Weak Boson Production Associated to Heavy Quark Jet Pairs at Hadron Colliders

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in collaboration with [hep-ph/0606102], [arXiv:0801.2374]

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Theory Seminar, SLAC, January, 2008

Outline

$\longrightarrow$ Introduction and Motivations

- EWSB — Searches of a Higgs boson
- New Physics — Single-Top Production

$\longrightarrow$ $W/Z\ b\bar{b}$ NLO QCD Calculation

- $\mathcal{O}(\alpha_s)$ Virtual and Real corrections

$\longrightarrow$ Numerical Results for the Tevatron

- theoretical uncertainties
- $m_{b\bar{b}}$ distributions
- Impact of non-zero bottom quark mass

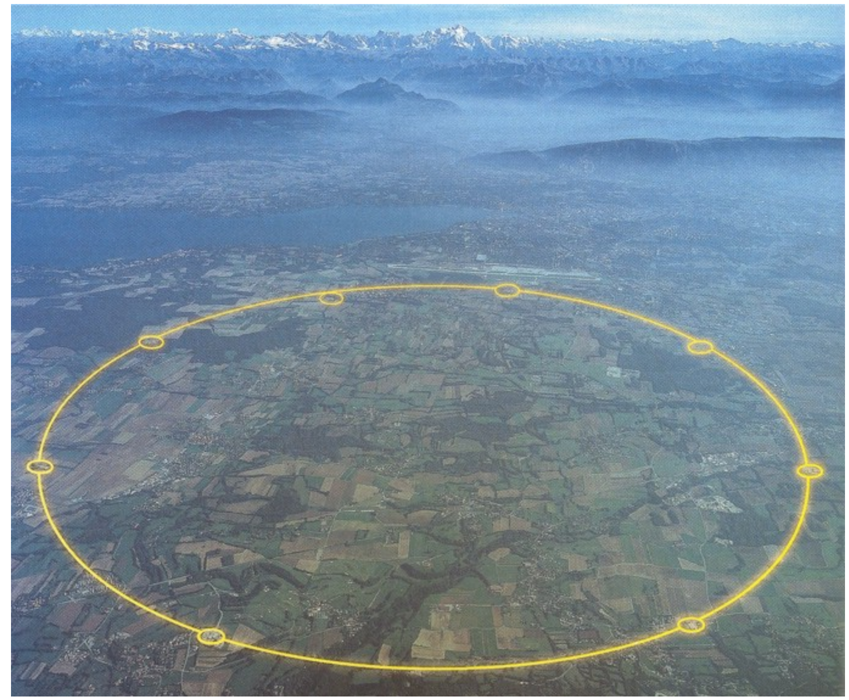
$\longrightarrow$ Summary and Outlook

Current and future High Energy Hadron Colliders

Tevatron, Fermilab

2 Km diameter $p\bar{p}$ collider at 1.96 TeV

LHC, Geneva



8.5 Km diameter pp collider at 14 TeV

Most important goals:

$\longrightarrow$ Explore mechanism of EWSB: SM Higgs boson?

$\longrightarrow$ Explore the energy spectrum beyond the weak scale: new physics?

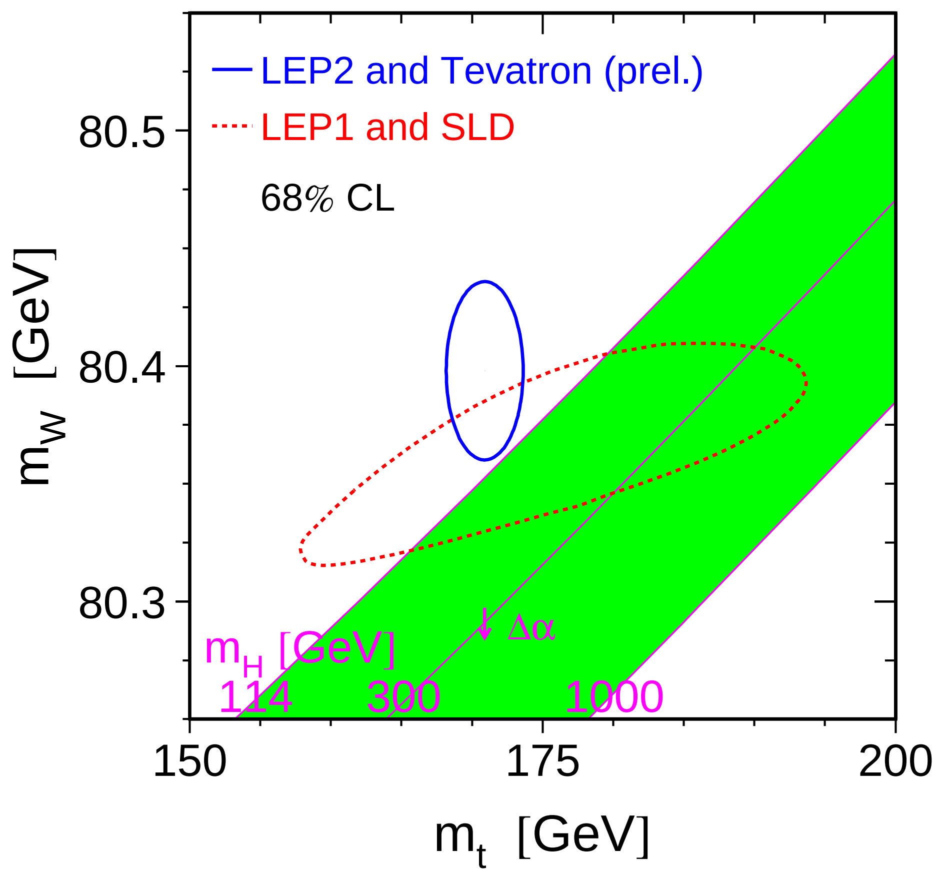
Some immediate challenges for the Tevatron:

$\longrightarrow$ Production of a light SM Higgs

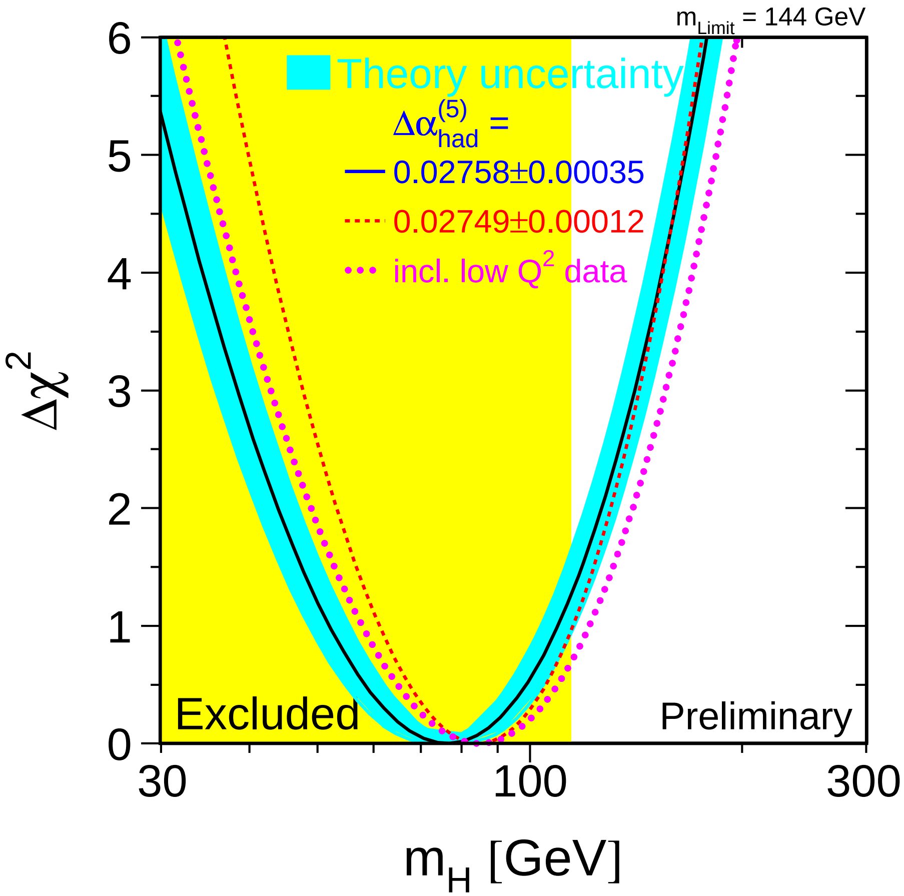
$\longrightarrow$ Single-top production

Precision EW Physics tests the consistency of the SM and constraints m_H

LEP, SLD, and Run I+II of the Tevatron have and are thoroughly testing the Standard Model (SM) of EW interactions (see LEP EWWG web page)



The Blue Band plot and constraints on m_H



$\longrightarrow$ "new": Summer 2007

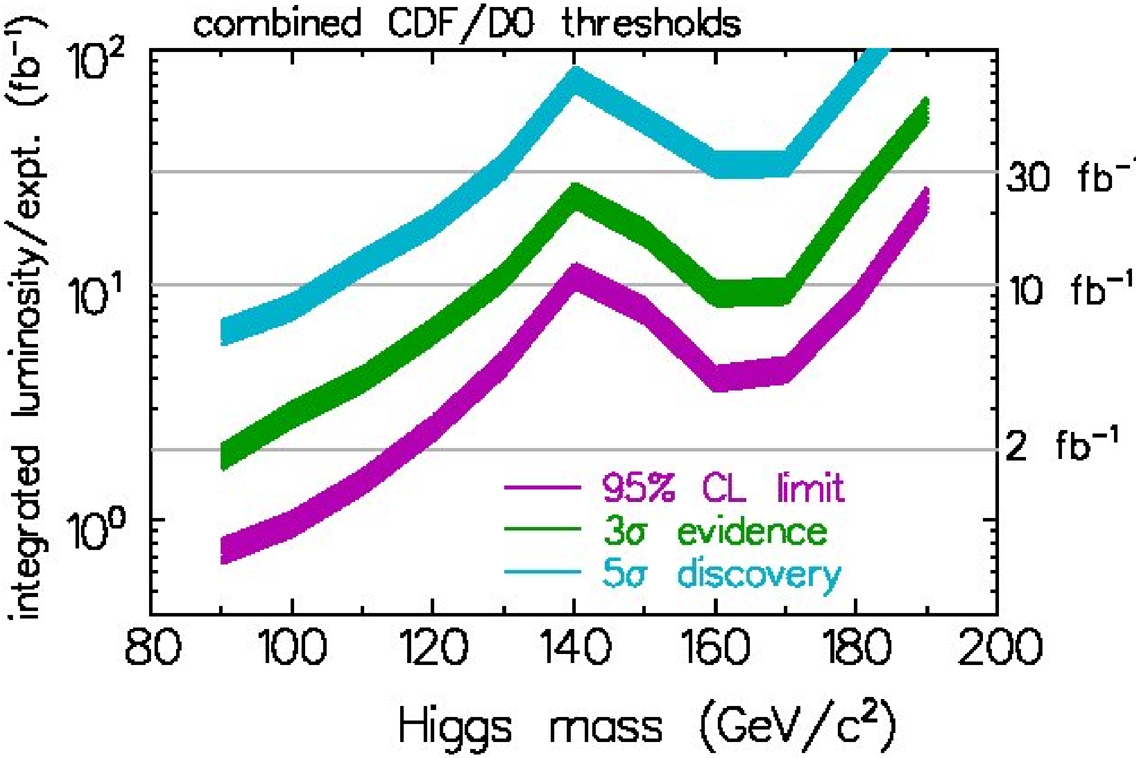
$$m_t = 170.9 \pm 1.8 \text{ GeV}$$

$$\begin{cases} m_H = 76^{+33}_{-24} \text{ GeV} \\ m_H < 144 - 182 \text{ GeV (95\% CL)} \end{cases}$$

