Closing in on the Higgs Boson

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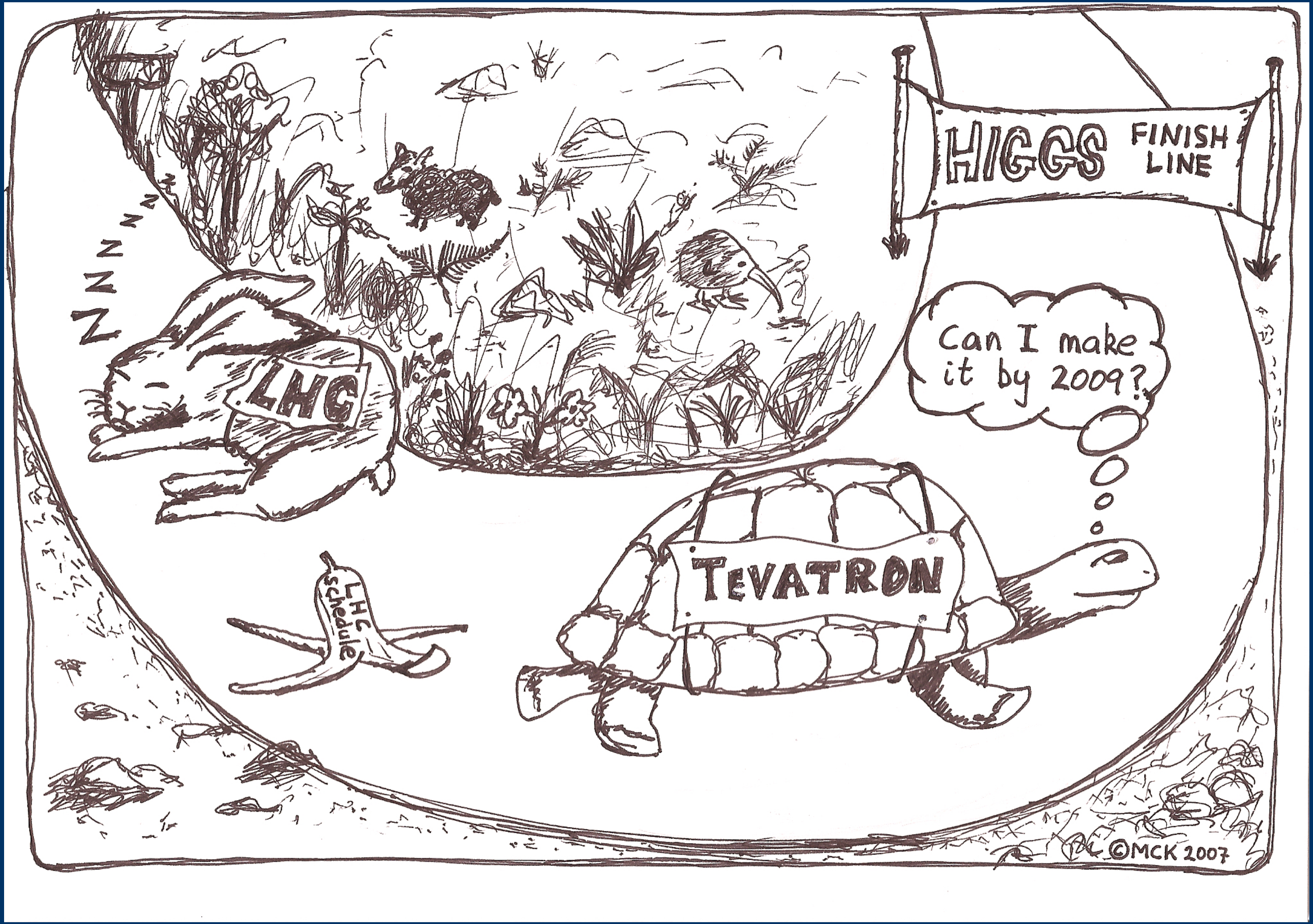
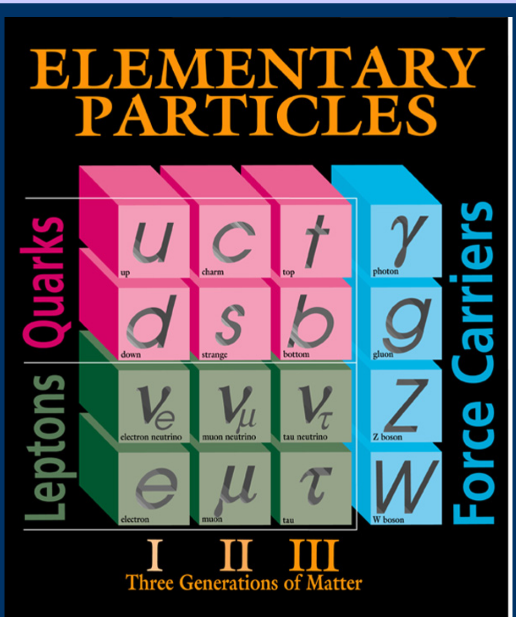
(Duke University, CDF and ATLAS collaborations)

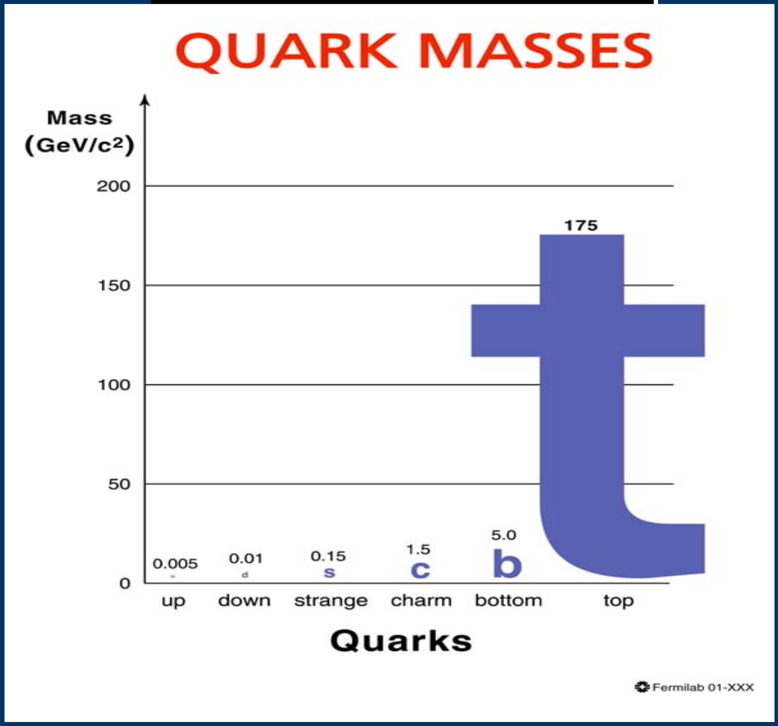
Lisboa, 2 October 2008



Some of the questions we should have a better understanding of in the next few years

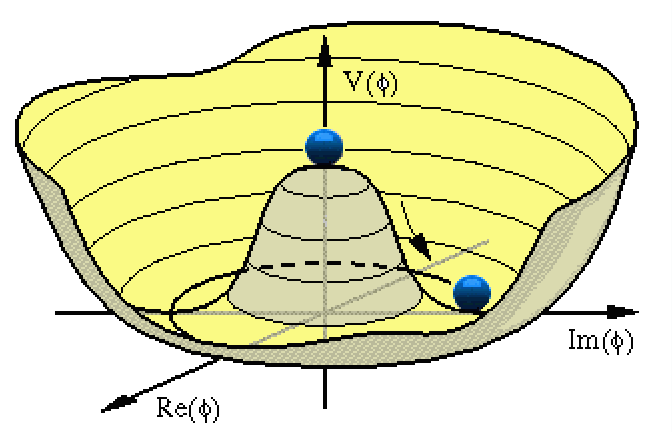
- What is the origin of mass, and the mechanism behind Electroweak Symmetry Breaking ?
  - Is there a Higgs ?
  - Other mechanisms ?
  - Why is the top quark so heavy ?
- What grander theory will supersede the "Standard Model" ?
  - Will any ?
  - Are there new symmetries ?
  - Are there extra dimensions ?
  - New strong dynamics (technicolor) ?
  - and, can we observe these scenarios?
- **The Tevatron is continuing towards answers leading up to the LHC era:**
  - Increasing W and top mass precision ⇒ constraining Higgs
  - Direct searches for Higgs (and a lot of other new physics) – starting to get interesting !





Why look for a Higgs Boson ?

- The electroweak gauge bosons are massive (M_W = 80 GeV, M_Z = 91 GeV)
  $\Rightarrow$ *somehow*, the electroweak symmetry is broken

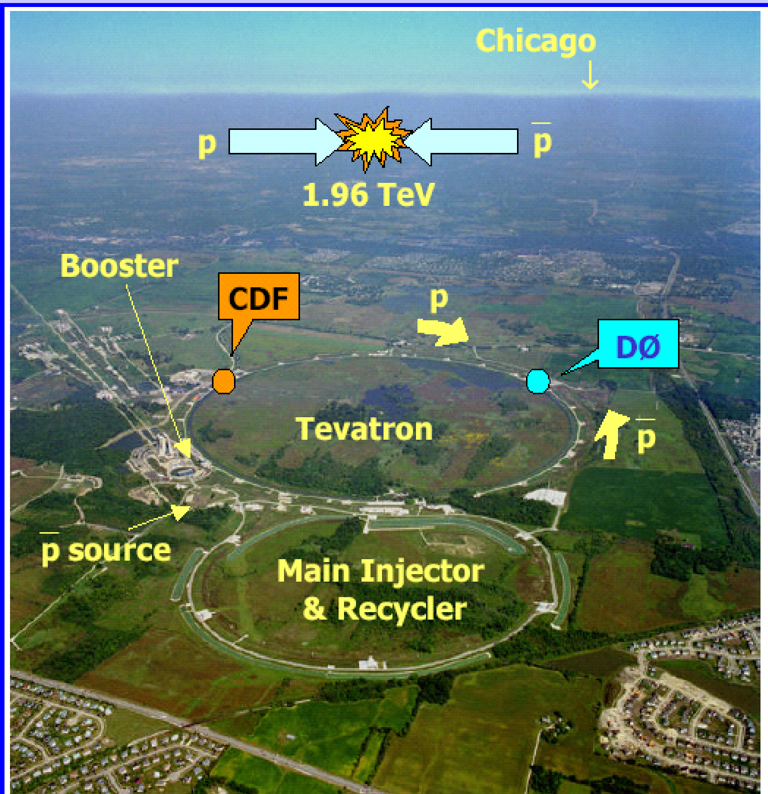


- The Standard Model postulates the breaking of the electroweak symmetry via the "Higgs Mechanism"
  - Endows the $W^\pm$ and Z^0 bosons with mass
  - There remains a massive spin-0 particle: **the Higgs boson**
  - Same mechanism can be used to generate lepton and quark masses
- In the Standard Model, the Higgs boson is the only undiscovered particle, making its discovery the most important goal currently in Particle Physics
- 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
  - However, there are good reasons to believe in alternative models, but the SM Higgs provides a stable target, and some more complicated models include something that's SM-like anyway

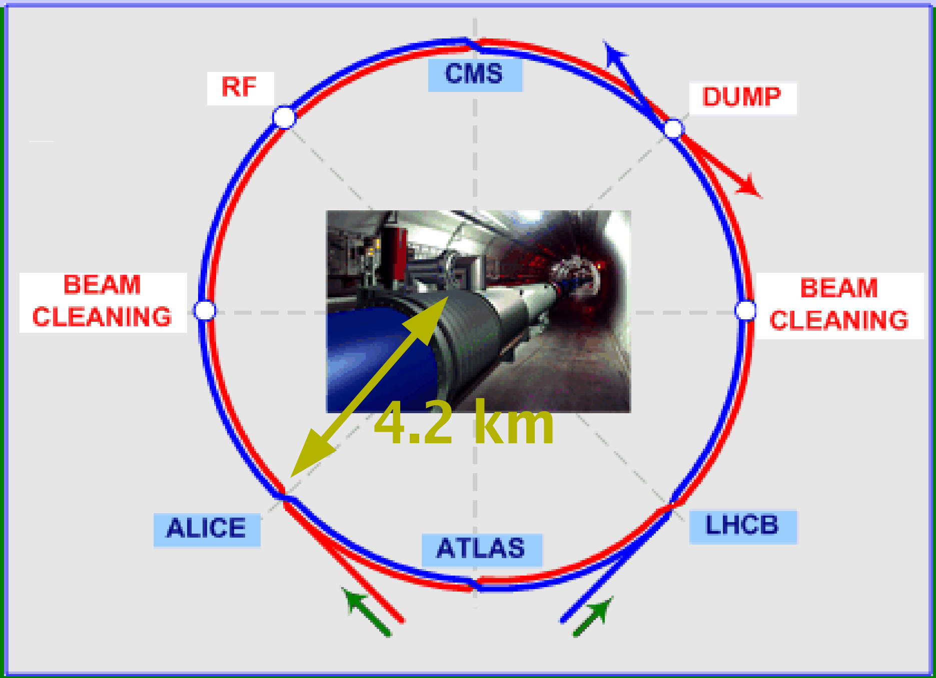
In this talk...

