Precise Predictions for Higgs Hunting at LHC

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Contents

1. Review of SM Higgs theory & experiment

Particle Masses (GeV)

Up 0.003	Charm 1.3	Top 175	Photon 0
Down 0.006	Strange 0.1	Bottom 4.3	Gluon 0
ν_e $<1 \times 10^{-8}$	ν_μ <0.0002	ν_τ <0.02	Z 91.187
Electron 0.000511	Muon 0.106	Tau 1.7771	$W^\pm$ 80.4

Questions

Why is there such a large range of quark masses ?

Why is there such a large range of lepton masses ?

Why are the neutrino masses so small ?

Why do the W and Z have mass, but the photon and the gluon do not ?

Electroweak Force Unification and the Higgs Mechanism

1961 – 1968 Glashow, Weinberg and Salam (GWS) developed a theory that unifies the electromagnetic and weak forces into one electroweak force.

Electromagnetic Force – mediator: photon (mass = 0) interact with charged particles

Weak Force – mediators: W^+,W^-, Z^0 (mass ~ 80-90 GeV/c^2) interact with quarks and leptons

SM EW Theory

The theory begins with four massless mediators for the electroweak force: $W_\mu^{1,2,3}$ and B_μ.

$$W_\mu^{1,2,3}, B_\mu \xrightarrow[\text{SSB}]{} W^+, W^-, Z^0, \gamma$$

This transformation is the result of spontaneous symmetry breaking. In the case of the electroweak force, it is known as the Higgs Mechanism.

Higgs Field and Higgs Boson

The neutral Higgs field permeates space and all particles acquire mass via their interactions with this field.

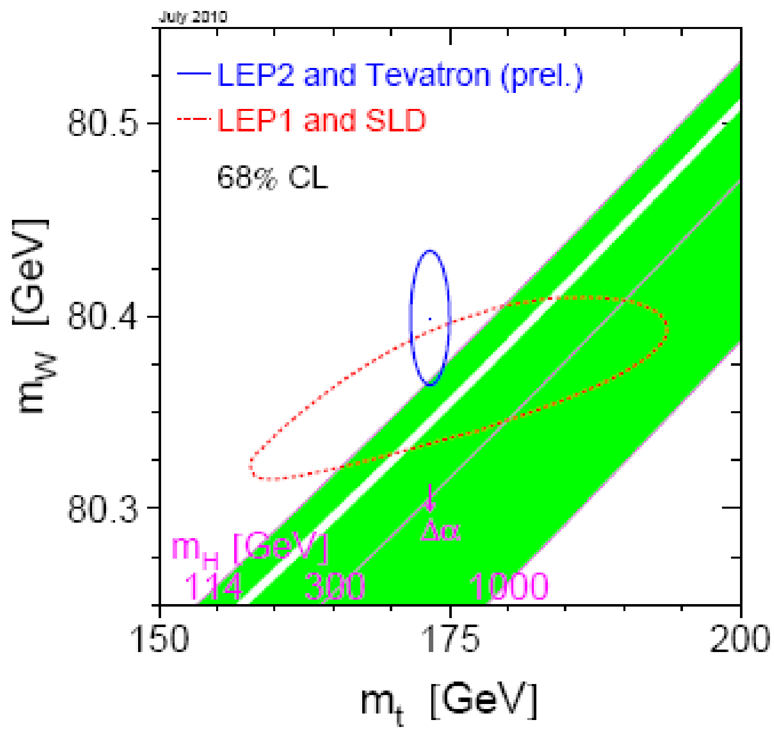
Higgs Boson

- charge (neutral), color (none),
- spin (= 0), coupling to (gauge, Yukawa), total width
- mass (~ 100GeV), CP (even, odd, mixture?)

Theoretical arguments (or prejudices) suggest $50\,\mathrm{GeV} \lesssim m_H \lesssim 800\,\mathrm{GeV}$

(with new physics at the TeV scale)

SM Higgs-boson mass range (from EW precision fits)



$$m_W = 80.399 \pm 0.023 \text{ GeV}$$

$$m_t = 173.3 \pm 1.1 \text{ GeV}$$

$$\Downarrow$$

$$M_H = 89^{+35}_{-26} \text{ GeV}$$

$$M_H < 158\,(185) \text{ GeV}$$

plus exclusion limits (95% c.l.):

$$M_H > 114.4 \text{ GeV (LEP)}$$

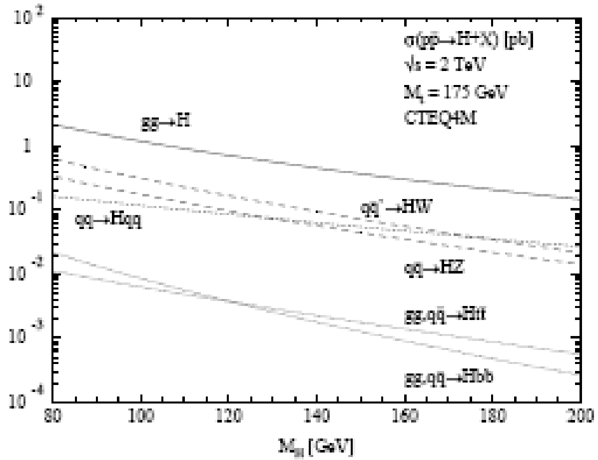
$$M_H \neq 158 - 173 \text{ GeV (Tevatron)}$$

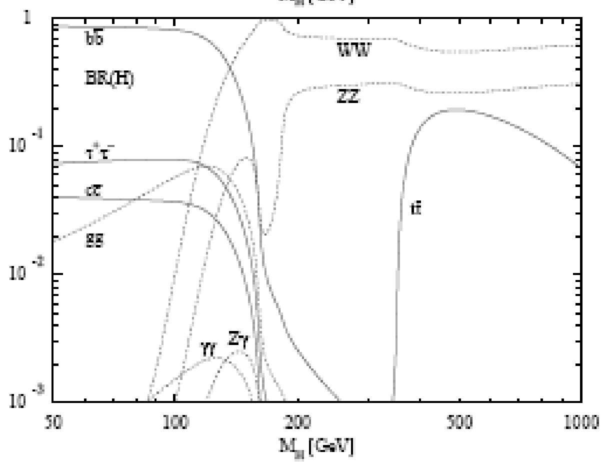
Radiative corrections are sensitive to the mass of virtual particles!

EW data prefer a light Higgs, 114.4GeV < M_H < 185 GeV, at 95% CL !

Tevatron Run II

Large potential for a light SM Higgs boson.





(M. Spira, Fortsch.Phys. 46 (1998) 203)

Lower mass region:

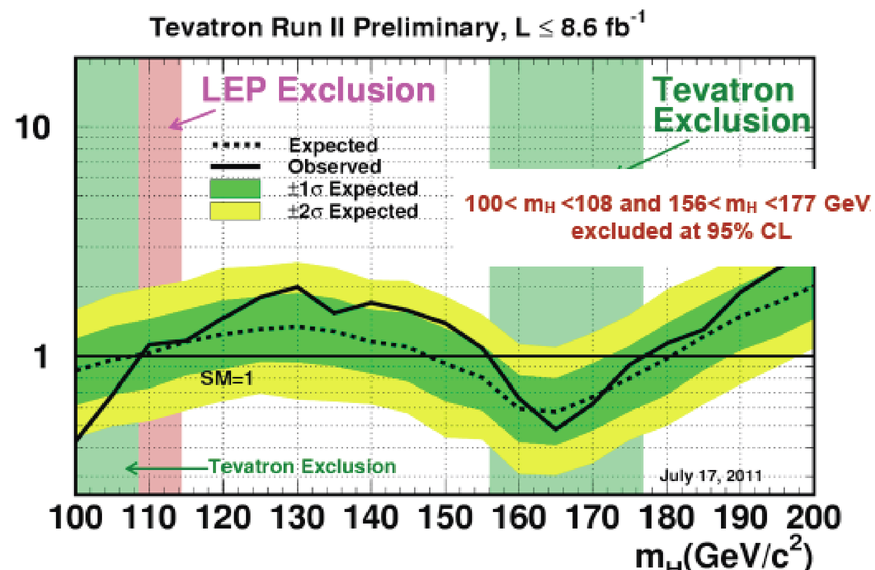
$$q\bar{q}' \to WH, H \to b\bar{b}$$

Higher mass region:

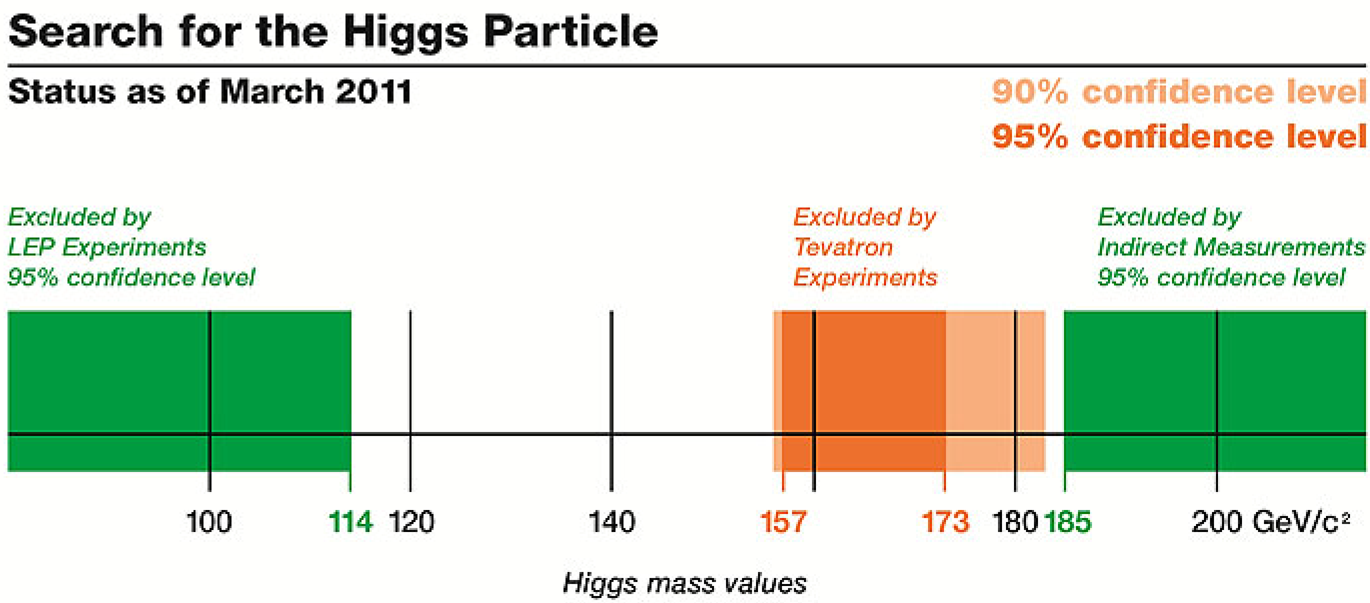
$$gg \to H, H \to W^+W^-$$

(smaller impact:

$q\bar{q} \to q'\bar{q}'H,\ q\bar{q}, gg \to t\bar{t}H$)



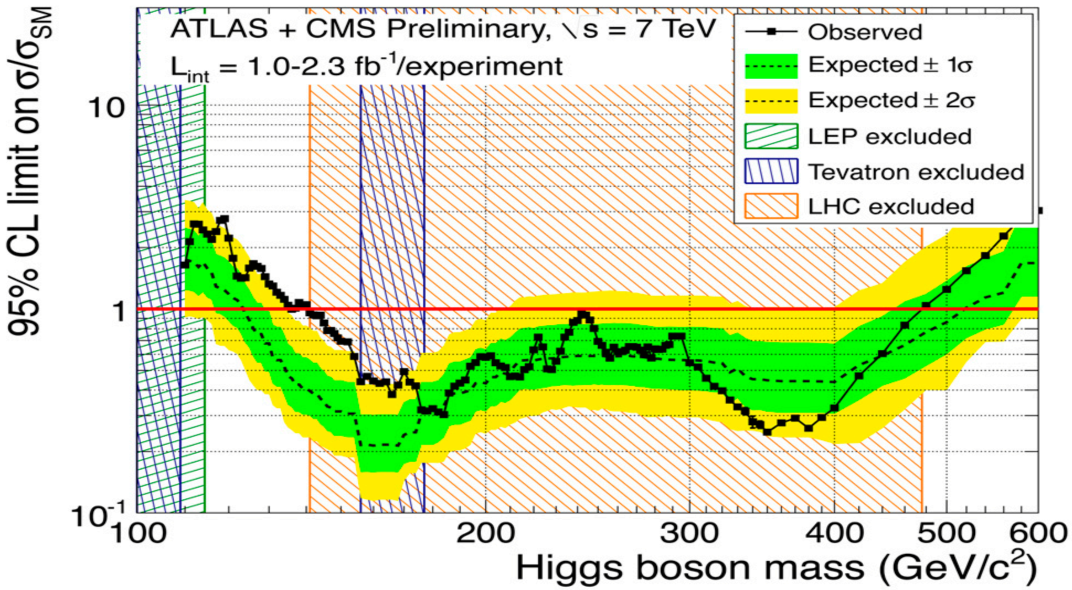
Exclusion region very important for LHC search strategies !



Improved analysis techniques and more data have made the Tevatron experiments more sensitive to the Higgs boson. **CDF and D0 exclude a significant portion of the high-Higgs-mass range.**

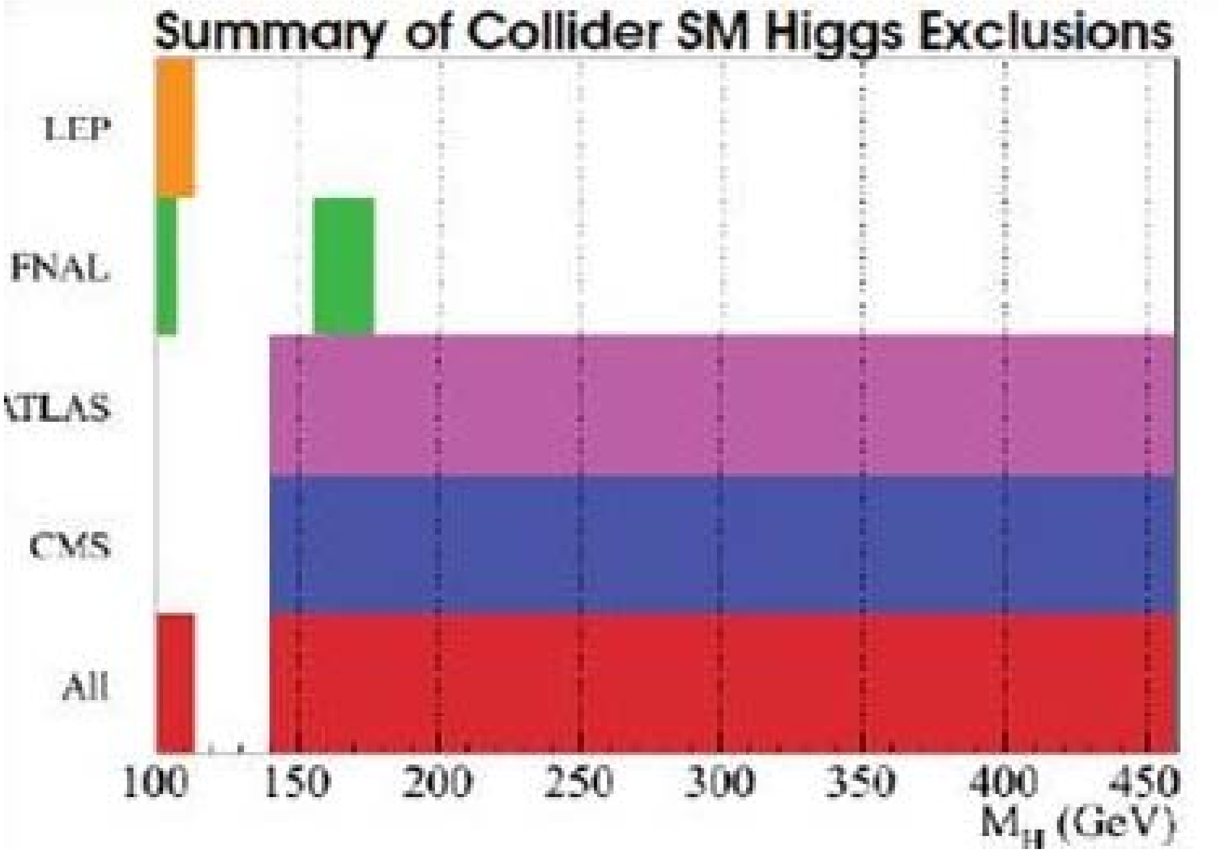
LHC (ATLAS, CMS)

NEW: **November 18, 2011**



ATLAS and CMS analyse the data samples of up to 2.3 (1/fb), combined results: exclusion SM Higgs mass range of 141-476 GeV at 95% CL, or 146-443 GeV at 99% CL .

SM Higgs exclusion in summary



M_H < 114 -140 GeV → most difficult !

Need precise theoretical understanding of both signal and background !

What we learn from Higgs finding?

- If H^0 exist as the SM expected, it will validate the GWS Electroweak Theory and complete the SM model.

- Measurements of the Higgs couplings and comparison with particle masses will verify mass-generating mechanism.

- If $m_H < 130$ GeV, it could support a theory beyond the SM, known as SUSY.

- If a Higgs boson with $m_H < 1$ TeV is not found, it would indicate that the Electroweak symmetry must be broken by a means other than the Higgs mechanism.

2. Precise Predictions for Higgs hunting

Why we need precision Higgs physics @ LHC ?

The Higgs physics potential @ LHC depends on <u>very accurate</u> <u>QCD predictions</u> (including EW corrections):

$-\!\!\longrightarrow$ precise prediction of both SM Higgs signals & backgrounds;

$-\!\!\longrightarrow$ precise input parameters, $\boldsymbol{\alpha_s}$ uncertainty…;

$\alpha_s(M_Z)$ from $0.1176(20) \rightarrow 0.1184(7)$, (2006-2010);

$-\!\!\longrightarrow$ luminosity monitors, PDF errors for LHC analyses...

the predicted event number for gg->H

$N = \mathscr{L}\ \sigma \sim \mathscr{L}\ \alpha_s{}^3 \times f_{g/p}{}^2 \Rightarrow$ **very sensitive to $\boldsymbol{\alpha_s}$, $\mathscr{L}$ and PDFs!**

$-\!\!\longrightarrow$ poorly convergent perturbative corrections (: $gg \rightarrow H$);

especially for QCD, theoretical uncertainty of **μ_f and μ_r** …

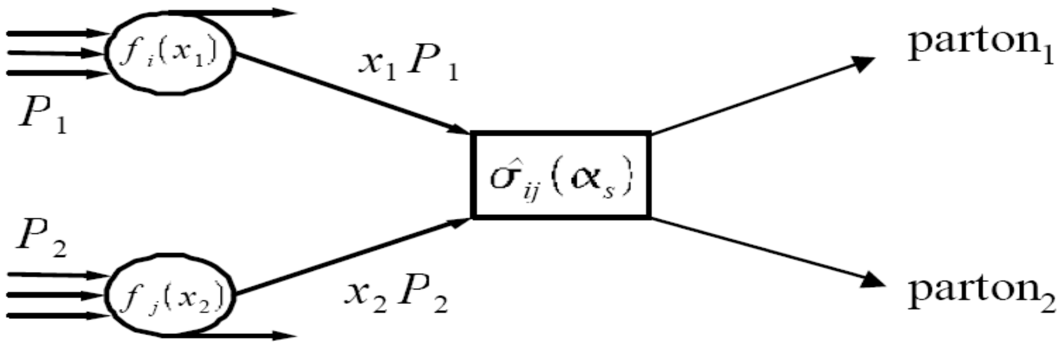
$-\!\!\longrightarrow$ several massive particle productions (ex.: Htt/Hbb, W/Zbb, ttbb, . . .);

numerical calculation errors in loop integrals,

$-\!\!\longrightarrow$ high multiple final states and subchannels (ex.: VVV , V + 3j, ttbb , . . .).

statistic errors in multi-final state phase space integration

The framework: QCD factorization theorem



$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}_{ij}\left(\alpha_s^m(\mu_R^2), x_1 P_1, x_2 P_2, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