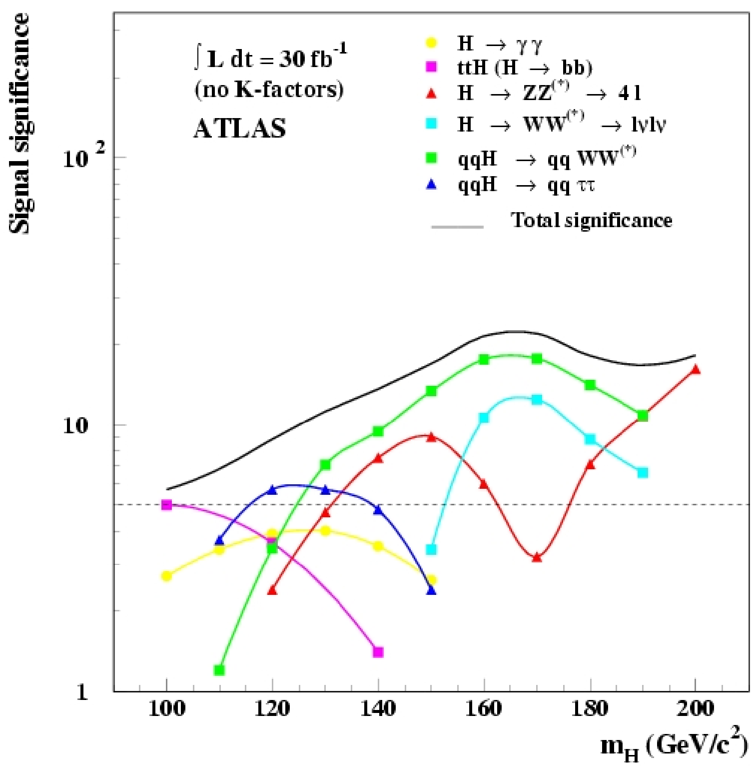
Direct searches: $m_H > 114.4$ GeV

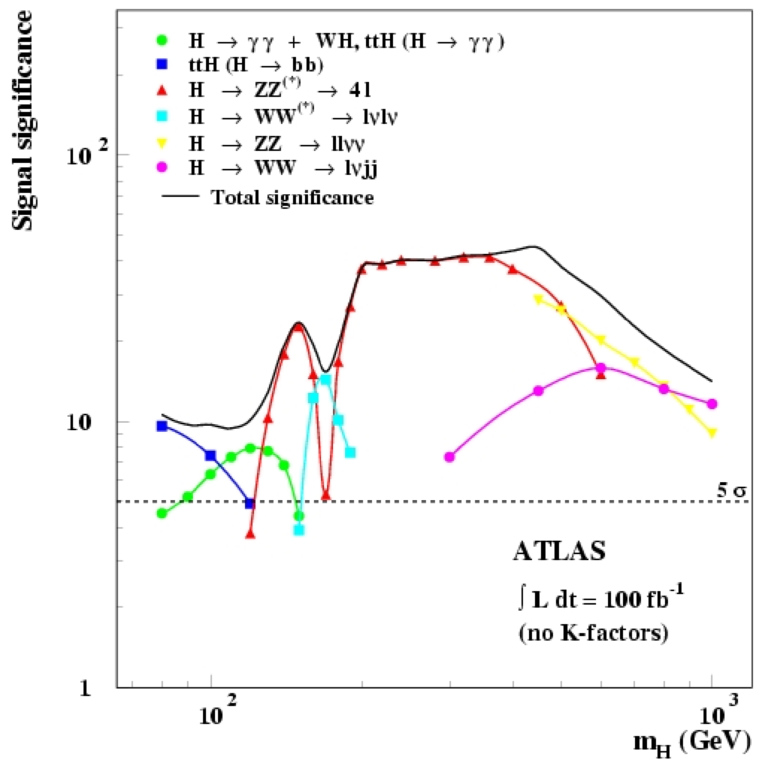
$\longrightarrow$ Searches for a light SM Higgs Boson

Tevatron Higgs searches



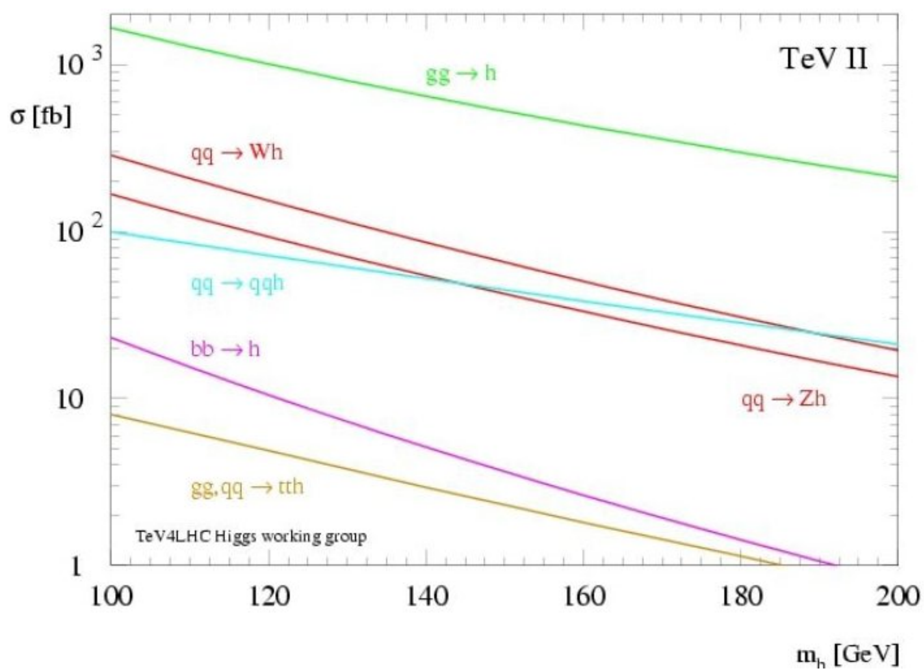
Projected Significance for LHC Higgs searches



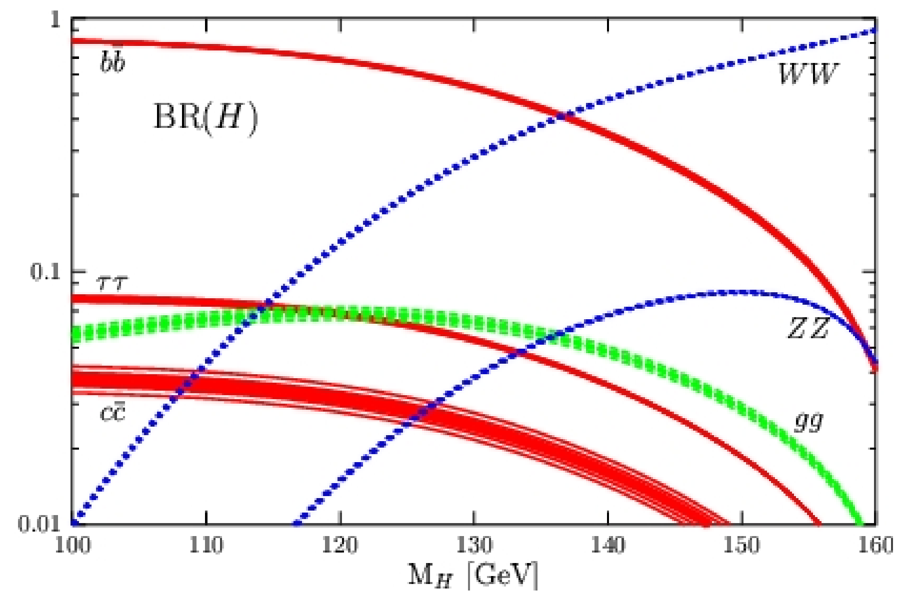


Associated production of SM Higgs with weak vector bosons at the Tevatron

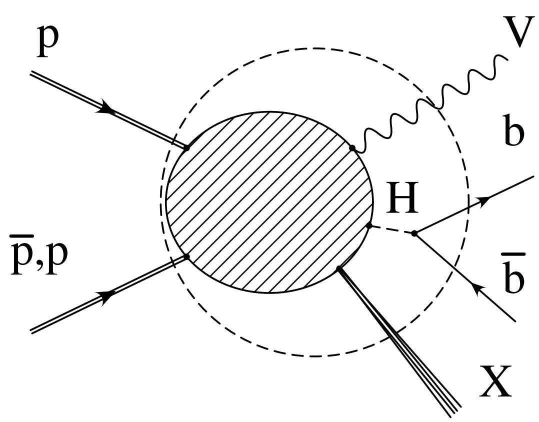
→ Cross sections for SM Higgs production @ Tevatron



→ SM Higgs decay branching ratios



Theoretical Studies of Signal



$\longrightarrow$ NNLO QCD corrections have been calculated for the signal

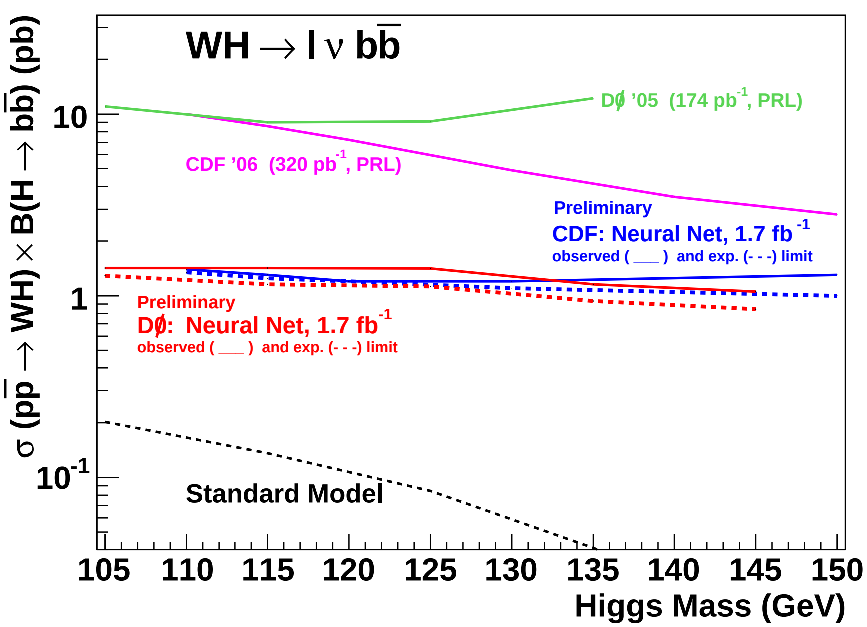
[O.Brien, A.Djouadi and R.Harlander, 2004]

$\longrightarrow$ $O(\alpha)$ EW corrections have been calculated for the signal

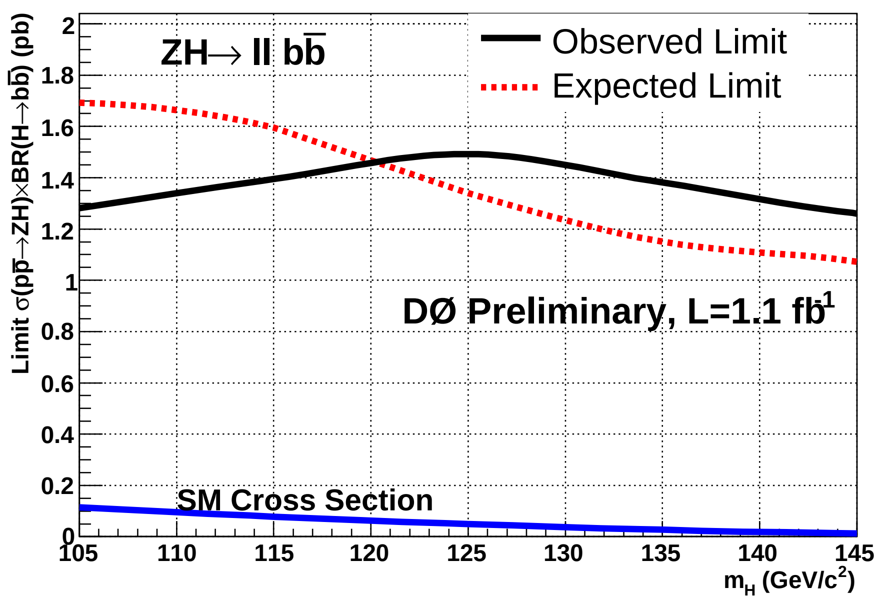
[M.L.Ciccolini, S.Dittmaier and M.Kramer, 2003]

Associated production of SM Higgs with weak vector bosons: some recent experimental results

→ Results for WH associated production, August 2007



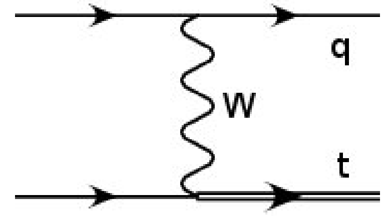
→ Results for ZH associated production, August 2007



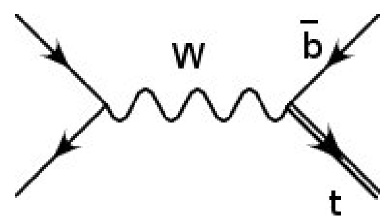
$\longrightarrow$ Single-top production

SM Single-Top production

LO diagrams for s and t channels:



(a)