- Introduction to the Tevatron and Large Hadron Collider(LHC)
- Will concentrate on the SM Higgs
  - Introduction to Higgs production and decay
  - status and prospects at the Tevatron
    - Will focus on CDF results (1 – 2fb^{-1}), but D0 also achieve very similar sensitivity in all search channels, and we'll combine all Tevatron (CDF+D0) results in the end
  - prospects at the LHC
  - Will not give a detailed check-list of analyses but rather try to convey what is necessary for discovery
- Will say something about MSSM Higgs searches, and other models, time permitting
- Conclusions

Tevatron vs. LHC

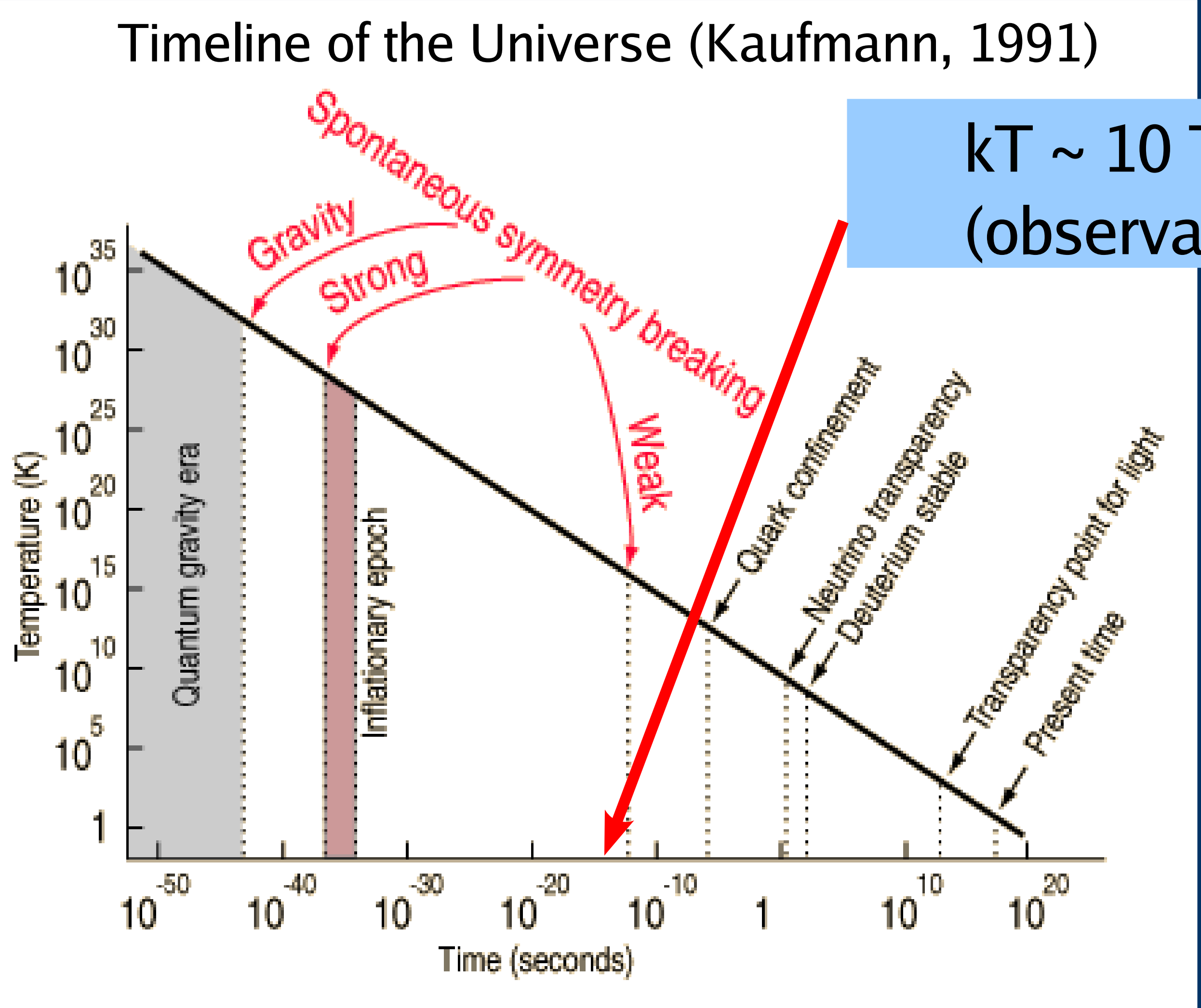


- 1.96 TeV p-p̄ collider
- 396 ns between bunches
- Has delivered ~3.5 fb^{-1} of data since 2002, and steadily accumulating more:
  - regularly see L > $2x10^{32}$ $cm^{-2}s^{-1}$
  - expect ~8-9 fb^{-1} by 2010



- 14 TeV p-p collisions
  - (c−v ~ 10 km/h !!)
- Expect collisions "soon" (hopefully!)
- ~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

So where does ~10 TeV get us ?



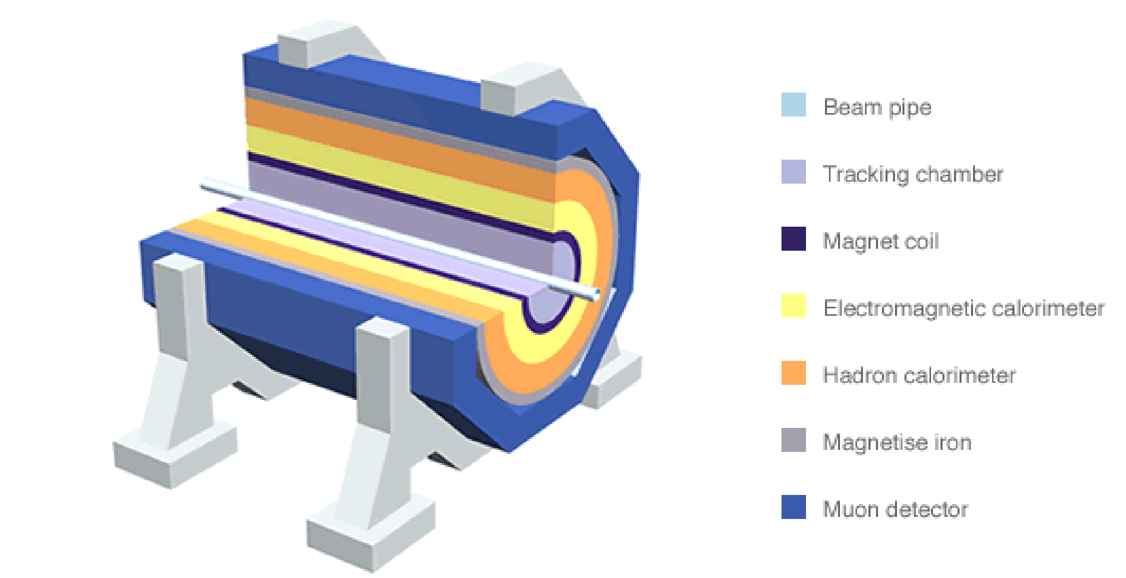
kT ~ 10 TeV $\rightarrow$ t ~ 10^{-14} s
(observable universe ~ 10 million km)

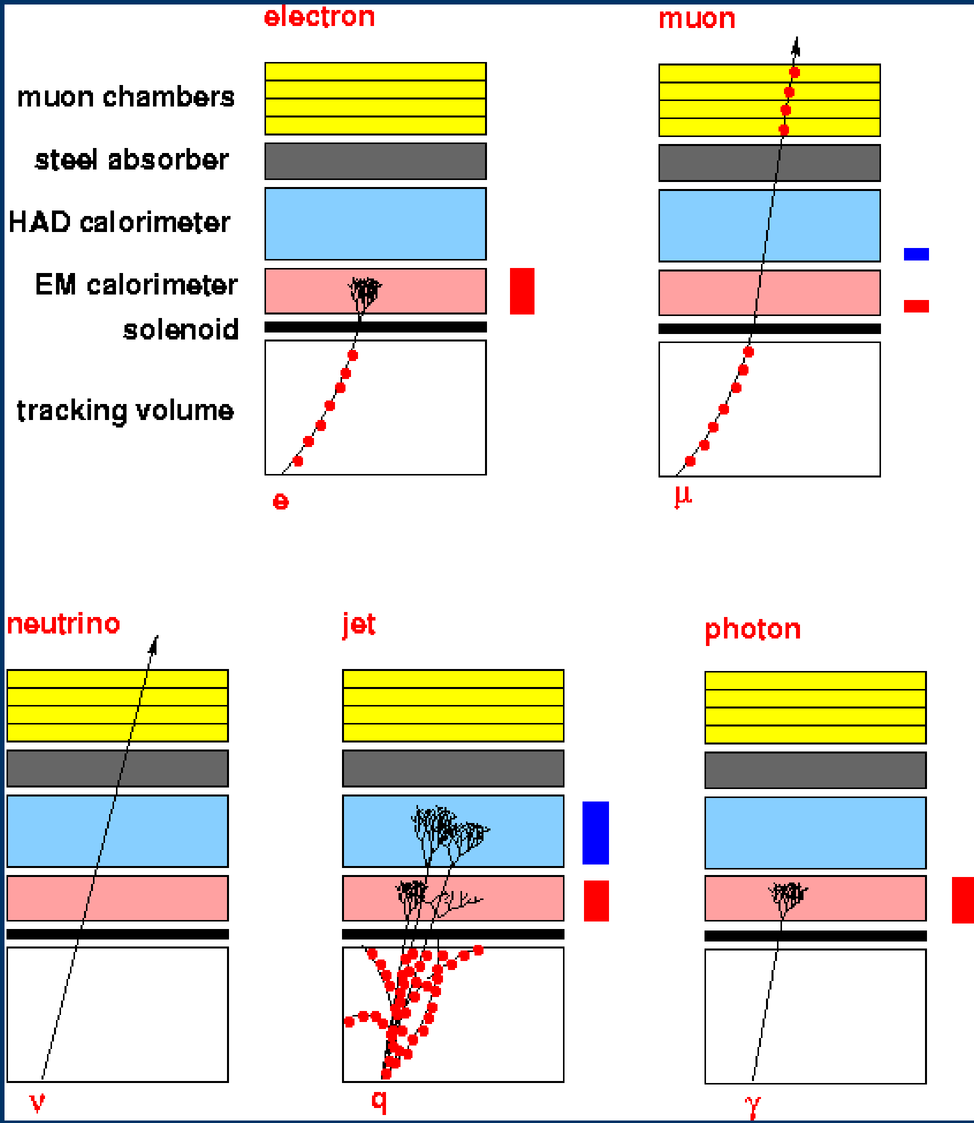
- Allows accessiblity to the energy scale of electroweak symmetry breaking
- compare with energy needed to explore the inflationary epoch...(and when the strong, EM, and weak forces were unified)

t ~ 10^{-32} s $\rightarrow$ kT ~ 10^{10} TeV !!
(observable universe ~ 4 m)

Detecting the results of high-energy collisions

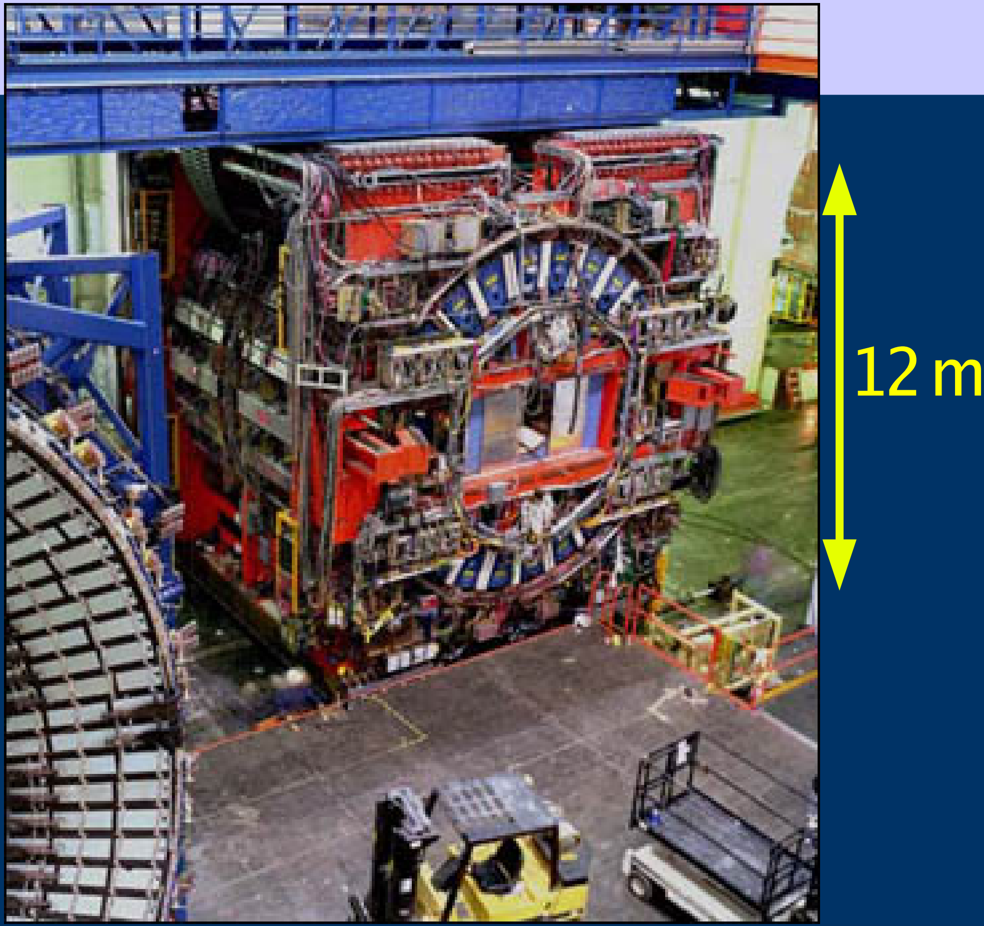
- All detectors in hadron collider experiments are broadly similar:
  - General purpose design
  - Inner detectors for precision tracking
  - Calorimeters for energy measurements
  - Outer muon detectors

