NEW RESULTS ON HIGGS PRODUCTION AT HADRON COLLIDERS

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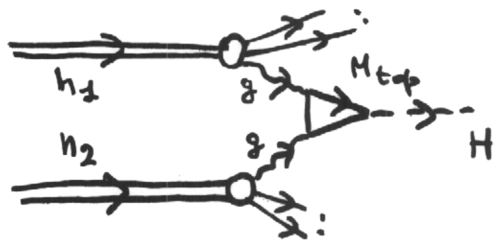
content :

direct production of SM Higgs boson

i.e. production mechanism

gg-fusion through a heavy-quark (top-quark) loop



dominant production mechanism both at the { Tevatron, LHC

Outline :

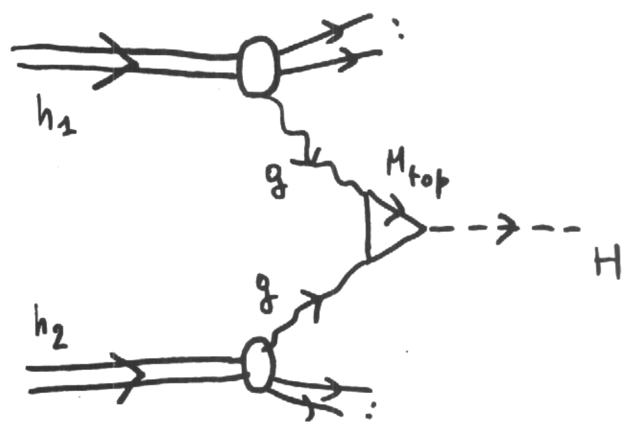
- introduction
- pQCD framework and status of th. calculations
- new (2001-02) pQCD calculations:
  - direct production (inclusive) — Harlander, hep-ph/0007289; de Florian-Grazzini + S.C. hep-ph/0102227, hep-ph/0106049; Harlander-Kilgore hep-ph/0102241, hep-ph/0201206; de Florian-Grazzini-Nason + S.C. (in progress)
  - direct production + jet veto — de Florian-Grazzini + S.C. hep-ph/0111164

- Some others recent results on QCD radiative corrections to <u>associated</u> production:
(H + something + X)

de Florian - Grazzini - Kunszt (hep-ph/9902483) Ravindran - Smith - van Neerven (hep-ph/0201114)	$H + 1$ jet at NLO ($M_{top} \to \infty$) (H at large $p_\perp$)
Beenakker - Dittmaier - Krämer - - Plümper - Spira - Zerwas (hep-ph/0107081) Reina - Dawson - Wackeroth (hep-ph/0109066)	$Ht\bar{t}$ at NLO
Del Duca - Kilgore - Oleari - - Schmidt - Zeppenfeld (hep-ph/0108030)	$H + 2$ jets at LO (M_{top} finite)

- **SM Higgs boson production at hadron colliders:**

dominant production mechanism is
gg-fusion through a heavy-quark (top-quark) loop



- Tevatron : gg-fusion $\sim 65\%$ of $\sigma_{Higgs}^{(total)}$
  for $100 \lesssim M_H \lesssim 200$ GeV

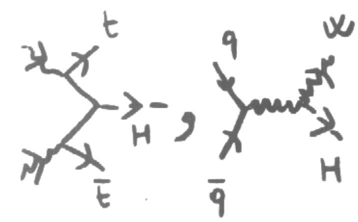
- LHC : gg-fusion exceedes all the other production channels
  by a factor of $8 \to 5$
  (M_H: $100 \to 200$ GeV)

  (when $M_H \sim 1$ TeV, gg-fusion still provides $\sim 50\%$ of $\sigma_{Higgs}^{(total)}$)

- **relevance for Higgs search** :
  - combine production ⊗ decay channel
  - consider signal and background : significance $S/\sqrt{B}$

to enhance significance in some channels :

i) consider associated production $Ht\bar{t}$, HW, HZ rather than direct production

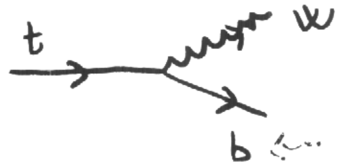


gg-fusion no longer dominant

ii) apply additional cuts on hadronic final state accompanying direct Higgs production

e.g. $gg \to H \to WW \to \ell^+ \ell^- \nu \bar{\nu}$

has important background from $t\bar{t}$, tW production



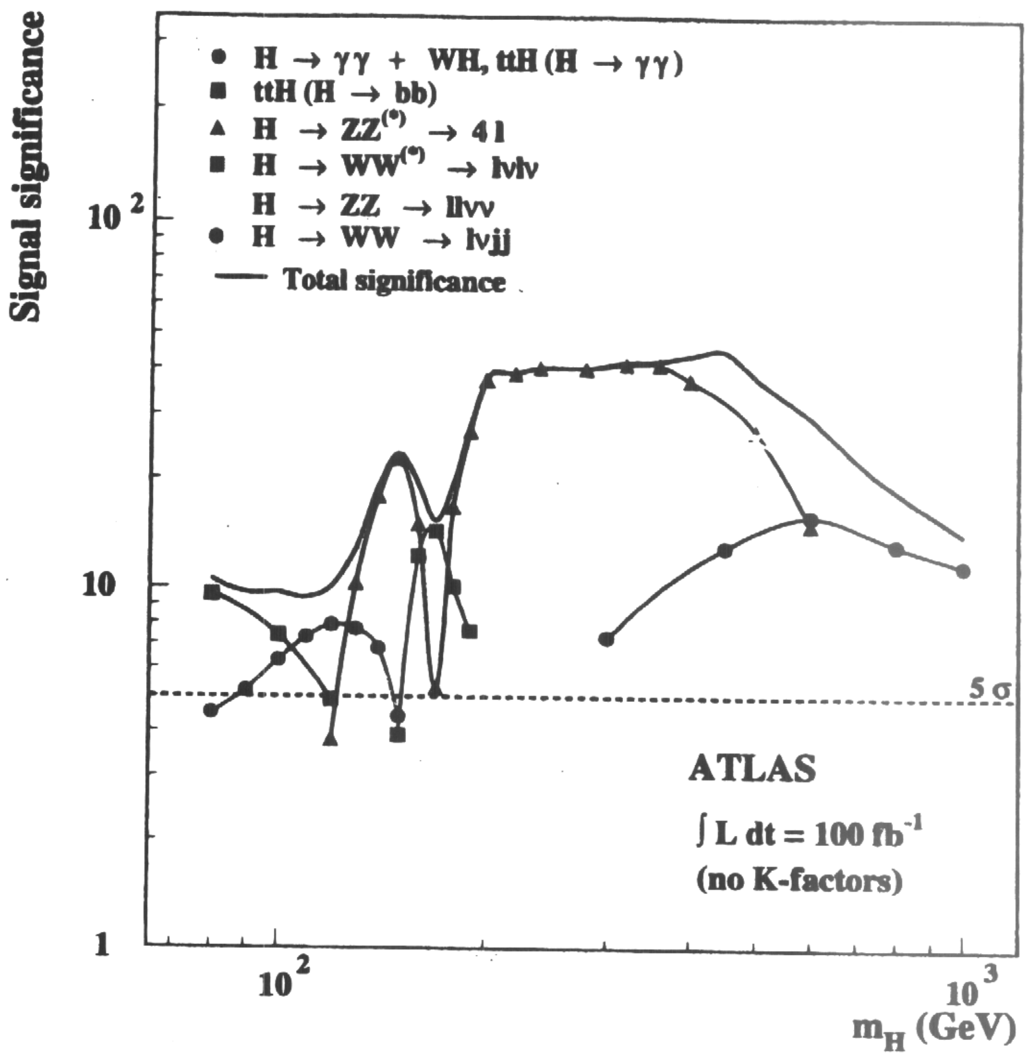
high-p_t jet

$\Downarrow$

reduce background by imposing jet veto $p_t^{jet} < p_t^{veto}$ on $H + X$ (jets)

LHC

from ATLAS TDR
(use PYTHIA MC : LO QCD ⊕ parton shower)



direct production : $H \to \gamma\gamma$ $(100 \lesssim M_H \lesssim 140\ \text{GeV})$

$H \to ZZ \to 4\ell,\ e^+e^-\nu\bar{\nu}$

$(130 \lesssim M_H \lesssim 700\ \text{GeV})$

direct production
+ jet veto : $H \to WW \to e^+e^-\nu\bar{\nu}$

$(150 \lesssim M_H \lesssim 190\ \text{GeV})$

Tevatron (from Tevatron Run II WS)

