Higher order QCD corrections for associated VH production at hadron colliders

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In collaboration with: M. Grazzini & F. Tramontano

Outline

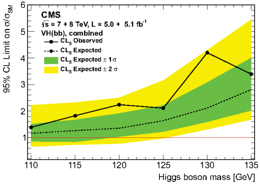
1. Associated VH production at hadron colliders
2. q_T-subtraction formalism at NNLO
3. Associated VH production at NNLO: numerical results
4. Conclusions

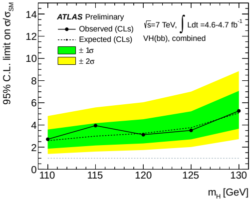
Motivations

Associated vector boson Higgs (VH) production (with $H \to b\bar{b}$ and $V \to l_1 l_2$ decay) is an important mechanism for discovery and study the properties of the Higgs boson.

- At the LHC it is important channel through boosted analysis with jet reconstruction and decomposition techniques [Butterworth et al.('08)].
- At the Tevatron is the main search channel in the low Higgs mass region.

To get closer to SM VH sensitivity with the LHC 2012 data, precise theoretical predictions needed $\Longrightarrow$ computation of higher-order QCD corrections.





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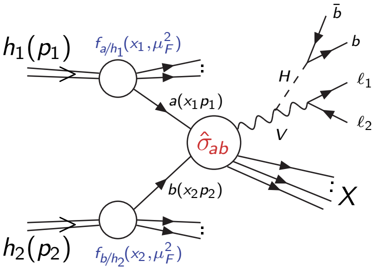

$$h_1(p_1) + h_2(p_2) \rightarrow V + H + X \rightarrow \ell_1\ell_2 + b\bar{b} + X$$

where $V = Z^0, W^\pm$ and $\ell_1\ell_2 = \ell^+\ell^-, \ell\nu_\ell$

According to the QCD factorization theorem:

$$d\sigma(p_1,p_2) = \sum_{a,b}\int_0^1 dx_1 \int_0^1 dx_2\, f_{a/h_1}(x_1,\mu_F^2)\, f_{b/h_2}(x_2,\mu_F^2)\, d\hat{\sigma}_{ab}(x_1p_1, x_2p_2; \mu_F^2).$$

$$d\hat{\sigma}_{ab}(\hat{p}_1,\hat{p}_2;\mu_F^2) = d\hat{\sigma}^{(0)}_{ab}(\hat{p}_1,\hat{p}_2;\mu_F^2) + \alpha_S(\mu_R^2)\, d\hat{\sigma}^{(1)}_{ab}(\hat{p}_1,\hat{p}_2;\mu_F^2) + \alpha_S^2(\mu_R^2)\, d\hat{\sigma}^{(2)}_{ab}(\hat{p}_1,\hat{p}_2;\mu_F^2,\mu_R^2) + \mathcal{O}(\alpha_S^3)\,.$$

In the following we do not consider QCD corrections to $H \rightarrow b\bar{b}$ decay.

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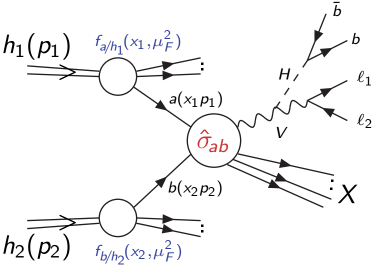

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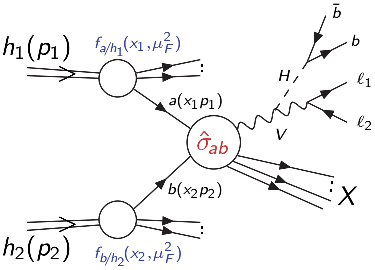

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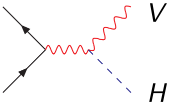
Associated *VH* production: total cross section



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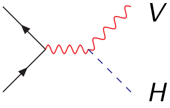

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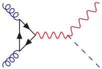

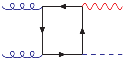

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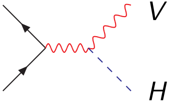

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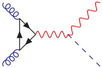
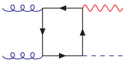

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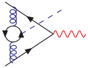
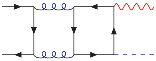

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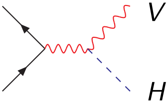

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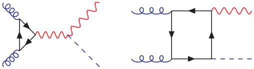

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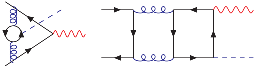

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Fully-Exclusive Cross Sections at NNLO in hadron-collisions

