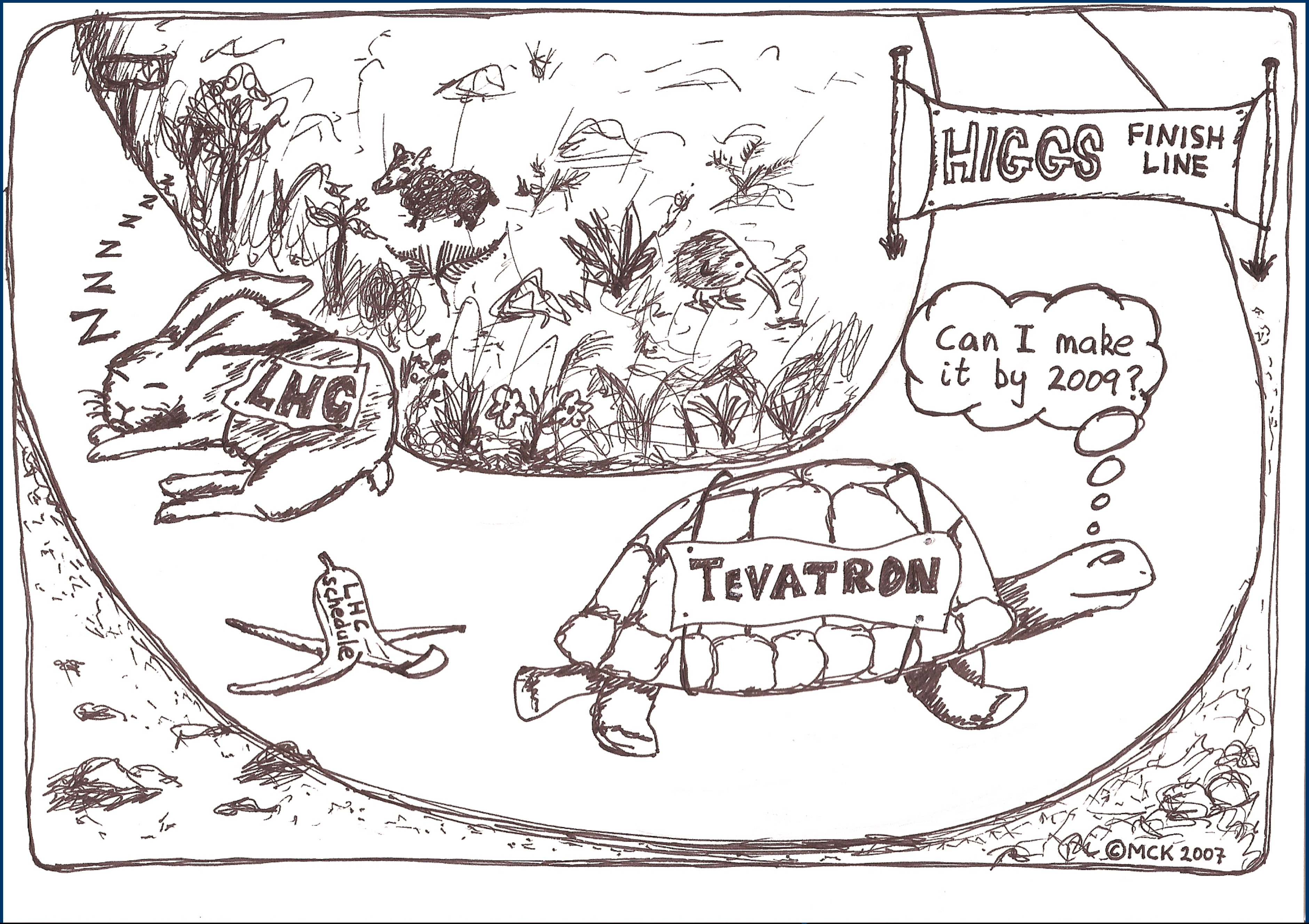
The Race to Find the Higgs

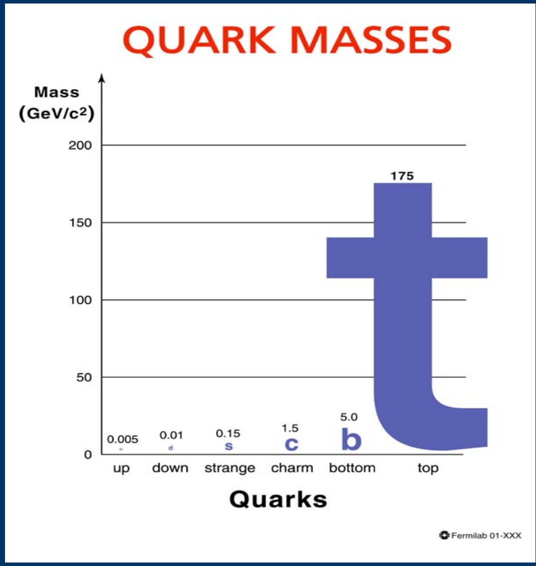


Mark Kruse
Duke University

PHENO 07, Prelude to the LHC
Madison WI, 7 May 2007

Why we're looking for “Higgs”

- The electroweak gauge bosons are massive (M_W = 80 GeV, M_Z = 91 GeV)
  $\Rightarrow$ *somehow*, the electroweak symmetry is broken
- The “Higgs mechanism” can accomplish this:
  - Interaction of a scalar “Higgs field” with the massless fields of the electroweak theory can cause electroweak symmetry breaking (EWSB) and endow the $W^{\pm}$ and Z^0 bosons with mass
  - There remains a massive spin-0 particle: **the Higgs boson**
  - Same mechanism can be used to generate lepton and quark masses



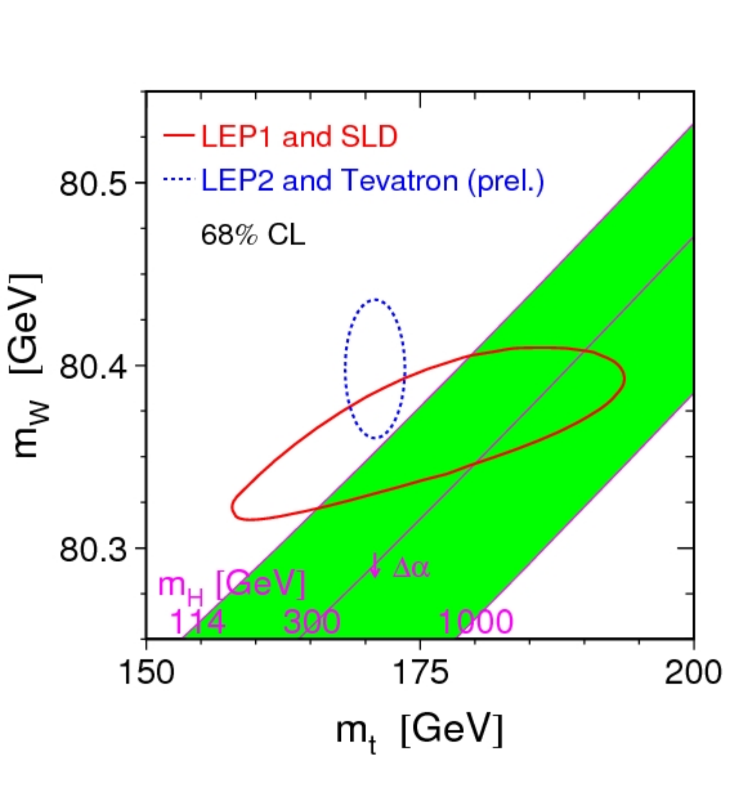
- In the Standard Model, the Higgs boson is the only undiscovered particle, making it the most sought after particle in HEP
- But why believe in the SM Higgs ?
  - There is no experimental evidence significantly contradicting the SM, within which a single Higgs potential provides the necessary EWSB for mass generation
  - Therefore, although there are good reasons to believe in alternative models, the SM Higgs provides a stable target, and more complicated models typically include something that's SM-like anyway

This talk....

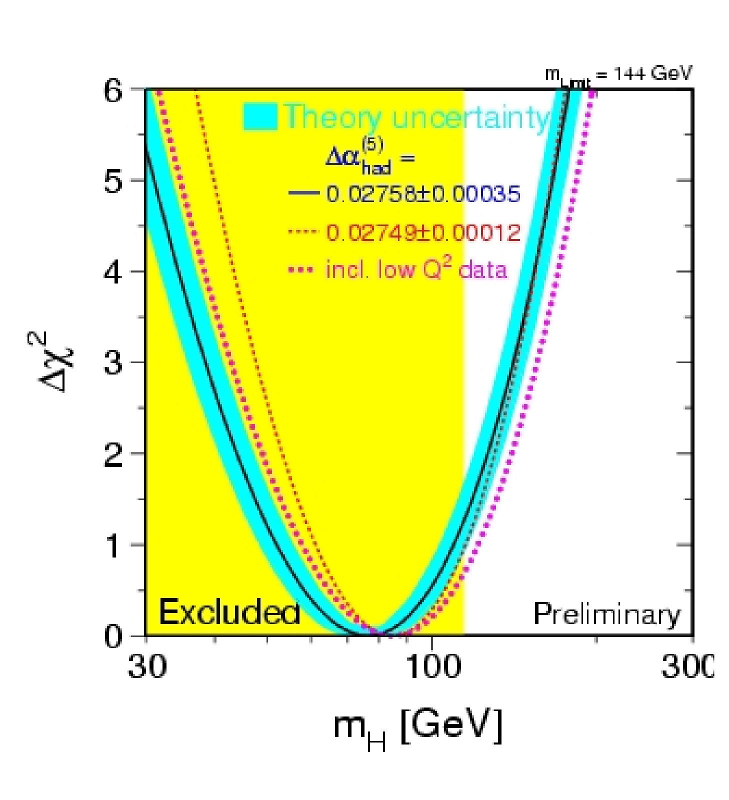
- Will concentrate on the SM Higgs
  - status and prospects at the Tevatron
  - prospects at the LHC
  - Will not give a detailed check-list of analyses but rather try to convey what is necessary for discovery
- Hope to have a little time to say something about MSSM Higgs searches, and other models

What we currently know about the SM Higgs

- Theoretical upper bound from the SM
  - ➔ $m_H < 1000\ \mathrm{GeV}/c^2$
- Lower bound from direct searches at LEP
  - ➔ $m_H > 114.4\ \mathrm{GeV}/c^2$



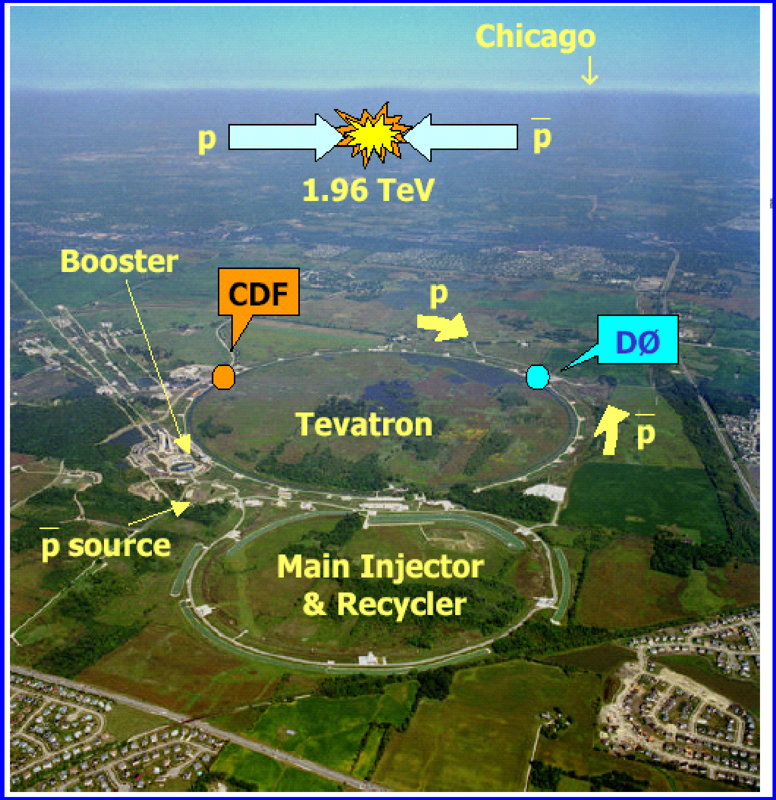
- Top and W mass precision now intriguingly constraining the Higgs sector

