Topics in Electroweak and Top quark Physics

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Aspen Winter Conference, February 2006

Outline

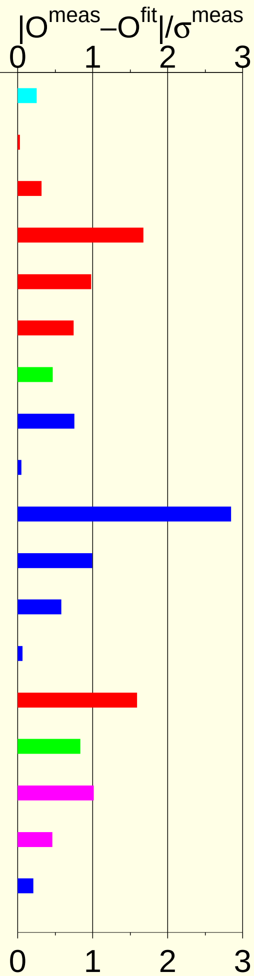
- Electroweak (EW) physics
  - ▷ EW precision physics: tensions and predictions.
  - ▷ Hadron colliders: W/Z production, W/Z rapidity distributions, $W/Z + jj$ and $W/Z + b\bar{b}$ production.
- Top quark physics
  - ▷ m_t: crucial to EW precision fits.
  - ▷ $t\bar{t}$ cross section: matching Monte Carlos to NLO QCD calculations.
  - ▷ top quark couplings: single top production, $t\bar{t}h$ production.

with emphasis on the status of theoretical predictions

Precision EW Physics . . .

LEP, SLD, and Run I+II of the Tevatron have and are thoroughly testing the Standard Model (SM) of EW interactions (see LEP EWWG web page)

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.410 ± 0.032	80.377
Γ_W [GeV]	2.123 ± 0.067	2.092
m_t [GeV]	172.7 ± 2.9	173.3



$\longrightarrow$ only high Q^2 data included

plus

direct measurements (Tevatron):

