Discovering the Higgs:
Tevatron status and LHC prospects

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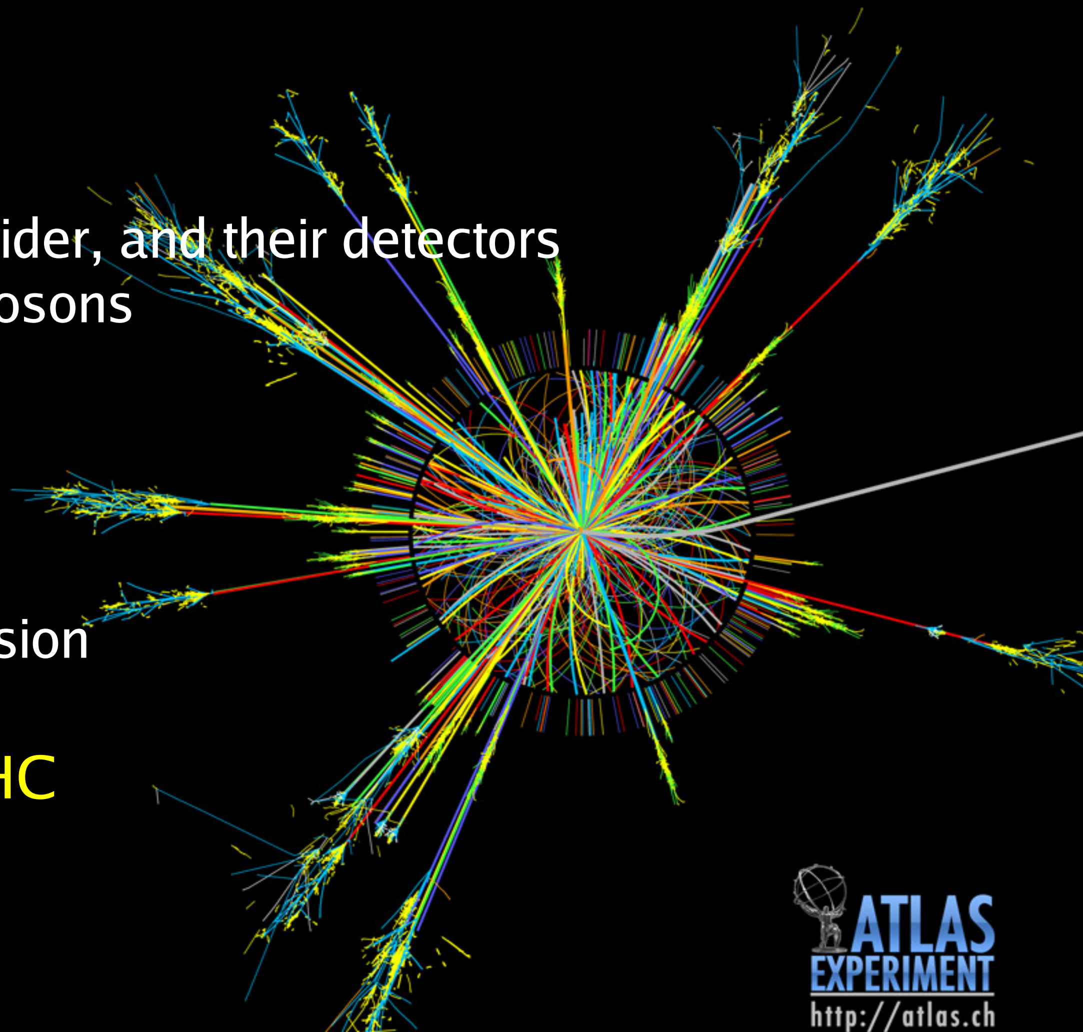
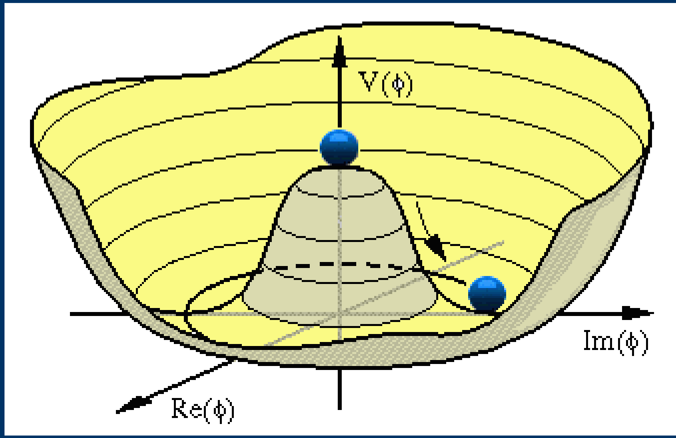
- Introduction
  - What we know about the Higgs
  - The Tevatron, Large Hadron Collider, and their detectors
  - Producing and detecting Higgs bosons
- Searches at the Tevatron
  - SM Higgs searches
  - BSM searches
  - Prospects for discovery, or exclusion
- Searches and prospects at the LHC
- Conclusions



Why look for a Higgs Boson ?

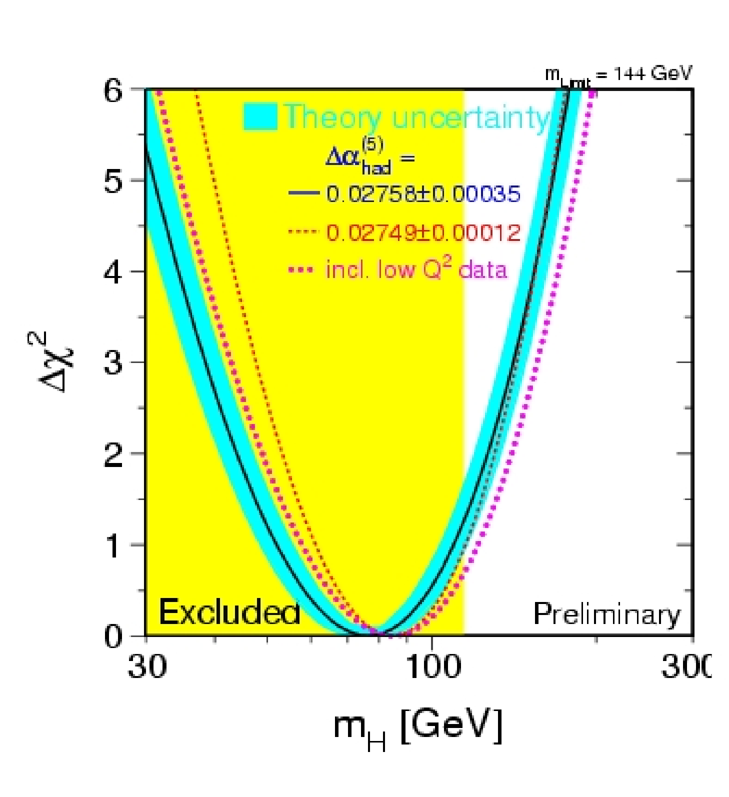
- The electroweak gauge bosons are massive (M_W = 80 GeV, M_Z = 91 GeV)
  $\Rightarrow$ *somehow*, the electroweak symmetry is broken
- The Standard Model postulates the breaking of the electroweak symmetry via the “Higgs Mechanism”:
  - Introduce complex doublet of scale fields, ϕ
  - Endows the $W^{\pm}$ and Z^0 bosons with mass (but not γ)
  - There remains a massive spin-0 particle: **the Higgs boson**
  - Yukawa interactions between the scalar fields and the leptons and quarks can also be used to generate their masses



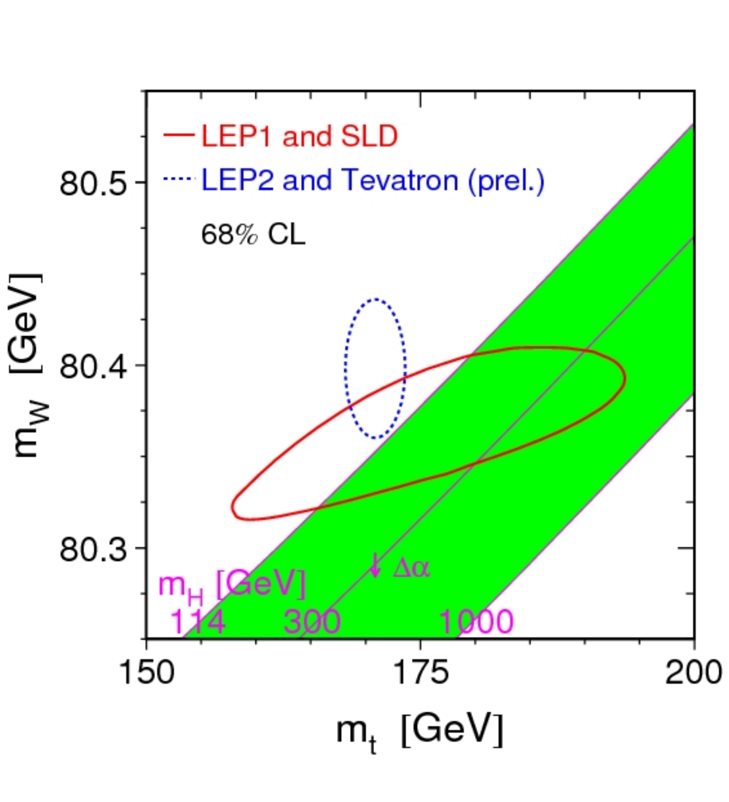
- In the Standard Model, the Higgs boson is the only undiscovered particle, making its discovery the most important goal currently in Particle Physics
- But why believe in the SM Higgs ?
  - There is no experimental evidence significantly contradicting the SM, within which a single Higgs potential provides 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 making our searches more general

