Charged Higgs Production and Bottom Partons

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- MSSM Higgs Bosons at the LHC
- Bottom Parton Description
- Charged Higgs Production at NLO

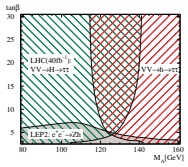
MSSM Higgs Bosons at the LHC

MSSM Higgs Sector

- two doublets predicted by SUSY
  → 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: $(m_b \tan\beta, m_t/\tan\beta)$

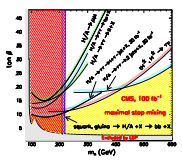
LHC search channels

- multitude of channels [ATLAS TDR (pre-LEP2)]
- complete coverage by WBF $h \to \tau\tau$ [TP, Rainwater, Zeppenfeld]
- mostly light scalar Higgs boson

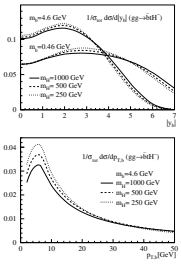


Tell it is 2HDM (MSSM?) ⇒ look for heavy Higgs bosons

- $H^0, A^0 \to \tau\tau, \mu\mu$ inclusive $gg \to \Phi$ and $gg \to b\bar{b}\Phi$
- $H^\pm \to \nu\tau, tb$ in $pp \to tH^-, W^+H^-, H^+H^-$
- apperance in SUSY cascades [Djouadi et al.]
- no other conclusive way but to find these particles



Bottom-Inclusive Cross Sections



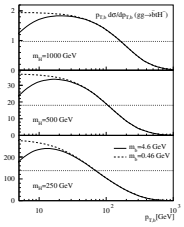
Exclusive production $gg \to \bar{b}tH^-$

– simple example, only one final state bottom jet

→ collinear bottom jets from gluon splitting, regularized by m_b

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

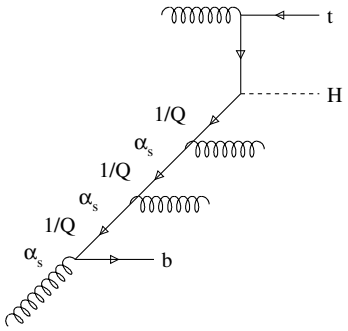
→ use bottom–inclusive cross section



→ possibly large logarithms $\log(p_{T,b}/m_b)$
check asymptotic behavior $d\sigma/dp_{T,b} \propto p_{T,b}/m_{T,b}^2$

→ inclusive total rate $\sigma \propto \log[(p_{T,b}^{\max}/m_b)^2 + 1]$

→ how large logarithms? resum?



