

SM/MSSM Higgs production at LHC



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Workshop on Diffraction at the LHC - Cracow 19/10 2007

Collaboration of S.Heinemeyer, V.Khoze, M.Ryskin, J.Stirling, M.T. and G.Weiglein

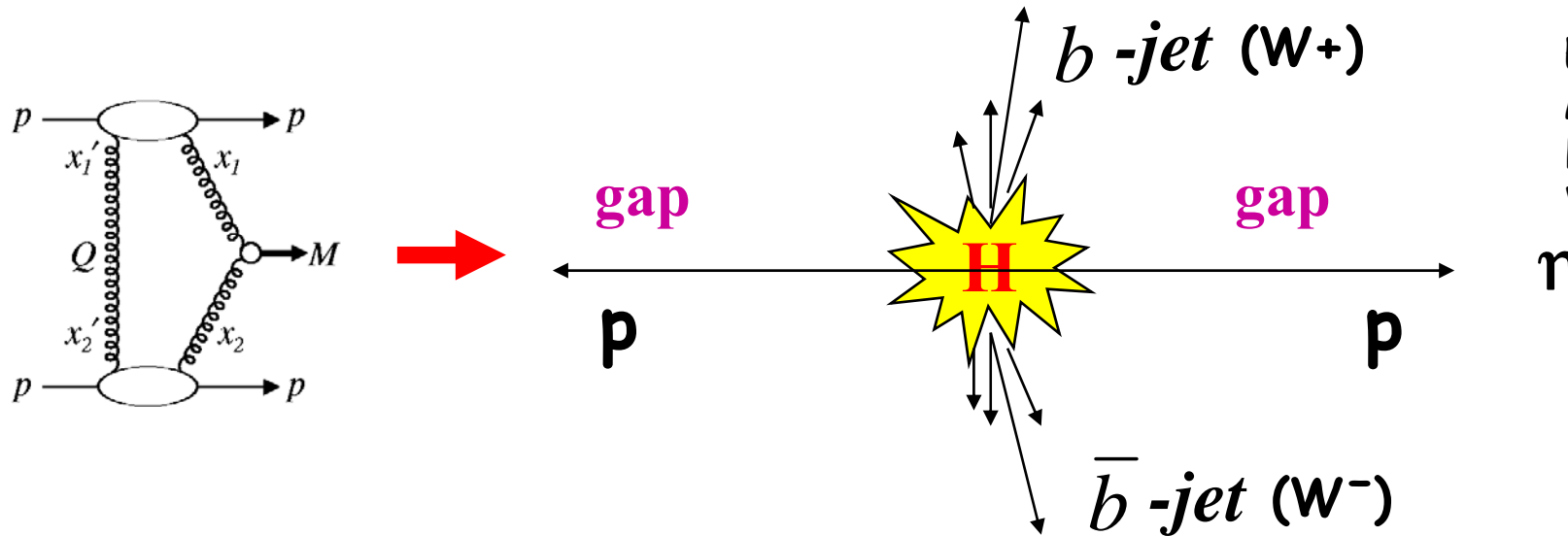
MSSM scan for CEP $H \rightarrow bb/WW/\tau\tau$ (arXiv:0708.3052 [hep-ph])

And also $h \rightarrow bb$ in M_{hmax} using FP420 (arXiv:0709.3035 [hep-ph]):

B. Cox, F. Loebinger, A. Pilkington

Central Exclusive Diffraction: Higgs Production

Exclusive DPE Higgs production $pp \rightarrow p H p$: 2-10 fb
 Inclusive DPE Higgs production $pp \rightarrow p+X+H+Y+p$: 50-200 fb



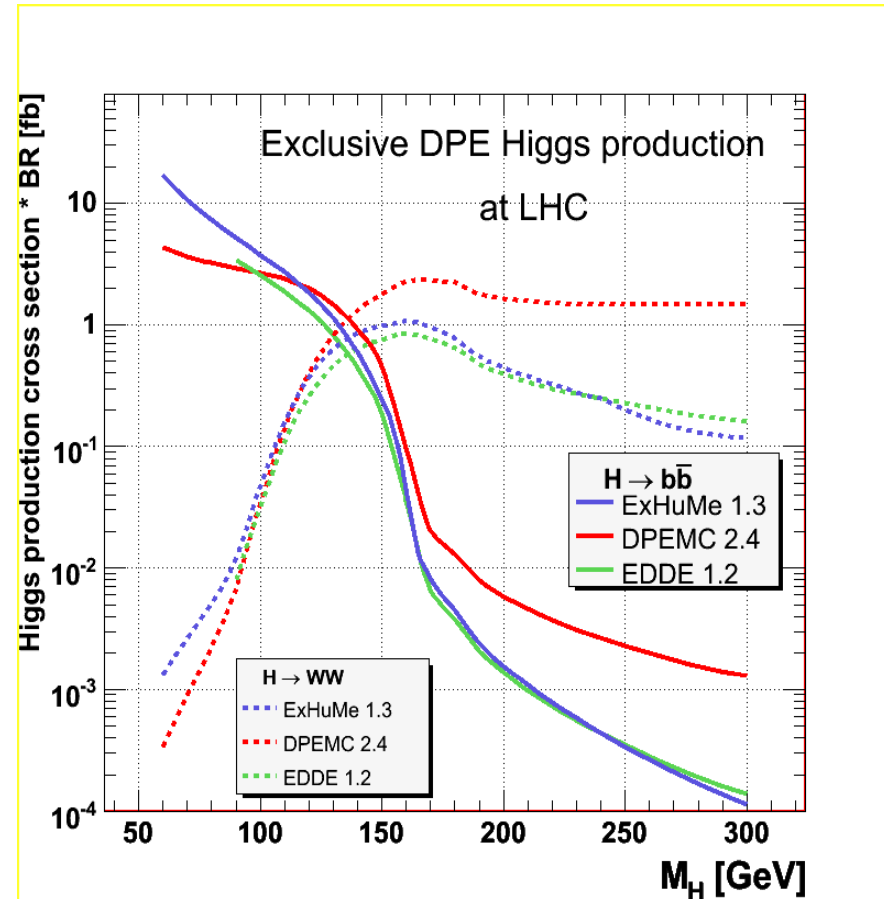
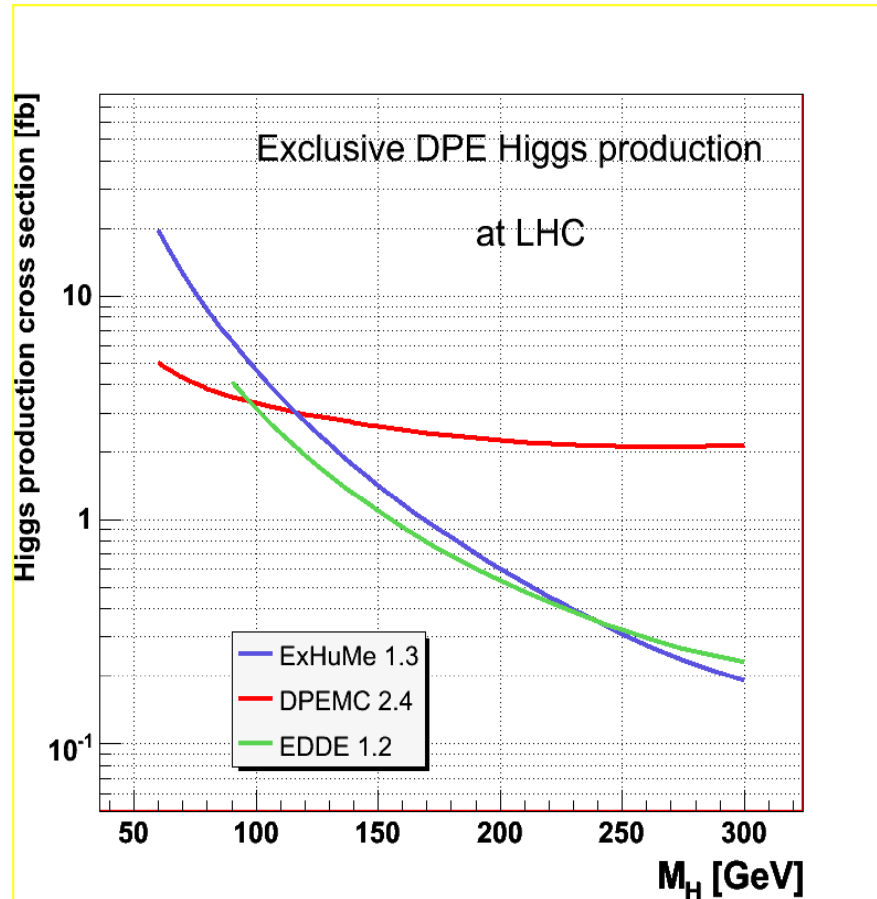
E.g. V. Khoze et al
 M. Boonekamp et al.
 B. Cox et al. ...
 V. Petrov et al.

Advantages of Exclusive:

M_h^2 measured in RP via missing mass as $\xi_1 \cdot \xi_2 \cdot s$
 bb: $J_z=0$ suppression of $gg \rightarrow bb$ bg | WW: bg almost negligible

bb: We need a L1-trigger of "central det.+220 RP" type, e.g.
 $2 \times E_{Tjet} > 40 \text{ GeV}$ + single-side RP220.

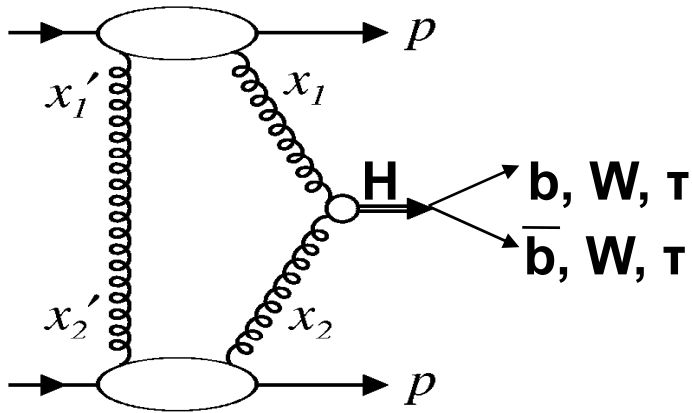
WW: Extremely promising for $M_h > 130 \text{ GeV}$: no trigger problems and a better M_h resolution for higher M_h .



Difference between DPEMC and (EDDE/ExHuMe) is an effect of Sudakov suppression factor growing as the available phase space for gluon emission increases with increasing mass of the central system

Models predict different physics potentials !

