Search for the MSSM Higgs bosons with the CMS detector at the LHC

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The MSSM phenomenology

- Two isospin Higgs doublets

$$\mathbf{H_1} = \begin{pmatrix} \mathbf{H_1^0} \\ \mathbf{H_1^-} \end{pmatrix} \textbf{ and } \mathbf{H_2} = \begin{pmatrix} \mathbf{H_2^+} \\ \mathbf{H_2^0} \end{pmatrix}$$

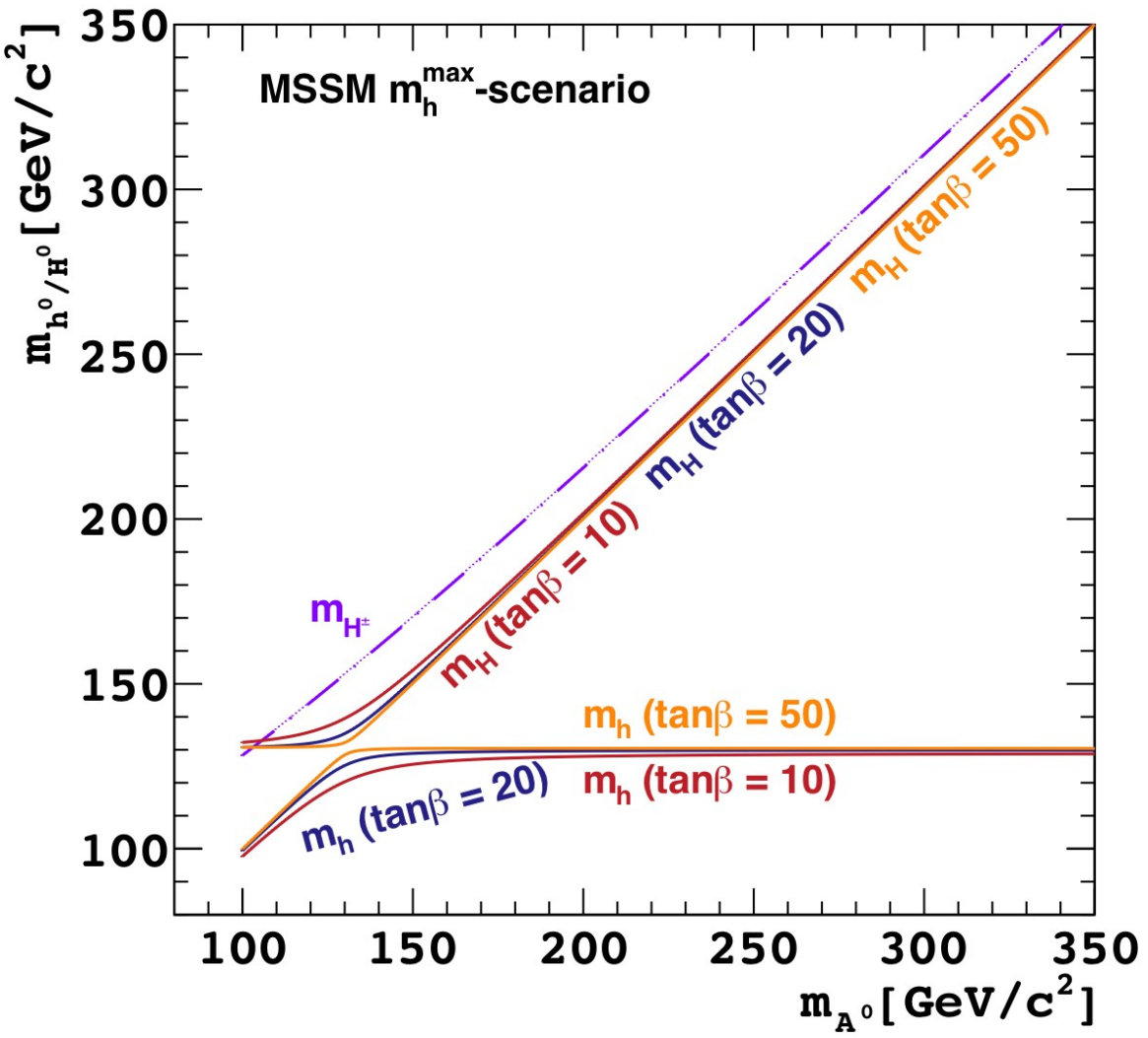
- After EW symmetry breaking: 5 physical Higgs bosons:

  h, H – scalar, CP even,
  A – pseudoscalar, CP odd,
  H^+, H^- – charged

- Two free parameters describe the Higgs sector at tree level: e.g. m_A and tanβ

- Fixed benchmark scenarios: m_h^{max} used in most of the shown results

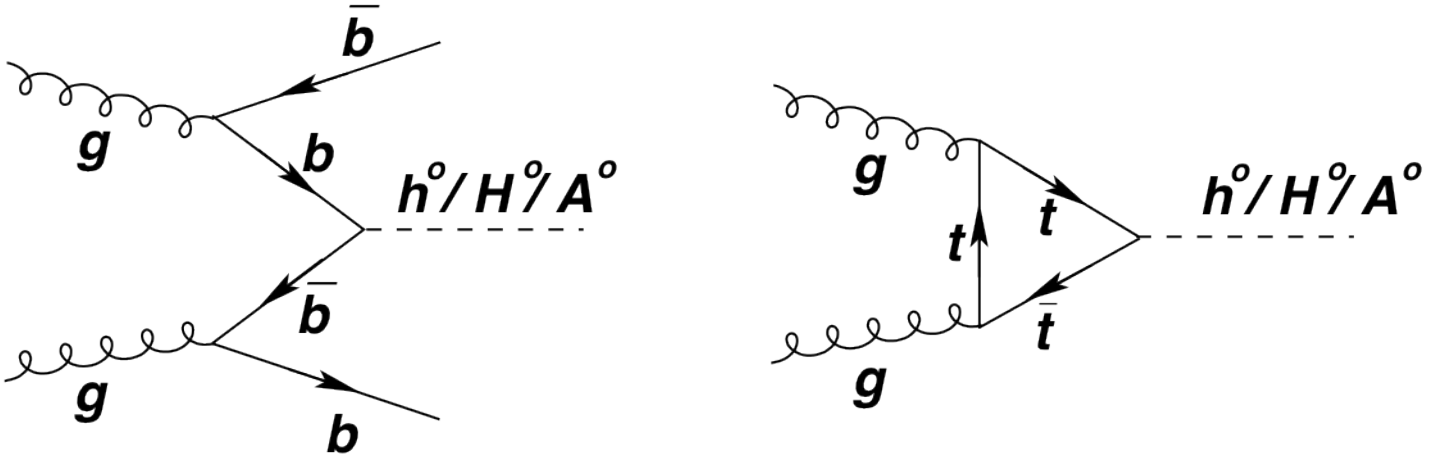
- MSSM predicts a light Higgs boson, $m_h < 135$ GeV.



MSSM neutral Higgs production and decays

Main production mechanisms: <u>bb-associated production</u> (large tanβ) and **<u>gluon-gluon fusion</u>** via with top and bottom loops (moderate tanβ).

Higgs couplings to down-type fermions ~tanβ, production rates are enhanced with respect to the SM.



Φ (h/H/A) decays to 3rd generation fermions enhanced at all masses

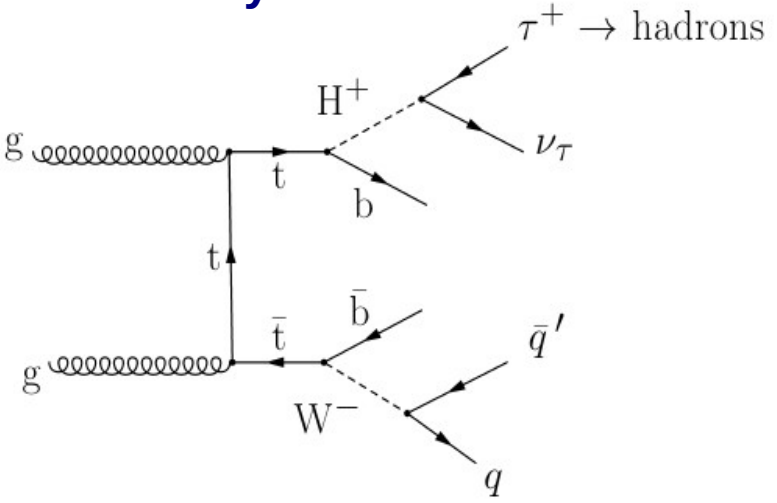
- b b (Br ~ 90%) - burdened by large QCD background,
- τ τ (Br ~ 10%) - possible hadronic and leptonic final states,
- μ μ (Br ~ 0.03%) - clean signature but low yield,
- SUSY particles (if allowed) – depends on additional parameters.

MSSM charged Higgs production and decays

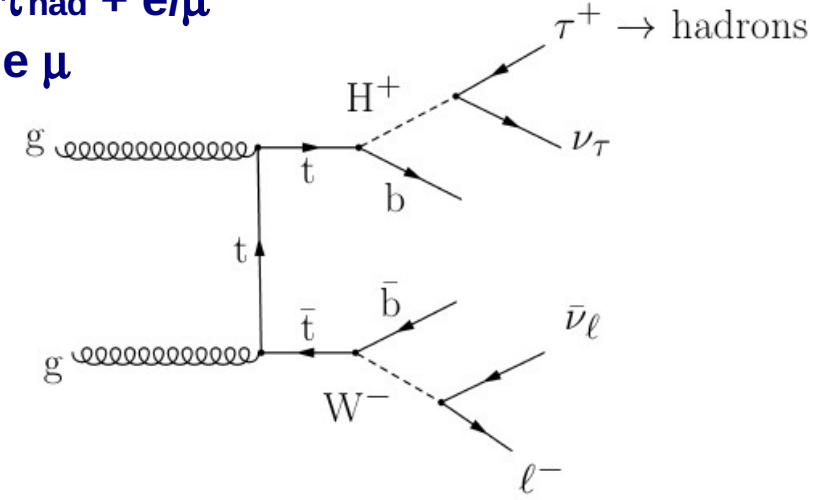
- **For $m_{H^+} < m_{top}$, the dominant production and decay modes:**
  $gg \rightarrow H^{\pm}W^{\mp}bb$, $H^{\pm} \rightarrow \tau\,\nu$

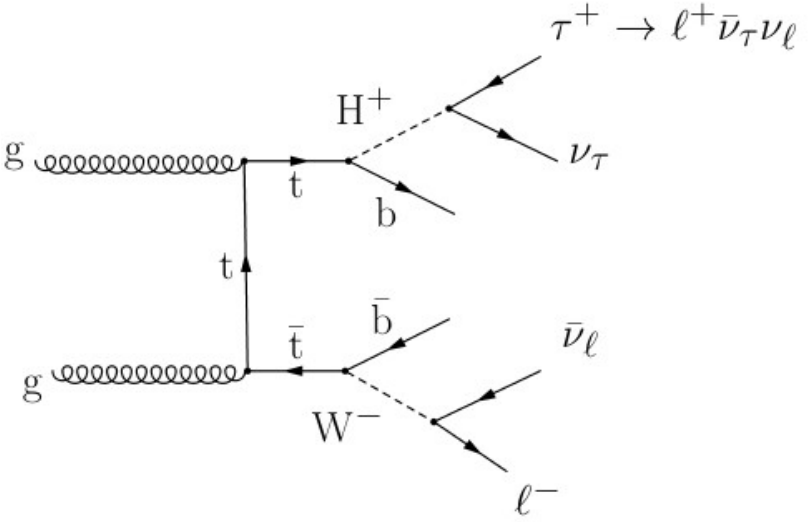
  * $Br(t \rightarrow H^{\pm}b) \neq 0$
  * $Br(H^{\pm} \rightarrow \tau\,\nu) \cong 1$ (large tanβ)

  Alters the τ yield in top pair decays.



