Higgs Searches beyond SM and MSSM at the LHC

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on behalf of the ATLAS and CMS Collaborations

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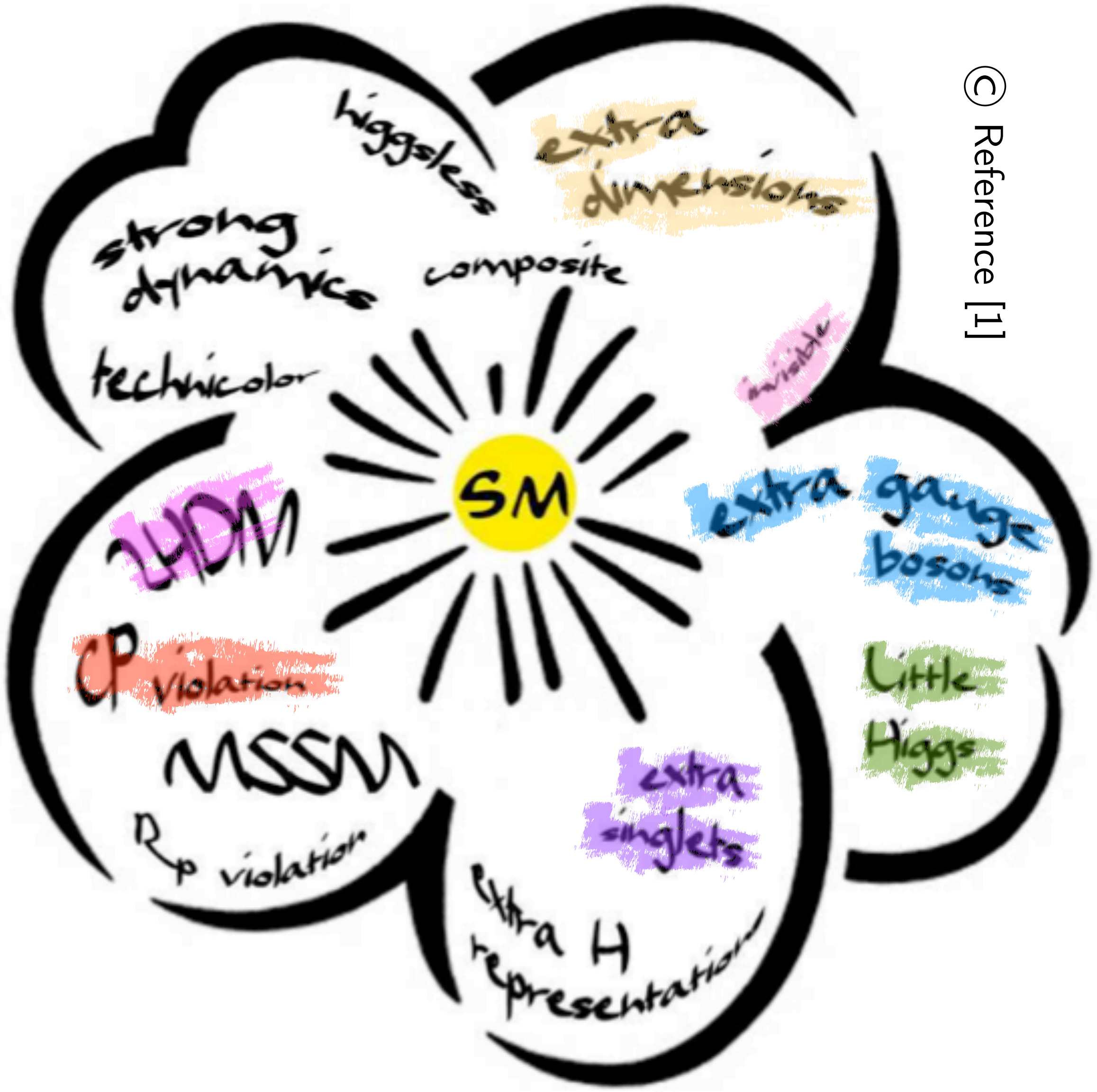
- The exploration of the TeV energy scale at LHC is expected to complete the success of the Standard Model
- The discovery (or the absence) of one or more Higgs bosons will lead to a *flowering of new physics*..
- Revealing the full details of the underlying mechanism of EWSB may be considerably more complex than what is foreseen by SM or MSSM
- There may be interplay between Higgs sectors and the not probed parts of the SM



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Not all the *petals* are discussed in this talk..

- No Higgless models, R-parity violation models, Compositeness, Technicolor, Strong Dynamic models are presented

CP-Violating two-Higgs Doublet Model (2HDM)

3 mass eigenstates H_1, H_2 and H_3 with mixed CP parities and different couplings to SM and SUSY particles

- As in the SM case, the *tree-level* MSSM Higgs sector is also *CP-conserving*
- But loop effects (involving CP-violating interactions to top and bottom squarks) may lead to *a most general CP-violating two-Higgs doublet model* (2HDM)
- CP-violation (either explicit or spontaneous) in the Higgs sector → mixing of neutral Higgs states of opposite CP and/or (direct) CP-violating Higgs interactions
- Mass eigenstates:

CP-violating 2DHM	**CP-conserving MSSM**
H_1, H_2 and H_3	h, H and A
$H^{\pm}$	$H^{\pm}$

- *Experimental limits*: no absolute lower bounds on Higgs boson masses and couplings exist, but:
  - In *decoupling limit* (lightest neutral $H_{2HDM} \rightarrow H_{SM}$) $M_H > 114.4$ GeV at 95% CL, but H_1 may have mass *smaller* than 70 GeV, escaping detection at LEP2
  - Charged Higgs: $M_{H\pm} > 78.6$ (76.7) GeV at 95% CL for 2HDM Type-I (2HDM Type-II) from LEP2 measurements - b→sγ decay implies $M_{H\pm} \geq 320$ GeV (2HDM Type-II)

CP-Violating (CPX) Discovery Potential

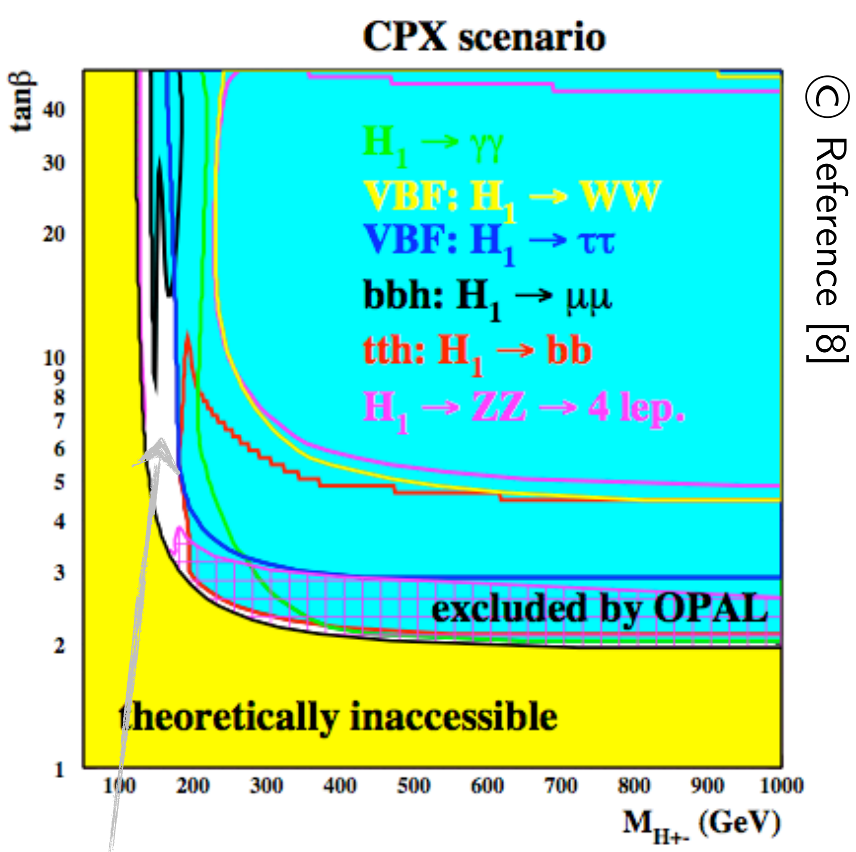
Discovery of at least one Higgs boson possible over most of the allowed region - No-lose theorem holds

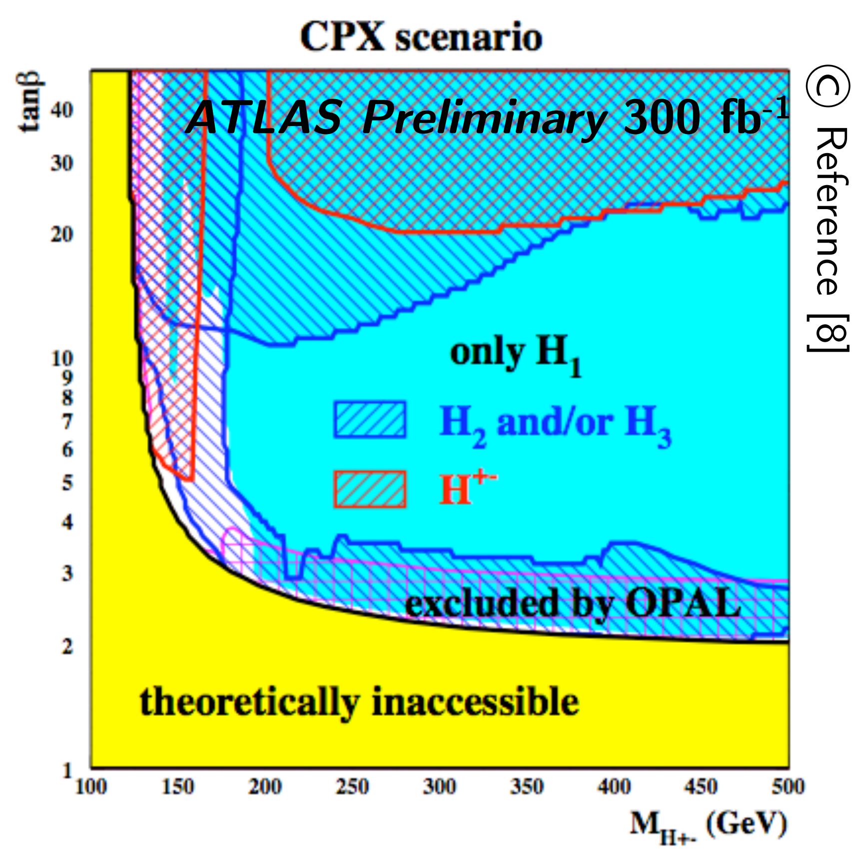
- In MSSM with large loop-induced CP-violating Higgs Yukawa interactions → *CPX benchmark scenario* chosen for phenomenological studies

