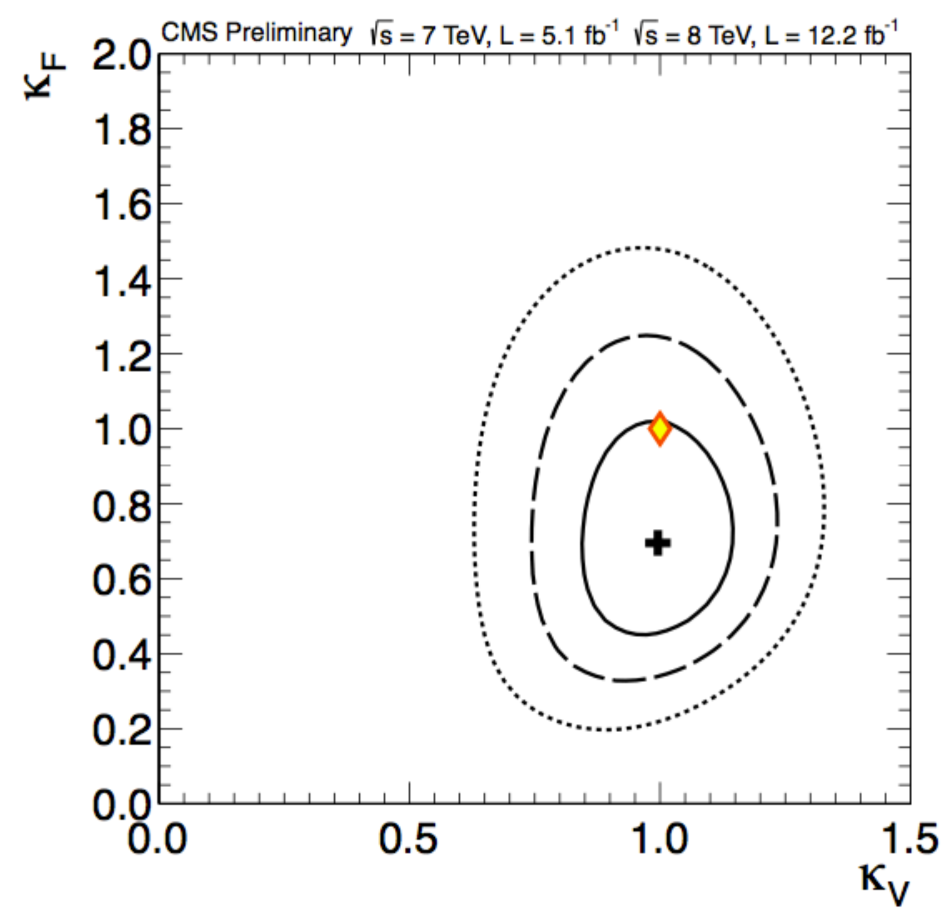
SM stability

$$\kappa_V = 1$$

$$\kappa_V \kappa_F = 1$$

SM is sufficient but not necessary





here assume Γ_{BSM} =0