Review of BSM neutral Higgs results in CMS

Charged14 (Uppsala)

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on behalf of the CMS collaboration

September 16, 2014

Outline

1. MSSM searches
   - $\Phi \to \tau^+\tau^-$
   - $b\Phi \to 3b$
   - $\Phi \to \mu\mu$
2. NMSSM searches
   - $h \to a_1 a_1 \to 4\mu$
3. 2HDM searches
   - $H \to hh, A \to Zh$ multileptons and γ
4. Extra Dimension searches
   - $X \to hh \to \gamma\gamma b\bar{b}$
   - $X \to hh \to b\bar{b}b\bar{b}$
5. Anomalous Higgs searches
   - LFV $h \to \mu\tau$
   - Invisible Higgs
6. Heavy Higgs searches
   - $H \to \gamma\gamma$
   - $H \to WW \to \ell\nu jj$

Theory

2HDM

$$H_1 = \begin{pmatrix} H^+ \\ H_u^0 \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

- Introduces one additional Higgs doublet
  - 2 neutral scalars: **h**, **H**
  - 1 neutral pseudoscalar: **A**
  - 2 charged scalars $\mathbf{H}^{\pm}$ (see Pietro's and Lauri's talks)
- 4 types depending on the coupling of leptons and quarks

Type I : all quarks coupled to the same Higgs doublet

Type II : up-type and down-type quarks couple to different doublets

- The light scalar is often assumed to be the discovered boson at $m_h = 125.03^{+0.26}_{-0.27}(stat)^{+0.13}_{-0.15}(syst)GeV$ (see Pavel's talk)

MSSM

- MSSM is a SUSY Type-2 2HDM with specific assumptions
- Mass relations determined by only 2 parameters at tree-level, e.g. $\tan\beta$, m_A
- $m_h \lesssim m_Z$, but radiative corrections are important $\rightarrow m_h \lesssim 130 GeV$

NMSSM

- Introduces one additional Higgs doublet and a complex Higgs singlet
  - 3 neutral scalars: $\mathbf{h}_1$, $\mathbf{h}_2$, $\mathbf{h}_3$
  - 2 neutral pseudoscalar: $\mathbf{a}_1$, $\mathbf{a}_2$
  - 2 charged scalars $\mathbf{H}^{\pm}$
- Higgs mass increased by mixing between doublet and singlet, less constraints on radiative corrections
- More natural Higgs mass

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$\Phi \to \tau^+\tau^-$

HIG-13-021

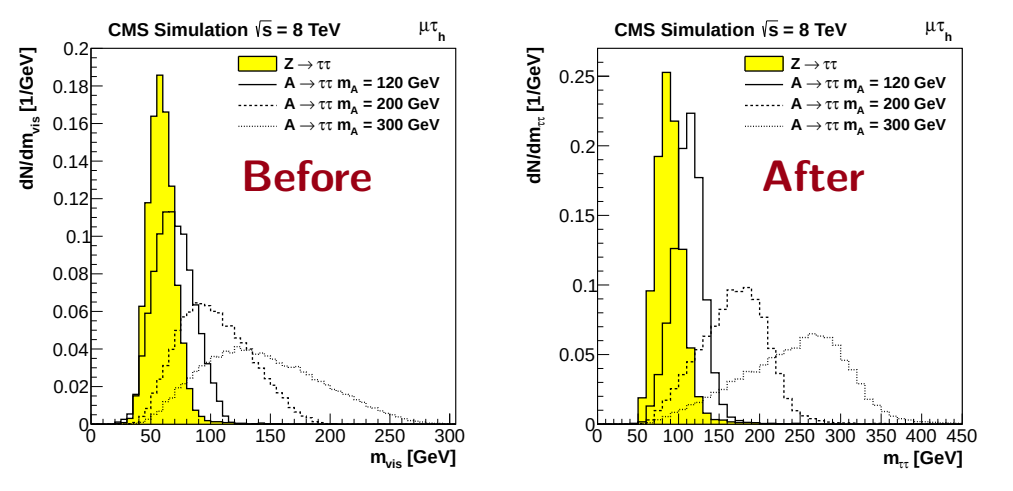
- Search for neutral Higges ($\Phi = h, H, A$) decaying into τ pairs
- Analysis strategy: identify and reconstruct τ candidates and look for peaks in $m_{\tau\tau}$ distribution

- Cosidered 5/6 τ decay modes - *ee* not considered (3.1%)

- Several hadronic τ topologies: one or three charged hadrons, or one charged hadron $+\gamma$

$m_{\tau\tau}$ reconstruction

- Reconstructed $\not{E}_T$ with MVA techniques and event-by-event estimate of $\not{E}_T$ resolution
- $m_{\tau\tau}$ value estimated with a likelihood approach given events kinematics

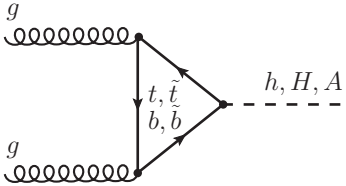


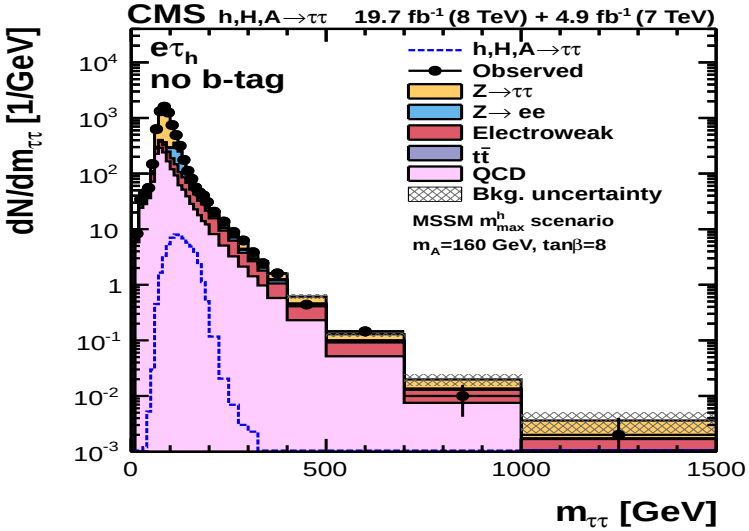
- Resolution $\sim 15 \div 20\%$ depending on channel

