Hadron Collider Theory: what would the experimental precision be good for?

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LHC2FC Institute, CERN, February 2009
Higgs Working Group (WG1)

- The Large Hadron Collider (LHC) will test new ground and answer some of the fundamental open questions of Particle Physics:
  - $\longrightarrow$ Electroweak (EW) symmetry breaking: Higgs mechanism?
  - $\longrightarrow$ New Physics (NP) in the TeV range?
  - $\longrightarrow$ ...
- Within WG1 the focus is on Higgs-boson physics. What would the experimental precision be good for?
  - $\longrightarrow$ test consistency of the Standard Model and its extensions;
  - $\longrightarrow$ discover one (or more) potential Higgs boson(s);
  - $\longrightarrow$ identify it (them): measure couplings, mass(es), quantum numbers.
- The incredible physics potential of the LHC and its upgrades relies on our ability to provide very accurate predictions:
  - $\longrightarrow$ Precision: $\sigma_{W/Z}$ as parton luminosity monitors (PDF's), constraints from precision fits, ...;
  - $\longrightarrow$ Discovery: precise prediction of signals/backgrounds;
  - $\longrightarrow$ Identification: precise extraction of parameters (α_s, m_t, M_W, M_H, $y_{t,b,\ldots}$, M_X, y_X, ...).

Outline

- Full details on LHC, LHC upgrades, and existing experimental analyses for Higgs-boson physics given in two plenary talks at this Institute:

  $\longrightarrow$ Kétévi A. Assamagan (LHC with 30 fb^{-1});

  $\longrightarrow$ Marco Pieri (LHC with 300 fb^{-1}, SLHC,VLHC).

  and in several parallel-session presentations.

- Overview of Higgs-boson physics at the LHC.

- Where precision matters (higher statistics w or w/o higher energy):

  $\longrightarrow$ precision fits;

  $\longrightarrow$ discovery;

  $\longrightarrow$ couplings, masses, quantum numbers.

- Theory: are we ready for precision Higgs-boson physics at the LHC and beyond?

What are we looking for?

- Spectrum of ideas to explain EWSB:

  $\longrightarrow$ Weakly coupled dynamics embedded into some more fundamental theory at a scale Λ (probably $\simeq$ TeV):

  $\Longrightarrow$ SM, 2HDM (MSSM), ... (Higgs Mechanism);

  $\longrightarrow$ little Higgs models, ...

  $\longrightarrow$ extra-dimension models, ...

  $\longrightarrow$ Strongly coupled dynamics at the TeV scale:

  $\longrightarrow$ Technicolor in its multiple realizations.

- SM Higgs boson, our learning ground:

  $\longrightarrow$ $\mathcal{L}_{Higgs}^{SM} = (D^\mu\phi)^\dagger D_\mu\phi - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$

  complex SU(2) doublet, reduced to one real massive scalar field upon EWSB via Higgs mechanism: $\langle\phi^\dagger\rangle = (0\ \frac{v}{\sqrt{2}})$, where $v = (-\mu^2/\lambda)^{-1/2}$;

  $\longrightarrow$ scalar particle, neutral, CP even, $m_H^2 = -2\mu^2 = 2\lambda v^2$;

  $\longrightarrow$ mass related to scale of new physics, but constrained by EW precision fits;

  $\longrightarrow$ minimally coupled to gauge bosons $\longrightarrow$ $M_W = g\frac{v}{2}$, $M_Z = \sqrt{g^2 + g'^2}\frac{v}{2}$;

  $\longrightarrow$ coupled to fermions via Yukawa interactions $\longrightarrow$ $m_f = y_f\frac{v}{2}$;

  $\longrightarrow$ three- and four-point self couplings: testing the potential.

- Beyond SM we could have:
  - $\longrightarrow$ more scalars and/or pseudoscalars particles over broad mass spectrum (elementary? composite?);
  - $\longrightarrow$ physical states mixture of original fields ($\rightarrow$ FCNC, ...);
  - $\longrightarrow$ no scalar (!);
  - $\longrightarrow$ several other particles (fermions and vector gauge bosons).

  If coupled to SM particles:
  - $\longrightarrow$ constraints from EW precision measurements should apply;
  - $\longrightarrow$ still lots of room for unknown parameters to be adjusted: little predictivity until discoveries won't populate more the physical spectrum.

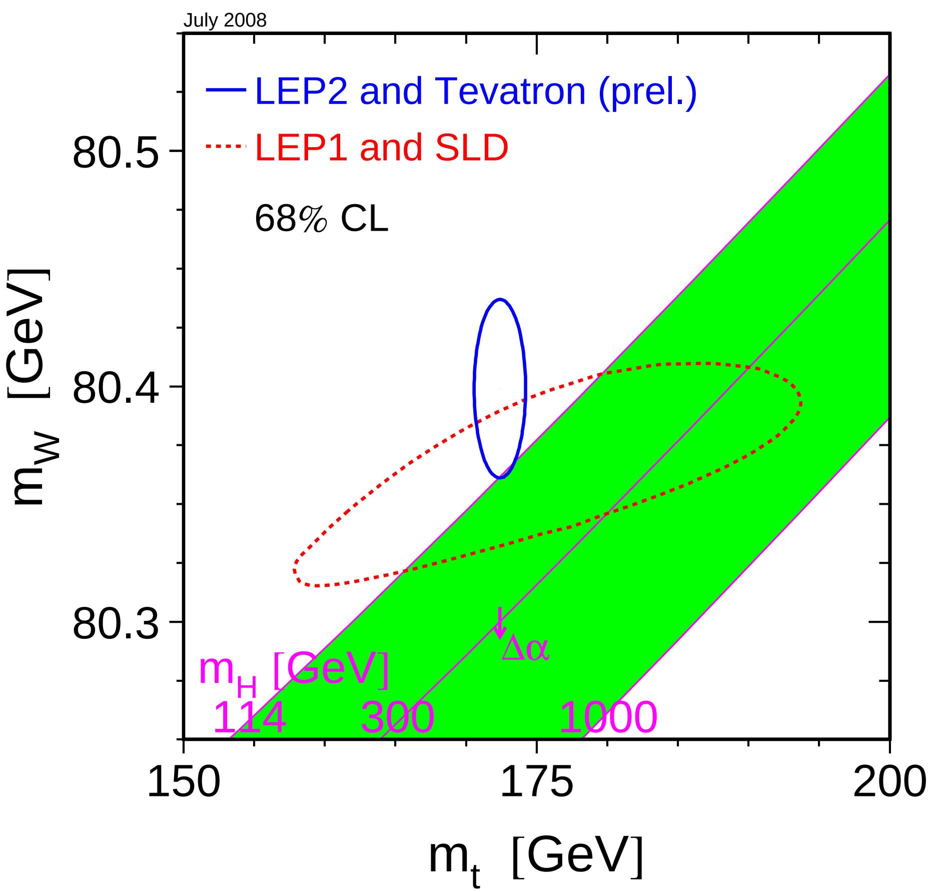
Upon discovery:

- measure mass (first crucial discriminator!);
- measure couplings to gauge bosons and fermions;
- test the potential: measure self couplings;
- hope to see more physics.

This program can greatly benefit from higher luminosity and/or energy.

SM Higgs boson: light mass strongly favored

Increasing precision will provide an invaluable tool to test the consistency of the SM and its extensions.



$$m_W = 80.399 \pm 0.025 \text{ GeV}$$

$$m_t = 172.4 \pm 1.2 \text{ GeV}$$

$$\Downarrow$$

$$M_H = 84^{+34}_{-26} \text{ GeV}$$

$$M_H < 154\,(185) \text{ GeV}$$

plus exclusion limits (95% c.l.):

$$M_H > 114.4 \text{ GeV (LEP)}$$

$$M_H \neq 170 \text{ GeV (Tevatron)}$$

- ▷ only SM unknown: Higgs-boson mass;
- ▷ strong correlation between M_W ($\sin\theta_W^{eff}$), m_t and M_H.

Experimental uncertainties, estimate

	Present	Tevatron	LHC	LC	GigaZ
$\delta(M_W)$(MeV)	25	27	10-15	7-10	7
$\delta(m_t)$ (GeV)	1.2	2.7	1.0	0.2	0.13
$\delta(M_H)/M_H$ (indirect)	30%	35%	20%	15%	8%

(U. Baur, LoopFest IV, August 2005)

Intrinsic theoretical uncertainties

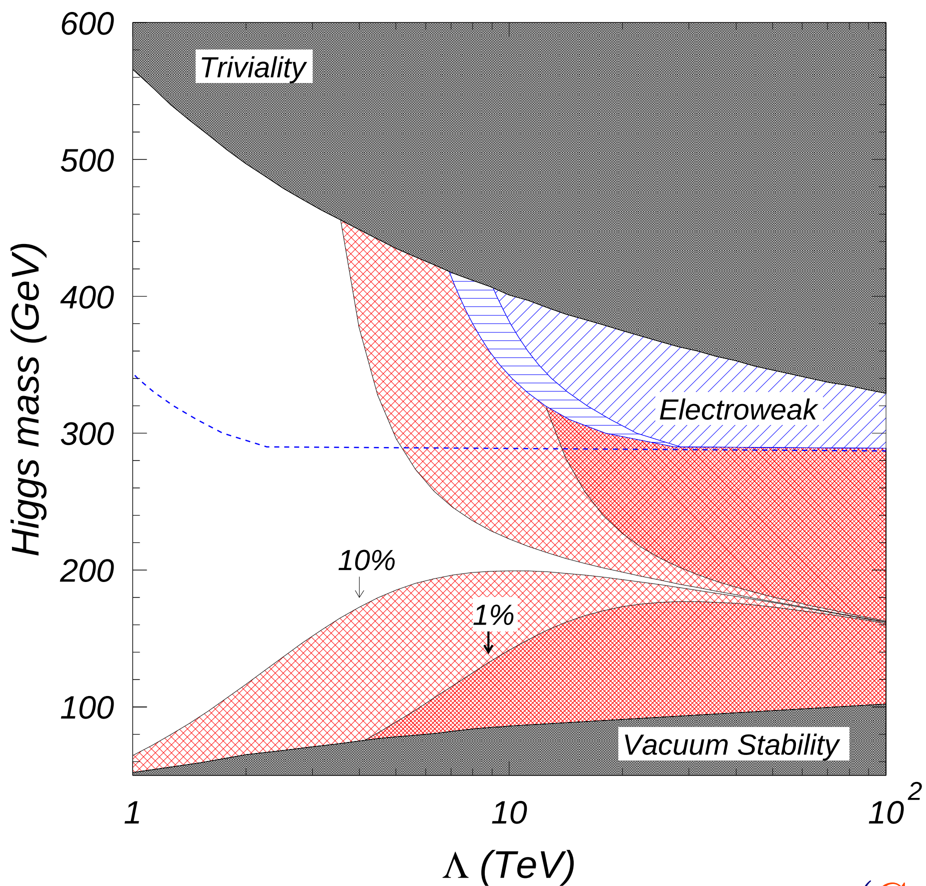
$\longrightarrow$ $\delta M_W \approx 4$ MeV: full $O(\alpha^2)$ corrections computed.

(M. Awramik, M. Czakon, A. Freitas, and G. Weiglein, PRD 69:053006,2004)

$\longrightarrow$ estimated: $\Delta m_t/m_t \sim 0.2\Delta\sigma/\sigma + 0.03$ (LHC)

(R. Frederix and F. Maltoni, JHEP 0901:047,2009)

SM Higgs: does a light Higgs constrain new physics?



$\Lambda \to$ scale of new physics

amount of fine tuning =

$$\frac{2\Lambda^2}{M_H^2}\left|\sum_{n=0}^{n_{max}} c_n(\lambda_i)\log^n(\Lambda/M_H)\right|$$

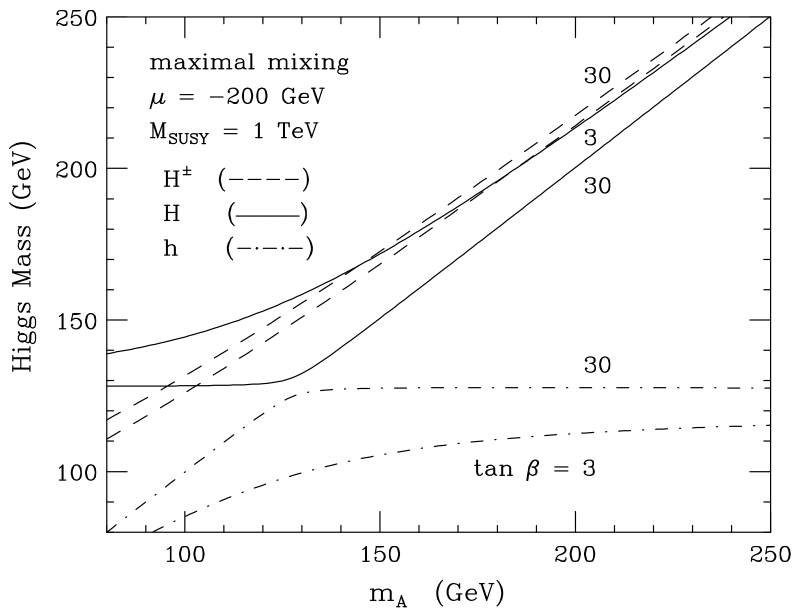
$\longleftarrow n_{max} = 1$

(C. Kolda and H. Murayama, JHEP 0007:035,2000)

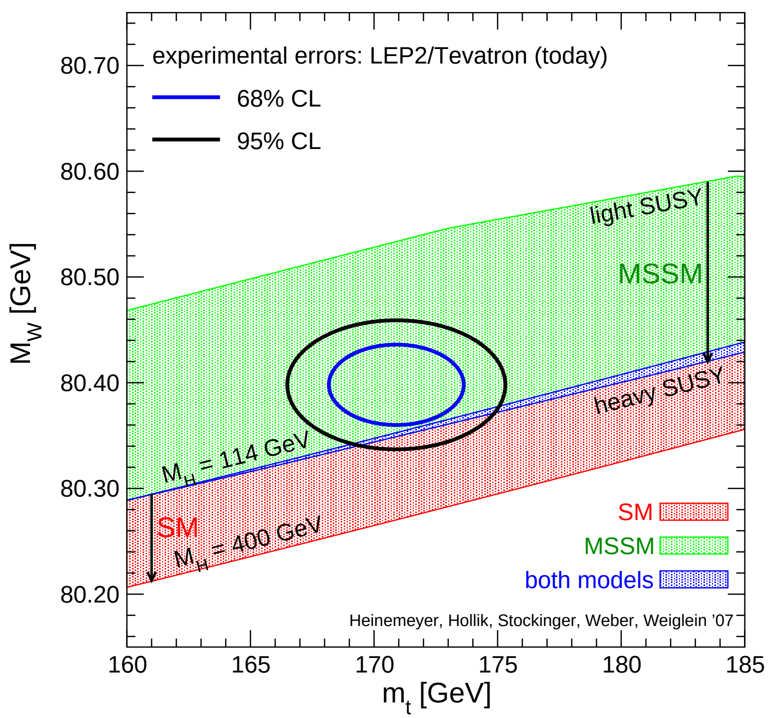
Light Higgs consistent with low Λ: new physics at the TeV scale.