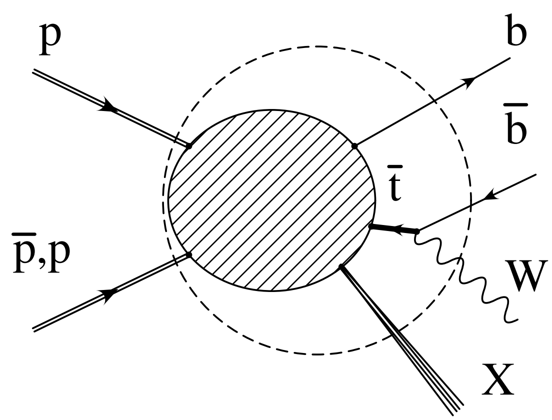
(b)

Wolfenstein parametrization of the CKM mixing matrix:

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-(\rho+i\eta)) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

So $t \rightarrow Wb$ almost 100% within the SM

Theoretical Studies of Signal

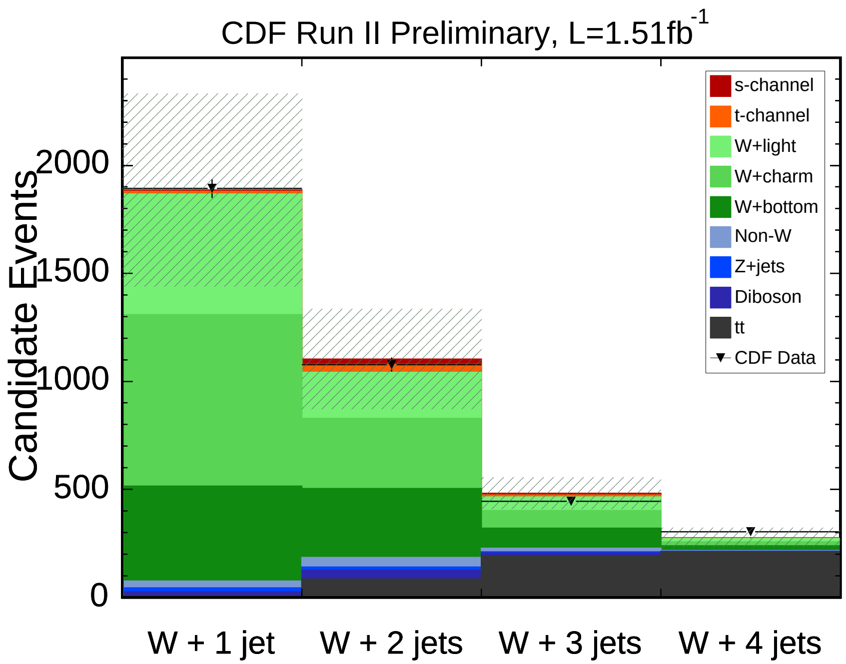


$\longrightarrow$ NLO QCD corrections have been thoroughly studied [T.Stelzer, Z.Sullivan and S.Willenbrock, 1998; B.W.Harris, E.Laenen, L.Phaf, Z.Sullivan and S.Weinzierl, 2002; ...]

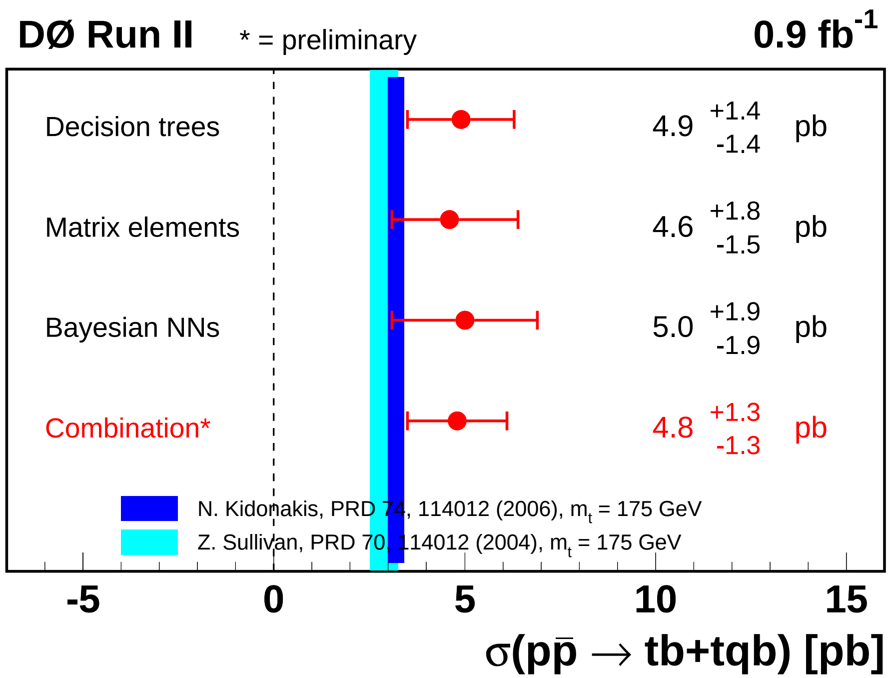
$\longrightarrow$ NLO EW corrections have been calculated for the (SM and MSSM) signal [M.Beccaria, G.Macorini, F.M.Renard and C.Verzegnassi, 2006]

SM Single-Top production: some recent experimental results

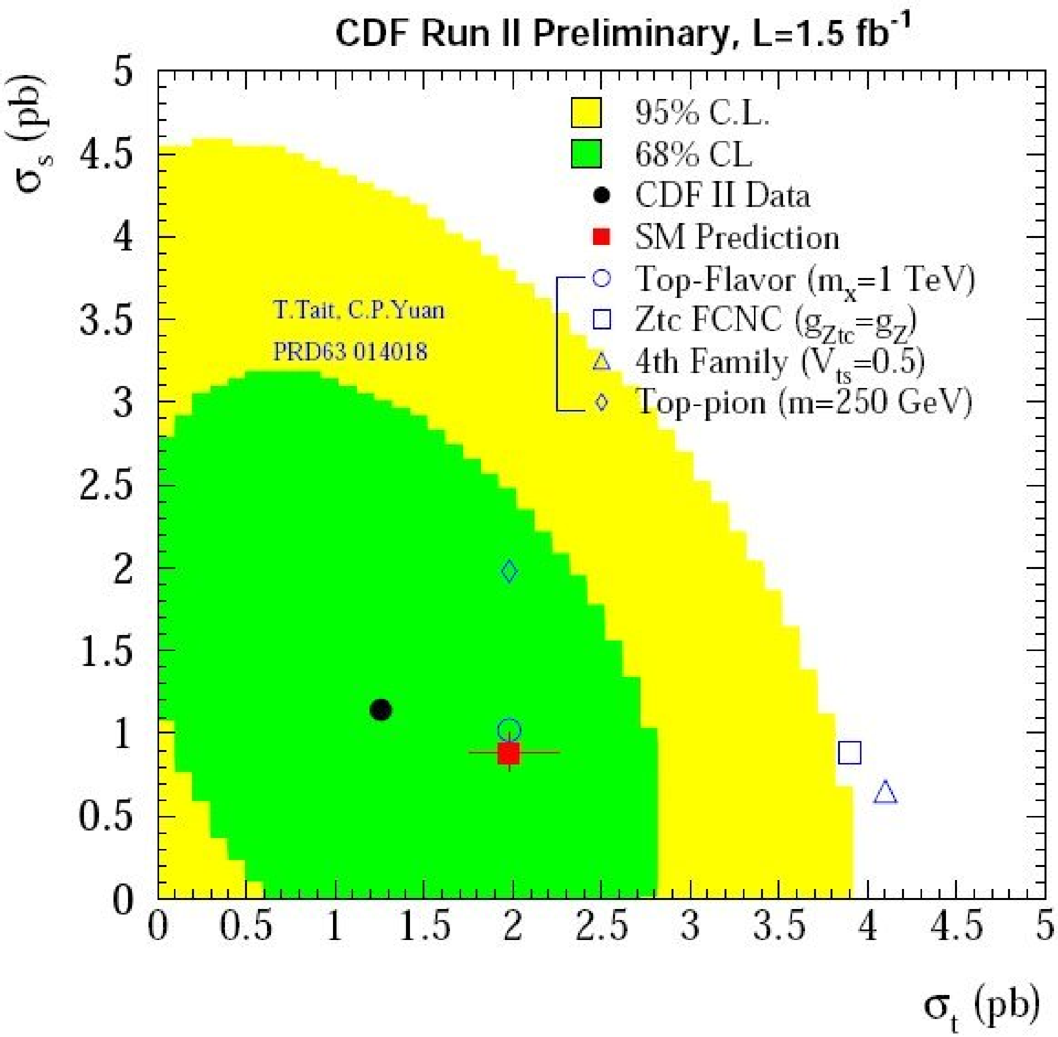
→ CDF data sample, August 2007



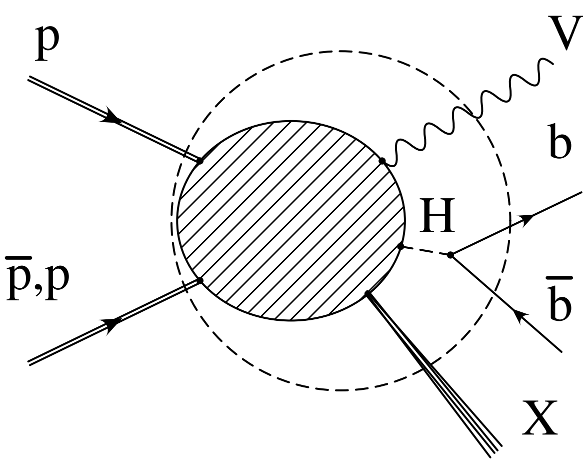
→ $D0$ evidence of single-top, March 2007



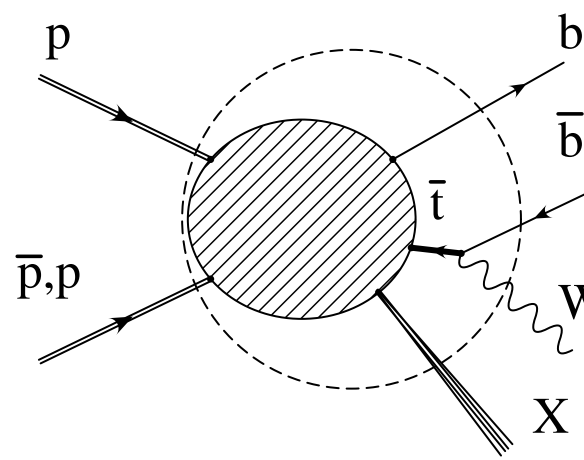
Putting constraints in models BSM



Light SM Higgs associated production with W and Z bosons



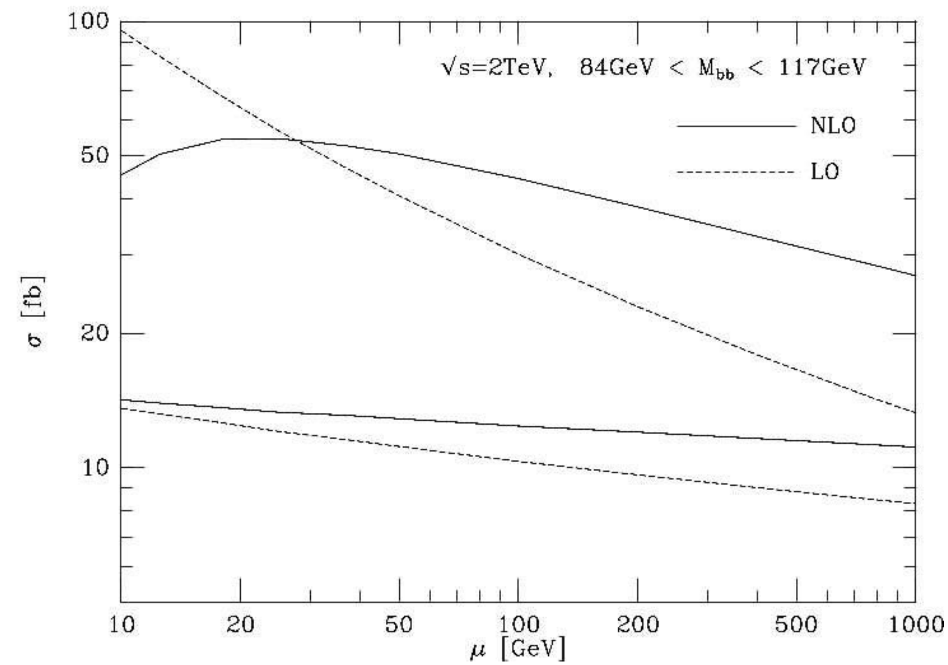
Single-Top production



$W/Z\ b\bar{b}$ QCD production most important irreducible background!

