NNLO QCD predictions for Higgs Physics at the LHC

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Outline

Motivations

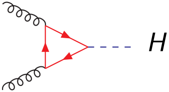
Understanding the origin of ElectroWeak symmetry breaking and the existence of the Higgs mechanism is a central issue in particle physics.

The exclusion/discovery of the Higgs boson and (possibly) the study of its properties depends, in various way, by theoretical predictions for Higgs boson cross sections.

To fully exploit the information contained in the experimental data from hadron colliders, precise theoretical predictions are needed
$\Longrightarrow$ computation of higher-order QCD corrections.

Inclusive Higgs Cross Sections at NNLO

Gluon Fusion



At LHC large gluon luminosity $\Rightarrow$ dominant production channel in the whole m_H range.

- NNLO QCD corrections in the large-m_t approx. [Harlander,Kilgore('02)]$\rightarrow$ggh@nnlo, [Anastasiou,Melnikov,Petriello('04)] [Ravindran,Smith,Van Neerven('03)].
  For $m_t \gg m_H$ top-loop dominate:
- NNLO corrections beyond large-m_t approx. [Marzani,Ball,Del Duca,Forte,Vicini('08)] [Harlander,Mantler,Marzani,Ozeren('09)],[Pag,Rogal,Steinhauser('09)].
  Accuracy of large-m_t approximation better than 1% for $100 \leq m_H \leq 300$ GeV.
- Large QCD corrections: $\sim +100\%$ at NLO, $\sim +25\%$ at NNLO.
  The bulk due to threshold ($\hat{s} \rightarrow m_H^2$) soft/collinear emissions: NNLL resummation gives a further $\sim +10\%$ correction [Catani,de Florian,Grazzini,Nason('03)].
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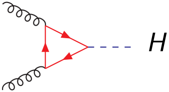

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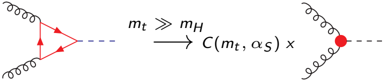

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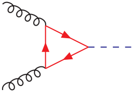

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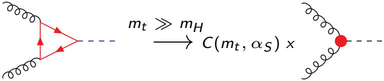

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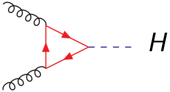

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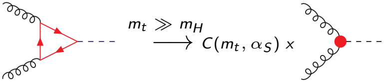

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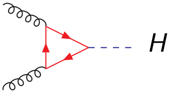

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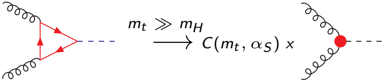

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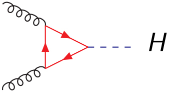

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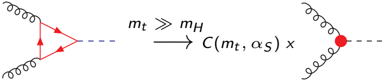

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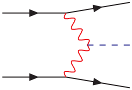

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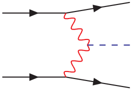

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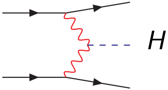

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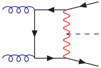

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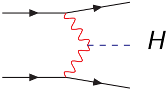

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  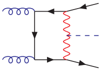

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  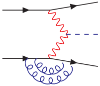

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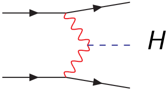

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  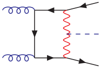

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  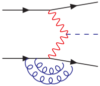

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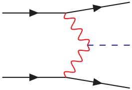

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  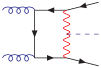

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  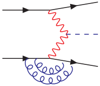

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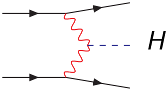

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  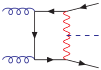

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  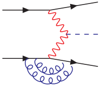

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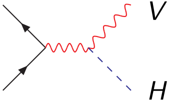

Main channel for low mass Higgs at the Tevatron. Important channel through boosted analysis at the LHC.

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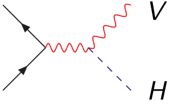

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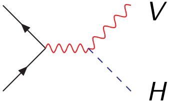

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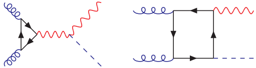

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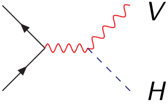

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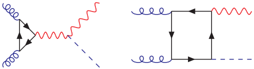

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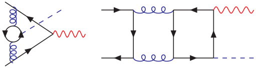

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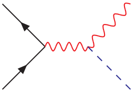

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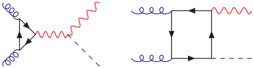

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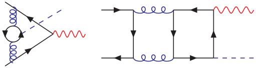

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Exclusive Higgs Cross Sections at NNLO

Fully-Exclusive Cross Sections at NNLO in hadron-collisions

- Experiments have finite acceptance: important to provide exclusive theoretical predictions.
- Beyond LO cancellation of Infrared (IR) singularities prevent straightforward implementation of numerical techniques.
- 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:
    $gg \to H$ [Anastasiou,Melnikov,Petriello('04)]→FEHIP
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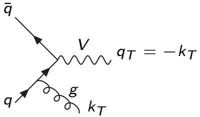
The q_T-subtraction method at NNLO [Catani,Grazzini('07)]

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

V is one or more colourless particles (W/Z bosons, photons, Higgs,...).