- **Final states to study:**
  - *** τ_{had} + jets**
  - *** τ_{had} + e/μ**
  - *** e μ**





Scope of this talk

- **Neutral Higgs (h/H/A) searches:**

  - **$\tau\,\tau$ channel** – 4.9 fb^{-1} at 7 TeV + 12.1 fb^{-1} at 8 TeV
    New updated CMS preliminary results as of Nov. 2012,
    CMS-PAS-HIG-12-050
  - **b b channel** – 4.0-4.8 fb^{-1} at 7 TeV
    Combined results of the analyses of all-hadronic and semi-leptonic decay channels from ICHEP 2012,
    CMS-PAS-HIG-12-026, CMS-PAS-HIG-12-027
  - **$\mu\,\mu$ channel** – 4.9 fb^{-1} at 7 TeV
    Analysis results of ICHEP 2012,
    CMS-PAS-HIG-12-011

- **Charged Higgs ($H^{\pm}$) searches:**

  - **$\tau\,\nu$ channel** – 2.0-2.3 fb^{-1} at 7 TeV
    Published analysis, arXiv:1205.5736

$$\Phi \longrightarrow \tau\ \tau$$

Tau reconstruction and b tagging

● τ reconstruction:

- τ pairs reconstructed in decays into leptons (e/μ) + hadrons (1 or 3 prong), or pure leptonic (e μ or μ μ),
- hadronic τ identification: Hadron Plus Strips (HPS) algorithm, cuts based on event topology and kinematics to account for different τ decay modes: $\pi^{\pm}$, $\rho^{\pm}$, a_1

→ see talk by R.Boniecki in the Young Researcher Session

● b-tagging:

- Combined Secondary Vertex (CSV) algorithm – reconstruction of secondary vertices together with track-based lifetime information in a jet,
- 3-D impact parameter (IP) is computed for each track,
- IP significance (IP/σ_{IP}) of tracks used to rank tracks in a vertex,
- likelihood discriminants based on the significance of second-ranked (“High Efficiency”) or third-ranked (“High Purity”) tracks,
- More information: CMS-PAS-BTV-11-004 (2012).

$\tau\tau$ - triggering and event selection

- **Trigger:** events selected by dedicated e+τ_{had}, μ+τ_{had}, eμ or $\mu\mu$ triggers

- **Event selection**

  - Lepton selection:

Electrons	**Muons**	**τ_{had}**
p_T > 20-24 GeV	p_T > 17-20 GeV	p_T > 20 GeV
$\|\eta\|$<2.1 (2.3 for eμ)	$\|\eta\|$<2.1	$\|\eta\|$<2.3
isolated	isolated	τ-identification

  - Opposite charge lepton pair, second lepton (eμ, $\mu\mu$) p_T > 10 GeV
  - Veto events with additional isolated leptons with p_T>15 GeV
  - MET (missing transverse energy) > 25 GeV (e+τ_{had})

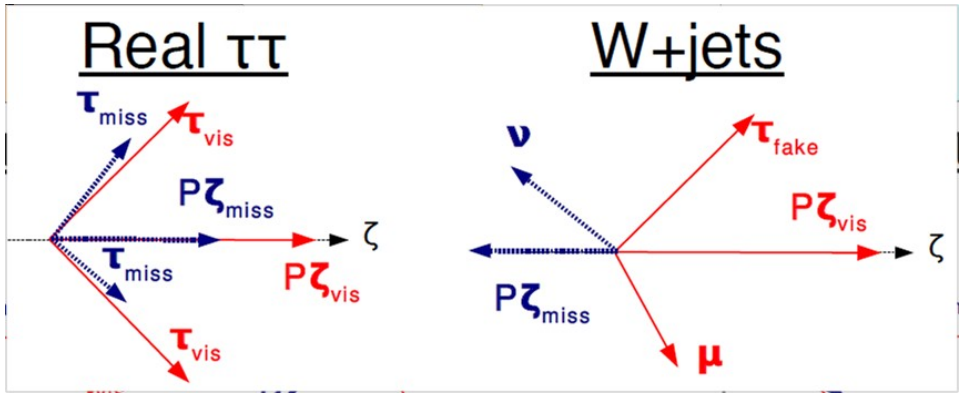
- Events analyzed in two categories: b-tag and non-b-tag (mostly sensitive to the b-associated Higgs production and the gluon-fusion process, respectively)

b-tag	**non-b-tag**
≤1 jet with p_T>30 GeV,	≤1 jet with p_T>30 GeV,
≥1 b-tagged jet with p_T>20 GeV	No b-tagged jet with p_T>20 GeV

$\tau\,\tau$ - event selection contd.

- Suppression of W+jets background: $e+\tau_{had}$, $\mu+\tau_{had}$: $M_T < 40$ GeV;

  $e\mu$, $\mu\mu$: ζ cut (ζ axis – the bisector of the directions of the visible τ decay products transverse to the beam direction)



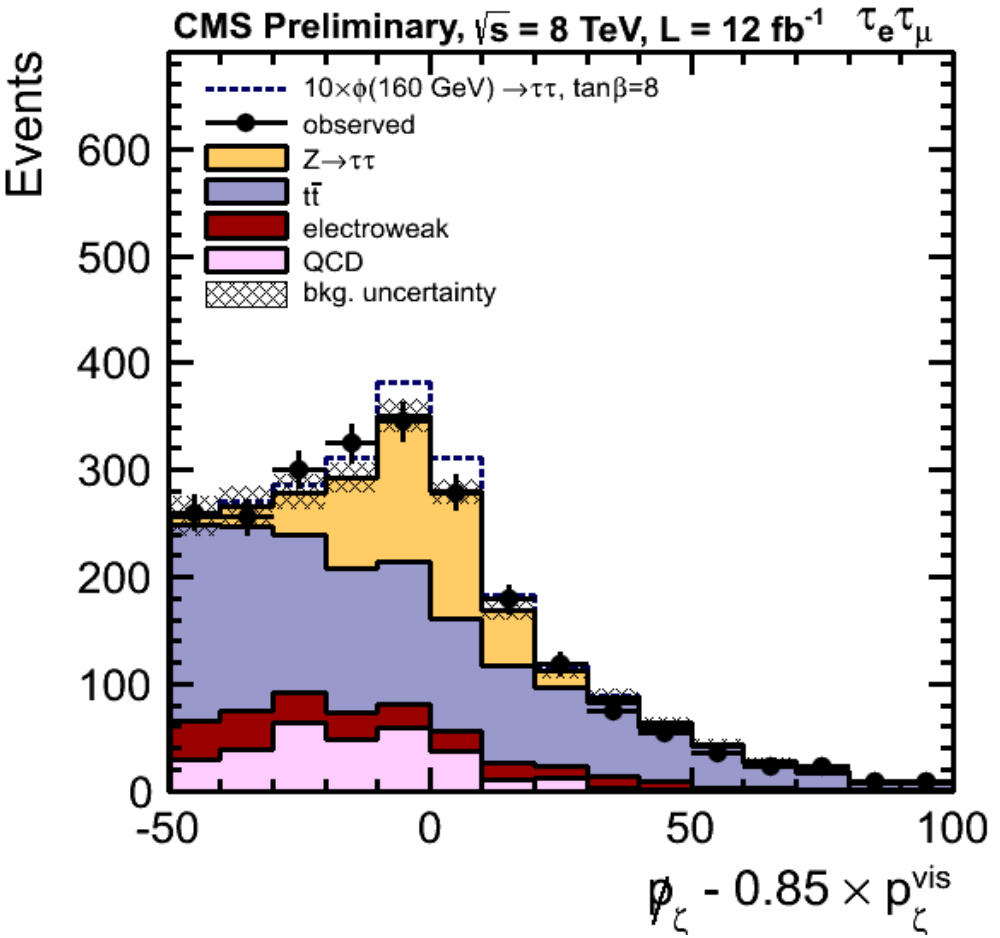
Projections of the visible decay product momenta and the MET vector onto ζ:

$$P_\zeta^{vis} = p_T^{(1)}\,\zeta + p_T^{(2)}\,\zeta$$

$$P_\zeta^{miss} = E_T^{miss}\,\zeta$$

This analysis:

$$P_\zeta^{miss} - 0.85 \times P_\zeta^{vis} > -25 \text{ GeV}$$



$\tau\,\tau$ - background estimation and data analysis

- **$\tau\,\tau$ mass reconstruction**

  Kinematic fit based on the likelihood technique, computes the invariant mass most compatible with the observed momenta of the visible tau decay products and MET

- **Background estimation**

  $Z \rightarrow \tau\,\tau$ – use the $Z \rightarrow \mu\mu$ sample from data and replace the muon by a simulated τ ("embedding"). Normalized to the measured $Z \rightarrow \mu\mu$ cross section,

  QCD multijet (with jet misidentification) – estimated from the yield of same-sign $\tau\,\tau$ events,

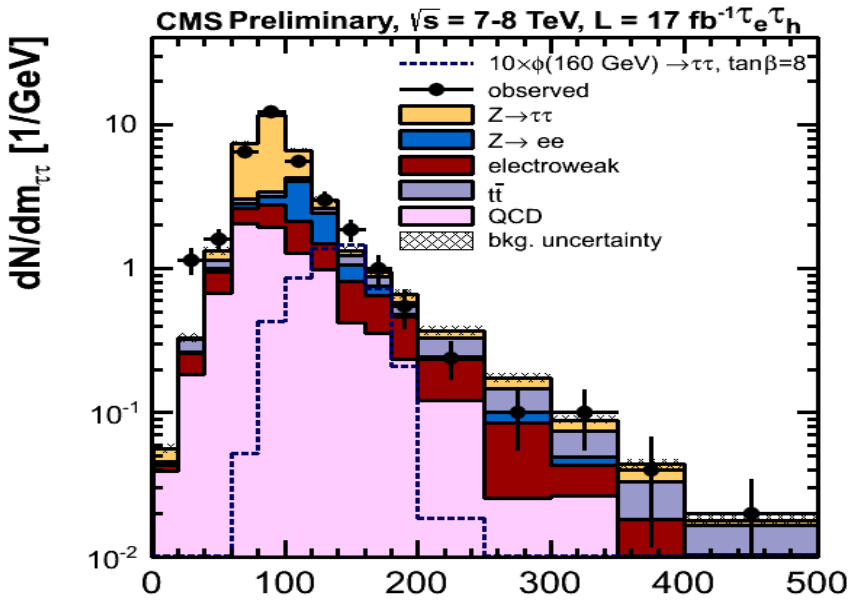
  W+jets – shape from MC and normalization from events with large M_T (hadronic), or from data with relaxed lepton isolation on one lepton (leptonic),

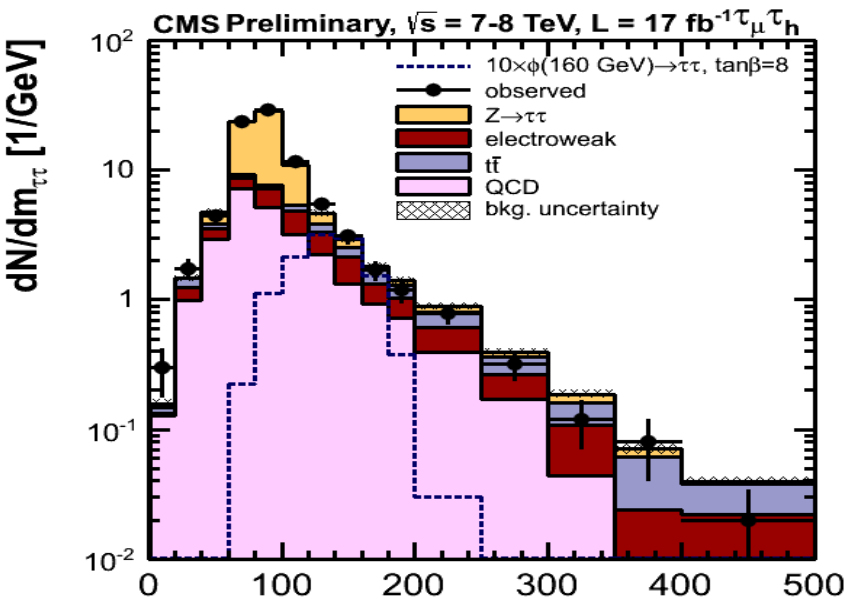
  Top pair, diboson, etc. – from MC; top pair normalized to the measured cross section,

