Search for a light NMSSM Higgs boson produced in supersymmetric cascades and decaying into a b-quark pair

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LHC Physics Discussion: Higgs
23 March 2015

What if it's not the SM Higgs?

- $\mathrm{H}(125)$ is consistent with expectation from SM, but
  - Gravity is not included in SM
  - The SM suffers from the hierarchy problem
  - Dark Matter is not included
  - Anomalous magnetic moment of the muon shows a $\sim 3\,\sigma$ discrepancy
- What if the Higgs at 125 GeV corresponds to a state of an extended Higgs sector which is not the lightest one?
  - Implies a light Higgs boson, possibly lighter than the Z boson
  - The best way of experimentally proving that $\mathrm{H}(125)$ is not the SM Higgs is to find additional Higgs bosons!

Would such a light Higgs be detectable at the LHC?

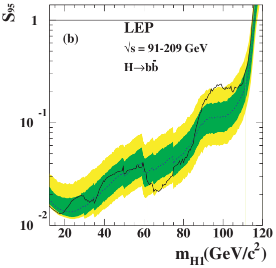
- Not in decays of the state at $\sim 126\ \mathrm{GeV}$ if mass of lightest Higgs $\gtrsim 63\ \mathrm{GeV}$

- This possibility has not been explored at the LHC so far; first LHC searches for light Higgses in this mass range are in progress

Slide taken from Georg Weiglein
Planck 2014, 05/2014

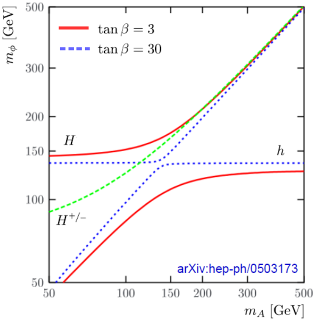
Light Higgs Searches at the LHC

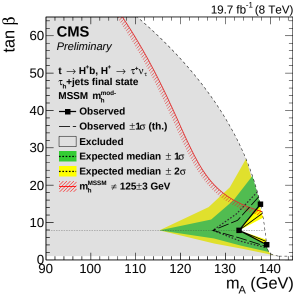
[Eur.Phys.J. **C47**, 547 (2006)]



- The LHC could very well have access to light Higgs bosons that were impossible to see at LEP
- Low Higgs mass range ($m_{\mathrm{h}} < m_{\mathrm{Z}^0}$) is largely unexplored at the LHC
- Only sporadically probed
  - ATLAS (HIGG-2014-04): $\phi \to \gamma\gamma$ probes $m_{\mathrm{Higgs}} > 65$ GeV
  - CMS (HIG-13-010)): $\phi \to \mathrm{a}_1\mathrm{a}_1 \to 4\mu$ probes $m_{\mathrm{Higgs}} < 2m_\tau$
- Variety of theoretical models predict light Higgs bosons which are not excluded by existing searches
  - Important condition: Accommodate ≈ SM-like $\mathrm{H}(125)$

- MSSM Higgs spectrum: h, H, A, $\mathrm{H}^{\pm}$

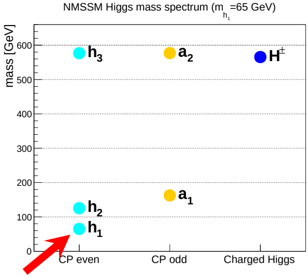




- A light MSSM Higgs is only possible through light A ($m_{\mathrm{A}} < 100$ GeV)
- Implies light $\mathrm{H}^{\pm}$ as well
- Strongly disfavoured by charged Higgs measurements (CMS-HIG-14-020)

Extended Higgs sector in the NMSSM

- NMSSM is extension of the MSSM
  - Additional singlet superfield
    - No gauge interactions
    - Interacts with itself and Higgs doublets
  - Resulting additional particles
    - 1 neutralino
    - 1 CP-odd Higgs
    - 1 CP-even Higgs
- Offers a solution to the μ problem of the MSSM



- How to accomplish light Higgs in accord with existing measurements?
  - Identify h_2 with SM-like $\mathrm{H}(125)$ $\rightarrow$ Small singlet component
  - h_1 should have large singlet component to evade LEP constraints

$\Rightarrow$ This is the idea of the modified P4 scenario of the NMSSM pointed out by G. Weiglein and O. Stål[1]

[1] O. Stål, G. Weiglein, Light NMSSM Higgs bosons in SUSY cascade decays at the LHC, JHEP **1201**, 071 (2012), 1108.0595.

Would such a light Higgs be detectable at the LHC?

