Beyond Standard Model Higgs Searches at CMS

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(On behalf of the CMS Collaboration)

Outline

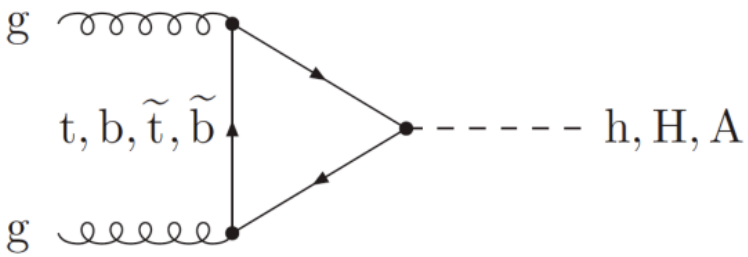
- Searches for Higgs
  - MSSM (with 7 TeV data)
  - Beyond MSSM (with 7 TeV data)
  - Fermiophobic (with 7 + 8 TeV data)

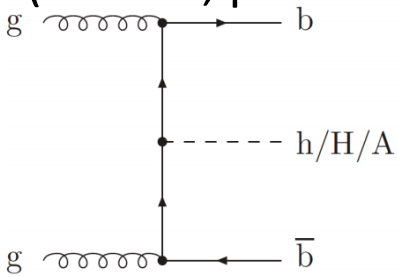
MSSM HIGGS @CMS (WITH 7 TEV DATA)

MSSM Higgs Phenomenology

- 2 Higgs doublets → 5 physical Higgs bosons: 3 neutrals and 2 charged

  – 3 φ neutrals: h, H (CP-even, scalars), and A (CP-odd, pseudo-scalar)

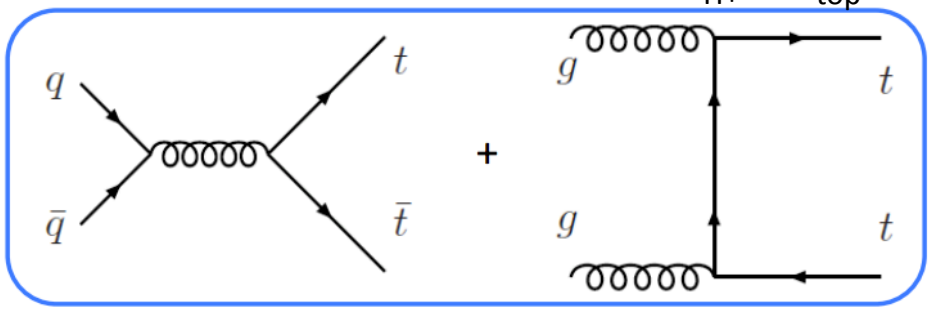




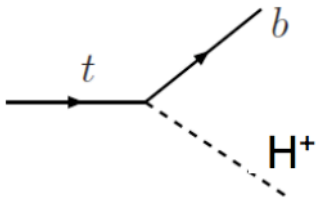
  - Dominant Decay modes are bb and ττ (tt relevant at large M_A and low tan β only, experimentally not accessible yet.)

  – 2 charged: H^+,H^-

$M_{H+} < m_{top}$: Standard Model tt production



with



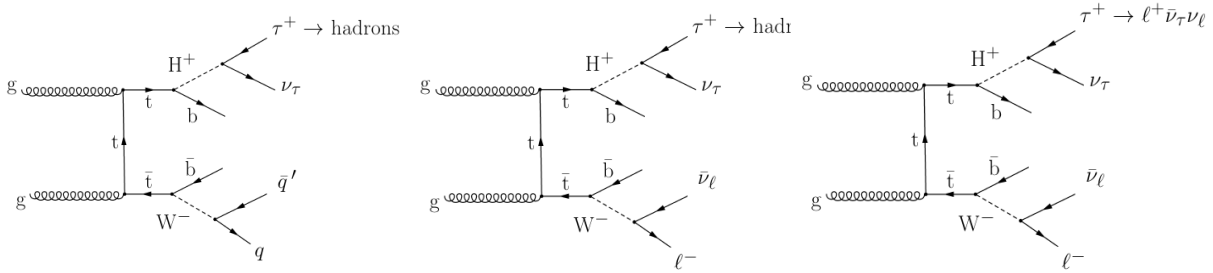
  - Dominant Decay mode: H^+ → τν

$M_{H+} > m_{top}$ not analyzed yet by CMS

MSSM Higgs Search Channels

- Charged Higgs $H^{\pm}$
  - pp → tt, with at least one t → $H^{+}b$, H^{+}→ τν with 3 final states
    - τ_{had}+ Jets
    - τ_{had}+ e/μ
    - e+μ

$$t\bar{t} \rightarrow H^{\pm}W^{\mp}b\bar{b}$$
$$t\bar{t} \rightarrow H^{\pm}H^{\mp}b\bar{b}$$



- Neutral Higgs φ: h + H + A
  - pp → φ, φ → ττ with 3 final states
    - e+μ
    - e+τ_{had}
    - μ+τ_{had}
  - pp → φb, φ → bb
    - Semileptonic b decays
    - Hadronic b decays
  - pp → φ, φ → μμ

MSSM: $H^{\pm} \rightarrow \tau\nu$ Event Selection

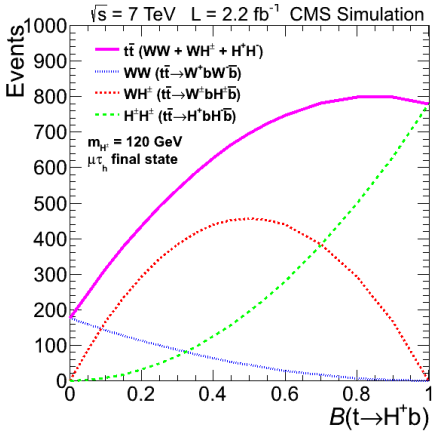
	τ_{had}+Jets *At least one b-jet*	e/μ+τ_{had}	e+μ
Trigger	$\tau_{had}+E_T^{miss}$	Electron+2 Jets/ single Muon	Electron+Muon
Lepton Selection		*Same as in top-quark pair production measurement*	
	$P_T^{\tau} > 40$ GeV very tight Tau Id.	$P_T^{e} > 35$ GeV $P_T^{\mu} > 30$ GeV isolated	$P_T^{e} > 20$ GeV $P_T^{\mu} > 20$ GeV isolated
Jets	≥ 3 Jets of $P_T > 30$ GeV ≥ 1 b-tagged	≥ 2 Jets of $P_T > 35$ (30) GeV ≥ 1 b-tagged	≥ 2 Jets of $P_T > 20$ GeV
E_T^{miss}	> 50 GeV $\Delta\phi(\tau_{had}, E_T^{miss}) < 160^o$	> 45 GeV for e+τ_{had} > 40 GeV for μ+τ_{had}	
		Opposite Charge Lepton Pair	

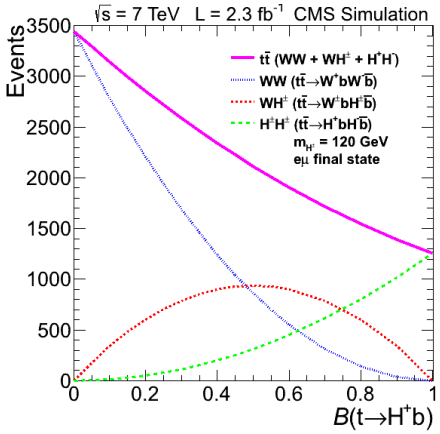
Veto Events with additional isolated Electrons or Muons

HIG-11-019 MSSM: H+→ τν Signal Extraction and Limits

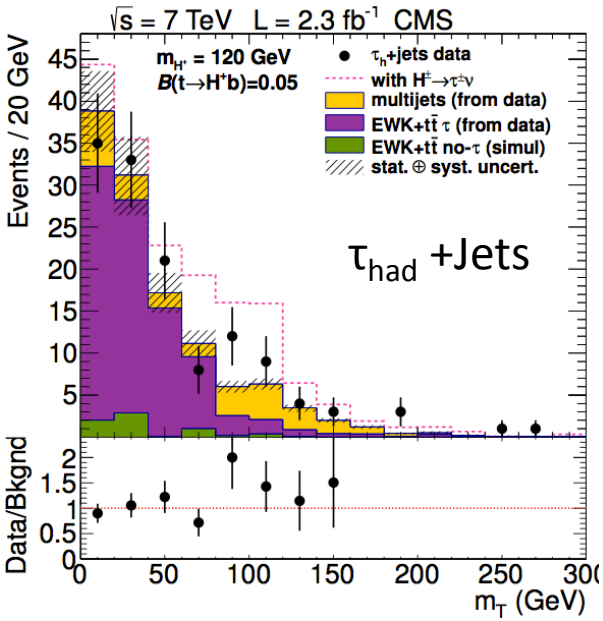
hep-ex/1205.5736

Note: non-zero BR(t→ H^+b) increases event yield in τ_{had}+Jets and e/μ+τ_{had} and decreases it in e+μ channel.

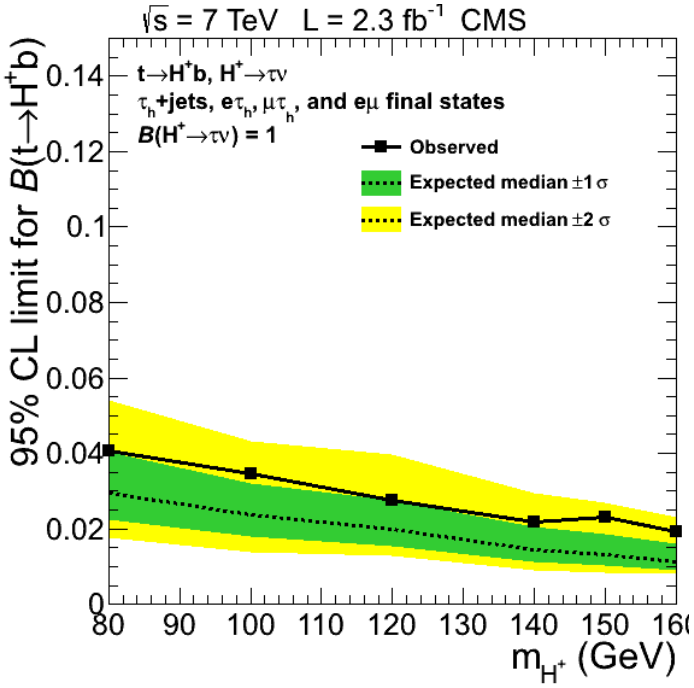




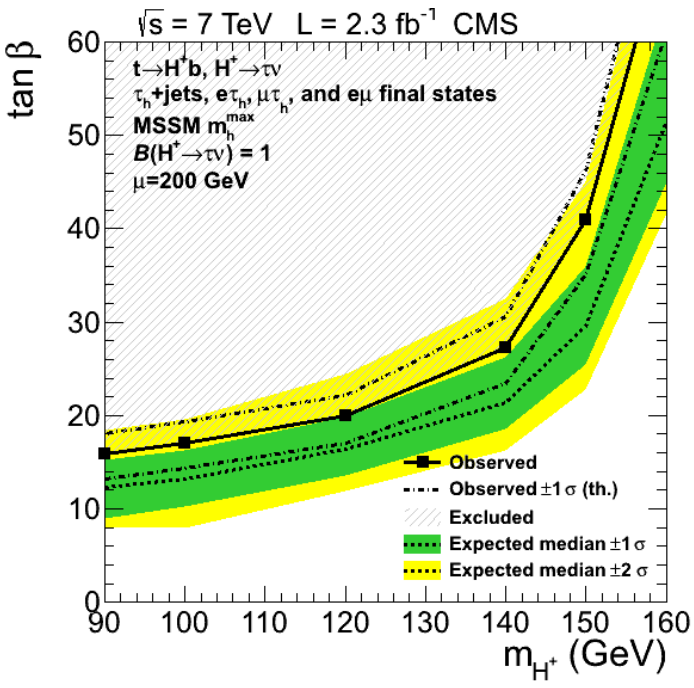
Event yields observed in three channels agree with expectation. Ex. $m(\tau_h + MET)_T$



Set limit on BR(t→H^+b).



Upper limit on BR(t → H^+b) in MSSM parameter space



MSSM: $\varphi \rightarrow \tau\tau$ Event Selection

Trigger

Events triggered by e+μ, e+τ_{had} and μ+τ_{had} Triggers
P_T thresholds 10-20 GeV

Lepton Selection

Electrons	**Muons**	**τ_{had}**
P_T > 10-20 GeV	P_T > 10-20 GeV	P_T > 20 GeV
$\|\eta\|$ < 2.1 (2.3 for e + μ)	$\|\eta\|$ < 2.1	$\|\eta\|$ < 2.3
isolated	isolated	Tau Id.
		Veto against e/μ

Opposite Charge Lepton Pair

Veto Events with additional isolated Leptons

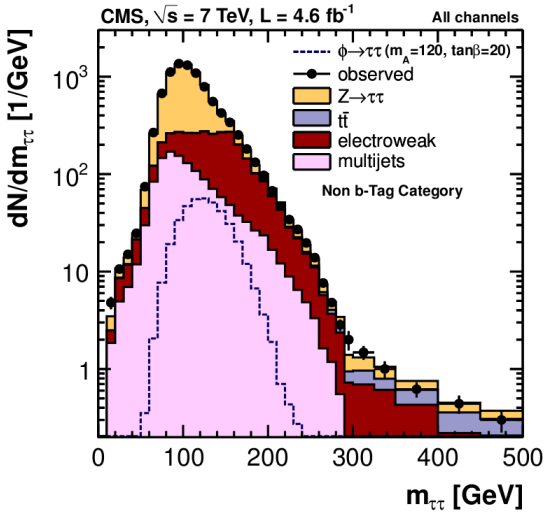
Suppression of W+jets Background

E_T^{miss} required to point in Direction of visible τ Decay products

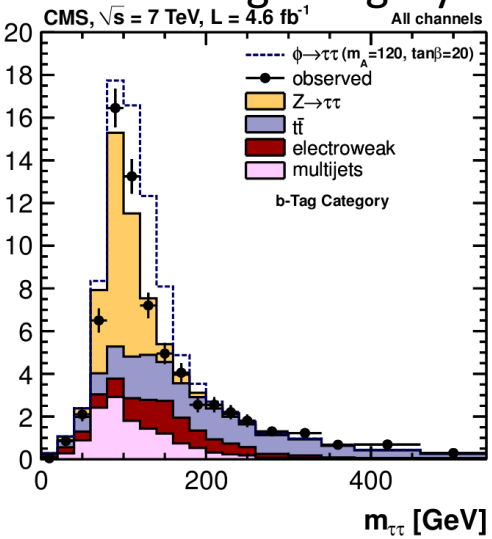
Selected Events analyzed in 2 Categories: no-b-Tag and b-Tag

MSSM: φ → ττ Limit

b-tag category



non-tag category



Mass of τ-pair reconstructed via likelihood technique:

- τ decay Kinematics
- Compatibility of reconstructed E_T^{miss} with ν hypotheses

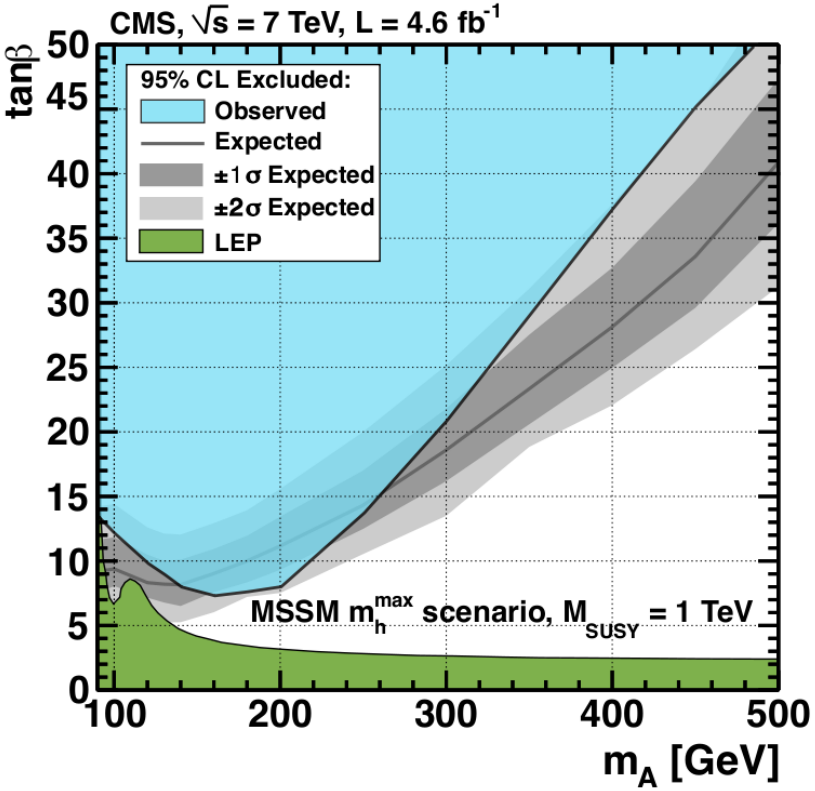
Distribution observed in data is in agreement with background expectation.

arXiv:1202.4083

Limit obtained by scanning tan(β) for each mass hypothesis M_A

- Cross-section x BR for gg→ φ and bb→ φ computed as function of M_A, tan(β)
- Dependence of M_h and $M_H$on tan(β) taken into account

hep-ex/12024083



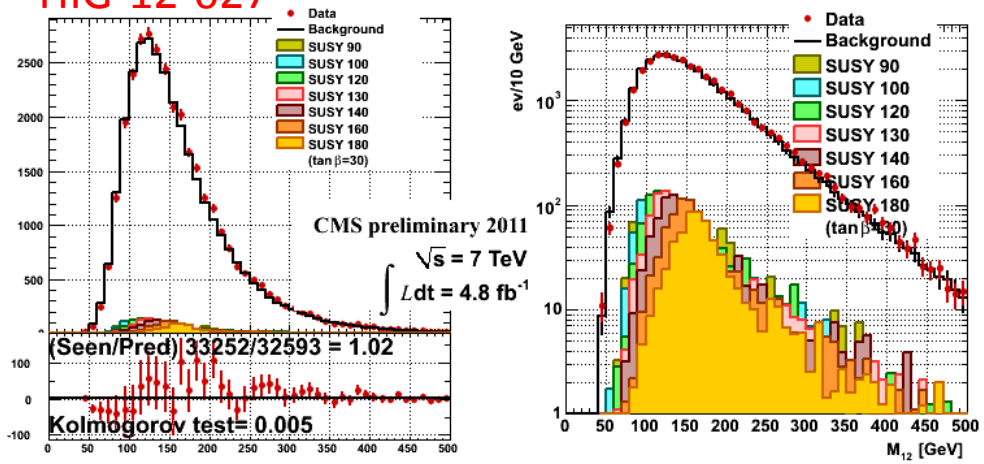
MSSM: φ→ bb Event Selection

	HIG-12-027 **Semileptonic**	**Hadronic** HIG-12-026
Trigger	Muon+1/2 Jets ≥ 1/2 b-tagged	2/3 Jets ≥ 2 b-tagged
Jets	≥ 2 Jets of P_T > 30 GeV + 3rd Jet of P_T > 20 GeV all 3 b-tagged	≥ 3 Jets: ✪ P_T^{1st} > 46 (60) GeV P_T^{2nd} > 38 (53) GeV P_T^{3rd} > 20 GeV all 3 b-tagged
Muon	P_T > 15 GeV (no Isolation applied)	-