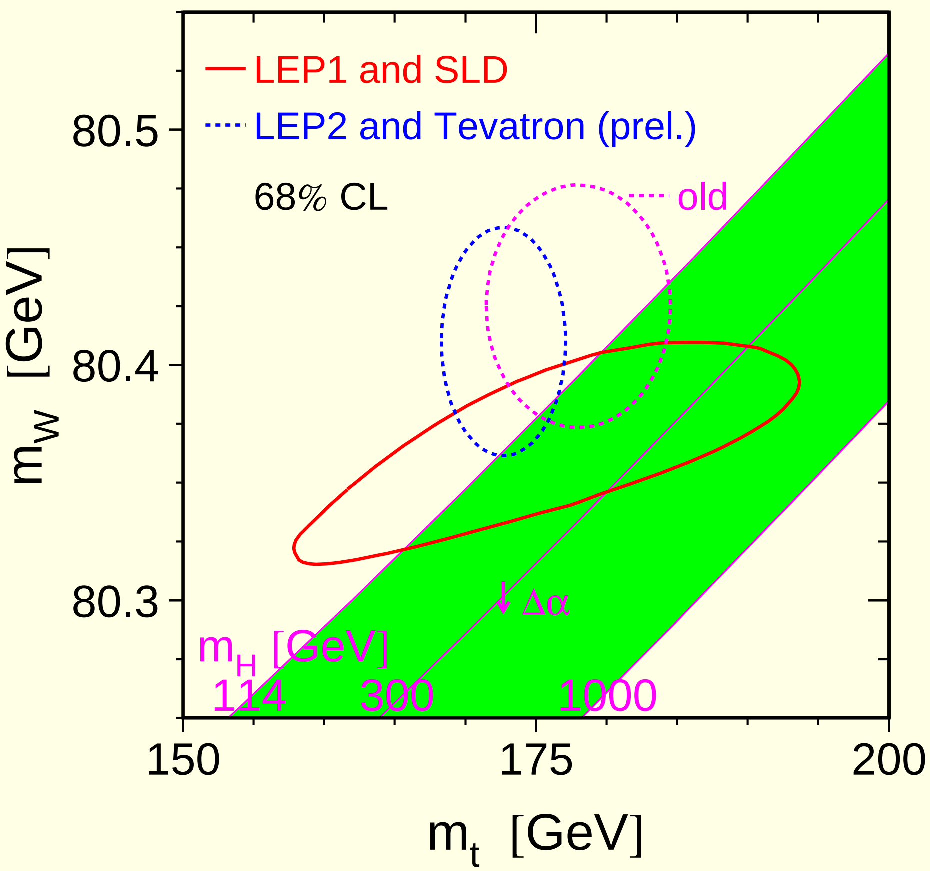
$$m_t = 172.7 \pm 2.9 \text{ GeV}$$

and

$$M_W = 80.452 \pm 0.059 \text{ GeV}$$

$$\Gamma_W = 2.102 \pm 0.106 \text{ GeV}$$

… tests the consistency of the SM and constrains M_H



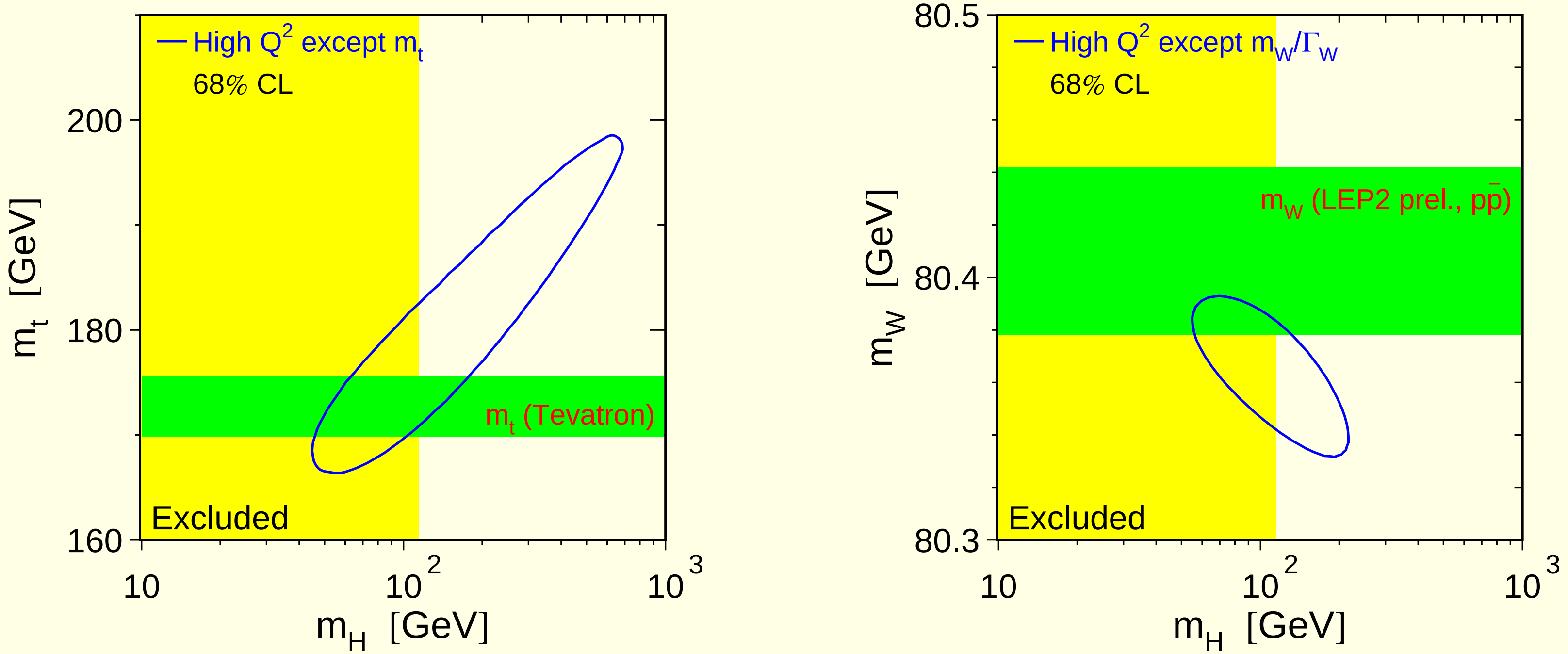
"old": early Summer 2005

$$m_t = 178.0 \pm 4.3 \text{ GeV}$$

"new": late Summer 2005

$$m_t = 172.7 \pm 2.9 \text{ GeV}$$

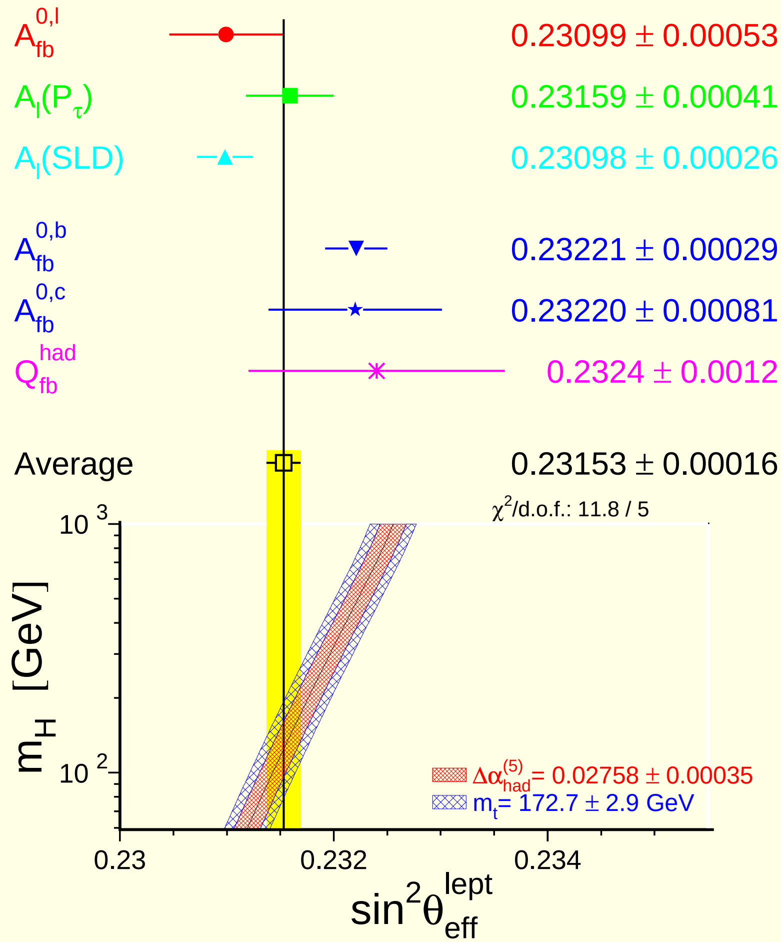
strong correlation between M_W ($\sin\theta_W^{eff}$), m_t and M_H

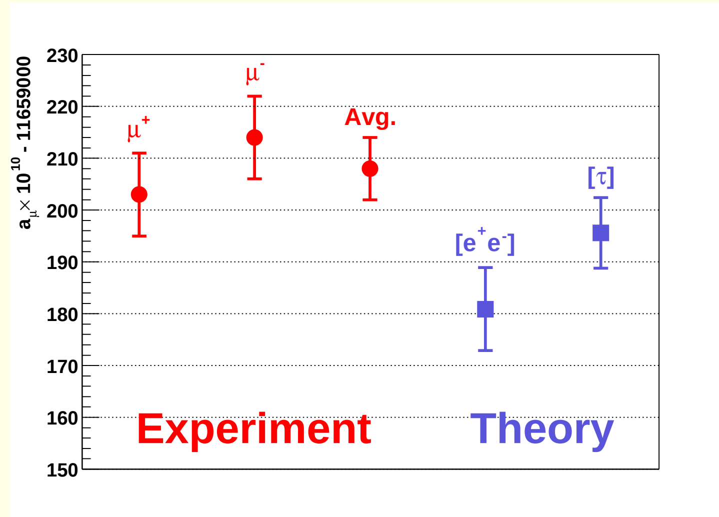


$$M_W/(\mathrm{GeV}) = 80.409 - 0.507\left(\frac{\Delta\alpha_h^{(5)}}{0.02767} - 1\right) + 0.542\left[\left(\frac{m_t}{178\,\mathrm{GeV}}\right)^2 - 1\right]$$
$$- 0.05719\ln\left(\frac{M_H}{100\,\mathrm{GeV}}\right) - 0.00898\ln^2\left(\frac{M_H}{100\,\mathrm{GeV}}\right)$$