Beyond SM: new physics at the TeV scale can be a better fit

Ex. 1: MSSM



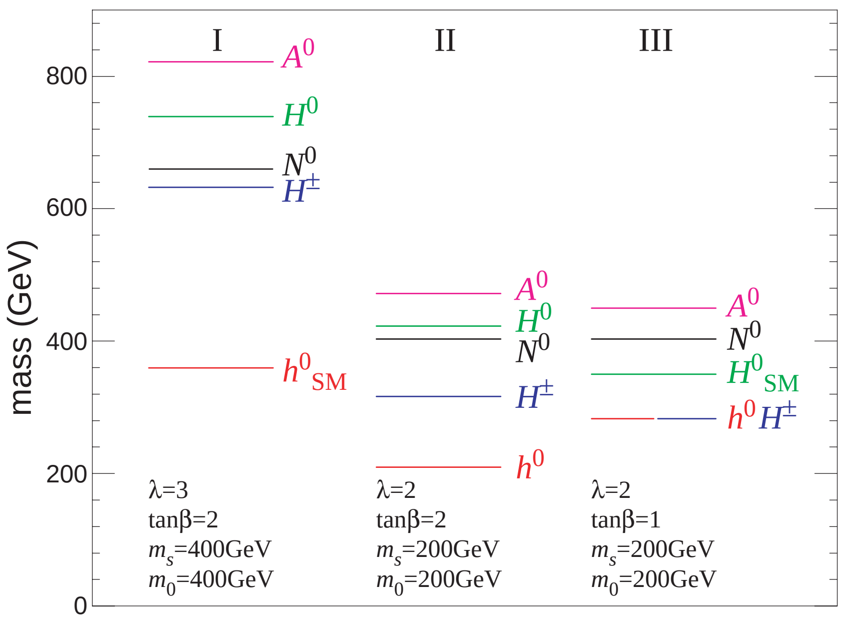
(M. Carena et al.)

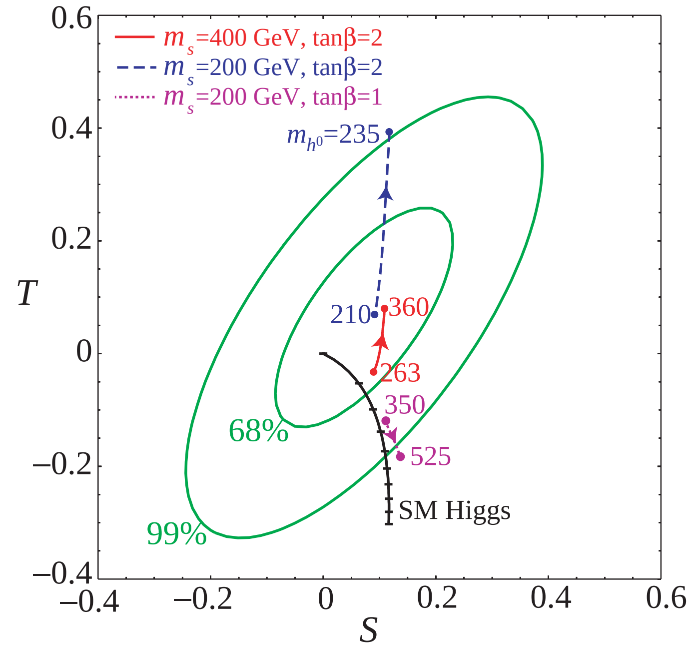


- ▷ a light scalar Higgs boson, along with a heavier scalar, a pseudoscalar and a charged scalar;
- ▷ similar although less constrained pattern in any 2HDM;
- ▷ MSSM main uncertainty: unknown masses of SUSY particles.

Beyond SM: new physics at the TeV scale can be a better fit

Ex. 2: "Fat Higgs" models

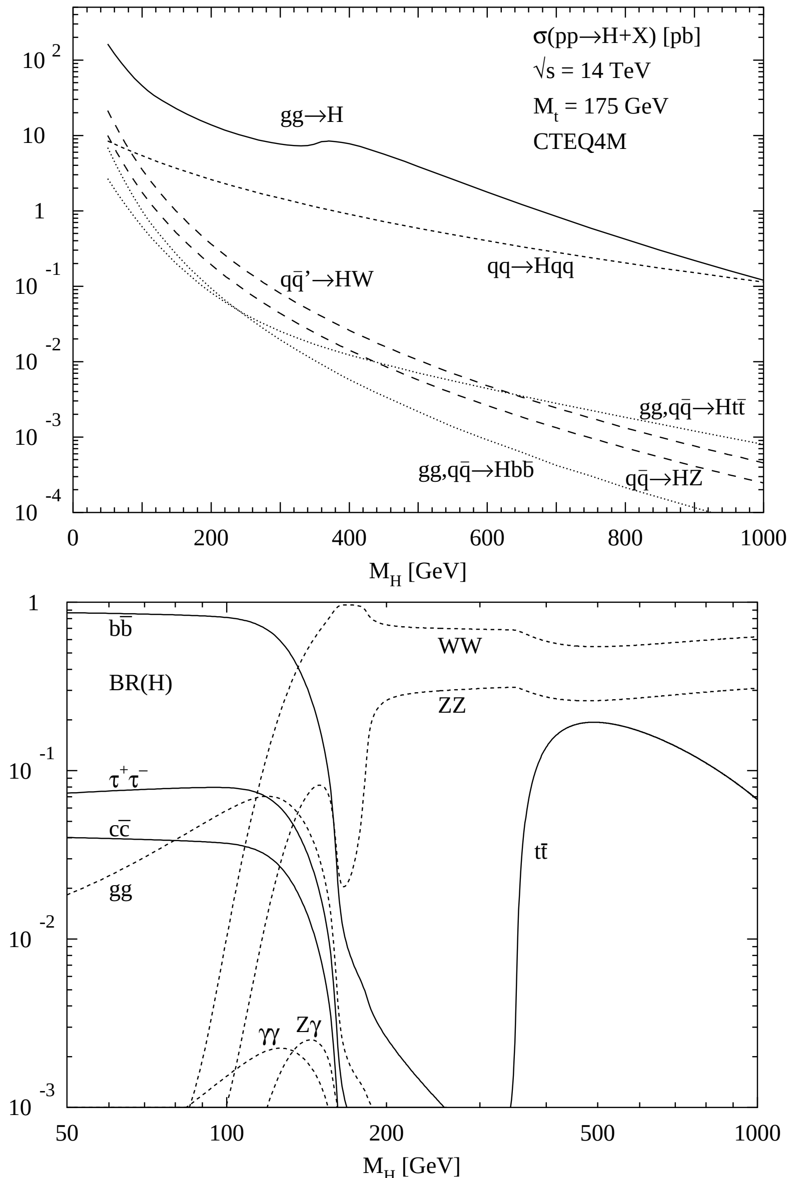




(Harnik, Kribs, Larson, and Murayama, PRD 70 (2004) 015002)

- ▷ supersymmetric theory of a composite Higgs boson;
- ▷ moderately heavy lighter scalar Higgs boson, along with a heavier scalar, a pseudoscalar and a charged scalar;
- ▷ consistent with EW precision measurements without fine tuning.

Discovering a SM Higgs boson at the LHC



(M. Spira, Fortsch.Phys. 46 (1998) 203)

Many channels have been studied:

Below 130-140 GeV:

$gg \to H\,,\; H \to \gamma\gamma, WW, ZZ$

$qq \to qqH\,,\; H \to \gamma\gamma, WW, ZZ, \tau\tau$

$q\bar{q}, gg \to t\bar{t}H\,,\; H \to \gamma\gamma, b\bar{b}, \tau\tau$

$q\bar{q}' \to WH\,,\; H \to \gamma\gamma, b\bar{b}$

Above 130-140 GeV:

$gg \to H\,,\; H \to WW, ZZ$

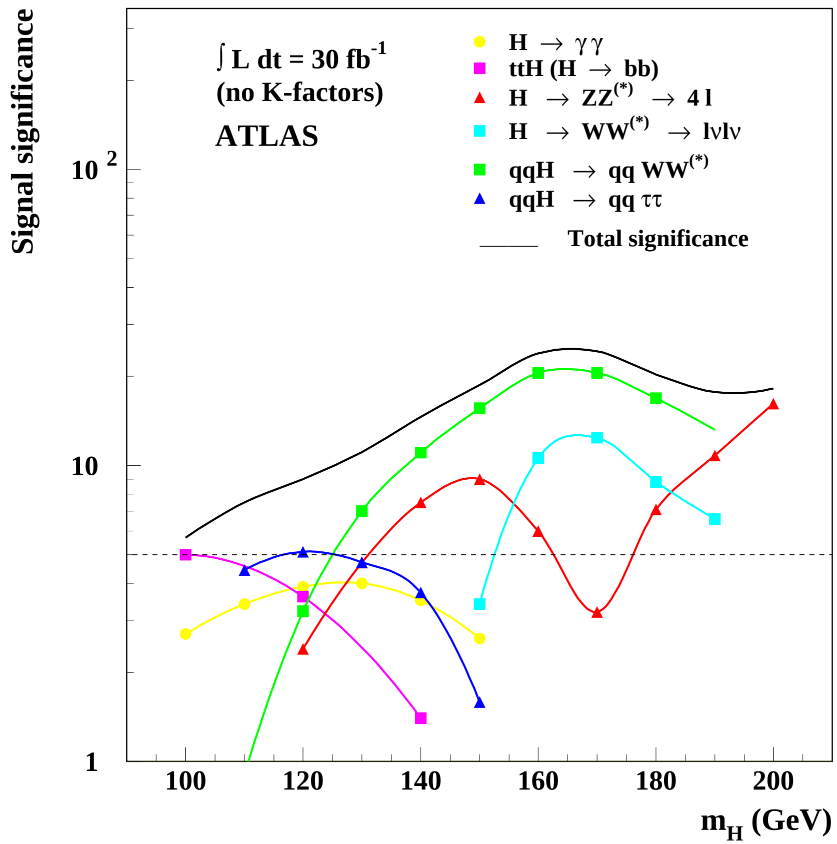
$qq \to qqH\,,\; H \to \gamma\gamma, WW, ZZ$

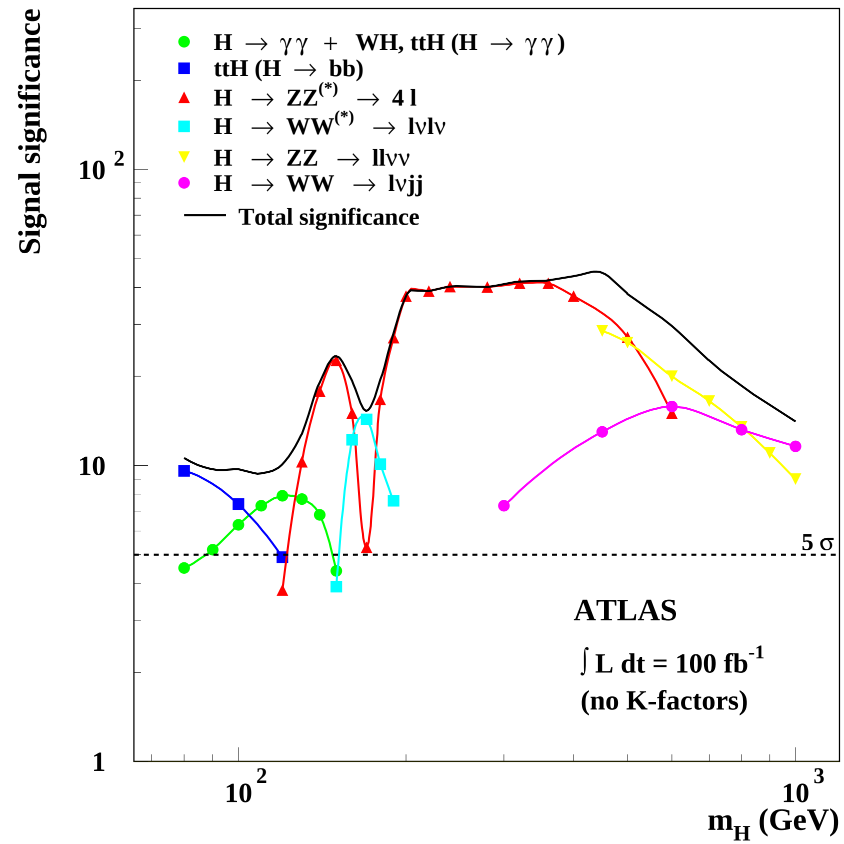
$q\bar{q}, gg \to t\bar{t}H\,,\; H \to \gamma\gamma, WW$

$q\bar{q}' \to WH\,,\; H \to WW$

$\longrightarrow$ see Assamagan's and Pieri's talks.