Central Exclusive Diffraction: Higgs production



- Khoze, Martin, Ryskin hep-ph/0111078
- Central system is 0^{++}
- If you see a new particle produced exclusively and with proton tags you know its quantum numbers
- Roman Pots give much better mass resolution than central detector

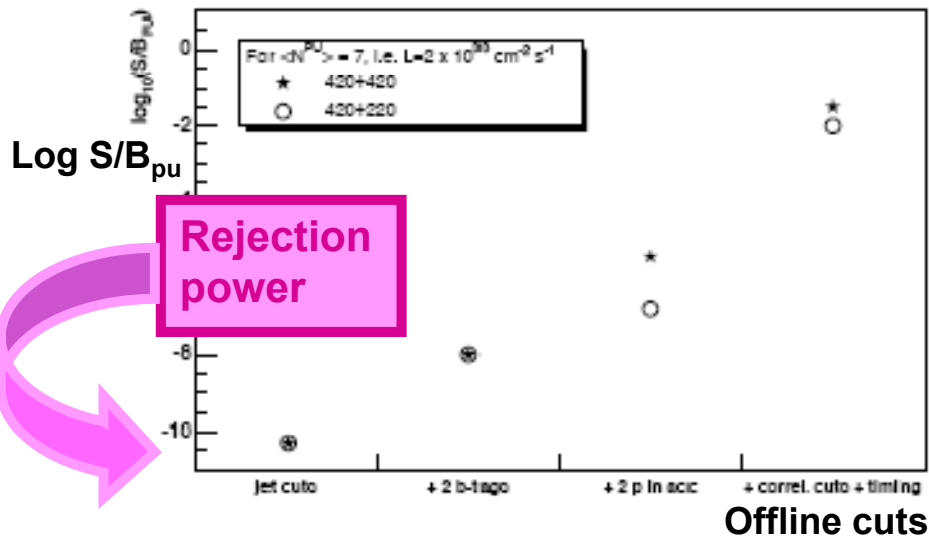
Discovery difficult in SM but well possible in MSSM

Pile-up is issue for Diffraction at LHC!

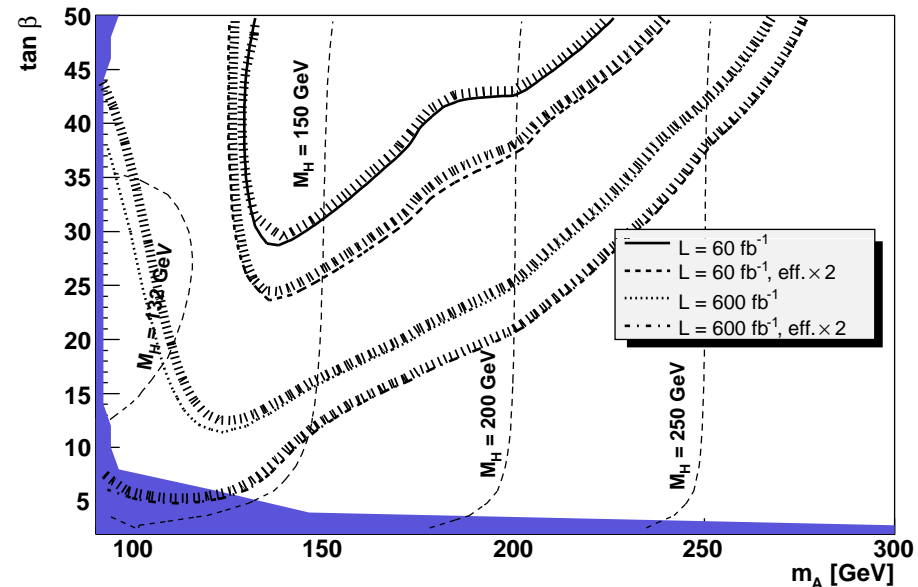
5sigma contours: $H \rightarrow b\bar{b}$, $\mu = -500 \text{ GeV}$

[Heinemayer, Khoze, Ryskin, Stirling, M.T., Weiglein arXiv: 0708.3052 [hep-ph]]

[CMS-Totem : Prospects for Diffractive and Fwd physics at LHC]



But can be kept under control !



MSSM and CED go quite well together

The *intense coupling regime* is where the masses of the 3 neutral Higgs bosons are close to each other and $\tan\beta$ is large

Extended Higgs sectors: “typical” features

Search for heavy MSSM Higgs bosons ($M_A, M_H \gg M_Z$):

Decouple from gauge bosons

⇒ no HVV coupling

⇒ no Higgs production in weak boson fusion

⇒ no decay $H \rightarrow ZZ \rightarrow 4\mu$

Large enhancement of coupling to $b\bar{b}$, $\tau^+\tau^-$ for high $\tan\beta$

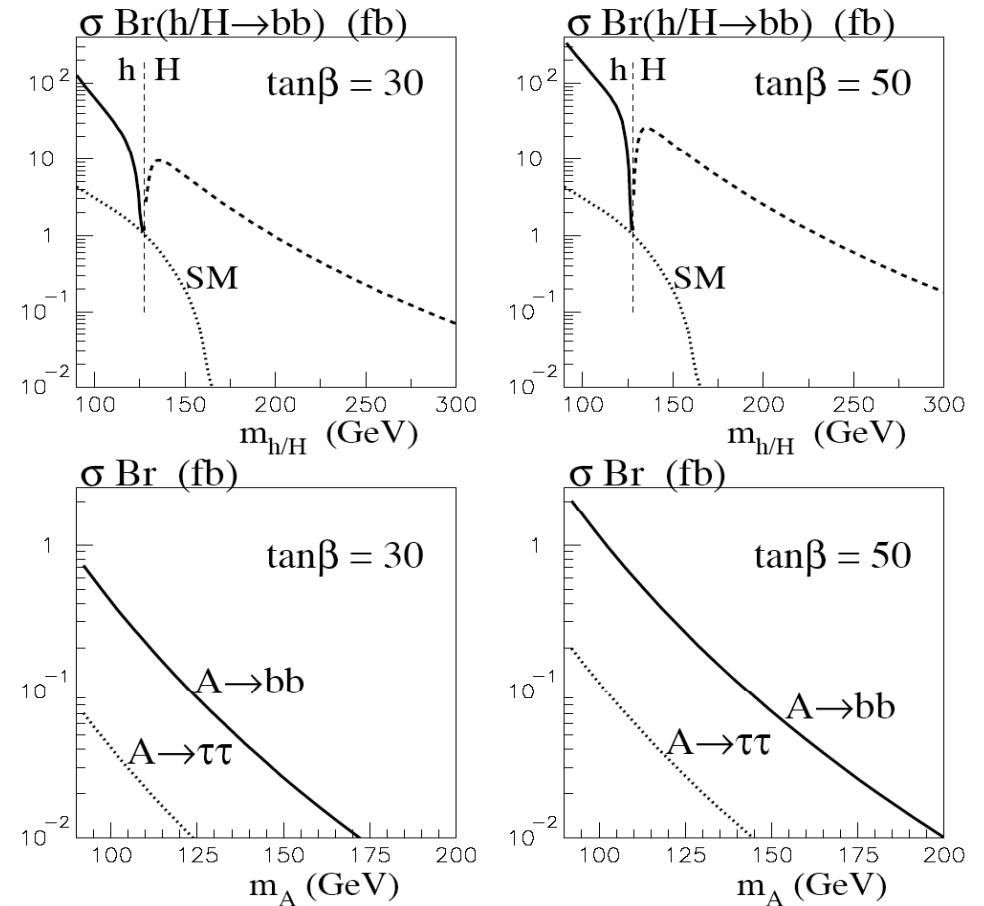
⇒ Decays into $b\bar{b}$ and $\tau^+\tau^-$ play a crucial role

“Typical” features of models with an extended Higgs sector:

- A light Higgs with SM-like properties, couples with about SM-strength to gauge bosons
- Heavy Higgs states that decouple from the gauge bosons

Studying the MSSM Higgs Sector by Forward Proton Tagging at the LHC, Georg Weiglein, EPS07, Manchester, 07/2007 – p.3

Central exclusive diffractive production



Well known difficult region for conventional channels, tagged proton channel may well be the *discovery channel* and is certainly a powerful *spin/parity filter*

Enhancement in MSSM for CED

The enhancement is evaluated using

$$\text{Ratio} = [\Gamma(H \rightarrow gg)[M, \tan\beta] * \text{BR}(H \rightarrow pp)[M, \tan\beta]]^{\text{MSSM}} / \Gamma(H \rightarrow gg)[M] * \text{BR}(H \rightarrow pp)[M]^{\text{SM}}$$

$$H = h, H, A; \quad p = W, b, \text{tau}; \quad M = M_A, M_H, M_h$$

The cross section is calculated as $\sigma^{\text{MSSM}} = \sigma^{\text{SM}} * \text{Ratio}$

$\sigma^{\text{SM}} = \text{KMR formula for CED production of Higgs}$

[Khoze, Martin, Ryskin '00, '01, '02], [Bialas, Landshoff '90], [Forshaw '05]

All MSSM quantities obtained using FeynHiggs code (www.feynhiggs.de)

[Heinemeyer, Hollik, Weiglein '99, '00], [Degrassi, Heinemeyer, Hollik, Slavich, Weiglein '03],

[Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein '07]

Benchmark scenarios

MSSM has very large number of parameters => introduce benchmarks in which all SUSY parameters are fixed and only M_A and $\tan\beta$ are varied.

(Higgs sector of MSSM at tree level governed by M_A and $\tan\beta$ [sauf M_Z and SM gauge couplings])

M_h^{\max} scenario:

- Parameters chosen such that max.possible M_h as a function of $\tan\beta$ is obtained (for fixed $M_{\text{SUSY}} = M_A = 1\text{TeV}$)

No-mixing scenario:

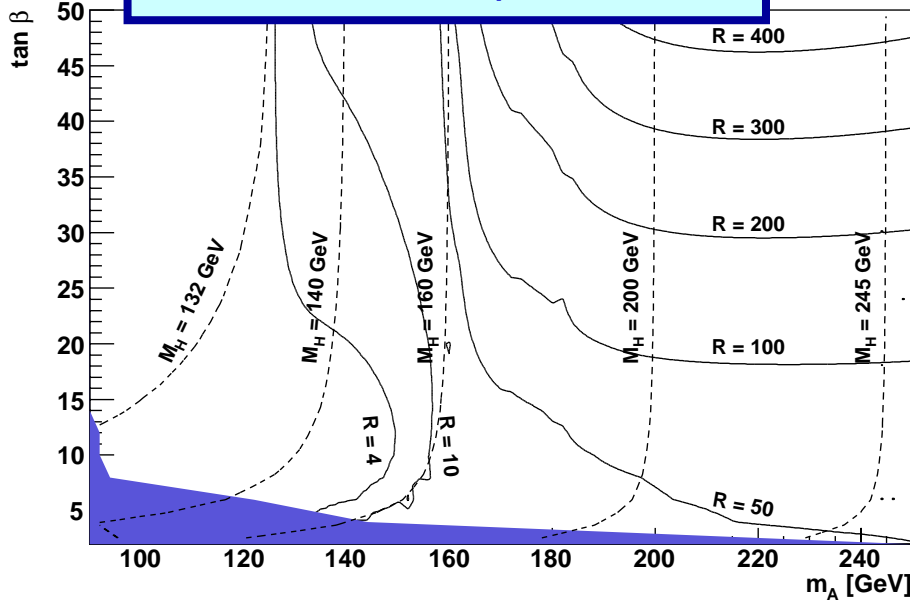
- The same as M_h^{\max} but with vanishing mixing in $t\tilde{}$ sector and with higher M_{SUSY} to avoid LEP Higgs bounds

