

# ***W+b Production at NLO***

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***W+b quark physics at the LHC***

***University of Oregon at Eugene --- September 2009***

In Collaboration With: *John Campbell, Keith Ellis, Fabio Maltoni, Laura Reina,  
Doreen Wackeroth and Scott Willenbrock*

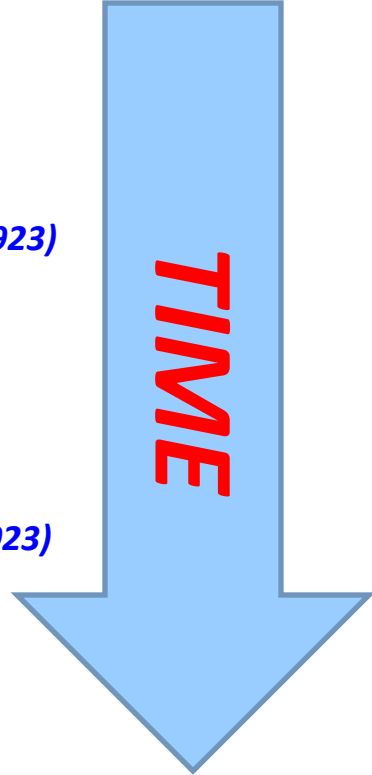
**arXiv:0809.3003 --- hep-ph/0606102 --- hep-ph/0611348**

# Highlights

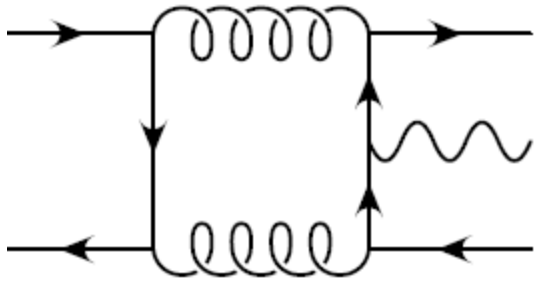
- We have computed parton level **NLO QCD corrections** to  $Wb$  production at hadron colliders
- We have used a **5FNS** (i.e. included a b-pdf) within the so called **simplified ACOT scheme**
- This allows **resummation of large logs** from the presence of heavy flavors and full **bottom mass** dependence
- With the CDF setup (arXiv:0909.1505) we get a **K-factor of 1.35**, but still a factor of 2 away from data!

# *V + heavy jets NLO Computations*

- Wc *(Giele, Keller, Laenen --- hep-ph/9511449)*
- Wbb *( [mb = 0] Ellis, Veseli --- hep-ph/9810489)*  
*( [mb ≠ 0] FFC, Reina, Wackerath --- hep-ph/0606102 / arXiv:0906.1923)*
- ZQ *(Campbell, Ellis, Maltoni, Willenbrock --- hep-ph/0312024)*
- ZQQ *( [mb = 0] Campbell, Ellis --- hep-ph/0312024)*  
*( [mb ≠ 0] FFC, Reina, Wackerath --- arXiv:0806.0808 / arXiv:0906.1923)*
- ZQj *(Campbell, Ellis, Maltoni, Willenbrock --- hep-ph/0510362)*
- Wbj *(Campbell, Ellis, Maltoni, Willenbrock --- hep-ph/0611348)*
- Wb *(Campbell, Ellis, FFC, Maltoni, Reina, Wackerath, Willenbrock --- arXiv:0809.3003 )*



# *Computing Loop Correction is (often) Hard!*



- *Involve large amount of Feynman diagrams*
- *Complexity of each diagram grows exponentially with the number of legs*
- *Need to solve complex tensor integrals*
- *Need to ensure numerical stability to allow integration over phase space*

***Wb production @ NLO: need pentagon topologies with massive b quark propagators!!!***

# Why NLO?

$$\hat{\sigma}(\alpha_s, \mu_F, \mu_R) = [\alpha_s(\mu_R)]^{n_\alpha} \left[ \underbrace{\hat{\sigma}^{(0)}}_{\text{LO}} + \frac{\alpha_s}{2\pi} \underbrace{\hat{\sigma}^{(1)}(\mu_F, \mu_R)}_{\text{NLO}} + \left(\frac{\alpha_s}{2\pi}\right)^2 \underbrace{\hat{\sigma}^{(2)}(\mu_F, \mu_R)}_{\text{NNLO}} + \dots \right]$$

