Searching for Supersymmetric Higgs Bosons at the LHC

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CERN

– Light neutral Higgs: no-lose-theorem

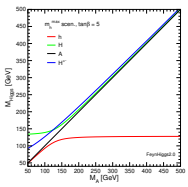
– Charged Higgs: bottom induced processes

– Heavy neutral Higgs: decay to two light Higgses

MSSM Higgs Bosons at the LHC

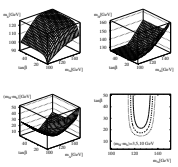
MSSM Higgs Sector

- Softly broken supersymmetric anomaly–free theory
- two doublets, coupling to up and down type fermions
  → five physical states $h^o, H^o, A^o, H^\pm$
  → mixing of scalars to mass eigenstates (mixing angle α)
  → more predictive than Standard Model (upper h^o mass limit)
- conveniently expressed as function of m_A and $\tan\beta \equiv v_2/v_1$
- Yukawa couplings to $H, A, H^\pm$: $m_b \tan\beta, m_t/\tan\beta$ (large m_A)
- typically one light, many heavy scalars [Heinemeyer, Weiglein]



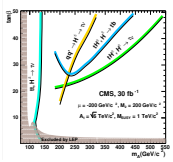
Find first Higgs boson

- complete coverage by WBF $h \to \tau\tau$ [TP, Rainwater, Zeppenfeld]
- problem: mass degeneracy [Boos, Djouadi, Mühlleitner, Nikitenko]
  $\Delta m_h/m_h \sim \sigma/\sqrt{N}$ ($\sigma \sim 1.5$ GeV for $\mu\mu, \gamma\gamma$ and $\sigma \sim 15$ GeV for $\tau\tau$)



Tell it is 2HDM (MSSM?) ⇒ look for heavy Higgs bosons

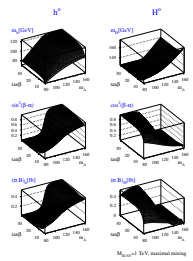
- $H^0, A^0 \to \tau\tau, \mu\mu$ inclusive $gg \to H$ and $gg \to b\bar{b}H$
- $H^\pm \to \nu\tau, tb$ in $pp \to tH^-, W^+H^-, H^+H^-$
  (n.b. SUSY loops) [Hollik et al, Kniehl et al]
- appearance in SUSY cascades [Datta, Djouadi, Guchait, Moortgat]
- no other conclusive way but to find these particles



1. Light Neutral Higgs

MSSM Higgs bosons in weak boson fusion [TP, Rainwater, Zeppenfeld]

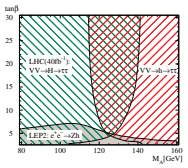
- SM cross section > 3 pb for light Higgs in $qq \to qqH$
  (tagging jet signature, central decay products, minijet veto)
- approximate 12 GeV $\tau\tau$ mass reconstruction at high $p_{T,h}$ [K.Ellis]
- MSSM decoupling region:
  (a) Higgs mass range after LEP2: $m_Z \ll m_h < 135$ GeV
  (b) production cross section: $g_{WWh} = \sin(\beta - \alpha) \sim 1$
  (c) branching fraction: $BR(h \to \tau\tau) > BR(H_{\rm SM} \to \tau\tau)$



$\to$ enhancement of rate: $pp \to qqh \to qq\tau\tau$

$\to$ heavy Higgs production at low m_A

$\to$ no–lose theorem for MSSM Higgs scalars



Attempts to escape this channel

- low $\tan\beta$: forbidden by LEP2
- $m_A = 91$ GeV and $m_h = 95$ GeV: wide open channel for H
- super–large mixing $A_t > 6$ TeV: enhanced WBF WW and $\gamma\gamma$ rate
- CP phases in A_t: coverage solid [Carena, Ellis, Wagner,...]
- funny couplings of all kind: again solid [Schumacher]
- many multiplets: go for WBF WW channel [Alves, Eboli, TP, Rainwater]

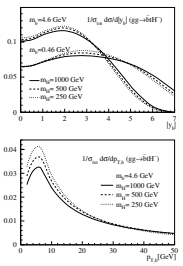
2. (Heavy) Charged Higgs

Most promising channel

– associated production $pp \to tH^- + X$ for large $\tan\beta$

– decay $H^\pm \to \nu\tau$ most promising [Assamagan, Coadou]

Exclusive production $gg \to \bar{b}tH^-$



– collinear bottom jets from gluon splitting, regularized by m_b

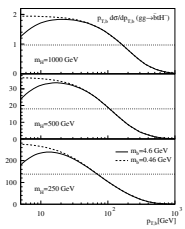
$\to$ experiment: forward jets, $p_{T,b}$ peaked at m_b (factor 1/6 for each tagged b)

$\to$ use bottom–inclusive cross section

$\to$ check asymptotic cross section behavior $d\sigma/dp_{T,b} \propto p_{T,b}/m_{T,b}^2$

$\to$ inclusive total rate $\sigma \propto \log(p_{T,b}^{\max}/p_{T,b}^{\min}) = \log(p_{T,b}^{\max}/m_b)$

$\to$ how large logarithms? resum?



Inclusive process $bg \to tH^-$

– resum large logarithms $\log(p_{T,b}/m_b)$ in exclusive process $gg \to \bar{b}tH^-$

– equivalent to bottom parton density and inclusive process $bg \to tH^-$

$\to$ $\mu_{F,b}$ 'transverse momentum size' of bottom parton

($\mu_{F,b} \equiv p_{T,b}^{\max}$; usually hard scale $\mu_{F,b} = M$)

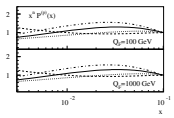
$\to$ numerical improvement or overestimate?

$\to$ (1) check bottom–inclusive total rate

(2) check bottom–inclusive t, H distributions

Total Rate: Bottom Factorization Scale

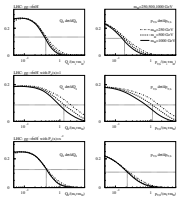
Perturbative bottom factorization scale from exclusive process [Boos, TP]



- two steps: first bottom virtuality $Q_b^{\max}$
- general exclusive process: $gg \to \bar{b} X_M$

  approximate gluon density $\mathcal{L} = \mathcal{L}_0/x^2$

  asymptotic behavior $\overline{|\mathcal{M}|^2} = S^2 \sigma_0 / Q_b^2$



$$\sigma = \frac{2\sigma_0 \mathcal{L}_0}{16\pi} \int_0^{S-M^2} \frac{dQ_b}{Q_b} F(Q_b)$$

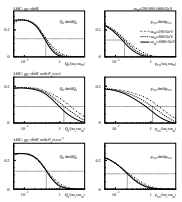
$\to$ $F(Q_b)$ known correction to asymptotic behavior $d\sigma/dQ_b \sim 1/Q_b$

$\to$ define $Q_b^{\max}$ at turning point $d^2 F(Q_b)/d(\log Q_b)^2 = 0$

$\to$ $Q_b^{\max} \sim M/2$ (hard scale argument $Q_b^{\max} \propto M$, not more than that!)

Second step: transverse momentum $p_{T,b}^{\max}$

- check explicitly: $Q_b \sim Q_b^{\max}$ also yields $p_{T,b} \sim p_{T,b}^{\max}$



$\to$ translate Q_b into $p_{T,b}$ point by point

$\to$ $p_{T,b}^{\max}/Q_b^{\max} \sim Q_b^{\max}/M$ yields $p_{T,b}^{\max} \sim Q_b^{\max}/2 \sim M/4$

(numerical study of $gg \to \bar{b} t H^-$: $\mu_{F,b} \sim M/5$)

So what did we learn from exclusive process?

