SUSY Higgs Searches in CMS

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for the CMS Collaboration

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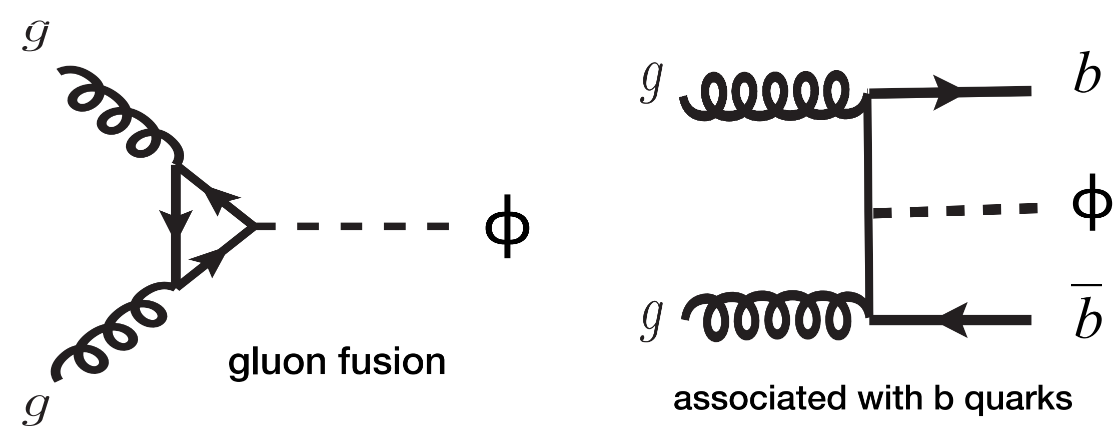
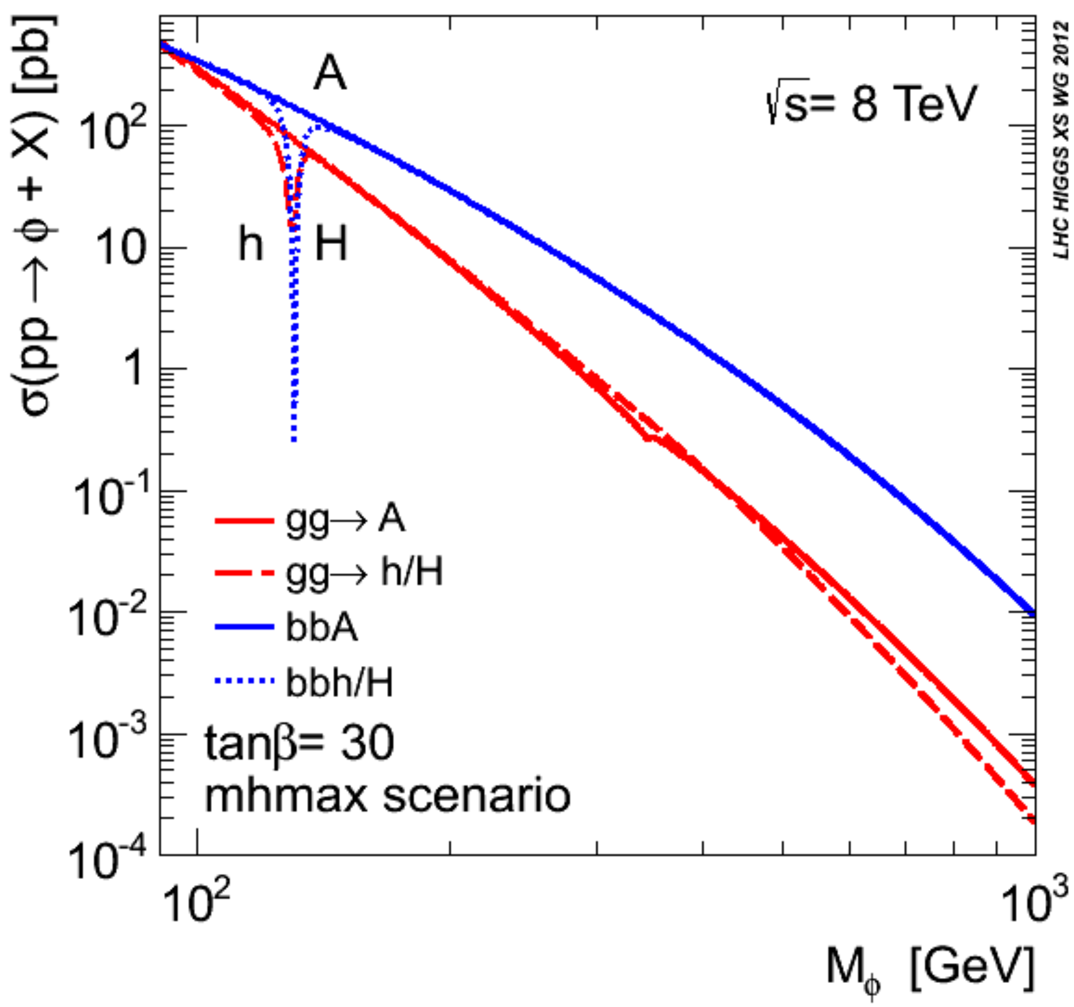
MSSM Higgs bosons

- The MSSM features two Higgs doublets.
- Symmetry spontaneously broken twice
- Higgs sector: Five Higgs particles
  - Three neutral: ϕ = h, H, A
  - Two charged: $H^{\pm}$
  - Observed 126 GeV state often identified as the lightest Higgs (h)
- At tree level, two independent parameters:
  - m_A or $m_{H\pm}$ (mass of the CP-odd or of the charged boson)
  - tan β (ratio of v.e.v. of the two Higgs doublets)
- The mass of the CP-odd Higgs boson A is usually ~degenerate with one of the CP-even bosons

Neutral Higgs bosons production





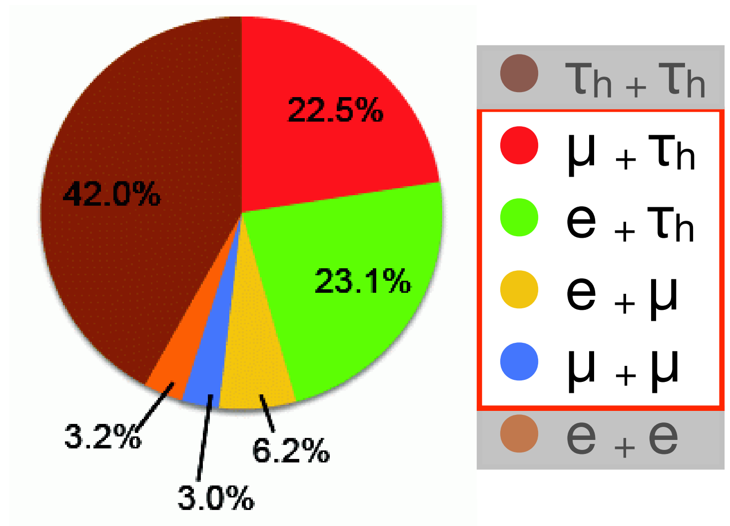
MSSM Higgs searches in CMS

Mode	Production	Channels	Luminosity 7 TeV	Luminosity 8 TeV	Documents
$\phi \to \tau\tau$	$gg \to \phi$	4	4.9 fb^{-1}	12.1 fb^{-1}	CMS PAS HIG-12-050
	$bb\phi$	4			
$\phi \to bb$	$bb\phi$	2	4.8 fb^{-1}	–	Phys. Lett. B 722 (2013) 207
$\phi \to \mu\mu$	$gg \to \phi$	1	4.9 fb^{-1}	–	CMS PAS HIG-12-011
	$bb\phi$	2			
$H^\pm \to \tau^\pm\nu$	$t \to H^+b$	4	4.9 fb^{-1}	–	JHEP 07 (2012) 143 CMS PAS HIG-12-052

MSSM $\phi \rightarrow \tau\tau$ search

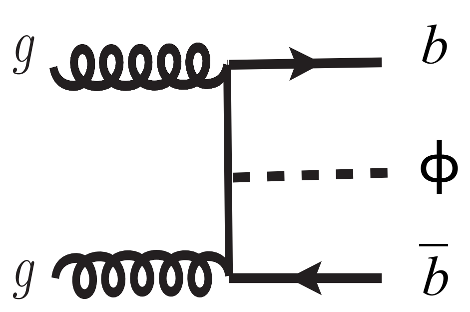
$\phi \rightarrow \tau\tau$ Search

- Good compromise between relatively large BR also at high masses and manageable backgrounds.



→ *channels included in CMS MSSM analysis*

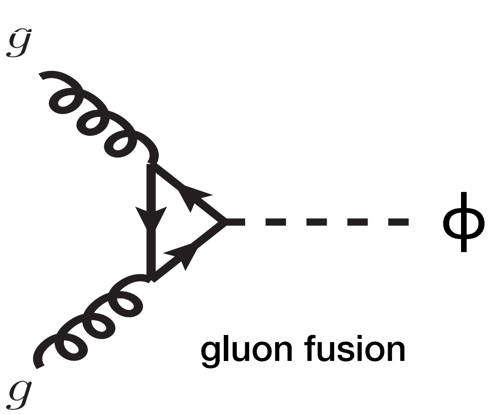
Production mechanisms & event categories



associated with b quarks

b-tag category

$\geq$ 1 b-tagged jet with $p_T > 20$ GeV
$\leq$ 1 jet with $p_T < 30$ GeV



gluon fusion

no b-tag category

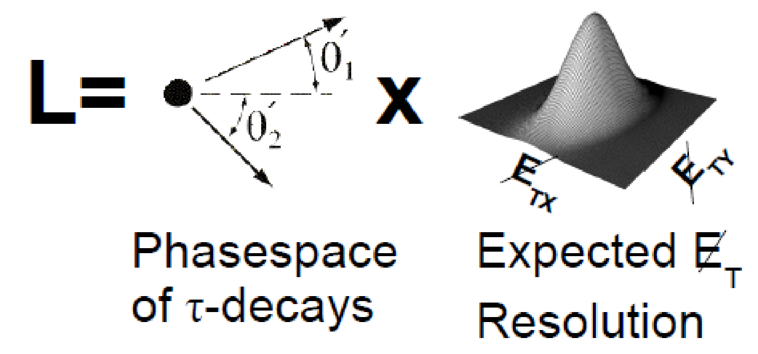
NO b-tagged jet with $p_T > 20$ GeV

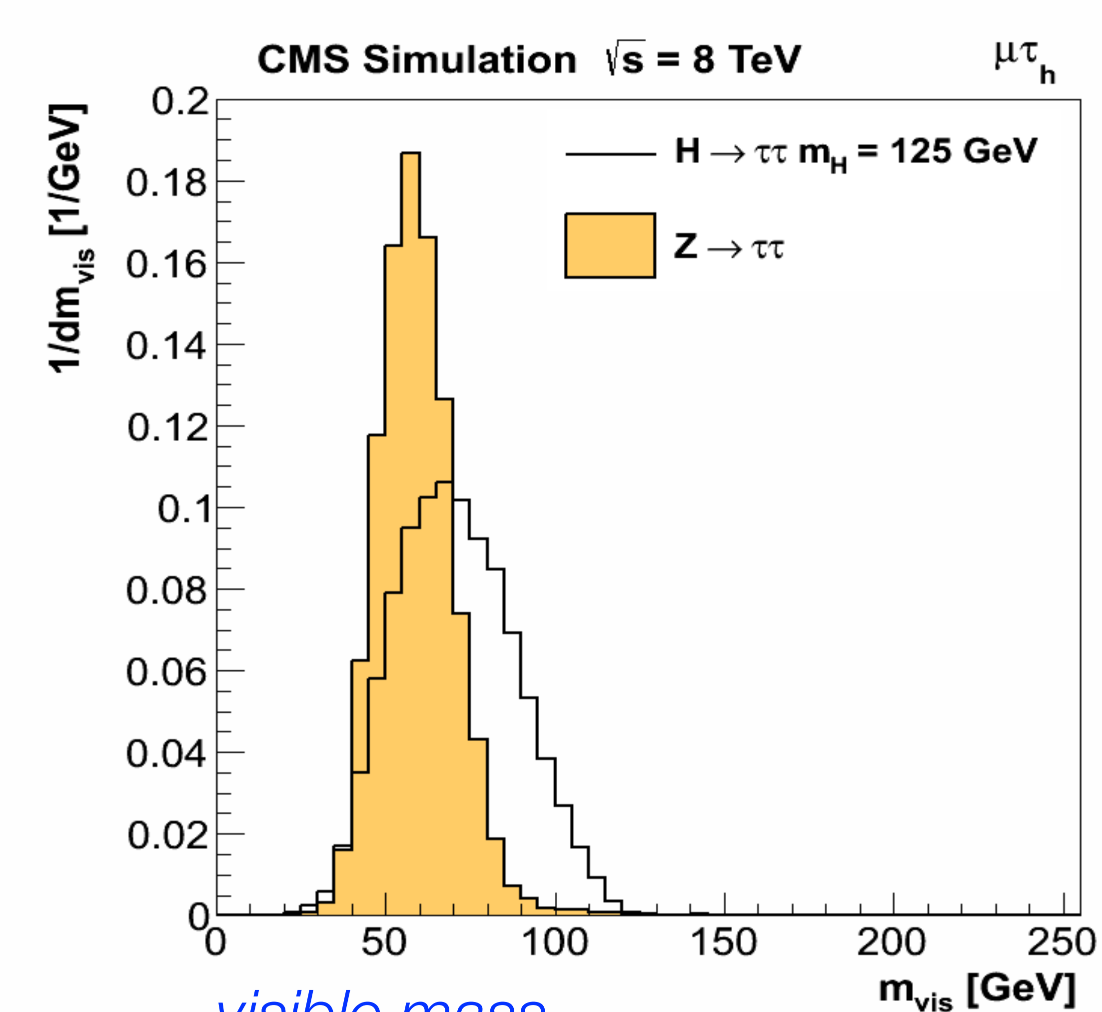
$\phi \to \tau\tau$: Trigger and selection

- **Triggers**
  - **τ+μ, τ+e**: cross triggers τ + lepton;
  - **e+μ**: cross trigger e + μ;
  - **μ+μ**: single- or di-muon triggers
- **Lepton selection**
  - **muons**: isolated; $p_T > 17 - 20$ GeV; $|\eta| < 2.1$
  - **electrons**: isolated; $p_T > 20 - 24$ GeV; $|\eta| < 2.1$, or 2.3 in eμ channel
  - **taus**: isolated ; $p_T > 20$ GeV, $|\eta| < 2.3$

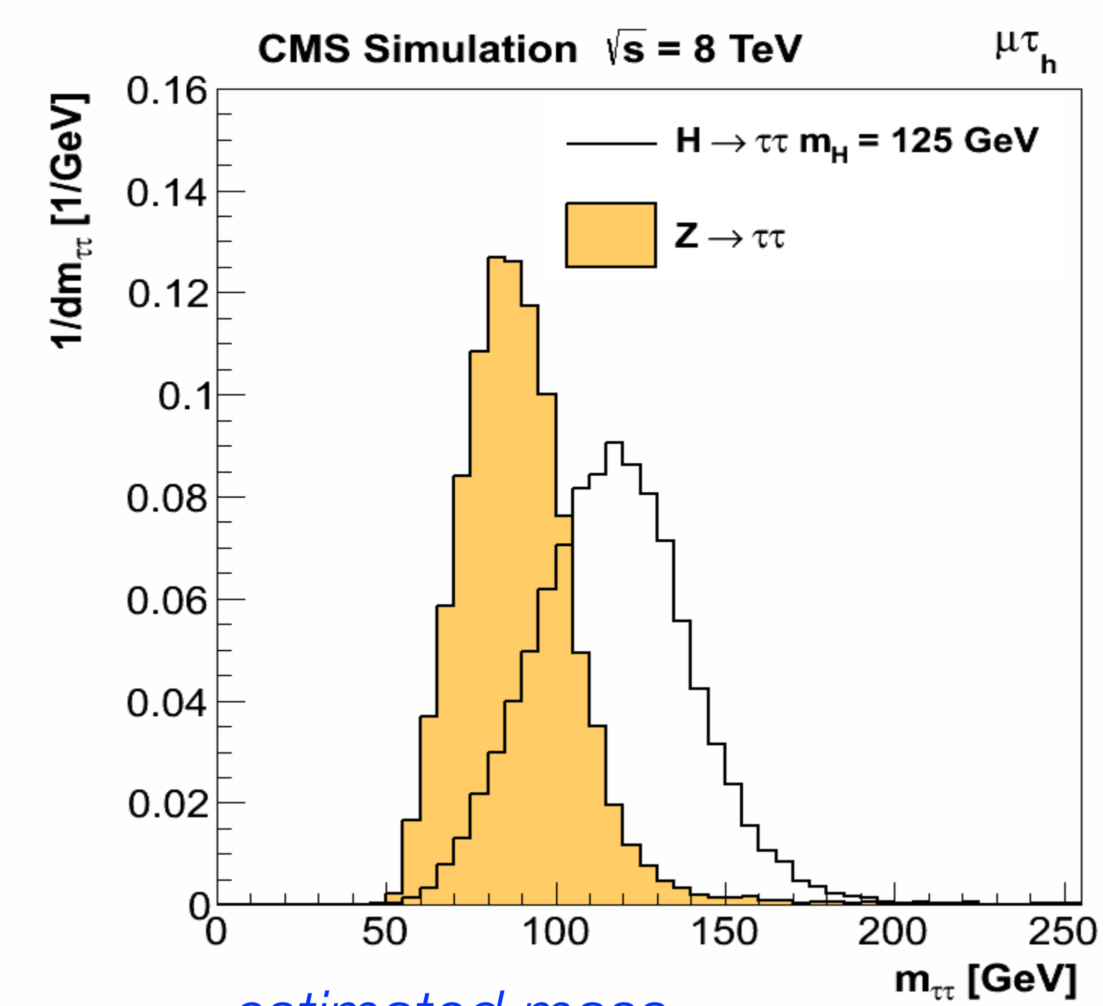
$\phi \rightarrow \tau\tau$: Reconstruction of τ-pair mass

- Invariant mass of $\tau\tau$ determined using a maximum likelihood fit.
- Estimated on event-by-event basis using four-momenta of visible decay products, E_x^{miss}, E_y^{miss}, expected E_T^{miss} resolution





visible mass



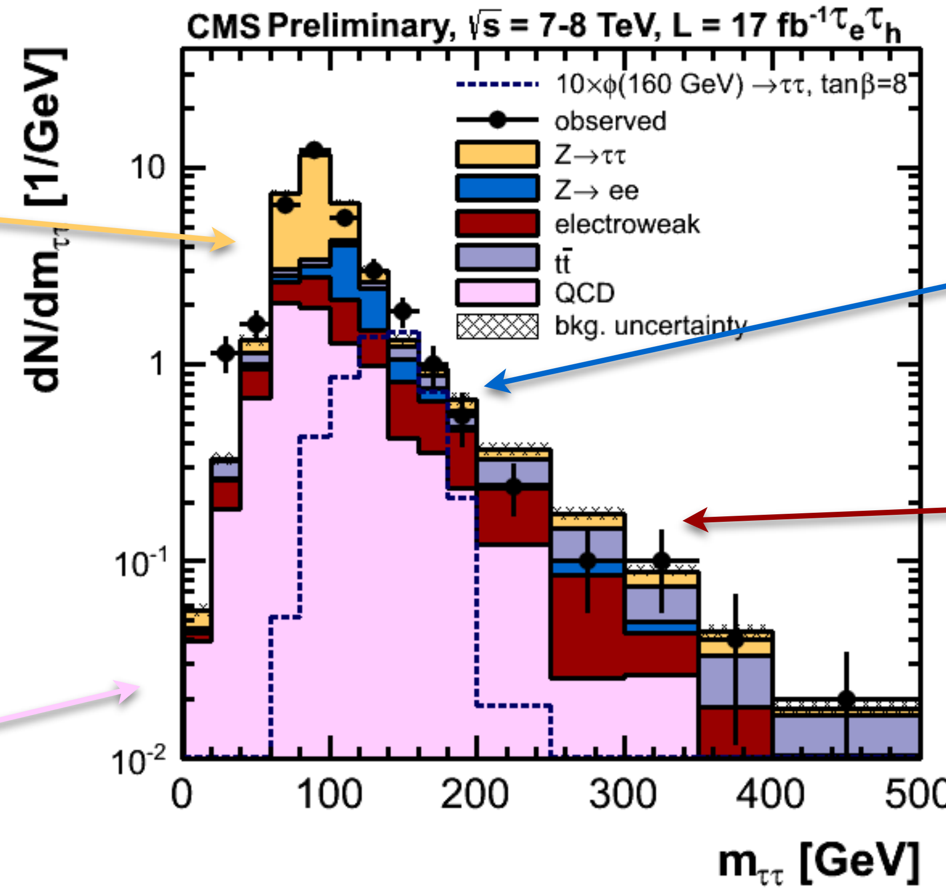
estimated mass

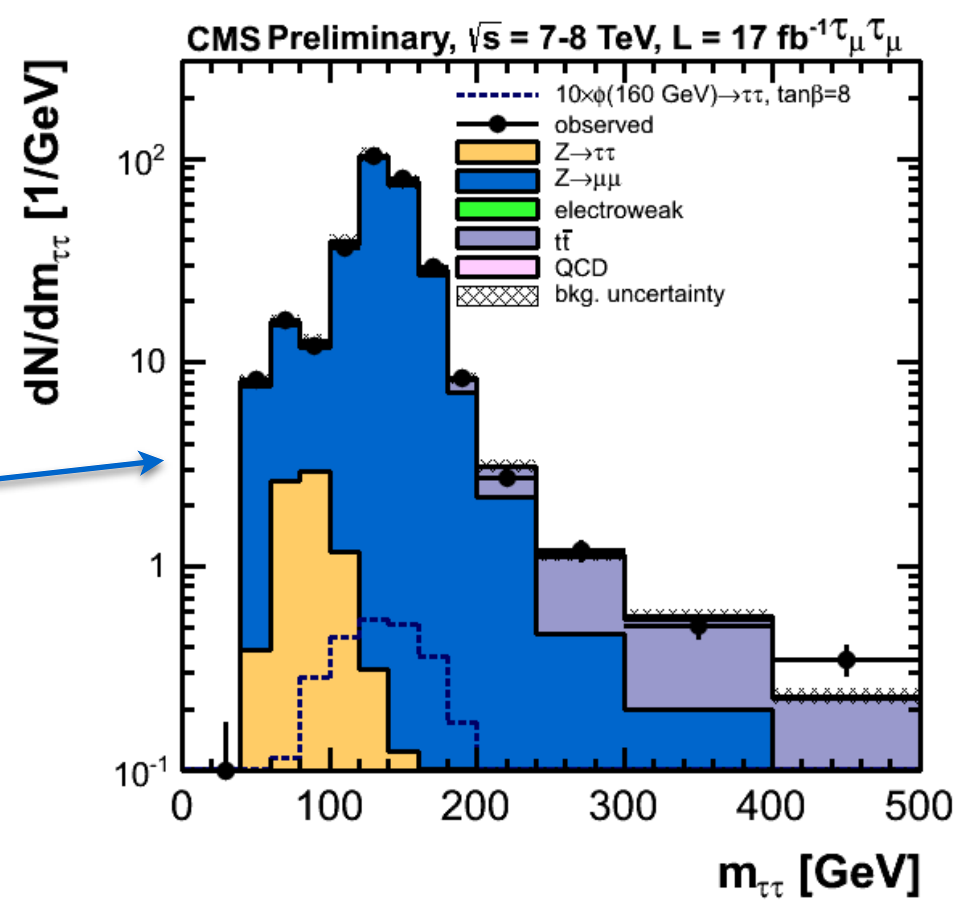
$\phi \to \tau\tau$: Background estimation

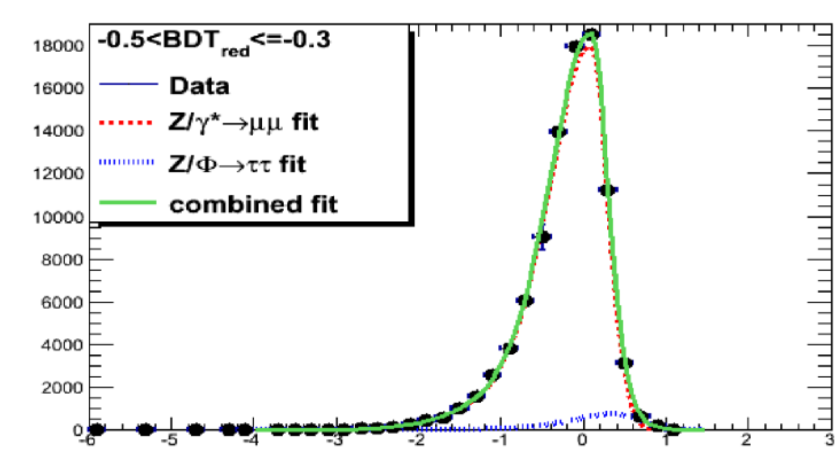
$Z \to \tau\tau$: Embedding, replace μ in $Z \to \mu\mu$ events by simulated τ decays; normalised by $Z \to \mu\mu$ events.