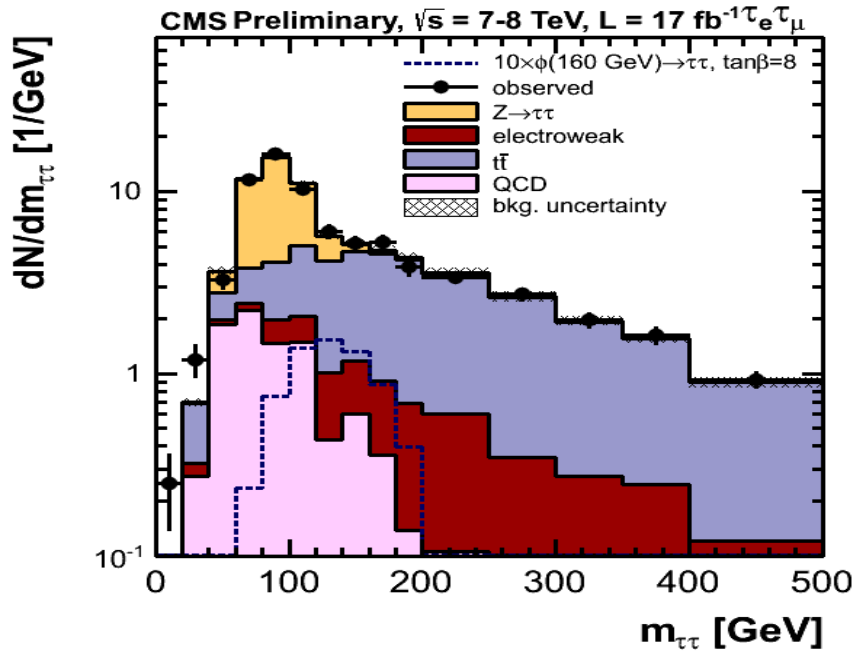
- **Results**

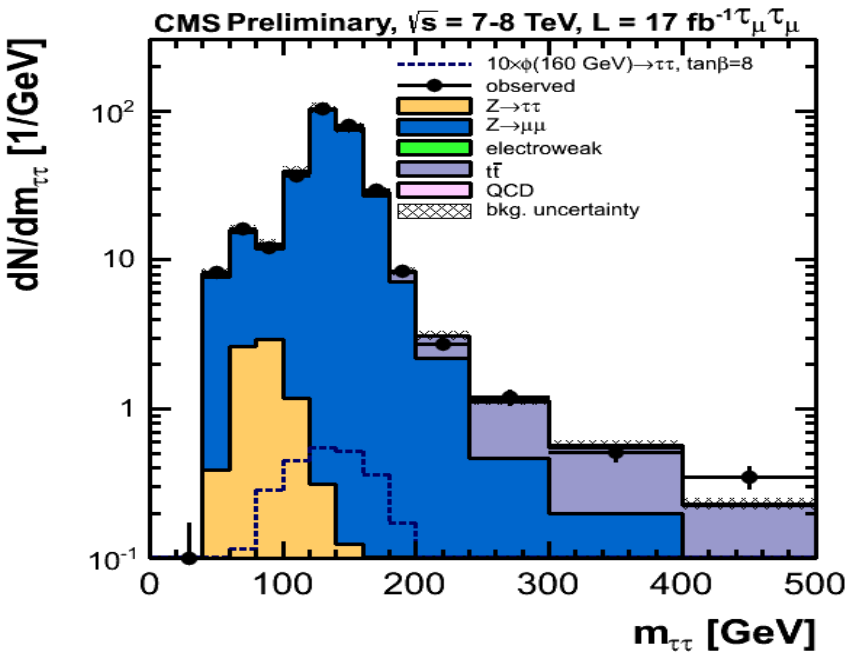
  Binned maximum likelihood fit to the $\tau\,\tau$ invariant mass spectrum, simultaneously performed for the four final states with two event categories each.