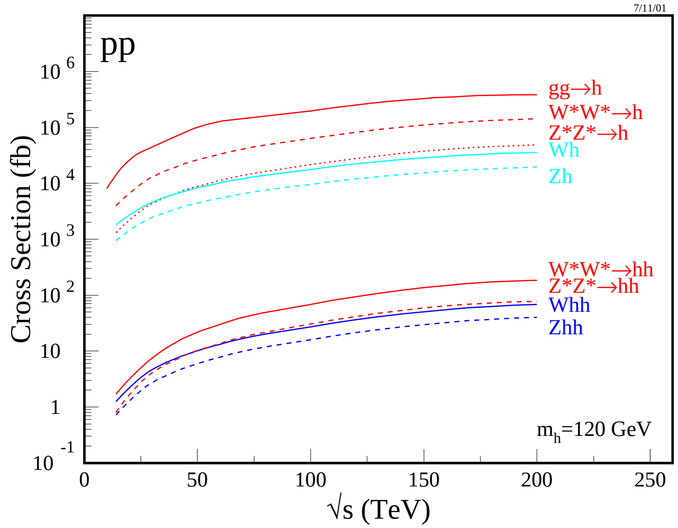
Discovery reach of the LHC for a SM Higgs boson

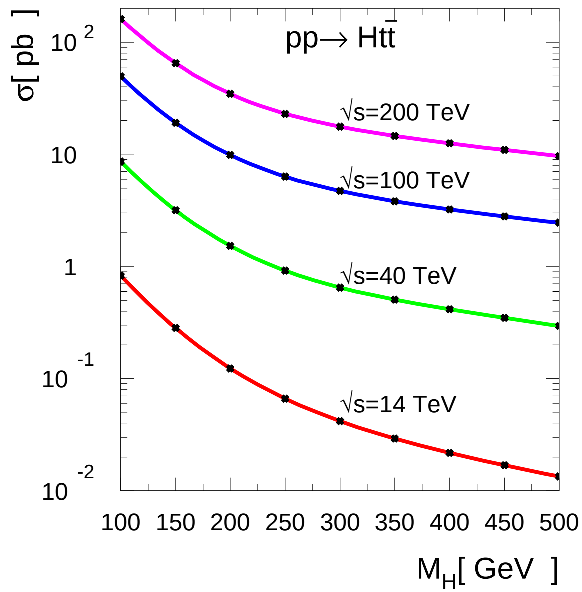




- ▷ Low mass region difficult at low luminosity: need to explore as many channels as possible;
- ▷ high luminosity reach needs to be updated;
- ▷ identifying the SM Higgs boson requires high luminosity, above 100 fb^{-1}: very few studies exist above 300 fb^{-1} (per detector).

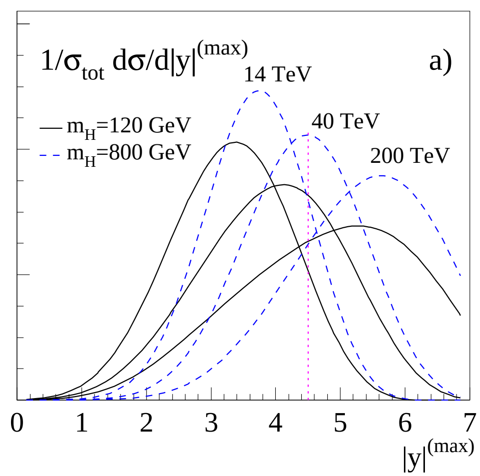
Higher energy: higher rates

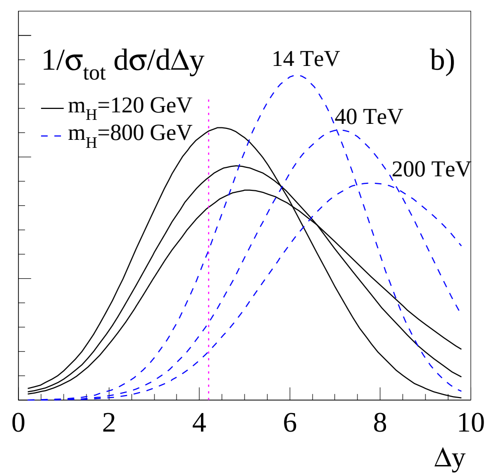




Higher energy: different dynamics

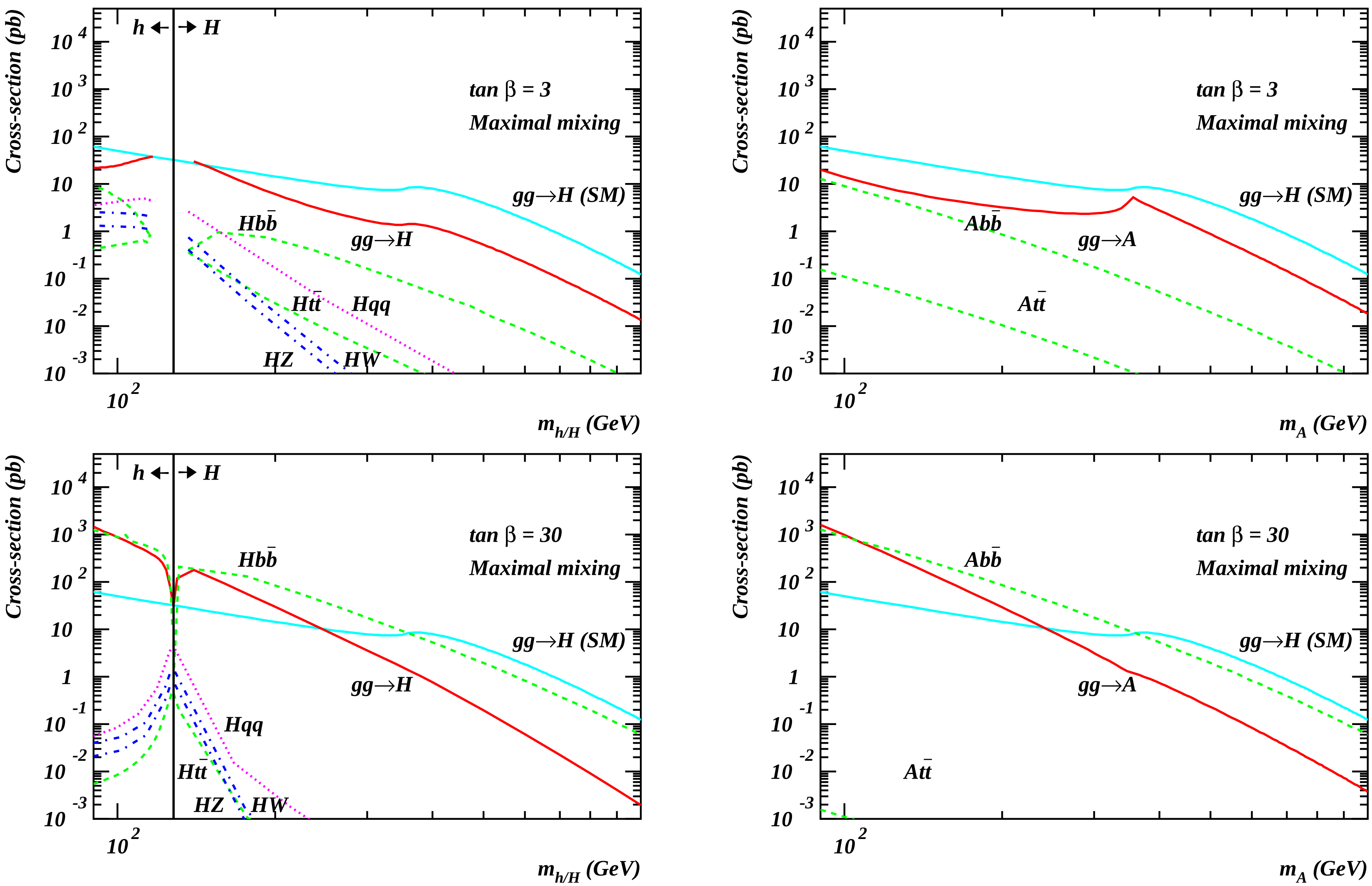
<u>Ex.</u>: rapidity and difference of rapidity of tagging jets in WBF.





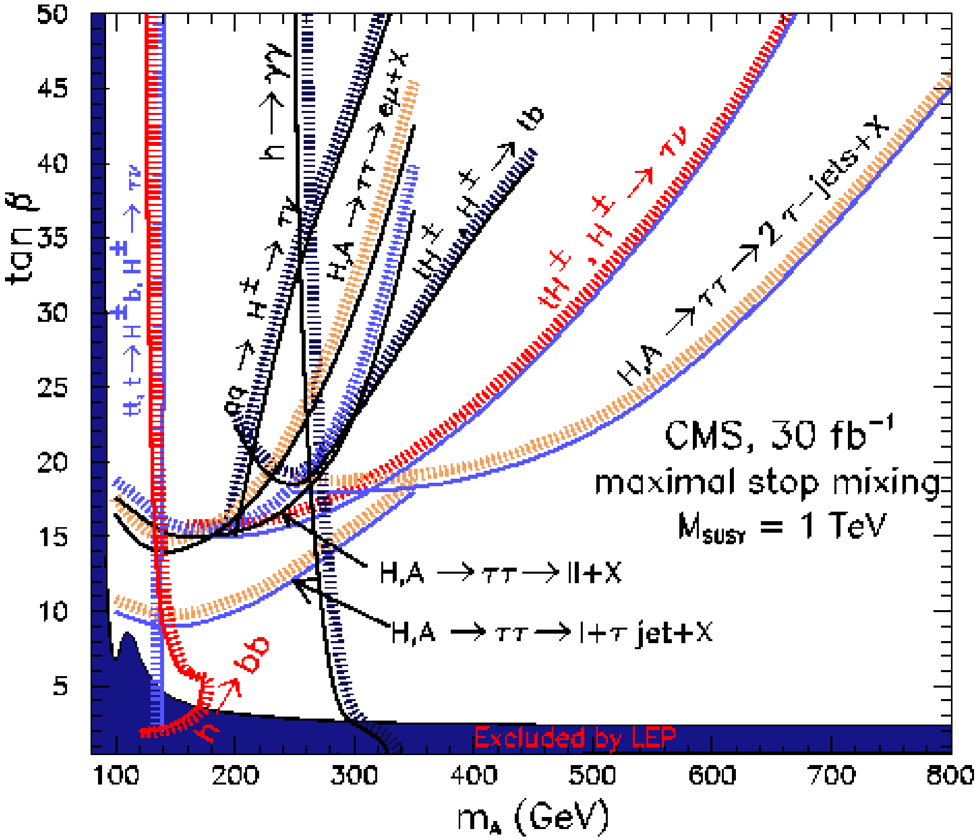
(U. Baur et al., Snowmass 2001, hep-ph/0201227)

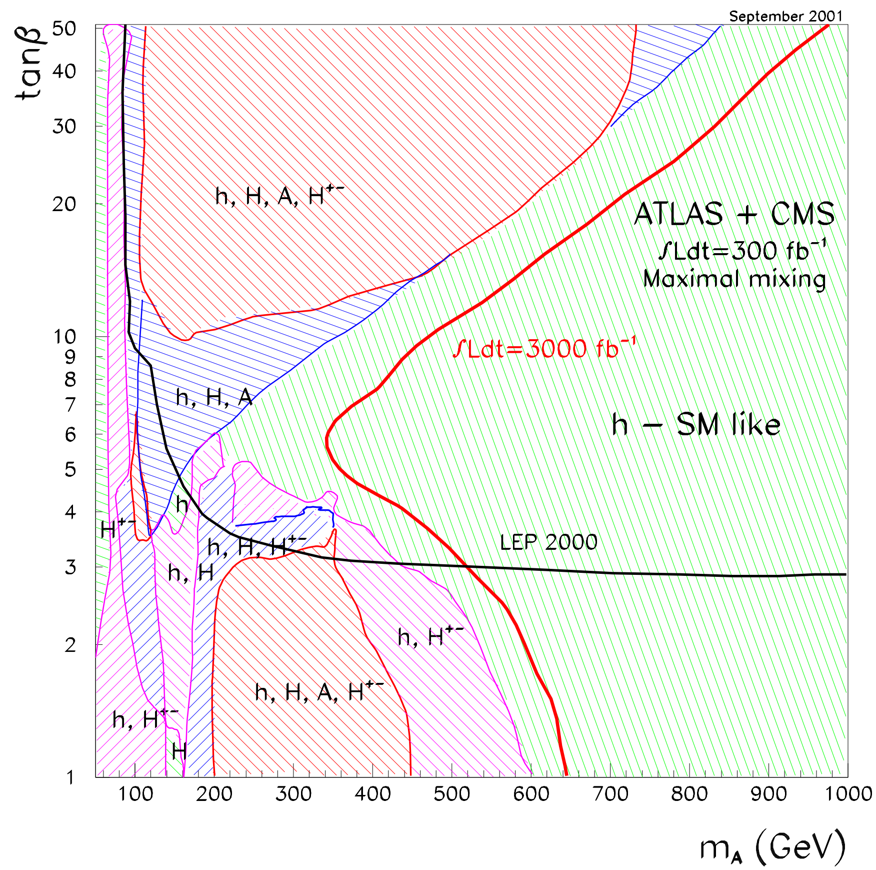
For comparison: MSSM Higgs-boson production rates at the LHC



to be matched to enhanced/suppressed decay rates with respect to SM Higgs boson.

Discovery reach of the LHC in the MSSM parameter space





Low luminosity, CMS only

High luminosity, ATLAS+CMS

SM Higgs boson: mass, width, spin and more

- Color and charge are given by the measurement of a given (production+decay) channel.

