MSSM Higgs Boson Production via Bottom Partons

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– Charged Higgs: bottom induced process

– Total rate

– Top and Higgs distributions

MSSM Higgs Bosons at the LHC

MSSM Higgs Sector

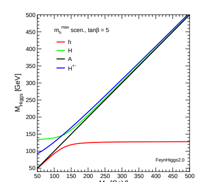
– Softly broken supersymmetric anomaly–free theory

– two doublets, coupling to up and down type fermions
$\longrightarrow$ five physical states $h^o, H^o, A^o, H^\pm$
$\longrightarrow$ mixing of scalars to mass eigenstates (mixing angle α)
$\longrightarrow$ 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)

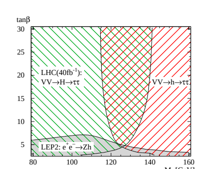
– typically one light, many heavy scalars [Heinemeyer, Weiglein]



Find first Higgs boson

– complete coverage by WBF $h \to \tau\tau$ [TP, Rainwater, Zeppenfeld; Schumacher]

– 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 $\tau\tau$)



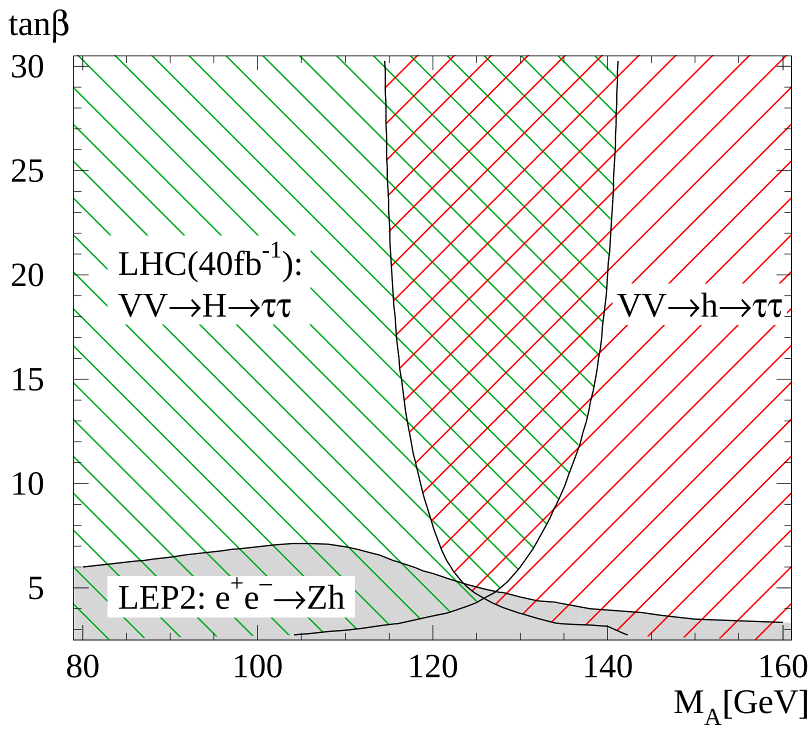
Tell it is 2HDM (MSSM?) $\Rightarrow$ look for heavy Higgs bosons

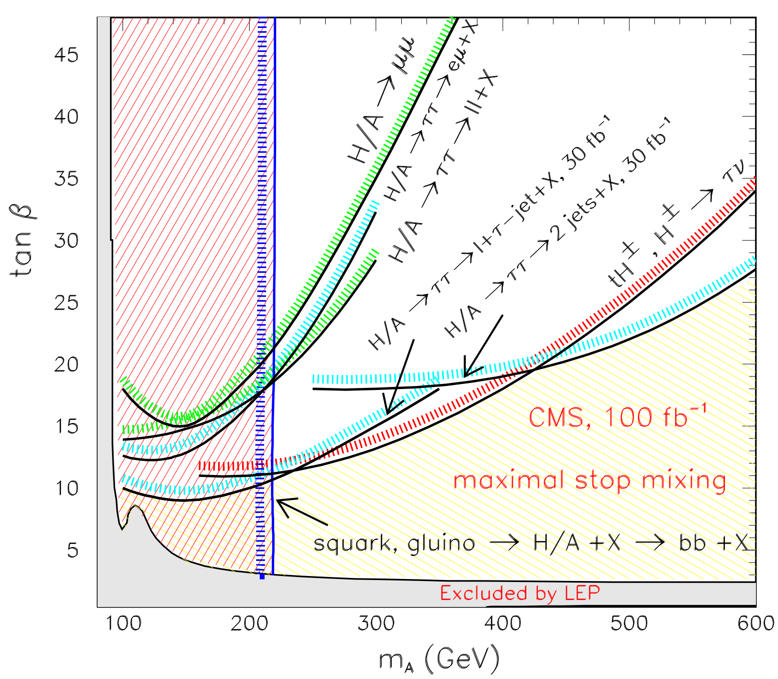
– $H^0, A^0 \to \tau\tau, \mu\mu$ inclusive $gg \to H$ and $gg \to b\bar{b}H$

