W/Z production with b-jets:
a challenging background

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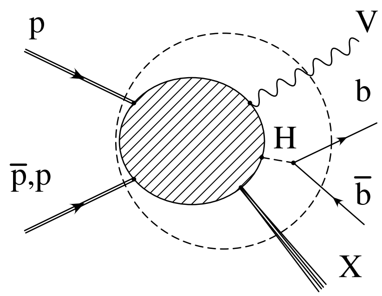
Università di Milano-Bicocca, Luglio 2010

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

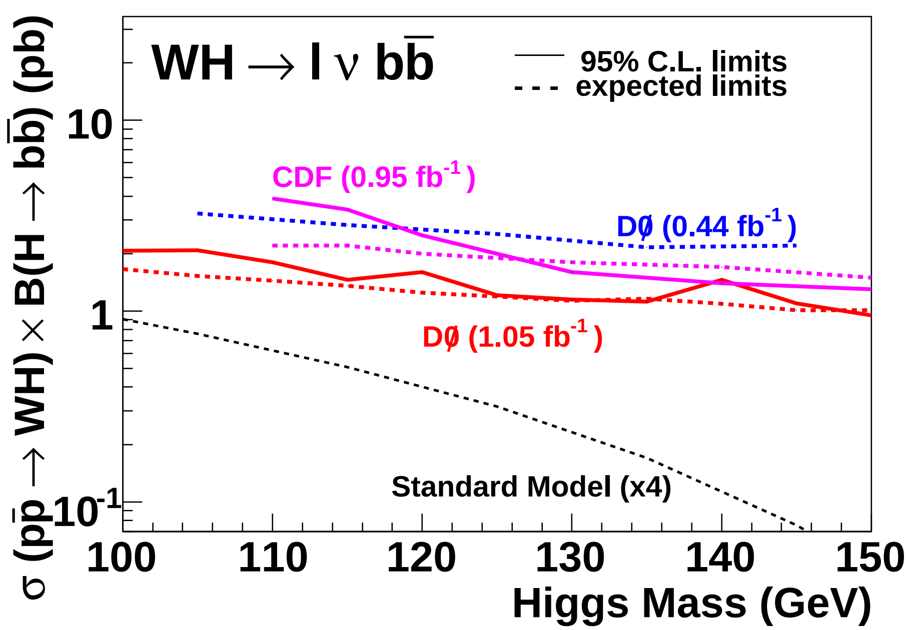
Associated production of SM Higgs with weak vector bosons

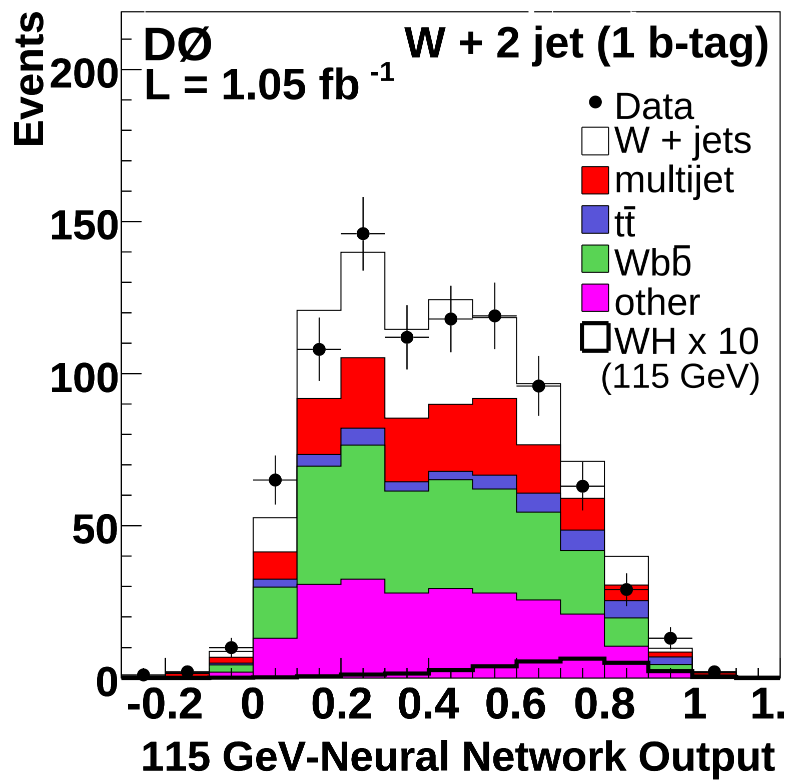


→ NNLO QCD corrections have been calculated for the signal [O.Brien, A.Djouadi and R.Harlander, 2004]

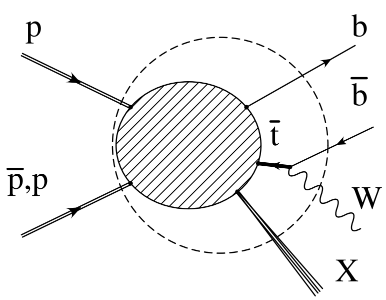
→ $O(\alpha)$ EW corrections have been calculated for the signal [M.L.Ciccolini, S.Dittmaier and M.Kramer, 2003]

→ Results for WH associated production, August 2008





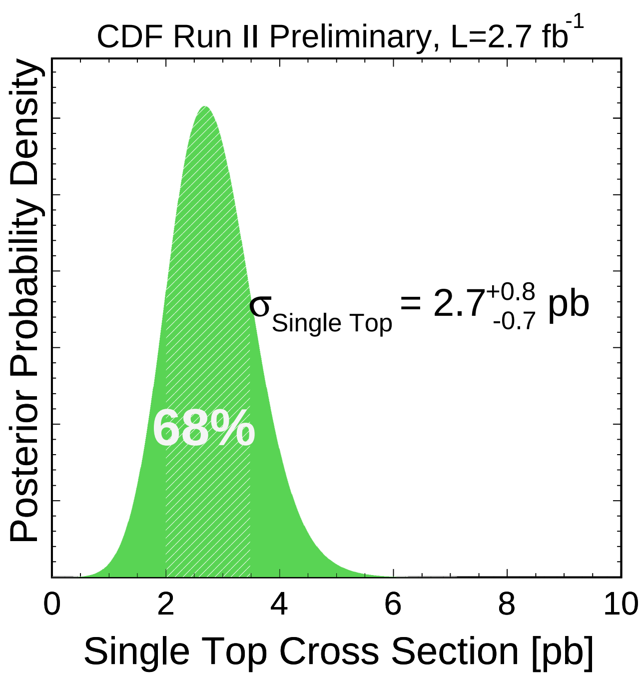
SM Single-Top production

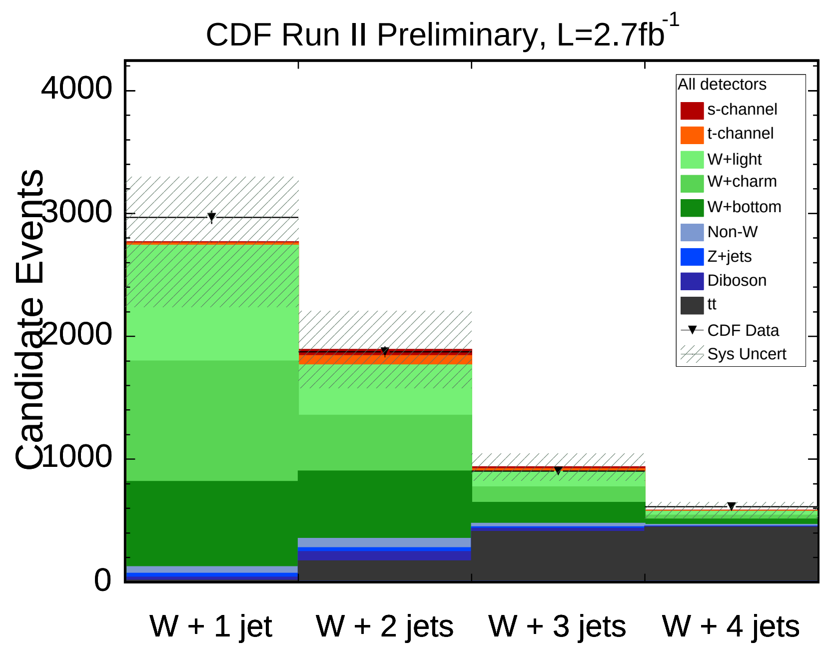


→ NLO QCD corrections have been thoroughly studied [T.Stelzer, Z.Sullivan and S.Willenbrock, 1998; B.W.Harris, E.Laenen, L.Phaf, Z.Sullivan and S.Weinzierl, 2002; . . .]

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

→ Summer 2008



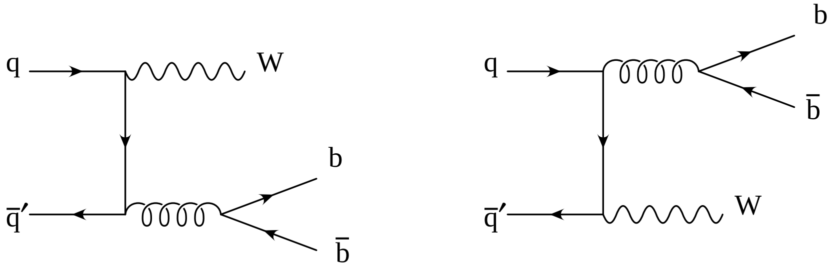


$Wb\bar{b}/Zb\bar{b}$ production at NLO, some history . . .

