NLO QCD corrections to $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$

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based on A.Bredenstein, A.Denner, S.D. and S.Pozzorini, JHEP 0808 (2008) 108 [arXiv:0807.1248], PRL 103 (2009) 012002 [arXiv:0905.0110] and JHEP 1003 (2010) 021 [arXiv:1001.4006]

Contents

$pp \to t\bar{t}b\bar{b}$ as background to $t\bar{t}H$ production at the LHC

At the LHC the background to some signals probably cannot be measured !

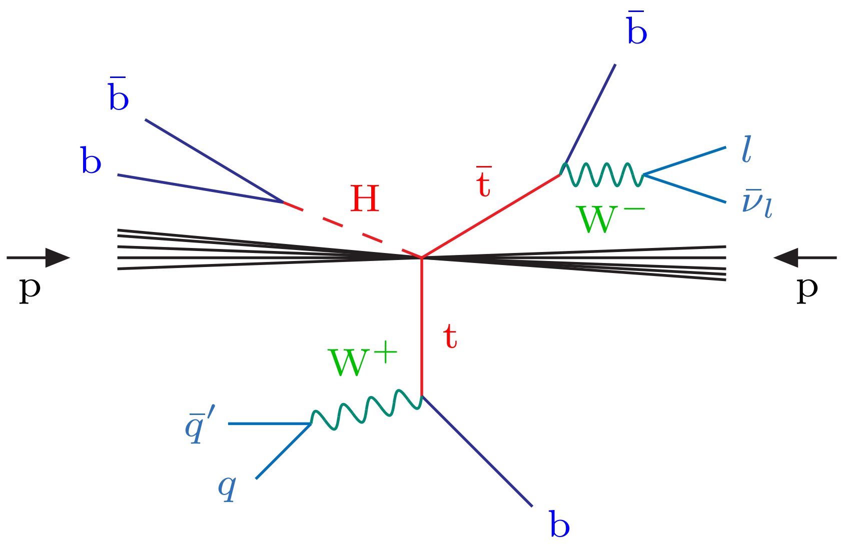
"Les Houches wishlist '05" of missing NLO predictions for "multi-leg" background:

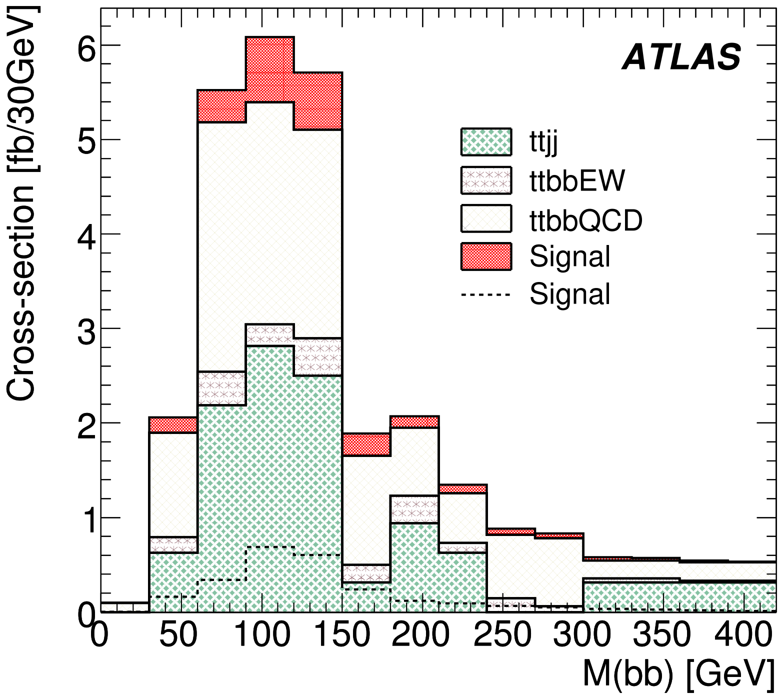
	background for
$\mathrm{pp} \to \mathrm{VV} + \mathrm{jet}$	$\mathrm{t\bar{t}H}$, new physics
WW+jet: S.D., Kallweit, Uwer '07,'09; Campbell, R.K.Ellis, Zanderighi '07 Wγ/WZ+jet: Campanario et al. '09/'10; ZZ+jet: Binoth et al. '09	
$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$	$\mathrm{t\bar{t}H}$
Bredenstein, Denner, S.D., Pozzorini '08,'09; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09	
$\mathrm{pp} \to \mathrm{t\bar{t}} + 2\mathrm{jets}$	$\mathrm{t\bar{t}H}$
Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '10	
$\mathrm{pp} \to \mathrm{VVb\bar{b}}$	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,'09; Bozzi et al. '07	
$\mathrm{pp} \to \mathrm{V} + 3\mathrm{jets}$	$\mathrm{t\bar{t}}$, new physics
W+3jets: R.K.Ellis, Melnikov, Zanderighi '09; Berger et al. '09 Z+3jets: Berger et al. '10	
$\mathrm{pp} \to \mathrm{VVV}$	SUSY tri-lepton
Lazopoulos et al. '07; Binoth, Ossola, Papadopoulos, Pittau '08; Hankele, Zeppenfeld '08	
$\mathrm{pp} \to \mathrm{b\bar{b}b\bar{b}}$	Higgs and new physics (added 2007)
$q\bar{q}$: Binoth, Greiner, Guffanti, Guillet, Reiter, Reuter '09	

$\hookrightarrow$ Many long-termed NLO calculations for theorists !
(several 10^4 diagrams, many "(wo)men-decades")