SM Higgs: what we know

- 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



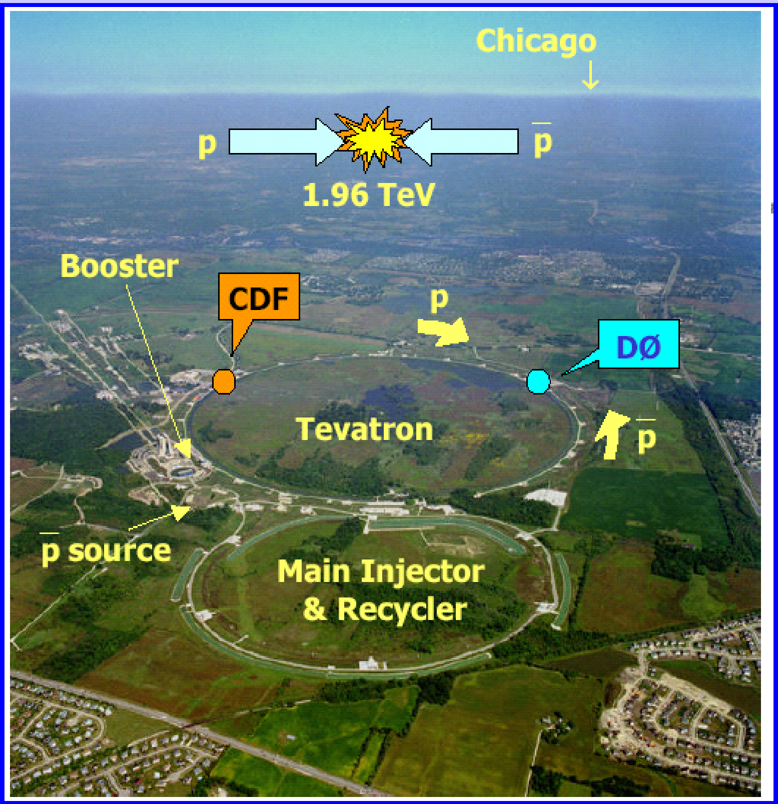
- Top and W mass measurements constraining the Higgs sector



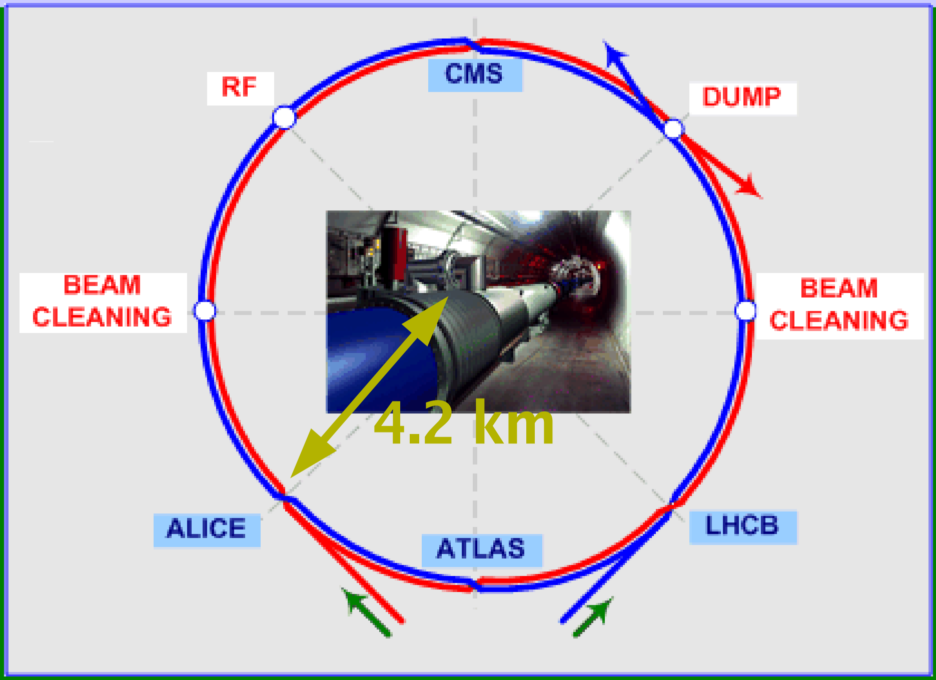
- Latest (LEPEWWG '09) fits to precision EW data
  - $m_H = 90^{+36}_{-27}$ GeV/c^2
  - $m_H < 163$ GeV/c^2 (95% CL)
  - $m_H < 190$ GeV/c^2 (when LEP limit included)

- The Tevatron is starting to exclude high mass Higgs bosons and will likely have at least ~2σ hints of, or rule out, a SM(-like) Higgs below 190 GeV by 2011

Tevatron → LHC



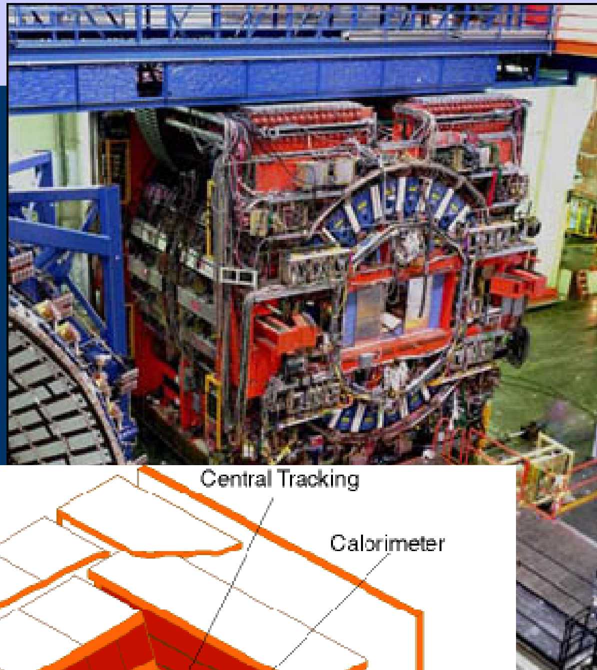
- 1.96 TeV p-p̄ collider
- 396 ns between bunches
- Has delivered ~6 fb^{-1} of data since 2002, and running smoothly:
  - expect ~10 fb^{-1} by end of 2010
  - Total of ~10,000 Higgs events **produced** (M_H = 120 GeV)



- ≤ 14 TeV p-p collisions
- Expect to turn on late 2009
- ~25 ns between proton bunches
- Low luminosity running (10^{33} $cm^{-2}s^{-1}$) to accumulate ~10 fb^{-1} by 2011
- Will eventually record ~100 fb^{-1} per year
- By 2012 will **produce** ~100,000 Higgs events per week (M_H = 120 GeV at 14 TeV)

