CMS discovery potential: Higgs bosons beyond the SM

Heavy neutral Higgs bosons: bbH/A with H/A→ττ

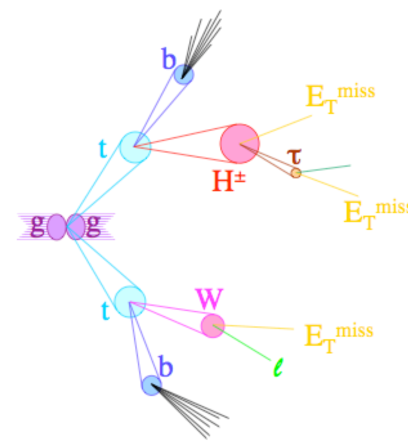
- ❒ ττ → e μ (CMS Note 2006/101)
- ❒ ττ → e jet (CMS Note 2006/075)
- ❒ ττ → μ jet (CMS Note 2006/105)
- ❒ ττ → jet jet (CMS Note 2006/126)

Light Charged Higgs bosons: tt → $H^{\pm}$bWb

- ❒ $H^{\pm} \to \tau\nu_\tau$, τ → jet, W → lν (CMS Note 2006/056)

Heavy Charged Higgs bosons: gg → t$bH^{\pm}$

- ❒ $H^{\pm} \to \tau\nu_\tau$, τ → jet, t → qqb (CMS Note 2006/100)
- ❒ $H^{\pm}$ → tb, tt → qqlνbb (CMS Note 2006/109)



MSSM Interpretation (CMS Physics TDR, vol. 2)

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Manchester
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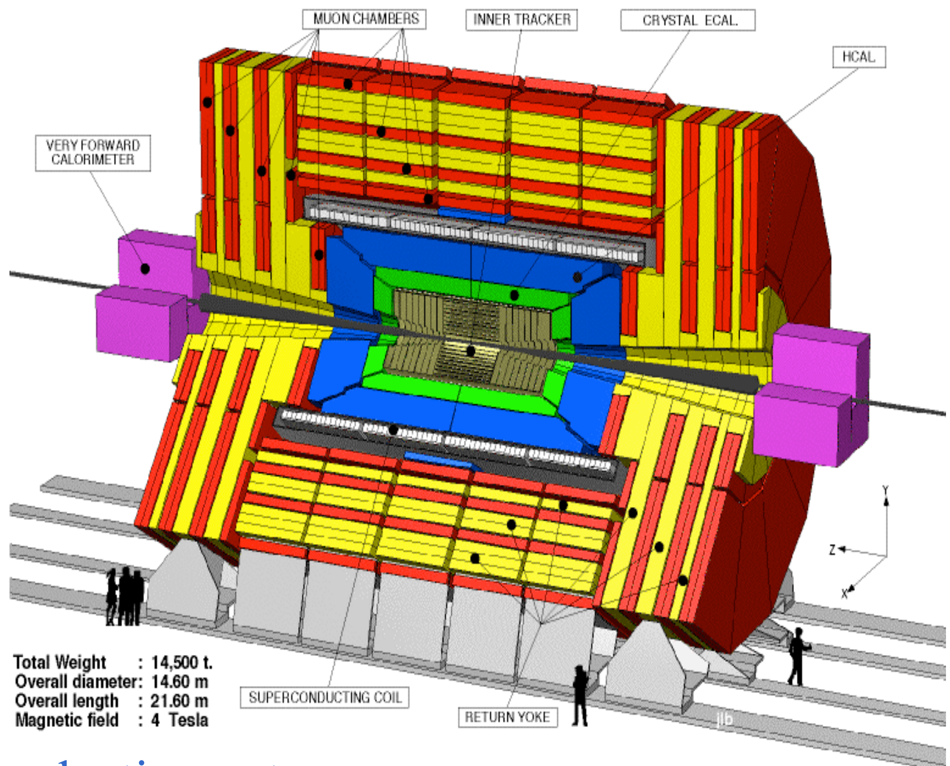
Introduction

- Full detector simulation and event reconstruction
- Low luminosity $\mathcal{L}=2\bullet10^{33}$ cm^{-2}s^{-1} (5 mini-bias events / bunch crossing, in- and out-of-time pile-up)
- $\int \mathcal{L}=30\text{-}60$ fb^{-1}
- Main MC event generator: Pythia
- Multi-parton final-states also with CompHEP, MadGraph, Alpgen
- tt production also with TopRex
- Tau decays with Tauola
- Large QCD multi-jet cross-section:
  - generator level preselection
  - factorise efficiencies of independent selection cuts
  - large samples with fast simulation
- PDF: event generation with CTEQ5L, systematics with CTEQ6.1M
- NLO background cross-section (where available)



MSSM Higgs sector

- **5 Higgs bosons: h, H, A, H^+, H^-**
- Tree level parameters: m_A, $\tan\beta$
- Tree level masses: $m^2_{h,H} = 1/2 \cdot (m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 + m_Z^2)^2 - 4 \cdot m_A^2 \cdot m_Z^2 \cdot \cos^2(2\beta)}$

  $m^2_{H^\pm} = m_A^2 + m_W^2$
- …couplings:

$$hdd \sim -\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cdot\cos(\beta-\alpha) \qquad huu \sim \cos\alpha/\sin\beta = \sin(\beta-\alpha) + \cot\beta\cdot\cos(\beta-\alpha)$$

$$Hdd \sim \cos\alpha/\cos\beta = \cos(\beta-\alpha) + \boxed{\tan\beta}\cdot\sin(\beta-\alpha) \qquad Huu \sim \sin\alpha/\sin\beta = \cos(\beta-\alpha) - \boxed{\cot\beta}\cdot\sin(\beta-\alpha)$$

$$Add \sim \boxed{\tan\beta} \qquad Auu \sim \boxed{\cot\beta}$$

$$H^+ud \sim m_d \cdot \boxed{\tan\beta}\cdot(1+\gamma_5) + m_u \cdot \boxed{\cot\beta}\cdot(1-\gamma_5)$$

  $\Rightarrow$ $H^\pm\tau\nu$ enhanced for large $\tan\beta$
- Decoupling limit $(m_A >> m_Z \quad \text{and} \quad |\cos(\beta-\alpha)| << 1)$:

$$m_A \sim m_H \sim m_{H^\pm} >> m_Z$$

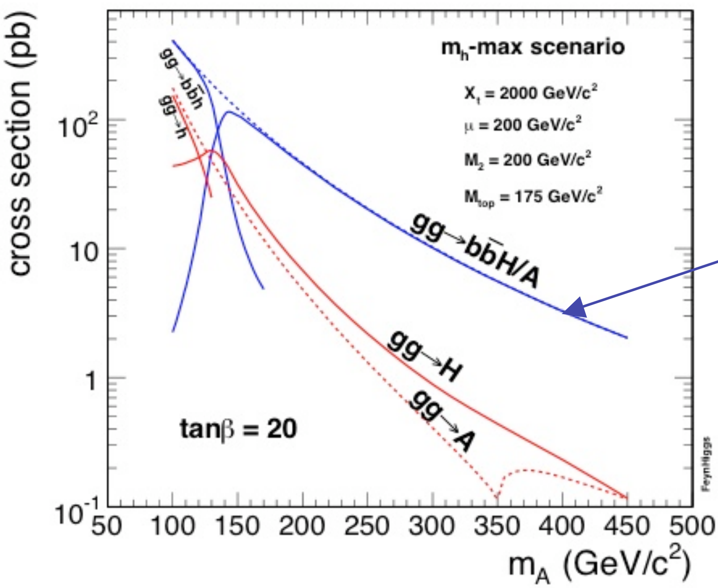
$$huu \sim hdd \sim 1 \quad \text{(SM like)}$$

$$Add \sim Hdd \sim \tan\beta$$

$$Auu \sim -Huu \sim \cot\beta$$

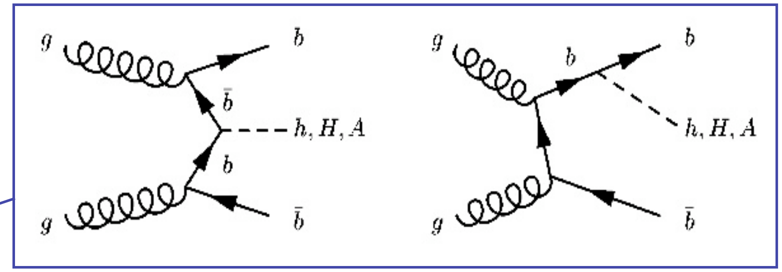
  $\Rightarrow$ Enhancement of bbH/A and H/A$\rightarrow\tau\tau$ for large $\tan\beta$
- Leading radiative corrections from (s)top and, at large $\tan\beta$, (s)bottom sector
- Cross-sections, branching ratios calculated by FeynHiggs2.3.2

MSSM heavy neutral Higgs



Other processes negligible
(VBF qq→qqH, Htt, HW, HZ)

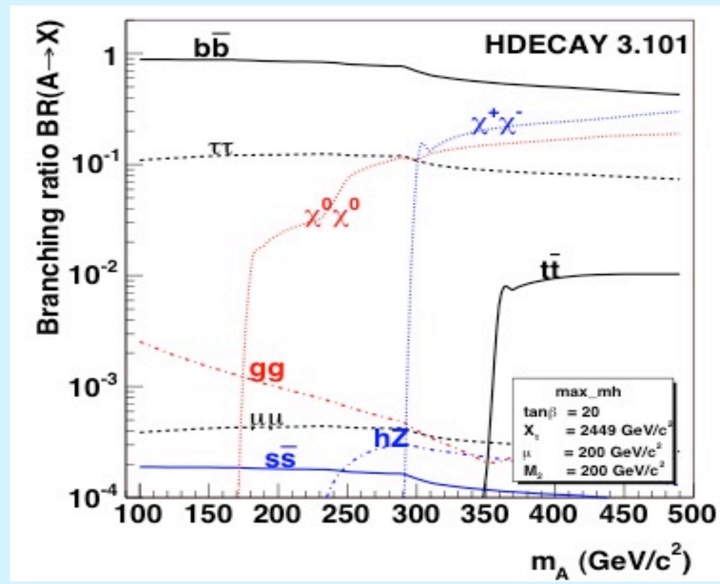
Dominant production process



m_h-max benchmark scenario (mSUGRA):

