# The transverse-momentum distribution of the Higgs boson at hadron colliders

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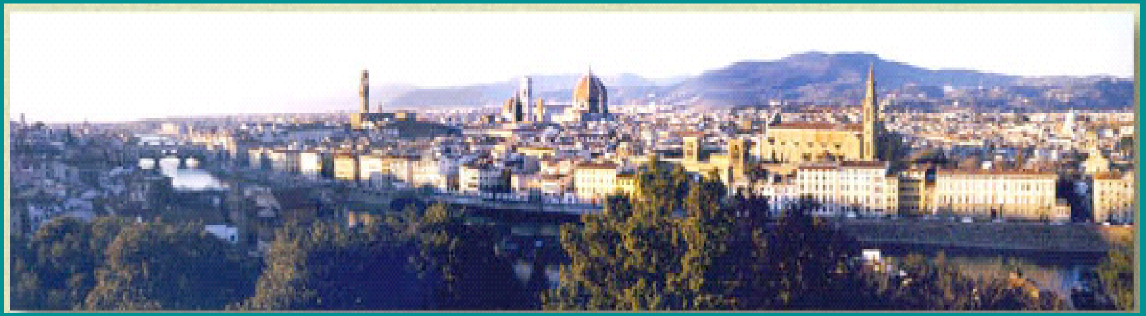


in collaboration with S.Catani, D.deFlorian, M.Grazzini

# The Higgs mechanism

- Standard Model: SU(2)xU(1) gauge theory

  $\Longrightarrow \quad \mathrm{m}_{l} = \mathrm{m}_{B} = 0$

- "Simple-minded" insertion of mass terms in the Lagrangian $\Longrightarrow$ both gauge invariance and renormalizability spoiled

- **<u>SSB</u>**: Goldstone bosons $\begin{cases} (\mathrm{m}=0) \text{ global simmetry} \\ (\mathrm{m}\neq 0) \text{ local simmetry} \end{cases}$

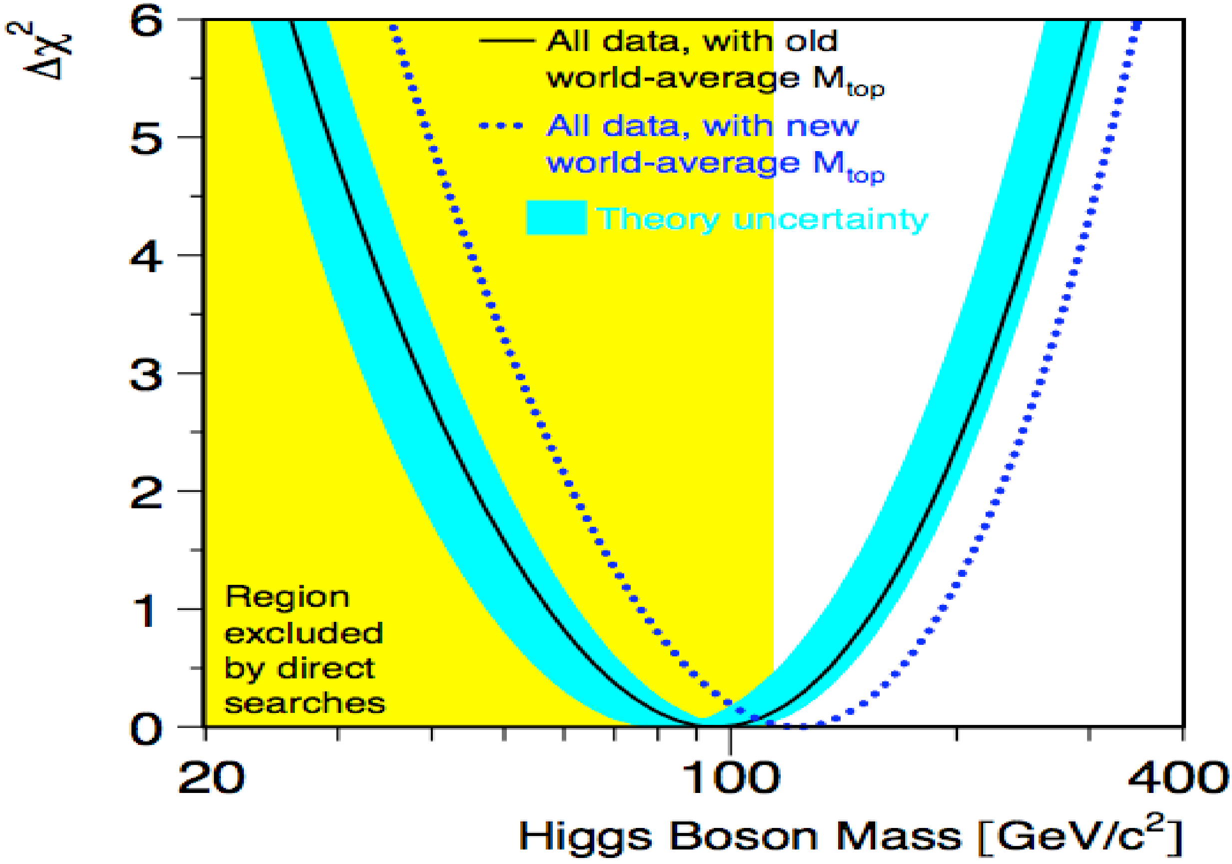
  Local SSB (Higgs mechanism) provides masses to $W^{+}$,$W^{-}$,$Z^{0}$ and leptons through trilinear Yukawa couplings.