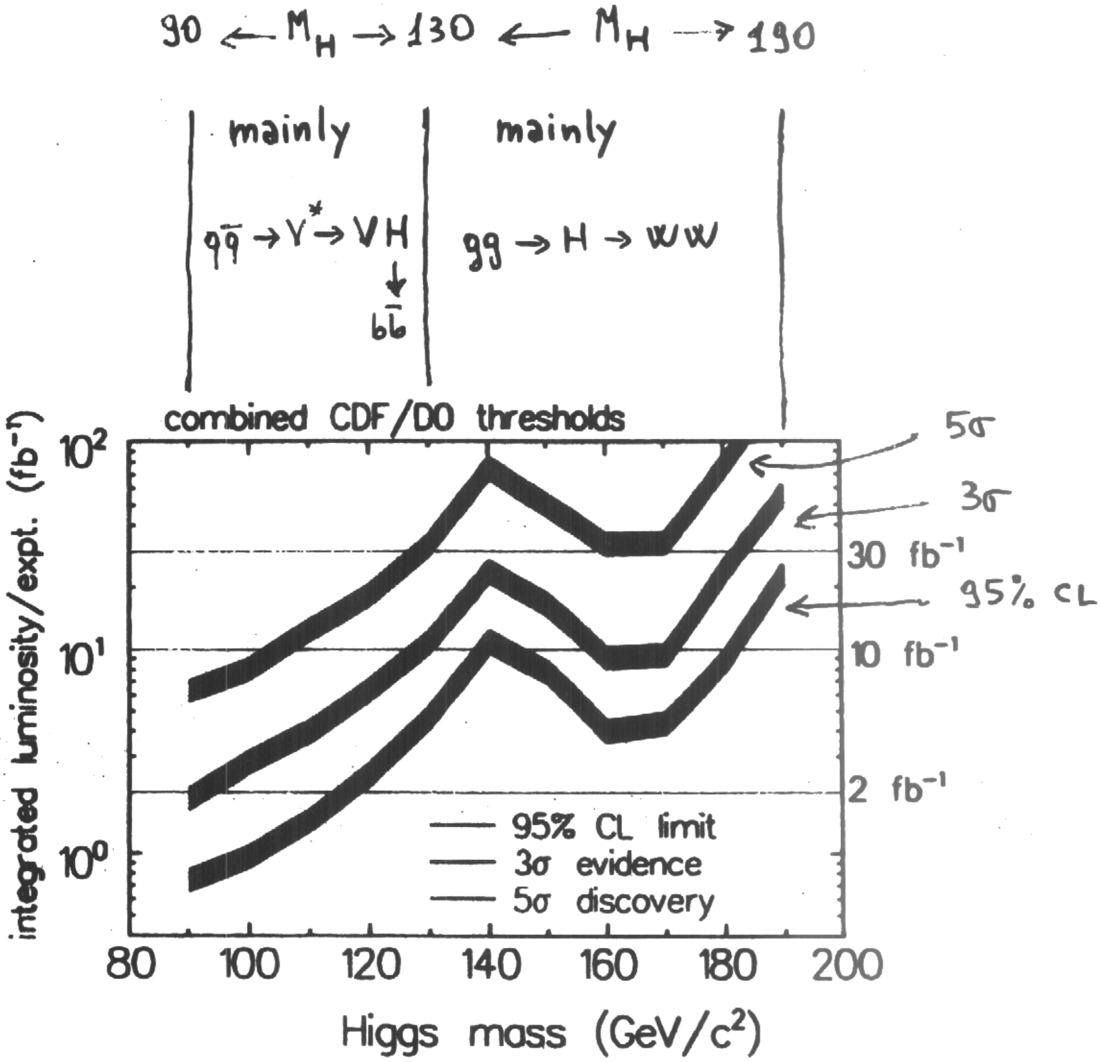


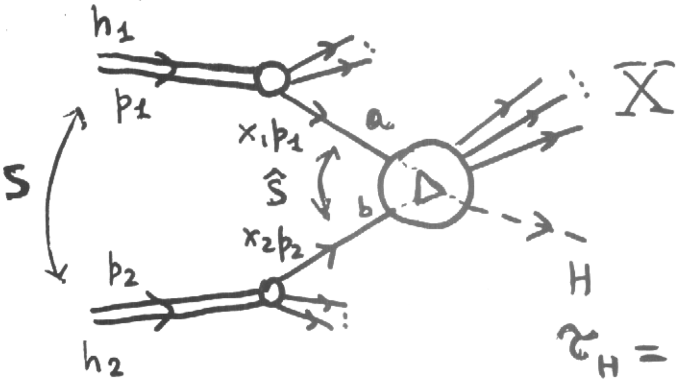
FIGURE 103. The integrated luminosity required per experiment, to either exclude a SM Higgs boson at 95% CL or discover it at the 3σ or 5σ level, as a function of the Higgs mass. These results are based on the combined statistical power of both experiments. The curves shown are obtained by combining the $\ell\nu b\bar{b}$, $\nu\bar{\nu}b\bar{b}$ and $\ell^+\ell^-b\bar{b}$ channels using the neural network selection in the low-mass Higgs region (90 GeV $\lesssim m_{h_{SM}} \lesssim$ 130 GeV), and the $\ell^\pm\ell^\pm jj$ and $\ell^+\ell^-\nu\bar{\nu}$ channels in the high-mass Higgs region (130 GeV $\lesssim m_{h_{SM}} \lesssim$ 200 GeV). The lower edge of the bands is the calculated threshold; the bands extend upward from these nominal thresholds by 30% as an indication of the uncertainties in b-tagging efficiency, background rate, mass resolution, and other effects.

direct production + jet veto : $H \to WW \to e^+e^-\nu\bar{\nu}$

$(130 \lesssim M_H \lesssim 190 \text{ GeV})$

INCLUSIVE HIGGS PRODUCTION : pQCD CROSS SECTION

- theoretical framework :
  based on pQCD improved "parton model"



$$\tau_H = \frac{M_H^2}{S}$$

$\Downarrow$ pQCD factorization formula

parton densities

$$\sigma(S, M_H^2) = \sum_{a,b} \int_0^1 dx_1\, dx_2\, f_{a/h_1}(x_1, \mu_F^2)\, f_{b/h_2}(x_2, \mu_F^2) \cdot \int_0^1 dz\, \delta\!\left(z - \frac{\tau_H}{x_1 x_2}\right) \hat{\sigma}_{ab}\left(\hat{s} = \frac{M_H^2}{z}, M_H^2\right)$$

hadronic cross section

- partonic cross section : $a + b \to H + \bar{X}$

$$\hat{\sigma}_{ab}(\hat{s}, M_H^2) = \frac{1}{\hat{s}} \sigma_0 M_H^2 G_{ab}(z) = \sigma_0\, z\, G_{ab}(z)$$

flux factor

Born level cross section

hard coefficient function $\left(\int_{PS} |ME|^2 \right)$

σ_0, G_{ab} : both depend on
$$\begin{cases} \mu_R, \mu_F \quad (\mu_R \sim \mu_F \sim M_H) \\ M_H / M_{top} \end{cases}$$

$$G_{ab}(z) = \alpha_s^2(\mu_R^2) \left[G_{ab}^{(0)}(z) + \frac{\alpha_s}{\pi} G_{ab}^{(1)}(z) + \left(\frac{\alpha_s}{\pi}\right)^2 G_{ab}^{(2)}(z) + \ldots \right]$$

perturbatively computable

LO $\delta_{ag}\delta_{bg}\delta(1-z)$ | NLO | NNLO

equivalently :

$$\sigma(S, M_H^2) = \sigma_0\, \tau_H \int_{\tau_H}^1 \frac{d\tau}{\tau} \mathcal{L}_{a/h_1, b/h_2}(\tau, \mu_F^2)\, G_{ab}(\tau_H/\tau)$$

parton luminosity

$$\mathcal{L}_{a/h_1, b/h_2}(\tau, \mu^2) \equiv \int_\tau^1 \frac{dx}{x} f_{a/h_1}(x, \mu^2)\, f_{b/h_2}\left(\frac{\tau}{x}, \mu^2\right)$$

– status of pQCD calculations

- full NLO Known — Djouadi-Graudenz-Spira-Zerwas, Dawson (1991)

  ⇓

  leads to large corrections

  $\sim + 80 \div 100\%$

- estimate of h.o. corrections suggest that they can still be sizeable — Krämer-Laenen-Spira (1998)

  Can we trust pQCD ?

  How large is Higgs σ ?

  ⇓

  h.o. calculations highly desirable

NEW RESULTS [all of them use large-M_{top} approximation (exact M_{top}-dependence not feasible at present)

- "approximate" NNLO (use soft-gluon approximation) — de Florian-Grazzini + S.C., Harlander-Kilgore (2001)

- complete NNLO — Harlander-Kilgore (2002)

- NNLO + soft-gluon resummation — de Florian-Grazzini-Nason + S.C. (2002)

most of the following presentation:

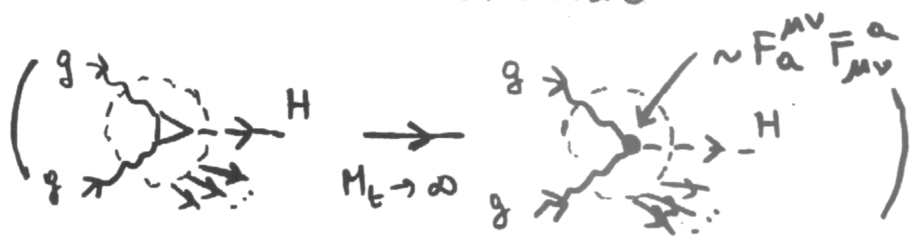
mainly based on soft-gluon approximation

- it gives a simpler physical picture of underlying dynamics
- if it works (It does!), it can be used
  - to evaluate still h.o. terms
  - to approximate (simplify) other (more cumbersome) calculations

– direct Higgs production in (almost) NNLO QCD

two approximations :
- i) large-M_{top} expansion
- ii) soft and virtual (+ leading collinear) contributions at NNLO

i) consider limit $M_{top} \to \infty$



Note : neglect $M_H / M_{top} \to 0$ in $G_{ab}(z)$

but Keep full M_t-dependence in σ_0 (Born level)