Small α_{eff} scenario:

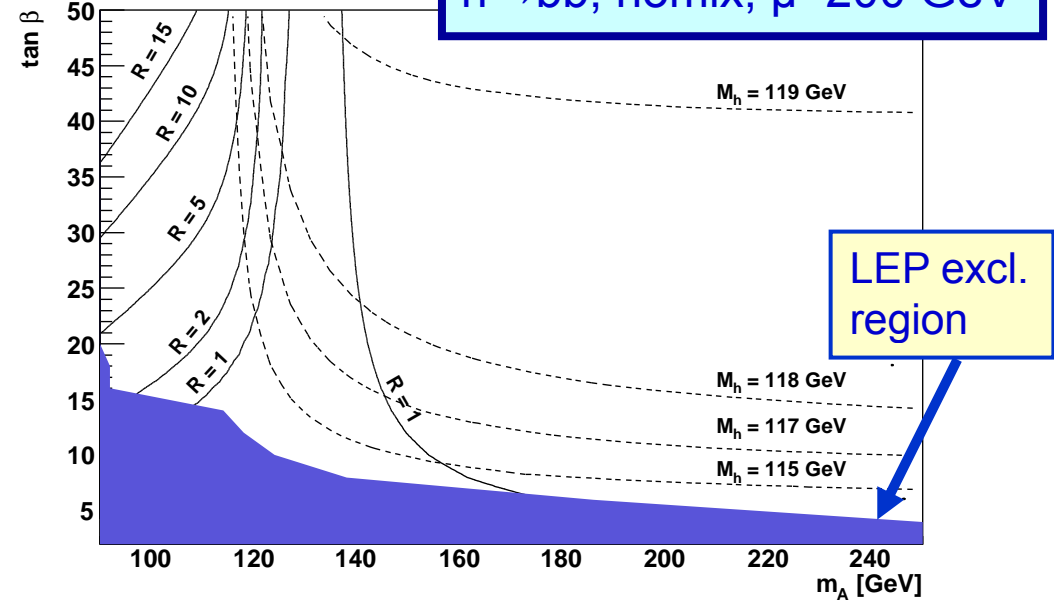
- For small α_{eff} , $h \rightarrow b\bar{b}$ and $h \rightarrow \tau\tau$ strongly suppressed (at large $\tan\beta$ and not too large M_A)
- Suitable for $h \rightarrow WW$

$R = \text{MSSM}[M, \tan\beta] / \text{SM}[M]$

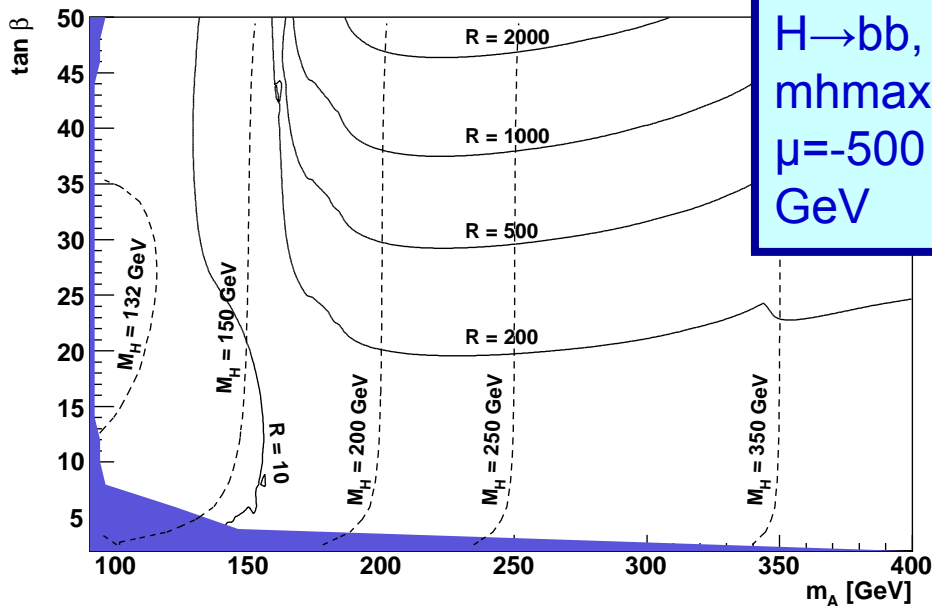
$H \rightarrow bb, m_{H\max}, \mu = 200 \text{ GeV}$



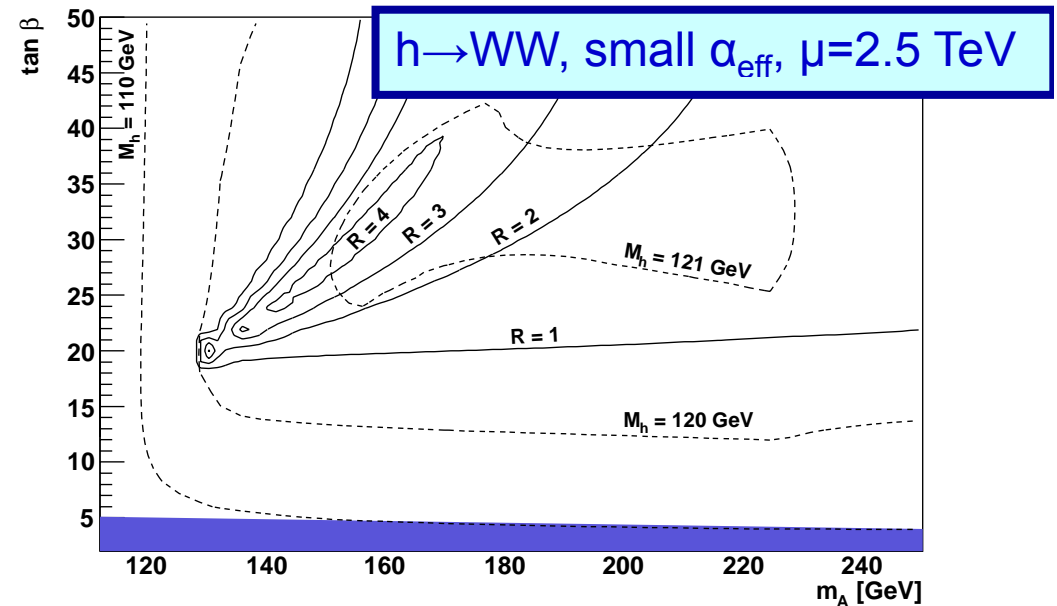
$h \rightarrow bb, \text{nomix}, \mu = 200 \text{ GeV}$



$H \rightarrow bb, m_{H\max}, \mu = -500 \text{ GeV}$



$h \rightarrow WW, \text{small } \alpha_{\text{eff}}, \mu = 2.5 \text{ TeV}$



Summary on MSSM enhancement

X-sections for bb and $\tau\tau$ enhanced most in nomix scenario.

X-sections for WW enhanced most in small α_{eff} scenario.

Enhancement increasing with $\tan\beta$.

$H \rightarrow bb$: up to 500 for $M_H \sim 180\text{--}300$ GeV and $\tan\beta \sim 50$ (2000 for $\mu = -500$ GeV)

$h \rightarrow bb$ ($\tau\tau$): up to 15 for $M_h \sim 115$ GeV and $\tan\beta \approx 50$

$h \rightarrow WW$: max. 4 for $M_h \sim 120\text{--}123$ GeV and $\tan\beta \sim 30$

Signal (statistical) significance

Signal significance S_{cp} found by solving equations (using program scpf by S.Bitukov)

$$\beta = 1/\sqrt{2\pi} \int_{S_{cp}}^{\infty} e^{-x^2/2} dx, \quad \beta = \sum_{s+B}^{\infty} \text{Pois}(i|B) \text{ (Type II error)}$$

CED Signal and CED Bg calculated using KMR formulas and FeynHiggs code:

$$S = \text{Lumi} * \sigma^{\text{MSSM}} * [\epsilon_{420} * I(\Delta M_{420}) + \epsilon_{\text{comb}} * I(\Delta M_{\text{comb}})], \quad I = \text{reduction due to mass window}$$

$$B = \text{Lumi} * [\epsilon_{420} * \int \sigma^{\text{BG}} \Delta M_{420} + \epsilon_{\text{comb}} * \int \sigma^{\text{BG}} \Delta M_{\text{comb}}]$$

S and B taken without syst.errors

σ^{BG} : Only exclusive processes considered because:

- 1) Contribution of inclusive processes considered to be negligible after including new HERA Pomeron pdfs - see Valery's talk at HERA-LHC 2007
- 2) Contribution of PU bg assumed to be negligible anticipating a big progress in developing cuts suppressing PU bg, such as track mult. and vtx rejection. **Note also that if SM Higgs exists, it will be first measured by standard techniques and the knowledge of its mass will be greatly exploited in diffractive searches.**

ϵ_{420} , ϵ_{comb} : selection efficiencies of 420+420 and 420+220 RP config. taken from CMS/Totem Note CERN-LHC 2006-039/G-124 [*Prospects for diffractive and forward physics at the LHC*]

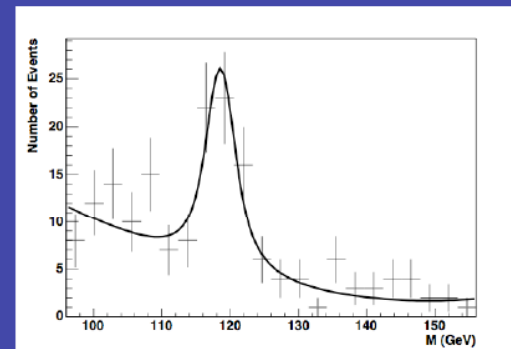
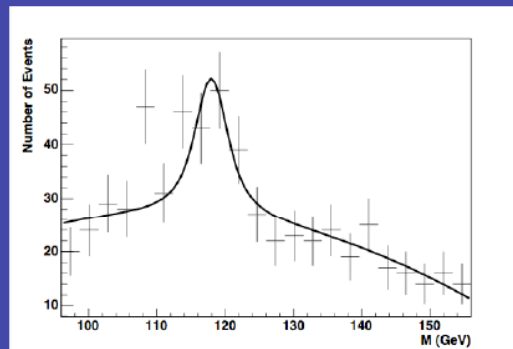
Selection efficiencies for $H \rightarrow bb$ (tautau)