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- At NLO general algorithms (e.g. Dipole formalism [Catani,Seymour('98)]) allow (relative) straightforward fully-exclusive calculations.
- At NNLO in hadronic collisions only few fully exclusive calculations exist:
  - Sector decomposition: [Binoth,Heinrich('00)]
    $gg \to H$ [Anastasiou,Melnikov,Petriello('04)]→FEHIP
    Drell-Yan [Melnikov,Petriello('06)]→FEWZ
  - q_T-subtraction:
    $gg \to H$ [Catani,Grazzini('07)]→HNNLO
    Drell-Yan [Catani,Cieri,de Florian,G.F.,Grazzini('09)]→DYNNLO
    Associated WH production [G.F.,Grazzini,Tramontano('11)]→ WNNLO
    Diphoton prod. [Catani,Cieri,de Florian,G.F.,Grazzini('11)]→2γNNLO
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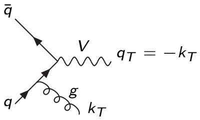
The q_T-subtraction formalism at NNLO

$$h_1(p_1) + h_2(p_2) \rightarrow V(M, q_T) + X$$

V is one or more colourless particles (vector bosons, leptons, photons, Higgs bosons,...) [Catani,Grazzini('07)].



- Key point I: at LO the q_T of the V is exactly zero.

$$d\sigma^V_{(N)NLO}|_{q_T \neq 0} = d\sigma^{V+\text{jets}}_{(N)LO} \quad ,$$

for $q_T \neq 0$ the NNLO IR divergences cancelled with the NLO subtraction method.

- The only remaining NNLO singularities are associated with the $q_T \rightarrow 0$ limit.
- Key point II: treat the NNLO singularities at $q_T = 0$ by an additional subtraction using the universality of logarithmically-enhanced contributions from q_T resummation formalism [Catani,de Florian,Grazzini('00)].

$$d\sigma^V_{N^nLO} \xrightarrow{q_T \rightarrow 0} d\sigma^V_{LO} \otimes \Sigma(q_T/M) dq_T^2 = d\sigma^V_{LO} \otimes \sum_{n=1}^{\infty} \sum_{k=1}^{2n} \left(\frac{\alpha_S}{\pi}\right)^n \Sigma^{(n,k)} \frac{M^2}{q_T^2} \ln^{k-1} \frac{M^2}{q_T^2} d^2 q_T$$

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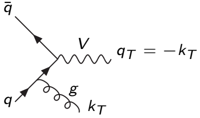

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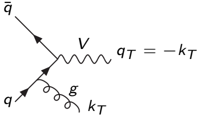

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The final result valid also for $q_T = 0$ is:

$$d\sigma^{V}_{(N)NLO} = \mathcal{H}^{V}_{(N)NLO} \otimes d\sigma^{V}_{LO} + \left[d\sigma^{V+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right] \quad ,$$

$$\textit{where} \quad \mathcal{H}^{V}_{NNLO} = \left[1 + \frac{\alpha_S}{\pi} \mathcal{H}^{V(1)} + \left(\frac{\alpha_S}{\pi} \right)^2 \mathcal{H}^{V(2)} \right]$$

- The choice of the counter-term has some arbitrariness but it must behave $d\sigma^{CT} \stackrel{q_T \to 0}{\longrightarrow} d\sigma^{V}_{LO} \otimes \Sigma(q_T/M) dq_T^2$ where $\Sigma(q_T/M)$ is universal.
- $d\sigma^{CT}$ regularizes the $q_T = 0$ singularity of $d\sigma^{V+\text{jets}}$: *double real* and *real-virtual* NNLO contributions, while (the finite part of) *two-loops virtual* corrections are contained in $\mathcal{H}^{V}_{NNLO}$.
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Associated *WH* production in NNLO QCD

G.F.,Grazzini,Tramontano arXiv:1107.1164

- A NLO calculation for $h_1 h_2 \to V + X$ requires:
  - $d\sigma_{LO}^{V+\text{jets}}$ (and $d\sigma_{LO}^{V}$).
  - $\mathcal{H}^{V(1)}$ [de Florian, Grazzini('01)]: contains the finite-part of the one-loop amplitude $c\bar{c} \to V$.
  - $d\sigma_{LO}^{CT}$: depends by the (universal) q_T-resummation coeff. A_1 and B_1.
- A NNLO calculation for $h_1 h_2 \to V + X$ requires also:
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Fully-exclusive NNLO calculation, implemented in the parton-level Monte Carlo code: [G.F.,Grazzini,Tramontano('11)]

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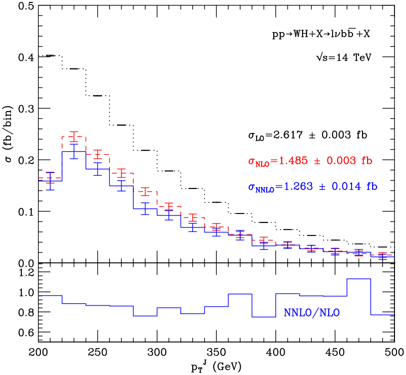
Numerical results
at the LHC and the Tevatron



$pp \to WH(\to l\nu\, b\bar{b})$
p_T spectra of the fat jet at the LHC@14TeV for $m_H = 120 GeV$ at LO (dots), NLO (dashes) and NNLO (solid).