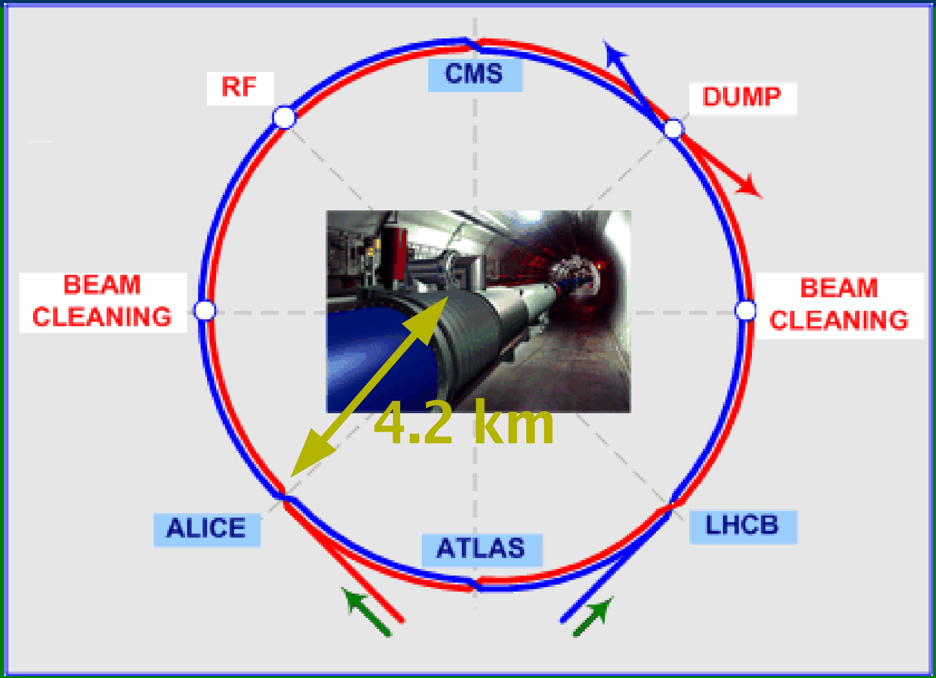


- Latest (March '07) fits to precision EW data
  - ➔ $m_H = 76^{+33}_{-24}\ \mathrm{GeV}/c^2$
  - ➔ $m_H < 144\ \mathrm{GeV}/c^2$ (95% CL)
  - ➔ $m_H < 182\ \mathrm{GeV}/c^2$ (when LEP limit included)

- If the SM Higgs exists, we'll find it soon, either at the Tevatron and/or LHC

Tevatron vs. LHC



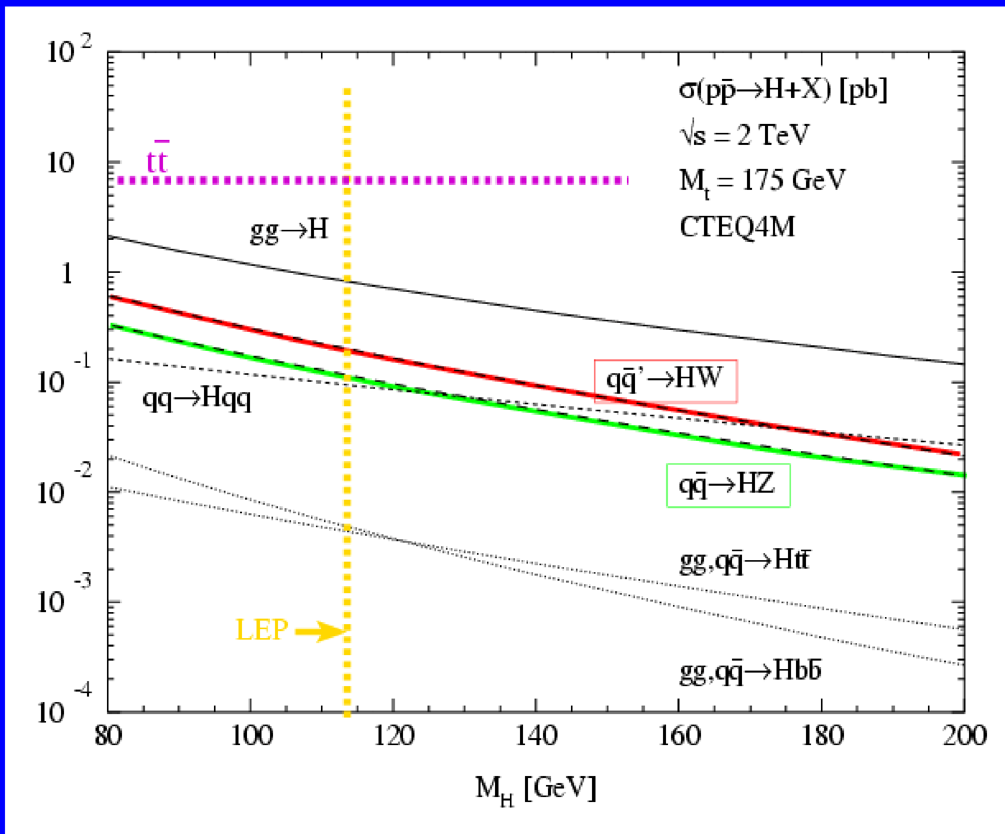


- 1.96 TeV p-p̄ collider
- 396 ns between bunches
- Has delivered ~2 fb^{-1} of data since 2002, and steadily accumulating more:
  - regularly see L > $2x10^{32}$ $cm^{-2}s^{-1}$
  - expect 6-8 fb^{-1} by 2009

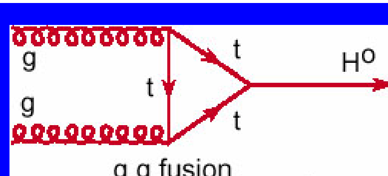
- 14 TeV p-p collisions
  - (c–v ~ 10 km/h !!)
- Expect to "turn on" 2008
- ~25 ns between proton bunches
- Low luminosity running (10^{33} $cm^{-2}s^{-1}$) to accumulate ~30 fb^{-1} by 2011
- Will eventually record ~100 fb^{-1} per year

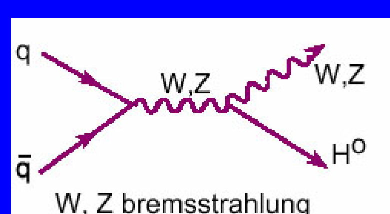
Higgs Production

Tevatron

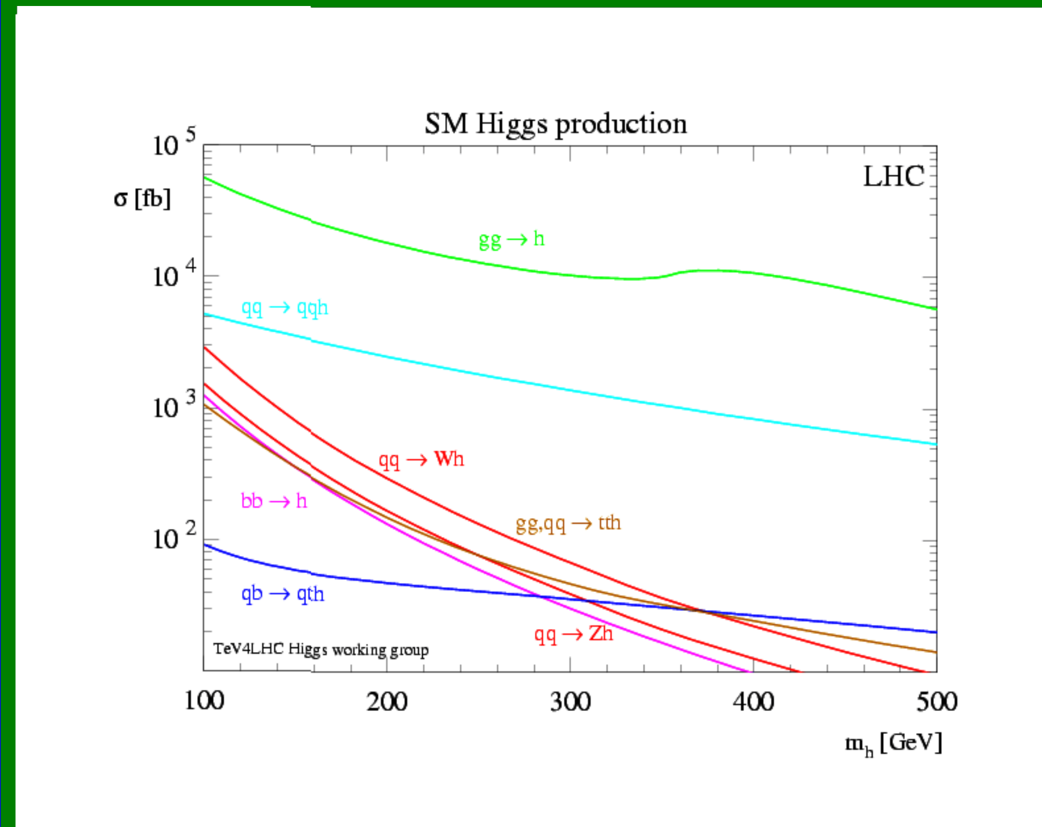


- Single Higgs production dominates
- Production in association with a vector boson order of magnitude less, but provides most sensitivity to low-mass searches

