Higgs Boson Physics

from indirect constraints to direct searches

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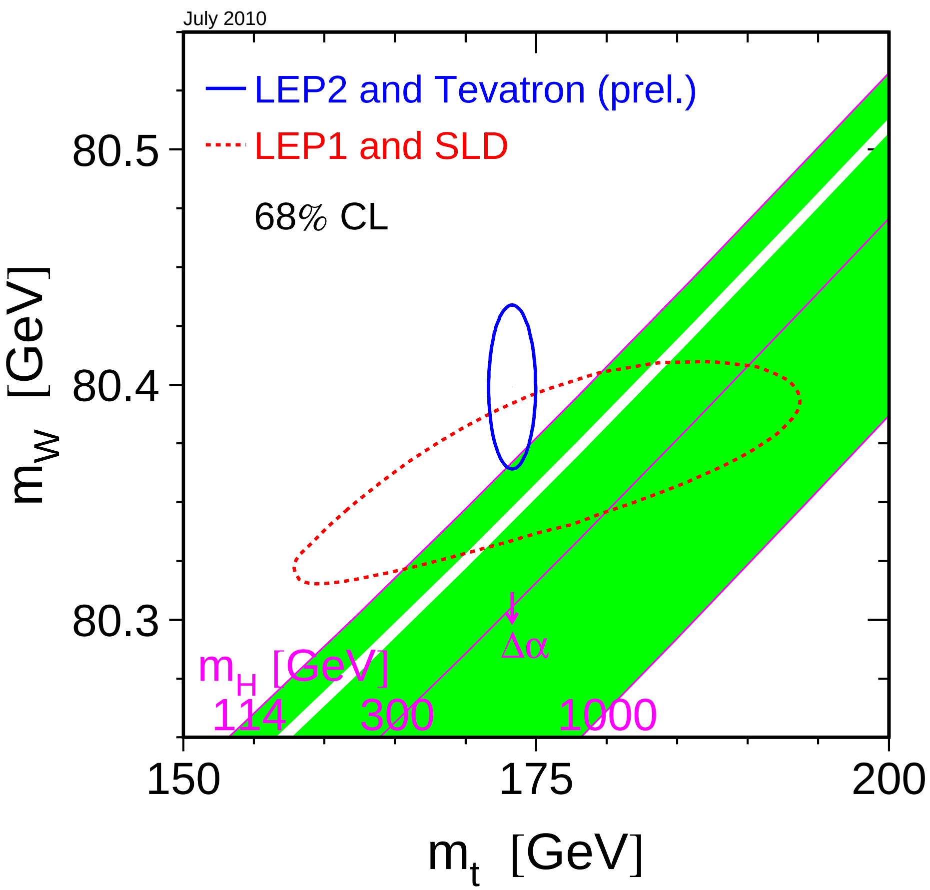
- Unveiling the origin of Electroweak Symmetry Breaking (EWSB): top priority of both the Tevatron and the LHC,
  - $\hookrightarrow$ Tevatron: can set exclusion limits;
  - $\hookrightarrow$ LHC: can discover related particles and their dynamics.

- Spectrum of ideas to explain EWSB: based on weakly or strongly coupled dynamics embedded into some more fundamental theory at a scale Λ ($\simeq$ TeV):
  - $\rightarrow$ Elementary Higgs: SM, 2HDM, SUSY (MSSM, NMSSM,...), ...
  - $\rightarrow$ Composite Higgs: technicolor, little Higgs models, ...
  - $\rightarrow$ Extra Dimensions: flat,warped, ...
  - $\rightarrow$ Higgsless models
  - $\rightarrow$ ...

- SM Higgs boson, our learning ground:
  - $-$ $\mathcal{L}_{Higgs}^{SM} = (D^\mu\phi)^\dagger D_\mu\phi - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2 \;\; (\mu^2 < 0):$
  - $-$ scalar particle, neutral, CP even, $m_H^2 = -2\mu^2 = 2\lambda v^2$;
  - $-$ minimally coupled to gauge bosons $\longrightarrow M_W = g\frac{v}{2}$, $M_Z = \sqrt{g^2 + g'^2}\frac{v}{2}$;
  - $-$ coupled to fermions via Yukawa interactions $\longrightarrow m_f = y_f\frac{v}{2}$;
  - $\hookrightarrow$ mass constrained by EW precision fits.

SM Higgs-boson mass range: constrained by EW precision fits

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



$$m_W = 80.399 \pm 0.023 \text{ GeV}$$

$$m_t = 173.3 \pm 1.1 \text{ GeV}$$

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$$M_H = 89^{+35}_{-26} \text{ GeV}$$

$$M_H < 158\,(185) \text{ GeV}$$

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

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

$$M_H \neq 158 - 175 \text{ GeV (Tevatron)}$$

focus is now on exclusion limits and discovery!

