Search for MSSM Higgs decaying into b quarks with CMS

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Outline

1. Motivation
2. The all-hadronic $b\Phi \rightarrow b(bb)$ analysis
3. The semileptonic $b\Phi \rightarrow b(bb)$ analysis
4. Results
5. Summary

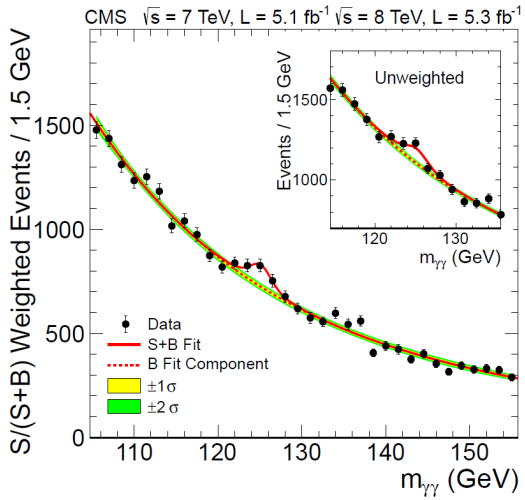
Neutral MSSM Higgs boson production

→ A Higgs boson has been observed

→ Question now is the structure of the Higgs sector

→ Are there any additional heavy Higgs particles?

→ One possible extension of the Standard Model: Supersymmetry

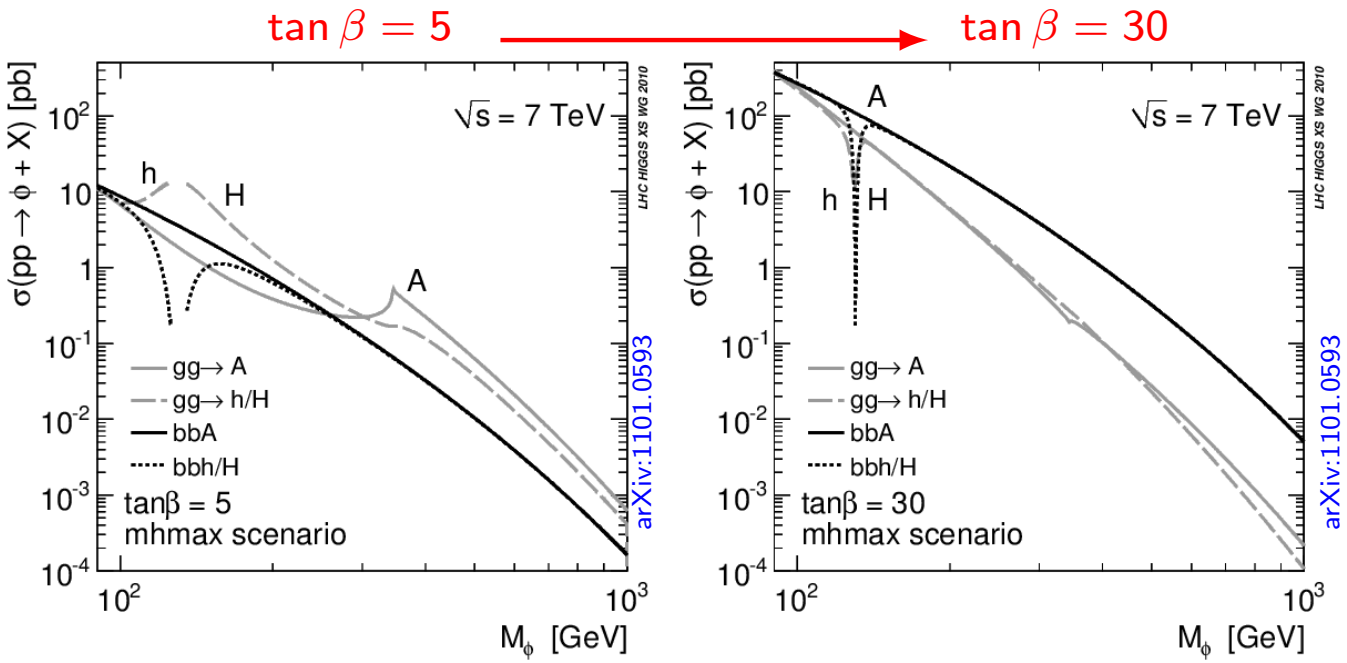


arXiv:1207.7235

Minimal Supersymmetric Standard Model (MSSM)

- Two scalar Higgs doublets, five particles
  - Three neutral (h, H, A)
  - Two charged ($H^{\pm}$)
- Higgs sector at tree level defined by
  1. Mass of pseudoscalar Higgs, M_A
  2. Ratio of vacuum expectation values, $\tan\beta$
- If MSSM is realised in nature → associate the boson observed at 126 GeV with one of the CP-even MSSM Higgs bosons
- Both the mass and the production rates of the observed boson in the various channels imply constraints in the MSSM parameter space

Neutral MSSM Higgs boson

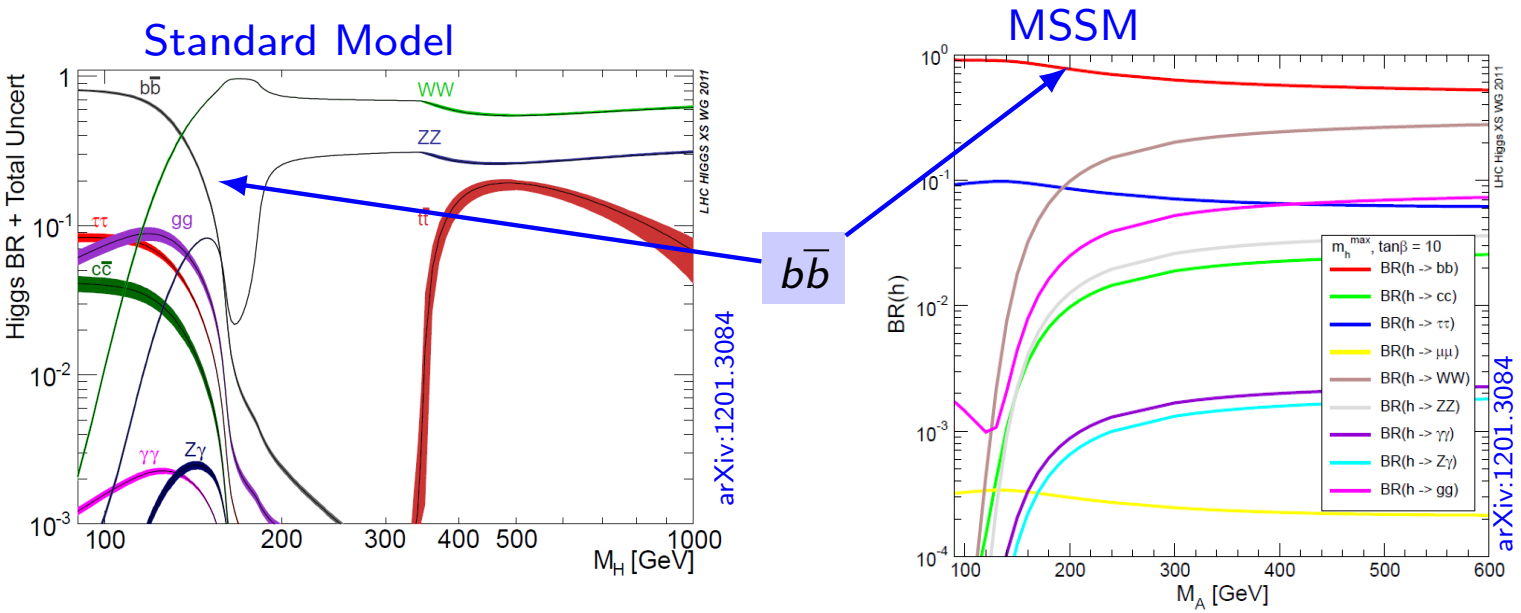


Production at the LHC:

- For relatively large values of $\tan\beta$
  - Higgs couplings to *u*-type fermions suppressed w.r.t. Standard Model
  - Couplings to *d*-type fermions enhanced by $\tan\beta$
  - Mass degeneration within experimental resolution *(except for decay into $\mu^+\mu^-$)*

  $\rightarrow$ Enhancement of Higgs production in association with *b* quarks by $\approx 2\tan^2\beta$

Higgs boson decay

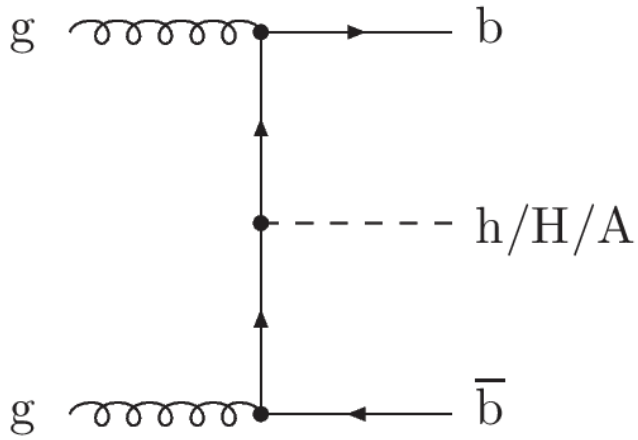


- Neutral MSSM Higgs decays dominantly to
  1. $b\bar{b} \rightarrow \sim 90\%$
- Unlike in the SM, also important contributions at very high masses!

