23rd International Conference on Supersymmetry and Unification of Fundamental Interactions
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BSM Higgs searches with the CMS experiment

Roberto Castello (CERN)
on behalf of CMS collaboration

Many reasons for going beyond

The Standard Model (SM)

- Effective theory of the strong and electroweak interactions of elementary particles
- Includes **Higgs mechanism** for the generation of the weak gauge boson and fermion masses

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Why going beyond?

- Grand Unified Theory (GUT)
- No candidates to account for Dark Matter
- *Fine–tuning* : radiative corrections to the m_H^2

Unveiling the whole frame

- Using the **Higgs-like boson** as a tool
- Interpreting results according to models

Dealing with the existing BSM frame(s)

Physics benchmark	Model Interpretation	CMS results
h-> invisible	Low scale SUSY, DM	**this talk**
h->μτ	LFV, Yukawa couplings	C. Caillol's talk
X->hh->bb+bb/γγ	Spin-0, spin-2 reson.	**this talk**
h->ZZ,WW,γγ (high mass)	EW singlet, 2HDM	P.Merkel's talk
H->hh, A->Zh (multilept. and γ)	2HDM, MSSM	**this talk**
A->Zh(bb/ττ)	2HDM	**this talk**
H->ZA(bb/ττ), A->ZH(bb/ττ)	2HDM	**this talk**
Φ->bb	MSSM	S. Alderweireldt's talk
Φ->ττ/μμ, bbA(ττ)	2HDM	C. Caillol's talk
X->a_1(μμ) a_2(μμ)	NMSSM, Dark SUSY	F. Ricci-Tam's talk
$H^{+/-}$->cs/τν/tb	MSSM	G.Kole's talk

Also: "Overviews of BSM Higgs Physics from ATLAS and CMS" plenary, T.Du Pree

Many (valid!) existing scenario: focusing on few of them or on *model–independent*

Catching the *invisible*

h→inv [*EPJC 74(2014)2980, CMS-PAS-HIG-14-058*]

h→inv+γ [*arXiv:1507.00359*]

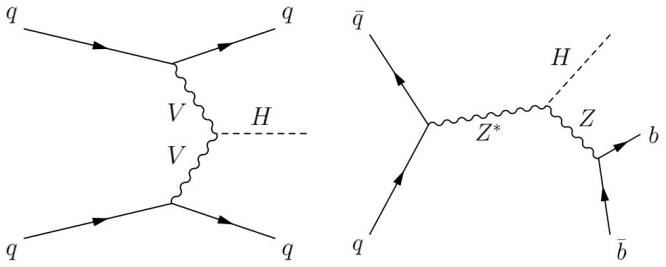
X→inv+V/j [CMS-*PAS-EXO-12-055*]

Invisible Higgs

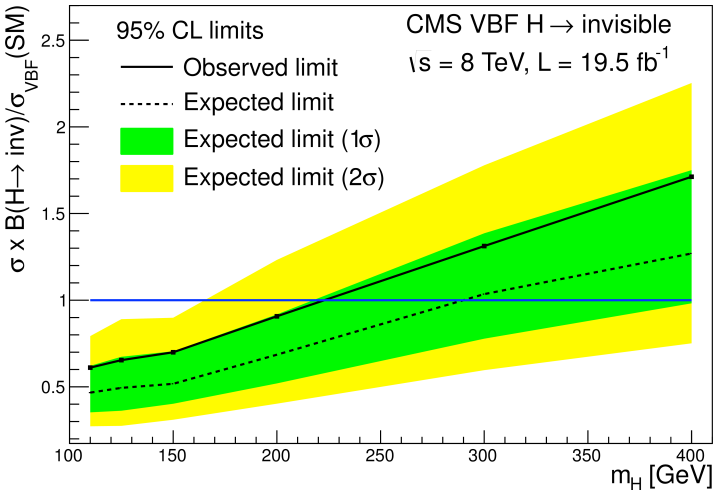
- Sensitive to non-SM decays of the observed h boson (or of additional Higgses)
- Indirect from SM visible decays, allowing $\Gamma_{BSM} > 0$ ($\kappa_V<1$) : BR_{BSM}= 0.57 (95% CL)

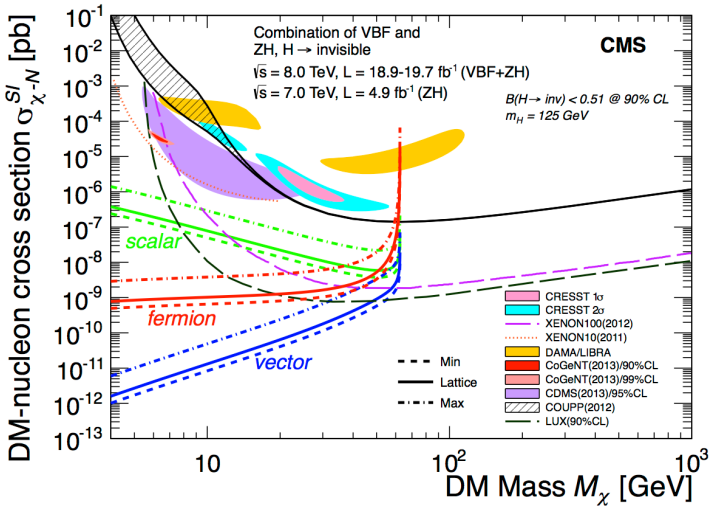
from [HIG-14-009]

- Direct searches:
  - In CMS: **Z(ll)h, Z(bb)h, VBF (updated!)**
  - VBF w/ parked data
    - pT > 35(30) GeV, M_{jj} > 700 GeV and $\Delta\eta_{jj}$ > 3.5
    - BR_{inv}=0.57 (exp. 0.40) at 125 GeV
  - VBF+ZH: BR_{inv}=0.47 (exp. 0.35) at 125 GeV



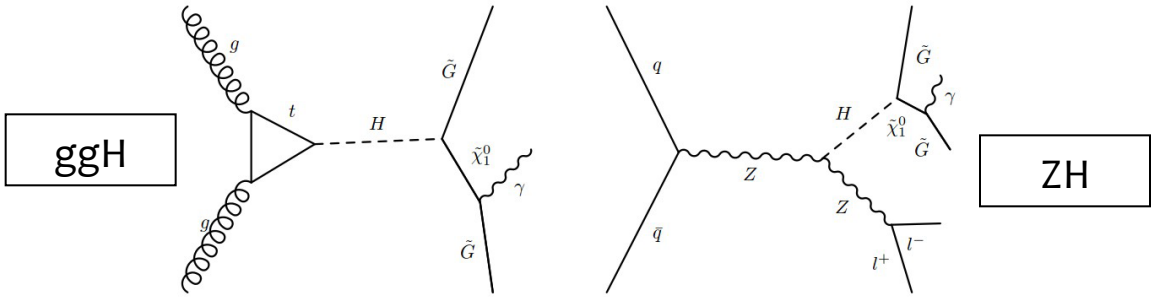
- Limits: model-independent and interpretation in terms of Higgs-portal of DM