- at NLO : very good ($< 5\%$) approximation when $M_H < 2 M_{top}$ (expected)

  and still accurate* to better than 10% when $M_H \lesssim 1$T

  see iii)

ii) evaluate h.o. pQCD contributions to $G(z)$ by expanding around $z \to 1$ $\left(z = \frac{M_H^2}{\hat{s}} \to 1 \Rightarrow \hat{s} = M_H^2 + \text{soft/virtual} \right)$

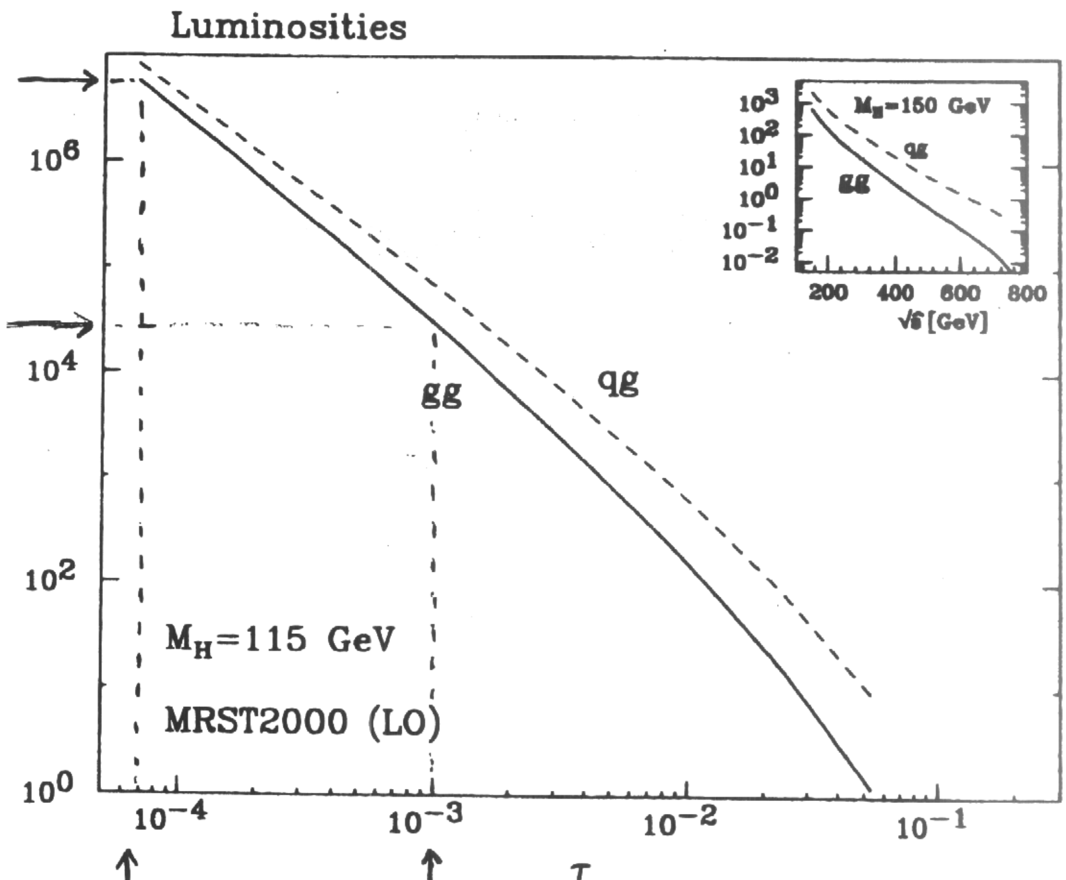
$\hat{s}$ ← partonic c.m. energy

- since pdf's are steeply falling at large x_1, x_2
  - $\Rightarrow \langle \hat{s} \rangle = \langle x_1 x_2 S \rangle$ is typically much smaller than S
  - $\Rightarrow \sigma_{part.}$ typically much closer to threshold than $\sigma_{had.}$
- validity of limit $z \to 1$ (i.e. $\sqrt{\hat{s}} = x_1 x_2 S \sim M_H$) depends on actual value of parton luminosities

fig.

(validity of limit $z \to 1$ justifies approximation $M_{top} \to \infty$ also when $M_H > 2 M_{top}$: soft ($\to$ large wavelenght) gluons insensitive to details (top-quark loop) at short distances)

parton luminosities at the LHC



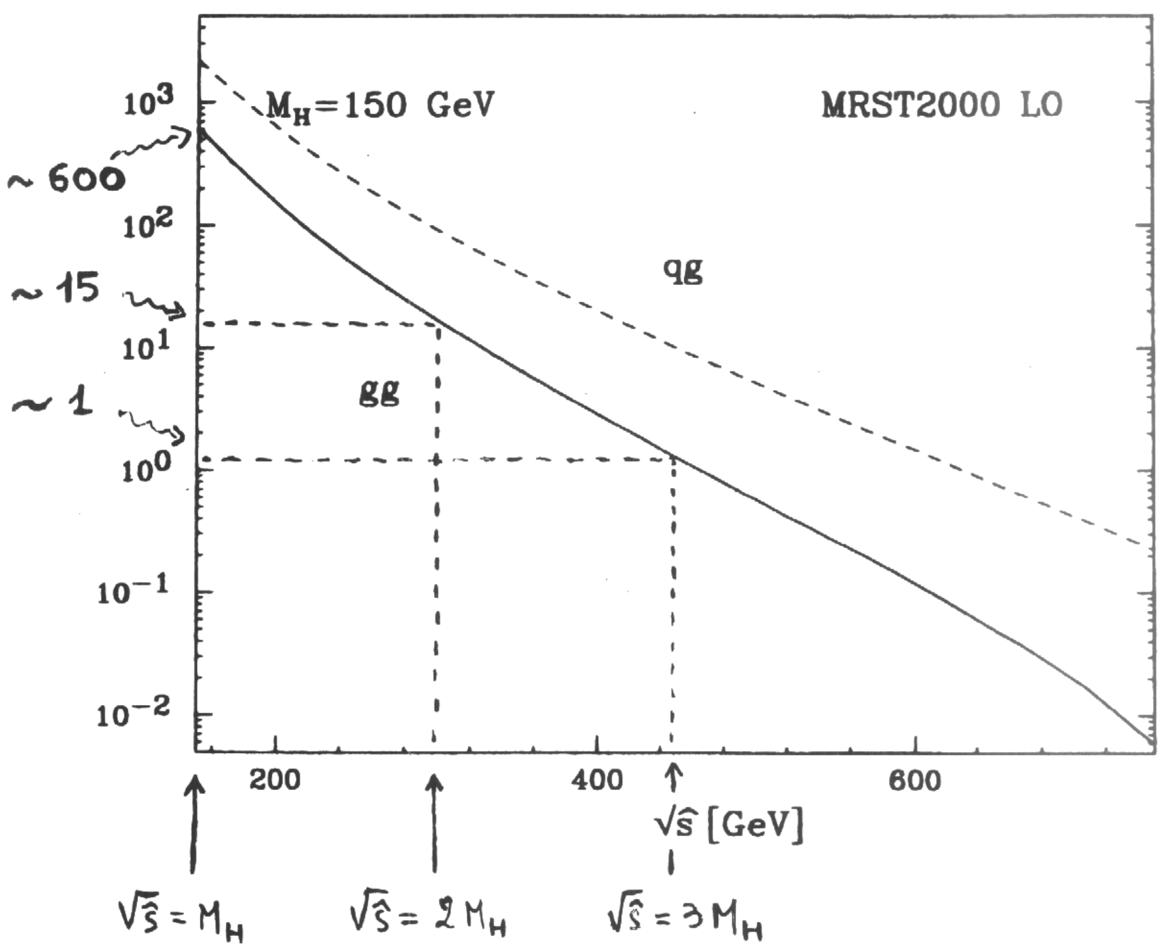
$\mathcal{L}_{ab}(\tau)$

$\tau = \hat{s}/s$

$\uparrow$ $\sqrt{\hat{s}} = M_H$ $\qquad$ $\uparrow$ $\sqrt{\hat{s}} \sim 3M_H$

$\mathcal{L}$ decreases by about 2 orders of magnitude when $\sqrt{\hat{s}}$ increases from M_H to $3M_H$

parton luminosities at the Tevatron



$\mathcal{L}(\tau)$

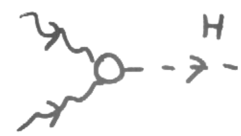
$\hat{s} = \tau s$

$\mathcal{L}$ decreases by almost 2 orders of magnitude when $\sqrt{\hat{s}}$ increases from M_H to $2M_H$