MSSM $\Phi \to bb$ searches

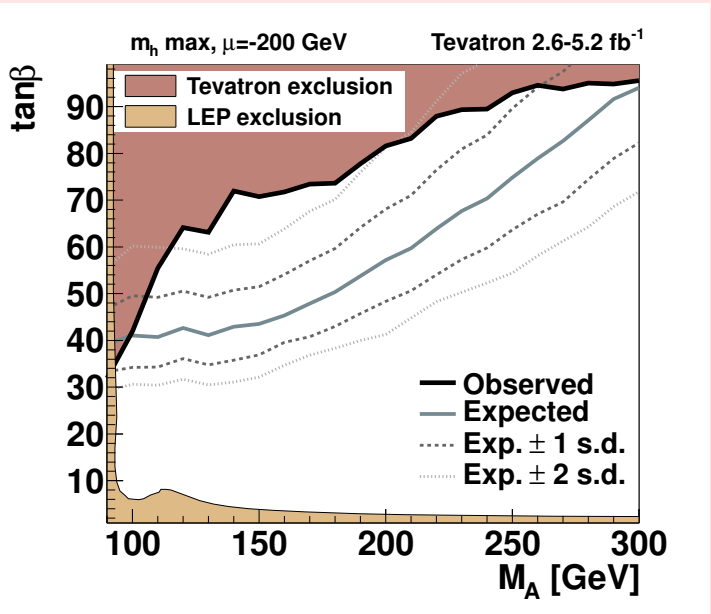
Signature:

- Search for Higgs decaying to a pair of b quarks + at least one additional b quark
- Signal would show up as a peak in the invariant mass distribution of the two leading jets
- Very large background, dominated by QCD multi-jet events



2011 CDF+D0 results (arXiv:1207.2757):

- $\sim 2\sigma$ excess around $M_\Phi \sim [120, 150]\,\mathrm{GeV}$



MSSM $\Phi \rightarrow bb$ searches at CMS

→ **Novel search at the LHC**

→ Has not been looked at before at CMS!

Searched for with CMS using two complementary approaches:

1. All-hadronic: Final state characterized purely by jets
2. Semi-leptonic: Requirement of additional non-isolated muon

All-hadronic $b\Phi \rightarrow b(bb)$ analysis

Challenging trigger due to large hadronic interaction rate:

- Dedicated trigger developed
- Requirement of at least 2 to 3 centrally ($|\eta| < 2.6$) produced jets
- Online b-tagging: Select ≥ 2 b-tagged jets based on the impact parameter significance of 2^{nd} most significant track w.r.t. primary vertex

Two scenarios for Higgs mass hypothesis:

1. Low mass scenario ($M_\Phi < 180$ GeV): $P_T^{jet1(2,3)} > 46\ (38,\ 20)$ GeV
   $\rightarrow$ integrated luminosity: 2.7 fb^{-1} at $\sqrt{s} = 7$ TeV
2. Medium mass scenario ($M_\Phi \geq 180$ GeV): $P_T^{jet1(2,3)} > 60\ (53,\ 20)$ GeV
   $\rightarrow$ integrated luminosity: 4.0 fb^{-1} at $\sqrt{s} = 7$ TeV

Additional offline cuts:

- $\Delta R > 1$ between two leading jets to suppress background from gluon splitting
- Offline b tagging for selected jets using *"Combined Secondary Vertex"* algorithm

The analysis strategy

Signature of the signal:

Events with at least three b-tagged jets (Triple b-tag sample)

Background:

- Dominated by QCD multi-jet production with three b jets and two b jets + one misidentified c or light-flavour jet
- Other backgrounds such as $t\bar{t}$ and Z + jets found to be small
- Analysis employs a data-driven technique to model the background
  - $\rightarrow$ Construction of background templates using events with two b-tagged jets (Double b-tag sample)

Background model in data

Construction of background templates in double b-tag sample similar to CDF analysis:

- Require at least 3 jets (sorted in p_T)
- Assign flavour assumption of b, c, udsg for untagged jet **X**

  → **bbX**, **bXb**, **Xbb**

→ Nine different templates

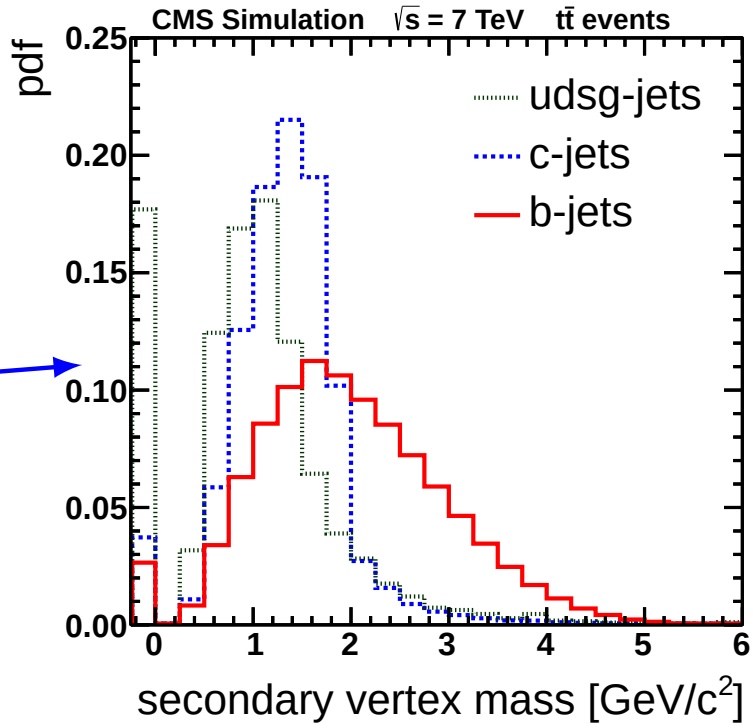
- Apply probability of the assumed flavour to be identified as b jet to the events
  - Probabilities extracted from background MC

- Templates have been constructed for the invariant dijet mass, M_{12}, distribution

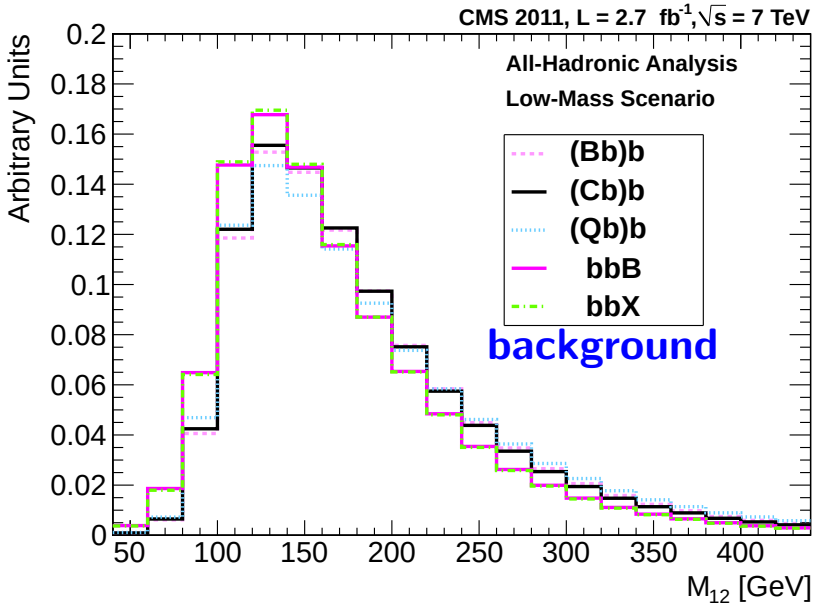
→ Need additional handle on the flavour composition of the events