$t\bar{t}H(\rightarrow b\bar{b})$ production – a problematic channel

“CSC book”,CERN-OPEN-2008-020



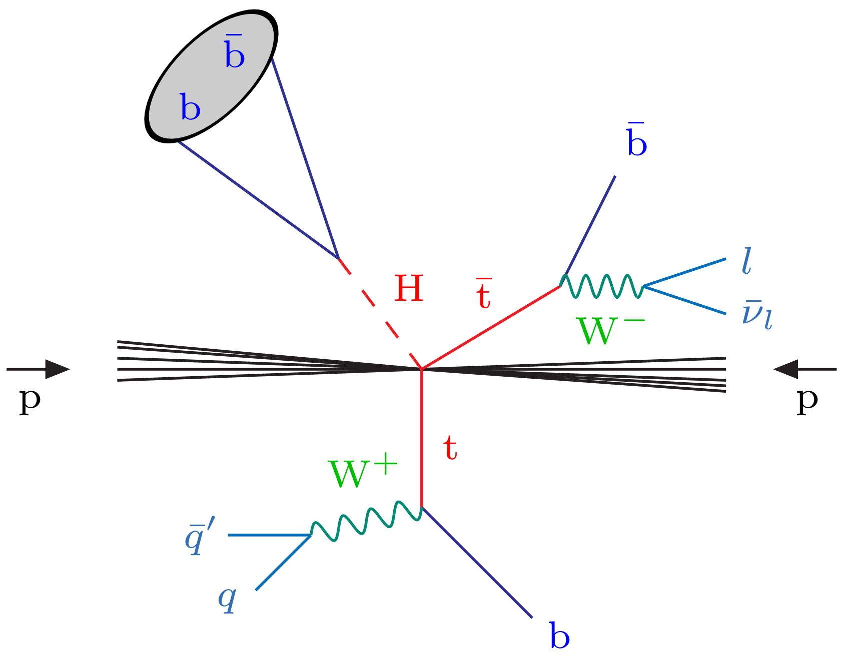


- Relevance: direct experimental access to $t\bar{t}H$ Yukawa coupling
- Problem: control background by $pp \rightarrow t\bar{t}b\bar{b}, t\bar{t} + \text{jets}$

  status 2008: signal not significant due to background contamination

  $\hookrightarrow$ activities:
  - ⋄ more sophisticated tricks in analysis
  - ⋄ NLO QCD prediction also for background

Idea under discussion: highly boosted "fat jets"



Butterworth et al. '08; ATL-PHYS-PUB-2009-088

$\hookrightarrow$ fat jet containing $\mathrm{b\bar{b}}$ pair from high-p_T Higgs (successful in WH/ZH revival!)

A theoretical study:

Plehn, Salam, Spannowsky '09

- fat jets: $p_\mathrm{T} > 200\,\mathrm{GeV}$ and $R = 1.5$
- substructures: $\mathrm{b\bar{b}}$ pair with $|m_{\mathrm{b\bar{b}}} - M_\mathrm{H}| < 10\,\mathrm{GeV}$, similar for $\mathrm{t} \to 3j$, etc.
- $S/\sqrt{B}$ still $\sim 2.2{-}2.6$
- S/B raised from ~ 0.1 to $0.2{-}0.4$
- background mainly due to $\mathrm{t\bar{t}b\bar{b}}$ (suppression of $\mathrm{t\bar{t}} + 2\mathrm{jets}$)

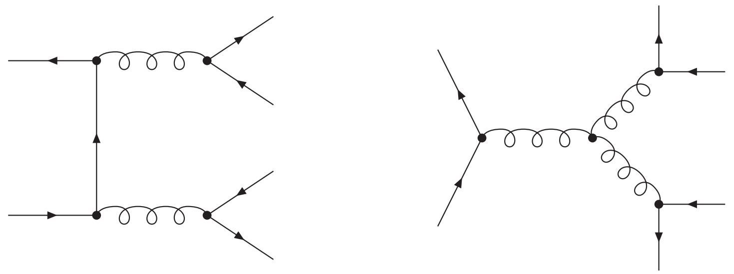
$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ at NLO QCD

The process $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ in NLO QCD

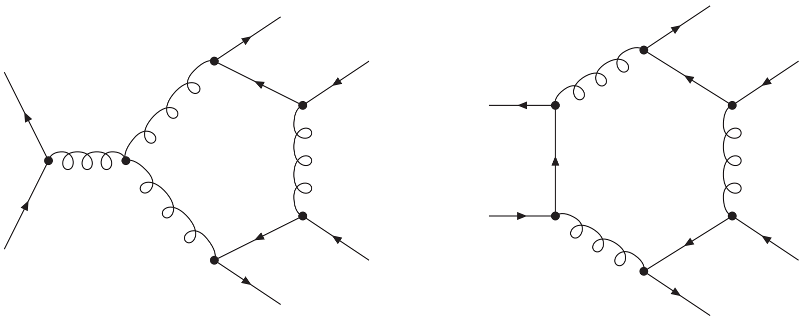
Bredenstein, Denner, S.D., Pozzorini ’08,’09; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek ’09

$q\bar{q} \to \mathrm{t\bar{t}b\bar{b}}$

LO: 7 tree graphs

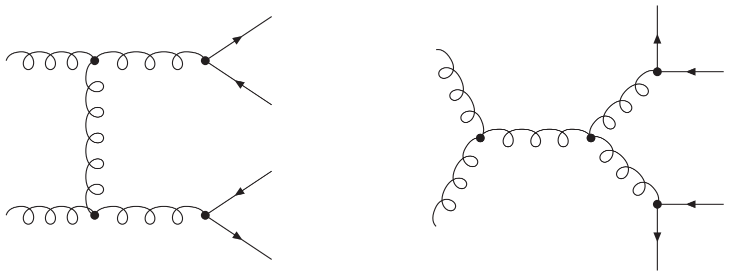


NLO: $\mathcal{O}(200)$ 1-loop diagrams
(24 pentagons, 8 hexagons)

