PREDICTIONS FOR THE PRODUCTION OF HIGGS AND SUSY PARTICLES @ THE TEVATRON AND LHC

Michael Spira (PSI)

I Introduction

II Higgs Boson Production

III SUSY Particle Production

IV Conclusions

I Introduction

- MSSM: 2 Higgs doublets $\xrightarrow[\text{ESB}]{}$ 5 Higgs bosons: $h, H, A, H^\pm$
- radiative corrections $\propto m_t^4 \Rightarrow M_h \lesssim M_Z \to 135\,\text{GeV}$ — Okada, … Haber, … Ellis, … Carena, … Hollik, … Zhang, … ⋮
- Tevatron/LHC: $gg \to \phi^0$ dominant for $tg\beta \lesssim 10$

  $gg \to b\bar{b}\phi^0$ dominant for $tg\beta \gtrsim 10$ F
- detection: (i) Tevatron: $q\bar{q} \to Wh/H \to Wb\bar{b}$ ($M_\phi \lesssim 130$ GeV)

  $gg \to b\bar{b}\phi^0$ @ large $tg\beta$

  (ii) LHC: $h \to \gamma\gamma, b\bar{b}$

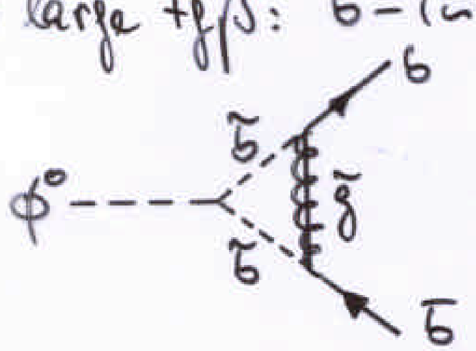
  $H, A \to \tau^+\tau^-$

  $H \to hh$

  $t \to bH^+$

  and: $VV \to h/H \to \tau^+\tau^-$ — Kauer, Plehn, Rainwater, Zeppenfeld

- large $tg\beta$: b-Yukawa couplings enhanced — Hall, … Carena, … Belyaev, …



$\propto \frac{\mu M_{\tilde{g}}\, tg\beta\, \alpha_s}{M_{SUSY}^2} \Rightarrow$ large $\mathcal{O}(100\%)$ — Coarasa, …

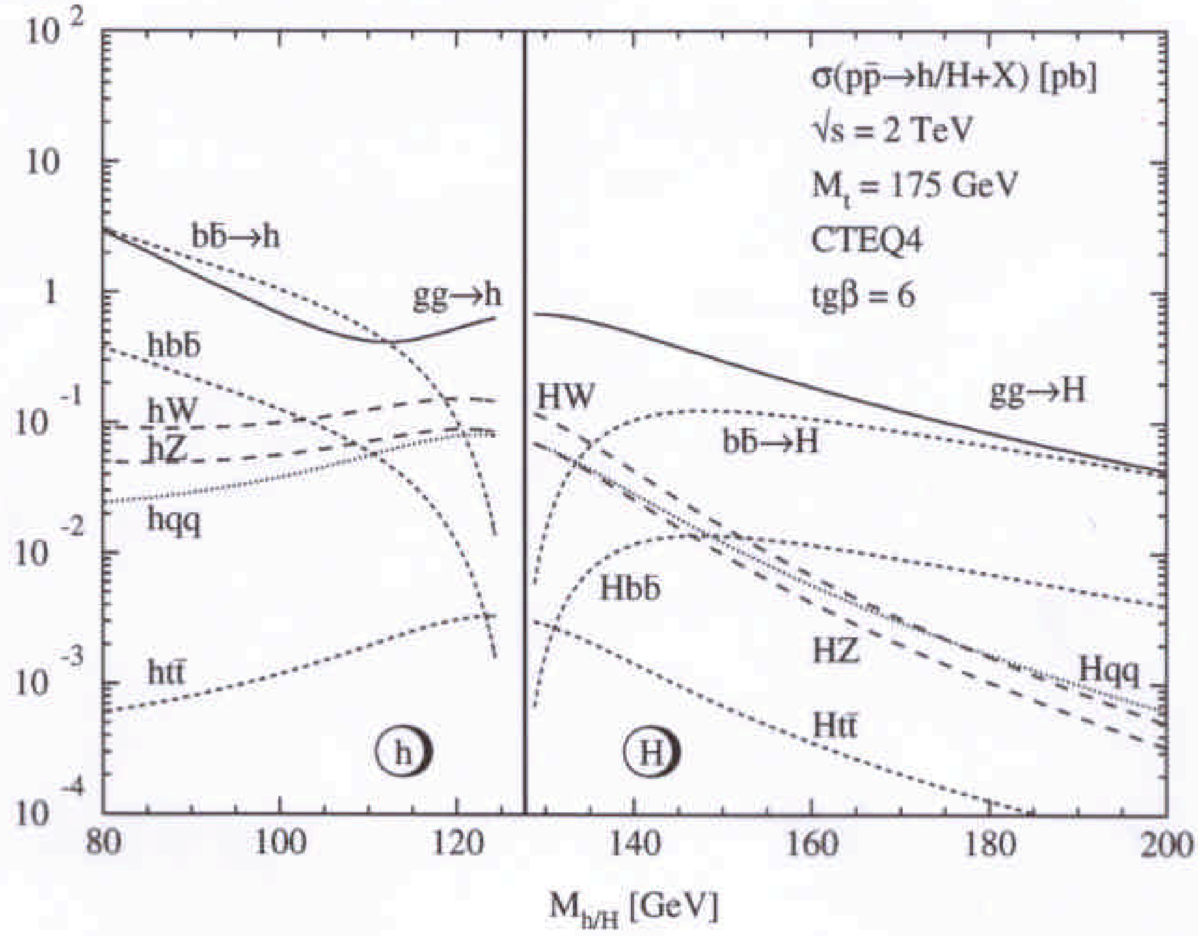
$\longrightarrow$ suppression/enhancement of g_b^ϕ

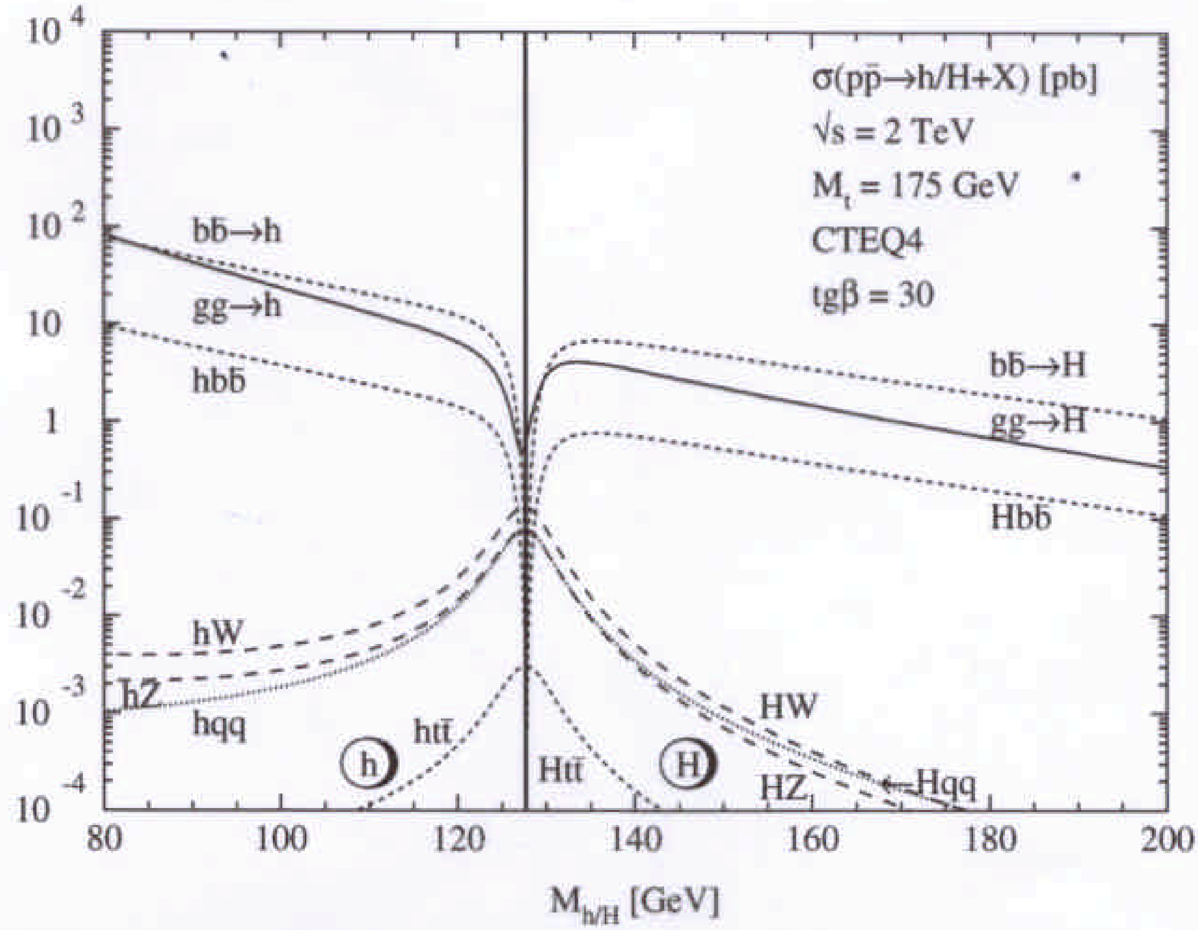
- sizeable region: $pp \to \tilde{g}\tilde{g} \to (\tilde{q}_L q)(\tilde{q}_R q)$ — Paige, …

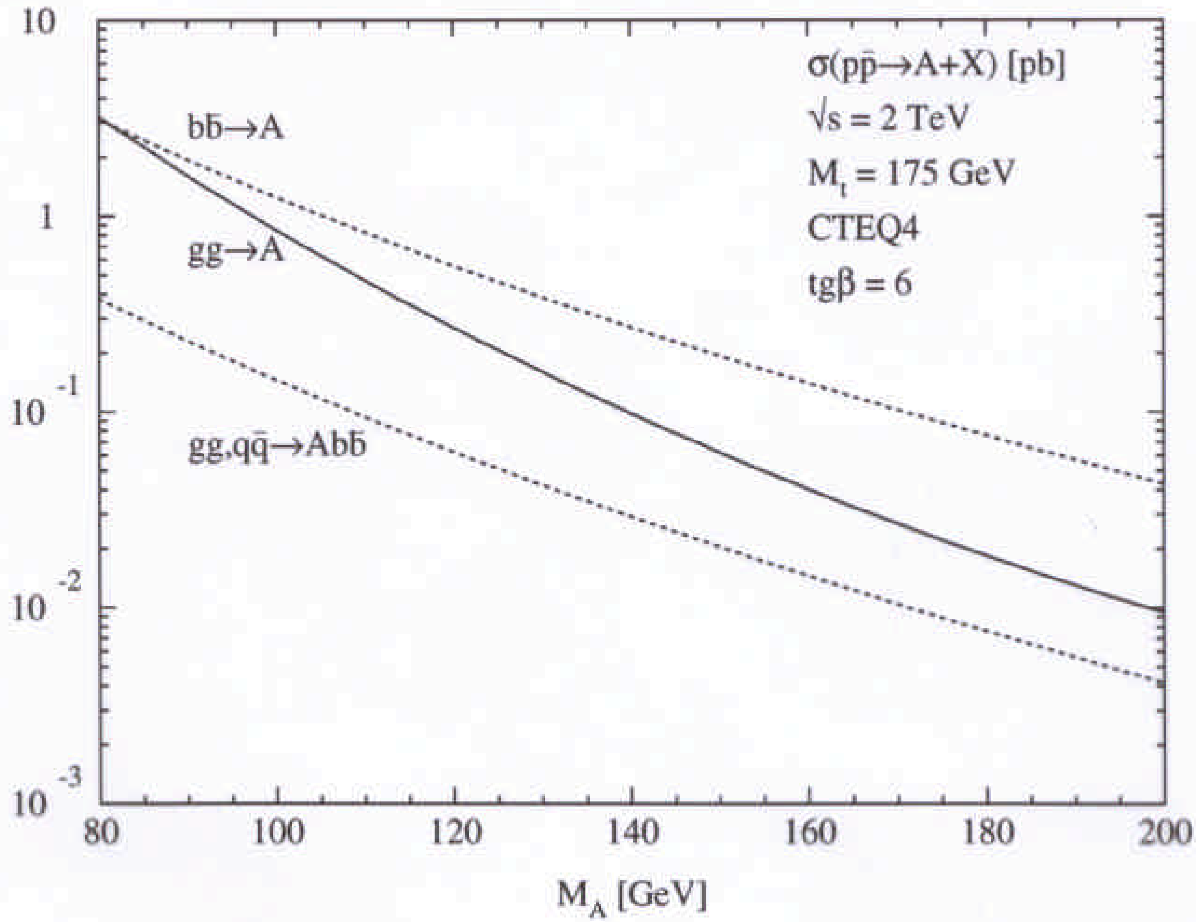
  $\tilde{q}_R \to \tilde{\chi}_1^0 q$

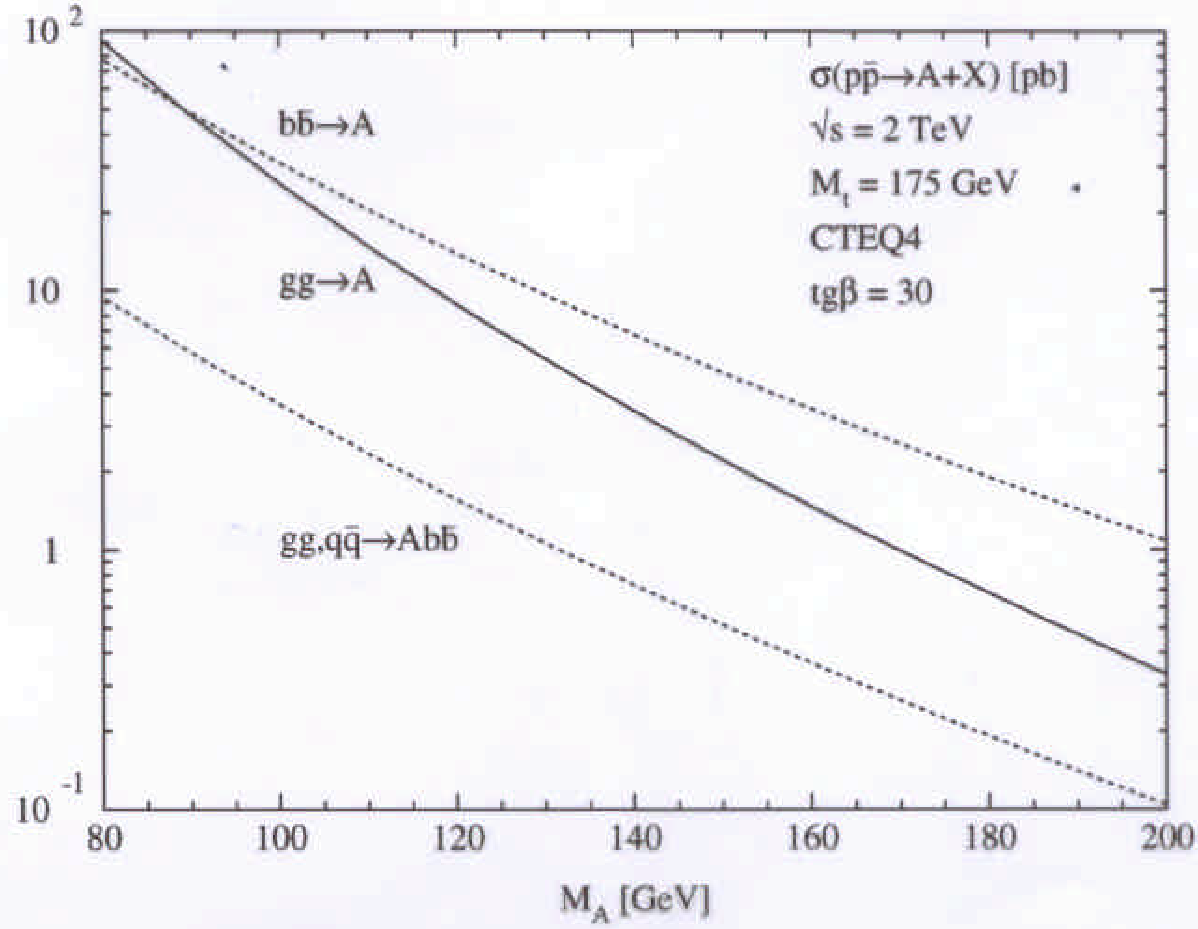
  $\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\chi}_1^0 h q$