A. Ferroglia, G. Ossola, M. Passera, A. Sirlin, PRD 65 (2002) 113002

W. Marciano, hep-ph/0411179





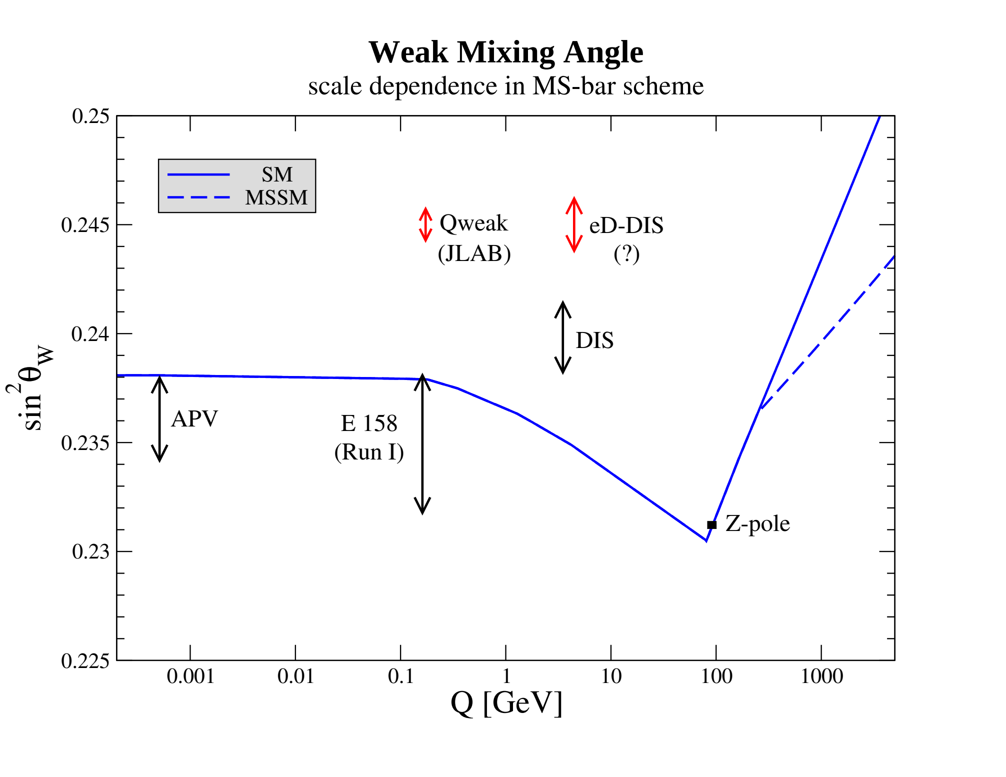
The muon $g-2$ collaboration

PRL 92 (2004) 161802

$$\sin^2\theta_W(M_Z)_{\overline{MS}} = 0.23101 + 0.00969\left(\frac{\Delta\alpha_h^{(5)}}{0.02767} - 1\right) - 0.00277\left[\left(\frac{m_t}{178\,\mathrm{GeV}}\right)^2 - 1\right]$$
$$+ \; 0.0004908\ln\left(\frac{M_H}{100\,\mathrm{GeV}}\right) + 0.0000343\ln^2\left(\frac{M_H}{100\,\mathrm{GeV}}\right)$$

$$\left(\sin\theta_W^{eff} = \sin\theta_W(M_Z)_{\overline{MS}} + 0.00028\right)$$

Low energy measurements of $\sin^2\theta_W$



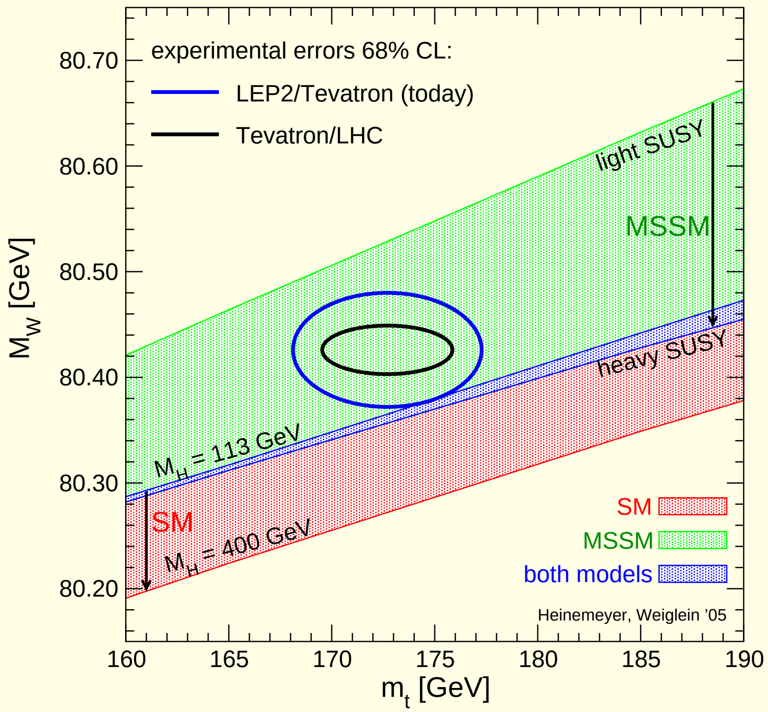
J. Erler, M. J. Ramsey-Musolf

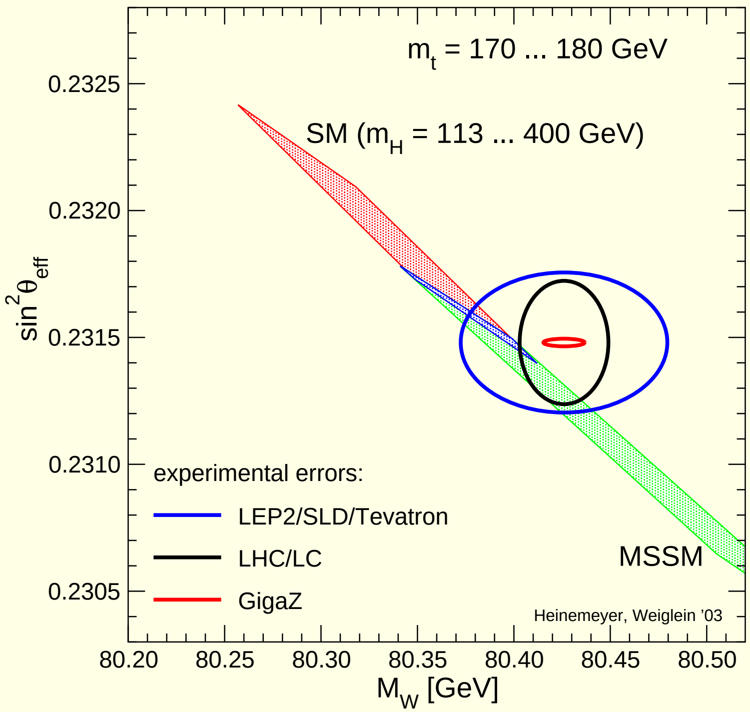
Prog.Part.Nucl.Phys. 54 (2005) 351

⟶ Running of $\sin^2\theta_W$ not unsatisfactory;

⟶ NuTeV (DIS) almost 3σ deviation still a puzzle.

Precision crucial to disentangle new physics





⟶ SM main uncertainty: Higgs boson mass.

⟶ MSSM main uncertainty: unknown masses of SUSY particles.

