Searches for the Higgs Boson

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- Introduction
  - The Higgs Boson
  - The LHC and the Tevatron
- Standard Model Higgs Boson
  - Searches at Tevatron
  - Prospects for LHC
- MSSM Higgs Bosons
  - Charged and Neutral Higgs bosons
- Summary and Outlook

THE ROYAL SOCIETY

IoP, Warwick, April 12th 2006

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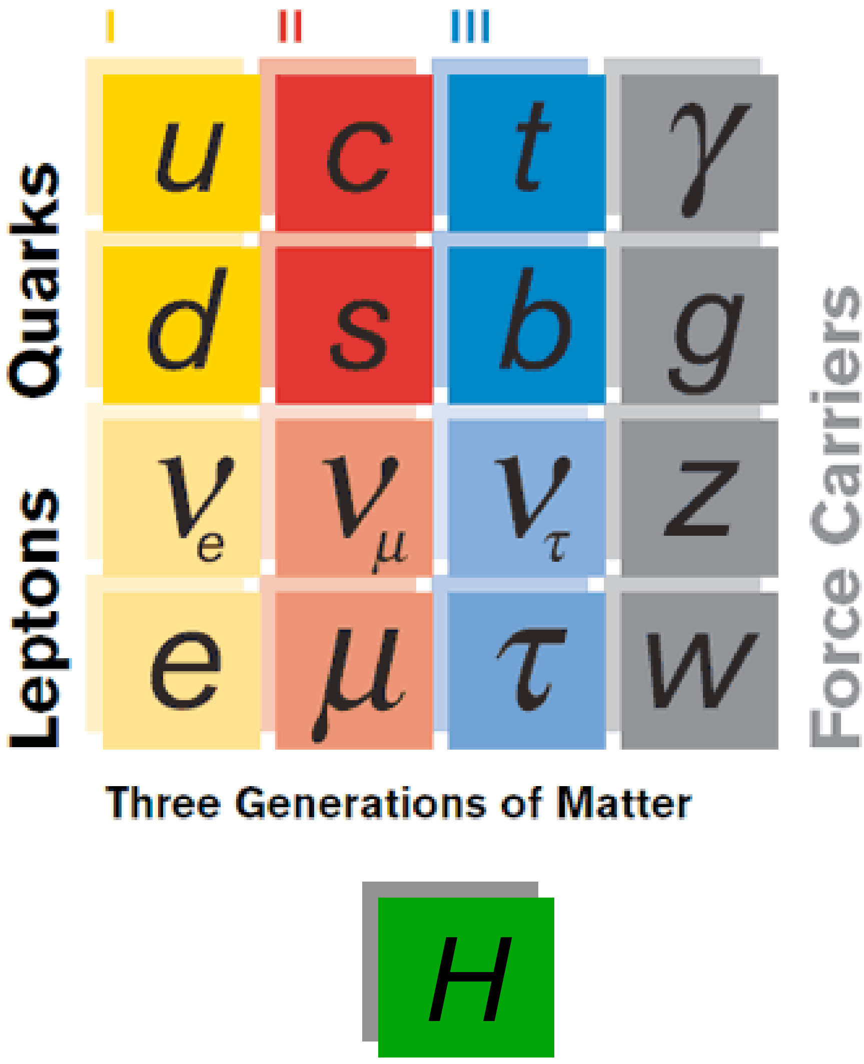
The Standard Model

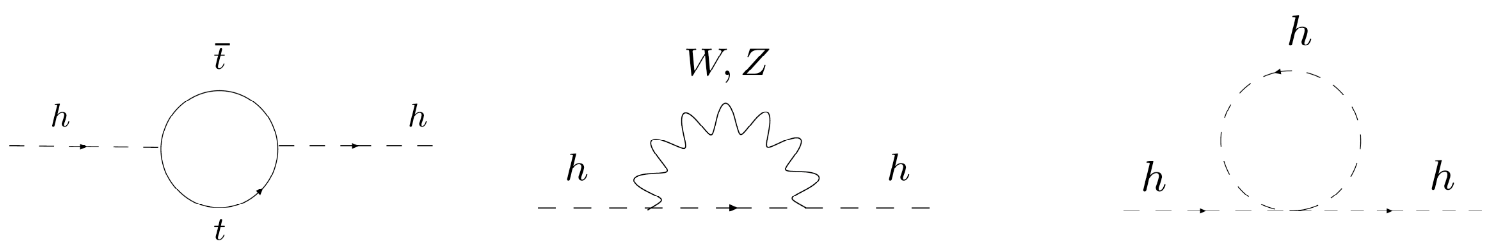
- Matter is made out of fermions:
  - quarks and leptons
  - 3 generations
- Forces are carried by Bosons:
  - Electroweak: γ,W,Z
  - Strong: gluons
- Higgs boson:
  - Gives mass to particles
  - Not found yet



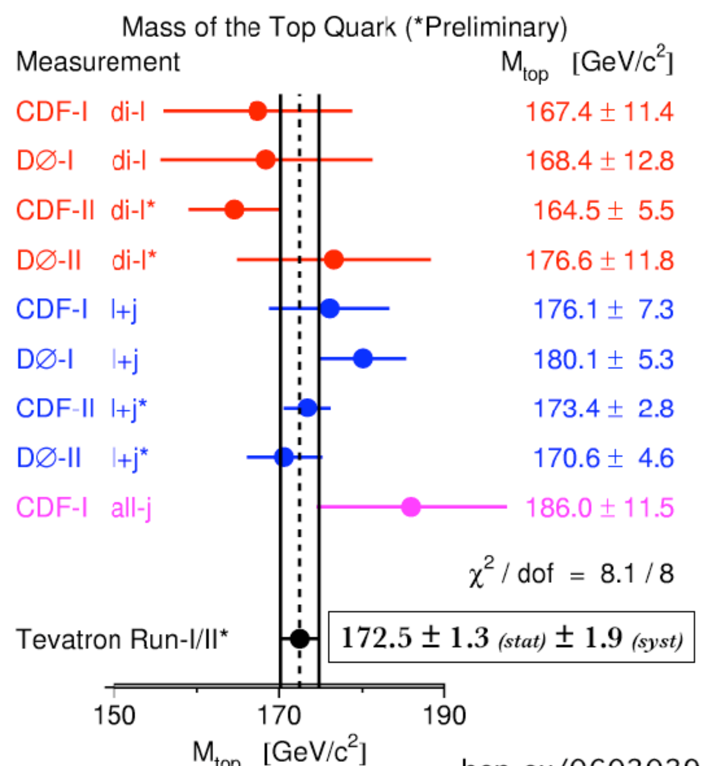
What We Know about the Higgs

- Large radiative corrections:

$$m^2_H \approx (200\text{ GeV})^2 = m^2_H{}^{tree} + \delta\, m^2_H{}^{top} + \delta\, m^2_H{}^{gauge} + \delta\, m^2_H{}^{higgs}$$



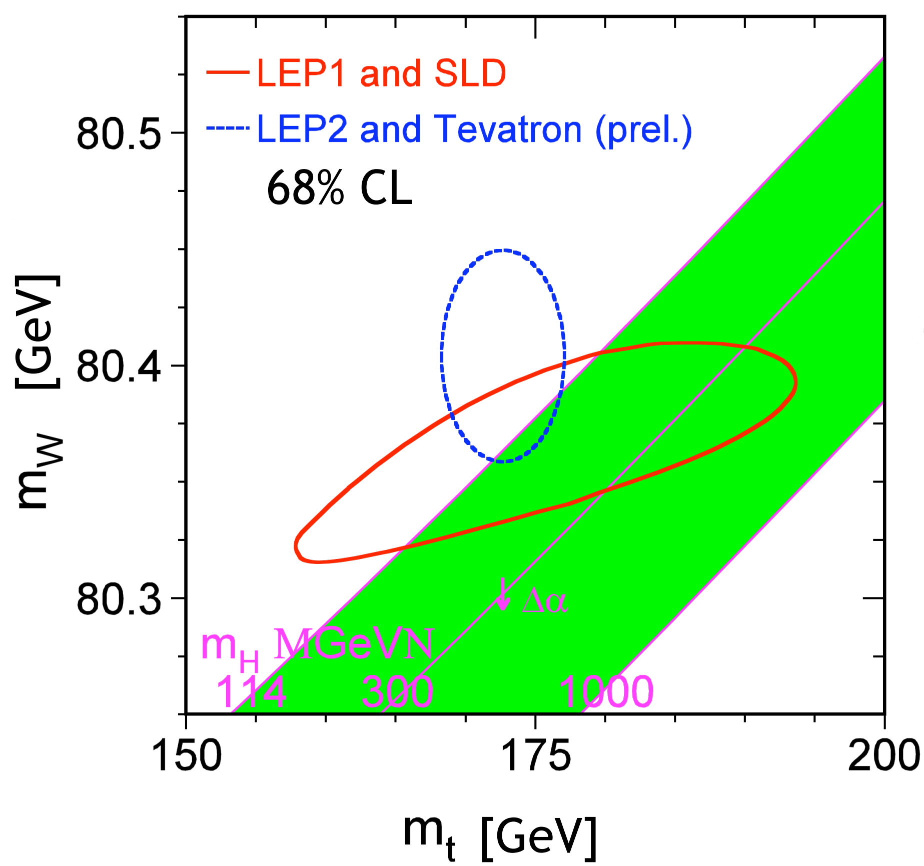
- Precision measurements of W and top mass constrain Higgs mass
  - Dependence is only logarithmic:
    - $M_W \propto \log(M_H)$
- Current world averages:
  - M_W=80.410 ± 0.032 GeV/c^2
  - m_{top}=172.5±2.3 GeV/c^2

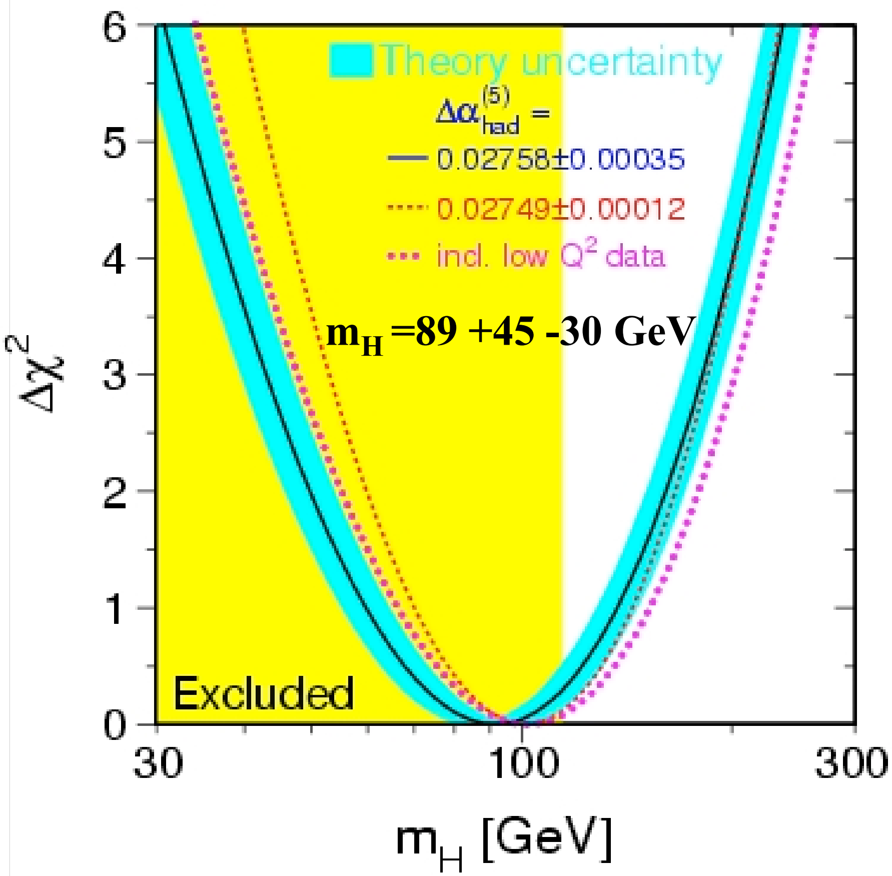


EW constraints on Higgs

m_H constrained in the Standard Model

LEPEWWG 18/03/06





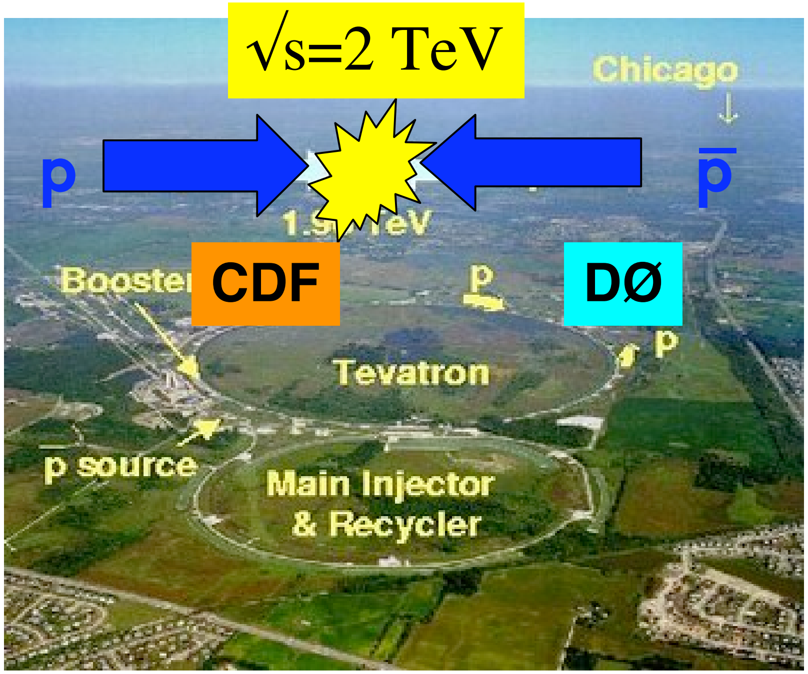
Direct searches at LEP2:
m_H>114.4 GeV @95%CL

m_H<175 GeV @95%CL
(< 207 GeV if LEP2 limit incl.)

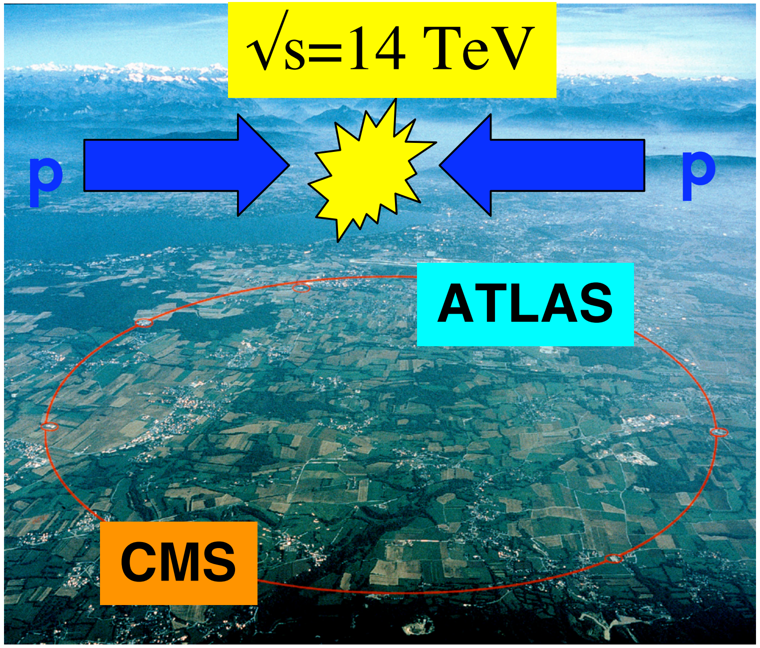
A light Higgs is favored => focus on this in this talk

Searching for the Higgs

Now: Tevatron (<2009)



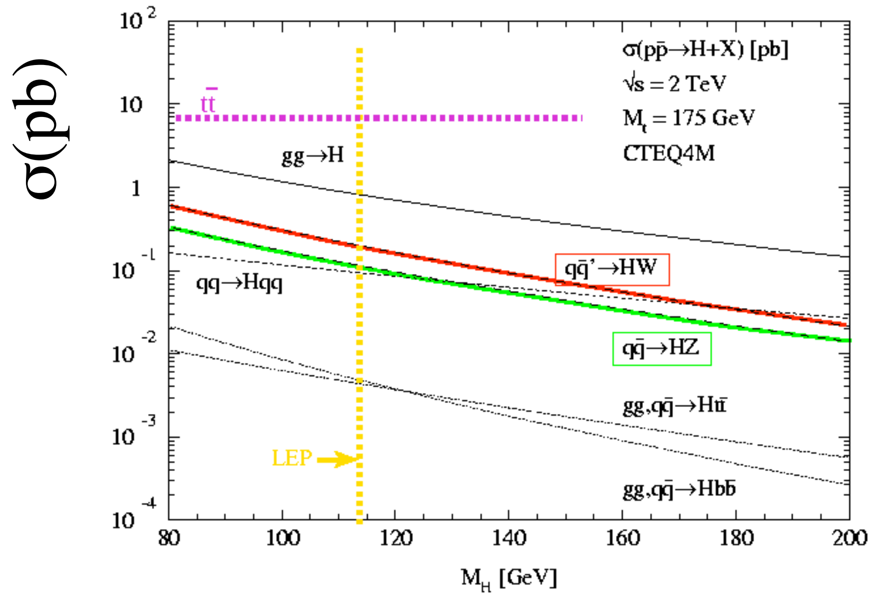
Future: LHC (>2007)



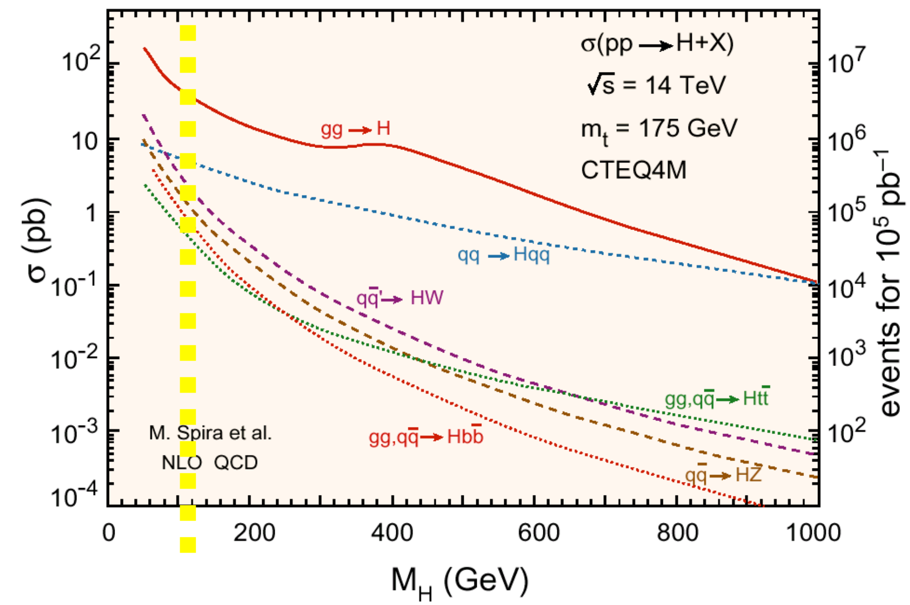
- Tevatron proton-antiproton collider at $\sqrt{s}$=2 TeV:
  - 1 fb^{-1} of data taken, 7 fb^{-1} more to come
- LHC proton proton collider at $\sqrt{s}$=14 TeV:
  - will take 10 fb^{-1}/year starting in 2008, 100 fb^{-1}/year after 2010
  - Pilot run in 2007

