Associated production of W/Z bosons with b-jets

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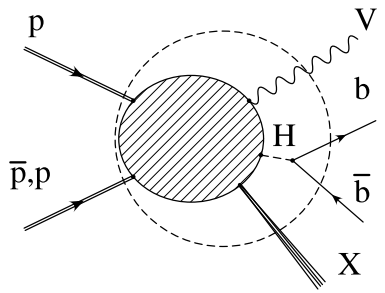
Workshop on Higgs Physics Phenomenology, Zürich, January 09

- Motivations: main background to
  - → WH/ZH associated production;
  - → $H/A + b\bar{b}$ and other signals of new physics;
  - → single-top production;
  - → $t\bar{t}$ production;
  - → several non-standard model signatures.
- New studies:
  - → $Wb\bar{b}/Zb\bar{b}$ at NLO, b massive (F. Febres Cordero, L. R., D. Wackeroth)
  - → $W + 1\,b$-jet, 4FNS and 5FNS merged at NLO (J. Campbell, K. Ellis, F. Febres Cordero, F. Maltoni, L. R., D. Wackeroth, S. Willenbrock)
- Outlook

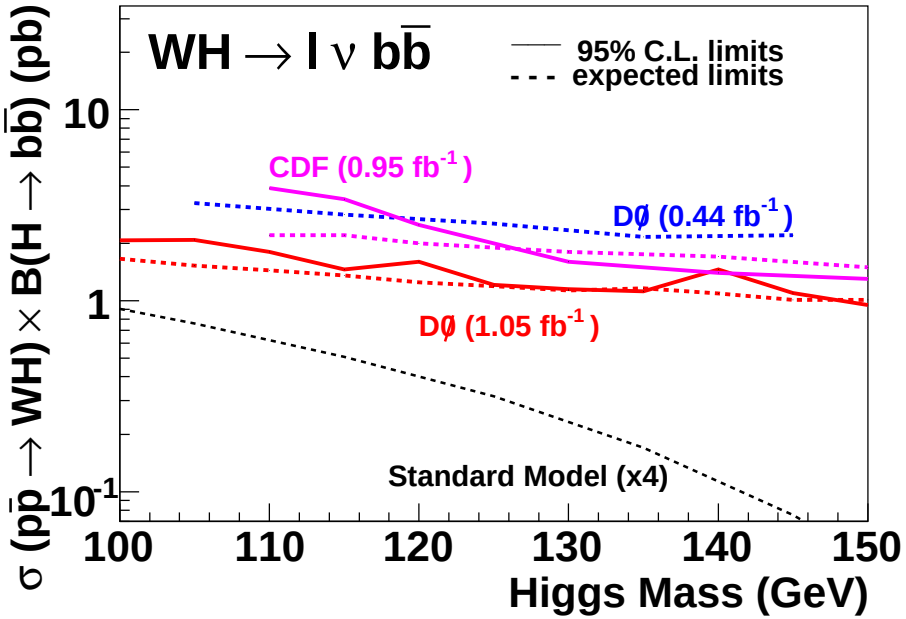
Associated production of SM Higgs with weak vector bosons

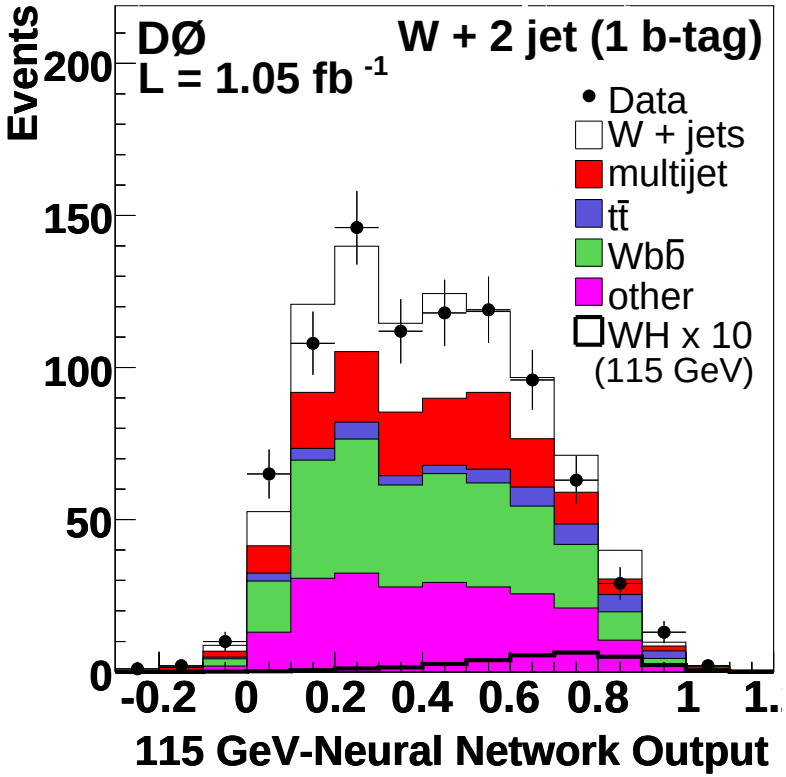


$\longrightarrow$ NNLO QCD corrections have been calculated for the signal [O.Brien, A.Djouadi and R.Harlander, 2004]

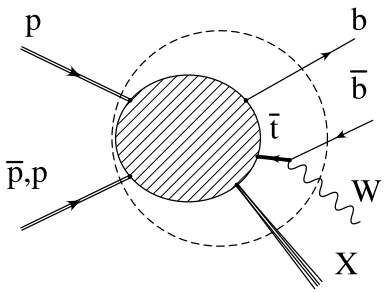
$\longrightarrow$ $O(\alpha)$ EW corrections have been calculated for the signal [M.L.Ciccolini, S.Dittmaier and M.Kramer, 2003]