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- In case of SUSY, such a light Higgs could be produced in a SUSY cascade, e.g. $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$; could be similar for other types of BSM physics

Would such a light Higgs be detectable at the LHC?

- Not in decays of the state at ~ 126 GeV if mass of lightest Higgs $\gtrsim 63$ GeV

- This possibility ha... so far; first L... ...nge are in pro...

BRAND NEW RESULTS
CMS-HIG-14-030

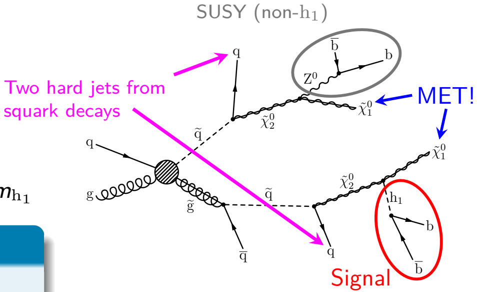
- In case of SUSY, such a light Higgs could be produced in a SUSY cascade, e.g. $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$; could be similar for other types of BSM physics

Event selection

- Direct production of h_1?
  - Suppressed due to reduced couplings to gauge bosons and fermions

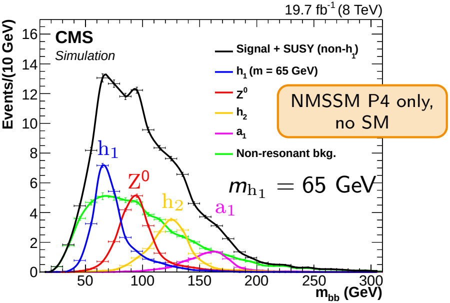
$\Rightarrow$ Search in SUSY cascades

- Signal: Peak in $m_{\mathrm{b}\bar{\mathrm{b}}}$ distribution at m_{h_1}



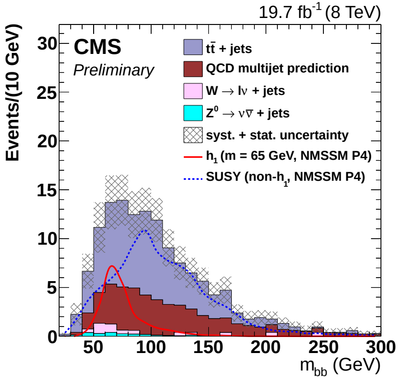
Event selection ($19.7\,\mathrm{fb}^{-1}$ at 8 TeV)

- H_T-trigger with threshold of 650 GeV
- $H_\mathrm{T} > 750$ GeV
- At least 4 jets (250,100,25,25)
- At least 2 b-tagged jets (not leading two)
- Select two b-tagged jets with minimal $\Delta R(b_1, b_2)$
- $\min \Delta R(b_1, b_2) < 1.5$
- $E_\mathrm{T}^\mathrm{miss} > 200$ GeV
- $\Delta\Phi(j_{1,2}, \vec{E}_\mathrm{T}^\mathrm{miss}) > 0.5 \Rightarrow$ QCD suppression



Background estimation

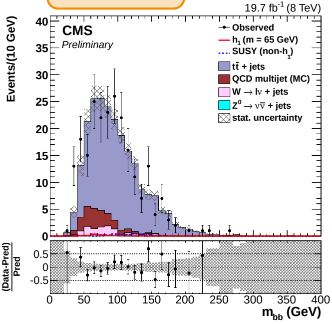
- Dominant background: $t\bar{t}$ + jets
  - Normalization: NLO
  - Shape: MC
  - Verified in control region
- QCD Multijet
  - Normalization: data-driven
  - Shape: data-driven
- Minor backgrounds: $Z^0 \to \nu\bar{\nu}$ and $W \to \ell\nu$ + jets
  - Normalization: NLO
  - Shape: MC



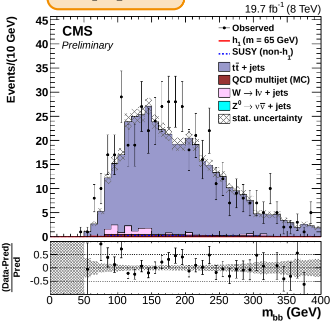
- $m_{b\bar{b}}$ shape is taken from MC
- Normalization from NLO
  - Verified in control region
  - E_T^{miss} sideband: $E_T^{miss} = [50,200]$ GeV + one isolated lepton (e, μ)

