Searching for Supersymmetric Higgs Bosons at the LHC

Tilman Plehn

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

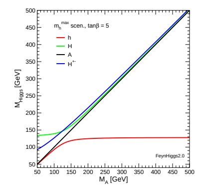
– Softly broken supersymmetric anomaly–free theory

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

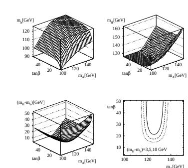
– typically one light, many heavy scalars [Heinemeyer, Weiglein]



Find first Higgs boson

– complete coverage by WBF $h \rightarrow \tau\tau$ [TP, Rainwater, Zeppenfeld]

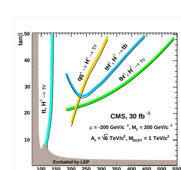
– problem: mass degeneracy [Boos, Djouadi, Mühlleitner, Nikitenko]
$\Delta m_h/m_h \sim \sigma/\sqrt{N}$ ($\sigma \sim 1.5$ GeV for $\mu\mu, \gamma\gamma$ and $\sigma \sim 15$ GeV for $\tau\tau$)



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

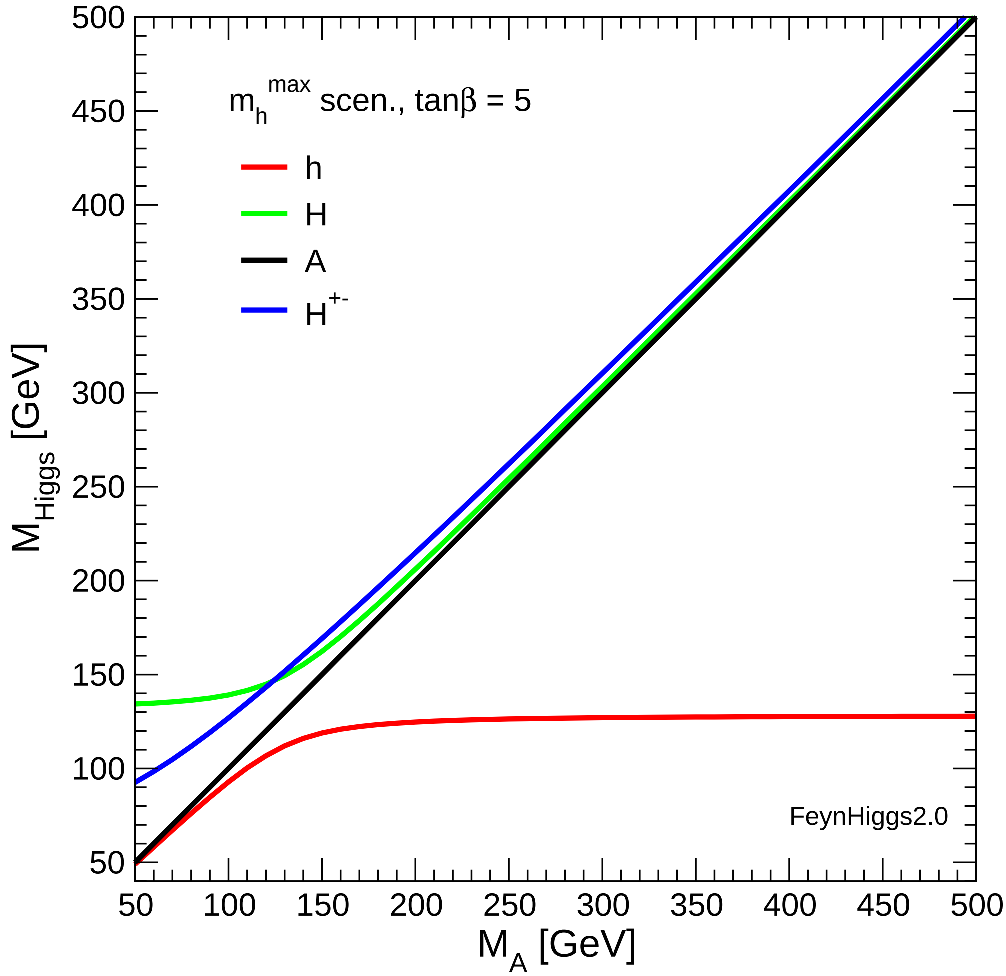
– $H^0, A^0 \rightarrow \tau\tau, \mu\mu$ inclusive $gg \rightarrow H$ and $gg \rightarrow b\bar{b}H$

– $H^\pm \rightarrow \nu\tau, tb$ in $pp \rightarrow tH^-, W^+H^-, H^+H^-$
(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



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

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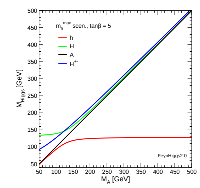

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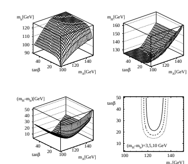

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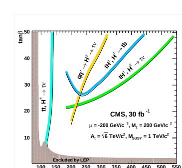

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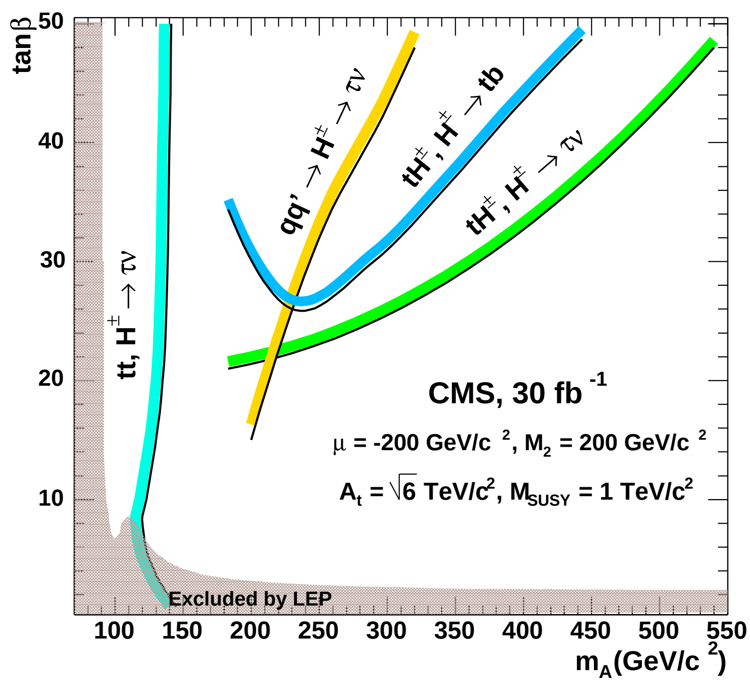


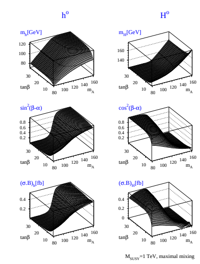
tanβ
50
40
30
20
10
100
150
200
250
300
350
400
450
500
550
m_A(GeV/c^2)
tt, $H^\pm \rightarrow \tau\nu$
qq' $\rightarrow H^\pm \rightarrow \tau\nu$
$tH^\pm$, $H^\pm \rightarrow tb$
$tH^\pm$, $H^\pm \rightarrow \tau\nu$
CMS, 30 fb^{-1}
μ = -200 GeV/c^2, M_2 = 200 GeV/c^2
$A_t = \sqrt{6}$ TeV/c^2, M_{SUSY} = 1 TeV/c^2
Excluded by LEP

