# NLO QCD corrections to $\mathrm{pp}/\mathrm{p\bar{p}} \to \mathbf{WW} + \mathbf{jet} + X$

Stefan Dittmaier

MPI Munich

in collaboration with S. Kallweit and P. Uwer

# Contents

# 1 Introduction

## Why is $\mathrm{pp}/\mathrm{p\bar{p}} \to \mathrm{WW} + \text{jet} + X$ interesting ?

- Important background process at the LHC (and for Tevatron Higgs searches)
  "Les Houches wishlist '05" for important missing NLO predictions:

| | background for |
|---|---|
| $\mathrm{pp} \to \mathrm{WW} + \mathrm{jet}$ | $\mathrm{H}$+jet, $\mathrm{t\bar{t}H}$, new physics (leptons + $\not{E}_\mathrm{T}$) |
| $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ | $\mathrm{t\bar{t}H}$ |
| $\mathrm{pp} \to \mathrm{t\bar{t}} + 2\mathrm{jets}$ | $\mathrm{t\bar{t}H}$ |
| $\mathrm{pp} \to \mathrm{VVb\bar{b}}$ | VBF $\to \mathrm{H} \to \mathrm{VV}$, $\mathrm{t\bar{t}H}$, new physics |
| $\mathrm{pp} \to \mathrm{VV} + 2\mathrm{jets}$ | VBF $\to \mathrm{H} \to \mathrm{VV}$ |
| VBF: Jäger et al. '06, Bozzi et al. '07 | |
| $\mathrm{pp} \to \mathrm{V} + 3\mathrm{jets}$ | $\mathrm{t\bar{t}}$, new physics |
| $\mathrm{pp} \to \mathrm{VVV}$ | SUSY tri-lepton |
| ZZZ: Lazopoulos et al. '07 | |

- A large fraction of W-pair events at the LHC show additional jet activity
  $\hookrightarrow$ EW gauge-boson coupling analysis

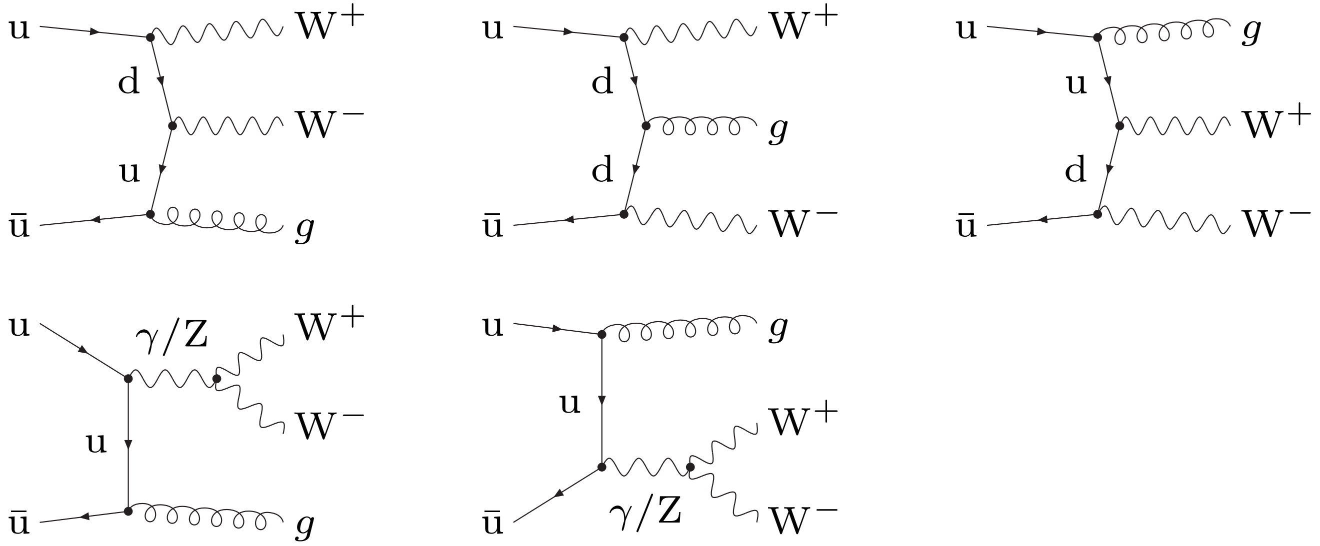
- Process is an important test ground before approaching more complicated many-particle processes at NLO.