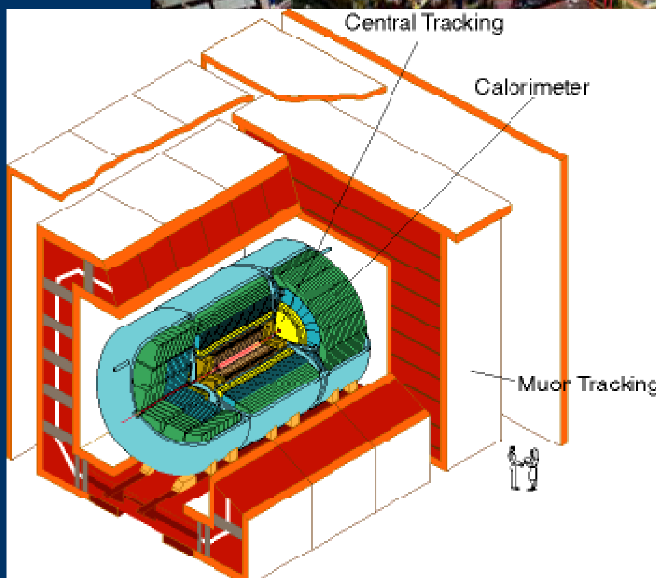
Detecting high-energy hadron collisions

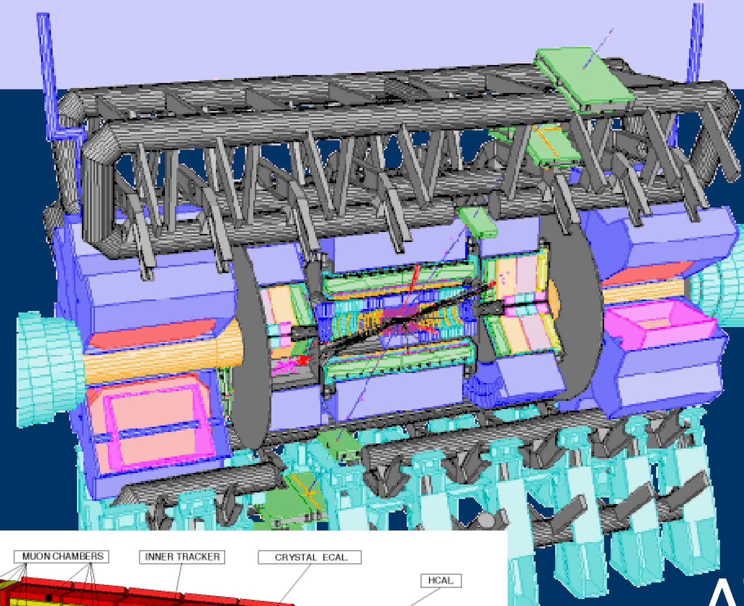
CDF



~10 m

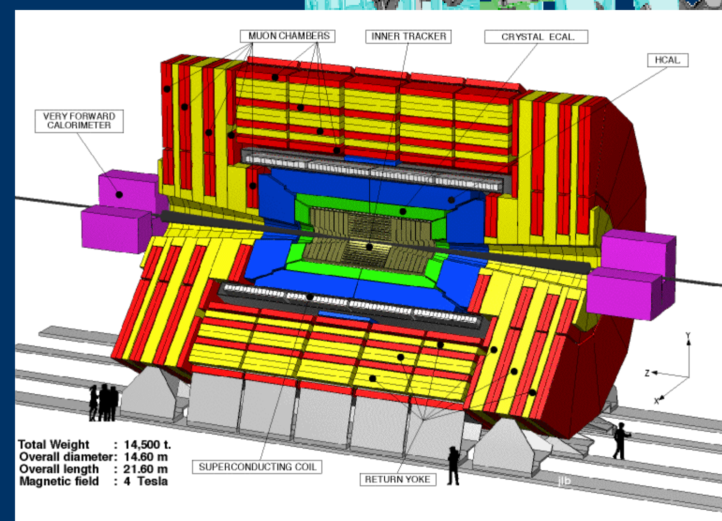
D0





~30 m

ATLAS

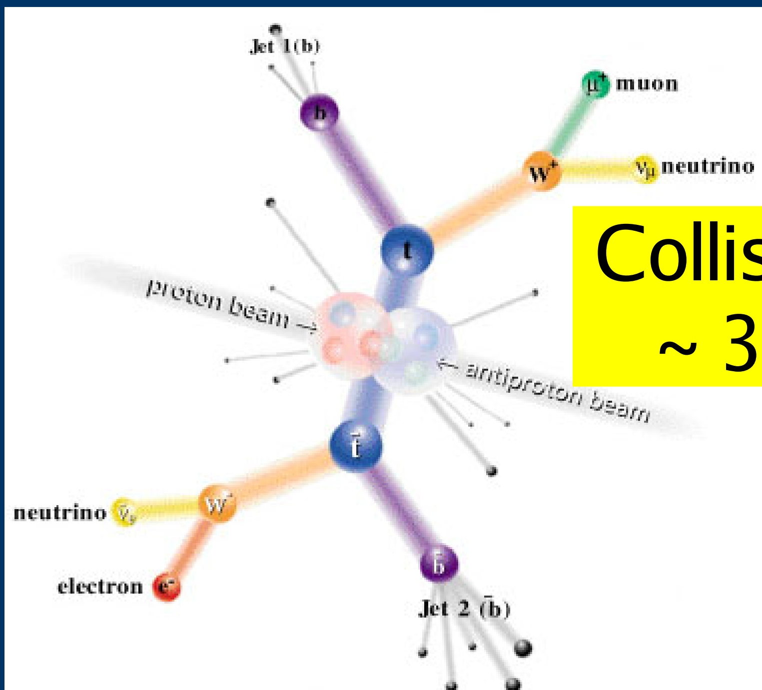


CMS

- Detectors in hadron collider experiments are broadly similar:
  - Inner detectors for precision tracking – momentum, secondary vertices
  - Calorimeters for energy measurements
  - Outer muon detectors
  - Most precise measurements in the transverse plane: E_T, P_T, $\not{E}_T$

Extracting the Physics from Collisions

- <u>**At the Tevatron:**</u>



Collision rate
~ 3 MHz

3 Tiered Trigger Systems to select "interesting" events

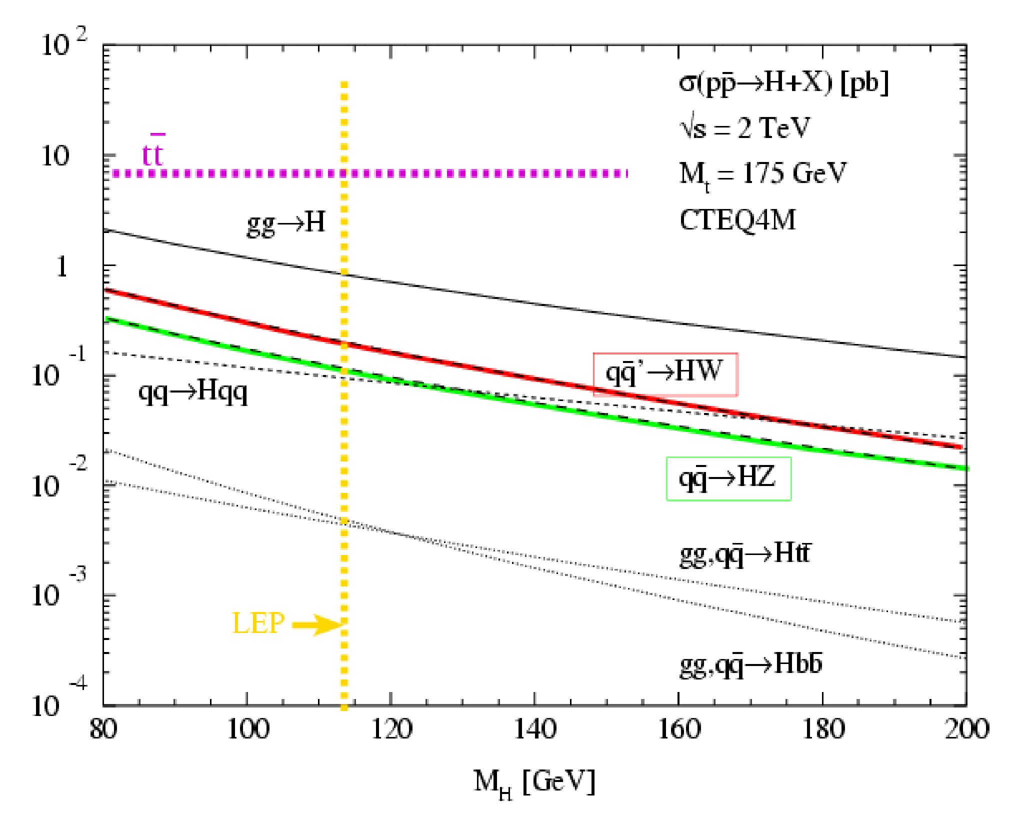
E.g. about 1 in 10^{12} collisions produces a Higgs event

Events written
to tape at ~50 Hz

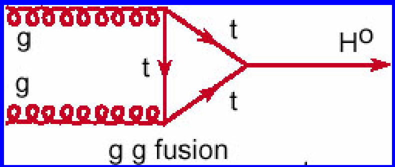
- <u>At the LHC</u> experiments have significantly greater challenges:
  - Trigger system to select ~10-100 much more complicated events per second from ~40 MHz rate

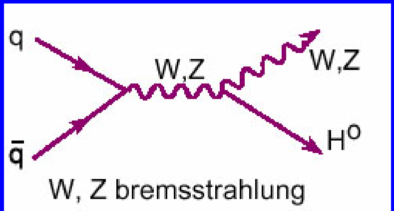
Higgs Production

Tevatron

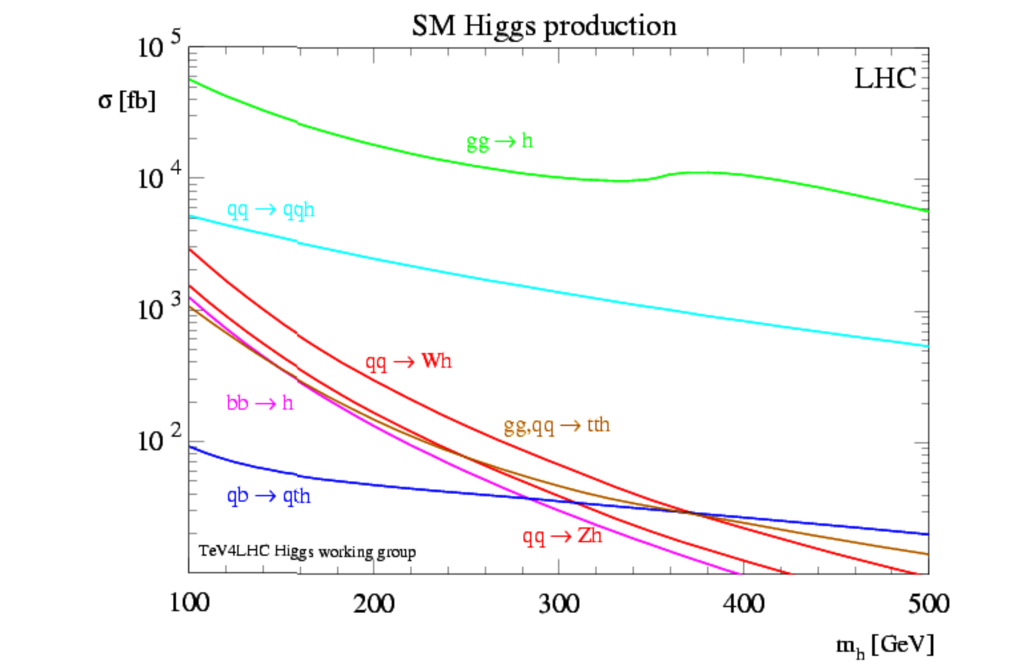


- Single Higgs production dominates
- Production in association with a vector boson order of magnitude less, but provides best sensitivity to low-mass searches

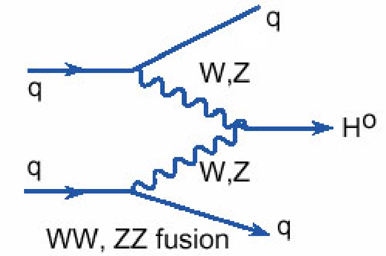




LHC (14 TeV)

