$t\bar{t}H$ Associated Production Process
Theory summary

LHC Higgs Cross Section Working Group

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Experimental conveners: Simon Dean (ATLAS), Chris Neu (CMS)

Available tools for signal and background

- Signal and background:
  - ▷ $pp \to t\bar{t}H$ (with $H \to b\bar{b}$, $t(\bar{t}) \to W^{\pm}b(\bar{b})$, and $W^{\pm}$ decaying to leptons?);
  - ▷ $pp \to t\bar{t}b\bar{b}$;
  - ▷ $pp \to W^+W^-b\bar{b}b\bar{b}$ (with $W^{\pm}$ decaying to leptons?).

- LO: both signal and background available from public codes like
  - ▷ HQQ (Spira, see $t\bar{t}H$ Wikipage)
  - ▷ Madgraph/Madevent (Maltoni, Stelzer, et al.);
  - ▷ MCFM (Campbell, Ellis)
  - ▷ ...

- NLO: first order QCD corrections calculated for
  - ▷ $t\bar{t}H$ (Beenakker, et al., Dawson, et al.);
  - ▷ $t\bar{t}H$ ($H \to b\bar{b}$) (in NWA) (Bevilacqua, et al.)
  - ▷ $t\bar{t}b\bar{b}$ (Bredenstein, et al., Bevilacqua, et al.)

  Several private codes, no public code available.

Goals for this meeting

- Start runs according to the set up agreed upon for this workshop (set-up file available on the $t\bar{t}H$ Wikipage).
- Aim at estimating theoretical errors from different sources:
  - ▷ from renormalization/factorization scales;
  - ▷ from α_s;
  - ▷ from PDFs;
  - ▷ from input parameters (e.g. m_t)?
- Identify and start providing useful distributions (input from Chris and Simon):
  - ▷ $t\bar{t}H$ and $t\bar{t}b\bar{b}$ distributions calculated at NLO;
  - ▷ all distributions involving $t(\bar{t})$ and $W^{\pm}$ decays calculated at LO.

  They should serve as guidelines for future analyses.

Error estimate

- ▷ scale dependence: $\mu_r = \mu_f$ varying in the interval $[\mu_0/2, 2\mu_0]$ $(\mu_0 = m_t + M_H/2)$;
- ▷ error from α_s and PDFs evaluated separately;
- ▷ error from PDFs: use two sets of PDF's with internal error analyses;
- ▷ used α_s consistent with PDF set.

$\longrightarrow$ can be improved

$pp \to t\bar{t}H$, theoretical uncertainty, LO

M_H [GeV]	σ_{LO} [fb], MSTW	σ_{LO} [fb], CTEQ	scale [%]	PDF [%]
90	213.17(9)		[-2.64+39.9]	[-2.59,+2.50]
100	162.70(7)	132.99(7)	[-2.62,+39.8]	[-2.63,+2.59]
110	126.06(6)		[-2.62,+39.6]	[-2.52,+2.43]
120	98.66(4)	80.45(4)	[-2.63,+39.8]	[-2.86,+2.29]
130	78.09(3)		[-2.621,+39.8]	[-2.39,+2.72]
140	62.43(3)	50.80(3)	[-2.63,+39.9]	[-2.57,+2.62]
150	50.35(2)		[-2.60,39.8]	[-2.34,+2.72]
160	40.98(2)		[-2.63,+39.6]	[-2.97,2.16]
170	33.62(1)		[-2.61,+39.9]	[-2.36,+2.85]
180	27.83(1)	22.57(1)	[-2.62,+39.7]	[-3.22,+2.28]

(S. Dittmaier,M. Krämer, M. Spira: MSTW2008)

(S. Dawson,L. Reina, D. Wacheroth: CTEQ6.6)