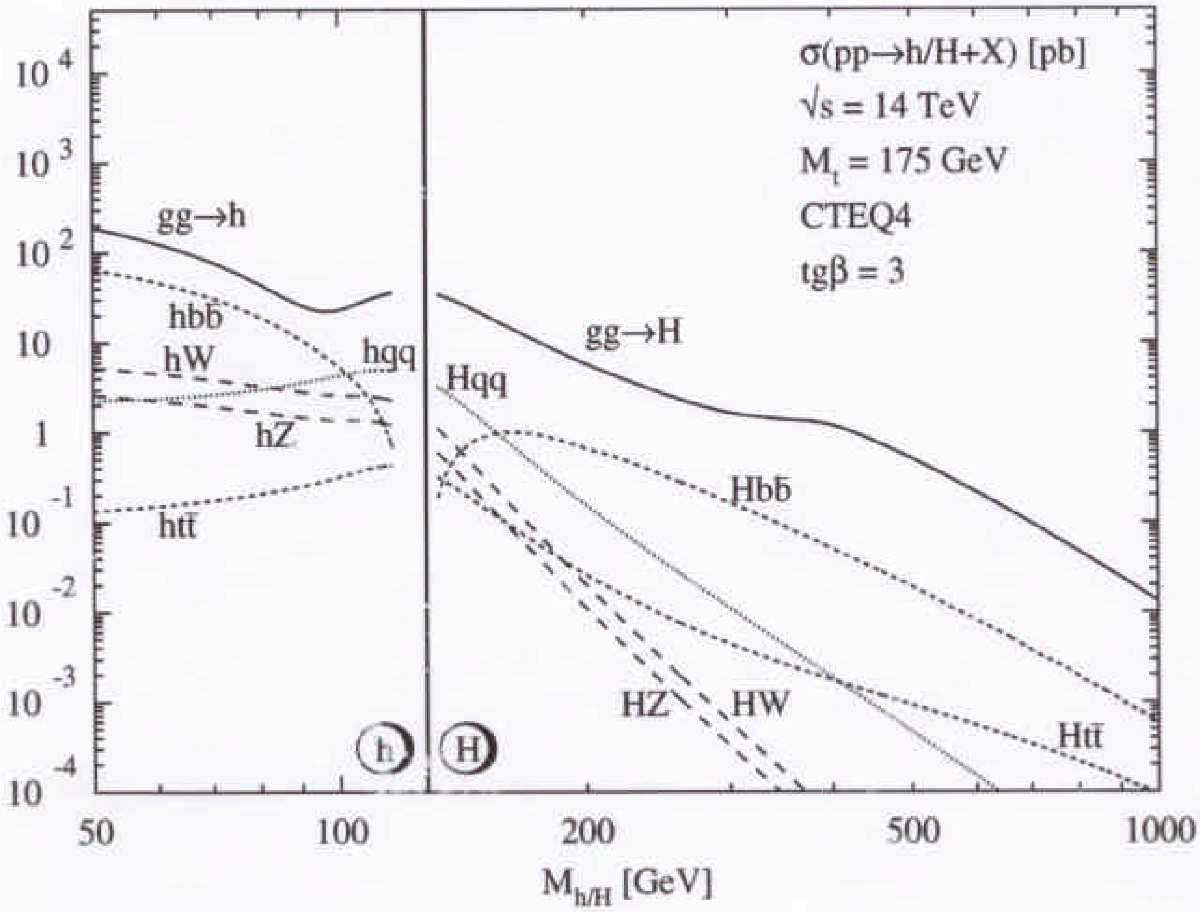
  $h \to b\bar{b}$

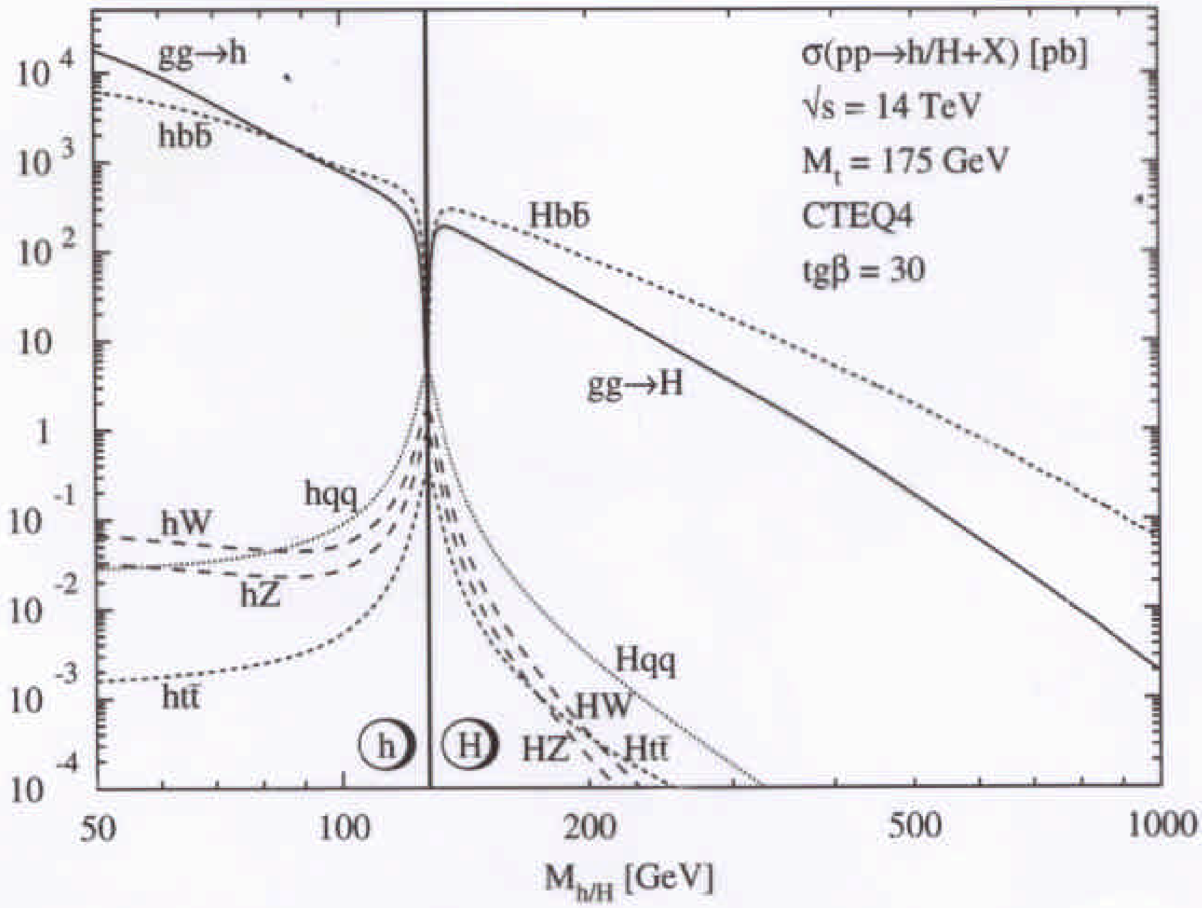

σ(pp̄→h/H+X) [pb]
√s = 2 TeV
M_t = 175 GeV
CTEQ4
tgβ = 6
bb̄→h
gg→h
hbb̄
hW
hZ
hqq
htt̄
HW
bb̄→H
gg→H
Hbb̄
HZ
Hqq
Htt̄
h
H
M_h/H [GeV]


σ(pp̄→h/H+X) [pb]
√s = 2 TeV
M_t = 175 GeV
CTEQ4
tgβ = 30
bb̄→h
gg→h
hbb̄
bb̄→H
gg→H
Hbb̄
hW
hZ
hqq
htt̄
Htt̄
HW
HZ
←Hqq
h
H
M_h/H [GeV]

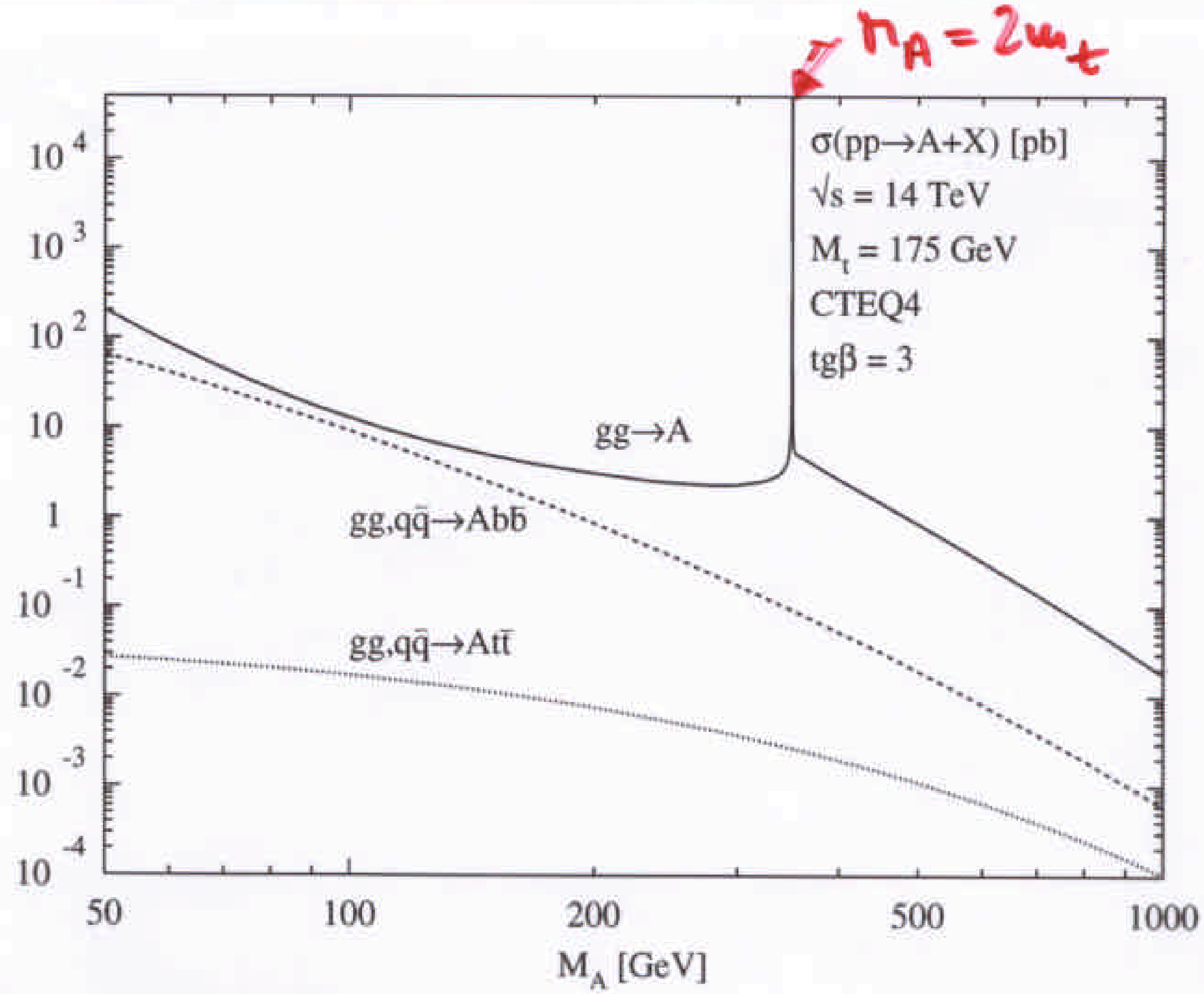

σ(pp̄→A+X) [pb]
√s = 2 TeV
M_t = 175 GeV
CTEQ4
tgβ = 6
bb̄→A
gg→A
gg,qq̄→Abb̄
M_A [GeV]

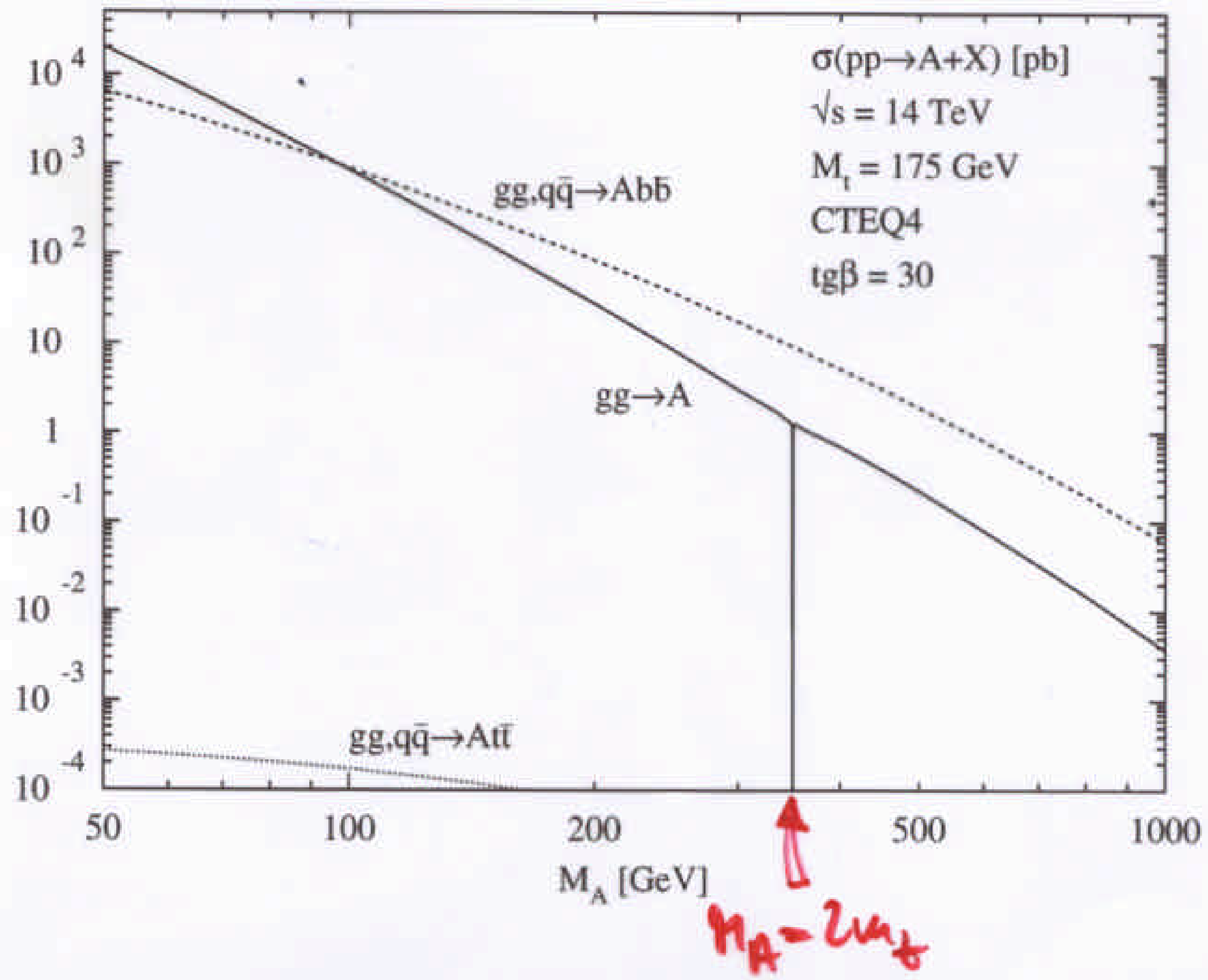

σ(pp̄→A+X) [pb]
√s = 2 TeV
M_t = 175 GeV
CTEQ4
tgβ = 30
bb̄→A
gg→A
gg,qq̄→Abb̄
M_A [GeV]


σ(pp→h/H+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4
tgβ = 3
gg→h
hbb̄
hW
hqq
hZ
htt̄
gg→H
Hqq
Hbb̄
HZ
HW
Htt̄
h
H
M_{h/H} [GeV]


σ(pp→h/H+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4
tgβ = 30
gg→h
hbb̄
Hbb̄
gg→H
hqq
hW
hZ
htt̄
Hqq
HW
HZ
Htt̄
h
H
M_{h/H} [GeV]

S.


m_A = 2m_t
σ(pp→A+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4
tgβ = 3
gg→A
gg,qq̄→Abb̄
gg,qq̄→Att̄
M_A [GeV]


σ(pp→A+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4
tgβ = 30
gg,qq̄→Abb̄
gg→A
gg,qq̄→Att̄
M_A [GeV]
m_A = 2m_t

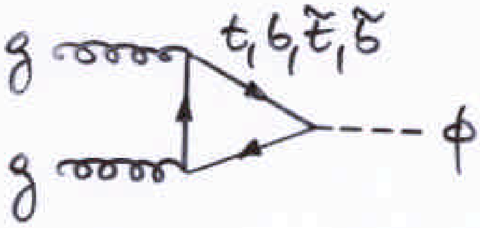
S.

• SUSY sector:

particle	spin	d.o.f	mass	
quark q_L	1/2	3	0	
quark q_R	1/2	3	0	
top t_L	1/2	3	m_t	
top t_R	1/2	3	m_t	
gluon g	1	16	0	
Photon γ	1	2	0	
$W^\pm$	1	3	M_W	
Z	1	3	M_Z	
Higgs $H^\pm$	0	1	$M_{H^\pm}$	
Higgs h, H	0	1	$M_{h,H}$	
Higgs A	0	1	M_A	
squark $\tilde{q}_L$	0	3	$m_{\tilde{q}}$	
squark $\tilde{q}_R$	0	3	$m_{\tilde{q}}$	
stop $\tilde{t}_1$	0	3	$m_{\tilde{t}_1}$	mixing $\tilde{t}_{L,R}$
stop $\tilde{t}_2$	0	3	$m_{\tilde{t}_2}$	
gluino $\tilde{g}$	1/2	16	$m_{\tilde{g}}$	Majorana fermion
chargino $\tilde{\chi}^\pm_{1,2}$	1/2	4	$m_{\tilde{\chi}^\pm_{1,2}}$	mixing
neutralino $\tilde{\chi}^0_{1..4}$	1/2	8	$m_{\tilde{\chi}^0_{1..4}}$	Majorana fermion

II Higgs Boson Production

(i) $gg \to \phi^0$



Georgi, ...
Gamberini, ...

- third generation dominant
- two-loop QCD corrections large: $+(10-100)\%$
  [moderate for large $tg\beta \to b$-loop] Spira, Djouadi, Graudenz, Zerwas, Kauffman, Da...
- $tg\beta \lesssim 5$: limit $m_t \gg M_\phi$ good approximation for K-factor
- NNLO: calculated for $m_t \gg M_\phi$ Kilgore, Harl...

  → further increase by $20-30\%$

  scale dependence: $\Delta \sim 10-15\%$
- soft gluon resummation: $\sim +10\%$ Catani, de Fl..., Grazzini, Nas...