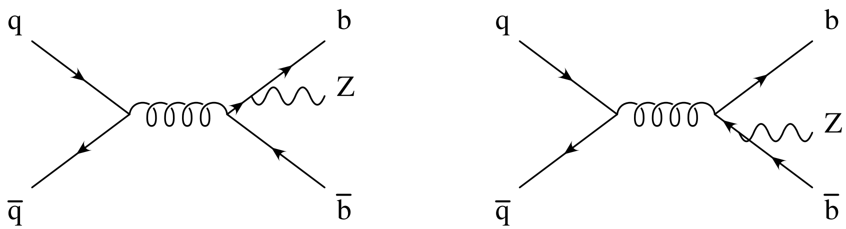
- $V \longrightarrow 4$ partons (1-loop massless amplitudes) (Bern, Dixon, Kosower (97))
- $p\bar{p}, pp \rightarrow Vb\bar{b}$ (at NLO, 4FNS, $m_b = 0$) (Campbell, Ellis (99))
- $p\bar{p}, pp \rightarrow Vb + j$ (at NLO, 5FNS) (Campbell, Ellis, Maltoni,Willenbrock (05,07))
- $p\bar{p}, pp \rightarrow Wb\bar{b}$ (at NLO, 4FNS, $m_b \neq 0$) (Febres Cordero, L.R., Wackeroth (06,09))
- $p\bar{p}, pp \rightarrow Zb\bar{b}$ (at NLO, 4FNS, $m_b \neq 0$) (Febres Cordero, L.R., Wackeroth (08,09))
- $p\bar{p}, pp \rightarrow W + 1\,b$-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

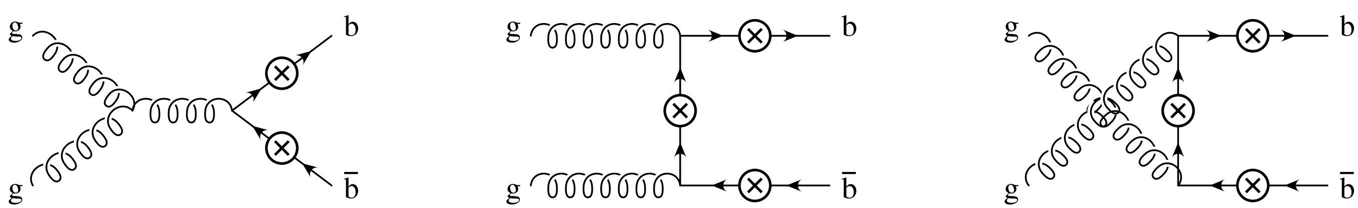
LO Feynman diagrams:



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



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



$gg \longrightarrow Zb\bar{b}$

Subprocesses at LO:

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

$\longrightarrow$ $Zb\bar{b}$: $q\bar{q} \rightarrow Zb\bar{b}$ and

$gg \rightarrow Zb\bar{b}$

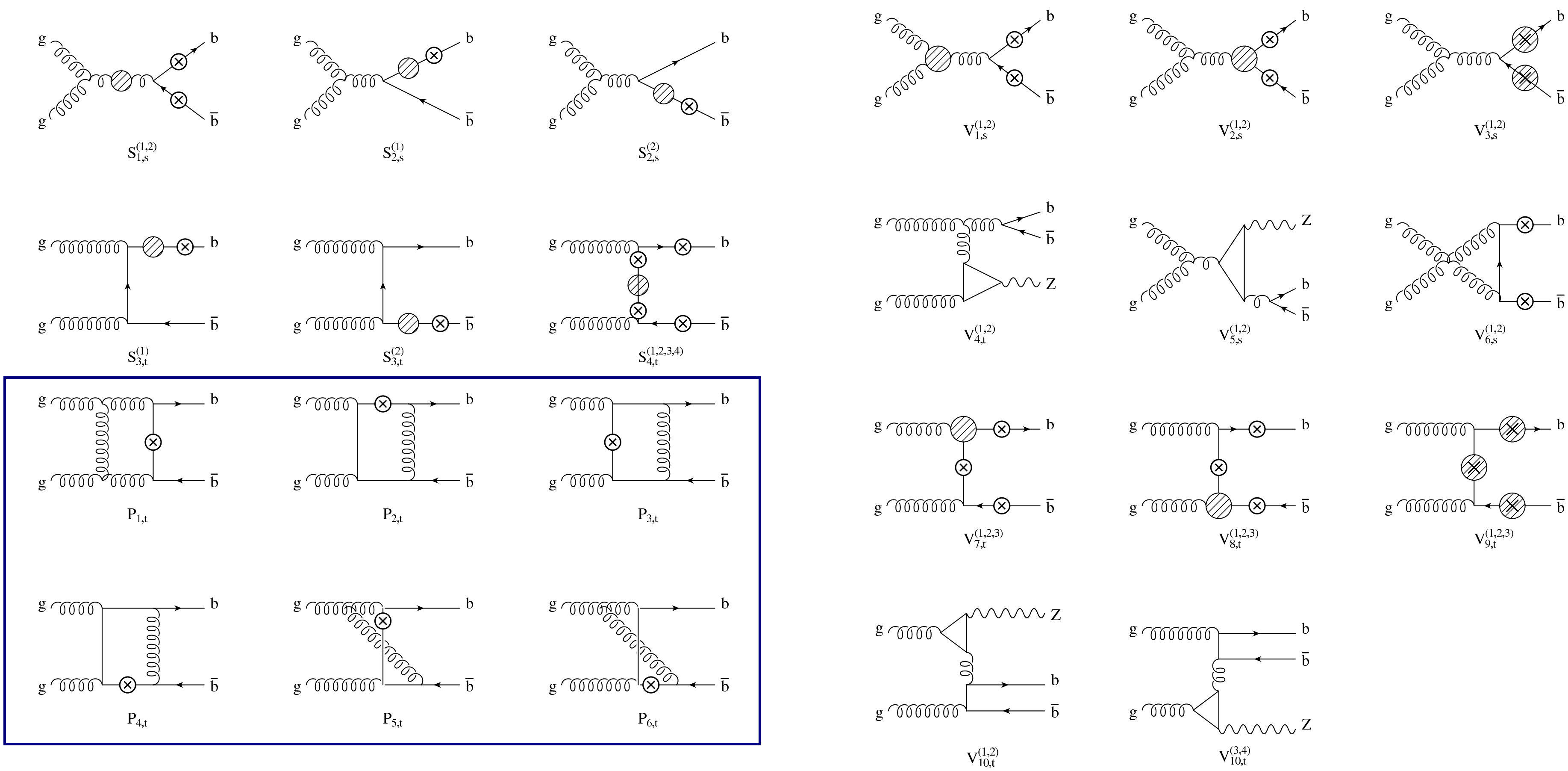
Including $O(\alpha_s)$ corrections

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

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

- 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 $q(\bar{q})g \to Zb\bar{b}+q(\bar{q})$

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



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

Virtual corrections: calculating $\hat{\sigma}_{ij}^{\text{virt}}$

$$\hat{\sigma}_{ij}^{\text{virt}} = \int d\,(PS_3)\,\overline{\sum}|\mathcal{A}_{\text{virt}}(ij \to W/Z\; b\bar{b})|^2$$

where:

$$\overline{\sum}|\mathcal{A}_{\text{virt}}(ij \to W/Z\; b\bar{b})|^2 = \sum_D \overline{\sum}\left(\mathcal{A}_0\mathcal{A}_D^\dagger + \mathcal{A}_0^\dagger\mathcal{A}_D\right) = \sum_D \overline{\sum} 2\mathcal{R}e\left(\mathcal{A}_0\mathcal{A}_D^\dagger\right)\;.$$

- $\longrightarrow$ Use dimensional regularization to regularize UV and IR divergencies.
- $\longrightarrow$ UV divergencies are canceled by a suitable set of counterterms.
- $\longrightarrow$ Calculate each diagram as linear combination of Dirac structures with coefficients that depend on both tensor and scalar integrals.
- $\longrightarrow$ Tensor integrals reduced analytically to scalar integrals and organized to avoid spurious divergences due to appearance of inverse power of Gram Determinant.
- $\longrightarrow$ IR divergencies will cancel with $\hat{\sigma}_{ij}^{\text{real}}$.

Checking boxes and pentagons using unitarity methods.

The one-loop amplitude can be written as

$$\mathcal{A}_{\text{virt}} = \sum_i d_i I_4^i + \sum_i c_i I_3^i + \sum_i b_i I_2^i + \sum_i a_i I_1^i + R$$

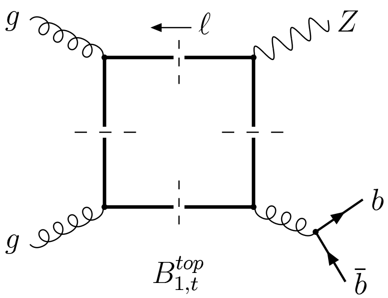
$\longrightarrow$ tadpoles, bubbles and vertices are easy in FD's language;

$\longrightarrow$ 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: calculating $\hat{\sigma}_{ij}^{\text{real}}$

$$\hat{\sigma}_{ij}^{\text{real}} = \int d\,(PS_4)\,\overline{\sum}|\mathcal{A}_{\text{real}}(ij \to W/Z\; b\bar{b} + k)|^2$$

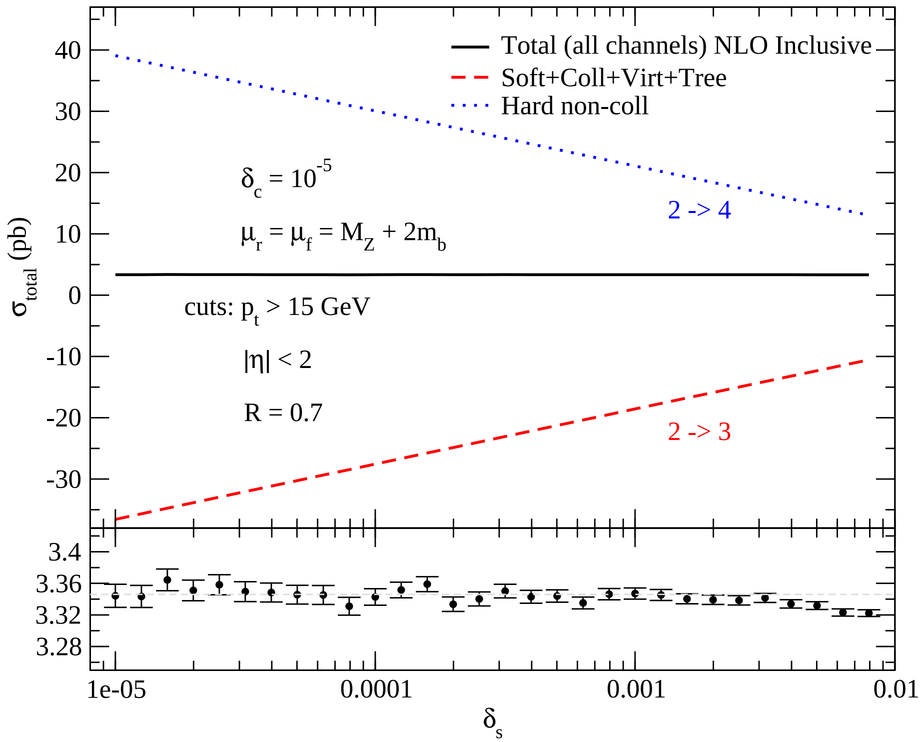
$\longrightarrow$ IR divergencies associated with the integration over the PS of the extra parton, can be extracted using the so called Phase Space Slicing (PSS) method with *two cutoffs*.

