- HELAC-NLO –
Developments and Applications

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Outline

- General motivation for NLO QCD calculations
- **HELAC-NLO** in a nutshell
- Applications: 2 -> 4 processes:
  - ttbb
  - ttjj
  - WWbb
- Summary & Outlook

HELAC-NLO Group:

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Introduction

- 8-10 partons in the final state @ LO, well separated to avoid divergences
- On the market automatic parton level tools which are completely self contained
- Provide amplitudes and integrators on their own
- Standard Model and beyond tools @ tree level (just few examples)

  - **ALPGEN, AMEGIC++/SHERPA, COMIX/SHERPA, HELAC-PHEGAS, MADGRAPH/MADEVENT, O'MEGA/WHIZARD, ...**

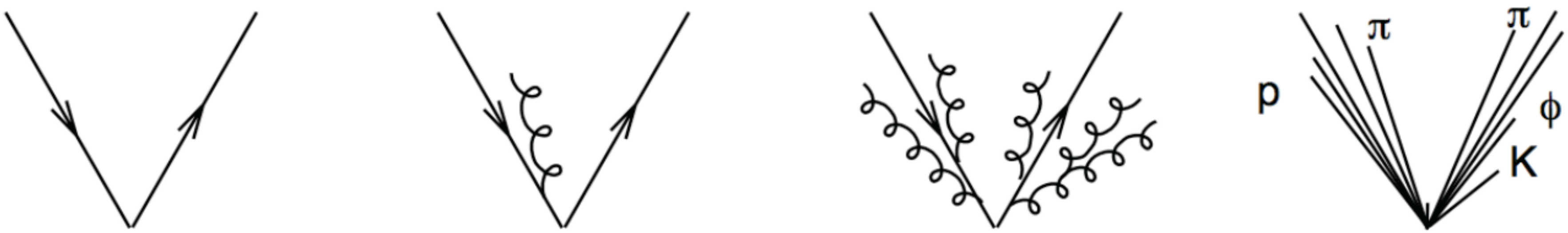
- General purpose Monte Carlo programs (parton shower, hadronization, multiple interactions, hadrons decays, etc.)

  - **HERWIG, HERWIG++, PYTHIA 6.4, PYTHIA 8.1, SHERPA, ...**

- High sensitivity to unphysical input scales, to improve accuracy of prediction higher order calculations are needed

Motivation for NLO

- Stabilizing the scale in the QCD input parameters most notably the strong coupling constant and PDFs
- Normalization and shape of distributions first known at NLO
- Many scale processes: V+ jets, VV + jets, ttH, tt + jets, njets ...
- Sometimes dynamical scales seem to work better for some observables
- How do we know which scale to choose ?
- Improved description of jets



Jets: LO *NLO* *Parton Shower* *Hadron Level*

Structure of NLO Calculations

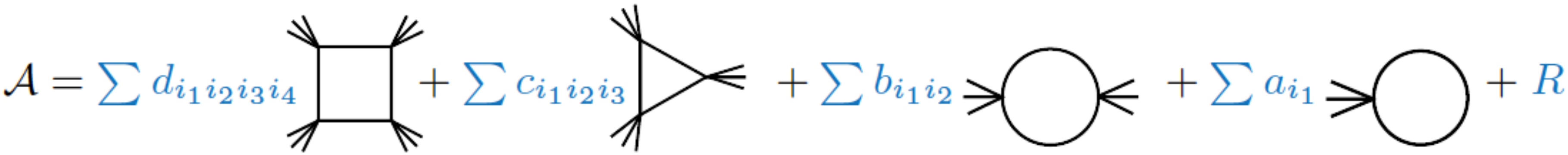
$$\sigma^{NLO} = \int_m d\sigma^B + \int_{m+1} d\sigma^R - \int_{m+1} d\sigma^A + \int_{m+1} d\sigma^A + \int_m d\sigma^V$$

$$\hookrightarrow \quad \int d\sigma^B + \int_{m+1} \left[d\sigma^R - d\sigma^D\right] + \int_m \left[d\sigma^V + d\sigma^I + d\sigma^{KP}\right]$$

- Our strategy in a few words
  - make it fully numeric
  - make it fully automatic
  - „montecarlize“ everything for speed

Virtual Corrections

- Decompose the amplitude into a basis of scalar integrals



$$\mathcal{A} = \sum_{I \subset \{0,1,\cdots,m-1\}} \int \frac{\mu^{(4-d)} d^d q}{(2\pi)^d} \frac{\bar{N}_I(\bar{q})}{\prod_{i \in I} \bar{D}_i(\bar{q})}$$

- Three main building blocks are needed
  - Evaluation of numerator function N(q)
  - Determination of coefficients via reduction method
  - Evaluation of scalar functions via **ONELOOP**

Van Hameren, '10

Virtual Corrections

- Reduction at integrand level – **OPP** method implemented in **CUTTOOLS**

- Computing numerator functions for specific values of loop momentum that are solutions of equations

$D_i(q) = 0$ for $i = 0, \ldots, M\text{-}1$

- It is customary to refer to these equations as quadruple (M = 4), triple (M = 3), double (M = 2) and single (M = 1) cuts

$$
\begin{aligned}
N(q) = & \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3) \right] \prod_{i \neq i_0, i_1, i_2, i_3}^{m-1} D_i \\
& + \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2) \right] \prod_{i \neq i_0, i_1, i_2}^{m-1} D_i \\
& + \sum_{i_0<i_1}^{m-1} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1) \right] \prod_{i \neq i_0, i_1}^{m-1} D_i \\
& + \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q; i_0) \right] \prod_{i \neq i_0}^{m-1} D_i \\
& + \tilde{P}(q) \prod_{i}^{m-1} D_i \,.
\end{aligned}
$$

Ossola,, Papadopoulos, Pittau '07, '08

Virtual Corrections

- Compute the rational terms $R = R_1 + R_2$
- R_1 originates from ϵ dependence of denominators

$$D_i \to \bar{D}_i - \tilde{q}^2$$

  - Computed within the framework of OPP reduction

Ossola,, Papadopoulos, Pittau '07, '08

- R_2 originates from ϵ dependence of numerators

$$\bar{q} = q + \tilde{q} \qquad \bar{\gamma}_\mu = \gamma_\mu + \tilde{\gamma}_\mu \qquad \bar{g}^{\mu\nu} = g^{\mu\nu} + \tilde{g}^{\mu\nu}$$

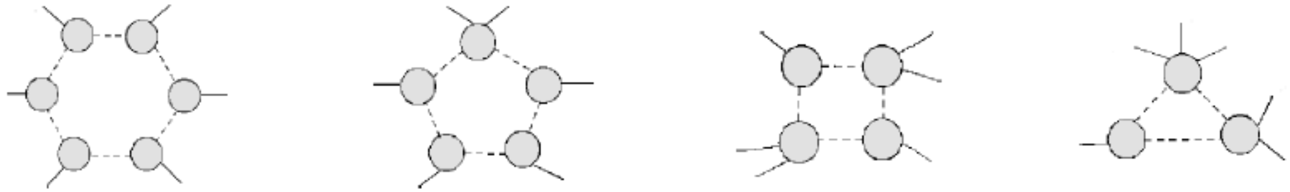
  - Computed with effective tree-level Feynman rules