  ⟹ process under theoretical control [$tg\beta \lesssim 5$]

- SUSY decays: $\phi^0 \to \tilde{\chi}^0_1 \tilde{\chi}^0_1$ [LSP]

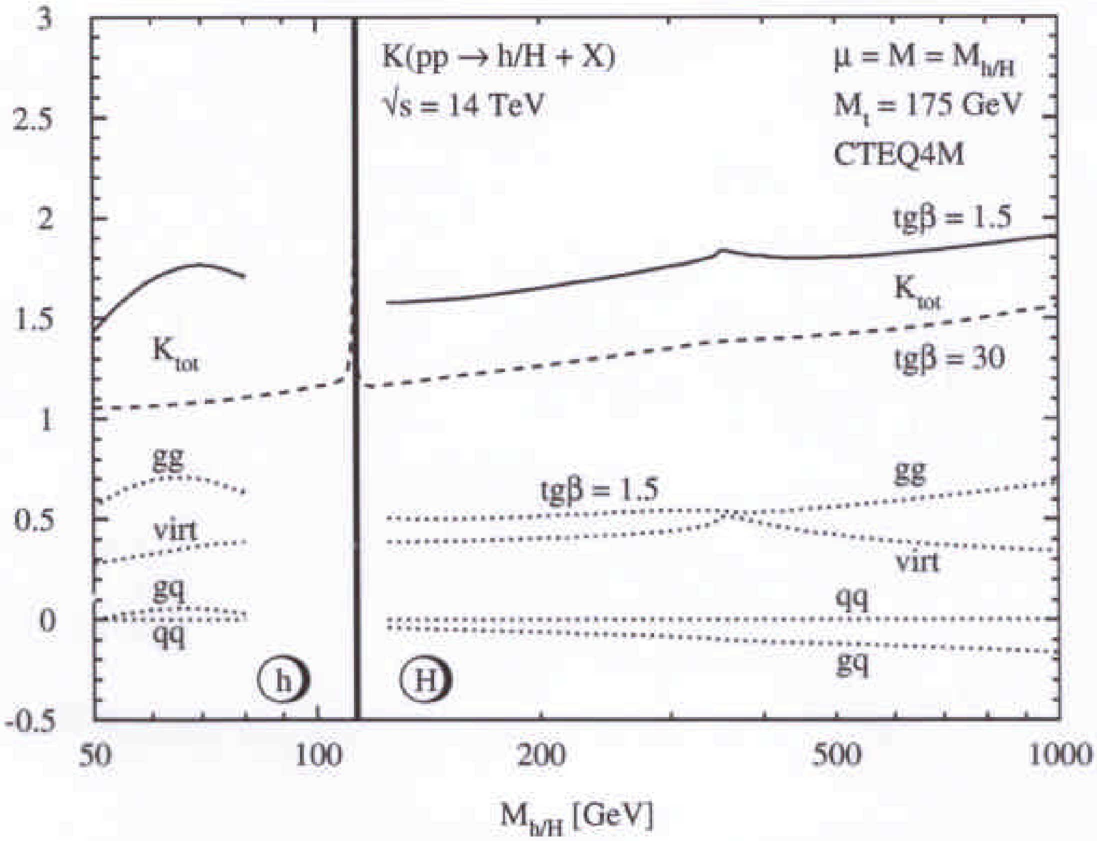
  ⟹ invisible Higgs

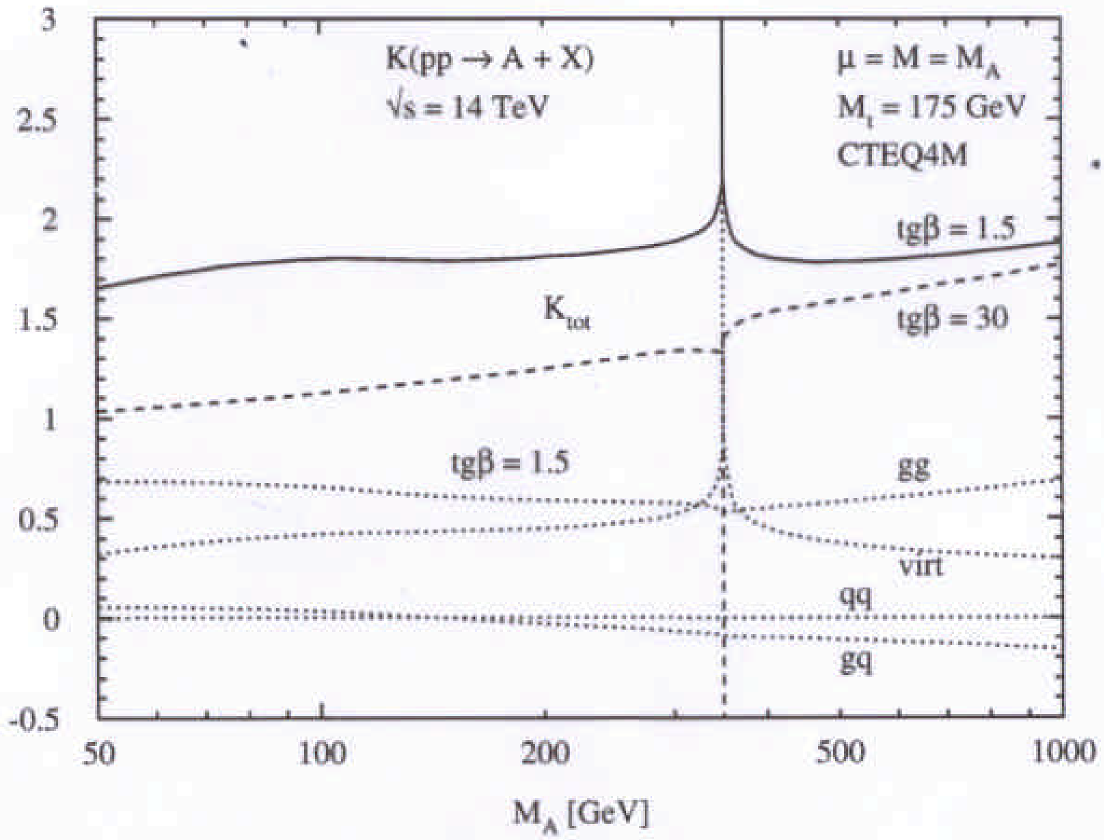
  → $\not{E}_T$ if $p_{T\phi} > 0$

⟹ $gg \to \phi^0 g$, $gq \to \phi^0 q$ dominant

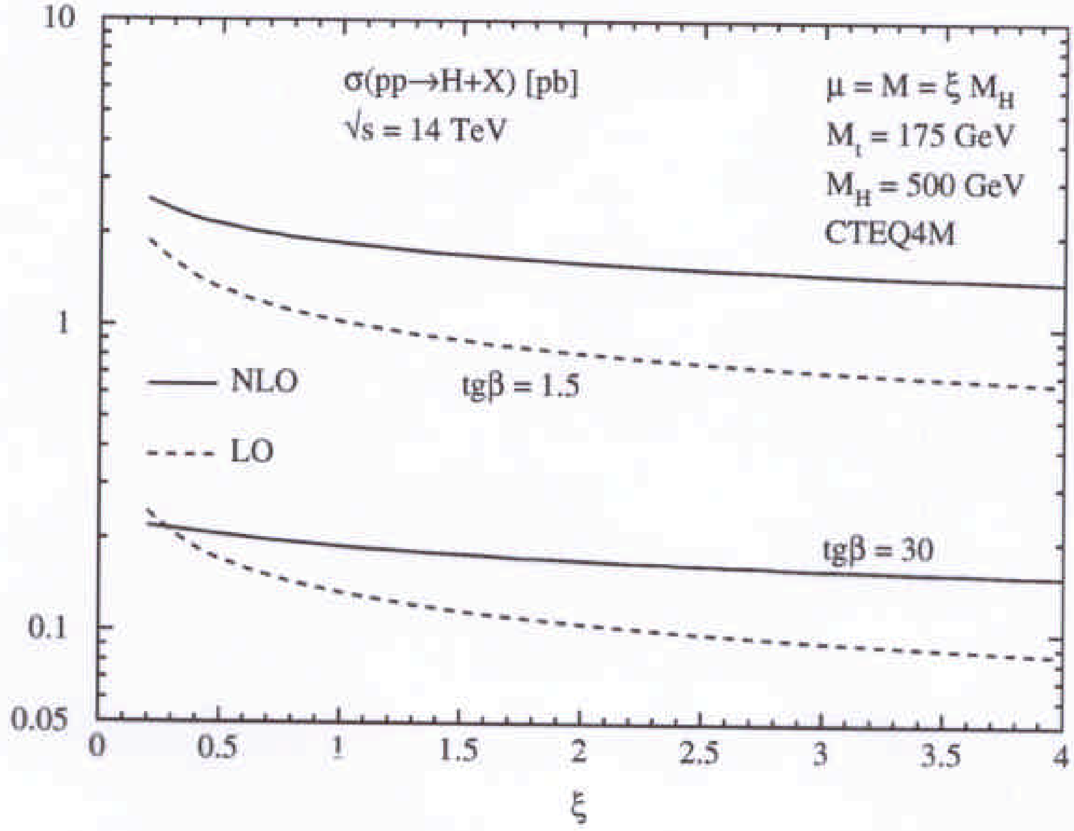
NLO corrections large: $+60-80\%$ Schmidt, de Florian, Kunszt, Grazzini