$pp \to t\bar{t}H$, theoretical uncertainty, NLO

M_H [GeV]	σ_{NLO} [fb] (MSTW)	σ_{NLO} [fb] (CTEQ)	scale (%)	α_s (%)
90	224.8(3)		[-9.8,+4.3]	[-0.3,+0.4]
100	170.4(2)	159.7(9)	[-9.6,+4.1]	[-0.4,+0.4]
110	130.8(2)		[-9.7,+3.7]	[-0.4,+0.2]
120	101.4(1)	94.6(6)	[-9.4,+3.4]	[-0.4,+0.3]
130	79.57(8)		[-9.3,+3.3]	[-0.2,+0.4]
140	63.06(6)	59.0(3)	[-9.1,+3.4]	[0.0,+0.6]
150	50.59(6)		[-9.2,+3.0]	[-0.2,+0.3]
160	41.01(4)		[-9.2,+2.7]	[-0.5,+0.2]
170	33.47(3)		[-9.2,+2.8]	[-0.5,+0.3]
180	27.55(3)	25.8(1)	[-9.1,+2.9]	[-0.4,+0.4]
190	22.93(3)		[-9.3,+2.8]	[-0.3,+0.3]
200	19.20(2)		[-9.2,+2.6]	[-0.4,+0.5]

(S. Dittmaier,M. Krämer, M. Spira: MSTW2008)

(S. Dawson,L. Reina, D. Wacheroth: CTEQ6.6)

Useful distributions, top priority

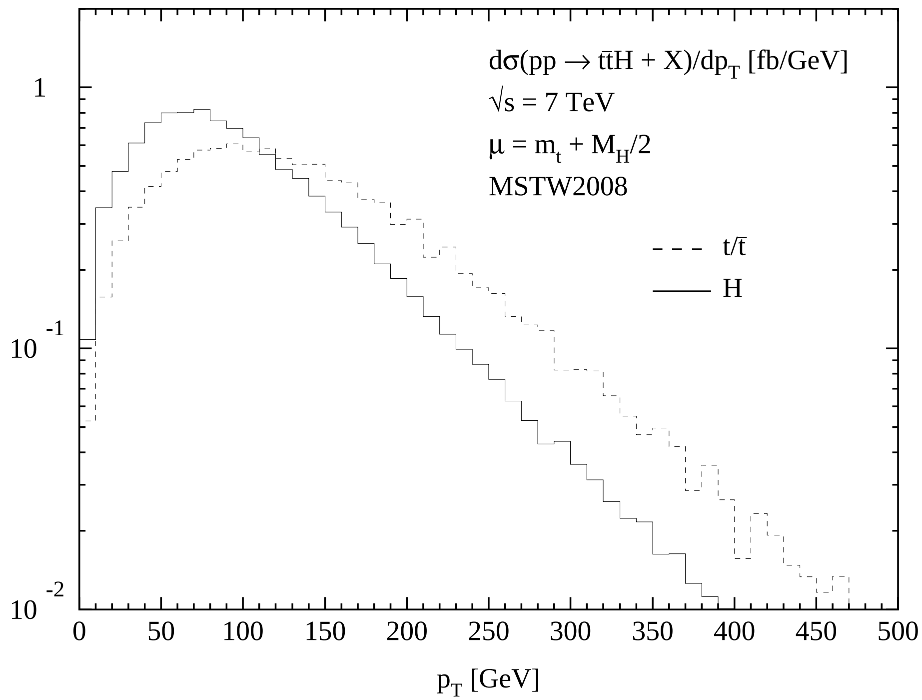
- study behavior of (using different PDFs):
  - ▷ $\frac{d\sigma}{dm(b\bar{b})}$, $\frac{d\sigma}{dp_T(b\bar{b})}$ ($b\bar{b}$ from $H \to b\bar{b}$);
  - ▷ $\frac{d\sigma}{dm(b_1 b_2)}$, $\frac{d\sigma}{dp_T(b_1 b_2)}$ ($b_1 b_2$ two leading b-jets);
  - ▷ $\frac{d\sigma}{d\eta(b_1 b_2)}$, $\frac{d\sigma}{d\phi(b_1 b_2)}$;
  - ▷ $\frac{d\sigma}{dH_T}$;
  - ▷ $\frac{d\sigma}{d(\text{sphericity})}$ (entire $t\bar{t}H$ system);
  - ▷ $\frac{d\sigma}{dN_{\text{jet}}}$;
  - ▷ $\frac{d\sigma}{dN_{\text{jet}+1}}$;
- study effect of jet veto, in *boosted* H regime ($p_T(b\bar{b}) > 200$ GeV), on:
  - ▷ $\frac{d\sigma}{dm(b\bar{b})}$, $\frac{d\sigma}{d\eta(b\bar{b})}$;
  - ▷ $\frac{d\sigma}{dm(b_1 b_2)}$, $\frac{d\sigma}{d\eta(b_1 b_2)}$.

