Minimal Supersymmetric Models

[Repetition]

Extension of the Standard Model

Supersymmetric partner for each SM particle

2 Higgs doublets

Minimal structure to guarantee cancellations of anomalies
Two Higgs fields needed to give masses to 'up'
and 'down' type quarks in a consistent way

New quantum number: R-parity R_p

Particles: $R_p = +1$

S-Particles: $R_p = -1$

R_p-conservation circumvents proton decay;
conservation of B-L

$$R_p = (-1)^{B+L+2S}$$

Motivation of SUSY

Avoid divergent quantum corrections to Higgs mass

Allows for unification of gauge couplings

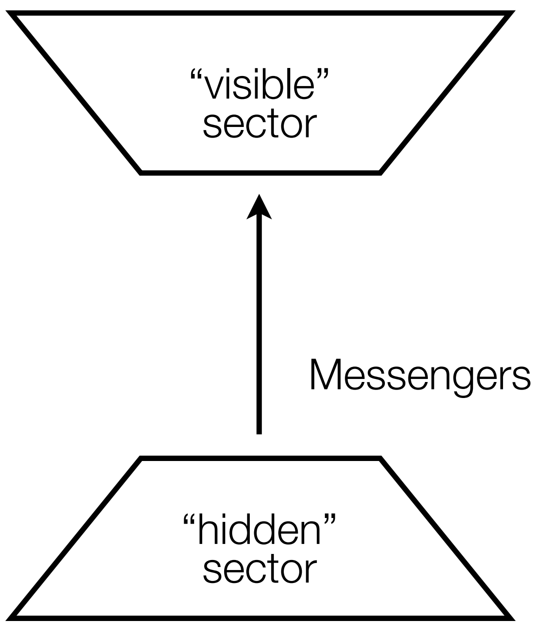
Existence of lightest supersymmetric particle (LSP);
candidate for dark matter

Minimal Supersymmetric Models

[Repetition]

Supersymmetry is not an exact symmetry

... as SUSY particles are not observed at low masses



completely neutral with respect to SM gauge group

Needs model(s) for (soft) symmetry breaking

Most models assume “hidden” sector ...

Hidden sector: particles neutral to SM gauge group

Visible sector: MSSM particle spectrum

SUSY breaking occurs in the hidden sector

Transmitted to MSSM by specific mechanism:

Gravity Mediated Supersymmetry Breaking (mSUGRA, cMSSM)

Gauge Mediated Supersymmetry Breaking (GMSB)

Anomaly Mediated Supersymmetry Breaking (AMSB)

LSP: Neutralino

LSP: Gravitino

SUSY breaking leads to extra parameters

Unconstrained models: 105 parameters (Masses, couplings, phases)

Constrained models: 4 or 5 parameters, assuming SUSY breaking scheme

Examples: mSugra, cMSSM ...

mSUGRA – A Constrained Model

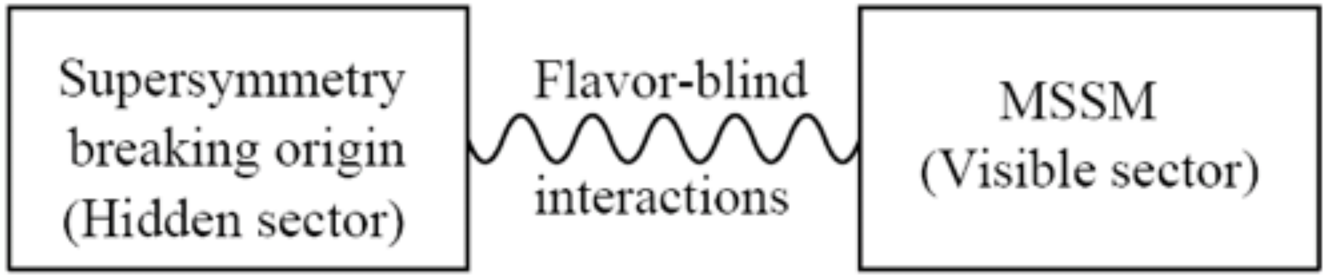
[Repetition]

Unification assumption

Assume universal masses for all bosons and fermions at the GUT (Grand Unification Theory) scale

Symmetry breaking assumption

Model where breaking is mediated by gravity



Results in

5 remaining parameters

m_0: universal boson (scalar) mass

$m_{1/2}$: universal gaugino mass

A_0: universal trilinear coupling

$\tan\beta$: ratio of the two Higgs VEVs (vacuum expectation values)

$\mathrm{sgn}(\mu)$: sign of the higgsino mass parameter

MSSM Higgs Sector

[Repetition]

Consider MSSM Higgs:

Two Higgs doublets ➛ 5 physical Higgs bosons: h, H, A, $H^{\pm}$ …

Enhanced coupling to 3rd generation …
Strong coupling to down-type fermions …
[at large tanβ get strong enhancements to h/H/A production rates]

Couplings: $g_{MSSM} = \xi \cdot g_{SM}$

ξ	t	b/τ	W/Z
h	cosα/sinβ	- sinα/cosβ	sin(α-β)
H	sinα/sinβ	cosα/cosβ	cos(α-β)
A	cotβ	tanβ	–

Mixing angels: α,β

α: Mixing of CP even Higgs H_u,H_d ➛ h,H
β: Mixing of charged fields $\phi^{\pm}_{1,2}$
[also: tanβ = v_u/v_d]

usually vanishing
[decoupling limit; $M_A \gg M_Z$]

Large tanβ:
Enhancement of Higgs couplings to b,τ …
[and decreased coupling to top …]

Searching for the MSSM Higgs

[Repetition]

A popular and well-studied extension …

Mass of light CP-even Higgs m_h < 135 GeV

For large parts of the parameter space
H ➛ bb and H ➛ ττ decays dominate
[and also $H^{\pm}$ ➛ $\tau^{\pm}\nu$; see later]

WW/ZZ decays are suppressed
for heavier CP-even Higgs H …
[decoupling limit]

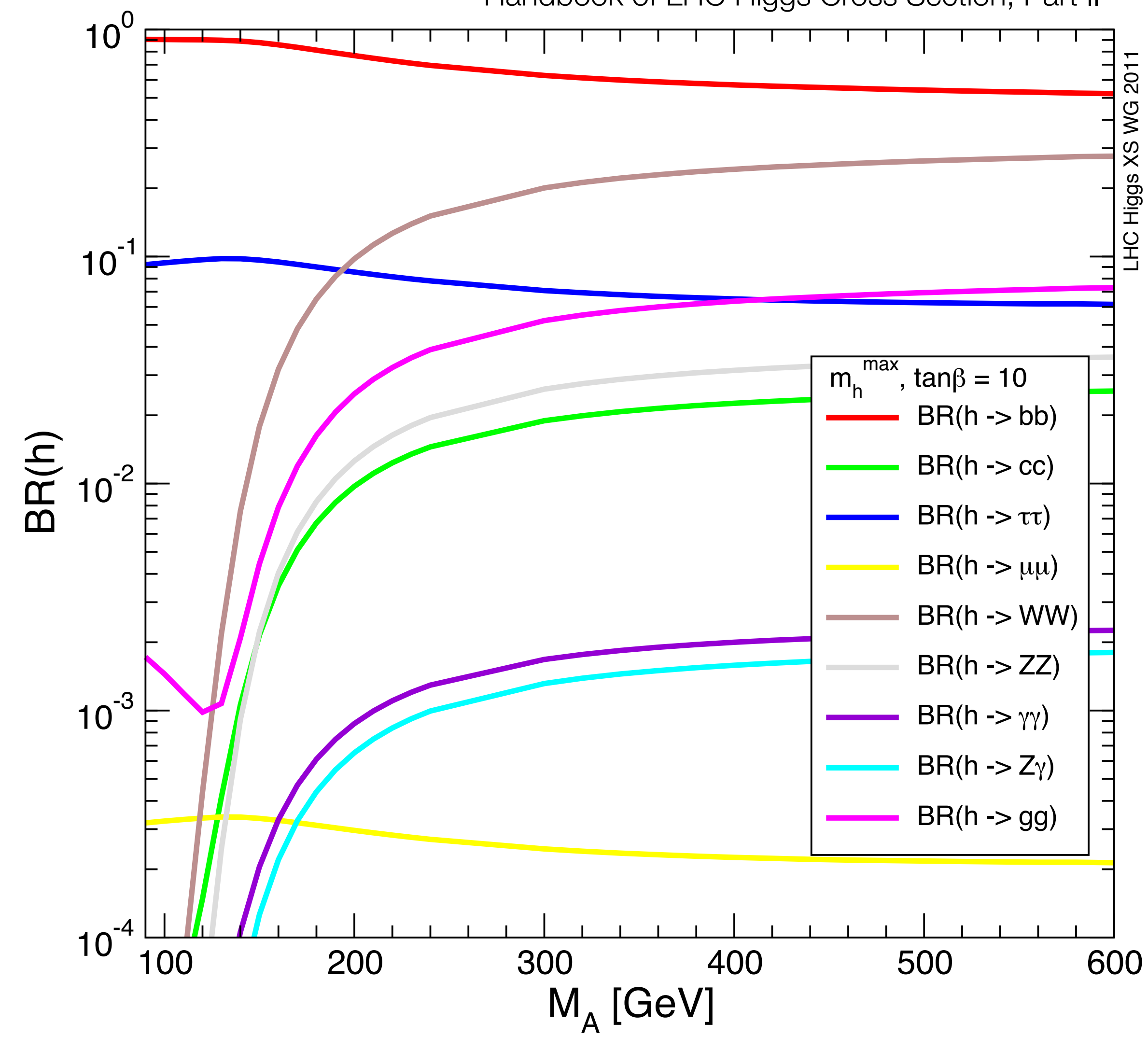
Use m_h^{max} Scenario …

[Carena et al.]

MSSM parameters chosen
to maximize m_h for given m_A, tanβ …

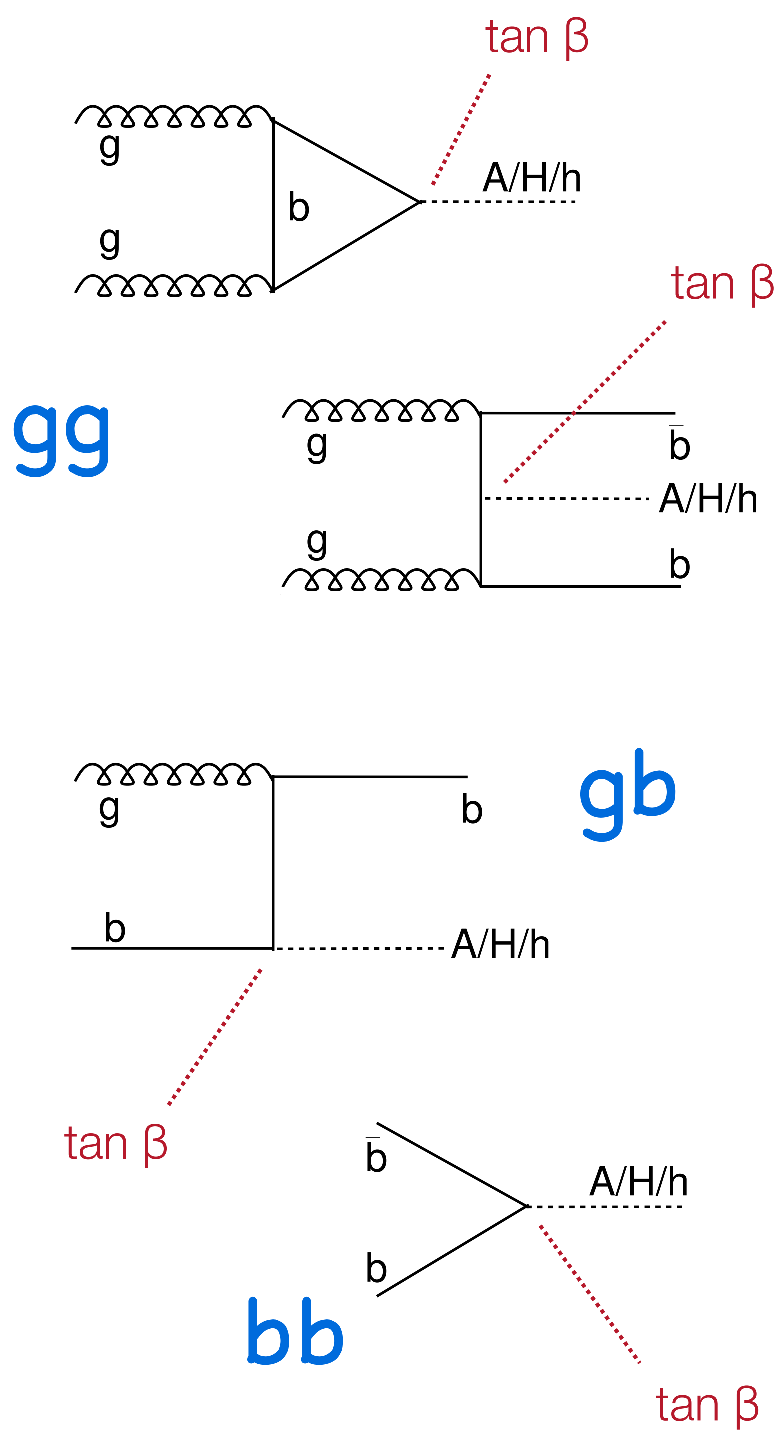
➛ M_A < 130 GeV: $m_h \approx m_A$, $m_H \approx$ 130 GeV
M_A > 130 GeV: $m_h \approx m_H$, $m_h \approx$ 130 GeV

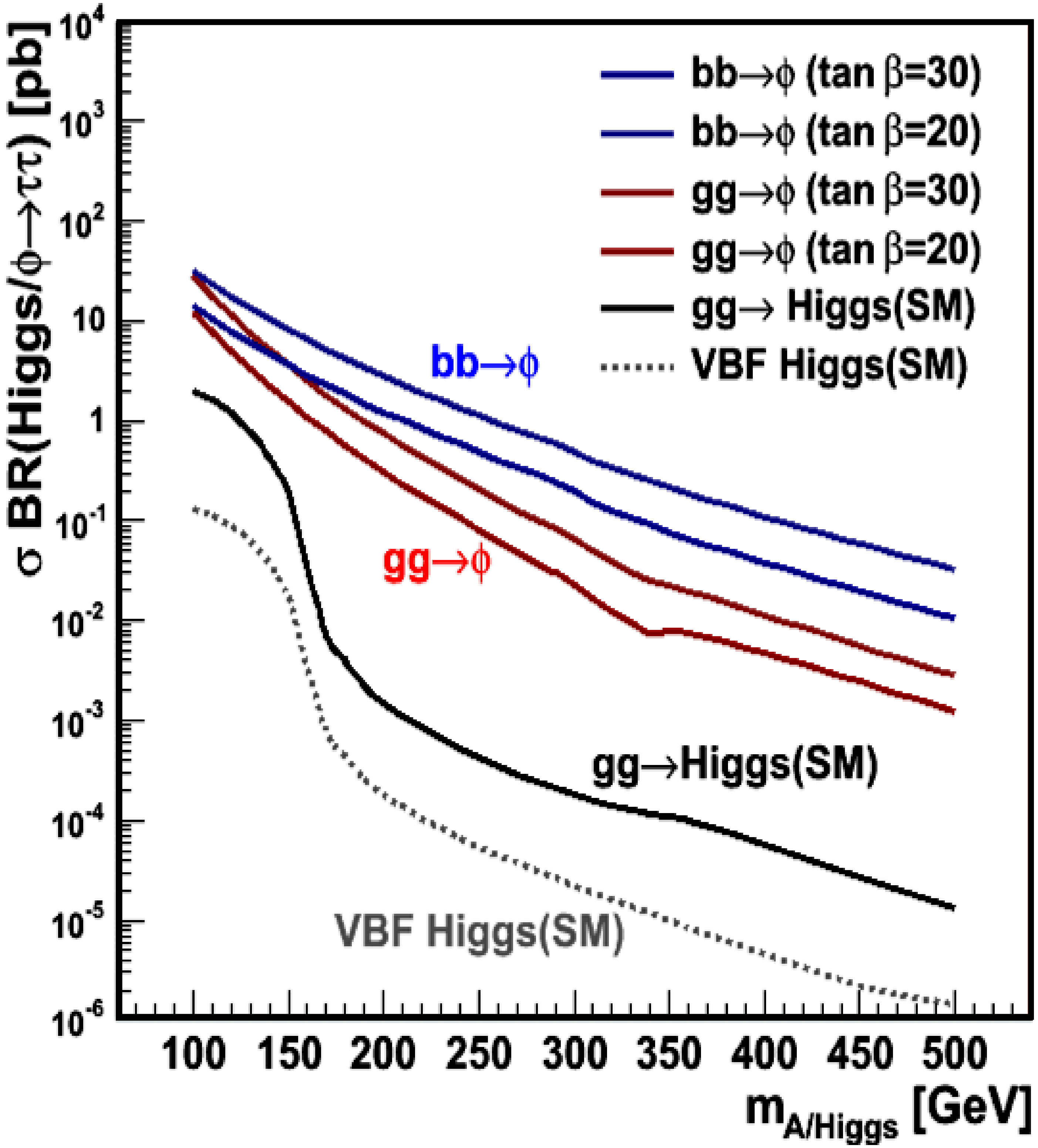
[arXiv:1201.3084]
Handbook of LHC Higgs Cross Section, Part II



MSSM Higgs Production

[Repetition]





[CMS]

MSSM Φ(h,H,A) ➛ ττ

Event Selection: eμ, $e\tau_h$, $\mu\tau_h$ signatures …
[oppositely charged; isolation]

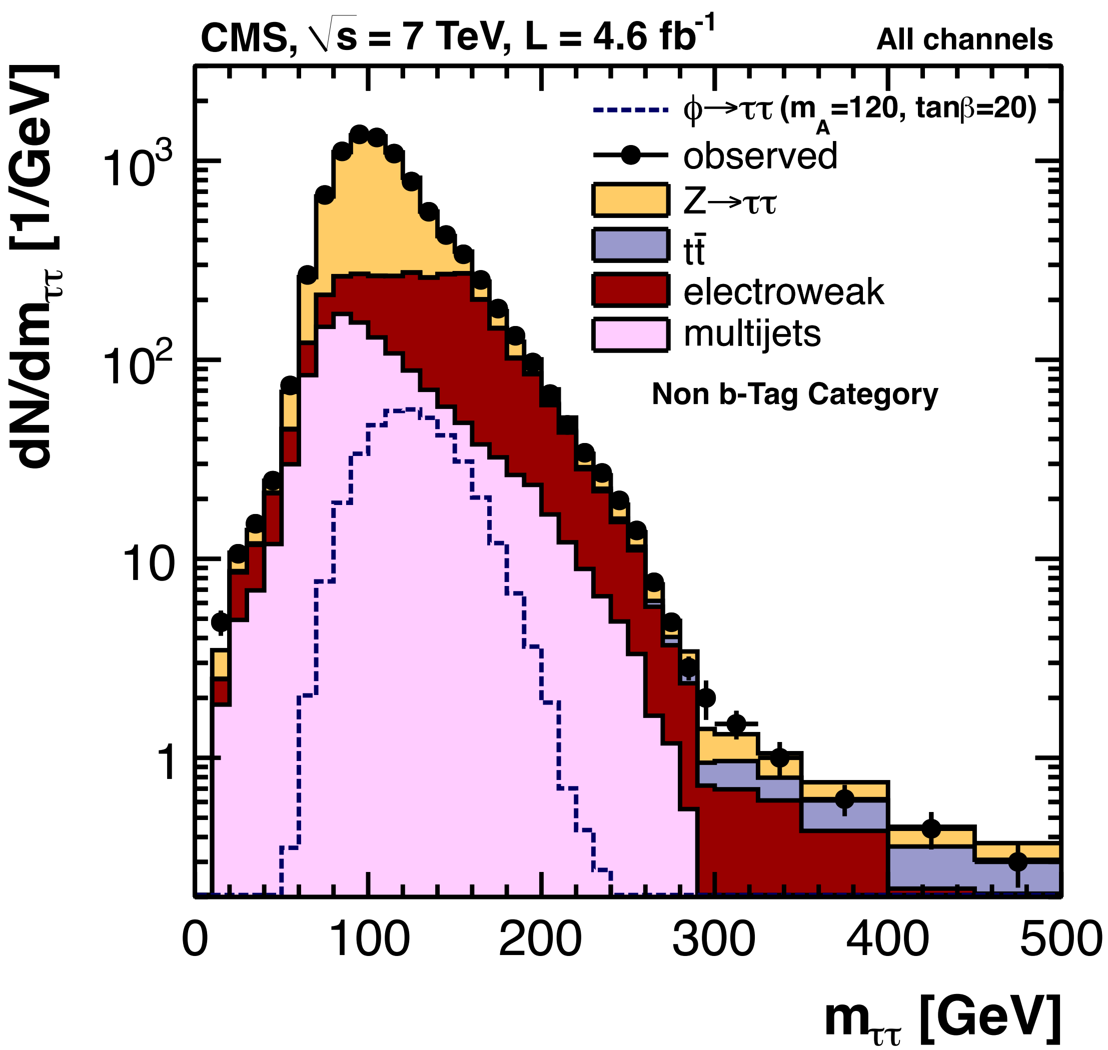
eμ : electron with |η| < 2.3; muon |η| < 2.1
$p_{T,1}$ > 20 GeV; $p_{T,2}$ > 10 GeV

$e\tau_h$: electron with p_T > 20 GeV; |η| < 2.1
hadronic τ with p_T > 20 GeV; |η| < 2.3

$\mu\tau_h$: muon with p_T > 17 GeV; |η| < 2.1
hadronic τ with p_T > 20 GeV; |η| < 2.3