suppress QCD

$\Delta R(b_1, b_2) < 1.5$



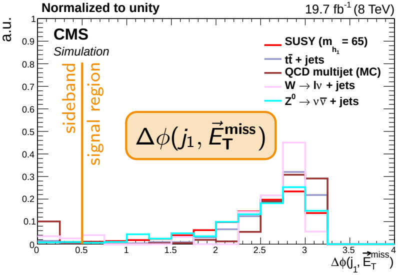
$\Delta R(b_1, b_2) > 1.5$

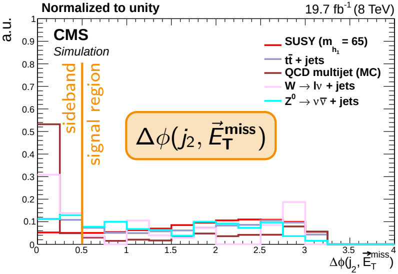


$t\bar{t}$ normalization from NLO consistent with data within errors

QCD multijet background

- Vast majority of QCD events suppressed by $E_T^{miss} > 200$ GeV
- Rest: Mainly fake-E_T^{miss} contributions due to mismeasurements of jets
  - $\vec{E}_T^{miss}$-vector aligned with one of the leading jets
  - High QCD suppression by requiring $\Delta\phi(j_1/j_2, \vec{E}_T^{miss}) > 0.5$
- Invert $\Delta\phi(j_2, \vec{E}_T^{miss})$-cut to get QCD enriched regions
  - Subtract $\mathrm{t\bar{t}}$ and minor EWK contributions using simulation
  - Used to estimate QCD contribution for $\Delta\phi(j_2, \vec{E}_T^{miss}) > 0.5$



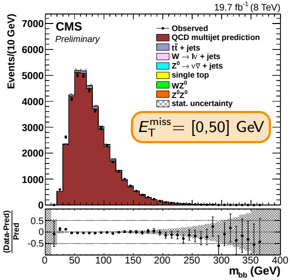


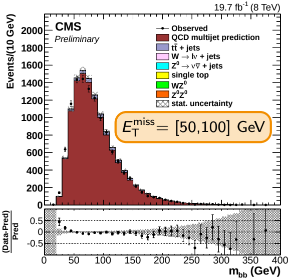
Validation in low-$E_{\mathrm{T}}^{\mathrm{miss}}$ control region

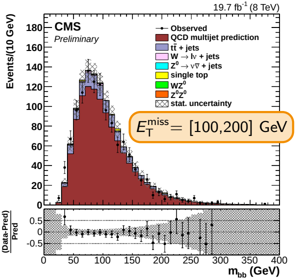
$$m(\mathrm{b}_1,\mathrm{b}_2)^{\text{estimated QCD}}_{\Delta\phi>0.5} = \left(m(\mathrm{b}_1,\mathrm{b}_2)^{\text{Data}} - m(\mathrm{b}_1,\mathrm{b}_2)^{\text{MC}}_{\text{non-QCD}}\right)_{\Delta\phi<0.5} \times f_{N,\text{QCD}}\left(E_{\mathrm{T}}^{\text{miss}}\right) \times f_{S,\text{QCD}}\left(E_{\mathrm{T}}^{\text{miss}}, f_{\mathrm{b}_i,\text{QCD}}\right)$$

Closure test of the method in low MET region ($\not{E}_{\mathrm{T}} < 200$ GeV)

(veto isolated leptons, highly QCD dominated)



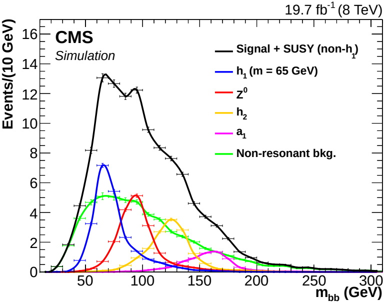


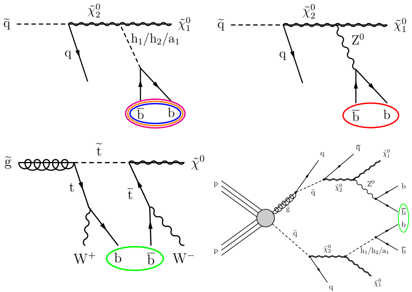


- The $m_{\mathrm{b}\bar{\mathrm{b}}}$ shape is well described by the method

Signal modelling

- Signal $m_{b\bar{b}}$ shape is modelled using NMSSM MC samples
  - Input created with NMSSMTools
  - PYTHIA6/MADGRAPH used for event generation
- NMSSM contributions in the signal region
  - $h_1 \rightarrow b\bar{b}$
  - $Z^0 \rightarrow b\bar{b}$
  - $h_2 \rightarrow b\bar{b}$
  - $a_1 \rightarrow b\bar{b}$
  - Non-resonant contributions
- Two approaches considered
  - Search for an h_1-peak over the SM expectations
  - Include non-h_1 contributions for NMSSM-specific interpretation



