Precision tests beyond the SM

How to intepret precision tests without assuming the SM?
Success of the SM fit ➔ only minimal deviations tolerable

Within a concrete and calculable model (e.g. MSSM), one can just compute observables as functions of parameters: MSSM fits as well as SM in wide regions of its (large!) parameter space, even slightly better in some corners

Use effective field theory approach to be general/agnostic

Extreme choice: effective theory without the Higgs field

$$\mathcal{L}_{eff} = \frac{v^2}{4} Tr\left(D_\mu \Sigma D^\mu \Sigma^\dagger\right) + \sum_i \tilde{c}_i \tilde{\mathcal{O}}_i(\Sigma, \tilde{\Lambda}, \ldots)$$

[Appelquist-Bernard, 1980; Longhitano, 1980; …]

More conservative: effective theory with the Higgs field

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}(\phi) + \sum_i c_i\, \mathcal{O}_i(\Phi, \Lambda, \ldots)$$

[Buchmuller-Wyler, 1986; Grinstein-Wise, 1991; …]

End of lecture 2

Beginning of lecture 3

Precision tests beyond the SM (continued)

In both approaches:

$$\begin{pmatrix} \sin^2\theta_{eff} \\ m_W \end{pmatrix} : \quad \log\frac{m_H}{m_Z} \to \log\frac{\widetilde{\Lambda}(m_H)}{m_Z} + \begin{pmatrix} K_\theta \\ K_W \end{pmatrix} [\widetilde{c}_i(c_i)]$$

where K's depend on unknown coefficients, which can be determined only with info on the fundamental theory

Case 1 (without Higgs field):

Cancellation possible in principle, but unlikely that strong interactions at TeV scale arrange for them (with no large effects on other precision observables)

Case 2 (with Higgs field):

Obvious correlation: Higgs mass can be increased beyond what permitted by SM fit if effective cutoff is low enough
Explicit examples (ad hoc, but simple) can be worked out

Practical parametrizations

Under mild (universality) assumptions, main new physics effects, contained in vector-boson self-energies, can be parametrized in terms of a few conventional parameters

[Peskin-Takeuchi+Golden-Randall+Holdom-Terning, 1990; …]

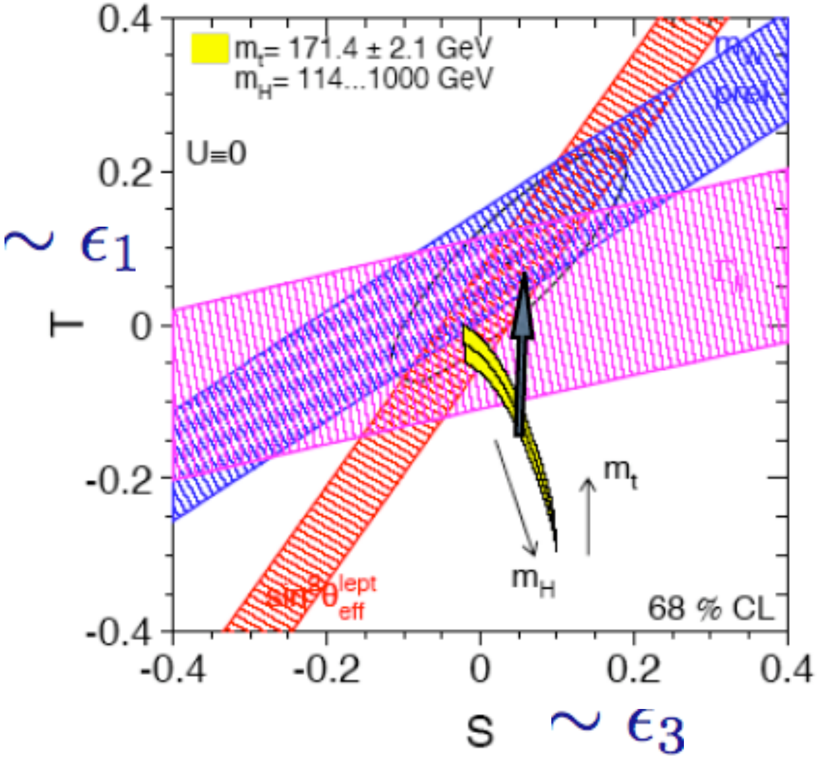
recently updated to properly include LEP2 constraints

[Barbieri-Pomarol-Rattazzi-Strumia, hep-ph/0405040]

Pushing m_h up needs new physics contributions to T (essentially Veltman's rho) in the positive direction (and of the right magnitude)

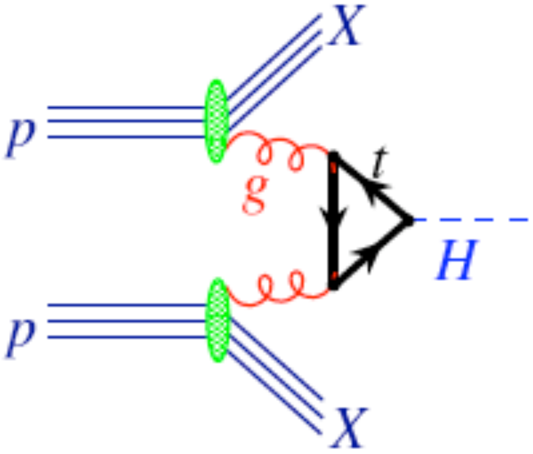
Various possibilities explored

[Peskin-Wells, hep-ph/0101342;
Barbieri et al, hep-ph/0607332;
Barbieri et al, hep-ph/0603188]



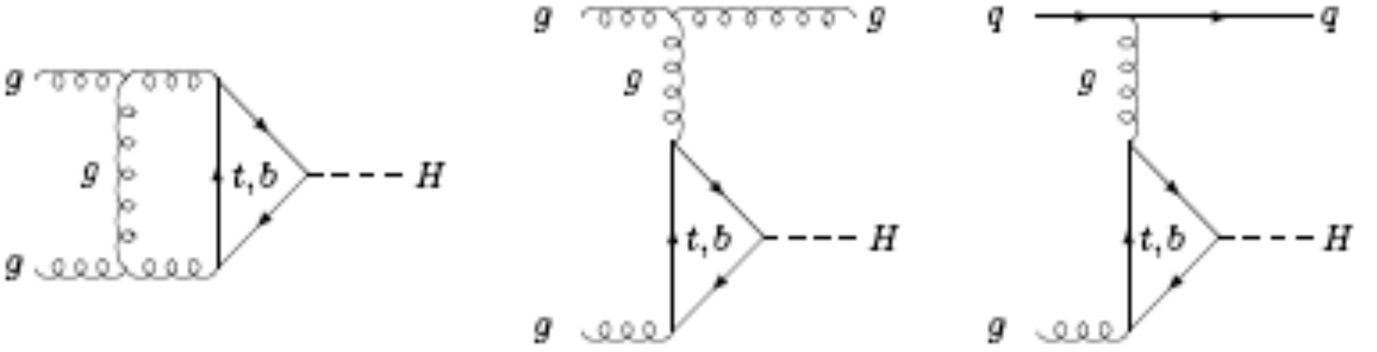
Higgs production at hadron colliders

g g ➔ H + X : gluon fusion
the dominant mechanism
at Tevatron & LHC



LO cross-section known for a long time
[Georgi-Glashow-Machacek-Nanopoulos, 1978]

NLO QCD correction were found to be unexpectedly large:
K_{NLO}~2-2.5 (Tevatron), K_{NLO}~1.7 (LHC)
with no appreciable decrease in the scale-dependence
[Spira-Djouadi-Graudenz-Zerwas, 1991-3-5; Dawson, 1991]



etc.

NNLO corrections to the gluon fusion cross-section

Useful approximation: effective Lagrangian for $m_t >> m_H$
(but better than 10% accuracy at NLO up to $m_H = 1$ TeV!)

$$\mathcal{L}_{ggH} = -\frac{1}{4}\frac{H}{v}C(\alpha_S)\,G^{\alpha}_{\mu\nu}G^{\mu\nu\,\alpha}$$

(dominant contributions come from soft partons,
which cannot resolve the heavy top quark loop!)

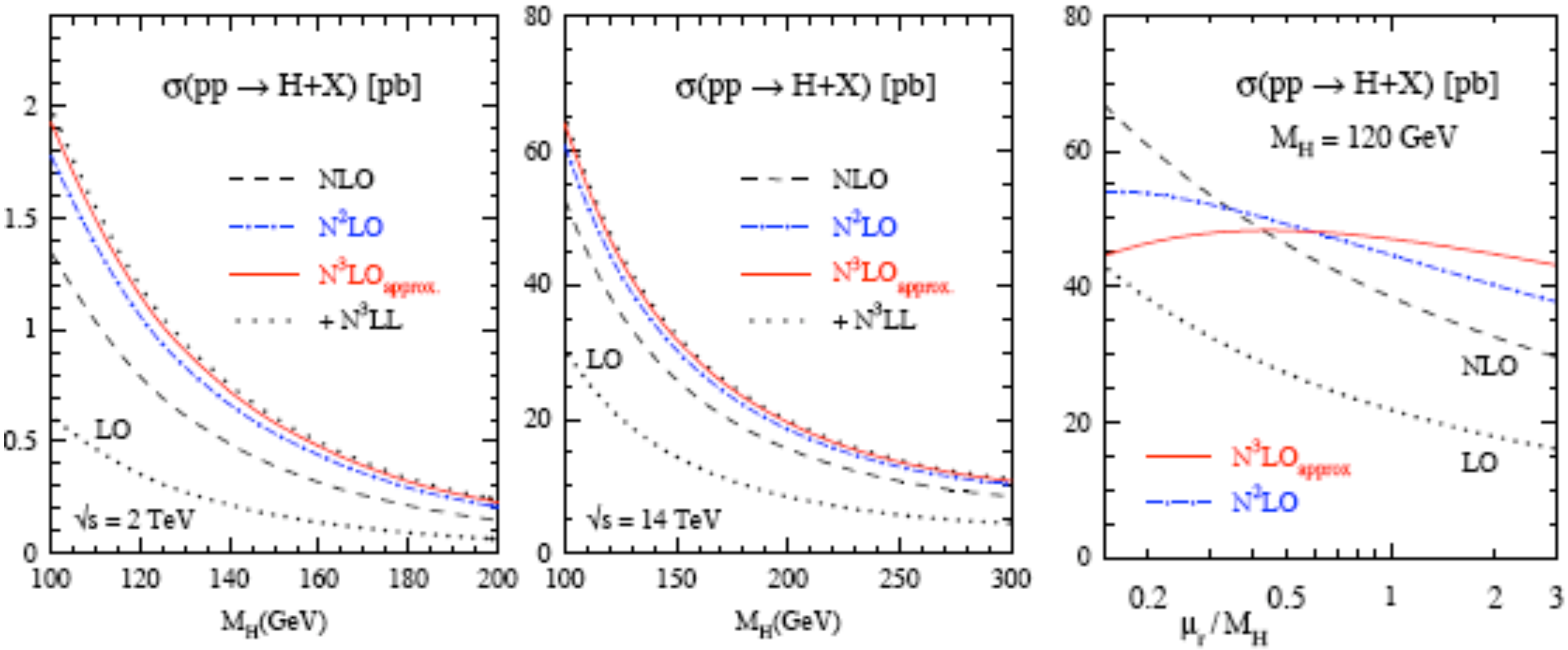
NNLO corrections now evalutated in this heavy-top limit
[Harlander-Kilgore, 00-02; Catani-deFlorian-Grazzini, 01; Anastasiou-Melnikov(-Petriello), 02-05; Ravindran-Smith-vanNeerven, 03-06]

$K_{NLLO/NLO}$~1.1-1.25 & reduced scale dependences

Some resummations of large logarithms also performed:
NNLL+N^{3}LL: 7-8% increase [CdFG-Nason, 03; Moch-Vogt, 05]

NLO-EW: 4-8% increase for $m_H < 2\ m_W$ [Degrassi et al, 04]

Some illustrative figures



[Moch-Vogt, hep-ph/0508265]

Important for Tevatron and LHC searches:

- Fully differential cross-sections are available
- NNLO event reweighting incorporated in MC (Pythia & MC@NLO)

q q ➔ q q H + X : weak boson fusion

LHC: by far the 2nd cross-section

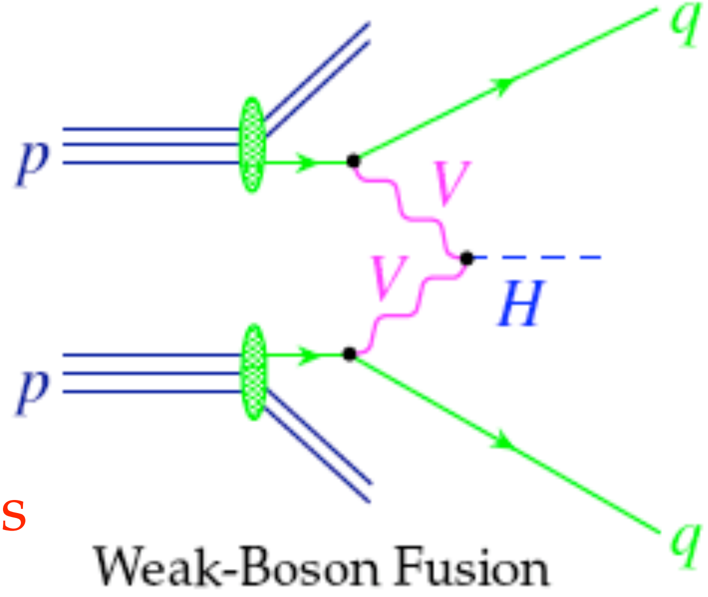
Tevatron: competes with WH/ZH

LO known for long

[(Jones-Petcov, 1979;) Cahn-Dawson, 1984]

Parton distribution of incoming valence quarks peaks at x~0.1-0.2

➔ two highly energetic outgoing quarks with E_T scale of order (a fraction of) m_V



Weak-Boson Fusion

Important to compare with background processes at NLO

e.g. gg➔Hjj [Figy-Oleari-Zeppenfeld, 2003; Campbell-Ellis-Berger, 2004]

Simple structure of (small) NLO QCD corrections

(no single-gluon exchange between incoming quarks)

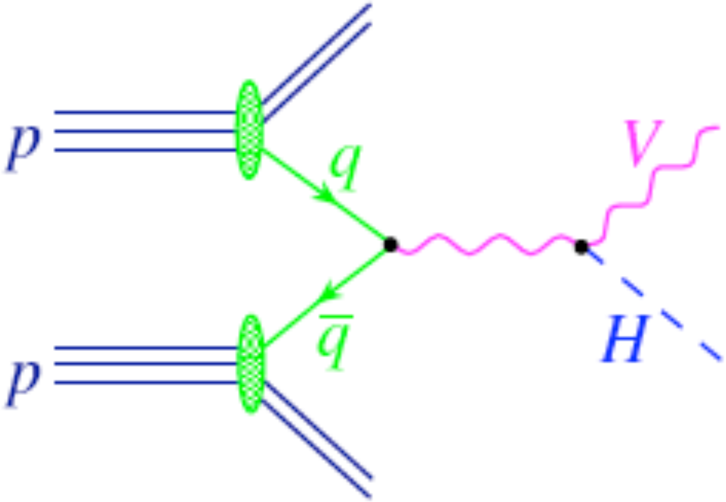
[Han-Valencia-Willenbrock, 1992]

K_{NLO}~1.1 with tiny scale dependence

(±5% for distributions, <2% for total cross-section)

q qbar ➔ V H + X : associated prod. with V=W,Z

Small cross-section
(especially at LHC)
but V-tagged signal!