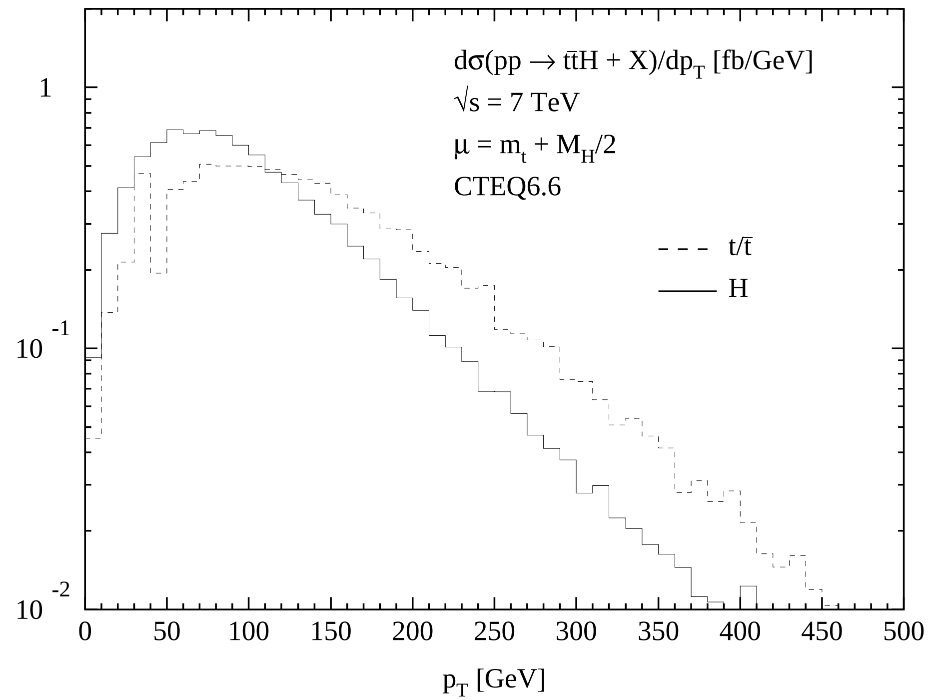
Useful distributions, lower priority

- study behavior of (using different PDFs):
  - ▷ $\frac{d\sigma}{dp_T(b_1)}$, $\frac{d\sigma}{dp_T(b_2)}$, $\frac{d\sigma}{dp_T(b_3)}$, $\frac{d\sigma}{dp_T(b_4)}$;
  - ▷ $\frac{d\sigma}{d\Delta R(b_1,b_2)}$, $\frac{d\sigma}{d\Delta R(b_2,b_3)}$, $\frac{d\sigma}{d\Delta R(b_3,b_4)}$, $\frac{d\sigma}{d\Delta R(b_1,b_4)}$;
  - ▷ $\frac{d\sigma}{d\Delta R(b_1,j_1)}$ (where j_1=extra jet);
  - ▷ $\frac{d\sigma}{d\Delta R(t,\bar{t})}$, $\frac{d\sigma}{d\Delta R(H,t)}$, $\frac{d\sigma}{d\Delta R(H,\bar{t})}$;
  - ▷ $\frac{d\sigma}{d\Delta R(H,W_1)}$, $\frac{d\sigma}{d\Delta R(H,W_2)}$;
  - ▷ $\frac{d\sigma}{d\Delta R(H,t\bar{t})}$;
  - ▷ $\frac{d\sigma}{d\Delta R(H,j_1)}$, $\frac{d\sigma}{d\Delta R(t,j_1)}$, $\frac{d\sigma}{d\Delta R(\bar{t},j_1)}$;
- study effect of jet veto, in *boosted H* regime ($p_T(b\bar{b}) > 200$ GeV), on:
  - ▷ $\frac{d^2\sigma}{dm(b\bar{b})dp_T(b\bar{b})}$, $\frac{d^2\sigma}{d\eta(b\bar{b})dp_T(b\bar{b})}$;
  - ▷ $\frac{d^2\sigma}{dm(b_1b_2)dp_T(b_1b_2)}$, $\frac{d^2\sigma}{d\eta(b_1b_2)dp_T(b_1b_2)}$.

