Exotic Higgs at CMS:

Light Higgs bosons searches beyond the 2HDM

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on behalf of the CMS collaboration

Overview

- Beyond the 2HDM - the NMSSM
- Search for $a_1 \rightarrow \mu^+\mu^-$ (HIG-12-004: 10.1103/PhysRevLett.109.121801)
- Search for $h \rightarrow 2a_1 \rightarrow 4\mu$ (HIG-13-010)
- Search for cascade decays with $h \rightarrow bb$ (HIG-14-030)

Beyond the 2HDM - the NMSSM

- Well motivated singlet extension to the MSSM
  - Solves the μ problem - dynamically generated by ⟨S⟩
  - Relaxes fine-tuning on Higgs mass - additional tree-level contribution
  - Opens up less constrained parameter space

- Light (pseudo)scalar Higgs boson sets NMSSM apart from MSSM
  - Offers much richer spectrum - $h_{1,2,3}$, $a_{1,2}$, $h^{\pm}$

- Will cover searches at CMS motivated by the NMSSM
  - Leaving out other searches with heavy Higgs, 2HDM Higgs, $h^{\pm}$, ...

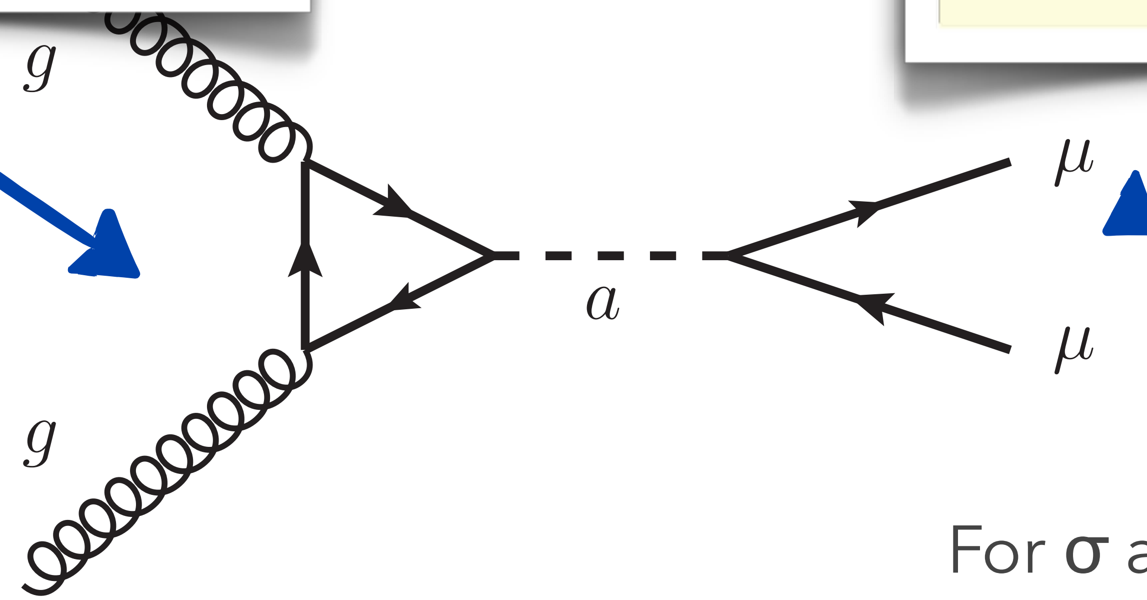
Search for $a_1 \rightarrow \mu^+\mu^-$

Motivation

- NMSSM: Focus on light a_1

$\sigma(gga)$ can potentially be large due to $C_{abb} \sim \tan(\beta)$, $\sigma \sim 10^4$pb - 10^7pb

BR ($a \rightarrow \mu\mu$) ~ $O(10^{-3})$, but dimuon invariant mass is powerful discriminant

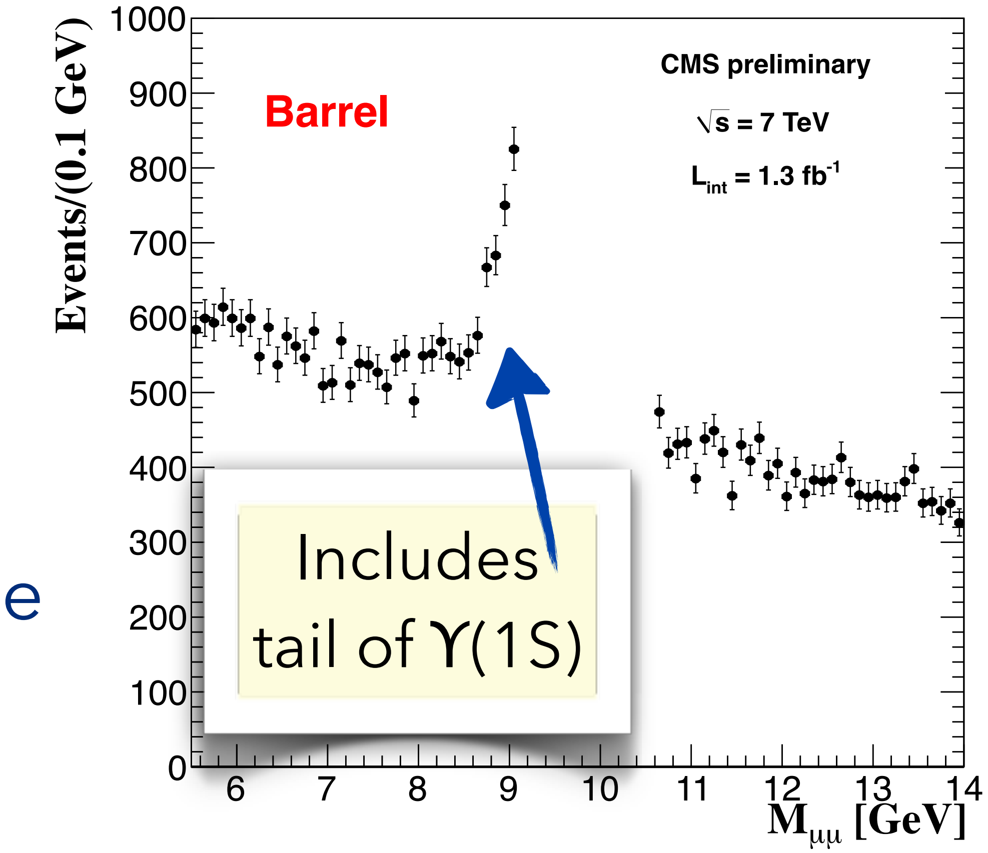


For σ and BR, see backup

- Search performed on 1.3 fb^{-1} of $\sqrt{s}$ = 7 TeV data, trigger on 2 OS muons, with $m_{\mu\mu} \in [5.5, 14]$ GeV
  - exclude 8.8 - 11.5 GeV to avoid bottomonium resonances

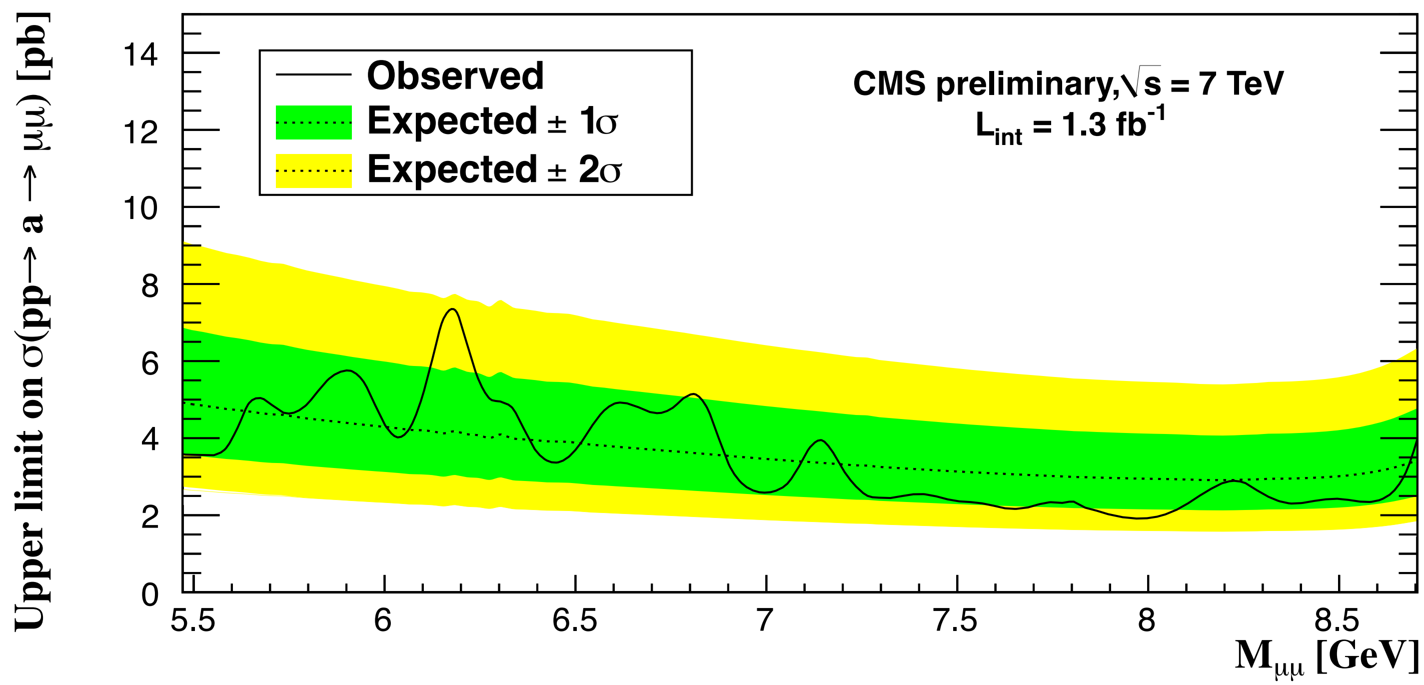
Strategy

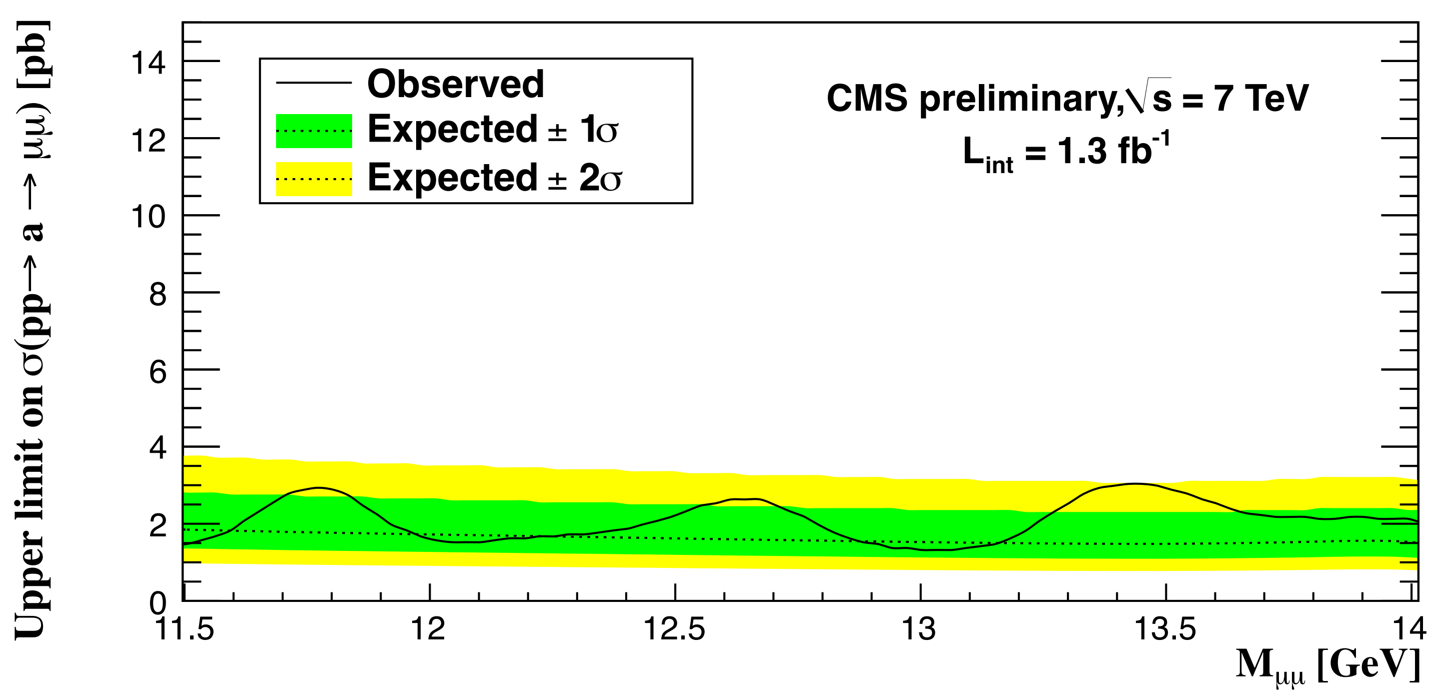
- Isolation requirement on μ to reject fakes & non-prompt μ from hadron decays
- Fit to $m_{\mu\mu}$ distribution using templates functions for signal & bkg
- **Background:** Non-resonant QCD
  - 1st order polynomial for shape
- **Background:** ϒ(1S/2S/3S)
  - Double crystal ball (CB) for each resonance
  - Fit ϒ(1S) to data, ϒ(2S/3S) relative to ϒ(1S)
- **Signal**
  - Mass points 30 MeV apart, Gaussian PDF for each
  - Width from detector resolution (Γ(a→μμ) ~ MeV)



Results

- No excess observed - set upper limit on σ×BR





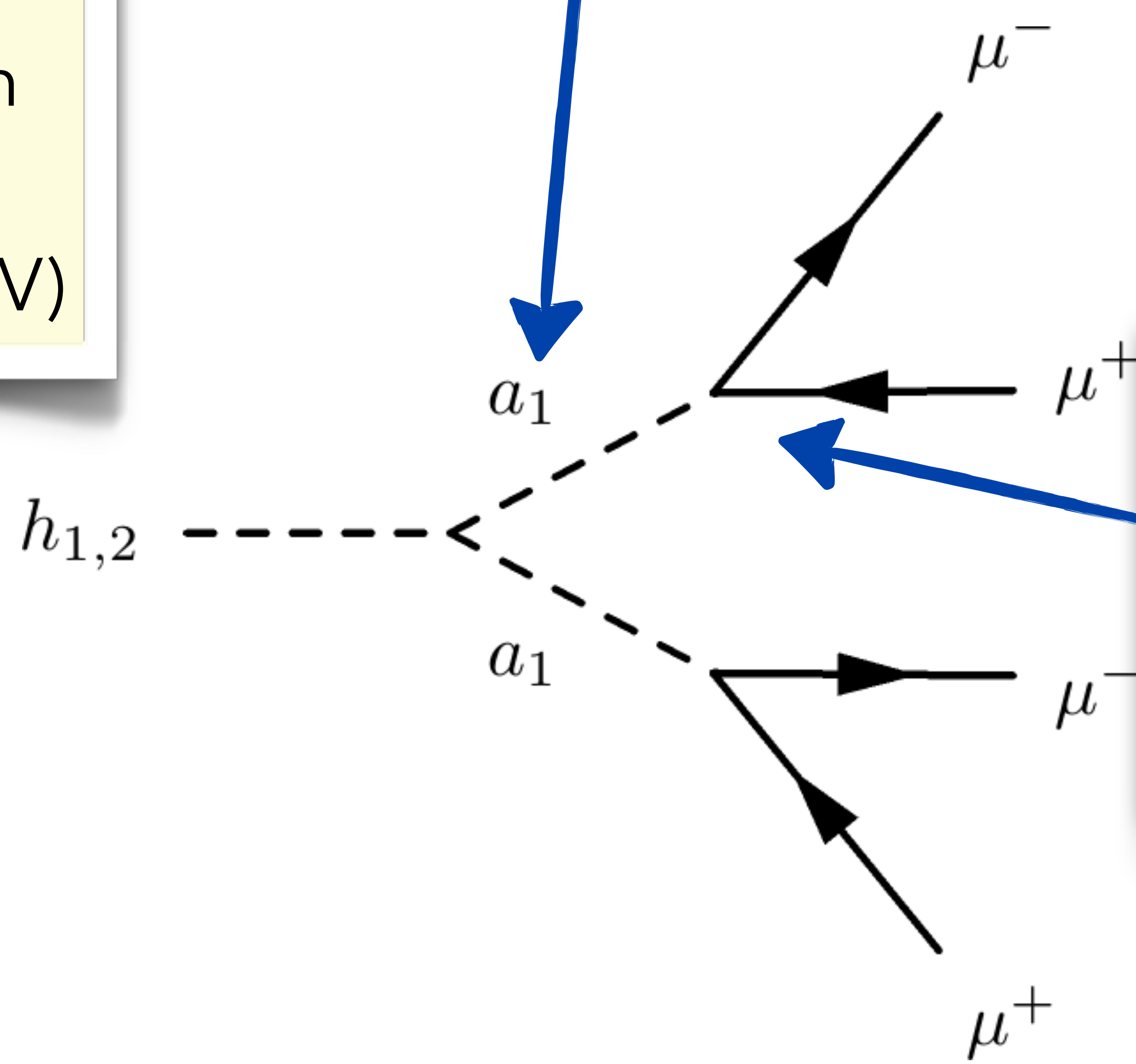
- Can interpret as limit on $\cos\theta_A$ for various tan β - see backup

