Developments on SM Higgs-boson cross sections and branching ratios

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Higgs Hunting 2011, Orsay, France

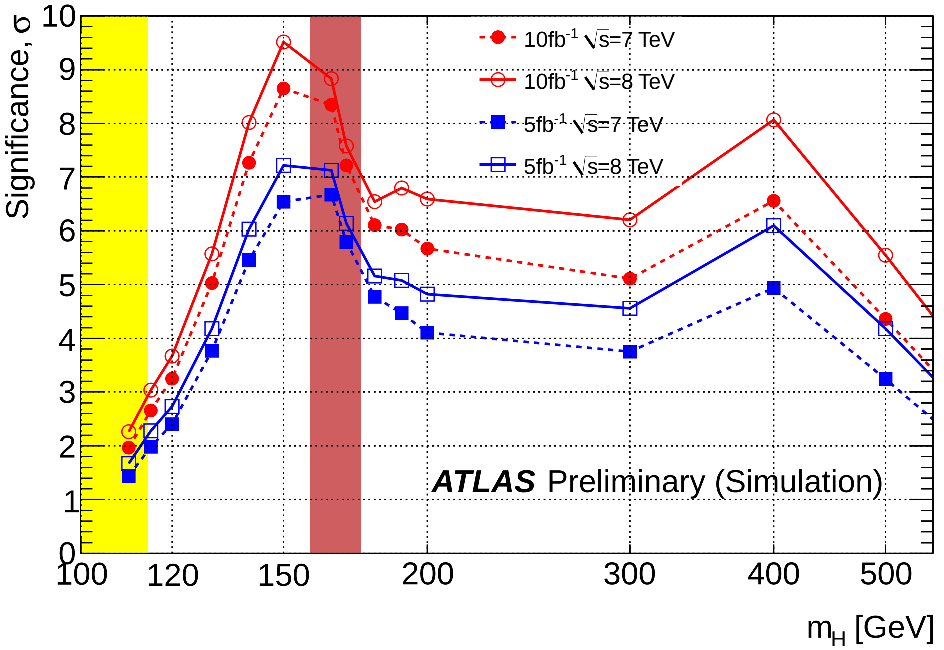
Outline

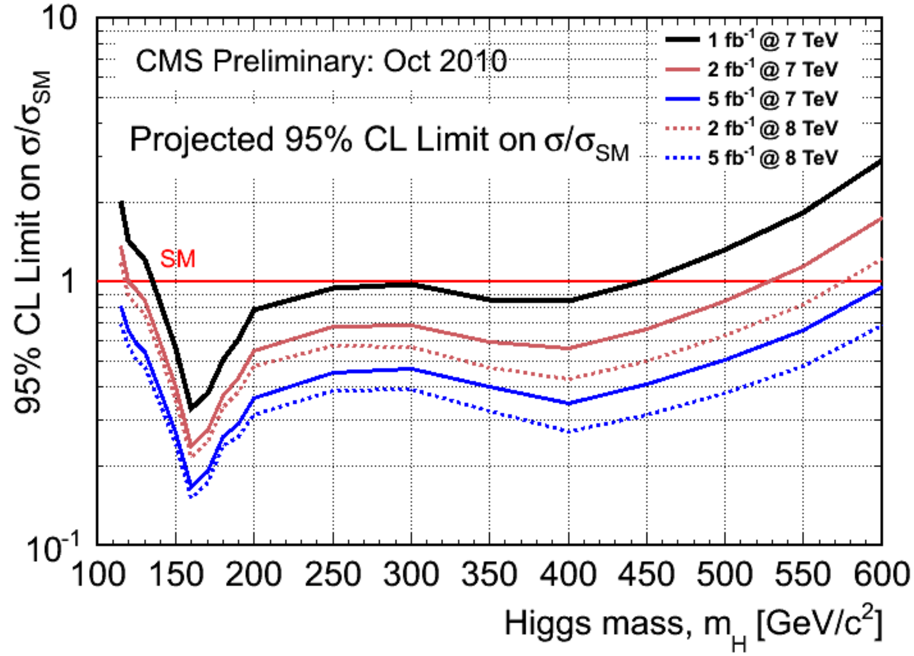
- Living through the most exciting time for Higgs physics: crucial to have access to the best theoretical predictions for SM Higgs-boson cross sections and branching ratios.
  - $\hookrightarrow$ foundation of the Tevatron exclusion limits;
  - $\hookrightarrow$ spirit of the LHC Higgs Cross Section Working Group (https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections).
- State of the art of inclusive results for a SM Higgs boson ($\rightarrow$ see Grazzini's talk for in depth analysis of main channels).
- Towards exclusive results:
  - $\hookrightarrow$ goals,
  - $\hookrightarrow$ challenges,
  - $\hookrightarrow$ highlights from existing studies.
- Results on branching ratios.

Motivation: with $\sqrt{s} = 7$ TeV and a few fb^{-1} ...

Combining mainly $H \to W^+W^-$, $H \to ZZ$, $H \to \gamma\gamma$, ATLAS and CMS indicate that,

- if no signal, the SM Higgs can be excluded up to 500 GeV;
- a 5σ significance for a SM Higgs in the 140 – 170 GeV mass range.
- gain by adding new channels and optimizing cuts ($\to$ see Metha's talk).