$\longrightarrow$ PSS with two cutoffs uses two unphysical parameters, δ_s and δ_c to isolate soft and collinear divergent regions, where IR singularities are extracted analytically.

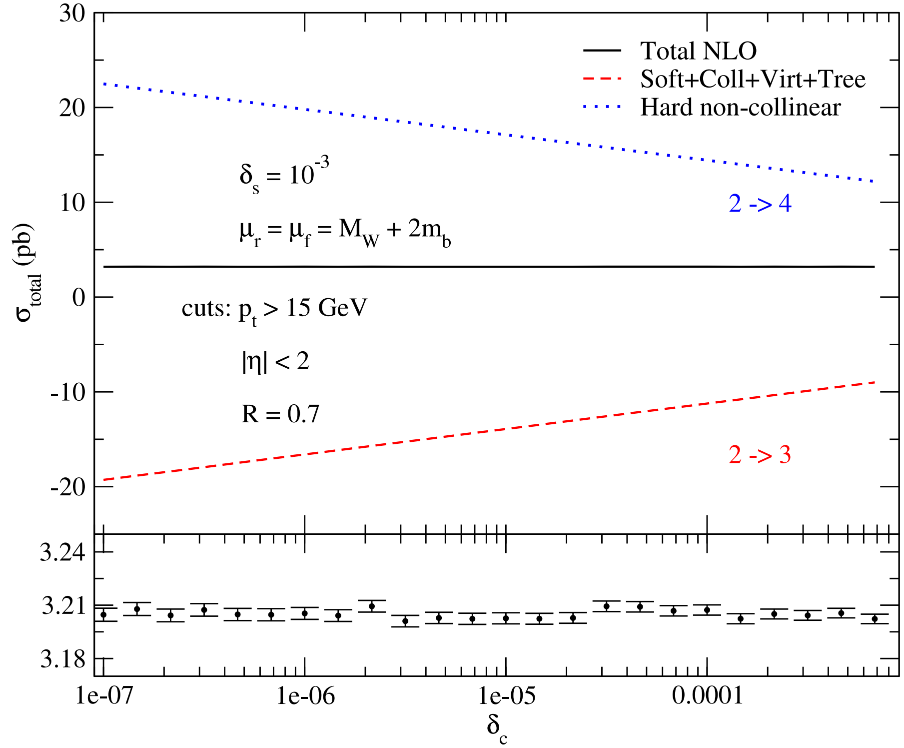
$\longrightarrow$ Same soft/collinear structure as $Ht\bar{t}/Hb\bar{b}$, tested against one-cutoff PSS and dipole subtraction method.

$\longrightarrow$ Physical quantities are independent of δ_s and δ_c, for small enough values of these parameters.

Check independence of the total cross section of δ_s and δ_c cuts



δ_s-dep. for the $Zb\bar{b}$ total cross section



δ_c-dep. for the $Wb\bar{b}$ total cross section

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

$\longrightarrow$ Results obtained fixing $\delta_s = 10^{-3}$ and $\delta_c = 10^{-5}$

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

Febres Cordero, L.R., Wackeroth (06-09)

- We use the k_T jet algorithm with $R = 0.7$ and study two cases:
  - $\longrightarrow$ Inclusive Cross Section: events with two $(b + \bar{b})$ or three $(b + \bar{b} + j)$ jets resolved contribute to the cross section.
  - $\longrightarrow$ 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:
  - $\longrightarrow$ Transverse momentum of the b-jets: $p_t > p_{t,\,min}$ (15-25 GeV) for both b and $\bar{b}$ jets.
  - $\longrightarrow$ 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.

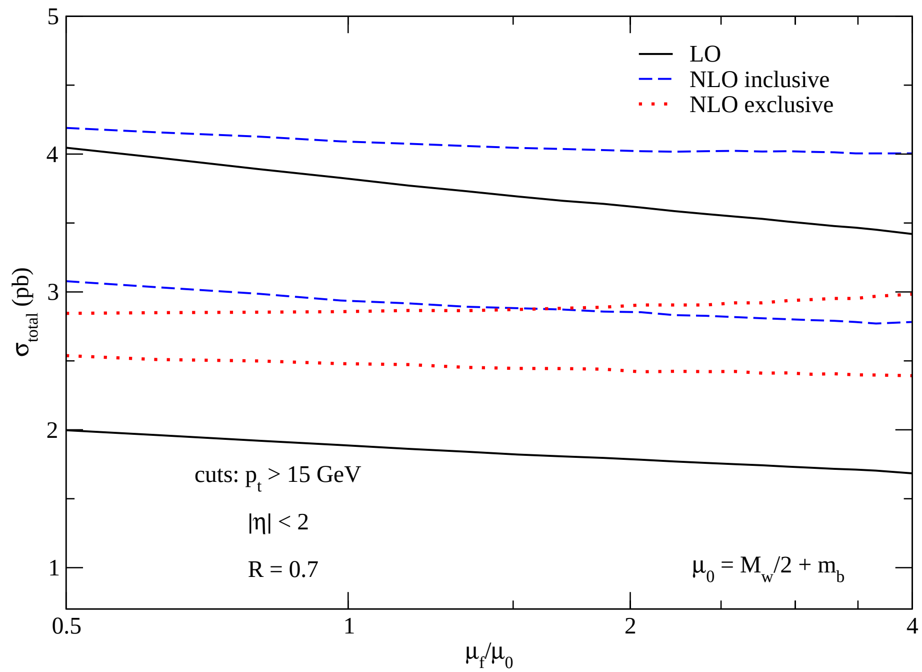
Tevatron: summary of LO and NLO total cross sections

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

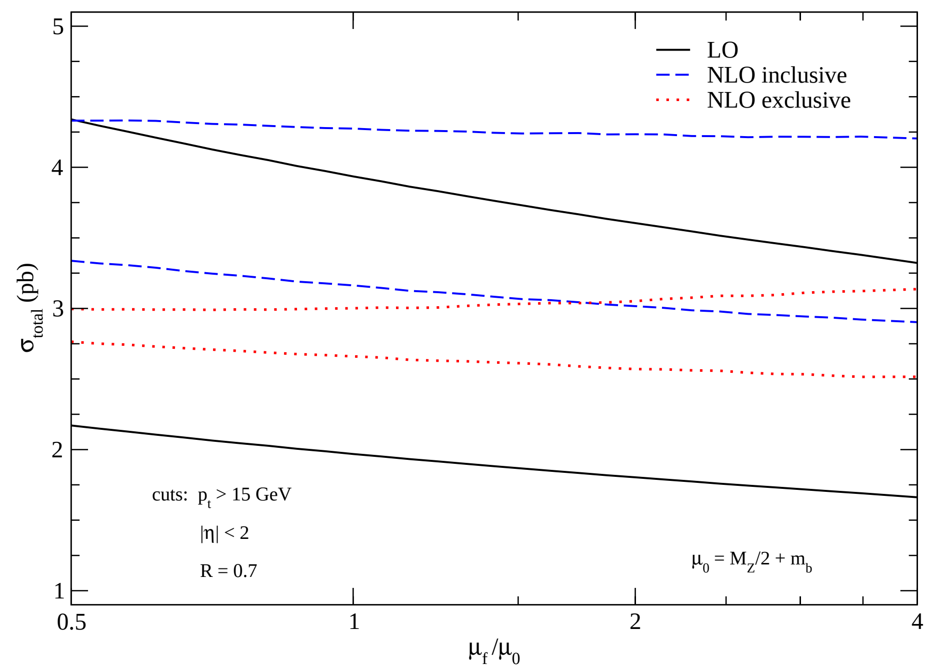
Cross Section, $Wb\bar{b}$	$m_b \neq 0$ (pb) [ratio]	$m_b = 0$ (pb) [ratio]
σ^{LO}	2.20[-]	2.38[-]
σ^{NLO} inclusive	3.20[1.45]	3.45[1.45]
σ^{NLO} exclusive	2.64[1.2]	2.84[1.2]