$\tau\,\tau$ – results in the b-tag category

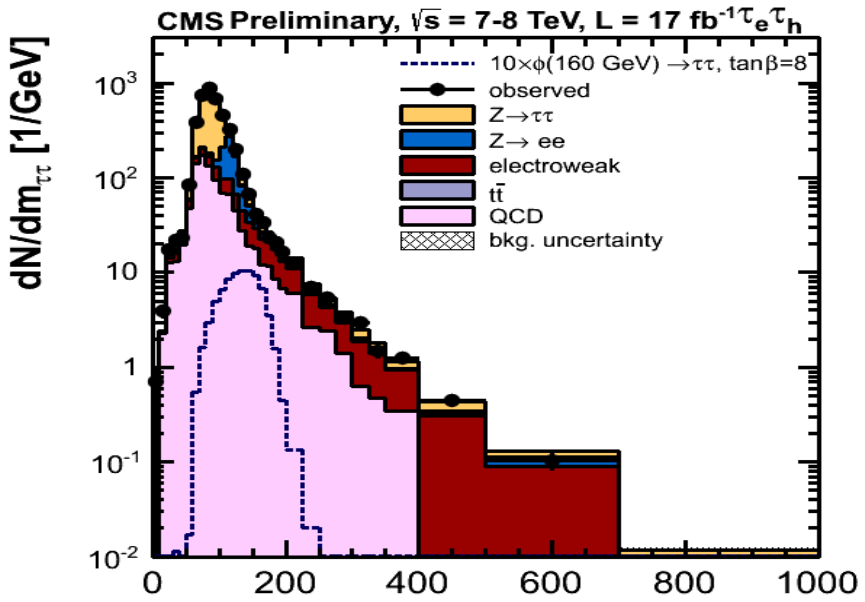


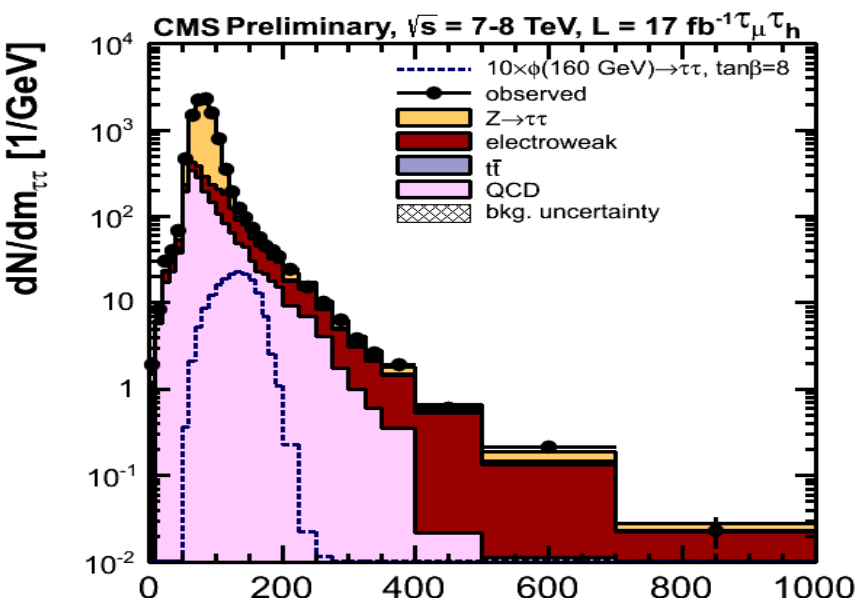


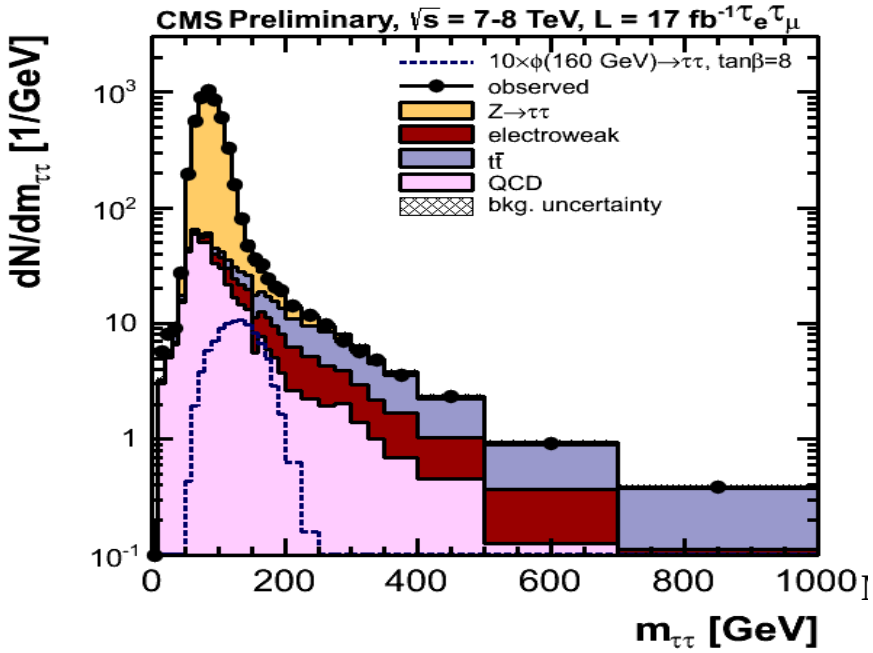


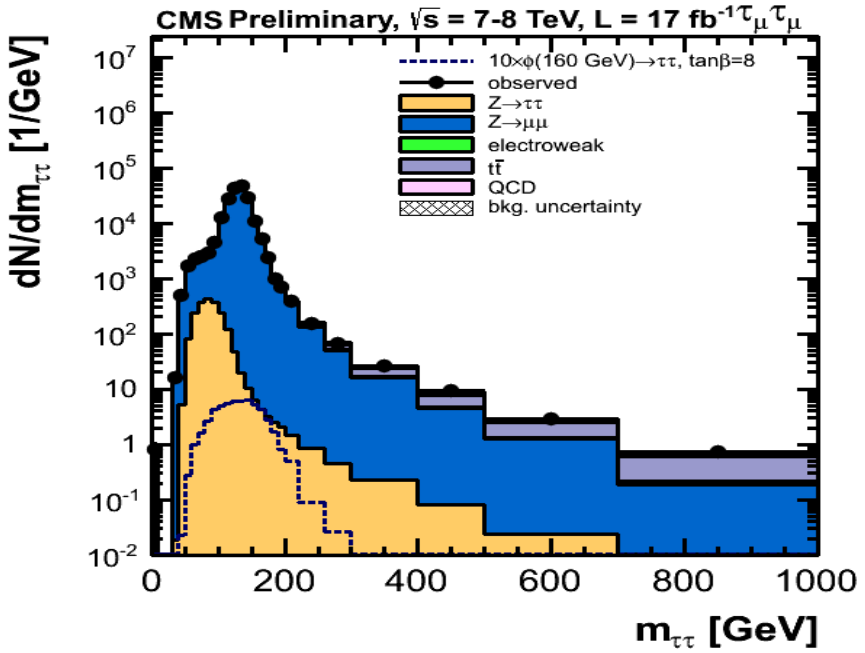


$\tau\,\tau$ – results in the non-b-tag category







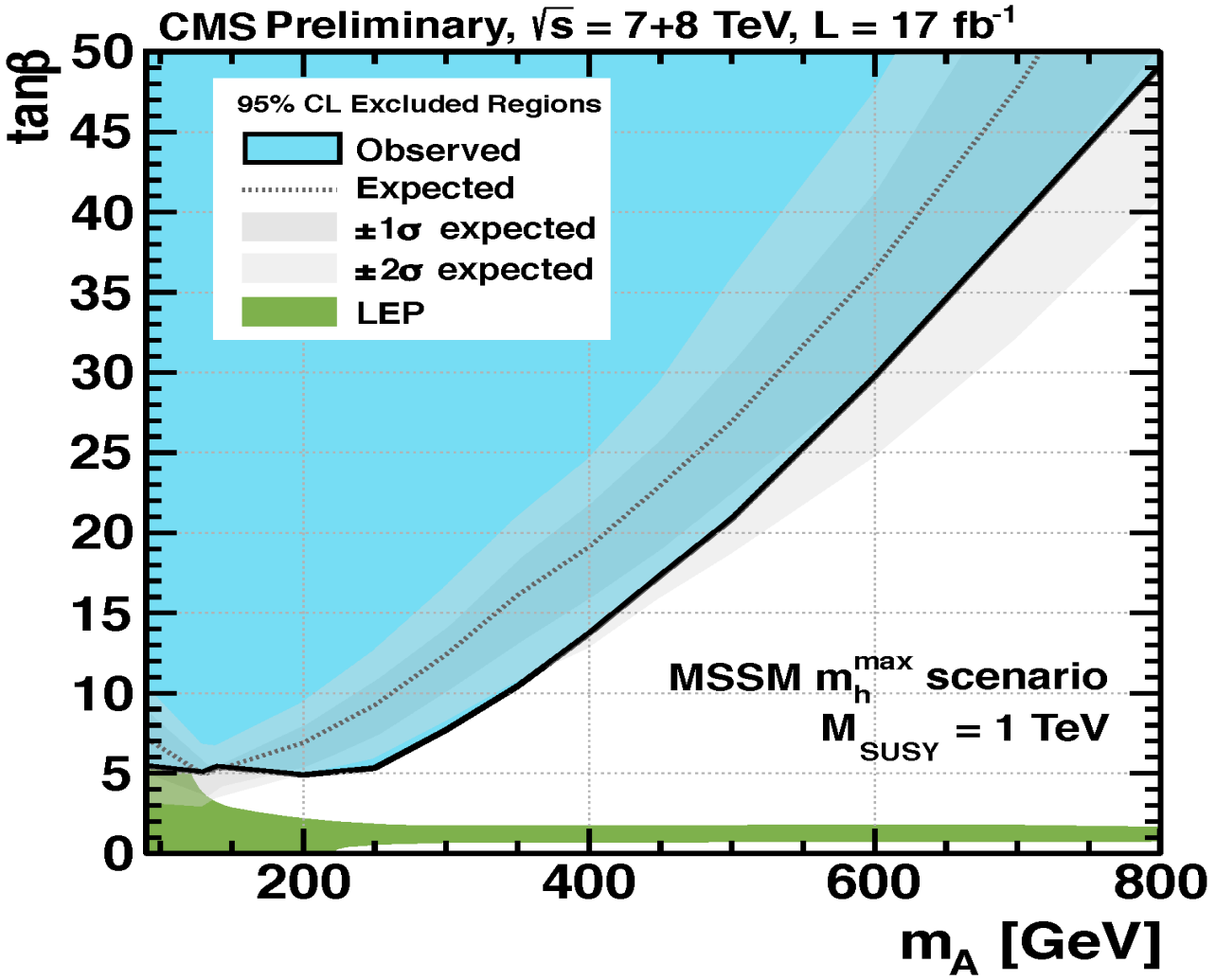


$\tau\tau$ – exclusion limits

Signal cross sections and their uncertainties provided by the LHC Higgs Cross Section Group (GGH@NNLO, HIGLU, BBH@NNLO)

No excess is seen over predicted SM background in any event category.

Rules out a significant portion of the parameter space previously unexplored - severely constrains the MSSM with tanβ reaching as low as 5 for any m_A<250 GeV in the m_h^{max} scenario.



$$\Phi \rightarrow b\,\bar{b}$$

b $\bar{b}$ - triggering, data selection and analysis

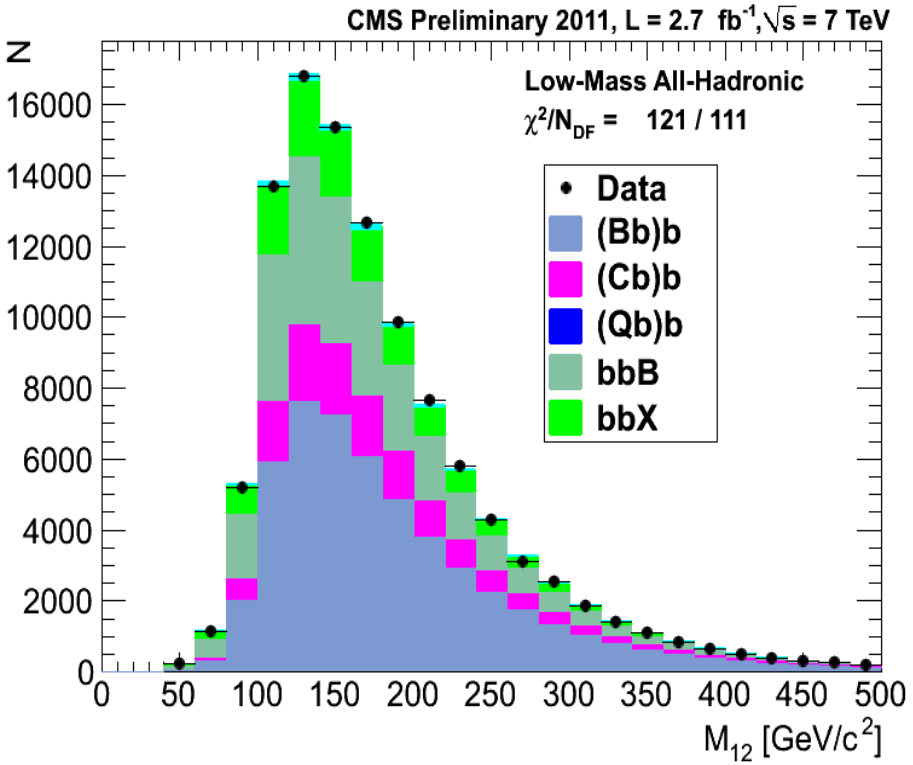
- Two event categories considered: **all-hadronic** (bbb) and **semi-leptonic** (bb with an additional muon)

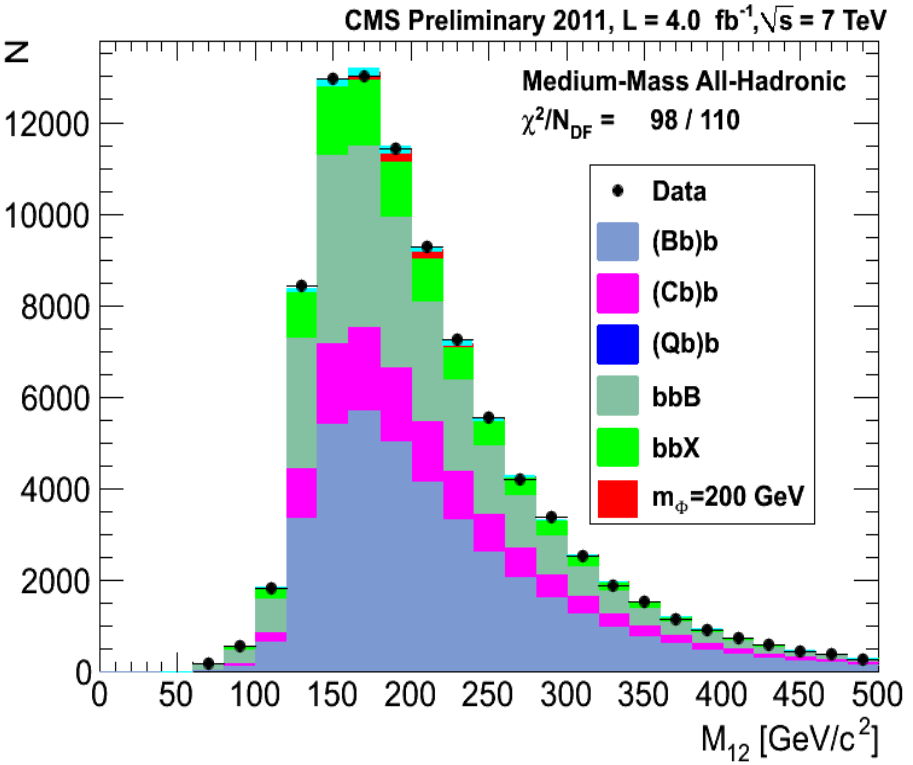
Trigger:	2 or 3 jets, ≥2 b-tagged,	1 muon + 1 or 2 jets, ≥1 b-tagged
Jet selection:	≥3 jets, $\|\eta\| < 2.2$, $P_T^{(1)} > 46(60)^*$ GeV, $p_T^{(2)} > 38(53)^*$ GeV, $p_T^{(3)} > 20$ GeV, 3 leading jets b-tagged, $\Delta R(1,2) > 1$	≥3 jets, $\|\eta\| < 2.6$, $p_T^{(1)} > 30$ GeV, $p_T^{(2)} > 30$ GeV, $p_T^{(3)} > 20$ GeV, 2 leading jets b-tagged, 3rd looser $\Delta R(i,j) > 1$
Muon selection:		$p_T > 15$ GeV, muon used in jet reconstruction

- **Background estimation:**
  - QCD (dominant) – from "double b-tag" events, i.e., 3-jet events with relaxed b-tag requirement on one jet – templates are constructed by assuming a true flavor of the untagged jet and scaling with the appropriate b-tagging probability.

*)for m_Φ<180 GeV (>180 GeV)