$W/Z\ b\bar{b}$ production

- NLO calculation, with $m_b = 0$ approximation available in MCFM [Z.Bern, L.Dixon and D.Kosower] [J.Campbell and R.K.Ellis]



[R.K.Ellis and S.Veseli, 1998]

$\longrightarrow$ Kinematical cuts imposed in massless approximation:

- $p^T_{b,\bar{b}} > m_b$,
- $(p_b + p_{\bar{b}})^2 > 4m_b^2$.

$\longrightarrow$ Error difficult to quantify ($\sim 10\%$ from LO estimates)

The Calculation

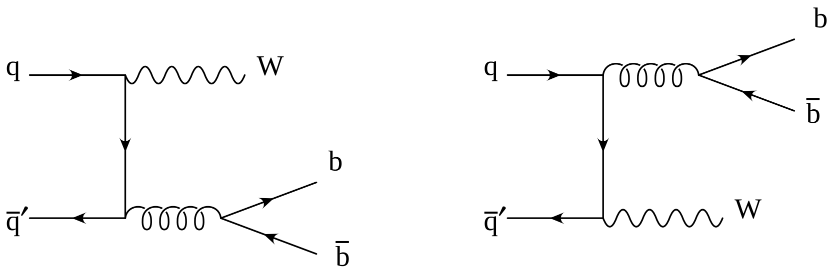
General Structure of Hadronic Cross Sections:

$$\sigma(p\bar{p}(p) \to W/Z\ b\bar{b}) =$$
$$\sum_{ij} \frac{1}{1+\delta_{ij}} \int dx_1 dx_2 \left[\mathcal{F}_i^p(x_1,\mu)\mathcal{F}_j^{\bar{p}(p)}(x_2,\mu)\hat{\sigma}_{ij}(x_1,x_2,\mu) + (x_1 \leftrightarrow x_2)\right]$$

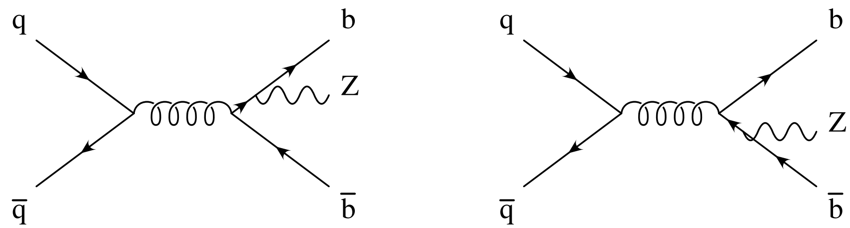
For large transfer momentum $\hat{\sigma}(x_1,x_2,\mu)$ can be calculated perturbatively in α_s

LO calculation with full m_b effects

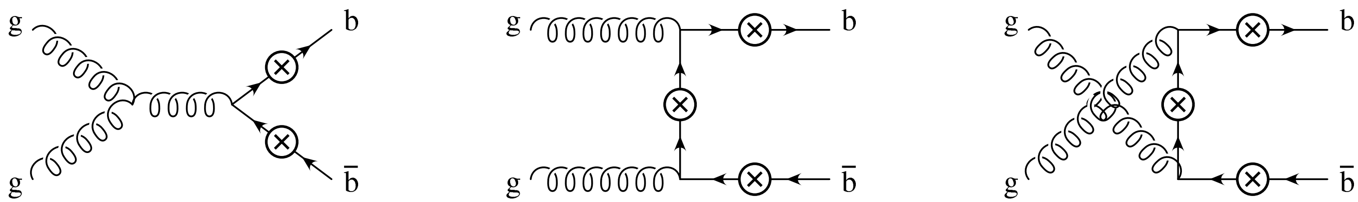
LO Feynman diagrams:



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



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



$gg \longrightarrow Zb\bar{b}$

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 $gg \rightarrow Zb\bar{b}$

LO calculation with full m_b effects (cont.)

$\longrightarrow$ Calculation straightforward, can be fully automatized.

But LO cross section has a large theoretical uncertainty:

$\longrightarrow$ Opening of new production channels at higher orders

$\longrightarrow$ Large dependence on renormalization and factorization scales

Including $\mathcal{O}(\alpha_s)$ corrections

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

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

- Virtual Corrections: one-loop diagrams $\times$ LO amplitude
  - $Wb\bar{b}$: $q\bar{q}' \to Wb\bar{b}$
  - $Zb\bar{b}$: $q\bar{q} \to Zb\bar{b}$ and $gg \to Zb\bar{b}$
- Real Corrections: tree level diagrams with extra parton
  - $Wb\bar{b}+k$: $q\bar{q}' \to Wb\bar{b}+g$ and $q(\bar{q})g \to Wb\bar{b}+q'(\bar{q}')$
  - $Zb\bar{b}+k$: $q\bar{q} \to Zb\bar{b}+g$, $gg \to Zb\bar{b}+g$ and $q(\bar{q})g \to Zb\bar{b}+q(\bar{q})$

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

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

where:

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

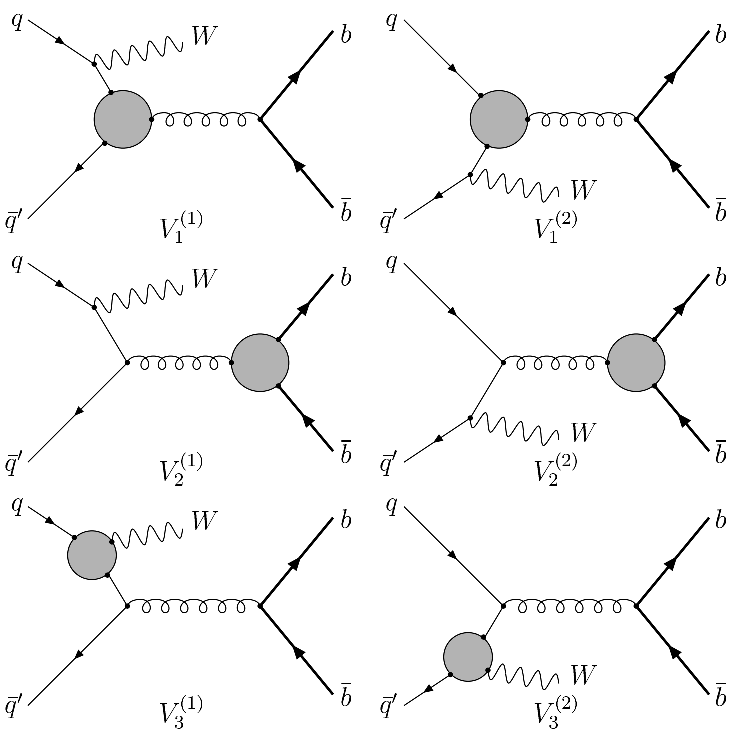
$\longrightarrow$ Use dimensional regularization to regularize UV and IR divergencies

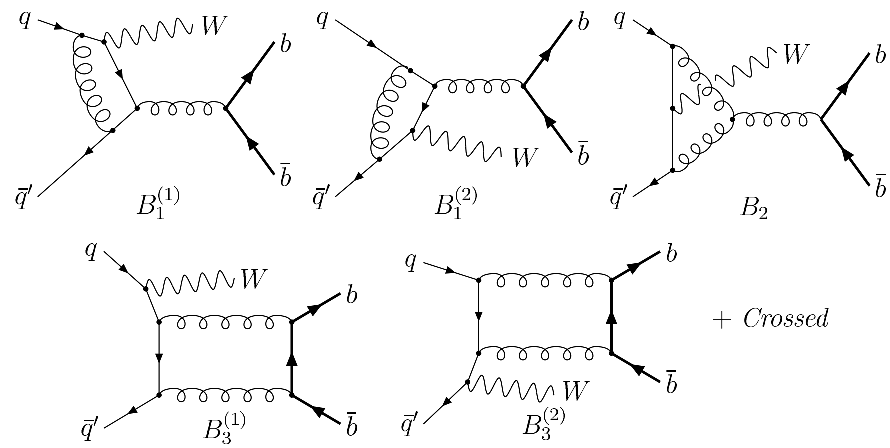
$\longrightarrow$ UV divergencies are canceled by a suitable set of counterterms

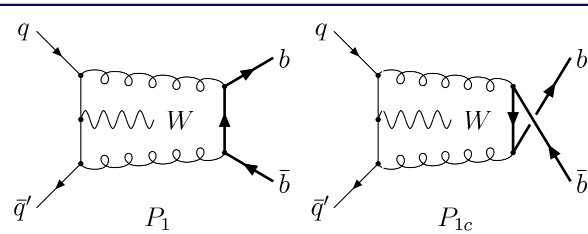
$\longrightarrow$ IR divergencies will cancel with $\hat{\sigma}_{ij}^{\rm real}$

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

Some of the $Wb\bar{b}$ Diagrams



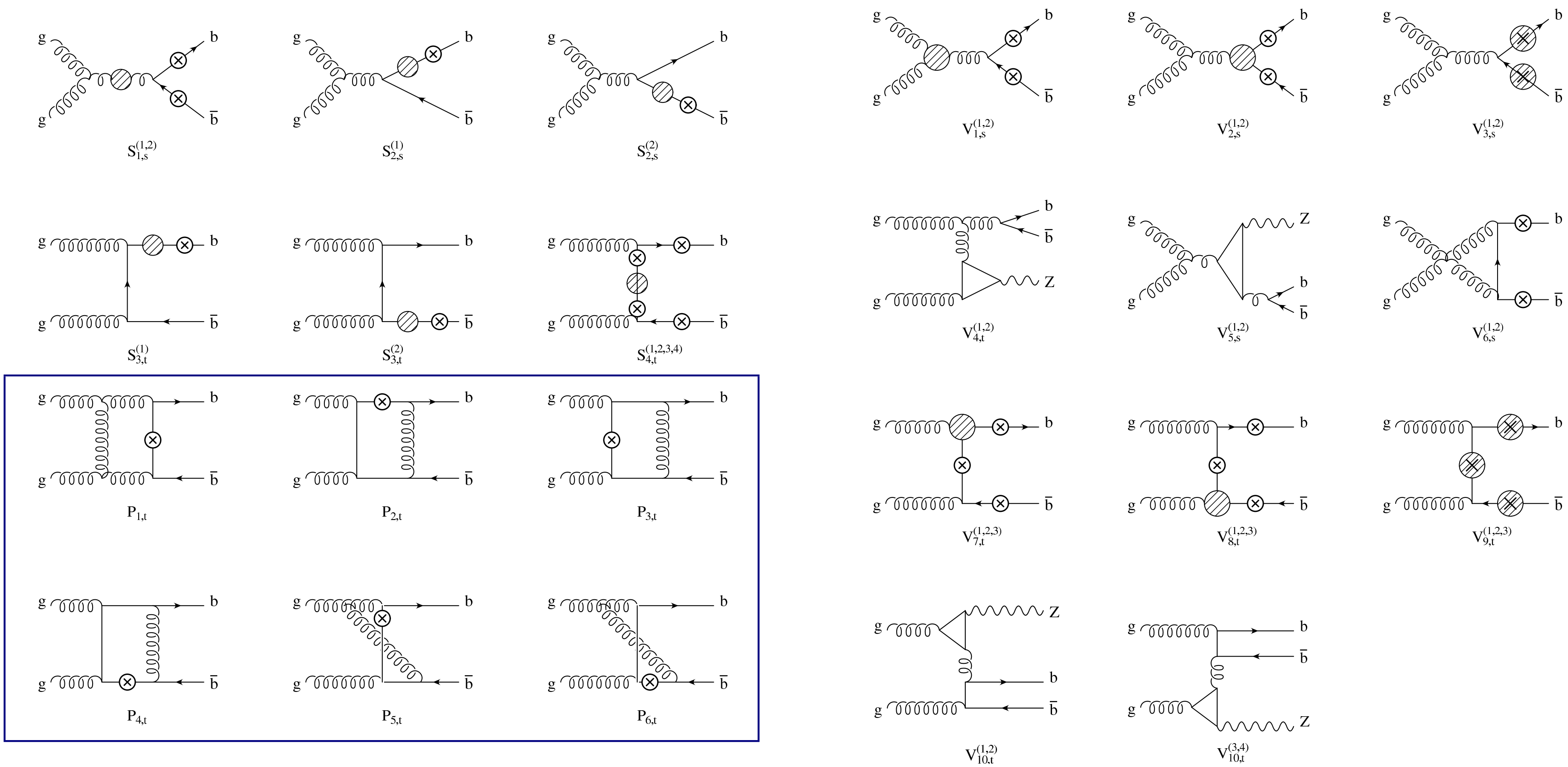




$\longrightarrow$ Counting: 2 diagrams at LO - $\sim$30 at NLO - 2 pentagons

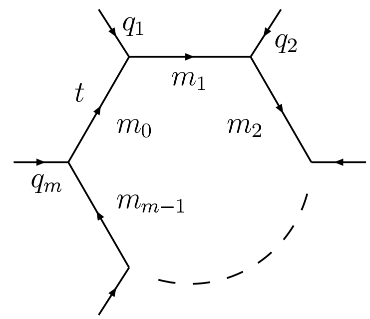
Virtual corrections: calculating $\hat{\sigma}_{ij}^{\text{virt}}$