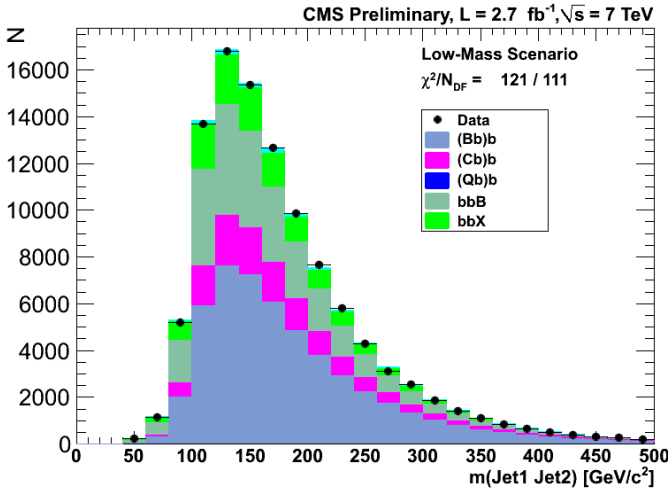
✪ Jet P_T Threshold depends on Higgs Mass hypothesis: lower (higher) Thresholds used for M_ϕ < 180 GeV (M_ϕ > 180 GeV), driven by Trigger Thresholds

MSSM: φ→ bb Limits

HIG-12-027

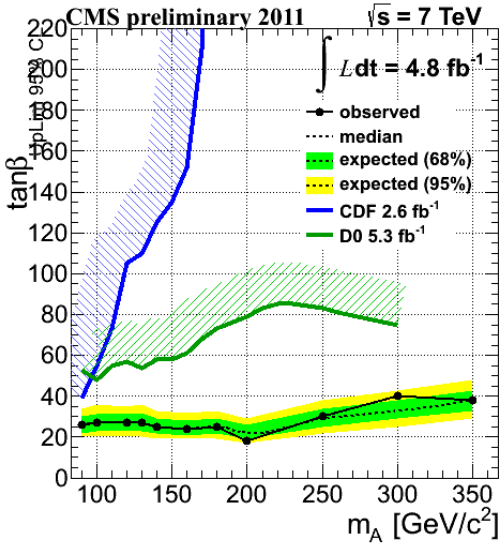


HIG-12-026

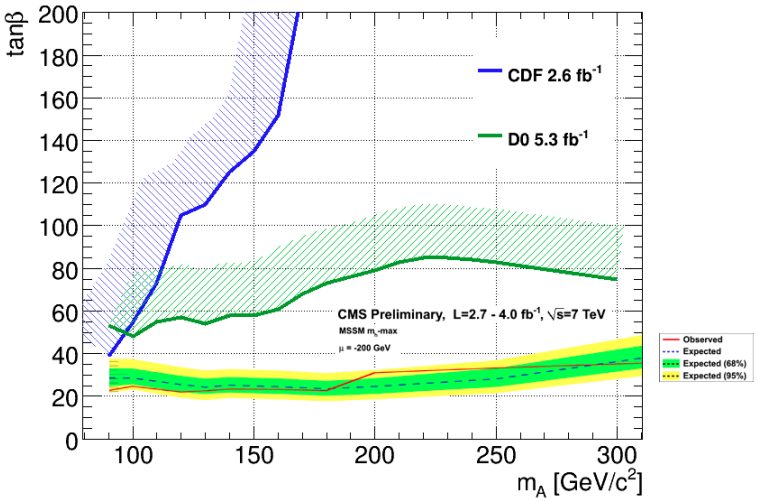


Data in agreement with background predictions

Set upper limit on pp→ φb production σ x BR(φ→bb) by fitting observed M_{12}istribution



Drawing of CMS result is approximate



φ→ μμ Event Selection and Limit

Trigger

Single Muon

Muon Selection

≥ 2 Muons

$P_T^{1st} > 30$ GeV

$P_T^{2nd} > 20$ GeV

$|\eta| < 2.1$

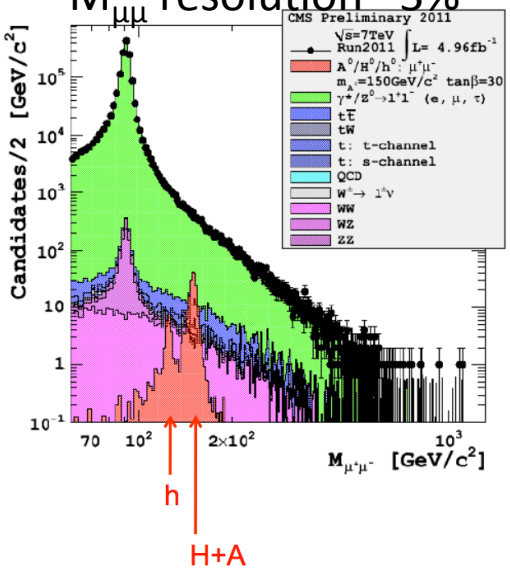
isolated

Opposite Charge Muon Pair

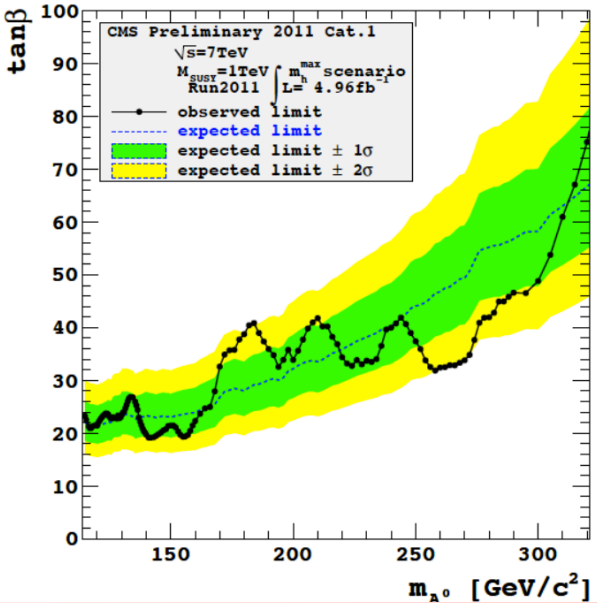
Suppression of tt Background

$E_T^{miss} < 30$ GeV

$M_{\mu\mu}$ resolution ~3%



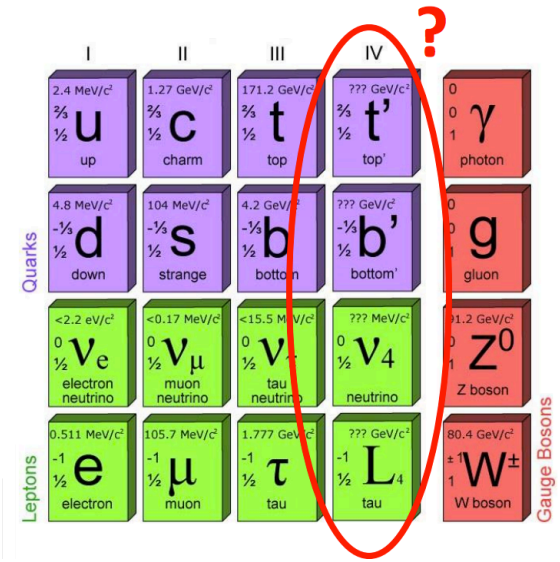
Observed di-Muon mass spectrum in agreement with background-only hypothesis

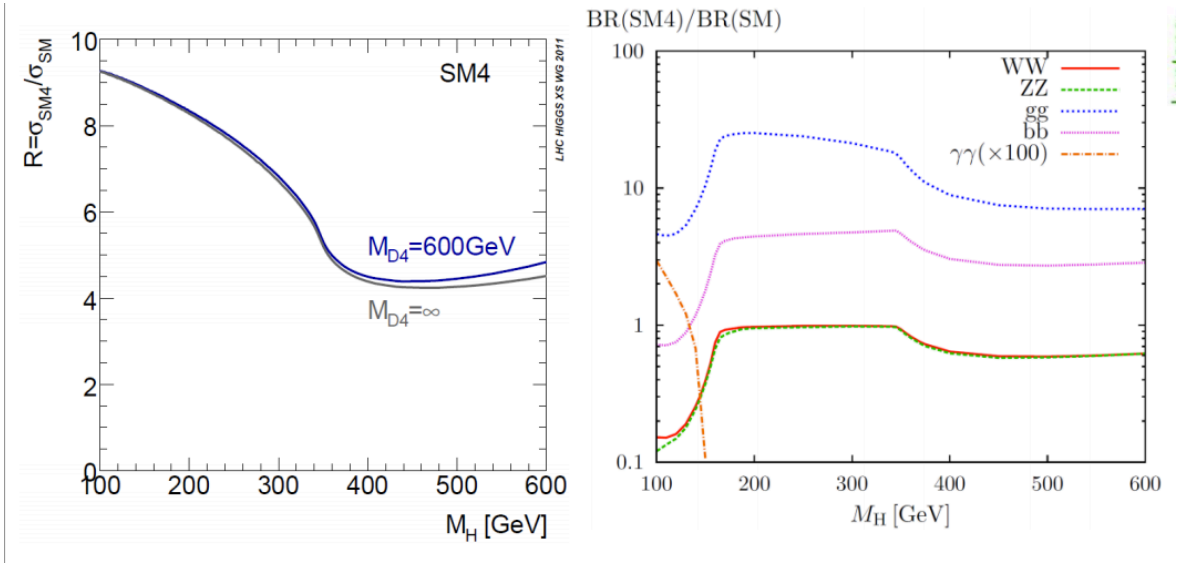


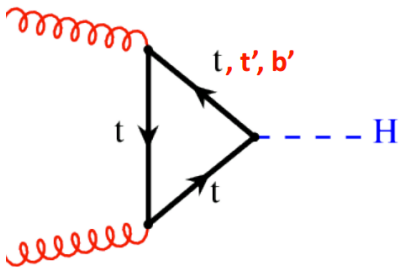
BEYOND MSSM HIGGS @CMS (WITH 7 TEV DATA)

Higgs in SM with 4th Generation

- Introduction of 4th generation fermions has large impact on Higgs production and decay rates
  - Gluon fusion enhanced up to ~ x 10
  - BRs for
    - WW, ZZ and γγ significantly decreased at low mass
    - gg and bb decreased at low mass and increased at high mass.







Reinterpret SM Higgs searches in the context of 4th generation model.

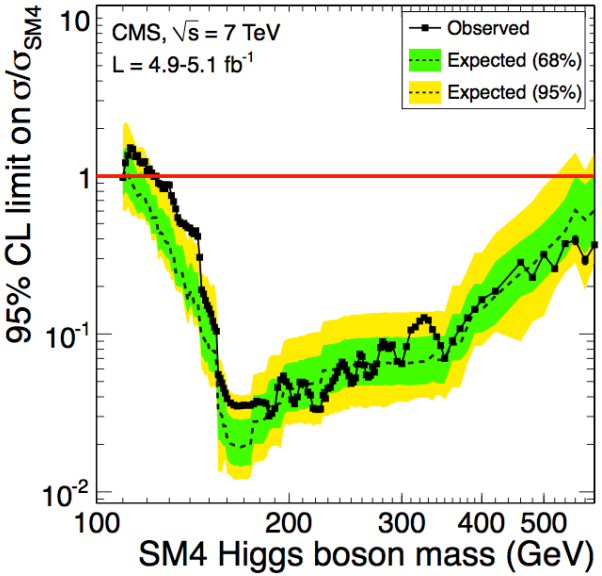
NMSSM: Limit on SM4 Higgs

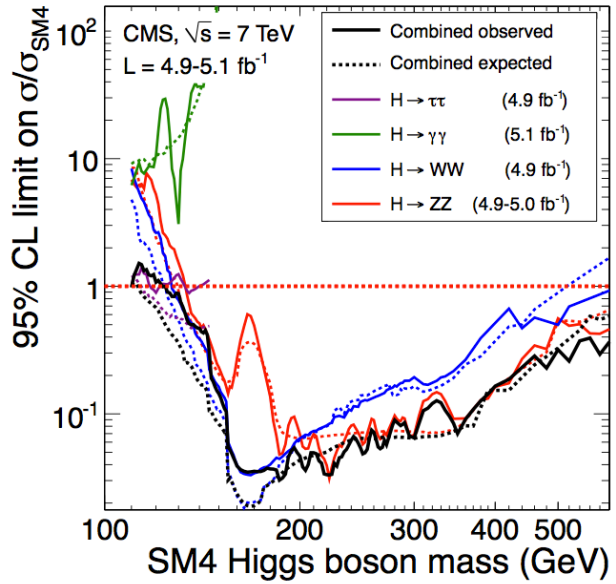
- Model parameters
  - LHC XS WG benchmark:

$$m_{d4} = m_{L4} = m_{\nu} = 600 \text{ GeV}$$

$$m_{u4} - m_{d4} = \left[1 + \frac{1}{5}\ln\left(\frac{m_H}{115}\right)\right] \cdot 50 \text{ GeV}$$

- Reinterpretation of existing SM search results @ 7 TeV
  - gg fusion dominates, neglect VBF and VH production
  - Channels contributing:
    - H → ττ
    - H →γγ
    - H → WW(2l2ν)
    - H → ZZ(4l, 2l2ν, 2l2q, 2l2τ)



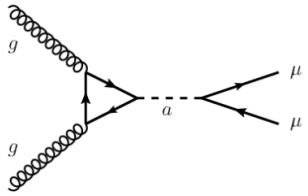


95% CL excluded SM4 m_H 123—600 GeV

NMSSM: a1 → $\mu^+ \mu^-$

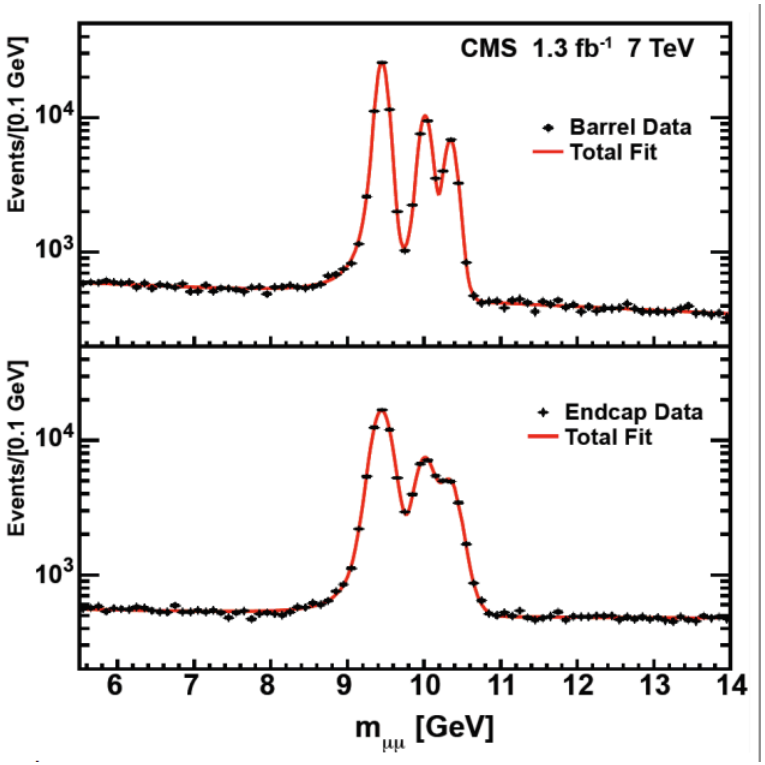
- Add a scalar singlet to MSSM Higgs family
  - 3 CP-even (h1, h2, h3) , 2 CP-odd (a1, a2), and H±
  - Must exist a ~10 GeV boson

$a1 = a \cdot \cos\theta_A + as \sin\theta_A$



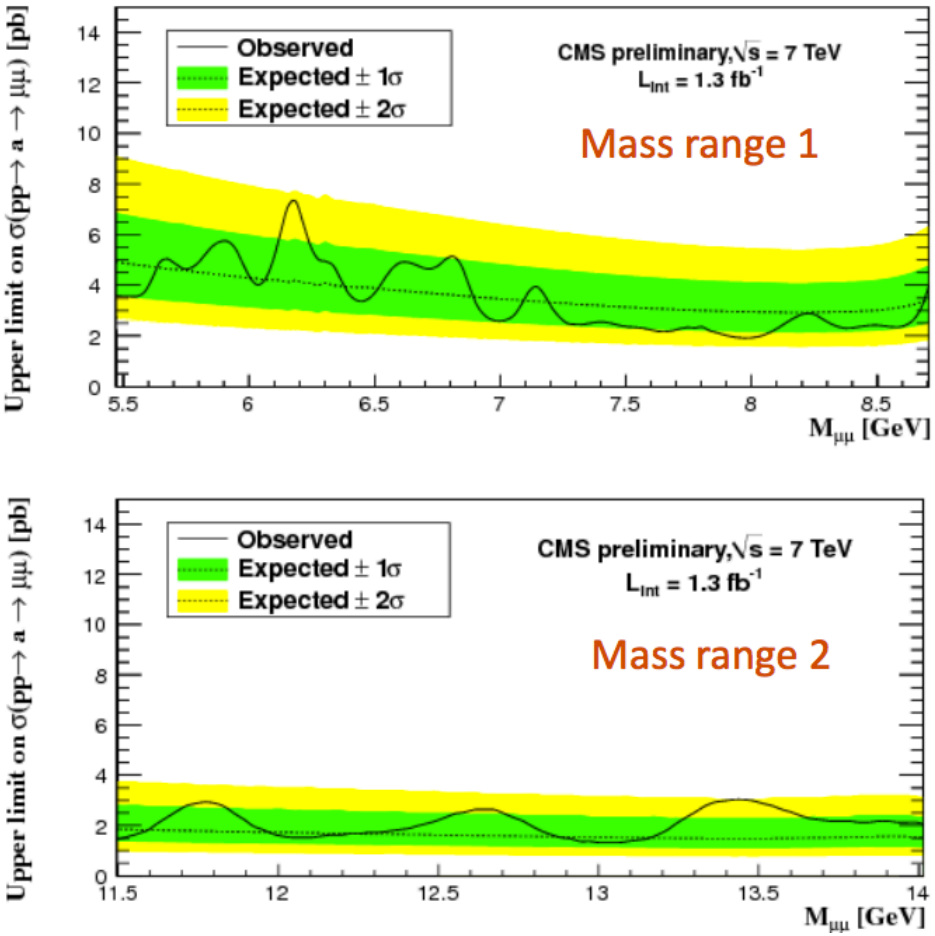
- Search around the Upsilon family
  - Better sensitivity than CDF due to larger production rate
  - Extended search range relative to BaBar ($m_a > m_\Upsilon(3S)$)
- Muon Selection:
  - pT>5.5 GeV |η|<2.4, track w 10 hits and at least one pixel hit
  - Isolation in a cone of DR = 0.3
  - Select dimuon with best vtx fit

- Backgrounds: QCD, and tails of bottomonium.
- Singal extraction:
  - Binned ML fit over 5.5 – 14 GeV
  - QCD: polynom O(1) Y(NS): 2 CB
  - Signal: mass scan in 30 MeV steps