## 2 Calculation of NLO corrections

### 2.1 Lowest-order prediction

6 partonic channels in LO: $\mathrm{u\bar{u}} \to \mathrm{WW}g, \;\; \mathrm{u}g \to \mathrm{WWu}, \;\; g\mathrm{\bar{u}} \to \mathrm{WW\bar{u}},$
(12 flavour channels for 2 gen.) $\mathrm{d\bar{d}} \to \mathrm{WW}g, \;\; \mathrm{d}g \to \mathrm{WWd}, \;\; g\mathrm{\bar{d}} \to \mathrm{WW\bar{d}}$

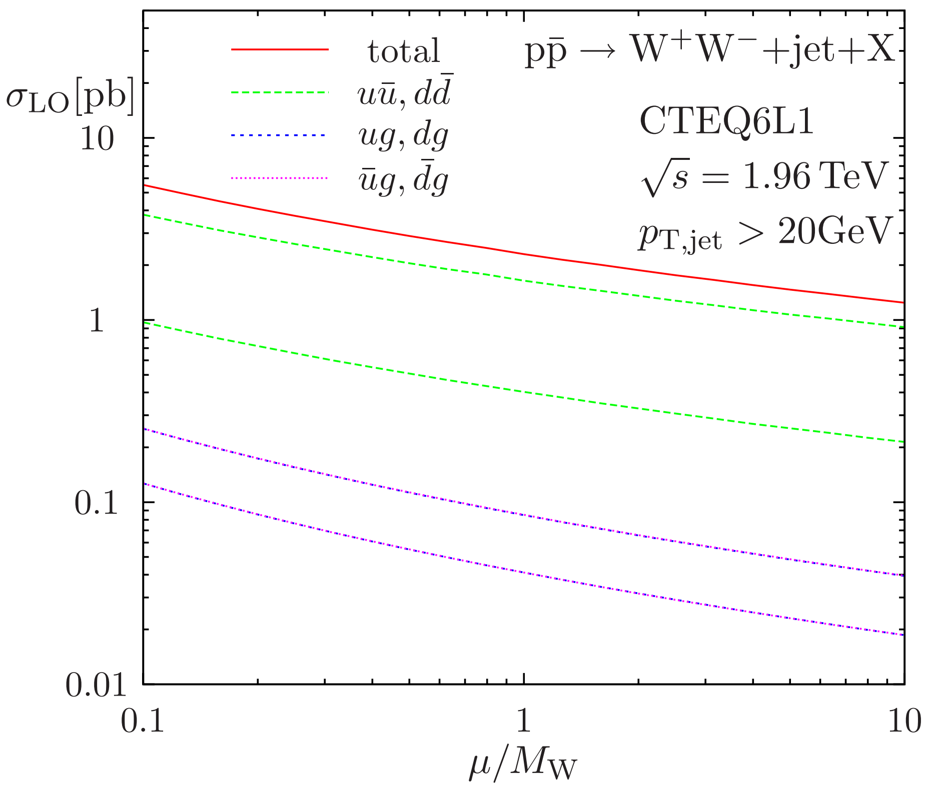
$\mathrm{u\bar{u}}$ diagrams:

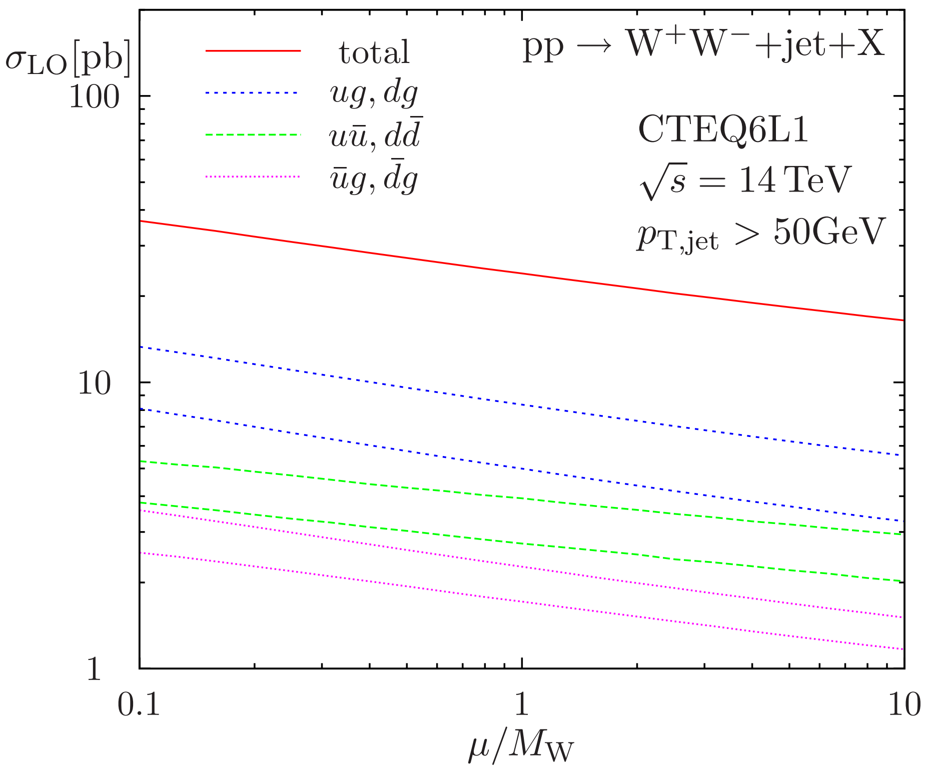



Features of the LO cross section:

- IR safety requires at least lower cut on $p_{\mathrm{T,jet}}$
  $\hookrightarrow$ apply jet algorithm for NLO cross section before cut on $p_{\mathrm{T,jet}}$
- LO hadron cross section $\propto \; \alpha_{\mathrm{s}}$
  $\hookrightarrow$ significant dependence on renormalization and factorization scales

# Scale dependence of LO cross sections:



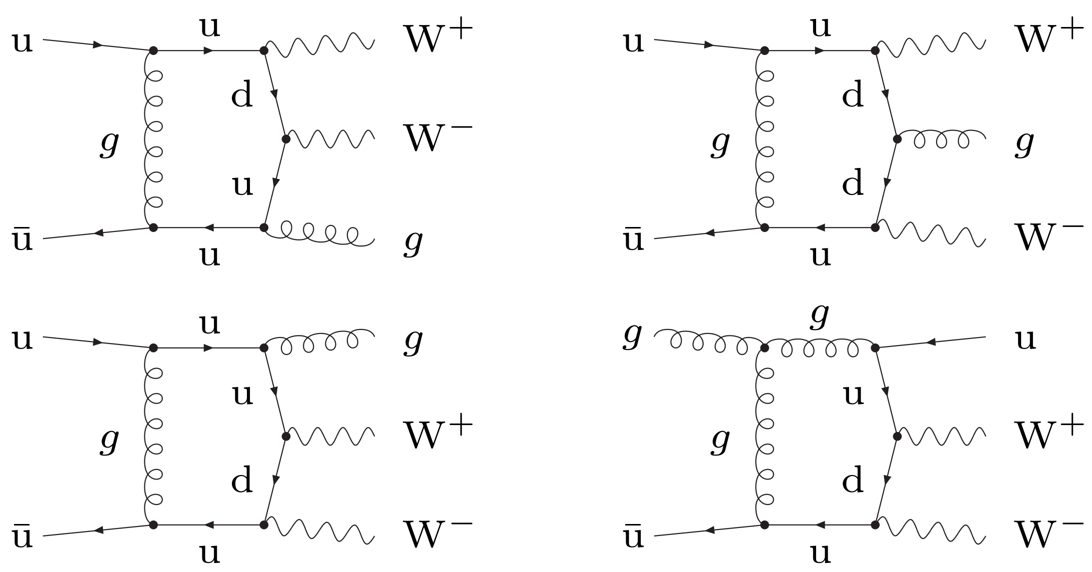

In LO: light final-state parton $\equiv$ jet $(\mu = \mu_{\rm ren} = \mu_{\rm fact})$

$\hookrightarrow$ no dependence on jet algorithm

## 2.2 Virtual corrections

# 1-loop diagrams $\sim\ 100$ for $q\bar{q} \to \mathrm{WW}g$

Most complicated 1-loop diagrams—pentagons of the types:




Algebraic reduction of amplitudes to standard form, e.g.

colour structure

$$\mathcal{M}_{q_i\bar{q}_j\to \mathrm{W}^+\mathrm{W}^- g_a} = \sum_{k=1}^{118}\sum_{\sigma=\pm} \underbrace{F_k^\sigma\,(\{p_i\cdot p_j\})} \overbrace{T^a_{ij}} \underbrace{\hat{\mathcal{M}}_k^\sigma\,(\{p_i\})}$$

invariant functions
containing loop integrals

standard spinor structures

$$\hat{\mathcal{M}}_1^\sigma = [\bar{v}_{\bar{q}}\not{\varepsilon}^*_{\mathrm{W}^+}\tfrac{1}{2}(1+\sigma\gamma_5)u_q](\varepsilon_g\varepsilon^*_{\mathrm{W}^-})$$