'*Remnant*': <u>neutral</u>, <u>scalar</u>, <u>massive</u> boson **<u>H</u>**

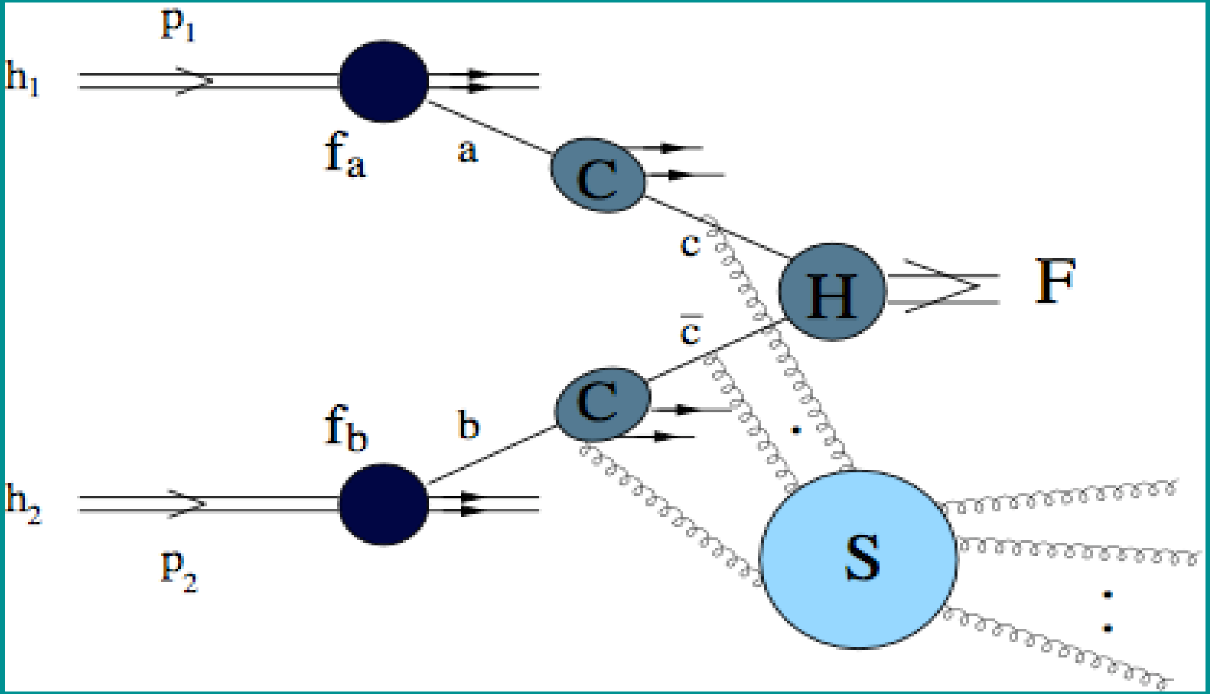
# Bounds on $m_H$

- Direct search at LEP : $m_H > 114.4\ GeV$
- EW fits: $m_H < 251\ GeV$

(Higgs loop contributions to EW observables)

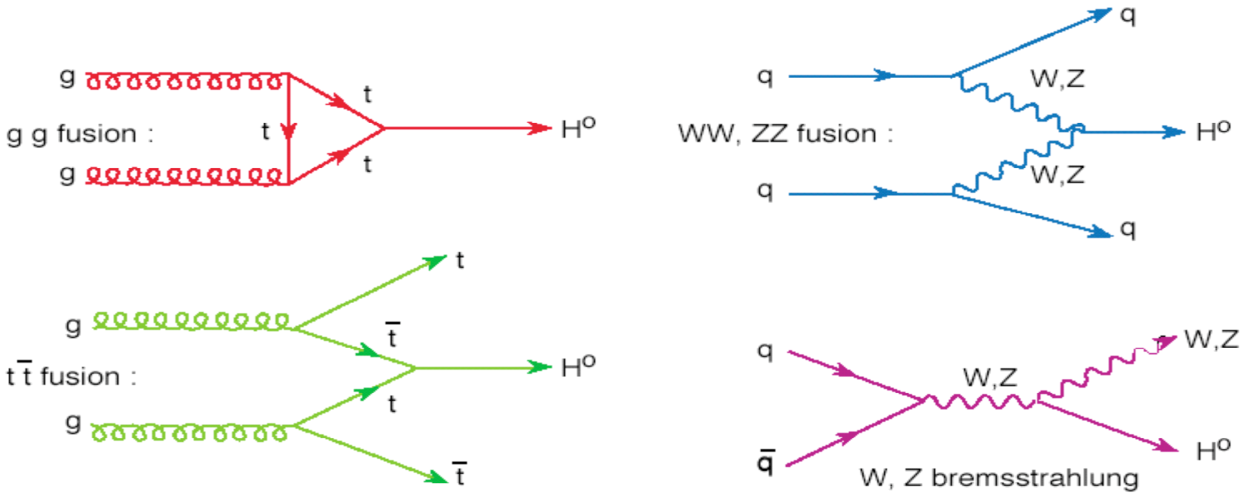


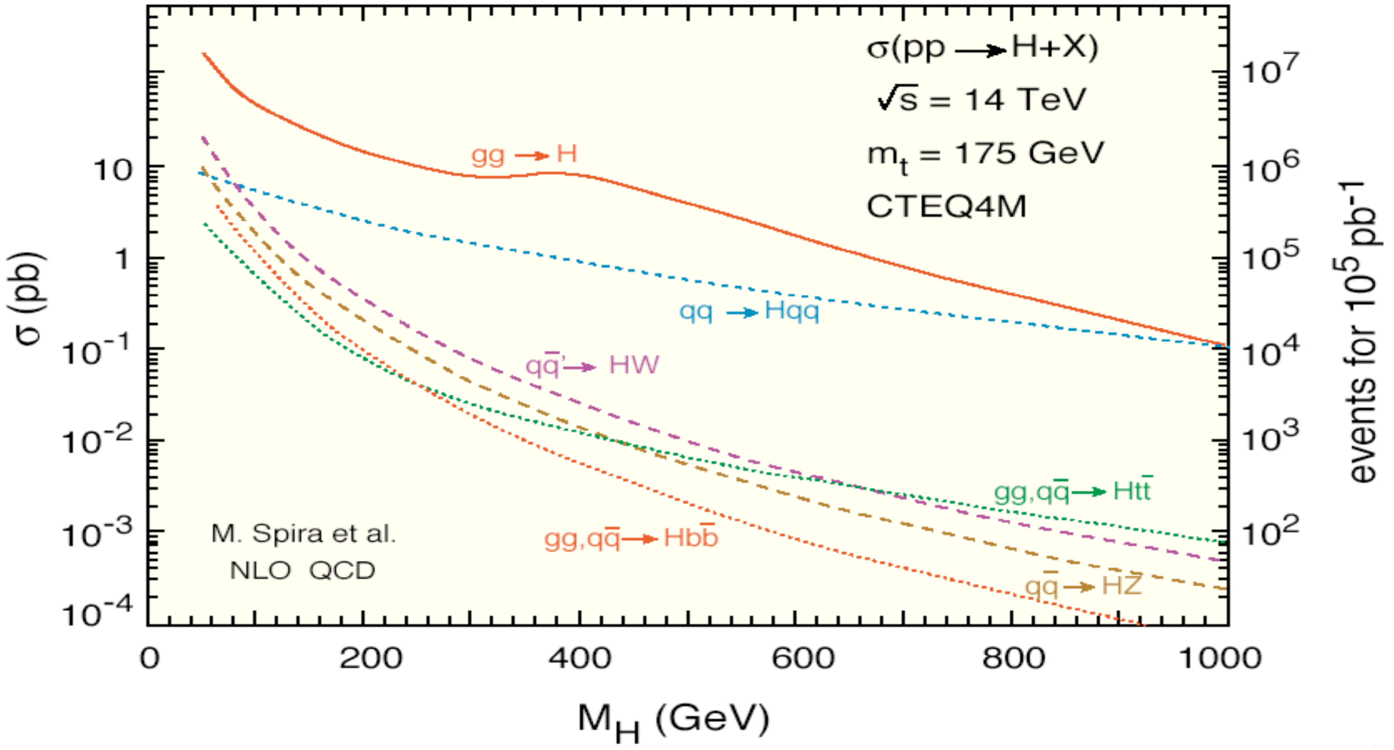
# Hadronic cross sections in perturbative QCD



