MSSM Higgs searches at the LHC

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Outline

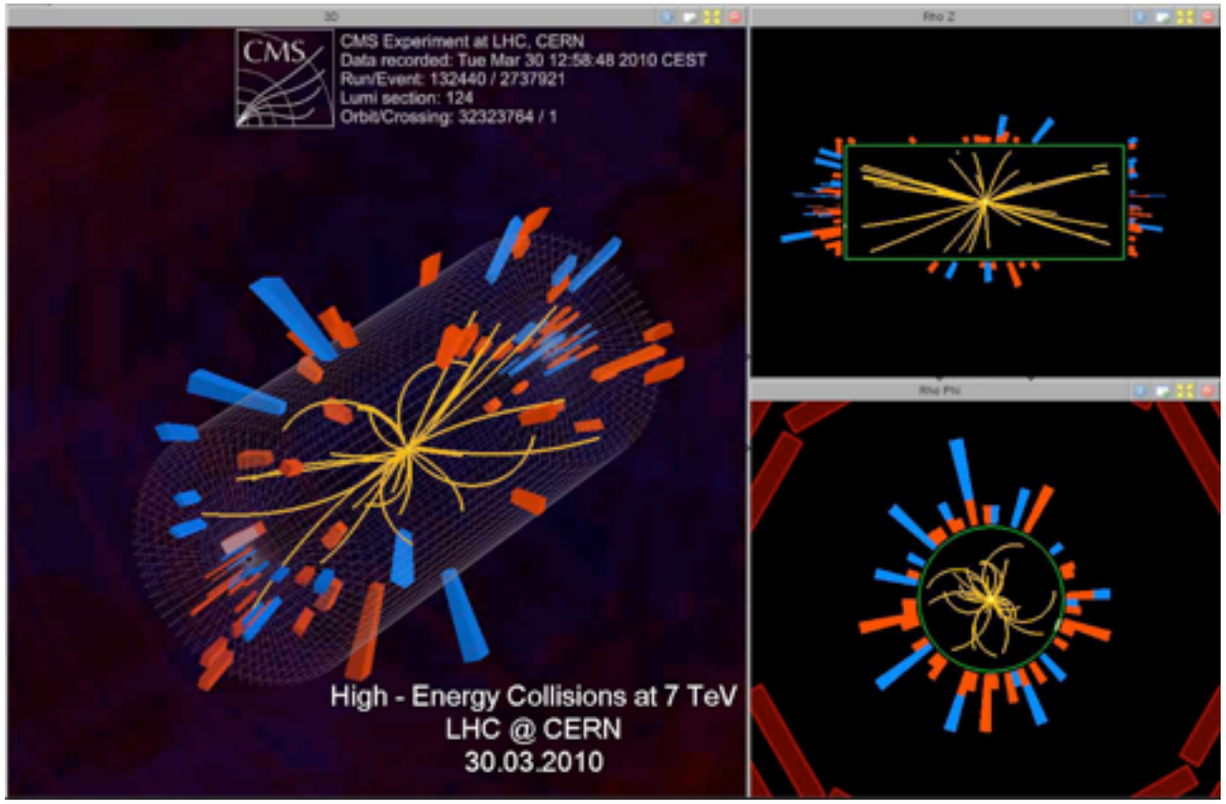
- Introduction
  - LHC, ATLAS and CMS
  - The MSSM Higgs sector
- Neutral Higgs boson searches
- Charged Higgs boson searches
- Conclusions

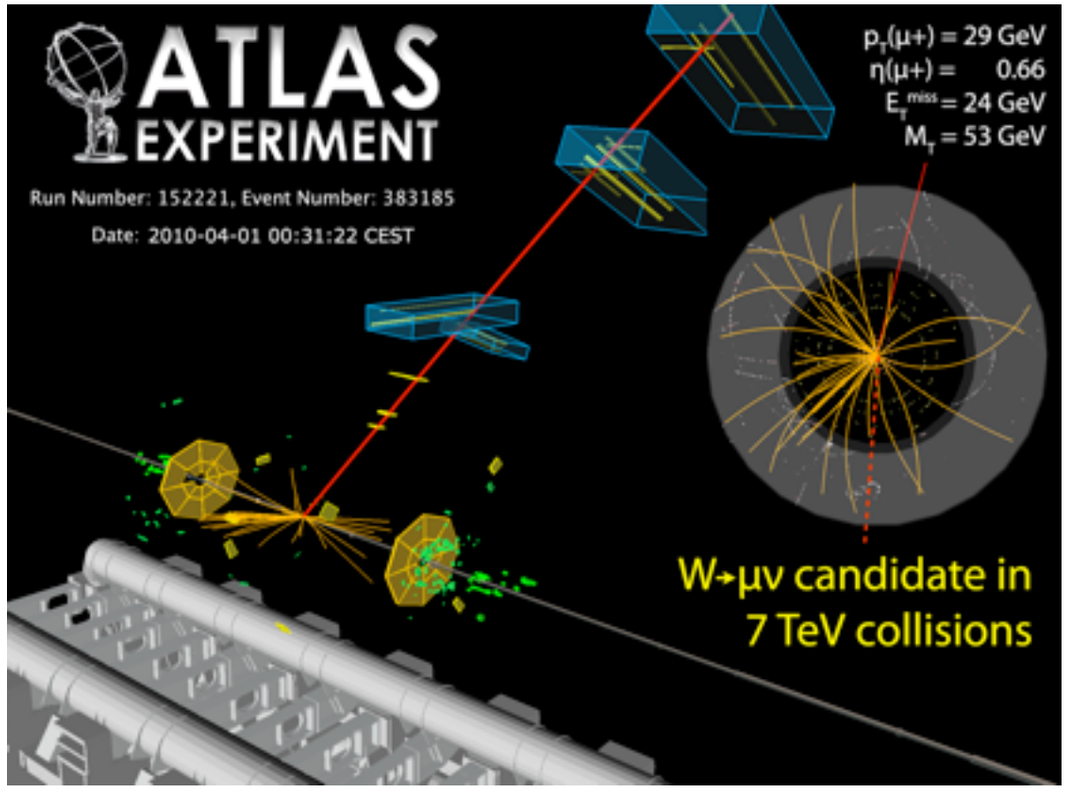
Results for $\sqrt{s} = 14\,\mathrm{TeV}$, from (unless indicated otherwise):

- Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics (CERN-OPEN-2008-020)
- CMS Physics Technical Design Report Vol.II (CERN/LHCC 2006-021)

LHC, ATLAS and CMS

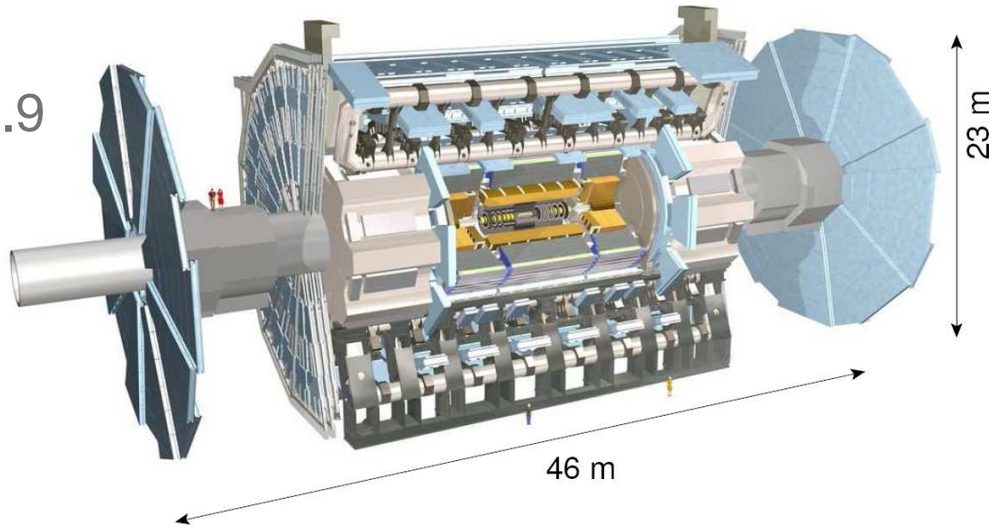
- The LHC is running!
  - At 7 TeV, with increasing luminosity
  - Experiments taking data

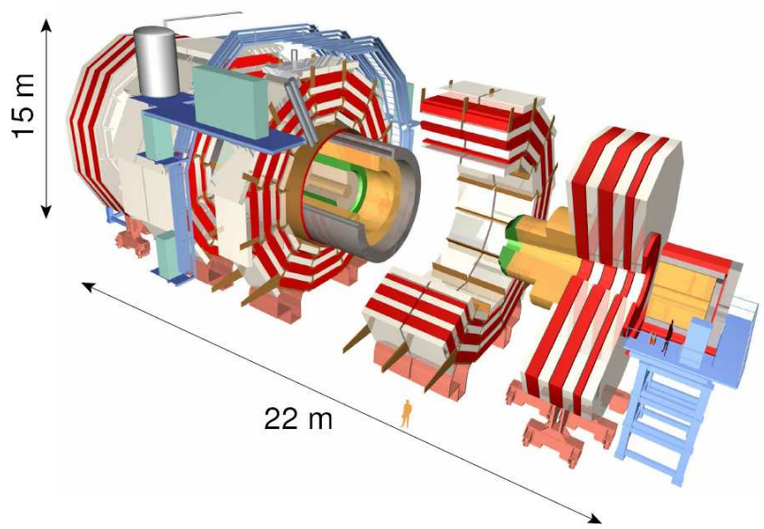




LHC, ATLAS and CMS

- Good, hermetic calorimetry
  - E_T^{miss} measurement, jet reconstruction up to |η| < 4.9
- Powerful Particle Identification
  - ~ 97% Muon efficiency, cleanest identification
  - ~ 80% Electron efficiency with jet rejection of 10^5
  - ~ 80% Photon efficiency with jet rejection of 10^3
  - ~ 60% b-tagging efficiency with light jet rejection of 10^2
  - ~ 50% hadronic τ efficiency with jet rejection of 10^2
- Excellent Electron, Photon and Muon energy / Pt resolution