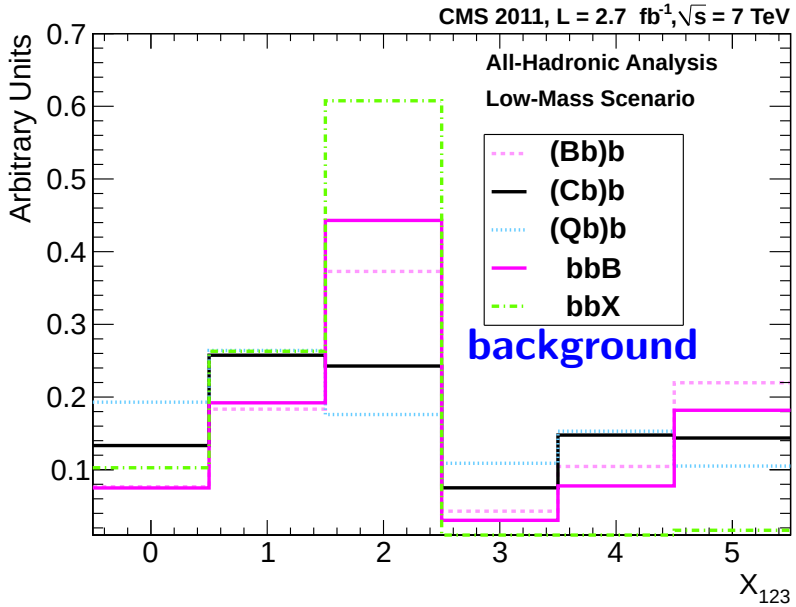
→ Secondary vertex mass sensitive to the flavour of jets

→ Construct "event btag", X_{123}



Background and signal templates



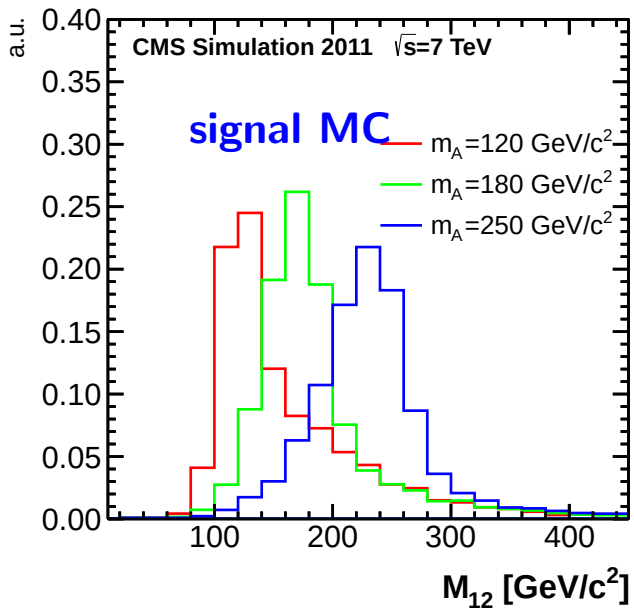


- Similar Background templates are merged :

$\rightarrow$ (Qb)b=Qbb+bQb

$\rightarrow$ Reduction from 9 to 5 templates!

- X_{123} helps to distinguish e.g. (Bb)b and (Qb)b
- Signal templates extracted from MC



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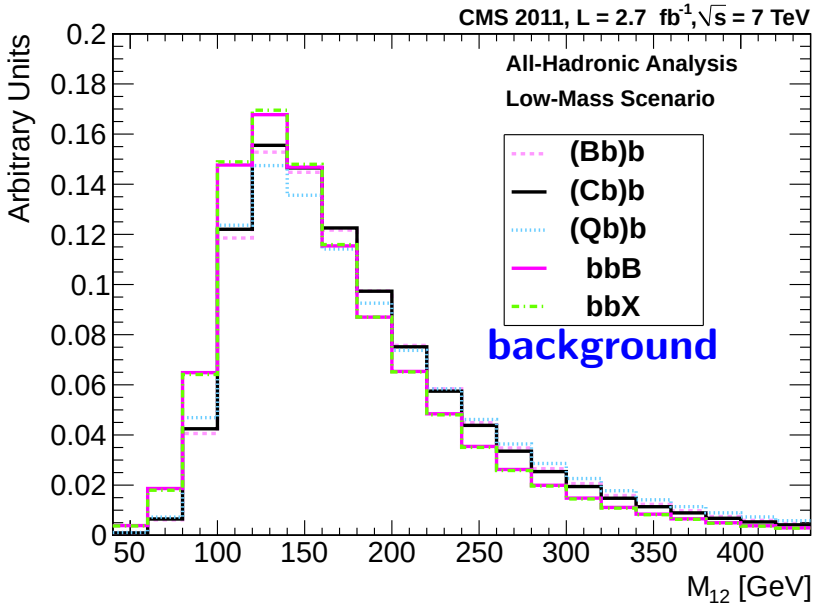

