Next-to-Leading Order tt + Jets Physics with HELAC-NLO

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Outline

- General Motivation for next-to-leading order calculations
- Why do we need **pp → ttH → ttbb, pp → ttbb** & **pp → ttjj** @ NLO ?
- **HELAC-NLO** framework in a nutshell
- Results for integrated and differential cross sections
- Summary & Outlook

HELAC-NLO Group:

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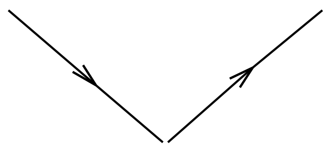
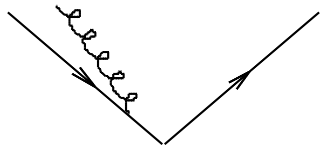
General Motivation for NLO

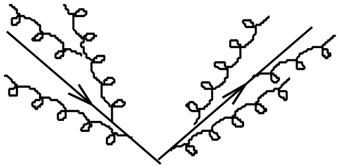
- Stabilizing the scale in the QCD input parameteres → the strong coupling constant and PDFs
- Normalization and shape of distributions first known at NLO
- Many scale processes: **V+ jets, VV + jets, ttH, tt + jets, n-jets ...**
- Sometimes dynamical scales seem to work better for some observables
- How to know that the scale is chosen properly ?
- Improved description of jets



LO

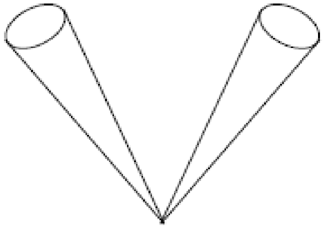


NLO



Parton Shower

1 Jet   2 Jet



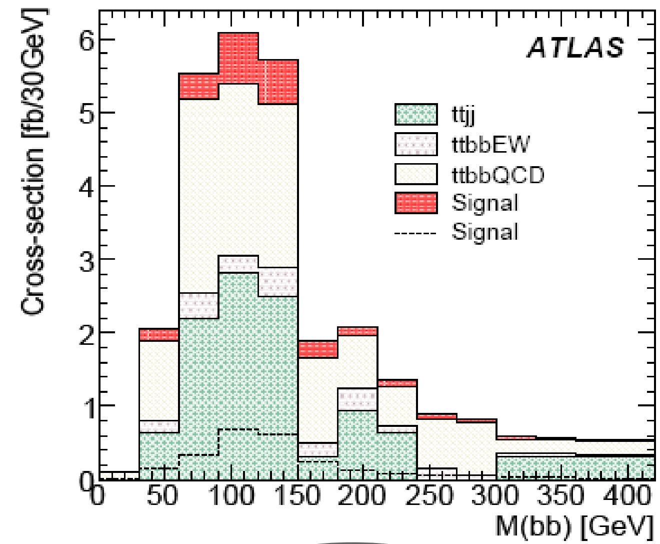
$pp \rightarrow ttH \rightarrow ttbb$

- **ttH:** potential discovery channel in low mass range where Higgs boson decay into **bb** pair

  $m_H \leq 135$ GeV

- Unique access to top & bottom Yukawa coupling
- Large QCD backgrounds: **ttjj & ttbb**
- **Problem 1** **combinatorial background of b-jets:** bb pair can be chosen incorectly, lack of distinctive kinematic feature of Higgs decay jets
- **Problem 2** **b-tagging efficiency:** two b-jets for Higgs candidate can arise from mistagged QCD light jets
- **Goal:** Backgrounds need to be very well controlled

ATLAS TDR, CERN-OPEN-2008-020

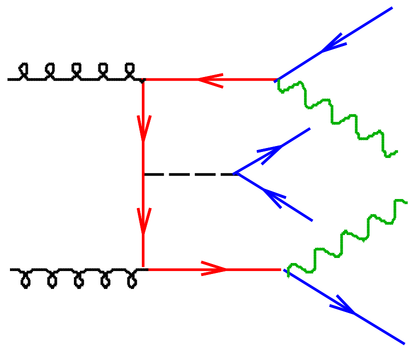


S/B ~ 1/9

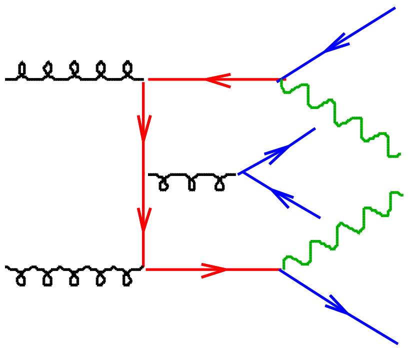
Summary table	Significance loose/tight	Luminosity
ATLAS (Lepton+jets)	2.2	30 fb^{-1}
CMS (Lepton+jets)	2.5/1.9	60 fb^{-1}
CMS(Combined)	3.9/3.3	60 fb^{-1}

G. Aad, J. Steggemann, ATLAS & CMS @ TOP 2008

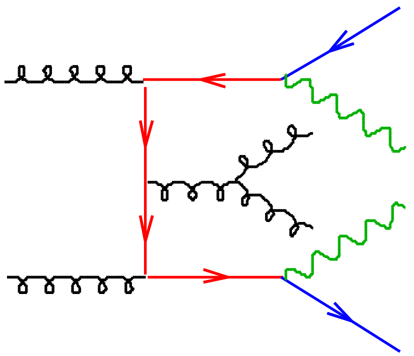
Example of Feynman Diagrams



Signal process **pp** → **ttH** → **ttbb**



Irreducible background process **pp** → **ttbb**



Reducible background process **pp** → **ttjj**

Theoretical Motivation

- NLO corrections to 2 → 4 is current technical frontier
- Complexity of calculations triggered creation of prioritized wishlist
- **ttbb** & **ttjj** productions range among the most wanted candidates