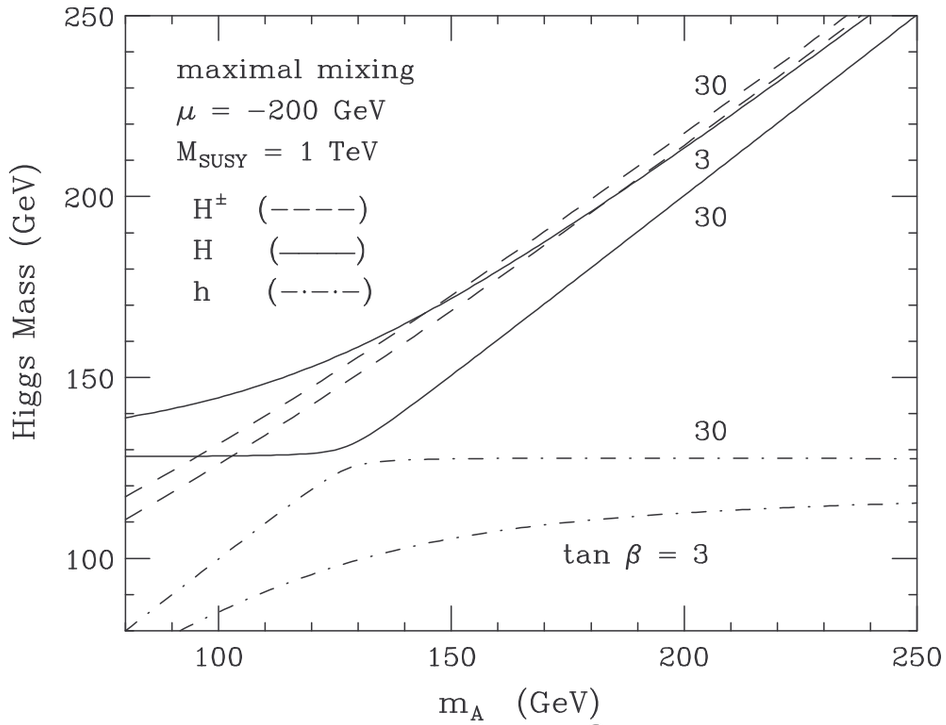


MSSM Higgs sector

- Two Higgs doublets, five physical states
  - three neutral: h, A and H
  - two charged: $H^{\pm}$
- Two parameters at tree level
  - Mass of the CP-odd boson: m_A
  - Ratio of the v.e.v.s: tan β
- Large loop corrections
  - $m_h < m_Z$ becomes $m_h \lesssim 130$ GeV
  - Fixed in benchmark scenarios (m_h-max used in most of the results)

    Carena, Heinemeyer, Wagner, Weiglein
    Eur. Phys. J. C26 (2003) pp. 601-7

- Masses

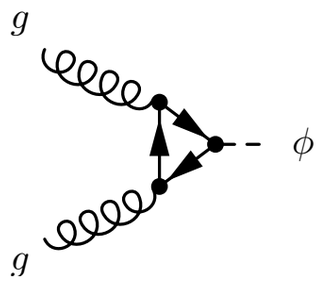


- Couplings (for large tan β)
  - W / Z suppressed, absent for A
  - Enhanced with respect to SM for 3rd generation and down type fermions
  - h is SM-like for large m_A

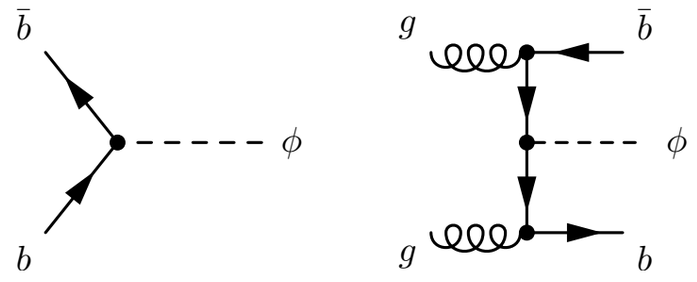
Neutral Higgs bosons: production and decays

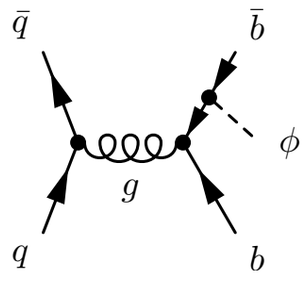
- Production $(\phi = h, H, A)$

Gluon fusion



b-quark associated production: dominant at large tan β



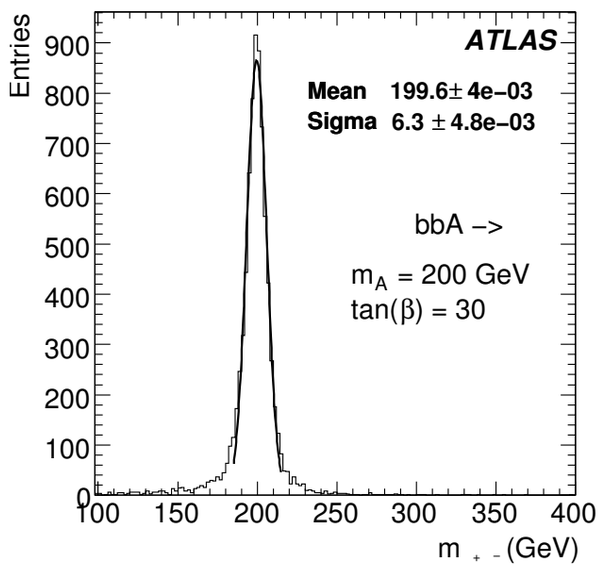


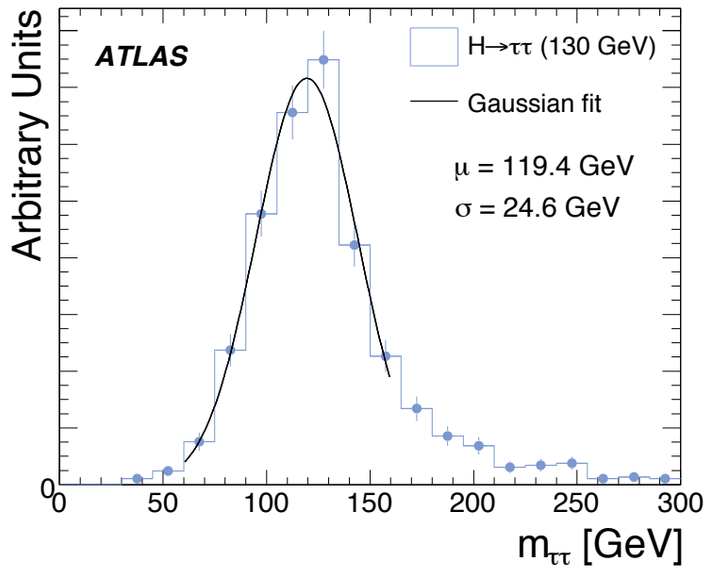
- Decay modes (typical values for the interesting regions of the parameter space)
  - bb with BR ~ 90% — Overwhelmed by QCD backgrounds
  - $\tau^+\tau^-$ with BR ~10% — Possibilities in leptonic and hadronic final states
  - $\mu^+\mu^-$ with BR ~ 0.03% — Clean signature, excellent mass resolution, low yield
  - SUSY particles if allowed — Depends strongly on additional parameters
- Mass degeneracy
  - Of at least two of them in most of parameter space
  - Handled by summing cross sections for searches

Neutral Higgs searches: $h/H/A \to \mu^+\mu^-$

ATLAS / CMS

- Motivation
  - Clean signal with excellent mass resolution (3% against 20% for ττ)
  - Potential to distinguish between h, H and A and provide measurement of tan β (from width)
  - Sensitivity for both gluon fusion (ATLAS) and b-associated production (ATLAS / CMS)
    - Drawback: small BR (enhanced for high tan β)
- Backgrounds
  - Dominant: Drell-Yan Z (+ jets)
  - $t\bar{t} \to b\bar{b}\mu^+\mu^-\nu\bar{\nu}$
  - WW / ZZ very small
  - Can be estimated from data using $\mu^+\mu^-, e^+e^-, e^\pm\mu^\mp$

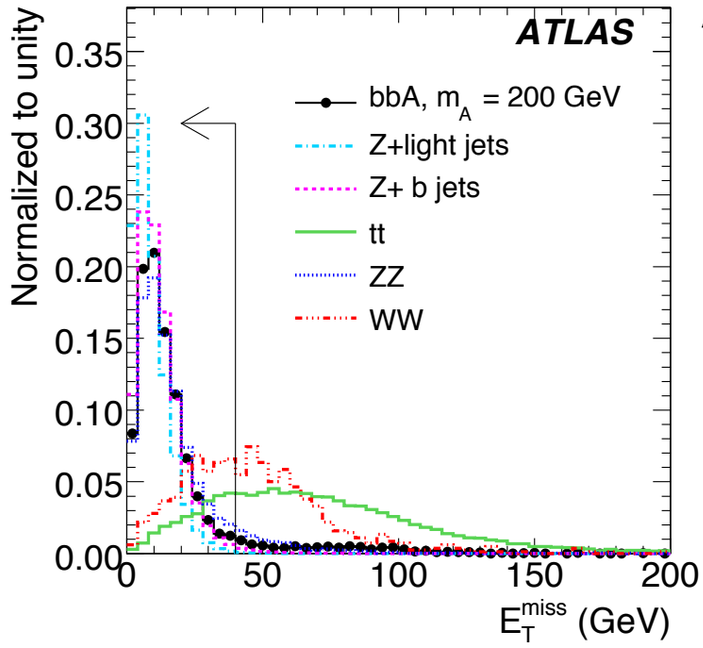




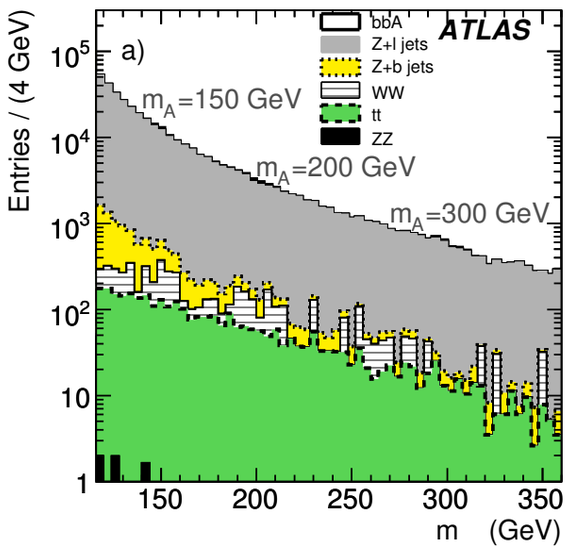
Neutral Higgs searches: $h/H/A \rightarrow \mu^+\mu^-$