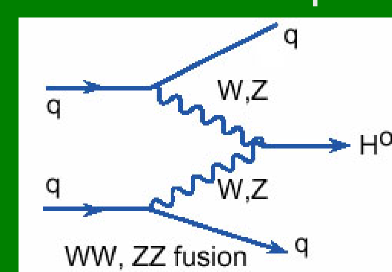




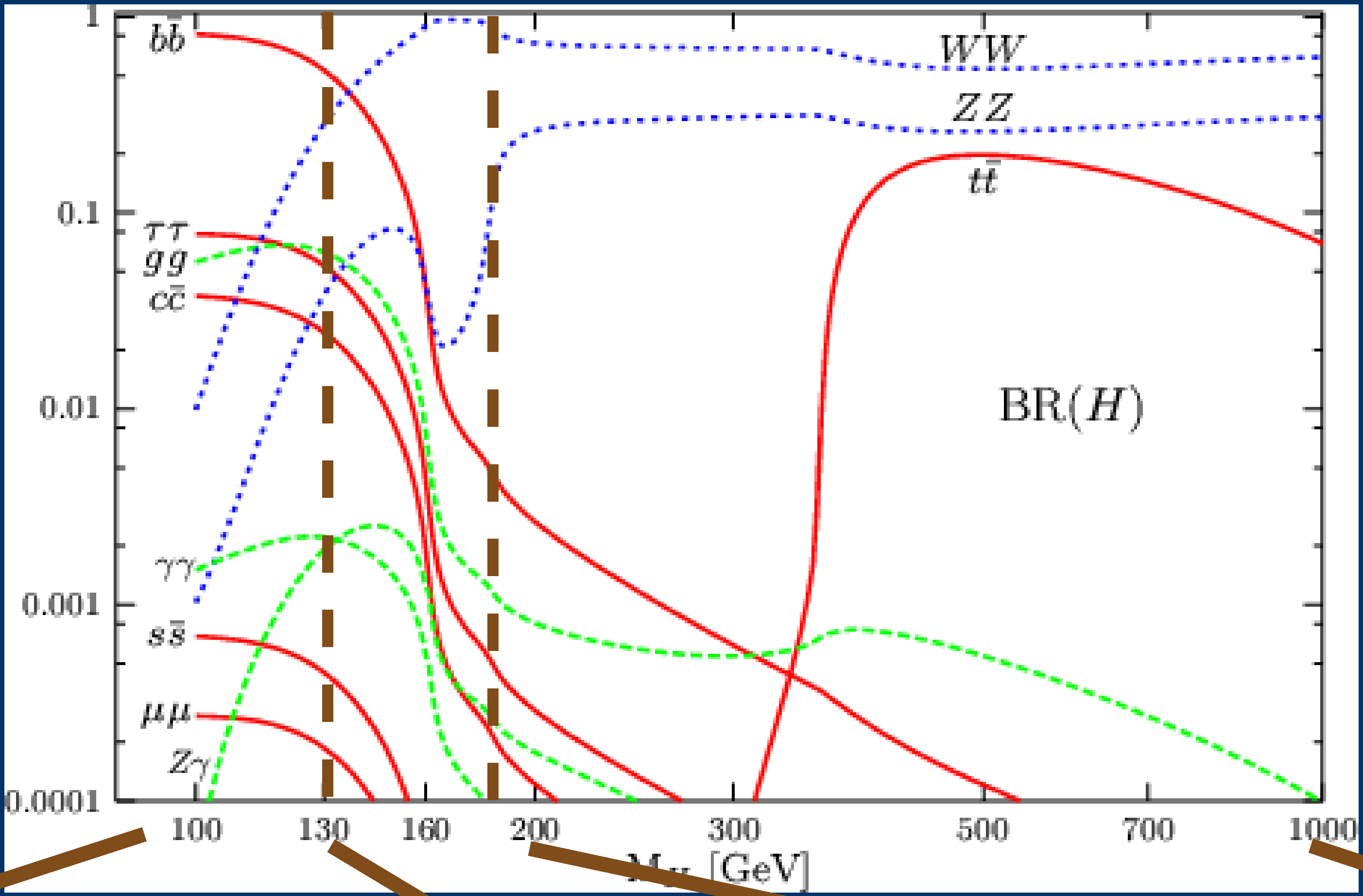
LHC



- gg→H two orders of magnitude greater
- qq→VH order of magnitude greater
- Vector boson fusion important



Higgs decay



$100 < M_H < 130$ | $130 < M_H < 180$ | $180 < M_H < 1000$

Light Higgs

- At the Tevatron, bb most important
  - Require VH production for sensitivity
  - Searches defined by vector boson decay
- At the LHC $\gamma\gamma$ most important

Intermediate Higgs

- Can exploit single Higgs production using WW* decay
- At the LHC ZZ* also important

Heavy Higgs

- No sensitivity at the Tevatron
- Dibosons dominate, with tt significant at >400 GeV

The perspective of numbers

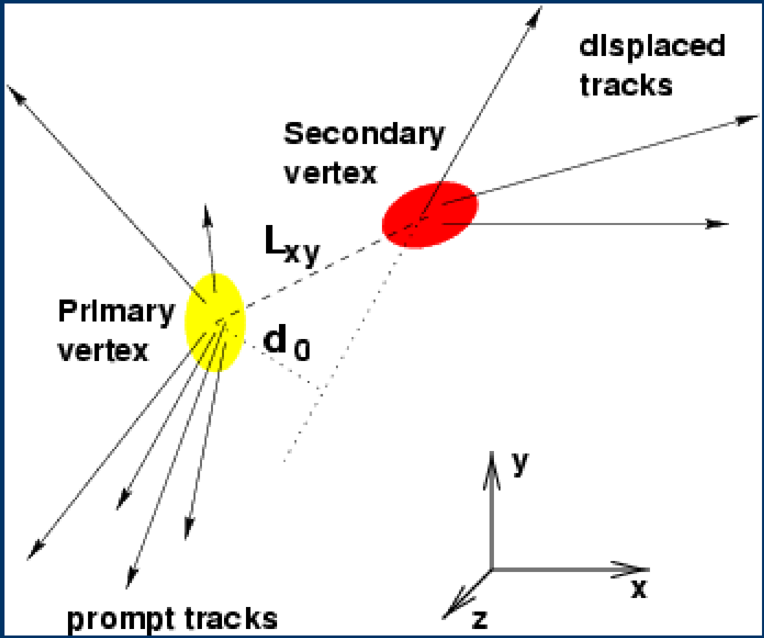
In 5 fb^{-1} of integrated luminosity:

TeV		LHC
	$M_H = 120$ GeV	
800 events produced	$qq \rightarrow WH$	9000 events produced
3500 events produced	$gg \rightarrow H$	200 000 events produced
	BR + trigger	
50 events	$WH \rightarrow l\nu\, bb$	600 events
2 events	$H \rightarrow \gamma\gamma$	200 events
	$M_H = 160$ GeV	
1500 events produced	$gg \rightarrow H$	140 000 events produced
	BR + trigger	
20 events	$H \rightarrow WW \rightarrow l\, \nu\, l\, \nu$	2000 events

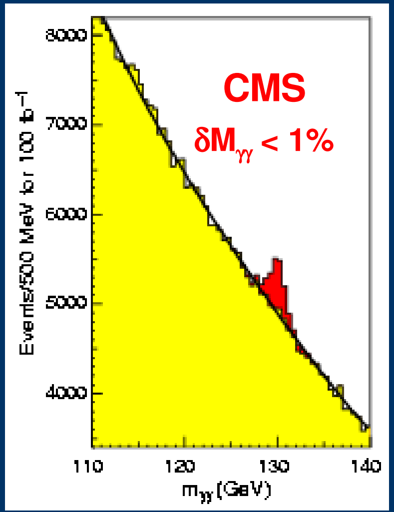
Then, event selection will further reduce signal with still more work needed to discriminate from the large backgrounds

Backgrounds for light Higgs

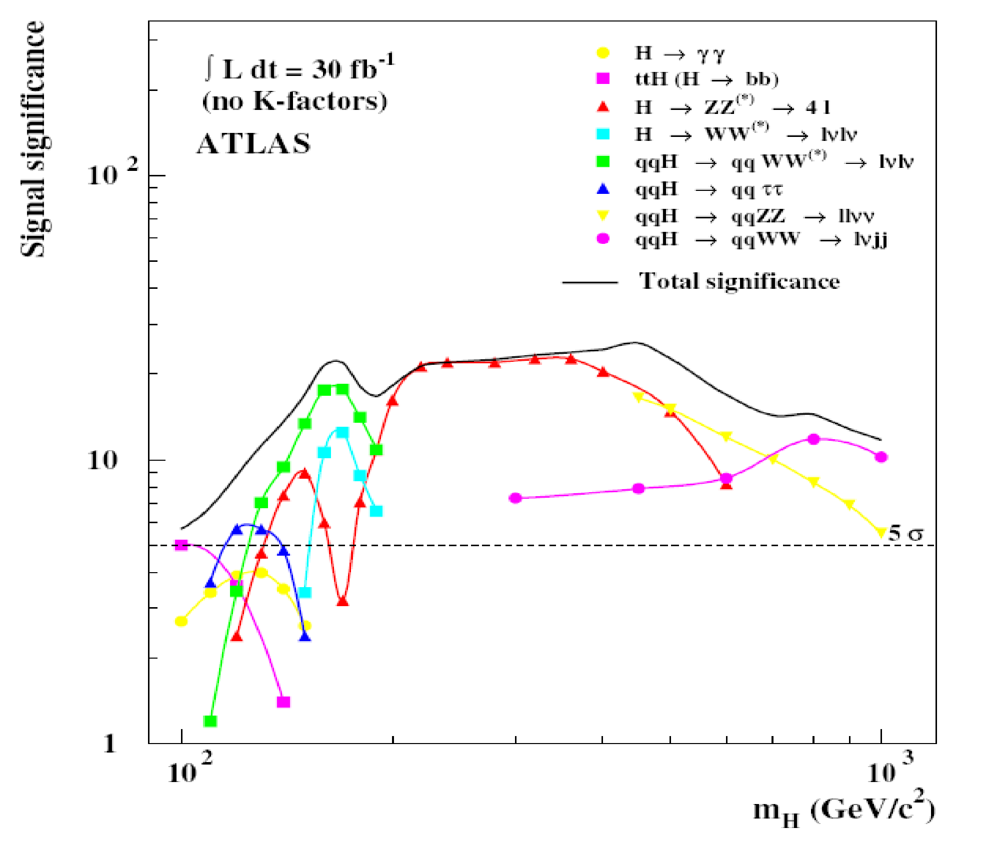
- For low-mass searches at the Tevatron crucial to "tag" jets from b's to reduce the huge V+jets background
  - Most powerful method is to measure secondary vertices from B decay
  - Efficiency to tag at least one b-jet ~60%
  - False tag rate ~0.5%
  - Reduces backgrounds by at least an order of magnitude
  - Relies heavily on Si detector performance
  - Other algorithms also exist (e.g. SLT)
  - Development of NN b-taggers could be important for Higgs discovery

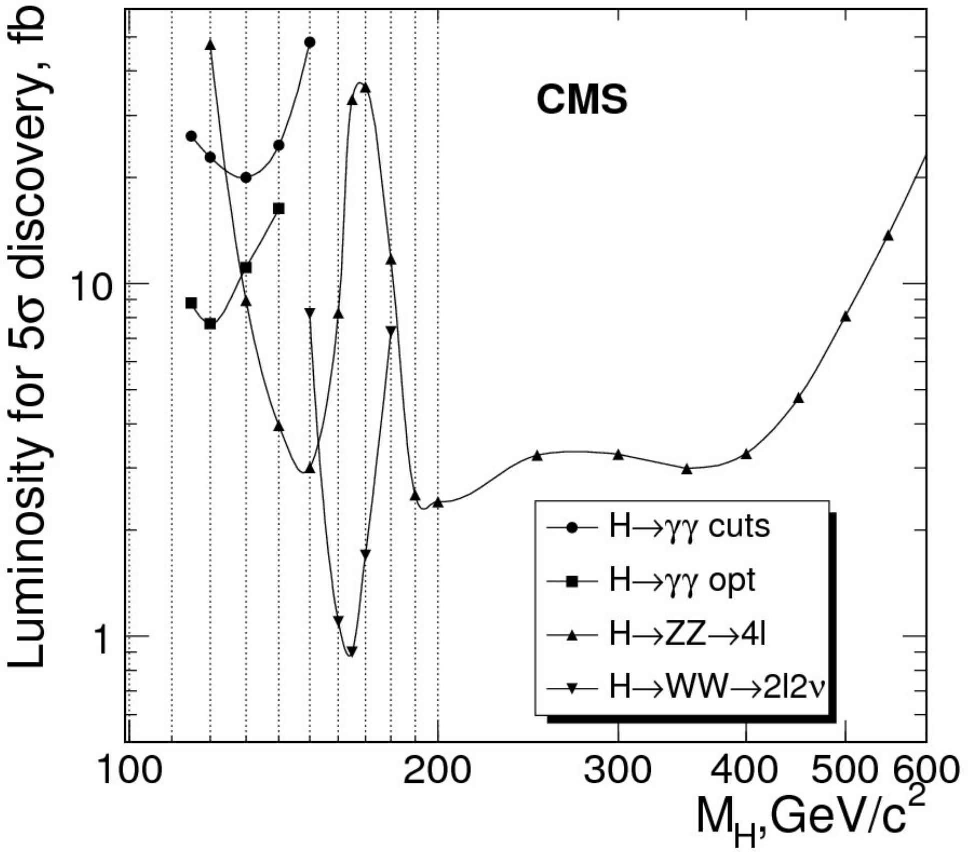


- At the LHC making any use of $H \rightarrow bb$ extremely difficult
  - $H \rightarrow \gamma\gamma$ most sensitive channel for light Higgs
  - Major background from prompt γ's, but $M_{\gamma\gamma}$ narrow



