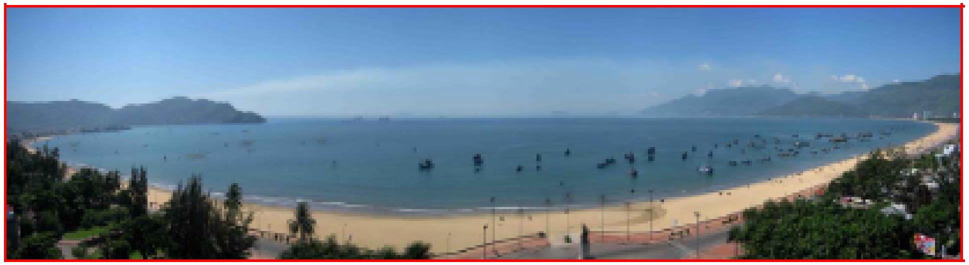
RENCONTRES DU VIETNAM



International Conference:

Beyond the standard model in particle physics

Quy Nhon, Vietnam 15-21 July 2012

Topics

Higgs boson physics
Top Physics
Heavy Flavors
Neutrinos
Supersymmetry
Dark matter
Extra dimensions
Technicolor and strong dynamics

Web site: http://confs.obspm.fr/RencontresVietnam/BTSM/index.htm

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Secretariat

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Qui Nhon is a coastal town in Center Vietnam. It is about one hour flight from Ho Chi Minh City and one hour and a haft from Hanoi. Qui nhon has an university for more than 50 years with 30 000 students with majors in science.

BSM Higgs Searches with CMS Experiment

Maxim Titov, CEA Saclay, France

On behalf of the

CMS

COLLABORATION

15-21 July 2012, Quy Nhon, Vietnam

Beyond the Standard Model Higgs: Outline of the Talk

There are many possibilities that change the precise predictions of the minimal Higgs sector (higgs doublet field) of the Standard Model

- **2 Higgs Doublet Model (2 HDM):**

3 neutral and 2 charged higgs Bosons

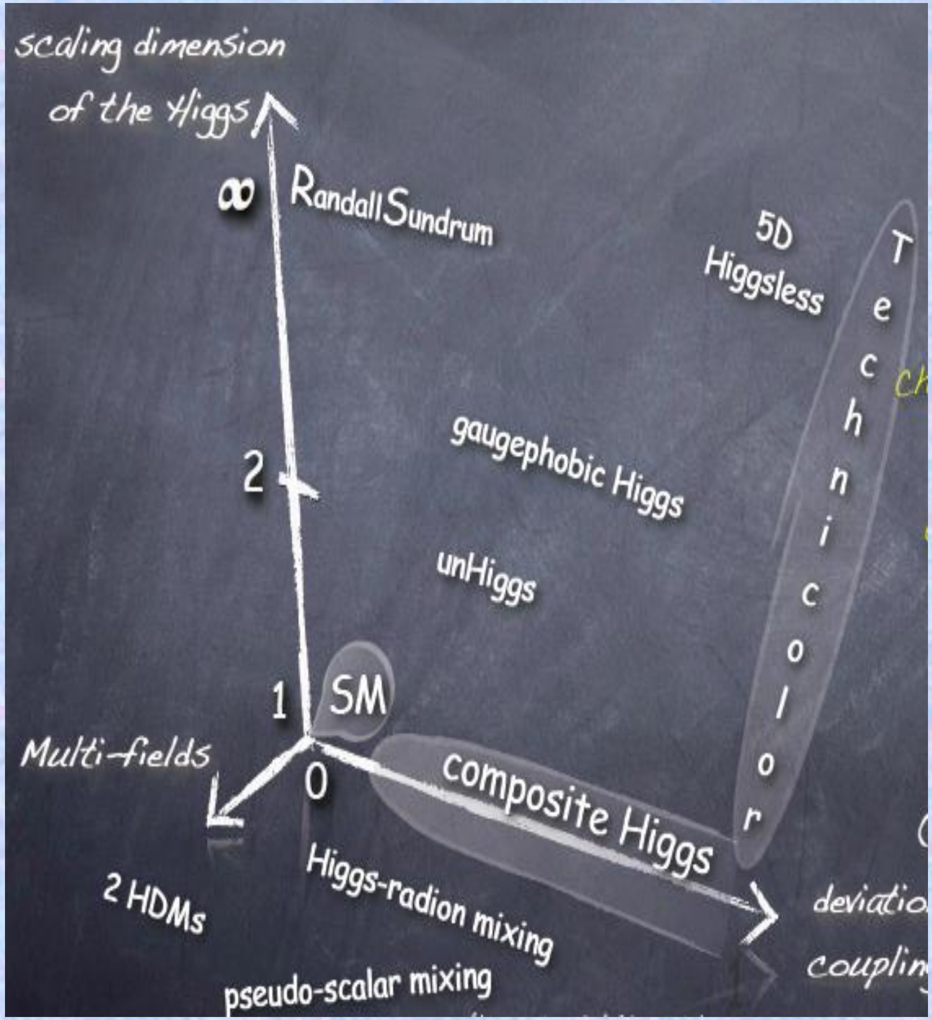
→ Minimal Supersymmetric Model (MSSM) requires 2HDM

- **Neutral Higgs boson: $\phi \rightarrow \tau\tau$, bb, $\mu\mu$**
- **Charged Higgs boson: $H^{+} \rightarrow \tau\nu$**

- **Higgs in Next-to-MSSM (nMSSM):**
  - **A very light CP-odd scalar boson $a_1 \rightarrow \mu\mu$**

- **Higgs in Exotic Models:**
  - **Doubly charged Higgs $\Phi^{++} \rightarrow l^{+}l^{+}$ (type-II See-Saw like models)**

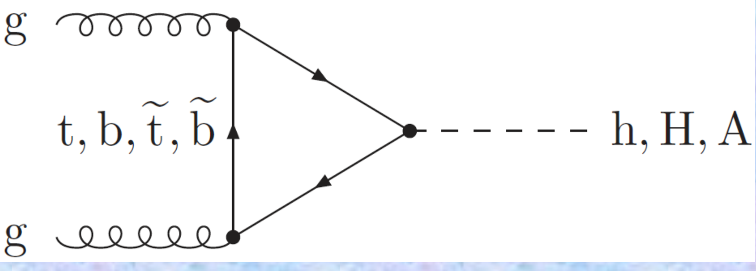
- **Extensions to the Standard Model:**
  - **Fermiophobic Higgs (changes low mass Higgs production and decays dramatically)**



There is now strong evidence for a Higgs-like sector → I will present CMS searches for potential Higgs bosons beyond the Standard Model

MSSM Neutral Higgs Bosons: φ(h, H, A)

Main production mechanisms:
h, H (CP-even, scalars)
A (CP-odd, pseudoscalar)



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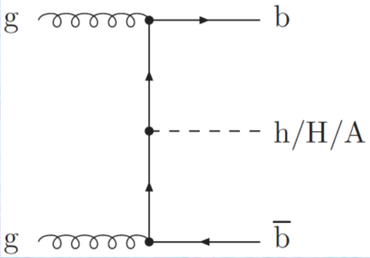
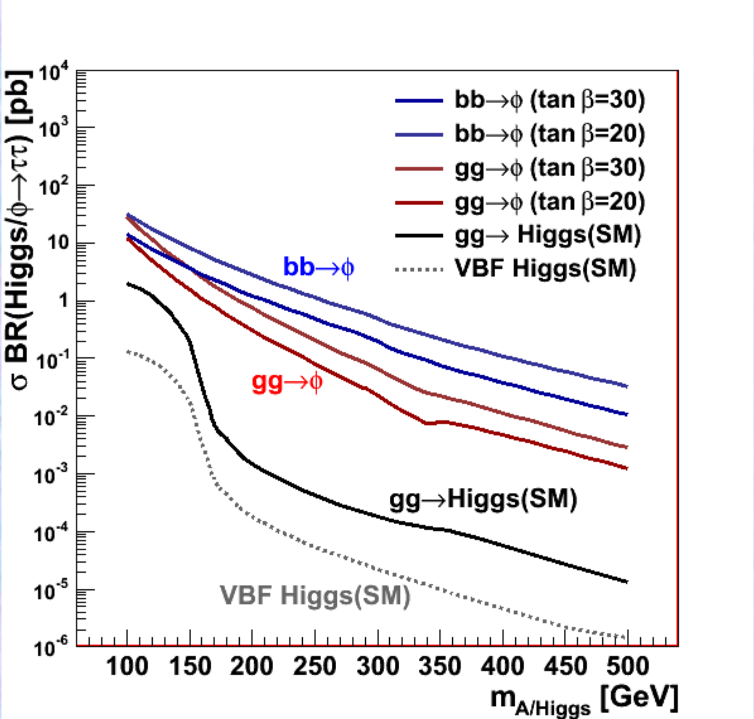
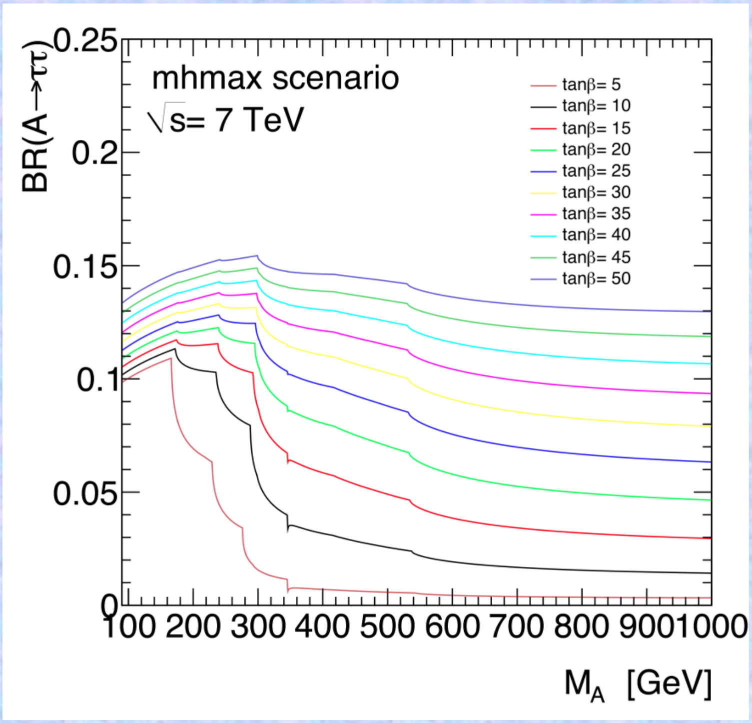


- **Production via gluon fusion (b, t loops) and associated b-quark annihillation**
- **Enhanced coupling to b-quarks and τ-leptons ($g^{MSSM}_{b\bar{b}H} = \tan\beta \cdot g^{SM}_{b\bar{b}H}$ → production rate enhanced × $\tan^2\beta$), b-associated production becomes dominant**
- **CMS searches in decays into b-bbar (90%), ττ (10%), μμ (0.04%)**





φ (h, A, H)→ bb Event Selection

Analysis Strategy:

$pp \rightarrow \varphi b, \varphi \rightarrow bb$

- Semileptonic b decays (jet containing a muon)
- Hadronic b decays

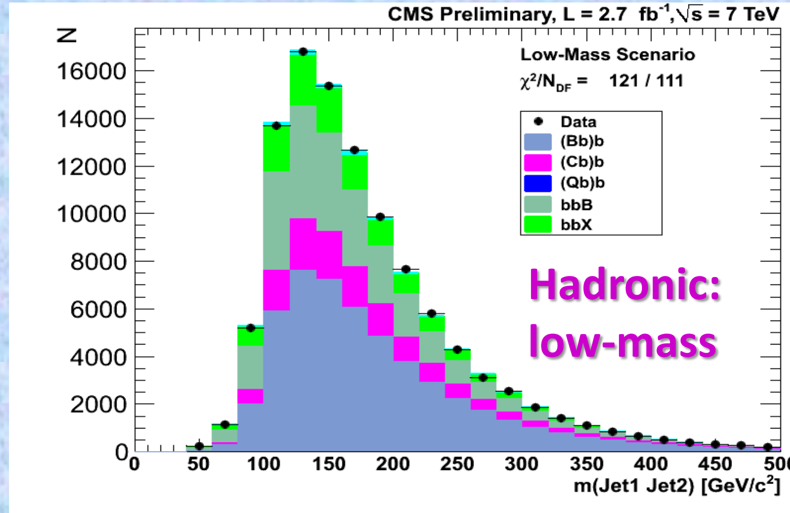
	Semileptonic	Hadronic
➢ **Trigger :**	Muon+1/2 Jets ≥ 1/2 b-tagged	2/3 Jets ≥ 2 b-tagged
➢ **Lepton (Muon):**	P_T > 15 GeV (no Isolation applied)	
➢ **Jets:**	≥ 2 Jets of P_T > 30 GeV + 3rd Jet of P_T > 20 GeV $\lvert\eta\rvert$(jets) < 2.6, all 3 b-tagged Muon is within one of two leading jets	≥ 3 Jets: P_T 1st > 46 (60)* GeV P_T 2nd > 38 (53)* GeV P_T 3rd > 20 GeV $\lvert\eta\rvert$(jets) < 2.2 all 3 b-tagged

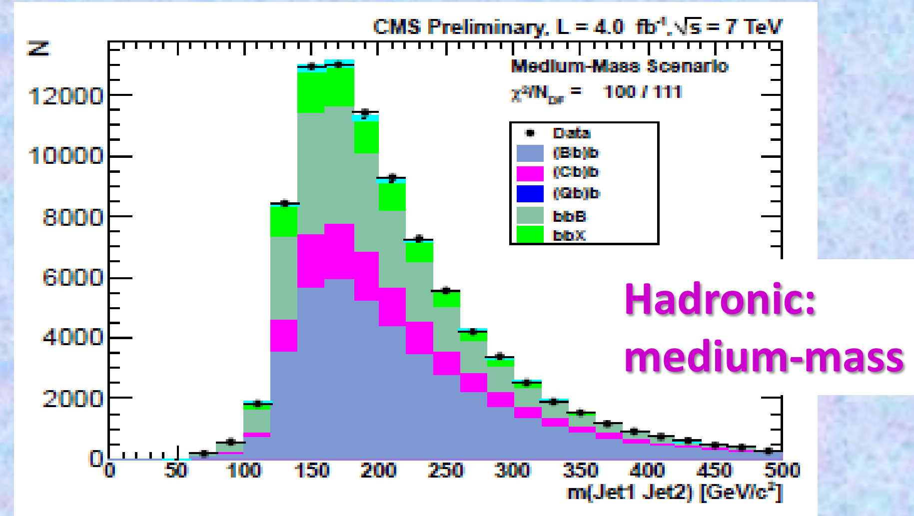
The major background, QCD, is estimated from data. The other backgrounds, ttbar and Z(bb)+jets are taken from MC.

