Associated production of a W or Z boson with bottom quarks at the Tevatron and the LHC

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$Z, W + b$-jets at hadron colliders

$p\bar{p}, pp \to Zb\bar{b}, Zb$ and $p\bar{p}, pp \to Wb\bar{b}, Wb$

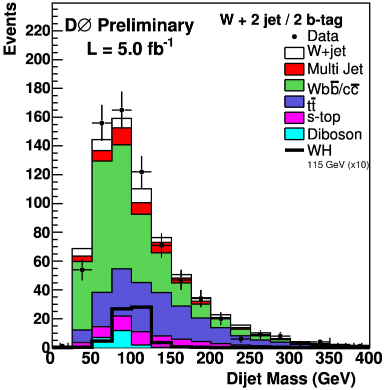
- are important background processes to
  - Standard Model (SM) Higgs boson searches for a light Higgs boson ($M_H < 135$ GeV):
    $p\bar{p}, pp \to WH$ and $p\bar{p}, pp \to ZH$ with $H \to b\bar{b}$,
  - single-top production, $t\bar{b}, \bar{t}b$ with $t \to W^+ b, \bar{t} \to W^- \bar{b}$,
  - searches for signals of physics beyond the SM,
- are interesting in their own right as testing grounds for perturbative QCD, and
- $W + 1b$-jet and $Z + 1b$-jet are sensitive to the b-quark content of the proton.

SM Higgs search at the Tevatron

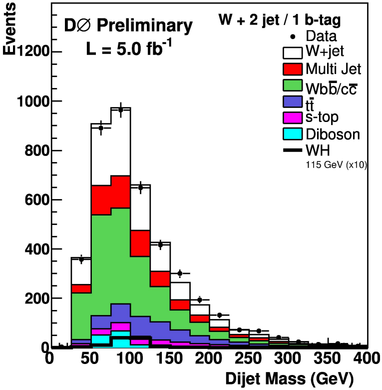
Light Higgs searches at the Tevatron mainly via $p\bar{p} \to W^{\pm}H \to b\bar{b}l^{\pm}\nu_l$ and $p\bar{p} \to ZH \to b\bar{b}l^{+}l^{-}$.

$M_{b\bar{b}}$ distributions for signal ($M_H = 115$ GeV) and backgrounds:

2 *b*s tagged



1 *b* tagged



DO Collaboration, D0note 5972-CONF (8/2009)

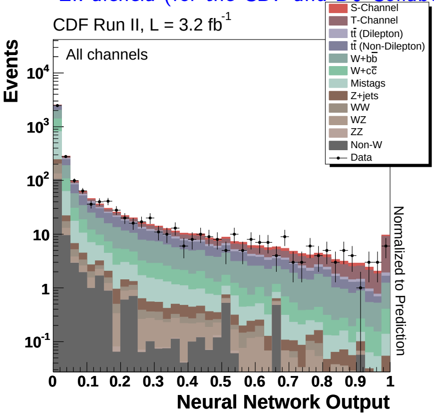
Single top production at the Tevatron

$\sigma_{s+t} = 2.3^{+0.6}_{-0.5}$ pb ($m_t = 175$ GeV)
CDF Collaboration, arXiv:0903.0885 [hep-ex]

$\sigma_{s+t} = 3.94 \pm 0.88$ pb ($m_t = 170$ GeV)
D0 Collaboration, arXiv:0903.0850 [hep-ex]

Background and signal prediction vs. CDF and D0 data:

E.Palencia (for the CDF and D0 Collaborations at Moriond09), arXiv:0905:4275 [hep-ex]



Event Yields in 2.3 fb^{-1} of DØ Data

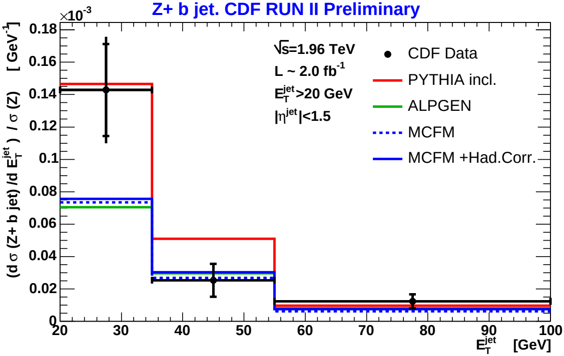
Electron + muon, 1 tag + 2 tags combined

Source	2 jets	3 jets	4 jets
s-channel *tb*	62 ± 9	24 ± 4	7 ± 2
t-channel *tqb*	77 ± 10	39 ± 6	14 ± 3
$W+b\bar{b}$	678 ± 104	254 ± 39	73 ± 11
$W+c\bar{c}$	303 ± 48	130 ± 21	42 ± 7
$W+cj$	435 ± 27	113 ± 7	24 ± 2
$W+jj$	413 ± 26	140 ± 9	41 ± 3
$Z+$jets	141 ± 33	54 ± 14	17 ± 5
Dibosons	89 ± 11	32 ± 5	9 ± 2
$t\bar{t} \rightarrow \ell\ell$	149 ± 23	105 ± 16	32 ± 6
$t\bar{t} \rightarrow \ell+$jets	72 ± 13	331 ± 51	452 ± 66
Multijets	196 ± 50	73 ± 17	30 ± 6
Total prediction	2,615 ± 192	1,294 ± 107	742 ± 80
Data	2,579	1,216	724