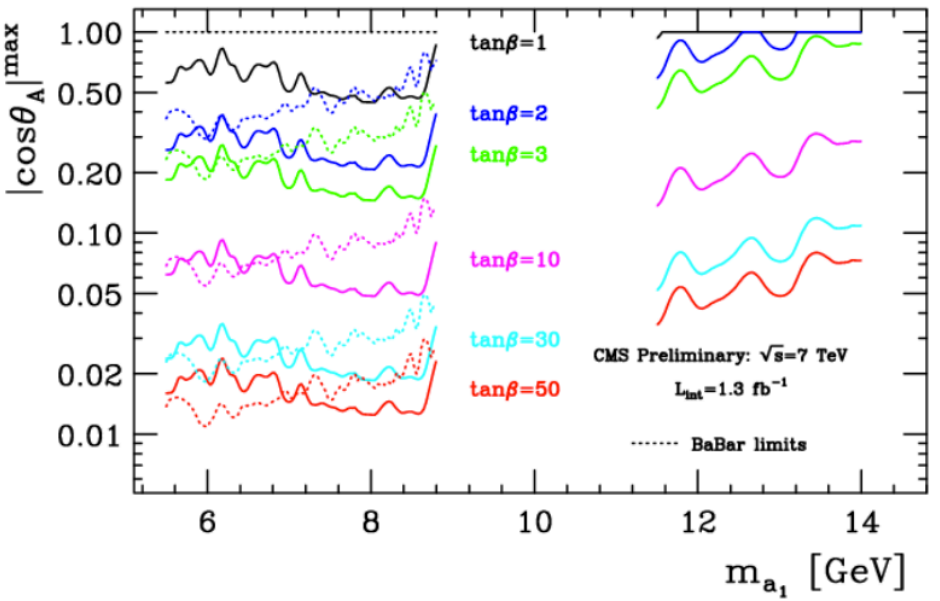


NMSSM: a1 →μ+ μ- Limits

Cross Section x BF Upper Limits

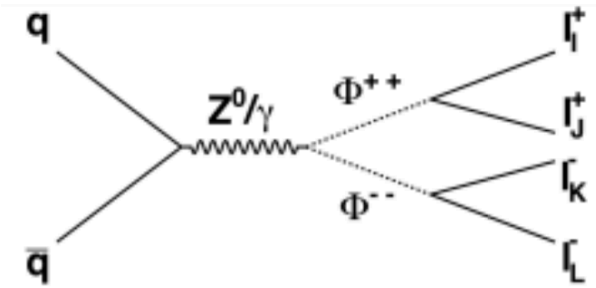


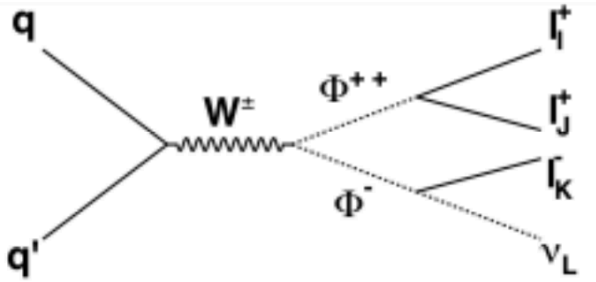
Limits and comparisons with BaBar



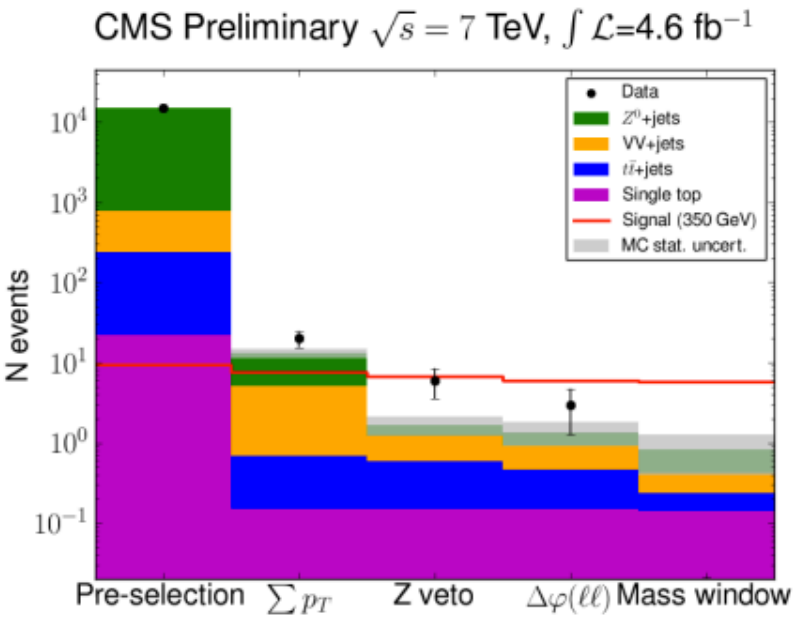
Doubly Charged Higgs Φ++

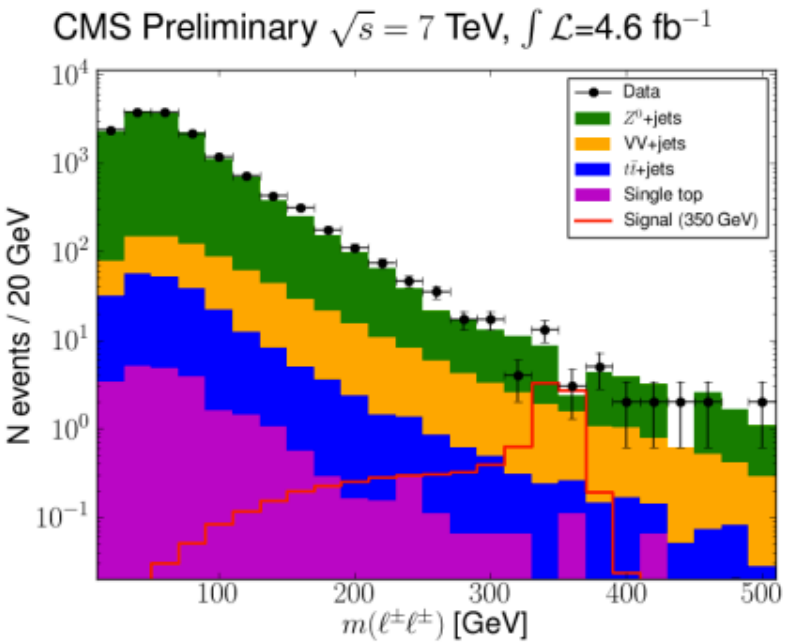
- Minimal Type II See-Saw Models
  - Predicts of additional scalar field that is a triplet under SU(2)L
- New Higgs-like particles: Φ++, Φ+, Φ0
  - If observed, would establish this mechanism as the most promising explanation for neutrino masses
- Search strategy
  - Produced in association with singly charged Higgs, or in pairs since Φ++, Φ+ are assumed to be degenerate
  - Unique experimental signature
    - SM backgrounds have fake leptons
  - Use same-sign lepton combinations of all flavors

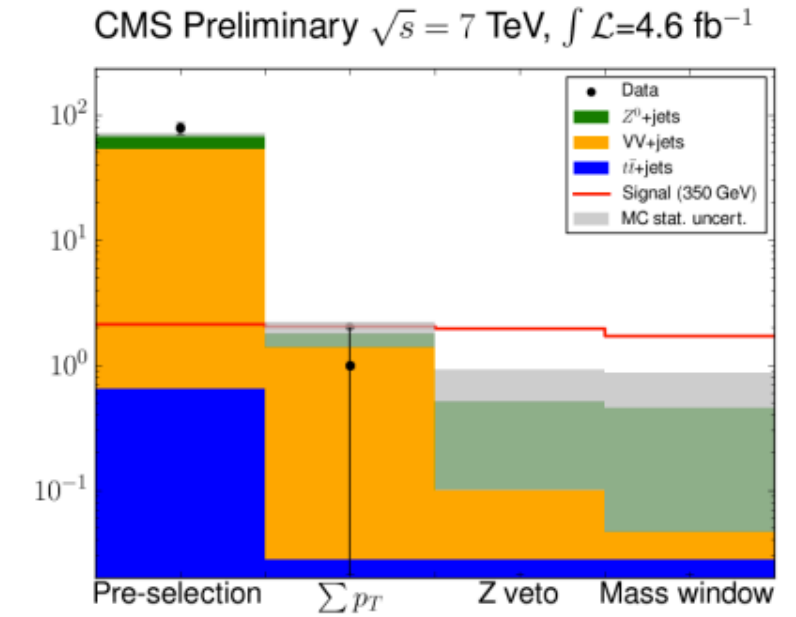


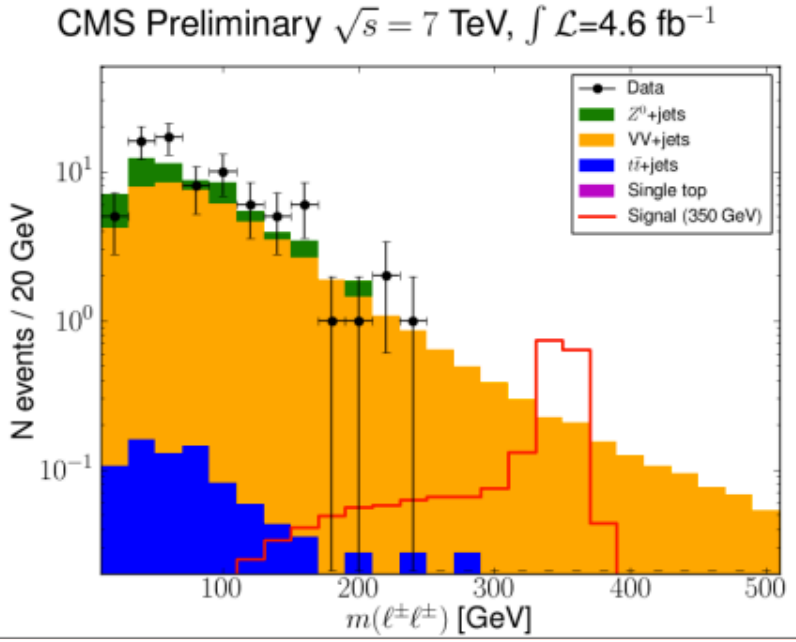


Doubly Charged Higgs Φ++ Search

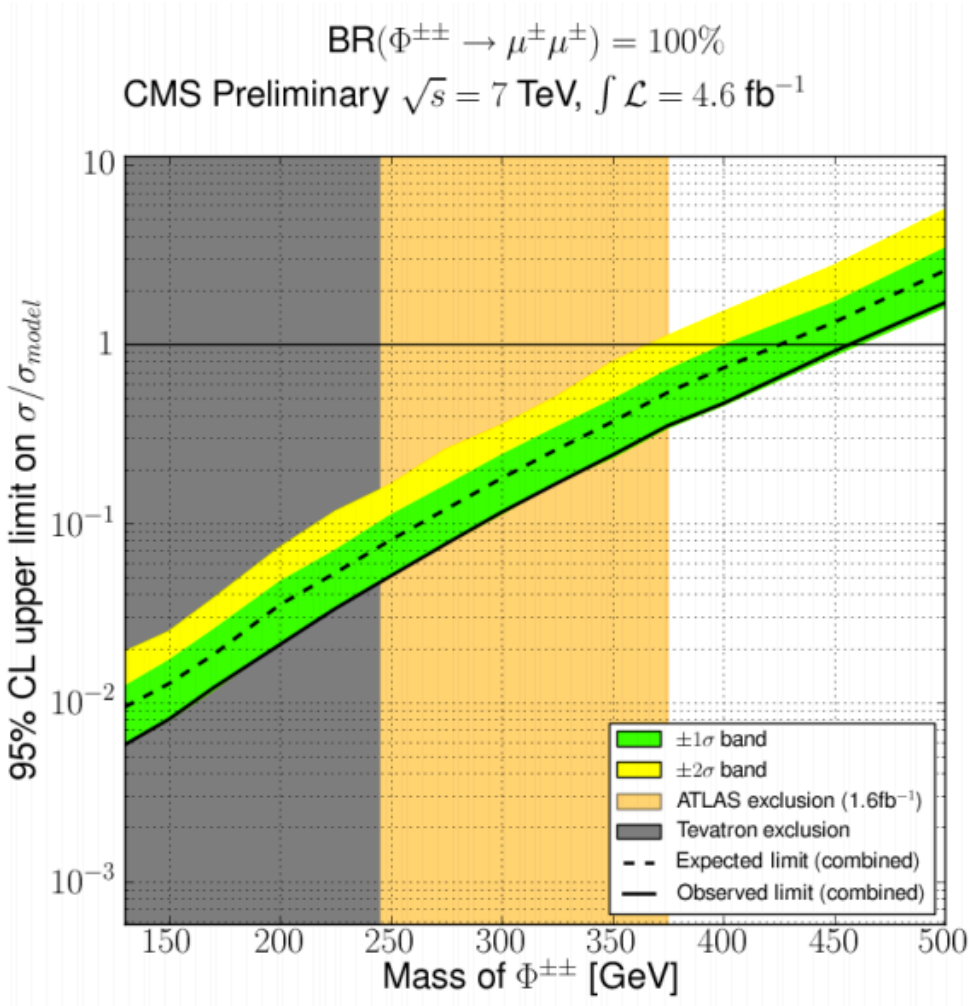


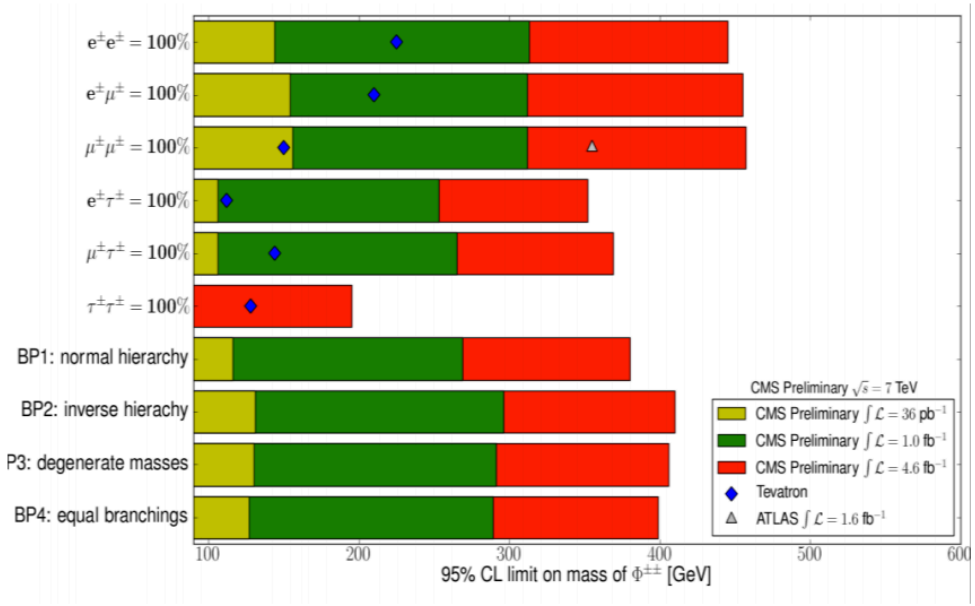






Doubly Charged Higgs Φ++ Limits

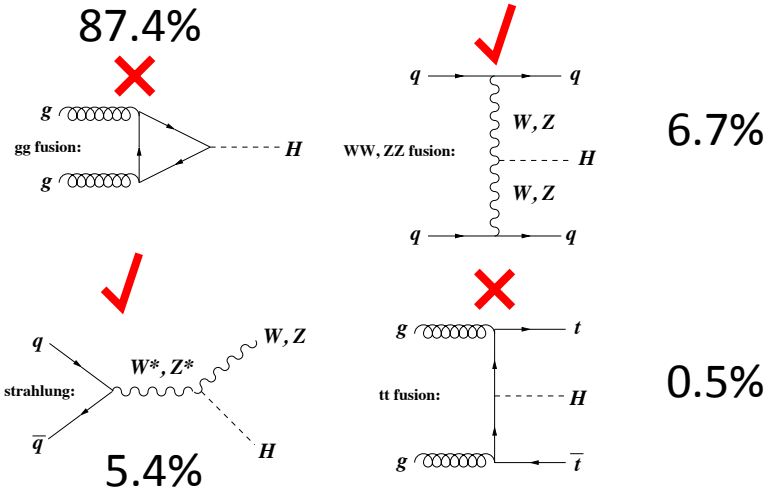


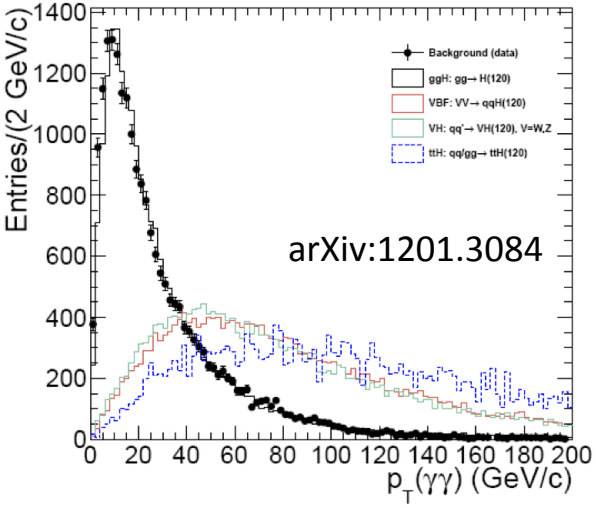


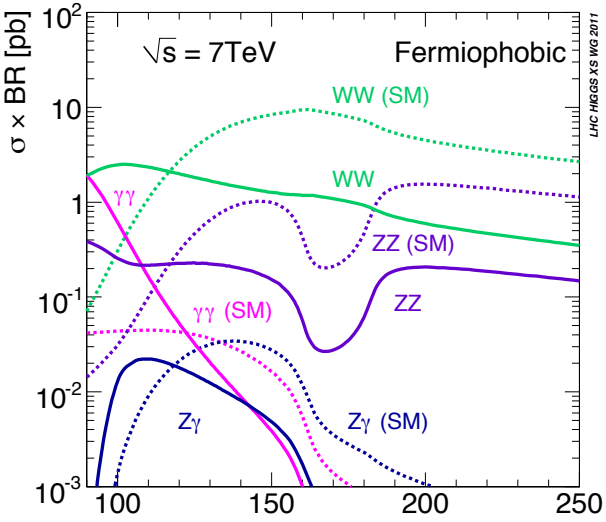
FERMIOPHOBIC HIGGS @CMS (WITH 7 AND 8 TEV DATA)

Fermiophobic Higgs

- SM Higgs results are very interesting
  - No excess in ττ, signal strength in γγ might be too large…
- Interest for beyond the SM scenario of EWSB (2 HDM)
  - FP is important part of Higgs program - couplings.
  - No coupling to fermions, driven by VBF and VH.
  - yields from FP comparable to SM Higgs at 125 GeV, due to increased BR to γγ.
- Jets (VBF) and leptons (VH) produced at LO.
  - Additional signatures (dijet, lepton, MET) tagging
  - Higgs is boosted