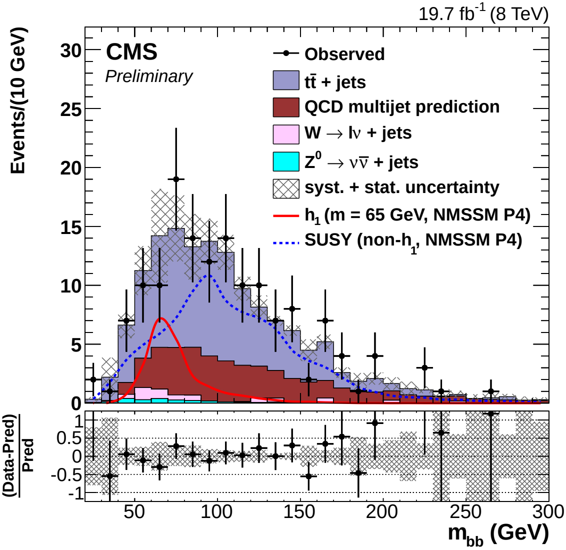


Systematic uncertainties

- Effect of systematic uncertainties quantified by their relative impact on expected cross section limit
  - Uncertainties with zero impact not listed
- Dominant uncertainties
  - $t\bar{t}$ normalization
  - QCD related uncertainties
- The analysis is statistics dominated

Systematics source	Event category	Type	Impact
Normalization of $t\bar{t}$	Background	rate	1.7 %
Normalization of QCD	Background	rate	2 %
Shape correction QCD	Background	shape + rate	3 %
QCD shape parameterization	Background	shape + rate	1 %
MC statistics $t\bar{t}$	Background	shape + rate	1.3 %
MC statistics $W \to \ell\nu$	Background	shape + rate	0.3 %
Luminosity	Signal + Background	rate	0.5 %
Trigger	Signal + Background	shape + rate	0.1 %
Pile-up	Signal + Background	shape + rate	0.1 %
PDF uncertainty	Signal	shape + rate	0.2 %
Offline b-tag (bc)	Signal + Background	shape + rate	1.0 %
Offline b-tag (udsg)	Signal + Background	shape + rate	0.05 %
Jet energy scale	Signal + Background	shape + rate	1.3 %
Jet energy resolution	Signal + Background	shape + rate	0.1 %
τ energy scale	Signal + Background	shape + rate	0.6 %

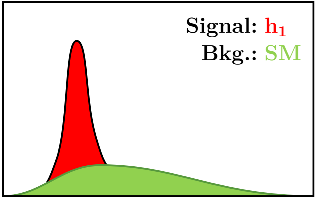
Background-only fit

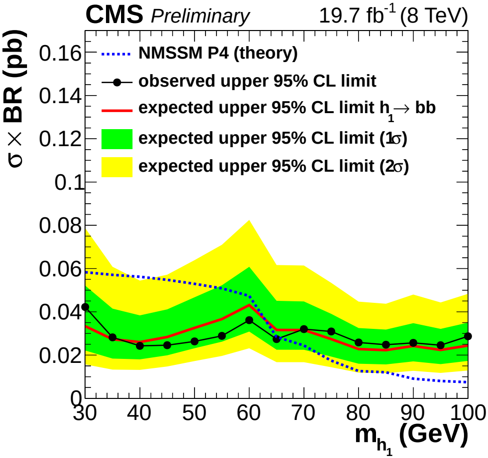


Unblinded results!

- Data are well described by background-only hypothesis
  - $\chi^2/\text{ndf} = 1.02$
- No indication of a signal!
  - Derive upper limits