QCD: Normalisation and shape from SS/OS

$Z \to \mu\mu$ for the $\mu\mu$ channel: shape from MC; normalisation from template fits to DCA significance







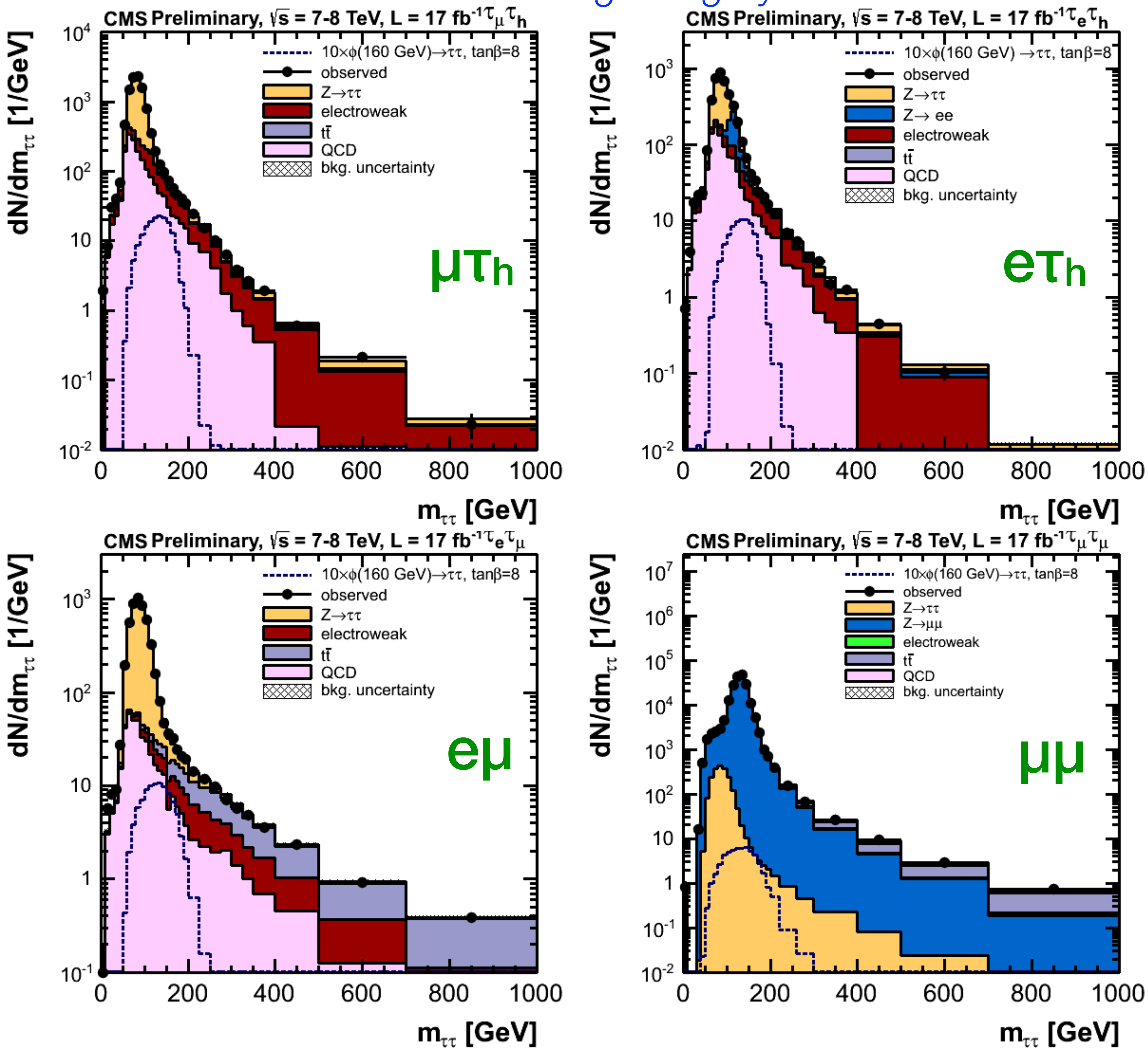
$Z \to ee/\mu\mu$: from simulation, corrected for jet$\to\tau$, e/$\mu\to\tau$ fake rate

Di-boson/W+jets: shape from simulation; normalisation from sideband

ttbar: shape from simulation; normalisation from sideband

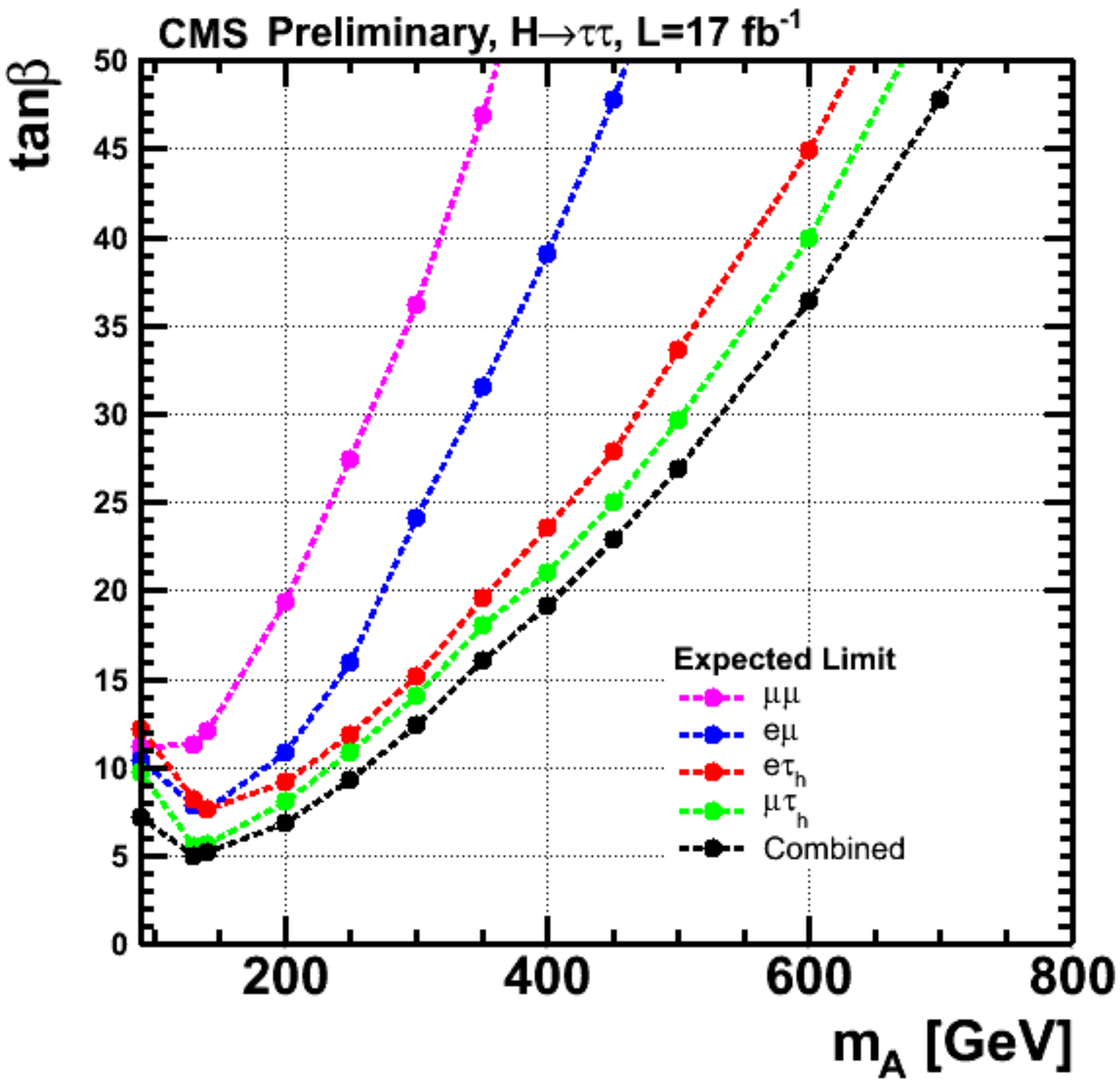
$\phi \rightarrow \tau\tau$: $m_{\tau\tau}$ distributions

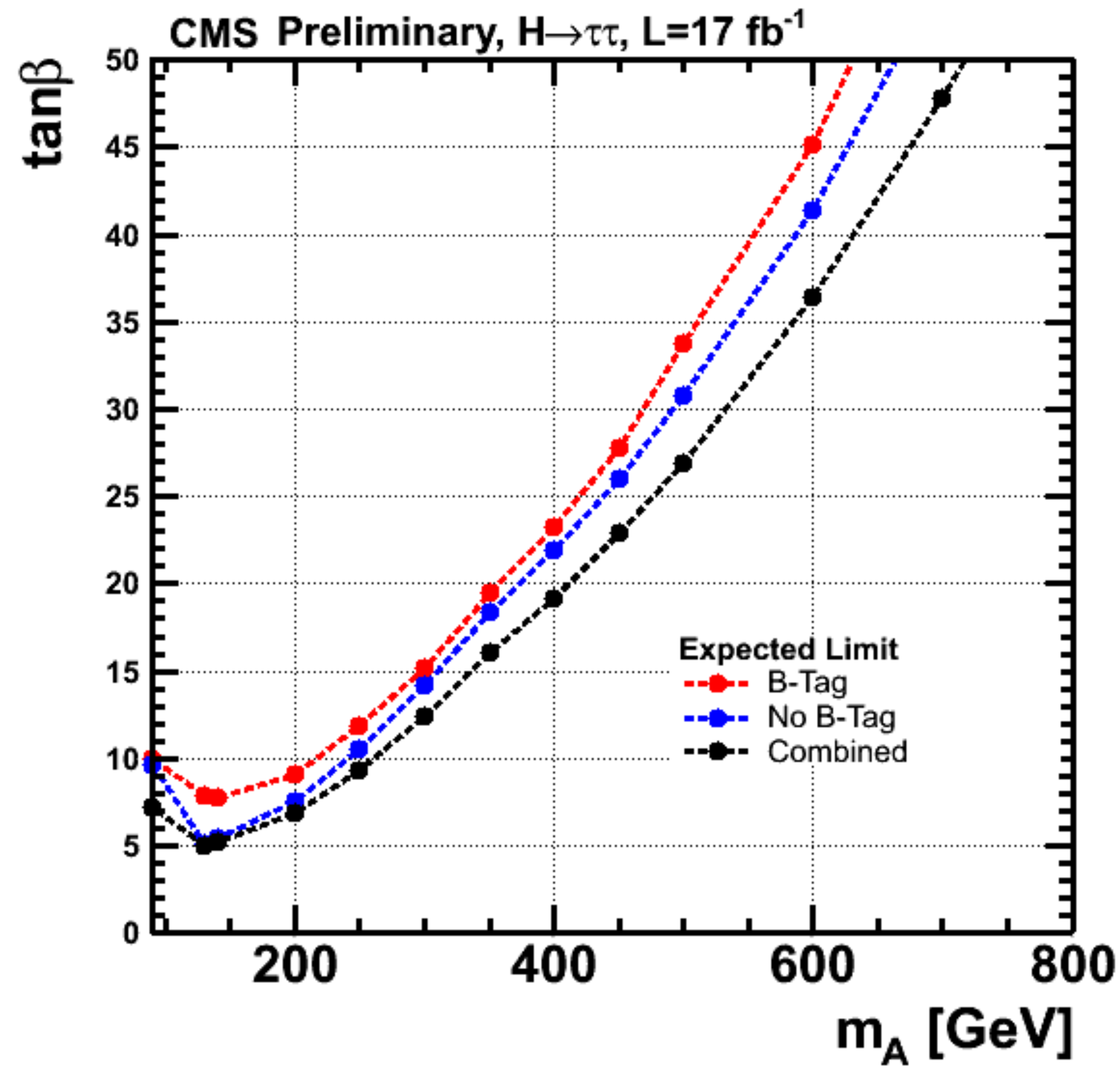
no b-tag category



- No excess observed.
- All distributions well described by background-only hypothesis.
- Same conclusions for b-tag category.

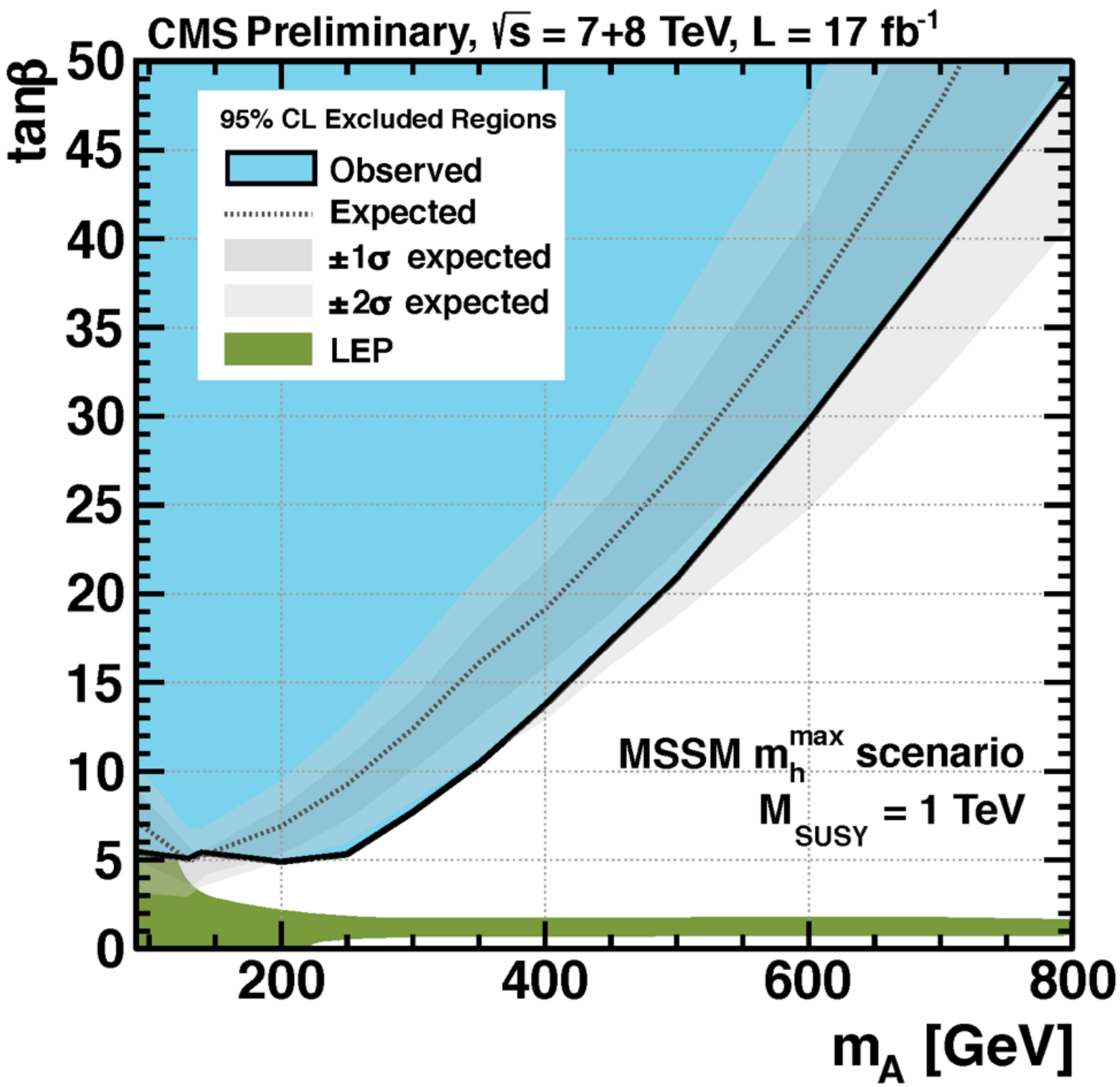
$\phi \to \tau\tau$: channels and categories sensitivity





- Sensitivity driven by semileptonic channels : e+τ , μ+τ
- At low probed masses (< 200 GeV) sensitivity of no-btag category is higher.
- At higher masses sensitivity of the two categories are comparable.

$\phi \to \tau\tau$: MSSM limits

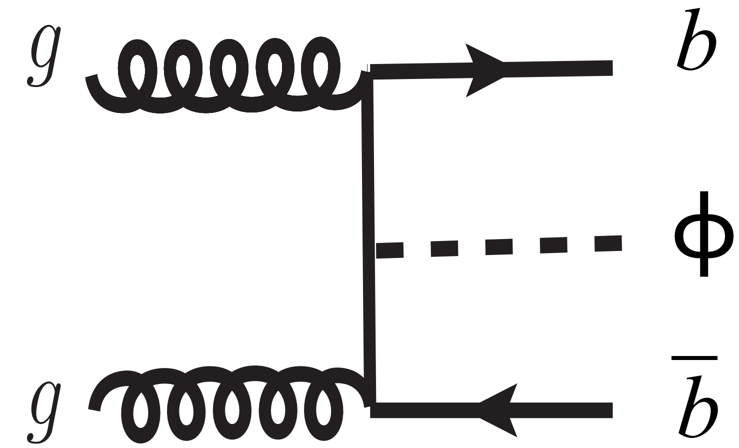


- Interpretation in the m_h^{max} scenario
- 95% CL exclusion limit in m_A–tanβ parameter space
  - tanβ < 5 for $m_A \leq 250$ GeV
  - Touching LEP constraint at low m_A.

MSSM $\phi \rightarrow bb$ search

MSSM ϕ → bb searches

- MSSM neutral Higgs boson decaying to b quakrs and produced in association with b quark(s)
  - Enhancement wrt SM for tan β > 1
  - Large BR(ϕ→bb) even at large masses
- Only b-jets (and radiation) in the final state:
  - Challenging triggers at the LHC