Two categories: b-tag, non b-tag
[Increased sensitivity via associated b-production]

non b-tag category



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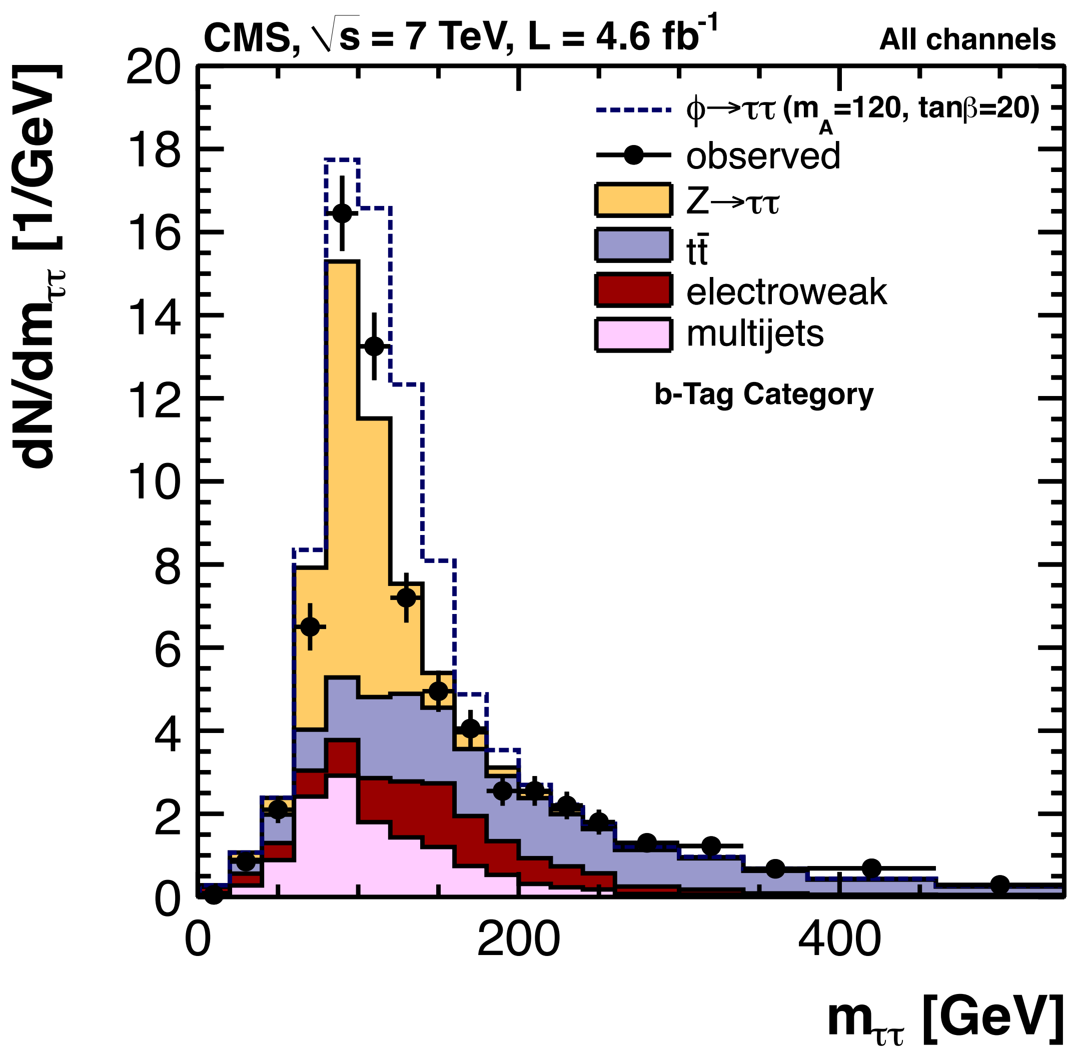

[CMS Collaboration, arXiv: 1202.4083]

[ATLAS]

MSSM Φ(h,H,A) ➤ ττ

Event Selection: eμ, eτ$_h$, μτ$_h$, τ$_h$τ$_h$ …
[oppositely charged; isolation]

eμ : electron with p_T > 15 GeV; |η| < 2.47
muon with p_T > 10 GeV; |η| < 2.5

eτ$_h$ & μτ$_h$: electron with p_T > 25 GeV; |η| < 2.47 …
muon with p_T > 20 GeV; |η| < 2.5 …
+ hadronic τ with p_T > 20 GeV; |η| < 2.5

τ$_h$τ$_h$: 2 taus $p_{T,1}$ & $p_{T,2}$ > 29 & 20 GeV

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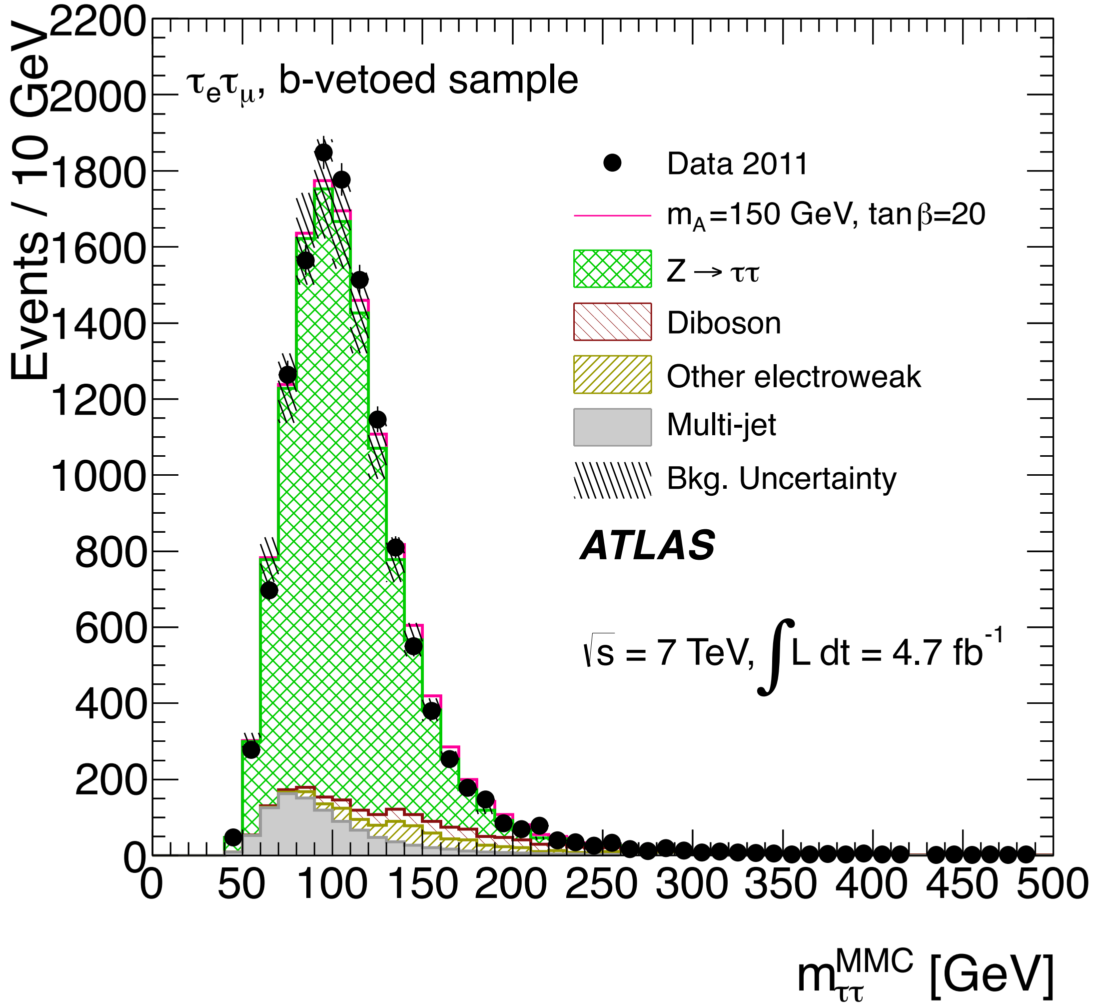

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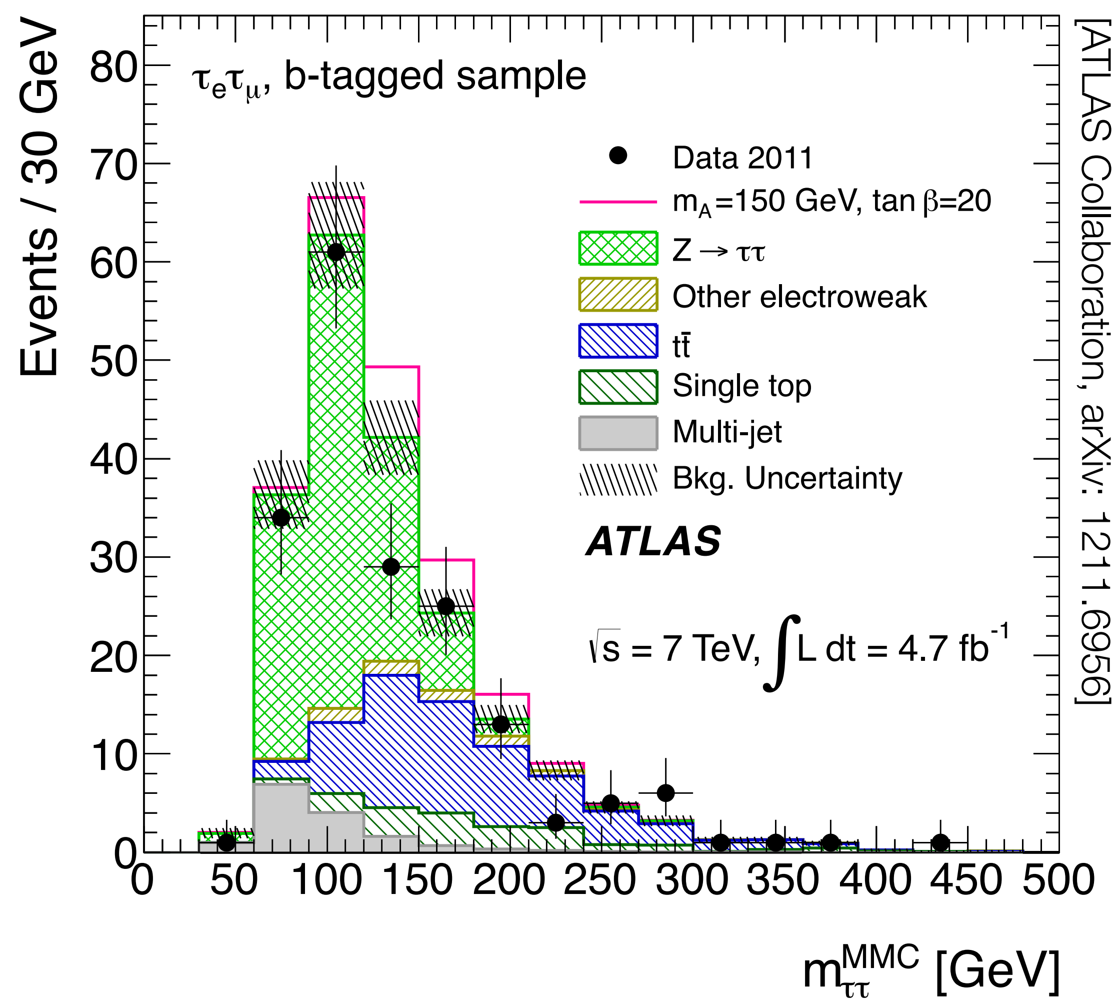

[ATLAS Collaboration, arXiv: 1211.6956]

[ATLAS]

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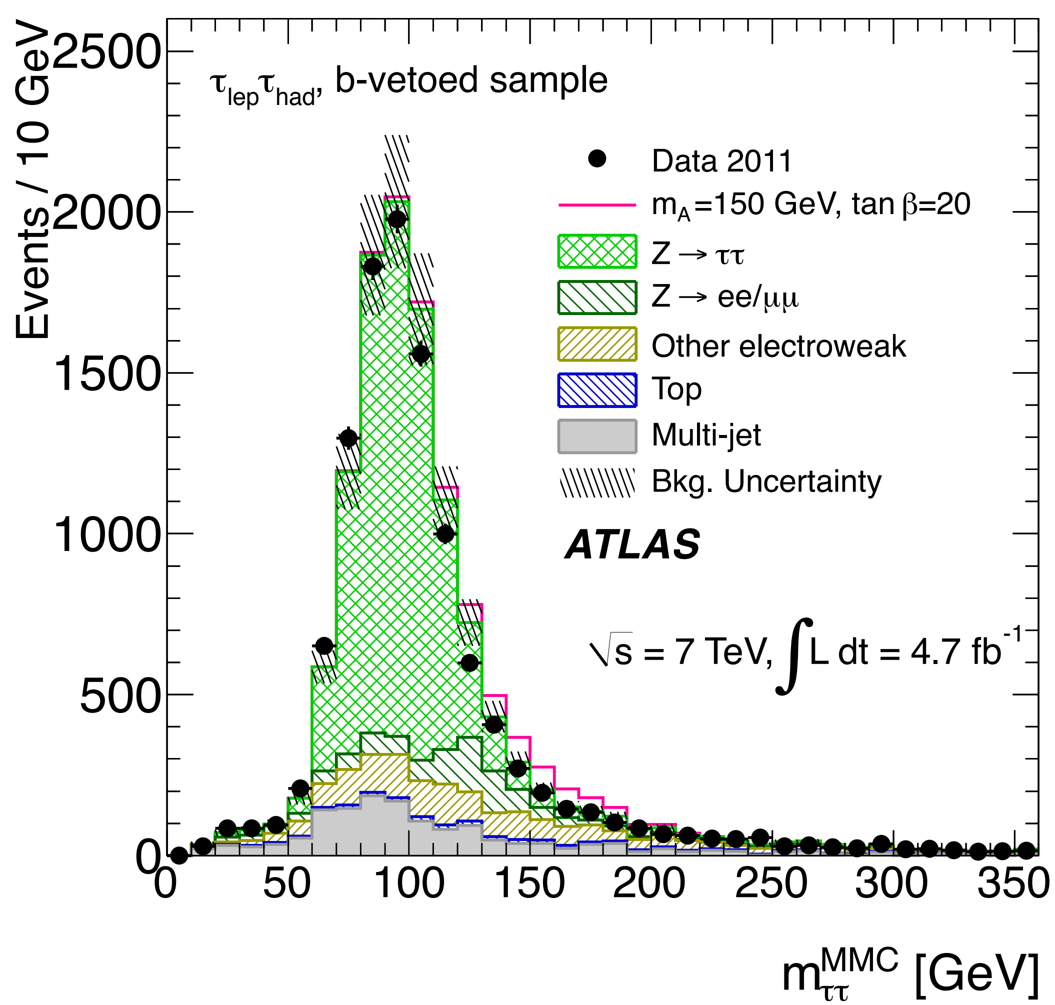

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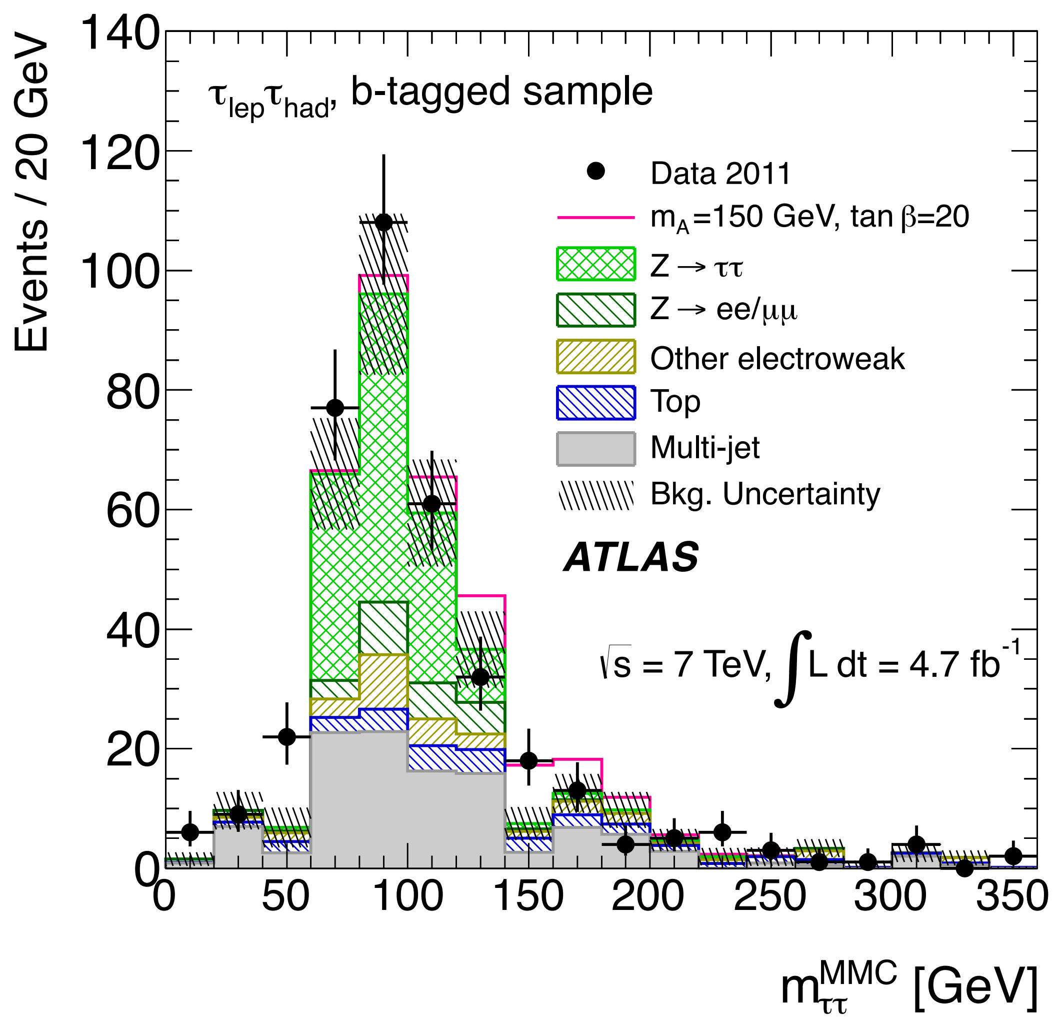

[ATLAS Collaboration, arXiv: 1211.6956]

[ATLAS]

MSSM Φ(h,H,A) ➤ ττ

Two categories: b-tag, non b-tag

[Increased sensitivity via associated b-production]

Event Selection: $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ …
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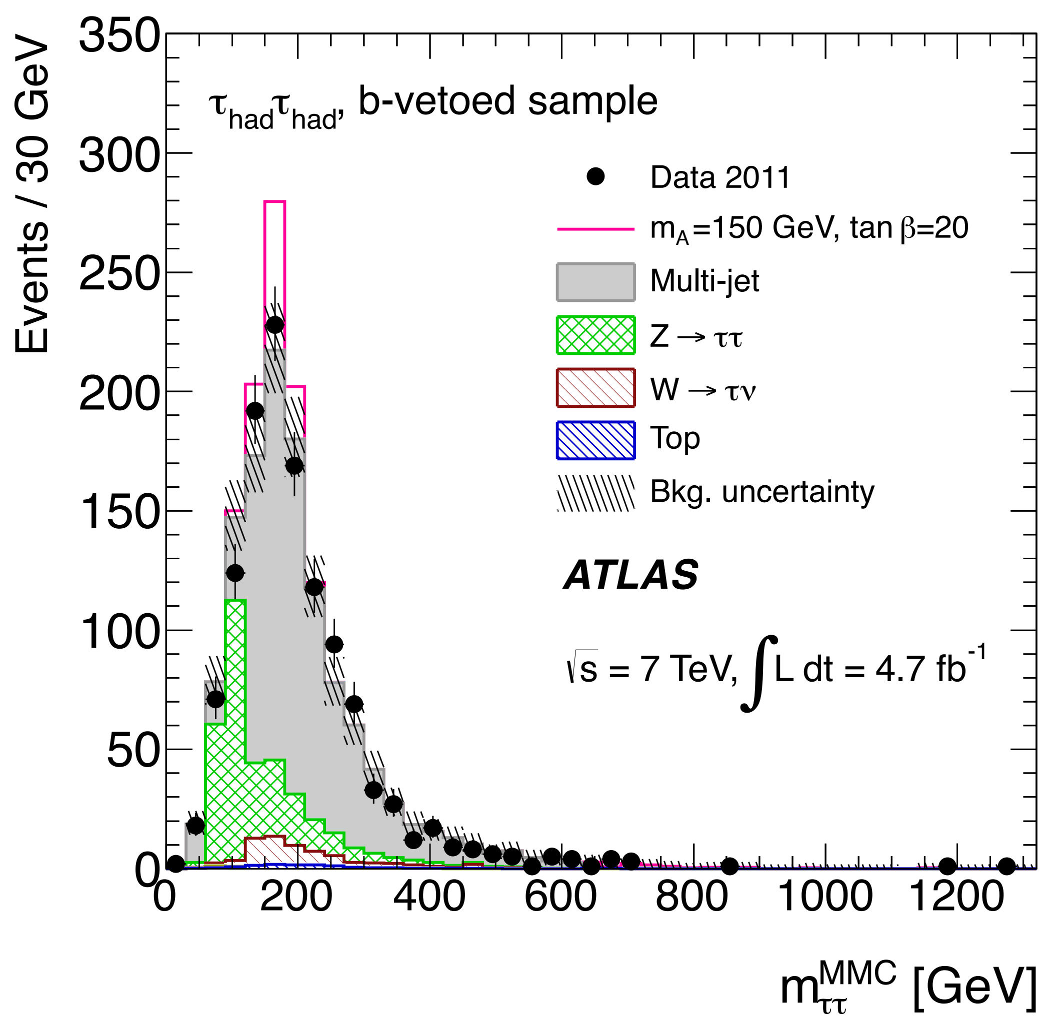