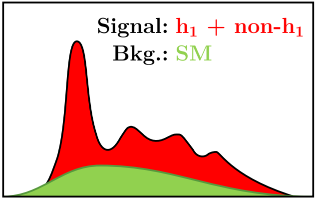
Upper limits – Higgs peak search





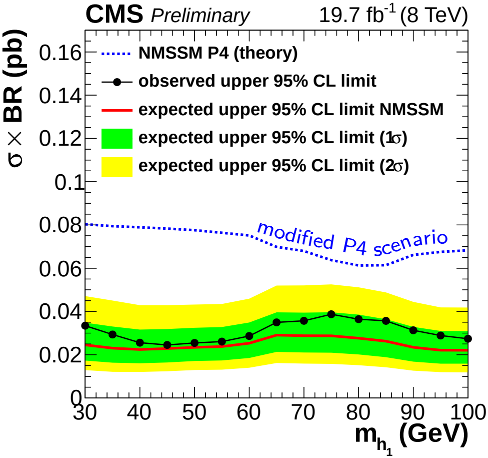
- Derived upper limits on $\sigma(\mathrm{pp} \to \mathrm{h}_1 + X) \times \mathcal{B}(\mathrm{h}_1 \to \mathrm{b\bar{b}})$ in the mass range of 30 – 100 GeV
- ⇒ Below 65 GeV our limits undershoot the light Higgs production predicted by the modified P4 scenario

Upper limits – NMSSM P4 scenario



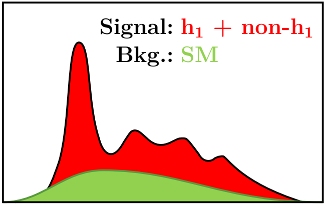
- Derived upper limits using also non-h_1 contributions to the $m(\mathrm{b}_1, \mathrm{b}_2)$-spectrum
  - Model-dependent interpretation within the NMSSM P4 scenario

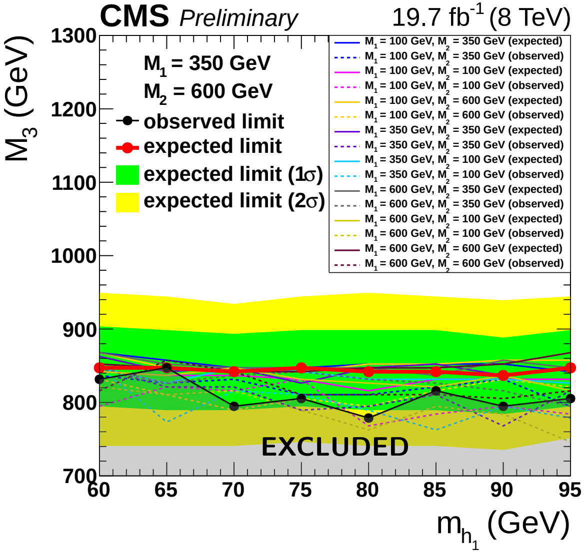
⇒ Analysis excludes the modified NMSSM P4 scenario with a scale of 1 TeV for coloured SUSY particles



NMSSM parameter scan – Decoupled squarks scenario

- Focus of the following results is on sensitivity to certain NMSSM scenarios, while previous interpretation was focusing on the light Higgs part
  - Model-dependent interpretation
- Different physics assumption than in previous studies using the P4 scenario
  - Decoupled scenario → only gluino-gluino production contributes
- Detailed NMSSM parameter scan
- Scanned mass parameters (squark mass parameter M_{SUSY} set to 2 TeV)
  - $m_{h_1} = 60 - 95$ GeV → driven by NMSSM parameter A_κ
  - $M_1/M_2 = 100 - 600$ GeV → gaugino masses
  - $M_3 = 800 - 1400$ GeV → gluino mass
- Calculate upper limits with the full NMSSM spectrum as "signal"
- Limits are presented in $M_3 - m_{h_1}$ plane for 3x3 combinations of M_1, M_2





- Main dependence on M_3
  - Drives the production cross section
- At most mild dependence on gaugino mass parameters M_1, M_2 and on Light Higgs mass m_{h_1}
  - Detailed overview for each M_1, M_2 combination in backup
- First result interpretation within a wider range of NMSSM Light Higgs scenarios

Summary

- First search for light NMSSM Higgs production in supersymmetric cascades at the LHC
  - http://cds.cern.ch/record/2002557
- Probing a theoretically well motivated Higgs mass range which was previously unexplored at the LHC
- Sensitivity in the range of modified NMSSM P4 scenario

- No signal observed
  - Upper limits on topological cross section $\sigma(\mathrm{pp} \to \mathrm{h}_1 + X) \times \mathcal{B}(\mathrm{h}_1 \to \mathrm{b}\overline{\mathrm{b}})$
- Analysis excludes the P4 scenario with $M_3 = M_{\mathrm{SUSY}} = 1$ TeV
- Model dependent interpretation within NMSSM parameter space
  - Decoupled squarks scenario
  - Limits depend mainly on gluino mass parameter M_3