Draggiotis, Garzelli, Papadopoulos, Pittau '09
Garzelli, Malamos, Pittau '09

Virtual Corrections

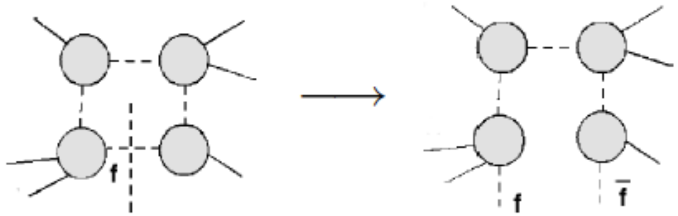
- In case of ttbb final state the integrand has the form

$$\mathcal{A}(q) = \sum \underbrace{\frac{N_i^{(6)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\cdots\bar{D}_{i_5}}} + \underbrace{\frac{N_i^{(5)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\cdots\bar{D}_{i_4}}} + \underbrace{\frac{N_i^{(4)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\cdots\bar{D}_{i_3}}} + \underbrace{\frac{N_i^{(3)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\bar{D}_{i_2}}} + \cdots$$



- **HELAC-1LOOP** evaluates numerically the numerators $N_i^6(q)$, $N_i^5(q)$, …
- with the values of the loop momentum q provided by **CUTTOOLS**
  - Generates all partitions of 6, 5, 4, … blobs attached to the loop and checks all possible flavors (colors) that can run inside
  - Hard cuts the loop (q is fixed) to get n+2 tree-like process

Van Hameren, Papadopoulos, Pittau '09
Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09



Real Emission

- **HELAC-DIPOLES** - complete, public, automatic Catani-Seymour dipoles
- Phase space integration of subtracted real radiation and integrated dipoles in both massless and massive cases

- Extended for arbitrary polarizations
  - Monte Carlo over polarization states of external particles
  - Monte Carlo over color

- Phase space restriction on the dipoles phase space
  - Less dipole subtraction terms per event
  - Increased numerical stability
  - Reduced missed binning problem
  - Large cancellations between subtracted real radiation and integrated dipoles

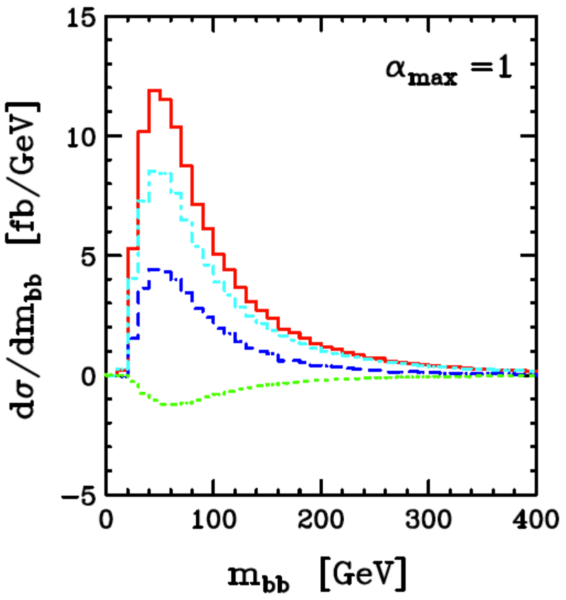
Czakon, Papadopoulos, Worek '09

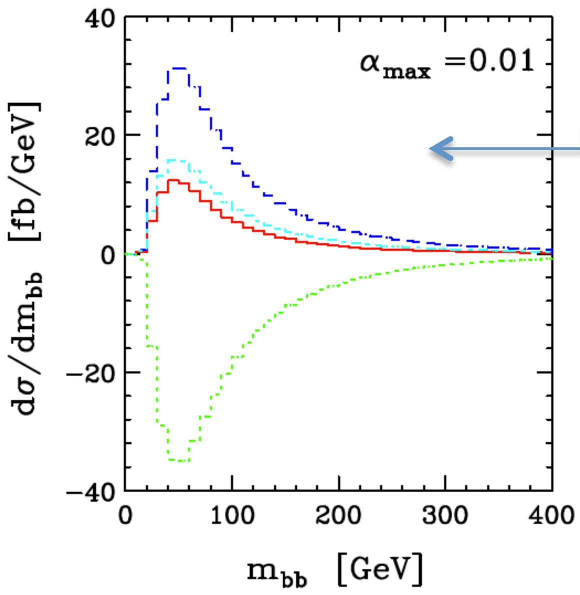
Real Emission

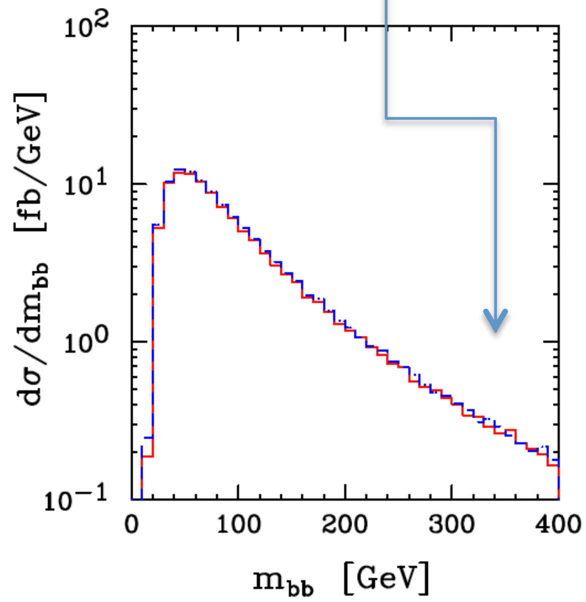
- ttbb production @ LHC as an example

Subtracted real emission
K + P operators
I operators
Full result

Cutoff independence !!!