LO long known [(Ioffe-Khoze, 1976;)
Glashow-Nanopoulos-Yildiz, 1978]

NLO QCD done [Han-Willenbrock, 1990]

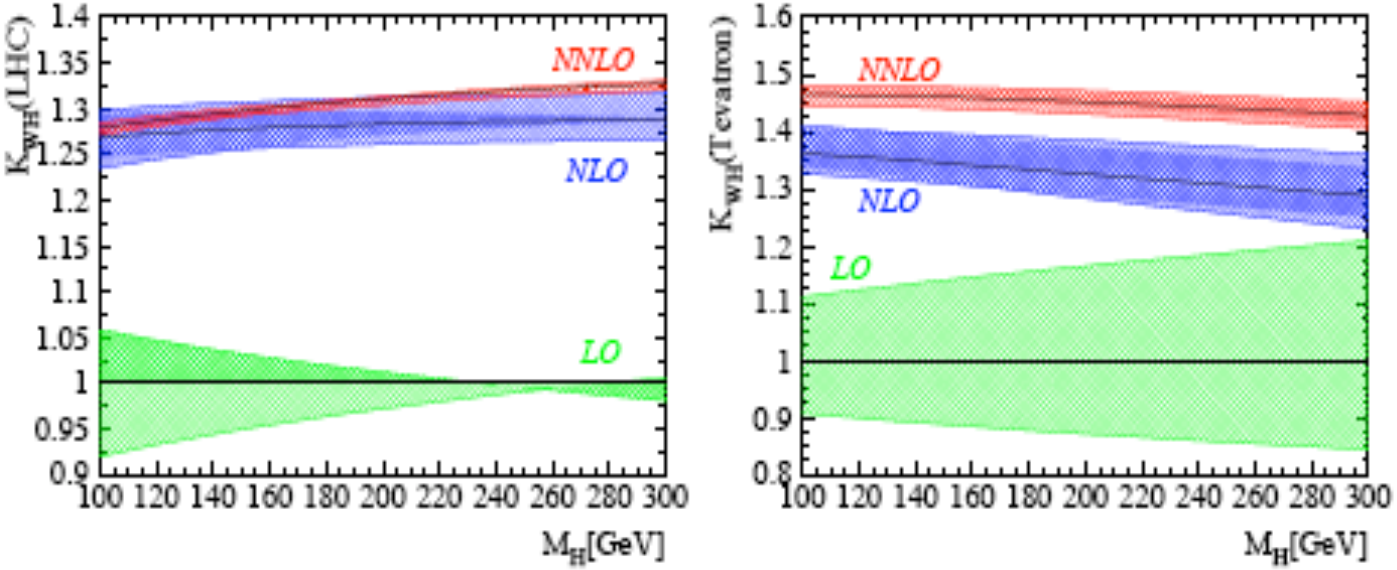
NNLO QCD also known
[Harnberg-vanNeerven-Matsura, 1991-2002; Harlander-Kilgore, 2002]

NLO-EW fully performed [Ciccolini-Ditttmaier-Kramer, 2003]

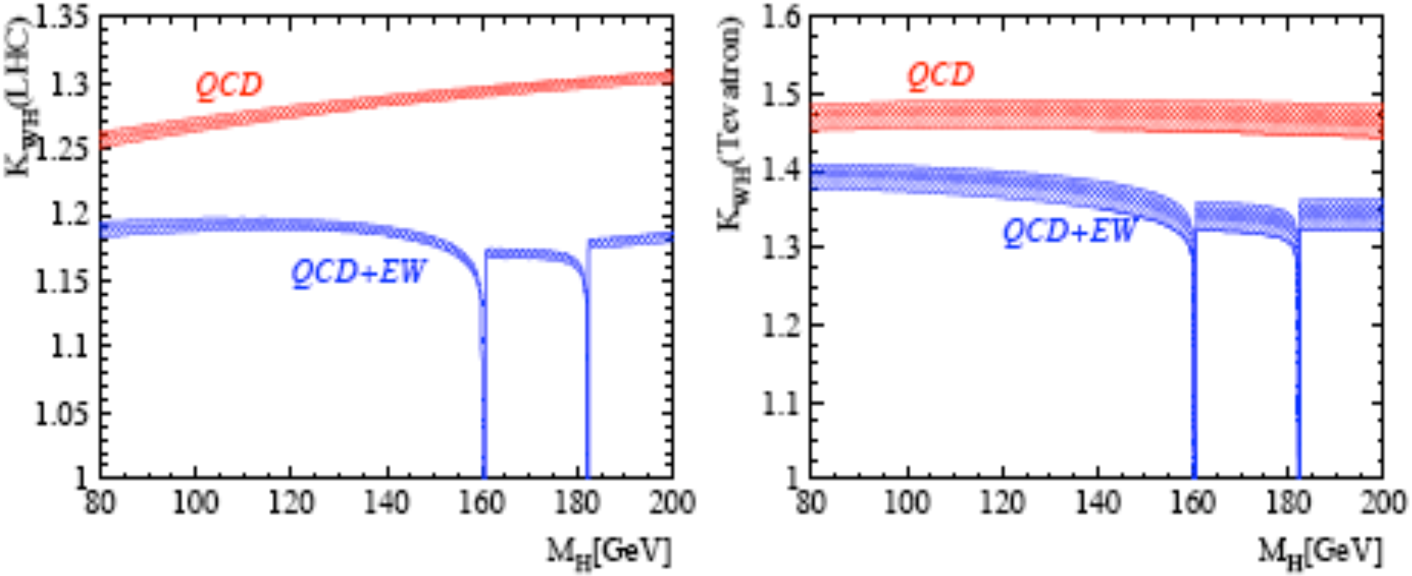
Present situation summarized in the following figures

Corrections to associated prod. with V=W,Z

[Brein-Djouadi-Harlander, 04]



[Brein et al, hep-ph/0402003]



q qbar, g g ➔ t tbar H + X : assoc. prod. with t tbar

LO [Kunszt, 1984]

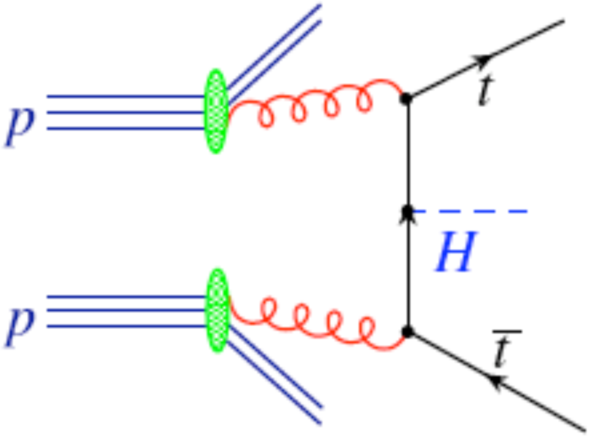
NLO

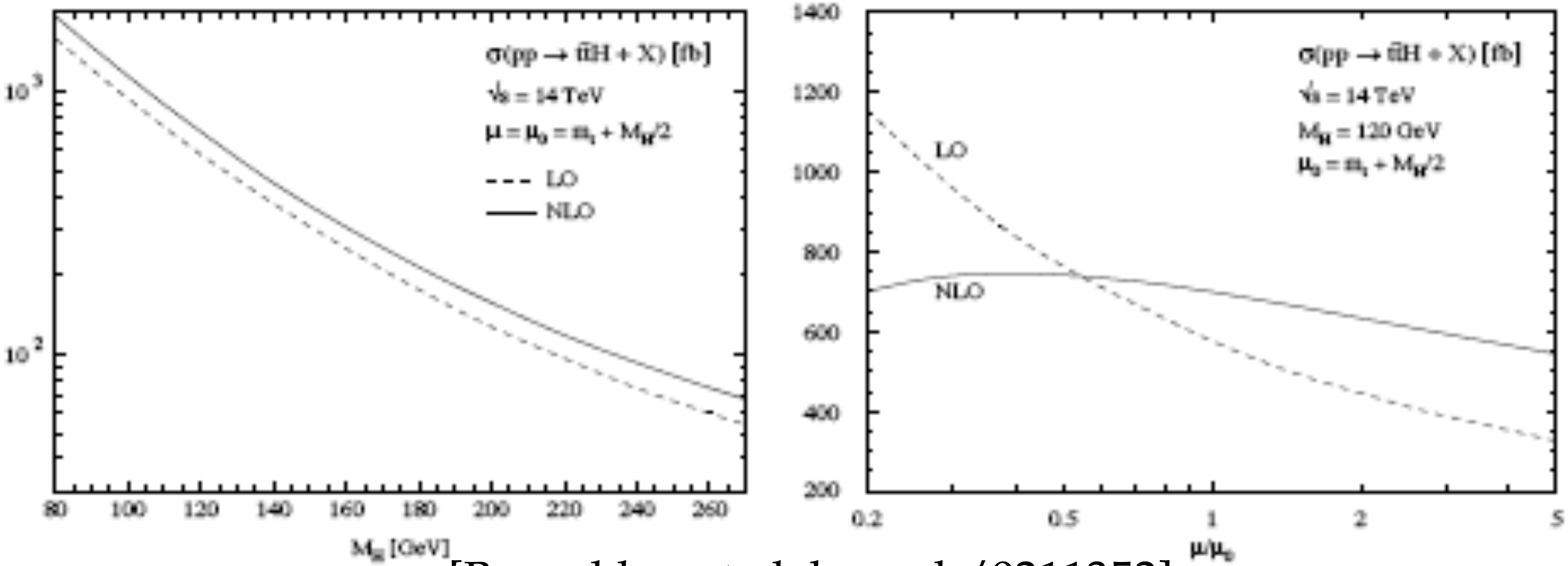
[Beenakker et al, 2001-3; Dawson et al, 2001-4]

small cross-section but t-pair tagging:

potentially relevant for the LHC

(with sufficient luminosity)





[Beenakker et al, hep-ph/0211352]

q qbar, g g → b bbar H + X : assoc. prod. with b bbar

Small cross-section in SM, may be strongly enhanced in some extensions, e.g. MSSM at large tan(beta)

Theoretical subtleties due to large ratio m_H/m_b: large logarithms from collinear bottom quarks

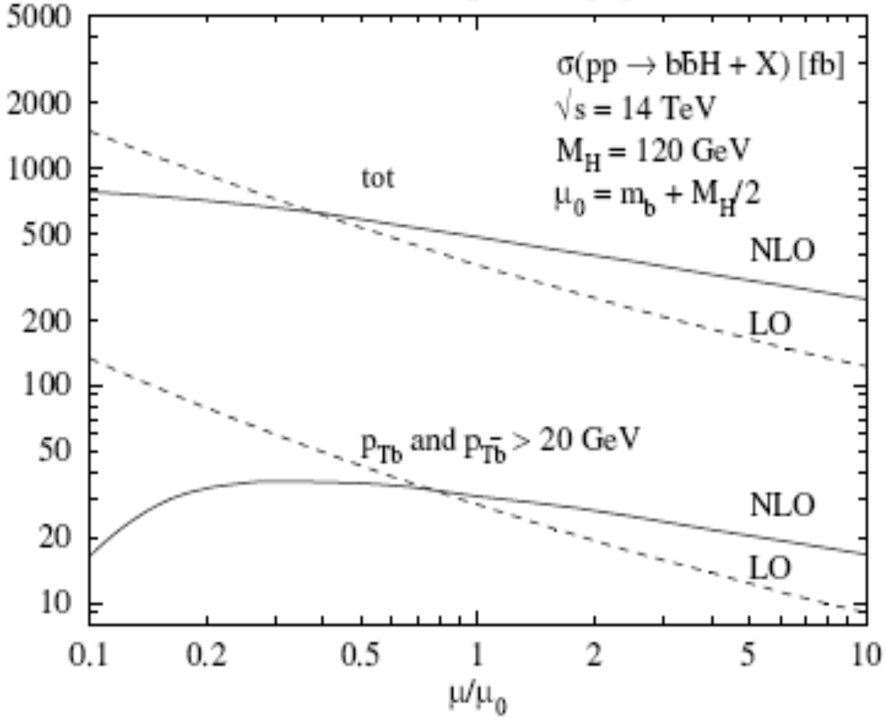
One extreme situation:
two high-p_T b-quark jets
(similar to t tbar H)

relevant processes are
gg, … → b bbar H

parton densities in 4FS
(non-resummed logs)

NLO QCD corrections known
[Dittmaier-Kramer-Spira, 2004]

Dittmaier, Krämer, Spira hep-ph/0309204



More on b bbar H production

Other extreme situation: no high-p_T b-quark jets

relevant process is b bbar ➔ H + X

parton densities in 5F scheme (resummed logs)

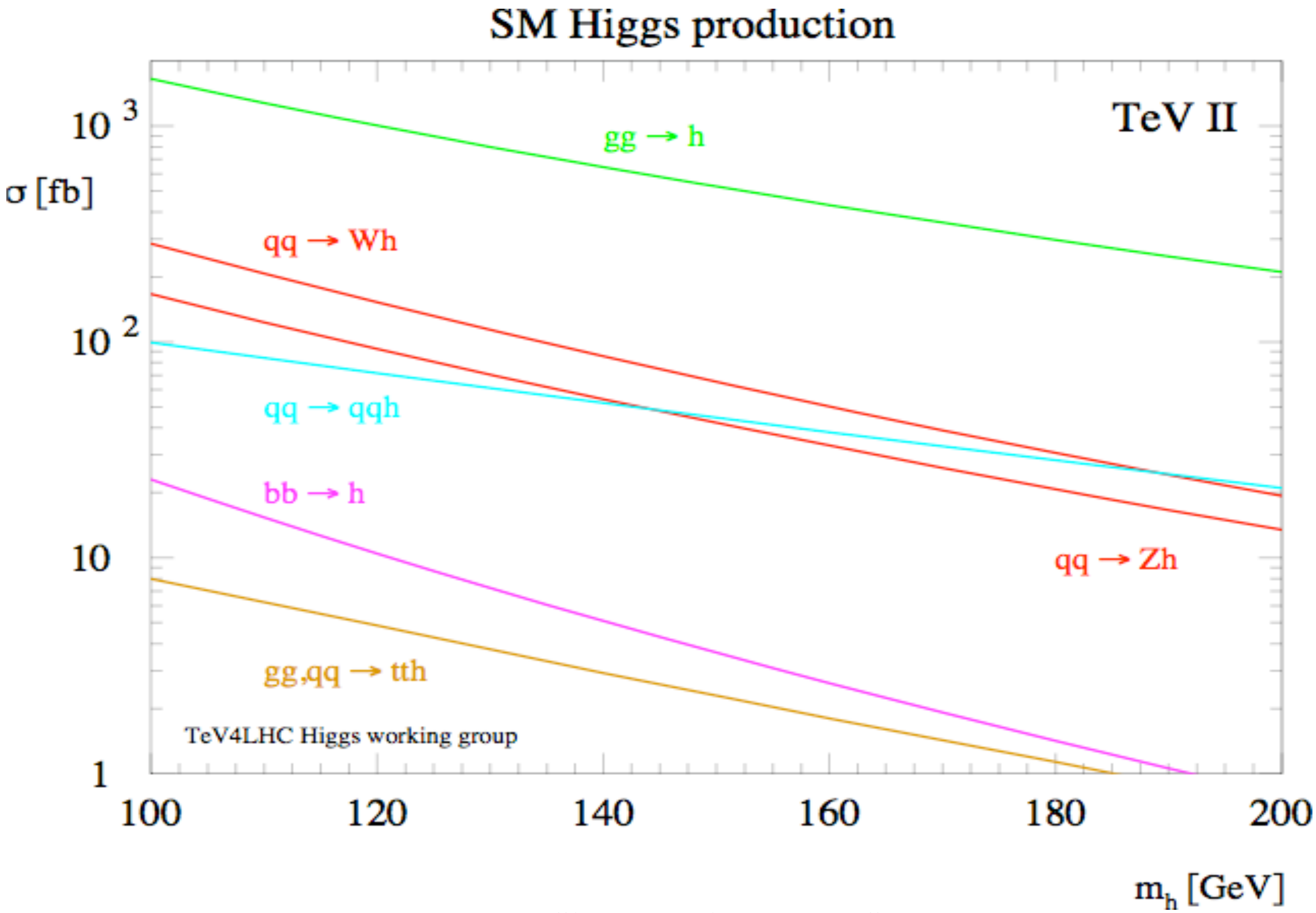
NLO [Barnett et al, 1988; Olness-Tung, 1988; Dicus-Willenbrock, 1989]