- 1) RP acceptances:** (420.and.420).or.(420.and.220).or.(220.and.420).or.(220.and.220)
 $Acc(\xi, t, \varphi): 0.002 < \xi < 0.2, 0.001 < t < 10 \text{ GeV}^2, 0 < \varphi < 2\pi$
- 2) jets:** either two b-tagged jets or two jets with at least one b-hadron decaying into μ
 $E_{T1} > 45 \text{ GeV}, E_{T2} > 30 \text{ GeV}, |\eta_{1,2}| < 2.5, |\eta_1 - \eta_2| < 1.1, 2.85 < |\varphi_1 - \varphi_2| < 3.43$
- 3) Kinematics constraints - matching criteria:** $0.8 < M_{2j}/M_{RP} < 1.2, |\xi_{2j} - \xi_{RP}| < 0.3$
- 4) L1 triggers:** OR between: a) 220-single side .and. 2jets ($E_T > 40 \text{ GeV}$)
b) 1 jet ($E_T > 40 \text{ GeV}$) + muon, c) 2jet $E_T > 90 \text{ GeV}$, d) leptonic triggers
- 5) Additional PU bg suppressors:** fast timing detector, track multiplicity

Conservatively assuming the same selection efficiencies for $H \rightarrow \text{tautau}$

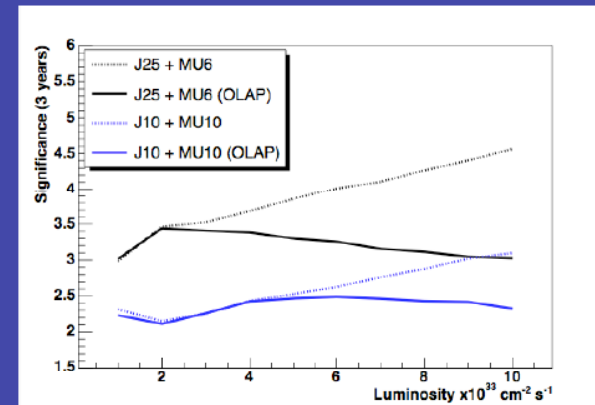
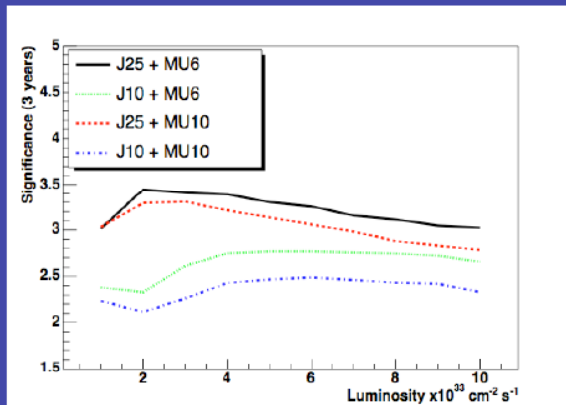
Example data sets

- Idea: Select at random the predicted number of events (after selection cuts) for each process for three years of data acquisition at each luminosity.
 - 30 fb⁻¹ at L=10³³ cm⁻² s⁻¹ and 300 fb⁻¹ at L=10³⁴ cm⁻² s⁻¹
- Fit the distributions with a null (background only) hypothesis and a signal + background hypothesis.
- The significance is then given by $(\Delta\chi^2)^{1/2}$.
- Example plots below for J25 + MU6 trigger at L=10³⁴ cm⁻² s⁻¹.
 - Same data set with (left) and without (right) overlap events.



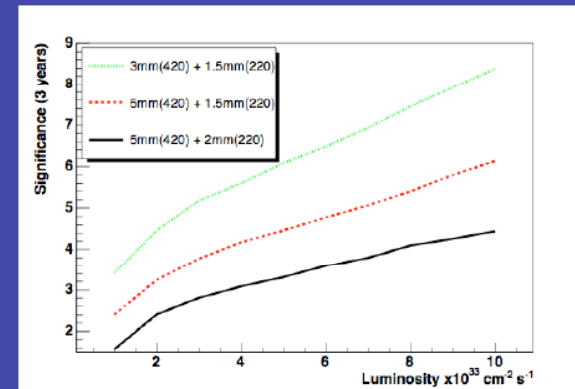
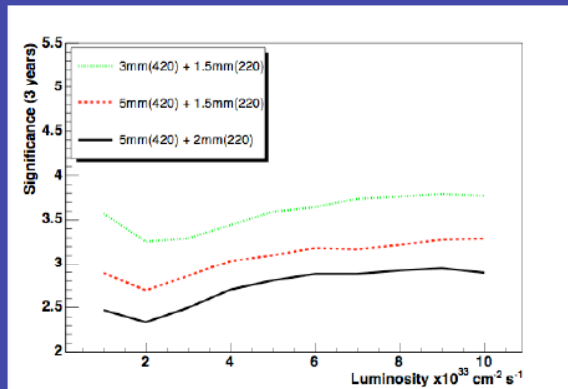
Significance (420 only)

- Repeat analysis 500 times at each luminosity for each trigger, to estimate the expected averaged significance.
- Results below for analysis with protons tagged only at 420m.



Significance (420 + 220)

- Not yet included the asymmetric analysis for one proton tagged at 220m and one at 420m. Use previous 'worse trigger' of J10 + MU10 (left). Significance can be much larger if detectors can get very close to the beam.
- Possibility for using 220m detectors in L1 trigger. Evaluate the potential for a 100% effective trigger (right). Significance or 220m-420m analysis only.



Optimum mass windows

To get high stat. significance but also reasonable signal statistics, we need to choose an optimum mass window.

$S \sim \Gamma(H \rightarrow gg)$ - increases with increasing $\tan\beta$:

Mass spectrum at large $\tan\beta$ is then a convolution of Breit-Wigner function with Gaussian function given by RP resolution \Rightarrow optimum mass window thus depends on $\Gamma(H \rightarrow gg)$ and mass (or $\tan\beta$ and mass).

B: depends linearly on the mass window

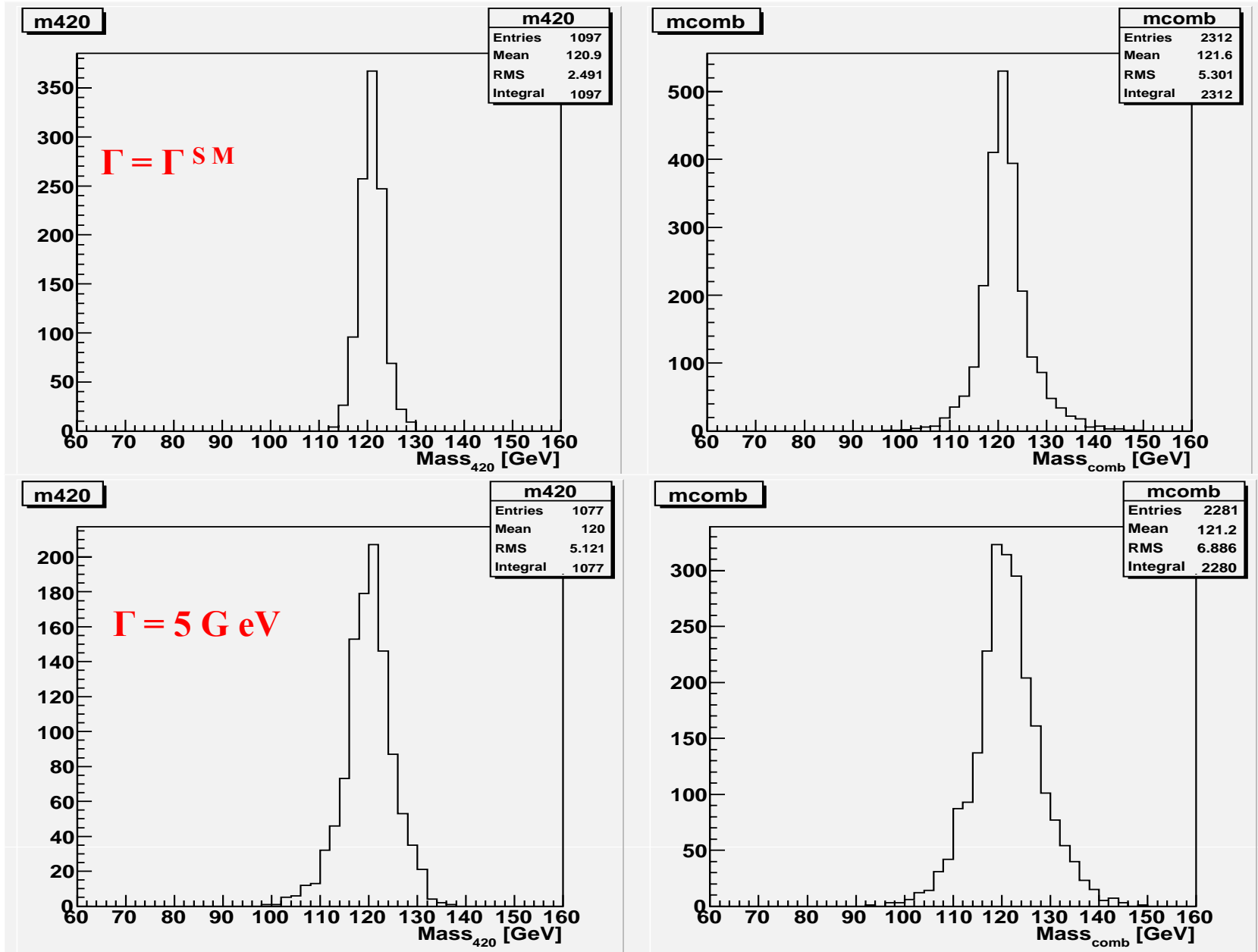
A natural choice: $\Delta M_{420} = 2 \cdot \sqrt{(\sigma_{420}^M)^2 + \Gamma^2}$, $\Delta M_{\text{comb}} = 2 \cdot \sqrt{(\sigma_{\text{comb}}^M)^2 + \Gamma^2}$,

Syst. cross-check:

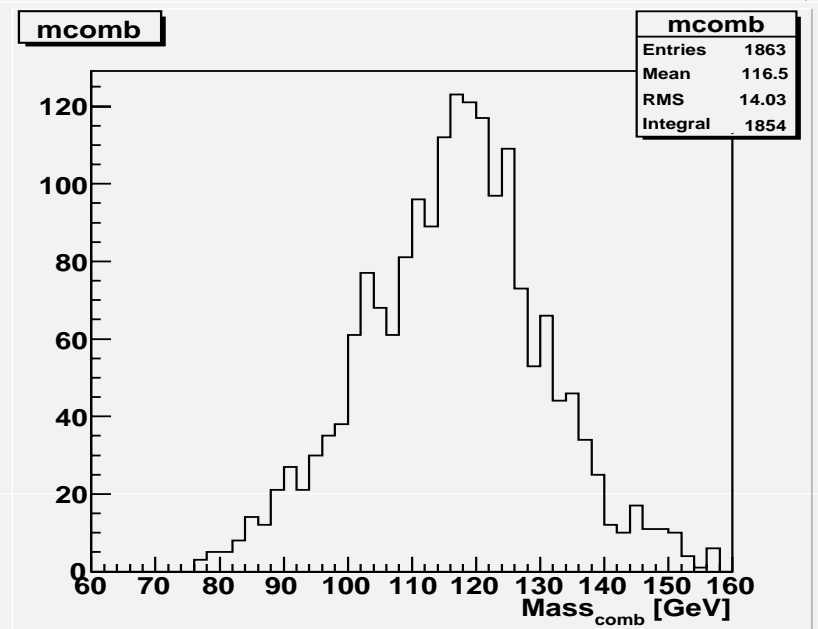
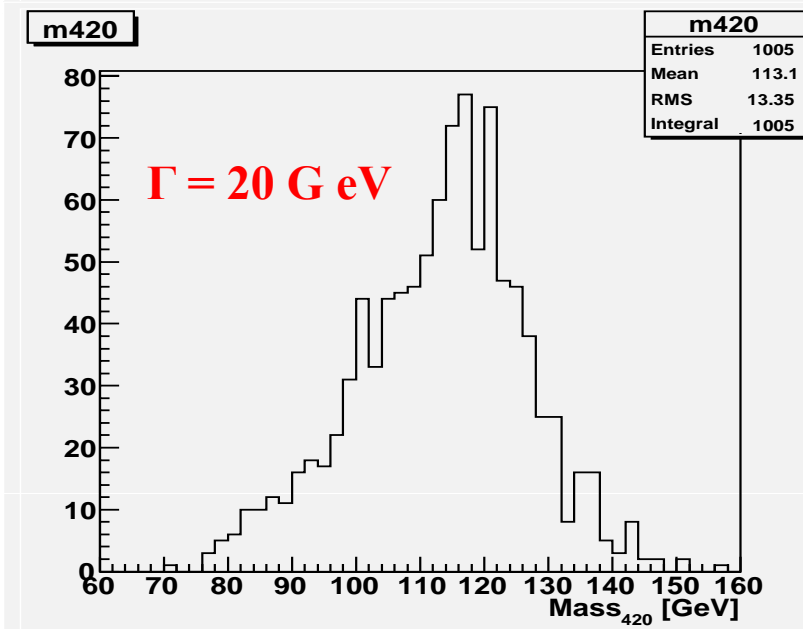
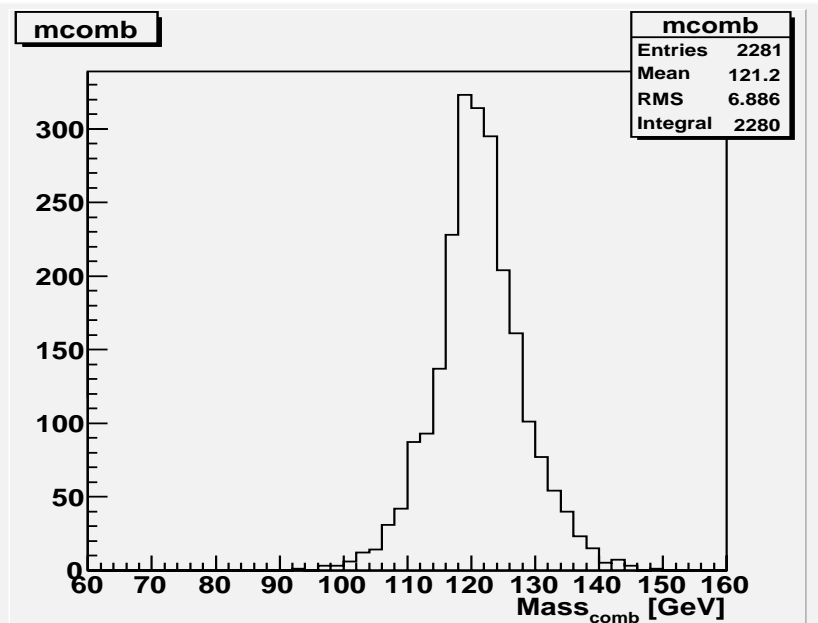
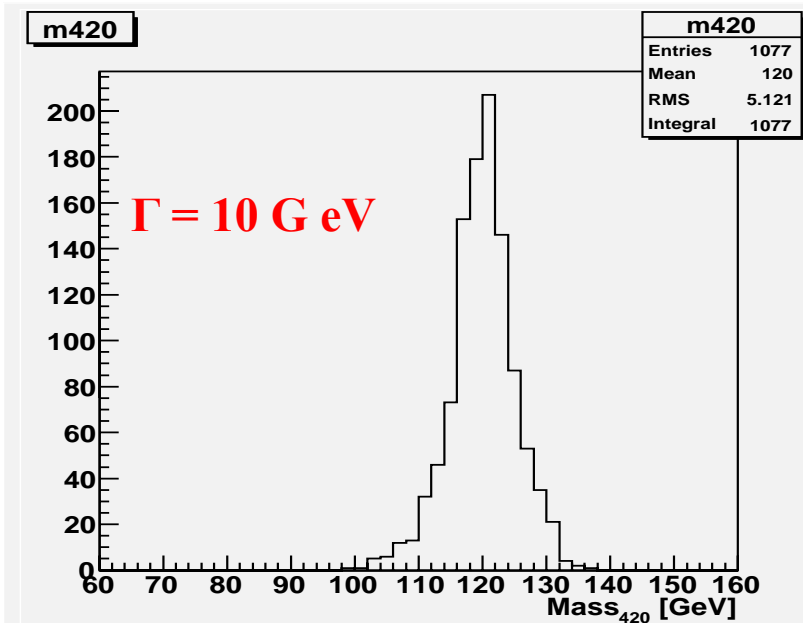
$\Delta M_{420} = \sqrt{(2.7\sigma_{420}^M)^2 + (1.5\Gamma)^2}$, $\Delta M_{\text{comb}} = \sqrt{(2.7\sigma_{\text{comb}}^M)^2 + (1.5\Gamma)^2}$,

Both options give very similar results, the former gives reduction $I_{420} = I_{\text{comb}} \sim 0.67$.

Mass spectra for different $\Gamma(H \rightarrow gg)$: ExHuMe



Mass spectra for different $\Gamma(H \rightarrow gg)$: ExHuMe

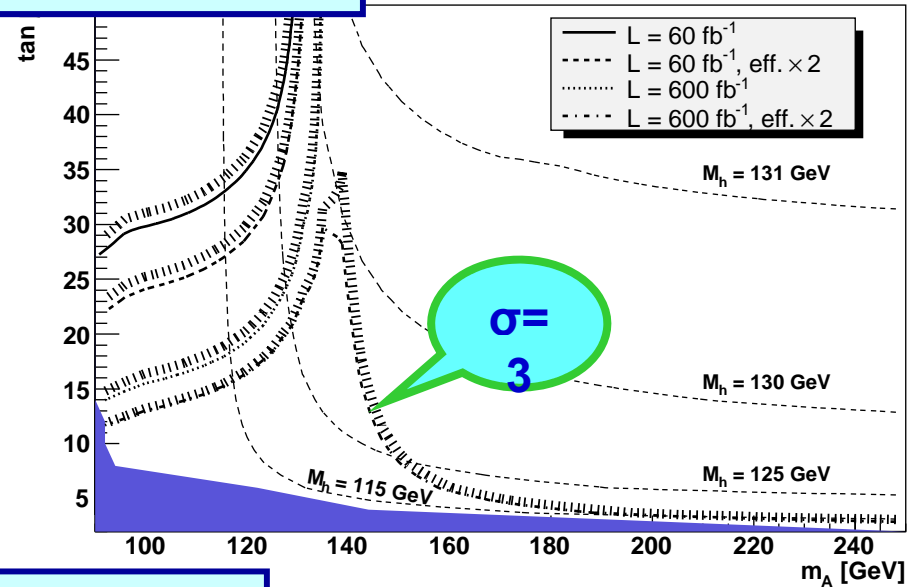
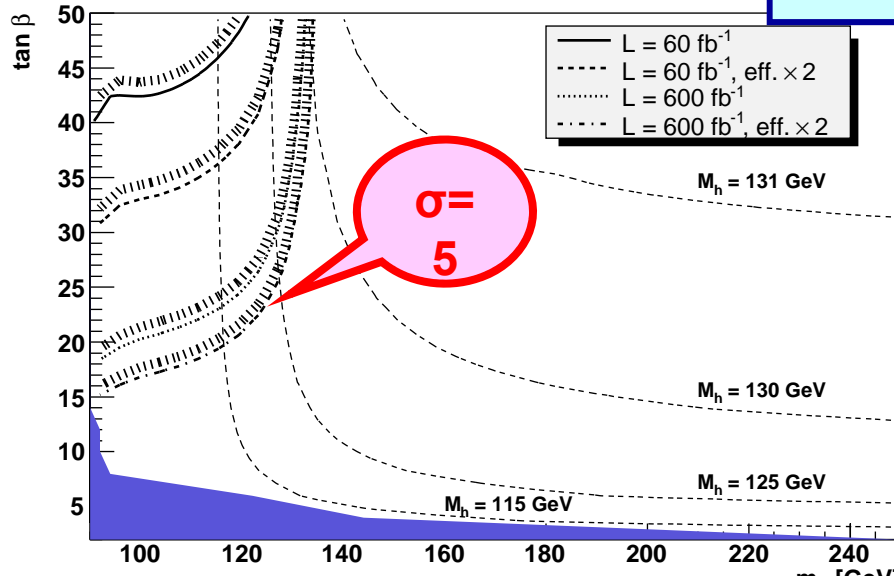