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

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

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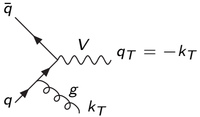

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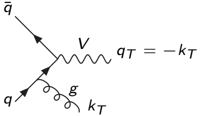

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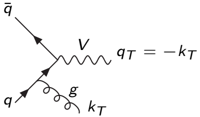

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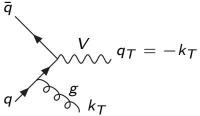

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Associated W-Higgs production at NNLO

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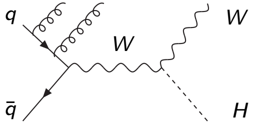

G.F.,Grazzini,Tramontano arXiv:1107.1164

It's a DY-like process

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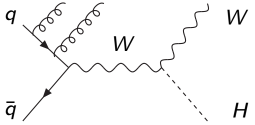

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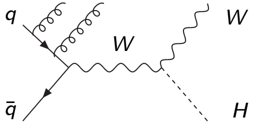

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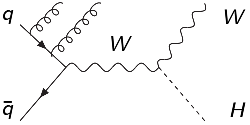

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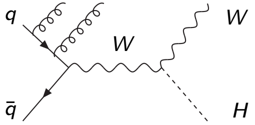

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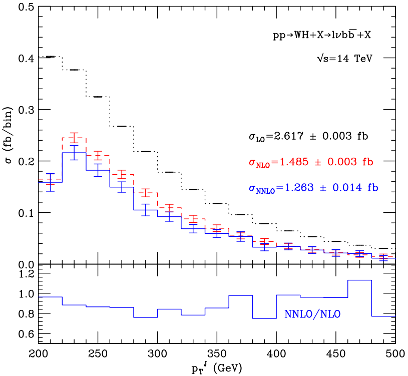

p_T spectra of the fat jet at the LHC for $m_H = 120 GeV$ at LO (dots), NLO (dashes) and NNLO (solid).

- Selection strategy of [Butterworth et al.('08)]: search a large-p_T Higgs boson thorough a collimated $b\bar{b}$ pair decay.
  Cuts:
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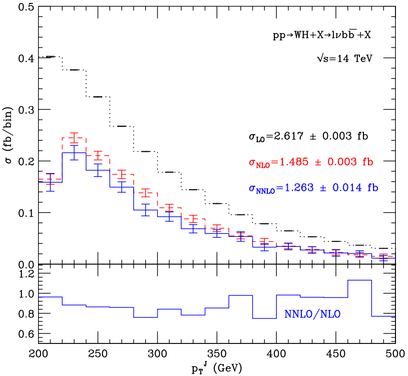
- Large negative higher-order corrections: NLO (NNLO) effects -52%/-36% (-6%/-19%), depending on the scale choice ($\mu_F = \mu_R = m_W + m_H$).
- Jet veto strongly affect the higher order corrections ⇒ stability of fixed order calculation challenged.



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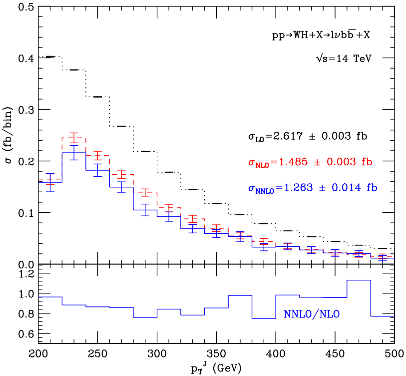

p_T spectra of the fat jet at the LHC for $m_H = 120\,GeV$ at LO (dots), NLO (dashes) and NNLO (solid).