$t\bar{t}H$ distributions, NLO

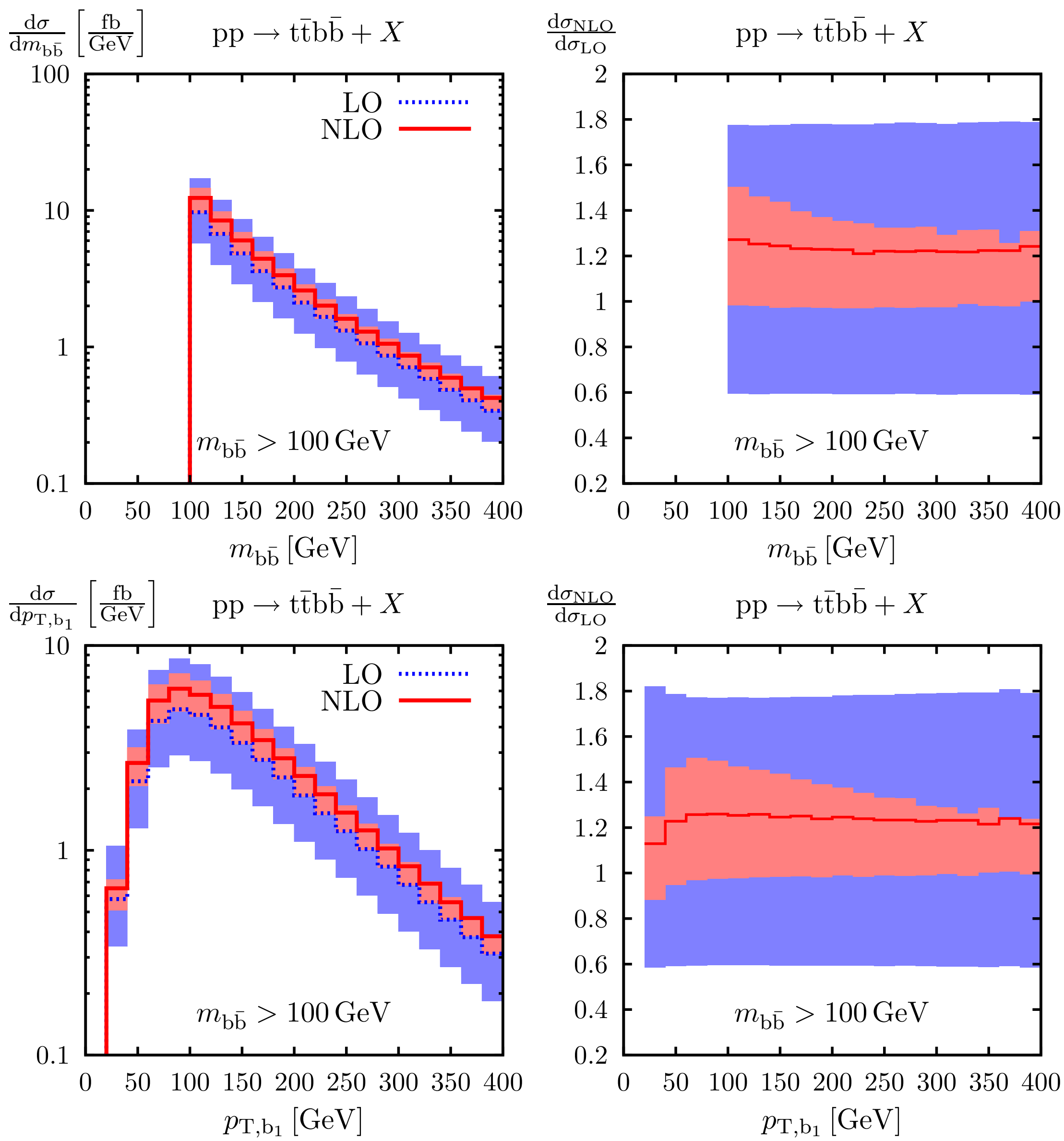
Along with total cross sections (see previous table), we can produce NLO distributions.