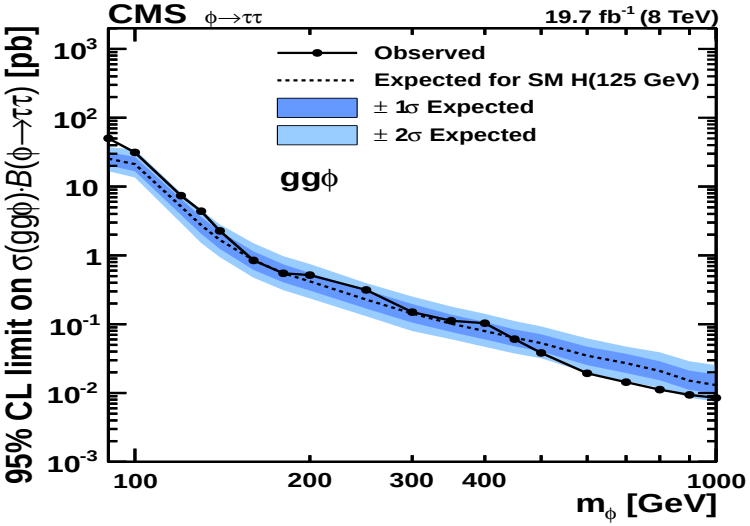
$\Phi \to \tau^+\tau^-$

HIG-13-021

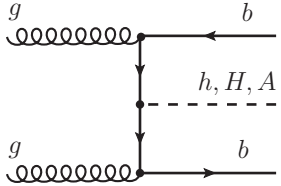
0 b-jets category

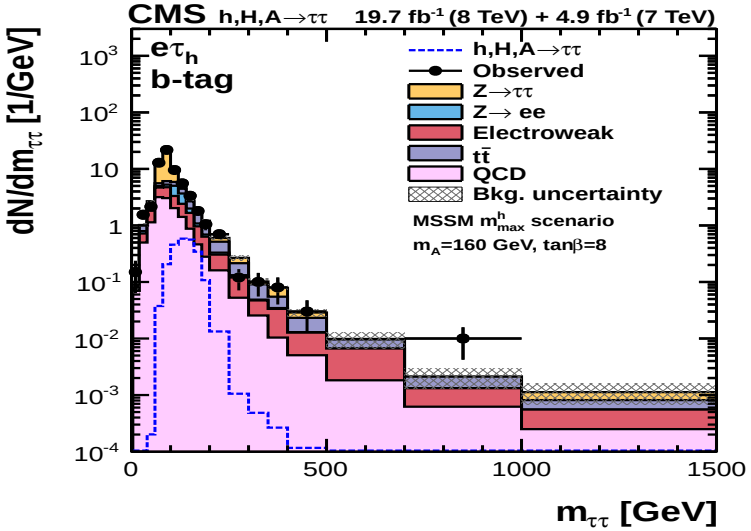


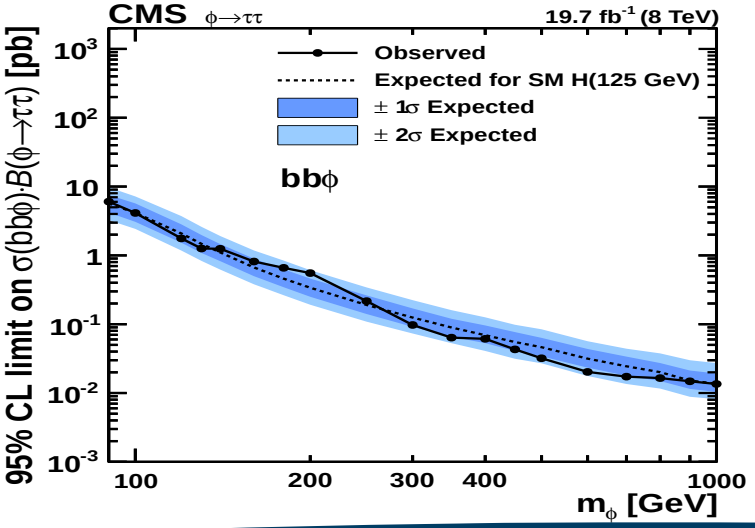




1 b-jet category

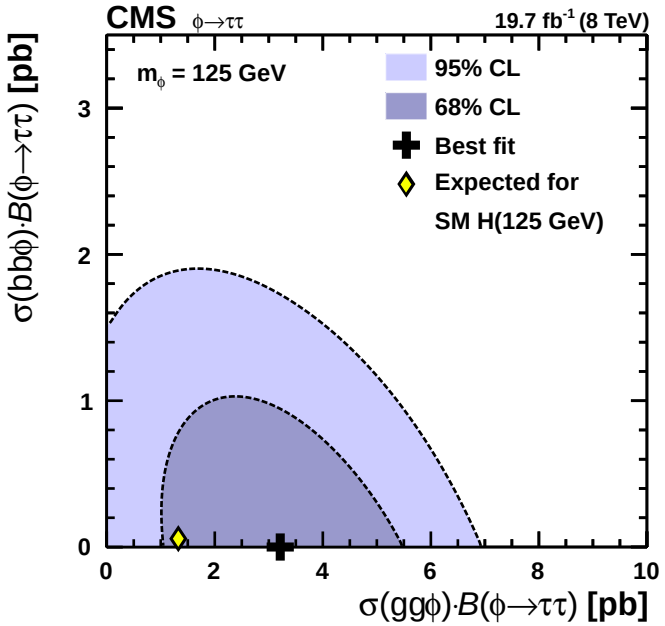


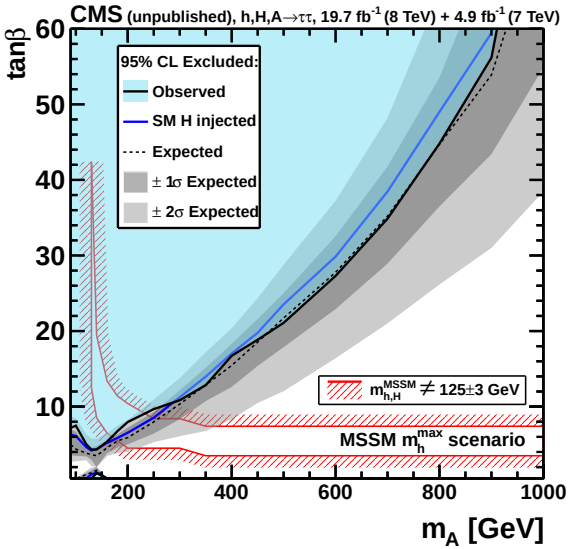


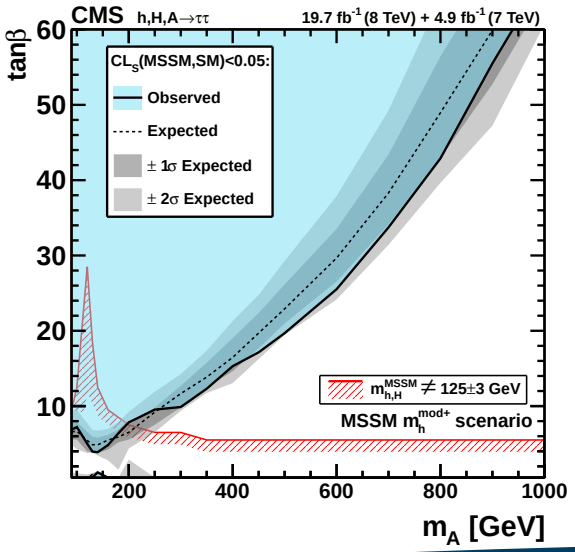


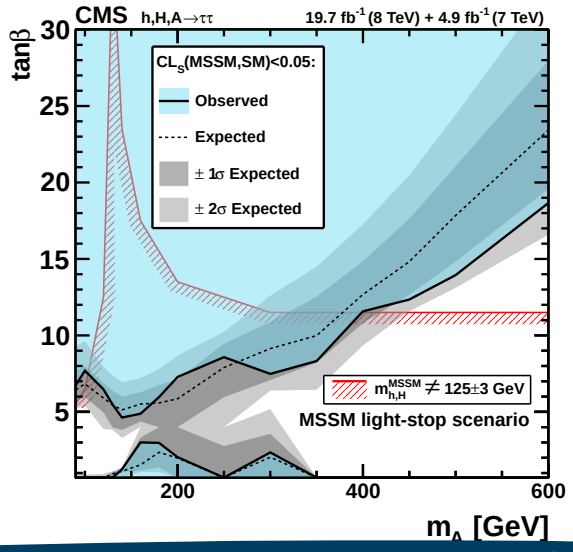
Post-Higgs discovery approach:

- Take into account the presence of the SM-like Higgs boson
- Test the MSSM hypothesis (H, h, A) vs the SM (h)
- More sensitivity to BSM physics: the SM boson can hide MSSM Higgs signals
- Likelihood scan of the 2D plane $gg\Phi - bb\Phi$
- Exclusion interpreted in different scenarios









$b\Phi \rightarrow b(b\bar{b})$

HIG-12-033

- Difficult channel due to the overwhelming QCD b-quark production
- Two different analyses, based on different triggers and strategies

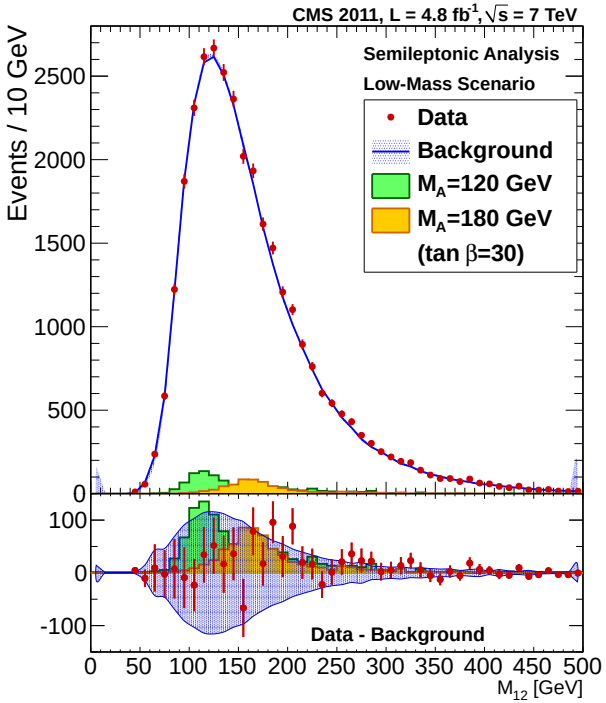
All-hadronic three jets request at trigger level, with online b.tagging requirements

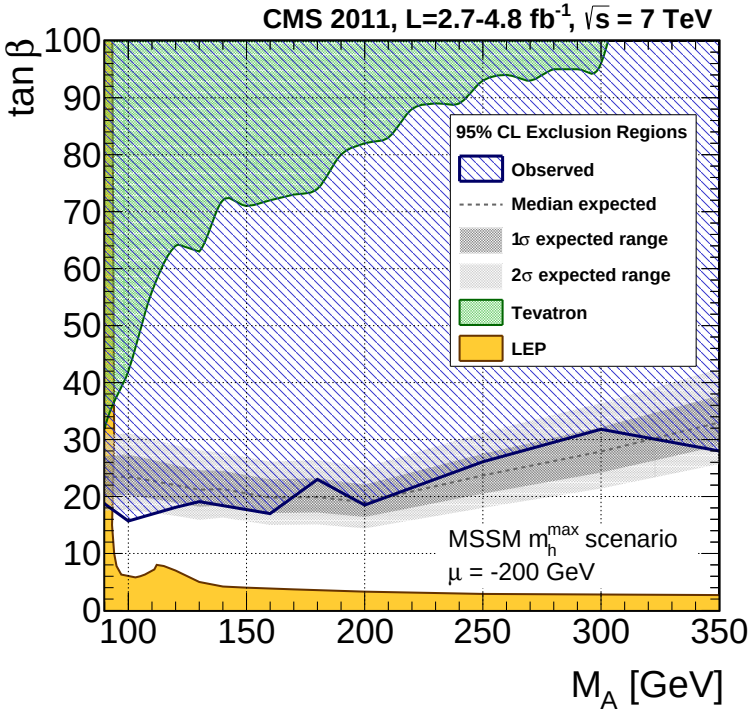
Semi-leptonic exploits the presence of one soft muon (also at trigger level) from HF decays

- Two different data-driven methods developed:

All-hadronic construction of m_{bb} templates for different flavour composition of the three jets, used to fit data to get the signal fraction

Semi-leptonic first method based on third-jet b-tagging probability matrices for 2-tag background reweighting; second independent method based on a custiomization of a kNN algorithm





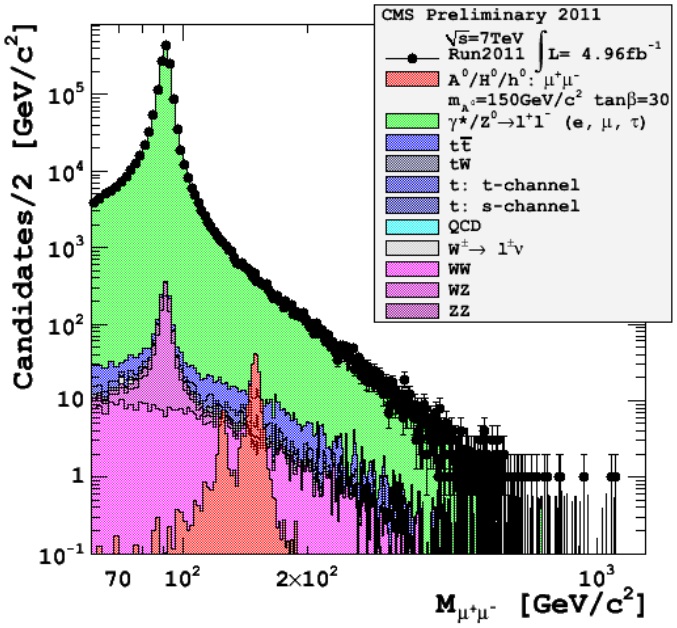
- Combined *All-hadronic* and *Semileptonic* result does not confirm 2σ excess observed by CDF for $m_A \approx 140 \div 160$ *GeV*

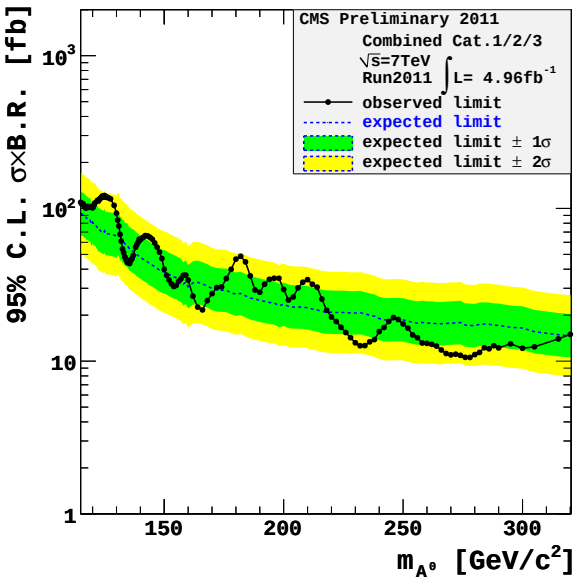
$\Phi \to \mu^+\mu^-$

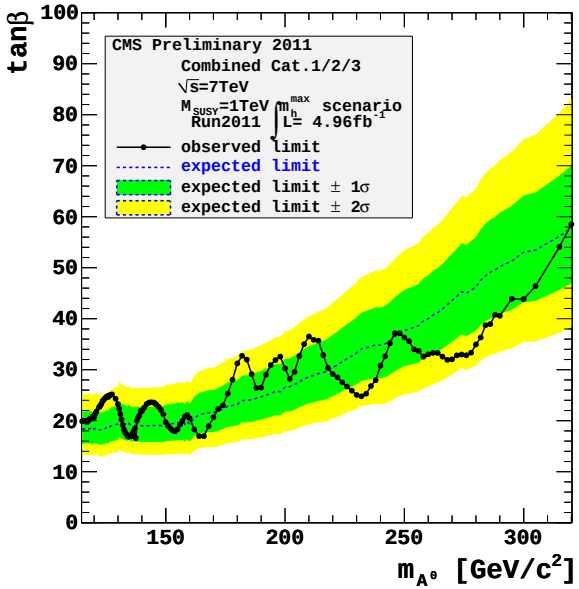
HIG-12-011

- MSSM analysis still based on 2011 data
- SM analysis updated to full luminosity [8], no BSM interpretation given (see Christine's talk)
- 3 exclusive categories based on the presence:

Cat 1 at least one b-tagged jet
Cat 2 an additional soft muon from heavy-flavoured quarks decay
Cat 3 none of the previous, for maximum gg-fusion sensitivity







- Experimental resolution can be better than $h - H - A$ mass separation $\to$ each contribution is fitted independently
- Exclusion limits obtained fitting $m_{\mu\mu}$ and interpreted in MSSM

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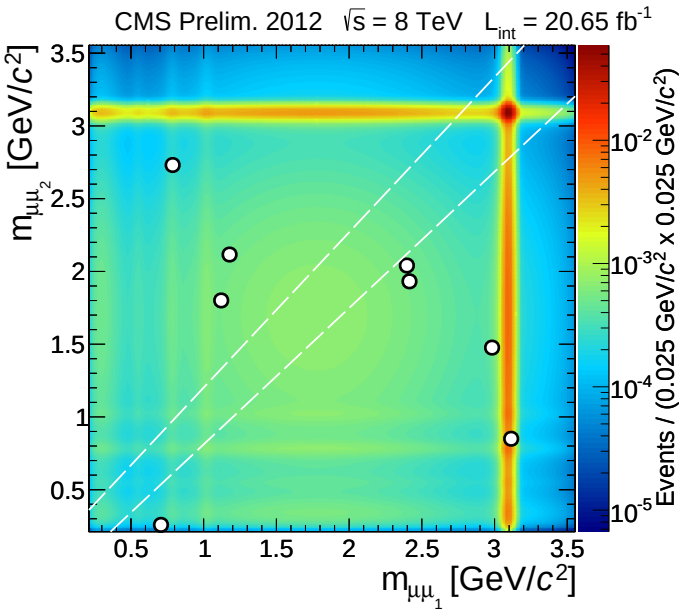
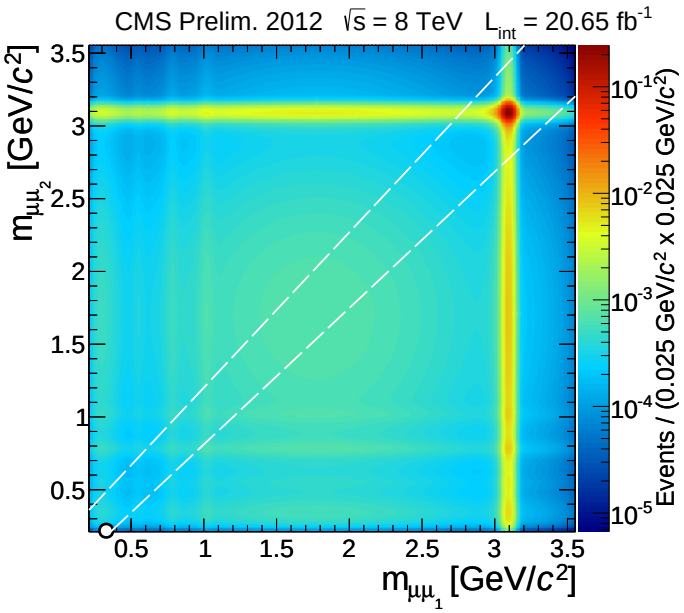
$h \to a_1 a_1 \to 4\mu$