Inclusive process $bg \to tH^-$

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

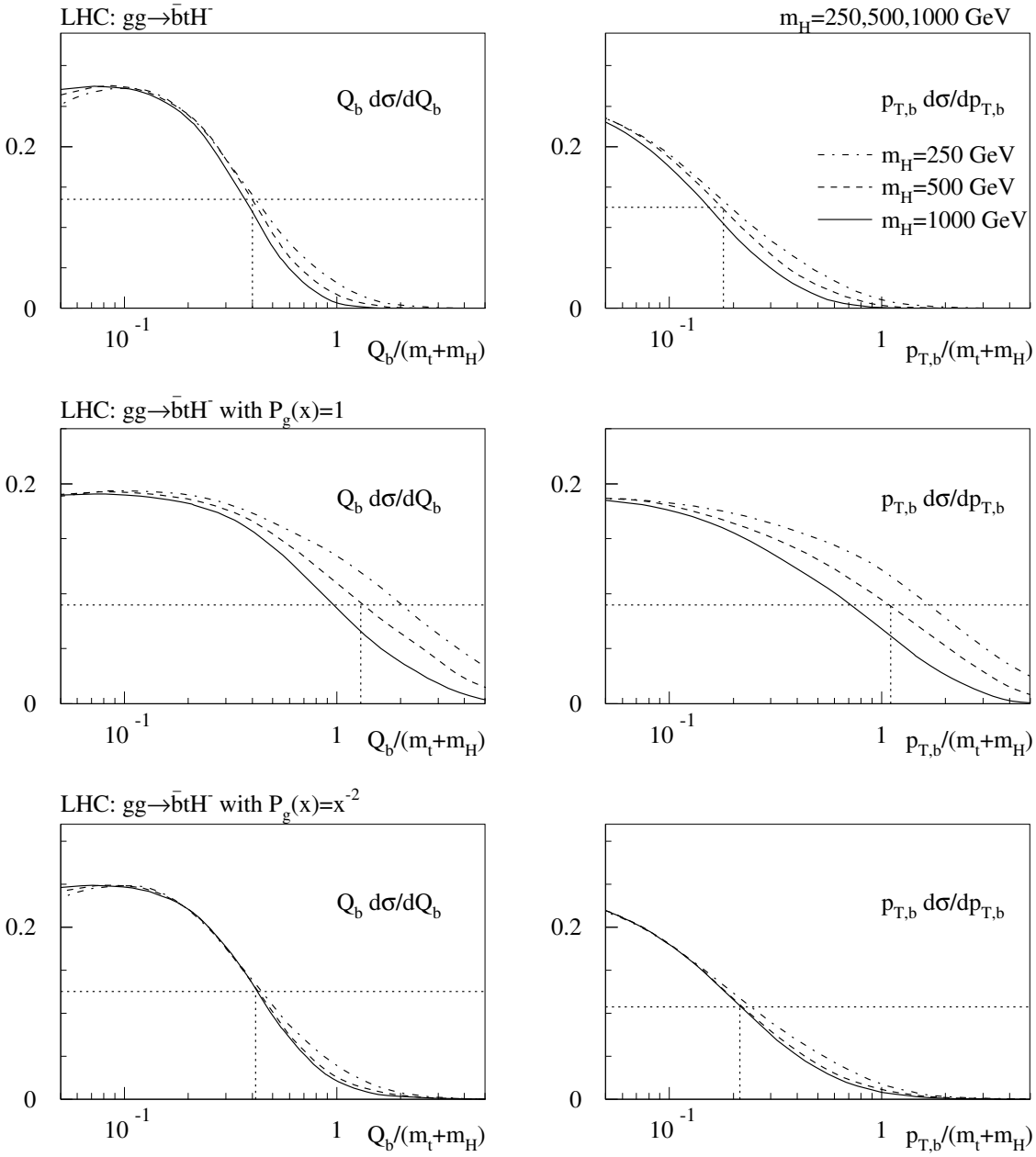
– equivalent to bottom parton density and inclusive process $bg \to tH^-$

– $\mu_{F,b}$ 'transverse momentum size' of inclusive bottom parton
$(\mu_{F,b} \equiv p_{T,b}^{\max})$

– usually matrix elements in limit $m_b \to 0$

→ numerical improvement or overestimate?

→ (1) check bottom–inclusive total rate
(2) check bottom–inclusive t, H distributions


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

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 $d\sigma/dQ_b \sim 1/Q_b$

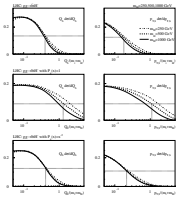
$\to$ $Q_b^{\max} \sim M/2$ (hard scale argument $Q_b^{\max} \propto M$, not more than that!)

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



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

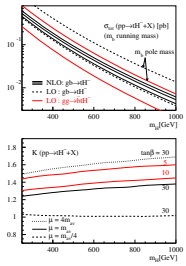
Total Rate: QCD Corrections

Next-to-leading Order QCD Calculation [TP]

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

– complete set of virtual and real SUSY corrections

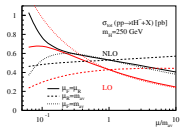
– running Yukawa couplings, everything else misleading



→ 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

→ NLO scale dependence $\pm 20\%$

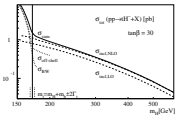
→ well defined limit $\mu_F \to m_b$ returns exclusive process $gg \to \bar{b}tH^-$