Because leading order (LO) predictions are only qualitative in normalization, due to poor convergence of expansion in  $\alpha_s(\mu)$

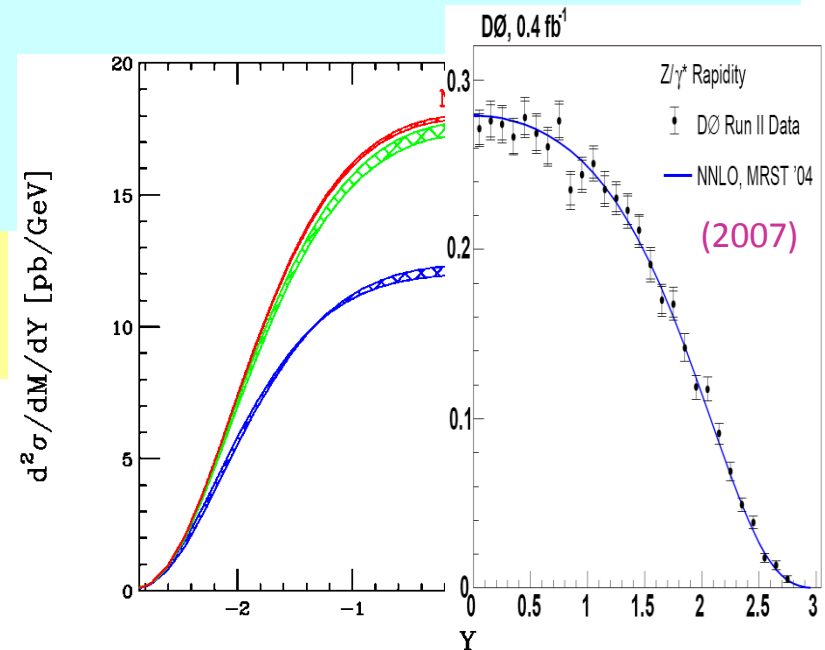
Example:  $Z$  production at Tevatron  
Distribution in rapidity  $Y$

$$Y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right)$$

$$\frac{d\sigma}{dY} \quad \text{has} \quad n_\alpha = 0$$

still ~50% corrections, LO  $\rightarrow$  NLO

TAKEN FROM Lance Dixon



Anastasiou, Dixon, Melnikov, Petriello (2004)

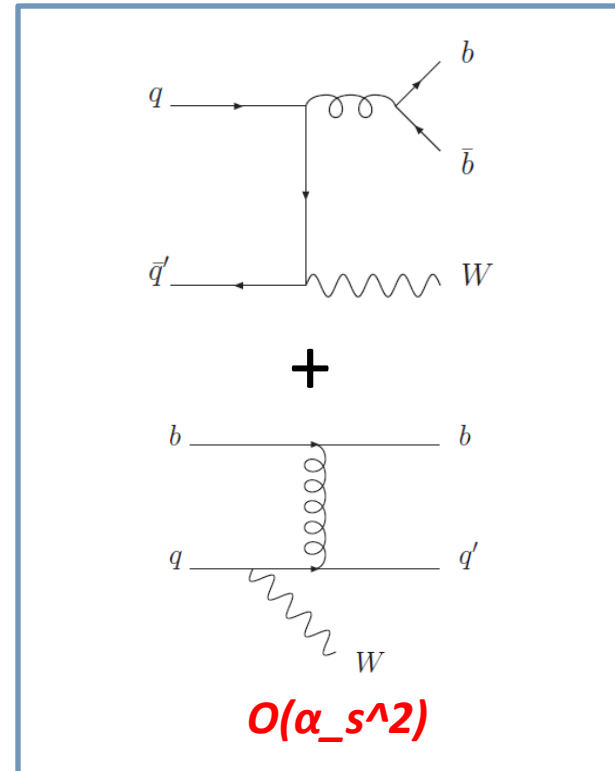
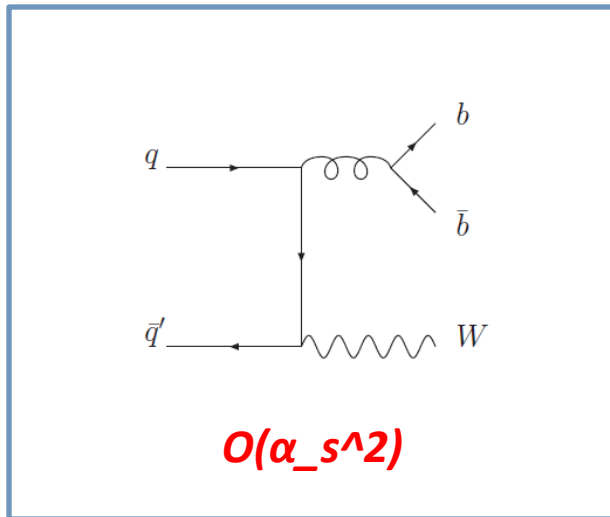
by NNLO, a precision observable