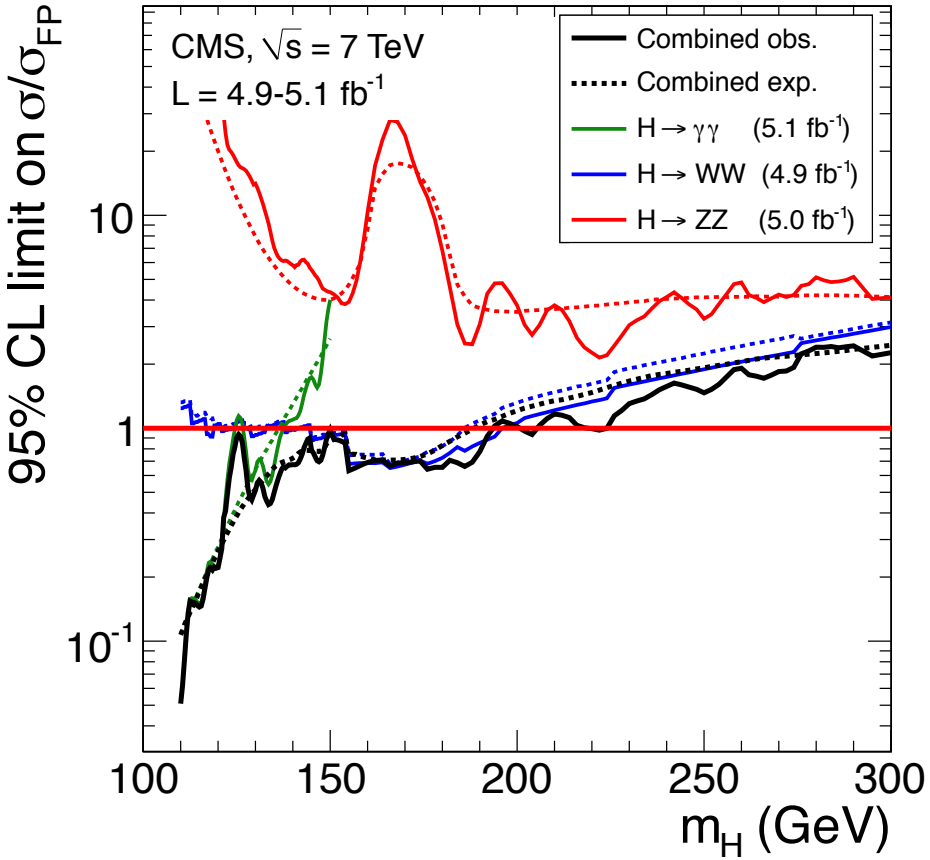




- 95% CL limits: Tevatron 119 GeV [arXiv:1109:0576v1], ATLAS 121 GeV [arXiv:1205.0701v1], CMS 194 GeV [arXiv1207.1130v1]

FP: Signal Signatures

- CMS submitted for publication arXiv:1207.1130:
  - combining γγ, WW, and ZZ analyses with 7 TeV
  - Excludes at 95% CL 110-194 GeV
  - Excludes at 99% CL except for 124.5—127 GeV and 147.5—155 GeV



FP: Signal Signatures

- Here present update of γγ analysis (main driver at low m) with 8 TeV.
  - Analysis techniques different from SM analysis
  - Four mutually exclusive sub-channels
    - Dijet-tagged 2 classes (VBF): high and low dijet mass (as in SM analysis)
      - S/B ~ 1 (mH = 120 GeV)
    - Lepton-tagged 2 classes (VH): *e* and μ
      - S/B ≧ 1
    - MET-tagged 1 class (Z(νν)H)
      - S/B < 1 (NEW CHANNEL)
    - Untagged 4 classes based on $|\eta_\gamma|$ and conv/non-conv
      - 2D
      - S/B << 1

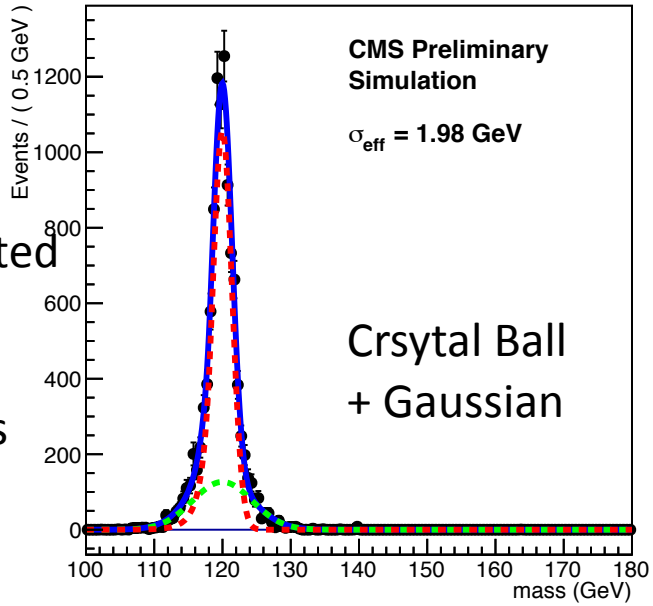
channel	leading photon	trailing photon
dijet-tag	p_T/m>60/120	p_T >25 GeV
lepton-tag	p_T/m>45/120	p_T >25 GeV
MET-tag	p_T/m>45/120	p_T >25 GeV
untagged	p_T/m>40/120	p_T/m>30/120

FP: γγ + Dijet tag – signal and bkg models

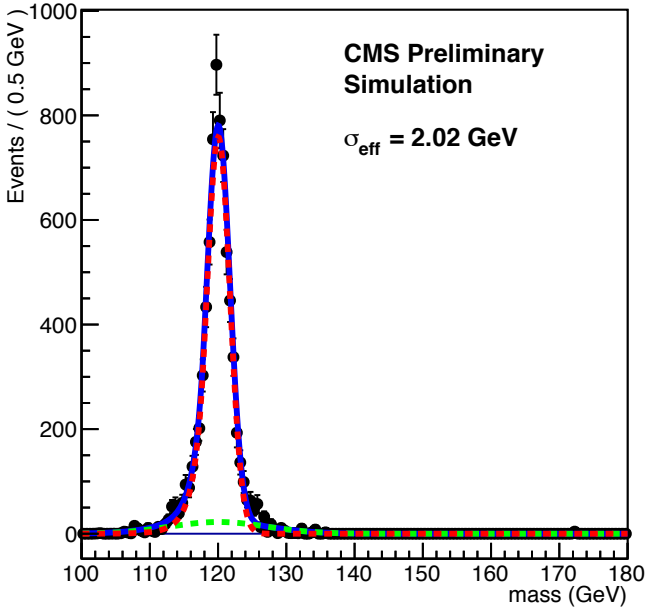
Require γγ + two jets separated in rapidity.

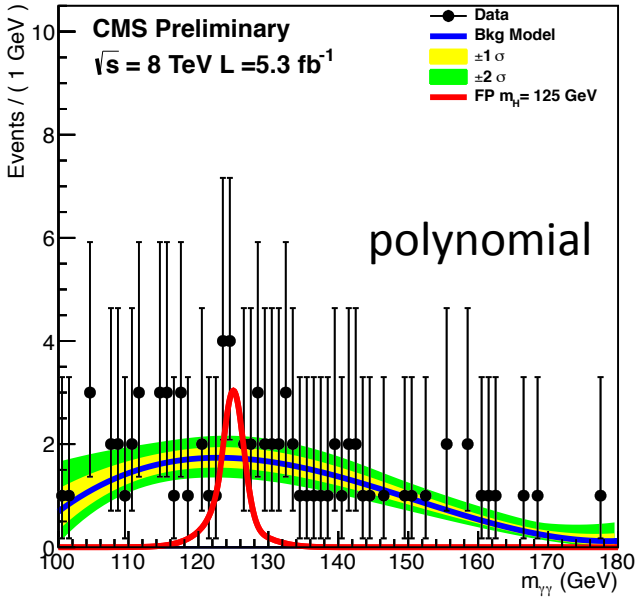
Separate events in 2 categories based on the dijet mass.

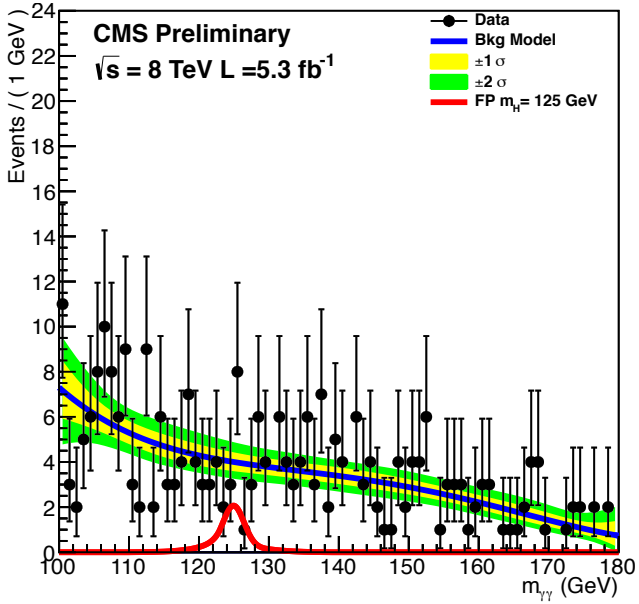
CAT1: 500 GeV < m_{jj}



CAT2: 250 GeV < m_{jj} < 500 GeV



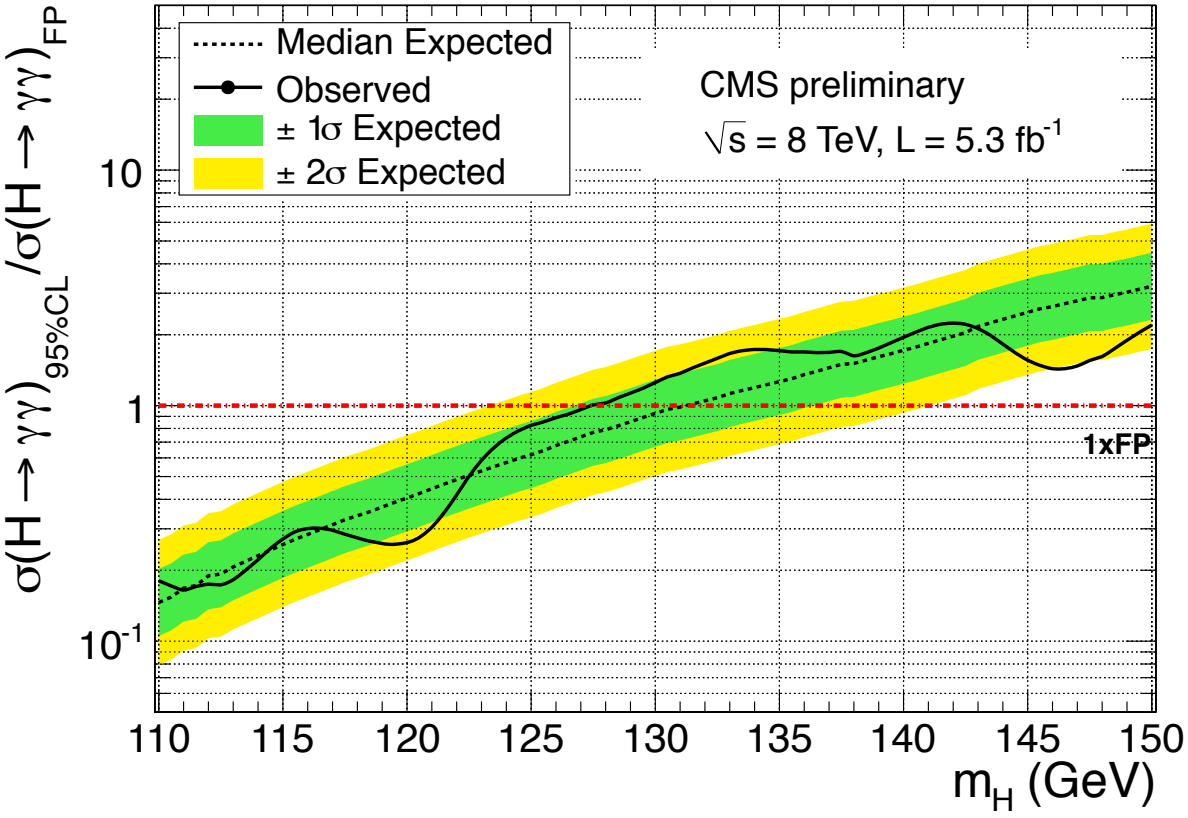




FP: Dijet tag - Limit 2012

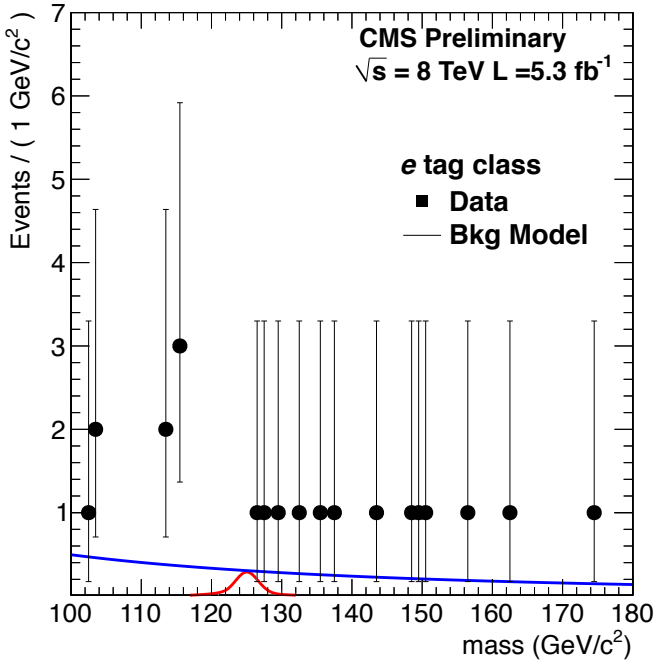
- Most sensitive channel
  - expected 95% CL exclusion:
    - mH < 131 GeV in 2011
    - mH < 131 GeV in 2012
- Jet specific systematic uncertainties :

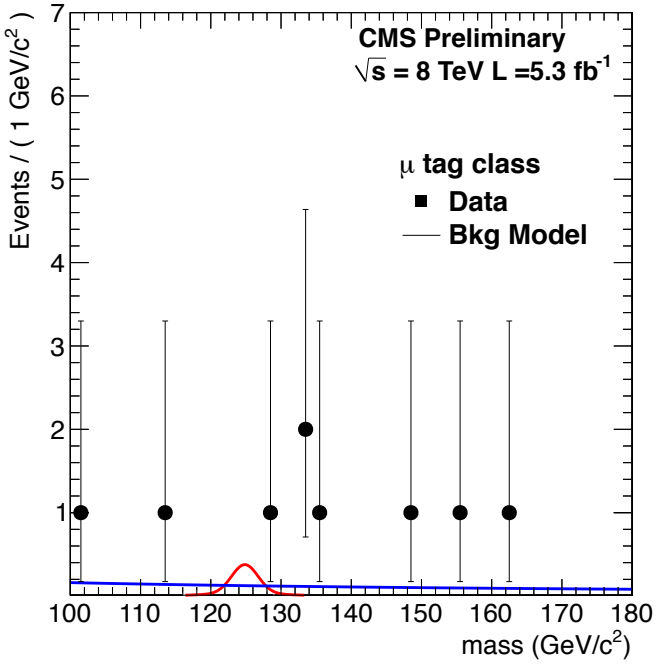
Systematics	VBF
JEC & JER	6%
tunes	8%
PDFs	1.5%
total	10%



FP: γγ + Lepton tag – signal and bkg modeling

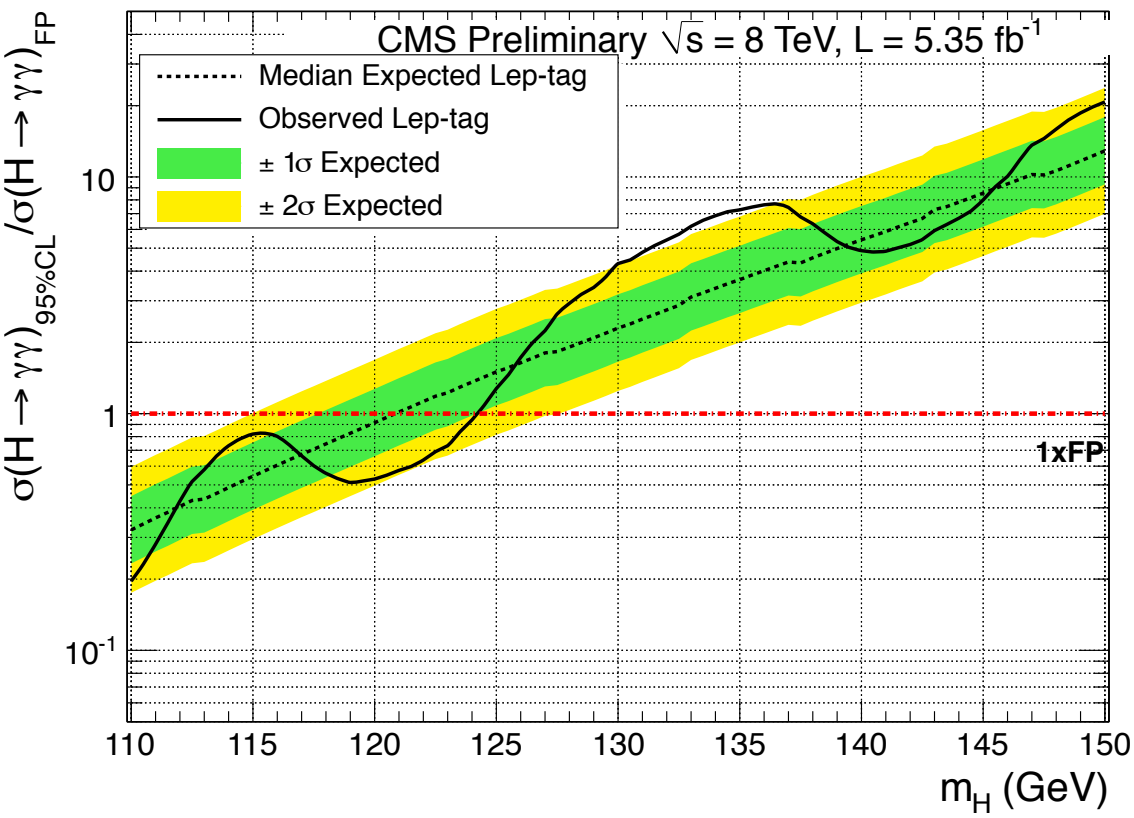
Require γγ + isolated lepton (e or μ)