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

Tevatron: scale dependence and theoretical uncertainty at NLO



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

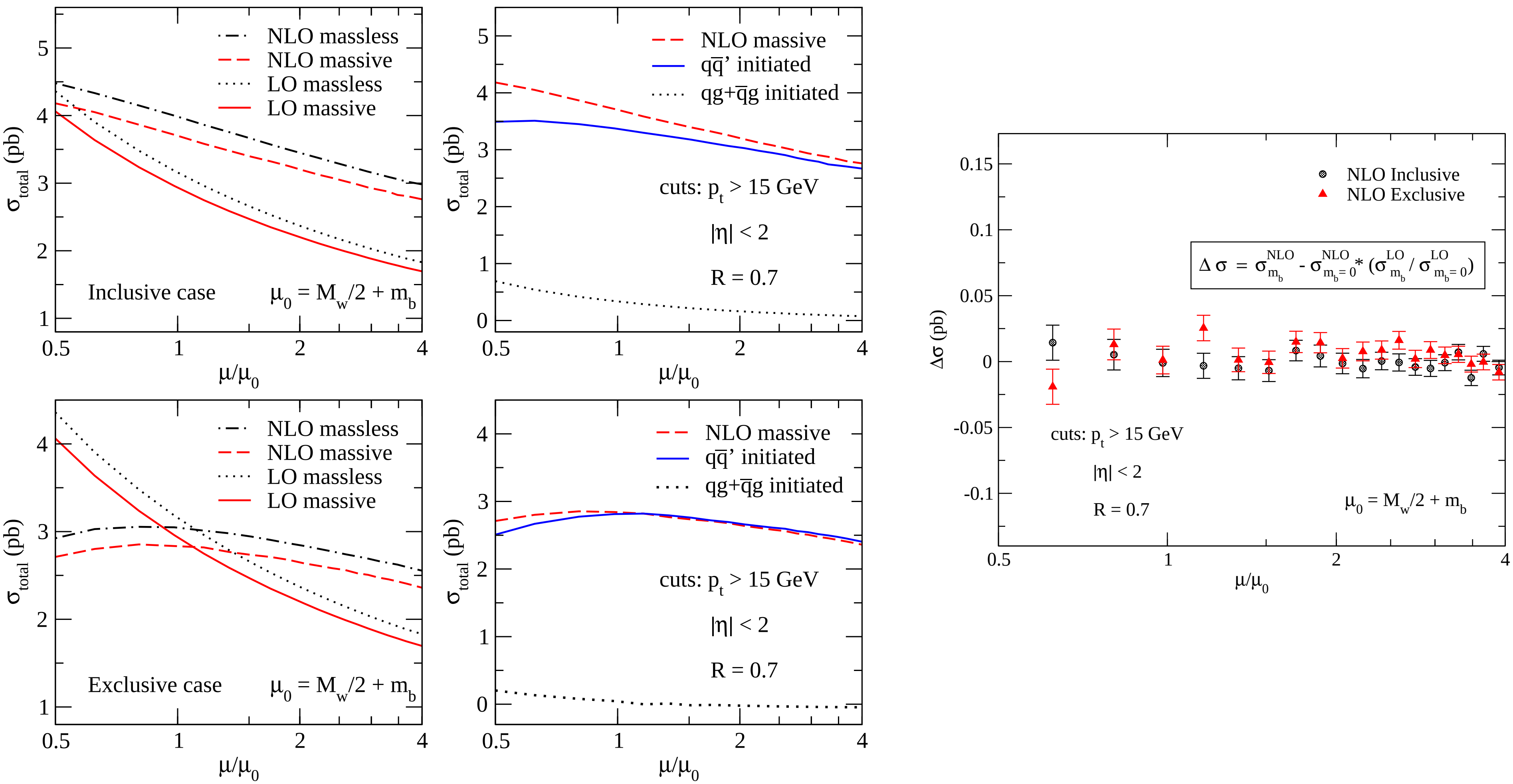


$Zb\bar{b}$: Tevatron (PRD 78 (2008) 074014)

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

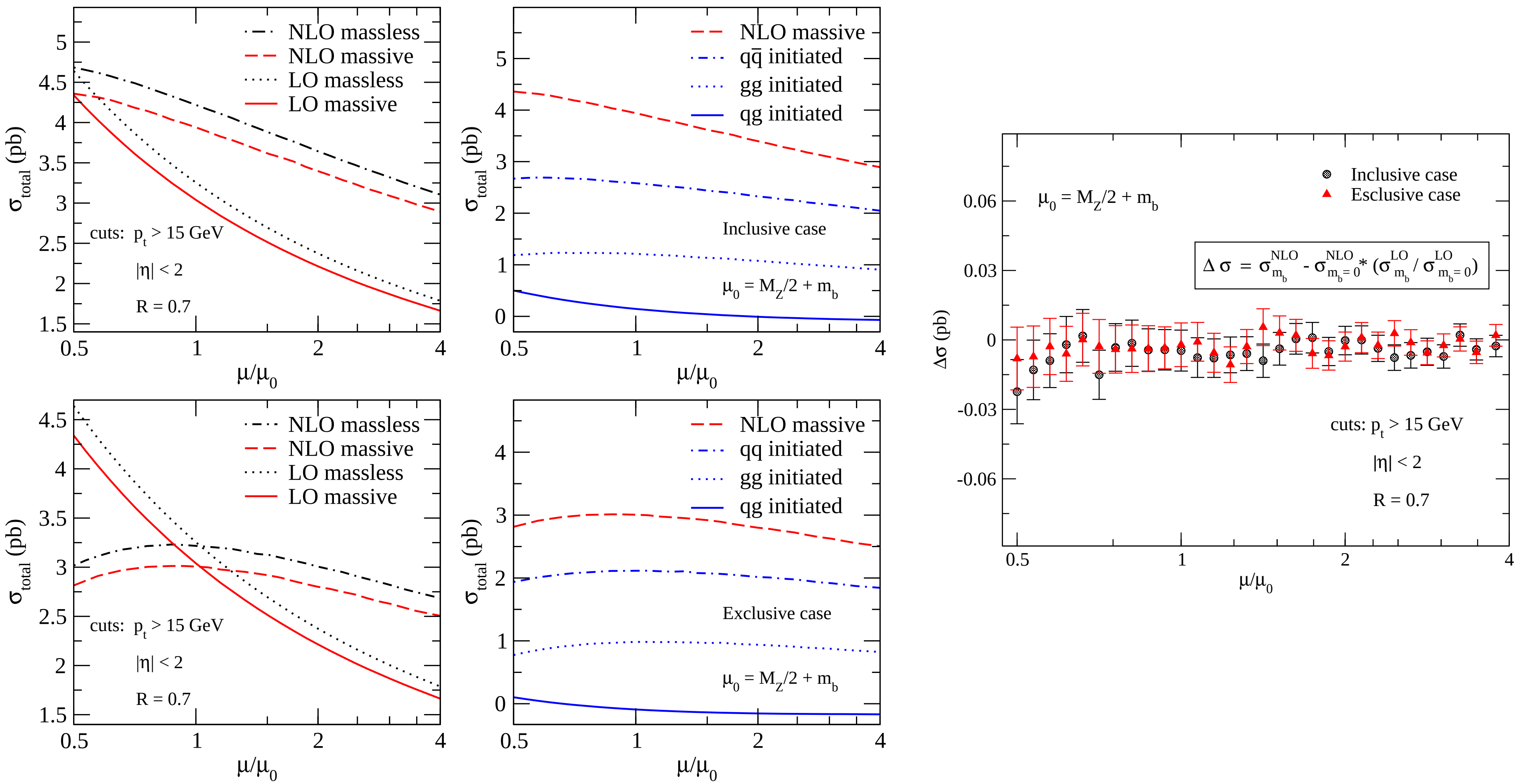
- LO uncertainty $\sim 40\%$.
- Inclusive NLO uncertainty $\sim 20\%$.
- Exclusive NLO uncertainty $\sim 10\%$.

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



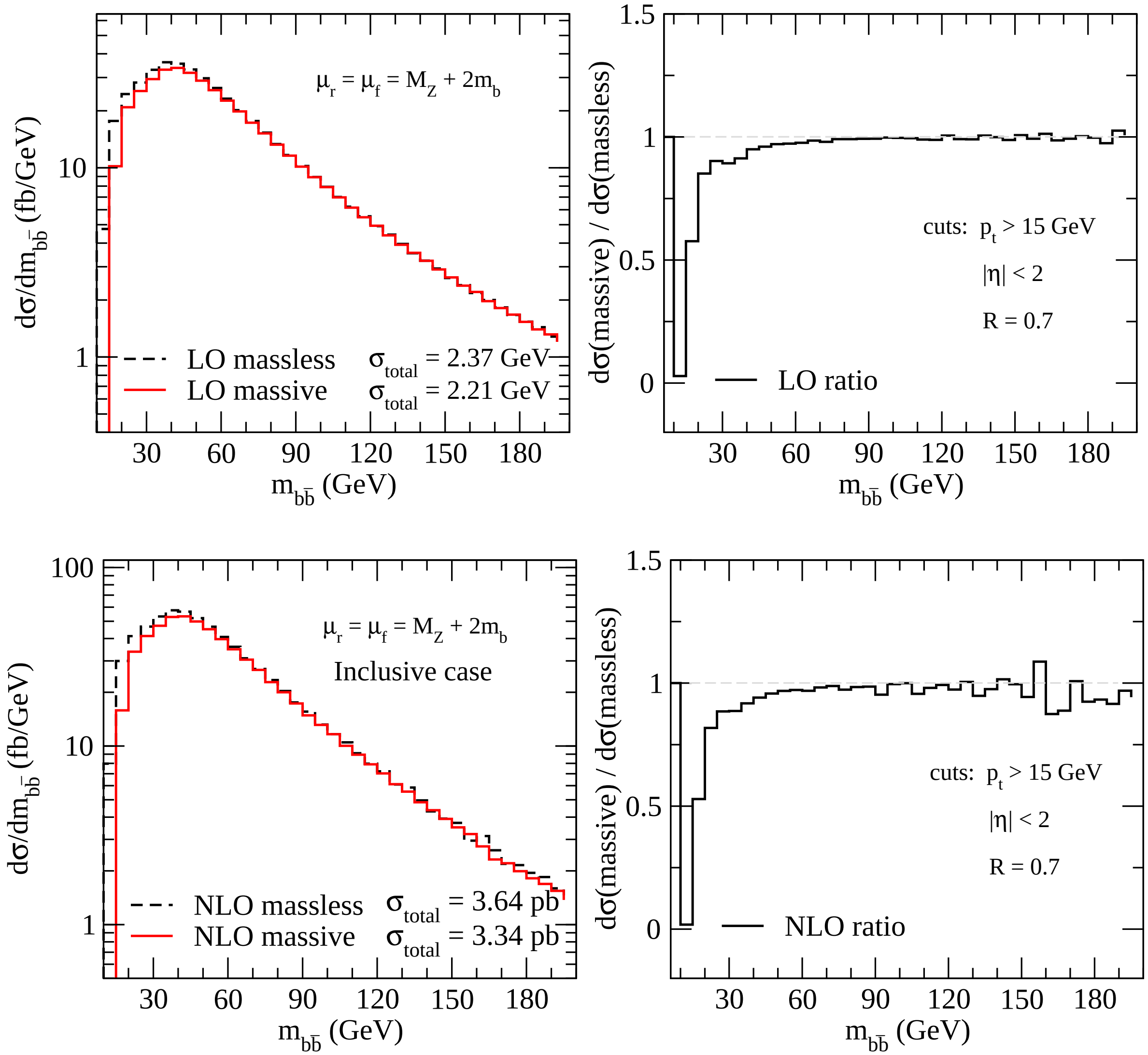
(PRD 78 (2008) 074014)