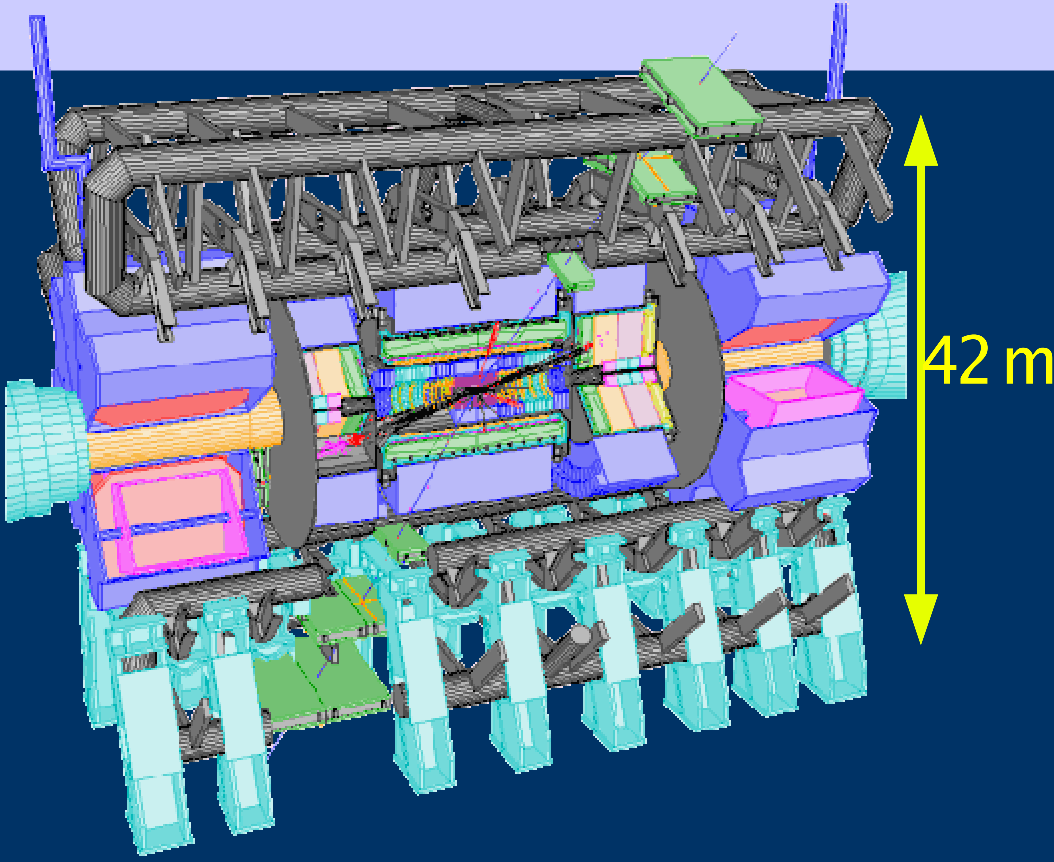




- Energies measured in the transverse plane: E_T , P_T

CDF vs. ATLAS



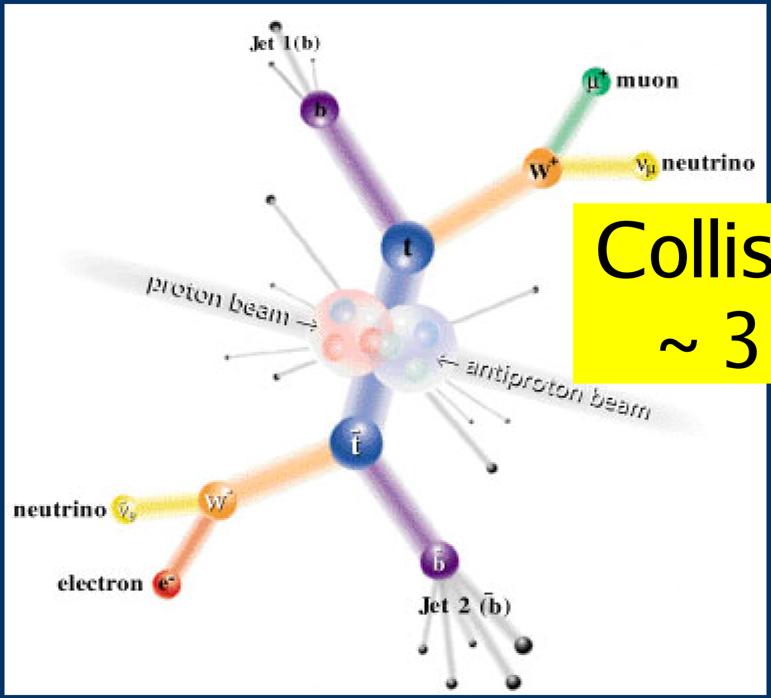


- One of 2 main detectors at the Tevatron (the other being D0)
- ~100 tons
- Run 1 (1992-1996): ~100 pb^{-1}
- Run 2 (2002-2009): 8-9 fb^{-1}
  - Currently ~3 fb^{-1} collected

- One of 3 main pp collider experiments at the LHC (the others being CMS and LHCb)
- ~10,000 tons
- Data taking to start 2008/09

Extracting the Physics from Collisions

- **At the Tevatron:**



3 Tiered Trigger Systems to select "interesting" events

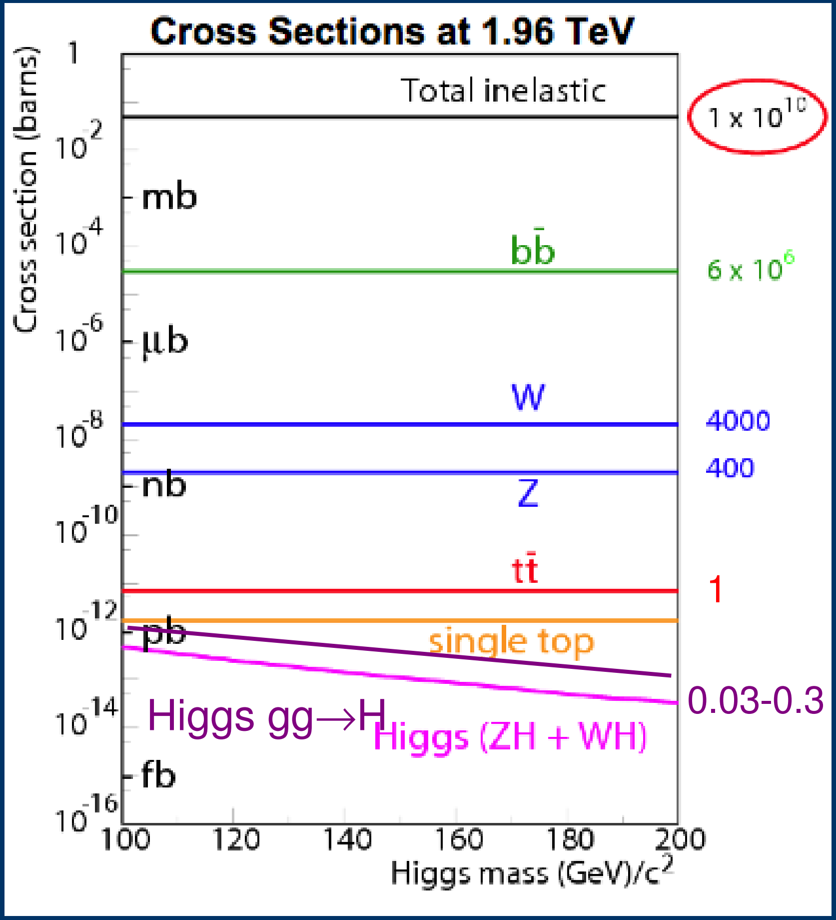
Collision rate ~ 3 MHz

E.g. about 1 in 10^{10} collisions produces a top quark event

Events written to tape at ~50 Hz

- **At the LHC** experiments have significantly greater challenges:
  - Trigger system to select ~10-100 events per second from ~100 MHz rate
  - Sufficient computing to analyse and store ~100 million events per year: ~50,000 2GHz PC's and Petabytes of diskspace !

Comparision of some cross-sections



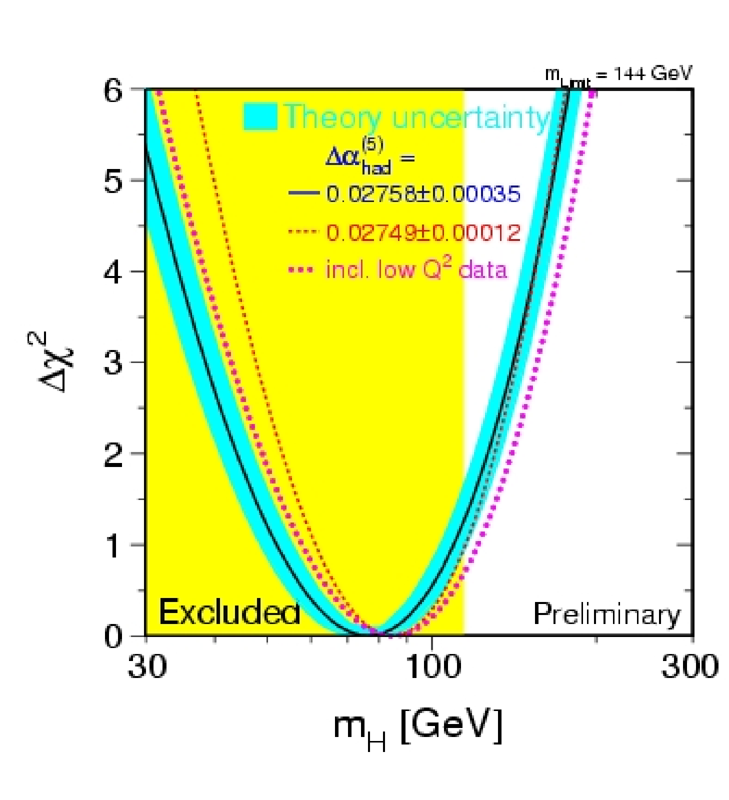
E.g. For a process with σ = 1pb, 1 fb^{-1} of data *produces* 1000 events from that process

At the Tevatron:

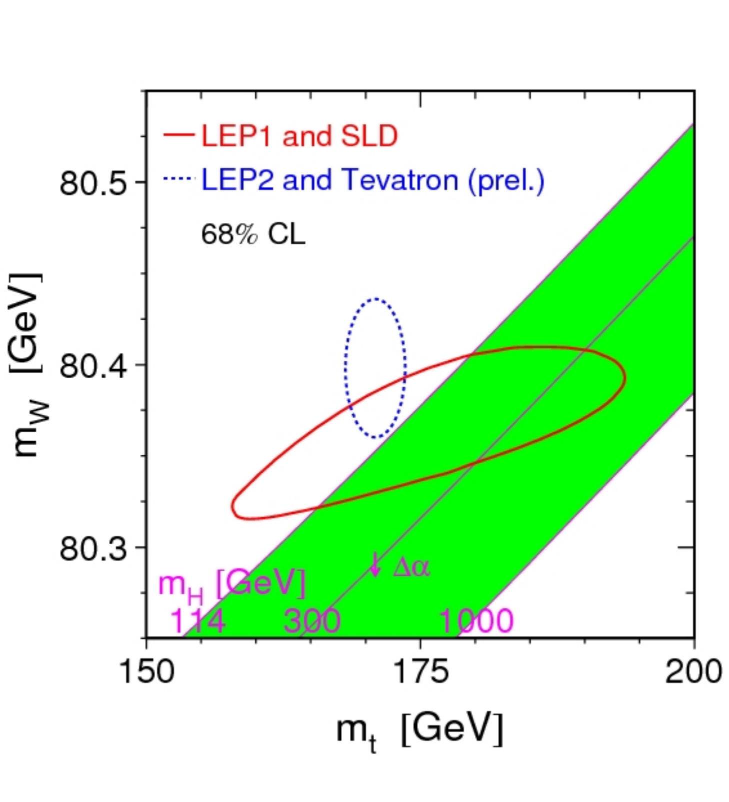
- **W and Z bosons**
  - Large cross-sections/statistics
  - Precision measurements and calibration samples
- **Diboson and top production**
  - Few pb cross-sections
  - Beginning program of precision measurements
  - Important calibration for Higgs searches
- **Higgs production**
  - Extremely challenging to extract only a few events produced over a total background more than 10 orders of magnitude larger
  - many search strategies, techniques, and tools required

What we currently know about the SM Higgs

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



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

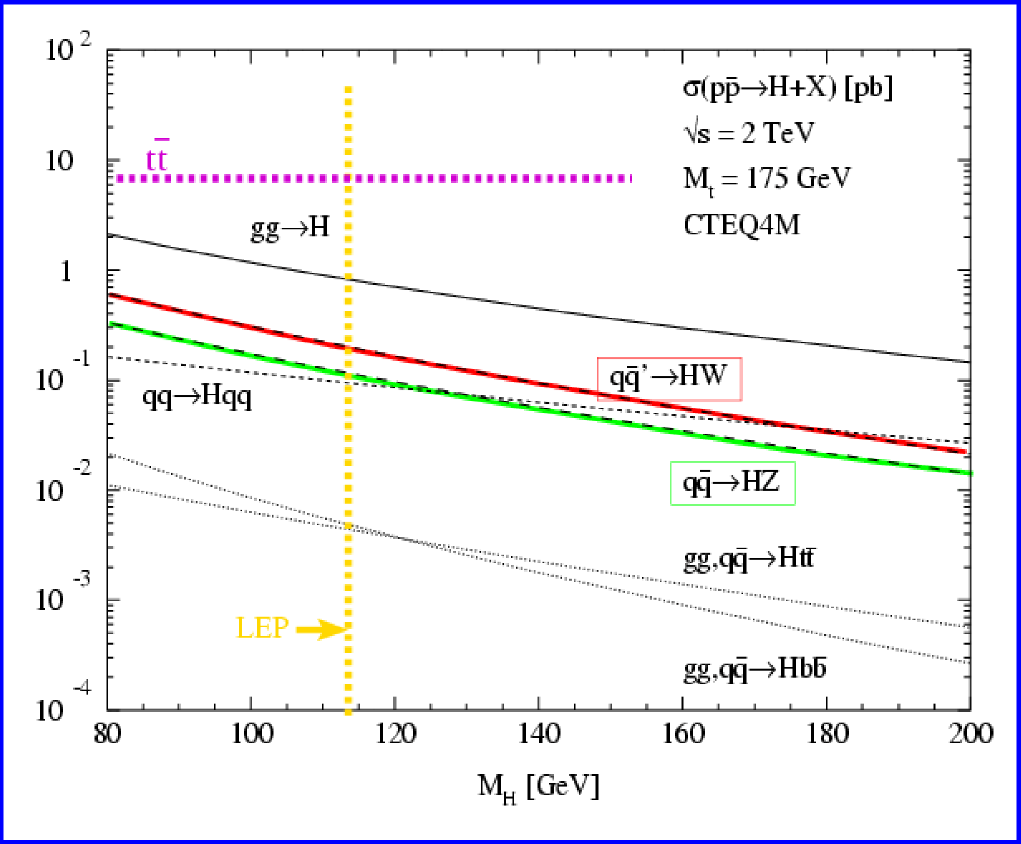


- Latest (March '08) fits to precision EW data
  - ➔ $m_H = 87^{+36}_{-27}$ GeV/c^2
  - ➔ $m_H < 160$ GeV/c^2 (95% CL)
  - ➔ $m_H < 190$ GeV/c^2 (when LEP limit included)

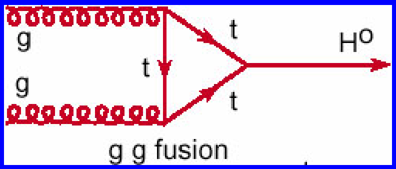
- The Tevatron and/or LHC will either find or rule out a SM Higgs within ~2 yrs