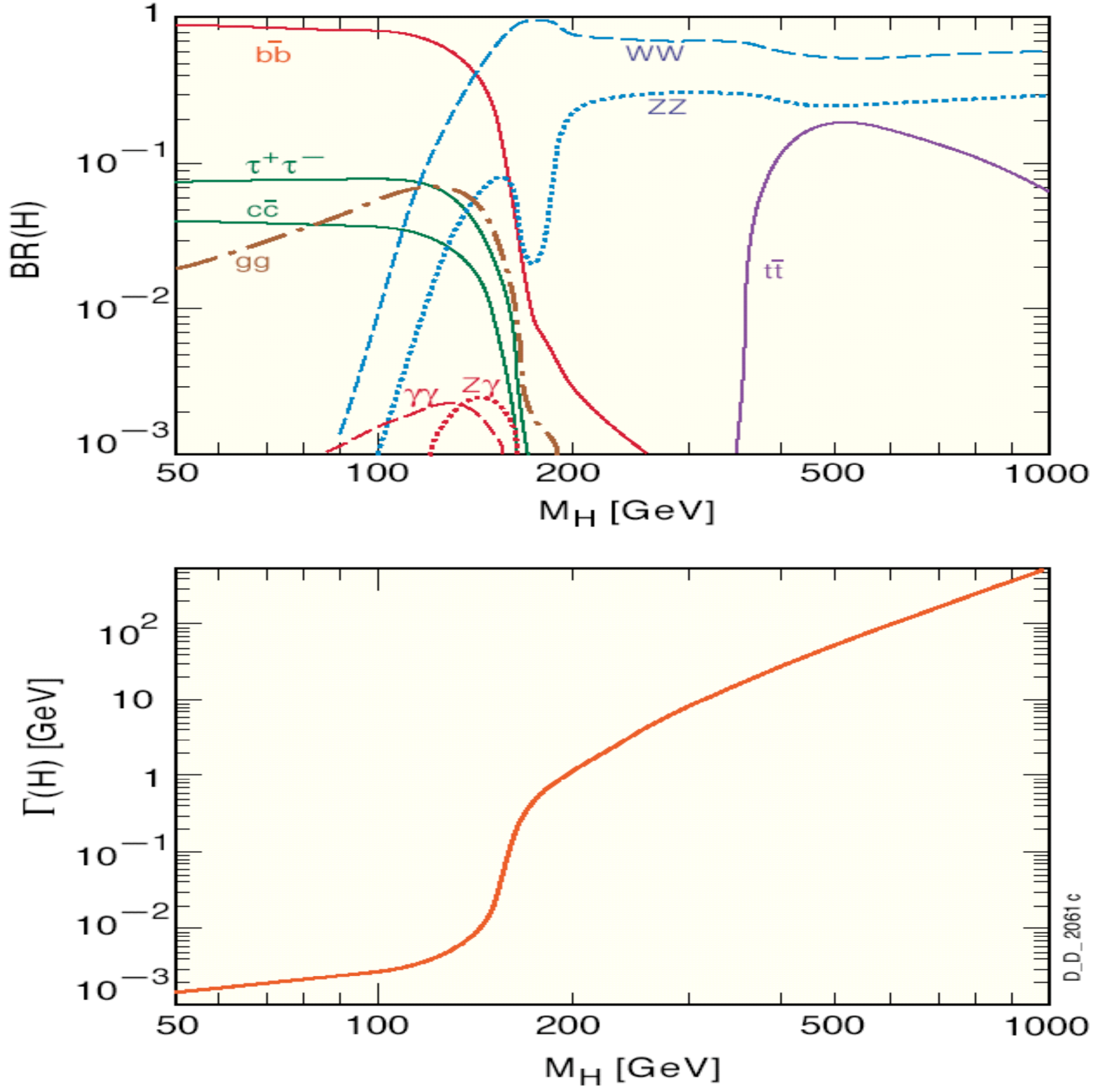
- $h_1, h_2$ = initial state hadrons (with momenta $p_1$,$p_2$)
- $f_a$,$f_b$ = parton distribution functions
- C = coefficient functions (partonic *splitting*)
- H = perturbatively computed partonic event
- F = final state particle(s)
- S = resummation of soft radiation from incoming partons