Sum over initial states

Parton Distributions

Factorization Scale

Point Cross Section

Order α_s^m

Renormalization Scale

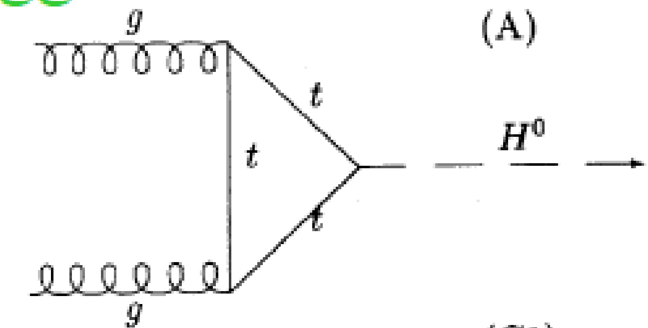
Precise predictions for production rate depend on good knowledge of '<u>strong coupling constant</u>', '<u>PDFs</u>' and 'partonic cross section' !!

nonperturbative quantities

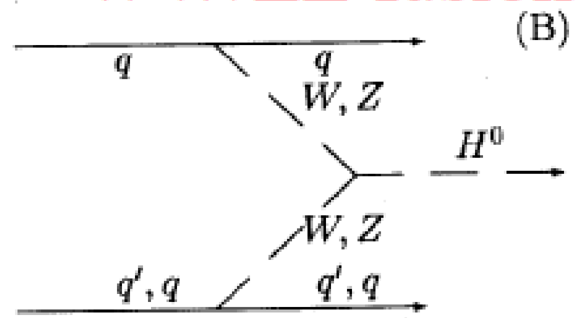
perturbative evaluation !

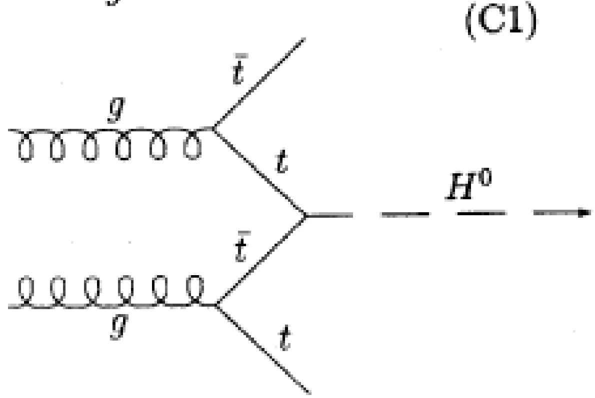
SM Higgs Production

gg fusion

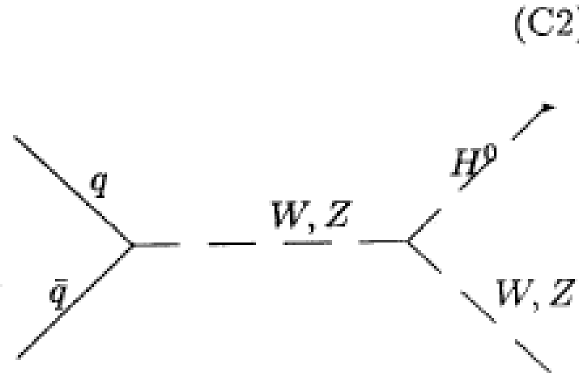


WW/ZZ fusion





associated $t\bar{t}H$



associated WH, ZH

(1) g-g fusion

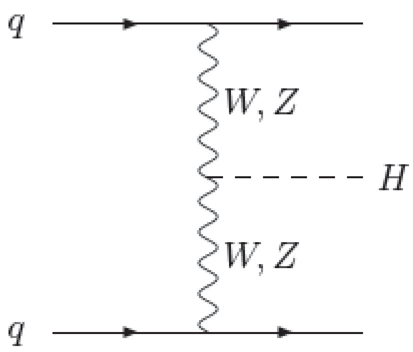
- QCD corrections
  - complete NLO: $80-100\%$
    Graudenz, Spira, Zerwas '93
    Djouadi, Graudenz, Spira, Zerwas '95
  - NNLO: 25%
    as expansion for $m_t \to \infty$
    matched with $\hat{s} \to \infty$
    Harlander, Kilgore '01,'02
    Catani, de Florian, Grazzini '01
    Anastasiou, Melnikov '02
    Ravindran, Smith, van Neerven '03, '04
    Anastasiou, Melnikov, Petriello '04
    Marzani et al. '08
    Harlander, Ozeren '09
    Pak, Rogal, Steinhauser '09

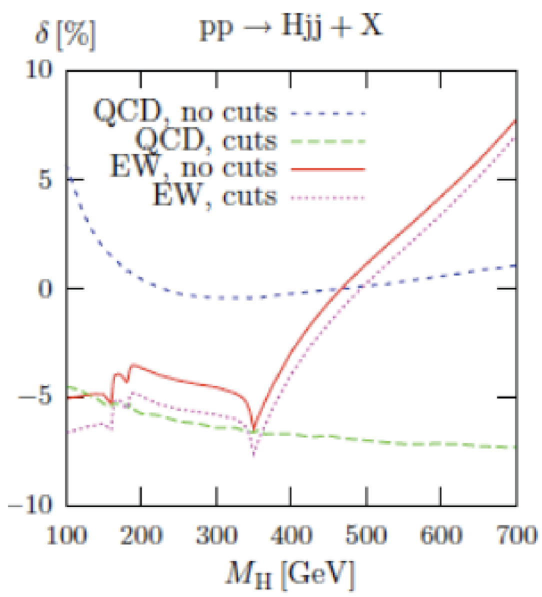
$$K = \frac{\sigma_{\mathrm{NNLO}}}{\sigma_{\mathrm{LO}}} \sim 2.0$$

  - resummation of soft-gluon contribution to NNLL: $6-9\%$
    leading soft contribution to NNNLO in limit $m_t \to \infty$
    Catani et al. '03, Moch, Vogt '05
    Laenen, Magnea '05; Idilbi et al. '05
    Ravindran '05,'06;
    Ravindran, Smith, van Neerven '06
    Ahrens et al. '08
- EW corrections
  - complete NLO $\sim \mathcal{O}(5\%)$
    Aglietti, Bonciani, Degrassi, Vicini '04, '06;
    Degrassi, Maltoni '04
    Actis, Passarino, Sturm, Uccirati '08
  - $\mathcal{O}(\alpha\alpha_s)$ corrections for $M_H \ll M_W$
    Anastasiou, Boughezal, Petriello '08
  - NLO for $\mathrm{H} + \mathrm{jet}$: $\lesssim 1\%$
    Keung, Petriello '09; Brein '10

(2) Vector boson fusion

VBF is very important in the Higgs-boson search @ LHC. The cross section is almost one order smaller than for gg fusion , but this channel is very attractive both for discovery and for precision measurements of the VVH couplings.





- QCD corrections increase the LO cross section by +5-10% .

T. Han, S. Willenbrock (1991)

- Evaluated for distributions @ NLO

T. Figy, C. Oleari, D. Zeppenfeld (2003)
J. Campbell, K. Ellis (2003)

- EW+QCD corrections have also been evaluated

M.Ciccolini, A.Denner, S.Dittmaier (2007)

- NNLO contributions computed within the structure function approach, the scale uncertainty reduced to the 1-2% level.

P.Bolzoni, F.Maltoni, S.Moch, M. Zaro (2010)

(2) <u>Vector boson fusion</u> (continue)

- Higgs boson production via VBF is the mechanism with the second largest rate in the SM and a clean experimental signature.

- In BSM, VBF can become the leading production mechanism.

• Factorizable contributions in QCD. It provides the bulk of all QCD corrections up to order α_s^2 to a precision better than 1%.

• Non-factorizable contributions in QCD. This class starts at order $\alpha_s^2\ /N^2_c$. It is estimated to contribute less than 1% to the total VBF cross section.

• Electroweak corrections to diagrams. A combination with the NNLO QCD ones to Higgs production via VBF has been reported.

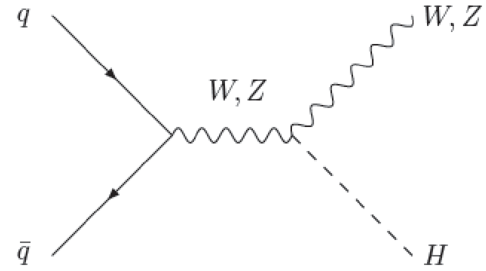
Paolo Bolzonia, (2011)

(3) WH/ZH production

- Most important channel for low mass Higgs @ LHC.

- Final lepton(s) provide the necessary background rejection.

- Probing information on the HWW and HZZ couplings.



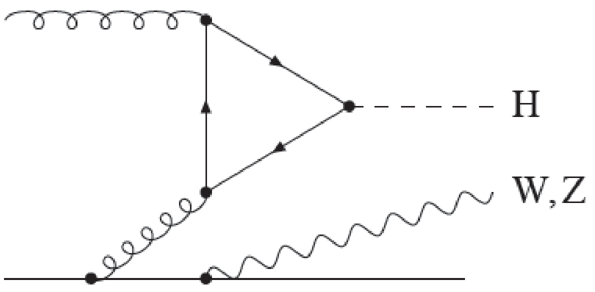
1. NLO QCD corrections can be obtained from those to Drell-Yan: +30%.
   T. Han, S. Willenbrock (1990)

2. Full EW corrections to cross section by -5 to -10%.
   M.L. Ciccolini, S. Dittmaier, M. Kramer (2003)

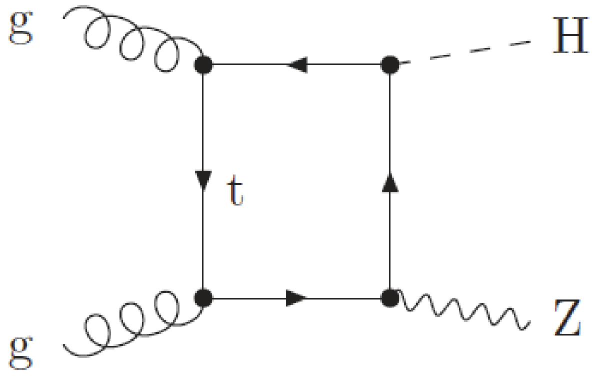
3. NNLO QCD corrections are essentially given by those of Drell-Yan.
   W. Van Neerven e al. (1991)

(3) WH/ZH production (continue)

There are additional diagrams where the Higgs is produced through a heavy quark loop.
These diagrams are expected to give a small contributions. *W. Van Neerven et al. (1991)*



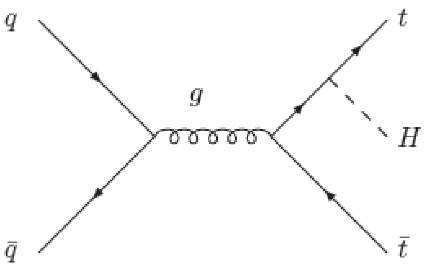
For ZH at NNLO additional diagrams from gg initial state must be considered: important at the LHC (+2-6 % effect).
O. Brein, R. Harlander, A. Djouadi (2000)

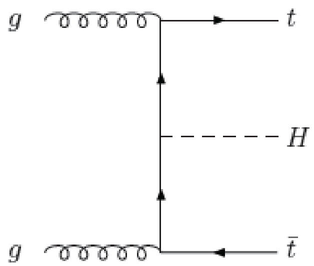


scale uncertainty up to NNLO reduced to the 2% level

(4) $t\bar{t}H$ production

It is related with measuring $t\bar{t}H$ Yukawa coupling.