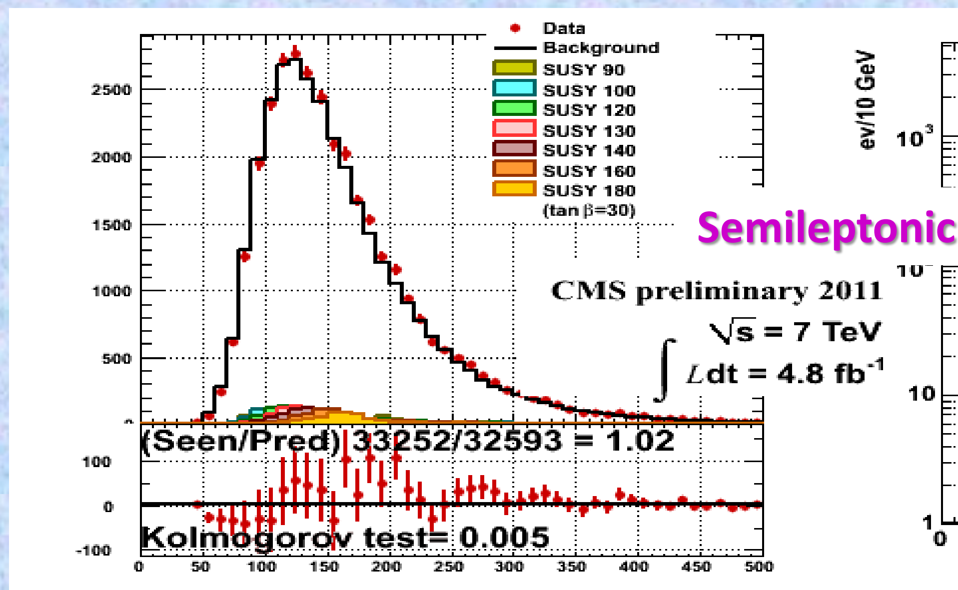
*Jet P_T Threshold depends on Higgs Mass hypothesis: lower (higher) Thresholds used for $M\varphi$ < 180 GeV ($M\varphi$ > 180 GeV), driven by Trigger Thresholds

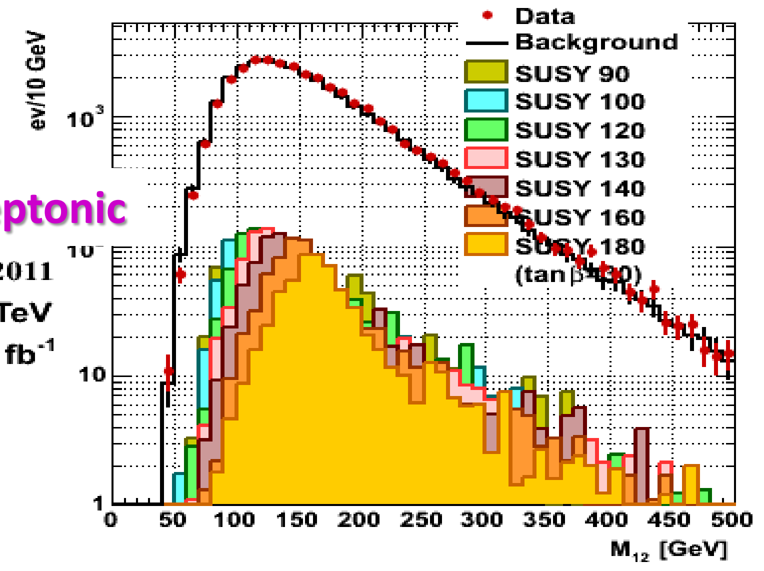
Search for φ (h, H, A) → bb: Dijet Mass Distribution

A significant excess in the di-jet mass distribution (M_{12}) of the two leading jets could be an evidence of a signal → data in agreement with background prediction (M_{12} resolution ~ 15%)





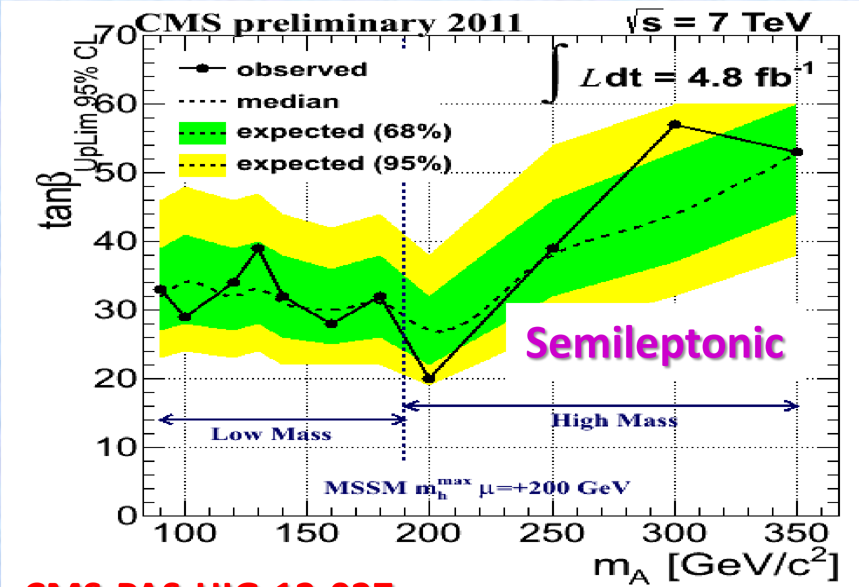


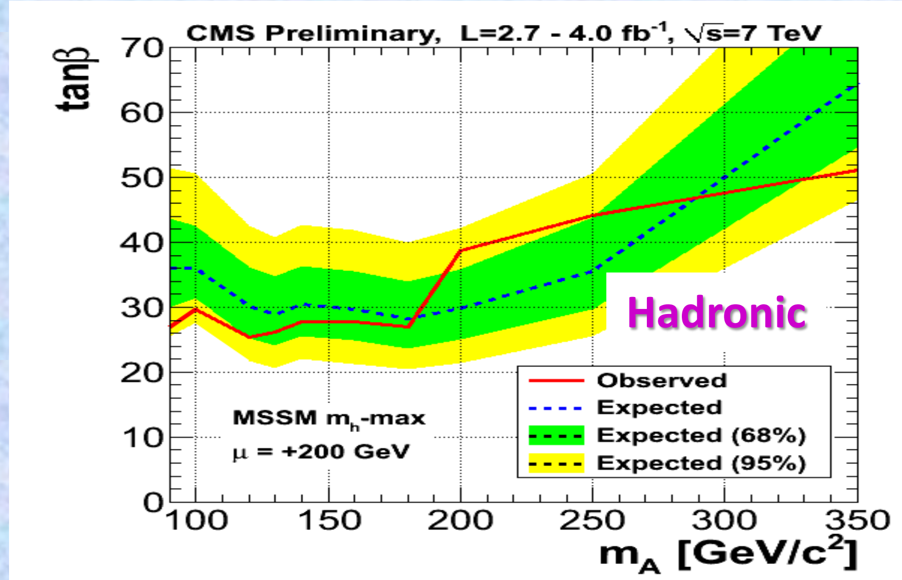


φ (h, H, A) → bb Exclusion Limit

- Set Upper Limit on pp → φb, φ→bb production by fitting observed M_{12} distribution.

  (Non-observation of φ →bb signal excludes region of large tanβ in MSSM Space)





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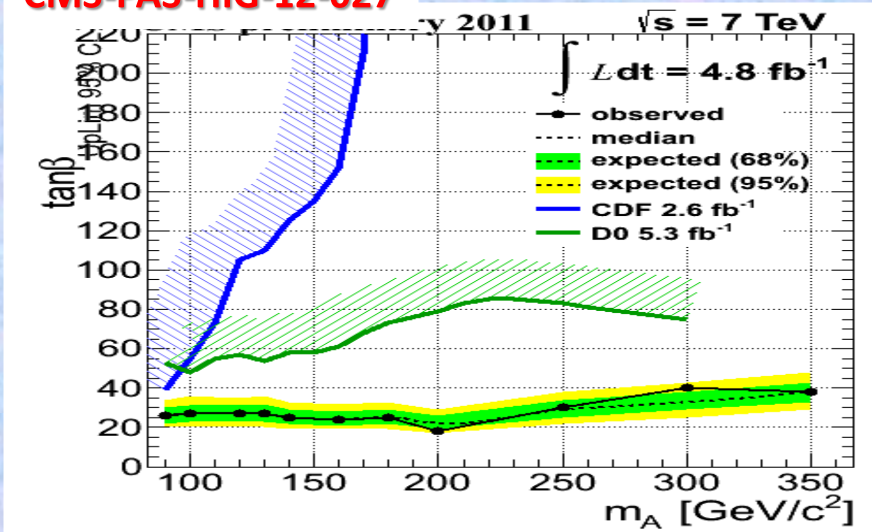

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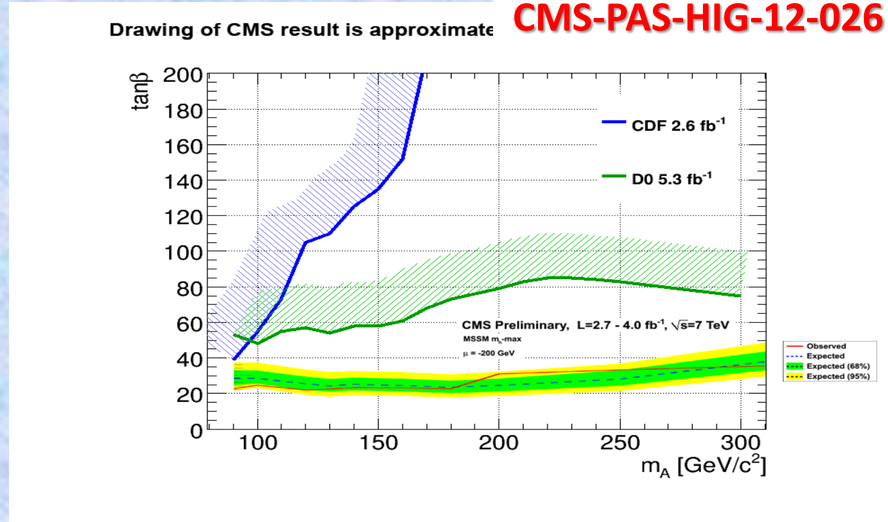


φ (h, H, A) → $\tau\tau$ Event Selection

Analysis Strategy:

$\varphi \rightarrow \tau\tau$ Signal searched for in 3 τ-decay channels:

$e+\mu$; $e+\tau_{had}$; $\mu+\tau_{had}$

τ_{had}: Particles produced in hadronic τ decay

Similar to SM H→ $\tau\tau$ search, but with b-tagged/no b-tag selection

- **Trigger:**

Events triggered by $e+\mu$, $e+\tau_{had}$ and $\mu+\tau_{had}$ Triggers, P_T thresholds 10-20 GeV/c

- **Leptons:**

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

- **Opposite Charge Lepton Pair**

- **Veto Events with additional isolated Leptons**

- **Large probability for having a b-jet in the central regions → select events in 2 Categories: non-b-Tag and b-Tag**
  - ❑ b-Tag : ≤ 1 jet with pT > 30 GeV, ≥ 1 b-Tagged Jet with pT > 20 GeV
  - ❑ Non b-Tag : ≤ 1 jet with pT > 30 GeV, No b-Tagged Jet with pT > 20 GeV

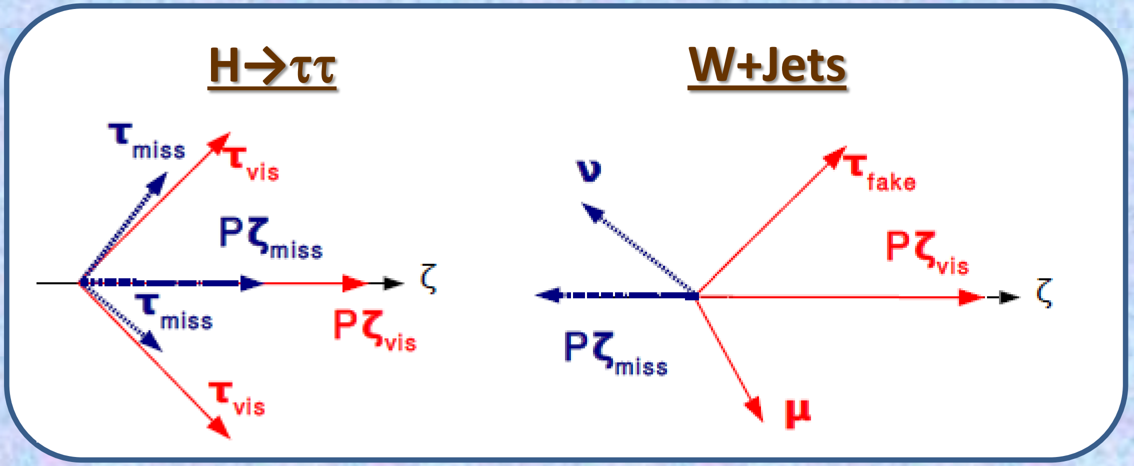
Search for φ → ττ: Background Estimation and Suppression

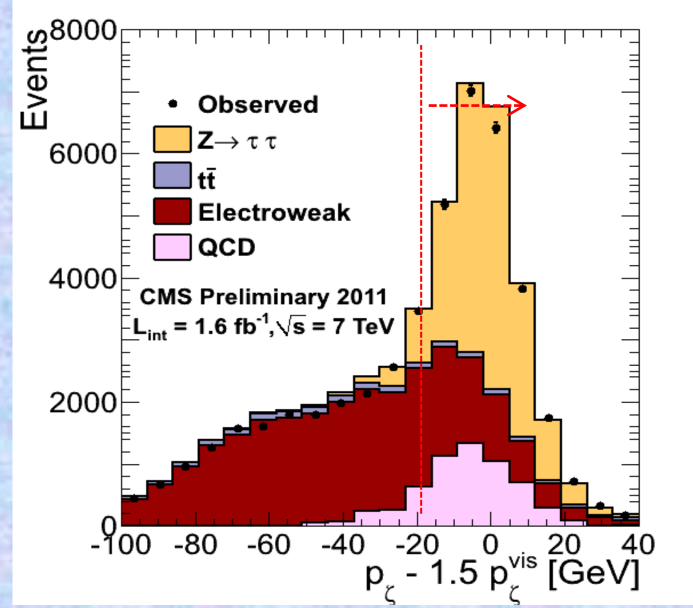
Major backgrounds : Z → ττ, Z → ee, μμ, QCD, W+Jets, ttbar, diboson.