Matching at threshold

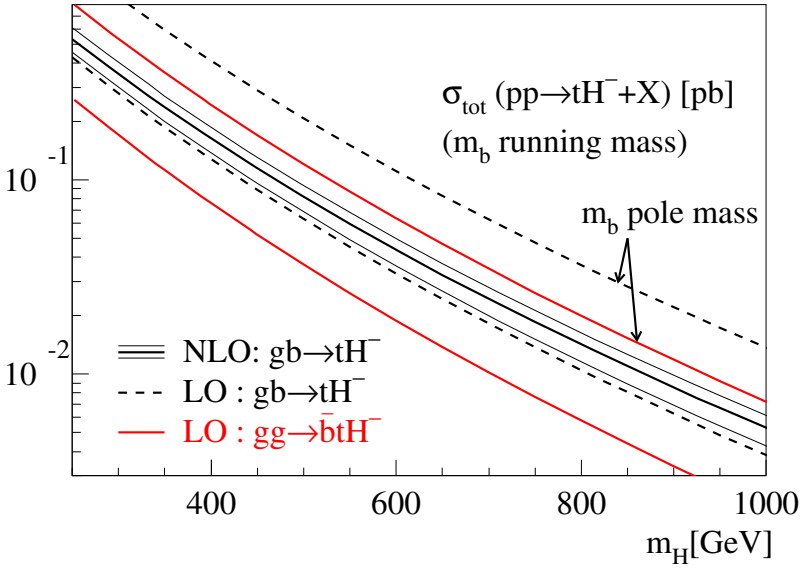
– $m_H < m_t - m_b$: top pair production and Breit–Wigner propagator
$m_H > m_t - m_b$: resummed off-shell process

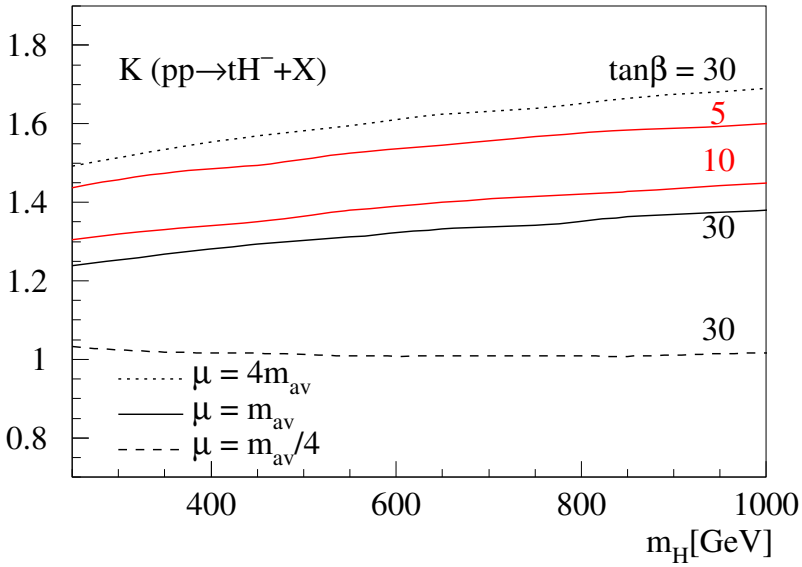
– double counting of $pp \to t\bar{t}^* \to t(\bar{b}H^-)$