- $\log(p_{T,b}/m_b)$ after integrating over bottom jet

  but 'large' logs at maximum $\log(M/(5m_b))$ [TP; Maltoni, Willenbrock]
- hard scale for inclusive process: $\mu_{F,b} \propto M$
- gg and bg processes: $\mu_{F,b} \sim M/5$ from partonic phase space

$\Rightarrow$ Total cross section with bottom partons understood

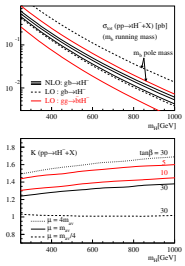
Total Rate: QCD Corrections

Next-to-leading Order QCD Calculation [TP]

– leading order uncertainty large for $bg \to tH^-$

– complete set of virtual and real SUSY corrections

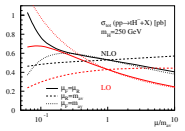
– running Yukawa couplings, everything else misleading



→ NLO correction $+30\% \cdots 40\%$ perturbatively stable [Zhu]

Scale Dependence

– renormalization scale dependence numerically dominant
$\mu_R \sim (m_t + m_H)/2$ natural choice [c.f. Higgs decays, Melnikov]



– factorization scale dependene critical only for small μ_F
$\mu_F \sim (m_t + m_H)/5$ from exclusive process

– problem at small scales: bottom induced process not dominant

→ NLO scale dependence $\pm 20\%$

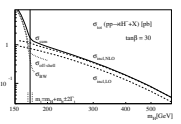
→ well defined limit $\mu_F \to m_b$ returns exclusive process $gg \to \bar{b}tH^-$

Matching at threshold

– $m_H < m_t - m_b$: top pair production and Breit–Wigner propagator
$m_H > m_t - m_b$: resummed off-shell process

– double counting of $pp \to t\bar{t}^* \to t(\bar{b}H^-)$

– subtract on-shell top pairs from NLO $bg \to tH^-$ process
(unique in small width approximation, see SUSY-pairs)



→ consistent matching by simply adding channels

Distributions for Inclusive Process

On to the distributions (preliminary)

– bottom parton description appropriate for total rate

→ Higgs and top distributions?

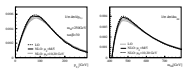
→ bottom partons established for exclusive cross sections?

(1) Inclusive kinematics

– bottom partons assuming small $p_{T,b} \ll p_{z,b}$

→ compare to exclusive $(2 \to 3)$ process which is part of NLO rate

→ run bottom factorization scale $\mu_F \to m_b$
switch off incoming bottoms, left with $gg \to \bar{b}tH^-$



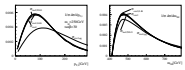
→ slightly harder distributions (due to x dependence of bottom PDF)

(2) Zero bottom mass

– agreement exclusive vs. inclusive cross section established

→ check with bottom mass dependent $pp \to \bar{b}tH^-$

→ perfect agreement with exclusive process for small m_b
very good agreement with physical bottom mass case



→ bottom parton picture altogether appropriate

SUSY-QCD Corrections

SUSY-QCD Loop Contributions [TP; Berger, Han, Jiang, TP]

– infrared finite but ultraviolet divergent SUSY loop contributions

– (1) universal corrections $y_b/(1+\Delta_b)$

[Carena, Garcia, Nierste, Wagner; Guasch, Häflinger, Spira]

(2) remaining explicit SUSY loop diagrams

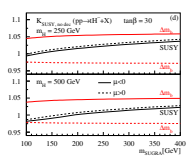
	m_0	$m_{1/2}$	$\tan\beta$	μ	m_H			$(\Delta_b)_{\rm resum}$	non–Δ_b
1a	100	250	10	420	477			-9.5%	3.0%
1b	200	400	30	511	535			-23.0%	-0.1%
2	1450	300	10	425	1503			-3.0%	-1.0%
3	90	400	10	633	719			-8.8%	3.0%
4	400	300	50	389	357			-32.0%	-0.4%
5	150	300	5	637	697			-7.7%	10.0%
	m_0	$m_{1/2}$	$\tan\beta$	μ	m_H	M_1	$M_{2,3}$		
6	150	300	10	402	476	480	300	-9.0%	3.0%
	Λ	$M_{\rm mes}$	$N_{\rm mes}$	$\tan\beta$	μ	m_H			
7	40×10^3	80×10^3	3	15	316	476		-7.8%	0.5%
8	100×10^3	200×10^3	1	15	421	538		-7.5%	0.5%

→ Δm_b corrections dominant for $\tan\beta \gtrsim 10$ (dependent on sign of μ)

→ explicit loop corrections negligible $\lesssim 10\%$ for generic mSUGRA

Decoupling of Running Parameters: $\alpha_s(\mu_R), y_{b,t}(\mu_R)$

– heavy SUSY particle loops ultraviolet divergent



→ SUSY counter terms for Standard Model parameters

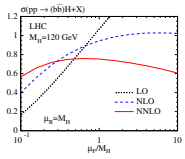
→ explicit decoupling necessary:

$m_{b,t}(\mu_R) \to m_{b,t}(\mu_R)[1+\alpha_s/(4\pi)C_F\log(\mu_R^2/m^2_{\rm heavy})]$

3. (Heavy) Neutral Higgs

Bottom induced production of neutral Higgses

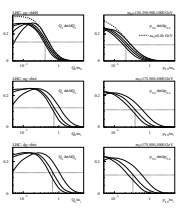
- rate enhanced by $\tan\beta^2$
- $gg \to b\bar{b}H$ exclusive versus $bg \to bH$ inclusive
  $bg \to bh$ exclusive versus $b\bar{b} \to H$ inclusive
- appropriate factorization scale $\mu_{F,b} \sim M/5 = m_h/5$
- check: $b\bar{b} \to H$ NNLO scale dependence [Harlander & Kilgore]
  $\mu_{R,b}$ variation for fixed $\mu_{F,b} \sim m_h/4$ well under control
  $\mu_{F,b}$ variation for fixed $\mu_{R,b} \sim m_h$ almost fixed point



- check: exclusive vs. inclusive total rate [Dittmaier, Spira, Krämer]

	M_H	$\sigma(q\bar{q}, gg \to b\bar{b}H + X)$ [fb]		$\sigma(b\bar{b} \to H + X)$ [fb]	
		LO	NLO	LO	NNLO
Tevatron	120	$3.9\,^{+3.5}_{-1.7}$	$8.0\,^{+3.1}_{-2.4}$	$8.6\,^{+4.7}_{-5.0}$	$10.5\,^{+0.3}_{-1.1}$
	200	$0.22\,^{+0.19}_{-0.09}$	$0.56\,^{+0.23}_{-0.18}$	$0.69\,^{+0.20}_{-0.26}$	$0.79\,^{+0.02}_{-0.03}$
LHC	120	$(5.3\,^{+2.7}_{-1.7})\times10^2$	$(7.3\,^{+2.0}_{-1.6})\times10^2$	$(4.8\,^{+4.3}_{-3.2})\times10^2$	$(7.2\,^{+0.4}_{-1.6})\times10^2$
	400	$4.3\,^{+2.4}_{-1.4}$	$8.1\,^{+2.2}_{-1.9}$	$7.4\,^{+2.4}_{-2.5}$	$9.8\,^{+0.2}_{-0.4}$

Side remark: single top production $qg \to \bar{b}tq'$ [Willenbrock et al]



- less steep quark densities, $x_1 \neq x_2$
- production above threshold

$\to Q_b^{\max} \sim m_t$

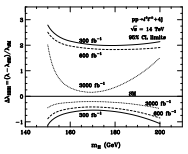
- generally $p_{T,b}^{\max} \sim Q_b^{\max}/2$

$\to \mu_{F,b} \sim m_t/2$ covered by quoted theoretical uncertainty

Heavy Higgs Decay to Light Higgses

SM Higgs pair production at the LHC [Baur, TP, Rainwater]

- $HH \to 4W$: believable detector simulation needed, not hopeless
  (use $m_{\rm vis}$ to determine λ_{HHH})
- $HH \to b\bar{b}\tau\tau$: miracle required
- $HH \to 4b$: several major miracles mandatory
  TESLA in better shape [Castanier, Gay,... ; Lafaye, Mühlleitner,...]
- $HH \to b\bar{b}\mu\mu$: at least small miracle would be helpful
  (might come out of $\mu\mu$ mass resolution)
- $HH \to b\bar{b}\gamma\gamma$: some enhancement needed



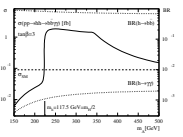
MSSM pair production $gg \to hh$ [Djouadi, Haber, Zerwas]