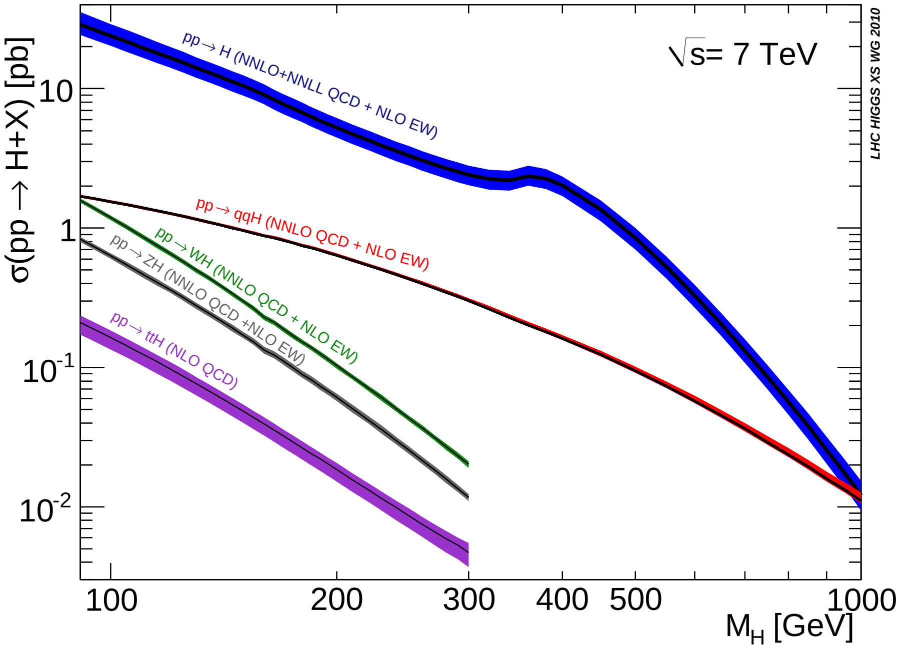


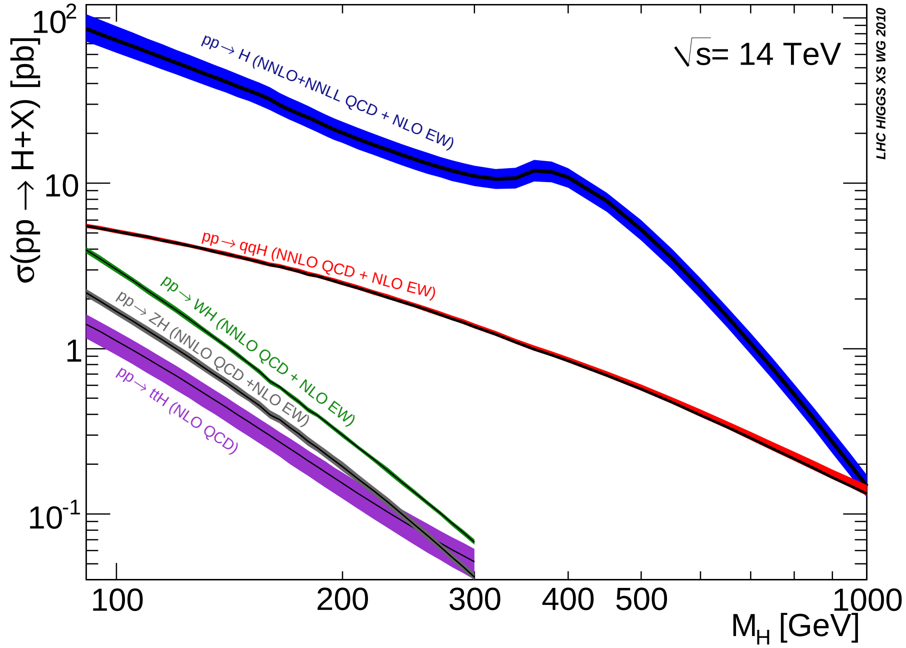


Need adequate theoretical input and careful matching between th. and exp.

Inclusive SM Higgs-boson production cross sections

(LHC Higgs Cross Section WG, 2010) (arXiv:1101.0593→ CERN Yellow Report)





Implemented a coherent Higgs precision program:

- ↪ all orders of calculated higher orders corrections included (tested with all existing calculations);
- ↪ common recipe for renormalization+factorization scale dependence;
- ↪ PDF and α_s errors following PDF4LHC prescription (→ see de Florian's talk);
- ↪ all other parametric errors included;
- ↪ theory errors combined according to common recipe.

For $\sqrt{s} = 7$ TeV (from S. Dittmaier's talk, BNL, May 2011)

	M_H	Uncertainties scale	PDF4LHC	NLO/NNLO/NNLO+ QCD	EW
ggF	< 500 GeV	6-10%	8-10%	$> 100\%$	5%
VBF	< 500 GeV	1%	2-7%	5%	5%
WH	< 300 GeV	1%	3-4%	30%	5-10%
ZH	< 300 GeV	1-2%	3-4%	40%	5%
$t\bar{t}H$	< 300 GeV	10%	9%	5%	?

For $\sqrt{s} = 14$ TeV

	M_H	Uncertainties scale	PDF4LHC	NLO/NNLO/NNLO+ QCD	EW
ggF	< 500 GeV	6-14%	7%	$> 100\%$	5%
VBF	< 500 GeV	1%	3-4%	5%	5%
WH	< 300 GeV	1%	3-4%	30%	5-10%
ZH	< 300 GeV	2-4%	3-4%	45%	5%
$t\bar{t}H$	< 300 GeV	10%	9%	15-20%	?

Based on several contributions:

Higgs process	$\sigma_{NLO,NNLO,NNLL,EW}$
$gg \to H$	S.Dawson, NPB 359 (1991), A.Djouadi, M.Spira, P.Zerwas, PLB 264 (1991) C.J.Glosser *et al.*, JHEP (2002); V.Ravindran *et al.*, NPB 634 (2002) D. de Florian *et al.*, PRL 82 (1999) R.Harlander, W.Kilgore, PRL 88 (2002) (NNLO) C.Anastasiou, K.Melnikov, NPB 646 (2002) (NNLO) V.Ravindran *et al.*, NPB 665 (2003) (NNLO) S.Catani *et al.* JHEP 0307 (2003) (NNLL) G.Bozzi *et al.*, PLB 564 (2003), NPB 737 (2006) (NNLL) C.Anastasiou, R.Boughezal, F.Petriello, JHEP (2008) (QCD+EW)
$q\bar{q} \to (W,Z)H$	T.Han, S.Willenbrock, PLB 273 (1991) M.L.Ciccolini, S.Dittmaier, and M.Krämer (2003) (EW) O.Brien, A.Djouadi, R.Harlander, PLB 579 (2004) (NNLO)
$q\bar{q} \to q\bar{q}H$	T.Han, G.Valencia, S.Willenbrock, PRL 69 (1992) T.Figy, C.Oleari, D.Zeppenfeld, PRD 68 (2003) M.L.Ciccolini, A.Denner,S.Dittmaier (2008) (QCD+EW) P.Bolzoni, F.Maltoni, S.O.Moch, and M.Zaro (2010) (NNLO)
$q\bar{q}, gg \to t\bar{t}H$	W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003) S.Dawson *et al.*, PRL 87 (2001), PRD 65 (2002), PRD 67,68 (2003)

Towards exclusive studies: including decays, cuts, jet vetos, backgrounds, . . .

- Provide distributions from NLO/NNLO/NNLL calculations.

▷ Study the impact of higher order corrections in the presence of cuts, jet vetos, etc.

▷ If cuts imposed on decay products, need to include decays and estimate higher order corrections to the new process

  - high multiplicity of final state makes calculation more involved (more and more NLO calculations coming on-line)
  - narrow width approximations often excellent approximation (top, light Higgs) (Ex.: Melnikov, Schulze, arXiv:1006.0910, arXiv:1102.1967)

▷ Interface with NLO Monte Carlo programs should be implemented and results compared: MC@NLO, POWHEG.

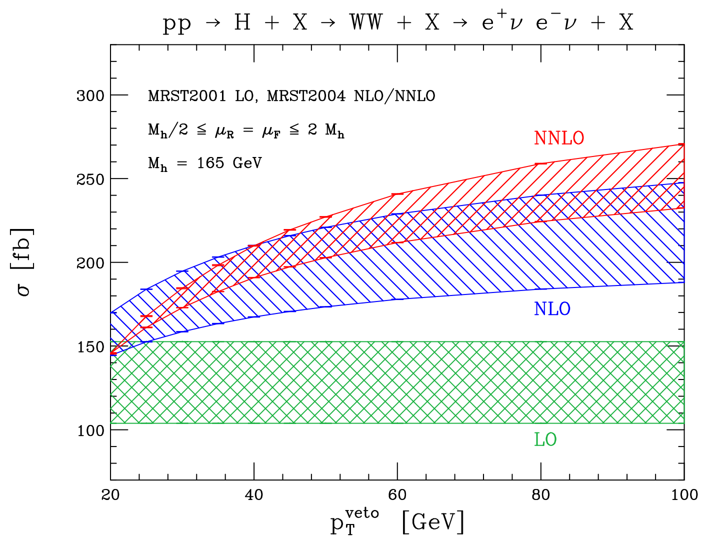
▷ Backgrounds need to be calculated with comparable accuracy.