Some of the $gg \to Zb\bar{b}$ Diagrams



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

Virtual corrections: calculating $\hat{\sigma}_{ij}^{\mathrm{virt}}$ - The Integrals



$$In^{\{0,\mu_1\ldots\mu_n\}}(q_1,\ldots,q_{m-1},m_0,\ldots,m_{m-1}) =$$

$$\int \frac{d^d t}{(2\pi)^d} \frac{\{1, t^{\mu_1}\cdots t^{\mu_n}\}}{[t^2-m_0^2][(t+q_1)^2-m_1^2]\cdots[(t+q_1+\cdots+q_{m-1})^2-m_{m-1}^2]} \,.$$

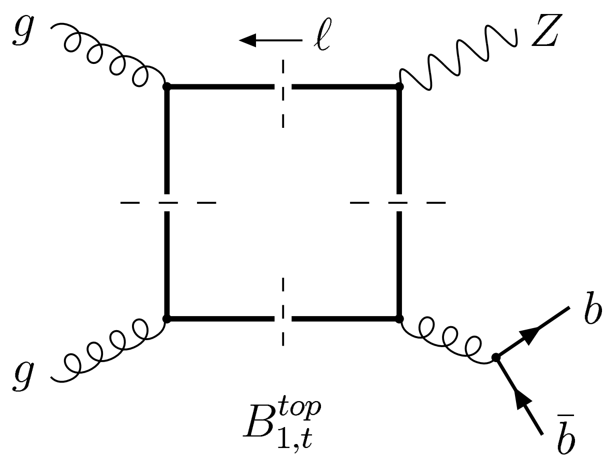
$\longrightarrow$ Tensor integrals reduced using the Passarino-Veltman (PV) method

$\longrightarrow$ Intermediate spurious divergencies — appearance of inverse powers of GDs

Challenging computation: At least two independent codes and non trivial checks

One check: Comparing to Unitarity Methods

We have compared analytically some of the most complex pieces of our calculation to results produced by using generalized unitarity [Z.Bern, L.Dixon and D.Kosower]



- Extract box contributions using BCF ansatz [R.Britto, F.Cachazo and B.Feng] and compare to coefficient of corresponding box in our calculation
- In the future we expect to use our results as playground for one-loop unitarity techniques including (up to 2) massive fermions lines

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 extracted using Phase Space Slicing (PSS) method with *two cutoffs* [J.F.Owens,L.J.Bergmann,B.W.Harris]

$\longrightarrow$ PSS introduces two unphysical parameters: δ_s and δ_c

Real corrections: calculating $\hat{\sigma}_{ij}^{\rm real}$ - PSS δ_s and δ_c cuts

1. Soft cut for extra parton: $E_g \leq \delta_s \sqrt{s}/2$ defines:

$$\hat{\sigma}^{\rm real} = \hat{\sigma}^{soft} + \hat{\sigma}^{hard}$$

   $\hat{\sigma}^{soft}$ calculated in the soft limit $(E_g \rightarrow 0)$.

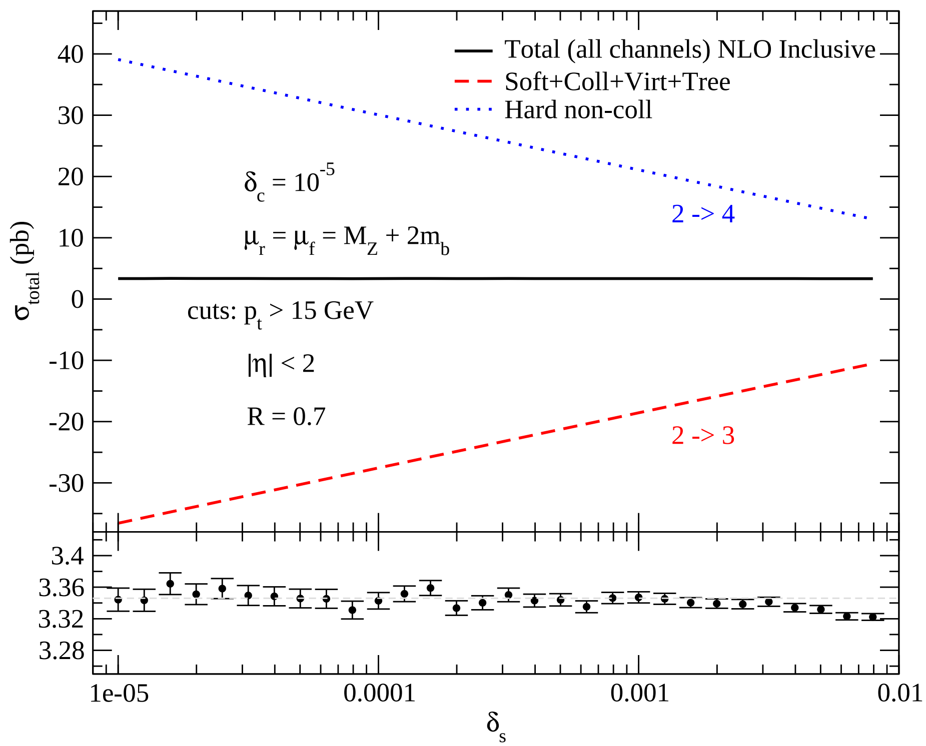
2. Collinear cut for extra parton: $(1 - \cos\theta) < \delta_c$ defines:

$$\hat{\sigma}^{hard} = \hat{\sigma}^{hard/coll} + \hat{\sigma}^{hard/non-coll}$$

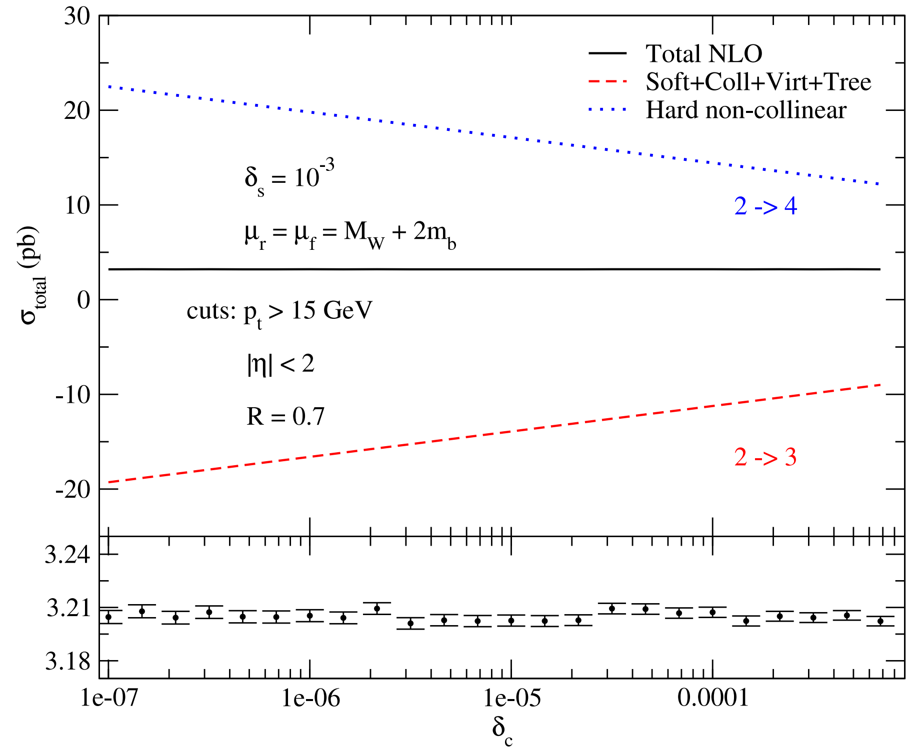
   $\hat{\sigma}^{hard/coll}$ calculated in the collinear limit $(\theta \rightarrow 0)$.

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

Independence of the total cross section of δ_s and δ_c cuts



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



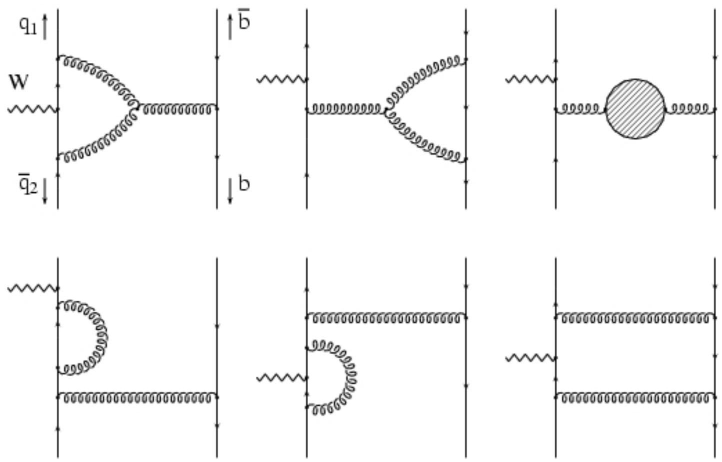
δ_c run for the $Wb\bar{b}$ total cross section

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

$\mathcal{O}(\alpha_s)$ corrections: combining virtual and real pieces

Virtual

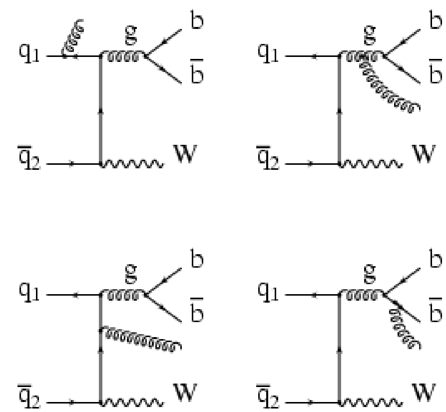
Sample of loop diagrams:



in $\overline{MS}$ renormalization scheme

Real

Sample of diagrams with extra parton:



PSS used to extract IR divergencies

$\longrightarrow$ After renormalization, $\hat{\sigma}^{\rm virt}$ is UV finite

$\longrightarrow$ IR-divergencies of $\hat{\sigma}^{\rm virt}$ canceled by IR-divergencies of $\hat{\sigma}^{\rm real}$

$\longrightarrow$ Remaining IR-divergencies reabsorbed into PDFs

$\longrightarrow$ Final Hadronic cross section is finite

Numerical Results for the Tevatron

Experimental Setup

$\longrightarrow$ CKM matrix: $V_{ud} = V_{cs} = 0.975$ and $V_{us} = V_{cd} = 0.222$

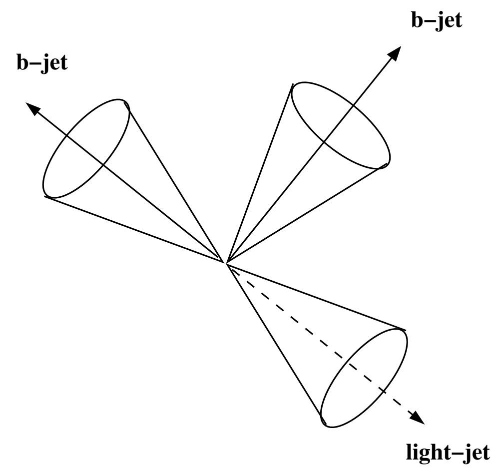
$\longrightarrow$ PDFs: LO results 1-loop evolution of α_s and CTEQ6L1, NLO results 2-loop evolution of α_s and CTEQ6M.

$\longrightarrow$ Mass Values: $M_Z = 91.1876$ GeV, $M_W = 80.410$ GeV and $m_t = 170.9$ GeV. A fixed bottom-quark mass $m_b = 4.62$ GeV

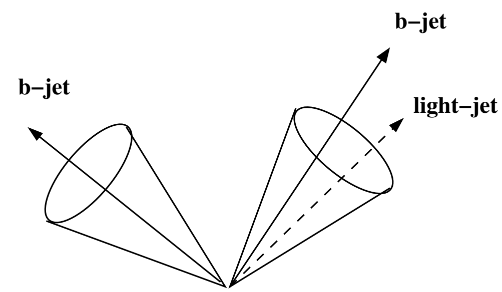
Jet Algorithm

We have used the k_T jet algorithm with pseudo-cone size $R = 0.7$.