ATLAS / CMS

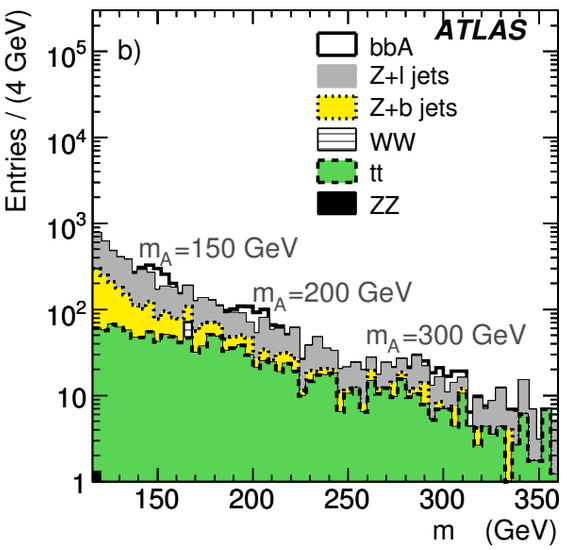
- Event selection
  - Trigger on single-mu or di-muons (> 90% efficiency)
  - High-Pt isolated muon(s) (20 GeV)
- Background reduction
  - Cuts on E_T^{miss}, jet activity and angle between muons to reject tt and WW
- B-tagging requirements
  - ATLAS: two independent optimizations
    - 0 b-jet, dominated by Z + jets
    - ≥1 b-jets, with important contribution from tt
  - CMS:
    - Two different strategies to increase efficiency for high and low-Pt b-jets



L = 30 fb^{-1}



0 b-tagged jet

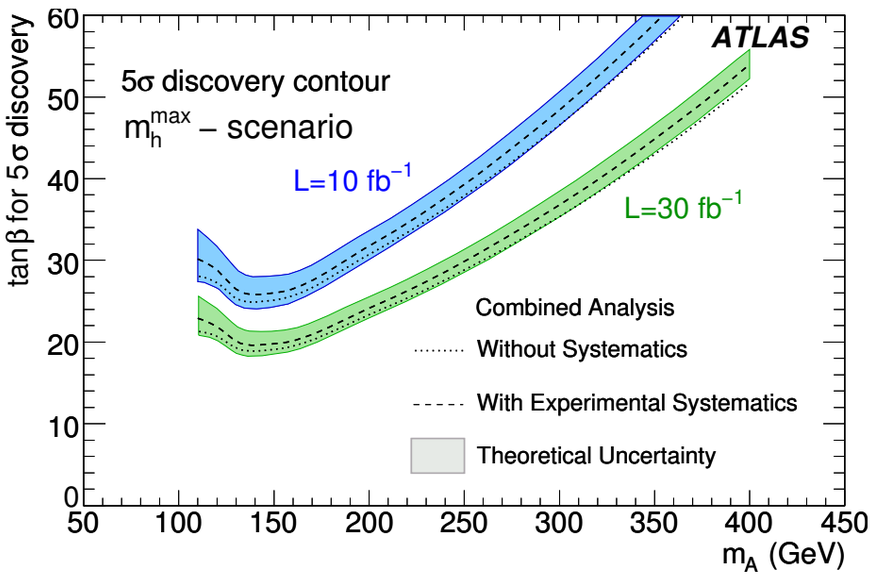


≥ 1 b-tagged jets

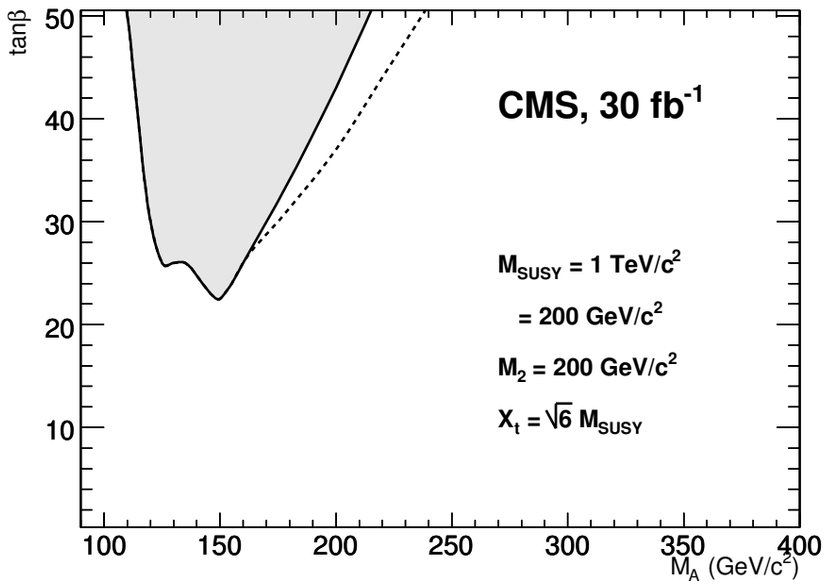
Neutral Higgs searches: $h/H/A \to \mu^+\mu^-$

ATLAS / CMS

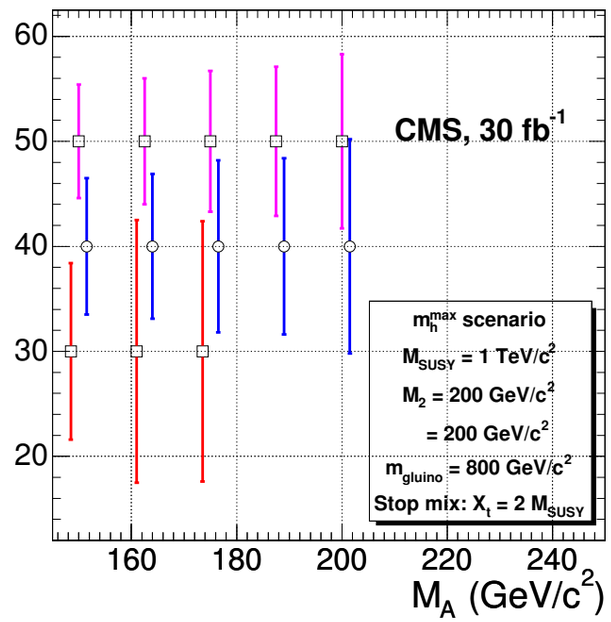
- Discovery potential
  - Low to intermediate masses for tan β > 20
  - Sensitivity to tan β from $m_{\mu\mu}$ peak width
- Systematic uncertainties
  - Theoretical (~ 17%)
- Experimental (5 - 12%)
  - Muon reconstruction efficiency, momentum scale and resolution
  - Jet energy scale and resolution
  - b-tagging efficiency and fake rate



Discovery contour



tan β measurement
for tan β = 30, 40, 50



(dashed line: no systematics)

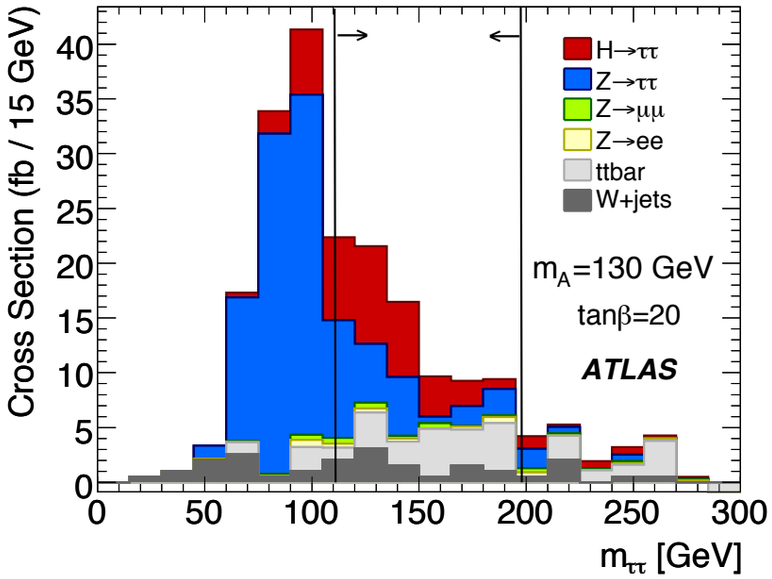
Neutral Higgs searches: $(b\bar{b})\, h/H/A \to \tau\tau$