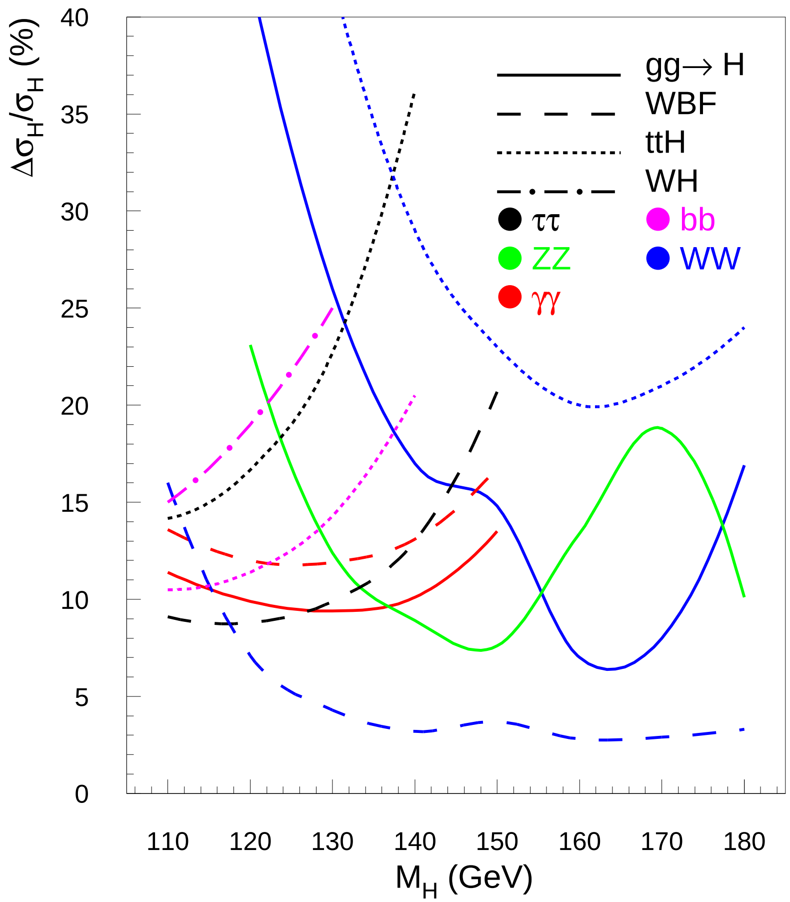
- The Higgs boson mass will be measured with 0.1% accuracy in $H \to ZZ^* \to 4l^\pm$, complemented by $H \to \gamma\gamma$ in the low mass region. Above $M_H \simeq 400$ GeV precision deteriorates to $\simeq 1\%$ (lower rates).

- The Higgs boson width can be measured in $H \to ZZ^* \to 4l^\pm$ above $M_H \simeq 200$ GeV. The best accuracy of $\simeq 5\%$ is reached for $M_H \simeq 400$ GeV.

- The Higgs boson spin could be measured through angular correlations between fermions in $H \to VV \to 4f$: need for really high statistics.

$\longrightarrow$ see Assamagan's and Pieri's talks.

The LHC can also measure most SM Higgs couplings at 10-30%



Consider all "accessible" channels:

- Below 130-140 GeV

  $gg \to H\,,\; H \to \gamma\gamma, WW, ZZ$

  $qq \to qqH\,,\; H \to \gamma\gamma, WW, ZZ, \tau\tau$

  $q\bar{q}, gg \to t\bar{t}H\,,\; H \to \gamma\gamma, b\bar{b}, \tau\tau$

  $q\bar{q}' \to WH\,,\; H \to \gamma\gamma, b\bar{b}$

- Above 130-140 GeV

  $gg \to H\,,\; H \to WW, ZZ$

  $qq \to qqH\,,\; H \to \gamma\gamma, WW, ZZ$

  $q\bar{q}, gg \to t\bar{t}H\,,\; H \to \gamma\gamma, WW$

  $q\bar{q}' \to WH\,,\; H \to WW$

Observing a given production+decay (p+d) channel gives a relation:

$$(\sigma_p(H)\mathrm{Br}(H \to dd))^{exp} = \frac{\sigma_p^{th}(H)}{\Gamma_p^{th}} \frac{\Gamma_d \Gamma_p}{\Gamma_H}$$

(D. Zeppenfeld, PRD 62 (2000) 013009; A. Belyaev et al., JHEP 0208 (2002) 041)

Associate to each channel $(\sigma_p(H) \times Br(H \to dd))$

$$Z_d^{(p)} = \frac{\Gamma_p \Gamma_d}{\Gamma} \qquad \begin{cases} \Gamma_p \simeq g_{Hpp}^2 = y_p^2 \to \text{production} \\ \Gamma_d \simeq g_{Hdd}^2 = y_d^2 \to \text{decay} \end{cases}$$

From LHC measurements, with given simulated accuracies and theoretical systematic errors (GF: 20%, WBF: 4%, ttH: 15%, WH: 7%):

- Determine in a model independent way ratios of couplings at the $10-20\%$ level, for example:

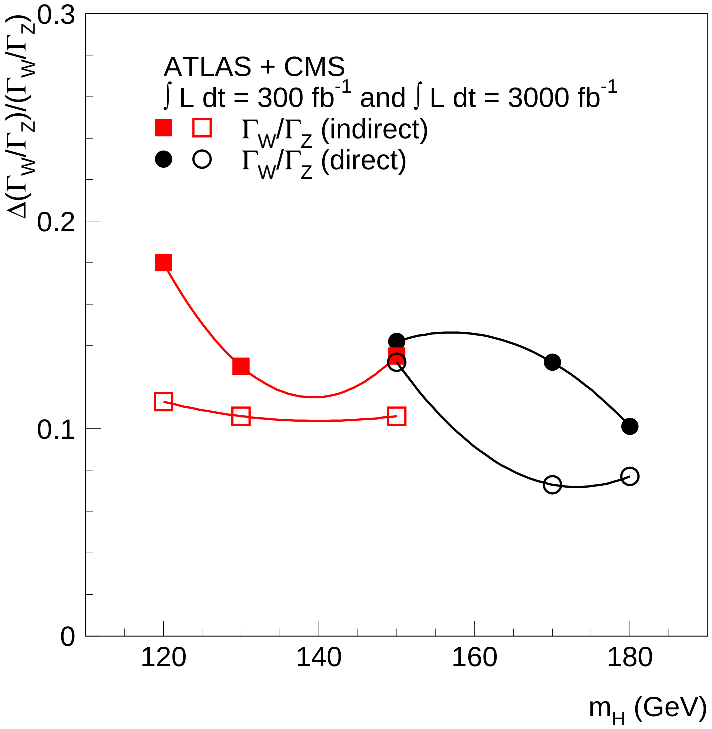
$$\frac{y_b}{y_\tau} \quad \longleftarrow \quad \frac{\Gamma_b}{\Gamma_\tau} = \frac{Z_b^{(t)}}{Z_\tau^{(t)}}$$

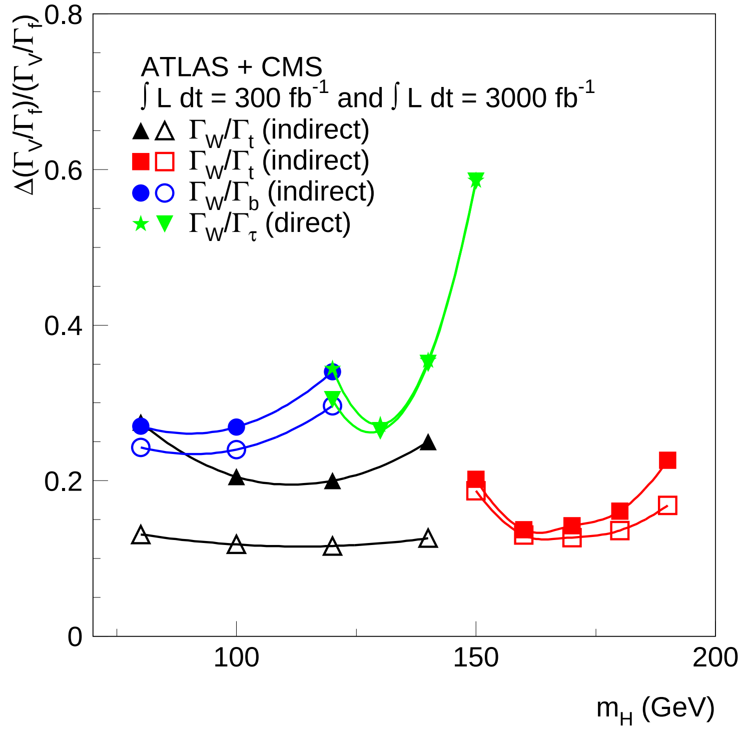
$$\frac{y_t}{y_g} \quad \longleftarrow \quad \frac{\Gamma_t}{\Gamma_g} = \frac{Z_\tau^{(t)} Z_\gamma^{(WBF)}}{Z_\tau^{(WBF)} Z_\gamma^{(g)}} \text{ or } \frac{Z_W^{(t)}}{Z_W^{(g)}}$$

  crucial to have many decay channels for the same production channel.

- determine individual couplings at the 10-30% level, assuming: $\Gamma_H \simeq \Gamma_b + \Gamma_\tau + \Gamma_W + \Gamma_Z + \Gamma_g + \Gamma_\gamma$, $\frac{\Gamma_W}{\Gamma_Z} = \left.\frac{\Gamma_W}{\Gamma_Z}\right|_{SM}$ and $\left(\frac{\Gamma_b}{\Gamma_\tau} = \left.\frac{\Gamma_b}{\Gamma_\tau}\right|_{SM}\right)$

Along these lines, exploring higher luminosity:





(F. Gianotti, M. Mangano, and T. Virdee, hep-ph/02040887)

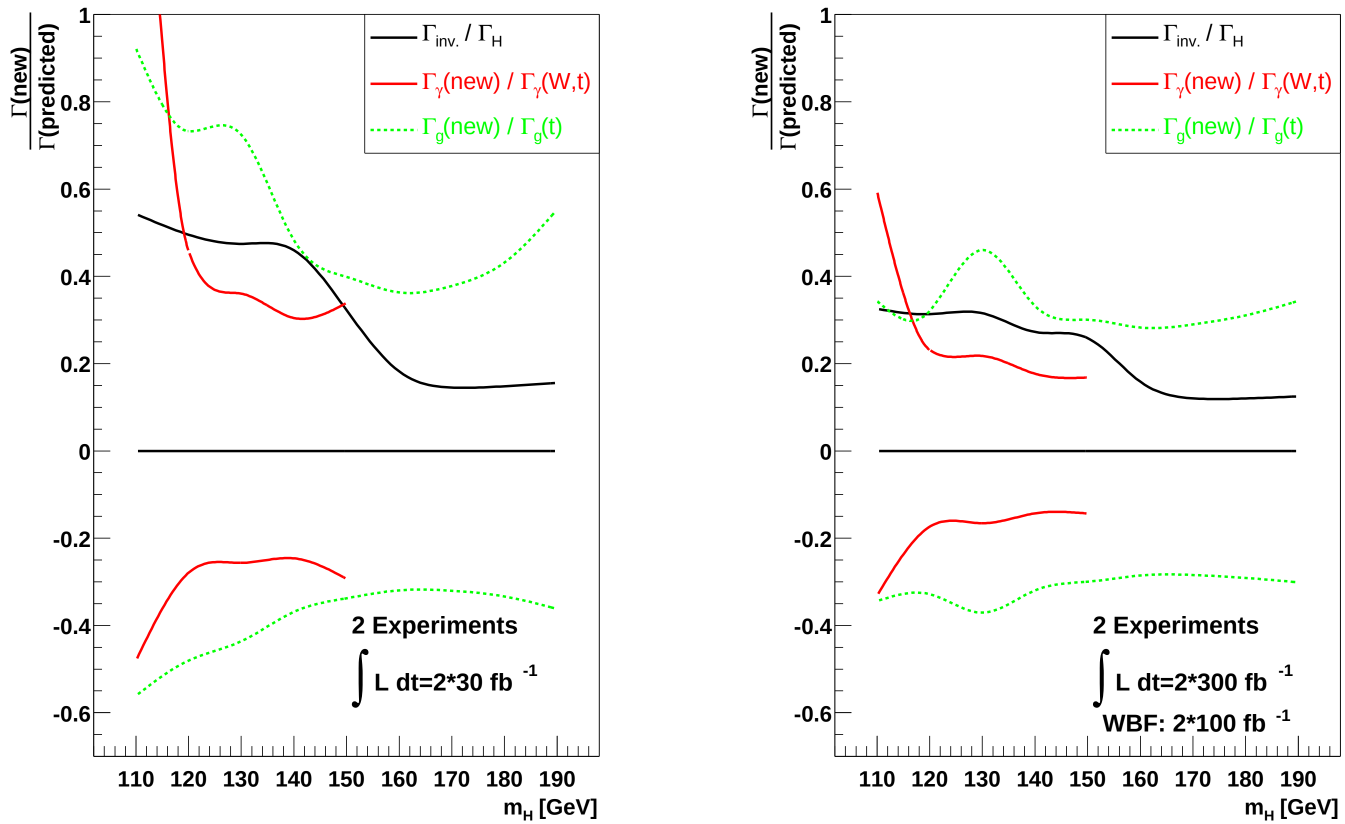
where the "indirect" ratios are obtained under some assumptions:

$$\frac{\Gamma_W}{\Gamma_Z} = \frac{Z_\gamma^{(g)}}{Z_Z^{(g)}} \;,\; \frac{\Gamma_W}{\Gamma_t} = \frac{Z_\gamma^{(WH)}}{Z_\gamma^{(g)}} \text{ or } \frac{Z_W^{(WH)}}{Z_W^{(g)}} \quad (\text{assuming } gg \to H \text{ is } t\text{-dominated})$$

$$\frac{\Gamma_W}{\Gamma_b} = \frac{Z_\gamma^{(t)}}{Z_b^{(t)}} \quad (\text{assuming } H \to \gamma\gamma \text{ is } W\text{-dominated})$$