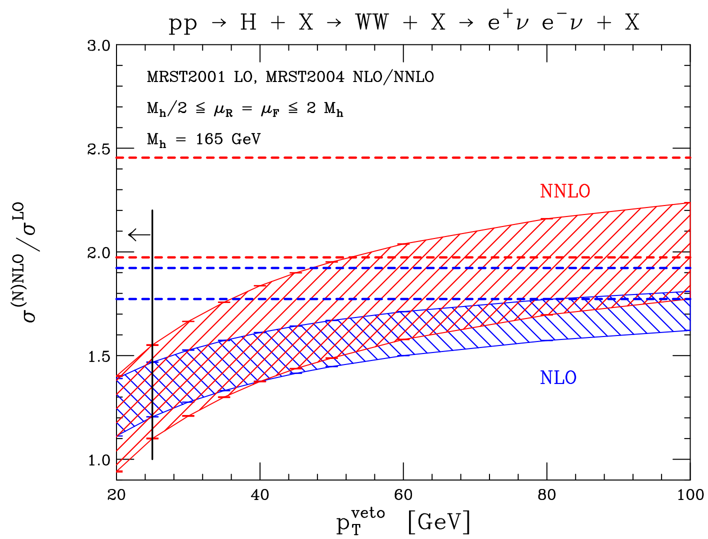
▷ Signal-background interference needs to be carefully adressed.

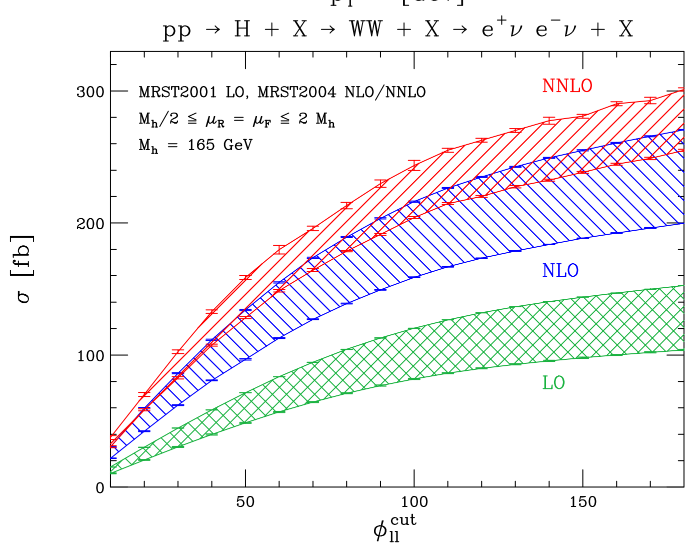
- More channel-specific issues . . .

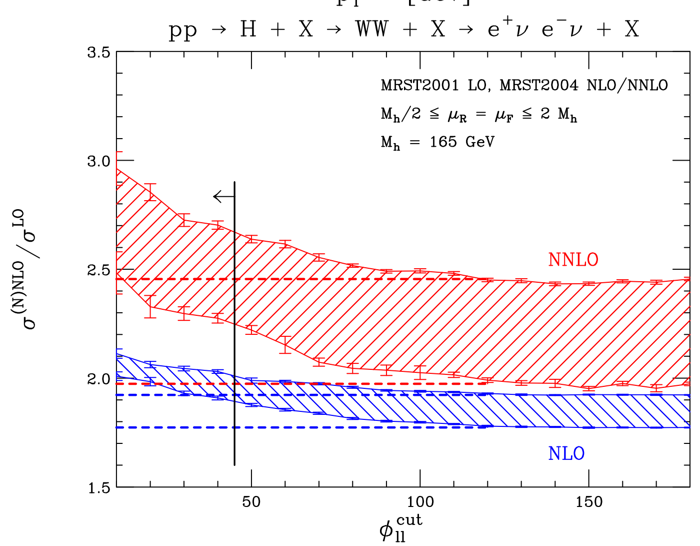
Magnitude of higher order corrections varies significantly with signal selection cuts and vetoes.

<u>Ex.</u>: $(gg \to) H \to W^+W^- \to l^+\nu l^-\bar{\nu}$









[Anastasiou,Dissertori,Stöckli (07)]
($\rightarrow$ see also Grazzini's talk)

Main issues:

- Inclusive studies not indicative for exclusive predictions.
- Logarithmic dependence from extra scales (cuts/vetos) interferes with usual μ_R and μ_F-dependence: difficult to estimate overall theoretical uncertainty (very cut/veto-dependent).
- Need to question stability of perturbative prediction
- Need dedicated studies, for all channels/analyses: availability of NLO (and NNLO if needed) codes becomes mandatory.

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The exercise we are now completing for SM Higgs searches is a glorious application of the incredible progress in NLO calculations over the past few years.

NLO: challenges have largely been faced and enormous progress has been made (→ see also Maltoni's talk)

- several independent codes based on traditional FD's approach
- several NLO processes collected and viable in MFCM [Campbell, Ellis]
- Enormous progress towards automation:
  - → Virtual corrections: new techniques based on unitarity methods and recursion relations
    - ▷ BlackHat [Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, Maitre]
    - ▷ Rocket [Ellis, Giele, Kunszt, Melnikov, Zanderighi]
    - ▷ HELAC+CutTools,Samurai [Bevilacqua, Czakon, van Harmeren, Papadopoulos, Pittau,Worek; Mastrolia, Ossola, Reiter, Tramontano]
  - → Real corrections: based on Catani-Seymour Dipole subtraction or FKS subtraction
    - ▷ Sherpa [Gleisberg, Krauss]
    - ▷ Madgraph (AutoDipole) [Hasegawa, Moch, Uwer]
    - ▷ Madgraph (MadDipole) [Frederix, Gehrmann, Greiner]
    - ▷ Madgraph (MadFKS) [Frederix,Frixione, Maltoni, Stelzer]

- virtual+real:
  - ▷ MadLoop+MadFKS [Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau]

- interface to parton shower well advanced:
  - ▷ POWHEG [Nason, Oleari, Alioli, Re]
  - ▷ MC@NLO [Frixione, Webber, Nason, Frederix, Maltoni, Stelzer]
  - ▷ aMC@NLO [Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli]