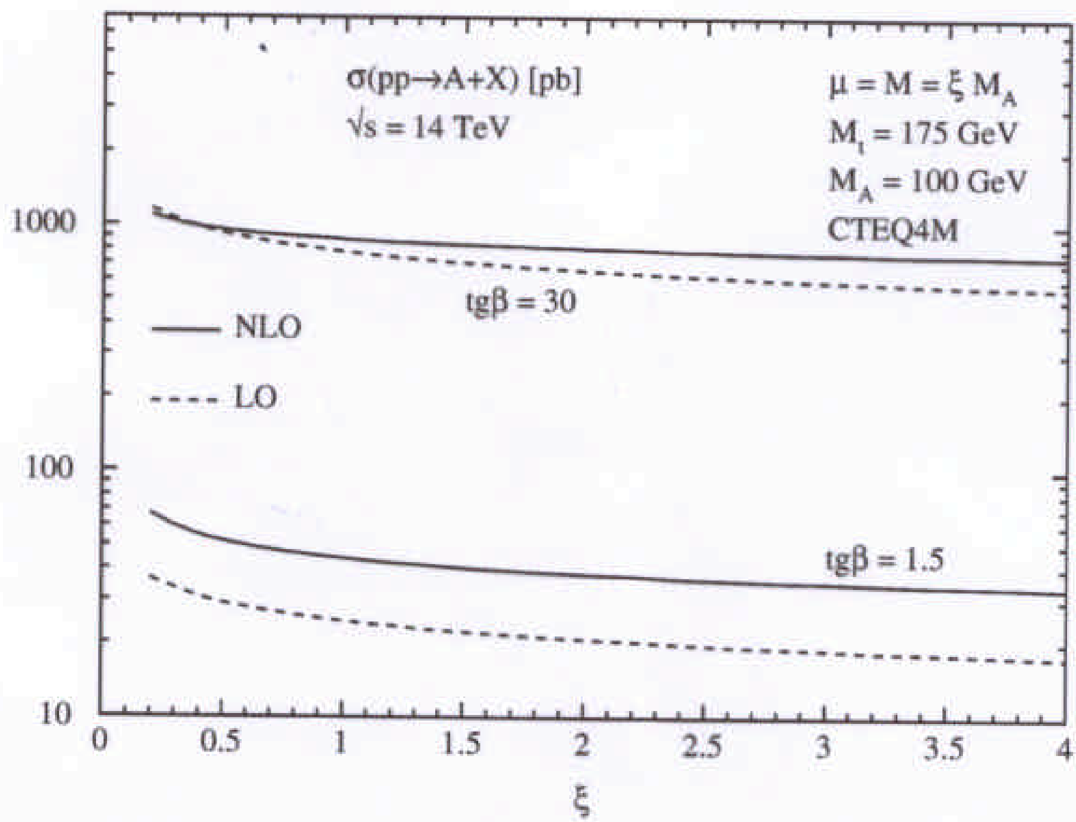
→ resummation: $\Delta \lesssim 15\%$



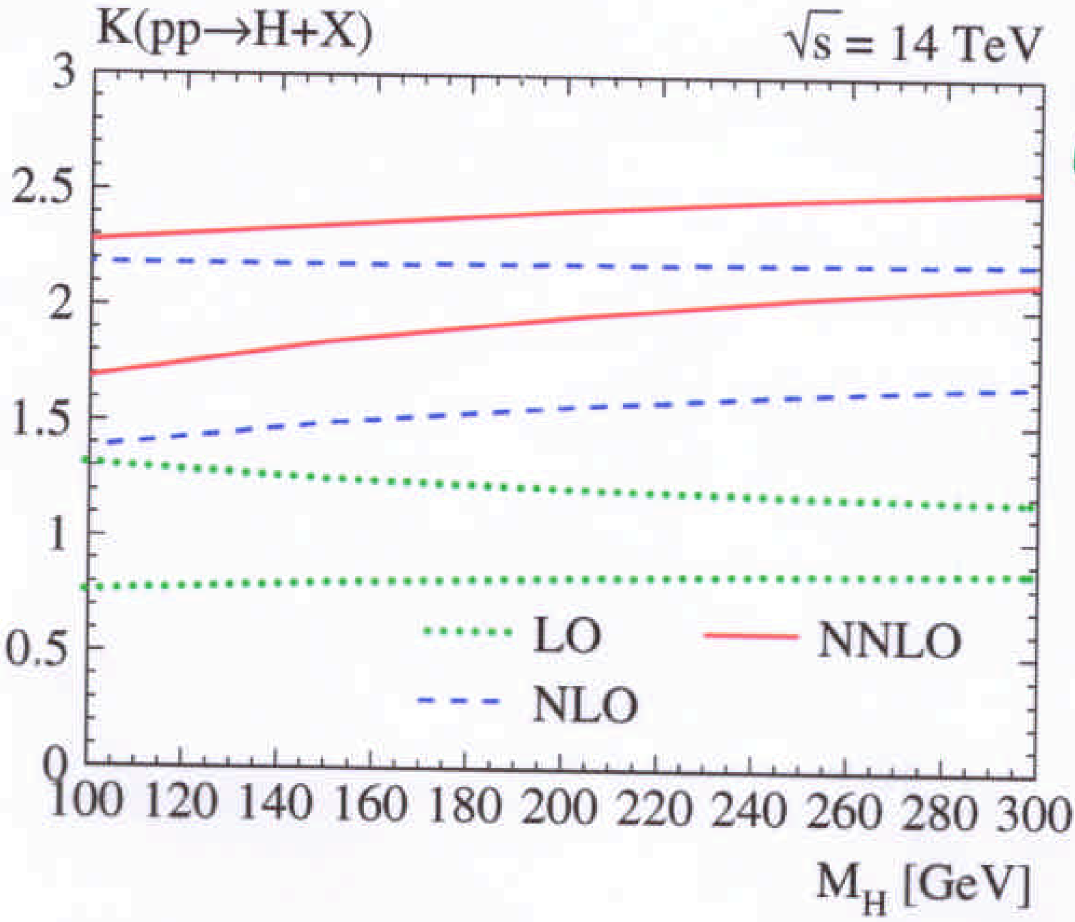


S., Djouadi, Graudenz, Zerwas

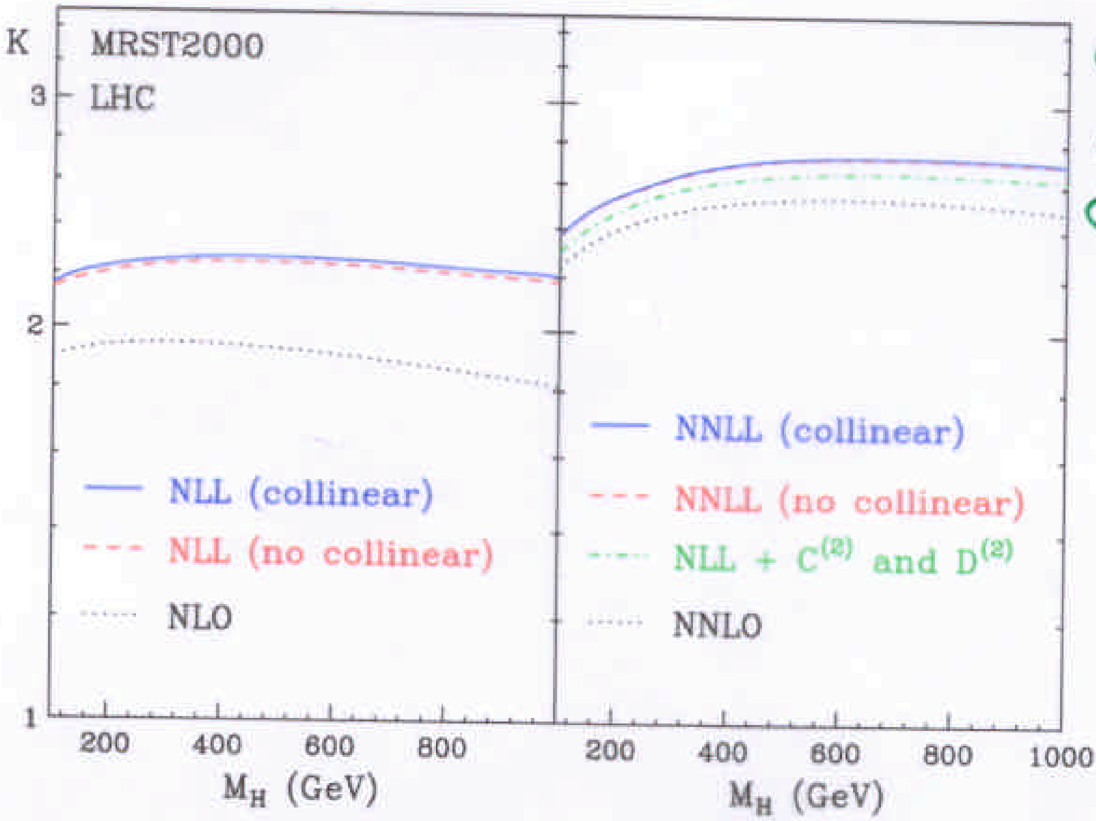




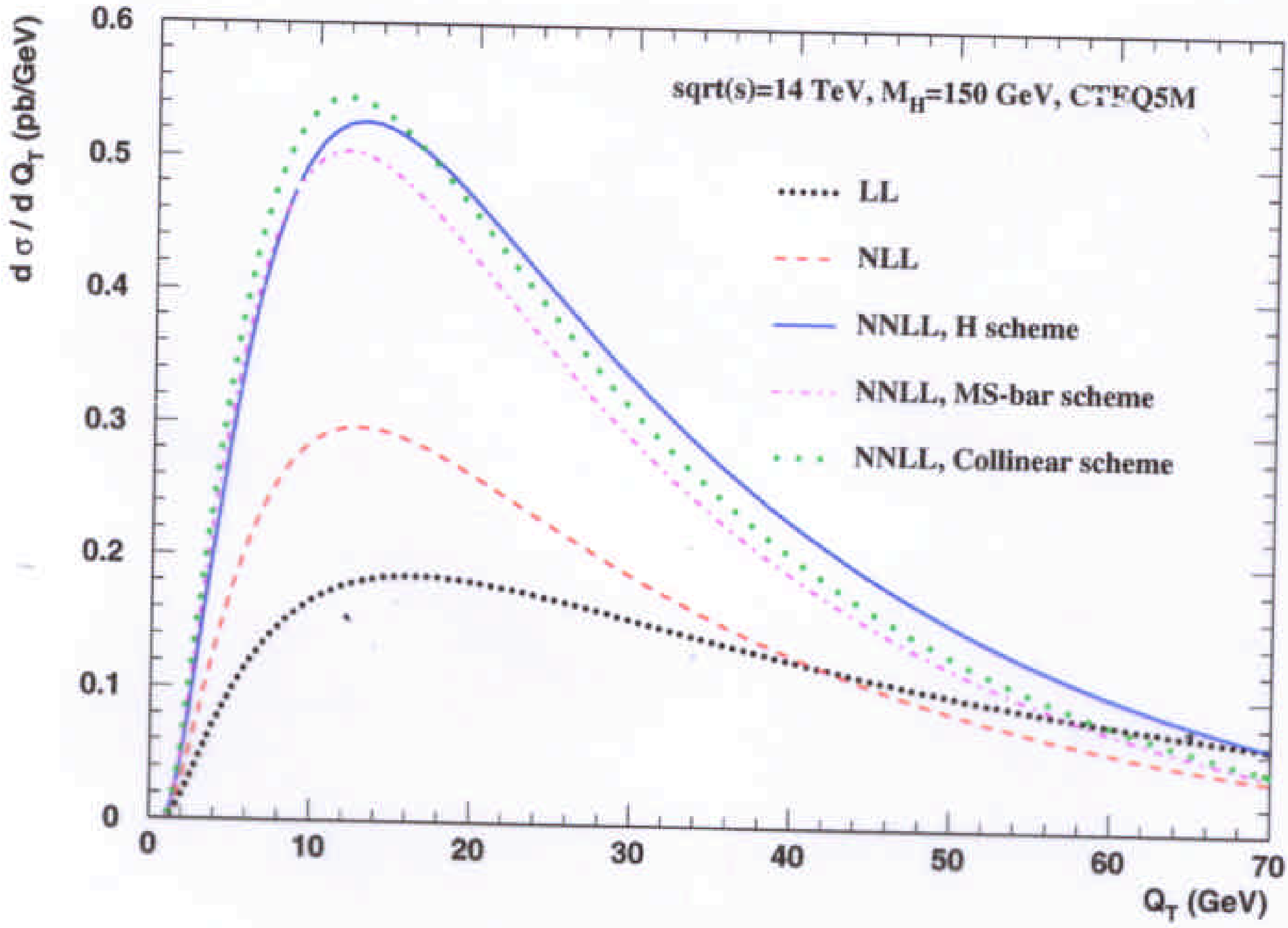
S., Djouadi, Graudenz, Zerwas



Harlander, Kilgore



Catani, de Florian, Grazzini, Nason

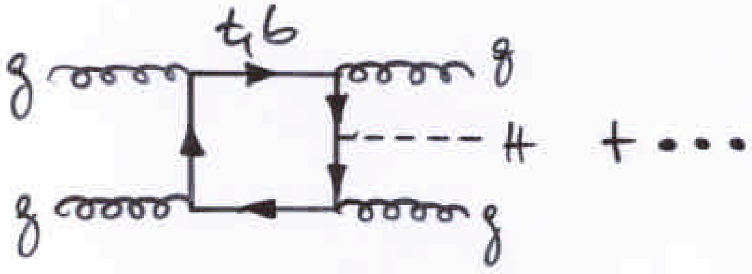


sqrt(s)=14 TeV, M_H=150 GeV, CTEQ5M
LL
NLL
NNLL, H scheme
NNLL, MS-bar scheme
NNLL, Collinear scheme
d σ / d Q_T (pb/GeV)
Q_T (GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
10
20
30
40
50
60
70

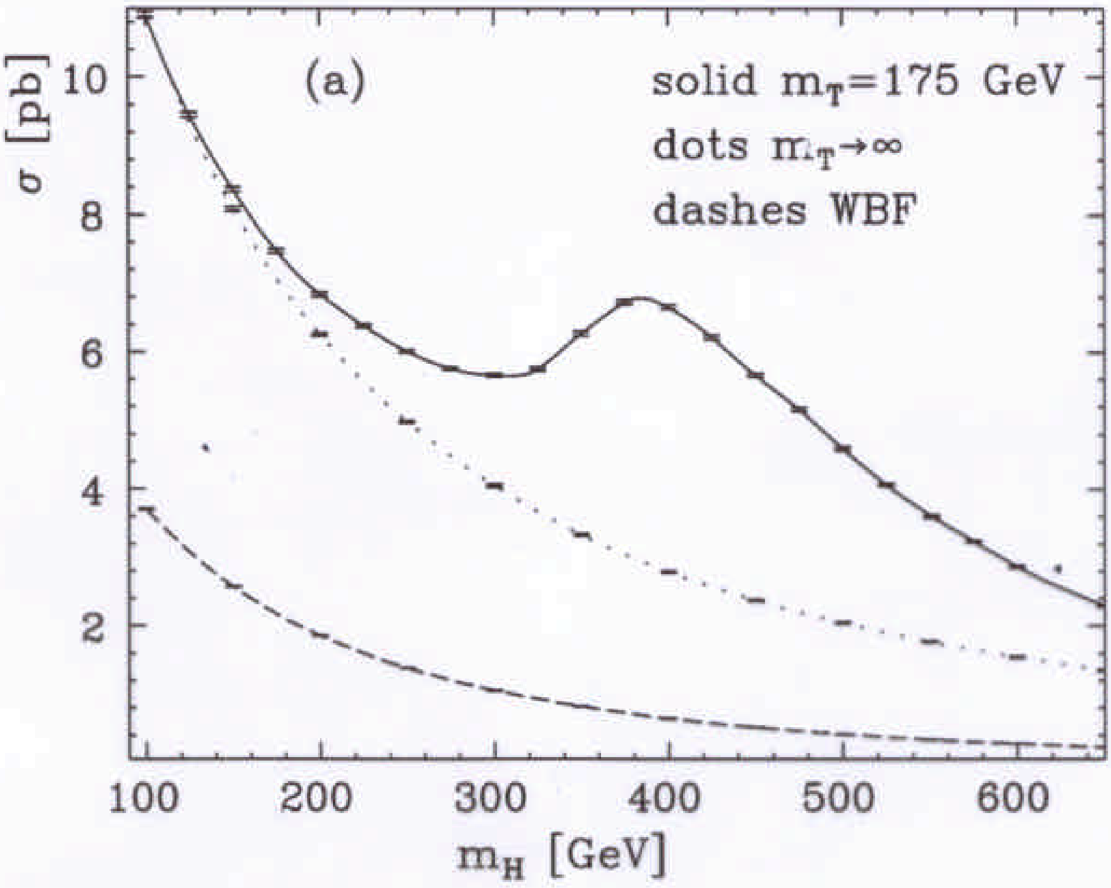
Balazs, Yuan

• $p\overset{(-)}{p} \to H + 2j$: full m_t dependence determined

$\Longrightarrow$ sizeable effect for larger Higgs masses



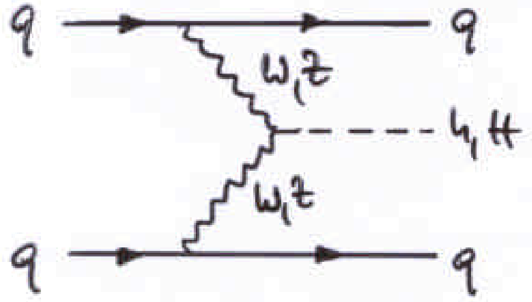
Dawson, Kauffman
Desai, Risal
[$m_t \to \infty$]



Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld

$p_{T_j} > 20$ GeV, $|\eta_j| < 5$, $R_{jj} > 0.6$

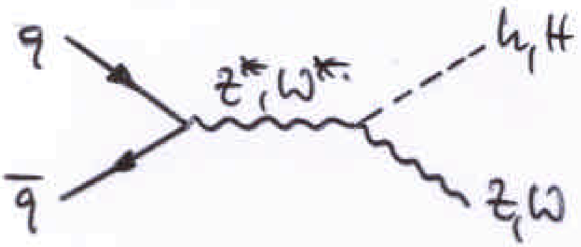
(ii) $VV \to h, H$



Cahn, Dawson
Hikasa
Altarelli, Mele, Pitolli

- $VV \to h, H \to \tau^+\tau^-$ important @LHC Plehn, Rainwater, Zeppenfeld
- QCD corrections ← DIS: + 10% small Han, Valencia, Willenbrock

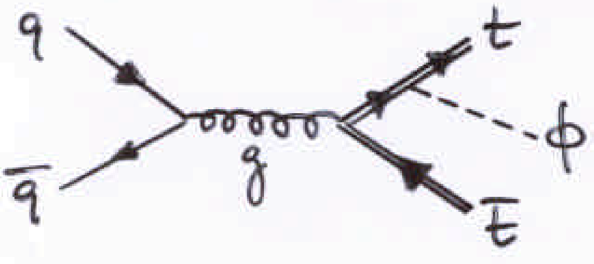
(iii) $V^* \to V + h/H$

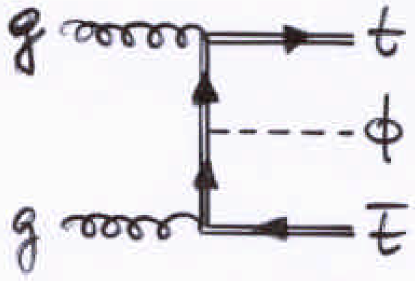


Glashow, Nanopoulos, Yildiz
Kunszt, Trocsanyi, Stirling

- $W^* \to Wh$, $h \to b\bar{b}$ most important process @ Tevatron
- QCD corrections ← Drell-Yan: + (30–40)% Han, Willenbrock

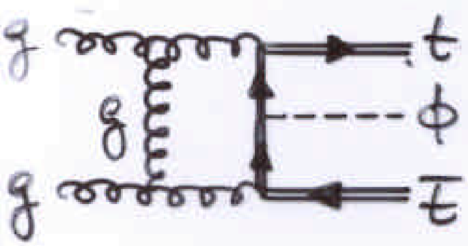
(iv) $gg, q\bar{q} \to t\bar{t}\phi$

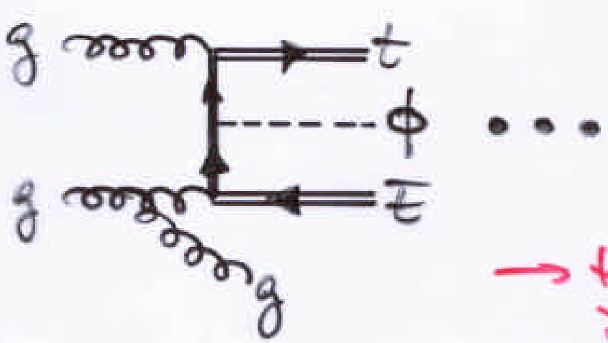




Künszt, Gunion, Marciano, Paige

- possible signature @ Tevatron   Goldstein, ...
- $t\bar{t}h \to t\bar{t}b\bar{b}$ important @ LHC   Gunion, Vega, Dai; ATLAS, CMS
- possibility to measure top-Yukawa cplg. @ LHC   Drollinger ...
- QCD corrections: calculated for H_{SM}

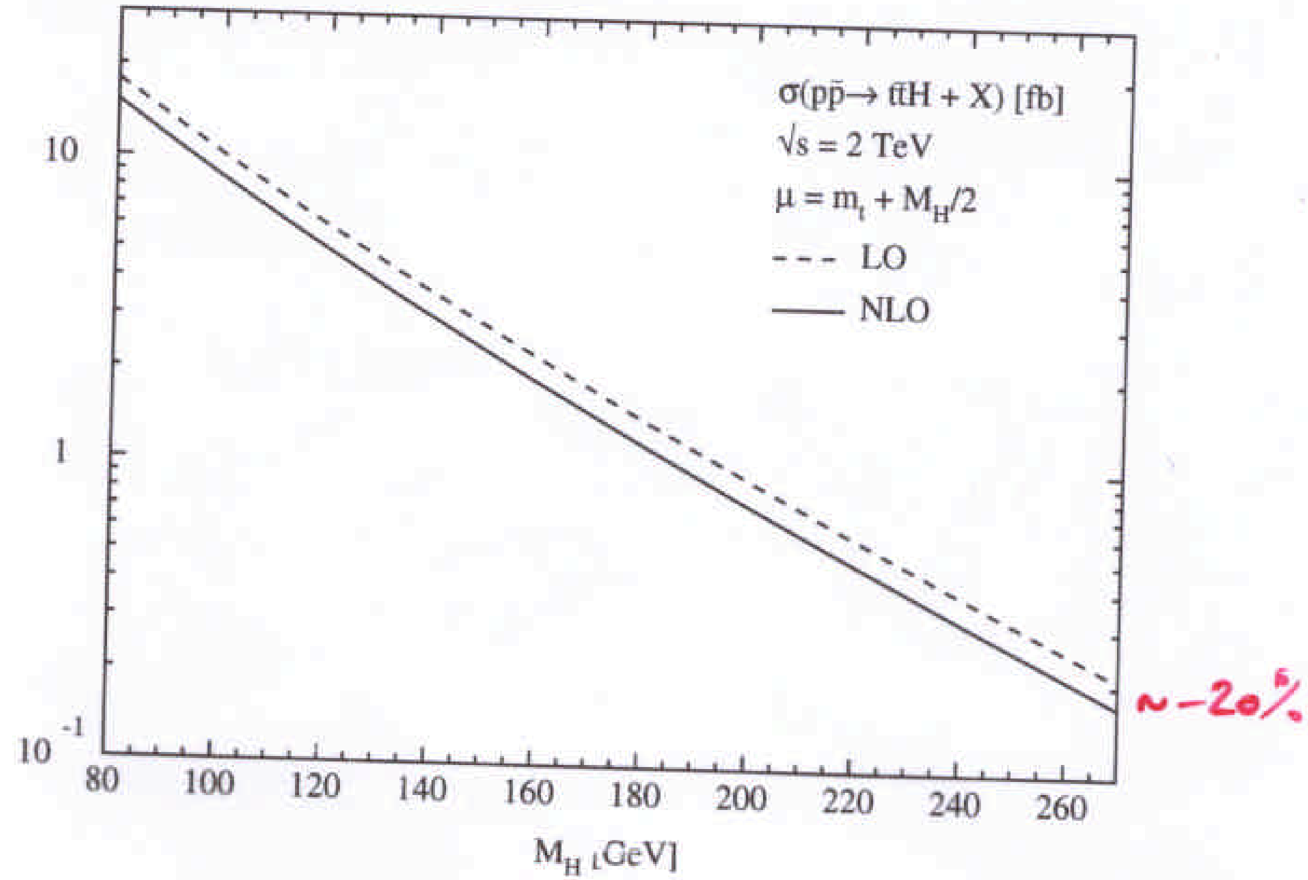


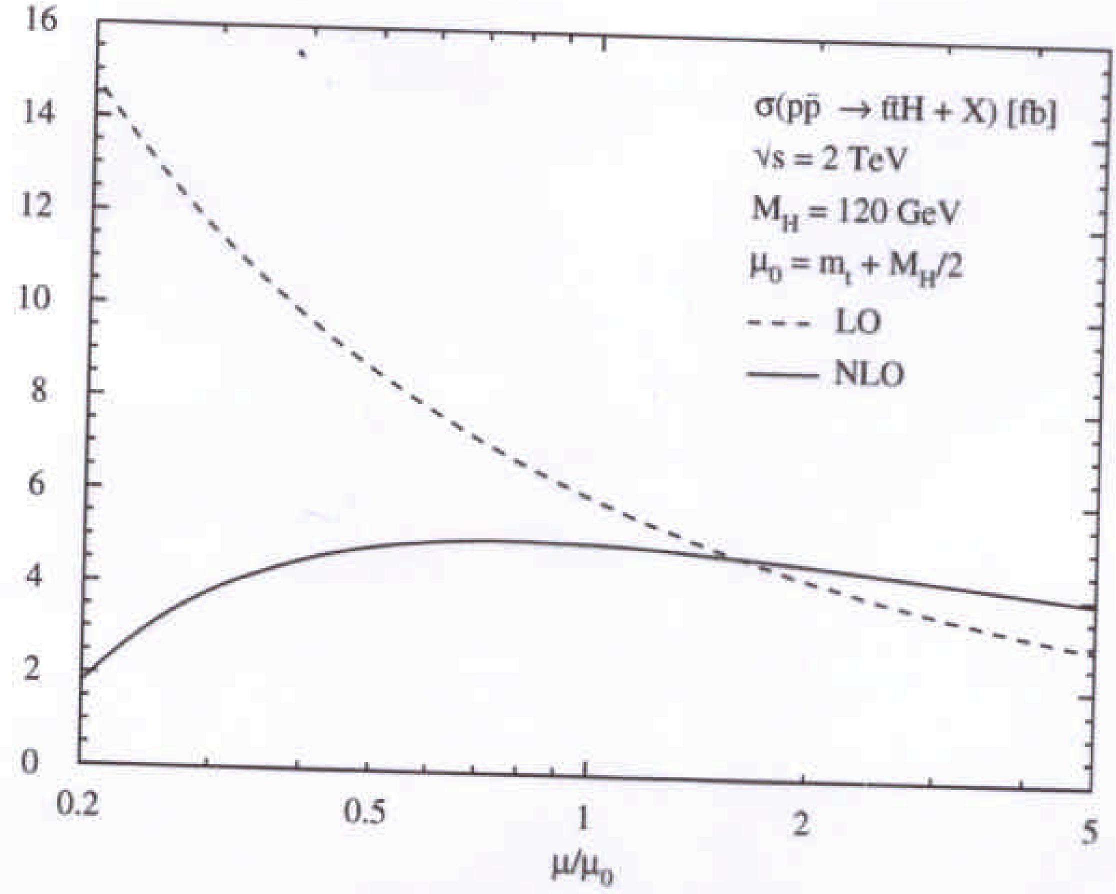


→ talk by S. Dittmaier

- $q\bar{q}$ initial state calculated by two groups:
  Beenakker, Dittmaier, Krämer, Plümper, S., Zerwas
  Dawson, Reina, Wackeroth
  → full agreement for Tevatron