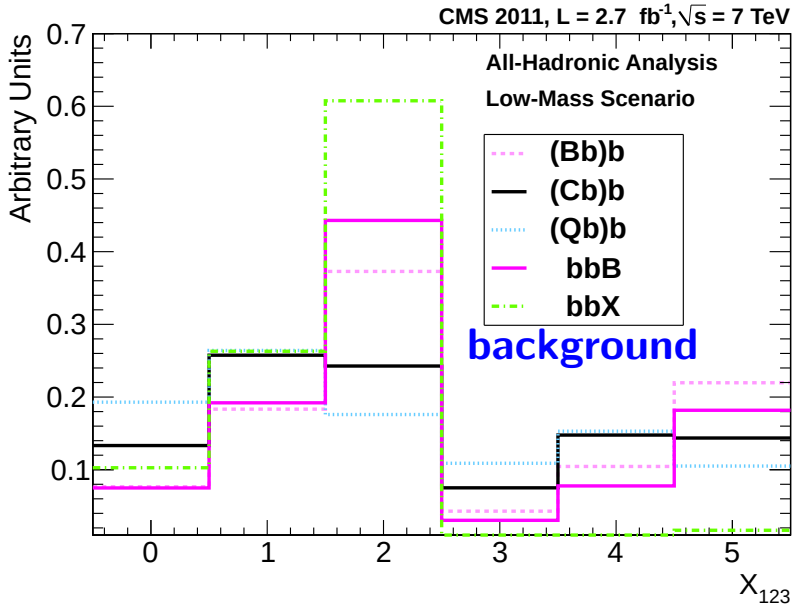

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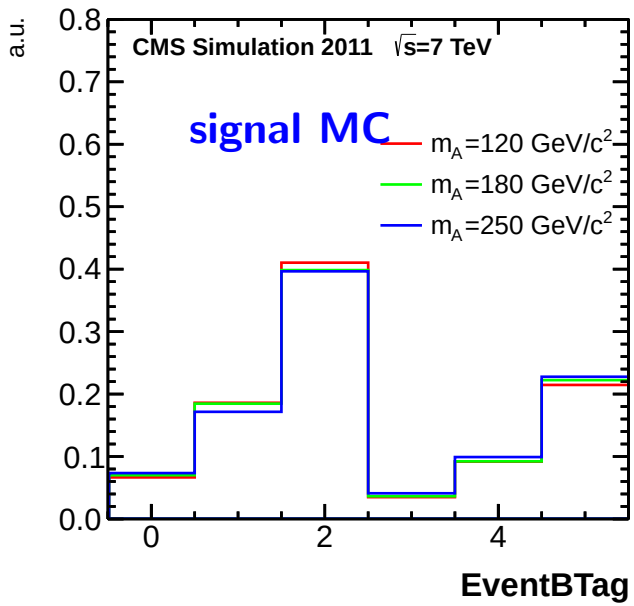
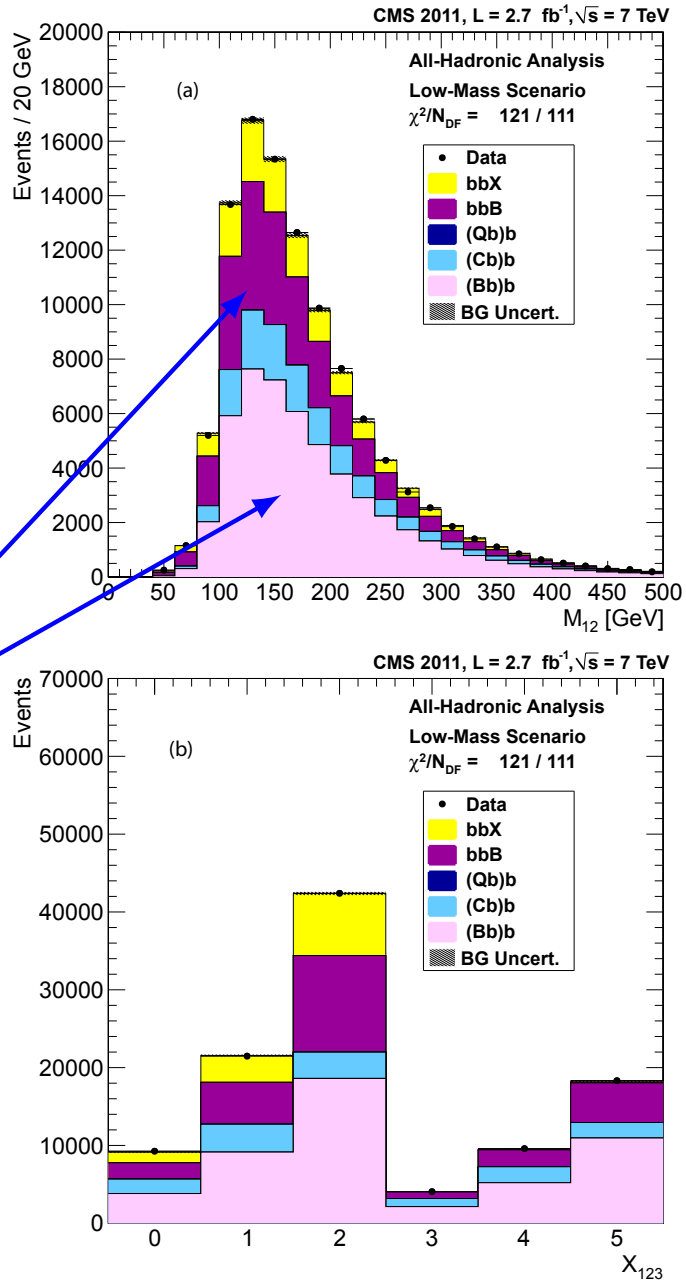


Background-only fit in signal region

Low mass scenario:

- Fit of linear combination of background templates in the signal region (triple b-tag sample)
- Good agreement of fit result with the data
- Background mainly ($\sim 70\%$) composed of three b jets
  (similar to MC prediction)
- No indication of an excess

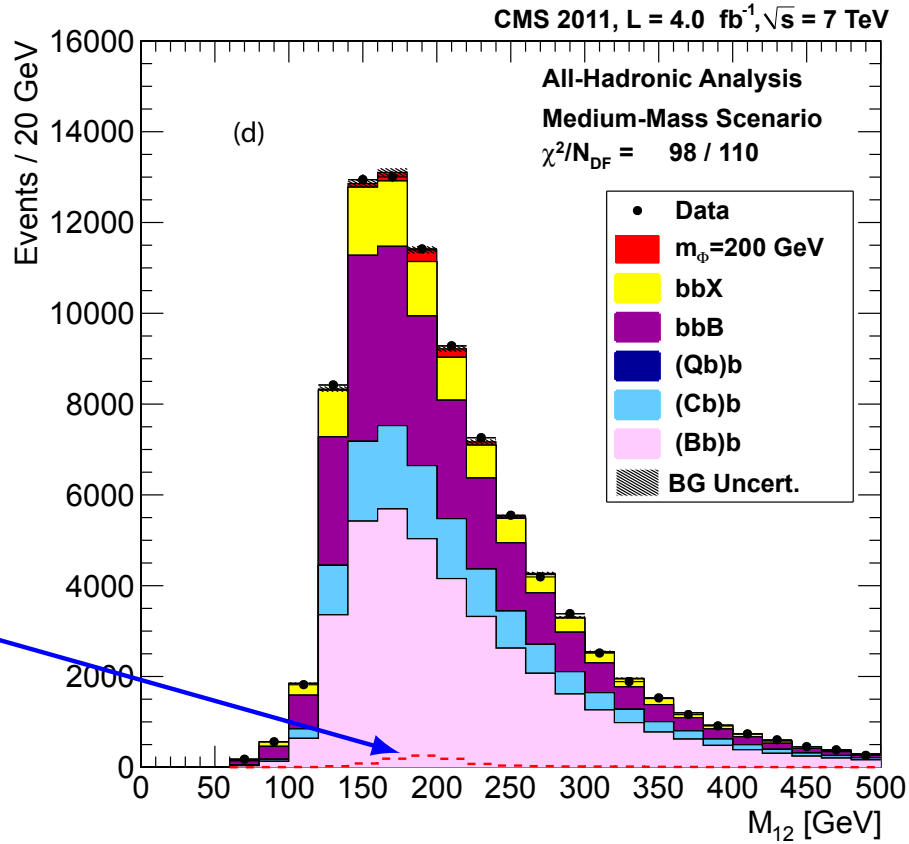


Background+signal fit in signal region

Medium mass scenario:

- Fit of linear combination of background + signal templates in the signal region (triple b-tag sample)
- Performed for Higgs masses from 90 to 350 GeV
- Shown: $M_\Phi = 200\ \mathrm{GeV}$
  - Good fit quality
  - Largest upward fluctuation: $\sim 1.4\sigma$

$\rightarrow$ No significant deviation from background observed



Semi-leptonic $b\Phi \rightarrow b(bb)$ analysis

- Sensitive to semileptonic decays of at least one b quark in the muon channel

Trigger:

- Similar trigger requirements as in all-hadronic analysis, but
  - requirement of a muon with $p_T > 12$ GeV,
  - lower jet p_T thresholds possible due to muon requirement

Offline selection cuts:

- Muon with $p_T > 15$ GeV associated to one of the two leading jets
- At least three centrally produced jets with $p_T^{\mathrm{jet}1,2(3)} > 30$ (20) GeV
- $\Delta R > 1$ between any pair of jet
- Offline b tagging for selected jets using *"Combined Secondary Vertex"* algorithm

$\rightarrow$ Data sample with integrated luminosity of 4.8 fb^{-1}

Background in semi-leptonic $b\Phi \rightarrow b(bb)$ analysis

- Application of two different methods for the data-driven background estimation

"B-Tag Matrix method":

$\rightarrow$ Utilisation of event sample in which the two leading jets are b-tagged

$\rightarrow$ Probability of third jet to be b-tagged: $P_b = \epsilon_b \cdot f_b + \epsilon_c \cdot f_c + \epsilon_q \cdot (1 - f_b - f_c)$

$\rightarrow$ ϵ taken from simulation (corrected for data/MC differences)

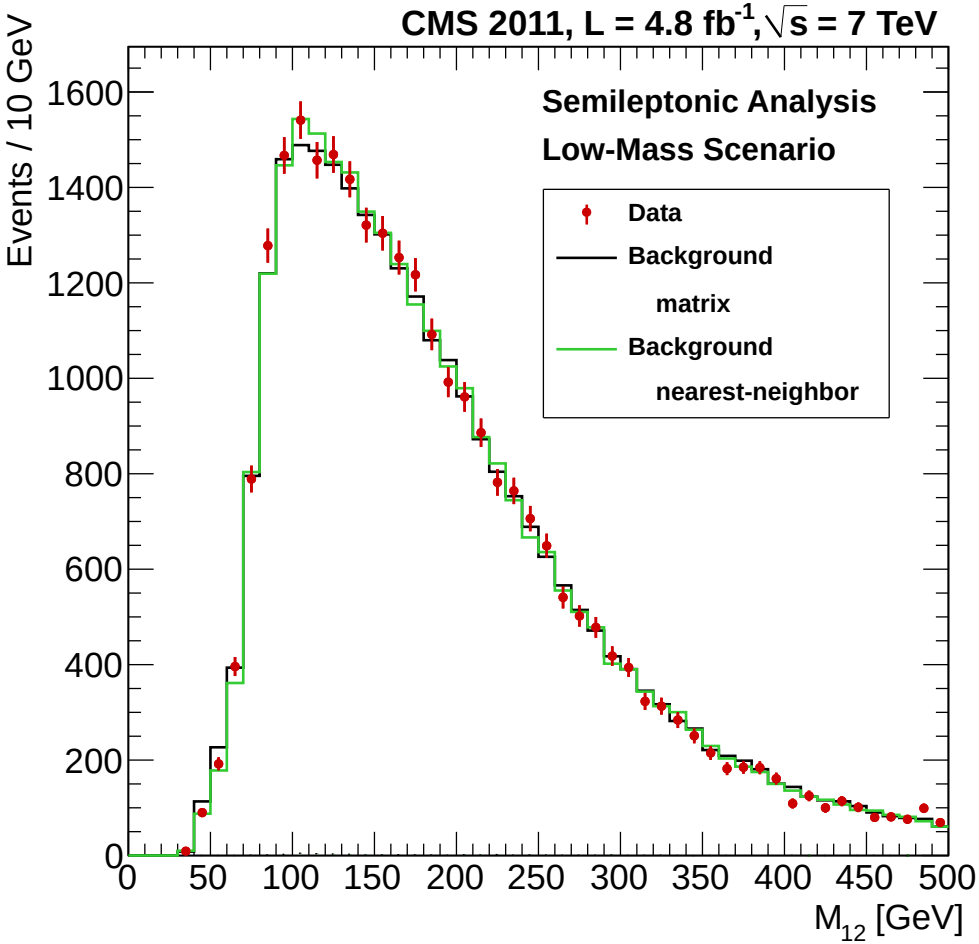
- Flavour fractions f extracted from data using a template fit to
  - Secondary vertex mass
  - Discriminant describing the probability that the associated tracks originate from the primary vertex