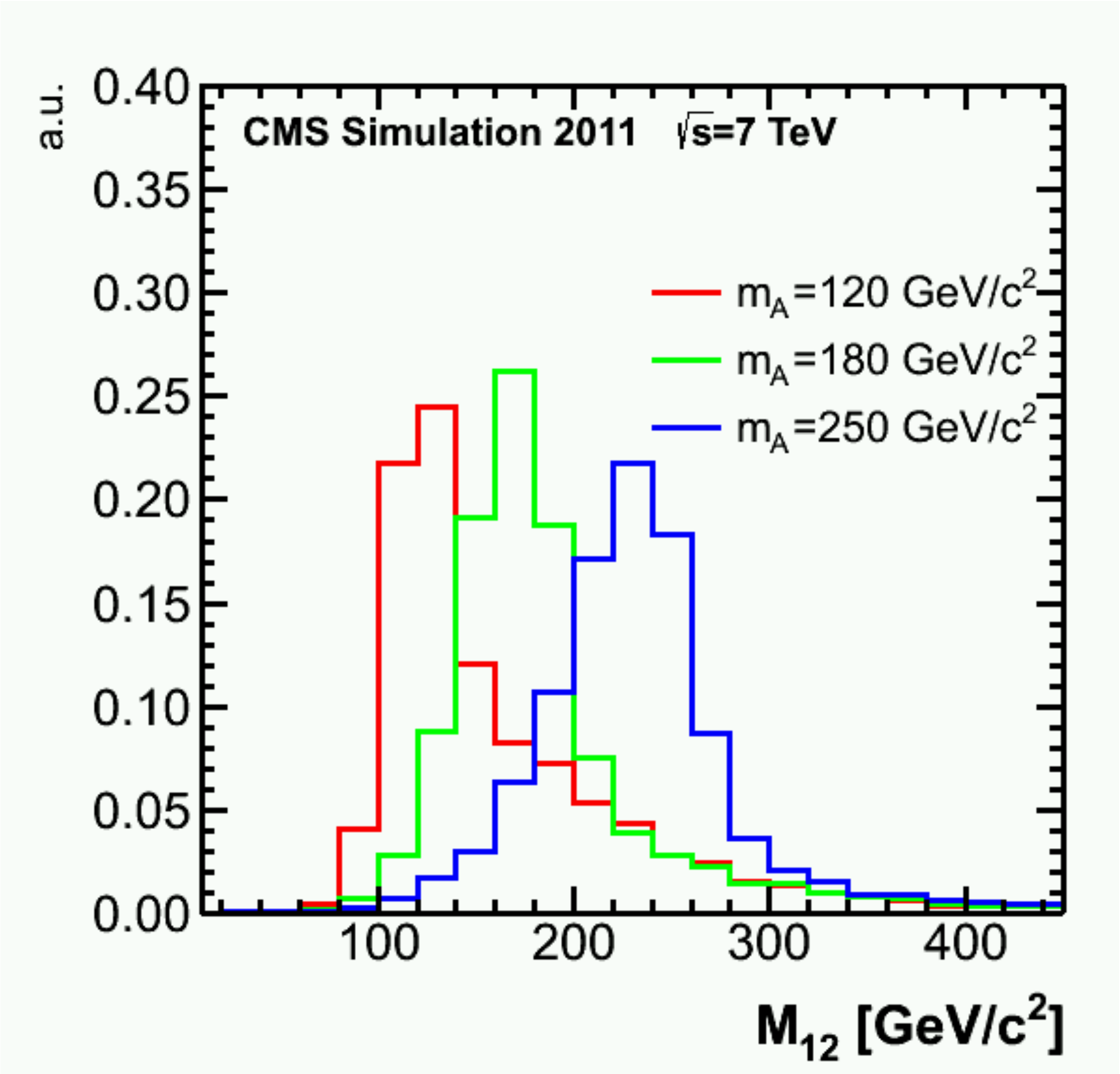
associated with b quarks

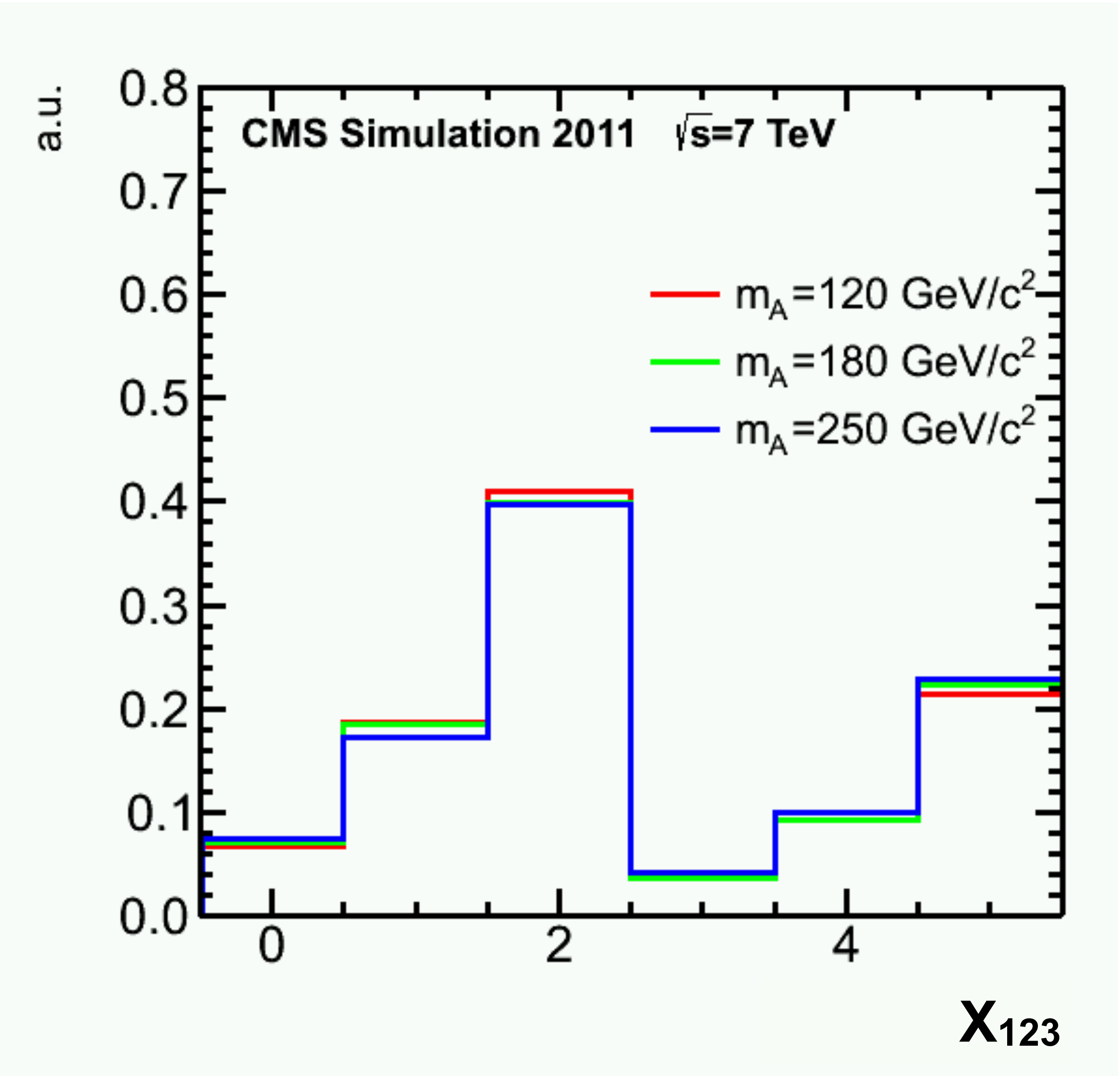
- Two complementary approaches:
  - "All-hadronic" trigger: requiring up to 3 jets; ≥ 2 b-tags (3 offline b-tags)
  - "Semileptonic" trigger: requiring 2 jets; ≥ 1 or 2 b-tags (3 offline b-tags); ≥ 1 muon from B-hadron decay
  - Almost independent samples (2–3% overlap)
- Data: 2.7 fb^{-1} – 4.8 fb^{-1} at 7 TeV (2011)
- Background: heavy flavour multi-jet, derived from the data.
- Signal would appear as a peak in the di-jet mass distribution in triple-btag sample.

MSSM $\phi \rightarrow bb$: Signal templates

(all-hadronic)

- Pythia in the 4-flavour scheme.
- Invariant mass M_{12} of the two leading jets.
- Variable X_{123} computed from the secondary vertex mass of the three leading jets, reflects the b-tag content of the event → further signal / background separation.

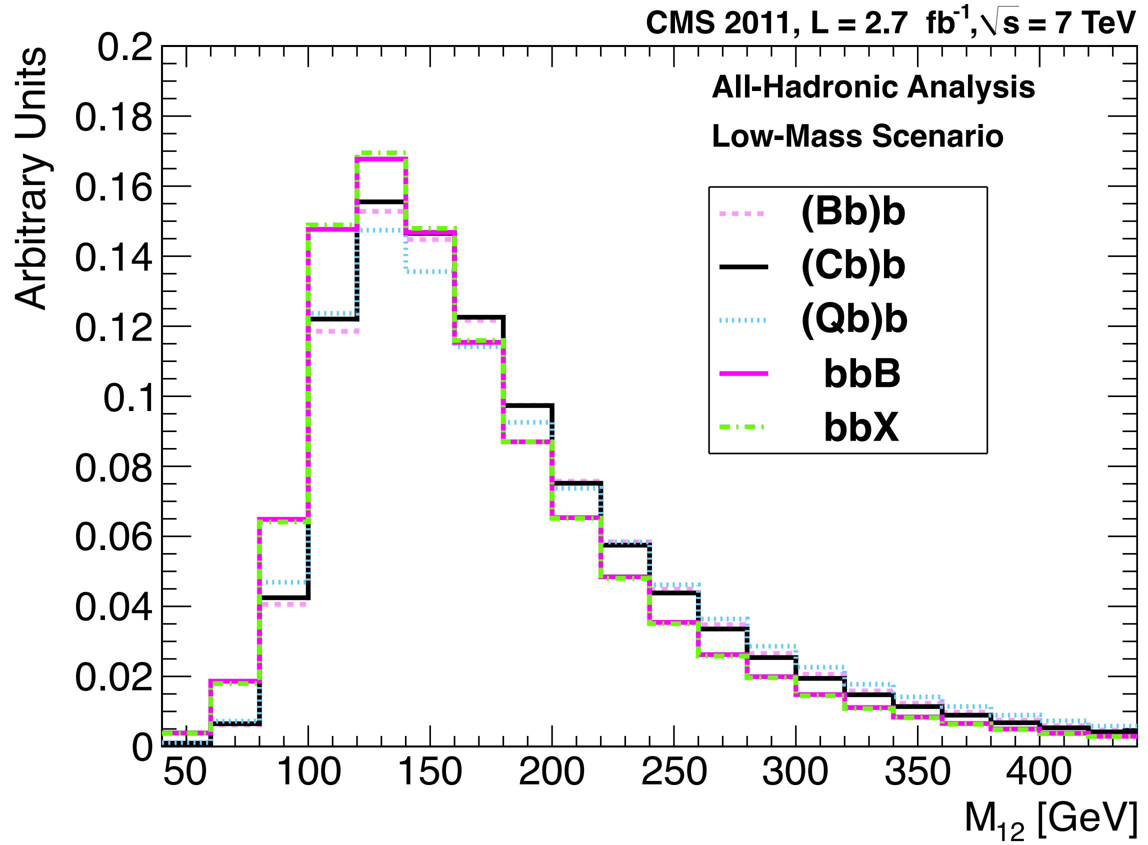


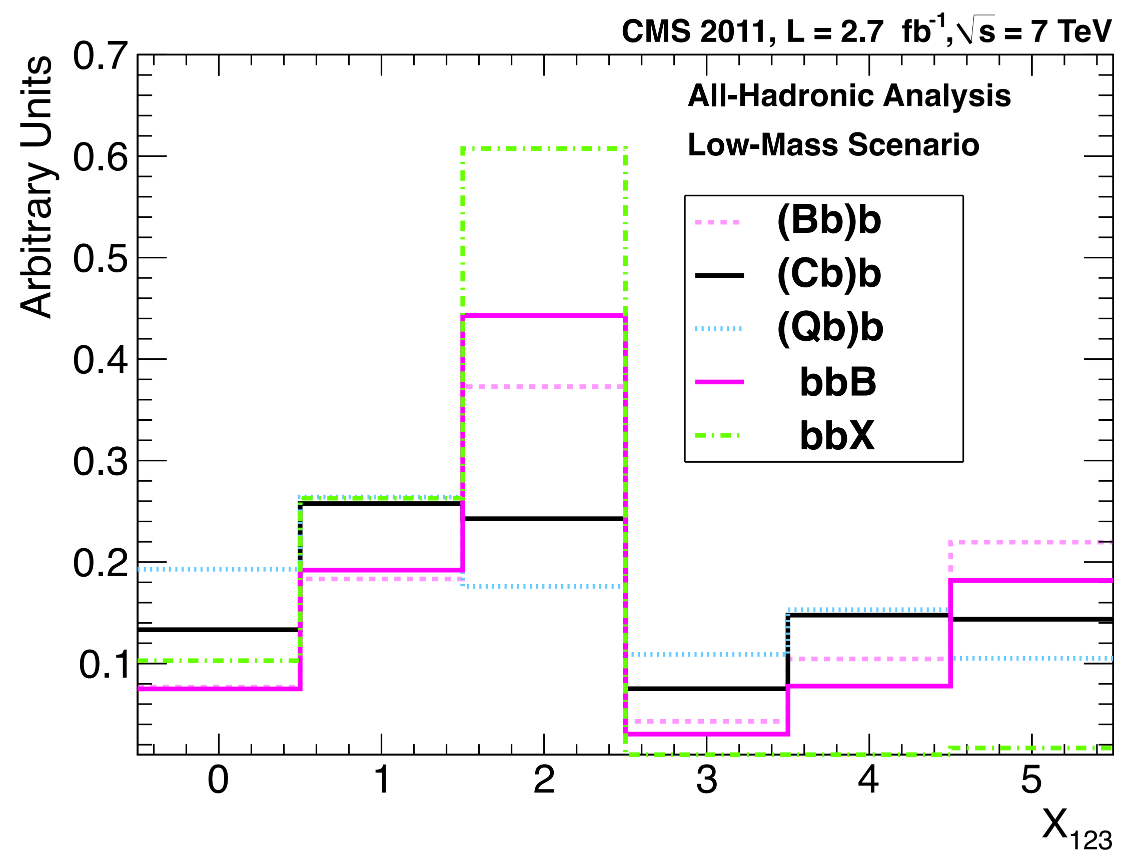


MSSM $\phi \to bb$: Background model

(all-hadronic)

- Data-driven background modelling from double b-tag sample.
- Untagged jet is weighted according to the b-tag probability and the corresponding SV mass index probability of assumed flavour.
- Almost identical templates merged
  - bbX = bbC + bbQ
  - (Fb)b = Fbb+bFb, where F=B,C,Q
- X_{123} gives further distinction between different flavour compositions.
- Five 2D templates: M_{12} vs. X_{123}
- Normalisation from fit to data spectrum.

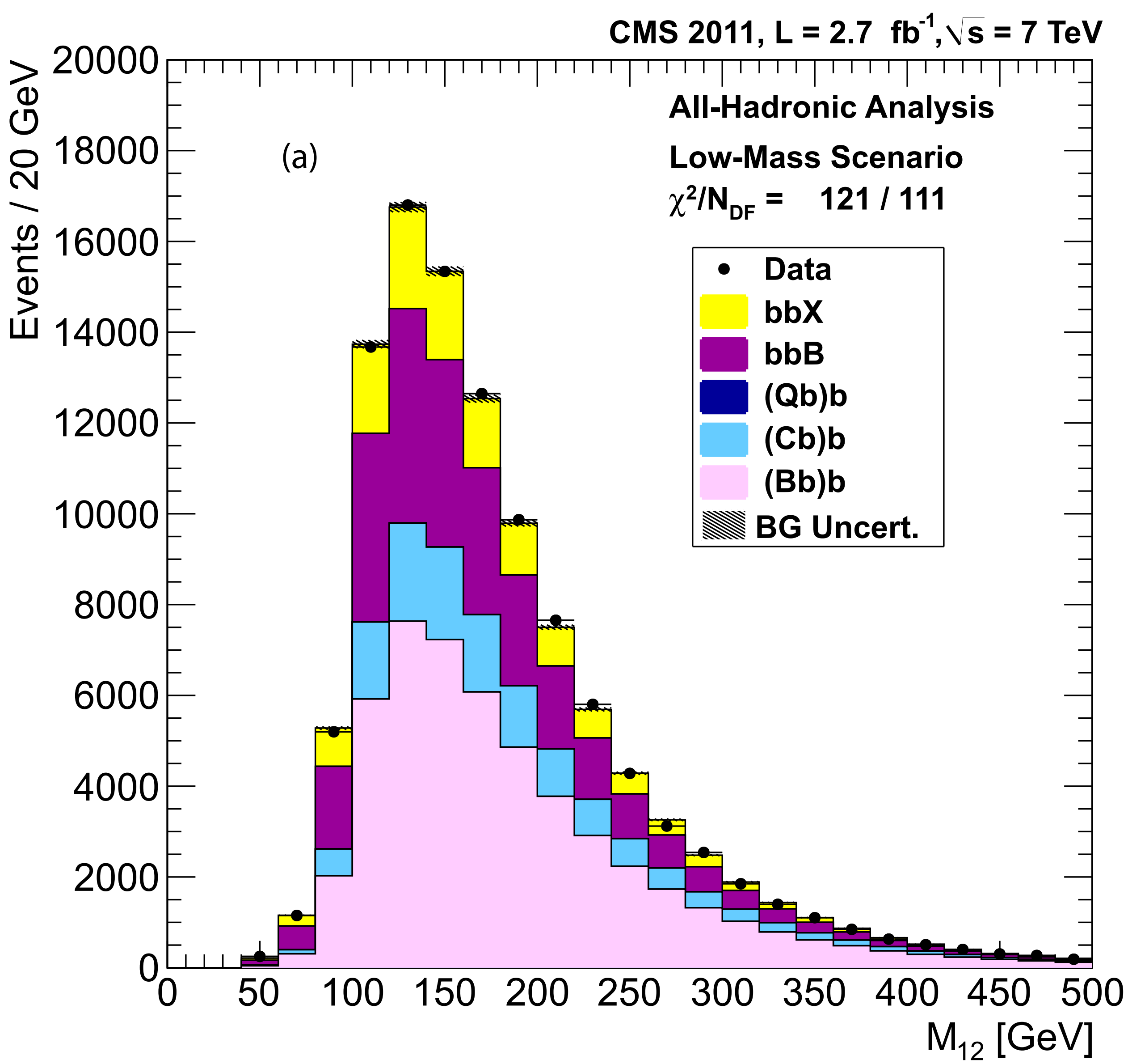


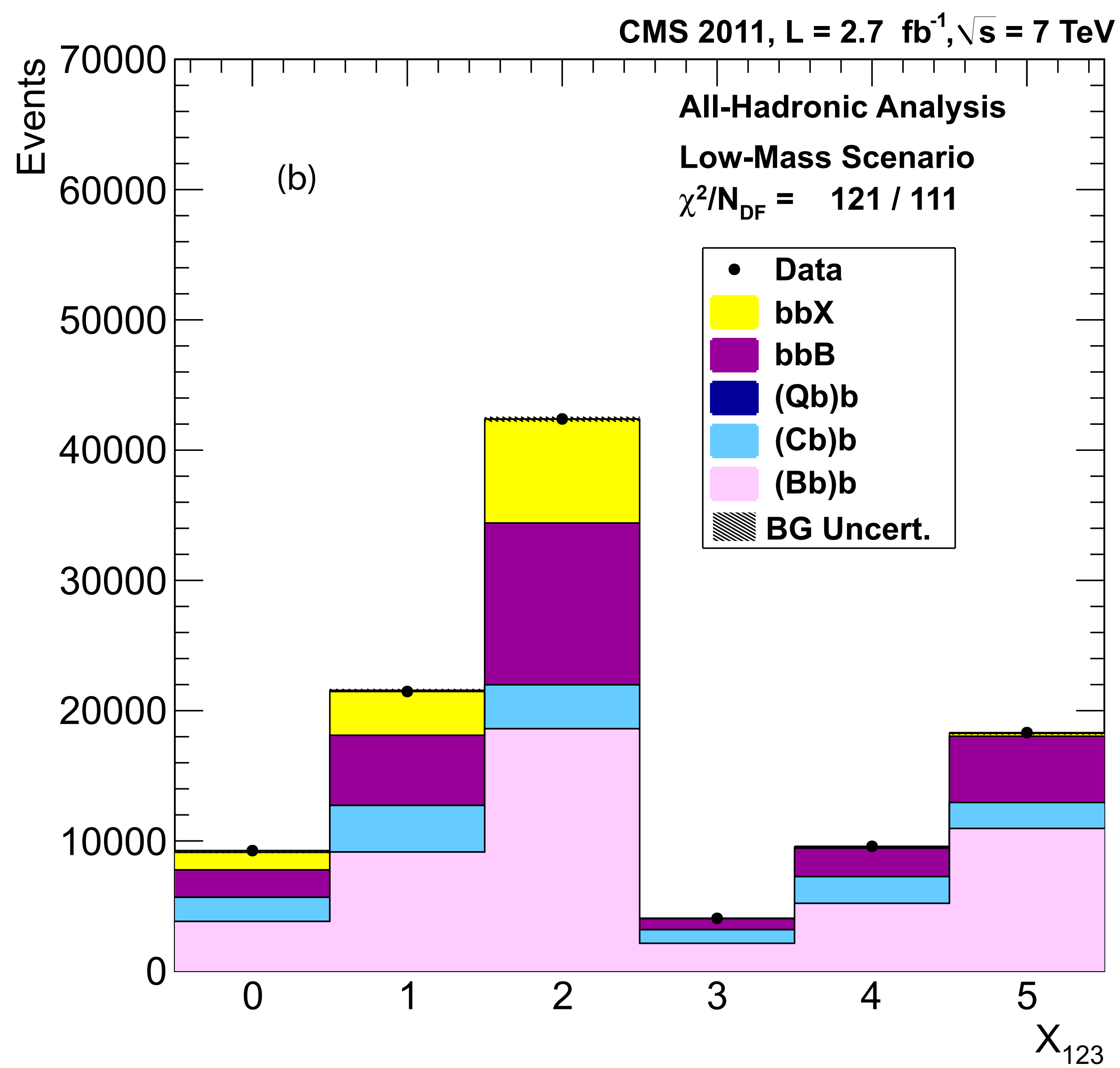


MSSM Φ → bb : Fit to data

(all-hadronic)

- Fit with background only templates with shapes obtained with double b-tag sample.
- About 73% contribution of real triple b jets.
- Excellent agreement with triple b-tag data

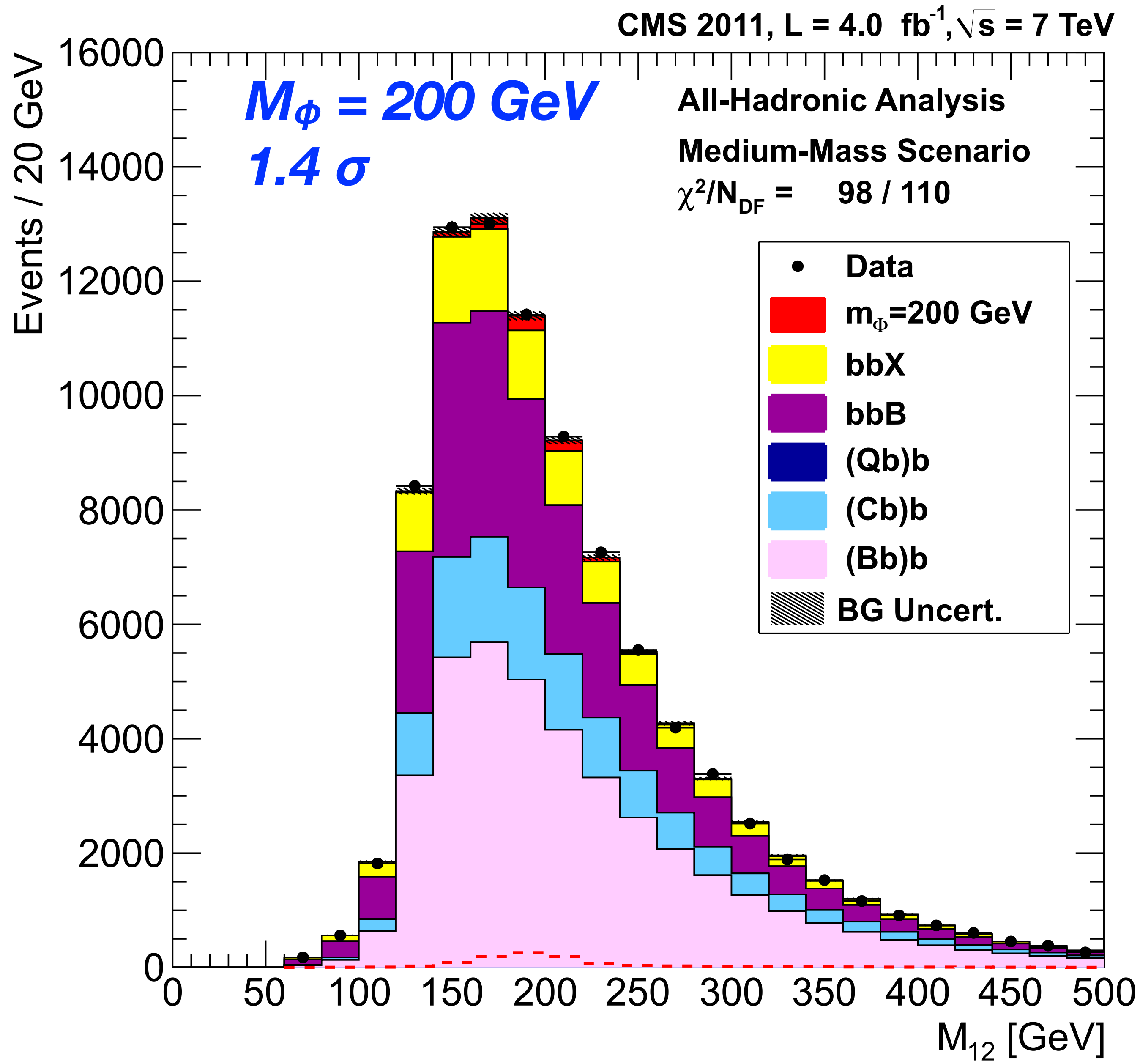




MSSM Φ → bb : Fit to data

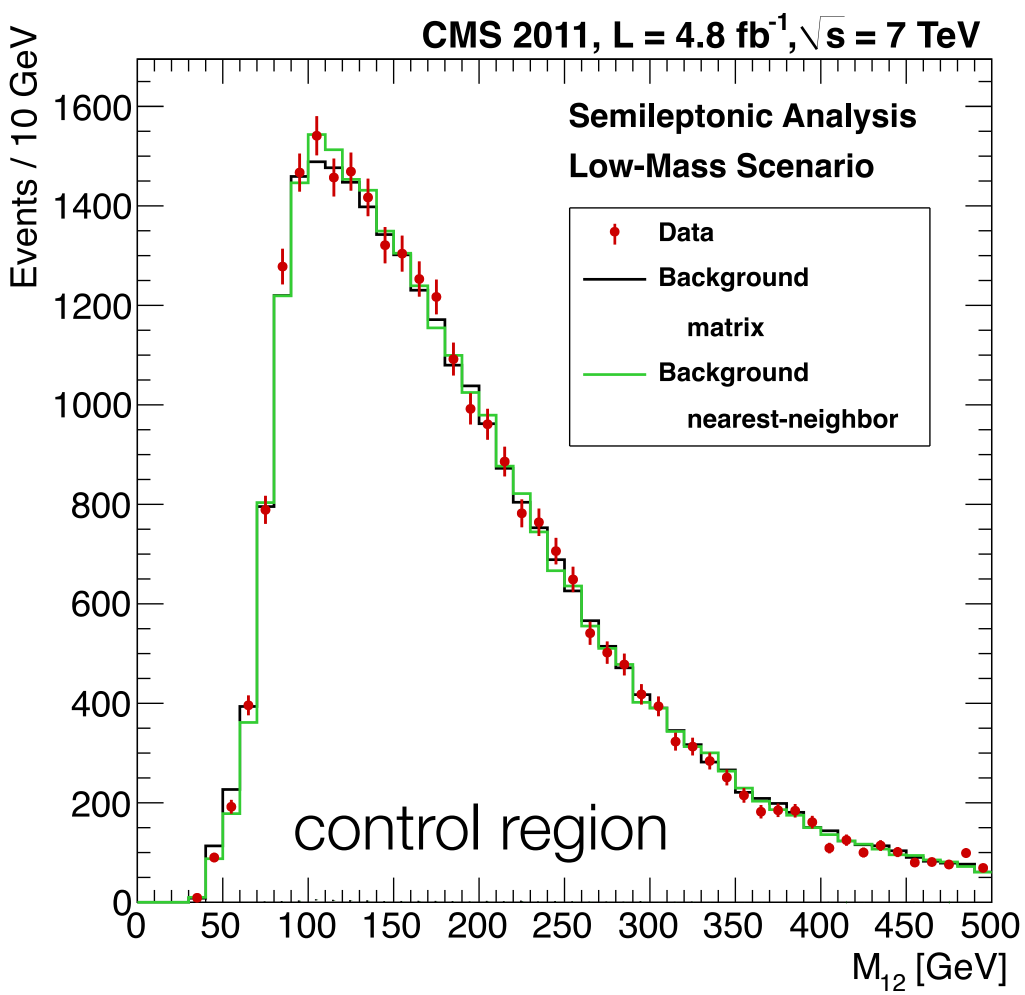
(all-hadronic)