* theoretical upper bound on m_h maximised for a given tanβ (fixed m_t, M_{SUSY})
* M_{SUSY}=1 TeV, μ=M_2=200 GeV, m_{gluino}=0.8M_{SUSY}, X_t=A_t-μcotβ=2M_{SUSY}, A_b=A_t

BR(H/A→ττ)~0.1 for tanβ>10



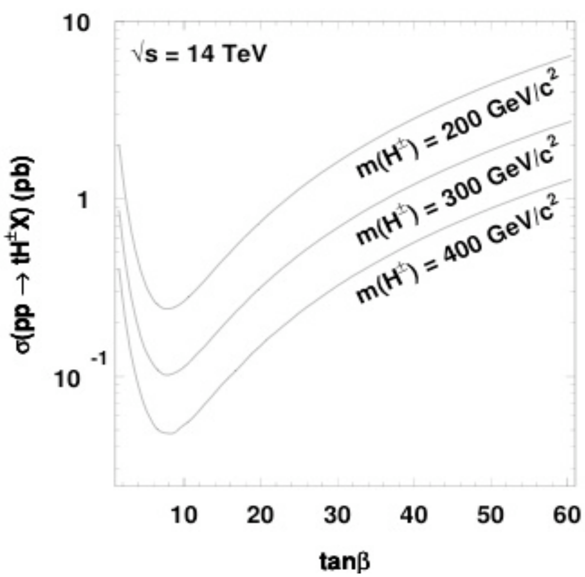
H/A→bb suffers from background

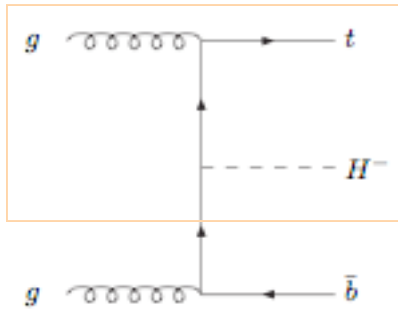
MSSM charged Higgs

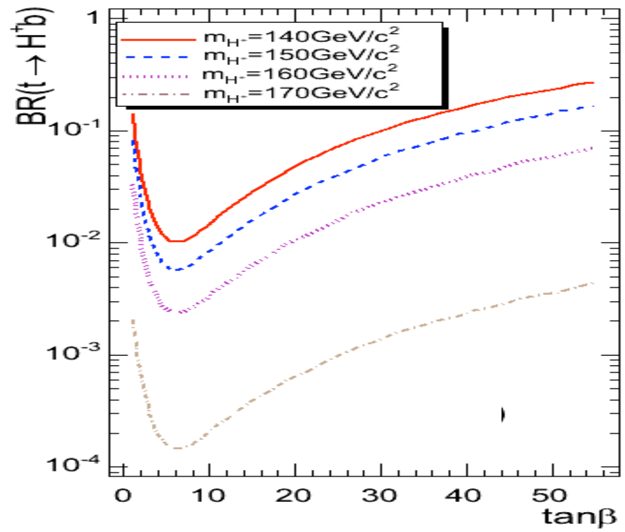
Production

$m_{H^\pm} < m_t$: from top quark decay [$\sigma(tt)_{NLO}$=840 pb]

$m_{H^\pm} > m_t$: $gg \to tbH^\pm$



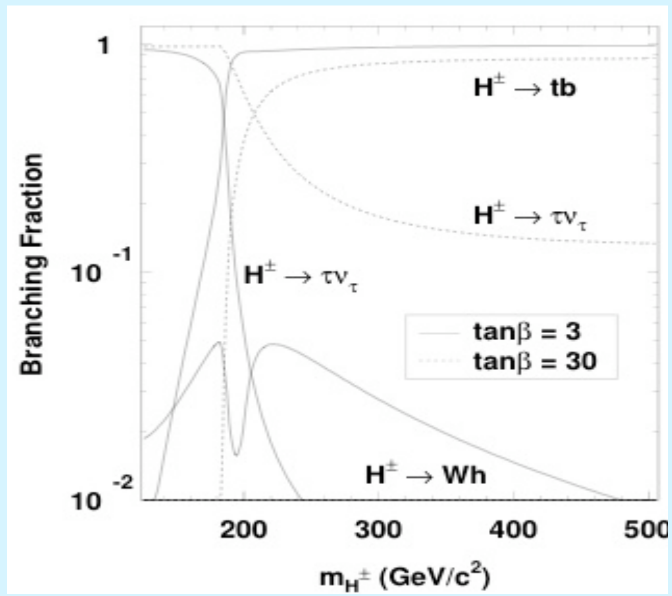




Decay

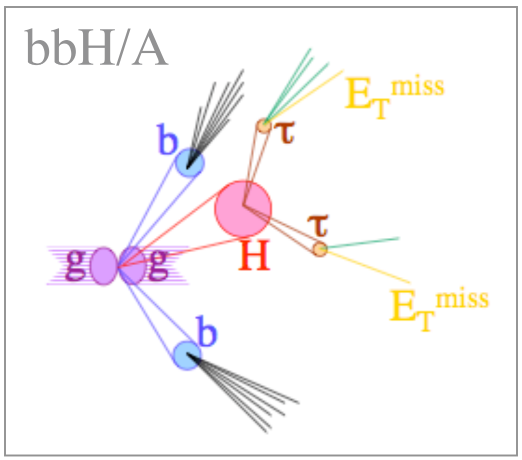
$m_{H^\pm} < m_t$: $H^\pm \to \tau\nu$ (BR~0.98 for tanβ>10)

$m_{H^\pm} > m_W$: $H^\pm \to tb$ important contribution at large tanβ from $H^\pm \to \tau\nu$

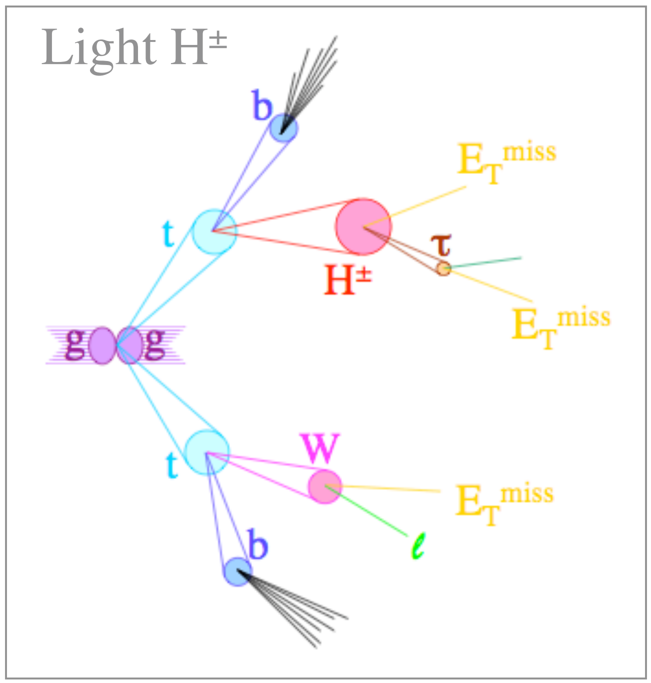


Final states: H/A→ττ, H±→τν

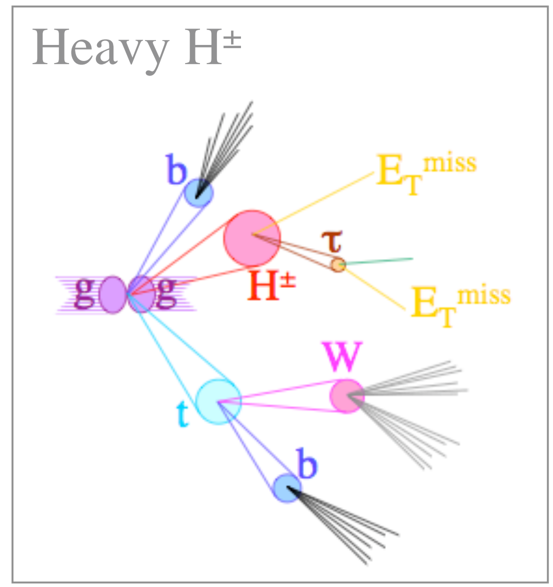
- Principal discovery channels for heavy MSSM Higgs at large tanβ:
  - H/A→ττ in associated bbH/A production
  - H±→τν in tt or associated tbH± production



Background:
j+j: QCD
l+j: tt, Z/γ*, bbZ/γ*, (Wt)
e+μ: tt, (Wt, Z/γ*)