$Z + b$-jet production at the Tevatron

	CDF Data	PYTHIA	ALPGEN	NLO
$\sigma(Z + b\,\text{jet})$	$0.86 \pm 0.14 \pm 0.12$ pb	–	–	0.51 pb
$\sigma(Z + b\,\text{jet})/\sigma(Z)$	$0.336 \pm 0.053 \pm 0.041\%$	0.35%	0.21%	0.21%
$\sigma(Z + b\,\text{jet})/\sigma(Z + \text{jet})$	$2.11 \pm 0.33 \pm 0.34\%$	2.18%	1.45%	1.88%

CDF Collaboration, arXiv:0812.4458



CDF Collaboration, arXiv:0812.4458

$W + b$jets at the Tevatron

$$\sigma_{b\ \mathrm{jets}} \times \mathcal{B}(W \to \ell\nu) = 2.74 \pm 0.27(\mathrm{stat.}) \pm 0.42(\mathrm{syst.})\ pb$$

$\Rightarrow$ 18% precision with $1.9\ \mathrm{fb}^{-1}$

CDF Collaboration, arXiv:0909.1407

Monte Carlo predictions:

- PYTHIA: 1.10 pb
- ALPGEN: 0.78 pb
- NLO QCD: coming up

Study of kinematic jet distributions is under way.

$W + b$jets and $Z + b$jets production at the LHC

- Renewed interest in $VH, H \to bb$ for light Higgs searches:
  - Requiring $p_T > 200$ GeV for both $V = W, Z$ and H reduces background and enhances kinematic significance.
  - $W + jet$ background is dominated by $Wb\bar{b}$.
  - Study of theoretical uncertainty in this new kinematic region is needed.

    ATLAS Collaboration, ATL-PHYS-PUB-2009-088
- $\delta\sigma(Zb\bar{b}, Z \to l^+ l^-)/\sigma = 30\%$ with $\mathcal{L} = 100\,\mathrm{pb}^{-1}$.
  CMS Collaboration, CMS PAS EWK-08-001

Status of SM predictions

	NLO QCD	NLO EW
WH, ZH	HW 1991/MY 1997/BDH 2003 (NNLO)	CDK 2003
single top	SSW 1997+1998/HLPSW 2002/CSBBY 2005	BMRV 2006
	CSY 2004/CY 2004/S 2004+2005	
$Wb\bar{b}$	EV 1998/FRW 2006+2009	
$Zb\bar{b}$	CE 2000/FRW 2008+2009	
ZQ	CEMW 2003	
Wc/Wb	GKL 1995/CEMW+FRW 2008	
ZQj	CEMW 2005	
WQj	CEMW 2006	

Han, Willenbrock (HW); Mrenna, Yuan (MY); Brein, Djouadi, Harlander (BDH); Ciccolini, Dittmaier, Krämer (CDK); Stelzer, Sullivan, Willenbrock (SSW); Harris, Laenen, Phaf, Sullivan, Weinzierl (HLPSW); Cao, Schwienhorst, Benitez, Brock, Yuan (CSBBY); Cao, Schwienhorst, Yuan (CSY); Cao, Yuan (CY); Sullivan (S); Beccaria, Macorini, Renard, Verzegnassi (BMRV); Ellis, Veseli (EV); Campbell, Ellis (CE); Campbell, Ellis, Maltoni, Willenbrock (CEMW); Giele, Keller, Laenen (GKL); Febres Cordero, Reina, W. (FRW)

CE/CEMW/EV implemented in MCFM (J.Campbell, K.Ellis, mcfm.fnal.gov)

CE/CEMW/EV assume massless bottom-quarks

FRW take into account full bottom-quark mass effects

$Wb\bar{b}$ and $Zb\bar{b}$ production at NLO QCD

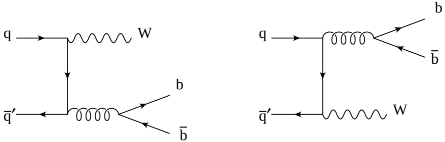
NLO QCD predictions are needed

- for theoretical stable predictions by decreasing the scale dependence,
- $\mathcal{O}(\alpha_s)$ corrections can strongly increase/decrease the total production rate, and
- $\mathcal{O}(\alpha_s)$ corrections can significantly affect the shape of kinematic distributions.

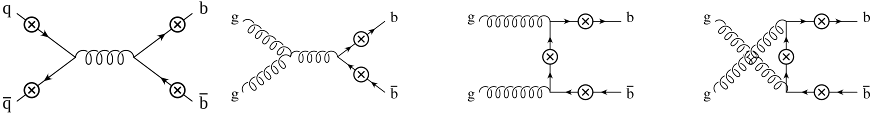
$\mathcal{O}(\alpha_s)$ corrections to $p\bar{p}, pp \rightarrow W/Zb\bar{b}$: technical details

Feynman-diagrams at LO QCD:

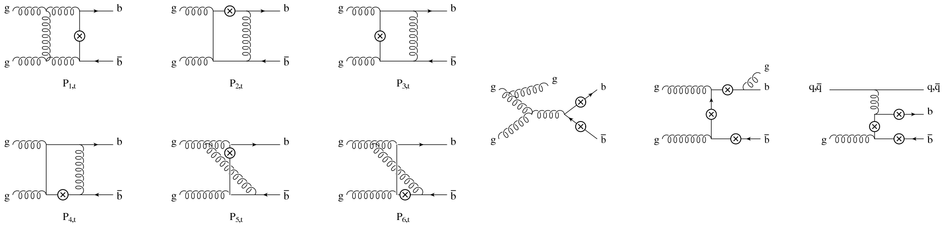
$Wb\bar{b}$:



$Zb\bar{b}$:



Examples of real and virtual $\mathcal{O}(\alpha_s)$ corrections to $p\bar{p}, pp \rightarrow b\bar{b}Z$:



NLO QCD total inclusive cross section to $p\bar{p}, pp \to Vb\bar{b}(V = W, Z)$:

$$\sigma_{NLO} = \sum_{ij=q\bar{q},gg,qg} \frac{1}{1+\delta_{ij}} \int dx_1 dx_2 [\mathcal{F}_i^p(x_1,\mu)\mathcal{F}_j^{\bar{p}}(x_2,\mu)\hat{\sigma}^{ij}_{\rm NLO}(x_1,x_2,\mu) + (1 \leftrightarrow 2)]$$

with the parton level cross sections

$$\hat{\sigma}^{ij}_{\rm NLO} = \hat{\sigma}^{ij}_{\rm LO} + \frac{\alpha_s}{\pi}\delta\hat{\sigma}^{ij}_{\rm NLO} \text{ with } \delta\hat{\sigma}^{ij}_{\rm NLO} = \hat{\sigma}^{ij}_{\rm virt} + \hat{\sigma}^{ij}_{\rm real}$$

$\hat{\sigma}^{ij}_{\rm virt}$:

- UV divergences: renormalized in $d = 4 - 2\epsilon$ dimensions by a suitable set of counterterms and finite parts are fixed in the $\overline{MS}$ scheme.
- IR divergences: regularized in $d = 4 - 2\epsilon$ dimensions $\Rightarrow$ soft and collinear singularities appear as poles in $\frac{1}{\epsilon^2}, \frac{1}{\epsilon}$. IR singularities are completely canceled by corresponding IR poles in

$\hat{\sigma}^{ij}_{\rm real}$:

- IR divergences: extracted by suitable cuts on the gluon phase space using phase space slicing and the remaining initial-state IR singularities are absorbed in PDFs (mass factorization).

Phase Space Slicing with two cut-off parameters: δ_s, δ_c

Phase Space Slicing: isolate the region of the $Vb\bar{b}+g$ phase space where

$$s_{ig} = 2p_i \cdot p_g = 2E_i E_g (1 - \beta_i \cos\theta_{ig}) \to 0$$

by introducing suitable cut-off parameters: Bergman, Baer, Ohnemus, Owens, Reno, ..., for a review see, e.g., B.Harris, J.Owens, PRD 65 (2002)

$$\hat{\sigma}^{ij}_{real} = \int d(PS_4)|\mathcal{A}_{real}(ij \to Vb\bar{b}+g)|^2 = \hat{\sigma}_{soft}(E_g < \frac{\sqrt{s}}{2}\delta_s) + \hat{\sigma}_{hard}(E_g > \frac{\sqrt{s}}{2}\delta_s)$$

In the soft limit ($E_g \to 0$):

$$d(PS_4) \xrightarrow{soft} d(PS_3)d(PS_g) = d(PS_3)\frac{d^{d-1}k}{(2\pi)^{d-1}2E_g}$$

$$|\mathcal{A}_{real}|^2 \xrightarrow{soft} (4\pi\alpha_s)|\mathcal{A}_{LO}|^2\Phi_{eik} \text{ with } \Phi_{eik} \propto \sum_{ij}\left(\frac{s_{ij}}{s_{ig}s_{jg}} - \frac{m_i^2}{s_{ig}^2} - \frac{m_j^2}{s_{jg}^2}\right)$$

$$\hat{\sigma}_{soft} = \int d(PS_3)|A_{LO}|^2 \int d(PS_g)\Phi_{eik}$$

Analytical integration in $d = 4 - 2\epsilon$: $\hat{\sigma}_{soft} \propto \frac{1}{\epsilon}, \frac{1}{\epsilon^2}$

... moreover

$$\hat{\sigma}_{hard} = \hat{\sigma}_{coll}((1-\cos\theta_{ig}) < \delta_c) + \hat{\sigma}_{non-coll}((1-\cos\theta_{ig}) > \delta_c)$$

In the collinear limit $(i \to i'g,\ p_i' = zp_i,\ p_g = (1-z)p_i)$

$$d(PS_4)(ij \to Vb\bar{b} + g) \xrightarrow{collinear} d(PS_3)(i'j \to Vb\bar{b}) z d(PS_g)$$

$$|\mathcal{A}_{real}(ij \to Vb\bar{b} + g)|^2 \xrightarrow{collinear} |A_{LO}|^2 (4\pi\alpha_s) \frac{2P_{ii'}(z)}{z\, s_{ig}}$$

with $P_{ii'}$ denoting the Altarelli-Parisi splitting functions.