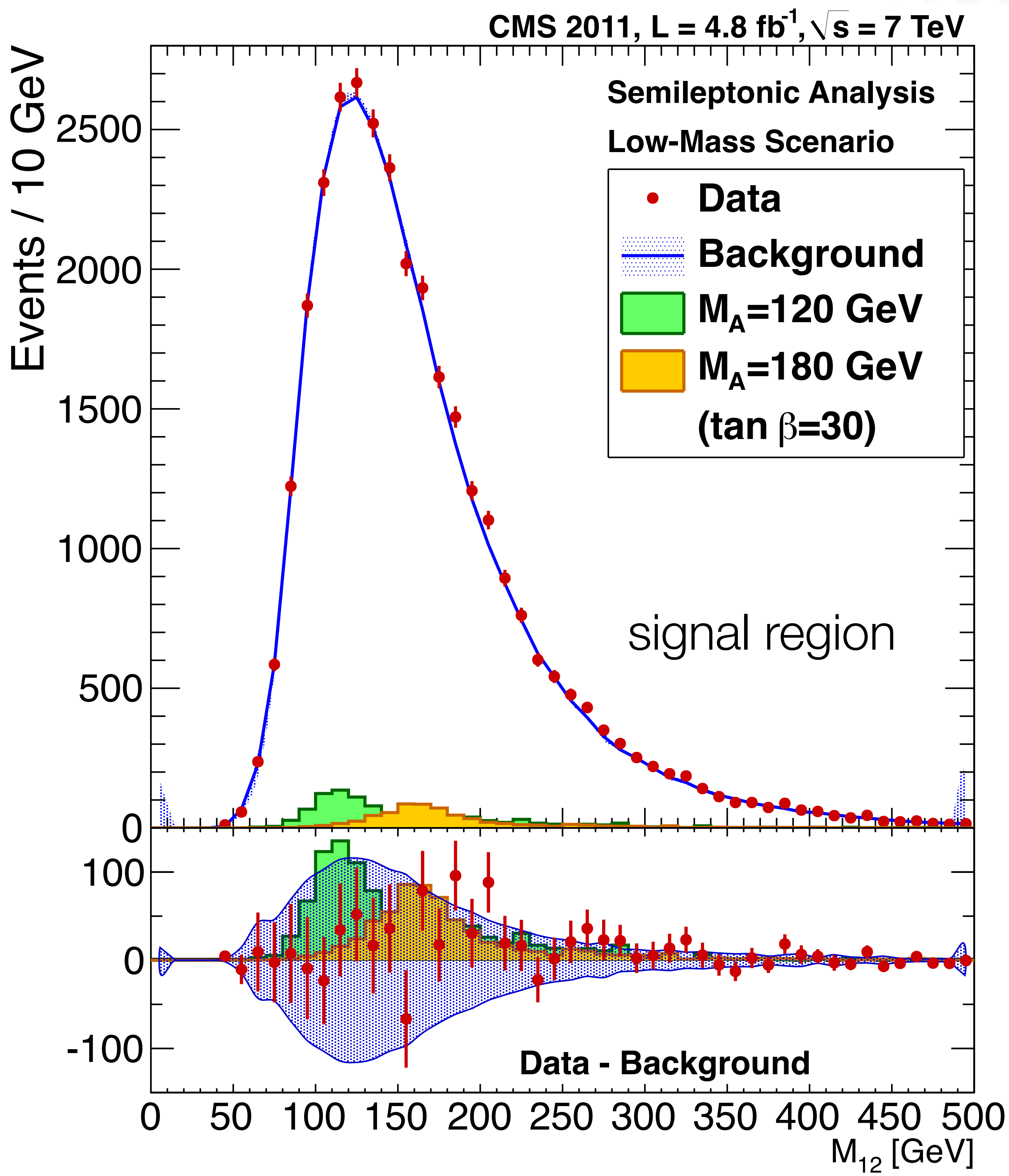
- Signal + background templates fits
  - Mass range 90 – 350 GeV
  - No significant excess observed at any mass



MSSM Φ → bb : Semileptonic analysis

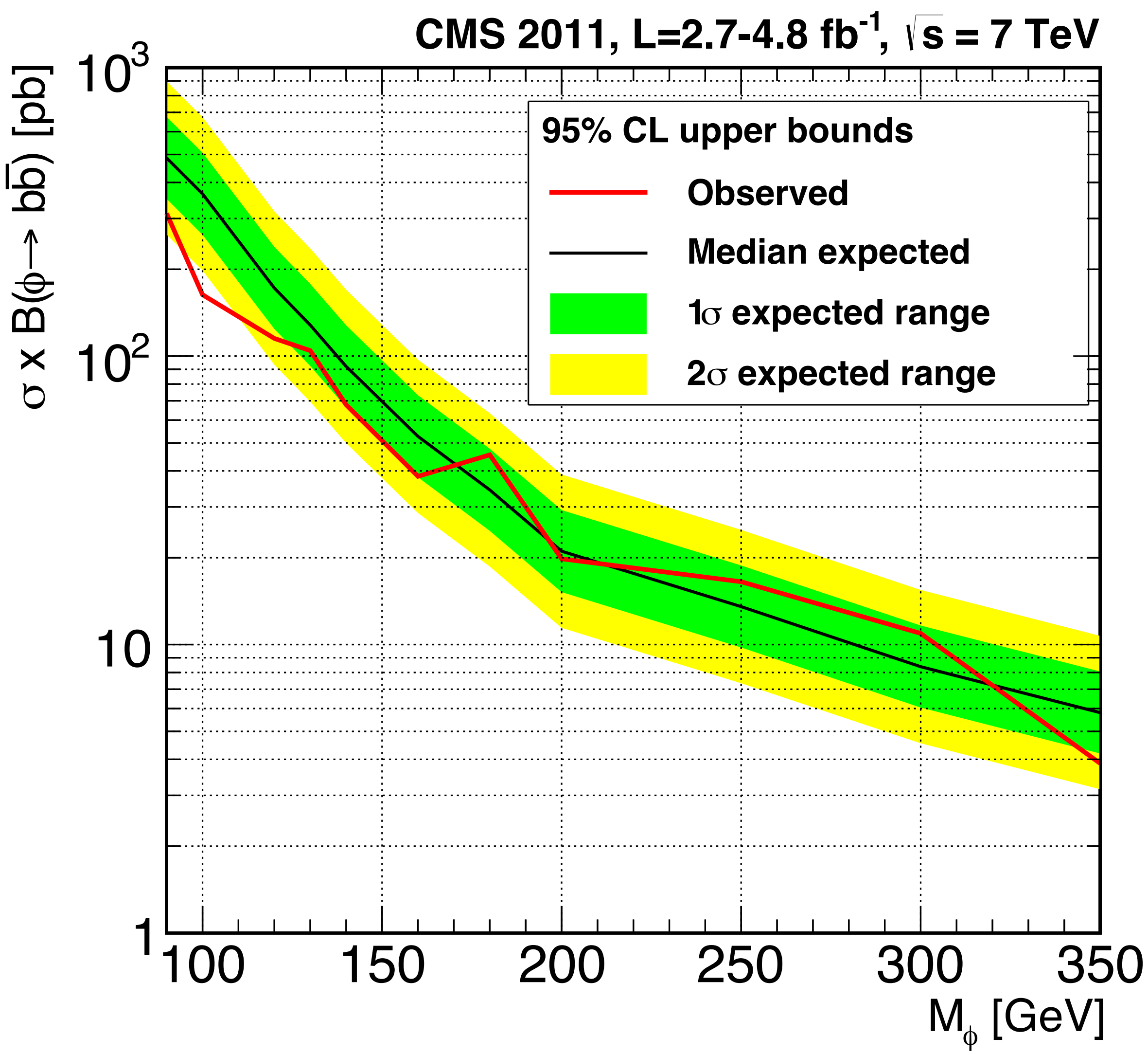
- Background normalisation and shape obtained from data in control regions.
  - Two independent methods using single and double b-tag data samples.
- Mass range 90 – 350 GeV.
- No significant excess observed at any mass.

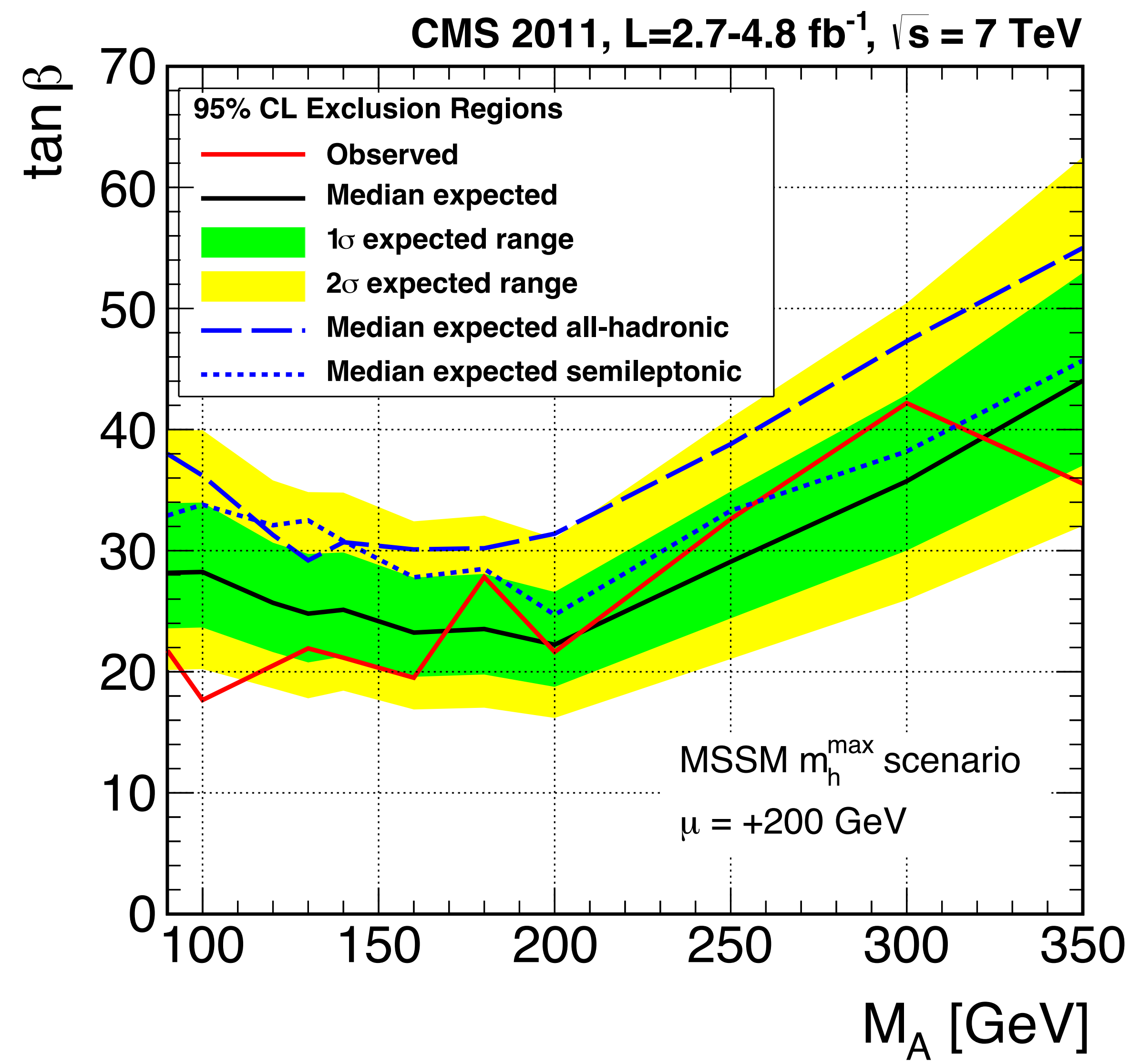




MSSM Φ → bb : Limits

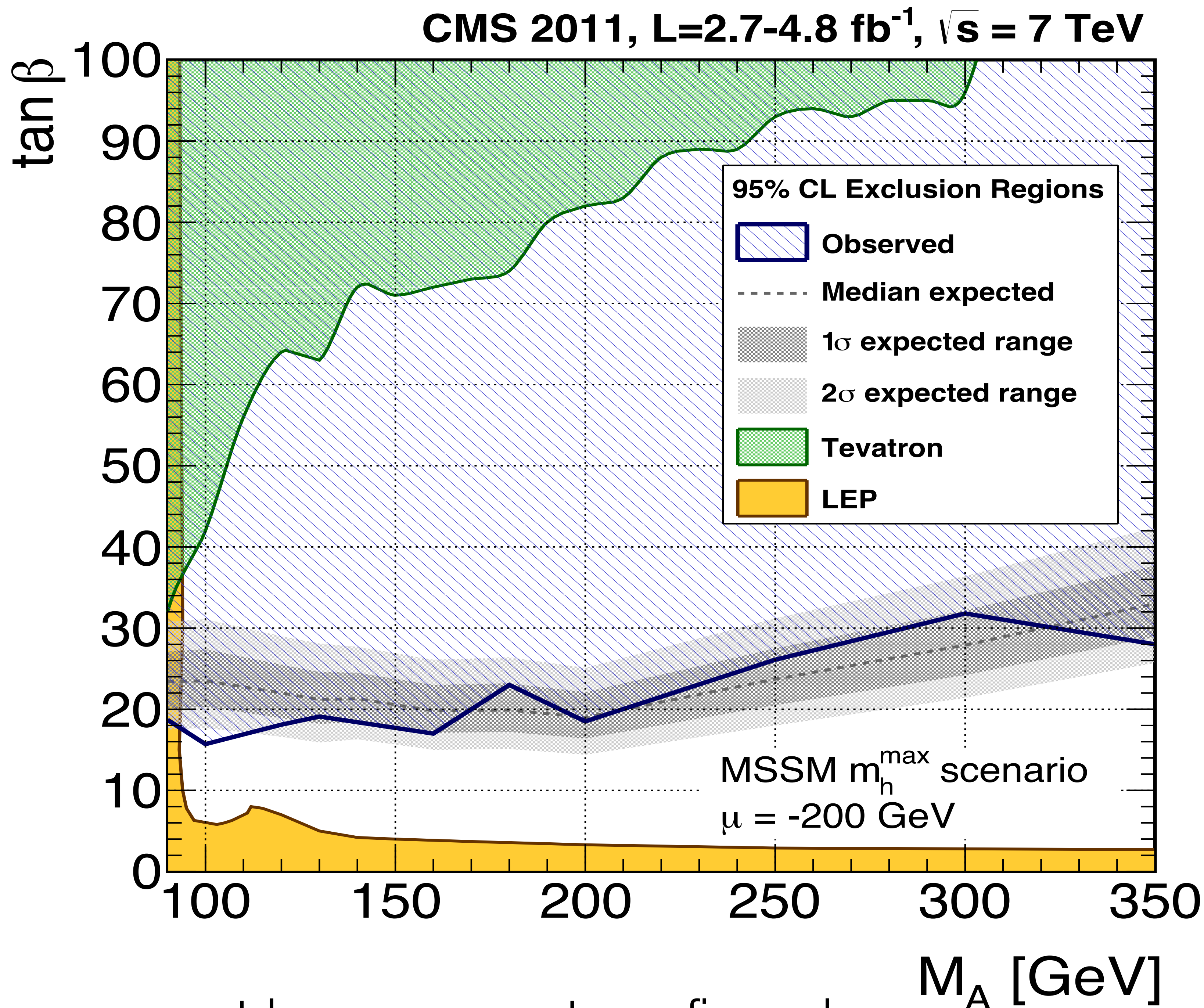
- All-hadronic and semileptonic analysis are almost orthogonal, 2-3% overlap (removed from all-hadronic dataset)
- Upper limits for σ×BR and tanβ vs m_A (NNLO 5-flavour scheme cross sections - Higgs XS WG)
- CMS convention: SUSY parameter μ = + 200 GeV





- For comparison with Tevatron, we also give results for μ = –200 GeV (next slide)

MSSM $\phi \to bb$: Comparison with Tevatron



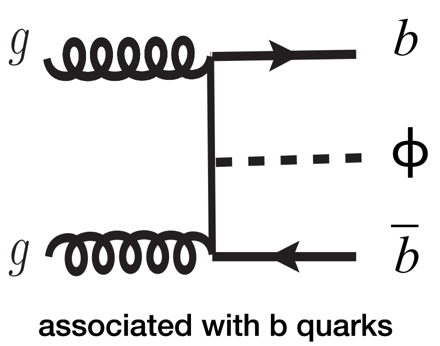
- CDF–D0 +2σ excess at low mass not confirmed.
- First time done at the LHC!
- World's best sensitivity in the bb channel, with 2011 data alone.

MSSM $\phi \rightarrow \mu\mu$ search

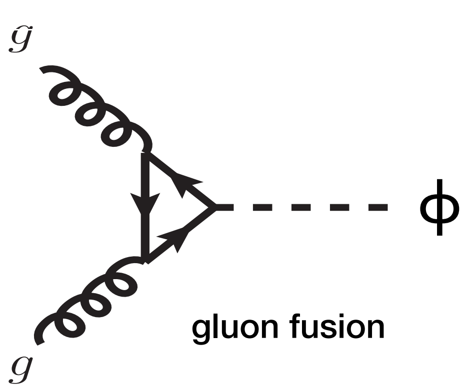
$\phi \to \mu\mu$ Search

- Excellent mass resolution and manageable backgrounds, but low BR.
- Signature: two oppositely charged, isolated muons with $p_{T1(2)} > 30\ (20)$ GeV, $|\eta| < 2.1$; missing $E_T < 30$ GeV.
- Background estimated from data, dominated by Drell-Yan.