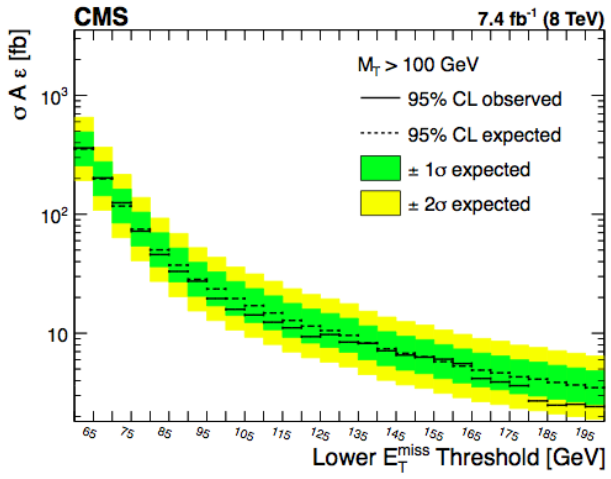
Quasi-invisible Higgs

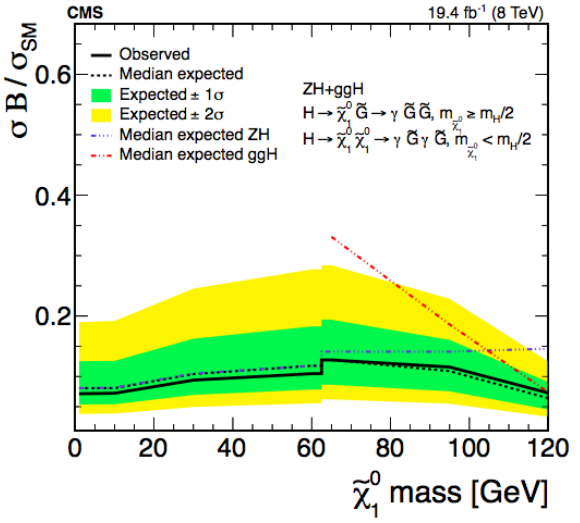
- H--> inv+γ : motivated by low-scale SUSY models
  - h decays into a **gravitino (Ğ)** and a **neutralino (χ_1^0)**, and $\chi_1 \rightarrow$ Ğ+γ



- Backgrounds: Z(νν)+γ, γ+jets, j->γ, e->γ, not sensitive to H-> Z(νν)+γ (x10 SM x-section)

Model-independent

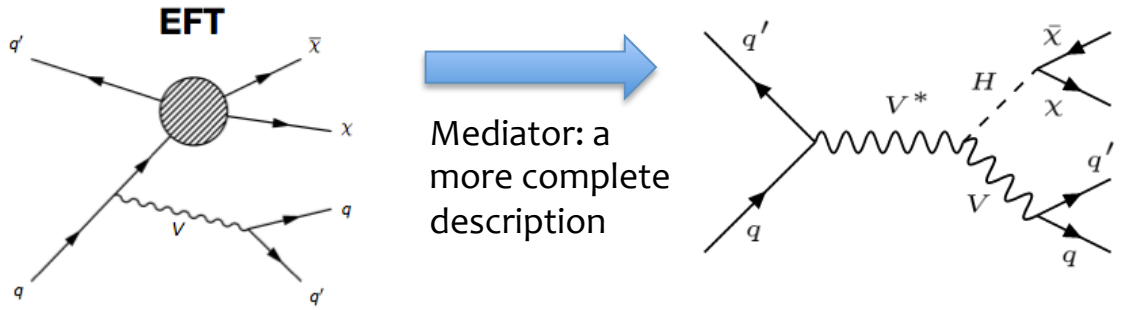




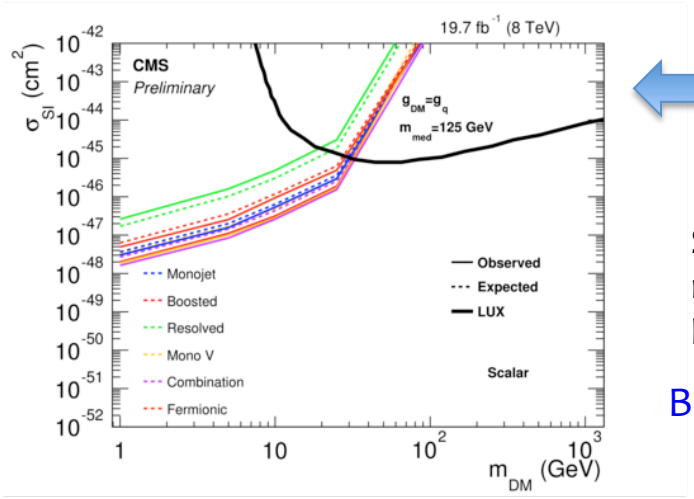
Gravitino/neutralino

Higgs as mediator: MET+V/j

- Spin-0 mediator for fermionic DM : high energy jet (or hadronic V) + large MET



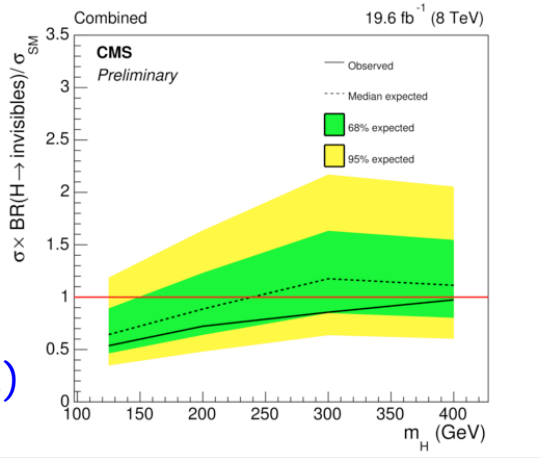
- *Mono*-jet: requiring $\Delta\phi$ (j,MET) >2.0 , MET>200 GeV, vetoing additional jets, e, μ, τ, γ
- Boosted V (using subjettiness) and resolved V(using MVA) categories



Scalar at m=125 GeV as mediator

SM Higgs as mediator, limits on BR_{inv}

BR_{inv}=0.53 (exp. 0.62)



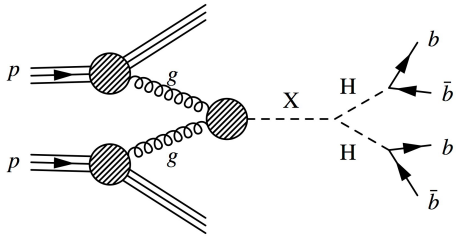
Exotic production mode for Higgs(es)

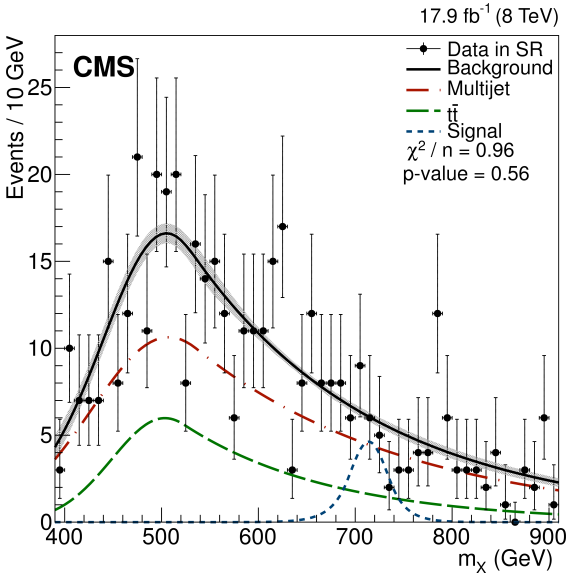
X→hh→γγbb [*CMS PAS-HIG-13-032*]

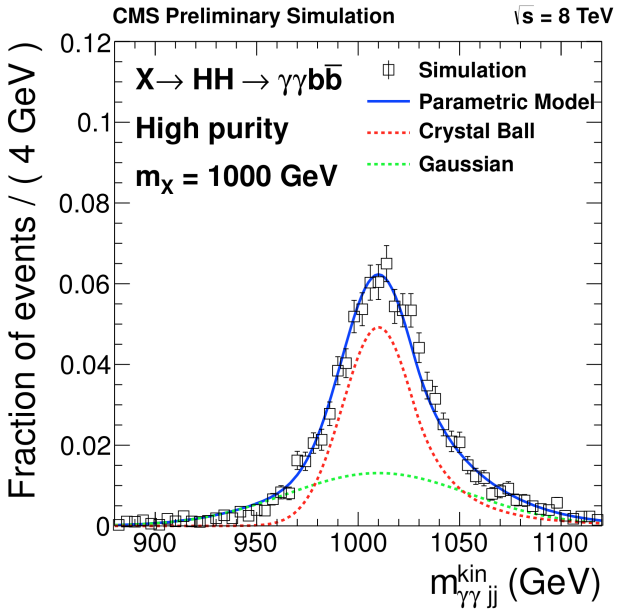
X→hh→bbbb [*arXiv:1503.04114*]