Background: tt, (W+3j)
No mass reconstruction



Background: tt, W+3j

Experimental tools: $H/A \to \tau\tau$, $H^{\pm} \to \tau\nu$

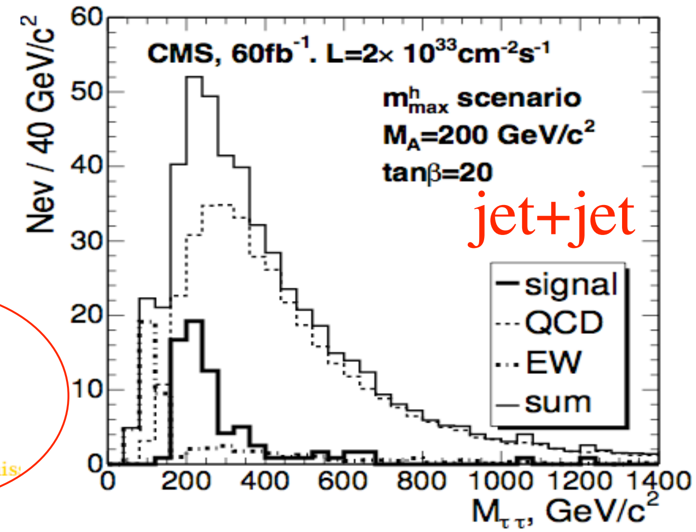
- τ-jet or lepton (e,μ) trigger (isolation, p_T cut)
- τ-identification against hadronic jets (vertex reconstruction, impact parameter measurement)
- Single b-tag to suppress Drell-Yan, QCD multi-jets, W+jets processes
- Central jet veto against tt background
- W and top mass reconstruction (to veto leptons from W in $\tau\tau \to l$+jet, to reconstruct the final state in $H^{\pm}$ search)
- Missing E_T reconstruction (neutrinos from Higgs or tau decay)
- Higgs mass reconstruction ($M^{\tau\tau}$ or $M_T^{\tau\text{-}E_T^{miss}}$)

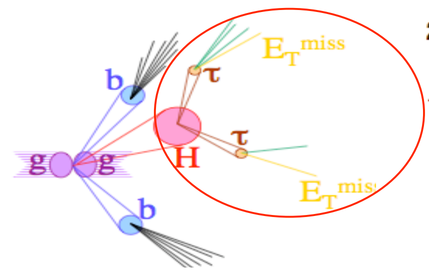
- Systematics dominated searches: measure systematics from data
  see e.g. $bbZ \to bbll$ [CMS Note 2006-099], $Z \to \tau\tau$ [CMS Note 2006-074]

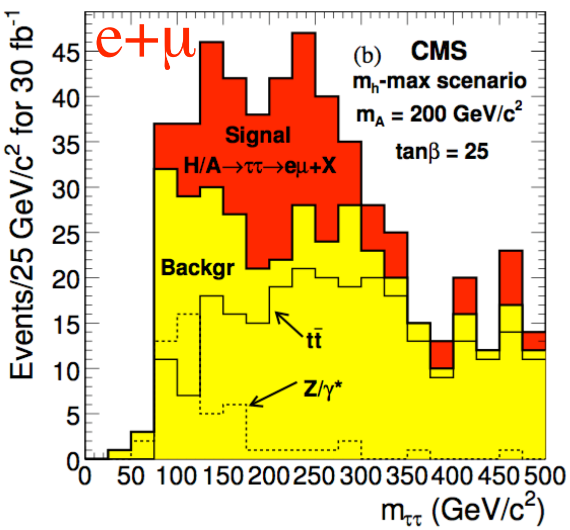
- Typical efficiency: <1%

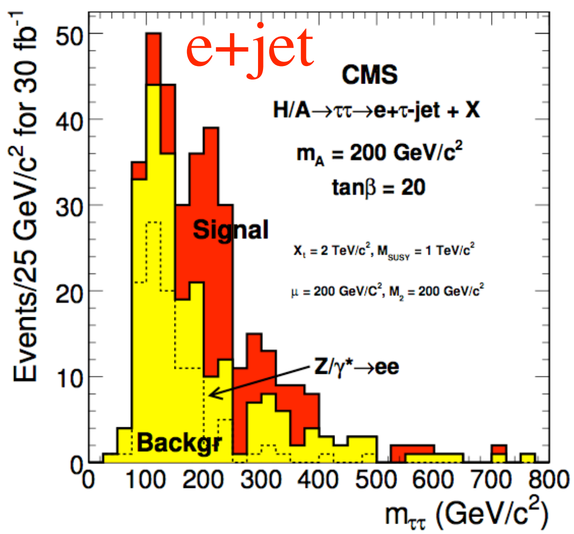
Higgs mass reconstruction: $H/A \to \tau\tau$

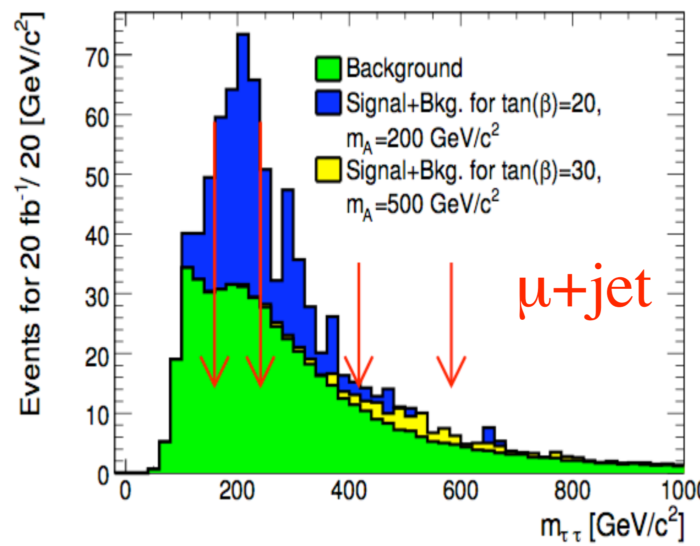
- Assume τ decay products collinearly emitted
- E_T^{ν} from missing E_T
- z-component from η of charged objects
- $\Delta\phi(\tau_1,\tau_2)<175$ degree
- $E_{\nu}>0$ (large inefficiency)
- Typical mass resolution: 20%





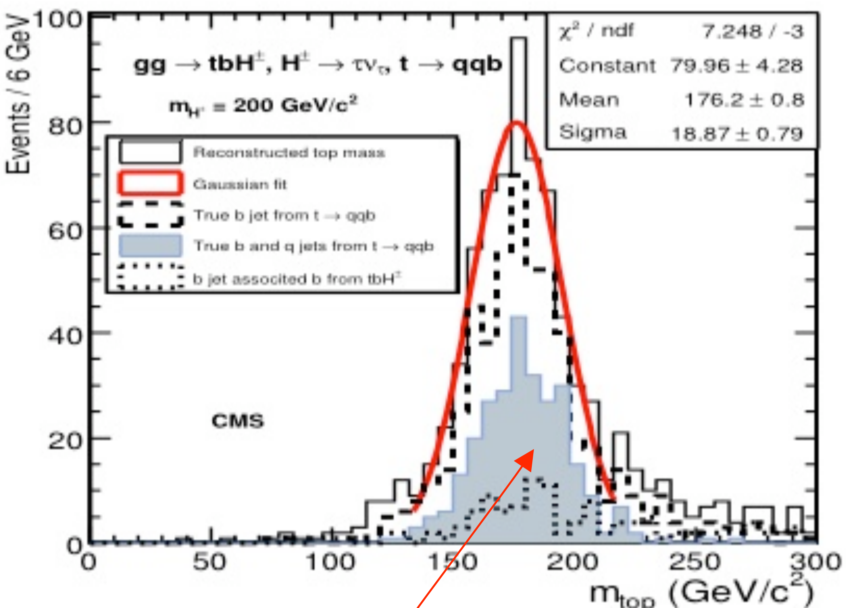






Mass reconstruction: heavy $H^{\pm}\rightarrow\tau\nu$

Top mass reconstruction

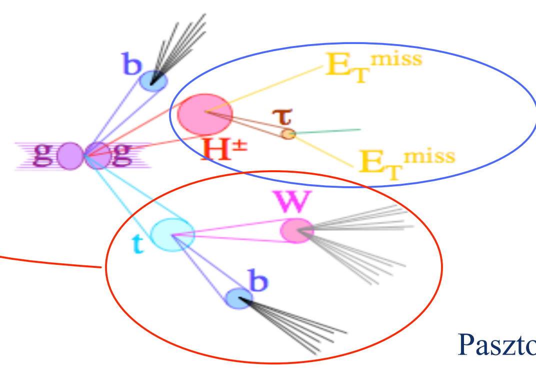


Minimize for all jet asociations :

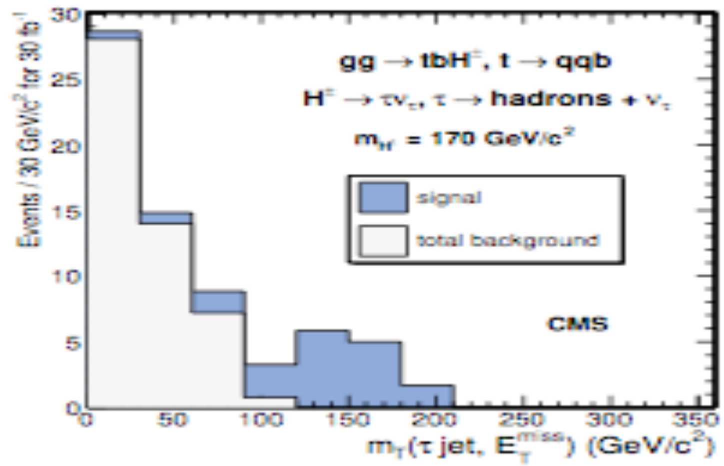
$$\chi^2 = ((m_{jj} - m_{W})/\sigma_{W})^2 + (m_{jjj} - m_{top})/\sigma_{top})^2$$