Production mechanisms & event categories

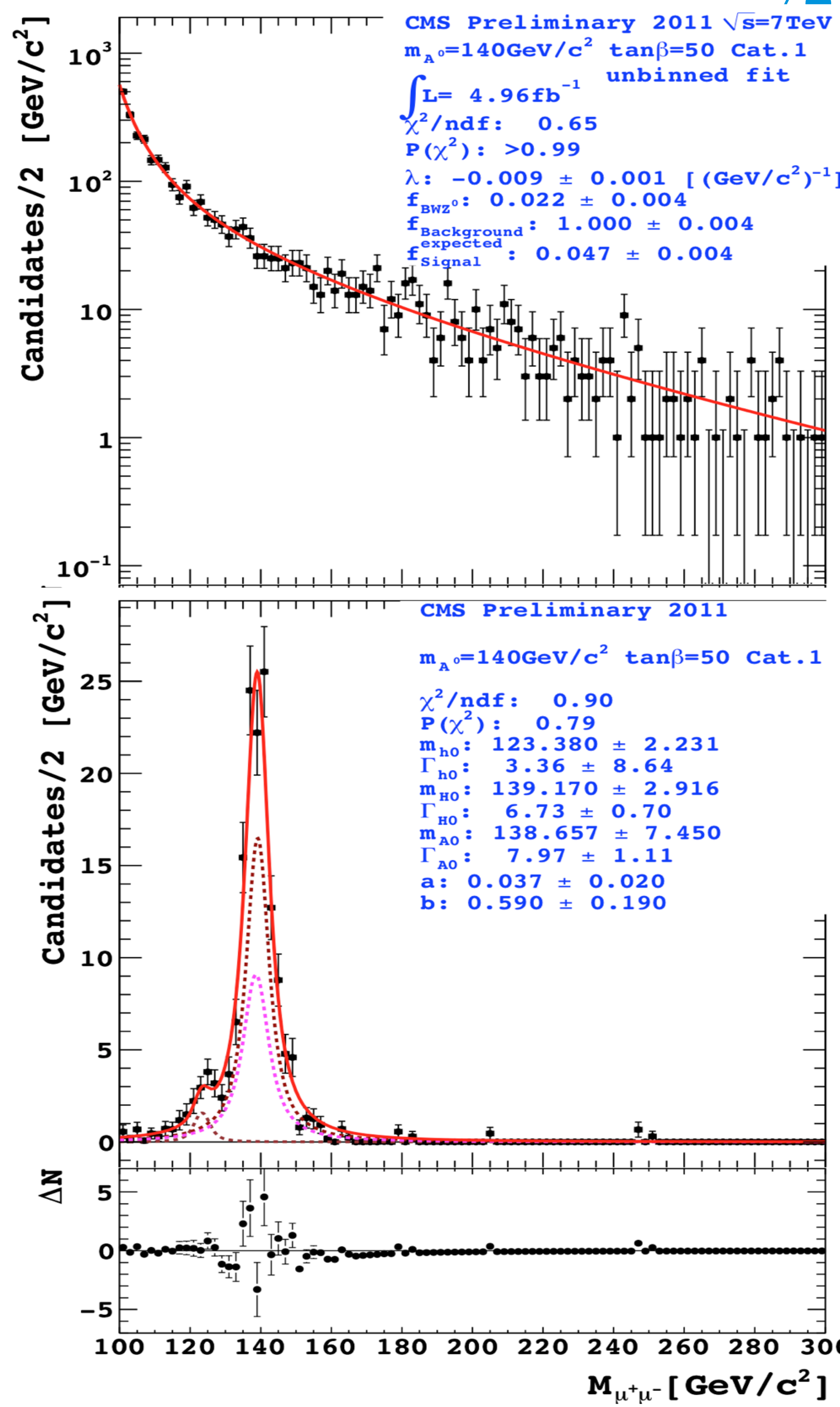


associated with b quarks	Category 1	≥ 1 b-tagged jet with $p_T > 20$ GeV, $\lvert\eta\rvert < 2.4$, $\Delta R(\mu,j) > 0.5$
	Category 2	veto on b-tagged jets ; a 3rd μ with $p_T > 3$ GeV, $\lvert\eta\rvert < 2.4$, $\Delta R(\mu,\mu) > 0.5$
gluon fusion	Category 3	all other events not in Categories 1,2



$\phi \to \mu\mu$: Strategy

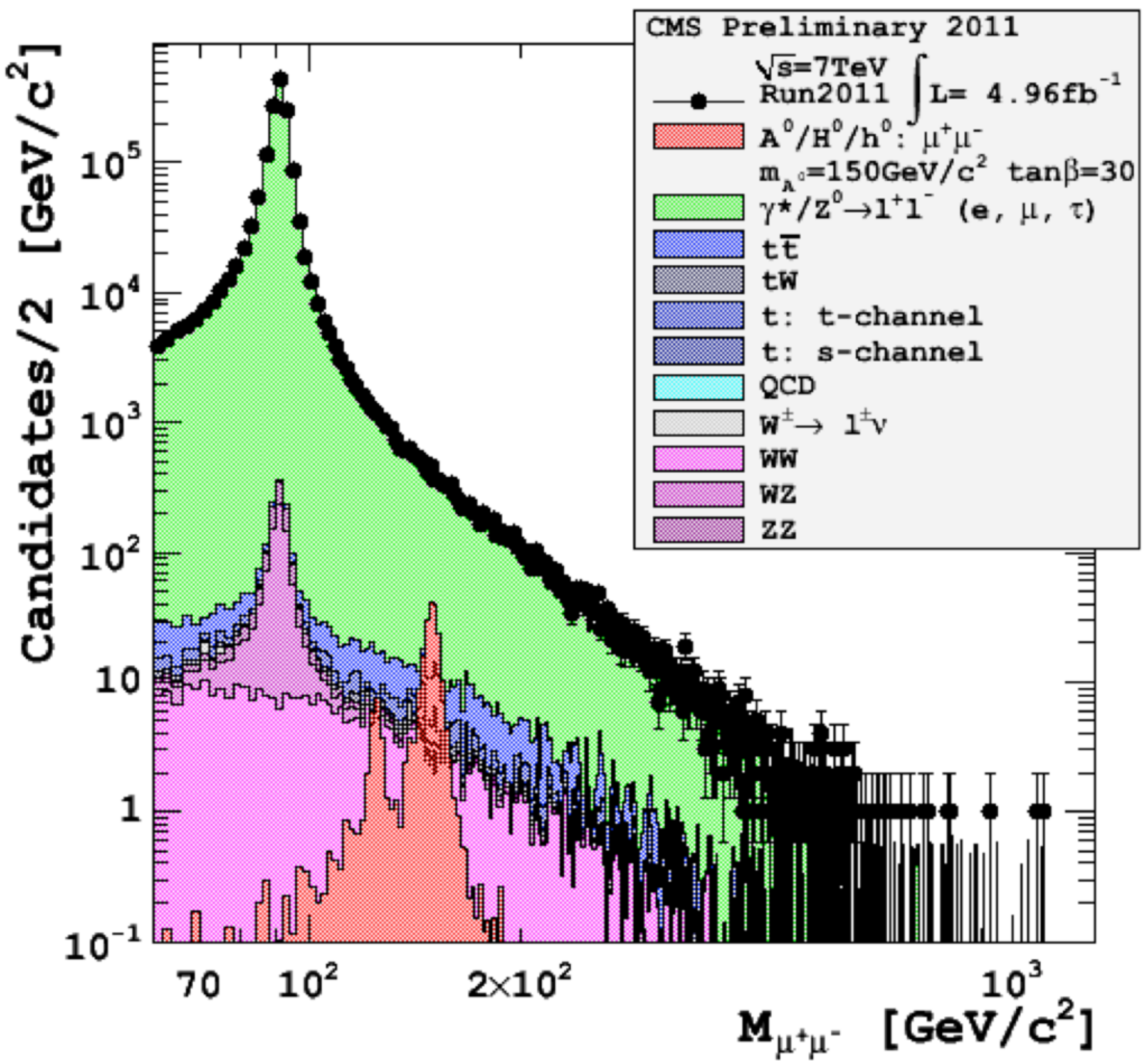
- **Background**:
  - Largest contribution Drell-Yan.
  - Linear combination of:
    - Breit-Wigner around the Z peak
    - Photon propagator contribution
  - Multiplied by the exponential part of the PDF
- **Signal**:
  - Linear combination of three Breit-Wigner; detector resolution taken into account
- **Unbinned likelihood fit of S + B hypothesis to data**



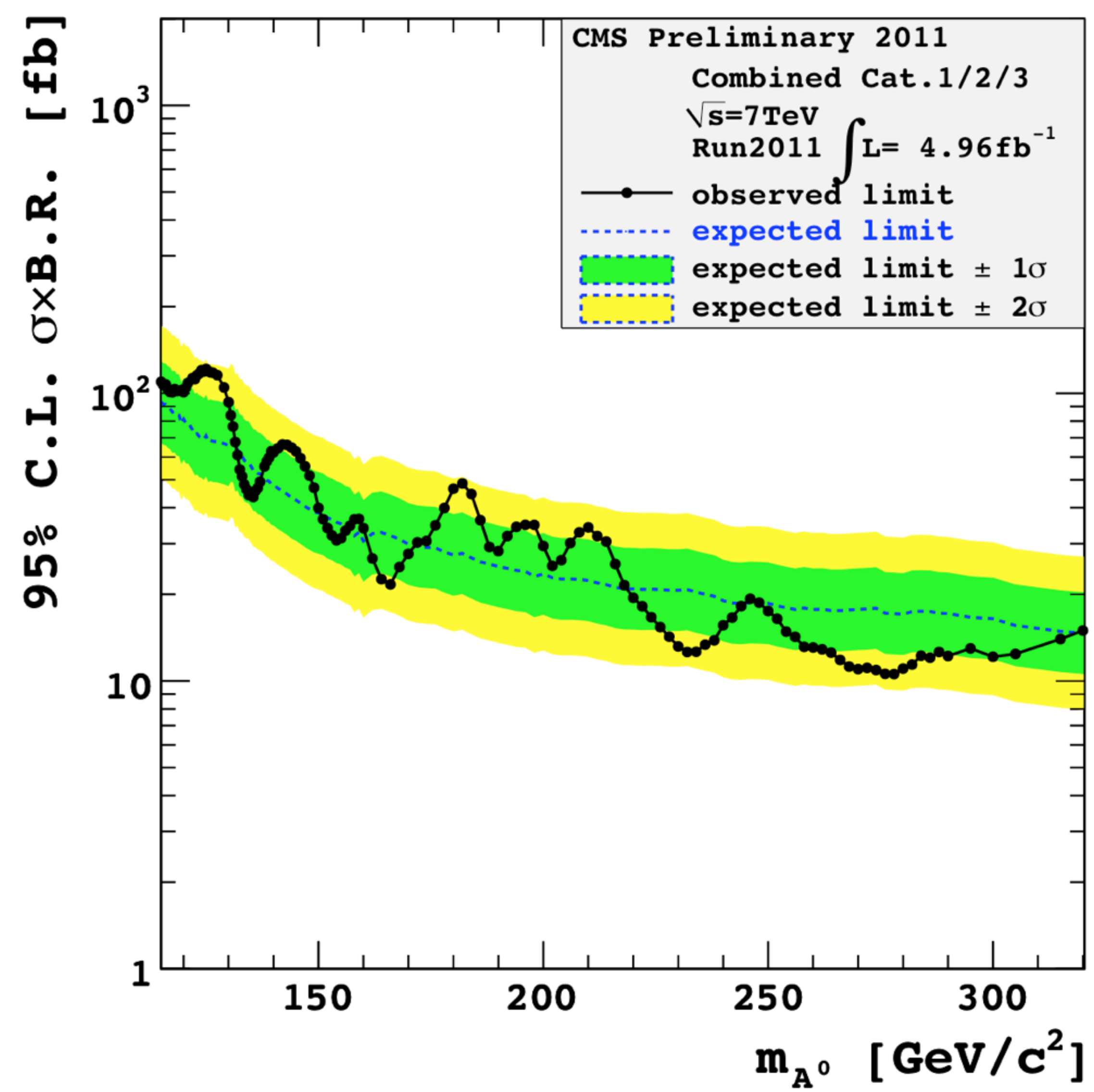
$\phi \to \mu\mu$: Results

- Combined result from 3 categories.
- No excess observed.

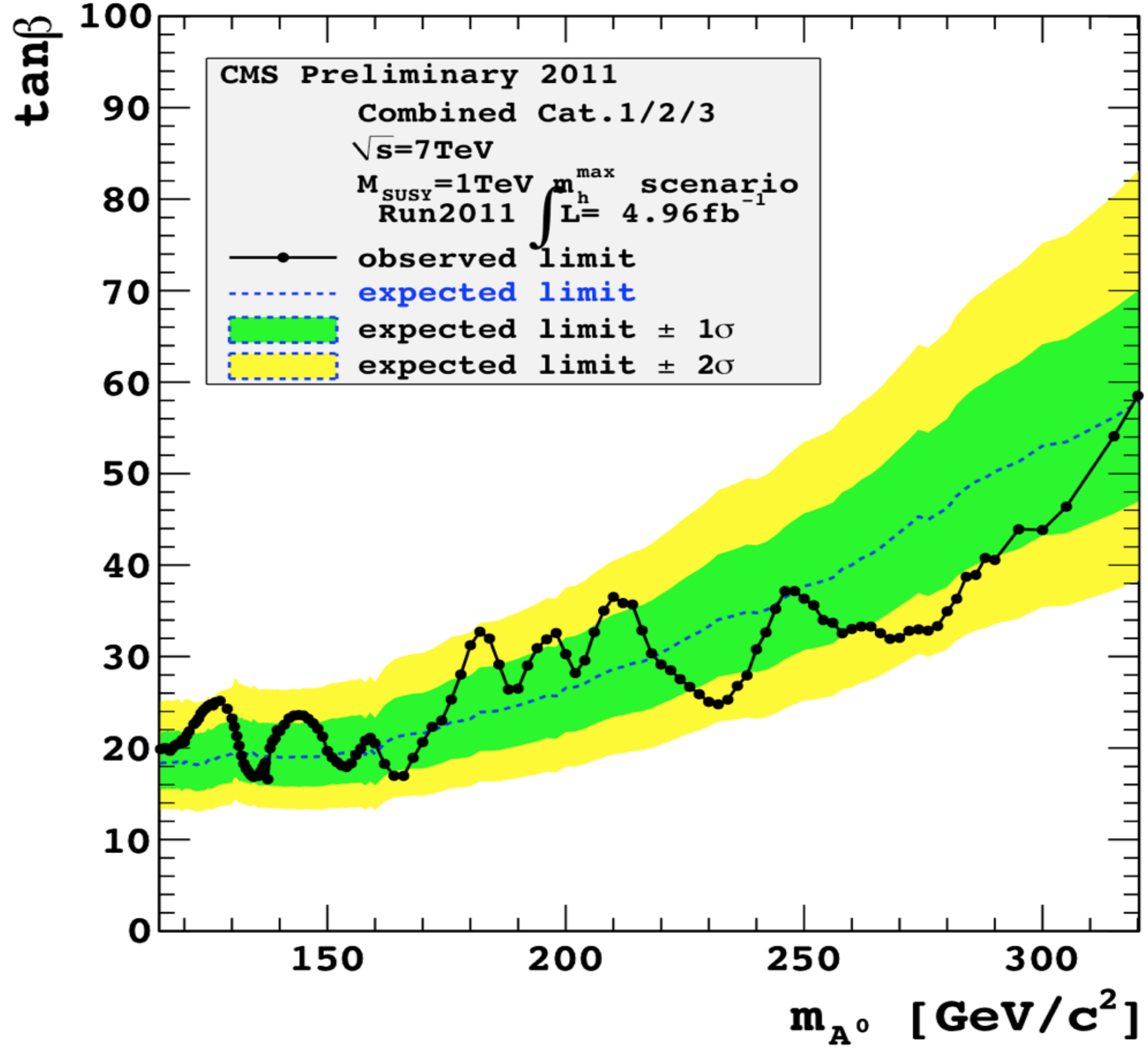
μ+μ- invariant mass distribution



95% CL upper limits on cross-section x BR



$\phi \rightarrow \mu\mu$: Results (II)

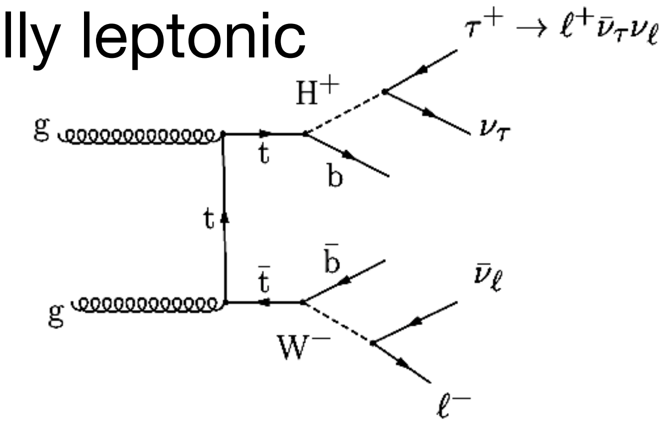


- Combined result from the three categories.
- 95% CL limits on tan β in the range 20 – 60.

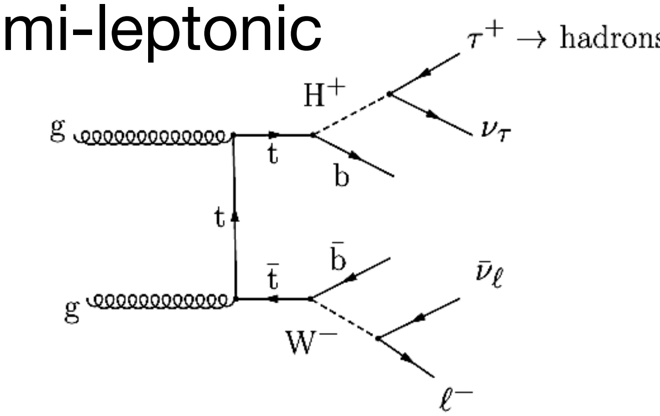
Light MSSM $H^{\pm}$ search

Light H± search in top decays

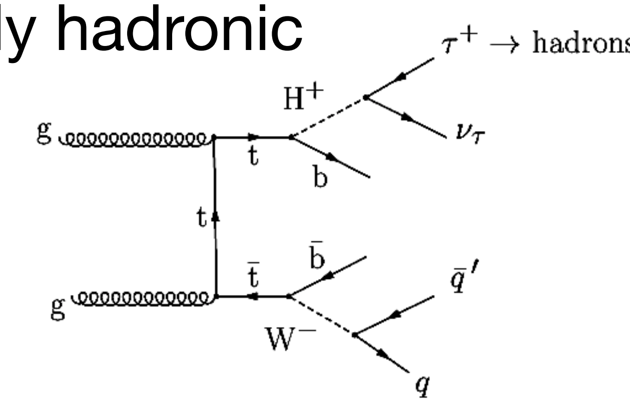
fully leptonic



semi-leptonic



fully hadronic

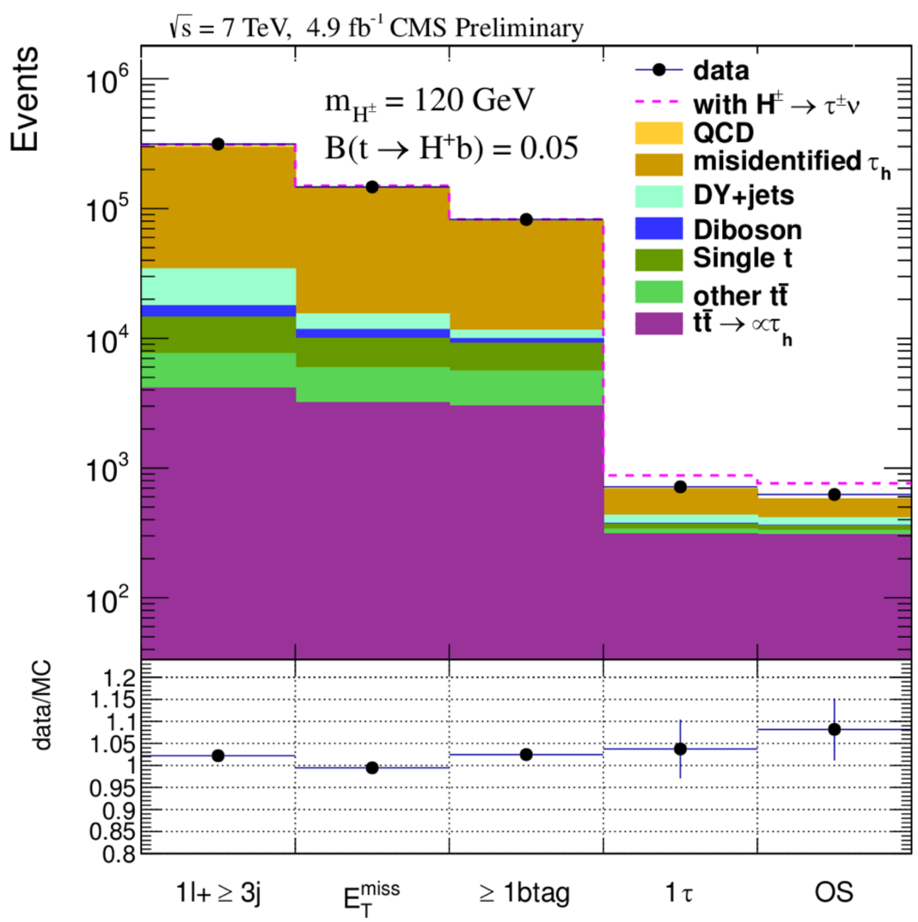


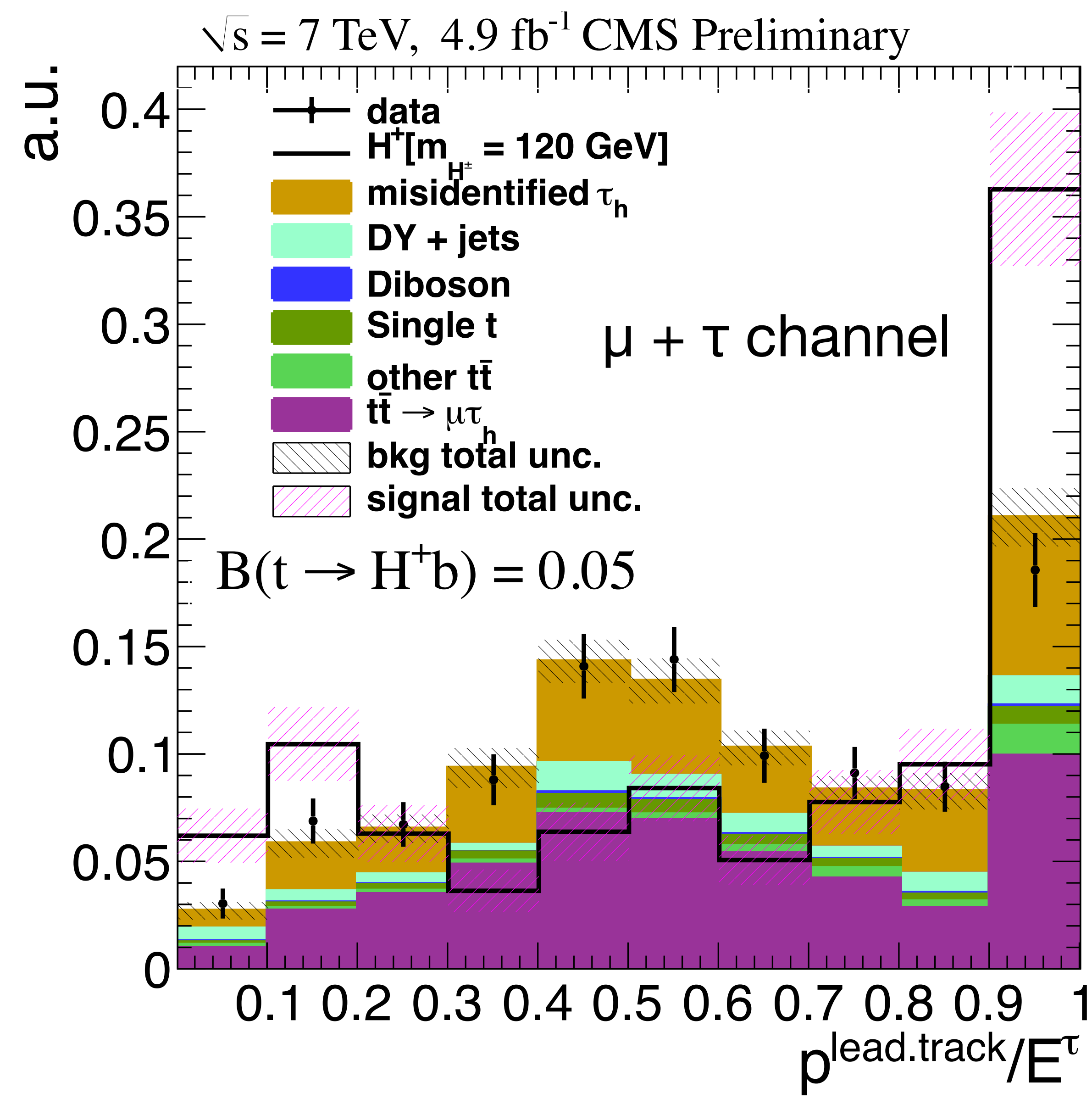
- Basic process: top pair production
  - Assuming $M_{H\pm} < M_{top} - m_{bottom}$: $t \rightarrow bH^{\pm}$ is allowed
- Dominant decay mode (tan β > 5) $H^+ \rightarrow \tau^+ \nu_\tau$
  - Assume BR($H^+ \rightarrow \tau^+ \nu_\tau$) = 100%
- Channels:
  - e + τ ; e + μ ; τ + jets (2.0 - 2.3 fb^{-1})
  - μ + τ (4.9 fb^{-1})