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



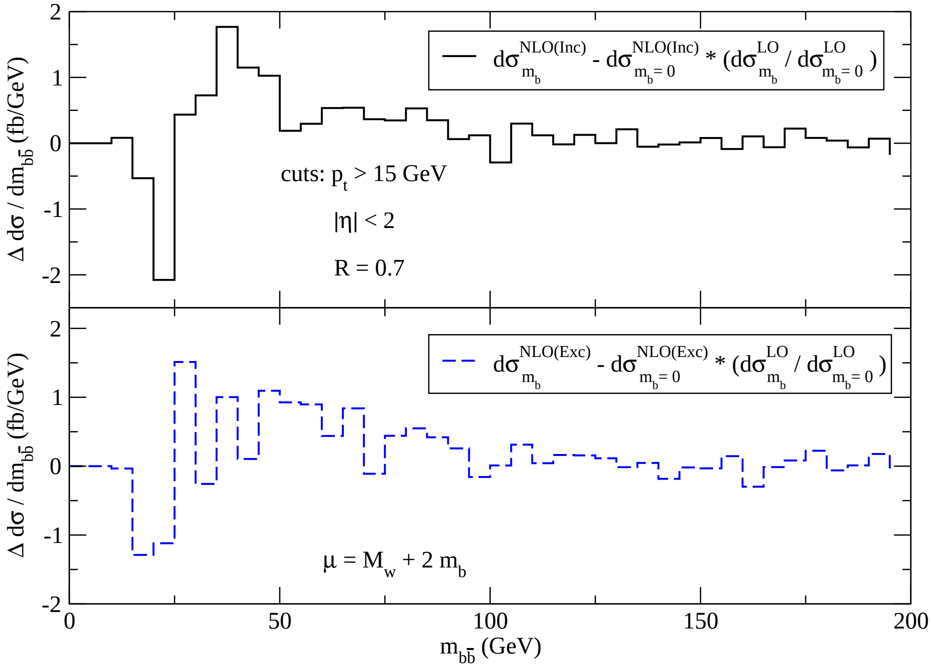
(PRD 78 (2008) 074014)

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

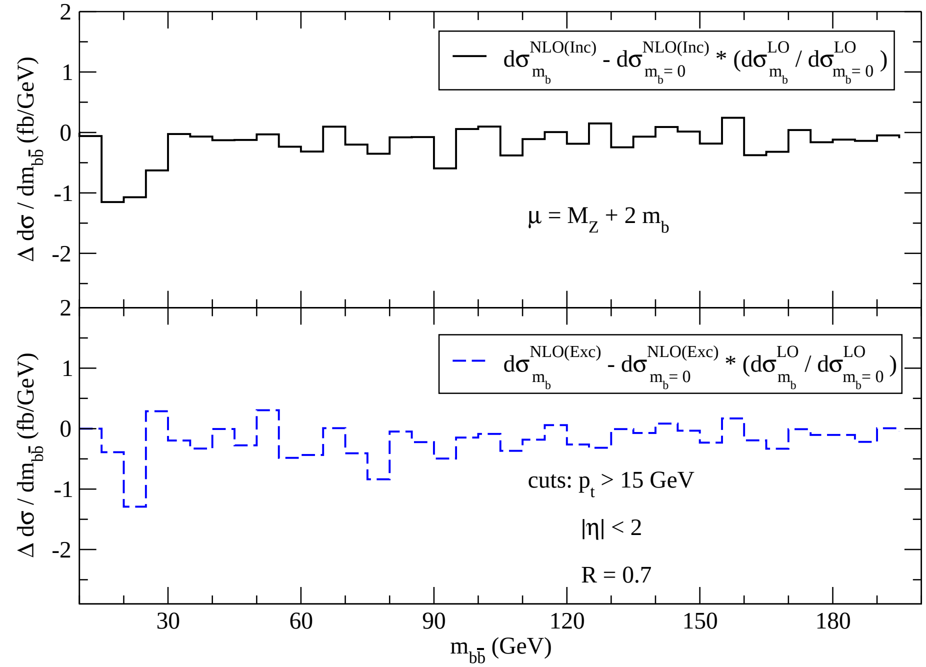


(PRD 78 (2008) 074014)

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



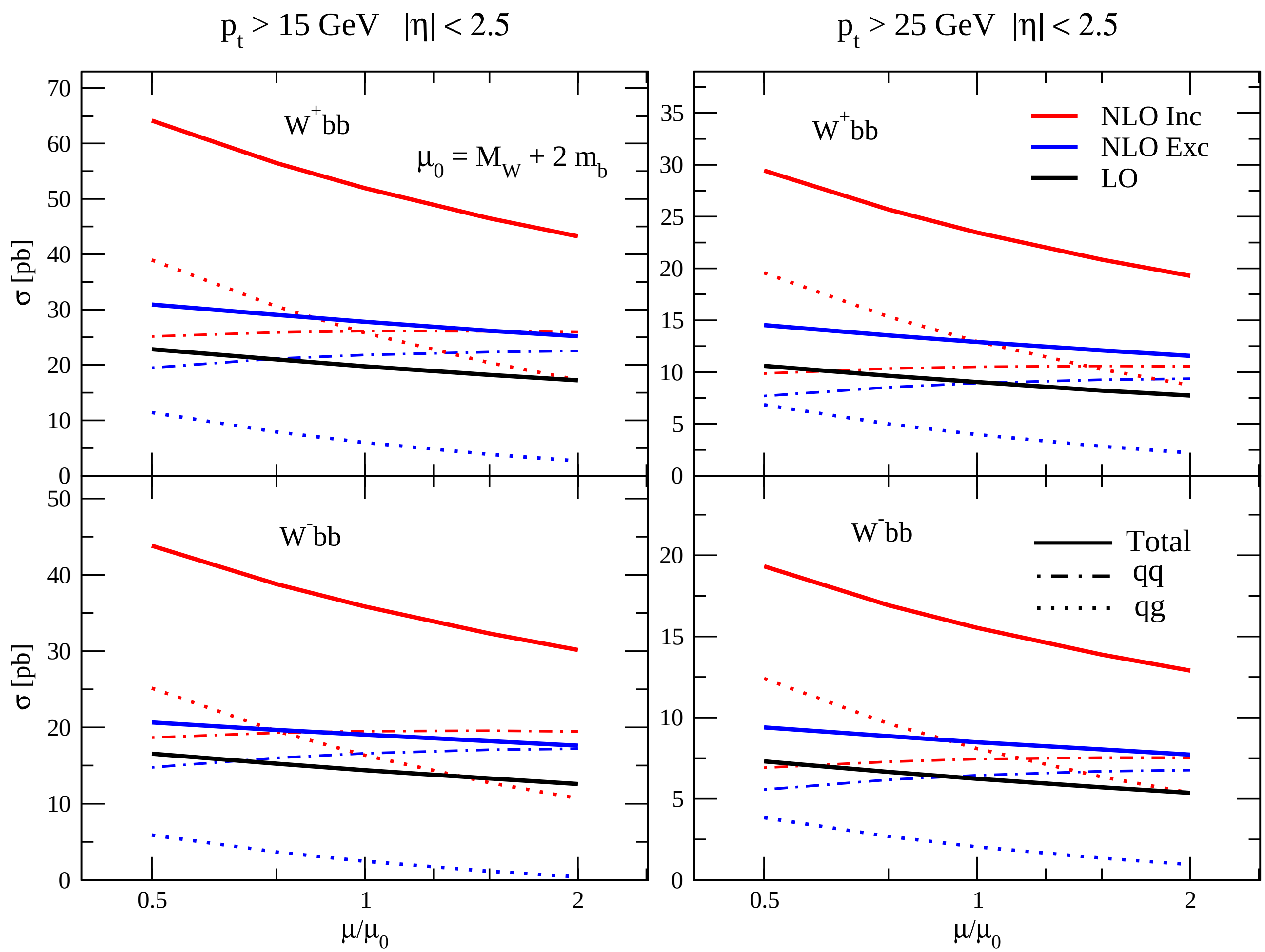
$Wb\bar{b}$: PRD 74 (2006) 034007



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

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

LHC: scale dependence and theoretical uncertainty at NLO

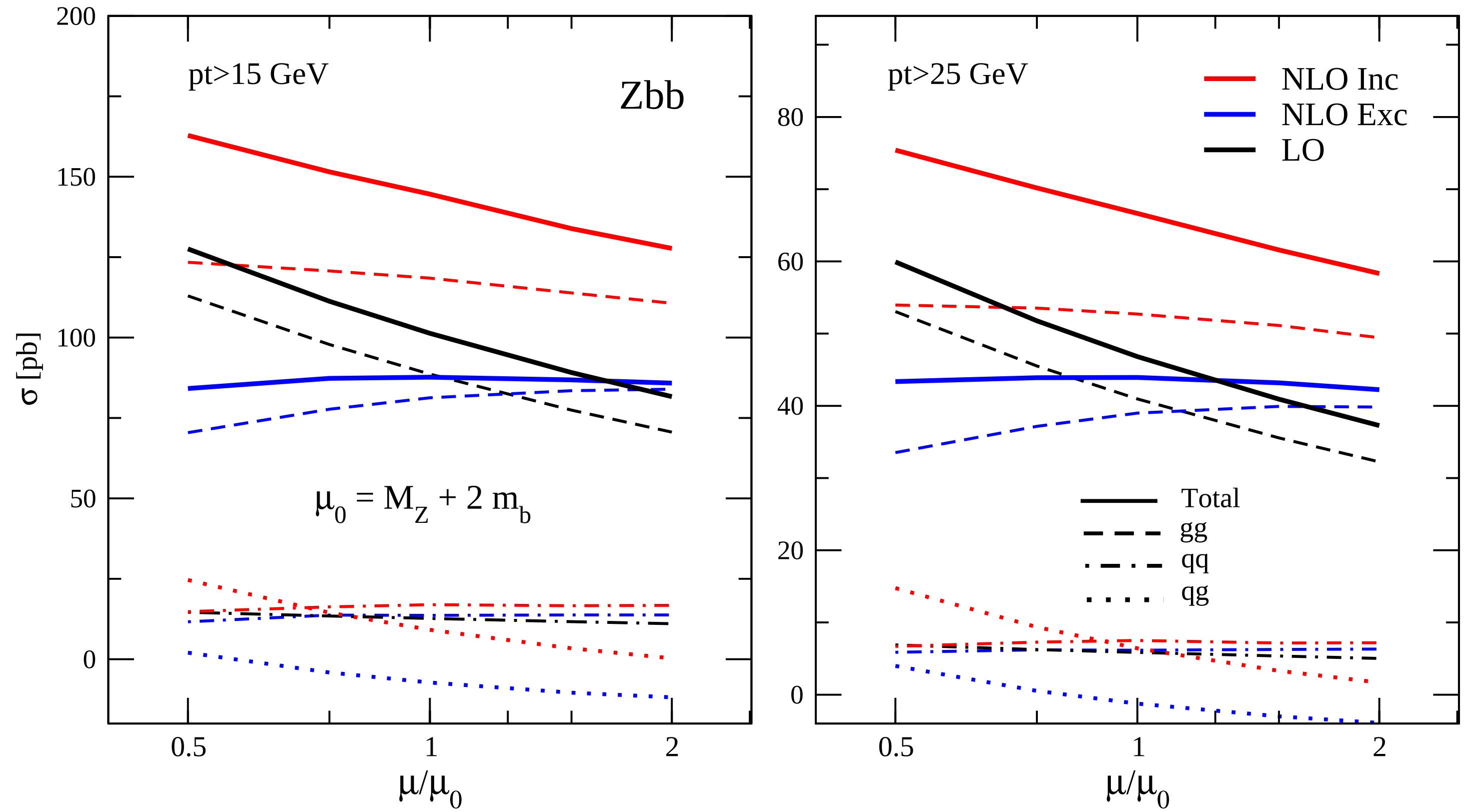


(PRD 80:034015, 2009)

⟶ NLO corrections very large, particularly for inclusive production;

⟶ large NLO scale-dependence (LO: 30%, NLO_{inc}: 50%, NLO_{exc}: 20%), induced by the opening of the $qg(\bar{q}g) \rightarrow Wb\bar{b} + q'(\bar{q}')$ channel;

⟶ theoretical uncertainty not only given by scale-dependence!



