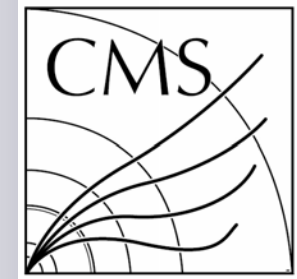


Higgs Search with the CMS detector at LHC

Satyaki
Bhattacharya

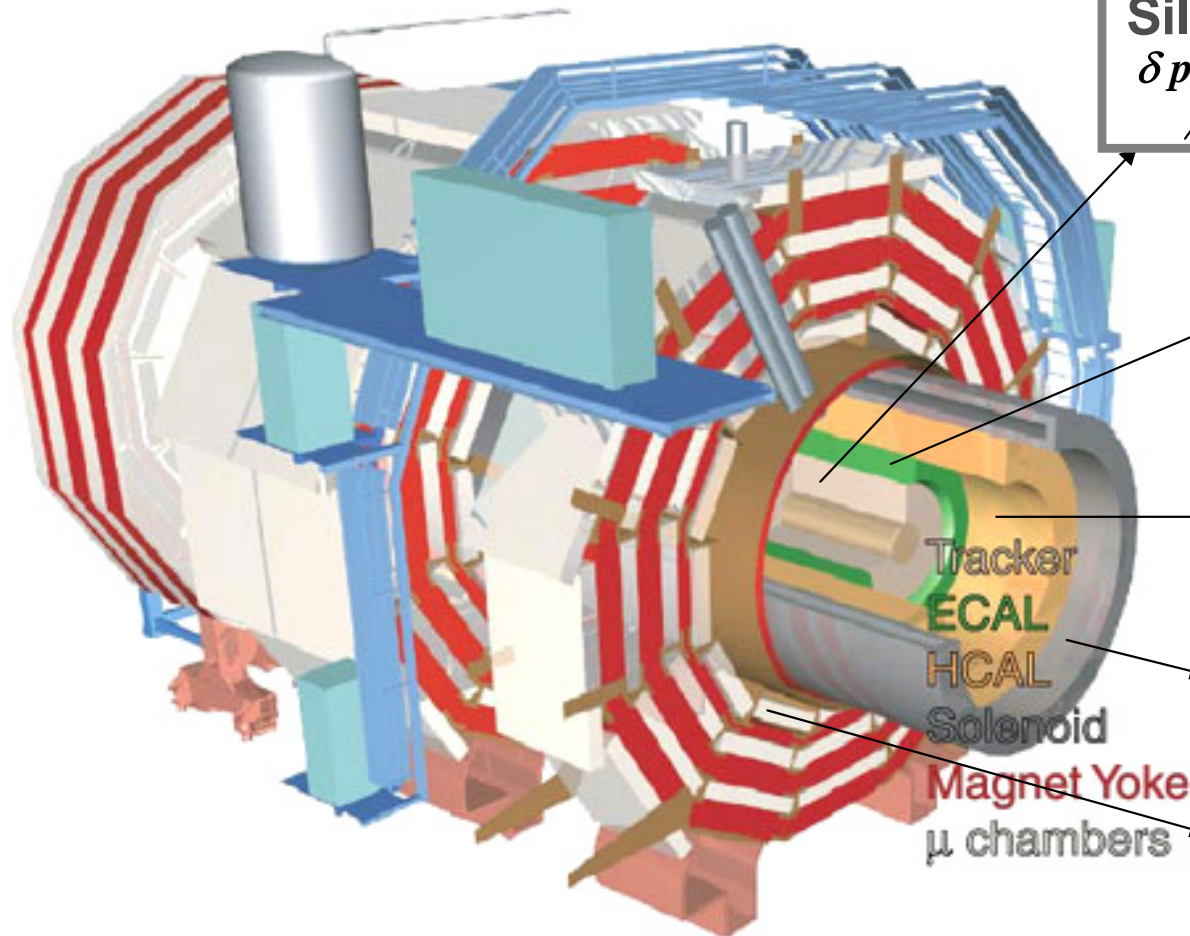




data taking starts 2007

Startup Luminosity $2 \times 10^{33} \text{ cm}^{-2}/\text{s}$

that is: 20 fb^{-1} per year



Silicon Tracker

$$\frac{\delta p_T}{p_T} \approx 15 \times p_T (\text{TeV}) \%$$

PbWO₄ ECAL

$$\frac{\sigma_E}{E} = \frac{1.5\%}{\sqrt{E}} \oplus 0.5\% \oplus \frac{0.15}{E}$$

sampling brass

HCAL $\frac{\sigma_E}{E} = \frac{120}{\sqrt{E}} \oplus 5\%$

solenoid
4Tesla field

MUON Chambers

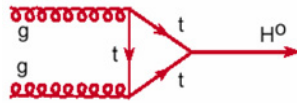
$$\text{global } \frac{\delta p_T}{p_T} \approx 1.0 - 1.5\% @ 100 \text{ GeV}$$

numbers are for barrel

Standard Model Higgs

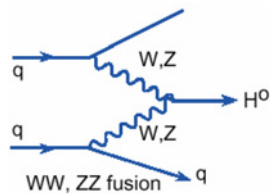
Higgs production at LHC

$gg \rightarrow H$



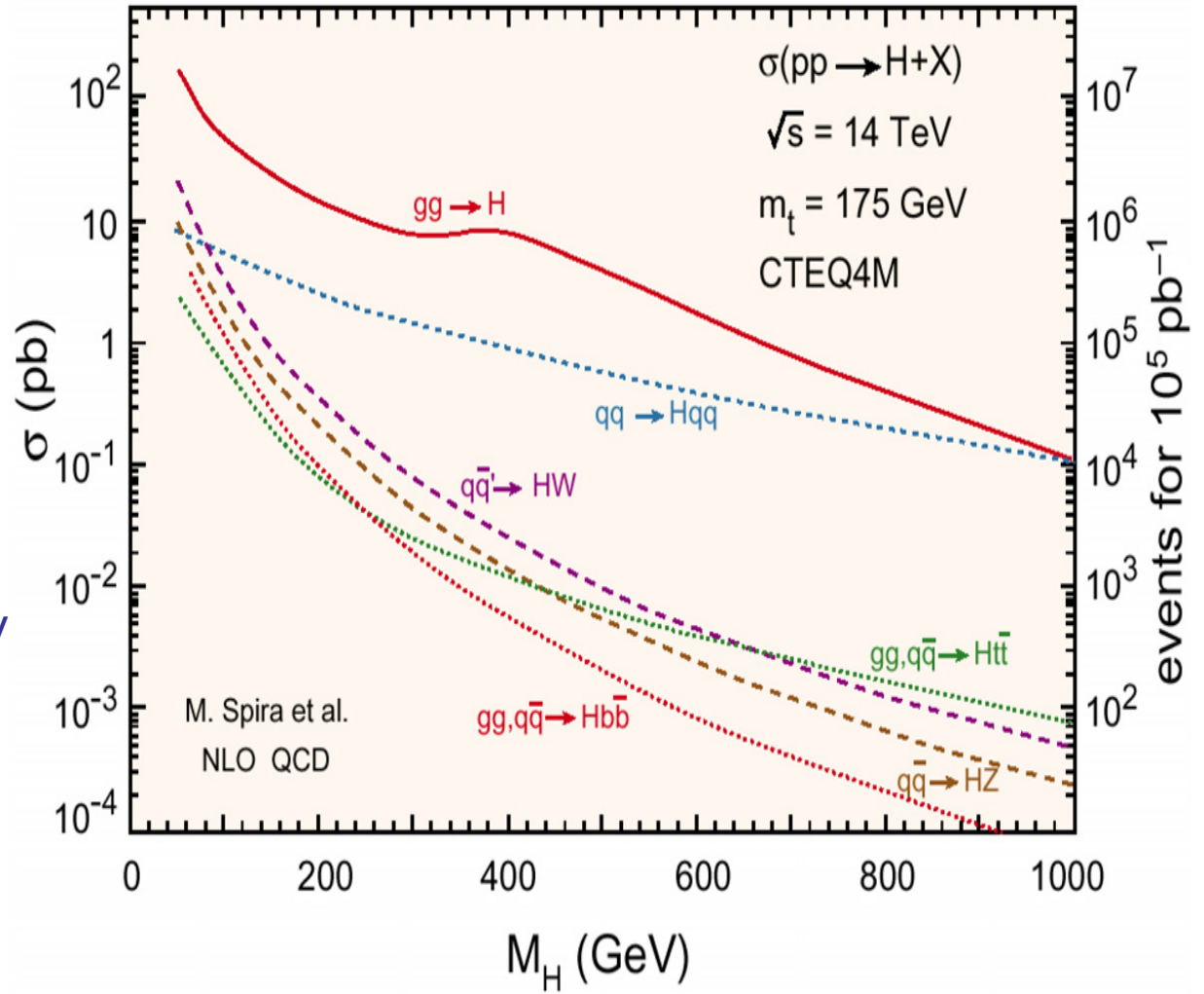
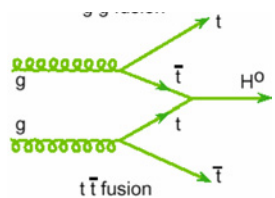
High gluon flux – dominant although loop process

Vector Boson Fusion (VBF)