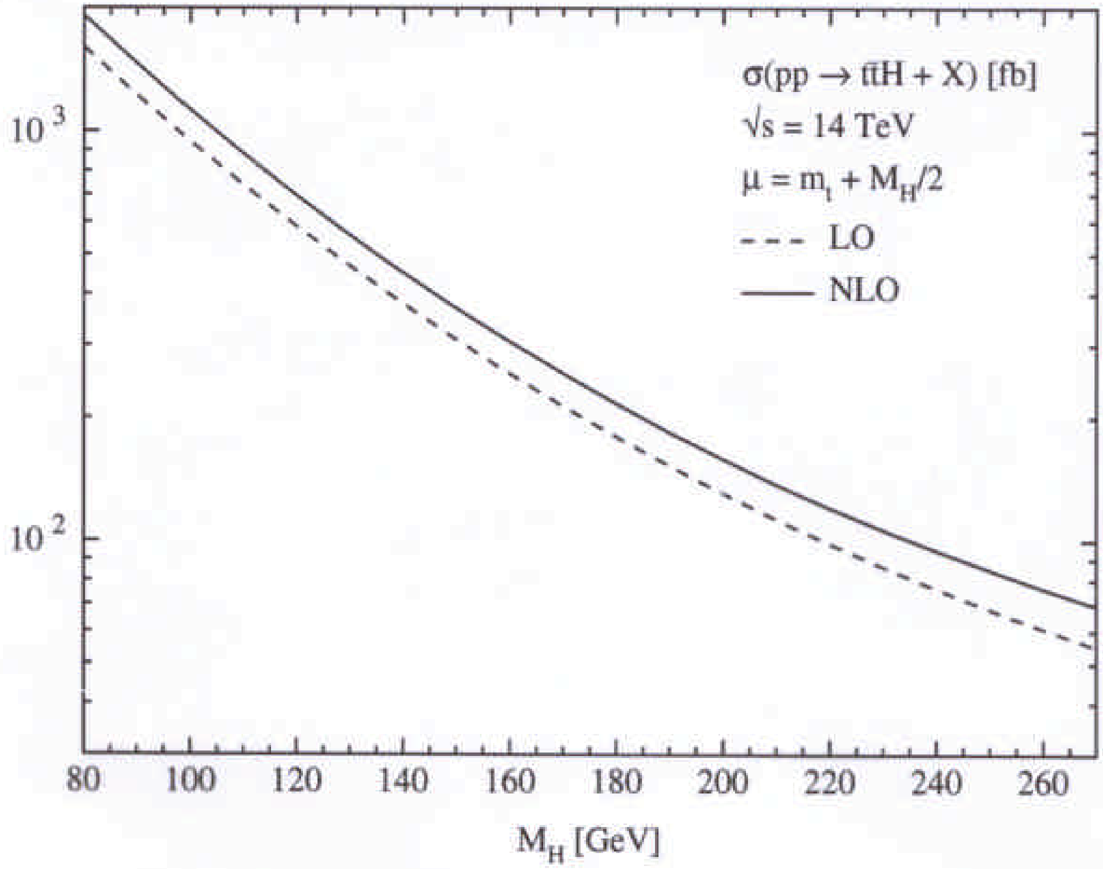
Tevatron



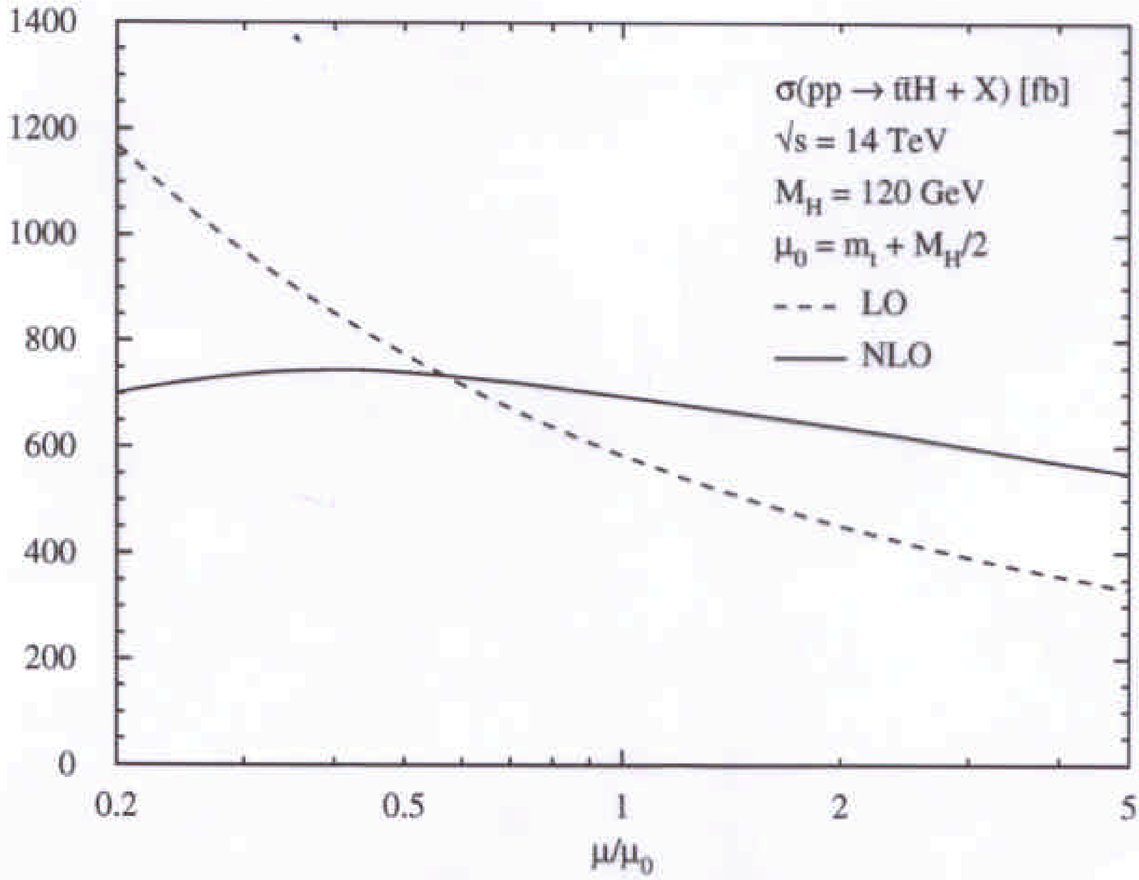


Beenakker, Dittmaier, Krämer, Plümper, S., Zerwas

LHC



~ +20%

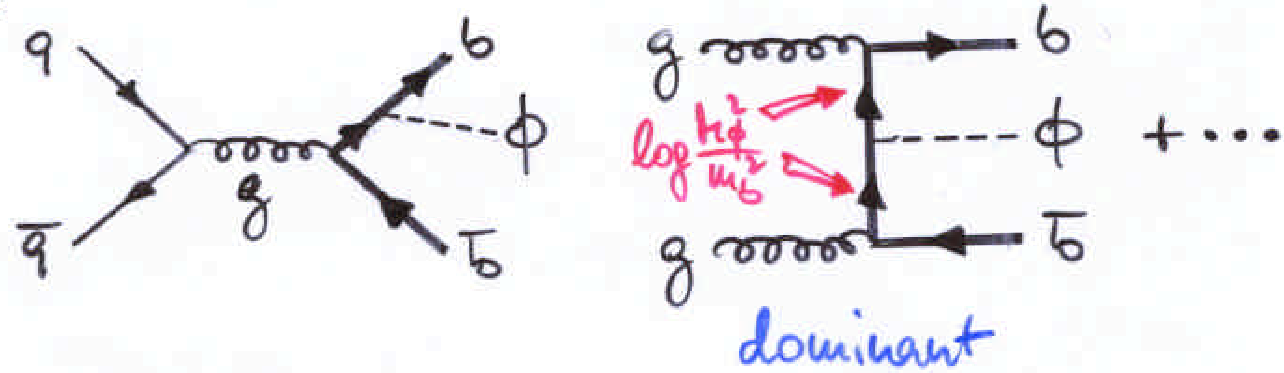


Beenakker, Dittmaier, Krämer, Plümper, S., Zerwas

(v) $gg, q\bar{q} \to b\bar{b}\phi$

- $b\bar{b}H / b\bar{b}A$ production dominant for large $tg\beta$ in MSSM
  $\Rightarrow$ significant contribution to $A/H \to \tau\tau, \mu\mu$

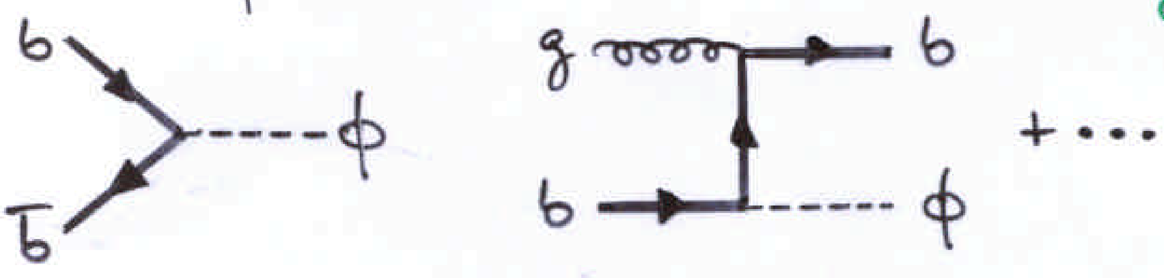
- LO:



large logs from phase space integration
$\longrightarrow$ absorbed in bottom PDFs
resummation $\equiv$ AP evolution

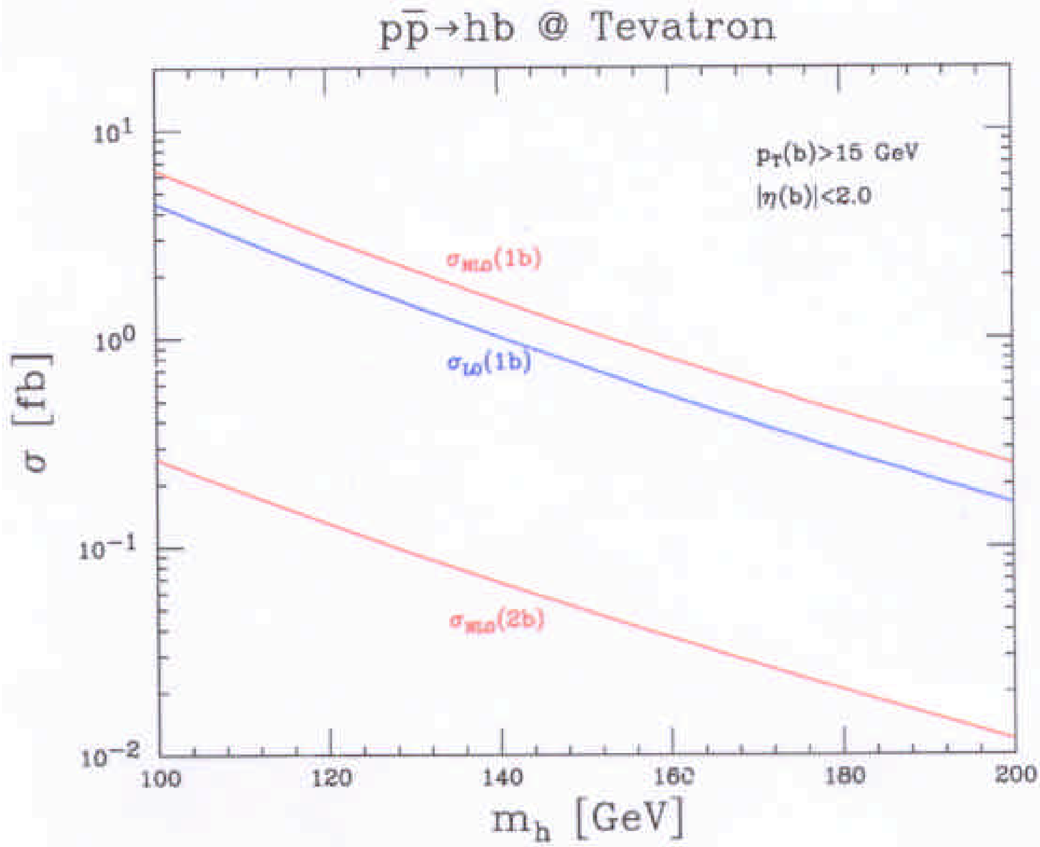
Dicus, Willebrock, Stelzer, Sull
Balazs, ...
Campbell, ...

- new processes:

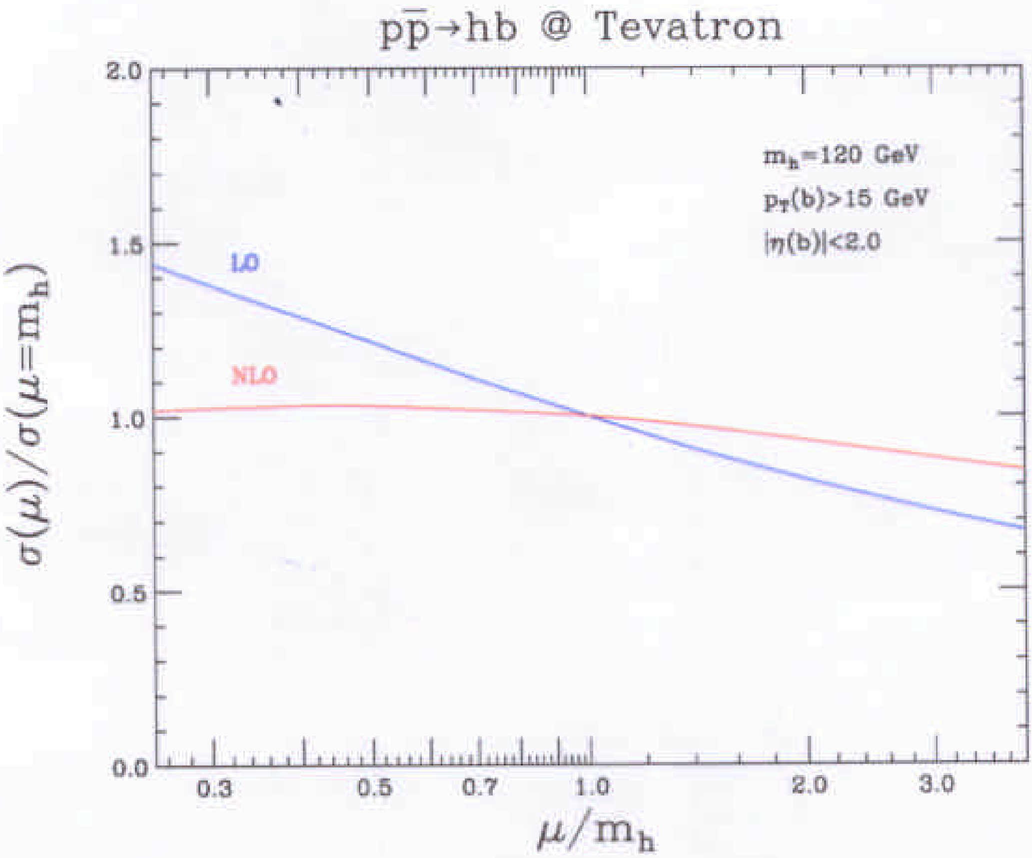


$$b(x,\mu^2) \longrightarrow b(x,\mu^2) - \frac{\alpha_s}{2\pi} P_{qg} \otimes g(x,\mu^2) \log \frac{\mu^2}{m_b^2}$$

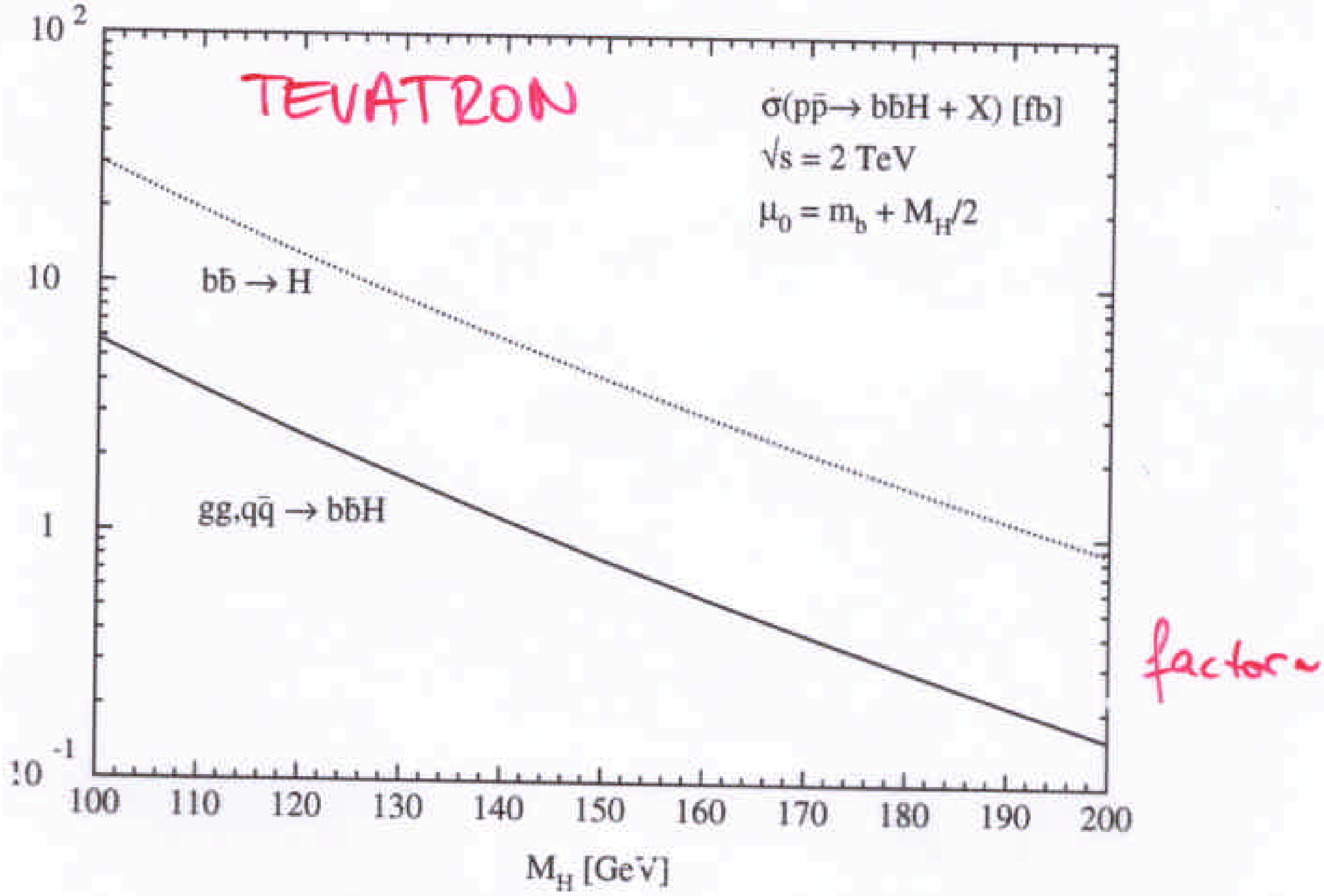
$\mu \sim M_\phi \Rightarrow$ resummed σ_{tot}