- NLO QCD corrections to **ttH** — *W. Beenakker, S. Dittmaier, M. Krämer, B. Plümper, M. Spira, P.M. Zerwas '01*
  L. Reina, S. Dawson '01, S. Dawson, L.H. Orr, L. Reina, D. Wackeroth '03
- NLO QCD corrections to **ttH → ttbb** — *G. Bevilacqua, M. Czakon, M.V. Garzelli, A. van Hameren, C.G. Papadopoulos,*
  R. Pittau, M. Worek '10 (Les Houches 2009)
- NLO QCD corrections to **ttbb** — *A. Bredenstein, A. Denner , S. Dittmaier , S. Pozzorini '08, '09, '10*
  G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M.Worek '09
- NLO QCD corrections to **ttjj** — *G. Bevilacqua, M. Czakon, C.G. Papadopoulos, M.Worek '10*

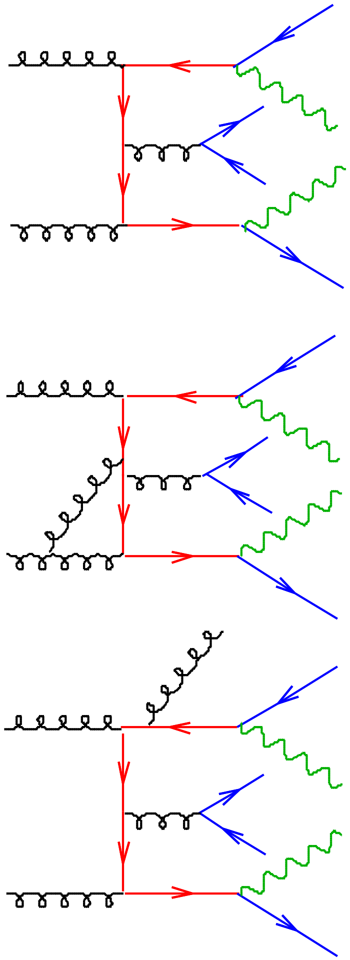
Goal: Demonstrate the power of **HELAC-NLO** system in realistic computation
with 6 external legs and massive partons

Structure of NLO Calculations

- <u>**Subtraction method for NLO calculation**</u>

S. Catani, M.H. Seymour '97
S. Catani, S. Dittmaier, M.H. Seymour, Z. Trocsanyi '02
M. Czakon, C. G. Papadopoulos, M. Worek '09

- Taken separately integrals are IR divergent → Only sum is finite
- Need to get individual contribution finite to perform MC integration



$$d\hat{\sigma}^{NLO} = \int_n d\hat{\sigma}^{LO} + \int_{n+1} d\sigma^{real} - \int_{n+1} d\sigma^{A} + \int_n d\sigma^{virt.} + \int_{n+1} d\sigma^{A} \Rightarrow$$

$$\int_{n+1} [d\sigma^{real} - d\sigma^{D}] + \int_n [d\sigma^{virt.} + d\sigma^{I} + d\sigma^{KP}]$$

- Local counter term added → proper approximation of $d\sigma^{real}$
- Process independent method, dipole functions, I and KP operators universal !

<u>**Our strategy in a few words:**</u>
- make it fully numeric
- make it fully automatic
- all summation via Monte Carlo

HELAC-NLO In A Nutshell

HELAC-PHEGAS

A. Kanaki, C. G. Papadopoulos '00
C. G. Papadopoulos '01
A. Cafarella, C. G. Papadopoulos, M. Worek '07

→ Event generator for all parton level processes at LO
→ http://helac-phegas.web.cern.ch/helac-phegas/

HELAC-1LOOP

A. van Hameren, C. G. Papadopoulos, R. Pittau '09

→ Evaluation of virtual one-loop amplitudes, based on **HELAC**

CUTTOOLS

G. Ossola, C. G. Papadopoulos, R. Pittau '07, '08
P. Draggiotis, M. V. Garzelli, C. G. Papadopoulos, R. Pittau '09

→ Reduction of tensor integrals and determination of coefficients via OPP reduction method
→ http://www.ugr.es/~pittau/CutTools

ONELOOP

→ Evaluation of scalar integrals (all divergent and finite scalar integrals are included)
→ http://annapurna.ifj.edu.pl/~hameren/

HELAC-DIPOLES

M. Czakon, C. G. Papadopoulos, M. Worek '09

→ Catani-Seymour dipole subtraction for massless and massive cases
→ Phase space integration of subtracted real radiation and integrated dipoles (**I** & **KP** operators)
→ Arbitrary polarizations & phase space restriction on dipoles contribution
→ http://helac-phegas.web.cern.ch/helac-phegas/

Virtual Timings

process	full color sum [s]	color sampling [s] (100 event average)
$gg \to t\bar{t}H^* \to t\bar{t}b\bar{b}$	0.77	0.20
$gg \to t\bar{t}b\bar{b}$	8.25	0.82
$gg \to t\bar{t}gg$	122.5	5.79

- Lahey Fortran Compiler on 3 GHz Intel Xeon
- Maybe a factor of 2 due to compiler and option (??)
- Random helicity everywhere !