- soft approximation is (slightly) better at the Tevatron than at the LHC

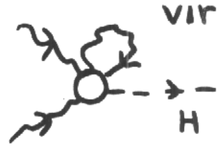
the large-z expansion

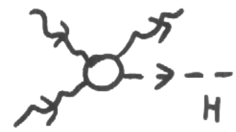
LO : $G^{(0)}_{gg}(z) = \delta(1-z)$



exact

NLO :





exact →

$$G^{(1)}_{gg}\left(z; \frac{M_H}{\mu_F}, \frac{M_H}{\mu_R}\right) = \underbrace{12\, D_1(z) + 6\, D_0(z) \ln M_H^2/\mu_F^2 +}_{\text{soft}}$$

$$+ \underbrace{\left(\frac{11}{2} + \frac{\pi^2}{6} + \frac{33-2N_f}{6} \ln \mu_R^2/\mu_F^2\right) \delta(1-z) +}_{\text{virtual}}$$

$$+ P^{reg}_{gg}(z) \ln \frac{(1-z)^2 M_H^2}{z \mu_F^2} + \frac{6 \ln z}{1-z} - \frac{11}{2} \frac{(1-z)^3}{z}$$

where $D_n(z) \equiv \left[\frac{\ln^n(1-z)}{1-z}\right]_+$

$$P^{reg}_{gg}(z) = 6\left[-1 + \frac{1-z}{z} + z(1-z)\right]$$

approximated

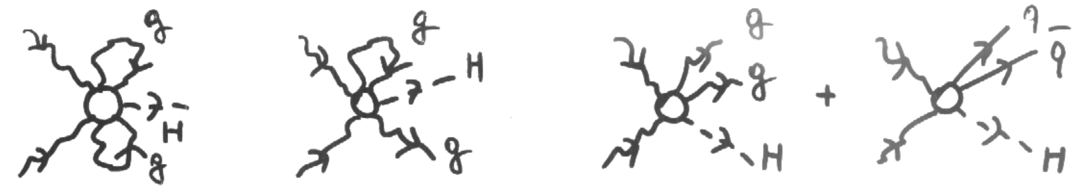
$$G^{(1)}_{gg} = \underbrace{12\, D_1 + 6\, D_0 + \left(\frac{11}{2} + \frac{\pi^2}{6} + \frac{33-2N_f}{6} \ln \frac{\mu_R^2}{\mu_F^2}\right)\delta(1-z)}_{\substack{\text{SOFT + VIRTUAL} \\ \text{(all singular distributions)}}} \underbrace{- 12 \ln(1-z)}_{\substack{O((1-z)^0) \\ \text{LEADING COLLINEAR} \\ \text{(hard collinear)}}} + \ldots$$

(formally) dominant when $z \to 1$ ⇝ $G^{(1)\,SV}_{gg}$

$$G^{(1)\,SVC}_{gg} = G^{(1)\,SV}_{gg} - 12 \ln(1-z)$$

next-to-dominant term of large-z expansion

NNLO:



virtual 2-loop | mixed real-virtual | double real

$G^{(2)SV}_{gg}(z)$: all singular distributions at $z=1$ $\quad \underbrace{D_3(z),\ D_2(z),\ D_1(z),\ D_0(z)}_{\text{soft}},\ \underset{\substack{\uparrow \\ \text{virtual}}}{\delta(1-z)}$

$$G^{(2)SVC}_{gg}(z) = G^{(2)SV}_{gg} - 72\ \ln^3(1-z)$$

next-to-dominant contribution when $z \to 1$

first computed by Kraemer-Laenen-Spira (1988)

exact: $$G^{(2)}_{gg}(z) = G^{(2)SVC}_{gg}(z) + O\left(\ln^2(1-z)\right)$$

almost $\sim (1-z)^2$ w.r.t. most singular $\left(\frac{\ln^3(1-z)}{1-z}\right)_+$

SV RESULT

LO NLO NNLO

$$G^{SV}_{gg}(z) = \alpha_s^2 \Big\{ \delta(1-z)\left[\ 1 + 0.548 + 0.105\ \right]$$
$$+ D_0(z)\left[\ 0 + \ 0 \ + 0.283\ \right]$$
$$+ D_1(z)\left[\ 0 + 0.428 - 0.040\ \right]$$
$$+ D_2(z)\left[\ 0 + \ 0 \ - 0.029\ \right]$$
$$+ D_3(z)\left[\ 0 + \ 0 \ + 0.092\ \right] + O(\alpha_s^3) \Big\}$$

for simplicity, set

$\mu_R = \mu_F = M_H = 115$ GeV

$M_{top} = 176$ GeV

$\alpha_S(M_H) = 0.112$

$N_f = 5$

N^3LO

- theoretical calculation (soft approximation):
  simultaneous and independent (different methods) calculations performed by two groups

  de Florian - Grazzini + S. C. hep-ph/0102227

  Harlander - Kilgore hep-ph/0102247

$$\Downarrow$$

analytical results fully agree

- we define two "approximated benchmarks":

SV : soft + virtual — formally dominant terms when $z \to 1$

SVC : SV + leading collinear — next-to-dominant terms when $z \to 1$

$$\text{i.e. } \quad NNLO \to \begin{cases} NNLO\text{-}SV = (\text{full NLO}) \oplus (SV \text{ at } NNLO) \\ NNLO\text{-}SVC = (\text{full NLO}) \oplus (SVC \text{ at } NNLO) \end{cases}$$

QUANTITATIVE STUDY

- parton distributions :
  we use MRST 2000 set (thanks to J. Stirling)

important feature

NNLO pQCD calculation has to be consistently used with NNLO pdf's

although full NNLO pdf's not yet available, the set includes "approximated" NNLO pdf's

based on NNLO approximation[1] of AP splitting functions, obtained by numerical interpolation of calculated[2] few N-moments

(1) Van Neerven - Vogt

(2) Larin, Nogueira, van Ritbergen, Retey, Vermaseren

- at the LHC : CTEQ5 ⇒ similar LO, NLO results (~10% difference with GRV 98)

- at the Tevatron : larger differences at LO

  - CTEQ5 ~ − 20%
  - GRV 96 ~ + 10%

to be kept in mind

e.g. $K^{H.O.} = \frac{\sigma^{H.O.}}{\sigma^{L.O.}}$

- estimated uncertainty on pdf luminosities :

  ~ ± 10% (CTEQ Coll.)

Results at the LHC

- scale dependence :

  reduced when h.o. are included ⤳ fig.

  e.g. $\frac{1}{2} M_H < \mu_F, \mu_R < 2 M_H$

  $$\Downarrow$$

  $$\sim \pm 20\% \text{ at NLO} \longrightarrow \begin{cases} \sim \pm 10\% \text{ at NNLO-SV} \\ \sim \pm 15\% \text{ at NNLO-SVC} \end{cases}$$

- K-factors :

  overall size of h.o. terms illustrated by $K^{H.O.} \equiv \dfrac{\sigma^{H.O.}(\mu_R, \mu_F)}{\sigma^{LO}(\mu_R = \mu_F = M_H)}$

  ⤳ fig.

LO → NLO → NNLO : shows convergence of pQCD expansion

Note : scale variations give only lower limit on "true" th. uncertainty due to missing h.o. terms (see e.g. : LO vs. NLO)

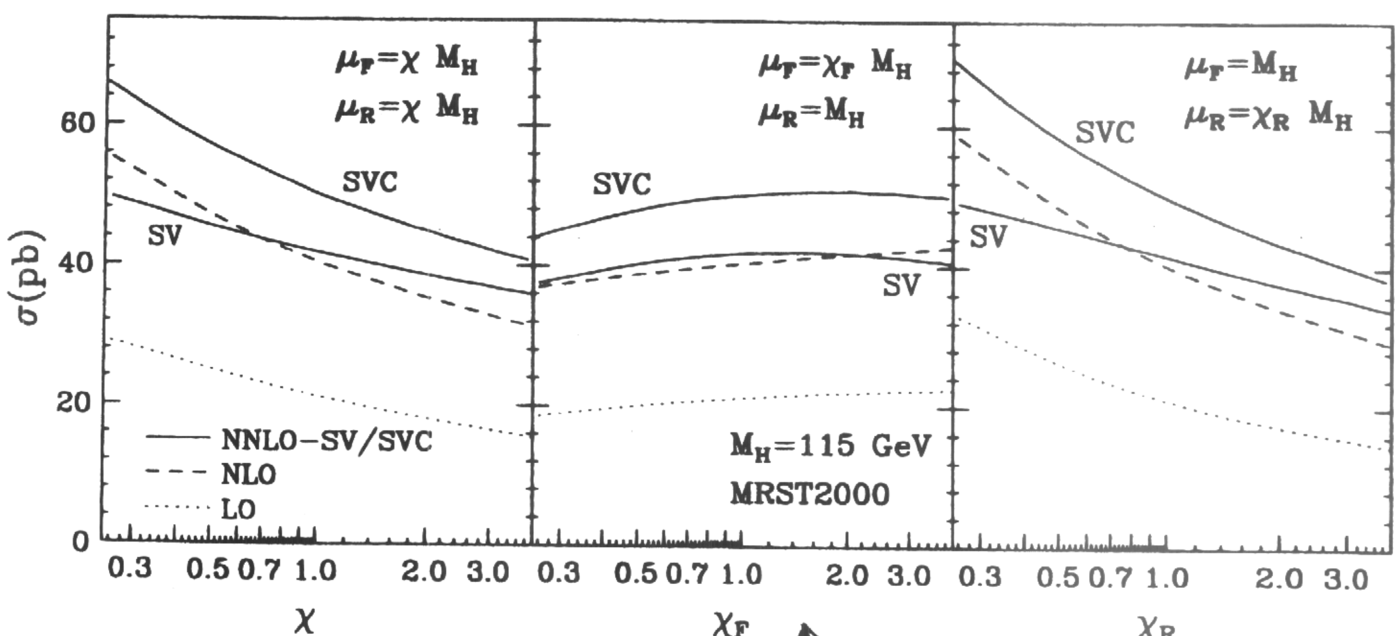
➡ NLO and NNLO bands do overlap : suggests that scale variations give a reliable estimate of h.o. terms