- New Precision Program: for signal and background processes in Higgs-boson production,
  - ▷ theoretical predictions: stability and control of the systematic errors;
  - ▷ theoretical predictions: test validity of existing results in different regimes and under different exclusive cuts;
  - ▷ enforce standards in multi-process studies/analyses (e.g.: combining different production channels, comparing signal and background, etc.);
  - ▷ make experimental selection process more transparent;
  - ▷ ...

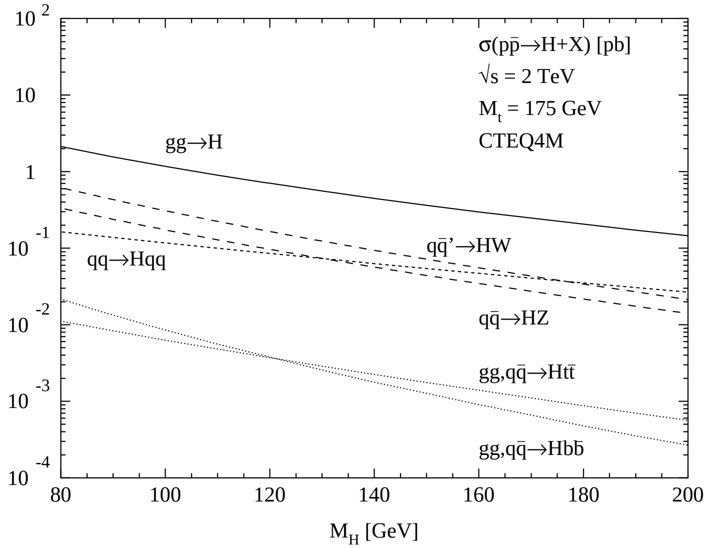
- Explore new techniques and new ideas to fully exploit the discovery potential,
  - ▷ boosted regimes (used for WH/ZH, and $t\bar{t}H$);
  - ▷ jet substructure (used for WH/ZH, and $t\bar{t}H$);

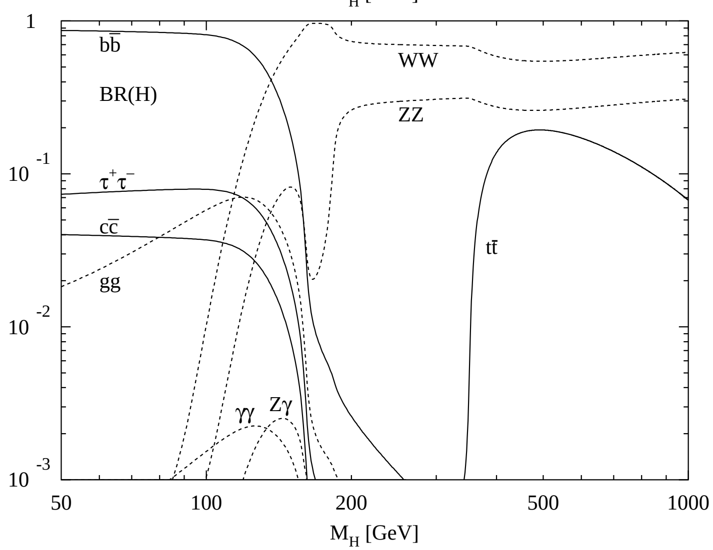
    (Butterworth, Davison, Rubin, Salam, arXiv:0802.2470),

    (Piacquadio,CERN-THESIS-2010-027, 2010),

    (Plehn, Salam, Spannowski,arXiv:0802.2470)
  - ▷ new variables (lower theoretical uncertainty, ...).

Tevatron: great potential for a light SM-like Higgs boson





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

Lower mass region:

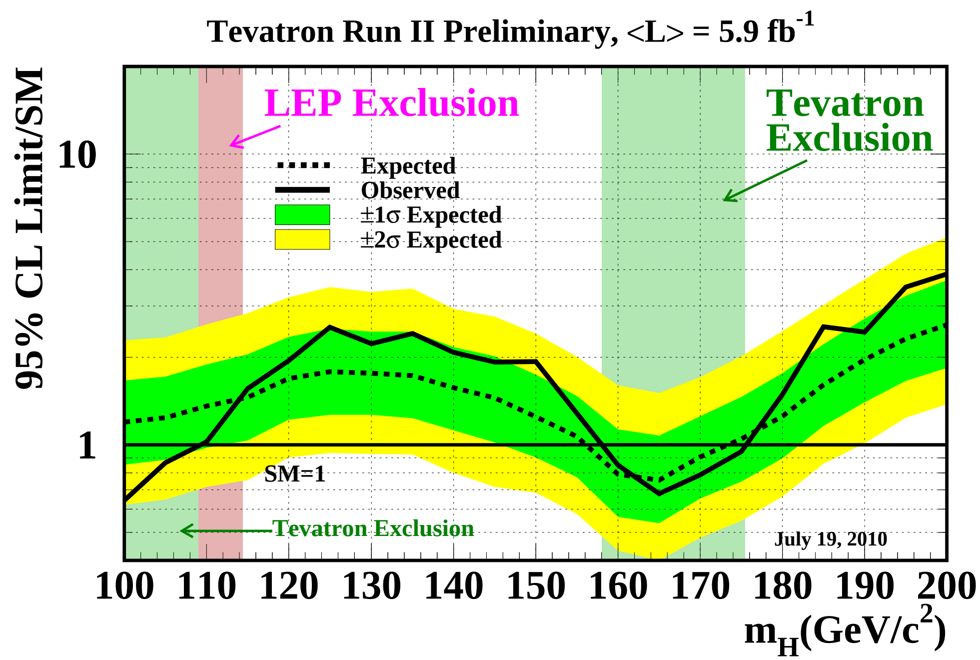
$$q\bar{q}' \to WH, H \to b\bar{b}$$

Higher mass region:

$$gg \to H, H \to W^+W^-$$

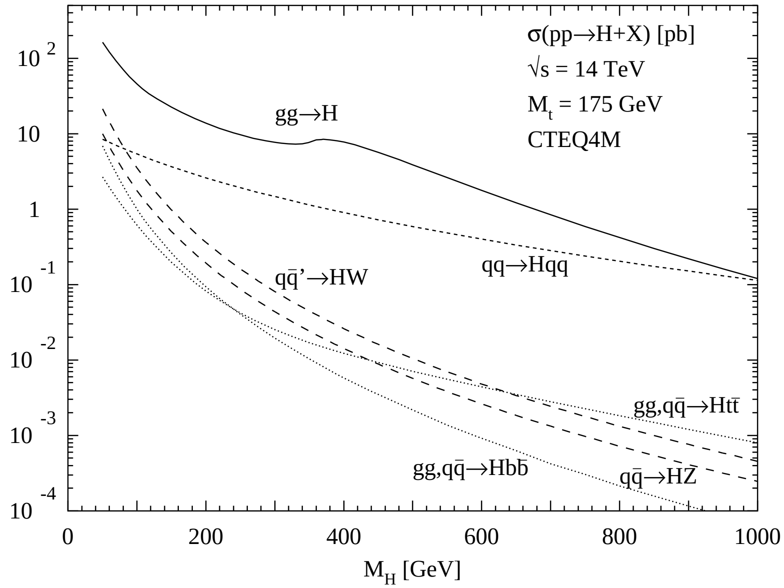
(smaller impact:

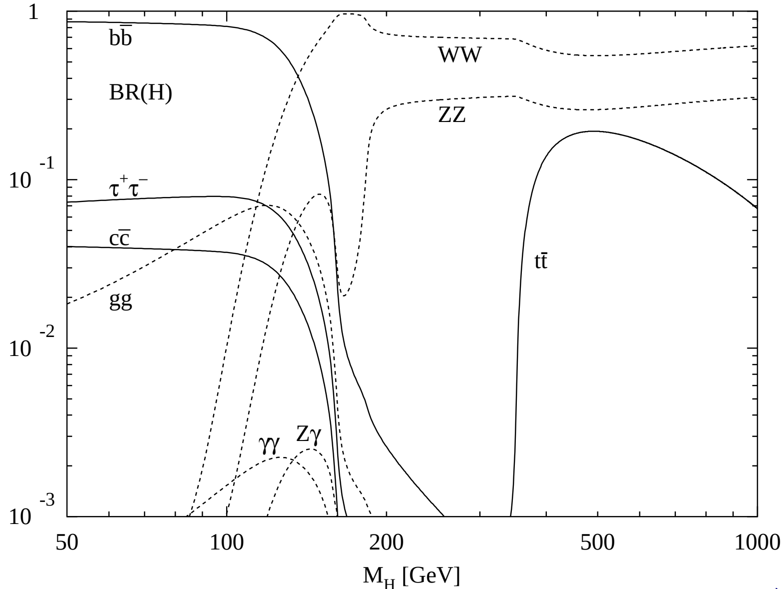
$q\bar{q} \to q'\bar{q}'H,\ q\bar{q}, gg \to t\bar{t}H$)



↪ Exclusion region very important for LHC search strategies.

LHC: entire SM Higgs-boson mass range accessible





(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:

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

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

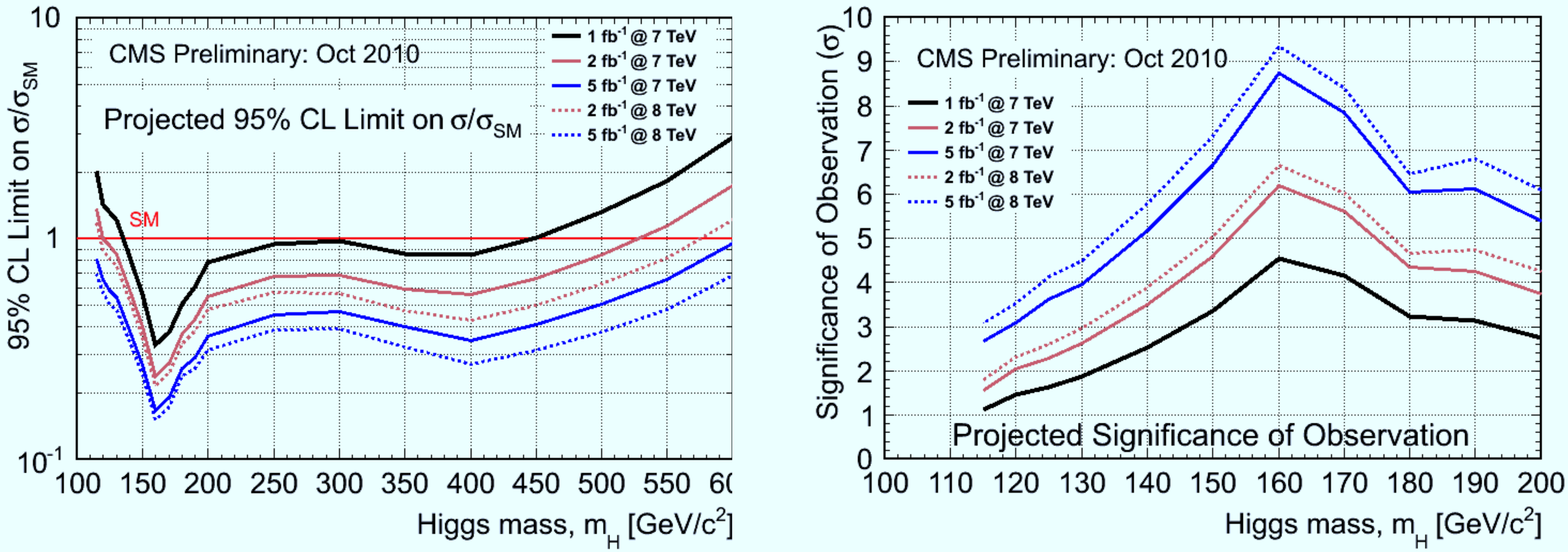
$q\bar{q}, gg \to t\bar{t}H\ ,\ H \to \gamma\gamma, WW$

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

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

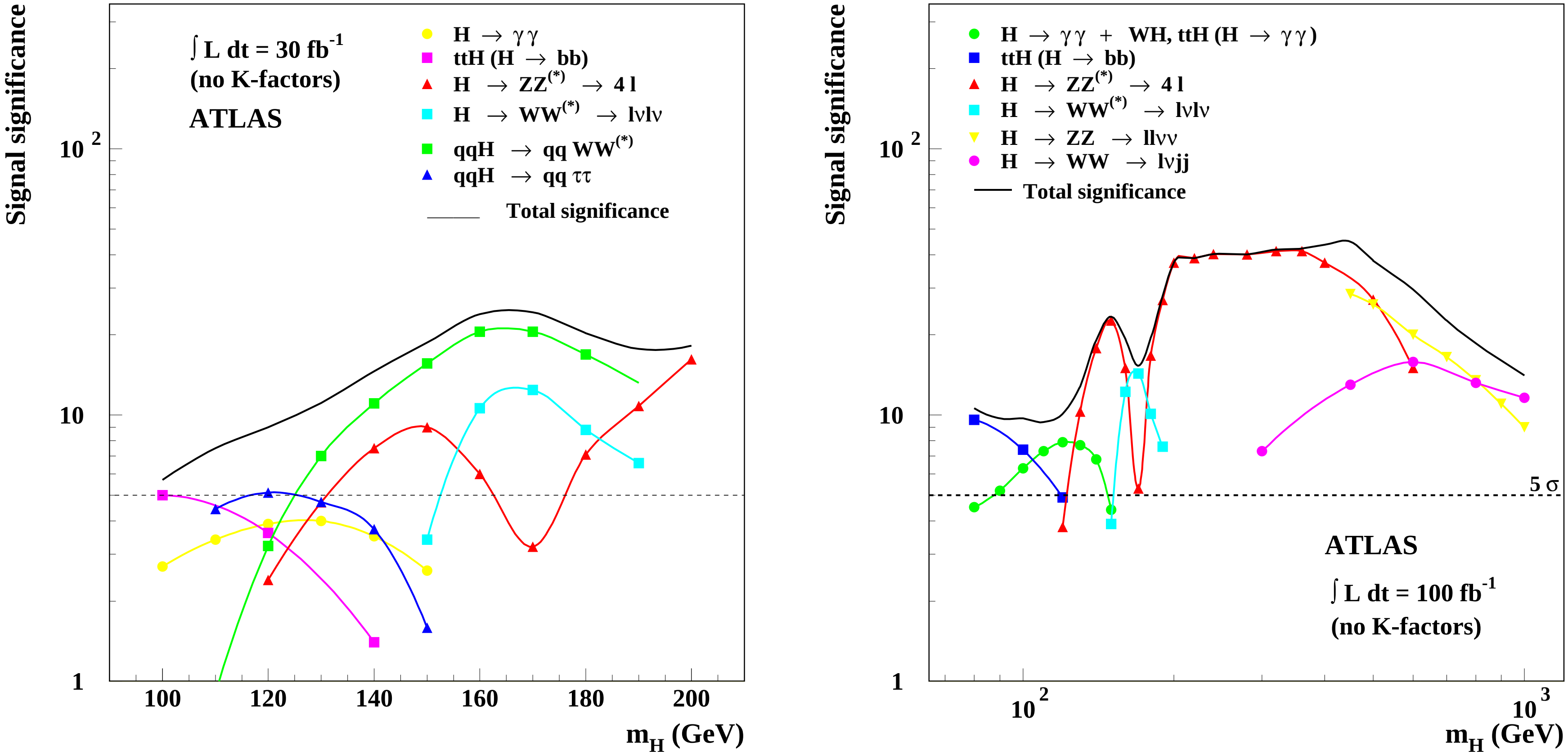
Combining only $H \to W^+W^-$, $H \to ZZ$, $H \to \gamma\gamma$, ATLAS and CMS indicate that,