$\longrightarrow$ 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



This is the same convention used by MCFM (all following massless results have been obtained using this program).

Experimental Cuts

- Transverse momentum of the b-jets: $p_t > p_{t,\ min}$ (15 GeV) for both b and $\bar{b}$ jets.
- Pseudorapidity: $|\eta| < \eta_{max}$ (2) for both b and $\bar{b}$ jets.
- We require both b-jets are tagged.
- If a jet passes p_t and η cuts we say it is resolved.

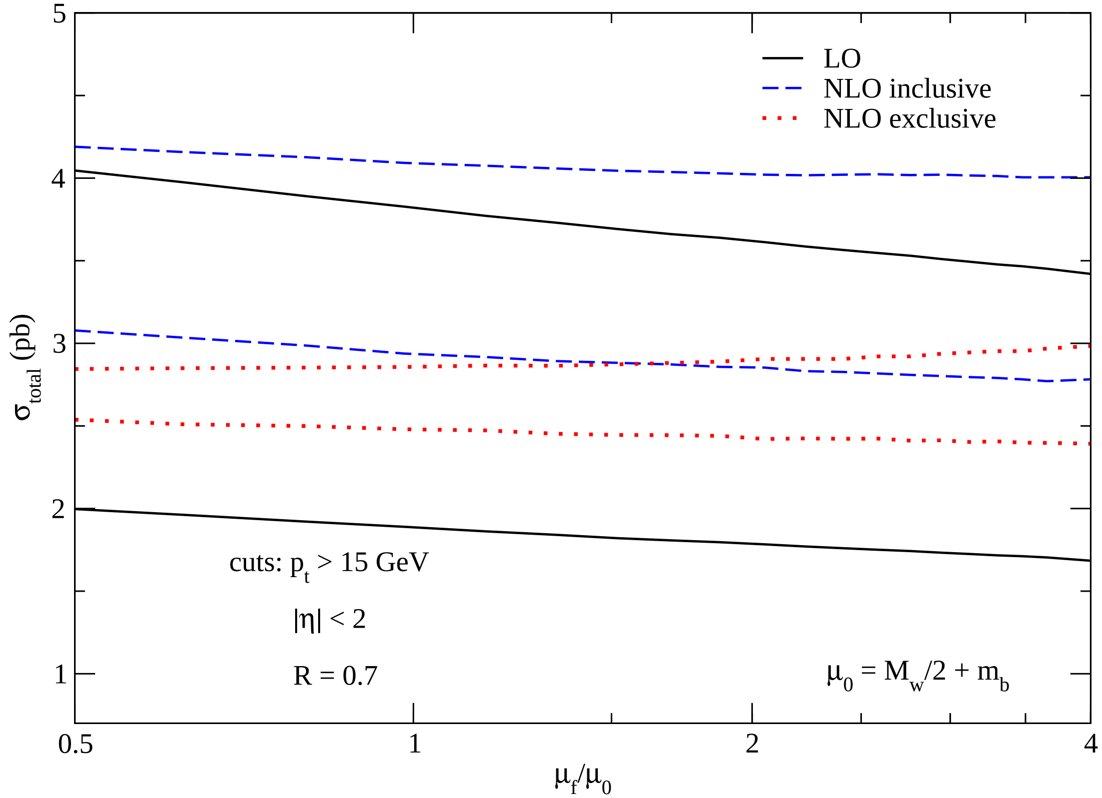
$Wb\bar{b}$: Production

NLO QCD corrections impact on total cross sections

Table 1: Summary of LO and NLO $Wb\bar{b}$ total cross sections, for both massive and massless calculation, setting $\mu_r = \mu_f = M_W + 2m_b$.

Cross Section	$m_b \neq 0$ (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]

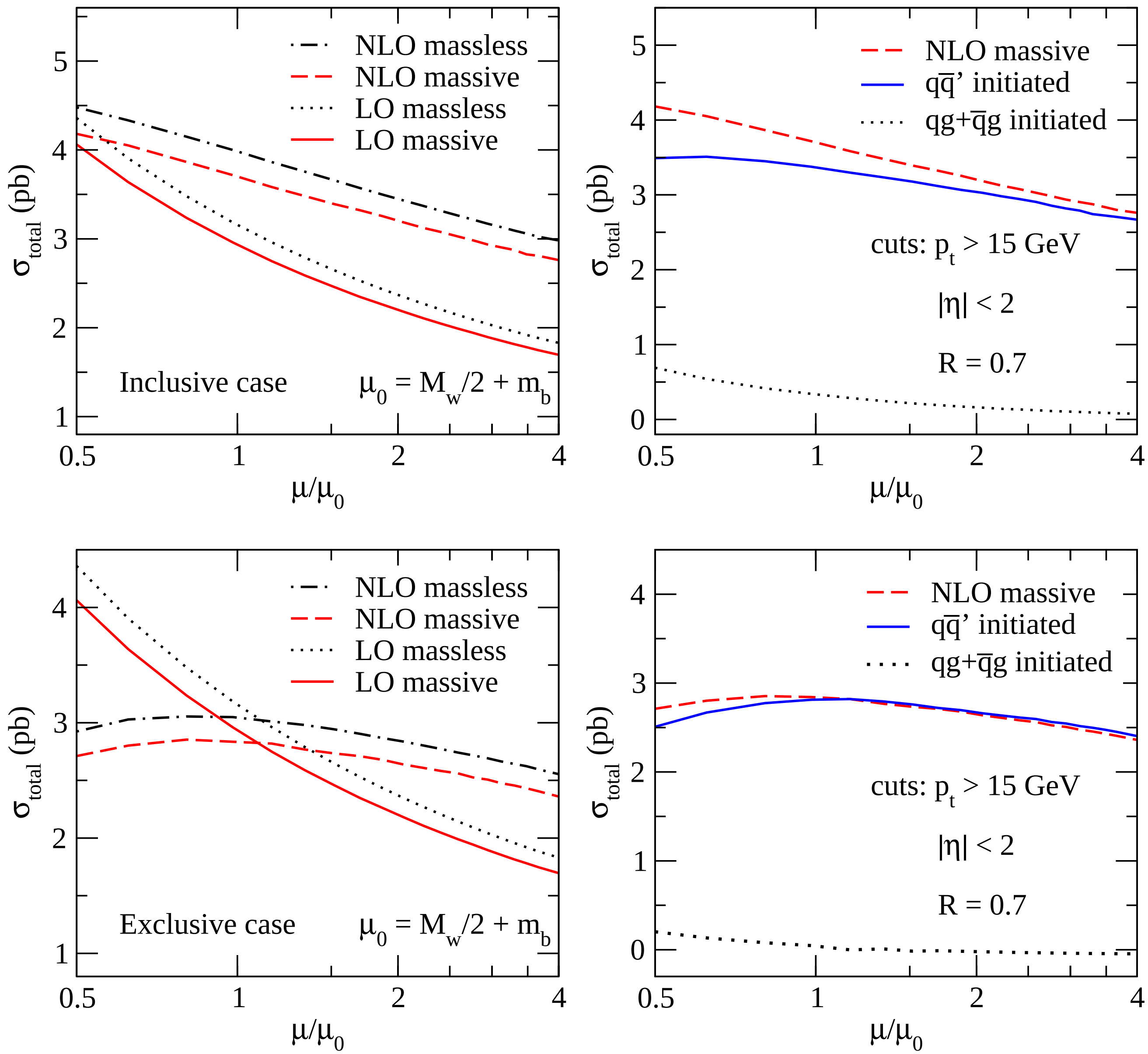
$Wb\bar{b}$: Scale Dependence and Theoretical Uncertainty



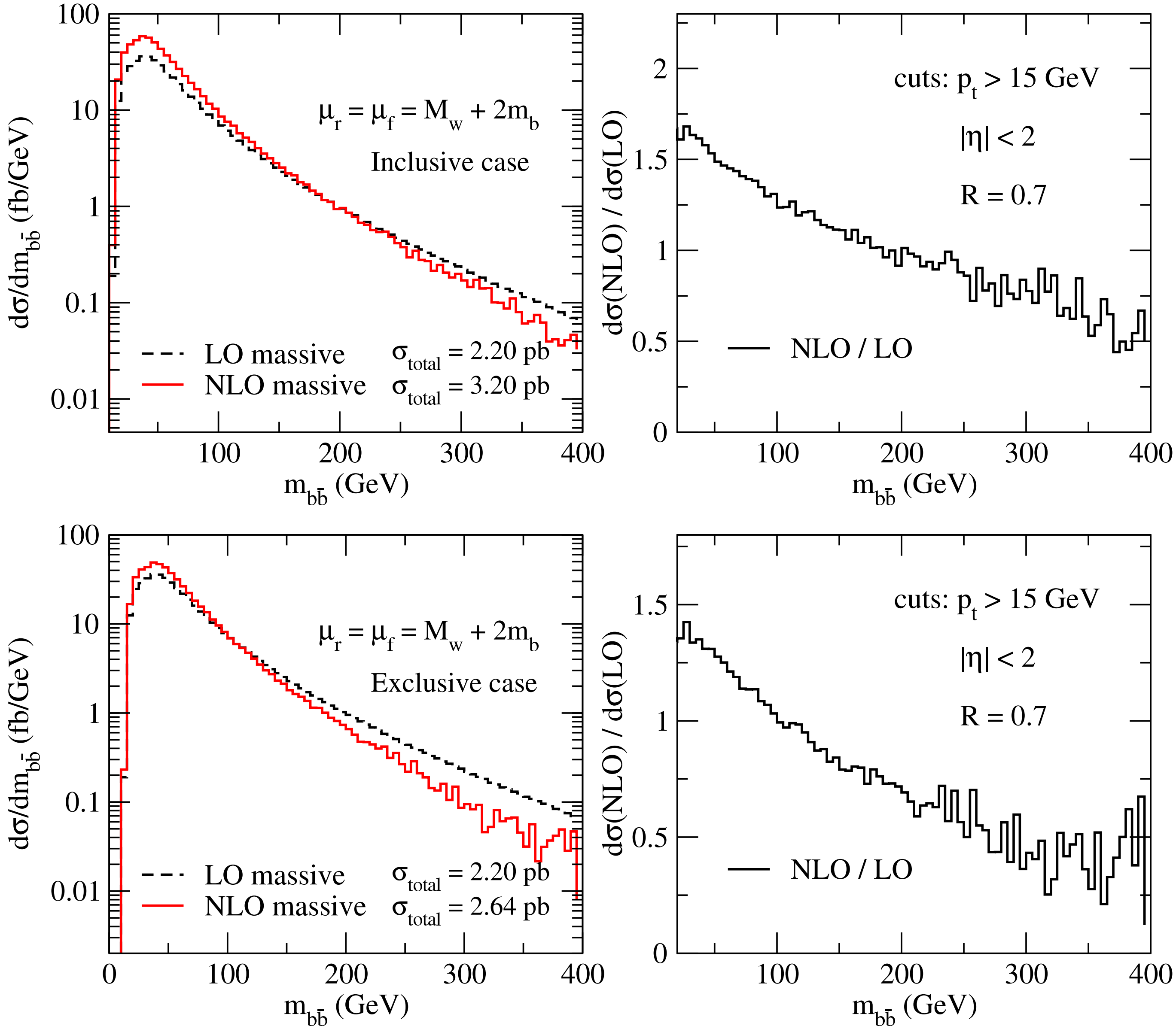
$\longrightarrow$ Bands obtained by varying both μ_R and μ_F between $\mu_0/2$ and $4\mu_0$ (with $\mu_0 = m_b + M_W/2$).