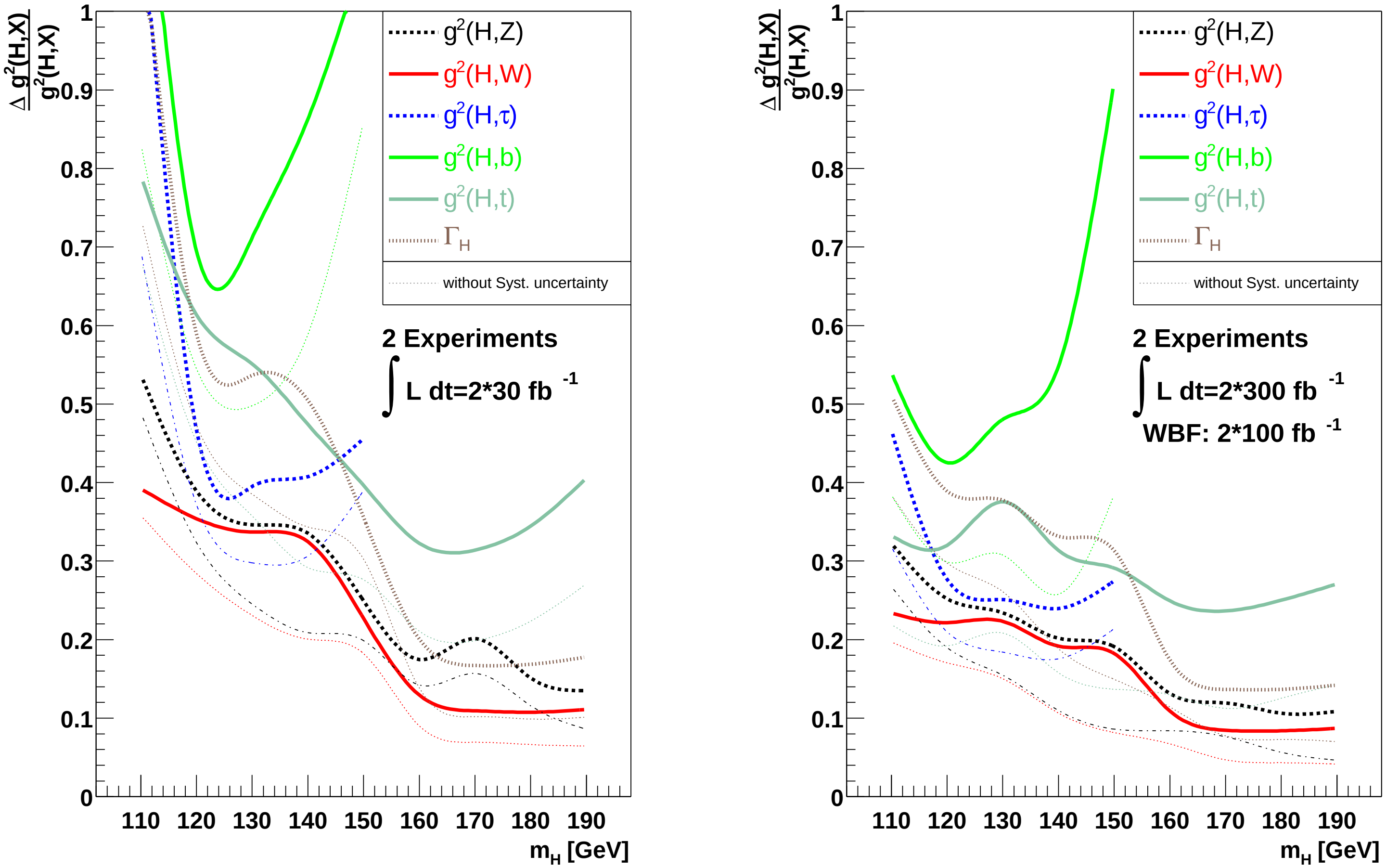
Toward a more model independent determination of Higgs couplings and width

Consider both a $\chi^2(x)$ and a likelihood function $L(x)$ over a parameter space (x) made of all partial widths plus $\Gamma_{\rm inv}$, $\Gamma_\gamma(\text{new})$, and $\Gamma_g(\text{new})$.



(M. Dührssen et al., PRD 70 (2004) 113009)

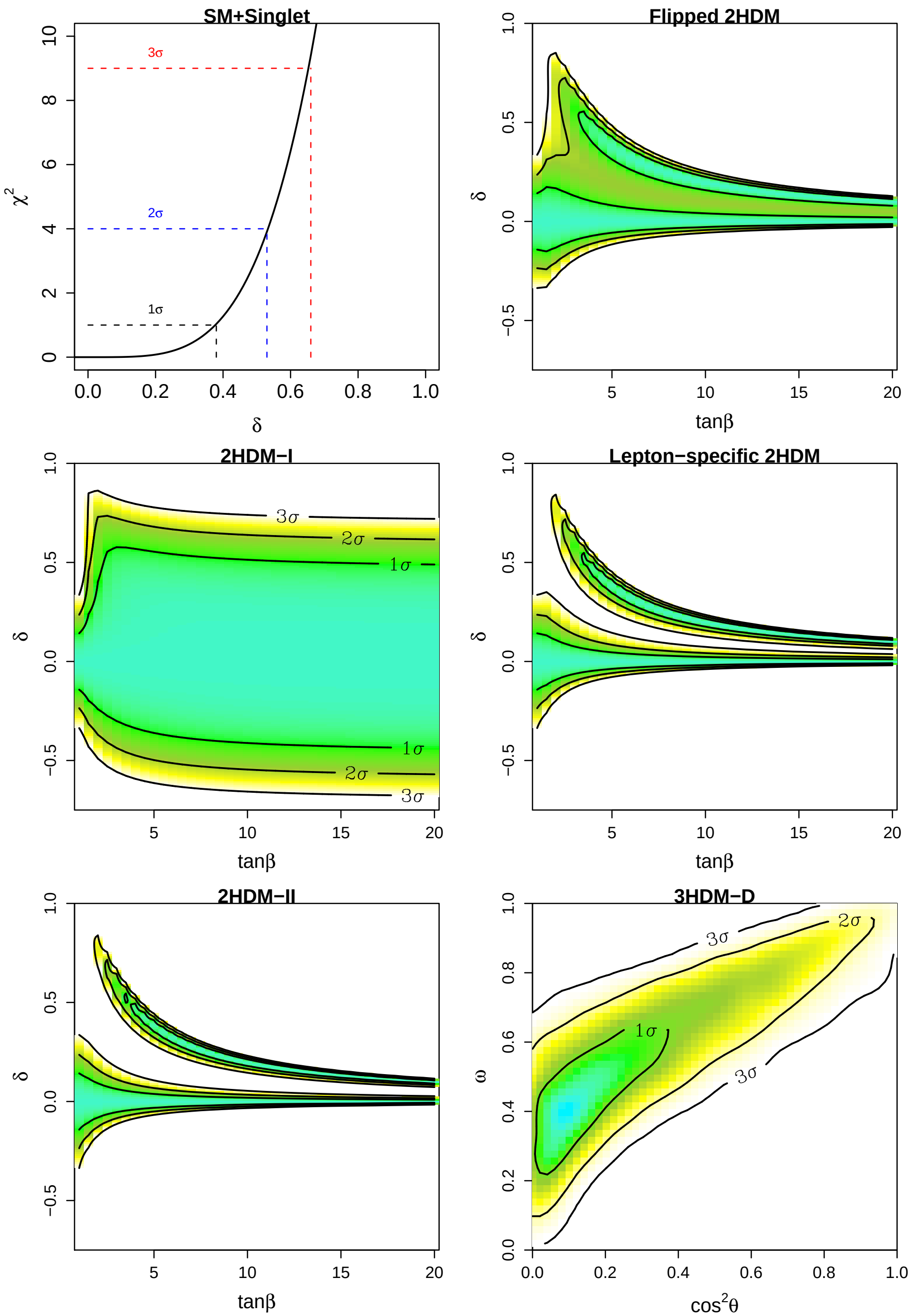
with the only assumption that: $g^2(H,V) < 1.05 \cdot g^2(H,V,SM) \quad (V = W,Z)$



(M. Dührssen et al., PRD 70 (2004) 113009)

- ▷ Most coupling within 10-40% at high luminosity (for light M_H);
- ▷ notice the impact of systematic uncertainties;
- ▷ of course, adding assumptions considerably lower the errors.

Looking for footprints of new physics:



Consider all extended Higgs sectors

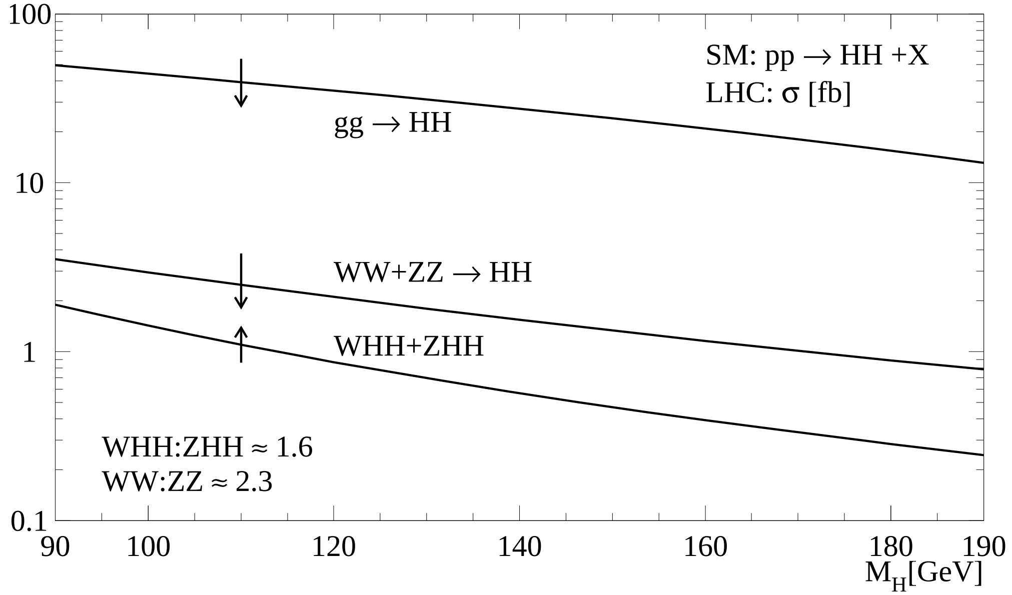
- involving $SU(2)_L$ doublets and singlets;
- with natural flavor conservation;
- without CP violation.

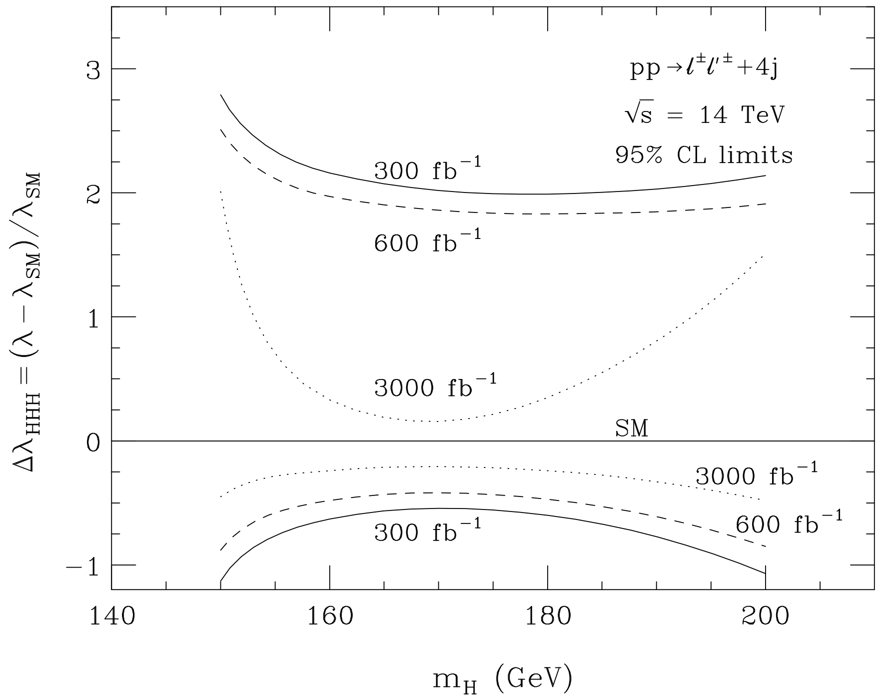
15 models have different footprints!

$\delta \longrightarrow$ decoupling parameter
($\delta = 0$: SM)

(V. Barger, H. Logan, G. Shaughnessy, arXiv:0902.0170)

The most difficult task: self couplings





(U. Baur, T. Plehn, D. Rainwater, PRD 67 (2003) 033003)

- ▷ mainly study 3H coupling (4H coupling too small);
- ▷ use: $gg \to HH \to W^+W^-W^+W^-$

Improving on theoretical uncertainties

accounting for higher order QCD effects at different levels

- Stability and predictivity of theoretical results, since less sensitivity to unphysical renormalization/factorization scales. First reliable normalization of total cross-sections and distributions. Crucial for:
  - $\longrightarrow$ precision measurements (M_W, m_t, M_H, $y_{b,t}$, $\ldots$);
  - $\longrightarrow$ searches for new physics (precise modelling of signal and background, reducing systematic errors in selection/analysis of data).
- Physics richness: more channels and more partons in final state, i.e. more structure to better model (in perturbative region):
  - $\longrightarrow$ differential cross-sections, exclusive observables;
  - $\longrightarrow$ jet formation/merging and hadronization;
  - $\longrightarrow$ initial state radiation.
- First step towards matching with algorithms that resum particular sets of large corrections in the perturbative expansion: resummed calculations, parton shower Monte Carlo programs.

Main challenges ...