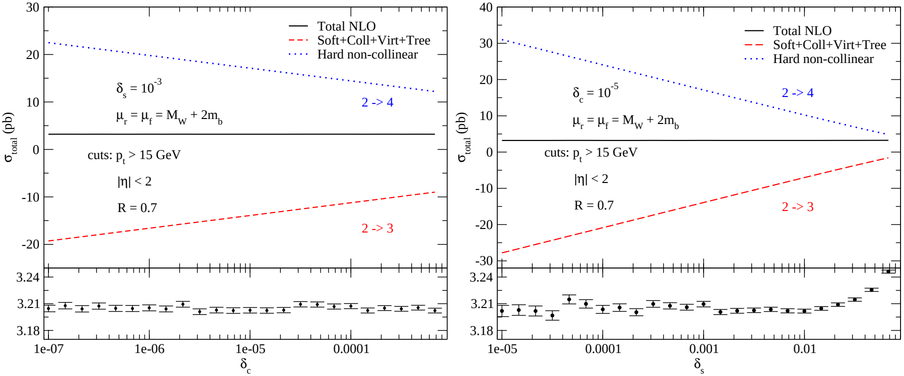
$$\hat{\sigma}_{coll} \propto \int d(PS_3)|A_{LO}|^2 \int d(PS_g) \sum_i \frac{P_{ii'}}{s_{ig}}$$

Analytical integration in $d = 4 - 2\epsilon$: $\hat{\sigma}_{coll} \propto \frac{1}{\epsilon}$.
The remaining real hard part

$$\hat{\sigma}_{non-coll} = \int d(PS_4)_{non-coll} |\mathcal{A}_{real}(ij \to Vb\bar{b} + g)|^2$$

is computed numerically.

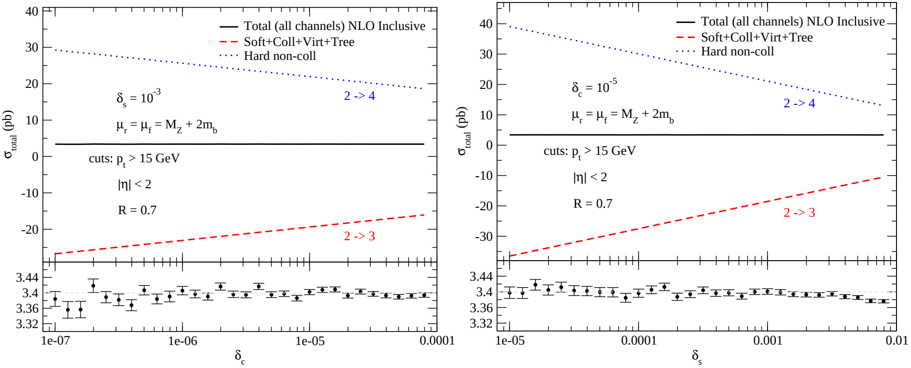
Cancellation of cut-off dependences in $\sigma_{\rm NLO}(Wb\bar{b})$



from F.Febres Cordero, L.Reina, DW, PRD74 (2006)

see also F.Febres Cordero, arXiv:0809.3829

Cancellation of cut-off dependences in $\sigma_{\rm NLO}(Zb\bar{b})$



from F.Febres Cordero, L.Reina, DW, PRD78 (2008)

see also F.Febres Cordero, arXiv:0809.3829

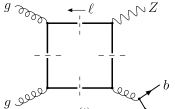
Numerical instabilities due to spurious divergences

- Veltman-Passarino reduction of high-ranked tensor integrals to scalar integrals involves inverse powers of so-called Gram Determinantes (GD), which may vanish in certain phase space regions, e.g.,

$$\frac{[s-(2m_b+M_V)^2]}{64}[M_V^4+(s-s_{b\bar{b}})^2-2M_V^2(s+s_{b\bar{b}})]s\,s_{b\bar{b}}\,\sin^2\theta_{b\bar{b}}\sin^2\phi_{b\bar{b}}$$

- Our solution:
  Reduction of powers of GD by combining gauge invariant subsets of diagrams and cancel propagators against numerators wherever possible before the reduction $\Rightarrow$ so far worked well for NLO QCD calculations of $2\to 3$ processes such as $t\bar{t}H, b\bar{b}H$ and $Vb\bar{b}$.

- Check with unitarity based method: F.Febres Cordero, arXiv:0809.3829
  One can extract the coefficients of the scalar integrals for a given scalar box integral by cutting the four corresponding propagators:



$B_{1,t}^{(1)}$

$$i/(\ell^2-m^2+i\epsilon)\to 2\pi\delta^{(+)}(\ell^2-m^2)$$

Numerical results

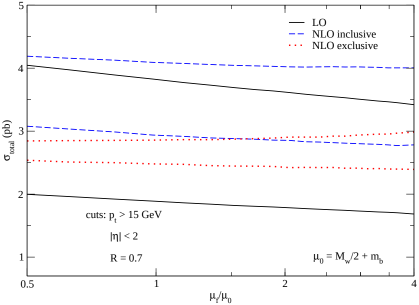
- Jet identification as implemented in MCFM: k_t jet algorithm with cone size $R = 0.7$
- We require all events to have a $b\bar{b}$ jet pair in the final state with

$$p_T^{b,\bar{b}} > 15, 25 \text{ GeV} \quad \text{and} \quad |\eta^{b,\bar{b}}| < 2(2.5)$$

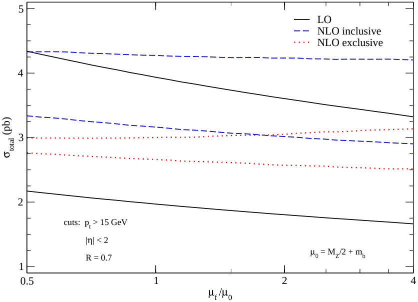
- The hard non-collinear extra parton is treated either *inclusively*, i.e. two- and three-jet events are included, or *exclusively*, i.e. exactly two b-quark jets are required in the event
- LO/NLO CTEQ6 set of PDFs with LO/NLO running of α_s for LO/NLO predictions