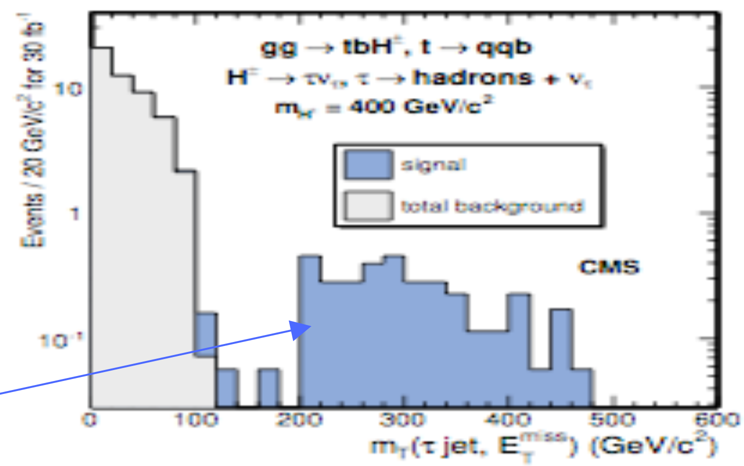
$$\sigma_{W} = 10\ \mathrm{GeV}$$

$$\sigma_{top} = 17\ \mathrm{GeV}$$



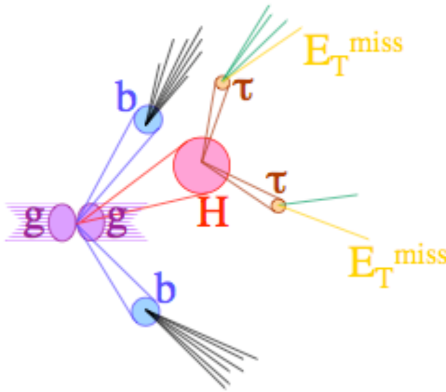
Higgs mass reconstruction

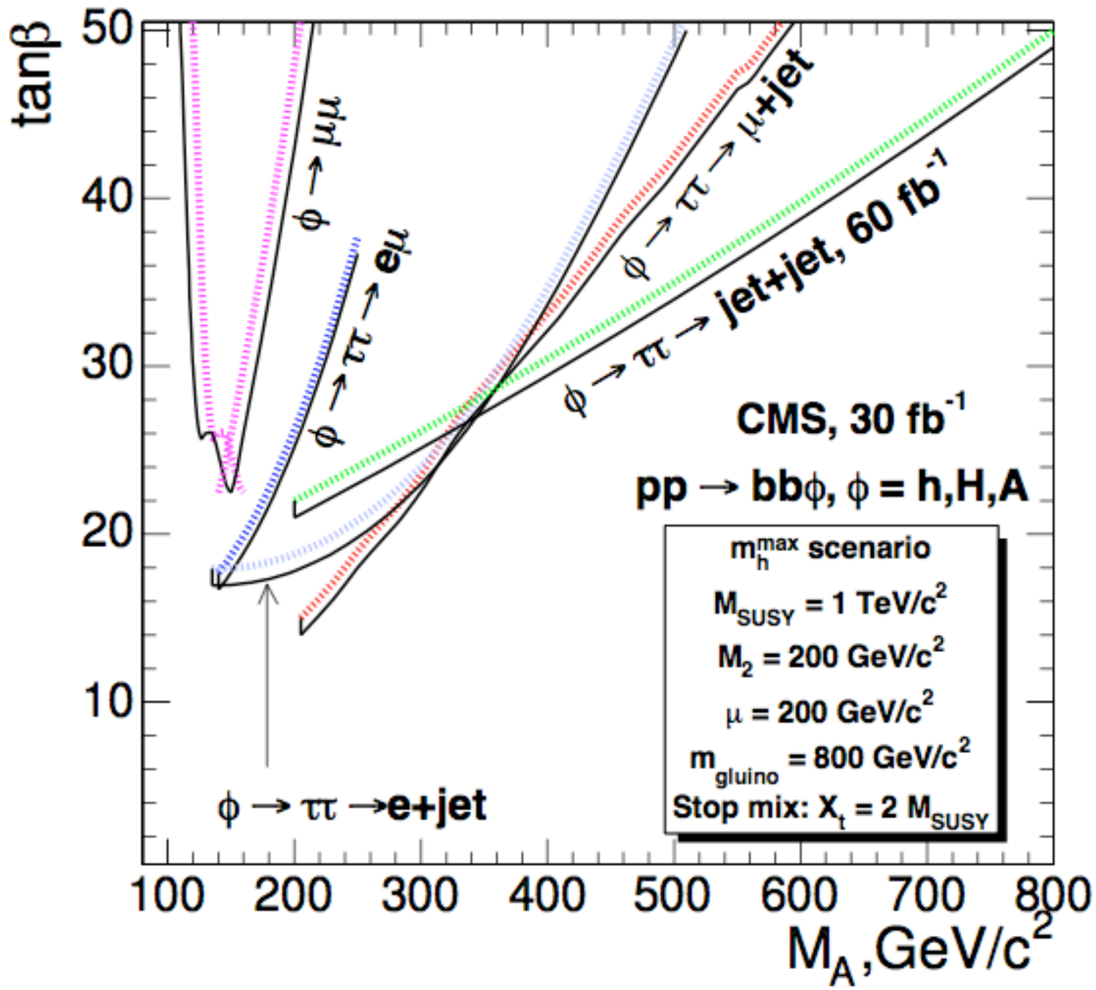




$$m_T = \sqrt{2 \cdot E_T^{\tau\,\mathrm{jet}} \cdot E_T^{miss} \cdot (1 - \Delta\phi(\tau\,\mathrm{jet}, E_T^{miss}))}$$

5σ discovery reach: pp→bbϕ



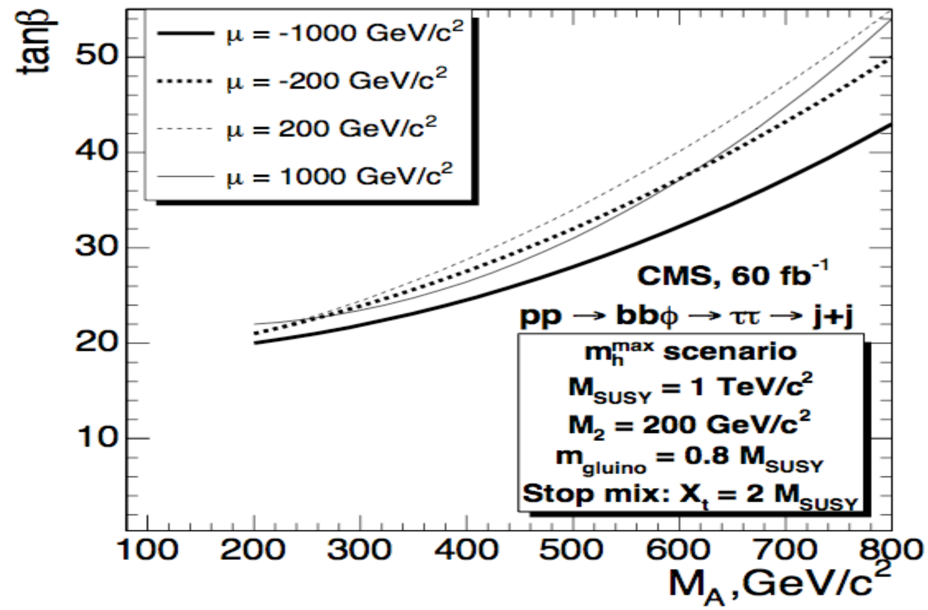


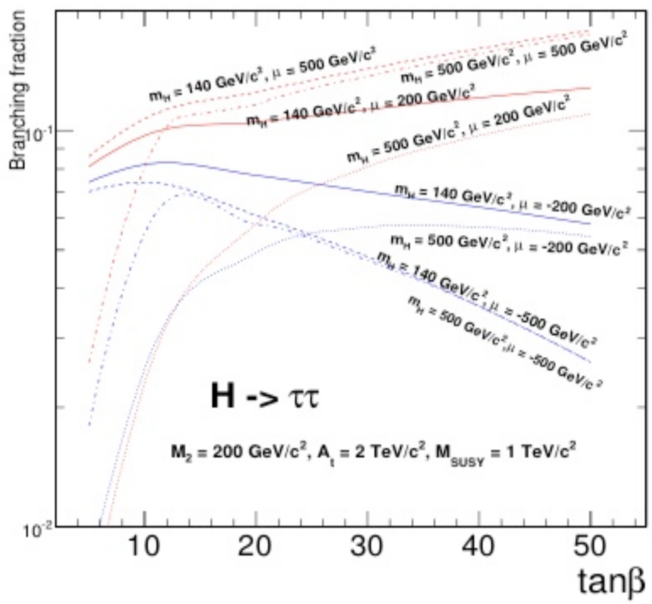
Systematic uncertainties included in signal significance

5σ discovery reach: μ dependence

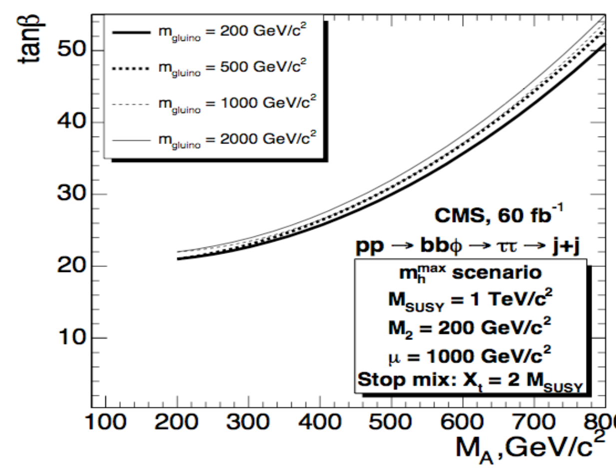
arXiv:0704.0619 [hep-ph]

- Extended m_h-max scenario: $\mu=\pm200, \pm500, \pm1000$
- Effects of SUSY radiative corrections and decay modes to SUSY particles
- Cross-section enhanced/reduced for large negative/positive values of μ
- Partially compensated by change in BR