Back-Up

Additional material

- Parameters of P4 scenario
- $t\bar{t}$ control region
- QCD multijet background estimation method
- Prefit distributions
- Fit results – Higgs peak search
- Fit results – NMSSM P4 scenario
- NMSSM parameter scan – Decoupled squarks scenario

Modified P4 scenario (Example parameter point)

Higgs sector parameters

- $\tan\beta = 2.6$
- $\lambda = 0.6$
- $A_\lambda = -510$ GeV
- $\kappa = 0.12$
- $A_\kappa = 161$ GeV
- $\mu_{\text{eff}} = -200$ GeV

Higgs masses		Neutralino & Chargino masses	
m_{h_1}	65 GeV	$\tilde{\chi}_1^0$	98 GeV
m_{h_2}	125 GeV	$\tilde{\chi}_2^0$	227 GeV
m_{h_3}	577 GeV	$\tilde{\chi}_3^0$	228 GeV
m_{a_1}	163 GeV	$\tilde{\chi}_4^0$	304 GeV
m_{a_2}	577 GeV	$\tilde{\chi}_5^0$	622 GeV
$m_{H^\pm}$	566 GeV	$\tilde{\chi}_1^\pm$	208 GeV
		$\tilde{\chi}_2^\pm$	622 GeV

Non-Higgs sector parameters (as a reference)

M_1	300 GeV	A_t	1145 GeV	M_{SUSY}	1 TeV
M_2	600 GeV	A_b	1145 GeV		
M_3	1 TeV	A_τ	1145 GeV		

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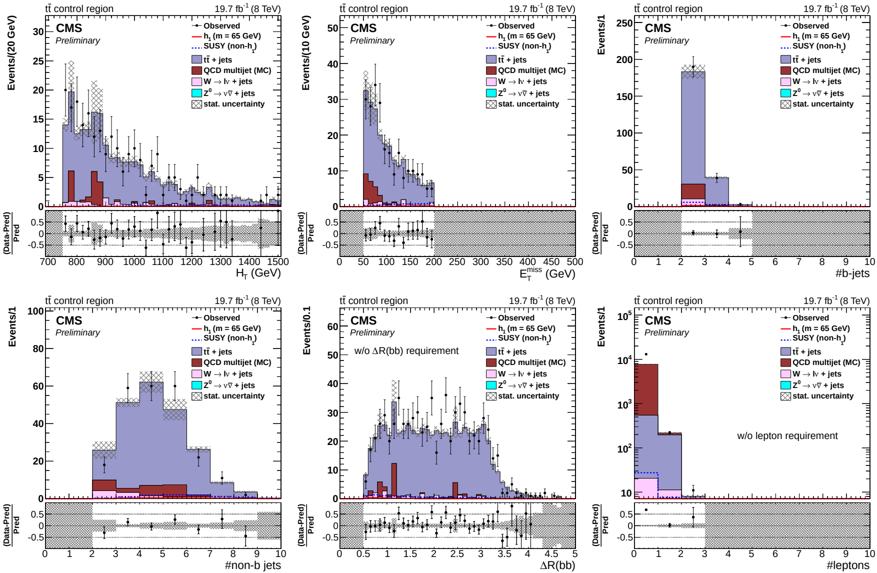
$t\bar{t}$ control region



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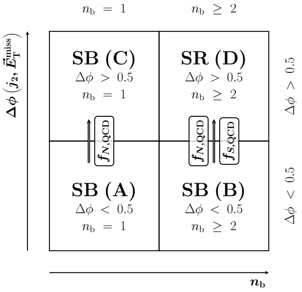
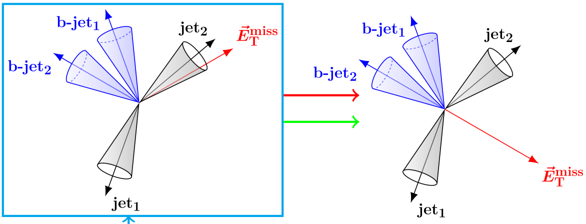
QCD multijet background



$\Delta\phi$ sideband $\Delta\phi$ signal region



$$m(b_1, b_2)^{\text{estimated QCD}}_{\Delta\phi>0.5} = \left(m(b_1, b_2)^{\text{Data}} - m(b_1, b_2)^{\text{MC}}_{\text{non-QCD}}\right)_{\Delta\phi<0.5} \times f_{N,\text{QCD}}\left(E_T^{miss}\right) \times f_{S,\text{QCD}}\left(E_T^{miss}, f_{b_i,\text{QCD}}\right)$$