CPX Scenario
$\tilde{M}_Q = \tilde{M}_t = \tilde{M}_b = M_{SUSY}, \quad \mu = 4\ M_{SUSY}, \quad \arg(A_t) = 90^\circ$
$\lvert A_t \rvert = \lvert A_b \rvert = 2M_{SUSY}, \quad \lvert m_{\tilde{g}} \rvert = 1$ TeV, $\arg(m_{\tilde{g}}) = 90^\circ$

→ *additional parameters*

- $M_{H\pm}$ and tanβ are the only free parameters (at Born level) - here $M_{SUSY} = 500$ GeV





study for smaller values of H_1 missing

Lightest neutral Higgs (left):

All Higgs production process and the most relevant decays → angular distributions of final state Higgs decay products studied

Overall Discovery Potential (right):

No updated study
Only LO cross sections
No systematic uncertainties
More investigation needed in the uncovered regions

Lepton Flavor Violating (LFV) Scenarios

$A/H \to \tau^{\pm}\mu^{\mp}$: most interesting channel to probe LFV at LHC

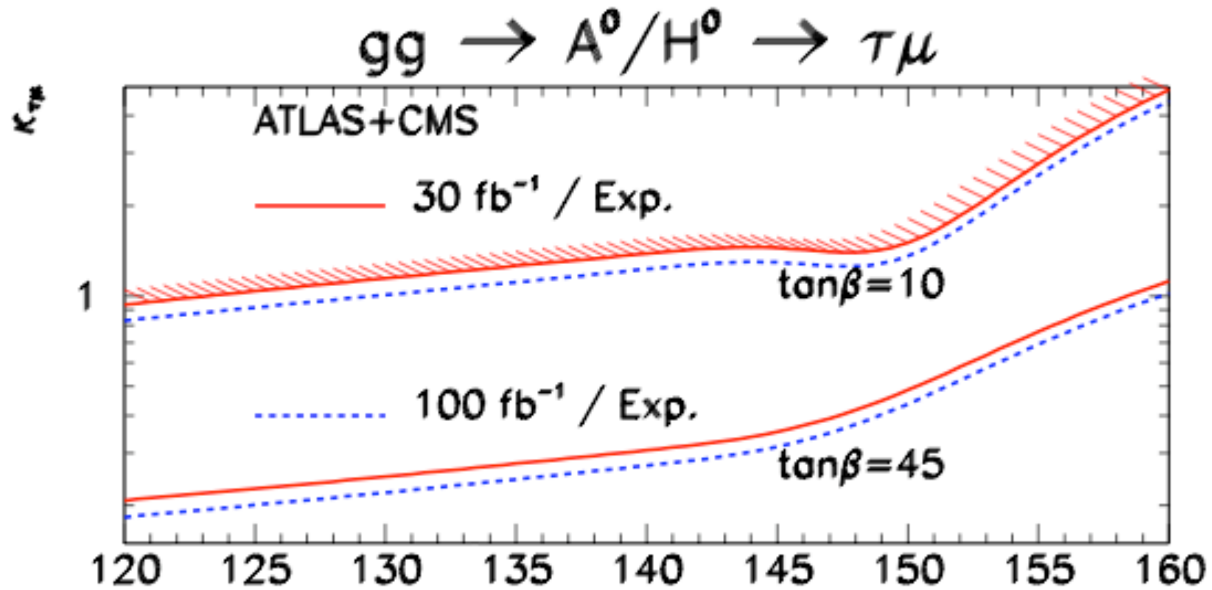
- In MSSM tree-level LF is protected by the soft supersymmetry breaking terms
- In models with several Higgs doublets, FCNC and LVF *exist at tree level* → *ad hoc* discrete symmetries (in 2HDM Type-I and 2HDM Type-II) are invoked to cope with the known experimental limits
  - LFV effects can arise in SUSY models with RH Majorana Neutrinos or with R-parity violation
- In **2HDM Type-III**, *no discrete symmetries are present* and FCNC and LFV exist → flavor changing couplings parameterized to agree with experimental constraints on FCNC and LFV couplings
- Experimentally:
  - $(g\text{-}2)_{\mu}$ deviation from SM prediction constraints the LFV $\lambda_{\tau\mu}$ coupling
  - At LHC bounds on LFV couplings can be obtained from $B_{(s)}$ decays, $\tau^{\pm} \to \mu^{\pm}\gamma$, $\tau \to cV$ $(V = h, A, H)$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tau\mu$ and $A/H \to \tau^{\pm}\mu^{\mp}$ (allowed in 2HDM Type-III)

Lepton Flavor Violating A/H→τμ at LHC

With 100 fb^{-1} LHC can improve sensitivity on $\lambda_{\mu\tau}$ by up to a factor 100 w.r.t (g-2) data

- Sensitivity in terms of the lepton flavor violating parameter $\kappa_{\tau\mu}$ defined by:

$$BR(A/H \to \tau\mu) = \kappa_{\tau\mu}^2 \left(\frac{2m_\mu}{m_\tau}\right) BR_{SM}(H \to \tau\tau)$$

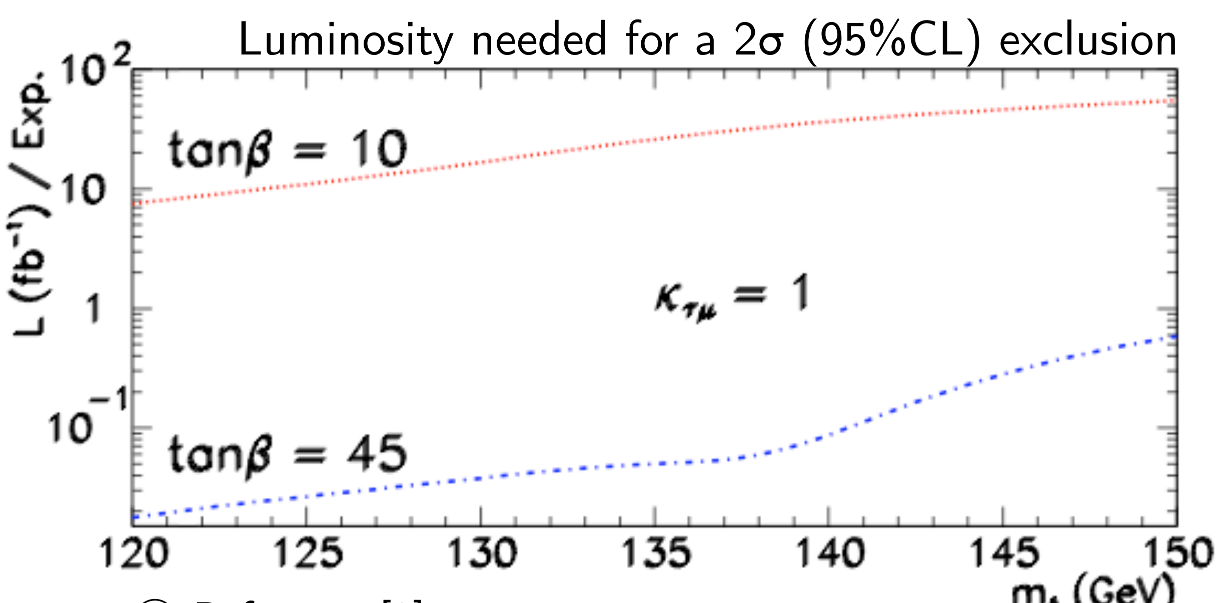


Analysis Details:

Low mass region

Final states with τ → had ν_τ (BR ~65%) or τ → $e\nu_e\nu_\tau$ (BR ~18%)

Backgrounds: MSSM A/H→ττ, Z(γ*) →ττ, W(→μ ν_μ) + jets and WZ, WW, tt



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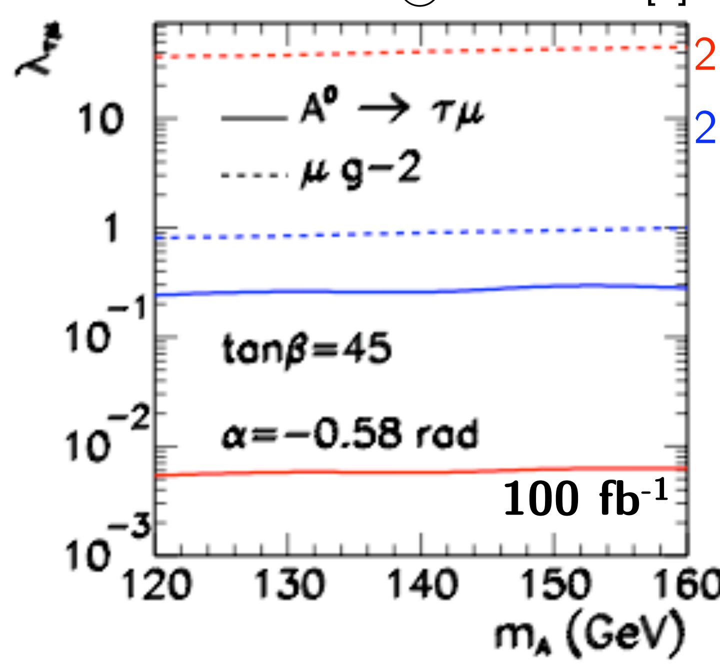


2HDM-III type a

2HDM-III type b

$a_\mu^{exp} = 11659203(8) \times 10^{-10}$

$a_\mu^{SM} = 11659177(7) \times 10^{-10}$

Higgs in Next-to-MSSM (NMSSM)

NMSSM solves MSSM μ-problem by adding one singlet S, at the cost of adding 3 more particles

- MSSM suffers from *μ-problem*: μ, the Higgs/higgsino mixing parameter, has *a priori* no knowledge about EWSB, but phenomenologically constrained around EW scale (μ~100-1000 GeV) or large cancellations needed
- Problem solved in NMSSM by adding a neutral singlet Higgs chiral super-field S

$$-\mathcal{L}_{\text{soft}} \supset m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_S|S|^2 + (\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + h.c.)$$