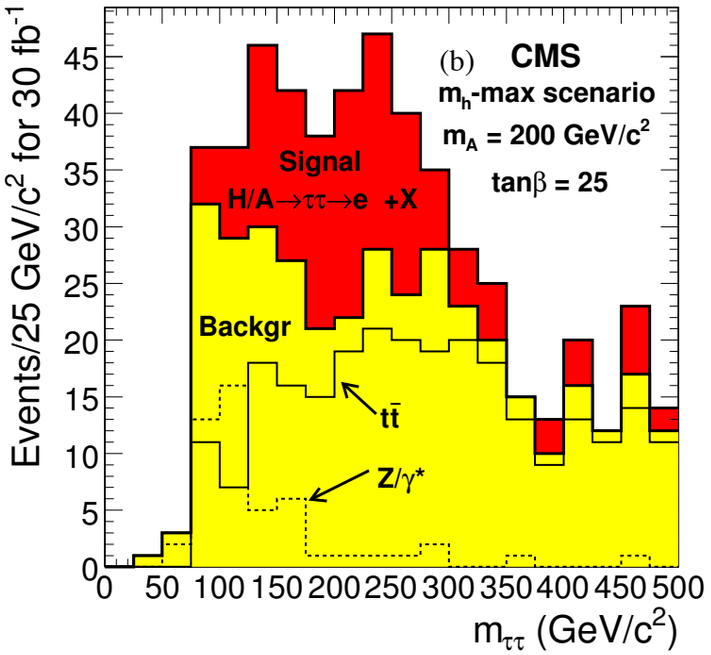
- Final states (tau decay products)
  - Leptons, leptons (ATLAS / CMS)
  - Leptons, hadrons (CMS, ATLAS to appear)
  - Hadrons, hadrons (CMS)
- Backgrounds
  - $Z \to \tau^+\tau^-$, $t\bar{t}$, $W + \text{jets}$
  - QCD multi-jets in hadronic case
  - $Z \to e^+e^-/\mu^+\mu^-$+ jets for leptonic decay
- Systematic uncertainties
  - tau fake rates
  - Jet energy scale / resolution and E_T^{miss}
  - b-tagging efficiency and purity
- Tau identification
  - Hadronic:
    - 1 or 3 tracks, $P_T^{leading} = 10, 20\,\text{GeV}$
    - Isolation in tracker
    - 50% efficiency with jet rejection > 100
  - Leptonic:
    - High-Pt isolated lepton
  - $m_{\tau\tau}$ using collinear approximation
- Background reduction
  - One or more b-tagged jets
  - Jet activity (tt, W + jets), di-lepton mass (Z)
  - CMS: lepton impact parameter, $m_T(\ell, E_T^{miss})$

Neutral Higgs searches: $(b\bar{b})\, h/H/A \to \tau\tau \to 2\ell 4\nu$

- Motivation
  - Leptons to trigger on
  - Lower backgrounds
    - Z + jets and tt mainly
- Event selection
  - ATLAS: Cut on di-lepton mass against $Z \to e^+e^-/\mu^+\mu^-$
  - CMS: Displaced lepton impact parameters
  - Jet veto against tt
  - One or more b-tagged jets (analysis with no b-tagging for early data)

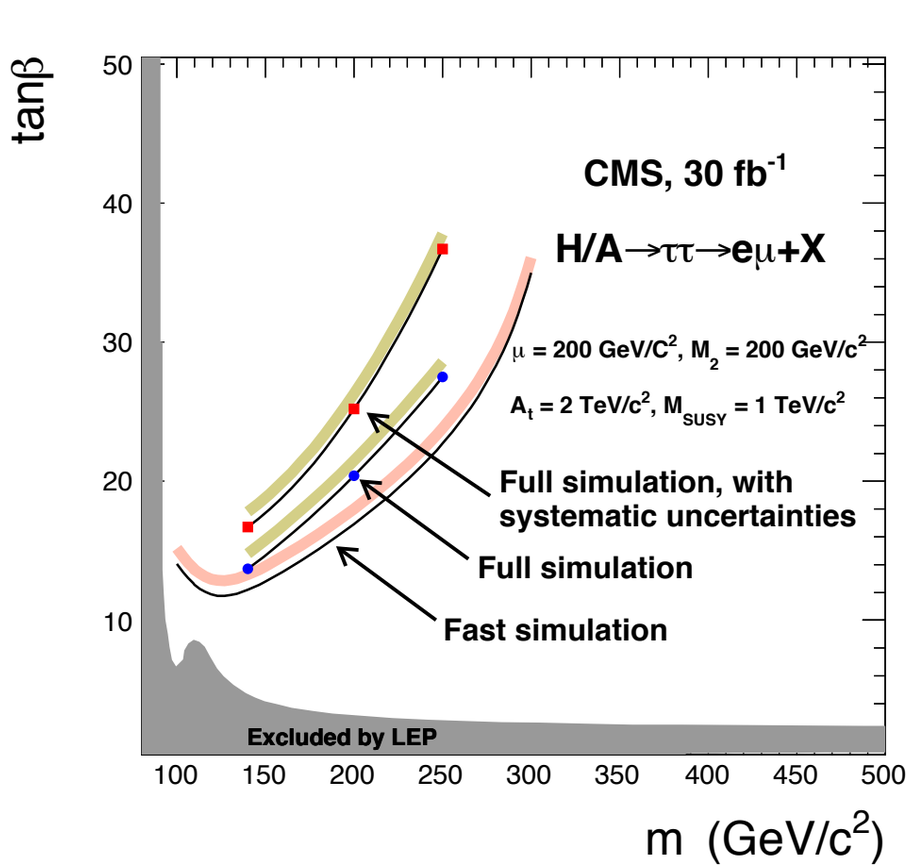
ATLAS (2ℓ) / CMS $(e\mu)$



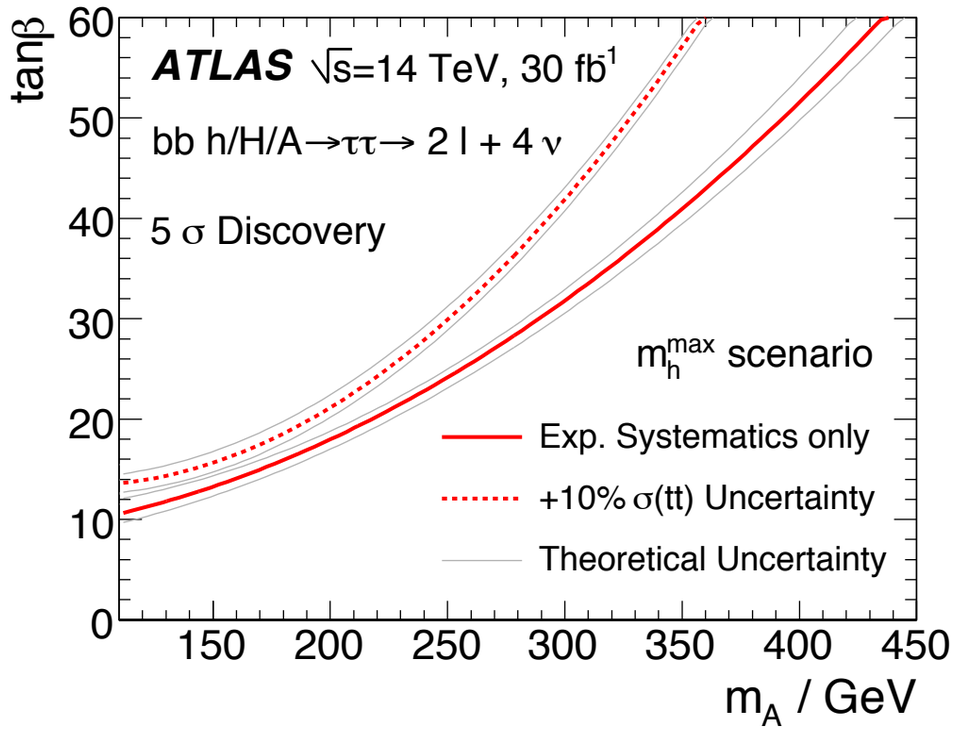


Neutral Higgs searches: $(b\bar{b})\, h/H/A \to \tau\tau \to 2\ell 4\nu$

- Discovery potential
  - Best at low masses
  - Decreases quickly with mass
    - High tan β needed



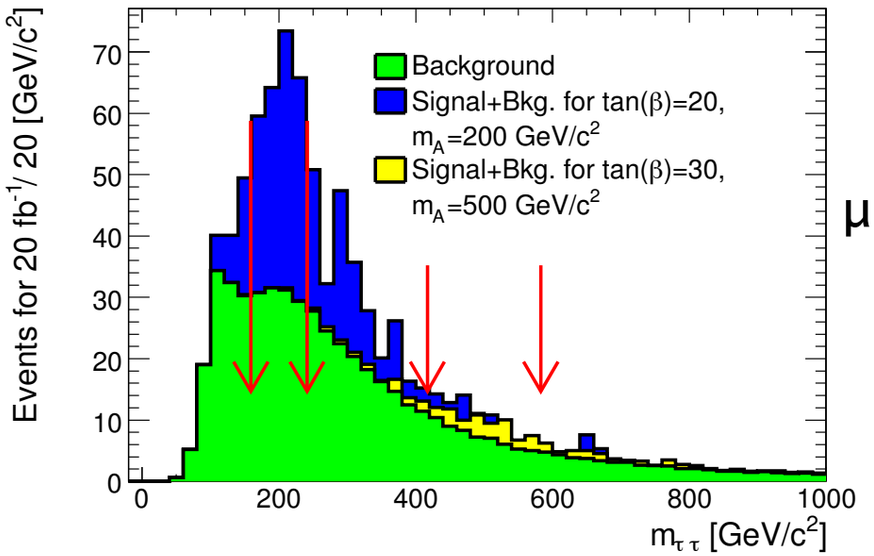
- Systematic uncertainties
  - $Z \to \tau^+\tau^-$ shape and normalization from data $(\text{modified } Z \to \mu^+\mu^-)$
  - tt yields
  - Jet energy scale and resolution
  - b-tagging efficiency