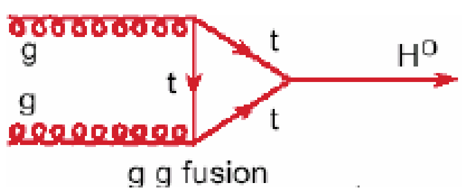
Higgs Production: Tevatron and LHC

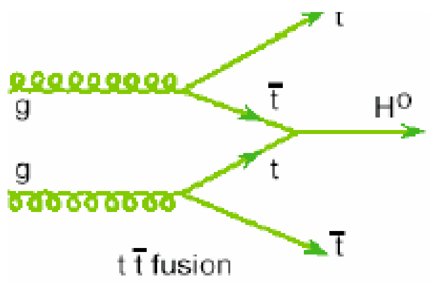
Tevatron

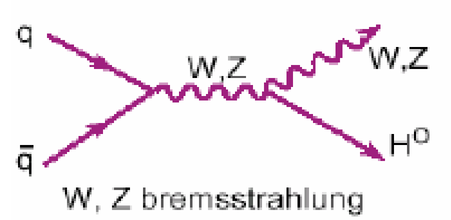


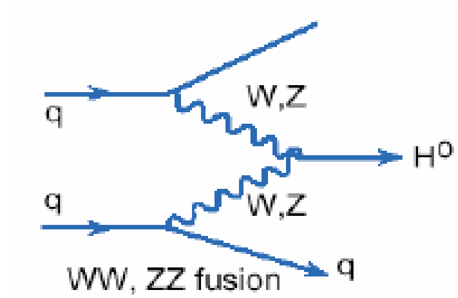
LHC







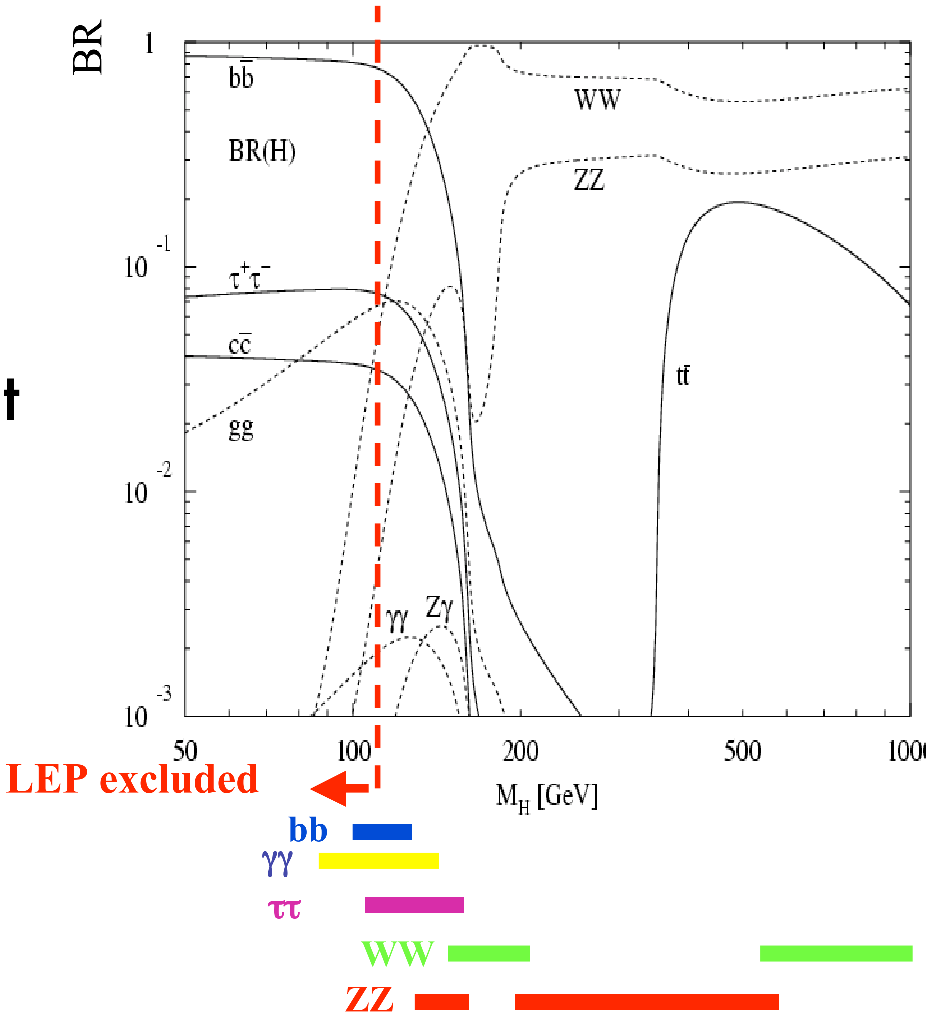




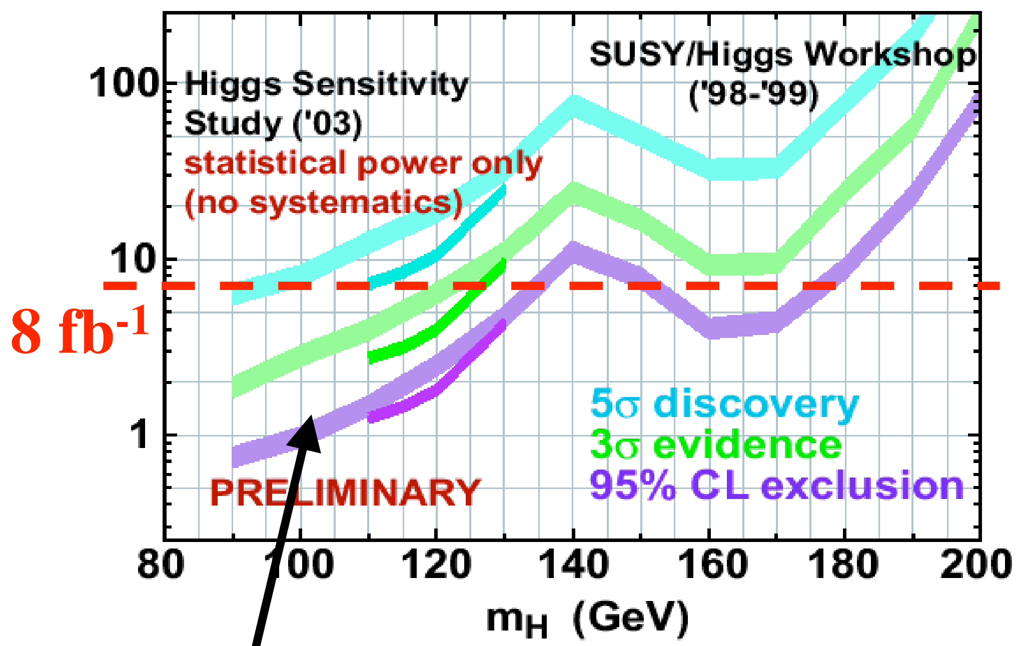
dominant: gg→ H, subdominant: HW, HZ, Hqq

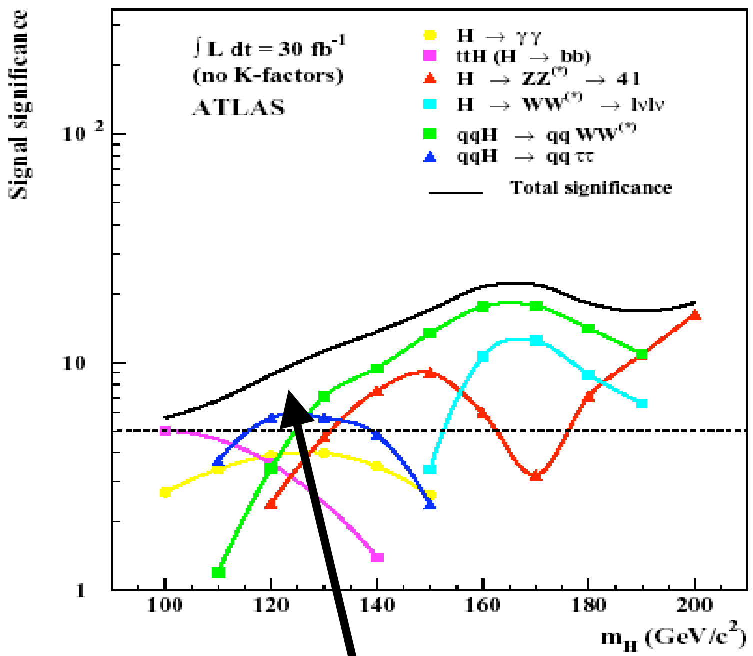
Higgs boson Decay

- Depends on Mass
- M_H<130 GeV/c^2:
  - bb dominant
  - ττ and WW subdominant
  - γγ small but useful
- M_H>130 GeV/c^2:
  - WW dominant
  - ZZ cleanest



Discovery at M_H<200 GeV/c^2



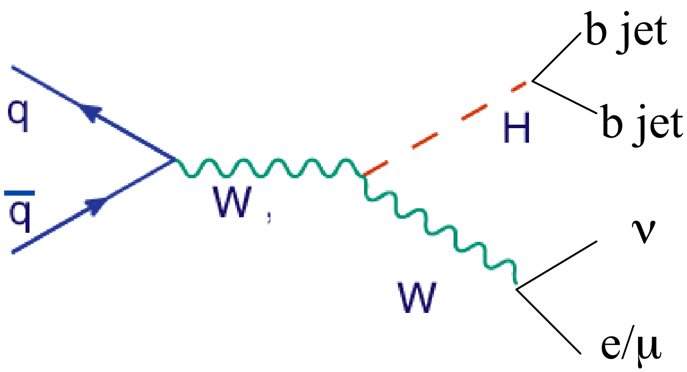


Uses WH, ZH with H->bb

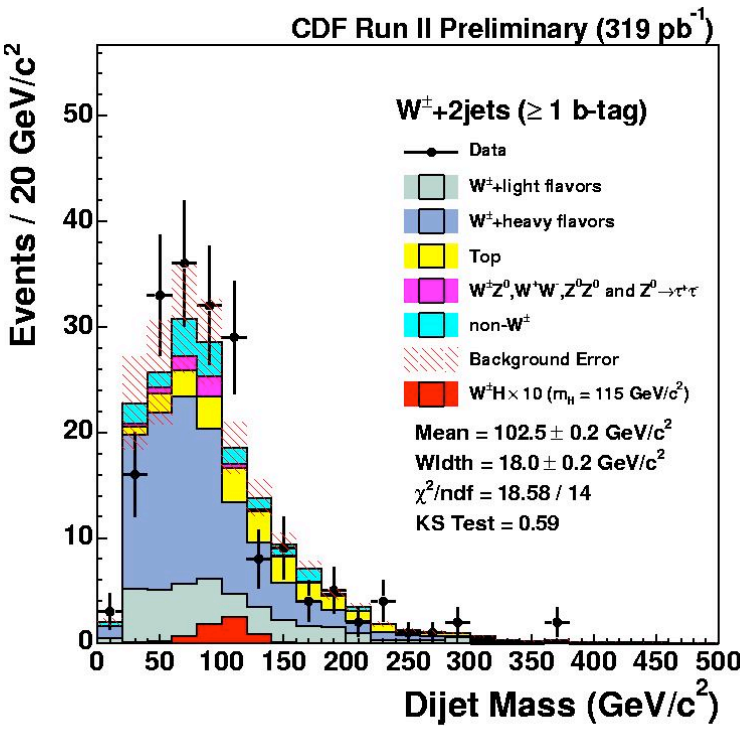
Uses three production and decay modes

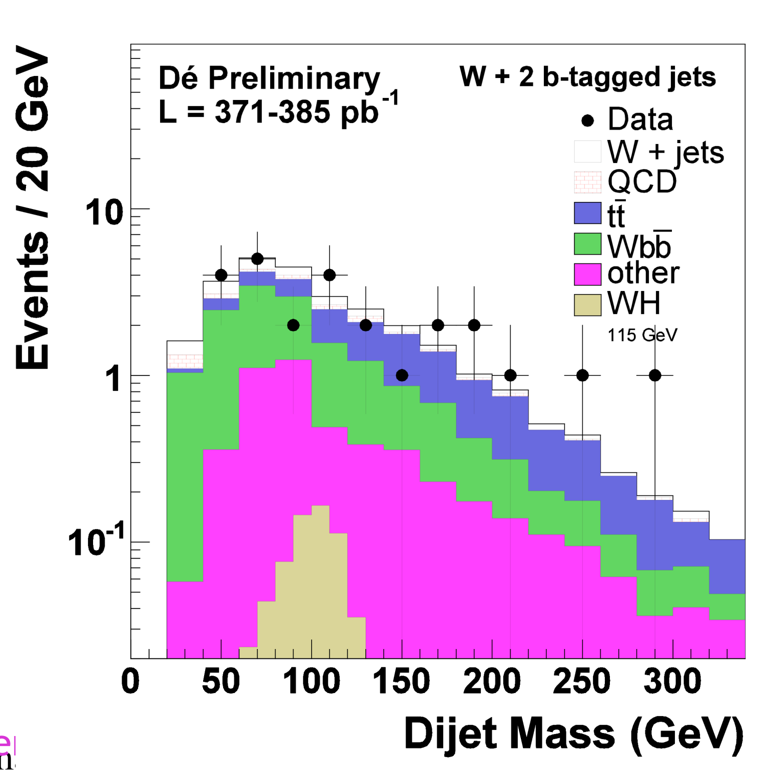
Many different final states and production modes at two colliders

Tevatron: WH→lνbb (l=e,μ)

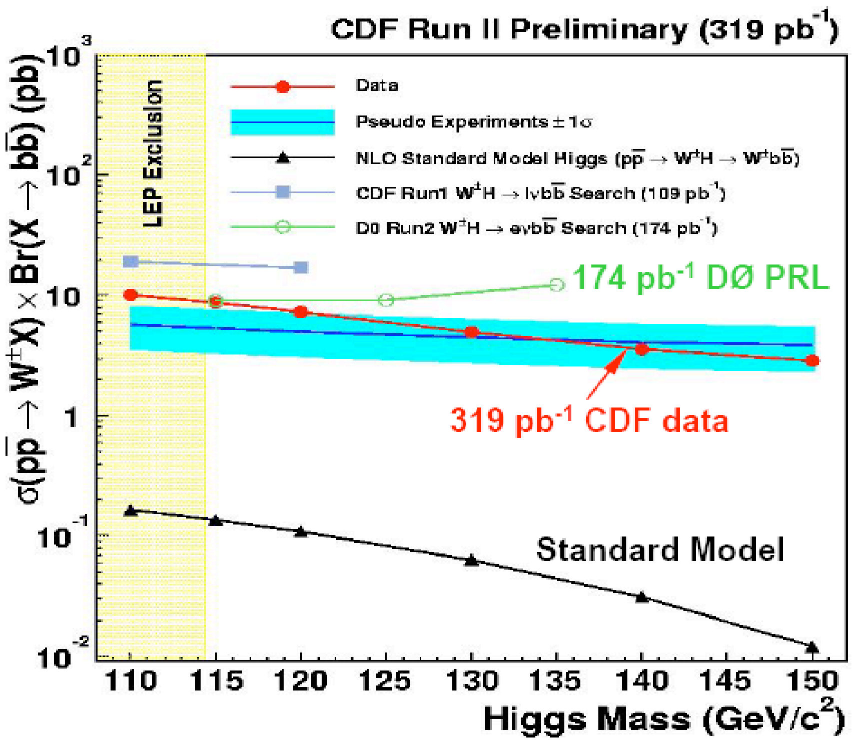


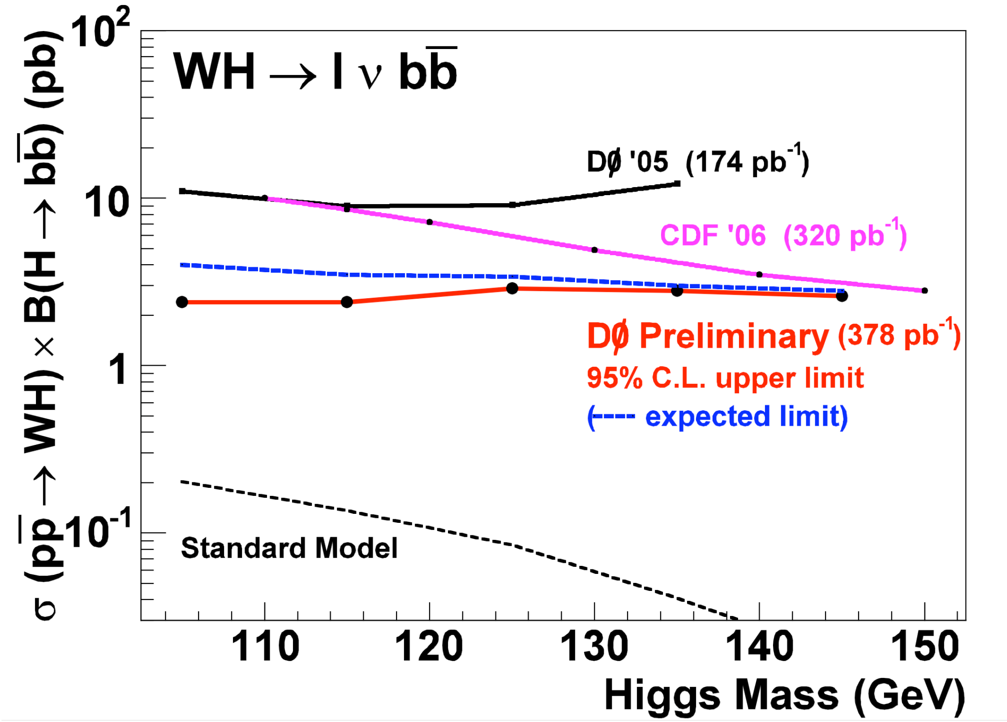
- Muon and electron channel combined:
  - 1 or 2 tagged b-jets
  - electron or muon with p_T > 20 GeV
  - E_T^{miss} > 20 GeV





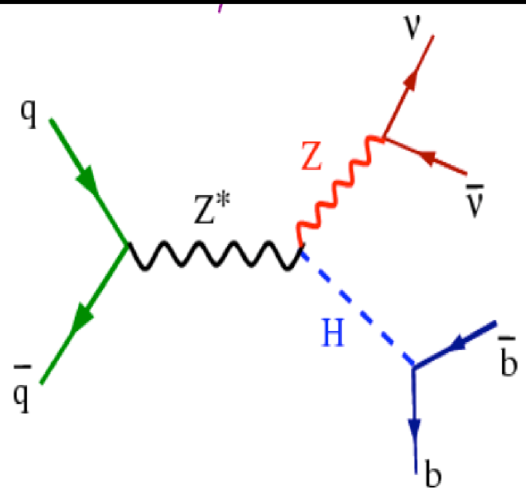
WH→lνbb, (l=e,μ)

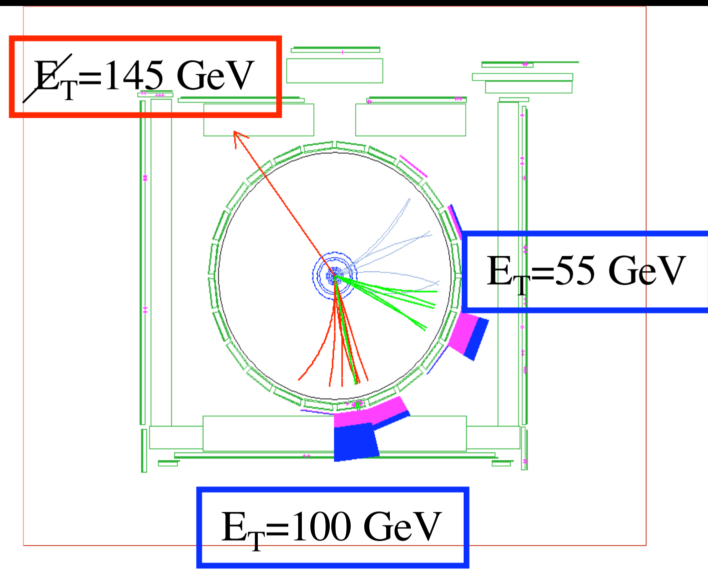


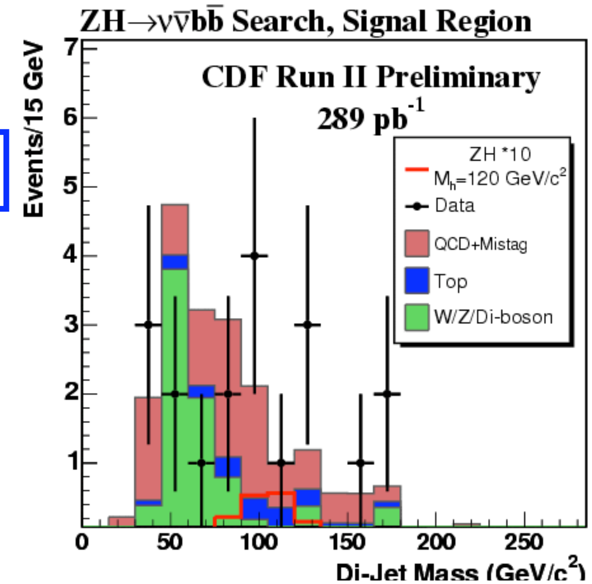


- Cross section limit about 20 times larger than SM cross section prediction
  - Expected limit similar between CDF and DØ

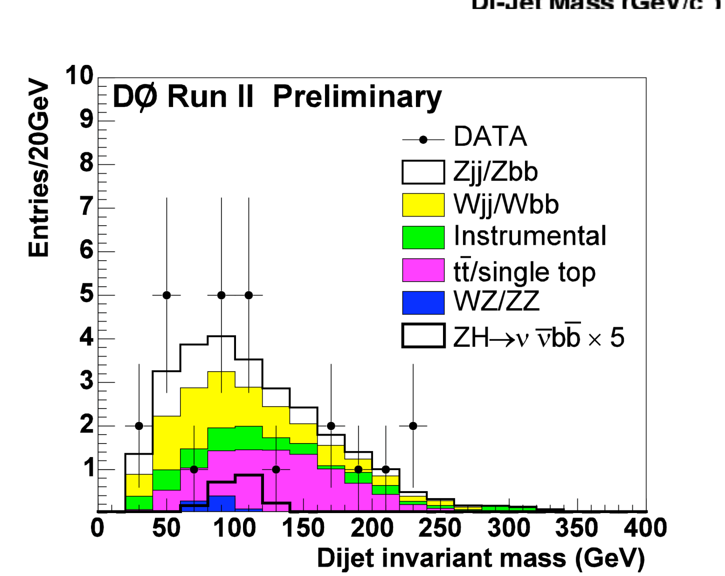
Tevatron: ZH→ννbb





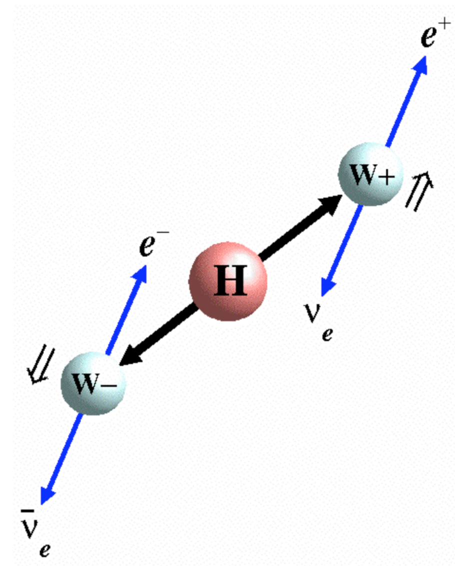


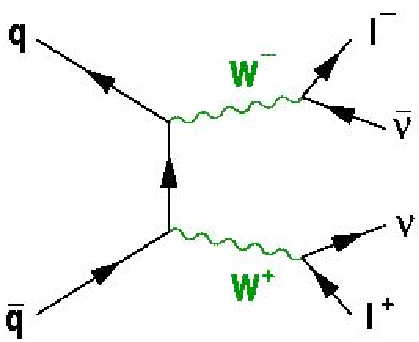
- Event selection:
  - ≥ 1 tagged b-jets
  - Two jets with E_T > 60/25 GeV
  - E_T^{miss} > 70 GeV
  - Lepton veto
- Key discriminating variable:
  - Invariant mass of two jets
  - Expect peak from H->bb decay