- 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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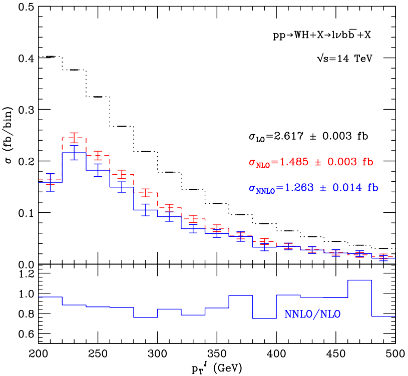

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Higgs transverse-momentum resummation at NNLL+NLO

State of the art: transverse-momentum (q_T) resummation

- The method to perform the resummation of the large logarithms of q_T is known
  [Dokshitzer,Diakonov,Troian ('78)], [Parisi,Petronzio('79)], [Kodaira,Trentadue('82)],[Altarelli et al.('84)], [Collins,Soper,Sterman('85)], [Catani,de Florian,Grazzini('01)] [Catani,Grazzini('10)]
- Various phenomenological studies of the Higgs boson transverse momentum distribution exist
  [Balasz,Yuan('00)],[Balasz,Huston,Puljak('01)],[Berger,Qiu('03)], [Kulesza,Stirling('03)],[Kulesza,Sterman,Vogelsang('04)]
- Recently various results for transverse momentum resummation in the framework of Effective Theories appeared
  [Mantry,Petriello('11), Becher,Neubert('11)].

Transverse momentum resummation

$$\frac{d\hat{\sigma}_{ab}}{dq_T^2} = \frac{d\hat{\sigma}_{ab}^{(res)}}{dq_T^2} + \frac{d\hat{\sigma}_{ab}^{(fin)}}{dq_T^2}; \qquad \int_0^{Q_T^2} dq_T^2 \left[\frac{d\hat{\sigma}_{ab}^{(fin)}}{dq_T^2}\right]_{f.o.} \overset{Q_T \to 0}{=} 0\,;$$

$$\int_0^{Q_T^2} dq_T^2 \left[\frac{d\hat{\sigma}_{ab}^{(res)}}{dq_T^2}\right]_{f.o.} \overset{Q_T \to 0}{\sim} 1 + \sum_n \sum_{m=1}^{2n} c_{nm}\, \alpha_S^n \log^m \frac{M^2}{Q_T^2}\,.$$

Resummation holds in impact parameter (b) space (Fourier-conjugated to q_T):

$$q_T \ll M \Leftrightarrow 1/b \ll M, \quad \log q_T^2/M^2 \gg 1 \Leftrightarrow \log M^2 b^2 \equiv L \gg 1$$

In the Mellin moments ($f_N \equiv \int_0^1 f(x) x^{N-1} dx$) space we have the exponentiated form:

$$\tilde{\sigma}_N(b, M) = \mathcal{H}_N(\alpha_S) \times \exp\{\mathcal{G}_N(\alpha_S, L)\}$$

$$\mathcal{G}_N(\alpha_S, L) = L\, g^{(1)}(\alpha_S L) + g_N^{(2)}(\alpha_S L) + \frac{\alpha_S}{\pi} g_N^{(3)}(\alpha_S L) + \cdots\,; \qquad \mathcal{H}_N(\alpha_S) = \sigma^{(0)}(\alpha_S, M)\left[1 + \frac{\alpha_S}{\pi}\mathcal{H}_N^{(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}_N^{(2)} + \cdots\right]$$

LL ($\sim \alpha_S^n L^{n+1}$): $g^{(1)}$, ($\sigma^{(0)}$); NLL ($\sim \alpha_S^n L^n$): $g_N^{(2)}$, $\mathcal{H}_N^{(1)}$; NNLL ($\sim \alpha_S^n L^{n-1}$): $g_N^{(3)}$, $\mathcal{H}_N^{(2)}$;

Perturbative unitarity constrain and resummation scale Q:

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Higgs q_T resummation at NNLL+NLO: HqT

- q_T-resummation formalism developed and applied for $gg \to H$ by [Catani, de Florian, Grazzini('01)], [Bozzi, Catani, de Florian, Grazzini('03,'06,'08)].
- Resummation performed up to NNLL+NLO. This means the inclusion of:
  - NNLL logarithmic contributions to all orders;
  - NNLO corrections (i.e. $\mathcal{O}(\alpha_S^2)$) at small q_T;
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- NLO+PS generators (MC@NLO/POWHEG) reach LL (and part of the NLL) plus NLO (i.e. $\mathcal{O}(\alpha_S)$) accuracy.
- New version with few improvements of the HqT numerical code: http://theory.fi.infn.it/grazzini/codes.html [de Florian, G.F., Grazzini, Tommasini arXiv:1109.2109]
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Higgs q_T resummation at NNLL+NLO: HqT