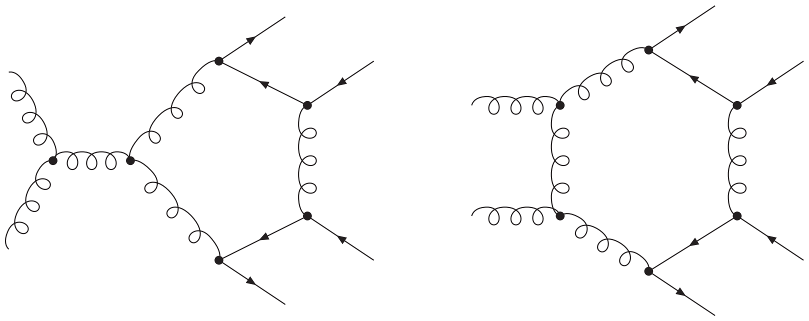


$\mathrm{gg} \to \mathrm{t\bar{t}b\bar{b}}$

LO: 36 tree graphs



NLO: $\mathcal{O}(\gtrsim 1000)$ 1-loop diagrams
(> 100 pentagons, 40 hexagons)



$2 \to 4$ processes define present “NLO multi-leg frontier".

Our Feynman-diagrammatic approach for virtual 1-loop corrections

$$\mathcal{M}_{1-\mathrm{loop}} = \sum_{\mathrm{(sub)diagrams}\ \Gamma} \mathcal{M}_\Gamma$$ generated with FeynArts (Küblbeck et al. '90; Hahn '01)

$$\mathcal{M}_\Gamma = \sum_n \underbrace{C^{(\Gamma)}}_{\text{colour factor}} \underbrace{F_n^{(\Gamma)}}_{\uparrow} \underbrace{\hat{\mathcal{M}}_n}_{\text{spin structures like } [\bar{u}_\mathrm{t}(k_\mathrm{t})\not{\varepsilon}_{\mathrm{g}_1}(k_{\mathrm{g}_1})v_{\bar{\mathrm{t}}}(k_{\bar{\mathrm{t}}})](\varepsilon_{\mathrm{g}_2}(k_\mathrm{g})\cdot k_\mathrm{t})\ldots}$$

invariant functions containing
1-loop tensor integrals $T^{\mu\nu\rho\ldots}$

$$T^{\mu\nu\rho\ldots} = (p_k^\mu p_l^\nu p_m^\rho \ldots) T_{kl\ldots} + (g^{\mu\nu} p_m^\rho \ldots) T_{00m\ldots} + \ldots$$

$T_{kl\ldots}$ = linear combination of scalar 1-loop integrals A_0, B_0, C_0, D_0

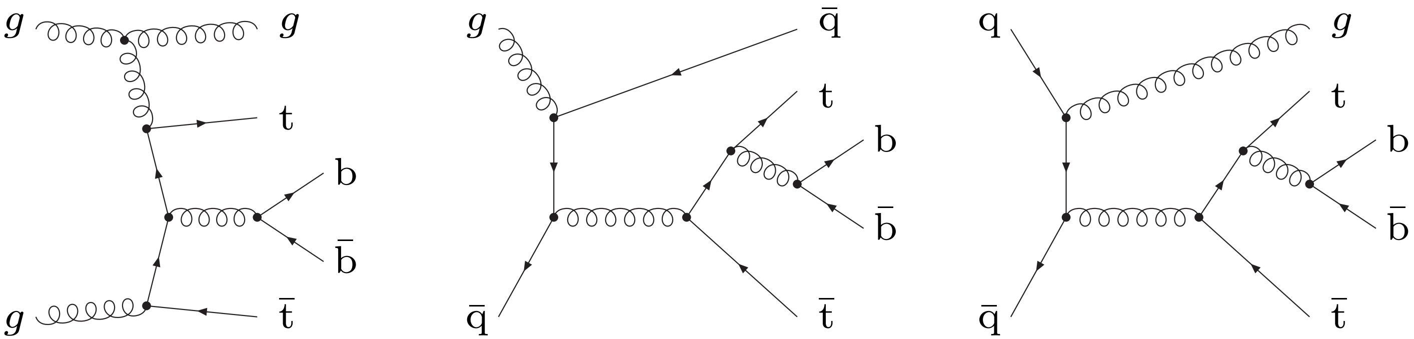
– recursively calculable à la Passarino/Veltman '79 for regular points

– specially designed methods for rescuing cases with small Gram dets. Denner, S.D. '05

– 5-/6-point integrals reduced to 4-point integrals Denner, S.D. '02,'05

Features:
– advantage: get all colour/spin channels in one stroke
$\hookrightarrow$ speed: $\mathcal{M}_{1-\mathrm{loop}}^{q\bar{q}/\mathrm{gg}\to\mathrm{t\bar{t}b\bar{b}}}$ in $\mathcal{O}(0.2\mathrm{sec}/\mathrm{event})$ very fast !
– lengthy algebra $\to$ automation (Mathematica)
– two independent calculations, one using features of FormCalc (Hahn)

Corrections due to real radiation



etc.