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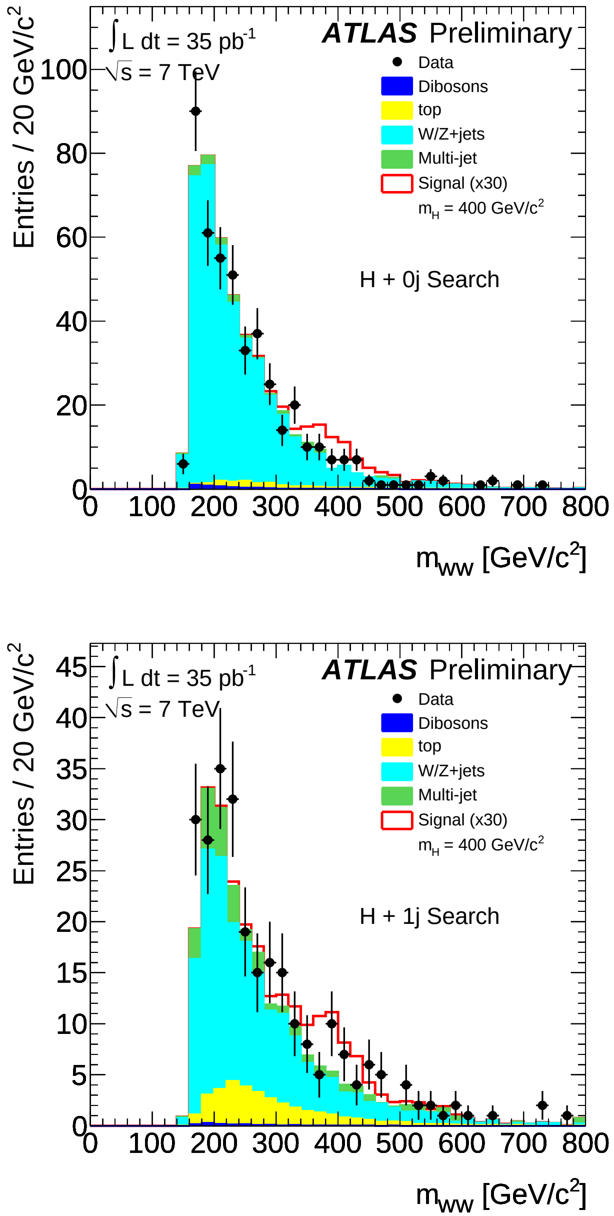
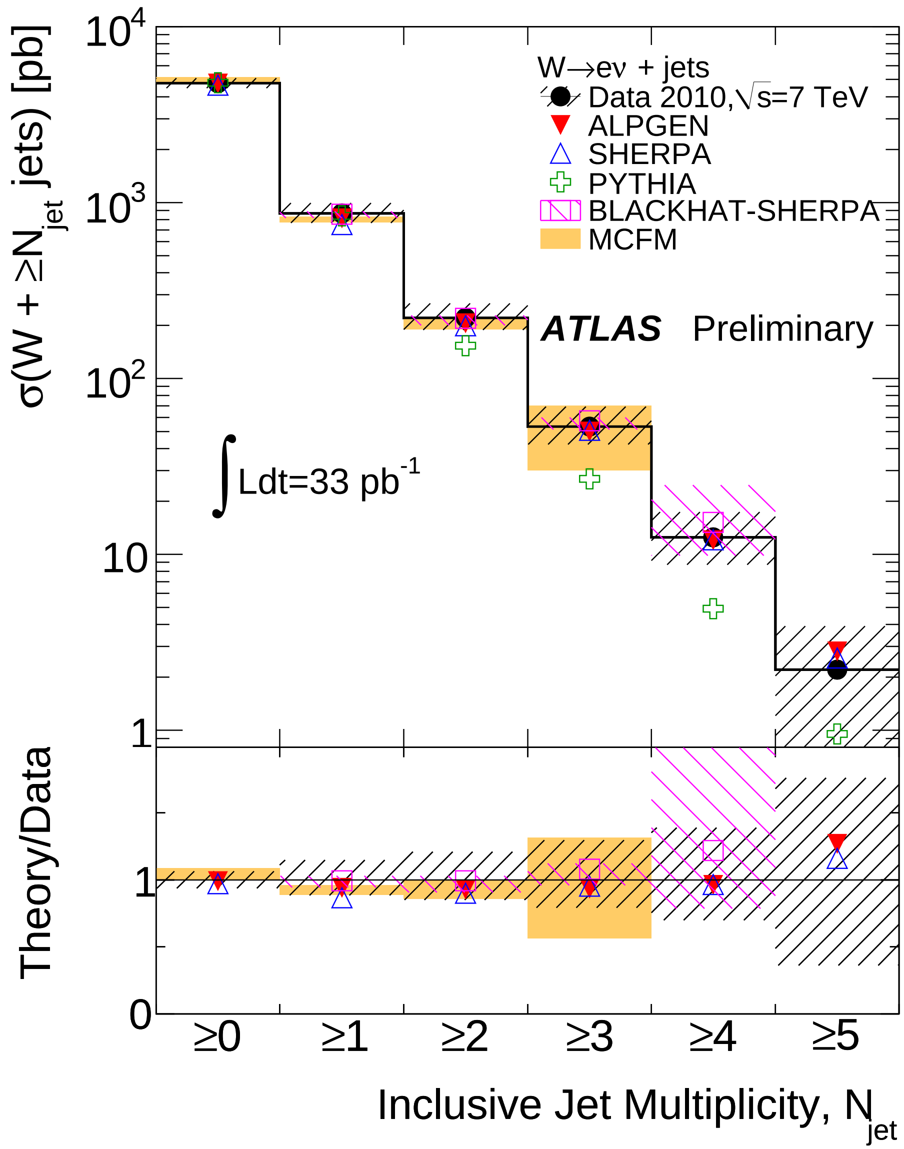
Tools that we can now use for signal and (high multiplicity) background.

A choice of examples to follow . . .

W+jets





Blackhat+Sherpa: W+3j, W+4j at NLO

$W + b$-jets: crucial background for WH production

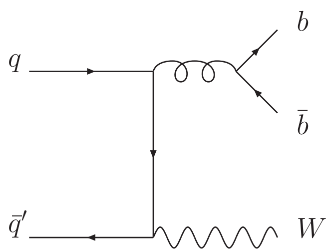
Two interesting signatures:

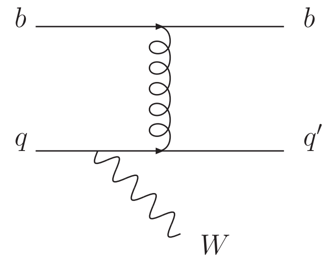
- $W + 2b$ jets ($m_b \neq 0$):
  - Febres Cordero, L. R., Wackeroth, arXiv:hep-ph/0606102, arXiv:0906.1923
  - Badger, Campbell, Ellis, arXiv:1011.6647
  - Oleari, L. R., arXiv.1105.4488 $\longrightarrow$ POWHEG
  - Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli $\longrightarrow$ aMC@NLO

- $W + 2$ jets with at least one b jet:
  - Campbell, Ellis, Febres Cordero, Maltoni, L. R., Wackeroth, Willenbrock, arXiv:0809.3003
  - the CDF collaboration, arXiv:0909.1505,
    Campbell, Febres Cordero, L. R., arXiv:1001.3362, arXiv:1001.2954
  - the ATLAS collaboration, A. Messina's talk at EPS 2011,
    Caola, Campbell, Febres Cordero, L. R., Wackeroth, arXiv:1107.3714