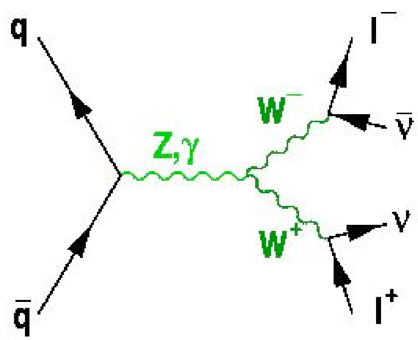


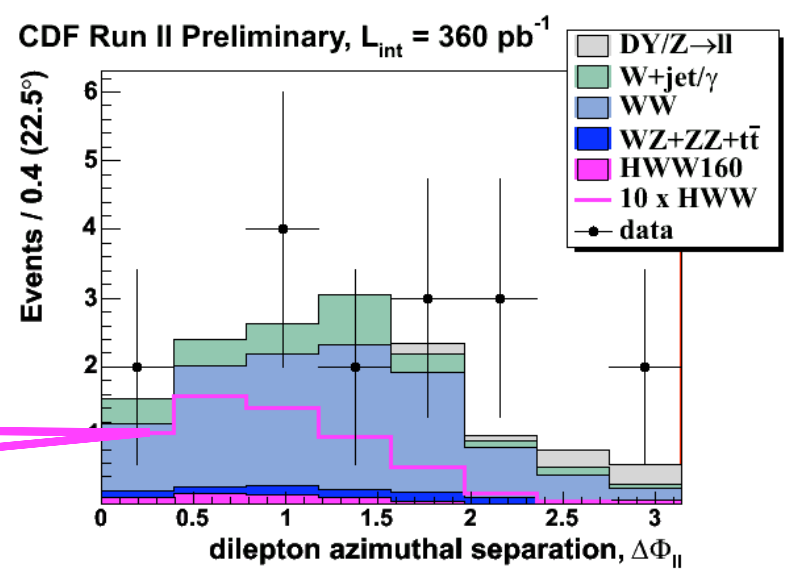
$H \to WW^{(*)} \to l^+l^-\nu\bar{\nu}$

- Higgs mass reconstruction impossible due to two neutrinos in final state
- Make use of spin correlations to suppress WW background:
  - Higgs has spin=0
  - leptons in $H \to WW^{(*)} \to l^+l^-\nu\nu$ are collinear
- Main background: WW production



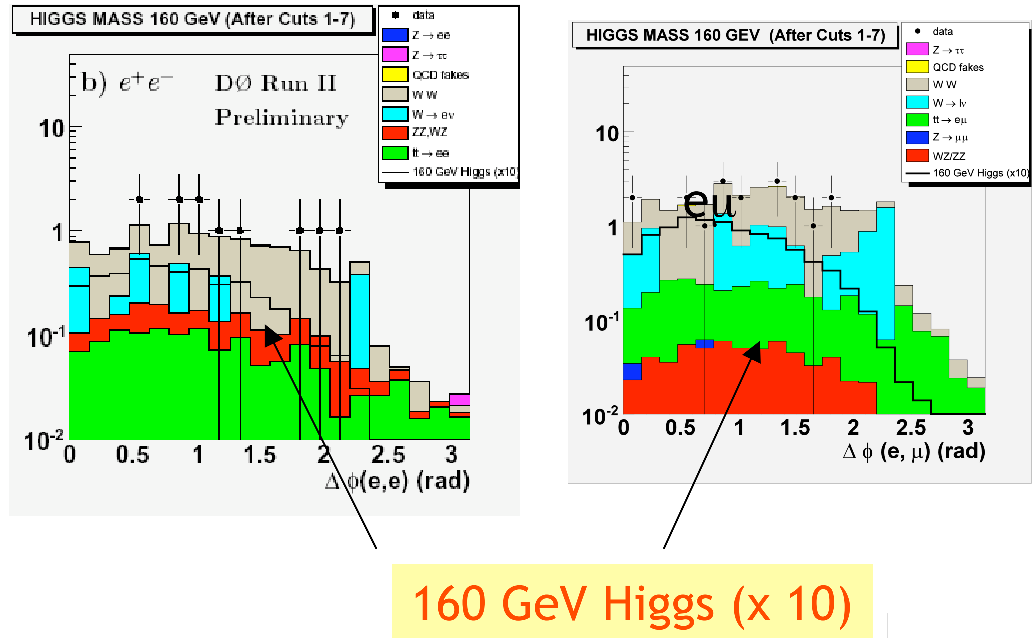


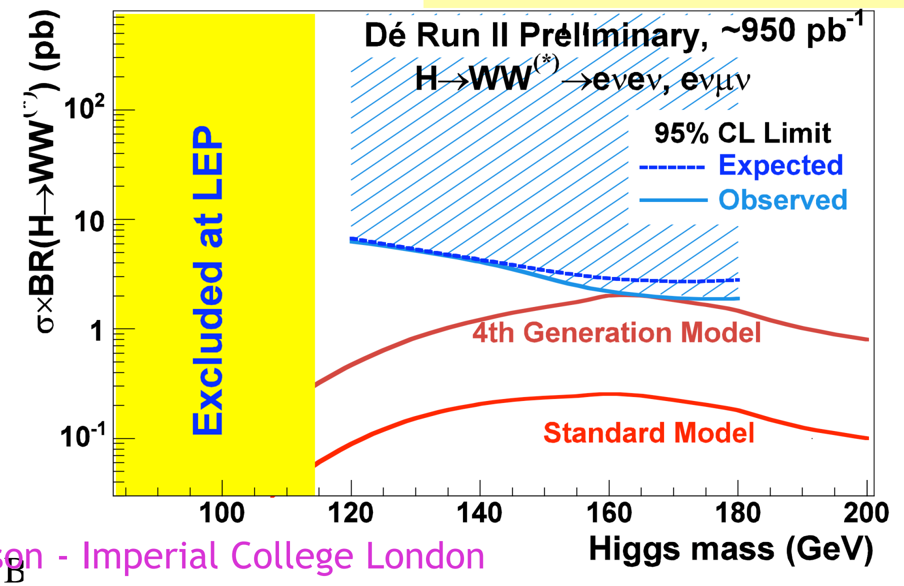




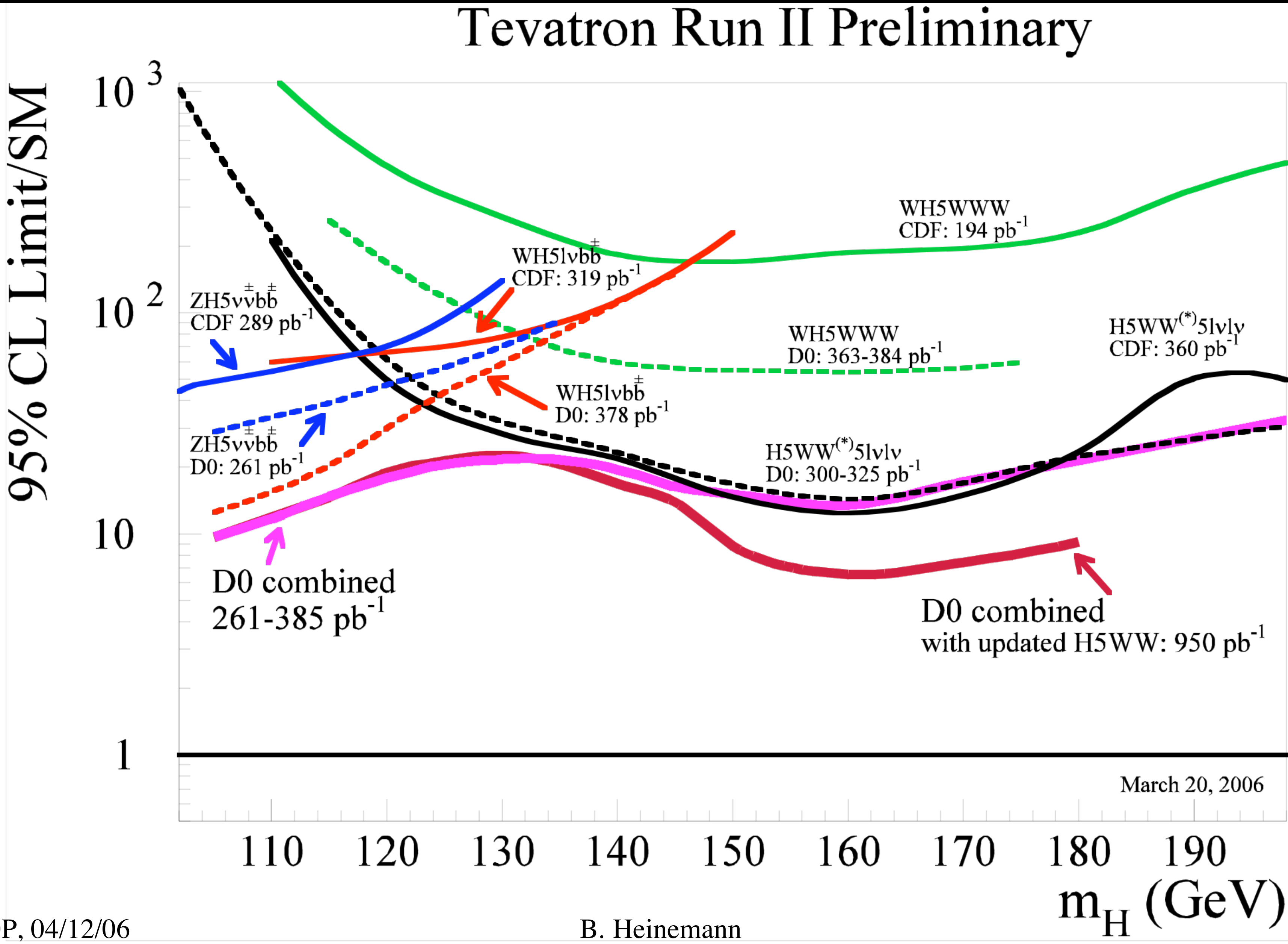
$H \to WW^{(*)} \to l^+l^-\nu\nu$ ($l=e,\mu$)

- DØ analysis: L= 950 pb^{-1}
- ee and eμ channels
- Event selection:
  - Isolated e/μ :
    - p_T > 15, 10 GeV
  - Missing E_T >20 GeV
  - Veto on
    - Z resonance
    - Energetic jets
- E.g. for M_H = 120 GeV:
  - 31 events observed
  - 32.7 +/- 2.3 (stat) predicted
  - Bkg systematic uncertainty: 15%
  - σ_{95} = 6.3 pb





Limits


Tevatron Run II Preliminary
95% CL Limit/SM
10 3
10 2
10
1
110
120
130
140
150
160
170
180
190
m H (GeV)
WH5WWW
CDF: 194 pb-1
WH5lνbb
CDF: 319 pb-1
ZH5ννbb
CDF 289 pb-1
WH5WWW
D0: 363-384 pb-1
H5WW(*)5lνlν
CDF: 360 pb-1
WH5lνbb
D0: 378 pb-1
ZH5ννbb
D0: 261 pb-1
H5WW(*)5lνlν
D0: 300-325 pb-1
D0 combined
261-385 pb-1
D0 combined
with updated H5WW: 950 pb-1
March 20, 2006

Can we close the Gap?

- Assume current analyses as starting point
  - Scale current systematic uncertainties by $1/\sqrt{L}$
- Reevaluated all improvements using latest knowledge

	Luminosity equivalent=$(S/\sqrt{B})^2$		
Improvement	WH->lvbb	ZH->vvbb	ZH->llbb
mass resolution	1.7	1.7	1.7
Continuous b-tag (NN)	1.5	1.5	1.5
Forward b-tag	1.1	1.1	1.1
Forward leptons	1.3	1.0	1.6
Track-only leptons	1.4	1.0	1.6
NN selection	1.75	1.75	1.0
WH signal in ZH	1.0	2.7	1.0
Product of above	8.9	13.3	7.2
CDF+DØ combination	2.0	2.0	2.0
All combined	17.8	26.6	14.4

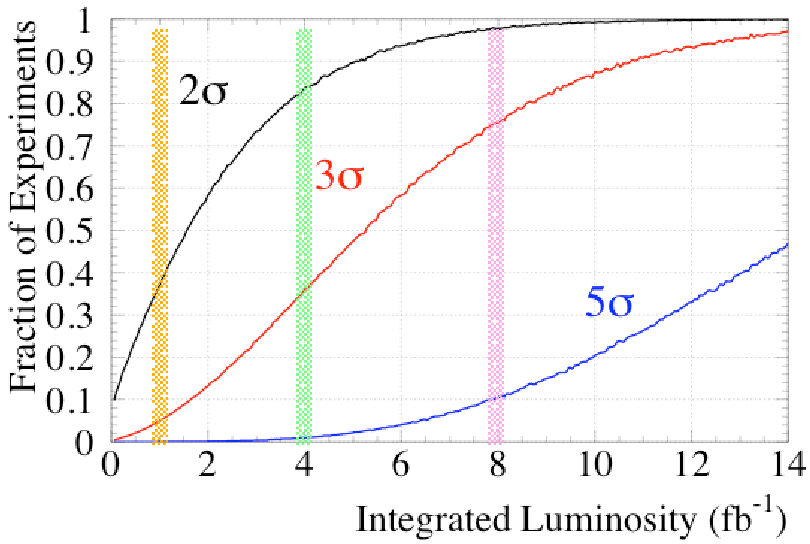
Expect factor ~10 improvements and CDF+DØ combination:

=> Need 2.5 fb^{-1} for 95%C.L. exclusion of 115 GeV Higgs

"God Does Not Play Dice" (with the Physicist)?

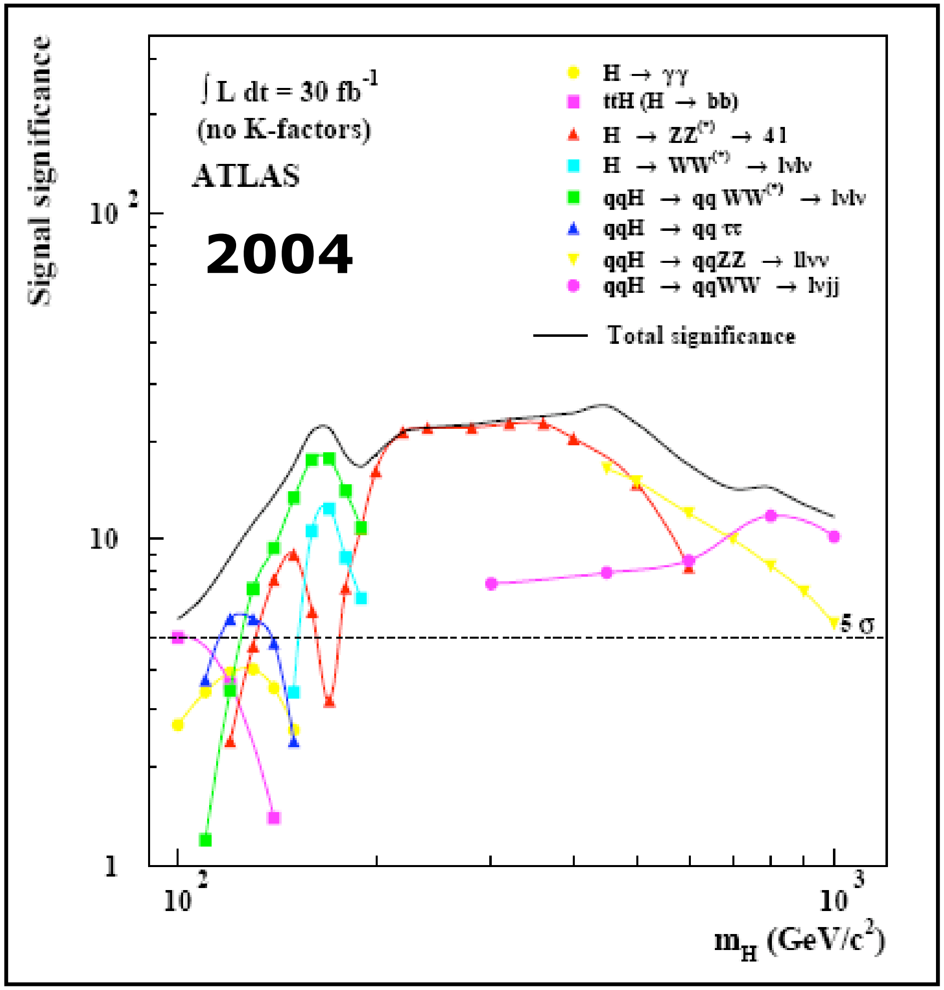
- All numbers given so far were
  - a 50% probability of an experiment achieving discovery or exclusion
  - We perform 1 experiment
- Could get statistically lucky or unlucky (m_H=115 GeV/c^2):
  - with L=1 fb^{-1}:
    - 5% chance for 3σ evidence
    - 0% chance for 5σ discovery
  - with L=4 fb^{-1}:
    - 35% chance for 3σ evidence
    - 2% chance for 5σ discovery
  - with L=8 fb^{-1}:
    - 75% chance for 3σ evidence
    - 10% chance for 5σ discovery

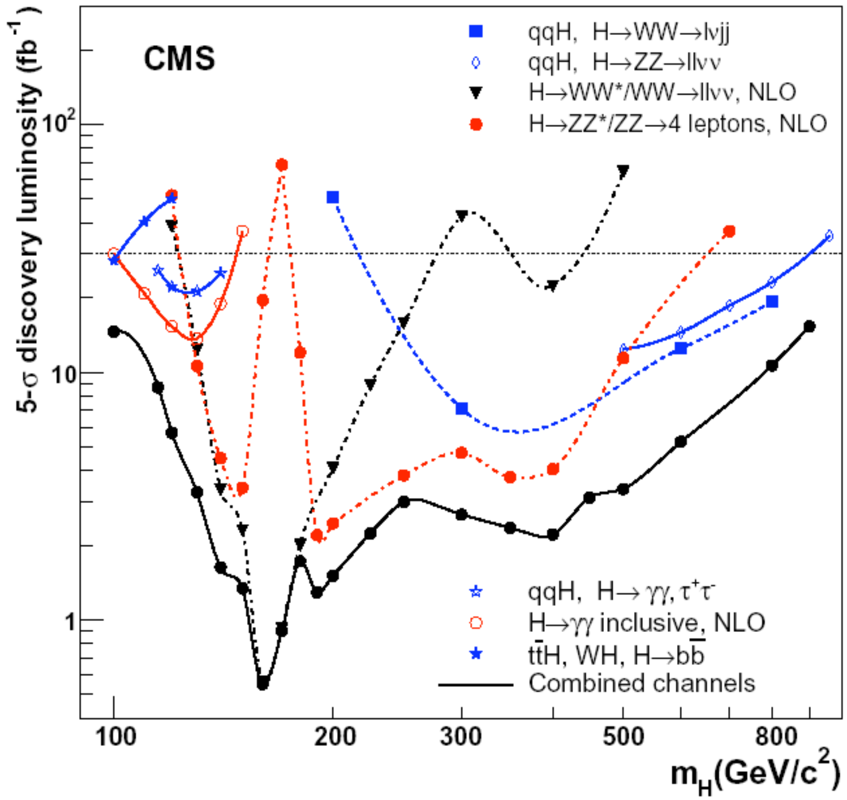
m_H=115 GeV/c^2



5σ discovery unlikely
=> Need LHC

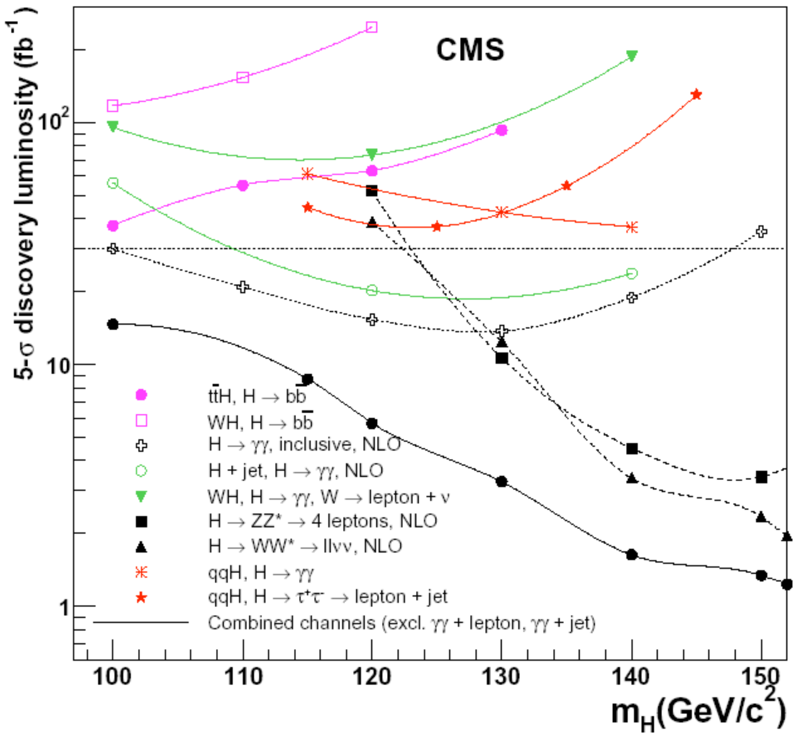
LHC SM Higgs Discovery Potential

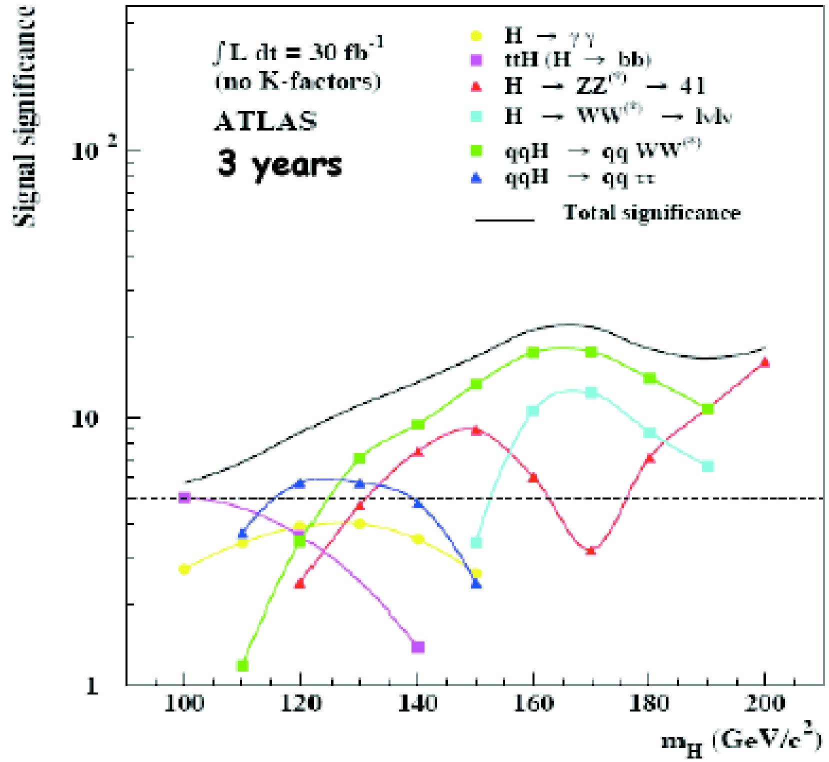




- Fast discovery for high mass, e.g. m_H>150 GeV/c^2
- Harder at low mass=> zoom into low mass region