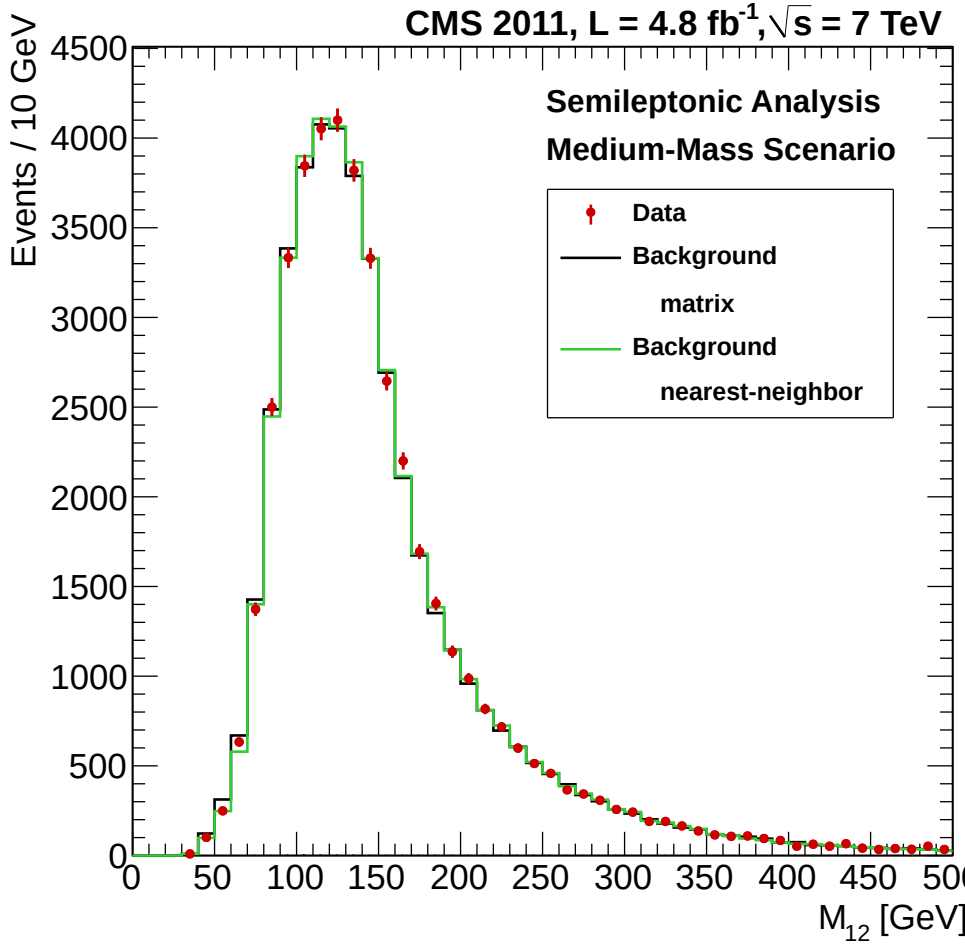
"Nearest-neighbour method":

- Usage of event sample in which the leading jet is b-tagged
- Methods estimates the probability that the three leading jets are b-tagged based on similar events in a multi-dimensional hyper-ellipsoid

Control region in semi-leptonic $b\Phi \rightarrow b(bb)$ analysis

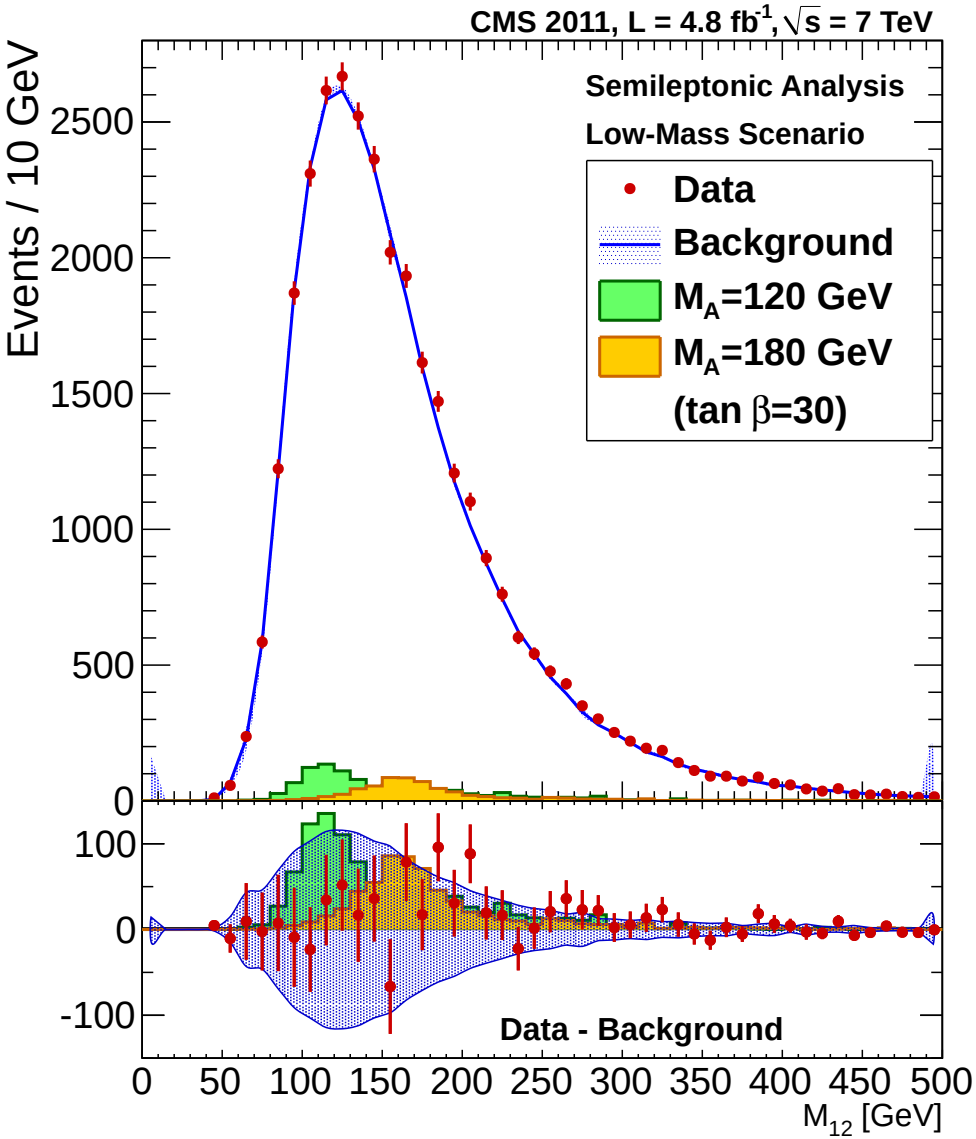
- Testing of background predictions in signal-depleted control region