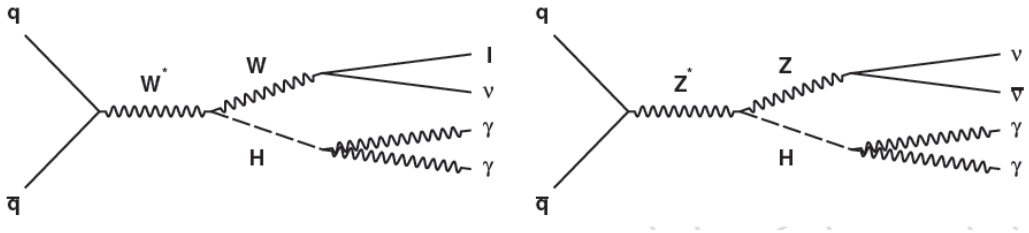
FP: Lepton tag – Limit 2012

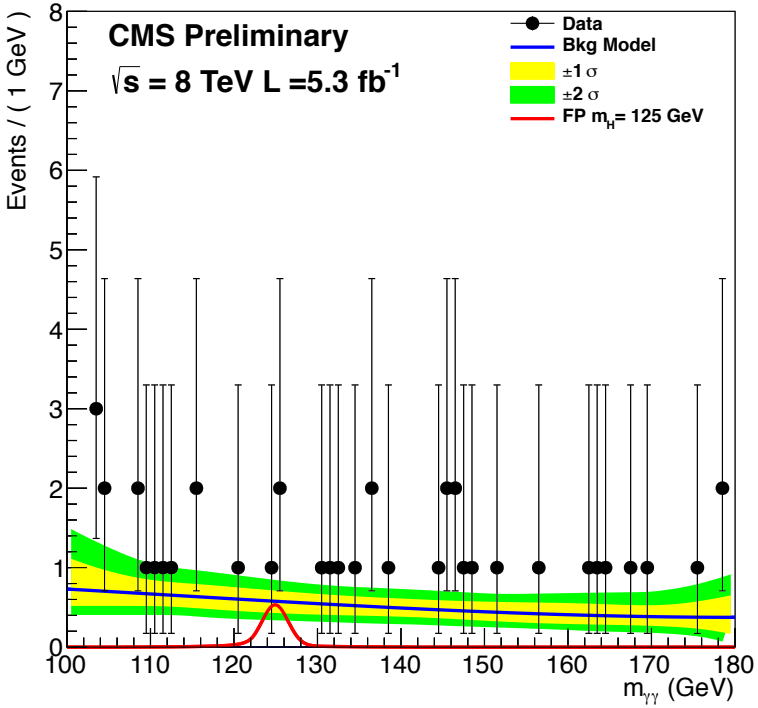
- Best S/B channel
- Powerful sensitivity
  - expected 95% CL exclusion:
    - mH < 122 GeV in 2011
    - mH < 121 GeV in 2012



FP: γγ + MET tag

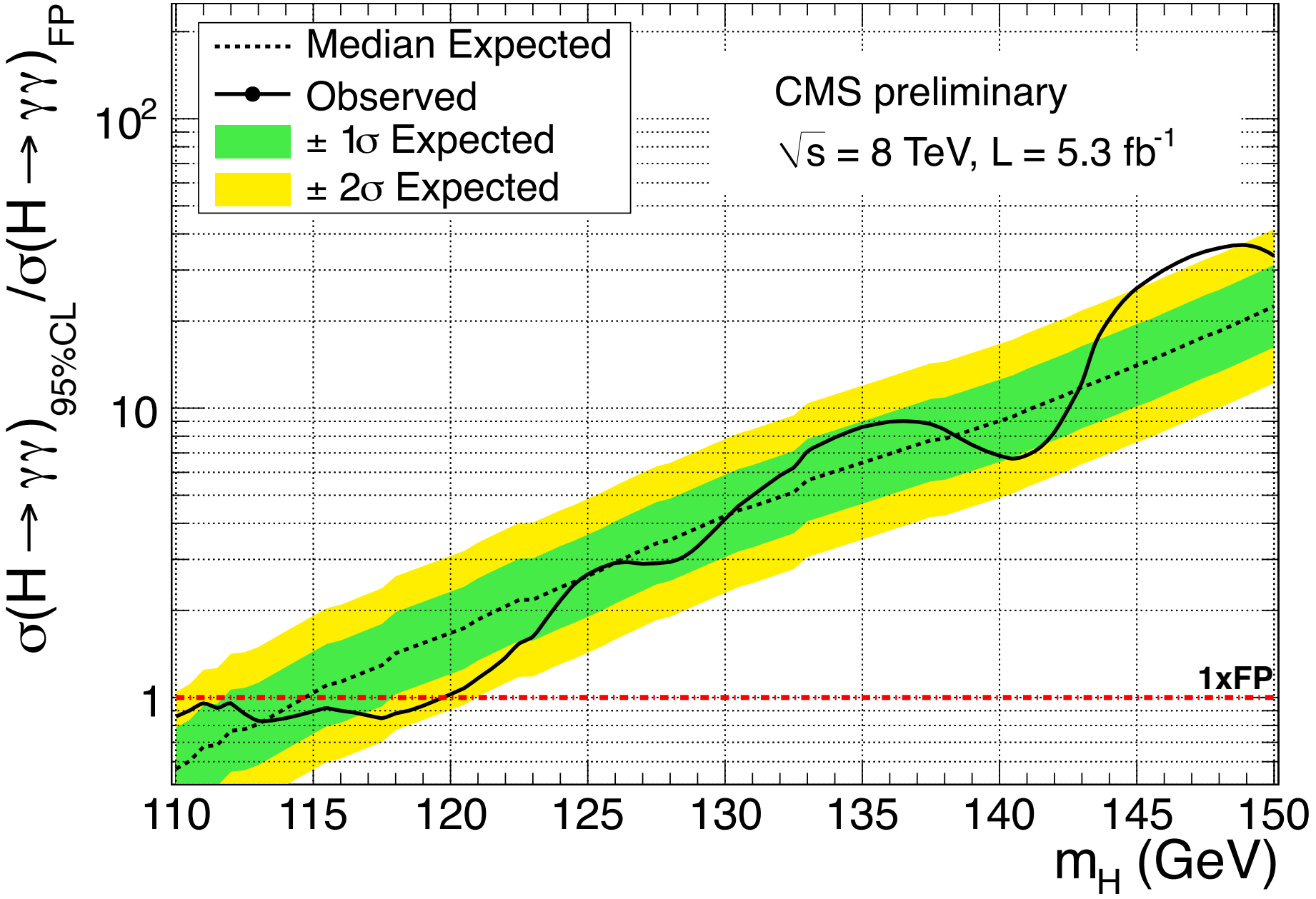
- New subchannel, not in the 2011 fermiophobic Higgs paper
- MET tag has high S/B in high MET region
- Complements the lepton tag analysis
- Signal from VH
  - ZH with Z->νν
  - WH with W->lν
    and not selected by lepton tag





- Main challenge
  - correct MET response
  - evaluate systematic
  - check PU dependence

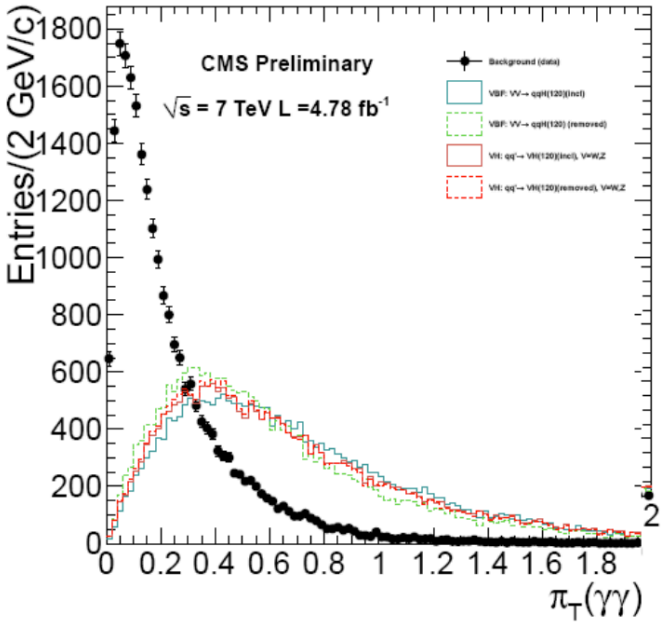
FP: MET tag – Limit 2012



FP: Untagged – 2D γγ

- ~70% of inclusively selected signal H→ γγ events are not tagged.
  - Use these events and the knowledge of boosted kinematics
- Construct 2D models for signal and bkg, relying on two observables,

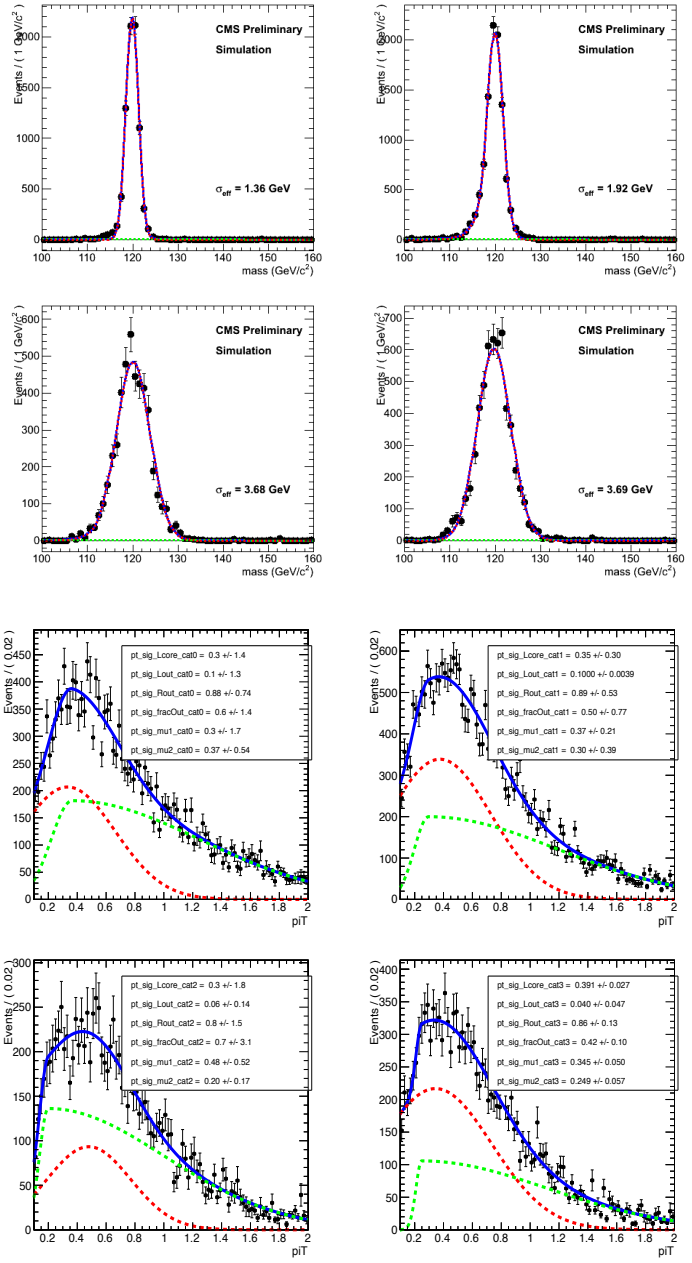
$$(m,\ \pi_T^{\gamma\gamma} \equiv p_T^{\gamma\gamma}/m^{\gamma\gamma})$$



- Event selection same as in Cut Based SM and
  - Remove data with high correlation $\pi_T < 0.1$
    - 30% less background
    - Negligible signal loss
- Remove events common with MET, lepton, and dijet tag, retaining discriminating power of π_T

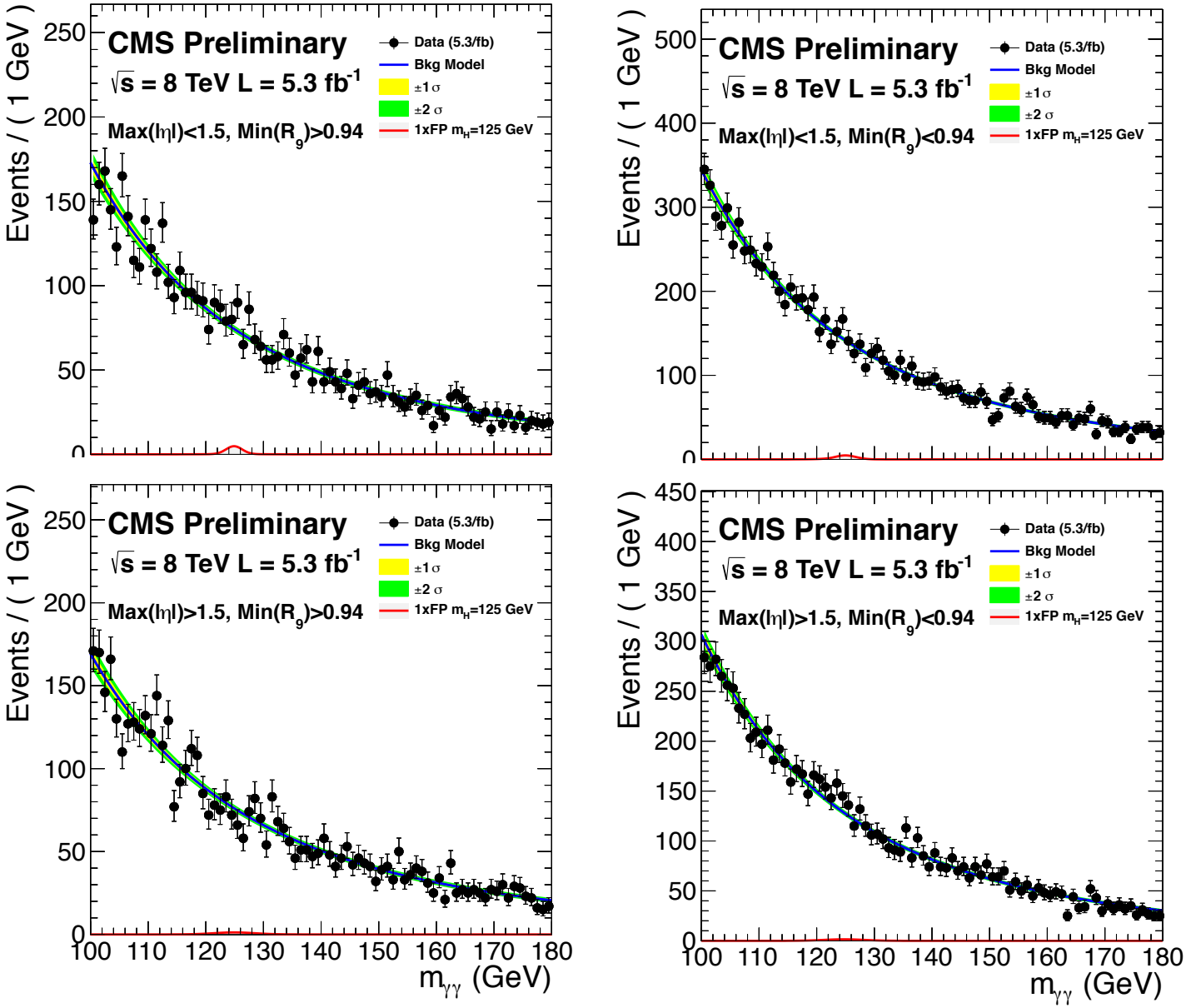
FP: Untagged - Signal Modeling (m, π_T)

- Parameterize each category in 2D space
- FP signal mass resolution dependence on π_T is negligible
  - Factorized PDFs
  - Mass model
    - Crystal Ball + Gaussian
  - π_T model is empirically determined:
    - Sum of Gaussian and Bifurcated Gaussian



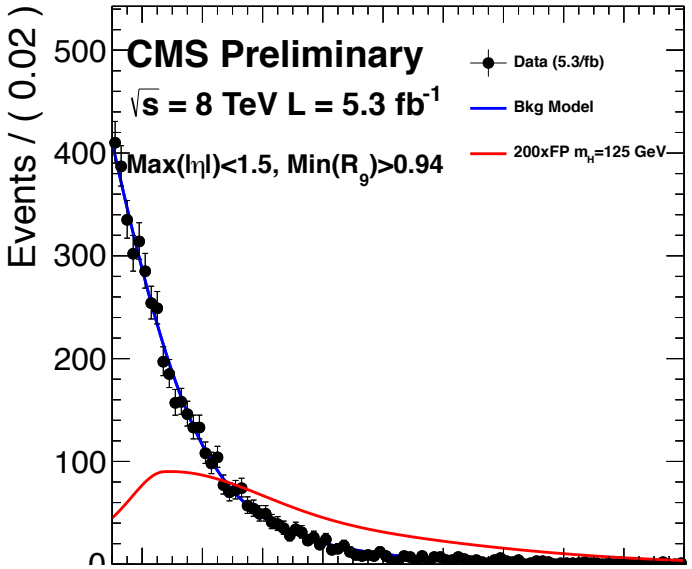
FP: Untagged - Background Modeling (m, πT)

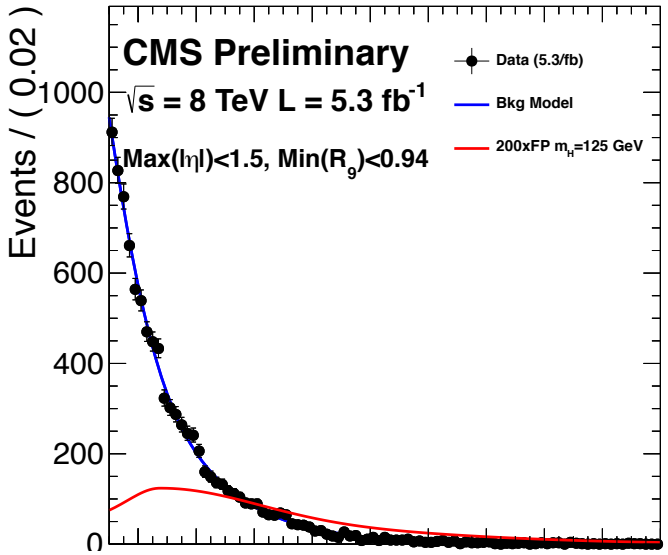
Include correlation in the background model $M_b^i(m_{\gamma\gamma}, \pi_T^{\gamma\gamma} \mid a_0, a_1) = m^{a_0 + a_1 \pi_T}$

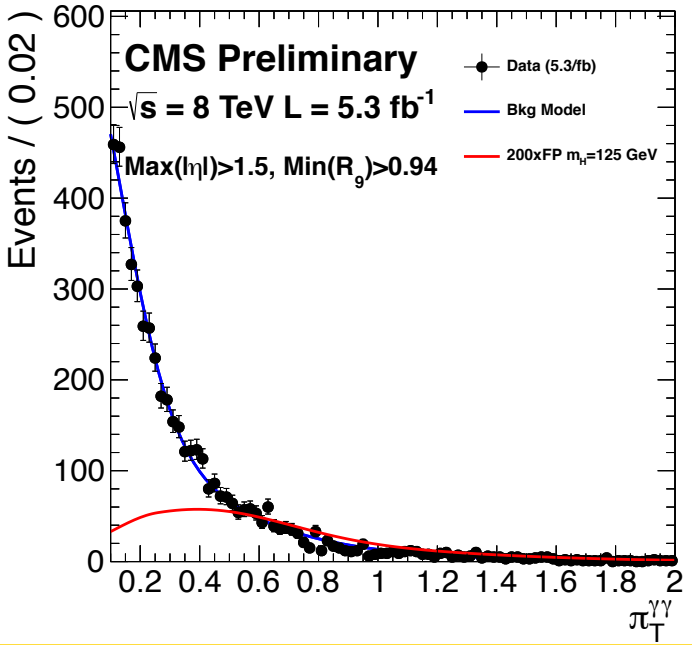


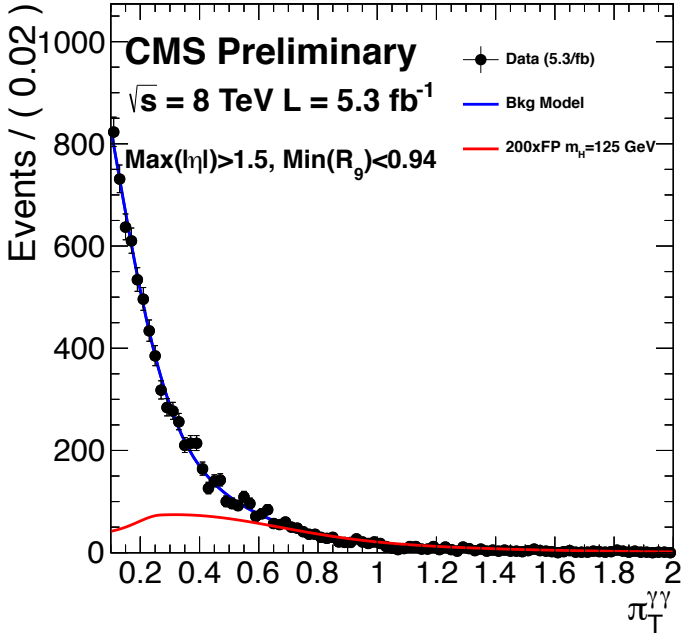
FP: Untagged - Background Modeling (m, πT)