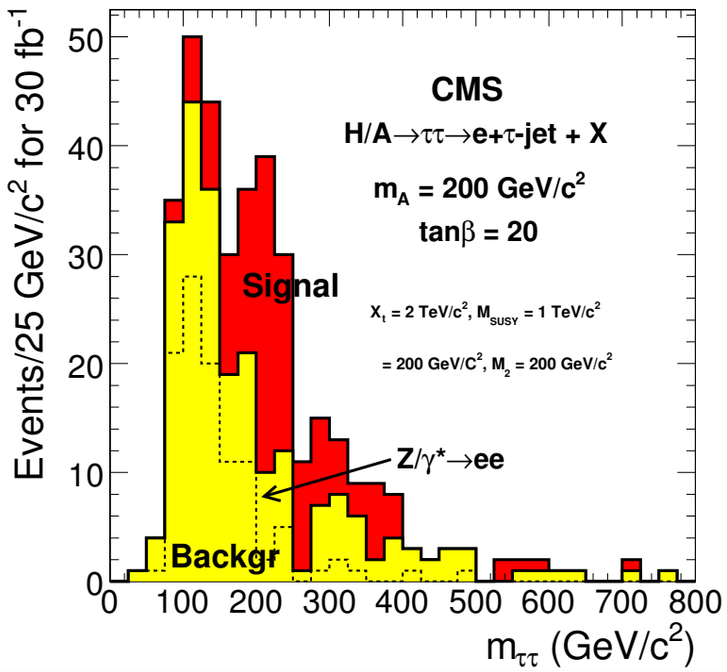
Neutral Higgs searches: $(b\bar{b})\, h/H/A \to \tau\tau \to (e/\mu)\,\mathrm{had}$

- Motivation
  - Good BR and lepton for trigger
- Backgrounds
  - tt, single top, Z + jets, W + jets, QCD
- Systematic uncertainties
  - b-tagging, jet energy scale, lepton ID
- Discovery potential
  - Low to intermediate masses at relatively low tan β
  - Challenging for high masses

CMS



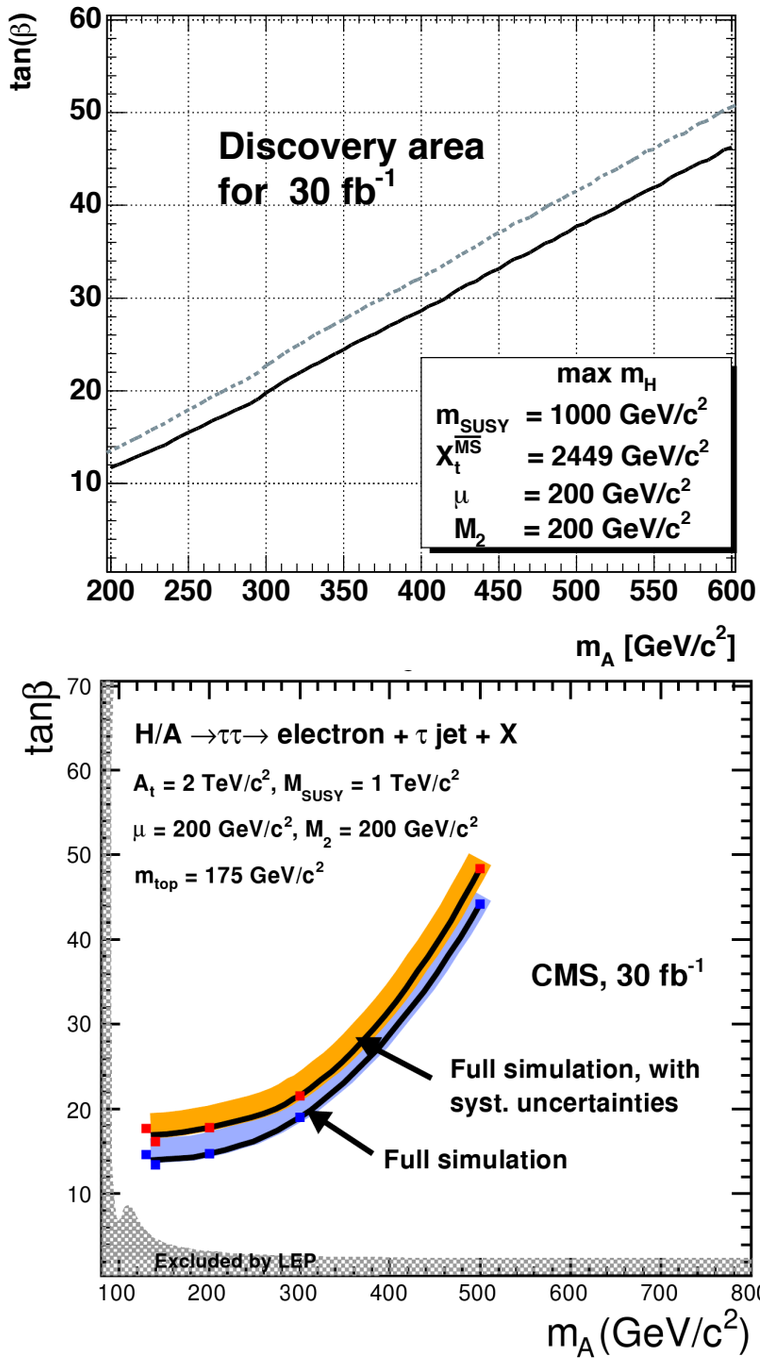
μ + jets



e + jets

Neutral Higgs searches: $(b\bar{b})\, h/H/A \to \tau\tau \to (e/\mu)\,\mathrm{had}$

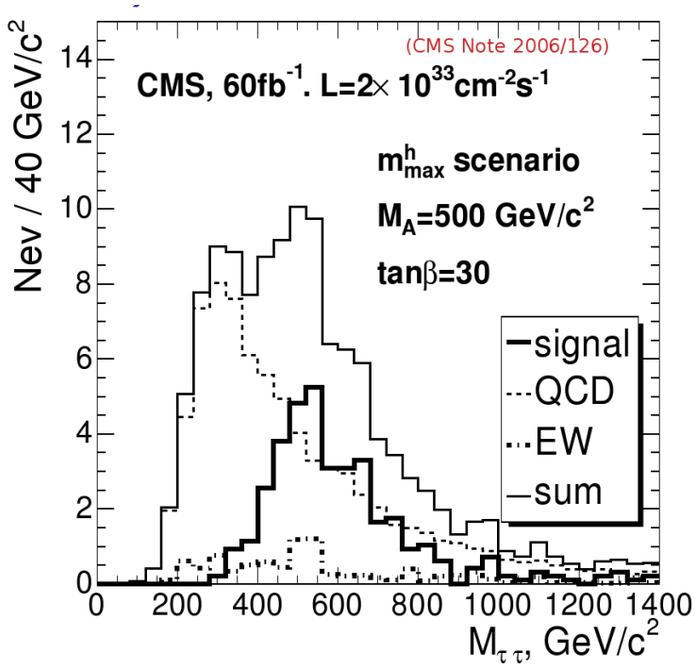
- Motivation
  - Good BR and lepton for trigger
- Backgrounds
  - tt, single top, Z + jets, W + jets, QCD
- Systematic uncertainties
  - b-tagging, jet energy scale, lepton ID
- Discovery potential
  - Low to intermediate masses at relatively low tan β
  - Challenging for high masses

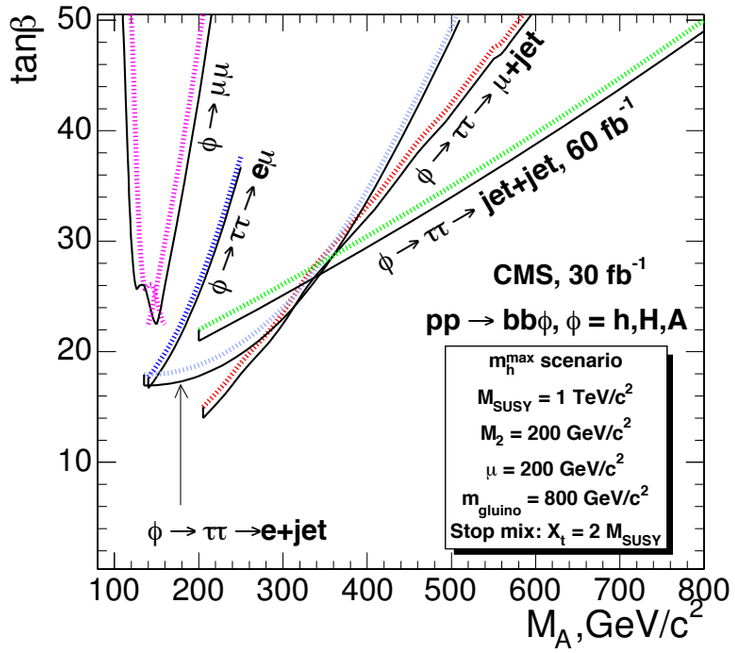


Neutral Higgs searches: $(b\bar{b})\, h/H/A \to \tau\tau \to \mathrm{had\ had}$

- Motivation:
  - High BR ($b\bar{b}$ not feasible)
  - Sensitivity for high masses
- Main background: QCD multi-jets
  - Estimated from data using same sign "tau's"
- Systematic uncertainties
  - Jet energy scale / resolution
  - τ fake rate from tracker misalignment

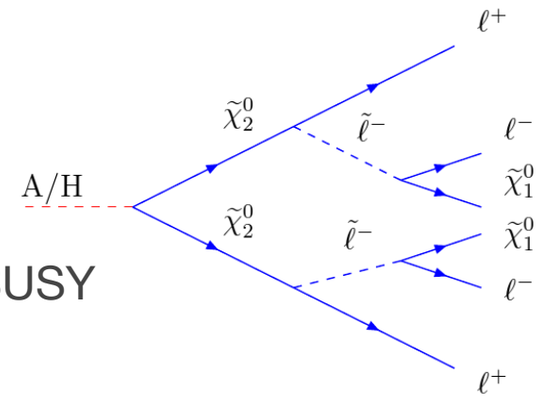
CMS





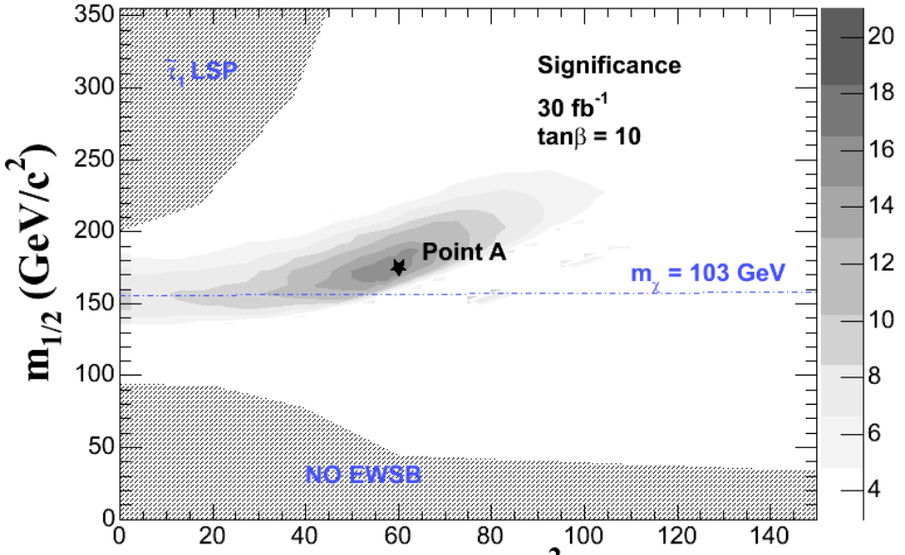
Neutral Higgs searches: $H/A \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow 4\ell + E_T^{miss}$