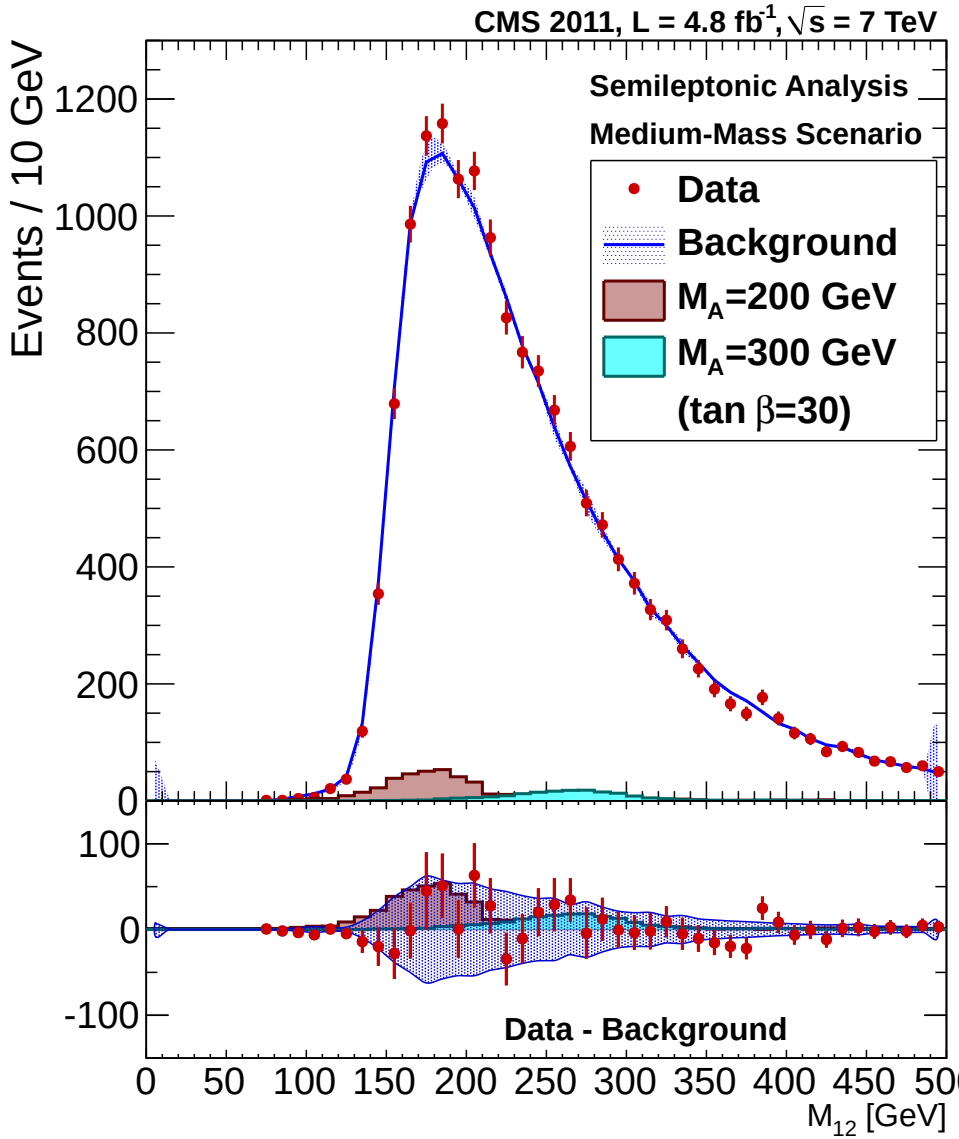




- Independent data sample used in the two methods $\rightarrow$ Combination of results

Signal region in semi-leptonic $b\Phi \rightarrow b(bb)$ analysis





- No indication of an excess

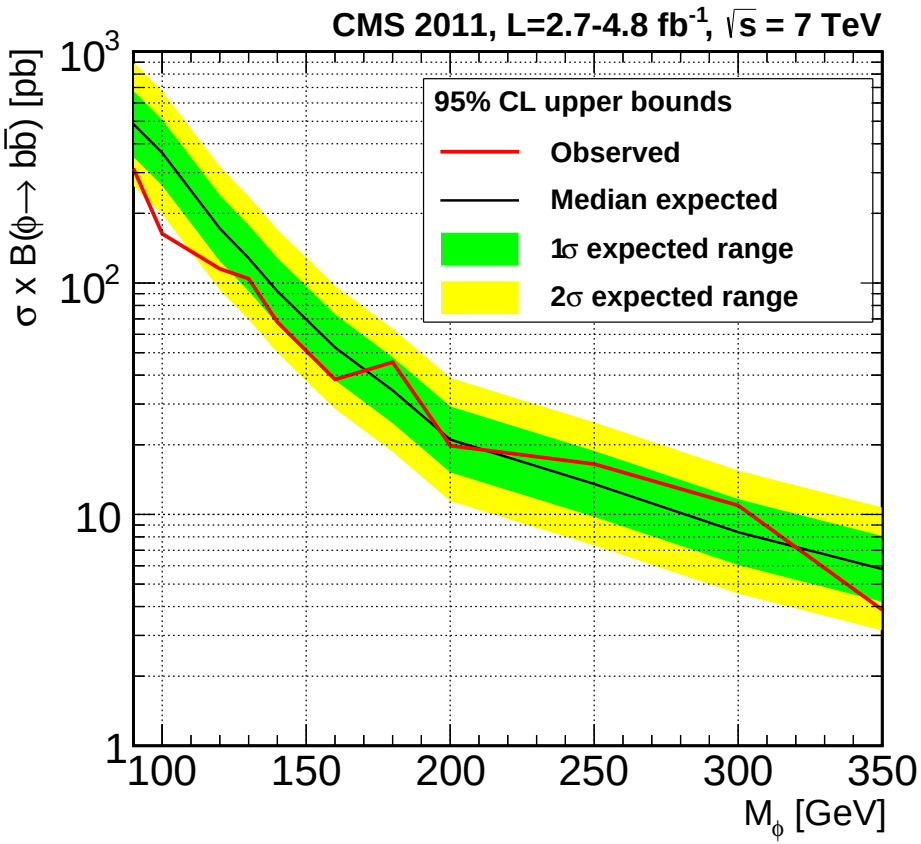
Combination and systematic uncertainties

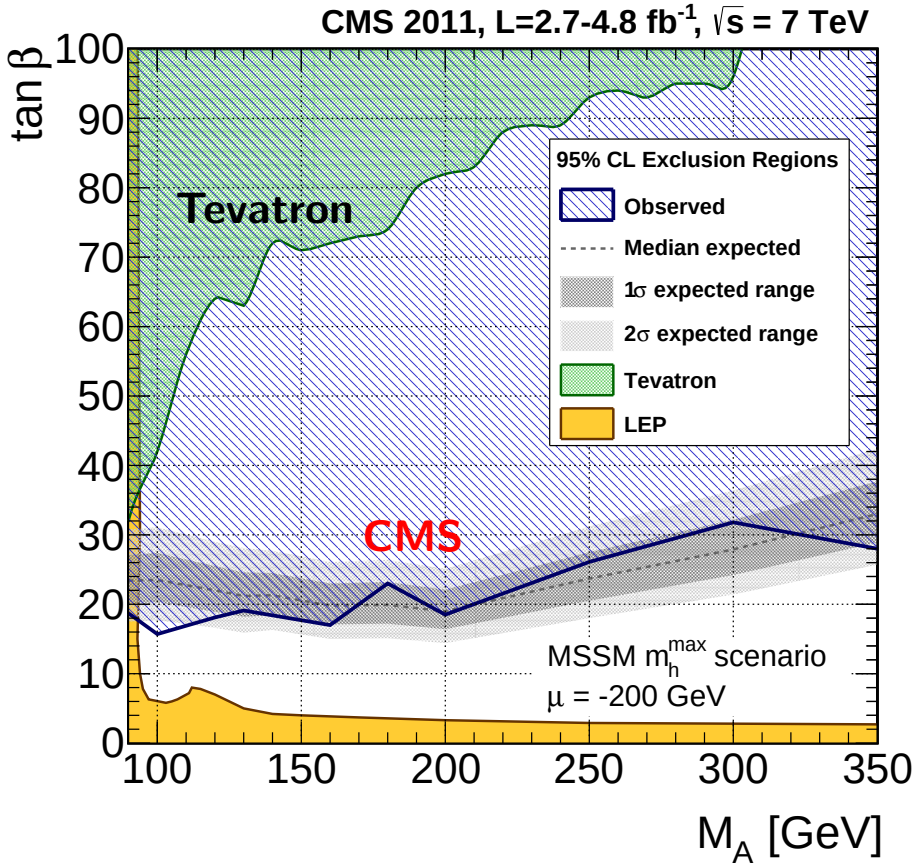
- Combination of results from semi-leptonic and all-hadronic analyses
  - Common events removed from all-hadronic analysis
  - Small statistical overlap of ($\sim 2.5\%$) due to requirement of additional muon and, hence, rather different selection cuts
  - Statistical and systematic uncertainties and correlations thoroughly treated