- **Z→ττ :** Use observed Z→μμ sample and replace muon by simulated tau ("embedding"). Normalized to the measured Z→μμ cross section.
- **QCD :** Estimated from SS/OS data.
- **W+jets :** Shape from MC and normalization from P_ζ sideband.
- **Top pair, Di-boson:** MC

Taus, in signal, are produced with large pT
→ neutrinos produced in the tau decay are collinear with the visible products.
Requiring E_T^{miss} to point in the direction of visible decay products
→ suppress W+jets and top backgrounds.

$$P_\zeta^{vis} = p_{T,1}\cdot\zeta + p_{T,2}\cdot\zeta$$
$$P_\zeta = P_\zeta^{vis} + E_T^{miss}\cdot\zeta$$

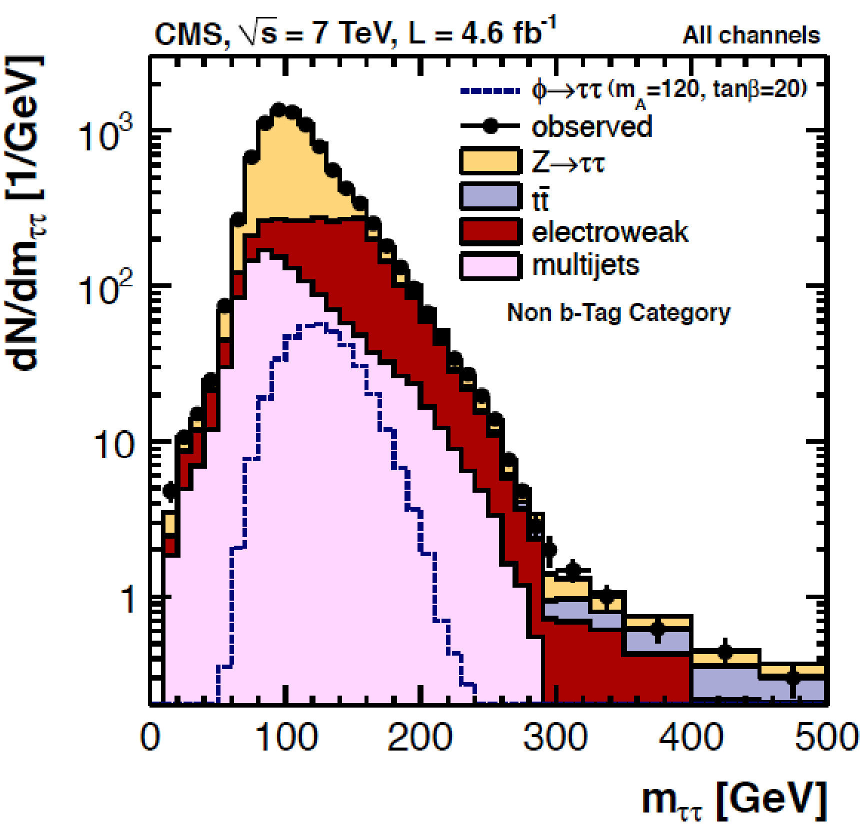


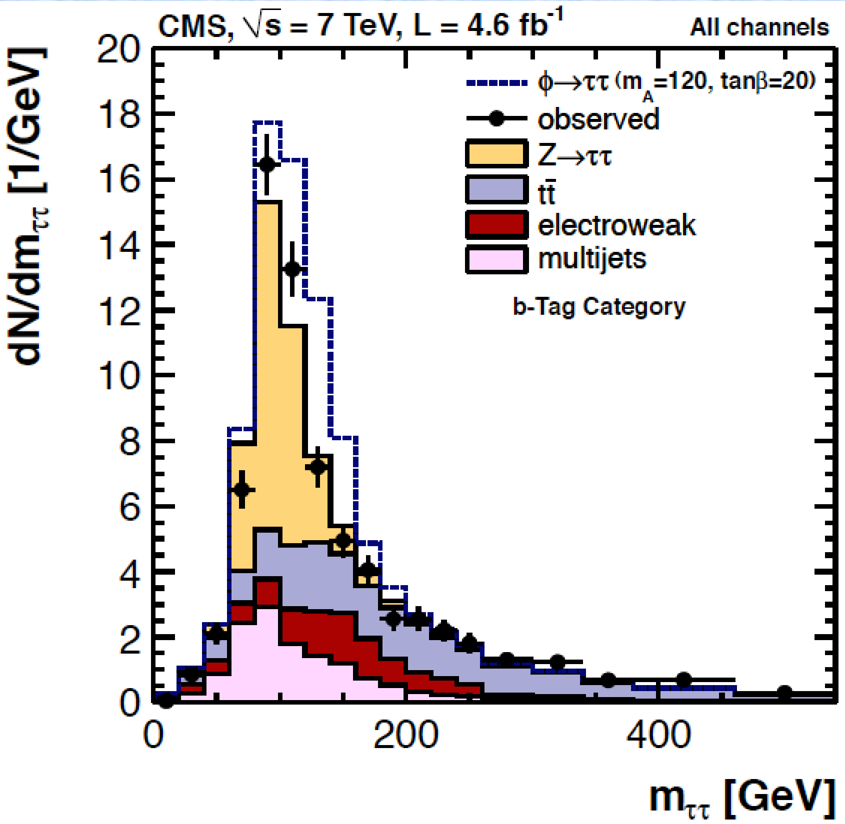


ττ mass Reconstruction

Mass of τ Lepton pair reconstructed via Likelihood technique, based on:

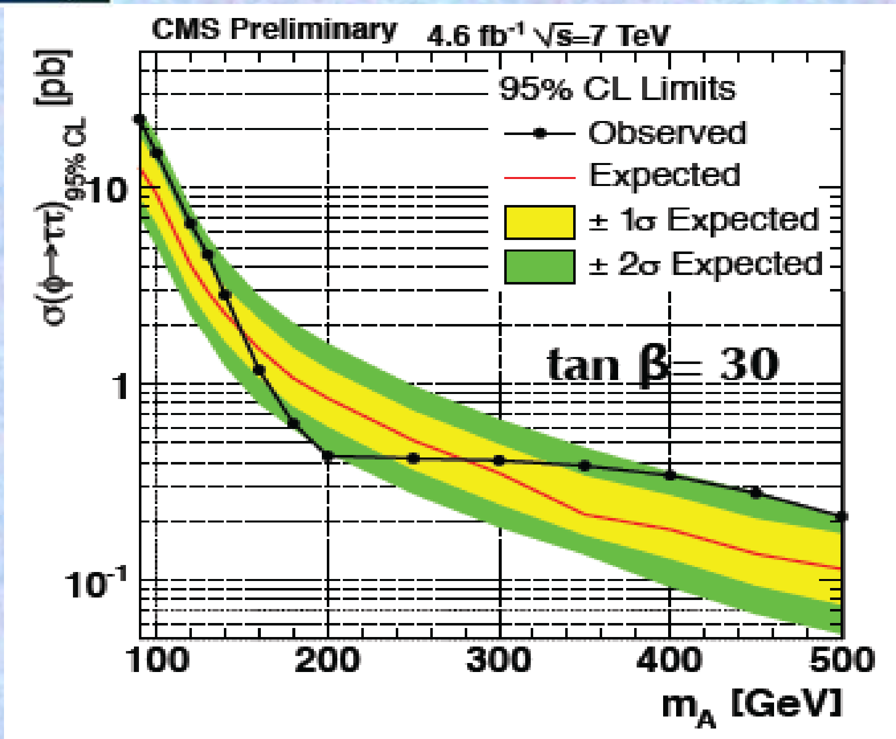
- **τ-decay Kinematics**
- **Kinematic Fit to improve mass resolution (compatibility of reconstructed E_T^{miss} with neutrino hypotheses) → δm(ττ)/m(ττ) ~20% (25% without KF)**





→Distribution observed in Data in Agreement with Background Expectation

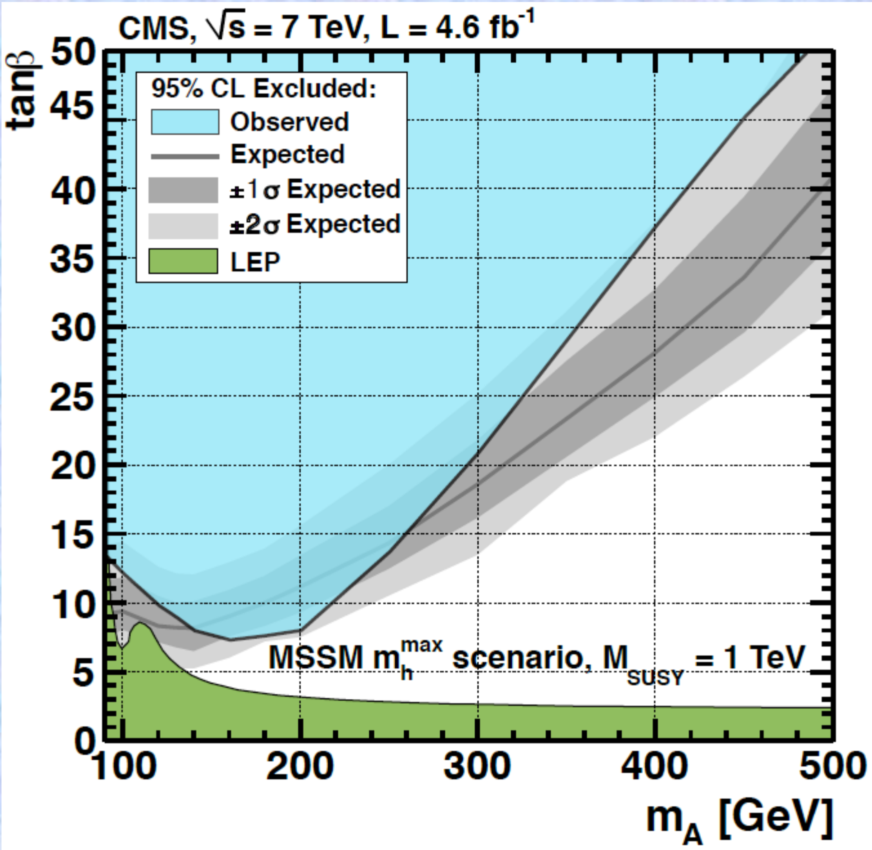
MSSM: φ (h, H, A) → ττ Exclusion Limit



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

CMS-PAS-HIG-11-029
arXiv: hep-ex/1202.4083



MSSM Limits obtained for:

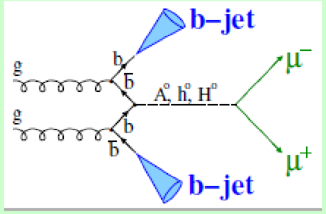
- M^{SUSY} = 1 TeV
- Stop mixing parameter $X_t = 2M_{SUSY}$
- Higgsino mass μ = 200 GeV
- Gluino mass M_g = 800 GeV
- Stop and sbottom trilinear couplings $A_b = A_t$

φ (h, H, A) → μμ Exclusion Limit

- Br($\phi \rightarrow \mu\mu$) ~ 0.04% is small, but →clean signature, tan β can be extracted from the signal mass $M_{A0} = M_{\mu+\mu-}$ and its width ($\Gamma_{\mu+\mu-}$)

Analysis Strategy:

- **Trigger:**
Single Muon



- **Lepton (Muon):**
>= 2 Muons
P_{T1} > 30 GeV, P_{T2} > 20 GeV
|η| < 2.1, isolated

- **Opposite Charge Lepton Pair**

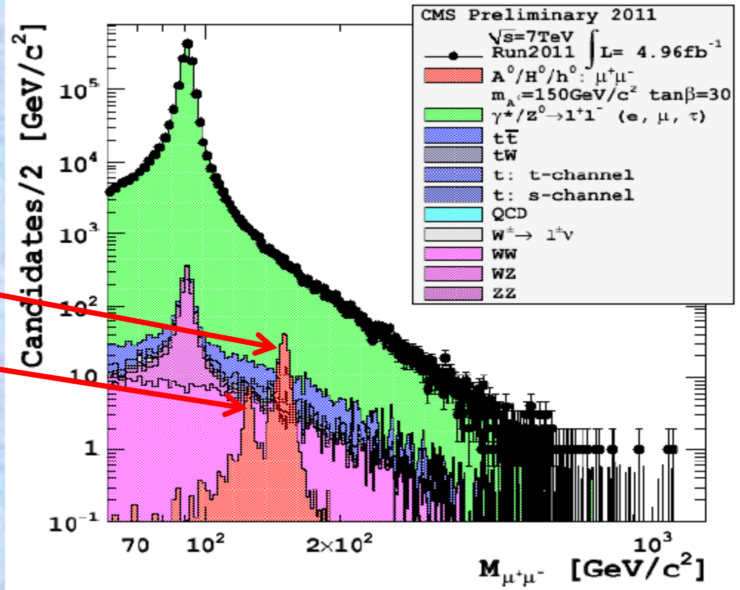
- **Suppression of tt background:**
E_T^{miss} < 30 GeV

- **Select events in 3 categories:**
1 b-tag jet /1 extra μ / anything else

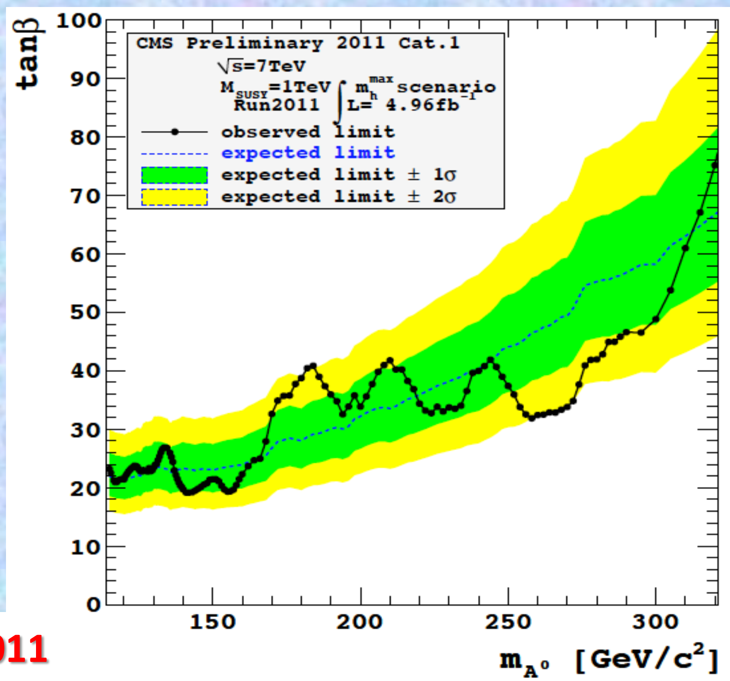
$M_{\mu+\mu-}$ Resolution ~ 3%

H+A

h



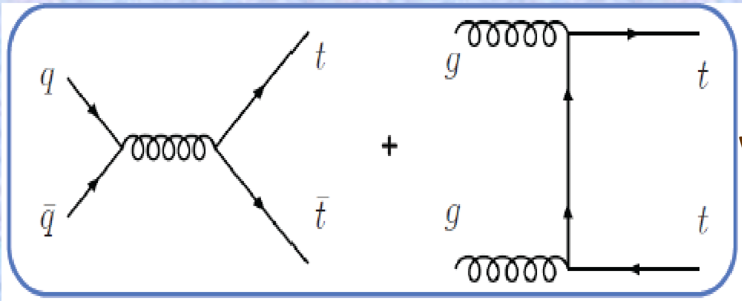
Observed di-Muon Mass Spectrum in Agreement with Background-only Hypothesis



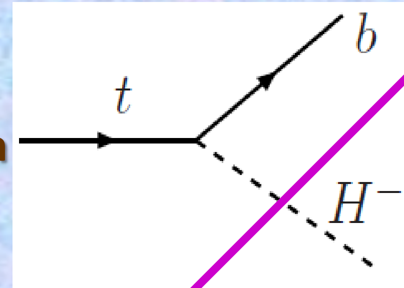
CMS-PAS-HIG-12-011

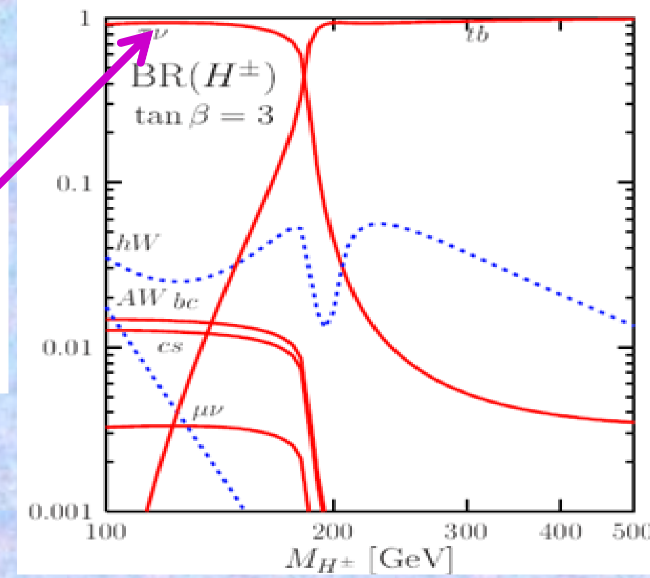
Charged MSSM Higgs Bosons

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



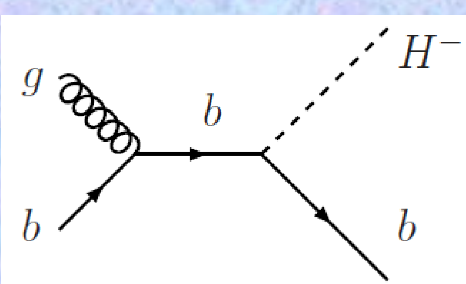
with





Dominant Decay mode: $H^+ \to \tau\nu$

➢ $M_{H+} > m_{top}$: (not yet analyzed by CMS)