Light H± search : Results

- Signal extraction:
  - τ + jets: fit transverse mass distribution of τ and E_T^{miss}
  - μ + τ: fit of R = $p^{lead.track}/E_\tau$
  - Other channels: event counting

μ + τ channel event selection

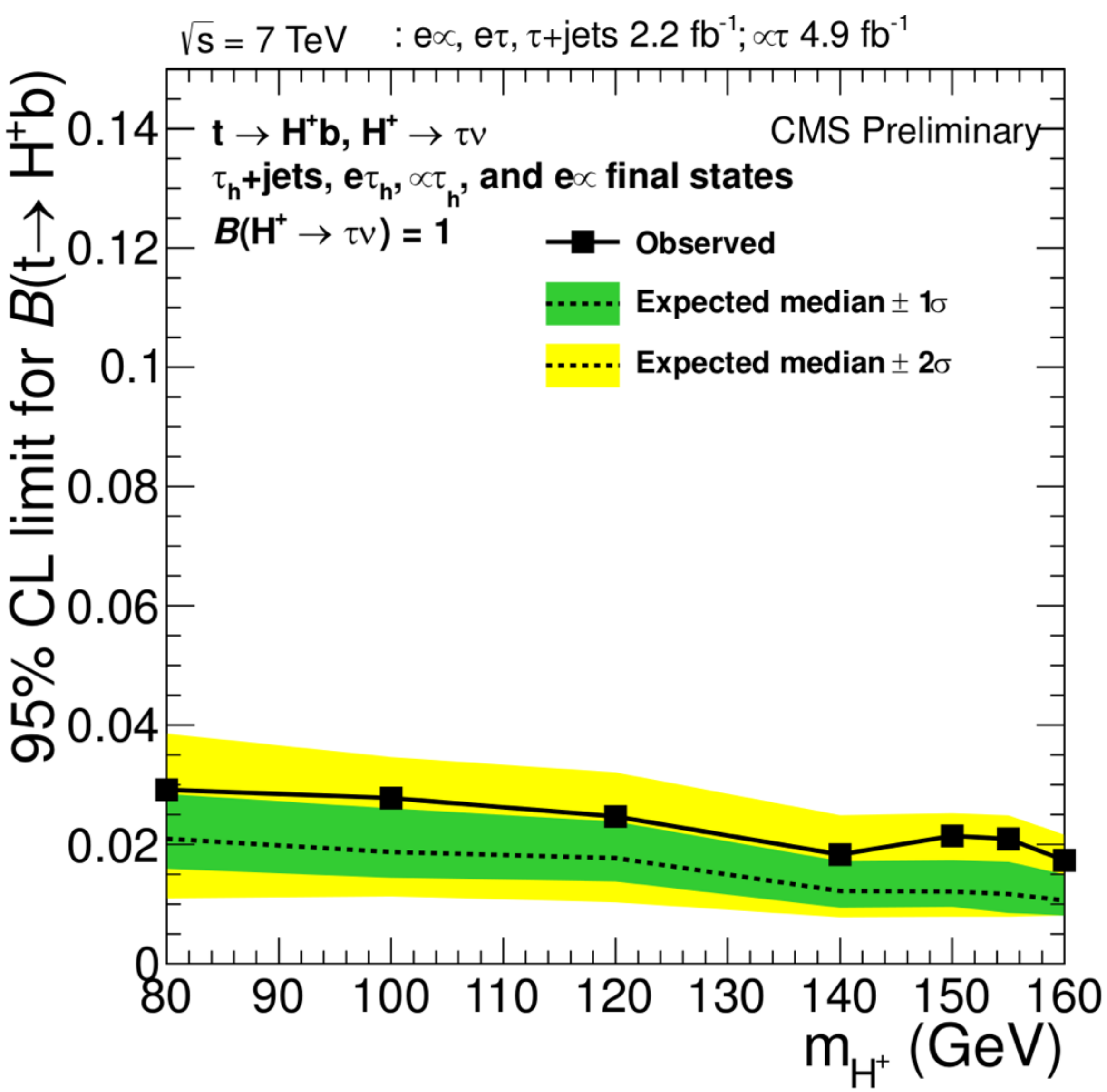


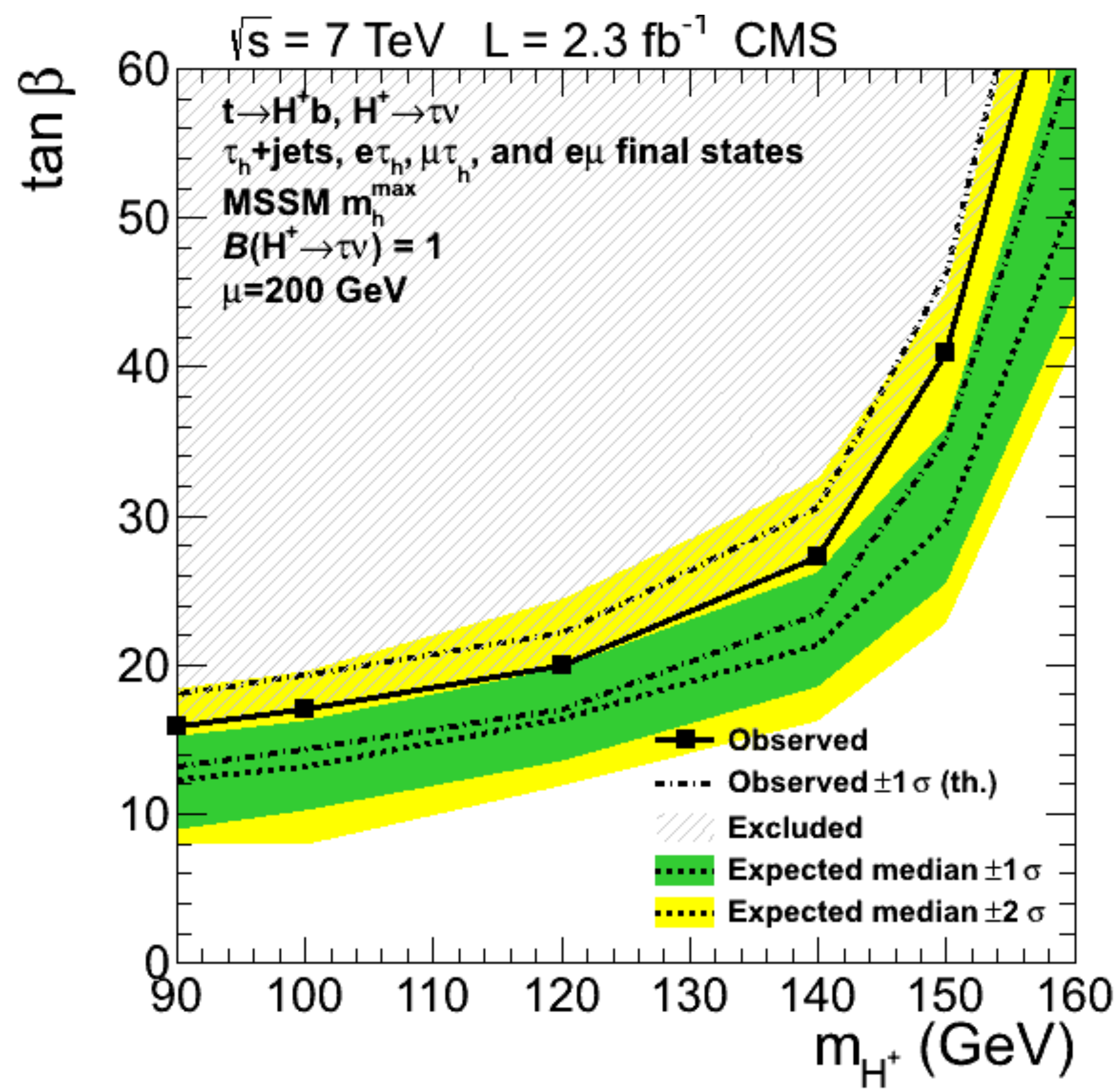


- No excess observed

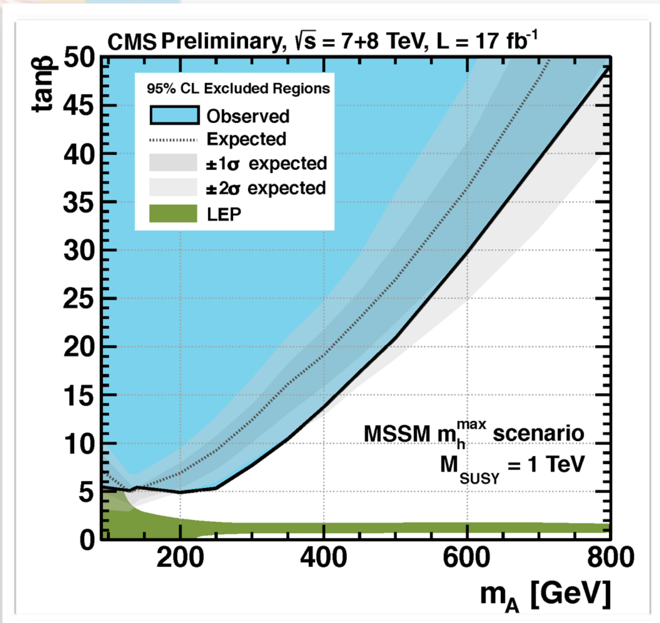
Light H± search : Limits

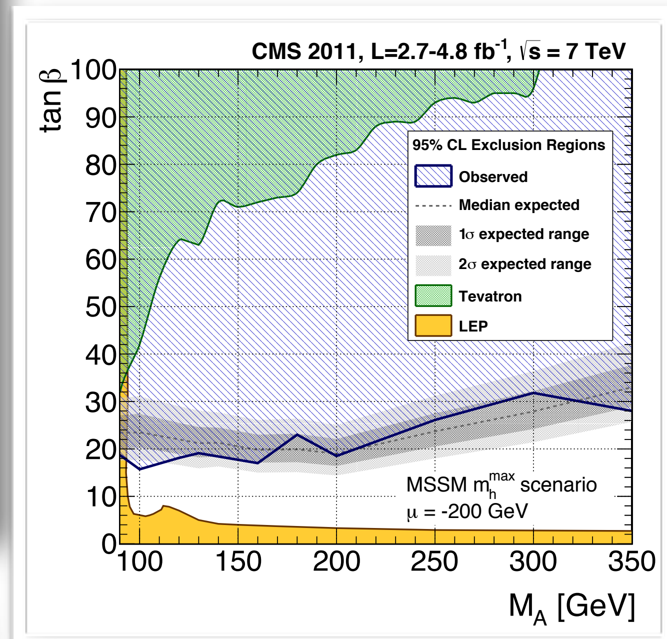
- Combined all channels
- 95% CL limits on BR(t → bH±) on the 2.3 – 4.9 fb^{-1} data sample
- 95% CL limits on tan β on the 2.3 fb^{-1} data sample.

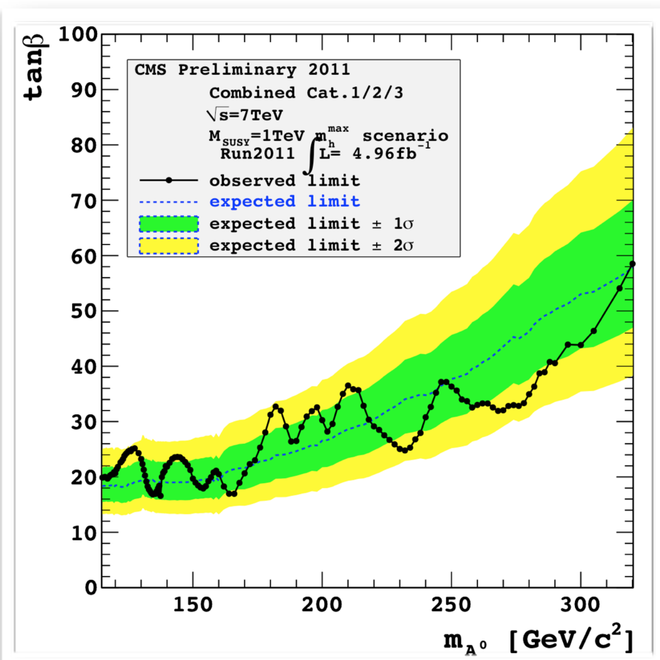


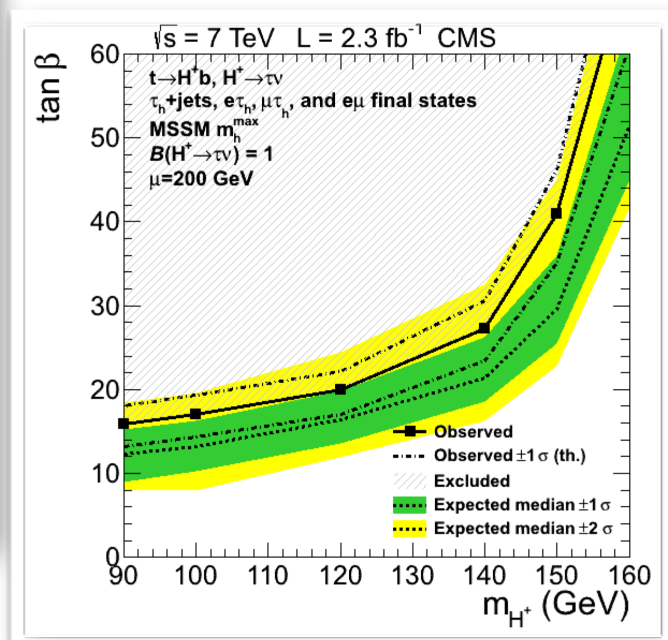


Summary





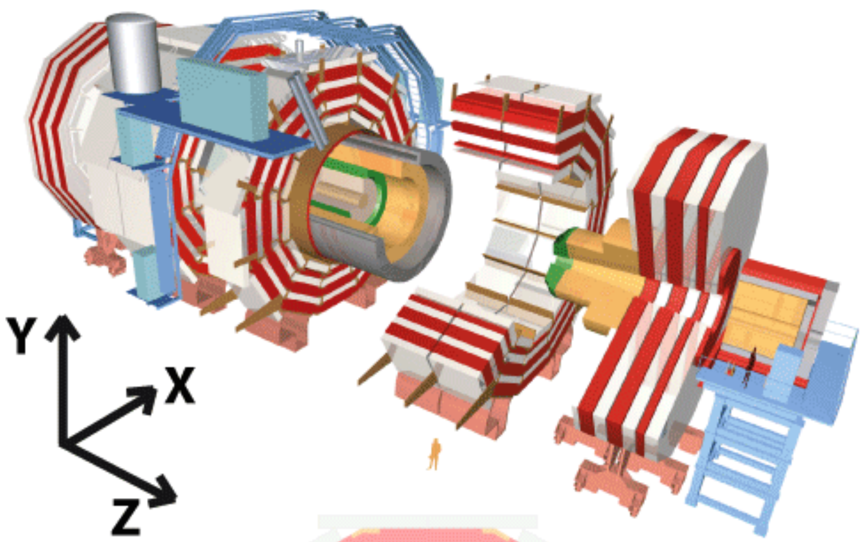


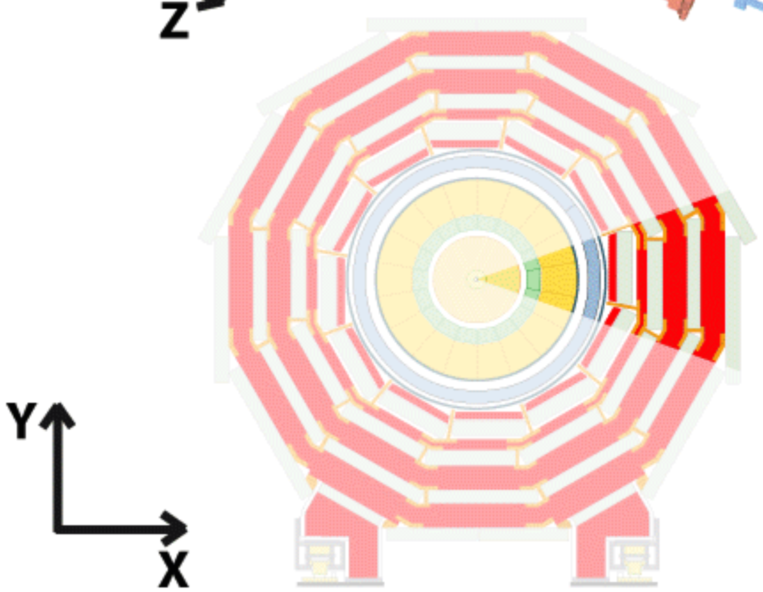


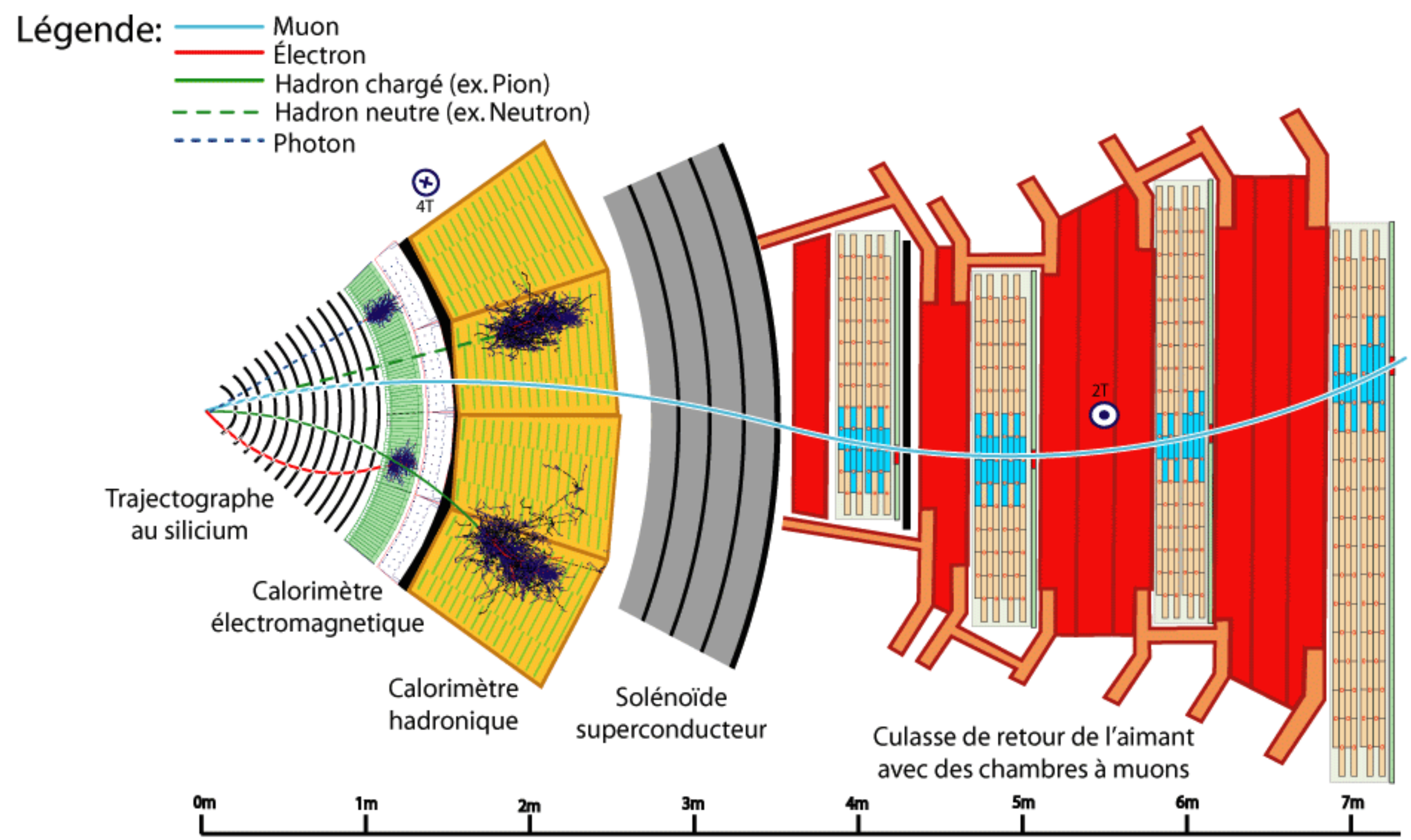
- Direct searches of MSSM Higgs in 4 major production/decay modes:
  - $\phi \rightarrow \tau\tau$: most stringent exclusion limits
  - $\phi \rightarrow bb$: novel at the LHC, do not confirm Tevatron excess
  - $\phi \rightarrow \mu\mu$: best mass resolution; high sensitivity even with low BR
  - $t \rightarrow H^{\pm}$: very stringent limits on branching fraction.
- No excess observed in MSSM Higgs searches.
- Further improvements in the analyses are possible.