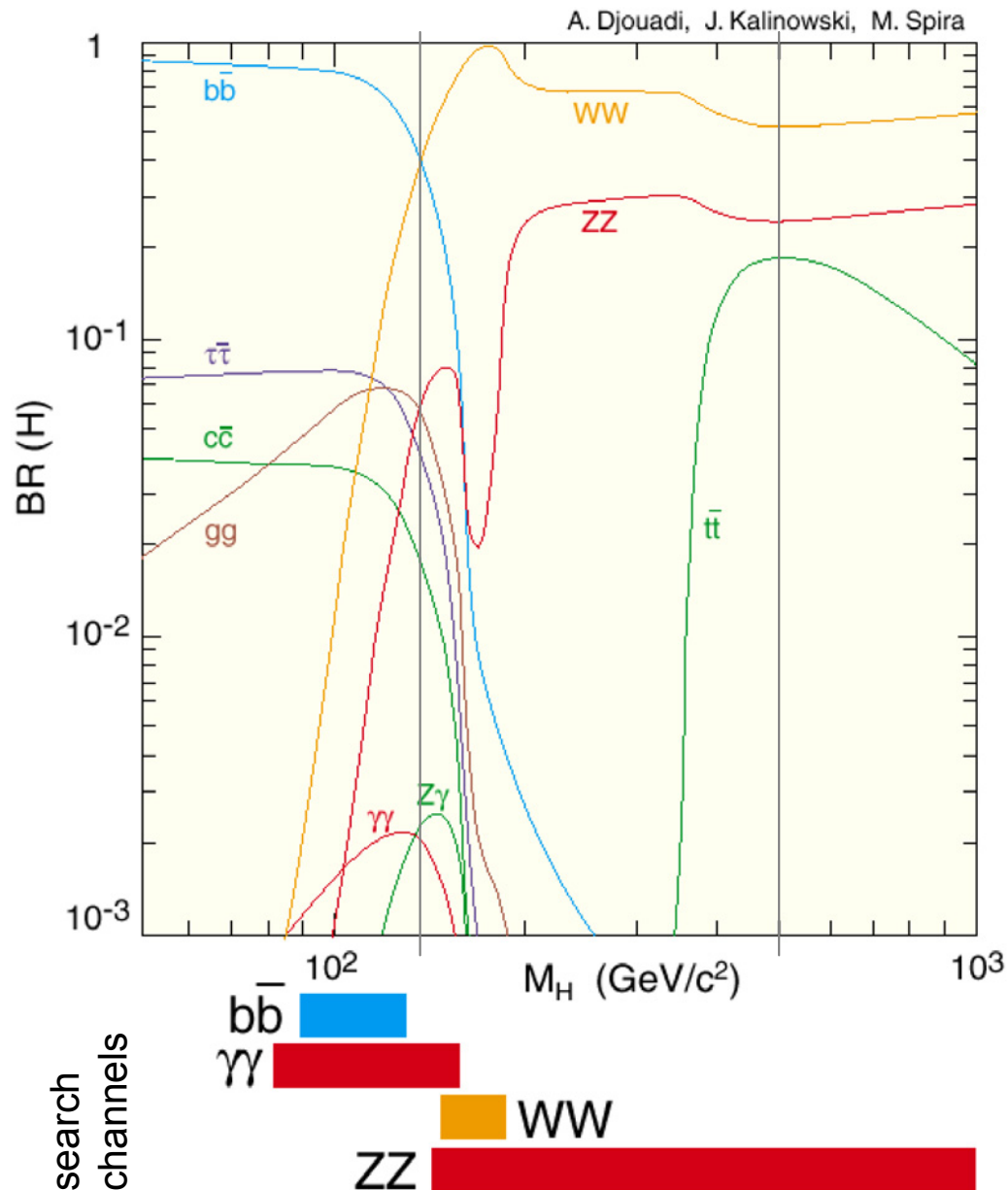


10% at $M_H = 100 \text{ GeV}$
 Comparable to $gg \rightarrow H$ at $M_H = 1 \text{ TeV}$

$t\bar{t}H$, $b\bar{b}H$, HW , HZ



Decays and Search Strategy



$M_H < \sim 140$ GeV

$H \rightarrow b\bar{b}$ dominant

$gg \rightarrow H \rightarrow b\bar{b}$: background too large

$t\bar{t}H \rightarrow t\bar{t}b\bar{b}$ possible

$H \rightarrow \gamma\gamma$ – small BR but very clean

$M_H < \sim 500$ GeV

120-200 GeV

$H \rightarrow WW^*/WW \rightarrow l\nu l\nu$ (serious $t\bar{t}$, Wtb background)

200-500 GeV

$H \rightarrow ZZ \rightarrow 4l$ gives highest sensitivity between 200-500 GeV

$M_H > \sim 500$ GeV

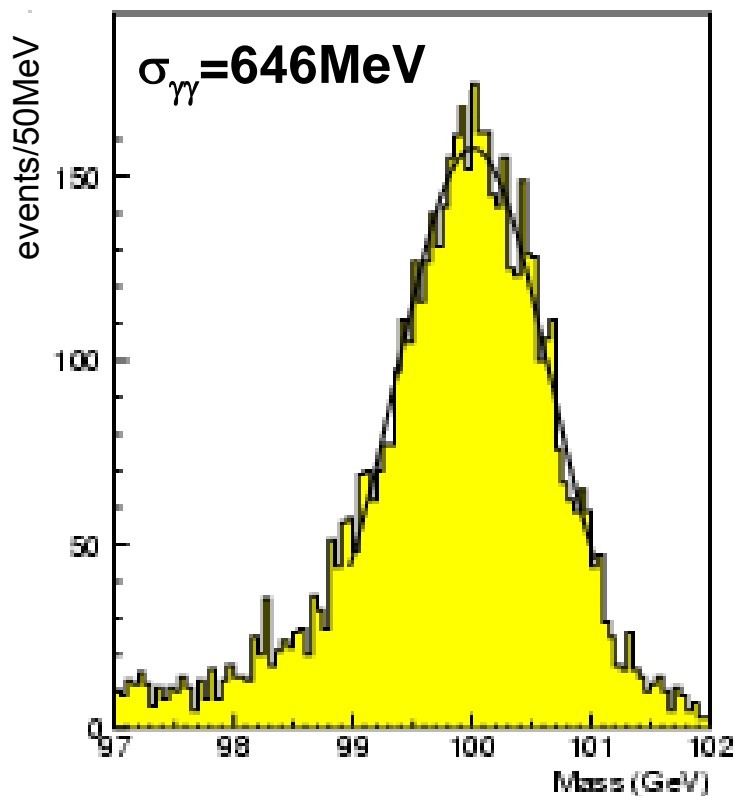
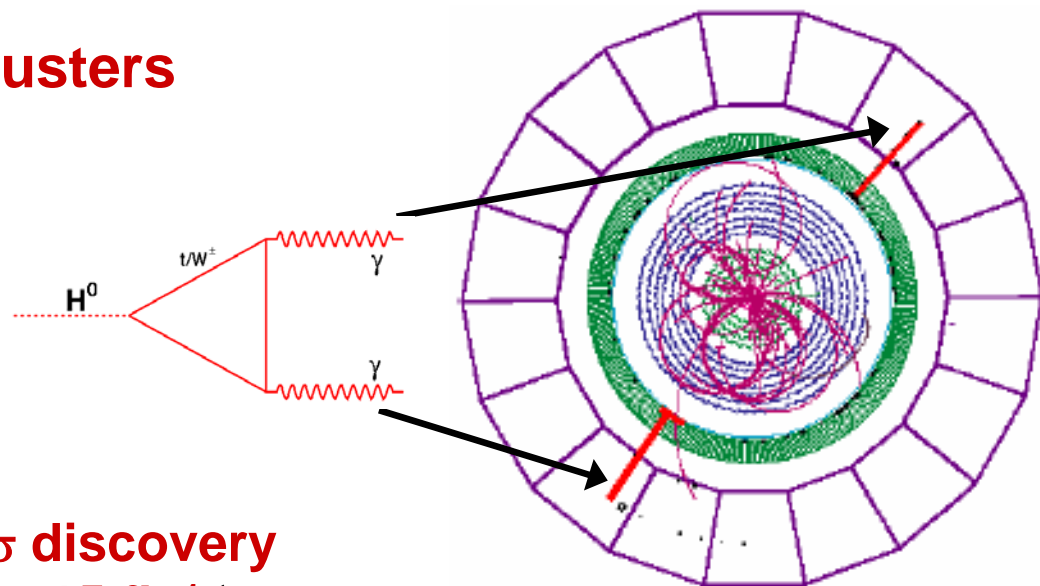
Γ_H large, use channels with large BR, $H \rightarrow ZZ/WW$

VBF x-sec large and can be used

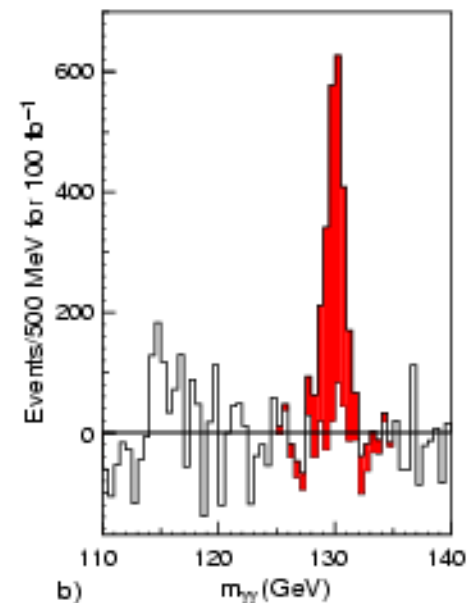
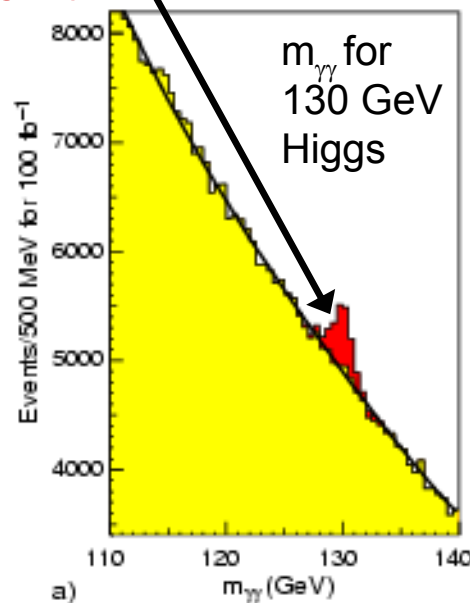
Low mass (<140 GeV): $H \rightarrow \gamma\gamma$

Two clean electromagnetic clusters
For unconverted photons

Backgrounds: $gg, qq \rightarrow \gamma\gamma, qg \rightarrow q\gamma$



**5 σ discovery
in $\sim 15 \text{ fb}^{-1}$**

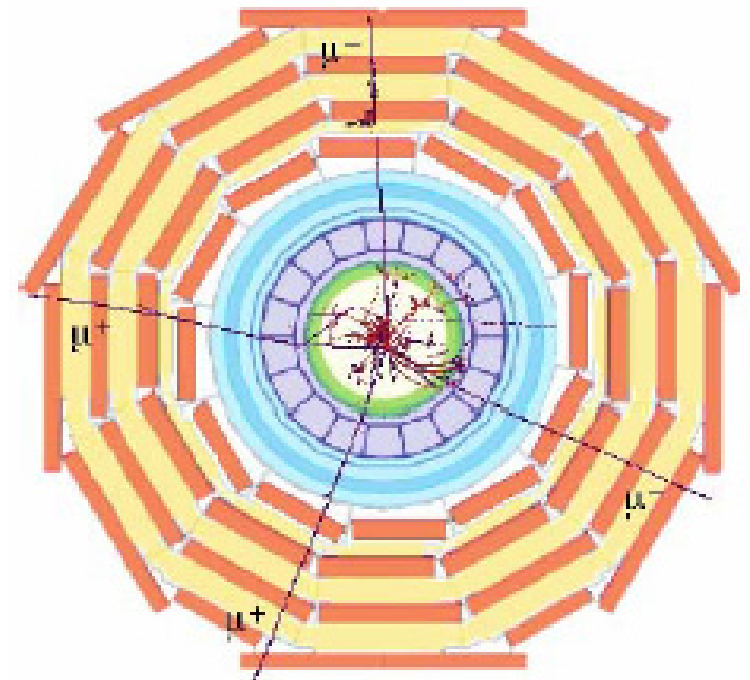
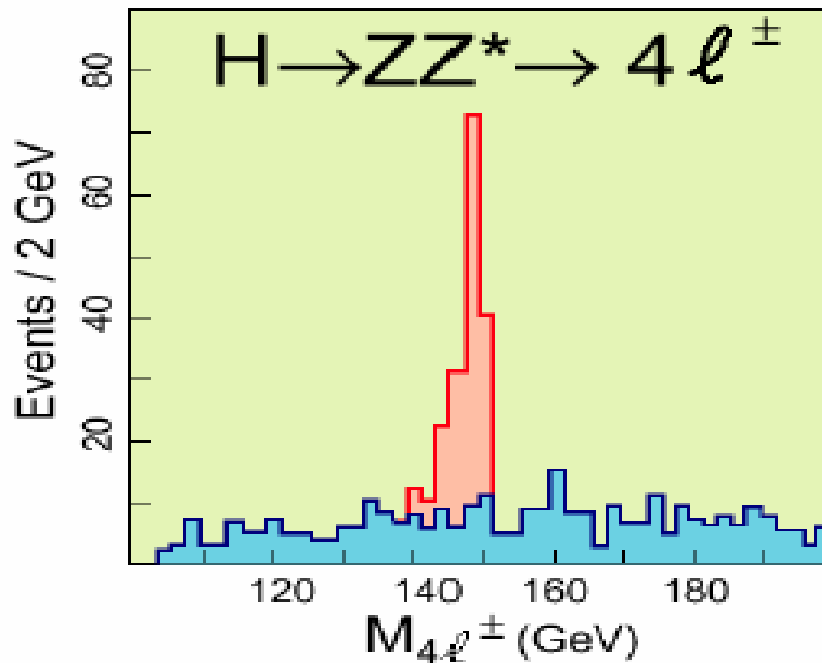
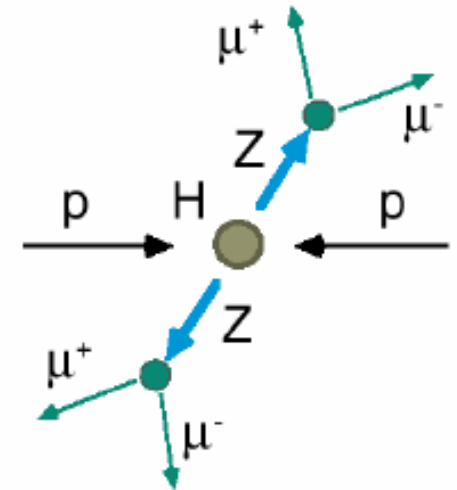