Scale dependence of $\sigma(W/Zb\bar{b})$ at the Tevatron

$p\bar{p} \rightarrow b\bar{b}W$ at the Tevatron



$p\bar{p} \rightarrow b\bar{b}Z$ at the Tevatron

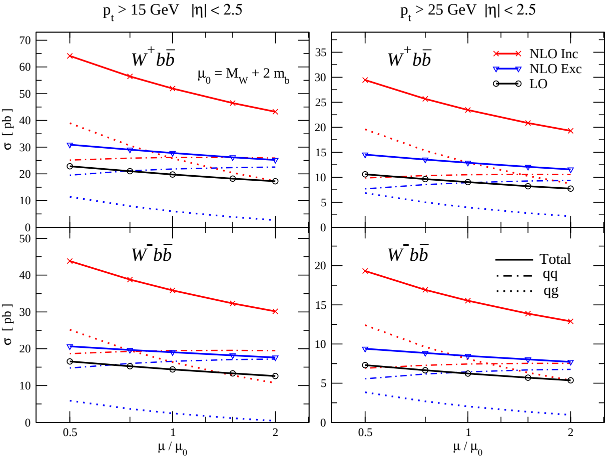


$$\delta\sigma_{NLO}/\sigma_{NLO} \approx 20\%(\text{inclusive}), 10\%(\text{exclusive})$$

$$K = \sigma_{NLO}/\sigma_{LO}(Zb\bar{b}) = 1.54(\text{inclusive}), 1.27(\text{exclusive})$$
$$K = \sigma_{NLO}/\sigma_{LO}(Wb\bar{b}) = 1.45(\text{inclusive}), 1.20(\text{exclusive})$$

from F.Febres Cordero, L.Reina, DW, PRD74 (2006); PRD78 (2008)

Scale dependence of $\sigma(W^\pm b\bar{b})$ at the LHC



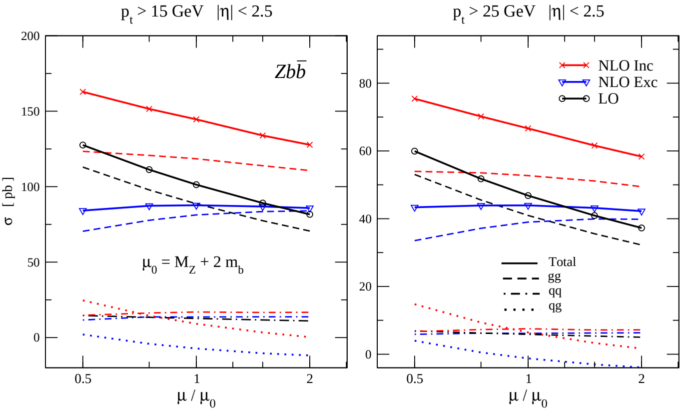
$$\delta\sigma_{NLO}/\sigma_{NLO} \approx 40\%(\text{inclusive}), 20\%(\text{exclusive})$$

$$K = \sigma_{NLO}/\sigma_{LO}(W^+ b\bar{b}) = 2.6(\text{inclusive}), 1.4(\text{exclusive})$$

$$K = \sigma_{NLO}/\sigma_{LO}(W^- b\bar{b}) = 2.5(\text{inclusive}), 1.3(\text{exclusive})$$

from F.Febres Cordero, L.Reina, DW, arXiv:0906.1923 [hep-ph]

Scale dependence of $\sigma(Zb\bar{b})$ at the LHC

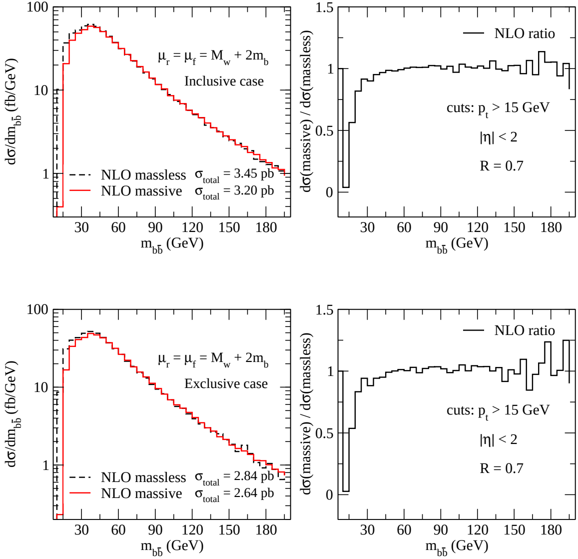


$\delta\sigma_{NLO}/\sigma_{NLO} \approx 26\%(\text{inclusive}), 3\%(\text{exclusive})$

$K = \sigma_{NLO}/\sigma_{LO}(Zb\bar{b}) = 1.4(\text{inclusive}), 0.9(\text{exclusive})$