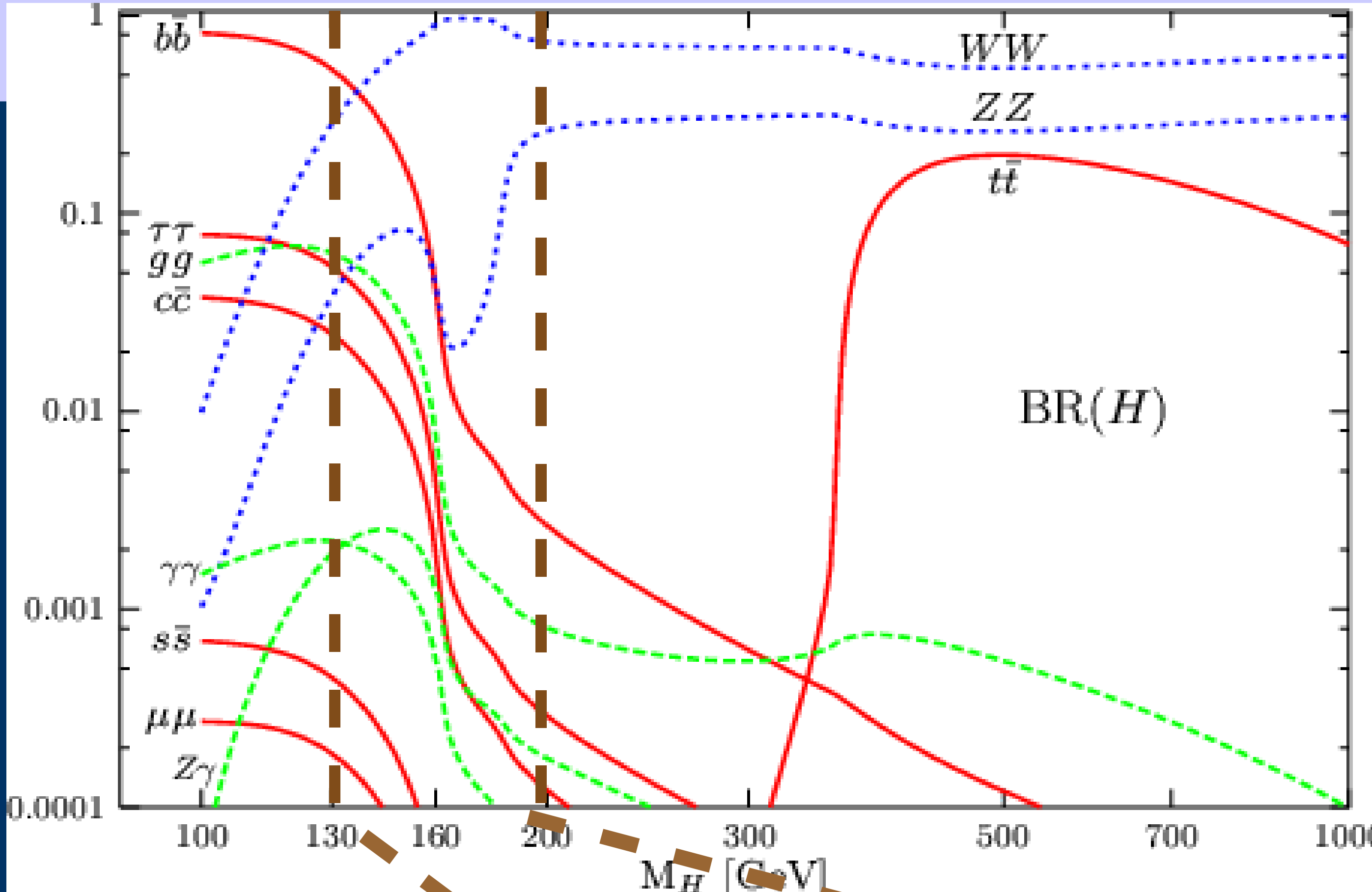


- gg→H two orders of magnitude greater
- qq→VH order of magnitude greater
- Vector boson fusion important



(See talk by R. Boughezal, Higgs I, for details on on recent developments)

Higgs decay



$100 < M_H < 130$

$130 < M_H < 200$

$200 < M_H < 1000$

Light Higgs

- At the Tevatron, bb most important
  - **Require VH production for sensitivity**
  - **Searches defined by vector boson decay**
- At the LHC γγ , ττ 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

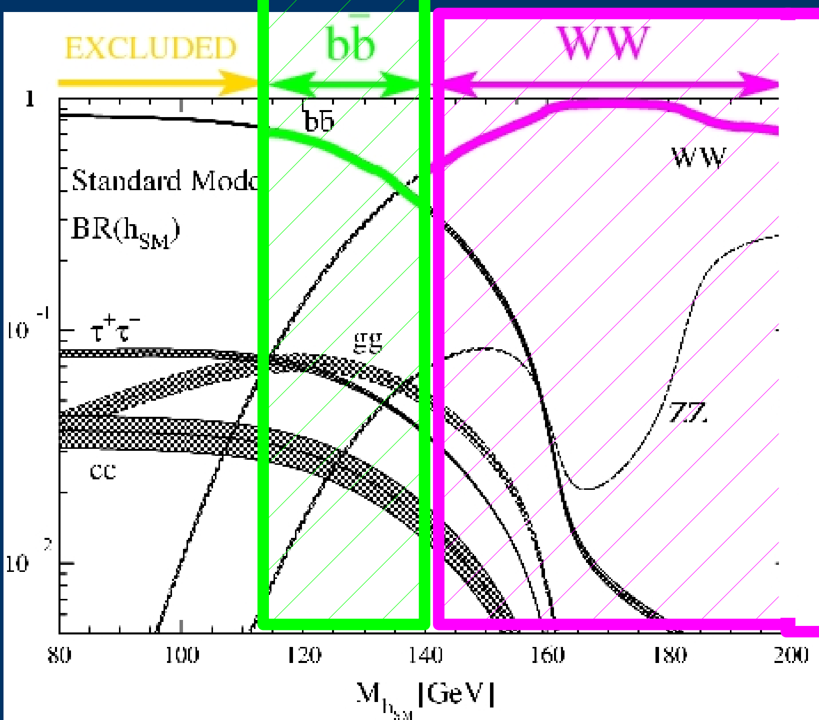
In 5 fb^{-1} of integrated luminosity:

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

SM Higgs searches at the Tevatron

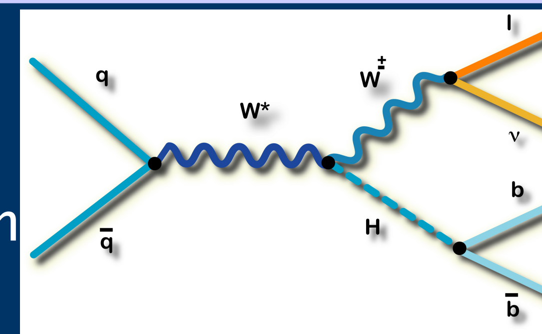
- Focus on WH and ZH production for "low" mass searches
  - WH → $l\nu$ bb : } most sensitive channels (talk by D. Price, Higgs I)
  - ZH → $\nu\nu$ bb : } most sensitive channels (talk by B. Jayatilaka, Higgs I)
  - ZH → ll bb : small BR, but clean signal (talk by Z. Shalhout, Higgs I)
  - WH/ZH → qq bb : large, difficult QCD backgrounds, but adds to combination
  - WH → $\tau\nu$ bb : can add some sensitivity but very difficult
  - Using H → $\tau\tau$: tough, but still contributes (talk by S. Chakrabarty, Higgs I)
  - H → $\gamma\gamma/Z\gamma$: little SM sensitivity, fermiophobic Higgs (talk by Xuebing Bu, Higgs I)

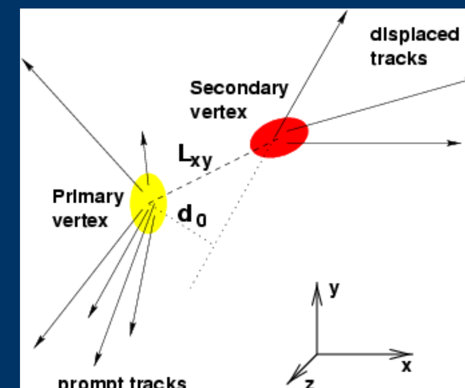


- Take advantage of gg → H for "high" mass
  - H → WW → $l\nu$ $l\nu$ provides most sensitivity (talks by J. Pursley and M. Kirby, Higgs II)
  - Contributes significantly down to ~125 GeV
  - WH/ZH → WWW/ZWW contributes
    - Same-sign dileptons
    - $l\nu$ $l\nu$ + jets
  - qqH → qqWW (Vector Boson Fusion) contributes 5-10% at the Tevatron

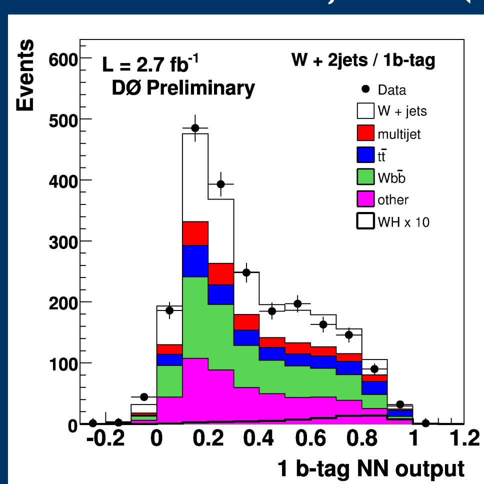
Challenges and techniques to finding Higgs at the Tevatron: low mass Higgs