- only way to access $\tan\beta < 10$ beyond no-lose theorem
- factor 20 enhancement of cross section

$\to$ $HH \to b\bar{b}\gamma\gamma$ best shot

$\to$ backgrounds hard to compute but under control

$\to$ 5σ with $300\,\text{fb}^{-1}$ possible for $\tan\beta = 3$



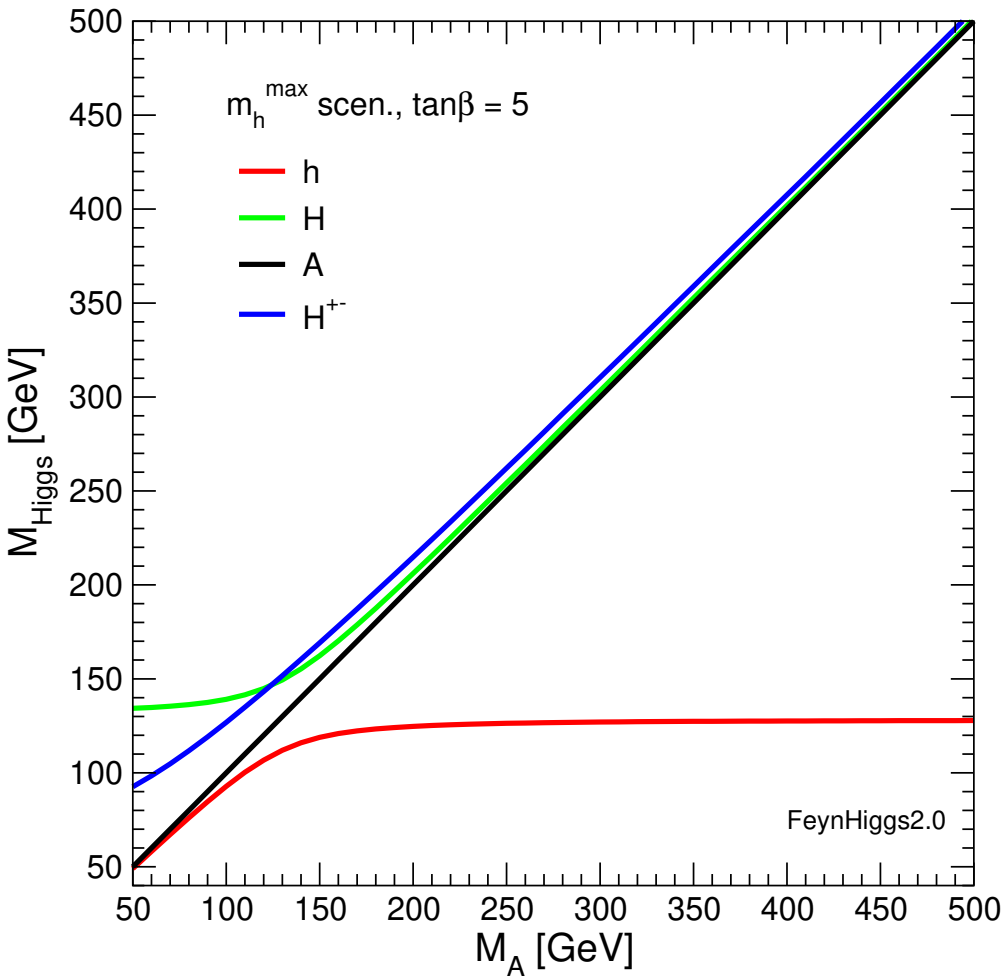
Conclusions

(1) One MSSM Higgs guaranteed to be seen
stable to variations of MSSM

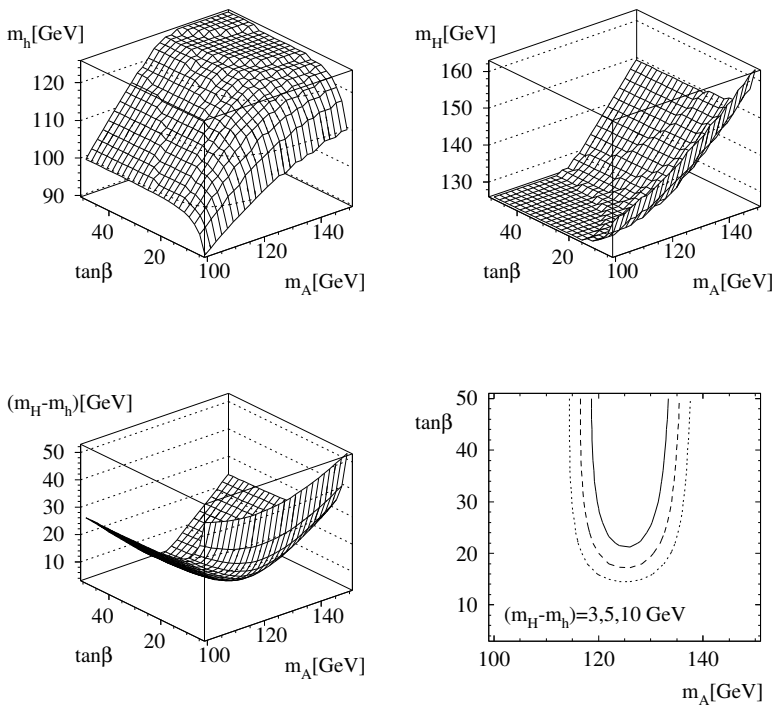
(2) heavy Higgs bosons necessary to tell it might be the MSSM
charged Higgs production with bottom jets understood

(2') NLO rate for charged Higgs production known:
NLO_1: inclusive process well defined
NLO_2: remaining scale uncertainty $\lesssim 20\%$
NLO_3: Δm_b corrections dominant in MSSM for large $\tan\beta$
NLO_4: non-factorizable corrections negligible in MSSM

(3) neutral Higgs production with $b\bar{b} \to H$ understood
signal $H^* \to hh \to b\bar{b}\gamma\gamma$ for small $\tan\beta$