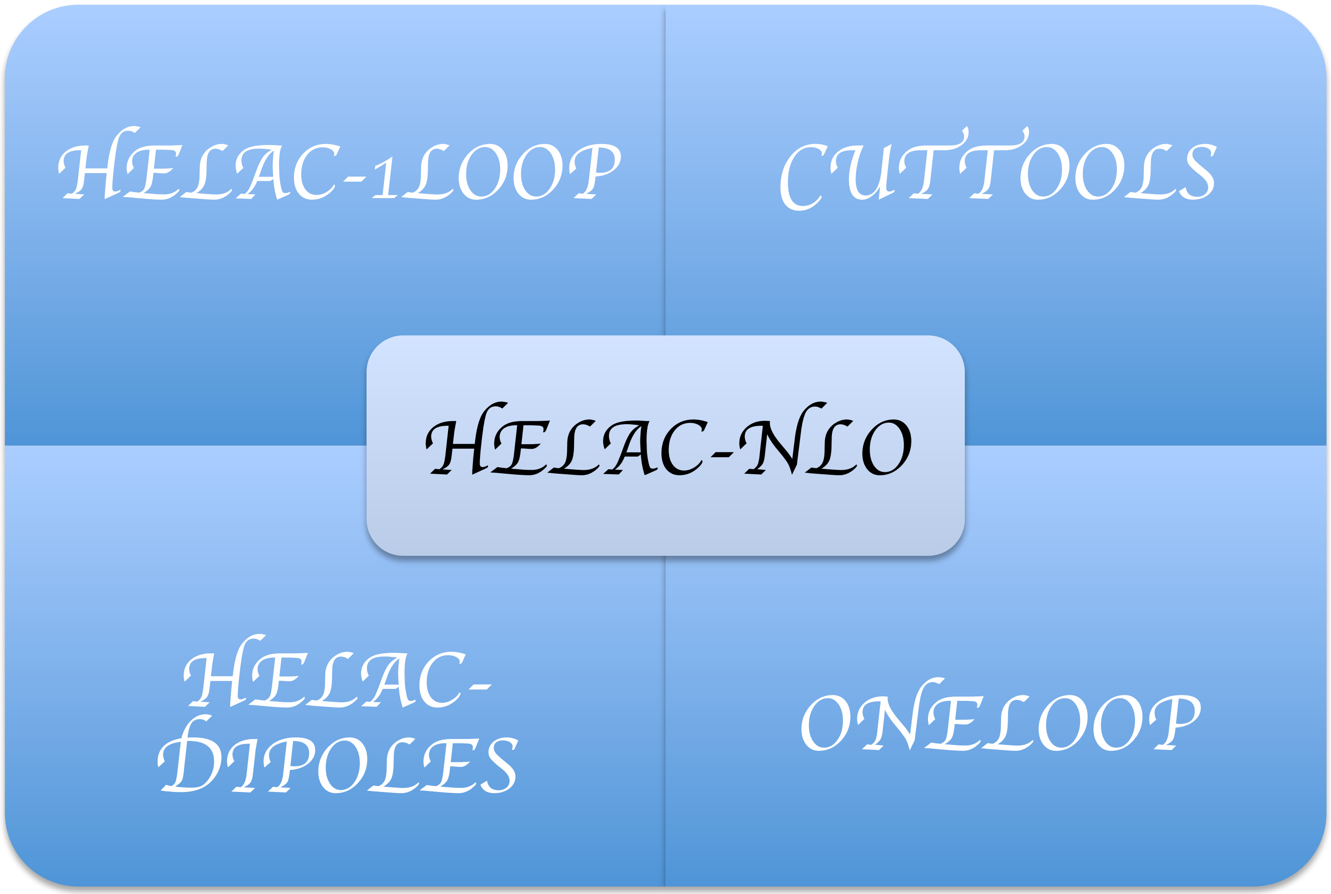


$$\alpha_{\mathbf{max}} \in (\mathbf{0}, \mathbf{1}]$$

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09

Evaluation of loop numerators N(q) and R_2

Reduction of tensor integrals, OPP coefficients and R_1



Catani-Seymour dipole subtraction for massless and massive cases

Evaluation of scalar integrals

Applications

pp -> ttbb & pp -> ttjj

pp -> ttbb @ LHC

- Integrated cross sections and scale dependence *Permille level agreement !*

Process	$\sigma^{\mathrm{LO}}_{[23,\ 24]}$ [fb]	σ^{LO} [fb]	$\sigma^{\mathrm{NLO}}_{[23,\ 24]}$ [fb]	$\sigma^{\mathrm{NLO}}_{\alpha_{\max}=1}$ [fb]	$\sigma^{\mathrm{NLO}}_{\alpha_{\max}=0.01}$ [fb]
$q\bar{q} \to t\bar{t}b\bar{b}$	85.522(26)	85.489(46)	87.698(56)	87.545(91)	87.581(134)
$pp \to t\bar{t}b\bar{b}$	1488.8(1.2)	1489.2(0.9)	2638(6)	2642(3)	2636(3)

$\xi \cdot m_t$	$1/8 \cdot m_t$	$1/2 \cdot m_t$	$1 \cdot m_t$	$2 \cdot m_t$	$8 \cdot m_t$
σ^{LO} [fb]	8885(36)	2526(10)	1489.2(0.9)	923.4(3.8)	388.8(1.4)
σ^{NLO} [fb]	4213(65)	3498(11)	2636(3)	1933.0(3.8)	1044.7(1.7)

$$\sigma_{\mathbf{LO}} = (\mathbf{1489.2 \pm 0.9})\ \mathbf{fb}$$

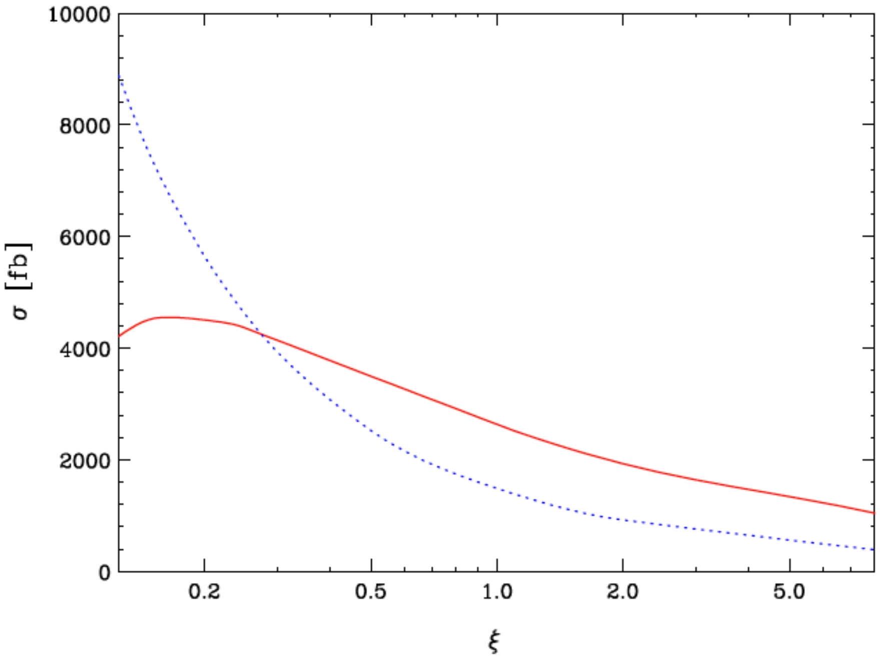
$$\sigma_{\mathbf{NLO}} = (\mathbf{2636 \pm 3})\ \mathbf{fb}$$

Scale dependence reduced:
70% @ LO down to **33% @ NLO**
K factor of **K = 1.77**
for quarks initial states only **K = 1.03**
With jet veto of 50 GeV **K = 1.20**

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09
Bredenstein, Denner, Dittmaier, Pozzorini '08, '09

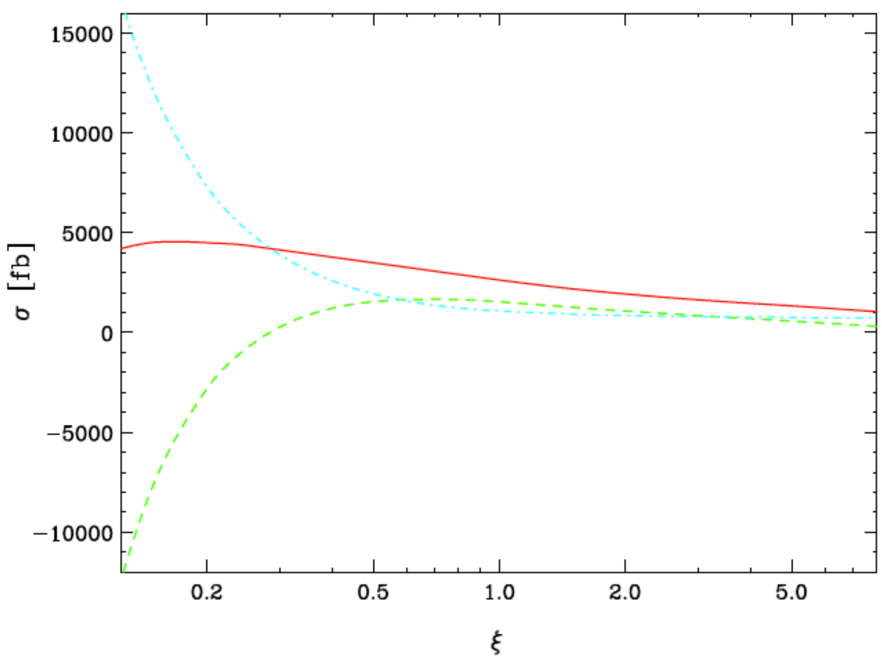
pp -> ttbb @ LHC

- Scale dependence graphically



Varying scale up or down by a factor two changes cross section by **70% @ LO** and by **33% @ NLO**

Scale dependence at NLO decomposed into contribution of *Virtual Corrections* & *Real Radiation*



Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09

Pp -> ttbb @ LHC

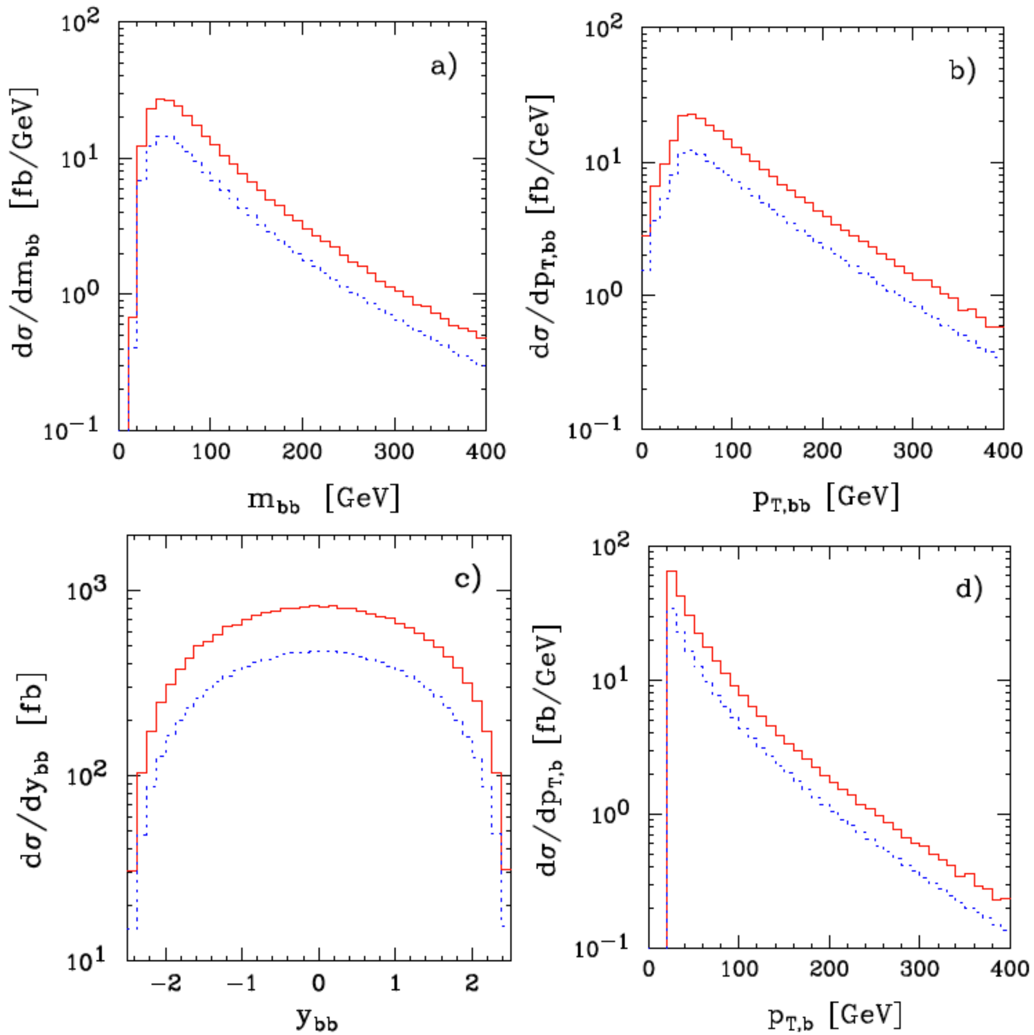
- Differential cross sections

- b-jet pair kinematics
  - Invariant mass
  - Transverse momentum
  - Rapidity distribution

- single b-jet kinematics
  - Transverse momentum

LO & *NLO*

- Relatively small variation compared to the size but shape change important



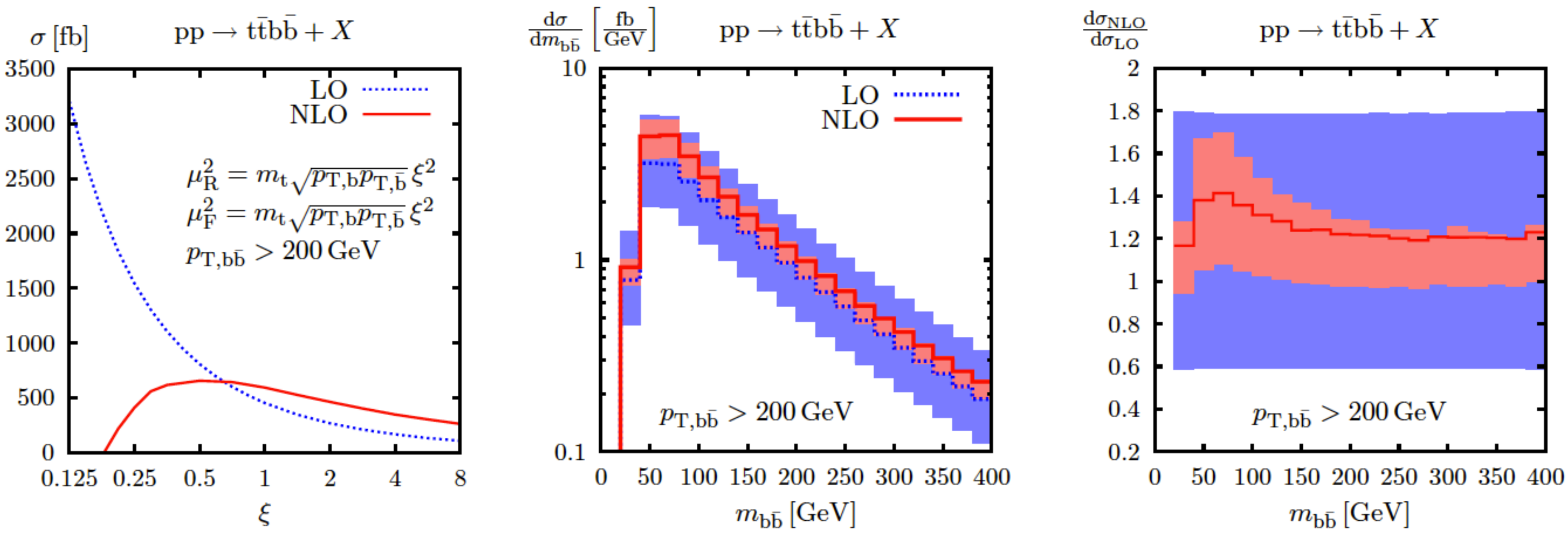
Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09

$pp \to t\bar{t}b\bar{b}$ @ LHC

- Broad study
- *Cross section in fb*
- *Dynamic scale*
- *m_{bb} distribution*
- *K-factor*

Bredenstein, Denner, Dittmaier, Pozzorini '10

Setup	$m_{b\bar{b},\mathrm{cut}}$	$p_{\mathrm{T},b\bar{b},\mathrm{cut}}$	$p_{\mathrm{jet,veto}}$	$p_{\mathrm{T,b,cut}}$	$y_{\mathrm{b,cut}}$	σ_{LO}	σ_{NLO}	K
I	100	-	-	20	2.5	$786.3(2)^{+78\%}_{-41\%}$	$978(3)^{+13\%}_{-21\%}$	1.24
II	-	200	-	20	2.5	$451.8(2)^{+79\%}_{-41\%}$	$592(4)^{+13\%}_{-22\%}$	1.31
III	100	-	100	20	2.5	$786.1(6)^{+78\%}_{-41\%}$	$700(3)^{+0.4\%}_{-19\%}$	0.89
IV	100	-	-	50	2.5	$419.4(1)^{+77\%}_{-40\%}$	$526(2)^{+13\%}_{-21\%}$	1.25