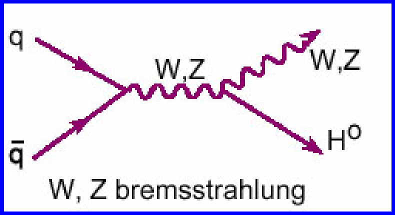
Higgs Production

Tevatron

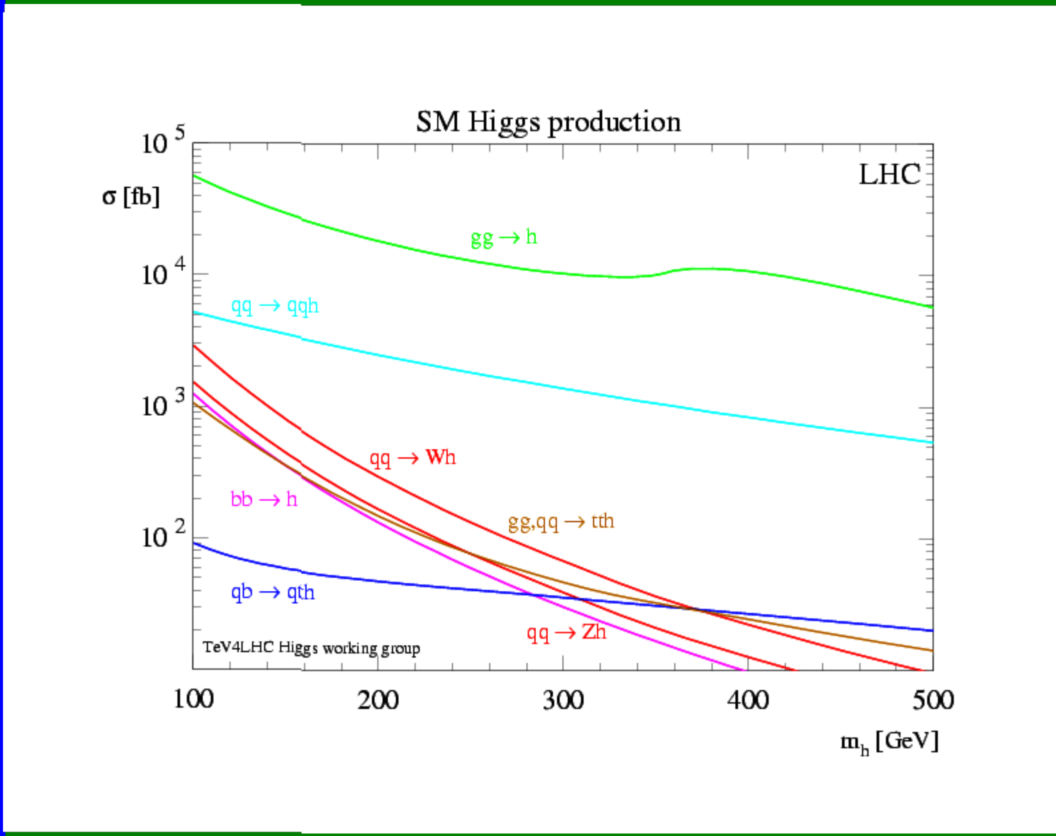


- Single Higgs production dominates
- Production in association with a vector boson order of magnitude less, but provides best sensitivity to low-mass searches

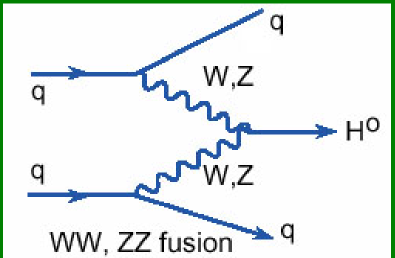




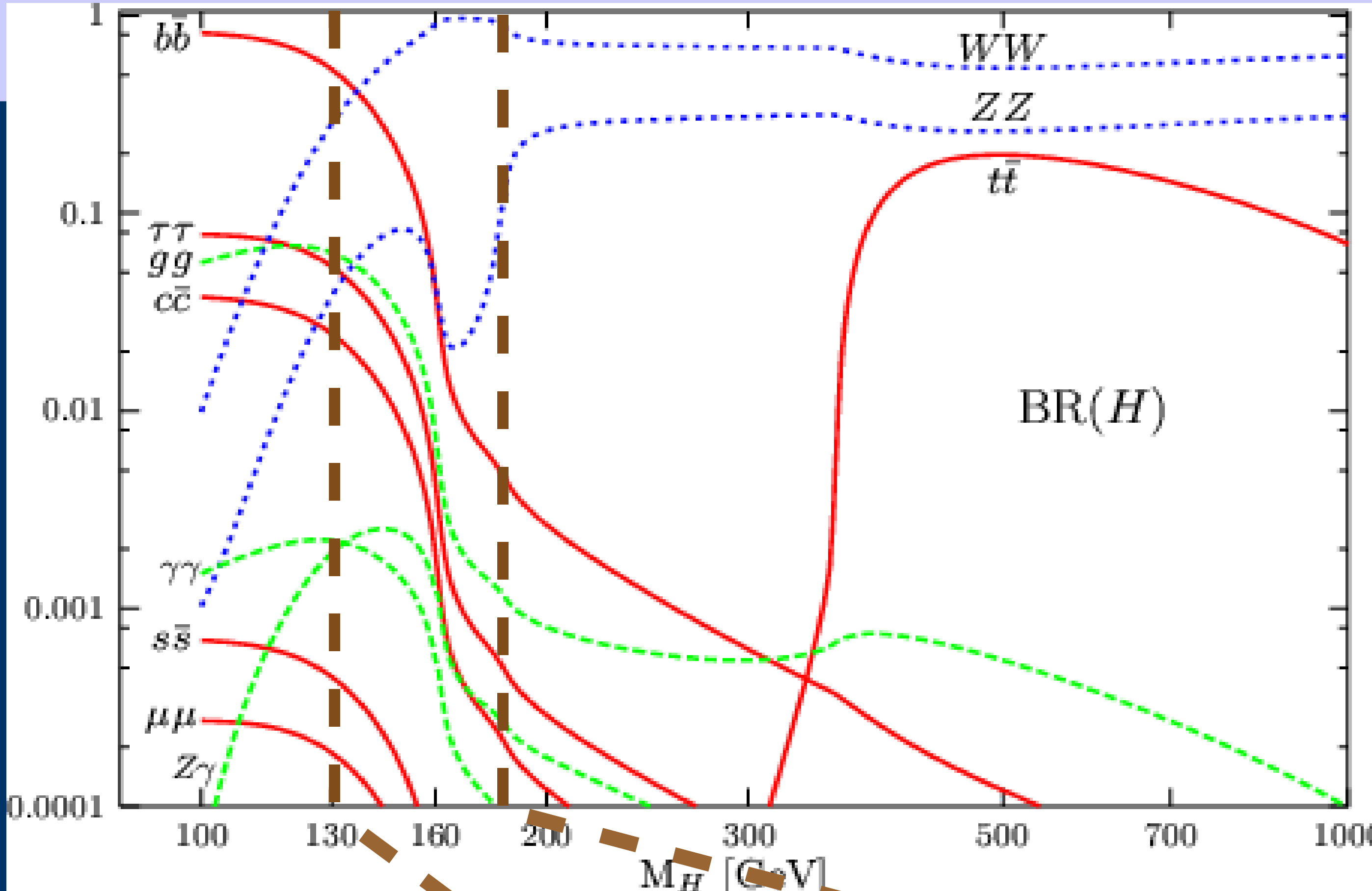
LHC



- $gg \to H$ two orders of magnitude greater
- $qq \to VH$ 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:

$M_H = 120$ GeV

TeV		LHC
800 events produced	$qq \rightarrow WH$	9000 events produced
3500 events produced	$gg \rightarrow H$	200 000 events produced

BR + trigger

TeV		LHC
50 events	$WH \rightarrow l\nu\, bb$	600 events
2 events	$H \rightarrow \gamma\gamma$	200 events

$M_H = 160$ GeV

TeV		LHC
1500 events produced	$gg \rightarrow H$	140 000 events produced

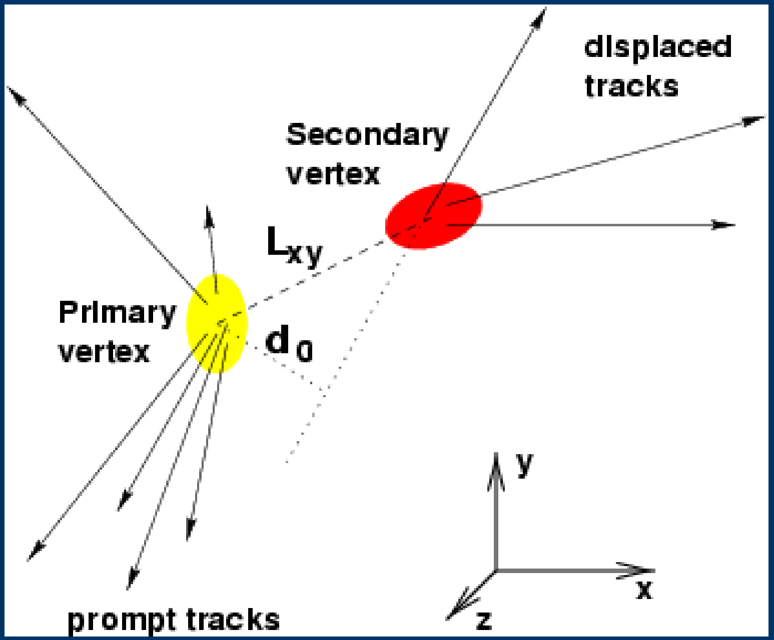
BR + trigger

TeV		LHC
20 events	$H \rightarrow WW \rightarrow l\,\nu\, l\,\nu$	2000 events

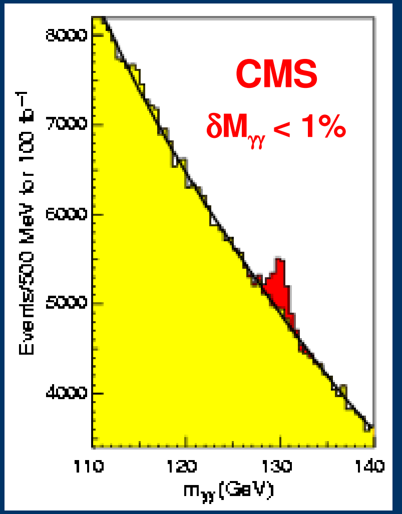
Then, event selection will further reduce signal with still more work needed to discriminate from the large backgrounds

Backgrounds for light Higgs

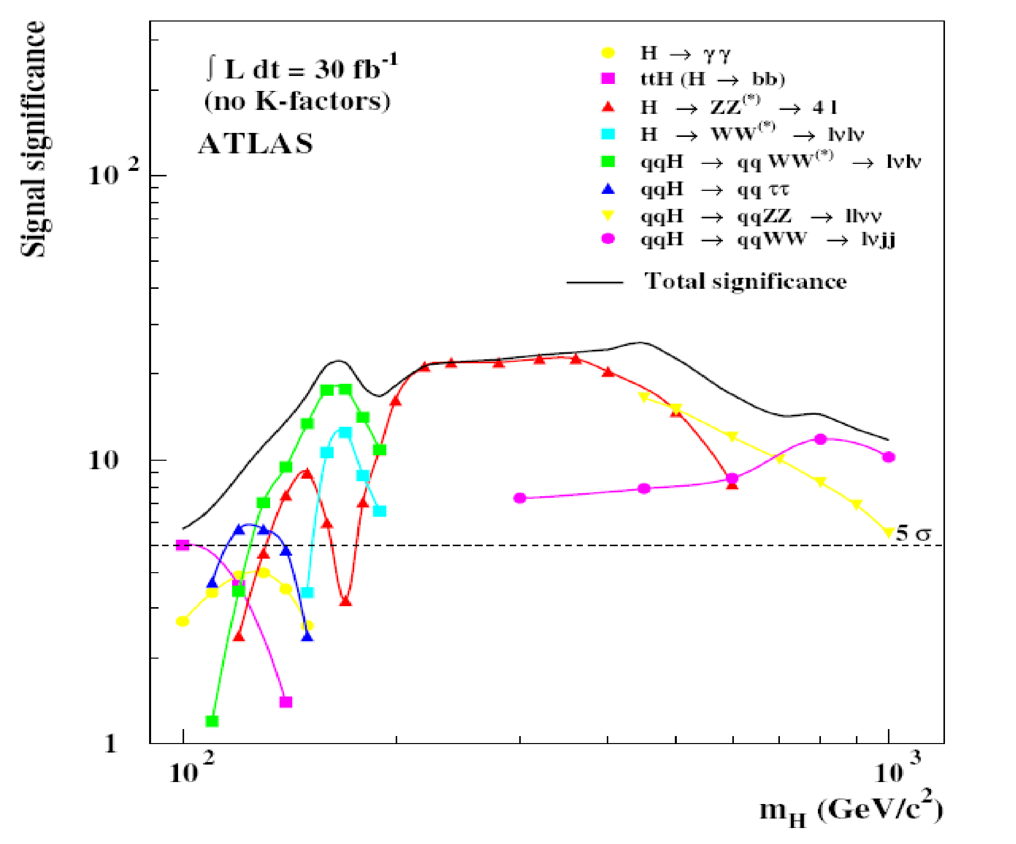
- For low-mass searches at the Tevatron crucial to “tag” jets from b's to reduce the huge V+jets background
  - Most powerful method is to measure secondary vertices from B decay
  - Efficiency to tag at least one b-jet ~60%
  - False tag rate ~0.5%
  - Reduces backgrounds by at least an order of magnitude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