$$H \rightarrow ZZ \rightarrow 4\ell$$

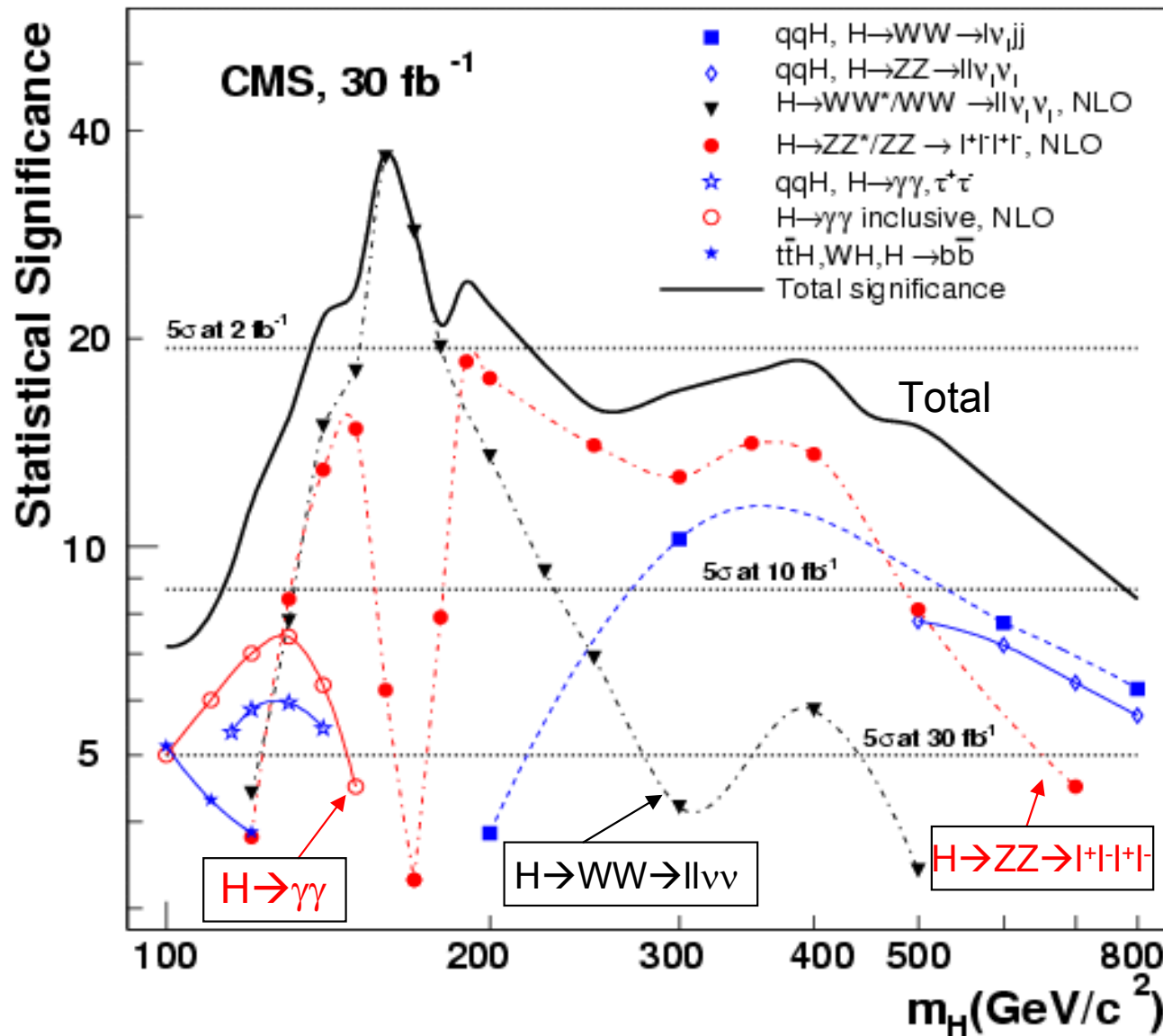
Clean, resolution better than 1 GeV

Discovery Luminosity:

Higgs Mass, GeV	120	130	140
4e; L for 5 σ discovery, fb ⁻¹	351	106	31
4 μ ; L for 5 σ discovery, fb ⁻¹	152	35	15



Discovery reach of CMS

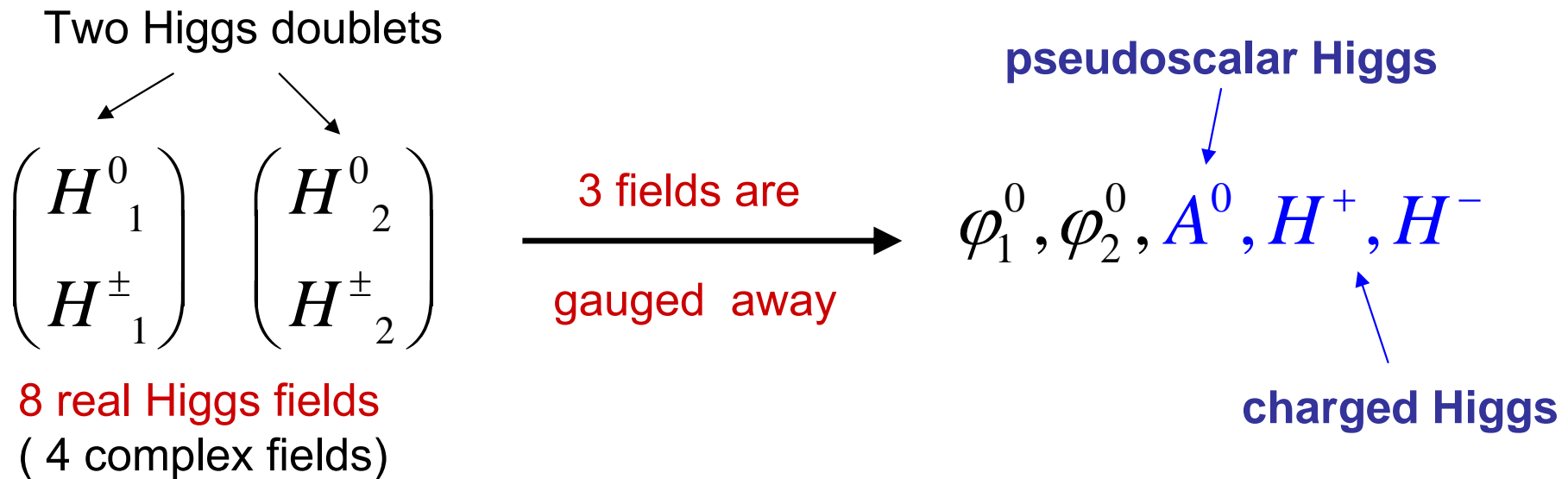


CMS can probe the entire “allowed” mass range

5σ discovery possible in few months in many channels

Higgs in MSSM

MSSM Higgs sector



heavy Higgs

light Higgs

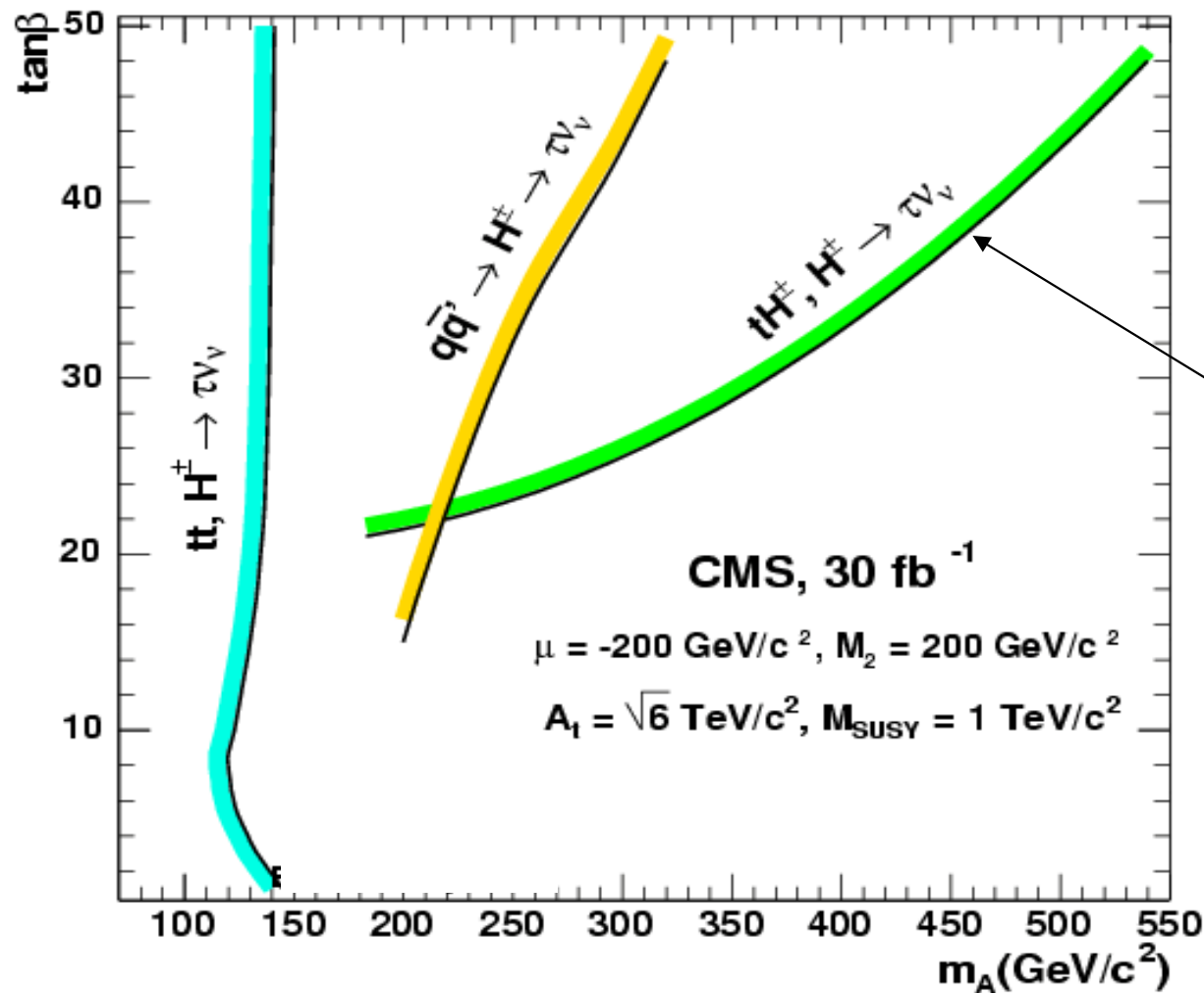
$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \varphi_1^0 \\ \varphi_2^0 \end{pmatrix}$$