$\longrightarrow$ Results for WH associated production, August 2008





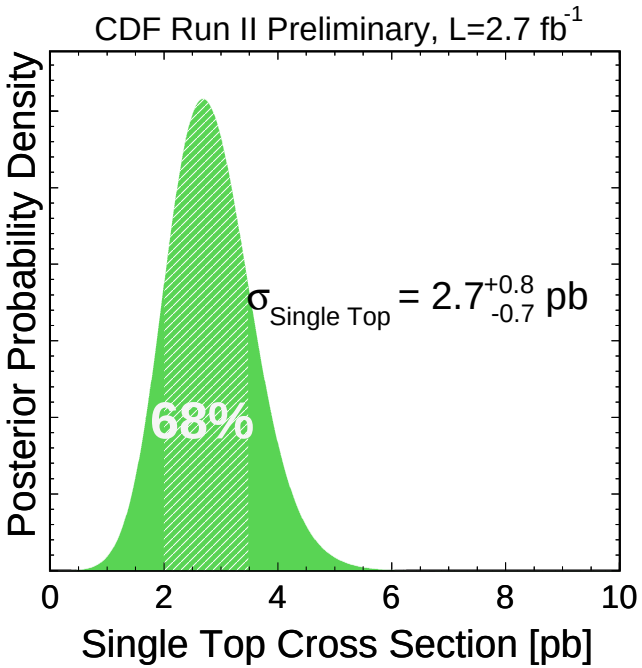
SM Single-Top production

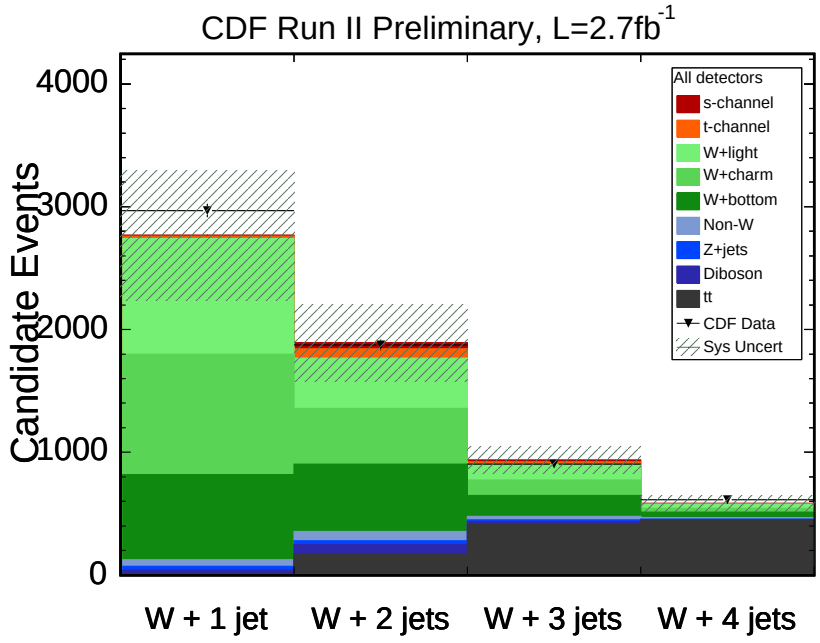


$\longrightarrow$ NLO QCD corrections have been thoroughly studied [T.Stelzer, Z.Sullivan and S.Willenbrock, 1998; B.W.Harris, E.Laenen, L.Phaf, Z.Sullivan and S.Weinzierl, 2002; . . .]

$\longrightarrow$ NLO EW corrections have been calculated for the (SM and MSSM) signal [M.Beccaria, G.Macorini, F.M.Renard and C.Verzegnassi, 2006]

$\longrightarrow$ Summer 2008



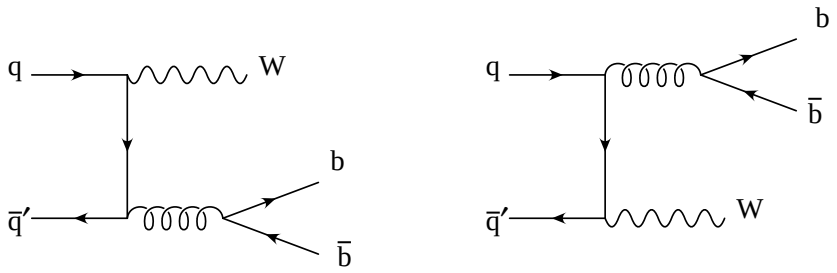


$Wb\bar{b}/Zb\bar{b}$ production at NLO, some history ...

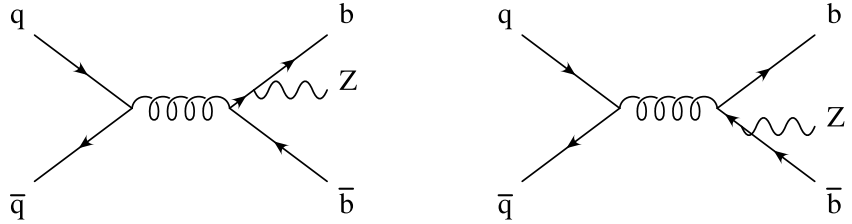
- $V \longrightarrow 4$ partons (1-loop massless amplitudes) (Bern, Dixon, Kosower (97))
- $p\bar{p}, pp \to Vb\bar{b}$ (at NLO, 4FNS, $m_b = 0$) (Campbell, Ellis (99))
- $p\bar{p}, pp \to Vb + j$ (at NLO, 5FNS) (Campbell, Ellis, Maltoni,Willenbrock (05,07))
- $p\bar{p}, pp \to Wb\bar{b}$ (at NLO, 4FNS, $m_b \neq 0$) (Febres Cordero, L.R., Wackeroth (06))
- $p\bar{p}, pp \to Zb\bar{b}$ (at NLO, 4FNS, $m_b \neq 0$) (Febres Cordero, L.R., Wackeroth (08))
- $p\bar{p}, pp \to W + 1\, b$-jet (at NLO, 5FNS+4FNS with $m_b \neq 0$) (Campbell, Ellis, Febres Cordero, Maltoni, L.R., Wackeroth, Willenbrock (08))

$Wb\bar{b}/Zb\bar{b}$ production with full m_b effects

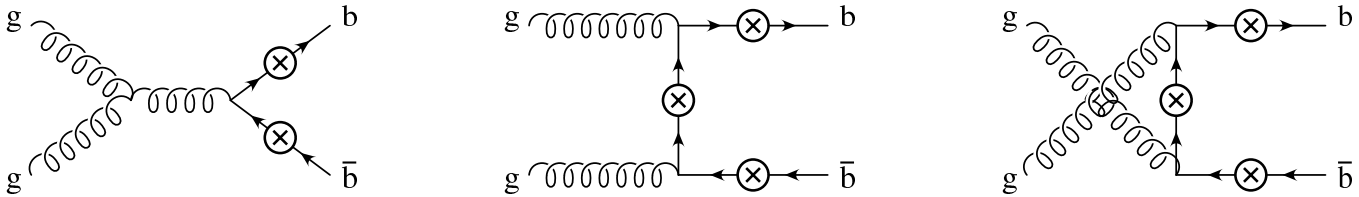
LO Feynman diagrams:



$q\bar{q}' \to Wb\bar{b}$



$q\bar{q} \to Zb\bar{b}$



$gg \to Zb\bar{b}$

Subprocesses at LO:

$\longrightarrow$ $Wb\bar{b}$: $q\bar{q}' \to Wb\bar{b}$

$\longrightarrow$ $Zb\bar{b}$: $q\bar{q} \to Zb\bar{b}$ and $gg \to Zb\bar{b}$

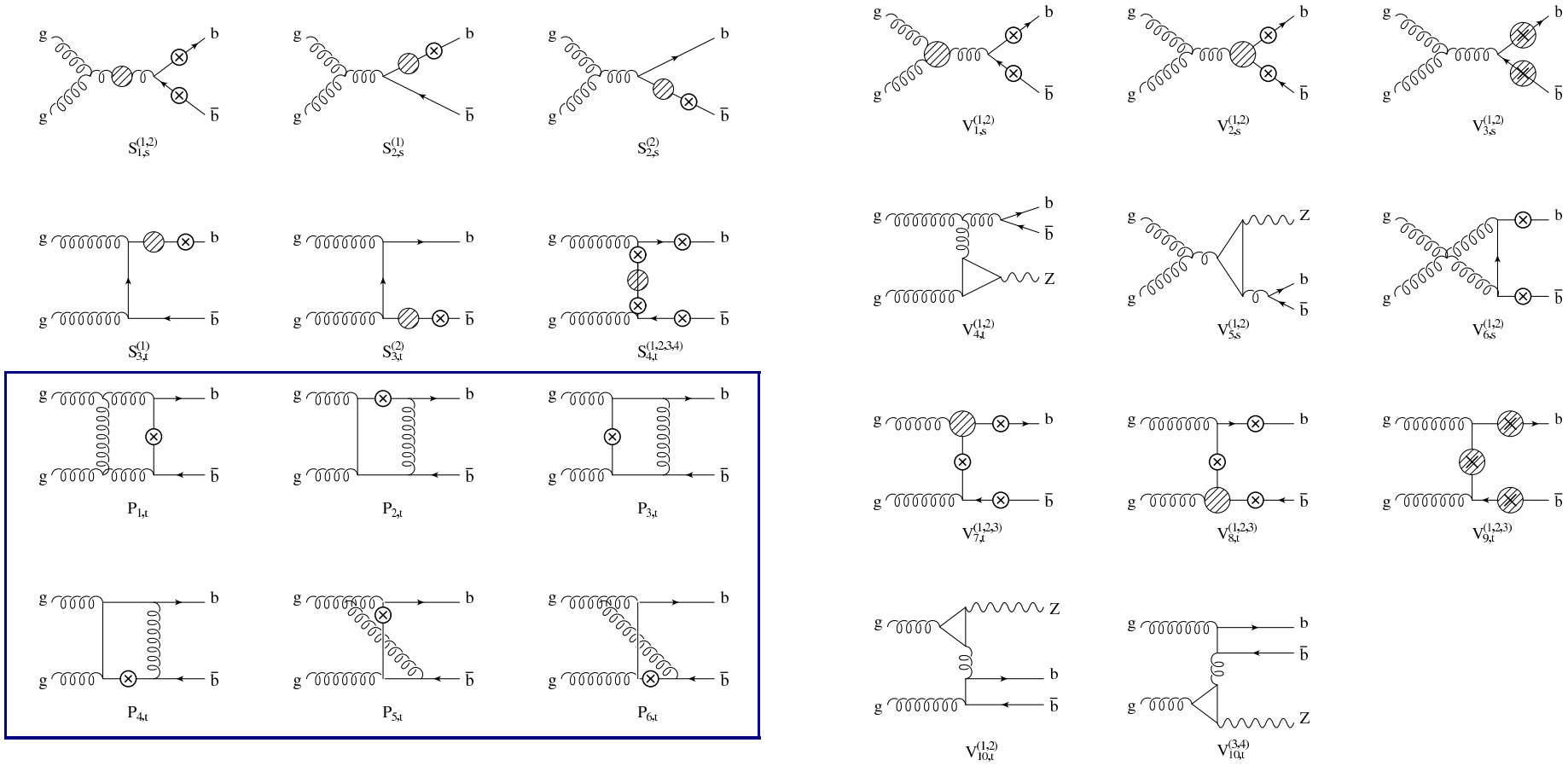
Including $O(\alpha_s)$ corrections

$$\begin{aligned}\hat{\sigma}_{ij}^{\rm NLO}(x_1,x_2,\mu) &= \alpha_s^2(\mu)\left\{f_{ij}^{\rm LO}(x_1,x_2)+\frac{\alpha_s(\mu)}{4\pi}f_{ij}^{\rm NLO}(x_1,x_2,\mu)\right\}\\ &\equiv \hat{\sigma}_{ij}^{\rm LO}(x_1,x_2,\mu)+\delta\hat{\sigma}_{ij}^{\rm NLO}(x_1,x_2,\mu)\ ,\end{aligned}$$

$$\delta\hat{\sigma}_{ij}^{\rm NLO} = \hat{\sigma}_{ij}^{\rm virt}+\hat{\sigma}_{ij}^{\rm real}\ .$$

- Virtual Corrections: consist of one-loop diagrams interfered with corresponding LO amplitude
  - $Wb\bar{b}$: one subprocess, $q\bar{q}'\to Wb\bar{b}$
  - $Zb\bar{b}$: two subprocesses, $q\bar{q}\to Zb\bar{b}$ and $gg\to Zb\bar{b}$
- Real Corrections: consist of tree level diagrams with one extra parton
  - $Wb\bar{b}+k$: two subprocess, $q\bar{q}'\to Wbb+g$ and $q(\bar{q})g\to Wb\bar{b}+q'(\bar{q}')$
  - $Zb\bar{b}+k$: three subprocesses, $q\bar{q}\to Zb\bar{b}+g$, $gg\to Zb\bar{b}+g$ and $q(\bar{q})g\to Zb\bar{b}+q(\bar{q})$

NLO at a glance: the $gg \to Zb\bar{b}$ virtual diagrams.



$\longrightarrow$ Counting: 8 diagrams at LO - $\sim$100 at NLO - 12 pentagons

Checking boxes and pentagons using unitarity methods.

The one-loop amplitude can be written as

$$\mathcal{M} = \sum_i d_i I_4^i + \sum_i c_i I_3^i + \sum_i b_i I_2^i + \sum_i a_i I_1^i$$

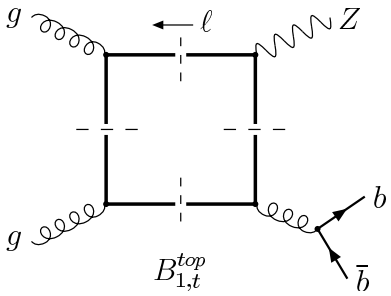
$\longrightarrow$ tadpoles, bubbles and vertices are easy in FD's language;

$\longrightarrow$ boxes and pentagons are the real hurdle (tensor integrals up to rank 4)

$\Downarrow$

I_4^i scalar 4-point functions originate from box and pentagon diagrams.

Calculating d_i with unitarity methods is a powerful check!

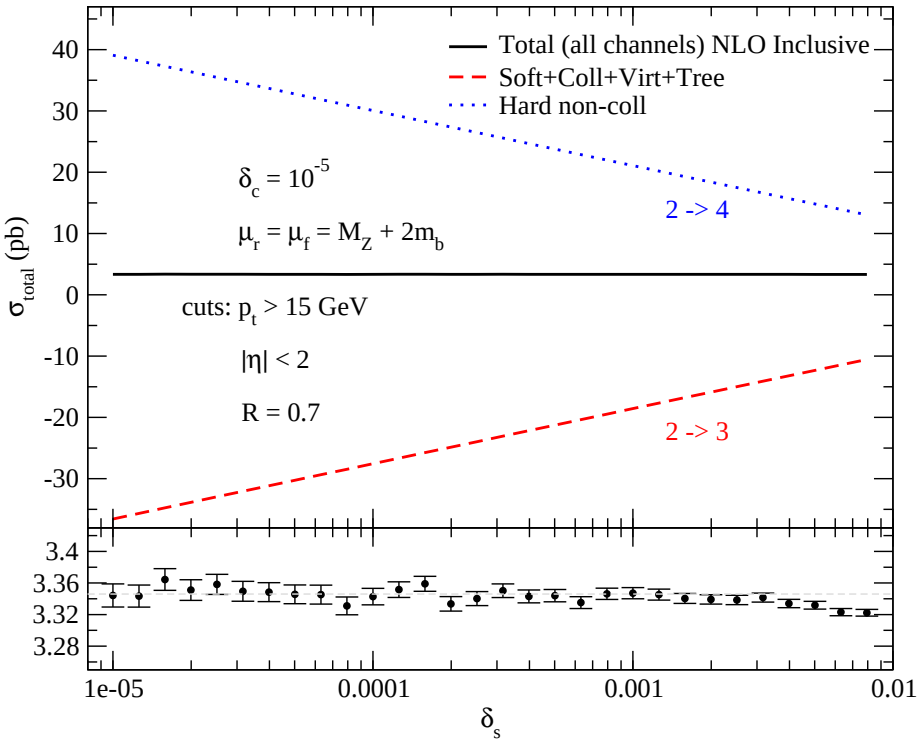


easy using quadrupole cuts!