1. Light Neutral Higgs

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

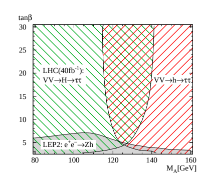
– SM cross section > 3 pb for light Higgs in $qq \to qqH$
(tagging jet signature, central decay products, minijet veto)

– 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

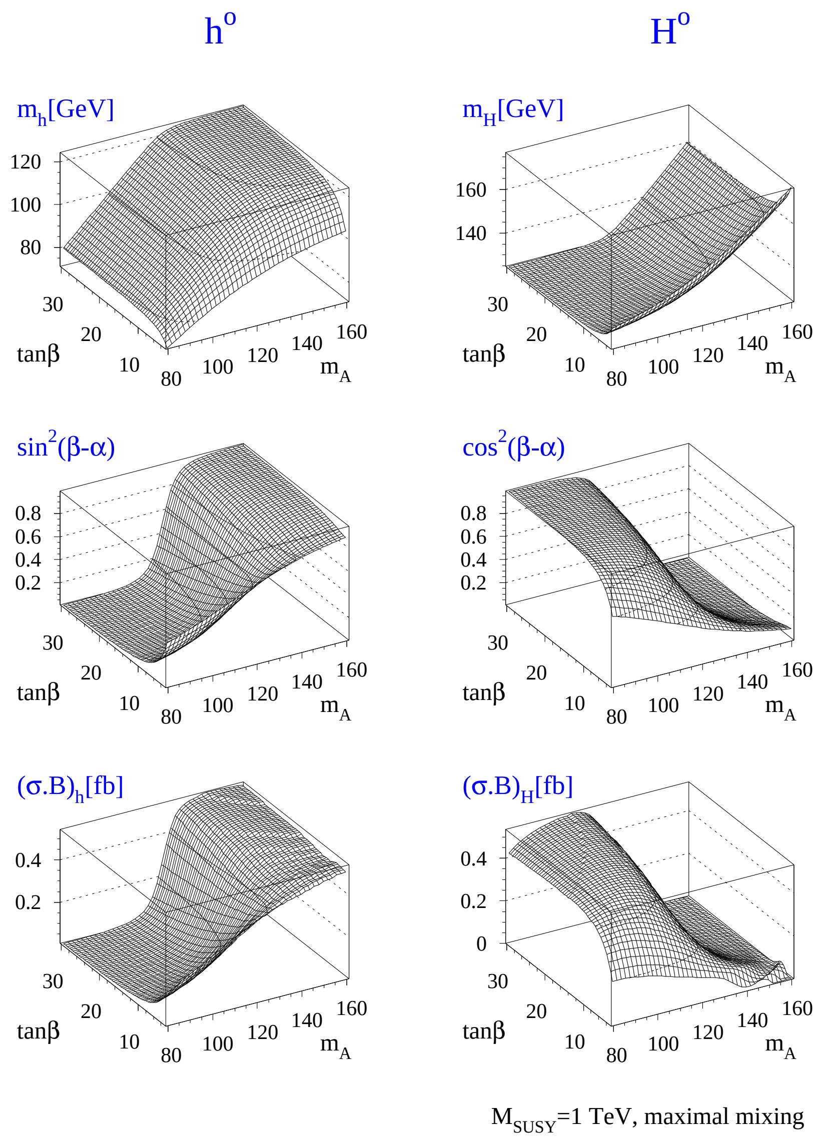
– $m_A = 91$ GeV and $m_h = 95$ GeV: wide open channel for H

– 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]



h°
H°
m_h[GeV]
m_H[GeV]
sin²(β-α)
cos²(β-α)
(σ.B)_h[fb]
(σ.B)_H[fb]
tanβ
m_A
M_SUSY=1 TeV, maximal mixing

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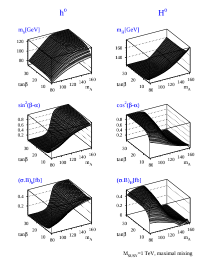

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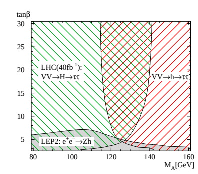

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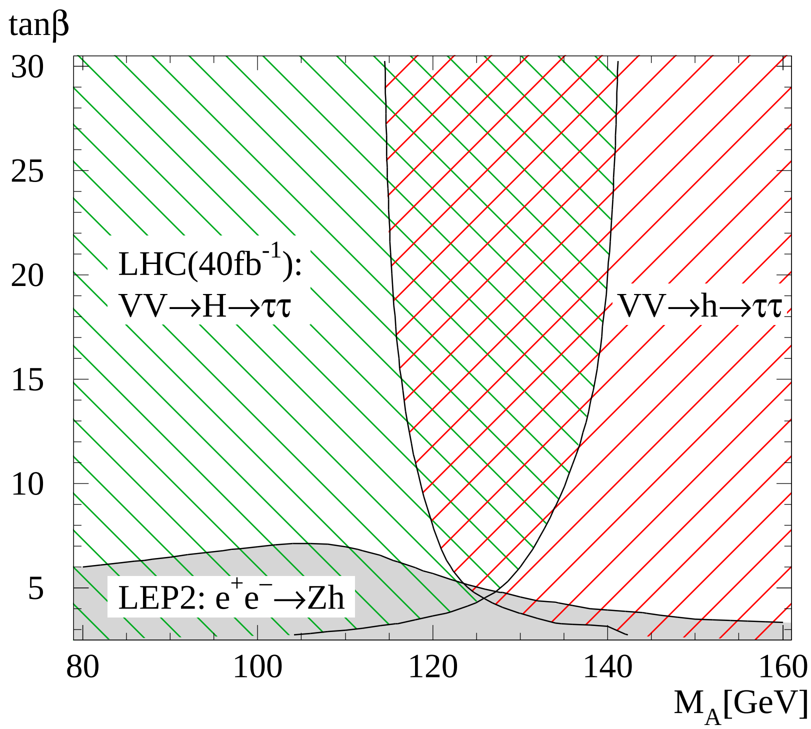

tanβ
30
25
20
15
10
5
LHC(40fb-1):
VV→H→ττ
VV→h→ττ
LEP2: e+e-→Zh
80
100
120
140
160
MA[GeV]

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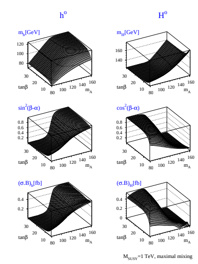

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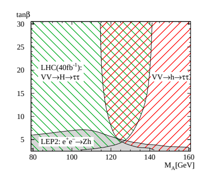

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2. (Heavy) Charged Higgs

Most promising channel

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

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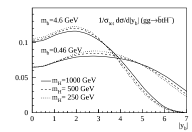

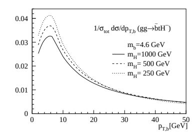

Exclusive production $gg \to \bar{b}tH^-$

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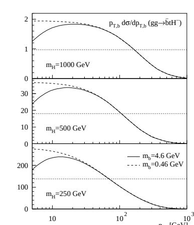
$\to$ how large logarithms? resum?