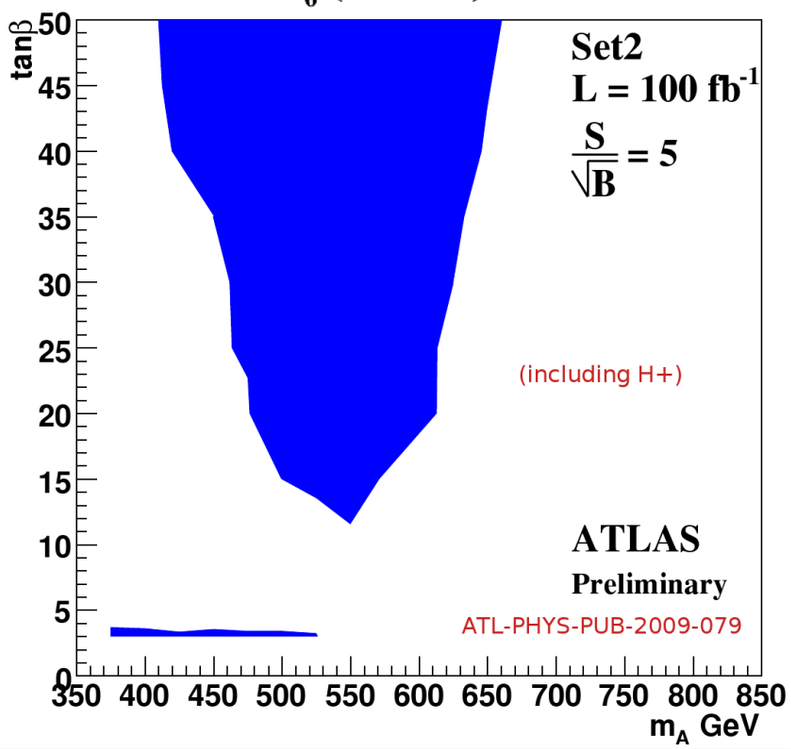
- Scenarios:
  - MSSM / mSugra points favoring decays to leptons



- Backgrounds: tt, ZZ, Zbb, SUSY
- Event selection:
  - 4-leptons with opposite signs and flavors
  - Upper and lower bounds on E_T^{miss}
  - Cuts on di-lepton mass and jet multiplicity
- Systematic uncertainties
  - Small from experimental side
  - Strongly model dependent

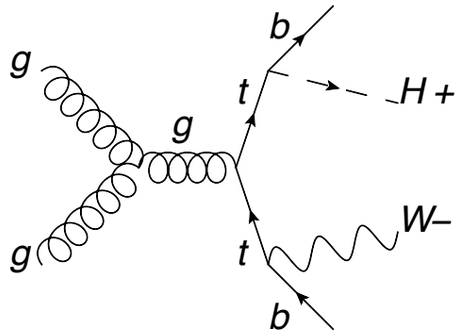
CMS PTDR

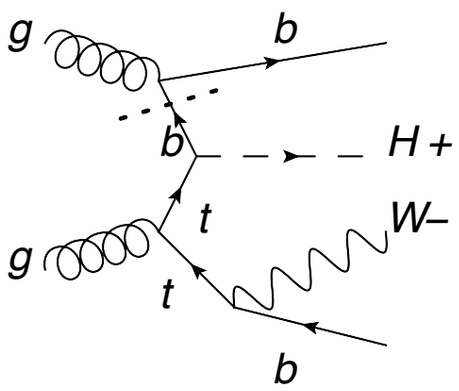


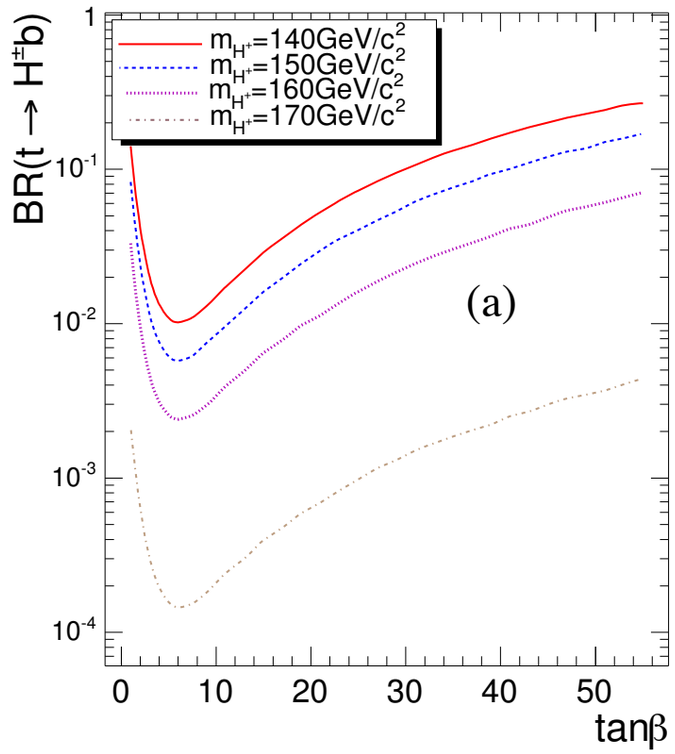


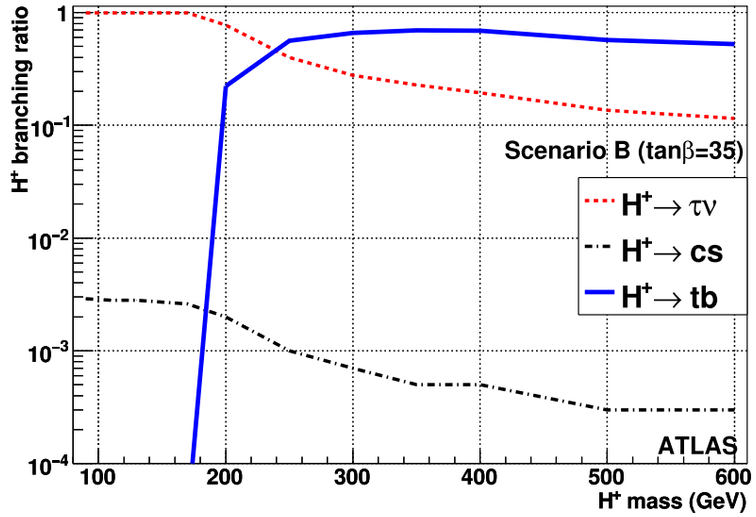
Charged Higgs boson: production and decays

- Light charged Higgs $(m_{H+} < m_t)$
  - Produced mainly through top decay
  - Decays mostly to τν
- Heavy charged Higgs $(m_{H+} > m_t)$
  - Produced mainly by gb or gg
  - Decays mostly to tb (or τν)
- Backgrounds
  - tt, W + jets, single top, QCD