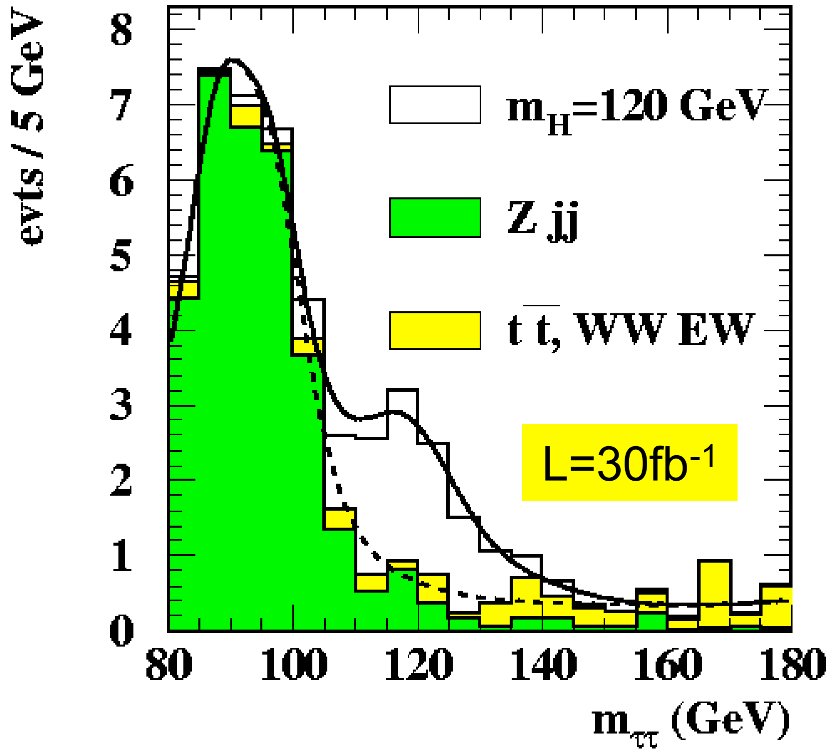
LHC: Low Mass Region





- LHC for m_H=115 GeV/c^2
  - L≈10 fb^{-1} for 5σ discovery for single experiment
    - CMS mostly sensitive to γγ decay
    - ATLAS more sensitive to ttH->ttbb and qqH->qqττ

115 GeV Higgs: LHC with $10 fb^{-1}$



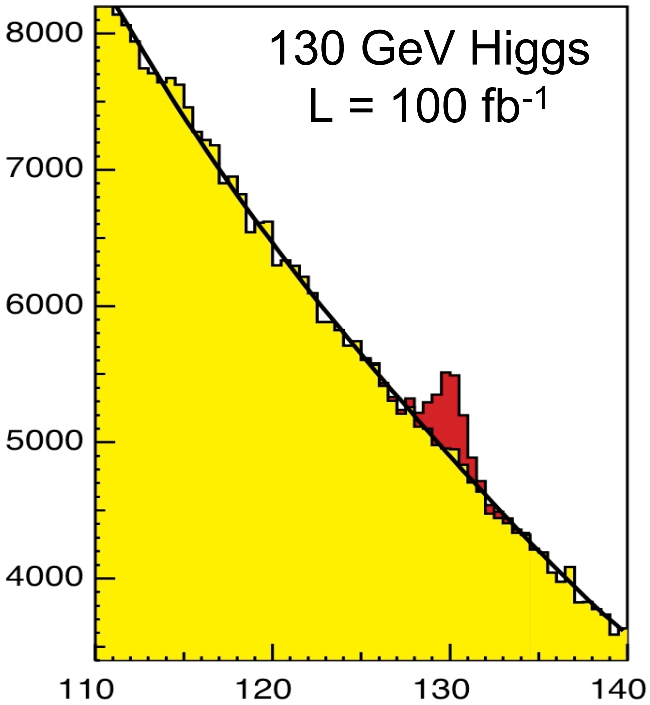
ATLAS

	H->γγ	ttH->ttbb	qqH->qqττ
S	150	15	~10
B	3900	45	~10
$S/\sqrt{B}$	2.4	2.2	~2.7

Large K-factor~2 not included

- Total $S/\sqrt{B}$=4.2
  - First evidence possible
- Difficult to know whether it is the Higgs boson
  - Important to see signal in each channel
    - Gives first idea about branching ratios
  - Diphoton channel will have nice peak, others not

130GeV Higgs: first year ($10fb^{-1}$)



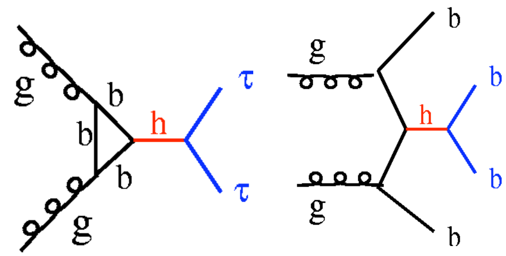
complete detector

	H->γγ	H->ZZ	qqH-> qqWW	qqH-> qqττ
S	120	5	18	~8
B	2500	<1	15	~6
S/√B	2.4	2.8	3.9	2.6

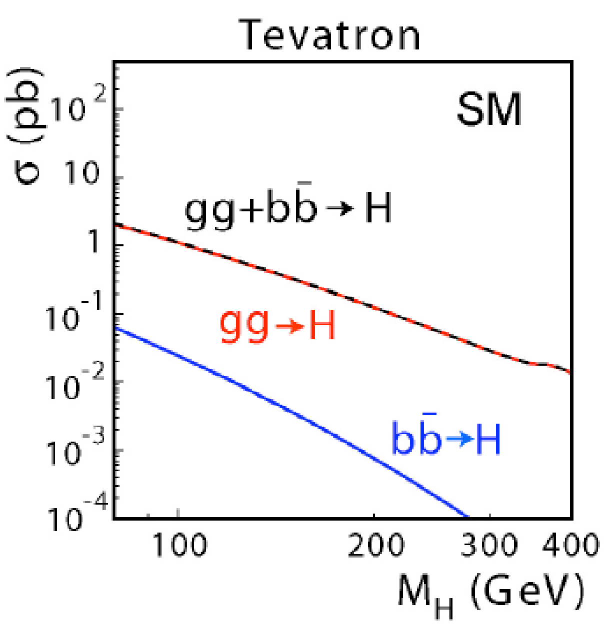
- Total S/√B=6
  - This is good!
- Now qqWW and ZZ channels contribute a lot
  - ttH channel really difficult now => cannot measure branching into b's
  - Nice peaks expected in γγ and ZZ

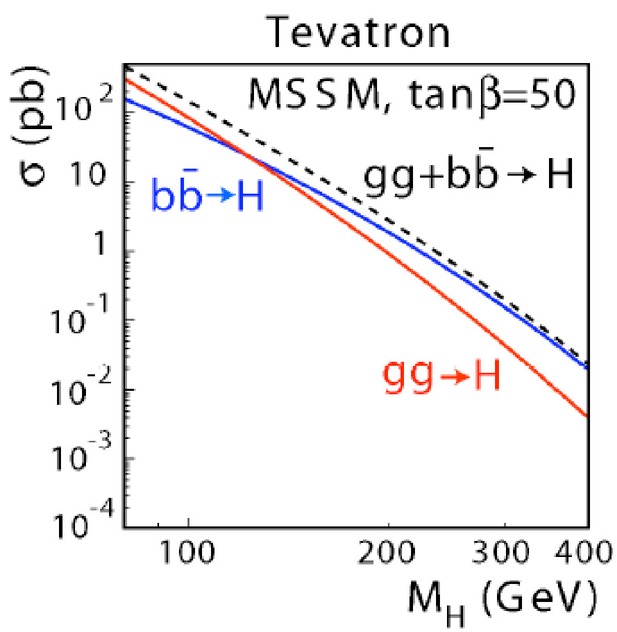
Higgs in the MSSM

- Minimal Supersymmetric Standard Model:
  - 2 Higgs-Fields: Parameter $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$
  - 5 Higgs bosons: h, H, A, $H^{\pm}$
- Neutral Higgs Boson:
  - Pseudoscalar A
  - Scalar H, h
    - Lightest Higgs (h) very similar to SM



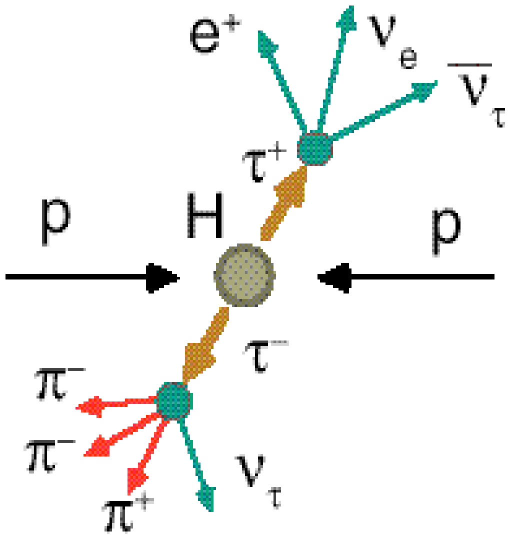
$$\sigma \times BR_{SUSY} = 2 \times \sigma_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{[9+(1+\Delta_b)^2]}$$



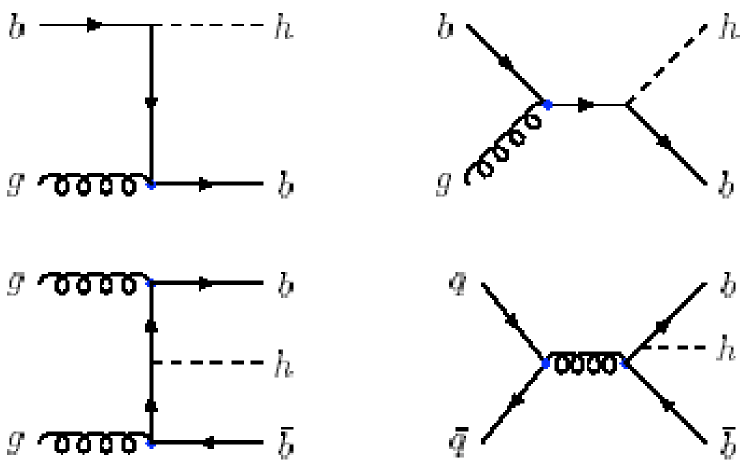


MSSM Higgs Selection

- $pp \rightarrow \Phi + X \rightarrow \tau\tau + X$:
  - One τ decays to e or μ
  - One τ decays to hadrons or e/μ
  - Use "visible mass", $m(\not{E}_T, l_1, l_2)$ for discrimination against background



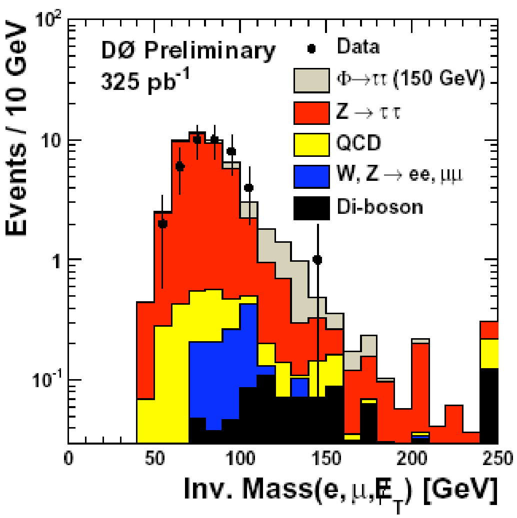
- $pp \rightarrow \Phi b + X \rightarrow bbb + X$:
  - Three b-tagged jets
    - $E_T > 35$, 20 and 15 GeV
  - Use invariant mass of leading two jets to discriminate against background



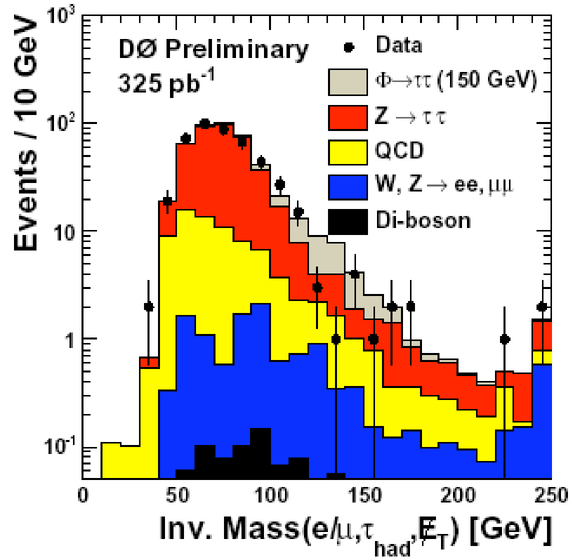
Φ =h/H/A

Mass Distributions

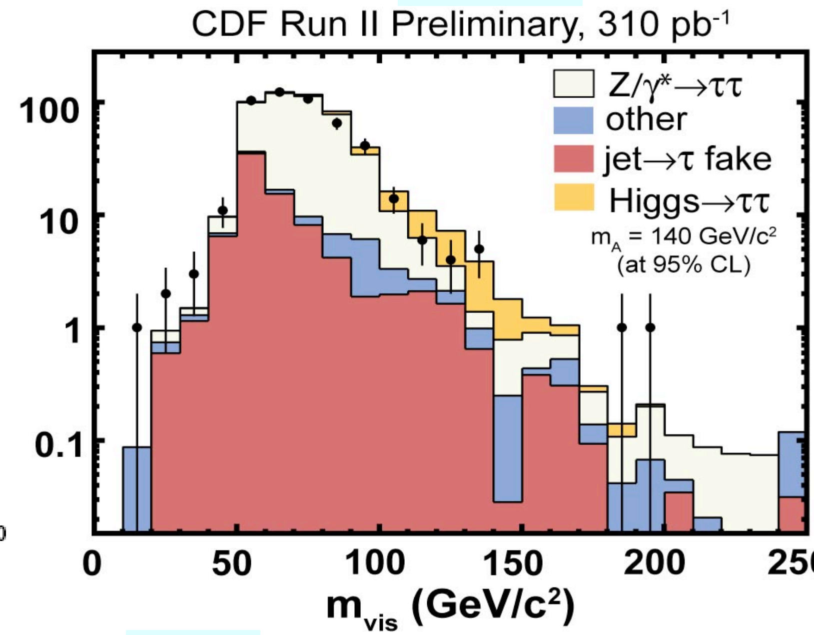
e+μ



e/μ+τ

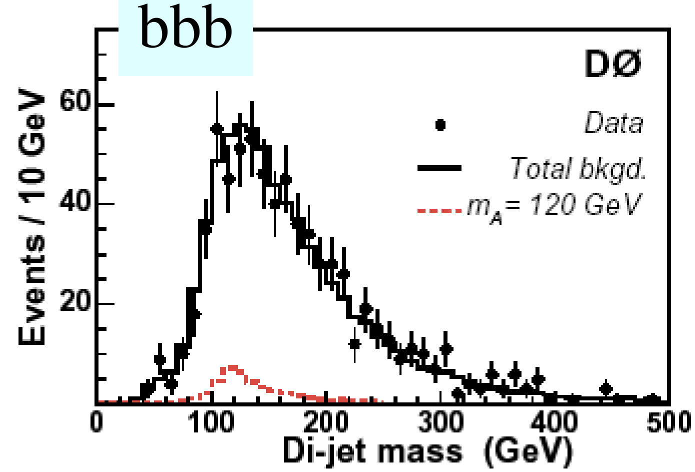


e/μ+τ



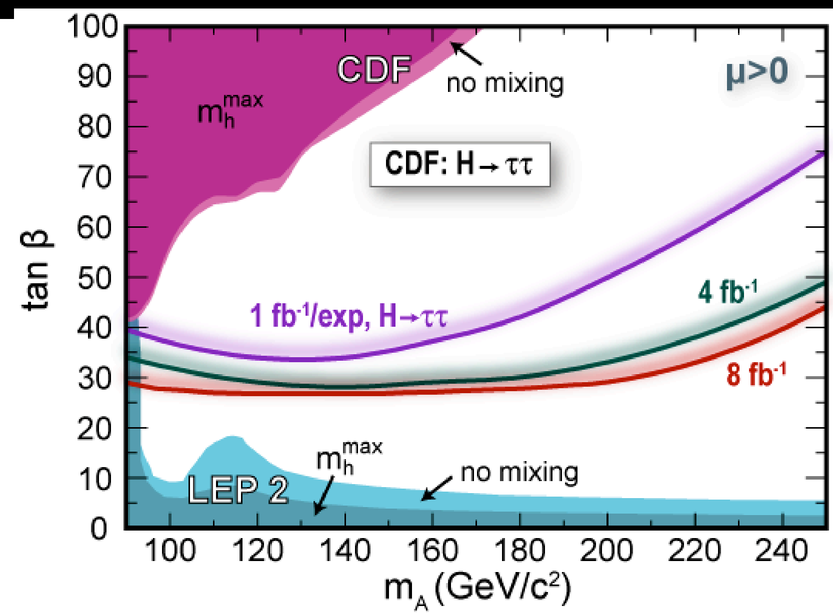
- Good agreement between data and background in all analyses
- No sign of deviation

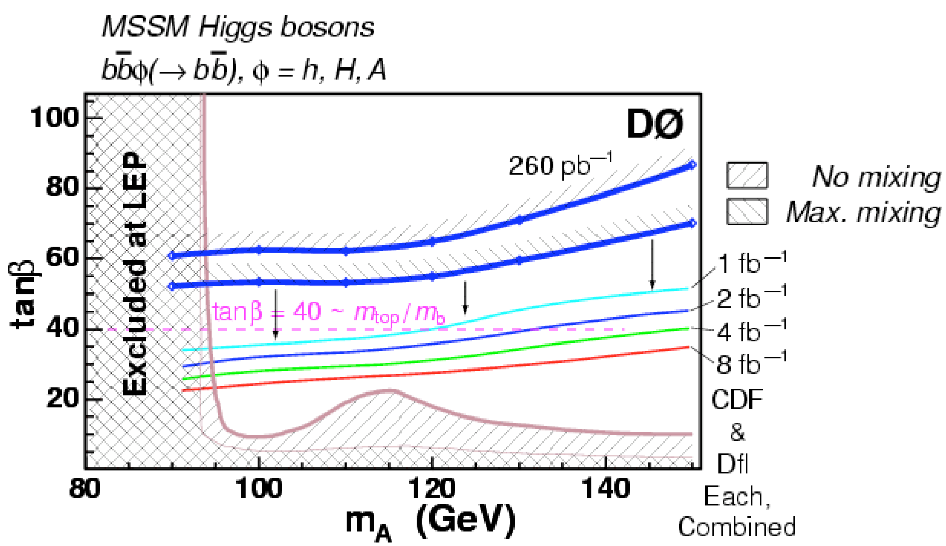
bbb

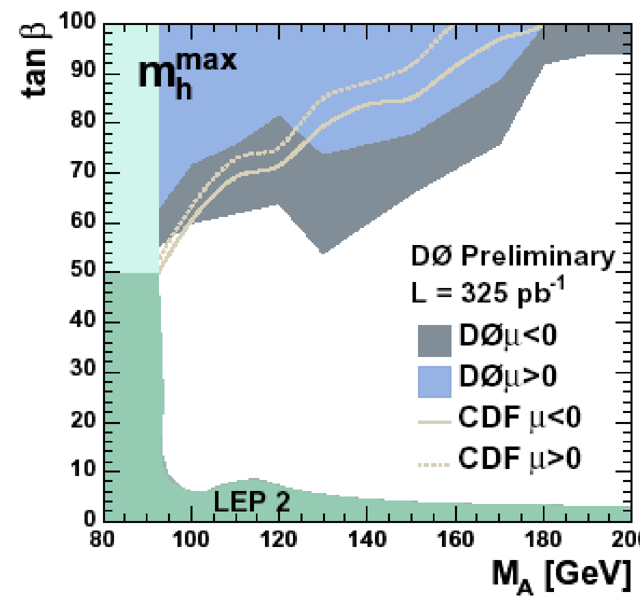


MSSM Higgs: Results

- $p\bar{p} \rightarrow A+X \rightarrow \tau\tau+X$
  - Sensitivity at high tanβ
  - Exploting regime beyond LEP
- $p\bar{p} \rightarrow Ab+X \rightarrow bbb+X$
  - Probes high tanβ if μ<0
  - Combined with ττ channel by D0
- Future (L=8 fb^{-1}):
  - Probe values down to 25-30!