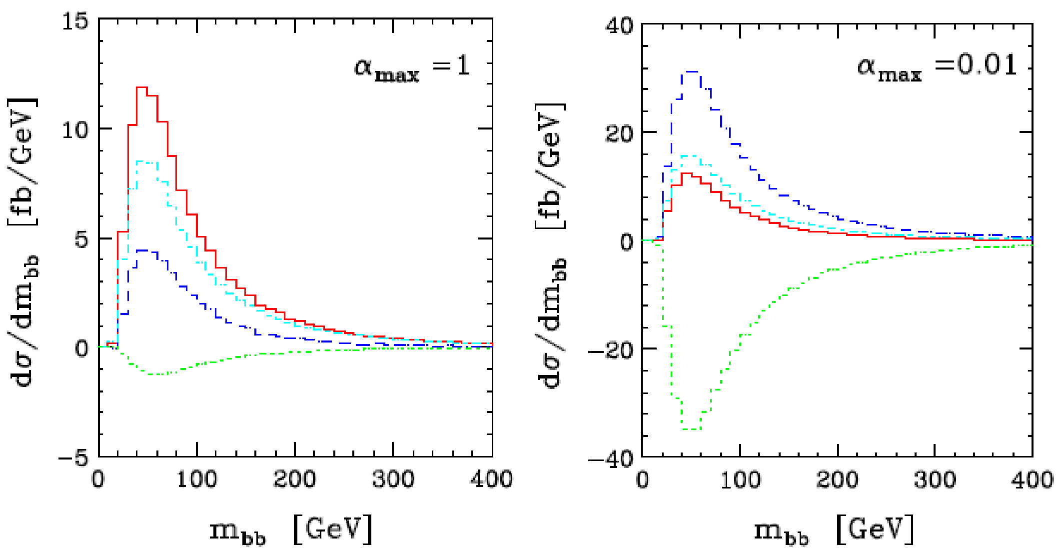
Real Emission Timings

Process	Real Emission + Dipoles [msec]	Real Emission [msec]	Nr Of Dipoles
$gg \to ggg$	3.8	1.0	27
$gg \to gggg$	8.5	2.6	56
$gg \to ggggg$	300	42	100
$u\bar{d} \to W^+ gggg$	9.3	2.4	56
$gg \to t\bar{t}b\bar{b}g$	12	2.9	55

- Timings obtained on Core 2 Duo 2.53 GHz machine with Intel Fortran
- All dipoles included ($\alpha_{max} = 1$)
- Random helicity everywhere !

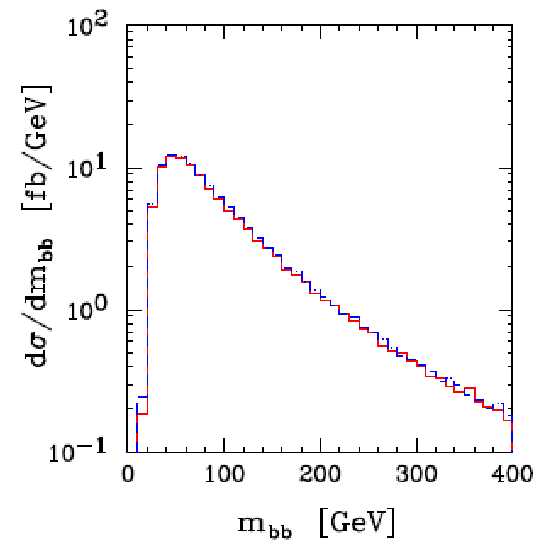
Real Emission for pp → ttbb

Different parts of real radiation contribution with different choices of α_{max}



Subtracted real emission
K + P operators
I operators
Full result

Internal check:
Cutoff independence !!



Phase space restriction on the dipoles phase space $\alpha_{max} \in (0,1]$

- Less dipole subtraction terms per event
- Increased numerical stability by decreasing size of dipole phase space
- Reduced missed binning problem
- Large cancellations between real radiation and integrated dipoles

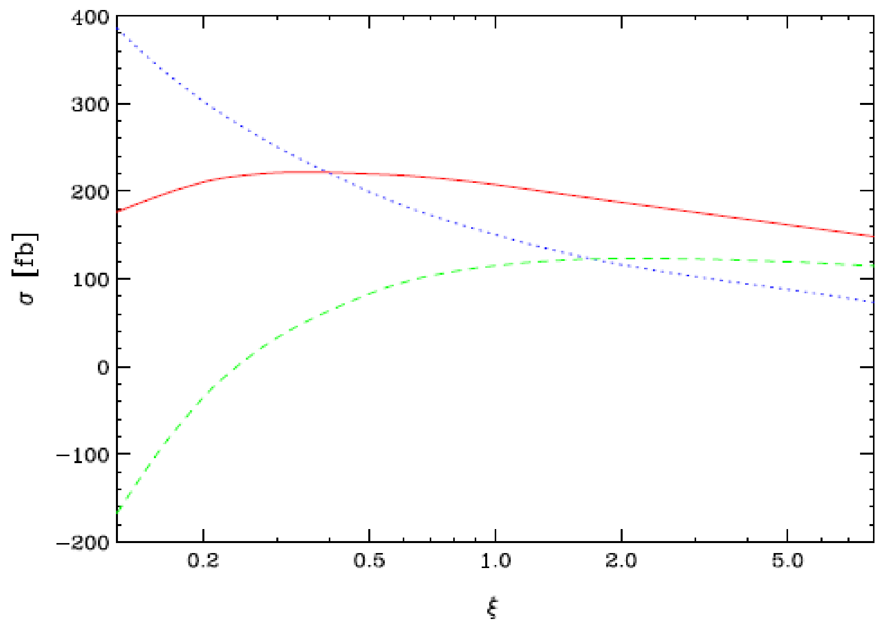
G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M. Worek '09

pp → ttH → ttbb @ LHC

$\sqrt{s}$ = 14 TeV
$p_T(j) > 20$ GeV
$|y(j)| < 2.5$
$\Delta R(j,j) > 0.8$
$\mu_R = \mu_F = m_{top} + m_H/2$
$m_H = 130$ GeV
CTEQ6L1, CTEQ6M
k_T algorithm R= 0.8

pp → ttH → ttbb @ LHC

Scale Dependence and Integrated Cross Sections



$$\sigma^{S}_{LO} = (150.375 \pm 0.077)\ \mathrm{fb}$$

$$\sigma^{S}_{NLO} = (207.268 \pm 0.150)\ \mathrm{fb}$$

$$\sigma^{S}_{NLO-veto} = (114.880 \pm 0.152)\ \mathrm{fb}$$

Scale dependence reduced:
33% at **LO** → **10%** at **NLO**
28% at **NLO with jet Veto** of 50 GeV