λ, κ = dimensionless couplings and $\mu = \mu_{eff} = \lambda < S >$

$<S>$ constrained by the Higgs potential minimization (100-1000 GeV)

$\rightarrow$ μ is *naturally* constrained to the EWSB scale

- Particle content (if CP is conserved):

NMSSM Higgs Sector
3 neutral scalars: H_1, H_2 and H_3
2 neutral pseudoscalars: A_1 and A_2
2 charged: $H^\pm$

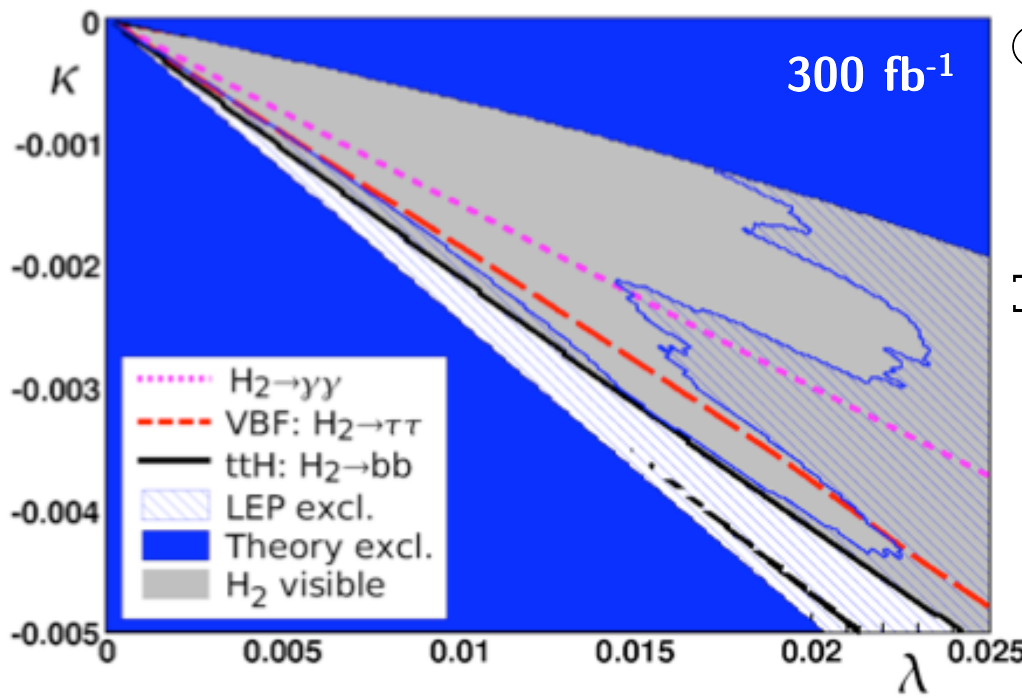
- *Five neutralinos*, from neutral fermion mixing with neutralinos
- Charged Higgs and charginos remain practically unchanged w.r.t. MSSM

NMSSM Discovery Potential at LHC

Limited discovery potential for NMSSM at LHC - No-lose theorem does not hold

- Six free parameters for Higgs sector: $\mu_{eff} = \lambda < S >$ - couplings λ, κ, A_λ, A_κ - $\tan\beta$
  $\rightarrow$ According to parameter choices, *different scenarios possible*
- Studies done in two benchmark scenarios:

Reduced coupling scenario: H_1 very light, H_2 SM-like with mass 120 GeV - $H_2 \rightarrow H_1 H_1$ allowed (BR ~6% $\rightarrow$ negligible)



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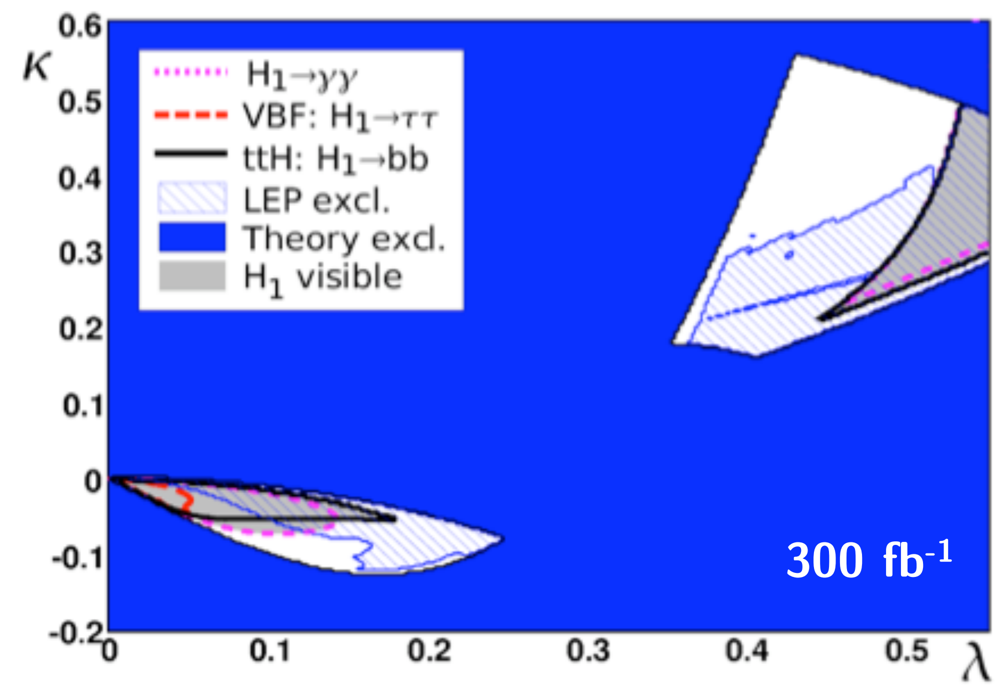
Light A_1 scenario: A_1 light, H_1 SM-like with mass 120 GeV - $H_1 \rightarrow A_1 A_1$ allowed and dominant (BR up to ~90%)



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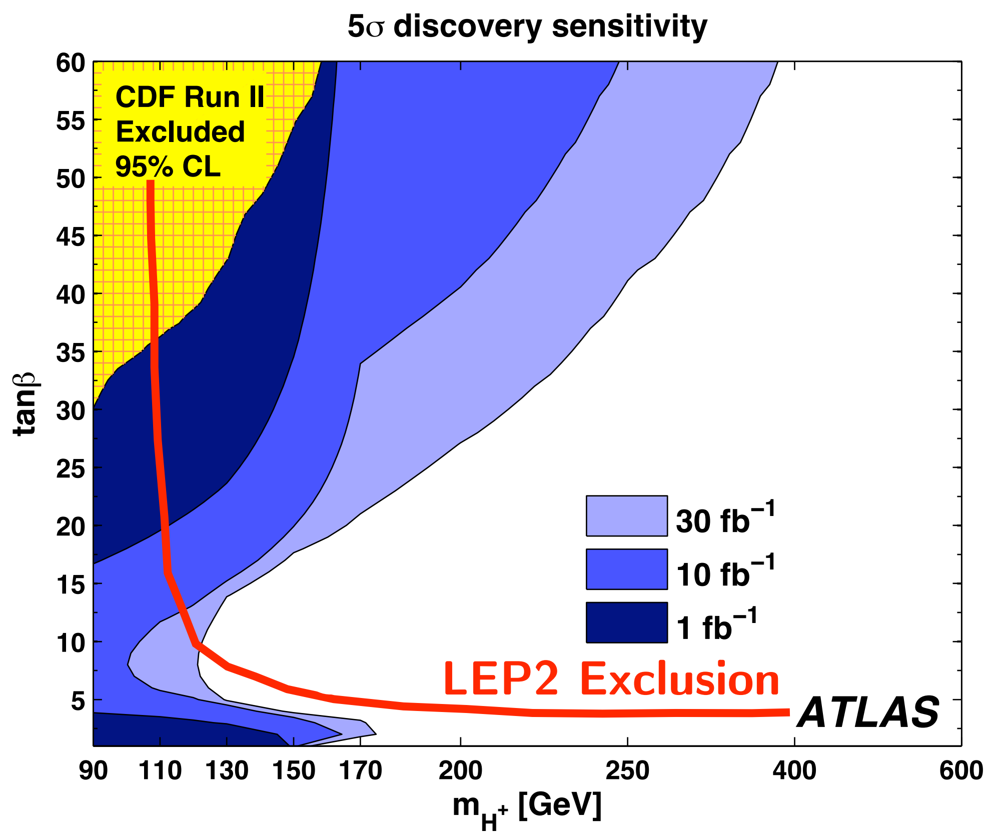
All other Higgs bosons: either highly reduced couplings or contribution in LEP-excluded region

- *NMSSM hard to probe at LHC due to reduced couplings and smaller production rates*

$H^\pm$ in NMSSM and Large Extra Dimensions

LHC discovery of $H^\pm$ possible through channels not relevant or not allowed in MSSM



1. **In NMSSM**, the lower limit on $M_{H\pm}$ (from LEP and $M^2_{H^\pm} = M^2_W + M^2_A$) no longer valid and parameter space is less constrained

   → *$H^\pm \to W^\pm h$ dominant decay mode* for low tanβ and $M_{H\pm} \sim 160$ GeV

- $H^\pm \to W^\pm h$: not relevant in LEP allowed regions of MSSM space (BR very small)

2. **In large Extra Dimension (ED) models**, right-handed neutrinos can freely propagate into the ED (bulk ν)
   - When interacting with SM fields on the brane they produce *Dirac neutrino masses* consistent with atmospheric oscillation observation
   - No additional Higgs bosons required by the model → 2HDM Type-II

     → *Allowed and studied decays like*

$$H^- \to \tau_R^- \bar{\nu} + \tau_L^- \psi,\ \psi = \text{bulk neutrino}$$

Doubly Charged Higgs at LHC

Doubly Charged Higgs have a clear signature at LHC, almost background free

- Doubly charged Higgs bosons predicted in several models
  - ***Left-Right Symmetric Model***: $SU_L(2) \otimes SU_R(2) \otimes U_{B-L}(1)$, broken to $SU_L(2) \otimes U_Y(1)$ by *a triplet of complex Higgs fields* - physical states: Δ_R^0, Δ_R^+ and Δ_R^{++} (and corresponding Left triplet) and a didoublet φ
  - ***Little Higgs Models***: SM Higgs boson is a pseudo-Goldstone boson of higher EW gauge symmetry after its breakdown into SU(2) x U(1) and remains light - physical states Δ *triplet* with masses O(1TeV)
  - *3-3-1 Models, Supersymmetric LR Models, etc.*
- *Clear signature at LHC* → charge conservation prevents doubly charged Higgs to decay into a quark pair
- Main production processes:
  - Singly (*WW*/$\varphi\varphi$ fusion) → cross section O(fb) for $|\eta| < 3$ and p_T >200 GeV
  - In pairs (s-channel, Z/γ^* or Z' exchange) → smaller cross section
- Decays: mostly to leptons or W^+W^+ final states (2 same-sign leptons and E_T^{miss})
- *Experimental limits* (TeVatron): $M(\Delta^{\pm\pm})$>150(127) GeV at 95% CL, for $I_3=\pm1$ (0)