Heinemeyer, Hollik, Weiglein


m_h[GeV]
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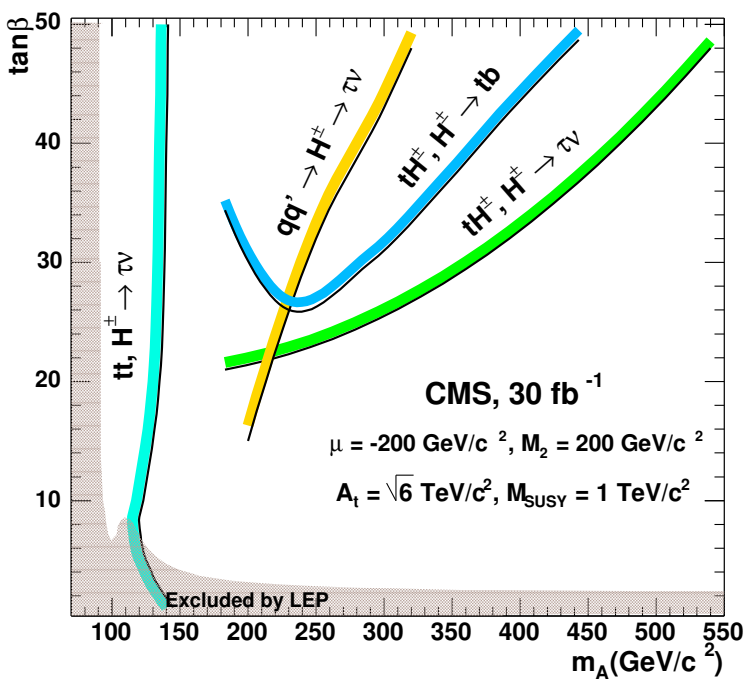
tanβ
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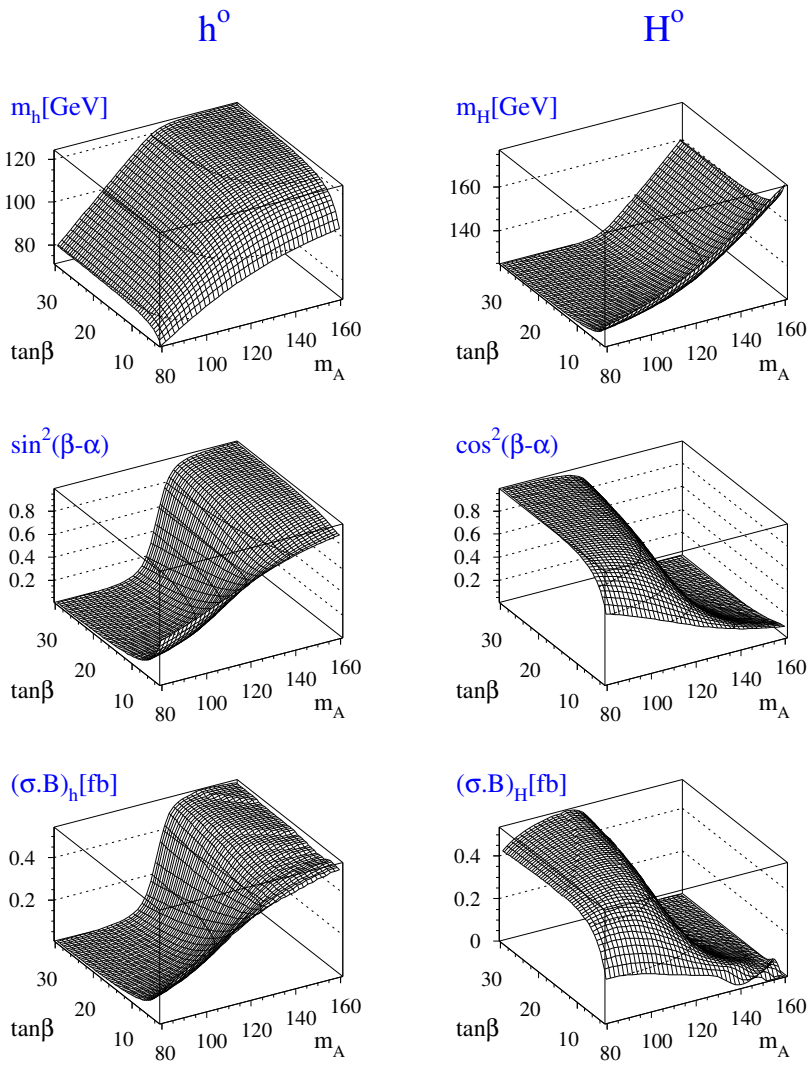
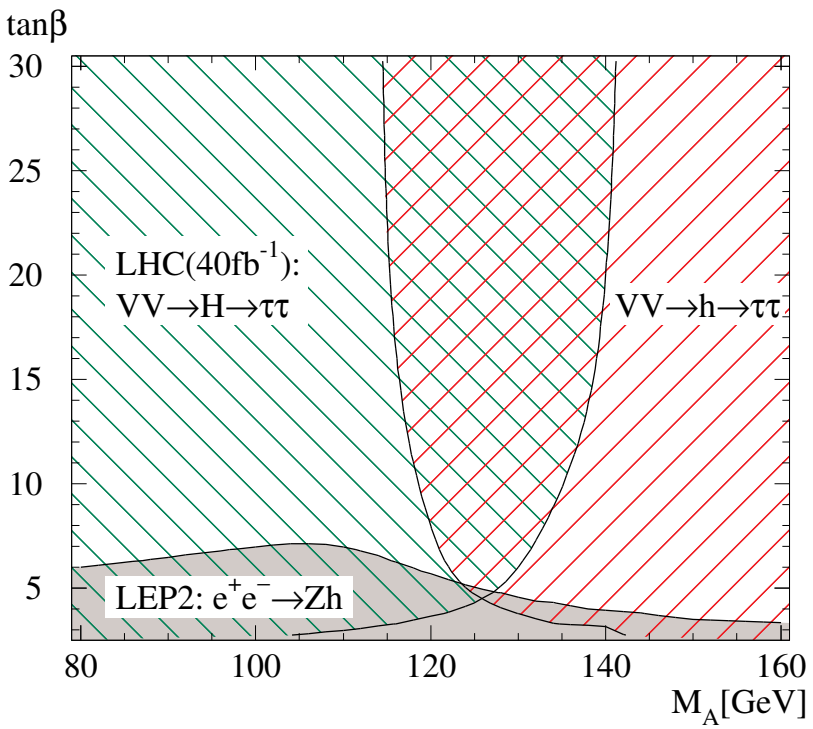
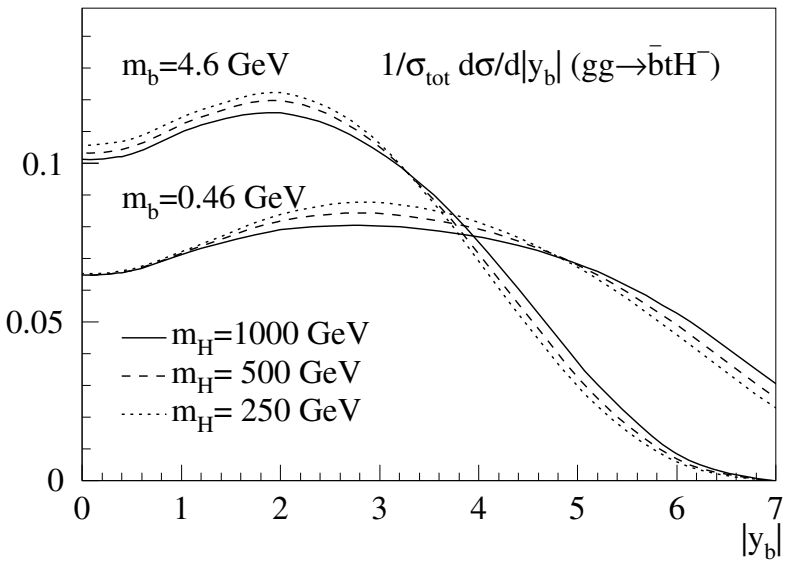
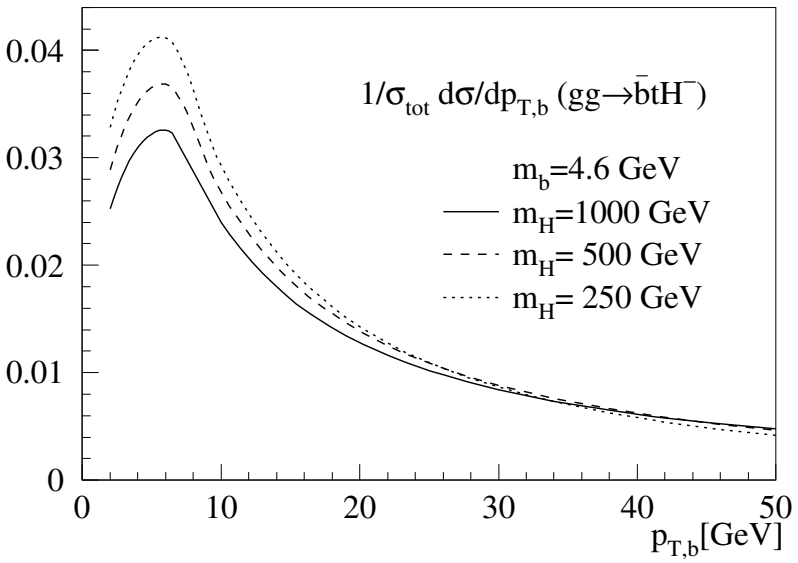
m_A(GeV/c^2)
tt, H^± → τν
qq' → H^± → τν
tH^±, H^± → tb
tH^±, H^± → τν
CMS, 30 fb^-1
μ = -200 GeV/c^2, M_2 = 200 GeV/c^2
A_t = √6 TeV/c^2, M_SUSY = 1 TeV/c^2
Excluded by LEP