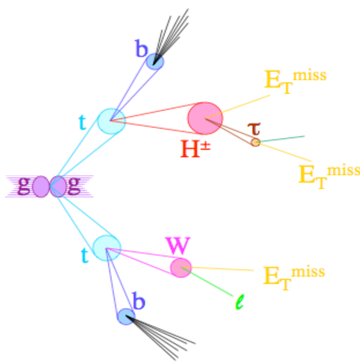


Other parameters (e.g. m_{gluino}) have smaller impact on the discovery potential:

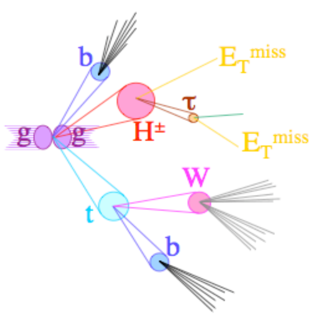


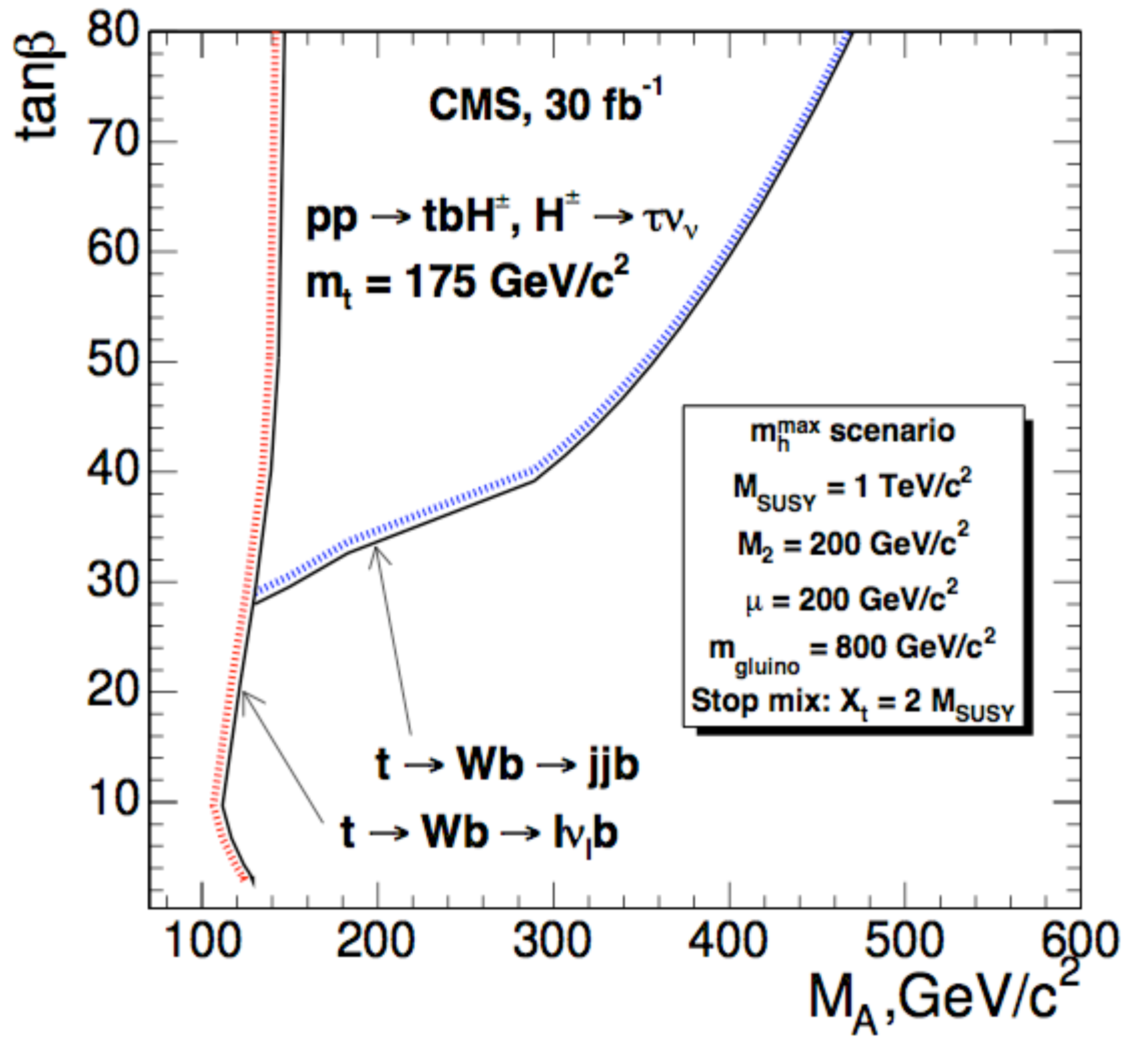
5σ discovery reach: $H^{\pm} \rightarrow \tau\nu$

- Low mass:
  $pp \rightarrow tt \rightarrow tH^{\pm}b$



- High mass, high tanβ:
  $gb \rightarrow tH^{\pm}$
  (NLO: $gg \rightarrow tH^{\pm}b$)

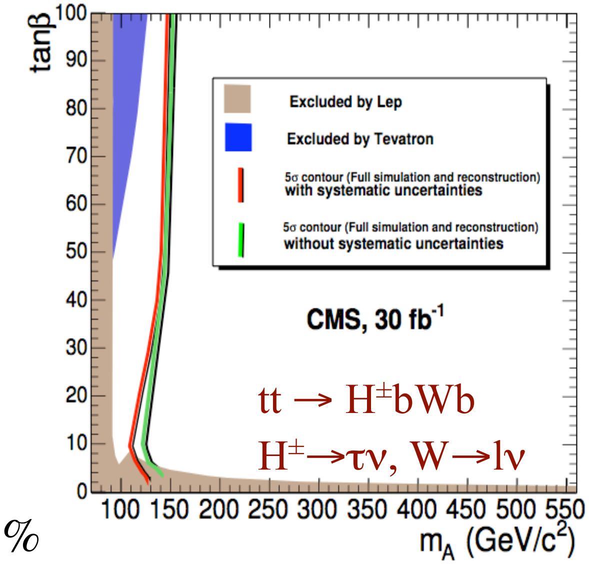


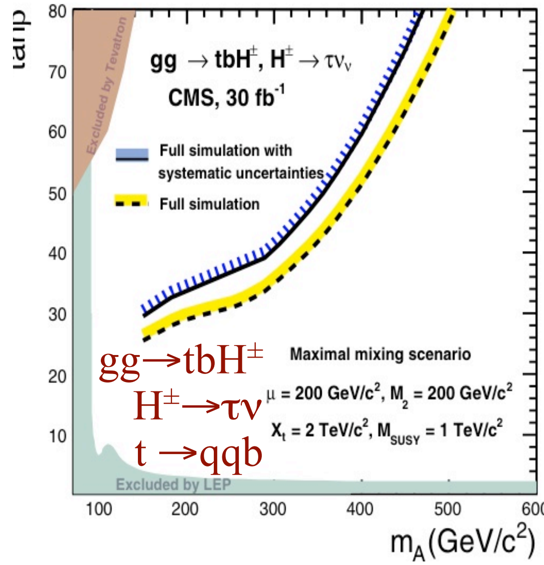


Systematic uncertainties included in signal significance

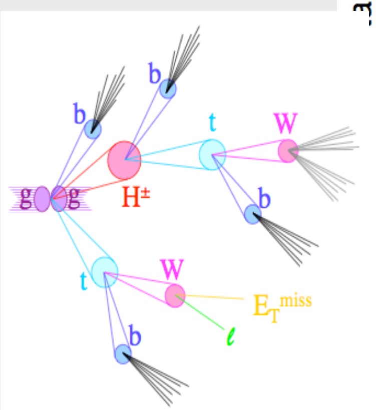
5σ discovery reach: dependence on systematics

τ-ID: 4%
b-tag: 5%
l-ID: 2%
3 jets: 6%
E_T^{miss}: 3%
Lumi: 5%
σ(tt): 6%
tt: 12%
b-mistag: 5%
τ-mistag: 2%
anti-b-tag: √3•5%
w+3j: 10%

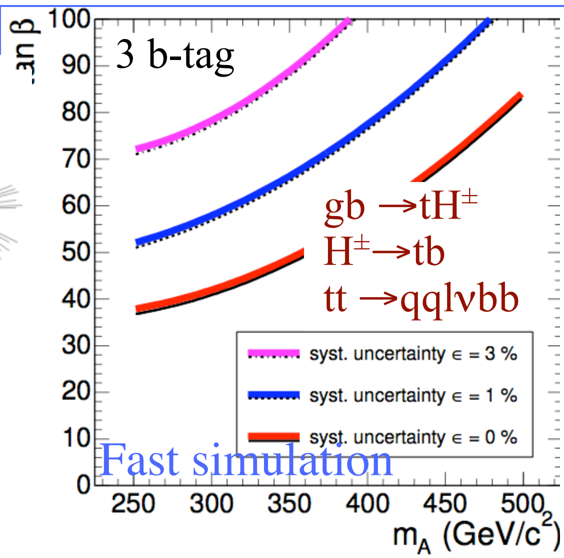


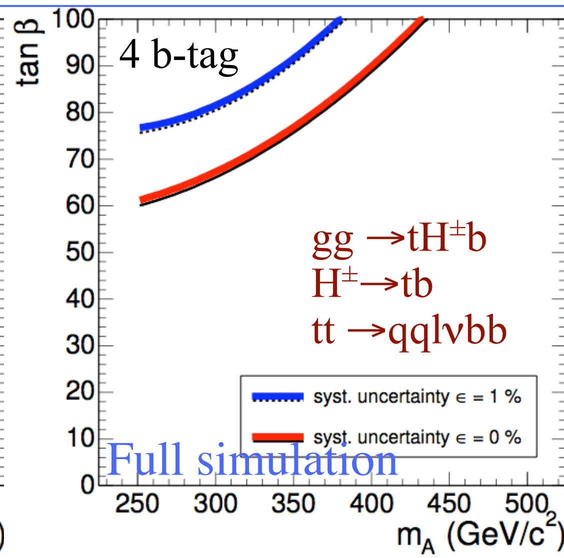


τ-ID: 8%
b-tag: 5%
3 jets: 2%
E_T^{miss}: 3%
σ(tt): 6%
tt: 11%
W+jets, QCD:
MC statistics
BKG: 1.7±1.0



