The transverse-momentum distribution of the Higgs boson at the Tevatron and the LHC

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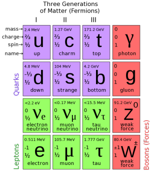
Outline

- The Higgs boson in the standard model
- Total cross section and transverse-momentum distribution
- Fixed order & resummed calculations
- `HqT` code and numerical predictions

Introduction

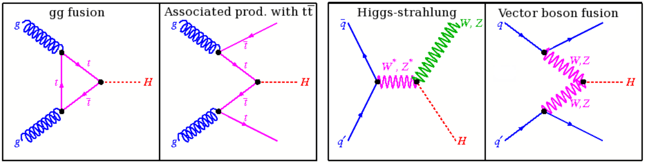
- Particles in the standard model:



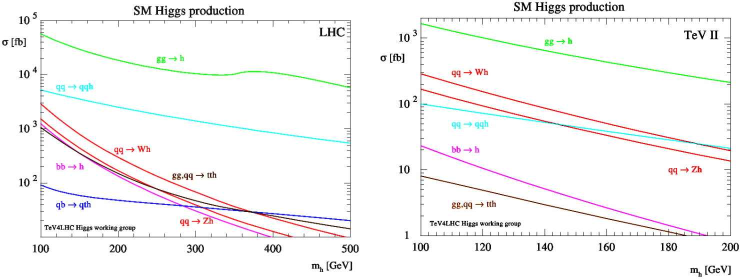
- *Standard model* based on *leptons* + *quarks* + *local gauge* $SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow g^a_\mu, W^\pm_\mu, Z^0_\mu, A_\mu \Rightarrow$ well predictive and tested by experiments
- What about masses of $W^\pm_\mu, Z^0_\mu$?
- At high energies, the cross section $\sigma(W^+W^- \Rightarrow W^+W^-)$ blows up

Standard solution:
spontaneous symmetry breaking $\Rightarrow$ new particle: Higgs boson

Higgs boson production at hadron colliders



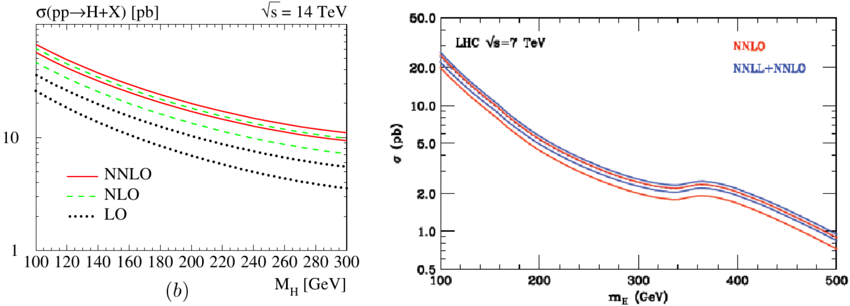
Main production channel is the gluon-gluon fusion, due to small-x enhancement of gluon PDFs at high-energy hadron colliders.



[Plots: "Tevatron-for-LHC Report: Higgs" hep-ph/0612172v2]

Total cross section predictions

Calculations of the total cross section for boson Higgs production at various orders of precision: from LO to NLO corrections of 80-100% and no overlapping between error bands, from NLO to NNLO corrections 10-25% and overlapping. Further 10-15% by NNLL threshold resummation.



[Plots: Harlander and Kilgore '02 - Catani,de Florian,Grazzini,Nason '03]

Differential distributions

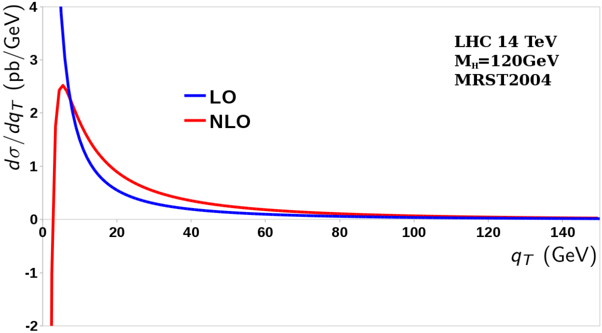
The total cross section is an ideal quantity and it is never really measured $\Rightarrow$ more exclusive calculations are actually needed.
To describe the Higgs kinematics we use the rapidity (η) and the transverse momentum (q_T) variables. For the Higgs production

- The shape of rapidity distribution $\left(\frac{d\sigma}{d\eta}\right)$ is mainly determined by the parton distribution functions (PDFs).
- Effect of initial state QCD radiation mainly encoded in the transverse momentum spectrum $\left(\frac{d\sigma}{dq_T}\right)$.