# ***W+b at LO***

***4FNS vs. 5FNS***

Or, considering 4 light quark flavors:

***FFNS vs. VFNS***

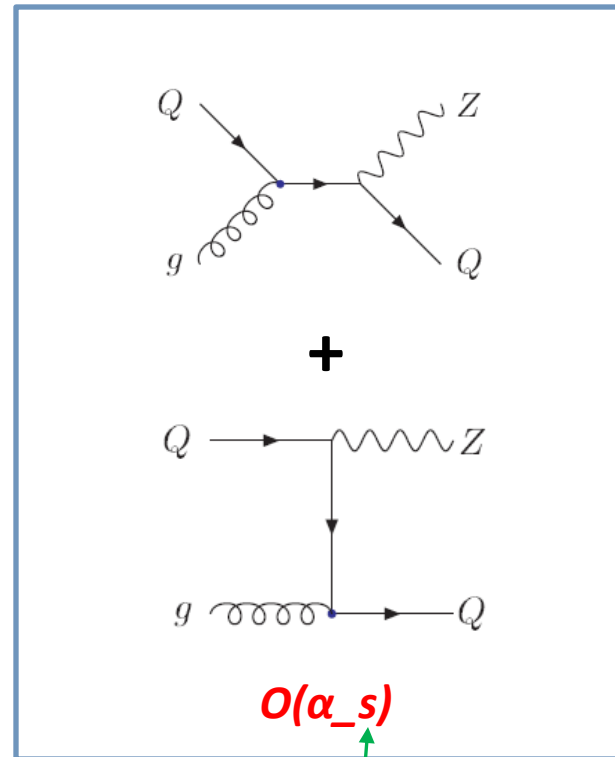
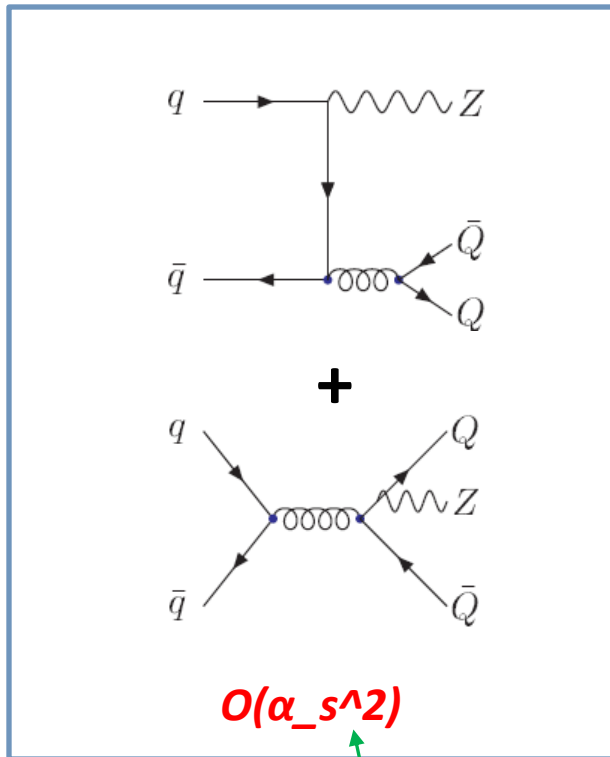