b $\bar{b}$ – results in the all-hadronic category

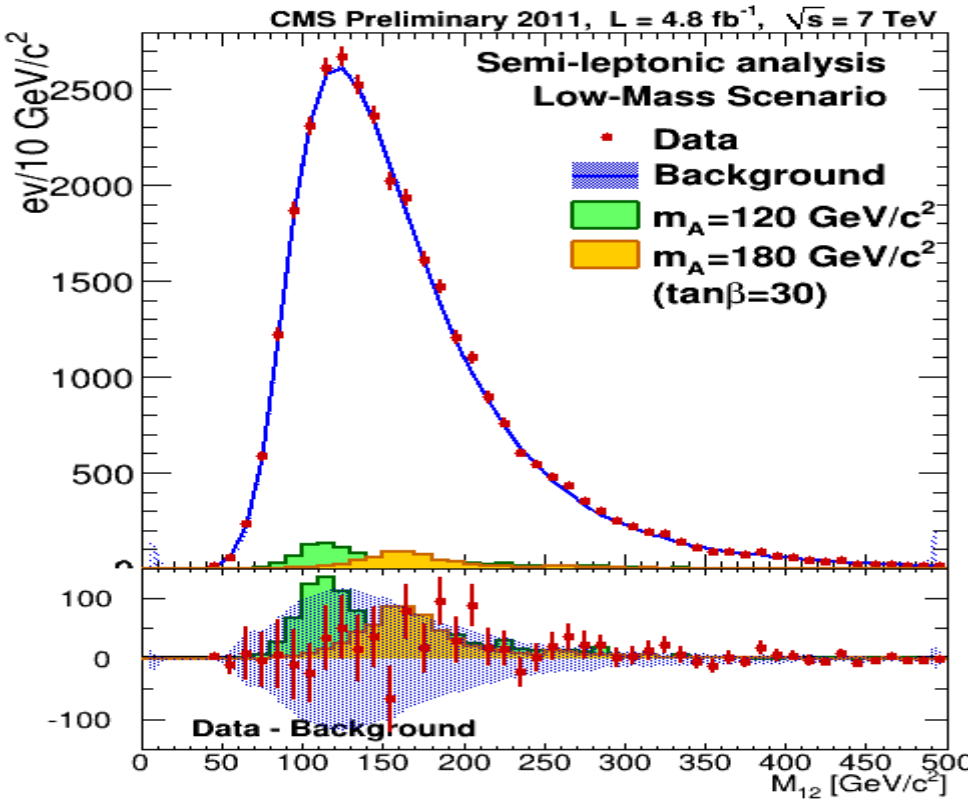


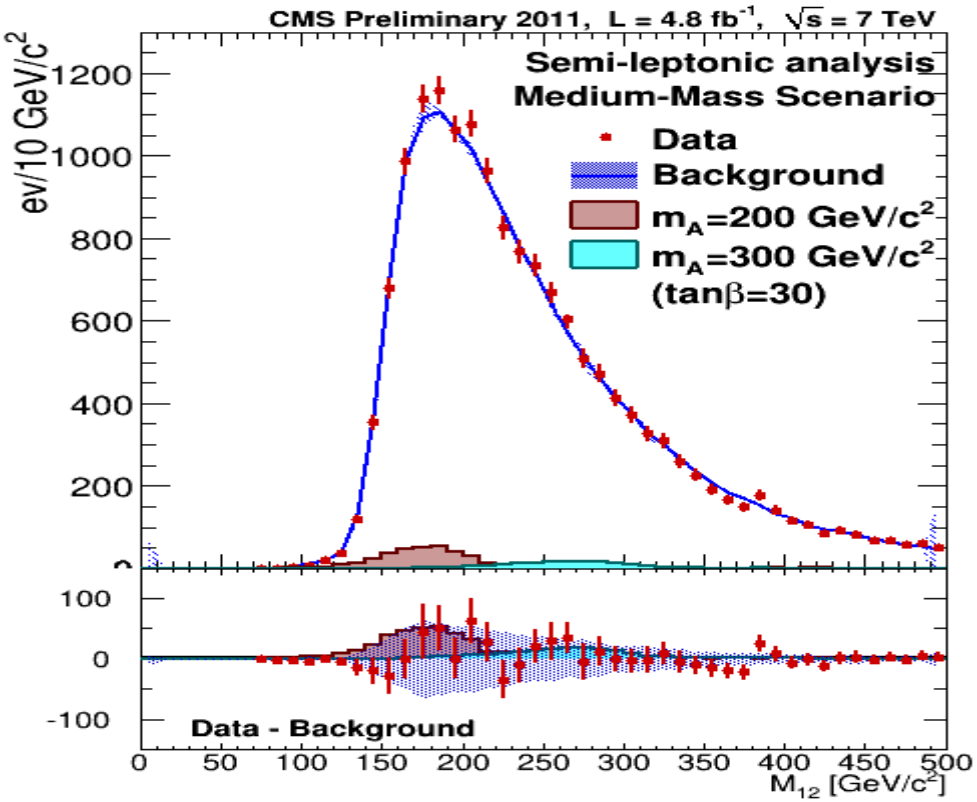


Signal extraction: fit of a linear combination of signal and background templates to the observed event yields in bins of the two leading jets' invariant mass (M12) and EventBTag, a dedicated variable that combines the b-tagging information of the three jets.

Good agreement with predicted SM background

b $\bar{b}$ – results in the semi-leptonic category



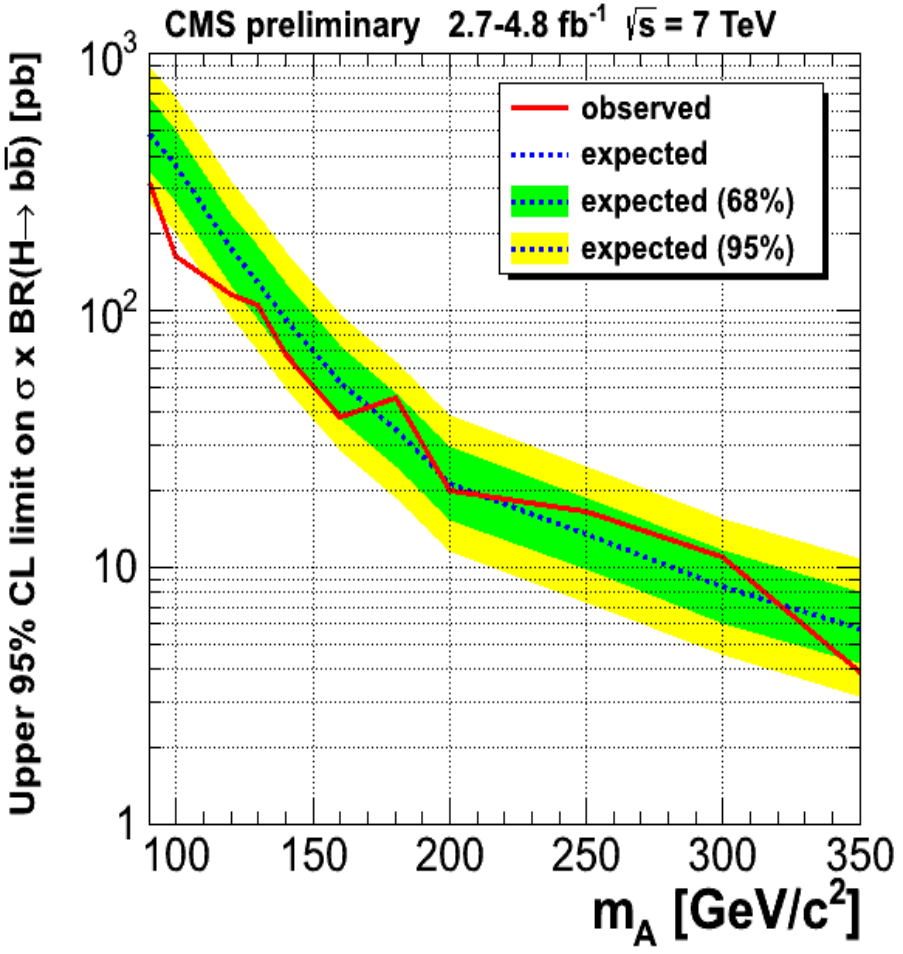


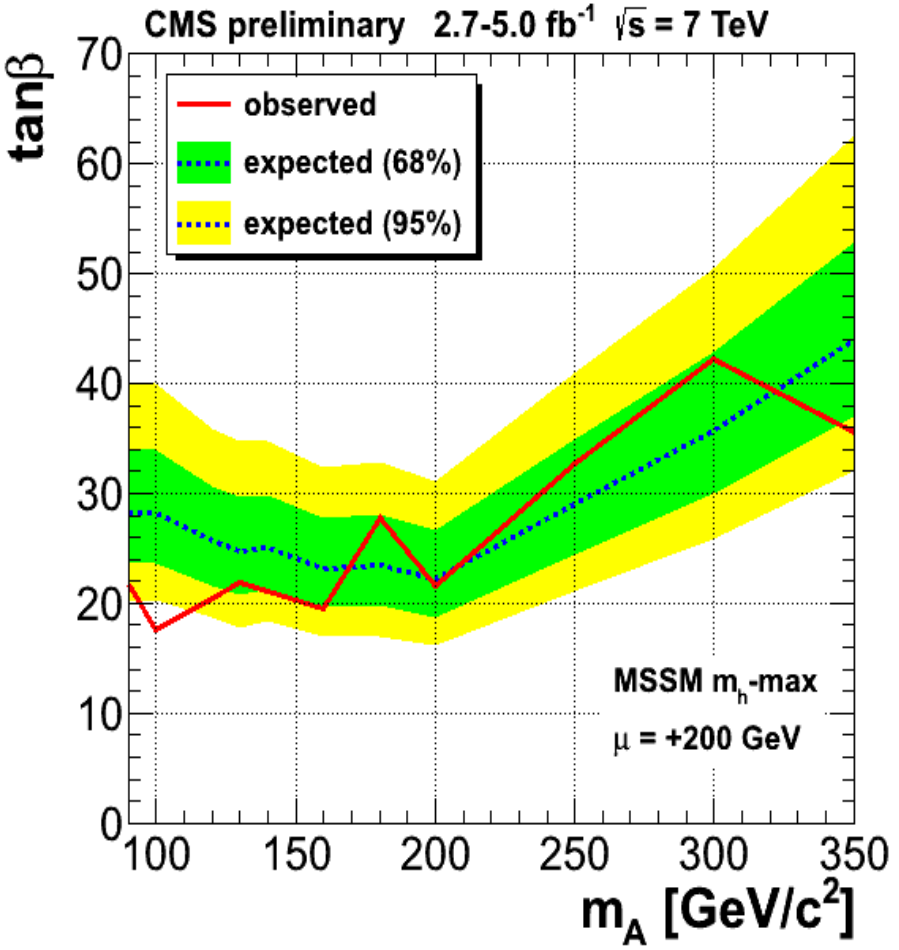
Two independent background estimates for each mass scenario: using double-tag ("B-tag Matrix method") and single-tag ("Hyperball method") samples, respectively.

Signal extraction: binned maximum-likelihood fit to the M_{12} distribution.

Good agreement with predicted SM background

b $\bar{b}$ – combined results





Stringent limits on the cross section for b-associated MSSM Higgs production in pp collisions

$$\Phi \rightarrow \mu^+ \mu^-$$

$\mu^+\mu^-$ - triggering, event selection and background estimation

- **Trigger:**

  Unprescaled single muon trigger

- **Data selection: 3 event categories**

Basic muon selection (Categories 1,2,3)	2 muons $p_T^{(1)}>30$ GeV $p_T^{(2)}>20$ GeV	$\|\eta\|<2.1$ isolated opposite charges

Category 1 - additionally ≥1 b-tagged jet: $p_T>20$ GeV, $|\eta|<2.4$, $\Delta R(\mu,j)>0.5$

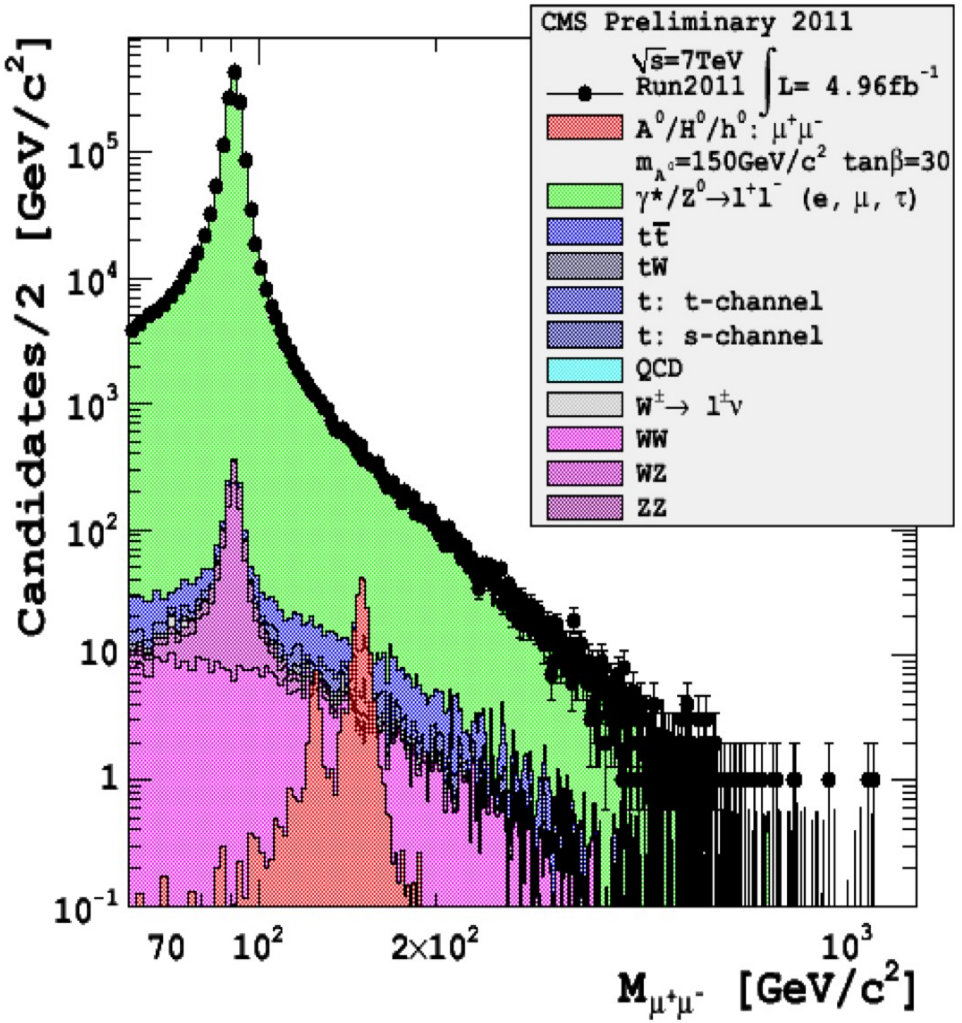
Category 2 - additionally a 3rd muon: $p_T>3$ GeV, $|\eta|<2.4$, $\Delta R(\mu,\mu)>0.5$