- Selection strategy of [Butterworth et al.('08)]: search a large-p_T Higgs boson thorough a collimated $b\bar{b}$ pair decay.
  Cuts:
  Leptons: $p_T^l > 30 GeV$, $|\eta^l| < 2.5$,
  $p_T^{miss} > 30 GeV$, $p_T^W > 200 GeV$.
  Jets: Cambridge/Aachen algorithm with R=1.2.
  Fat jet (contain the $b\bar{b}$) $p_T^J > 200 GeV$, $|\eta^J| < 2.5$
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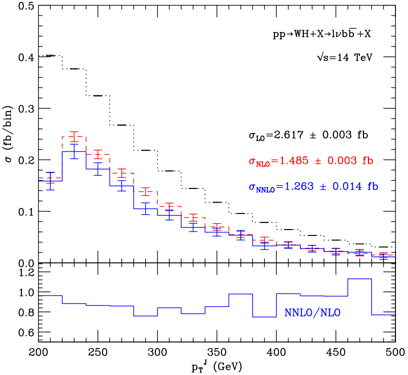
- Large negative higher-order corrections: NLO (NNLO) effects -52%/-36% (-6%/-19%), depending on the scale choice (factor two around $\mu_F = \mu_R = m_W + m_H$).
- Jet veto strongly affect the higher order corrections ⇒ stability of fixed order calculation challenged.



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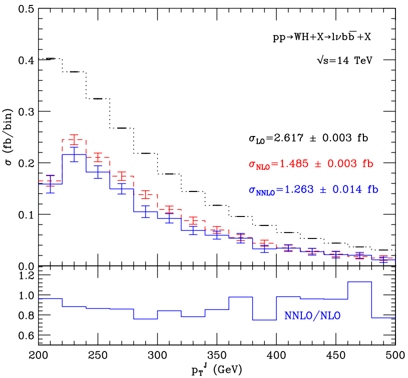

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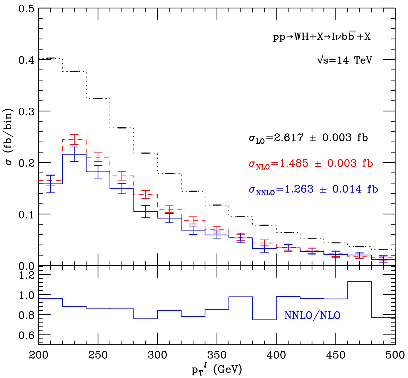

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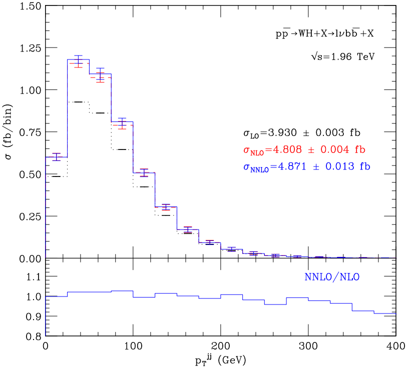
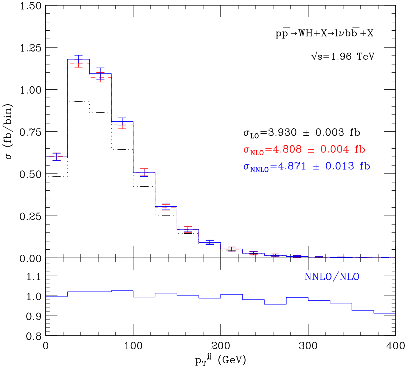


$p\bar{p} \to WH(\to l\nu\, b\bar{b})$
p_T spectra of the dijet system at the Tevatron for $m_H = 120 GeV$ at LO (dots), NLO (dashes) and NNLO (solid).

- Cuts:
  Leptons: $p_T^l > 20 GeV$, $|\eta^l| < 2$, $p_T^{miss} > 20 GeV$.
  Jets: k_T algorithm with R=0.4.
  Exactly two jets (with $p_T > 20 GeV$ and $|\eta| < 2$) at least one of them has to be a b jet (with $|\eta| < 1$).
- Higher-order corrections: NLO (NNLO) effects from +13% to +30% (from −1% to +4%) depending on the scale choice (factor two around $\mu_F = \mu_R = m_W + m_H$). The scale dependence is at the level of about ±1% both at NLO and NNLO.
- The shape of the distribution is stable against perturbative corrections. Perturbative expansion under good control.