Background:
tt+jets, ttbb

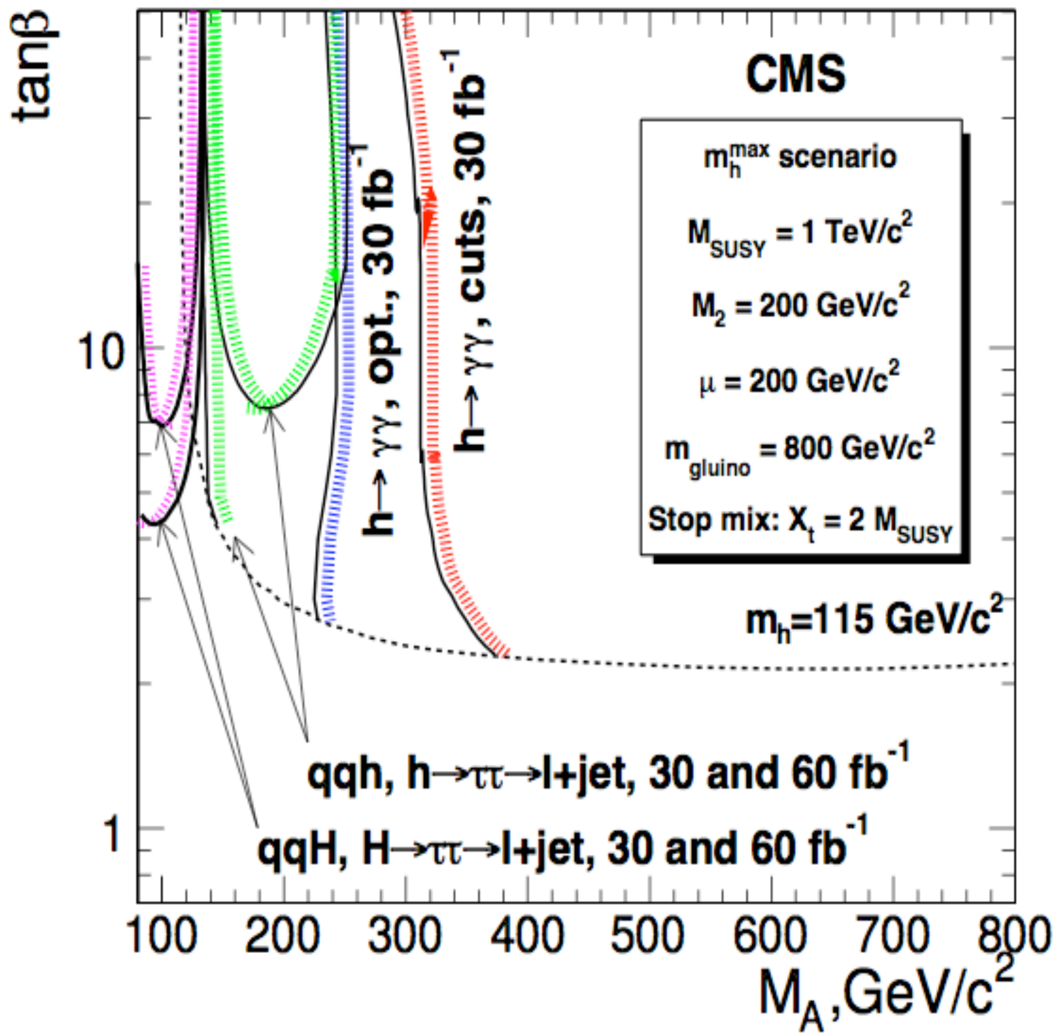




b-tag: 5%
mis-tag: >5%
σ(tt+jets)

5σ discovery reach: light neutral Higgs

- Small and intermediate tanβ not covered by H/A→ττ searches
- Reinterpretation of the SM Higgs searches in MSSM:
  - Inclusive pp→h+X with h→γγ
  - VBF qq→qqh/H with h/H→ττ→l+jet



Summary

- Studies with full detector simulation and event reconstruction of principal discovery channels in MSSM at low luminosity:
  - bbH/A, H/A→ττ with all possible ττ final states considered
  - Light $H^{\pm}\rightarrow\tau\nu$ with lepton trigger
  - Heavy $H^{\pm}\rightarrow\tau\nu$ in fully hadronic final state (almost background free)
- Discovery potential with 30 fb^{-1} established
  - bbH/A: reach extending down to m_A=200 GeV, tanβ=13
  - $H^{\pm}$: weakest potential m_A=110 GeV at tanβ=10
    light and heavy $H^{\pm}$ search potential meet at m_A=130 GeV and tanβ=28
- SM Higgs searches reinterpreted in MSSM (h→γγ, qqh/H→qqττ) cover the low and intermediate tanβ region
- More realistic (LO ME) simulations of tt+jets events and inclusion of b-tagging systematics shows no sensitivity for heavy $H^{\pm}\rightarrow tb$ with single lepton trigger
- **Searches systematics dominated**, work ongoing on how to best use the first data to understand the backgrounds and the systematics

More BSM Higgs results from CMS

MSSM:

- bbH/A, H/A → μμ (CMS Physics TDR, vol. 2; CMS AN 2005/033)
- bbH/A, H/A → bb (CMS Note 2006-080)
- Zh, Z → ll, h → bb (CMS Note 2006-063)
- H/A → $\chi^0_2\chi^0_2$ → 4l + E_T^{miss} (CMS Note 2006-125)
- Invisible Higgs decay in VBF (CMS AN 2006-060, CMS Note 2003/033)
- h → bb in SUSY cascades (CMS Note 2006-090)

Randall-Sundrum extra dimensions:

- Radion → hh → γγbb, ττbb, bbbb (CMS Note 2005-007)

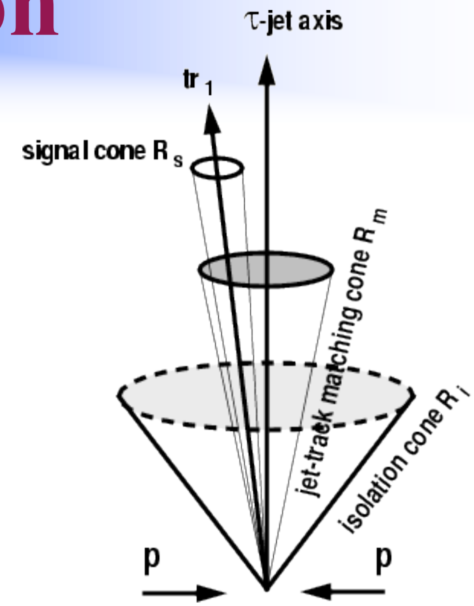
Double charged Higgs in Littlest Higgs model:

- $H^{++}H^{--}$ → 4μ (CMS Note 2006-081)
- $H^{++}H^{--}$ → nμ + (4-n)τ , n=1-3 (CMS Physics TDR, vol. 2; CMS AN 2006-081)

Backup

τ-jet identification

- Reconstruct τ-jet by iterative cone algorithm in η-φ (ΔR=0.4) around calorimeter jet, E_T>40-150 GeV
- Leading track in ΔR_m=0.1 of τ-jet, p_T>10-35 GeV ($p_T/E_T^{\tau\text{-jet}}$>0.8 for heavy H± search)
- Quality cuts on leading track (#hits, χ^2, IP_T<0.3 mm)
- Signal cone ΔR_s=0.04-0.07 around leading track with 1 or 3 tracks
- Tracker isolation: no track with p_T>1 GeV between ΔR_s and ΔR_i=0.4-0.5 cones
- Tau direction from sum of track momenta
- Energy correction using MC calibration (single τ-jets)
- Opposite charge for τ candidates (for H/A → ττ)
- Electron rejection, e.g. E_T^{max}(HCAL cell)>2 GeV, 0.2-0.35<$E^{HCAL}/p^{leading}$<1.1-1.5 (upper cut against q-jets rich in neutral hadrons)



H/A → ττ → e+jet search:
Efficiency: 15-35%
Purity: 96-98%
Background suppression:
0.27% for QCD

Heavy H±→τν search:
Efficiency: 12-24%
Purity: 98.5-99.8%
Background suppression:
1.65% for QCD