Exploiting double higgs

- Motivations: SM has σ_{NNLO} (pp->hh, 8TeV) ~ 10 fb, but enhanced in BSM
- hh --> bbbb, large BR (h--> bb)=0.57
  - Combined Multi-variate algorithm for b-tagging, based on track and vertices no jet cone limitations
- hh --> γγbb, high $M_{\gamma\gamma}$ resolution
  - Cuts based on H->γγ , b-jet categorization
- Strategy: fitting the background + modeling of the signal in M_{bbbb} or $M_{\gamma\gamma jj}$

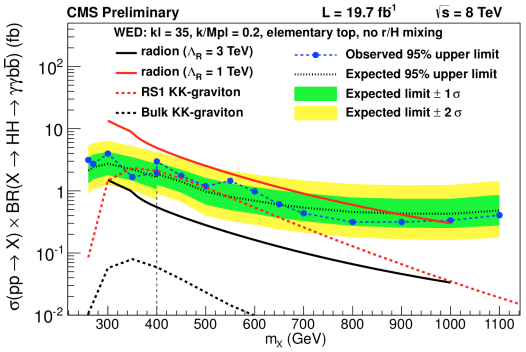


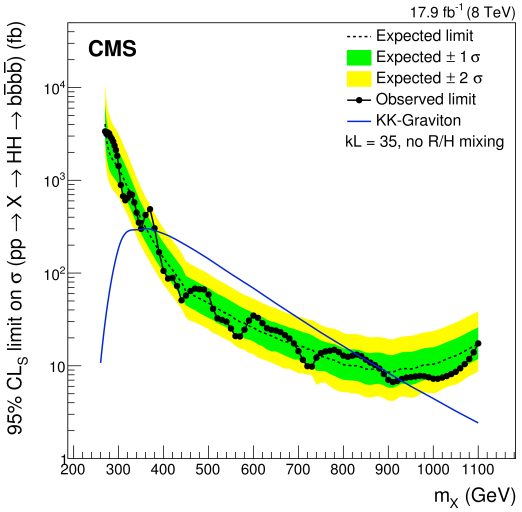


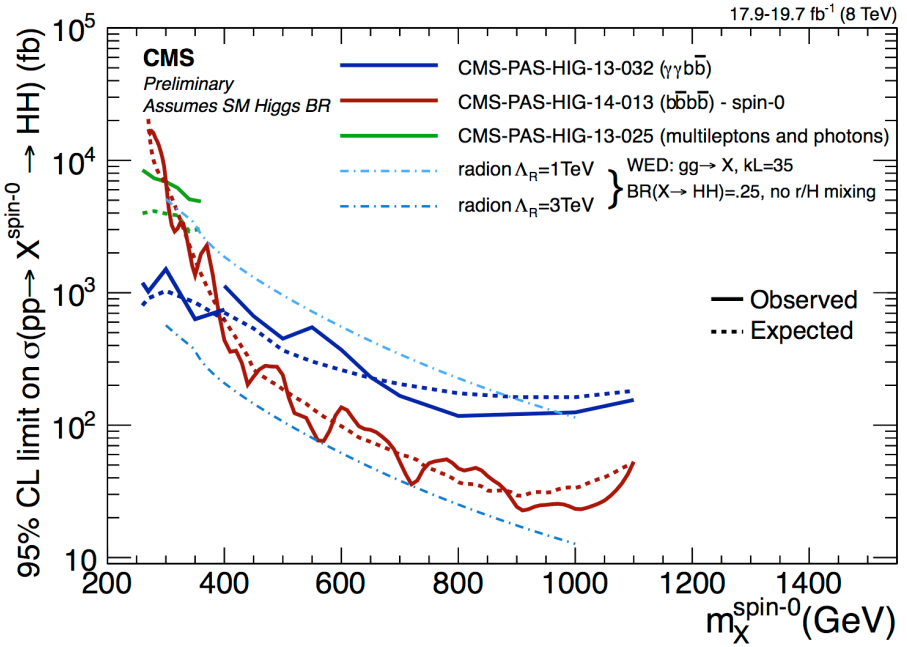


The interpretations

- Upper limits on generic resonances (gg-->X-->hh) xBR
- Interpretations: Radion (spin-0), KK (spin-2), MSSM scalar extension







- No significant excess in data range [270-1100] GeV
- Setting more stringent limits on some models

Why not more than one Higgs doublet?

A→Zh and H→hh(multi-leptons)[*PRD 90(2014)112013*]

A→Zh(bb/ττ)[*Phys.Lett.B 748(2015)221, CMS-PAS-HIG-14-034*]

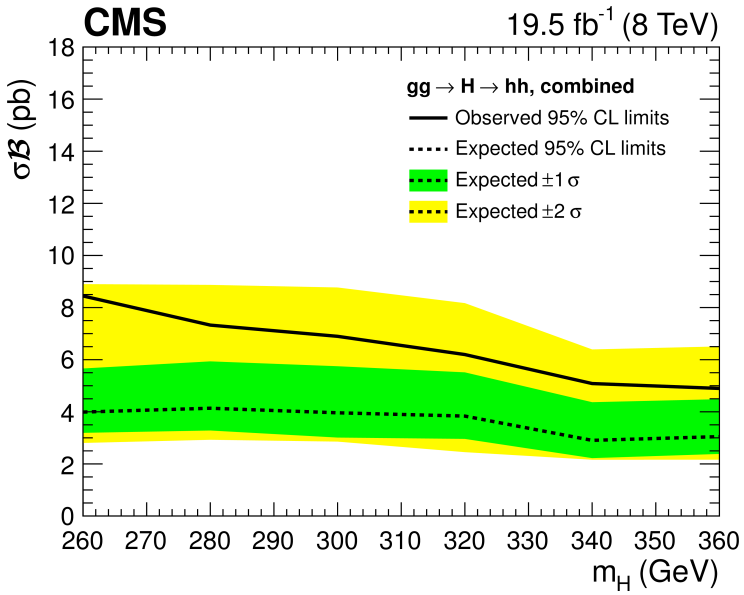
A→ZH(bb/ττ), H→ZA(bb/ττ)[*CMS-PAS-HIG-15-001*]

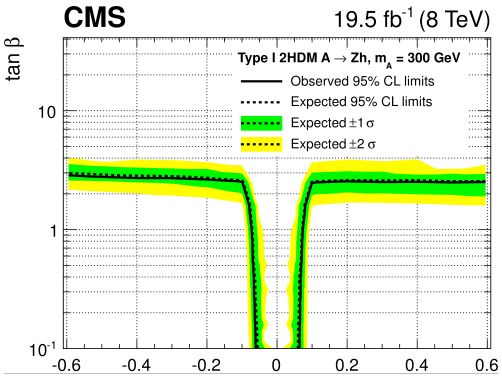
The 2HDMs as benchmark

- A simple SM extension, the Two Higgs Doublets Models
  - Motivated by SUSY (MSSM): enhanced H->hh and A->Zh at low tanβ
  - Effective low-energy axions theories requires two Higgs doublets
  - Can accommodate baryon asymmetry: flexibility scalar mass spectrum + CP violation
- Two scalar doublets (ϕ_1, ϕ_2) : 3 neutral H, h (CP-even) A (CP-odd), +2 charged H±
- 2HDM inputs: M_h, M_H, M_A, $M_{H+/-}$, tanβ, α
- Types can be distinguished by the H couplings:
  - Type I: modified couplings for bosons w.r.t. fermions → $k_V \sim \sin(\beta-\alpha)$, $k_f \sim \cos\alpha/\sin\beta$
  - Type II: modified couplings for up-fermions w.r.t. down-fermions (MSSM case)
  - Alignment limit: $\cos(\beta-\alpha) \sim 0$ → $h_{2HDM} = h_{SM}$
- Mass hierarchy:
  - *Usual:* where SM-like Higgs boson is the lightest (e.g. A-->Zh, H--> hh)
  - But also *inverted*, twisted custodial symmetry (e.g. H-->ZA) [arXiv:hep-ph/0703051]