Source	all-hadronic	semi-leptonic	type
Trigger efficiency	10%	$3-5\%$	rate
Online b-tagging efficiency	32%	-	rate
b-tagging efficiency	$10-13\%^{\dagger}$	12%	shape/rate
b-tagging efficiency dependence on topology	6%	-	rate
Jet Energy Scale	$1.4-6.8\%$	$^{+2.5}_{-3.1}\%$	shape/rate
Jet Energy Resolution	$0.6-1.3\%$	1.9%	shape/rate
Muon momentum scale	-	0.2%	rate
Muon momentum resolution	-	0.6%	rate
Signal Monte Carlo statistics	$1.1-2.6\%$		rate
Integrated luminosity	2.2%		rate
PDF and α_s uncertainties*	$3-6\%$	$^{+(2.5-4.7)}_{-(2.7-4.4)}\%$	rate
Renormalisation and fragmentation QCD scale*	$6-28\%$		rate
Underlying event and parton showering*	4%		rate

Systematic uncertainties are implemented as nuisance parameters in the fit

95% CL upper limits





→ Observed combined limits statistically in agreement with expected limits!

→ In particular no confirmation of excess at low m_A as seen by CDF/D0

→ Combined result translated to the MSSM framework as functions of the mass of the pseudoscalar Higgs, m_A, and $\tan\beta$

→ CMS results more sensitive to MSSM parameter space

Summary

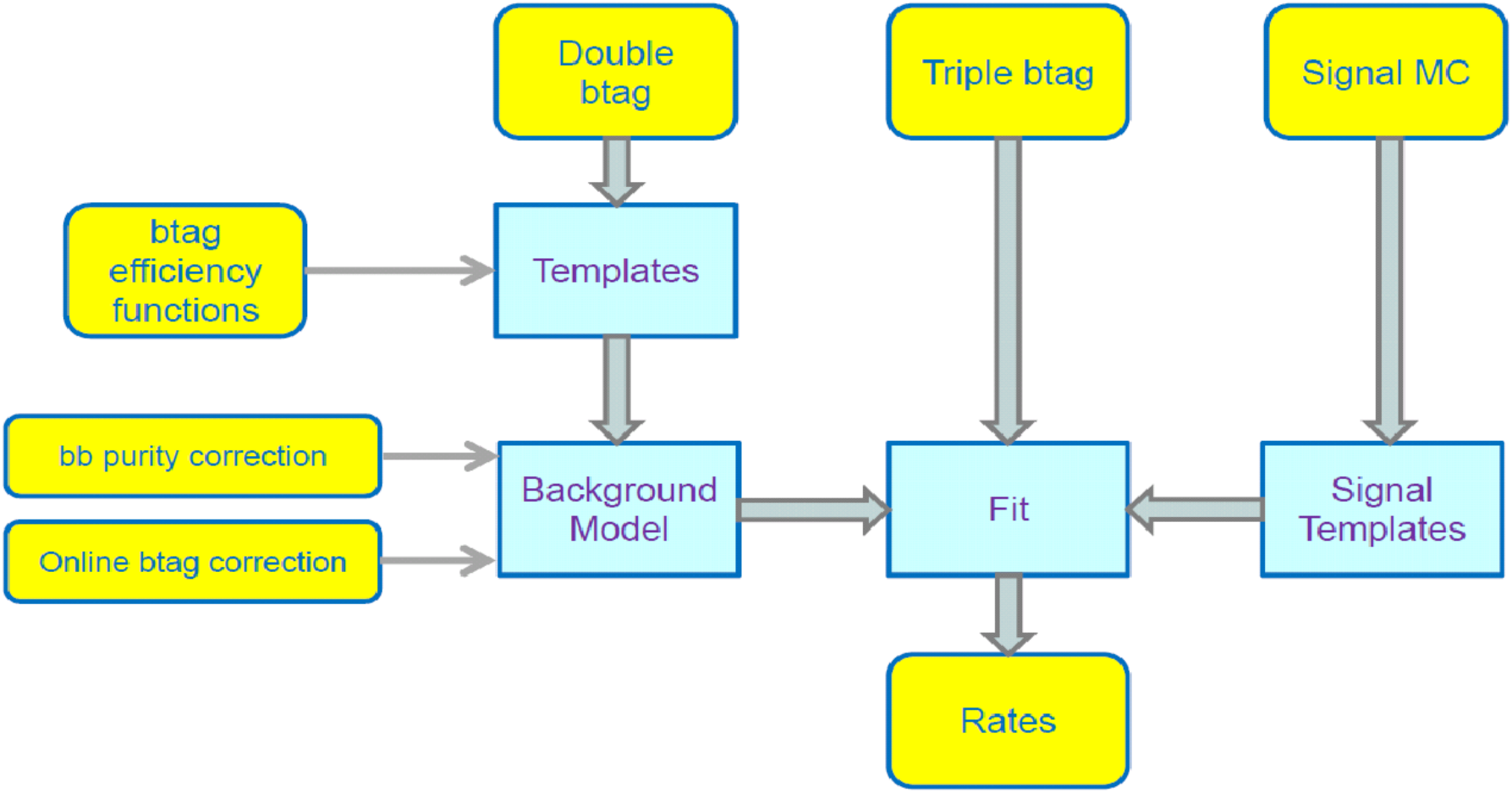
- A search for a MSSM Higgs boson decaying into a pair of b quarks and produced in association with at least one additional b quark was performed[a b]
- Measurement performed for the first time at CMS, novel at LHC
  - Paper published last month!
- No evidence for an excess of events was found
- The results from a all-hadronic and semi-leptonic analyses have been combined
- Limits as functions of $\tan\beta$ and m_A have been derived and found to exclude a considerable amount of the MSSM parameter space
- Currently most stringent MSSM Higgs limits in this decay channel

[a] CMS Collaboration, Phys. Lett. B 722, Issues 4-5 (2013) 207.

[b] `https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12033TWiki`

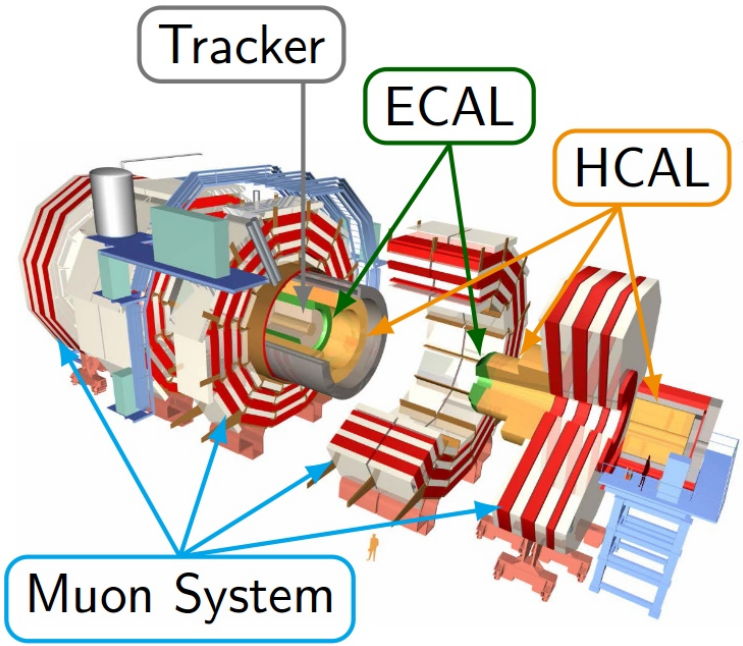
Backup

The analysis strategy



The CMS detector

- CMS is one of the large multi-purpose experiments at LHC



- Presented analysis extensively use in particular muon system, tracker, and calorimeter
- Application of particle flow techniques for optimised reconstruction of all particles in the event
  - Extensive combination of all CMS sub-detector systems

Background model in data

Construction of background templates in double b-tag sample:

- Require at least 3 jets (sorted in p_T)
- Assign flavour assumption of b, c, udsg for untagged jet **X**