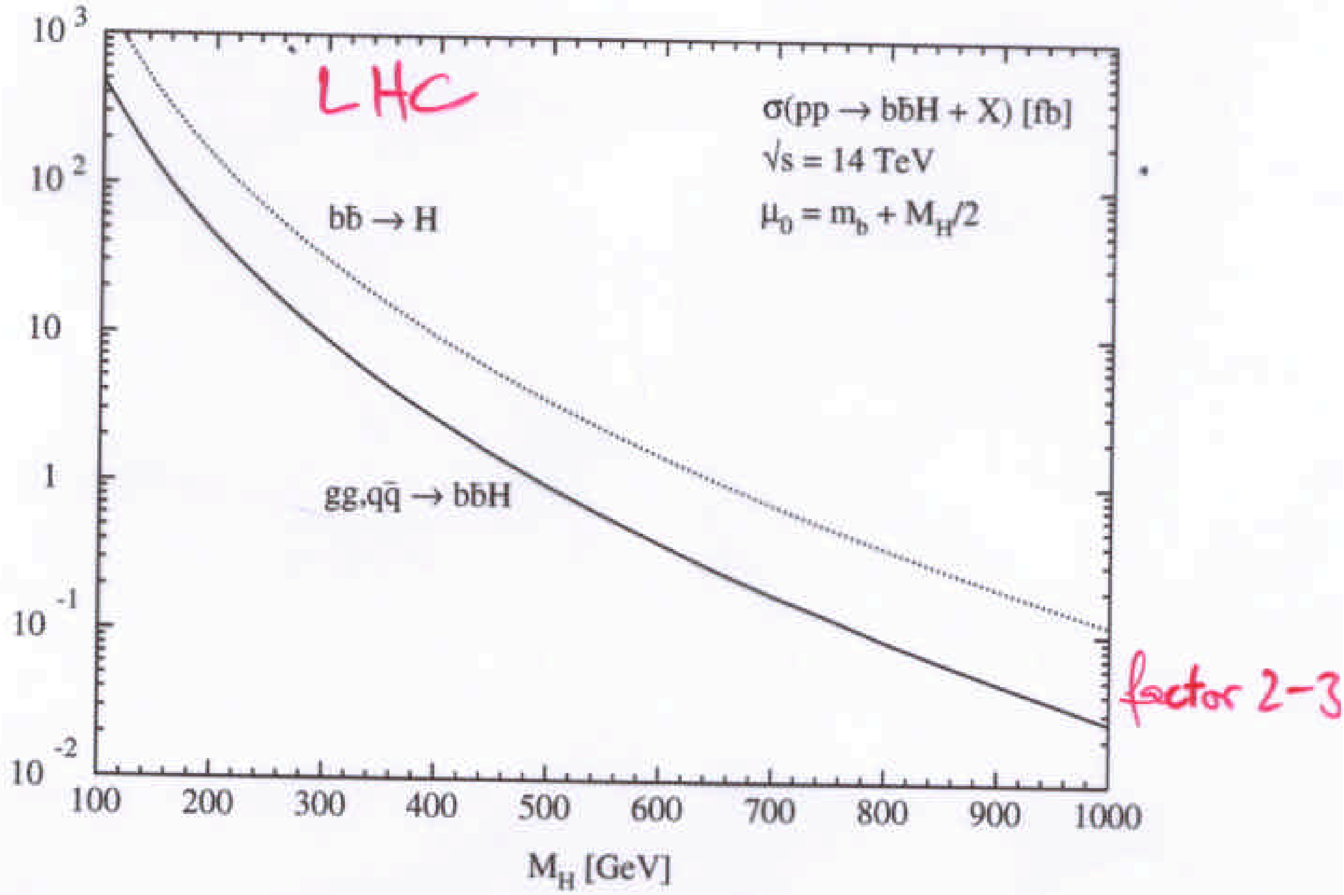


~40%



Campbell, Ellis, Maltoni, Willenbrock

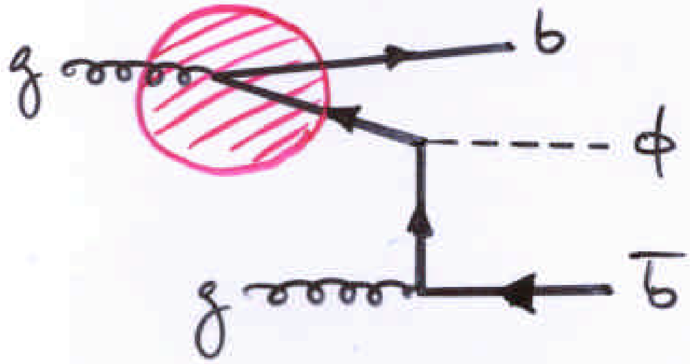

TEVATRON
σ(pp̄→ bb̄H + X) [fb]
√s = 2 TeV
μ0 = mb + MH/2
bb̄ → H
gg,qq̄ → bb̄H
10 2
10
1
10 -1
100
110
120
130
140
150
160
170
180
190
200
MH [GeV]
factor ~


LHC
σ(pp → bb̄H + X) [fb]
√s = 14 TeV
μ0 = mb + MH/2
bb̄ → H
gg,qq̄ → bb̄H
10 3
10 2
10
1
10 -1
10 -2
100
200
300
400
500
600
700
800
900
1000
MH [GeV]
factor 2–3

- factorization in high-energy limit:

$$\frac{d\sigma^{(2\to3)}}{dp_{Tb}} = \frac{2p_{Tb}}{m_b^2+p_{Tb}^2}\left[\frac{\alpha_s}{2\pi}P_{qg}\otimes\hat{\sigma}_{gb}\otimes\frac{d\mathcal{L}^{gg}}{d\tau}\right]\Bigg|_{\substack{m_b\to0\\ p_{Tb}=0}} + \mathcal{O}\left[(p_{Tb}^2+m_b^2)\right.$$

dominant



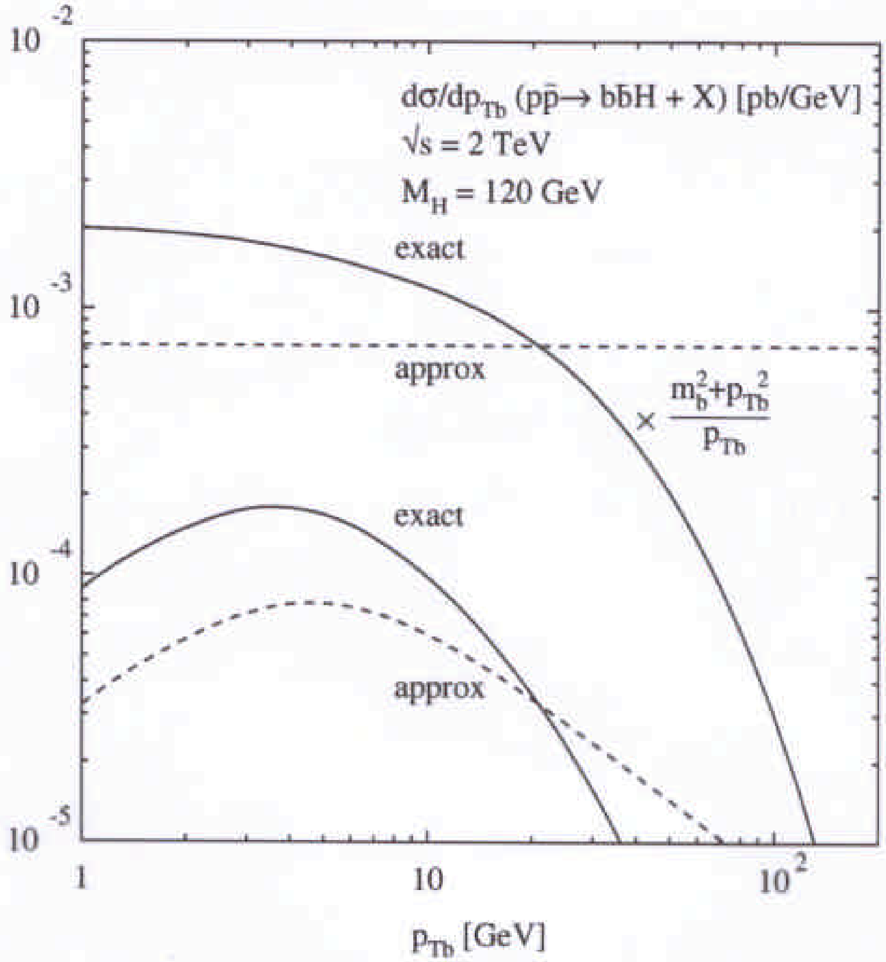
- total cross section: $[\mu_F \sim M_\phi]$

$$\sigma \sim \underbrace{\underbrace{\int_0^{\mu_F} dp_{Tb}\,\frac{2p_{Tb}}{m_b^2+p_{Tb}^2}}_{\log\frac{m_b^2+\mu_F^2}{m_b^2}}\left[\frac{\alpha_s}{2\pi}P_{qg}\otimes g\otimes g\otimes\hat{\sigma}_{bg}\right]}_{\tilde{b}(x,\mu_F^2)}\Bigg|_{\substack{p_{Tb}=\\ m_b\to}}$$

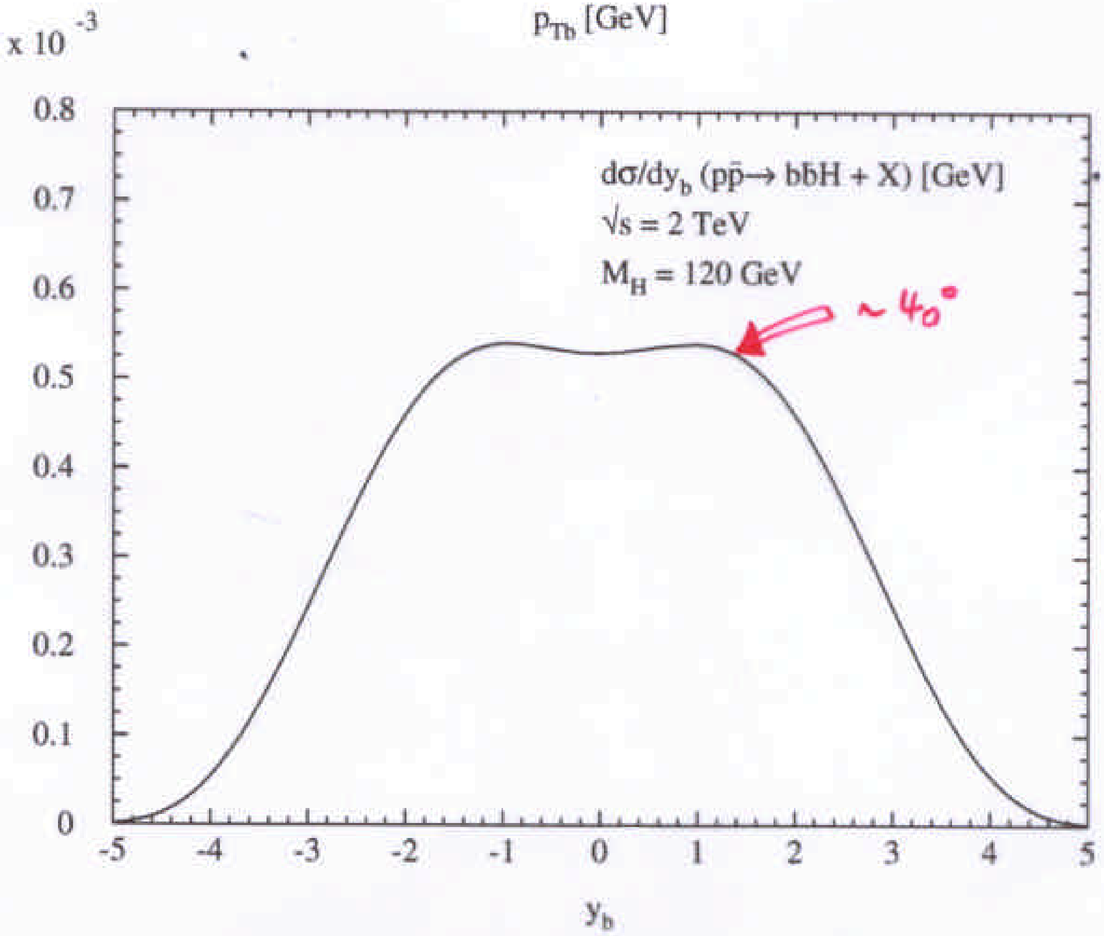
$\Rightarrow$ crucial condition:

$$\frac{d\sigma^{(2\to3)}}{dp_{Tb}} \propto \frac{2p_{Tb}}{m_b^2+p_{Tb}^2} \quad \text{up to } p_{Tb}\sim M_\phi$$

TEVATRON

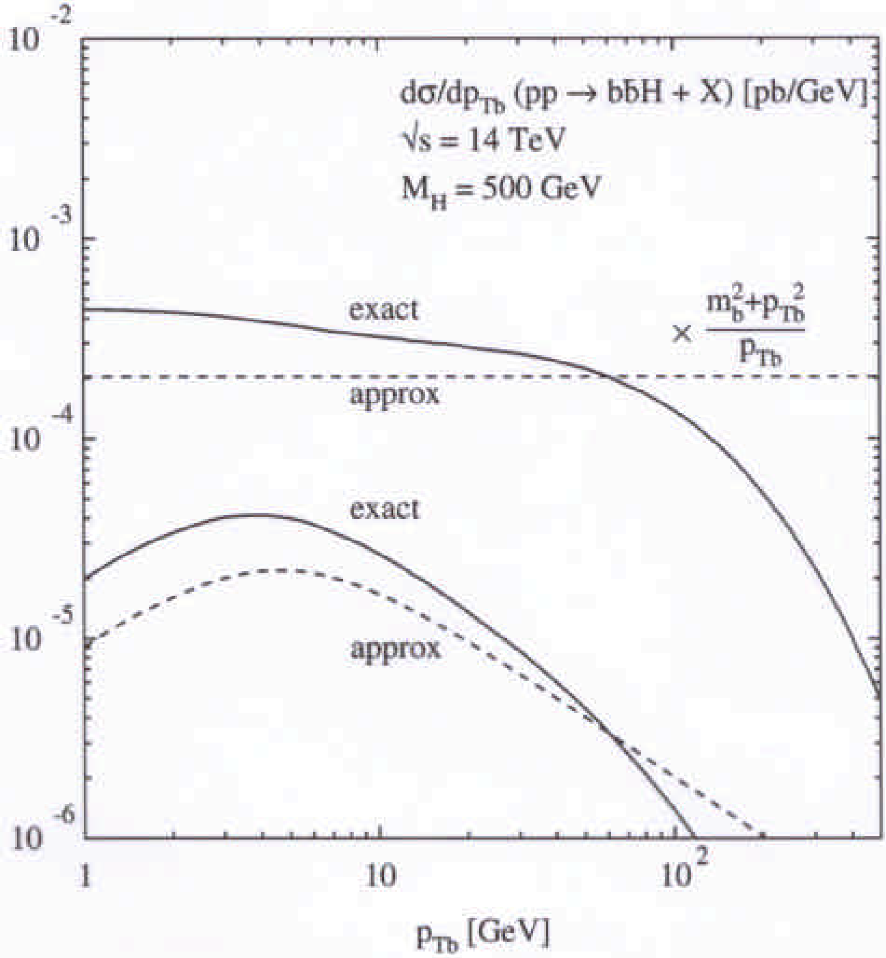


$d\sigma/dp_{Tb}$ ($p\bar{p} \to b\bar{b}H + X$) [pb/GeV]
$\sqrt{s}$ = 2 TeV
M_H = 120 GeV
exact
approx
$\times \frac{m_b^2+p_{Tb}^2}{p_{Tb}}$
exact
approx
p_{Tb} [GeV]

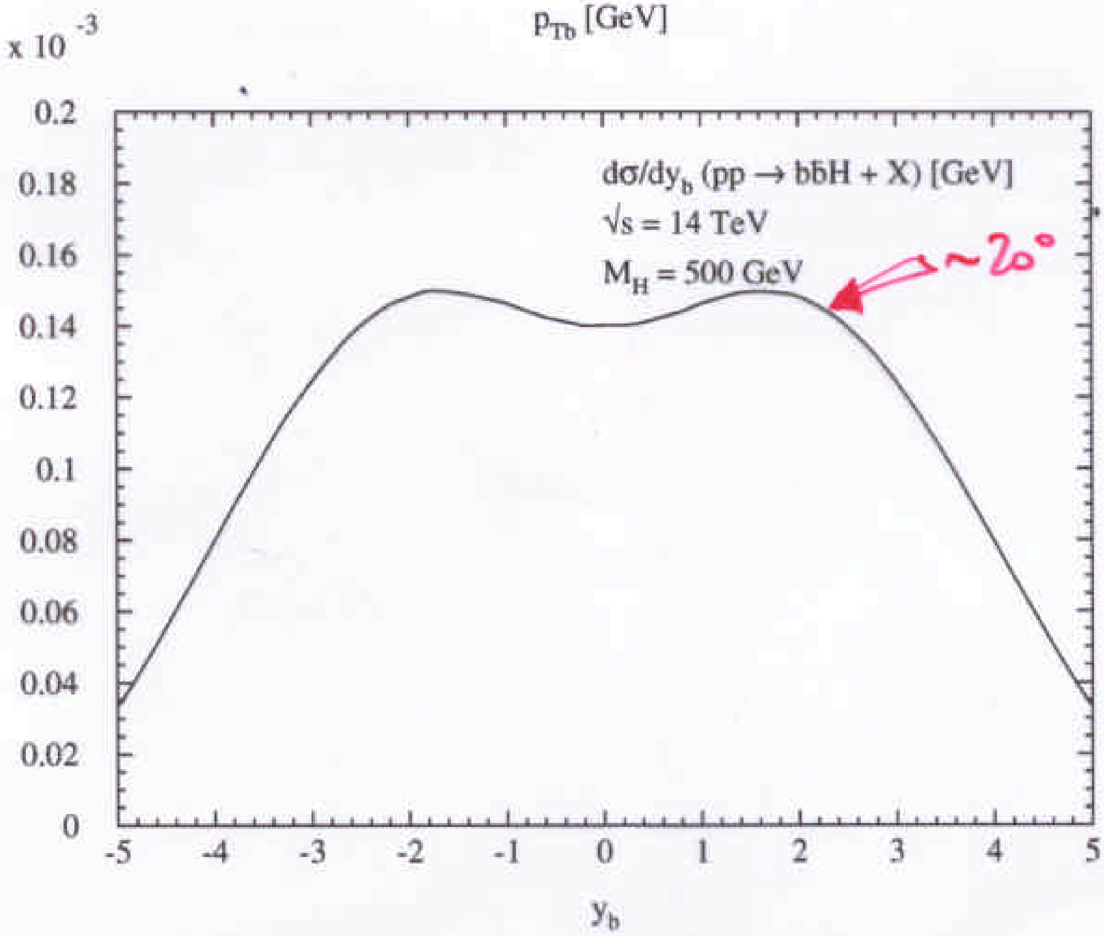


x 10^{-3}
$d\sigma/dy_b$ ($p\bar{p} \to b\bar{b}H + X$) [GeV]
$\sqrt{s}$ = 2 TeV
M_H = 120 GeV
~ 40°
y_b