- Empirical model
  - Exponential + Gaussian
- FP Signal x 200 shown in red for reference





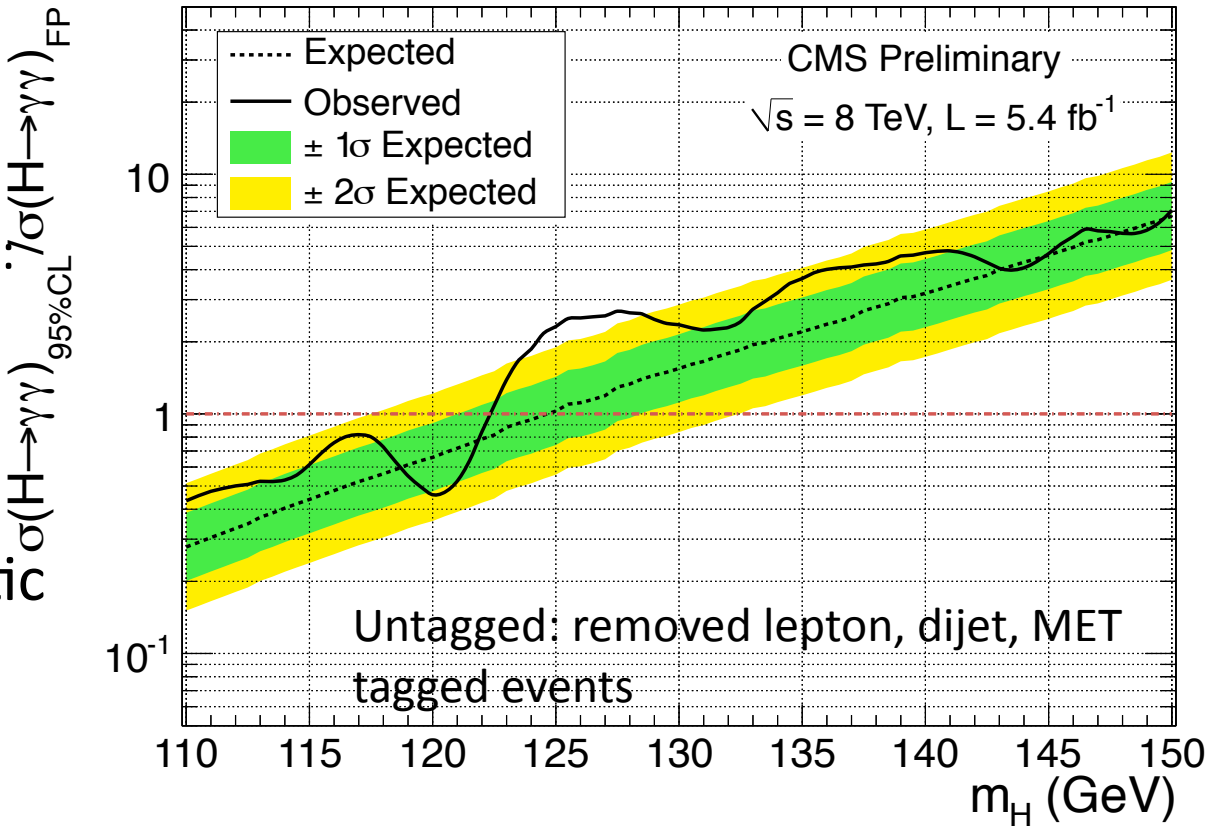




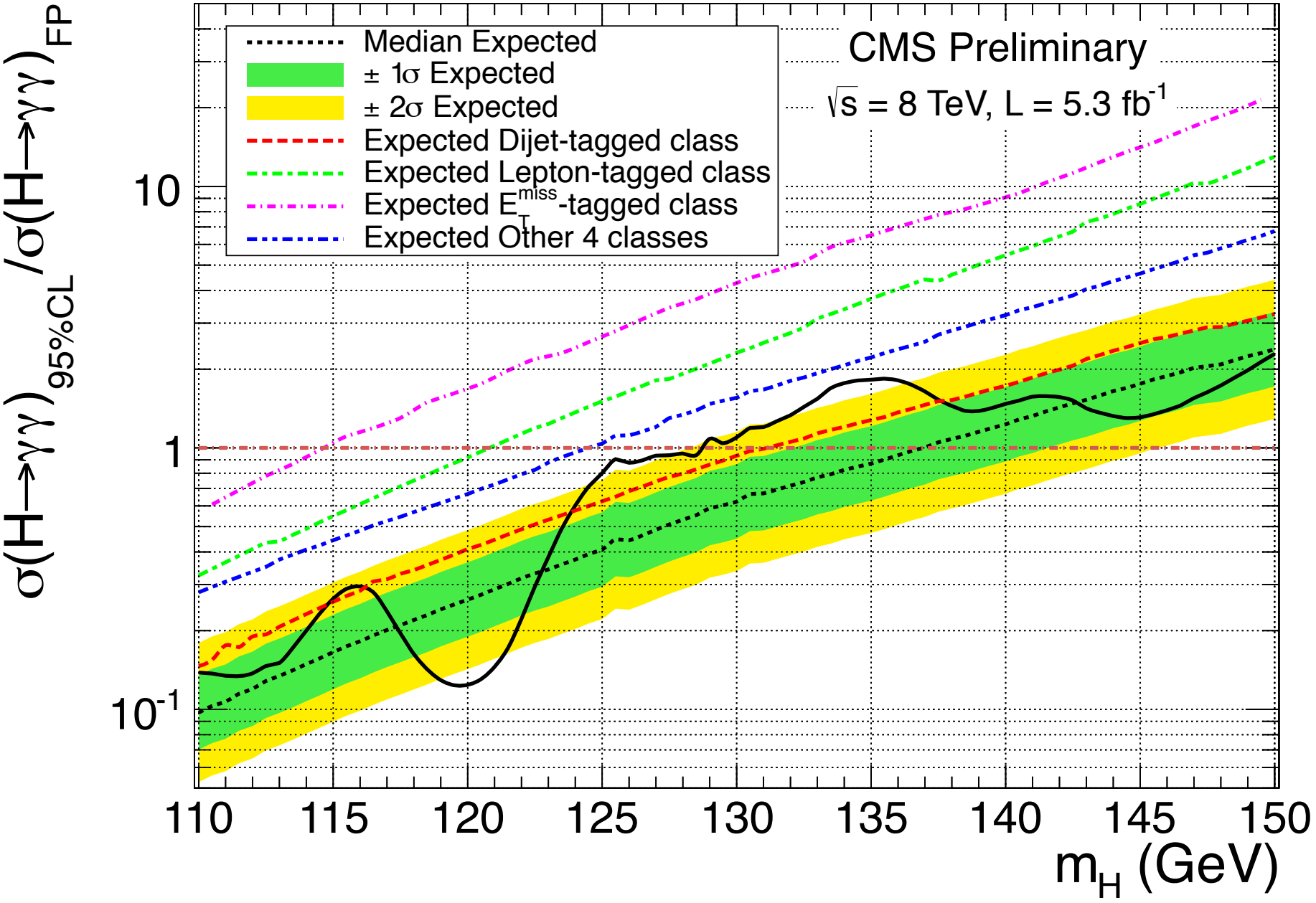
$$\mathcal{K}_b(\pi_{\mathrm{T}}^{\gamma\gamma}|\tau_B, f_d, \sigma_G) = f_d\mathcal{E}(\pi_{\mathrm{T}}^{\gamma\gamma}|\tau_B) + (1-f_d)\mathcal{G}(\pi_{\mathrm{T}}^{\gamma\gamma}|0,\sigma_G)$$

FP: Untagged – Limit 2012

- Low S/B channel
- Still powerful sensitivity due to 2D
  - expected 95% CL exclusion:
    - mH < 123 GeV in 2011
    - mH < 124 GeV in 2012
- Small additional systematic w.r.t SM analysis.
  - 1% due to signal shape

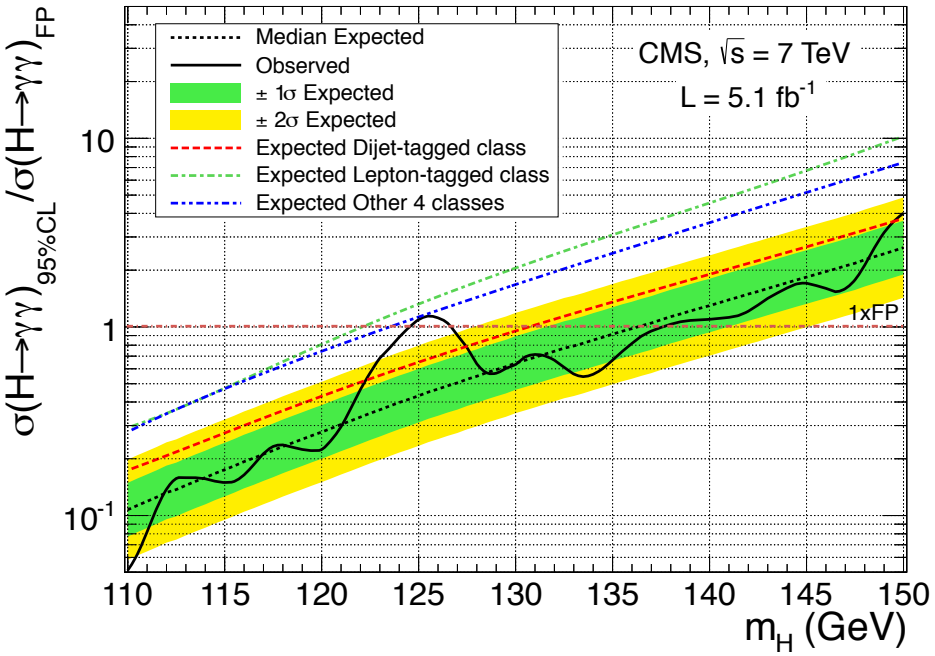


FP: 2012 Combined Limit in γγ channel

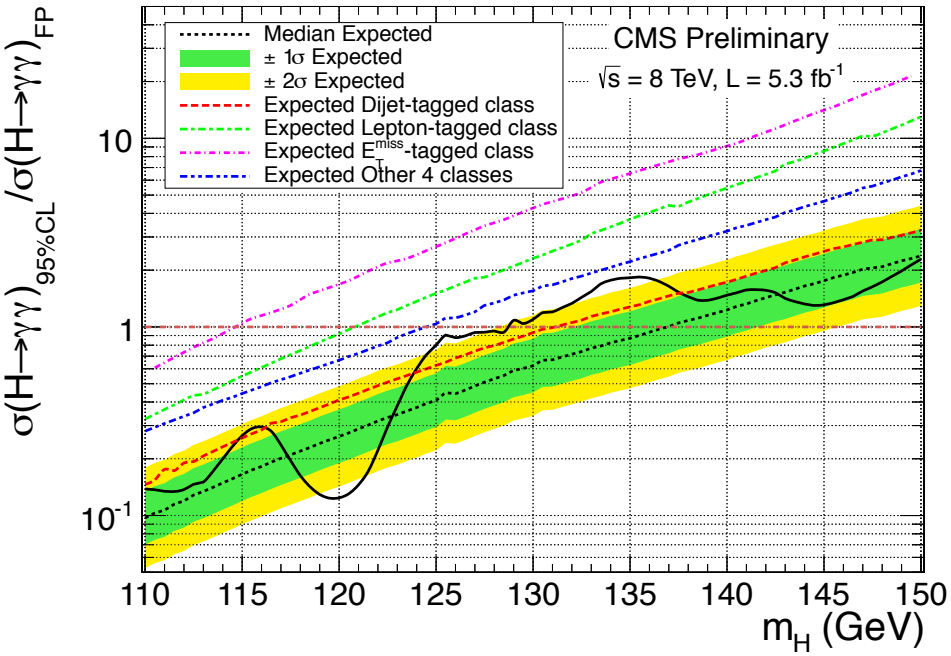


2011 , 2012 Limits on FP Higgs in γγ channel

7 TeV



8 TeV



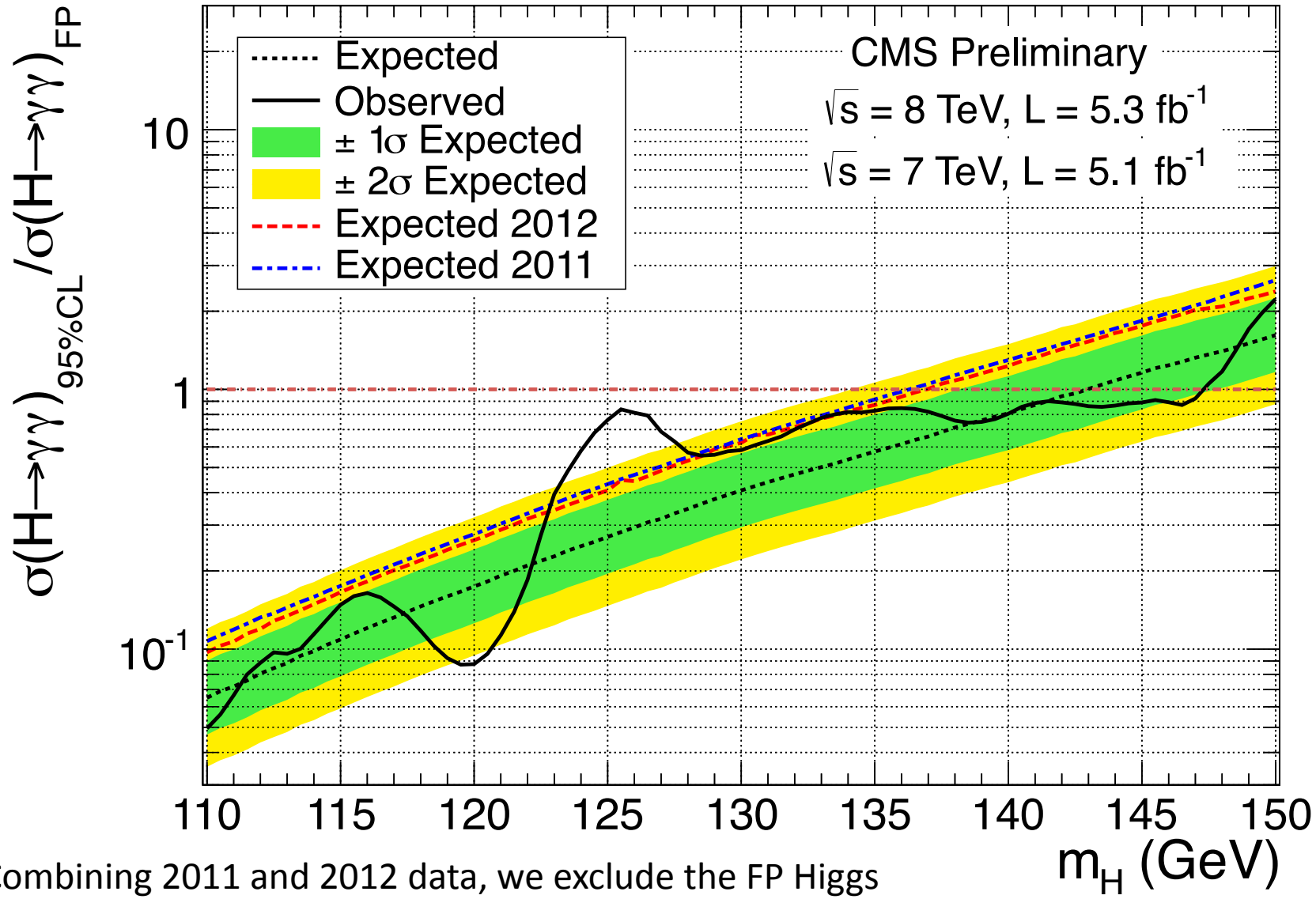
HIG-12-009

HIG-12-022

Main contribution to the limit is in dijet-tag, somewhat less in untagged sub-channel