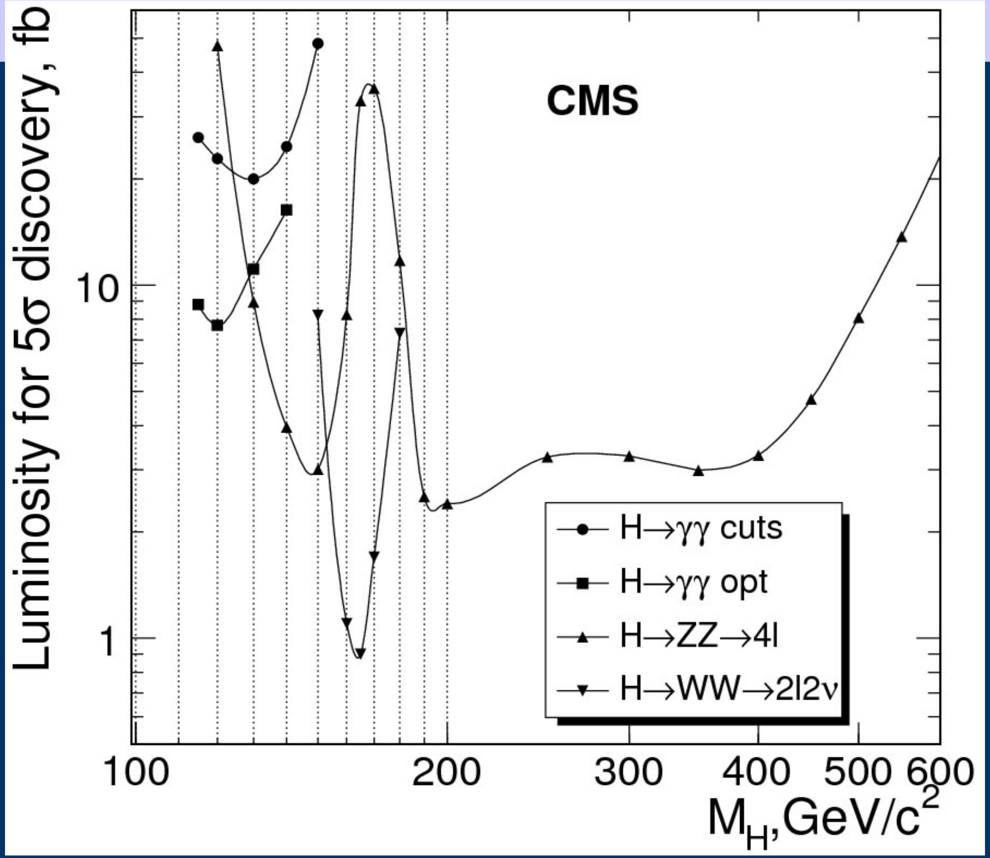


- At the LHC making any use of $H \rightarrow bb$ extremely difficult
  - $H \rightarrow \gamma\gamma$ most sensitive channel for light Higgs
  - Major background from prompt γ's, but $M_{\gamma\gamma}$ narrow



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

The road to Higgs at the Tevatron requires:

Standard Model Higgs search channels

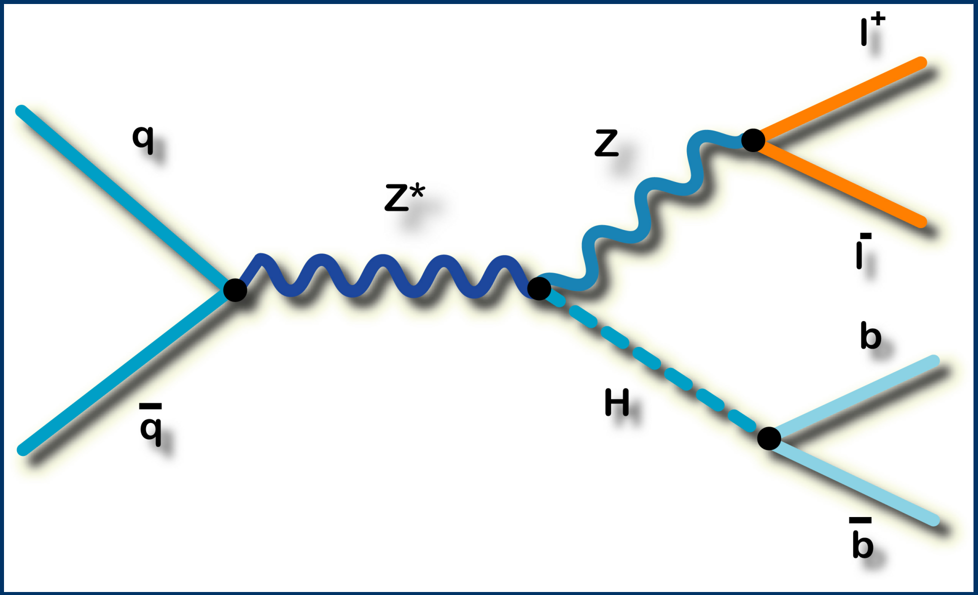
Production	Decay		Relative BR	N_{prod} in 2fb^{-1} (M_H)
$qq \to VH$	$H \to b\bar{b}$	$W \to (e/\mu)\nu$	14%	50 (120 GeV)
		$W \to \tau\nu$	7%	25
		$W \to qq$	41%	145
		$Z \to ee/\mu\mu$	3%	10
		$Z \to \tau\tau$	1.5%	5
		$Z \to \nu\nu$	8%	28
		$Z \to qq$	26%	92
$qq \to VH$	$H \to WW \to \ell\nu\ell\nu$	$W \to \ell\nu$	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: production/decay
- Improved triggers
  - displaced tracks
  - missing energy triggers
- Improved b-tagging
  - progress on NN b-taggers
  - forward b-tagging
- Improved lepton ID
- Improved Jet energy resolution
- Advanced analysis techniques
  - NN's, ME techniques, others
  - combining channels, expts

All these efforts in full swing now with further improvements expected in the next year or so

Examples of recent Tevatron analyses exploiting new strategies

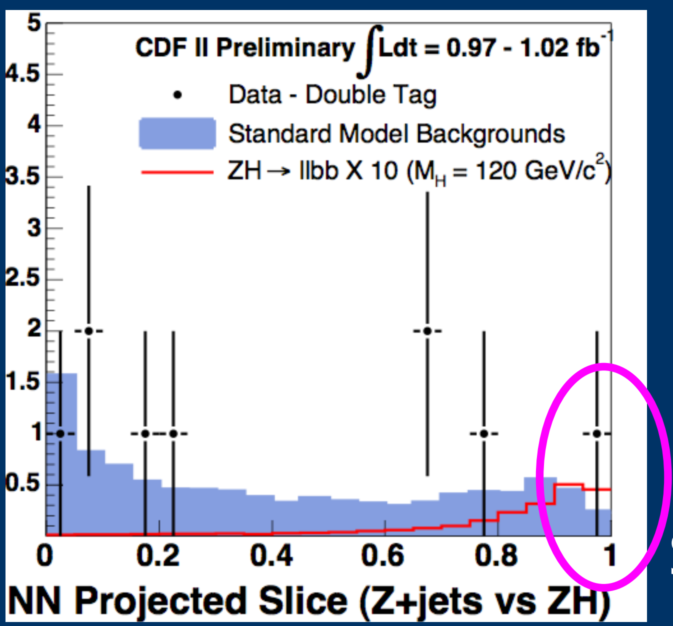
❶ ZH → $l\,l$ bb



- 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 → *l l* bb

- Suffers from smallest branching ratio of all the low-mass Higgs searches
- However, has made significant innovations to optimize signal discrimination from background
  - Use of advanced discriminants: Neural Nets(NN), Matrix-Element (ME) techniques
  - Extensive studies of optimizing b-tagging and lepton identification
  - 5 events produced → ~1 after selection
  - Signal / Background ~ 100
- 95% CL limits set as a function of m_H , from fitting NN output distribution



S/B ~ 1/4

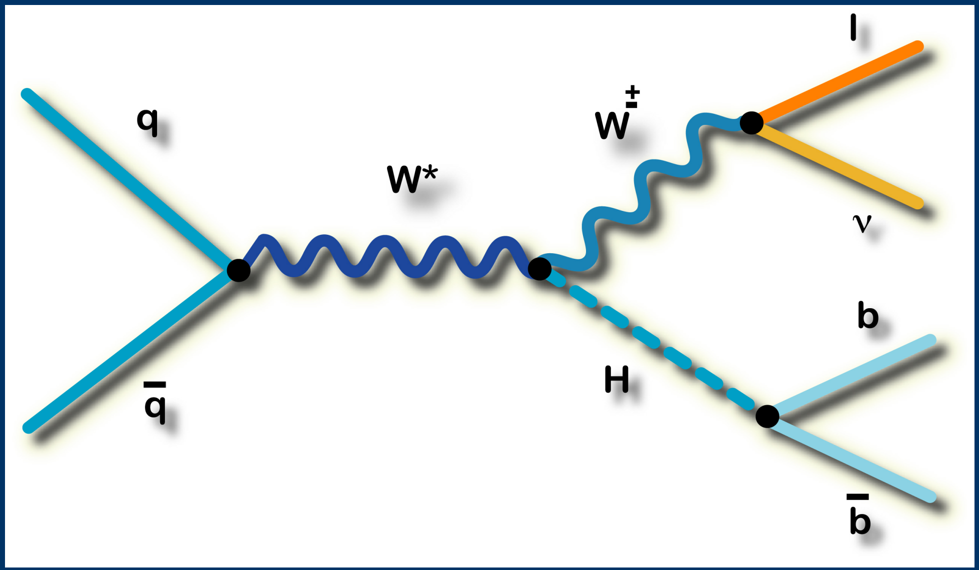
New results (Aug '08) using 2 fb^{-1} of data

Results at m_H = 115GeV: 95%CL Limits/SM

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF NN	2.4	1.8	11.8	11.6
CDF ME(120)	2.0	1.4	15.2	11.8

Examples of Tevatron searches, continued...

❷ WH $\rightarrow l \nu$ bb

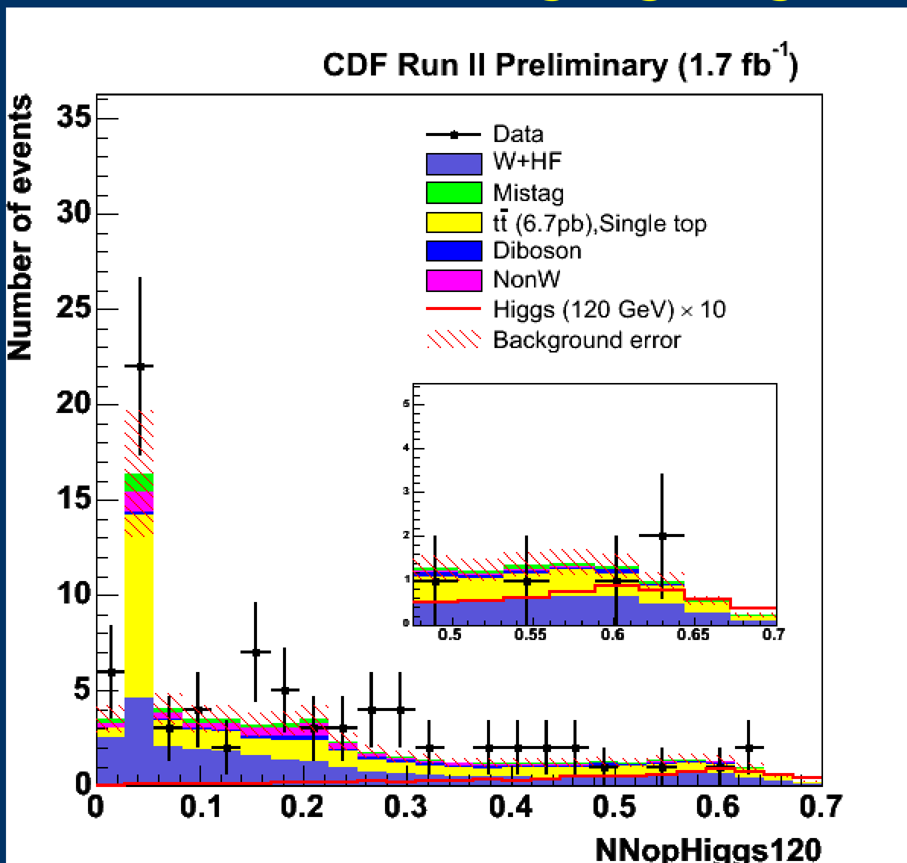


- Signature:
  - 1 high-P_T lepton
  - Large missing E_T
  - 2 high-E_T jets, at least one of which is tagged as originating from a b-quark
- Main backgrounds:
  - 60% W + jets
  - t-tbar, single top

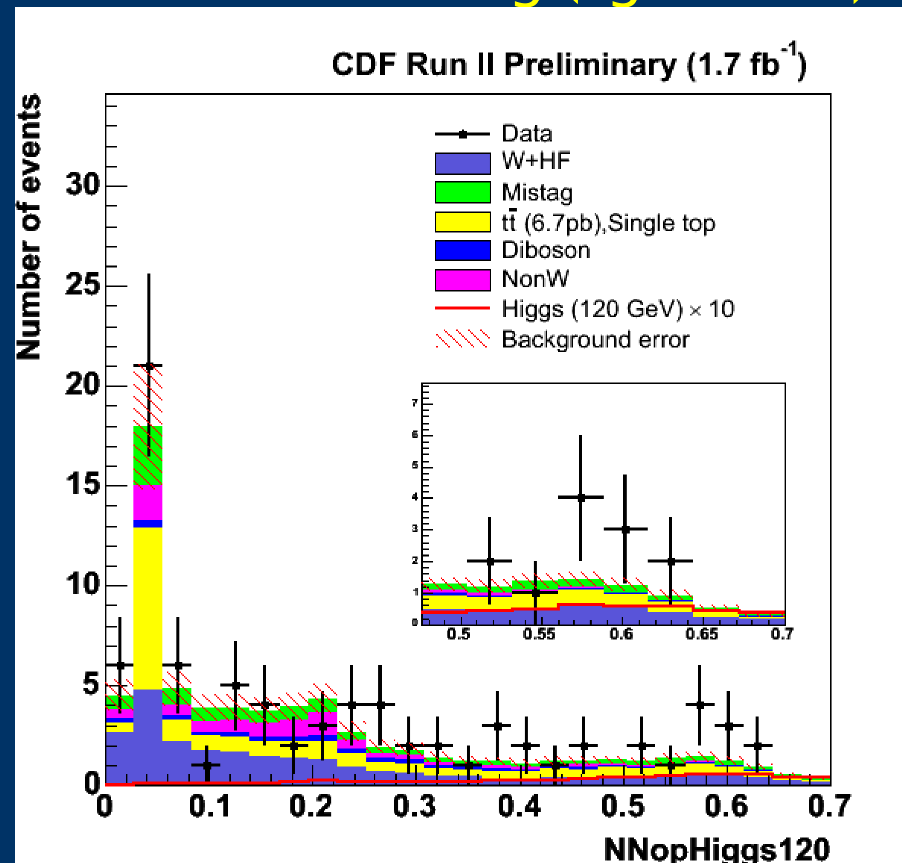
$WH \to l\nu bb$

- Neural Net approach using several input kinematic variables (dijet mass most powerful but others contribute significantly)

Double-tag (tight-tight)