Inclusive process $bg \to tH^-$

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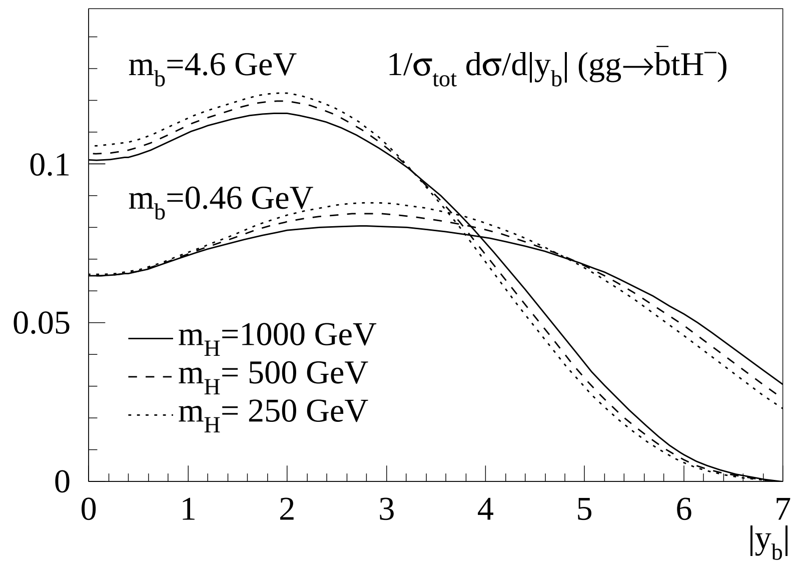
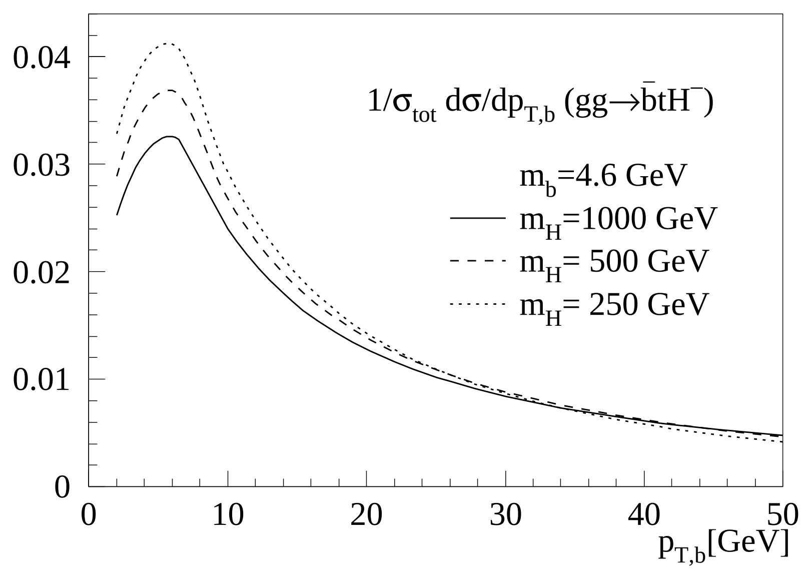


m_b=4.6 GeV
$1/\sigma_{tot}\ d\sigma/d|y_b|\ (gg\to\bar{b}tH^-)$
m_b=0.46 GeV
m_H=1000 GeV
m_H= 500 GeV
m_H= 250 GeV
0.1
0.05
0
0
1
2
3
4
5
6
7
$|y_b|$



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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]

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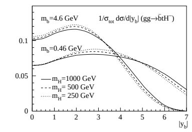

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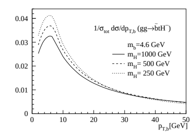

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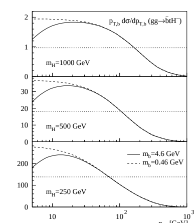

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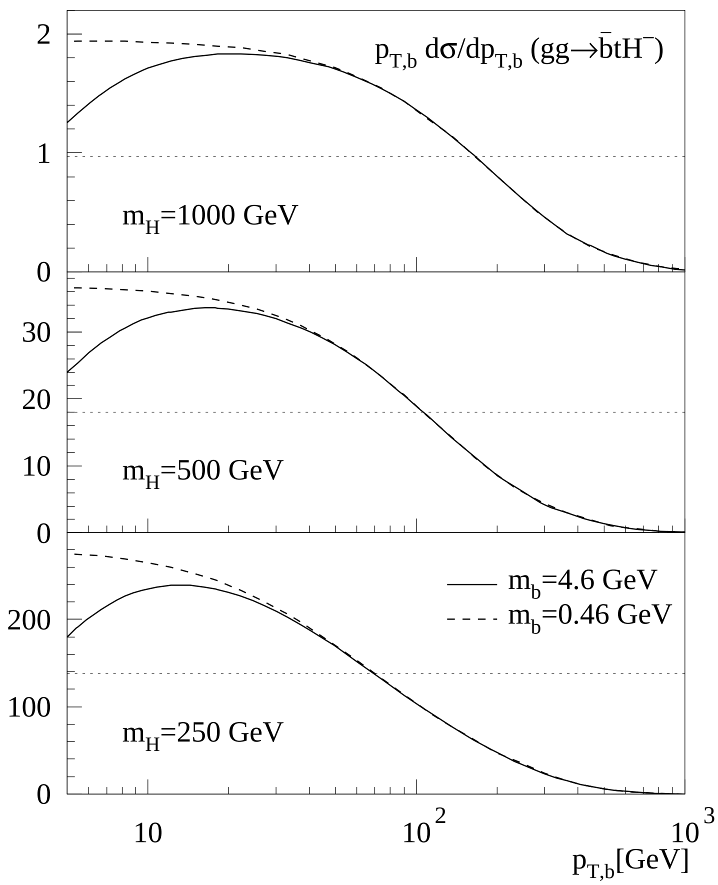

$p_{T,b}\, d\sigma/dp_{T,b}\ (gg \to \bar{b}tH^-)$
m_H=1000 GeV
m_H=500 GeV
m_H=250 GeV
m_b=4.6 GeV
m_b=0.46 GeV
0
1
2
10
20
30
100
200
10
10^2
10^3
$p_{T,b}$[GeV]

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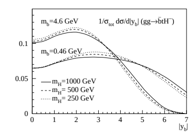

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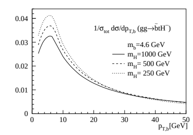

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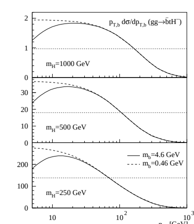

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Total Rate: Bottom Factorization Scale

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

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

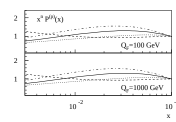
– general exclusive process: $gg \to \bar{b} X_M$
approximate gluon density $\mathcal{L} = \mathcal{L}_0/x^2$
asymptotic behavior $\overline{|\mathcal{M}|^2} = S^2 \sigma_0 / Q_b^2$

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

$\to$ $F(Q_b)$ 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!)