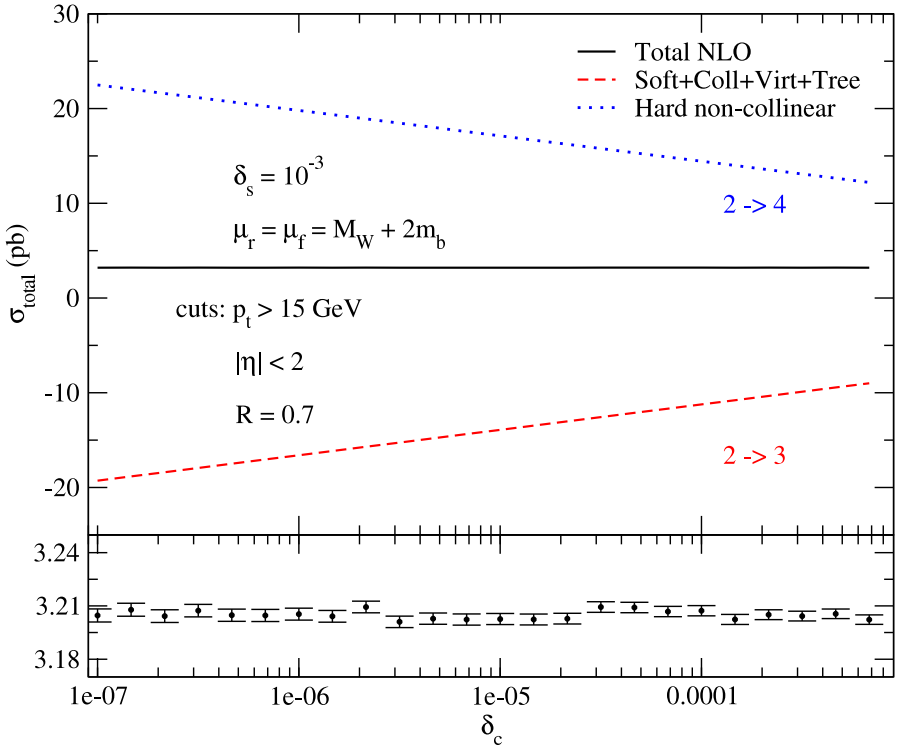
Britto,Cachazo,Feng

Bern,Dixon,Kosower

Real corrections: phase space slicing with 2 cutoffs.



δ_s run for the $Zb\bar{b}$ total cross section



δ_c run for the $Wb\bar{b}$ total cross section

$\longrightarrow$ Cross section independent of unphysical cutoffs δ_s and δ_c

$\longrightarrow$ In the following we fix $\delta_s = 10^{-3}$ and $\delta_c = 10^{-5}$

$W/Z + 2\,b$-jets

Febres Cordero, L.R., Wackeroth (06-08)

- We use the k_T jet algorithm with $R = 0.7$ and study two cases:
  - → Inclusive Cross Section: events with two $(b + \bar{b})$ or three $(b + \bar{b} + j)$ jets resolved contribute to the cross section.
  - → Exclusive Cross Section: only events with two $(b + \bar{b})$ jets resolved contribute to the cross section.

  Same convention used by MCFM (used to obtain the results for $m_b = 0$).
- b-jet kinematical cuts:
  - → Transverse momentum of the b-jets: $p_t > p_{t,\ min}$ (15-25 GeV) for both b and $\bar{b}$ jets.
  - → Pseudorapidity: $|\eta| < \eta_{max}$ (2-2.5) for both b and $\bar{b}$ jets.
- PDF: for LO results we use 1-loop evolution of α_s and CTEQ6L1, while for NLO results 2-loop evolution of α_s and CTEQ6M.

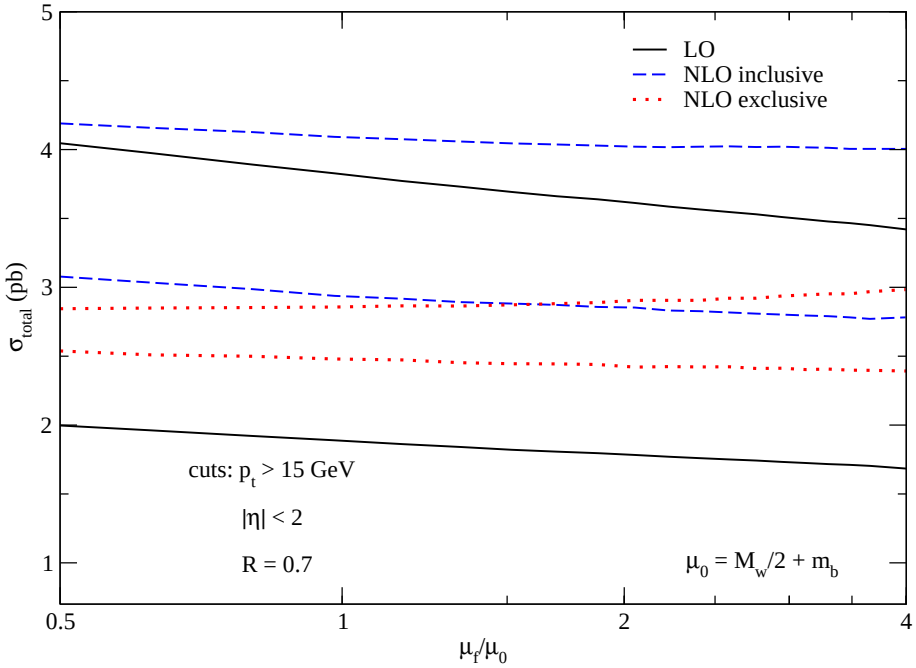
Summary of LO and NLO total cross sections, Tevatron

massive and massless calculation, setting $\mu_r = \mu_f = M_V + 2m_b$ $(V = W, Z)$.

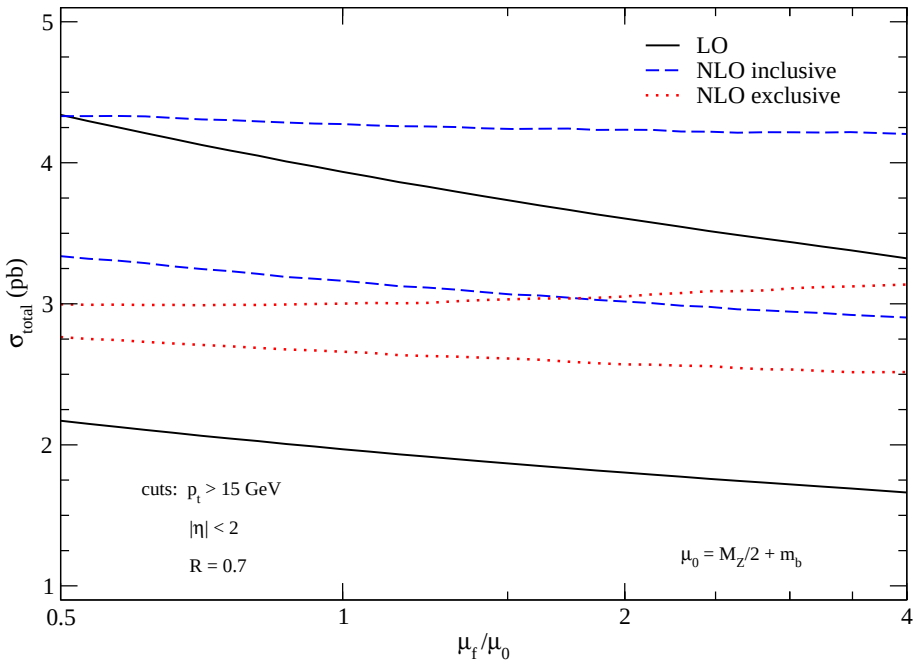
Cross Section, $Wb\bar{b}$	$m_b \neq 0$ (pb) [ratio]	$m_b = 0$ (pb) [ratio]
$\sigma^{\rm LO}$	2.20[-]	2.38[-]
$\sigma^{\rm NLO}$ inclusive	3.20[1.45]	3.45[1.45]
$\sigma^{\rm NLO}$ exclusive	2.64[1.2]	2.84[1.2]

Cross Section, $Zb\bar{b}$	$m_b \neq 0$ (pb) [ratio]	$m_b = 0$ (pb) [ratio]
$\sigma^{\rm LO}$	2.21[-]	2.37[-]
$\sigma^{\rm NLO}$ inclusive	3.34[1.51]	3.64[1.54]
$\sigma^{\rm NLO}$ exclusive	2.75[1.24]	3.01[1.27]

Scale dependence and theoretical uncertainty at NLO, Tevatron



$Wb\bar{b}$: Tevatron (PRD 74 (2006) 034007)