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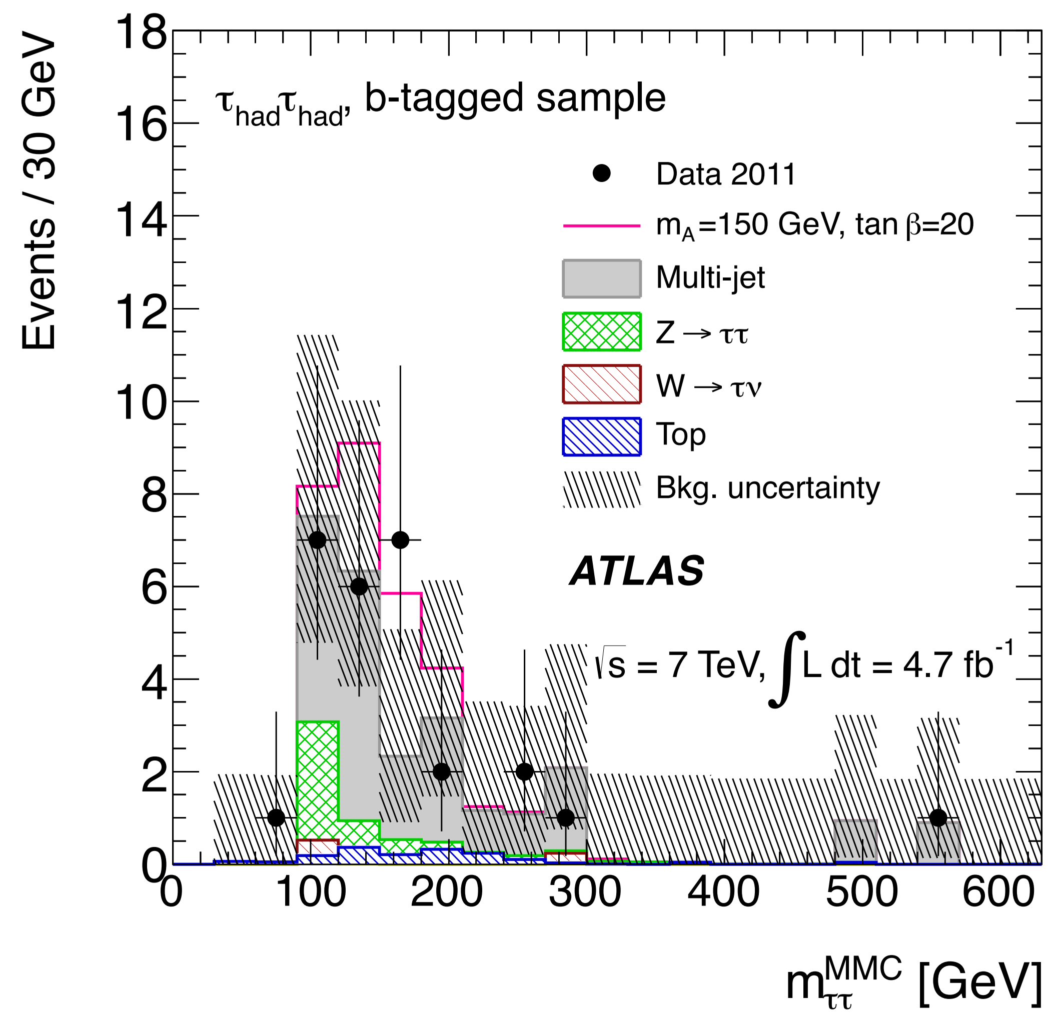
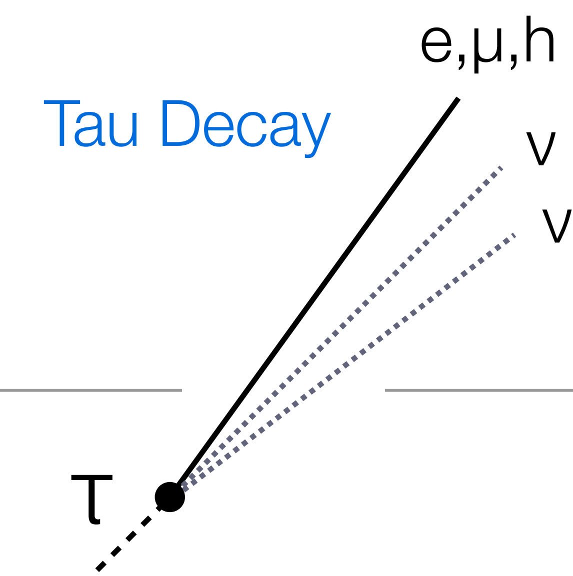


[ATLAS Collaboration, arXiv: 1211.6956]

Invariant ττ-Mass Reconstruction



Possible techniques:

[see NIM A654 (2011) 48]

A. Transverse mass method …

B. Collinear approximation technique …

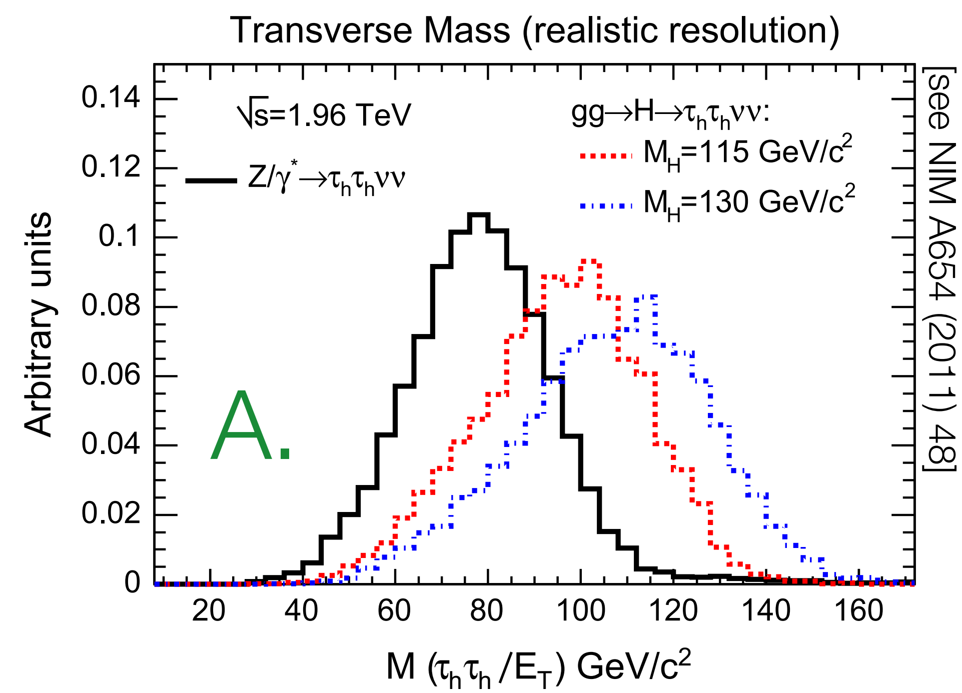
C. Missing mass calculator technique …

Method A:

$$M^2(\tau_{\text{vis}_1}, \tau_{\text{vis}_2}, \not{E}_T) = P^\mu P_\mu$$

$$P^\mu = P^\mu(\tau_{\text{vis}_1}) + P^\mu(\tau_{\text{vis}_2}) + P^\mu(\not{E}_T)$$

with $P^\mu(\not{E}_T) = (\sqrt{\not{E}_{T_x}^2 + \not{E}_{T_y}^2}, \not{E}_{T_x}, \not{E}_{T_y}, 0)$



Method B:

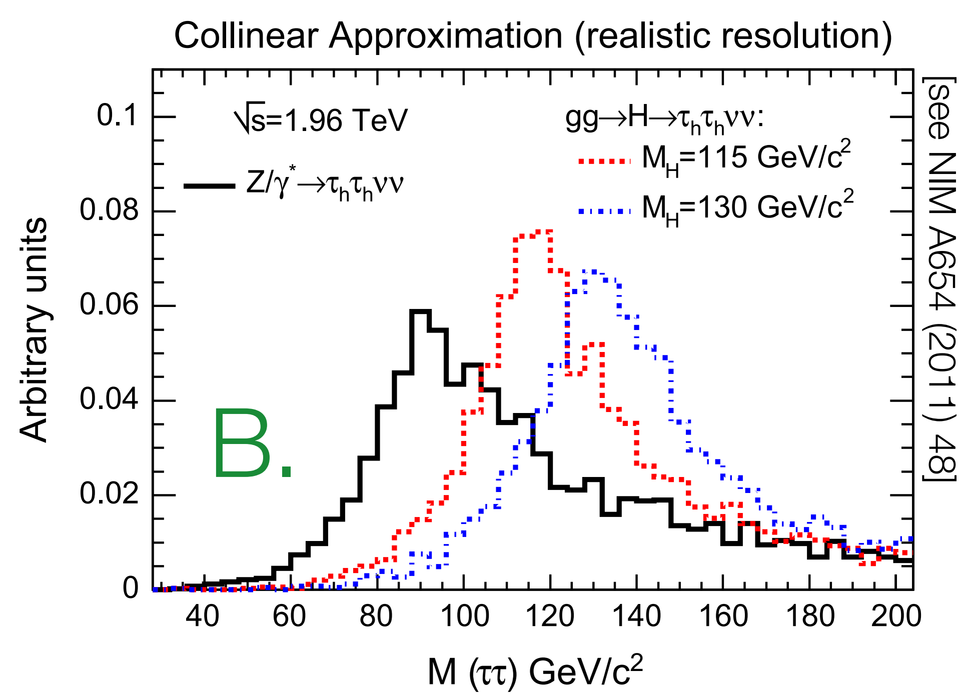
similar to A, but assume neutrinos collinear
to visible τ-decay products [works well if ττ system is boost]

$$\not{E}_{T_x} = p_{\text{mis}_1} \sin\theta_{\text{vis}_1} \cos\phi_{\text{vis}_1} + p_{\text{mis}_2} \sin\theta_{\text{vis}_2} \cos\phi_{\text{vis}_2}$$

$$\not{E}_{T_y} = p_{\text{mis}_1} \sin\theta_{\text{vis}_1} \sin\phi_{\text{vis}_1} + p_{\text{mis}_2} \sin\theta_{\text{vis}_2} \sin\phi_{\text{vis}_2}$$

➛ $M_{\tau\tau} = m_{\text{vis}} / \sqrt{x_1 x_2}$

with $x_{1,2} = p_{\text{vis}_{1,2}} / (p_{\text{vis}_{1,2}} + p_{\text{mis}_{1,2}})$



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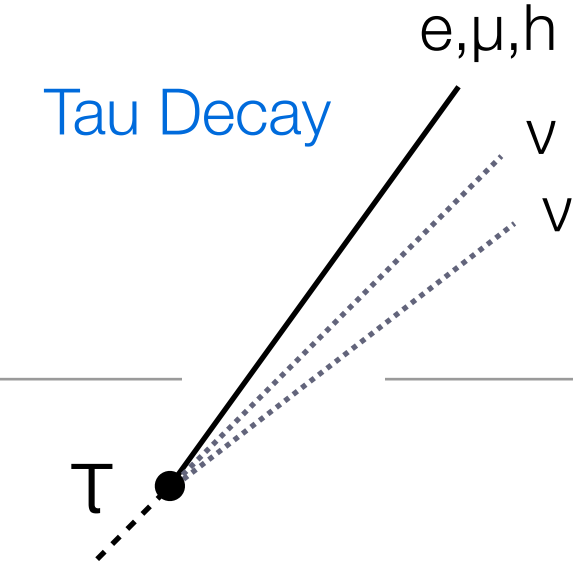

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[see NIM A654 (2011) 48]

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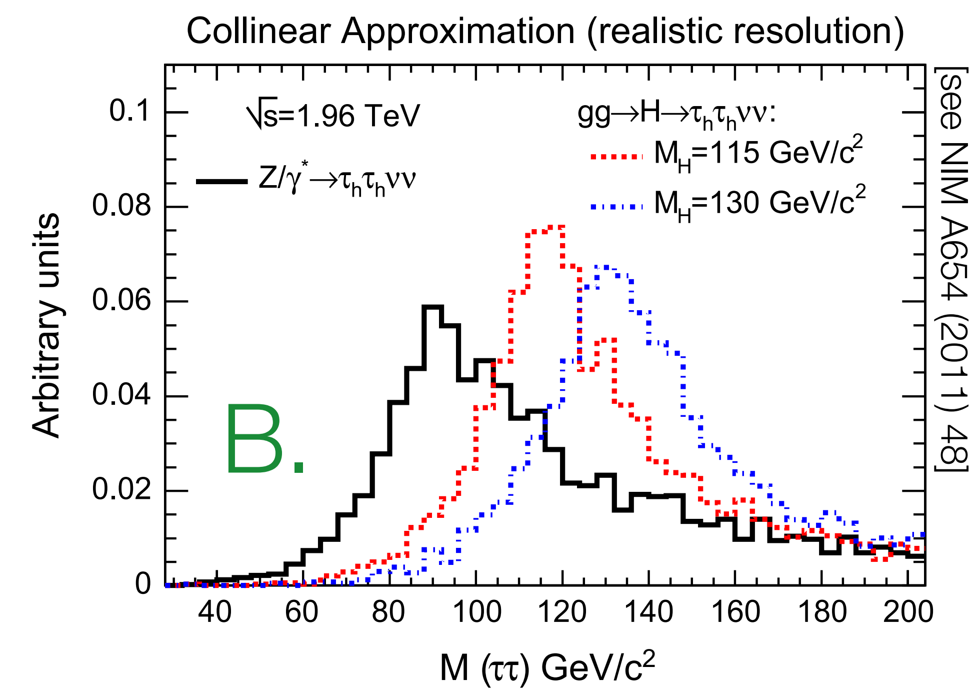


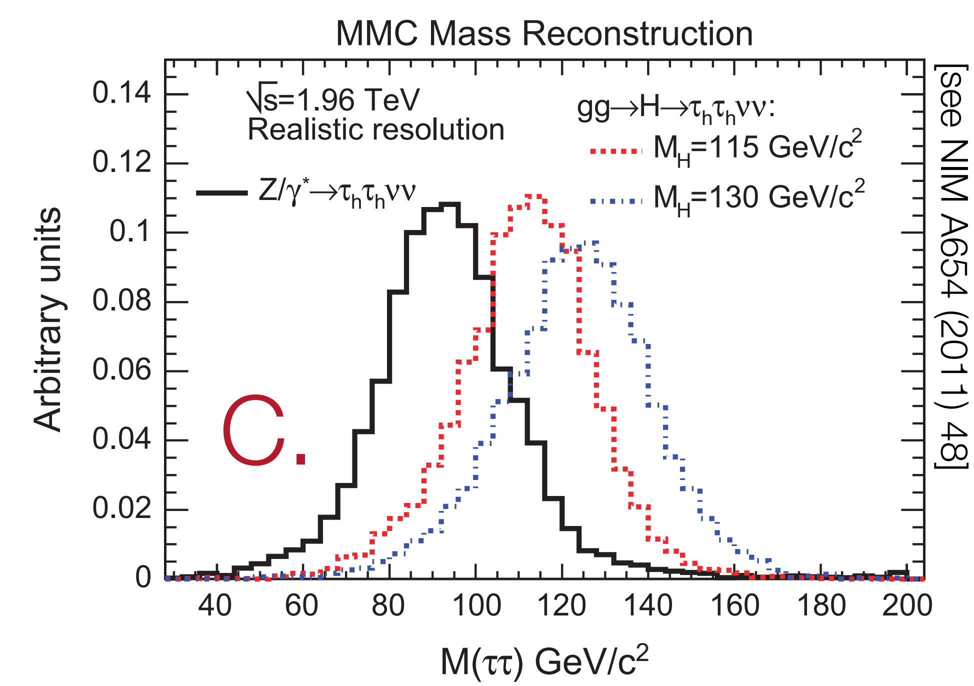
Method B: …

Method C:

A step beyond collinear approximation assuming angle Δϕ between neutrino and visible τ-decay products to be non-zero …

Results in 4 equations with 6-8 unknowns depending on τ-decay mode (hadronic, leptonic) …

Use likelihood method with PDFs $\mathcal{P}(\Delta R, p_T)$ to find best estimate for invariant mass M(ττ) …



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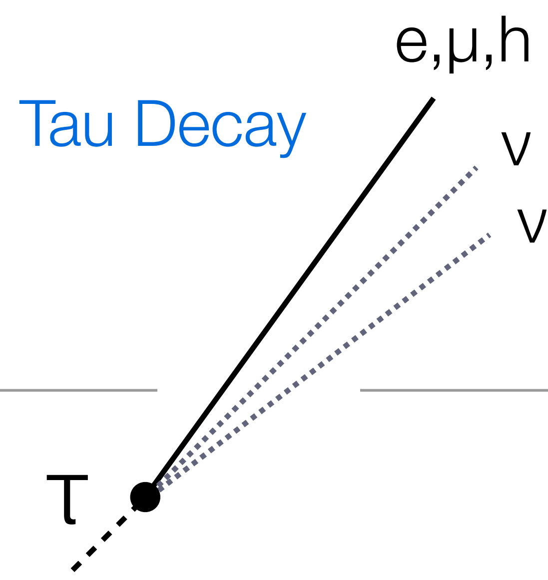

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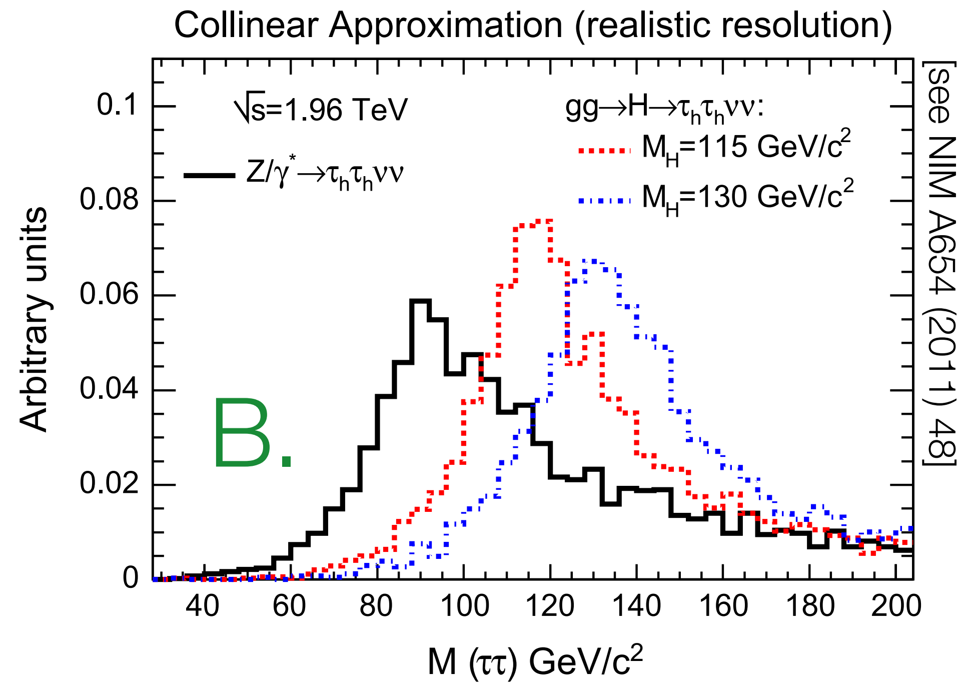
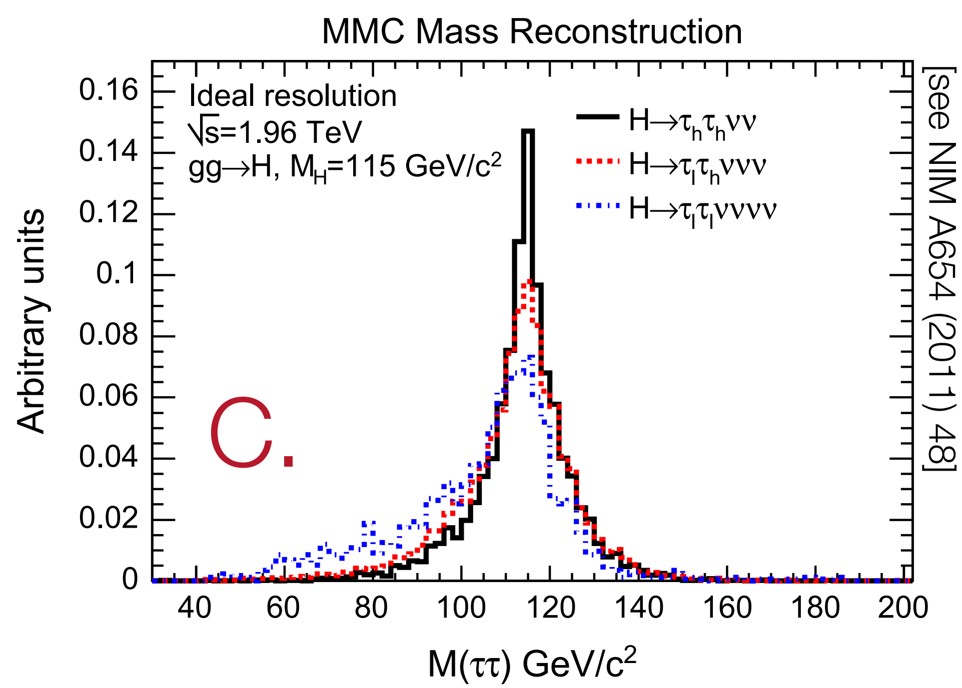


Method B: …

Method C:



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Statistical Analysis

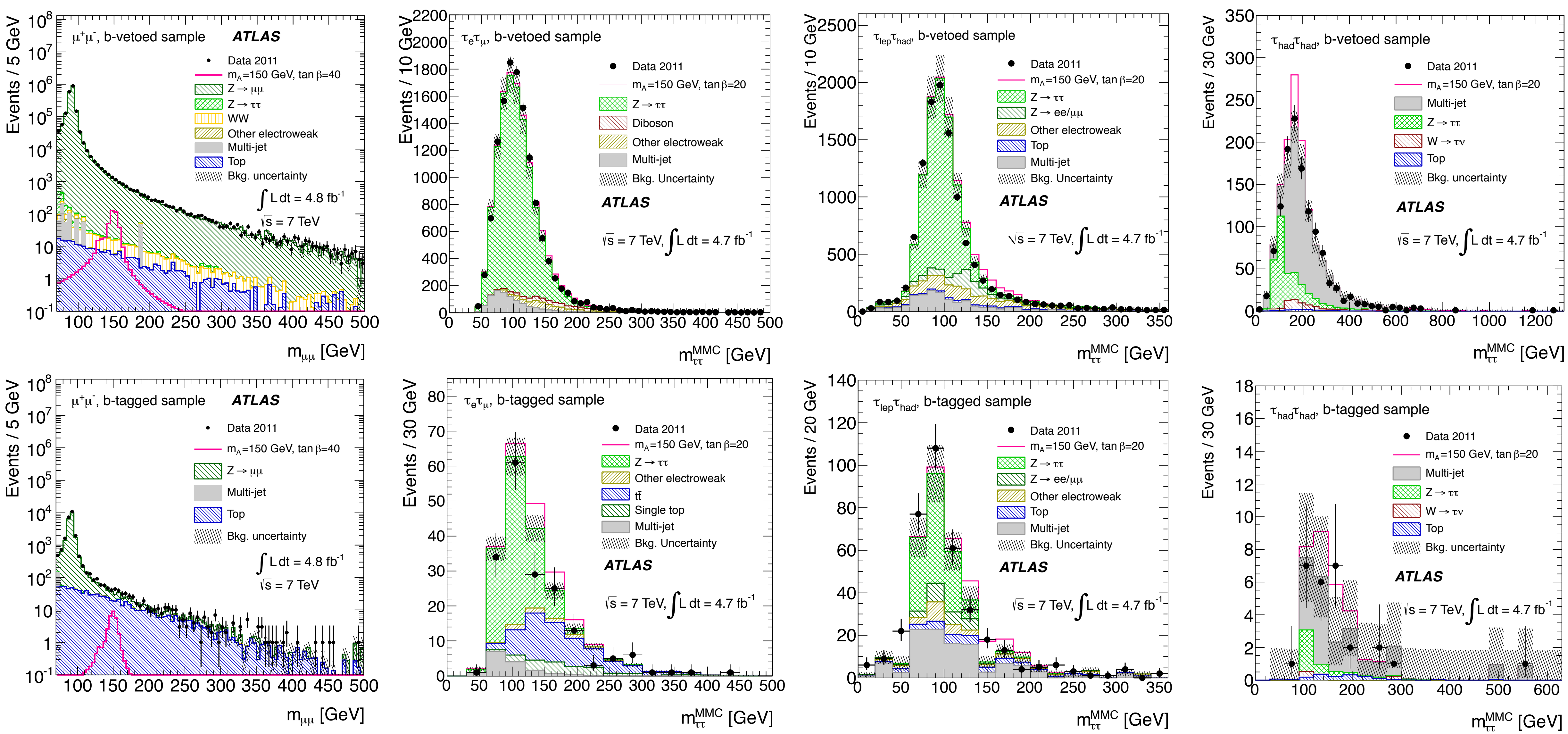
[ATLAS Collaboration, arXiv: 1211.6956]

Binned Likelihood Fit …

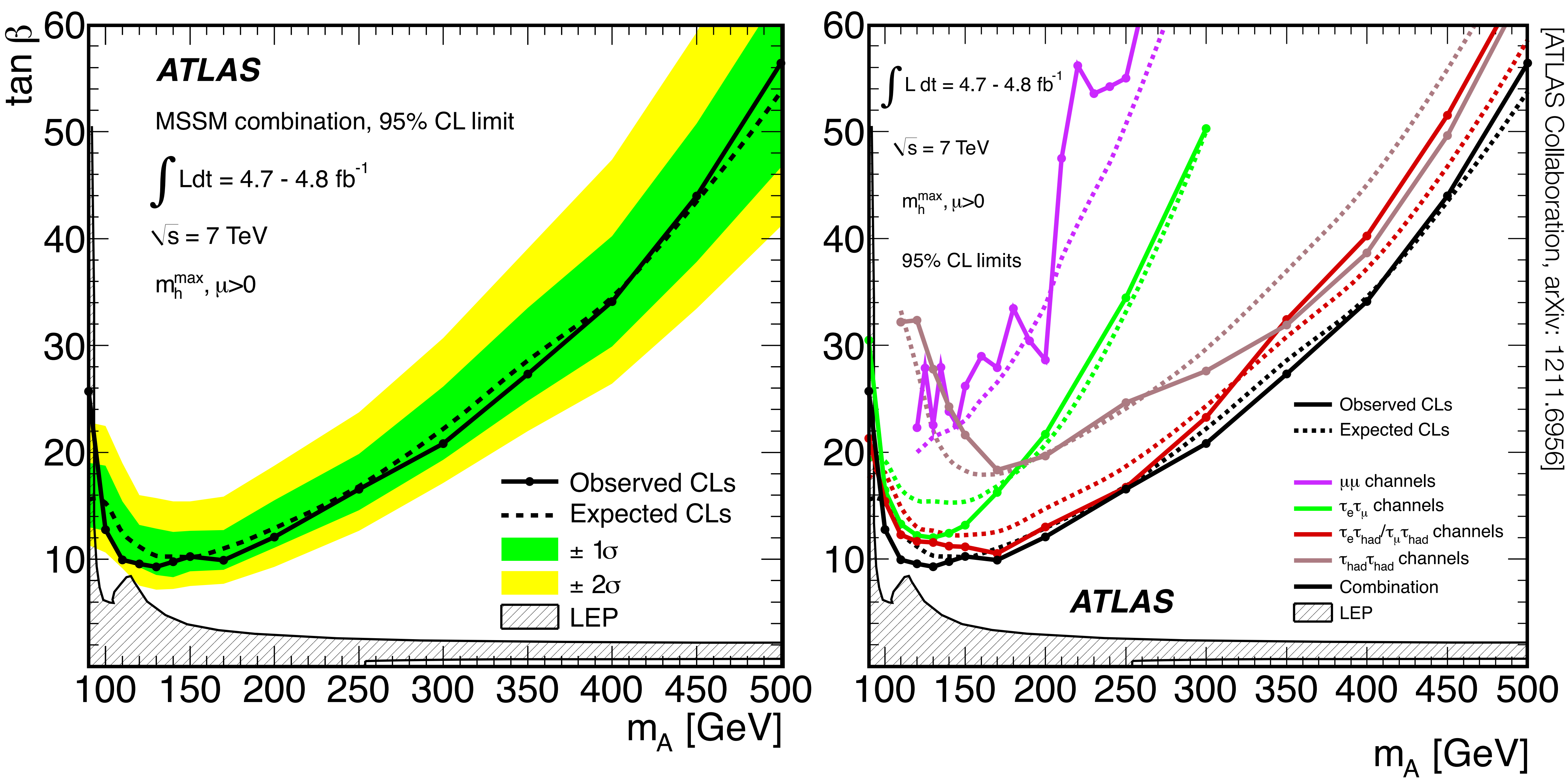
[e.g. ATLAS, arXiv:1211.6956]

$$\mathcal{L}(\mu, \boldsymbol{\theta}) = \prod_{j\,=\,\text{bin and category}} \mathcal{F}_{\mathrm{P}}\left(N_j \mid \mu \cdot s_j + b_j\right) \prod_{\theta_i} \mathcal{F}_{\mathrm{G}}\left(\theta_i \mid 0, 1\right)$$

μμ | eμ | τlepτhad | τhadτhad



95% Confidence Limit – m_h^{max} Scenario



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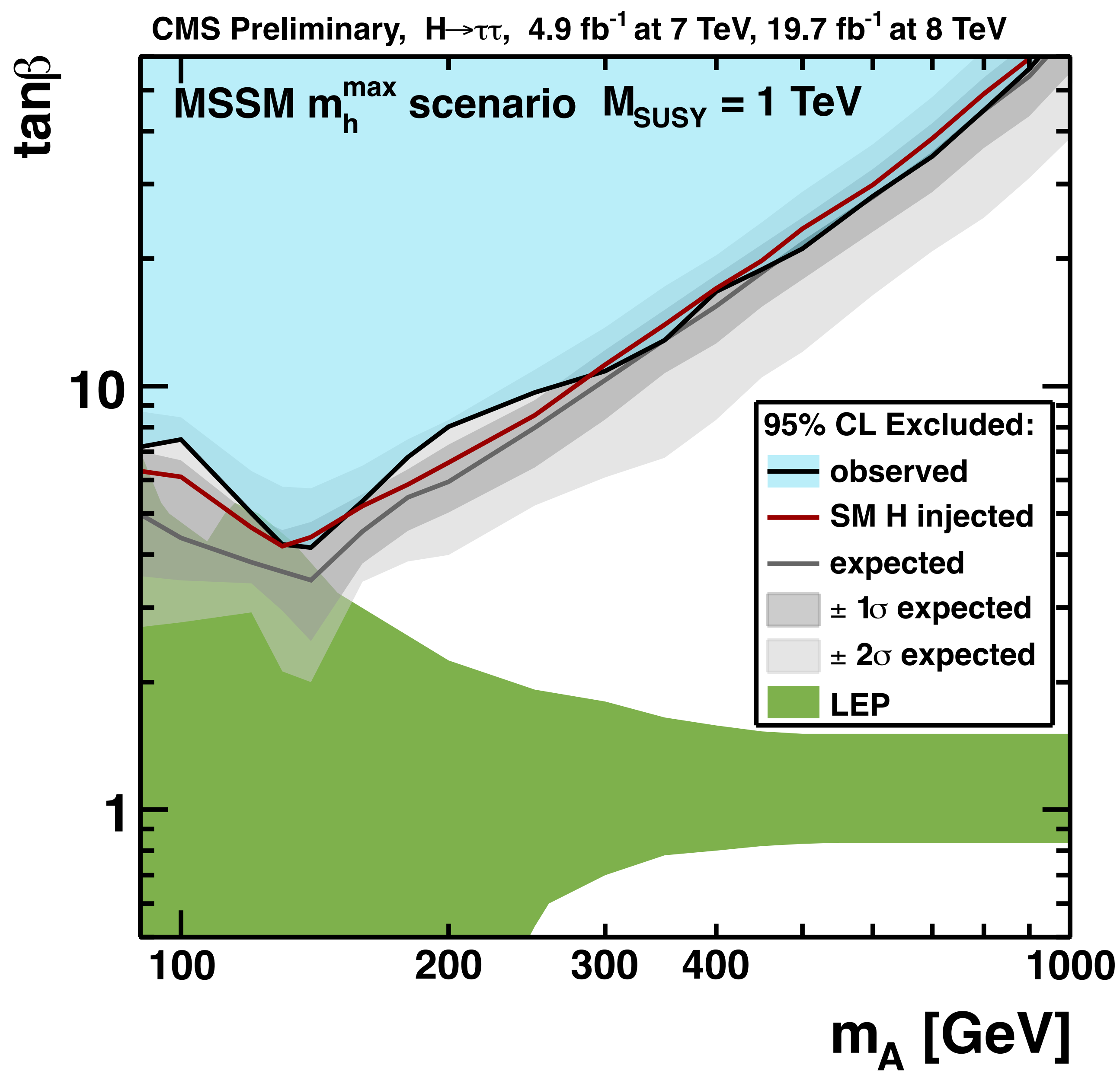
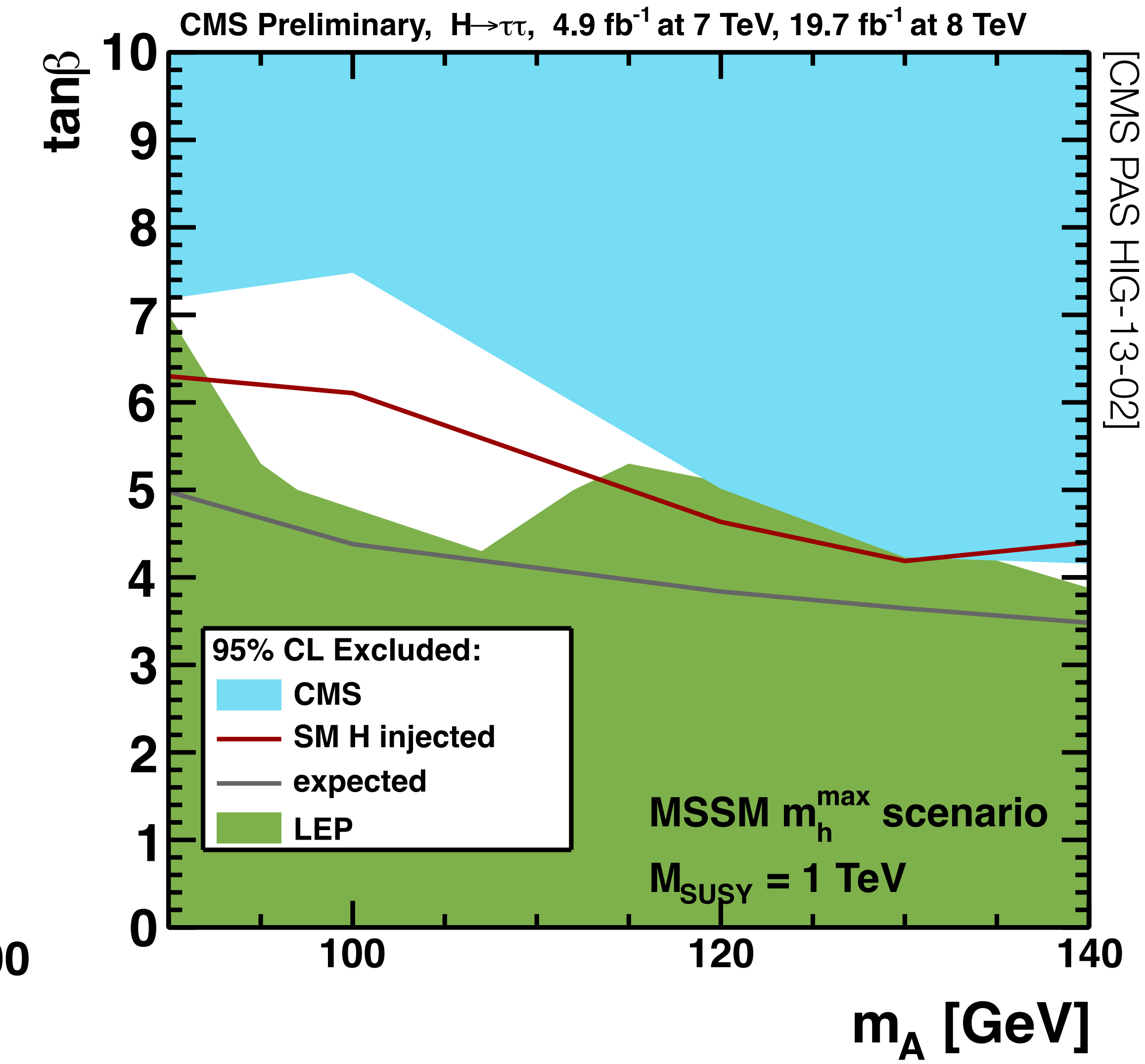
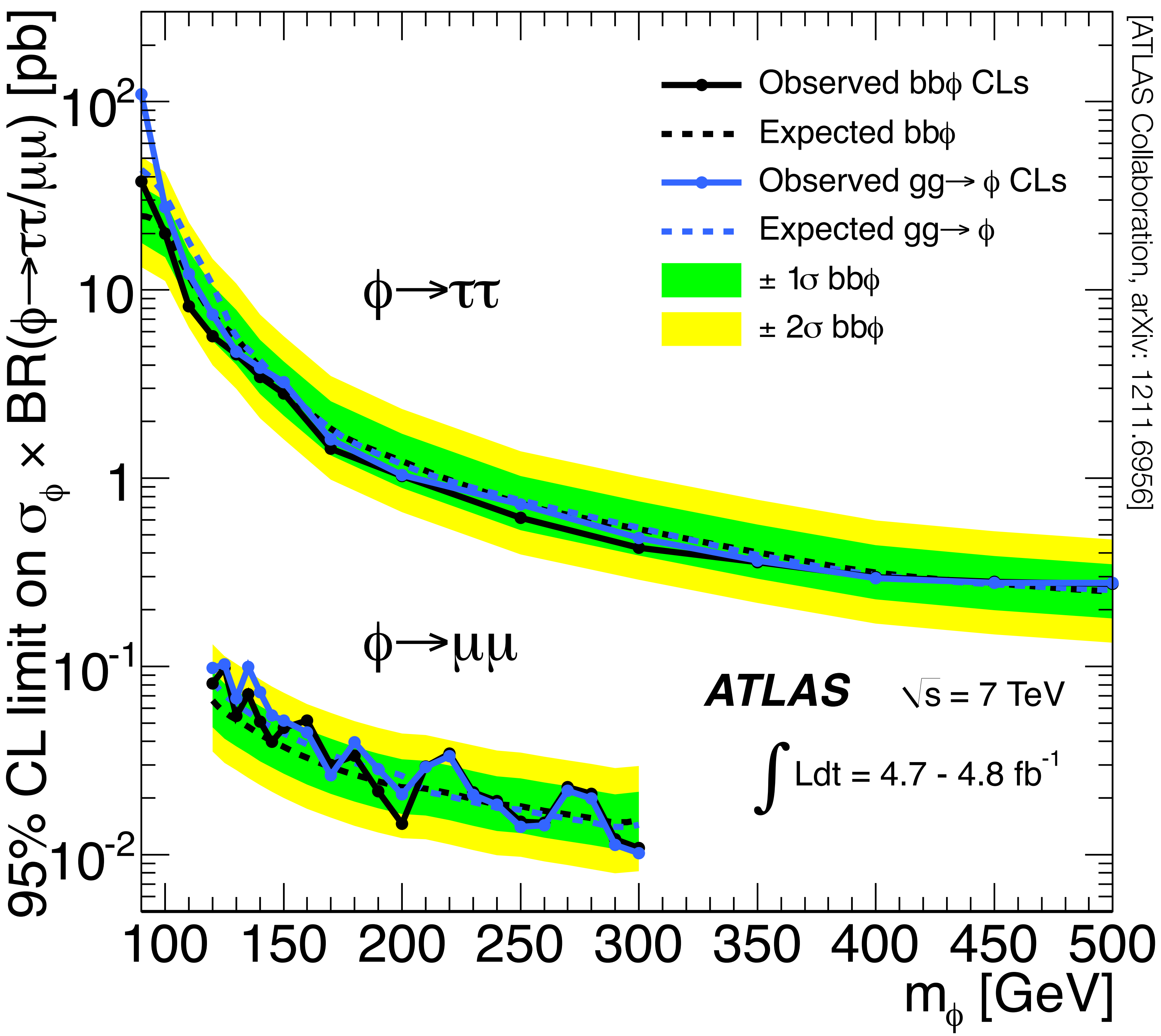




95% Confidence Limit – Generic Model



LHC BSM Higgs Searches

[Repetition]

BSM Scenarios:

[see e.g. PDG: Status of Higgs Boson Physics]

Supersymmetric Extensions …

One neutral Higgs with close to SM properties (h); two extra neutral Higgs bosons (H,A), one SM-like;
two charged Higgs bosons ($H^{\pm}$); potential departures from SM Higgs decay rates (e.g. h ➛ bb) …

Two Higgs-Doublet Models (2-HDMs)…

Simple extension with 7 free parameters; different types, distinguished based on coupling to fermions …
Type-I: only one doublet couples to fermions; Type-II (SUSY): ϕ_1/ϕ_2 couples to up/down-type fermions …

Composite Higgs Scenarios …

Idea: Higgs is composite bound state; e.g. Little Higgs Models; partial compositeness …
Extra particles at the TeV scale (Z′, W′, …); extra Higgs bosons; charged and doubly charged Higgs bosons …

Higgs Triplet Models …

Add electroweak triplet scalar to SM; motivation: neutrinos acquire Majorana mass …
Extra Higgs bosons, in particular doubly charged Higgs ($H^{\pm\pm}$); fermiophobic Higgs (also for 2HDM) …

Fermiophobic Higgs

BSM Model with two Higgs doublets and no coupling to fermions …

Theory predictions:
Use numbers from NNLO VBF, WH/ZH …
EW radiative corrections are unknown assign ±5%.