(Dittmaier, Krämer, Spira, confirmed by Dawson, Reina, Wackeroth)

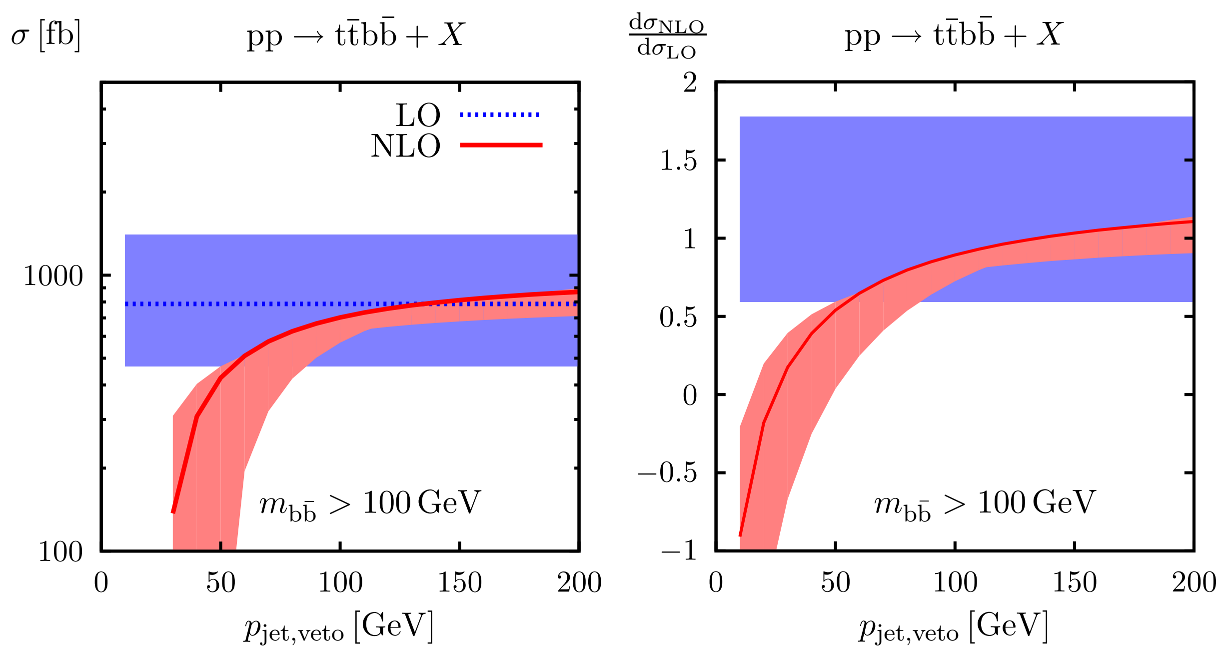
$t\bar{t}b\bar{b}$ distributions: background, NLO