K factor of **K = 1.38** **(K = 0.76)**
NLO QCD Corrections **38%** **(-24%)**

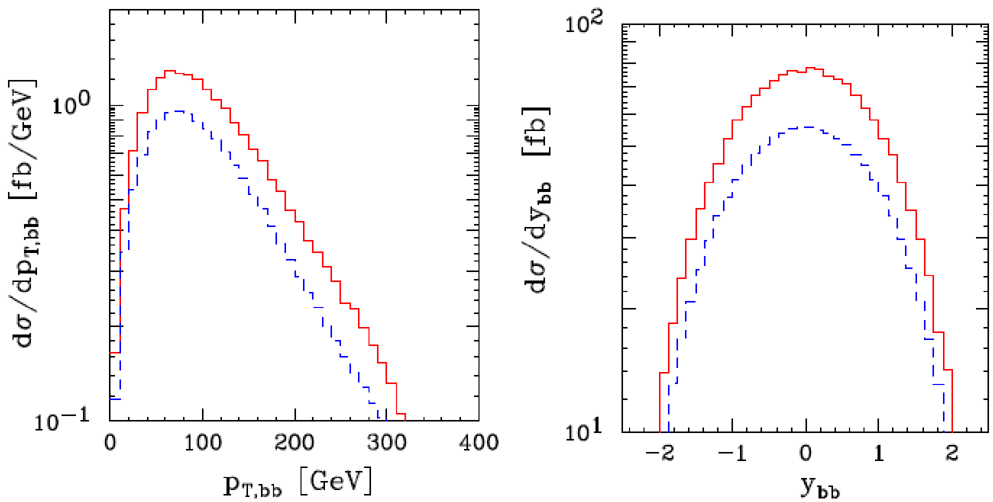
G. Bevilacqua, M. Czakon, M.V. Garzelli, A. van Hameren, C.G. Papadopoulos, R. Pittau, M. Worek '10 (Les Houches 2009)

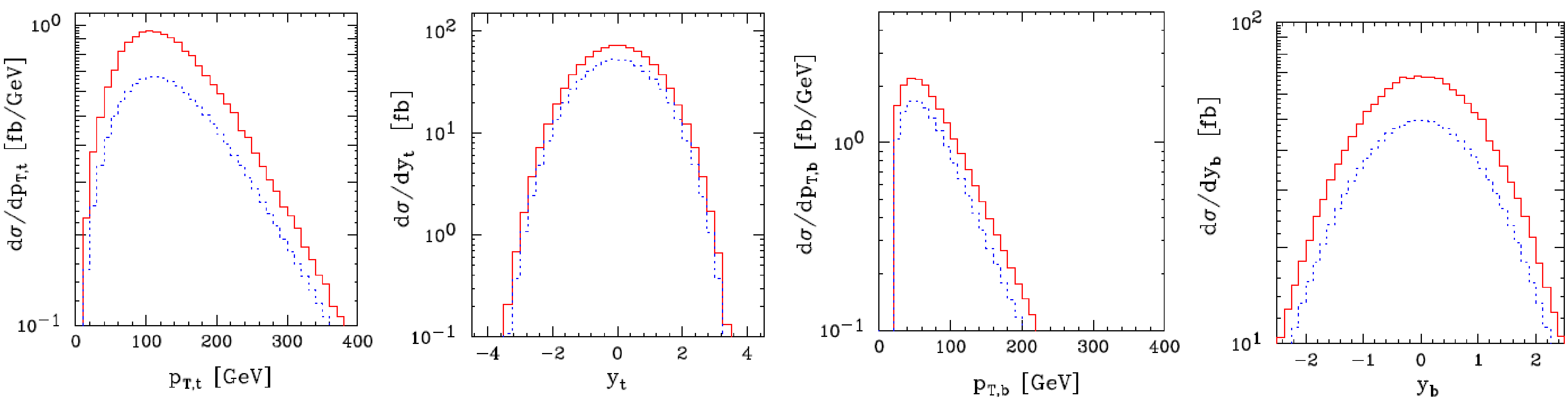
pp → ttH → ttbb @ LHC

LO & NLO

- **bb pair kinematics**
  - → Transverse momentum
  - → Rapidity distribution

- **single b & top kinematics**
  - → Transverse momentum
  - → Rapidity distribution





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CTEQ6L1, CTEQ6M
k_T algorithm R = 0.8

pp → ttbb @ LHC

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M. Worek '09
A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini '08, '09

Permille level agreement!

Process	$\sigma^{\text{LO}}_{[23,\,24]}$ [fb]	σ^{LO} [fb]	$\sigma^{\text{NLO}}_{[23,\,24]}$ [fb]	$\sigma^{\text{NLO}}_{\alpha_{\max}=1}$ [fb]	$\sigma^{\text{NLO}}_{\alpha_{\max}=0.01}$ [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)

m_{top} = 172.6 GeV

$\xi \cdot m_t$	$1/8 \cdot m_t$	$1/2 \cdot m_t$	$1 \cdot m_t$	$2 \cdot m_t$	$8 \cdot m_t$
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)

$$\sigma^{\text{LO}}_{t\bar{t}b\bar{b}} = 1489.2 \begin{array}{l} +1036.8\ (70\%) \\ -\ \ 565.8\ (38\%) \end{array} \text{ fb}$$

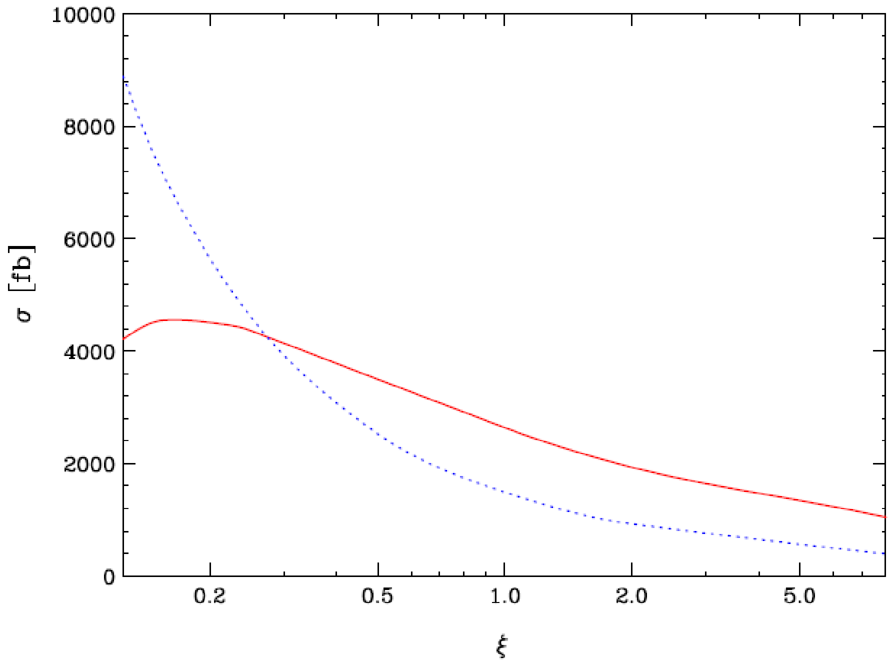
$$\sigma^{\text{NLO}}_{t\bar{t}b\bar{b}} = 2636 \begin{array}{l} +862\ (33\%) \\ -703\ (27\%) \end{array} \text{ fb}$$