All masses, x-sections, BRs and mixing angle α are determined by two parameters

$\tan\beta$ – ratio of vacuum expectation values of the two doublets

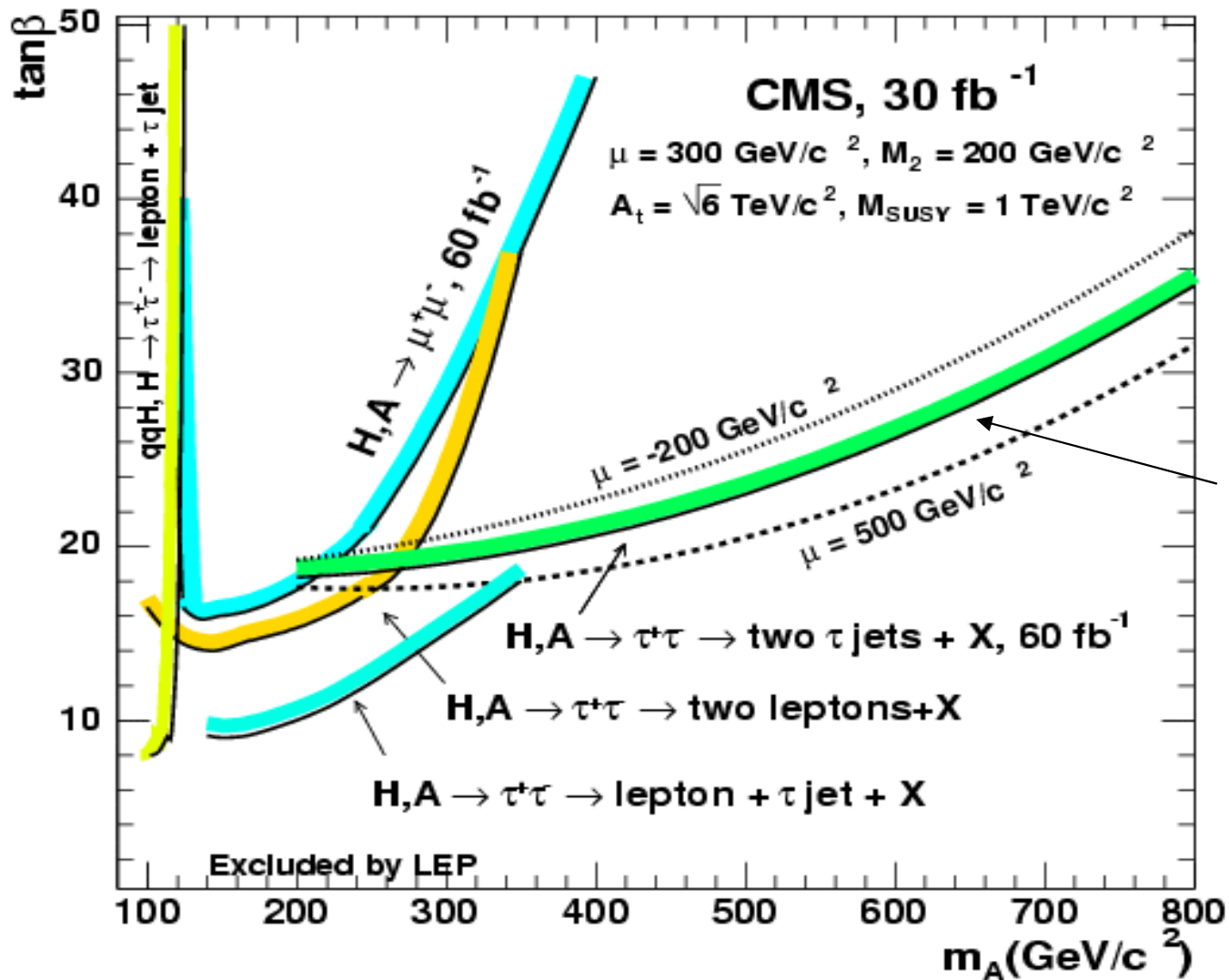
M_A – mass of pseudoscalar Higgs A

H[±] discovery @ 30 fb⁻¹



For charged higgs associated production with top is dominant

A/H discovery @ 30 fb⁻¹



At large $\tan\beta$ A/H coupling to down type fermion is strong and H production with $b\bar{b}$ and H decay to τ become important

$A/H \rightarrow \tau^+\tau^- \rightarrow \text{jets} + X$

Signal:

$gg \rightarrow bbH/A$ and $gg \rightarrow H/A$

$H/A \rightarrow \tau^+\tau^-$

$M_A = 500 \text{ GeV}$ $\sigma \cdot \text{Br} = 0.188 \text{ pb}$

$M_A = 200 \text{ GeV}$ $\sigma \cdot \text{Br} = 9.53 \text{ pb}$

backgrounds:

$Z/\gamma^* \rightarrow 2\tau$, multijets faking τ

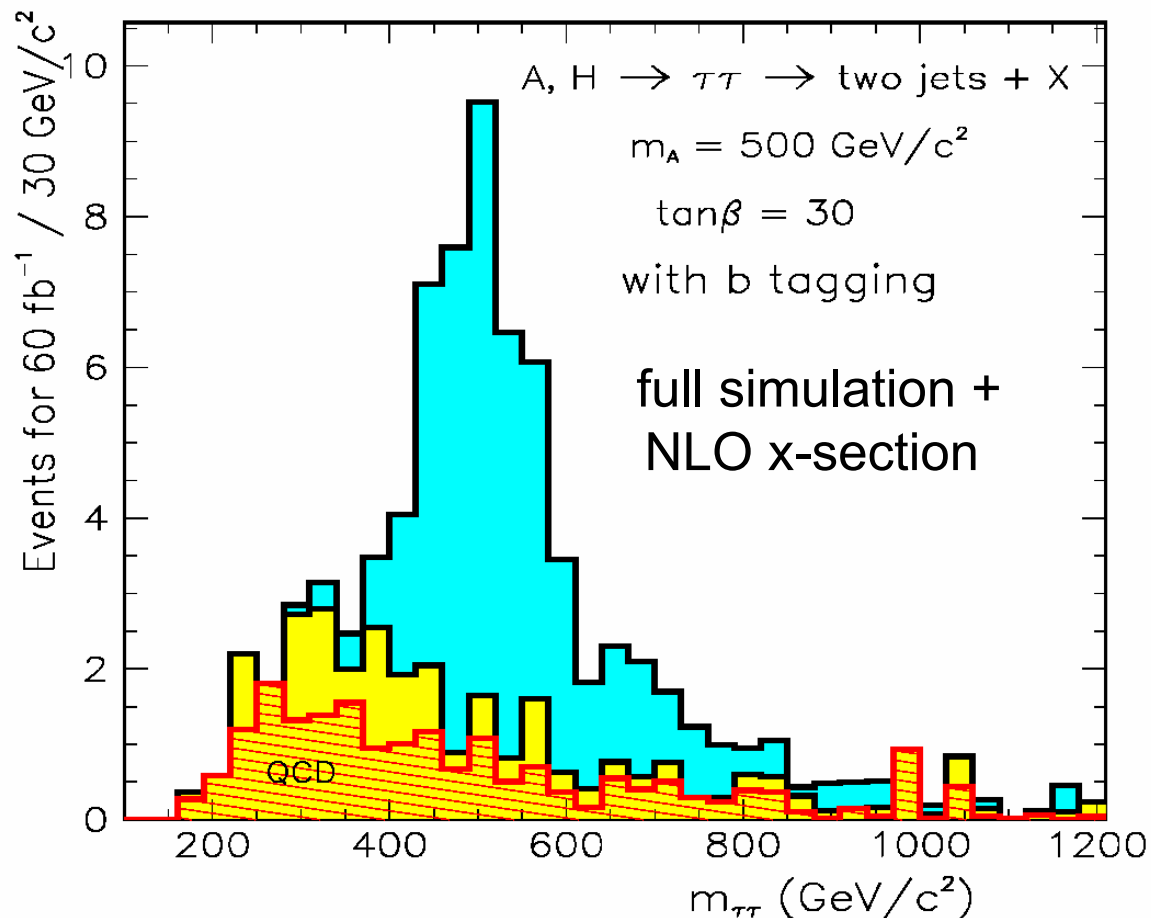
$t\bar{t}$ and $W+\text{jet}$ with $W \rightarrow \tau\nu$

reduce background by requiring:

narrow τ jet,

b-tag, central jet veto. τ impact

parameter, vertexing



~15% mass resolution

Summary

- CMS is capable of searching SM Higgs over the entire allowed mass range between LEP M_H limit and \sim TeV (unitarity bound)
- Atleast one MSSM Higgs will be found in entire M_A - $\tan\beta$ plane
- **5σ discovery possible in few months**
- Few hundred MeV mass resolution from $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$ for low-intermediate mass Higgs
- Also
 - CP and spin of Higgs can be measured with 100fb^{-1}