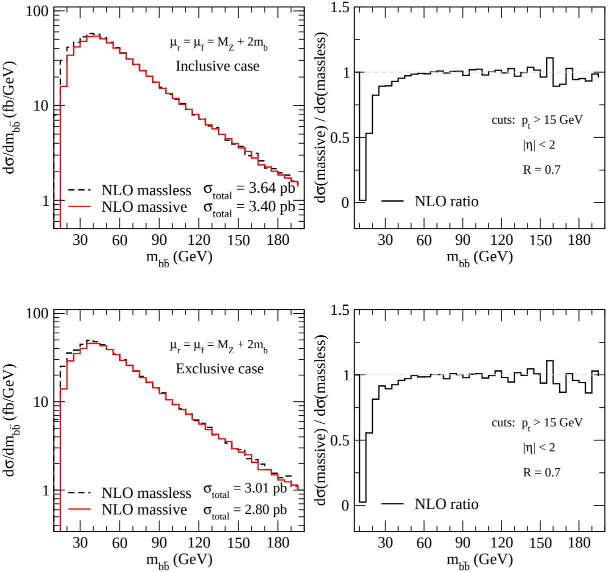
from F.Febres Cordero, L.Reina, DW, arXiv:0906.1923 [hep-ph]

b-quark mass effects in $d\sigma_{\mathrm{NLO}}(Wb\bar{b})/dM_{b\bar{b}}$ (Tevatron)



from F.Febres Cordero, L.Reina, DW, PRD74 (2006)

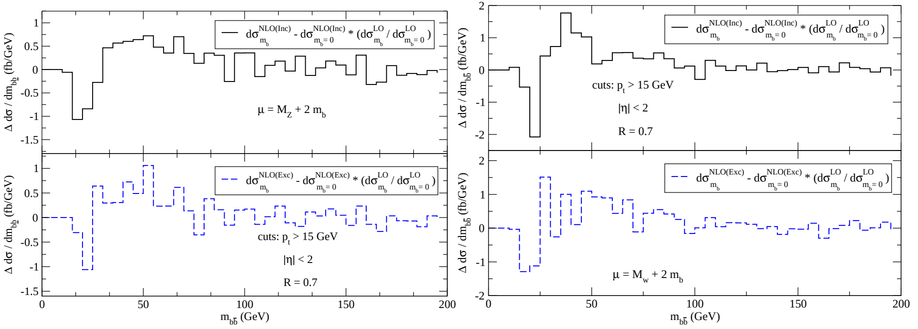
b-quark mass effects in $d\sigma_{\rm NLO}(Zb\bar{b})/dM_{b\bar{b}}$ (Tevatron)



from F.Febres Cordero, L.Reina, DW, PRD78 (2008)

Rescaling of NLO ($m_b = 0$) with LO ratios

$$\Delta \frac{d\sigma}{dm_{b\bar{b}}} = \frac{d\sigma^{NLO}}{dm_{b\bar{b}}}(m_b \neq 0) - \frac{d\sigma^{NLO}}{dm_{b\bar{b}}}(m_b = 0)\,\frac{d\sigma^{LO}(m_b \neq 0)}{d\sigma^{LO}(m_b = 0)}\;.$$



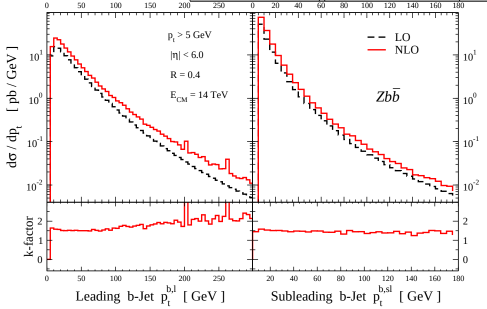
from F.Febres Cordero, L.Reina, DW, PRD74 (2006); PRD78 (2008)

$Zb\bar{b}$ Studies for CMS

Inclusive production of $Z + 2\,b$ jets using the following setup F.Febres Cordero, L.Reina (2009):

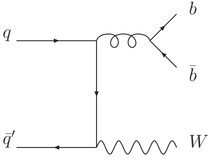
- $p_T^b > 5$ GeV and $|\eta_b| < 6$;
- k_T jet algorithm with $R = 0.4$;
- dynamical and fixed scales $\mu_0^2 = M_Z^2 + (p_T^{b,1})^2 + (p_T^{b,2})^2$

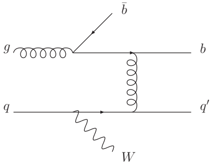
	Fixed scale	Dyamical scale
σ_{LO} (pb)	525^{+130}_{-99}	522^{+128}_{-97}
σ_{NLO} (pb)	812^{+122}_{-97}	815^{+116}_{-100}



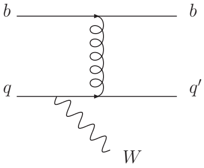
Improving predictions for *Wb* production

Assuming that there is only one high-p_t b-quark in the event increases the production rate and introduces a sensitivity to b quark PDFs:





where $gq \to Wb\bar{b}q'$ (one low p_T b) is equivalent to



convoluted with a b-quark PDF

Improving predictions for Wb production

Large logarithms proportional to $\log(Q^2/m_b^2)$ may arise due to initial and final-state collinear $g \to b\bar{b}$ splitting.

- Initial-state collinear logarithms $[\alpha_s \log(M_W^2/m_b^2)]^n$ can be resummed by using a b-quark PDF at $\mu_F = Q = M_W$ which is determined perturbatively from DGLAP evolution equations. Approximate solution of DGLAP equation with initial condition $b(x,\mu^2) = 0$ at $\mu = m_b$:

$$\tilde{b}(x,\mu^2) = \frac{\alpha_s(\mu^2)}{2\pi} \log(\frac{\mu^2}{m_b^2}) \int_x^1 \frac{dz}{z} P_{qg}(z) g(\frac{x}{z},\mu^2)$$

  Aivazis *et al*, hep-ph/9312319; Collins, hep-ph/9806259; Olness, Scalise, PRD57 (1998); see also Stelzer *et al*, hep-ph/9705398

- Improved prediction for qg-initiated process by including a subset of higher-order corrections.