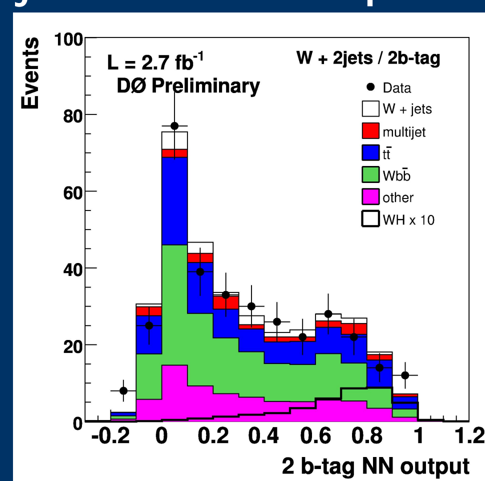
- Low mass: WH + ZH with H → bb
  - Main background (W/Z + jets and multijets) 3-4 orders of magnitude greater than signal after basic analysis selection
  - Crucial to “tag” jets from b's
    - Most powerful method is to measure secondary vertices from B decays (~50% to b-tag ≥1 jet)
    - Reduces backgrounds by at least order of magnitude
    - Other algorithms using additonal information also useful
  - Backgrounds still large (W/Z + h.f., multijets, dibosons, top)
  - Maximise use of kinematic differences between signal and background using multivariate techniques: NN's, BDT's, Matrix element methods, etc. (dijet mass most powerful)
  - Example:





S/B ~ 1/20 in high NN output bins

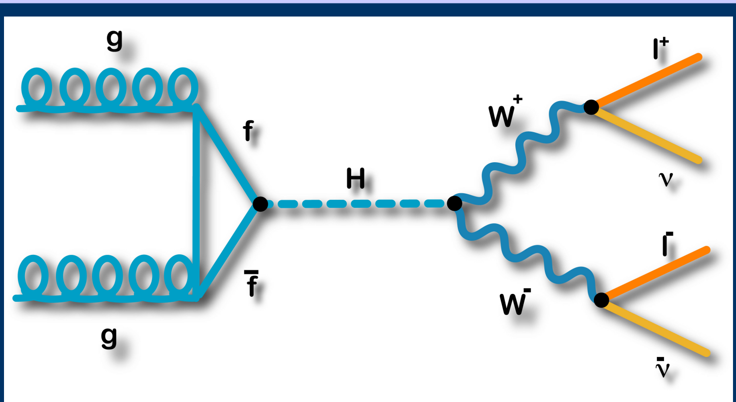


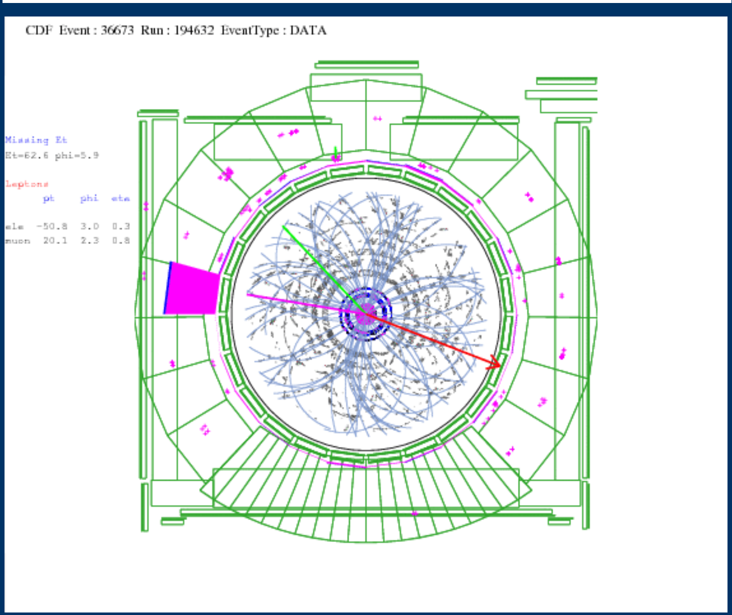


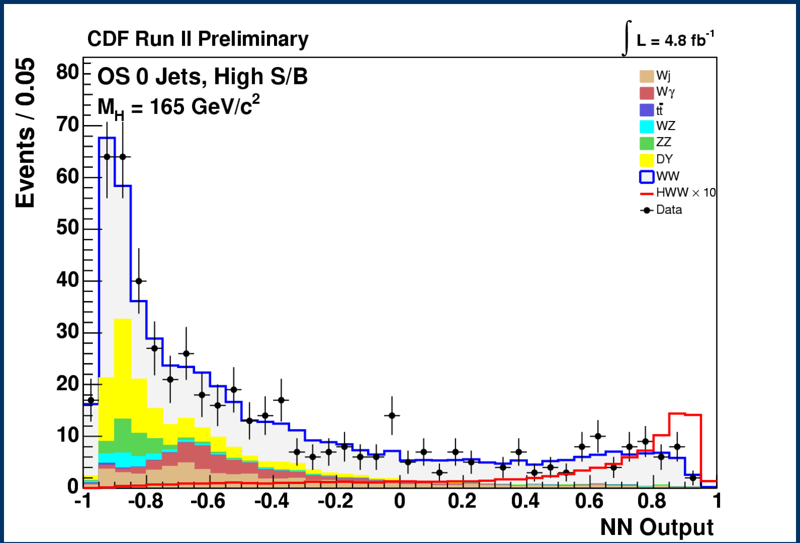
- 95% CL cross-section limits set by fitting the NN output distributions
- Both CDF and D0 combine all channels and produce a combined Tevatron limit

Challenges and techniques to finding Higgs at the Tevatron: high mass Higgs

- High mass: $gg \rightarrow H \rightarrow WW^* \rightarrow l\nu\, l\nu$
  - Main background is SM WW production (~30-50 times greater cross-section)
  - Include $WH/ZH \rightarrow WWW/ZWW$, VBF
  - Utilise different S/B for different jet multiplicities and for same-sign dilepton events
  - Maximise use of kinematic differences between signal and background using multivariate techniques: NN's, Matrix element methods, etc. (variable that contributes most sensitivity is $\Delta\phi(l_1,l_2)$)
  - Example:







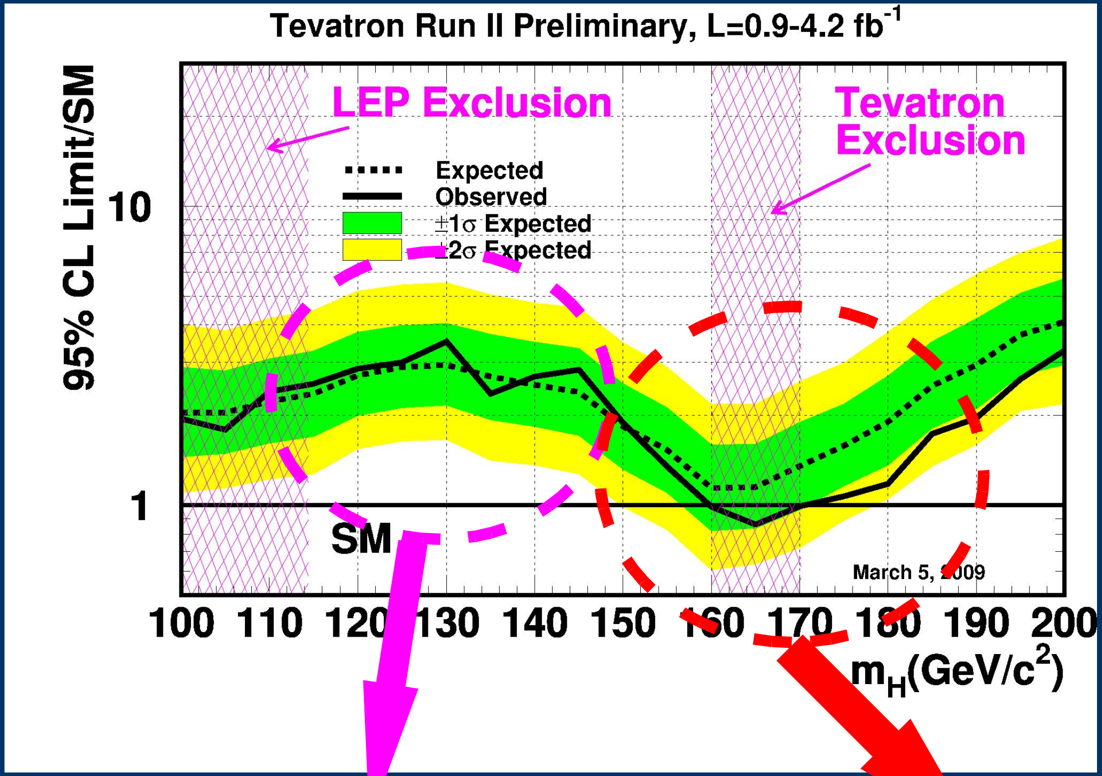
- Combines NN and ME techniques
- S/B ~ 1/3 in high NN output bins
- No signal seen – extract cross-section limits using likelihood fits to NN output distributions

Testing our sensitivity for low mass Higgs

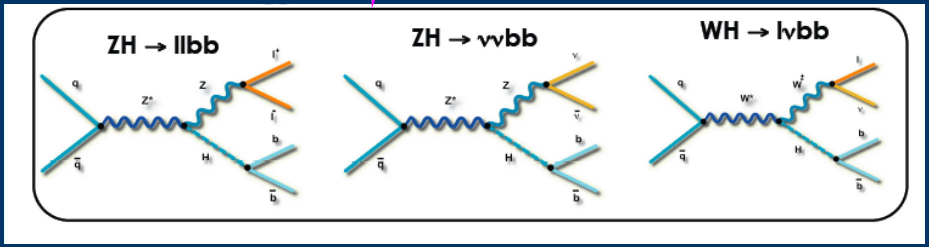
- Very fortunate to have measurable SM processes at the Tevatron with similar final states to test our procedures and sensitivities
  - Milestone 1: measure WW/WZ/ZZ cross-sections using leptonic decay of one vector boson and the hadronic decay of the other:
    - Cross sections >1 (but <2) order of magnitude greater
    - Both experiments have observed these processes