Doubly Charged Higgs LHC Sensitivity

LHC will be able to probe a large region of unexplored parameter space in the triplet Higgs sector

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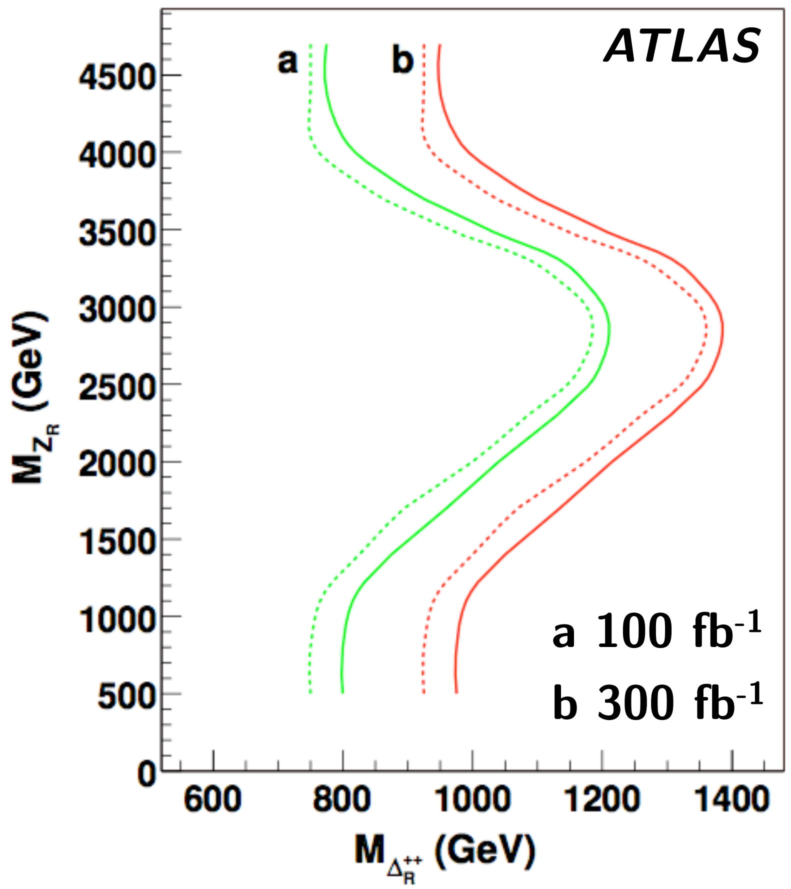


Left-Right Symmetric Models: $\Delta_R^{++}\ \Delta_R^{--} \rightarrow 4l$

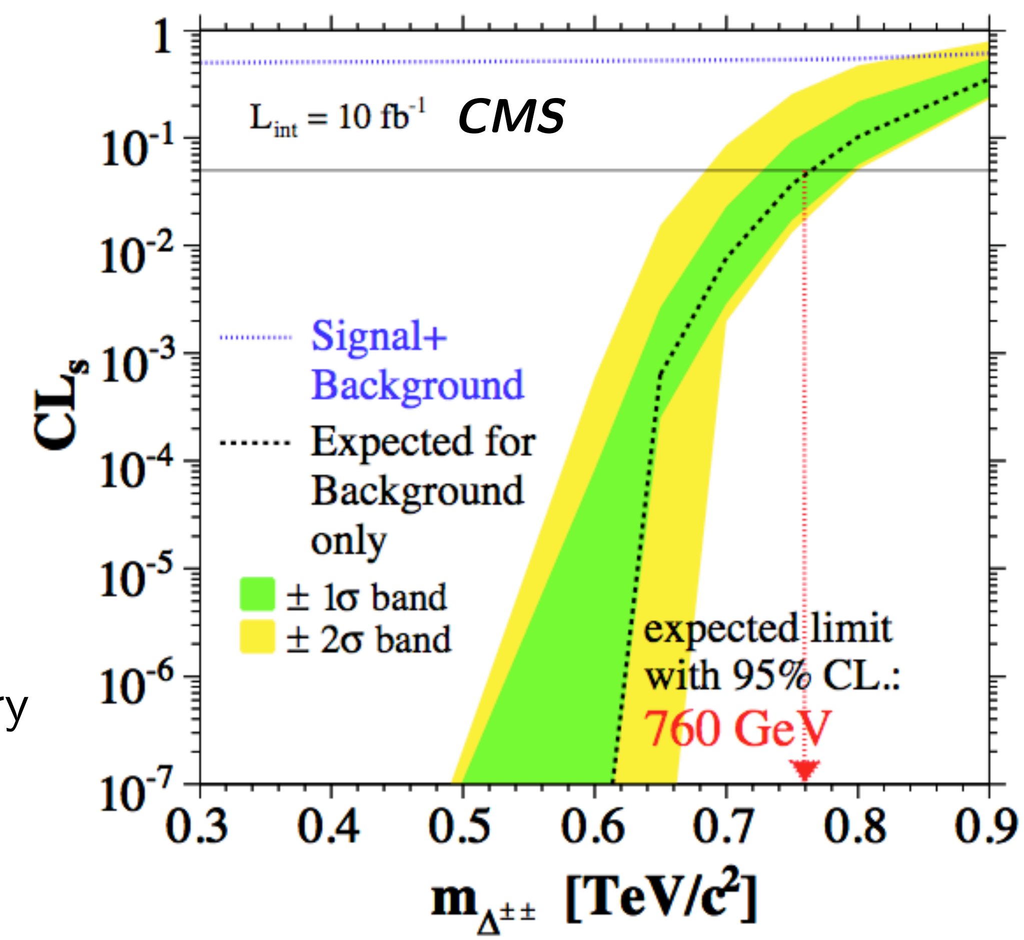
Analysis details :

- Δ_R^{++} coupling to fermions not known
- Analysis performed assuming 100% BR to leptons
- Background negligible → **golden channel**
- Discovery = observation of 10 events with 4 (dashed contour) or 3 (full contour) final state leptons

Little Higgs Models: $\Delta^{++}\ \Delta^{--} \rightarrow 4l$

Analysis details :

- Analysis performed assuming 100% BR into muons
- Background free channel → **golden channel**
- Log-likelihood method to estimate exclusion/discovery
- Uncertainties included



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Higgs/Radion in Randall-Sundrum Models

An extra scalar field φ mixes with the Higgs - Always one of the two scalars detectable, on some regions both

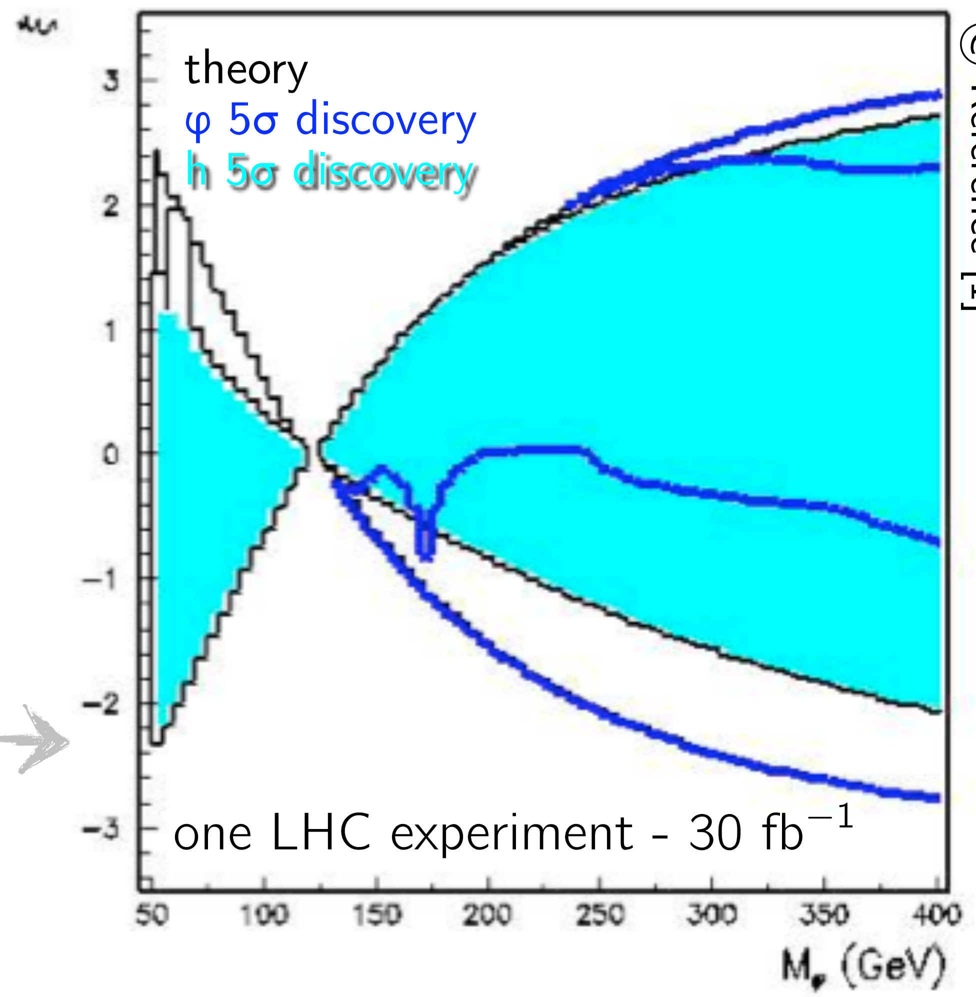
- Randall-Sundrum models of localized gravity → all SM fields (including the Higgs, originally) confined to one or two TeV *branes* - gravity is a *bulk* field in 5D
- Two massless excitations described by the 5D metric tensor: the graviton and the *radion φ_0*, a real scalar field with
  - *Mass* in [~10 GeV, Λ_π], Λ_π = cutoff of the effective theory
  - *Couplings* to SM fields similar to the Higgs, large effective coupling to gluons