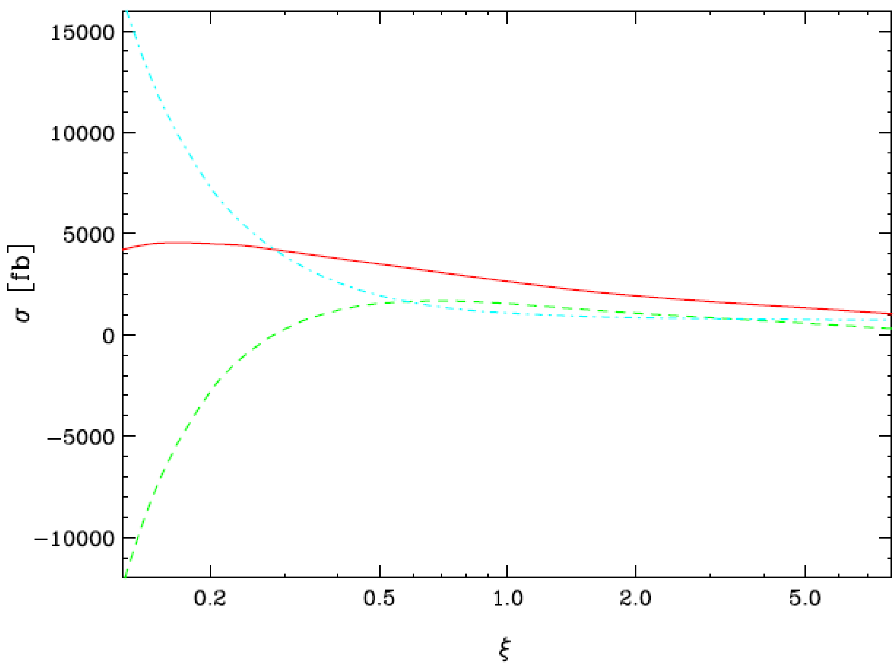
Scale dependence reduced:
70% at **LO** → **33%** at **NLO**

K factor of **K = 1.77**
for quarks only **K = 1.03**
With jet veto of 50 GeV **K = 1.20**

pp → ttbb @ LHC

Scale Dependence





- Varying scale up or down by a factor 2 changes cross section by **70%** at **LO** and by **33%** at **NLO**

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

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pp → ttbb @ LHC

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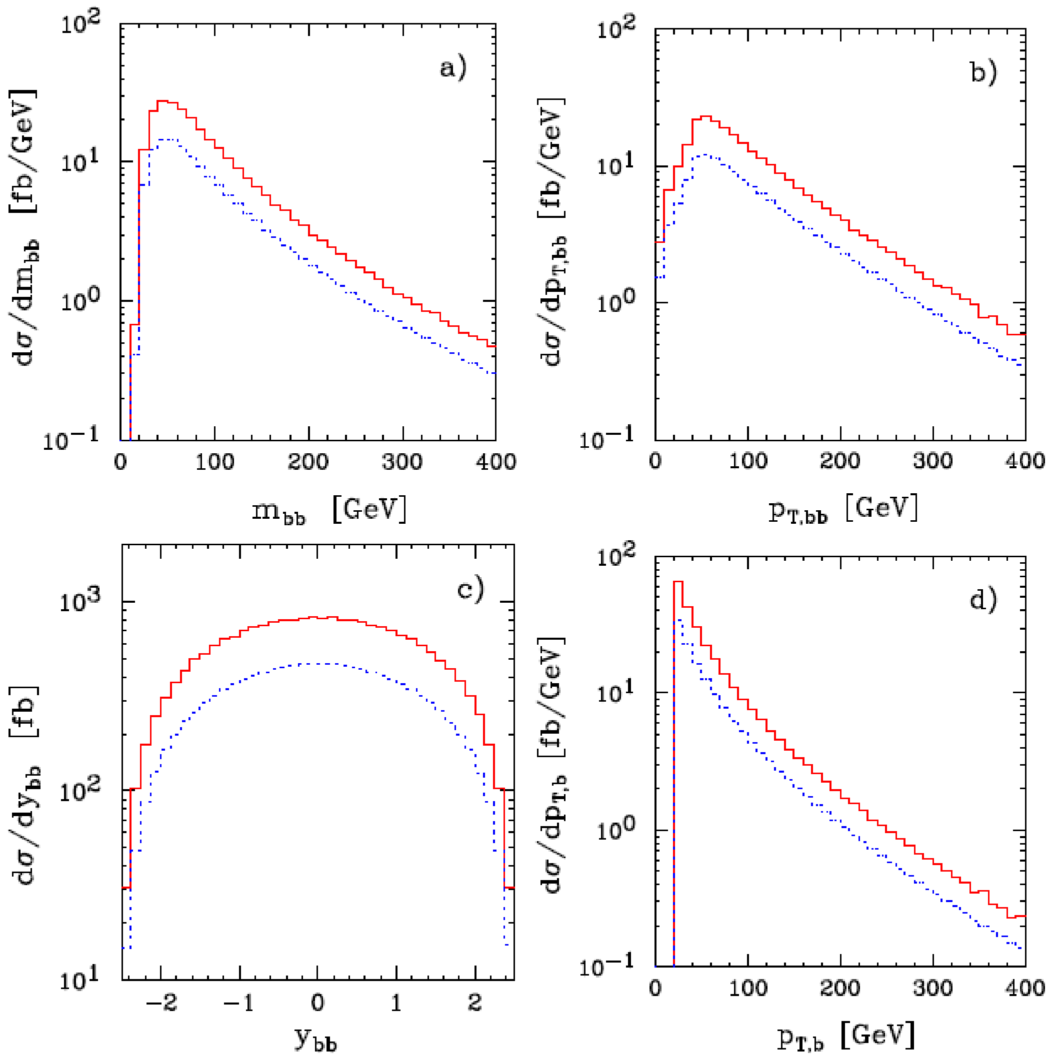