Higgs discovery at the LHC

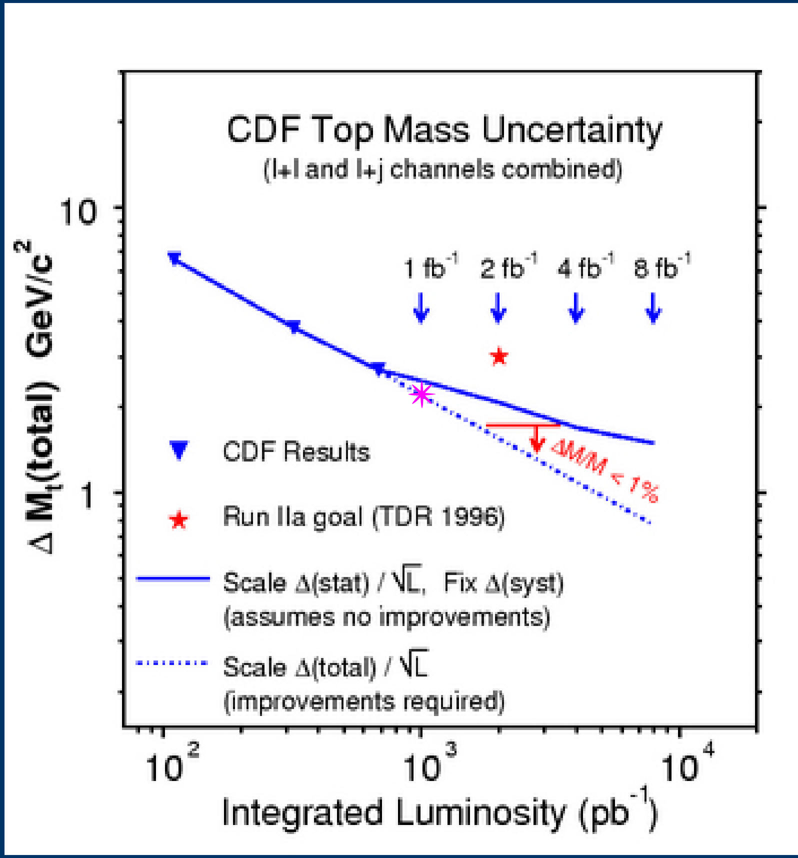




- Expect:
  - With ~1 fb^{-1} (in first few months of running):
    - discovery if Higgs mass around 160 GeV
  - With ~10 fb^{-1} (after 1-2 years):
    - discovery or exclusion of SM Higgs over entire mass range
- A light Higgs makes discovery tougher at the LHC

Can the Tevatron Tortoise beat the LHC hare ?

- An important reminder:
  - With dedication and ingenuity we can surpass our expectations
  - A recent example is the top mass



Where we are now:

✳ CDF combined: 170.5 ± 2.2 GeV
CDF+D0 : 170.9 ± 1.8 GeV

The road to Higgs at the Tevatron requires:

Standard Model Higgs search channels

Production	Decay		Relative BR	N_{prod} in 2fb^{-1} (M_H)
$qq \to VH$	$H \to b\bar{b}$	$W \to (e/\mu)\nu$	14%	50 (120 GeV)
		$W \to \tau\nu$	7%	25
		$W \to qq$	41%	145
		$Z \to ee/\mu\mu$	3%	10
		$Z \to \tau\tau$	1.5%	5
		$Z \to \nu\nu$	8%	28
		$Z \to qq$	26%	92
$qq \to VH$	$H \to WW \to \ell\nu\ell\nu$	$W \to \ell\nu$	20%	4 (160 GeV)
		$W \to qq$	41%	7
		$Z \to \ell\ell$	4%	0.7
		$Z \to \nu\nu$	8%	1.5
		$Z \to qq$	27%	5
$gg \to H$	$H \to WW$	$WW \to ee/\mu\mu/e\mu\,\nu\nu$	5%	27 (160 GeV)
		$WW \to e\tau/\mu\tau/\tau\tau\,\nu\nu$	6%	33
		$WW \to (e/\mu)\nu\,qq$	30%	160
$gg \to H$	$H \to b\bar{b}$			950 (120 GeV)
$gg \to H$	$H \to \tau\tau$	At least one $\tau \to \ell\nu\nu$	58%	56 (120 GeV)
Rare SM production/decays				
$qq \to b\bar{b}H$	$H \to b\bar{b}$			
	$H \to WW$			
$qq \to t\bar{t}H$	$H \to b\bar{b}$			
$gg \to H$	$H \to ZZ$	$ZZ \to \ell\ell\ell\ell$		
		$ZZ \to \ell\ell\nu\nu$		
		$ZZ \to \ell\ell qq$		
$qq \to VH$	$H \to \tau\tau$	$V \to \ell\ell/\nu\nu/\ell\nu$		
$gg \to H$	$H \to \gamma\gamma$			
$qq \to VH$	$H \to \gamma\gamma$	$V \to \ell\ell/\nu\nu/\ell\nu$		
$gg \to H$	$H \to Z\Upsilon$			
$gg \to H$	$H \to ZJ/\psi$			

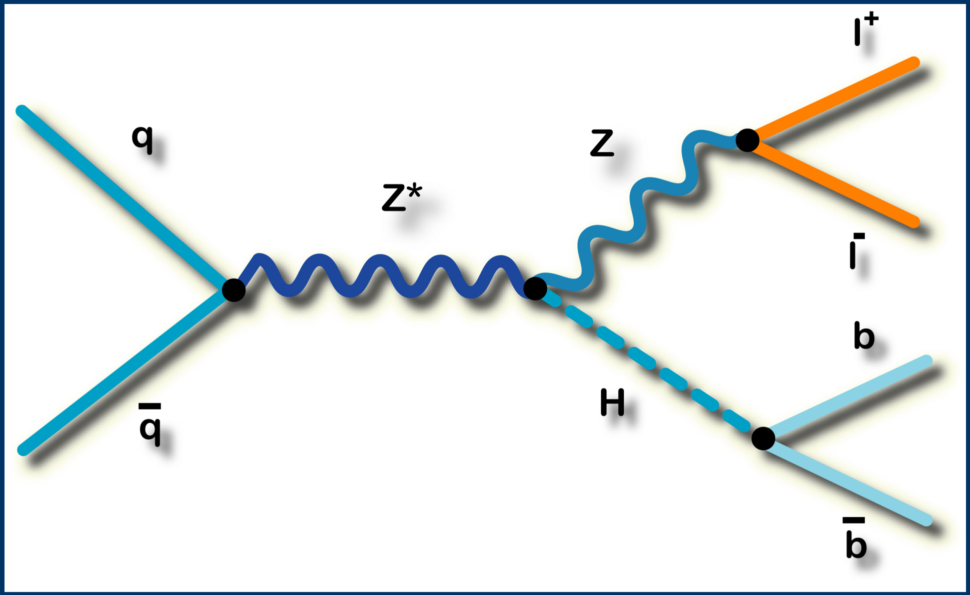
- Covering all bases
- Improved triggers
  - displaced tracks
  - missing energy triggers
- Improved b-tagging
  - progress on NN b-taggers now quite advanced
  - forward b-tagging
- Improved lepton ID
  - Inclusion of taus
  - filling the “gaps”
- Improved Jet energy resolution
- Advanced analysis techniques
  - NN's, ME techniques, others
  - combining channels, expts

Many of these efforts still relatively young

- expect vast improvements in current analyses

Examples of recent Tevatron analyses exploiting new strategies

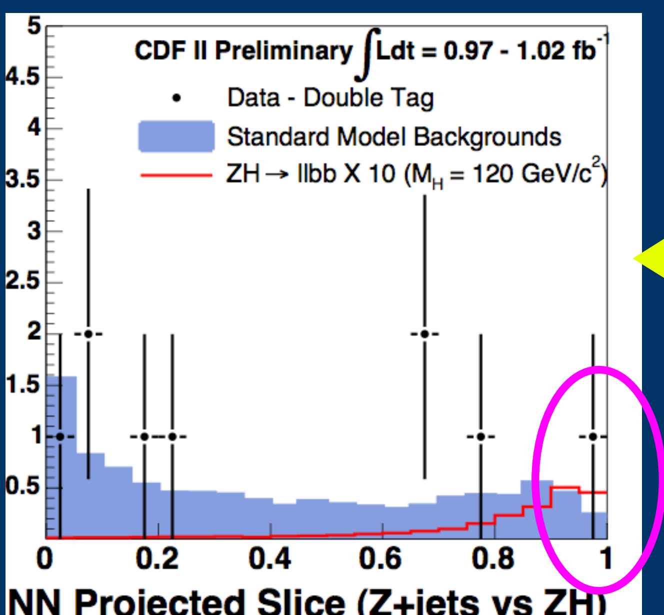
❶ ZH $\rightarrow l\, l$ bb



- Signature:
  - 2 high-P_T leptons consistent with originating from a Z decay
  - 2 high-E_T jets, at least one of which is tagged as originating from a b-quark
  - No missing E_T
- Main backgrounds:
  - 85% Z + jets
  - 8% t-tbar

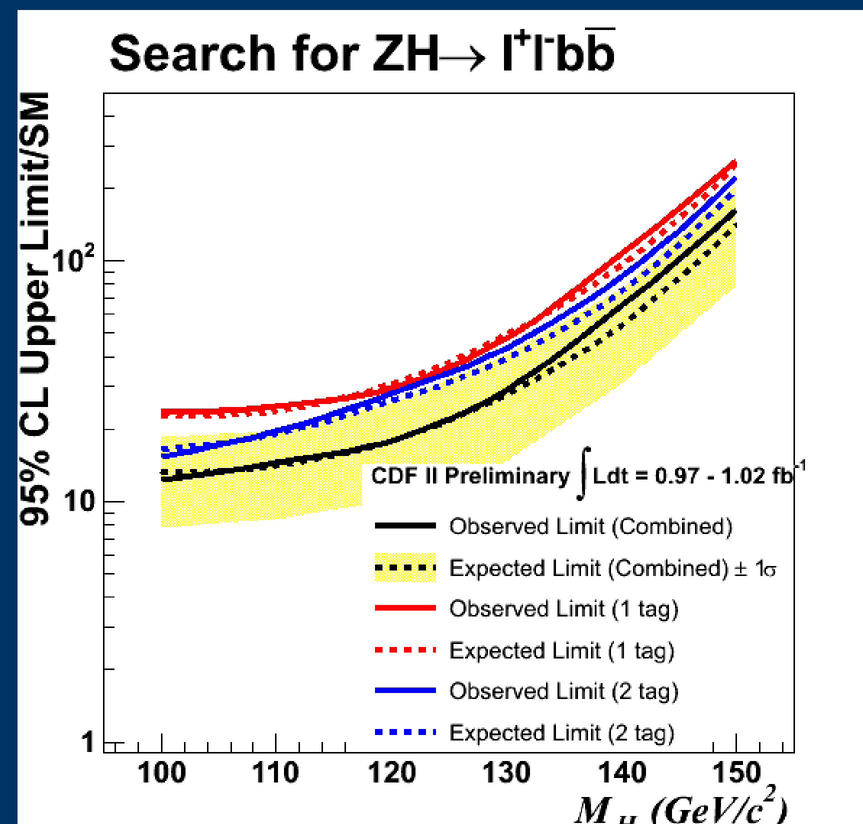
$ZH \rightarrow l\,l\,bb$ (CDF)