Four integrated luminosity scenarios

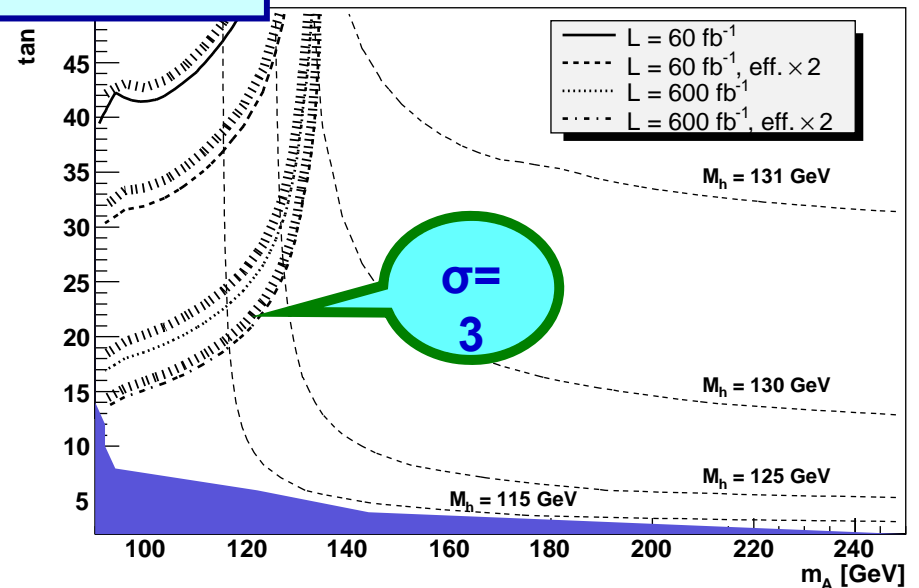
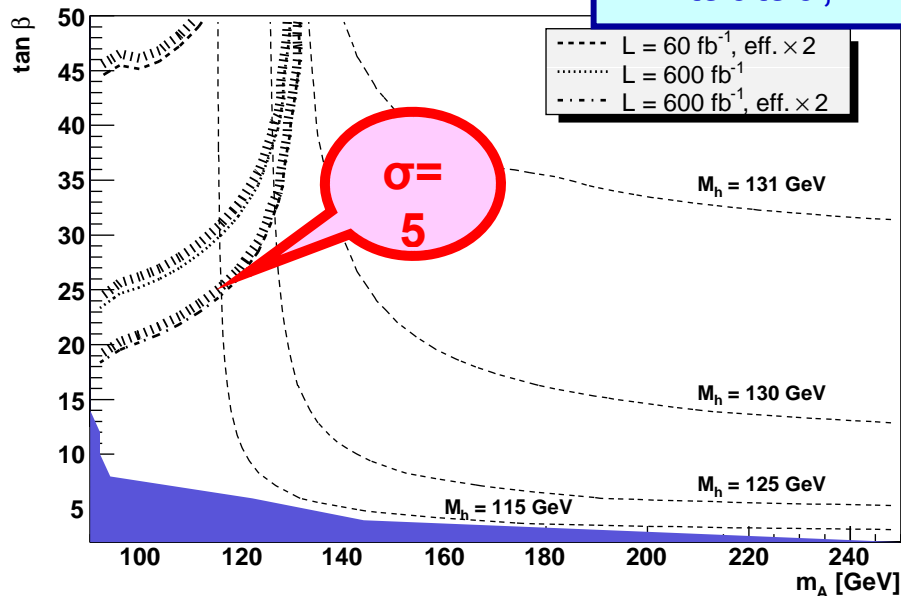
1. $L = 60\text{fb}^{-1}$: 30 (ATLAS) + 30 (CMS): 3 yrs with $L=10^{33}\text{cm}^{-2}\text{s}^{-1}$
2. $L = 60\text{fb}^{-1}$, $\text{eff}\times 2$: like 1. but assuming doubled exper. eff.
3. $L = 600\text{fb}^{-1}$: 300 (ATLAS) + 300 (CMS) : 3 yrs with $L=10^{34}\text{cm}^{-2}\text{s}^{-1}$
4. $L = 600\text{fb}^{-1}$, $\text{eff}\times 2$: like 3. but assuming doubled exper. eff.

Stat. significance for $h \rightarrow bb$ (tautau): from 5 to 3

$h \rightarrow bb$, m_{hmax} , $\mu = 200$ GeV

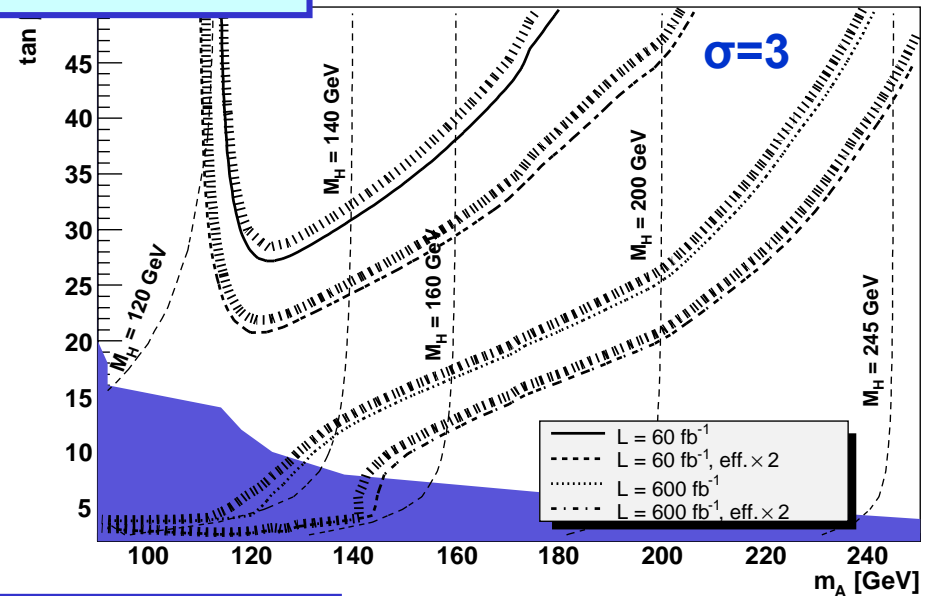
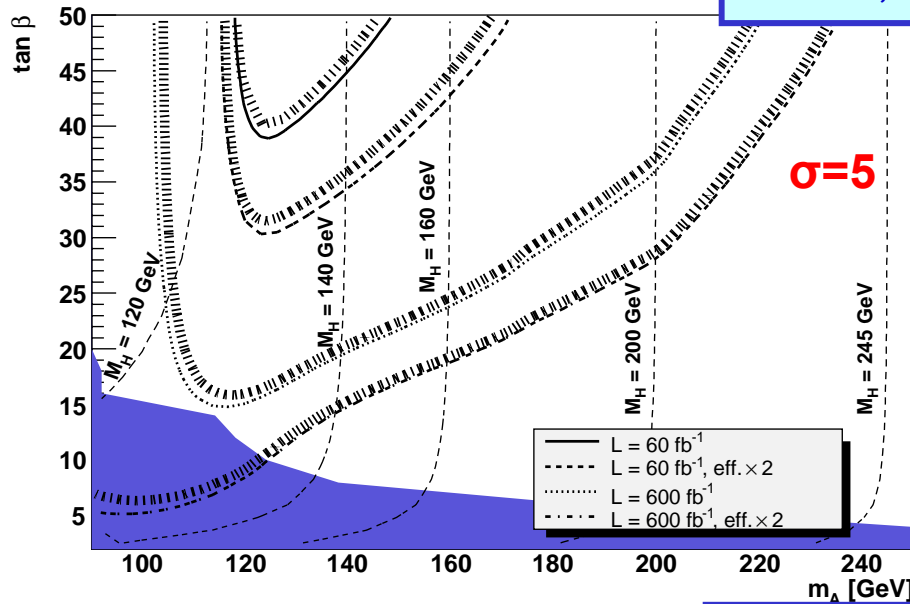


$h \rightarrow \text{tautau}$, m_{hmax} , $\mu = 200$ GeV

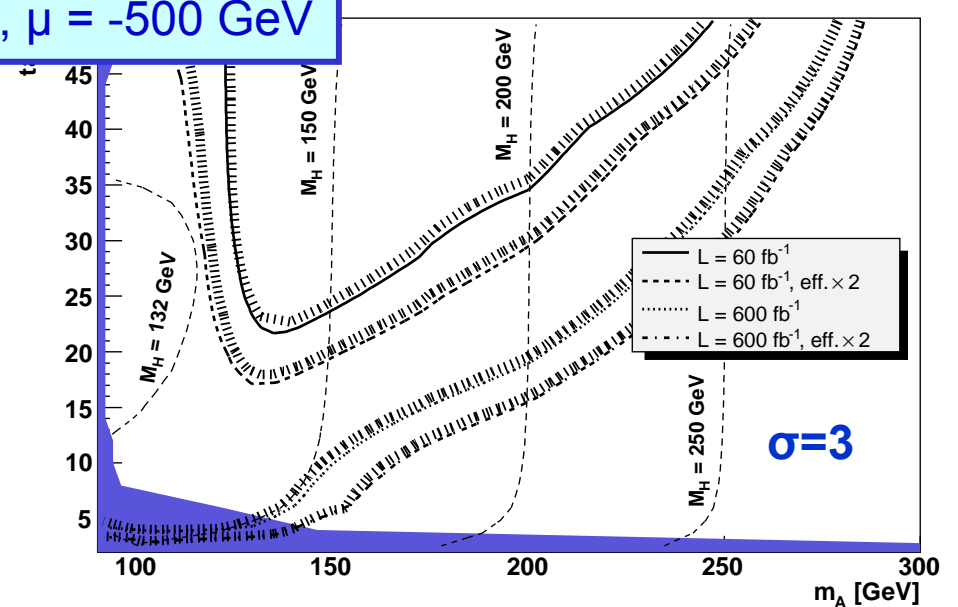
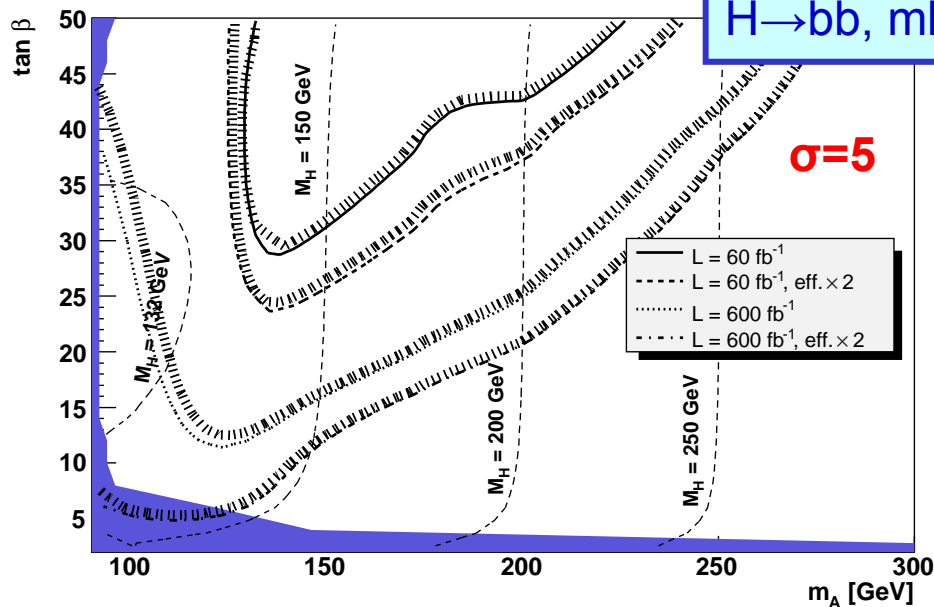