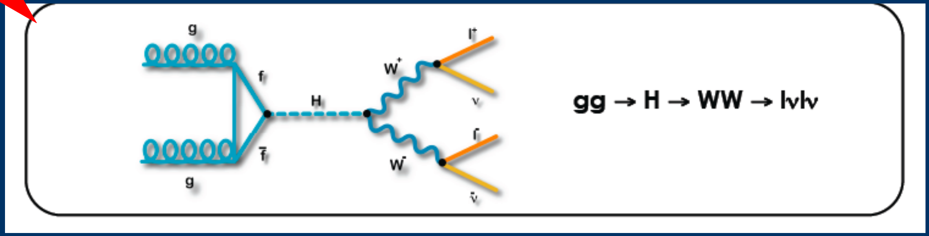
      (talks by M. Hurwitz and J. Pursley, Higgs II)
  - Milestone 2: measure WZ/ZZ with Z $\rightarrow$ bb and the leptonic decay of the other vector boson
    - σ(WZ/ZZ) x BR(Z $\rightarrow$ bb) 2-5 times that of σ(WH/ZH) x BR(H $\rightarrow$ bb)
    - This is much harder but getting close to evidence for these processes
    - Important to understand the expected vs observed sensitivity of these measurements to validate Higgs search techniques
  - Milestone 3: find, or exclude WH/ZH with H $\rightarrow$ bb

Tevatron results



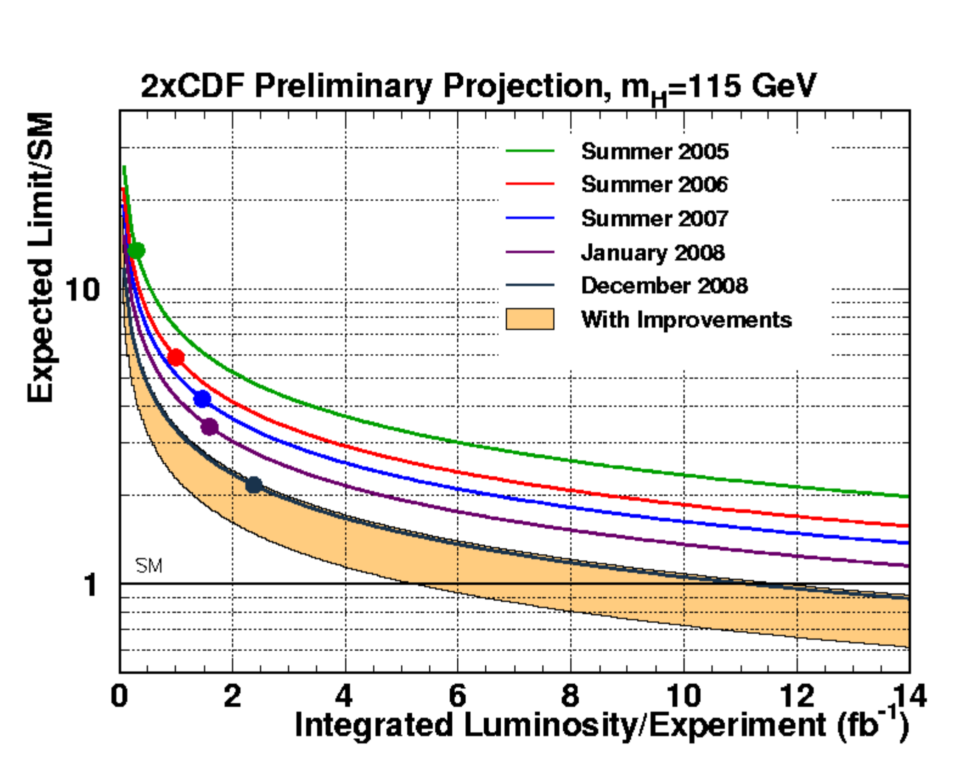
- Combine all channels from both experiments (from March 2009)
- First exclusion (at 95% CL) of a SM Higgs at a hadron collider
  - Excluded between 160 and 170 GeV
  - Major milestone for the Tevatron Higgs effort
  - Updated results using ~5 fb^{-1} will widen this exclusion window (~month)
- At 120 GeV only about 2.5 x SM (new results will be < 2 x SM)

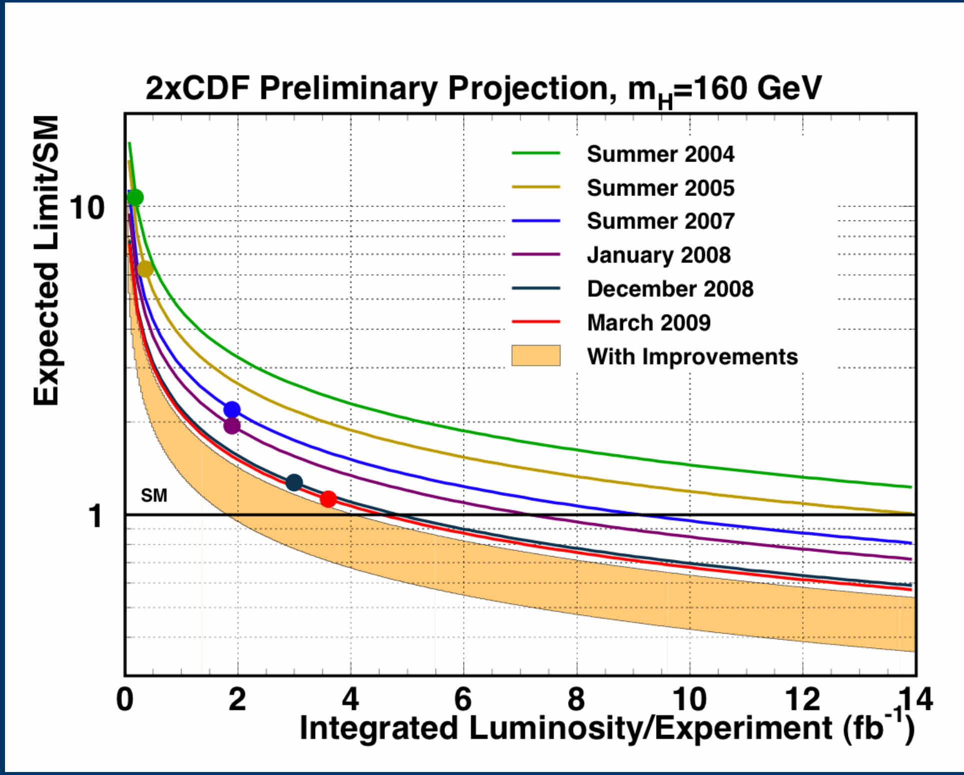




- Still making analysis improvements to achieve better sensitivity than from luminosity alone: extended coverage for leptons, better understanding of “control” regions, further exploration of advanced statistical techniques, ...

Tevatron SM Higgs prospects



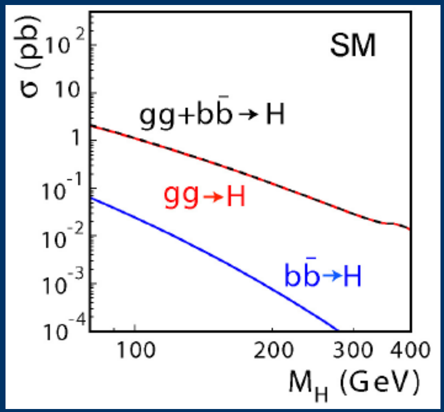


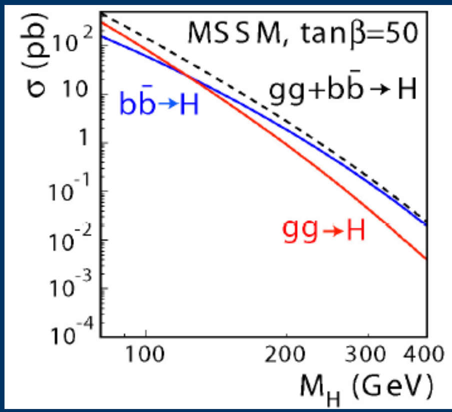
- Solid lines are the improvements with luminosity only ($\sim 1/\sqrt{\mathcal{L}}$)
- The shaded regions correspond to the ranges of expected improvements beyond luminosity
- The Tevatron will run at least through 2010 and accumulate 9-10 fb^{-1} by the end of 2010