HIG-13-010

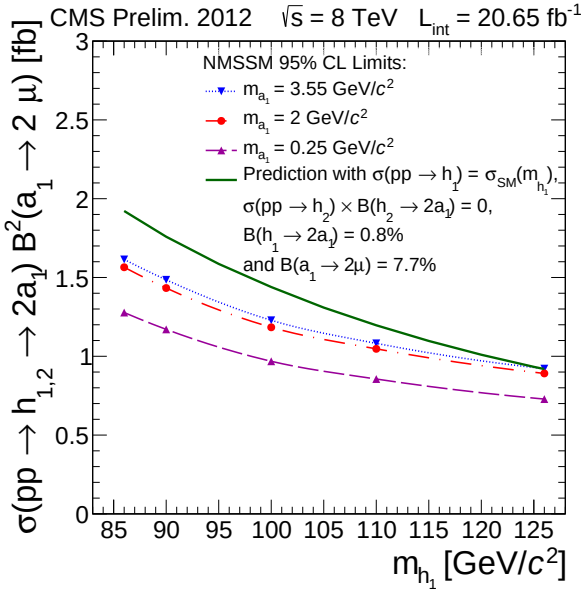
- Model-independent search for events containing 2 $\mu^+\mu^-$ pairs of the same mass
- Possible NMSSM / Dark SUSY signature: a_1 pseudoscalar can be light ($\sim$ few GeV)
- Sensitive for $m_{\mu\mu} < 5GeV$ (otherwise $a_1 \to bb$ dominates)
- Backgrounds from J/ψ, muons from heavy flavours (estimated in data sidebands)
- 1 event observed in SR (expected 3.8 ± 2.1)



Background Region



Signal Region



Exclusion limit in NMSSM

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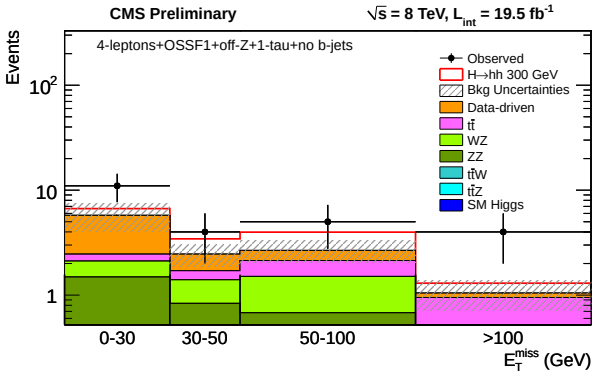
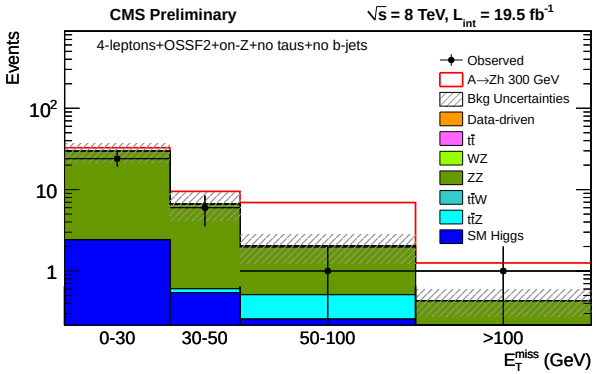
$H \to hh, A \to Zh$ multileptons and γ

HIG-13-025

- Cut & count search for signatures of $H \to hh$ and $A \to Zh$ with di-photon and di-lepton triggered final states
- Categorization by number of ℓ, τ, γ, b-jets, OSSF pairs, on/off-shell Z, $\not{E}_T$ bins
- Data-driven estimation of lepton fakes and asymmetric γ conversions
- Background evaluated in $m_{\gamma\gamma}$ sidebands for di-photon final states





H → hh

	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau\tau$	$h \to bb$	$h \to \gamma\gamma$
$h \to WW^*$	✓	✓	✓	X	✓
$h \to ZZ^*$	-	✓	✓	✓	✓
$h \to \tau\tau$	-	-	✓	X	✓
$h \to bb$	-	-	-	X	X
$h \to \gamma\gamma$	-	-	-	-	X

A → Zh

	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau\tau$	$h \to \gamma\gamma$
$Z \to ll$	✓	✓	✓	✓
$Z \to qq$	X	✓	X	X
$Z \to \nu\nu$	X	✓	X	X

- Small excess in one particular channel: $4\ell+\tau_h$, Z off-shell (local p-value 1.5%, global 5%), no significant deviations elsewhere

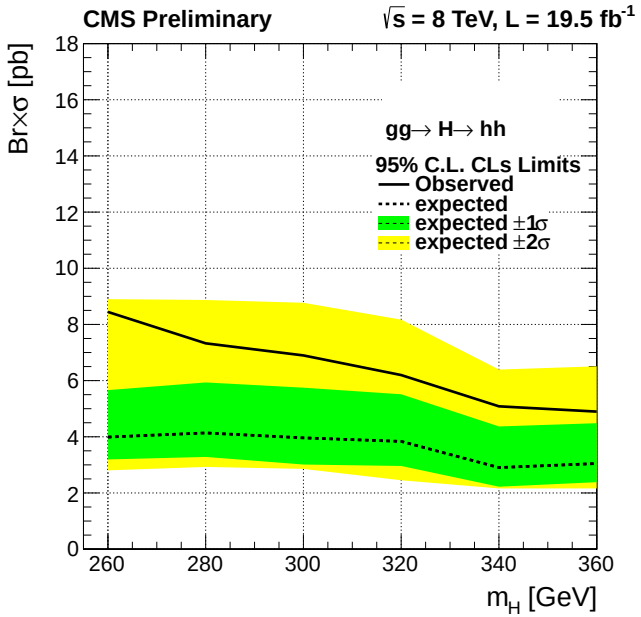
$H \to hh, A \to Zh$ multileptons and γ

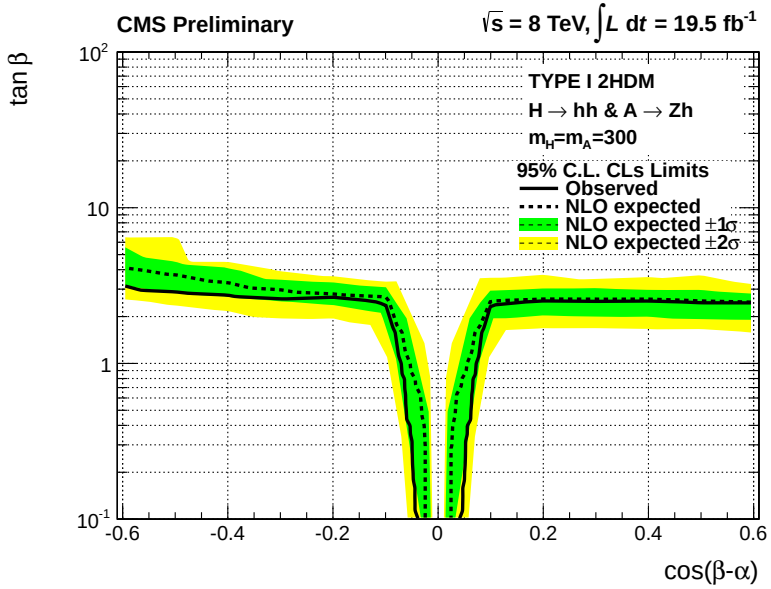
HIG-13-025

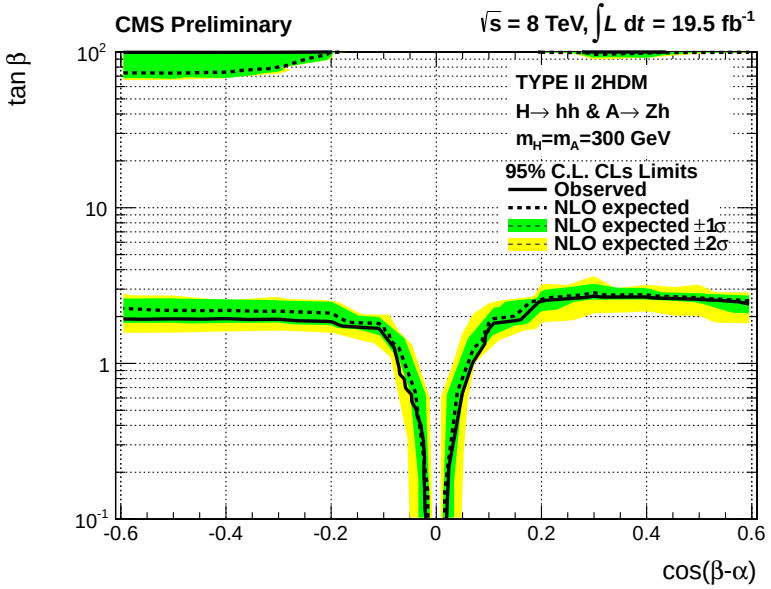
- Combination of all channels for $H \to hh$ and $A \to Zh$
- Excess significance reduced when combined with other channels
- Recast $\sigma \times Br$ limits in 2HDM Type-I and Type-II parameter space:

  α mixing angle between the two doublets

  $\tan\beta$ ratio of the v.e.v. of the two doublets
- $\cos(\beta - \alpha) \to 0$ case is SM-like couplings (alignment limit)
- Low $\tan\beta$ regions excluded







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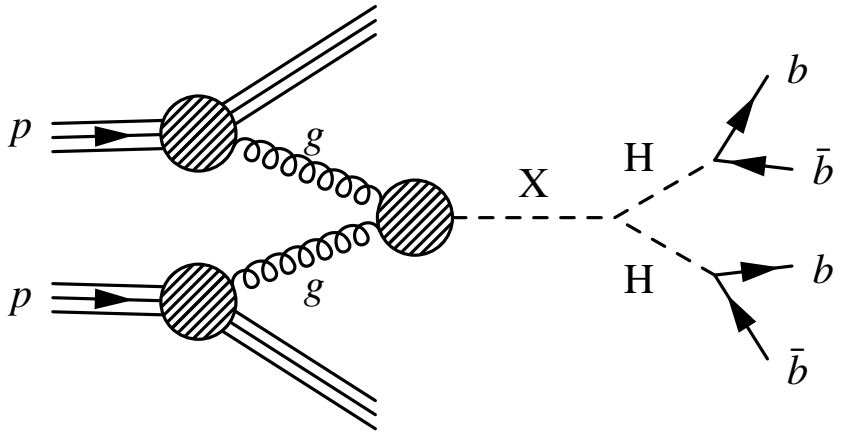
Warped Extra Dimensions

Warped Extra Dimensions in a nutshell

- **WED** models: radion (spin-0) and KK-graviton (spin-2)
- Radion mass depends on ED *stabilization mechanism*
- Graviton mass depends on the *geometry* of the ED
- σ_X depends on decay constant Λ_R (radion) or product of the curvature and lenght of ED kL (gravition)
- Coupling with h is possible, and the $X \to hh \to YYYY$ decay chain can be observable at LHC
- h is assumed to be the SM-like Higgs boson

CMS searches

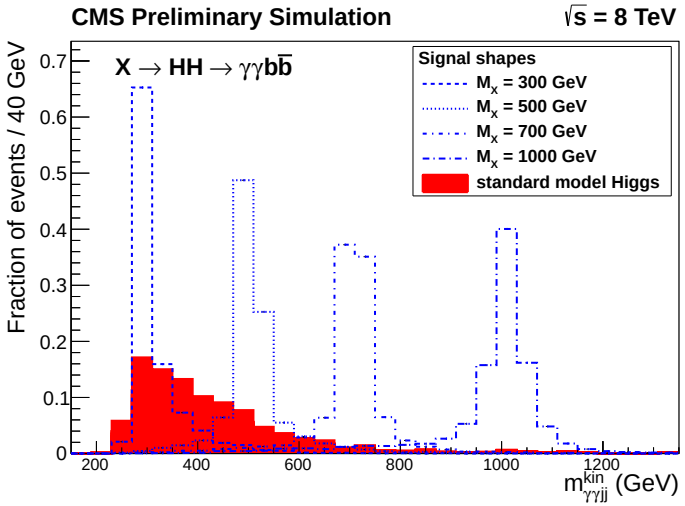
- Considered only non-boosted regime ($m_X < 1100 GeV$)
- Gluon-fusion production and $X \to hh$ decay
- Two final states considered:
  - $h \to \gamma\gamma$, $h \to b\bar{b}$: clean final state, low yield ($Br(h \to \gamma\gamma) \approx 0.26\%$)
  - $h \to b\bar{b}$, $h \to b\bar{b}$: large Br, huge QCD background