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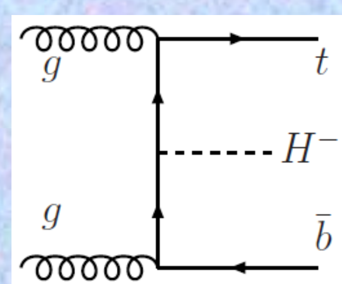
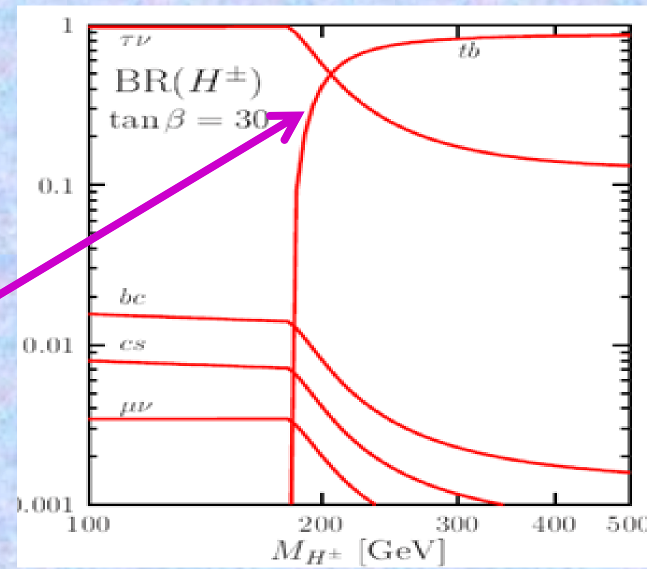
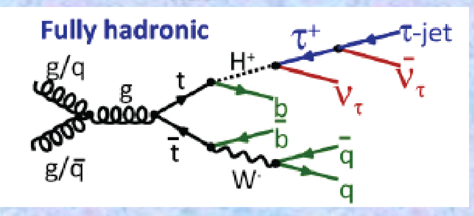
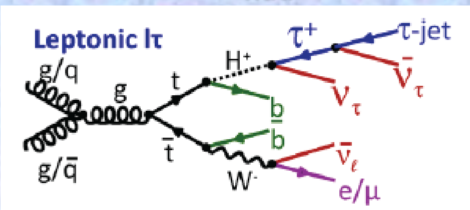
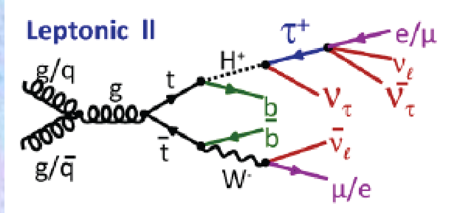




Dominant Decay mode: $H^+ \to tb$

Strategy: Search for $tt \to H^+W^-bb$ or H^+H^- bb final states with $H \to \tau\nu$

MSSM $H^+ \to \tau\nu$ Event Selection

	τ_{had}+Jets	e/μ+τ_{had}	e+μ
			

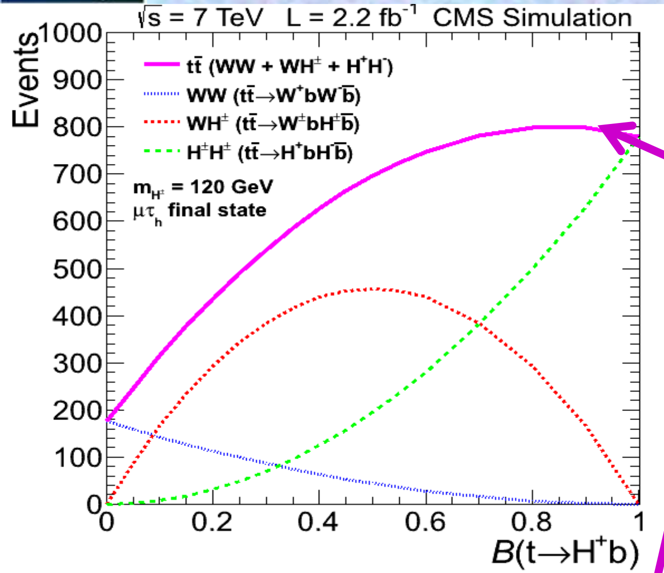
Analysis Strategy:

	τ_{had}+Jets	e/μ+τ_{had}	e+μ
➢ **Trigger**	$\tau_{had}+E_T^{miss}$	Electron+2 Jets+missing H_T / single Muon	Electron+Muon
➢ **Leptons:**	P_T^{τ} > 40 GeV tight Tau Id.	P_T^{e} > 35 GeV P_T^{μ} > 30 GeV isolated P_T^{τ} > 20 GeV	P_T^{e} > 20 GeV P_T^{μ}> 20 GeV isolated
➢ **Jets:**	3 Jets P_T > 30 GeV 1 b-tagged	2 Jets P_T > 35 (30) GeV 1 b-tagged	2 Jets P_T > 20 GeV
➢ **E_T^{miss} :**	> 50 GeV $\Delta\phi(\tau_{had},E_T^{miss})$ < 160º	> 45 GeV for e+τ_{had} > 40 GeV for μ+τ_{had}	

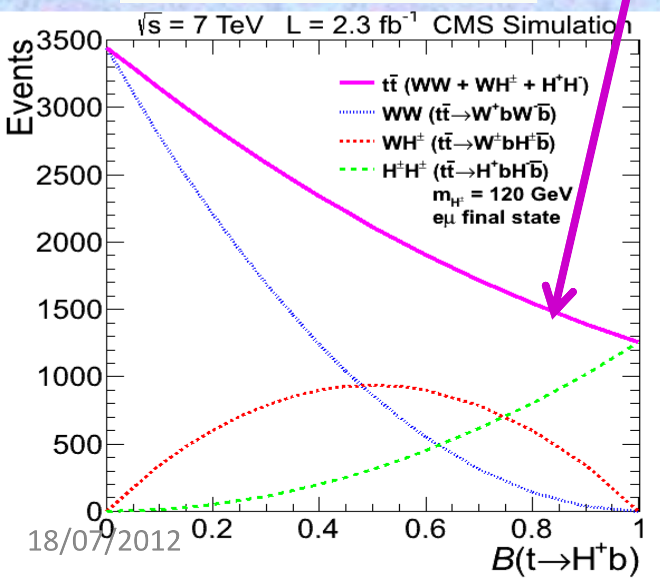
➢ **Opposite Charge Lepton Pair**

➢ **Veto Events with additional isolated Electrons or Muons**

H⁺→ τν Event Extraction



number of expected events assuming $BR(H^+ \to \tau^+\nu)=1$



Non-zero BR(t → H+b) →

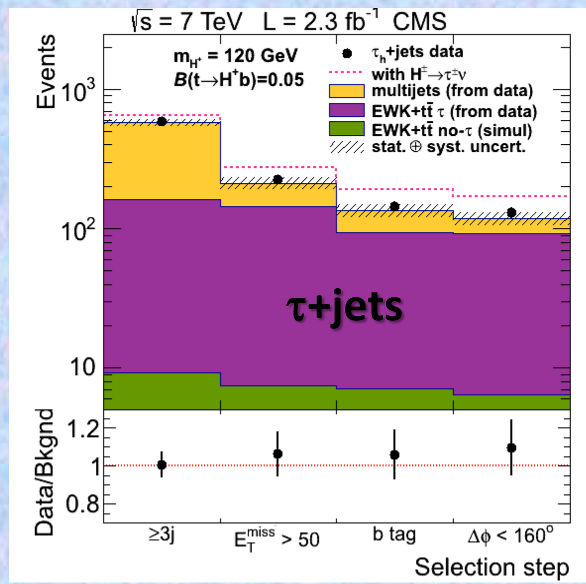
- **Increases** event yield in τ(had)+Jets and e/μ+τ(had) channels
- **Decreases** event yield in e+μ channel with BR(t → H+b)

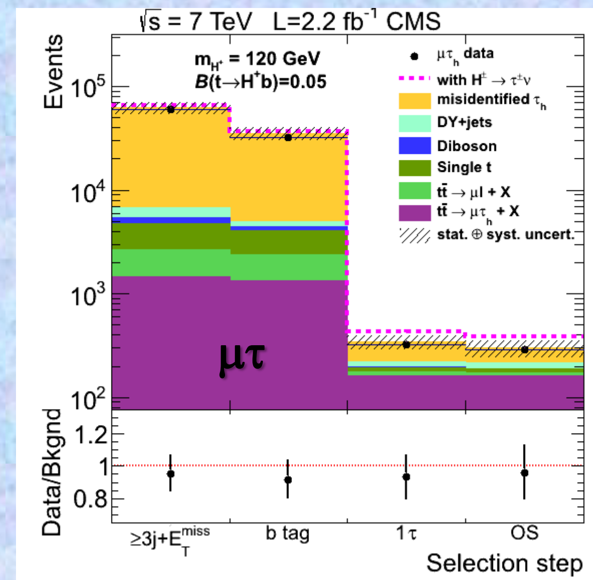
The signal is modelled as the excess of events yields in presence of H⁺:

N_{excess} =

$N_{tt}^{MSSM} - N_{tt}^{SM} = N_{WH}\, 2(1-x)x + N_{HH}\, x^2 + N_{tt}^{SM}\, ((1-x)^2 - 1)$,