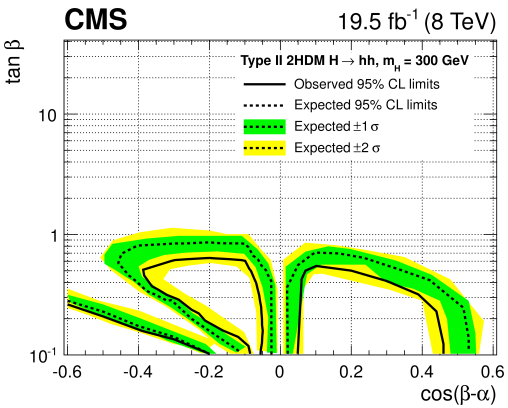
H-->hh and A-->Zh

- Final states: multi-leptons (via ZZ, WW) and di-photons + leptons
- Assuming SM BR for h, limits on σxBR vs. m_A and m_H within [260-360] GeV
  - No enhancement, upper exclusion limit of 7 pb for H-->hh and 2 pb on A-->ZH
- Probing 2HDMs at low tanβ in the cos(β-α) − tanβ plane





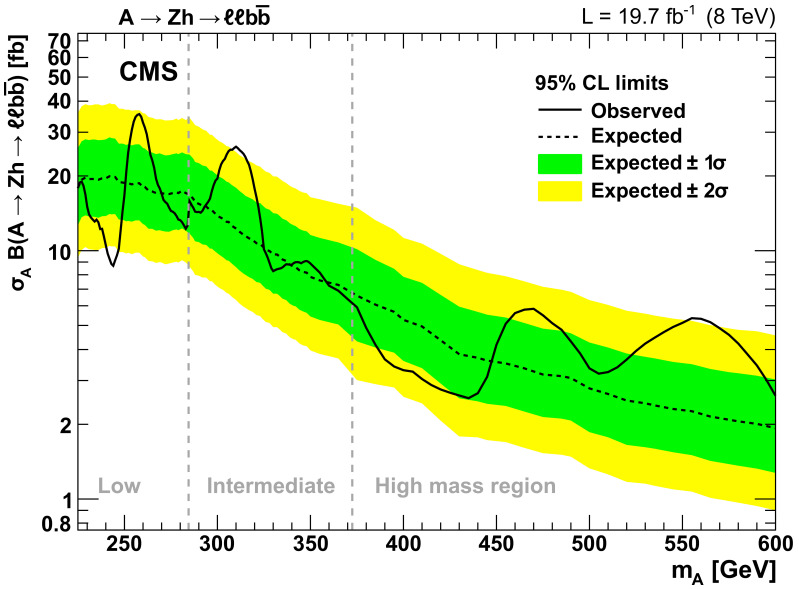
e.g.Type I A-->Zh

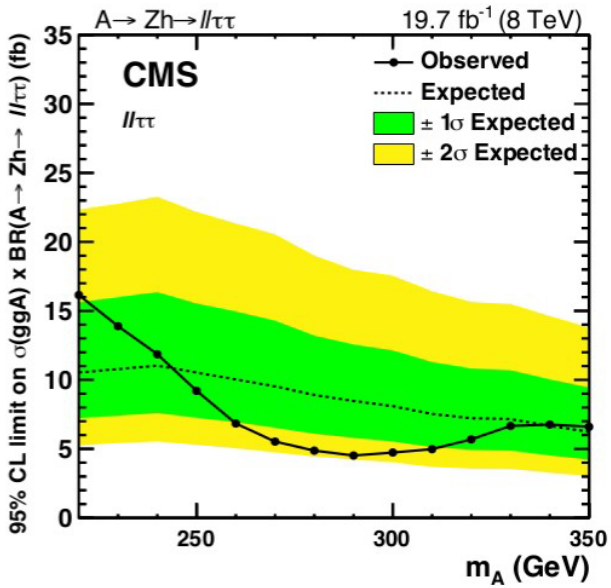


e.g.Type II H→hh

A-->Zh -->ll bb/ττ

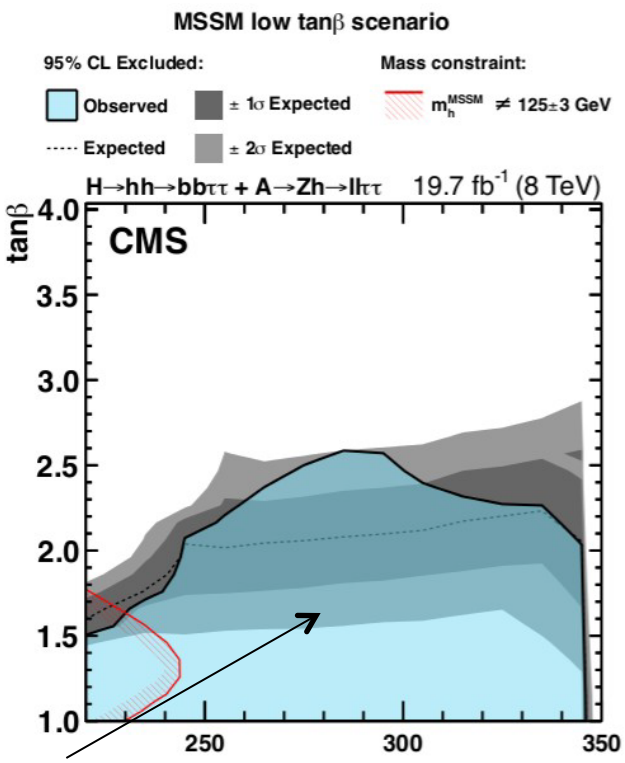
- A-->Zh-->llbb
  - Results extracted from 2D fit to M_{llbb} and BDT in the signal region
  - Narrow width approximation for A, but dependence from Γ_A studied for $M_A > 2\ m_t$
  - No significant excess in data: model-independent limits and 2HDM type-II limits
- A-->Zh-->llττ
  - Fitting the fully reconstructed m_A from Z and ττ 4-vectors
  - No significant excess in data: model-independent limits, 2HDM type-II + MSSM limits