– $H^\pm \to \nu\tau, tb$ 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


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]



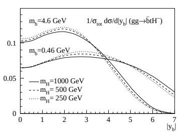
tan β
m_A (GeV)
45
40
35
30
25
20
15
10
5
100
200
300
400
500
600
H/A → μμ
H/A → ττ → eμ+X
H/A → ττ → ll+X
H/A → ττ → l+τ-jet+X, 30 fb⁻¹
H/A → ττ → 2 jets+X, 30 fb⁻¹
tH±, H± → τν
CMS, 100 fb⁻¹
maximal stop mixing
squark, gluino → H/A +X → bb +X
Excluded by LEP

(Heavy) Charged Higgs

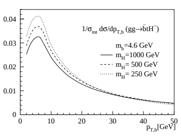
Most promising channel

– 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

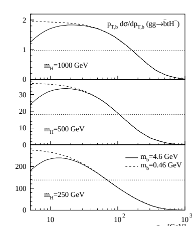
$\to$ experiment: forward jets, $p_{T,b}$ peaked at m_b (factor $1/6$ for each tagged b)

$\to$ use bottom–inclusive cross section

$\to$ check asymptotic cross section behavior $d\sigma/dp_{T,b} \propto 1/p_{T,b}$

$\to$ 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 $bg \to tH^-$

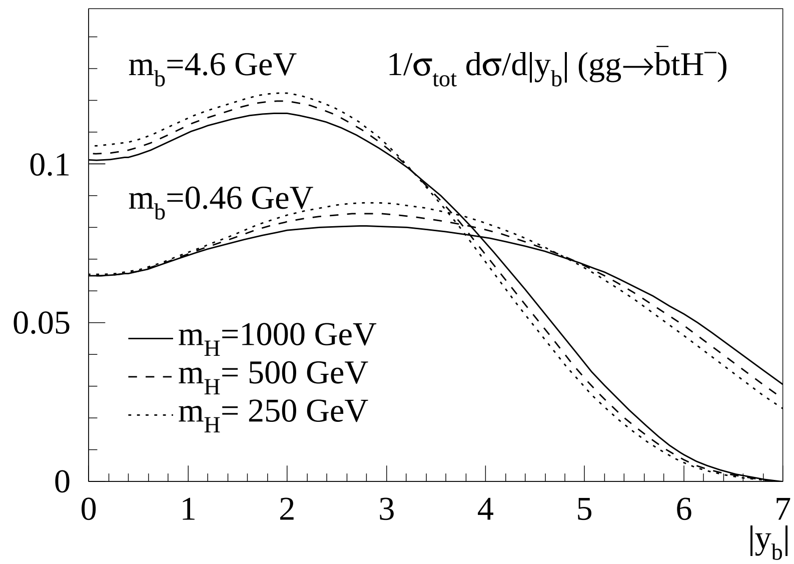
$\to$ $\mu_{F,b}$ ‘transverse momentum size’ of bottom parton

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

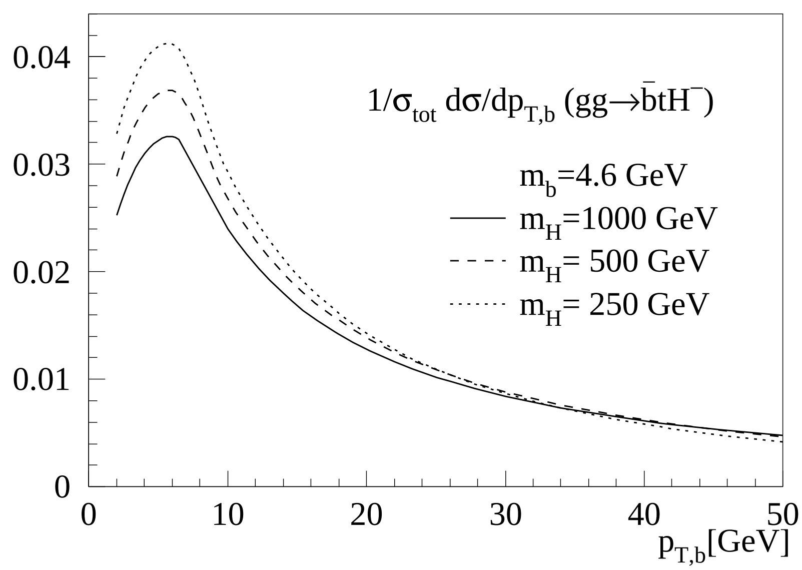
$\to$ numerical improvement or overestimate?