– scale dependence at the LHC

vary $\mu_R = \mu_F$

vary μ_F

vary μ_R



maximum at NNLO

$$\frac{1}{2} M_H < \mu_R, \mu_F < 2 M_H$$

$$\Downarrow$$

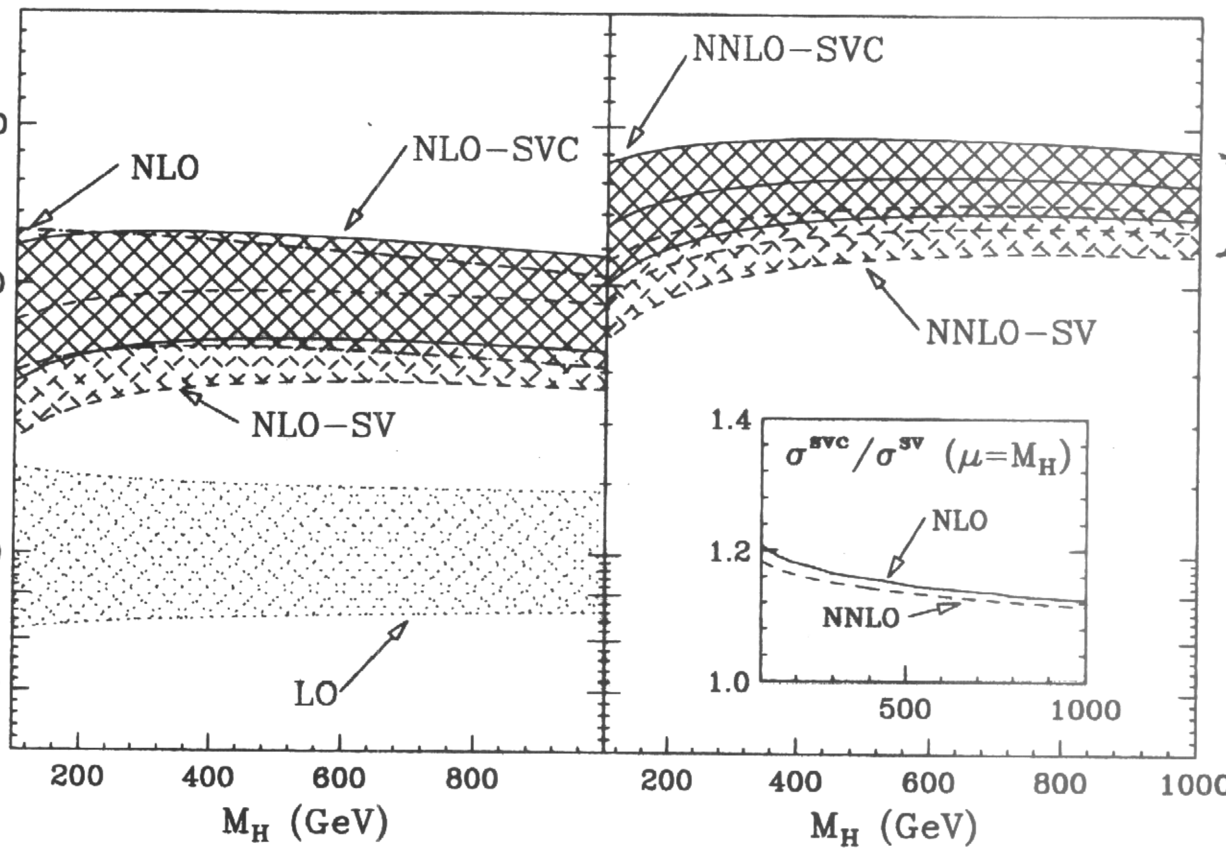
$\sim \pm 20\%$ at NLO $\longrightarrow$ $\begin{cases} \sim \pm 10\% \text{ at NNLO-SV} \\ \sim \pm 15\% \text{ at NNLO-SVC} \end{cases}$

– K-factors at the LHC

- bands obtained from scale variations $\frac{1}{2} M_H < \mu_R, \mu_F < 2 M_H$
- at NLO : NLO-SV < full NLO $\lesssim$ NLO-SVC

↓ similar expectation at NNLO (⇝ confirmed : full NNLO smaller than NNLO-SVC by ~ 5%)

[effect of NNLO pdf's w.r.t. NLO pdf's : σ^{NNLO}(NNLO pdf) decreases by ~ 10% w.r.t. σ^{NNLO}(NLO pdf)]



for a light Higgs :

NNLO increases σ by ~ 15÷25% w.r.t. NLO

(NNLO ~ 2.2÷2.4 LO)

[since NLO ~ 1.9 LO ⇒ better convergence of pQCD expansion]

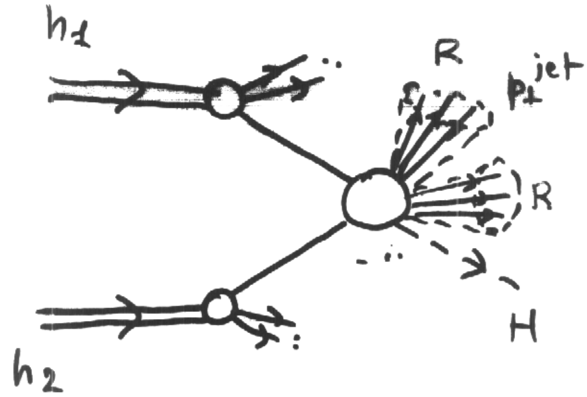
Note : LO vs. NLO : bands do not overlap

NLO vs. NNLO : bands start to overlap

DIRECT HIGGS PRODUCTION WITH JET VETO

$h_1 + h_2 \to H + \text{jets}$

impose jet veto on final-state jets:
for each jet $p_\perp^{jet} < p_\perp^{cut}$
(jet cone size $R = 0.4$)



– our calculation:

subtract σ for high-$p_\perp$ jet production $\left(\max_{\{jet\}} p_\perp^{jet} > p_\perp^{cut} \right)$

$$\sigma^{veto}(p_\perp^{cut}; S, M_H^2) = \sigma^{incl.}(S; M_H^2) - \Delta\sigma(p_\perp^{cut}; S, M_H^2)$$

computed by using <u>NLO MC program</u> for H+jet production $\leftarrow$ fully numerical, implementation of any exp. cuts

de Florian - Kunszt - Grazzini

- both NLO and NNLO results are new

- only $\sigma^{incl.}$ is approximated at NNLO in the plots (no soft approximation in $\Delta\sigma$)

- including full NNLO : $K \to K - \Delta K$, $\Delta K \simeq \begin{cases} 0.12 & \text{(LHC)} \\ 0.20 & \text{(Tevatron)} \end{cases}$

– jet veto at the LHC

- σ decreases by decreasing $p_\perp^{cut}$ $\rightsquigarrow$ fig.

- i) size of h.o. corrections also decreases by decreasing $p_\perp^{cut}$ $\rightsquigarrow$ fig.

  <u>but</u>

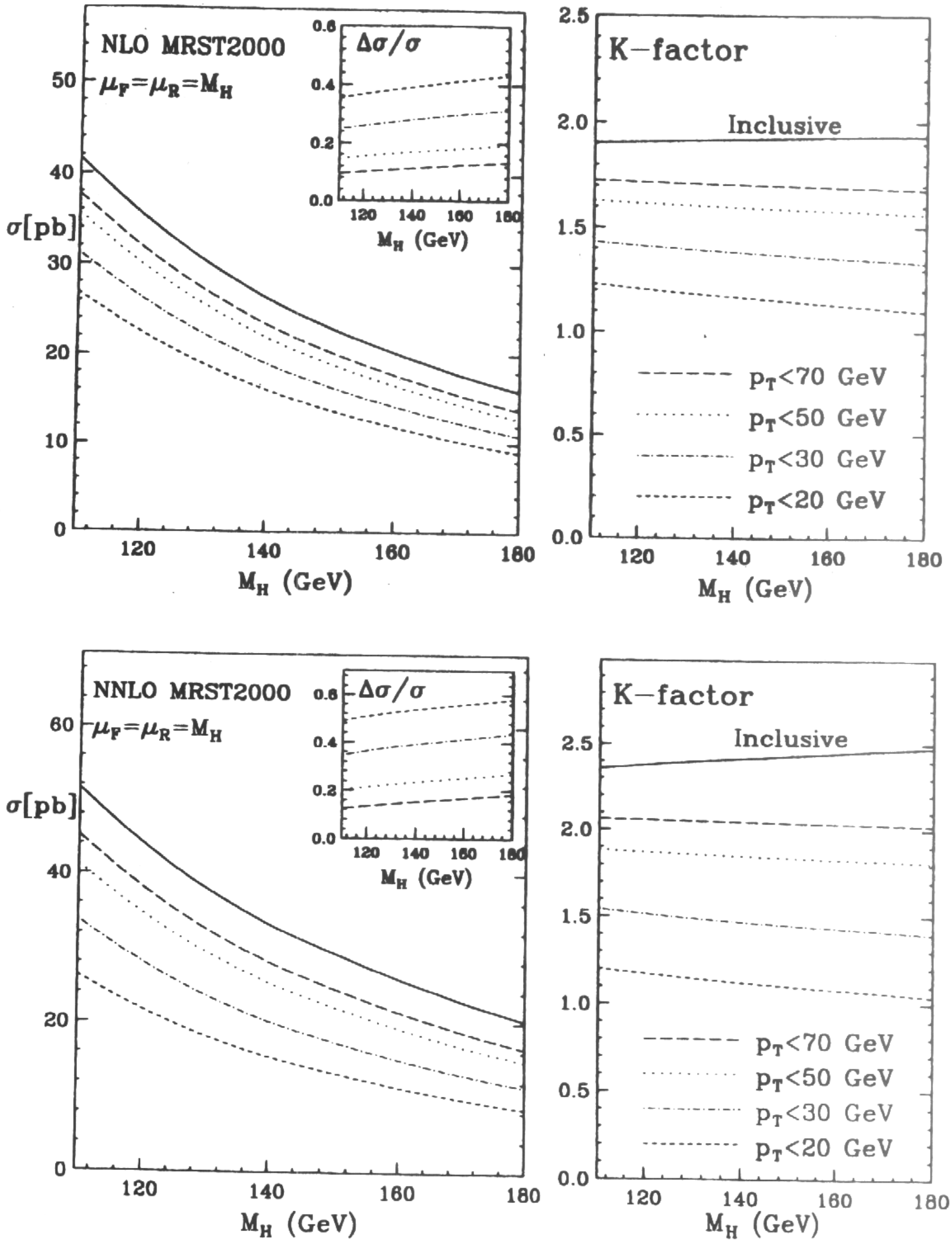
  ii) it increases again at very small $p_\perp^{cut}$ (see e.g. $p_\perp^{cut} = 15$ GeV) $\rightsquigarrow$ fig.