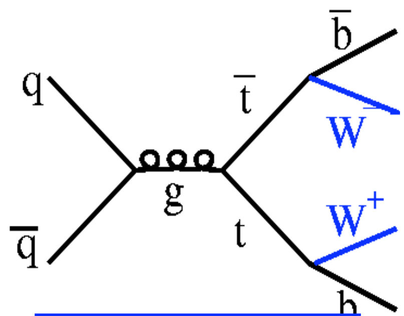




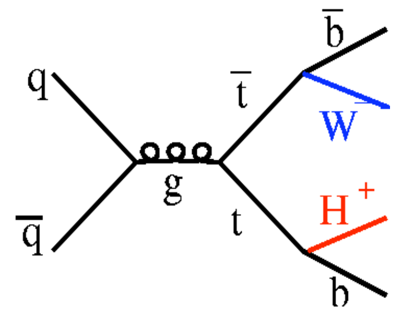
Charged Higgs: H±

- SM Top decay:
  - BR(t->Wb)≈100%
- If m(H±)<m(top):
  - Top decays to H±b
  - H± decays different to W±
- top cross section analyses sensitive to H± production:
  - Dilepton+jj+X
  - Lepton+τ+jj+X
  - Lepton+1b+jjj+X
  - Lepton+2b+jj+X

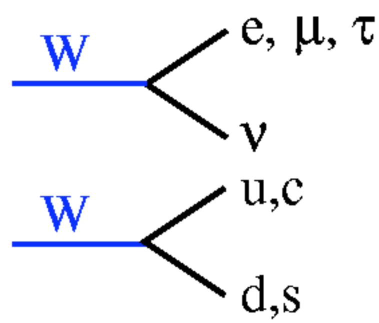
SM top decay



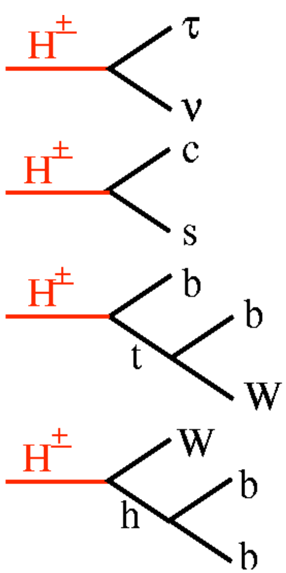
top decay to H±



W± decay

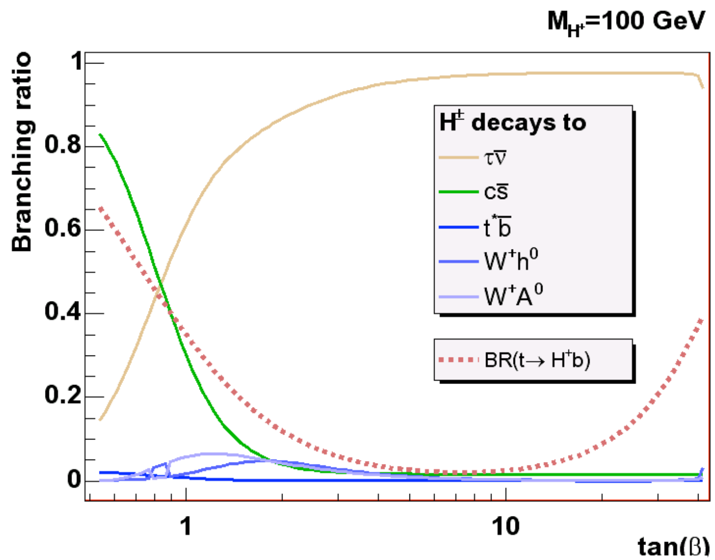


H± decay

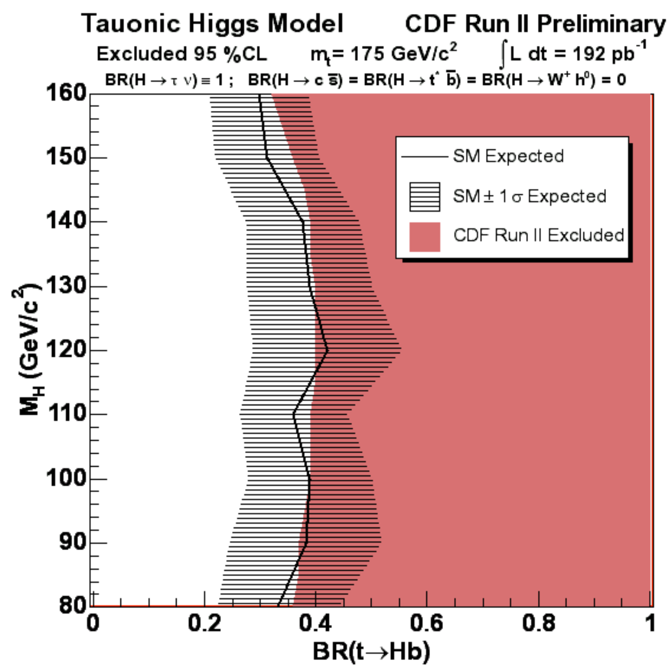


$H^{\pm}$ Branching Ratios

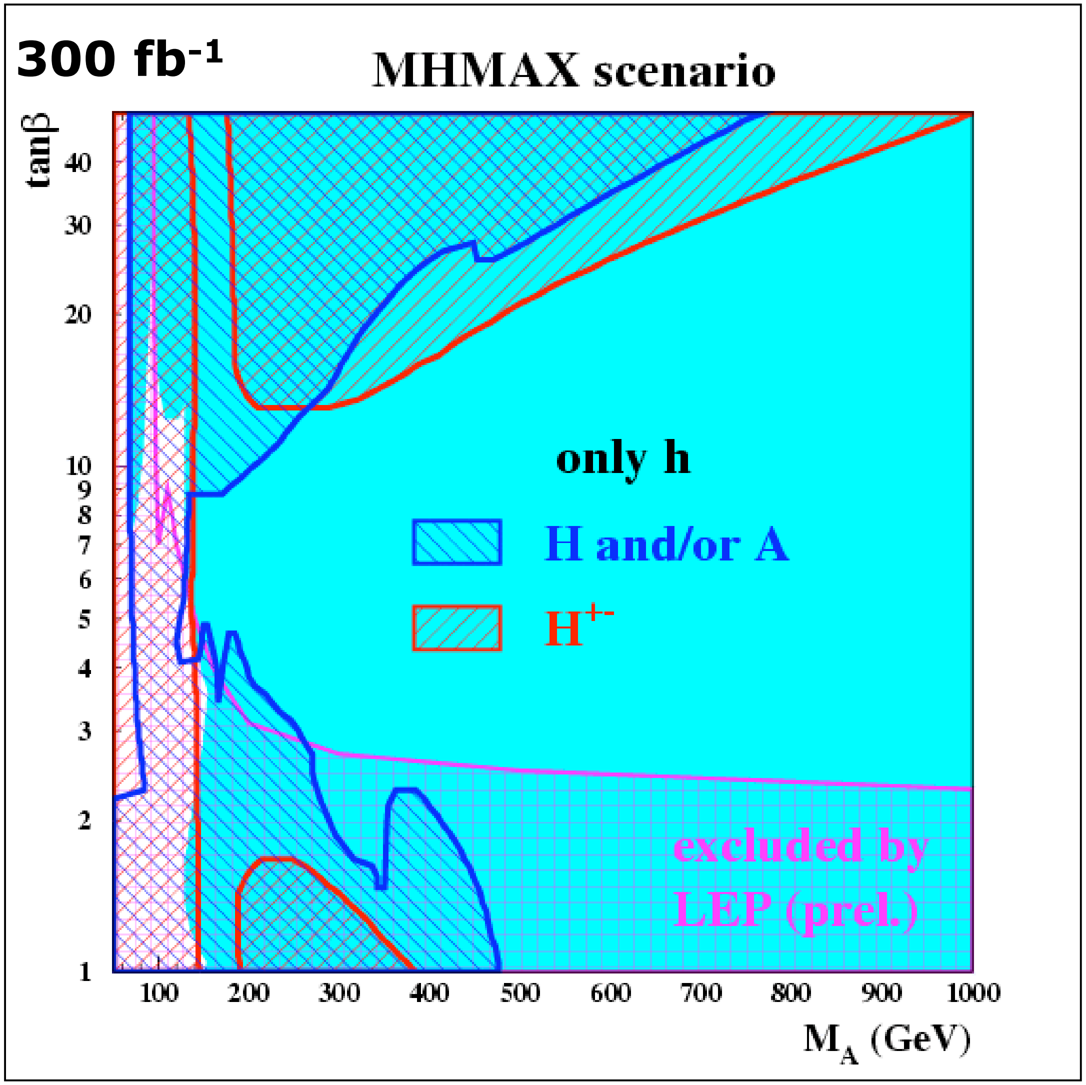
- $BR(t \to H^{\pm}b)$:
  - Large at low and high $\tan\beta$
- $H^{\pm}$ Decay:
  - $H^{\pm} \to \tau\nu$
  - $H^{\pm} \to cs$
  - $H^{\pm} \to t^{*}b \to Wbb$
  - $H^{\pm} \to Wh \to Wbb$



- Constrain BR of t->bH$^{\pm}$:
  - Use top production measurements
  - Assume $BR(H^{\pm} \to \tau\nu)=100\%$
  - Result: $BR(t \to bH^{\pm}) < 40\%$
- More complicated model dependent limts also available



MSSM Higgs Bosons at LHC

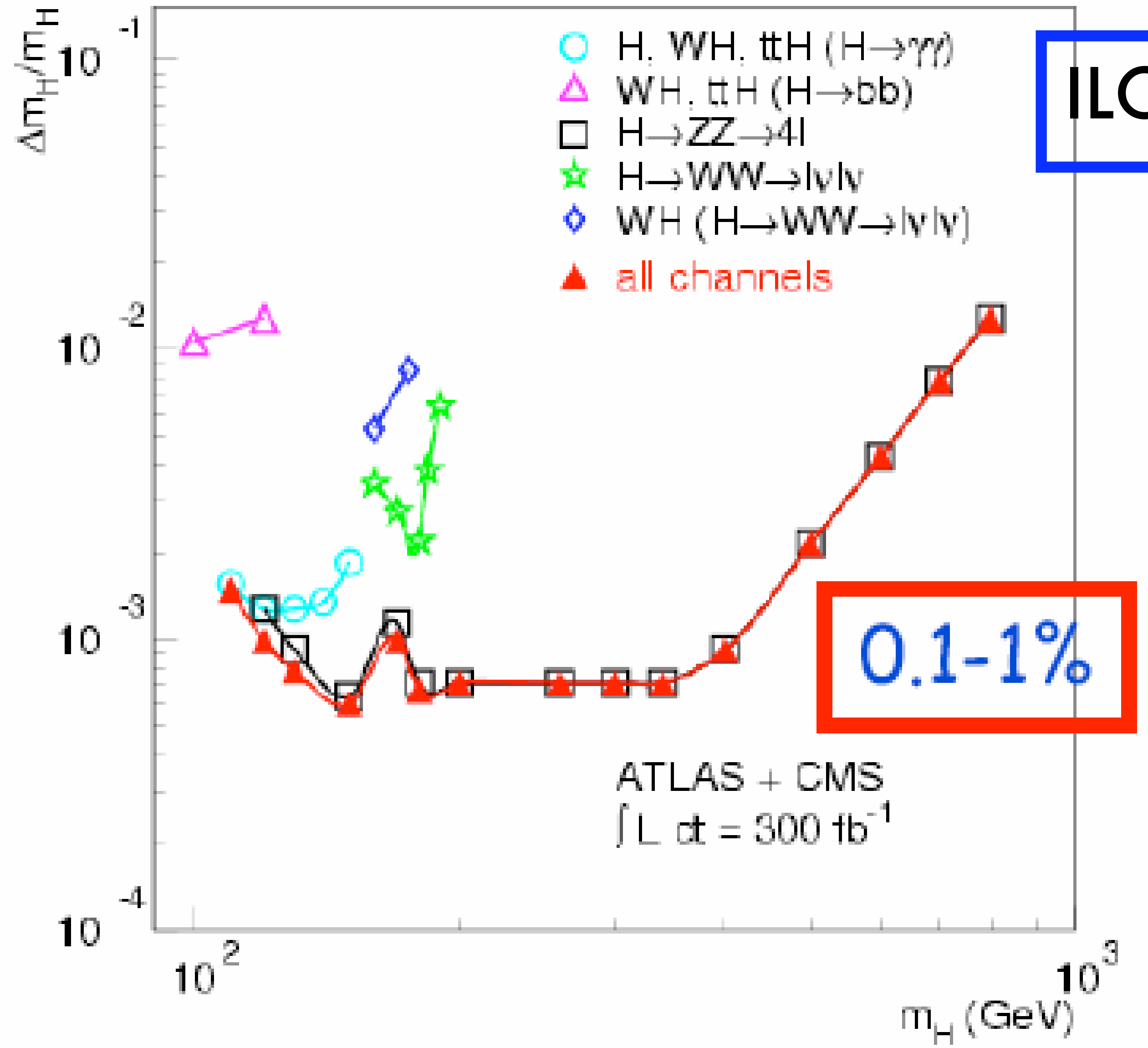


- At least one Higgs boson observable in all models
- Often only one Higgs Boson observable
- Could also be produced in SUSY cascades:
  - Depends on model how well this can be exploited

How do we know what we have found?

- After discovery we need to measure:
  - The mass
  - The spin
  - The branching ratio into all fermions
    - Verify coupling to mass
  - The total width
    - Are there invisible decays?

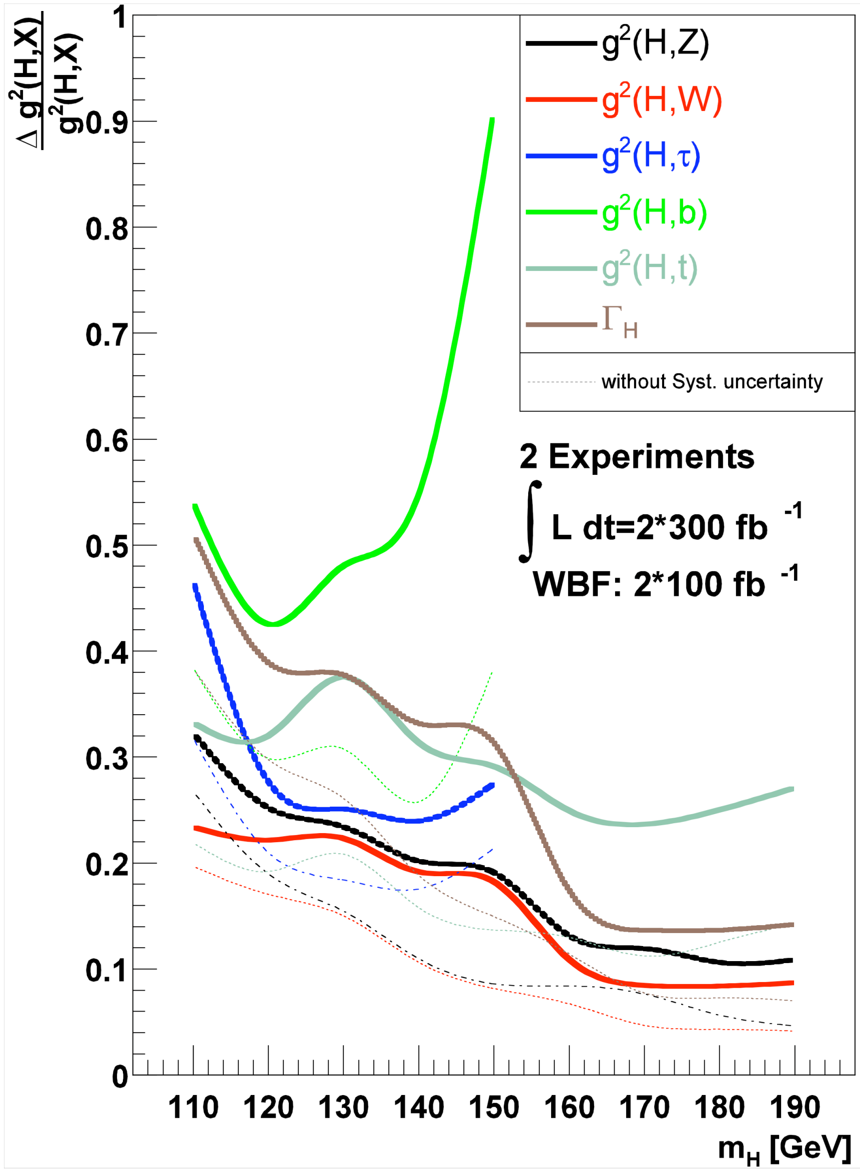
Mass



ILC: Δm_H=40 MeV

0.1-1%

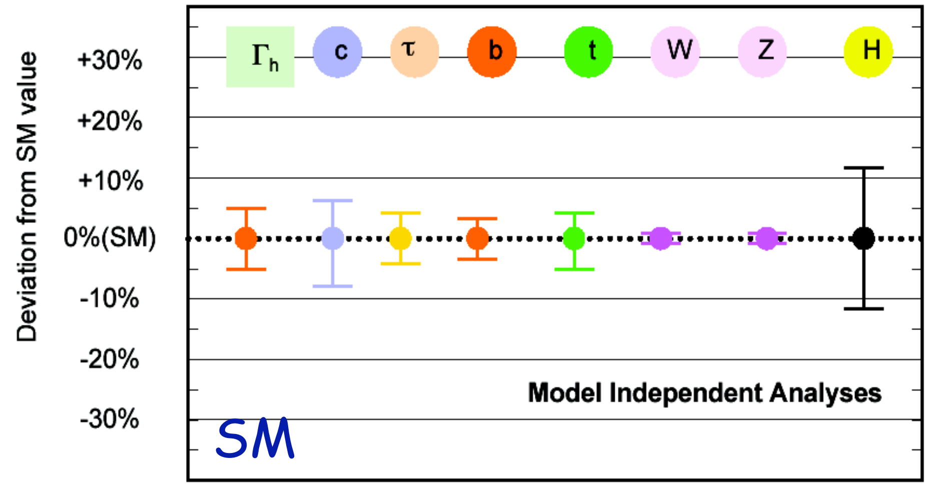
Couplings at LHC

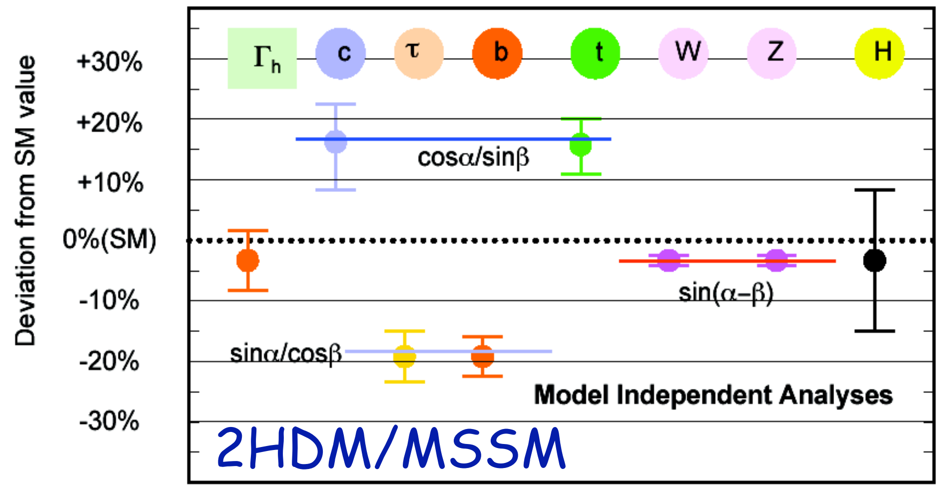


- Measure the couplings of the Higgs to as many particles as possible:
  - H->ZZ
  - H->γγ
  - H->WW
  - H->ττ
  - H->bb
- And in different production modes:
  - gg->H, ttH (tH coupling)
  - WW->H (WH coupling)