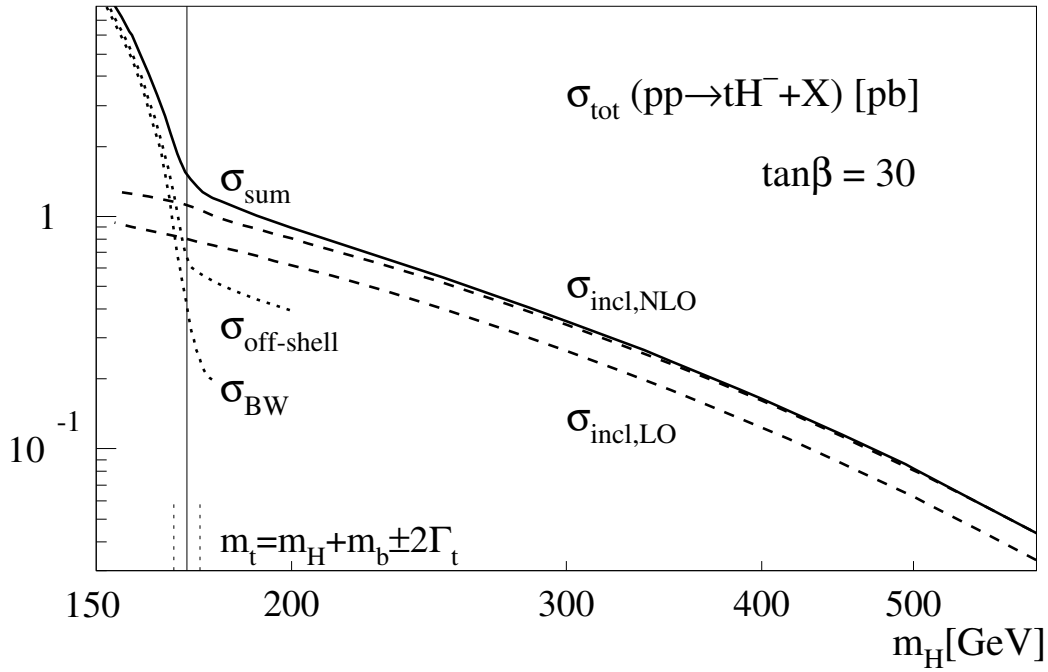
– subtract on-shell top pairs from NLO $bg \to tH^-$ process
(unique in small width approximation, see SUSY-pairs Prospino2.0)



→ consistent matching by simply adding channels


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]


σ_{tot} (pp→tH⁻+X) [pb]
tanβ = 30
σ_{sum}
$\sigma_{incl,NLO}$
$\sigma_{off\text{-}shell}$
σ_{BW}
$\sigma_{incl,LO}$
$m_t=m_H+m_b\pm2\Gamma_t$
1
10^{-1}
150
200
300
400
500
m_H[GeV]

Distributions for Inclusive Process

On to the distributions [Berger, Han, Jiang, TP]

– bottom parton description appropriate for total rate

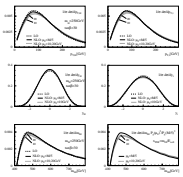
→ Higgs and top distributions?

→ bottom partons established for exclusive cross sections?

(1) Test zero transverse momentum approximation

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

→ compare inclusive process and (massless) exclusive $(2 \to 3)$ process
(as it is part of NLO rate)



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

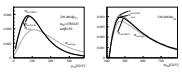
→ slightly harder distributions (due to x dependence of bottom PDF)

(2) Test zero bottom mass approximation

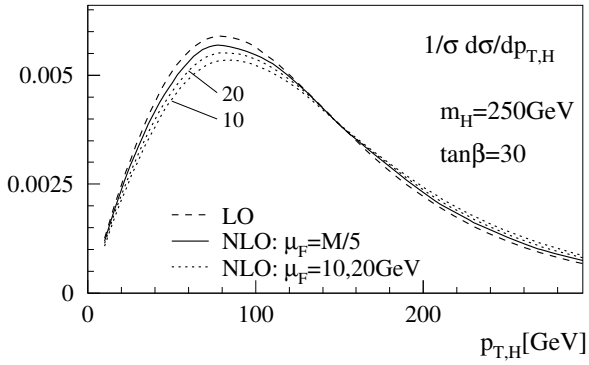
– agreement exclusive vs. inclusive cross section established

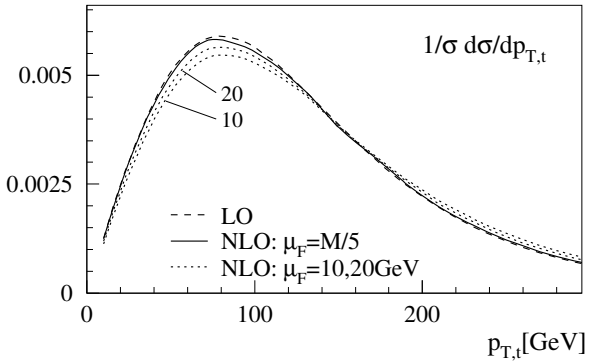
→ check with bottom mass dependent $pp \to \bar{b}tH^-$