- if no signal, the SM Higgs can be excluded in the range 140 – 200 GeV;
- a 5σ significance for a SM Higgs in the 160 – 170 GeV mass range;
- in the low mass region ($\hookleftarrow$ new strategies, new ideas).



where also $WH, H \to b\bar{b}$ (highly boosted) and VBF with $H \to \tau\tau$ were used.

LHC: high luminosity projections (old)



- ▷ Low mass region still difficult at low luminosity.
- ▷ Channels like $WH, H \to b\bar{b}$ absent even at 30 fb^{-1}.
- ▷ Updated studies would probably show very different features.

Crucial to have access to the best theoretical predictions for Higgs-boson cross sections and branching ratios.

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The LHC Higgs Cross Sections Working Group
(https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections)

Two stages:

- inclusive observables (studies done in 2010) (arXiv:1101.0593$\rightarrow$ Yellow Book);
- exclusive observables (studies started in 2011).

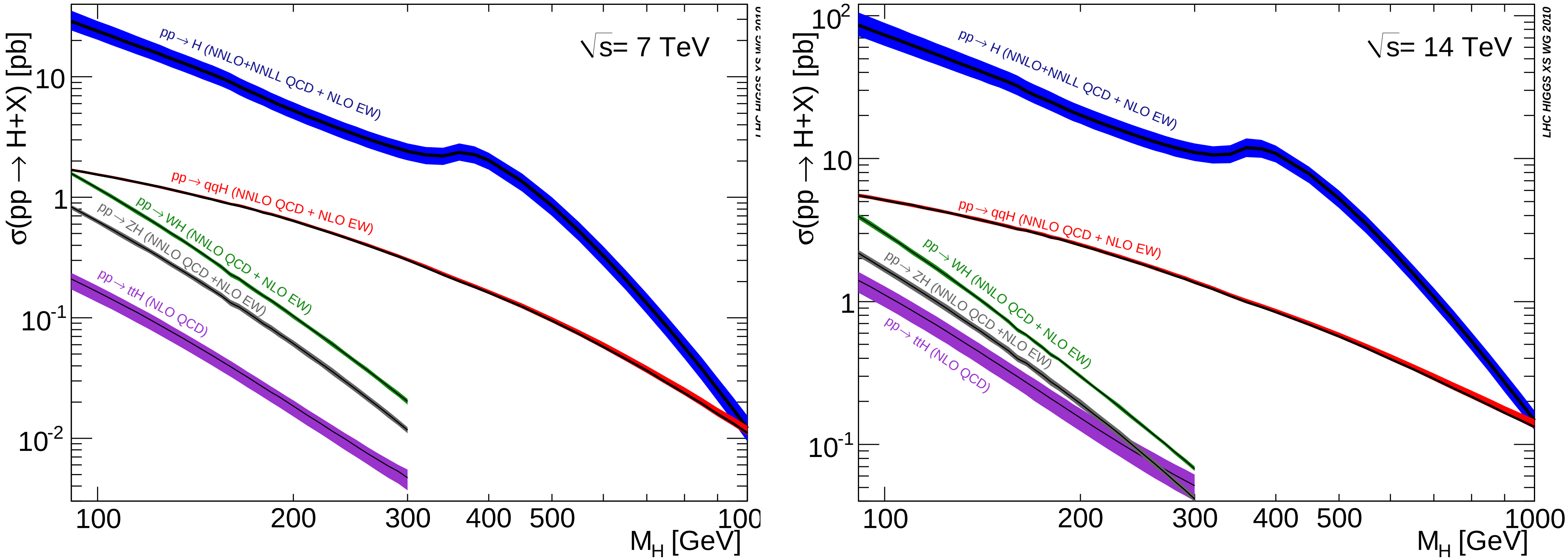
Ten subgroups:

- 4 SM production modes + 2 MSSM subgroups;
- branching ratios;
- PDF;
- NLO Monte Carlo;
- Higgs pseudo-observables.

Goals:

- implementing a coherent Higgs precision program;
- provide working tools to the experiments in a timely fashion.

Inclusive SM Higgs Production: theoretical predictions and their uncertainty



- 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;
- all other parametric errors included;
- theory errors combined according to common recipe.