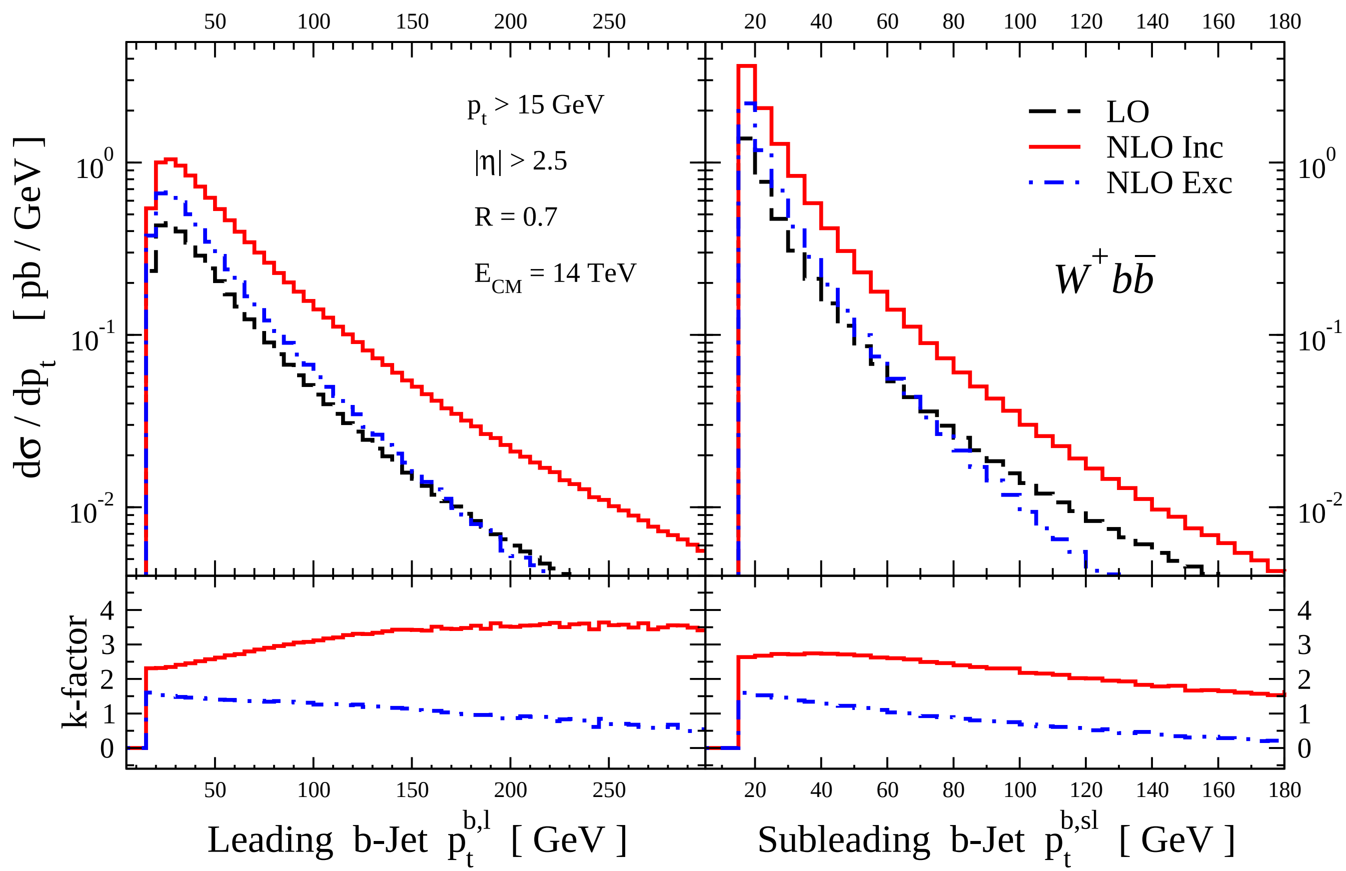
⟶ NLO corrections still large, particularly for inclusive production;

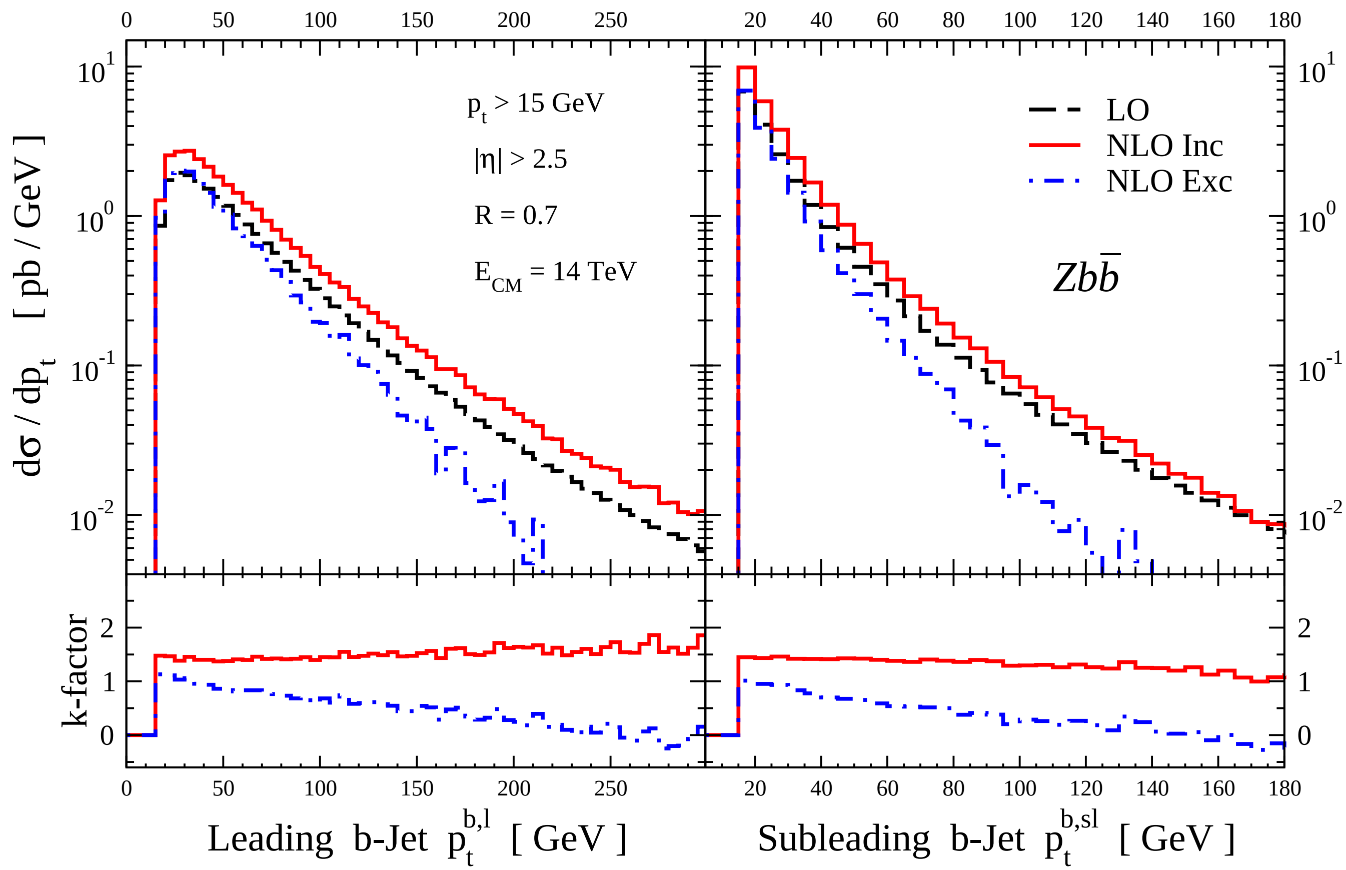
⟶ more moderate NLO scale-dependence (LO: 50%, NLO_{inc}: 30%, NLO_{exc}: 5%): $qg(\bar{q}g) \to Zb\bar{b} + q(\bar{q})$ channel not as dominant.