Experimental uncertainties, estimate

	Present	Tevatron	LHC	LC	GigaZ
$\delta \sin^2 \theta_W^{eff} (\times 10^{-5})$	14	63	14-20	6	1.3
$\delta(M_W)$(MeV)	34	27	10-15	7-10	7
$\delta(m_t)$ (GeV)	5.1	2.7	1.0	0.2	0.13
$\delta(M_H)/M_H$ (indirect)	60%	35%	20%	15%	8%

U. Baur, LoopFest IV, August 2005

Intrinsic theoretical uncertainties

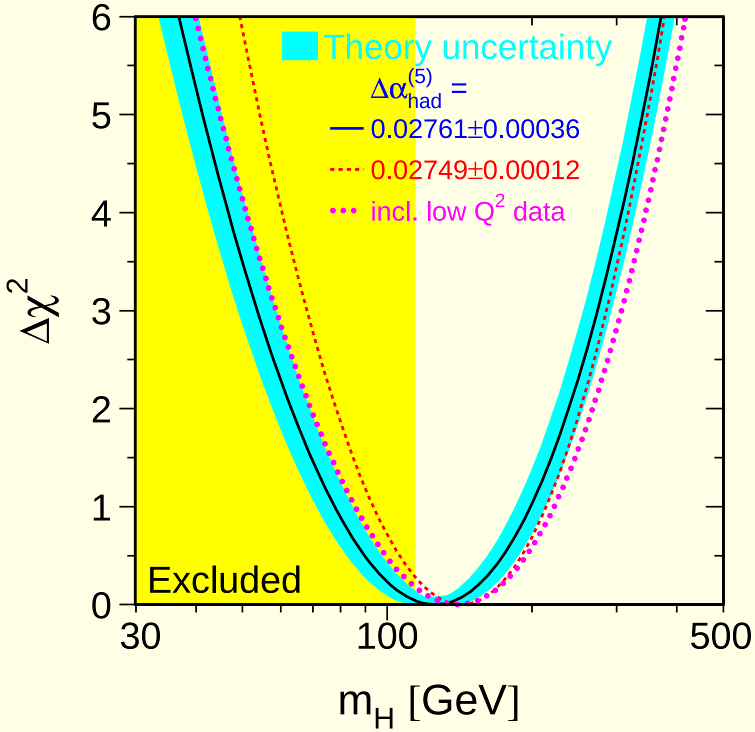
$\longrightarrow$ $\delta M_W \approx 4$ MeV: full $O(\alpha^2)$ corrections computed.

M. Awramik, M. Czakon, A. Freitas, G. Weiglein

$\longrightarrow$ $\delta \sin^2 \theta_W^{eff} \approx 5 \times 10^{-5}$: full fermionic $O(\alpha^2)$ corrections computed, bosonic $O(\alpha^2)$ in progress.

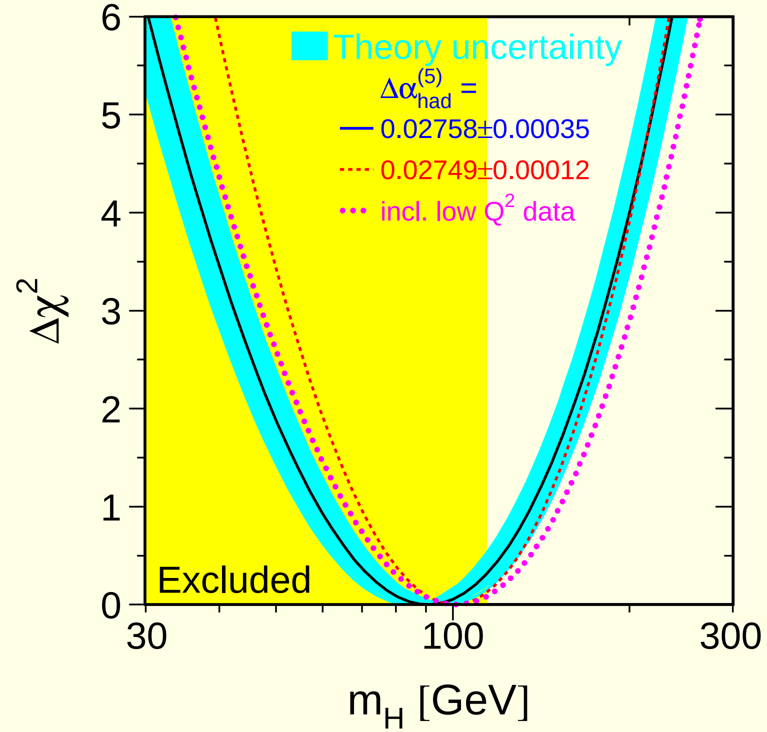
M. Awramik, M. Czakon, A. Freitas, G. Weiglein

Summary at a glance



Before Summer 2005

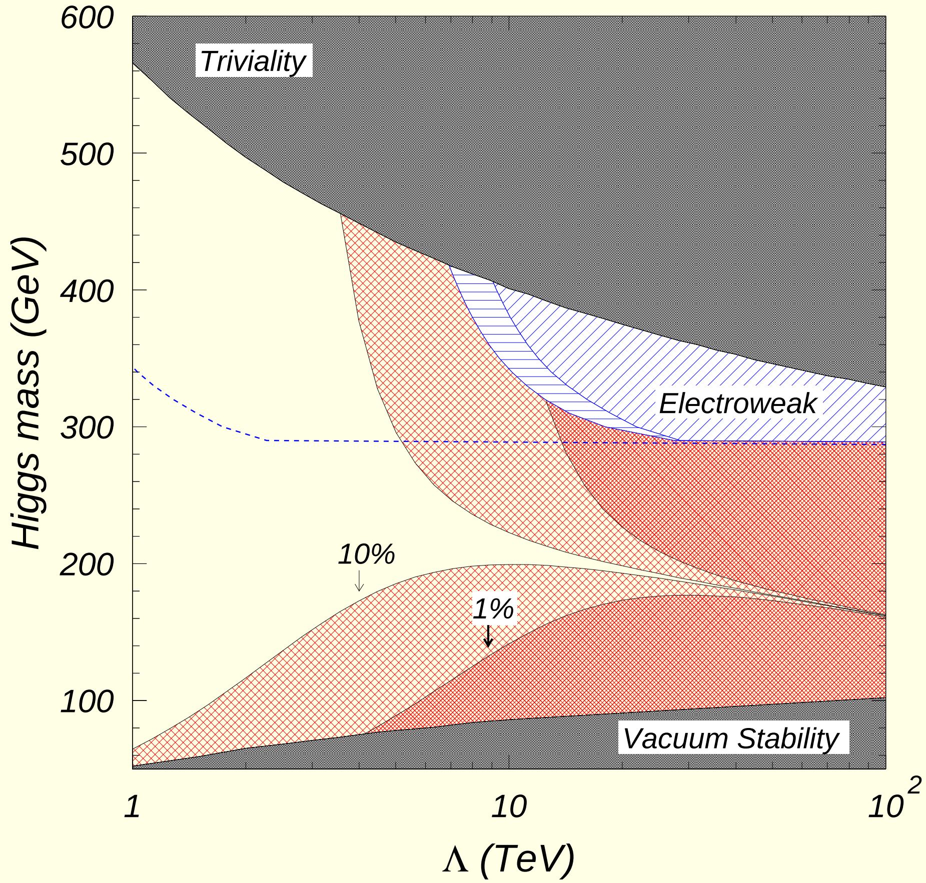
$$\begin{cases} M_H = 117^{+67}_{-45} \ \text{GeV} \\ M_H < 251 \ \text{GeV} \ \ (95\% \ \text{CL}) \end{cases}$$