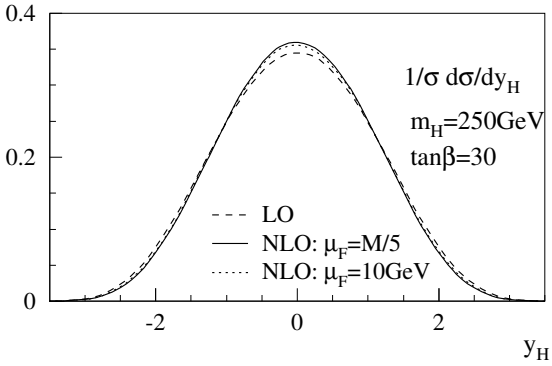
→ perfect agreement with exclusive process for small m_b
very good agreement with physical bottom mass case

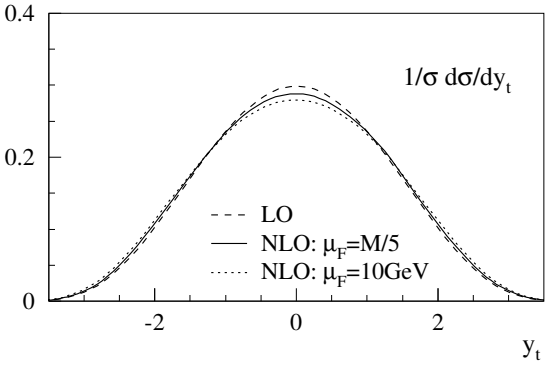


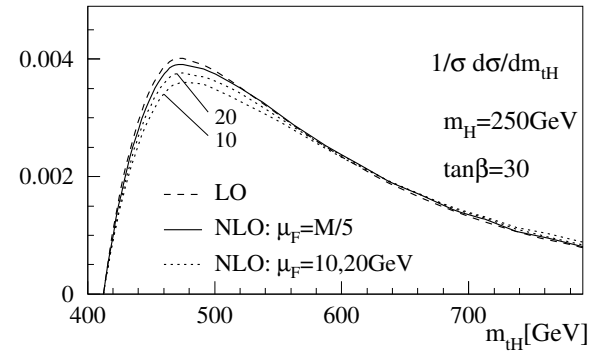
→ bottom parton picture altogether appropriate

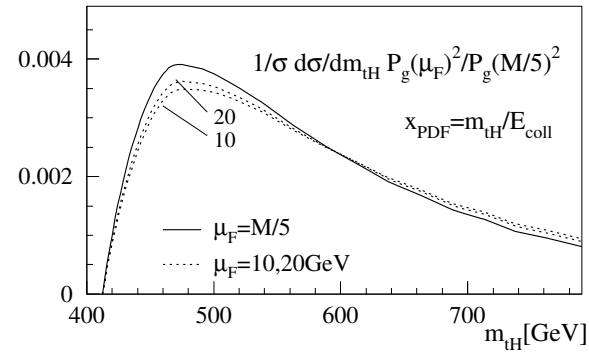

1/σ dσ/dp$_{T,H}$
m$_H$=250GeV
tanβ=30
20
10
LO
NLO: μ$_F$=M/5
NLO: μ$_F$=10,20GeV
0.005
0.0025
0
0
100
200
p$_{T,H}$[GeV]


1/σ dσ/dp$_{T,t}$
20
10
LO
NLO: μ$_F$=M/5
NLO: μ$_F$=10,20GeV
0.005
0.0025
0
0
100
200
p$_{T,t}$[GeV]


1/σ dσ/dy$_H$
m$_H$=250GeV
tanβ=30
LO
NLO: μ$_F$=M/5
NLO: μ$_F$=10GeV
0.4
0.2
0
-2
0
2
y$_H$


1/σ dσ/dy$_t$
LO
NLO: μ$_F$=M/5
NLO: μ$_F$=10GeV
0.4
0.2
0
-2
0
2
y$_t$


1/σ dσ/dm$_{tH}$
m$_H$=250GeV
tanβ=30
20
10
LO
NLO: μ$_F$=M/5
NLO: μ$_F$=10,20GeV
0.004
0.002
0
400
500
600
700
m$_{tH}$[GeV]


1/σ dσ/dm$_{tH}$ P$_g$(μ$_F$)^2/P$_g$(M/5)^2
x$_{PDF}$=m$_{tH}$/E$_{coll}$
20
10
μ$_F$=M/5
μ$_F$=10,20GeV
0.004
0.002
0
400
500
600
700
m$_{tH}$[GeV]