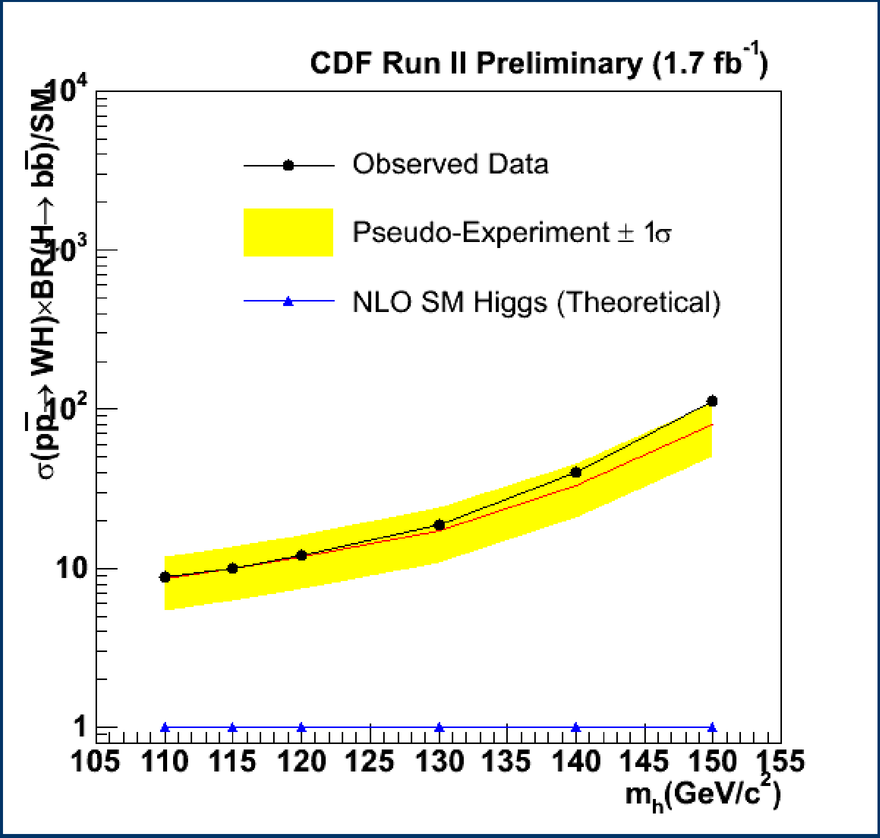


Double-tag (tight-loose)



WH → $l\,\nu$ bb

- WH → $l\,\nu$ bb expected to provide the most sensitivity for low-mass searches at the Tevatron (with ZH → $\nu\nu$bb not far behind)
- Many improvements recently completed using ~2.5 fb^{-1} and more on the way
  - Inclusion of single tag category
  - Better optimization of b-tagging in general (incl. NN b-tagger)
  - Matrix element method recently completed (using machinery from the single top search)
  - Have added foward lepton categories
  - Eventually will include τ decay channels

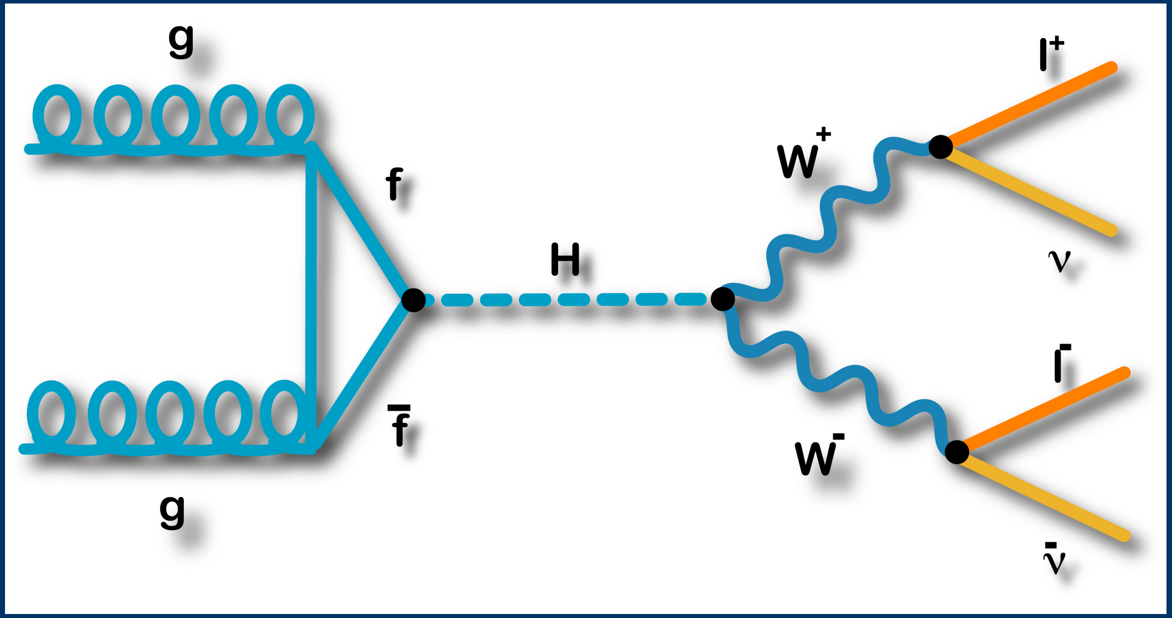


Latest 95% CL / σ_{SM} results (Aug '08) at mH=115

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF NN	2.7	8.3	5.8	5.0
CDF ME+BDT	2.7	7.8	5.6	5.7

Examples of Tevatron searches, continued...

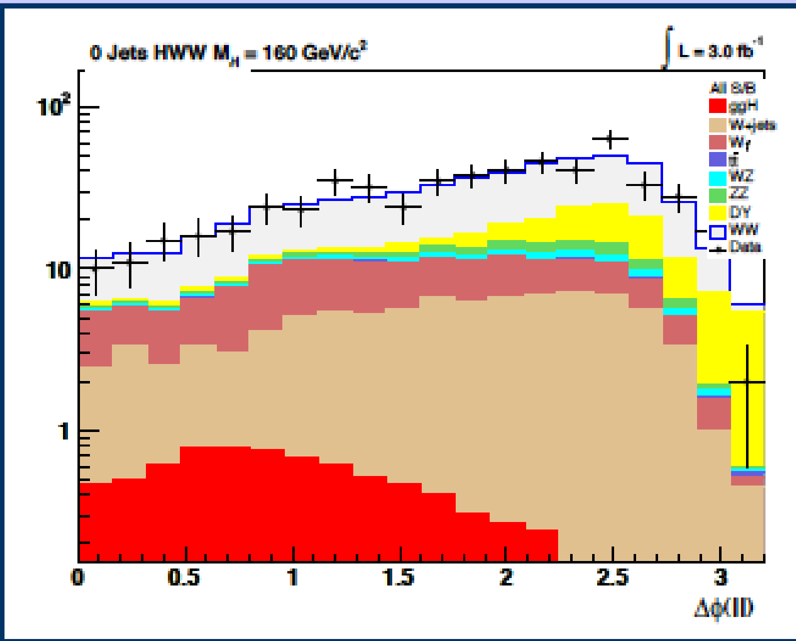
❸ $H \to WW^* \to l \nu l \nu$

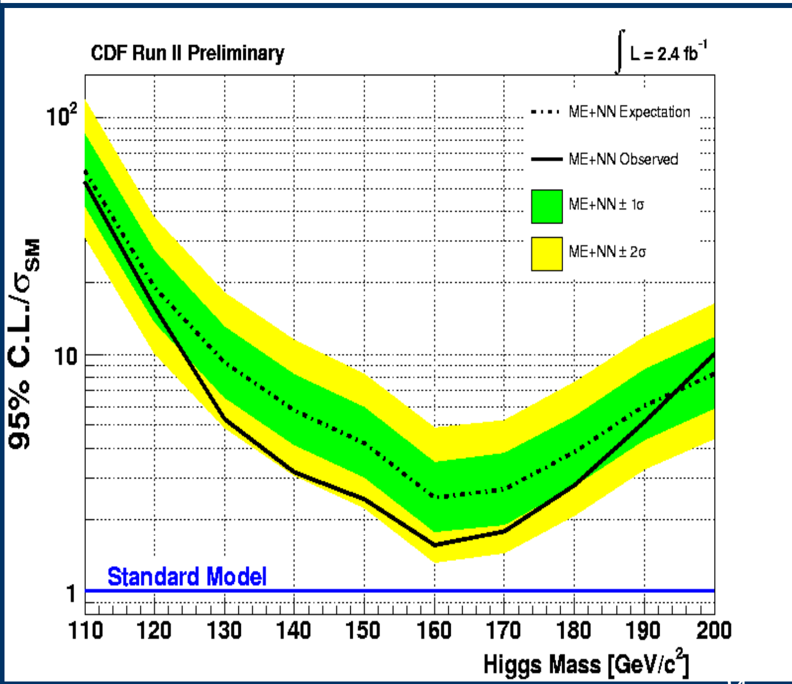


- Signature:
  - 2 high-P_T leptons
  - Large missing E_T
- Main backgrounds:
  - 50% WW
  - 30% Drell-Yan

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

- Spin correlation: leptons tend toward same direction
- Other kinematics and ME information fed into a NN
- Also vastly increased lepton acceptance compared to previous analyses
  - Increases signal acceptance by ~70%
  - Expect ~4 signal events at M_H=160 in 1 fb^{-1}
- Fit NN output distribution to obtain 95% CL limits
- Recently (last week) updated to 3 fb^{-1} and:
  - Inclusion of vector-boson-fusion process and VH→VWW processes (potentially ~30% gain)
  - Better optimization of NN's
  - At mH = 160 GeV, expected (observed) limits from **CDF only** are 1.8 (1.7) times σ_{SM}
  - Will be very close to σ_{SM} when combined with D0 (was hoping to ready this week!....first exclusion at a hadron collider immenent)
- The H→ WW* analyses are our most sensitive for a given mass, and are competitive with the VH analyses down to ~130 GeV

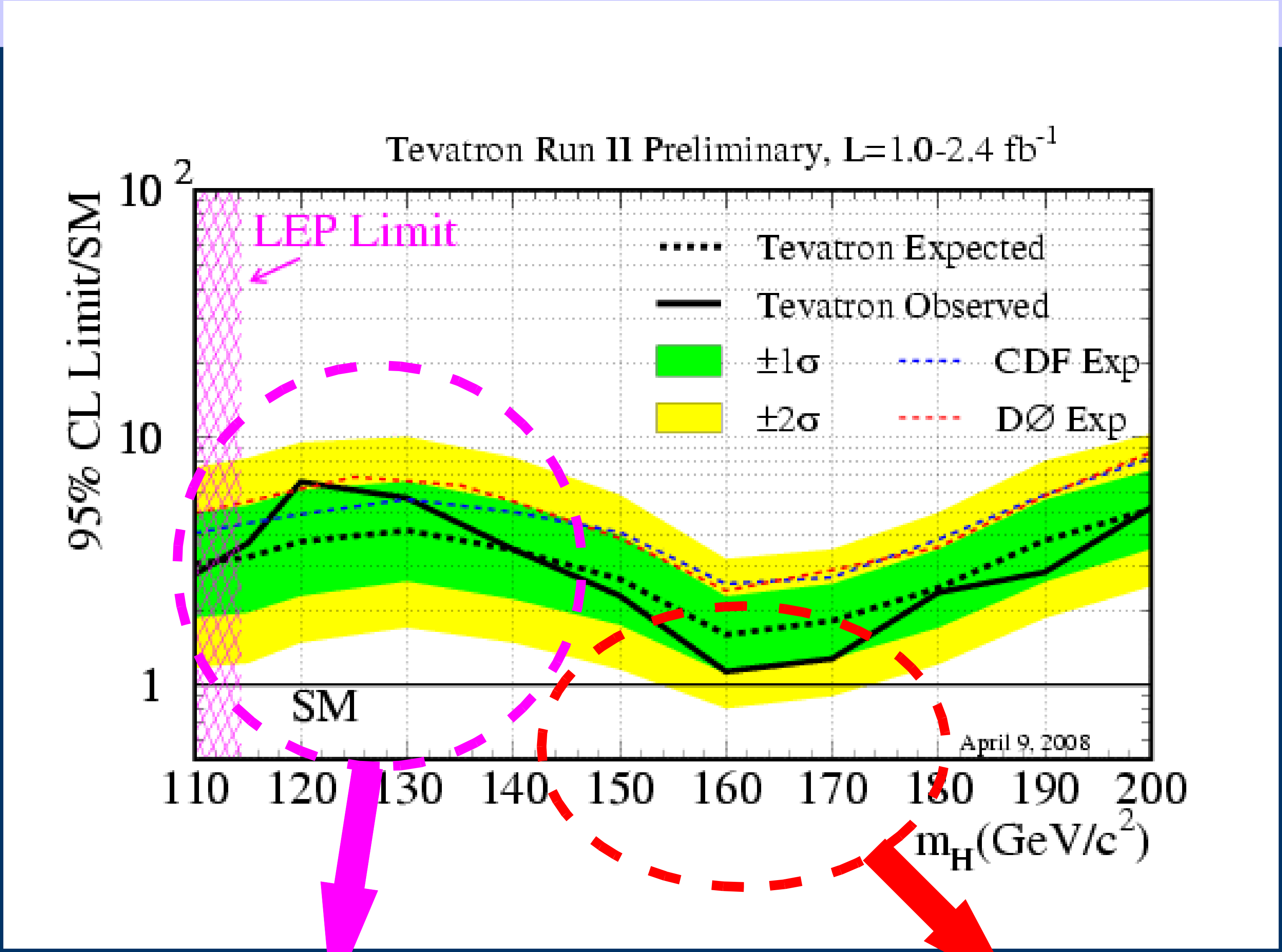


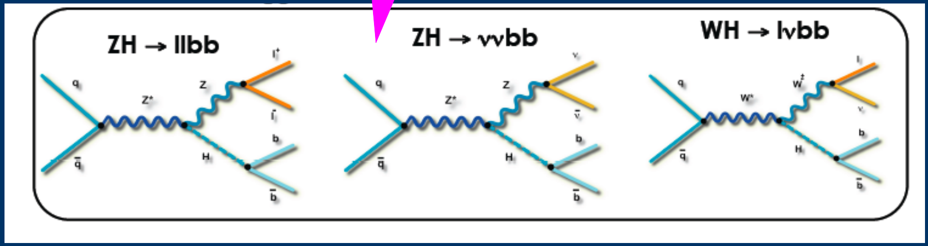


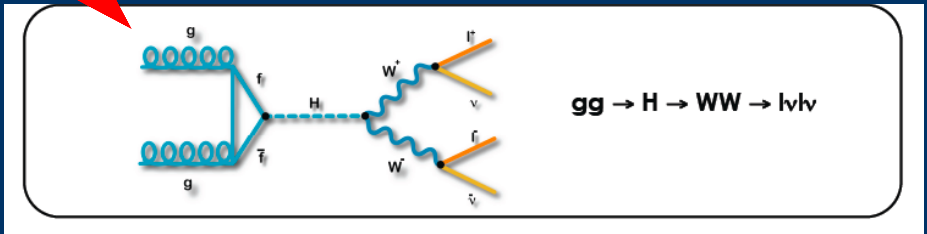
Many other SM searches – using every possible mode to extract maximum signal

- WH $\rightarrow$ WWW: using same sign leptons
  - Adds sensitivity for high mass searches
  - Provides search channel for fermiophobic Higgs bosons
- ZH $\rightarrow$ $\nu\nu$bb: Missing E_T + jets
  - Difficult to model large QCD background but huge improvements lately to make this channel comparable to WH $\rightarrow$ $l\ \nu$ bb
- VH $\rightarrow$ qqbb: 4 jet mode
  - Difficult but does add some sensitivity to low mass searches
- H $\rightarrow$ $\tau\tau$ with 2 jets
  - Search that simultaneously includes VH, VBF, and gg $\rightarrow$ H channels
  - Useful benchmark for the LHC
- And, a few other lower sensitivity searches, but every bit helps !