2011 + 2012 Limit and p-value in γγ channel

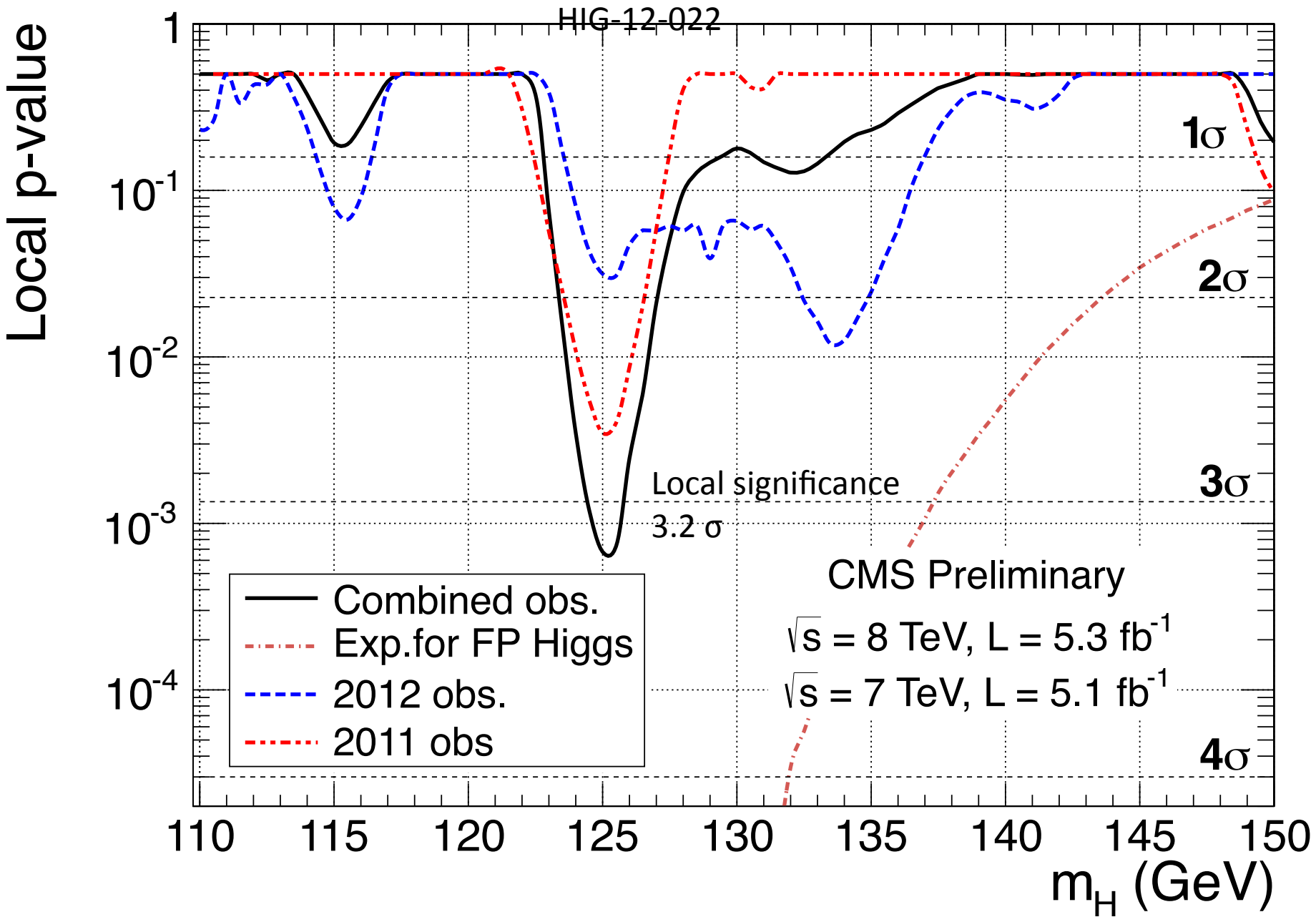
HIG-12-022



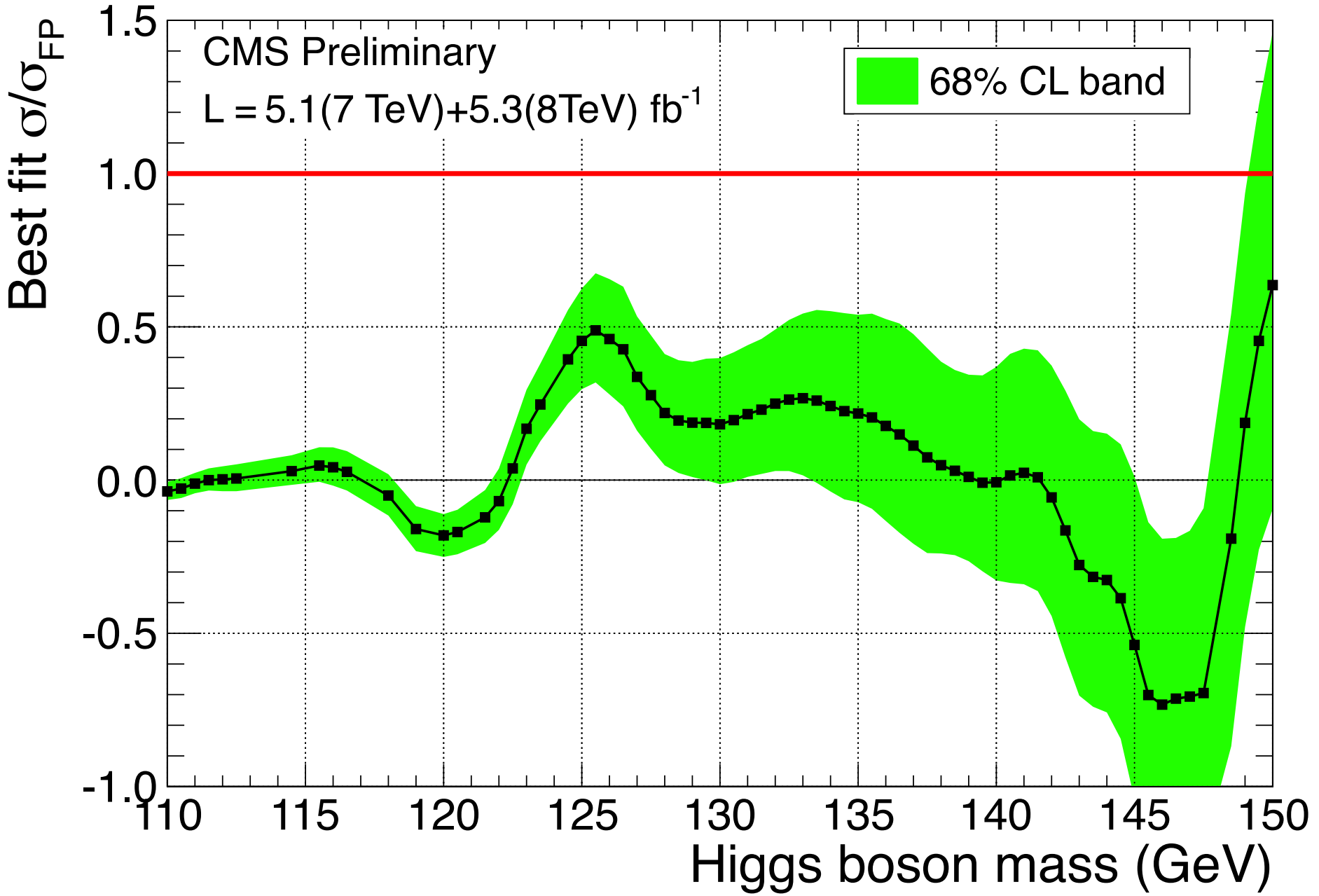
Combining 2011 and 2012 data, we exclude the FP Higgs in almost the entire search range

at 95% CL in the mass range 110—147 GeV, at 99% CL in the mass range 110—134 GeV

2011 + 2012 Limit and p-value in γγ channel



Best-fit value of FP signal strength in γγ channel



Conclusions

- No sign of BSM Higgs in CMS yet.
- Stringent Limits are set on MSSM Higgs Production
- The observed state @ ~125 GeV is excluded at 99% CL under the fully-fermiophobic hypothesis.
  - The excess shows tension with FP signal: best fit signal rate 0.49±0.18
- Continue with improved analyses to probe further BSM parameter space.

BACKUP

Dijet tag sub-channel

- Same as SM [HIG-12-015]
  - 2 dijet-tagged classes (VBF)
    - same event selection
    - same detector systematics
    - just different interpretation
- Exploit forward jet kinematics
  - Change w.r.t 2011:
    - introduce 2 VBF categories
    - expected to improve sensitivity by 10 %

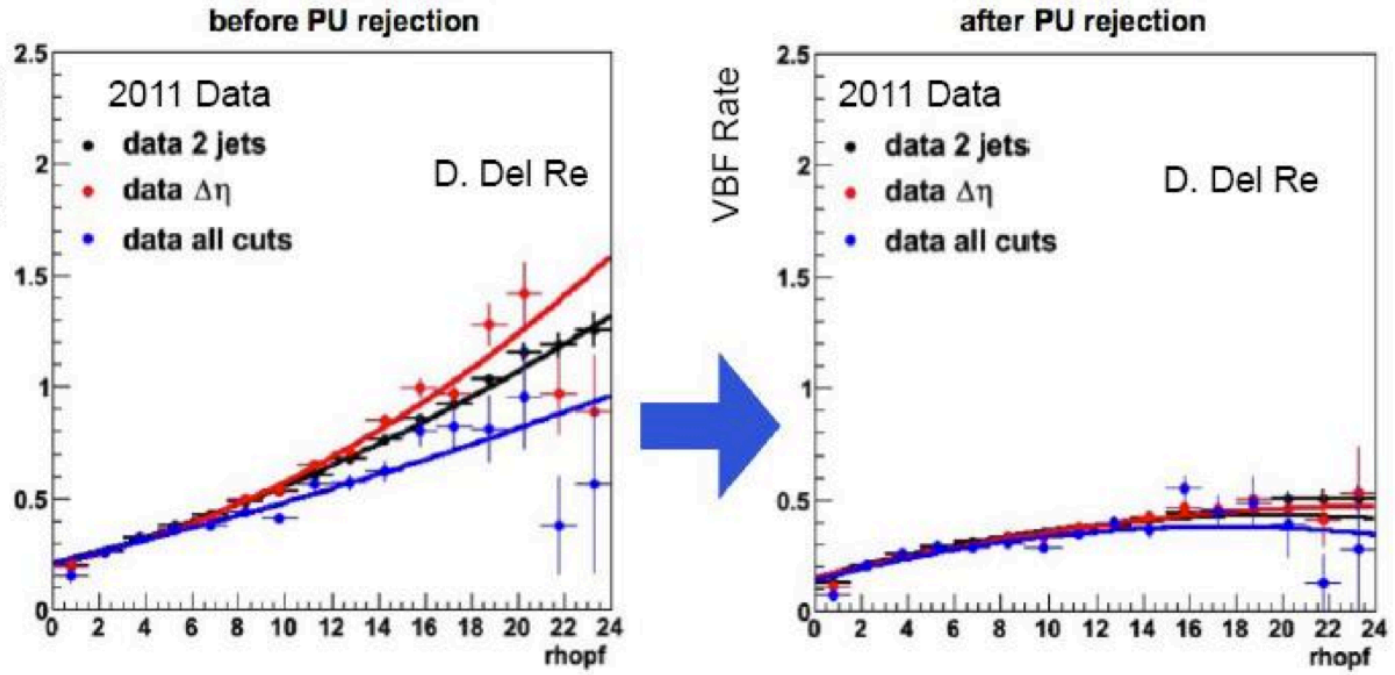
Variable	cut VBF	category 1	category 2
$p_T^{\gamma_1}/m_{\gamma\gamma}$	$> 55/120$ GeV	$> 60/120$ GeV	$> 60/120$ GeV
$p_T^{\gamma_2}$	> 25 GeV	> 25 GeV	> 25 GeV
p_T^{j1}	> 30 GeV	> 30 GeV	> 30 GeV
p_T^{j2}	> 20 GeV	> 30 GeV	> 20 GeV
$\lvert\Delta\eta_{j_1 j_2}\rvert$	> 3.5	> 3.0	> 3.0
$\lvert Z\rvert$	< 2.5	< 2.5	< 2.5
$M_{j_1 j_2}$	> 350 GeV	> 500 GeV/c^2	> 250 GeV/c^2
$\lvert\Delta\phi(\mathrm{jj}, \gamma\gamma)\rvert$	> 2.6	> 2.6	> 2.6

Dijet tag background in 2012

- Effect comes from PU Jets
  - Mitigated with new Jet ID
- Cut based approach
  - The same as SM [HIG-12-015]

Loose WP with jetID eff > 95%

jetη	β^*	RMS
$\eta < 2.5$	$< 0.2 \log(N_{vtx} - 0.64)$	< 0.06
$2.5 < \eta < 2.75$	$< 0.3 \log(N_{vtx} - 0.64)$	< 0.05
$2.75 < \eta < 3$	-	< 0.05
$3 < \eta < 4.7$	-	< 0.055



Lepton tag – event selection

- ID's updated for 2012
  - new photon ID
  - new lepton ID
- Cross section of WH, ZH are comparable with VBF but pay price for subdecay BR:
  - B(Z->ll) ~7%, B(W->lv) ~ 20%
- Require at least one isolated lepton
  - electron-tag: $|\eta_e| < 2.5$, pTe > 20 GeV
  - muon-tag: $|\eta_\mu| < 2.4$, pTμ > 20 GeV
  - minimal R separation from photons
  - minimal separation m(e, γ) from Z0 (electron tag)
- Consider 2 classes: electron and muon
- Low background rate
  - suppress standard QCD backgrounds;
  - predominant background is EWK, W/Z+γ-like

Lepton tag – data and bkg MC yields

For 100 < m < 160

Bkg. sample	electron-tag	muon-tag
$W(l\nu)\gamma$	0	0.12
$Z\gamma$	4.2	0.12
VV	0.04	0.12
$\gamma\gamma$+jets	0.09	0.03
$W^{\pm}\gamma\gamma$	0.41	0.85
$Z\gamma\gamma$	0.45	0.48
$t\bar{t}\gamma\gamma$	0.026	0.022
Reducible	4.31	0.65
Irreducible	0.89	1.35
Total MC	5.2	2.0
Data	19	8

- Model background from data
- Use MC to cross check
  - In 2011 the yields were smaller so we used bkg MC and Control Sample to derive bkg shape, and normalize it to data.
  - In 2012 we derive bkg shape from data from fits of power law function, and normalize to data.

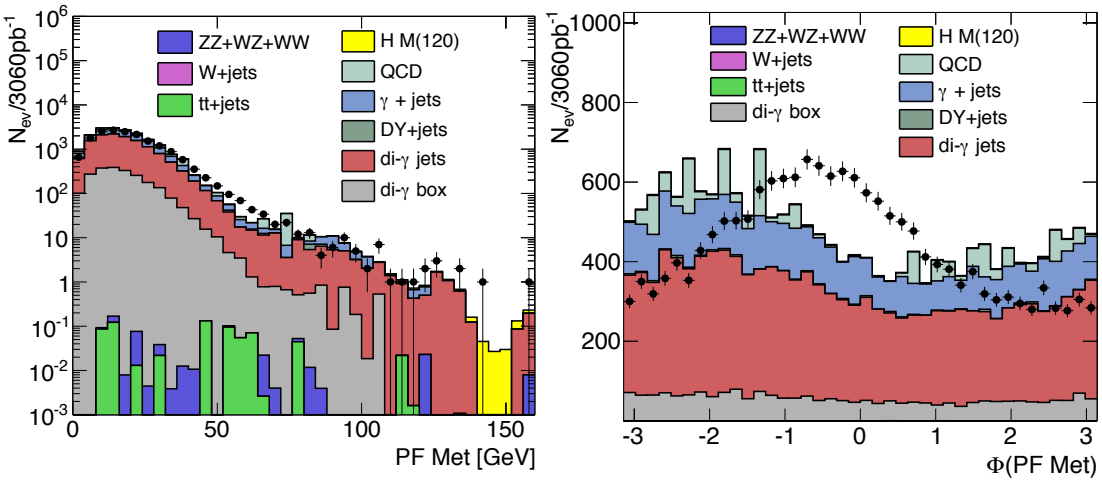
PFMET correction

- Use recommendation of JetMET Group, PFMET

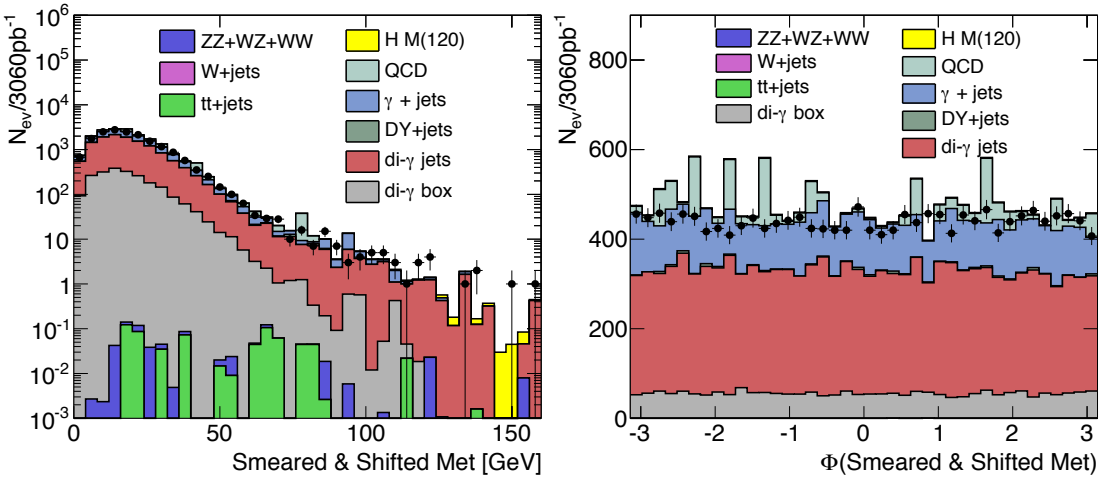
- Measured MET is driven by
  - detector noise
  - imperfection of jet energy reconstruction
  - mis-alignment of the subdetectors

- 3 steps of correction
  1. PFMET smearing (MC)
  2. PFMET shifting
  3. jet response scaling (Data)

Before correction

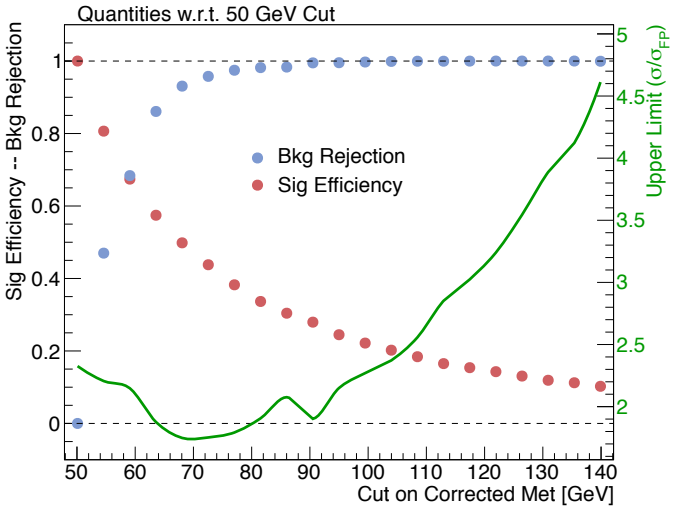


After correction

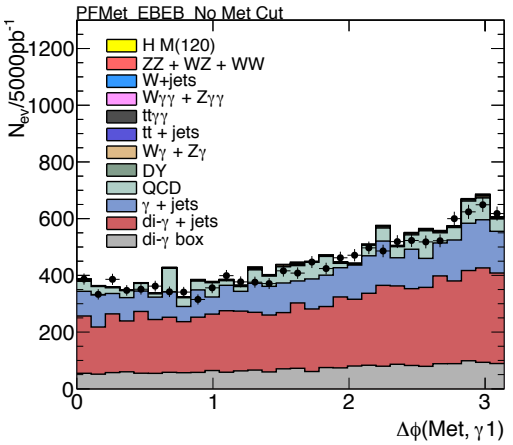


MET tag – event selection

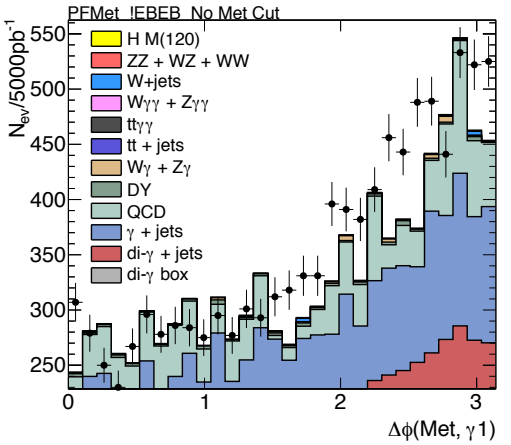
- Two isolated photons + MET
  - $p_T(\gamma_1)/m_{\gamma\gamma} > 45/120$ GeV
    $p_T(\gamma_2) > 25$ GeV
- Only EBEB photon pairs
  - issue with MET if PFPho in EE
  - for now drop EE, as most of signal is from EBEB
- PFMET>70 GeV



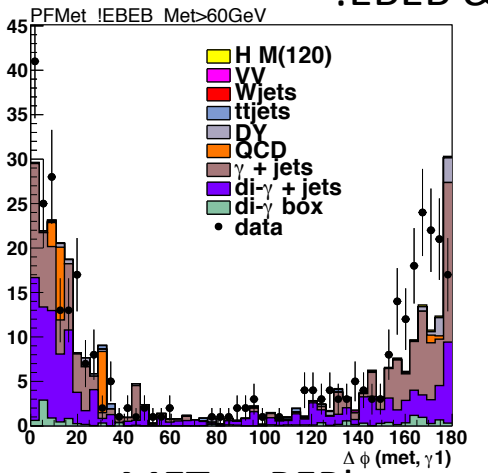
EBEB & MET>0



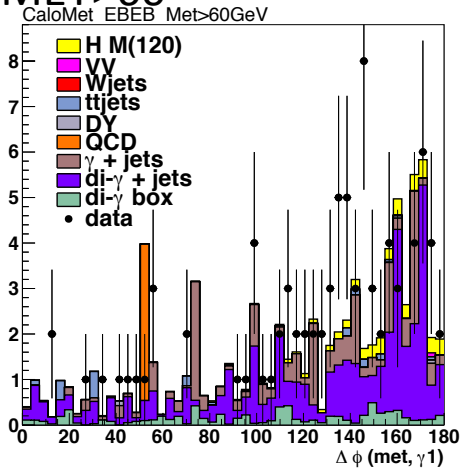
!EBEB & MET>0



!EBEB & MET>60



MET w PFPho



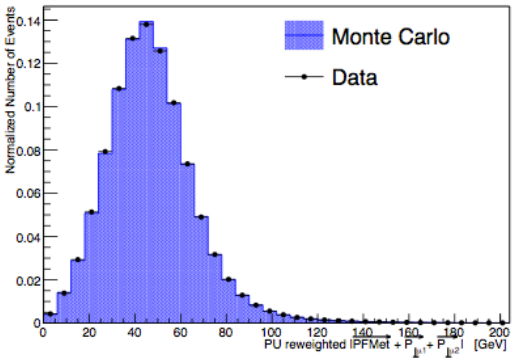
MET w Calo Pho

MET cut scale factor and uncertainty

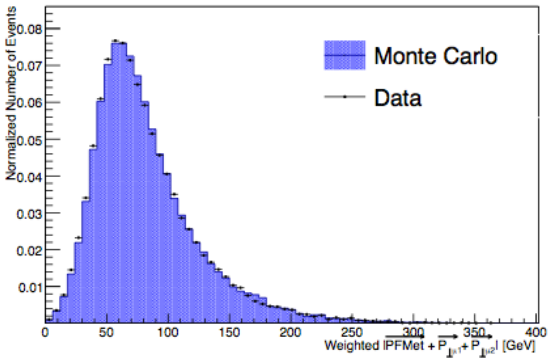
- Control sample (CS) Use Z-> μμ process to mimic Higgs process; treat two muons as neutrinos
- Construct $\overrightarrow{PFMet} + \overrightarrow{pt_{\mu 1}} + \overrightarrow{pt_{\mu 2}}$
- Compute scale factor (SF) = ε(Data) / ε(MC) and uncertainty

Reweight CS events in 2D (pT, η) to ZH signal MC before obtaining SF

SF (MET=70GeV) ≈ 0.958±0.003. Assign as conservative systematic.