→ *Higgs/radion mixing* with *ξ mixing parameter:* physical mass-eigenstates ***h*** and ***φ***

- Trilinear terms in Higgs/radion sector → $\varphi \to hh$ and $h \to \varphi\varphi$ decays *allowed*
- *Light Higgs discovery at LHC different from SM or MSSM* and depending on |ξ| and M_φ/M_h
- Regions with *both h and φ detectable*

h and $gg \to \varphi \to ZZ^* \to 4l$ 5σ detectability

$M_h = 120$ GeV, $\Lambda = 5$ TeV



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LHC Sensitivity to Higgs/Radion

LHC will be able to probe this model and disentangle the two scalars

- Higgs/radion sector free parameters : M_φ, M_h, ξ and $\Lambda_\varphi = \sqrt{6}\,\Lambda_\pi$
- Several radion decays at LHC investigated

$$\varphi \to \gamma\gamma,\ \varphi \to ZZ^{(*)} \to 4l,\ \varphi \to hh \to b\bar{b}\tau\tau,$$
$$\varphi \to hh \to b\bar{b}\gamma\gamma,\ \varphi \to hh \to b\bar{b}b\bar{b}$$

evaluated from $\dfrac{S/\sqrt{B}(\varphi; ZZ)}{S/\sqrt{B}(h; ZZ)} = \dfrac{\Gamma_{\varphi\to gg} BR(\varphi \to ZZ)}{\Gamma_{h\to gg} BR(h \to ZZ)} \sqrt{\dfrac{\sigma_h^{ZZ}}{\sigma_\varphi^{ZZ}}}$

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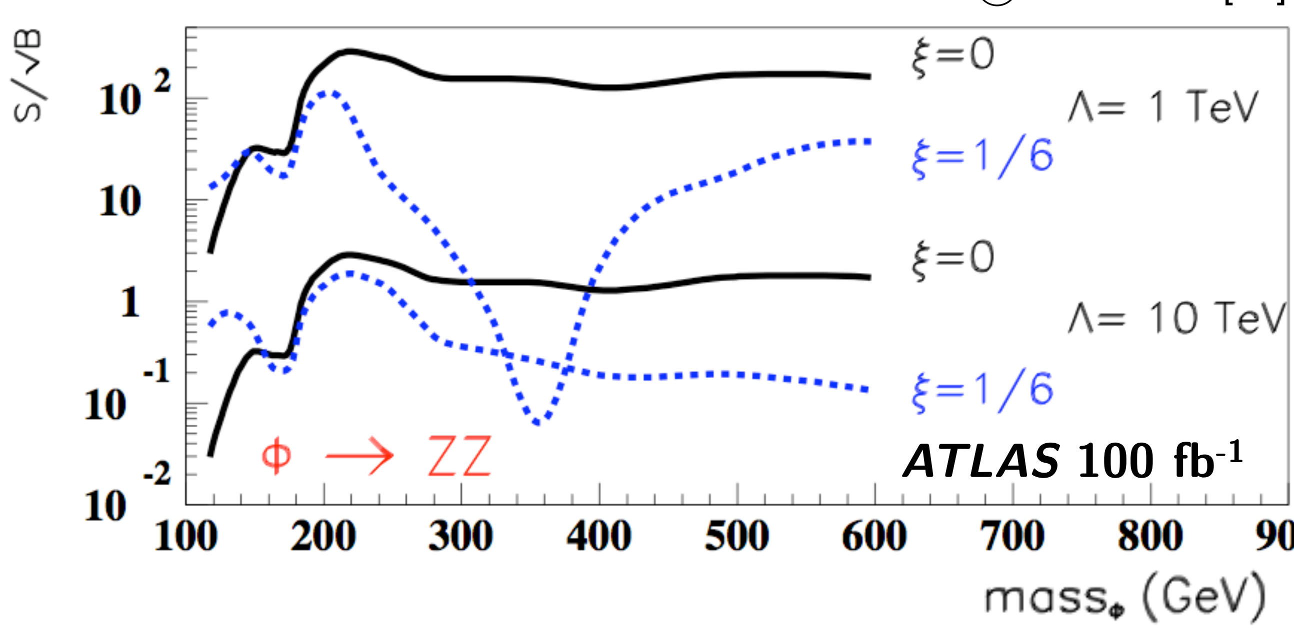

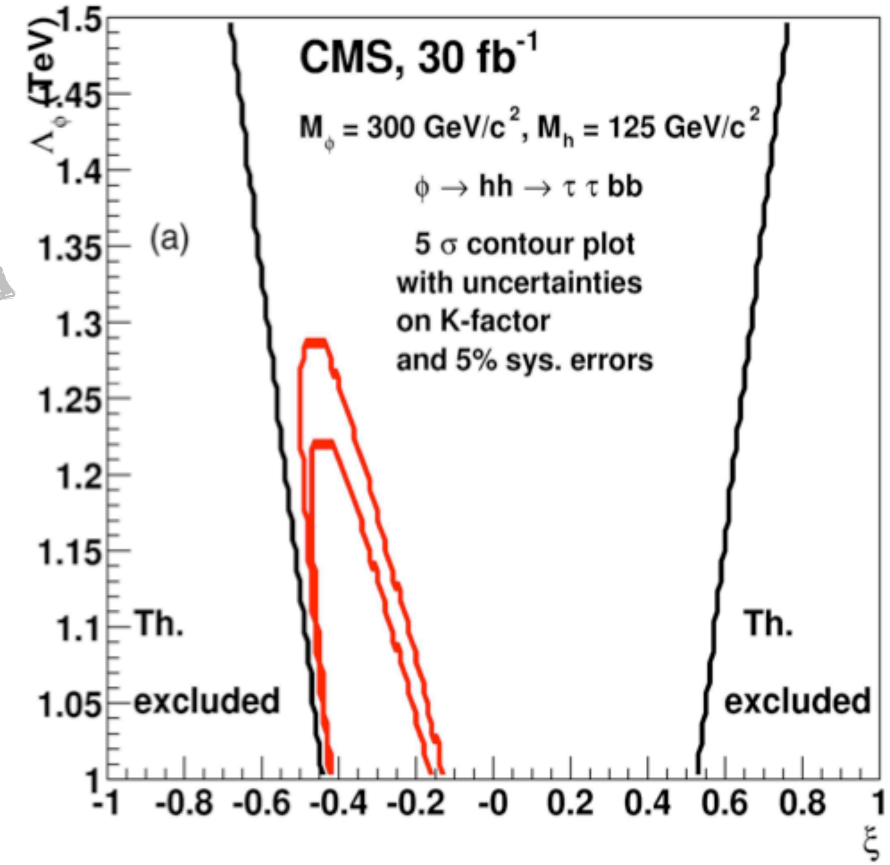

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Analysis Details

Single and dilepton w/ and w/o jets triggers
Two jets with E_T>30 GeV and |η|<2.4, at least one tagged as b-jet
Cut-based analysis
ttbar and W+jets backgrounds

Invisible Higgs

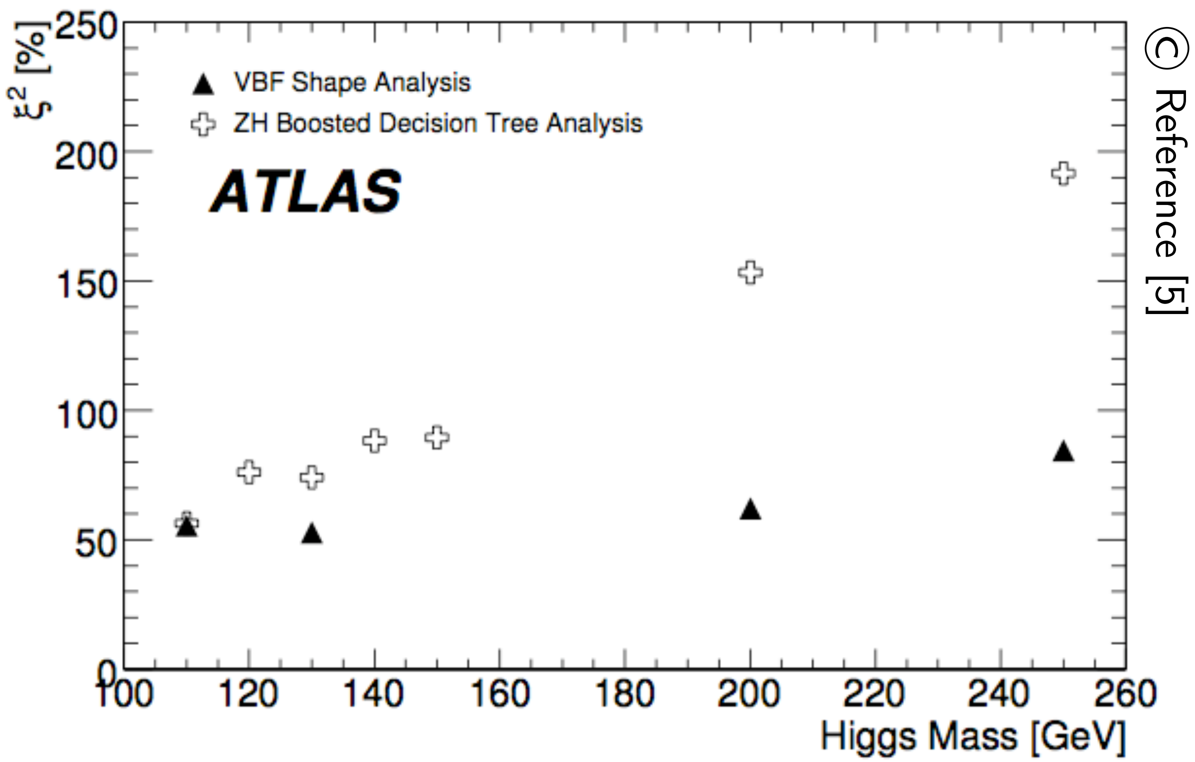
Absence of signal at LHC may translate into an upper limit on BR(H→inv)