**For the 5FNS, within the so called sACOT scheme  $W+2b$  with  $m_b \neq 0$  is needed!**

(small digression...)

# Z+b at LO

4FNS vs. 5FNS



***Let's have a quick look at our  
inputs***

# **W b + X: *divide et impera***

W bb (FF)

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

$$q\bar{q}' \rightarrow Wb\bar{b}g$$

$$gq \rightarrow Wb\bar{b}q'$$

W bj (VF)

$$bq \rightarrow Wbq'$$

$$bq \rightarrow Wbq'g$$

$$bg \rightarrow Wbq'\bar{q}$$

$$gq \rightarrow Wb\bar{b}q'$$

[FFC,Reina,Wackerroth]

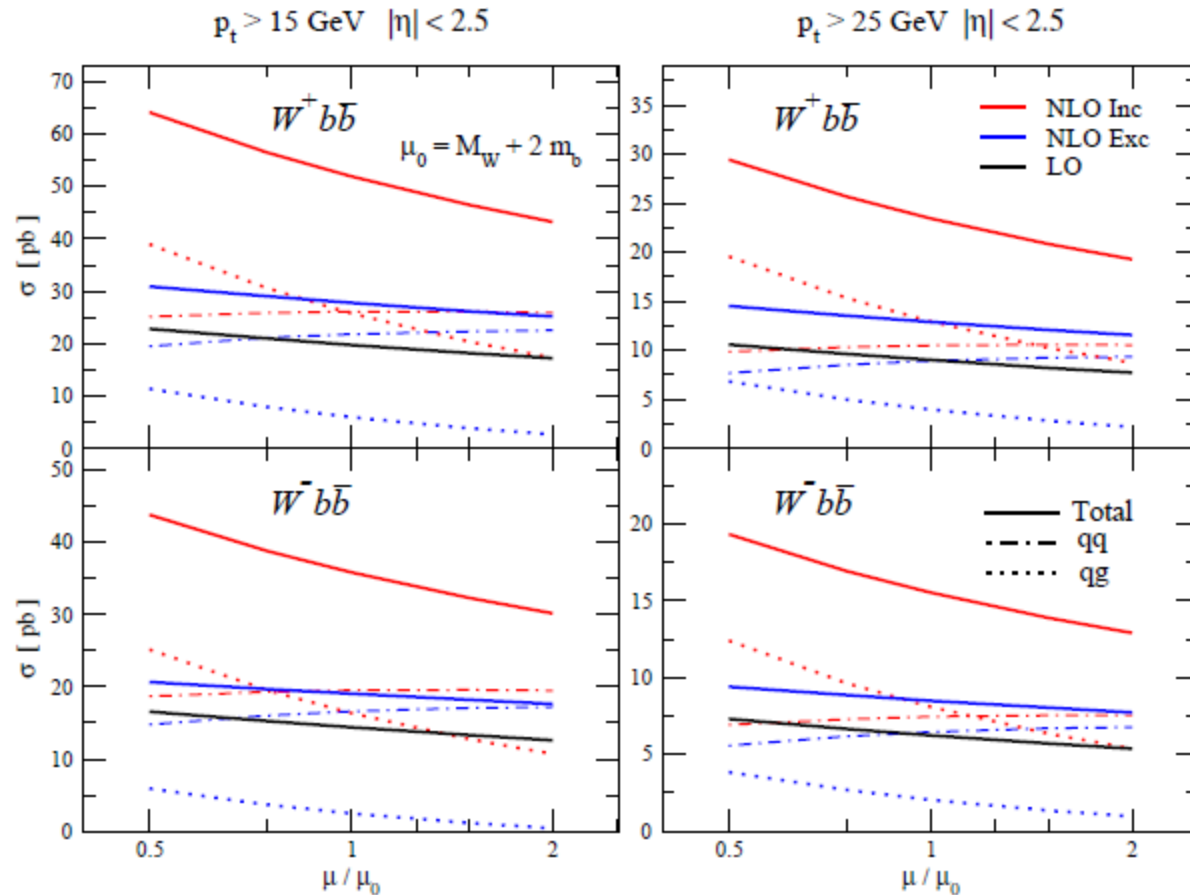
hep-ph/0606102 --- arXiv:0906.1923

[Campbell,Ellis,Maltoni,Willenbrock]