  $\Downarrow$

  h.o. contributions become important because $\ln \frac{(1-z)^2 Q^2}{(p_\perp^{cut})^2}$ becomes LARGE

Jet veto at the LHC

σ K-factor



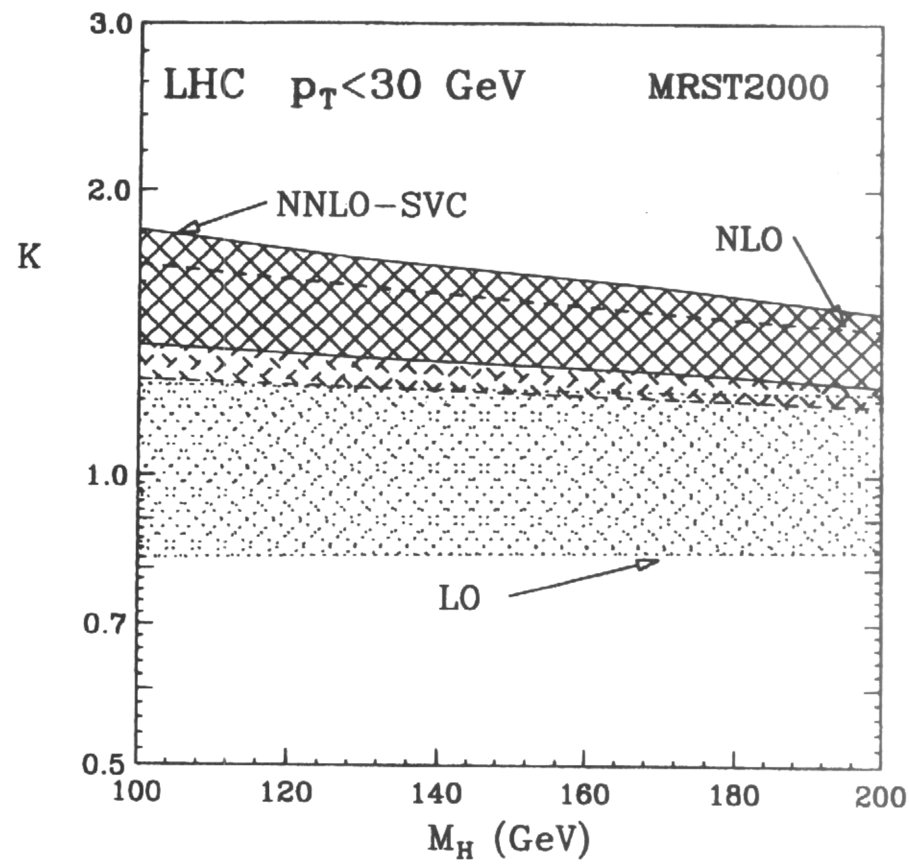
NLO

NNLO (SVC)

- when $p_T^{cut} = 30$ GeV, NNLO terms increase NLO result by only $\sim 10\%$

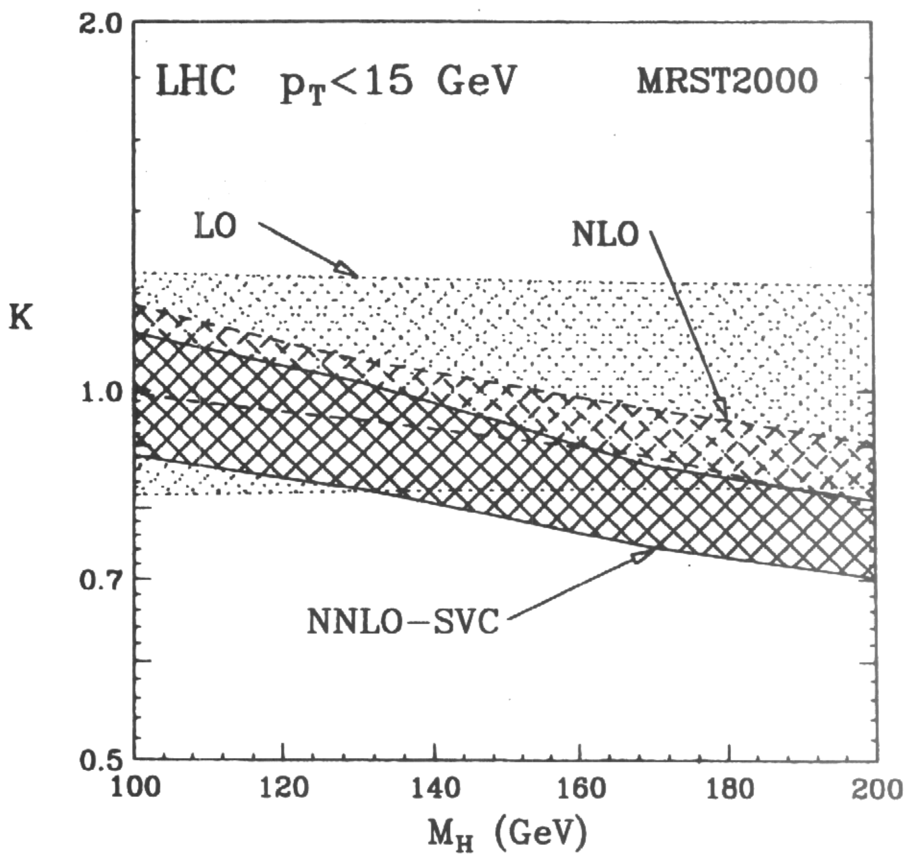
– jet veto at the LHC

$p_\perp^{cut} = 30$ GeV



- jet veto at the LHC

$p_\perp^{cut} = 15$ GeV

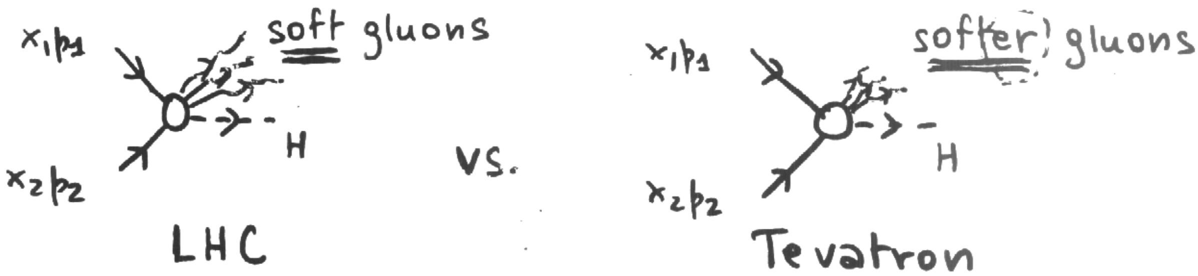


at small $p_\perp^{cut}$, fixed-order pQCD expansion starts to become unreliable

Results at the Tevatron Run II

- overall qualitative features similar to the LHC

- main quantitative differences:
  they are due to the fact that Higgs production at the Tevatron is closer to threshold than at the LHC $\Rightarrow$ Tevatron more sensitive to soft gluons



$\Downarrow$

<u>inclusive production</u>: $\rightsquigarrow$ fig.