➛ Gluon fusion and ttH production forbidden …
No change in VBF and VH processes …

Big enhancement (10x) to $\gamma\gamma$ branching

Yields for FP Higgs at 125 GeV comparable to SM: $\gamma\gamma$, ZZ, WW …

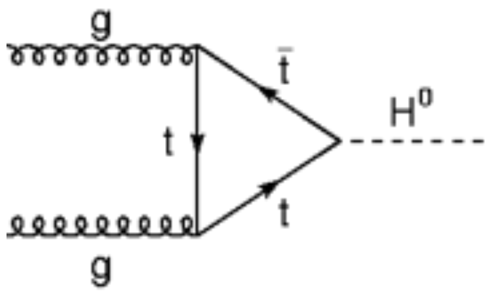
Analysis strategy:

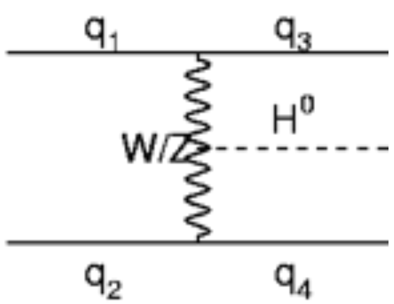
Re-analysis/re-interpretation of H ➛ WW, $\gamma\gamma$, ZZ … and exploit different event topology

WW, $\gamma\gamma$: re-analysis; H ➛ $\gamma\gamma$/WW + dijets/leptons…
VBF and VH ➛ utilize that Higgs is boosted …

For ZZ: re-interpretation of existing analysis …

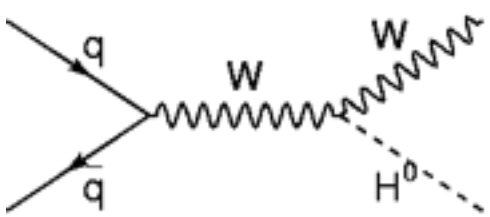
gg Fusion ✗

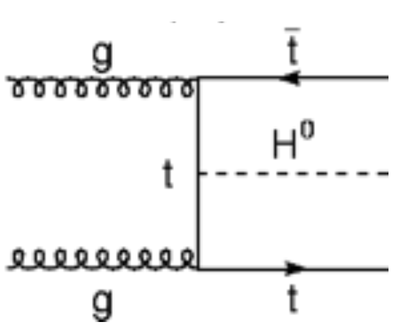




VV Fusion (VBF) ✓

Higgs Strahlung (VH) ✓





tt Fusion ✗

Fermiophobic Higgs

[from R. Tanaka, 2011]

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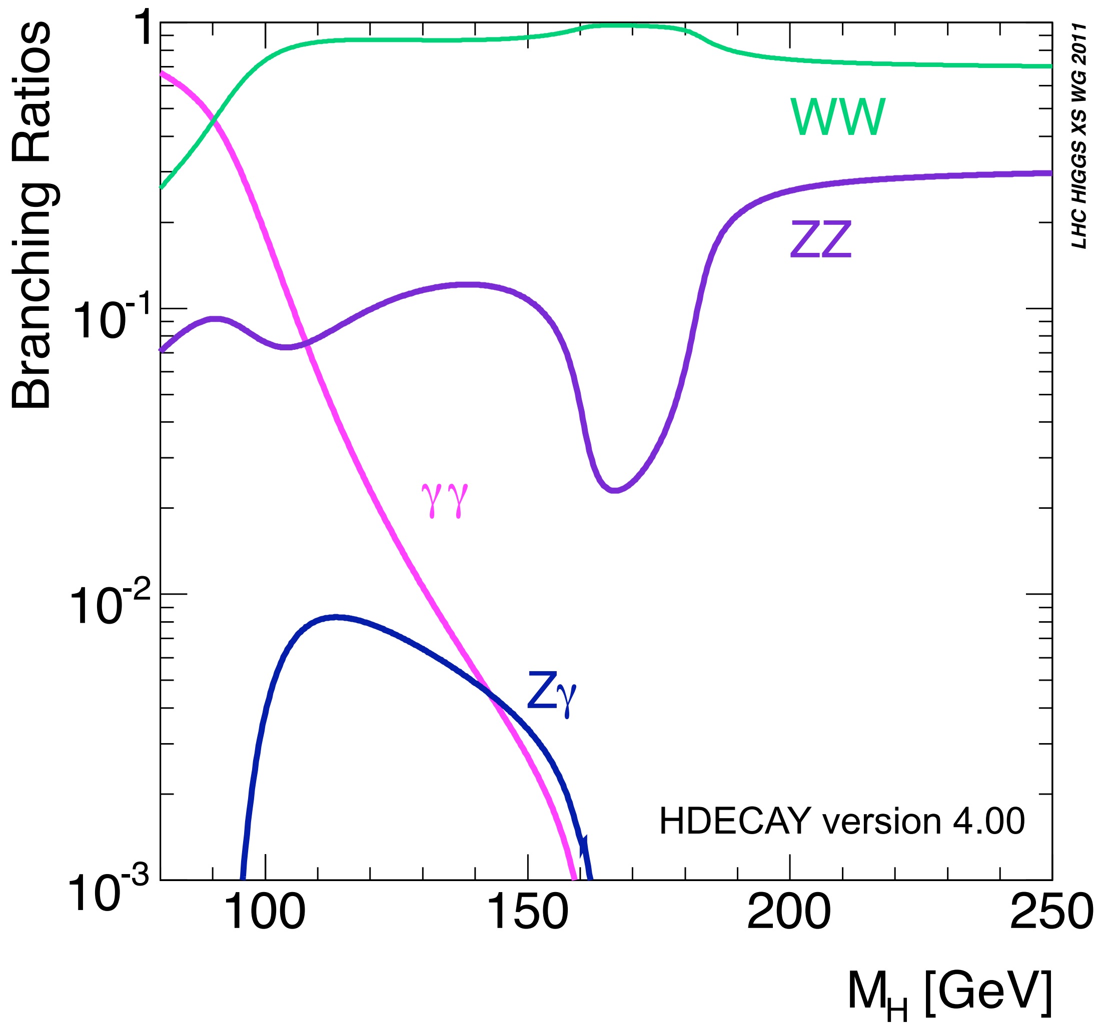
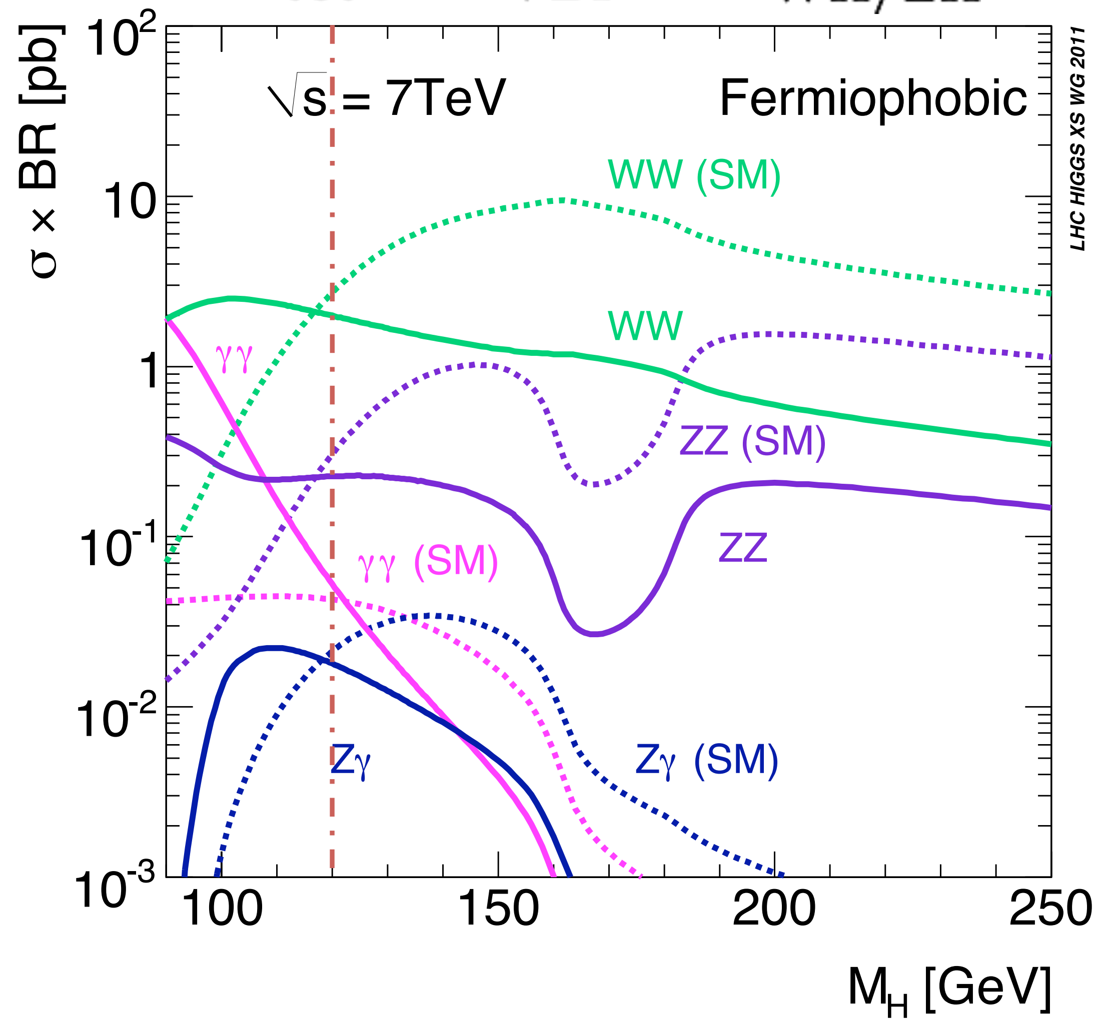
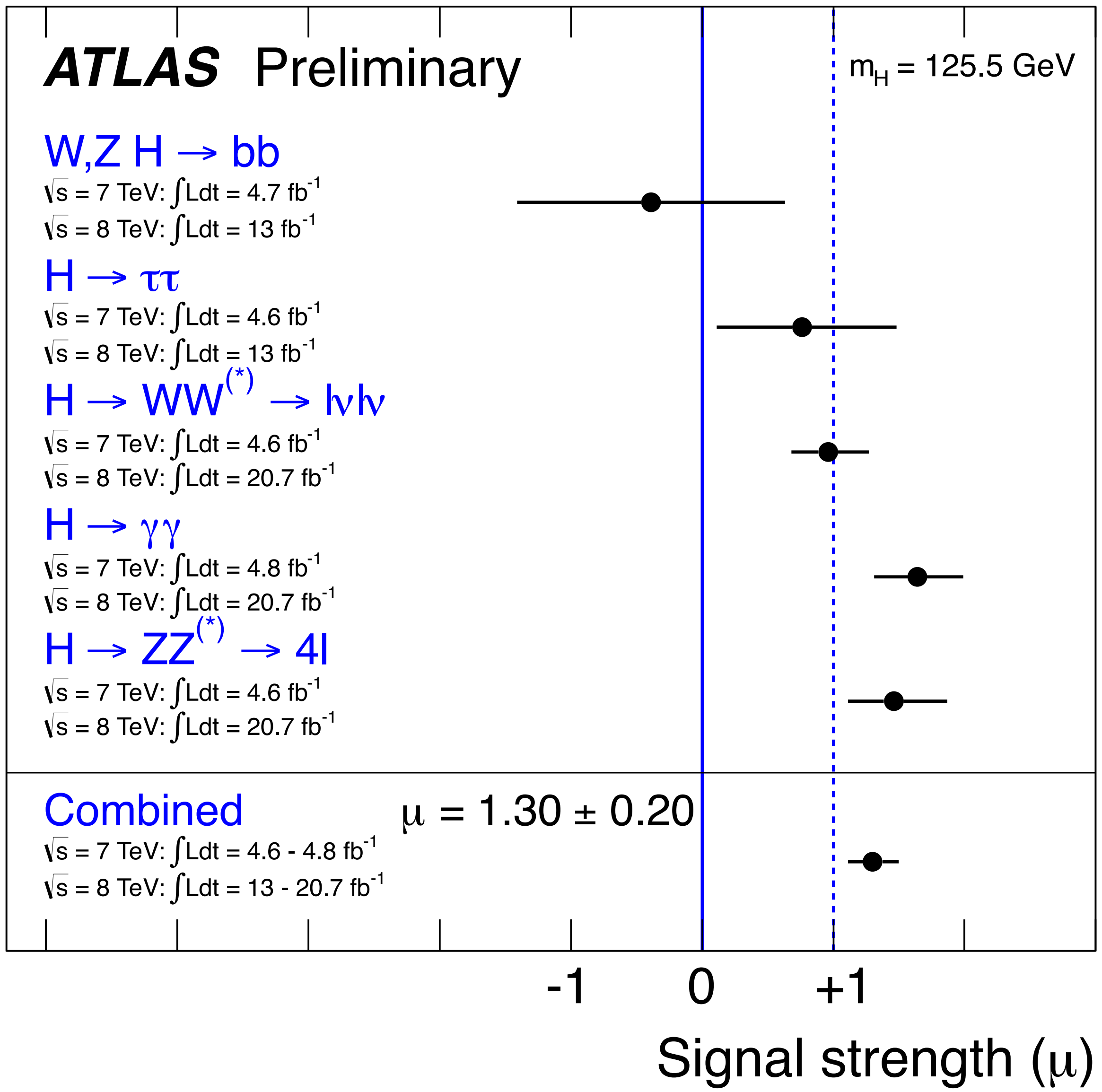
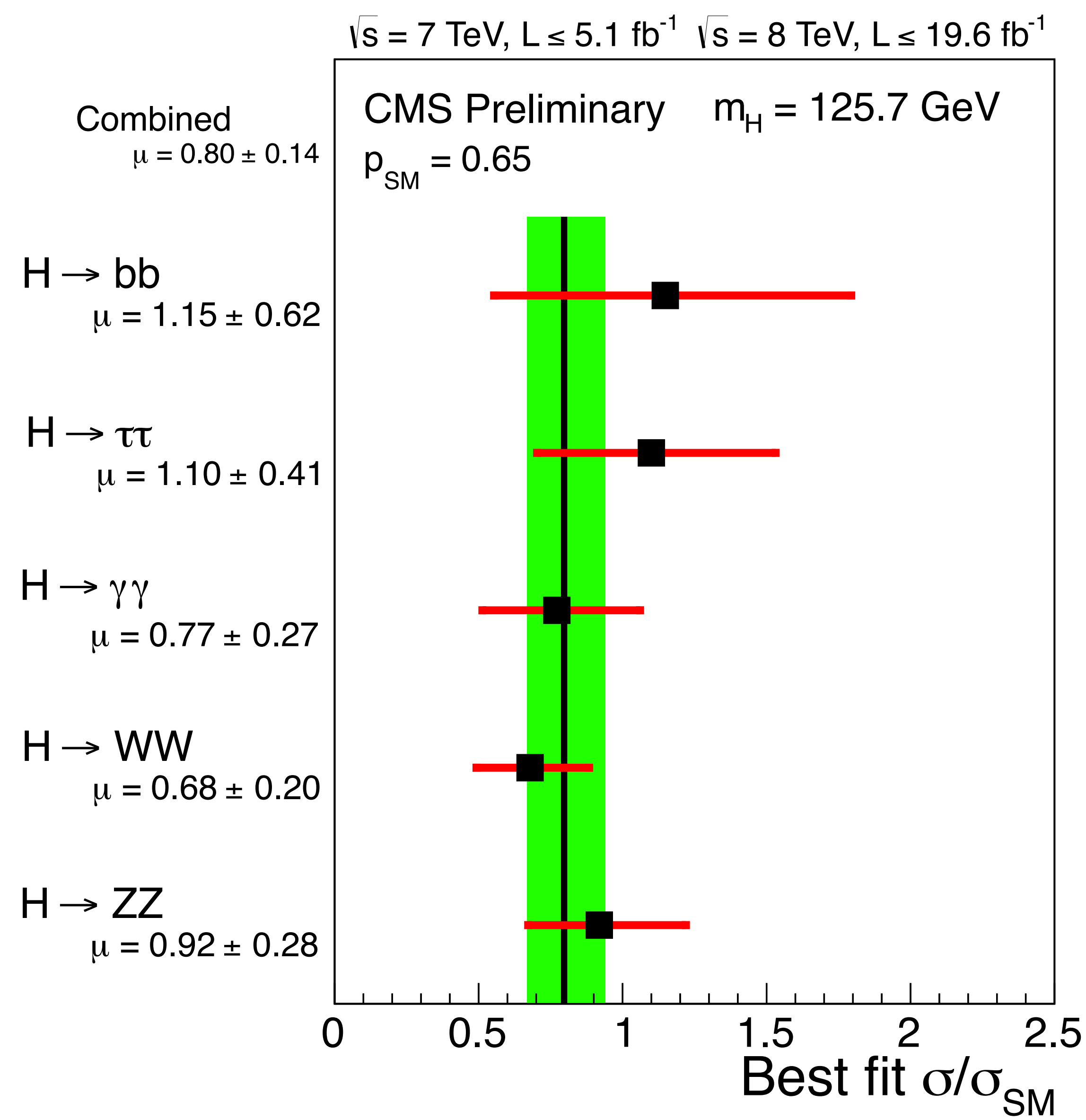


$$\sigma_{\rm tot} = \sigma_{\rm VBF} + \sigma_{\rm WH/ZH}$$



Fermiophobic Higgs





ATLAS: $\mu = 1.30 \pm 0.20$

CMS: $\mu = 0.80 \pm 0.14$

Fermiophobic Higgs

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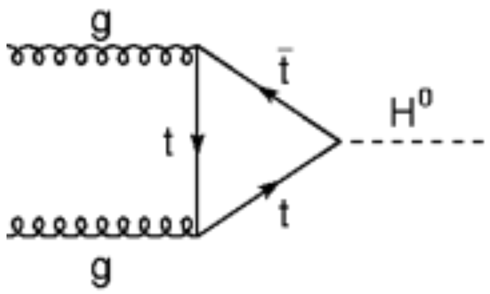

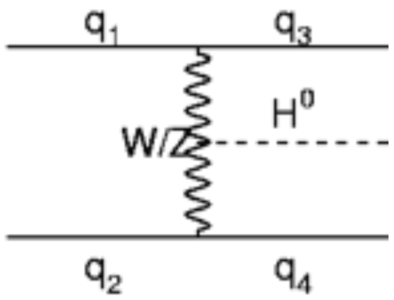

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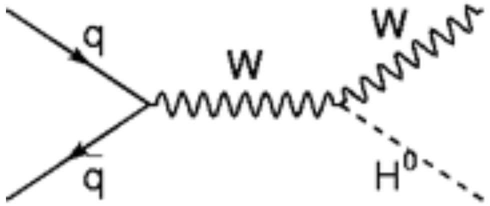
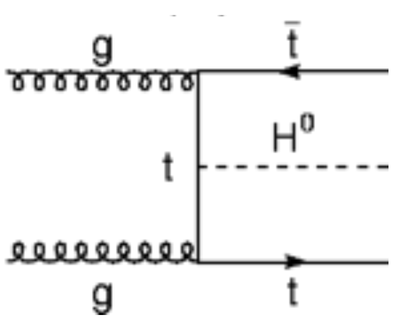
Higgs Strahlung (VH) ✓





tt Fusion ✗

Fermiophobic Higgs

Summary of analysis channels and sub-channels included

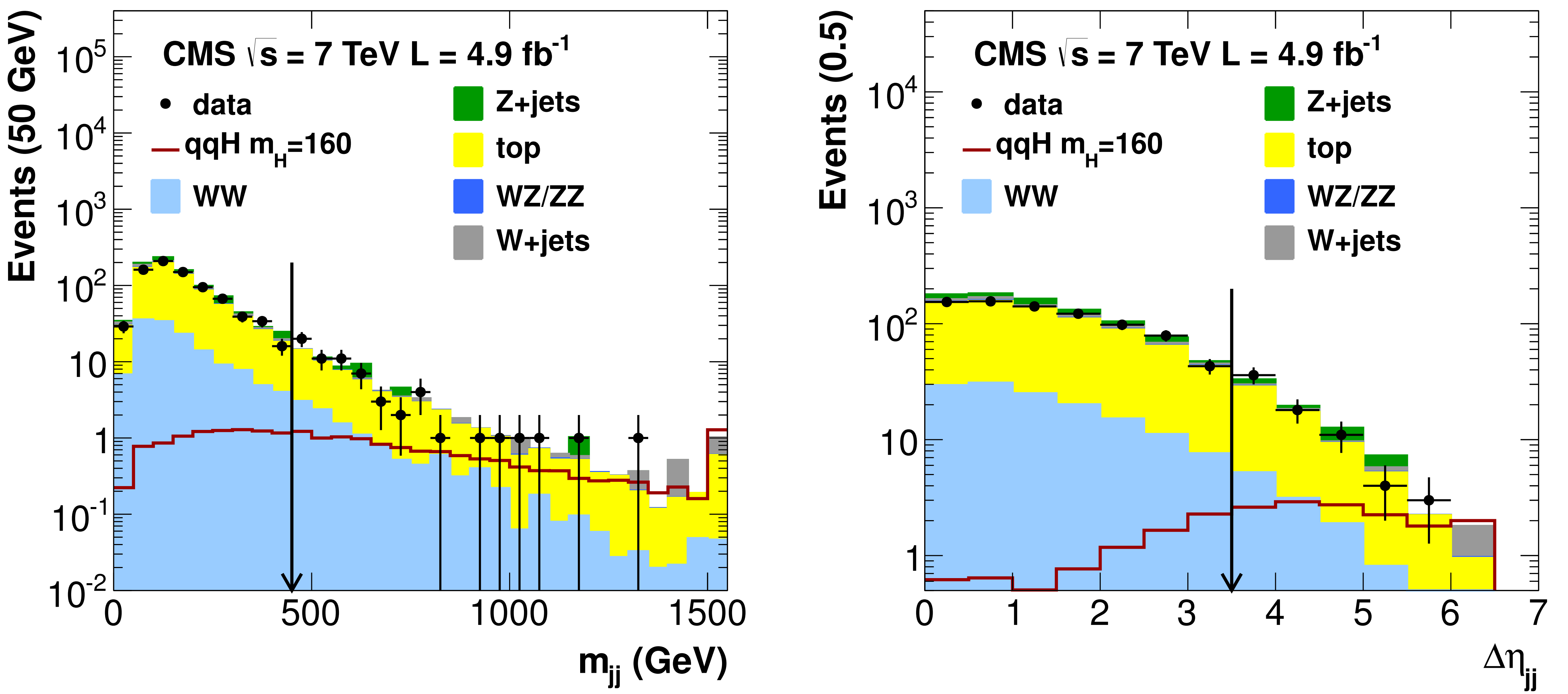
[CMS, JHEP 09 (2012) 111]

Channel	m_H range (GeV)	Sub-channels	Luminosity (fb^{-1})	Reference
H→ $\gamma\gamma$	110–150	4	5.1	[17]
H→ $\gamma\gamma$ + dijet	110–150	1	5.1	[17]
H→ $\gamma\gamma$ + lepton	110–150	2	5.1	
H→WW→ $2\ell 2\nu$	110–300	4	4.9	[18]
H→WW→ $2\ell 2\nu$ + dijet	110–300	1	4.9	[18]
H→WW→ $2\ell 2\nu$ + lepton	110–300	1	4.9	
H→ZZ→ 4ℓ	110–300	3	5.0	[19]
H→ZZ→ $2\ell 2\nu$	250–300	2	5.0	[20]
H→ZZ→ $2\ell 2$q	130–165, 200–300	6	5.0	[21]
H→ZZ→ $2\ell 2\tau$	180–300	8	5.0	[22]