- Data sample: 1 fb^{-1}
  - 5 events produced → 1 after selection
  - Signal / Background ~ 100
- Compared to original analysis of fitting the dijet mass spectrum:
  - 2D NN ≡ 250% more data
  - Improved jet corrections based on missing-E_T projection ≡ 30% more data
  - b-tagging optimization ≡ 50% more data
  - Looser lepton ID ≡ 60% more data
  - Total improvement ≡ ~7 times more data
- Limits comparable to the current WH→ lνbb and ZH→ ννbb analyses

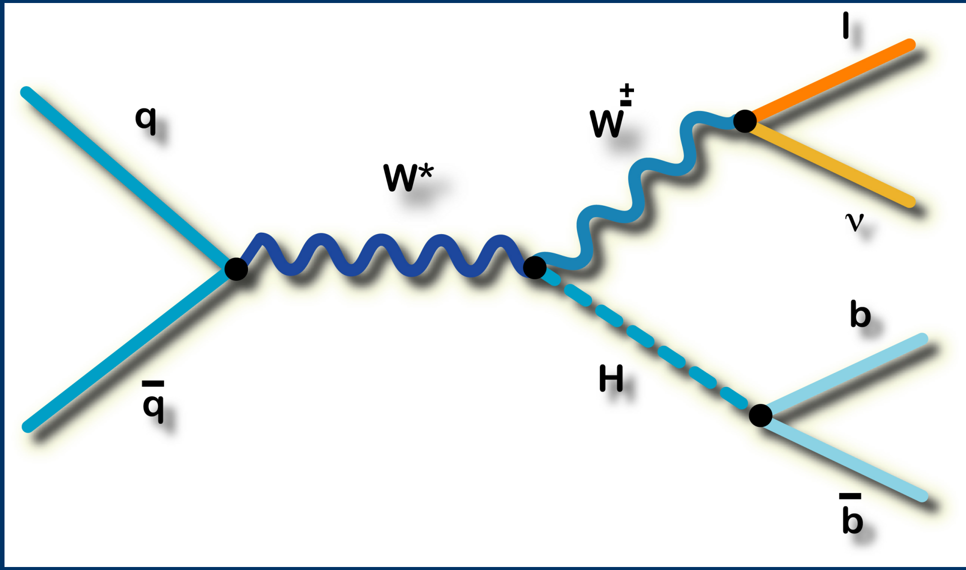


Z+jets slice

S/B ~ 1/4



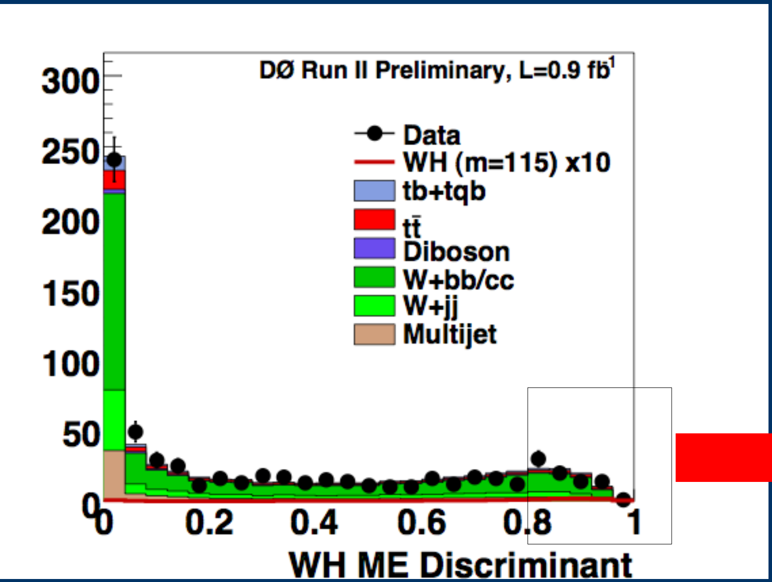
❷ WH → $l\,\nu$ bb



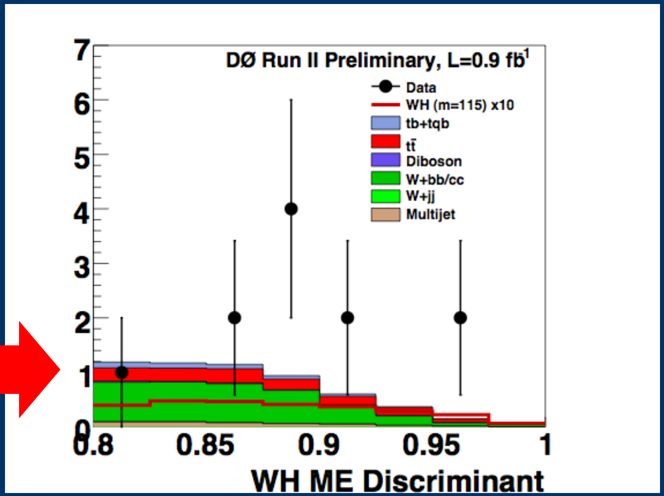
- Signature:
  - 1 high-P_T lepton
  - Large missing E_T
  - 2 high-E_T jets, at least one of which is tagged as originating from a b-quark
- Main backgrounds:
  - 60% W + jets
  - t-tbar, single top

WH → $l\nu$ bb (D0)

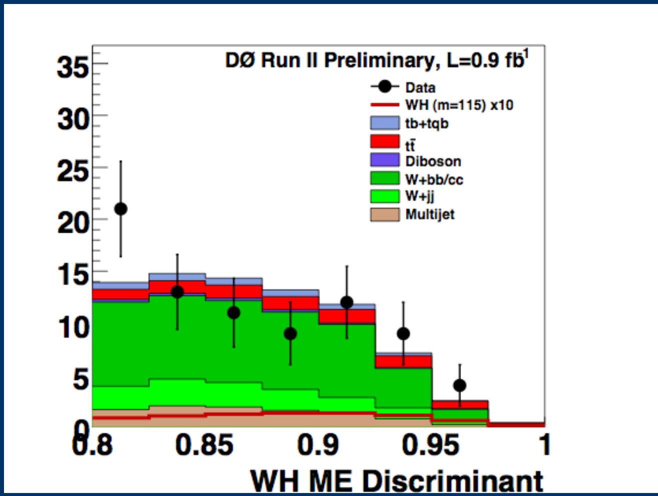
- Matrix-element approach used from D0's single top evidence analysis



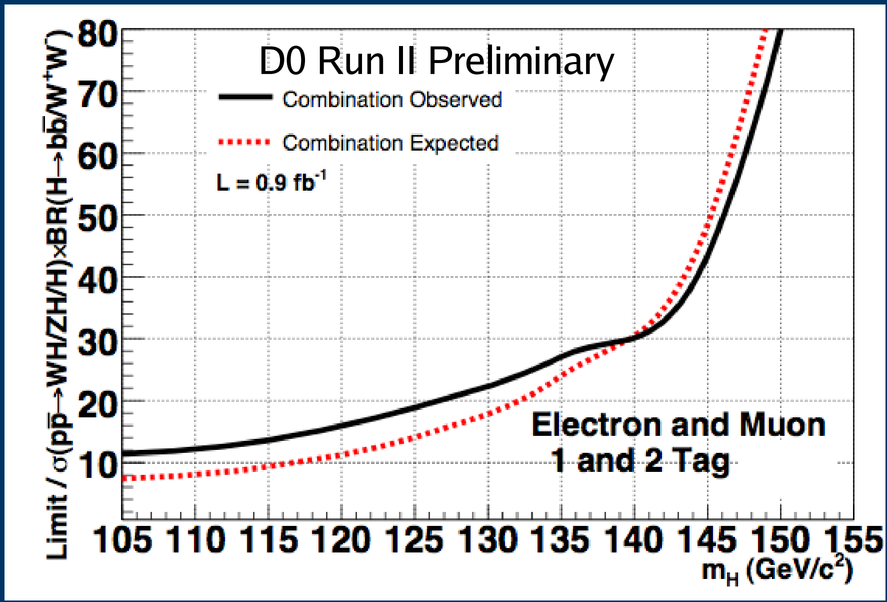
single-tag



double-tag

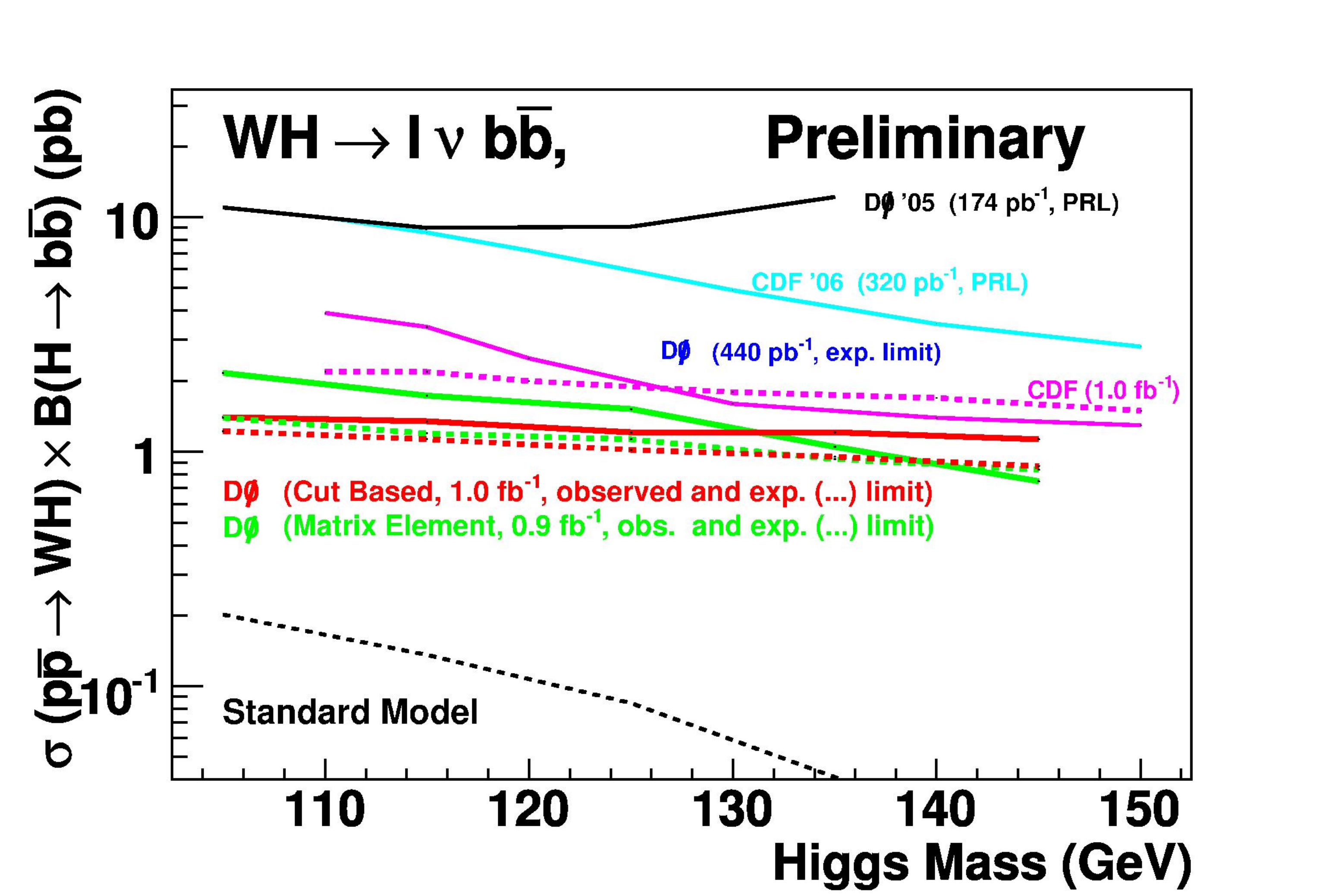


- Not yet using full muon acceptance
- B-tagging still optimized for single top
- Expect 30% better limit than the more traditional dijet mass fit