# $H^0$ production at hadron colliders:

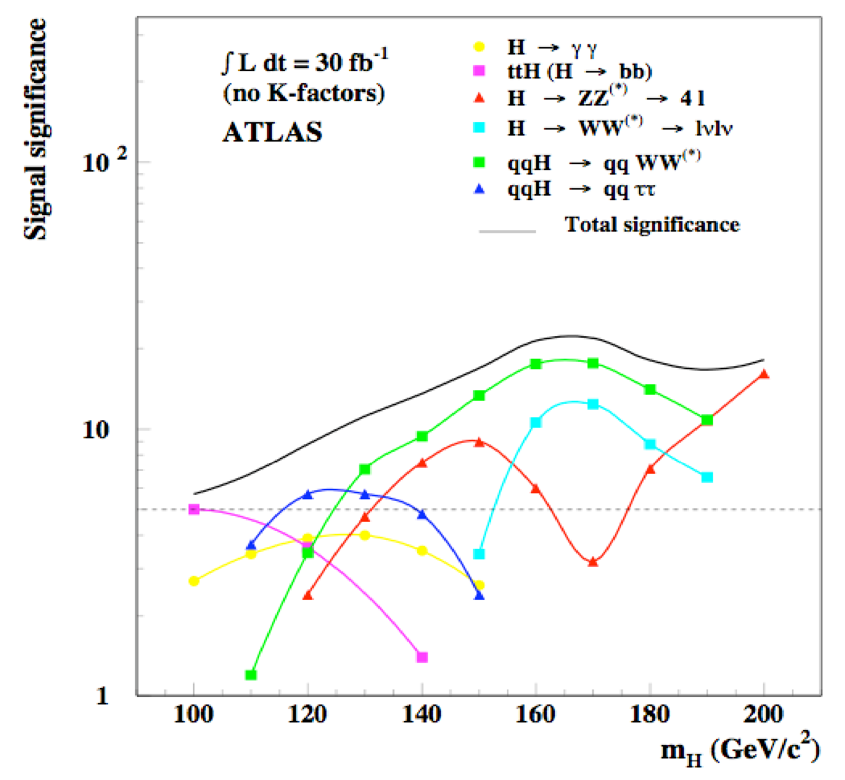




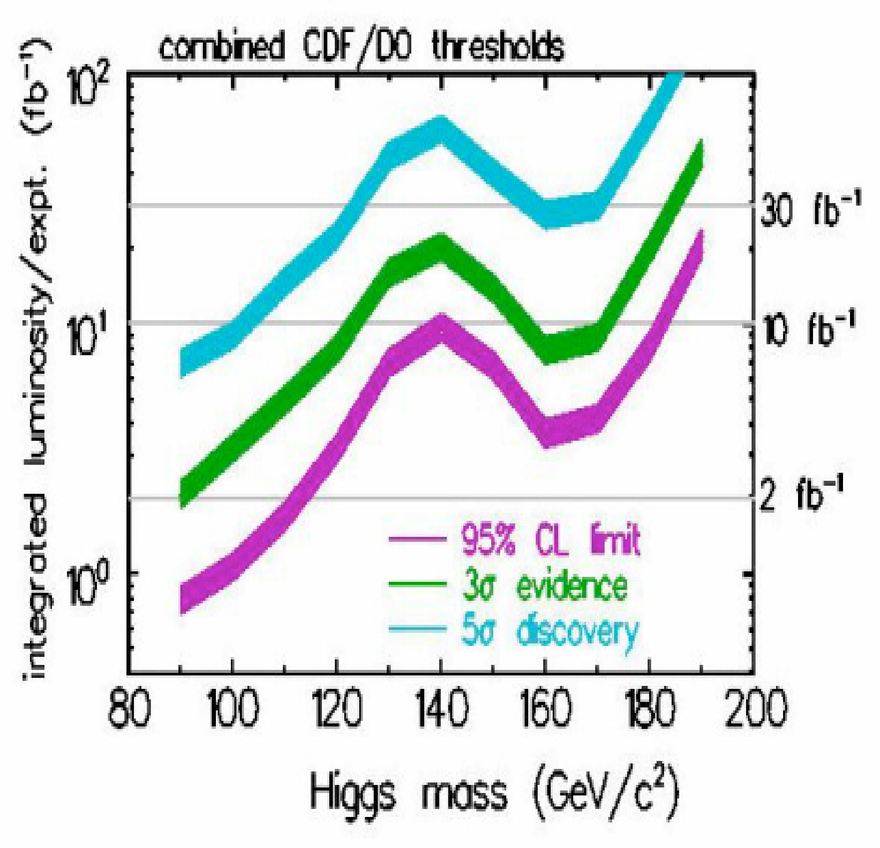
# SM Higgs
# Branching ratios and total decay width



# Possibilities of Higgs signal at hadron colliders



LHC-Atlas



Tevatron Run II

# Why studying $p_T$ distribution?

- Detector's resolution, kinematical acceptance and efficiency, (and, thus, event modeling) $\Rightarrow$ $p_T$-dependent
- The knowledge of the shape of the $p_T$ spectrum can *dictate analyses and triggering strategies*
- Useful to enhance *signal/background* ratio ($\gamma\gamma$, 4 leptons channels): application of $p_T$ -cuts in the process of event-selection
  (Davatz, Dissertori, Dittmar, Grazzini, Pauss hep-ph/04022218)

# The $p_T$-spectrum

- most of the events
- multiple emission of *soft gluons*
- $\alpha^n_s \rightarrow \alpha^n_s \log^m(M_H/q_T)$ con $(1 < m < 2n)$
- calculation techniques:

  - *parton showering*

  (MonteCarlo: Pythia, Herwig)

  - resummation

  (Parisi,Petronzio;1979)
  (Dokshitzer,Diakonov,Troian;1980)
  (Collins,Soper,Sterman;1985)

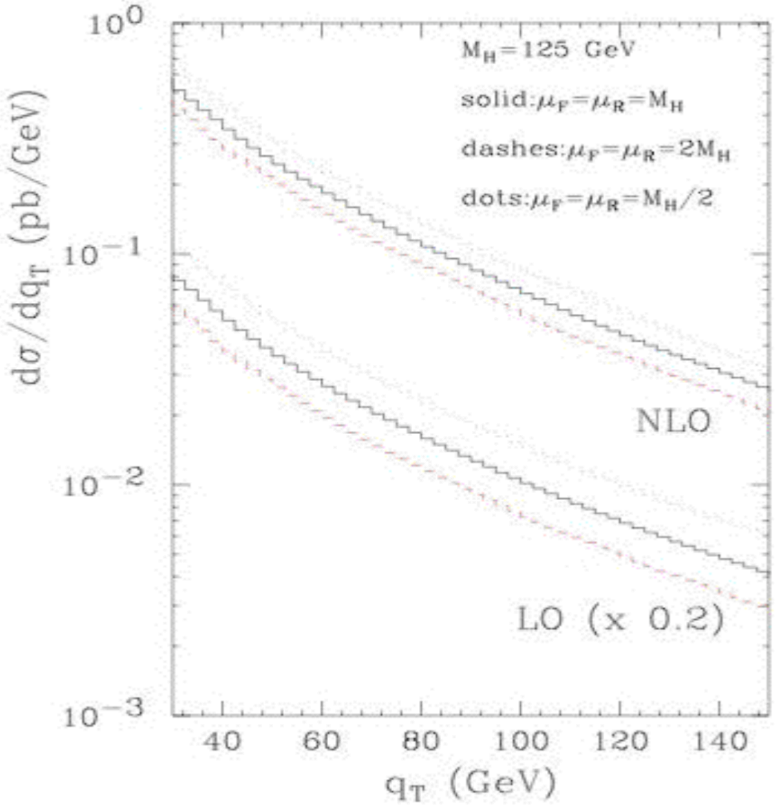
M
A
T
C
H
I
N
G

- perturbative expansion in $\alpha_s(M^2_H) \Rightarrow$ reliable
- LO=O($\alpha^3_s$) known from the eighties

  (Ellis,Hinchliffe,Soldate,
  van der Bij; 88)
- NLO= O($\alpha^4_s$) evaluated first numerically,later analitically:

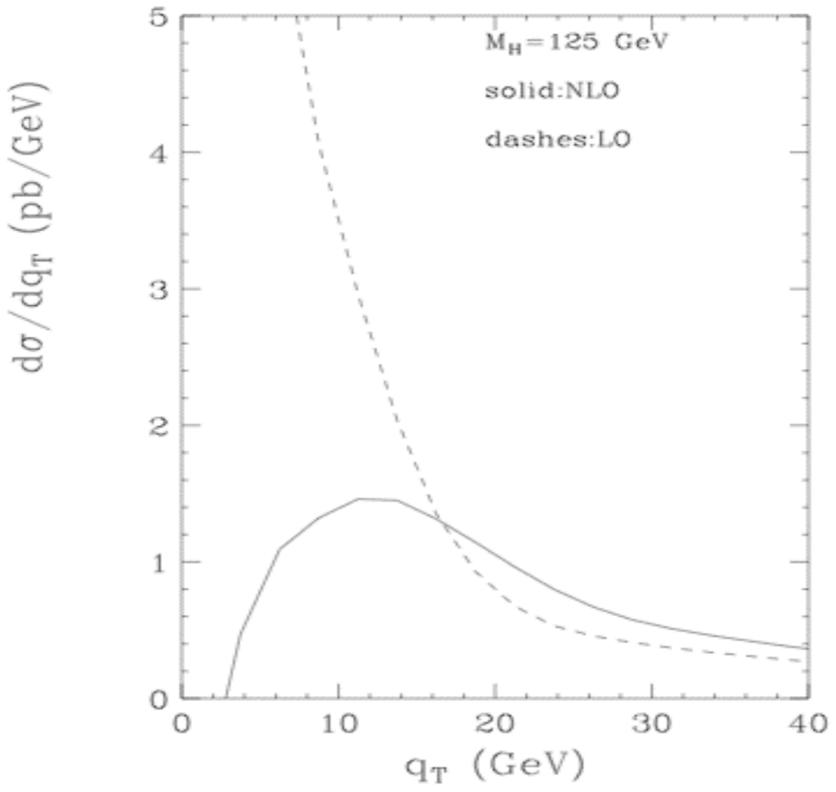
  (deFlorian, Grazzini, Kunzst;99)
  (Glosser, Schmidt; 02)
  (Ravindran,Smith,vanNeerven;02)