Search for $h \to 2a_1 \to 4\mu$

Motivation

- 4μ final state from scalar decays via pseudoscalar pair:
  - **NMSSM** - h pair produces very light a_1, $m_{a1} = 0.25 - 3.55$ GeV

Can be discovered h(125), or scalar with similar mass (scanned 86 - 150 GeV)



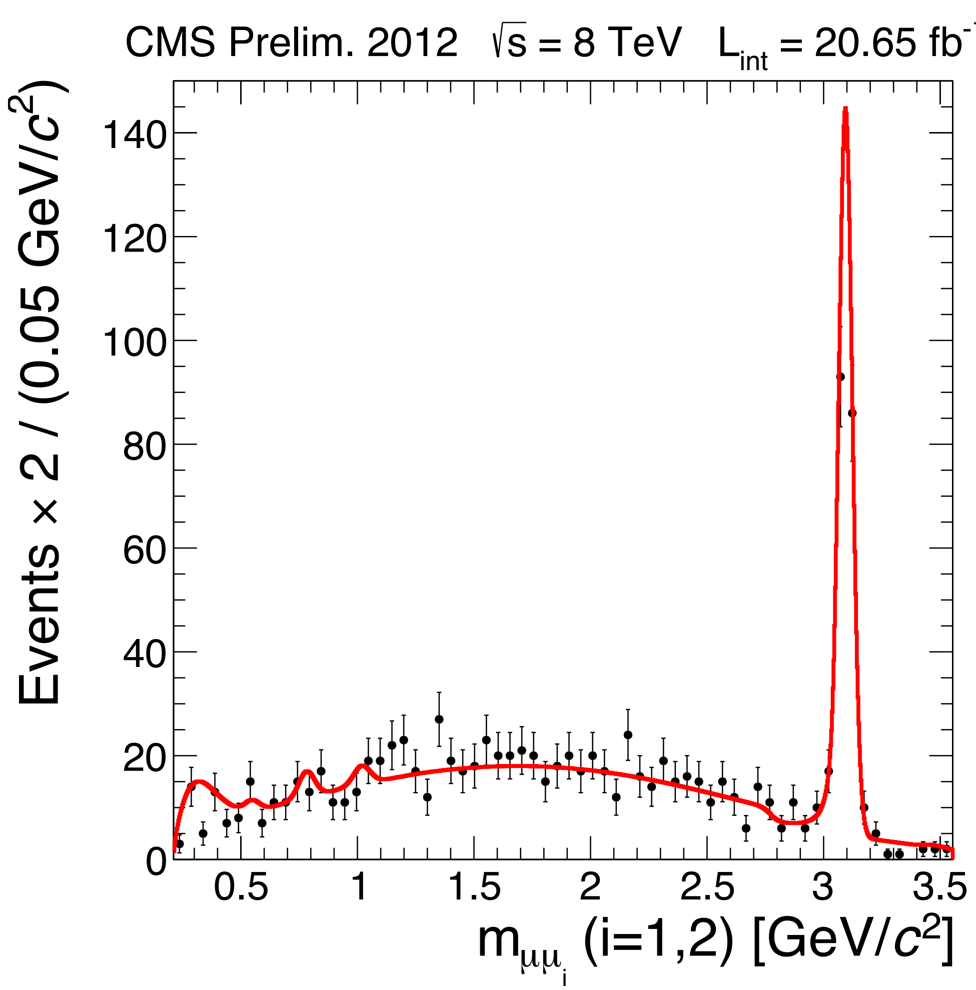
BR($a_1 \rightarrow \mu^+\mu^-$) sizeable in this m_{a1} region as coupling ~ m_ℓ

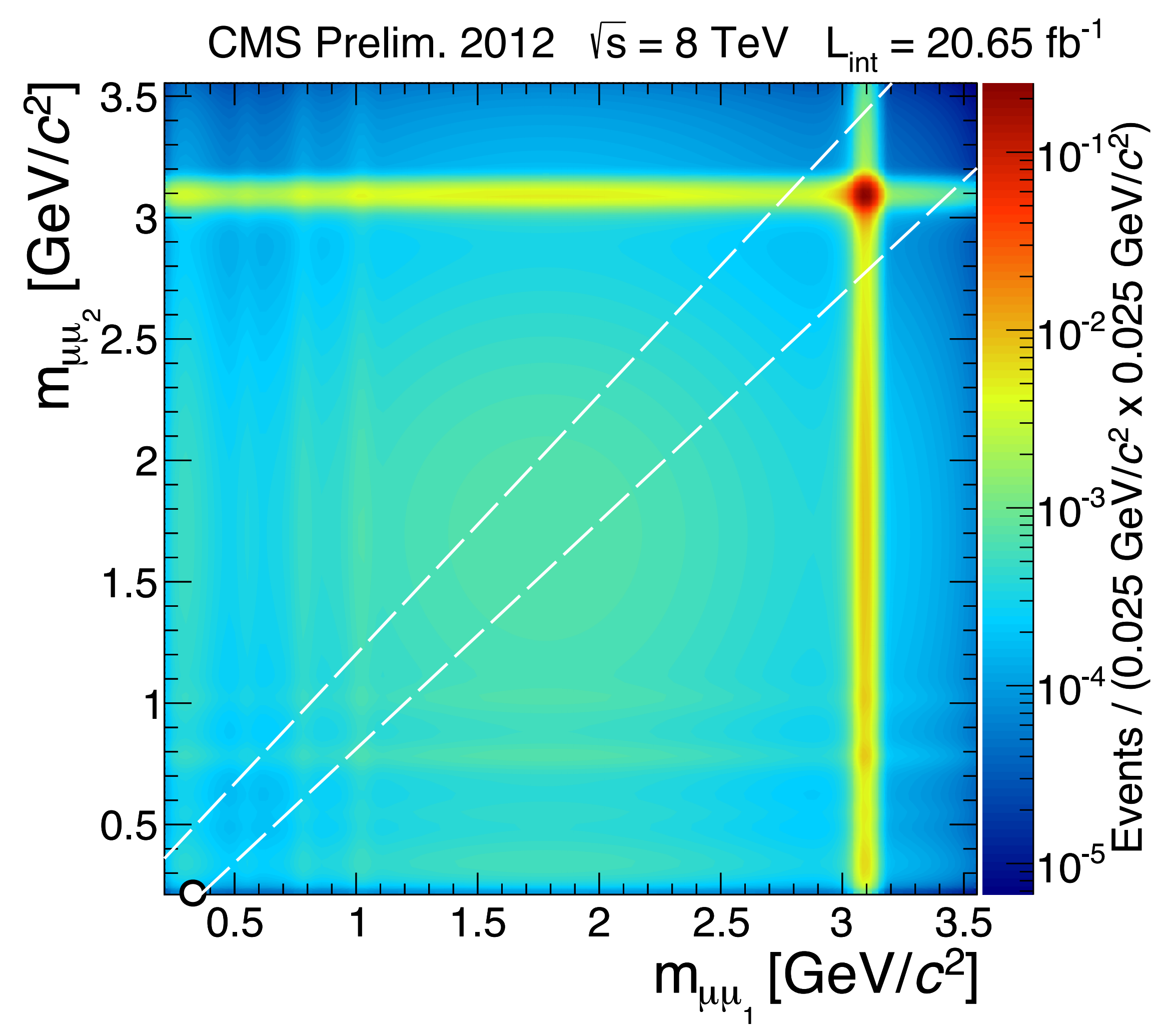
Search strategy

- Performed on 20.65 fb^{-1} of $\sqrt{s}$ = 8 TeV data, dimuon trigger
- Require ≥ 4 μ, 1+ must have $|\eta| < 0.9$
    - Avoids trigger simulation issues in forward region
- Form OS pairs based on common vertex or small ΔR
- Dimuon pairs must be isolated
    - Suppress dimuons from jets
- Require 2 dimuon pairs, invariant masses compatible within detector resolution
- Signal efficiency: 11 - 35%, dependent on m_{a1}

Backgrounds

- $b\bar{b}$ **background** (1.8 ± 0.6 evts) - double semileptonic decays, resonances (ω, ϕ, J/Ψ)
    - 2D template in plane of dimuon invariant masses
    - Constructed as product of 1D distributions rich in $b\bar{b}$ events

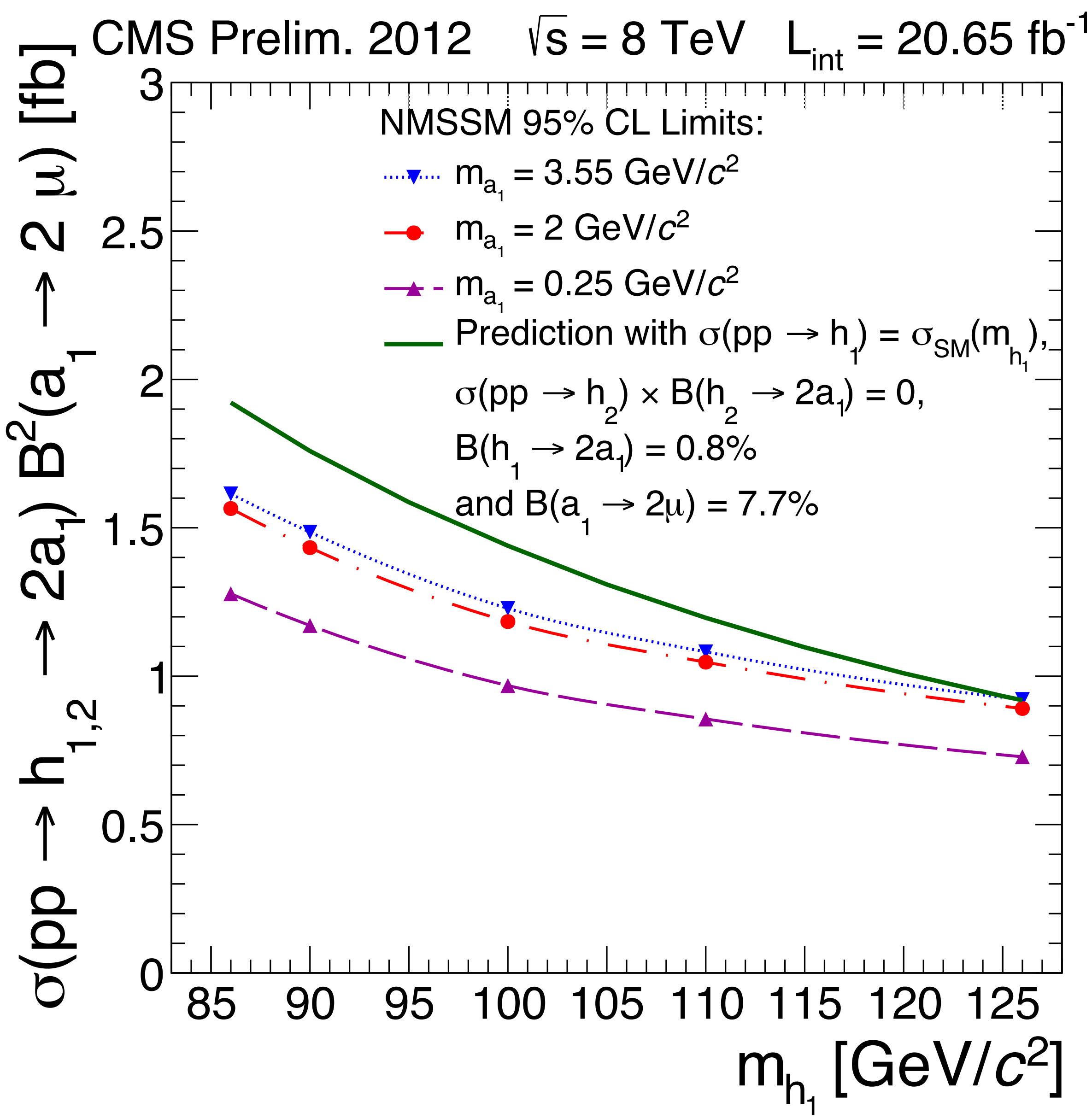


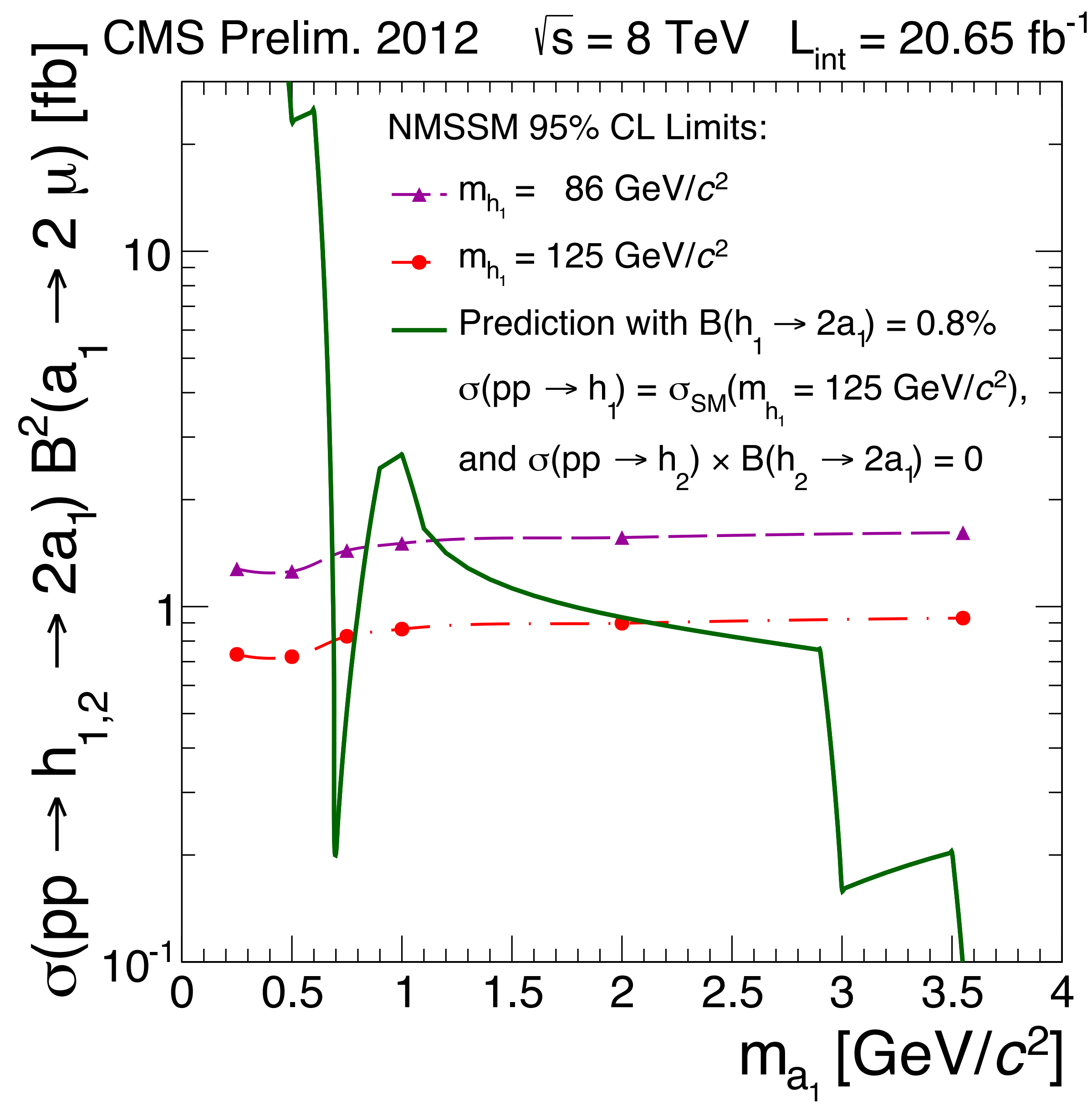


- **J/Ψ pair production (2 ± 2 evts)** - from Pythia8, scaled to data

Results

- 1 event in signal diagonal region, expect 3.8 ± 2.1 background evts
- Set limit on σ × BR in NMSSM





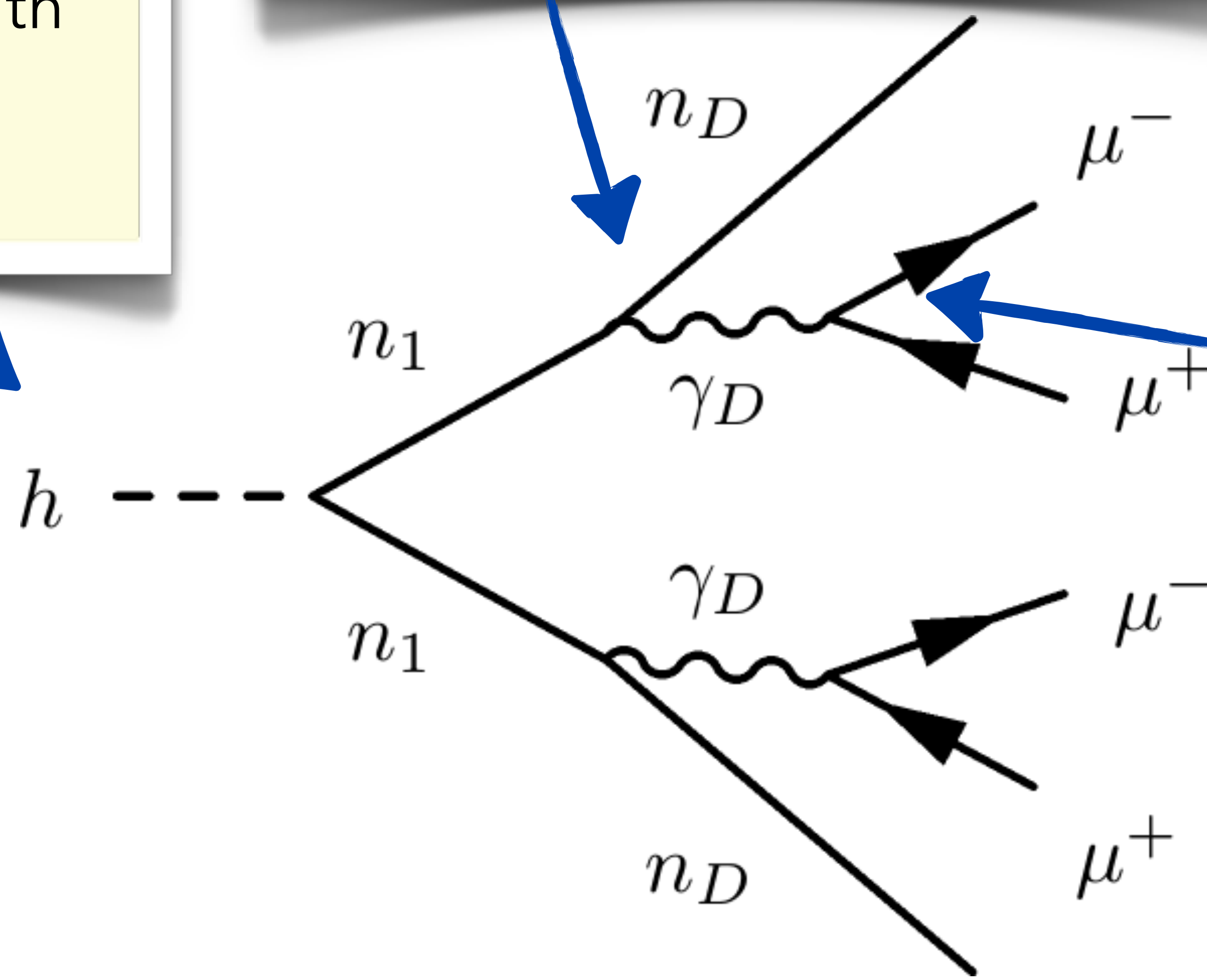
Dark SUSY

- 4μ final state from other scalar decays:
  - **Dark SUSY** - motivated by e^+ excess.