Couplings at the ILC

- Measure branching ratios very precisely
  - LHC can measure some decays to 20-40% precision
  - ILC can measure them to better than 5%
- Precision necessary to tell us about the underlying model

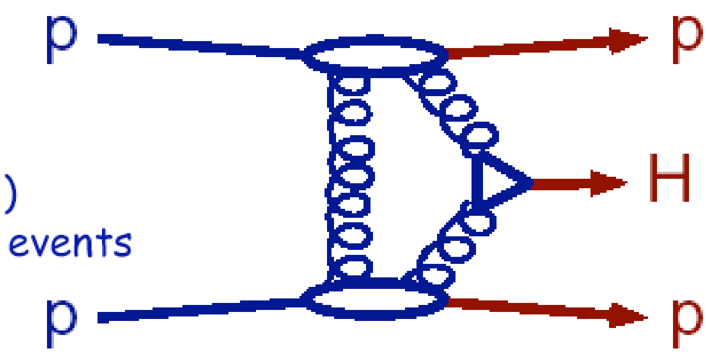




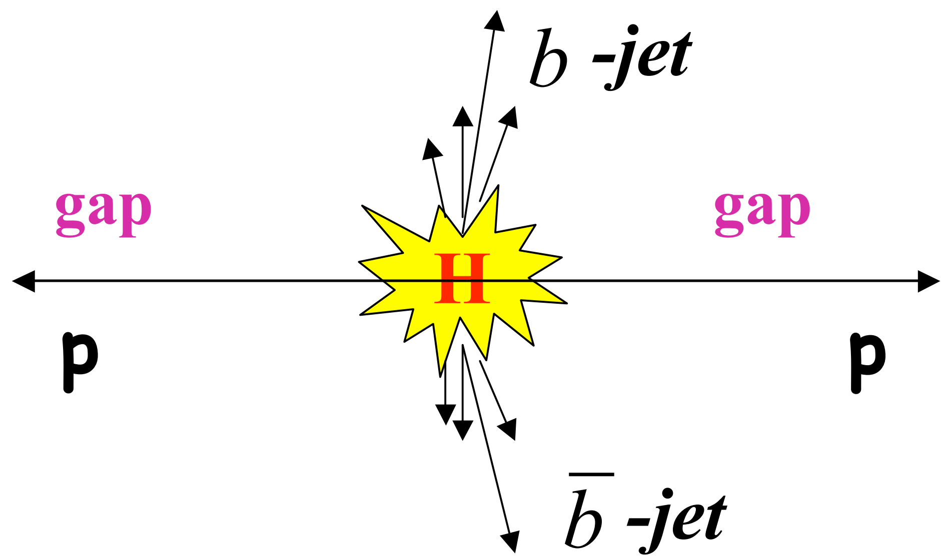
Exclusive Higgs Production

- State of the art calculation (V. Khoze, A. Martin, M. Ryskin)
  - Cross section: 3-10 fb
  - Other calculation:
    - 0.01-100 times different
- Advantages:
  - Can only make particles with quantum number of vacuum (0++)
    - Will know the spin and parity!
  - Excellent Mass resolution:
    - 2 GeV (by tagging protons with Roman Pots)
  - Background suppression:
    - J_z=0 selection rule

SM Higgs: ($30 fb^{-1}$)
11 signal vs 12 bkg events

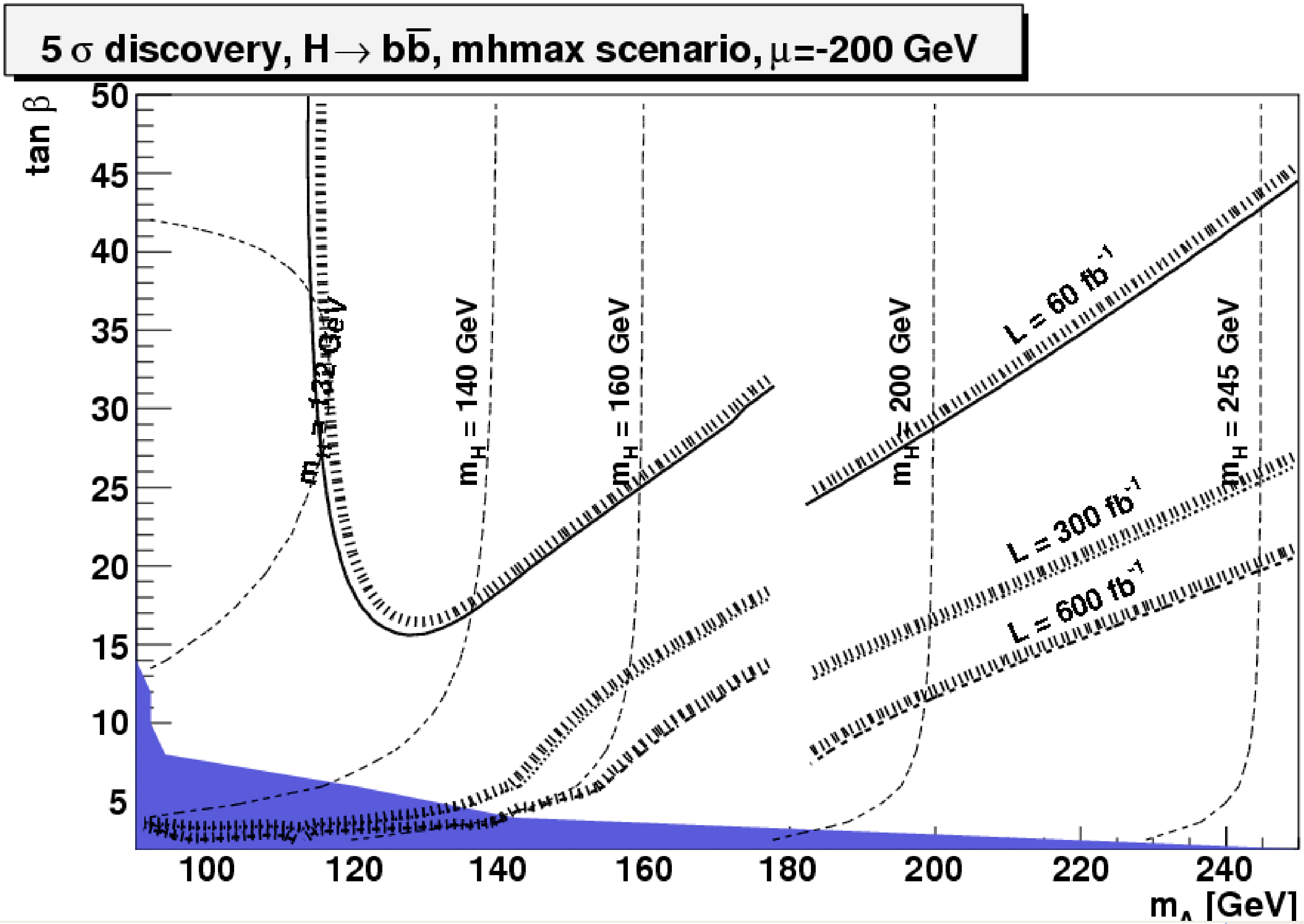


$$M_H^2 = (p + \overline{p} - p' - \overline{p}')^2$$



See: www.fp420.com

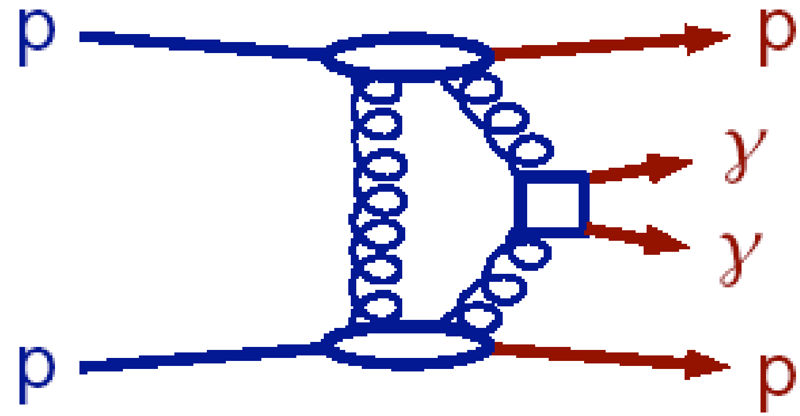
Good Potential in MSSM

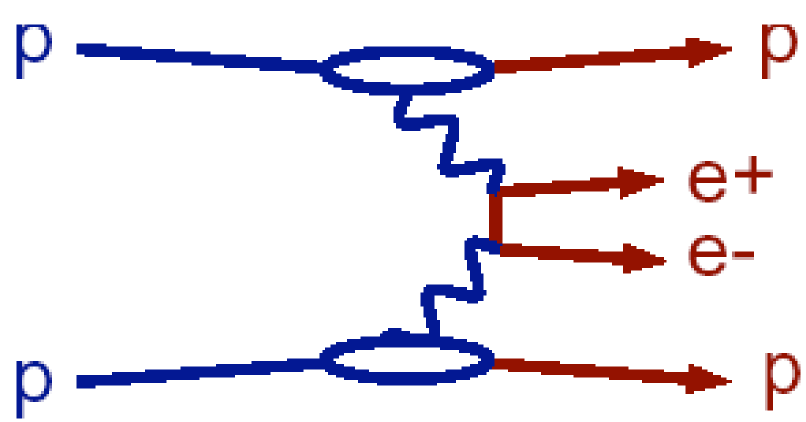


V.A.Khoze, S.Heinemeyer, W.J.Stirling, M.Ryskin M. Tesevsky and G. Weiglein in progress

Other Exclusive Processes

- Test theory at the Tevatron:
  - Exclusive diphoton
  - Exclusive dielectron (luminosity monitor)
- Theoretical predictions:
  - Diphoton calculated by KMR
  - Dielectron precisely known





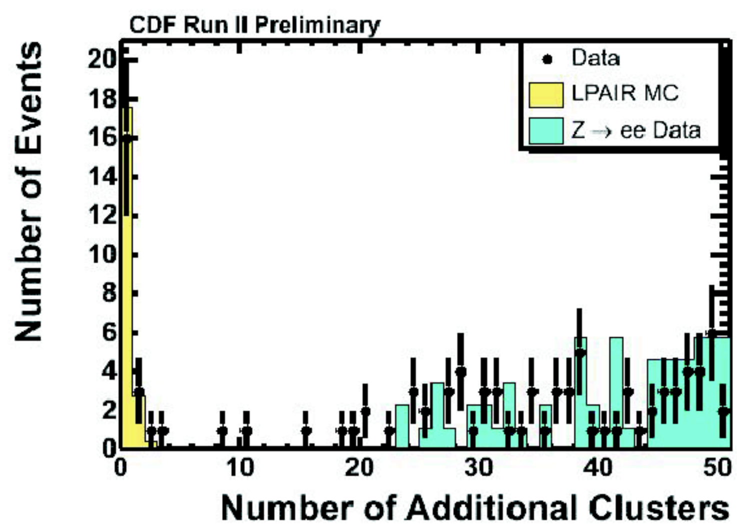
Observation of pp–>eepp (!)

- Observed 16 events
- Probability of background fluctuation:
  - 5×10^{-8} (=5.4σ)
- First observation at hadron collider:
  - Agrees with prediction

$$\sigma_{MEASURED} = 1.6\ ^{+0.5}_{-0.3}\ (stat) \pm 0.3\ (sys)\ pb$$

Theory: $\sigma_{LPAIR} = 1.711 \pm 0.008\ pb$

Fakes:	$0.0\ ^{+0.1}_{-0.0}$ events
Cosmic:	negligible
Exclusive:	$0.0\ ^{+0.3}_{-0.0}$ events
Dissociation:	2.1 ± 0.3 events
Total:	***$2.1\ ^{+0.7}_{-0.3}$ events***



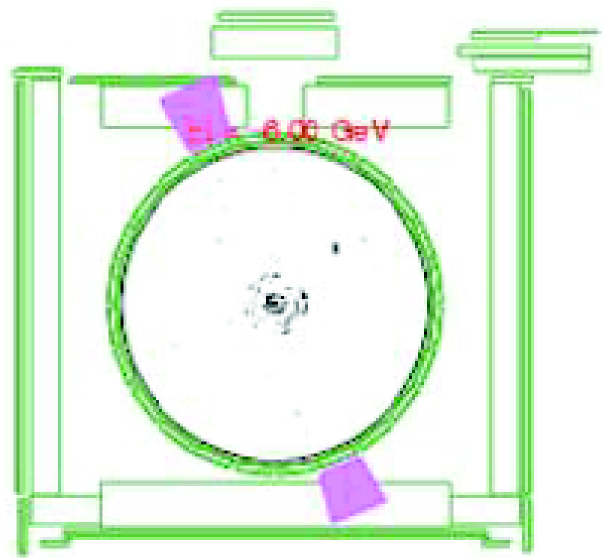
Evidence for pp->$\gamma\gamma$pp !

- Observed 3 events
- Probability of background fluctuation:
  - 1.1×10^{-3} (=3.3σ)
- First evidence for this process:
  - Agrees with KMR prediction!

Fakes:	$0.0^{+0.1}_{-0.0}$ events
Cosmic:	negligible
Exclusive:	$0.0^{+0.05}_{-0.00}$ events
Dissociation:	$0.0^{+0.05}_{-0.00}$ events
Total:	$\mathbf{0.0^{+0.2}_{-0.0}}$ **events**

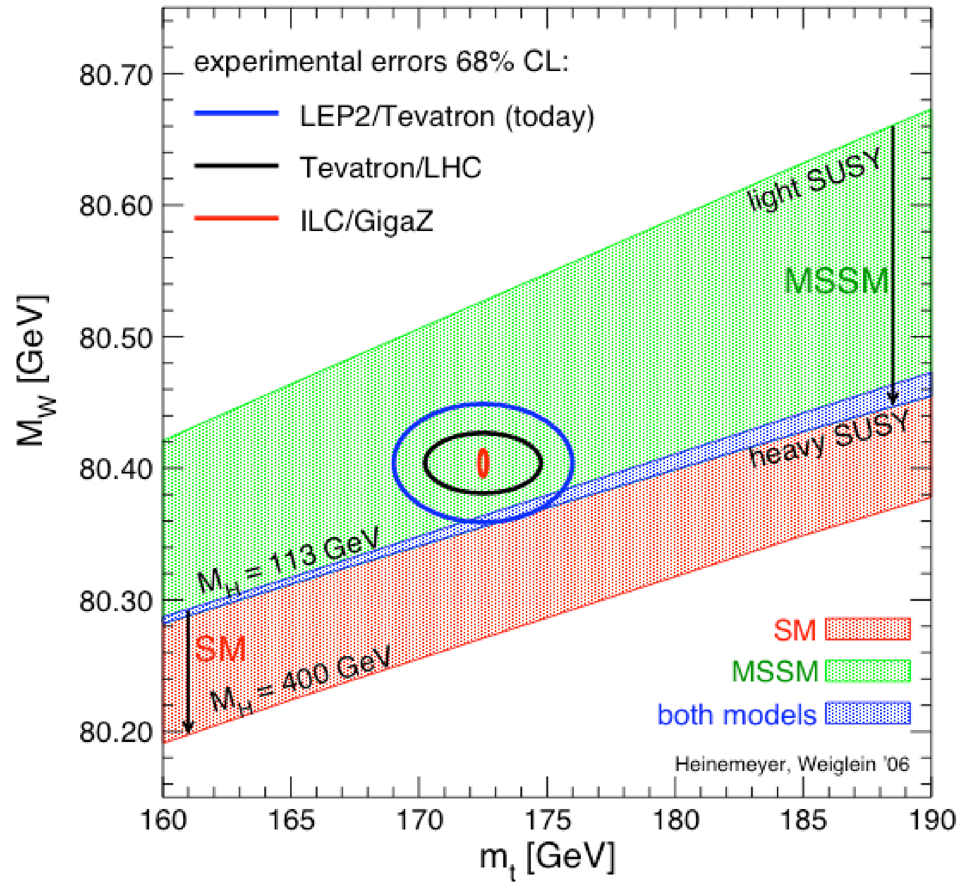
$$\sigma_{MEASURED} = 0.14\ ^{+0.14}_{-0.04}\ (stat) \pm 0.03\ (sys)\ pb$$

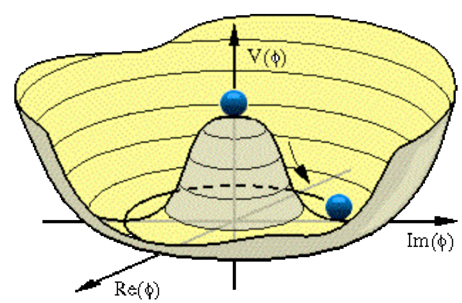
Theory: $\sigma_{KRM} = 0.04 \pm (\times 3\text{–}5)\ pb$



Conclusions

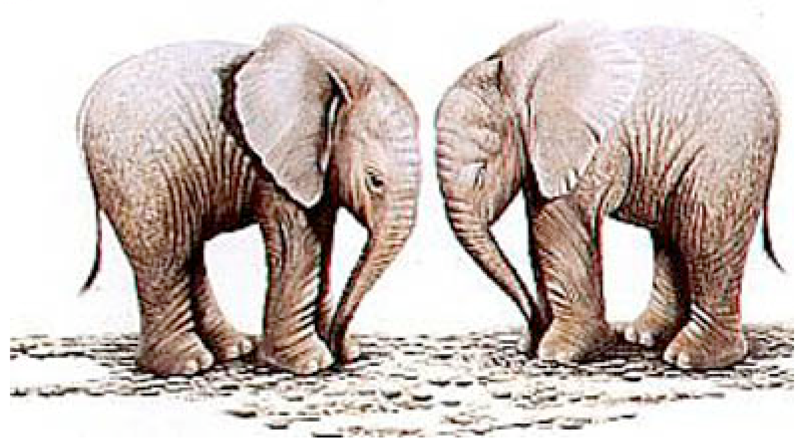
- The Higgs boson is a major target of current and future colliders
  - Tevatron can find evidence
  - LHC will discover at least one Higgs boson
  - Most likely require ILC to probe Higgs sector sufficiently well
- Precision tests of Higgs sector:
  - Consistency with indirect constraints from m_{top}, m_W?
  - Mass, width and couplings
  - Is there more than one Higgs boson?
- It is the most wanted particle ever => let's find it!