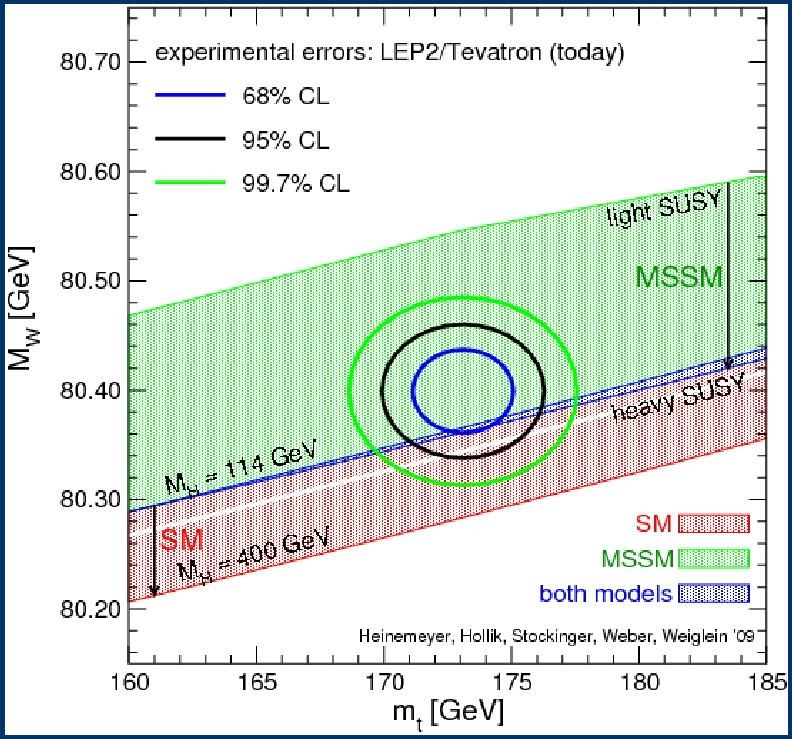
- Can now state with reasonable confidence that by 2011 the Tevatron will have either excluded the mass range above the LEP limit up to ~190 GeV, or seen at least hints of a SM(-like) Higgs in this range

Higgs searches in Supersymmetric models

- In MSSM (simplist SUSY extension to SM) two Higgs doublet fields result in 5 Higgs's ($H^\pm$, h, H, A) after Symmetry Breaking. $\tan\beta$ = ratio of VEVs of the two doublets
- M_A and $\tan\beta$ typically chosen to describe the MSSM sector. ϕ denotes h,H or A
- Coupling of A to down type quarks and leptons (e.g. b's, τ's) enhanced by $\tan\beta$ (cross sections enhanced by $\tan^2\beta$)
- So, even though the channels $gg \to \phi \to \tau\tau$, bb do not provide significant sensitivity to SM Higgs searches they do in some MSSM scenarios



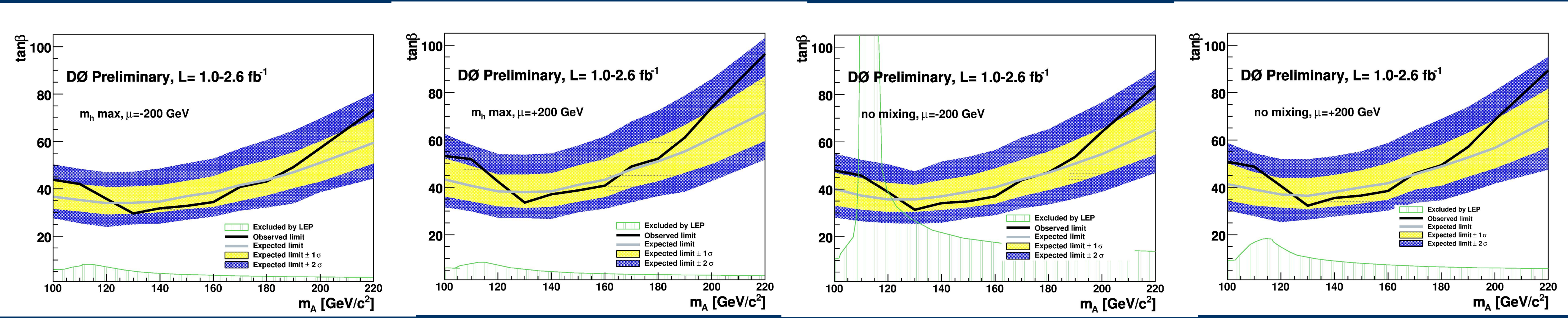




- Tevatron searches for $\phi \to \tau\tau$, $b\phi \to b\tau\tau$, $b\phi \to bbb$
- And for the charged Higgs in $t \to H^\pm b$
- Further motivation: As our top and W mass measurements get more precise, the MSSM sector seems to be getting more favourable.

MSSM results

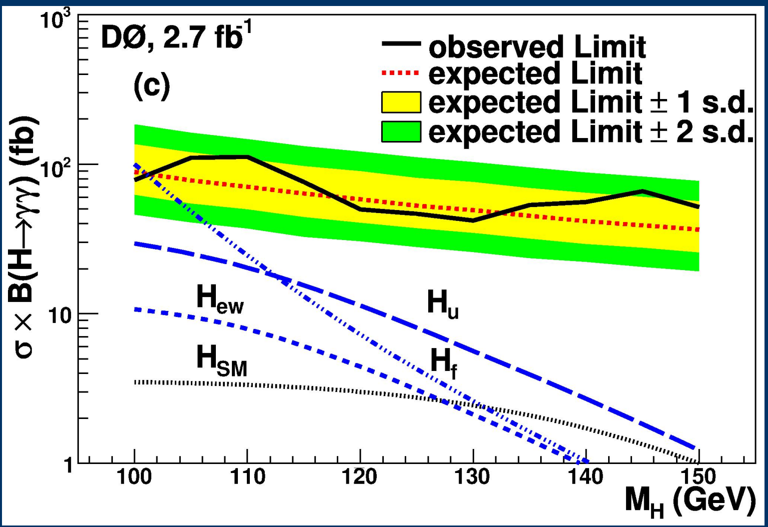
- Details of MSSM searches in talks by J. Conway and F. Ritzadinova in Higgs III session
- D0 have combined $\phi \to \tau\tau$, $b\phi \to b\tau\tau$, $b\phi \to bb$ searches:

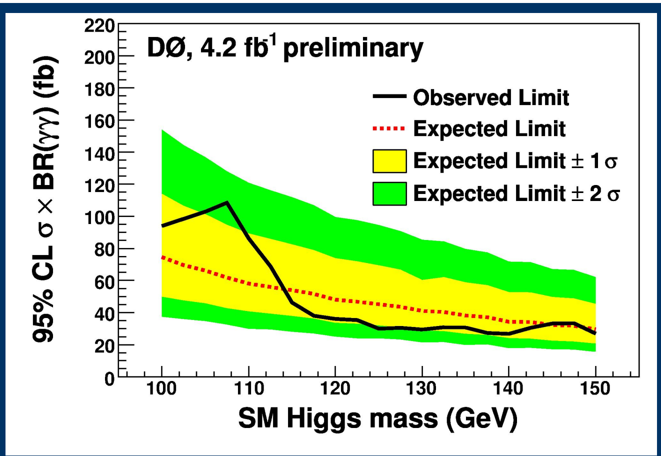


- Limits on tanβ vary from about 30-100 depending on M_A and scenario
  - Starting to probe interesting region of tanβ ~ 35 (= m_{top}/m_{bottom})
- New results and CDF+D0 combination (in the pipeline) could soon further restrict the MSSM model (see talk by L. Bellantino for more discussion)

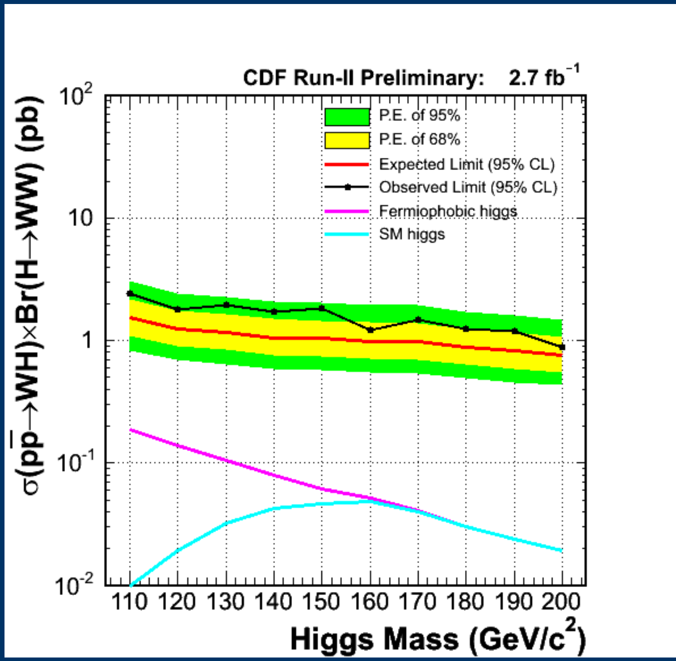
Fermiophobic Higgs bosons

- In models where the Higgs couplings to fermions are supressed, Higgs decays to vector bosons can be significantly enhanced:
  - Low mass: $H \to \gamma\gamma / Z\gamma$ dominates (c.f. SM BR($H \to \gamma\gamma$) ~ 0.2% around 120 GeV)
  - High mass: only makes a difference for M_H < ~140 GeV
- Tevatron searches for $H \to \gamma\gamma$, $WH \to WWW$: examples:





- h_f = benchmark scenario of no fermion couplings and SM couplings to vector boson
- From $H \to \gamma\gamma$ search have set lower limits limits on M_{hf} comparable to the LEP limit of M_{hf} > 110 GeV



- see talk by Xuebing Bu, in Higgs I, for more details

- $WH \to WWW$ searches give us additional sensitivity in higher mass regions

There are many other possibilities, some of which we are also looking for...

- More complicated SUSY variants, NMSSM, ...
- Technicolor models
- Topcolor models ⇒ tt resonances
- “Little Higgs” models
- Higgs triplet models
- Hidden valley models,   etc.....