LO calculation

Z. Kunszt (1984)

It was considered as an important discovery channel in low mass region: H -> $b\bar{b}$, trigging on the leptonic decay of one of the top. It requires good b-tagging efficiency .

NLO corrections increase the cross section by about 20 %.

W.Beenakker, S. Dittmaier, B.Plumper, M. Spira, P. Zerwas (2002)
S. Dawson, L. Reina (2003))

Why higher order?

• **Stability and predictivity of theoretical results**, less sensitivity to

μ_f and μ_r scales.

• **When higher order corrections are large.** (test the convergence of the perturbative expansion) This may happen when:

→ processes involve **multiple scales**, leading to large logarithms of the ratio(s) of scales;
→ **new parton level subprocesses** first appear at next higher order;
→ **new dynamics** first appear at NLO;
→ . . .

• **When a really reliable error estimate is needed.**

Calculation challenges :

- **Multiplicity and Massiveness of final state**: complex events leads to complex calculations. For a $2 \to N$ process one needs:

$-\!\!\to$ calculation of the $2 \to N+1$ (NLO) or $2 \to N+2$ (NNLO) real corrections;

$-\!\!\to$ calculation of the 1-loop (NLO) or 2-loop (NNLO) $2 \to N$ virtual corrections.

- **Flexibility of NLO/NNLO calculation programs**:

$-\!\!\to$ general efficient algorithms suitable for automation;

$-\!\!\to$ easily satisfy experimental requirements .

- **Good precision control of theoretical predictions**:

$-\!\!\to$ theoretical uncertainty, numerical stability….

State of the QCD calculation at hadron colliders

Relative order	$2 \to 1$	$2 \to 2$	$2 \to 3$	$2 \to 4$	$2 \to 5$	$2 \to 6$
1	LO					
α_s	NLO	LO				
α_s^2	NNLO	NLO	LO			
α_s^3		NNLO	NLO	LO		
α_s^4			NNLO	NLO	LO	
α_s^5				NNLO	NLO	LO

(from N. Glover)

Green light $\longrightarrow$ Done

Red light $\longrightarrow$ Still work in progress

NLO: $V + b\bar{b}/t\bar{t}$, $VV + j$, VVV, $H + 2j$, $t\bar{t} + j$, $V + 3j$, $t\bar{t}b\bar{b}$, ...

NNLO: $q\bar{q}, gg \to Q\bar{Q}$ (Czakon, Mitov, Moch: analytical for $m_Q^2 \ll s$, exact numerical estimate (06-08)), $q\bar{q} \to W^+W^-$ (Chachamis,Czakon:at $O(m_W^2/s)$ (08))
(plus: NNLO splitting functions (Moch,Vermaseren,Vogt (04))).

Higgs process	$\sigma_{NLO,NNLO}$ (QCD only)
$gg \to H$	S.Dawson, NPB 359 (1991), A.Djouadi, M.Spira, P.Zerwas, PLB 264 (1991) C.J.Glosser *et al.*, JHEP (2002); V.Ravindran *et al.*, NPB 634 (2002) D. de Florian *et al.*, PRL 82 (1999) R.Harlander, W.Kilgore, PRL 88 (2002) (NNLO) C.Anastasiou, K.Melnikov, NPB 646 (2002) (NNLO) V.Ravindran *et al.*, NPB 665 (2003) (NNLO) S.Catani *et al.* JHEP 0307 (2003) (NNLL) G.Bozzi *et al.*, PLB 564 (2003), NPB 737 (2006) (NNLL) C.Anastasiou, R.Boughezal, F.Petriello, JHEP (2008) (QCD+EW)
$q\bar{q} \to (W,Z)H$	T.Han, S.Willenbrock, PLB 273 (1991) O.Brien, A.Djouadi, R.Harlander, PLB 579 (2004) (NNLO)
$q\bar{q} \to q\bar{q}H$	T.Han, G.Valencia, S.Willenbrock, PRL 69 (1992) T.Figy, C.Oleari, D.Zeppenfeld, PRD 68 (2003)
$q\bar{q}, gg \to t\bar{t}H$	W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003) S.Dawson *et al.*, PRL 87 (2001), PRD 65 (2002), PRD 67,68 (2003)
$q\bar{q}, gg \to b\bar{b}H$	S.Dittmaier, M.Krämer, M.Spira, PRD 70 (2004) S.Dawson *et al.*, PRD 69 (2004), PRL 94 (2005)
$gb(\bar{b}) \to b(\bar{b})H$	J.Campbell *et al.*, PRD 67 (2003)
$b\bar{b} \to (b\bar{b})H$	D.A.Dicus *et al.* PRD 59 (1999); C.Balasz *et al.*, PRD 60 (1999). R.Harlander, W.Kilgore, PRD 68 (2003) (NNLO)

NLO: Recently completed calculations (since Les Houches 2005): all relevant to Higgs-boson physics!

Process ($V \in \{Z, W, \gamma\}$)	Calculated by
$pp \to V$+2 jets(b)	Campbell,Ellis,Maltoni,Willenbrock (06)
$pp \to Vb\bar{b}$	Febres Cordero,Reina,Wackeroth (07-08)
$pp \to VV$+jet	Dittmaier,Kallweit,Uwer (WW+jet) (07)
	Campbell,Ellis,Zanderighi (WW+jet+decay) (07)
	Binoth,Karg,Kauer,Sanguinetti (09)
$pp \to VV$+2 jets	Bozzi,Jäger,Oleari,Zeppenfeld (via WBF) (06-07)
$pp \to VVV$	Lazopoulos,Melnikov,Petriello (ZZZ) (07)
	Binoth,Ossola,Papadopoulos,Pittau (WWZ,WZZ,WWW) (08)
	Hankele,Zeppenfeld ($WWZ \to 6$ leptons, full spin correlation) (07)
$pp \to H$+2 jets	Campbell,Ellis,Zanderighi (NLO QCD to gg channel)(06)
	Ciccolini,Denner,Dittmaier (NLO QCD+EW to WBF channel) (07)
$pp \to H$+3 jets	Figy,Hankele,Zeppenfeld (large N_c) (07)
$pp \to t\bar{t}$+jet	Dittmaier,Uwer,Weinzierl (07), Ellis,Giele,Kunszt (08)
$pp \to t\bar{t}Z$	Lazopoulos,Melnikov,Petriello (08)
$gg \to WW$	Binoth,Ciccolini,Kauer,Kramer (06)
$gg \to HH, HHH$	Binoth,Karg,Kauer,Rückl (06)
$pp \to t\bar{t}b\bar{b}$	Bredenstein et al., Bevilacqua et al. (09)
$pp \to V$+3jets	Berger et al., Ellis et al. (09)

3. NNLO calculation

What we meet in NNLO calculation ?

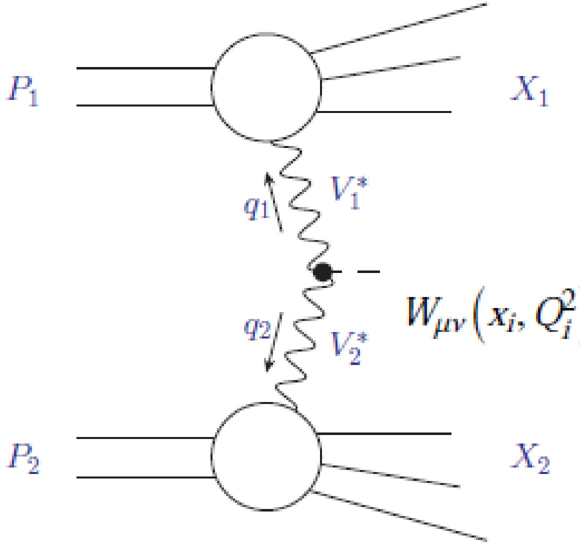
- At NNLO we find problems, such as, complex matrix element and integration over multiparton PS *et al*.
- The IR manipulation in NNLO computation as in NLO.
- The problem in numerical calculation:
  Although IRs up to NNLO cancel between real and virtual contributions, they prevent a straightforward implementation of numerical techniques.
- The results at NNLO are very stable with respect the μ_f and μ_r scales.

a. NNLO (VBF)

Structure function approach

→ double deep-inelastic scattering (DIS)

T. Han, (1992)



This approximation builds on the absence (or smallness) of the QCD interference between the two inclusive X_1 and X_2.

DIS hadronic tensor $W_{\mu\nu}$

$$W_{\mu\nu}(x_i, Q_i^2) = \left(-g_{\mu\nu} + \frac{q_{i,\mu} q_{i,\nu}}{q_i^2}\right) F_1(x_i, Q_i^2) + \frac{\hat{P}_{i,\mu}\hat{P}_{i,\nu}}{P_i \cdot q_i} F_2(x_i, Q_i^2) + i\epsilon_{\mu\nu\alpha\beta} \frac{P_i^\alpha q_i^\beta}{2P_i \cdot q_i} F_3(x_i, Q_i^2)$$

Where $Q_i^2 = -q_i^2$, $x_i = Q_i^2/(2P_i \cdot q_i)$ $\quad s_i = (P_i + q_i)^2$ $\quad \hat{P}_{i,\mu} = P_{i,\mu} - \frac{P_i \cdot q_i}{q_i^2} q_{i,\mu}$.