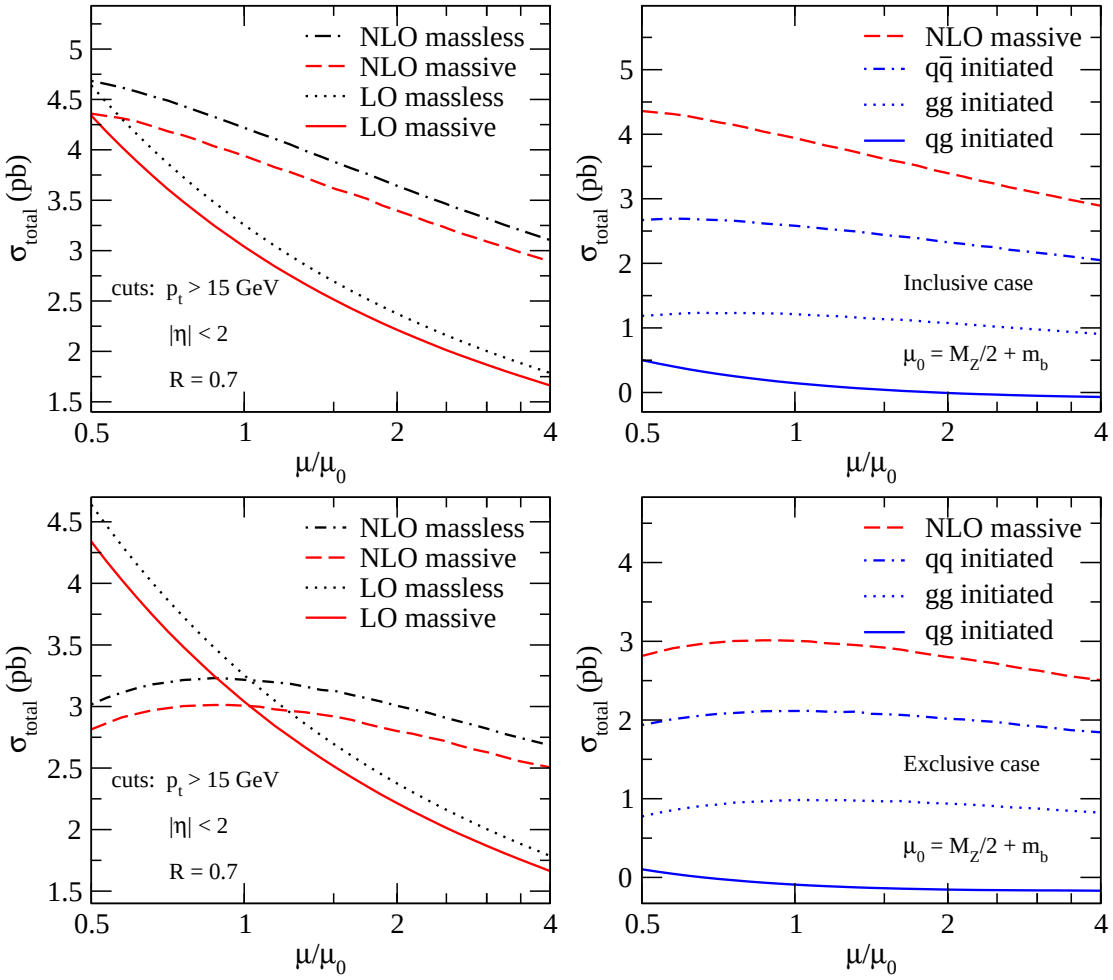


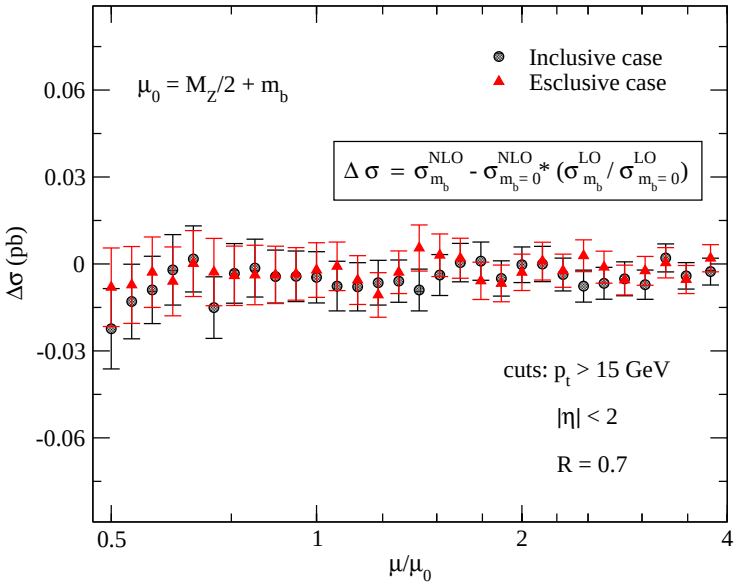
$Zb\bar{b}$: Tevatron (PRD 78 (2008) 074014)

$\longrightarrow$ Bands obtained by varying both μ_R and μ_F between $\mu_0/2$ and $4\mu_0$ (with $\mu_0 = m_b + M_V/2$ $(V = W, Z)$).

- LO uncertainty $\sim 40\%$.
- Inclusive NLO uncertainty $\sim 20\%$.
- Exclusive NLO uncertainty $\sim 10\%$.

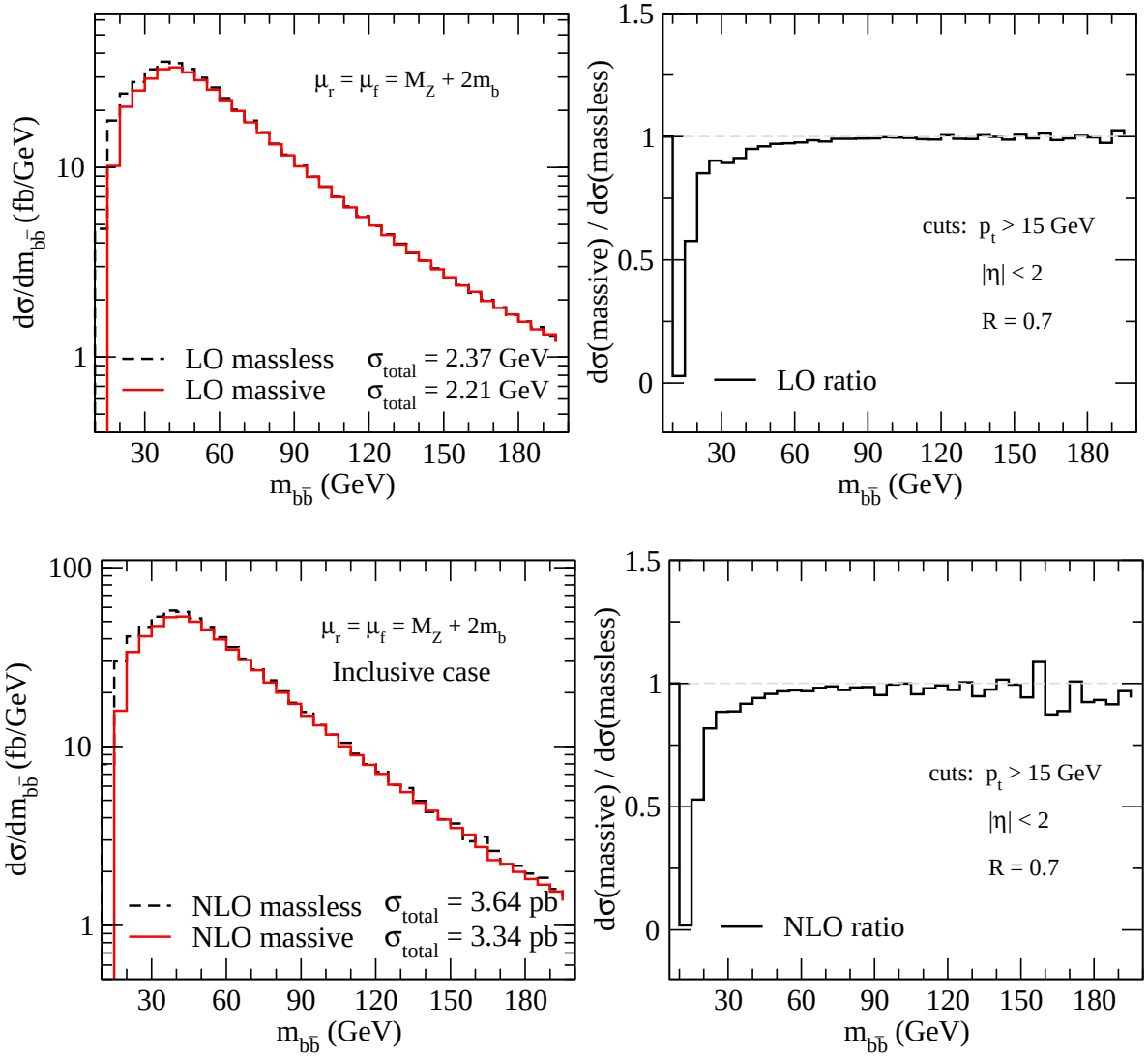
$Zb\bar{b}$, scale dependence: LO vs NLO and massless vs massive