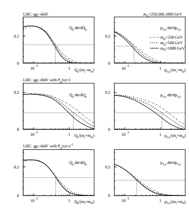


Second step: transverse momentum $p_{T,b}^{\max}$

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



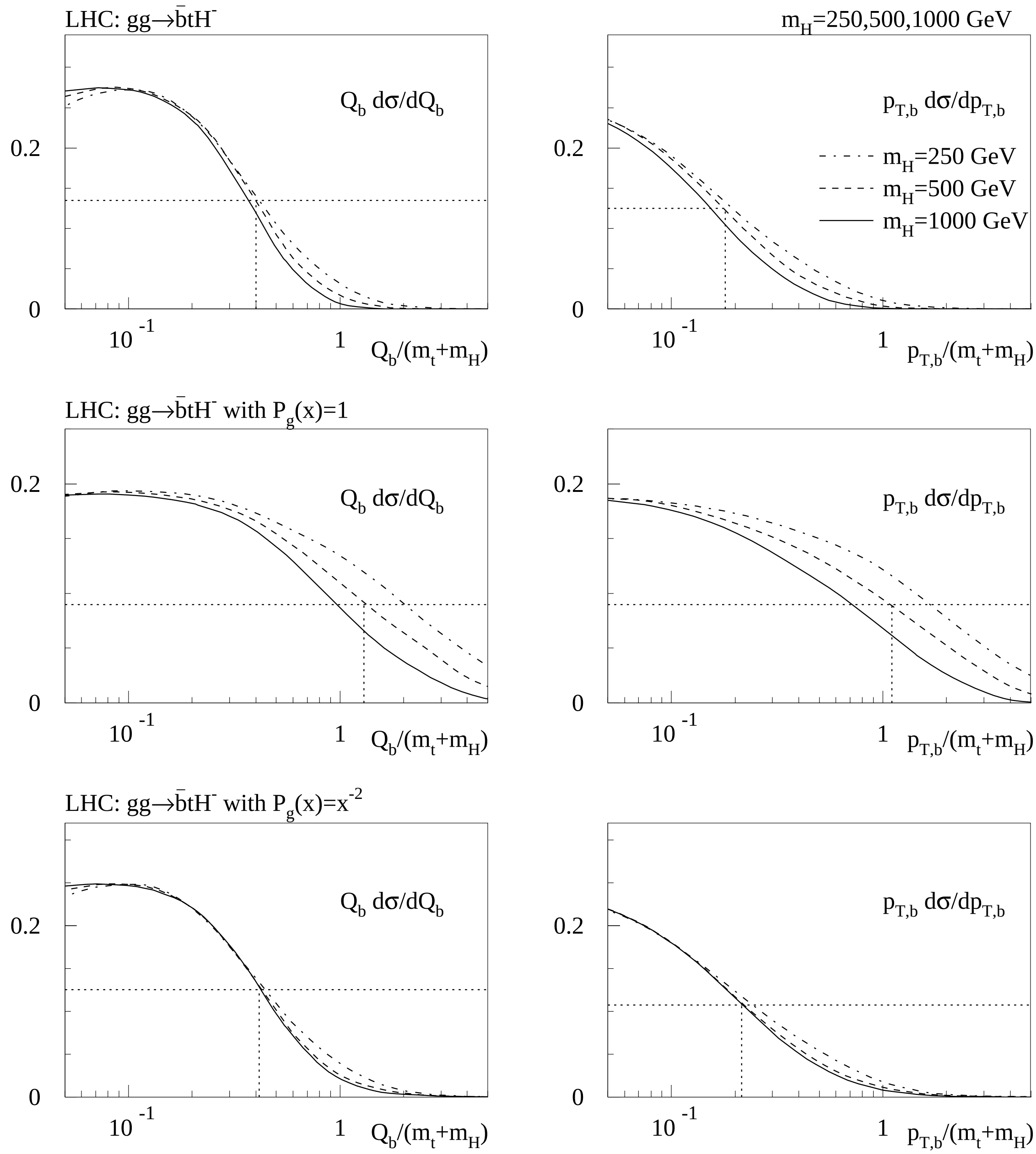
So what did we learn from exclusive process?

– $\log(p_{T,b}/m_b)$ after integrating over bottom jet
but 'large' logs at maximum $\log(M/(5 m_b))$ [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



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
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
0.2
0
10^-1
1

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

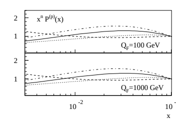
– general exclusive process: $gg \to \bar{b} X_M$
approximate gluon density $\mathcal{L} = \mathcal{L}_0 / x^2$
asymptotic behavior $\overline{|\mathcal{M}|^2} = S^2 \sigma_0 / Q_b^2$

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

$\to$ $F(Q_b)$ 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!)

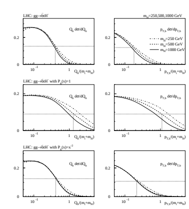


Second step: transverse momentum $p_{T,b}^{\max}$

– 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]

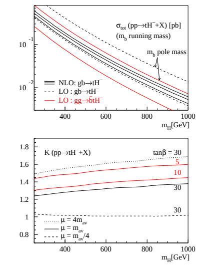
– hard scale for inclusive process: $\mu_{F,b} \propto M$

– 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]



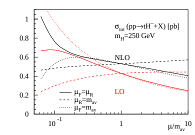
– leading order uncertainty large for $bg \to tH^-$

– complete set of virtual and real SUSY corrections

– running Yukawa couplings, everything else misleading

$\to$ 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

$\to$ NLO scale dependence $\pm 20\%$

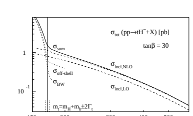
$\to$ well defined limit $\mu_F \to m_b$ returns exclusive process $gg \to \bar{b}tH^-$

Matching at threshold

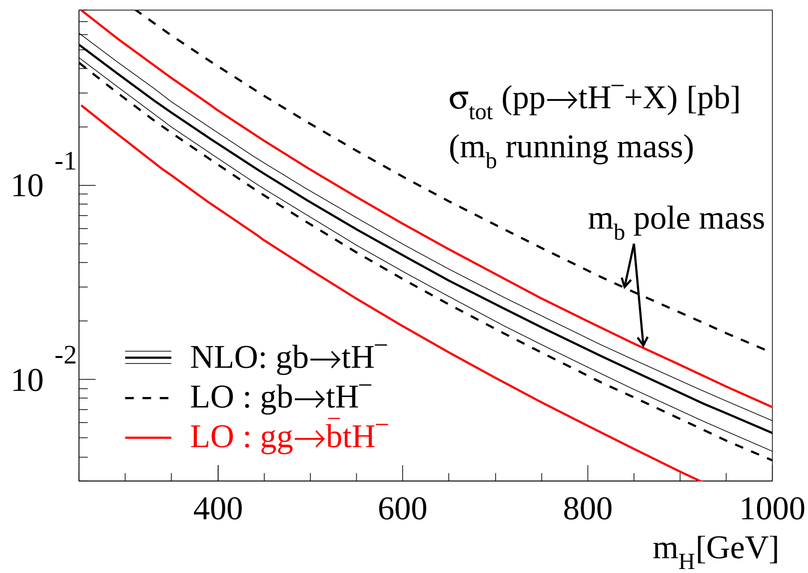
– $m_H < m_t - m_b$: top pair production and Breit–Wigner propagator
$m_H > m_t - m_b$: resummed off-shell process

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

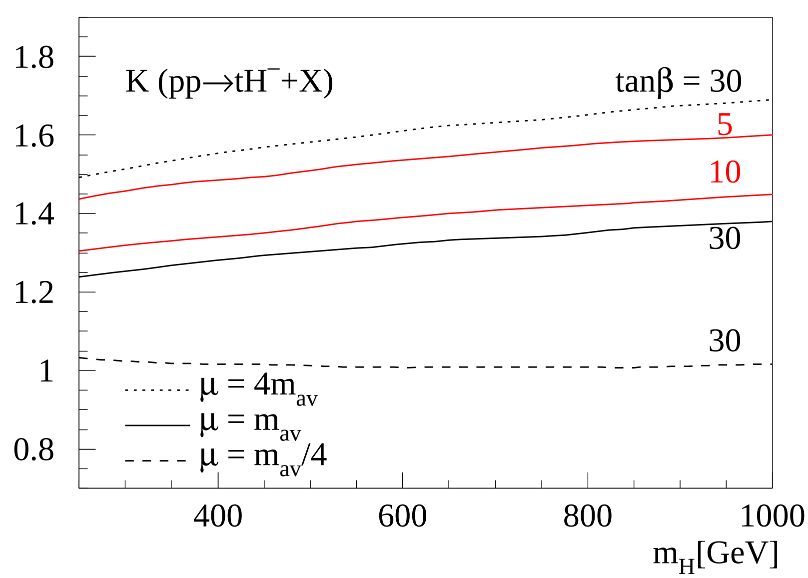
– subtract on-shell top pairs from NLO $bg \to tH^-$ process
(unique in small width approximation, see SUSY-pairs)