Prospects at the LHC

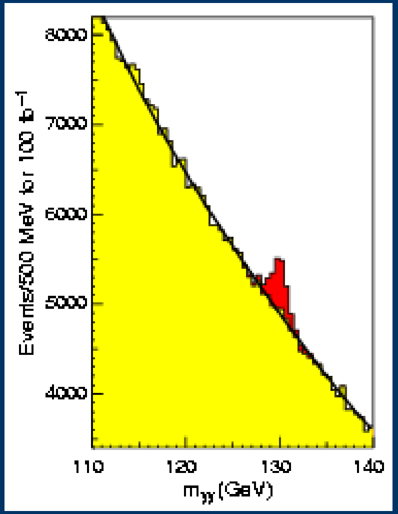
- If the Tevatron does find something we're not going to know what it is
  - The orders of magnitude greater cross sections at the LHC will allow for measurements of branching ratios and "Higgs" properties to help resolve what description of the universe we find ourselves in
  - In addition, the mass reach at the LHC allows for the possibilty of finding many more new particles that might be associated with this theory

- If the Tevatron doesn't find something, then the LHC will be our only tool in the next decade to unravel what is happening at the Fermi (TeV) scale (something has to be ?)
  - Even then, the precision measurements of couplings necessary to fully understand whatever new regime we find ourselves in will require an ILC and/or muon collider (in my view necessary to continue our exploration of the very early universe)

- Either way, the LHC era will be crucial to furthering our understanding of Nature

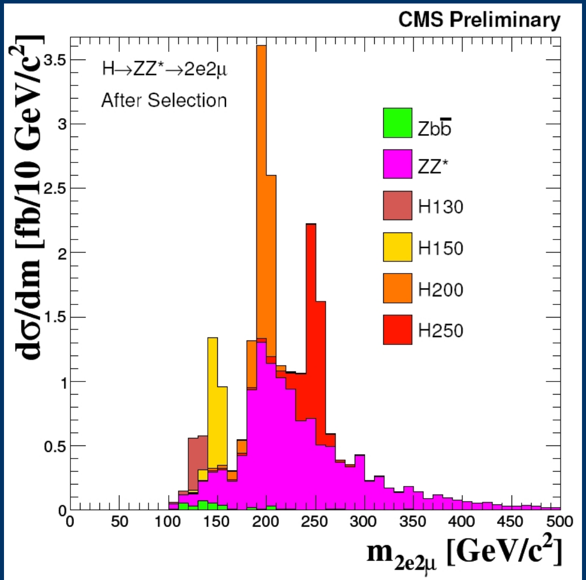
Light "Higgs" at the LHC (115 < M_H < 140 GeV)

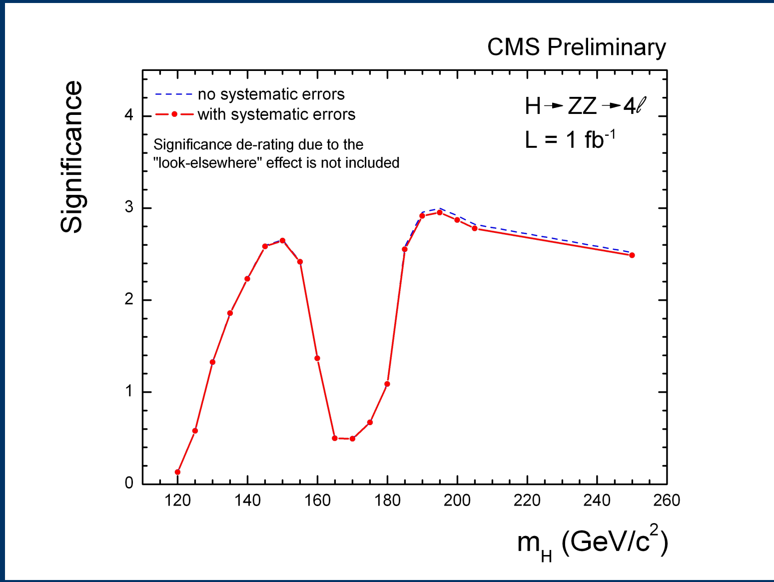
- About 2 orders of magnitude greater cross-sections for gg$\rightarrow$ H and qq $\rightarrow$ qqH (via vector boson fusion) compared to the Tevatron (assuming 14 TeV – about a factor of 2 less at 10 TeV)
- About 1 order of magnitude greater cross-section for qq' $\rightarrow$ W/Z + H
- This together with greater difficulty in distinguishing signal from the huge backgrounds for H $\rightarrow$ bb makes the most sensitive SM low mass Higgs channels,
  gg $\rightarrow$ H $\rightarrow \gamma\gamma$, qq $\rightarrow$ qqH $\rightarrow$ qq$\tau\tau$
  - An interesting associated production mode is ttH $\rightarrow$ ttbb – need a lot of data but nice test of coupling to the heaviest quark
- H $\rightarrow \gamma\gamma$:
  - major background from prompt γ's but peak narrow
  - requires accurate mass reconstruction: good γ energy and direction measurements
- qq $\rightarrow$ qqH $\rightarrow$ qq$\tau\tau$:
  - at M_H = 120 GeV BR(H $\rightarrow \tau\tau$) ~ 7%
  - distinct jets signature: forward, large η separation, large M_{jj}
  - Use both leptonically and hadronically decaying taus
  - More details in talk by R. Rahmat, Higgs I



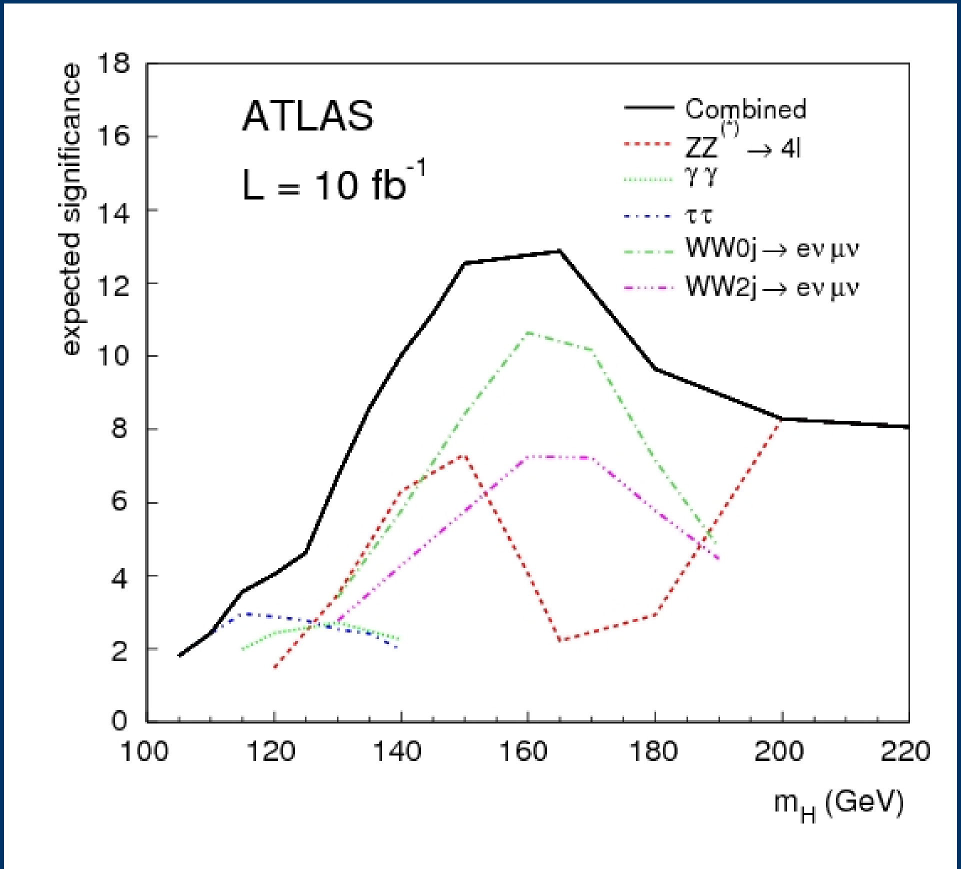
Heavy "Higgs" at the LHC (M_H > 140 GeV)

- Mostly focus on gg $\rightarrow$ H $\rightarrow$ WW/ZZ
- Tevatron has excluded masses between 160 and 170 GeV (and widening!) using H $\rightarrow$ WW $\rightarrow l\nu\, l\nu$ (l = e or μ)
- However, H $\rightarrow$ WW* still very effective down to ~125 GeV
- H $\rightarrow$ ZZ* $\rightarrow 4\, l$ considered the "golden" mode
  - Very effective for M_H > ~130 GeV (except for region around $2M_W$)
  - Full mass reconstructions (requiring good e/μ reconstruction)
  - Clean signature with relatively small backgrounds
  - Will require more than $1fb^{-1}$ for 3σ effect





SM Higgs discovery at the LHC



- Expect with ~10 fb^{-1} (after ~2 years) discovery or exclusion of SM Higgs over entire mass range

- See talks by H. Yang, A. Drodzetsky, and G. Carrillo-Montoya in Higgs III session
- MSSM at the LHC? See talk by T. Vickey in Higgs III session

To summarise....

- There has been no hint of a Higgs (SM or otherwise) so far at the Tevatron
- At the Tevatron:
  - the exclusion window around 165 GeV is widening
  - if there is no Higgs less than 190 GeV, the Tevatron will exclude all masses up to this by 2011
  - if there is a SM-like Higgs around 120 GeV the Tevatron has a very good chance to see evidence for it by 2011
  - The breadth of low mass searches also allows for non-SM Higgs
- The LHC will open up a new era of discovery potential. If nothing is found at the Tevatron, it will be up to the LHC to discover new Fermi scale physics. If the Tevatron does see hints of something it will be up to the LHC esperiments to figure out what it is
- Higgs, no Higgs, or what else ?.
  .....that will be the question we should answer in the next few years and that will change our description of the universe