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

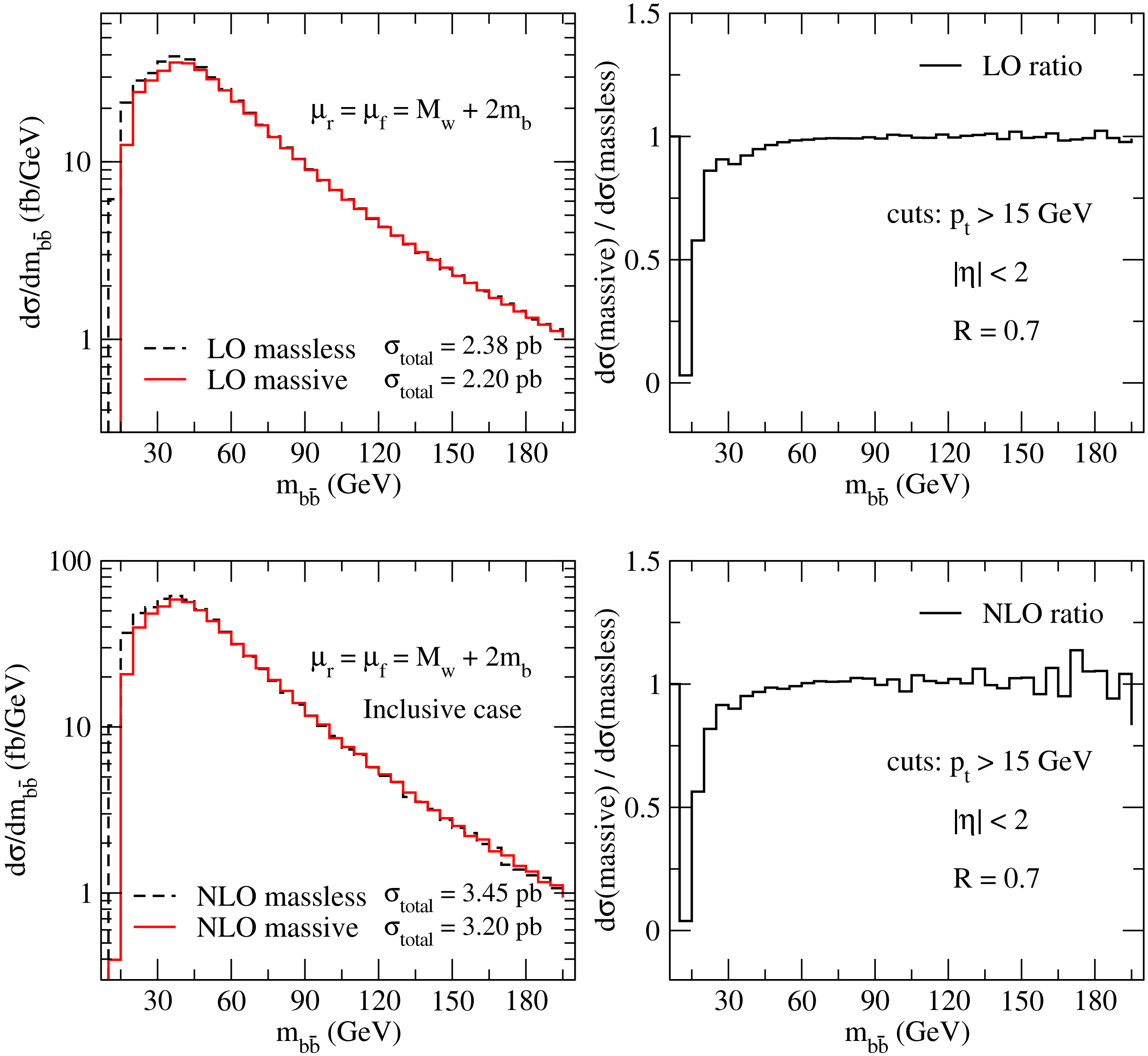
$Wb\bar{b}$: Scale Dependence for massive and massless calculations



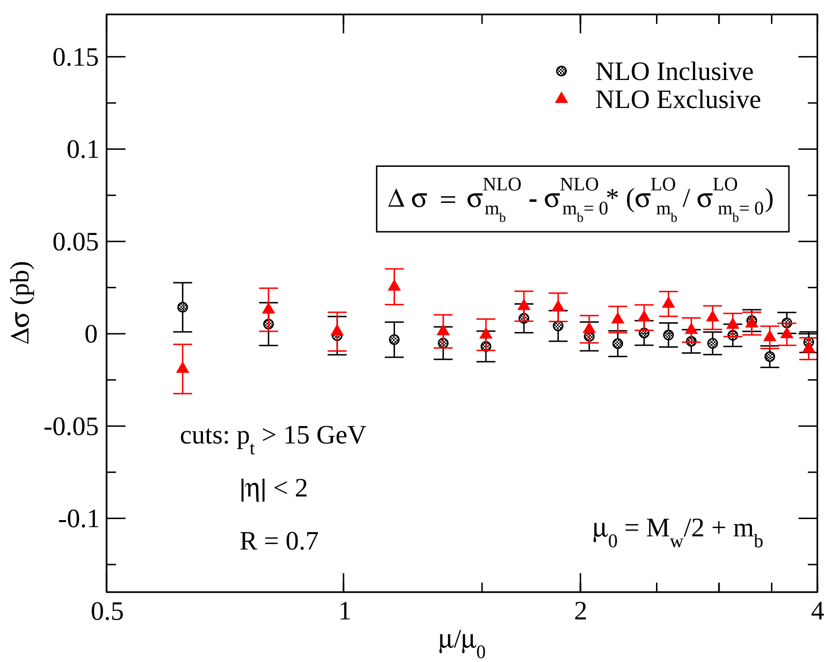
$Wb\bar{b}$: $m_{b\bar{b}}$ distributions, LO-NLO comparison

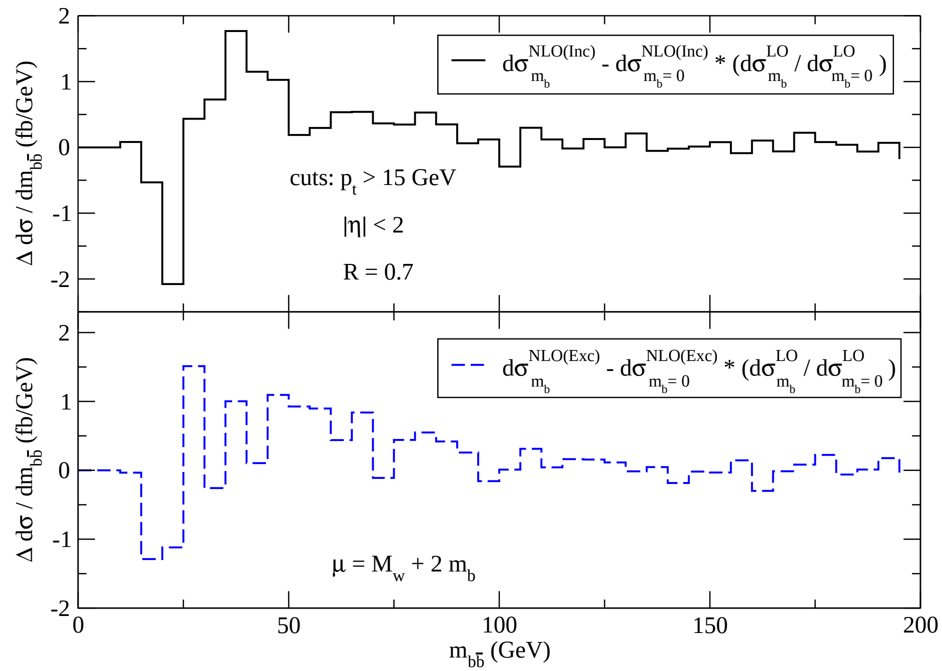


$Wb\bar{b}$: $m_{b\bar{b}}$ distributions, massive-massless comparison



$Wb\bar{b}$: m_b effects, LO-NLO comparison





$$\Delta\sigma = \sigma^{\rm NLO}(m_b \neq 0) - \sigma^{\rm NLO}(m_b = 0)\, \frac{\sigma^{\rm LO}(m_b \neq 0)}{\sigma^{\rm LO}(m_b = 0)}\,.$$

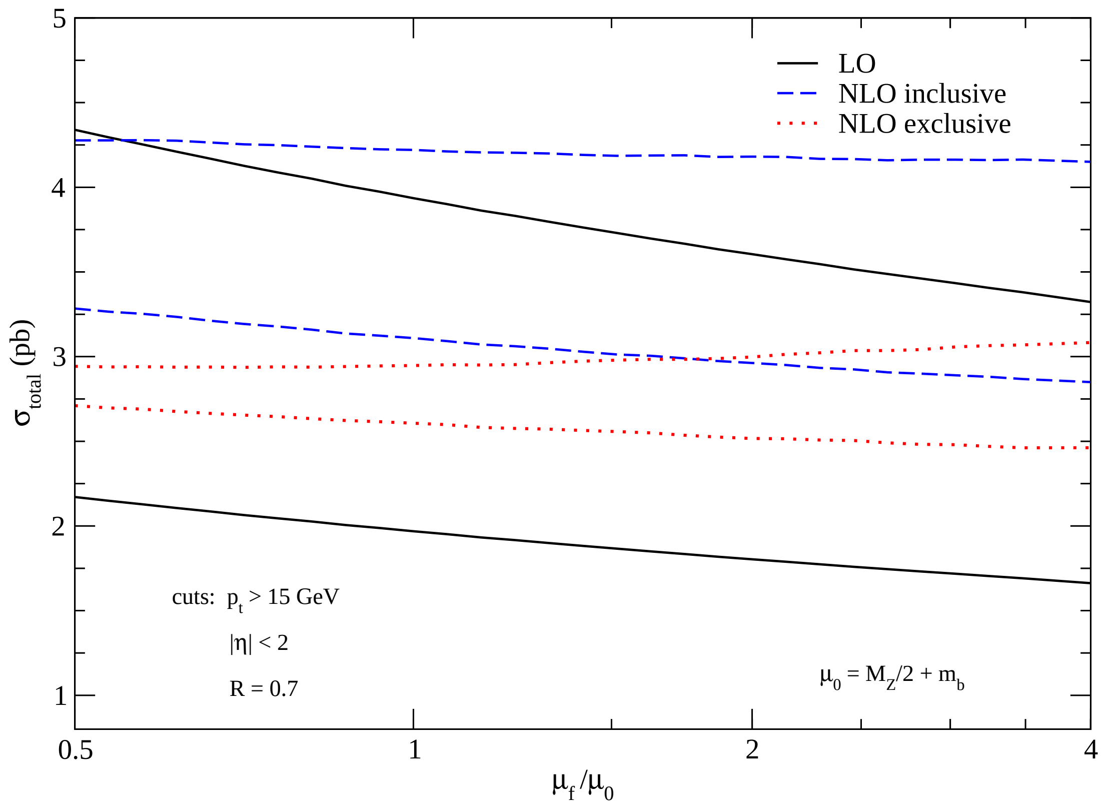
$Zb\bar{b}$ Production

NLO QCD corrections impact on total cross sections:

Table 2: Summary of LO and NLO $Zb\bar{b}$ total cross sections, for both massive and massless calculation, setting $\mu_r = \mu_f = M_Z + 2m_b$.

Cross Section	$m_b \neq 0$ (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]

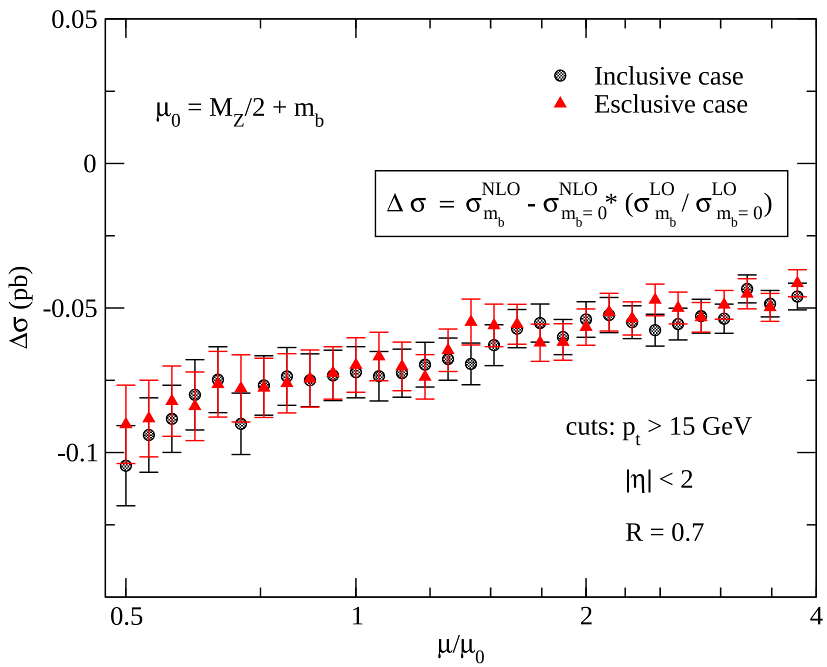
$Zb\bar{b}$: Scale Dependence and Theoretical Uncertainty

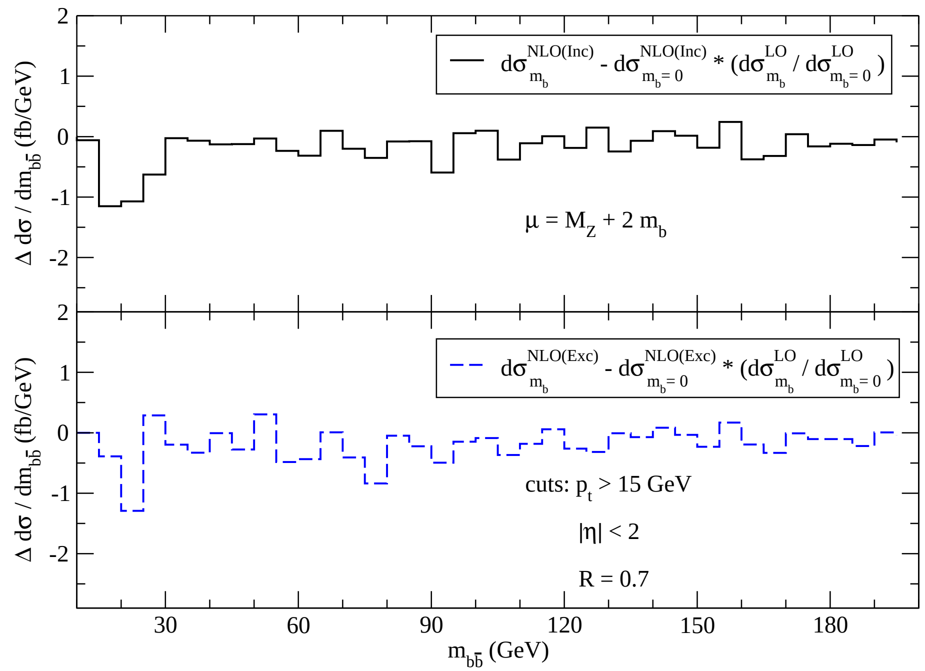


⟶ Bands obtained by varying both μ_R and μ_F between $\mu_0/2$ and $4\mu_0$ (with $\mu_0 = m_b + M_W/2$).