- size of NLO, NNLO corrections (K-factors) larger than at the LHC

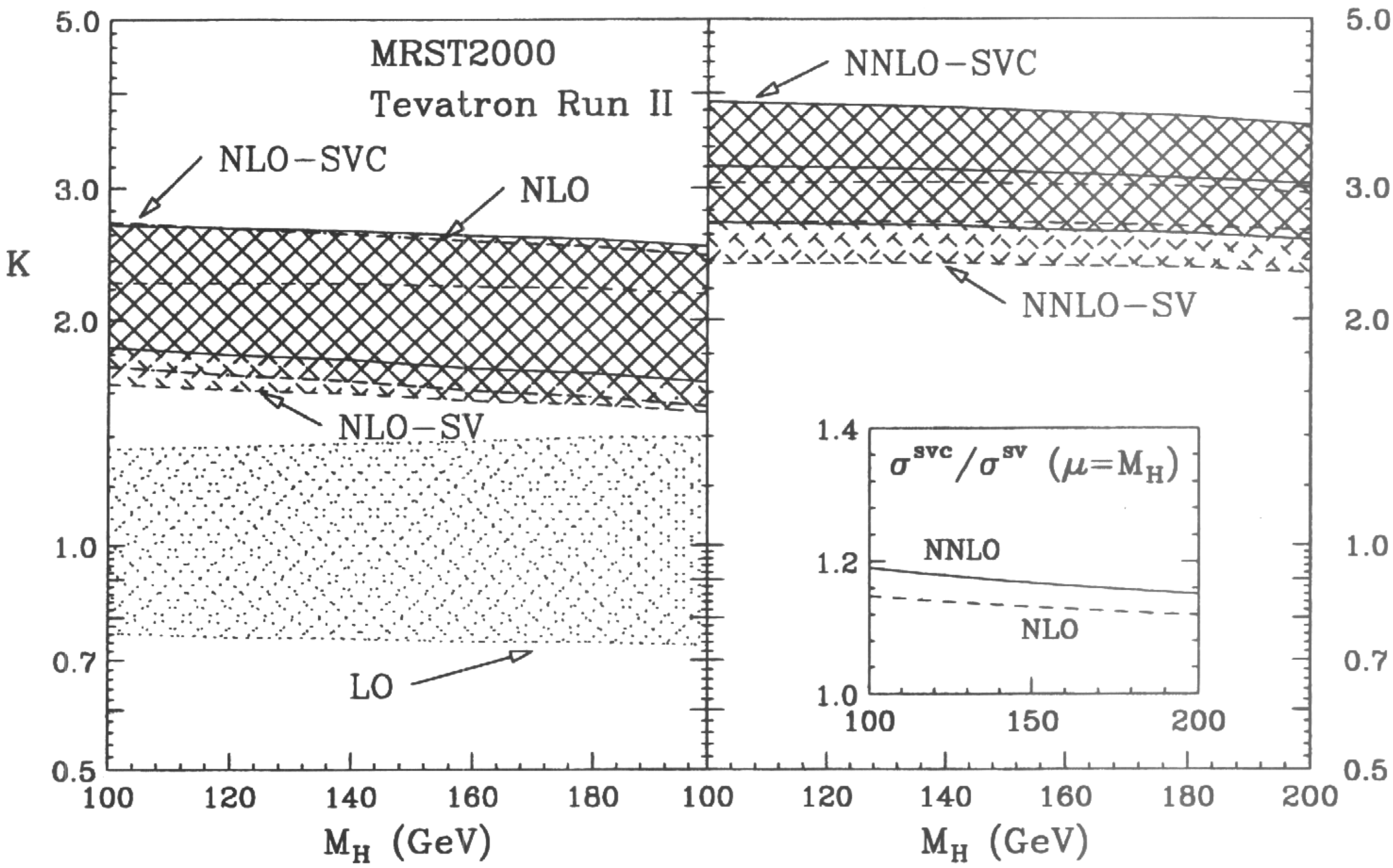
- beyond NNLO terms can still be significant

<u>direct Higgs + jet veto</u>:

- at fixed $p_\perp^{cut}$, effect of jet veto smaller than at the LHC $\rightsquigarrow$ fig.

- at small $p_\perp^{cut}$ ($p_\perp^{cut} \sim 15\,\text{GeV}$), $\rightsquigarrow$ fig.
  $p_\perp^{cut}$ dependence from beyond NNLO terms less important than at the LHC

K-factor at the Tevatron Run II

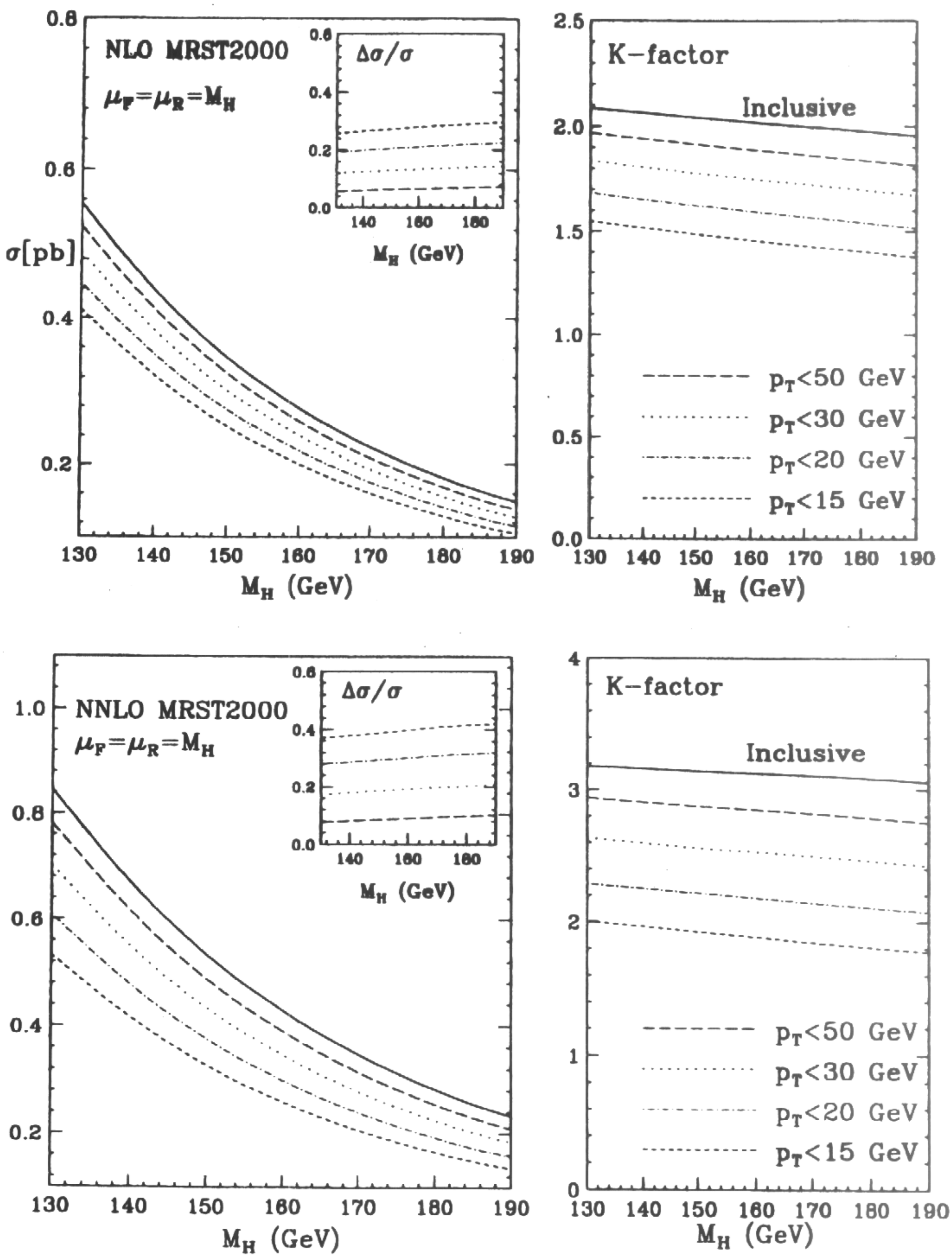


- full NNLO smaller than NNLO-SVC by ~ 7%

- NNLO increases σ by ~ 50% w.r.t. NLO (NNLO ~ 3 LO)

Jet veto at the Tevatron

σ   K-factors



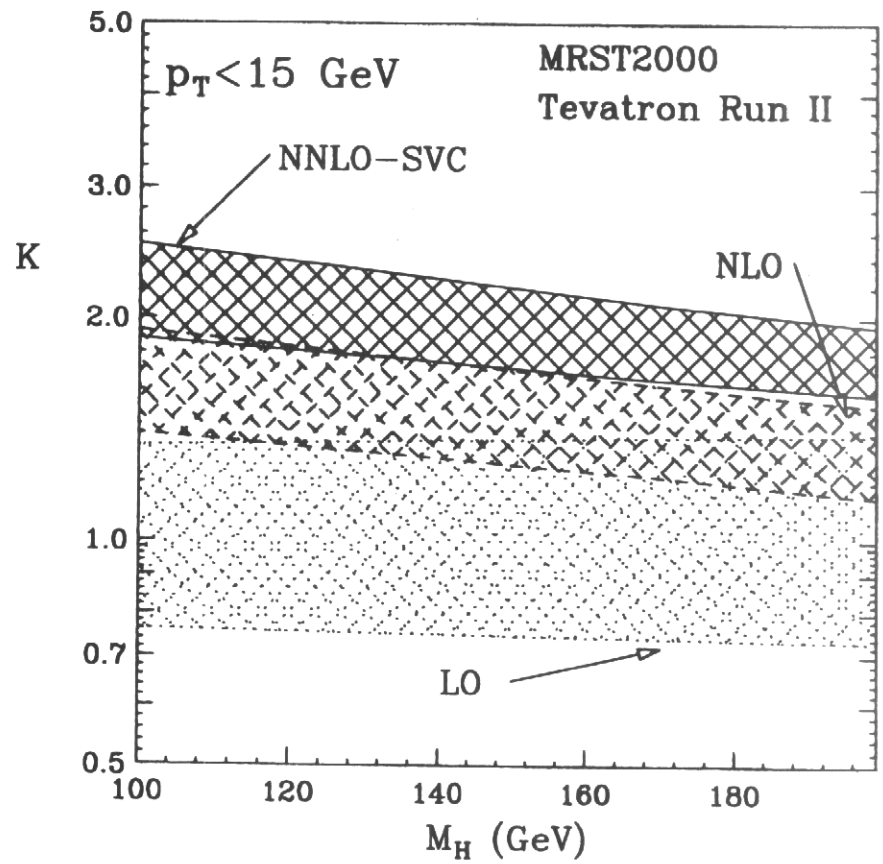
NLO

NNLO
(SVC)