	$W^+b\bar{b}$			
	$m_b \neq 0$	$m_b = 0$	$m_b \neq 0$	$m_b = 0$
	$p_T^b > 15$ GeV		$p_T^b > 25$ GeV	
	$\sqrt{s} = 10$ TeV			
σ_{LO} (pb)	$14.4^{+2.6}_{-2.1}$	$15.5^{+2.7}_{-2.2}$	$6.49^{+1.3}_{-1.0}$	$6.67^{+1.3}_{-1.1}$
$\sigma_{NLO,inc}$ (pb)	$33.6^{+7.8}_{-5.6}$	$36.4^{+8.1}_{-6.2}$	$14.6^{+3.6}_{-2.5}$	$15.1^{+3.6}_{-2.7}$
$\sigma_{NLO,exc}$ (pb)	$18.6^{+1.7}_{-1.6}$	$20.3^{+1.7}_{-1.8}$	$8.37^{+0.84}_{-0.77}$	$8.67^{+0.85}_{-0.87}$
	$\sqrt{s} = 14$ TeV			
σ_{LO} (pb)	$19.8^{+3.1}_{-2.5}$	$21.3^{+3.2}_{-2.7}$	$9.02^{+1.6}_{-1.3}$	$9.26^{+1.6}_{-1.3}$
$\sigma_{NLO,inc}$ (pb)	$51.9^{+12}_{-8.7}$	$56.3^{+13}_{-9.6}$	$23.4^{+6.0}_{-4.2}$	$24.3^{+5.9}_{-4.5}$
$\sigma_{NLO,exc}$ (pb)	$27.8^{+3.1}_{-2.5}$	$30.4^{+3.5}_{-2.8}$	$12.9^{+1.6}_{-1.3}$	$13.4^{+1.6}_{-1.5}$

	$Zb\bar{b}$			
	$p_T^b > 15$ GeV		$p_T^b > 25$ GeV	
	$m_b \neq 0$	$m_b = 0$	$m_b \neq 0$	$m_b = 0$
	$\sqrt{s} = 10$ TeV			
σ_{LO} (pb)	55.1^{+16}_{-12}	57.6^{+18}_{-13}	$24.6^{+7.6}_{-5.4}$	$25.1^{+8.4}_{-5.9}$
$\sigma_{NLO,inc}$ (pb)	82.5^{+12}_{-11}	84.5^{+14}_{-12}	$36.0^{+3.9}_{-4.6}$	$36.1^{+6.4}_{-5.2}$
$\sigma_{NLO,exc}$ (pb)	$52.1^{+0.0}_{-1.7}$	$53.5^{+0.2}_{-2.4}$	$24.6^{+0.3}_{-1.2}$	$24.7^{+0.3}_{-1.6}$
	$\sqrt{s} = 14$ TeV			
σ_{LO} (pb)	101^{+26}_{-20}	106^{+30}_{-22}	$46.8^{+13.1}_{-9.6}$	$46.8^{+12.7}_{-9.9}$
$\sigma_{NLO,inc}$ (pb)	145^{+20}_{-17}	148^{+24}_{-19}	$66.6^{+8.8}_{-8.3}$	$66.1^{+10.5}_{-9.1}$
$\sigma_{NLO,exc}$ (pb)	$88.4^{+0.0}_{-3.0}$	$90.0^{+0.0}_{-1.6}$	$43.7^{+0.0}_{-1.6}$	$43.5^{+0.4}_{-1.9}$

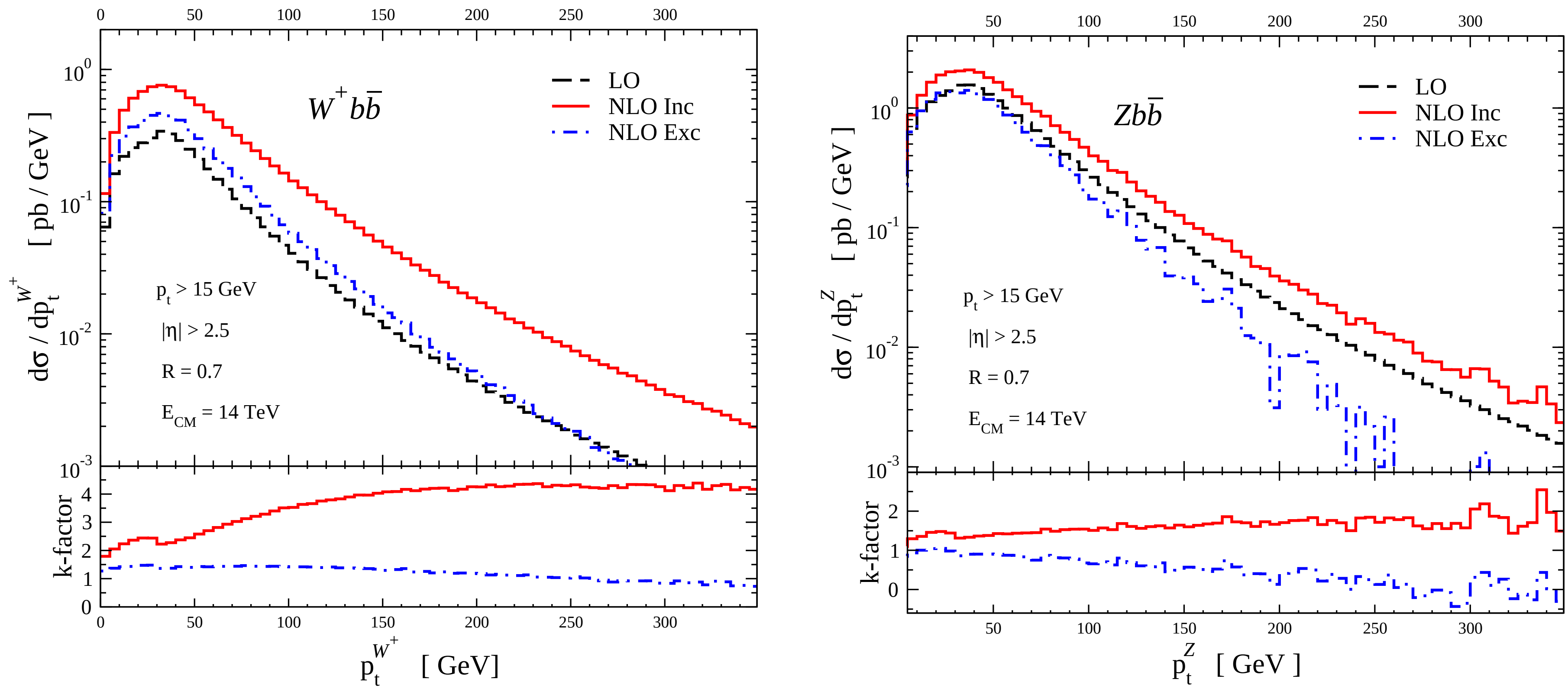
LHC: some interesting NLO distributions . . .





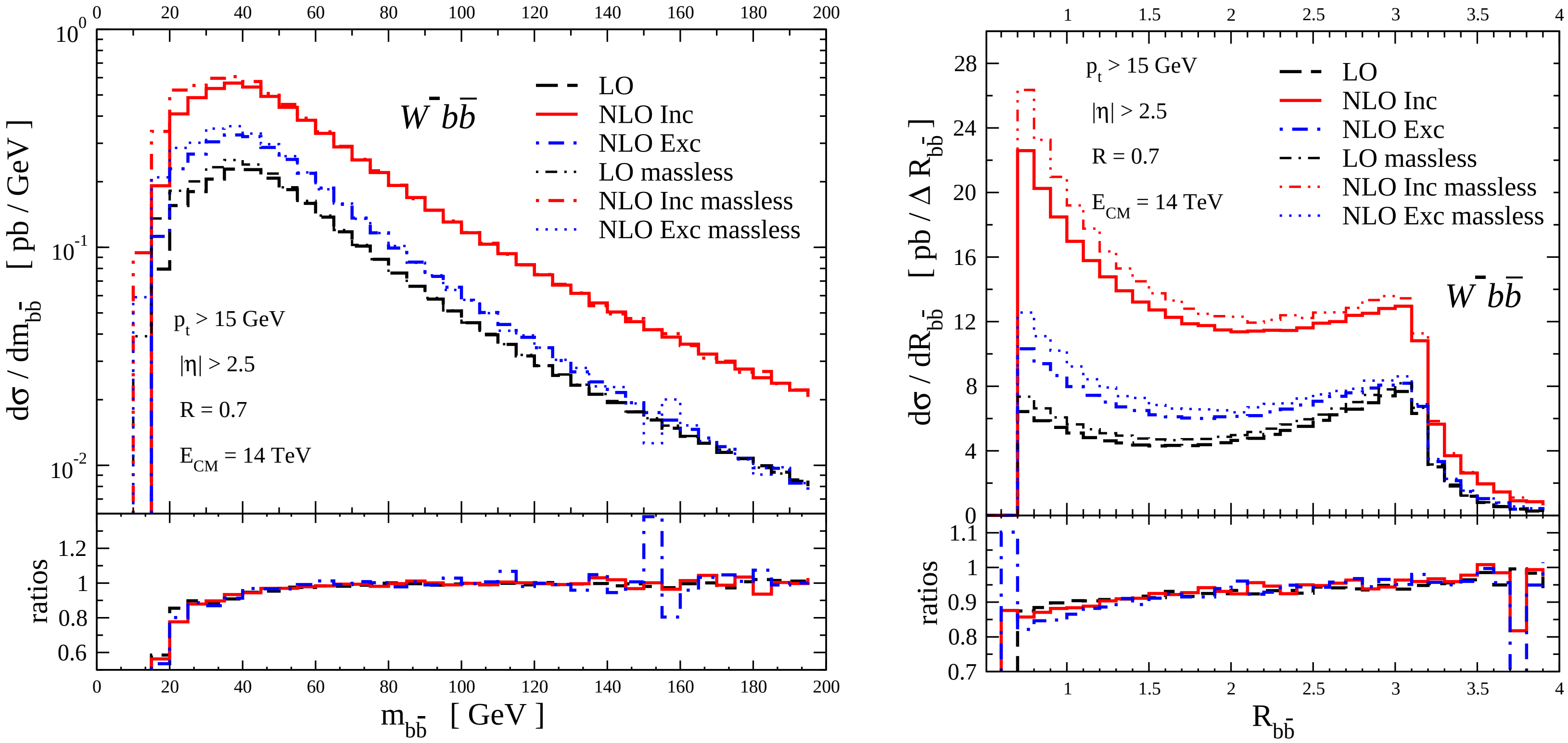
⟶ NLO distributions cannot be rescaled from LO ones via a K-factor;