Select QCD dominated sideband $\rightarrow$ $m(b_1, b_2)$ shape

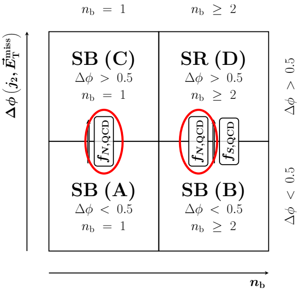
Normalization fixed by $\Delta\phi$ SignalRegion/Sideband ratio

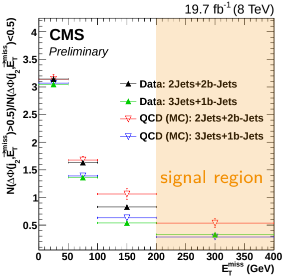
Correct $m(b_1, b_2)$ shape, since correlated with $\Delta\Phi(j_2, \vec{E}_T^{miss})$

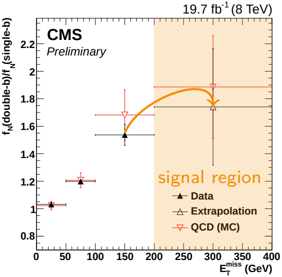
QCD multijet background – Normalization factor

$$m(\mathrm{b}_1,\mathrm{b}_2)^{\text{estimated QCD}}_{\Delta\phi>0.5} = \left(m(\mathrm{b}_1,\mathrm{b}_2)^{\text{Data}} - m(\mathrm{b}_1,\mathrm{b}_2)^{\text{MC}}_{\text{non-QCD}} \right)_{\Delta\phi<0.5} \times f_{N,\text{QCD}}\left(E_{\mathrm{T}}^{\text{miss}}\right) \times f_{S,\text{QCD}}\left(E_{\mathrm{T}}^{\text{miss}}, f_{\mathrm{b}_i,\text{QCD}}\right)$$

Normalization fixed by $\Delta\phi$ SignalRegion/Sideband ratio







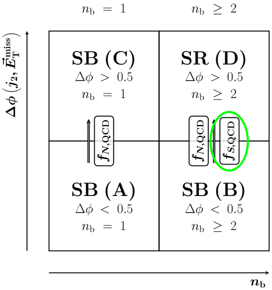
$$f_{N,\text{QCD}} = \frac{\#\text{Events with } \Delta\phi > 0.5}{\#\text{Events with } \Delta\phi < 0.5}$$

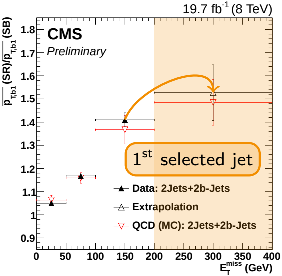
- $f_{N,\text{QCD}}$ measured in single-b sample (center)
  - b-jet is paired with 3rd untagged jet
  - Double-b/Single-b correction (right) applied → extrapolated from QCD MC
  - All other cuts applied
- Double-b/Single-b difference (QCD MC) in $E_{\mathrm{T}}^{\text{miss}}$ bin > 200 GeV is used as systematic uncertainty on the normalization

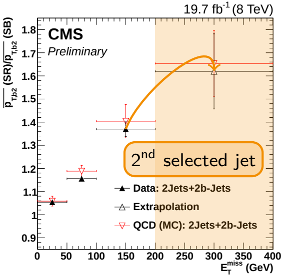
QCD multijet background – Shape correction

$$m(\mathrm{b}_1,\mathrm{b}_2)^{\text{estimated QCD}}_{\Delta\phi>0.5} = \left(m(\mathrm{b}_1,\mathrm{b}_2)^{\text{Data}} - m(\mathrm{b}_1,\mathrm{b}_2)^{\text{MC}}_{\text{non-QCD}}\right)_{\Delta\phi<0.5} \times f_{N,\text{QCD}}\left(E_{\text{T}}^{\text{miss}}\right) \times f_{S,\text{QCD}}\left(E_{\text{T}}^{\text{miss}}, f_{\mathrm{b}_i,\text{QCD}}\right)$$

Correct $m(\mathrm{b}_1,\mathrm{b}_2)$ shape, since correlated with $\Delta\Phi(j_2, \vec{E}_{\text{T}}^{\text{miss}})$