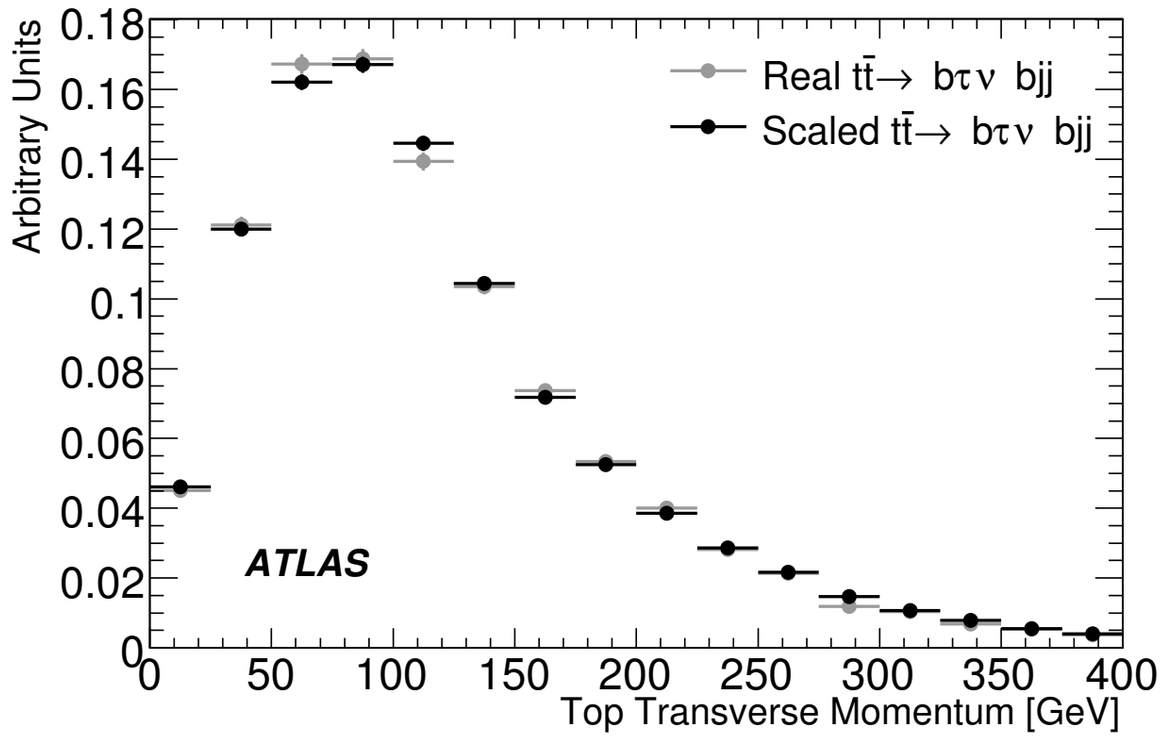




Light charged Higgs boson searches $(m_{H^+} < m_t)$

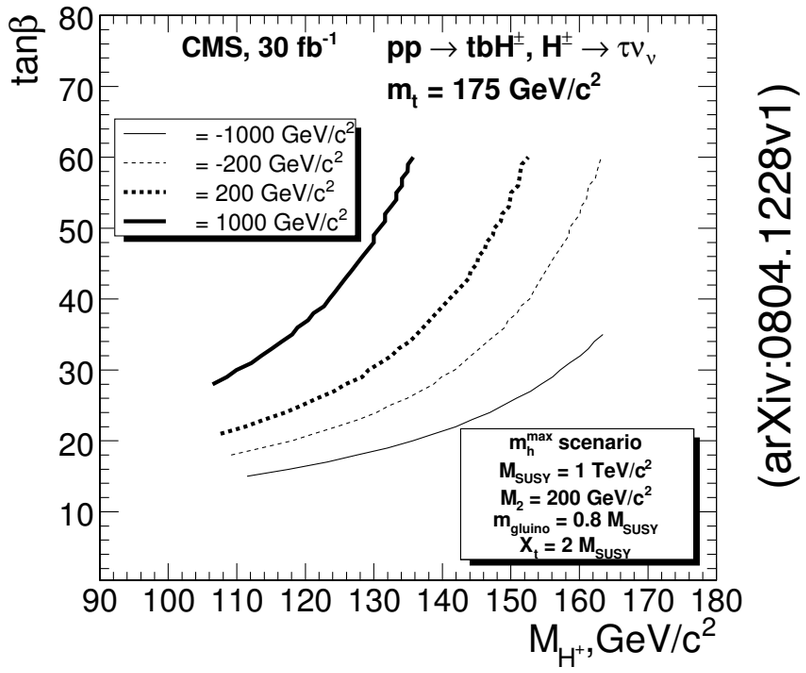
- Final states:
  - τ → hadrons, W → qq (ATLAS) → High yields
  - τ → ℓ ν, W → qq (ATLAS) → Isolated lepton from τ
  - τ →hadrons, W → ℓ ν (ATLAS / CMS) → Isolated lepton from W
- Backgrounds
  - tt, W + jets, QCD, single top
- Common features
  - Presence of tau, large E_T^{miss}, b and light jets
    - ATLAS: H^+ transverse mass reconstruction
- Systematic uncertainties
  - tt cross section, estimated from data (ATLAS)
  - b / τ-tagging efficiencies and fake rates
  - Jet energy scale

$t\bar{t}$ estimation from $\mu\nu b\mu\nu b$

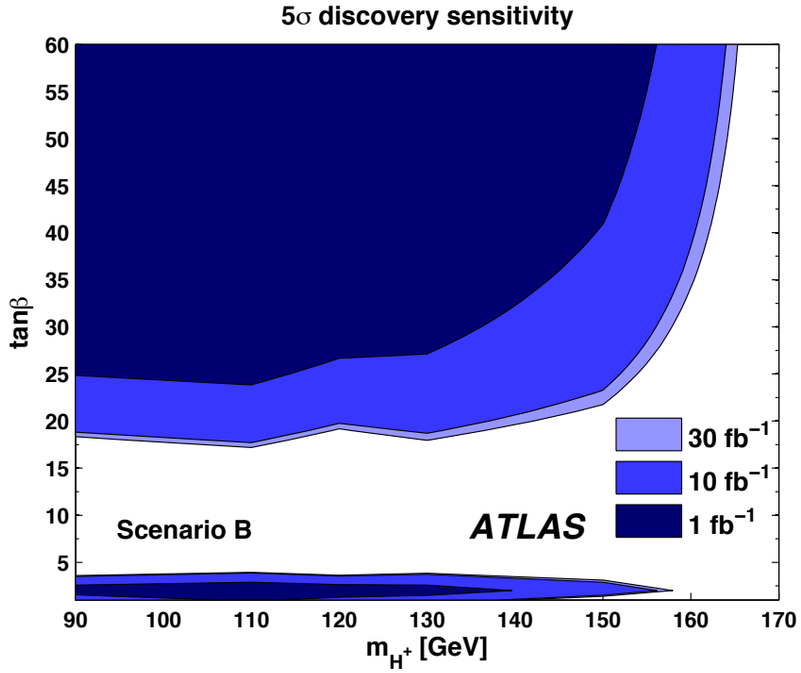


Light charged Higgs boson searches $(m_{H+} < m_t)$

- τ → hadrons, W → qq (ATLAS)
  - Trigger on tau + E_T^{miss} (+ jets)
  - τ-jet, 2 b-tagged jets, at least 2 more
  - Veto on isolated lepton, tt reduced with likelihood discriminant
- τ →lν, W → qq (ATLAS)
  - Trigger on lepton + E_T^{miss}
  - Isolated lepton, at least 4 jets, 2 b-tagged, large E_T^{miss}
  - Hadronic W and top mass reconstruction
- τ →hadrons, W →lν (ATLAS / CMS)
  - Trigger on lepton (+ E_T^{miss}, ATLAS)
  - At least 3 jets, 1 b and 1 τ-tagged (or more ATLAS)
  - Large E_T^{miss}, isolated lepton



(arXiv:0804.1228v1)

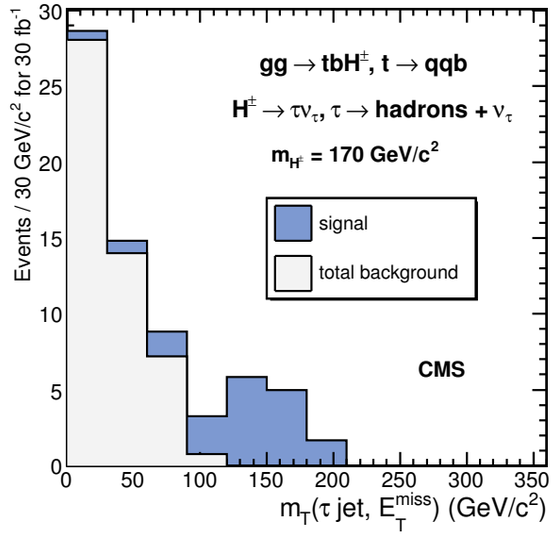


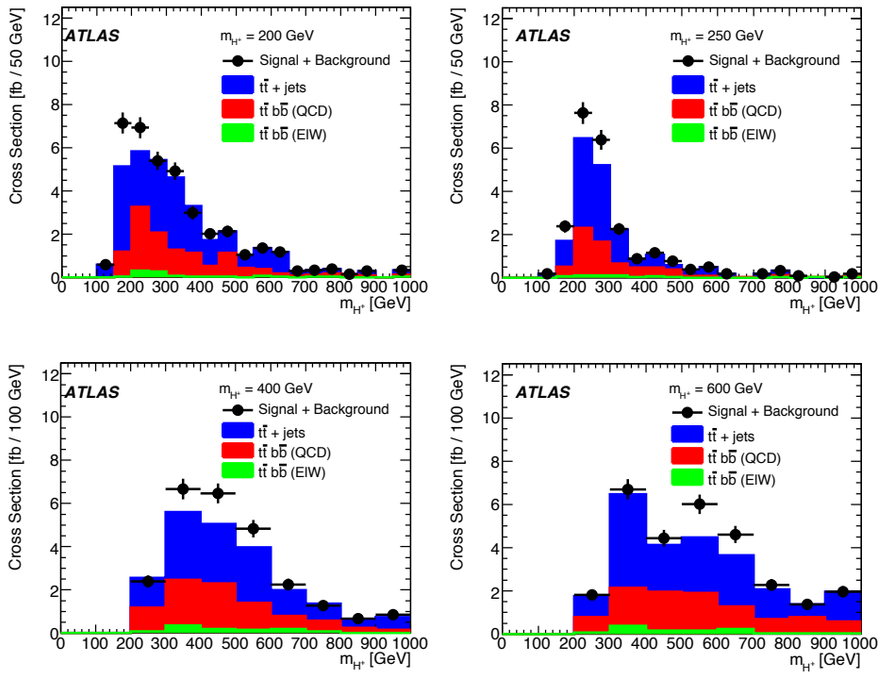
τ → hadrons, W → qq
m_h-max,μ = 200 GeV

Heavy charged Higgs boson searches $(m_{H^+} > m_t)$

ATLAS / CMS

- Final states $(gg \to tbH^+ \text{ and } gb \to tH^+)$
  - $H^+ \to \tau\nu\,(W \to qq,\, \tau \to \text{hadrons})$
    - Similar to light charged Higgs analysis
    - CMS: Requires hard tau and jets
    - ATLAS: Likelihood discriminant based on tau, jets and E_T^{miss}
  - $H^+ \to tb\,(W \to qq \text{ and the other } W \to \ell\nu)$
    - 5 or 6 jets, 3 or 4 b-tagged
    - Constraints on W and t mass
    - Difficulties from combinatorics, likelihood used (ATLAS)