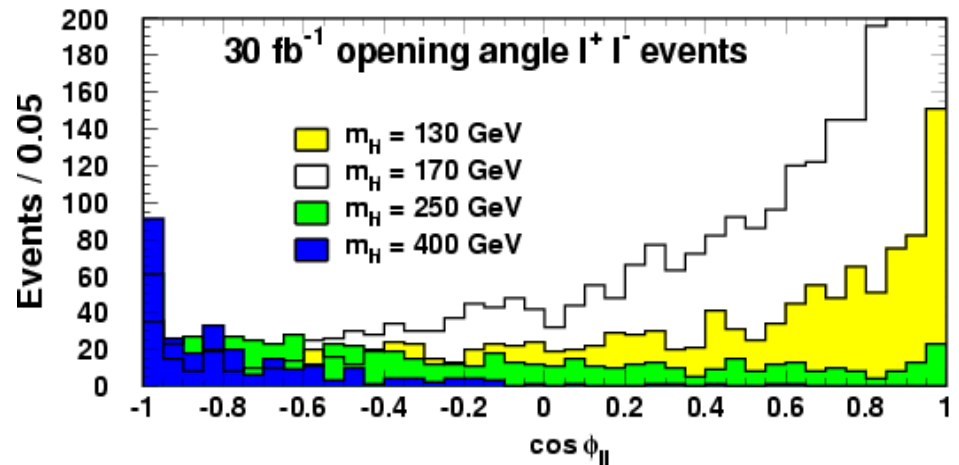
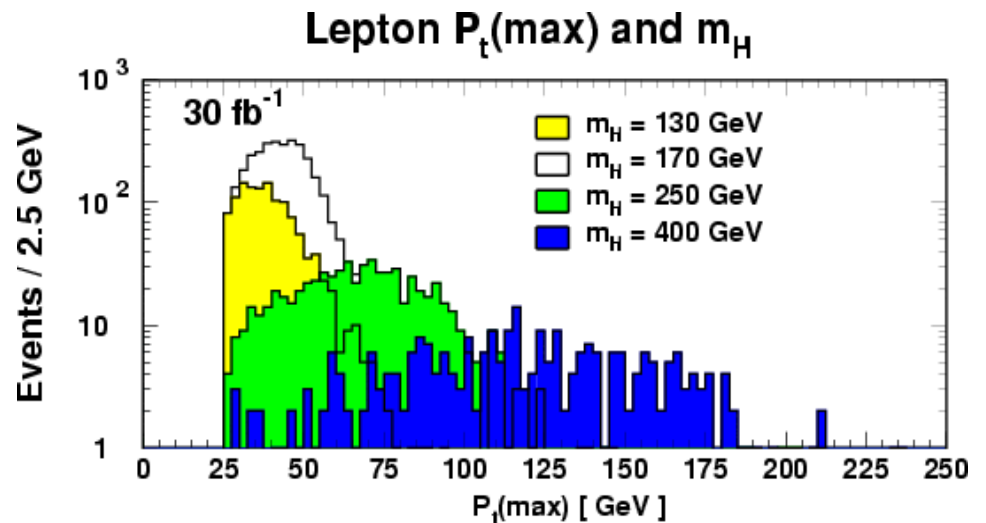
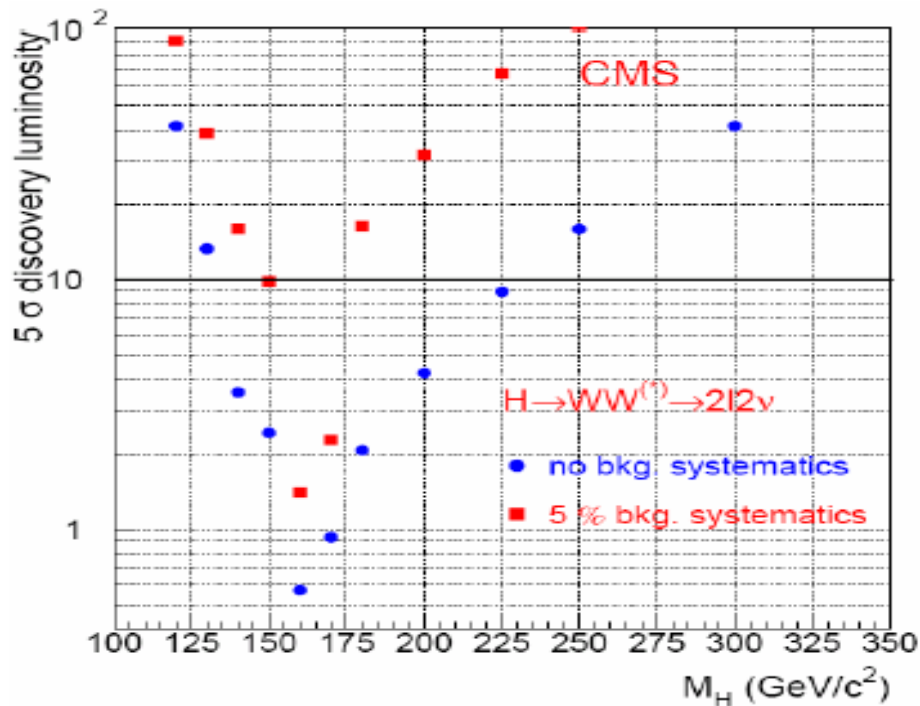


Extras

Interm. Mass: $H \rightarrow WW \rightarrow l'l'X$

Isolated leptons + E_T^{miss}

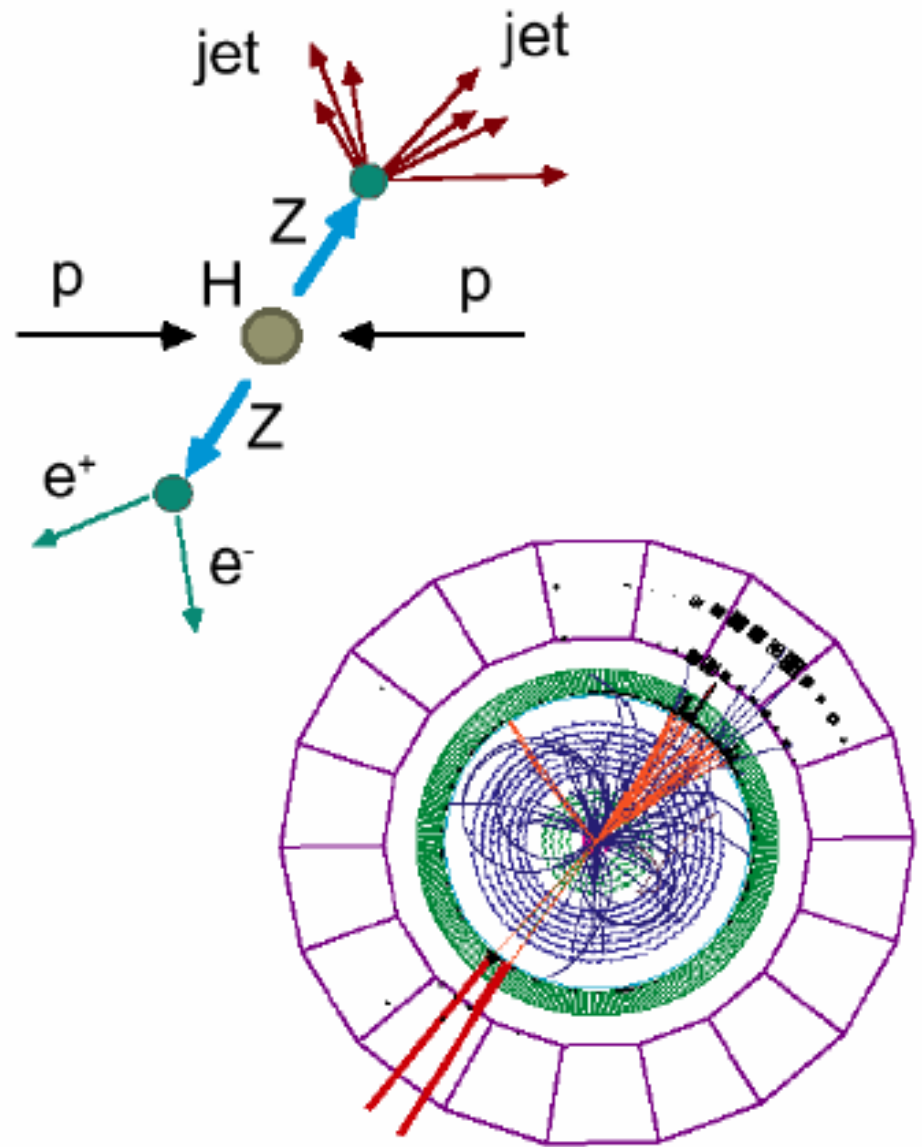
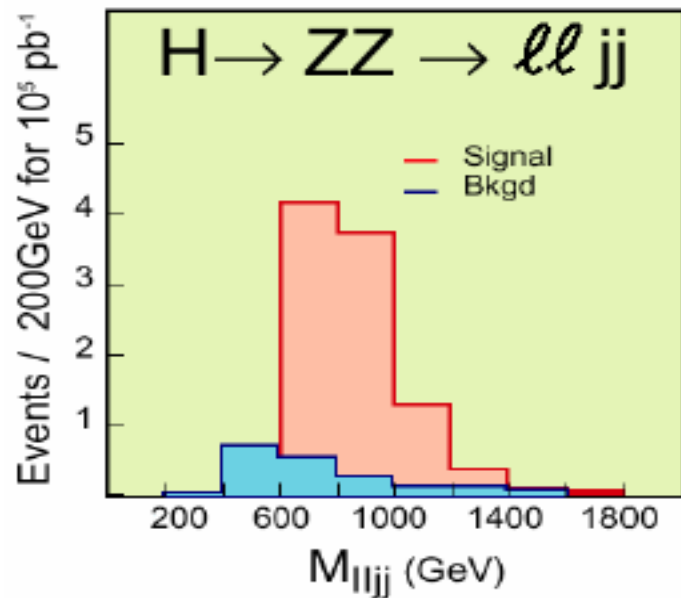
$t\bar{t}$ serious background
 → Require central jet veto



High Mass: $ZZ \rightarrow lljj$

$H \rightarrow ZZ \rightarrow lljj$ has large branching fraction at higher masses.

Mass reconstruction possible but Γ_H is large



$t\bar{t}H, H \rightarrow b\bar{b}$

Preselection: 1 isolated lepton + atleast 6 jets

Likelihood based analysis:

$L_{\text{event}} = \text{Anti b-tag prob. of W jets} \times \text{b-tag prob of other jets} \times \text{Mass prob. of W,t,t} \times \text{sorting of b-jet energies}$

Pick jet combinations with highest L_{event} .

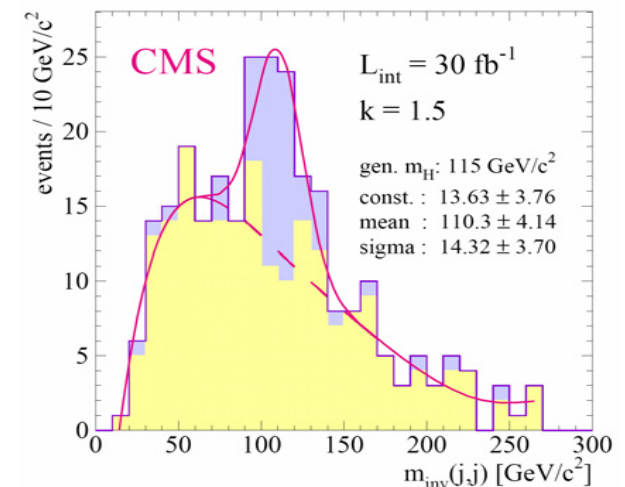
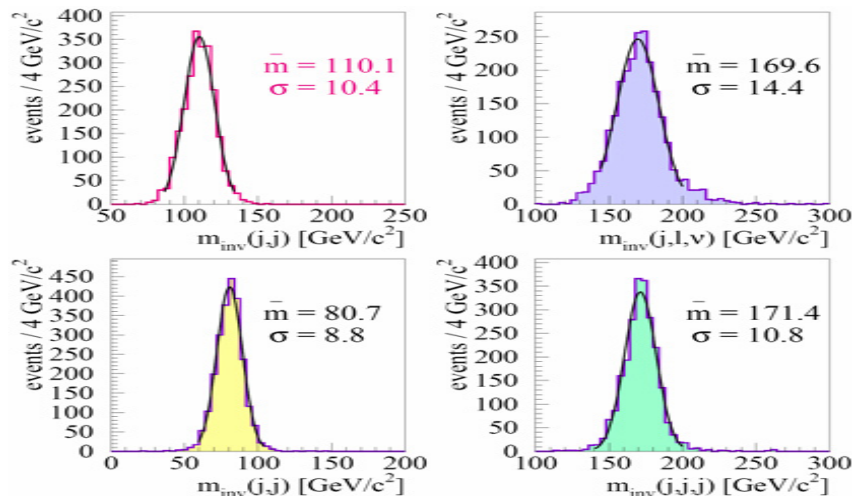
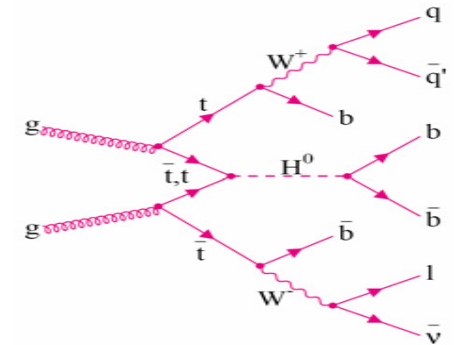
Select event based on 3 likelihood functions, then count

Events around mass window.