In practice the higgs transverse momentum spectrum plays a key role $\Rightarrow$ its accurate knowledge could help to find strategies to improve statistical significance of the data analysis.

Higgs q_T distribution

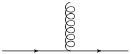
The Higgs boson can have $q_T \neq 0$ only if there is at least one recoiling parton.



In the limit $q_T \to 0$ the predictivity of the theory fails: at LO $\frac{d\sigma}{dq_T}$ diverge to $+\infty$ and at NLO there is an unphysical peak and then diverge to $-\infty$.

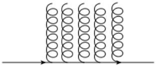
The problem comes from soft gluon emission

Resummation



The problem comes from the emission of soft and collinear gluons that gives terms of order $Log\left(\frac{M_H^2}{q_T^2}\right) \equiv L$: if $M_H^2 \sim q_T^2 \Rightarrow L \simeq 0$ but if $M_H^2 \gg q_T^2 \Rightarrow L \gg 1$

If we resum the emission of ∞ soft gluons we can reorganise the series as follow



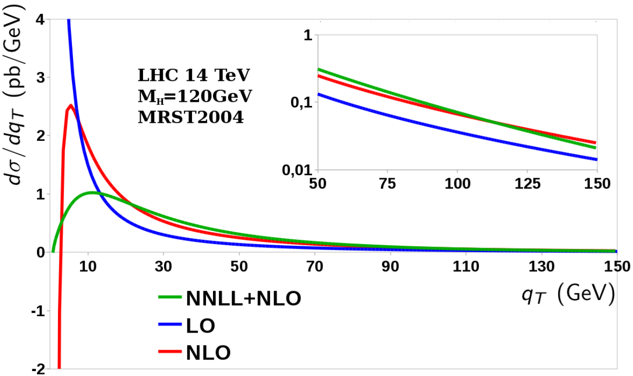
$$\sum_n \alpha_s^n \to \sum_{n,m} \alpha_s^n L^m$$

Note: we can introduce a new unphysical resummation scale Q^2 ($Q^2 \sim M_H^2$), analogous to the factorization and renormalization scales: $Log\left(\frac{M_H^2}{q_T^2}\right) = Log\left(\frac{M_H^2}{Q^2}\right) + Log\left(\frac{Q^2}{q_T^2}\right)$

This resummation is effectively carried out by standard event generators at the LL accuracy. The analytical resummation is instead developed up to the NNLL level.

HqT *results: resummed vs fixed order*

HqT: http://theory.fi.infn.it/grazzini/codes.html



Now there is no divergence in $q_T \to 0$ and no unphysical peak.
HqT is currently used at the Tevatron and the LHC through a reweighting procedure.

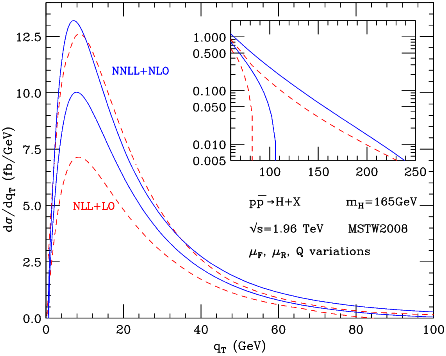
Recent developments: HqT2.0

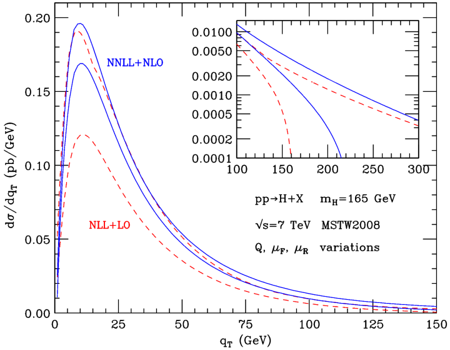
- The present version of HqT is based on a crude estimate of some second-order functions ($\mathcal{H}_N^{(2)}$ and $A^{(3)}$), but now the exact results are known and implemented.
- Exact treatment of resummation scale.
- Interface with LHAPDF.
- Compatibility with: `gfortran, f77, g77, g95`.