$X \to hh \to \gamma\gamma b\bar{b}$

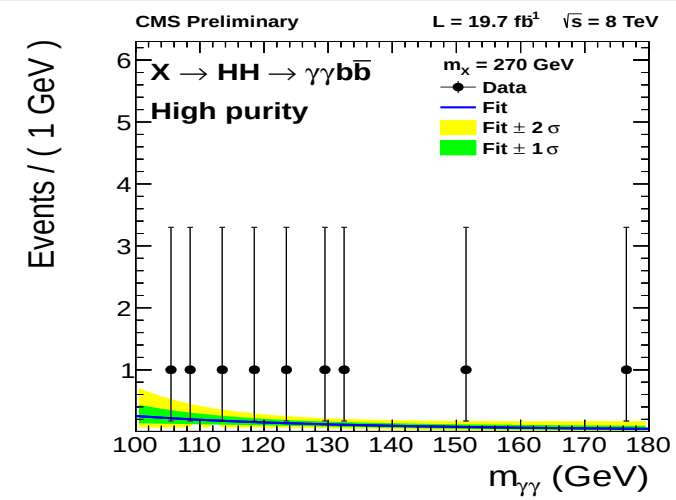
HIG-13-032

- Large $Br(h \to b\bar{b})$, excellent $h \to \gamma\gamma$ efficiency and resolution
- Three different b-tagging categories (0, 1, 2 tagged jets, first one only as a cross-check)
- Two different strategies depending on the mass range (Low ≤ 400, High $> 400 GeV$)



Low Mass

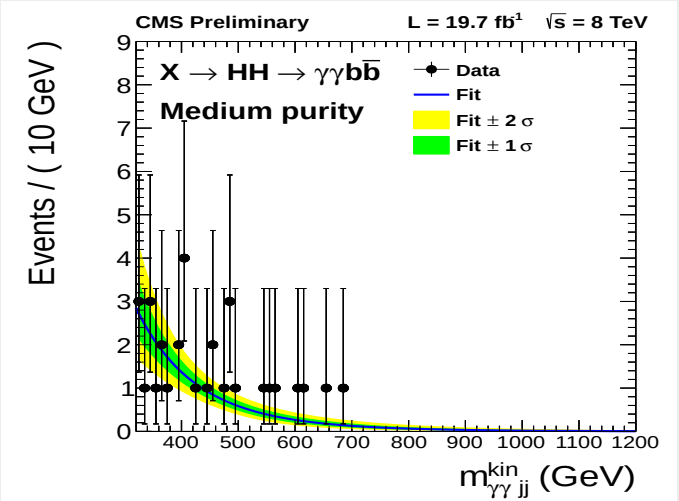
Fit the $m_{\gamma\gamma}$ spectrum ($H \to \gamma\gamma$ style) after cutting on m_{jj} and $m_{\gamma\gamma jj}$



High Mass

Apply kinematic fit to $m_{jj} = 125 GeV$

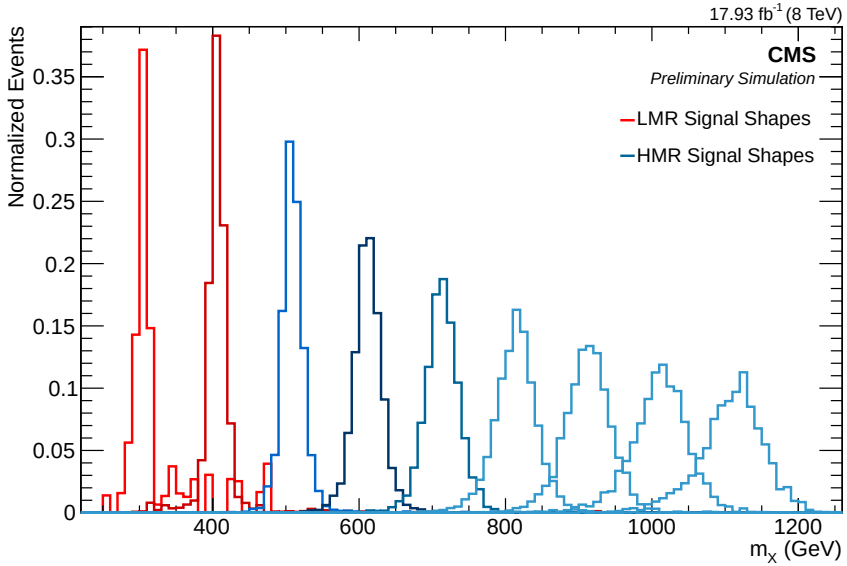
Direct fit to m_X, after $m_{\gamma\gamma}$ and m_{jj} cuts

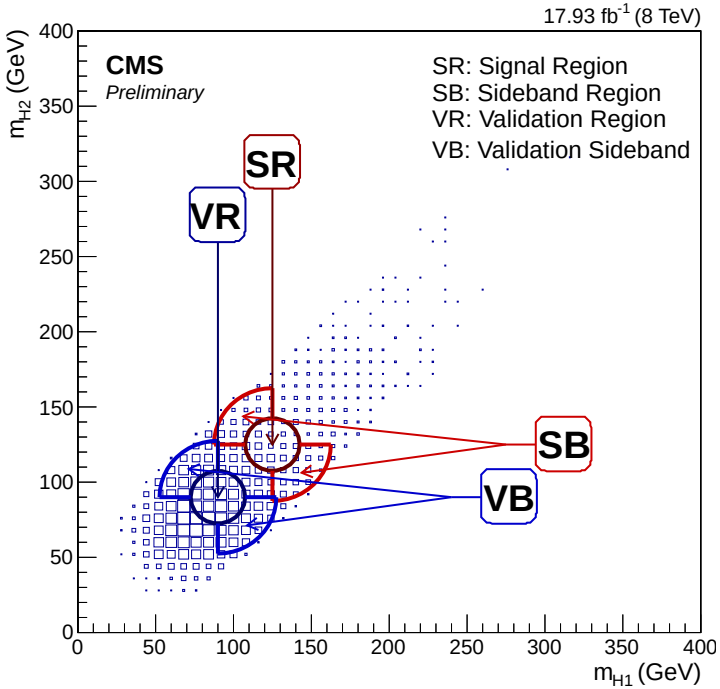


$X \to hh \to b\bar{b}b\bar{b}$

HIG-14-013

- Susteinable jet p_T thresholds thanks to b-tagging at trigger level
- Final state with 4 b-jets, three reconstructible resonances
- Kinematic fit applied to b-jet pairs to have $m_{jj} = 125 GeV$
- $m_{4b} \sim 10 \div 15\%$ after kin. fit
- Look for narrow resonances in the m_{bbbb} spectrum





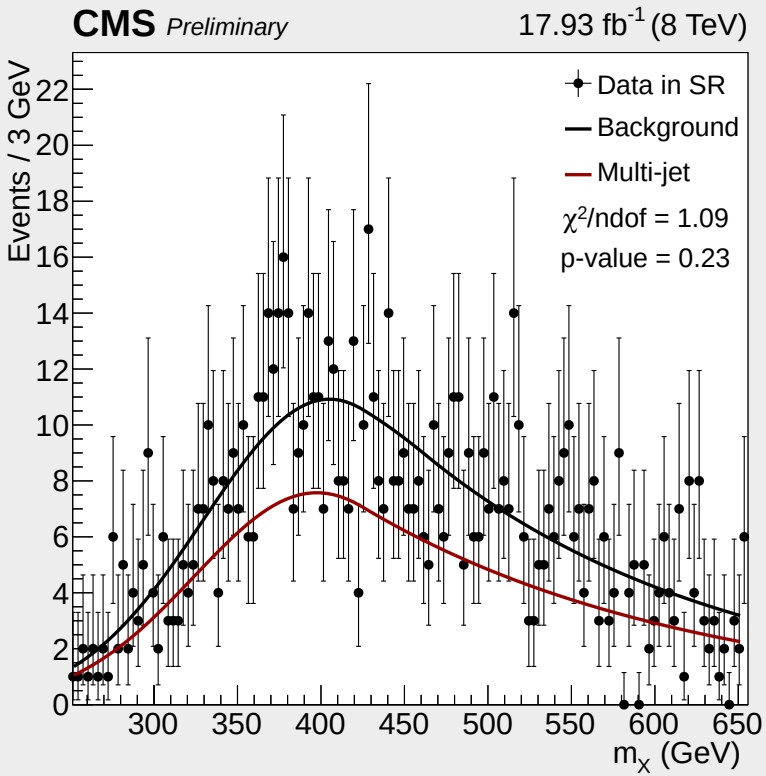
- Huge multijet (estimated from data) and $t\bar{t}$ (from MC) backgrounds
- Background shape functional form extrapolated from Sideband Regions to Signal Region
- Method tested and verified in the Validation Sidebands and Validation Region
- Cross-check by inverting the 4th b-tag

$X \to hh \to b\bar{b}b\bar{b}$

HIG-14-013

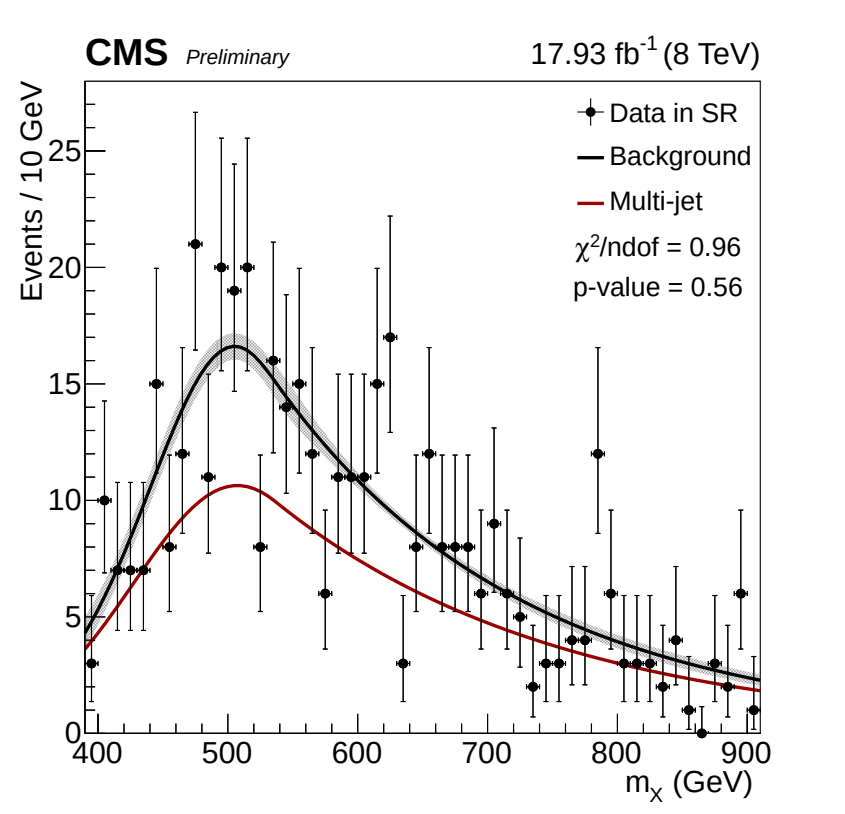
- Two mass regions (Low < 440, High $> 450\,GeV$) with different candidate reconstruction choices