Since Summer 2005

$$\begin{cases} M_H = 91^{+45}_{-32} \ \text{GeV} \\ M_H < 186 - 219 \ \text{GeV} \ \ (95\% \ \text{CL}) \end{cases}$$

Combined theoretical constraints



$\Lambda \rightarrow$ scale of new physics

amount of fine tuning =

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

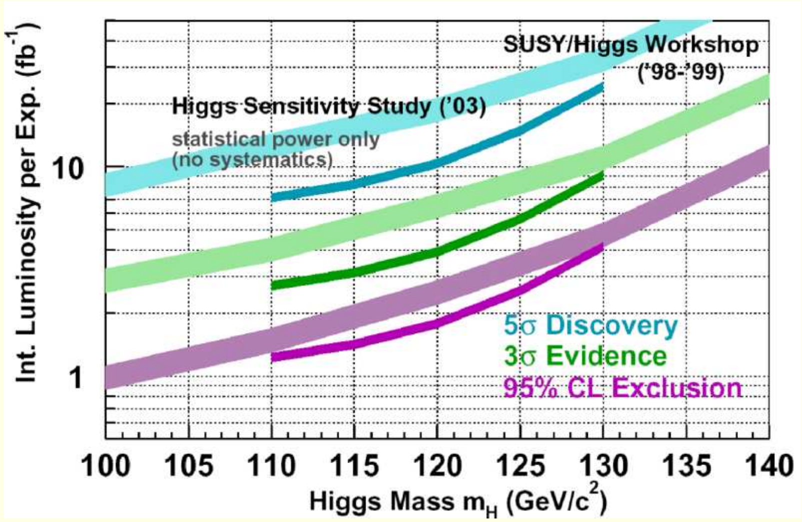
$\longleftarrow n_{max} = 1$

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

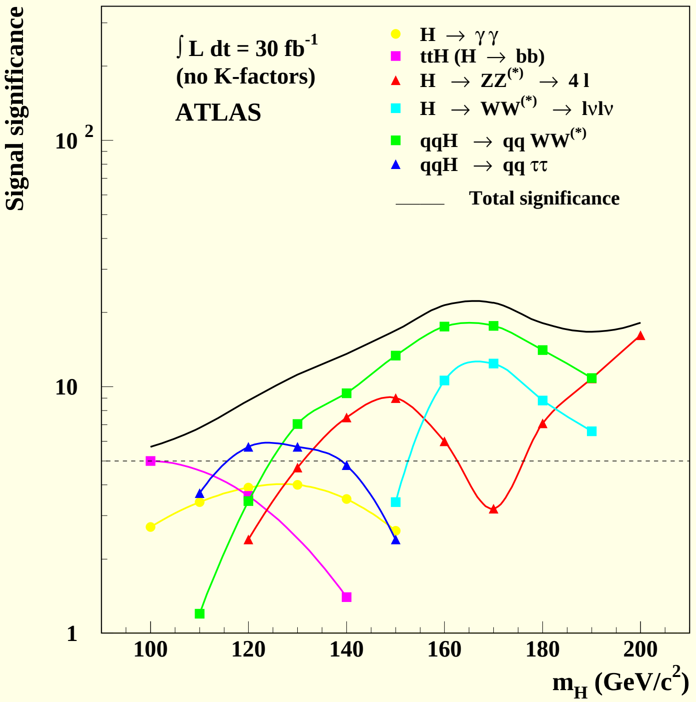
Light Higgs consistent with low Λ: new physics at the TeV scale.

Discovering a Higgs boson more crucial then ever

Tevatron



LHC



$\longrightarrow$ WH and ZH associated production

$\longrightarrow$ $Hb\bar{b}$ in MSSM-like models ($y_b = \tan\beta y_b^{SM}$)

In low mass region:

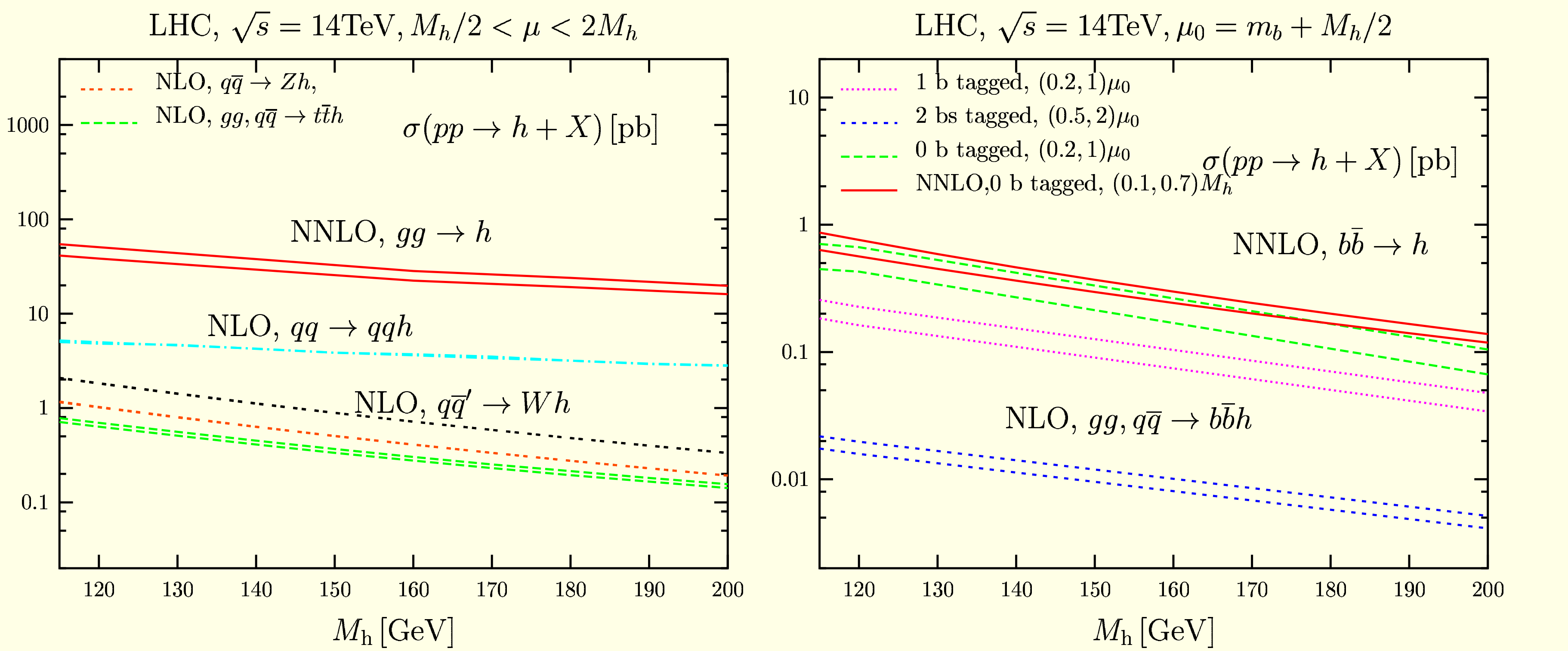
$\longrightarrow$ weak boson fusion

$\longrightarrow$ $t\bar{t}H$ associated production

$\longrightarrow$ inclusive with $H \to \gamma\gamma$

Theoretical predictions: overview

QCD predictions for total cross sections to Higgs production processes are under good theoretical control:



Caution:

- ▷ uncertainties only include μ_R/μ_F dependence
- ▷ uncertainties from PDF's are not included (but should improve)

Of direct interest to the Tevatron

- WH and ZH: QCD corrections at NNLO

  O. Brien, A. Djouadi, R. Harlander, PLB 579 (2004) 149

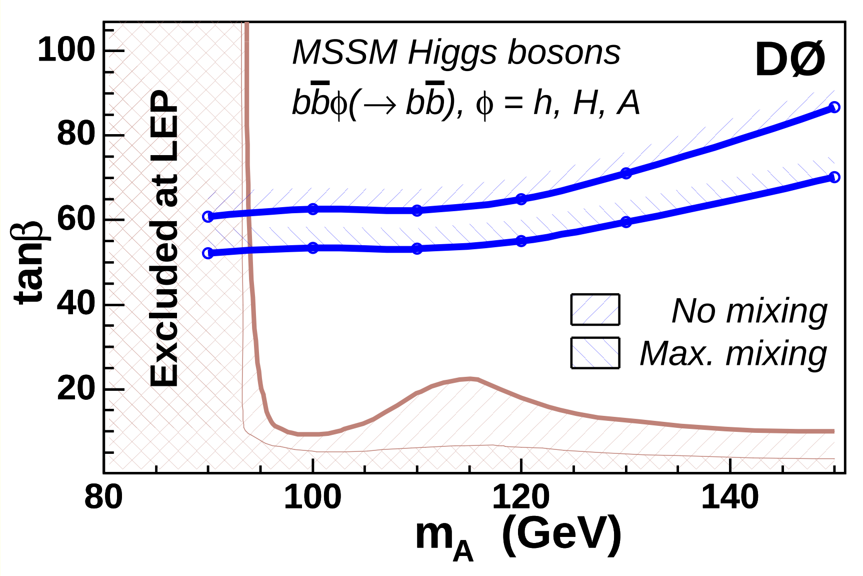
- $Hb\bar{b}$: QCD corrections at NLO in both 4FNS ($q\bar{q}, gg \to Hb\bar{b}$) and 5FNS ($bg \to bH$ and $b\bar{b} \to H$): very good agreement.

  J. Campbell, K. Ellis, F. Maltoni, S. Willenbrock, PRD 67 (2003) 095002

  S. Dawson, C. Jackson, L.R., D. Wackeroth, PRD 69 (2004) 074027, PRL 94 (2005) 031802

  S. Dittmaier, M. Krämer, M. Spira, PRD 70 (2004) 074010

First measurements already constrain MSSM parameter space



Tevatron/LHC : single W/Z boson production

- QCD corrections to W/Z boson total cross sections known at NNLO

  R. Hamberg, W. L. van Nerveen, T. Matsuura, NPB 359 (1991) 343,

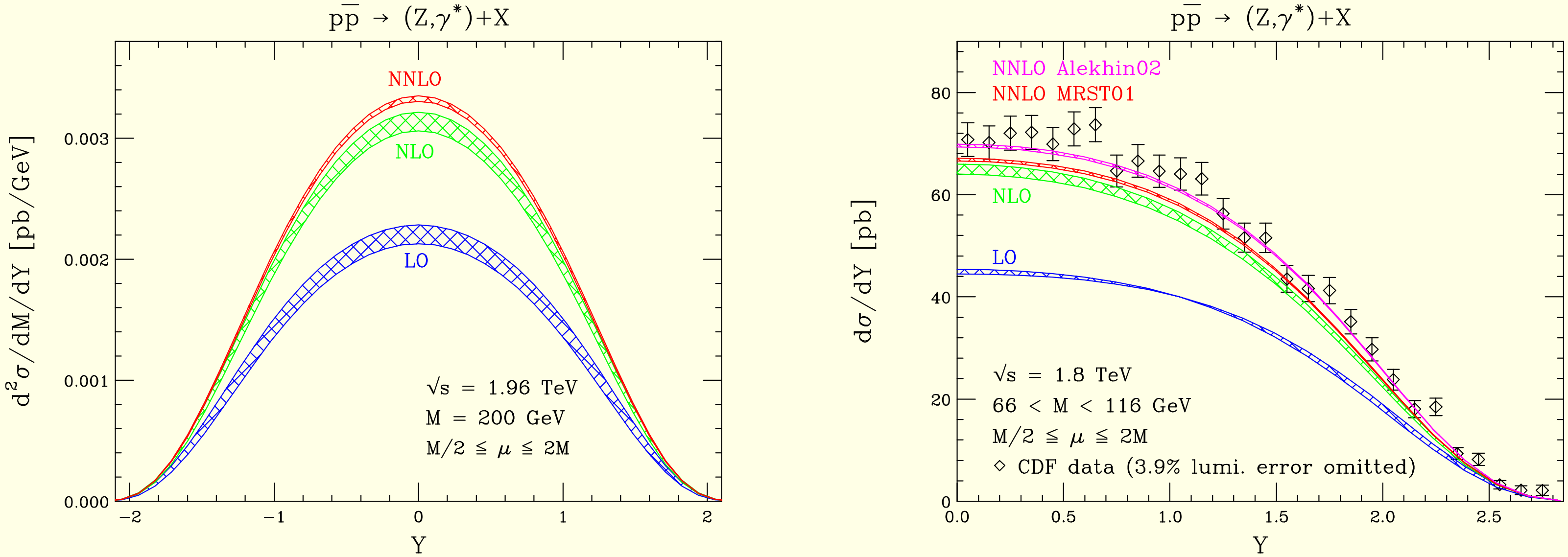
  W. L. van Neerven and E. B. Zijlstra, NPB 382 (1992) 11

- W/Z p_T distributions include resummed QCD corrections

  C. Balazs, J. W. Qiu, C. P. Yuan, PLB 355 (1995) 548

- Rapidity distributions of the Z boson calculated at NNLO

  C. Anastasiou, L. Dixon, K. Melnikov, F. Petriello, PRL 91 (2003) 182002



Testing NNLO PDF's $\Longrightarrow$ "parton-parton luminosity" monitors

- At the percent level ($\approx 1\%$) EW corrections become important.

  In particular if:

  ▷ QCD corrections are small (ex.: W/Z cross section ratio);

  ▷ enhanced by large logs:

  $\longrightarrow$ $\ln(\hat{s}/m_f^2)$ (collinear logs, near W/Z resonance),

  $\longrightarrow$ $\ln(\hat{s}/M_{W/Z}^2)$ (Sudakov logs, when l^+l^- or $l\nu$ have large invariant mass);

  ▷ precision measurement (M_W, M_Z, ...).