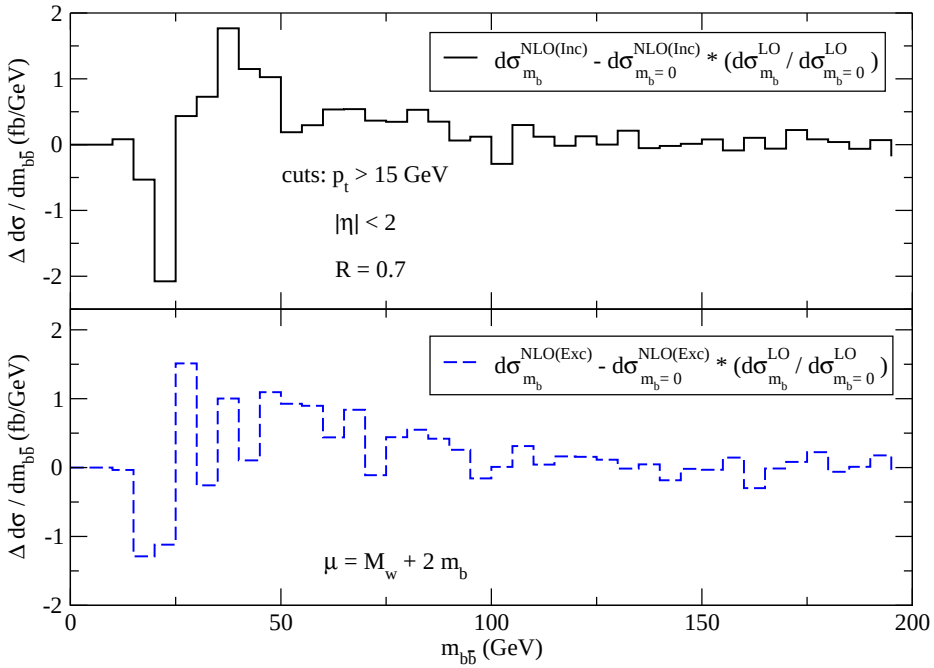
(PRD 78 (2008) 074014)

$Zb\bar{b}$: $m_{b\bar{b}}$ distributions, massive vs massless

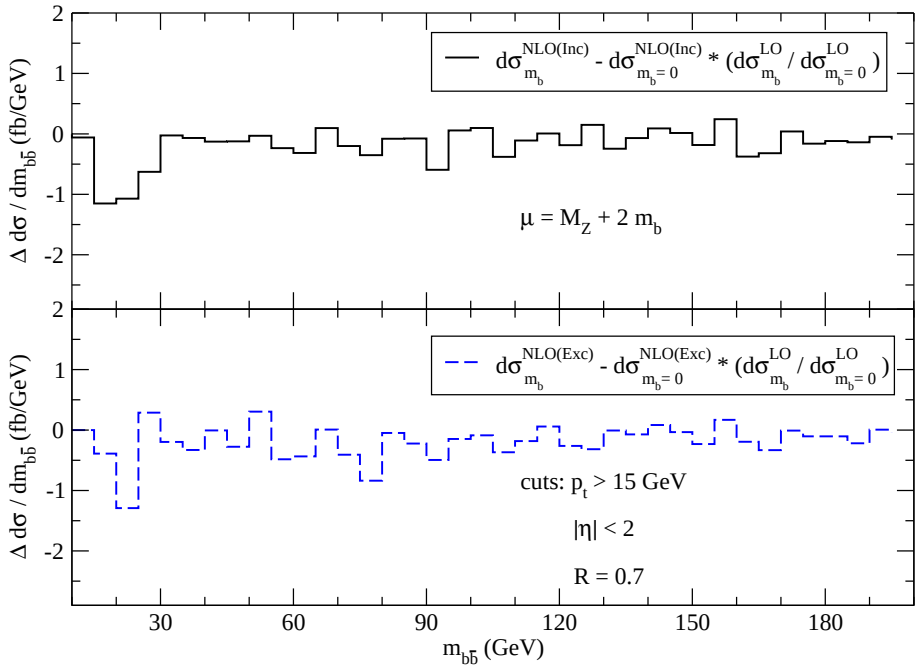


(PRD 78 (2008) 074014)

$Wb\bar{b}/Zb\bar{b}$, $m_{b\bar{b}}$ distributions: testing rescaling LO $\rightarrow$ NLO