Low Mass



- h candidates built with the best Δm_{jj} pairs

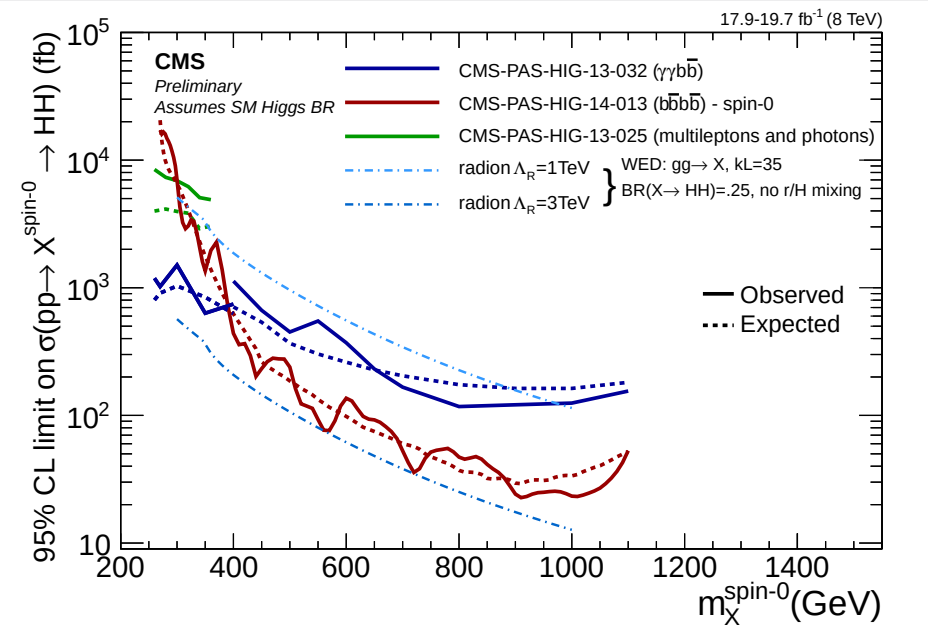
High Mass



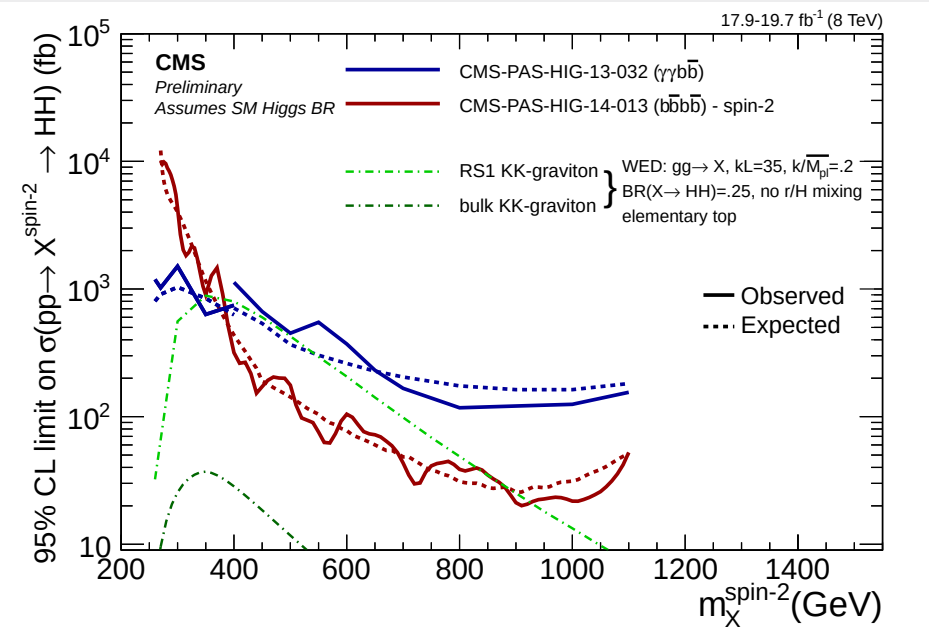
- Jets paired if close enough ($\Delta R < 1.5$)
- For $m_X > 740\,GeV$, h boost requirement introduced

$X \to hh$ combination

Radion



KK-graviton



- Assumed $Br(X \to hh) = 25\%$ and SM $Br(h \to \gamma\gamma)$ and $Br(h \to b\bar{b})$
- $X \to hh \to \gamma\gamma bb$ is more sensitive at low mass $m_X < 400 GeV$ (cleaner final state), $X \to hh \to b\bar{b}b\bar{b}$ advanteged by larger yield at higher masses
- $\Lambda_R = 1 TeV$ Radion excluded, close to $\Lambda_R = 3 TeV$ range
- RS1 KK-graviton excluded for ($m_X \lesssim 900 GeV$), larger gap to reach the bulk KK-graviton

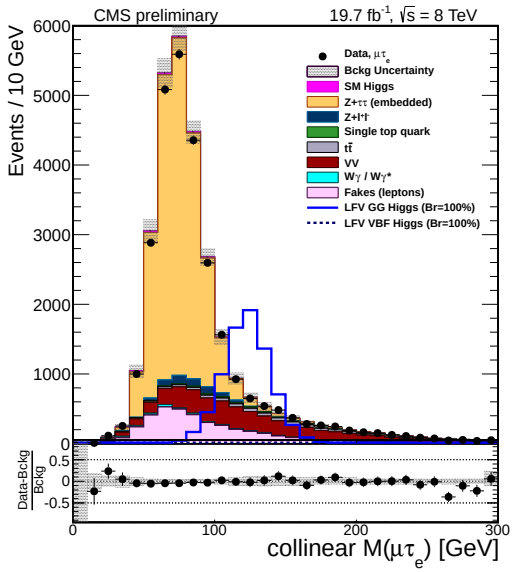
Outline

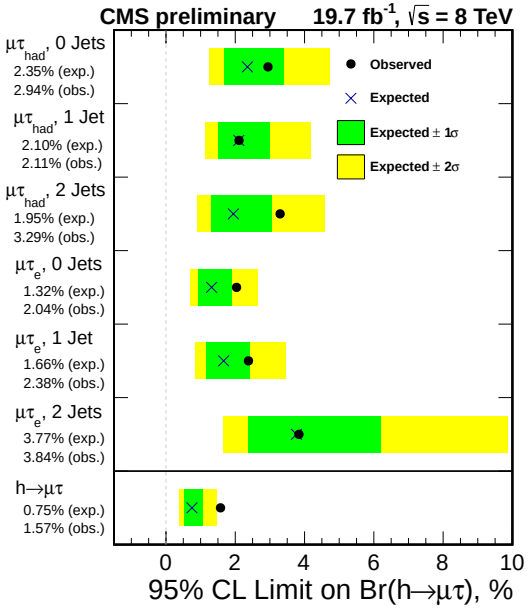
1. MSSM searches
   - $\Phi \to \tau^+\tau^-$
   - $b\Phi \to 3b$
   - $\Phi \to \mu\mu$
2. NMSSM searches
   - $h \to a_1 a_1 \to 4\mu$
3. 2HDM searches
   - $H \to hh, A \to Zh$ multileptons and γ
4. Extra Dimension searches
   - $X \to hh \to \gamma\gamma b\bar{b}$
   - $X \to hh \to b\bar{b}b\bar{b}$
5. Anomalous Higgs searches
   - LFV $h \to \mu\tau$
   - Invisible Higgs
6. Heavy Higgs searches
   - $H \to \gamma\gamma$
   - $H \to WW \to \ell\nu jj$

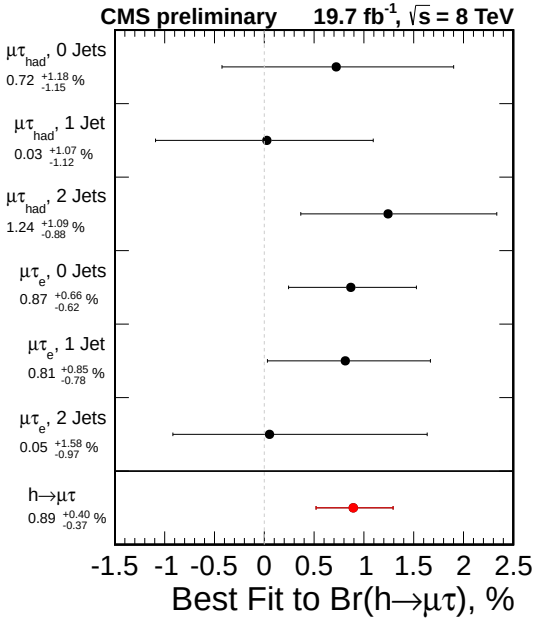
Lepton Flavour Violating $h \to \mu\tau$

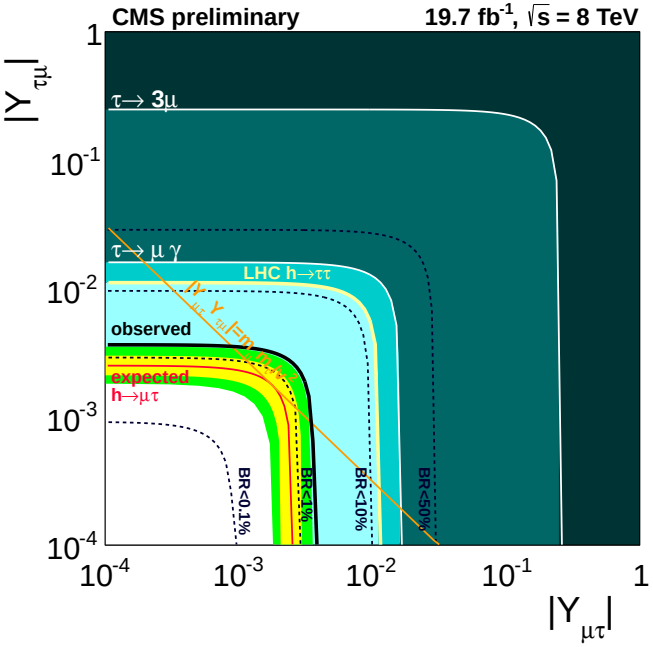
HIG-14-005

- Search for two final states $h \to \mu\tau_e$ and $h \to \mu\tau_h$
- Reconstruct collinear $m_{\tau\mu}$ and look in the 125 GeV region
- Higher sensitivity w.r.t. re-interpreting $h \to \tau\tau$ search
- Small excess observed (2.5σ), best fit $Br(h \to \mu\tau)$ provided: $0.89^{+0.40}_{-0.37}$% (expected 0%)
- Strict constrain for the $Y_{\mu\tau}$ couplings









Invisible Higgs

HIG-13-030

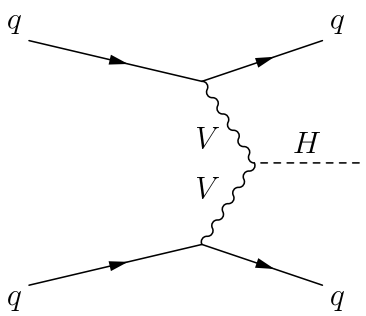
- Search for non-standard Higgs decay modes, and additional bosons with similar production modes and large invisible branching fraction
  - 3 final states for 2 production modes:

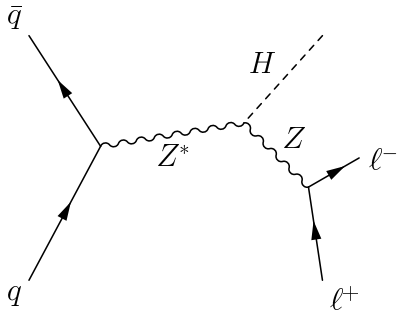
    VBF: two jets, high $\Delta\eta$ and m_{jj}

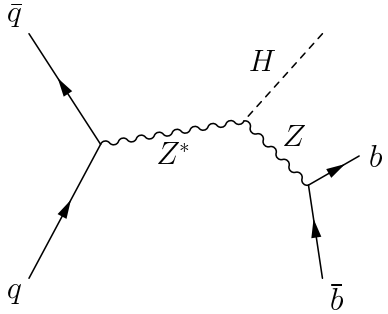
    $Z \to \ell\ell$: two leptons in the final state

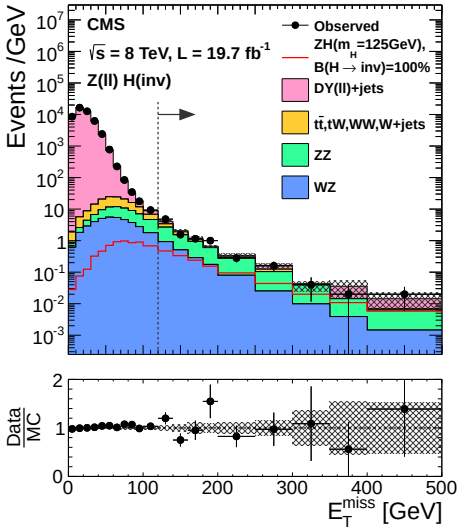
    $Z \to bb$: b-jet regression, $\not{E}_T$ categorization, BDT fit
  - Competitive constraints from h width indirect measurement (see Pavel's talk)
  - Interpretation in Higgs portal model of Dark Matter
    - Stable DM particles couple to Higgs sector
    - Different scenarios if DM is scalar, vector or fermion

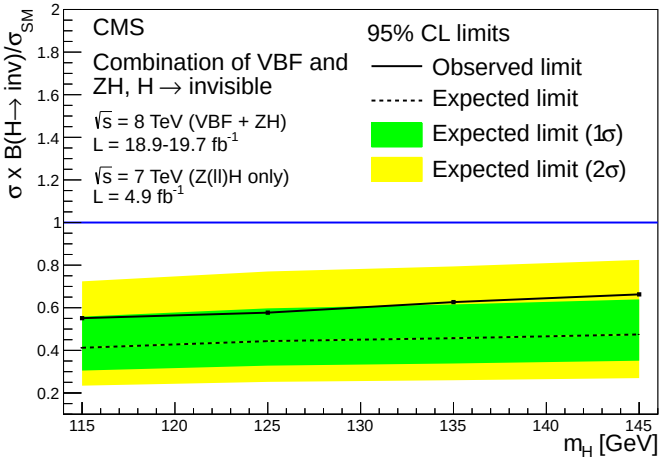
  Caveat : strong assumptions on a complex model