## Two independent strategies for evaluation of loop amplitudes

- Analogous to NLO calculation for $\mathrm{pp} \to \mathrm{t\bar{t}H}$ and $\mathrm{pp} \to \mathrm{t\bar{t}}$+jet
  Beenakker et al. '01,'02 Dittmaier, Uwer, Weinzierl '07
  - ◇ diagrams generated with FEYNARTS 1.0 Küblbeck, Böhm, Denner '90
    and reduced with in-house MATHEMATICA routines $\longrightarrow$ FORTRAN
  - ◇ analytical extraction of soft / collinear singularities Beenakker et al. '02; S.D. '03
  - ◇ reduction of 5-point to 4-point integrals according to Denner, S.D. '02
    $\hookrightarrow$ no (leading) inverse Gram det's $\longrightarrow$ sufficient numerical stability
  - ◇ outlook: process will be used as further test ground for
    more sophisticated tensor reduction methods Denner, S.D. '05
    used at NLO EW for $\mathrm{e}^+\mathrm{e}^- \to 4f$ Denner et al. '05
- Alternative calculation with available tools
  - ◇ diagrams generated with FEYNARTS 3.2 Hahn '00
  - ◇ algebraic reduction/numerics with FORMCALC 5.2/LOOPTOOLS Hahn, Perez-Victoria '98
    [i.e. 5pt fcts. à la Denner, S.D. '02 and regular scalar integrals with FF (v.Oldenborgh '91)]
  - ◇ singular scalar box integrals checked against results of Bern, Dixon, Kosower '93

## Strategy for extracting or translating IR (soft / collinear) singularities:

**Idea:** convert integrals $I^{(D)}$ in $D=4-2\epsilon$ dim.

$\rightarrow$ 4-dim. integrals $I^{(\lambda)}$ with mass regulator $\lambda$

**Procedure:** consider finite and reg.-scheme-independent difference

$$\left[I^{(D)} - I^{(D)}_{\mathrm{sing}}\right]\Big|_{D\to4} = \left[I^{(\lambda)} - I^{(\lambda)}_{\mathrm{sing}}\right]\Big|_{\lambda\to0}$$

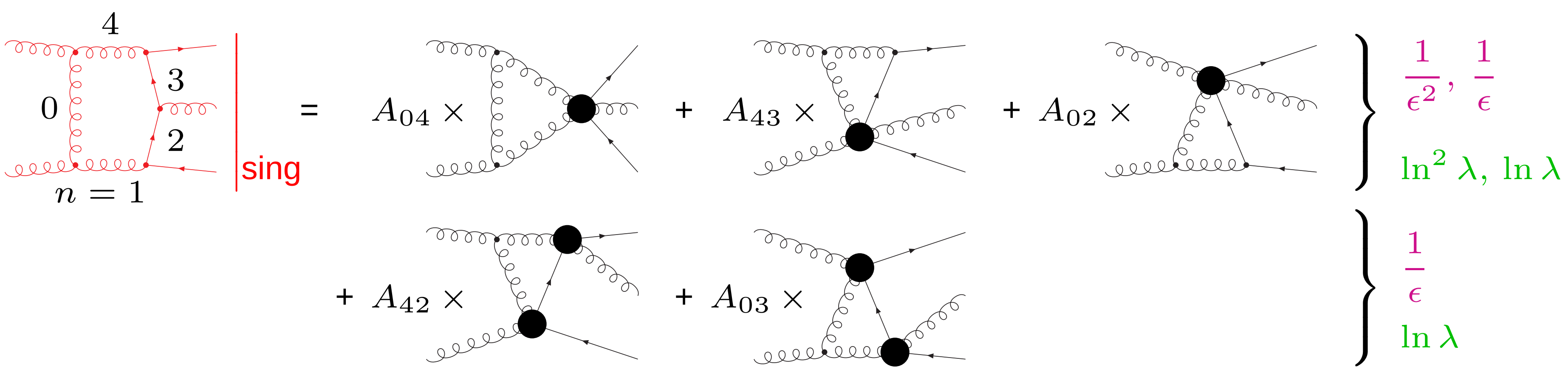
$$\Rightarrow\ I^{(D)} = I^{(D)}_{\mathrm{sing}} + \left[I^{(\lambda)} - I^{(\lambda)}_{\mathrm{sing}}\right]\Big|_{\lambda\to0} + \mathcal{O}(\epsilon)$$