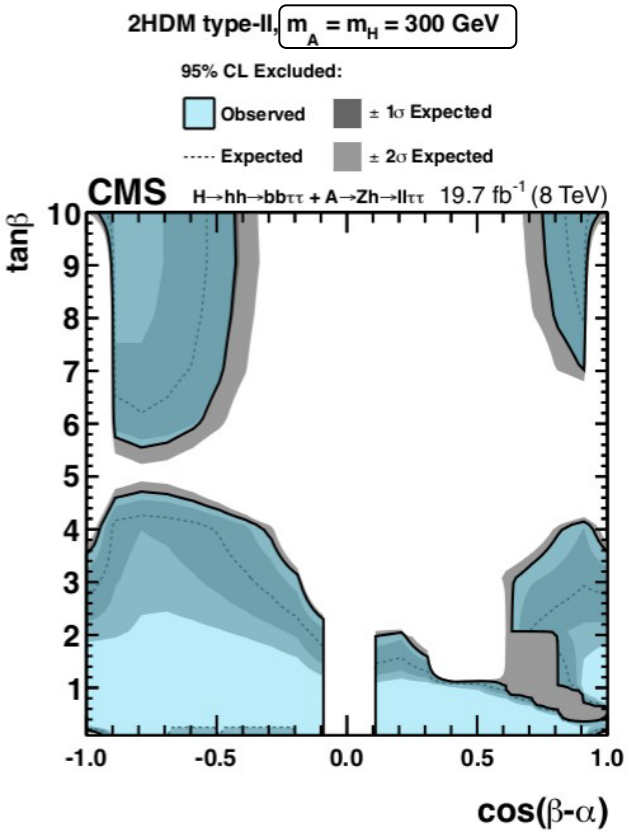




Combination of H-->hh and A-->Zh

- Same channels H-->HH-->bbττ, A-->Zh --> llττ , two interpretations:
  - MSSM exclusion in the plane tanβ vs. m_A
  - 2HDM type II with $m_H = m_A = 300$ GeV





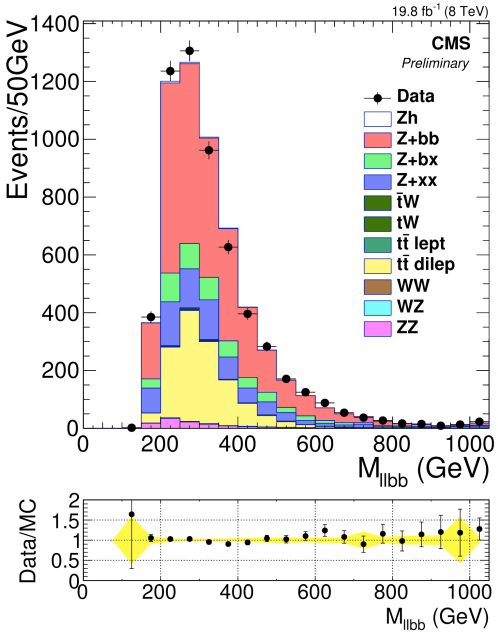
Low tanβ: H--> hh and A-->Zh cross section would be enhanced in MSSM

H/A --> Z+A/H (Z --> ll and A/H --> bb/ττ)

H-->ZA: dominant decay modes for tanβ~1, $M_H > M_A + M_Z$

llbb final state

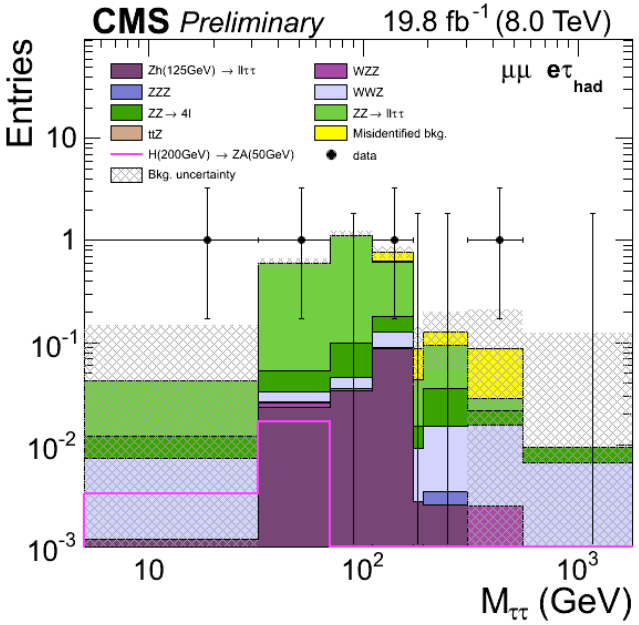
- Large BR (A/H-->bb)
- Background from ttbar and Z+bb
- Data driven bkg normalization:
  - Fit M_{ll} and b-tag discriminants



- *Cut and count* in (M_{llbb},M_{bb}) bins

llττ final state

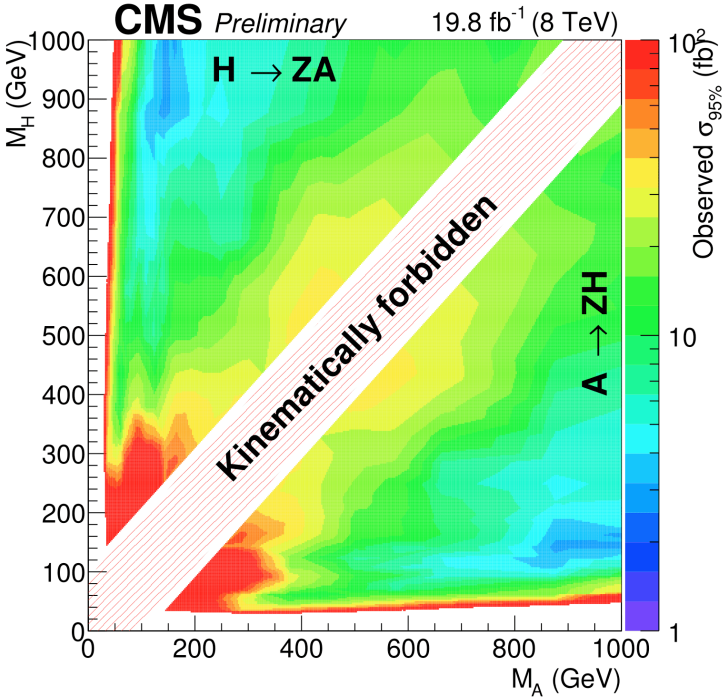
- Small BR (A/H ->ττ)
- Background from ZZ and fakes
- Mττ reconstructed using the two taus and the MET (SVfit)



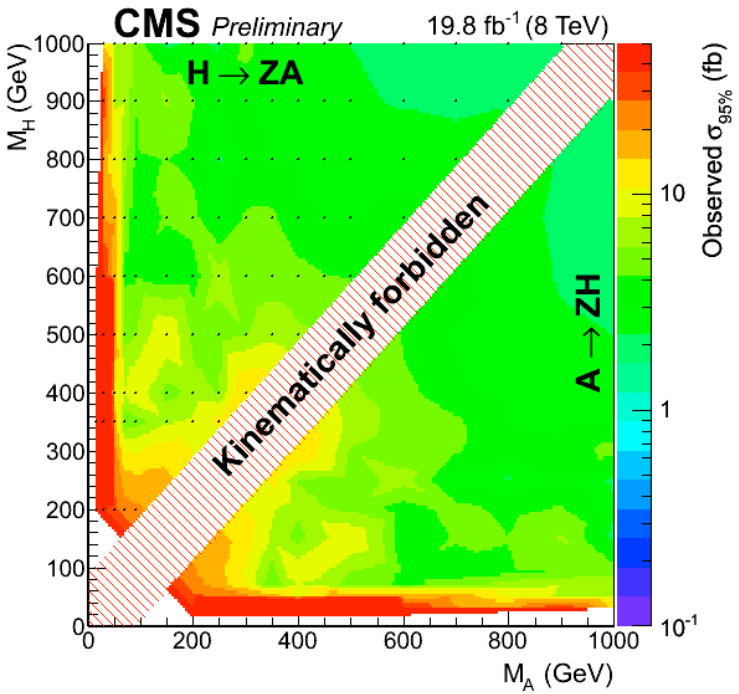
- Shape-based and cut and count

Model independent exclusion limits

- No assumption of signal model in the analysis and determination of mass grid
- No *significant* excess observed in data
  - excluding cross section xBR values down to 10 fb for *llbb final states models*