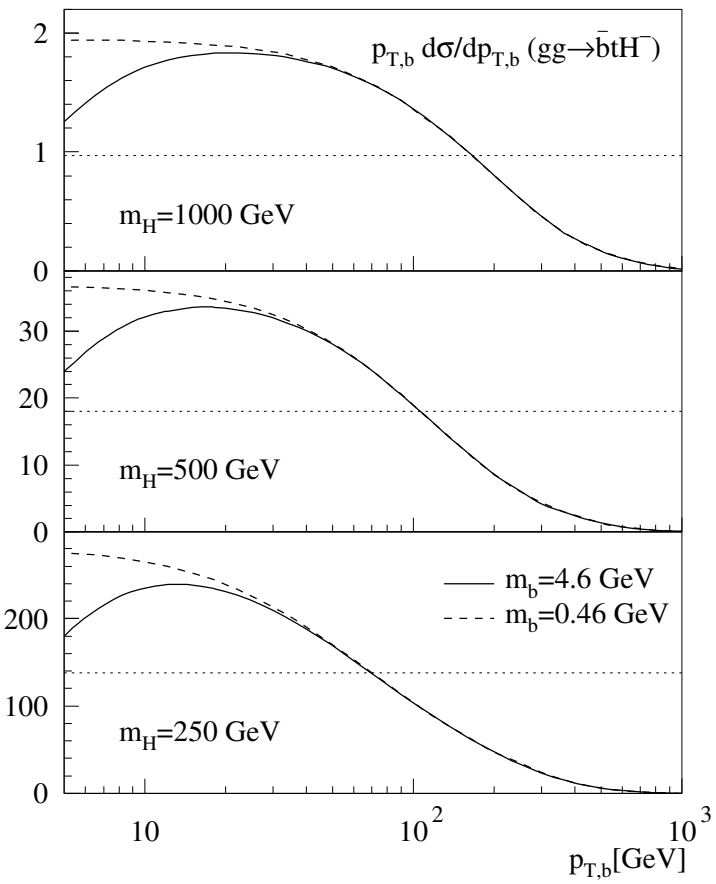


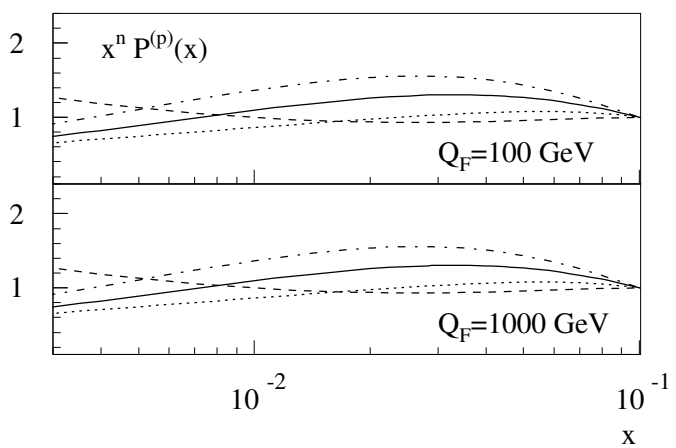
M_{SUSY}=1 TeV, maximal mixing

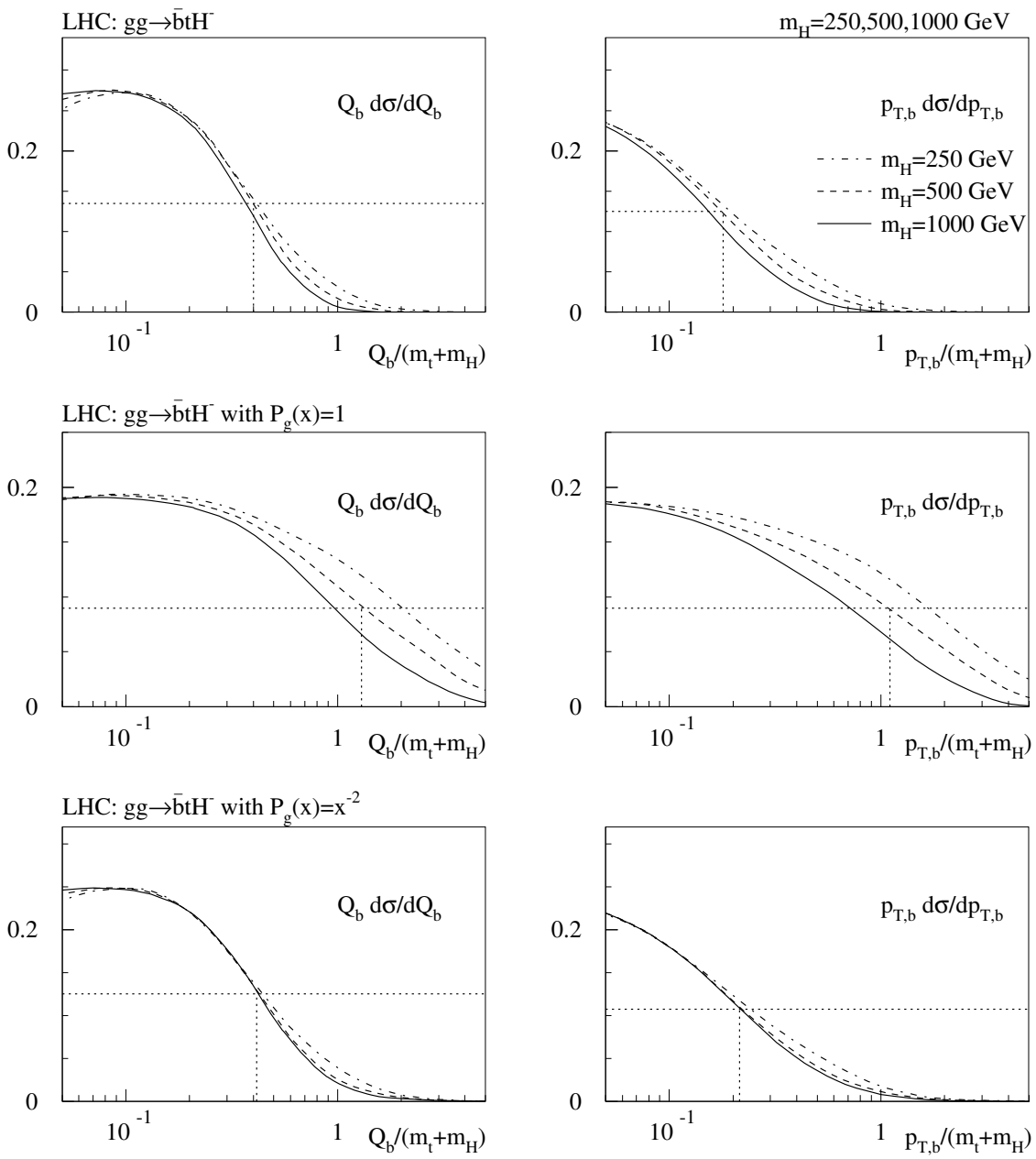

tanβ
30
25
20
15
10
5
LHC(40fb-1):
VV→H→ττ
VV→h→ττ
LEP2: e+e−→Zh
80
100
120
140
160
MA[GeV]

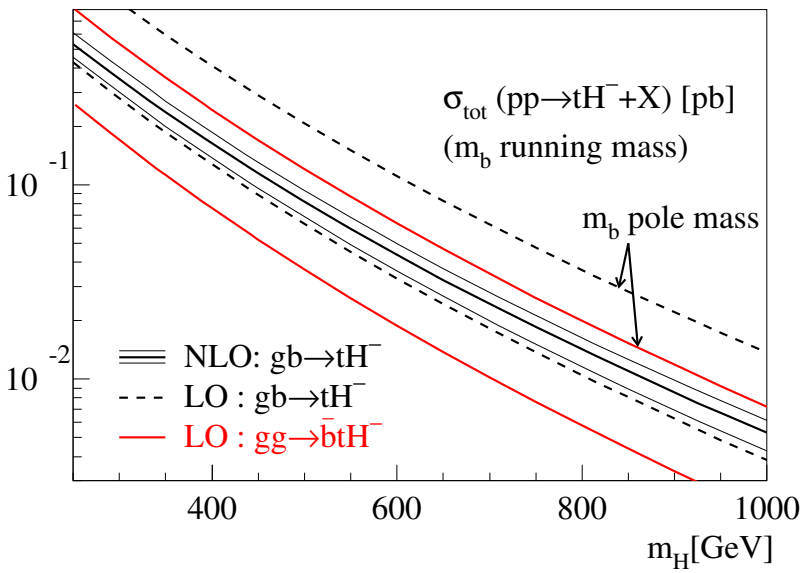

m_b=4.6 GeV
$1/\sigma_{tot}\ d\sigma/d|y_b|$ ($gg\to\bar{b}tH^-$)
m_b=0.46 GeV
m_H=1000 GeV
m_H= 500 GeV
m_H= 250 GeV
0.1
0.05
0
0
1
2
3
4
5
6
7
$|y_b|$