- $q\bar{q}' \to Wb\bar{b}$ is included with full mass dependence at NLO.

Improving predictions for *Wb* production

There are a variety of processes that must be included at NLO 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. $bq \to Wbq'g$ at tree level ($m_b = 0$)
5. $bg \to Wbq'\bar{q}$ at tree level ($m_b = 0$)
6. $gq \to Wb\bar{b}q'$ at tree level ($m_b \neq 0$) $[-\tilde{b}q \to Wbq']$

Separation and jet identification cuts:

Tevatron:	$p_{Tj} > 15$ GeV	$\|\eta_j\| < 2$
LHC:	$p_{Tj} > 25$ GeV	$\|\eta_j\| < 2.5$
$\|\Delta R_{b\bar{b}}\| > 0.7$		$\|\Delta R_{bj}\| > 0.7$

If $|\Delta R_{b\bar{b}}| < 0.7$, the two b-quarks are considered to be one b-jet.

J.Campbell *et al.*, PRD79 (2009), arXiv:0809.3003

Results for *Wb* production: $\sigma_{LO,NLO}$

	Exclusive cross sections (pb)	
Collider	Wb	
	[LO($q\bar{q}'$)+LO(bq)] NLO($q\bar{q}'$)+NLO($bq/bg/qg$)(qg)	$\frac{\sigma_{NLO}}{\sigma_{LO}}$
TeV $W^{\pm}$	[5.28+0.75=6.03] 8.02+0.62=8.64(-0.05)	1.43
LHC W^{+}	[30.2+54.3=84.5] 40.0+48.4=88.4(22.6)	1.05
LHC W^{-}	[21.6+31.4=53.0] 29.8+29.4=59.2(12.6)	1.12
	Inclusive cross sections (pb)	
Collider	$Wb+X$	
	[LO($q\bar{q}'$)+LO(bq)] NLO($q\bar{q}'$)+NLO($bq/bg/gq$)(qg)	$\frac{\sigma_{NLO}}{\sigma_{LO}}$
TeV $W^{\pm}$	[7.56+1.81=9.37] 11.77+2.40=14.17(0.77)	1.51
LHC W^{+}	[39.3+106.0=145.3] 53.6+136.1=189.7(68.9)	1.31
LHC W^{-}	[27.9+67.0=94.9] 39.3+88.2=127.5(44.6)	1.34

from J.Campbell *et al.*, PRD79 (2009), arXiv:0809.3003

Inclusive: $W+1jet$ with one b jet and may be other jets (up to two at NLO)

Exclusive: $W+1jet$ with exactly one b jet (could also be ($b\bar{b}$))

Results for $W(b\bar{b})$ production: $\sigma_{LO,NLO}$

	Exclusive cross sections (pb)	
Collider	$W(b\bar{b})$	
	[LO($q\bar{q}'$)] NLO($q\bar{q}'$)+NLO(gq)	$\frac{\sigma_{NLO}}{\sigma_{LO}}$
TeV $W^{\pm}$	[2.66] 3.73-0.02=3.71	1.39
LHC W^{+}	[17.6] 22.7+11.7=34.4	1.95
LHC W^{-}	[12.9] 17.2+6.5=23.7	1.84
	Inclusive cross sections (pb)	
Collider	$W(b\bar{b})+X$	
	[LO($q\bar{q}'$)] NLO($q\bar{q}'$)+NLO(gq)	$\frac{\sigma_{NLO}}{\sigma_{LO}}$
TeV $W^{\pm}$	[2.66] 4.17+0.39=4.56	1.71
LHC W^{+}	[17.6] 25.1+35.9=61.0	3.47
LHC W^{-}	[12.9] 18.9+23.6=42.5	3.29

from J.Campbell *et al.*, PRD79 (2009), arXiv:0809.3003

Scale dependence of $\sigma_{LO,NLO}$ in Wb production

	Exclusive cross sections (pb)
Collider	Wb [LO($\mu_r + \mu_f$)] NLO($\mu_r + \mu_f$)
TeV $W^\pm$	$\left[6.03\times(1^{+0.27+0.02}_{-0.19-0.03})\right]$ $8.64\times(1^{+0.13+0.004}_{-0.12-0.003})$
LHC W^+	$\left[84.5\times(1^{+0.27+0.11}_{-0.19-0.14})\right]$ $88.4\times(1^{+0.11+0.08}_{-0.11-0.10})$
LHC W^-	$\left[53.0\times(1^{+0.27+0.12}_{-0.19-0.14})\right]$ $59.2\times(1^{+0.12+0.08}_{-0.11-0.10})$
	Inclusive cross sections (pb)
Collider	$Wb + x$ [LO($\mu_r + \mu_f$)] NLO($\mu_r + \mu_f$)
TeV $W^\pm$	$\left[9.37\times(1^{+0.27+0.02}_{-0.19-0.03})\right]$ $14.17\times(1^{+0.15+0.0002}_{-0.13-0.001})$
LHC W^+	$\left[145.3\times(1^{+0.27+0.12}_{-0.19-0.14})\right]$ $189.7\times(1^{+0.16+0.07}_{-0.13-0.10})$
LHC W^-	$\left[94.9\times(1^{+0.27+0.12}_{-0.19-0.15})\right]$ $127.5\times(1^{+0.16+0.08}_{-0.13-0.10})$