- q_T-resummation formalism developed and applied for $gg \to H$ by [Catani,de Florian, Grazzini('01)], [Bozzi,Catani,de Florian,Grazzini('03,'06,'08)].
- Resummation performed up to NNLL+NLO. This means the inclusion of:
  - NNLL logarithmic contributions to all orders;
  - NNLO corrections (i.e. $\mathcal{O}(\alpha_S^2)$) at small q_T;
  - NLO corrections (i.e. $\mathcal{O}(\alpha_S^2)$) at large q_T;
  - NNLO result for the total cross section (upon integration over q_T).
- NLO+PS generators (MC@NLO/POWHEG) reach LL (and part of the NLL) plus NLO (i.e. $\mathcal{O}(\alpha_S)$) accuracy.
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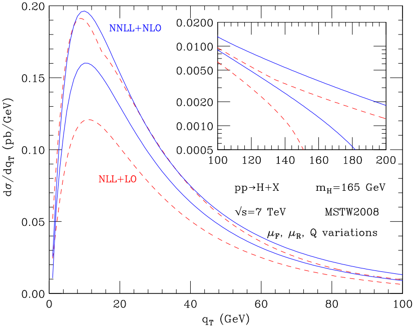
Resummed results: q_T spectrum of the Higgs boson at the LHC $\sqrt{s} = 7$ TeV



- The NNLL+NLO band obtained varying μ_R, μ_F, Q independently:
$$1/2 \le \{\mu_F/m_Z, \mu_R/m_Z, 2Q/m_Z, \mu_F/\mu_R, Q/\mu_R\} \le 2$$
to avoid large logarithmic contributions ($\sim \ln(\mu_F^2/\mu_R^2)$, $\ln(Q^2/\mu_R^2)$) in the evolution of the parton densities and in the the resummed form factor.
- Fractional difference with respect to the reference result: NNLL+NLO, $\mu_R = \mu_F = 2Q = m_Z$.
- NNLL+NLO scale dependence is $\pm 10\%$ at the peak, $\pm 8\%$ at $q_T = 30$ GeV and $\pm 10\%$ at $q_T = 50$ GeV. At large q_T the resummed result looses predictivity (anyway NLO and NNLL+NLO bands overlap).
- NNLO PDFs uncertainty (at 68% CL) on NNLL+NLO prediction.

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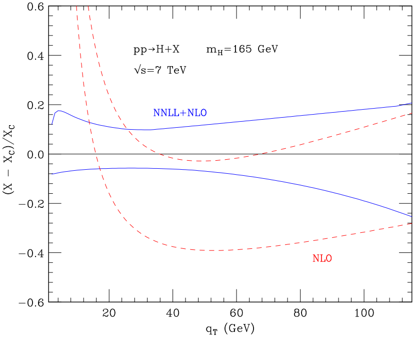

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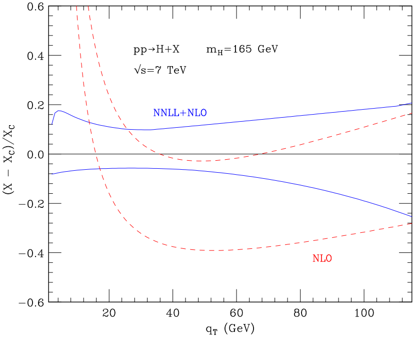

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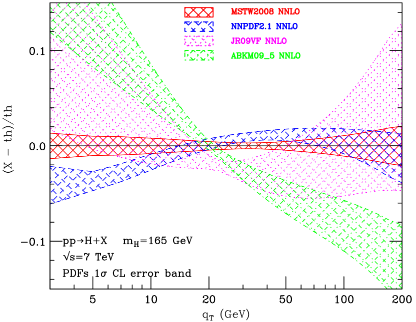

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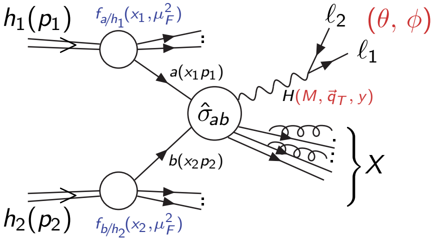
Higgs q_T-resummation with decay dependence: HRes

de Florian, G.F., Grazzini, Tommasini arXiv:1203.6321 D. Tommasini Ph.D. project('12)



- Experiments have finite acceptance: important to provide exclusive theoretical predictions.
- Analytic resummation formalism inclusive over soft-gluon emission: not possible to apply selection cuts on final state partons.