$\to$ 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]

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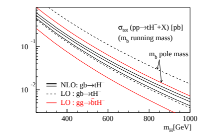

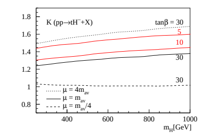

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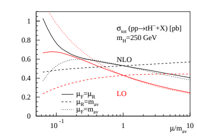

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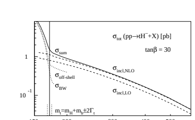

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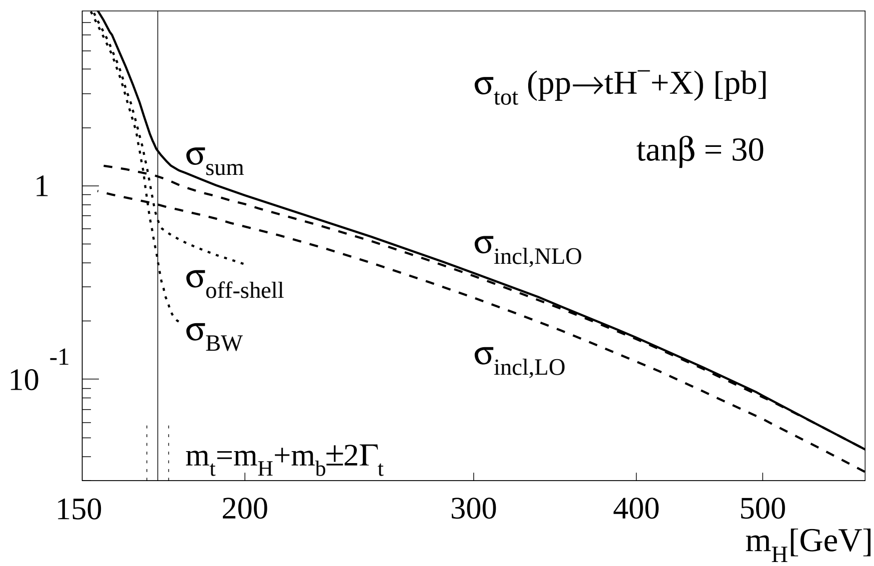


σ_tot (pp→tH⁻+X) [pb]
tanβ = 30
σ_sum
σ_incl,NLO
σ_off-shell
σ_BW
σ_incl,LO
1
10 -1
m_t=m_H+m_b±2Γ_t
150
200
300
400
500
m_H[GeV]

Distributions for Inclusive Process

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

– bottom parton description appropriate for total rate

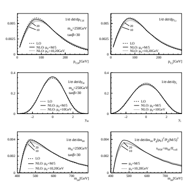
→ Higgs and top distributions?

→ 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 $gg \to \bar{b}tH^-$

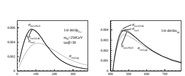
→ slightly harder distributions (due to x dependence of bottom PDF)

(2) Test zero bottom mass approximation

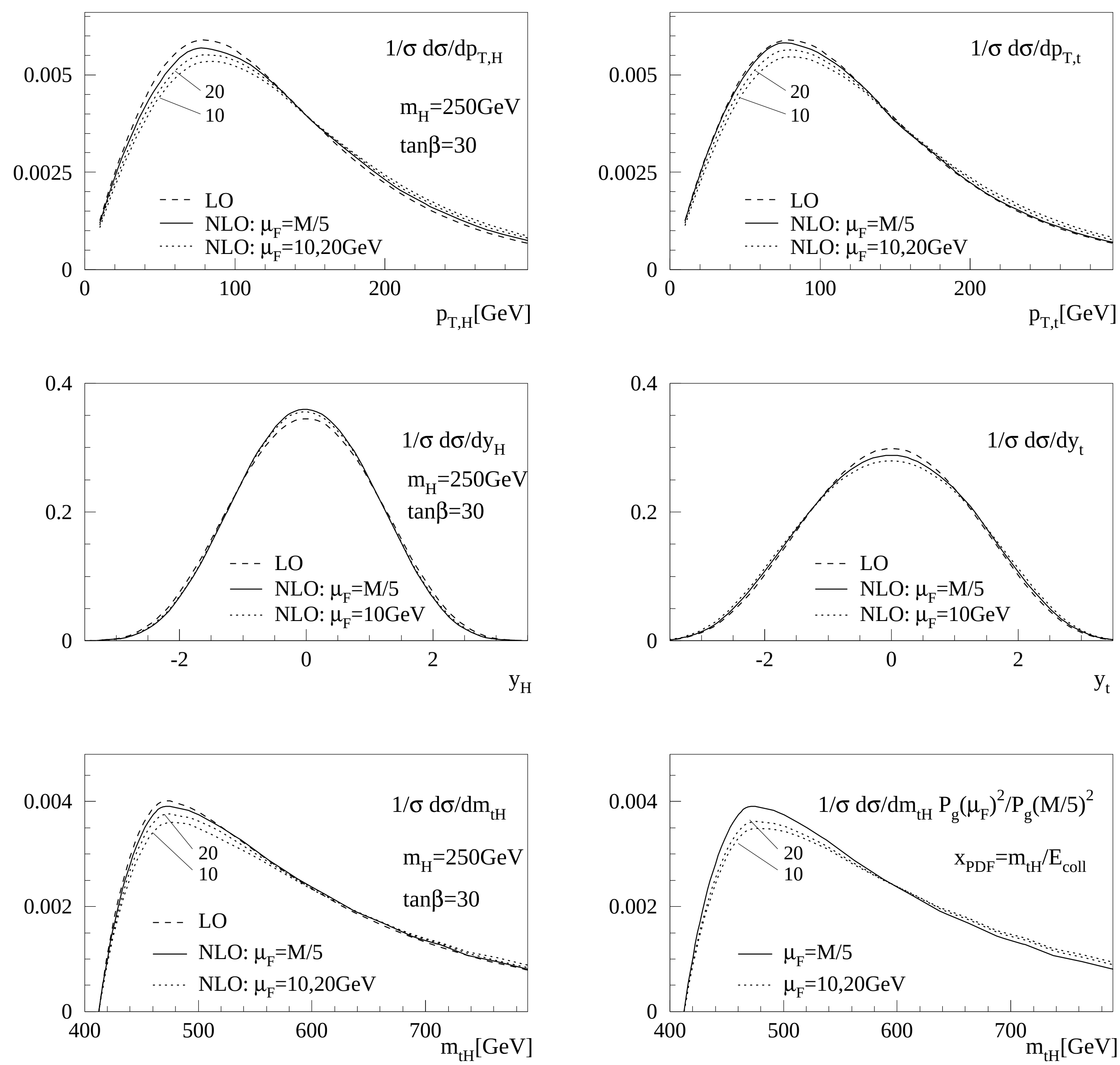
– agreement exclusive vs. inclusive cross section established