Salient features:

- fast evaluation of amplitudes $\longrightarrow$ spinor methods / MADGRAPH Stelzer, Long
- multi-channel Monte Carlo integration over phase space
- soft and collinear divergences
  $\hookrightarrow$ dipole subtraction formalism

  Catani, Seymour '96; S.D. '99
  Phaf, Weinzierl '01
  Catani, S.D., Seymour, Trócsányi '02

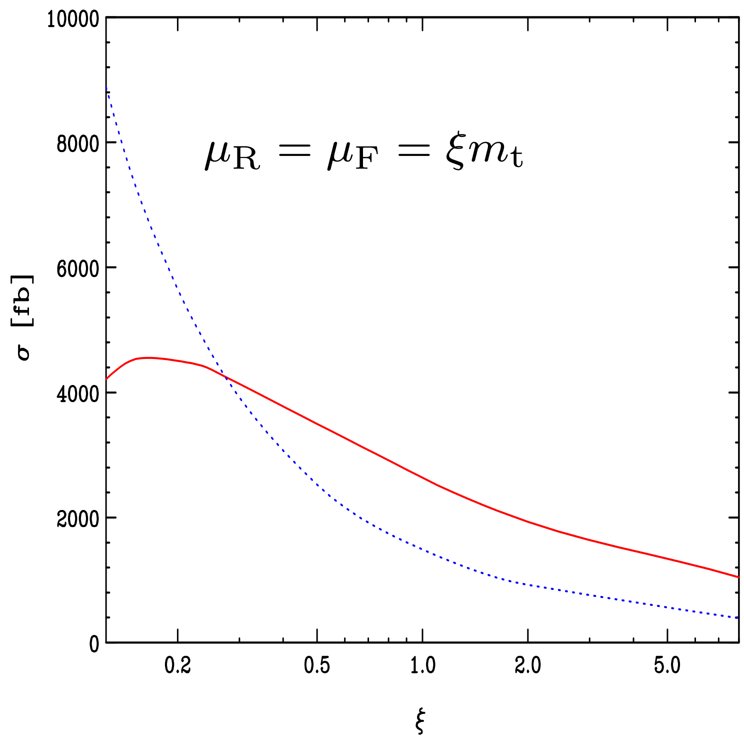
$$\sigma^{\rm NLO} = \underbrace{\int_{m+1}\left[{\rm d}\sigma^{\rm real} - {\rm d}\sigma^{\rm sub}\right]}_{\text{finite}} + \underbrace{\int_{m}\left[{\rm d}\sigma^{\rm virtual} + {\rm d}\bar\sigma_1^{\rm sub}\right]}_{\text{finite}} + \int_0^1 {\rm d}x\, \underbrace{\int_{m}\left[{\rm d}\sigma^{\rm fact}(x) + \left({\rm d}\bar\sigma^{\rm sub}(x)\right)_+\right]}_{\text{finite}}$$

- two alternative IR regularizations: dim. reg. / mass reg. (small $m_{\rm q}, m_{\rm b}$)