Conclusions

- heavy Higgs bosons necessary to tell it might be the MSSM
- bottom initiated process $bg \to tH^-$ appropriate
  with proper factorization scale $\mu_{F,b} \sim M/5$
- NLO_1: inclusive process well defined
  NLO_{2a}: total cross section prediction improved
  NLO_{2b}: distributions predicted correctly
  NLO_3: $30\% \cdots 40\%$ enhancement of σ_{tot} in 2HDM
  NLO_4: remaining scale uncertainty $\lesssim 20\%$
  NLO_5: Δ_b corrections dominant in MSSM for large $\tan\beta$
  NLO_6: part of Prospino2.1

SUSY-QCD Corrections

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

– infrared finite but ultraviolet divergent SUSY loop contributions

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

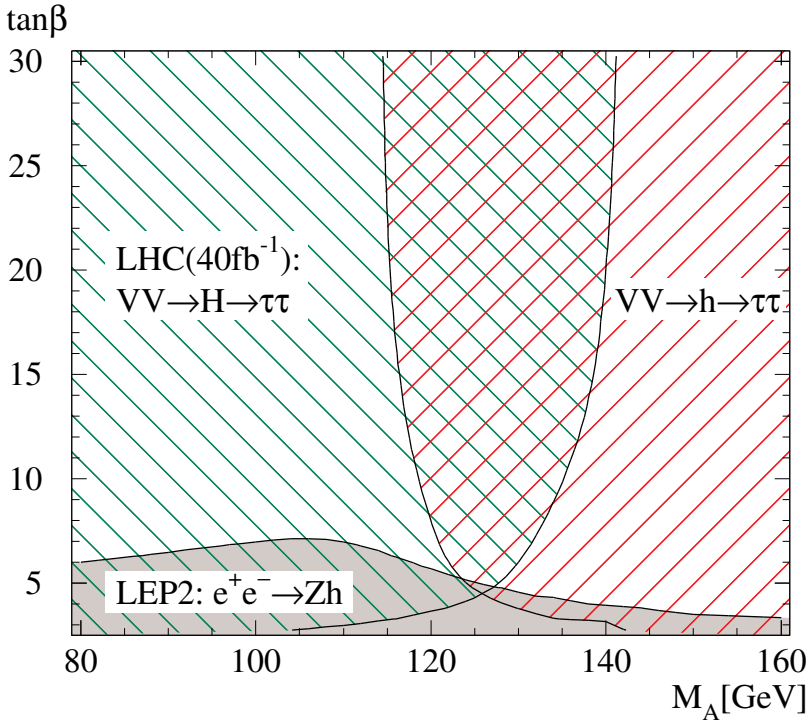
[Carena, Garcia, Nierste, Wagner; Guasch, Häflinger, Spira]