Fermiophobic Higgs

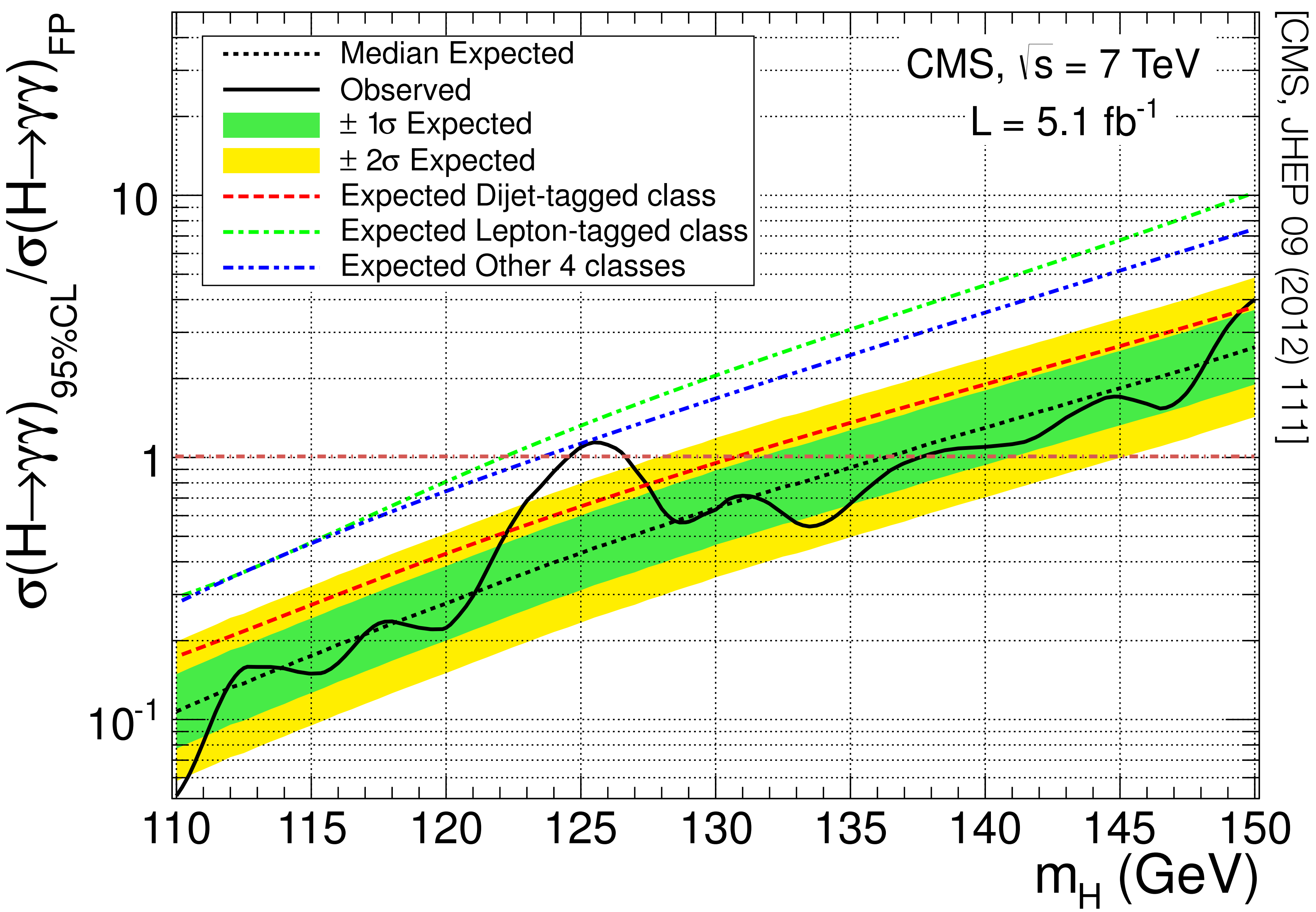
Invariant di-jet mass, m_{jj} and rapidity difference $\Delta\eta_{jj}$
after the H ➛ WW selection

[CMS, JHEP 09 (2012) 111]



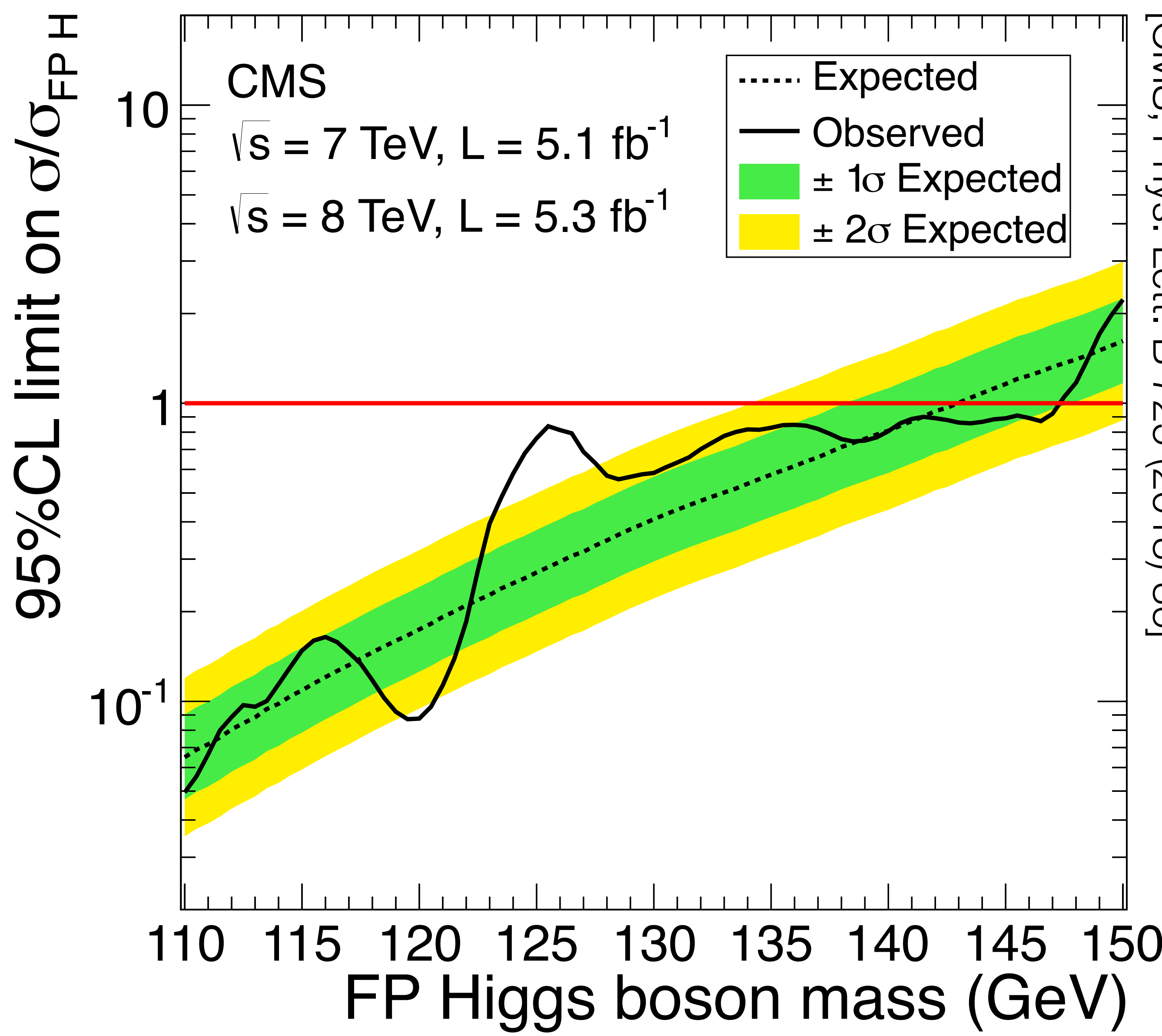
Fermiophobic Higgs

95% Confidence limit on FP Higgs Cross Section



Fermiophobic Higgs

95% Confidence limit on FP Higgs Cross Section
[2013 Update]

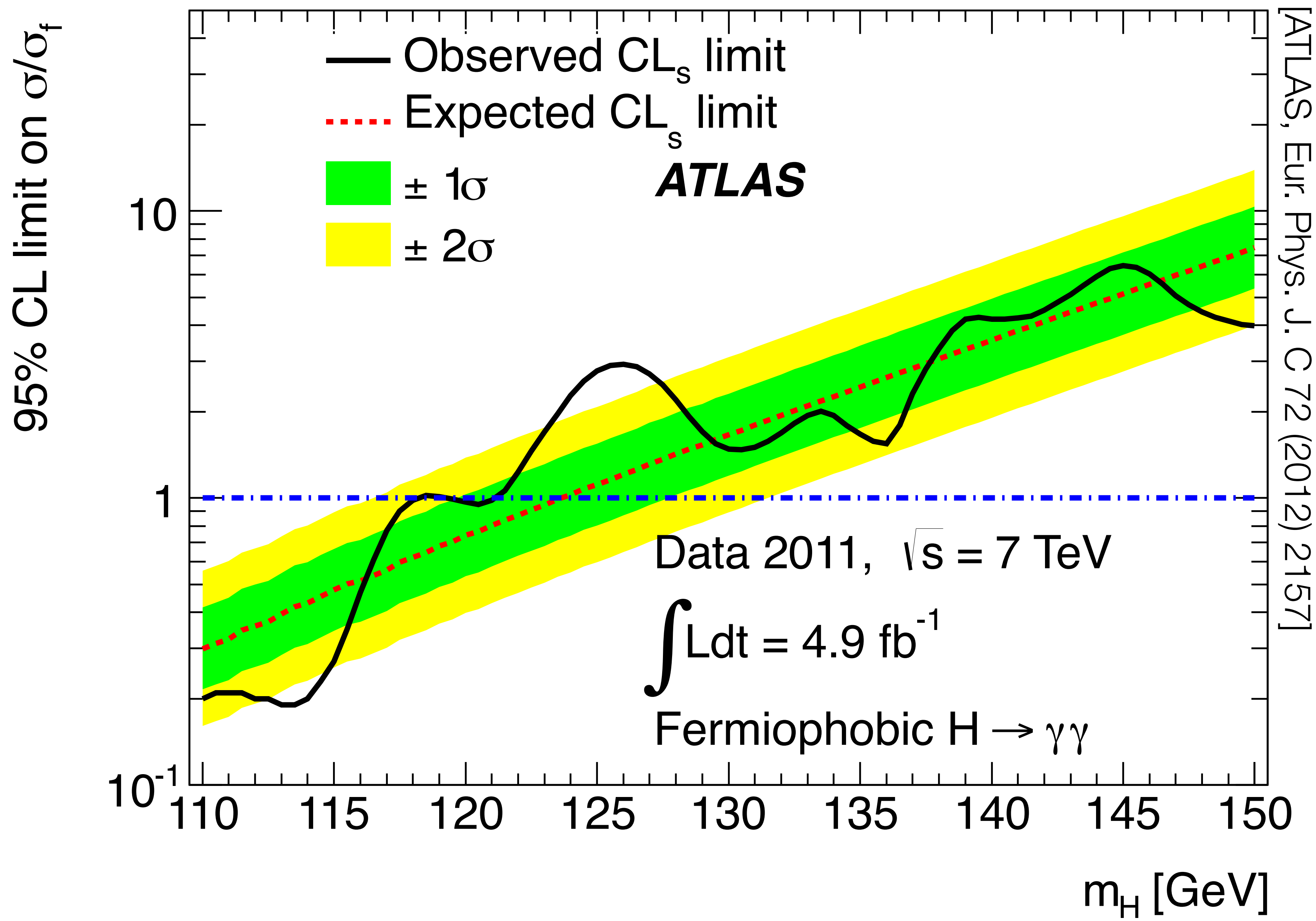


[CMS, Phys. Lett. B 725 (2013) 36]

[ATLAS]

Fermiophobic Higgs

95% Confidence limit on FP Higgs Cross Section
[Re-interpreting only di-photon decay events]



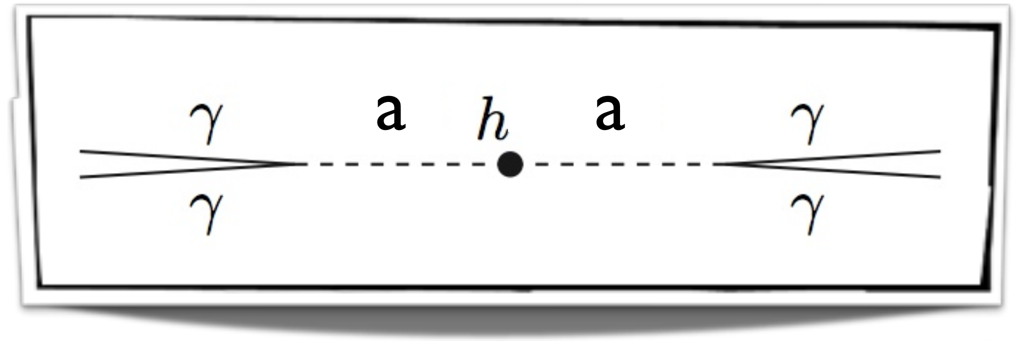
[ATLAS]

Another Reinterpretation: H ➤ aa ➤ 4γ

SUSY Models:

2HDM – CP-odd Higgs very light; fermiophobic
NMSSM – 3 CP-even ($h_{1,2,3}$) and 2 CP-odd ($a_{1,2}$) Higgs

[coupling of light Higgs to SM particles weak …]



[100 MeV ≤ m_a ≤ 400 MeV]

Event signature:

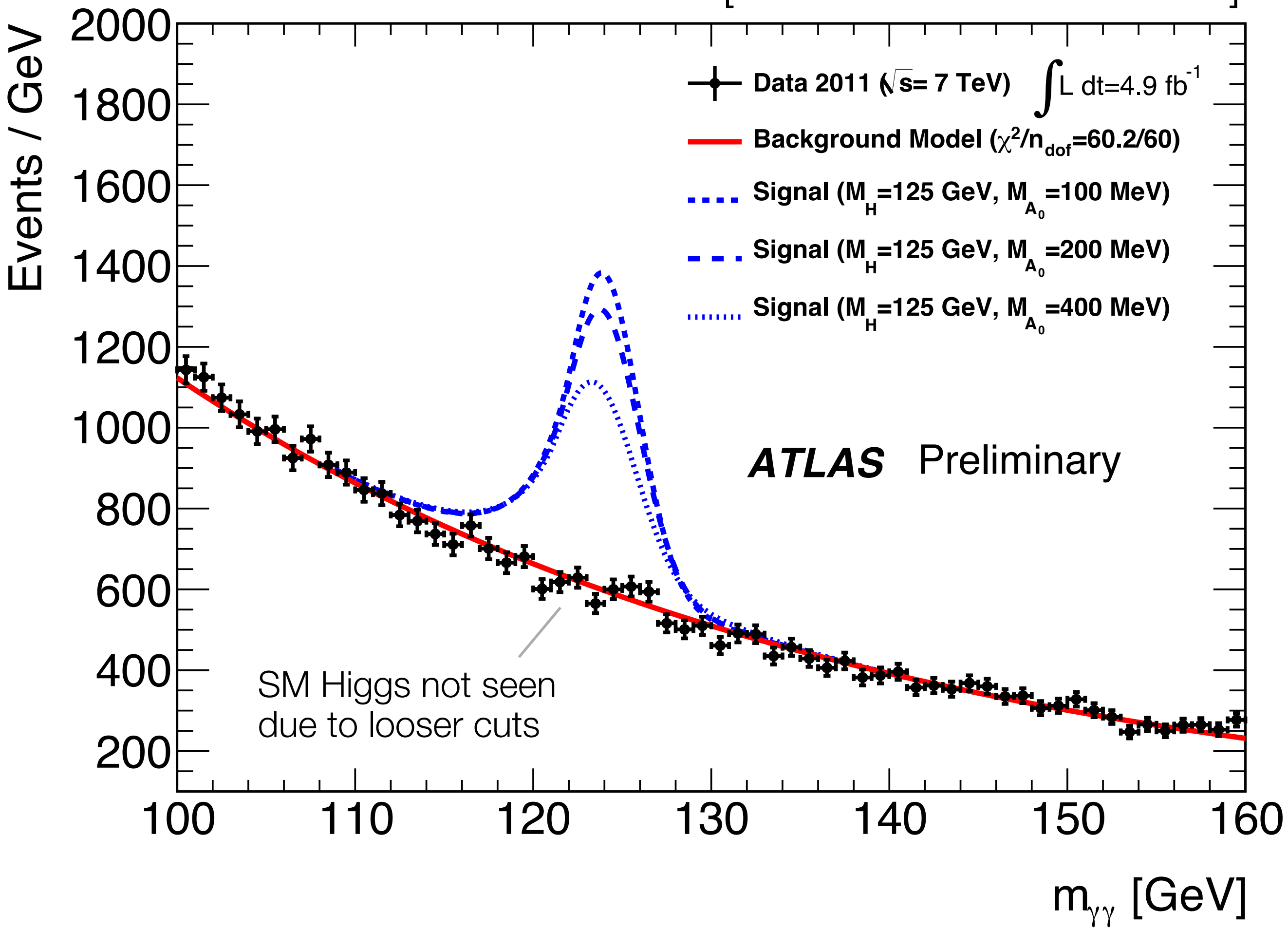
2 high E_T 'photons' …

Decay photons reconstructed as one EM cluster due to large boost …

Event selection similar as for SM Higgs analysis …

… but somewhat looser.

[ATLAS-CONF-2012-079]



Result:

$\sigma_h \times BR < 0.1$ pb [@95% CL]
for 115 GeV < m_h < 140 GeV

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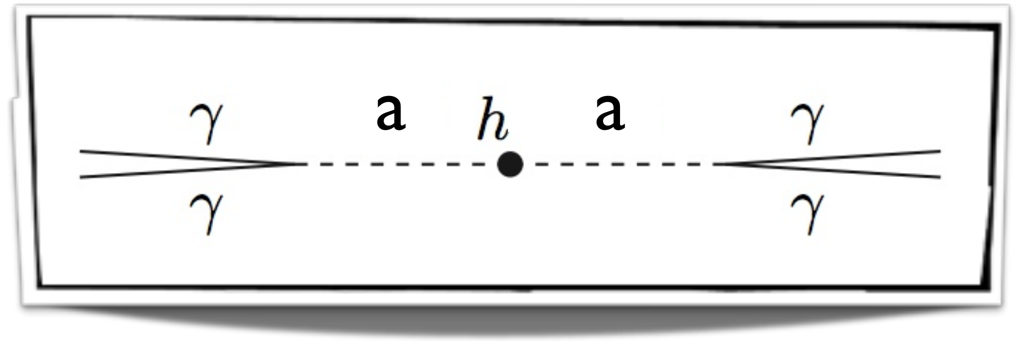

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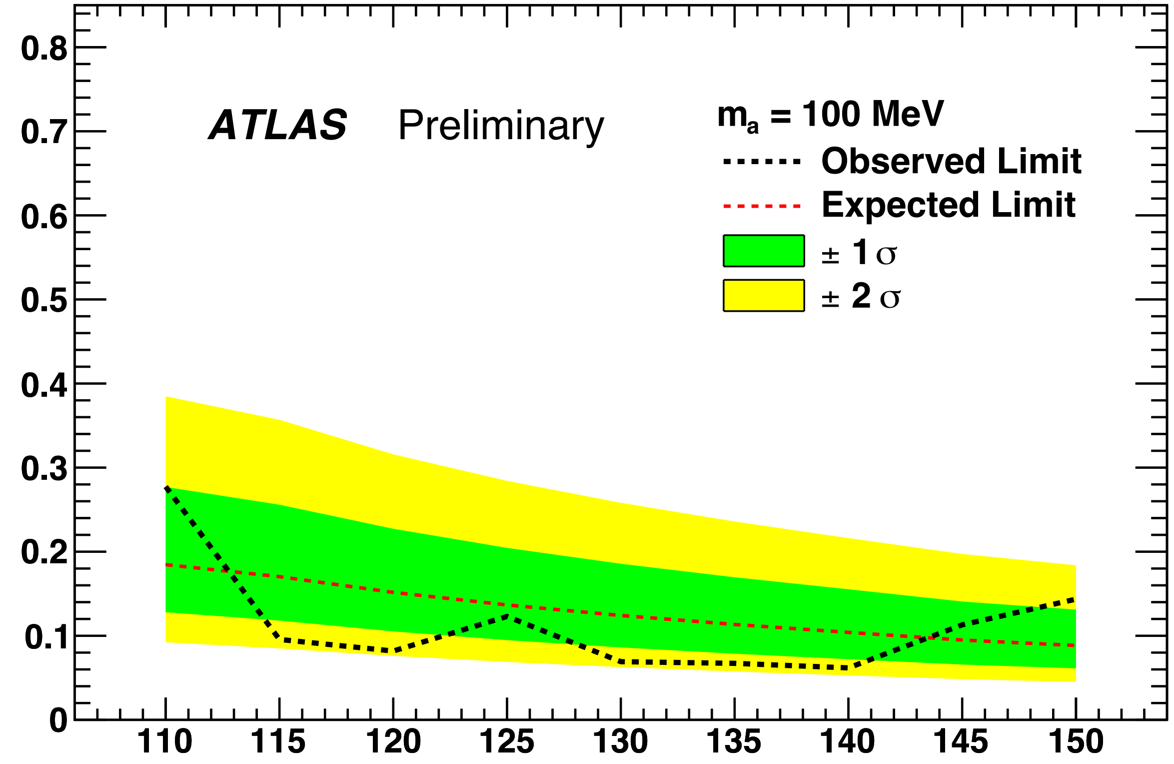