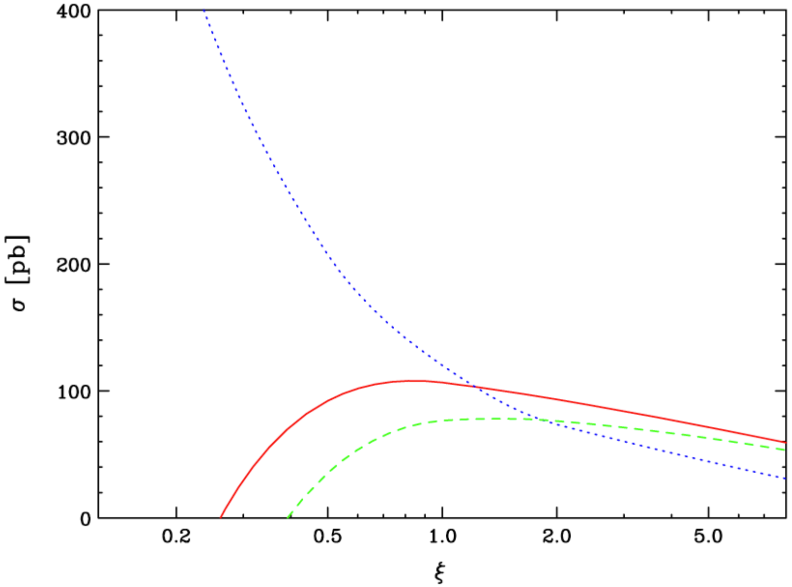


Pp -> ttjj @ LHC

- Scale dependence & integrated cross sections

Bevilacqua, Czakon, Papadopoulos, Worek '10

Process	σ^{LO} [pb]	Contribution
$pp \to t\bar{t}jj$	120.17(8)	100%
$qg \to t\bar{t}qg$	56.59(5)	47.1%
$gg \to t\bar{t}gg$	52.70(6)	43.8%
$qq' \to t\bar{t}qq'$, $q\bar{q} \to t\bar{t}q'\bar{q}'$	7.475(8)	6.2%
$gg \to t\bar{t}q\bar{q}$	1.981(3)	1.6%
$q\bar{q} \to t\bar{t}gg$	1.429(1)	1.2%



$$\sigma_{\mathbf{LO}} = (\mathbf{120.17 \pm 0.08})\ \mathbf{pb}$$

$$\sigma_{\mathbf{NLO}} = (\mathbf{106.94 \pm 0.17})\ \mathbf{pb}$$

$$\sigma_{\mathbf{NLO}}^{\mathbf{veto}} = (\mathbf{76.58 \pm 0.17})\ \mathbf{pb}$$

Scale dependence reduced:
72% @ LO down to **13% @ NLO**
54% @ NLO with **jet veto** of 50 GeV

K factor of **K = 0.89** (**K = 0.64**)
Negative shift of **11%** (**36%**)

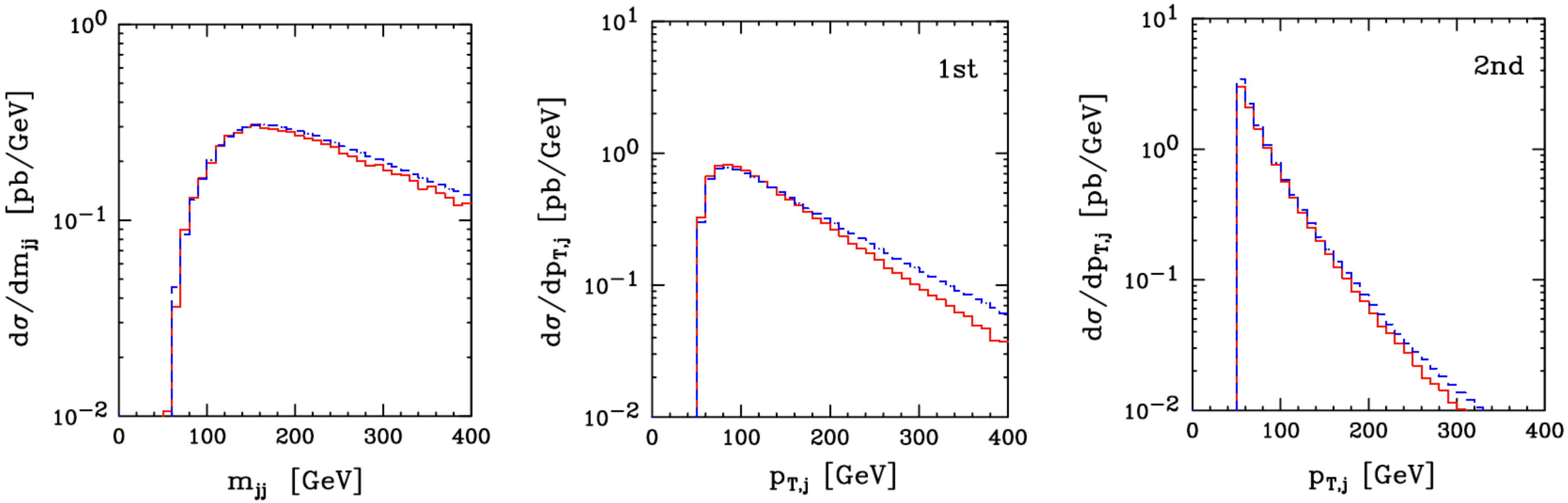
pp -> ttjj @ LHC

- Differential cross section

LO & *NLO*

- *m_{jj}* size of the corrections transmitted to distributions for low p_T, shapes change for hight p_T

- *p_T of 1st hardest & 2nd hardest jet* (ordered in p_T) altered shapes up to **39% & 28%** in tails