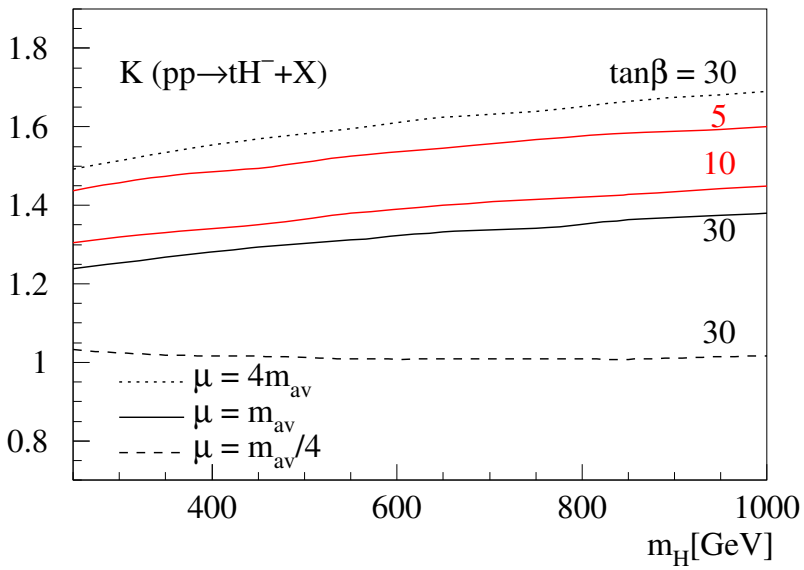

$1/\sigma_{tot}\ d\sigma/dp_{T,b}$ ($gg\to\bar{b}tH^-$)
m_b=4.6 GeV
m_H=1000 GeV
m_H= 500 GeV
m_H= 250 GeV
0.04
0.03
0.02
0.01
0
0
10
20
30
40
50
$p_{T,b}$[GeV]

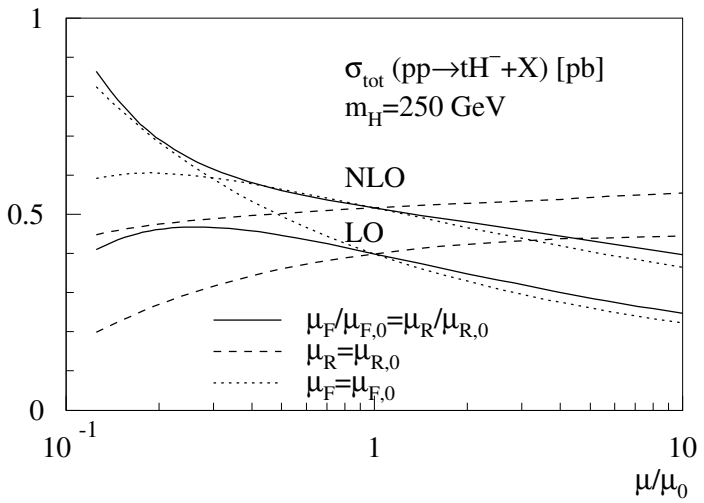

$p_{T,b}\, d\sigma/dp_{T,b}\ (gg \to \bar{b}tH^-)$
m_H=1000 GeV
m_H=500 GeV
m_H=250 GeV
m_b=4.6 GeV
m_b=0.46 GeV
$p_{T,b}$[GeV]

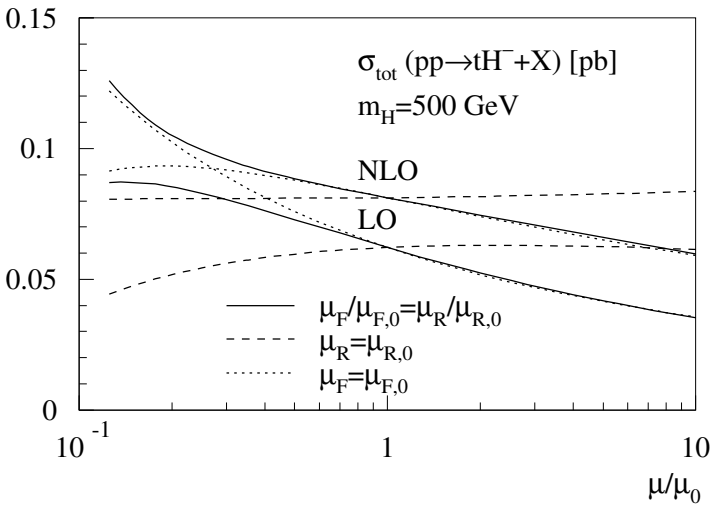

2
1
$x^n P^{(p)}(x)$
Q_F=100 GeV
2
1
Q_F=1000 GeV
10^{-2}
10^{-1}
x

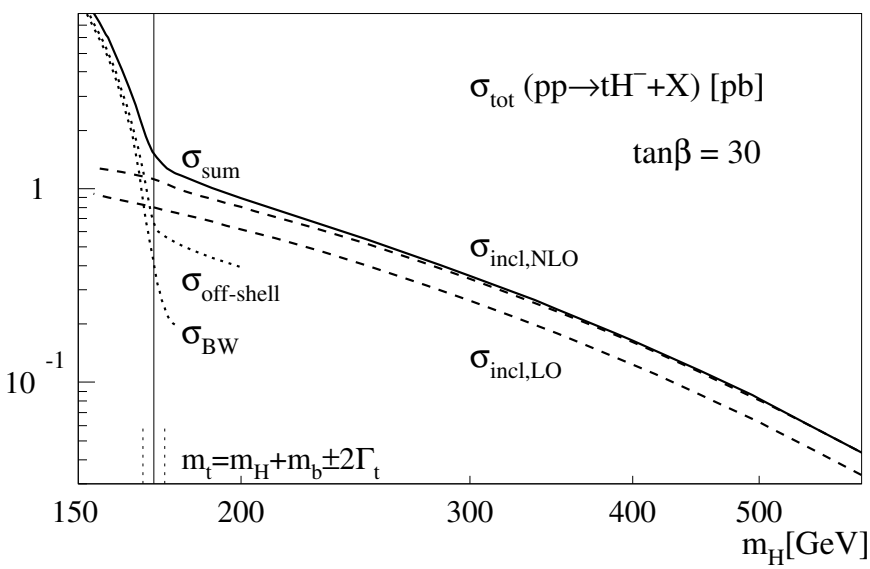

LHC: gg→b̄tH⁻
m_H=250,500,1000 GeV
Q_b dσ/dQ_b
p_T,b dσ/dp_T,b
m_H=250 GeV
m_H=500 GeV
m_H=1000 GeV
0.2
0
10^-1
1
Q_b/(m_t+m_H)
p_T,b/(m_t+m_H)
LHC: gg→b̄tH⁻ with P_g(x)=1
LHC: gg→b̄tH⁻ with P_g(x)=x^-2

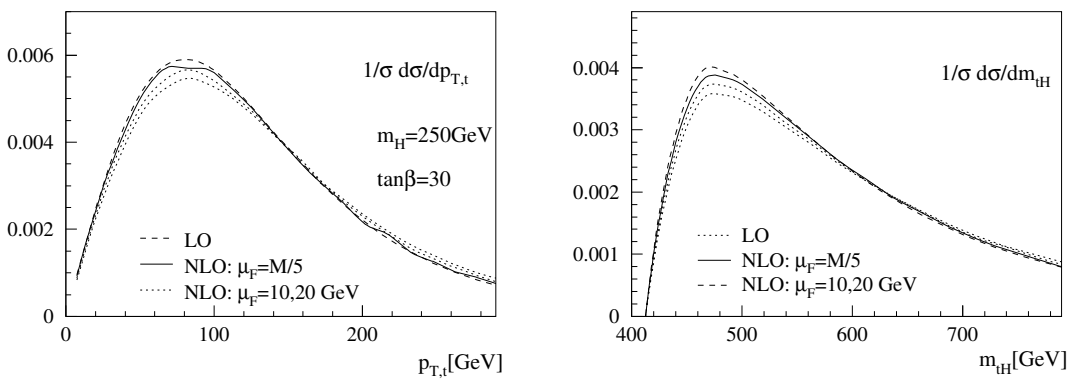

σ_{tot} (pp→tH⁻+X) [pb]
(m_b running mass)
m_b pole mass
NLO: gb→tH⁻
LO : gb→tH⁻
LO : gg→b̄tH⁻
10⁻¹
10⁻²
400
600
800
1000
m_H[GeV]