NNLO cross-section now available [Harlander-Kilgore, 2003]

Hybrid method for 1 high-p_T b-quark jet (5FS & 4FS)

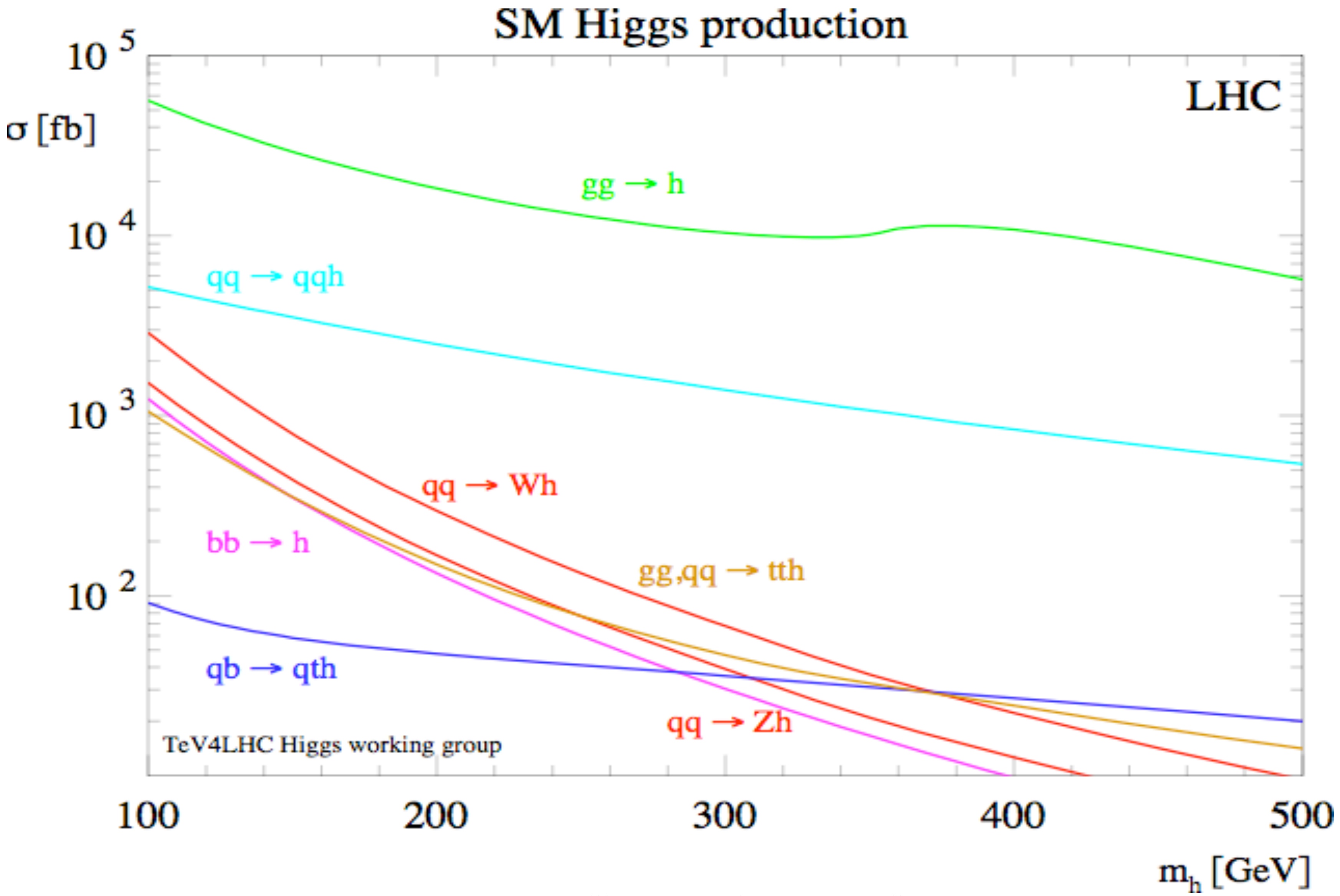
In general, considerable numerical discrepancies between 2 methods, minimized by choosing factorization scale $m_H/4$

SM Higgs production at the Tevatron



[hep-ex/0612172]

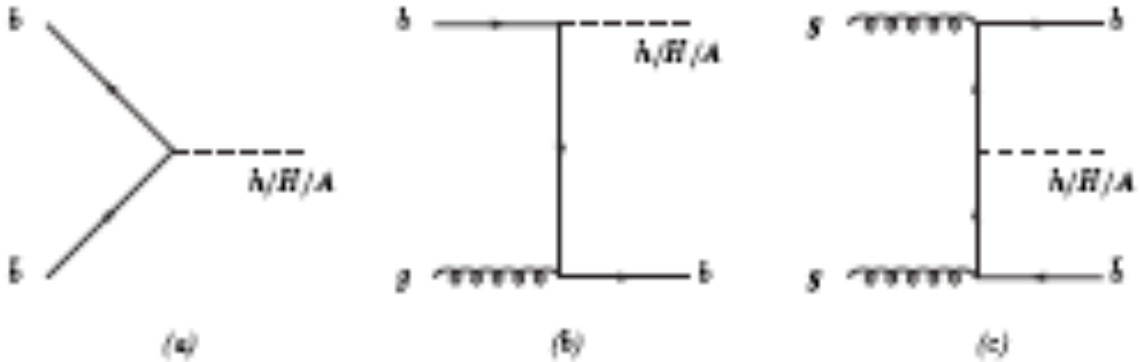
SM Higgs production at the LHC



[hep-ex/0612172]

Comments on MSSM Higgs production

For the MSSM neutral Higgs bosons, the production mechanisms are the same as for the SM Higgs, with modified couplings: possible strong enhancements [for large tan(beta)] of gluon-gluon fusion (via the bottom loop) and of associated production with b-bar



For the charged Higgs boson above the top quark scale, the dominant mechanism (among several ones) is the associated production of H^- t bbar or H^+ tbar b

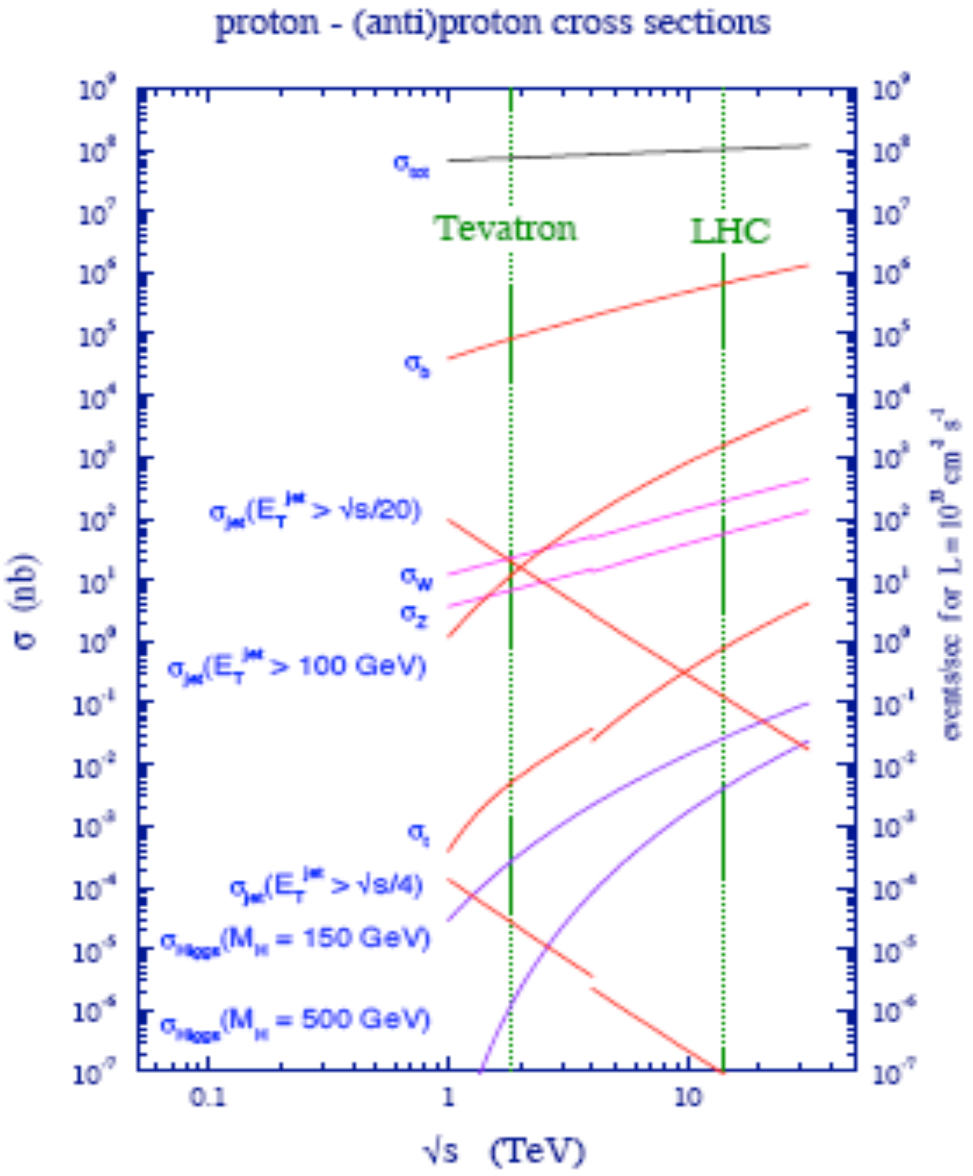
F. Zwirner
University & INFN, Padova

The Hunt for the Higgs particle

Part 3

Cern Academic Training, 27/2-1/3/2007

The challenge of Higgs searches at hadron colliders



[Gianotti, 2004]

Tevatron searches [CDF, D0]

$p\,\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

Two main branches depending on m_H:

- pp ➔ VH, H ➔ bbbar ($m_H < 135\text{-}140$ GeV)

Can use lepton tag from V=W,Z to suppress background (mostly Wbb, Zbb, tt, WZ)
Additional help from distributions of b-jets and leptons
Understanding detector response and systematics in background shape crucial for discovery (no sharp peaks)

- pp ➔ HX, H ➔ W^+W^- ➔ dileptons ($135\text{-}140 \text{ GeV} < m_H$)

Backgrounds: WW, tt ➔ WW(b)(b), …
Can exploit angular correlations: for signal, charged leptons prefer to be at small angles

Present Tevatron analyses [CDF, D0]

$$p\,\overline{p} \longrightarrow W\,H \longrightarrow l\,\nu\,b\,\overline{b} \qquad (2)$$

1 isolated lepton + 2 jets (1 or 2 b-tagged) + $E_{T,miss}$

Similarly:

$$p\,\overline{p} \longrightarrow Z\,H \longrightarrow \nu\,\overline{\nu}\,b\,\overline{b}\,,\;\; l^{+}\,l^{-}\;\,b\,\overline{b} \qquad (3)$$

$$p\,\overline{p} \rightarrow W\,H \rightarrow W\;\,W^{+}\,W^{-} \;\rightarrow 6 \text{ final states}$$

$$p\,\overline{p} \rightarrow H \rightarrow W^{+}\,W^{-} \;\rightarrow l^{+}\,\nu\,l^{-}\,\overline{\nu} \qquad (4)$$

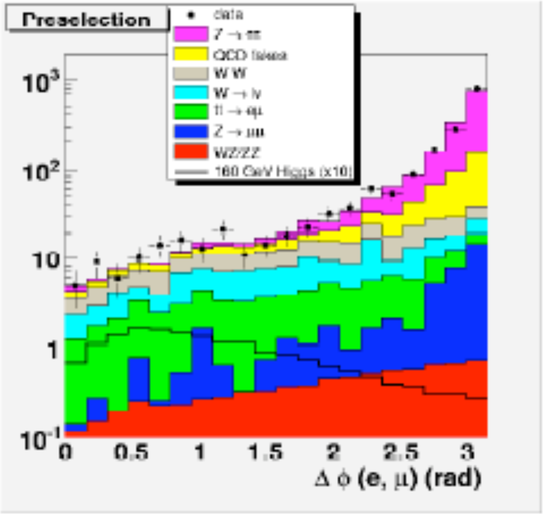
one analysis for $p\,\overline{p} \rightarrow W\;\,H \rightarrow \not{l}\,\nu\;b\,\overline{b}$

Analyzed in 2006: 360-1000 pb^{-1} at CDF, 260-950 pb^{-1} at D0
Expected total luminosity per experiment: from 4 to 8 fb^{-1}

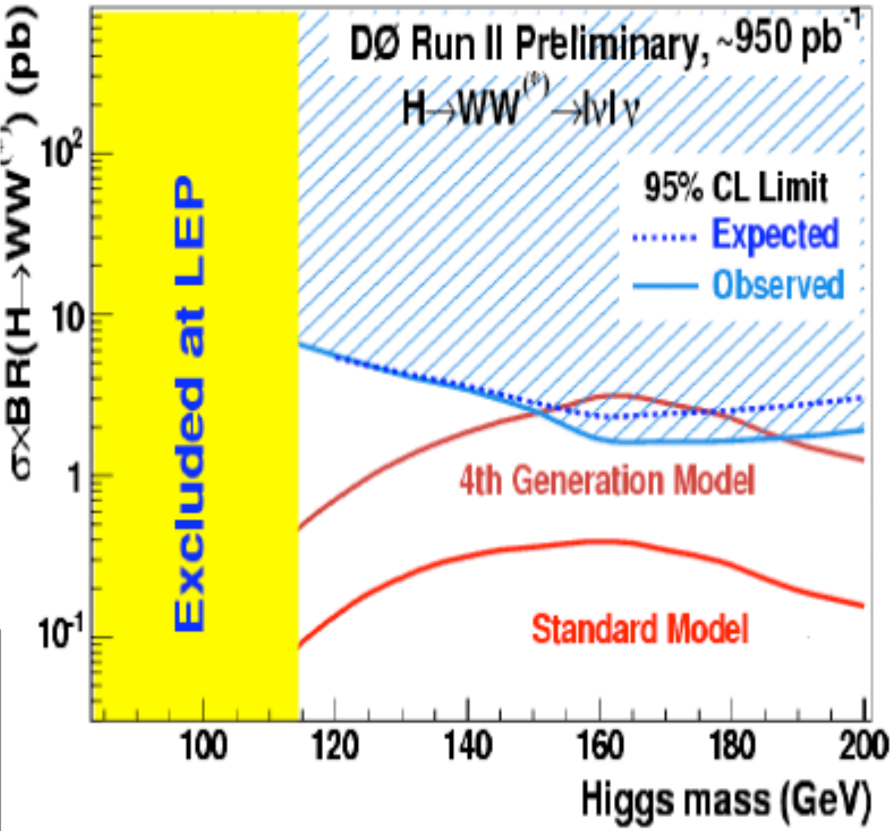
Example: the H ➔ W W* D0 analysis

Search in the ee, eμ and μμ + Missing E_T final states

The WW background is reduced using the spin correlations: smaller ll angle in the Higgs signal