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Applications

Pp ($p\bar{p}$) -> WWbb

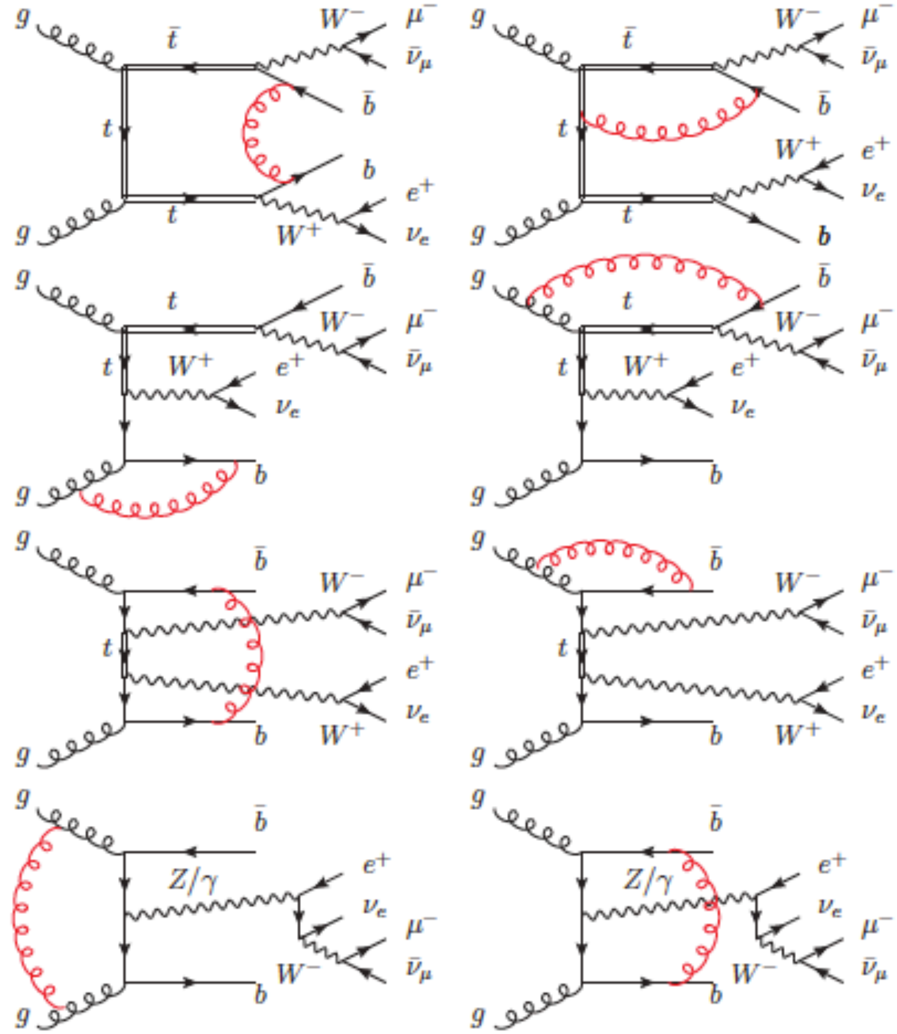
$pp\ (p\bar{p})$ -> WWbb

- Complete off-shell effects @ NLO
- Double-, single- and non-resonant top contributions of the order $O(\alpha_s^3\alpha^4)$
- Complex-mass scheme for unstable top
- W gauge bosons are treated off-shell

$$pp(p\bar{p}) \rightarrow e^+\nu_e\mu^-\nu_\mu b\bar{b} + X$$

- Sum over helicities and color via MC
- LO + V obtained by reweighting of tree level unweighted events
- Dipole channels for subtracted real part

- Check of Ward identity for virtual part
- Cancellation of divergences
- α_{max} independence test for real part



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pp ($p\bar{p}$) -> WWbb

- Integrated cross sections for inclusive cuts
  - $p_T(b) > 20$, GeV, $p_T(l) > 20$ GeV, $p_T(\text{miss}) > 30$ GeV
  - $|y(b)| < 4.5$, $|y(l)| < 2.5$, $\Delta R(jj) > 0.4$, $\Delta R(jl) > 0.4$

TeVatron	σ_{LO} [fb]	$\sigma_{\mathrm{NLO}}^{\alpha_{\max}=1}$ [fb]	$\sigma_{\mathrm{NLO}}^{\alpha_{\max}=0.01}$ [fb]
anti-k_T	34.922 ± 0.014	35.705 ± 0.047	35.697 ± 0.049
k_T	34.922 ± 0.014	35.727 ± 0.047	35.723 ± 0.049
C/A	34.922 ± 0.014	35.724 ± 0.047	35.746 ± 0.050

LHC	σ_{LO} [fb]	$\sigma_{\mathrm{NLO}}^{\alpha_{\max}=1}$ [fb]	$\sigma_{\mathrm{NLO}}^{\alpha_{\max}=0.01}$ [fb]
anti-k_T	550.54 ± 0.18	808.46 ± 0.98	808.29 ± 1.04
k_T	550.54 ± 0.18	808.67 ± 0.97	808.86 ± 1.03
C/A	550.54 ± 0.18	808.74 ± 0.97	808.28 ± 1.03