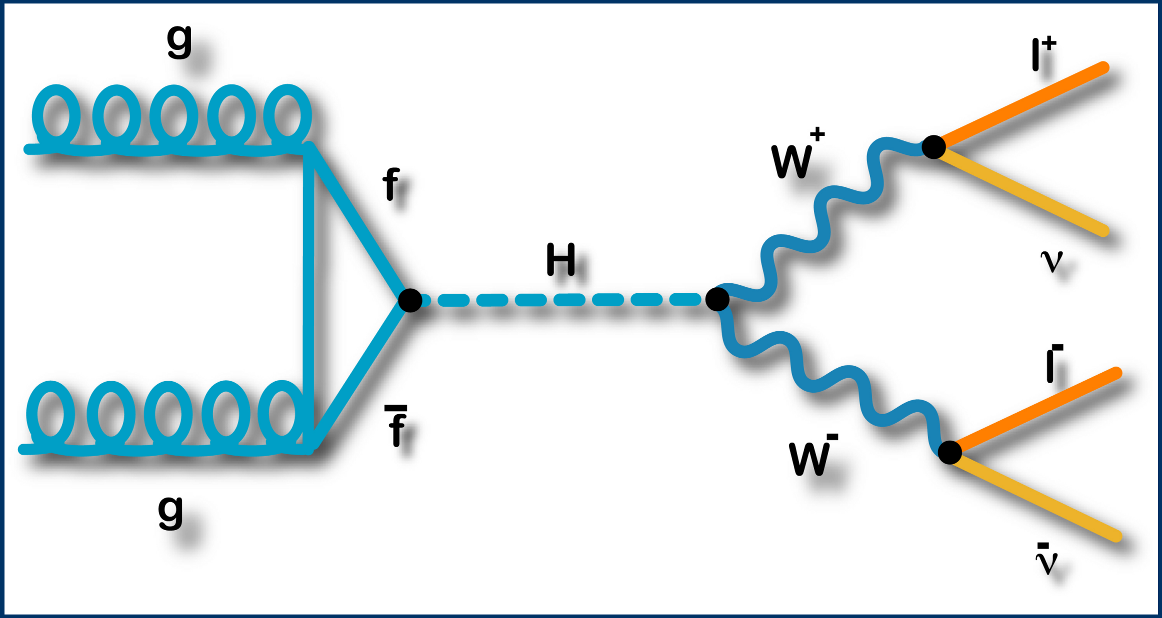


WH $\to l \nu$ bb should be the most sensitive low-mass channel at the Tevatron

- many analyses, but still a long way to go
- CDF/D0 combination crucial



❸ $H \rightarrow WW^* \rightarrow l\,\nu\,l\,\nu$

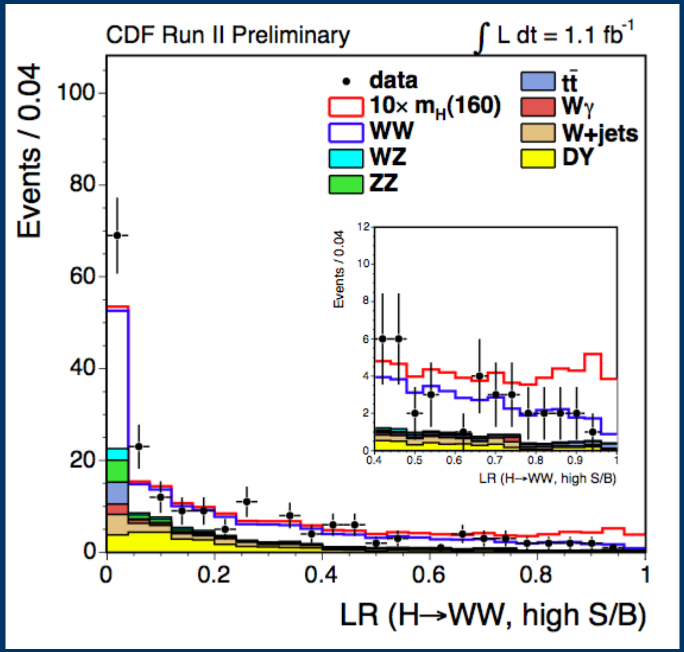


- Signature:
  - 2 high-P_T leptons
  - Large missing E_T

- Main backgrounds:
  - 50% WW
  - 30% Drell-Yan

$H \to WW^* \to l\nu l\nu$ (CDF)

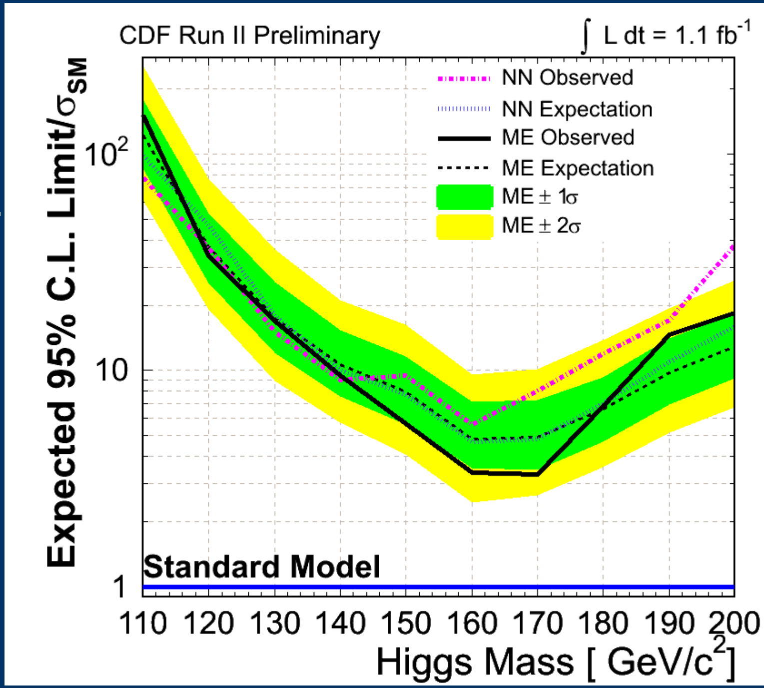
- Matrix-element technique
- Also uses increased lepton acceptance borrowed from CDF's WZ discovery analysis
  - Increases signal acceptance by ~70%
  - Expect ~4 signal events at M_H=160 in 1 fb^{-1}
- Significant gains over previous cut-based analysis
- Observed (expected) limit < 3.5 (5) times SM



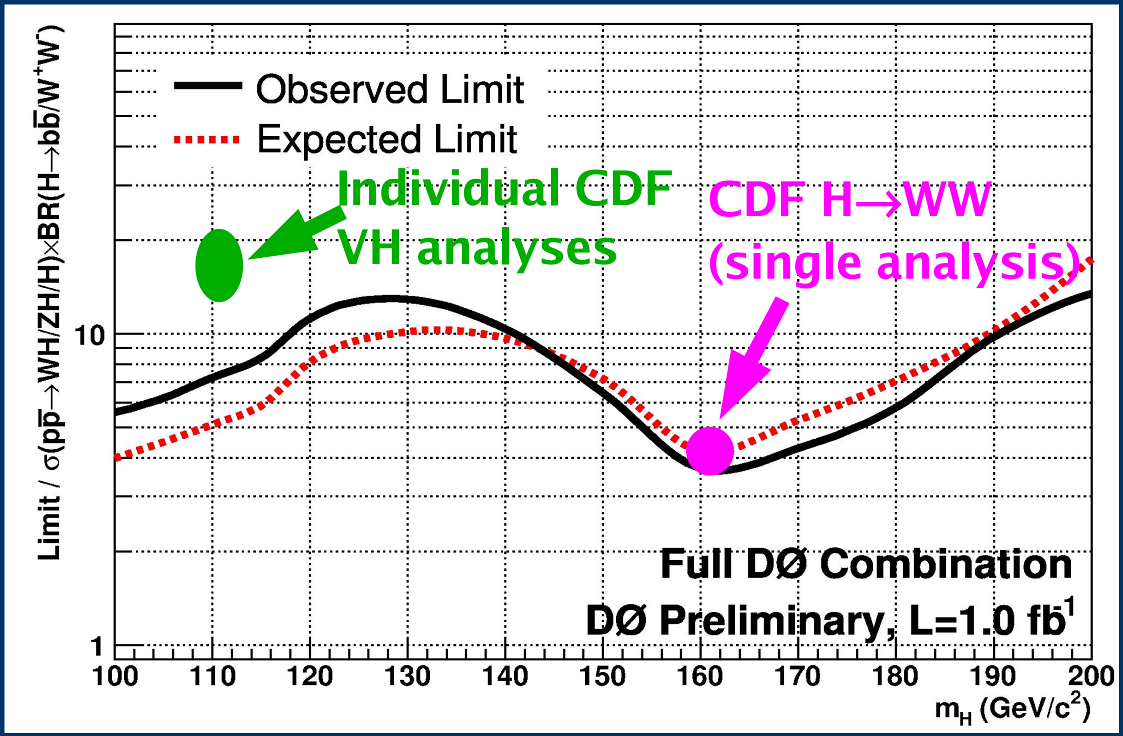
$$LR = \frac{P_{Higgs}(M_H)}{P_{Higgs}(M_H) + \sum_i f_{\mathrm{bkg,i}} P_{\mathrm{bkg,i}}}$$

- But can still do better with same data:
- CDF has a new NN analysis with very similar sensitivity but for different reasons, therefore, can benefit from combining these approaches – this is being done now

- The H→ WW* analyses are our most sensitive for a given mass, and are competitive with the VH analyses down to ~130 GeV