Recent Tevatron Combination (March 2008)



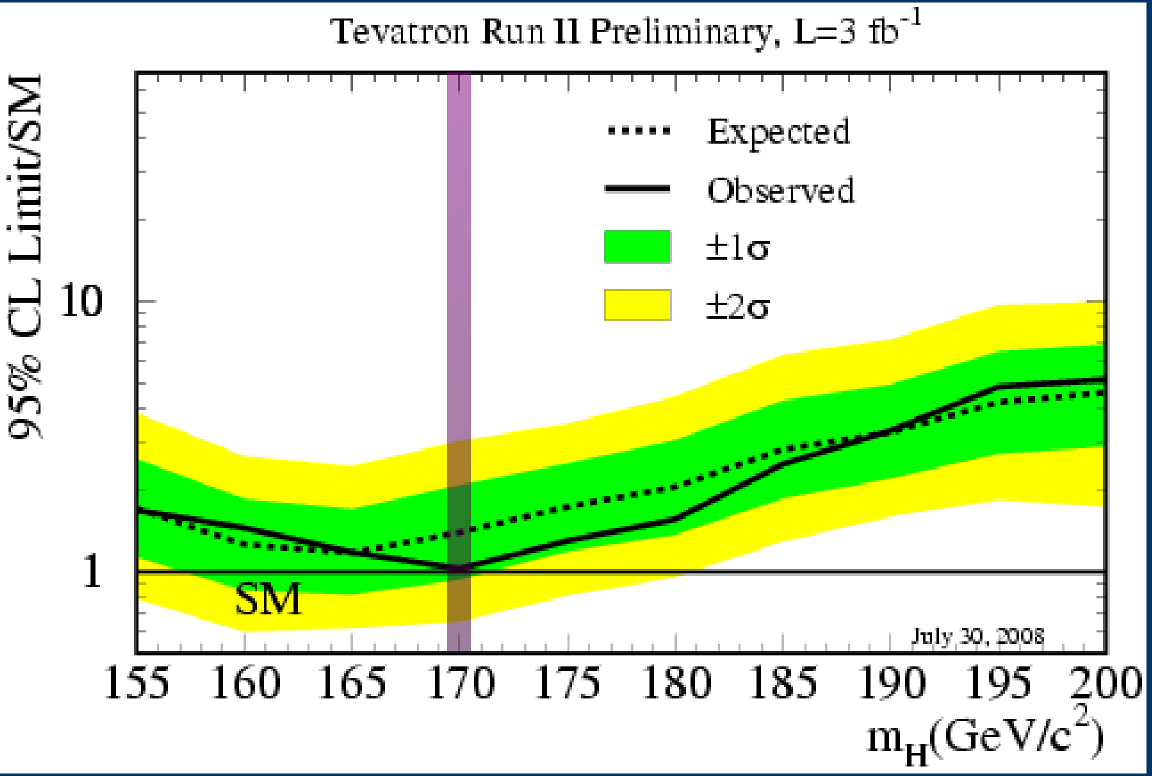




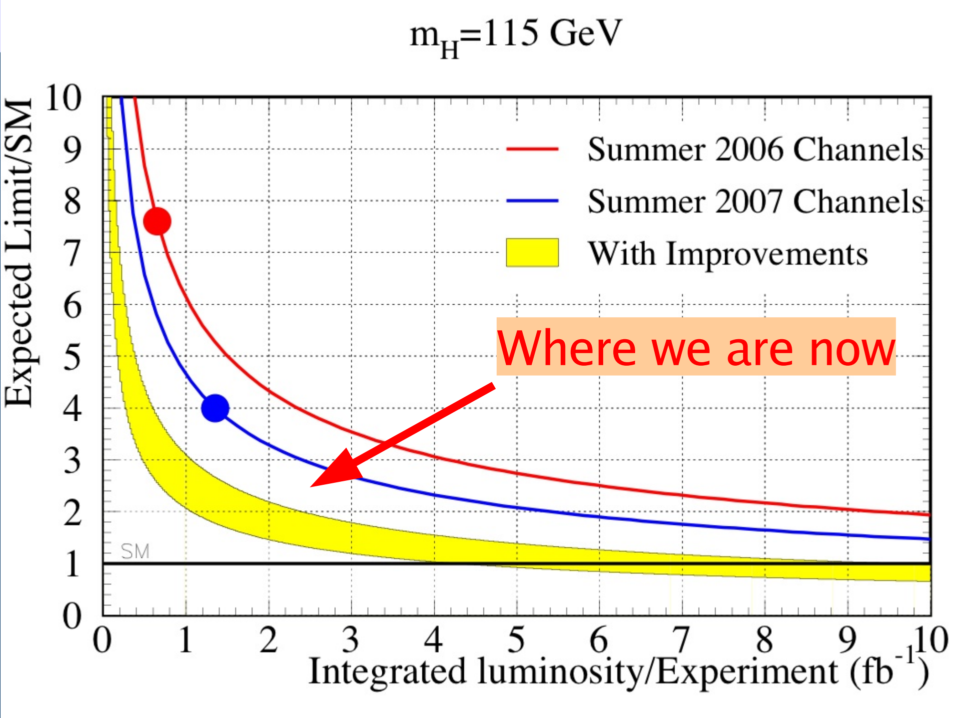
- At m_H = 160 the observed limit is now 1.1 x σ_{SM} !!
- Expected (obs.) limits/σ_{SM} of:
  3.3(3.8) at 115 GeV
  1.6(1.1) at 160 GeV
  (arXiv:0804.3423)
- Latest results not yet combined with D0 – happening now! -- but high-mass search just combined (Aug '08)....

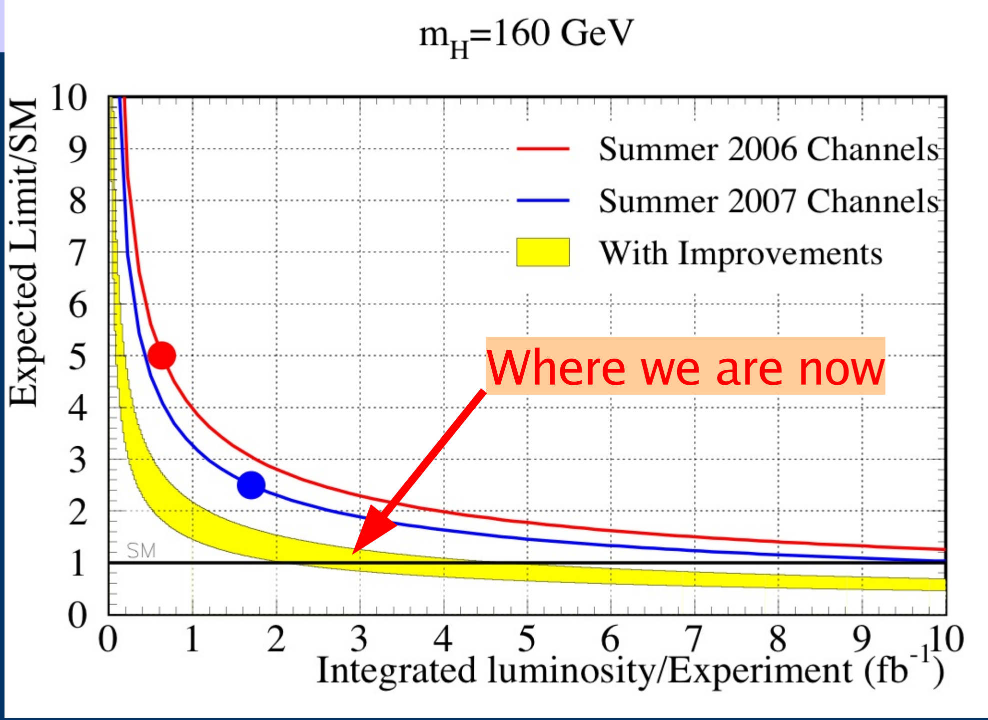
...new high mass limits just approved last month

- We have excluded at 95% C.L. the production of a Higgs boson at m_H = 170 GeV
- Combined CDF and D0 results using 3 fb^{-1} of data
- Expect within the next couple of years a large exclusion region, or possible evidence, with the full Tevatron dataset and more analysis improvements to increase sensitivity



Projections: combined Tevatron sensitivity





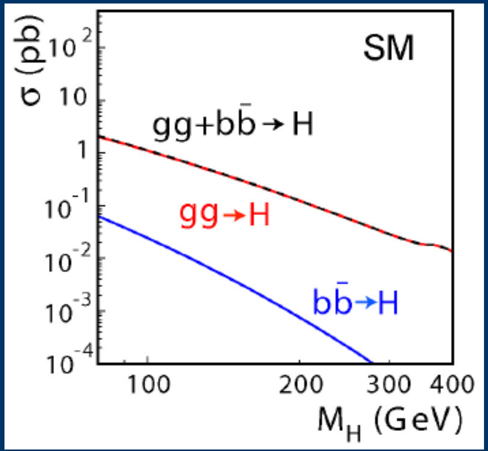
The yellow band represents the range of expected limits between improvements that are already verified and quantified through extensive studies, and those that require more work but are ultimately achievable.

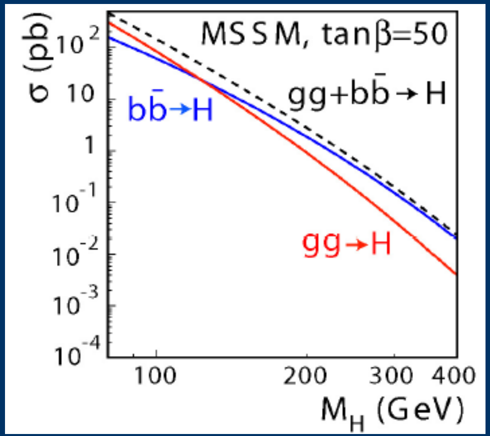
- Starting to exclude Higgs bosons at masses around 160 GeV
- Important milestone for the Tevatron, and interesting for the LHC
- To exclude (if it's not there!) at lower masses will need 6-8 fb^{-1}
  - within reach if the Tevatron runs in 2010 (very likely now)

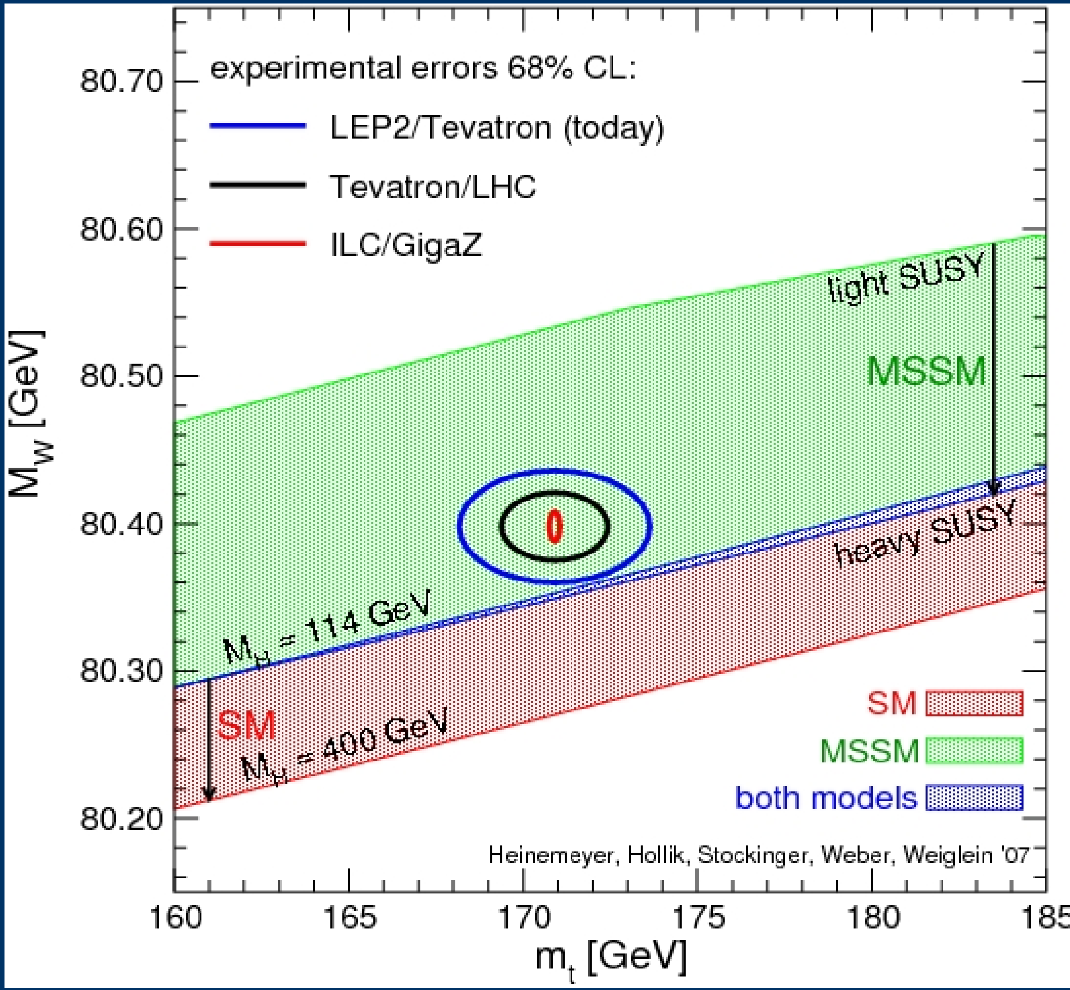
What about Supersymmetry, or other "Beyond SM" possibilities ?