Stat. significance for $H \rightarrow bb$: from 5 to 3

$H \rightarrow bb$, nomix, $\mu = 200$ GeV

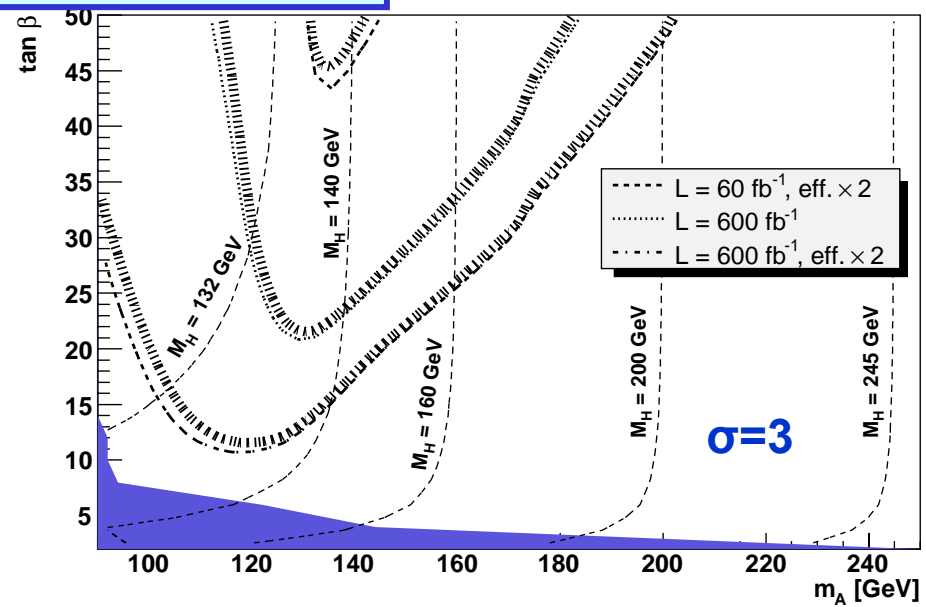
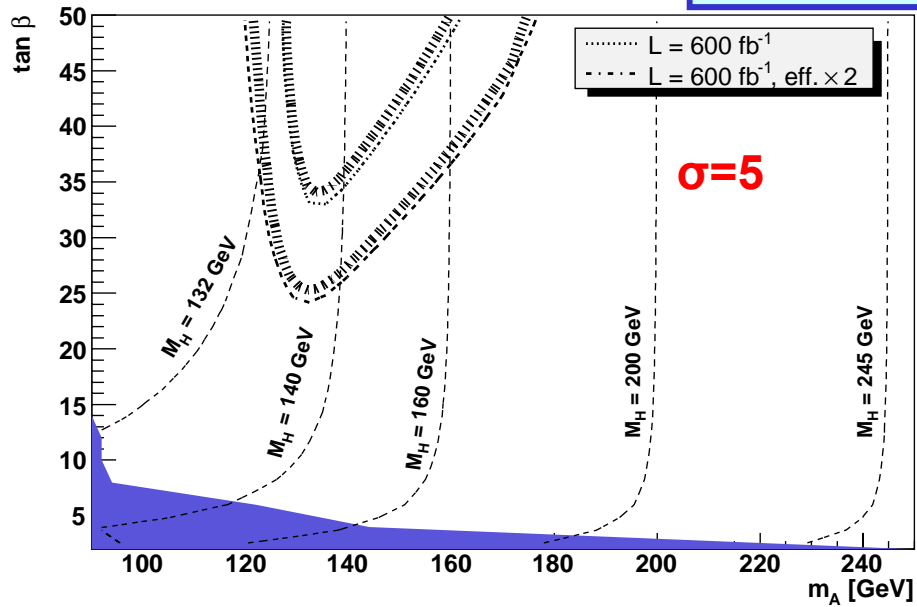


$H \rightarrow bb$, mhmax, $\mu = -500$ GeV



Stat. significance for $H \rightarrow \tau\tau$: from 5 to 3

$H \rightarrow \tau\tau$, $m_{H^{\max}}$, $\mu = 200$ GeV



Discovery numbers ($\sigma > 5.0$) for $L = 60 \text{ fb}^{-1}$

- $h \rightarrow bb$: mhmax, $\mu=200 \text{ GeV}$:**

$M_h \sim 90 \text{ GeV}$, $\tan\beta=40$: $S=29$, $B=24$, **$S=46$**
 $M_h \sim 90 \text{ GeV}$, $\tan\beta=50$: $S=42$, $B=30$, **$S=67$**
 $M_h \sim 110 \text{ GeV}$, $\tan\beta=44$: $S=32$, $B=32$, **$S=51$**
 $M_h \sim 120 \text{ GeV}$, $\tan\beta=50$: $S=32$, $B=28$, **$S=48$**

- $H \rightarrow bb$: mhmax, $\mu=200 \text{ GeV}$:**

null

- $H \rightarrow bb$: mhmax, $\mu=-500 \text{ GeV}$:**

$M_H \sim 138 \text{ GeV}$, $\tan\beta=30$: $S=25$, $B=14$, **$S=38$**
 $M_H \sim 138 \text{ GeV}$, $\tan\beta=50$: $S=124$, $B=65$, **$S=175$**

In optimum mass windows Total signal

- $h \rightarrow bb$: nomix, $\mu=200 \text{ GeV}$:**

$M_h \sim 90 \text{ GeV}$, $\tan\beta=36$: $S=30$, $B=24$, **$S=46$**
 $M_h \sim 90 \text{ GeV}$, $\tan\beta=50$: $S=57$, $B=36$, **$S=90$**
 $M_h \sim 108 \text{ GeV}$, $\tan\beta=40$: $S=57$, $B=33$, **$S=52$**
 $M_h \sim 113 \text{ GeV}$, $\tan\beta=50$: $S=41$, $B=35$, **$S=61$**

- $H \rightarrow bb$: nomix, $\mu=200 \text{ GeV}$:**

$M_H \sim 125 \text{ GeV}$, $\tan\beta=40$: $S=28$, $B=21$, **$S=43$**
 $M_H \sim 125 \text{ GeV}$, $\tan\beta=50$: $S=43$, $B=26$, **$S=64$**

- $H \rightarrow bb$: nomix, $\mu=-500 \text{ GeV}$:**

$M_H \sim 125 \text{ GeV}$, $\tan\beta=34$: $S=28$, $B=21$, **$S=42$**
 $M_H \sim 125 \text{ GeV}$, $\tan\beta=50$: $S=67$, $B=35$, **$S=99$**

The numbers S and B for $L=120, 600, 1200$ obtained by scaling the above by 2,10,20.

Some other interesting numbers

$h \rightarrow WW$: small α_{eff} , $\mu=2$ TeV: maximum number of signal events around **10-11** – but only for $M_h \sim 121$ GeV and $20 < \tan\beta < 50$

Information about SM Higgs: the higher M_A , the more SM-like h gets.

The following for $M_A=250$ GeV:

- $h \rightarrow bb$: m_{hmax} , $\mu=200$ GeV:
 $127 < M_h < 131$ GeV, $4 < \tan\beta < 50$:

Lumi=60: S=3.2, B=14, $\sigma=0.8$

Lumi=120: S=6.5, B=27, $\sigma=1.1$

Lumi=600: S=32, B=135, $\sigma=2.6$

Lumi=1200: S=64, B=270, $\sigma=3.7$

$h \rightarrow bb$: nomix, $\mu=200$ GeV:

$115 < M_h < 119$ GeV, $4 < \tan\beta < 50$:

Lumi=60: S=4, B=20, $\sigma=0.8$

Lumi=120: S=8, B=39, $\sigma=1.2$

Lumi=600: S=40, B=195, $\sigma=2.7$

Lumi=1200: S=79, B=389, $\sigma=3.7$

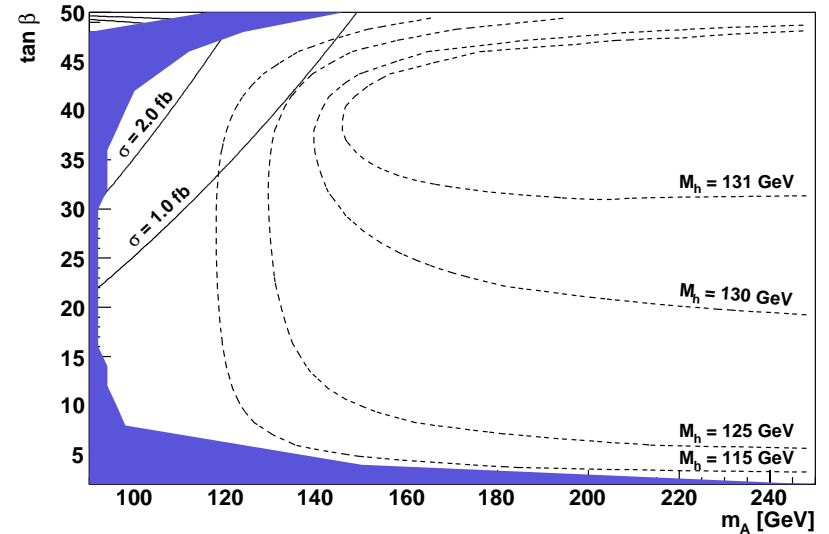
Semi-exclusive CP-odd A production

CED production of pseudoscalar A is strongly suppressed by P-even selection rule.

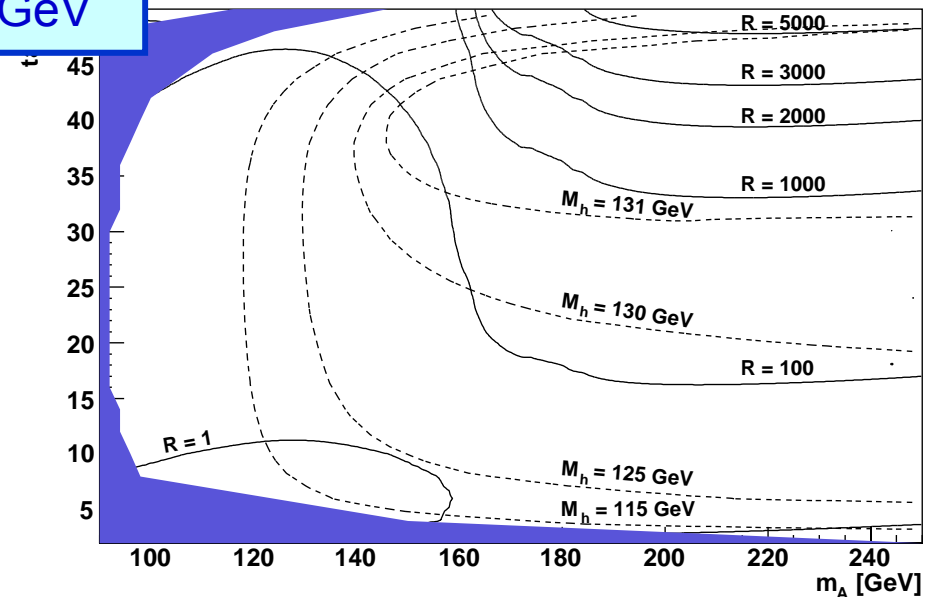
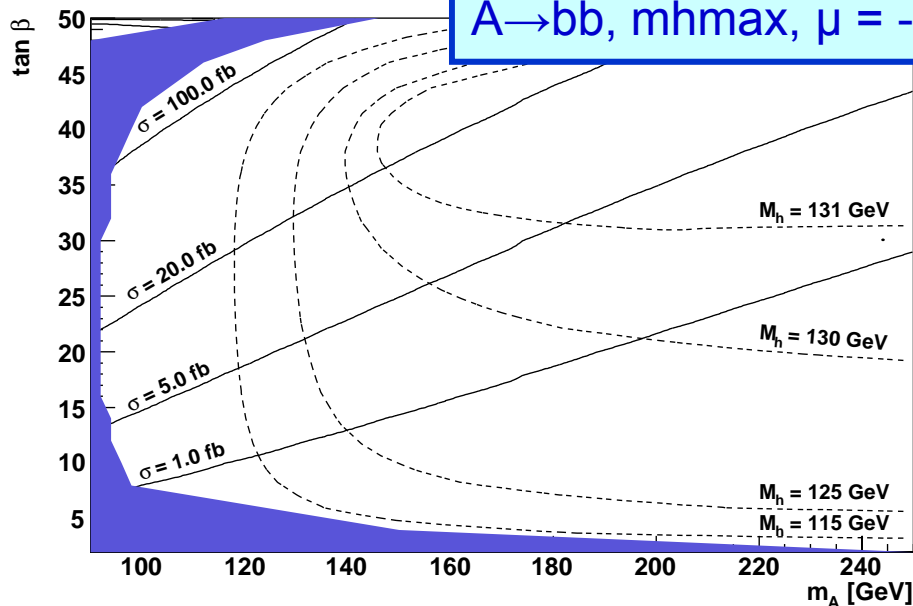
Consider 'semi-exclusive' A production:
 $pp \rightarrow X + H, A + Y$ where H, A separated by large rap.gaps from proton remnants X and Y.