- **b-jet pair kinematics**

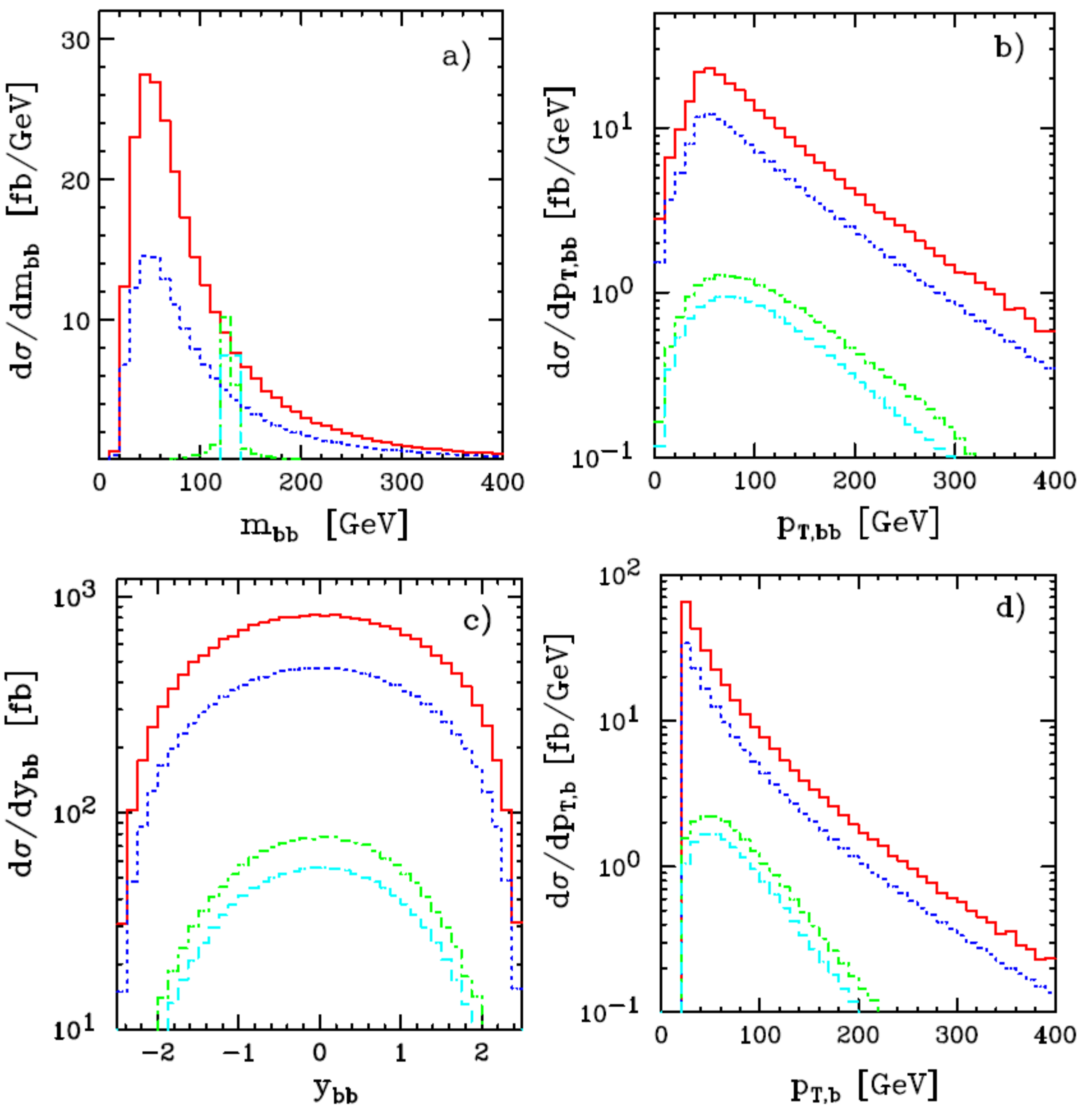
→ Invariant mass distribution
→ Transverse momentum
→ Rapidity distribution

- **single b-jet kinematics**

→ Transverse momentum

- **LO** & **NLO**
- Relatively small variation compared to the size but shape change important

Signal & Background pp → ttbb



Background pp → ttbb
LO & **NLO**

Signal pp → ttH → ttbb
LO & **NLO**

On-shell top !