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

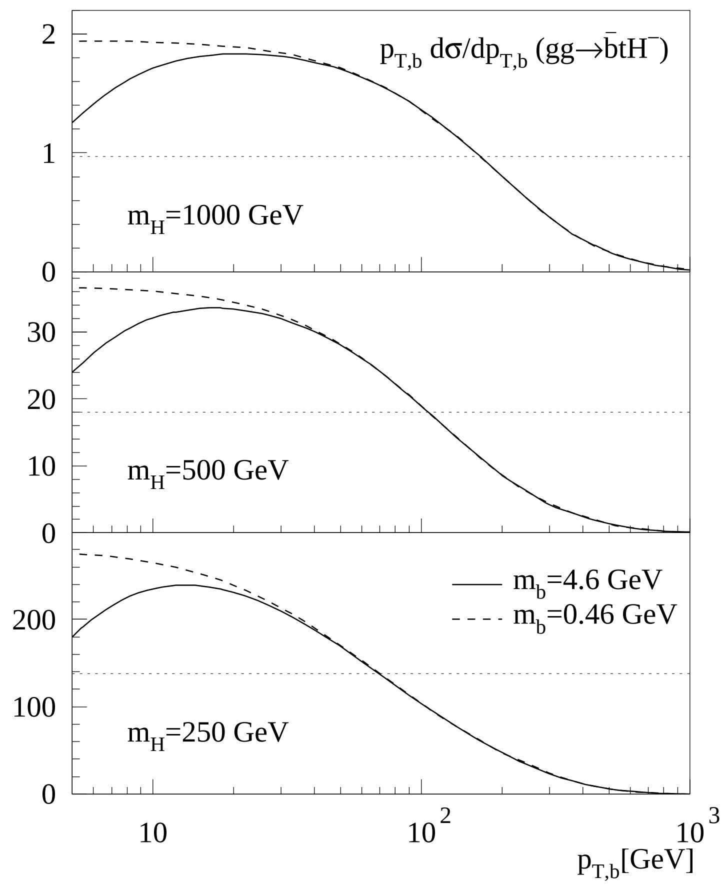
(2) check bottom–inclusive t, H distributions



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
$|y_b|$



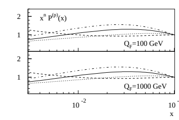
$1/\sigma_{tot}\, d\sigma/dp_{T,b}$ ($gg\to\bar{b}tH^-$)
m_b=4.6 GeV
m_H=1000 GeV
m_H= 500 GeV
m_H= 250 GeV
0.04
0.03
0.02
0.01
0
0
10
20
30
40
50
$p_{T,b}$[GeV]



$p_{T,b}\, d\sigma/dp_{T,b}\ (gg\to\bar{b}tH^-)$
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]

Total Rate: Bottom Factorization Scale

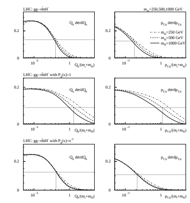
Perturbative bottom factorization scale from exclusive process [Boos, TP]



– two steps: first bottom virtuality $Q_b^{\max}$

– general exclusive process: $gg \to \bar{b} X_M$

asymptotic behavior $\overline{|\mathcal{M}|^2} = S^2 \sigma_0 / Q_b^2$; $\mathcal{L} = \mathcal{L}_0 / x^2$



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

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

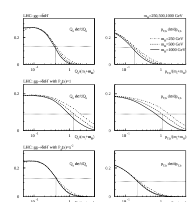
$\to$ define $Q_b^{\max}$ at turning point $d^2F(Q_b)/d(\log Q_b)^2 = 0$

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

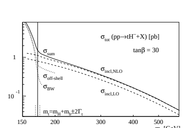
(numerical study of $gg \to \bar{b}tH^-$: $\mu_{F,b} \sim M/5$)

So what did we learn from exclusive process?