LHC



dσ/dp_Tb (pp → bb̄H + X) [pb/GeV]
√s = 14 TeV
M_H = 500 GeV
exact
approx
× (m_b² + p_Tb²) / p_Tb
exact
approx
10^-2
10^-3
10^-4
10^-5
10^-6
1
10
10^2
p_Tb [GeV]



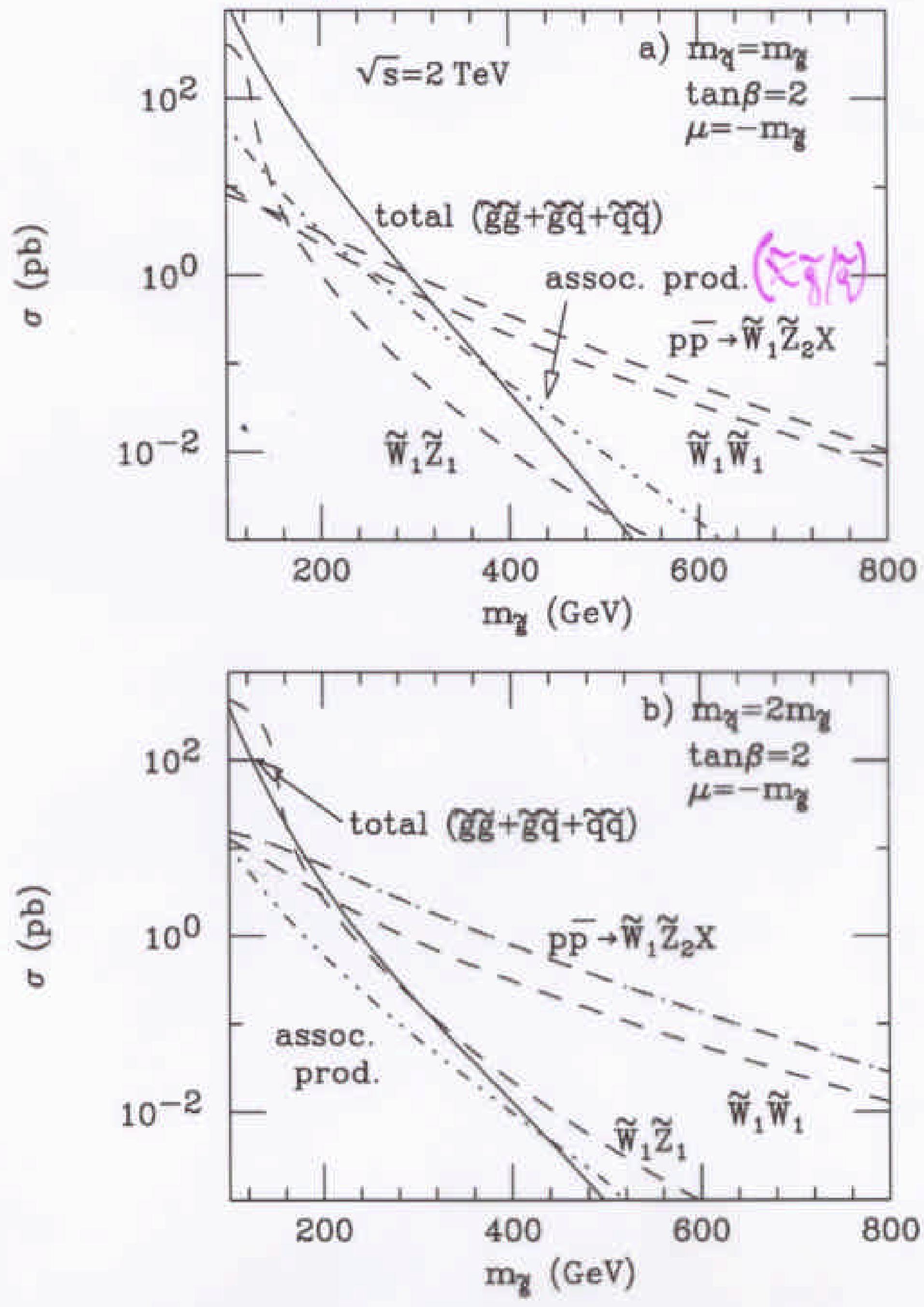
x 10^-3
dσ/dy_b (pp → bb̄H + X) [GeV]
√s = 14 TeV
M_H = 500 GeV
~20°
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-5
-4
-3
-2
-1
0
1
2
3
4
5
y_b

III SUSY Particle Production

- strong: $p\overset{(-)}{p} \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\bar{\tilde{q}}, \tilde{q}\tilde{q}$ [NLO]
- weak: $p\overset{(-)}{p} \to \tilde{\chi}^0_i\tilde{\chi}^0_j, \tilde{\chi}^\pm_i\tilde{\chi}^0_j, \tilde{\chi}^\pm_i\tilde{\chi}^\mp_j, \tilde{\ell}\bar{\tilde{\ell}}$ [NLO]
- associated: $p\overset{(-)}{p} \to \tilde{g}\tilde{\chi}^0_i, \tilde{g}\tilde{\chi}^\pm_i, \tilde{q}\tilde{\chi}^0_i, \tilde{q}\tilde{\chi}^\pm_j$ [LO/NLO]

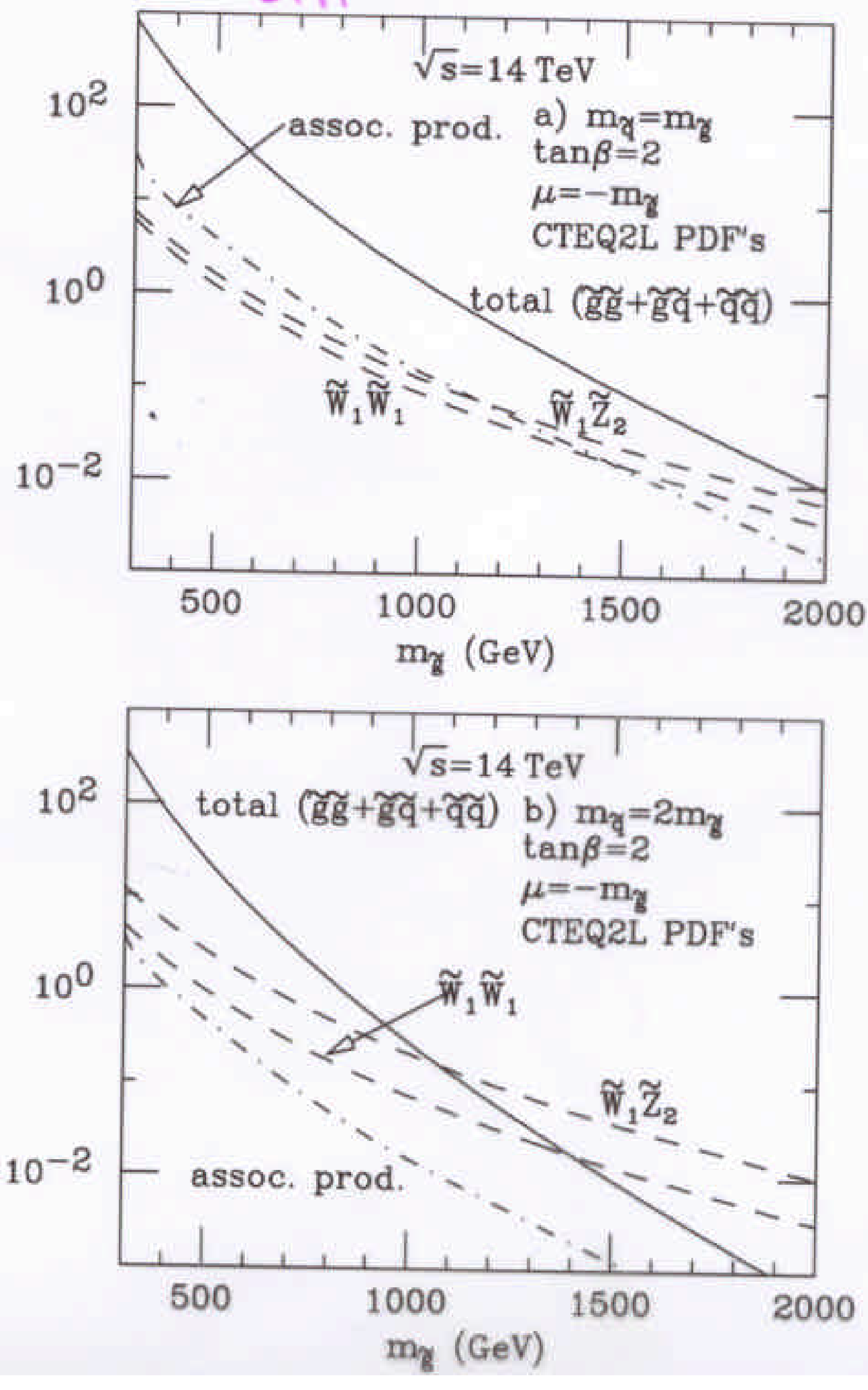
Tevatron [$p\bar{p}$, 2 TeV]

Baer, Chen, Paige, Tata



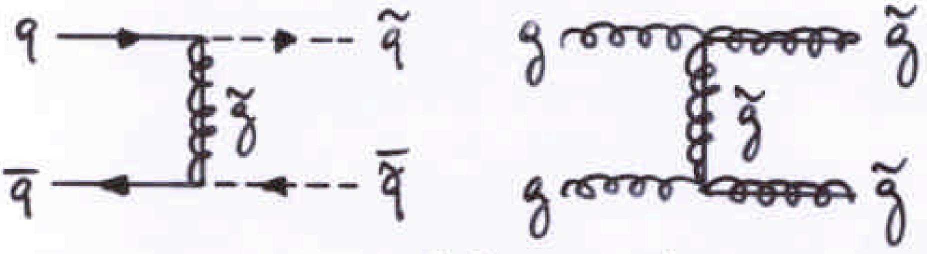
LHC
[pp, 14 TeV]

Baer, Chen, Paige, Tata



(i) $p\overset{(-)}{p} \to \tilde{q}\tilde{q}, \tilde{q}\bar{\tilde{q}}, \tilde{g}\tilde{g}, \tilde{g}\tilde{q}$

- mass degenerate squarks → no stops



- σ_{tot} → mass determination

  $\frac{\Delta\sigma_{LO}}{\sigma_{LO}} \sim 100\%$ ⟹ NLO needed

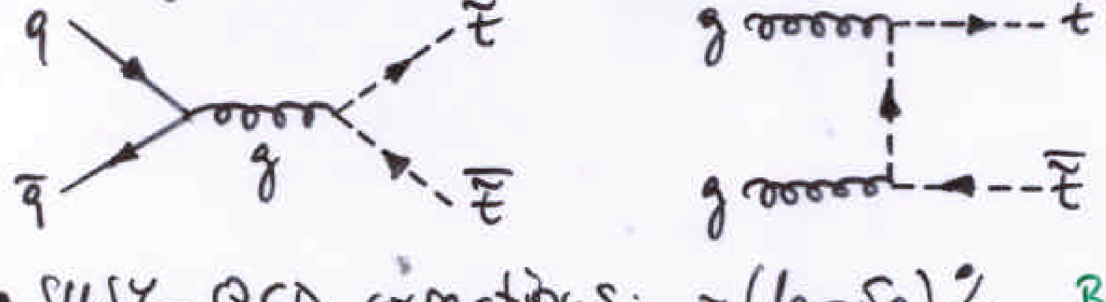
- SUSY-QCD corrections large: 10–80 % — Beenakker, Hö[illegible], S., Zerwas

  → $\frac{\Delta\sigma}{\sigma} \sim 10\text{–}15\%$

- only depending on $m_{\tilde{g}}, m_{\tilde{q}}$
- mass shifts @ Tevatron: ~ 30 GeV

(ii) $p\overset{(-)}{p} \to \tilde{t}\bar{\tilde{t}}$

- mixing effects: $\tilde{t}_L, \tilde{t}_R \to \tilde{t}_1, \tilde{t}_2$

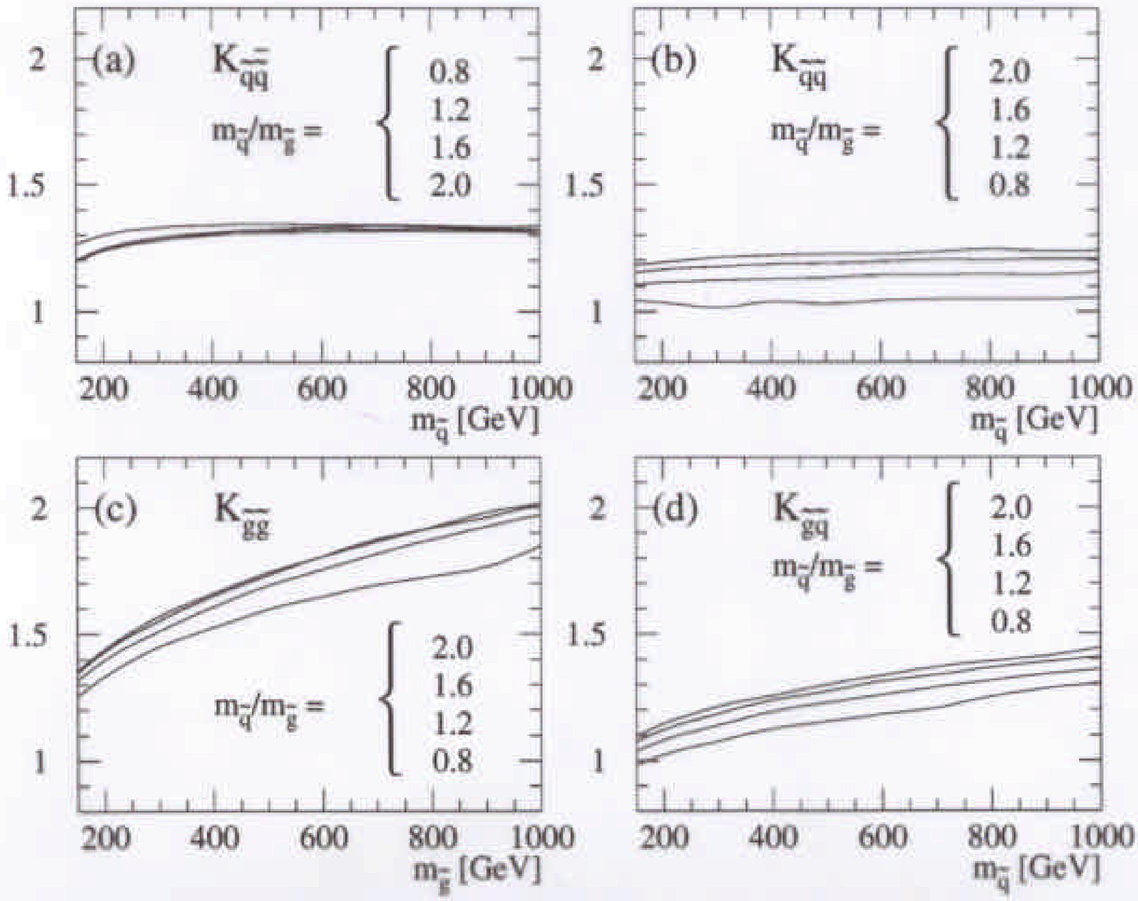


- SUSY-QCD corrections: ~(10–50)% — Beenakker, Krämer, Plehn, S., Zerwas
- scale dependence: $\Delta \sim 15\%$
- dependence on $\theta_{\tilde{t}}, m_{\tilde{g}}, m_{\tilde{q}}$ weak

LHC [pp, 14 TeV]

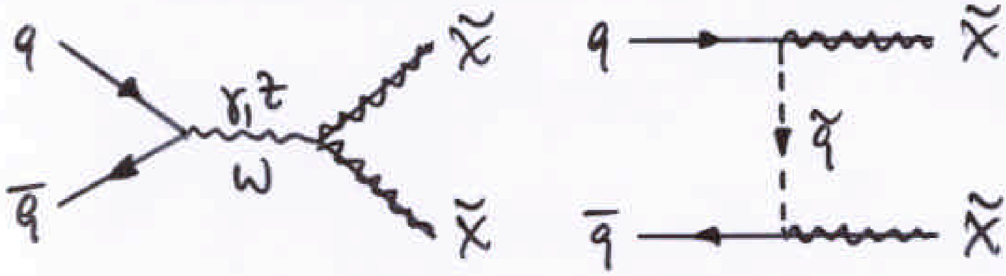
$$K = \frac{\sigma_{NLO}}{\sigma_{LO}}$$

Beenakker, Höpker, S., Zerwas



(iii) $p\overset{(-)}{p} \to \tilde{\chi}\tilde{\chi}$

- several SUSY parameters involved: $M_1, M_2, \mu, tg\beta$



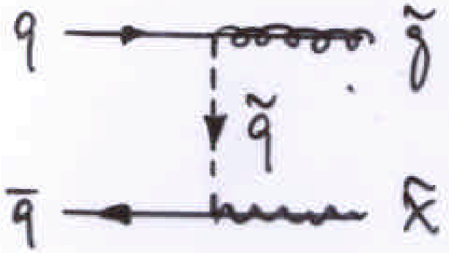
Dawson, Eichten, Quigg

- SUSY-QCD corrections: $\sim (20-50)\%$ [larger than for Drell-Yan]