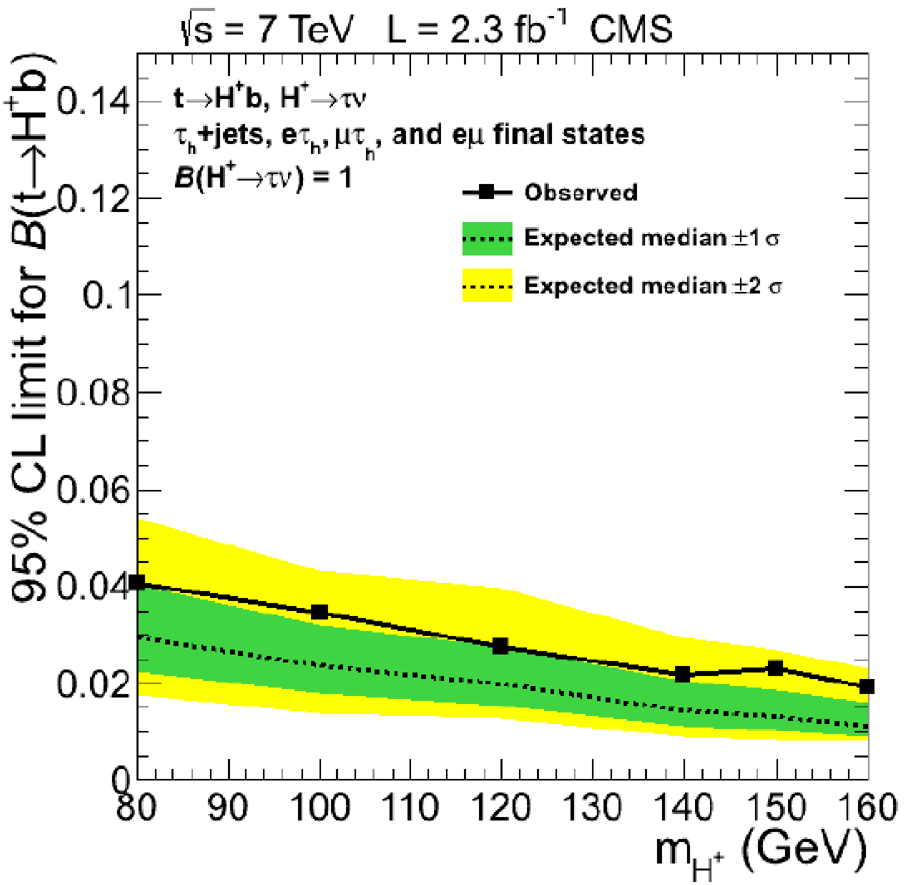
$x = BR(t \to H^+b)$

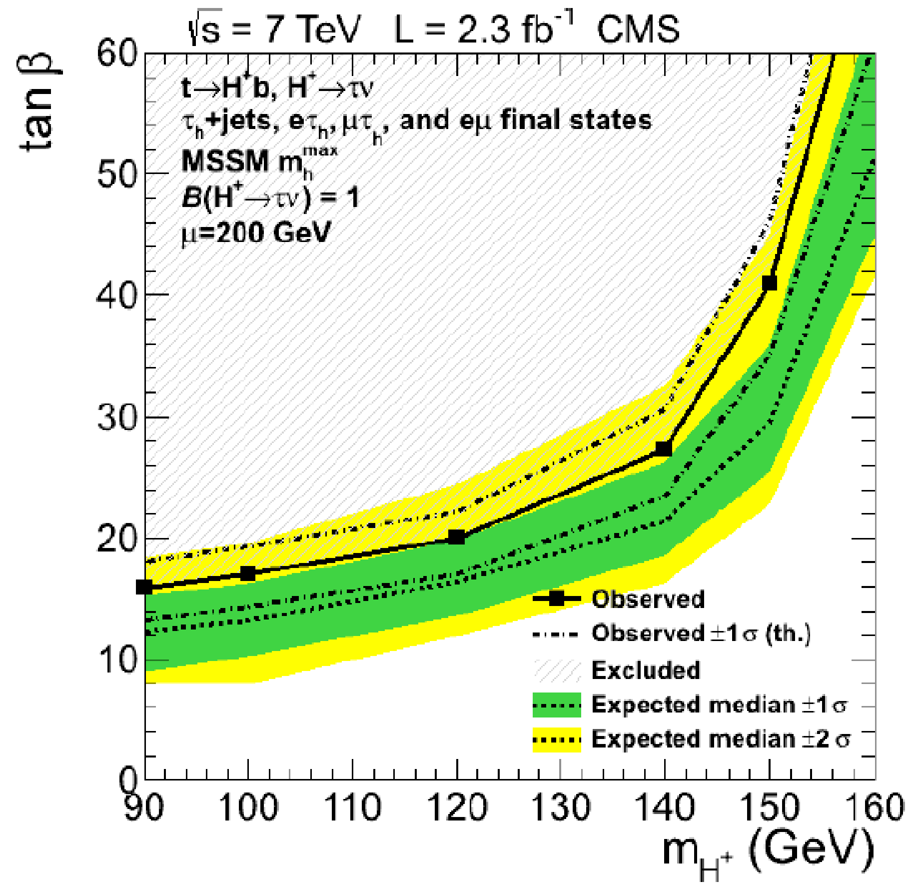




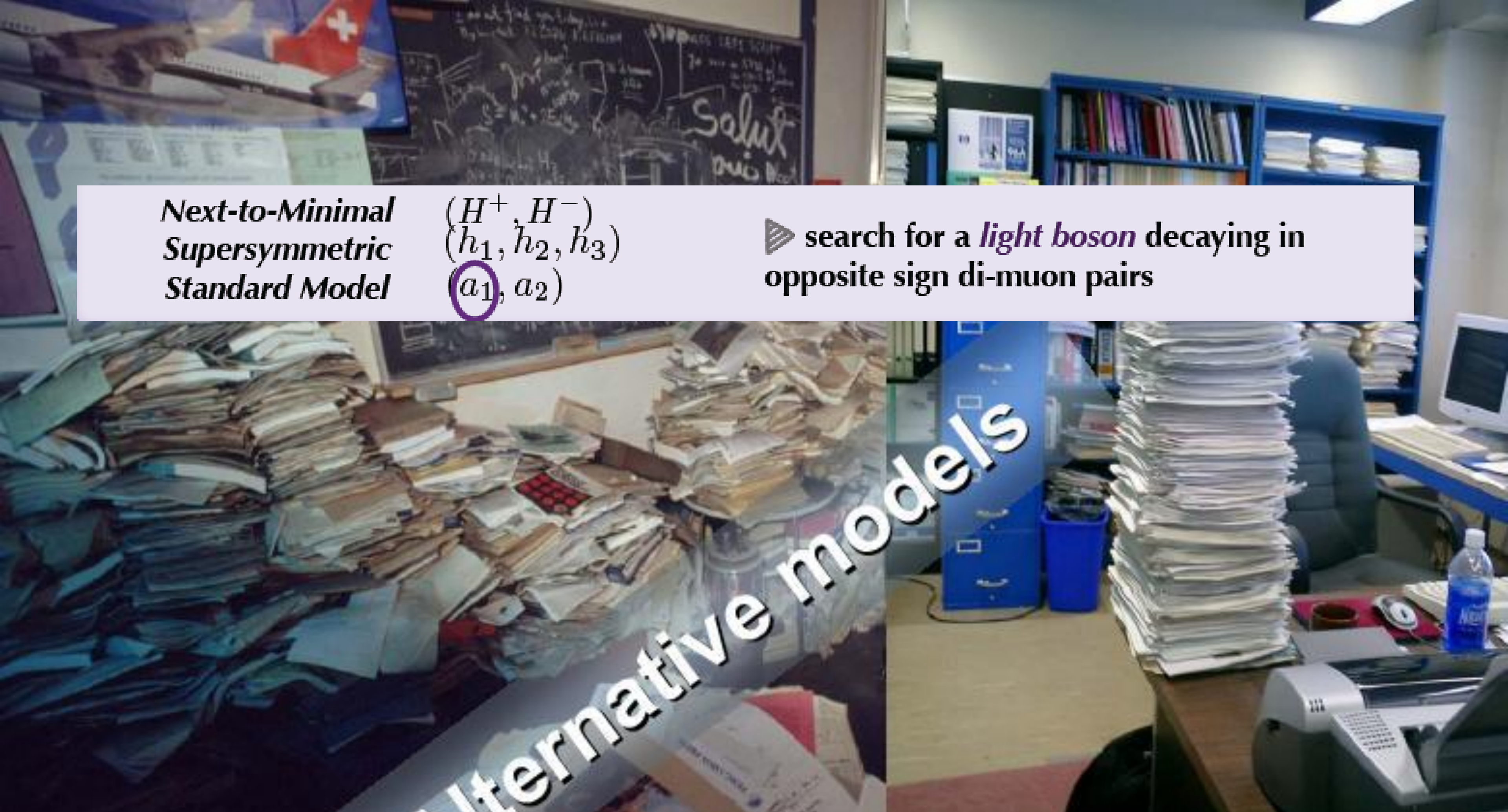
Charged Higgs ($H^+ \rightarrow \tau\nu$) Exclusion Limit

Upper limit on BR($t \rightarrow H^+b$) excludes region of large tanβ in MSSM Parameter space for M_{H+} / M_A ≤ Mtop:





CMS-PAS-HIG-11-019
arXiv: hep-ex/1205.5736



Alternative models

Next-to-Minimal	(H^+, H^-)	search for a *light boson* decaying in opposite sign di-muon pairs
Supersymmetric	(h_1, h_2, h_3)	
Standard Model	(a_1, a_2)	

non SUSY *it means: *non exclusively SUSY*

SM with 4th generation (SM4) — cross sections enhanced w.r.t. SM

▶ interpretation in SM4 of the same analyses used for SM Higgs searches

Minimal Seesaw Model of type II — *triplet of Higgs fields* → • doubly charged Higgs

▶ search for double charged Higgs in 3 or more leptons final states

Minimal Seesaw Model of type II, *2HDM type I*, *technicolor*, ... → • Neutral Fermiophobic Higgs →

- ZZ — same SM signatures
- WWW — three leptons final state
- $\gamma\gamma + X$ — combination of exclusive (lepton and jet tagged) channels and the non tagged one

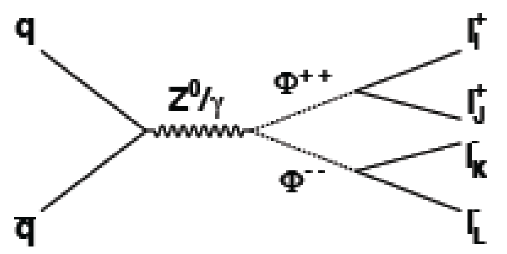
Searches for Doubly Charged Higgs $\Phi^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$

- **Triplet Higgs-field in Minimal Type II See-Saw Models** (the triplet is responsible for neutrino masses, the couplings directly linked to the mass matrix):
  - Prediction of additional scalar field that is a triplet under $SU(2)_L$
  - New Higgs-like particles: Φ^{++}, Φ^{+}, Φ^{0}

    (if observed, would establish this mechanism as the most promising explanation)

- **CMS search for Φ++ and Φ+**
  - Produced in association with singly charged Higgs or in pairs since Φ++, Φ+ are assumed to be degenerate
  - Unknown neutrino mass matrix → unknown branching ratios (assume BR to leptons only)
  - Six standard searches covered, where $BR(\Phi^{++} \rightarrow l^{+}l^{+}) = 100\%$
  - Four additional model dependent points (BP1-BP4) to probe different characteristic of neutrino mass matrix

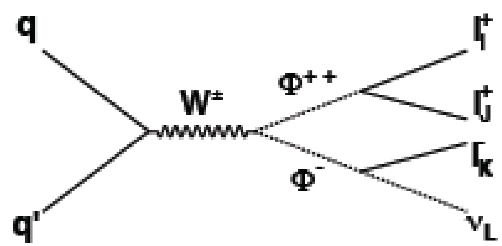
pair production



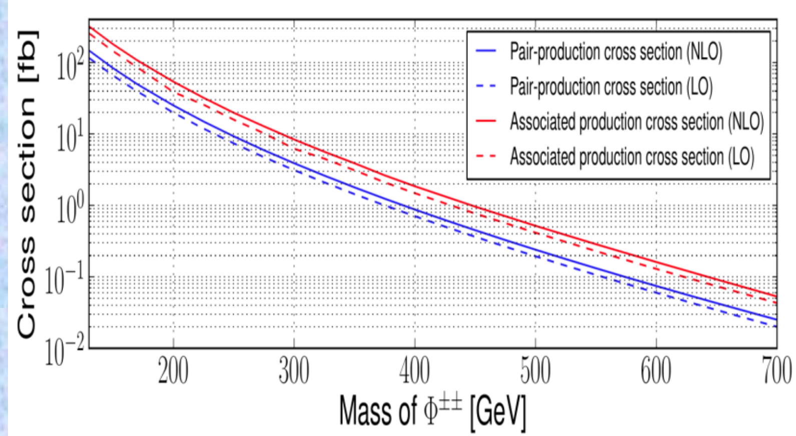
4 lepton selection

$\Phi^{++/--}$ would decay to same sign leptons, also flavor violation

associated production



3 lepton selection



$\Phi^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$ Event Selection

➢ **Unique Experimental Signature: 3 or 4 leptons in the final state → use same-sign di-lepton combinations of all flavors (no SM background with real leptons)**

Trigger:

- dilepton triggers: 17/8 GeV for ee, eμ; varying for μμ

Analysis Strategy:

Lepton selection:

- At least two leptons with pT > 20 / 10 GeV
- Loose isolation requirement
- Veto of low invariant mass resonances (< 12 GeV)

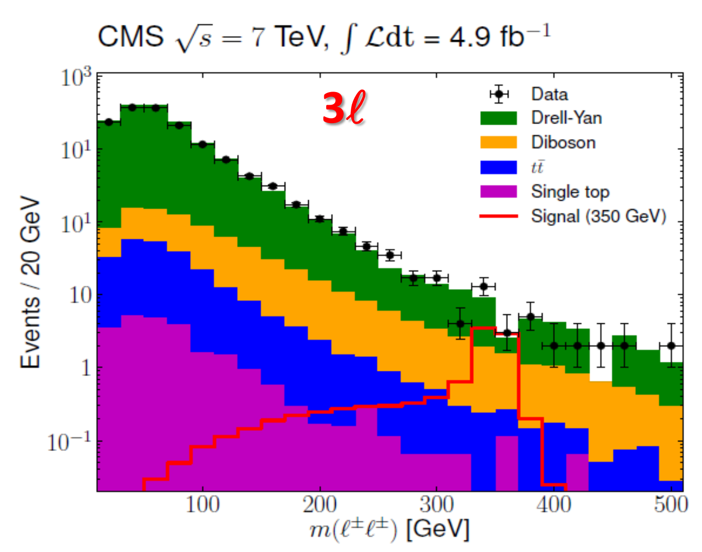
Topological cuts on leptons depending on final states:

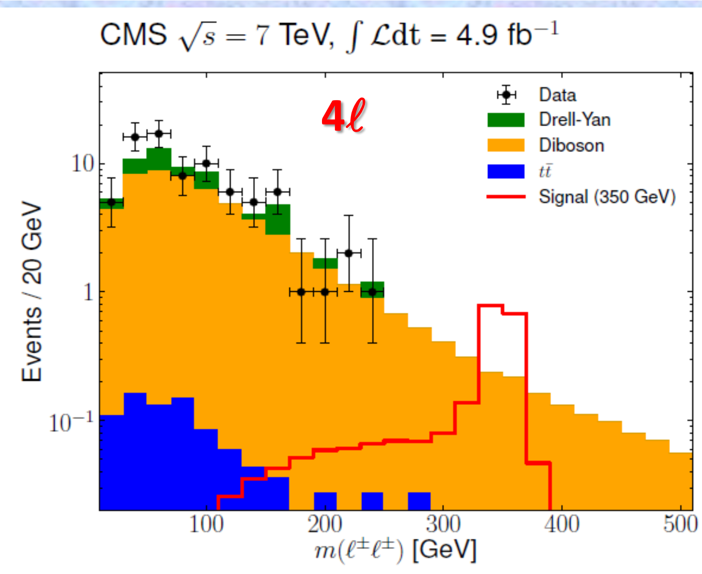
- Σp_T cuts on leptons (depend on m_ϕ)
- Tight isolation of leptons
- Z veto, E_t^{miss}
- Cut on $\Delta\phi$ between leptons

❑ Events are counted in the mass window depending on the Higgs boson mass considered

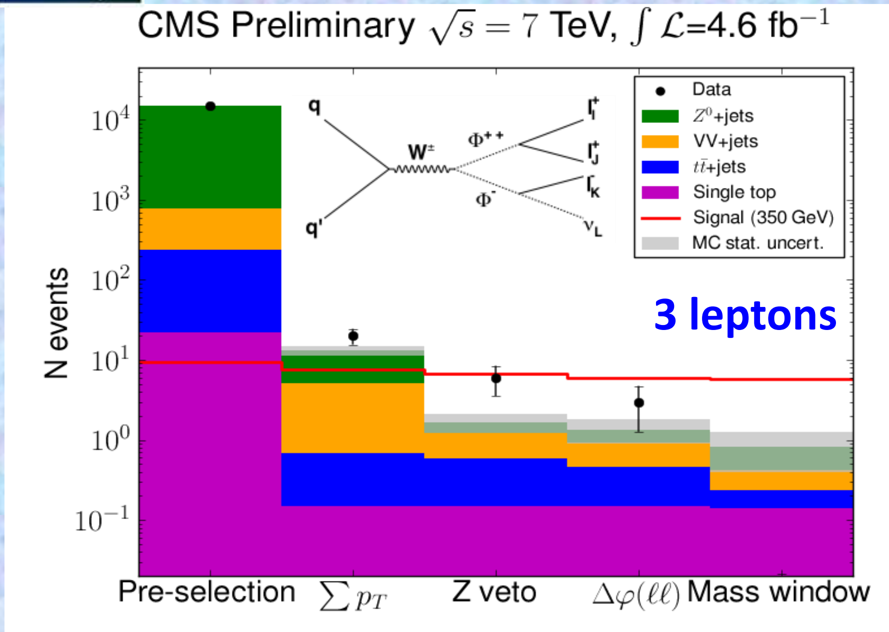
❑ Selections are optimized as a function of $m\Phi$ separately for $\ell\ell$, $\ell\tau_h$, and $\tau_h\tau_h$ events, where ℓ = e, m

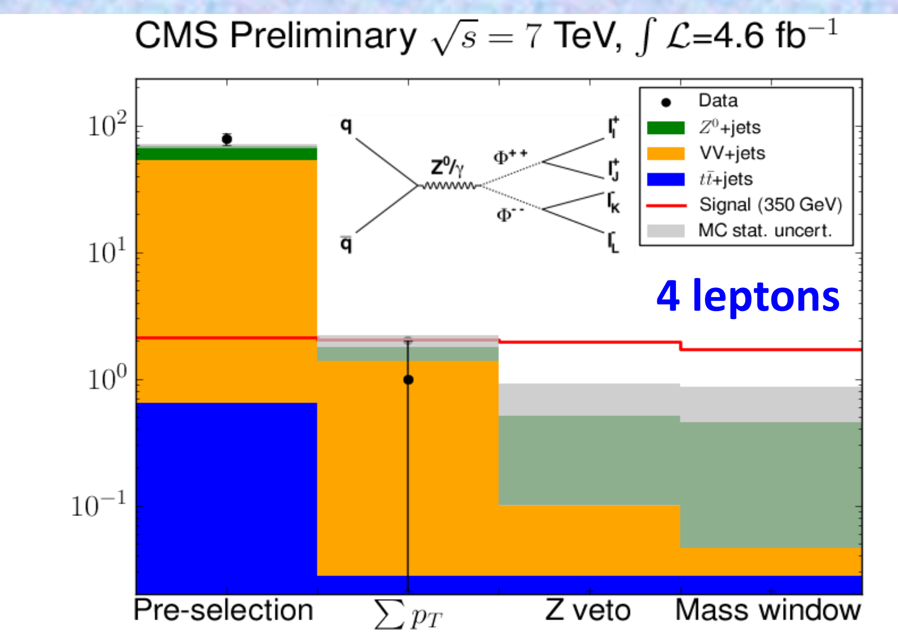
❑ Backgrounds are estimated from sidebands





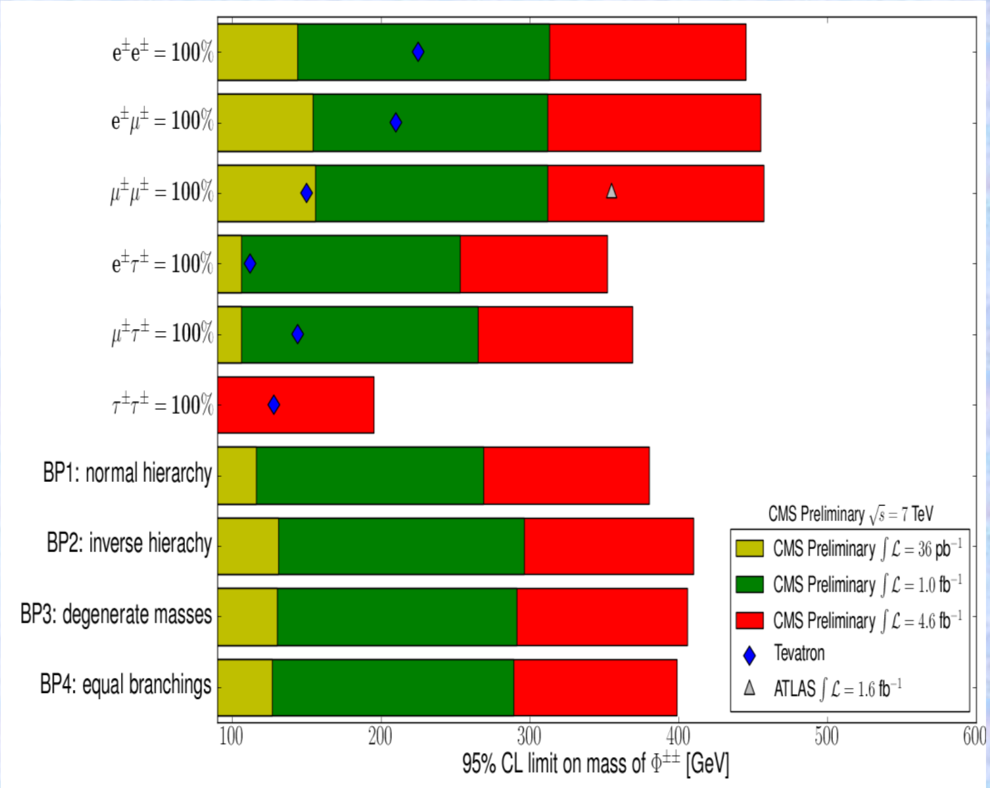
Doubly Charged Higgs $\Phi^{\pm\pm}$: Exclusion Limits