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

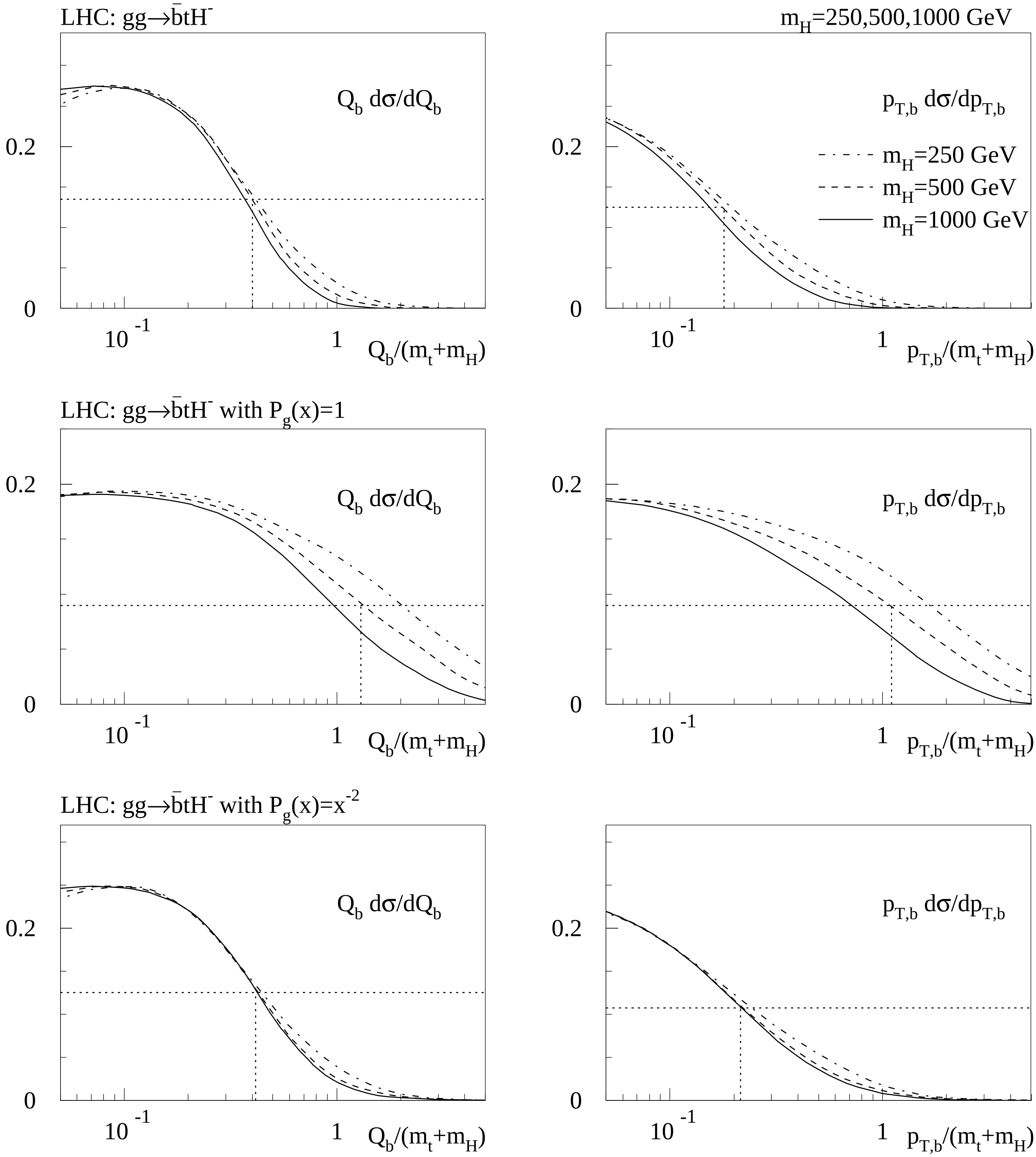
but 'large' logs at maximum $\log(M/(5m_b))$ [TP; Maltoni, Willenbrock]

– gg and bg processes: $\mu_{F,b} \sim M/5$ from partonic phase space



$\Rightarrow$ Total cross section with bottom partons understood

[Dittmaier, Spira, Krämer]


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

Distributions for Inclusive Process

On to the distributions (preliminary)

– bottom parton description appropriate for total rate

→ Higgs and top distributions?

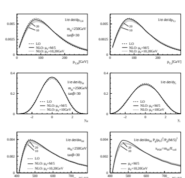
→ bottom partons established for exclusive cross sections?

(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 $gg \to \bar{b}tH^-$



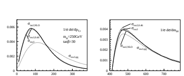
→ slightly harder distributions (due to x dependence of bottom PDF)