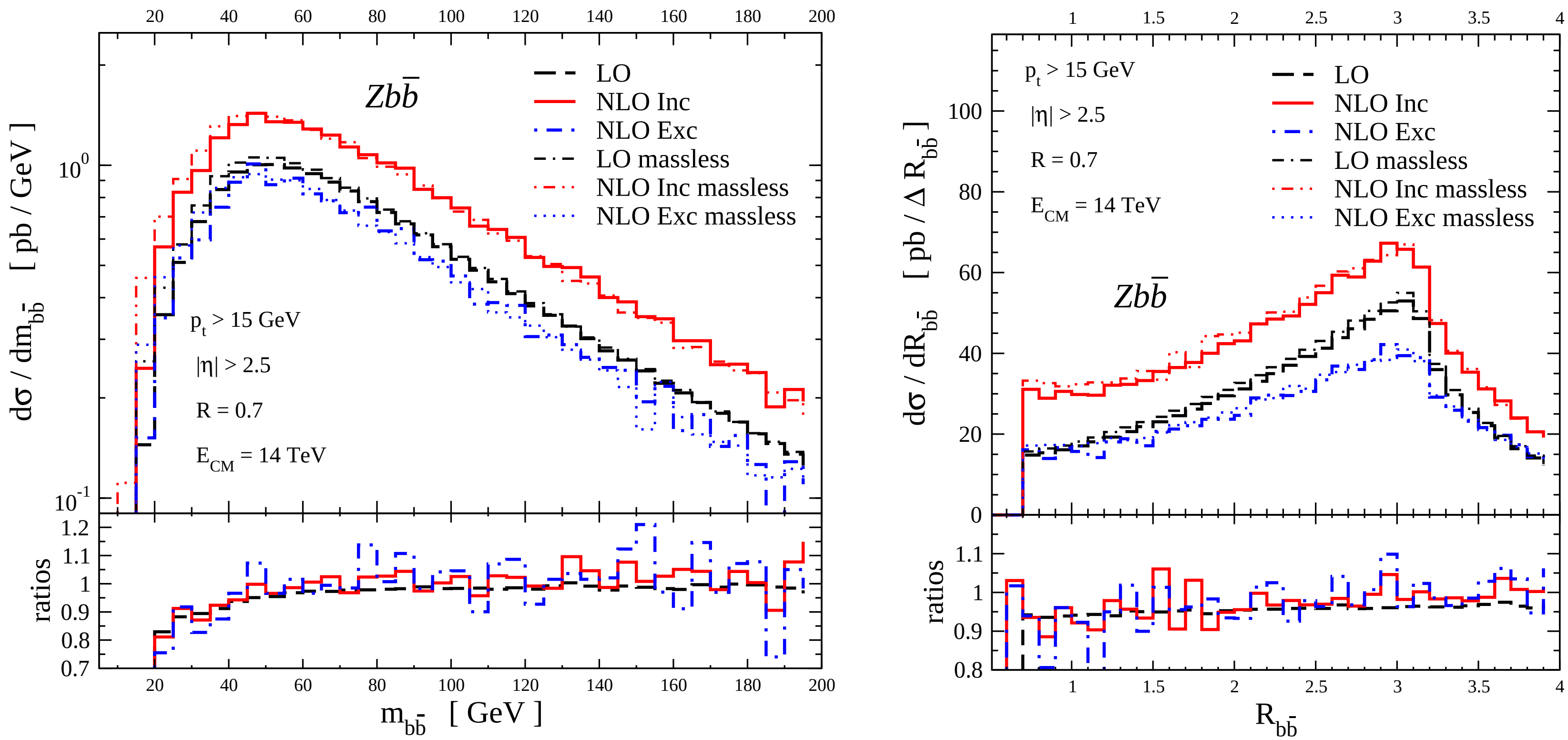
⟶ large corrections in particular for $Wb\bar{b}$ and in the inclusive case.



$W^+ b\bar{b}$
LO
NLO Inc
NLO Exc
p_t > 15 GeV
$|\eta|$ > 2.5
R = 0.7
E_{CM} = 14 TeV
$d\sigma / dp_t^{W^+}$ [pb / GeV]
k-factor
$p_t^{W^+}$ [GeV]
$Zb\bar{b}$
LO
NLO Inc
NLO Exc
p_t > 15 GeV
$|\eta|$ > 2.5
R = 0.7
E_{CM} = 14 TeV
$d\sigma / dp_t^{Z}$ [pb / GeV]
k-factor
p_t^{Z} [GeV]

Comparison with massless b-quark results ...





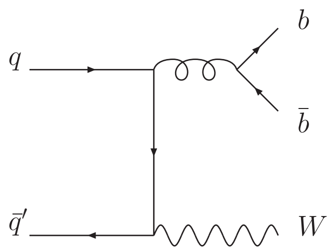
$Zb\bar{b}$
LO
NLO Inc
NLO Exc
LO massless
NLO Inc massless
NLO Exc massless
$p_t > 15$ GeV
$|\eta| > 2.5$
R = 0.7
E_{CM} = 14 TeV
$d\sigma / dm_{b\bar{b}}$ [pb / GeV]
$m_{b\bar{b}}$ [GeV]
ratios
$d\sigma / dR_{b\bar{b}}$ [pb / $\Delta R_{b\bar{b}}$]
$R_{b\bar{b}}$

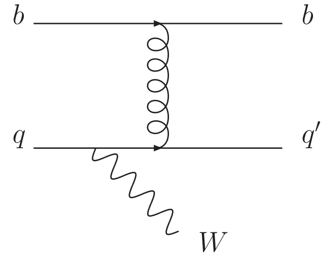
$W + 1\, b$-jet

Campbell, Ellis, Febres Cordero, Maltoni, L.R., Wackeroth, Willenbrock

(PRD 79:034023, 2009)

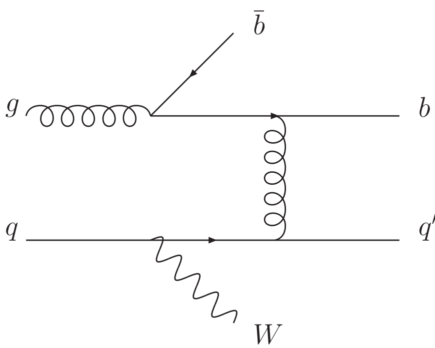
Consistently combine 4FNS ($m_b \neq 0$) and 5FNS ($m_b = 0$) at NLO in QCD:



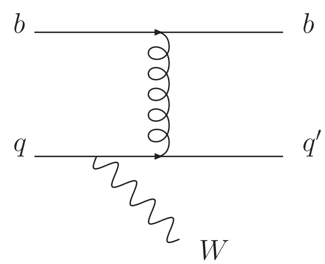


$+ \quad O(\alpha_s)$ corrections

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



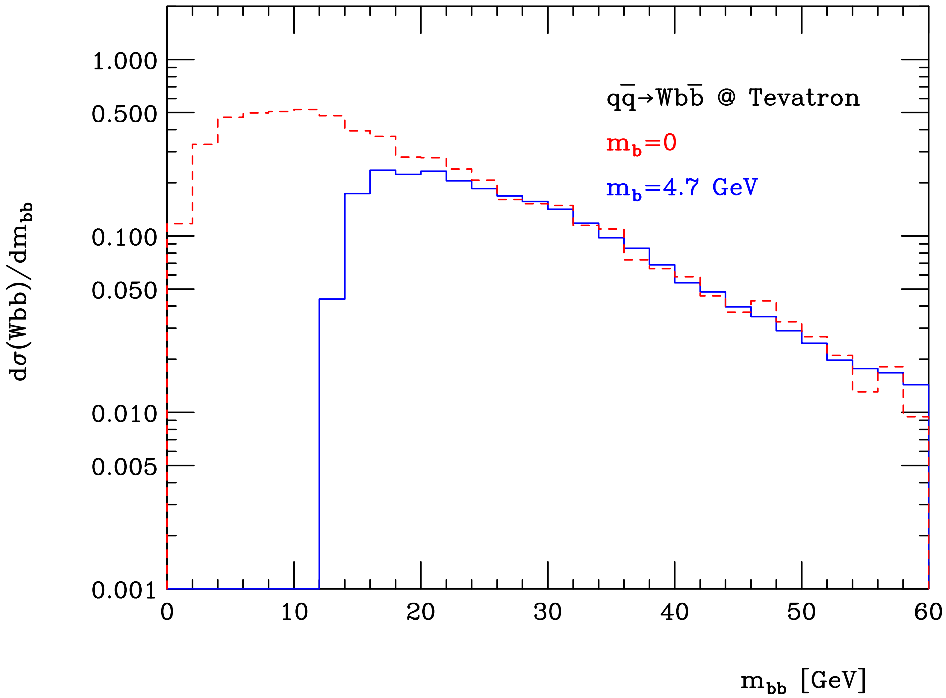
$\longrightarrow$



$$b(x,\mu) = \frac{\alpha_s}{2\pi} \ln \frac{\mu^2}{m_b^2} \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) g(y,\mu)$$

$\longrightarrow$ indeed: a fully consistent NLO 5FNS calculation (S-ACOT scheme).

- improved scale dependence: NLO corrections to $gq \rightarrow Wb\bar{b}q'$ 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 $\Delta R = 0.7$:
  - $\longrightarrow$ Wb, $W(b\bar{b})$ (exclusive)
  - $\longrightarrow$ 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 ($qg \to Wb\bar{b}+q'$)

Comparison with CDF measurement: a puzzle?

CDF Note 9321:

$$\sigma_{\rm b-jet}(W + b\,\text{jets}) \cdot Br(W \to l\nu) = 2.74 \pm 0.27(\text{stat}) \pm 0.42(\text{syst})\ \text{pb}$$

(Neu, Thomson, Heinrich)

ALPGEN prediction: 0.78 pb

From our $W + 1b$ calculation:

$$\sigma_{\rm b-jet}(W + b\,\text{jets}) \cdot Br(W \to l\nu) = 1.22 \pm 0.14\ \text{pb}$$

$\longrightarrow$ consistency of theoretical results (good!);

$\longrightarrow$ waiting for experimental distributions to compare to;

$\longrightarrow$ important to have a separate analysis from $D0$!

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

- Provide input to experimental studies:
  - ▷ DØ, CDF: $W+b$ study, Higgs and single-top working groups;
  - ▷ CMS Higgs working group: provide parton level distributions with specific cuts and interface with NLO parton shower Monte Carlo (POWHEG):
    - → study $Z+2b$ as background to $H\to ZZ$ inclusive production;
    - → study $Z+2b$ and $Z+1b$ to measure b-PDF.
  - ▷ ATLAS study of WH with $H\to b\bar{b}$ in boosted regime (Butterworth, Piacquadio, et al.).

- $Z+1b$-jet using both 4FNS with $m_b\neq 0$ and 5FNS NLO calculations:
  - ▷ $bg\to Zb$ 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 $m_b\neq 0$).

  quite different pattern: one loop corrections to $q\bar{q},gg\to b\bar{b}Z$ are now a piece of the NNLO 5FNS calculation, comparable to two-loop corrections to (and double parton emission from) $bg\to Zb$ (?)

- Possible to use $Z + 1b$ to measure b-PDF? $\longrightarrow$ reduce the PDF error in $H + 1b$ production?
- Resum large final state collinear logs from $g \to b\bar{b}$ splitting in $Wg \to Wb\bar{b}$ (and $Zg \to Zb\bar{b}$).
- Need too investigate NLO corrections to $qg(\bar{q}g) \to Wb\bar{b} + q'(\bar{q}')$? (now within reach)