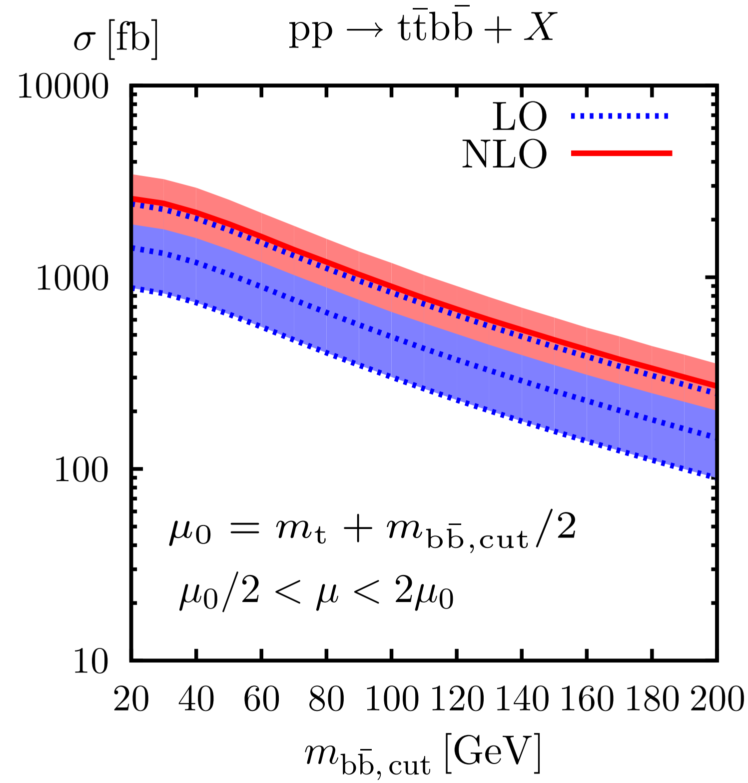
Phenomenological results

NLO cross section for constant scale choice

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09



Bredenstein, Denner, S.D., Pozzorini '09



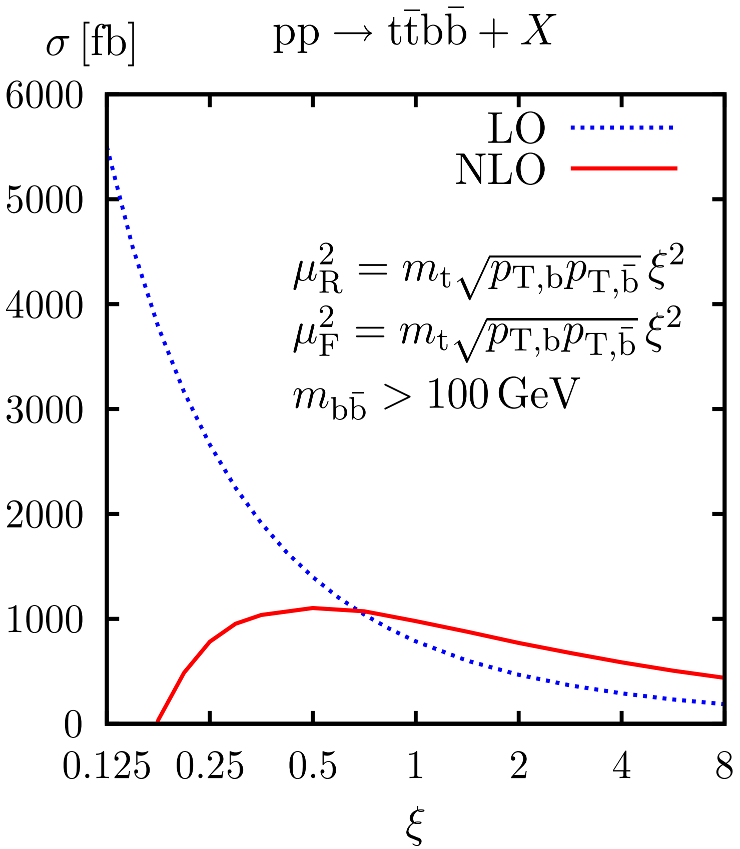
Main results:

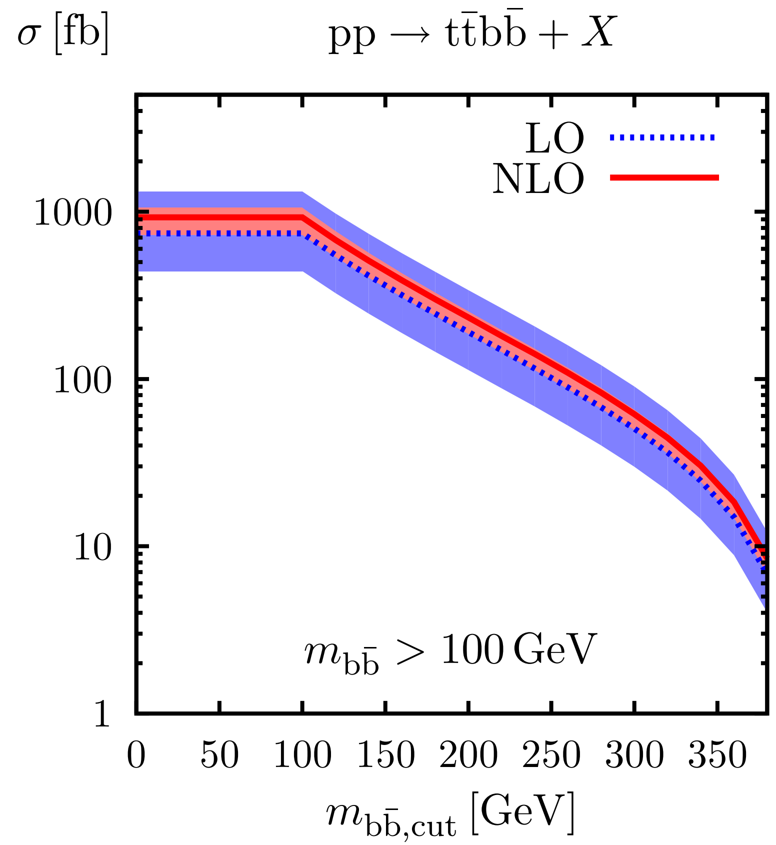
- results of the two groups agree at the 0.1% level
- correction very large at central scale $\mu_{R/F} = m_t$: $K = 1.77$
- NLO scale dependence still large: $\sim 33\%$ for $\mu_0/2 < \mu_{R/F} < 2\mu_0$ ($\sim 70\%$ at LO)

$\hookrightarrow$ further theoretical and/or phenomenological tricks necessary to stabilize analysis