(2) Zero bottom mass

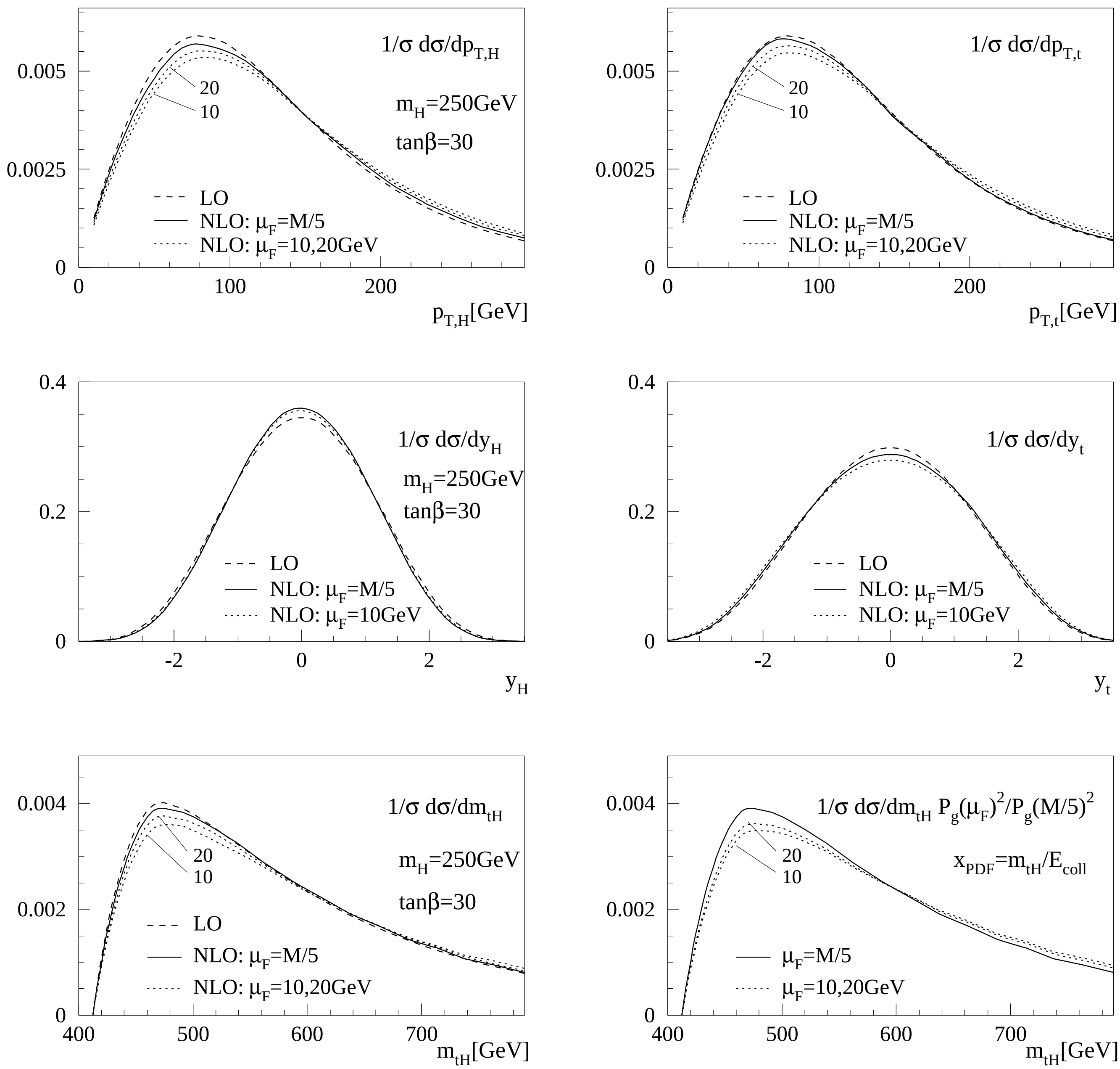
– agreement exclusive vs. inclusive cross section established

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

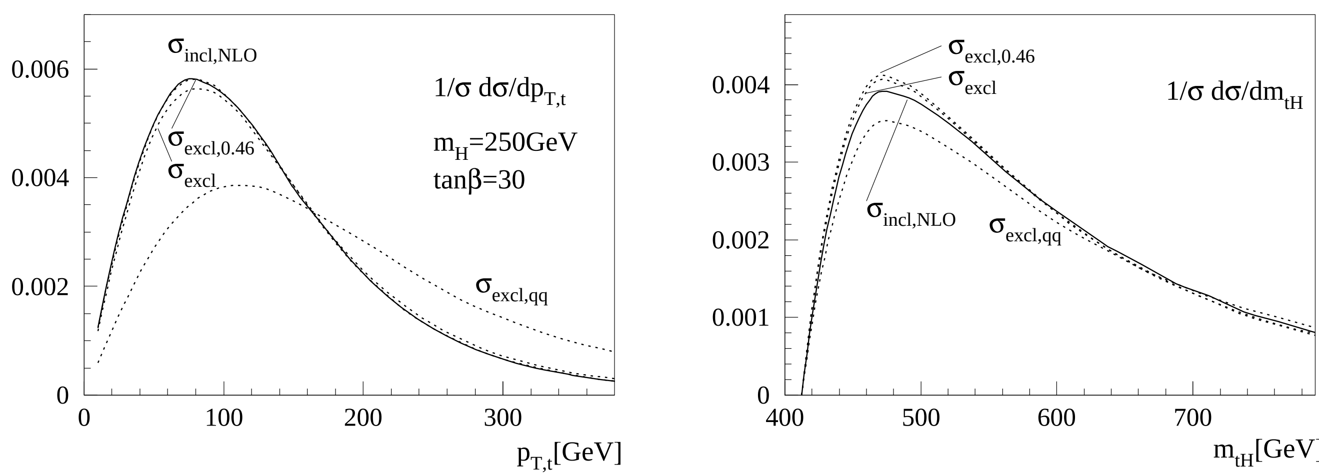
→ perfect agreement with exclusive process for small m_b
very good agreement with physical bottom mass case