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, . . .

- Obtain distibutions 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 (very few NLO calculations exist)
  - narrow width approximations often excellent approximation (top, light Higgs) (Melnikov, Schulze, arXiv:1006.0910, arXiv:1102.1967)
- Interface with NLO Monte Carlo would be best:
  - MC@NLO: $gg \to H$, W/ZH;
  - POWHEG: $gg \to H$, $q\bar{q}'H$.
- Backgrounds need to be calculated with comparable accuracy.

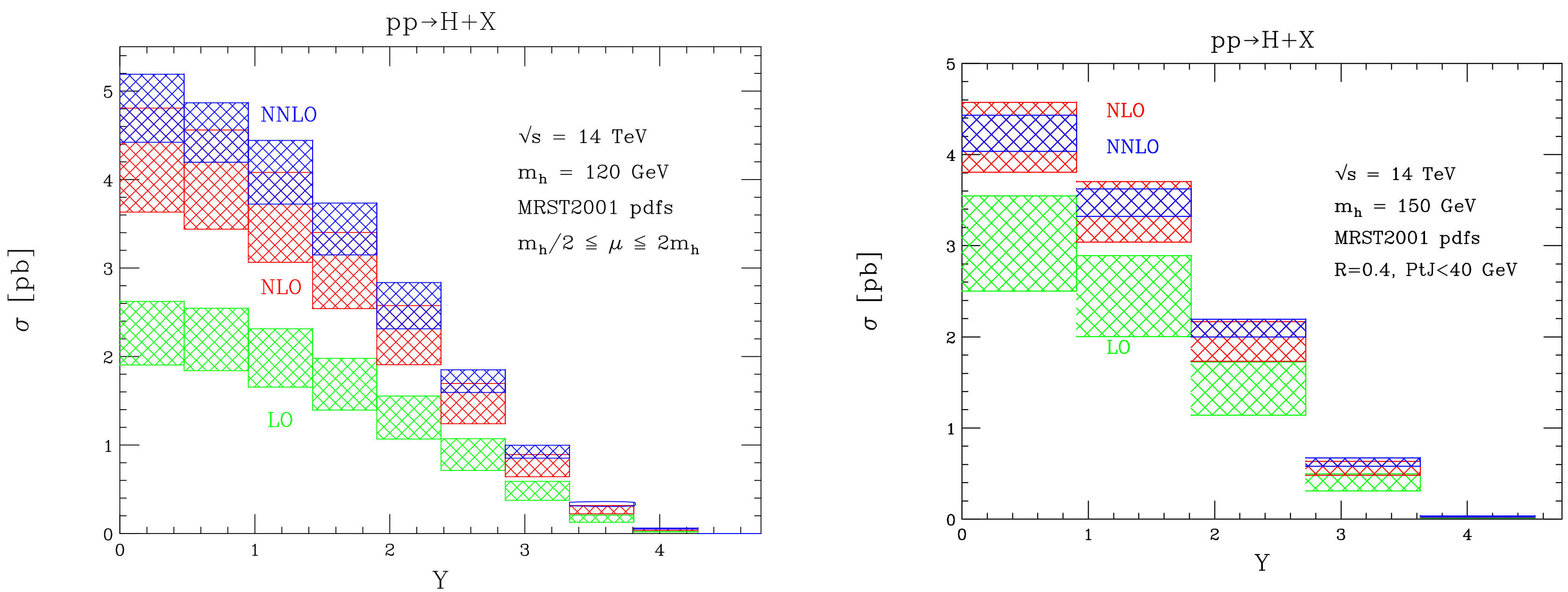
Ex. 1: Exclusive NNLO results: $gg \to H$, $H \to \gamma\gamma, WW, ZZ$

Extension of (IR safe) subtraction method to NNLO

$\longrightarrow$ HNNLO[Catani,Grazzini (05)]

$\longrightarrow$ FEHiP [Anastasiou,Melnikov,Petriello (05)]

Essential tools to reliably implement experimental cuts/vetos.