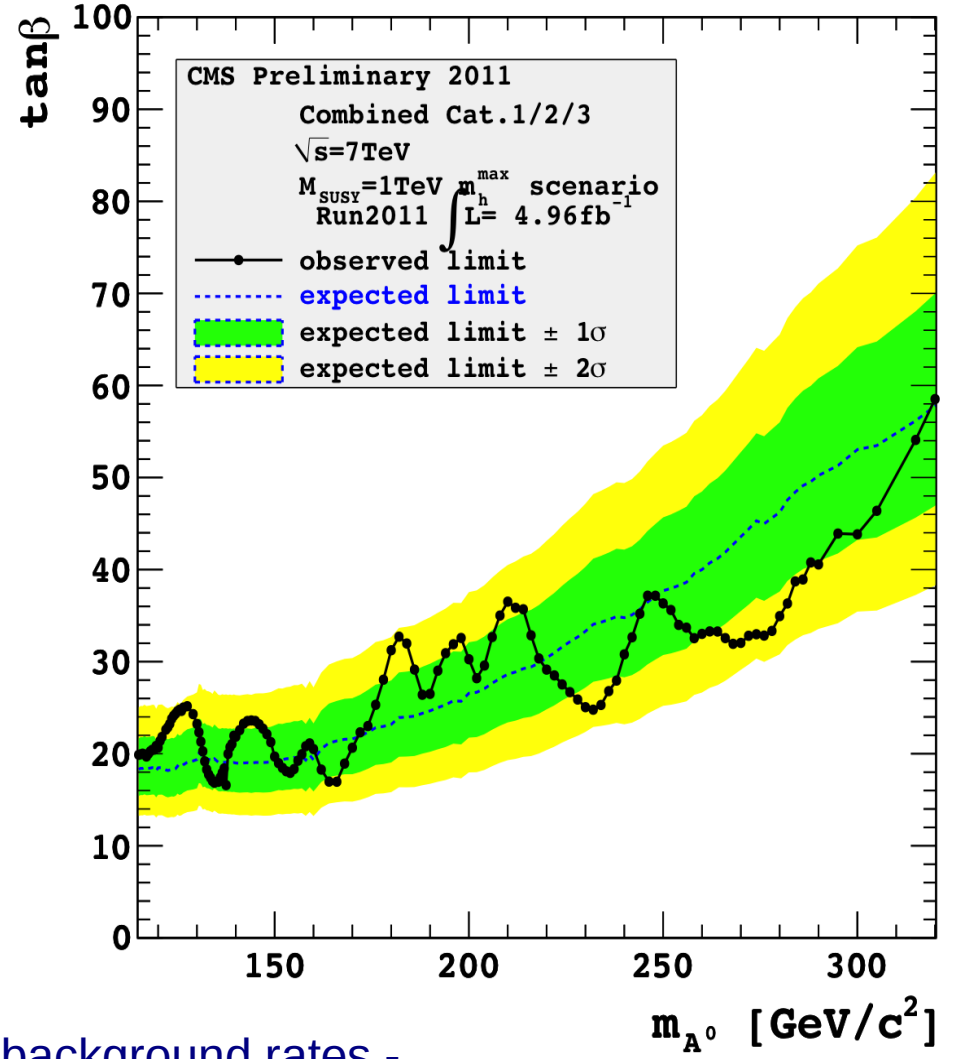
- MET < 30 GeV

- **Background and signal estimation:**

- Drell-Yan (Zbb), top pair (Category 1), W^+W^- (Category 3), etc. – estimated from MC, final result and exclusion limits obtained from a fit of a theoretical function to the invariant mass distribution from the data.

$\mu^+\mu^-$ – combined result from 3 event categories





No excess seen over predicted SM background rates -
95% CL limit on $\sigma \times \mathbf{Br}(\mu\mu) < 40\text{-}20$ fb for $m_A = 150\text{-}300$ GeV

$$H^{\pm} \longrightarrow \tau\ \nu$$

Charged Higgs: triggering and event selection

- **Final states studied:** τ_{had}+jets, τ_{had}+e/μ, e+μ

- **Selections**

	τ_{had}+jets	τ_{had}+e/μ	e+μ
Trigger	τ_{had}+MET	electron+2jets / single muon	electron+muon
Lepton	p_T>40 GeV	p_T>35/30/20 GeV (e/μ/τ)	p_T>20 GeV
selection	tight τ-id*	isolated / tight τ-id*	isolated
Jet	≥3 jets	≥2 jets	≥2 jets
Selection	p_T>30 GeV	p_T>35 (30) GeV	p_T>30 GeV
	≥1 b-tagged	≥1 b-tagged	≥1 b-tagged
MET	>50 GeV	>45 GeV (e), 40 GeV (μ)	
	$\Delta\phi(\tau_{had},MET)$<160		

- Opposite charge lepton pair (τ_{had}+e/μ, eμ)
- $p^{trk}/p^{\tau had}$ > 0.7 (τ_{had}+jets – reduces the amount of τ from W decays)
- Veto events with additional isolated electrons or muons

*) only 1-track τ selected

Charged Higgs: signal and background estimation

Background

*** τ_{had}+jets**

- QCD – from data events passing selection criteria except τ-id, weighting by fake rates of jet misidentification as τ measured in the control region,
- EWK top pair – estimated by selecting events with muons instead of τ_{had} and replacing reconstructed muons with simulated taus,

*** τ_{had} + e/μ**

- W+jets, top pair – from data, using fake-rate jet$\rightarrow\tau$ method,
- other backgrounds from MC,

*** e+μ**

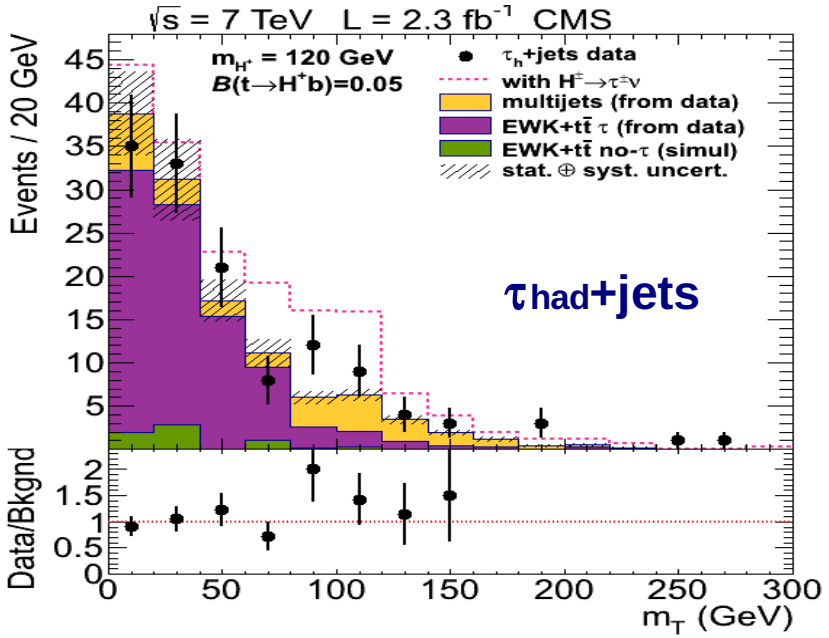
- all backgrounds from MC.

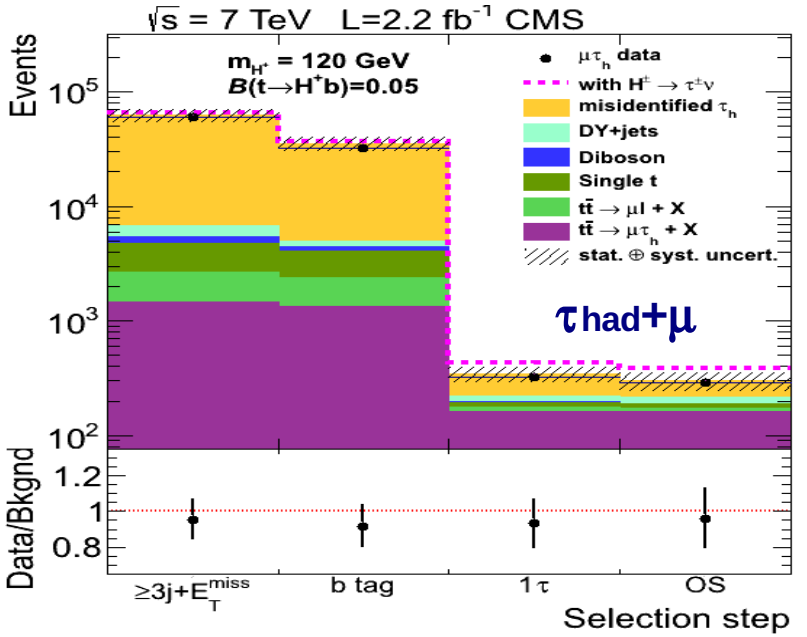
Signal extraction

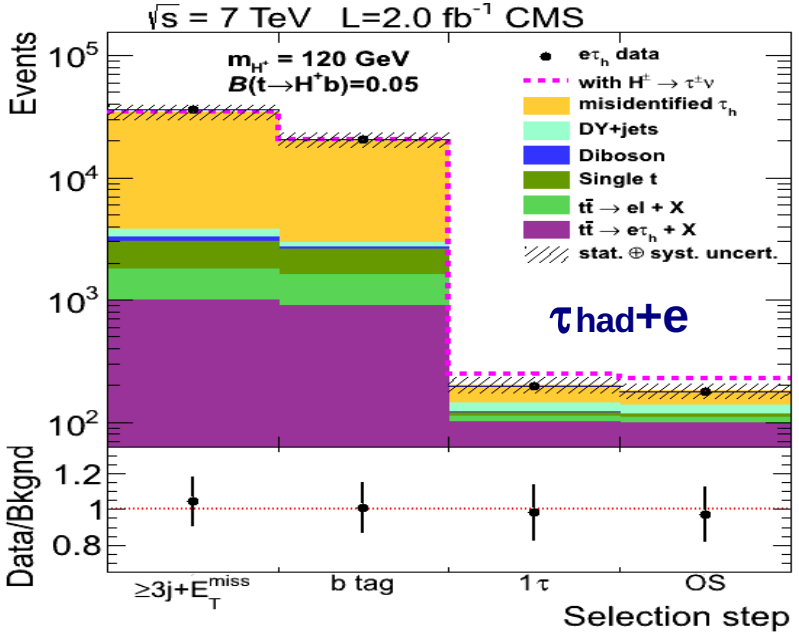
*** τ_{had}+jets:** binned maximum-likelihood fit to the measured M_T distribution,

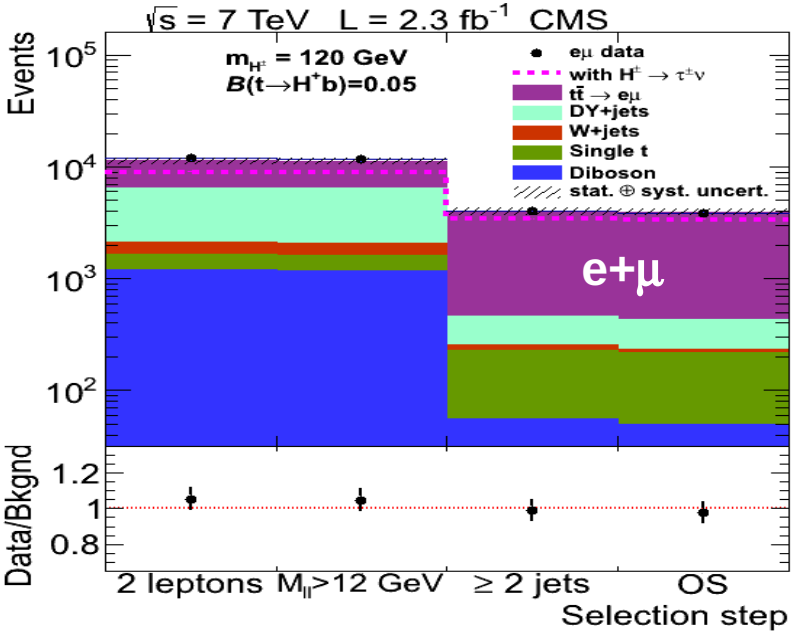
*** τ_{had}+e/μ, e+μ:** event counting only.