Beenakker, Kräme
Klasen, Plehn, S., Zer

- scale dependence: $\Delta \sim 10\%$

(iv) $p\overset{(-)}{p} \to \tilde{g}\tilde{\chi}$



Dawson, Eichten, Quigg

- sizeable cross section @ Tevatron, LHC
- SUSY-QCD corrections: two groups

  1.) Berger, Klasen, Tait

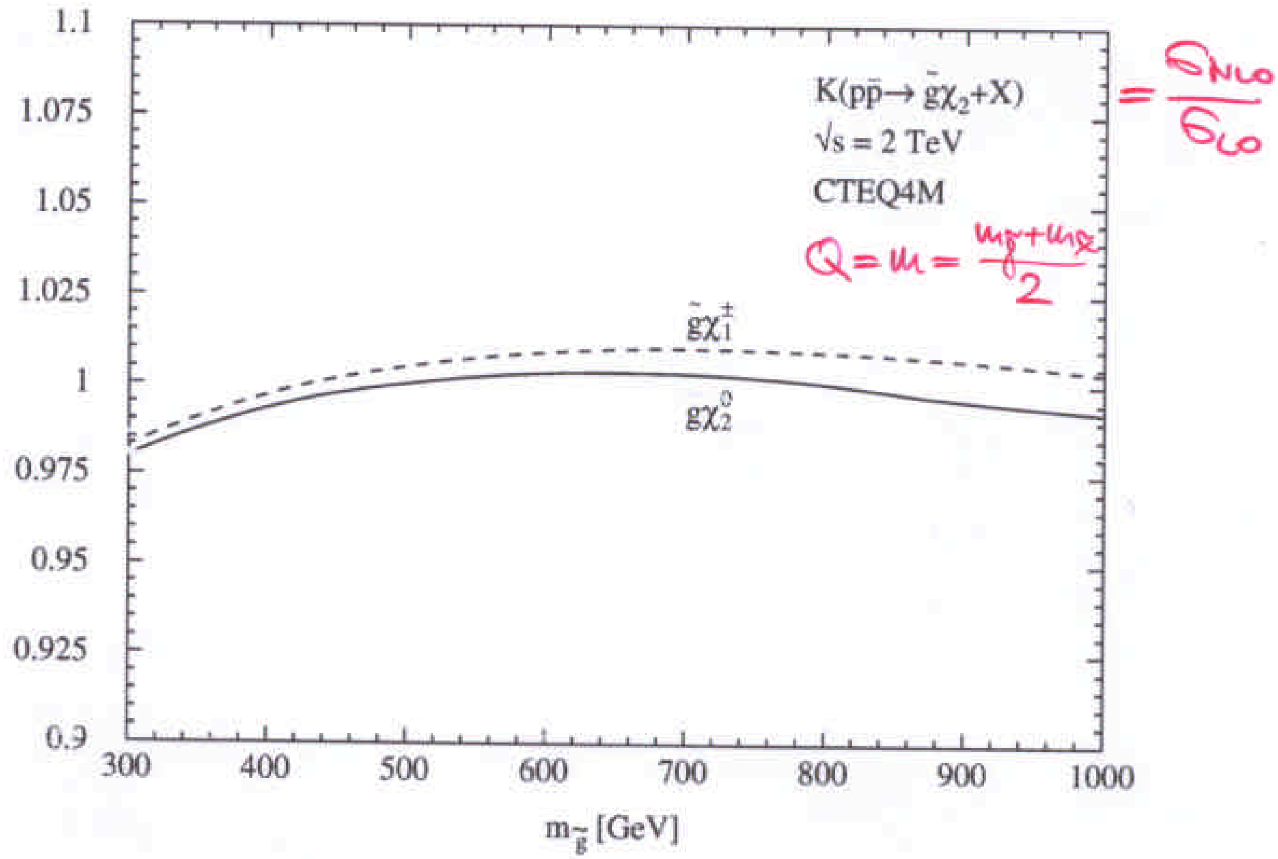
  2.) Beenakker, Krämer, Plehn, S., Zerwas

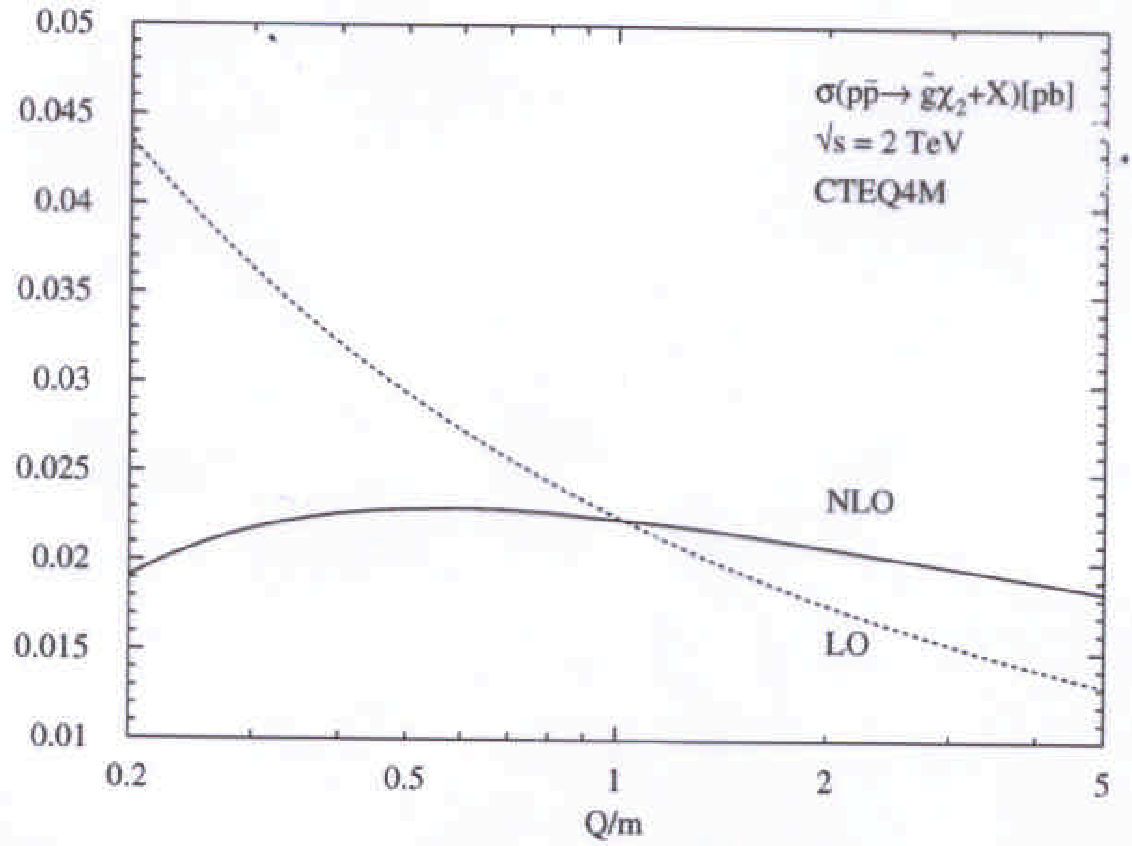
  Tevatron: small

  LHC: $+(10-20)\%$ moderate F

- scale dependence: $\Delta \sim 15\%$ F

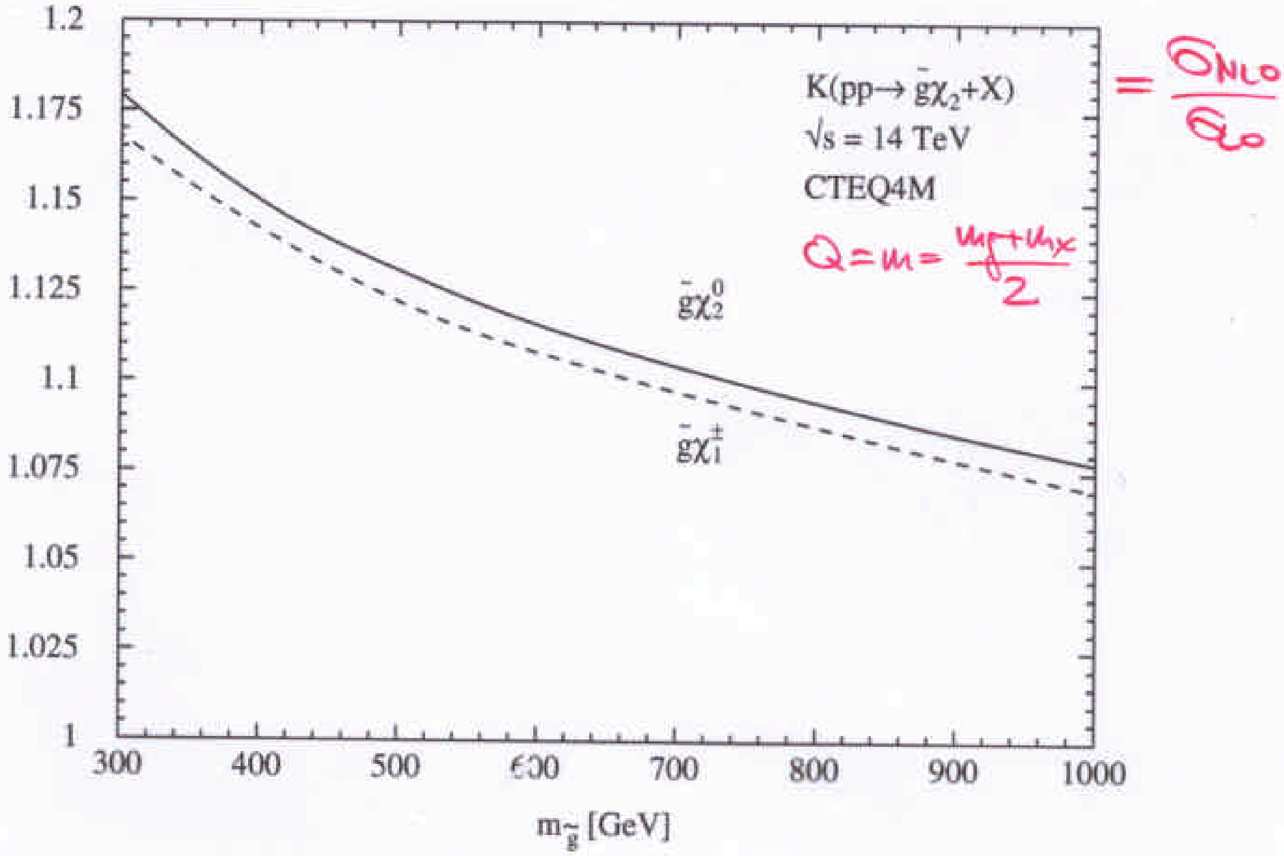
TEVATRON

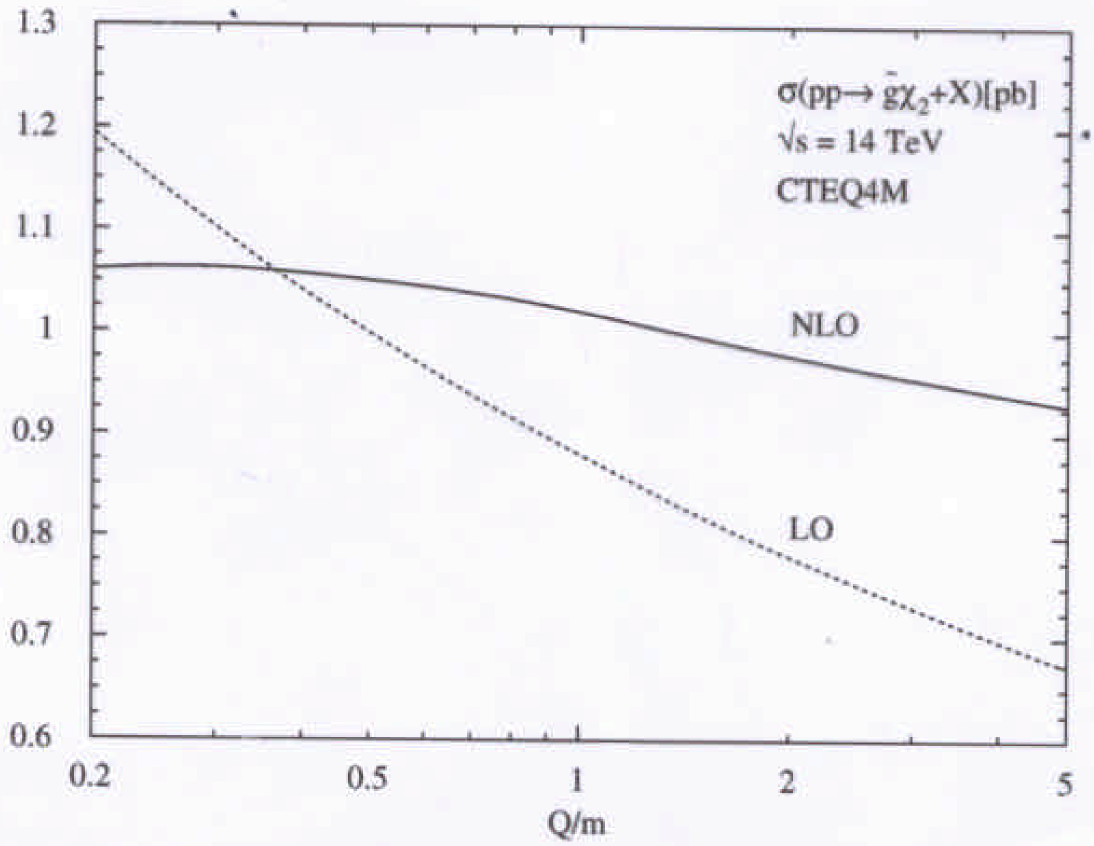




Beenakker, Krämer, Plehn, S., Zerwas

LHC





Beenakker, Krämer, Plehn, S., Zerwas

IV Conclusions

- Higgs + SUSY: most [SUSY-] QCD corrections to production processe known at hadron colliders

  ⇒ theoretical status nearly complete

- large corrections to many processes

  ⇒ important contributions

  [← already used @ Tevatron]

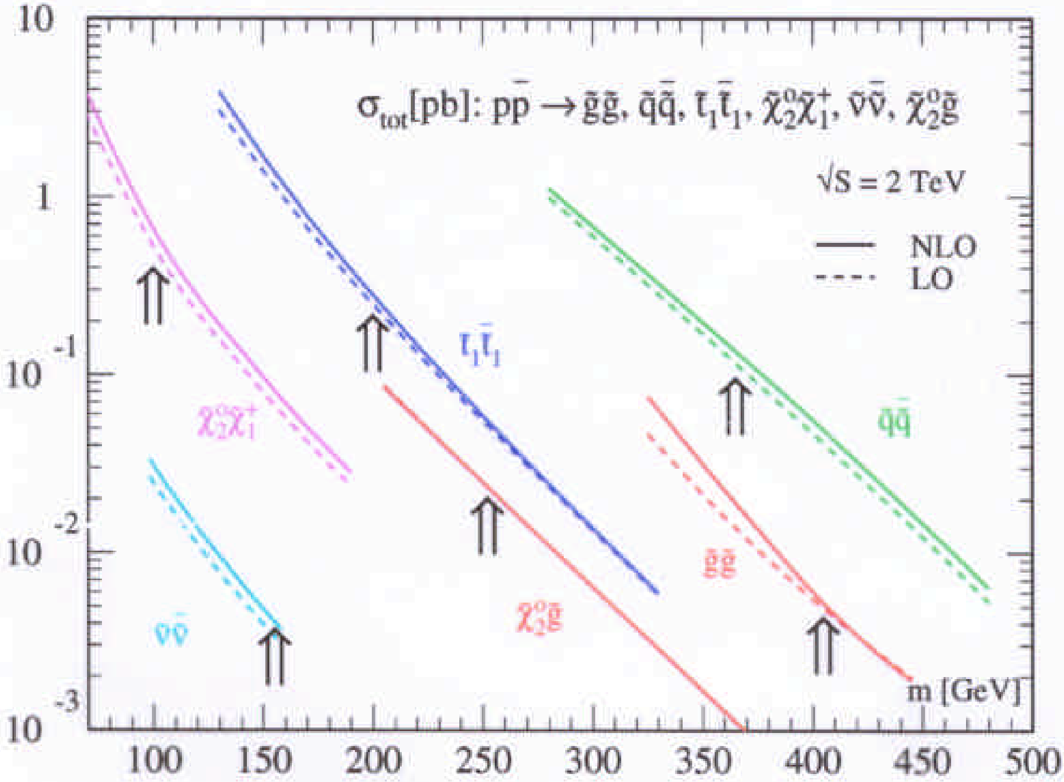
- theoretical uncertainties $\lesssim 15\%$

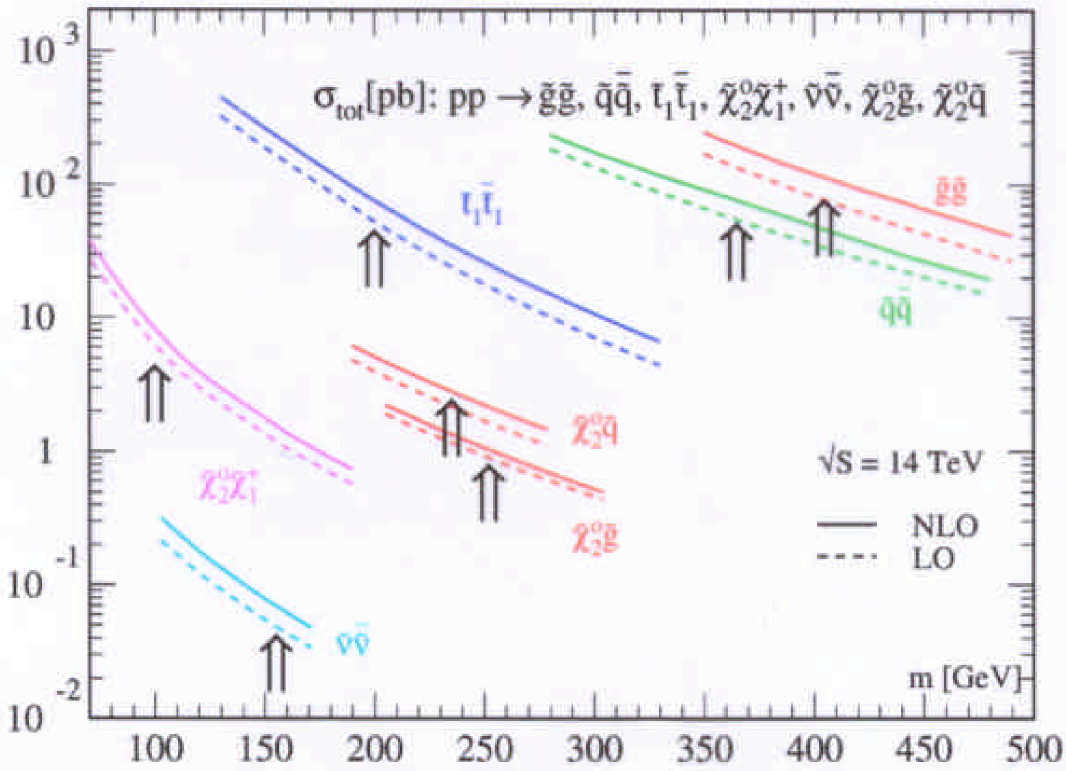
- SUSY-electroweak corrections ?

- programs available: HIGLU, V2VH, VV2H, HQQ, PROSPINO, ...

http://www.desy.de/~spira

PROSPINO





Beenakker, Höpker, Krämer, Plehn, S., Zerwas