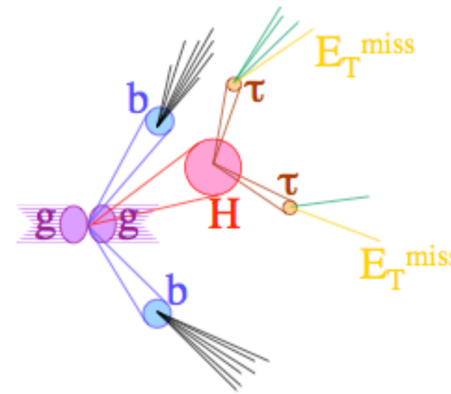
b-tagging

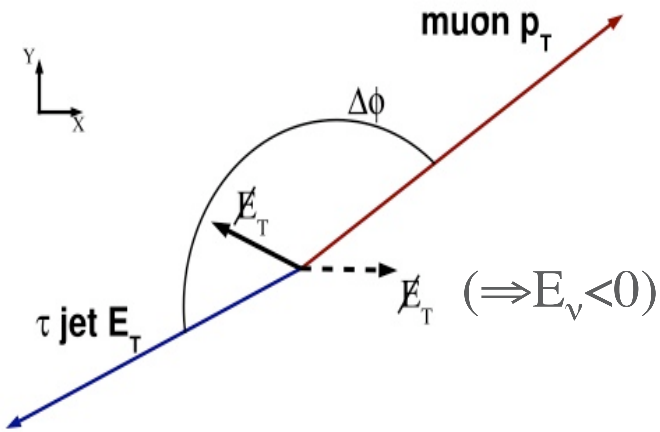
- Non-τ-jets reconstructed with iterative cone algorithm (ΔR=0.5)
- Energy correction using MC calibration (low lumi QCD multi-jets, γ+jet)
- bbH/A: soft b-jets in E_T with flat distribution in η:
  $<$40% signal events for m_A=200 GeV have b-jet with E_T>20 GeV and $|\eta|<2.4$
- Only **single b-tag** and **veto events with additional central jets** to suppress tt
- **Track counting:** at least N(=2-3) tracks with (2D transverse or 3D) impact parameter significance (>2)
  - efficiency (H/A→ττ→μj, m_A=200-500 GeV): 17-26% (purity: 95%)
  - 67% for tt, 46% for Wt, mistag 1% for W+jet, 3% for Z/γ*
- **Combined secondary vertex based algorithm:** information from track impact parameter significances, topological and kinematic vertex variables (charged multiplicity, invariant masses, energy and rapidity of particles, 2ndary vertex significance)
  - efficiency (H/A→ττ→ej, m_A=130-500 GeV): 30-37%
  - 69% for tt, 59% for Wt, mistag 3% for W+jet, 2% for Z/γ*

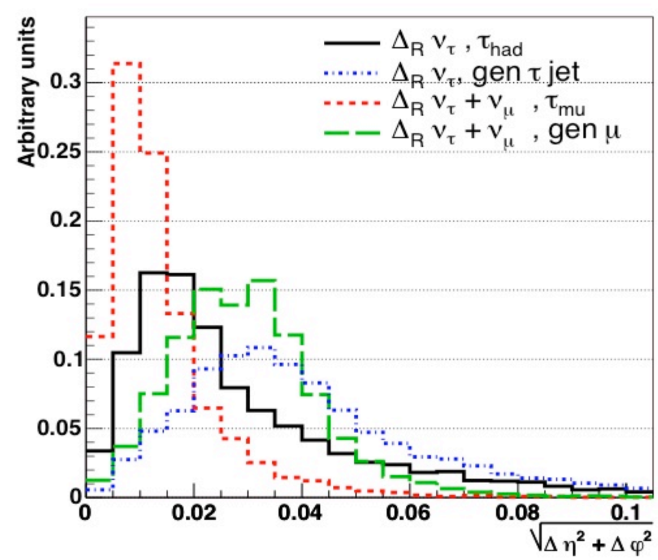
Heavy $H^\pm \to \tau\nu$ search	Efficiency	b from $t \to bW$	b from $tbH^\pm$	q from $W \to qq$
Track counting	63.4%±0.40%	54.8%	24.4%	14.9%
Combined 2ndary vertex	61.7%±0.31%	60.9%	25.6%	8.4%

Higgs mass reconstruction: H/A→ττ

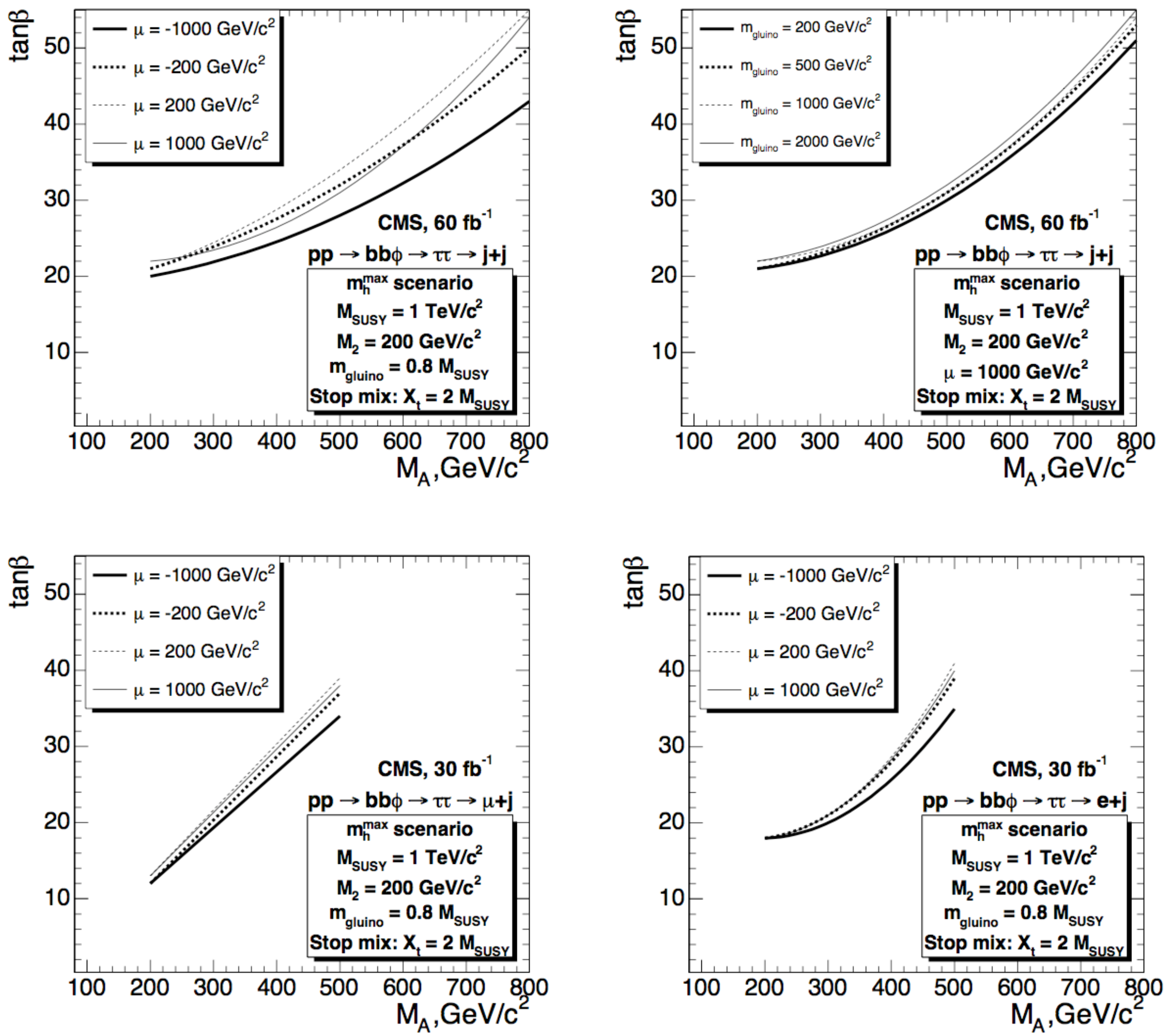
- Assume τ decay products collinearly emitted (for m_A>200 GeV, $\gamma > m_A/2 * m_\tau > 59$
- E_T^ν from missing E_T
- z-component from η of charged objects
- $\Delta\phi(\tau_1,\tau_2)$<175 degree
- E_ν>0 (large inefficiency)
- Typical mass resolution: 20%





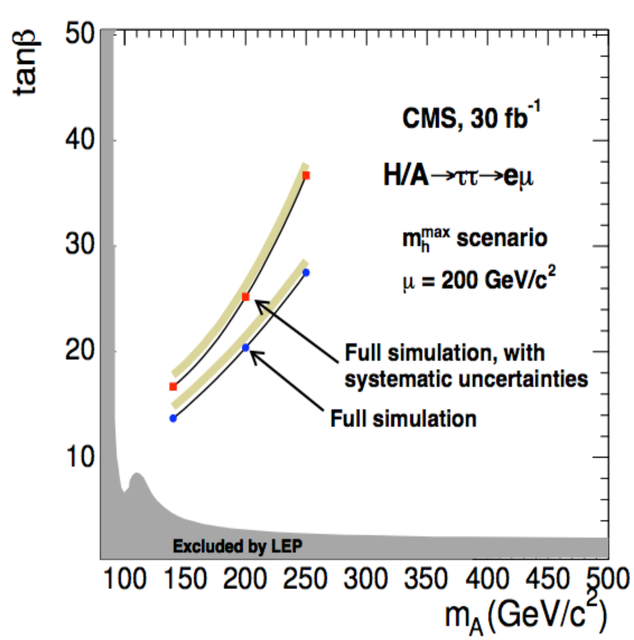


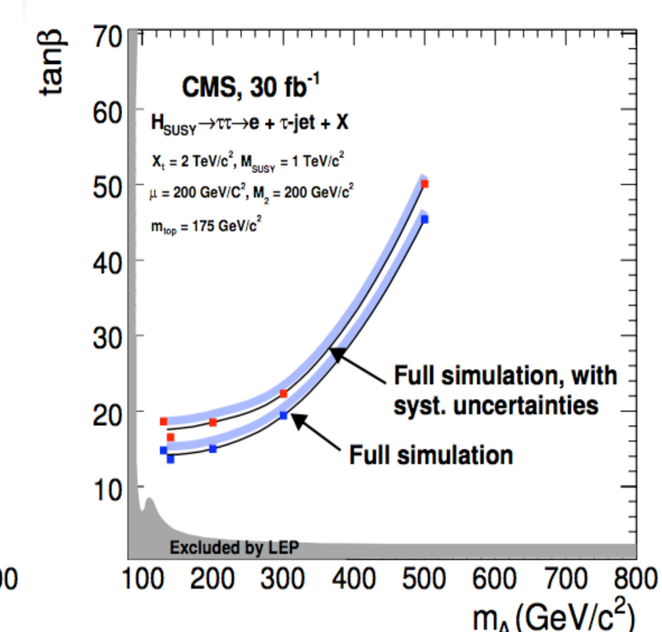
5σ reach variations with MSSM parameters