→ 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



$1/\sigma\ d\sigma/dp_{T,H}$
m_H=250GeV
tanβ=30
20
10
LO
NLO: μ_F=M/5
NLO: μ_F=10,20GeV
$p_{T,H}$[GeV]
$1/\sigma\ d\sigma/dp_{T,t}$
$p_{T,t}$[GeV]
$1/\sigma\ d\sigma/dy_H$
NLO: μ_F=10GeV
y_H
$1/\sigma\ d\sigma/dy_t$
y_t
$1/\sigma\ d\sigma/dm_{tH}$
m_{tH}[GeV]
$1/\sigma\ d\sigma/dm_{tH}\ P_g(\mu_F)^2/P_g(M/5)^2$
$x_{PDF}=m_{tH}/E_{coll}$
μ_F=M/5
μ_F=10,20GeV

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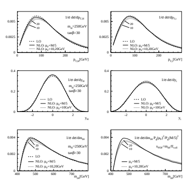

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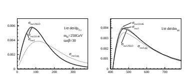

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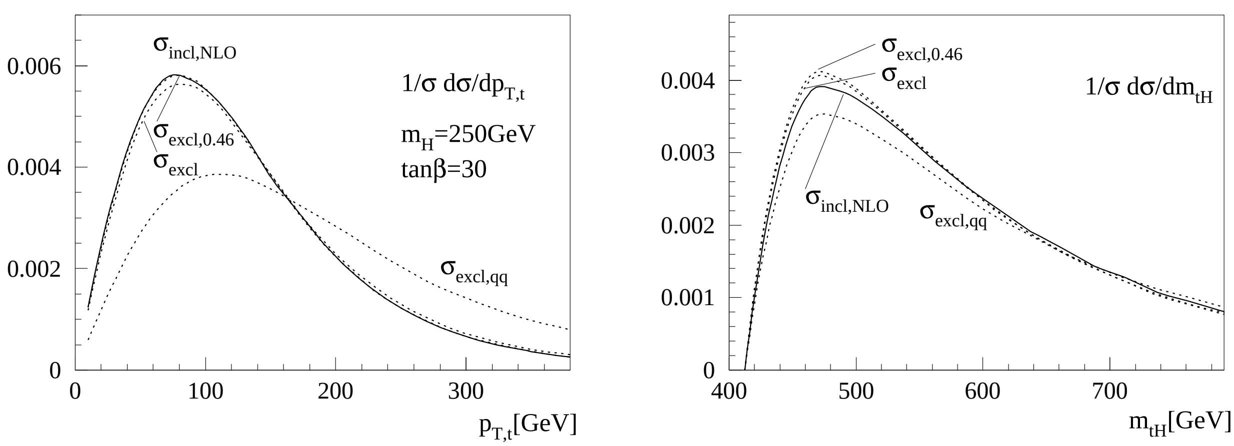

σincl,NLO
1/σ dσ/dpT,t
mH=250GeV
tanβ=30
σexcl,0.46
σexcl
σexcl,qq
0.006
0.004
0.002
0
0
100
200
300
pT,t[GeV]
σexcl,0.46
σexcl
1/σ dσ/dmtH
σincl,NLO
σexcl,qq
0.004
0.003
0.002
0.001
0
400
500
600
700
mtH[GeV]

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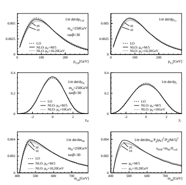

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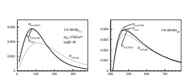


$\longrightarrow$ bottom parton picture altogether appropriate

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			$(\Delta_b)_{\text{resum}}$	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_{mes}	N_{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

3. (Heavy) Neutral Higgs

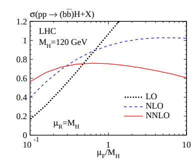
Bottom induced production of neutral Higgses

– 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]

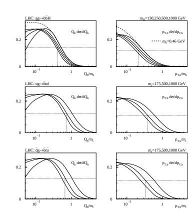
	M_H	$\sigma(q\bar{q}, gg \to b\bar{b}H + X)$ [fb]		$\sigma(b\bar{b} \to H + X)$ [fb]	
		LO	NLO	LO	NNLO
Tevatron	120	$3.9\,^{+3.5}_{-1.7}$	$8.0\,^{+3.1}_{-2.4}$	$8.6\,^{+4.7}_{-5.0}$	$10.5\,^{+0.3}_{-1.1}$
	200	$0.22\,^{+0.19}_{-0.09}$	$0.56\,^{+0.23}_{-0.18}$	$0.69\,^{+0.20}_{-0.26}$	$0.79\,^{+0.02}_{-0.03}$
LHC	120	$(5.3\,^{+2.7}_{-1.7})\times 10^2$	$(7.3\,^{+2.0}_{-1.6})\times 10^2$	$(4.8\,^{+4.3}_{-3.2})\times 10^2$	$(7.2\,^{+0.4}_{-1.6})\times 10^2$
	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, $x_1 \neq x_2$

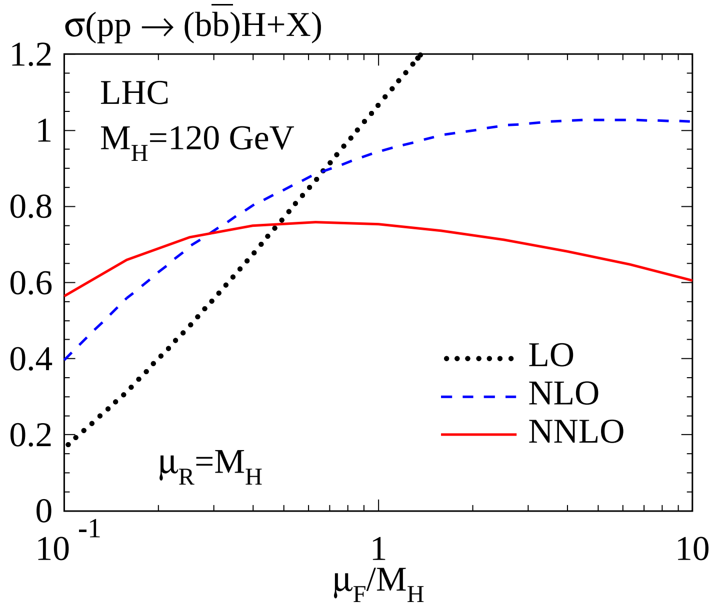
– production above threshold

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



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

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



Harlander, Kilgore

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_{vis} to determine λ_{HHH})

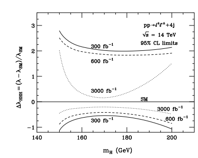
– $HH \to b\bar{b}\tau\tau$: miracle required

– $HH \to 4b$: 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)



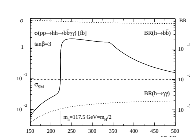
– $HH \to b\bar{b}\gamma\gamma$: some enhancement needed