Neutralino n_1 couples to 'dark' neutralino n_D & photon γ_D, m_D ~ O(1) GeV

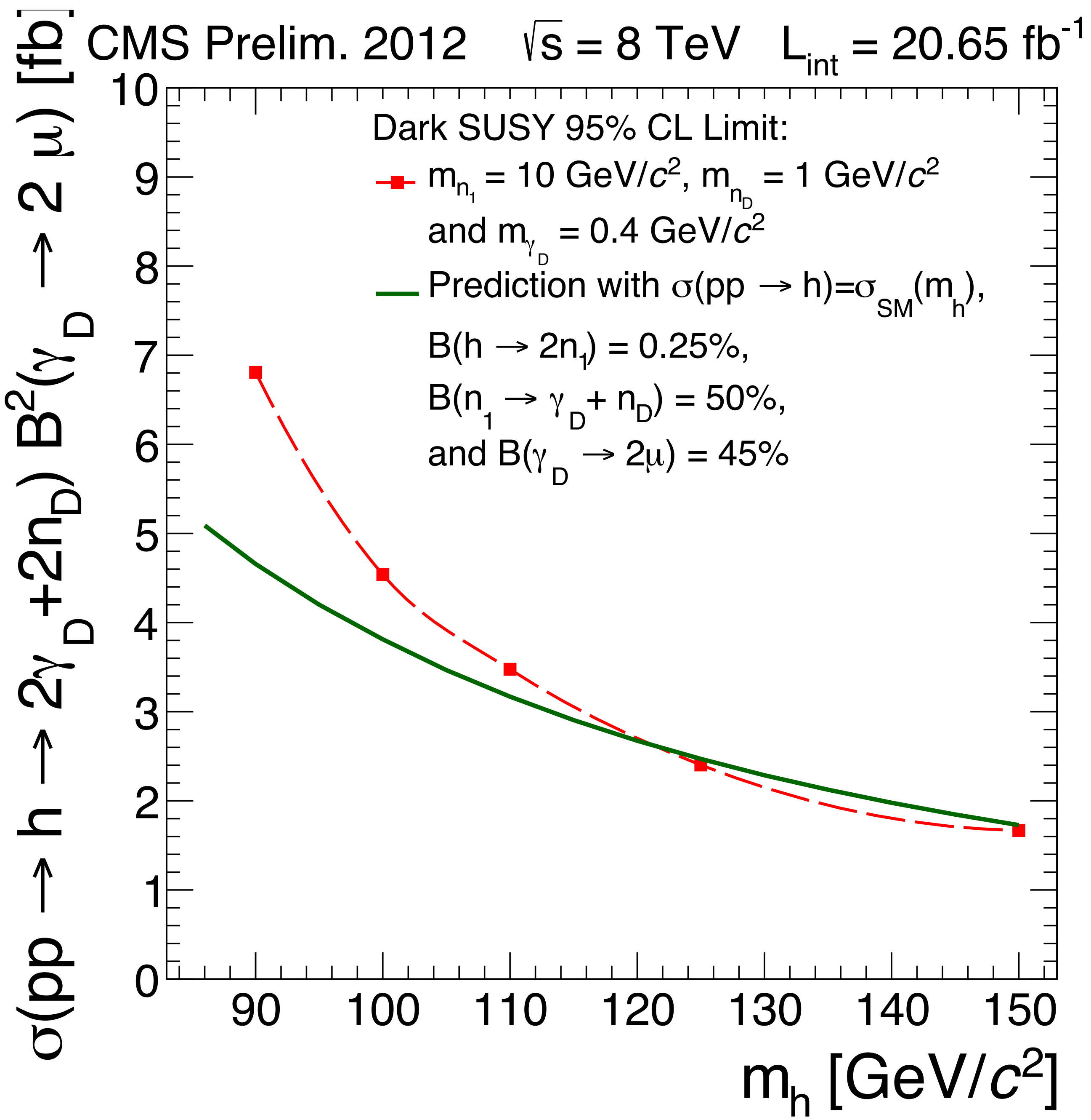
Discovered h(125), or another scalar with similar mass (86 - 150 GeV)

Dark photon couples to SM via photon mixing, BR ≲ 45%



Results

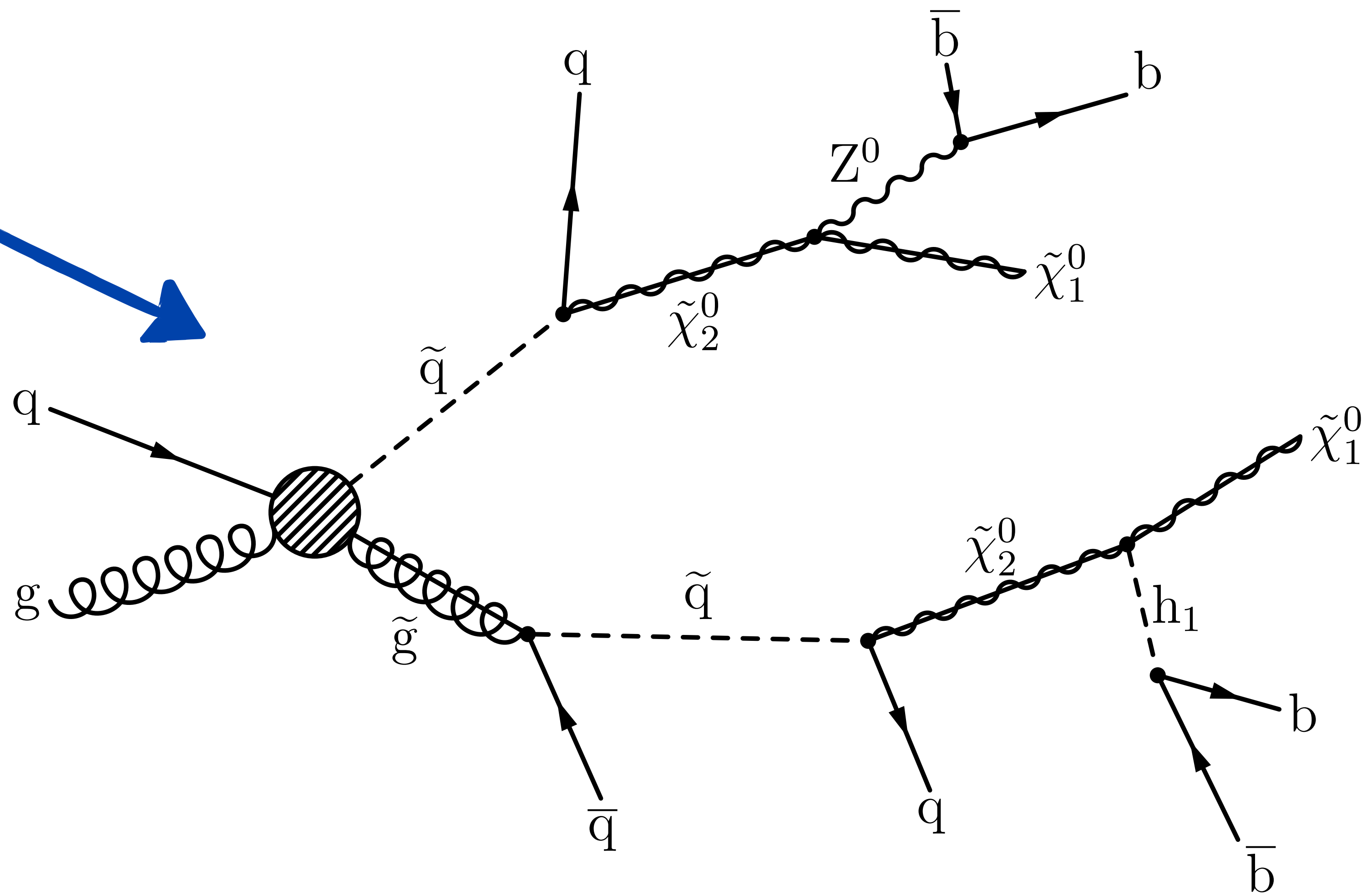
- In context of Dark SUSY:
  - Assumes m_{n1} = 10 GeV, m_{nD} = 1 GeV, $m_{\gamma D}$ = 0.4 GeV



Search for cascade decays with $h \rightarrow bb$

Channel

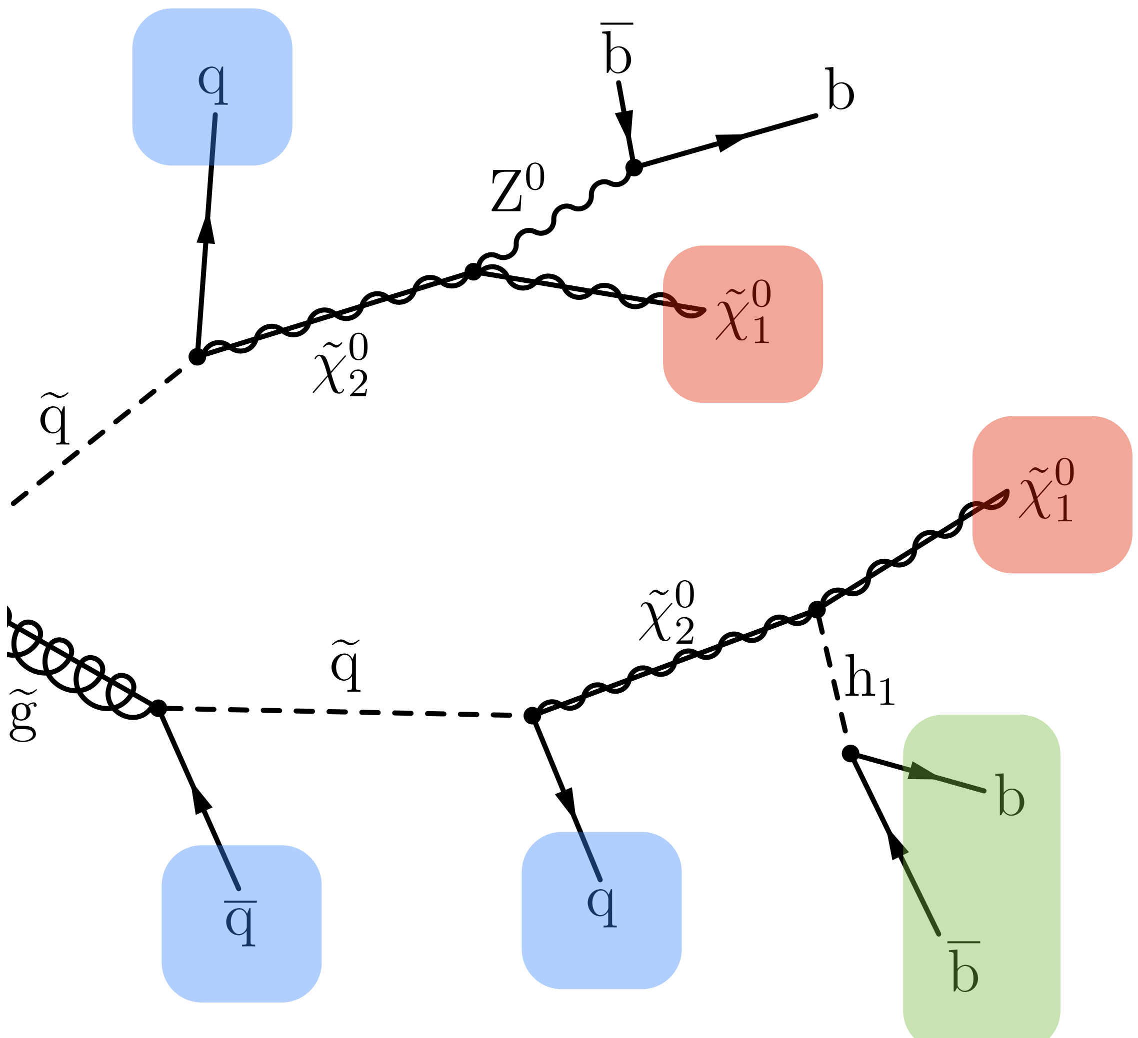
- $h_2 = h(125)$, h_1 is light (30 - 100 GeV) with large singlet component
    - h_1VV coupling reduced, h_1 evades standard detection
    - Instead produced by **cascade decays**
- Modified P4 scenario*
    - $M_{\tilde{q}}, M_{\tilde{g}}$ ~ 1 TeV
    - $\tilde{q}\tilde{g}, \tilde{q}\tilde{q}, (\tilde{g}\tilde{g})$ production
- Decoupled squark scenario
    - $M_{\tilde{q}} \gg M_{\tilde{g}}$
    - $\tilde{g}\tilde{g}$ production dominant



*P4 scenario: http://arxiv.org/abs/1108.0595, http://arxiv.org/abs/0801.4321

Search strategy

- Performed on 19.7 fb^{-1} of $\sqrt{s}$ = 8 TeV data
- Utilise H_T trigger, threshold 650 GeV