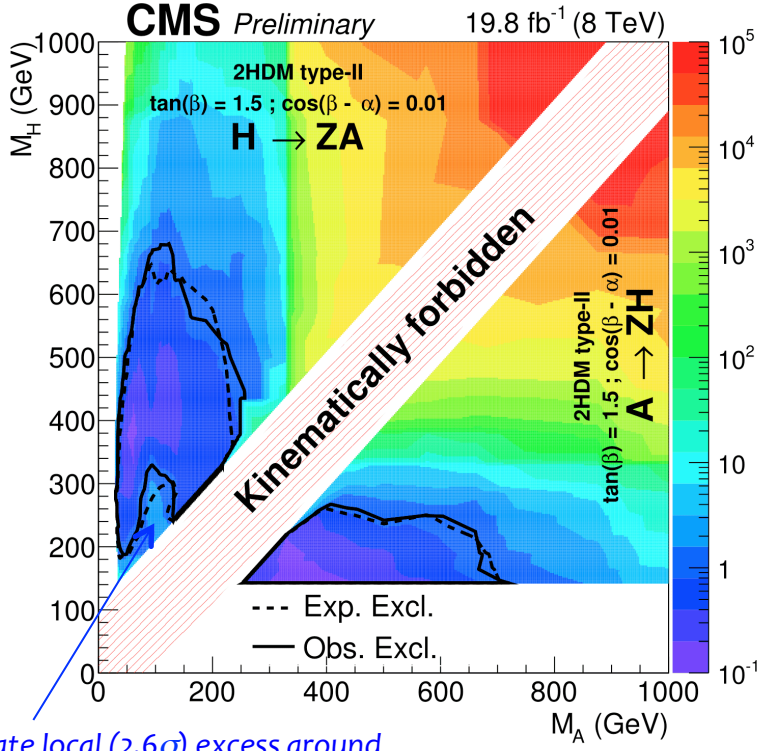
H/A-->Z(ll)A/H(bb)

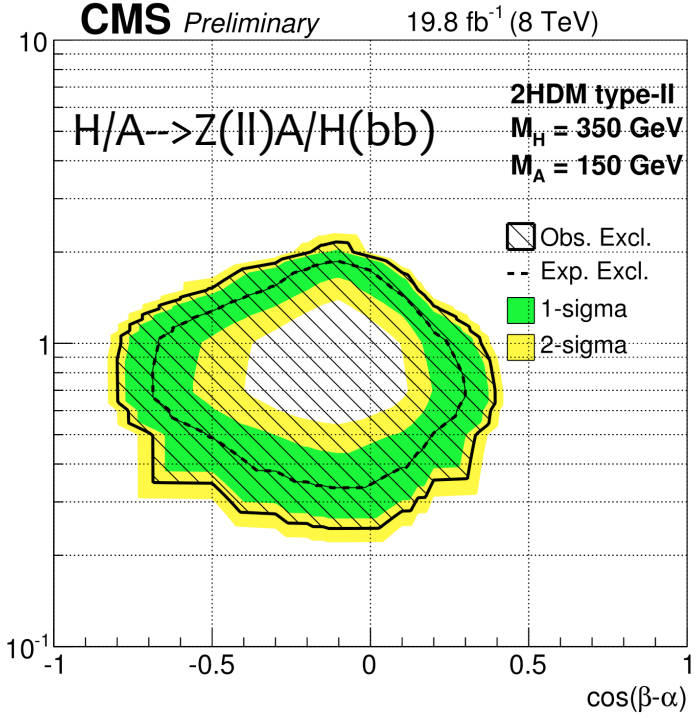


H/A-->Z(ll)A/H(ττ)

Limits on 2HDM type-II

- Limit on cross section rescaled by the efficiency and acceptance of the model
  - Non-degenerate H and A, m_h = 125 GeV, $m_{H+/-}$ = max(m_H ,m_A), cos(β – α)=0.01, tanβ=1.5
  - Limit as function of m_H and m_A : significant exclusion in the sensitive region
    - Loss in sensitivity once the A/H -> ttbar decays open





Moderate local (2.6σ) excess around (M_{bb}, M_{Zbb})= (93,286) GeV…

Summary

- The new discovered Higgs boson:
  - adds constraints to viability of many alternative models
  - used as a probe for searches beyond SM

- Many complementary searches in the BSM frame
  - *Indirect*, e.g. by invisible decays of neutral Higgs
    - Probing BR_{inv} = O(40%)
    - Combination of most sensitive channels can expect to reach Br_{inv} = O(20%)
  - *Direct*: model-independent results and interpretations according to benchmark models:
    - Low mass SUSY, Gravitons, Radions, generic 2HDM, MSSM,…

- Results consistent with SM expectations
- Few moderate fluctuations. **No clear evidence of BSM physics**

…but LHC Run2 is just ahead of us

BACKUP

The H-->hh and A-->Zh (multileptons final states)

Multi-leptons/di-photons + leptons final state

- di-lepton/photons triggers, event categ. according to nr. (l, γ), ME_T, nr. b-tag jets

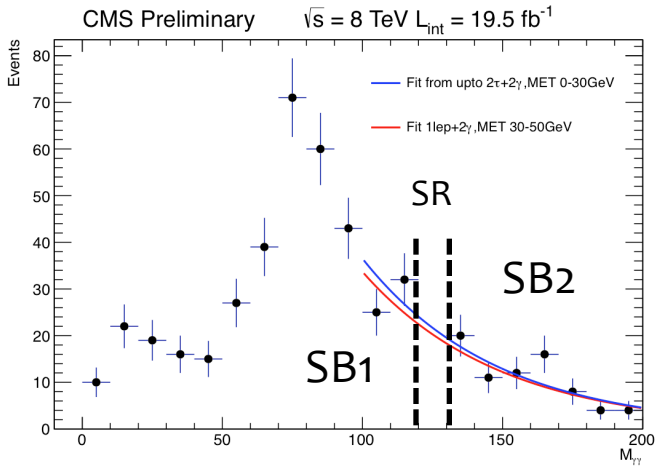
	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau\tau$	$h \to \gamma\gamma$
$Z \to ll$	✓	✓	✓	✓
$Z \to qq$	X	✓	X	X
$Z \to \nu\nu$	X	✓	X	X

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

Signal extraction method: cut and count

Backgrounds

- Reduced by isolation, vertex requirement, M(ll)>12 GeV, 120<M(γγ)<130 GeV
- Multi-leptons (>1l):
  - **Fakes** from Z+j, WW+j (mis-id factor from data)
  - **ttbar**: fake rate (±50%) cross section (±10%)
  - **Irreducible VV+jets** (MET smearing up to 25%)
  - **γ conversions** (data driven factor, up 2.1% for $e^{\pm}$)
- Di-photons+leptons:
  - **Fit background shapes** in $2\tau_h$+2γ side-bands
  - Normalized to #events in SB in other channels