5σ discovery reach: dependence on systematics

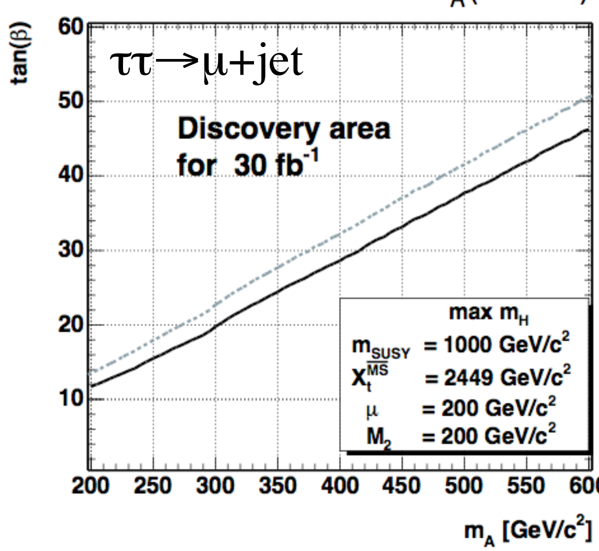
l-ID: 2+2%
b-tag: 5%
b-mistag: 5%
E scale: 4-11%
lumi: 3%
σ(tt): 6%
$\sigma(Z/\gamma^*)$: 1%
$\sigma(bbZ/\gamma^*)$: 14%
tt: 12%
tW: 15%
Z/γ^*: 9%
bbZ/γ^*: 16%

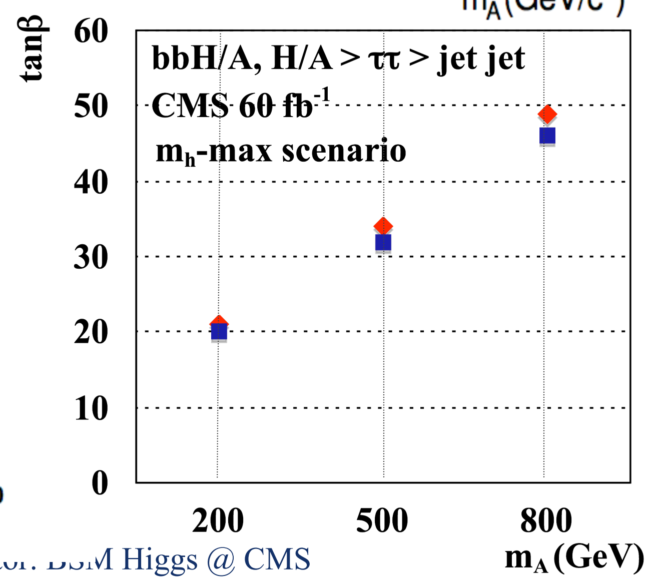




e-ID: 2%
b-tag: 5%
b-mistag: 5%
E scale: 4-12%
lumi: 3%
σ(tt): 5.6%
$\sigma(Z/\gamma^*)$: 1%
$\sigma(bbZ/\gamma^*)$: 14%
tt: 11%
tW,Wj: 14%
Z/γ^*: 8%
bbZ/γ^*: 16%

E_{HCAL} scale: 3%
f shape: 12%
tt: 12%
E scale: 6%
B-mistag: 5%
Z/γ^*: 8%
E scale: 6%
$\sigma(bbZ/\gamma^*)$: 14%
bbZ/γ^*: 16%





QCD: 5-20%
(from data, stat. error)

bbH/A→bbττ →bbμj selection

Offline tau:

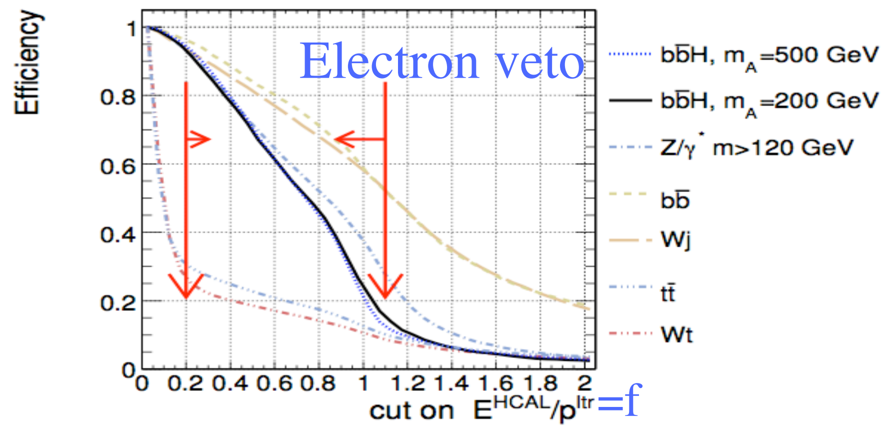
- Iterative cone algorithm (ΔR=0.4)
- Full tracker isolation
- 1 or 3 tracks in tau cone
- tau direction from sum of track momenta
- Calorimeter energy with MC calibration

Background rejection:

- Leading track p_T>10 (20) GeV for 1-(3-) prongs
- Opposite charge of tau leptons
- Single b-tag: ≥2 tracks with $S(IP_T)>2$
- Central jet veto (E_T^{calib}>20 GeV, $|\eta|<2.4$)
- $m_T(\mu\text{-}E_T^{miss})<60$ GeV against W's
- Electron veto for 1-prongs $0.2<E_{HCAL}/E_{leading\_track}<1.1$ (upper cut against events rich in neutral hadrons)

$M_{\tau\tau}$ reconstruction (assuming ν's collinearly emitted with τ):

- 120 < $\Phi(p_T^{\mu},E_T^{jet})$ < 175 deg
- $E_{\nu 1}>0$, $E_{\nu 2}>0$
- Mass window (159-241 GeV for M_A=200 GeV) [Resolution: 21, 16% for M_A=200, 500 GeV]



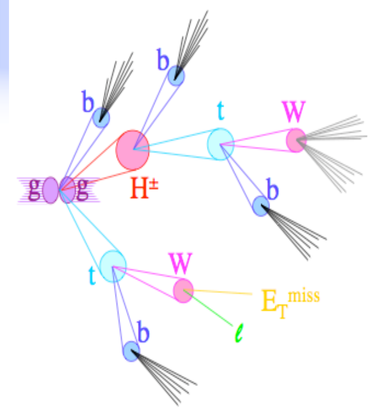
Background estimate from data, non-Z/γ*:

- invert electron veto cut: f< 0.1
- $N_{bkg}=N_{obs}^{f<0.1} * (N^{0.2<f<1.1}/N^{f<0.1})$
- ratio from MC or tt data
- systematics 12.4%:
  3% HCAL energy scale,
  12% shape of distribution

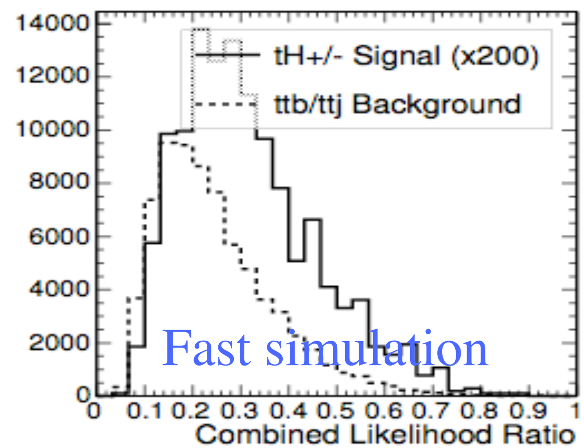
Z/γ*:

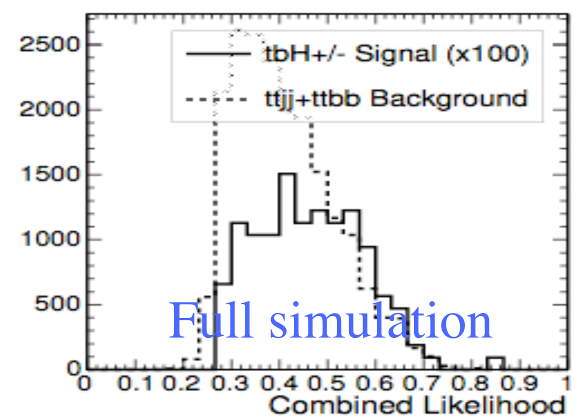
- cross-section from DY ll measurement
- 8% (15%) systematics for ττ (bbττ):
  6% (3% jet scale, 5% E_T^{miss}),
  5% b-mistag for ττ,
  14% cross-section (bbll measurement)

Search for H±→tb



- Production: gb→tH± (LO) or gg→tbH± (NLO)
  issue: merging the two processes in full simulation
- Final state: ttb(b)→WWbbb(b) →qqlνbbb(b)
- Signal: muon + 3 or 4 b-jets
- Background from tt+jets including b-jets
- Selection:
  - muon with p_T>20 GeV, |η|<2.5
  - 5 or 6 jets with p_T>25 GeV, |η|<2.5
  - 3 or 4 b-jets with P_b>1.0 or 0.5
  - kinematic fit (W and top mass constraint) converge
  - Selection of optimal jet association (based on kin. fit, b-tagging, kinematics of b-jet from H)
  - Likelihood ratio (b-tagging and for ttb case kin. fit, jet kinematics)
  - No mass reconstruction
- Systematics:
  - b-tagging efficiency: 5%, mis-tag: 5-10%
  - Theoretical uncertainties on tt+jets cross-section





Final LEP results (m_h-max scenario)