→ Bottom parton picture altogether appropriate



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]



σincl,NLO
1/σ dσ/dpT,t
mH=250GeV
tanβ=30
σexcl,0.46
σexcl
σexcl,qq
0.006
0.004
0.002
0
0
100
200
300
pT,t[GeV]
σexcl,0.46
σexcl
1/σ dσ/dmtH
σincl,NLO
σexcl,qq
0.004
0.003
0.002
0.001
0
400
500
600
700
mtH[GeV]

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			$(\Delta_b)_{\text{resum}}$	non–Δ_b
1a	100	250	10	420	477			-10.2%	3.0%
1b	200	400	30	511	535			-23.5%	-0.1%
2	1450	300	10	425	1503			-0.9%	-1.0%
3	90	400	10	633	719			-9.5%	3.0%
4	400	300	50	389	357			-31.0%	-0.4%
5	150	300	5	637	697			-8.0%	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	-9.5%	3.0%
	Λ	M_{mes}	N_{mes}	$\tan\beta$	μ	m_H			
7	40×10^3	80×10^3	3	15	316	476		-8.1%	0.5%
8	100×10^3	200×10^3	1	15	421	538		-7.1%	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

(Heavy) Neutral Higgs

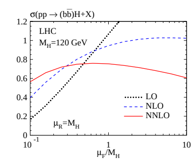
Bottom induced production of neutral Higgses

– 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



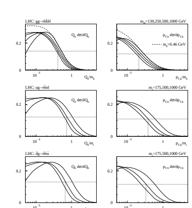
– check: exclusive vs. inclusive total rate [Dittmaier, Spira, Krämer]