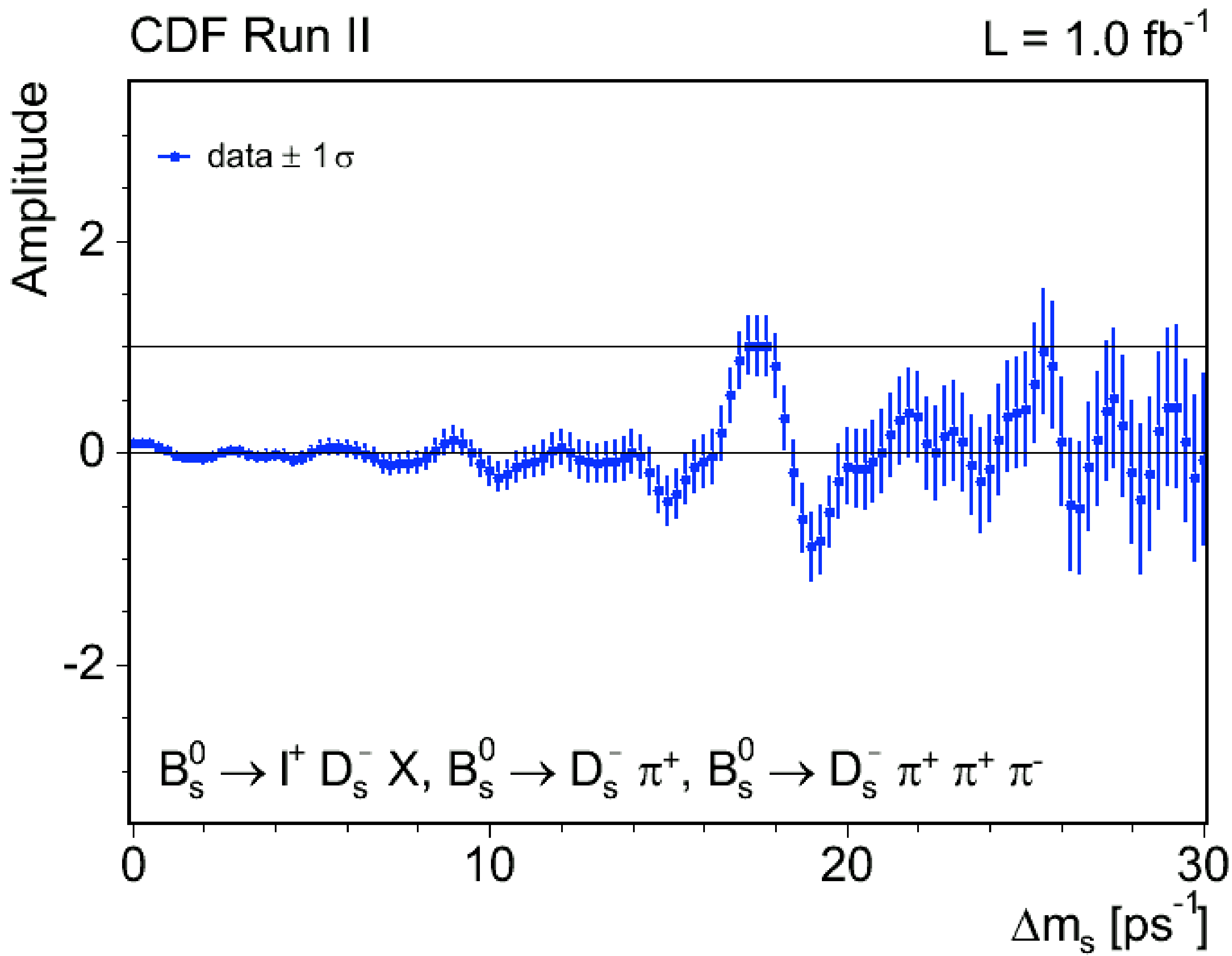
Higgs found by Google

Popular search method: Google Image Search



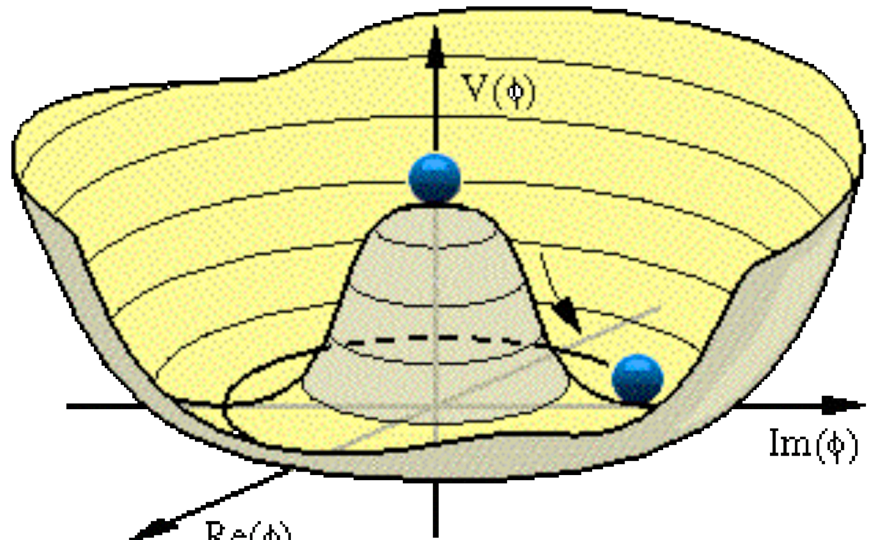
Paintings by artist called
Warwick Higgs

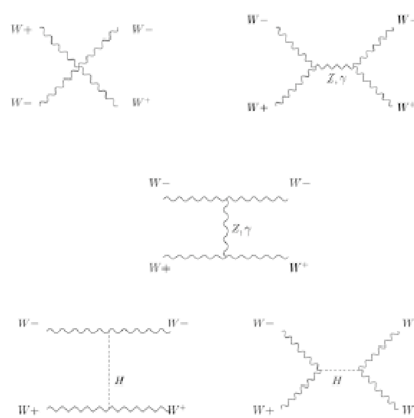
CDF B_s Mixing Result



The Higgs Boson

- Symmetry breaking caused by scalar Higgs field
- vacuum expectation value of the Higgs field $<\phi> = 246$ GeV/c^2
  - gives mass to the W and Z gauge bosons, $M_W \propto g_W <\phi>$
  - fermions gain a mass by Yukawa interactions with the Higgs field, $m_f \propto g_f <\phi>$
  - Higgs boson couplings are proportional to mass
- Higgs boson prevents unitarity volation of WW cross section





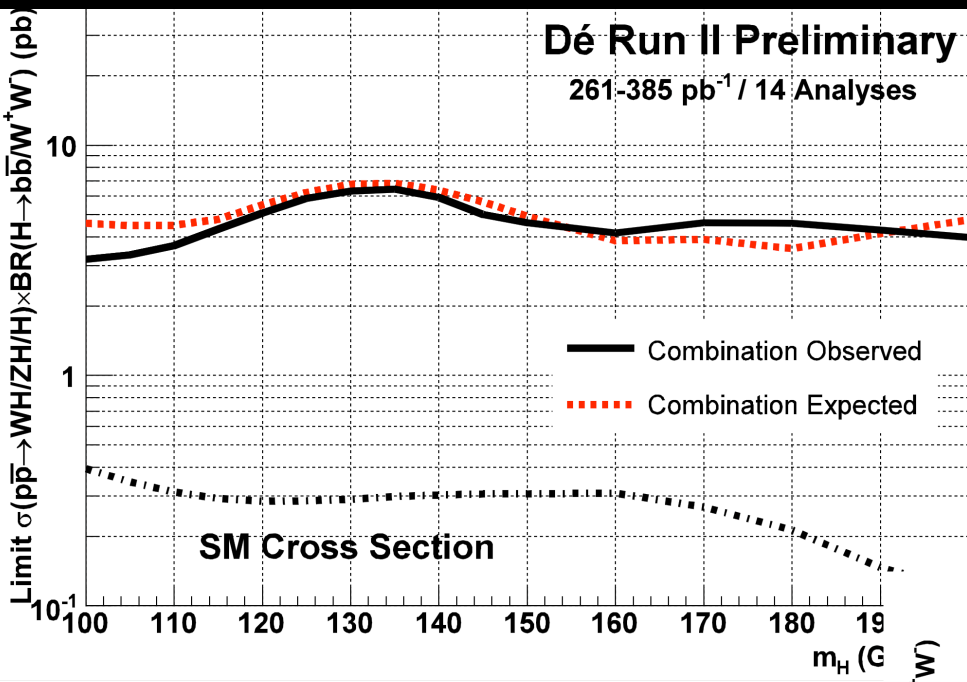
$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

Terms which grow with energy cancel for E >> M_H

This cancellation requires $M_H < 800$ GeV

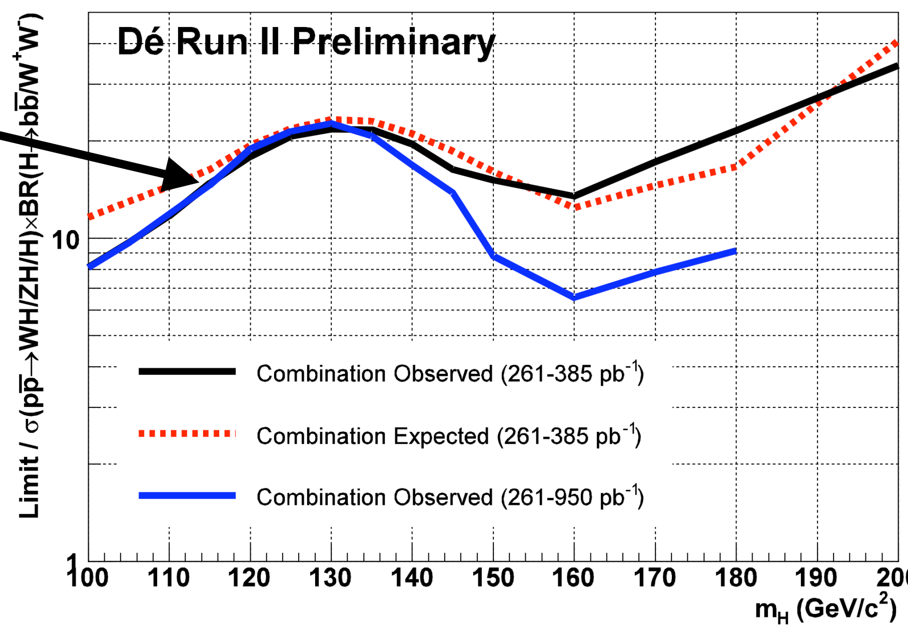
Combined limit



- New combined limit from all SM Higgs search channels!
- 14 orthogonal search channels (incl. single and double-tag analyses and WHγ lνbb w. missed lepton)
- Full account taken of systematic uncertainties
- High mass region benefits from HγWW analyses

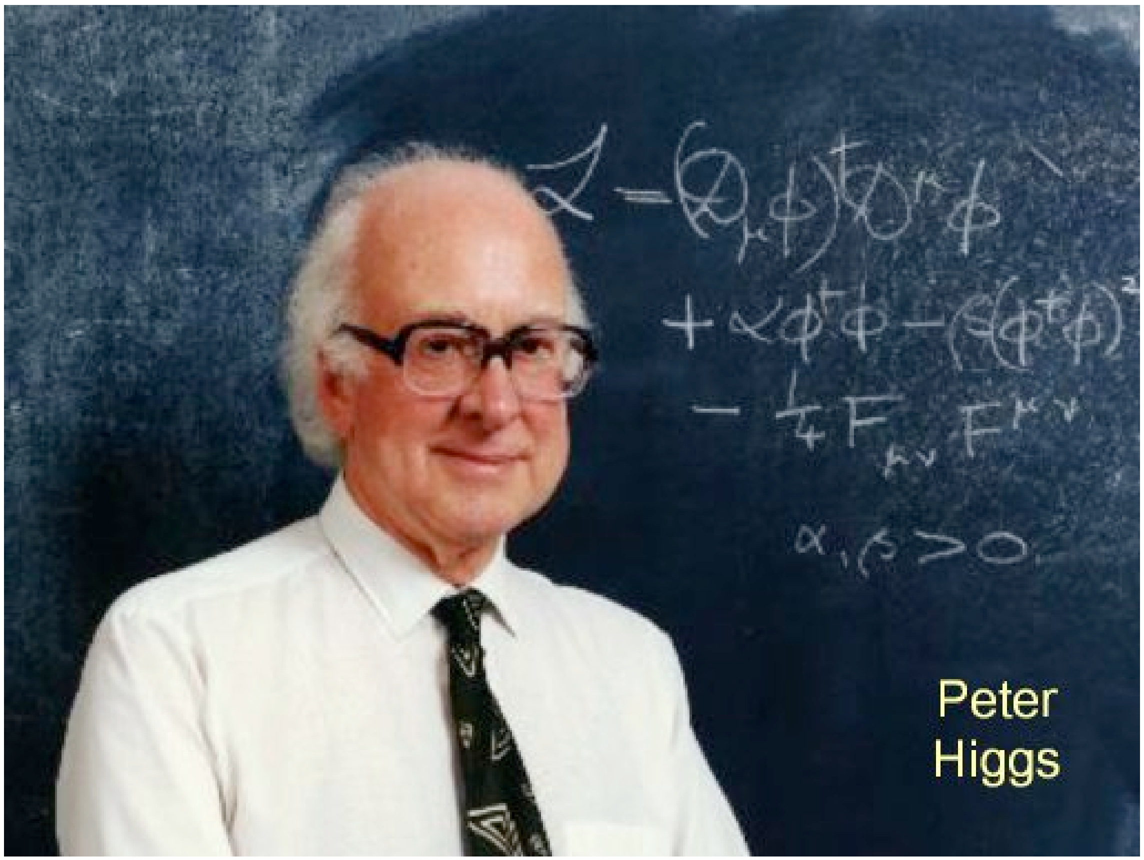
Currently a factor 15 away from m_H =115 GeV

- With L= 2 fb^{-1}, both experiments, NN b-tagging, NN analyses, track-cal jets, increased acceptance, new channels, full cross efficiency, and reduced systematics:
  - Cross section factor = 1.2



Searching for the Higgs

Peter Higgs in Edinburgh

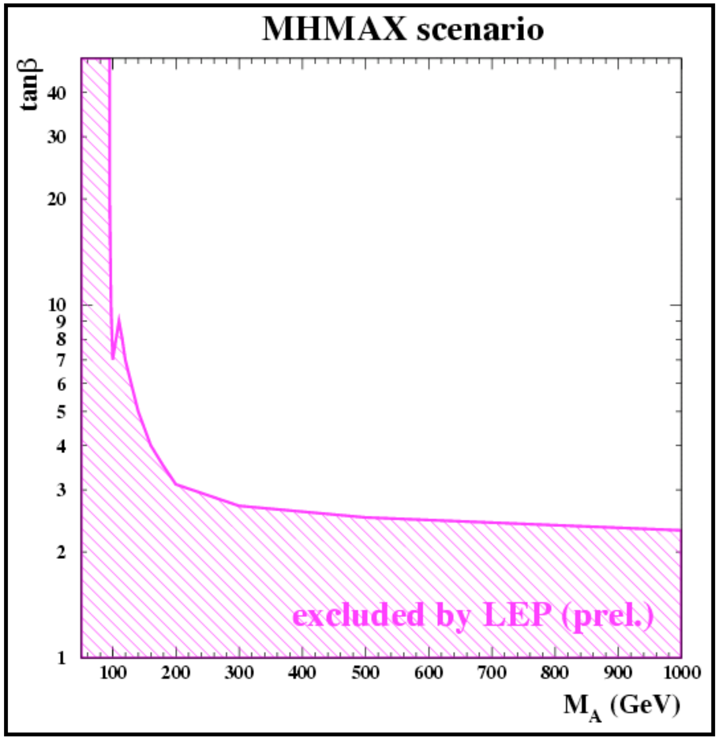


Discovery potential in tanβ vs M_A plane

Is at least 1 Higgs boson observable in the entire parameter space?

How many Higgs bosons can be observed?

Can the SM be discriminated from extended Higgs sectors?



- two expected data volumes

  30 fb^{-1} @ low lumi

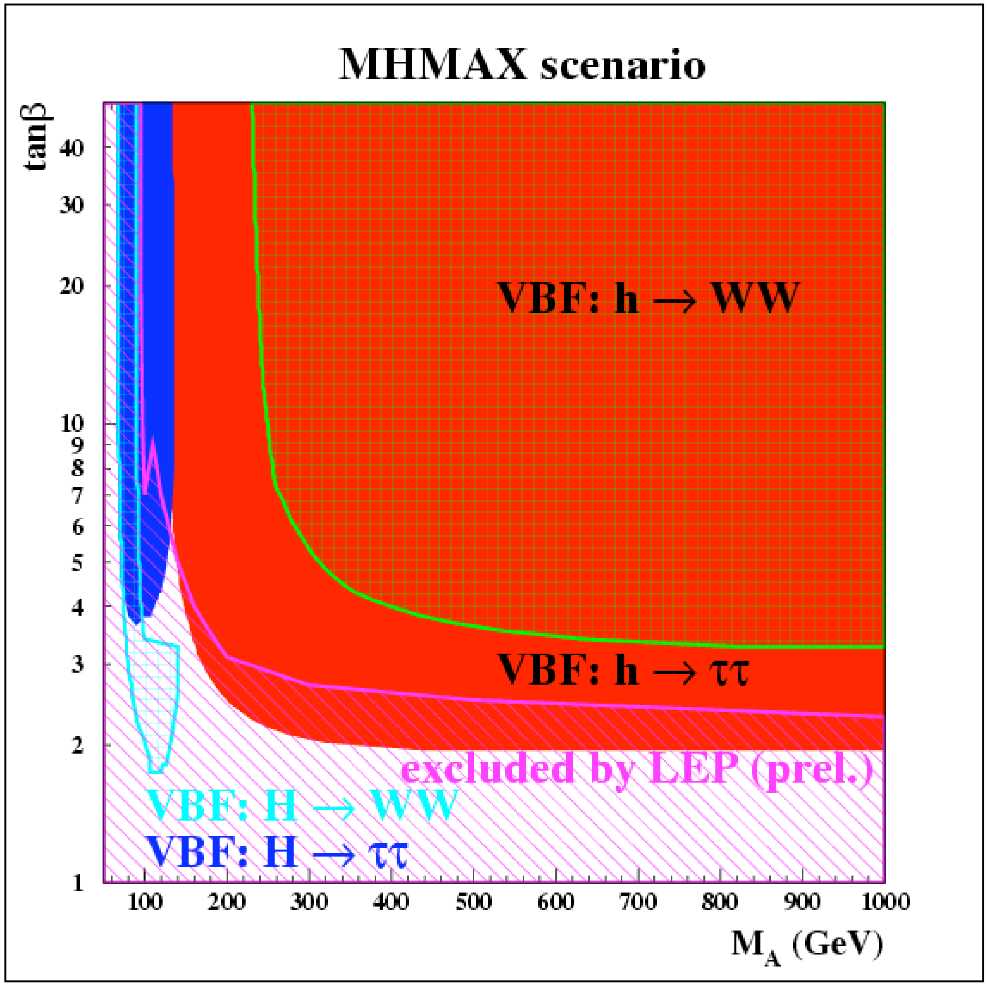
  300 fb^{-1} = 30 fb^{-1}@ low lumi.

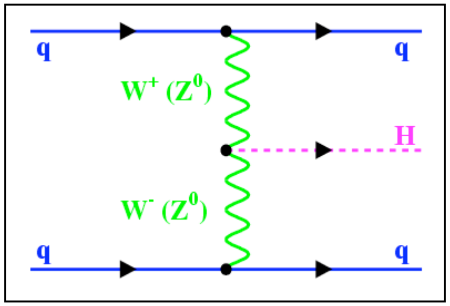
  + 270fb^{-1} @high lumi
- discovery = 5 sigma excess

  using Poissonian statistics
- no systematic uncertainties yet

LEP tanβ exclusion: no exclusion for m_t larger ~183 GeV !

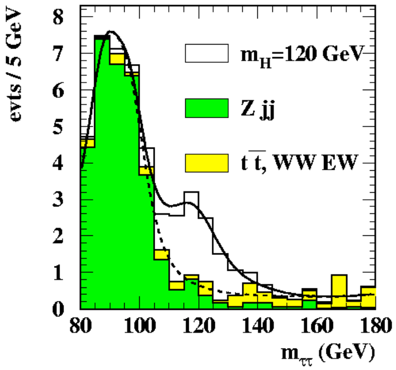
H,h Discovery Potential $30 fb^{-1}$





studied for M_H>110GeV at low lumi running

almost gurantees discovery of at least one h or H with 30 fb^{-1}

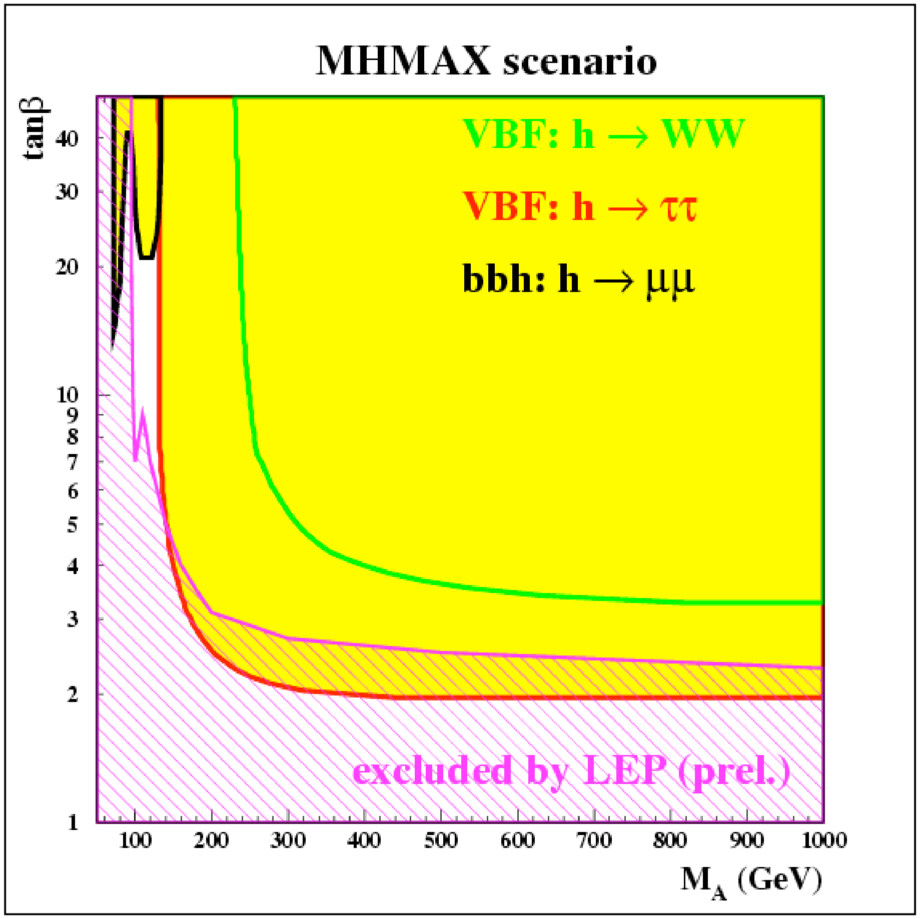


SM like h with 30 fb^{-1}

$\tau\tau \rightarrow ll4\nu$

Backup Slides

h Discovery Potential $30fb^{-1}$



In Maximal Mixing Scenario:
VBF h→ττ covers most of the MSSM plane with $30fb^{-1}$