X--> hh

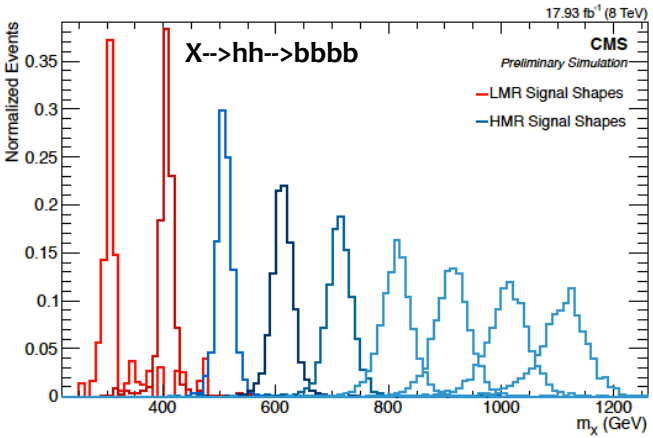
Motivations: SM has σ (gg->hh, 8TeV) ~ 10 fb, but enhanced in BSM

hh --> bbbb: large BR (h--> bb)=0.57

hh --> γγbb: high $M_{\gamma\gamma}$ resolution

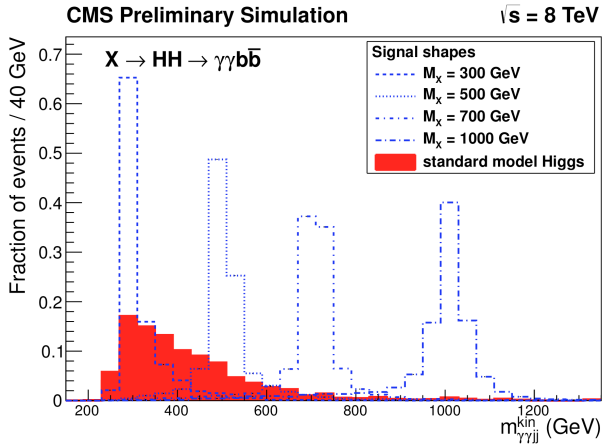
final state with b-jets

- **Combined MultiVAriate** algo (vertices, no jet cone limitation)
- CMVA wp : ε_b~ 75% ε_{ucsd}~ 3%
- **Kinematic fit** on reco b-jets at 125 GeV: σ(M_{bb}) improves by 20%/ 40%



final state with γ

- **Signal σ(Mγγ) ~ 1 GeV** driven by the γ energy resolution/direction (vertex)
- Energy gaussian smearing on γ candidate to match data resolution
- **Bkg rejection:** $e^{\pm}$-veto, cuts on shower shape, γ-isolation



Signal extraction method --> shape based

X--> hh

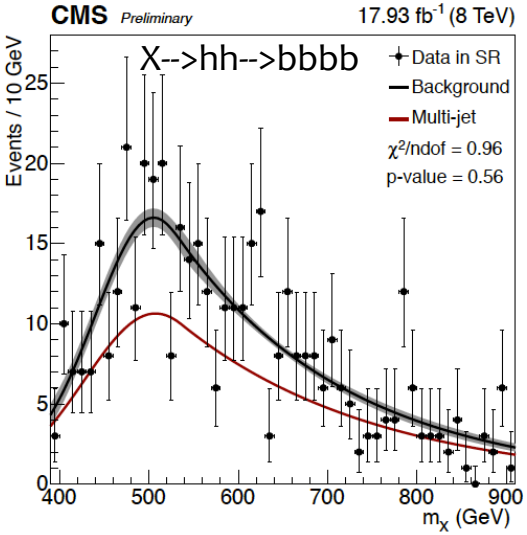
Fit techniques

γγbb

- $M_{\gamma\gamma jj}$ for m_X> 400 GeV, $M_{\gamma\gamma}$ for m_X< 400 GeV
- Signal: sum of Crystal Ball + Gaussian
- Bkg: polynomial function fitting (data driven)

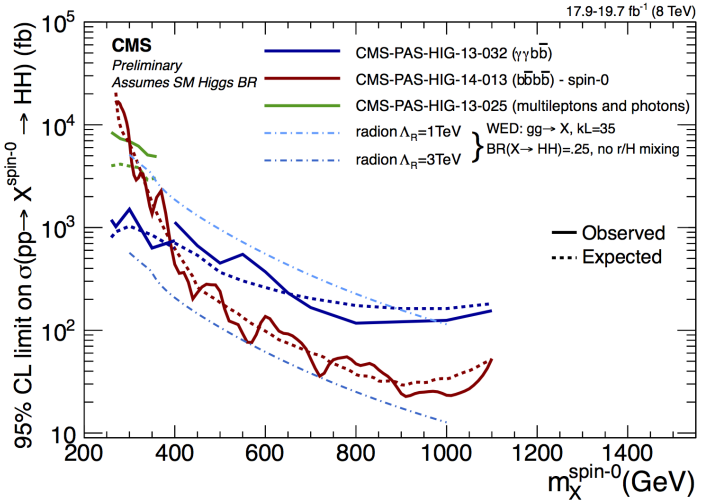
bbbb

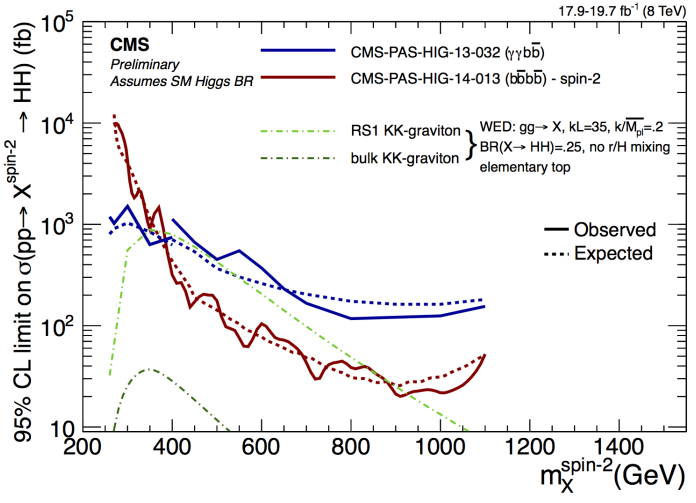
- Bkg: fit to QCD multi-jet m_X (after ttbar subtraction) using GaussExp (syst. 2% – 26%)



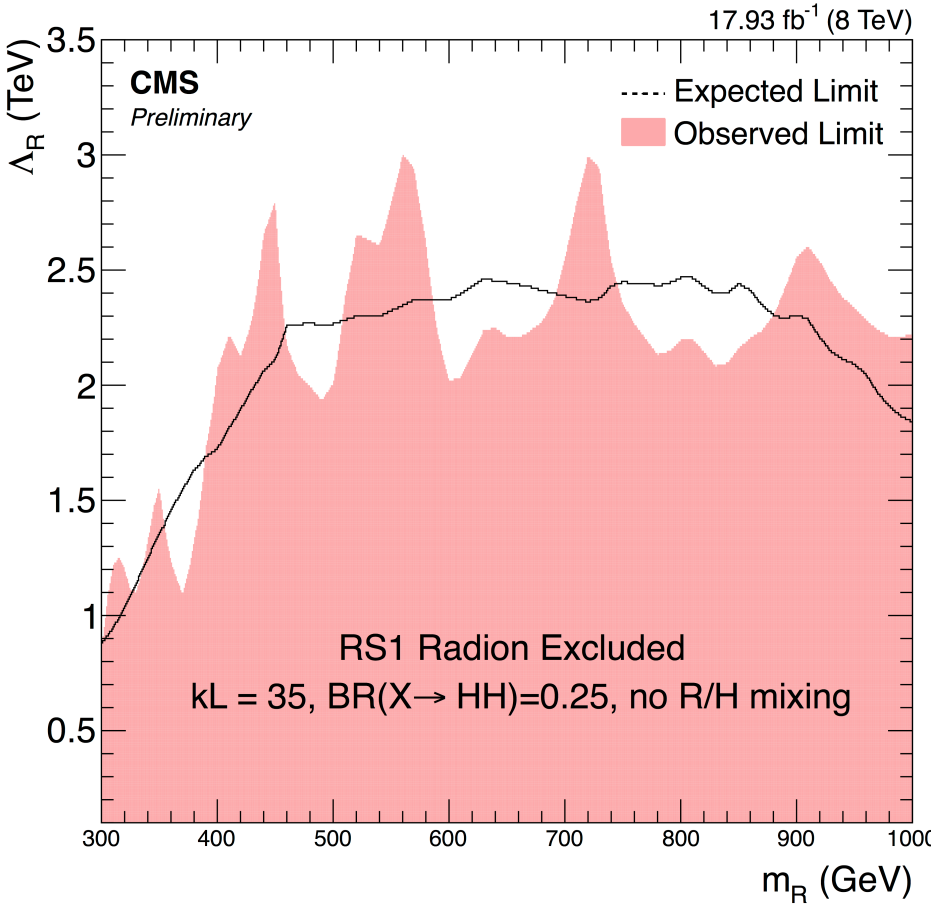
Upper limits on generic resonant σ (gg-->X-->hh) xBR

- Model-interpretation: Radion (spin-0), KK (spin-2), MSSM scalar extension..