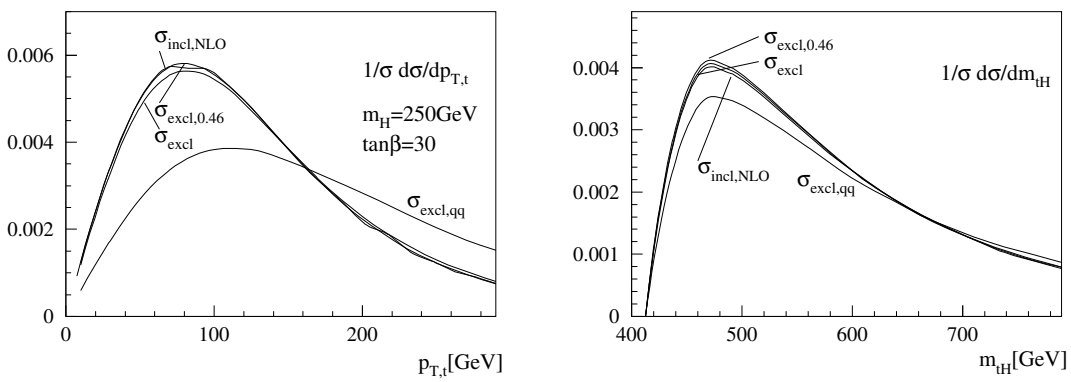

K (pp→tH⁻+X)
tanβ = 30
5
10
30
30
μ = 4m_{av}
μ = m_{av}
μ = m_{av}/4
1.8
1.6
1.4
1.2
1
0.8
400
600
800
1000
m_H[GeV]

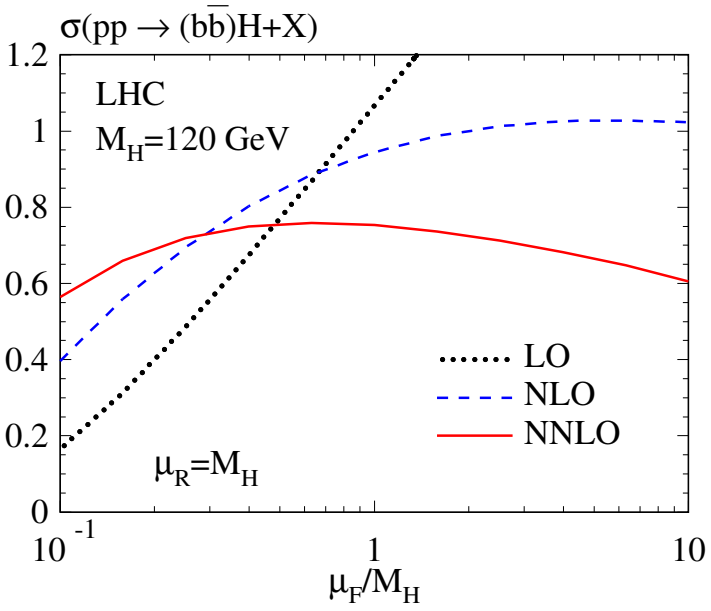

1
0.5
0
σ_{tot} (pp→tH$^-$+X) [pb]
m_H=250 GeV
NLO
LO
$\mu_F/\mu_{F,0}=\mu_R/\mu_{R,0}$
$\mu_R=\mu_{R,0}$
$\mu_F=\mu_{F,0}$
10^{-1}
1
10
μ/μ_0


0.15
0.1
0.05
0
σ_{tot} (pp→tH$^-$+X) [pb]
m_H=500 GeV
NLO
LO
$\mu_F/\mu_{F,0}=\mu_R/\mu_{R,0}$
$\mu_R=\mu_{R,0}$
$\mu_F=\mu_{F,0}$
10^{-1}
1
10
μ/μ_0


σ_tot (pp→tH⁻+X) [pb]
tanβ = 30
σ_sum
σ_incl,NLO
σ_off-shell
σ_BW
σ_incl,LO
m_t=m_H+m_b±2Γ_t
1
10^-1
150
200
300
400
500
m_H[GeV]


0.006
0.004
0.002
0
0
100
200
$p_{T,t}$[GeV]
$1/\sigma\ d\sigma/dp_{T,t}$
m_H=250GeV
tanβ=30
LO
NLO: μ_F=M/5
NLO: μ_F=10,20 GeV
0.004
0.003
0.002
0.001
0
400
500
600
700
m_{tH}[GeV]
$1/\sigma\ d\sigma/dm_{tH}$
LO
NLO: μ_F=M/5
NLO: μ_F=10,20 GeV


σincl,NLO
σexcl,0.46
σexcl
σexcl,qq
1/σ dσ/dpT,t
mH=250GeV
tanβ=30
0.006
0.004
0.002
0
0
100
200
pT,t[GeV]
σexcl,0.46
σexcl
σincl,NLO
σexcl,qq
1/σ dσ/dmtH
0.004
0.003
0.002
0.001
0
400
500
600
700
mtH[GeV]