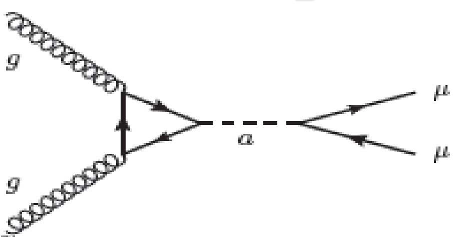
The best ever Limit:

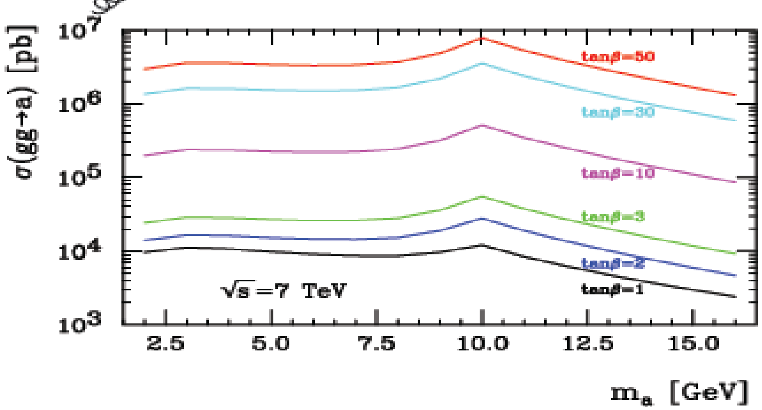
CMS-PAS-HIG-12-005
arXiv: hep-ex/1207.2666



nMSSM: Light Pseudoscalar Higgs $a_1 \rightarrow \mu^+ \mu^-$

- **Next-to-Minimal Supersymmetric Standard Model (nMSSM):**
  - ❖ Adds singlet scalar field, thereby expanding the Higgs sector to three CP-even (h_1, h_2 and h_3), two CP-odd (a_1, a_2) and two charged scalars (H^+, H^-)
  - ❖ A light (~ 10GeV) boson is produced (this model can survive also with a Higgs at 125 GeV!)
- **CMS search for $a_1 \rightarrow \mu^+\mu^-$:**





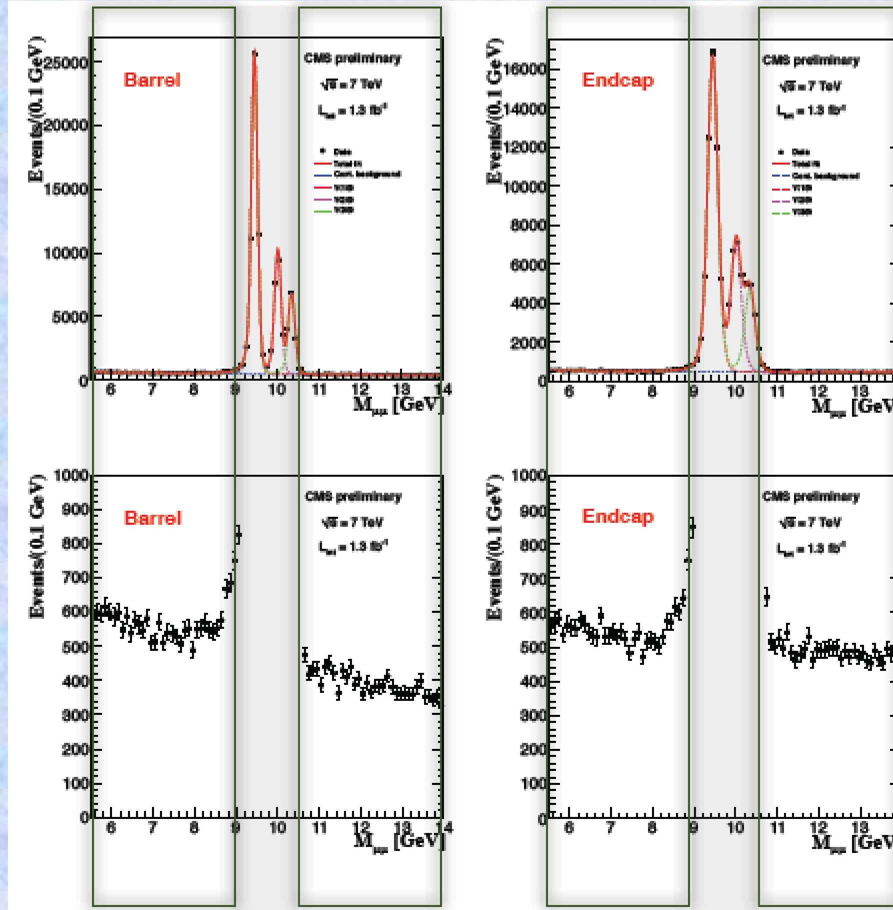
Analysis Strategy:

Preselection:

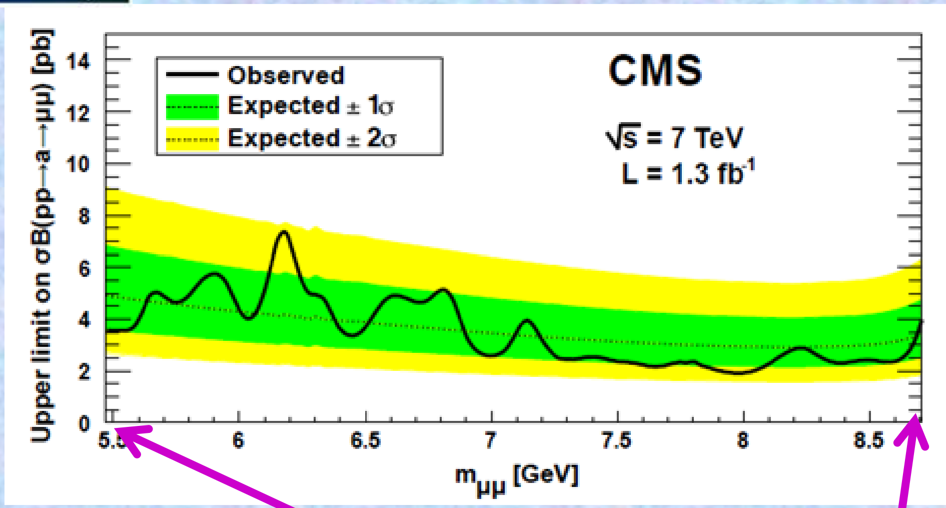
- Choose isolated opposite sign dimuons: $p_{T\mu}$ > 4 GeV & $p_{T\mu\mu}$ > 6 GeV
- Search above/below the upsilon peaks in dimuon invariant mass

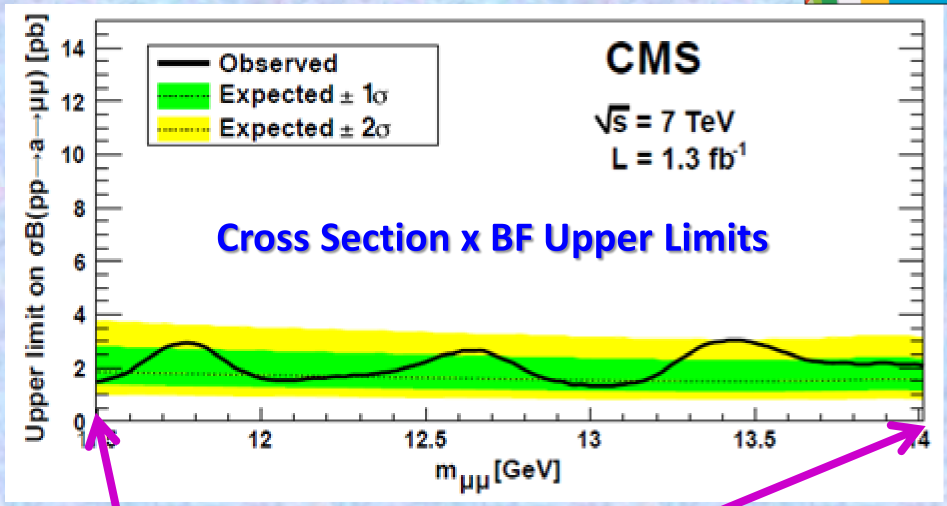
$5.5 < M_{\mu\mu} < 9$ GeV

$11.5 < M_{\mu\mu} < 14$ GeV



nMSSM a1 → $\mu^+ \mu^-$: Exclusion Limits

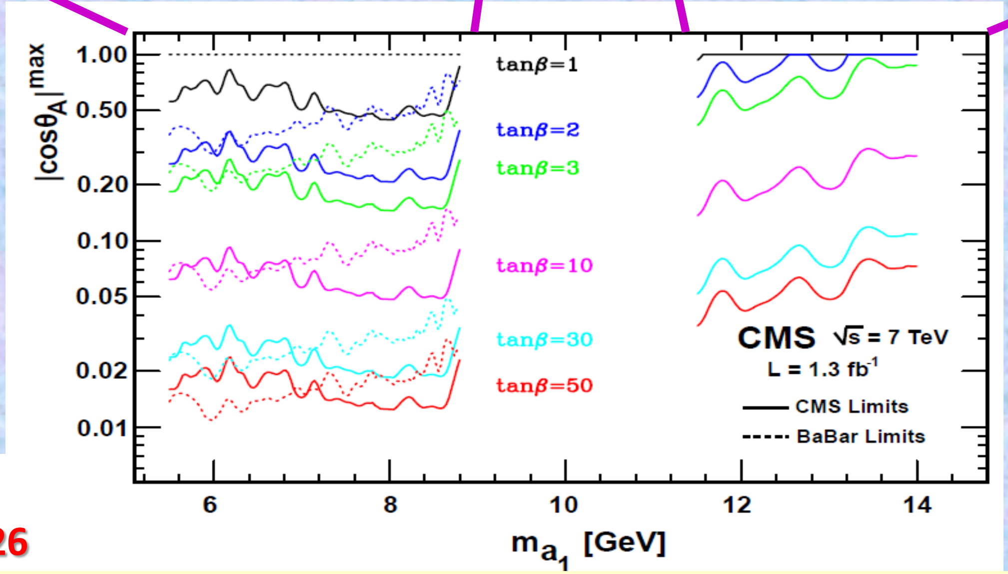




Interpretation in nMSSM:

Three parameters:
$m(a_1), \tan\beta, \cos\theta_A$

$$a_1 = \cos\theta_A a_{MSSM} + \sin\theta_A a_S$$



Upper limits to $\cos\theta_A$ as a function of m(a1) for several values of $\tan\beta$

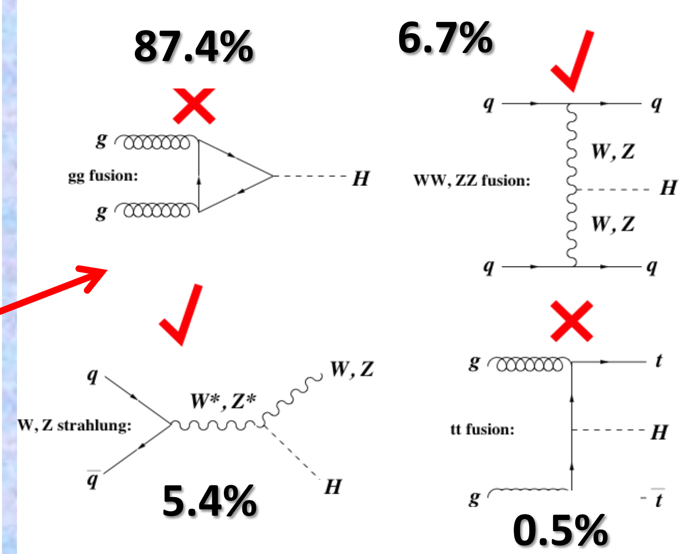
(also compared with BaBar)

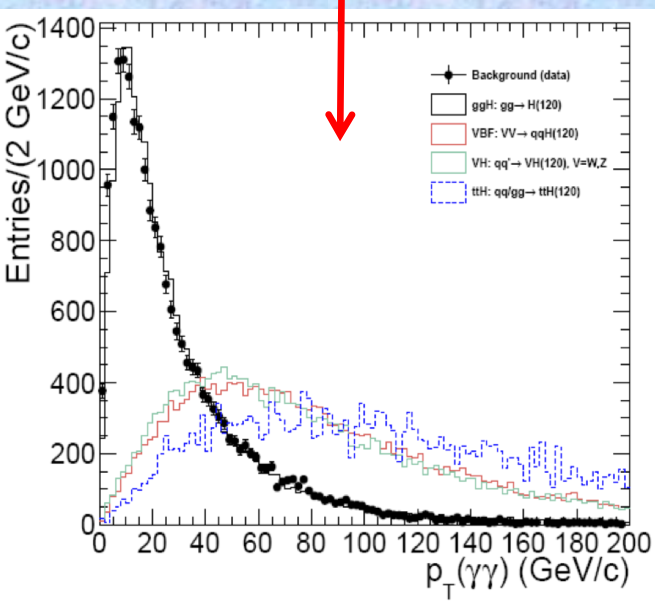
CMS-PAS-HIG-12-004
arXiv: hep-ex/1206.6326

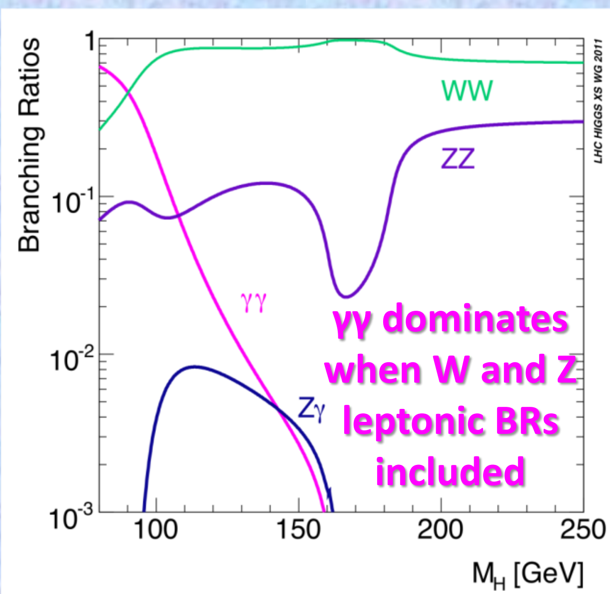
No significant excess of events observed in 1.3 (fb-1) @ 7 TeV
→ exclusion limits set at the level of 2 – 6 pb for σ x Br