Radion exclusion in the X-->hh-->bbbb



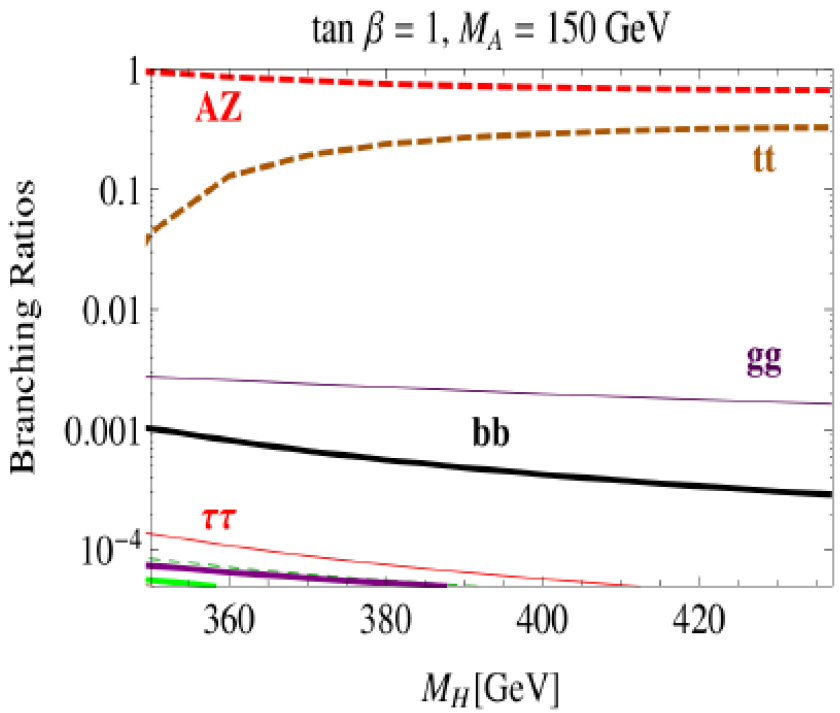
- Λ_R = radion decay constant
- m_R is the mass of the radion.
- WED scenario:
  - kL = 35
  - no radion-Higgs mixing
  - elementary top.
- The production cross section for the radion varies as (1/sqrt(Λ_R))

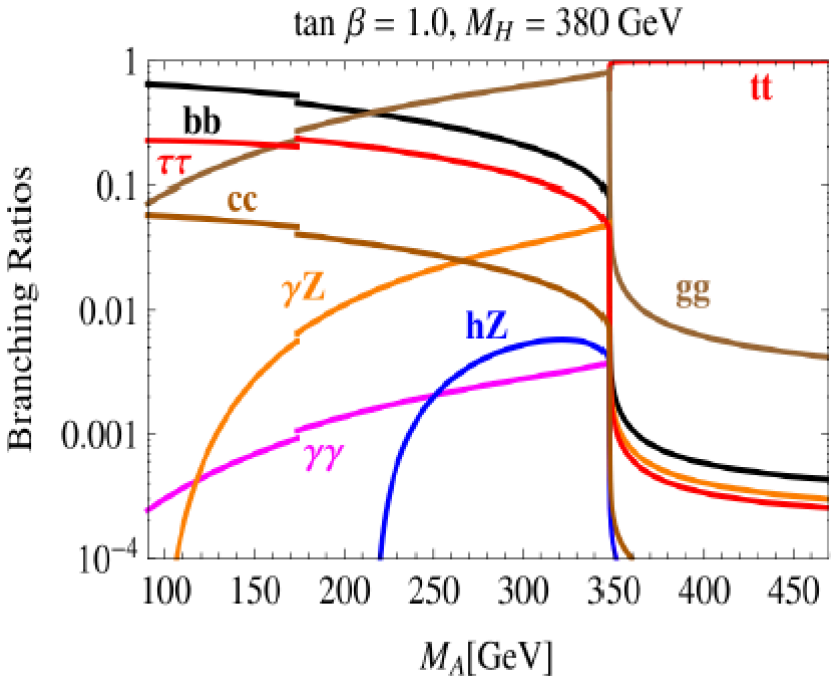
Caveat:

- Radion produced through gluon fusion. Top loop k-factors taken to be identical to that of the Higgs,
- Br(R->HH) = 0.25 for m_R > 300 GeV. Below that value, the branching fraction falls rapidly and must be computed.

H/A --> Z+A/H decays

For $M_H > M_A + M_Z$

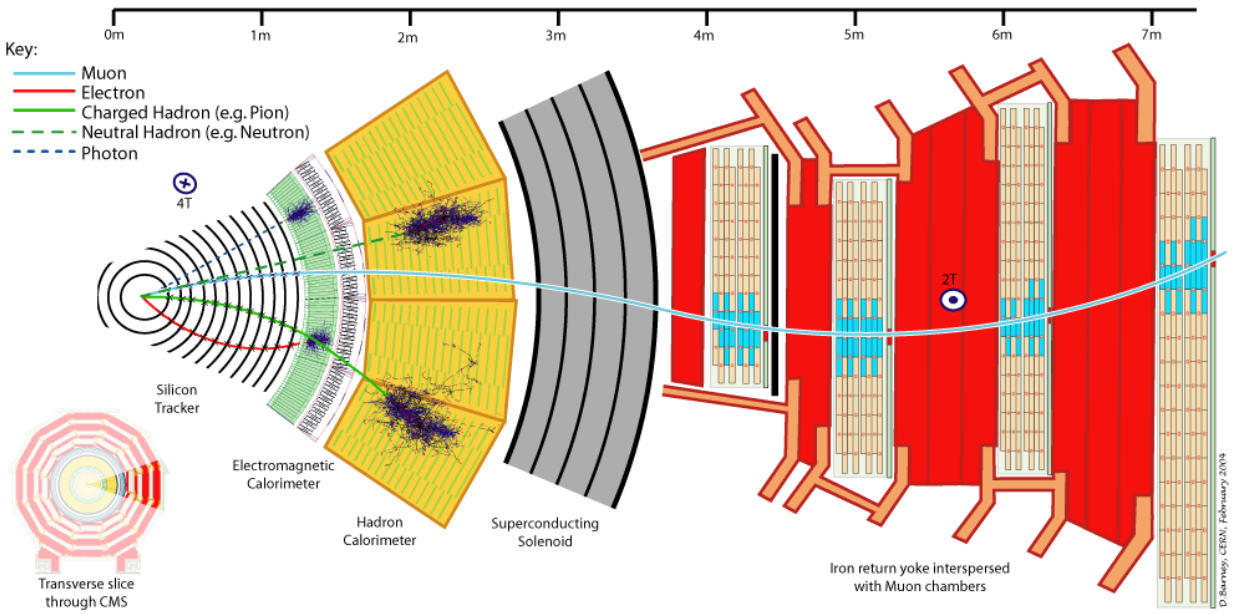




arXiv:1304.0028

The tool: a Compact Muon Solenoid

- From particle reconstruction: muons, electrons, hadrons (charged and neutral), photons



… to physics objects: muons, electrons, jets, photons

- Excellent detector performance:
  - Track-finding efficiency is more than 99%
  - Transverse momentum resolution: $\sigma(p_T)/p_T$= 1.5 - 3% for tracks of p_T ~ 100 GeV
  - Energy resolution for electrons and photons: $\sigma(E)/E$~ 1 %