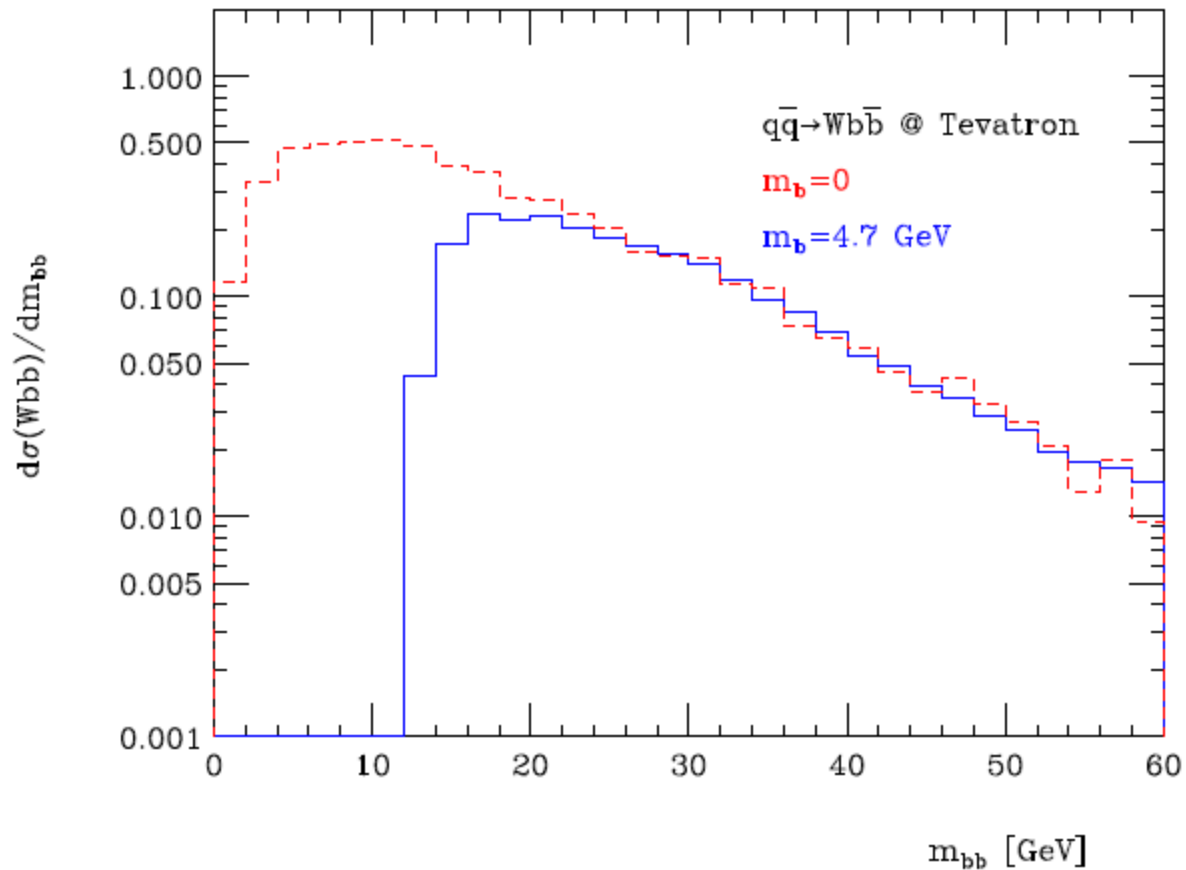
hep-ph/0611348

**W b+X & W(bb) + X @ NLO (VF)**

# 4FNS Contains Very Large Corrections



# *Massless 5FNS considerably overestimates total cross sections*



# ***W+b Configurations at NLO:***

- Exclusive production:
  - W+b: a W with a single jet containing a single b-quark
  - W+(bb): a W with a single jet containing two b-quarks
- Inclusive
  - W+b+X: a W with a single jet containing a single b-quark and up to two extra jets (one of which can be a b-jet)
  - W+(bb)+X: a W with a single jet containing two b-quarks and a possible extra (light) jet

# ***W+b at hadron colliders***

- Total (exclusive) cross sections at the Tevatron and LHC

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

Collider	Exclusive cross sections (pb)	
	$Wb$	$W(bb)$
TeV $W^+(=W^-)$	[5.28+0.75=6.03] 8.02+0.62(-0.05)=8.64	[2.66] 3.73-0.02=3.71
LHC $W^+$	[30.2+54.3=84.5] 40.0+48.4(22.6)=88.4	[17.6] 22.7+11.7=34.4
LHC $W^-$	[21.6+31.4=53.0] 29.8+29.4(12.6)=59.2	[12.9] 17.2+6.5=23.7
	$W_j$	
TeV $W^+(=W^-)$	[1410]	1790
LHC $W^+$	[14240]	15810
LHC $W^-$	[11040]	12040