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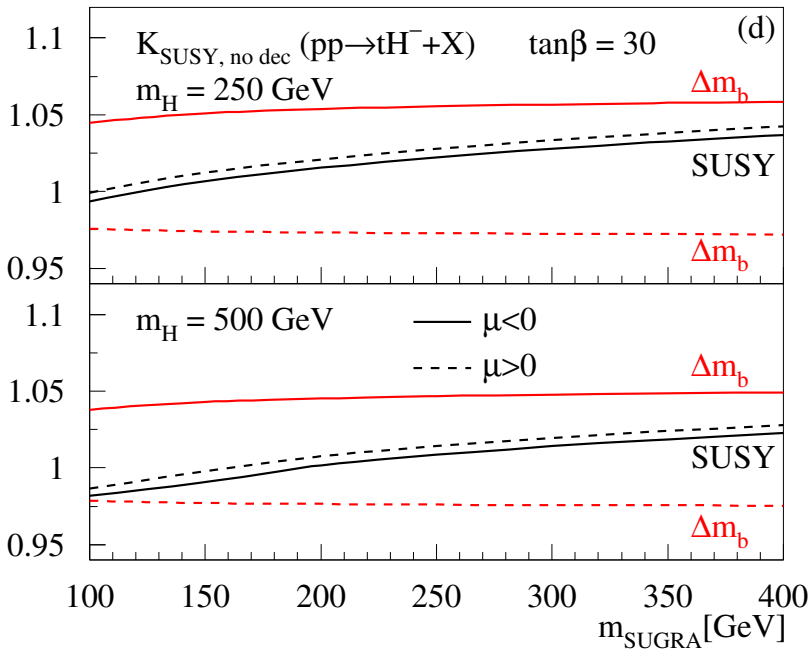
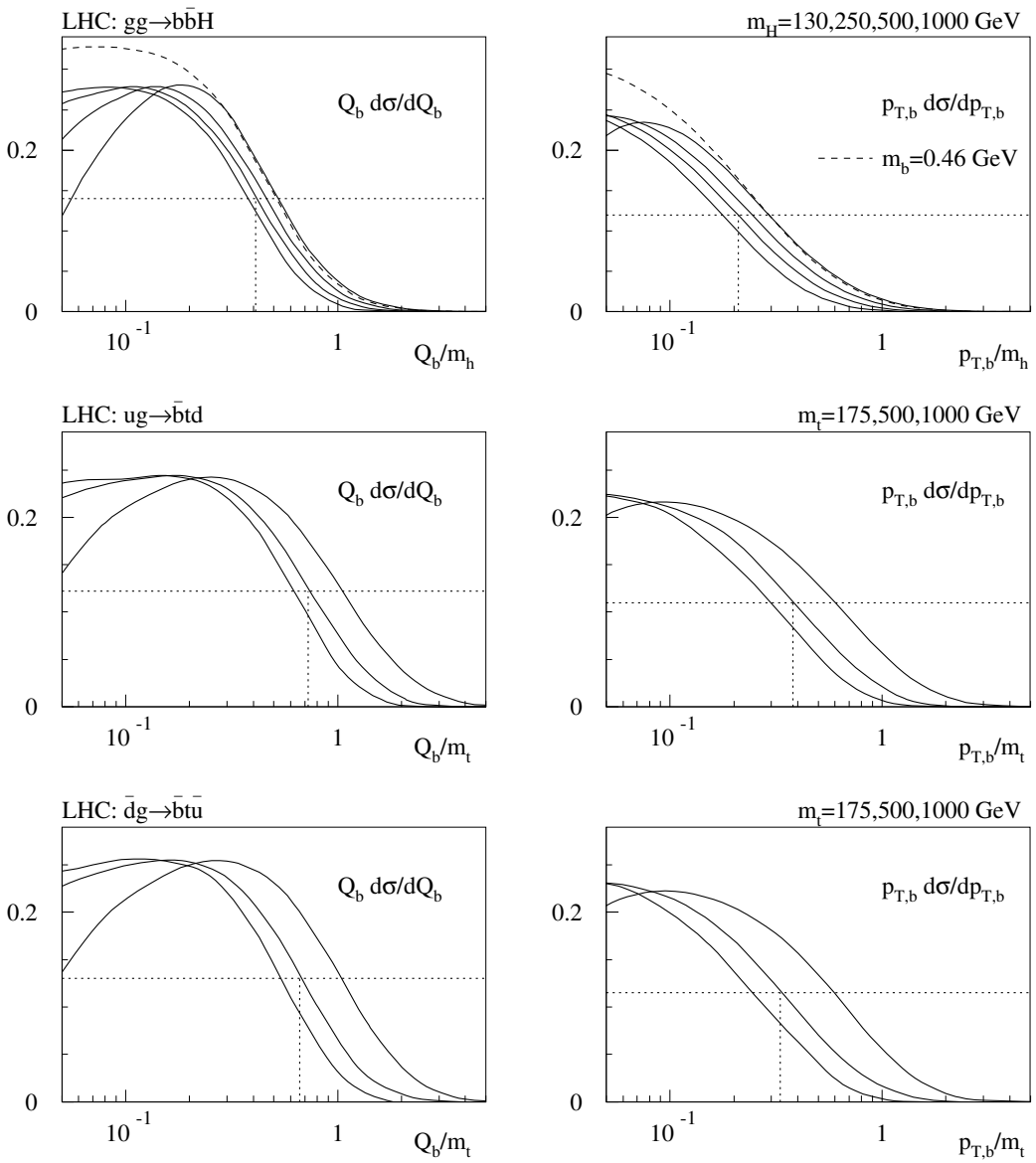
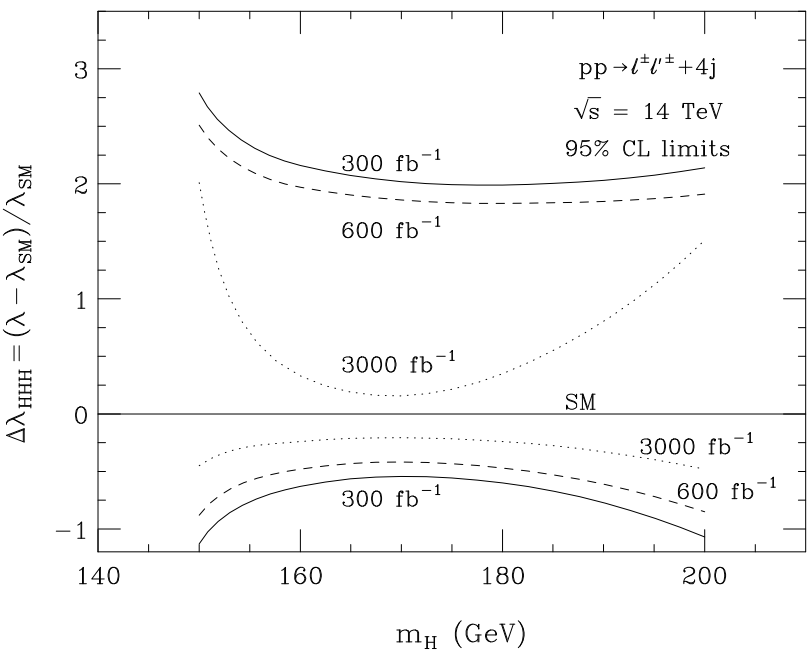
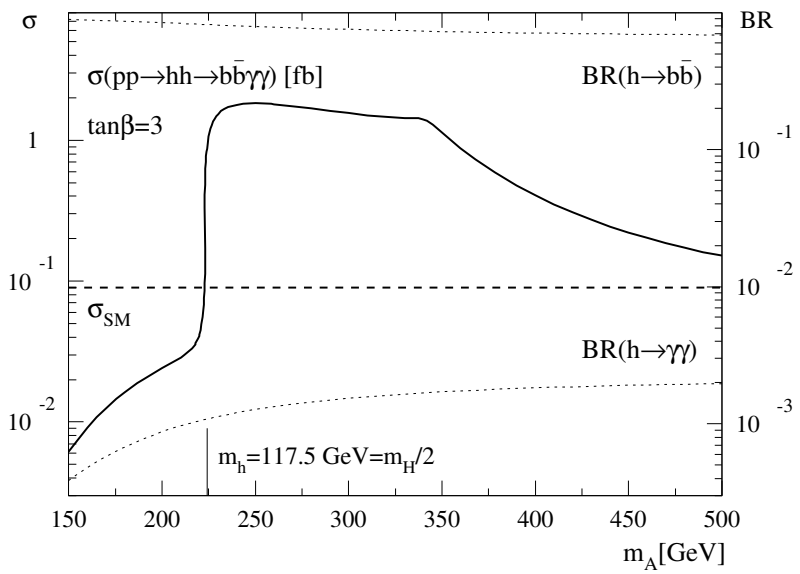

(d)
$K_{SUSY,\ no\ dec}$ (pp→tH$^-$+X)
tanβ = 30
m_H = 250 GeV
Δm_b
SUSY
Δm_b
m_H = 500 GeV
μ<0
μ>0
Δm_b
SUSY
Δm_b
1.1
1.05
1
0.95
100
150
200
250
300
350
400
m_{SUGRA}[GeV]


LHC: gg→bb̄H
m_H=130,250,500,1000 GeV
$Q_b\ d\sigma/dQ_b$
$p_{T,b}\ d\sigma/dp_{T,b}$
m_b=0.46 GeV
0.2
0
10^{-1}
1
Q_b/m_h
$p_{T,b}/m_h$
LHC: ug→b̄td
m_t=175,500,1000 GeV
$Q_b\ d\sigma/dQ_b$
$p_{T,b}\ d\sigma/dp_{T,b}$
0.2
0
10^{-1}
1
Q_b/m_t
$p_{T,b}/m_t$
LHC: d̄g→b̄tū
m_t=175,500,1000 GeV
$Q_b\ d\sigma/dQ_b$
$p_{T,b}\ d\sigma/dp_{T,b}$
0.2
0
10^{-1}
1
Q_b/m_t
$p_{T,b}/m_t$


pp→ℓ±ℓ'±+4j
√s = 14 TeV
95% CL limits
300 fb−1
600 fb−1
3000 fb−1
SM
3000 fb−1
600 fb−1
300 fb−1
3
2
1
0
−1
140
160
180
200
mH (GeV)
ΔλHHH = (λ − λSM)/λSM


σ
BR
σ(pp→hh→bb̄γγ) [fb]
BR(h→bb̄)
tanβ=3
1
10 -1
10 -1
10 -2
σSM
BR(h→γγ)
10 -2
10 -3
mh=117.5 GeV=mH/2
150
200
250
300
350
400
450
500
mA[GeV]