In a nutshell:

One or two LO processes, depending on choice of 4FNS vs 5FNS:

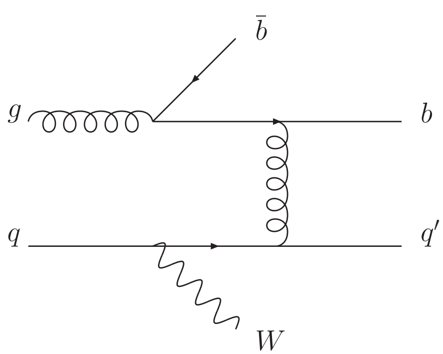




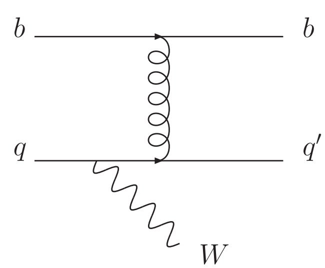
$+ \qquad O(\alpha_s)$ corrections

Correspondently, at NLO:

1. $q\bar{q}' \to Wb\bar{b}$ at tree level and one loop $(m_b \neq 0)$
2. $q\bar{q}' \to Wb\bar{b}g$ at tree level $(m_b \neq 0)$
3. $bq \to Wbq'$ at tree level and one loop $(m_b = 0)$
4. $bq \to Wbq'g$ and $bg \to Wbq'\bar{q}$ at tree level $(m_b = 0)$
5. $gq \to Wb\bar{b}q'$ at tree level $(m_b \neq 0) \to$ avoiding double counting:



$\longrightarrow$



$$\boxed{b(x,\mu) = \frac{\alpha_s}{2\pi} \ln\frac{\mu^2}{m_b^2} \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) g(y,\mu)}$$

- $W + 2b$ jets: processes $1+2+5$
- $W + 2$ jets with at least one b jet: processes $1+\cdots+5$.

Comparison with CDF measurement: a puzzle?

CDF Note 9321 (arXiv:0909.1505):

$$\sigma_{\mathrm{b-jet}}(W + b\,\mathrm{jets}) \cdot Br(W \to l\nu) = 2.74 \pm 0.27(\mathrm{stat}) \pm 0.42(\mathrm{syst})\ \mathrm{pb}$$

[Neu, Thomson, Heinrich]

From our $W + 1b$ calculation:

[Campbell, Febres Cordero, L.R.]

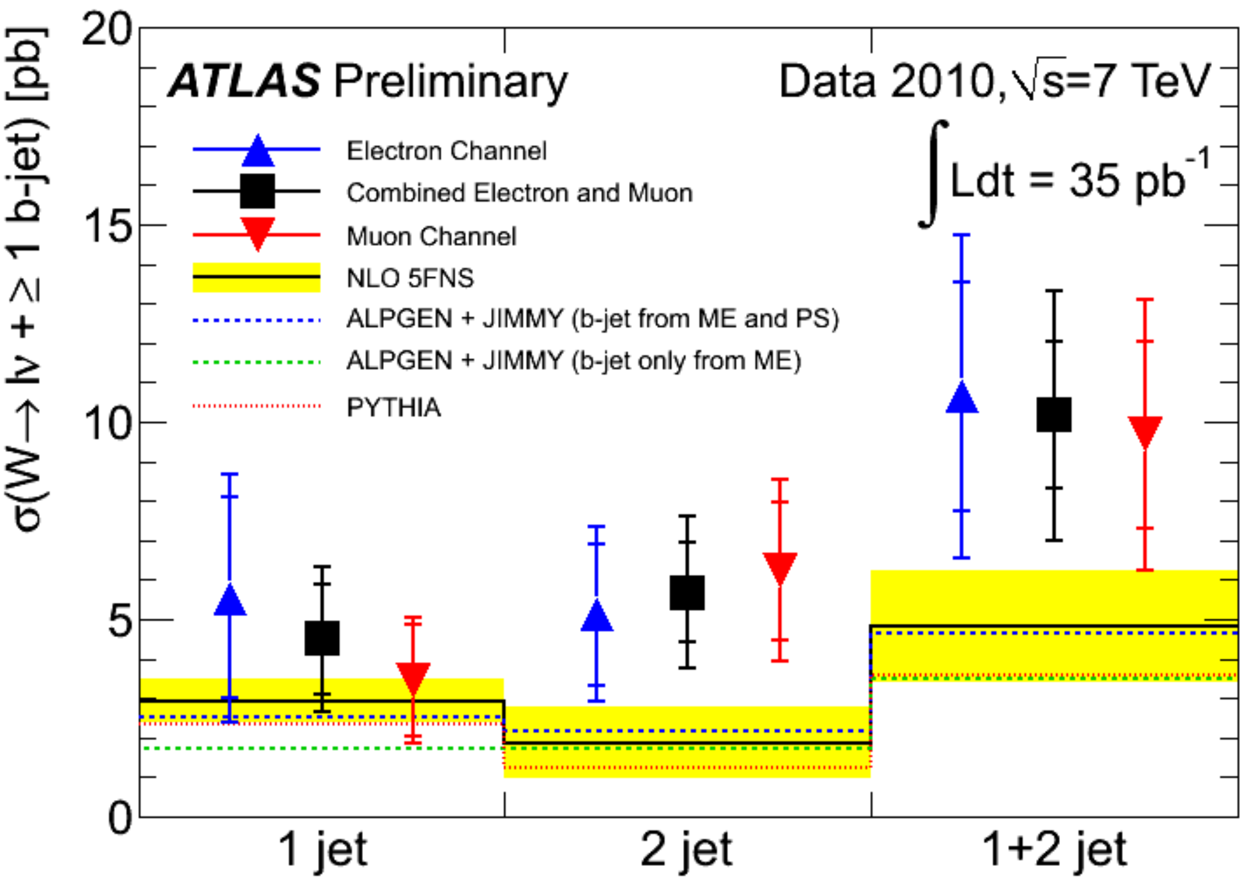
$$\sigma_{\mathrm{b-jet}}(W + b\,\mathrm{jets}) \cdot Br(W \to l\nu) = 1.22 \pm 0.14\ \mathrm{pb}$$

For comparison:

ALPGEN prediction: 0.78 pb

PYTHIA prediction: 1.10 pb

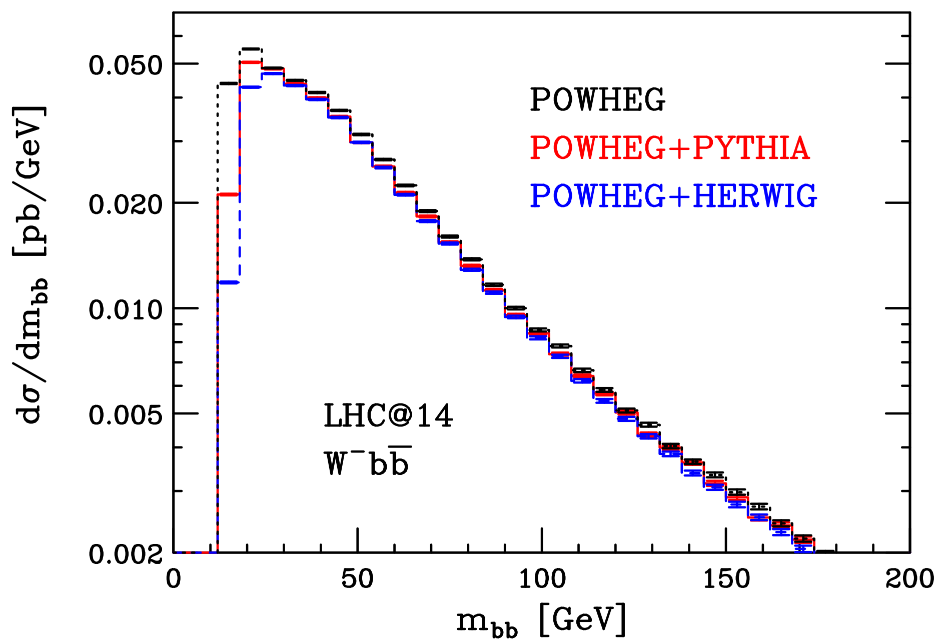
Comparison with ATLAS

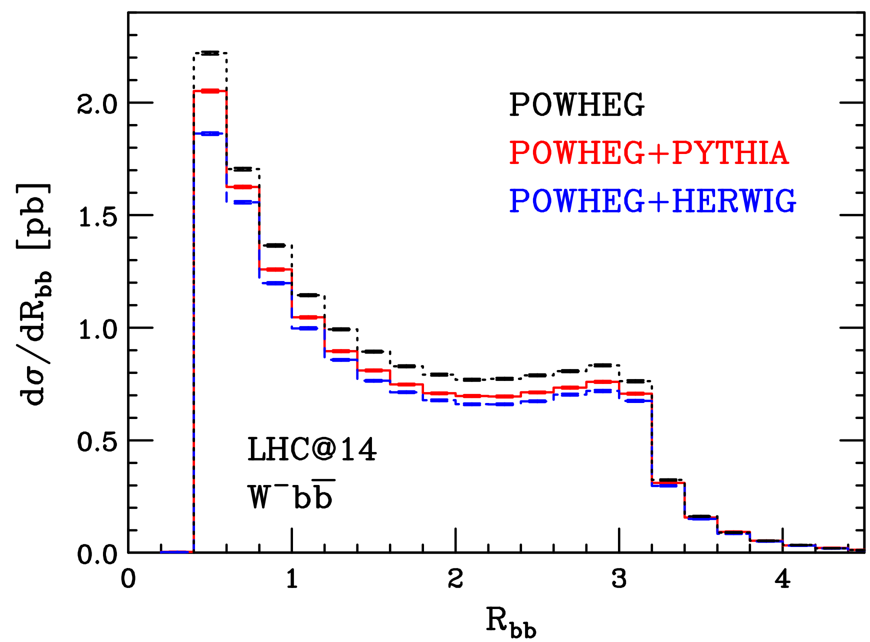


[Golling, Messina, et al.]

Further development: $Wb\bar{b}$ implemented in POWHEG and MC@NLO, including $W \to l\nu_l$ decay.

Distribution sample:



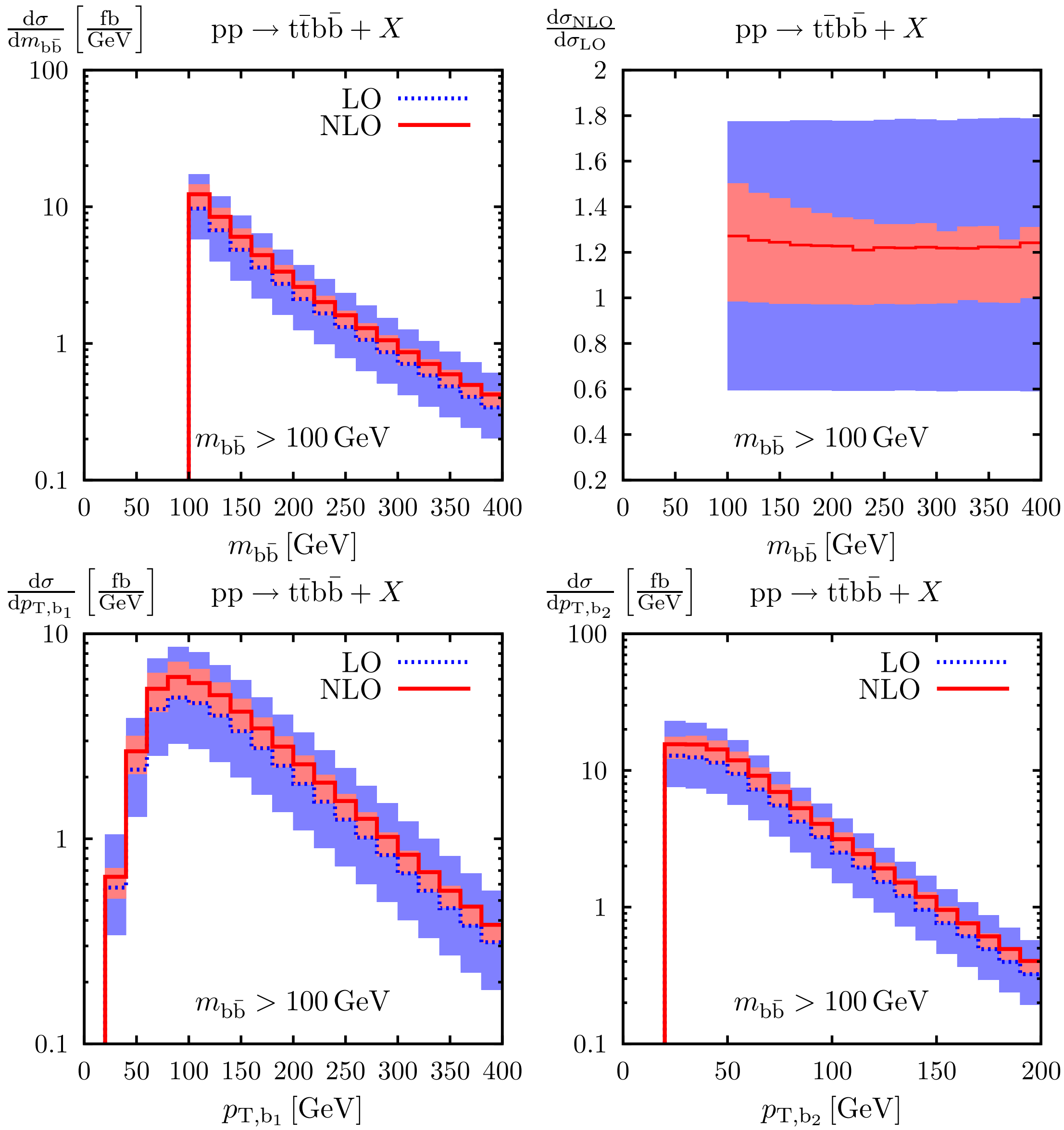


- used to estimate showering and hadronization uncertainties;
- $bq \to bq'W$ process being implemented.