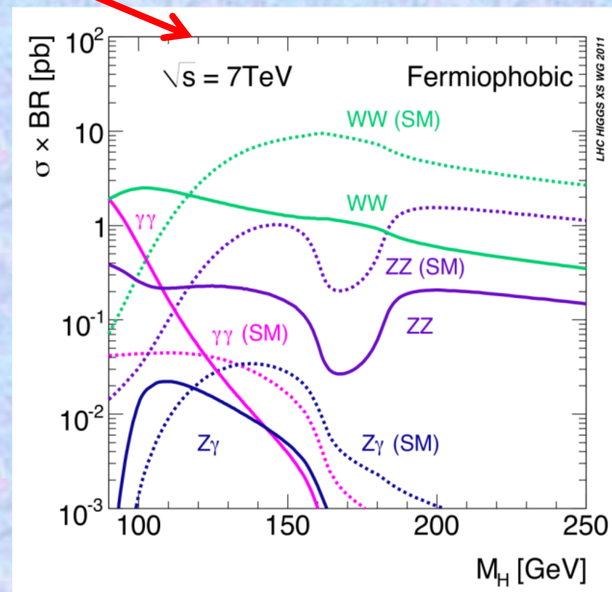
Fermiophobic Higgs

- **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
- **Fermiophobic Higgs**
  - No couplings to fermions (Vector boson fusion (VBF) or associated VH production only)
  - Low mass higgs decays change dramatically
  - Higgs is boosted (exploit presence of two tag jets in forward region or associate W and Z (leptons)

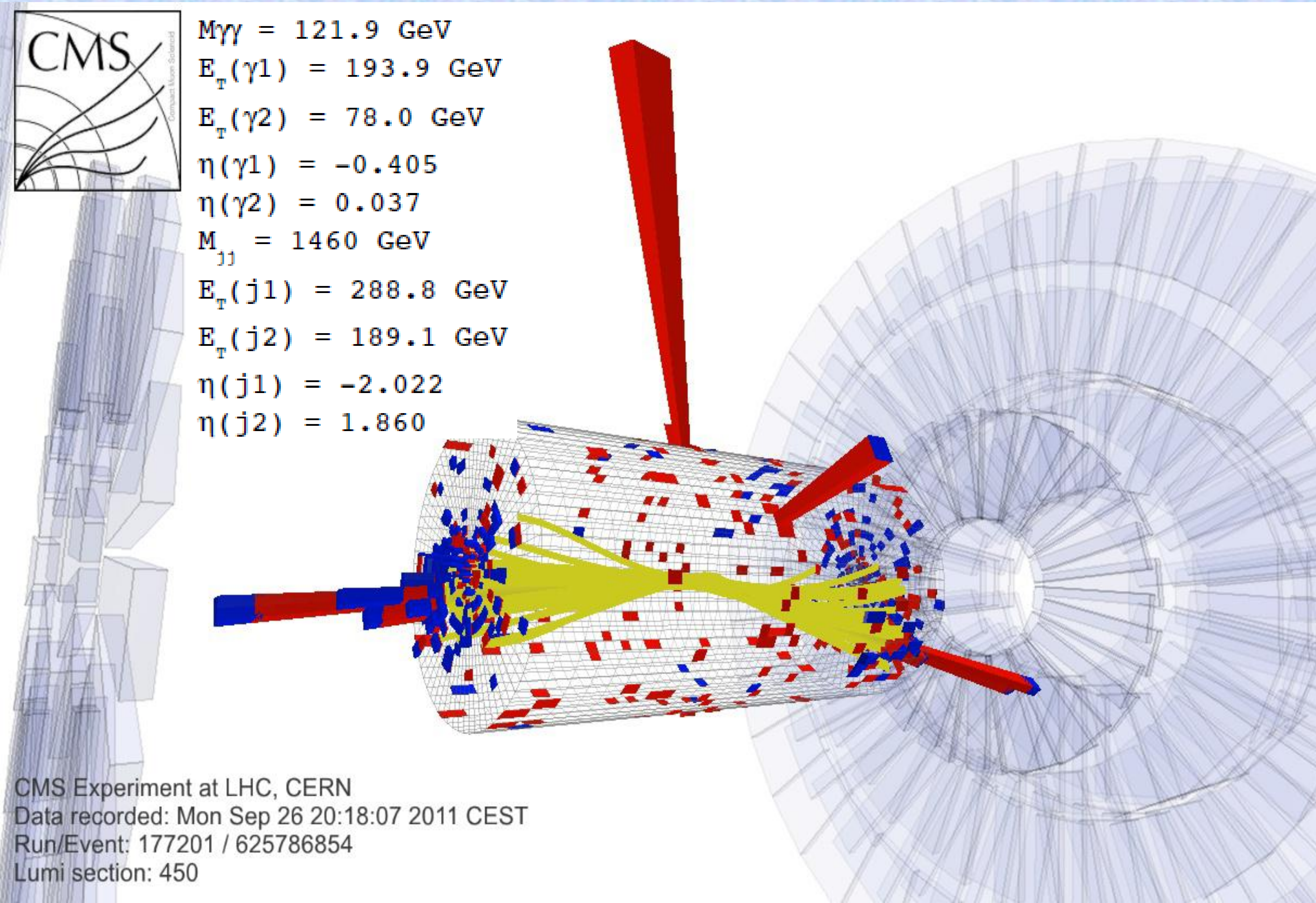








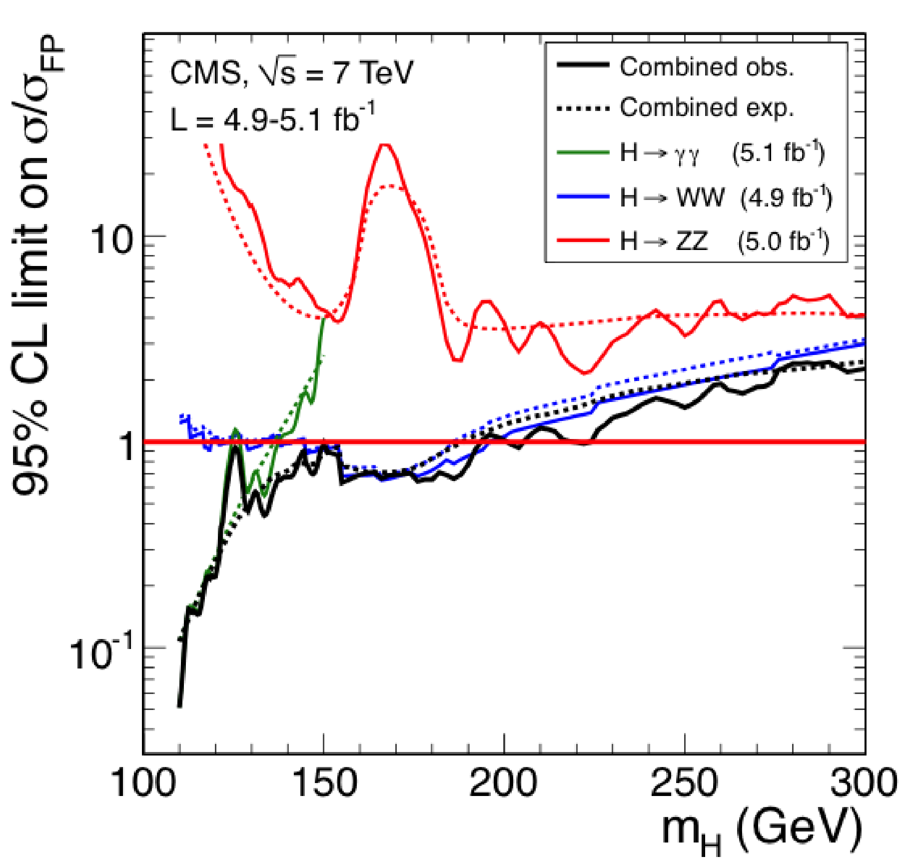
Di-jet Tagged $\gamma\gamma$ Event

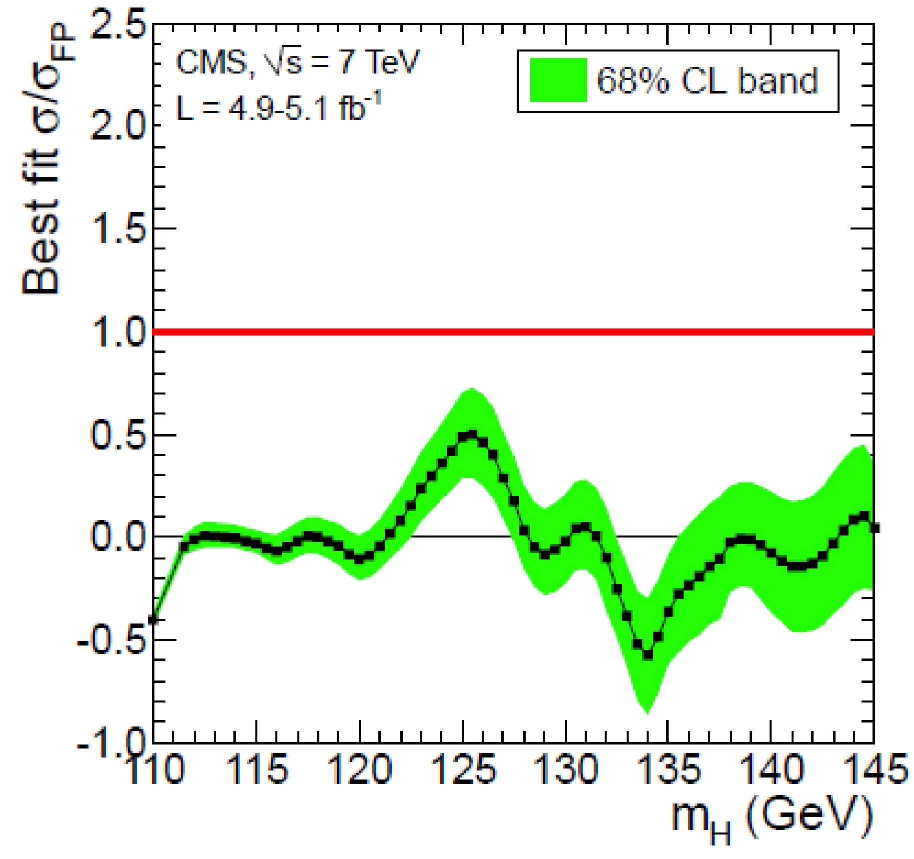


Fermiophobic Higgs: Combined 2011 Exclusion Limit

Combination of γγ, WW, ZZ analysis at 7 TeV (4.9 – 5.1 fb-1):

- **Excludes at 95% CL 110-194 GeV**
- **Excludes at 99% CL except for 110-124.5 GeV, 127 -147.5 GeV and 155-180 GeV**





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

Fermiophobic Higgs → γγ Analysis (2012)

Update of γγ analysis @ 8 TeV → analysis techniques different from SM analysis

7+8 TeV

Four mutually exclusive sub-channels:

- **Dijet-tagged 2 classes (VBF): S/B ~1 (mH ~ 120 GeV)**
  γγ and two jets separated in rapidity, high & low dijet mass

- **Lepton-tagged 2 classes(VH): S/B >~ 1**
  isolated e and μ: pT > 20 GeV, Z veto

- **MET-tagged (Z(νν)H): S/B < 1 (new, not used in 2011)**
  MET tag has high s/B in the high E_T^{miss} > 70 GeV region, complements the lepton tag analysis

- **Untagged 4 classes based on $|\eta_\gamma|$ and conv/non-conv: S/B << 1**
  Construct 2D models for signal and bkg, relying on two observables: $(m,\ \pi_T^{\gamma\gamma} \equiv p_T^{\gamma\gamma}/m^{\gamma\gamma})$

Analysis Strategy:

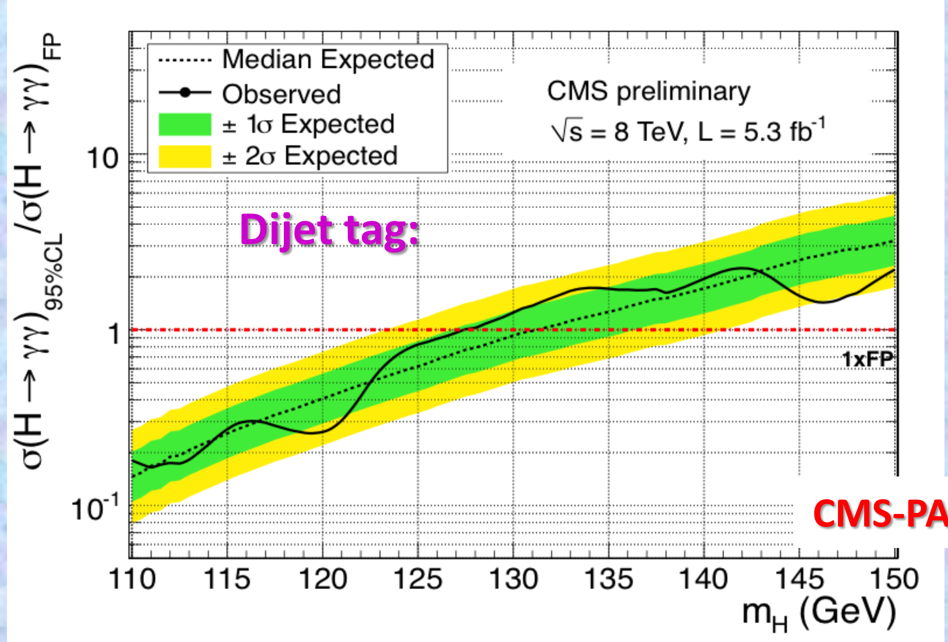
$p_T(\gamma\gamma)$ has a good discriminant power against the background it's used in addition to $m(\gamma\gamma)$ to model the background

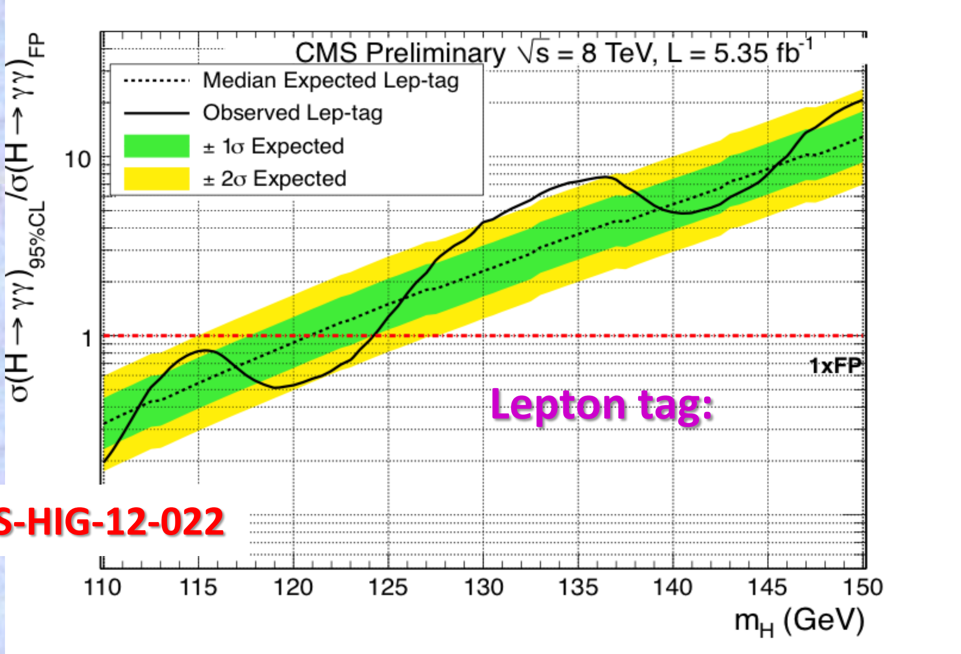
channel	leading photon	trailing photon
dijet-tag	$p_T/m > 60/120$	$p_T > 25$ GeV
lepton-tag	$p_T/m > 45/120$	$p_T > 25$ GeV
MET-tag	$p_T/m > 45/120$	$p_T > 25$ GeV
untagged	$p_T/m > 40/120$	$p_T/m > 30/120$

besides the diphoton selection, a dedicated analysis has been developed to enhance the sensitivity to the FP model