α_{max} *independence test*

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$pp\ (p\bar{p})$ -> WWbb

❑ LO & NLO scale dependence

TeVatron

$$\sigma_{LO} = 34.922\ ^{+40\%}_{-26\%}\ fb$$

$$\sigma_{NLO} = 35.727\ ^{-4\%}_{-8\%}\ fb$$

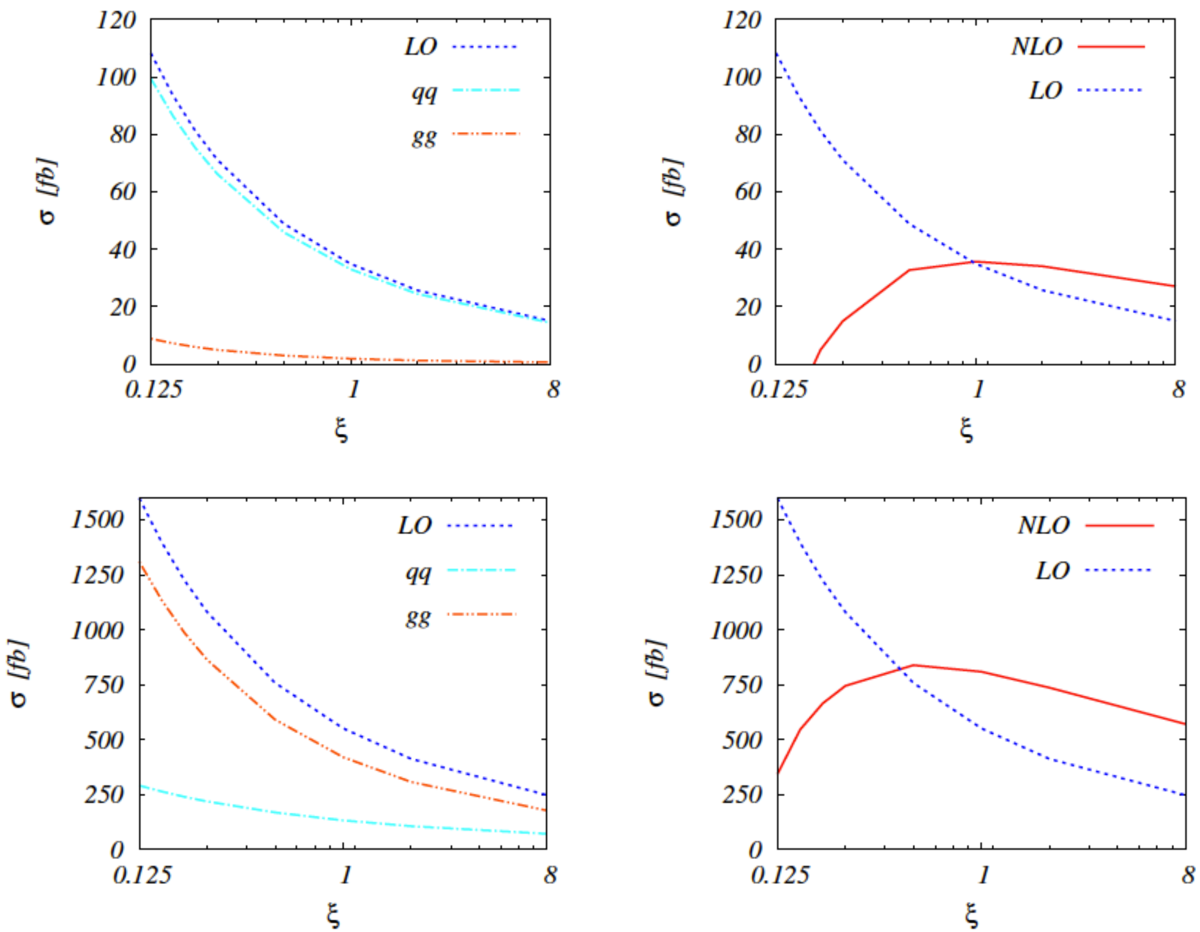
$$K = 1.023$$

LHC

$$\sigma_{LO} = 550.538\ ^{+37\%}_{-25\%}\ fb$$

$$\sigma_{NLO} = 808.665\ ^{+4\%}_{-9\%}\ fb$$

$$K = 1.47$$



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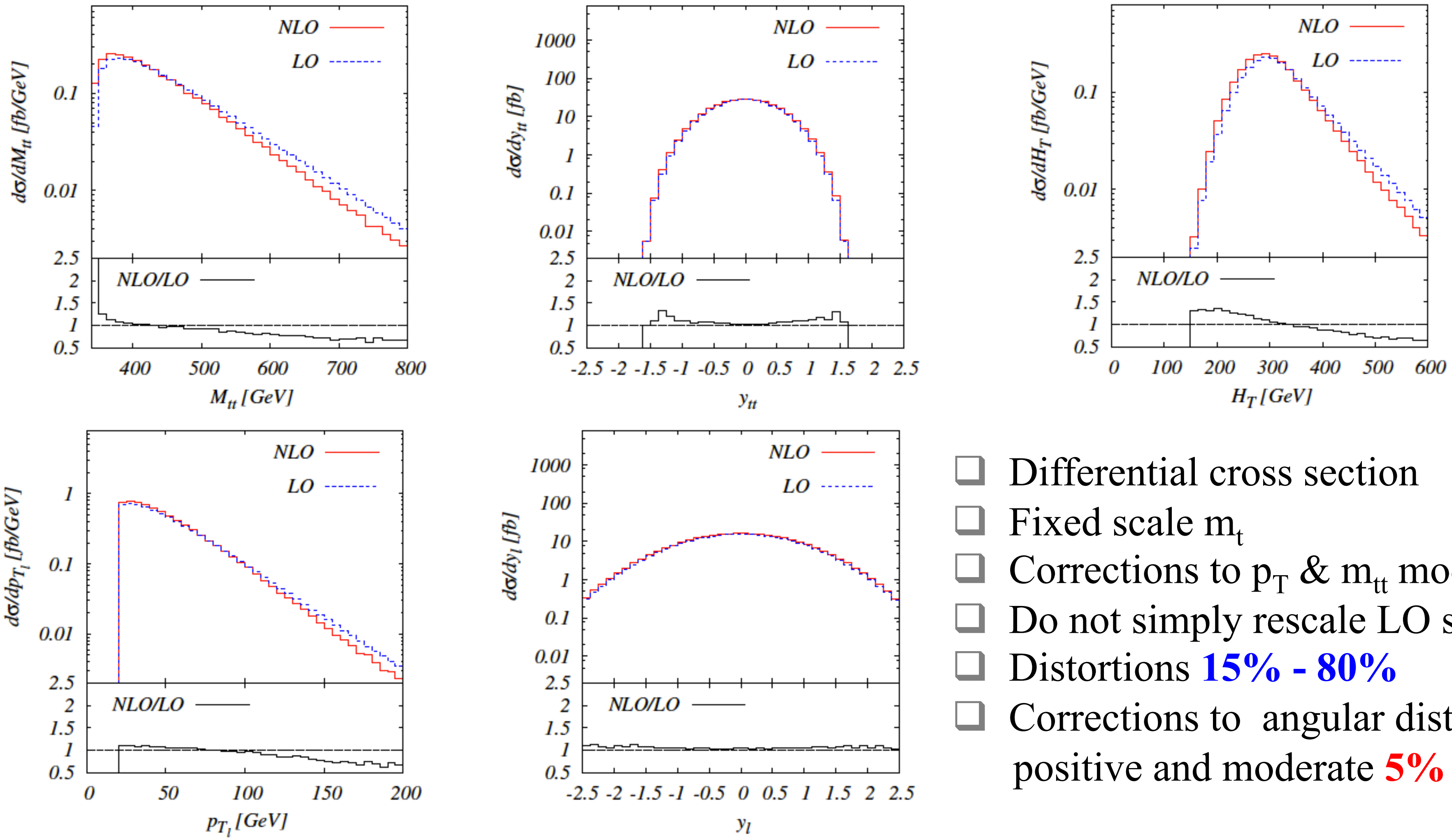
$\mathcal{P}p\bar{p}$ -> WWbb

TeVatron



- Differential cross section
- Fixed scale m_t
- Corrections to p_T & m_{tt} moderate
- Do not simply rescale LO shapes
- Distortions **15% - 80%**
- Corrections to angular distributions positive and moderate **5% - 10%**

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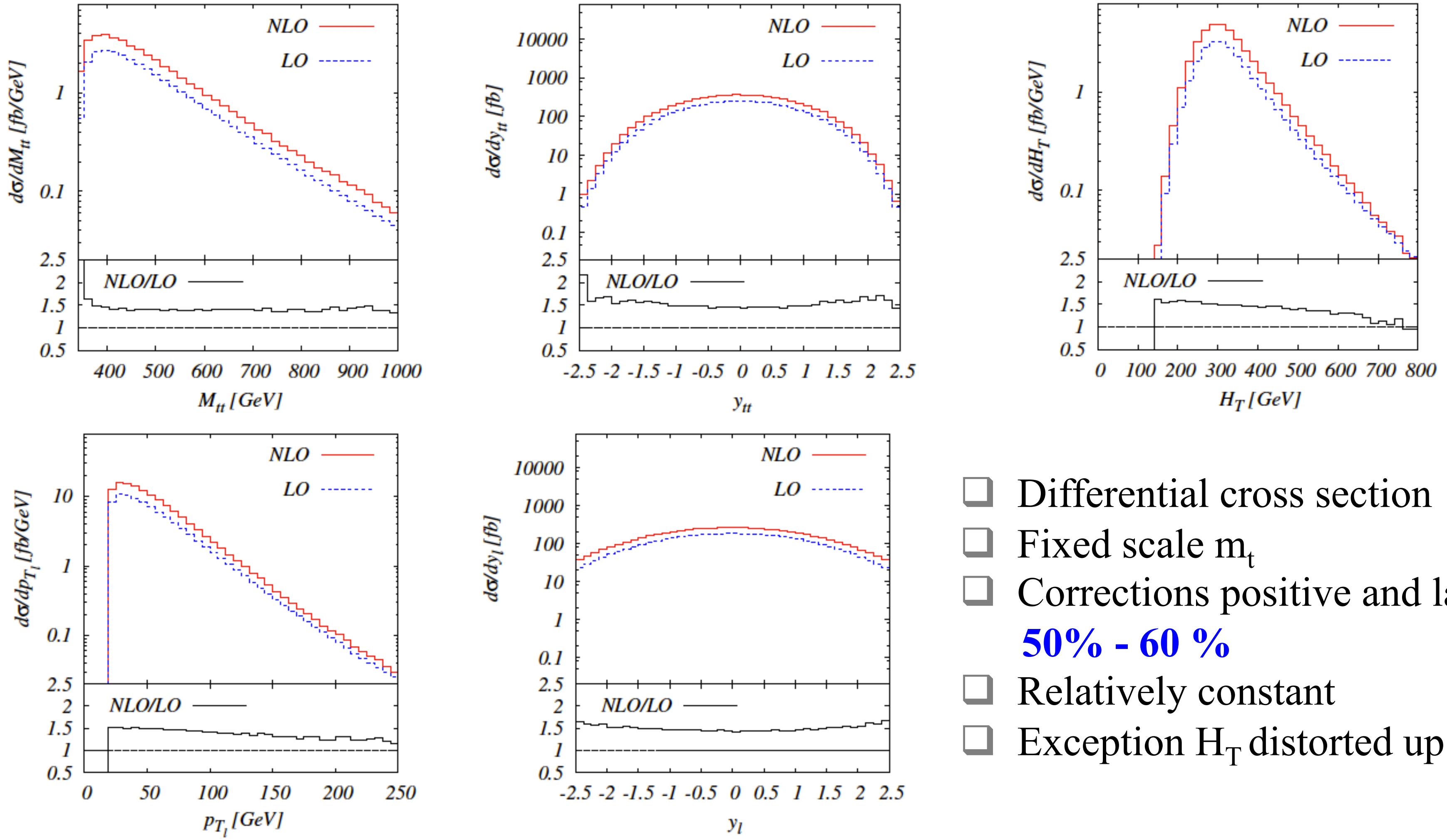
Pp -> WWbb