Status of Tevatron SM Higgs searches: 1 fb^{-1}



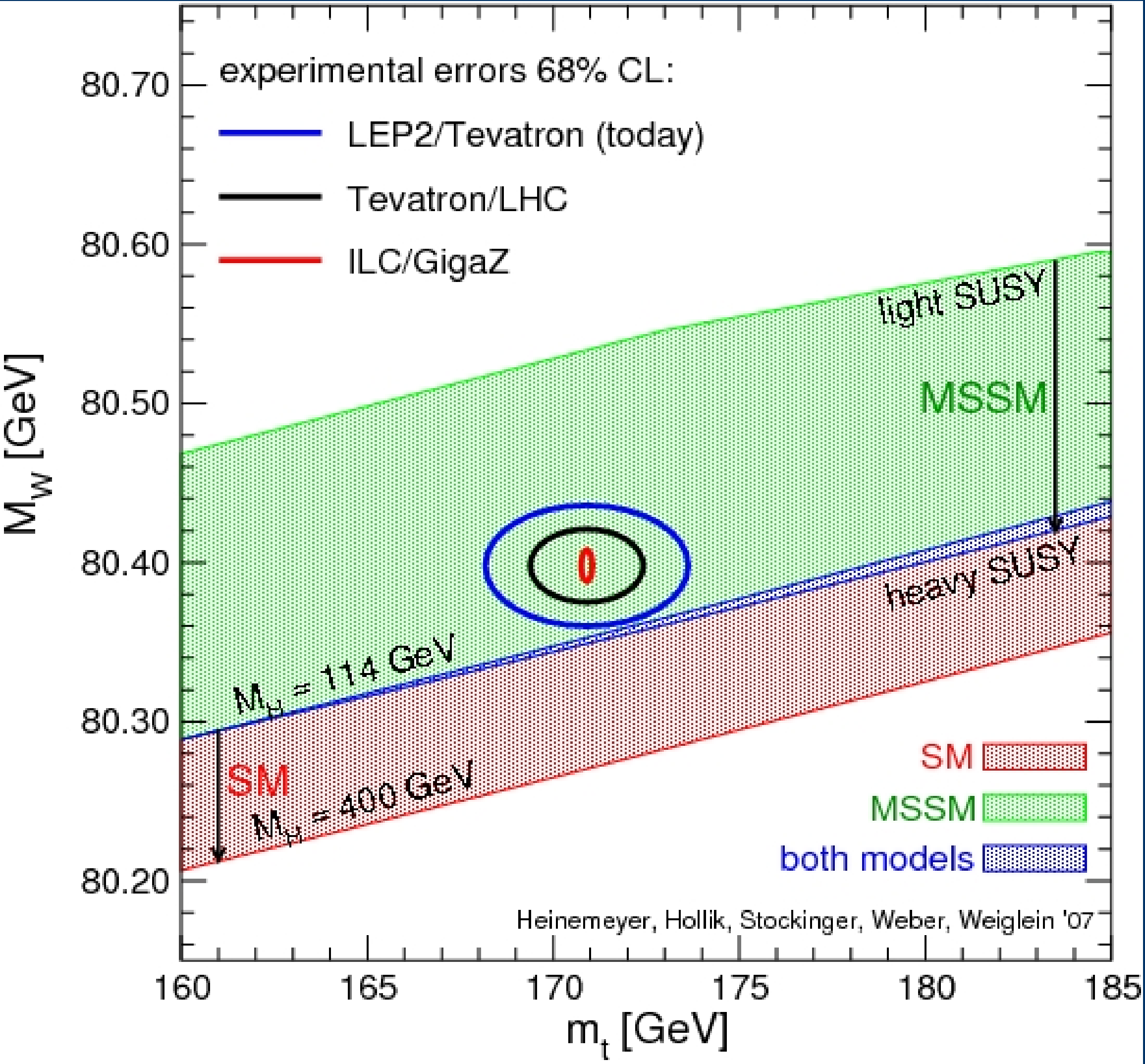
- CDF combination not yet ready
- *Some* improvements initiated for *some* analyses, but still a lot of work to do:
  - At M_H = 115 can expect CDF/D0 combination of current analyses to give limit/SM ~ 5 ⇒ ~25 times more data needed
  - At M_H = 160, limit/SM ~ 3 ⇒ ~10 times more data

- So significant improvements needed if Higgs is to be seen at the Tevatron with 6 -8 fb-1 – but these improvements are gaining momentum – looks like we'll be close !

What about SUSY ?

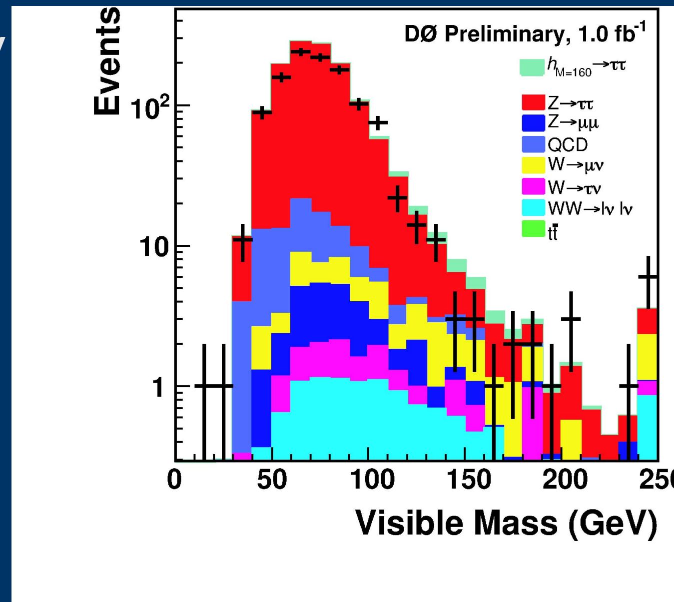
After all, as our top and W mass measurements get more precise, the MSSM sector is getting more and more favourable !

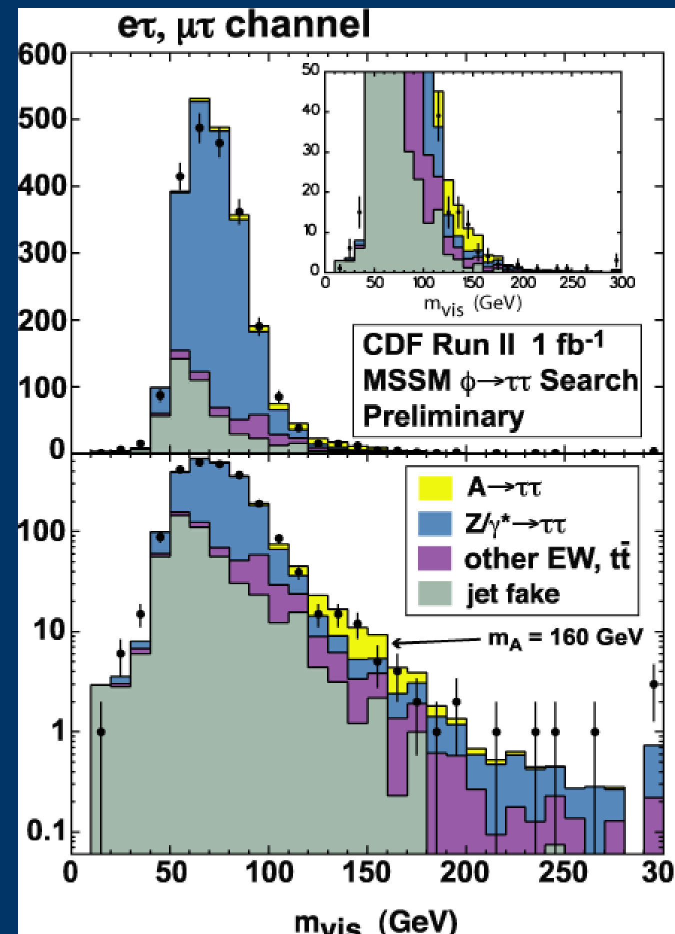
- In MSSM two Higgs doublets resulting in 5 Higgs's
- Coupling to down type quarks and leptons (such as b's and t's) enhanced for large tanβ and low m_A
- So, even though the channels $gg \rightarrow H \rightarrow \tau\tau$, bb do not provide significant sensitivity to SM Higgs searches they do in some MSSM scenarios

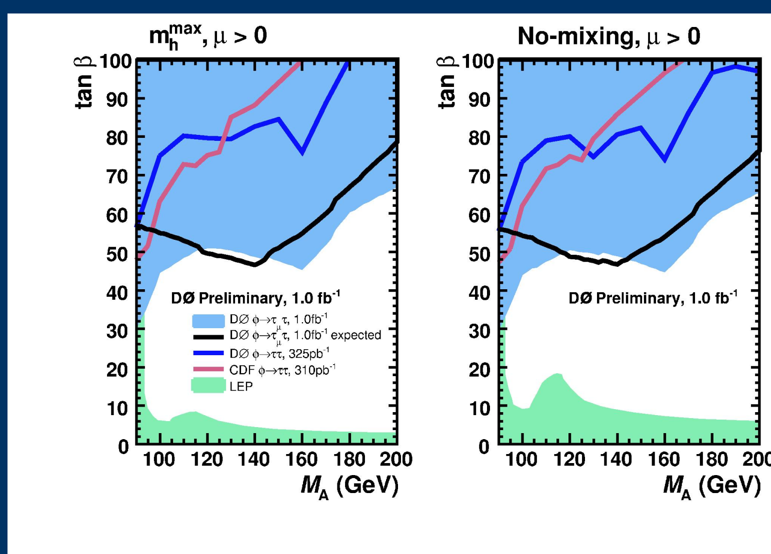


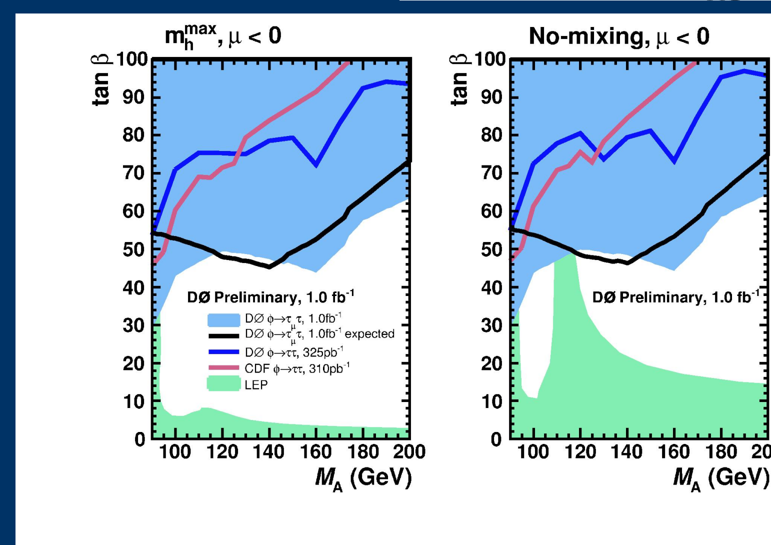
Search for $\phi \rightarrow \tau\tau$

- One τ required to decay leptonically
- Recontruct $M_{\tau\tau}$ using visible energy
- No significant excess seen $\rightarrow$ limits set in $\tan\beta - M_A$ plane for the no-mixing, and m_h^{max} benchmark scenarios