Efficiencies: 115 GeV H = 1.3%

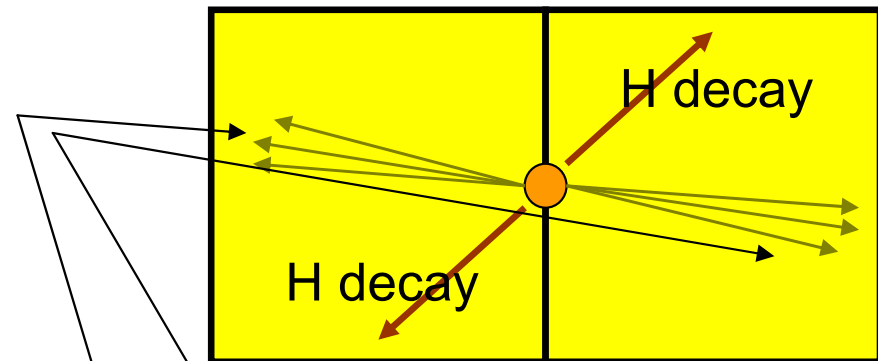
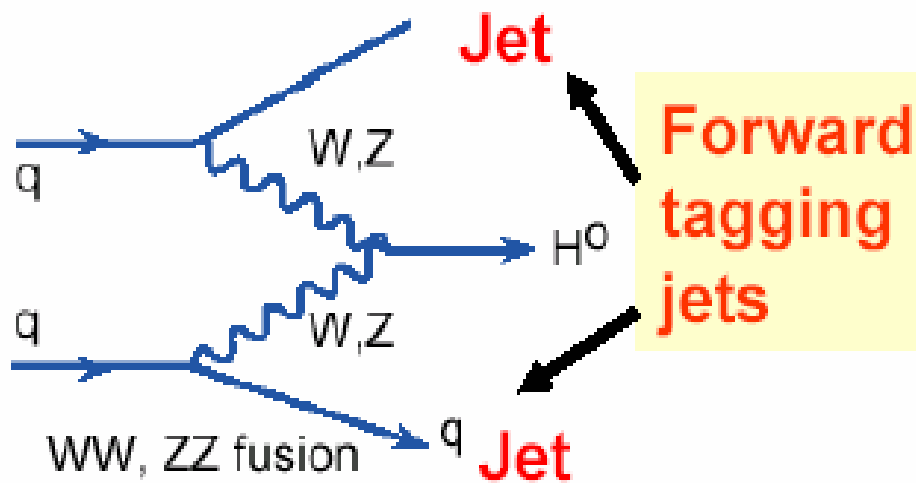
$t\bar{t}b\bar{b} = 0.4\%$, $t\bar{t}Z = 0.2\%$

(full detector simulation done)



Reconstructed masses of H,W,t, \bar{t}

VBF : New channel

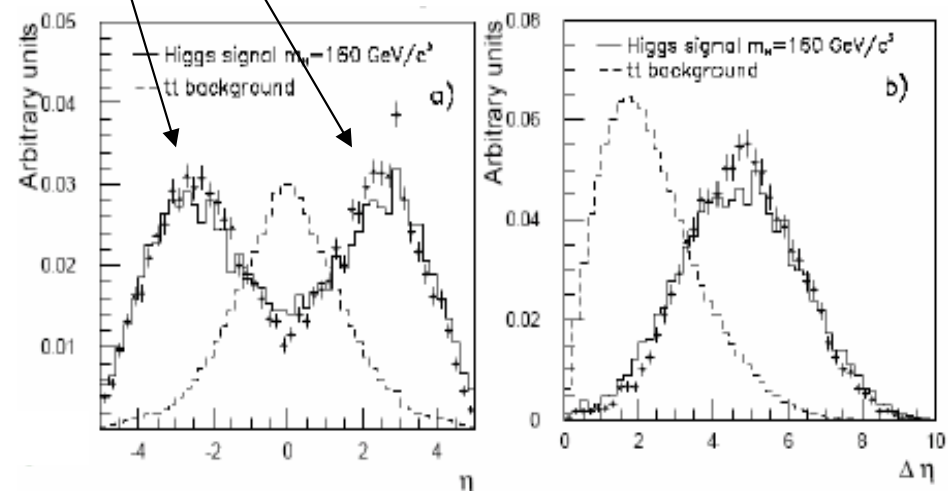


Features:

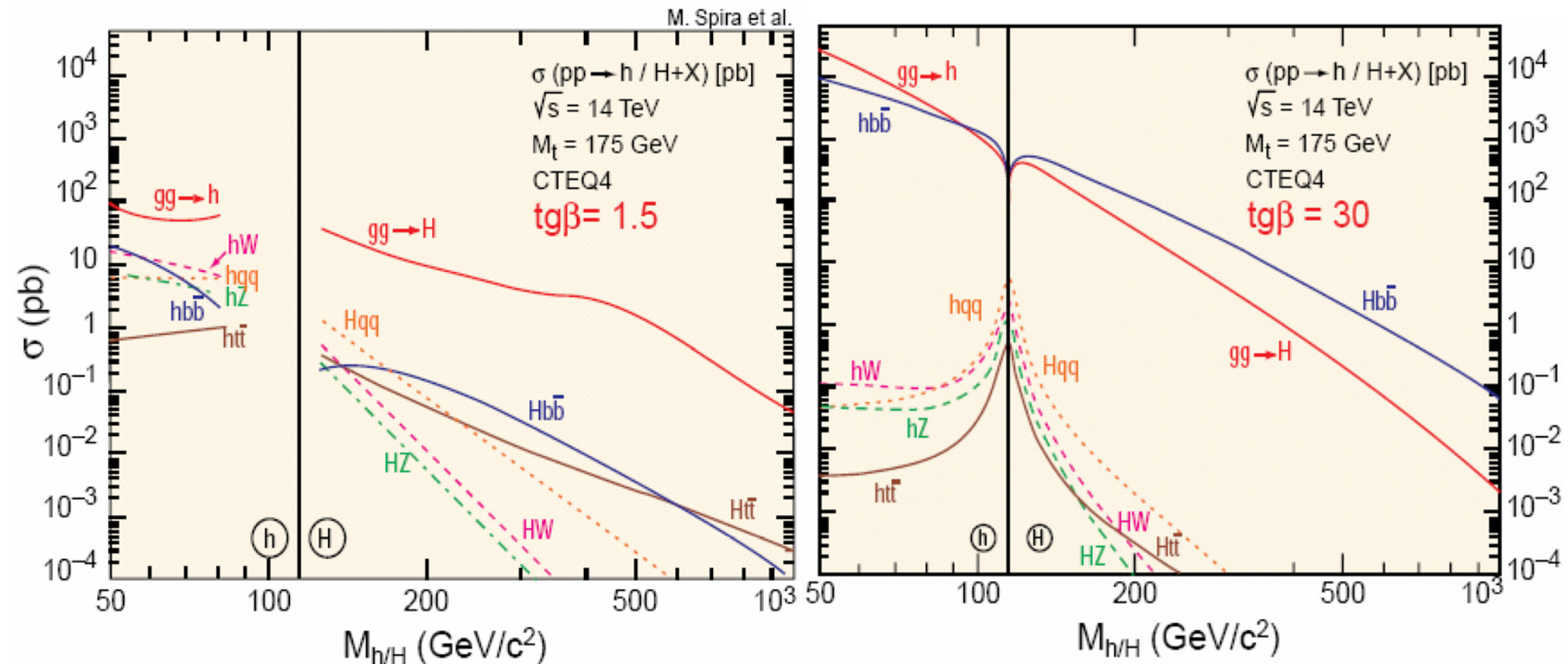
Forward tagged jets
Relatively high p_T Higgs

Important at very high mass
(10% at low mass, total at very high mass)

Very useful for WW^* , also used for $\gamma\gamma, \tau+\tau^-$ at lower mass

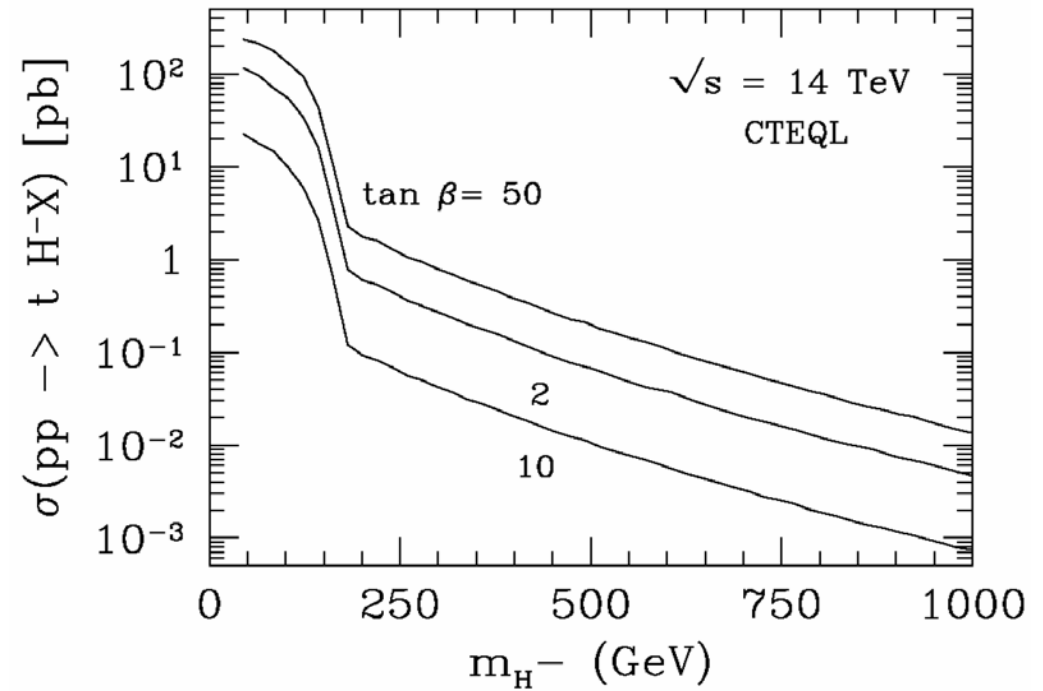
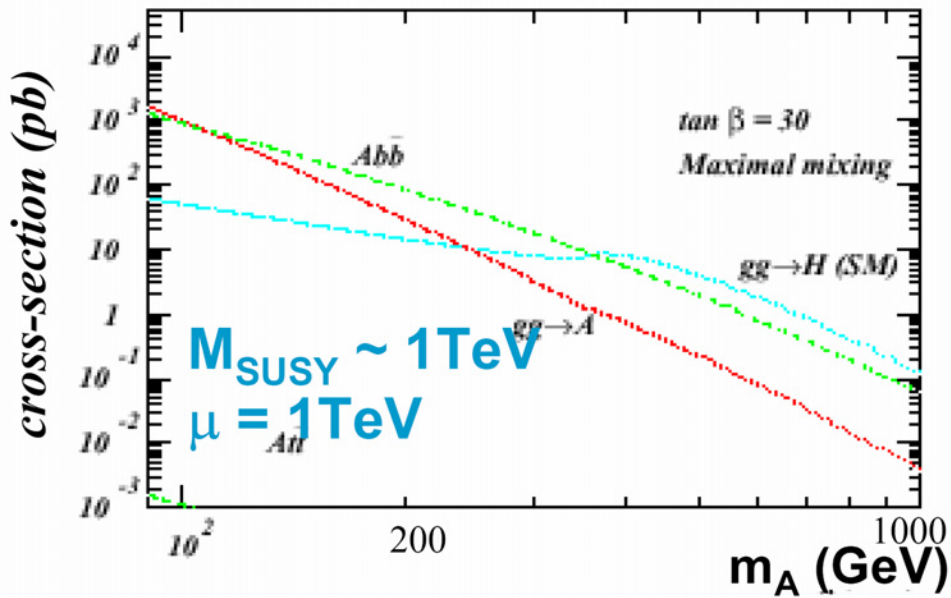