Advantages

No substantial approximations up to NNLL+NLO
A reliable estimate of the error band due to the scale dependence is now possible.

Numerical predictions at the Tevatron and the LHC





The estimate of the perturbative uncertainty is obtained by performing scale variations in the ranges $\frac{mH}{2} \leq \{\mu F, \mu R, 2Q\} \leq 2mH$, with the constraints $0.5 \leq \frac{\mu F}{\mu R} \leq 2$ and $0.5 \leq \frac{Q}{\mu R} \leq 2$.

Perturbative uncertainty at LHC (Tevatron) at NNLL+NLO ranges from about $\pm 8\%(\pm 14\%)$ at the peak to about $\pm 12\%(\pm 25\%)$ at $q_T = 75$GeV.

At large values of q_T the resummed result looses predictivity: better to use fixed order.

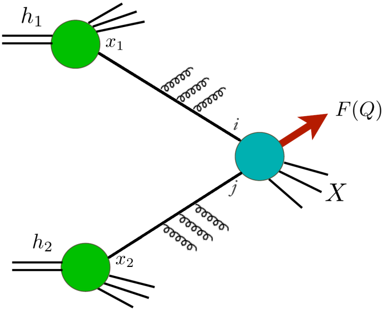
Conclusions and perspectives

Obtained results:

- Full implementation in the code `HqT` for the Higgs q_T spectrum up to the NNLL+NLO accuracy.
- Study of the theoretical uncertainties due truncation of the perturbative expansion (and PDFs).
- The code will be soon available online.

The code is expected to be a useful tool for physics studies at the Tevatron and the LHC.

(Backup) Perturbative QCD at hadron colliders



Factorization theorem: separation between low and high energy scales

$$\sigma_{h_1 h_2 \to F+X}(P_1, P_2; s) = \sum_{i,j} \int_0^1 dx_1 \int_0^1 dx_2 \overbrace{f_{i,h_1}(x_1, \mu_F^2) f_{j,h_2}(x_2, \mu_F^2)}^{\text{universal parton densities}} \cdot \underbrace{\hat{\sigma}_{ij \to F+X}(x_1 P_1, x_2 P_2; \hat{s} = x_1 x_2 s, \mu_F^2)}_{\text{calculable in QCD perturbation theory}}$$

(Backup) Resummation the main idea

$d\hat{\sigma}_{i,j} = \sum_{n,m} \alpha_s^n L^m d\hat{\sigma}_{i,j;n,m} = d\sigma^{(res)} + d\sigma^{(fin)}$

NLL+LO

$\alpha_s L^2$	$\alpha_s L$	...	**(fin)**	$\mathcal{O}(\alpha_s)$	(LO)
$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	$\mathcal{O}(\alpha_s^2)$	(NLO)
... **(res)**	...	...	...	...	...
$\alpha_s^n L^{2n}$	$\alpha_s^n L^{2n-1}$	$\alpha_s^n L^{2n-2}$	...	$\mathcal{O}(\alpha_s^n)$	$(N^n LO)$
LL	NLL	NNLL	...	...	

NNLL+NLO

$\alpha_s L^2$	$\alpha_s L$	...	**(fin)**	$\mathcal{O}(\alpha_s)$	(LO)
$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	$\mathcal{O}(\alpha_s^2)$	(NLO)
... **(res)**	...	...	...	...	...
$\alpha_s^n L^{2n}$	$\alpha_s^n L^{2n-1}$	$\alpha_s^n L^{2n-2}$	...	$\mathcal{O}(\alpha_s^n)$	$(N^n LO)$
LL	NLL	NNLL	...	...	

- Ratio of two successive rows: $O(\alpha_s L^2)$
- Ratio of two successive columns: $O(1/L)$