  $O(\alpha)$ corrections to W/Z production fully calculated.

  S. Dittmaier and M. Krämer, PRD 70 (2002) 073007

  U. Baur, D. Wackeroth, PRD 70 (2004) 073015

  MRSTQED2004 $\longrightarrow$ contain QED corrections.

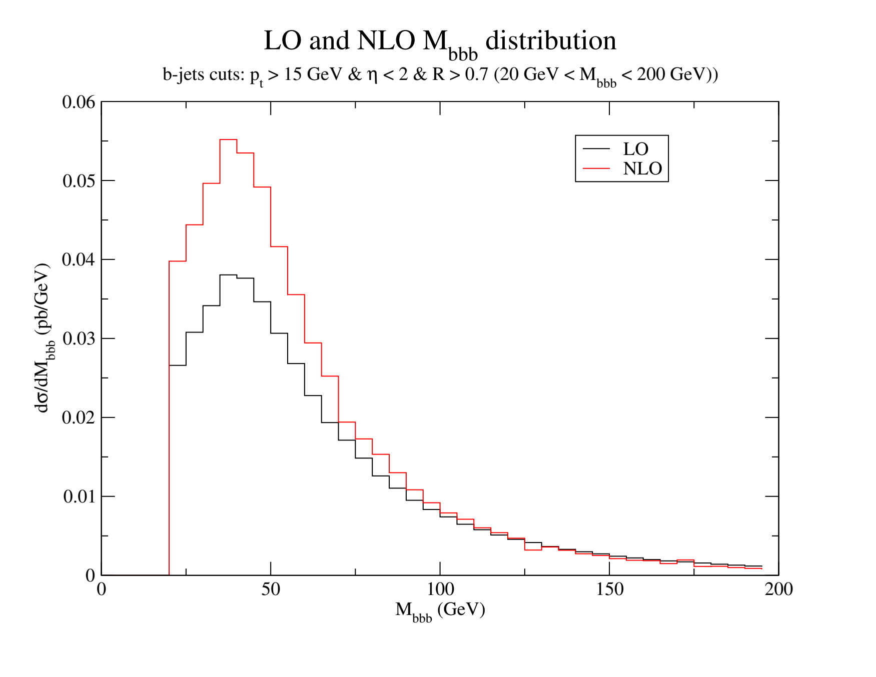
- Tev4LHC EW working group: "tuned comparison" of existing calculations: HORACE,WGRAD/ZGRAD, WINHAC/ZINHAC, RESBOS, PYTHIA+PHOBOS, ...

W/Z production with jets: $W/Z + jj$ and $W/Z + b\bar{b}$

- $W/Z + jj$ and $W/Z + b\bar{b}$ important background to $W/Z + H$ and single top production.
- NLO QCD corrections to $W/Z + jj$ and $W/Z + b\bar{b}$ (in the $m_b \to 0$ limit) known and coded in MCFM (now version 4.2)