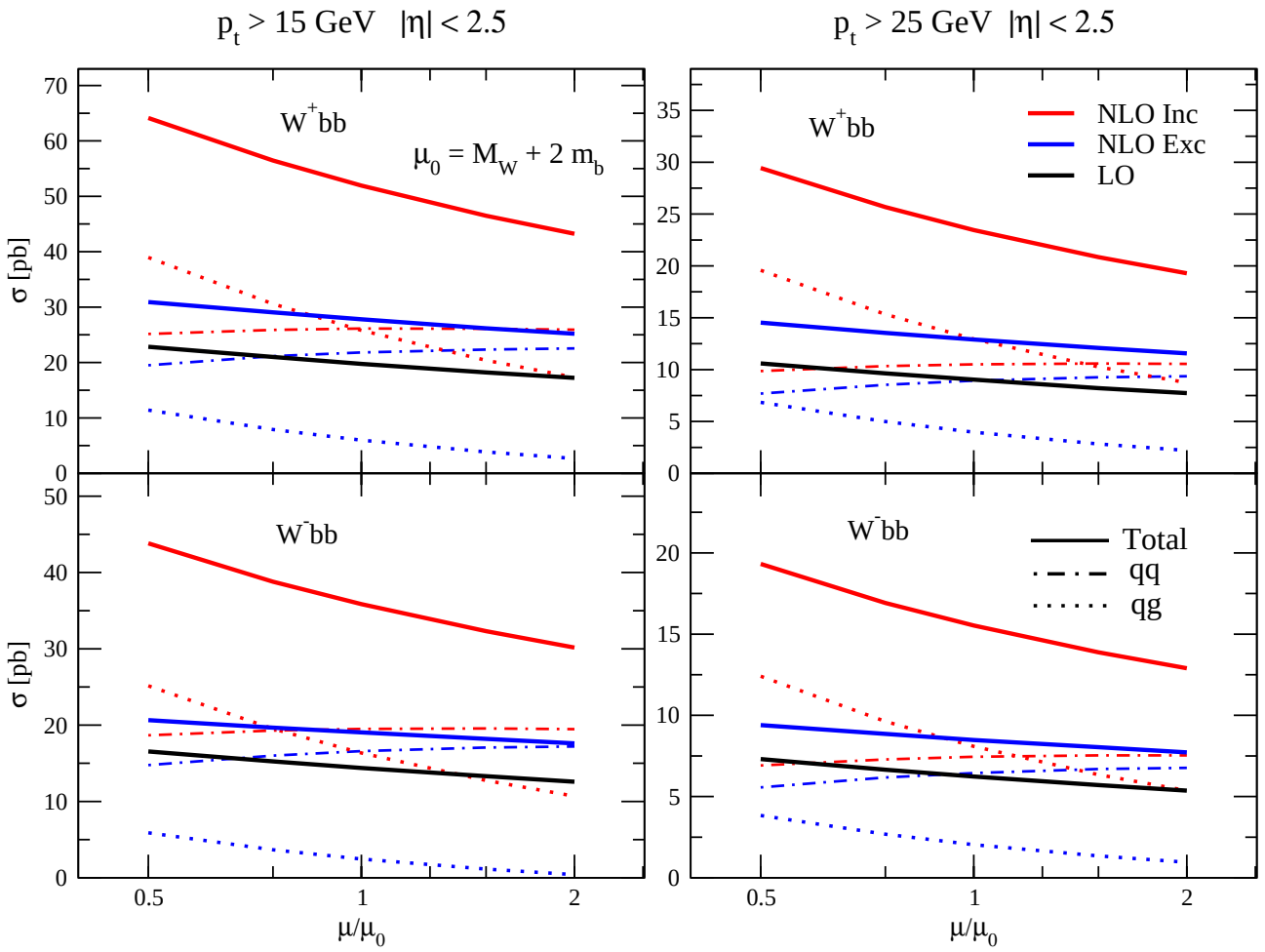
$Wb\bar{b}$: PRD 74 (2006) 034007



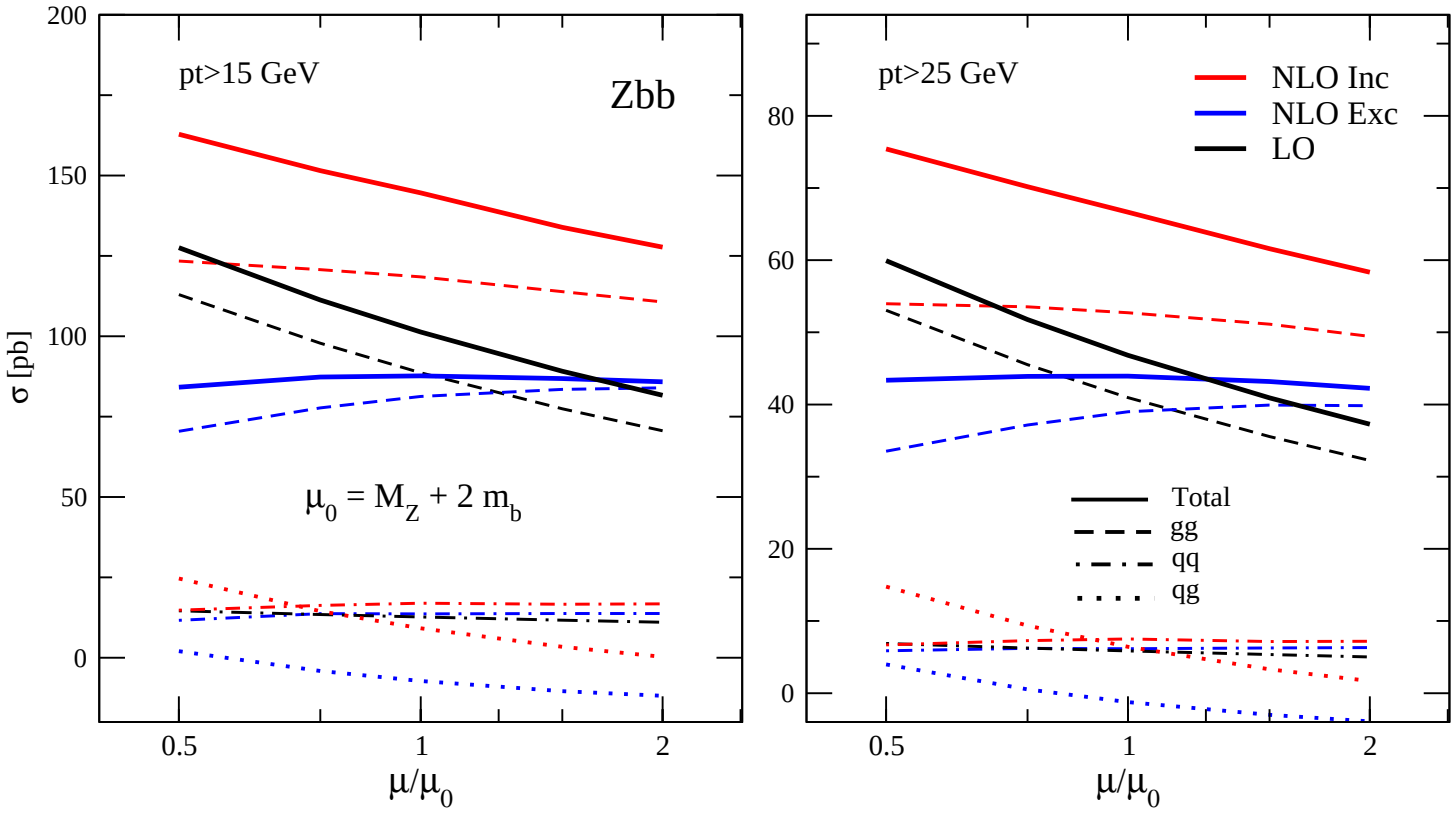
$Zb\bar{b}$: PRD 78 (2008) 074014

Clear effect in the low $m_{b\bar{b}}$ invariant mass region.