from J.Campbell *et al.*, PRD79 (2009), arXiv:0809.3003

Scale dependence of $\sigma_{LO,NLO}$ in $W(b\bar{b})$ production

	Exclusive cross sections (pb)
Collider	$W(b\bar{b})$ $[\text{LO}(\mu_r+\mu_f)]$ $\text{NLO}(\mu_r+\mu_f)$
TeV $W^{\pm}$	$\left[2.66\times(1^{+0.27+0.04}_{-0.19-0.04})\right]$ $3.71\times(1^{0.12+0.01}_{-0.11-0.01})$
LHC W^{+}	$\left[17.6\times(1^{+0.27+0.09}_{-0.19-0.10})\right]$ $34.4\times(1^{+0.23+0.03}_{-0.16-0.04})$
LHC W^{-}	$\left[12.9\times(1^{+0.27+0.09}_{-0.19-0.11})\right]$ $23.7\times(1^{+0.21+0.03}_{-0.15-0.04})$
	Inclusive cross sections (pb)
Collider	$W(b\bar{b})+X$
	$[\text{LO}(\mu_r+\mu_f)]$ $\text{NLO}(\mu_r+\mu_f)$
TeV $W^{\pm}$	$\left[2.66\times(1^{+0.27+0.04}_{-0.19-0.04})\right]$ $4.56\times(1^{+0.17+0.03}_{-0.14-0.02})$
LHC W^{+}	$\left[17.6\times(1^{+0.27+0.09}_{-0.19-0.10})\right]$ $61.0\times(1^{+0.33+0.02}_{-0.21-0.02})$
LHC W^{-}	$\left[12.9\times(1^{+0.27+0.09}_{-0.19-0.11})\right]$ $42.5\times(1^{+0.32+0.02}_{-0.21-0.03})$

from J.Campbell *et al.*, PRD79 (2009), arXiv:0809.3003

$W + b$jets at the Tevatron: comparison with experiment

See F.Febres Cordero's talk at *Northwest Terascale Research Projects: $W/Z + b$ physics at the LHC* (University of Oregon), for details:
J.Campbell, F.Febres Cordero, L.Reina (2009)

- only accept events with exactly 1 or 2 jets
- jet cross section instead of event-level: weight of events with two b-jets counts twice

$$\sigma_{b\ \mathrm{jets}} \times \mathcal{B}(W \to \ell\nu) = 2.74 \pm 0.27(\mathrm{stat.}) \pm 0.42(\mathrm{syst.})\ pb$$

CDF Collaboration, arXiv:0909.1407
Monte Carlo predictions:

- PYTHIA: 1.10 pb
- ALPGEN: 0.78 pb
- LO: $0.91^{+0.29}_{-0.20}$ pb, NLO QCD: 1.22 ± 0.14 pb

Possible improvements for *Zb* production

Work in progress (see L.Reina's talk at *Northwest Terascale Research Projects: $W/Z + b$ physics at the LHC* (University of Oregon), for details):

- Combination of the NLO calculations of $Zb\bar{b}$ ($m_b \neq 0$) and Zbj ($mb = 0$,MCFM) by carefully subtracting contributions that are included in both calculations.
- Compared to *Wb* production there is much more overlap between these two calculations.
- There are $Hb\bar{b}$-like contributions such as $gg \to Zb\bar{b}$ where we expect 4FNS and 5FNS to be consistent within their theoretical uncertainties.
- For $Wb\bar{b}$-like contributions such as $q\bar{q} \to Zb\bar{b}$, where the Z is radiated off initial-state light quarks, we expect to see a similar improvement as in the *Wb* case.

Conclusion and Outlook

$Wb\bar{b}$ and $Zb\bar{b}$ production:

- The associated production of a weak gauge boson and one or two b-quark jets constitutes an important background to SM Higgs boson searches at the Tevatron, single top production and to searches for signals of physics beyond the SM at both the Tevatron and the LHC.
- We calculated and studied the impact of NLO QCD corrections to $Wb\bar{b}$ and $Zb\bar{b}$ production on the total production rate and the $M_{b\bar{b}}$ distribution and compared our results with a calculation based on the massless b-quark approximation (MCFM).

Conclusion and Outlook

- Findings:
  - factorization and renormalization dependence is considerably reduced: $\delta\sigma_{NLO}/\sigma_{NLO} \approx 20\%(\text{inclusive}), 10\%(\text{exclusive})$,
  - bottom-quark mass effects can amount to about 8% of σ_{NLO} and considerably impact the shape of the $M_{b\bar{b}}$ distribution,
  - bottom-quark mass effects can be sufficiently well described by rescaling $\sigma_{NLO}(m_b = 0)$ with $\sigma_{LO}(m_b \neq 0)$.
- We improved the NLO QCD calculation of Wb production by combining the NLO QCD calculations of $Wb\bar{b}(m_b \neq 0)$ with $Wbj(m_b = 0)$ (MCFM). The latter resums initial-state collinear singularities ($\alpha_s \log(M_W^2/m_b^2)$) to all orders by using a b-quark PDF. We studied observables to Wb and $W(b\bar{b})$ production and found modest NLO corrections in the Wb case but large corrections to $W(b\bar{b})$.
- Possible further improvements:
  - resummation of final-state collinear singularities
  - applications of alternative jet algorithms (Wb)
  - qg initiated process at NLO QCD ($W/Zb\bar{b}$)