- Reduction effect due to cut on "soft" radiation
- For large p_T^{cut} less than 20% of the inclusive cross section is lost

- jet veto at the Tevatron Run II

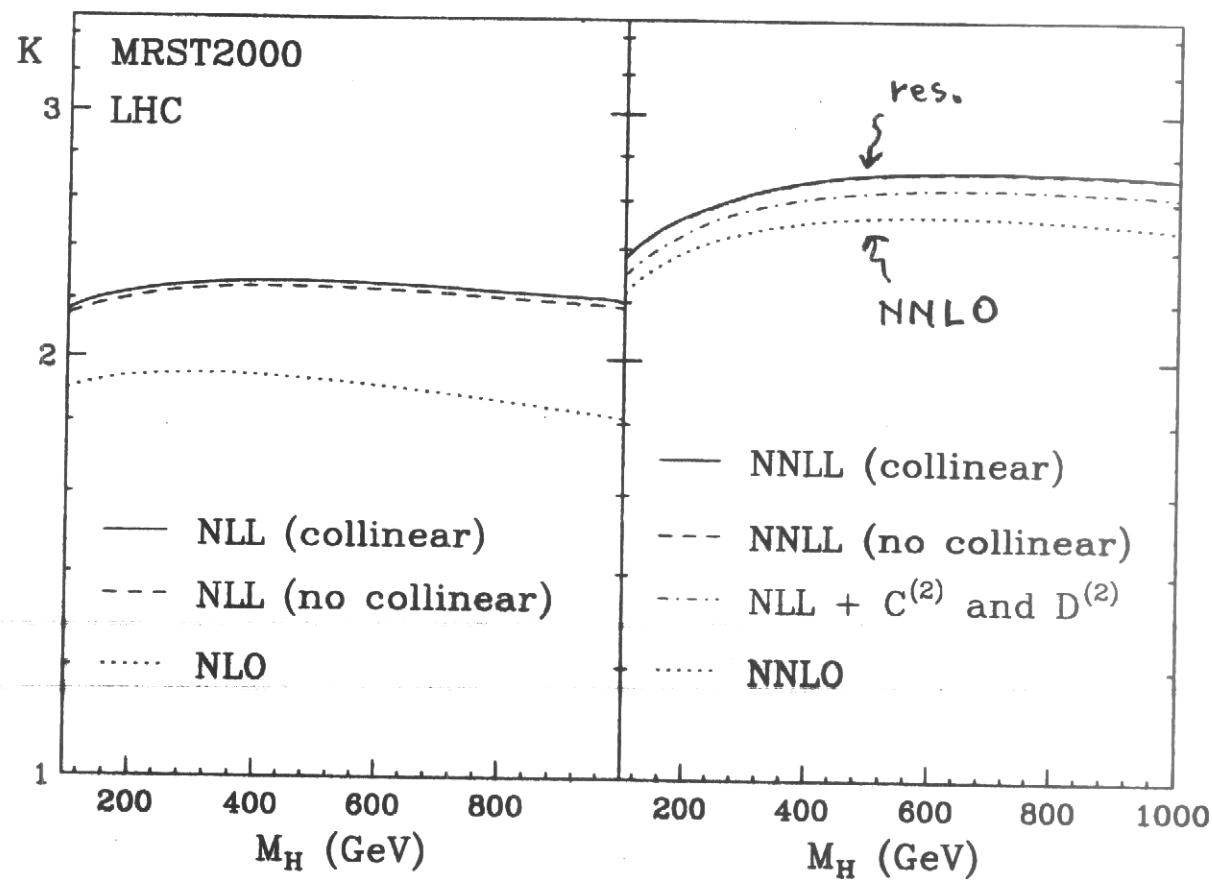
$p_\perp^{cut} = 15$ GeV



difference NNLO vs. NLO mainly due to corresponding difference in inclusive cross section (NNLO vs. NLO)

- all-order soft-gluon summation at the LHC

de Florian - Grazzini - Nason + S. C.
(preliminary)



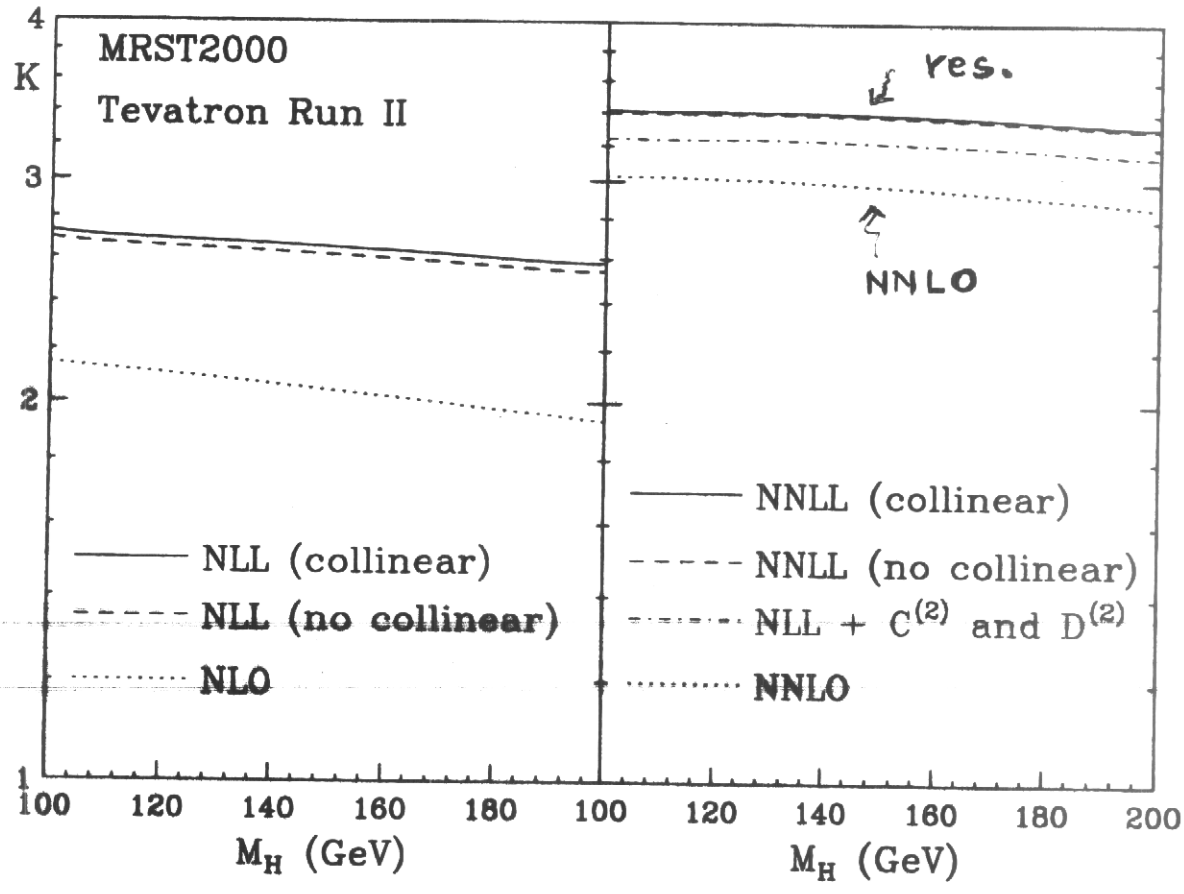
NNLL resummation increases NNLO
by ~ 6 ÷ 9 %
$M_H \sim 100$ $M_H \sim 1$ TeV

($K_{res.} \sim 2.4 \div 2.7$)
light H heavy H

[recall : NNLO increases NLO
by ~ 20% (light H)]

– all-order soft-gluon summation at the Tevatron

de Florian - Grazzini - Nason + S. C.
(preliminary)



NNLL resummation increases NNLO

by ~ 12 ÷ 16 % ($K_{res.} \sim 3.4$)

$M_H \sim 100$ 200 GeV

[recall : NNLO increases NLO by ~ 50%]

CONCLUSIONS

- NNLO result
  (and validity of its soft-gluon approximation)
  + soft-gluon resummation

  ⬇

we can reliably estimate direct Higgs production by using pQCD

- inclusive production:

  NNLO effects
  - moderate at the LHC
  - sizeable at the Tevatron

  h.o. terms (resummation)
  - not sizeable at the LHC ⇝ fig.
  - more significant at the Tevatron

- jet veto:

  small $p_\perp^{veto}$ reduces NLO, NNLO terms
  - sizeably at the LHC
  - moderately at the Tevatron

  at low $p_\perp^{veto}$ ($p_\perp^{veto} \sim 15\,\mathrm{GeV}$), $p_\perp^{veto}$-dependence at the LHC can sizeably be affected by beyond NNLO terms

- some more work still needed to <u>precisely</u> quantify theoretical uncertainties
  (pdf dependence, scale dependence, missing h.o. terms, ..)