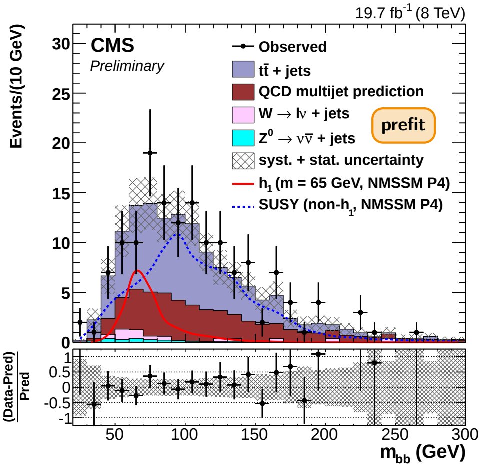




$$f_{\mathrm{b}_i,\text{QCD}} = \frac{\overline{p_{T,\mathrm{b}_i}}(\#\text{Events with } \Delta\phi > 0.5)}{\overline{p_{T,\mathrm{b}_i}}(\#\text{Events with } \Delta\phi < 0.5)}$$

- $f_{\mathrm{b}_i,\text{QCD}}$ applied as scale factor on the two b-tagged jets
  - Correction factor for data and $E_{\text{T}}^{\text{miss}} > 200$ GeV is extrapolated from QCD MC
- Uncertainty of these correction factors is taken into account as shape uncertainty

Prefit distributions



- Data are already well described by prefit background distributions

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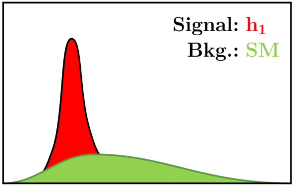
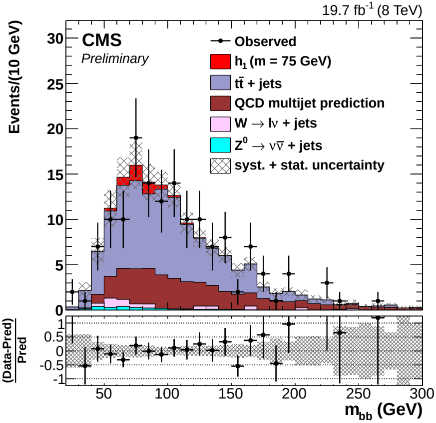
Fit results – Higgs peak search



- Probed mass range from 30 GeV to 100 GeV
- Maximum upward deviation of 0.49σ at $m_{\mathrm{h}_1} = 75$ GeV



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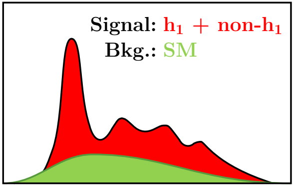
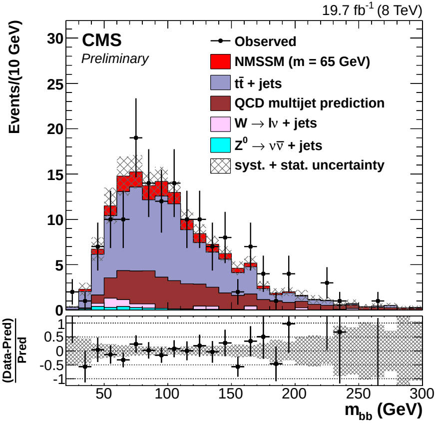


- Fitted NMSSM cross sections
  - Model-dependent measurement
- Maximum upward deviation of 0.99σ at $m_{\mathrm{h}_1} = 75$ GeV



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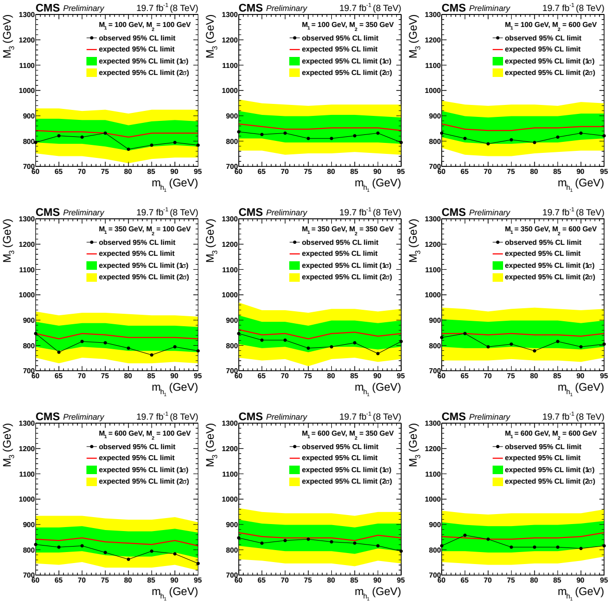
NMSSM parameter scan – Decoupled squarks scenario



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