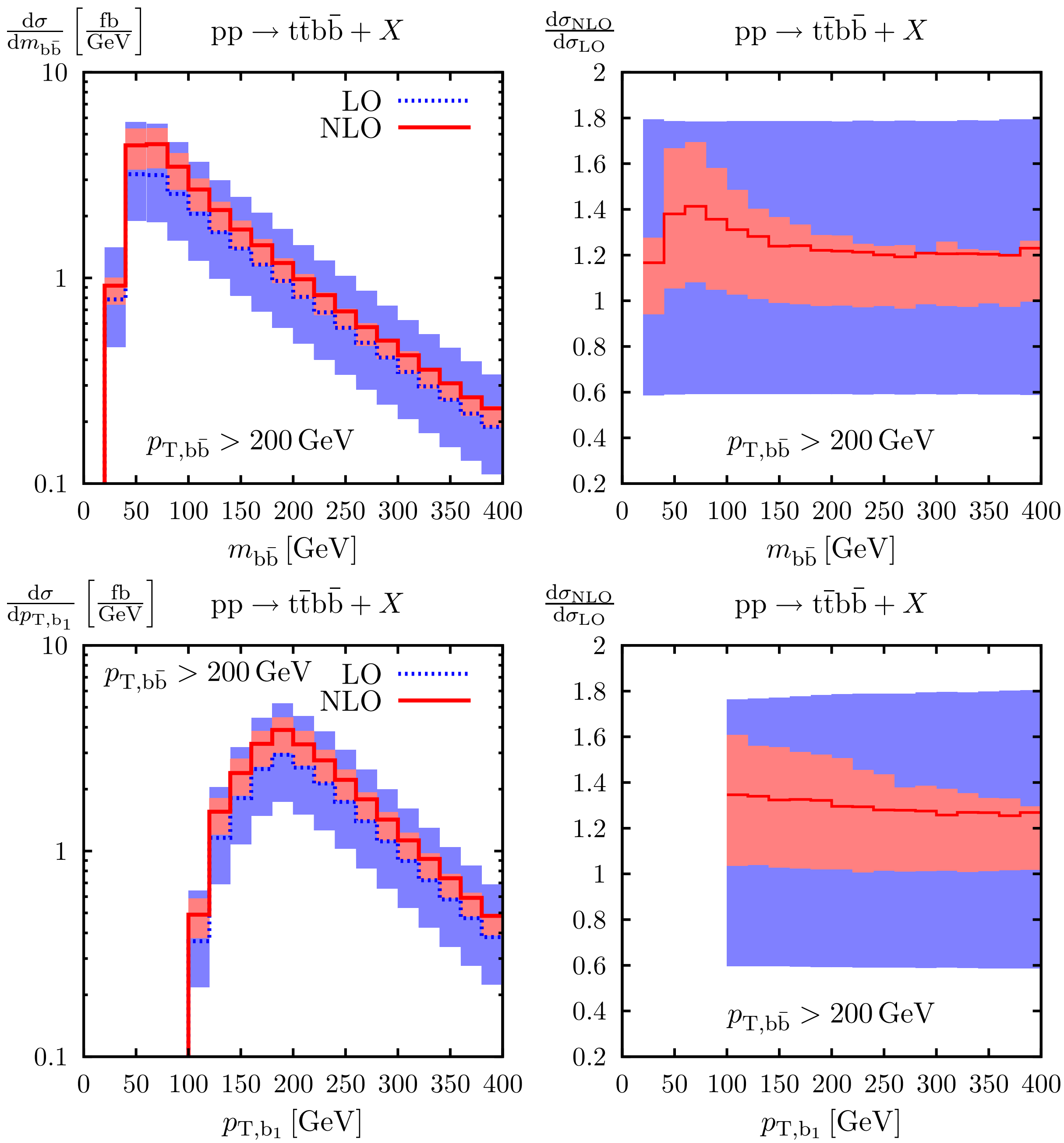
(Bredenstein, Denner, Dittmaier, Pozzorini, arXiv:1001.4006, Les Houches 09)

Important to observe that:

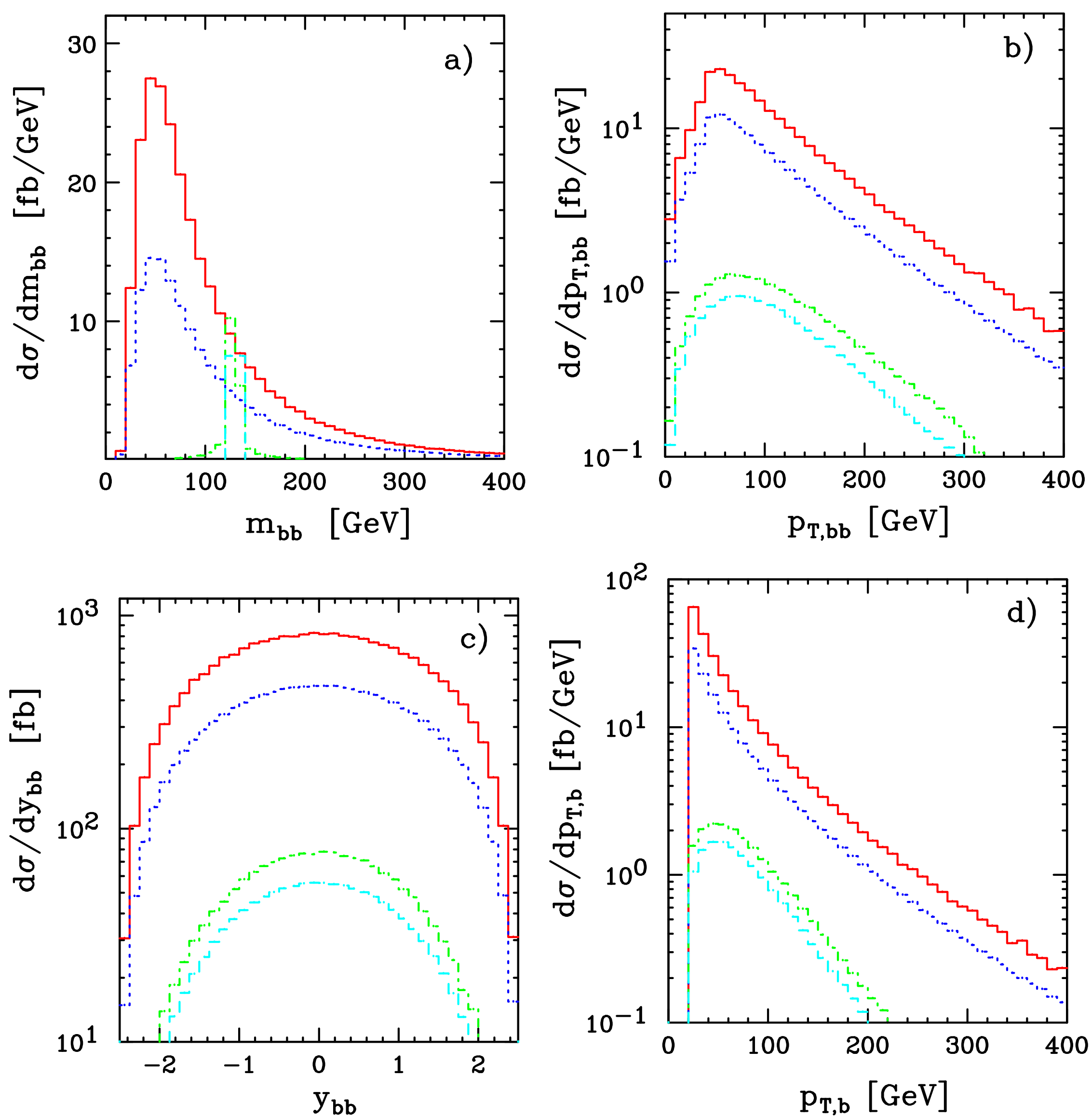
- best to use dynamical scale ($\mu^2 = m_t\sqrt{p_{T,b}p_{T,\bar{b}}}$)
- effect of jet veto on extra light jet:



- regime of *boosted Higgs*:

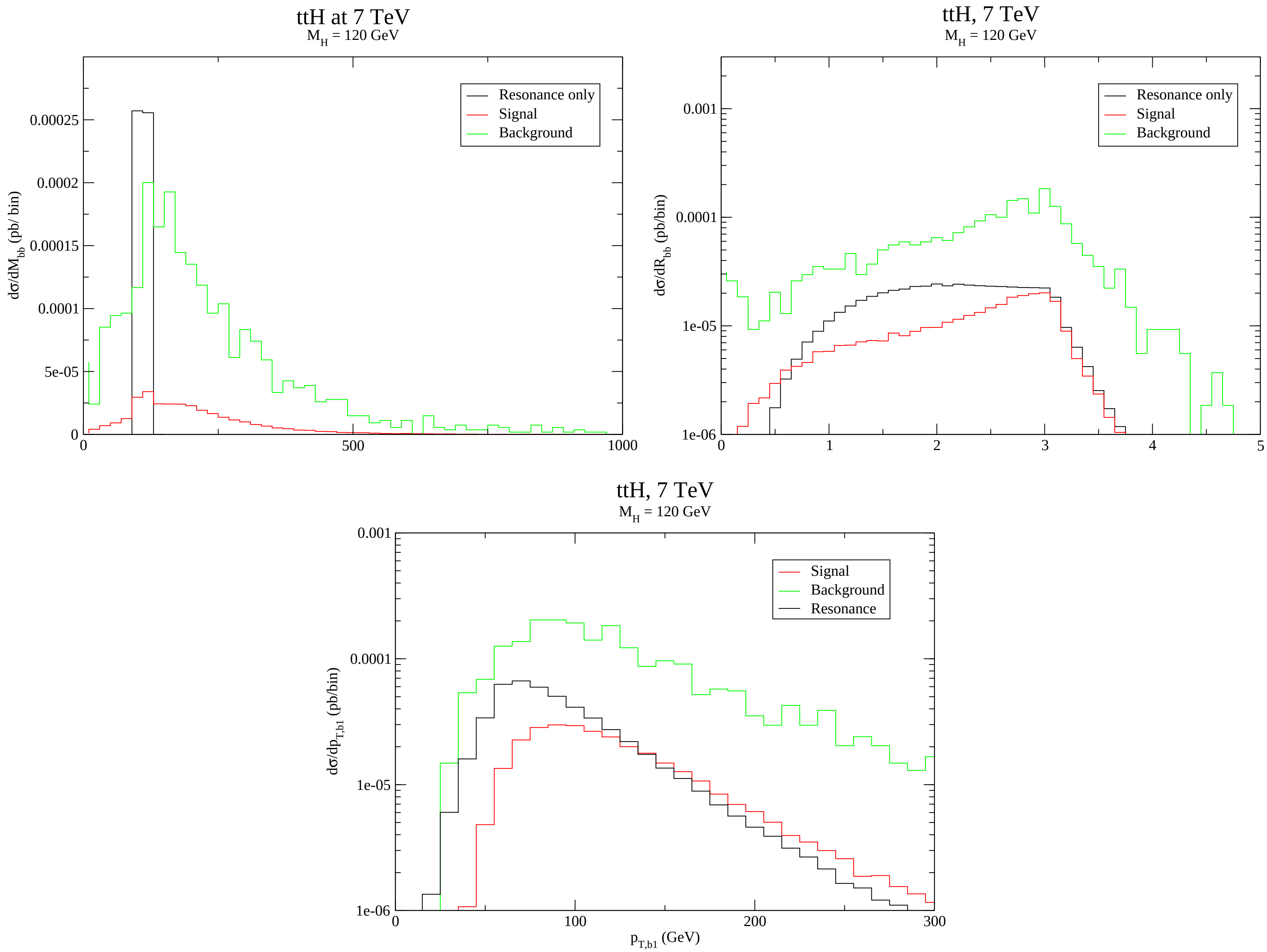


$t\bar{t}b\bar{b}$ distributions: signal vs background, NLO



(Bevilaqua, Czakon, Garzelli, van Hameren, Papadopoulos, Pittau, Worek, arXiv:0907.4723, Les Houches 09, signal calculated in NWA)

$W^+W^-b\bar{b}b\bar{b}$ distributions, LO



(Dawson, Hartanto)

Goals for this workshop

- Cross checks.
- Full account of theoretical uncertainty.
- How difficult is to release the NLO codes? or make them part of MCFM?
  Or interface them with POWHEG?
  Is that crucial to experimental analyses?
- Are we missing important corrections/contributions (e.g.: QCD+EW)?
- Explore behavior of NLO corrections in different kinematic regimes,
  ex.: jet-veto, boosted H, etc.
- What do we learn from LO distributions of fully decayed final state?