Apart from these interference effects, the factorization in above equation is still exact at LO and NLO.

$$d\sigma = \frac{1}{2S} 2G_F^2 M_{V_1}^2 M_{V_2}^2 \frac{1}{\left(Q_1^2 + M_{V_1}^2\right)^2} \frac{1}{\left(Q_2^2 + M_{V_2}^2\right)^2} W_{\mu\nu}\left(x_1, Q_1^2\right) \mathcal{M}^{\mu\rho} \mathcal{M}^{*\nu\sigma} W_{\rho\sigma}\left(x_2, Q_2^2\right) \times$$
$$\times \frac{d^3 P_{X_1}}{(2\pi)^3 2E_{X_1}} \frac{d^3 P_{X_2}}{(2\pi)^3 2E_{X_2}} ds_1 ds_2 \frac{d^3 P_H}{(2\pi)^3 2E_H} (2\pi)^4 \delta^4 (P_1 + P_2 - P_{X_1} - P_{X_2} - P_H) .$$

Then we can get the NNLO QCD predictions with explicit expressions for the ***DIS structure functions*** ***F_i^V (i=1,2,3, V=Z,W)*** for Higgs production in VBF.

But the factorization is not exact at NNLO and the we need to add the ***non-factorizable corrections***.

P. Bolzoni , (2010), C. Csaki, (2004)

b. Hadronic VH^0 +jet at NLO QCD

- crucial background for **VH^0** production ($V=W,Z^0$)
- important part of the **NNLO QCD** correction for **VH^0** production

(1) WH^0 + jet production at LHC

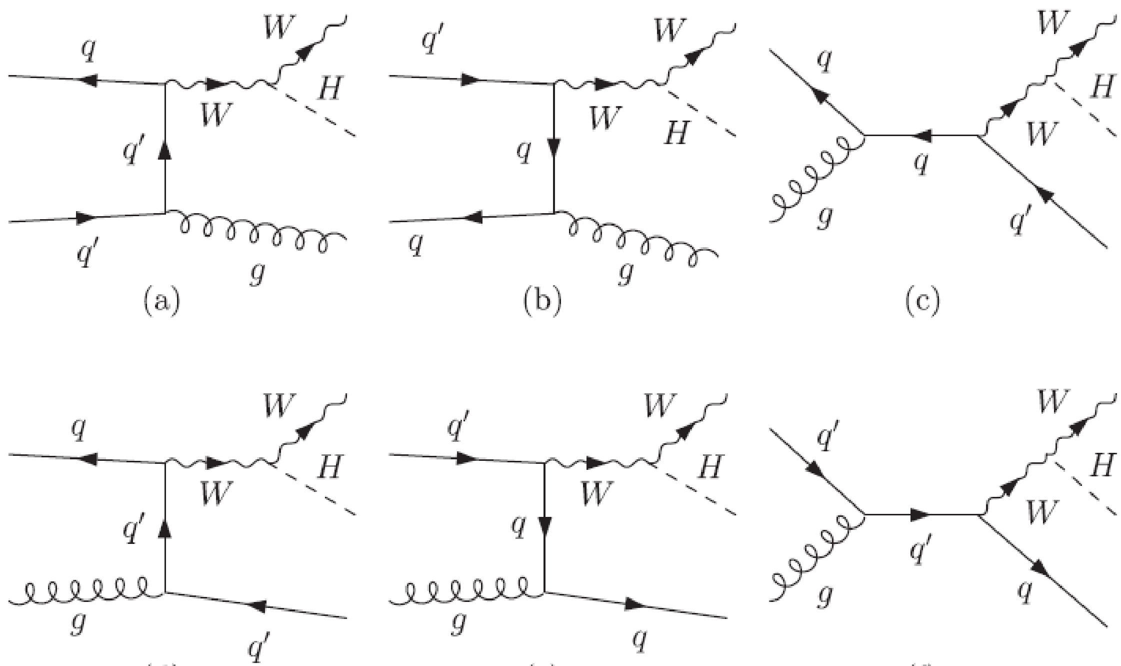
J.J.Su, et al, (2010)

The LO partonic processes for the WH^0+jet production process:

$$\bar{q}(p_1) + q'(p_2) \to W^-(p_3) + H^0(p_4) + g(p_5),$$

$$\bar{q}(p_1) + g(p_2) \to W^-(p_3) + H^0(p_4) + \bar{q}'(p_5),$$

$$q'(p_1) + g(p_2) \to W^-(p_3) + H^0(p_4) + q(p_5),$$



(a) (b) (c)

(d) (e) (f)

Real emission partonic processes:

$$(1)\ gg \to W^- H^0 \bar{q}' q, \qquad (4)\ gq' \to W^- H^0 gq,$$

$$(2)\ \bar{q}q' \to W^- H^0 gg, \qquad (5)\ \bar{q}q' \to W^- H^0 q'' \bar{q}'',$$

$$(3)\ g\bar{q} \to W^- H^0 g\bar{q}', \qquad (6)\ \bar{q}\bar{q}'' \to W^- H^0 \bar{q}' \bar{q}'',$$

$$(6)\ \bar{q}\bar{q}'' \to W^- H^0 \bar{q}'\bar{q}'',$$

$$(7)\ q''\bar{q} \to W^- H^0 \bar{q}' q'',$$

$$(8)\ q''\bar{q}'' \to W^- H^0 q\bar{q}',$$

$$(9)\ q'\bar{q}'' \to W^- H^0 q\bar{q}'',$$

$$(10)\ q'q'' \to W^- H^0 qq''.$$

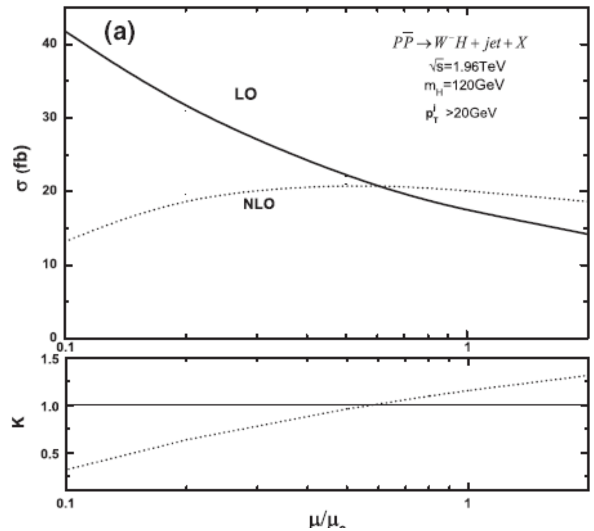
5FNS, $\mu_r = \mu_f = \mu_0 \equiv \frac{1}{2}(m_W + m_H)$ and $m_H = 120$ GeV

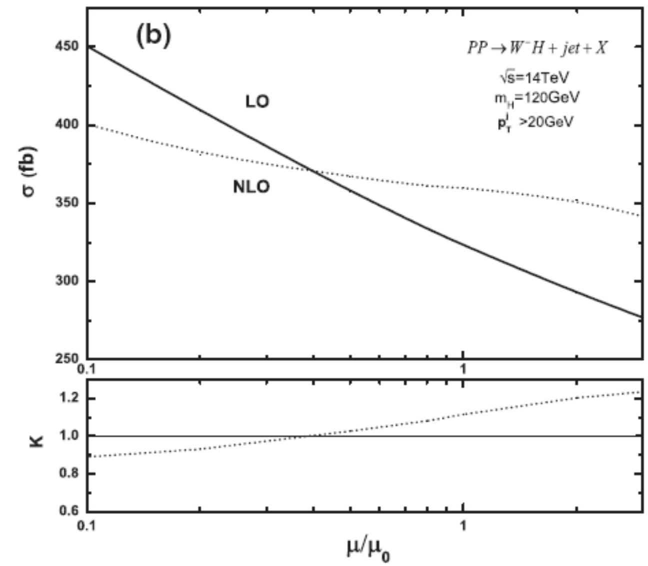
$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.97418 & 0.22577 & 0 \\ -0.22577 & 0.97418 & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

Jet algorithm: $R = 1 \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$

inclusive scheme:(I) we demand $p_T^j > p_{T,j}^{\rm cut}$ for the one-jet events, and for the two-jet events we apply the constraint of $p_T^j > p_{T,j}^{\rm cut}$ on the leading jet but not on the second jet, where the leading jet and the second jet are characterized by E_T(the leading jet) $> E_T$(the second jet).

<u>exclusive scheme: (II)</u> the event with the second jet $p_T^{\text{second jet}} > p_{T,j}^{cut}$ is rejected .





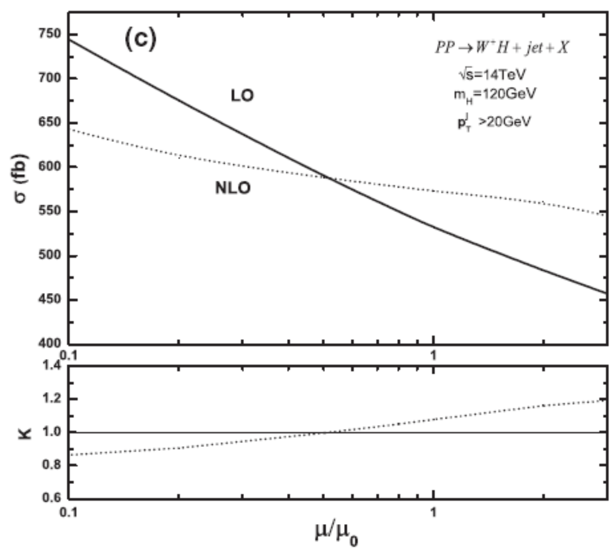


FIG. 4. The LO, NLO corrected cross sections and the corresponding K-factor ($K(\mu) \equiv \sigma_{\rm NLO}(\mu)/\sigma_{\rm LO}(\mu)$) versus the factorization/renormalization scale ($\mu = \mu_r = \mu_f$) by applying the inclusive scheme with $p_{T,j}^{\rm cut} = 20$ GeV. (a) for $p\bar{p}/pp \to W^- H^0 j + X$ at the Tevatron, (b) for $pp \to W^- H^0 j + X$ at the LHC, (c) for $pp \to W^+ H^0 j + X$ at the LHC.