**Note:** mass-singular part can be universally constructed from 3-point integrals

Beenakker et al. '01

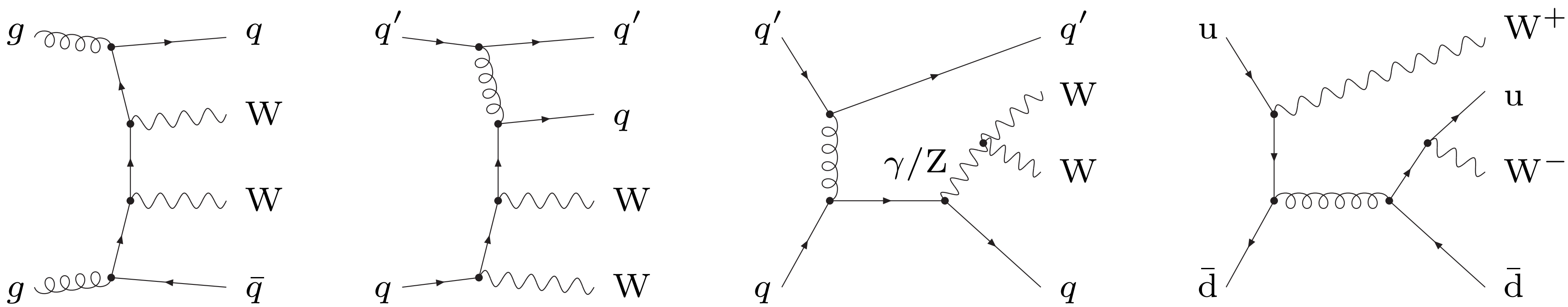
$\hookrightarrow$ general result known explicitly S.D. '03

An example from $gg \to \mathrm{t\bar{t}}g$:



## 2.3 Real corrections

Some diagrams with 1-parton emission:




etc.

$q\bar{q}$, $qg$, $g\bar{q}$, $gg$ channels from generic amplitudes $0 \to \mathrm{WW}q\bar{q}gg$ and $0 \to \mathrm{WW}q\bar{q}q'\bar{q}'$

$\hookrightarrow$ 136 flavour channels for 2 generations !

Features of the amplitude calculation:

Two independent evaluations of helicity amplitudes

- application of conventional (4-dimensional) spinor techniques
- alternative evaluation based on MADGRAPH Stelzer, Long '94

# Phase-space integration of real corrections

- Two independent versions of Monte Carlo integrators,
  one entirely based on multi-channel technique Berends, Pittau, Kleiss '94 Kleiss, Pittau '94
- extraction and integration of soft / collinear singularities via dipole subtraction formalism Catani, Seymour '96
- tuned comparison of all non-singular LO parts to $\mathrm{WW}+1\mathrm{jet}$ and $\mathrm{WW}+2\mathrm{jets}$ with SHERPA 1.0.8 (Gleisberg et al. '03) and WHIZARD 1.50 (Kilian '01)

  $\hookrightarrow$ agreement within stat. errors (typically $1{-}2\sigma$)

  Results for hadronic cross sections at Tevatron and LHC:

| process | $\sigma[\mathrm{pb}]$ | $\sigma_{\mathrm{SHERPA}}[\mathrm{pb}]$ | $\Delta\sigma/$stat. error |
|---|---|---|---|
| $\mathrm{p\bar{p}} \to \mathrm{WW}+1\mathrm{jet}$ | $2.10456(94)$ | $2.10562(78)$ | $-0.87$ |
| $\mathrm{p\bar{p}} \to \mathrm{WW}+2\mathrm{jets}$ | $0.42431(22)$ | $0.42437(13)$ | $-0.23$ |
| $\mathrm{pp} \to \mathrm{WW}+1\mathrm{jet}$ | $46.453(16)$ | $46.4399(94)$ | $+0.70$ |
| $\mathrm{pp} \to \mathrm{WW}+2\mathrm{jets}$ | $31.555(17)$ | $31.5747(63)$ | $-1.08$ |

. . . detailed survey of results $\to$ diploma thesis of S.Kallweit '06

## 2.4 Checks and status of the calculation

Summary of checks:

- UV structure of virtual correction
- soft and collinear structure in real and virtual corrections
- different methods for real-emission amplitudes, checked against MADGRAPH
- integration of $2 \to 4$ parts checked against SHERPA and WHIZARD
- all ingredients confirmed in second, independent calculation