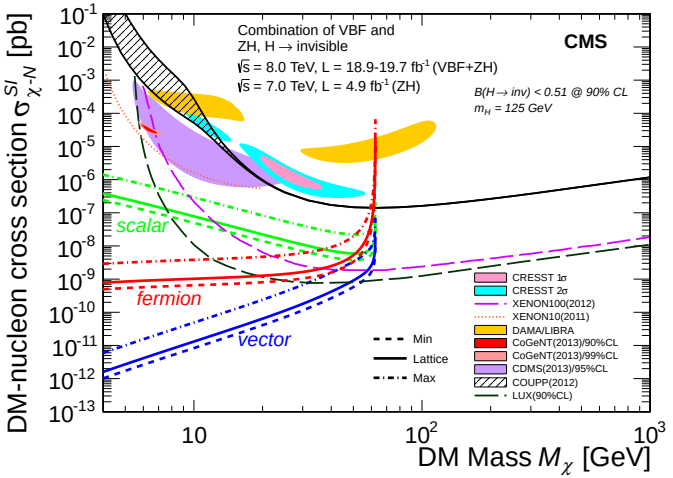












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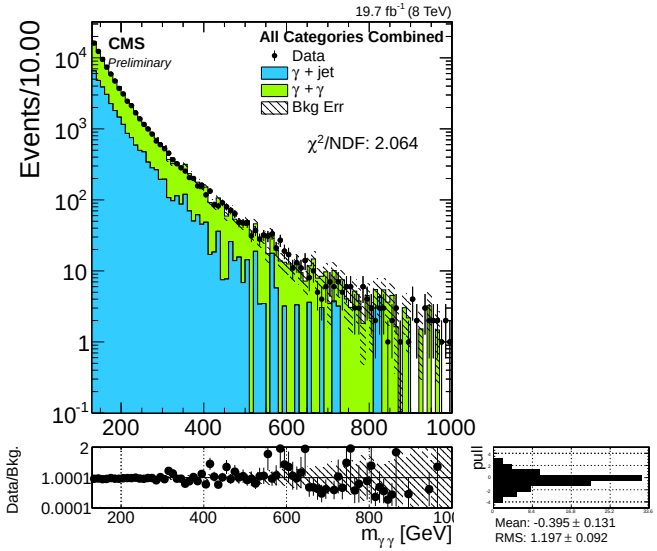
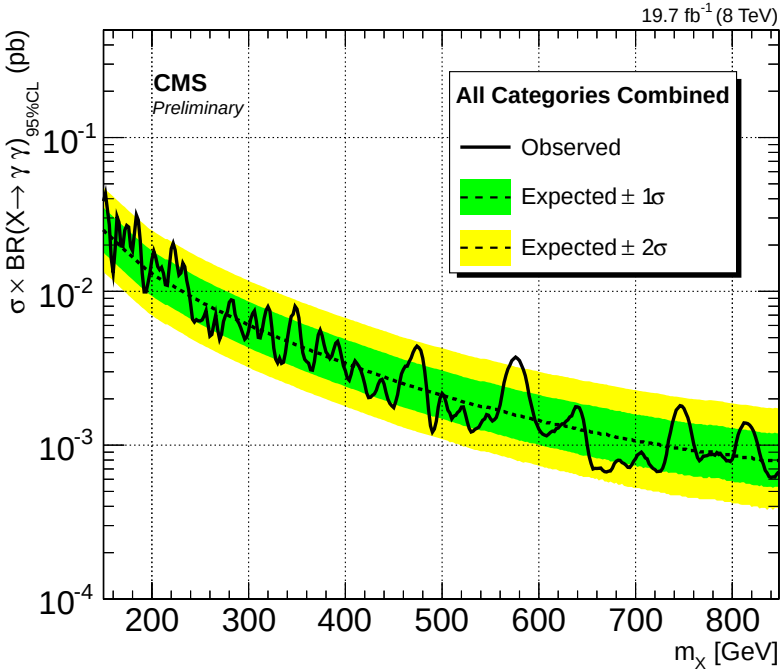
   - LFV $h \to \mu\tau$
   - Invisible Higgs
6. Heavy Higgs searches
   - $H \to \gamma\gamma$
   - $H \to WW \to \ell\nu jj$

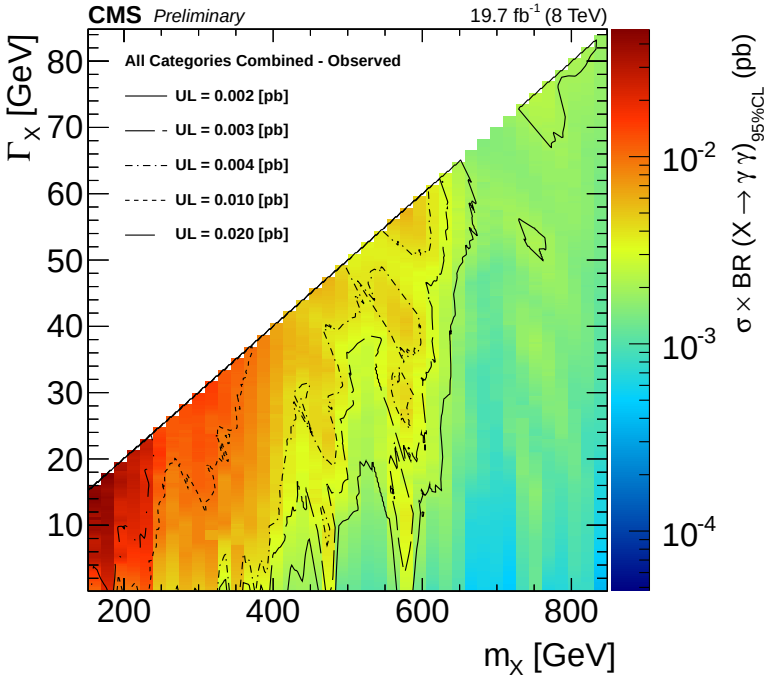
High mass $H \to \gamma\gamma$

HIG-14-006

- Extension of the SM $H \to \gamma\gamma$ search
- Spot bumps in the di-photon invariant mass after γ identification
- Considering signal width up to 10% of the resonance mass
- Takes into account both spin-0 and spin-2 signals
- Limit on $\sigma \times Br$ and in the m_X-Γ_X plane







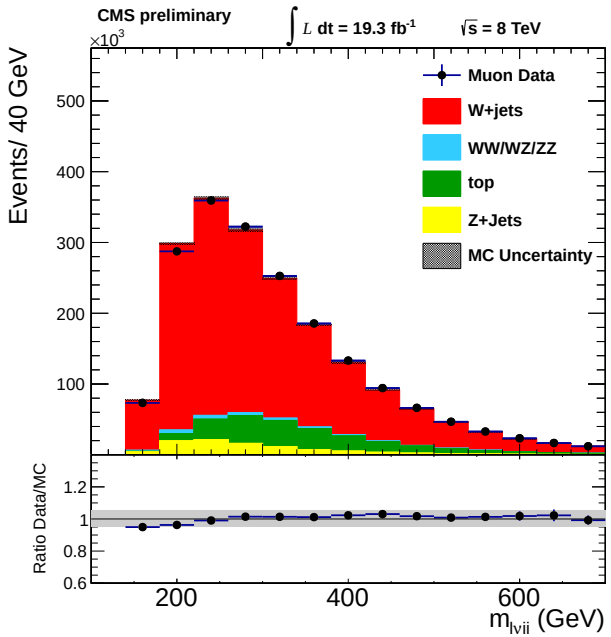
High Mass $H \to WW \to \ell\nu jj$

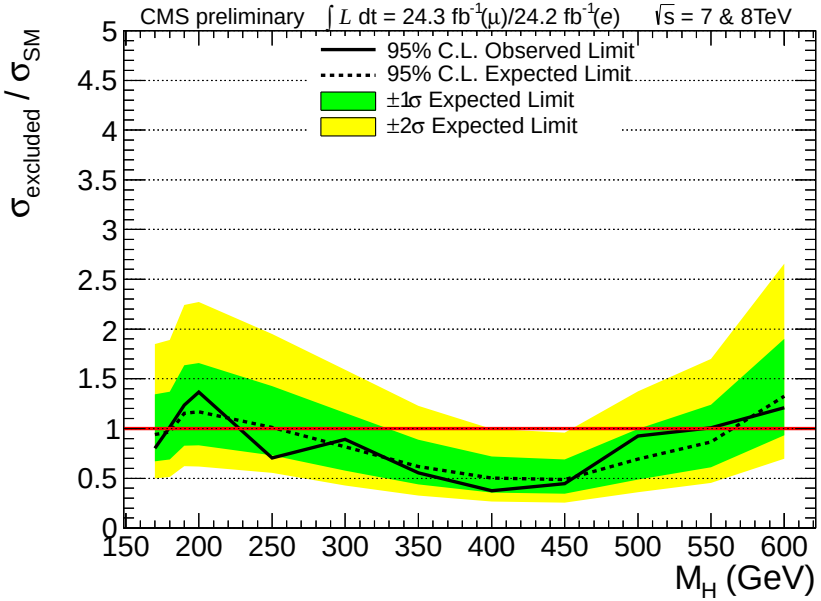
HIG-13-027

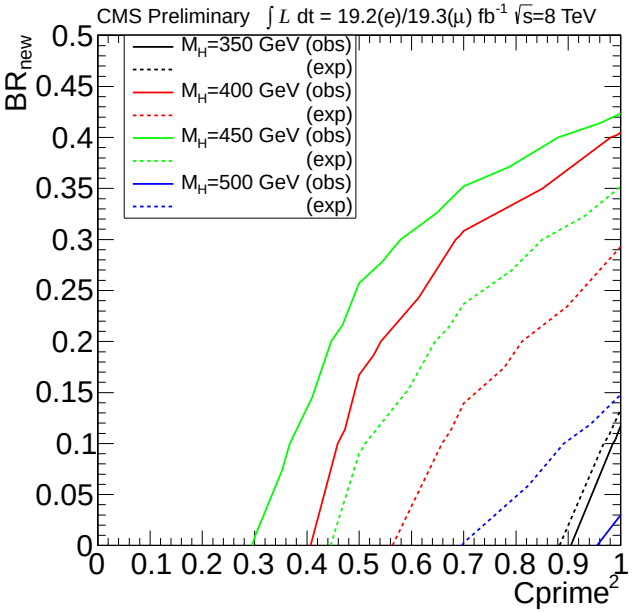
Electroweak Scalar Singlet theory

- An scalar singlet is introduced
- A new heavy Higgs H is present, and mixes with h
- H couplings parametrized by C'^2 ($= 1$ is SM-like)
- Additional contribution Br_{new} to new H decays
- Exclusion limits as a function of m_H, C'^2, Br_{new}

- Search for an heavy Higgs $H \to WW$ with one lepton ($\ell = e, \mu$) in the final state
- Likelihood angular discriminator for bkg. separation