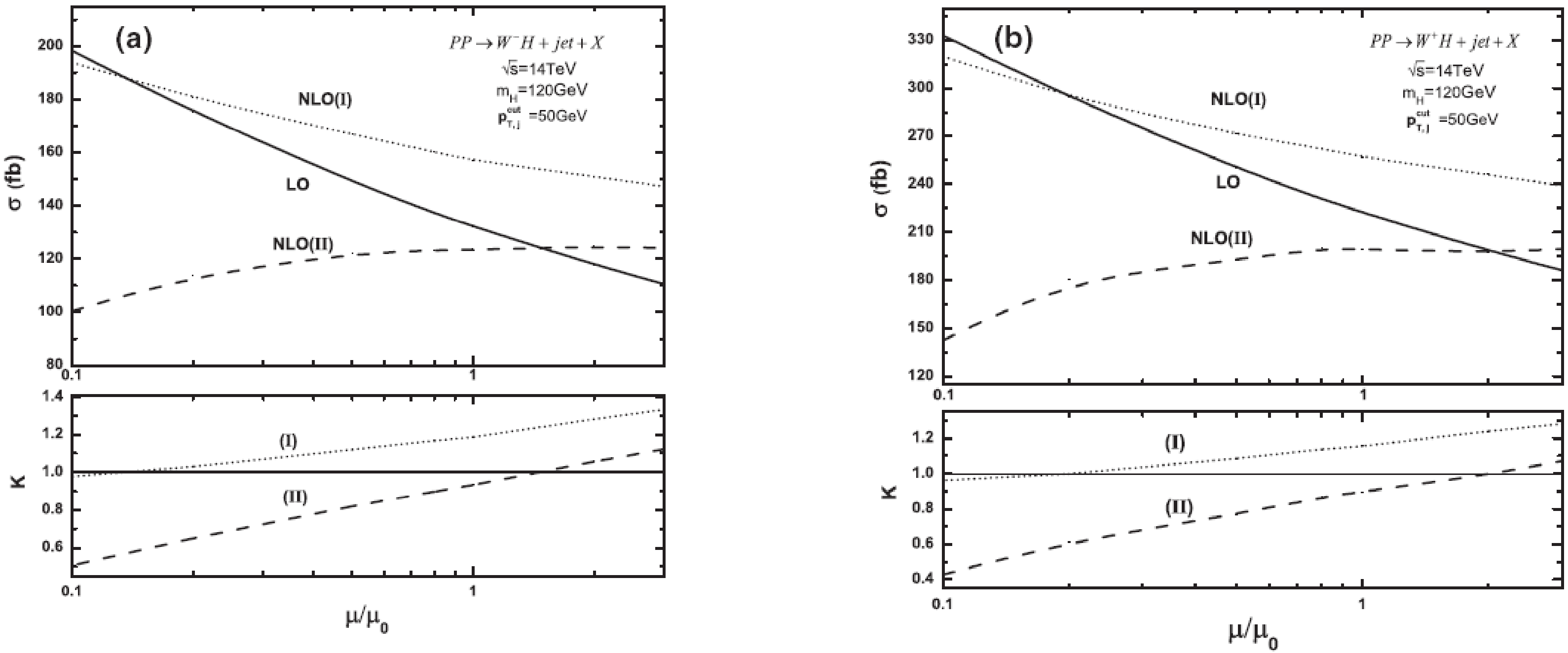
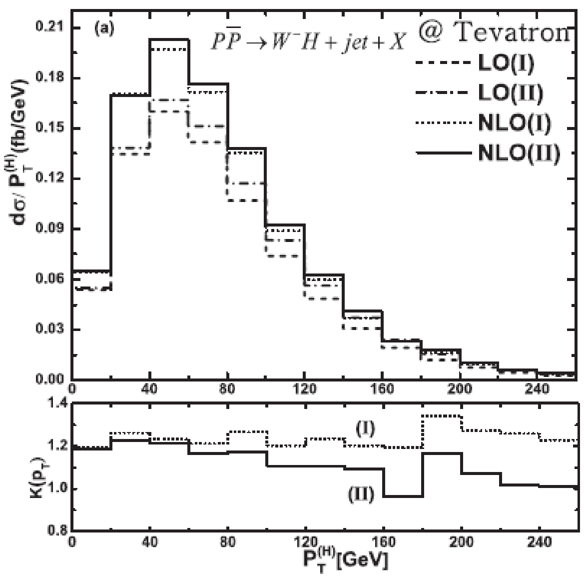
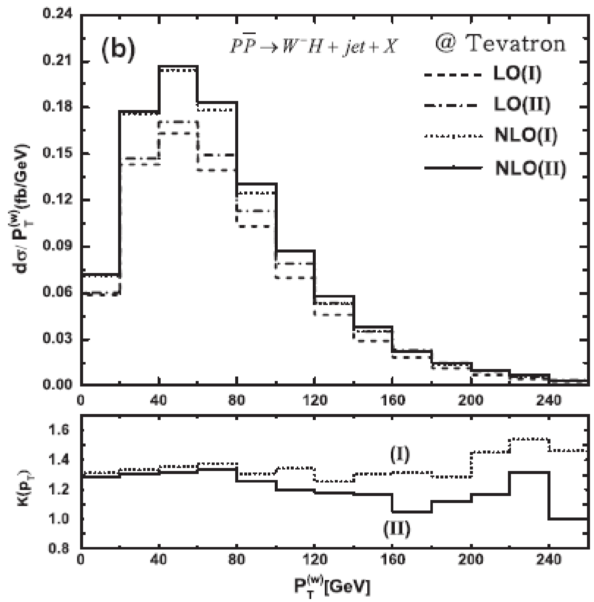


FIG. 5. The LO, NLO corrected cross sections and the corresponding K-factor ($K(\mu) \equiv \sigma_{\mathrm{NLO}}(\mu)/\sigma_{\mathrm{LO}}(\mu)$) at the LHC by taking $p_{T,j}^{\mathrm{cut}} = 50$ GeV and adopting separately (I) the inclusive scheme and (II) exclusive scheme. (a) for $pp \to W^- H^0 j + X$, (b) for $pp \to W^+ H^0 j + X$.

TABLE I. The numerical results for the LO, NLO QCD corrected cross sections and their corresponding K-factors ($K(\mu) \equiv \sigma_{\rm NLO}(\mu)/\sigma_{\rm LO}(\mu)$) by applying the inclusive scheme with $p_{T,j}^{\rm cut} = 20$ GeV, and taking $m_H = 120$ GeV and different values of scale μ for the process $p\bar{p} \to W^-H^0j + X$ at the Tevatron Run II, the processes $pp \to W^-H^0j + X$ and $pp \to W^+H^0j + X$ at the LHC. In this table we denote $\mu_0 = \frac{1}{2}(m_W + m_H)$, $\mu_1 = \sqrt{\frac{1}{2}[(p_T^W)^2 + (p_T^H)^2 + m_W^2 + m_H^2]}$ and $\mu_2 = \sqrt{(p_T^W)^2 + (p_T^H)^2 + m_W^2 + m_H^2}$.

Process	μ (GeV)	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	K
	$0.5\mu_0$	21.949(3)	21.01(2)	0.96
$p\bar{p} \to W^-H^0j + X$	μ_0	17.440(2)	20.08(2)	1.15
	$2\mu_0$	14.167(2)	18.61(1)	1.31
$\sqrt{s} = 1.96$ TeV	μ_1	16.0128(8)	19.60(1)	1.22
	μ_2	14.457(1)	18.79(1)	1.30
	$0.5\mu_0$	357.58(2)	367.2(2)	1.03
$pp \to W^-H^0j + X$	μ_0	323.03(2)	360.2(2)	1.12
	$2\mu_0$	292.76(2)	352.1(2)	1.20
$\sqrt{s} = 14$ TeV	μ_1	306.023(8)	350.9(1)	1.15
	μ_2	291.63(1)	347.9(1)	1.19
	$0.5\mu_0$	589.49(5)	588.0(3)	0.997
$pp \to W^+H^0j + X$	μ_0	531.37(3)	572.9(3)	1.08
	$2\mu_0$	483.21(4)	561.0(3)	1.16
$pp \to W^+H^0j + X\sqrt{s} = 14$ TeV	μ_1	503.36(2)	561.2(2)	1.12
	μ_2	479.93(2)	556.4(2)	1.16