Large hadronic activity

2 non-b-tagged jets

H_T > 750 GeV

Missing energy

E_T^{Miss} > 200 GeV

$\Delta\phi(j_1/j_2, E_T^{Miss}) > 0.5$ *(suppress QCD)*

h_1 tagging

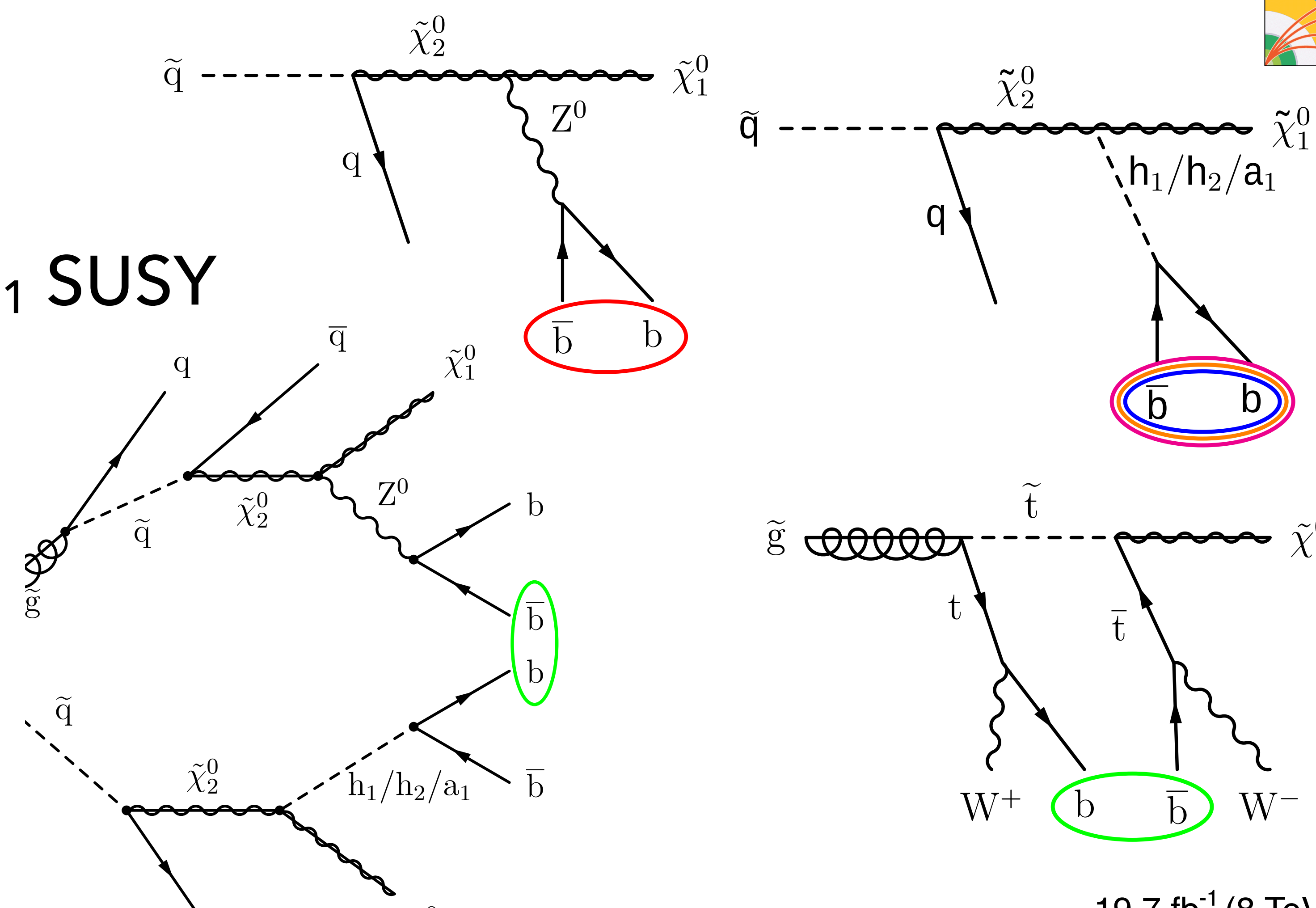
≥ 2 b-tagged jets

$\min[\Delta R(b_i, b_j)] < 1.5$

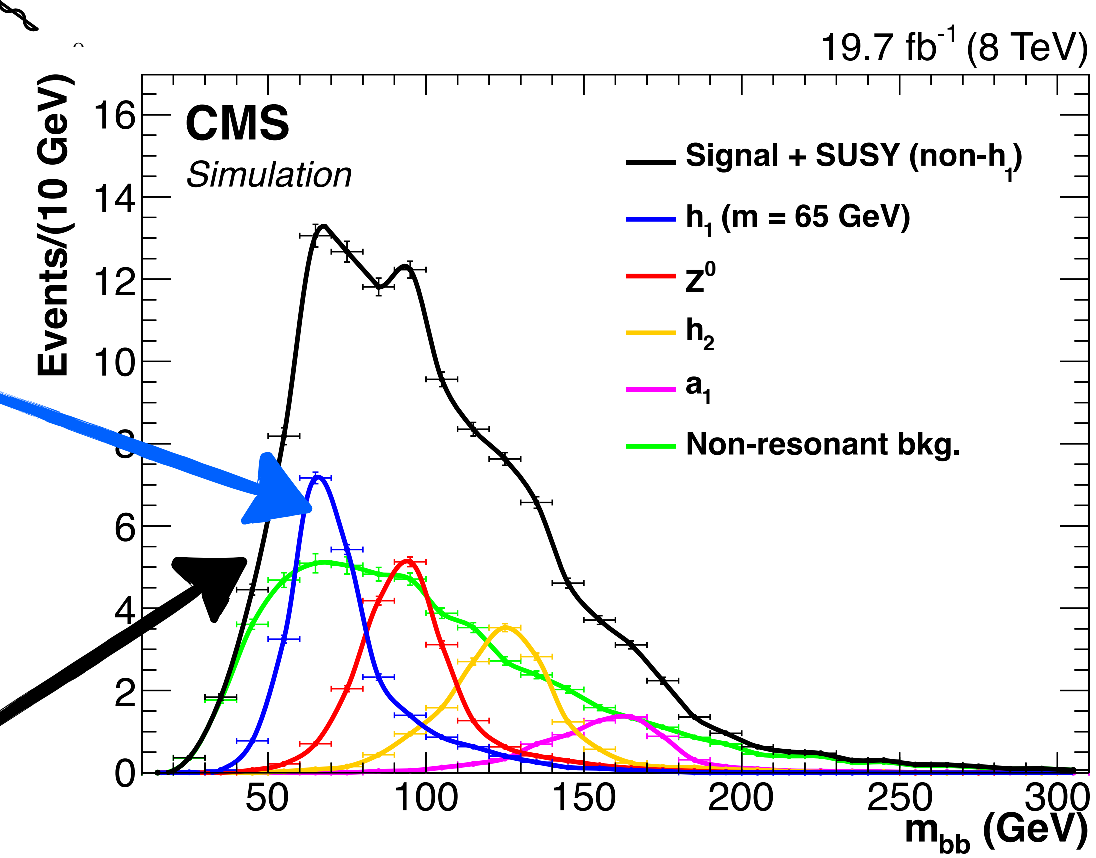
→ Search for peak in m_{bb} distribution

Signal modelling

- Use Madgraph+Pythia
- Complications from non-h_1 SUSY processes:
    - $Z \rightarrow bb$
    - $h_2/a_1 \rightarrow bb$
    - Non-resonant



- 2 approaches to look for excess:
    - Simple h_1 bump hunt (model-independent) - only valid if signal does not contaminate bkg control regions
    - Include other NMSSM-specific contributions



Background estimation

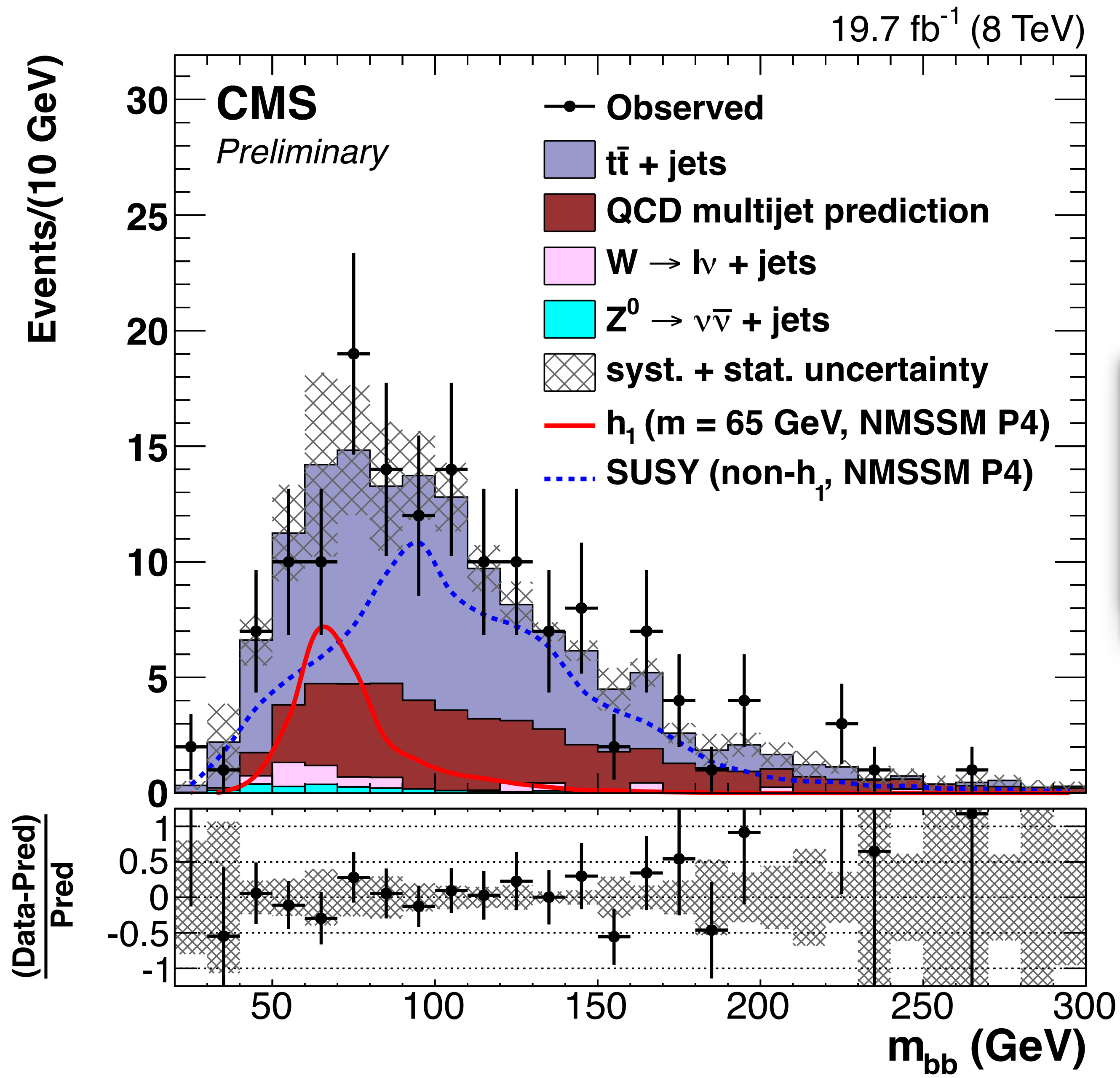
- $t\bar{t}$ **background (82.5 ± 16.5 events)** - semi- & di-leptonic decays
  - From MC: shape from Madgraph + Pythia, normalised to NLO
  - Validated in sideband region - low E_T^{miss} and 1 isolated e/μ (no QCD)

- **QCD background (56.4 ± 24.8 events)** - E_T^{miss} from mismeasured jets
  - E_T^{miss} aligned with jet, use $\Delta\phi(j, E_T^{miss}) > 0.5$ to suppress in SR
  - Data-driven estimate using $\Delta\phi(j_2, E_T^{miss}) < 0.5$ selection

- **Other BG (7.1 ± 1.1 events):** $Z \to \nu\nu$, $W \to \ell\nu$ from MC

Results

- Perform background-only fit to m_{bb} distribution in data with background templates
  - Good agreement with SM backgrounds



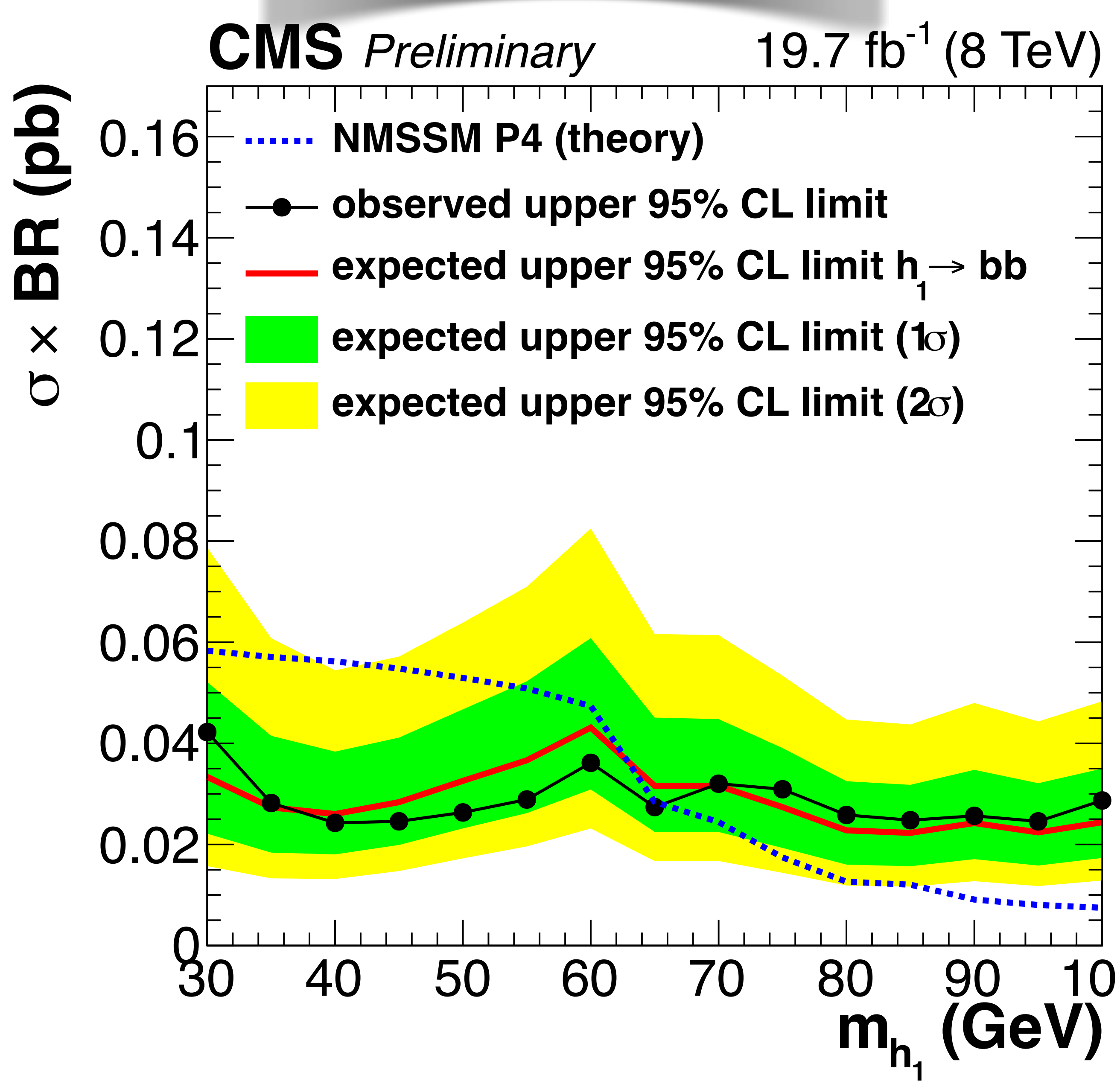
Good sensitivity to P4 scenario

Results

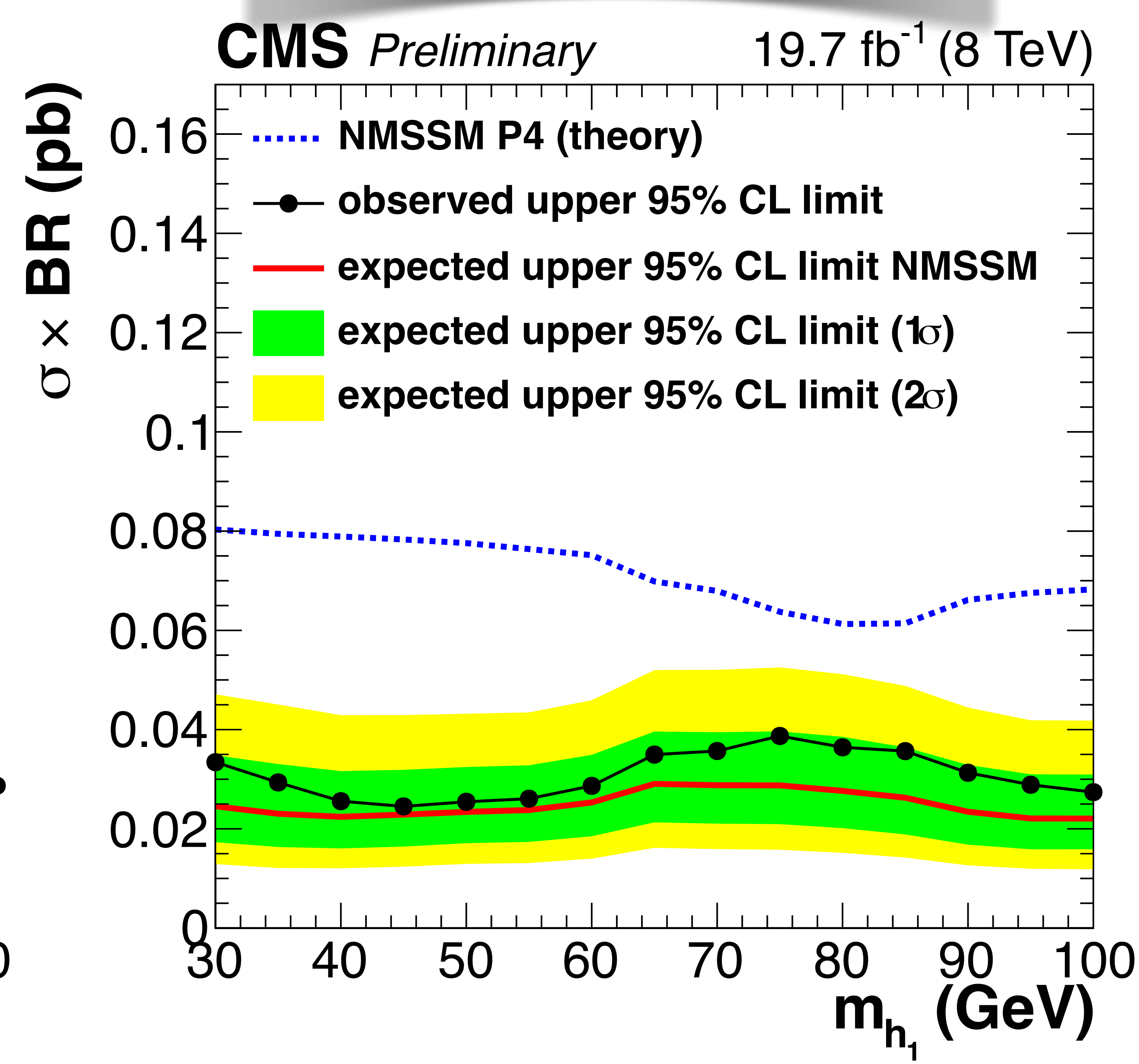
- $h_1 \to bb$ resonance fit & full modified P4 scenario

  - No significant excess, set upper limits on $\sigma(pp \to h_1) \times BR(h_1 \to bb)$