(a) Before Z kinematic reweighting



(b) After Z kinematic reweighting

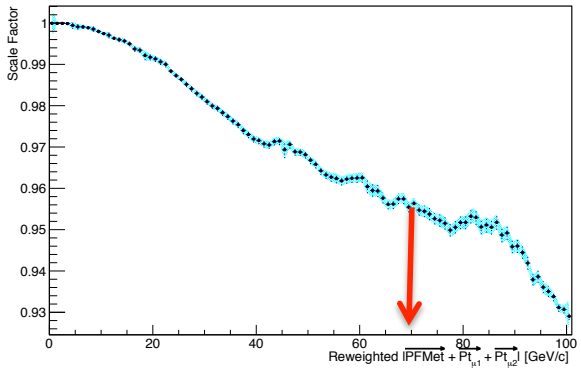


Figure 38: Missing Transverse Energy distribution in $Z \to \mu\mu$ data and Monte Carlo sample before and after the Z kinematic reweighting

Systematics

Source		Uncertainty	
Photon identification efficiency:	barrel	1.0%	
	endcap	2.6%	
R_9 >0.94 efficiency	barrel	4%	
(results in class migration)	endcap	6.5%	
		$R_9 > 0.94$	$R_9 < 0.94$
Energy resolution ($\Delta\sigma/E_{MC}$):	barrel low η, high η	0.22%, 0.61%	0.24%, 0.59%
	endcap low η, high η	0.91%, 0.34%	0.30%, 0.53%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	barrel low η, high η	0.19%, 0.71%	0.13%, 0.51%
	endcap low η, high η	0.88%, 0.19%	0.18%, 0.28%
Integrated luminosity		2.2% , 5% (2012)	
Trigger efficiency: One or more photons $R_9 < 0.94$ in endcap		0.4%	
	Other events	0.1%	
Vertex finding efficiency		0.4%	
Dijet tagging efficiency (VBF process)		10%	
Charged lepton identification efficiency:		1.0%	
2D Signal Model		1%	
Vector boson fusion process cross section (scale)		+0.5% -0.3%	
Vector boson fusion process cross section (PDF)		+2.7% -2.1%	
Associated production with W/Z cross section (scale)		+1.8% -1.8%	
Associated production with W/Z cross section (PDF)		+4.2% -4.2%	
$H \to \gamma\gamma$ BR in the FP model		5%	

MET tag 5%

DRAFT

Likelihood Model

- Extended likelihood function based on sum of PDFs for the signal and bkg shapes

$$L(\omega|\vec{\theta}) = \frac{e^{-(rN_s+N_b)}(rN_s + N_b)^N}{N!}\prod_{i=1}^{N}(rN_s P_s^i(\omega|\vec{\theta}_s) + N_b P_b^i(\omega|\vec{\theta}_b))$$

$$\omega \equiv \{m_{\gamma\gamma}, p_T, \ldots\}$$

where is a set of physical observables, P_s and P_b are signal and background probability density functions (PDF) for observables , and θ_s and θ_b are sets of shape parameters which defi

$$P^i = M^i(m_{\gamma\gamma}|\pi_T^{\gamma\gamma}) \times K^i(\pi_T^{\gamma\gamma})$$

- In case of two physical observables (e.g. $m_{\gamma\gamma}$, π_T), PDFs for signal and background are 2-D, and can be expressed as

$$P^i = M^i(m_{\gamma\gamma}) \times K^i(\pi_T^{\gamma\gamma})$$

where the correlation between two observables is taken into account.
In the case

$$P^i = \prod_{k=1}^{K} M^{i,k}(m_{\gamma\gamma}|\pi_T^{\gamma\gamma}) \times K^{i,k}(\pi_T^{\gamma\gamma})$$

es to a simple product of

Background Modeling Mass

$$P_b^i = M_b^i(m_{\gamma\gamma} \mid \pi_T^{\gamma\gamma}) \times K_b^i(\pi_T^{\gamma\gamma})$$

- Different models were tested for 2-D approach to account for correlation
  - 1 power with quadratic correlation to π_T.

$$M_b^i(m_{\gamma\gamma}, \pi_T^{\gamma\gamma} \mid a_0, a_1, a_2) = m^{a_0 + a_1\pi_T + a_2\pi_T^2}$$

  - 1 power with linear correlation to π_T

$$M_b^i(m_{\gamma\gamma}, \pi_T^{\gamma\gamma} \mid a_0, a_1) = m^{a_0 + a_1\pi_T}$$

  - 1 power factorized

$$M_b^i(m_{\gamma\gamma} \mid a_0) = m^{a_0}$$

  - 4th order polynomial factorized

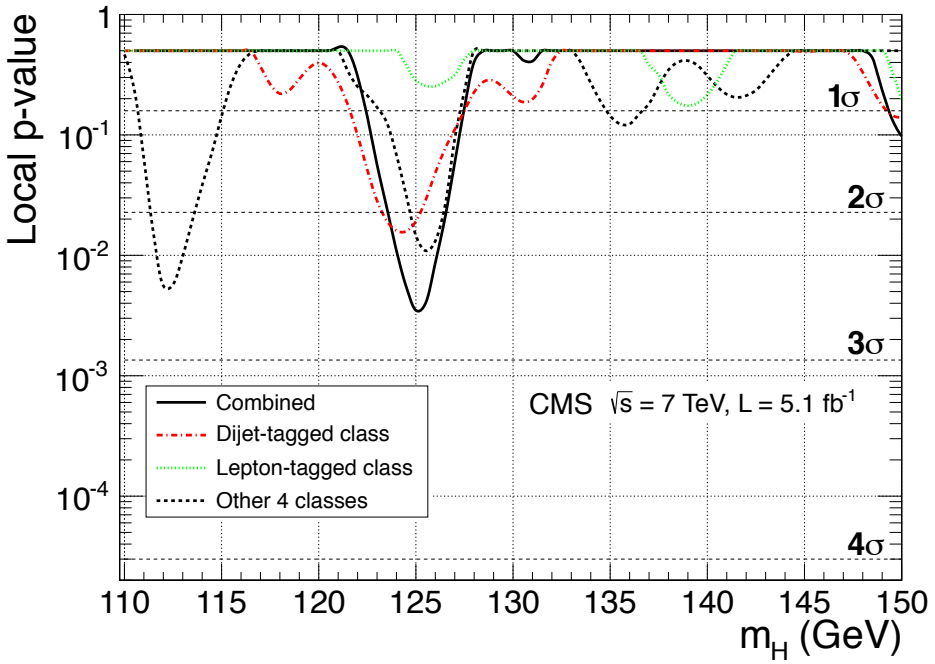
$$M_b^i(m_{\gamma\gamma} \mid b_1, b_2, b_3, b_4) = \mathrm{Bern}(m, b_1, b_2, b_3, b_4)$$

- Proceed to **do a real 2-D fit and include linear correlation (m, π_T) in the model of mass**.

2011, 2012 p-value

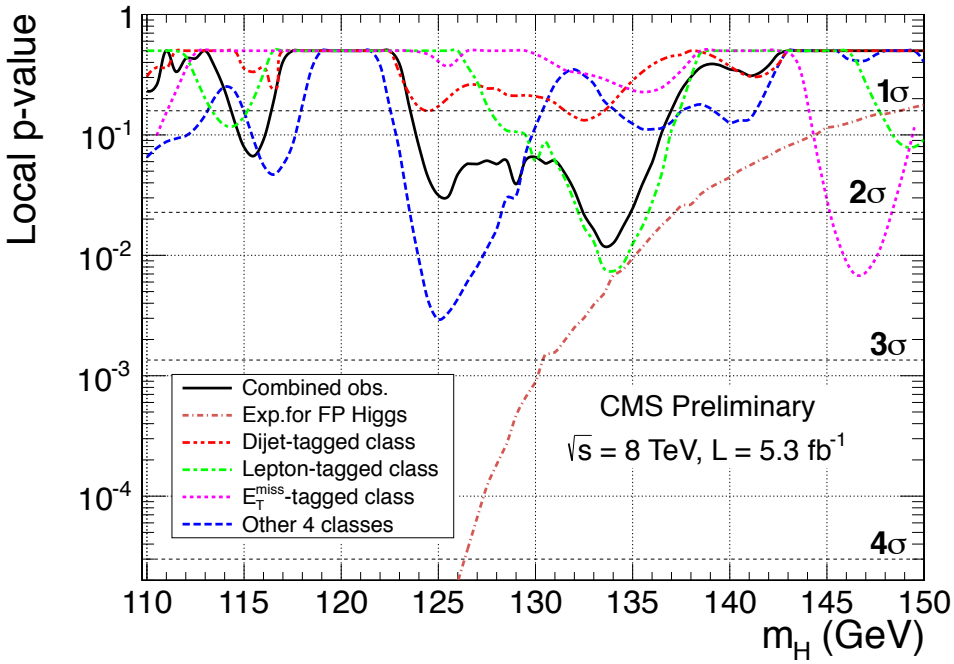
Added MET tag

7 TeV 2011



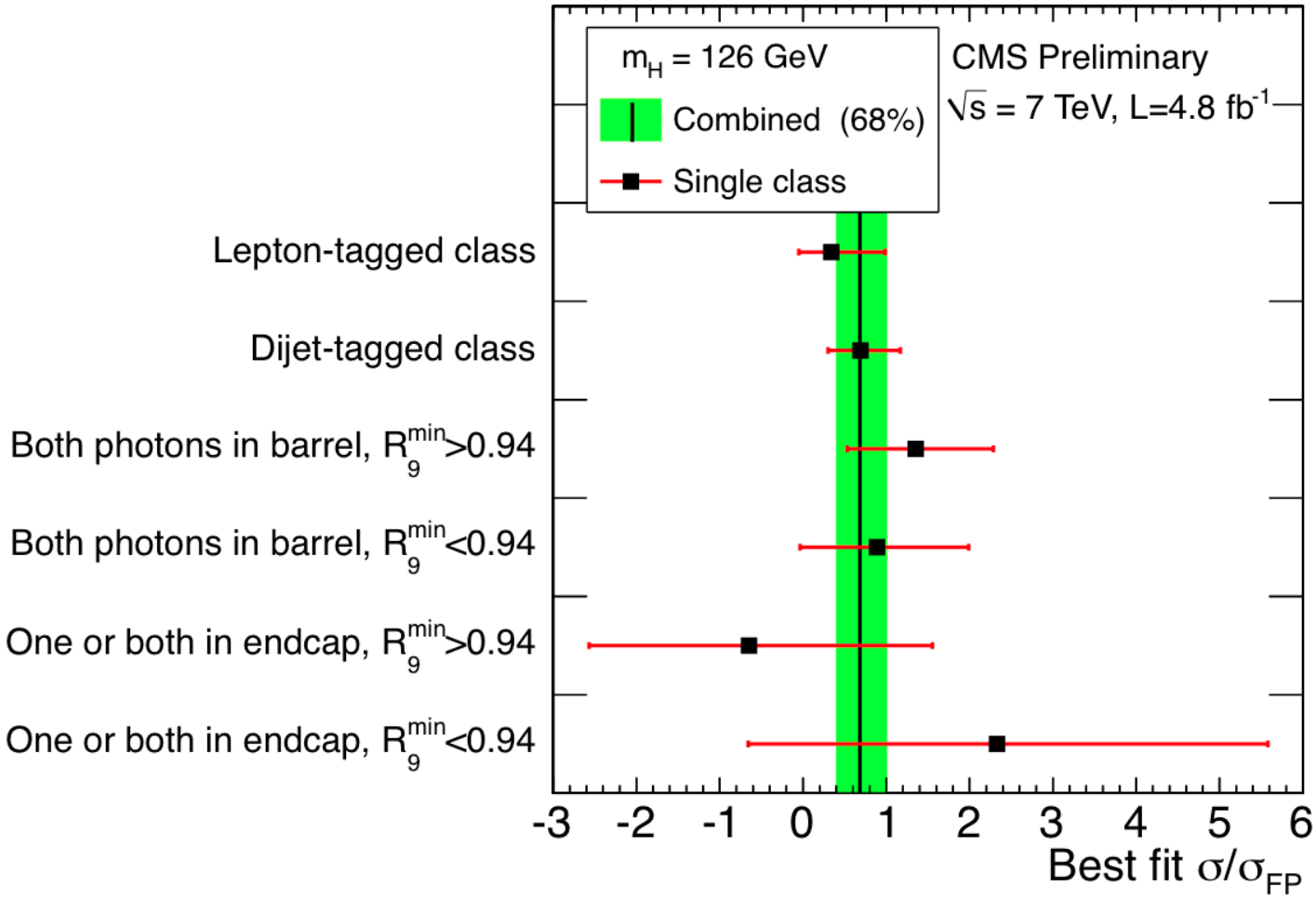
HIG-12-009

8 TeV 2012



HIG-12-022

Best Fit per sub-channel with 7 TeV data

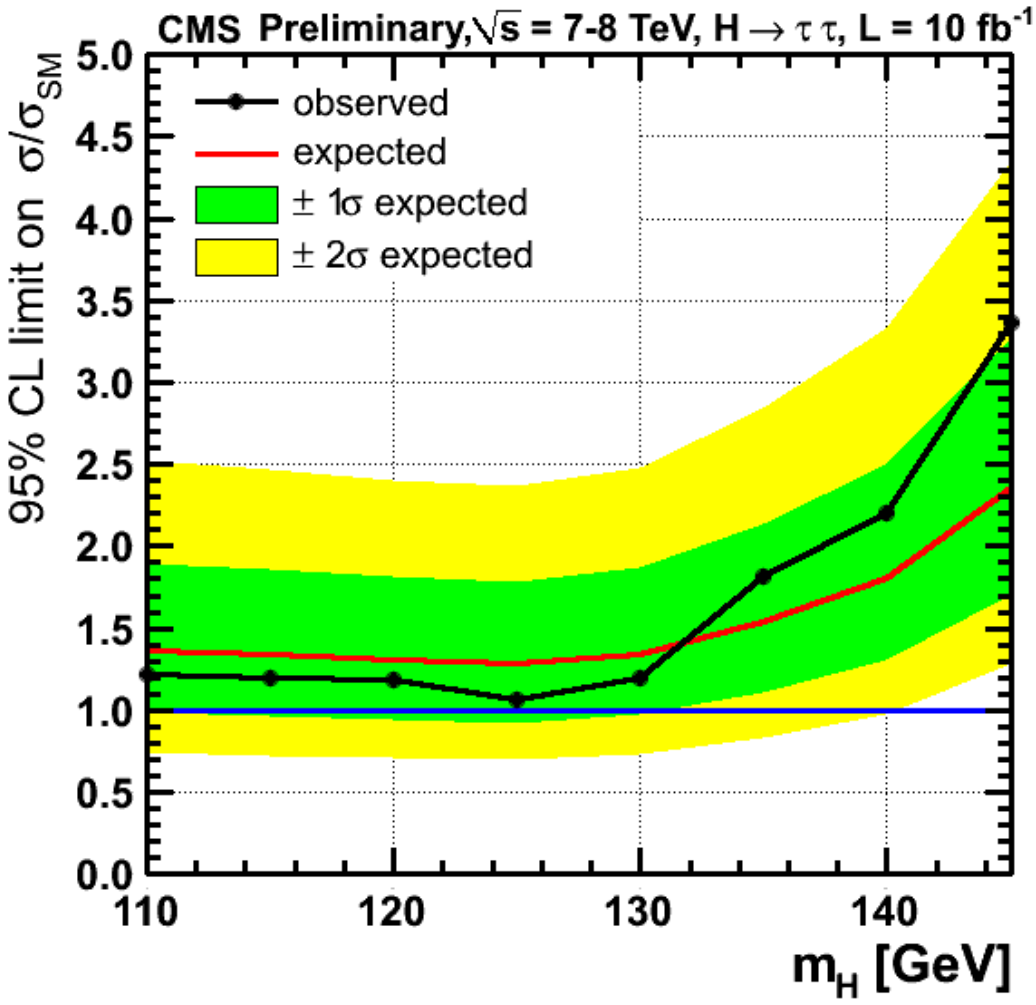


MSSM Higgs Phenomenology

- At Born level Higgs sector of MSSM described by 2 Parameters: M_A, tan β

$$M^2_{H^+} = M^2_A + M^2_W$$

$$M^2_{h/H} = \frac{1}{2}\left(M^2_A + M^2_Z \mp \sqrt{(M^2_A + M^2_Z)^2 - 4M^2_A M^2_Z \cos^2 2\beta} \right)$$

$$\alpha = \frac{1}{2}\arctan(\tan 2\beta \frac{M^2_A + M^2_Z}{M^2_A - M^2_Z})$$

Limit on SM H →ττ