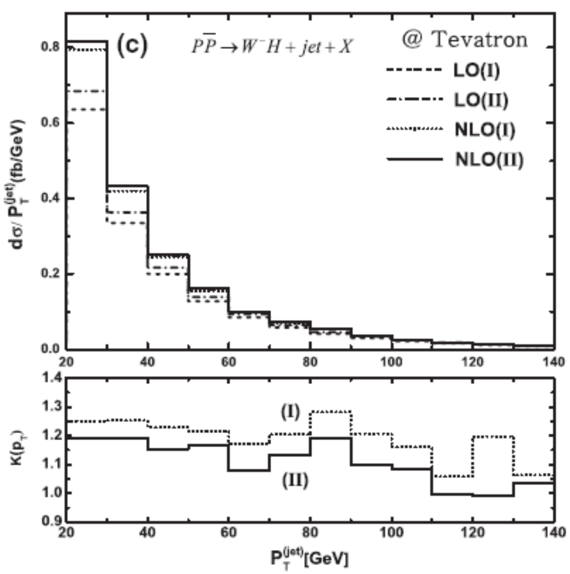
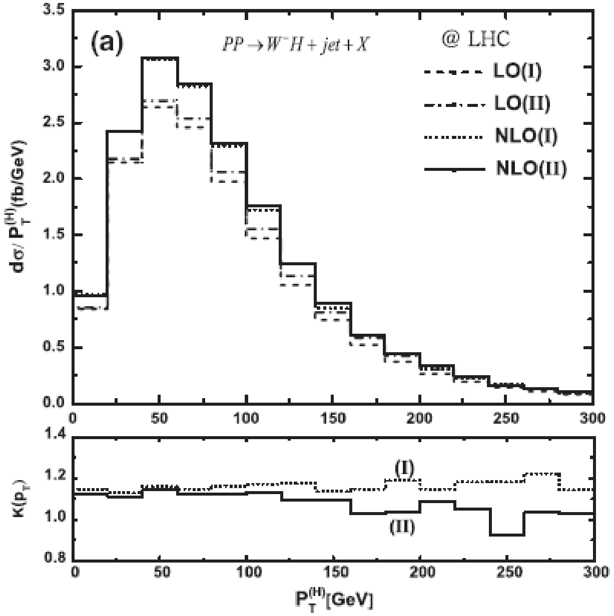
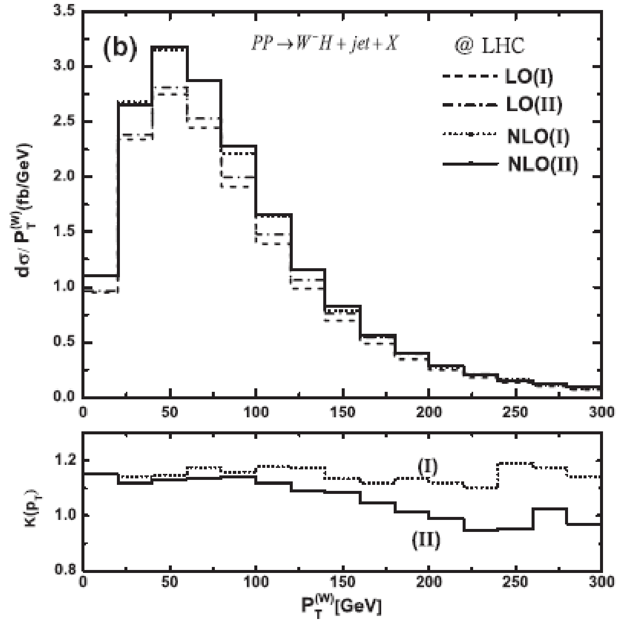


FIG. 6. The LO and NLO QCD corrected distributions of the transverse momenta of final particles and corresponding K-factors $(K(p_T) \equiv \frac{d\sigma_{\rm NLO}}{dp_T} / \frac{d\sigma_{\rm LO}}{dp_T})$ for the process $p\bar{p} \to W^- H^0 j + X$ at the Tevatron with $m_H = 120$ GeV. The distributions labeled by (I) and (II) are for the $\mu = \mu_1$ and $\mu = \mu_0$ respectively. (a) for H^0-boson, (b) for W^--boson, (c) for final leading jet.





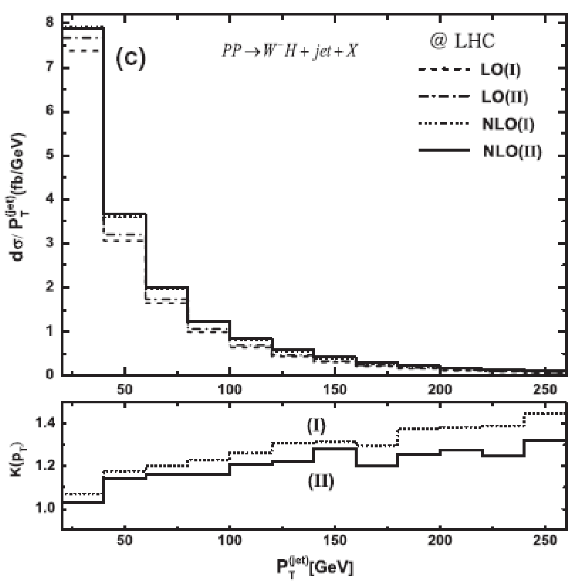


FIG. 7. The LO and NLO QCD corrected distributions of the transverse momenta of final particles and corresponding K-factors $(K(p_T) \equiv \frac{d\sigma_{\rm NLO}}{dp_T} / \frac{d\sigma_{\rm LO}}{dp_T})$ for the process $pp \to W^- H^0 j + X$ at the LHC with $m_H = 120$ GeV. The distributions labeled by (I) and (II) are for the $\mu = \mu_1$ and $\mu = \mu_0$ respectively. (a) for H^0-boson, (b) for W^--boson, (c) for final leading jet.

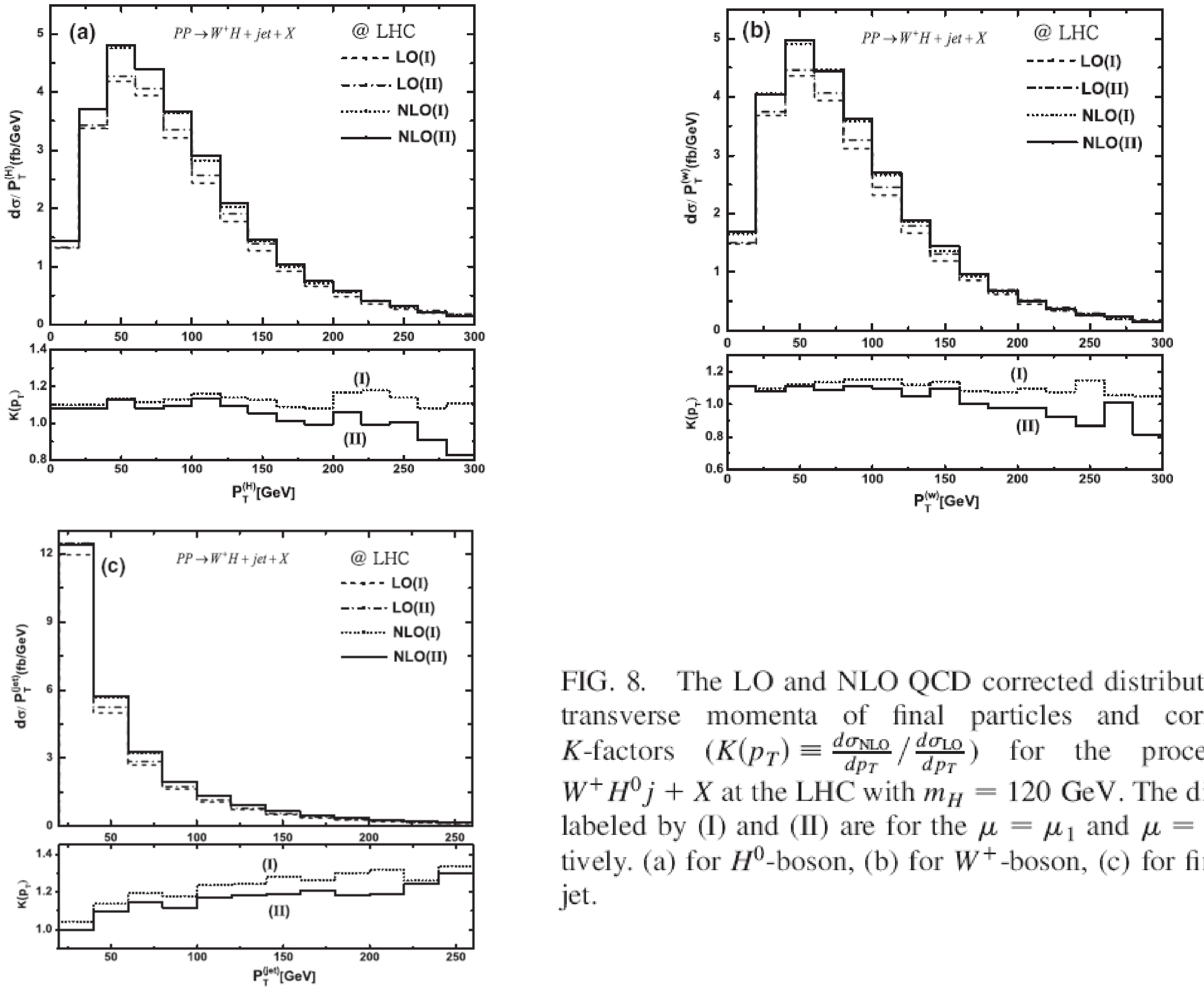


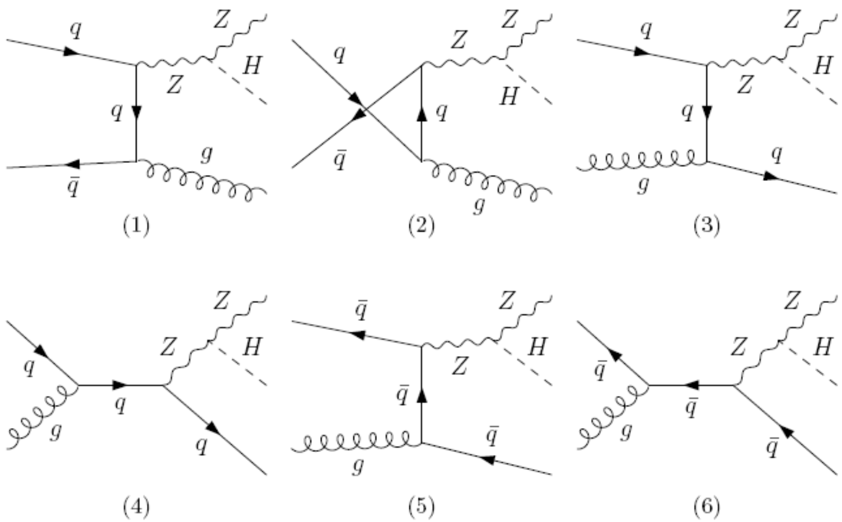
FIG. 8. The LO and NLO QCD corrected distributions of the transverse momenta of final particles and corresponding K-factors $(K(p_T) \equiv \frac{d\sigma_{\rm NLO}}{dp_T} / \frac{d\sigma_{\rm LO}}{dp_T})$ for the process $pp \to W^+H^0j + X$ at the LHC with $m_H = 120$ GeV. The distributions labeled by (I) and (II) are for the $\mu = \mu_1$ and $\mu = \mu_0$ respectively. (a) for H^0-boson, (b) for W^+-boson, (c) for final leading jet.