$h_1 \to bb$ resonance

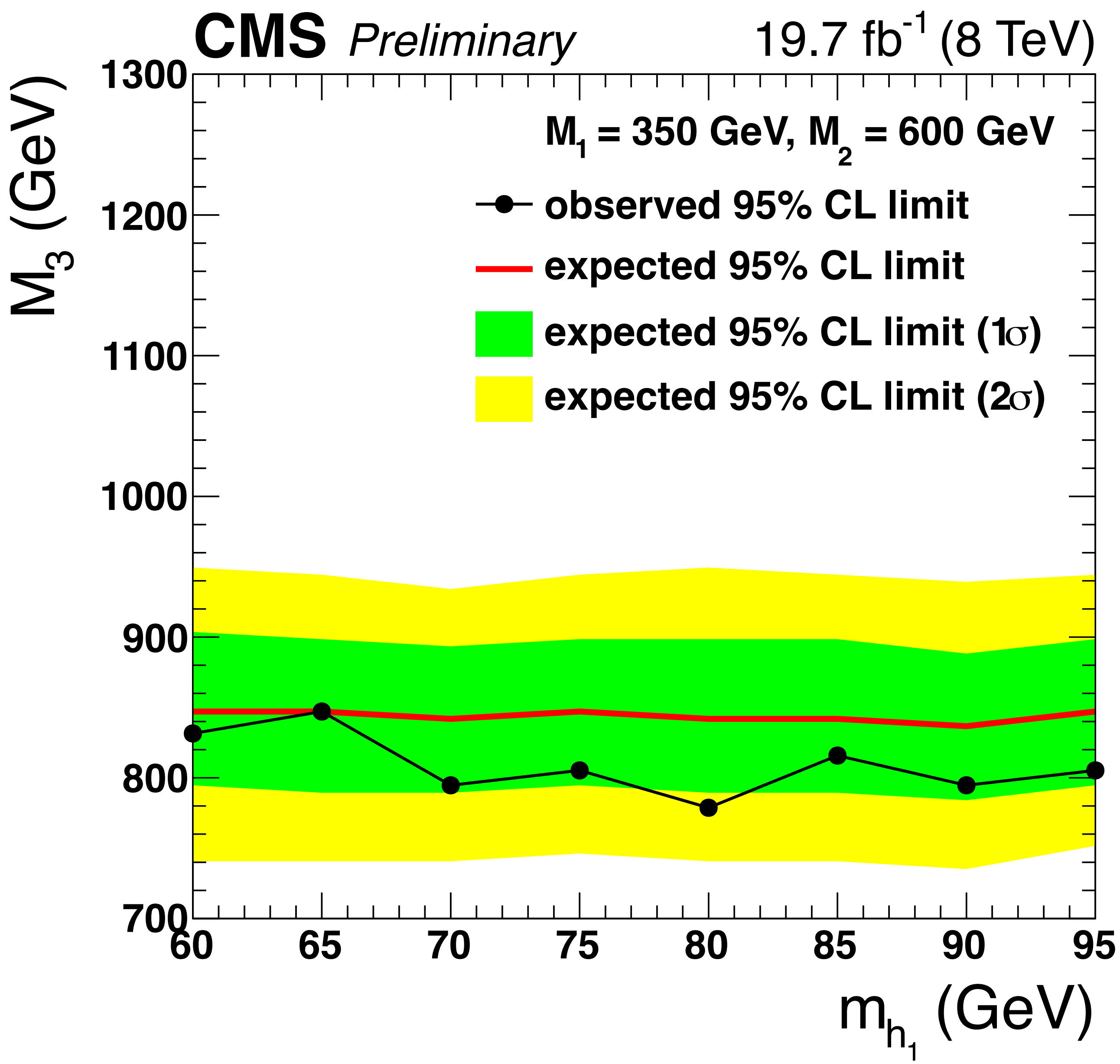


Inc. non-h_1 contributions



Results

- **Decoupled squark scenario** - only gluino-gluino production
  - Use all NMSSM contributions in signal shape
  - Convert to exclusion limit in M_3 (gluino mass) - m_{h1} plane



Summary

- Variety of low-mass scenarios explored with Run 1 data

- More searches in progress
  - $\tau\tau\tau\tau$ (m_{a1} = 4 - 9 GeV), $\mu\mu\tau\tau$ (m_{a1} < 40 GeV), $\mu\mu bb$ (m_{a1} = 25 - 65 GeV)

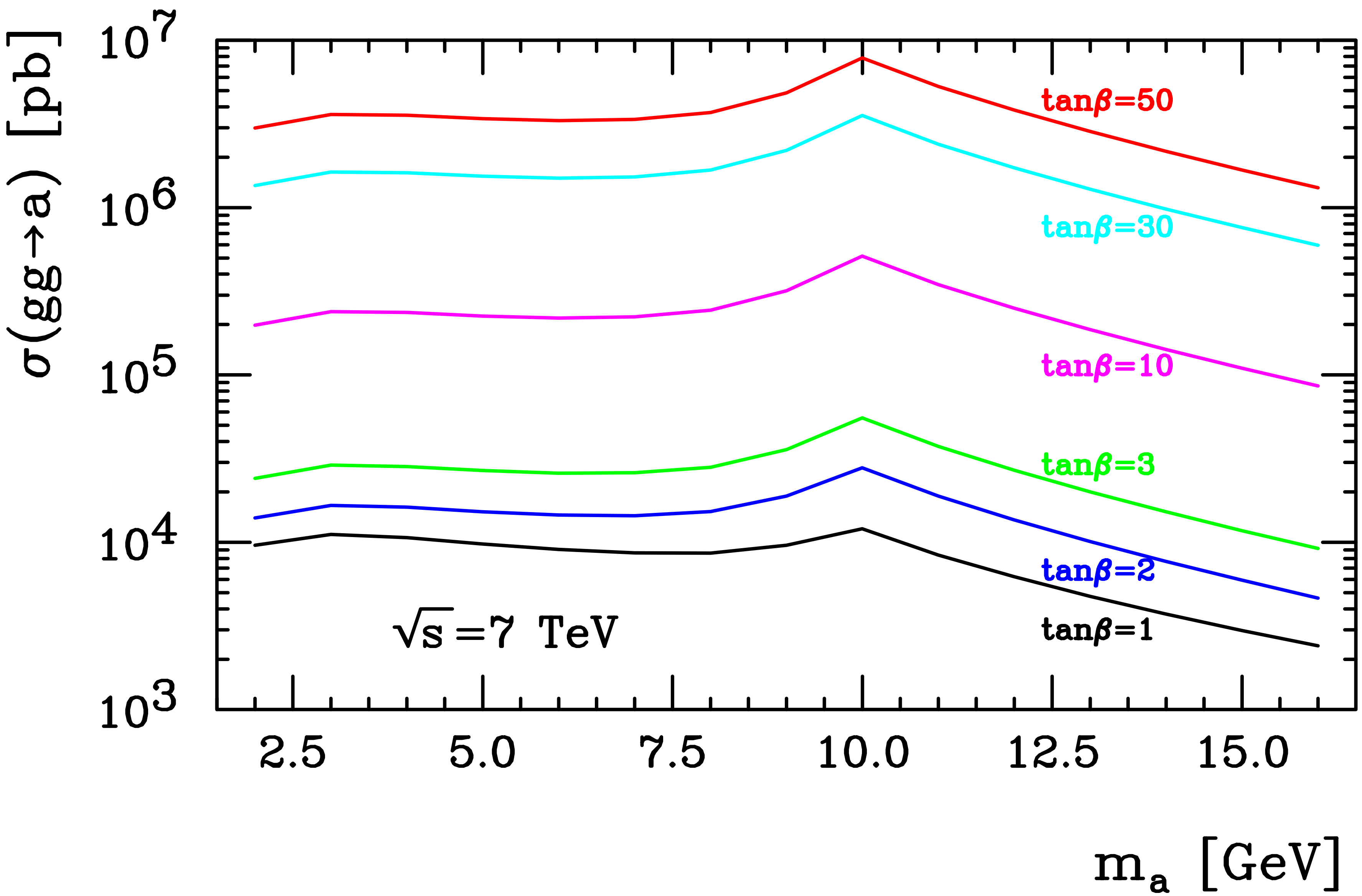
- NMSSM offers an attractive alternative to standard MSSM searches

- Looking forward to Run 2
  - Increased $\sqrt{s}$ → increased $\sigma(pp \to h/a)$
  - Increased luminosity → increased potential for rarer channels

Backup

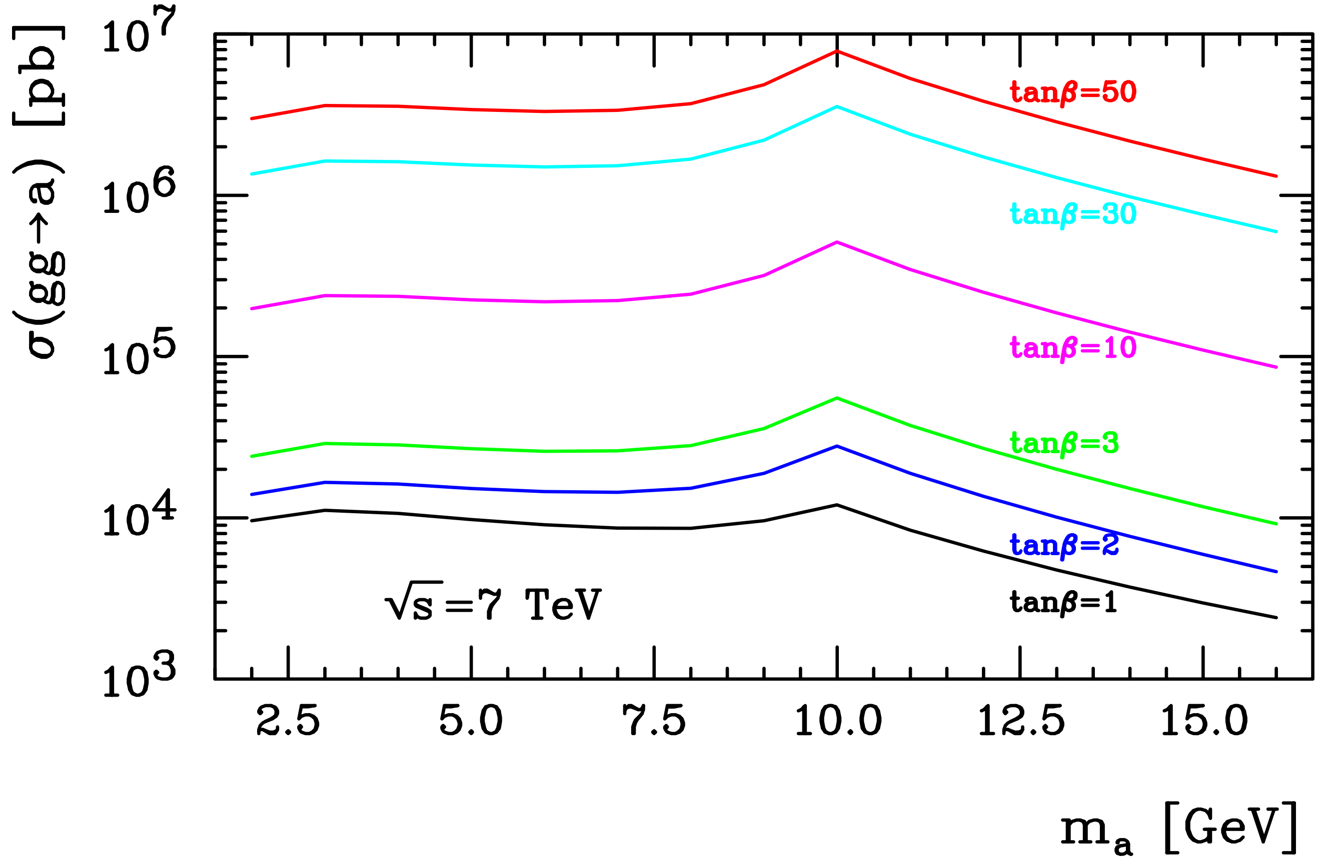
$gg \rightarrow a \rightarrow \mu\mu$

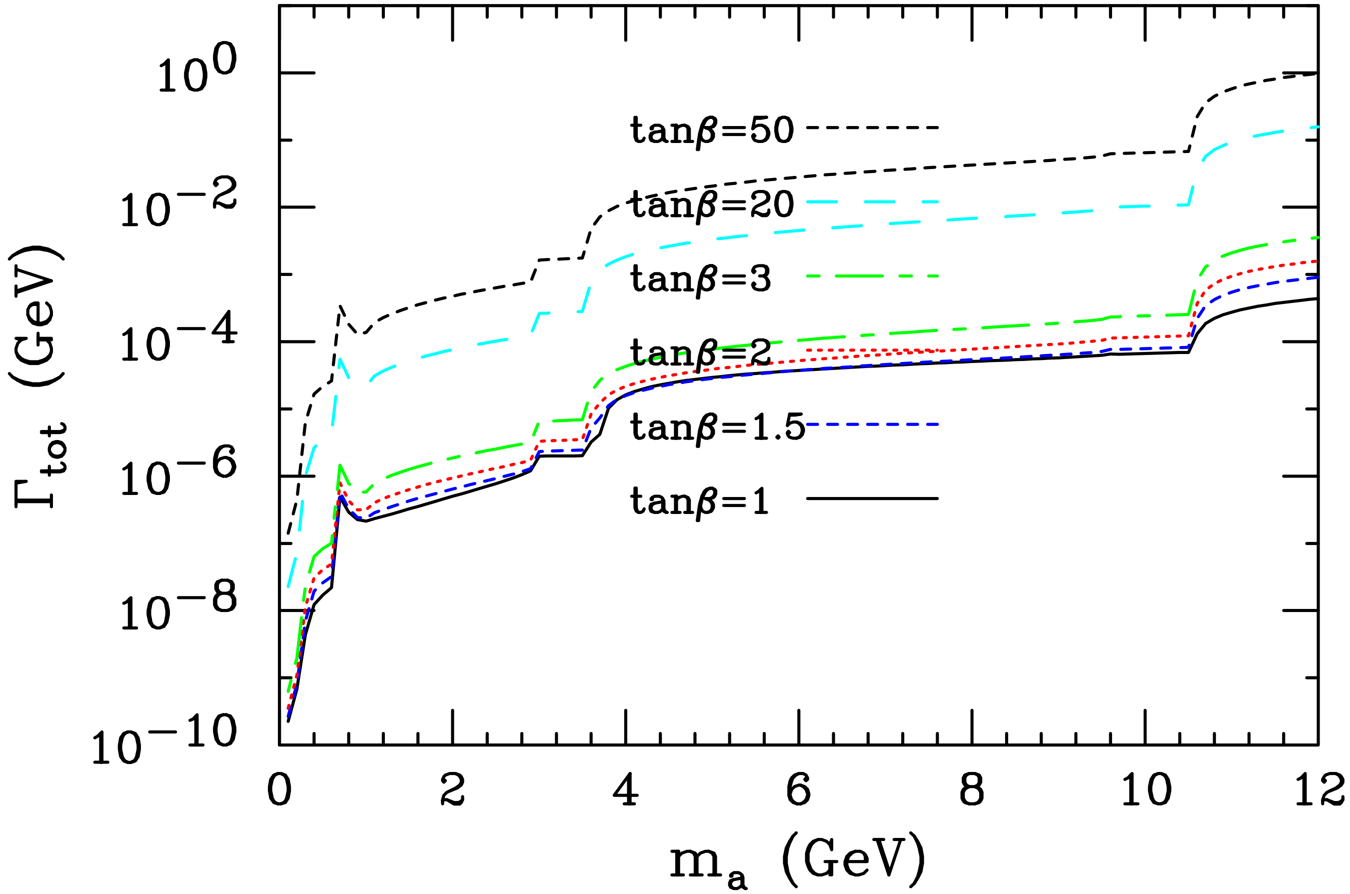
σ(gg → a) at 7 TeV

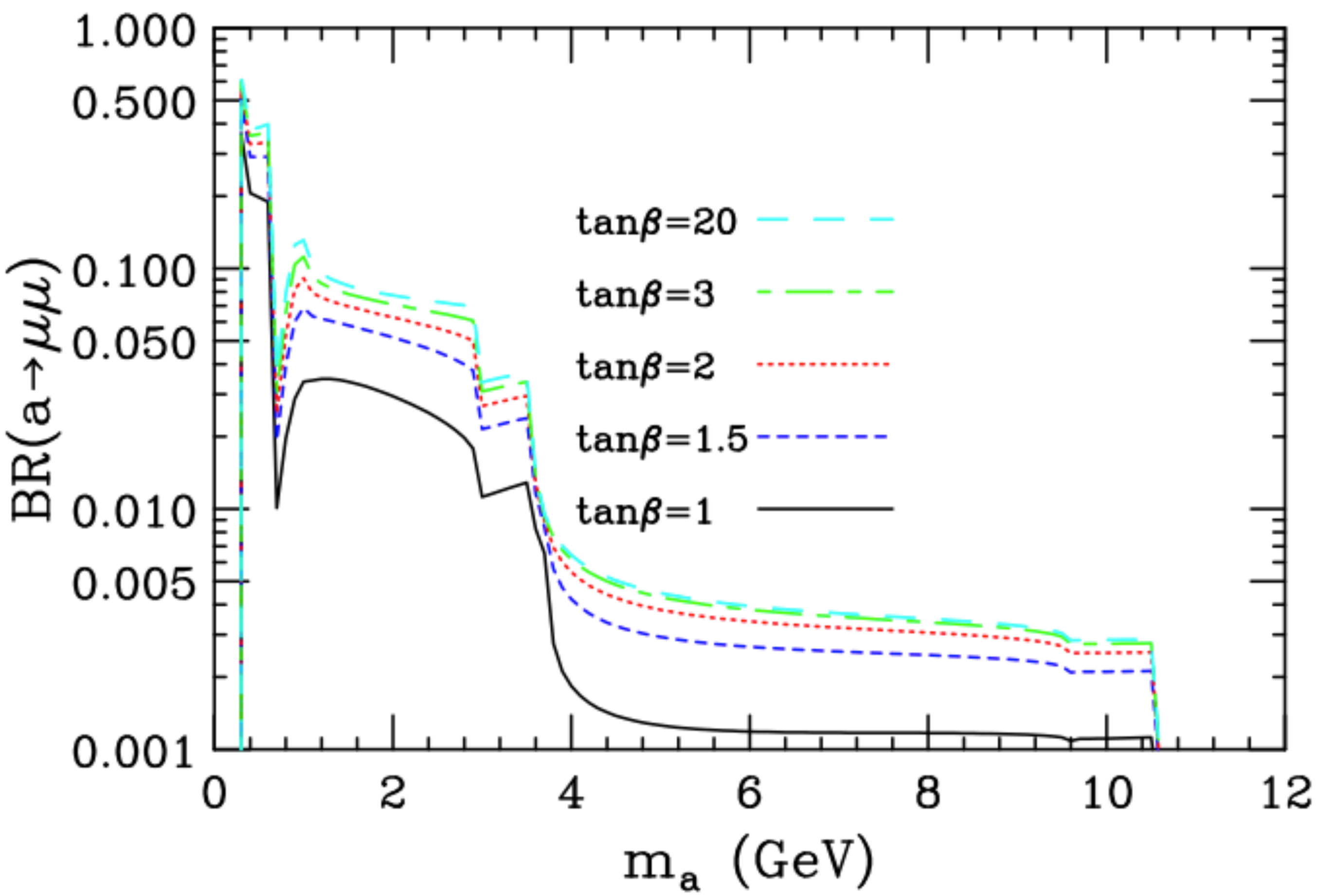


$\sigma(gg\to a)$ [pb]
10^7
10^6
10^5
10^4
10^3
tanβ=50
tanβ=30
tanβ=10
tanβ=3
tanβ=2
tanβ=1
$\sqrt{s}$=7 TeV
2.5
5.0
7.5
10.0
12.5
15.0
m_a [GeV]