# ***W+b+X at hadron colliders***

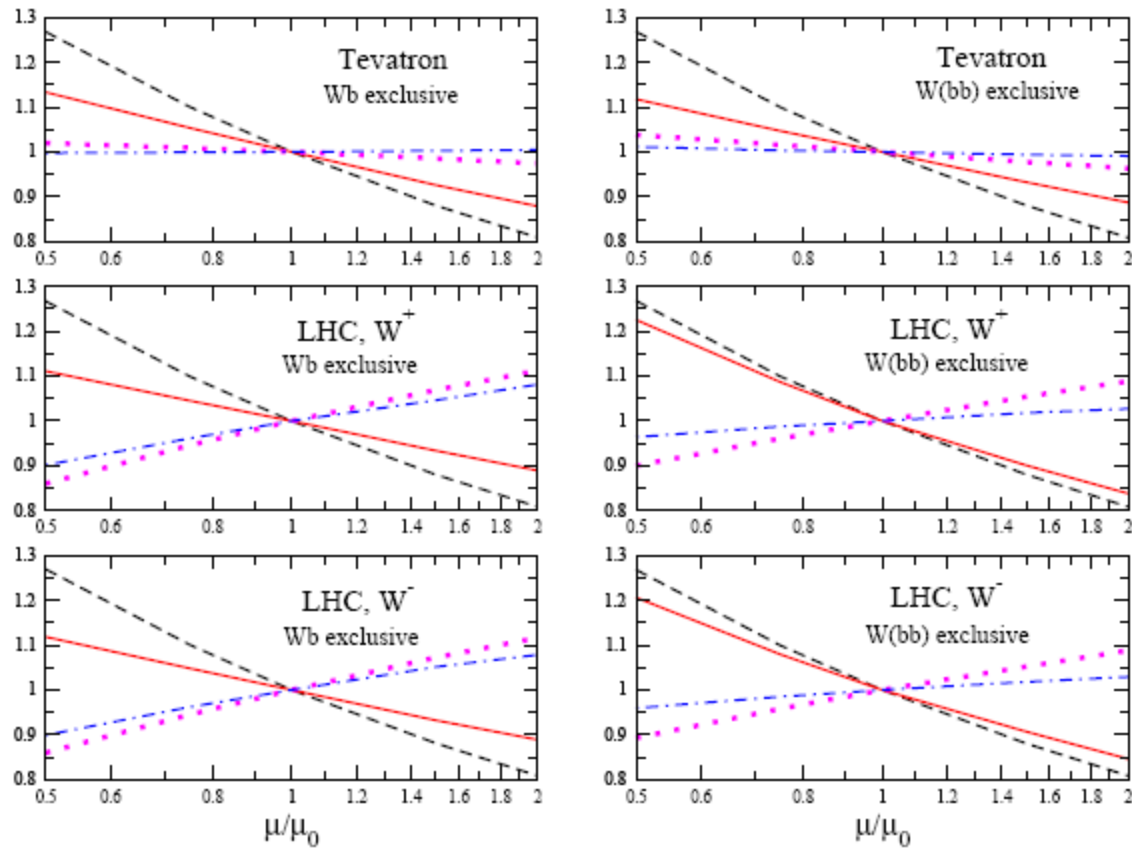
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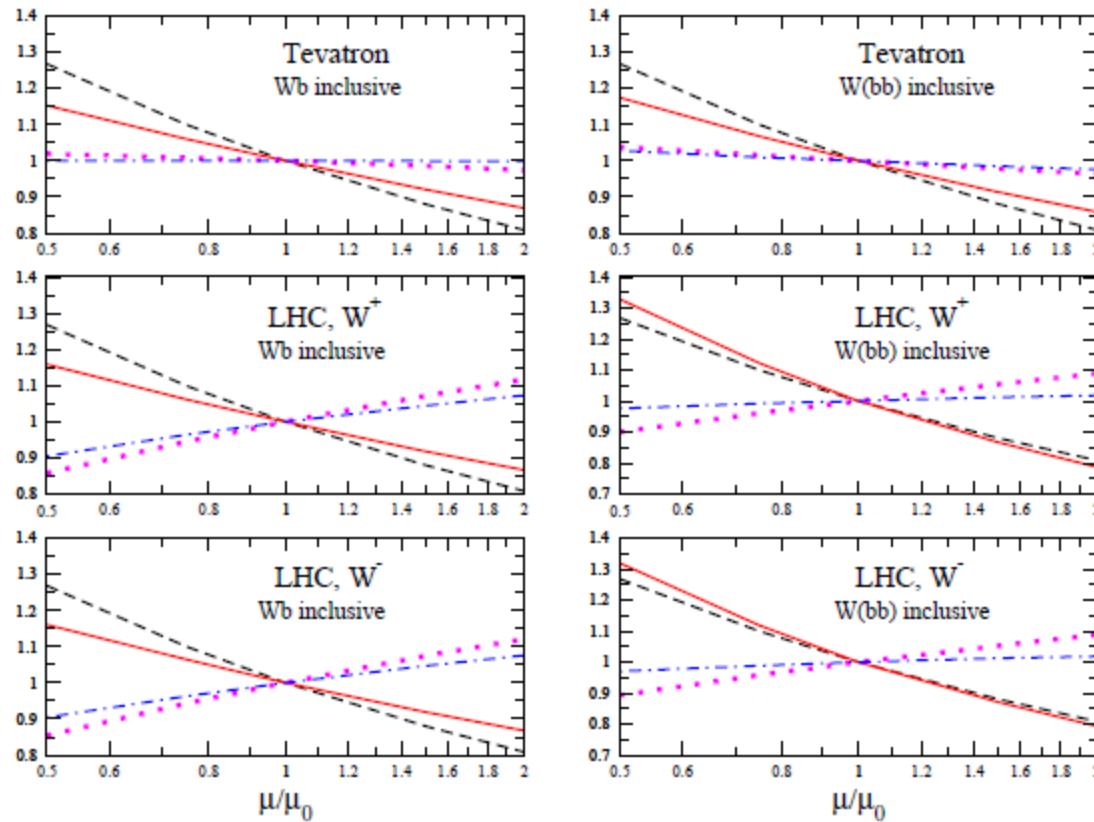
Collider	Inclusive cross sections (pb)	
	$Wb + X$	$W(bb) + X$
TeV $W^+(=W^-)$	[7.56+1.81=9.37] 11.77+2.40(0.77)=14.17	[2.66] 4.17+0.39=4.56
LHC $W^+$	[39.3+106.0=145.3] 53.6+136.1(68.9)=189.7	[17.6] 25.1+35.9=61.0
LHC $W^-$	[27.9+67.0=94.9] 39.3+88.2(44.6)=127.5	[12.9] 18.9+23.6=42.5
	$Wj + X$	
TeV $W^+(=W^-)$	[1410] 2030	
LHC $W^+$	[14240] 20000	
LHC $W^-$	[11040] 15220	