$t\bar{t}b\bar{b}$ at NLO: background for $t\bar{t}H, H \to b\bar{b}$.

[Bredenstein, Denner, Dittmaier, Pozzorini, arXiv:0905.0110, arXiv:1001.4006]

[Bevilacqua, Czakon, Papadopoulos, Pittau, Worek, arXiv:0907.4723]



best central scale choice:

$$\mu_0^2 = m_t \sqrt{p_T^b p_T^{\bar{b}}}$$

hard b jet often from initial state gluons

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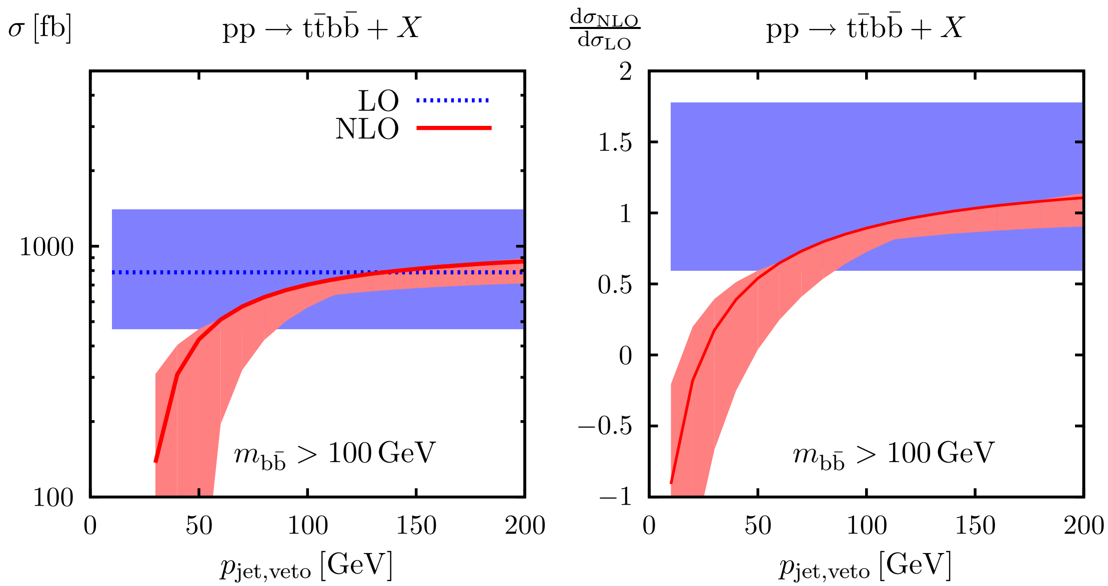
different from $t\bar{t}H$

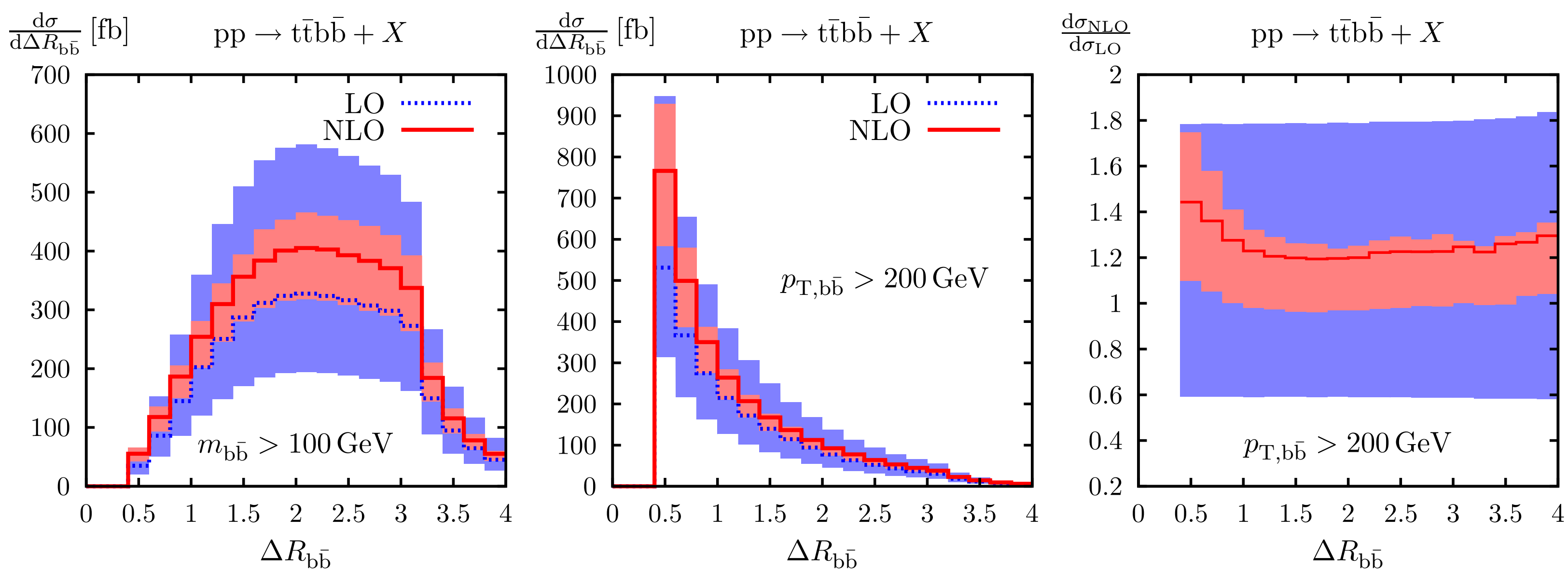
(Bredenstein, et al.)

Important to observe that:

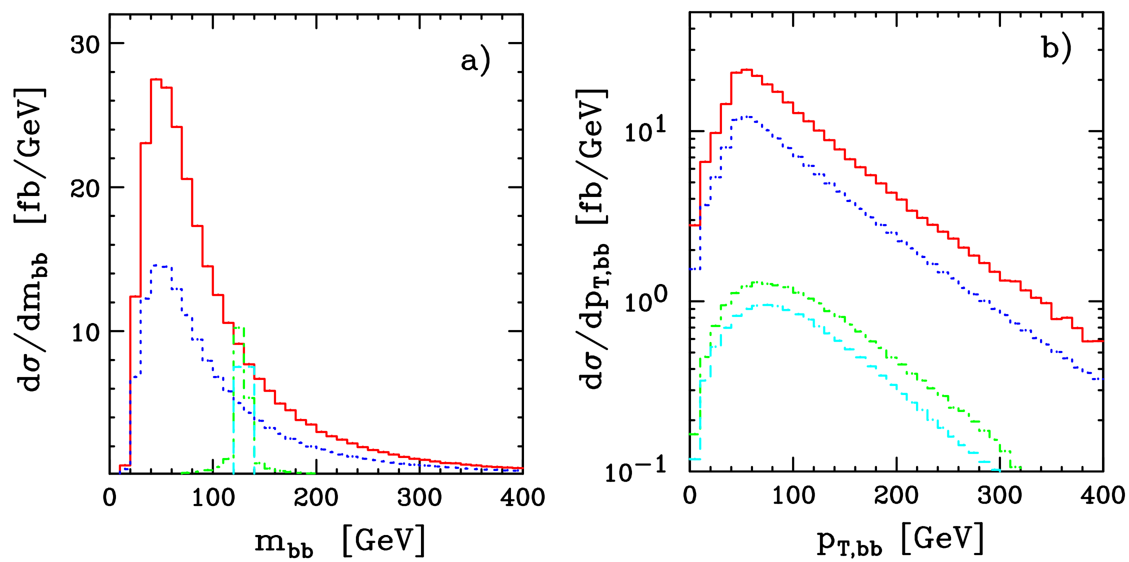
- effect of jet veto on extra light jet:



- regime of *boosted Higgs*:



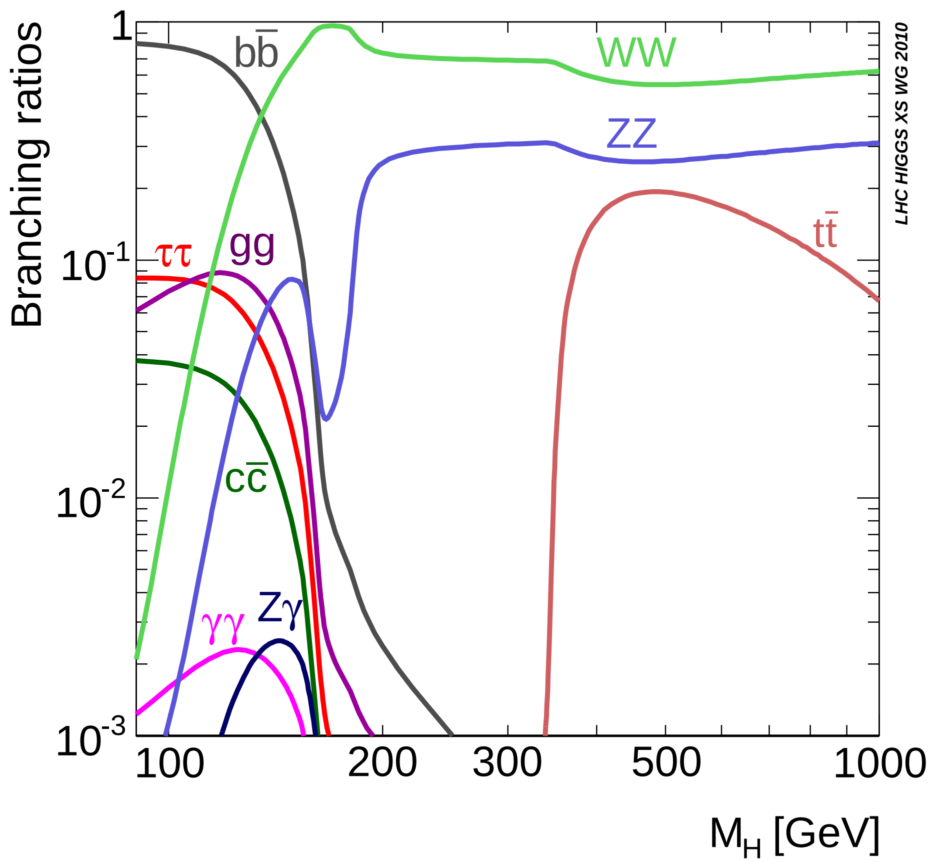
$t\bar{t}b\bar{b}$ distributions: signal vs background, at NLO



(Bevilacqua, Czakon, Garzelli, van Hameren, Papadopoulos, Pittau, Worek,
arXiv:1003.1241, Les Houches 09)

- ▷ $t\bar{t}b\bar{b}$ background: LO and NLO;
- ▷ $t\bar{t}H$ with $H \to b\bar{b}$: LO and NLO, calculated in NWA (valid for small M_H);
- ▷ to be revisited within the Higgs Cross Section WG (exclusive studies);
- ▷ signal now available in aMC@NLO ($\to$ see also Maltoni's talk)

SM Branching Ratios



uncertainties:

- theoretical (QCD, EW)
- parametric (m_c, m_b, ...)

linearly combined.

Tools:

- HDECAY [Djouadi, Kalinowski, Müllheitner, Spira]
- Prophecy4f [Bredenstein, Denner, Dittmaier, Mück, Weber]
- EW-NLO corrections to $H \to \gamma\gamma$ and $H \to gg$ [Actis, Passarino, Sturm, Uccirati]

Strategy (from D. Rebuzzi's talk, BNL, May 2011)

- ↪ Calculate decay partial width as accurate as possible for each decay mode.
- ↪ Calculate branching ratio from full set of partial width.
- ↪ Define Higgs total width as

$$\Gamma_H = \Gamma^{\text{HDECAY}} - \Gamma_{ZZ}^{\text{HDECAY}} - \Gamma_{WW}^{\text{HDECAY}} + \Gamma_{4f}^{\text{Profecy4f}}$$

where

$$\Gamma_{4f}^{\text{Profecy4f}} = \Gamma_{H\to WW^*\to 4f} + \Gamma_{H\to ZZ^*\to 4f} + \Gamma_{WW/ZZ-int}$$

Results (preliminary, to be compared with [Baglio, Djouadi, arXiv:1012.0530])

Process	QCD	EW	Total
$H\to b\bar{b}$	$\sim 0.1-0.2\%$	$1-2\%$ ($M_H \le 135$ GeV)	$\sim 3-4\%$
$H\to c\bar{c}$	$\sim 0.1-0.2\%$	$1-2\%$ ($M_H \le 135$ GeV)	$\sim 10-13\%$
$H\to \tau\tau$		$1-2\%$ ($M_H \le 135$ GeV)	$\sim 3-6\%$
$H\to t\bar{t}$	$\sim 5\%$	$2-5\%$ ($M_H \le 500$ GeV)	$\sim 5-10\%$
$H\to WW/ZZ\to 4f$	$< 1\%$	0.5% ($M_H \le 500$ GeV)	$\le 2\%$
$H\to gg$	$\sim 10\%$	$\sim 1\%$	$\sim 15-17\%$
$H\to \gamma\gamma$	$< 0.5\%$	$< 1\%$	$\sim 1\%$

Conclusions and Outlook

- We are living through a new era in Higgs-boson physics: looking for direct evidence.
- Higgs-boson precision physics has given a first coherent set of predictions for inclusive observables: Higgs-boson production cross sections and branching ratios.
- Short term: study exclusive observables, including decays, background processes, and experimental cuts.
- Long term: carry through a precision program that also include measurements of Higgs-boson properties, to identify possible candidates:
  - the LHC will play an important role but need very high luminosity;
  - LHC measurements will be important indications but are intrinsically model dependent;
  - a high energy Linear Collider could be the best if not the only environment to complete and conclude the investigation of EWSB.