MSSM Higgs Production



$gg \rightarrow H$ most important at low mass and low $\tan\beta$
 light higgs production x-sections similar to SM higgs
at high $\tan\beta$ $gg/qq \rightarrow Hb\bar{b}$ dominant for heavy Higgs
 for H^\pm $t\bar{t} \rightarrow tH\bar{b}$ is most important

MSSM Higgs Production (ii)



Higgs Production in MSSM(details)

- H/A production

- $gg \rightarrow H/A, gg/q\bar{q} \rightarrow b\bar{b}H/A$
- $g(AVV)=0 \rightarrow$ no VBF
- At large $\tan\beta$
 - VBF suppressed for H
 - $g(A/Hbb)$ enhanced \rightarrow $\sim 90\%$ $b\bar{b}H/A$ for $\tan\beta > 10$ and $M_A > 300$ GeV
- H SM-like near lower mass limit (high $\tan\beta$, small M_A) \rightarrow VBF significant

- h production

- h SM-like for $M_A > m_h^{\max}$

Φ	$g(\Phi uu)$	$g(\Phi dd)$	$g(\Phi VV)$
h	$\cos\alpha/\sin\beta$ $\rightarrow 1$	$-\sin\alpha/\cos\beta$ $\rightarrow 1$	$\sin(\beta-\alpha)$ $\rightarrow 1$
H	$\sin\alpha/\sin\beta$ $\rightarrow 1/\tan\beta$	$\cos\alpha/\cos\beta$ $\rightarrow \tan\beta$	$\cos(\beta-\alpha)$ $\rightarrow 0$
A	$1/\tan\beta$	$\tan\beta$	0

Higgs couplings with up(u) down(d) fermions and vector bosons (v)

- H^\pm production

For $M_{H^\pm} < M_t$: $tt \rightarrow tH^\pm b$

For $M_{H^\pm} > M_t$:

- $gg \rightarrow tbH^\pm, H^+H^-, W^\pm H^\pm$
- $gb \rightarrow tH^\pm$
- $qq \rightarrow H^\pm$

channels considered for a SUSY Higgs

- $H/h \rightarrow \gamma\gamma, b\bar{b}$
 - $H \rightarrow b\bar{b}$ in $WH, t\bar{t}H$
 - $h \rightarrow \gamma\gamma$ in $Wh, t\bar{t}h \rightarrow l\gamma\gamma$
- $H/h \rightarrow ZZ^*/ZZ \rightarrow 4l$
- $h/H/A \rightarrow \tau^+\tau^- \rightarrow (e/\mu)j\cancel{E}_T, e\mu\cancel{E}_T, jj\cancel{E}_T$
 - Including $qqH, t\bar{t}H, WH$
- $H^+ \rightarrow \tau^+\nu$ from $t\bar{t}$
- $H^+ \rightarrow \tau^+\nu, H^+ \rightarrow t\bar{b}$ for $M_{H^+} > M_t$
- $A \rightarrow Zh$ with $h \rightarrow b\bar{b}$
- $A \rightarrow \gamma\gamma$
- $H/A \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_2, \tilde{\chi}^0_i \tilde{\chi}^0_j, \tilde{\chi}^+_1 \tilde{\chi}^-_2$
- $H^\pm \rightarrow \tilde{\chi}^\pm_2 \tilde{\chi}^0_2$

A/H \rightarrow $\tau^+\tau^- \rightarrow$ jets + X (detailed efficiency)

Table Selection efficiency from full simulation and complete reconstruction for $gg \rightarrow b\bar{b}H$, $H \rightarrow \tau\tau$ with $m_A = 200$ and $500 \text{ GeV}/c^2$. Shown are the production rate with $\tan\beta = 30$, the efficiencies for preselection, Level-1 and Calo+Pxl Tau Trigger and off-line τ identification (E_T cuts, isolation, p_T cuts). Also shown are the efficiency and the numbers of events expected in 60 fb^{-1} for the full (trigger + off-line) one- and one- or three-prong selections. The last three rows show the total off-line efficiency with variable p_T cuts.

	$m_A = 200 \text{ GeV}/c^2$	$m_A = 500 \text{ GeV}/c^2$
$\sigma(A,H) \times \text{BR}(H \rightarrow \tau\tau) \times \text{BR}(\tau \rightarrow \text{hadrons})$	9.53 pb	0.188 pb
$E_T^{j1}, E_T^{j2} > 45 \text{ GeV}, \eta_{j1} , \eta_{j2} < 2.4$	30.9%	74.9%
Level-1 and HLT Calo+Pxl Tau Trigger	32%	36%
Off-line τ identification		
$E_T^{j1}, E_T^{j2} > 60 \text{ GeV}$	66.3%	91.4%
Isolation	60.6%	84.2%
$p_T^{\text{max}} > 40 \text{ GeV}/c$	21.0%	53.6%
isolation, $p_T^{\text{max}} > 40 \text{ GeV}/c$, one track in $\Delta r < 0.04$	8.3%	19.5%
isolation, $p_T^{\text{max}} > 40 \text{ GeV}/c$, one or three tracks in $\Delta r < 0.04$	11.4%	36.2%
Total efficiency (preselection, trigger, off-line τ identification)		
isolation, $p_T^{\text{max}} > 40 \text{ GeV}/c$, one track in $\Delta r < 0.04$	0.54%	4.8%
isolation, $p_T^{\text{max}} > 40 \text{ GeV}/c$, one or three tracks in $\Delta r < 0.04$	0.75%	8.9%
Events for 60 fb^{-1}		
isolation, $p_T^{\text{max}} > 40 \text{ GeV}/c$, one track in $\Delta r < 0.04$	3088	541
isolation, $p_T^{\text{max}} > 40 \text{ GeV}/c$, one or three tracks in $\Delta r < 0.04$	4273	1006
Off-line τ identification with variable p_T cut		
$p_T^{\text{max}} > 40 \text{ GeV}/c$ and $p_T^{\text{max}}/E_T^{\text{jet}} > 0.4$	20.0%	33.9%
isol., $p_T^{\text{max}} > 40 \text{ GeV}/c$, $p_T^{\text{max}}/E_T^{\text{jet}} > 0.4$, one track in $\Delta r < 0.04$	8.1%	13.1%
isol., $p_T^{\text{max}} > 40 \text{ GeV}/c$, $p_T^{\text{max}}/E_T^{\text{jet}} > 0.4$, one or three tracks in $\Delta r < 0.04$	10.8%	23.8%

$H \rightarrow \tau\tau \rightarrow \text{leptons}$

Signal: $gg \rightarrow H$ or $gg \rightarrow b\bar{b}H$, $H \rightarrow \tau\tau$, $\tau \rightarrow \text{leptons}$

$\sigma \cdot \text{Br}$ is $\sim 100 - 900 \text{ fb}$

at high $\tan\beta$ $b\bar{b}H$ strongly dominant.

Background: leptonic final states of
 Z/γ^* , $t\bar{t}$, $b\bar{b}$, WW , WZ

require isolated leptons, $p_t > 20 \text{ GeV}$

(isolated=no tracks with $p_t > 2 \text{ GeV}$ in $\Delta R = 0.3$)

eliminates $b\bar{b}$ background

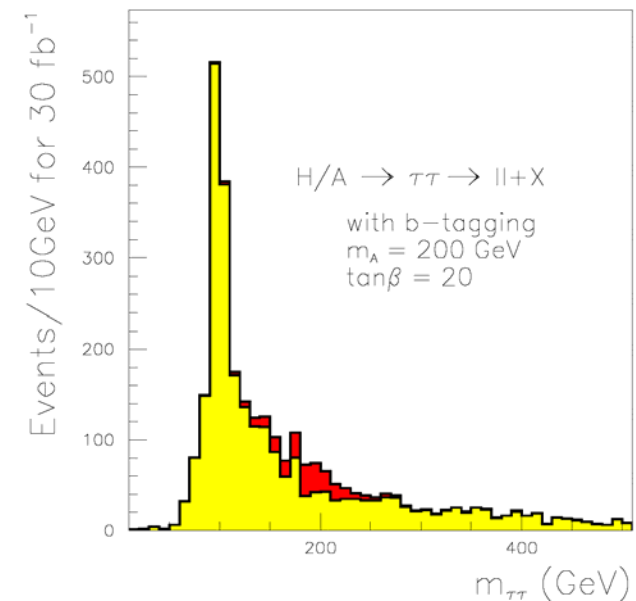
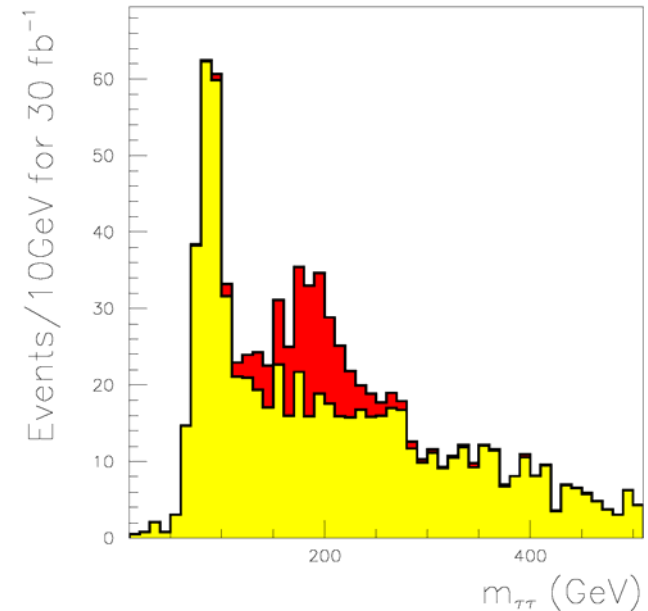
$c\tau$ of $\tau \sim 90 \mu\text{m}$. Use impact parameter of leptons to identify τ