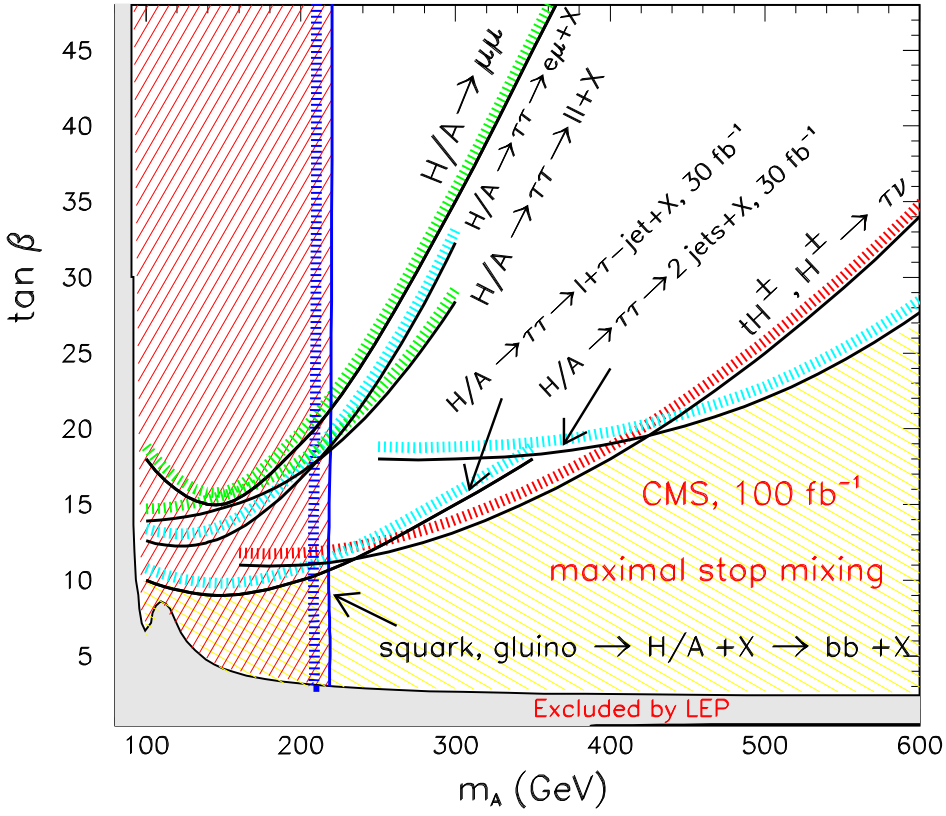
(2) remaining explicit SUSY loop diagrams

	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%

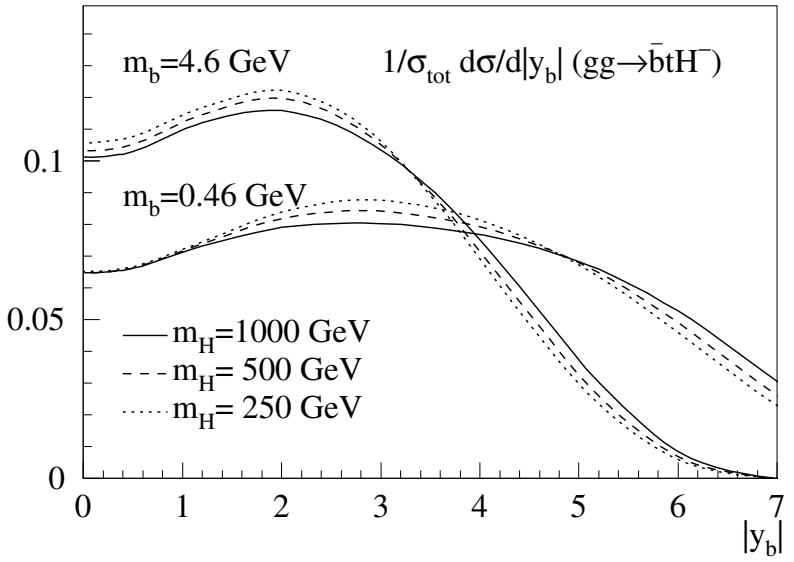
→ Δm_b corrections dominant for $\tan\beta \gtrsim 10$ (dependent on sign of μ)

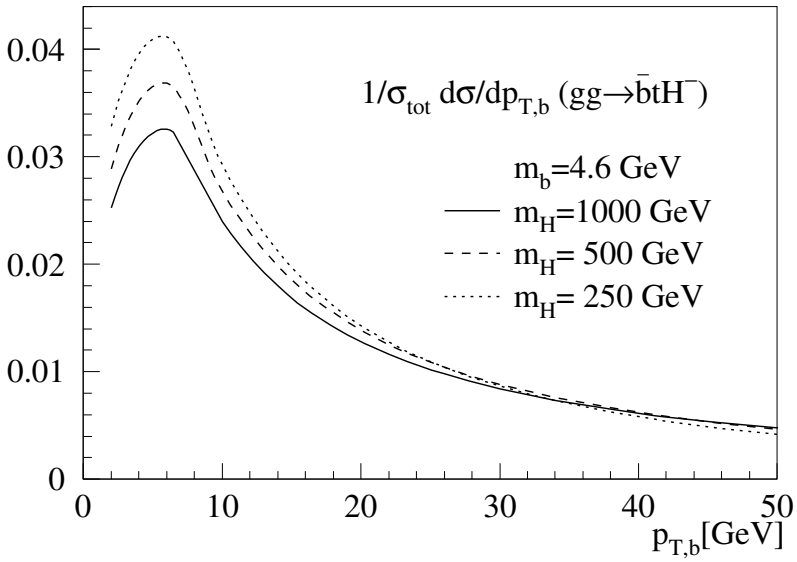
→ explicit loop corrections negligible $\lesssim 10\%$ for generic mSUGRA