# Fixed-order calculation



- Importance of radiative corrections (K=NLO/LO~60%)
- K almost constant
- Both LO and NLO increase at low $p_T$
- Scale dependence reduced going from LO to NLO
- Scale variation at LO (~35%) highly underestimates NLO radiative corrections

# Divergence at low $p_T$

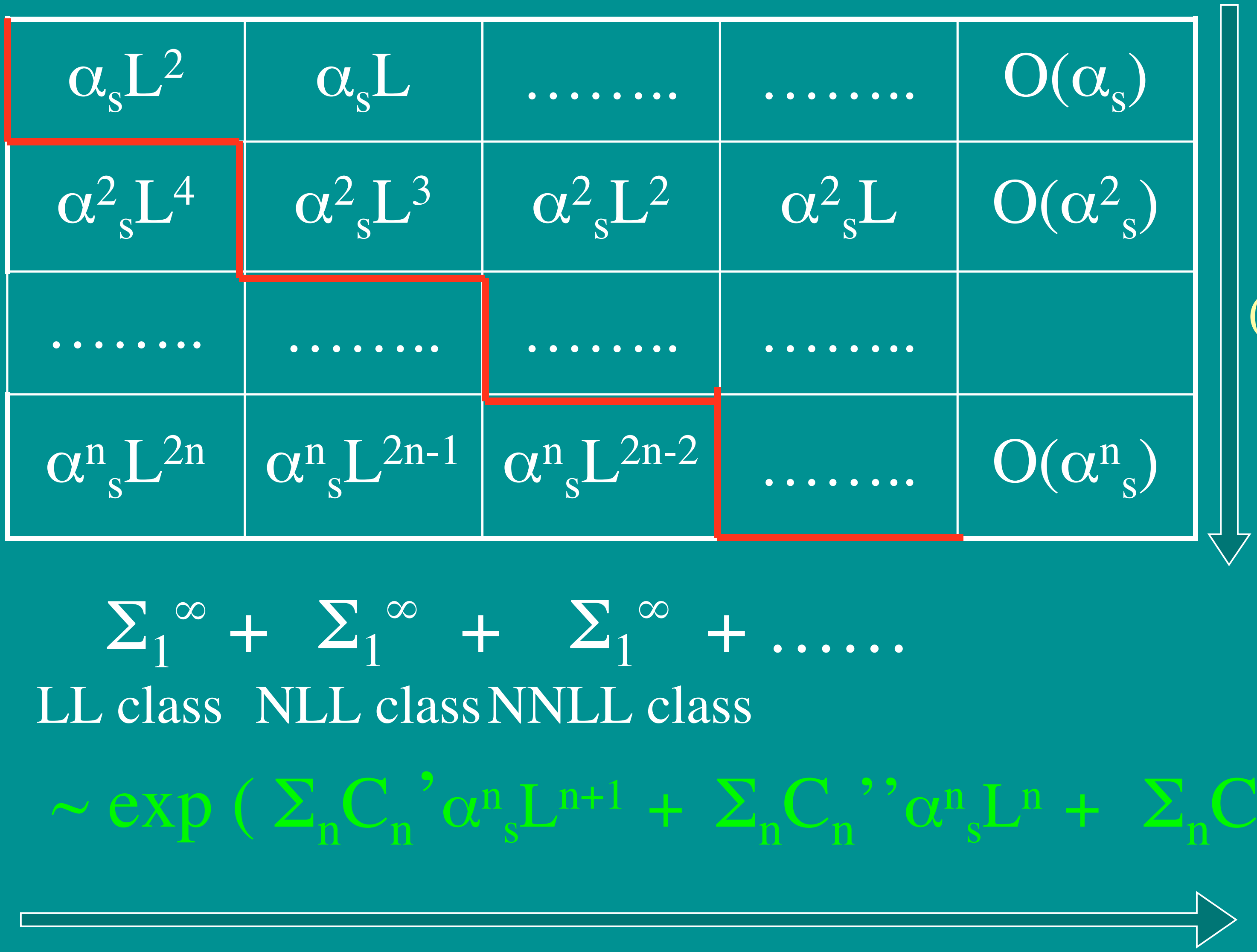


- In general, the *n-th* perturbative order includes terms of type $(\alpha^n_s/p_T^2)\,\log^m(M_H/p_T)$

  $\Rightarrow$ divergence!
- Compensation of positive (m=2n-1) and negative (m=2n-2) terms

  $\Rightarrow$non-physical peak at NLO
- It is necessary an *all-orders resummation* of logarithmic contributions to obtain reliable predictions

# Resummation: the main idea



| | | | | |
|---|---|---|---|---|
| $\alpha_s L^2$ | $\alpha_s L$ | …….. | …….. | $O(\alpha_s)$ |
| $\alpha^2_s L^4$ | $\alpha^2_s L^3$ | $\alpha^2_s L^2$ | $\alpha^2_s L$ | $O(\alpha^2_s)$ |
| …….. | …….. | …….. | …….. | |
| $\alpha^n_s L^{2n}$ | $\alpha^n_s L^{2n-1}$ | $\alpha^n_s L^{2n-2}$ | …….. | $O(\alpha^n_s)$ |

Fixed
Order
(rel.ord.: $\alpha_s L^2$)

$\Sigma_1^\infty$ + $\Sigma_1^\infty$ + $\Sigma_1^\infty$ + ……

LL class NLL class NNLL class

$$\sim \exp\left( \Sigma_n C_n' \alpha^n_s L^{n+1} + \Sigma_n C_n'' \alpha^n_s L^n + \Sigma_n C_n''' \alpha^n_s L^{n-1} \right)$$

Resummation (rel.ord: 1/L)

# Some formulas…….

- Resummation formula

$$\frac{d\sigma^{(\text{res.})}}{dq_T^2\,dQ^2} = \sum_{a,b,c} \int_0^1 dx_1 \int_0^1 dx_2 \int_0^\infty db \frac{b}{2} J_0(bq_T)\, \sigma_{c\bar{c}}^{(LO)}\, \delta(Q^2 - x_1 x_2 s)$$

$$\cdot\, (f_{a/h_1} \otimes C_{ca}) \left(x_1, \frac{b_0^2}{b^2}\right) (f_{b/h_2} \otimes C_{\bar{c}b}) \left(x_2, \frac{b_0^2}{b^2}\right) S_c(Q, b)$$

  - One usually works in *b*-space (*b=impact parameter=* $p_T$-conjugate variable), where multiple emission effects do factorize and where $p_T$-conservation is evident