Scale dependence and theoretical uncertainty at NLO, LHC



preliminary

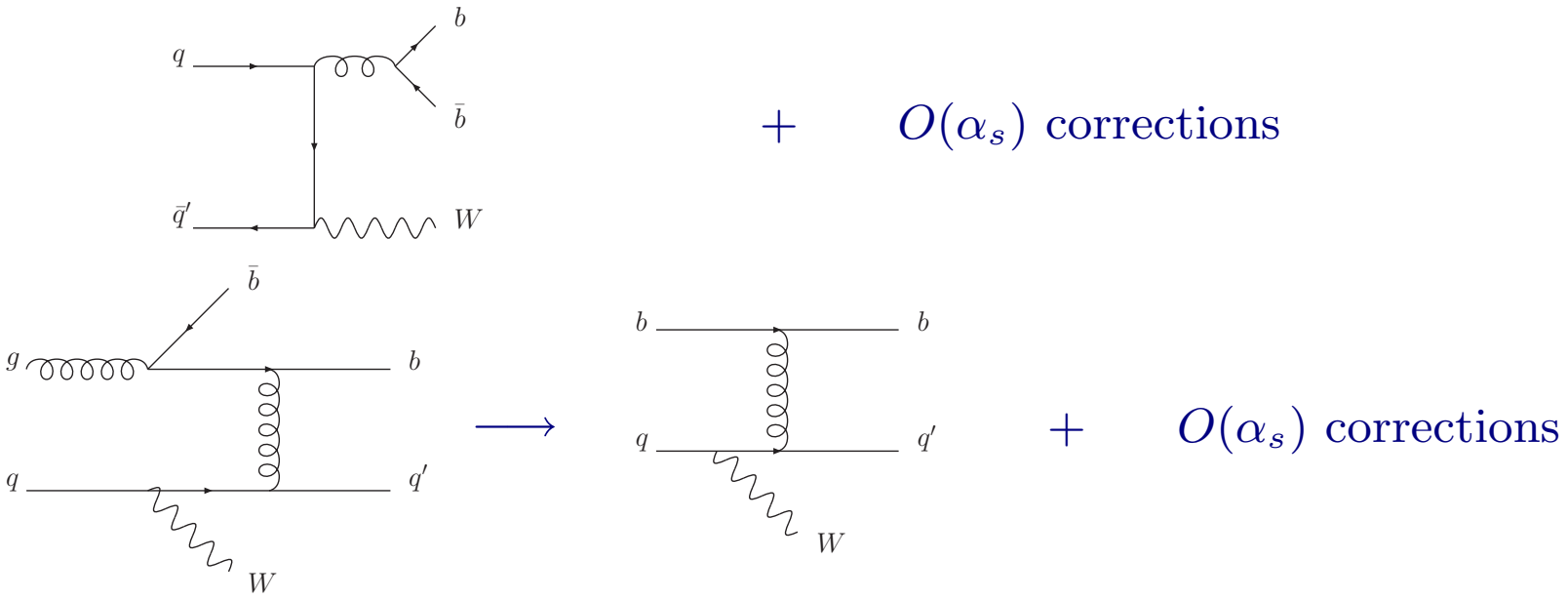


Cross Section, $Zb\bar{b}$ (pb)	$p_T^b > 15$ GeV	$p_T^b > 25$ GeV
$\sigma^{\rm LO}$	101.3 ($\pm$22%)	46.8 ($\pm$23%)
$\sigma^{\rm NLO}$ inclusive	144.6 ($\pm$12%)	66.6 ($\pm$13%)
$\sigma^{\rm NLO}$ exclusive	87.7 ($\pm$3%)	43.9 ($\pm$2%)

$W + 1\,b$-jet

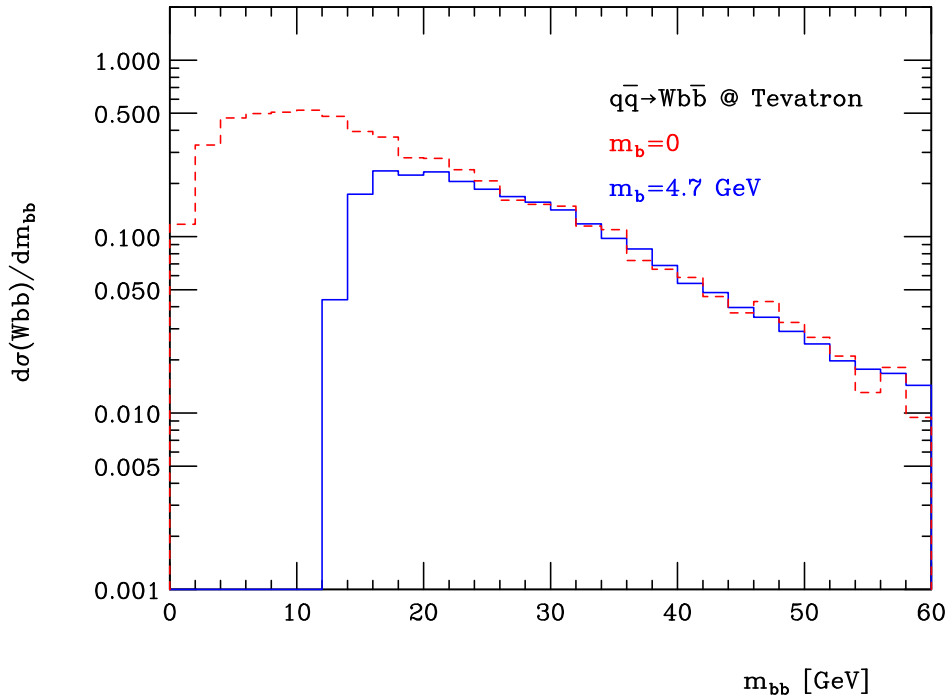
Campbell, Ellis, Febres Cordero, Maltoni, L.R., Wackeroth, Willenbrock (0809.3003)

Consistently combine 4FNS ($m_b \neq 0$) and 5FNS ($m_b = 0$) at NLO in QCD:



1. $q\bar{q}' \to Wb\bar{b}$ at tree level and one loop ($m_b \neq 0$)
2. $q\bar{q}' \to Wb\bar{b}g$ at tree level ($m_b \neq 0$)
3. $bq \to Wbq'$ at tree level and one loop ($m_b = 0$)
4. $bq \to Wbq'g$ and $bg \to Wbq'\bar{q}$ at tree level ($m_b = 0$)
5. $gq \to Wb\bar{b}q'$ at tree level ($m_b \neq 0$) ($\to$ avoiding double counting.)

- improved scale dependence: NLO corrections to $gq \to Wb\bar{b}q'$ partially included;
- need to keep $m_b \neq 0$ for final state b quarks (one b quark has low p_T)



- four signatures studied: exclusive/inclusive, with single and double-b jets, using $p_T^j > 15$ GeV, $|\eta^j| < 2 - 2.5$, cone algorithm with $\Delta R = 0.7$:
  - $\to$ Wb, $W(b\bar{b})$ (exclusive)
  - $\to$ Wb and $Wb + j$, $W(b\bar{b})$ and $W(b\bar{b}) + j$ (inclusive)

  which can be combined to obtain different backgrounds, ...
- both contributions play important complementary roles (Tevatron/LHC, inclusive/exclusive);

- NLO results at a glance:

	Exclusive cross sections (pb)	
Collider	Wb	$W(b\bar{b})$
TeV $W^+(=W^-)$	8.02+0.62[-0.05]=8.64	3.73-0.02[-0.02]=3.71
LHC W^+	40.0+48.4[22.6]=88.4	22.7+11.7[11.7]=34.4
LHC W^-	29.8+29.4[12.6]=59.2	17.2+6.5[6.5]=23.7

	Inclusive cross sections (pb)	
Collider	$Wb+X$	$W(b\bar{b})+X$
TeV $W^+(=W^-)$	11.77+2.40[0.77]=14.17	4.17+0.39[0.39]=4.56
LHC W^+	53.6+136.1[68.9]=189.7	25.1+35.9[35.9]=61.0
LHC W^-	39.3+88.2[44.6]=127.5	18.9+23.6[23.6]=42.5

$\longrightarrow$ first number: Processes $1+2$ (pure 4FNS)

$\longrightarrow$ second number: Processes $3+\cdots+5$ (pure 5FNS plus $qg \to Wb\bar{b}+q'$)

$\longrightarrow$ number in square brackets: Process 5 alone ($qg \to Wb\bar{b}+q'$)

Ongoing and future activity on $W/ZQ\bar{Q}$ production ...

- Final results for $W/Zb\bar{b}$ production at the LHC soon to appear.
- Provide input to experimentalists:
  - ▷ D∅, CDF, both Higgs and single-top working groups: provide parton level distributions with specific cuts;
  - ▷ CMS Higgs working group: provide parton level distributions with specific cuts and interface with NLO parton shower Monte Carlo (POWHEG).
- $Z + 1b$-jet using both 4FNS with $m_b \neq 0$ and 5FNS NLO calculations: quite different pattern!
  - ▷ $bg \to Zb$ at tree level and one loop (with $m_b = 0$);
  - ▷ $bg \to Zb + g$, $bq \to Zb + q$ (with $m_b = 0$);
  - ▷ $q\bar{q}, gg \to Zb\bar{b}$ at tree level and one loop (with $m_b \neq 0$);
  - ▷ $q\bar{q}, gg \to Zb\bar{b} + g$ and $gq(g\bar{q}) \to Zb\bar{b} + q(\bar{q})$ (with $m_b \neq 0$).

  NNLO $bg \to Zb$ could be comparable to 4FNS NLO.