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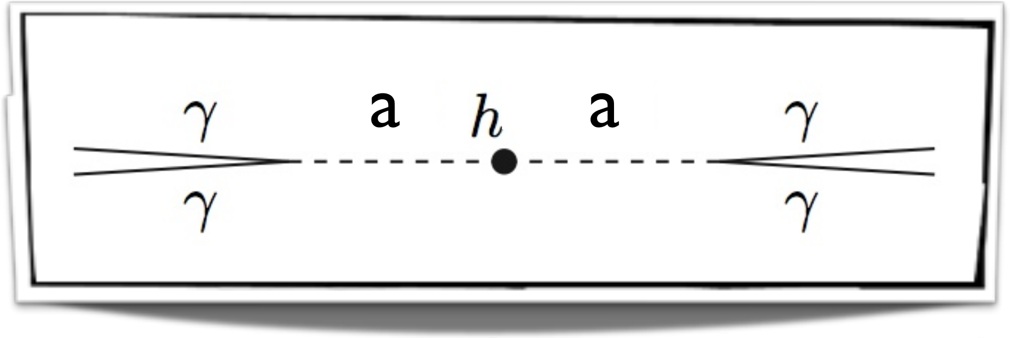

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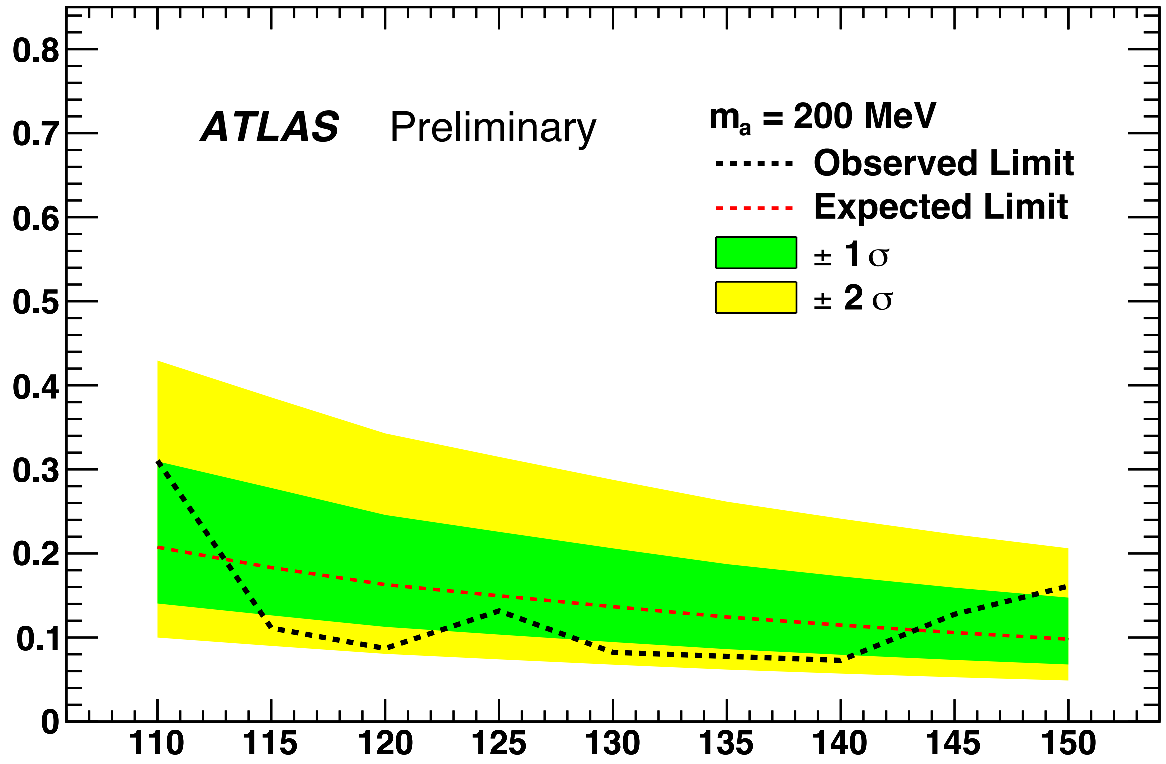

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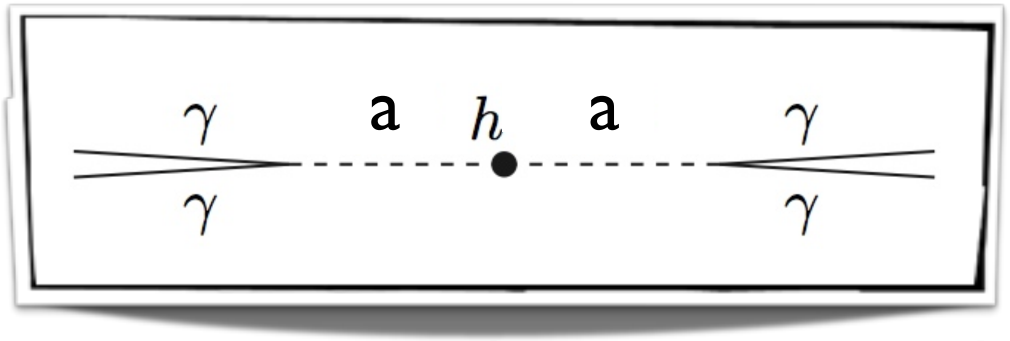

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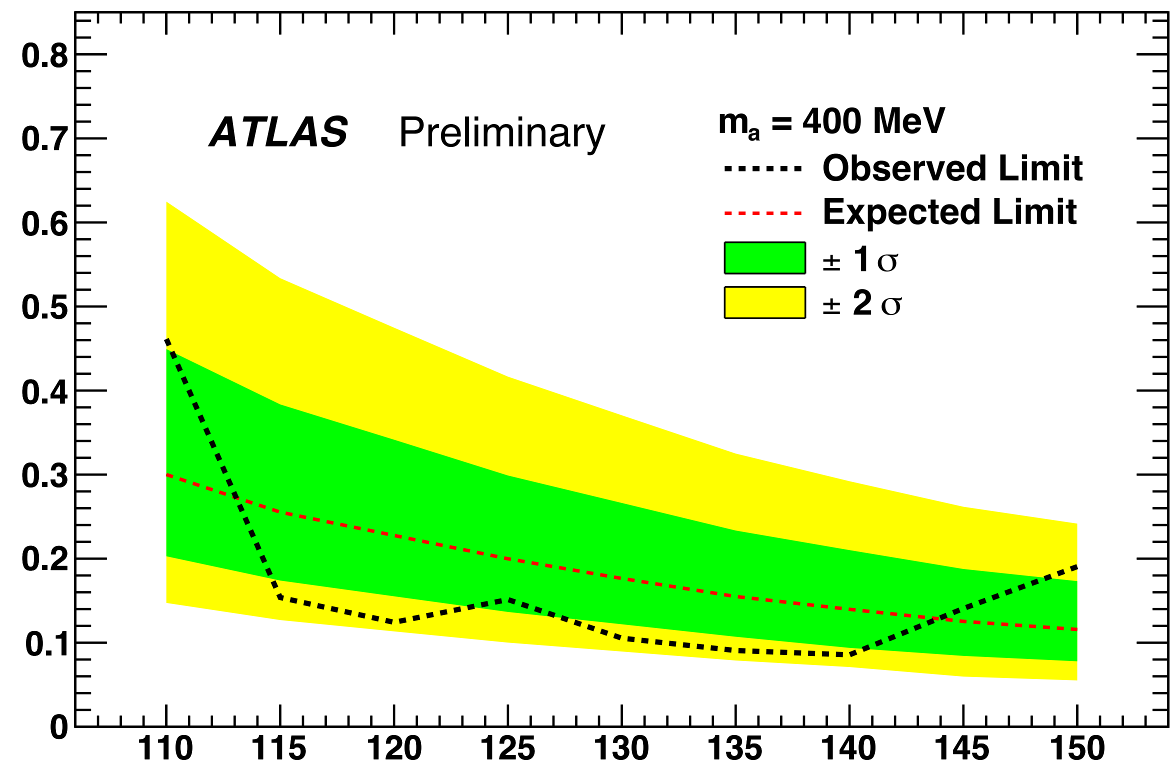

Result:

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for 115 GeV < m_h < 140 GeV

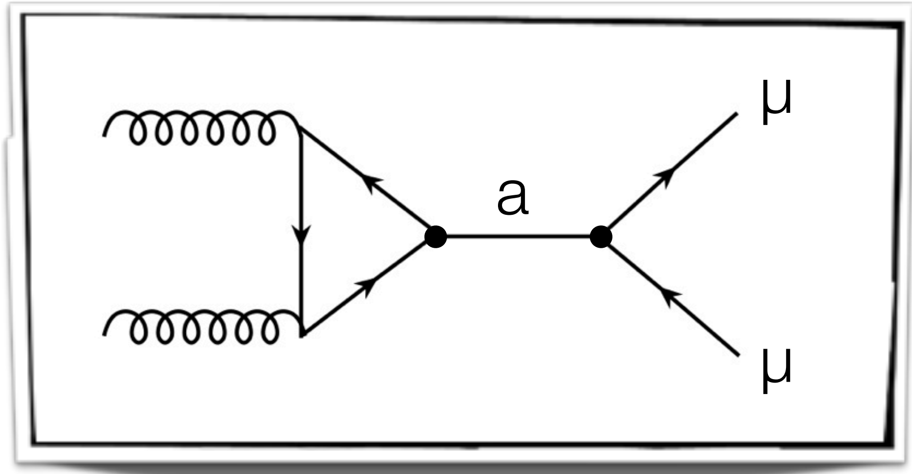
Search for CP-odd Light Higgs via a ➛ μμ

SUSY Models:

2HDM – CP-odd Higgs very light

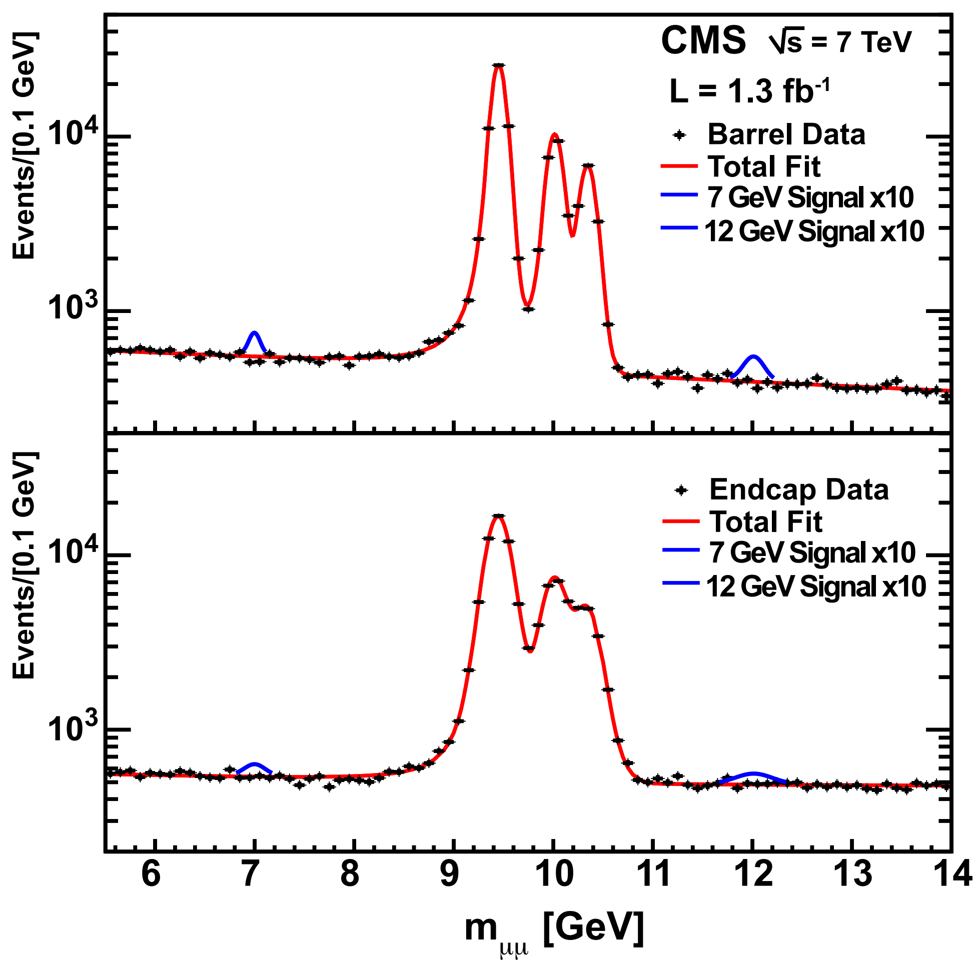
NMSSM – 3 CP-even ($h_{1,2,3}$) and 2 CP-odd ($a_{1,2}$) Higgs

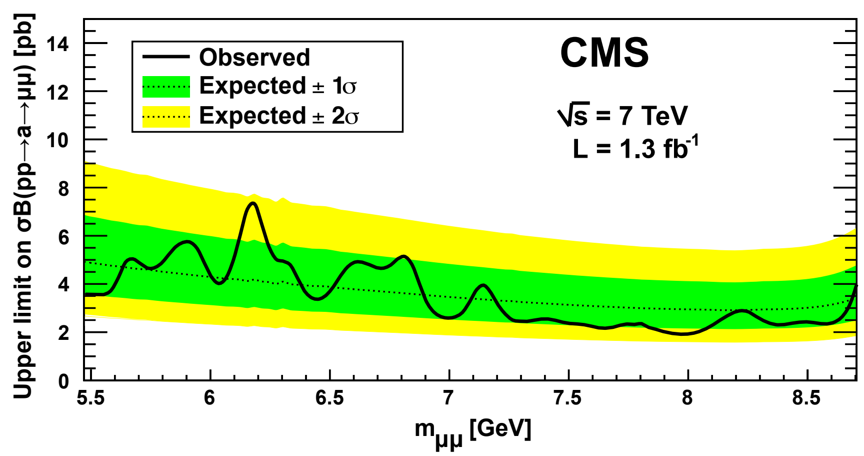
[coupling of light Higgs to SM particles weak …]

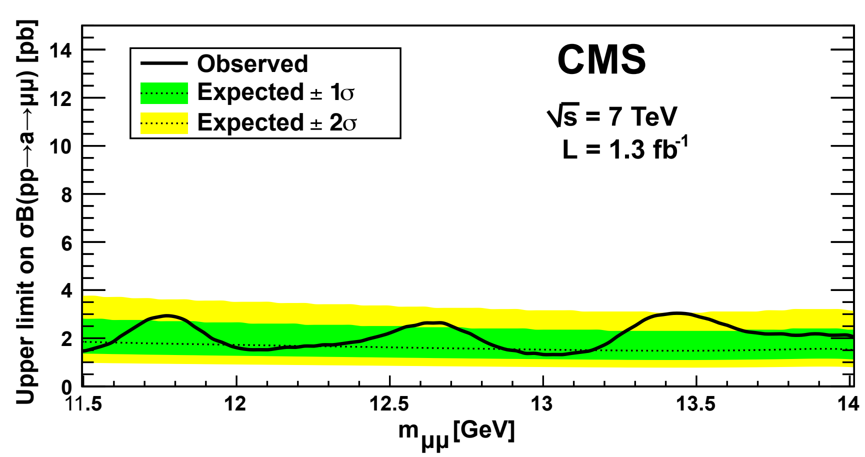


[5.5 GeV ≤ m_a ≤ 8.8 GeV]
[11.5 GeV ≤ m_a ≤ 14 GeV]

[CMS, PRL 109 (2012) 121801]







Left:

Dimuon invariant for barrel (↑) and end cap (↓)

Right:

Upper limits at 95% CL on $\sigma \cdot B(pp \to a \to \mu^+\mu^-)$

Search for Higgs ➛ 2a + X ➛ 4μ + X

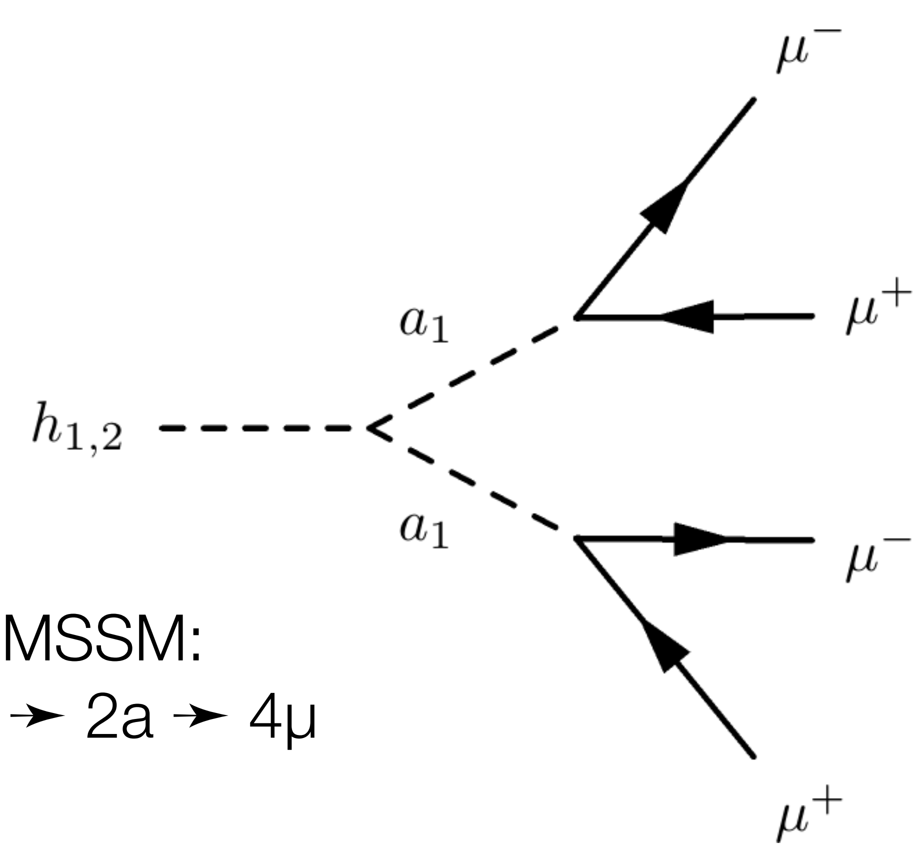
[CMS PAS HIG-13-010]

SUSY Models:

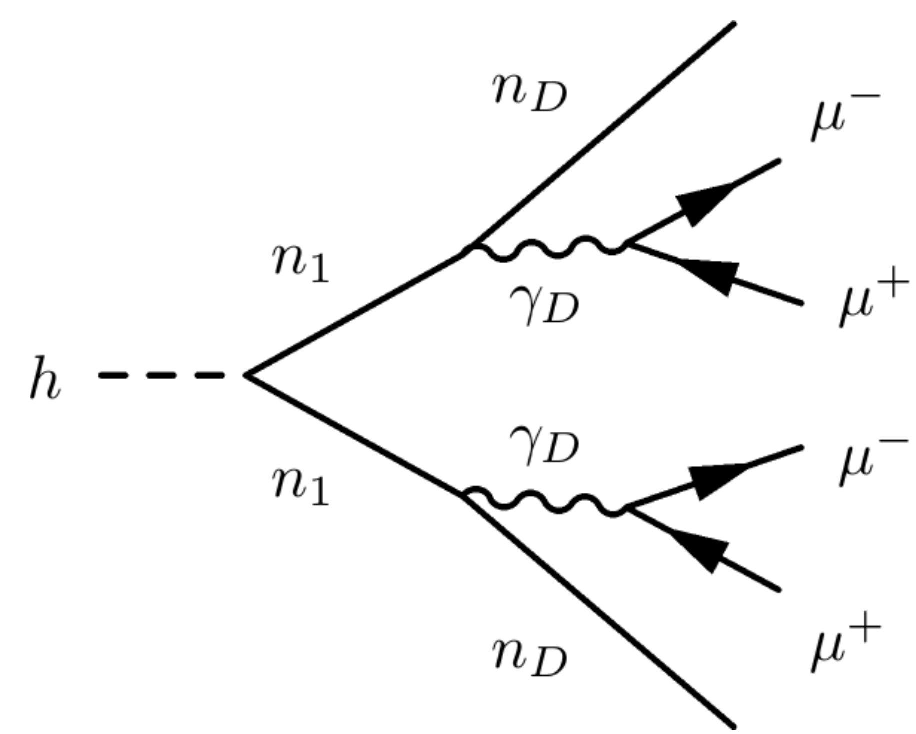
NMSSM – 3 CP-even ($h_{1,2,3}$) and 2P-odd ($a_{1,2}$) Higgs

Dark SUSY – light massive photons γ_D, lightest neutralino n_1 non-stable; n_1 ➛ $n_D + \gamma_D$ …

[n_D dark neutralino; γ_D dark photon, $m_{\gamma D} < O(1\ \text{GeV})$; DM mass scale at ~ 1 TeV]



NMSSM:
h ➛ 2a ➛ 4μ



Dark SUSY:
h ➛ $2n_1$ ➛ $2n_D + 2\gamma_D$ ➛ $2n_D + 4\mu$

[CMS]

Search for Higgs ➛ 2a + X ➛ 4μ + X

[CMS PAS HIG-13-010]

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[n_D dark neutralino; γ_D dark photon, $m_{\gamma D} < O(1\ \text{GeV})$; DM mass scale at ~ 1 TeV]

Selection:

4 muon; 2 isolated pairs

Mass: $m_{\mu\mu} < 5$ GeV; $m_{\mu\mu 1} \approx m_{\mu\mu 2}$

…

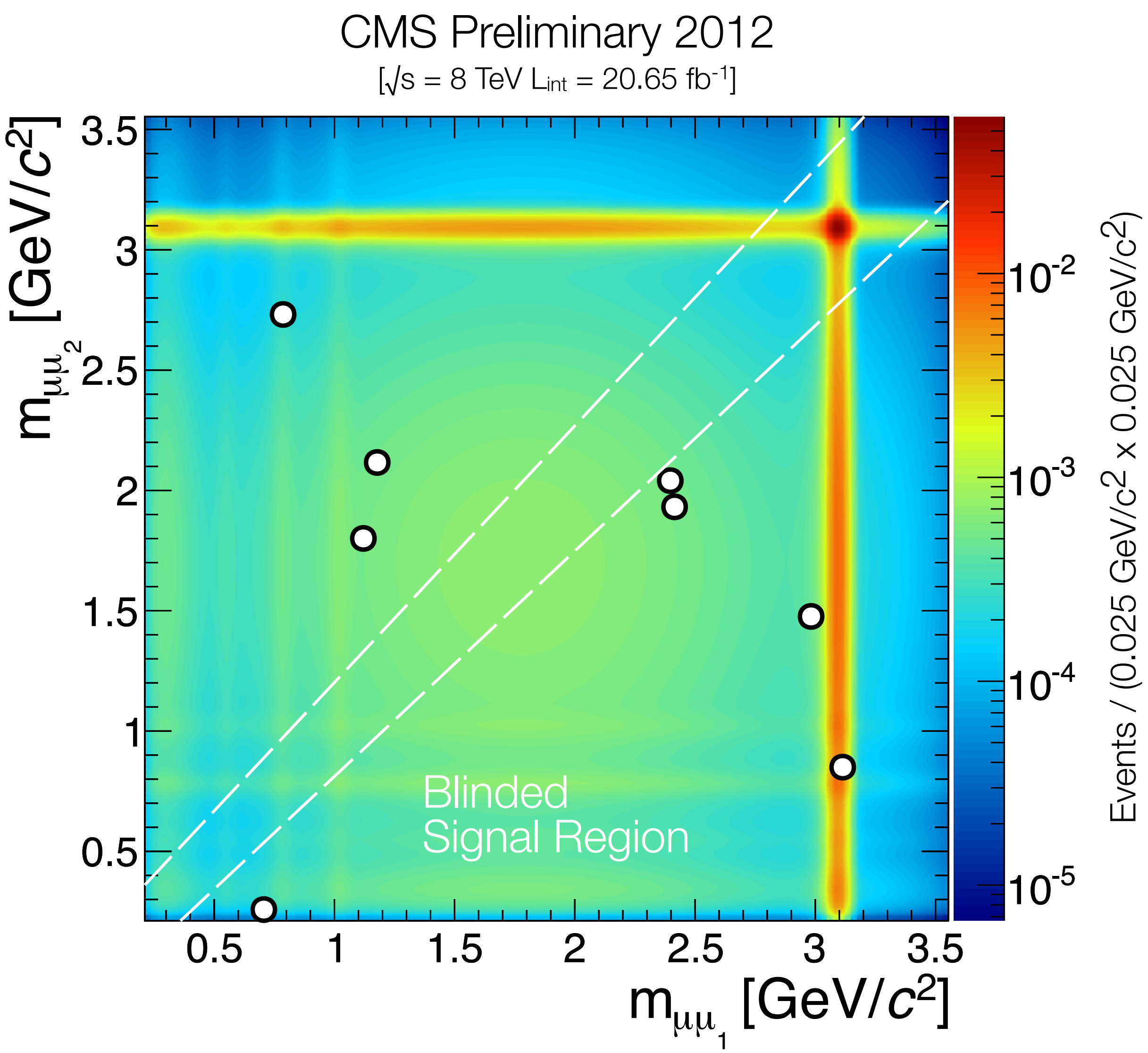
Background:

bb via double leptonic decays

J/Ψ pair production

Blinded Analysis …

[8 events outside $m_{\mu\mu 1} \approx m_{\mu\mu 2}$ region]



[CMS]

Search for Higgs ➛ 2a + X ➛ 4μ + X

[CMS PAS HIG-13-010]

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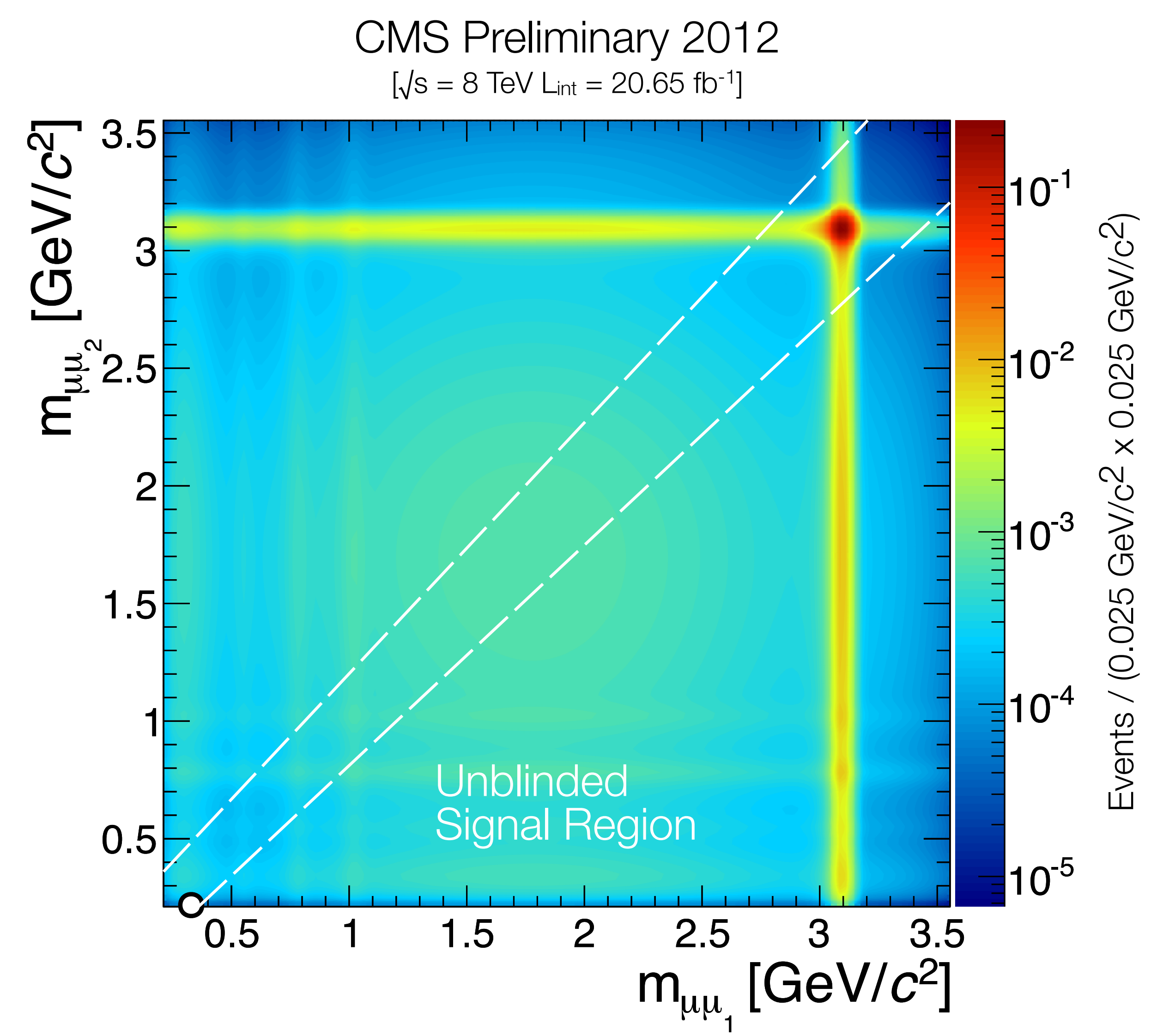
…

Background:

bb via double leptonic decays
J/Ψ pair production

One signal found …

[Background expectation: 3.8 ± 2.1]



Search for Higgs ➛ 2a + X ➛ 4μ + X

[CMS PAS HIG-13-010]

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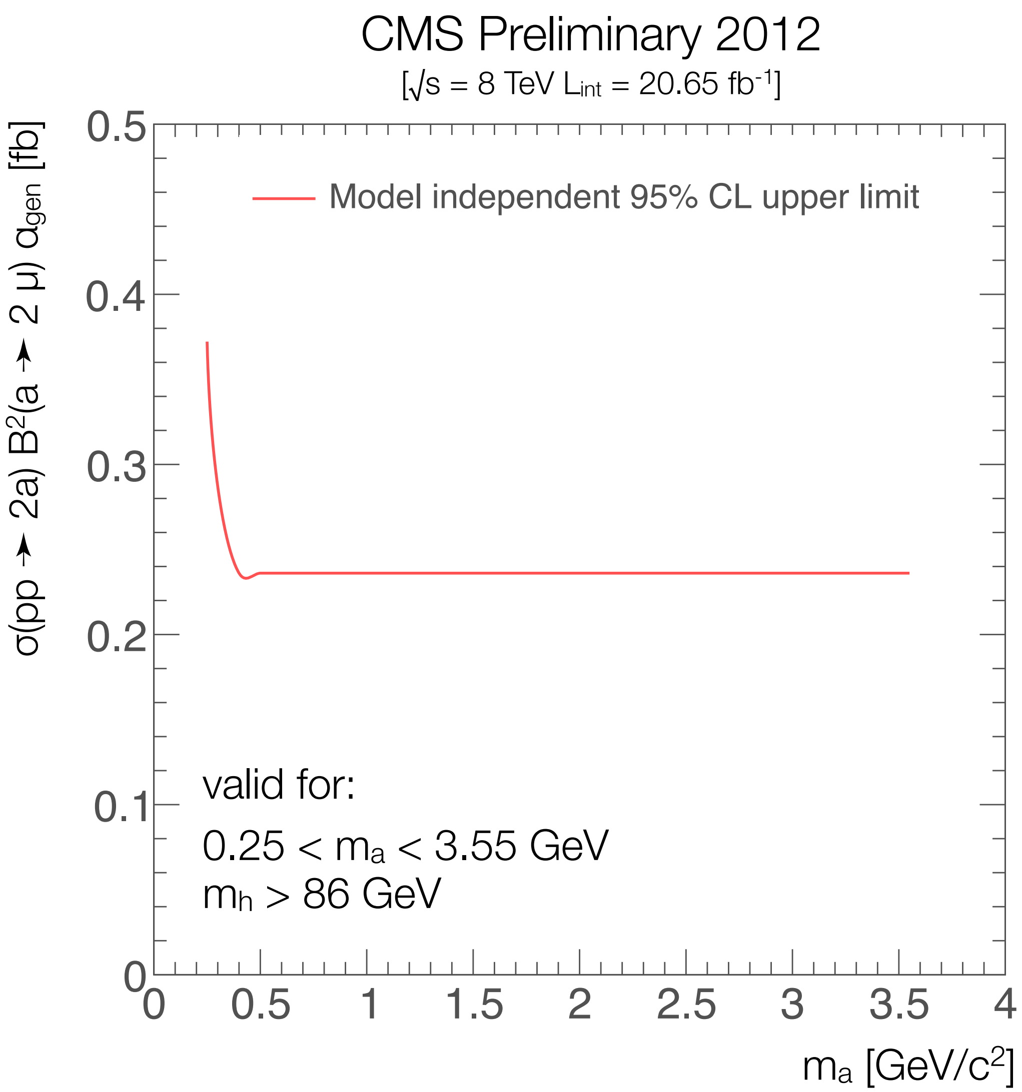

Generic

Search for Higgs ➛ 2a + X ➛ 4μ + X

[CMS PAS HIG-13-010]

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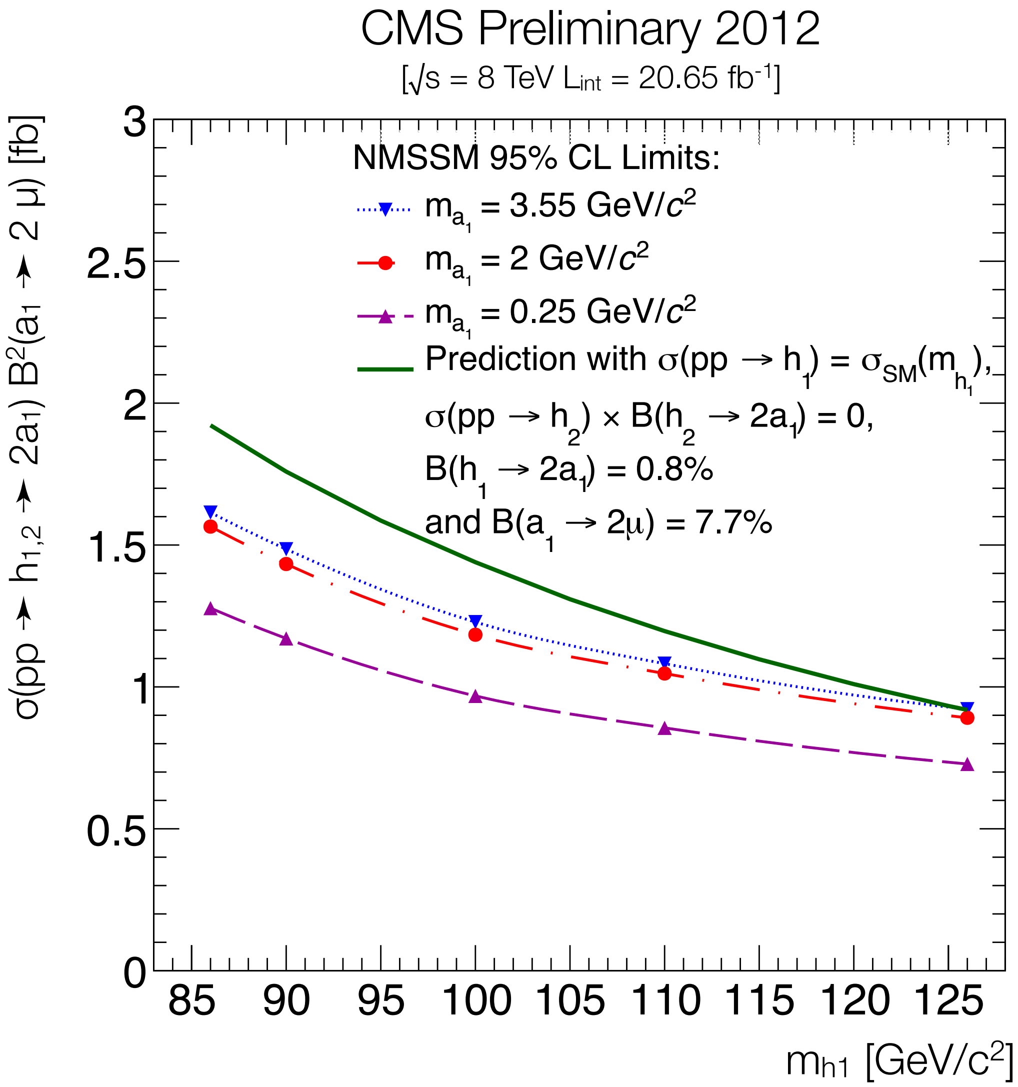

NMSSM

Search for Higgs ➛ 2a + X ➛ 4μ + X

[CMS PAS HIG-13-010]

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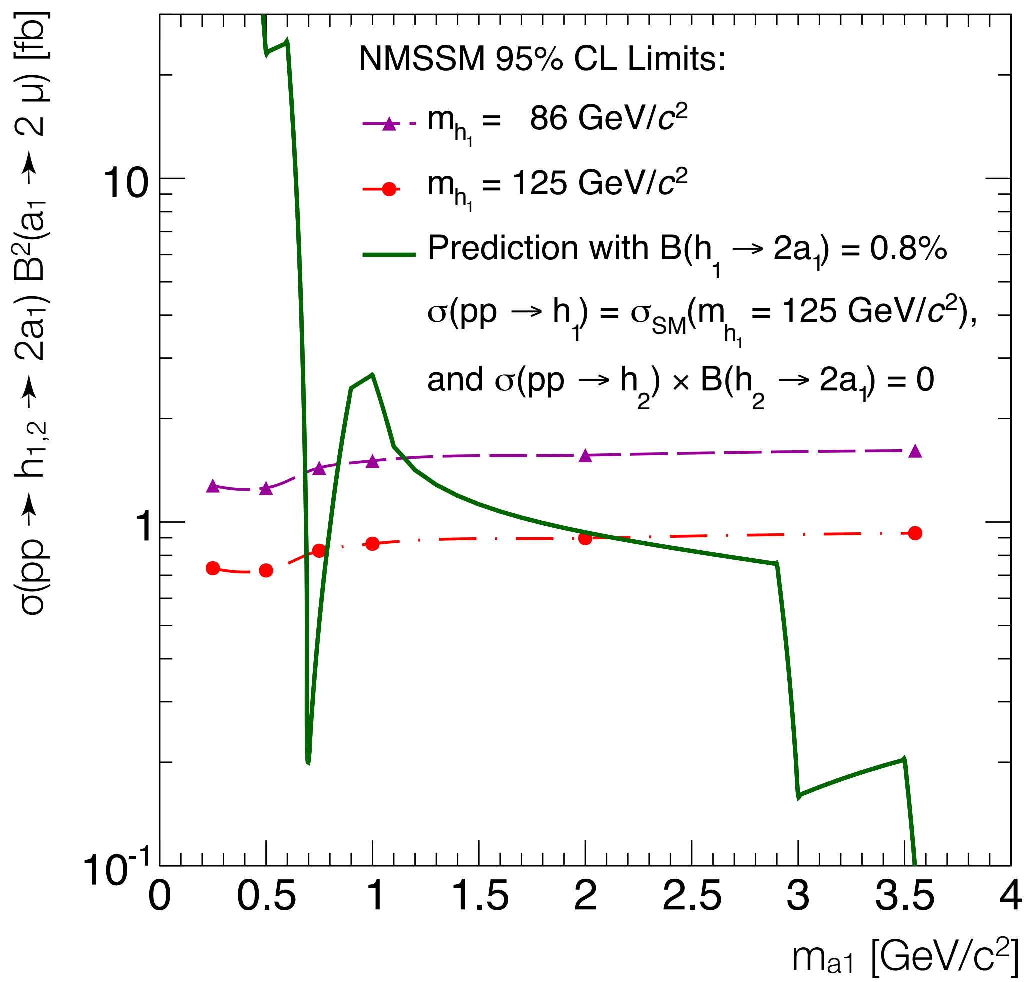
CMS Preliminary 2012

[$\sqrt{s}$ = 8 TeV L_{int} = 20.65 fb^{-1}]



NMSSM

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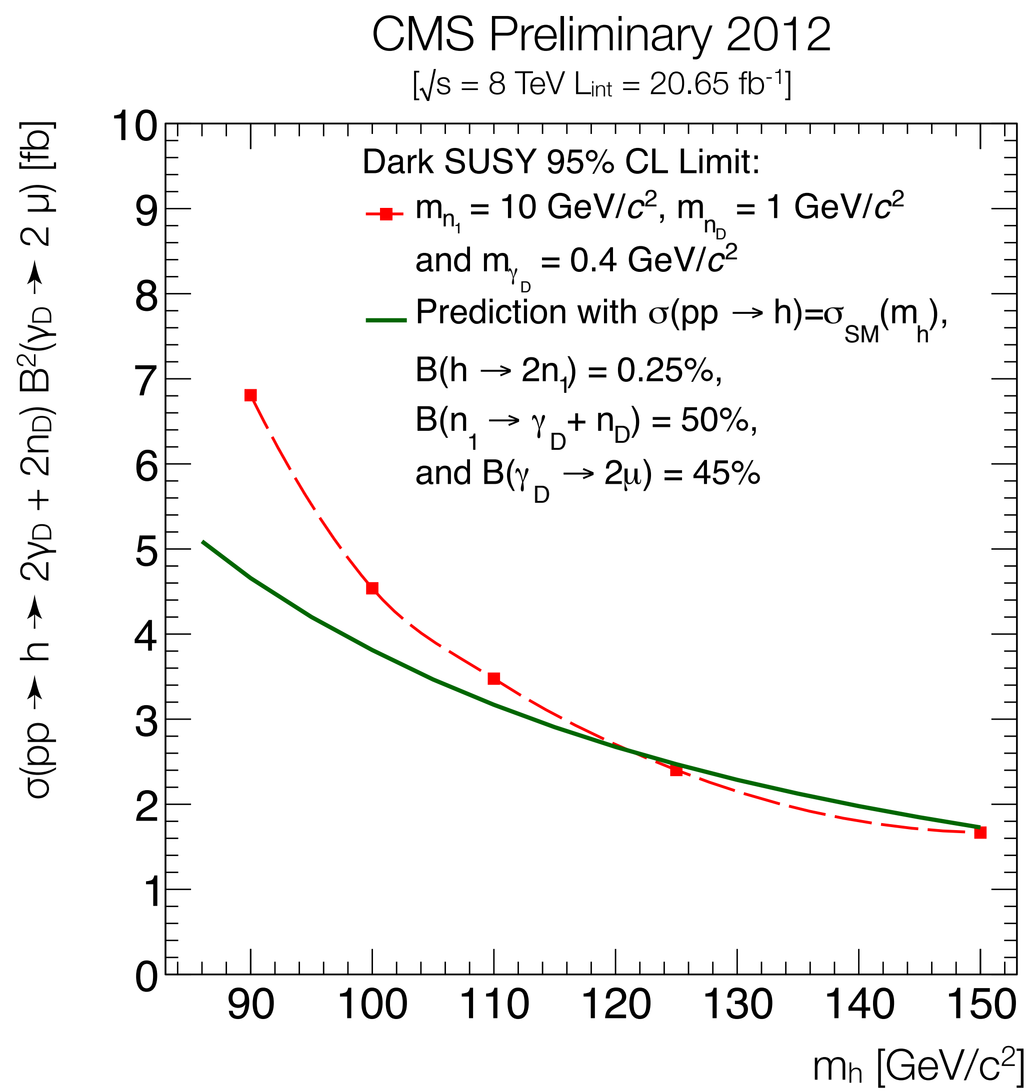

Dark SUSY