back up

How CMS detects particles

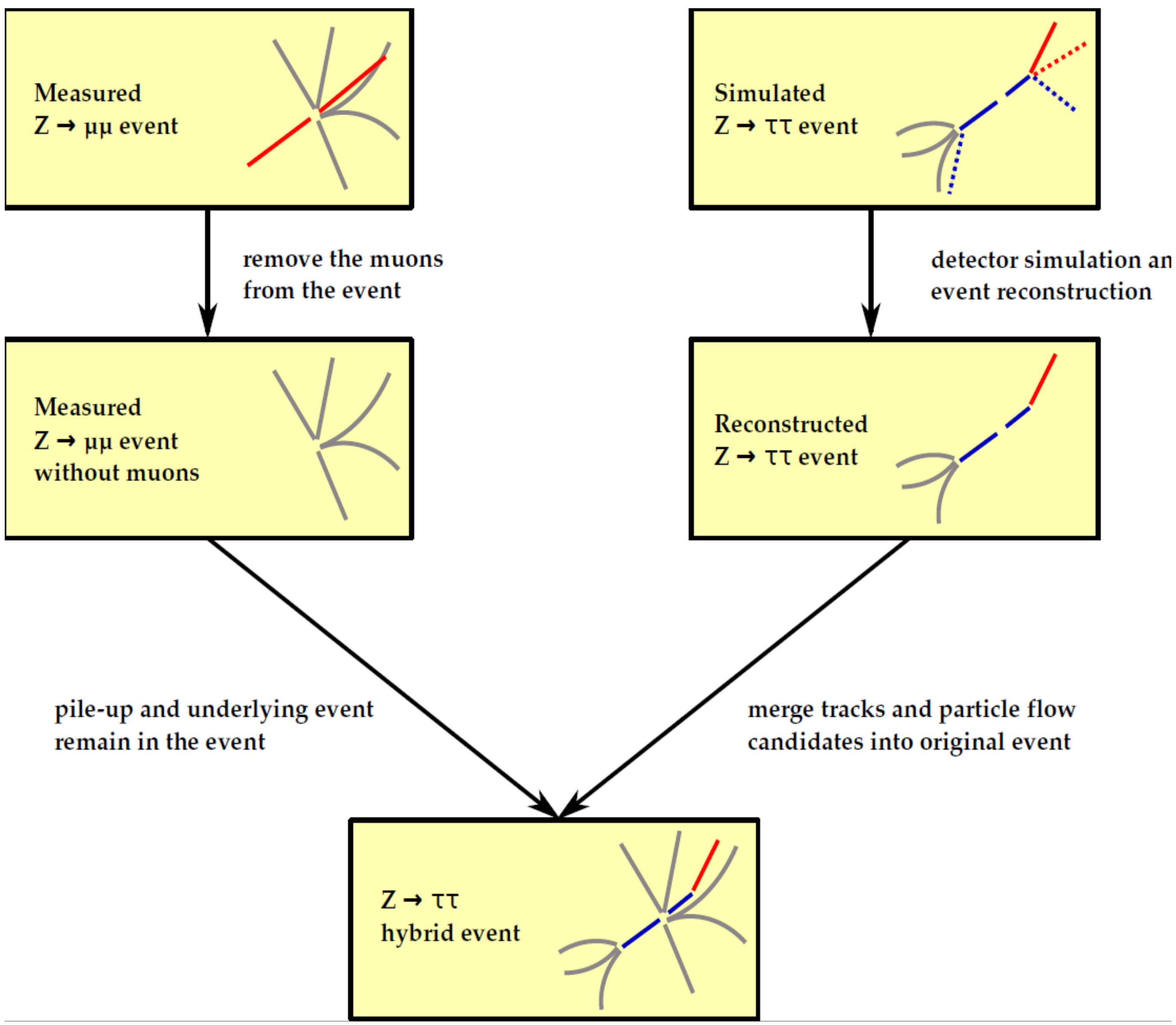


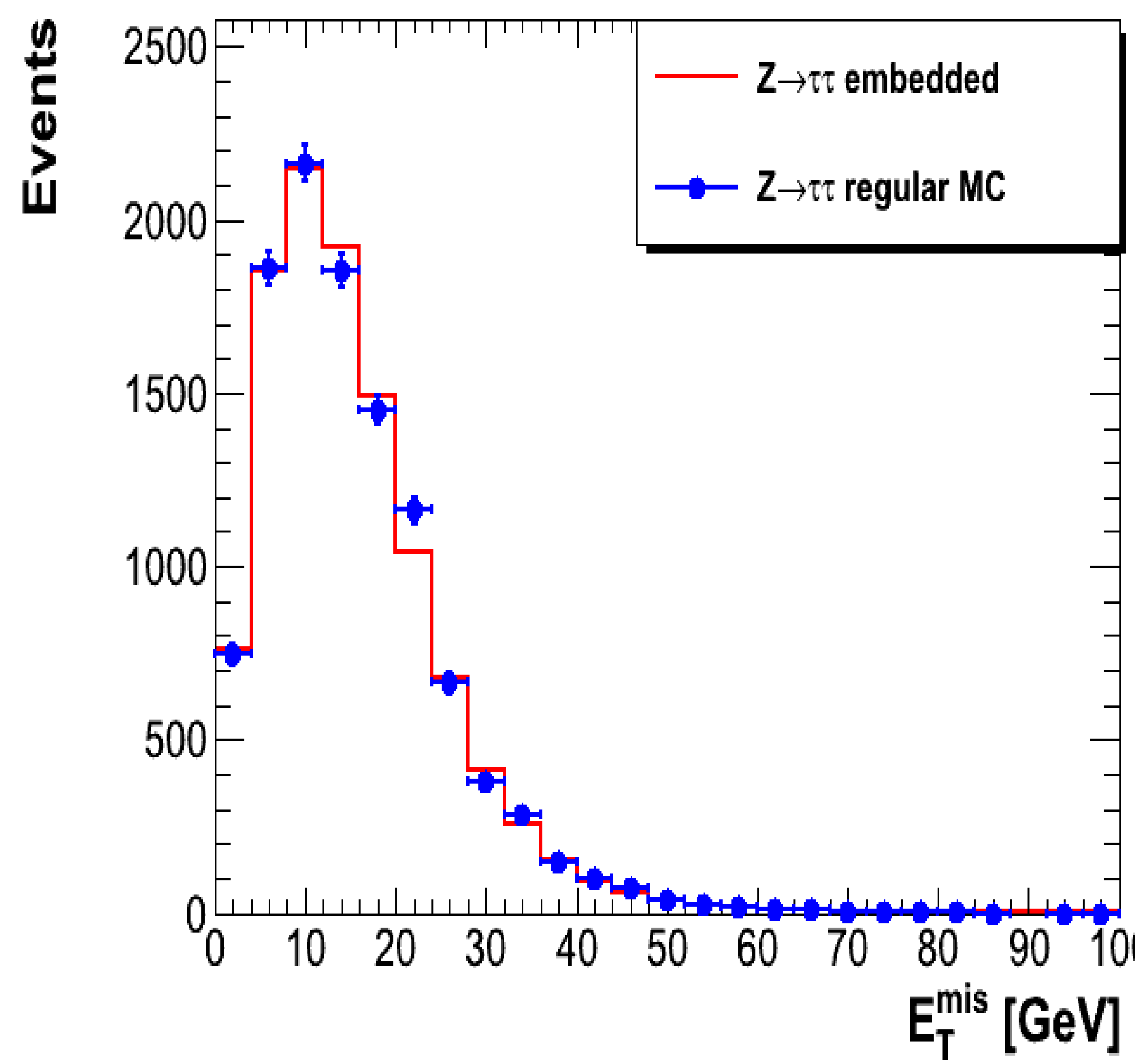




H→ττ : Embedding

- Z→ττ is the main irreducible background.
- Estimated from embedded sample: μ in Z→μμ events replaced by simulated τ.
- Normalised from Z→μμ events.



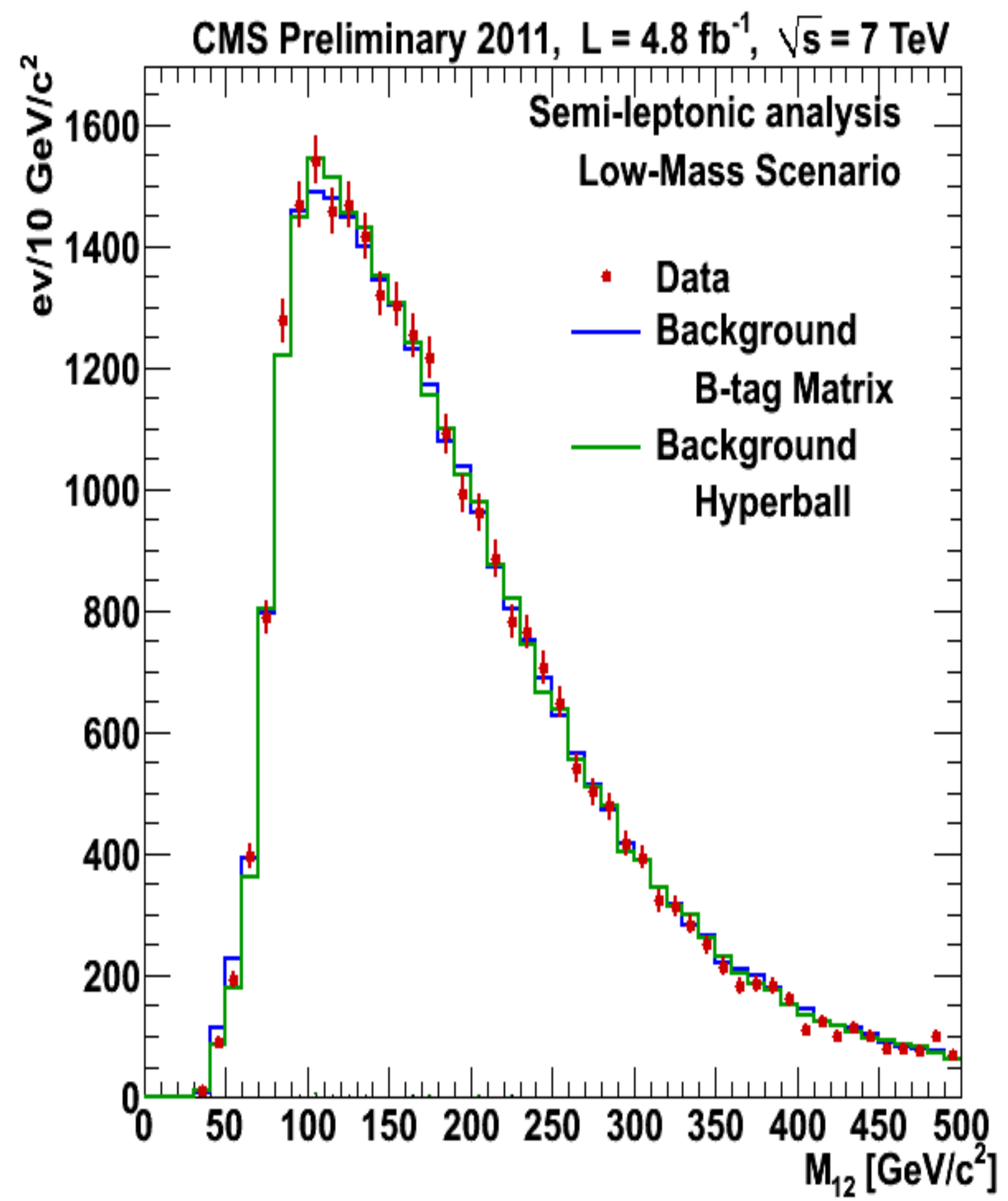


MSSM Φ → bb

Event selection	All-hadronic	Semi-leptonic
Triggers	≥ 2 or 3 Jets ≥ 2 b-tagged Jets	≥ 1 Muon ≥ 1 or 2 Jets ≥ 1 or 2 b-tagged Jets
Jets	≥ 3 Jets p_T^{1st} > 46 (60) GeV p_T^{2nd} > 38 (53) GeV p_T^{3rd} > 20 GeV 3 leading Jets b-tagged	≥ 3 Jets $p_T^{1st,2nd}$ > 30 GeV p_T^{3rd} > 20 GeV 3 leading Jets b-tagged
Muon	–	≥ 1 Muon, p_T > 15 GeV

MSSM $\Phi \to bb$ (semileptonic)

- Background estimation – semi-leptonic
- BTagMatrix
  - B-tag probability matrices (*bbj* sample).
  - B-tag eff from MC, flavour fractions from data
  - $F(x; bbb) = F(x; bbj) \otimes P^{3^{rd}\,jet}_{b-tag}(\ldots)$
- Hyperball (nearest neighbour)
  - Sample *bjj* (excl *bbj* sample)
  - Compute the fraction *f* of similar events passing full selection.
  - $F(x; bbb) = F(x; bjj) \otimes f$
- The two methods are combined
  - Use bin-per-bin weighted average of B-tag Matrix and Hyperball prediction to get background shape.



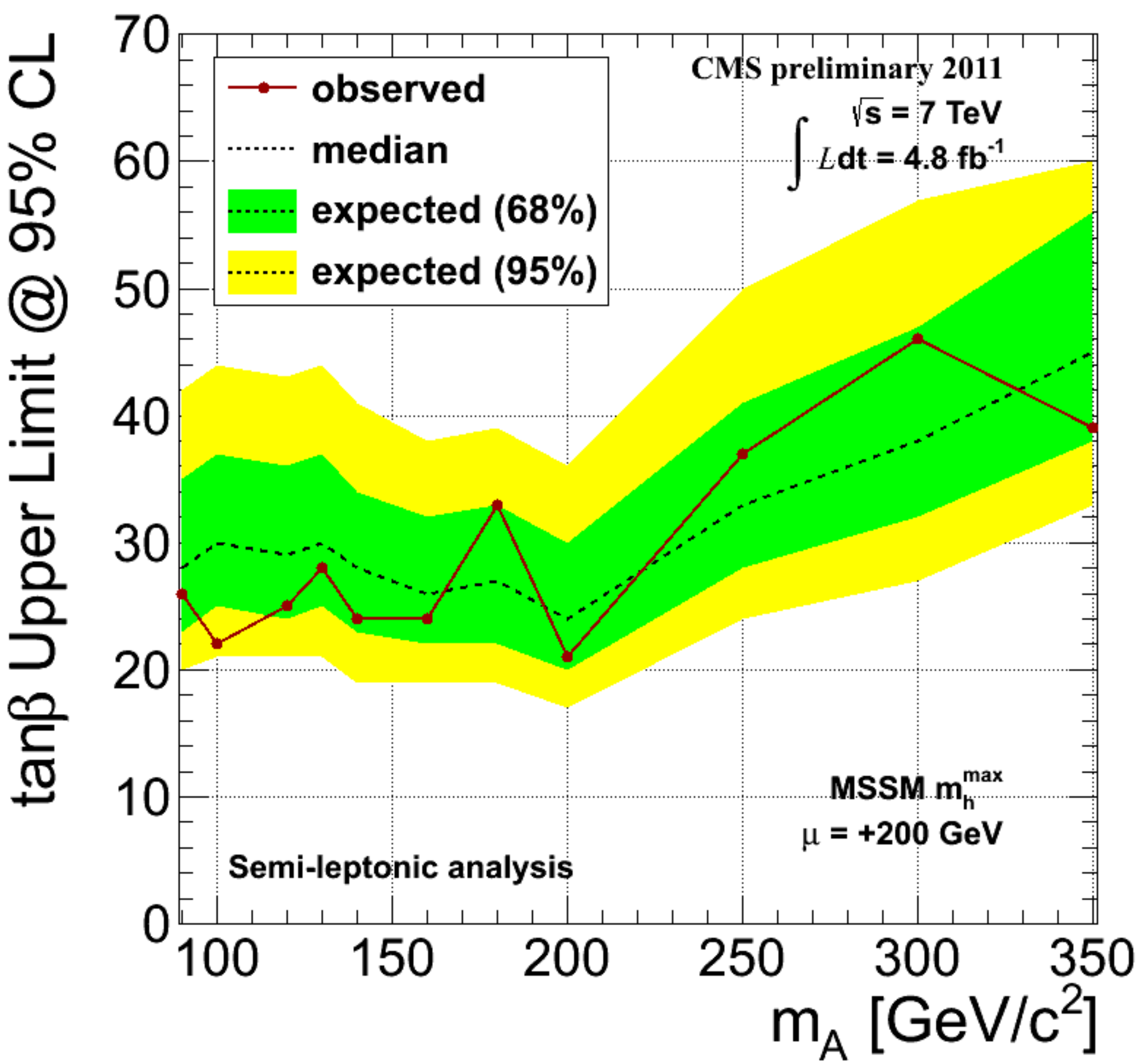
MSSM ϕ → bb Systematics

- Systematic uncertainties on the signal yield

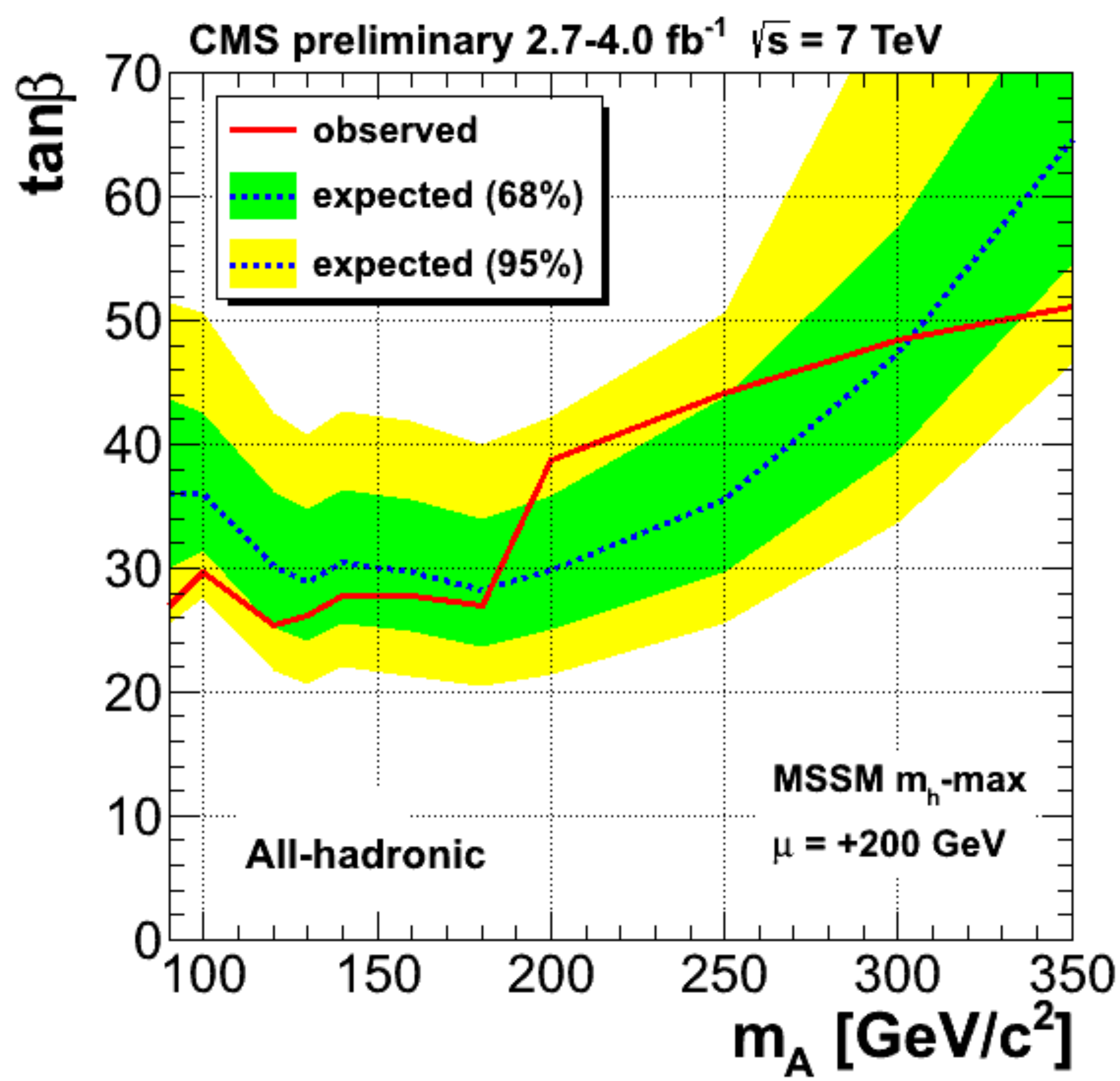
Source	All-hadronic	Semileptonic	Type
Trigger efficiency	10%	3 – 5%	rate
Online b-tagging efficiency	32%	–	rate
Offline b-tagging efficiency	10–13%†	12%	shape/rate
b-tagging efficiency dependence on topology	6%	–	rate
Jet energy scale	1.4–6.8%	3.1%	shape/rate
Jet energy resolution	0.6–1.3%	1.9%	shape/rate
Muon momentum scale and resolution	–	1%	rate
Signal Monte Carlo statistics	1.1–2.6%		rate
Integrated luminosity	2.2%		rate
PDF and α_s uncertainties	3–6%*	2.7–4.7%*	rate
Factorization and renormalization QCD scale	6–28%*		rate
Underlying event and parton showering	4%*		rate