reduces Z/γ^* , $t\bar{t}$ backgrounds

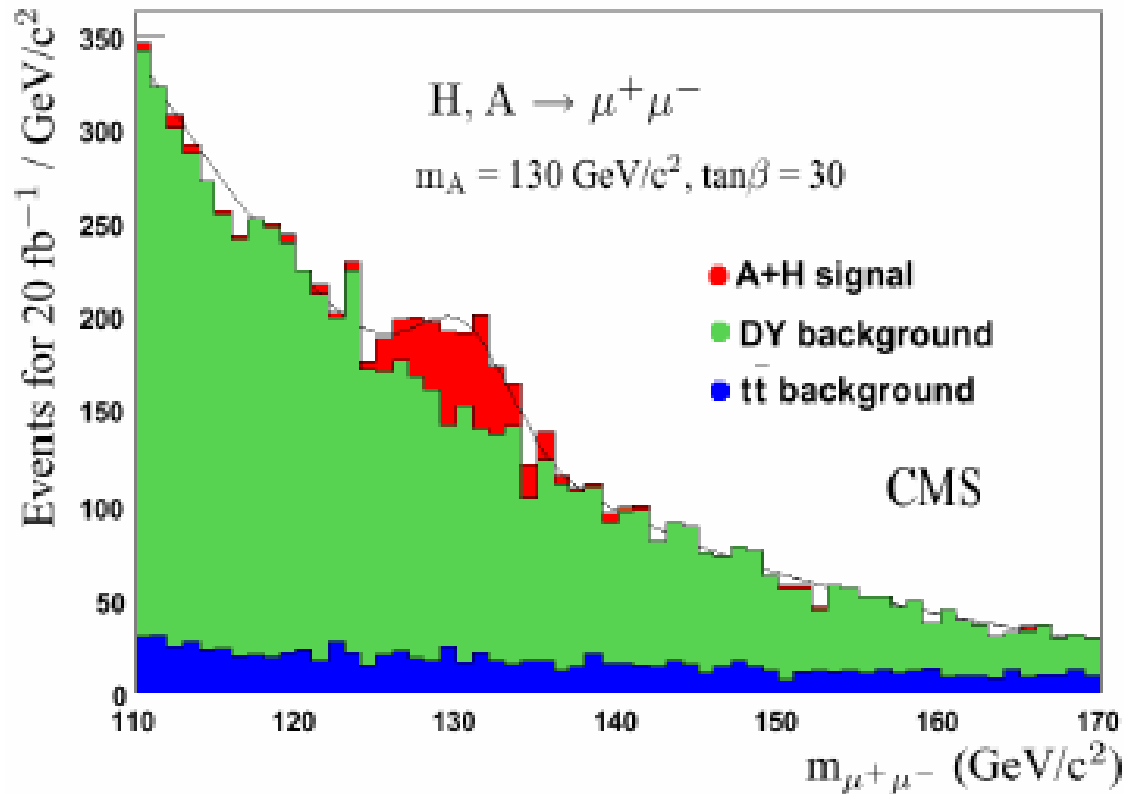
require 1 jet with $p_t > 20 \text{ GeV}$ and b-tag

\rightarrow kills Drell Yan

This channel should be useful even if sparticles are light



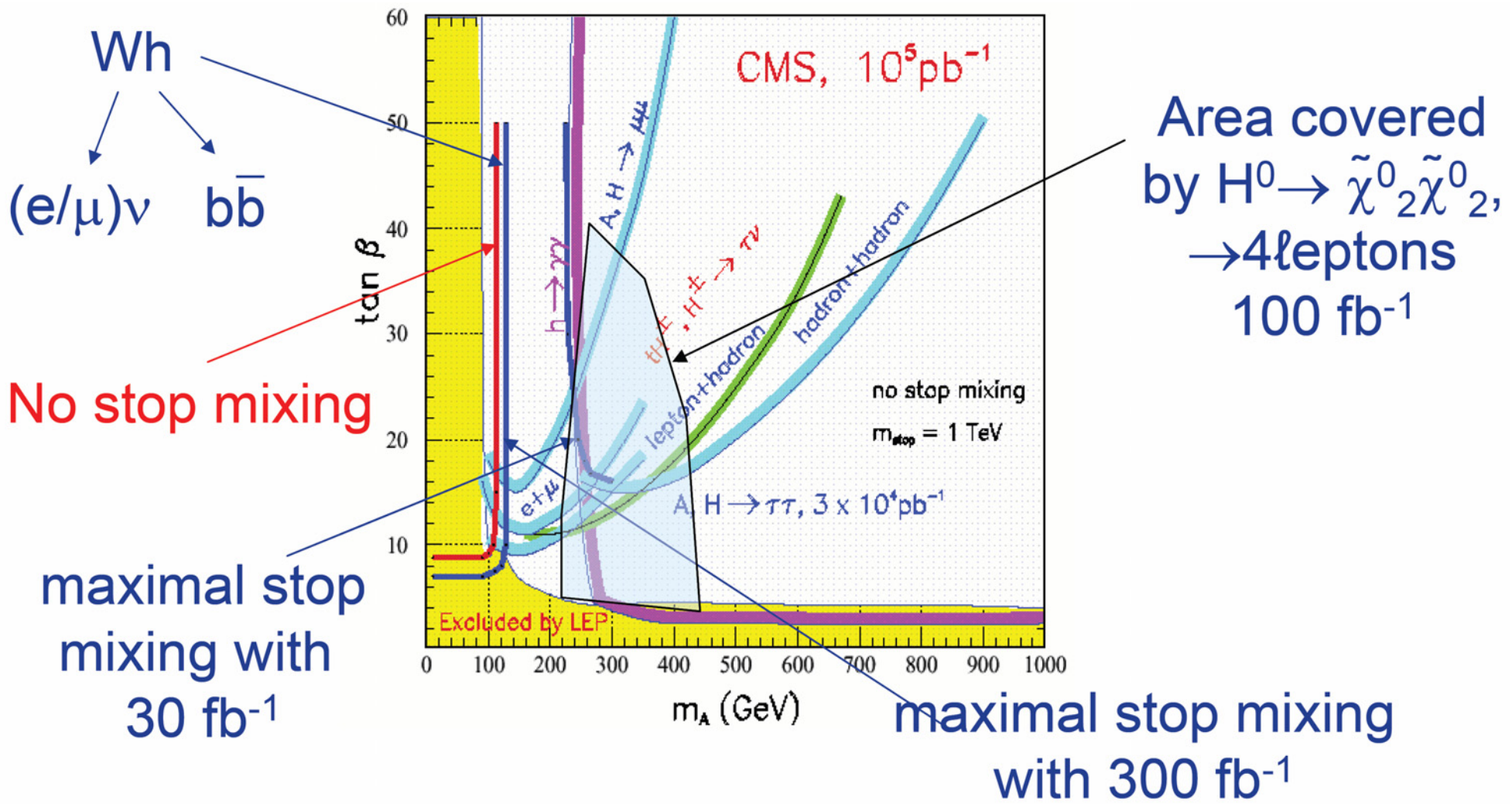
$H/A \rightarrow \mu^+\mu^-$



- $pp \rightarrow b\bar{b}H/A + X$
with $H/A \rightarrow \mu^+\mu^-$
 - 2 soft ($E_T < 50 \text{ GeV}$) b jets
 - Use b-tag against Z/γ^* background
 - Use central jet veto against $t\bar{t}$

Mass resolution 1%, $|m_H - m_A| \sim 2 \text{ GeV} \rightarrow H/A$ peaks superimposed (mass difference can be upto $\sim 5.5 \text{ GeV}$)

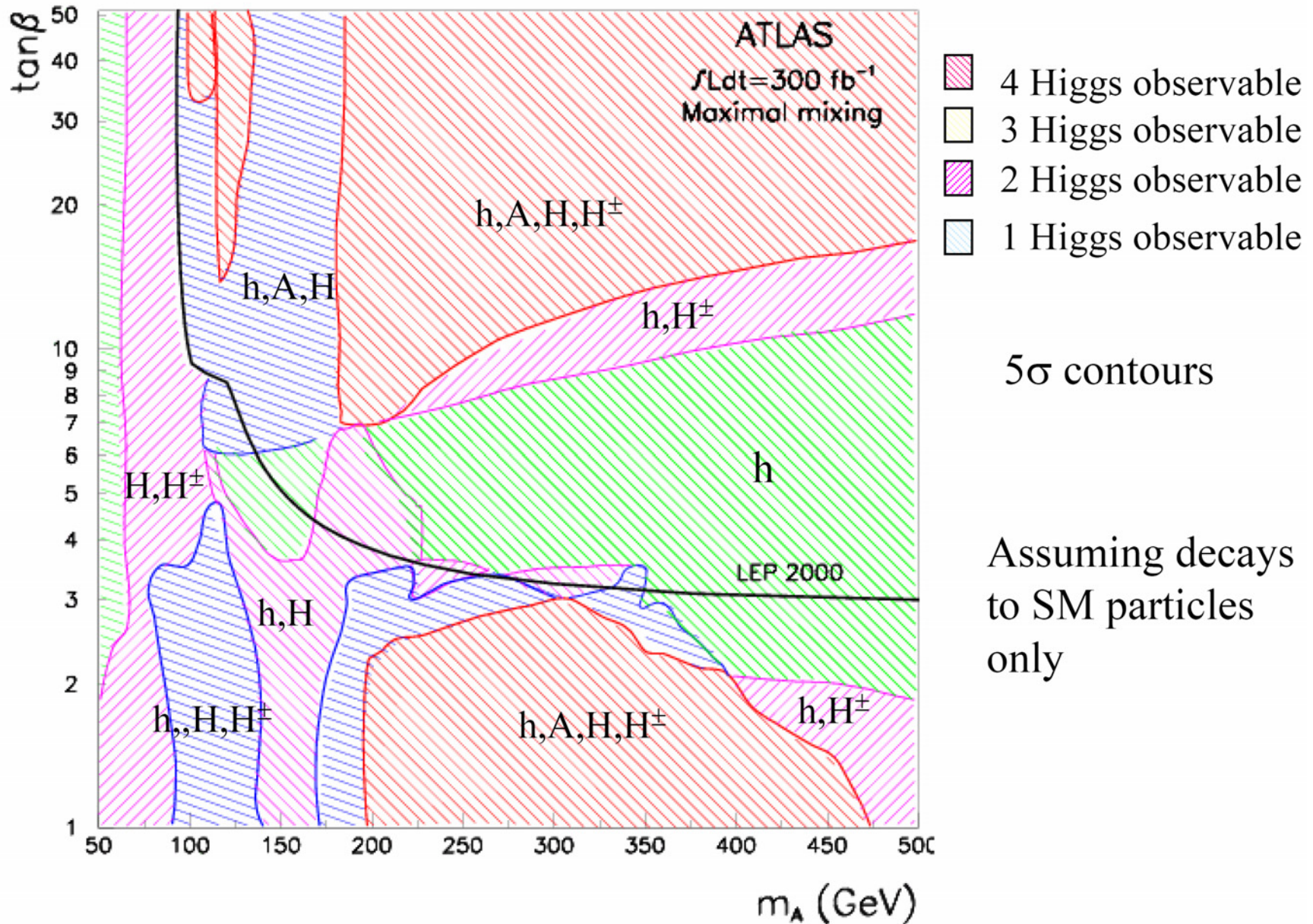
MSSM Discovery reach



Ref: Paris Spiccas, Physics at LHC, Vienna, 2004

MSSM discovery reach (ii)

MSSM Higgs bosons



CMS Trigger Rates

Trigger	HLT Threshold (GeV)	HLT Rate (Hz)	CPU time per Lvl-1 event (ms)	Lvl-1 Rate (Hz)
1e, 2e	29, 17	33, 1	160	4.3
1 γ , 2 γ	80, (40,25)	4, 5		
1 μ , 2 μ	19, 7	25, 4	710	3.6
1 τ , 2 τ	86, 59	3, 1	130	3.0
jet \times E _T ^{miss}	180 \times 123	5	50	3.4
1, 3, 4 jets	657, 247, 113	9		
e \times jet	19 \times 45	2	165	0.8
Inclusive b jets	237	5	300	0.5

CMS total level1 rate is 16 kHz at startup
Total High Level Trigger (HLT) is 100 Hz.