	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

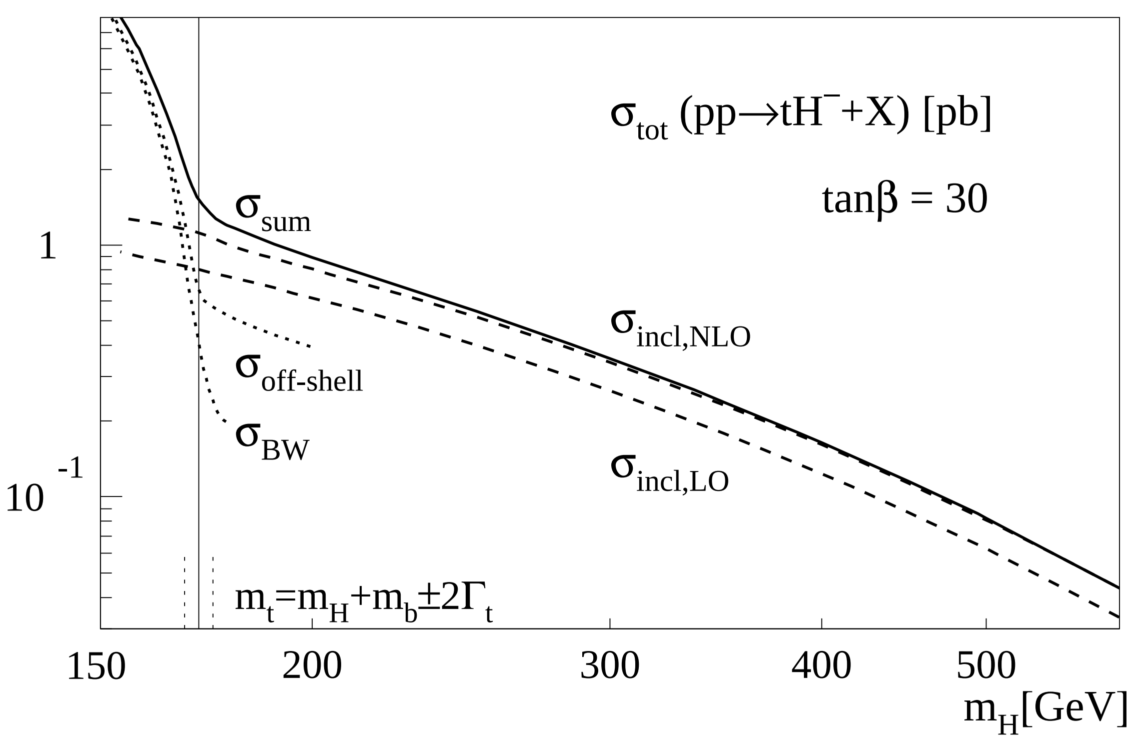
Conclusions

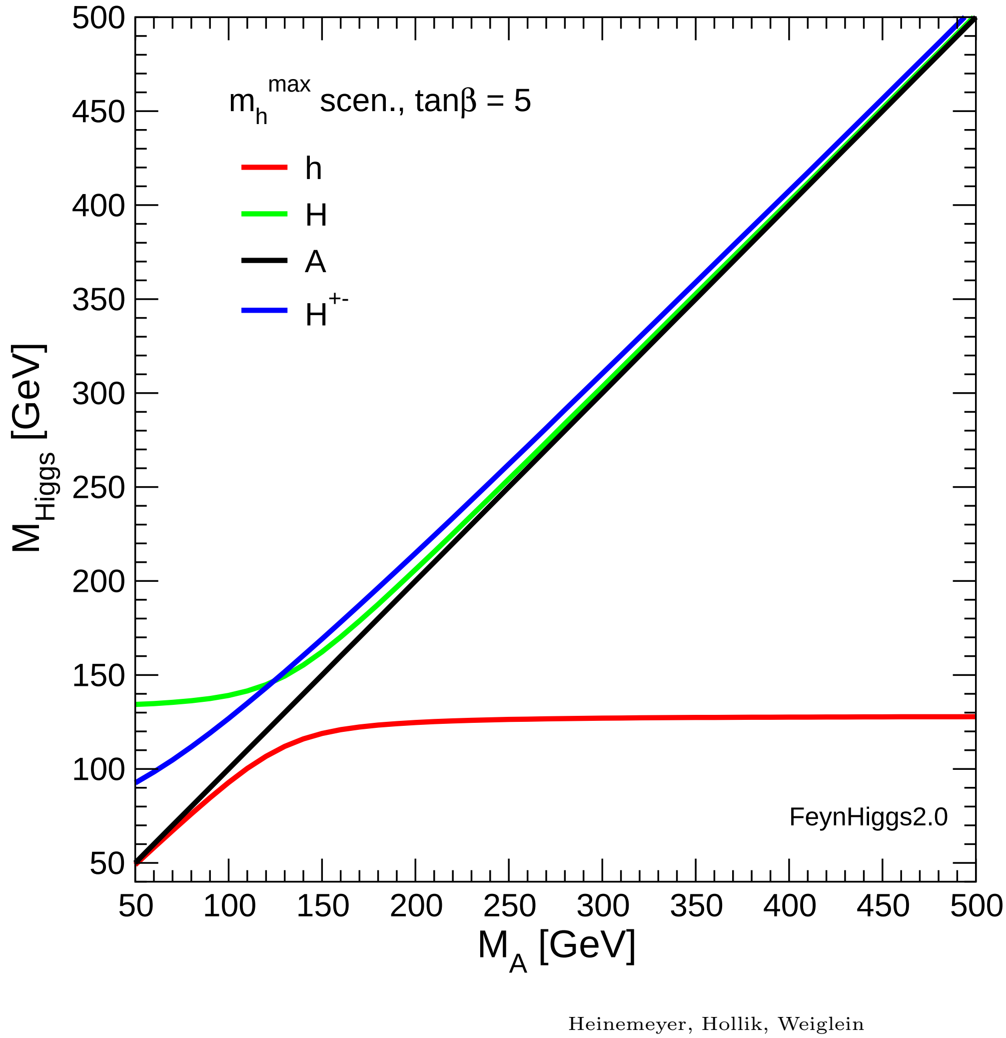
Bottom parton picture works fine

– total rate correct with appropriate factorization scale

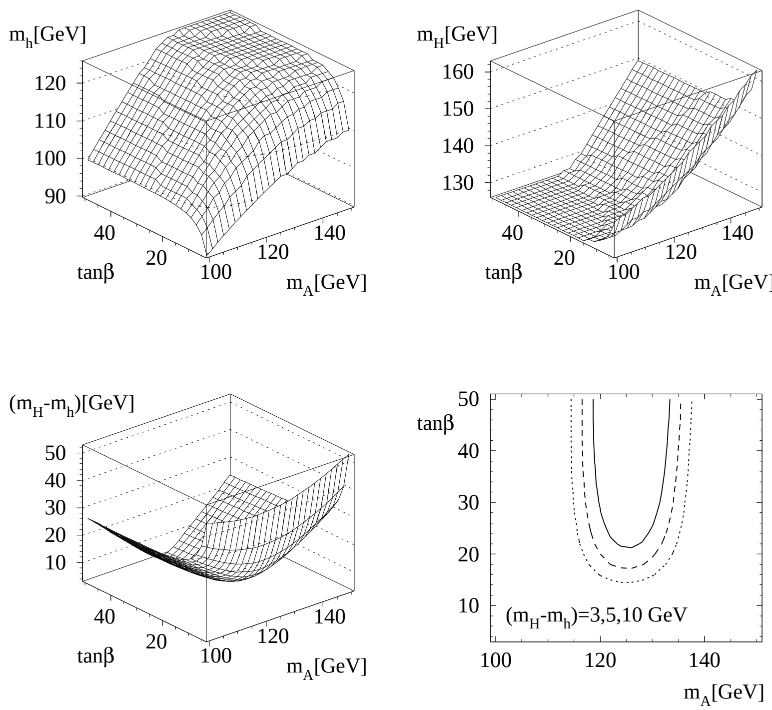
– top and Higgs distributions correctly described

– we also understand why

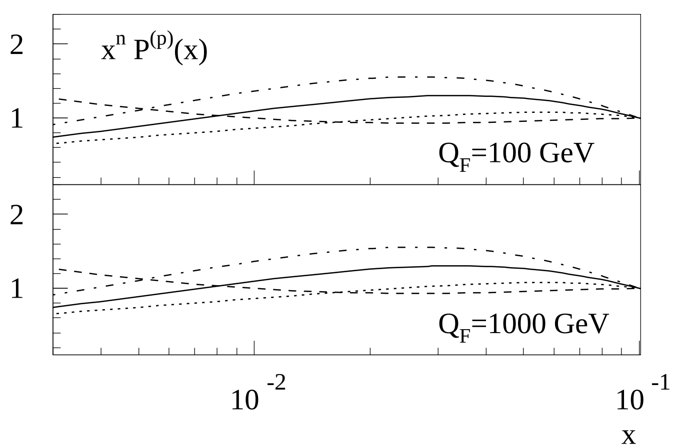




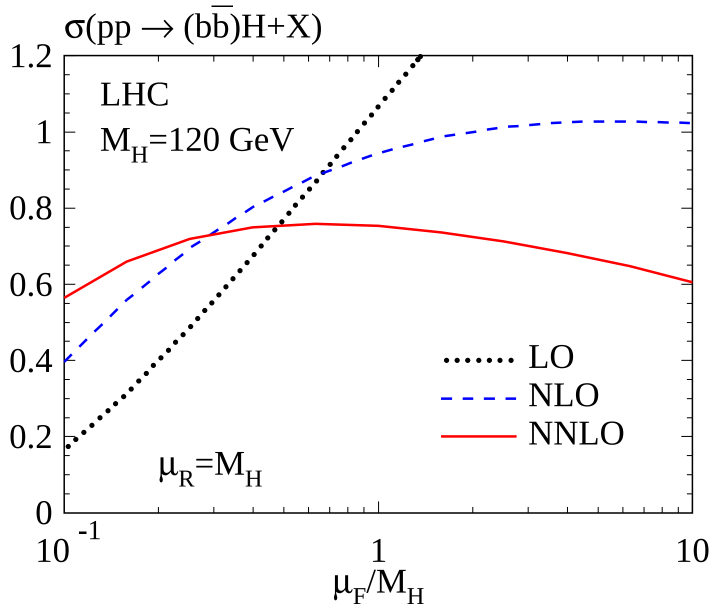
m_h^max scen., tanβ = 5
h
H
A
H^+-
FeynHiggs2.0
M_Higgs [GeV]
M_A [GeV]
50
100
150
200
250
300
350
400
450
500
Heinemeyer, Hollik, Weiglein



m_h[GeV]
120
110
100
90
40
20
tanβ
100
120
140
m_A[GeV]
m_H[GeV]
160
150
140
130
40
20
tanβ
100
120
140
m_A[GeV]
(m_H-m_h)[GeV]
50
40
30
20
10
40
20
tanβ
100
120
140
m_A[GeV]
tanβ
50
40
30
20
10
(m_H-m_h)=3,5,10 GeV
100
120
140
m_A[GeV]



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



Harlander, Kilgore