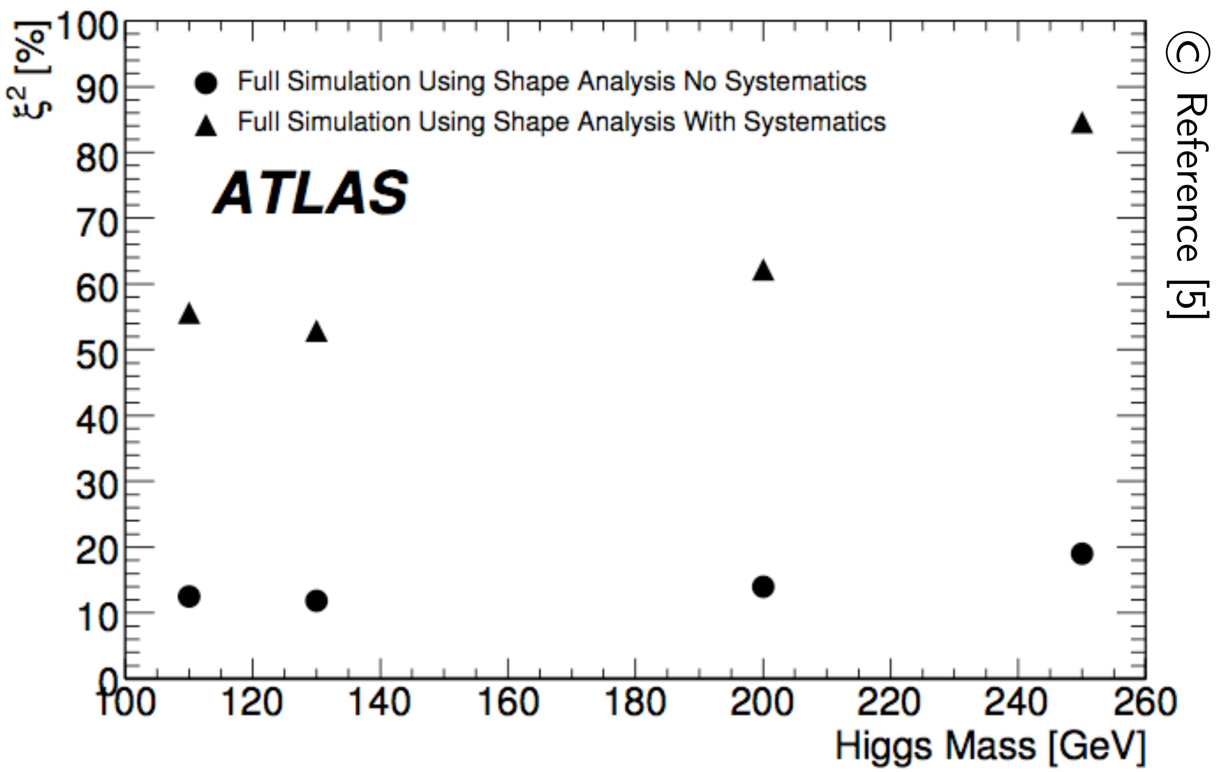
- *Higgs boson(s) invisible decay width* foreseen in SUSY and in beyond MSSM models like large Extra Dimensions, R-parity violation models, Majoron models, dark matter models containing a stable singlet scalar, etc.
- What is invisible depends on the model: graviscalars, Kaluza-Klein neutrinos, neutralinos etc. will all escape detection
  - Modification of SM production modes and decays *expected*
- *Trigger*: need a visible signature → *vector boson fusion (VBF)* and *ttH*, *ZH* Higgs productions (*WH* impossible due to high background)
- No mass reconstruction → *discovery = excess of events w.r.t. predicted SM background*, therefore stringent experimental requirements:
  - Good signal-to-background ratio, optimal background knowledge (from data, soon)
  - Optimal jet detection and missing E_T reconstruction
- SM Higgs production rates and couplings assumed

Invisible Higgs LHC Sensitivity

LHC can reach sensitivities as low as 50% of SM cross section for 100% decay to invisible - Model independent

- LHC sensitivity expressed in terms of the parameter $\xi^2 = BR(H \to \text{invisible}) \cdot \frac{\sigma_{BSM}}{\sigma_{SM}}$
- *Topological search, completely model-independent*
- *Caveat*: pile-up (not included here) may reduce sensitivity





Analysis details

SM Higgs cross sections and 100% invisible BR

VBF and ZH production process - SM backgrounds only

E_T^{miss} + forward jet trigger (VBF) - lepton triggers (ZH)

Cut-based and Boosted Decision Tree analyses

95% CL, *including systematic uncertainties*

VBF channel w/ and w/o Systematics

Systematic uncertainties deteriorate dramatically the sensitivity

Summary

- *We should not limit our attention to the singly weakly interacting Higgs of the SM*
- There may be a close link between the Higgs sector and CP or lepton-flavor violation, and one should consider the possibility of non-standard Higgs representations such as singlets or triplets, or novel decay patterns, including invisible modes
- A light Higgs scalar (arising in NMSSM or in CP-violating models) can still be allowed by LEP constraints
- All searches for non-SM and non-MSSM Higgs particles are very demanding in integrated luminosity $\rightarrow$ *no possibility for early discoveries*
- All the searches on the Higgs sector complemented by searches for other evidence of New Physics
- And ... from the theoretical point of view, the absence of Higgs boson(s) at the TeV scale would be, in any case, an interesting outcome from LHC (but experimentalists might be disappointed!)

Many thanks to P. Gagnon, M. Schumacher, G. Polesello, K. A. Assamagan, M. Schram, A. Nikitenko, C. Mariotti for the useful discussions and the help!

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NMSSM

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[13] K. A. Assamagan *et al.*, *"The hadronic τ Decay of a heavy charged Higgs in models with singlet neutrino in large Extra Dimensions"*, ATL-PHYS-2001-019

Doubly Charged Higgs

[14] G. Azuelos *et al.*, *"Prospects for the Search for a Doubly-Charged Higgs in the Left-Right Symmetric Model with ATLAS"*, SN-ATLAS-2005-049

Radion Searches

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Backup Slides

Two-Higgs-Doublet Models

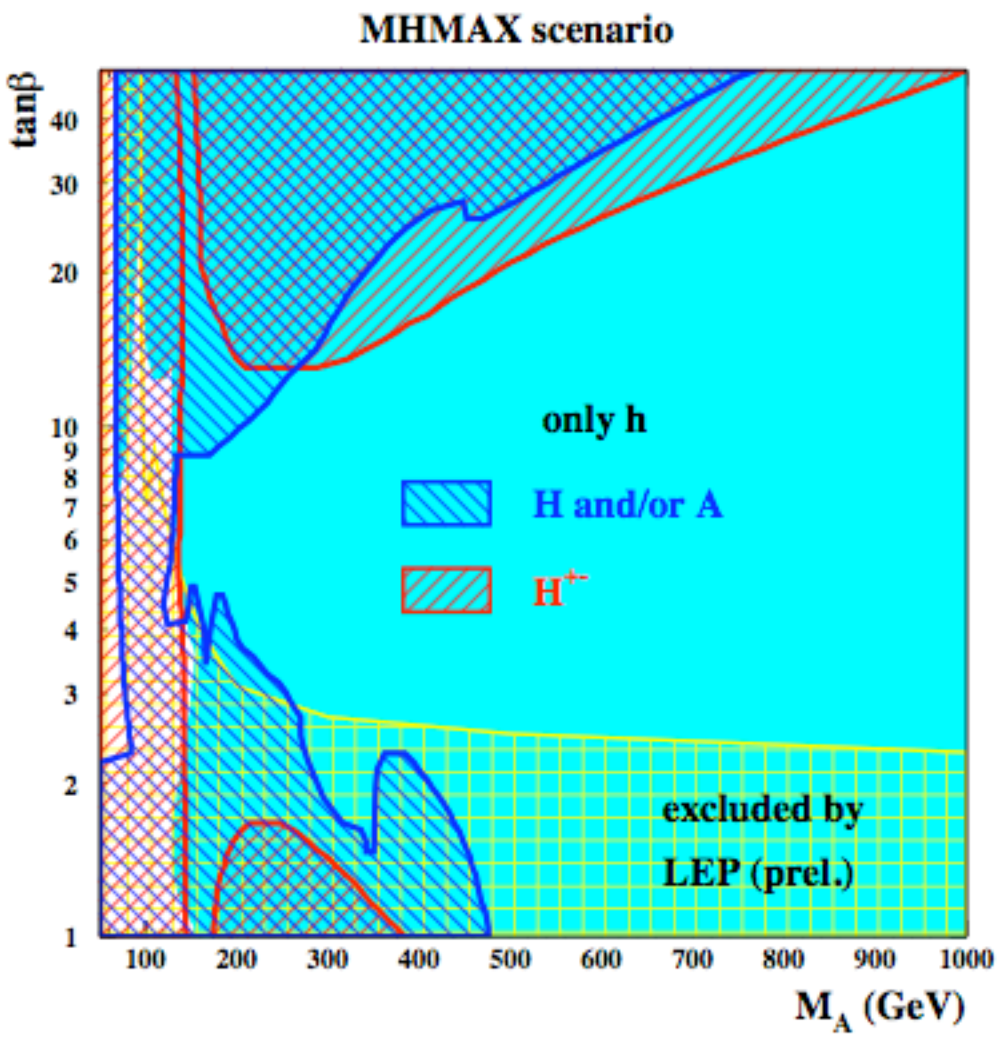
- Differentiated by the possible Higgs-fermion Yukawa couplings