Concluding Remarks

Run-I BSM Higgs searches orview

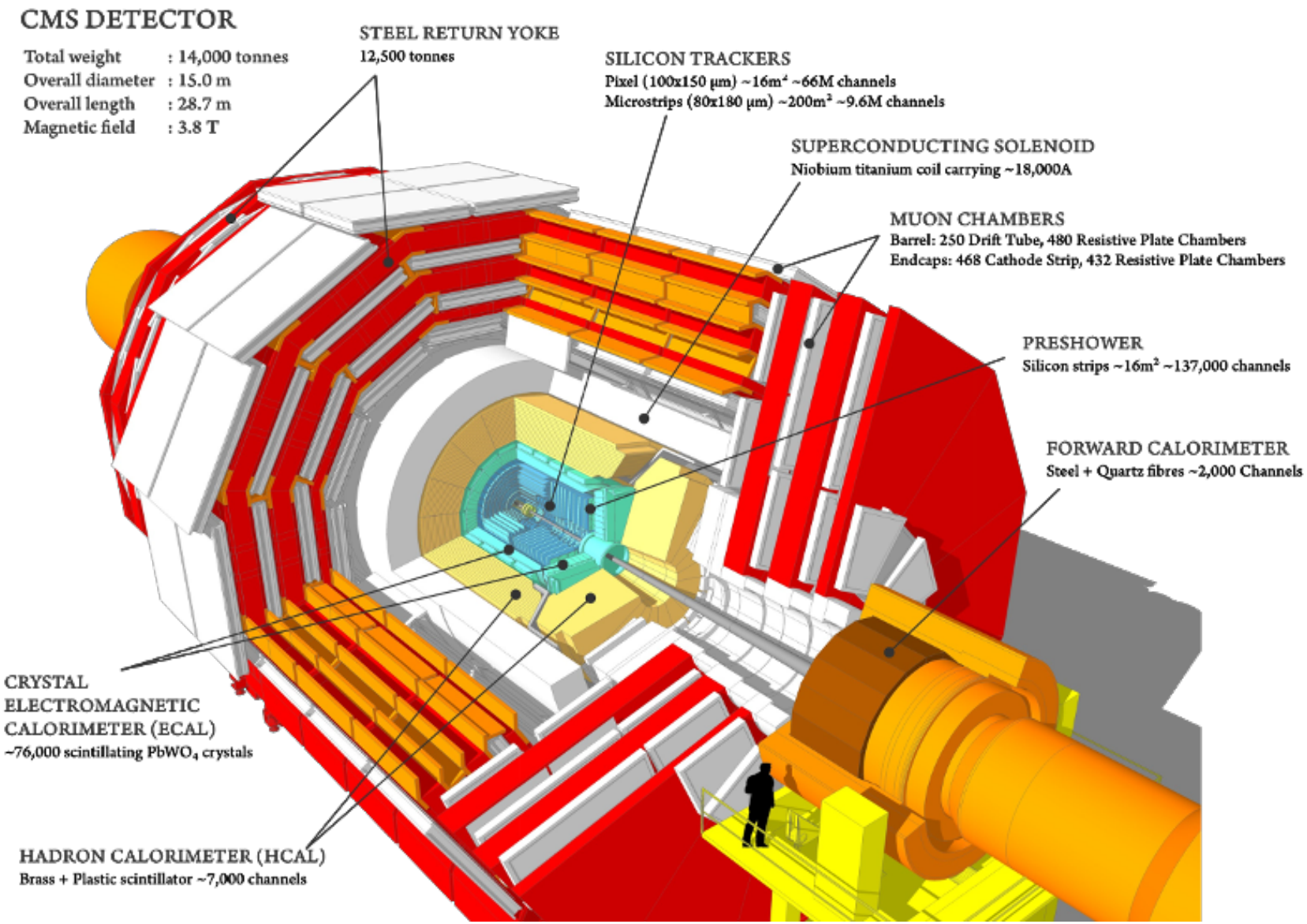
- We found a (SM-like) Higgs boson and we are measuring its properties
- Strong interest now addressed to the extended Higgs sector and its signatures
- Use the discovery to enhance our sensitivity to BSM physics
- Started with very specific models (e.g. MSSM), now turning towards more generic theories
- No strong hints of BSM physics so far in LHC Run-I

Run-II perspectives

- Analyses already preparing for LHC Run-II at $\sqrt{s} = 13\,TeV$
- Expected sensitivity boost especially for high mass resonances searches
- Ready to look for rare SM processes, e.g. Higgs self-couplings, WW scattering
- If *new physics* exists, it may show up in the Higgs sector!

Backup slides

The CMS experiment



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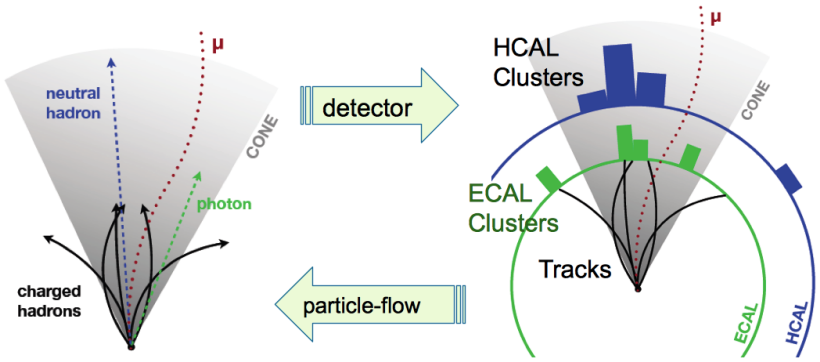
Tau reconstruction at CMS

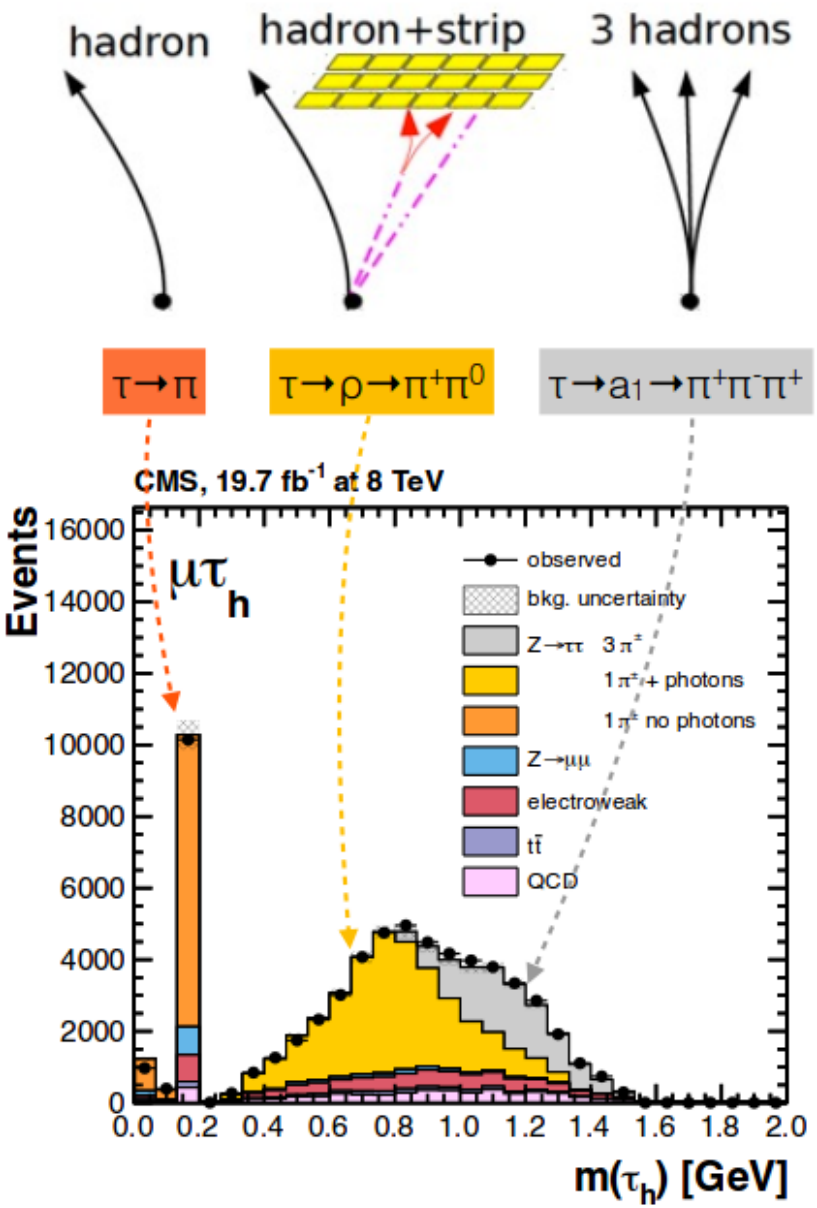
- $m_\tau = 1.777 GeV$, $c \cdot \tau = 87 \mu m$
- $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau = 17.36\%$
- $\tau^- \to e^- \bar{\nu}_e \nu_\tau = 17.85\%$

Decay Mode	Resonance	BR [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to \pi^- \nu_\tau$	$\pi(140)$	11.6
$\tau^- \to \pi^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to \pi^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	10.8
$\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$		4.8
Other hadronic modes		1.7
All hadronic modes		64.8

PDG

- Particle candidates reconstructed with the Particle Flow algorithm
- τ_h reconstructed with the HPS (Hadron Plus Strip) algorithm





2 Higgs Doublet Model

- Two scalar $SU(2)$ doublets Φ_1 and Φ_2
- A soflty broken Z_2 symmetry which forbids FCNC
- No CP-violation in the Higgs sector
- Lagrangian parametrization: $\tan\beta, m_{12}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$
- Physical parametrization: $\tan\beta, \beta-\alpha, m_{12}^2, m_h, m_H, m_A, m_{H^\pm}$
- **Custodial limit** The 2HDM Higgs sector has a custodial symmetry when $m_H = m_{H^\pm}$ or $m_A = m_{H^\pm}$
- **Alignment limit** The light CP even Higgs h has SM-like couplings for $\beta-\alpha = \frac{\pi}{2}$
- **Decoupling limit** The 2HDM is phenomenologically indistinguishable from the SM for $m_{12}^2 >> v^2$
- Note that relations between Lagrangian and physical parameters are of the form

$$\lambda_1 = \frac{m_H^2\cos^2\alpha + m_h^2\sin^2\alpha - m_{12}^2\tan\beta}{v^2\cos^2\beta}$$

  Perturbativity requires that in the decoupling limit $\beta-\alpha \to \frac{\pi}{2}$ and that heavy Higgs masses are "fine tuned"
- Types of models can be distinguished by Yukawa couplings:

Type	u_R	d_R	e_R
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Type III	Φ_2	Φ_2	Φ_1
Type IV	Φ_2	Φ_1	Φ_2

Minimal SuperSymmetric Standard Model

Scenario	Mass (GeV)	Parameters	Phenomenology
$\mathbf{m_h^{max}}$	$m_h \sim 135$	stop mix. par. $X_t = 2\,TeV$	-
$\mathbf{m_h^{mod+}}$	$m_h \sim 125$	m_h^{max} with $X_t = 1.5\,TeV$	compatible with $(g-2)_\mu$
$\mathbf{m_h^{mod-}}$	$m_h \sim 125$	m_h^{max} with $X_t = -1.9\,TeV$	compatible with $B(b \to s\gamma)$
light-stop	$m_h \sim 125$	$M_{stop} \sim 340\,GeV$	$\tilde{t} \to t\chi_0$ suppressed, reduced ggH
light-stau	$m_h \sim 125$	$M_{stau} \sim 245\,GeV$	enhanced $H \to \gamma\gamma$ rate
tauphobic	$m_h \sim 125$		Reduced coupling to down-type fe
low $\mathbf{m_H}$	$m_H \sim 125$	$M_A \sim 110\,GeV$	Scan the $\tan\beta - \mu$ parameters

Higgs singlet

- An additional electroweak scalar singlet is introduced in the SM Lagrangian
- A new physical scalar boson, with mass $m_H > m_h$, mixes with the $m_h = 125 GeV$ scalar boson
- The couplings of the two gauge bosons h, H are rescaled by scale factors C, C'
- Unitarity condition requires $C^2 + C'^2 = 1$
- Heavy scalar can decay to other particles with unkown branching ratio Br_{new}
- Heavy Higgs cross-section modified by factor $\mu' = C'^2(1 - Br_{new})$
- New width is $\Gamma' = \Gamma \frac{C'^2}{(1-Br_{new})}$
- $\Gamma' < \Gamma$, reweighting of the Higgs line-shape
- Results presented as a function of m_H, C'^2, Br_{new}

Lepton Flavour Violating Higgs Decays

- LFV Higgs decays are possible if theory renormalization requirement is dropped
- Without giving up renormalizability, other theories allow LFV decays: more than one Higgs doublets, composite Higgs, RS models
- Virtual Higgs can mediate decays $\tau \to \mu$, $\tau \to e$, $\mu \to e$
- $\mu \to e$ strongly constrained by null searches of $\mu \to e\gamma$
- $\tau \to \mu$, $\tau \to e$ constraints come from $\tau \to \mu\gamma$ and $\tau \to e\gamma$ and $g-2$ measuments, leading to $Br(H \to \tau\mu) < 13\%$ and $Br(H \to \tau e) < 13\%$
- Analysis puts a constrain on $Br(H \to \mu\tau)$, which can be interpreted in terms of the LFV Higgs Yukawa coupling

The LFV Lagrangian is:

$$L_v = \cdots - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h$$

The decay width is:

$$\Gamma(H \to l^\alpha l^\beta) = \frac{m_h}{8\pi}(|Y_{l^\beta l^\alpha}|^2 + |Y_{l^\alpha l^\beta}|^2)$$

where $l^\alpha, l^\beta = e, \mu, \tau$. This translates into the Higgs Branching ratio:

$$Br(H \to l^\alpha l^\beta) = \frac{\Gamma(H \to l^\alpha l^\beta)}{\Gamma(H \to l^\alpha l^\beta) + \Gamma_{SM}}$$

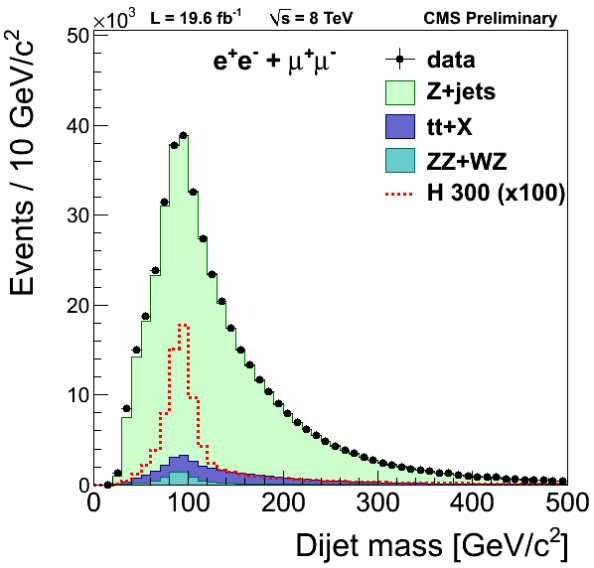
Theoretical naturalness limit:

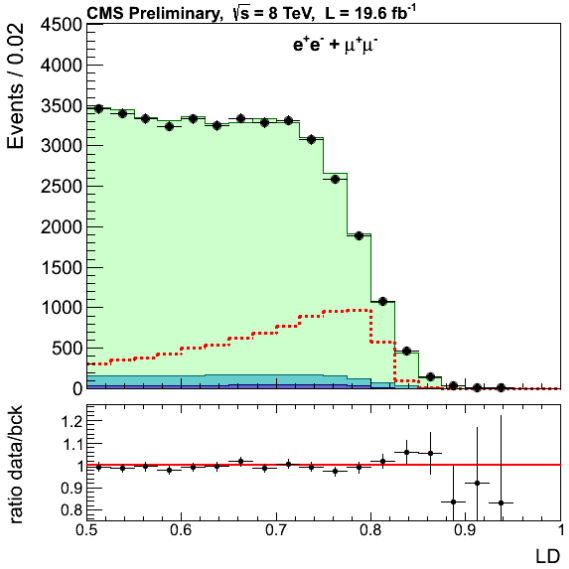
$$Y_{ij}Y_{ij} \lesssim m_i m_j / v^2$$

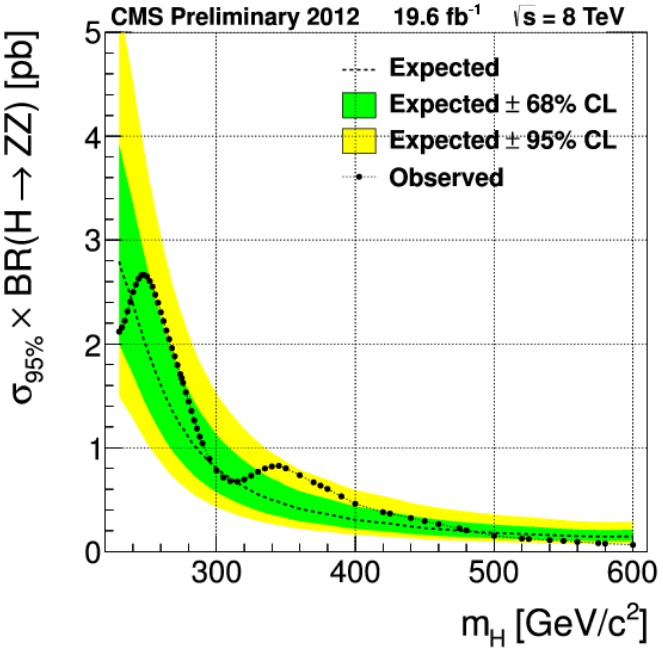
$H \to ZZ \to \ell\ell qq$

HIG-12-024

- Look for high-mass scalar boson decaying into ZZ pairs with 2ℓ 2 jets final state
- Categorization by number of b-tagged jets to enhance sensitivity to $Z \to b\bar{b}$ (0, 1, 2)
- Likelihood angular discriminant using the 2 production and 3 decay angles in the process



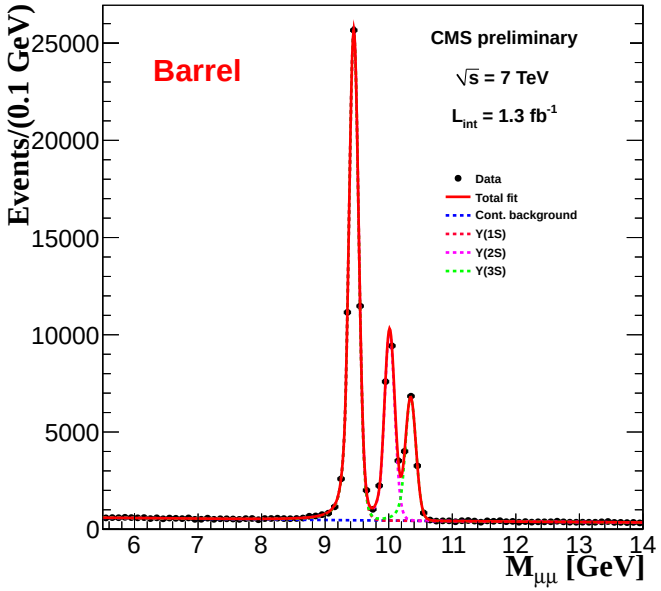


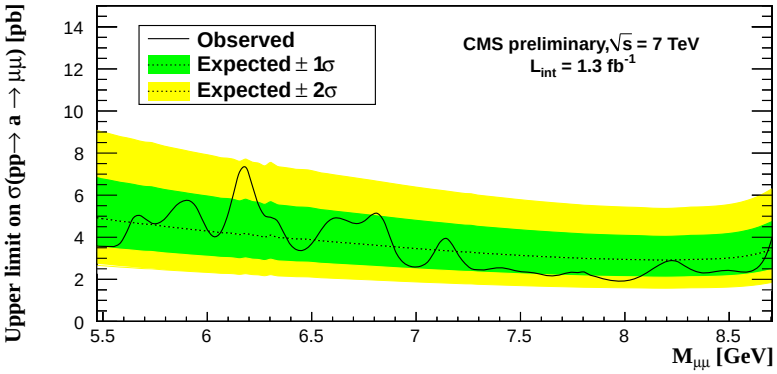


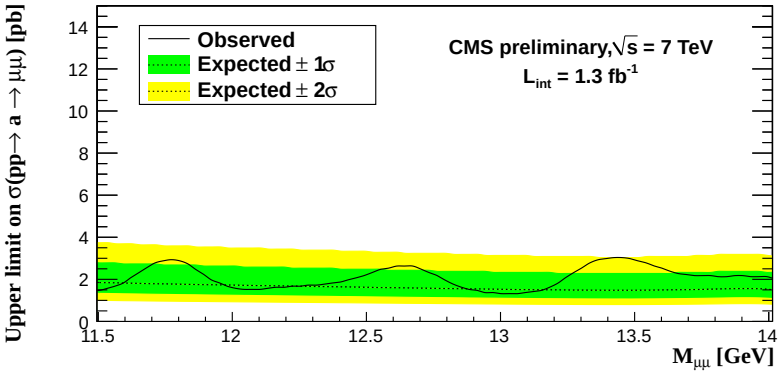
$a \to \mu^+\mu^-$

HIG-12-004

- Look for low-mass dimuon resonances
- Avoid region around Υ mass windows ($5.5 - 8.8$ GeV and $11.5 - 14$ GeV)
- Light pseudoscalars may have avoided detection at LEP
- Possible in NMSSM scenarios
- Better limits than BaBar for $m_a < \Upsilon_{1S}$, and only limits available for $m_a > \Upsilon_{3S}$

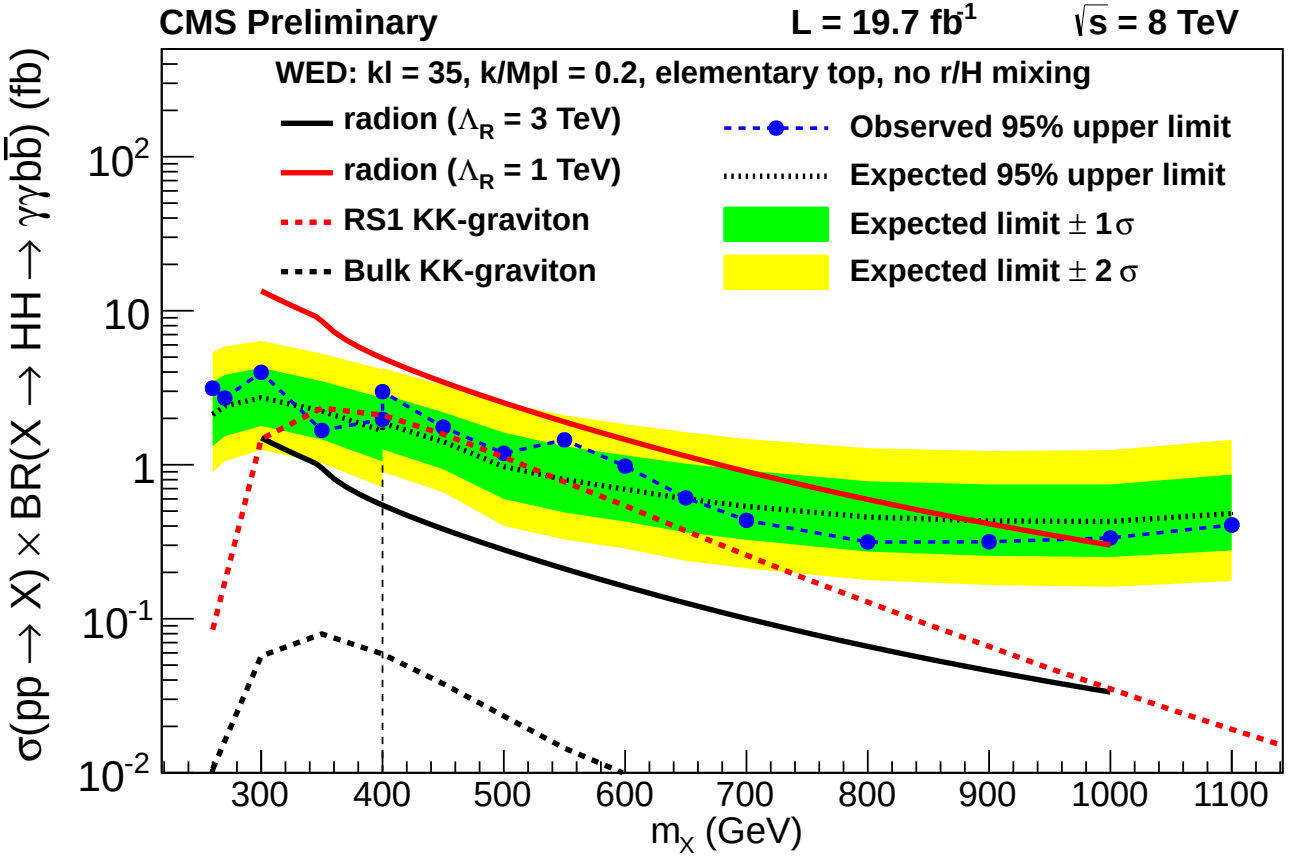






$X \to hh \to \gamma\gamma b\bar{b}$

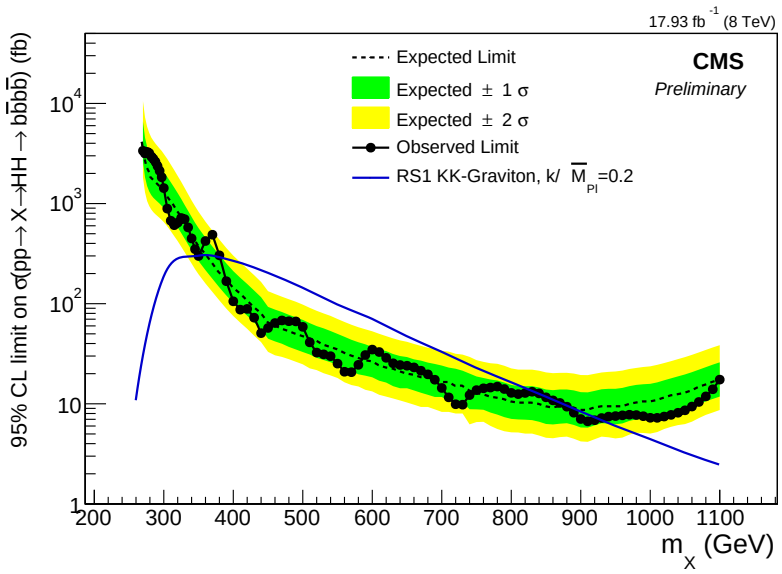
HIG-13-032



- Exclusion limits on the total $\sigma(pp \to X) \times Br(X \to hh \to \gamma\gamma b\bar{b})$
- Radion scale $\Lambda_R = 1\,TeV$ ruled out up to 970 GeV, not sensitive enough for $\Lambda_R = 3\,TeV$
- Some sensitivity also for the RS1 KK graviton
- Cross-section of the graviton in bulk model suppressed w.r.t. RS1

$X \to hh \to b\bar{b}b\bar{b}$

HIG-14-013



- Small excess ($\approx 2\sigma$) at $m_X = 380\,GeV$
- Exclusion limit expressed as model-independent $\sigma \times Br(X \to hh \to b\bar{b}b\bar{b})$
- Calculated $\sigma \times Br$ for RS1 KK-graviton superimposed

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