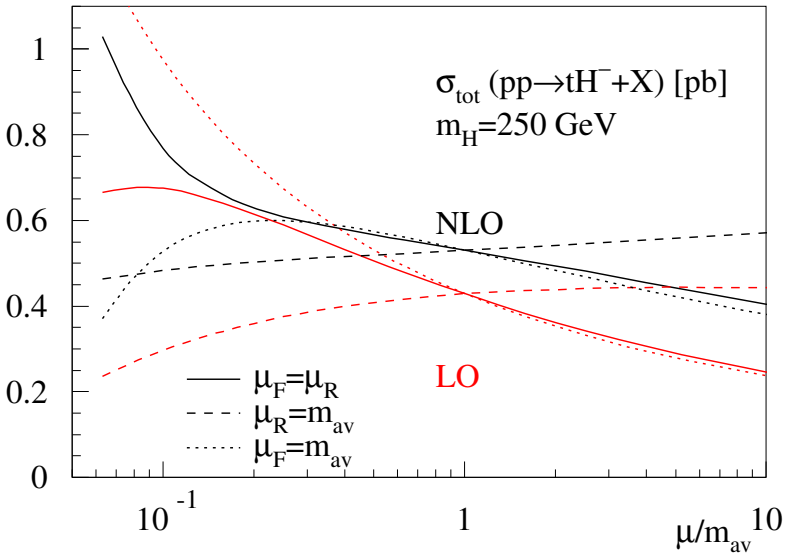

tanβ
30
25
20
15
10
5
LHC(40fb-1):
VV→H→ττ
VV→h→ττ
LEP2: e+e−→Zh
80
100
120
140
160
MA[GeV]

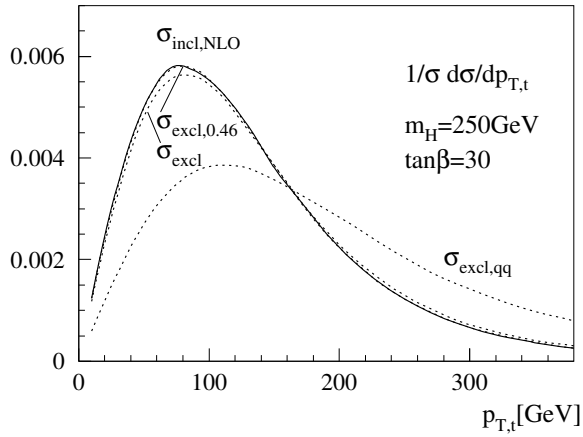


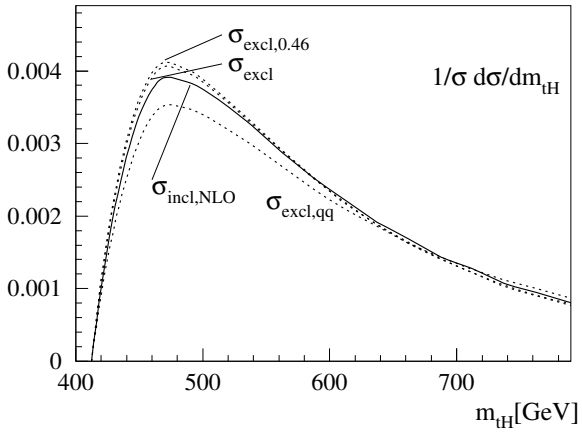
Datta, Djouadi, Guchait, Moortgat


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]


1
0.8
0.6
0.4
0.2
0
σ_{tot} (pp→tH⁻+X) [pb]
m_H=250 GeV
NLO
LO
$\mu_F=\mu_R$
$\mu_R=m_{av}$
$\mu_F=m_{av}$
10^{-1}
1
10
μ/m_{av}


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
300
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]