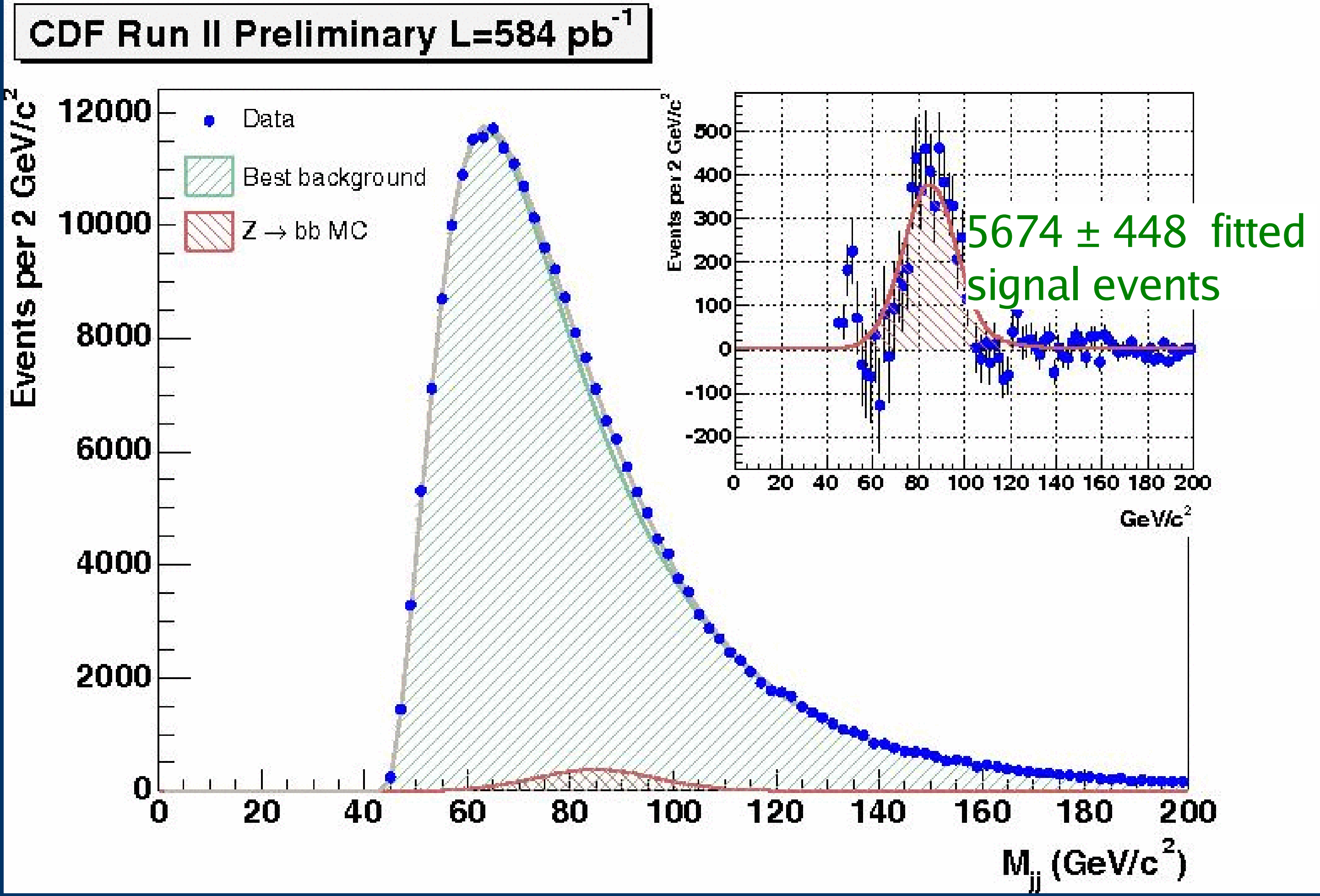






Search for H → bb

- Z → bb observed over a huge background spectrum
- At M_H = 120 would expect about 5 SM Higgs events in this spectrum (difficult to trigger on)

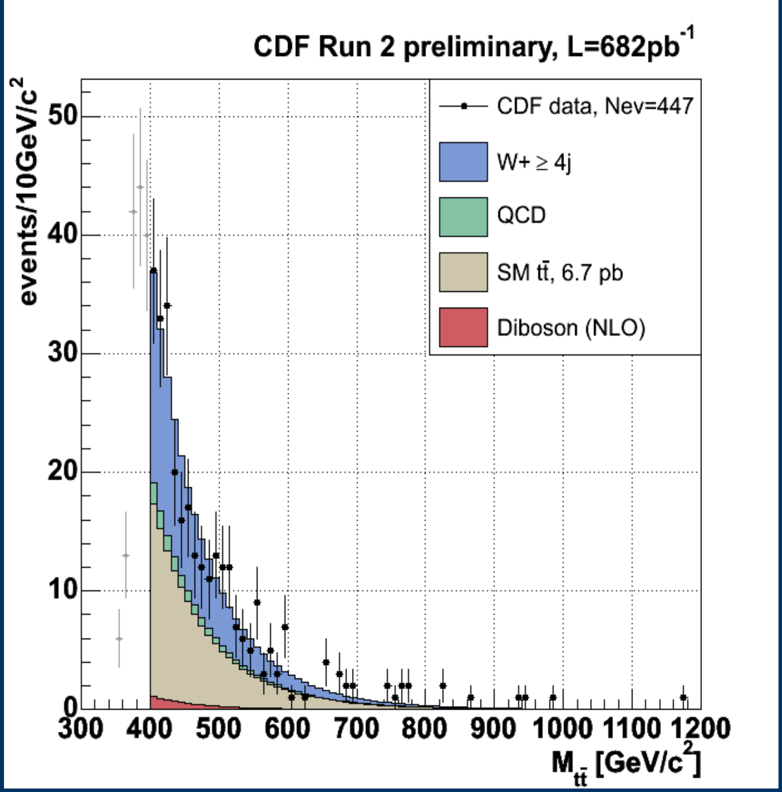


- Huge tan β enhancement required to see anything

- Searches for φ → bb use bbφ → 4b for greater sensitivity

Of course, all this is predicated on a Higgs existing: there are many other possibilities, some of which we are also looking for…

- More complicated SUSY variants
- Technicolor models
- Topcolor models ⇒ tt resonances
- "Little Higgs" models
- Higgs-less models

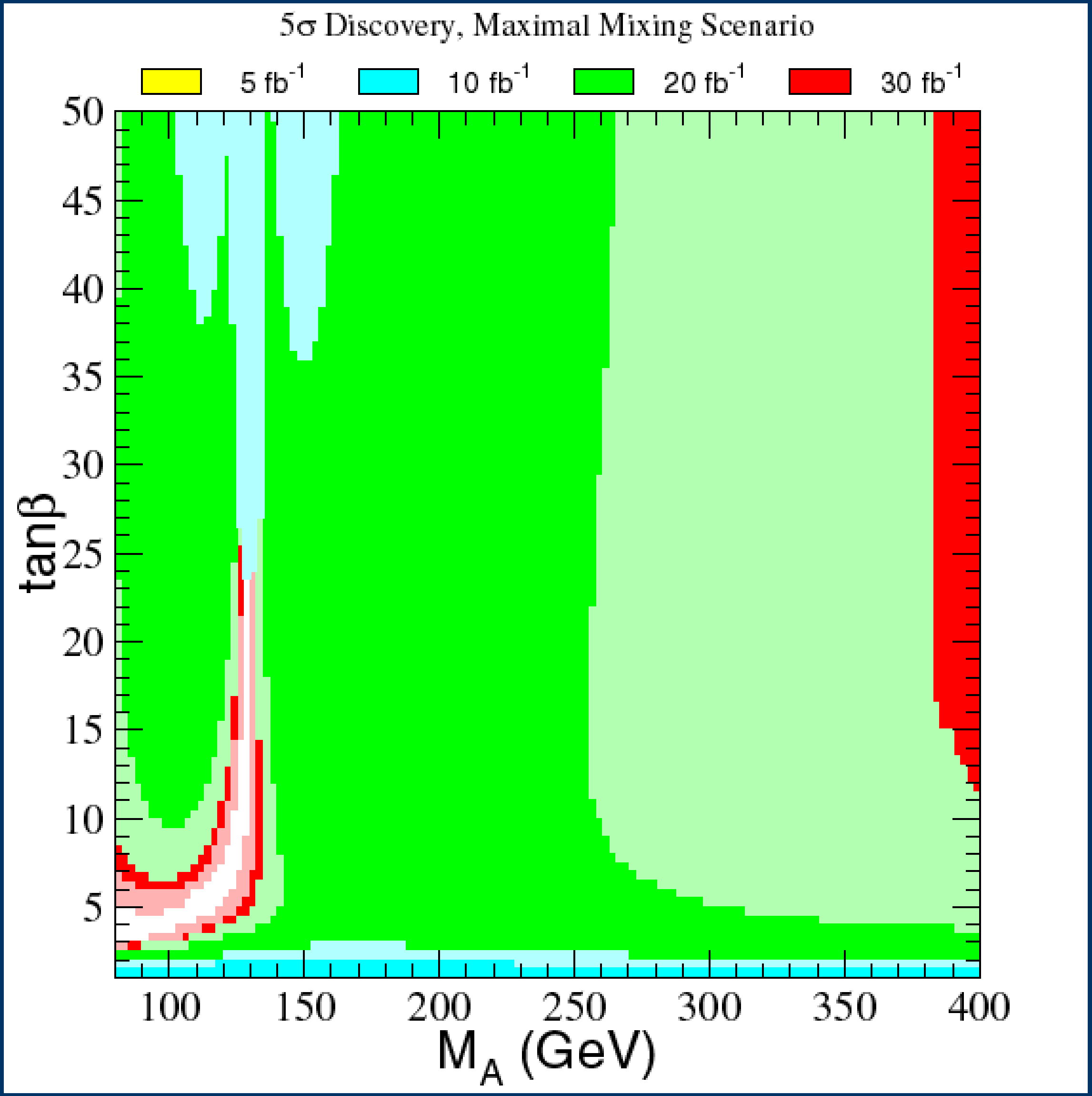


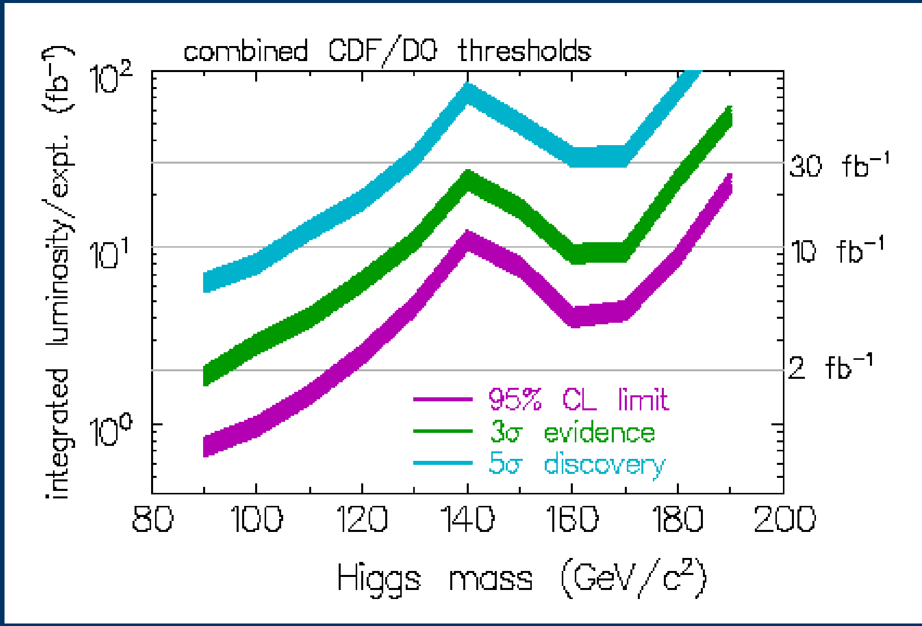
latest tt invariant mass spectrum from CDF

Closing remarks

- The excellent recent performance of the Tevatron has sparked the realisation that a Higgs might be seen before LHC, thus motivating a huge push by both experiments to optimize our sensitivity. Its discovery at the Tevatron will rely on:
  - Its existence !
  - More high quality data
  - Further development of advanced techniques and search strategies
- The LHC will open up a new era of discovery potential. If nothing is found at the Tevatron, the experience gained will still greatly benefit the LHC experiments
  - The tortoise (TeV) can help the hare (LHC) across the finish-line !

Backup slides





With 5 fb^{-1} expect to:

- exclude SM Higgs up to 130 GeV
- possibly achieve a 3σ result for m_H ~ 115-120 GeV