- Multiplicity and Massiveness of final state: complex events leads to complex calculations. For a $2 \to N$ process one needs:
  $\longrightarrow$ calculation of the $2 \to N+1$ (NLO) or $2 \to N+2$ real corrections;
  $\longrightarrow$ calculation of the 1-loop (NLO) or 2-loop (NNLO) $2 \to N$ virtual corrections;
  $\longrightarrow$ explicit cancellation of IR divergences (UV-cancellation is standard).

- Flexibility of NLO/NNLO calculations via Automation:
  $\longrightarrow$ algorithms suitable for automation are more efficient and force the adoption of standards;
  $\longrightarrow$ faster response to experimental needs (think to the impact of projects like MCFM (J. Campbell and R. K. Ellis)).

- Matching to Parton Shower Monte Carlos.
  $\longrightarrow$ MC@NLO (S. Frixione and B. Webber)
  $\longrightarrow$ POWHEG (P. Nason et al.)

- NLO: challenges have largely been faced and enormous progress has been made. In a nutshell:
  - → traditional approach (FD's) becomes impracticable at high multiplicity;
  - → new techniques based on unitarity methods and recursion relations offers a powerful and promising alternative, particularly suited for automation;
  - → interface to parton shower Monte Carlos well advanced.

- When is NLO not enough?
  - → When NLO corrections are large, to tests the convergence of the perturbative expansion. This may happen when:
    - ▷ processes involve multiple scales, leading to large logarithms of the ratio(s) of scales;
    - ▷ new parton level subprocesses first appear at NLO;
    - ▷ new dynamics first appear at NLO;
    - ▷ ...
  - → When truly high precision is needed (very often the case!).
  - → When a really reliable error estimate is needed.

NLO: Recently completed calculations (since Les Houches 2005): all relevant to Higgs-boson physics!

Process ($V \in \{Z, W, \gamma\}$)	Comments
$pp \to V$+2 jets(b)	Campbell,Ellis,Maltoni,Willenbrock (06)
$pp \to Vb\bar{b}$	Febres Cordero,Reina,Wackeroth (07-08)
$pp \to VV$+jet	Dittmaier,Kallweit,Uwer (WW+jet) (07)
	Campbell,Ellis,Zanderighi (WW+jet+decay) (07)
	Binoth,Karg,Kauer,Sanguinetti (in progress)
$pp \to VV$+2 jets	Bozzi,Jäger,Oleari,Zeppenfeld (via WBF) (06-07)
$pp \to VVV$	Lazopoulos,Melnikov,Petriello (ZZZ) (07)
	Binoth,Ossola,Papadopoulos,Pittau (WWZ,WZZ,WWW) (08)
	Hankele,Zeppenfeld ($WWZ \to$ 6 leptons, full spin correlation) (07)
$pp \to H$+2 jets	Campbell,Ellis,Zanderighi (NLO QCD to gg channel)(06)
	Ciccolini,Denner,Dittmaier (NLO QCD+EW to WBF channel) (07)
$pp \to H$+3 jets	Figy,Hankele,Zeppenfeld (large N_c) (07)
$pp \to t\bar{t}$+jet	Dittmaier,Uwer,Weinzierl (07)
	Ellis,Giele,Kunszt (in progress)
$pp \to t\bar{t}Z$	Lazopoulos,Melnikov,Petriello (08)
$gg \to WW$	Binoth,Ciccolini,Kauer,Kramer (06)
$gg \to HH, HHH$	Binoth,Karg,Kauer,Rückl (06)

Process ($V \in \{Z, W, \gamma\}$)	Comments
NLO calculations remaining at Les Houches 2007	
$pp \to t\bar{t}\, b\bar{b}$	relevant for $t\bar{t}H$ (1)
$pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$
$pp \to VV\, b\bar{b}$,	relevant for WBF $\to H \to VV$, $t\bar{t}H$
$pp \to VV$+2jets	relevant for WBF $\to H \to VV$ (2)
$pp \to V$+3jets	various new physics signatures (3)
$pp \to b\bar{b}b\bar{b}$	Higgs and new physics signatures (4)
Calculations beyond NLO added at Les Houches 2007	
$gg \to W^*W^*\ \mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs (5)
NNLO $pp \to t\bar{t}$	normalization of a benchmark process (6)
NNLO to WBF and Z/γ+jet	Higgs couplings and SM benchmark (7)

(1) $q\bar{q} \to t\bar{t}b\bar{b}$ calculated by A. Bredenstein, A. Denner, S. Dittmaier, and S. Pozzorini (08).

(2) WBF contributions calculated by G. Bozzi, B. Jäger, C. Oleari, and D. Zeppenfeld (06-07).

(3) leading-color contributions calculated by: R. K. Ellis, et al. (08-09); Z. Bern et al. (08-09).

(4) T. Binoth et al., in progress.

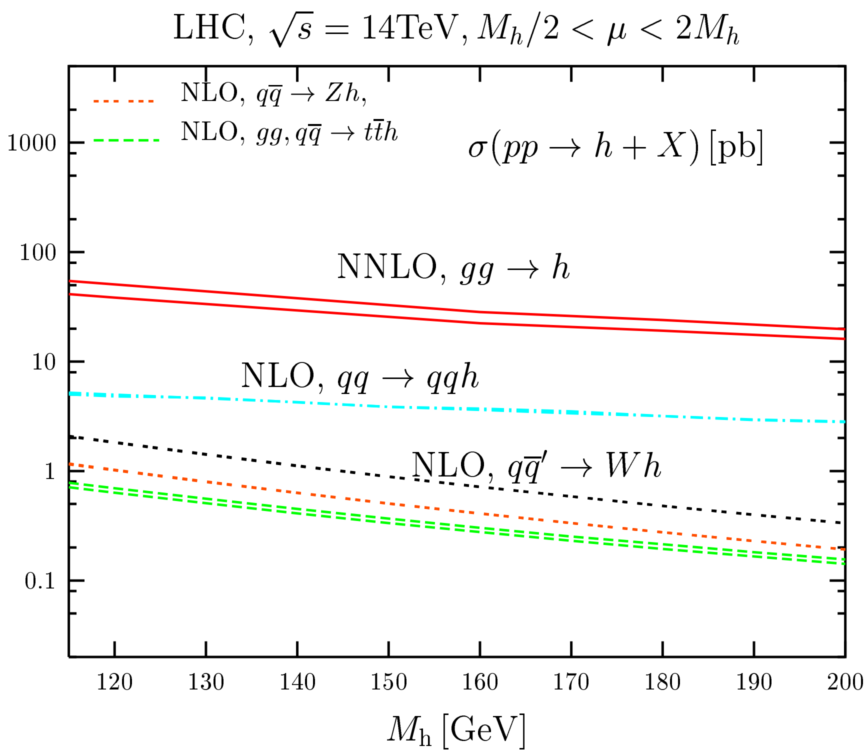
(5) $q\bar{q} \to WW$ calculated by G. Chachamis, M. Czakon, and D. Eiras (08) (small M_W).

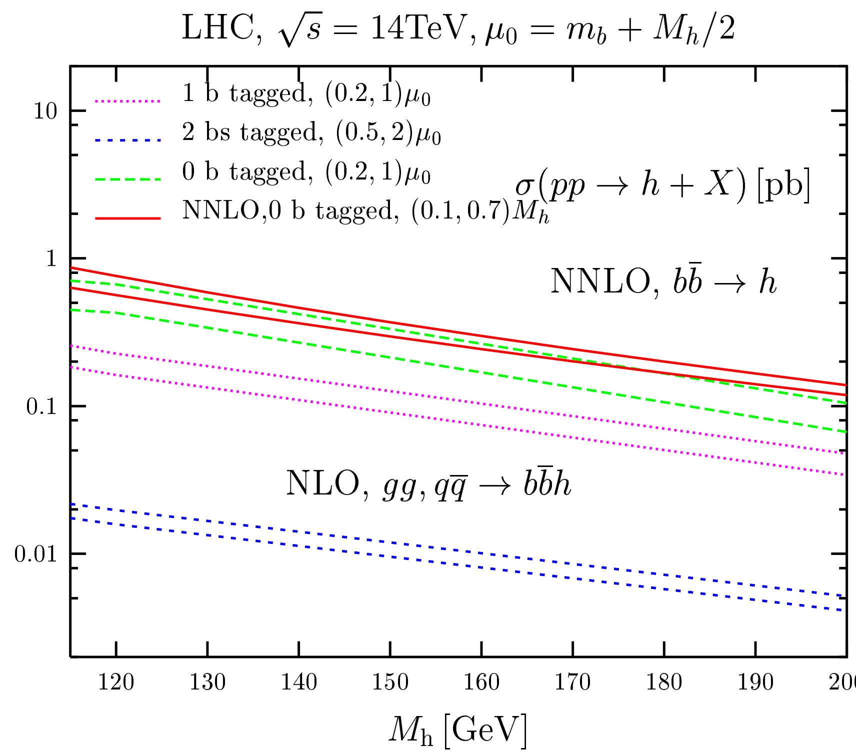
(6) M. Czakon, A. Mitov, and S. Moch (06-08) (analytical for $m_Q^2 \ll s$, exact numerical estimate).

(7) A. Gehrmann-De Ridder, T. Gehrmann, et al., work in progress.

SM Higgs-boson production: theoretical precision at a glance.

QCD predictions for total cross sections of Higgs-boson production processes are under good theoretical control:



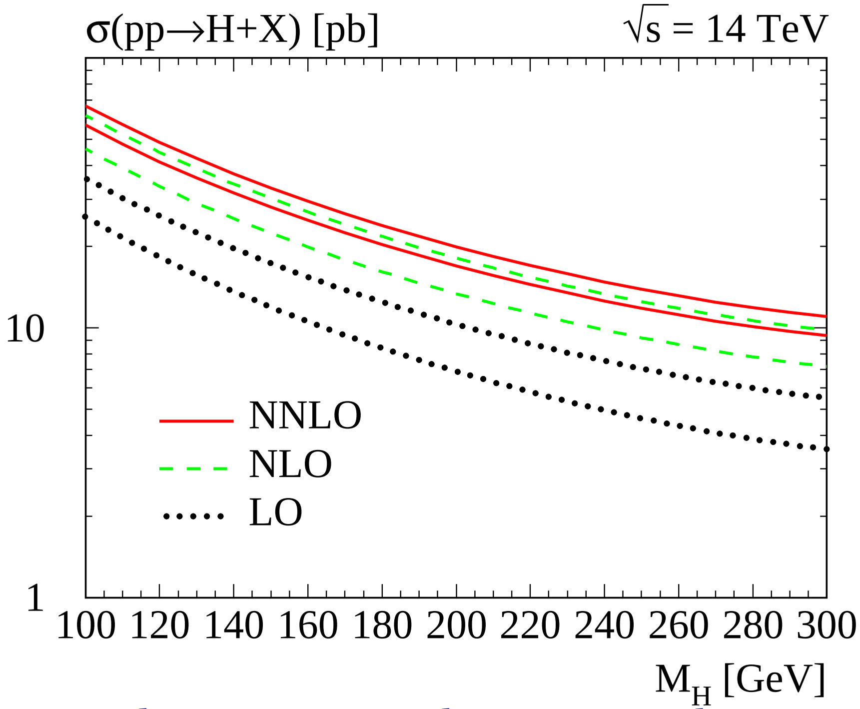


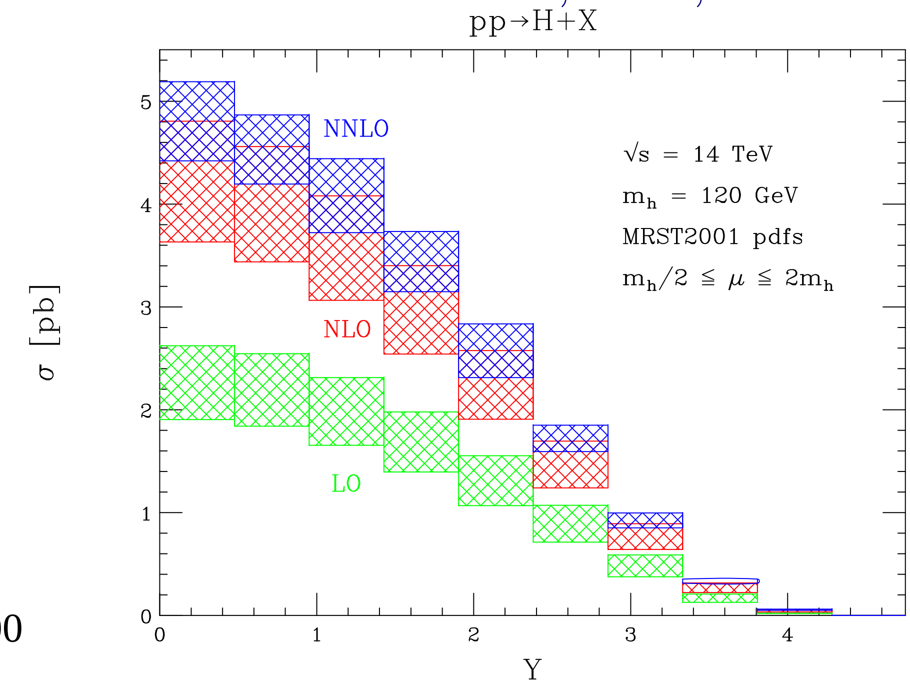
Caution: in these plots uncertainties only include μ_R/μ_F scale dependence, PDF's uncertainties are not included.