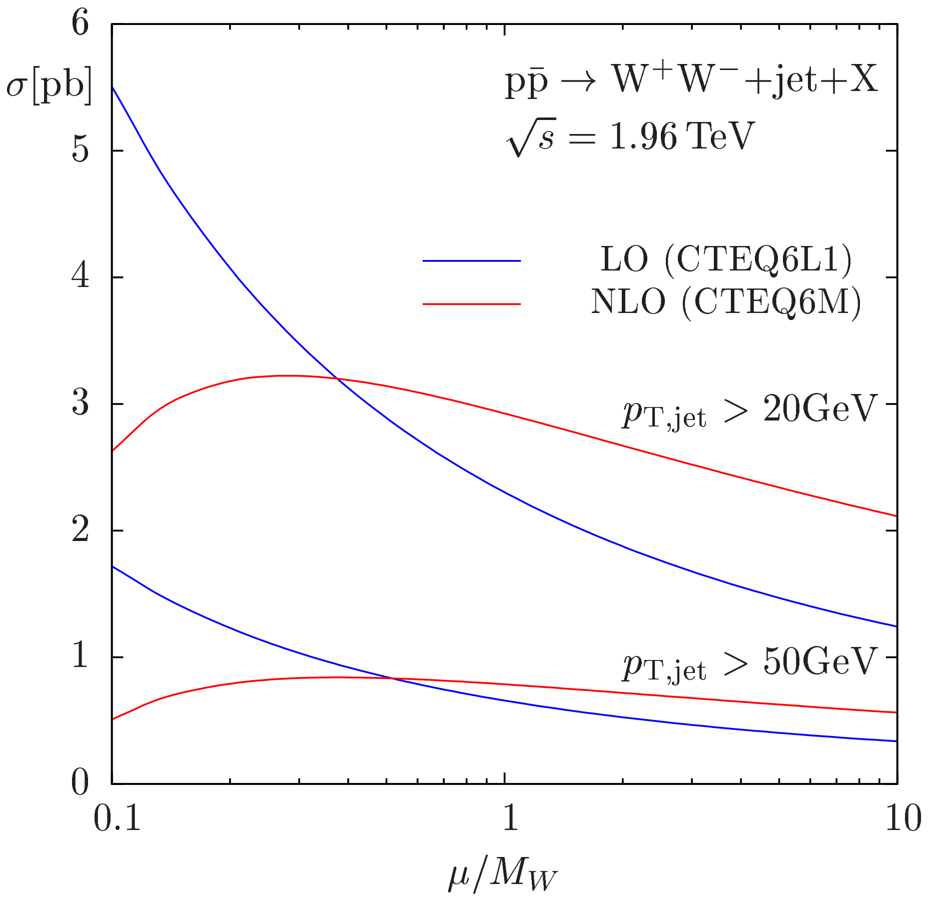
Status of the calculation:

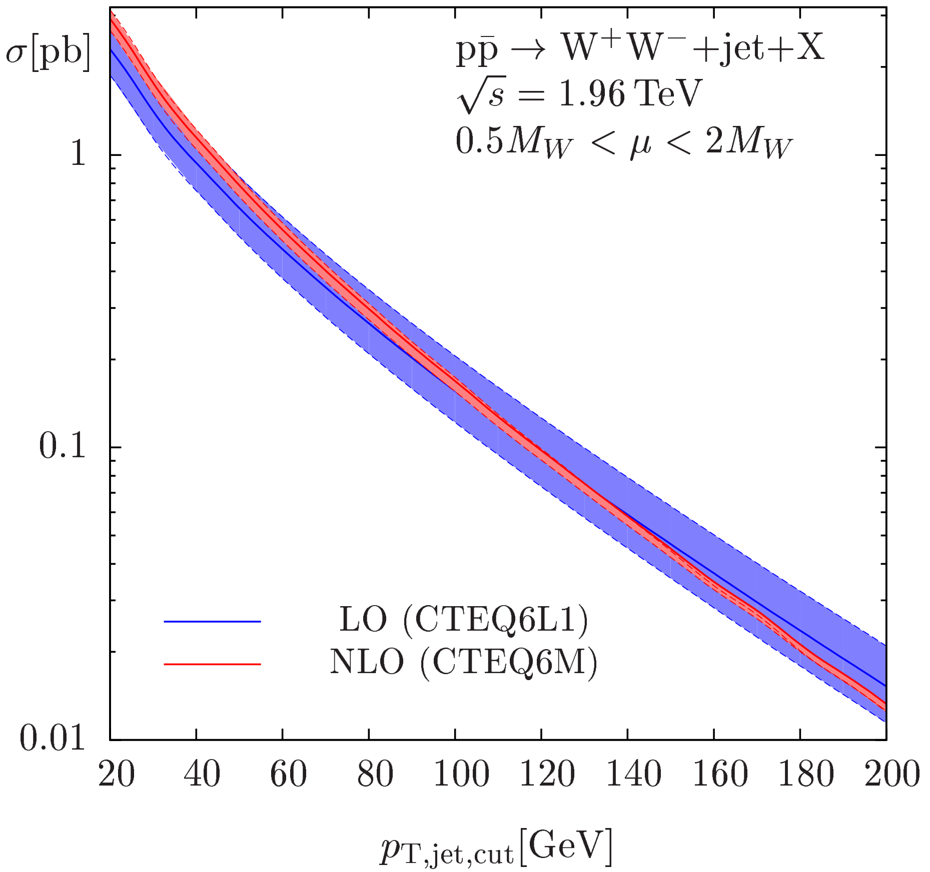
- NLO QCD calculation completed
  $\hookrightarrow$ first results on $\sigma_{\mathrm{NLO}}$ for Tevatron and LHC
- more numerical results including distributions in progress
- input from experimentalists welcome
  $\hookrightarrow$ jet definition, cuts, (in-)stability of W bosons, etc.