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

$Zb\bar{b}$: m_b effects, LO-NLO comparison





$$\Delta\sigma = \sigma^{\mathrm{NLO}}(m_b \neq 0) - \sigma^{\mathrm{NLO}}(m_b = 0)\ \frac{\sigma^{\mathrm{LO}}(m_b \neq 0)}{\sigma^{\mathrm{LO}}(m_b = 0)}\ .$$

Summary

- We have calculated the NLO QCD corrections to $W/Z\ b\bar{b}$ production at hadron colliders including full bottom-quark mass effects
- 40% LO uncertainty is reduced to 20% for inclusive NLO production and to 10% for exclusive NLO production
- Mass effects reduce by 7% to 9% the total cross section
- Our results are of relevance to the search for a SM-like Higgs particle and to the measurement of single-top production, both processes of great interest to the high energy community.

Outlook

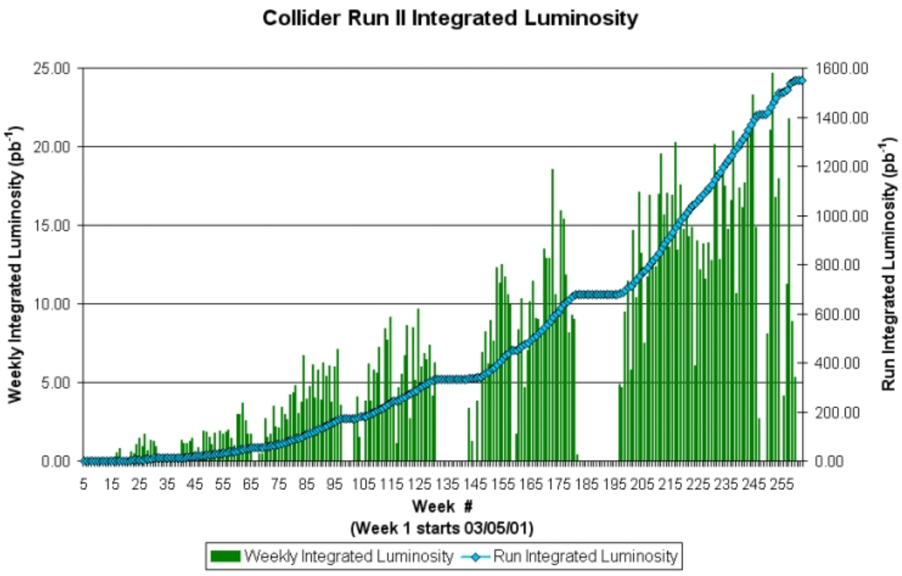
- Currently studying the impact of our calculation on for single-top searches, where we also consider final states with less than two b-quarks

- LHC results are on the way. Since at the LHC gluon initiated processes are enhanced, we expect some fundamental differences to appear

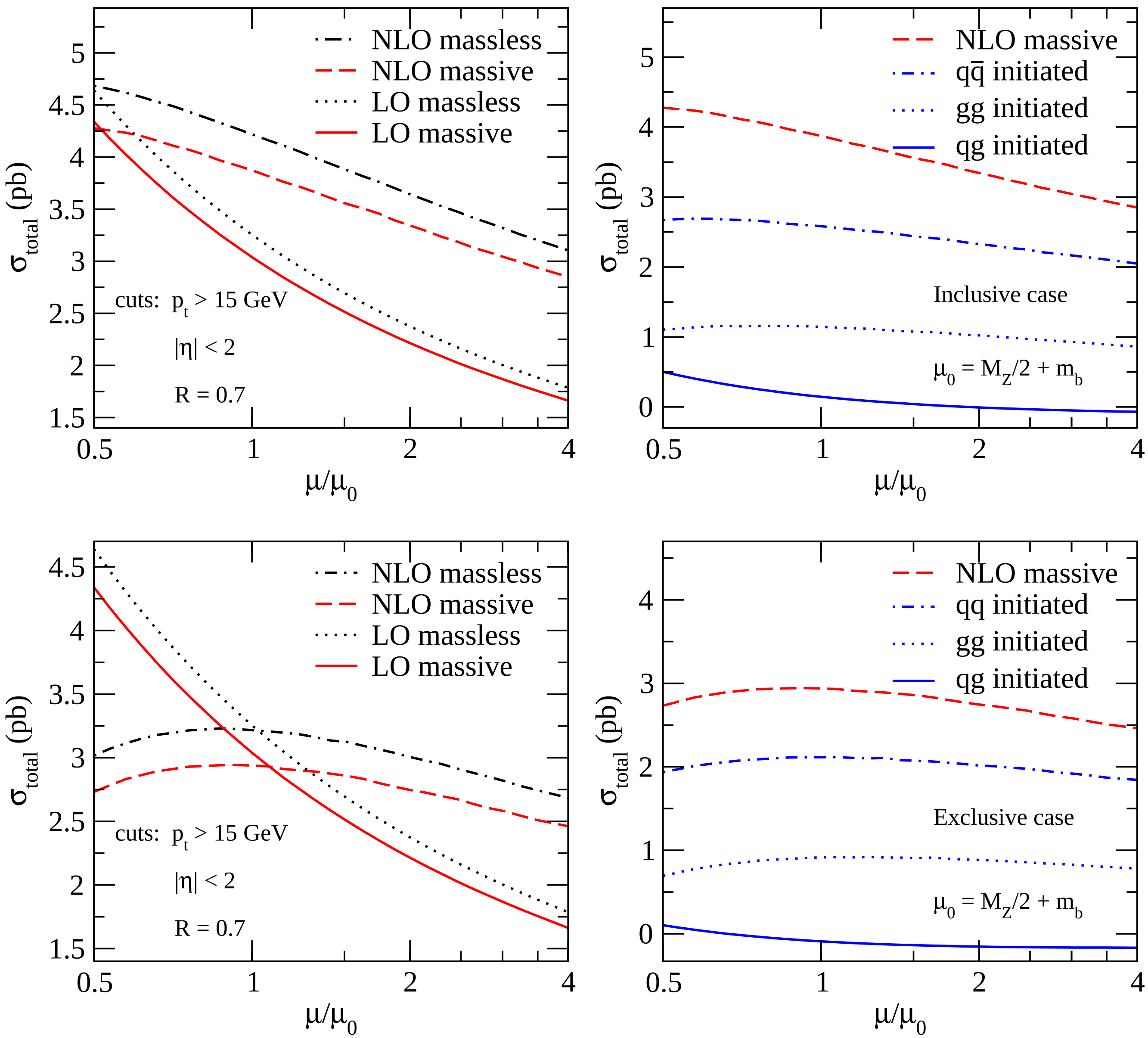
- Natural extension to other important processes like $\gamma t\bar{t}$, $Zt\bar{t}$ and $\gamma b\bar{b}$ production

- We expect to use our analytical results as a play-ground for more automated techniques for one-loop computations `BlackHat collaboration [D.Maitre, WCLHC talk]`

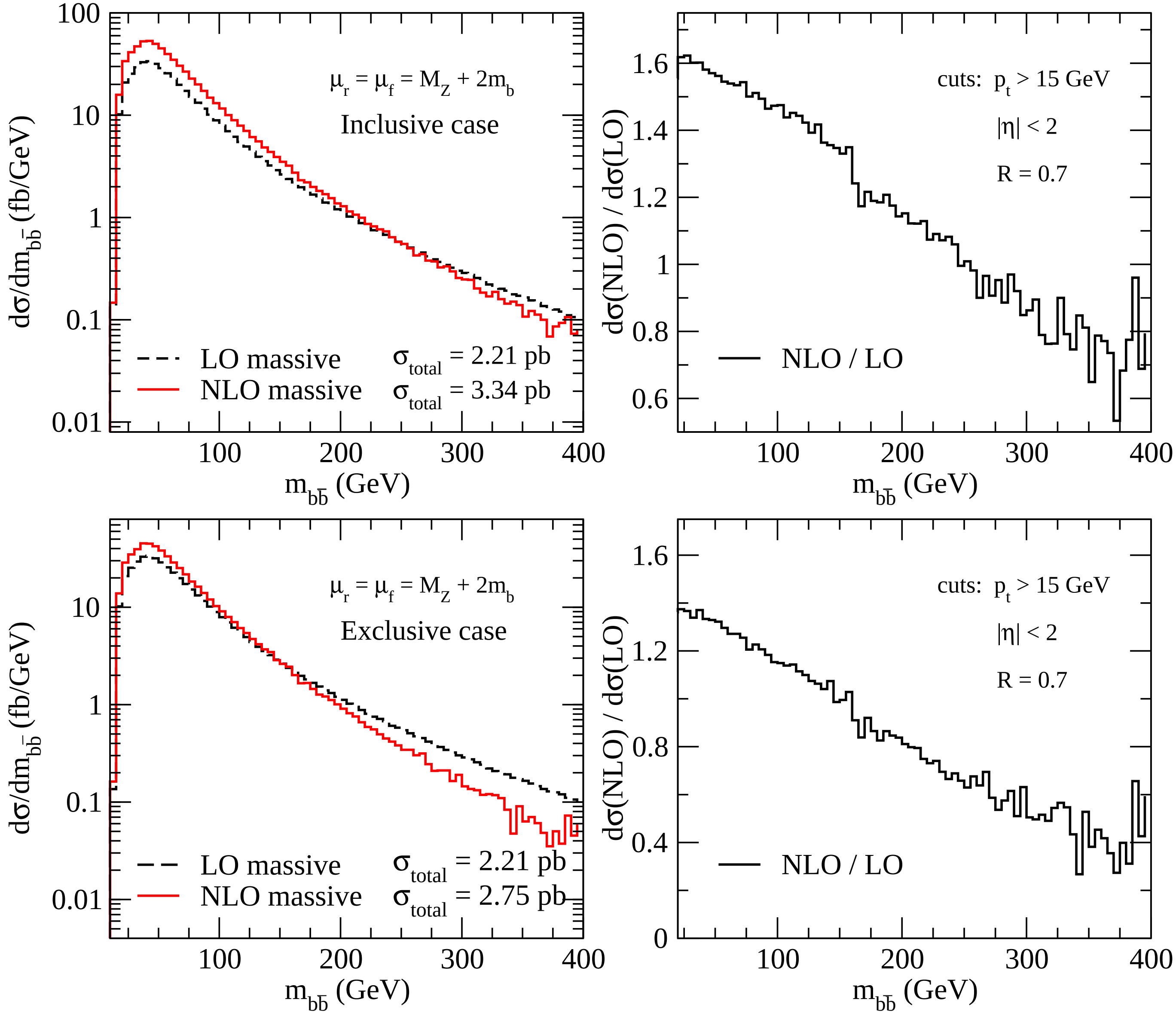
Back up slide - Tevatron Luminosity



Scale Dependence for massive and massless calculations



$Zb\bar{b}$: $m_{b\bar{b}}$ distributions, LO-NLO comparison



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