- Sudakov factor

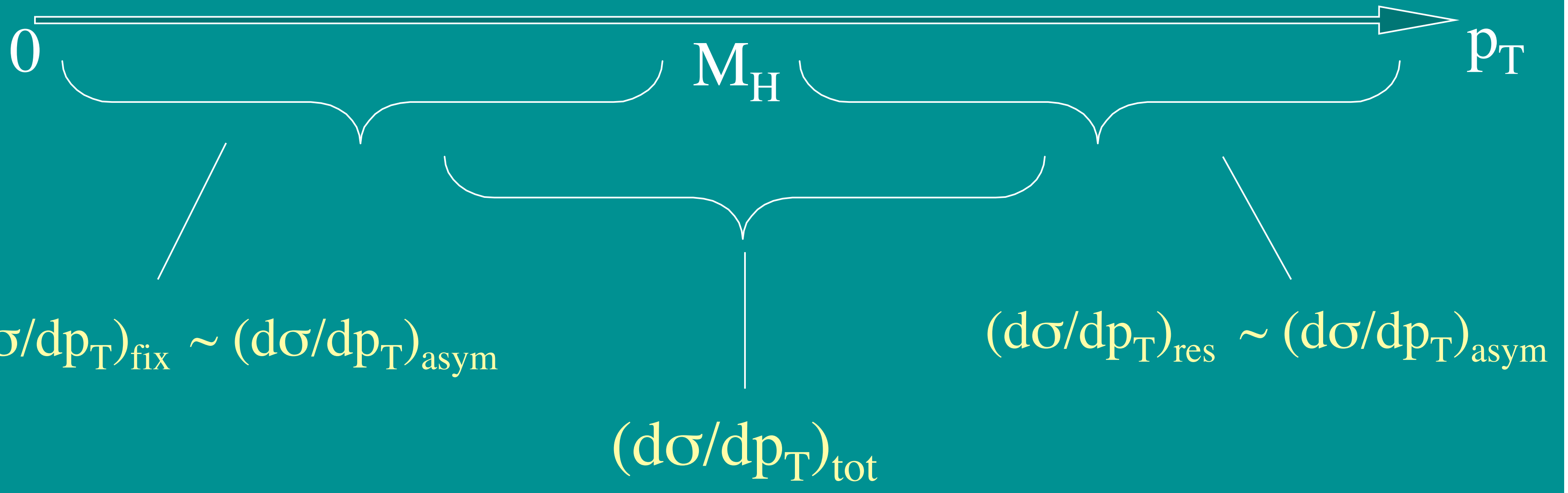
$$S_c(Q,b) = \exp\left\{ -\int_{b_0^2/b^2}^{Q^2} \frac{dq^2}{q^2} \left[ A_c(\alpha_S(q^2)) \ln\frac{Q^2}{q^2} + B_c(\alpha_S(q^2)) \right] \right\}$$

  - $A_1$,$A_2$,$B_1$ *universal* and already known (Kodaira,Trentadue;1982) (Catani,D'Emilio,Trentadue;1985)
  - $B_2$ recently evaluated for gg->H process (deFlorian,Grazzini;2000)

# The “matching” procedure

$$(d\sigma/dp_T)_{tot} = (d\sigma/dp_T)_{res} + (d\sigma/dp_T)_{fix} - (d\sigma/dp_T)_{asym}$$

- $(d\sigma/dp_T)_{res}$ = resummation
- $(d\sigma/dp_T)_{fix}$ = fixed order
- $(d\sigma/dp_T)_{asym}$ = expansion of resummation formula to the same order



$(d\sigma/dp_T)_{fix} \sim (d\sigma/dp_T)_{asym}$

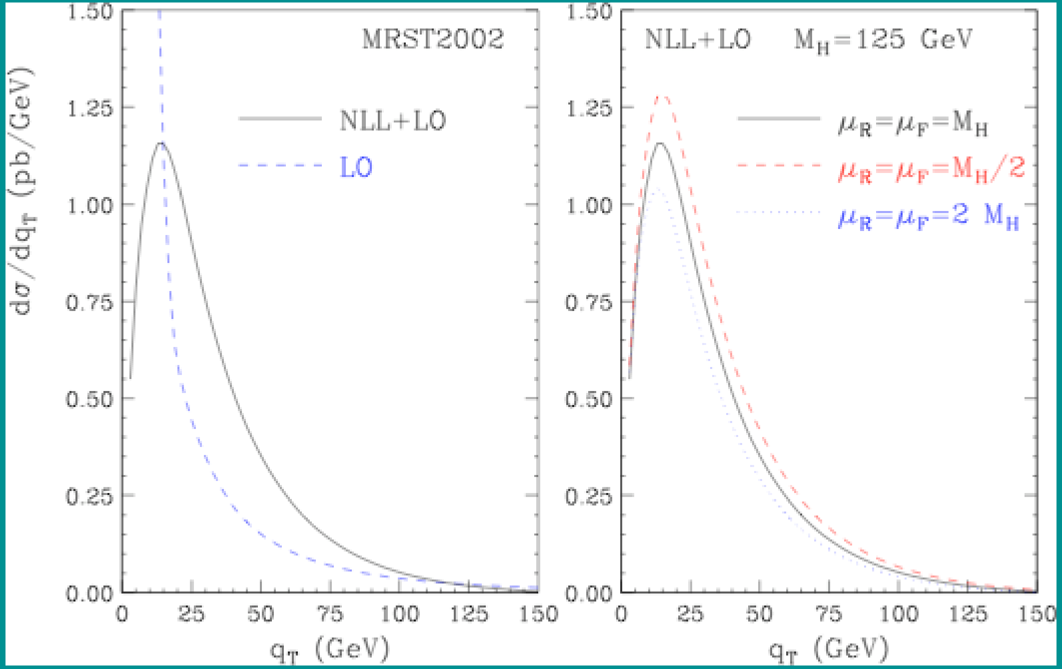
$(d\sigma/dp_T)_{res} \sim (d\sigma/dp_T)_{asym}$

$(d\sigma/dp_T)_{tot}$

# Our calculation

- Includes the most complete information available up to now:
  - *Resummation at NNLL order at low $p_T$*
  - *Perturbative calculation at NLO at high $p_T$*
  - *Matching at $O(\alpha_S^4)$*
- Improve the implementation formalism allowing a very precise *matching* at low $\mathrm{p_T}$