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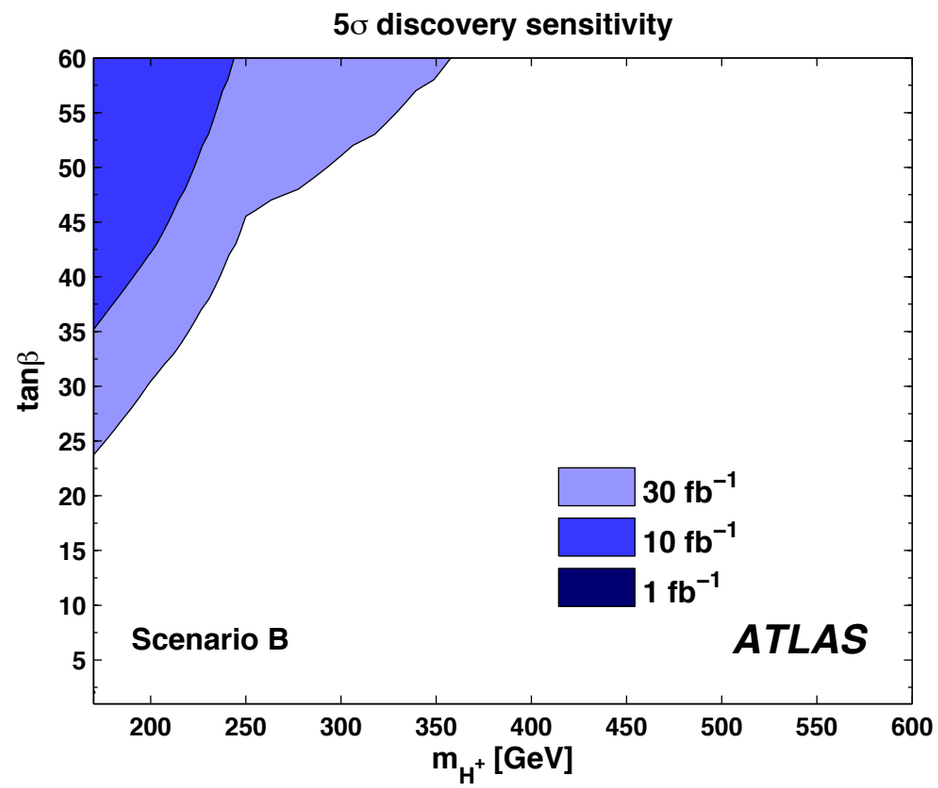
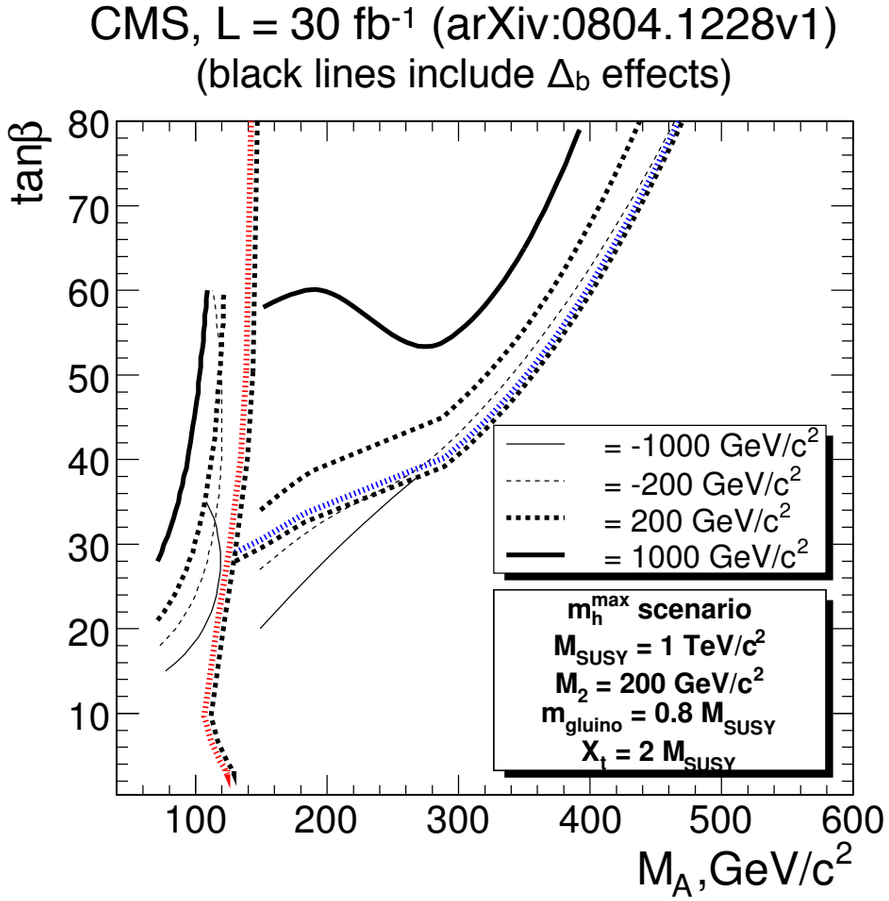
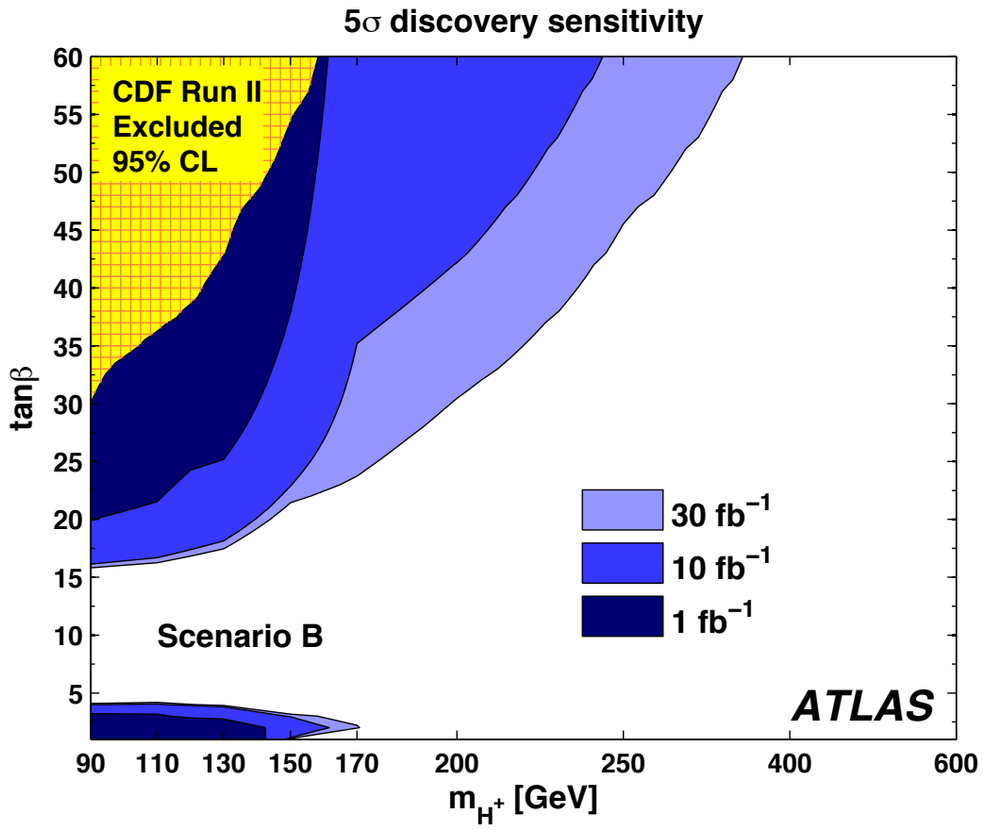
    - CMS: Requires hard tau and jets
    - ATLAS: Likelihood discriminant based on tau, jets and E_T^{miss}
  - $H^+ \to tb\,(W \to qq \,\text{and the other}\, W \to \ell\nu)$
    - 5 or 6 jets, 3 or 4 b-tagged
    - Constraints on W and t mass
    - Difficulties from combinatorics, likelihood used (ATLAS)



Charged Higgs boson expected discovery potential





- Good sensitivity at low masses and/or high tan β, dominated by $H^+ \rightarrow \tau\nu$
- Difficult in intermediate tan β
  - Decays to SUSY particles might be an alternative

Conclusions

- Good discovery potential for MSSM Higgs at LHC
  - At least one Higgs boson will be found if present
  - Large regions of parameter space can be covered, some need high statistics

- Neutral Higgs boson
  - Sensitivity dominated by $h/H/A \to \tau^+\tau^-$, coverage up to m_A ~ 800 GeV
  - $h/H/A \to \mu^+\mu^-$ helps at low masses and gives narrow peak

- Charged Higgs boson
  - Good sensitivity at low masses and high tan β with $H^+ \to \tau\nu$

Backup slides

MSSM scenarios studied

Neutral Higgs to SUSY particles, mSUGRA

Point	m0 (GeV/c2)	m1/2 (GeV/c2)	A0 (GeV/c2)	tanβ	sign(μ)
CMS A	60	175	0	10	+
CMS B	80	200	0	5	+
CMS C	50	150	0	5	+
ATLAS A	400	165	0	20	+
ATLAS B	125	165	0	20	+

ATLAS, charged Higgs

Scenario	OBS	m_t (GeV)	M_{SUSY} (GeV)	μ (GeV)	M2, M3 (GeV)	A_t
A	H^+ to SUSY suppressed	175	500	200	1000	1000
B	m_h-max	170	1000	200	200, 800	Xt(2000) + μ/tan β

Neutral Higgs to SUSY particles, MSSM (ATLAS)

Set	M1 (GeV)	M2 (GeV)	μ (GeV)	m_{sl}, m_{stau} (GeV)	m_{sg}, m_{sq} (GeV)
1	90	180	-500	250	1000
2	100	200	-200	150, 250	800, 1000

- M_{SUSY} : soft-SUSY breaking mass
- μ: Higgsino mixing parameter
- $m_{1/2}$, M1, M2: gaugino masses
- M3: gluino mass
- m_0: scalar masses
- A0: trilinear coupling
- m_tX_t: off-diagonal entry in stop mass matrix