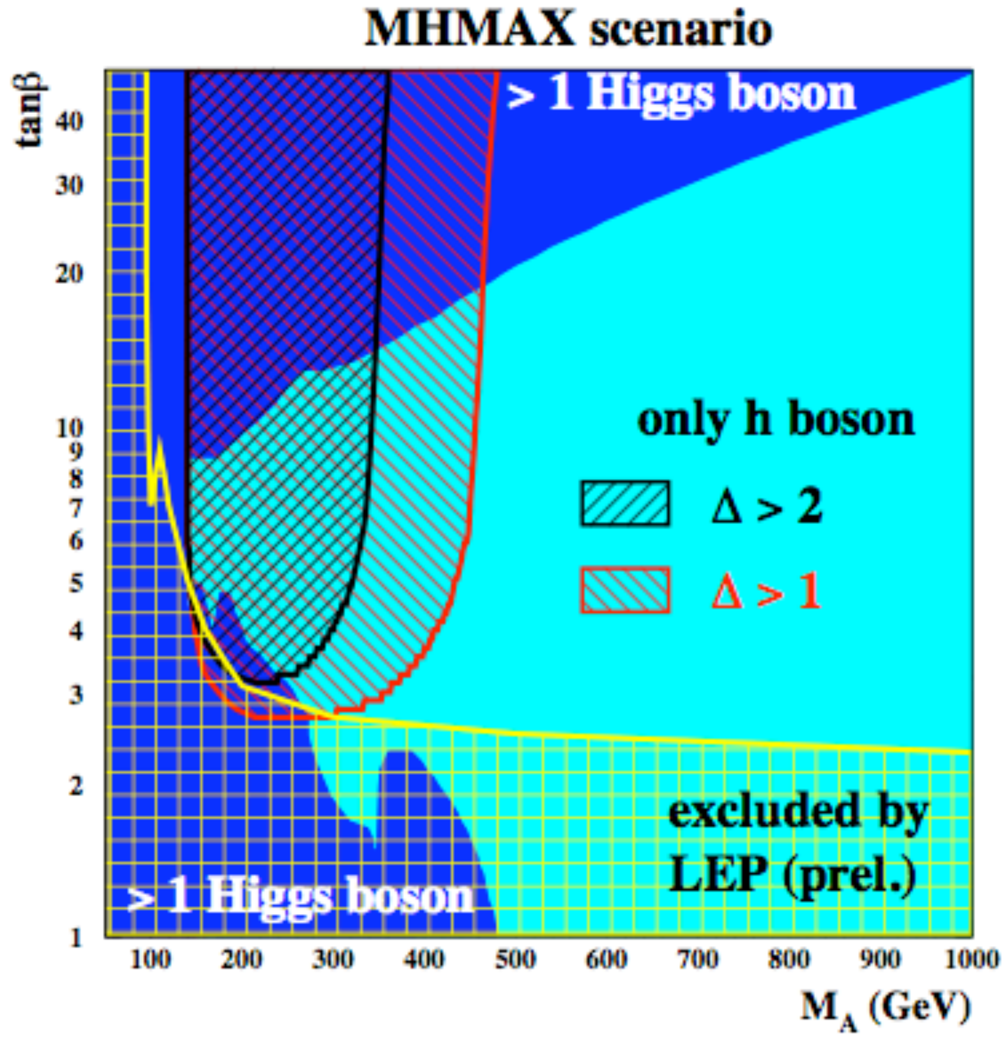
Two-Higgs Doublet Models (2HDM)	
General 2HDM	two identical (hypercharge-one) scalar doublets Φ_1 and Φ_2
2HDM Type-I	one Higgs doublet couples to both up-type and down-type fermions, and the other Higgs doublet does not couple at all to the fermions
2HDM Type-II	one Higgs doublet couples to up-type fermions and the other Higgs doublet couples to down-type fermions.
2HDM Type-III	a 2HDM with all possible Higgs-fermion couplings allowed

- MSSM is a 2HDM Type-II

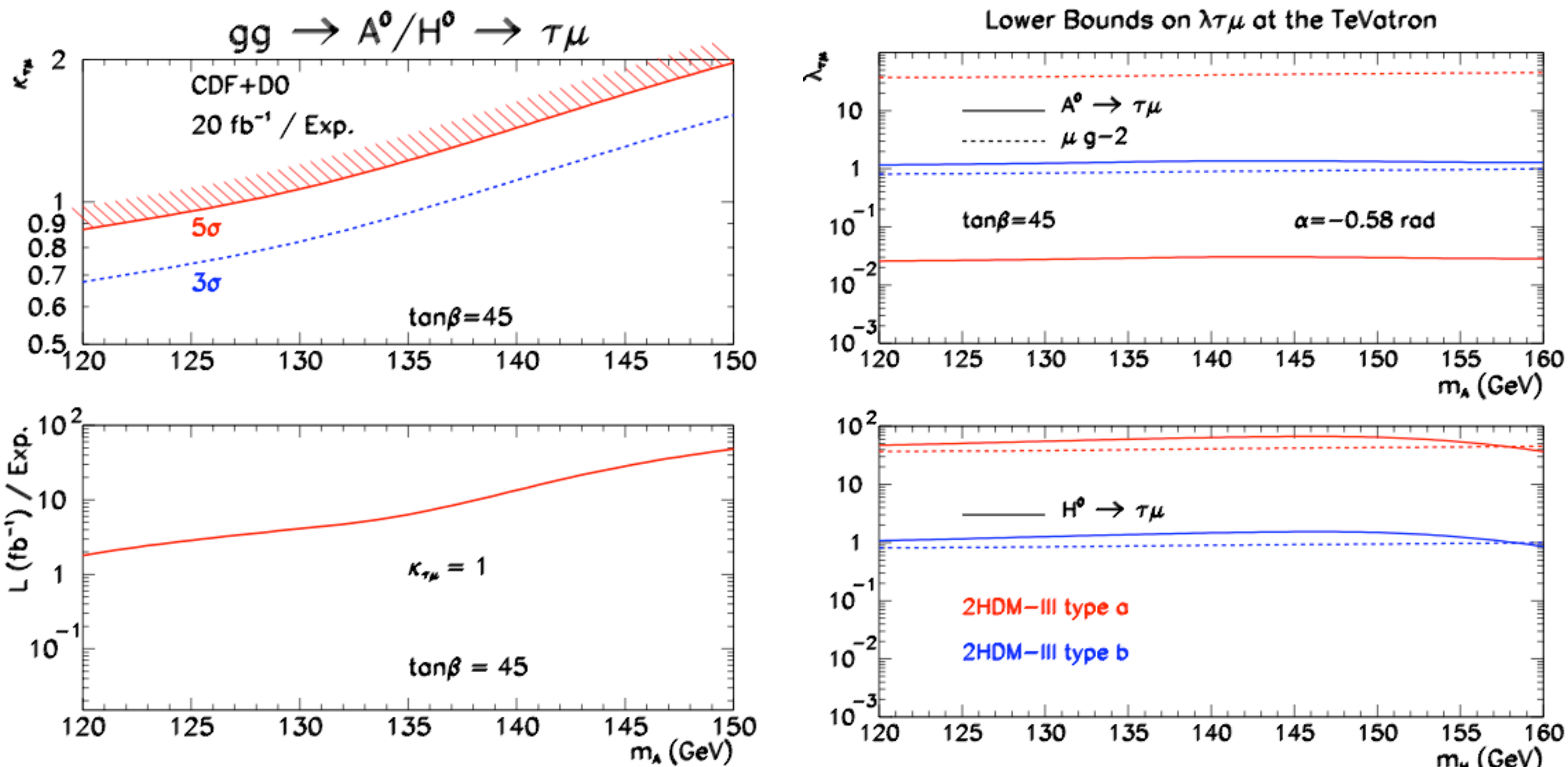
- discovery potential in the CP-conserving **MAX** (large value of the Higgs mass) scenario

CPC MAX Scenario
$\tilde{M}_Q = \tilde{M}_t = \tilde{M}_b = M_{SUSY}, \; A_t = A_b = \sqrt{6}\, M_{SUSY},$
$m_{\tilde{g}} = 1$ TeV, $\mu = m_{\tilde{B}} = m_{\tilde{W}} = 200$ GeV