NLO cross section for dynamical scale choice

Bredenstein, Denner, S.D., Pozzorini '10





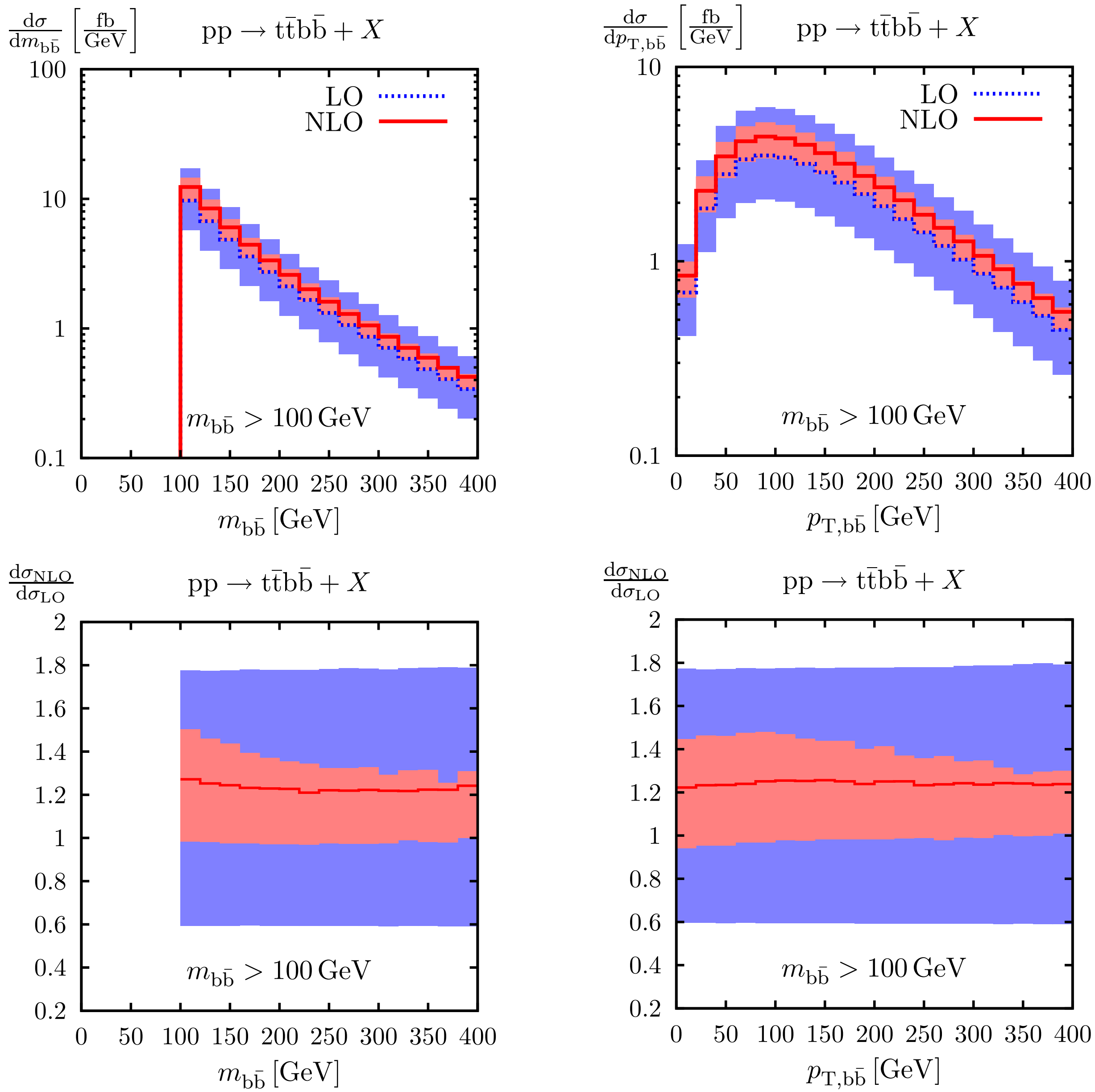
Dynamical scale: $\mu_0^2 = m_t\sqrt{p_{T,b}p_{T,\bar{b}}}$

- smaller correction at central scale $\mu_{R/F} = \mu_0$: $K = 1.24$ $(m_{b\bar{b}} > 100\,\text{GeV})$
- NLO scale dependence reduced: $\sim 21\%$ for $\mu_0/2 < \mu_{R/F} < 2\mu_0$ ($\sim 78\%$ at LO)

Distributions for $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$ at NLO

Invariant mass and p_T of the $\mathrm{b\bar{b}}$ pair:

Bredenstein, Denner, S.D., Pozzorini ’10

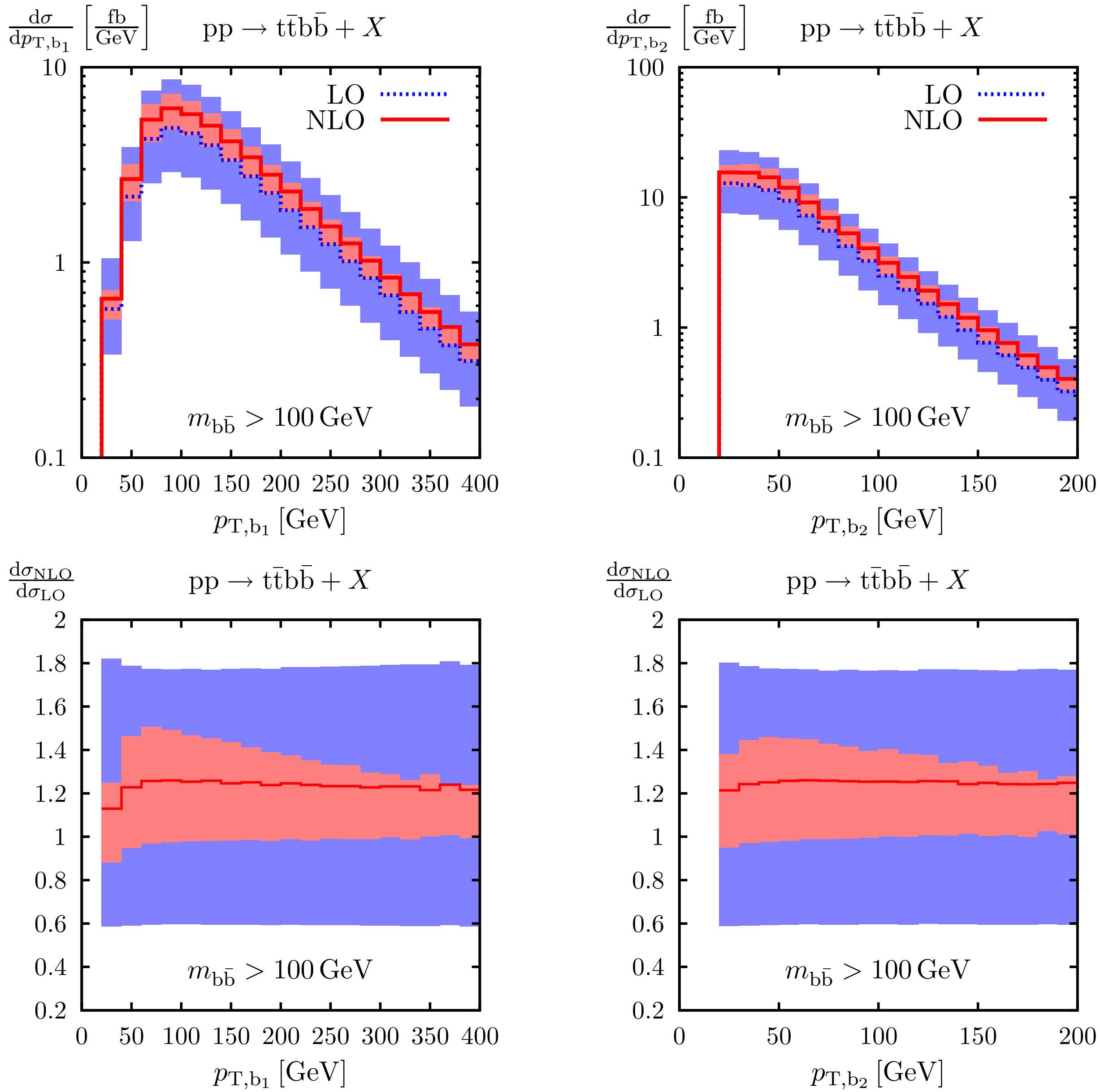


Corrections show little phase-space variations

Distributions for $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$ at NLO

p_T of the b quarks ($p_{\mathrm{T,b_1}} > p_{\mathrm{T,b_2}}$):

Bredenstein, Denner, S.D., Pozzorini '10



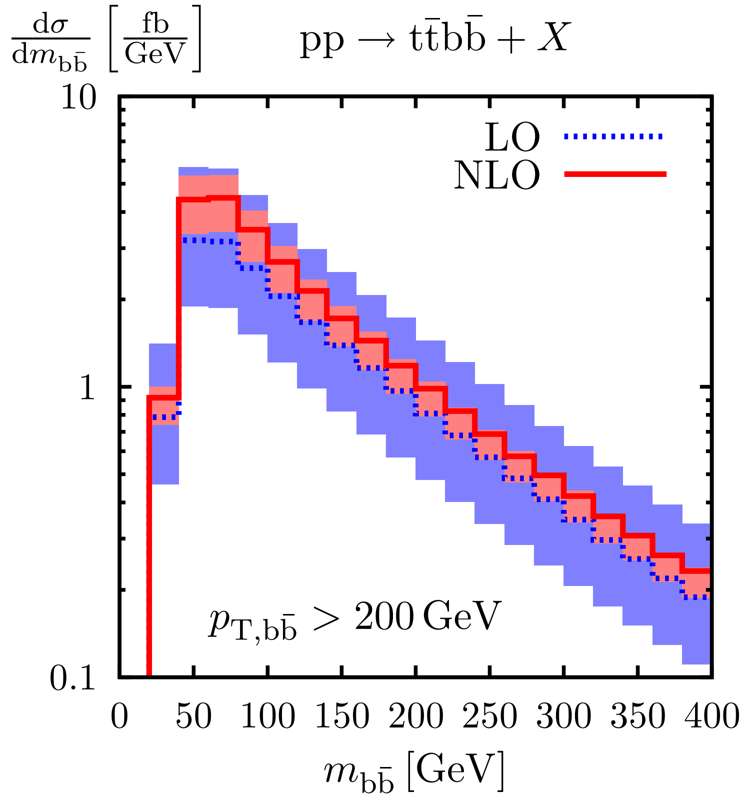
Corrections show little phase-space variations

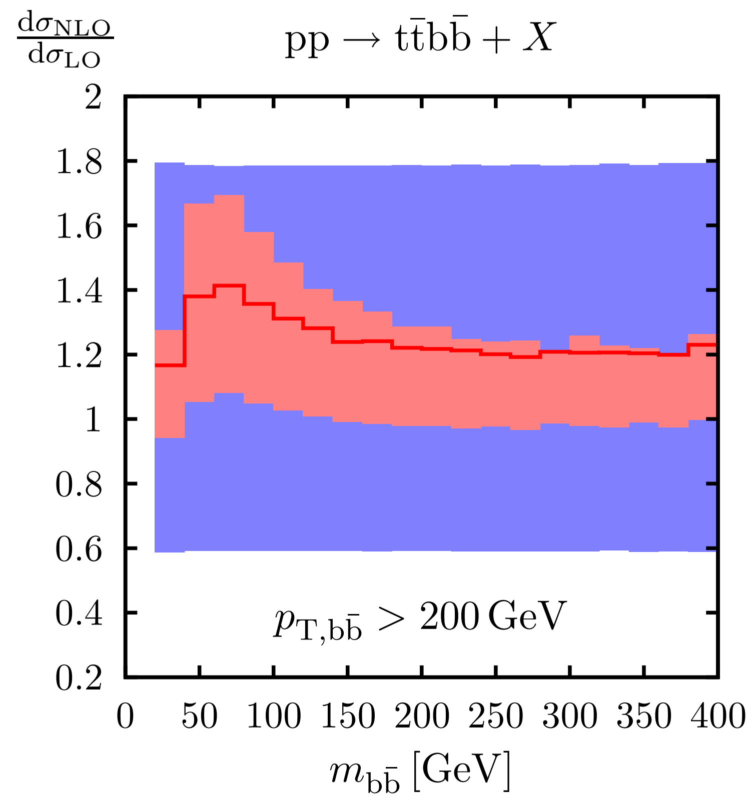
Simulating $\mathrm{H} \to \mathrm{b\bar{b}}$ with high p_T

$\hookrightarrow$ impose cuts $p_{\mathrm{T,b\bar{b}}} > 200\,\mathrm{GeV}$

Invariant mass of the $\mathrm{b\bar{b}}$ pair:

Bredenstein, Denner, S.D., Pozzorini '10





Note: corrections induce distortion in signal region !