Charged Higgs – results in the 4 final states

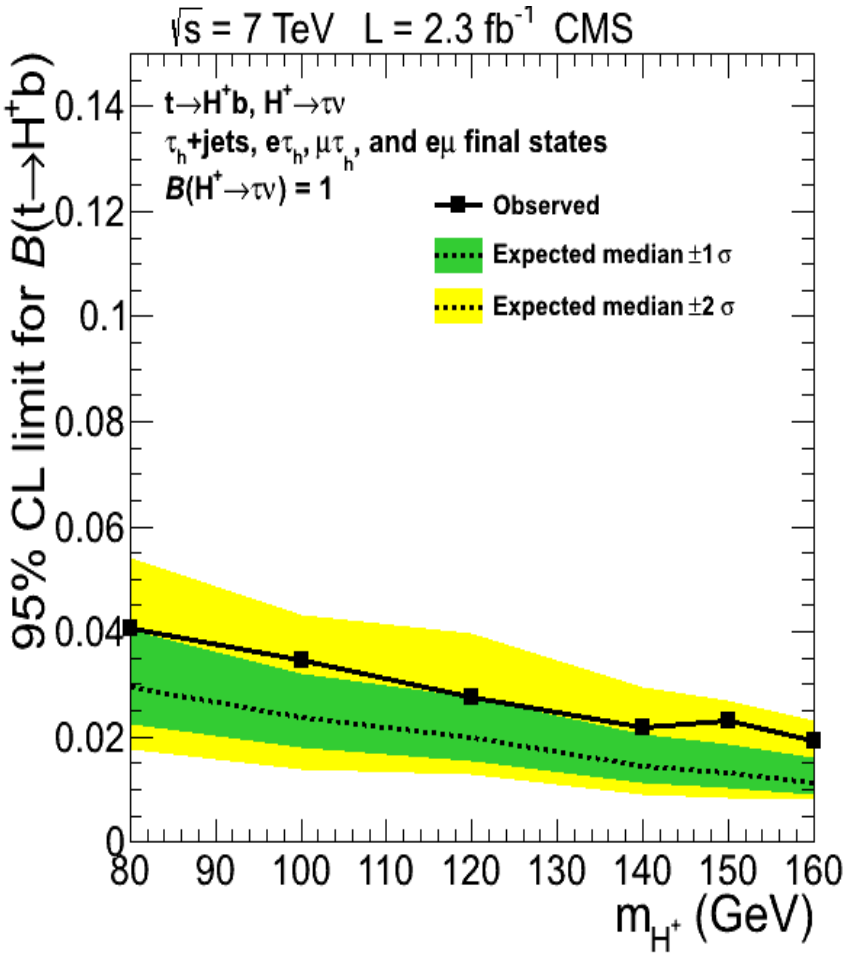


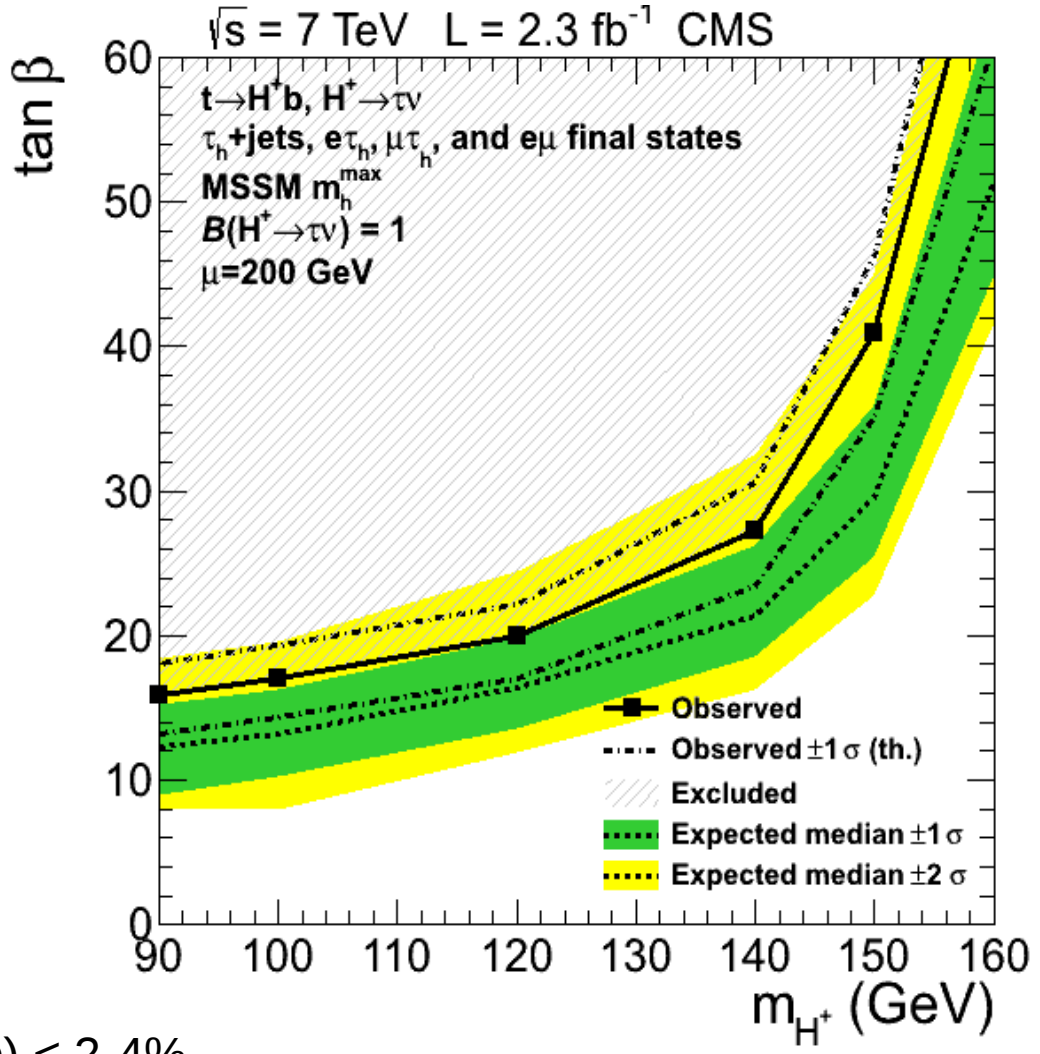






Charged Higgs – exclusion limits





Significant constraint on Br($t \to H^{\pm} b$) < 2-4%

Summary

- CMS data provide no evidence of the MSSM in the Higgs sector so far.

- New results from the $\Phi \rightarrow \tau\,\tau$ decay channel which combine 2011 and 2012 data provide the most stringent limits on the MSSM $m_A/\tan\beta$ parameter space to date. A significant improvement in the explored parameter space has been obtained, with 95% CL exclusion limits going as low as $\tan\beta=5$ for any $m_A<250$ GeV.

- The lower sensitivity $\Phi \rightarrow b\,b$ and $\mu\,\mu$ decay channels studied from 2011 data confirm parts of the obtained exclusion limits.

- Independent stringent limits in the MSSM $m_{H^+}/\tan\beta$ plane are derived from charged Higgs boson searches from the 2011 data and a significant constraint is obtained on on the $t \rightarrow H^+ b$ decay branching fraction.

- There is more to come from the 2012 data!

Backup slides

The m_h^{max} scenario

In the MSSM m_h^{max} benchmark scenario, the definitions of theory parameters are the following:

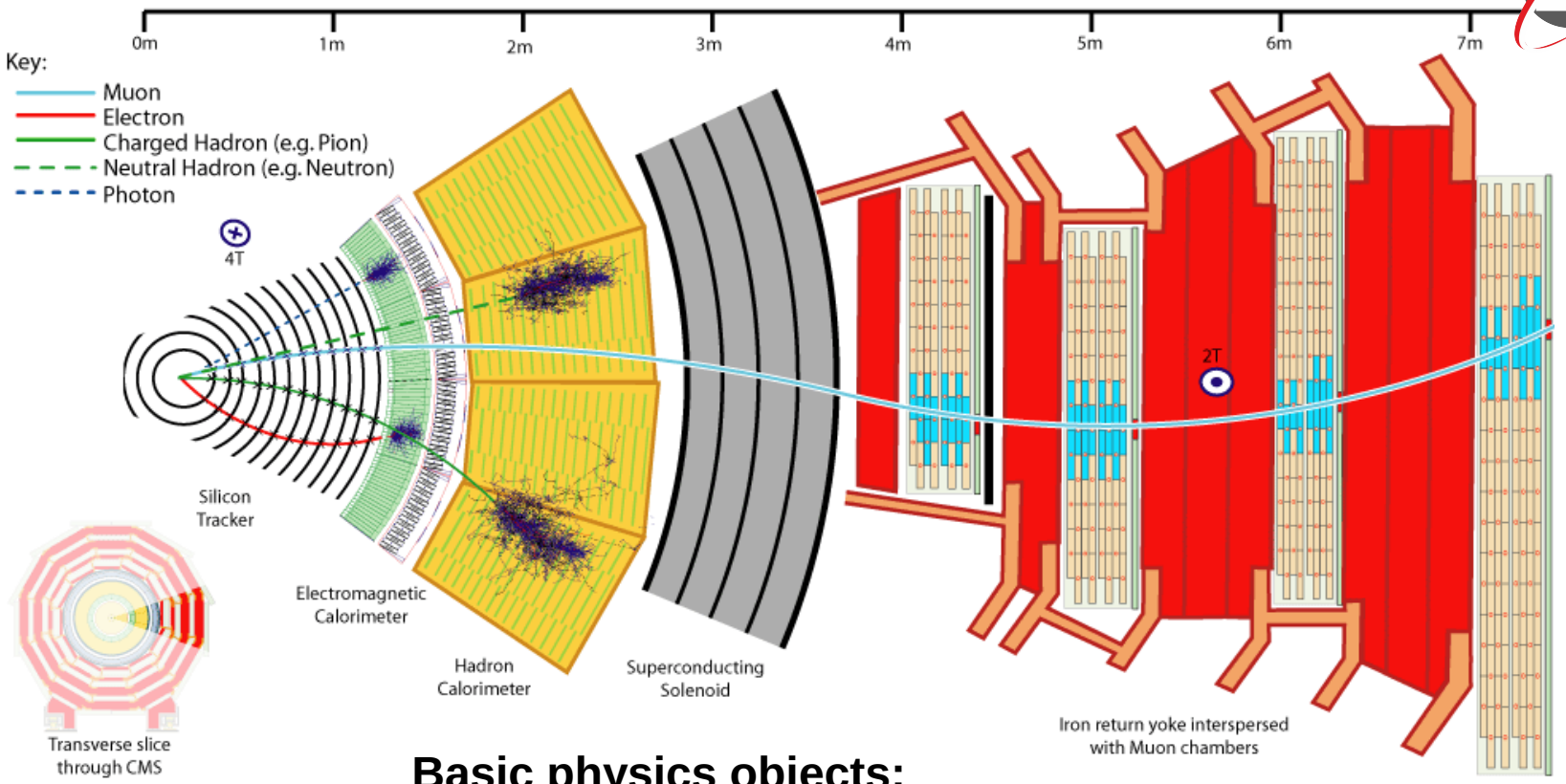
M_{SUSY} = 1 TeV/c^2 ; $X_t = 2M_{SUSY}$; μ = 200 GeV/c^2 ;
M_g = 800 GeV/c^2 ; M_2 = 200 GeV/c^2 ; $A_b = A_t$;
M_3 = 800 GeV/c^2 .

Here:
M_{SUSY} denotes the common soft SUSY-breaking squark mass of the third generation;
$X_t = A_t - \mu/\tan\beta$ is the stop mixing parameter;
A_t and A_b are the stop and sbottom trilinear couplings, respectively;
μ is the Higgsino mass parameter;
M_g is the gluino mass; and
M_2 is the SU(2)-gaugino mass parameter.

The value of M_1 is fixed via the unification relation $M_1 = (5/3)\, M_2 \sin\theta_W / \cos\theta_W$.