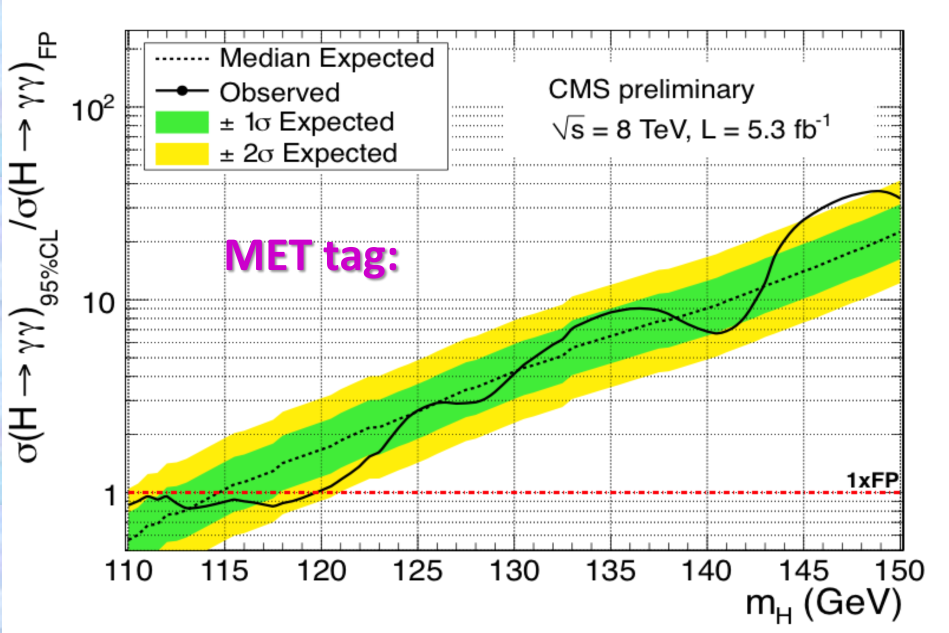
	E_T^{miss} tag	Dijet high m_{jj}	Dijet low m_{jj}	Lepton tag	Untagged (a)	Untagged (b)	Untagged (c)	Untagged (d)
Signal ($m_H = 120$ GeV)	3.8	21.5	15.3	5.7	29.2	37.9	18.5	22.0
Data ($115 < m_{\gamma\gamma} < 125$ GeV)	4	20	36	6	683	1712	902	1755
Data ($100 < m_{\gamma\gamma} < 180$ GeV)	41	84	271	30	4992	9546	5105	8574
σ_{eff} (GeV)	1.91	1.98	2.02	2.0	1.44	2.00	3.72	3.76

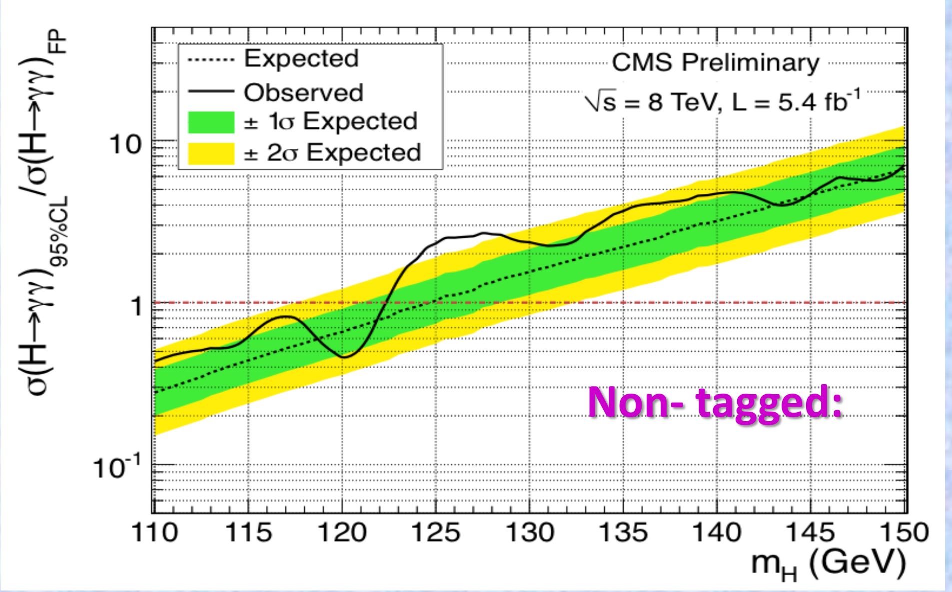
Fermiophobic Higgs → γγ in 2012: Exclusion Limits



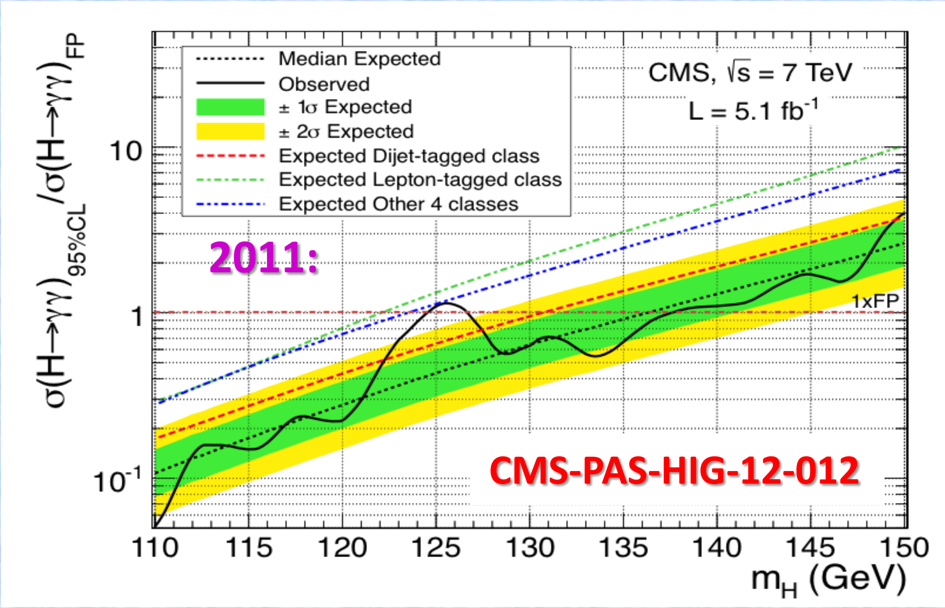


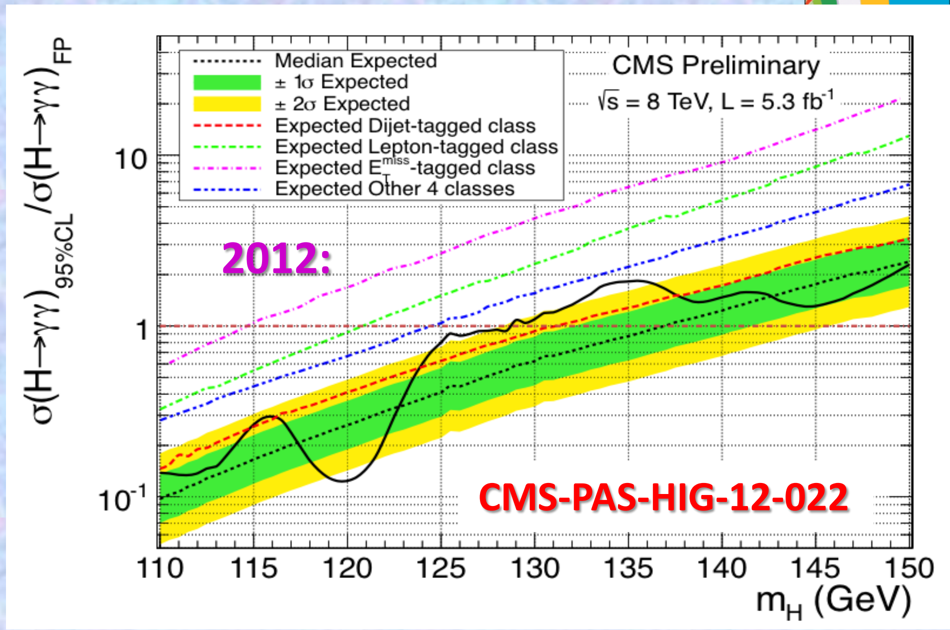
CMS-PAS-HIG-12-022

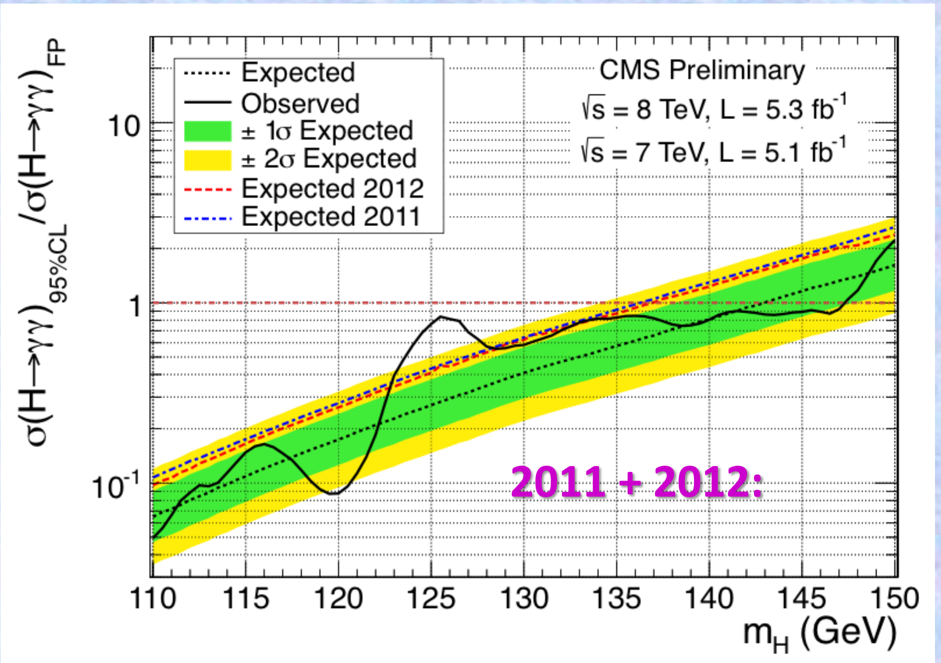




Fermiophobic Higgs → γγ in 2011/ 2012: Exclusion Limits





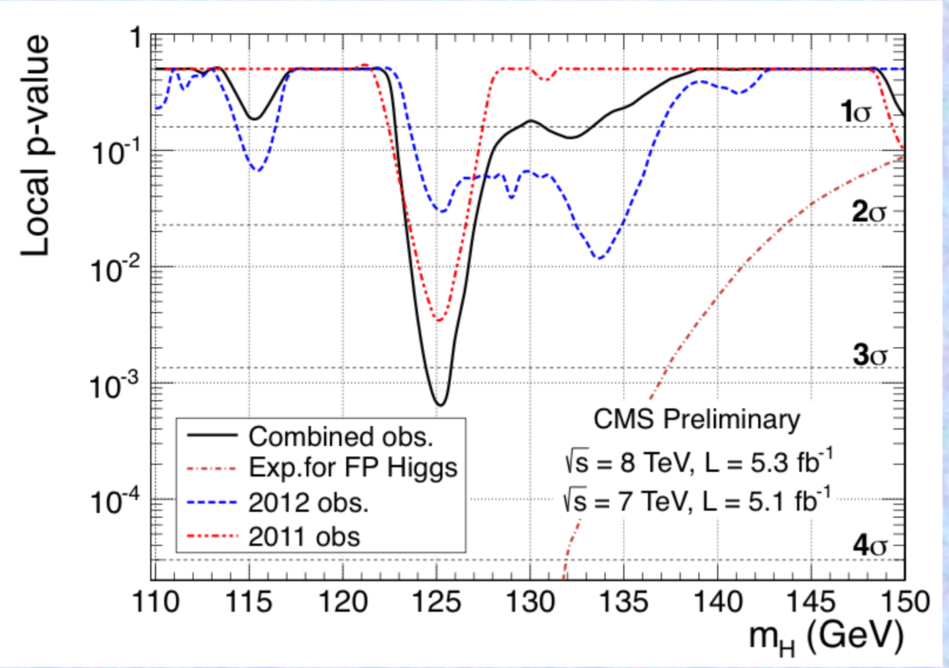


Combining 2011 and 2012 data, we exclude the FP Higgs in almost the entire search range:

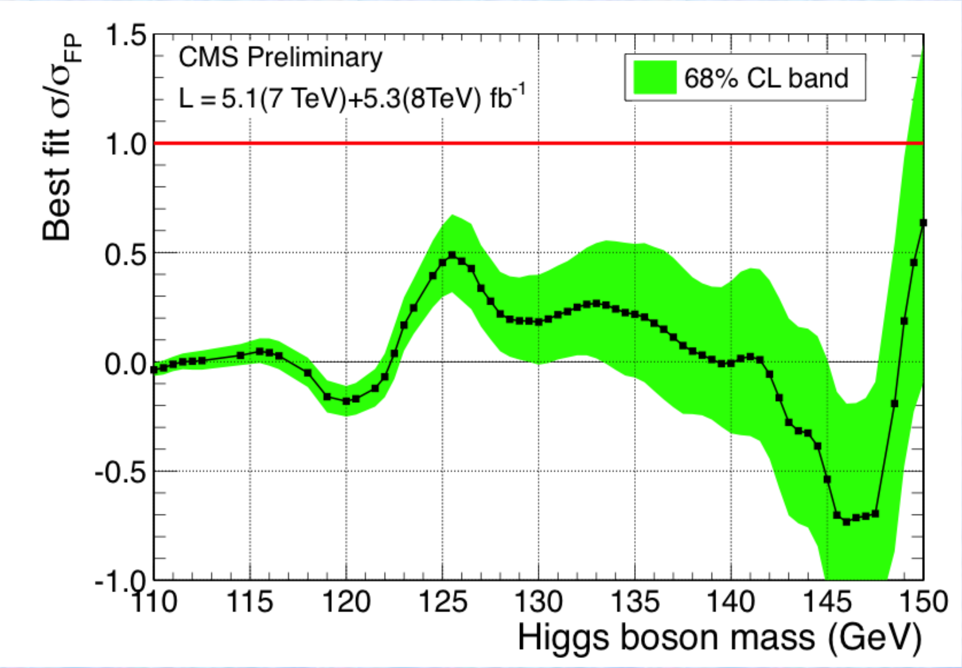
- **95% CL in the mass range 110—147 GeV**
- **99% CL in the mass range 110—134 GeV**

Fermiophobic Higgs → γγ (2011+2012): p-value and signal strength

p-value:



Signal strength:



- **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**

Summary and Outlook

- CMS made searches sensitive to beyond the minimal Higgs of the Standard Model

- No evidence for non-standard higgs production or decay is found → stringent limits set on the production of Higgs boson in several models beyond the SM

- The MSSM Higgs parameter space is being constrained using modes with bbbar, di-tau and $\mu\mu$

- The small excess seen in $\gamma\gamma$ channel does not look like it is due to fermiophobic higgs

More BSM Higgs search results from 2012 LHC runs are expected soon.