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

– only way to access $\tan\beta < 10$ beyond no-lose theorem

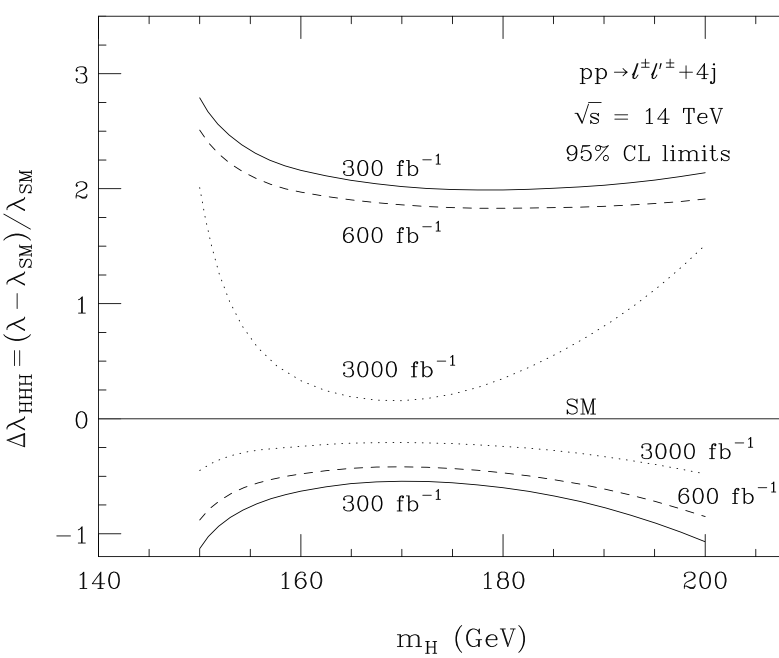
– factor 20 enhancement of cross section

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



$\to$ backgrounds hard to compute but under control

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



$pp \to \ell^{\pm}\ell'^{\pm}+4j$
$\sqrt{s}$ = 14 TeV
95% CL limits
300 fb^{-1}
600 fb^{-1}
3000 fb^{-1}
SM
3000 fb^{-1}
600 fb^{-1}
300 fb^{-1}
$\Delta\lambda_{HHH} = (\lambda - \lambda_{SM})/\lambda_{SM}$
3
2
1
0
−1
140
160
180
200
m_H (GeV)

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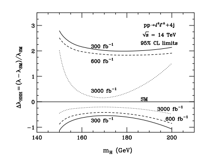

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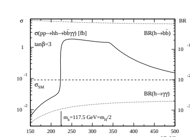
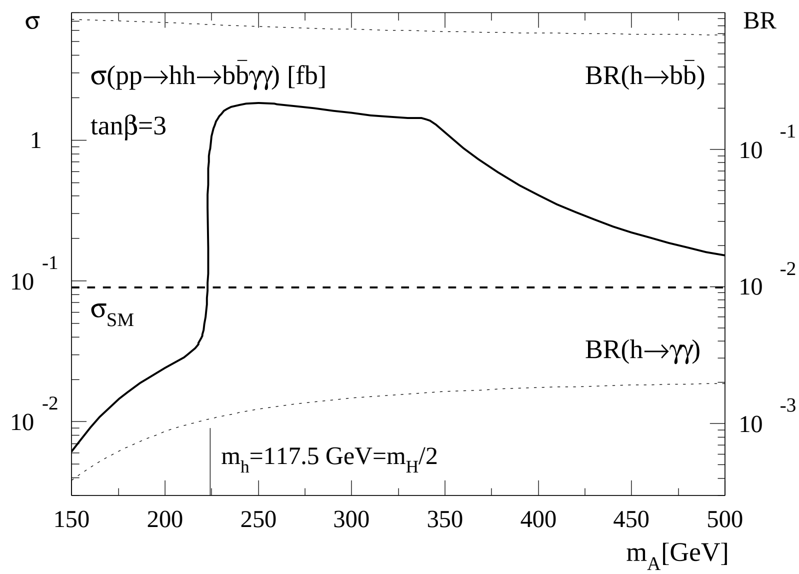


$\to$ 5σ with $300\,\text{fb}^{-1}$ possible for $\tan\beta = 3$


σ
BR
σ(pp→hh→bb̄γγ) [fb]
BR(h→bb̄)
tanβ=3
1
10^-1
10^-1
10^-2
10^-2
σ_SM
BR(h→γγ)
10^-2
10^-3
m_h=117.5 GeV=m_H/2
150
200
250
300
350
400
450
500
m_A[GeV]

Conclusions

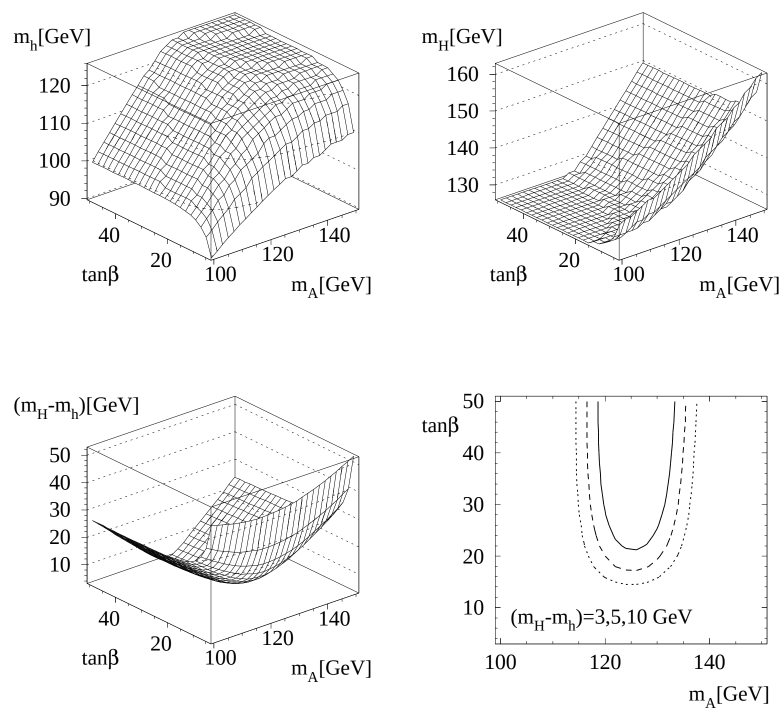
(1) One MSSM Higgs guaranteed to be seen
stable to variations of MSSM

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

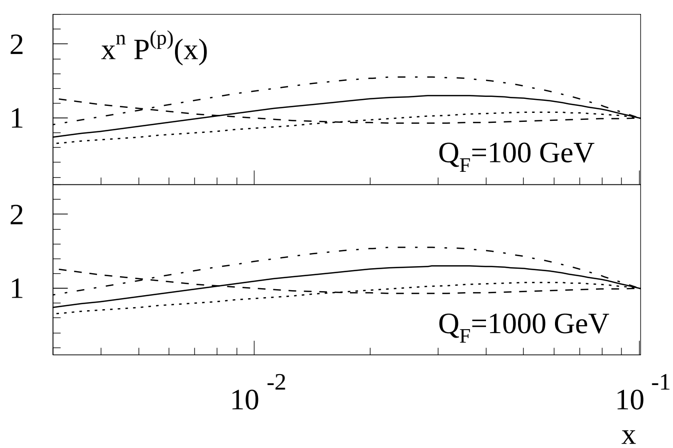
(2') NLO rate for charged Higgs production known:
NLO_1: inclusive process well defined
NLO_2: remaining scale uncertainty $\lesssim 20\%$
NLO_3: Δm_b corrections dominant in MSSM for large $\tan\beta$
NLO_4: non-factorizable corrections negligible in MSSM