Conclusions

Conclusions

$\mathrm{pp} \to \mathrm{t\bar{t}H}(\to \mathrm{b\bar{b}})$ at the LHC

- important for Higgs Yukawa coupling determination
- experimentally very challenging:
  signal swamped by background in experimental studies
  $\hookrightarrow$ more sophisticated tricks in analysis needed (fat jets at high p_{T}?)
  NLO predictions for background in data-driven analysis
- $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ = most important background process

$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ at NLO QCD

- calculated by our group with Feynman-diagrammatic technique
  $\hookrightarrow$ fast and numerically stable evaluation
- dynamical scale choice needed to receive good perturbative stability
  $\hookrightarrow$ reduced scale uncertainty / relatively flat K factors in distributions
- background in LO-based experimental studies even underestimated
- NLO cross section confirmed in 2nd calculation at 0.1% level

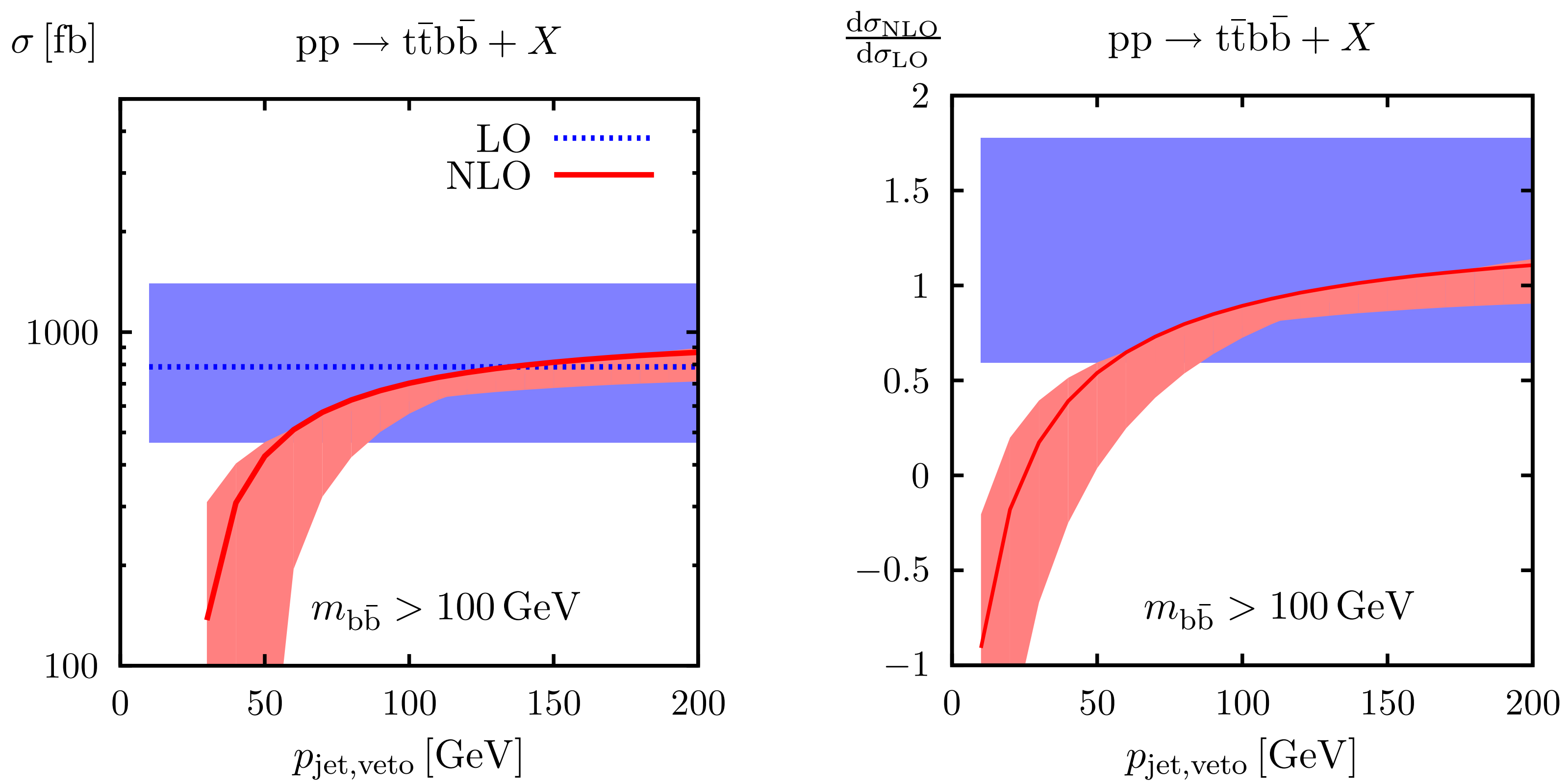
New experimental analysis of $\mathrm{pp} \to \mathrm{t\bar{t}H}(\to \mathrm{b\bar{b}})$ highly desirable

Backup slides

Reduction of large corrections via jet veto ?

$\hookrightarrow$ veto against jets with $p_{T,\text{jet}} > p_{\text{jet,veto}}$

Bredenstein, Denner, S.D., Pozzorini '10



- trade-off: $p_{\text{jet,veto}}$ too large $\to$ no reduction of σ
  $p_{\text{jet,veto}}$ too small $\to$ perturbative instability
- compromise: $p_{\text{jet,veto}} \sim 100\,\text{GeV}$ $\to$ $K \sim 0.9$, scale uncertainty $\sim 20\%$