Finally, the 5 flavor schema is used.

Particle-flow technique in CMS

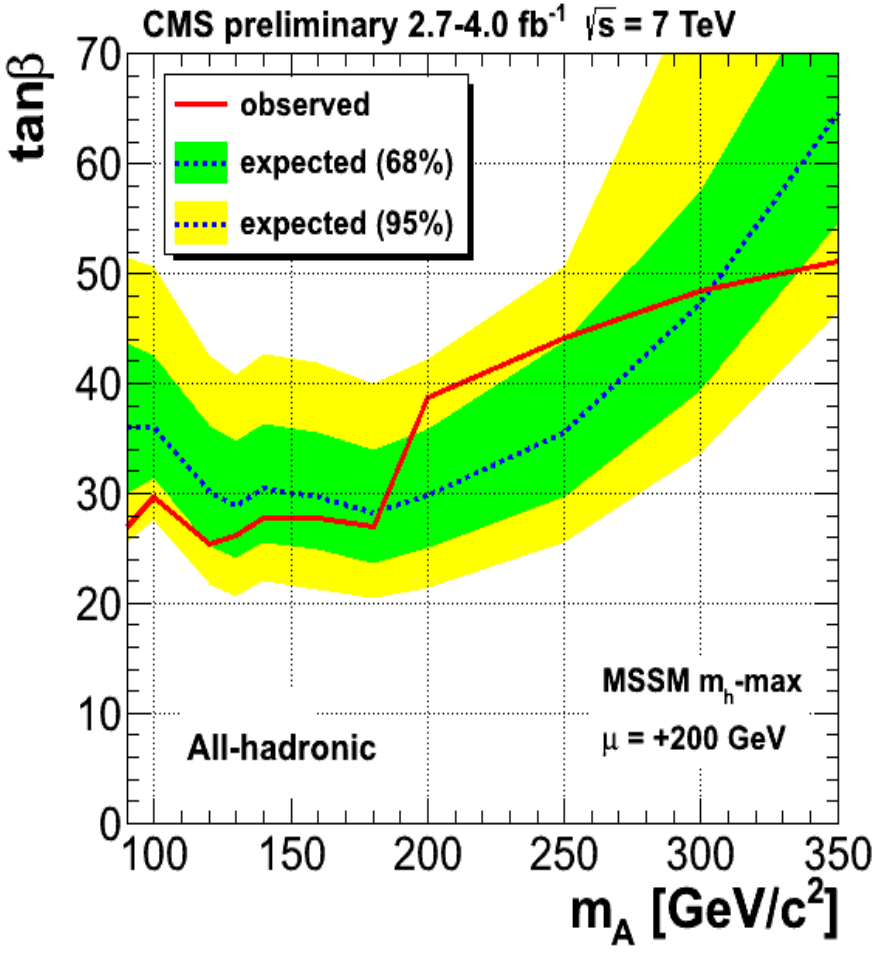


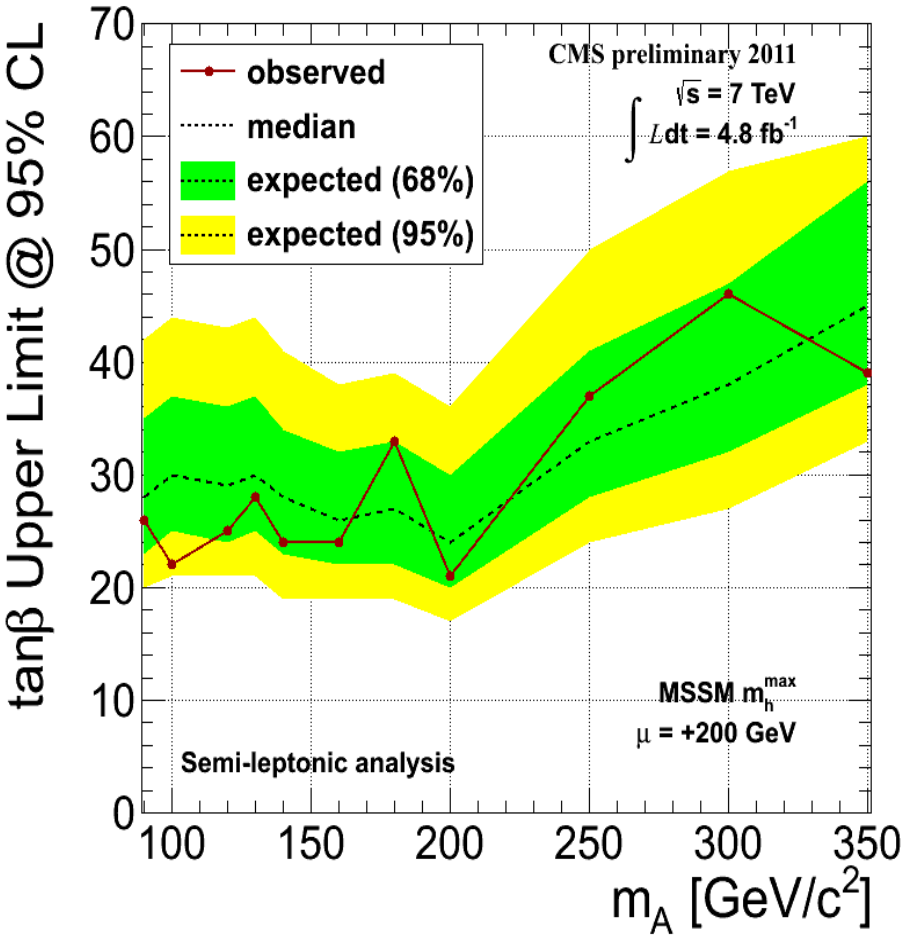
Basic physics objects:

Muon: matching tracks in inner tracker and muon chambers
Electron: EM cluster with an associated track
Photon: EM cluster without a matched track

Jet: cluster in EM and hadronic calorimeters (and inner tracker)
Tau: narrow jet with matching track
MET: p_T required to balance all of these

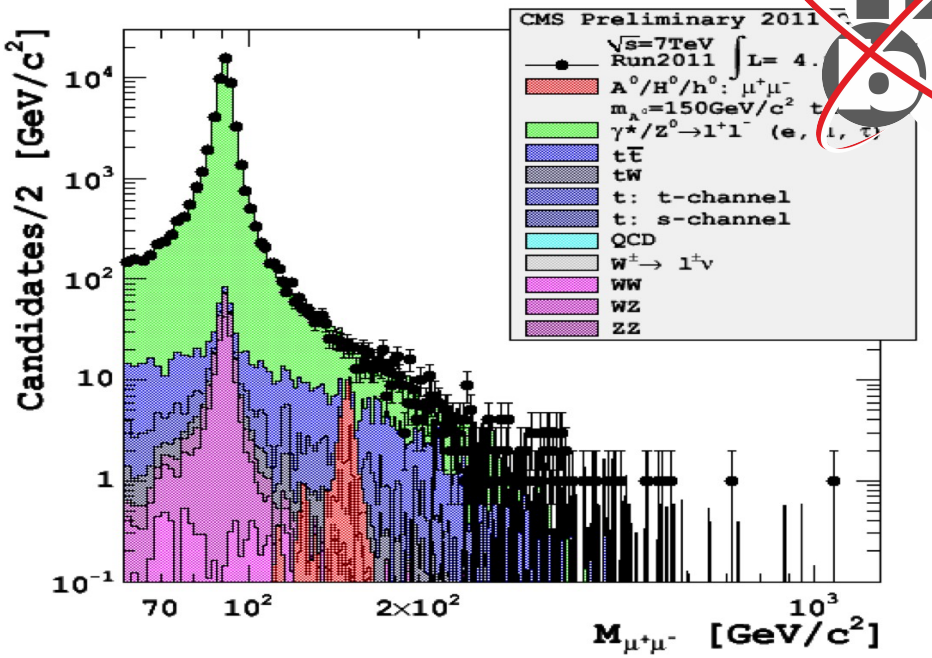
b b – exclusion limits from the all-hadronic and semi-leptonic analyses

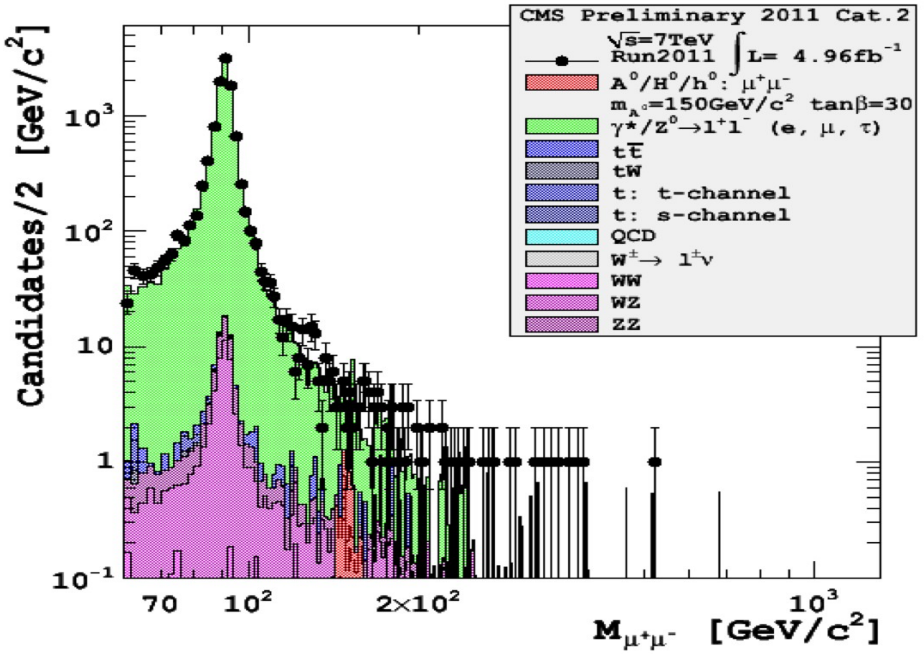


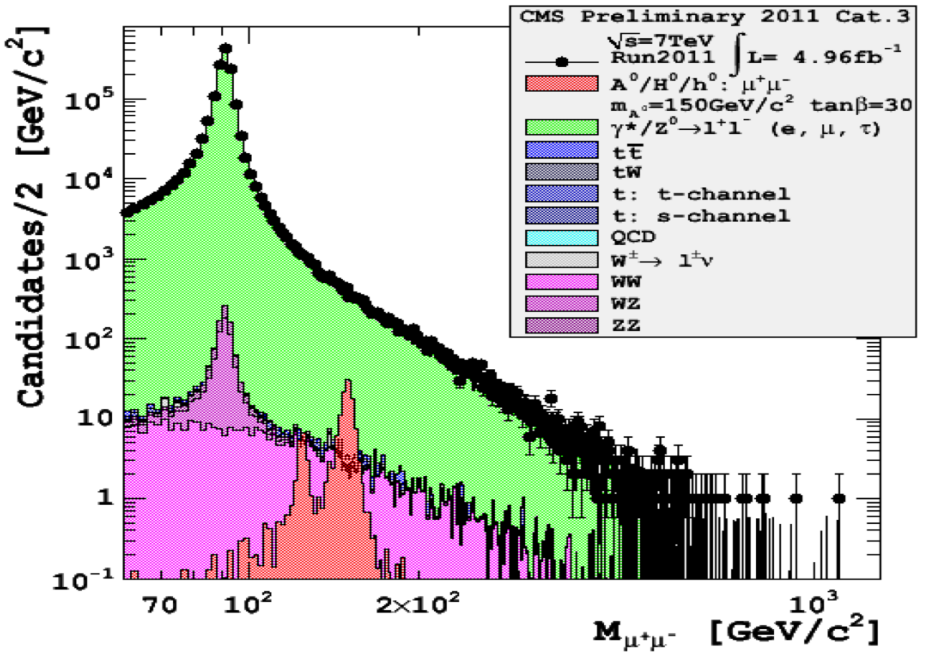


μ μ – results from 3 categories

Category 1: μ μ + b
Category 2: μ μ + 3rd muon
Category 3: μ μ







μ μ – combined exclusion limits