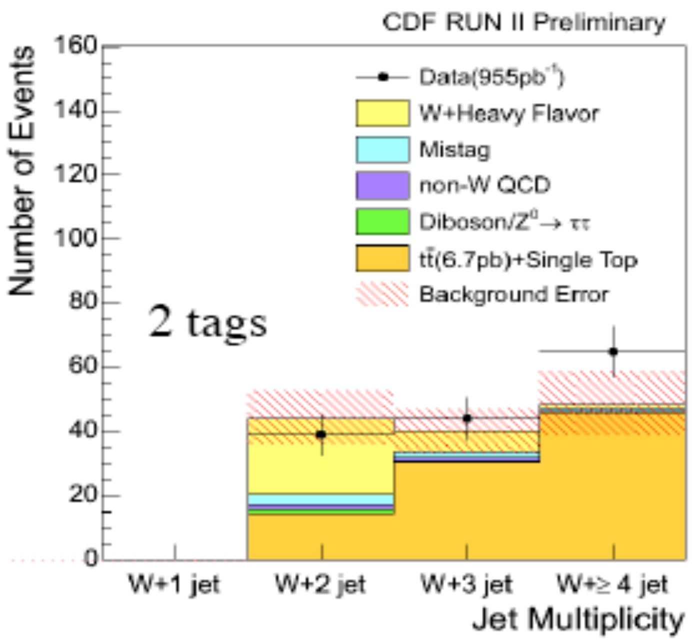


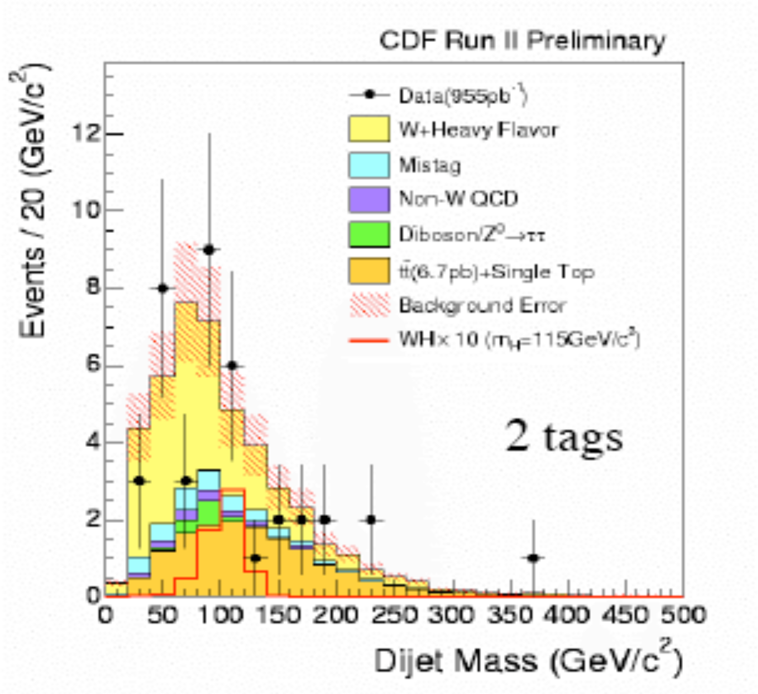
10 ee events vs 10.3±0.6 expected
18 eμ events vs 24.4±1.5 expected
9 μμ events vs 9.8 ± 0.8 expected



Example: a WH CDF analysis $(W\to l\nu)(H\to bb)$

e/μ + Missing E_T + 2jets (≥ 1 b-tag)



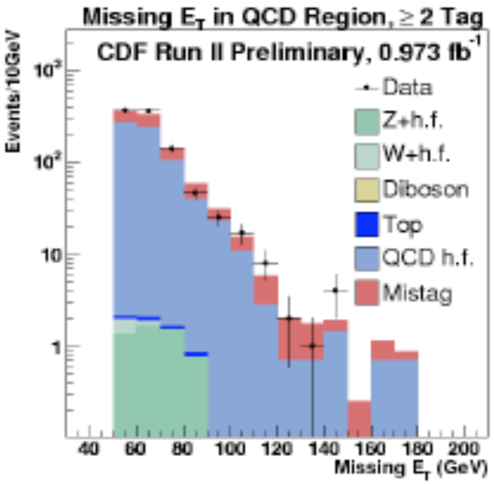


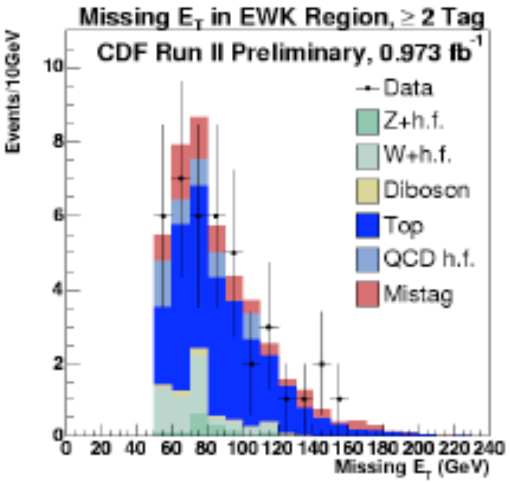
Main challenges:

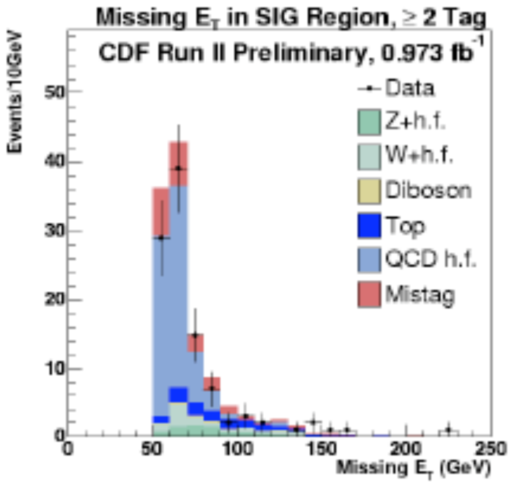
- control of the Wbb and top backgrounds
  (shape and normalization)
- dijet mass resolution

Example: a ZH CDF analysis $(Z \rightarrow \nu\nu)(H \rightarrow bb)$

Missing E_T + 2jets (≥ 1 b-tag) + 0 lepton







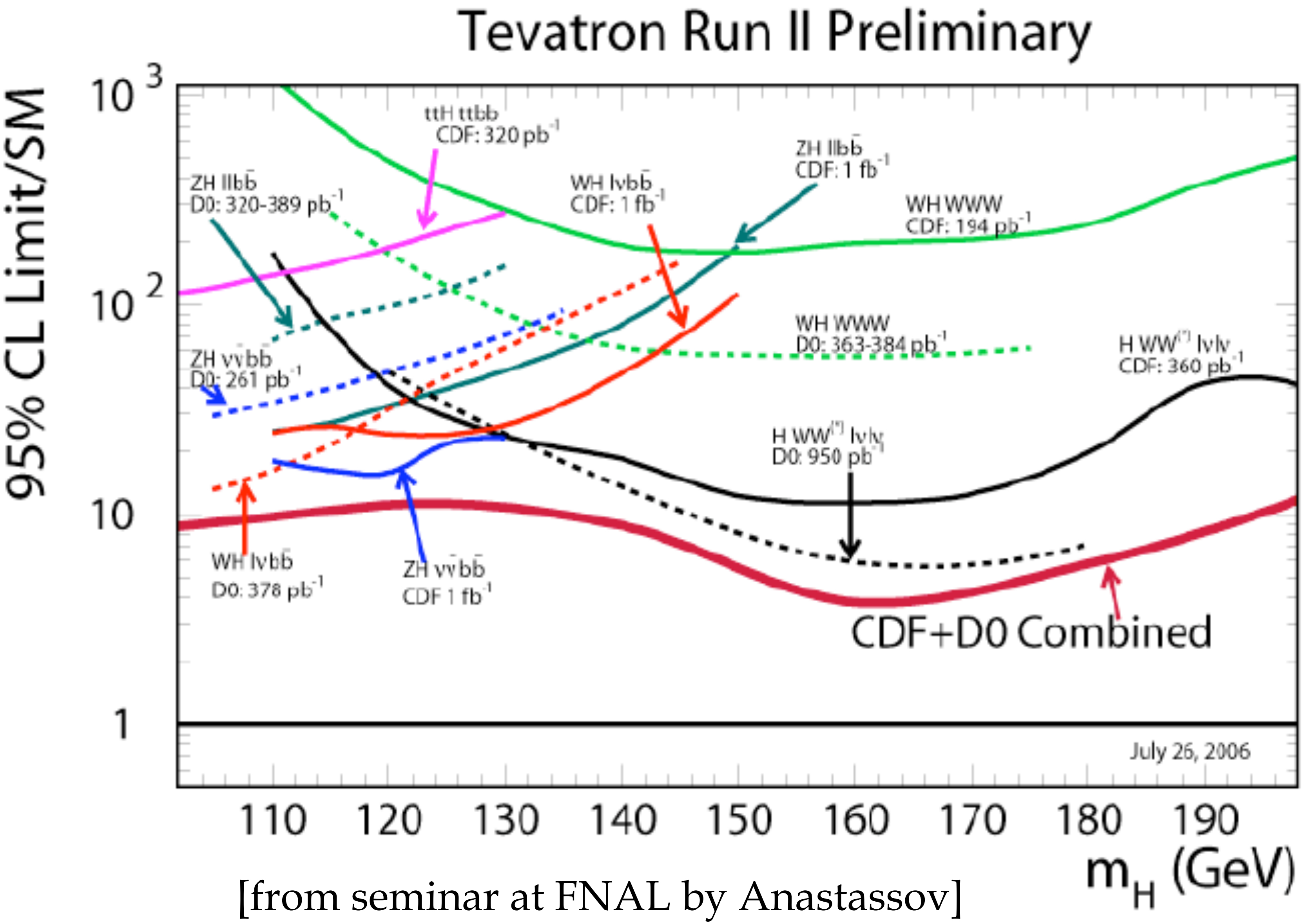
Control regions: QCD = MET close to a jet – EWK = ≥ 1 lepton

Main challenges: control of the QCD background (shape and normalization)

dijet mass resolution

(This search is also sensitive to WH with "missed" lepton)

2006 combined CDF and D0 results



[from seminar at FNAL by Anastassov]

2006 summary and outlook [hep-ex/0612044]

Combine 16 channels…:

$[W \to (e/\mu)\nu](H \to bb$ 1 and 2-tags$)$

$[Z \to ee/\mu\mu]$ $(H \to bb$ 1 and 2-tags$)$

$[Z \to \nu\nu)]$ $(H \to bb$ 1 and 2-tags$)$

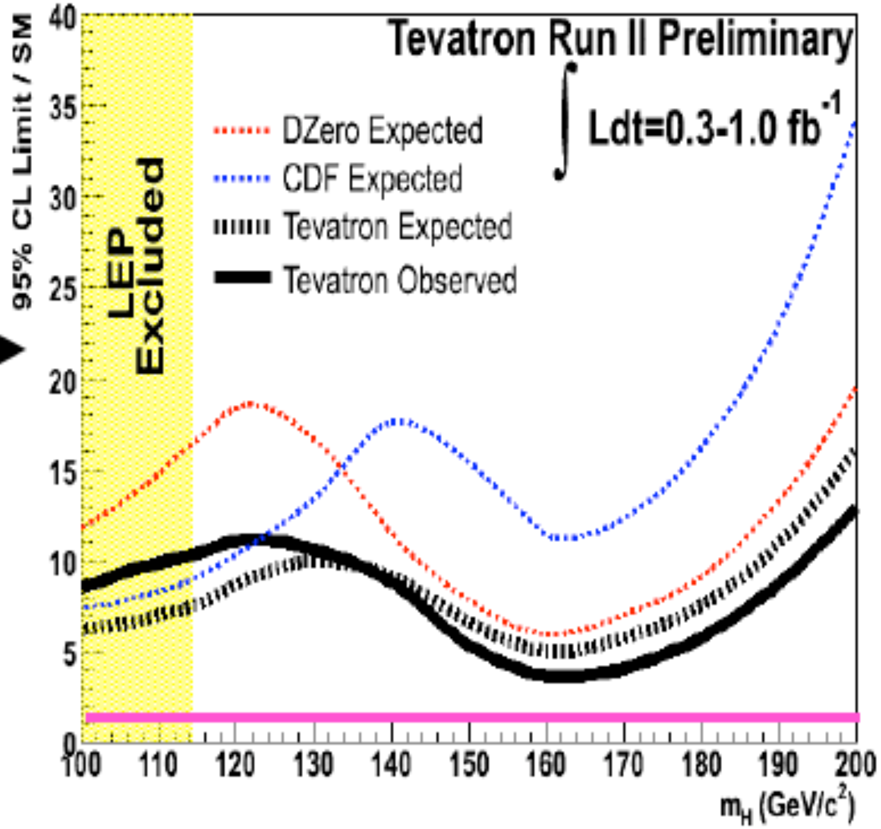
$[W \to (e/\mu)\nu][H \to W\{W \to (e/\mu)\nu\}]$

$[H \to WW \to (e/\mu)\nu(e/\mu)\nu]$

Combine two experiments

(equivalent to one with 1.3 fb^{-1})