J. Campbell, R. K. Ellis, S. Veseli, see mcfm.fnal.gov

- NLO QCD corrections to $Wb\bar{b}$ including full m_b effects soon available

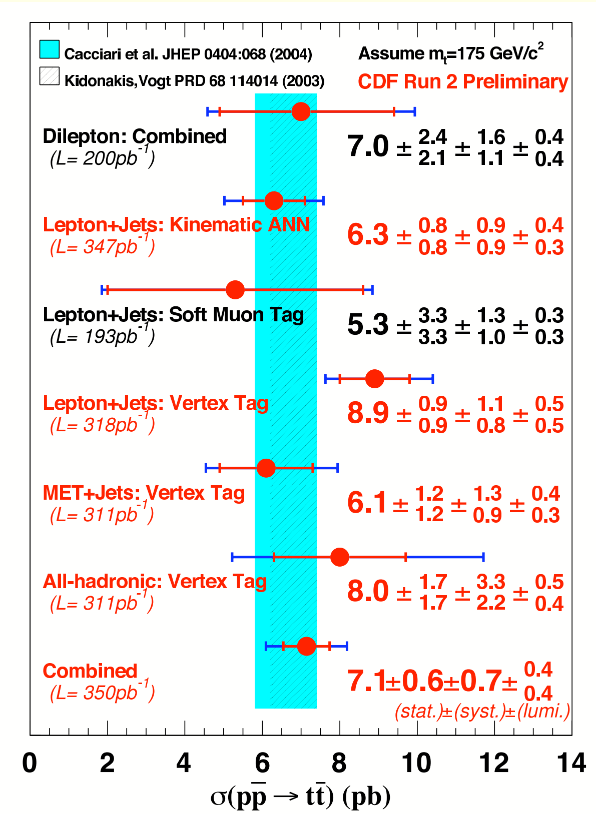


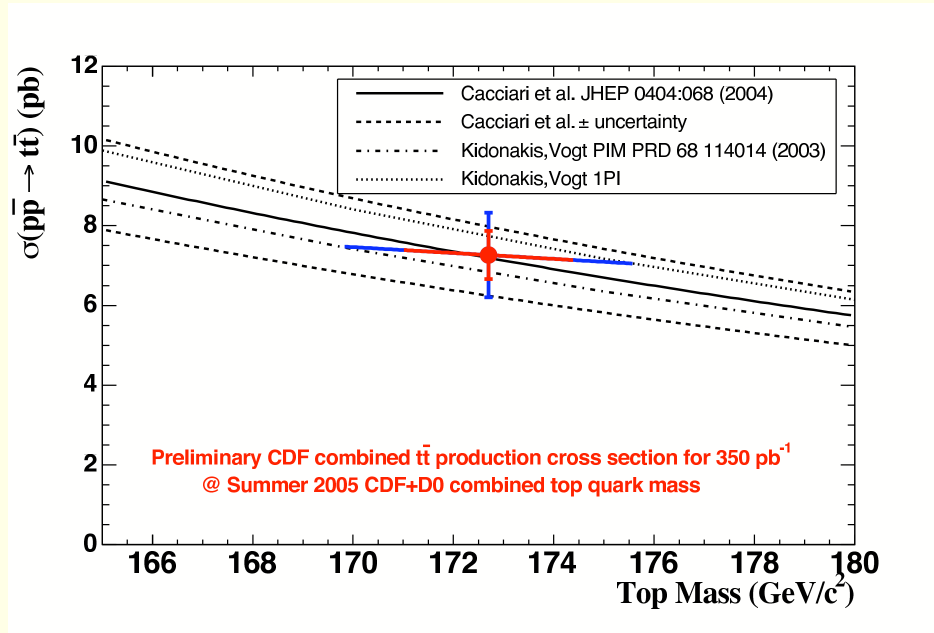
F. Febres-Cordero, L.R, D. Wackeroth

Preliminary

$Zb\bar{b}$: in preparation

$t\bar{t}$ production: very refined prediction





M. Cacciari, S. Frixione, M. Mangano, P. Nason, JHEP 04 (2004) 68

$\longrightarrow$ NLO QCD corrections to heavy quark production well established

P. Nason, R. K. Ellis, S. Dawson, NPB 303 (1988) 607

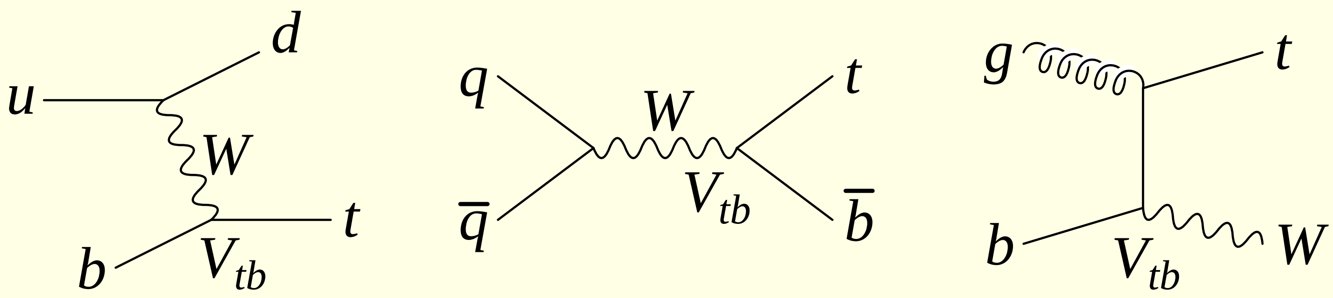
W. Beenakker, H. Kujif, W. L. van Nerveen, J. Smith, PRD 40 (1989) 54

$\longrightarrow$ Resummed soft QCD corrections at NNLO and NLL or NNLL:

R. Bonciani, S. Catani, M. Mangano, P. Nason, NPB 529 (1998) 424

N. Kidonakis and R. Vogt, PRD 68 (2003) 1140014

Single top production: measuring V_{tb}



(a) (b) (c)

- Direct measurement of V_{tb}
- s-channel and t-channel have distinct signatures
- NLO QCD corrections calculated for total cross section and distributions

B. W. Harris, E. Laenen, L. Phaf, Z. Sullivan, S. Weinzierl, PRD 66 (2002) 054024

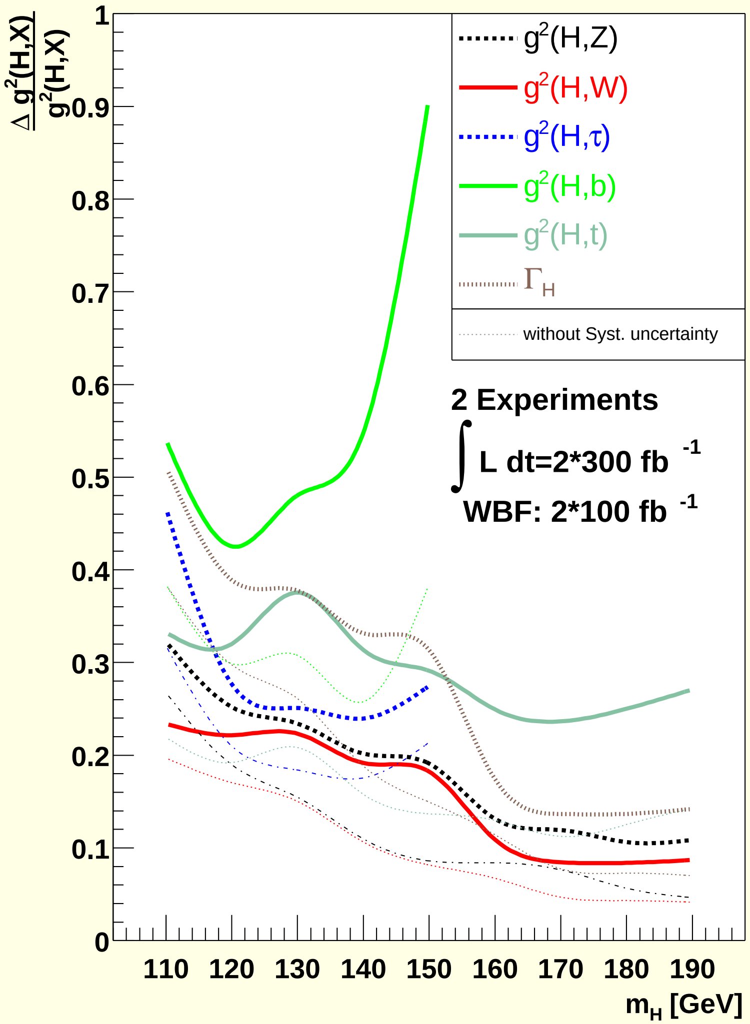
Z. Sullivan, PRD 70 (2004) 114012

J. Campbell, R. K. Ellis, F. Tramontano, PRD 70 (2004) 094012

Q.-H. Cao, R. Schwienhorst, C.-P. Yuan, PRD 71 (2005) 054023

	Theory	CDF	DØ
s-channel	$(0.88 \pm 0.14)\,\mathrm{pb}$	$< 13.6\,\mathrm{pb}$	$< 6.4\,\mathrm{pb}$
t-channel	$(1.98 \pm 0.30)\,\mathrm{pb}$	$< 10.1\,\mathrm{pb}$	$< 5.0\,\mathrm{pb}$

$t\bar{t}H$ production: measuring the top Yukawa coupling



At the LHC : $q\bar{q}, gg \rightarrow t\bar{t}H$ with

- $M_H \leq 130$ GeV: $H \rightarrow b\bar{b}, \tau\tau$
- $M_H \geq 130$ GeV: $H \rightarrow WW$

M. Dührssen et al., PRD 70 (2004) 113009, hep-ph/0407190;

A. Belyaev, L.R., JHEP 0208 (2002) 041

D. Zeppenfeld et al., PRD 62 (2000) 013009

$$\delta y_t / y_t \approx 10\text{-}20\%$$

$$\Updownarrow$$

At a LC : $\delta y_t / y_t \approx 5\%$ ($\sqrt{s} = 800$ GeV)

NLO QCD corrections fully calculated: th. uncertainty reduced to 15-20%

W. Beenakker, S. Dittmaier, Plümper, M. Spira, P. Zerwas

S. Dawson, C. Jackson, L. Orr, L.R., D. Wackeroth

Summary

- EW precision fits still not conclusive: need prove/disprove the existence of a Higgs boson.
- EW physics (as well as top physics) now played at hadron colliders:

  $\longrightarrow$ QCD corrections well under control;

  $\longrightarrow$ Many interesting new measurements (Z-rapidity, single top, ...);

  $\longrightarrow$ matching of higher order calculations with event generators under construction/testing;

  $\longrightarrow$ huge statistics coming with the LHC;

  $\longrightarrow$ EW corrections may become important soon.

  Great potential!

- Next stage: the ILC (see Snowmass working group reports).