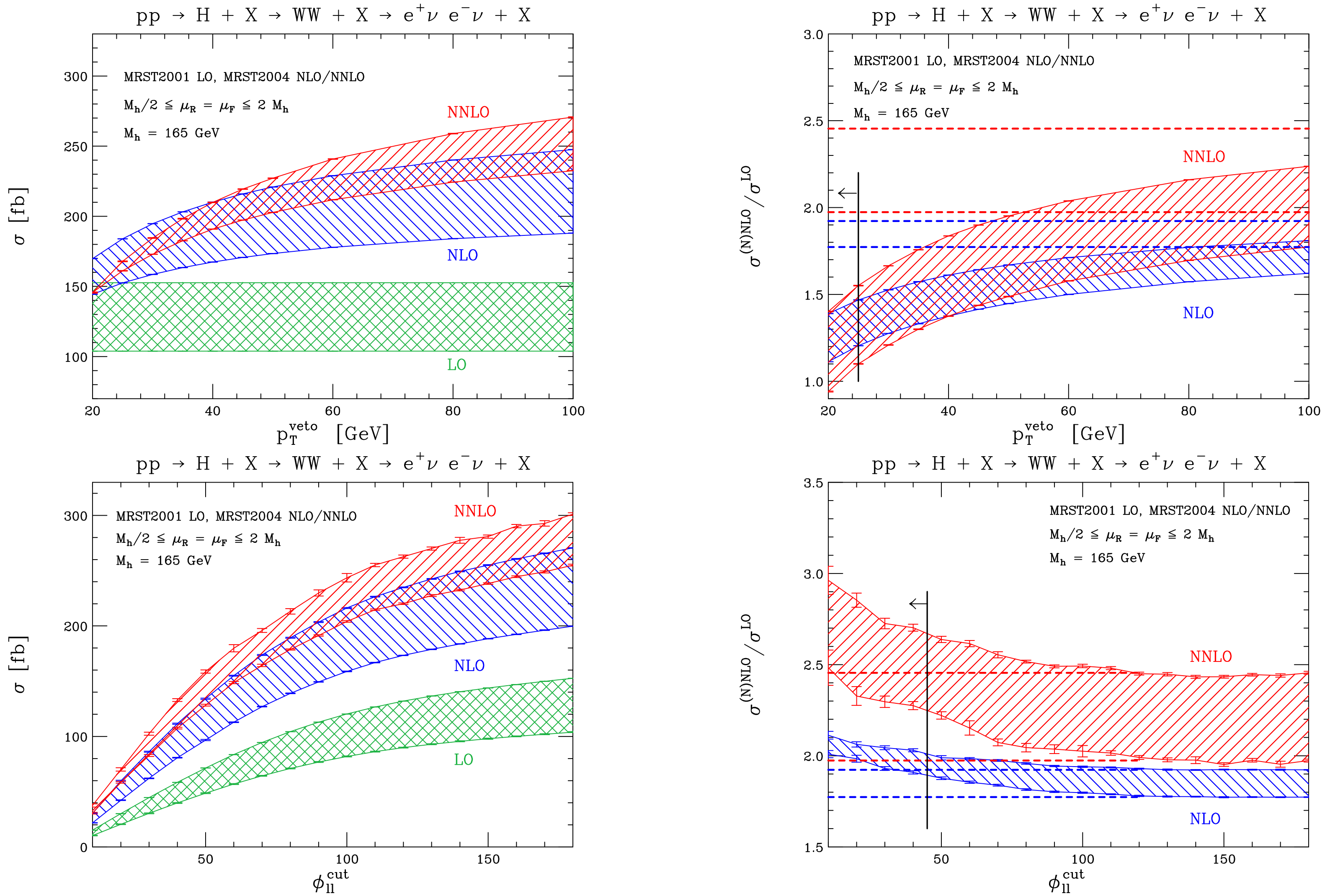


[Anastasiou,Melnikov,Petriello (05)]

jet veto (to enhance $H \to WW$ signal with respect to $t\bar{t}$ background) seems to improve perturbative stability of y-distribution $\longrightarrow$ jet veto is removing non-NNLO contributions.

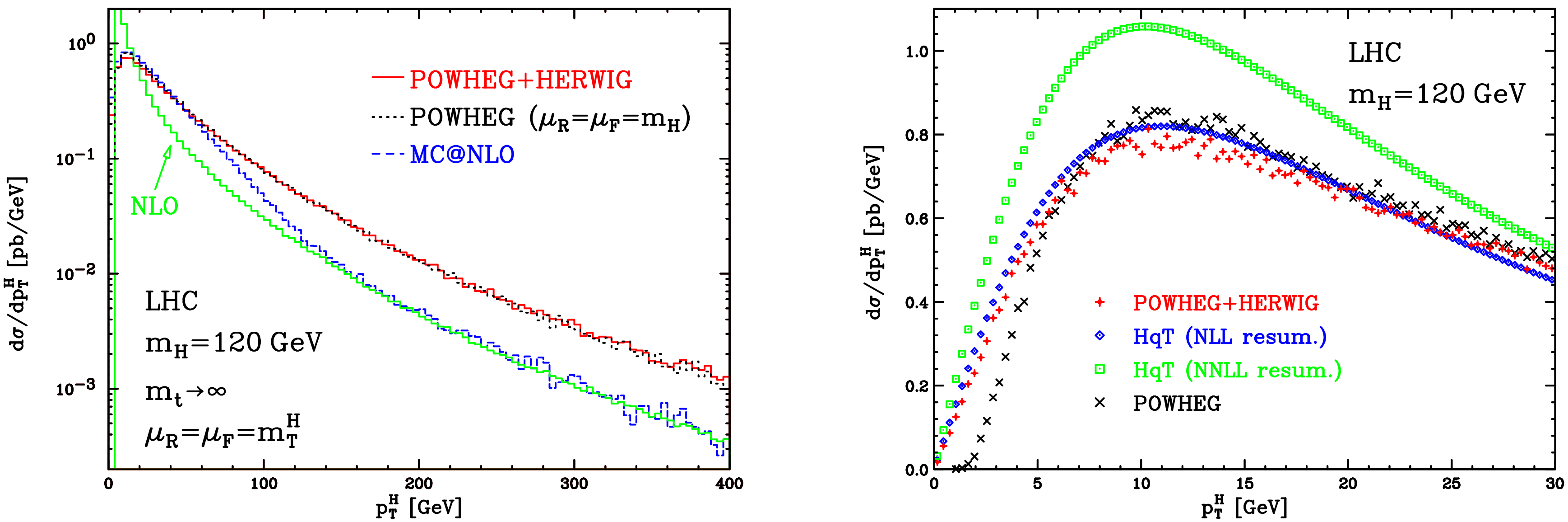
Full fledged $(gg \to)H \to W^+W^- \to l^+\nu l^-\bar{\nu}$