95% CL limit / SM cross section



With realistic improvements,

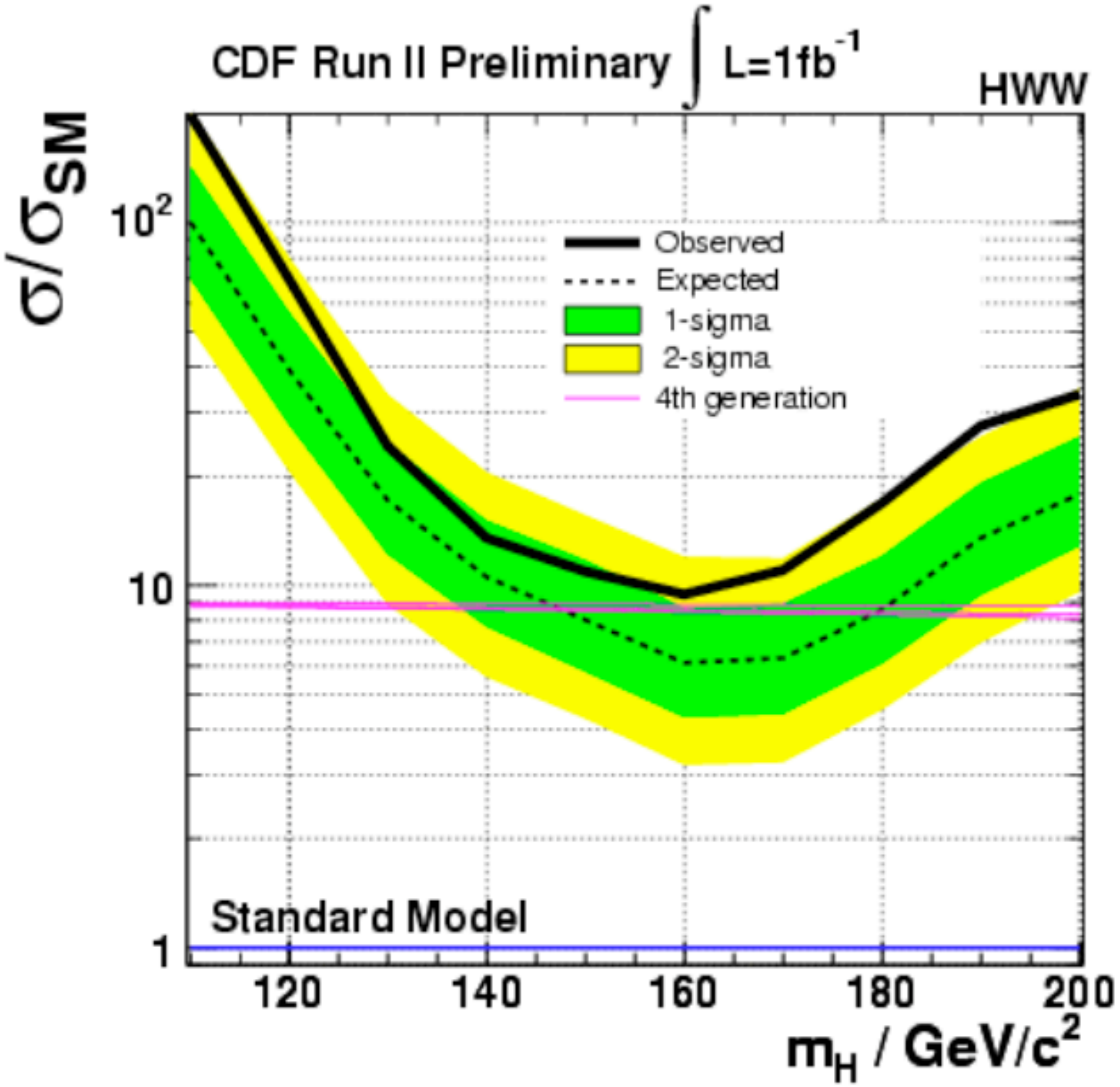
95%CL = SM with

3 fb^{-1} @ 115 GeV

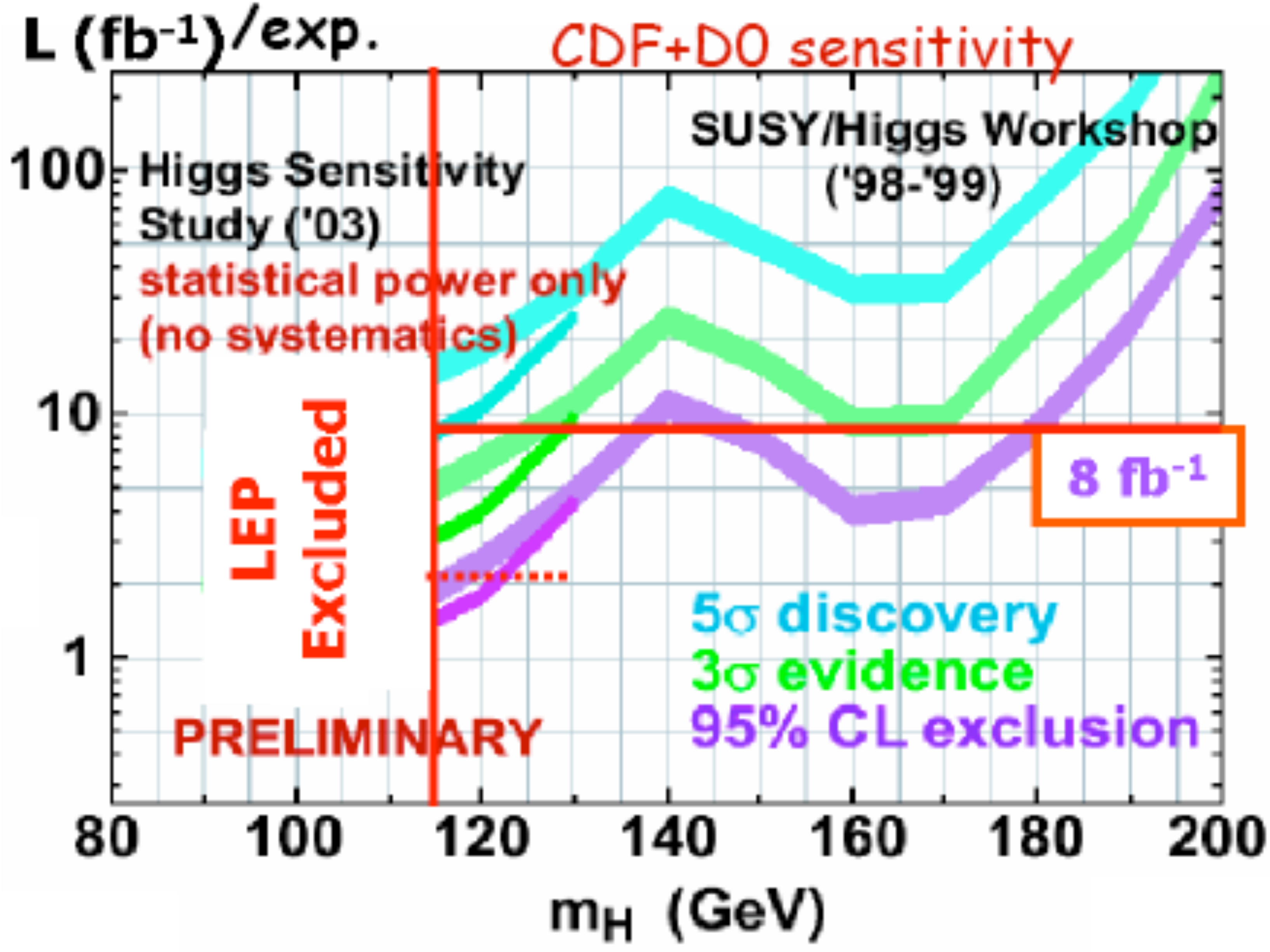
5 fb^{-1} @ 160 GeV

8 fb^{-1} from 115 to 185 GeV

A recent CDF update on H→WW→dileptons



More on the expectations for a SM Higgs



MSSM Higgs Tevatron serches

Tevatron might be sensitive to MSSM neutral Higgs bosons in the region of very large tan(beta)~m_t/m_b, when (H,A) couplings to b and tau strongly enhanced [strong constraints, however, from rare B-decays]

Bounds difficult to interpret: strong model-dependence due to large 1-loop threshold corrections to bottom mass

Decay modes: b-bbar (~90%) and tau-tau (~10%)

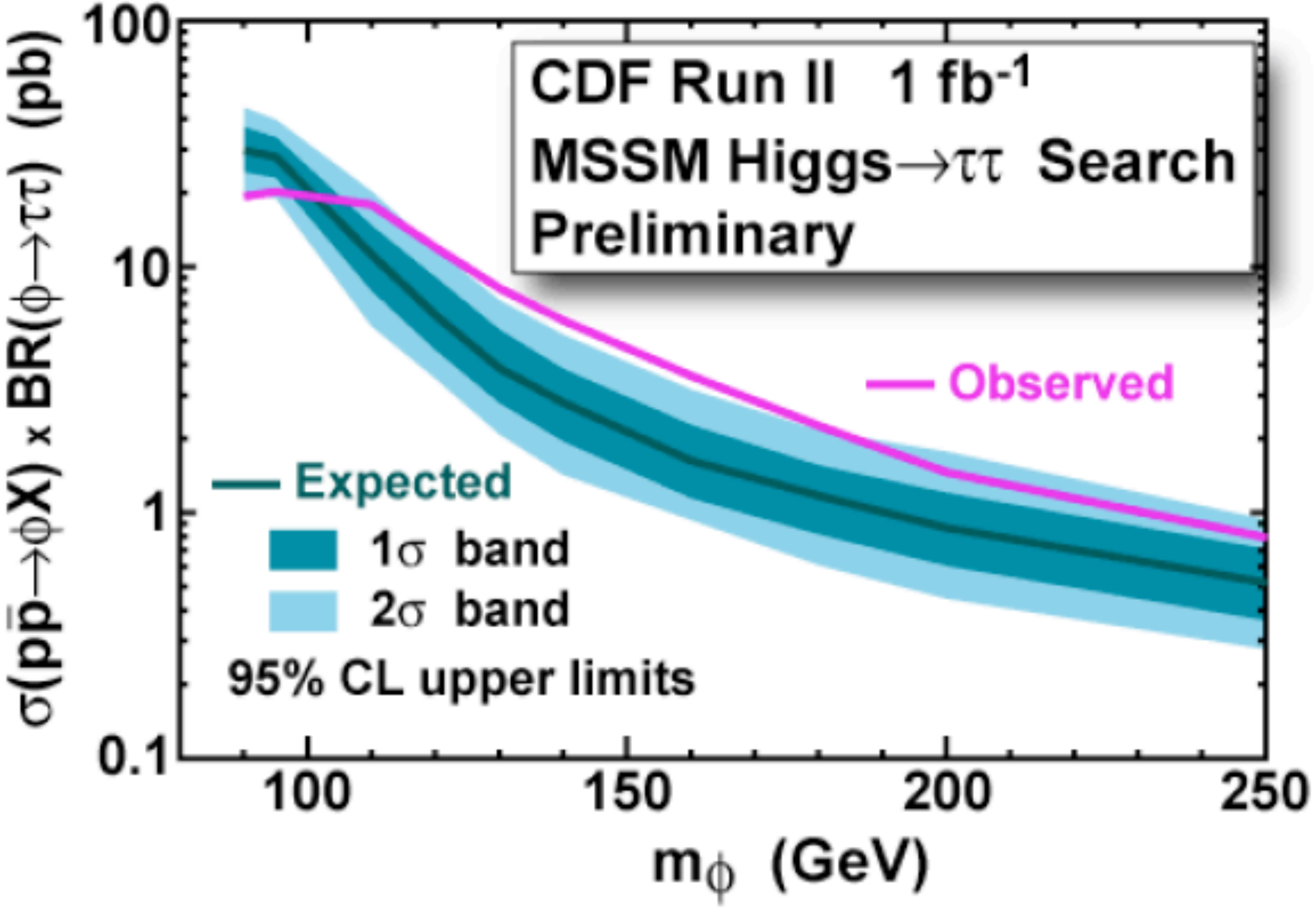
Possible signals (Phi=h,H,A):

Phi→b-bbar in association with 1 or 2 b-jets

Inclusive Phi→ tau-tau

In addition, some sensitivity to $t \rightarrow H^+ b$

A recent CDF result on inclusive Higgs ➔ tau tau



[CDF note 8676, winter 2007] (e+had, mu+had, e+mu) channels

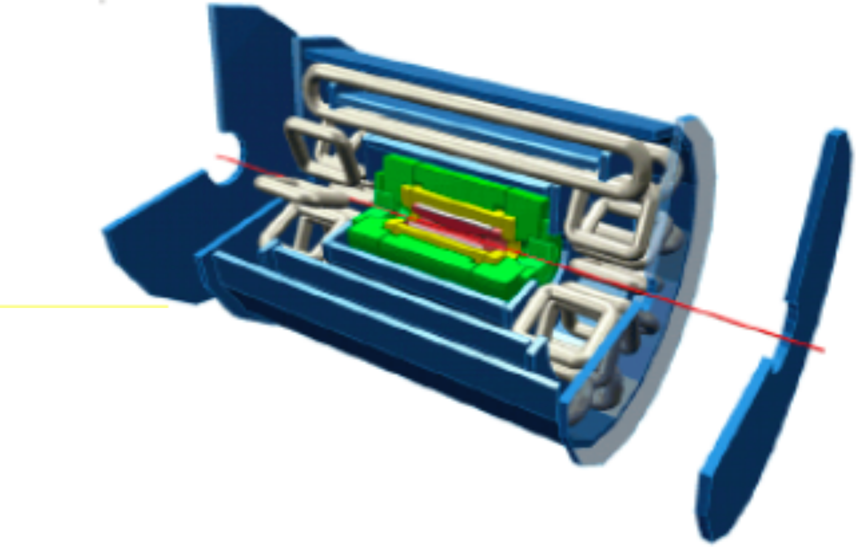
Higgs hunting in pp collisions at the LHC

The framework:

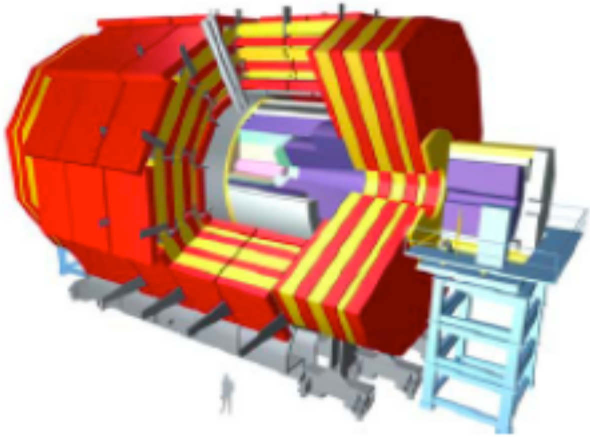
- Calibration run in Dec 2007 at 0.9 TeV c.m. energy
- 1st physics run in 2008 at 14 TeV c.m. energy (0.1-1 fb^{-1}?)
- More physics runs in 2009+…: from 10 to 100 fb^{-1}/year?