a_1 properties

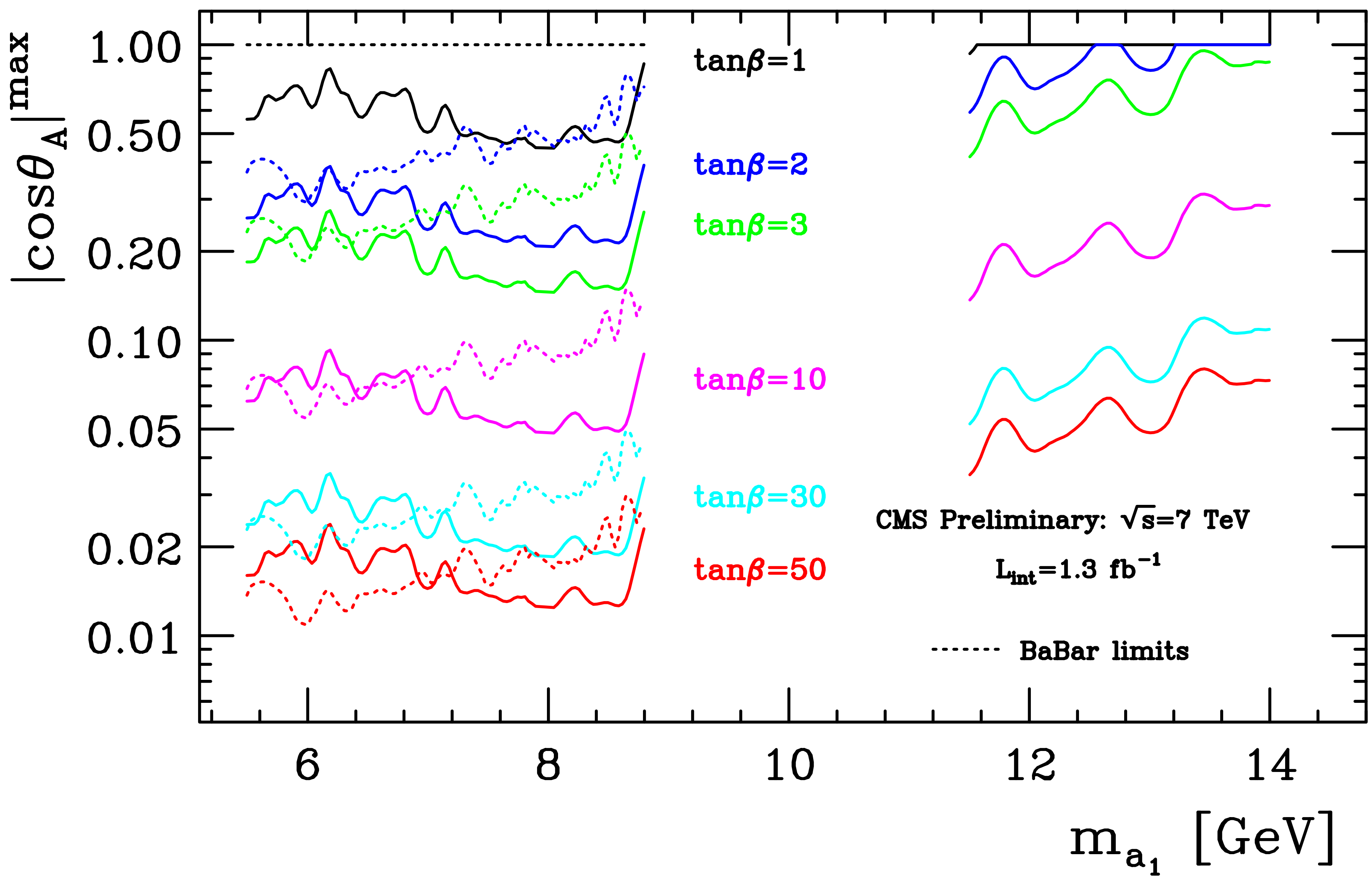






Results

- Can interpret as limit on $\cos\theta_A$ for various tan β
  - $\cos\theta_A$ = mixing angle for a_1 between MSSM doublet pseudoscalar & additional NMSSM singlet pseudoscalar



Better than BaBar limit for m_a > 7.5 GeV (tanβ=50), m_a > 6.5 GeV (tanβ=2)

Double crystal-ball

ATLAS-CONF-2014-031

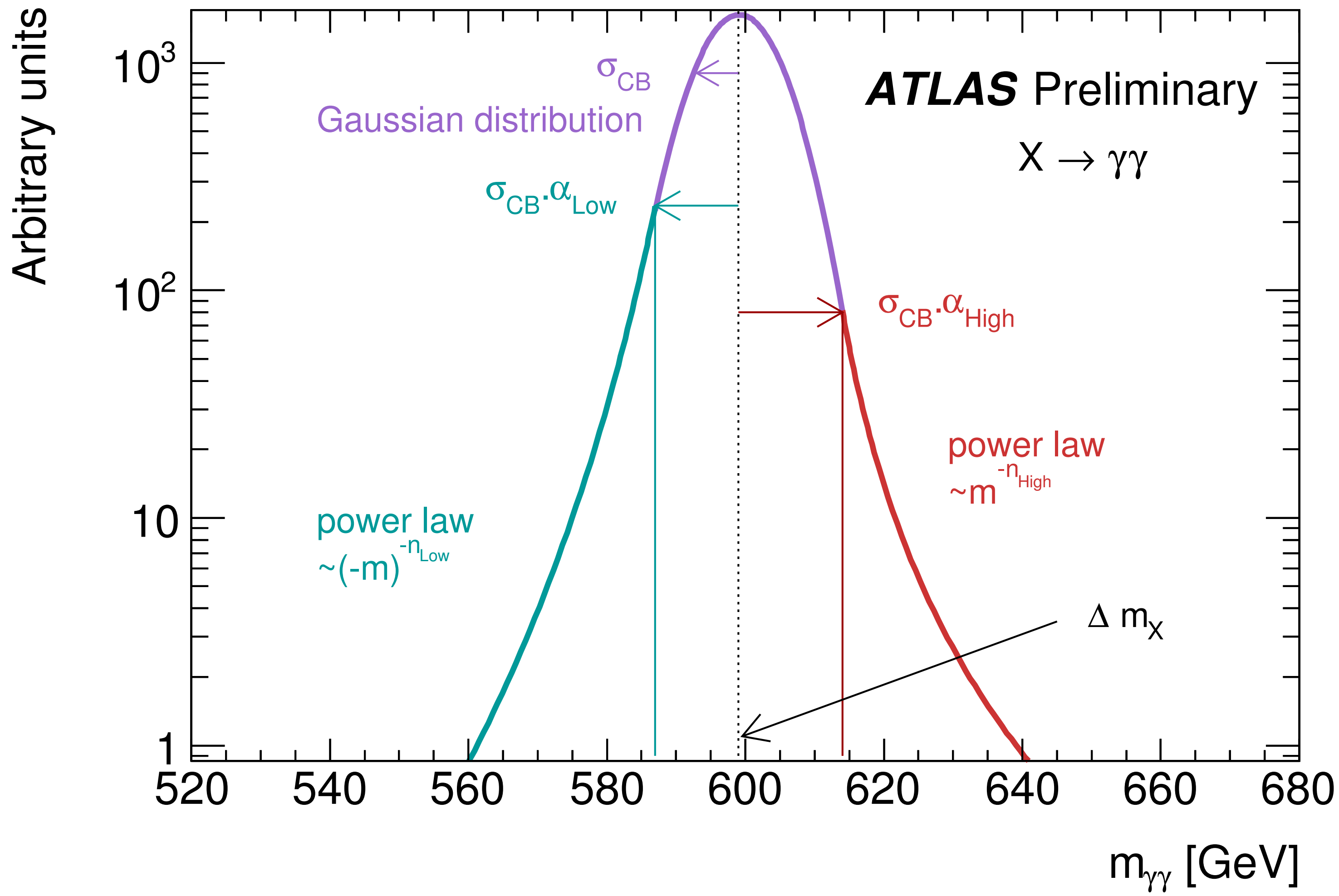


Figure 6: Description of the double-sided Crystal Ball function parameters: $\Delta m_X = m_X - \mu_{CB}$, where μ_{CB} is the peak of the Gaussian distribution, σ_{CB} represents the width of the Gaussian part of the function, α_{Low} (α_{High}) is the point where the Gaussian becomes a power law on the low (high) mass side, n_{Low} (n_{High}) is the exponent of this power law.

Backup

$h \rightarrow 2a \rightarrow 4\mu$

BR(a → XX)

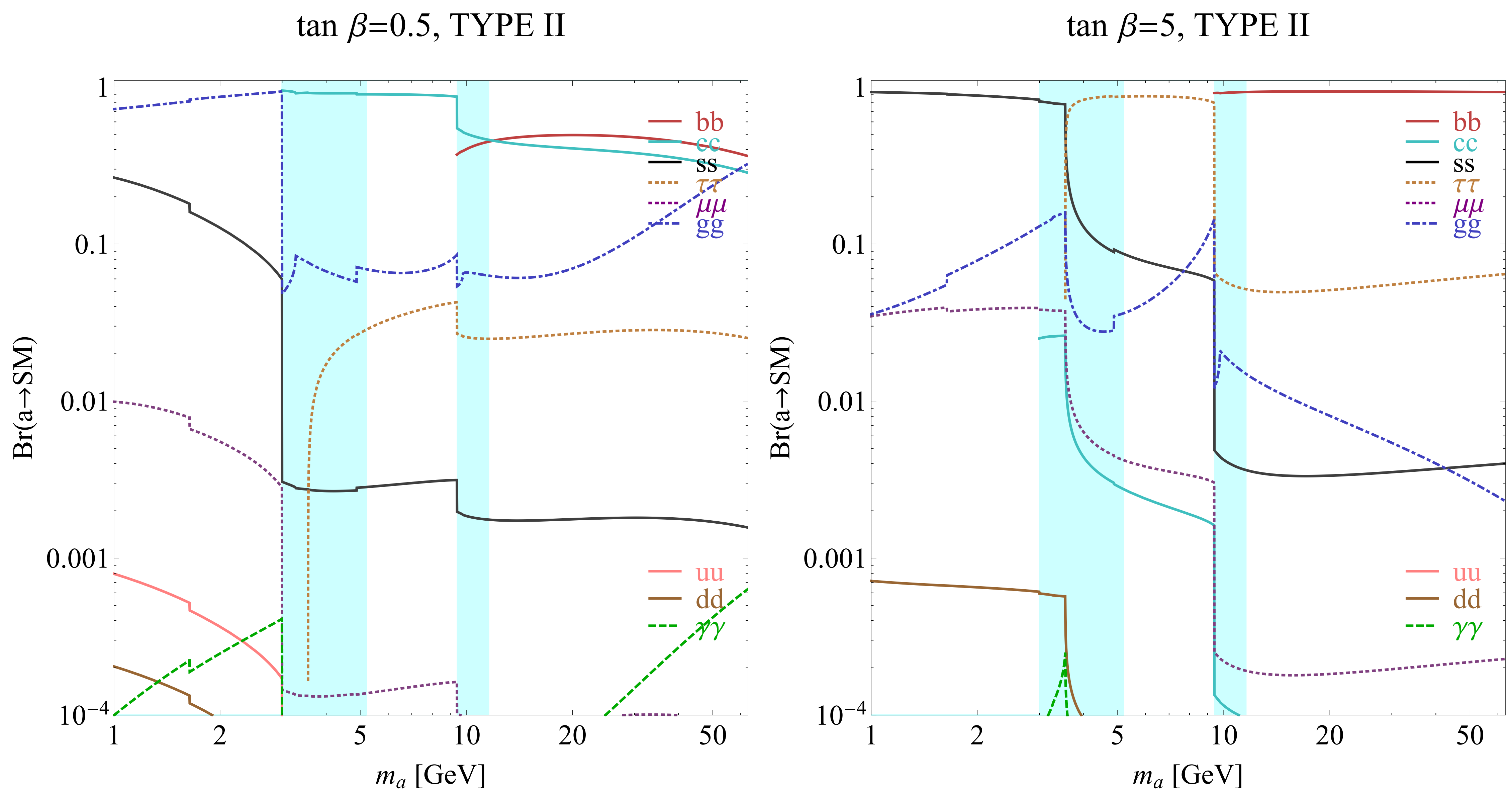


FIG. 7: Branching ratios of a singlet-like pseudoscalar in the 2HDM+S for Type II Yukawa couplings. Decays to quarkonia likely invalidate our simple calculations in the shaded regions.

BR(a → XX)

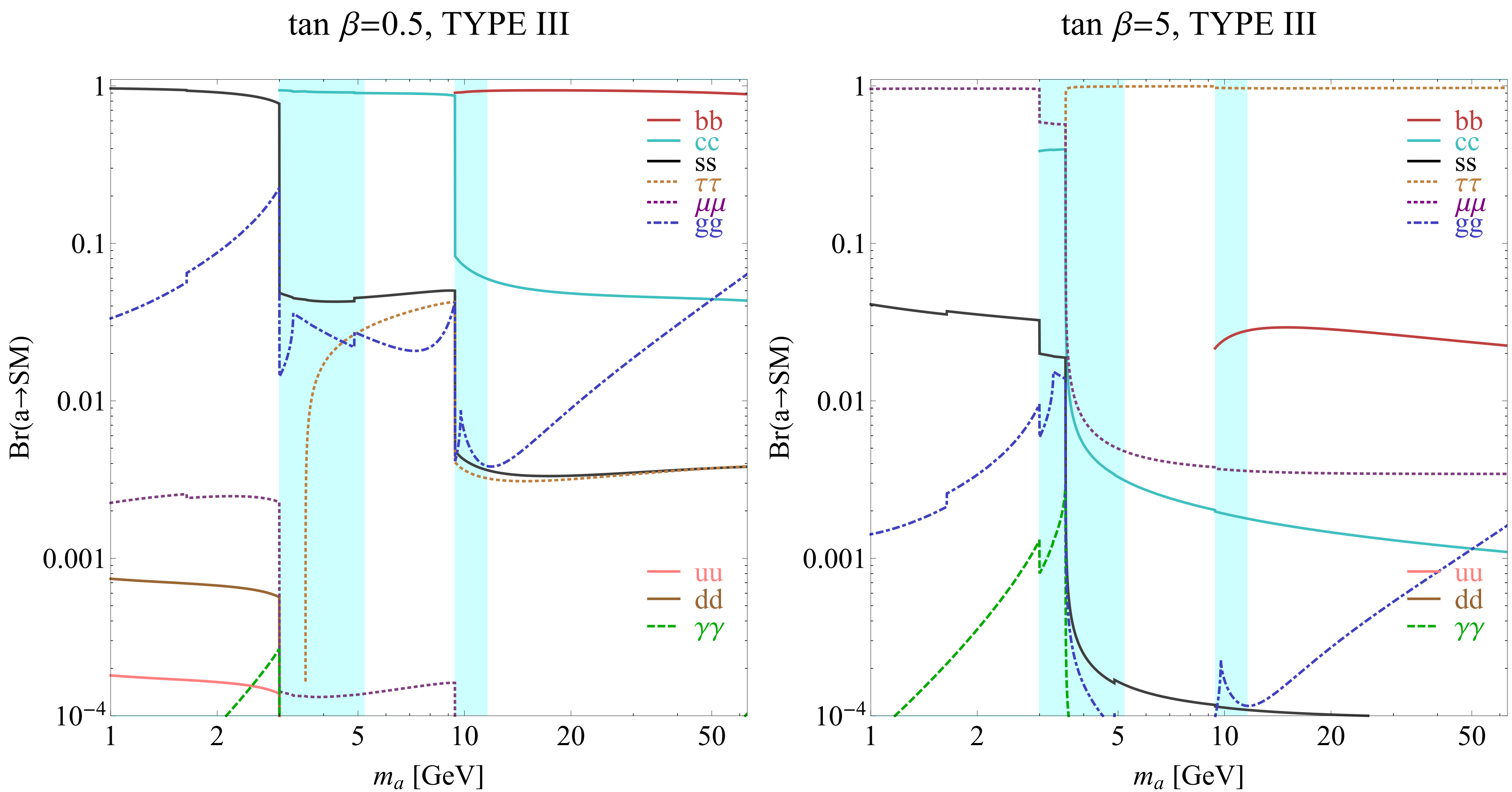


FIG. 8: Branching ratios of a singlet-like pseudoscalar in the 2HDM+S for Type III Yukawa couplings. Decays to quarkonia likely invalidate our simple calculations in the shaded regions.