## 3 Numerical results PRELIMINARY !

LO versus NLO cross section at the Tevatron:

S.D., Kallweit, Uwer '07




$(\mu = \mu_{ren} = \mu_{fact})$

$\hookrightarrow$ Scale dependence stabilizes at NLO

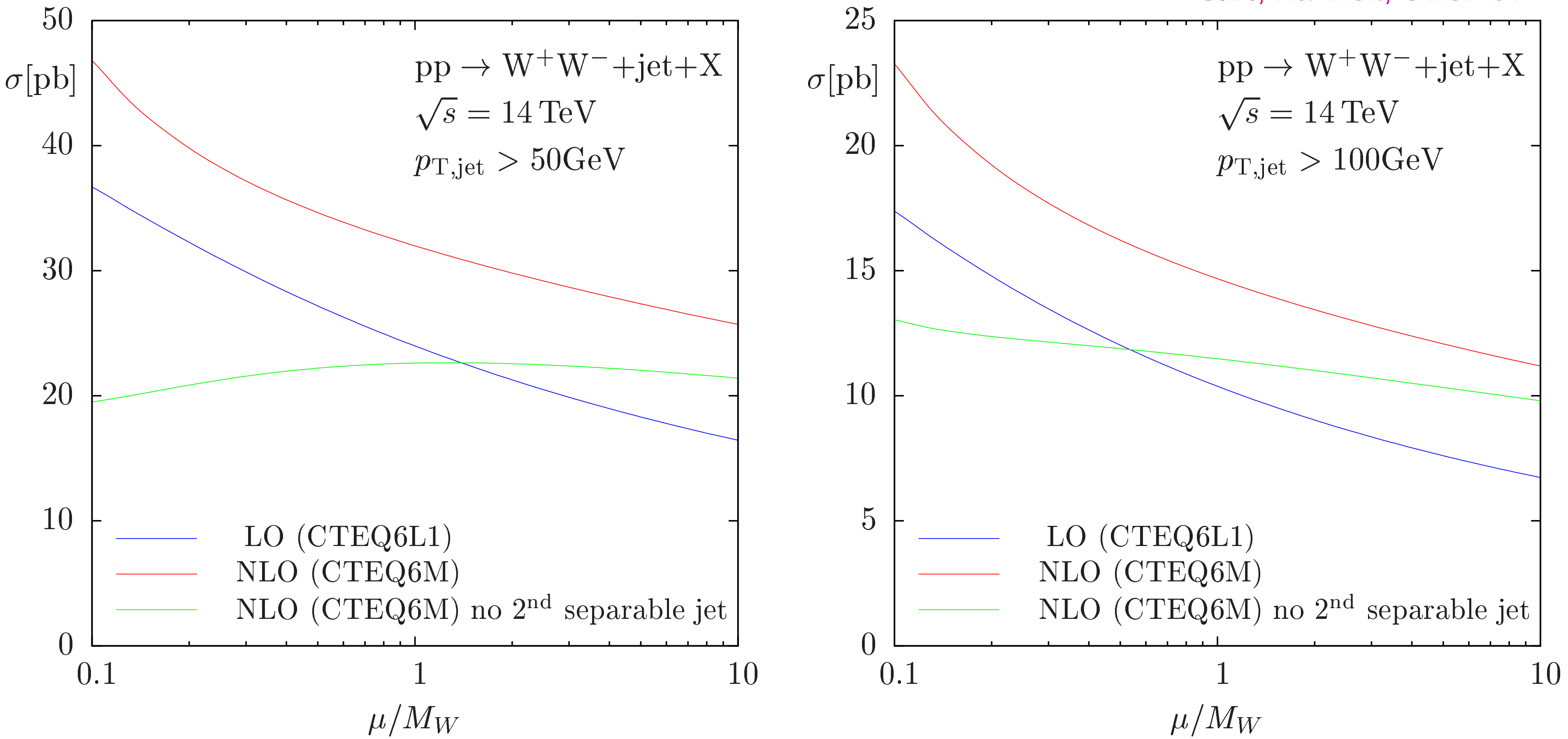
Jet definition:

algorithm of S.D.Ellis, Soper '93

with $R = 1$ for jets

## LO versus NLO cross section at the LHC: **PRELIMINARY !**

S.D., Kallweit, Uwer '07

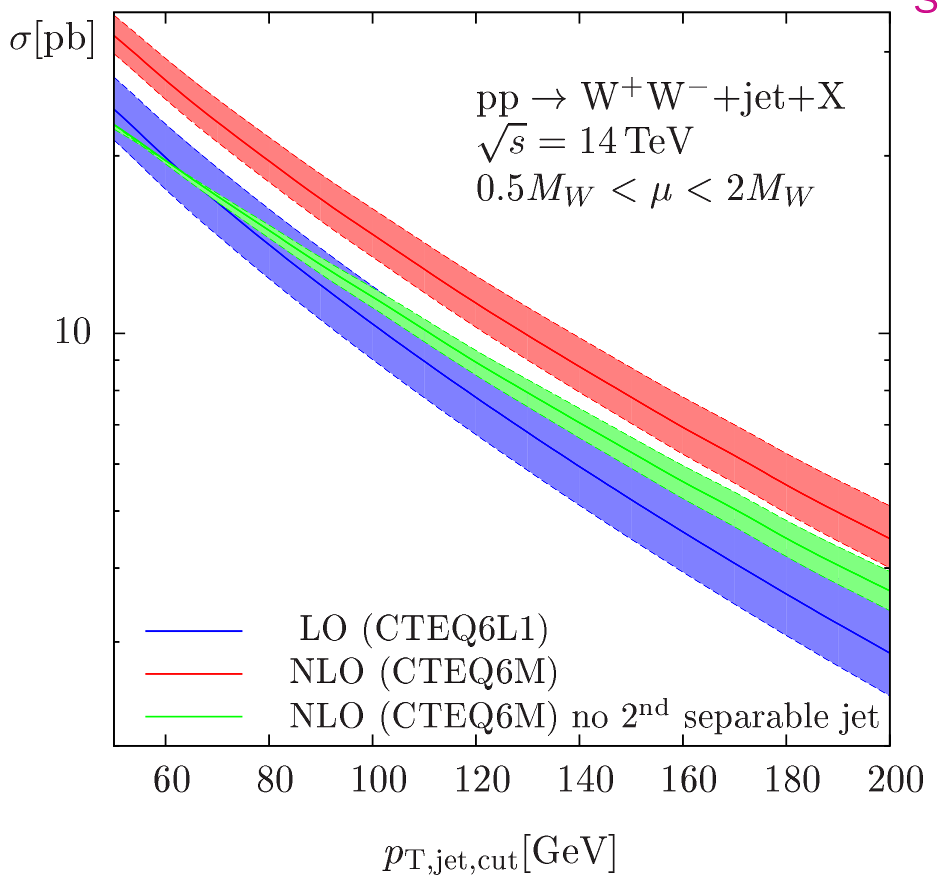



$(\mu = \mu_{\rm ren} = \mu_{\rm fact})$

- scale dependence stabilizes at NLO for genuine $\mathrm{WW}$+jet production
- but: significant scale dependence introduced by $\mathrm{WW}$+2jets events

# LO versus NLO cross section at the LHC: (continued) **PRELIMINARY !**

S.D., Kallweit, Uwer '07




$$(\mu = \mu_{\mathrm{ren}} = \mu_{\mathrm{fact}})$$

## 4 Conclusions

### The process $\mathrm{pp}/\mathrm{p\bar{p}} \to \mathrm{WW} + \text{jet} + X$

- important background process for Higgs and other searches at Tevatron/LHC

  $\hookrightarrow$ process on the top of the "Les Houches NLO wishlist '05"

- $\mathrm{WW}$(+jets) production used for EW gauge-boson coupling analysis at the LHC

### NEW: $\mathrm{pp}/\mathrm{p\bar{p}} \to \mathrm{WW} + \text{jet} + X$ at NLO QCD

- Tevatron: NLO correction stabilize LO cross sections
- LHC: significant reduction of scale uncertainty for genuine $\mathrm{WW}$+jet production,
  but: significant scale dependence via $\mathrm{WW}$+2jets events
- example is important test ground for NLO methods for many-particle processes

  $\hookrightarrow$ methods not yet exhausted,
  more complicated applications ($2 \to 4$) feasible !