LHC



- Differential cross section
- Fixed scale m_t
- Corrections positive and large **50% - 60 %**
- Relatively constant
- Exception H_T distorted up to **80%**

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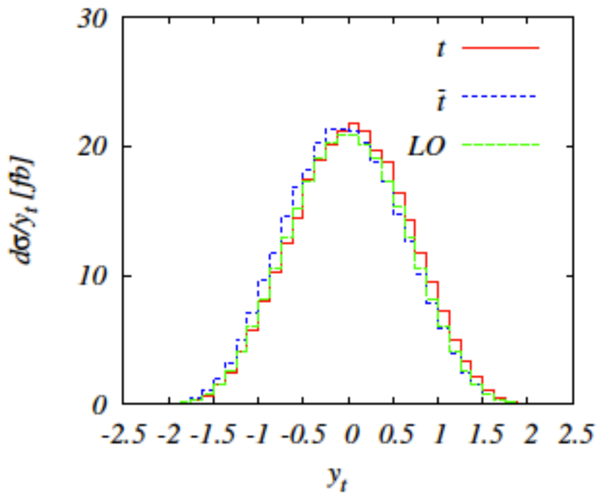
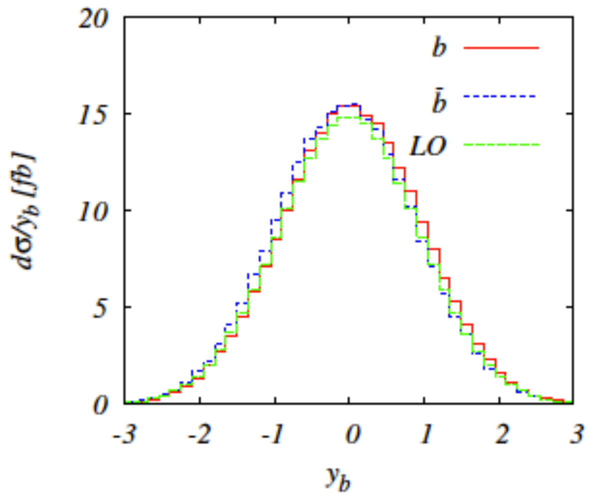
$p\bar{p}$ -> WWbb

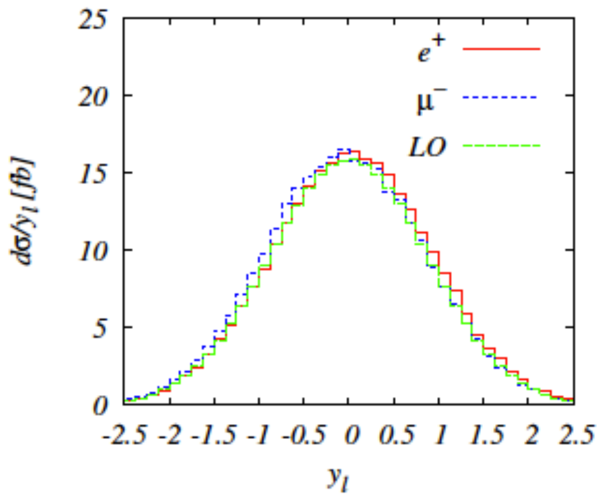




$$A^t_{FB} = 0.051$$

$$A^b_{FB} = 0.033$$

$$A^{\ell^+}_{FB} = 0.034$$



- Asymmetry @ TeVatron

$$A^t_{FB} = \frac{\int_{y>0} N_t(y) - \int_{y<0} N_t(y)}{\int_{y>0} N_t(y) + \int_{y<0} N_t(y)}$$

$$A^{\bar{t}}_{FB} = -A^t_{FB}$$

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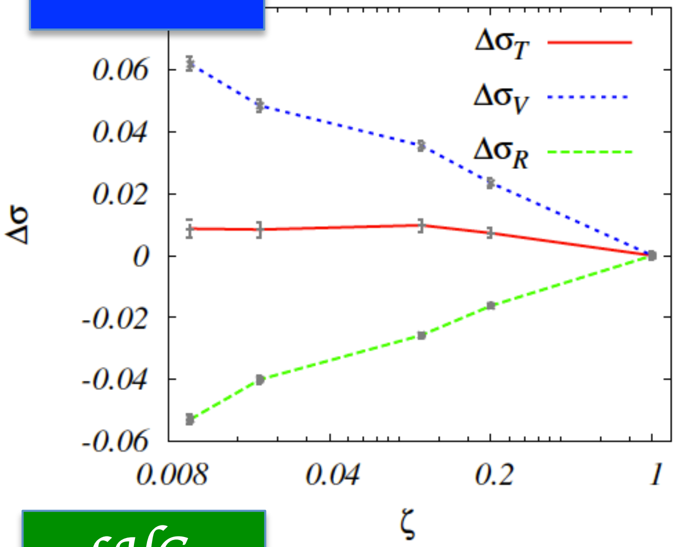
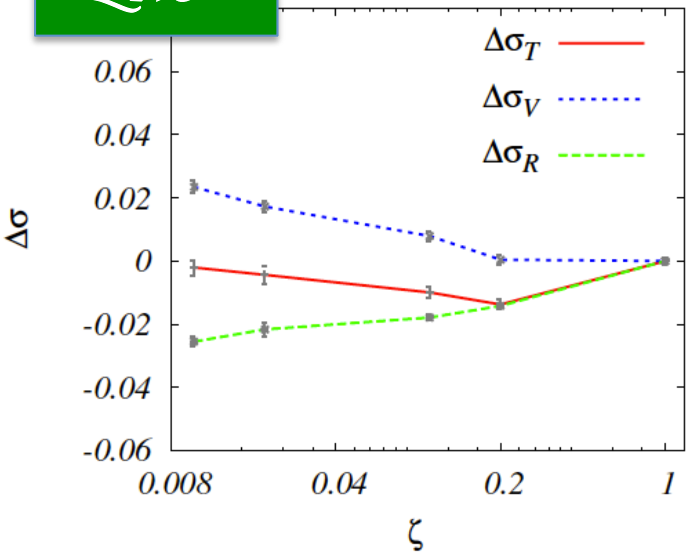
$pp\ (p\bar{p})$ -> WWbb

TeVatron



LHC



- Size of the non-factorizable corrections
- Full result versus narrow width approximation
- Rescaling coupling tWb by some large factors

- **+1.0%** TeVatron and **-1.2%** LHC for inclusive cuts

- Dependence of NLO cross section and individual contributions on rescaling parameter ζ

$$\Gamma_{rescaled} = \zeta \Gamma_t$$

$$\Delta\sigma_i(\zeta) = (\sigma_i(\zeta) - \sigma_i(\zeta = 1))/\sigma_{\mathrm{T}}(\zeta = 1)$$

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Summary & Outlook

- **ttbb, WWbb** completed by two groups, *Permille level agreement in both cases!*
- **ttjj**

  See Stefan Kallweit talk on Saturday

- **HELAC-NLO**
  - Complete tool at NLO built around **HELAC-PHEGAS:** **HELAC-1LOOP, CUTTOOLS, ONELOOP & HELAC-DIPOLES**
  - Much wider study for ttjj: variation of the center of mass energy, jet algorithms, cone size in jet algorithm, transverse momentum cuts, ...
  - Other processes from NLO Wishlist under attack
  - Constant improvements in speed and functionality

http://helac-phegas.web.cern.ch/helac-phegas/