(3) neutral Higgs production with $b\bar{b} \to H$ understood

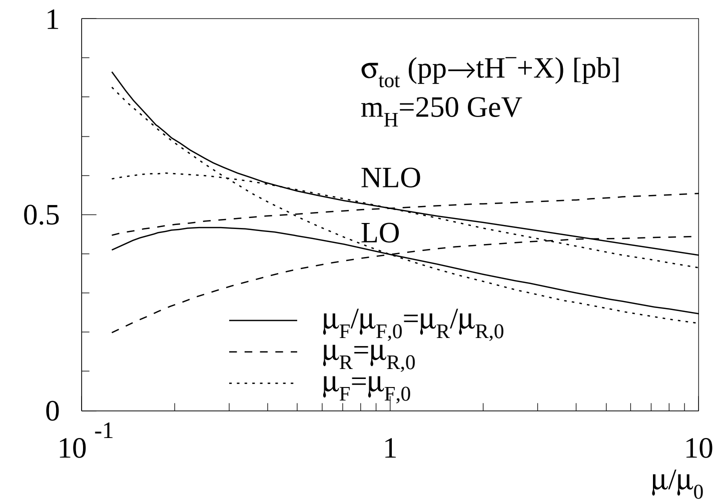
(4) signal $H^* \to hh \to b\bar{b}\gamma\gamma$ for small $\tan\beta$



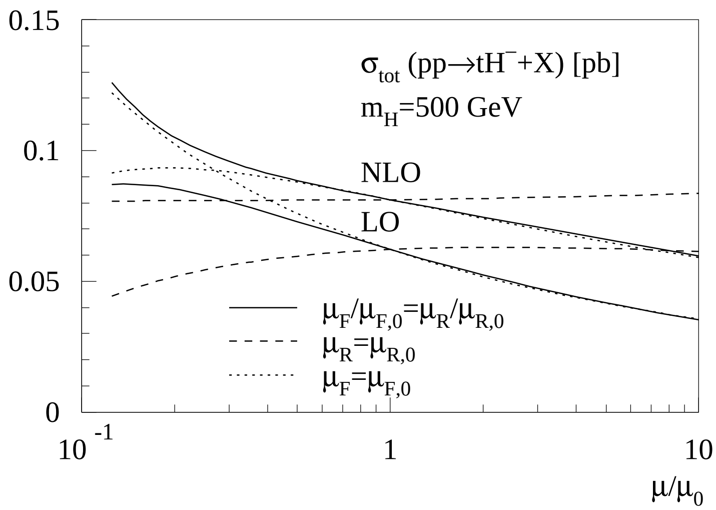
m_h[GeV]
120
110
100
90
40
20
tanβ
100
120
140
m_A[GeV]
m_H[GeV]
160
150
140
130
40
20
tanβ
100
120
140
m_A[GeV]
(m_H-m_h)[GeV]
50
40
30
20
10
40
20
tanβ
100
120
140
m_A[GeV]
tanβ
50
40
30
20
10
(m_H-m_h)=3,5,10 GeV
100
120
140
m_A[GeV]



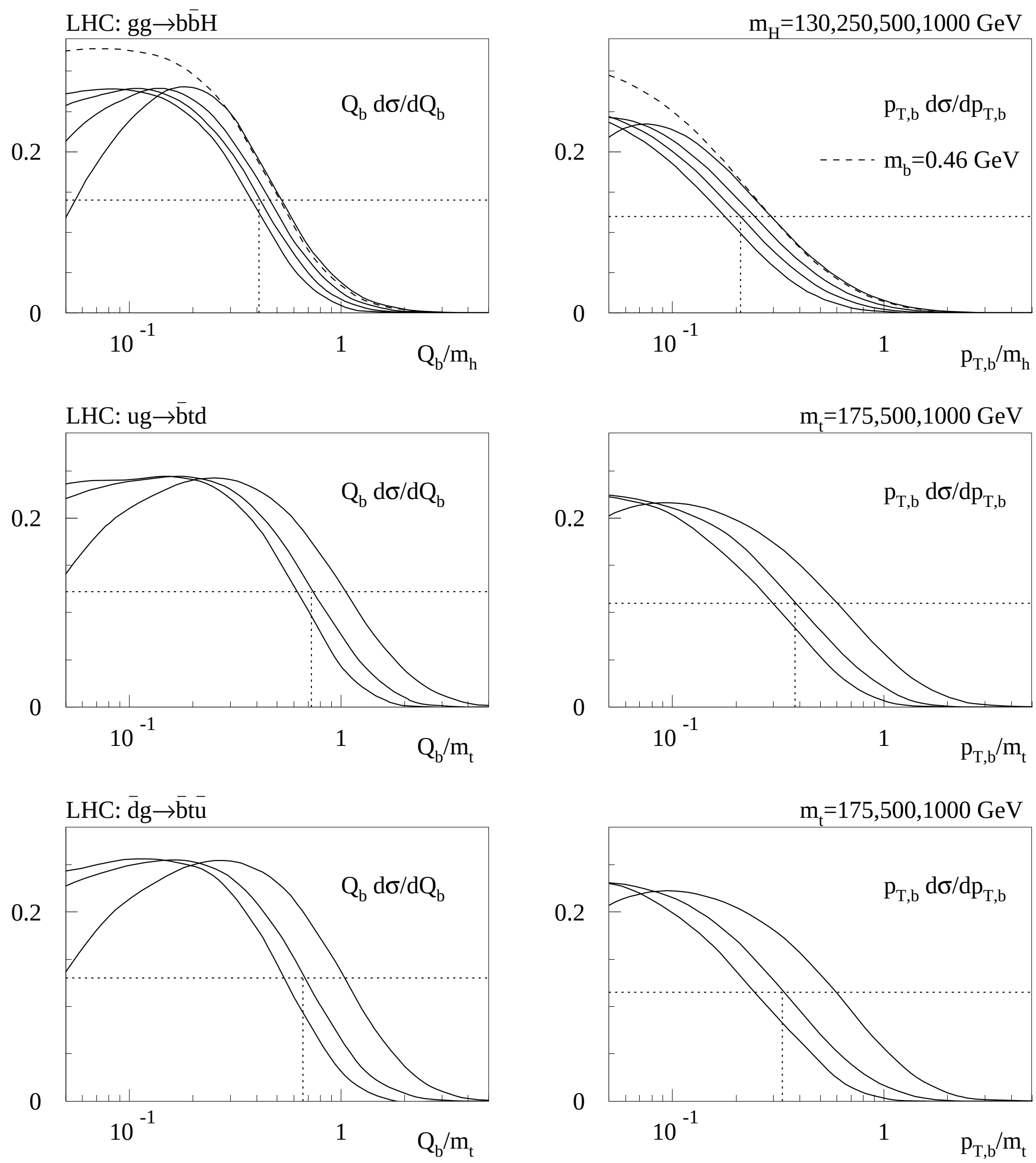
x^n P^(p)(x)
2
1
Q_F=100 GeV
2
1
Q_F=1000 GeV
10^-2
10^-1
x



1
0.5
0
10 -1
1
10
μ/μ0
σtot (pp→tH⁻+X) [pb]
mH=250 GeV
NLO
LO
μF/μF,0=μR/μR,0
μR=μR,0
μF=μF,0



0.15
0.1
0.05
0
10 -1
1
10
μ/μ0
σtot (pp→tH⁻+X) [pb]
mH=500 GeV
NLO
LO
μF/μF,0=μR/μR,0
μR=μR,0
μF=μF,0


LHC: gg→bb̄H
m_H=130,250,500,1000 GeV
Q_b dσ/dQ_b
p_T,b dσ/dp_T,b
m_b=0.46 GeV
Q_b/m_h
p_T,b/m_h
LHC: ug→b̄td
m_t=175,500,1000 GeV
Q_b/m_t
p_T,b/m_t
LHC: d̄g→b̄t̄ū
0.2
0
10^-1
1