The VBF h→ττ channel is also important for other MSSM scenarios

VBF h→ττ

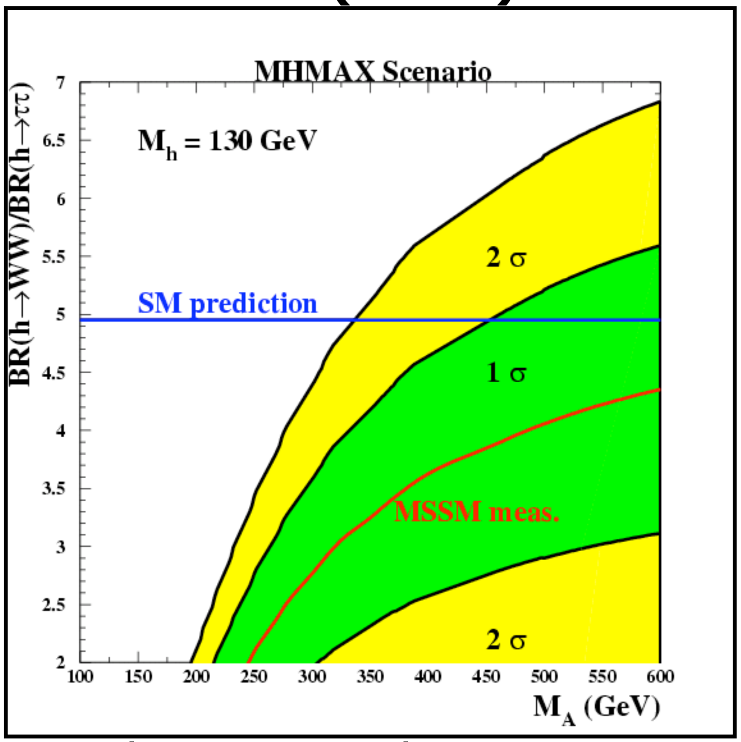
Experimental Challenge:

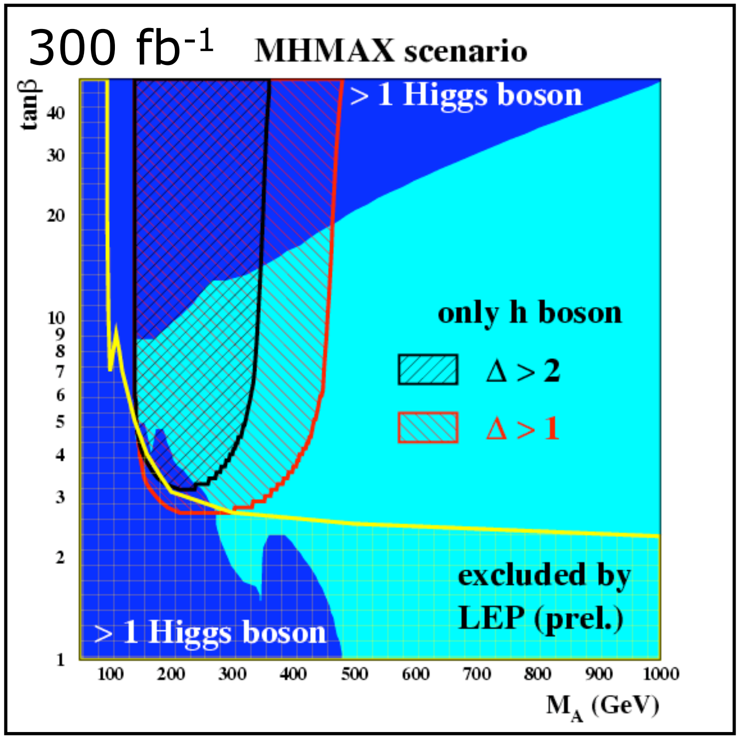
Missing E_t Reconstruction

SM vs MSSM Higgs discrimination

- estimate of sensitivity from rate measurements in VBF channels ($30fb^{-1}$)
- compare expected measurement of R in MSSM with prediction from SM

$$R = \frac{BR(h \rightarrow WW)}{BR(h \rightarrow \tau\tau)} \qquad \Delta = |R_{MSSM} - R_{SM}| / \sigma_{exp}$$



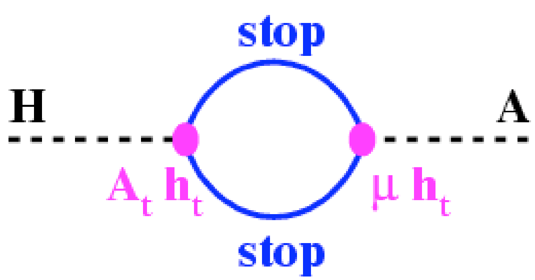


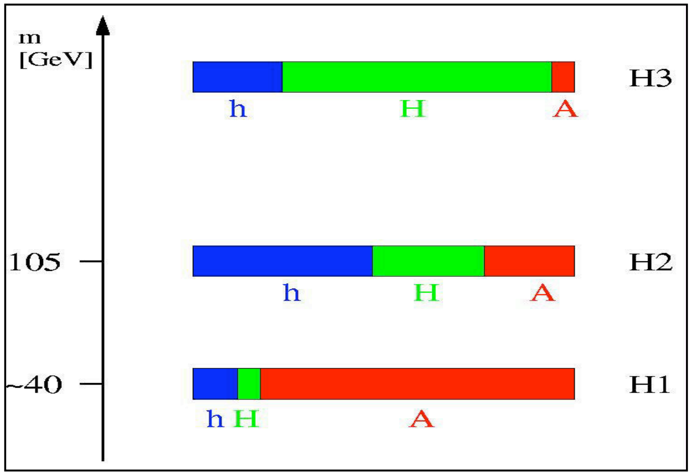
- only statistical errors
- assume M_h exactly known

needs further study incl. sys. errors

The CP violating CPX scenario

- CP conserving at Born level, but CP violation via complex **A_t, A_b M_{gl}**

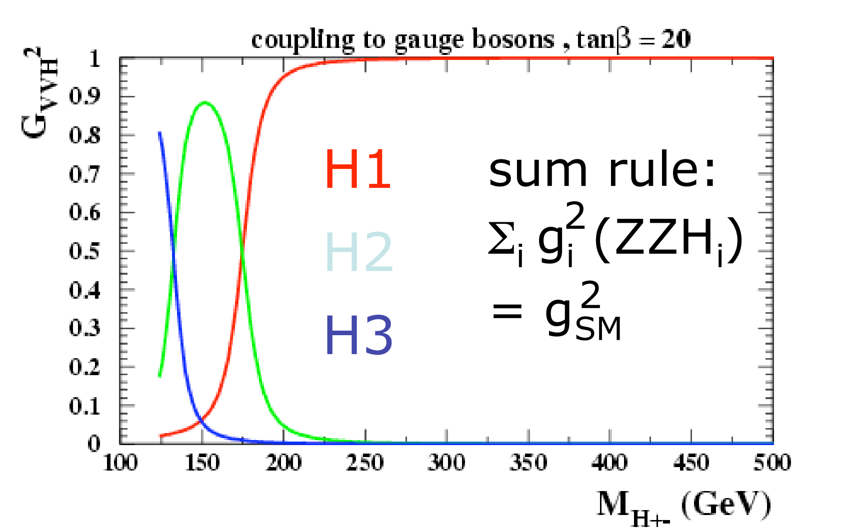




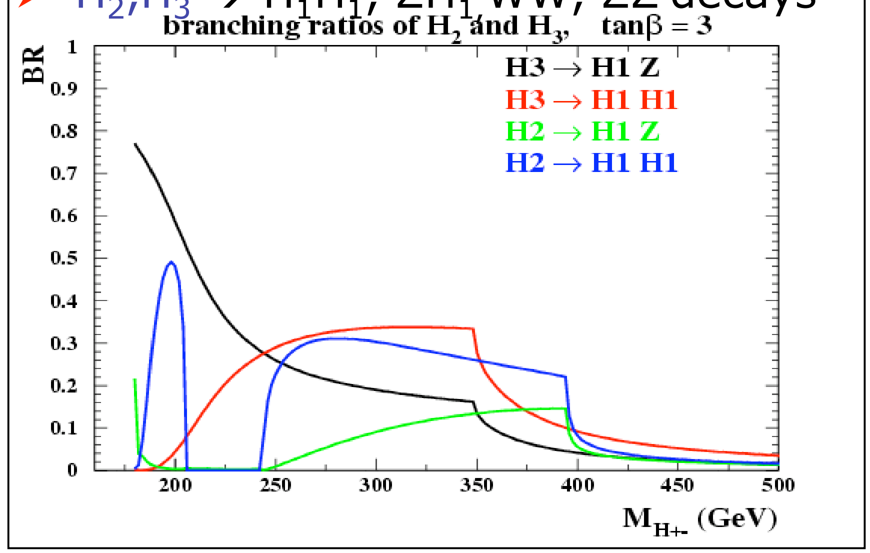
- CP eigenstates h, A, H mix to mass eigenstates H_1, H_2, H_3
- maximise effect → CPX scenario (Carena et al., Phys.Lett B495 155(2000))
  $\arg(A_t)=\arg(A_b)=\arg(M_{gluino})=90$ degree
- scan of Born level parameters: $\tan\beta$ and M_{H+-}

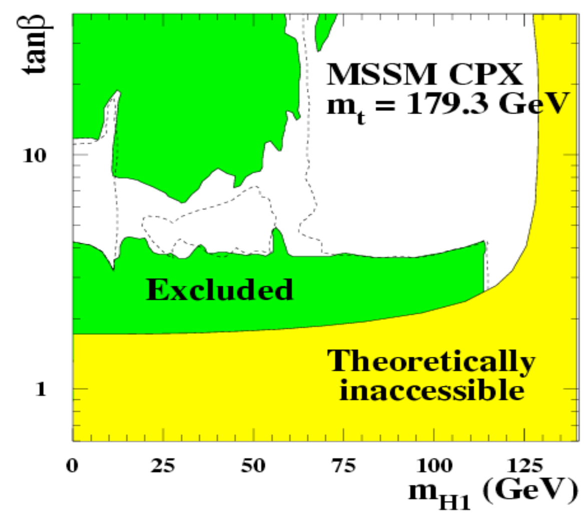
CPX Phenomenology

➢ H_1, H_2, H_3 coupling to W,Z



➢ $H_2, H_3 \rightarrow H_1H_1$, ZH_1, WW, ZZ decays





❖ no absolute limit on mass of H_1 from LEP

❖ strong dependence of excluded region

on value for m_{top}

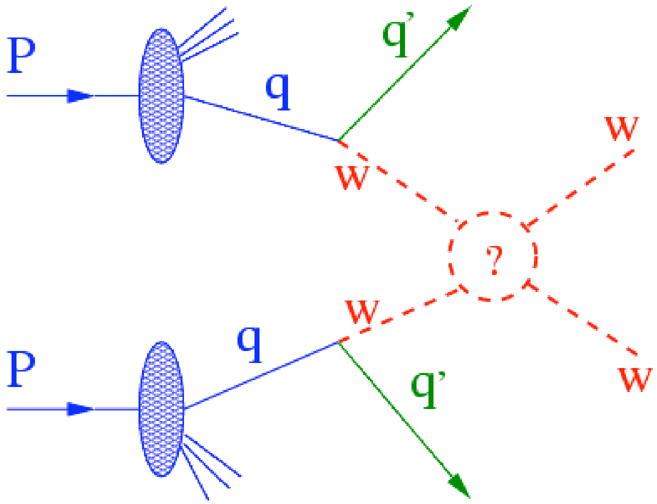
on calculation used FeynHiggs vs CPH

What if there is no Higgs?

-$W_L W_L$ cross section would violate unitarity since amplitude perturbative expansion in energy (s): $\sigma \sim s^2/v^2 + s^4/v^4 \ldots$

-Need either a Higgs boson with m_h<1 TeV or some new physics (e.g. SUSY, Technicolor)

-Tevatron and LHC probe relevant scale of 100 GeV - 1 TeV!



=> We will find something (higgs or more extraodinary) in the next 10 years!

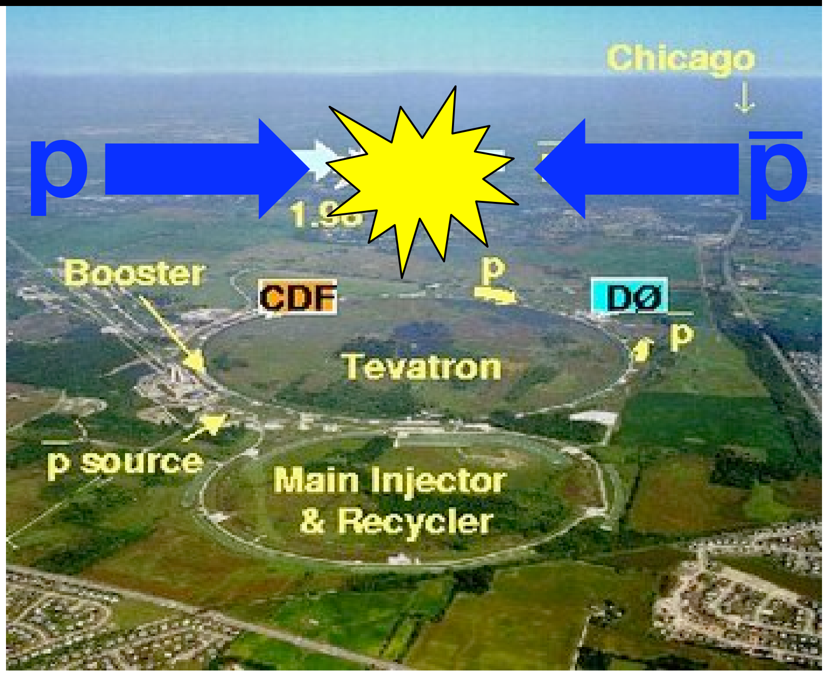
CDF and the Tevatron

Tevatron Run II

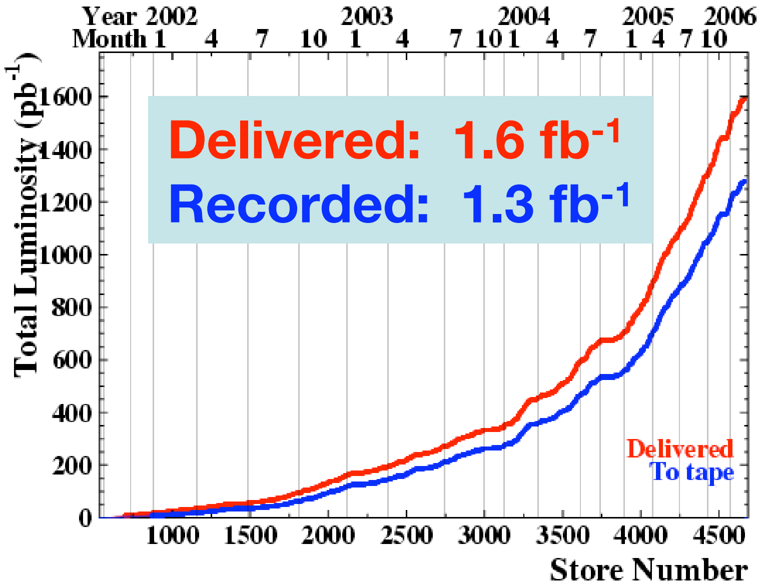
- World's highest energy collider
- Tevatron Accelerator:

	√s(TeV)	Δt(ns)	L(cm^{-2} s^{-1})
Run II	1.96	396	1.7×10^{32}

Key parameter: $N = \sigma \cdot \int L dt$



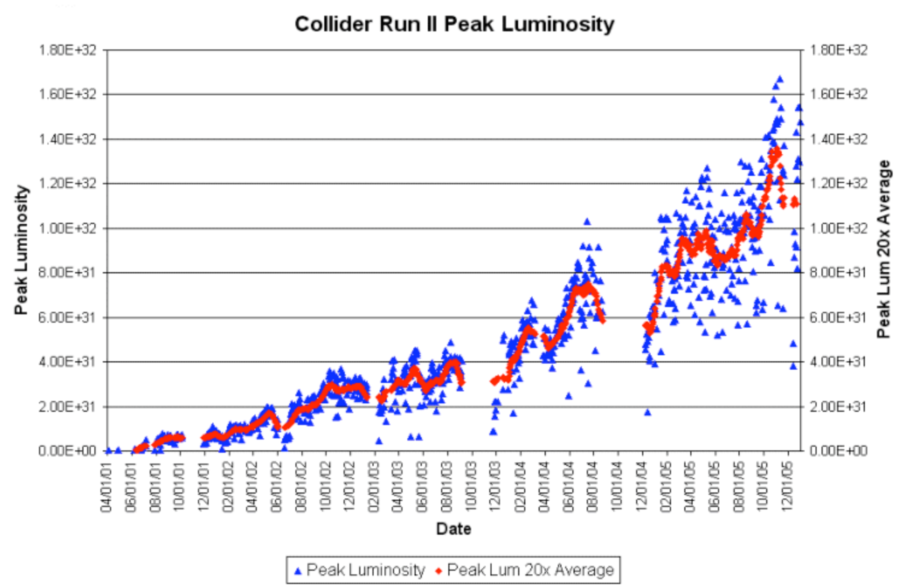
- Integrated luminosity >1.5 fb^{-1} by now:
  - CDF data taking efficiency about 83%
- Integrate $\int L dt$=4-8 fb^{-1} by 2009



Tevatron Luminosity

Congratulations Fermilab!

Fermilab has set a world record for peak luminosity of a hadron collider! Operations established store 4431 at 9:11 a.m. yesterday, October 4, with an initial luminosity, or brightness, of 141E30 $cm^{-2}sec^{-1}$. This record exceeds the previous Tevatron record by almost 8 percent, and it exceeds the world record for peak luminosity of a hadron collider achieved 23 years ago by the ISR proton-proton collider at CERN. The ISR achieved a peak luminosity of 140E30 $cm^{-2}sec^{-1}$ at a collision energy of 62 GeV. The Tevatron produces collisions between protons and antiprotons at a collision energy of 1960 GeV. The peak luminosity of the Tevatron has greatly increased since Fermilab began Run II in March 2001, and Fermilab expects to improve the Tevatron peak luminosity even further.



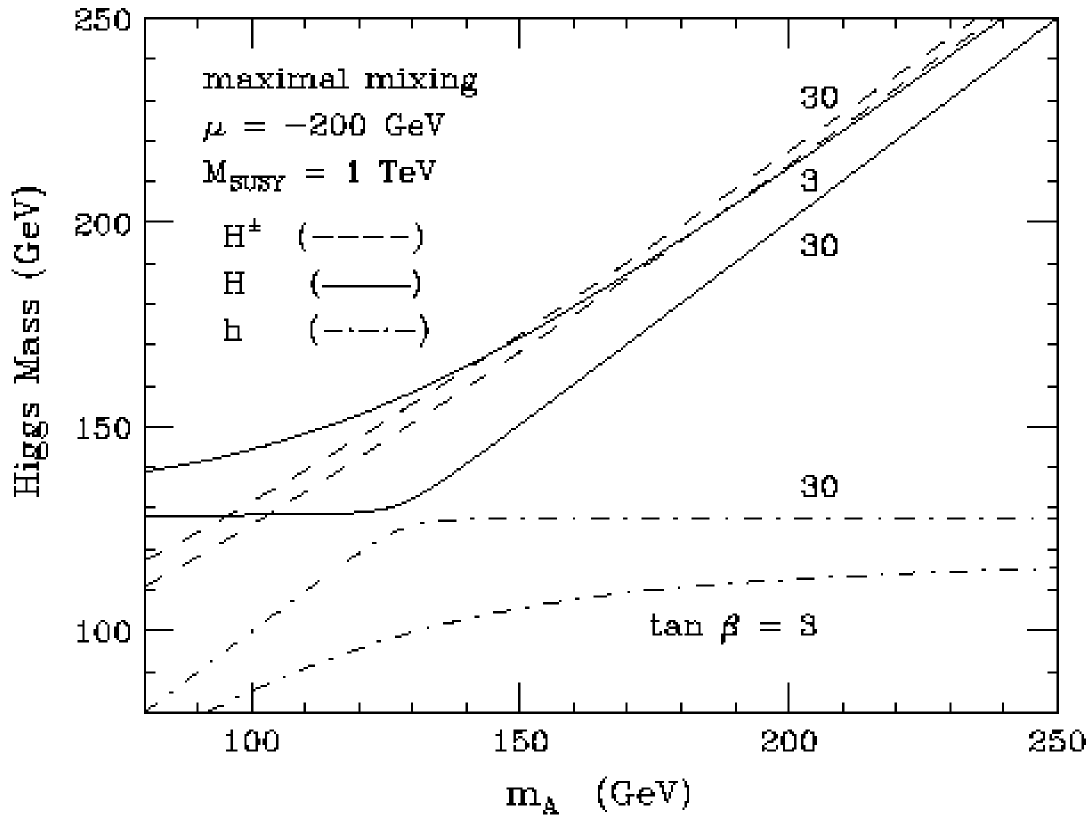
Tevatron Has Another Peak Luminosity Record in 2006

The Tevatron collider set a new peak luminosity record at 3:28 this morning, January 6. Store 4581 reached 171E30 cm^{-2} sec^{-1}. Congratulations.

CPConserving Benchmark Scenarios

At $M_A >> M_Z$ or $M_A \sim M_{h,max}$ and $\tan\beta >> 1$, the heavy bosons degenerate in mass while the h decouples at $M_h \sim 130$ GeV (decoupling regime of MSSM)

Maximum M_h depends on stop mixing Xt



Examples:

- MHMAX scenario maximal m_h < 135 GeV ($X_t \sim \mathrm{sqrt}(6)*M_S$)
- Nomixing scenario small m_h < 116 GeV ($X_t = 0$)