MSSM $\phi \rightarrow bb$ Limits

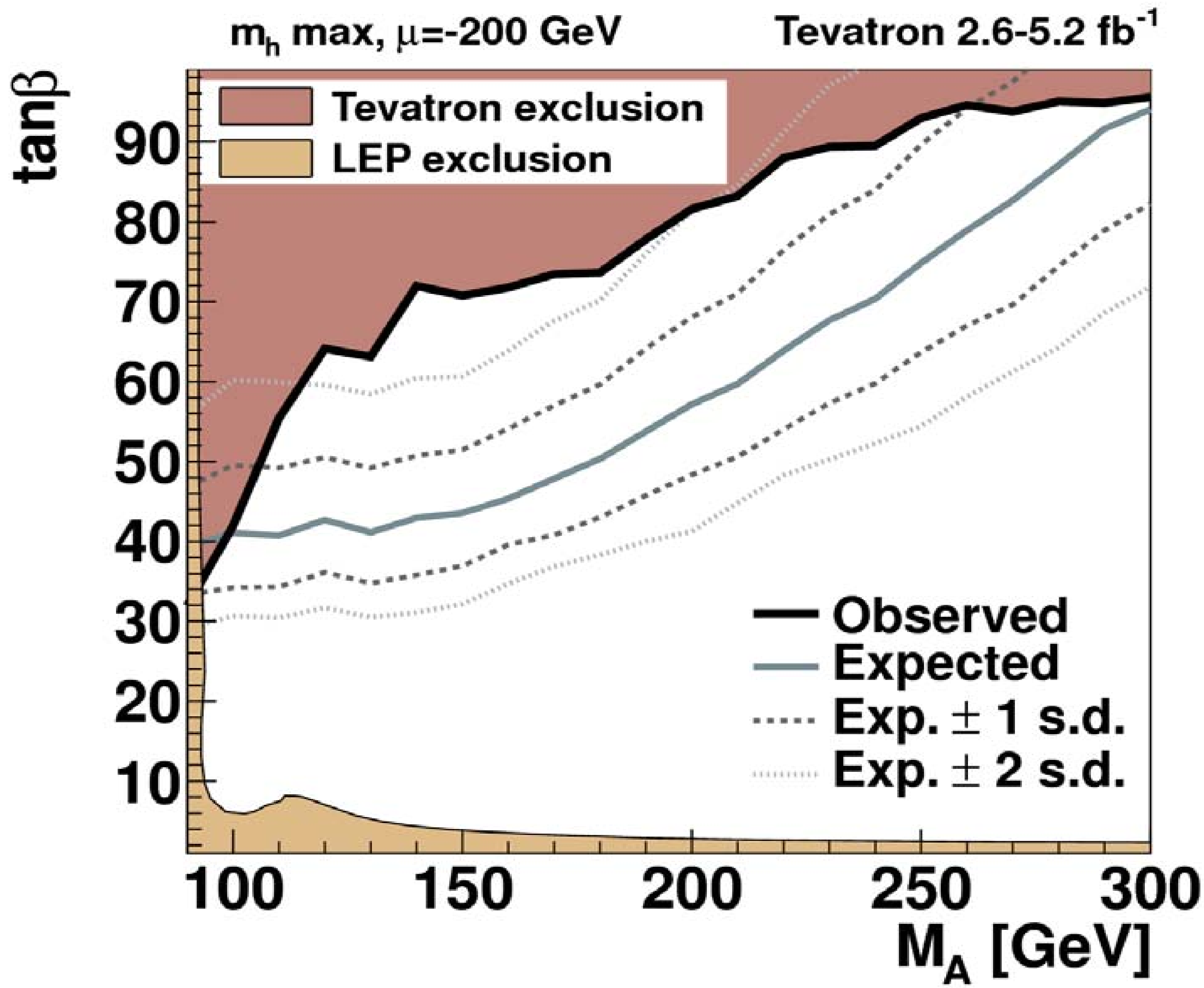
Semileptonic



All-hadronic

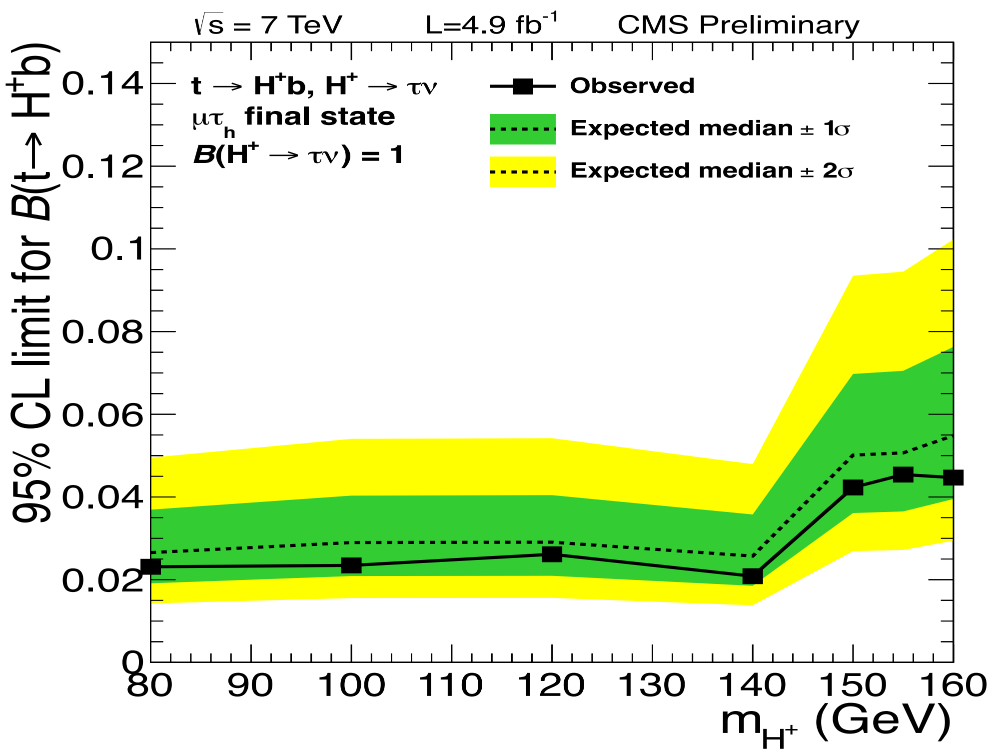


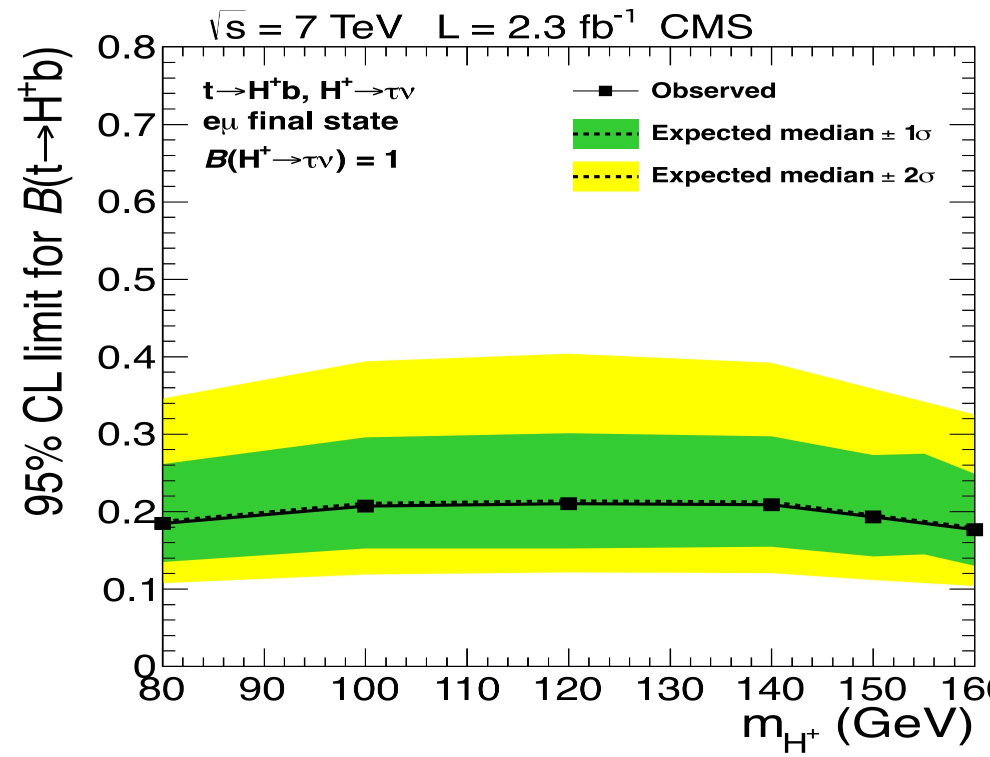
$\phi \to bb$ Tevatron

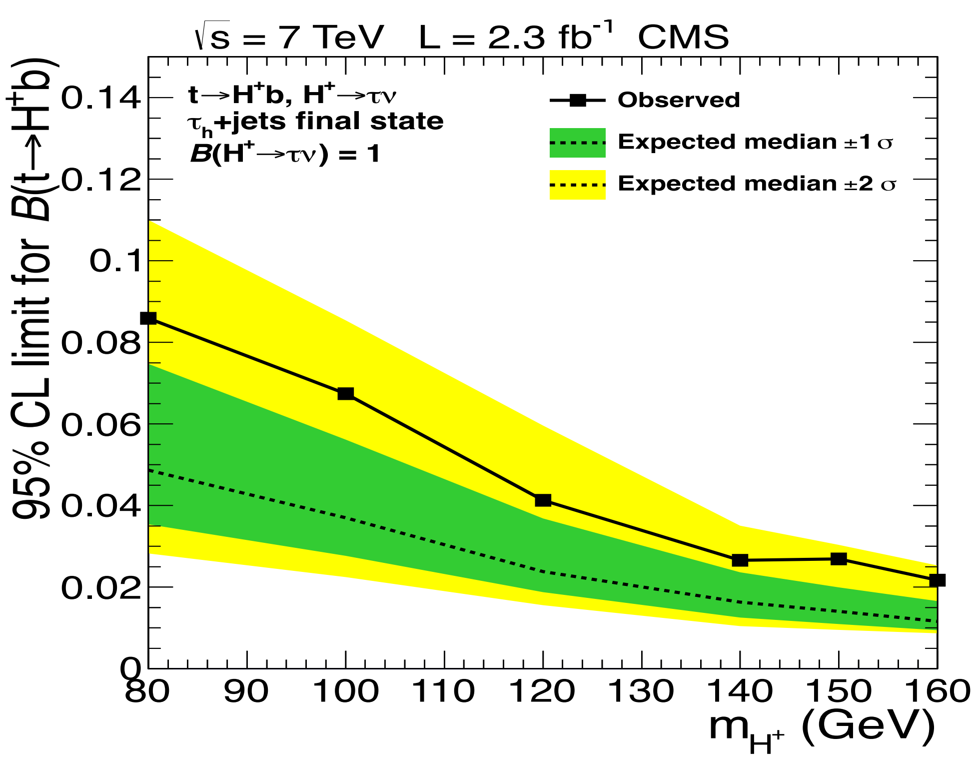


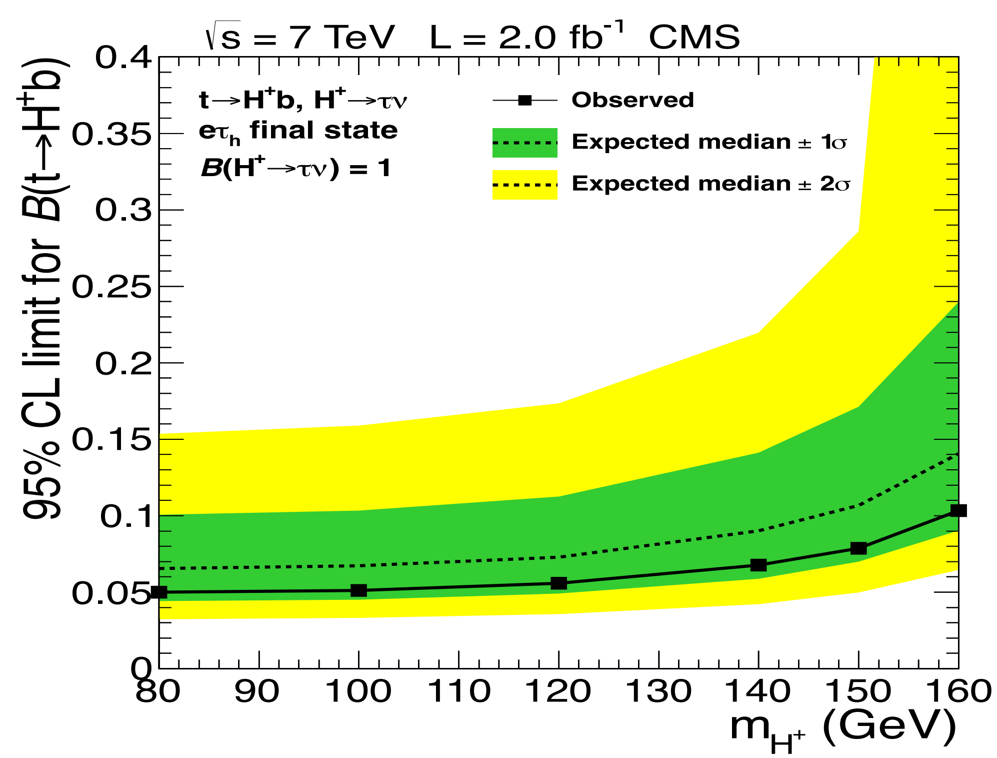
Light H± search

Limits individual channels



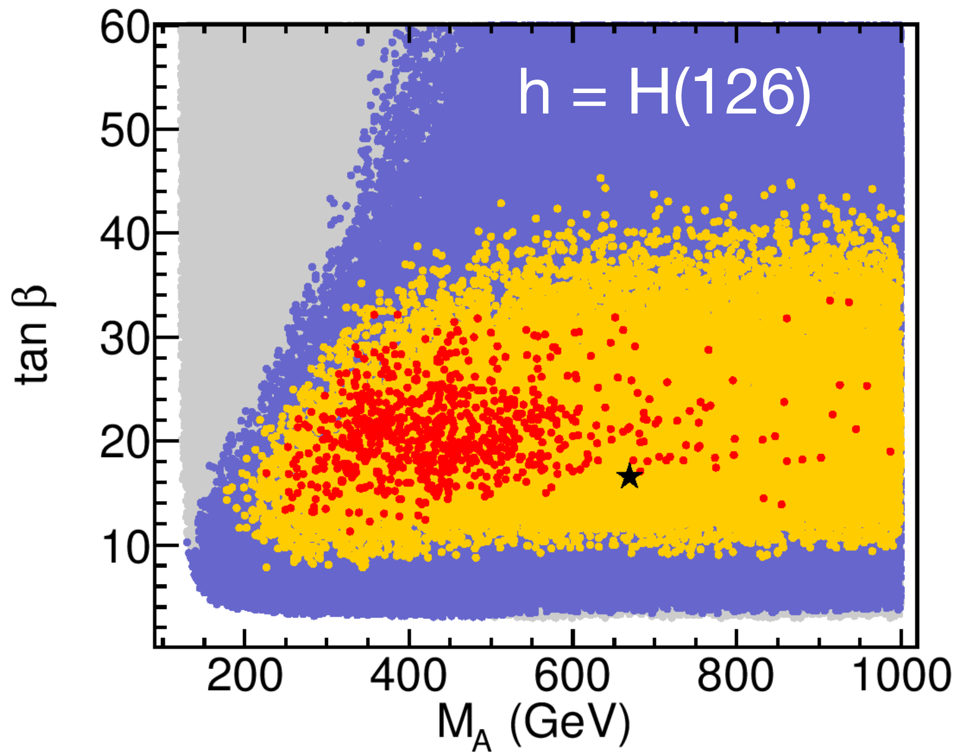


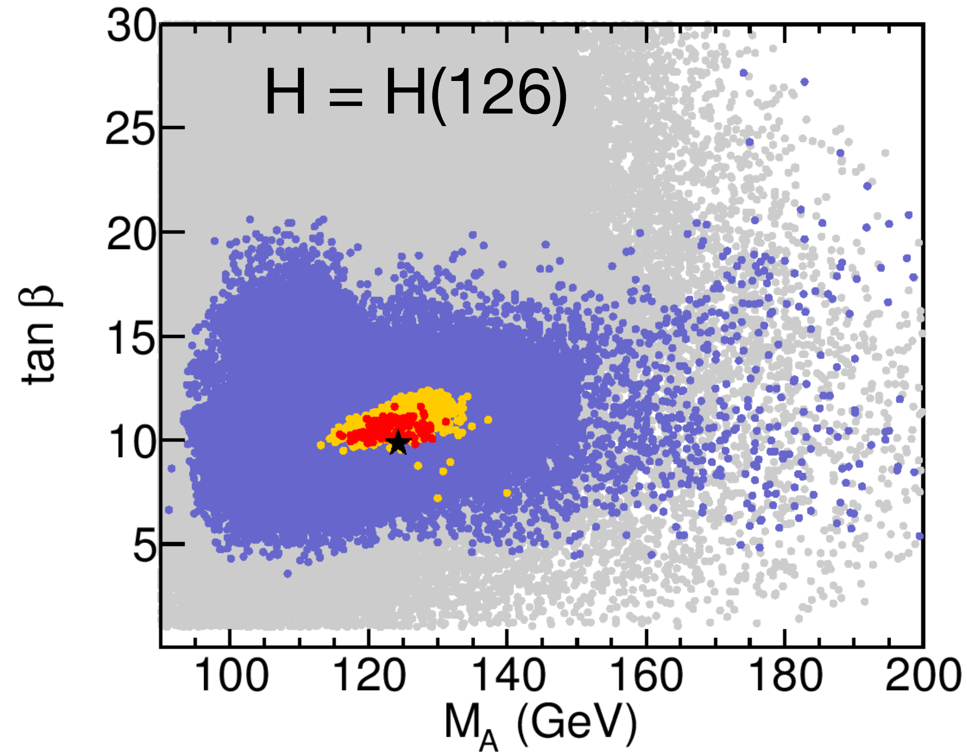




MSSM & the H(126) state

- Is the observed H(126) state consistent with the MSSM?
- Exemplary study: P. Bechtle et al; Eur. Phys. J. C 73:2354 (2013)
  - Phenomenological MSSM with seven free parameters (pMSSM-7).
  - Fit various rates of cross section times BR measured at LHC and Tevatron, as well as low energy measurements under hypotheses: “light”, h = H(126); “heavy”, H = H(126)

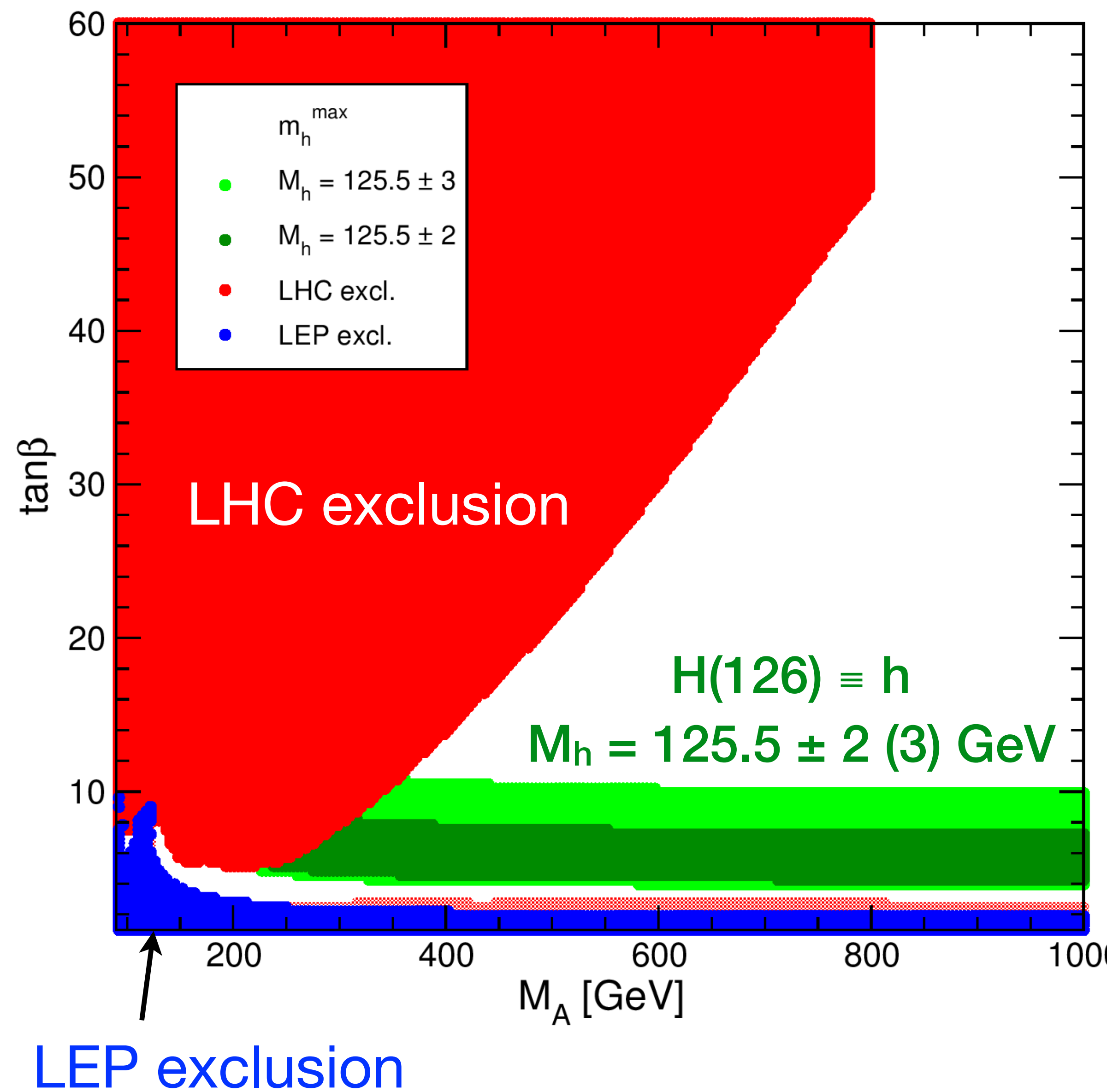




  - MSSM and SM fit well the data. MSSM “light” hypothesis fits better the data than the “heavy” hypothesis.
  - Important to search at large Higgs masses at large tan β.

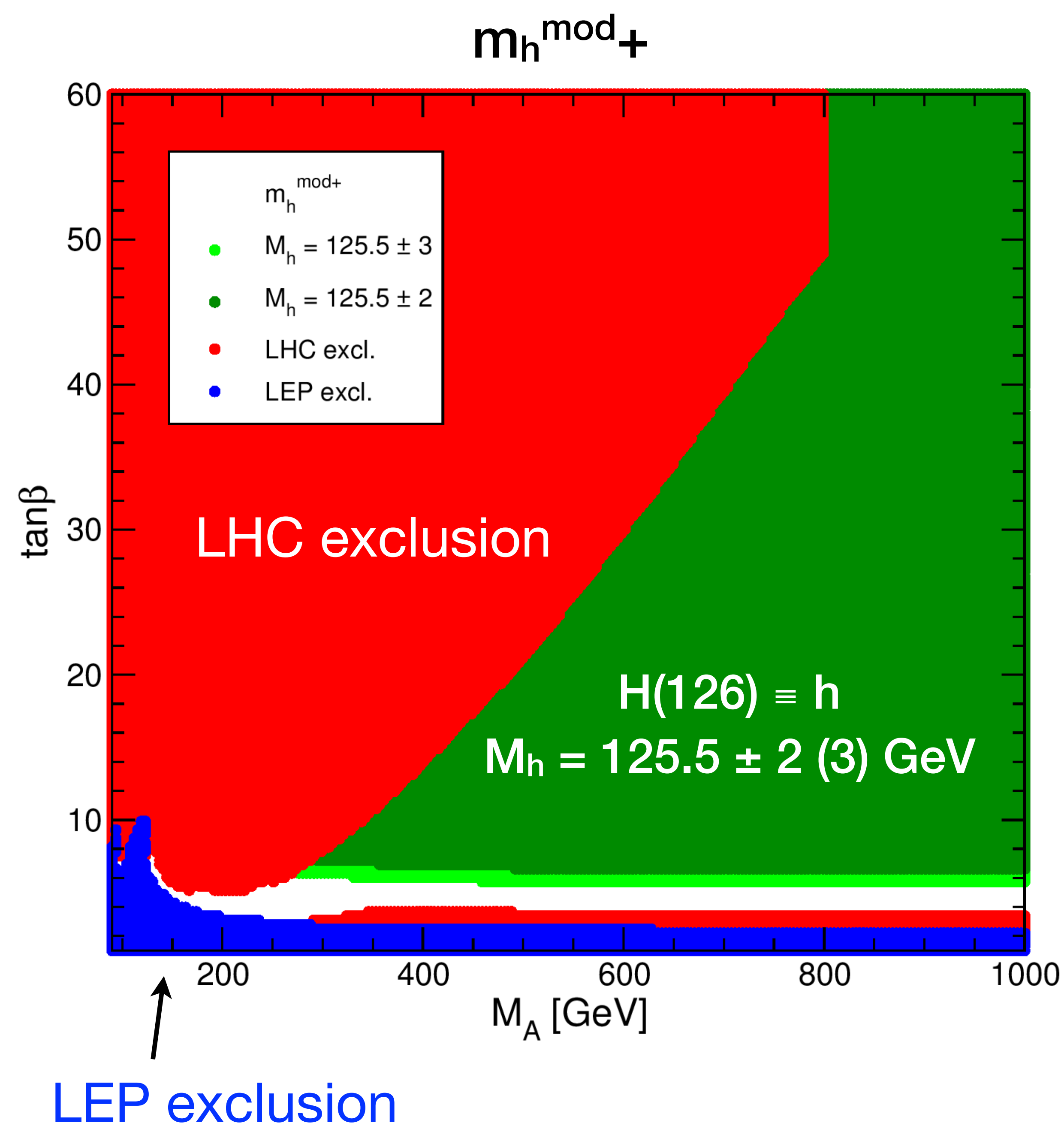
MSSM Benchmark Scenarios after the Discovery of a Higgs-like Particle

- M. Carena et al, arXiv:1302.7033
- **mhmax scenario**:
  - compatibility with the new H(126) observed state achieved only in a relatively small region of the parameter space.
  - nevertheless still useful
    - conservative lower bounds for tree level parameters of Higgs sector
    - widely used in the past



MSSM Benchmark Scenarios after the Discovery of a Higgs-like Particle

- M. Carena et al, arXiv:1302.7033
- **m_h^{mod} scenarios**:
  - proposal follow m_h^{max} design: maximise the lightest CP-even Higgs mass at large values of M_A for a given value of tanβ
  - reduce $|X_t/M_{SUSY}|$ that gives rise to the largest positive contribution to M_h from the radiative corrections
  - two scenarios possible: different signs and values for X_t/M_{SUSY}
  - (+) sign: better agreement with (g-2) measurements
  - (–) sign: better agreement with BR(b → sγ) measurements



MSSM Benchmark Scenarios after the Discovery of a Higgs-like Particle

- M. Carena et al, arXiv:1302.7033
- **light stop scenario**
  - gives sizeable contribution to the gg → h production rate
- **light stau scenario**
  - can enhance the Γ (h → γγ) significantly at high tan β
- **τ-phobic Higgs scenario**
  - produces sizeable variations of Γ (h → bb) and Γ (h → ττ) wrt SM values
- **low-M_H scenario**
  - identifies the observed H(126) state with the heavy CP-even MSSM Higgs boson with SM-like properties;
  - low value of the mass of the CP-odd Higgs boson;
  - mass of the light CP-even below LEP limits;
  - useful benchmark for light charged Higgs bosons.