  → **bbX**, **bXb**, **Xbb**

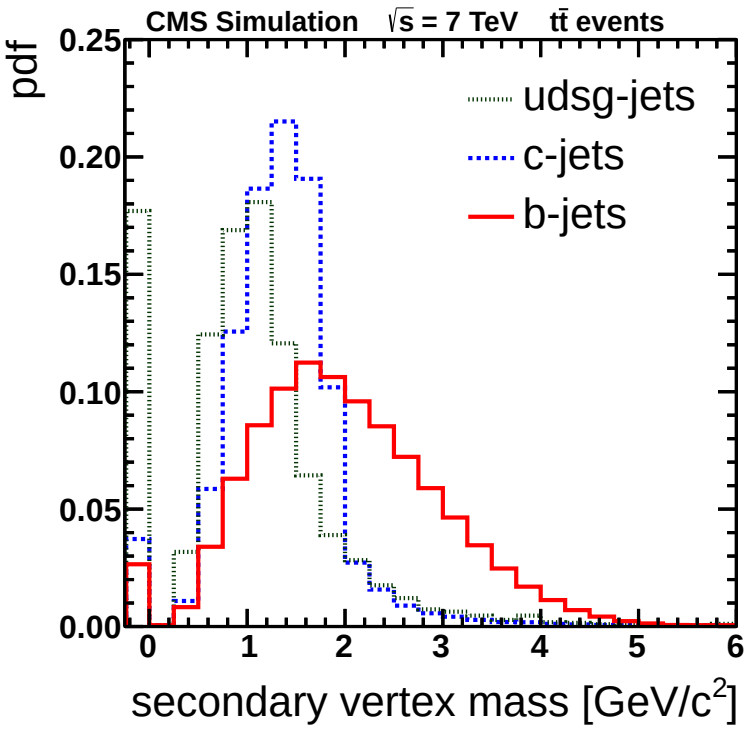
→ Nine different templates

- Apply probability of the assumed flavour to be identified as b jet to the events

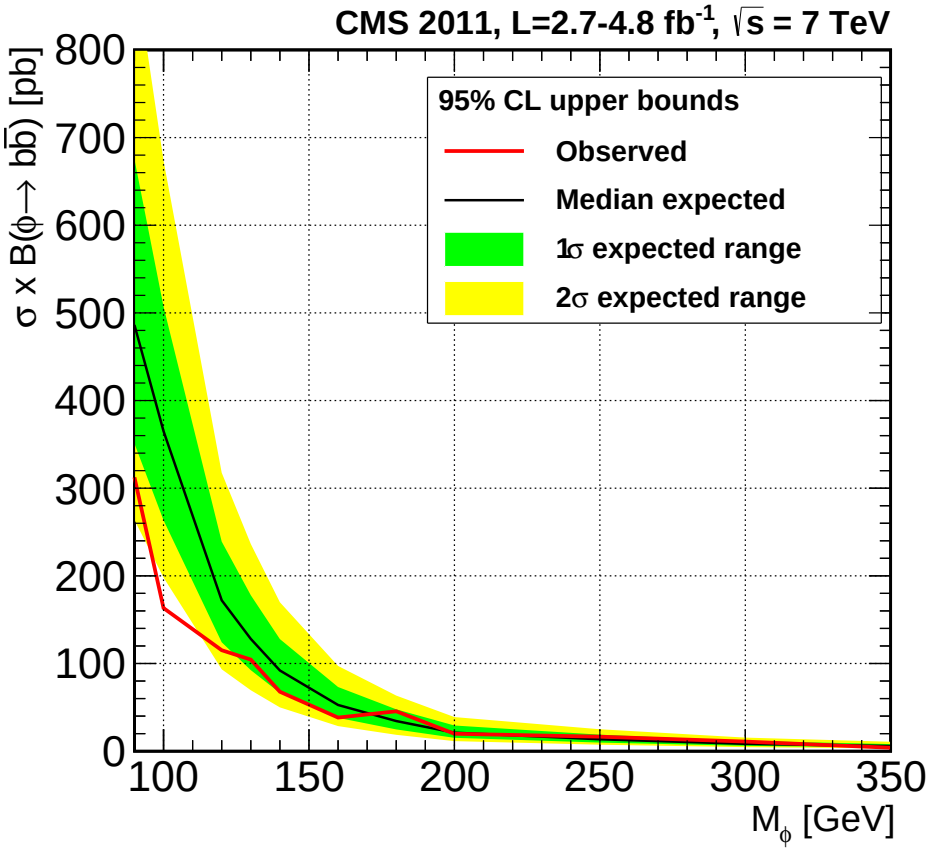
- $B_j = 0$ if $M_{\mathrm{SV}} \leq 1\ \mathrm{GeV}$
- $B_j = 1$ if $1 < M_{\mathrm{SV}} \leq 2\ \mathrm{GeV}$
- $B_j = 2$ if $M_{\mathrm{SV}} > 2\ \mathrm{GeV}$

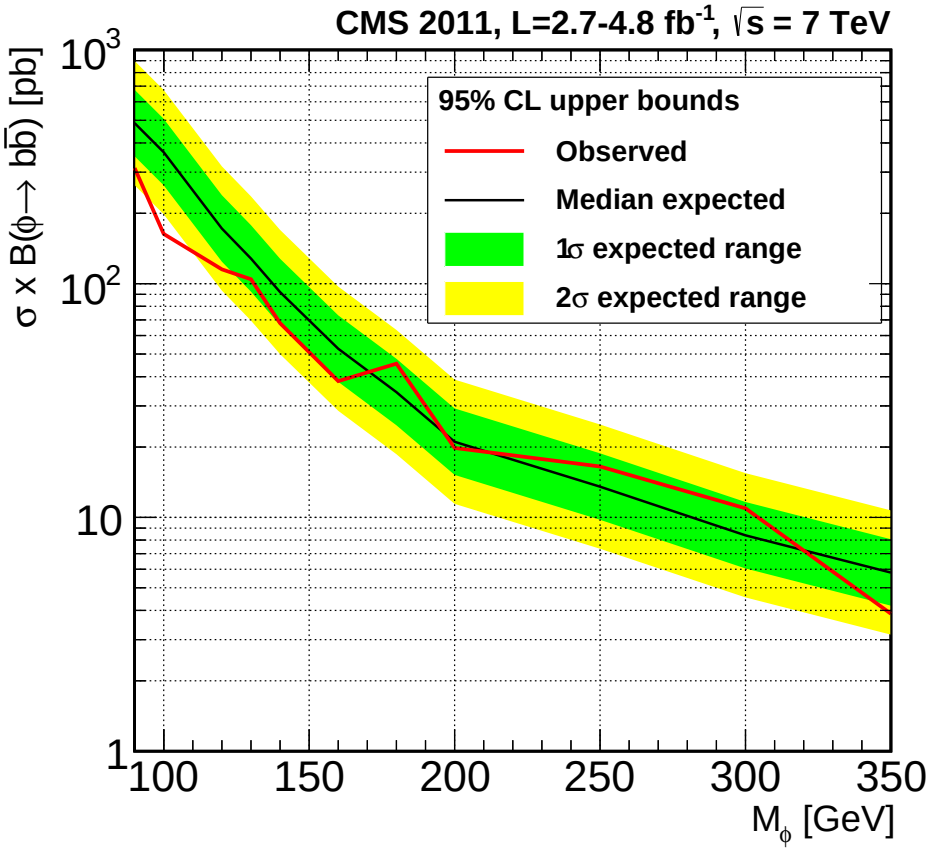
→ EventBTag$= T_{12} + T_3$

- $T_{12} = 0$ if $B_1 + B_2 < 2$
- $T_{12} = 1$ if $2 \leq B_1 + B_2 < 3$
- $T_{12} = 2$ if $B_1 + B_2 \geq 3$
- $T_3 = 0$ if $B_3 < 2$
- $T_3 = 3$ if $B_3 = 2$



95% CL upper limits on cross sections × branching ratio





- Shown in linear and logarithmic scale

→ Observed combined limits statistically in agreement with expected limits!

→ In particular no confirmation of excess at low m_A as seen by CDF/D0

$m_h^{\max}$ scenario

- Designed to yield maximum value of light MSSM Higgs mass, m_h
- $M_{\mathrm{SUSY}} = 1$ TeV
- $X_t = 2M_{\mathrm{SUSY}}$
- $\mu = +200$ GeV
- $M_{\mathrm{gluino}} = 800$ GeV
- $M_2 = 200$ GeV
- $A_b = A_t$
- $M_3 = 800$ GeV
- $X_t = A_t - \mu/\tan\beta^2$