Large x-section than CED but also larger QCD bg.

A → tautau, mhmax, μ = -700 GeV



A → bb, mhmax, μ = -700 GeV



Conclusions

- Detailed analysis of prospects for CED production of CP-even Higgs bosons, $pp \rightarrow p + H, h + p$.
- **$h \rightarrow bb$** : almost complete coverage of M_A - $\tan\beta$ plane at 3σ level at $L=600\text{fb}^{-1}$, effx2
CED channel may yield crucial information on bottom Yukawa coupling and CP properties
- **$H \rightarrow bb$** : discovery of a 140 GeV Higgs boson for all values of $\tan\beta$ with $L=600\text{fb}^{-1}$, effx2
- Semi-exclusive production of A looks challenging

If standard techniques to search for SM Higgs fail, then the diffractive MSSM search may become the Higgs discovery project.

One of the easiest recognition patterns for the MSSM Higgs would be the broader mass spectrum compared to that expected for the SM Higgs case.

BACKUP SLIDES

Selection cuts for $H \rightarrow bb$ at $M_h = 120$ GeV

$$\text{cut 1} = N_{\text{jet}} > 1$$

$$\text{cut 2} = E_{T,\text{jet1}} * \text{JES} > 45 \text{ GeV} \quad \wedge \quad E_{T,\text{jet2}} * \text{JES} > 30 \text{ GeV}$$

$$\text{cut 3} = |\eta_{\text{jet1}}| < 2.5 \quad \wedge \quad |\eta_{\text{jet2}}| < 2.5$$

$$\text{cut 4} = |\eta_{\text{jet1}} - \eta_{\text{jet2}}| < 1.1 - \text{equiv. to } 60^\circ < \eta_{\text{jet1,2}} < 120^\circ \text{ in Higgs cms (used in KMR formulas)}$$

$$\text{cut 5} = 2.85 < |\phi_{\text{jet1}} - \phi_{\text{jet2}}| < 3.43$$

$$\text{cut 7} = 0.85 < M_{\text{dijet}}/M_{420} < 1.15, \quad 0.8 < M_{\text{dijet}}/M_{\text{comb}} < 1.2$$

$$\text{cut 9} = 118 < M_{420} < 122, \quad 115 < M_{\text{comb}} < 125$$

$$\text{cut 10} = \text{both jets b-tagged (Discr} > 1.0)$$

$$\text{cut 11} = |\xi_{\text{jet}}^{\text{L}} - \xi_{420}^{\text{R}}|/\xi_{420}^{\text{R}} < 0.3 \quad \wedge \quad |\xi_{\text{jet}}^{\text{R}} - \xi_{420}^{\text{L}}|/\xi_{420}^{\text{L}} < 0.3,$$

$$|\xi_{\text{jet}}^{\text{L}} - \xi_{\text{comb}}^{\text{R}}|/\xi_{\text{comb}}^{\text{R}} < 0.3 \quad \wedge \quad |\xi_{\text{jet}}^{\text{R}} - \xi_{\text{comb}}^{\text{L}}|/\xi_{\text{comb}}^{\text{L}} < 0.3,$$

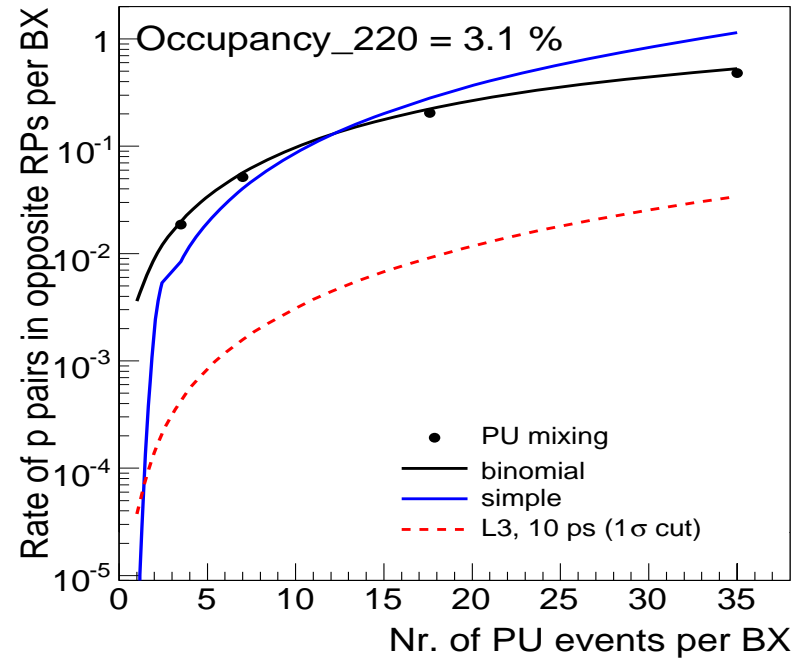
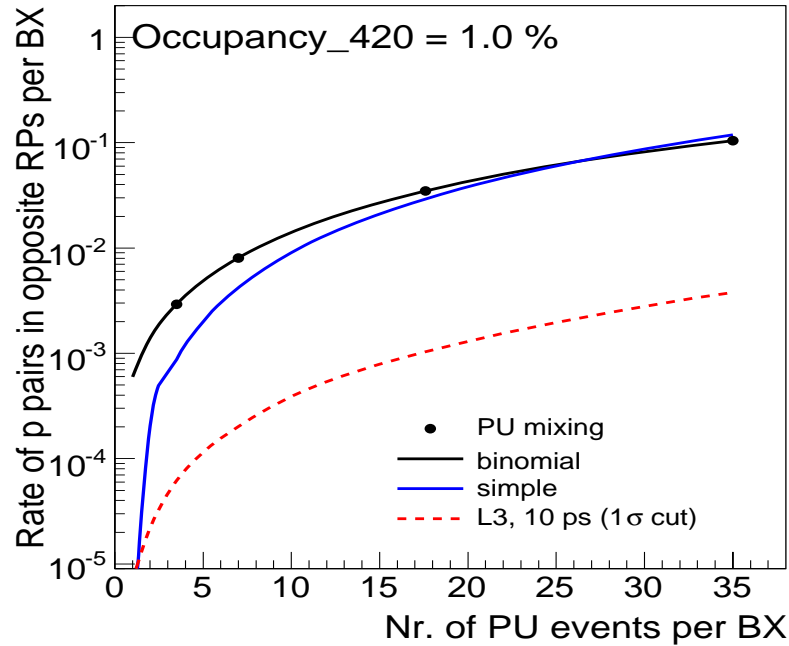
$$0.002 < \xi_{420} < 0.04 \quad \wedge \quad 0.002 < \xi_{\text{comb}} < 0.04$$

$$\text{cut L1} = (\text{Acc}_{220}^{\text{L}} > 0 \vee \text{Acc}_{220}^{\text{R}} > 0) \quad \wedge \quad (E_{T,\text{jet1,2}} > 40 \text{ GeV})$$

Efficiencies for SM $\Gamma(H \rightarrow gg) \sim \text{MeV}$

M_h [GeV]	Acc_{420}	Acc_{comb}	Acc_{220}	ϵ_{420}	ϵ_{comb}	ϵ_{220}
100	0.37	0.13	0.0	0.012	0.008	0.0
120	0.31	0.25	0.0	0.017	0.025	0.0
140	0.25	0.37	0.0	0.016	0.051	0.0
160	0.19	0.49	0.0	0.015	0.076	0.0
180	0.14	0.60	0.0	0.012	0.096	0.0
200	0.09	0.69	0.0	0.004	0.11	0.0
300	0.0	0.76	0.13	0.0	0.125	0.02

Fake rates



Analytical formula for Rate of p pairs seen in opposite RPs per BX:

$$\mu = \text{Acc} * N^{\text{PU}}, \quad \mu_{\text{LR}} = \text{Acc}_{\text{LR}} * N^{\text{PU}}$$

$$N^{\text{RP}}/\text{BX}(\text{binomial}) = 2 * \exp(-\mu) * [\cosh(\mu) - 1] + 1 - \exp(-\mu_{\text{LR}})$$

$$N^{\text{RP}}/\text{BX}(\text{simple}) = N^{\text{PU}} * (N^{\text{PU}} - 1) * \text{Acc} * \text{Acc}$$

$$L3 = (N^{\text{RP}}/\text{BX})/Q, \quad Q = \text{red.fact.from quartic det. based on } \sigma_{\text{t}}=10 \text{ ps}$$

$$Q \sim 30 \text{ for } 220 \text{ and } 420, \text{ for } N^{\text{PU}} = 3.5$$

$$\sim 13 \text{ for } 220 \text{ and } 23 \text{ for } 420, \text{ for } N^{\text{PU}} = 35$$

Courtesy
Sasha Kupčo
(Prague)

S/B for Lumi = 30 fb⁻¹

|| 3.5 || 7.0 || 17.6 || 35.0

Jetcuts || 19.2/33.3E10 || 19.2/35.7E10 || 19.2/39.2E10 || 19.2/35.6E10

Jetcuts || 6.4 / 7.5E8 || 6.4 / 8E8 || 6.4 / 8.5E8 || 6.4 / 7.7E8
+2btag || || || ||

||420 | comb || 420 | comb || 420 | comb || 420 | comb

Jetcuts || 2.1 | 1.6 || 2.1 | 1.6 || 2.1 | 1.6 || 2.1 | 1.6
+2btag || / | / || / | / || / | / || / | /
+RP || 2.3E6 | 10.5E6 || 5.4E6 | 29.6E6 || 28E6 | 130E6 || 77.8E6 | 293E6

All cuts || 0.6 / | 0.9 / || 0.6 / | 0.9 / || 0.6 / | 0.9 / || 0.6 / | 0.9 /
+timing || 85 | 80 || 190 | 300 || 1600 | 970 || 8200 | 5700