b-jet pair kinematics

→ Invariant mass distribution
→ Transverse momentum
→ Rapidity distribution

single b-jet kinematics

→ Transverse momentum

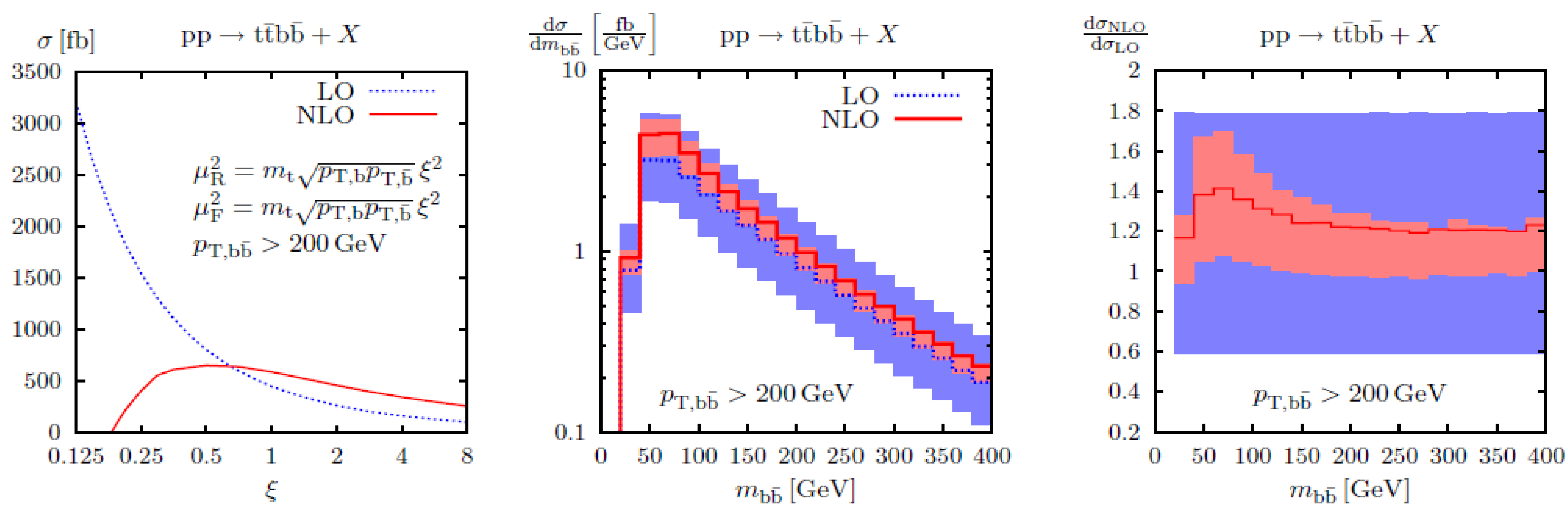
G. Bevilacqua, M. Czakon, M.V. Garzelli, A. van Hameren, C.G. Papadopoulos, R. Pittau, M. Worek '10 (Les Houches 2009)

pp → ttbb @ LHC

A. Bredenstein, A. Denner , S. Dittmaier , S. Pozzorini '10

- LO & NLO integrated cross sections in fb
- Scale variations by factor 2
- K-factors

Setup	$m_{b\bar{b},cut}$	$p_{T,b\bar{b},cut}$	$p_{jet,veto}$	$p_{T,b,cut}$	$y_{b,cut}$	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



Scale dependence for dynamic scale m_{bb} distribution   Dynamic K-factor

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

$\sqrt{s} = 14$ TeV
$p_T(j) > 50$ GeV
$|y(j)| < 4.5$
$\Delta R(j,j) > 1.0$
$\mu_R = \mu_F = m_{top}$
CTEQ6L1, CTEQ6M
k_T algorithm $R = 0.8$

$pp \rightarrow ttjj$ @ LHC

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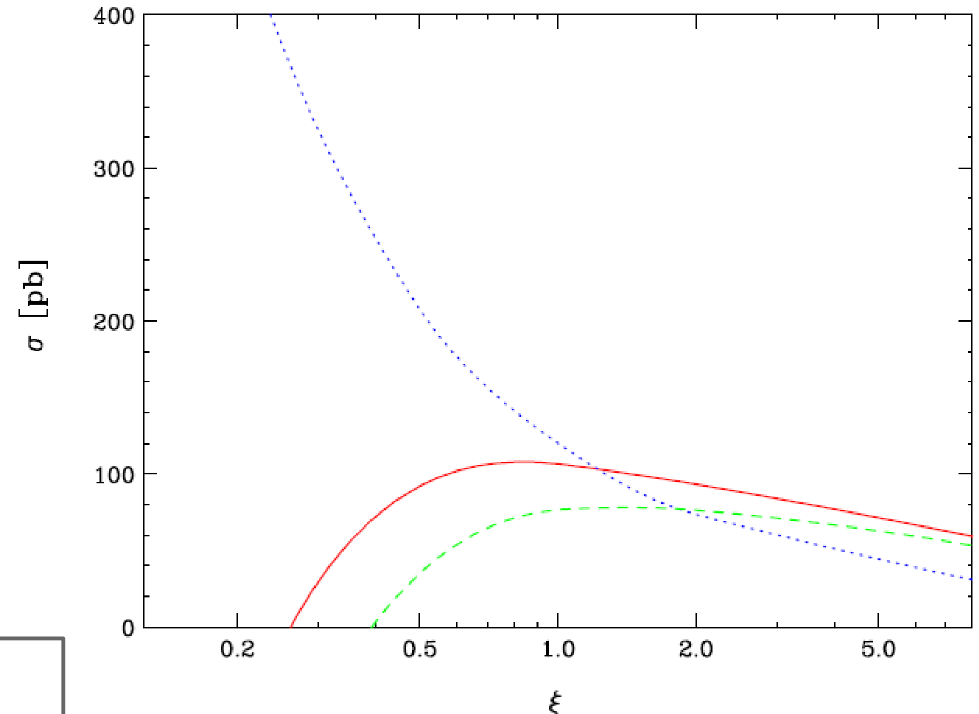
Process	σ^{LO} [pb]	Contribution
$pp \rightarrow t\bar{t}jj$	120.17(8)	100 %
$qg \rightarrow t\bar{t}qg$	56.59(5)	47.1 %
$gg \rightarrow t\bar{t}gg$	52.70(6)	43.8 %
$qq' \rightarrow t\bar{t}qq', \; q\bar{q} \rightarrow t\bar{t}q'\bar{q}'$	7.475(8)	6.2 %
$gg \rightarrow t\bar{t}q\bar{q}$	1.981(3)	1.6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

$$\sigma^{NLO}_{pp\rightarrow t\bar{t}jj+X} = (106.94 \pm 0.17) \text{ pb}$$

$$\sigma^{NLO}_{pp\rightarrow t\bar{t}jj+X}(p_{T,X} < 50 \text{ GeV}) = (76.58 \pm 0.17) \text{ pb}$$