Two general-purpose detectors:

ATLAS A Toroidal LHC ApparatuS



CMS Compact Muon Solenoid



Bibliography for recent ATLAS and CMS point of view

CMS:

CMS Physics TDR, CERN/LHCC 2006-021

ATLAS:

ATLAS TDR 15 (CERN/LHCC/99-15) [in part obsolete]

WBF analysis:

S.Asai et al, hep-ph/0402254

H ➔ gamma gamma:

talk by Carminati, Physics at LHC 2006

Higgs physics overview:

talk by Unal, Physics at LHC 2006

The gold-plated signal

$$p\,p \rightarrow H + X \qquad H \rightarrow Z\,Z \rightarrow l^{+}\,l^{-}\;l'^{+}\,l'^{-} \quad (l, l' = e, \mu)$$

ZZ branching ratio sizeable for $m_H > 130$ GeV
(with a dip between WW and ZZ thresholds)

Clean signal ("gold-plated") but low statistics
Three channels: 2e2mu, 4e, 4mu

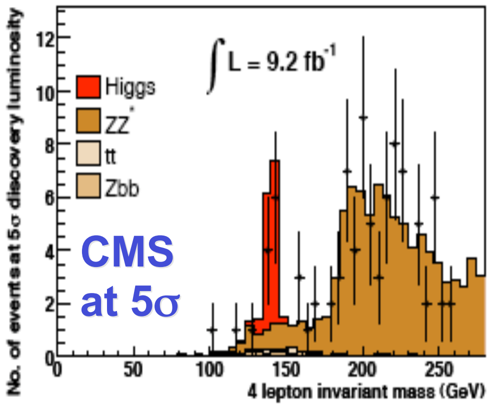
Background to 4l signal: ZZ(*) (irred.); Zbb, tt (red.)
Suppressed by isolation cuts & anti-impact parameter

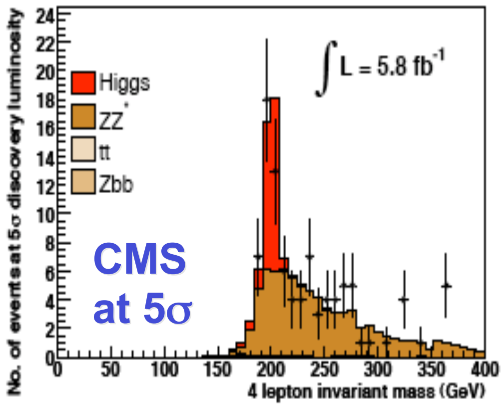
Key points: e/mu identification, energy resolution

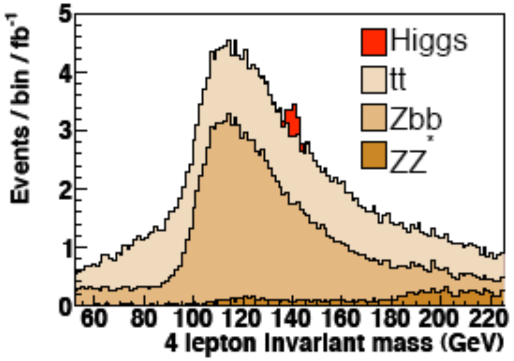
Can be used to measure mass, width & cross-section

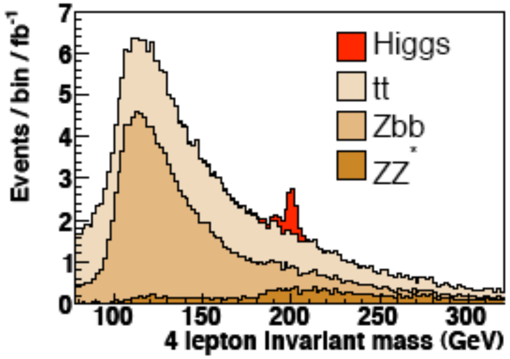
Some 4l analyses

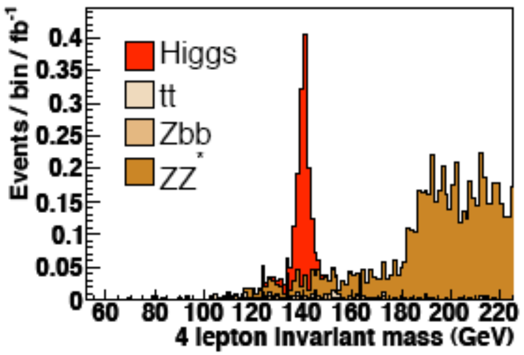
eeμμ

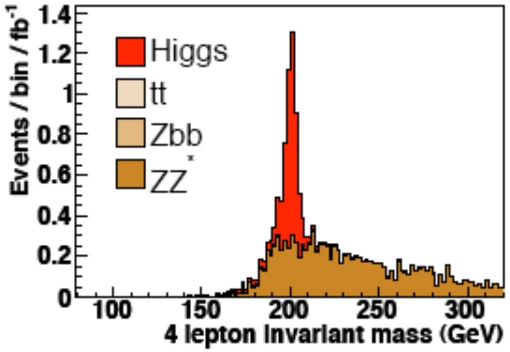












The di-leptonic WW signal at the LHC

$$p\,p \rightarrow H + X \qquad H \rightarrow W^+\,W^- \rightarrow l^+\,\nu\,l'^-\,\overline{\nu}' \quad (l, l' = e, \mu)$$

A discovery mode for 150 GeV < m_H < 180 GeV

Signal:

opposite charge dileptons (ee,emu,mumu) + $E_{T,miss}$

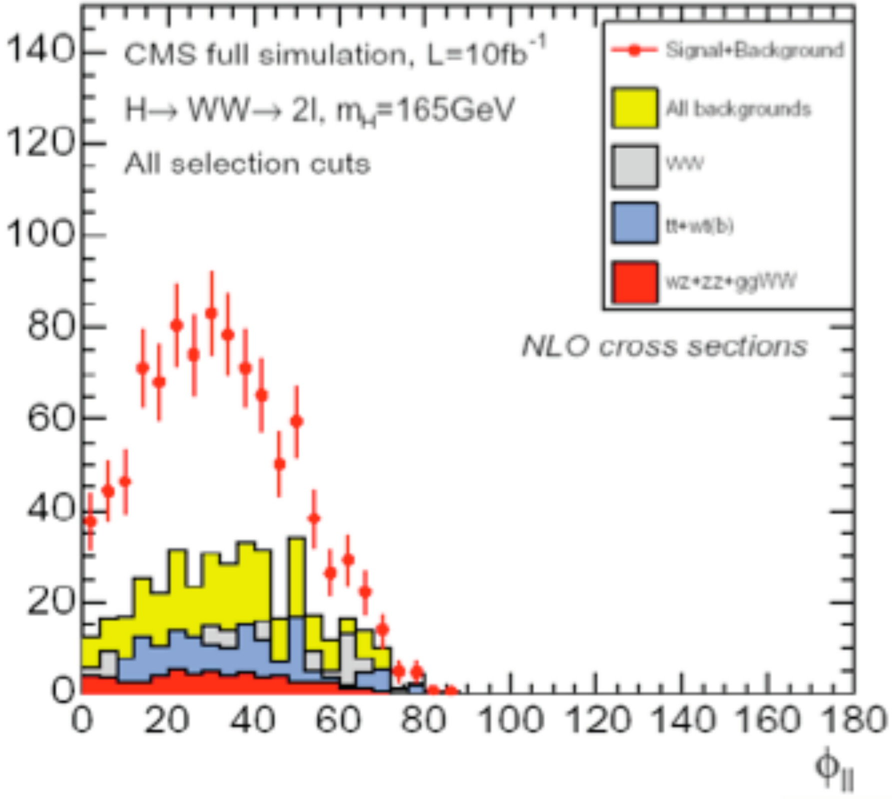
Backgrounds:

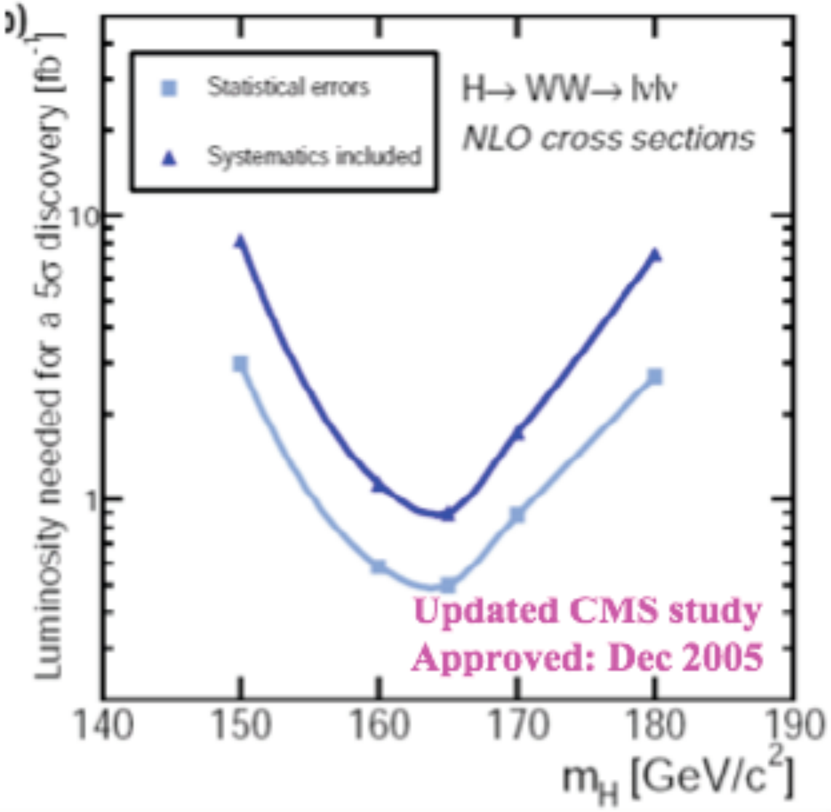
tt (jet veto), WW (angular correlation)

Difficulties:

- Counting experiment, no sharp mass peak
(only transverse mass with Jacobian peak)
- Relies heavily on accurate estimate of the background
(can use control regions to extrapolate to signal region)

Some recent studies of H➔WW➔dileptons





Updated CMS study
Approved: Dec 2005

The (inclusive) two-photon signal $p\,p \to H + X \qquad H \to \gamma\gamma$

Rare decay [BR~1-2×10^{-3} for 115<m_H (GeV)<150]: hopeless for Tevatron, clean but difficult signal for light Higgs at the LHC

Signal: 2 high-E_T isolated photons; narrow peak in diphoton invariant mass distribution after isolation and p_T cuts
Irreducible background: 2 prompt photons (QCD continuum)
Reducible backgrounds: jet-jet & jet-photon events with jets misidentified as photons; photons from particle decays
Background directly evaluated from data outside the peak

Need well-understood detector: ECAL, HCAL, tracking
some key-points: EM calorimetry, particle identification

Simulations can use NLO MC tools for signal & background

Also some exclusive analyses possible: WBF, H+1-jet, etc.

Inclusive two-photon in CMS (cut-based)

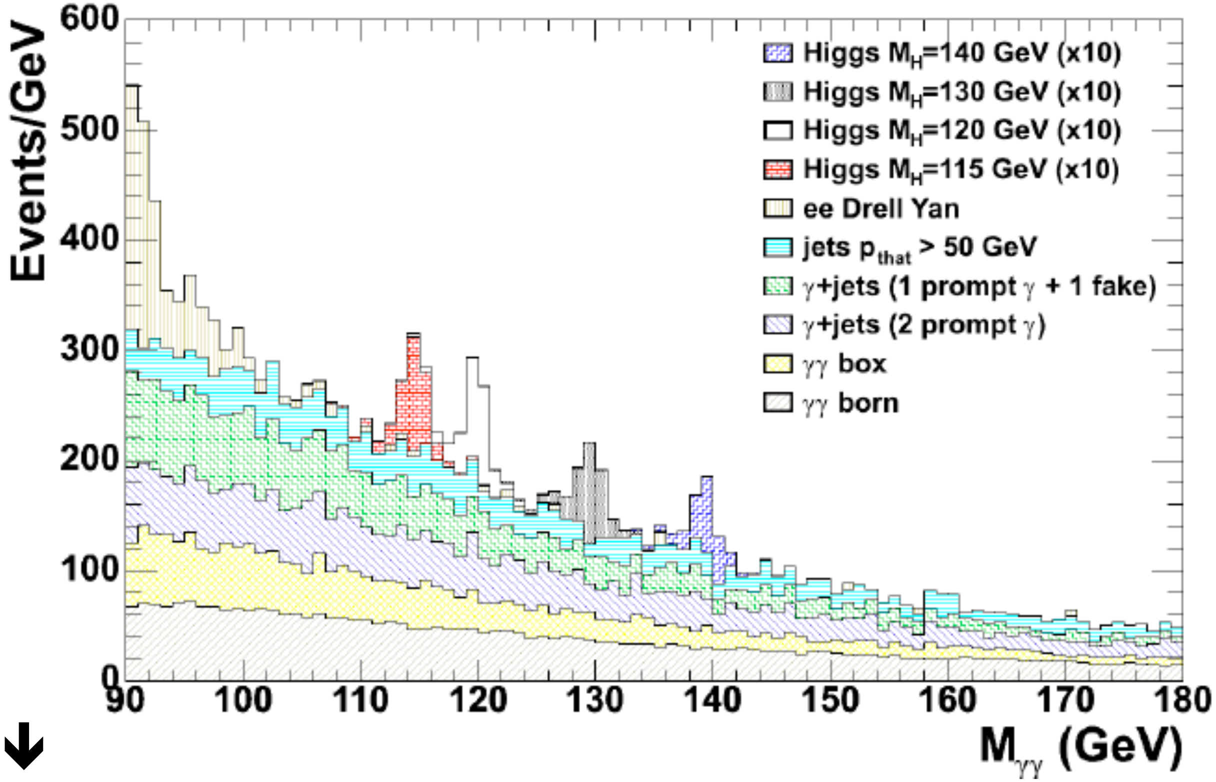
Cut-based analysis
(conservative)

1 fb^{-1} (signals x 10)➔

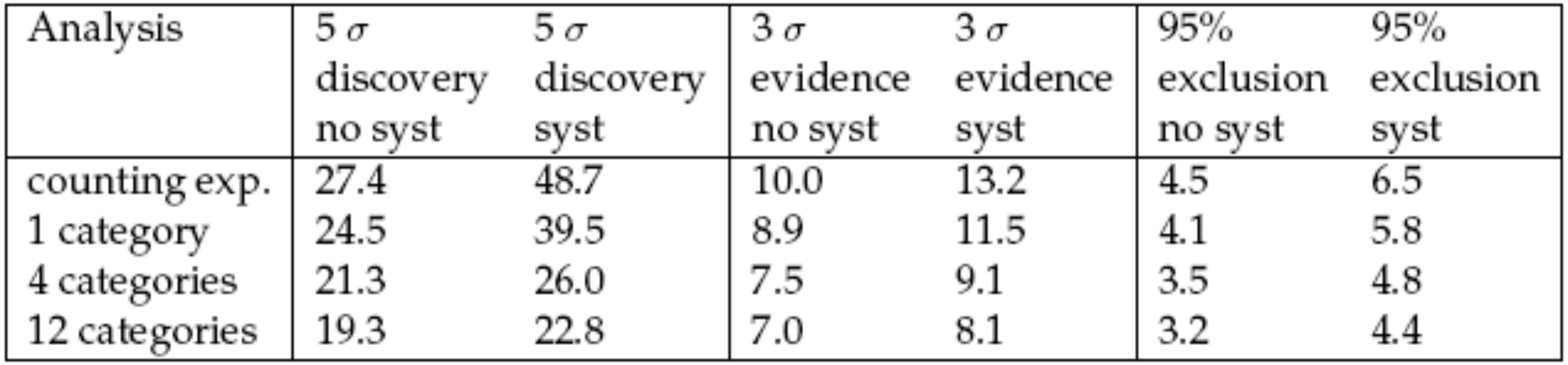
For $m_H < 140$ GeV:

5-sigma discovery
with < 30 fb^{-1}

95% c.l exclusion
with ~ 5 fb^{-1}



m_H=120 GeV 🡇

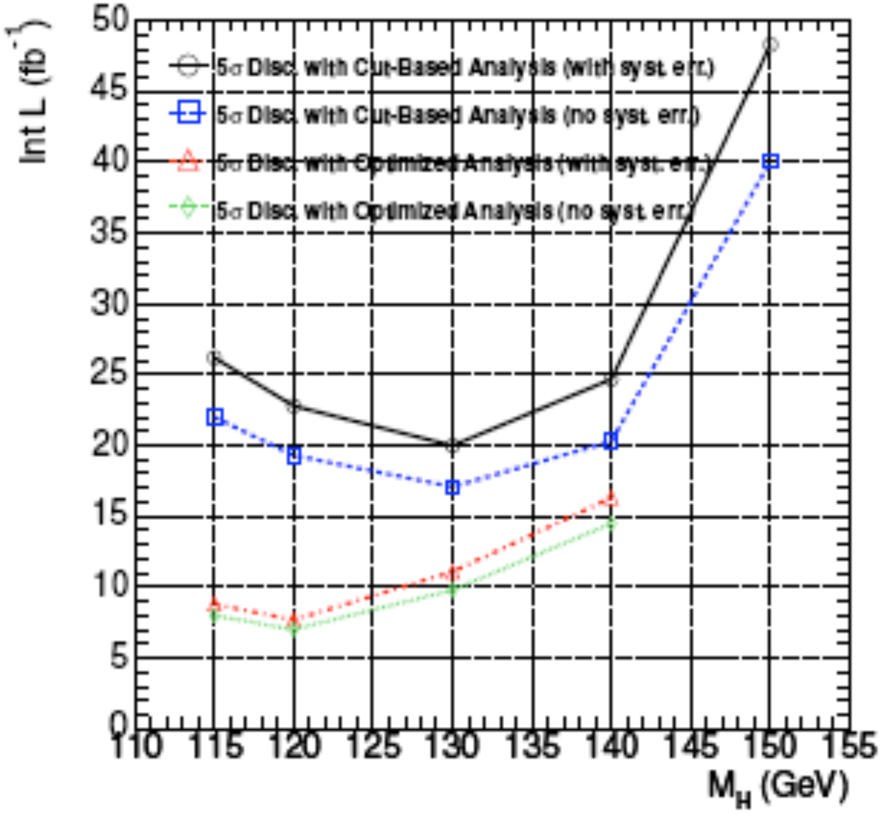


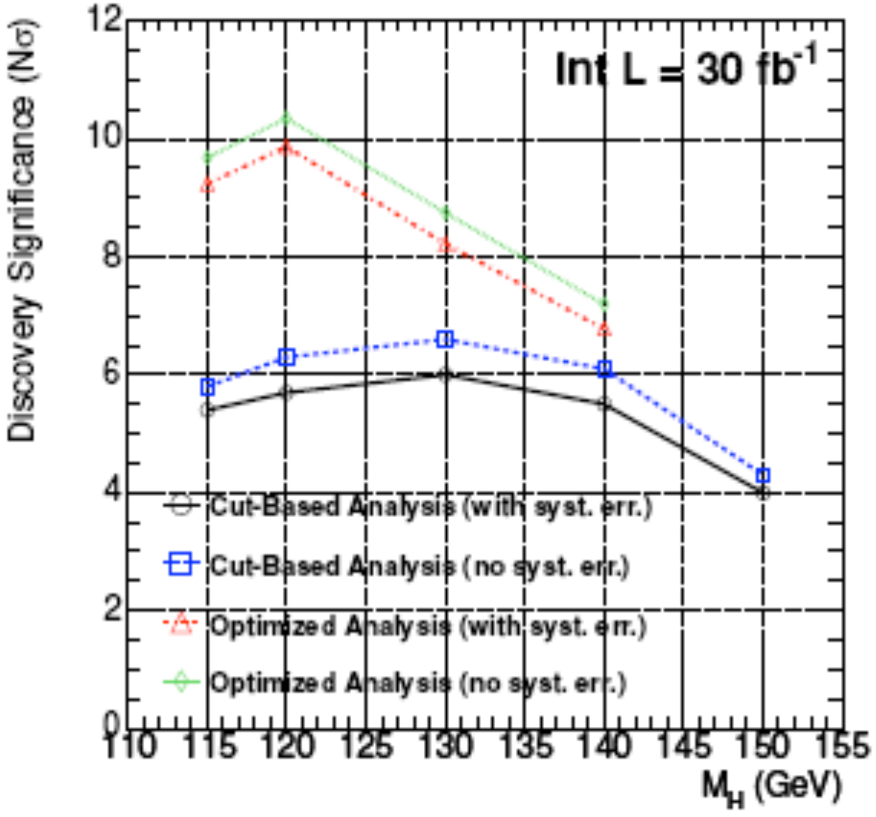
Analysis	5 σ discovery no syst	5 σ discovery syst	3 σ evidence no syst	3 σ evidence syst	95% exclusion no syst	95% exclusion syst
counting exp.	27.4	48.7	10.0	13.2	4.5	6.5
1 category	24.5	39.5	8.9	11.5	4.1	5.8
4 categories	21.3	26.0	7.5	9.1	3.5	4.8
12 categories	19.3	22.8	7.0	8.1	3.2	4.4

[CMS TDR 8.2 CERN/LHCC 2006-021]

Inclusive two-photon in CMS (optimised)

Optimised analysis using photon isolation and kinematics
(event-by-event estimate of s/b) (neural network)
Must be sure that signal and background distributions are well simulated
Uncertainties in significance-luminosity from poor background knowledge





[CMS TDR 8.2 CERN/LHCC 2006-021]

Inclusive two-photon in ATLAS

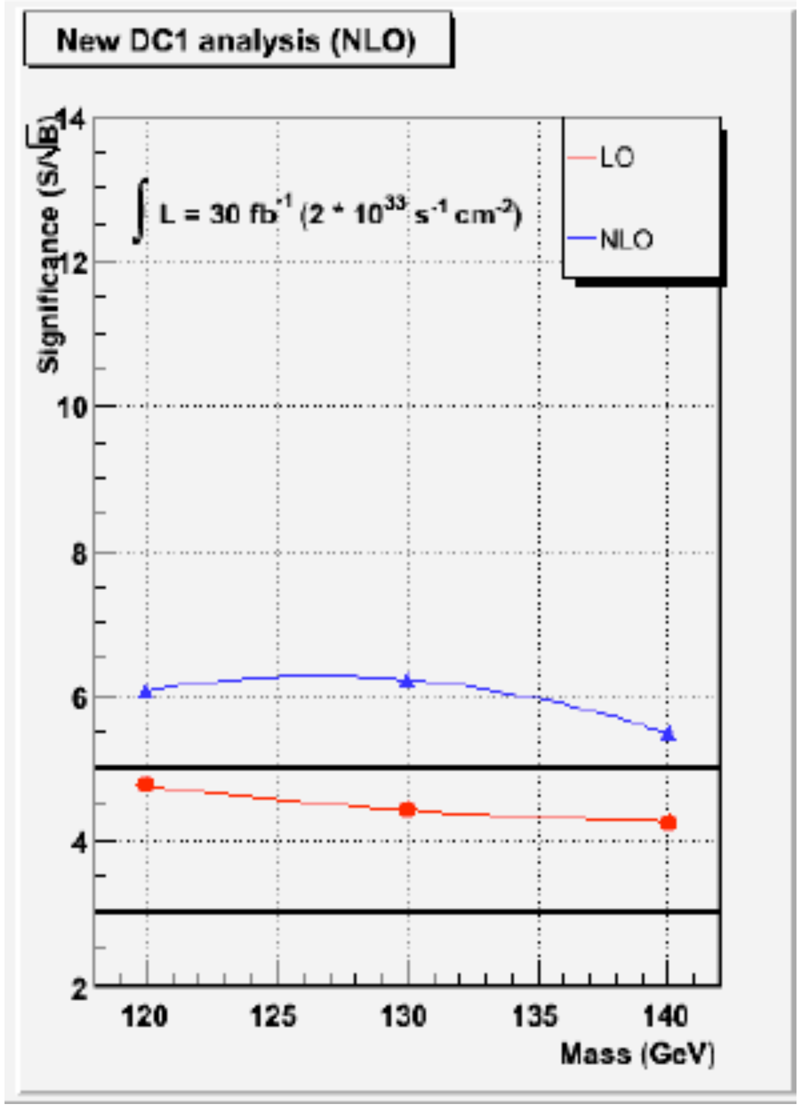
Large uncertainty on significance ~30%

~3-sigma with 10 fb^{-1} and basic analysis

There are ways to do better (5-sigma): distributions (likelihood ratios method) combined analysis with WBF & H+1-jet

Signal and background rates: NLO low lumi (30fb-1)

Mass (GeV)	120	130	140
σ (GeV)	1.36	1.42	1.51
Signal	815	758	610
Birreducible	14100	11472	9552
Breducible	3967	3396	2839
S/ √(B)	6.06	6.22	5.48



[Carminati, in Physics at LHC 2006]

More options for discovering a light SM Higgs boson

$t\bar{t}H \quad \text{with} \quad H \rightarrow b\bar{b}\ ?$

Some early studies were too optimistic, because of an imperfect simulation of the QCD backgrounds:

t-tbar-b-bbar (irreducible) & j-j-b-bbar (reducible)
(also t-tbar-Z with Z➔b-bbar)

Recent studies: S & B very similar in shape

Besides systematics on signal's shape (~ 10%), severe systematics with shape of irr+red QCD backgrounds
➔(so far) cannot claim discovery for any luminosity

$$\frac{S}{\sqrt{B}} \rightarrow \frac{S}{\sqrt{B(1+B\Delta^2)}} \rightarrow \frac{S/B}{\Delta}$$

🡸 Saturates for infinite luminosity

🡸 Background shape uncertainty

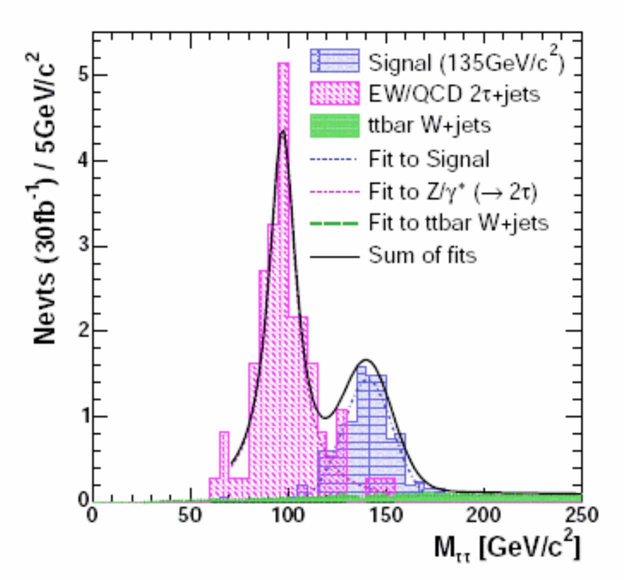
NLO background calculation may be performed some day

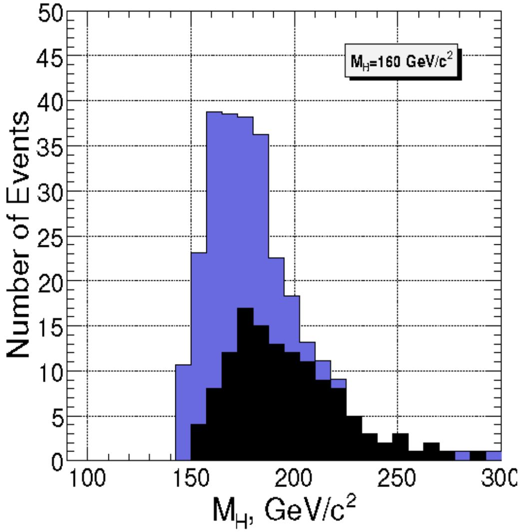
Weak boson fusion: qqH ➔ qqWW or qqtautau

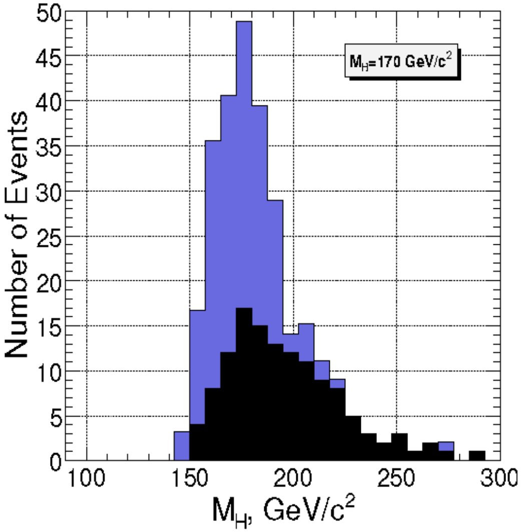
Viable signals and corresponding backgrounds:

q q W W ➔ tag-jets + (l nu) + (jj)
tt, Wbt, W+jets, Z+jets, WW, ZZ, WZ, QCD

q q tau tau ➔ tag-jets + (lept.) + (had.)
(also potentially very important for light MSSM h)







Additional signal channels at higher luminosity

Weak boson fusion:

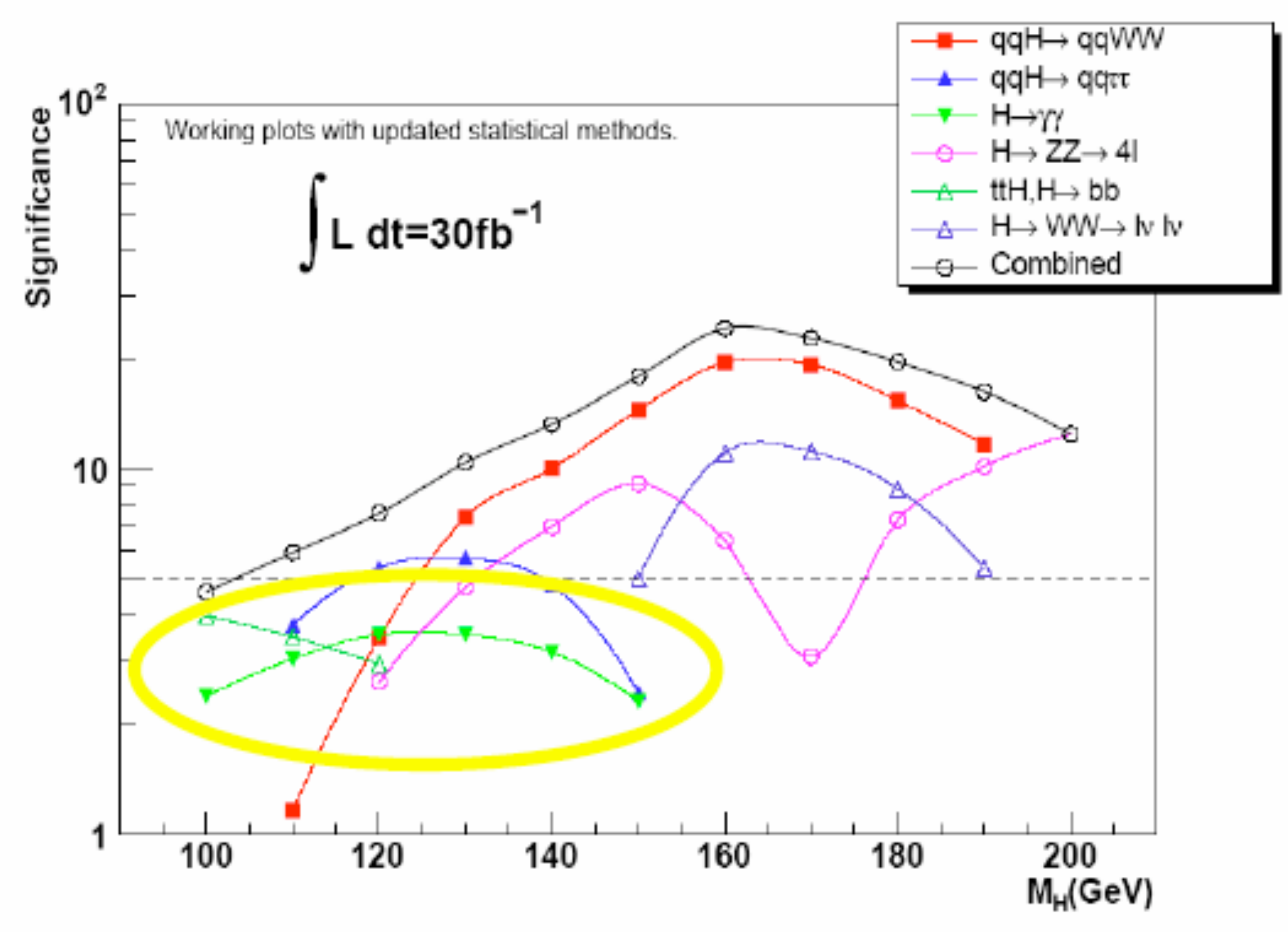
- qqH ➔ qq + gamma-gamma
- qqH ➔ qq + ZZ ➔ qq + 4l