The magnitude of higher order corrections varies significantly with the signal selection cuts.



[Anastasiou,Dissertori,Stöckli (07)]

$gg \to H$ implemented in MC@NLO and POWHEG



[Alioli, Nason, Oleari, Re, (08)]

→ general good agreement with PYTHIA;

→ comparison MC@NLO vs POWHEG understood;

→ comparison with resummed NLL and NNLL results under control.

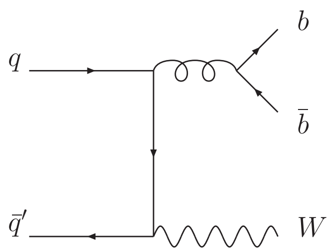
Recently completed NLO calculations: most are relevant backgrounds to Higgs-boson physics!

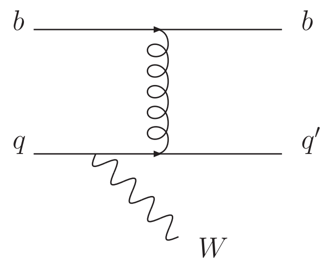
Process ($V \in \{Z, W, \gamma\}$)	Calculated by
$pp \to V$+2 jets(b)	Campbell,Ellis,Maltoni,Willenbrock (06)
$pp \to V b\bar{b}$	Febres Cordero,Reina,Wackeroth (07-08)
$pp \to W b\bar{b}$	Campbell,Ellis (10)
$pp \to VV$+jet	Dittmaier,Kallweit,Uwer (WW+jet) (07)
	Campbell,Ellis,Zanderighi (WW+jet+decay) (07)
	Binoth,Karg,Kauer,Sanguinetti (09)
$pp \to VV$+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)
arXiv:1102.1967	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 (08)
$pp \to t\bar{t}Z$	Lazopoulos,Melnikov,Petriello (08)
$gg \to WW$	Binoth,Ciccolini,Kauer,Kramer (06)
$gg \to HH, HHH$	Binoth,Karg,Kauer,Rückl (06)
$pp \to t\bar{t}\, b\bar{b}$	Bredenstein et al., Bevilacqua et al. (09)
$pp \to V$+3jets	Berger et al., Ellis et al. (09)
$pp \to W$+4jets	Berger et al. (10)

Ex. 2: $W + 1\, b$-jet: crucial background for WH production

[Campbell, Ellis, Febres Cordero, Maltoni, L.R., Wackeroth, Willenbrock (09)]

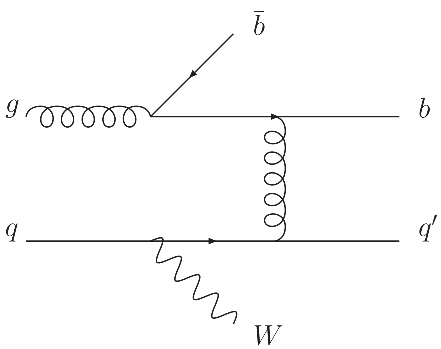
Consistently combine 4FNS ($m_b \neq 0$) and 5FNS ($m_b = 0$) at NLO in QCD:



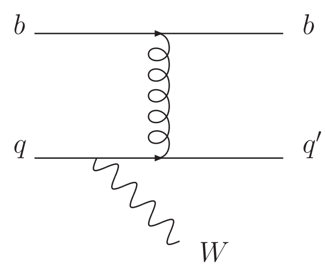


$+ \quad O(\alpha_s)$ corrections

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:



$\longrightarrow$



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

$\longrightarrow$ indeed: a fully consistent NLO 5FNS calculation (S-ACOT scheme).

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 gives 0.78 pb, PYTHIA 1.10 pb)

Outlook:

- need to compare more observables;
- need D0 measurement;
- need to compare with LHC measurements (coming soon);
- match $Wb\bar{b}$ with NLO Monte Carlo (soon to be released in POWHEG).

Conclusions and Outlook

- We are living through a new era in Higgs boson physics: looking for direct evidence.
- SM 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: the LHC can carry through a precision program that also include measurements of Higgs boson properties, to identify it.
  - high luminosity required;
  - strategies depend on itermediate discoveries;
  - more sophisticated techniques available by then.