*Consistent 5FNS allows full treatment at the different kinematical regimes!*

# Scale Uncertainty of Exclusive Cross Section



# Scale Uncertainty of Inclusive Cross Section



***Let's compare to CDF data!***

# W+b at the Tevatron: CDF Analysis

arXiv:0909.1505,  $1.9 \text{ fb}^{-1}$ , *see Evelyn's talk!*

	Cut	} Acceptance estimated from LO
Electron Pt	20 GeV	
Electron eta	1.1	
Missing Energy	25 GeV	
Jet Pt	20 GeV	
Jet eta	2	
Delta R	0.4	

CTEQ6M pdfs, and factorization/renormalization  
scale set in the range  $(1/2, 2) \times (M_w)$

# W+b at the Tevatron: CDF Analysis

arXiv:0909.1505,  $1.9 \text{ fb}^{-1}$ , *see Evelyn's talk!*

*Some other important differences with respect to our (arXiv:0809.3003) setup:*

Semi-inclusive: Accept only events with exactly 1 or 2 jets (veto 3 jets events)

Jet level cross sections instead of Event level cross section: double the weight of events with two b-jets

# W+b at the Tevatron: CDF Analysis

## RESULTS:

Bin	$Wb$		$W(b\bar{b})$	
	LO	NLO	LO	NLO
1 jet	$0.44^{+0.14}_{-0.10}$ (0.41 + 0.03)	$0.62^{+0.07}_{-0.07}$ (0.59 + 0.03)	$0.10^{+0.04}_{-0.02}$	$0.13^{+0.01}_{-0.02}$ (0.13 + 0.00)
1+2 jets	$0.65^{+0.21}_{-0.15}$ (0.58 + 0.07)	$0.90^{+0.11}_{-0.11}$ (0.81 + 0.09)	$0.10^{+0.04}_{-0.02}$	$0.16^{+0.03}_{-0.03}$ (0.15 + 0.02)

Bin	$Wb\bar{b}$	
	LO	NLO
2 jet	$0.16^{+0.06}_{-0.04}$	$0.16^{+0.002}_{-0.012}$

jet cross sections

**LO:  $0.91^{+0.29}_{-0.20}$  pb**

**NLO:  $1.22 (\pm 0.14)$  pb**

$\sigma_{b\text{-jets}}(W+b\text{-jets}) \cdot \text{BR}(W \rightarrow l\nu) = 2.74 \pm 0.27 \text{ (stat)} \pm 0.42 \text{ (syst) pb}$

ALPGEN: 0.78 pb

PYTHIA: 1.10 pb

# Summary

- Presented results for  $W+b$  production including **NLO QCD** corrections within the **VFNS**
- **Scale dependence** is considerably reduced as compared to LO results, down to about **12%**
- With CDF setup, **quantum corrections increase** total cross section by **35%**, but still leave a **discrepancy** of about a **factor of 2** with data
- Comparison of distributions is under way (**Is there a better agreement for larger jet  $E_t$  cuts?**)

# Outlook

- Contributions from events with jets with two b-quarks amount to about 12%: **Should improve by adding proper fragmentation functions**
- **NLO showering** (a la MC@NLO or POWHEG) is now within reach
- Are we concerned about jet algorithm **infrared safety?** (might be unexpected given good theory/data agreement in W/Z+light jets)

# *Outlook*

- See Laura's talk (more about theoretical status of  $W/Z+2b$ -jets production)
- See Doreen's talk (theoretical improvements on  $W/Z+b$ -jets descriptions)