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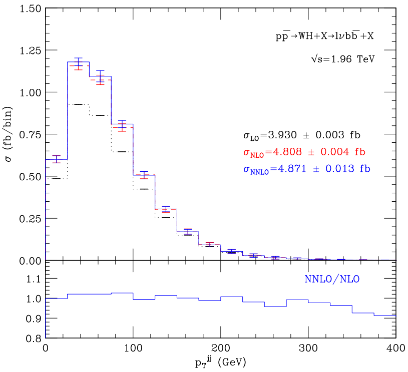

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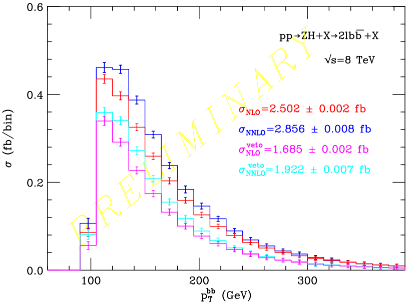
G.F.,Grazzini,Tramontano (in preparation)



$pp \to ZH(\to 2l\, b\bar{b})$
p_T spectra of the $b\bar{b}$ system at the LHC for $m_H = 125 GeV$ at NLO and NNLO with and without the jet veto.

- $gg \to HZ$ top-loop $\sim g^2\lambda_t^2\alpha_S^2$ (non DY-like) corrections included.
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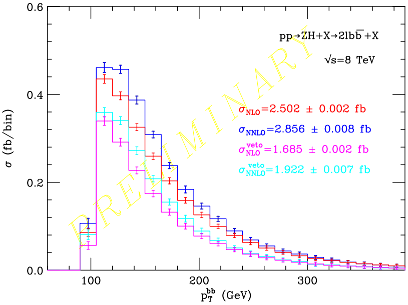

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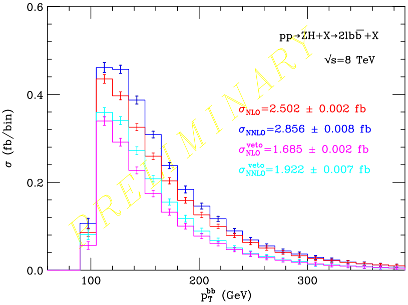

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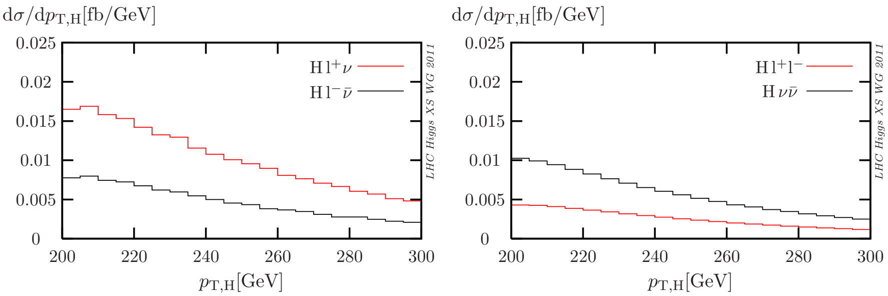

Yellow Report II:arXiv:1201.3084

Distributions in $p_{T,H}$ for $pp \to WH \to l\nu H$ (NNLO QCD + NLO EW) and for $pp \to ZH \to ll/\nu\nu H$ (NLO QCD + NLO EW) at $\sqrt{s} = 7\ TeV$.
Boosted setup: $|\eta_l| < 2.5$, $p_{T,l} > 20$ GeV, $p_{T,\nu} > 25$ GeV, $p_{T,H} > 200$ GeV, $p_{T,W/Z} > 190$ GeV.

We produced similar results at $\sqrt{s} = 8\ TeV$.

Conclusions

- Calculation of NNLO QCD corrections to VH production in hadron collision using the q_T-subtraction formalism, included in a fully-exclusive parton-level Monte Carlo code.
- NNLO corrections can be important:
  large and negative: $\sim -20\%$ for the WH fat-jet analysis at the LHC@14 TeV when a jet veto is applied;
  sizeable for the CMS analysis at the LHC;
  moderate for the WH Tevatron analysis.
- Outlook/Work in progress:
  Public release of the parton-level numerical code.
  Inclusion of the higher-order QCD correction to $H \to b\bar{b}$ decay.
  Extension to the ZH production.
  Inclusion of $H \to WW/ZZ \to 2l2\nu/4l$ decay.
  Comparison with parton-shower Monte Carlo predictions.
  Study of the NNLO uncertainty band: first reliable estimate of perturbative uncertainty.