Ex. 1: $gg \to H$, the main production mode

Harlander,Kilgore (03); Anastasiou,Melnikov,Petriello (03)

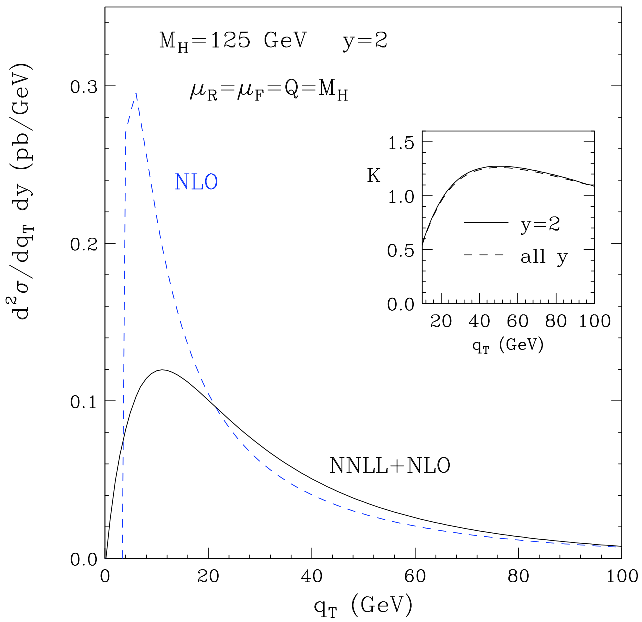
Ravindran,Smith,van Neerven (04)





- dominant production mode in association with $H \to \gamma\gamma$ or $H \to WW$ or $H \to ZZ$;
- dominated by soft dynamics: effective ggH vertex can be used ($3 \to 2$-loop);
- perturbative convergence LO $\to$ NLO (70%) $\to$ NNLO (30%): residual 15% theoretical uncertainty.

Inclusive cross section, resum effects of soft radiation:



large $q_T \xrightarrow{q_T > M_H}$

perturbative expansion in $\alpha_s(\mu)$

small $q_T \xrightarrow{q_T \ll M_H}$

need to resum large $\ln(M_H^2/q_T^2)$

Bozzi,Catani,De Florian,Grazzini (04-08)

Update: Going from MRST2002 to MSTW2008 greatly affects the LHC cross section: from 30% ($M_H = 115$ GeV) to 9% ($M_H = 300$ GeV) !

De Florian,Grazzini (09)

Exclusive NNLO results: e.g. $gg \to H \to \gamma\gamma, WW, ZZ$

Extension of (IR safe) subtraction method to NNLO:

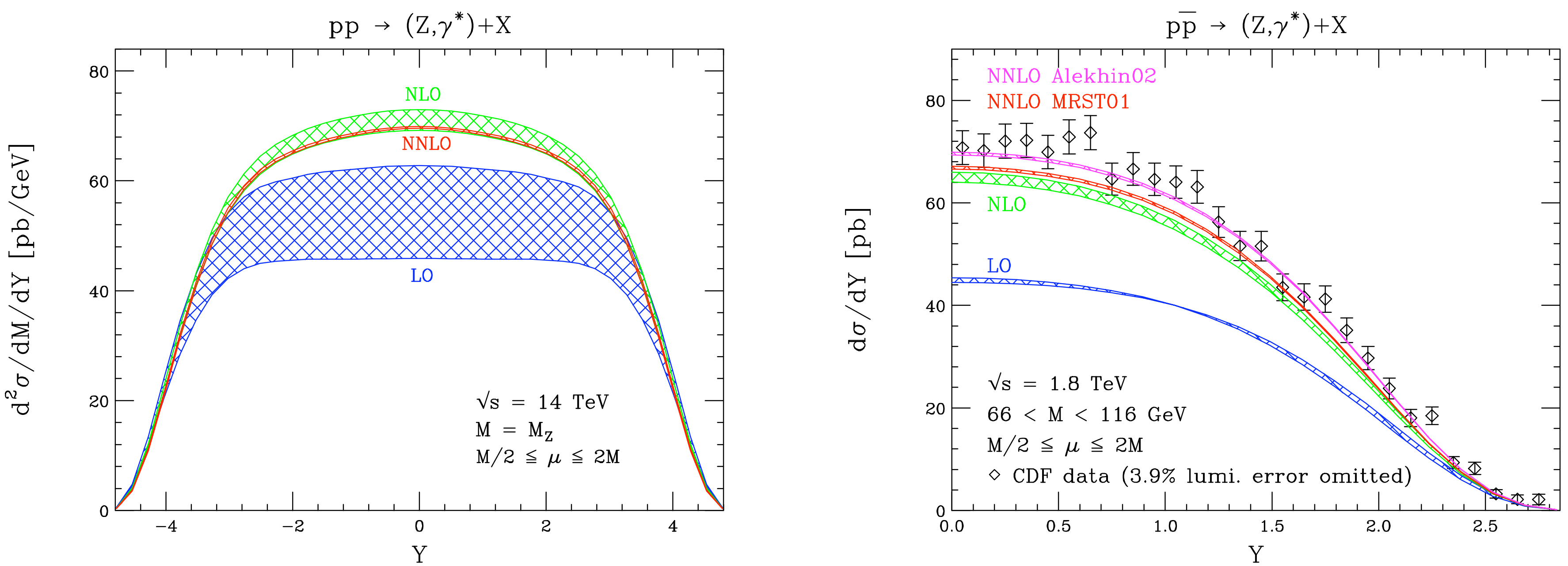
$\longrightarrow$ HNNLO (Catani,Grazzini)

$\longrightarrow$ FEHiP (Anastasiou,Melnikov,Petriello)

Ex. 2: $W/Z + X$ production, testing parton luminosity.

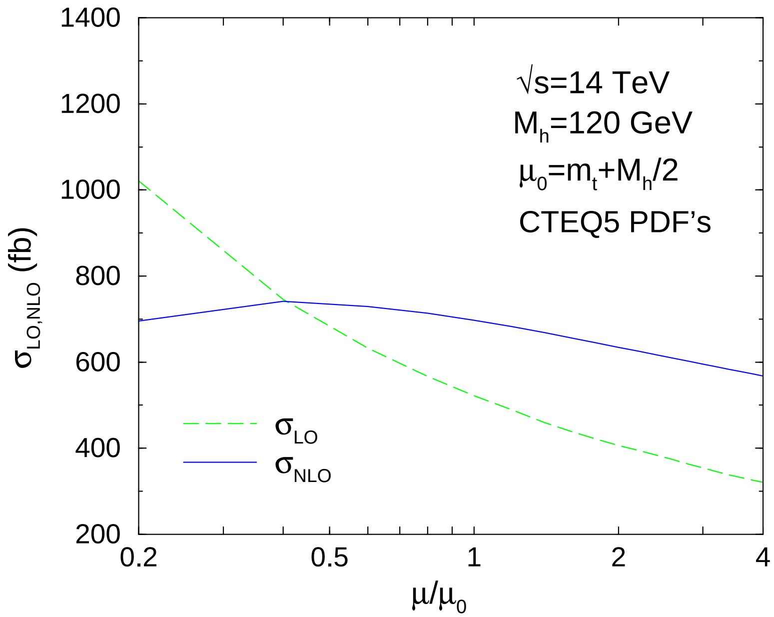
Anastasiou,Dixon,Melnikov,Petriello (03)

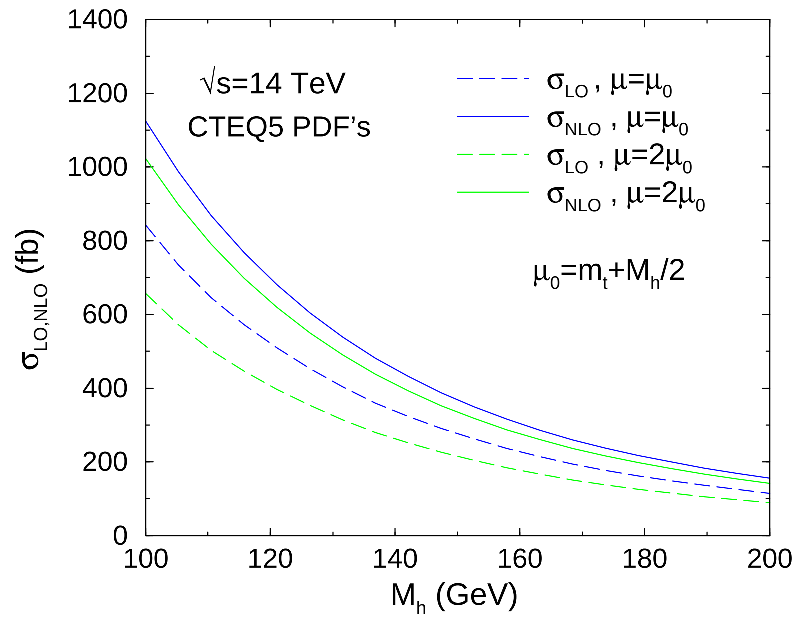
Rapidity distributions of W and Z boson calculated at NNLO:



- W/Z production processes are standard candles at hadron colliders.
- Testing NNLO PDF's: parton-parton luminosity monitor, detector calibration (NNLO: 1% residual theoretical uncertainty).

Ex. 3: $pp \to t\bar{t}H$, crucial to explore Higgs couplings.

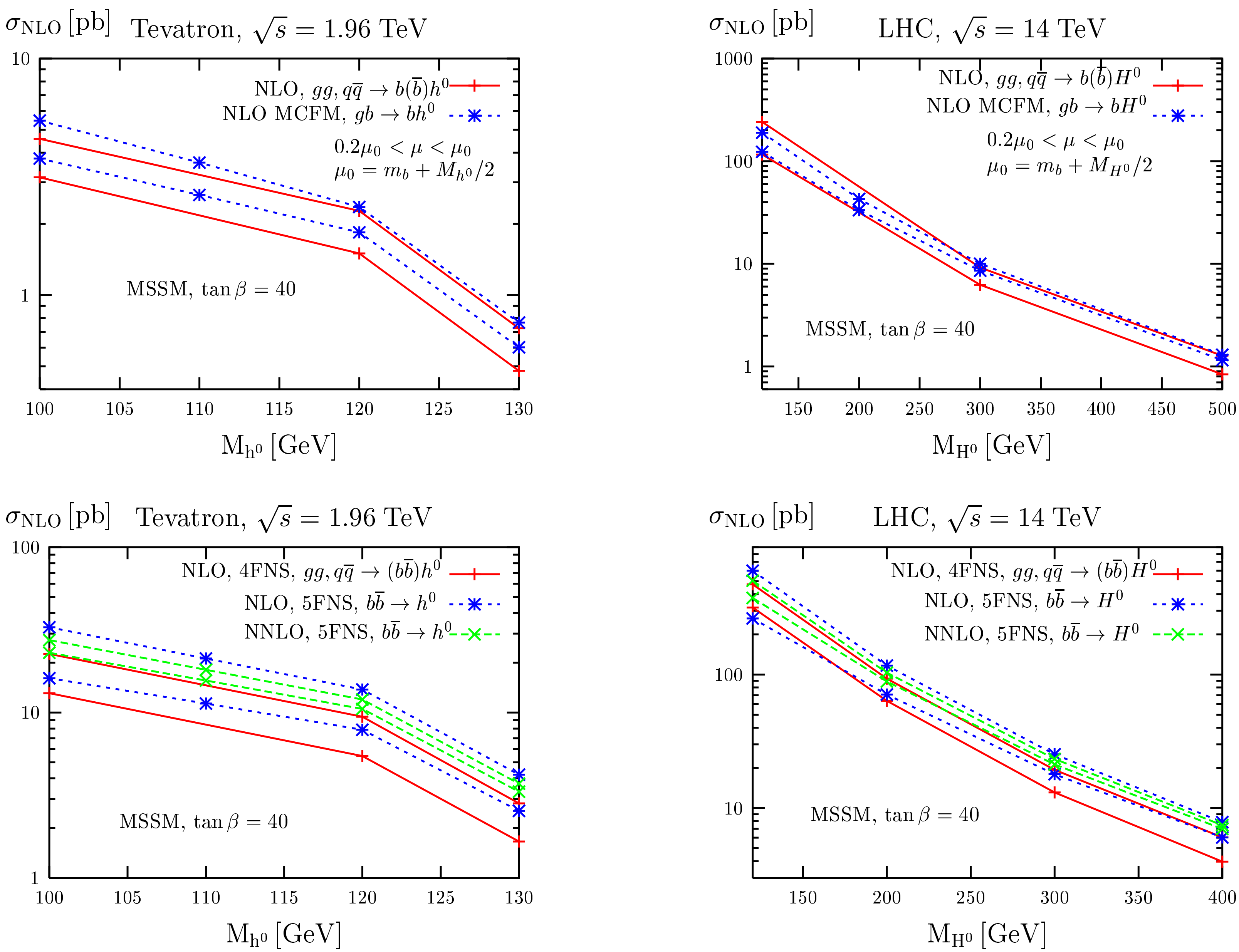




Dawson, Jackson, Orr, L.R., Wackeroth (01-03)

- Fully massive $2 \to 3$ calculation: testing the limit of FD's approach (pentagon diagrams with massive particles).
- Independent calculation: Beenakker et al., full agreement.
- Theoretical uncertainty reduced to about 15%
- Several crucial backgrounds: $t\bar{t}+j$ (NLO, Dittmaier,Uwer,Weinzierl), $t\bar{t}b\bar{b}$, $t\bar{t}+2j$, $VV+b\bar{b}$.

Ex. 4: $pp \to b\bar{b}H$, hint of enhanced b-quark Yukawa coupling



Dawson, Jackson, L.R., Wackeroth (05)

Ex. 5: $pp \to b\bar{b}W/Z$, crucial but not well-understood background.