Dark SUSY

- http://arxiv.org/abs/0810.0713
- http://arxiv.org/abs/0901.0283
- http://arxiv.org/abs/1002.2952

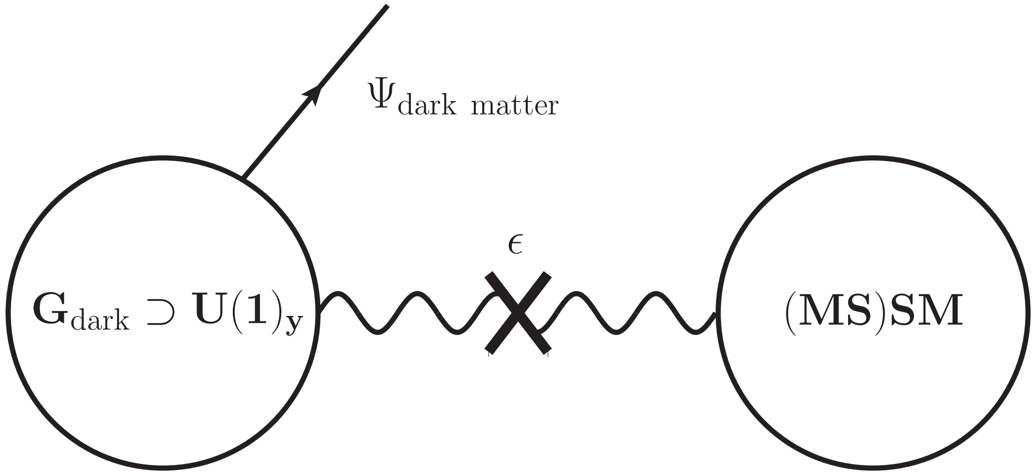
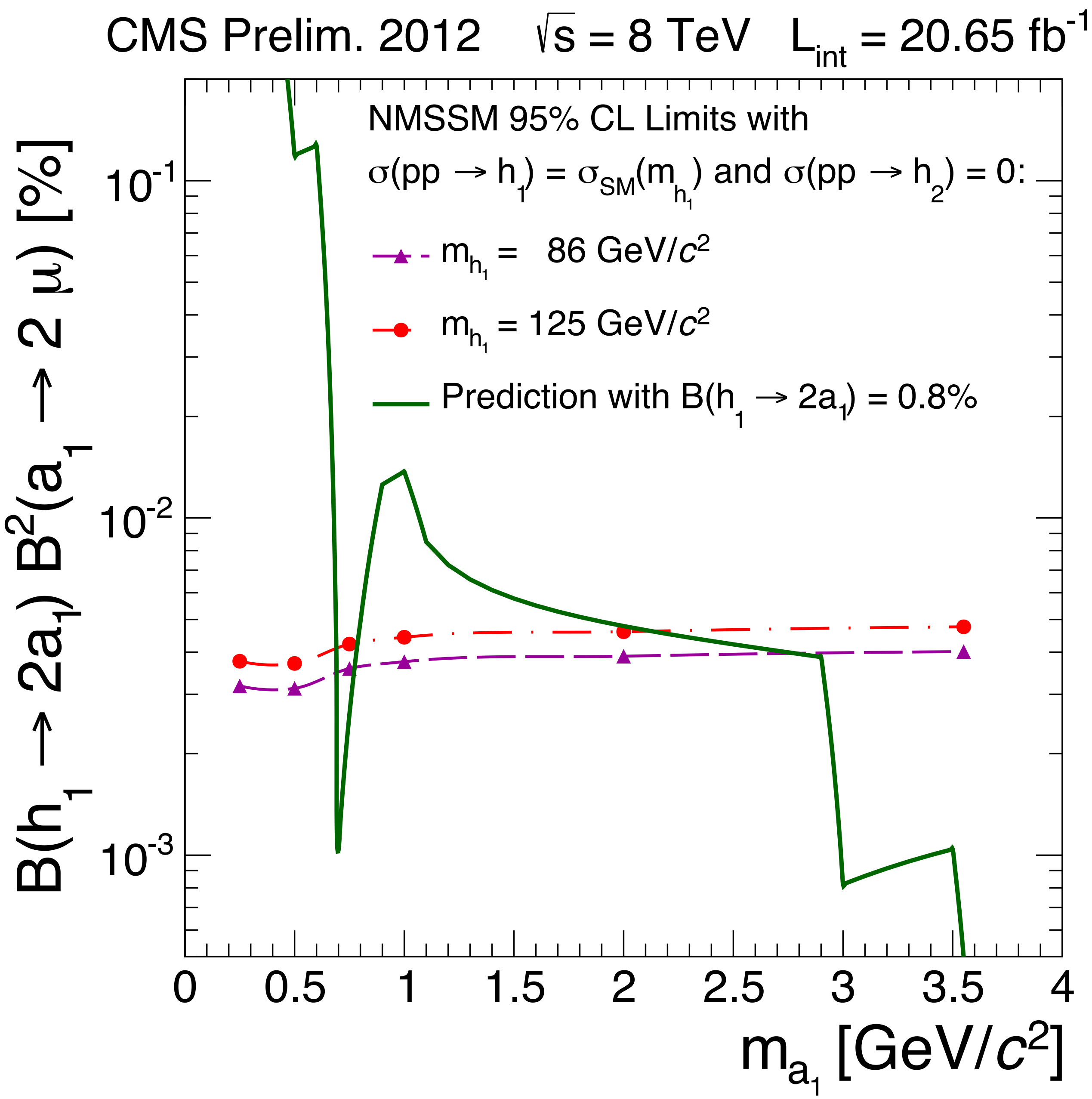


Figure 1: A schematic illustration of the minimal setup we consider in this paper. The dark sector and the SM are connected through kinetic mixing term suppressed by $\epsilon \lesssim 10^{-3}$. The dark matter multiplet may or may not couple directly to the SM. Supersymmetric extensions of this scenario are also discussed.

Limits



Assumes $\sigma(pp \rightarrow h_1) = \sigma_{SM}$,

$\sigma(pp \rightarrow h_2) = 0$

Backup

$h_1 \rightarrow bb$

P4 scenario

Table 1: Input and output parameters for the five benchmark NMSSM points.

Point	P1	P2	P3	P4	P5
GUT/input parameters					
sign($\mu_{\rm eff}$)	+	+	+	−	+
$\tan\beta$	10	10	10	2.6	6
m_0 (GeV)	174	174	174	775	1500
$M_{1/2}$ (GeV)	500	500	500	760	175
A_0	-1500	-1500	-1500	-2300	-2468
A_λ	-1500	-1500	-1500	-2300	-800
A_κ	-33.9	-33.4	-628.56	-1170	60
NUHM: M_{H_d} (GeV)	-	-	-	880	-311
NUHM: M_{H_u} (GeV)	-	-	-	2195	1910
Parameters at the SUSY scale					
λ (input parameter)	0.1	0.1	0.4	0.53	0.016
κ	0.11	0.11	0.31	0.12	-0.0029
A_λ (GeV)	-982	-982	-629	-510	45.8
A_κ (GeV)	-1.63	-1.14	-11.4	220	60.2
M_2 (GeV)	392	392	393	603	140
$\mu_{\rm eff}$ (GeV)	968	968	936	-193	303
CP even Higgs bosons					
$m_{h_1^0}$ (GeV)	120.2	120.2	89.9	32.3	90.7
R_1	1.00	1.00	0.998	0.034	-0.314
t_1	1.00	1.00	0.999	0.082	-0.305
b_1	1.018	1.018	0.975	-0.291	-0.644
BR($h_1^0 \to bb$)	0.072	0.056	7×10^{-4}	0.918	0.895
BR($h_1^0 \to \tau^+\tau^-$)	0.008	0.006	7×10^{-5}	0.073	0.088
BR($h_1^0 \to a_1^0 a_1^0$)	0.897	0.921	0.999	0.0	0.0
$m_{h_2^0}$ (GeV)	998	998	964	123	118
R_2	-0.0018	-0.0018	0.005	0.999	0.927
t_2	-0.102	-0.102	-0.095	0.994	0.894
b_2	10.00	10.00	9.99	1.038	2.111
BR($h_2^0 \to bb$)	0.31	0.31	0.14	0.081	0.87
BR($h_2^0 \to t\bar{t}$)	0.11	0.11	0.046	0.0	0.0
BR($h_2^0 \to a_1^0 Z^0$)	0.23	0.23	0.72	0.0	0.0
$m_{h_3^0}$ (GeV)	2142	2142	1434	547	174
CP odd Higgs bosons					
$m_{a_1^0}$ (GeV)	40.5	9.1	9.1	185	99.6
t'_1	0.0053	0.0053	0.0142	0.0513	-0.00438
b'_1	0.529	0.528	1.425	0.347	-0.158
BR($a_1^0 \to bb$)	0.91	0.	0.	0.62	0.91
BR($a_1^0 \to \tau^+\tau^-$)	0.085	0.88	0.88	0.070	0.090
$m_{a_2^0}$ (GeV)	1003	1003	996	546	170
Charged Higgs boson					
$m_{h^\pm}$ (GeV)	1005	1005	987	541	188

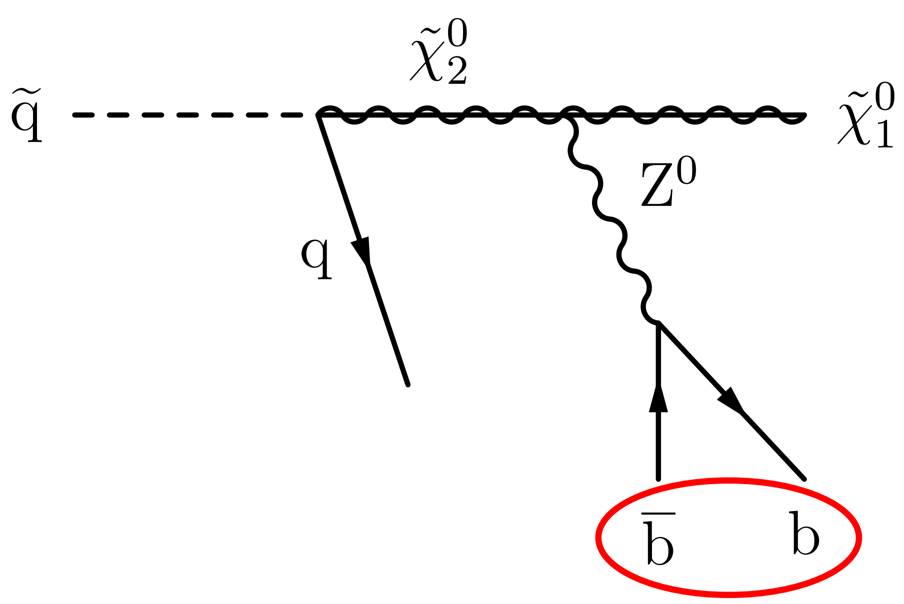
Table 2: LSP properties and relic density for the five benchmark NMSSM points.

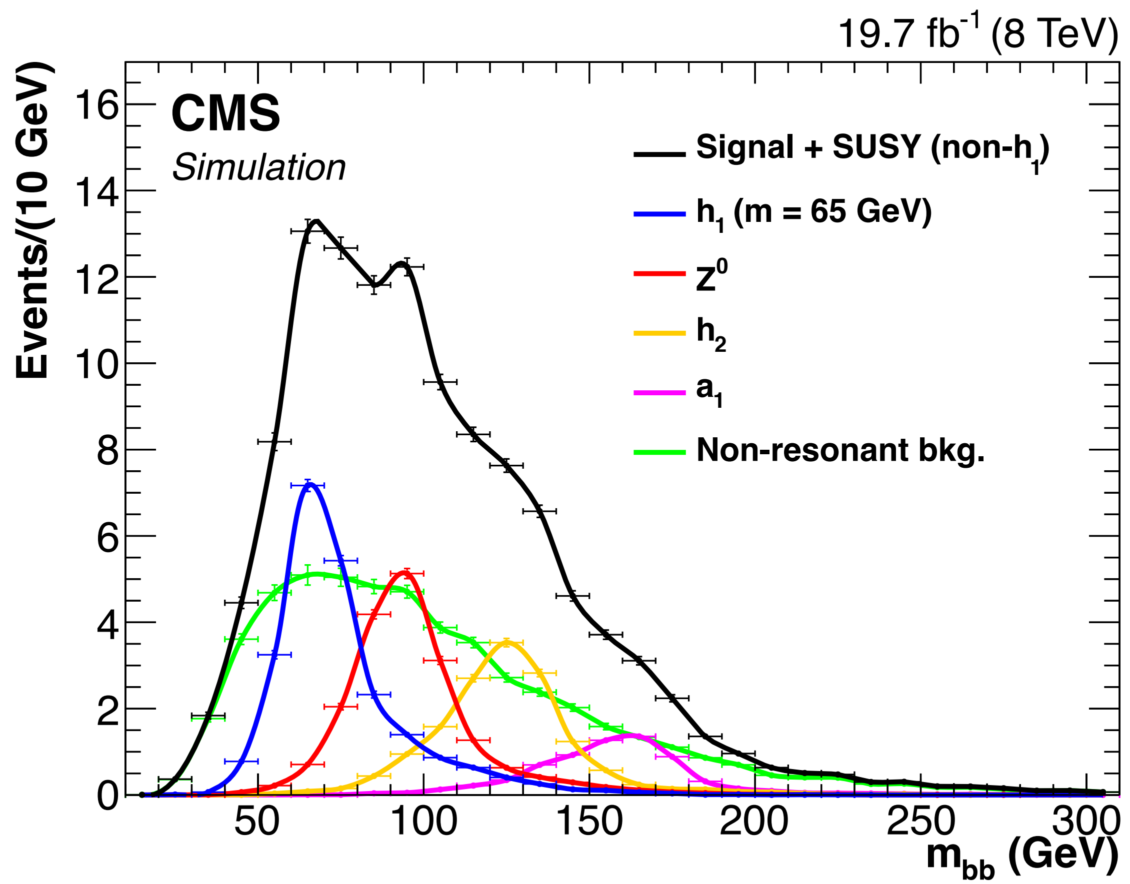
Point	P1	P2	P3	P4	P5
Dark matter					
LSP (χ_1^0) mass (GeV)	208	208	208	101	70.4
N_{11}	0.999	0.999	0.999	-0.039	0.977
N_{12}	-0.008	-0.008	-0.009	0.043	-0.098
N_{13}	0.048	0.048	0.050	-0.028	0.178
N_{14}	-0.015	-0.015	-0.016	0.405	-0.068
N_{15}	0	0	0.003	0.912	-0.003
$\Omega_{\rm CDM}h^2$	0.099	0.099	0.130	0.099	0.105

arxiv: 0801.4321

Signal modelling

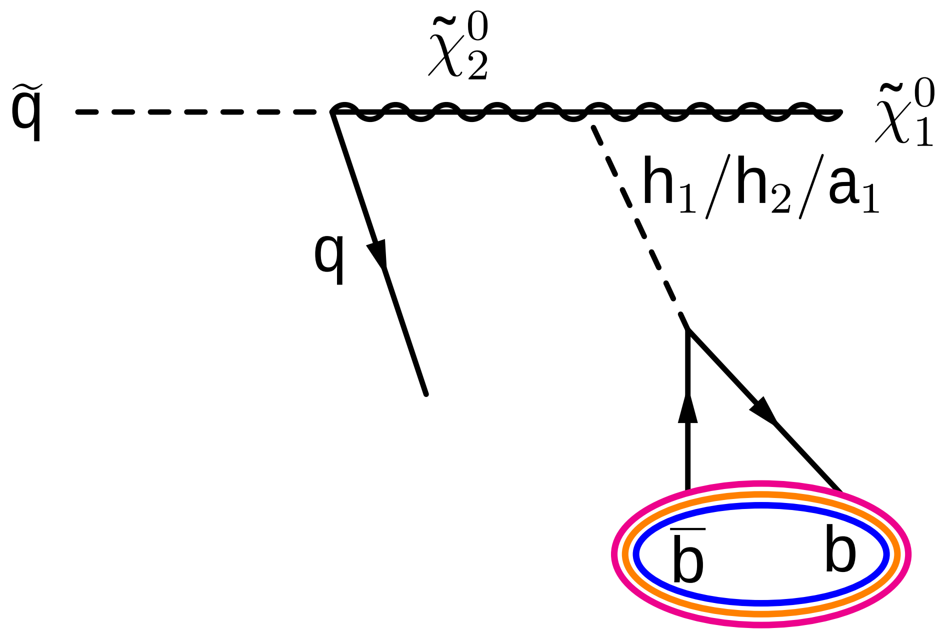
- Signal modelled with Madgraph+Pythia
- Complications from non-h_1 SUSY processes:
  - $Z \to bb$