Lepton Flavor Violating A/H→τμ at TeVatron



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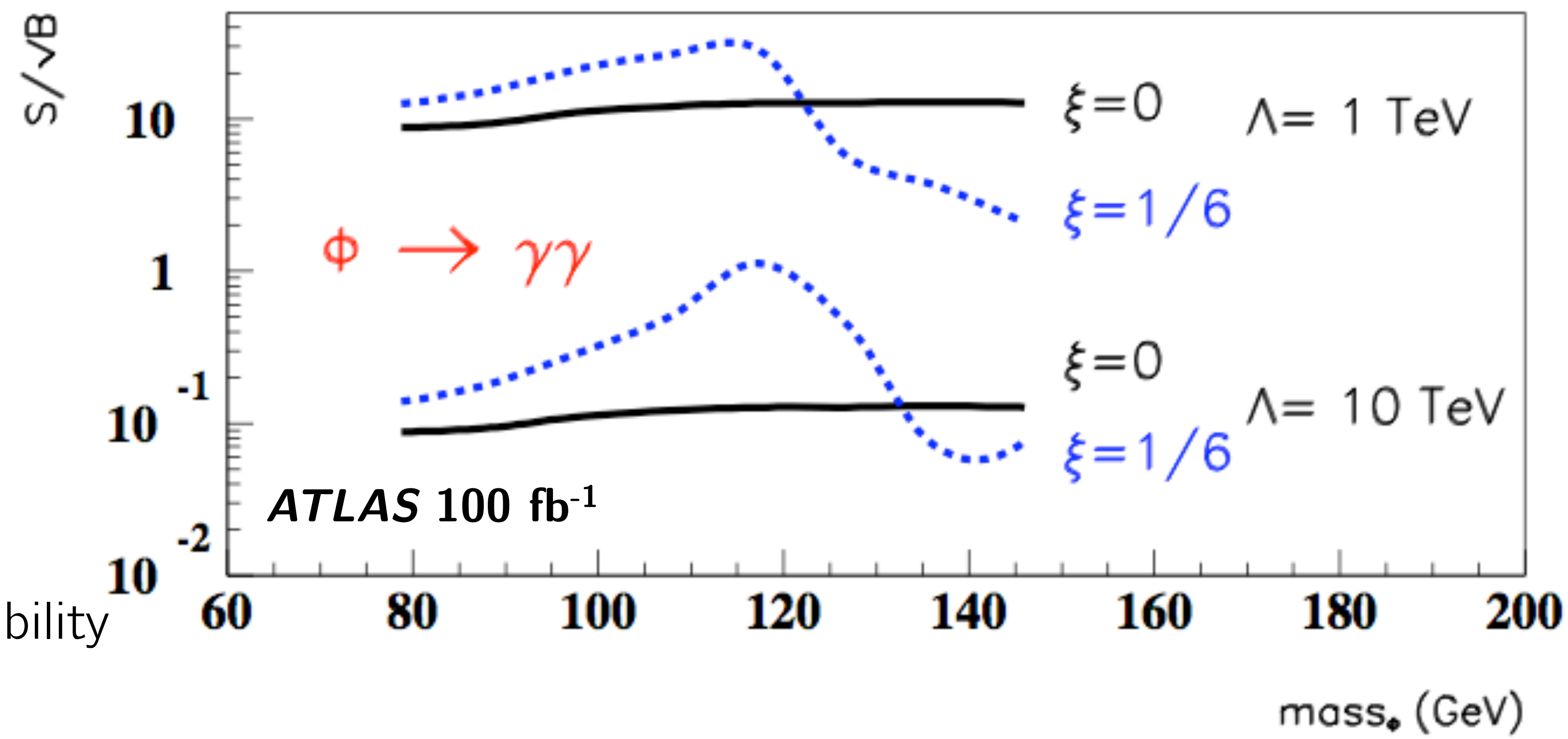
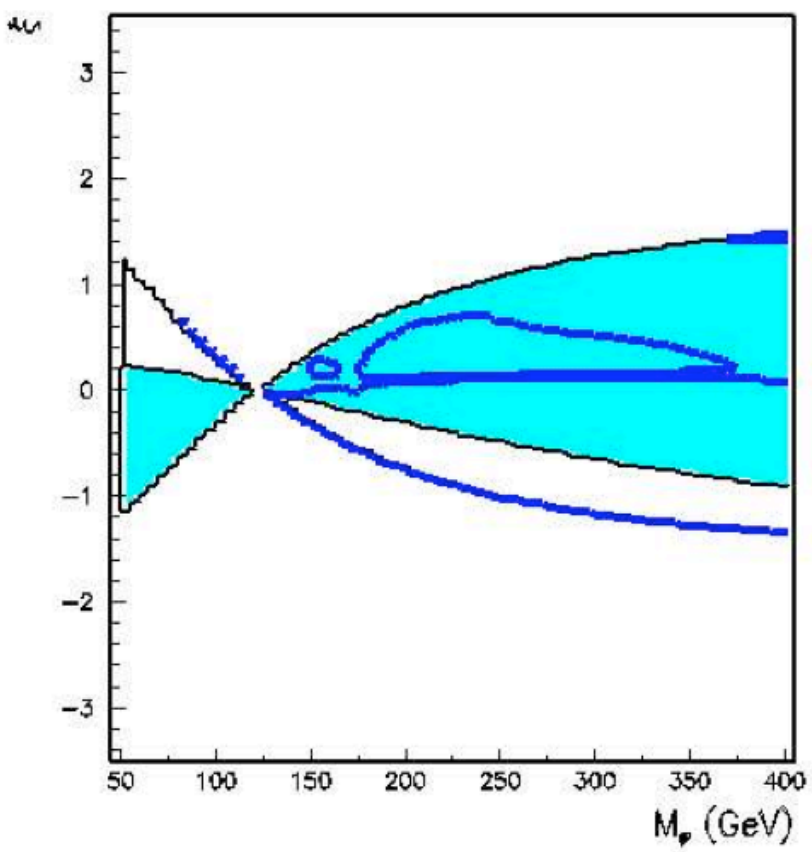
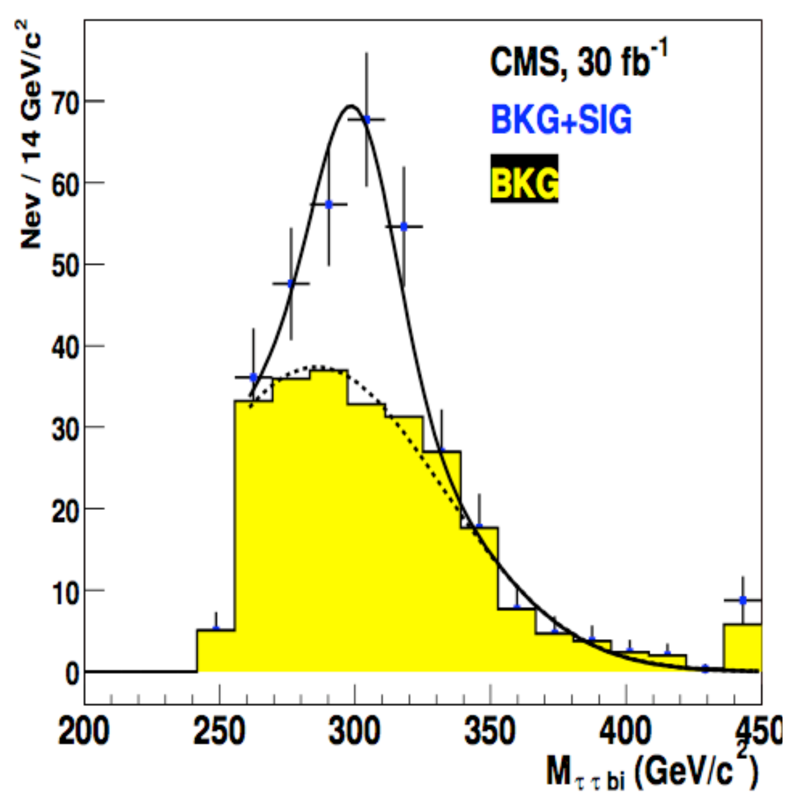
Higgs/Radion in Randall-Sundrum Models

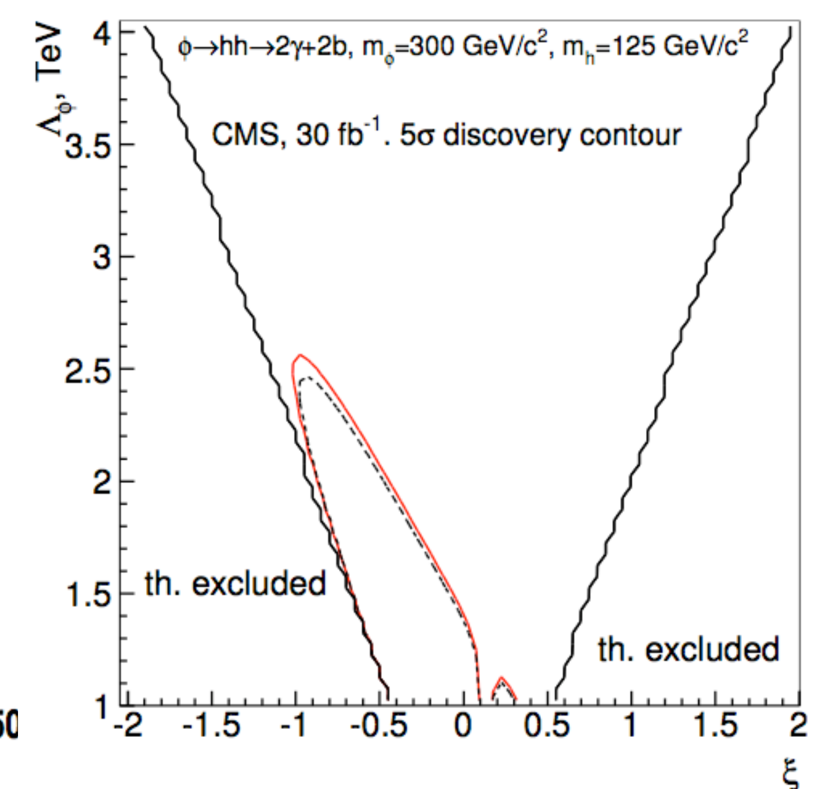


h and $gg \to \varphi \to ZZ^* \to 4l$ 5σ detectability

$M_h = 120$ GeV, $\Lambda = 2.5$ TeV



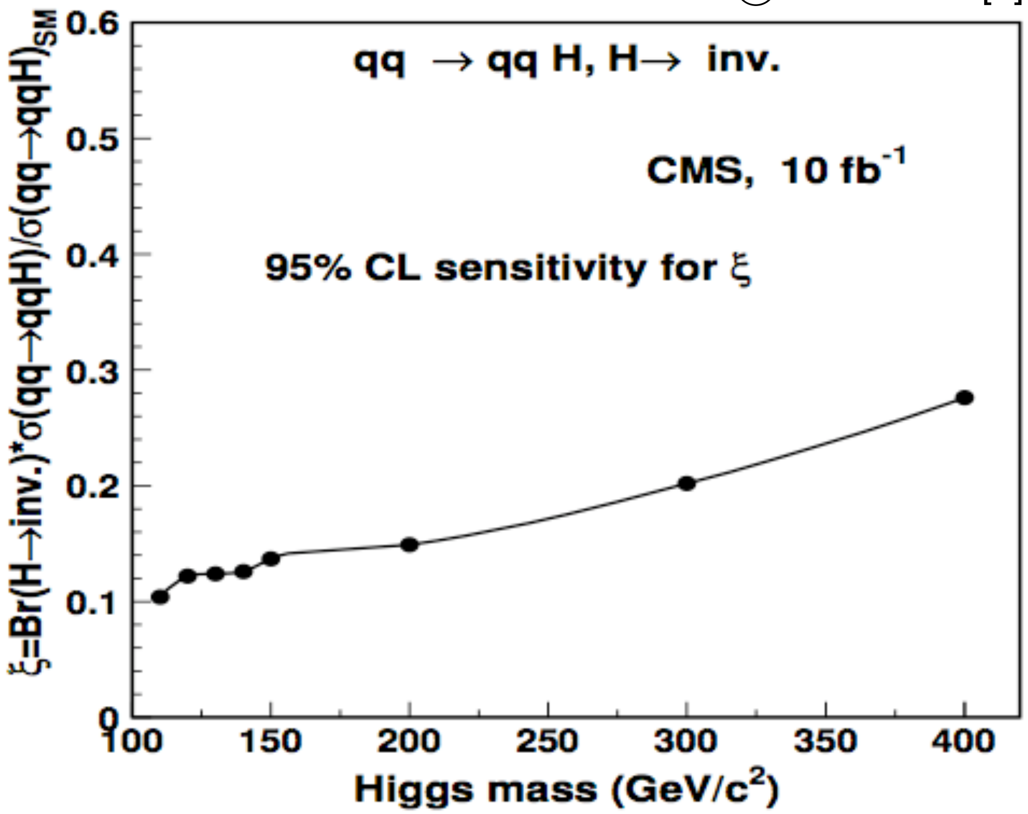




Invisible Higgs CMS Sensitivity

- LHC sensitivity expressed in term of the ξ parameter $\xi = BR(H \to \text{invisible}) \cdot \frac{\sigma_{BSM}}{\sigma_{SM}}$
- Missing ET plus forward jet trigger for qqH - lepton triggers for ZH
- *Caveat*: pile-up (not included here) may reduce sensitivity

Ⓒ Reference [1]



Analysis details

SM Higgs cross sections and 100% invisible BR

qqH production process - SM backgrounds

Cut-based analysis

Systematic uncertainties NOT included