$\longrightarrow$ $V \longrightarrow 4$ partons (1-loop massless amplitudes) (Bern, Dixon, Kosower (97))

$\longrightarrow$ $p\bar{p}, pp \to Vb\bar{b}$ (at NLO, 4FNS, $m_b = 0$) (Campbell, Ellis (99))

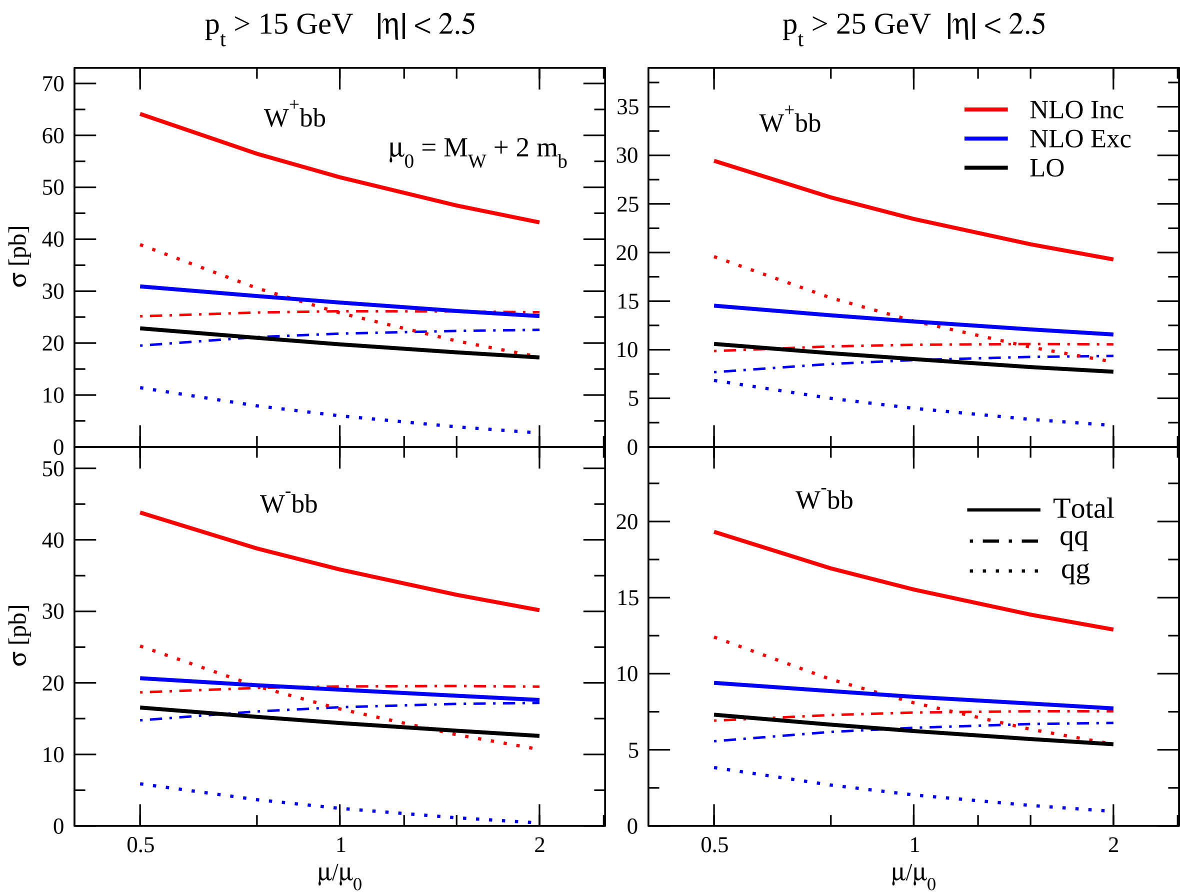
$\longrightarrow$ $p\bar{p}, pp \to Vb + j$ (at NLO, 5FNS) (Campbell, Ellis, Maltoni, Willenbrock (05,07))

$\longrightarrow$ $p\bar{p}, pp \to Wb\bar{b}$ (at NLO, 4FNS, $m_b \neq 0$) (Febres Cordero, L.R., Wackeroth (06))

$\longrightarrow$ $p\bar{p}, pp \to Zb\bar{b}$ (at NLO, 4FNS, $m_b \neq 0$) (Febres Cordero, L.R., Wackeroth (08))

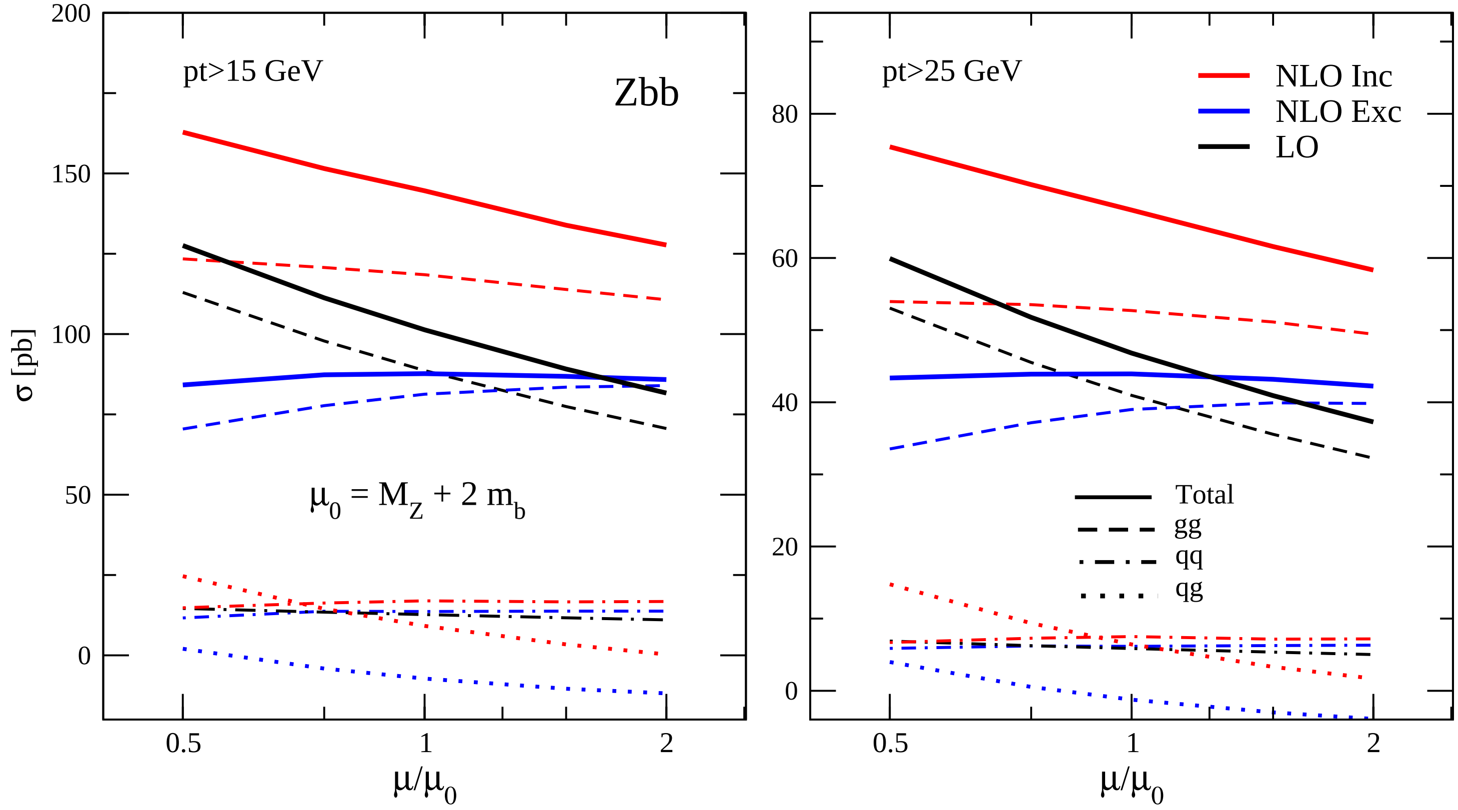
$\longrightarrow$ $p\bar{p}, pp \to W + 1\, b$-jet (at NLO, 5FNS+4FNS with $m_b \neq 0$) (Campbell, Ellis, Febres Cordero, Maltoni, L.R., Wackeroth, Willenbrock (08))

Scale dependence and theoretical uncertainty at NLO, LHC



preliminary!

- New NLO contribution ($qg \to Wb\bar{b}q'$) worsen scale dependence;
- exclusive cross section more stable than inclusive one.

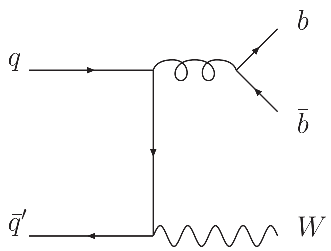


Cross Section, $Zb\bar{b}$ (pb)	$p_T^b > 15$ GeV	$p_T^b > 25$ GeV
$\sigma^{\rm LO}$	101.3 ($\pm$22%)	46.8 ($\pm$23%)
$\sigma^{\rm NLO}$ inclusive	144.6 ($\pm$12%)	66.6 ($\pm$13%)
$\sigma^{\rm NLO}$ exclusive	87.7 ($\pm$3%)	43.9 ($\pm$2%)

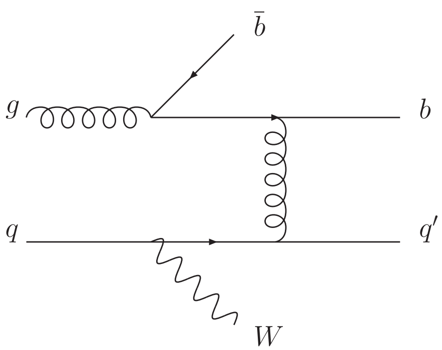
$W + 1\, b$-jet

Campbell, Ellis, Febres Cordero, Maltoni, L.R., Wackeroth, Willenbrock (0809.3003)

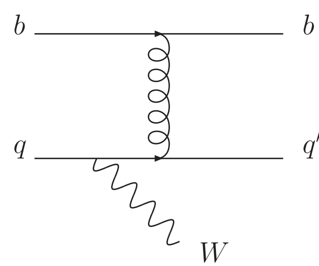
Combine 4FNS ($m_b \neq 0$) and 5FNS ($m_b = 0$) NLO QCD results to get a more precise theoretical prediction of a crucial background.



$+ \quad O(\alpha_s)$ corrections



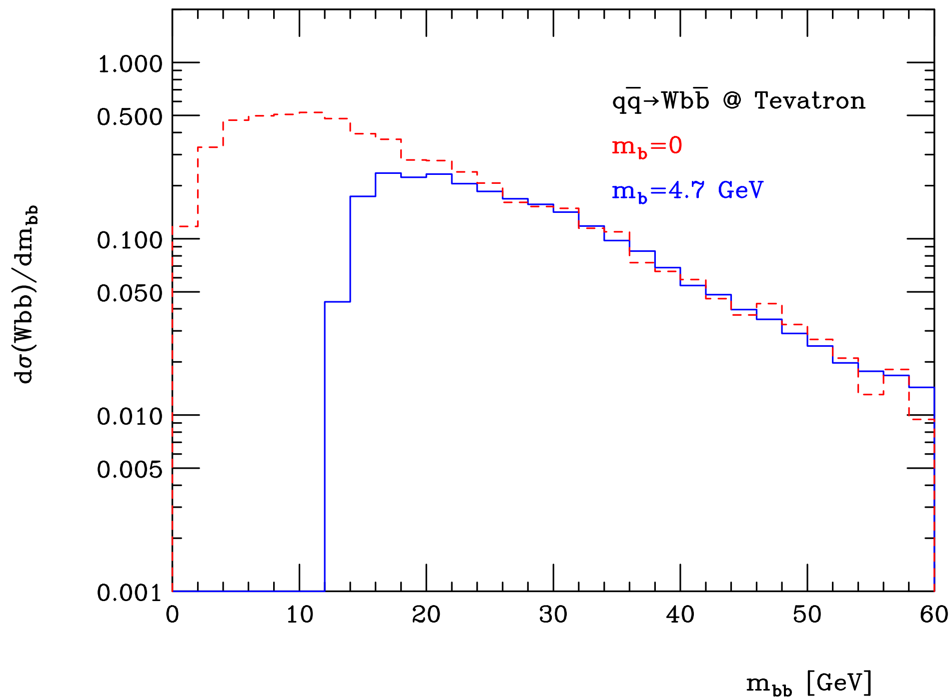
$\longrightarrow$



$+ \quad O(\alpha_s)$ corrections

- consistently combine 4FNS and 5FNS to avoid double counting
- improved scale dependence
- both contributions play important complementary roles (Tevatron/LHC, inclusive/exclusive)

- need to keep $m_b \neq 0$ for final state b quarks (one b quark has low p_T)



- four signatures studied: exclusive/inclusive, with single and double-b jets, using $p_T^j > 15$ GeV, $|\eta^j| < 2 - 2.5$, cone algorithm with $\Delta R = 0.7$:

  $\longrightarrow$ Wb, $W(b\bar{b})$ (exclusive)

  $\longrightarrow$ $Wb + Wb + j$, $W(b\bar{b} + W(b\bar{b}) + j$ (inclusive)

  which can be combined to obtain different backgrounds, adapted to different jet schemes, resummation of final state large logarithms, ...

As part of this workshop and the Les Houches 2009 workshop:

- ▷ Final results for $W/Zb\bar{b}$ production at the LHC soon to appear.
- ▷ Provide input to experimentalists:
  - D∅, CDF, both Higgs and single-top working groups: provide parton level distributions with specific cuts;
  - CMS Higgs working group: provide parton level distributions with specific cuts and interface with NLO parton shower Monte Carlo (POWHEG).
- ▷ $Z + 1b$-jet using both 4FNS with $m_b \neq 0$ and 5FNS NLO calculations: quite different pattern!
- ▷ Can we get information on b-PDF?
- ▷ $H + 1b$-jet using both 4FNS and 5FNS calculations.

Conclusions and Outlook

- The LHC with high luminosity and its upgrades (SLHC, VLHC) will have access to Higgs-boson precision physics.
- While we wait for discoveries ...
- Using the SM as a "template", we can test our ability to pinpoint the properties of to-be-discovered scalar and pseudoscalar particles:
  - ▷ revisit existing studies;
  - ▷ identify main sources of systematic uncertainty;
  - ▷ work at reducing them, both theoretically and experimentally.
- Building on solid SM ground, start exploring beyond SM scenarios in as much generality as possible, looking for differences in "footprints".