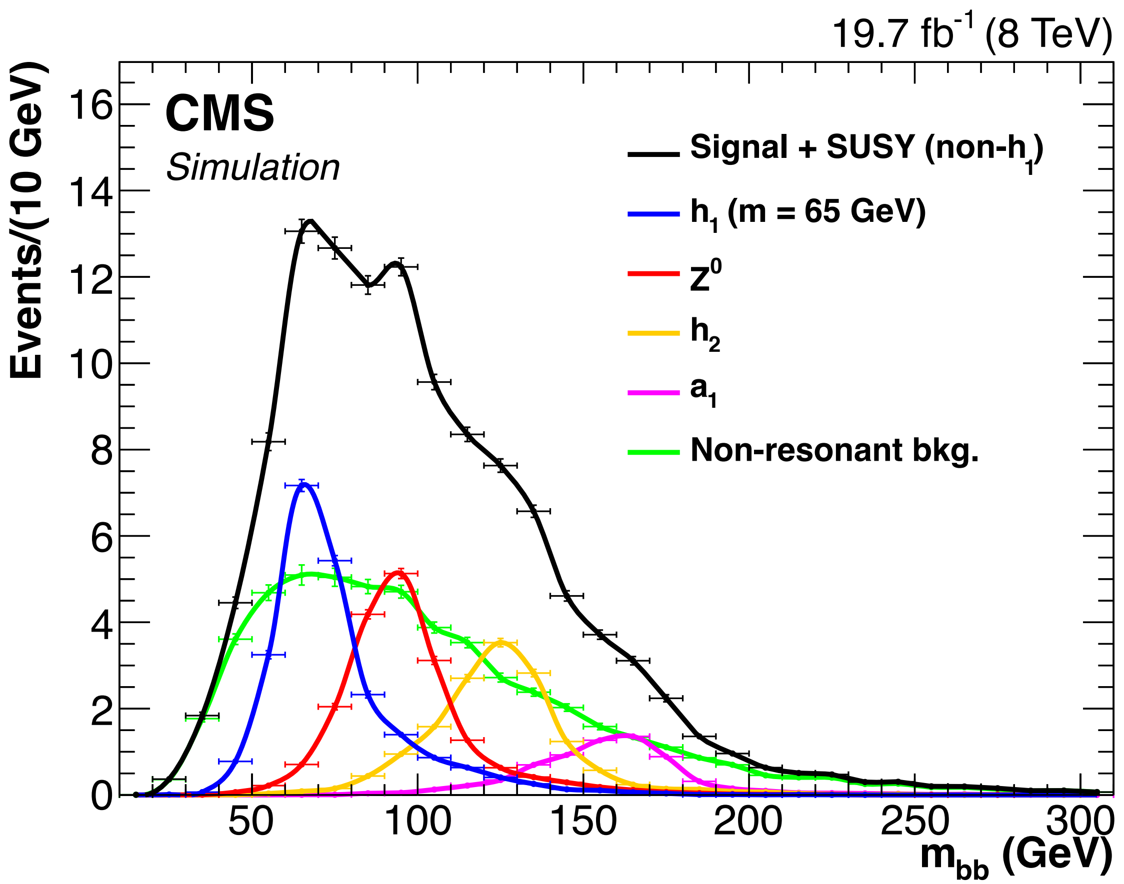




Signal modelling

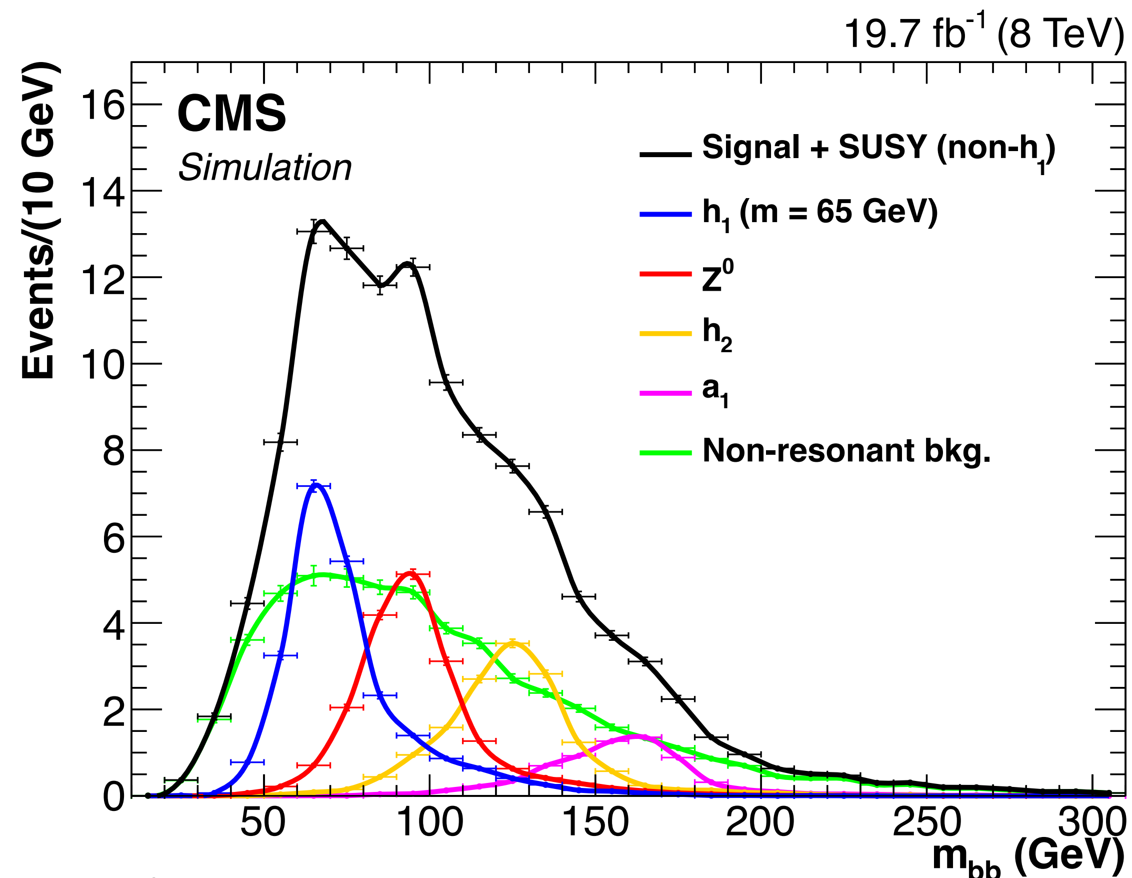
- Signal modelled with Madgraph+Pythia
- Complications from non-h_1 SUSY processes:
  - $Z \to bb$
  - $h_2/a_1 \to bb$

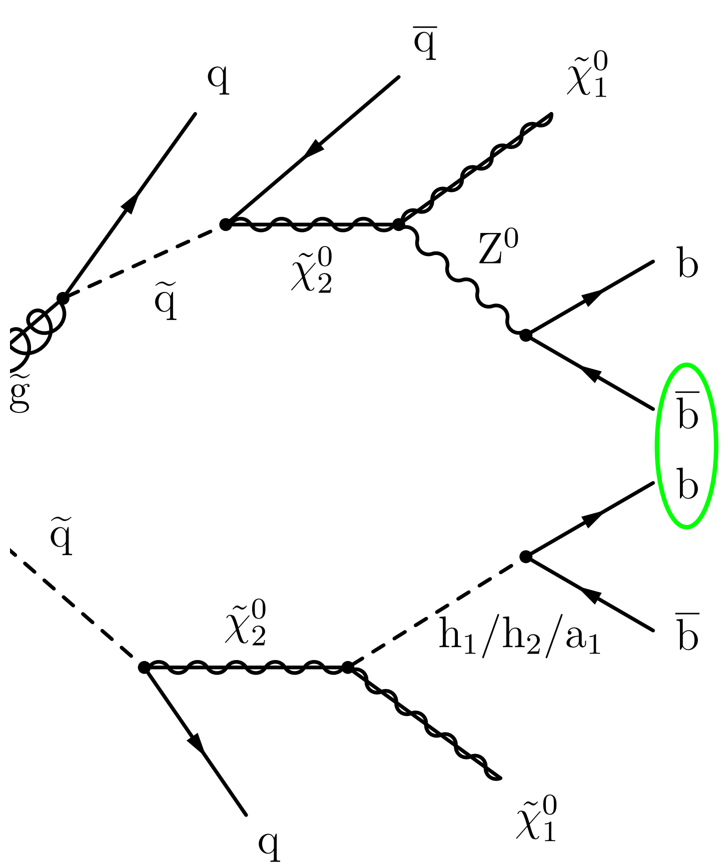


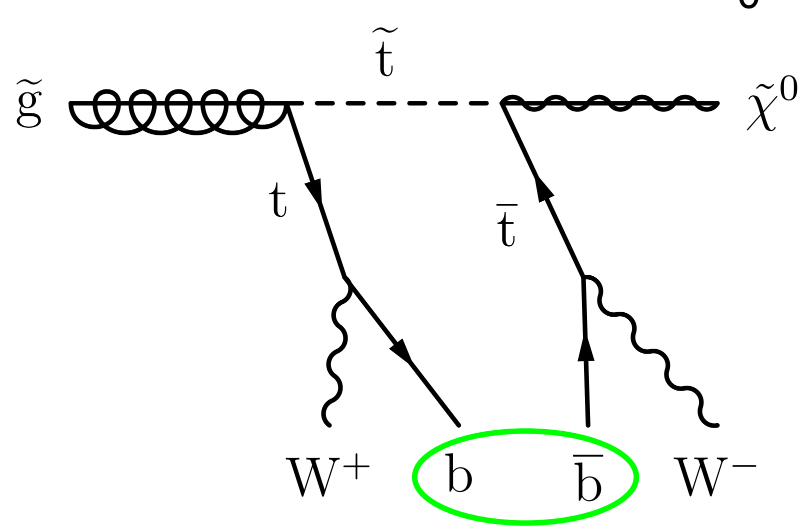


Signal modelling

- Signal modelled with Madgraph+Pythia
- Complications from non-h_1 SUSY processes:
  - $Z \rightarrow bb$
  - $h_2/a_1 \rightarrow bb$
  - Non-resonant







P4 scenario yields

Table 6: Expected event yields for the various signal (NMSSM P4 scenario, $m_{\mathrm{h}_1} = 65\,\mathrm{GeV}$) and background contributions and the rate observed in data.

Contribution	Rate
$\mathrm{h}_1 \to \mathrm{b}\bar{\mathrm{b}}$	22.7±3.1
SUSY (non-h_1)	92.4±13.6
$\mathrm{t}\bar{\mathrm{t}}$	82.5±16.5
QCD	56.4±24.8
$\mathrm{W} \to \ell\nu$	4.8±1.0
$\mathrm{Z}^0 \to \nu\bar{\nu}$	2.3±0.5
total expected background	146±42.8
data	148±12.2

h1 → bb systematics

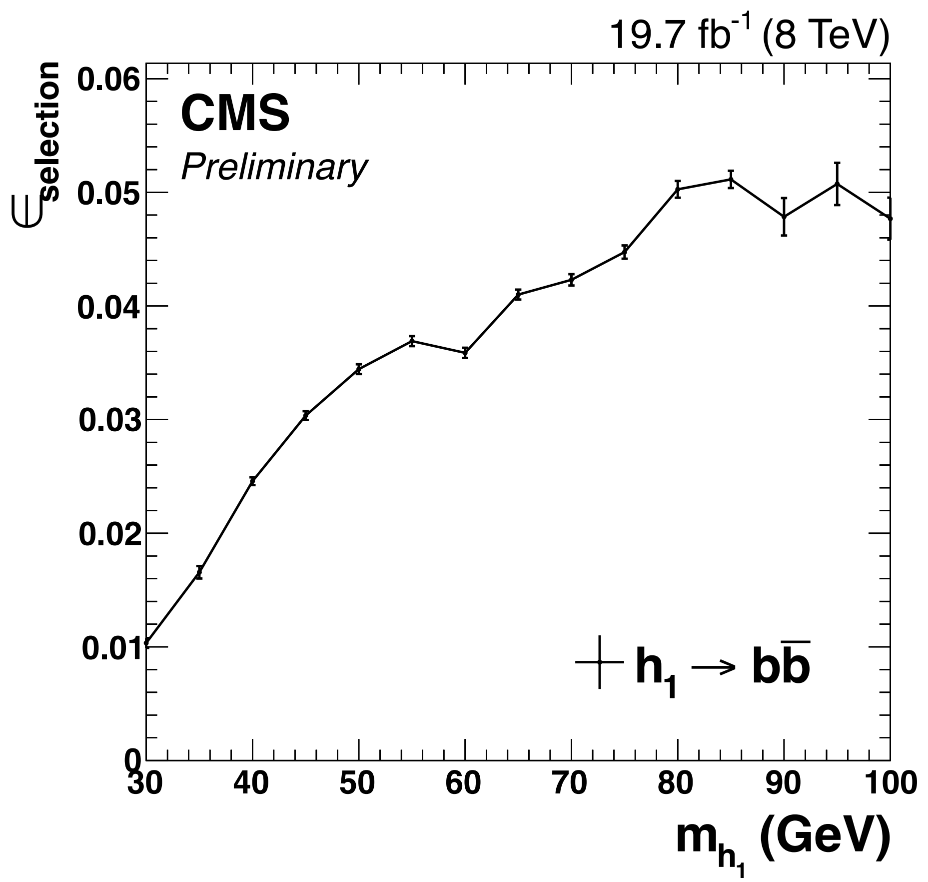
Table 5: Systematic uncertainties and their relative impact on the expected limit. The impact numbers have been averaged across the Higgs mass points.

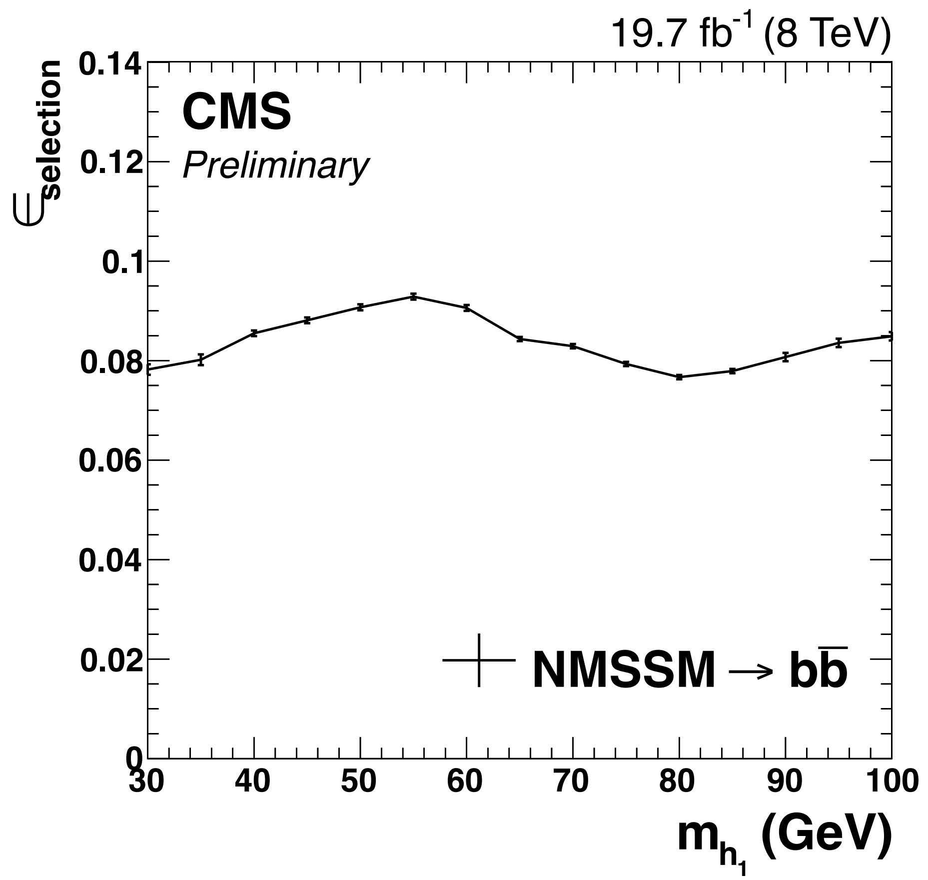
Systematics source	Event category	Type	Impact
Normalization of $t\bar{t}$	Background	rate	1.7 %
Normalization of QCD	Background	rate	2 %
Shape correction QCD	Background	shape + rate	3 %
QCD shape parameterization	Background	shape + rate	1 %
MC statistics $t\bar{t}$	Background	shape + rate	1.3 %
MC statistics $W \to \ell\nu$	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 %
JES	Signal + Background	shape + rate	1.3 %
JER	Signal + Background	shape + rate	0.1 %
τ energy scale	Signal + Background	shape + rate	0.6 %

The shape altering systematics were accounted for in the fits and upper limit determination via nuisance parameters. The systematic uncertainties with non-negligible impact on the expected upper limit are listed in Table 5.

→ Uncertainties are stats-dominated

$h1 \rightarrow bb$ efficiency





Selection efficiency including h1 matching efficiency

Subtlety at 60 GeV - above 60 GeV, $h_2 \rightarrow h_1 h_1$ possible, thereby increasing b-jet multiplicity, which affects the b-veto on the 2 leading non-b-jets

Selection efficiency in modified P4 scenario

Decoupled squark limits