Associated production with W/Z/ttbar:

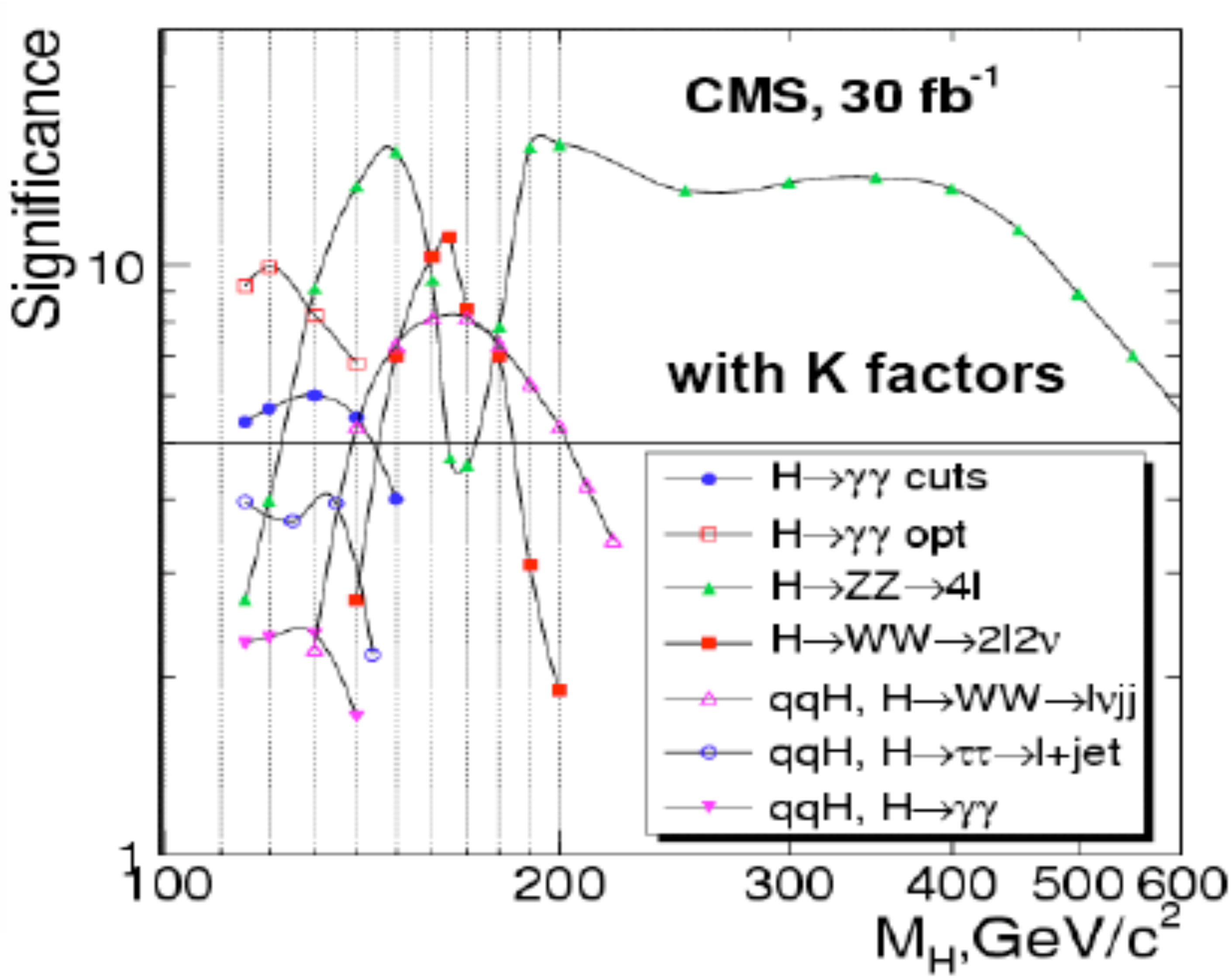
- ttH ➔ tt + gamma-gamma
- WH ➔ 1l + $E_{T,miss}$ + gamma-gamma
- ZH ➔ 2l + gamma-gamma

Updated signal significances in ATLAS with 30 fb^{-1}

[Carminati for ATLAS, in Physics at LHC 2006]

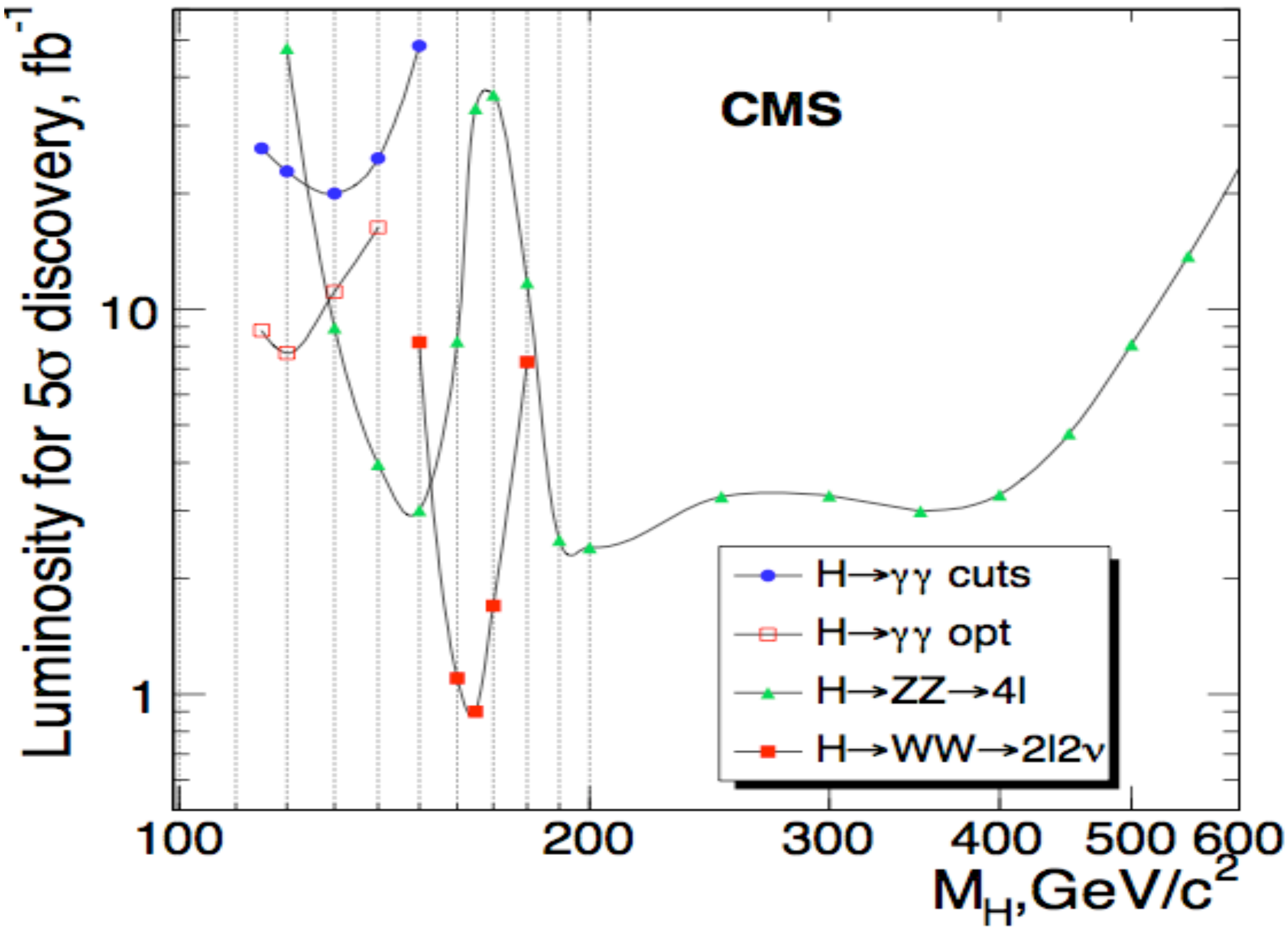


Signal significances in CMS with 30 fb^{-1}



[CMS TDR 8.2 CERN/LHCC 2006-021]

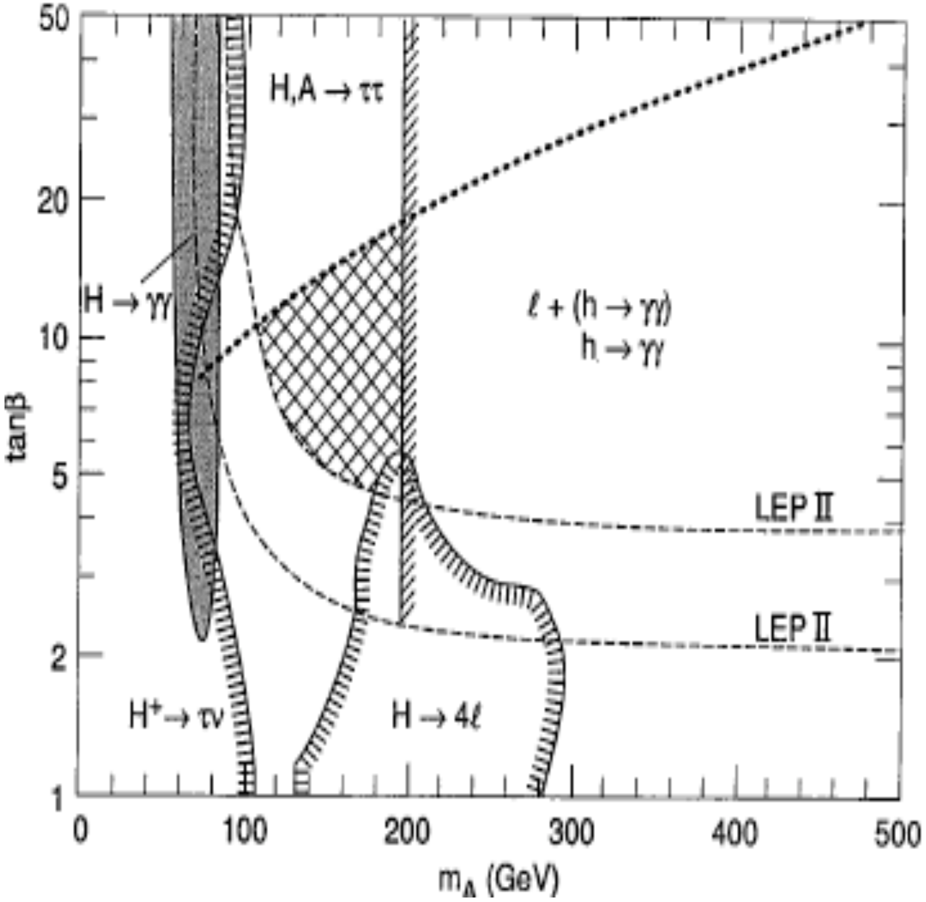
Luminosity requirements in CMS



MSSM Higgs bosons at the LHC

An ultra-simplified initial study

(and a personal memory)



[Z.Kunszt & FZ, LHC workshop, Aachen 1990]

Huge amount of work by now, it would take very long to describe it

A very complicated problem:

- Many parameters
- Many new particles around

SUSY-Higgs searches intertwined with SUSY-particle searches

"Benchmark scenarios" used so far to optimize detectors and analyses

Likely that data will focus the analyses as long as they come and are progressively understood

Some scenarios for the LHC (I)

Dangerous to make detailed predictions in a problem with too many variables only partially under control:

- Machine performance in time
- (Sub-)detector performance and understanding in time
- Some SM backgrounds with theory uncertainties, that will be understood from the actual data
- Tevatron still operating at full steam for a while
- What Nature has chosen for us at the TeV scale

At best, I can envisage some rough short-term scenarios

The search for a SM-like Higgs above 130 GeV will proceed rather autonomously: with well-understood detectors, few-10 fb^{-1} should be enough for clear discovery/exclusion

In the meantime, "easy" signals of new physics could have shown up or been ruled out/constrained

Some scenarios for the LHC (II)

Already 4 cases! Conservatively, assume no NP at this stage

If Higgs found, enjoy! Then go on with the study of its properties in all possible channels and keep looking for NP

If Higgs not found, attack the SM-favoured region between 115 and 130 GeV: several difficult channels (for different reasons) will need to be considered (gamma-gamma, ttbarH, qqH). Eventually, the answer should come. In the meantime, scan also many BSM variations (MSSM,…).

In the worst (and less likely case) that no signal is found:

- Elementary but BSM Higgs that “hides” for some reason
- No elementary Higgs but strong interations at TeV scale

Several years will have passed, useless to extrapolate too far

Personal, temporary conclusions (I)

- A light, SM-like Higgs boson looks for now the best bet for the LHC (still a bet, however, and finding the Higgs for $m_H < 130$ GeV may take time and non-negligible effort).

- Theoretical prejudice (naturalness) suggests that such Higgs is accompanied by new physics at the LHC scale, most likely supersymmetry, perhaps something different. Such new physics may be manifest before completing the Higgs search.

- Experiment and down-to-Earth phenomenology suggest that new physics may be pushed to scales inaccessible to the LHC

A puzzle, perhaps with some clever solution that theorists are unable to figure out without direct information from the LHC

Personal, temporary conclusions (II)

Theory has been ahead of experiment for many decades:
times may be ripe for experiment to strike back!

One can conceive subtle (and malicious, thus unlikely) scenarios where finding out the physics of EW symmetry breaking at the LHC could be more difficult than expected

In any case, and most importantly:

THE ERA OF SPECULATIONS ON WEAK SCALE IS AT ITS END: THE LHC VERDICT IS COMING AND WE ARE ALL LOOKING FORWARD TO IT!