(2) **Z^0H^0 + jet production at LHC**

J.J.Su, et al, (2011)

The LO partonic processes for the Z^0H^0+jet production process:

$$q\ (p_1) + \bar{q}\ (p_2) \to Z^0\ (p_3) + H^0\ (p_4) + g\ (p_5),$$
$$q\ (p_1) + g\ (p_2) \to Z^0\ (p_3) + H^0\ (p_4) + q\ (p_5),$$
$$\bar{q}\ (p_1) + g\ (p_2) \to Z^0\ (p_3) + H^0\ (p_4) + \bar{q}(p_5),$$



Real emission partonic processes:

$$
\begin{aligned}
&(1)\ g(p_1)\ g(p_2) \to Z^0(p_3)\ H^0(p_4)\ q(p_5)\ \bar{q}(p_6),\\
&(2)\ q(p_1)\ \bar{q}(p_2) \to Z^0(p_3)\ H^0(p_4)\ g(p_5)\ g(p_6),\\
&(3)\ q(p_1)\ g(p_2) \to Z^0(p_3)\ H^0(p_4)\ q(p_5)\ g(p_6),\\
&(4)\ \bar{q}(p_1)\ g(p_2) \to Z^0(p_3\ H^0(p_4)\ \bar{q}(p_5)\ g(p_6),\\
&(5)\ q(p_1)\ \bar{q}(p_2) \to Z^0(p_3)\ H^0(p_4)\ q'(p_5)\ \bar{q}'(p_6),\\
&(6)\ q(p_1)\ \bar{q}'(p_2) \to Z^0(p_3)\ H^0(p_4)\ q(p_5)\ \bar{q}'(p_6),\\
&(7)\ q(p_1)\ q'(p_2) \to Z^0(p_3)\ H^0(p_4)\ q(p_5)\ q'(p_6),\\
&(8)\ \bar{q}(p_1)\ \bar{q}'(p_2) \to Z^0(p_3)\ H^0(p_4)\ \bar{q}(p_5)\ \bar{q}'(p_6),
\end{aligned}
$$

$$q, q' = u, d, c, s, b.$$

There are totally 95 real emission partonic channels !

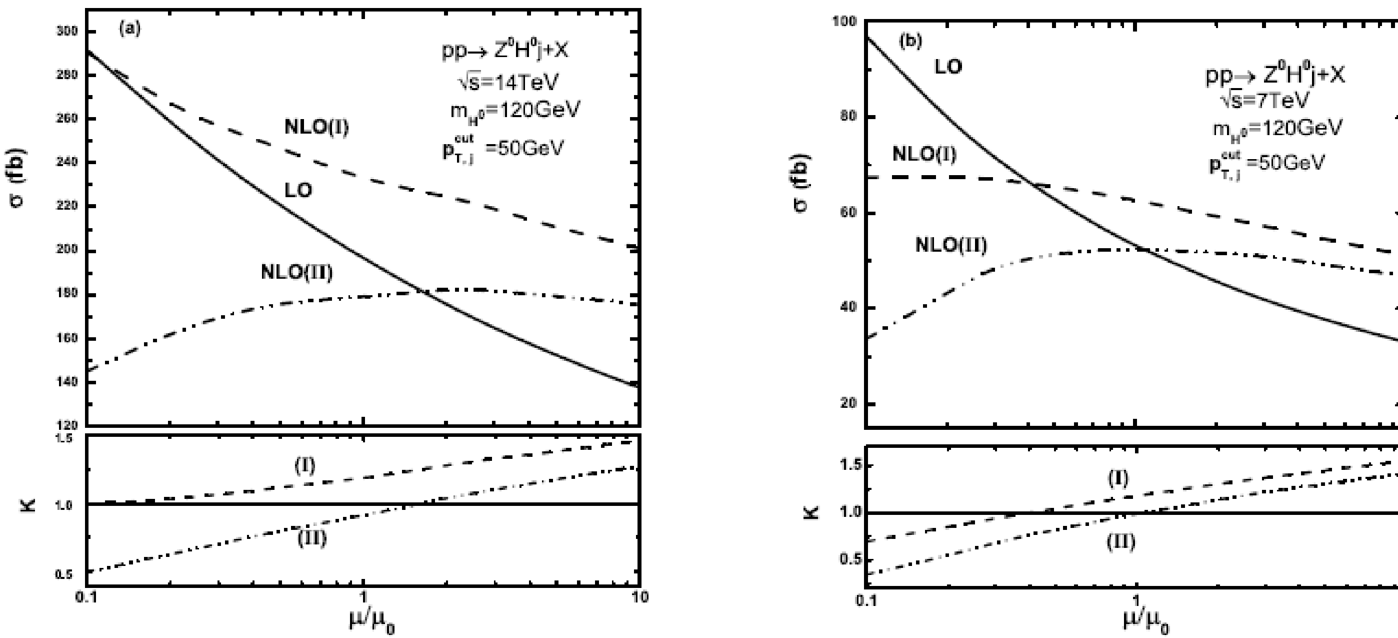


Figure 3. The LO, NLO QCD corrected cross sections and the corresponding K-factor ($K(\mu) \equiv \sigma_{NLO}(\mu)/\sigma_{LO}(\mu)$) versus the factorization/renormalization scale μ for the $pp \to Z^0H^0j + X$ process at the LHC by adopting the inclusive scheme (Scheme I) and exclusive scheme (Scheme II), separately. (a) at the $\sqrt{s} = 14\ TeV$ LHC. (b) at the $\sqrt{s} = 7\ TeV$ LHC.

$pp \to Z^0H^0j + X$	$m_H(GeV)$	$\sigma_{LO}(fb)$	$\sigma^{(I)}_{NLO}(fb)$	$\sigma^{(II)}_{NLO}(fb)$	$K^{(I)}$	$K^{(II)}$
$\mu = \mu_0 = 105.594\ GeV$	120	196.25(1)	232.2(2)	178.7(2)	1.1832	0.9106
$\sqrt{s} = 14\ TeV$	150	108.18(1)	121.8(1)	91.7(1)	1.1259	0.8477
$\mu = \mu_0 = 105.594\ GeV$	120	53.116(3)	62.67(7)	52.50(7)	1.1799	0.9884
$\sqrt{s} = 7\ TeV$	150	28.239(2)	33.61(4)	28.16(3)	1.1903	0.9972

Table 1. The numerical results for the LO, NLO QCD corrected cross sections and the corresponding K-factor ($K \equiv \frac{\sigma_{NLO}}{\sigma_{LO}}$) with $\mu = \mu_0$ and $m_H = 120\ GeV$,$150\ GeV$ for the $pp \to Z^0H^0j + X$ process at the LHC by applying the Scheme I and Scheme II event selection schemes with $p^{cut}_{T,j} = 50\ GeV$.

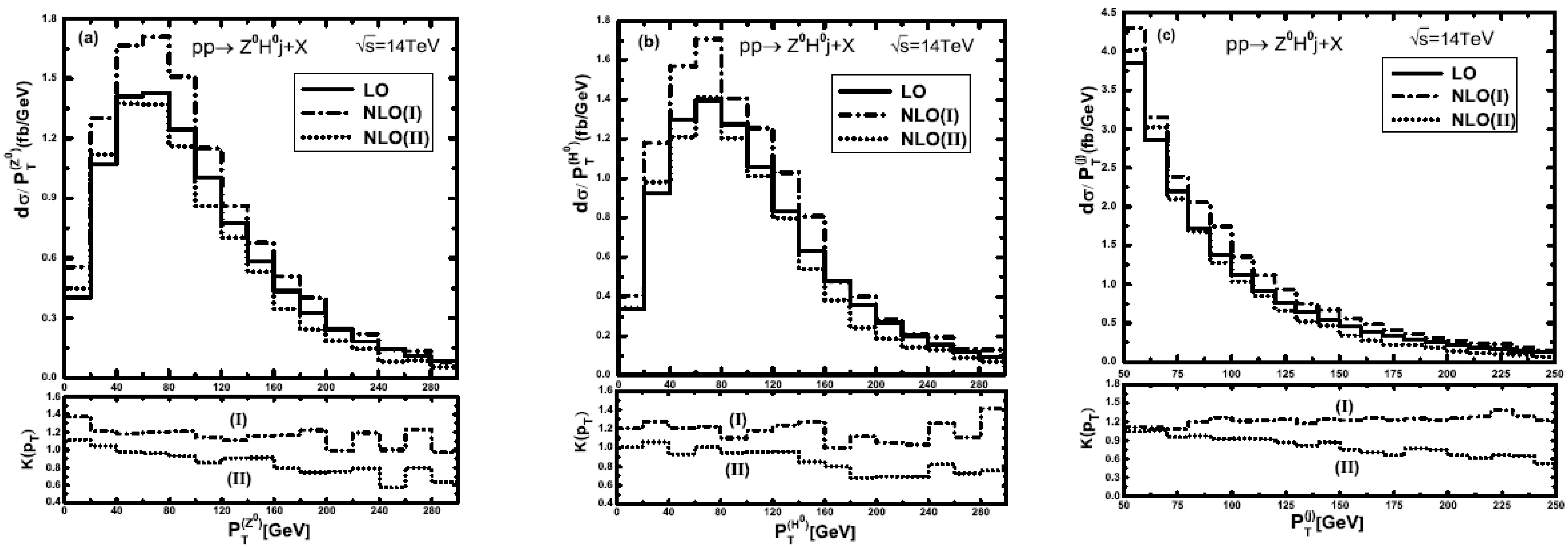


Figure 4. The LO, NLO QCD corrected distributions of the transverse momenta of the final particles and the corresponding K-factors ($K(p_T) \equiv \frac{d\sigma_{NLO}}{dp_T}/\frac{d\sigma_{LO}}{dp_T}$) for the $pp \to Z^0 H^0 j + X$ process at the LHC with $m_H = 120\ GeV$ and $\sqrt{s} = 14\ TeV$. (a) Z^0-boson, (b) Higgs-boson, (c) final leading jet.

4. Summary

1. The understanding of higher order QCD at LHC is very crucial.
2. Progress in QCD activity for Higgs production, but there raised new problems.
3. QCD/EW NLO or NNLO corrections to Higgs physics studies could be as significant as ~O(10%), which are at the same level to or larger than the expected experiment accuracy and have to be taken into account.
4. Need more precision studies for Higgs physics, require good control of theoretical predictions:

   multi-point integrals; multi-body PS integral;
   resonance problem; computing power;
   convergence of perturbative calculations;
   MC techniques , etc .

We have to handel the loop and PS integrations case-by-case in most cases.

Thanks !