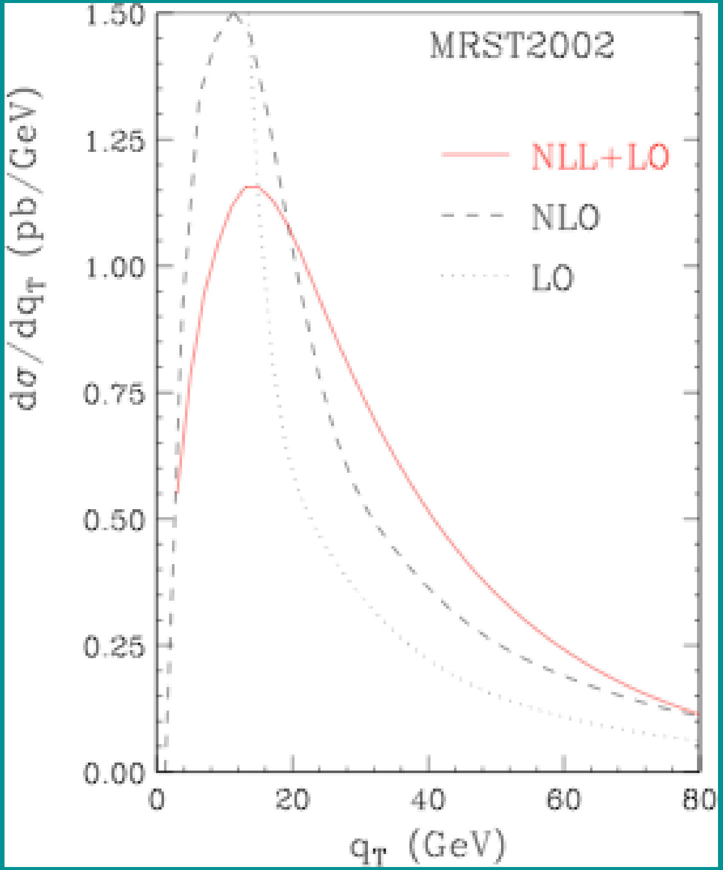
# Results for gg-->HX at NLL+LO



giuboz, Catani, deFlorian, Grazzini;
PLB 564 (2003), 65-72
hep-ph/0302104

- Relevant effect of resummation for $p_T < 100$ GeV
- Scale dependence: 10% around the peak

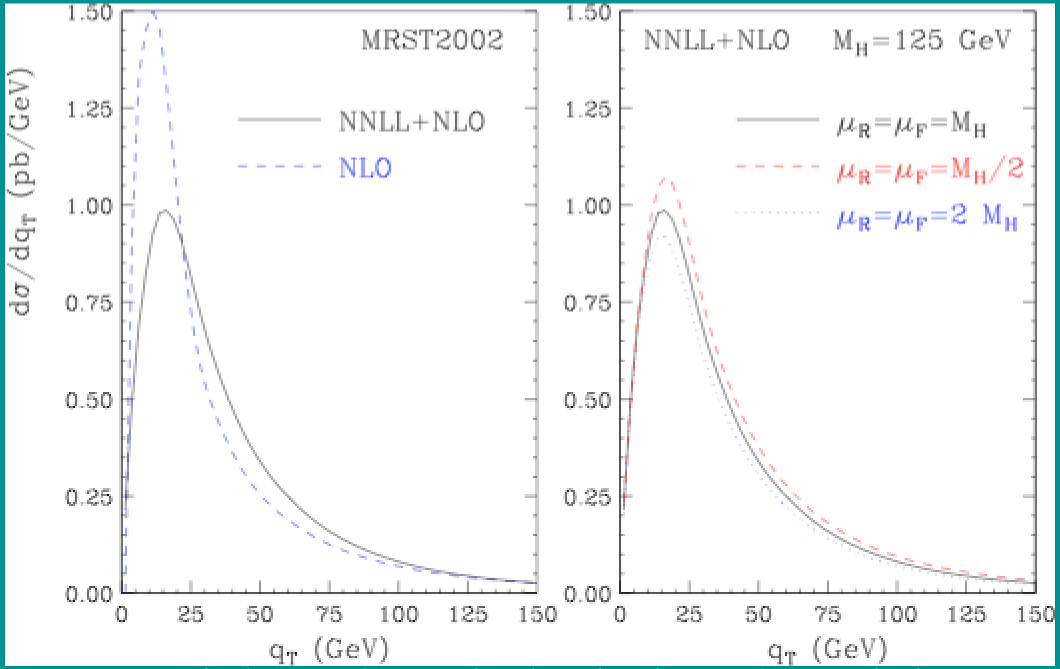
# LO, NLO, NLL+LO comparison



- At intermediate $p_T$ the distribution increases, going from LO to NLO and, subsequently going from NLO to NLL+LO

⇒ importance of resummation at intermediate $p_T$ with respect to higher perturbative order!

# Results for gg-->HX at NNLL+NLO



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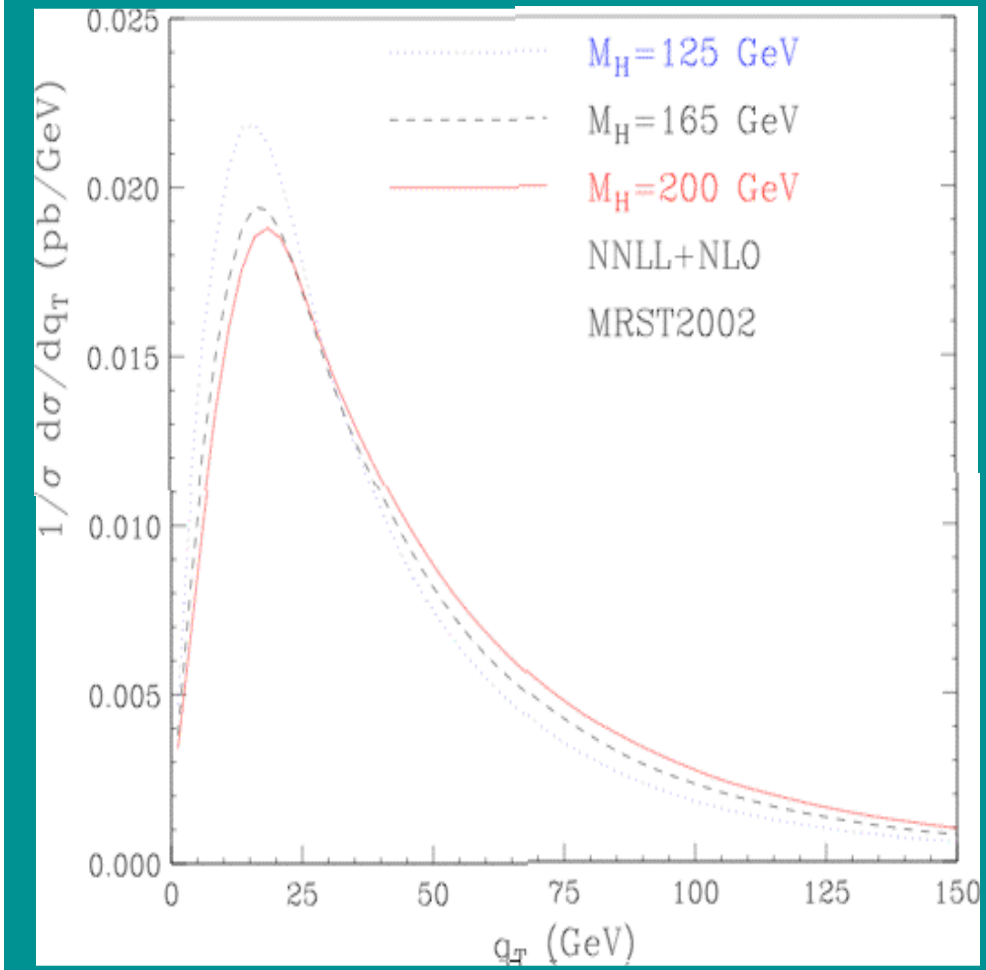
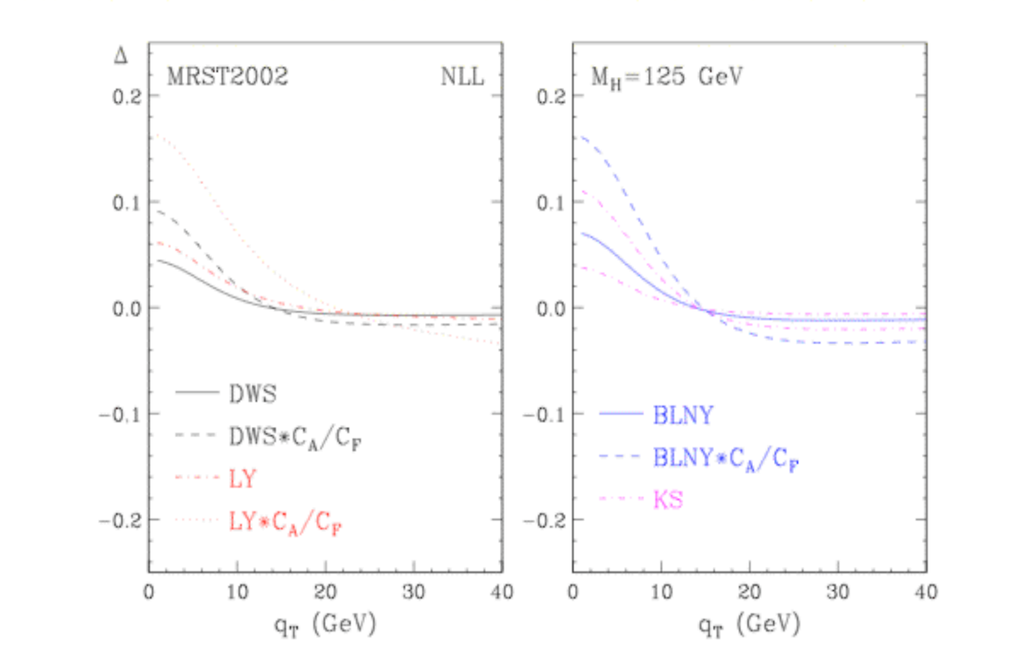
- At $p_T \sim$ 50 GeV the resummation effect increases the result by 40% with respect to NLO
- Peak slightly lower than NLL+LO, tail slightly higher (explanation: $\sigma_{tot}$(NNLO) ~ $\sigma_{tot}$(NLO) )
- Scale dependence: 8% around the peak ⇒ lower than NLL+LO