- Included the full dependence of Higgs decays: $H \to \gamma\gamma$, $H \to WW \to 2l2\nu$, $H \to ZZ \to 4l$, possible to apply cuts on Higgs boson and decay products variables.
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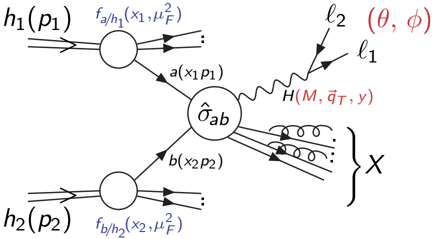

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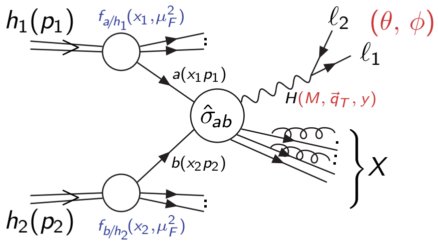

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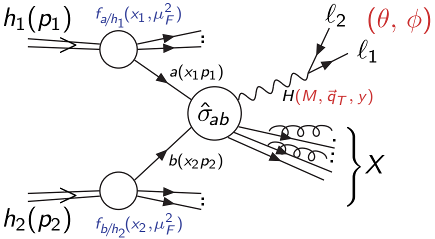

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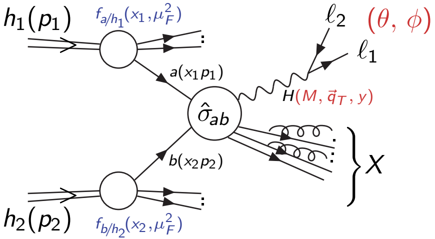

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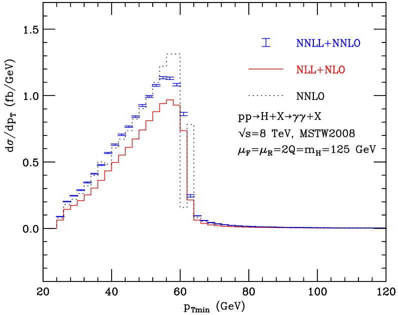
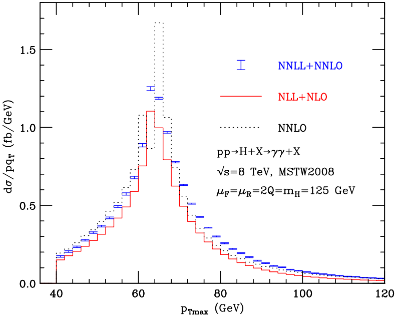
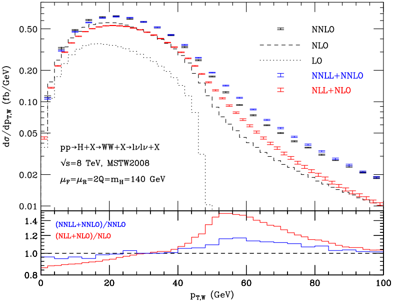


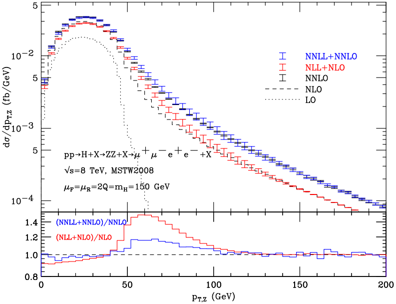


Distributions in p_{Tmin} and p_{Tmax} for the $H \to \gamma\gamma$ signal at the LHC, obtained by NNLO and resummed calculations.

CUTS: $|\eta| < 2.5$, $p_{Tmin} > 25$ GeV, $p_{Tmax} > 40$ GeV.

HRes: Higgs q_T-resummation with decay dependence





Average p_T spectrum of the W bosons for $pp \to H + X \to WW + X \to 2l2\nu + X$ (left) and Z bosons for $pp \to H + X \to ZZ + X \to \mu^+\mu^-e^+e^- + X$ (right) at the LHC obtained by NNLO and resummed calculations.

CUTS ($H \to WW$): $|\eta^l| < 2.5$, $p_T^l > 25$ GeV, $p_T^{miss} > 30$ GeV, $m_{ll} > 12$ GeV.

CUTS ($H \to ZZ$): $|\eta^l| < 2.5$, $p_T^l > 5$ GeV, $m_1 > 50$ GeV, $m_2 > 12$ GeV where m_1 (m_2) (next-to-) closest to m_Z lepton pair invariant mass).

Conclusions

- The most relevant Standard Model Higgs inclusive cross sections known with high precision through NNLO QCD.
- Calculations implemented in public available codes: ggh@nnlo, vh@nnlo, bbh@nnlo, higlu, ihixs, vbfnnlo.
- Threshold resummation effects are relevant.
- Important progress in NNLO fully-exclusive calculations. E.g.
  - Fully exclusive NNLO QCD calculation for associated W-Higgs production through q_T-subtraction method.
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