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

- In MSSM two Higgs doublets resulting in 5 Higgs's ($H^{\pm}$, h, H, A)
- Coupling to down type quarks and leptons (such as b's and τ'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

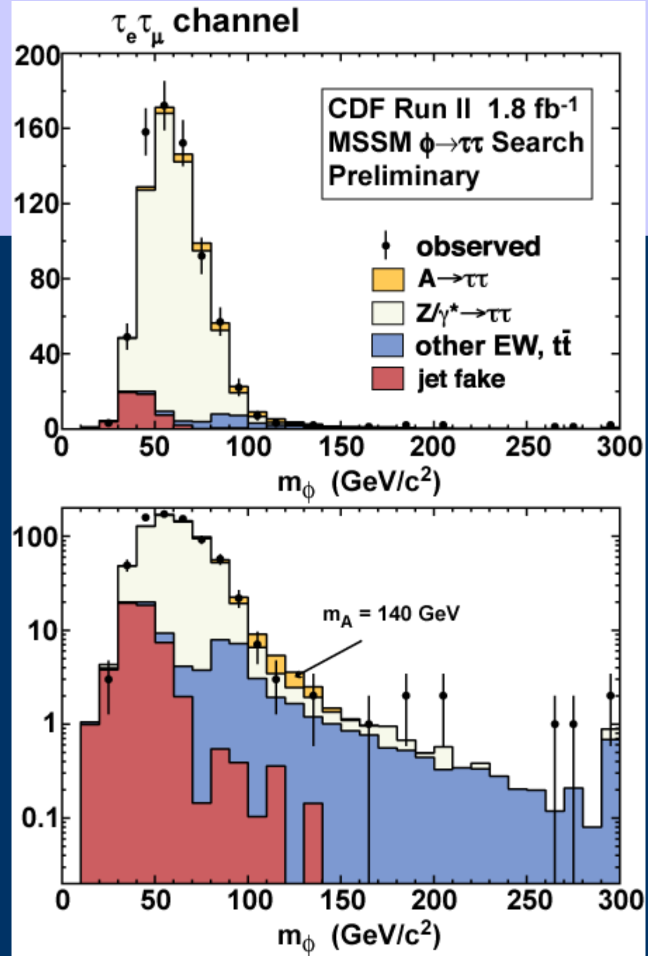


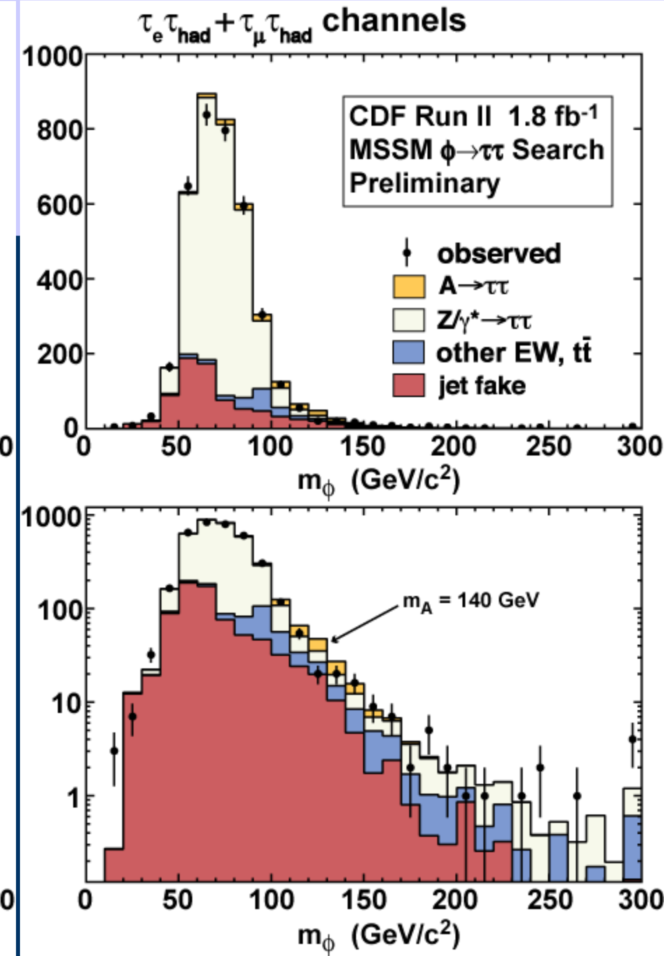


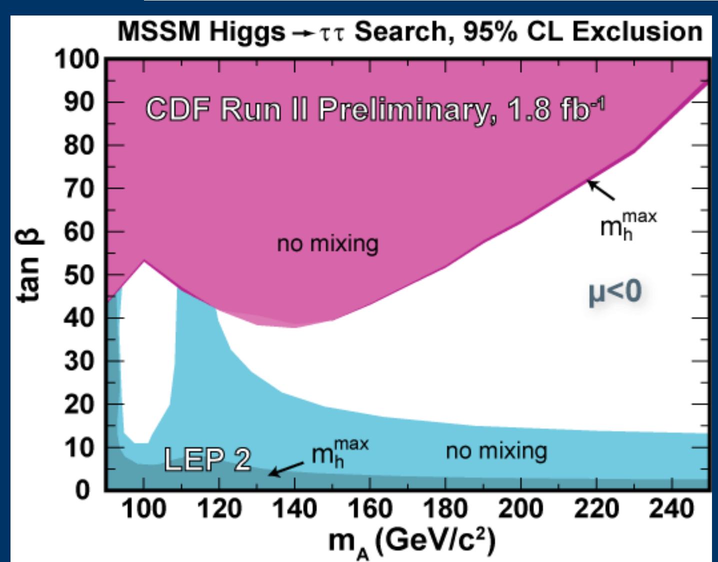


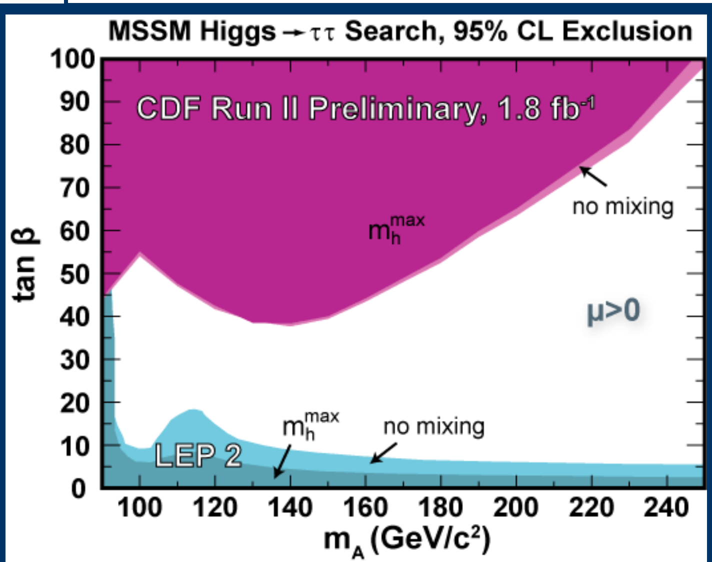
Search for $\phi \to \tau\tau$

- One τ required to decay leptonically
- Recontruct $M_{\tau\tau}$ using visible energy
- No significant excess seen $\to$ limits set in $\tan\beta$ – M_A plane for the no-mixing, and m_h^{max} benchmark scenarios
- Combining results with D0 (who have comparable limits) will further exclude this MSSM phase space







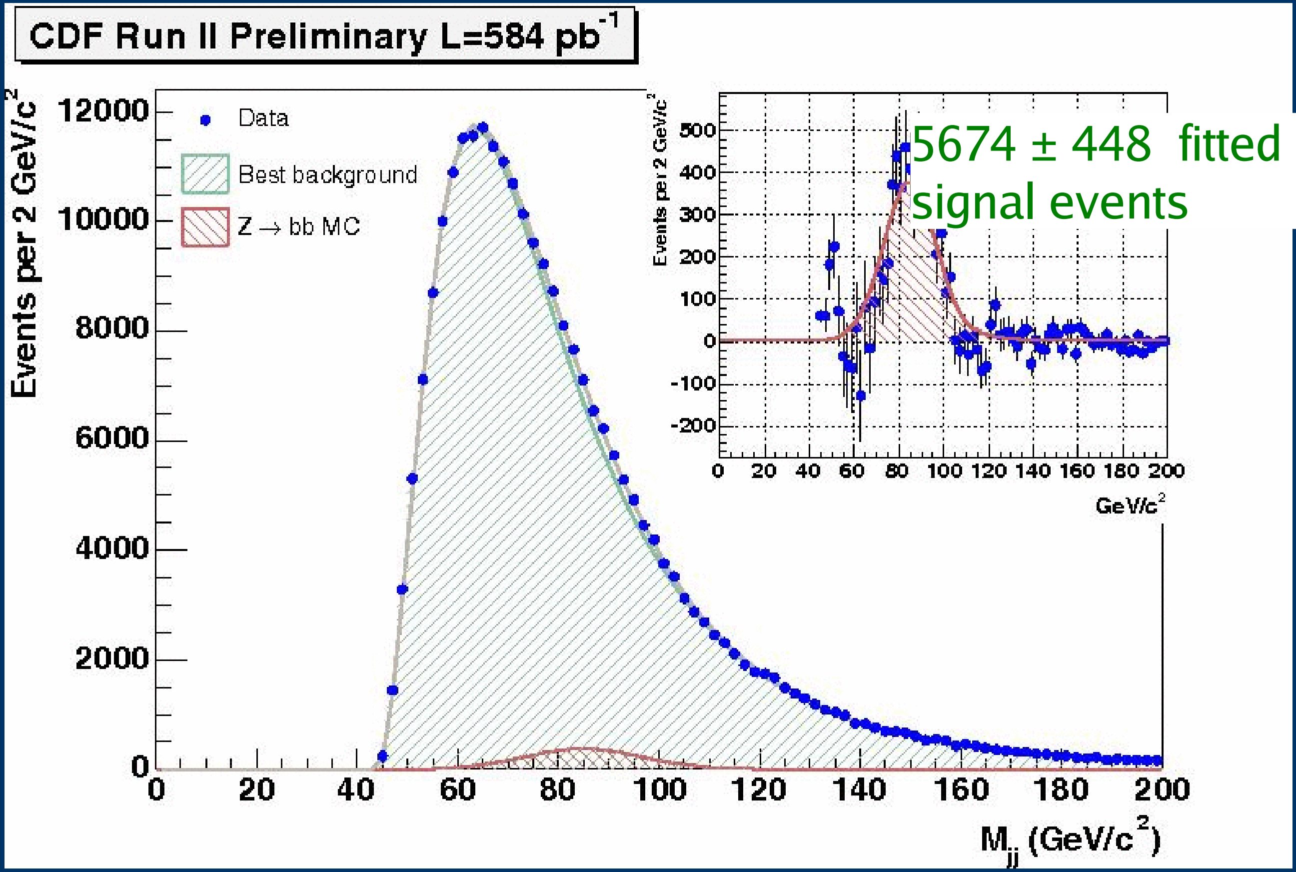


Search for $\phi \to bb$

- $Z \to bb$ observed over a huge background spectrum

- At M_H = 120 would expect about **5** SM Higgs events in this spectrum (difficult to trigger on)

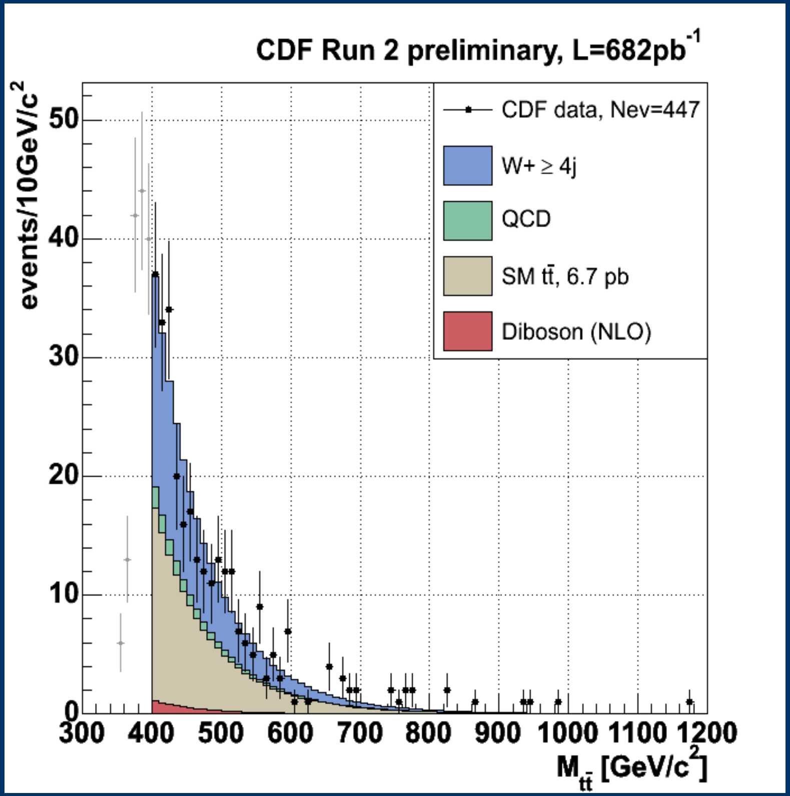
- Huge tan β enhancement required to see anything



- Searches for $\phi \to bb$ use $bb\phi \to 4b$ for greater sensitivity, but are extremely difficult analyses. Though they have been performed and will be used in combination with the $\tau\tau$ analyses to further exclude MSSM parameter space

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
- ....and more.....



latest tt invariant mass spectrum from CDF

- If we find something at the Tevatron we'll need to wait for the LHC to know what it is !!

Closing remarks

- The excellent recent performance of the Tevatron has sparked the realisation that a Higgs could 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
  - Combining CDF and D0 results
- If a SM-"like" Higgs boson exists and it is light (as it is now looking) it will take the LHC a couple of years to make a discovery, and also a couple more years for the Tevatron to make any significant statement – could be a horse race !
- 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
- A very interesting and exciting time in particle physics