# Predictions for different values of $M_H$



- Results normalized to respective total cross sections
- At higher $M_H$, the peak shifts at higher $p_T$ values
- In general, increasing $M_H$ tail becomes more important and the peak is lowered

# Non-perturbative effects



- $p_T$-distribution receives important non-perturbative contributions at low $p_T$ (high b) region
- Several different recipes to include them

(Davies,Webber,Stirling;1985)
(Ladinsky,Yuan;1994)
(Brock,Landry,Nadolsky,Yuan;2002)
(Kulesza,Stirling;2003)

- In our case, deviations from purely perturbative result are at most 8% for $p_T$>10 GeV

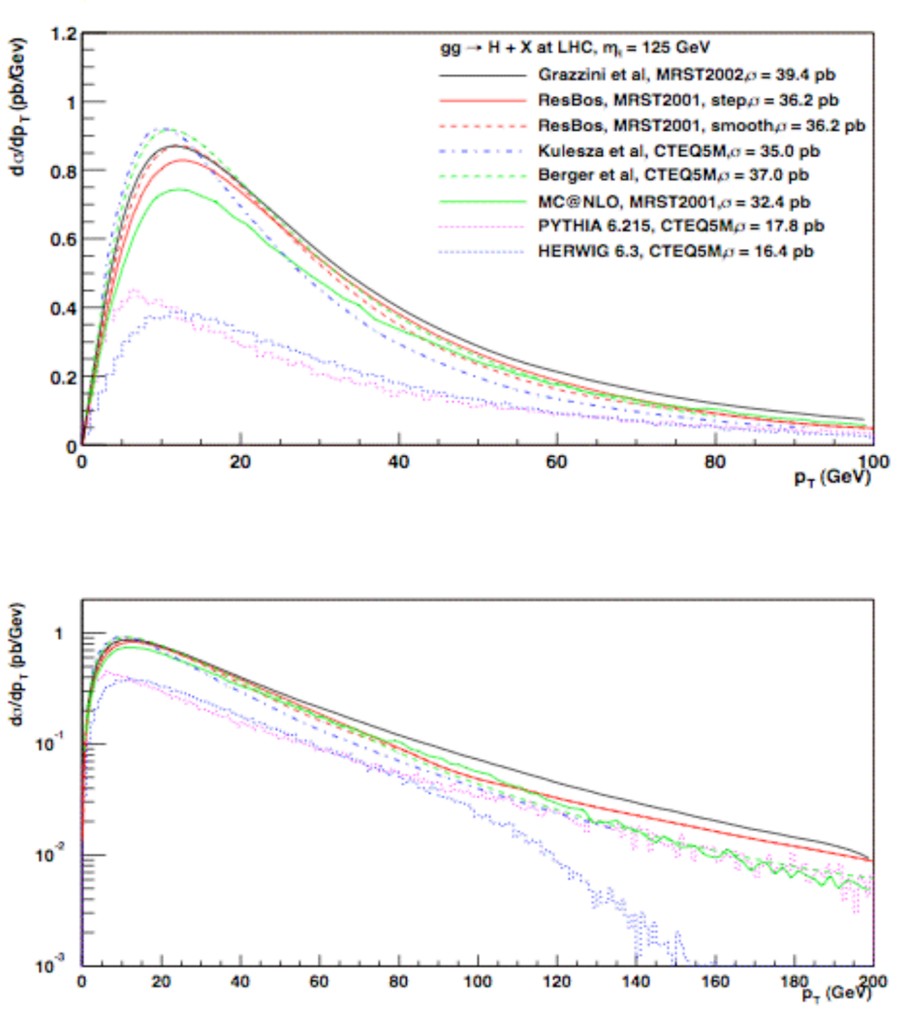
# Parton showering vs. resummation

1. Include LL, universal and indipendent from process under study
2. Allows exact treatment of branching kinematics
3. Needs matrix elements corrections at high $p_T$
4. Apart from MC@NLO, retains LO normalization and scale dependence

1. Include all logs, both universal and process dependent
2. Useful only for processes inclusive over final state
3. The *matching* allows a prediction over all the spectrum
4. Retains normalization and scale dependence of higher perturbative order

# Comparison with others $p_T$-spectra

(Balazs, Grazzini, Huston, Kulesza, Puljak, hep-ph/0403052)



- PYTHIA,HERWIG normalized to LO
- Low/intermediate $p_T$ ($p_T$<100 GeV): predictions are consistent
- High $p_T$: HERWIG not supplied with NLO matrix elements
- Peak position: 12-14 GeV for all curves
- *Are the discrepancies experimentally resolvable?*

# Conclusions and outlook

- Importance of resummation at low and intermediate $p_T$
- Matching with fixed order at **$O(\alpha_s^4)$**
- Stability of the main features of the distribution with respect to perturbative uncertainties (*scales*, *higher orders*)
- Good control over non-perturbative contributions
- *Extension to other processes (DY, SUSY, Heavy Ions (?), …)*