Scale dependence reduced:
72% at **LO** → **13%** at **NLO**
54% at **NLO with jet Veto** of 50 GeV

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

m_{top} = 172.6 GeV

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

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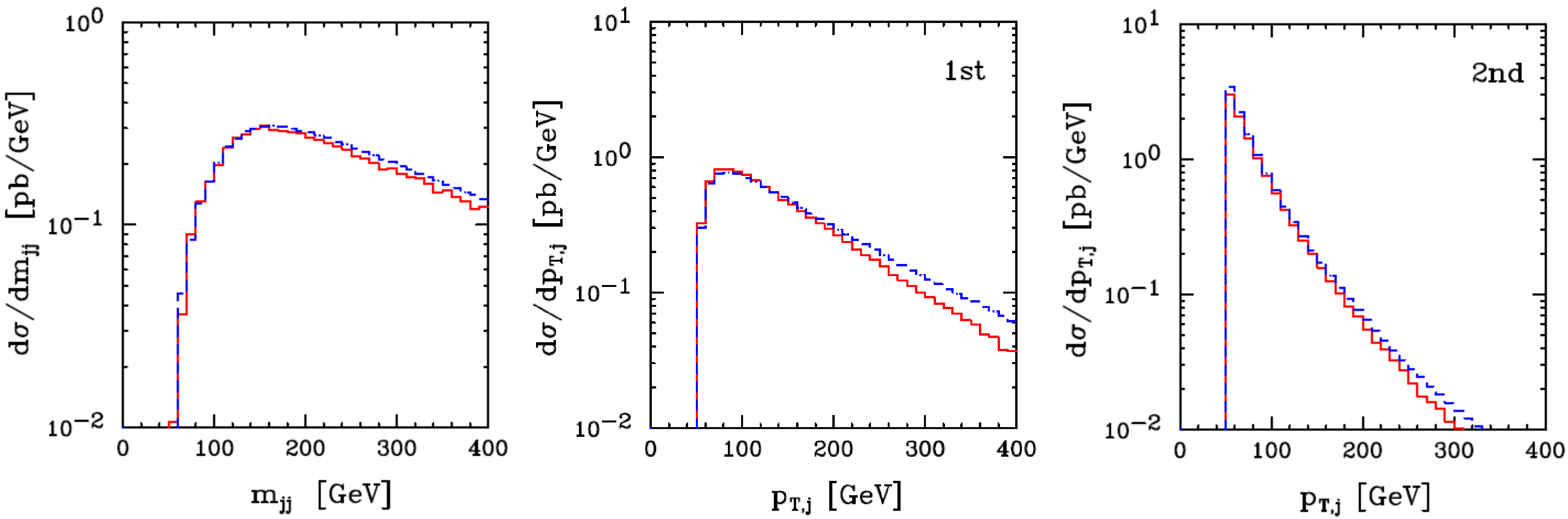


invariant mass of 2 jet system
→ size of the corrections transmitted to the distributions for low p_T
→ shapes change for hight p_T

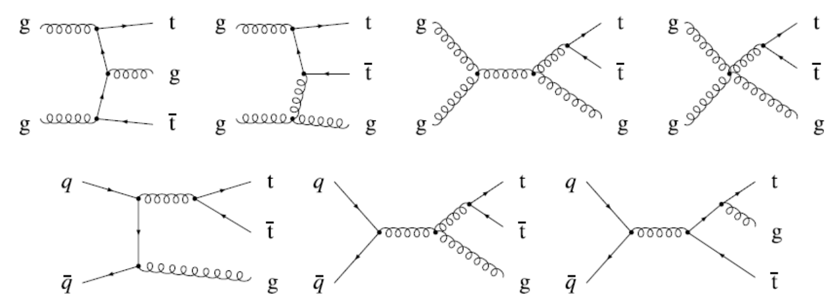
p_T of 1st hardest and 2nd hardest jet (ordered in p_T)

altered shapes up to **-39%, -28%** in tails

LO & **NLO**

pp → ttj @ LHC

- Results of previous study of **pp → ttj** have been reproduced for the first time !
- Cross section for different values of p_T jet cut
- Behavior of the corrections for different setups
- Argument that our conclusions for **pp → ttjj** will remain true for other input parameters



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$p_{T,\mathrm{jet,cut}}$ [GeV]	$\sigma_{t\bar{t}\mathrm{jet}}$ [pb] LO	NLO
20	$710.8(8)^{+358}_{-221}$	$692(3)3^{-40}_{-62}$
50	$326.6(4)^{+168}_{-103}$	$376.2(6)^{+17}_{-48}$
100	$146.7(2)^{+77}_{-47}$	$175.0(2)^{+10}_{-24}$
200	$46.67(6)^{+26}_{-15}$	$52.81(8)^{+0.8}_{-6.7}$

S. Dittmaier, P. Uwer, S. Weinzierl '07, '09

$\sigma_{\mathrm{HELAC\_NLO}}$ = 376.6(6) pb

K_{20} = 0.97 (-3%)
K_{50} = 1.15 (15%)
K_{100} = 1.19 (19%)
K_{200} = 1.13 (13%)

Summary & Outlook

- Automated approach **HELAC-NLO**

- First results have already been presented:

  - ♣ **pp → ttj** (3 independent groups)
  - ♣ **pp → ttbb** (2 independent groups)
  - ♣ **pp → ttH → ttbb**
  - ♣ **pp → ttjj**

- Results of previous study of **pp → ttj** have been reproduced for the first time

- Phenomenological study for pp → ttH → ttbb, pp → ttbb, pp → ttjj

- Much wider study for pp → ttjj: variation of the center of mass energy, cone size in jet algorithm, transverse momentum cuts, jet vetoes, ...

- Other general & automatic systems: **BLACKHAT/SHERPA, ROCKET/MCFM, GOLEM, ...**

Outlook

More 2 $\rightarrow$ 4 processes in preparation

Single boson	Diboson	Triboson	Heavy flavor
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 5j$	$ZZ + \leq 5j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 3j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 2j$
$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$		$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		$b\bar{b}\, t\bar{t}$
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 5j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		