Searches for New Phenomena Beyond the Standard Model

Lecture 2: Higgs

Dr. Steven Worm
CERN / Rutherford Appleton Laboratory

CERN School Thailand
Chulalongkorn University
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Outline

- Introduction to Searches
  - Standard Model– why search for something new?
  - The role of Detectors for searches
  - Search basics, plus an example (top)
- Searches for new Phenomena: Higgs
  - A little theory
  - Indirect searches and what they teach us
  - Status of searches for Higgs
- Searches for new Phenomena: Supersymmetry
  - Why Supersymmetry?
  - Status of SUSY searches
- Searches for new Phenomena: Exotica
  - Exotic detectors?
  - Many different models!
- Conclusions and new results from LHC

Standard Model, *Effective Theory*

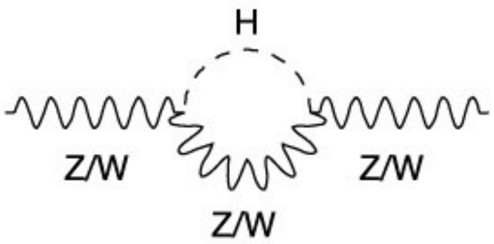
- Standard Model is extremely successful
  - Precision test of electroweak theory… agreement is impressive
  - Well tested description for interactions ≤ O(100 GeV)

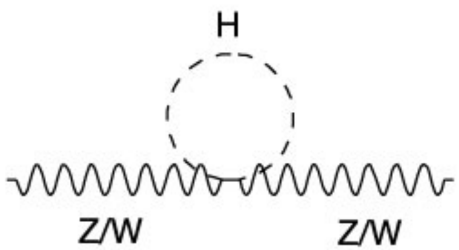
- Some obvious flaws however
  - Underlying mechanism of electroweak symmetry breaking (EWSB) unknown
  - if nothing else, gravity is not included and will be important near the Planck scale

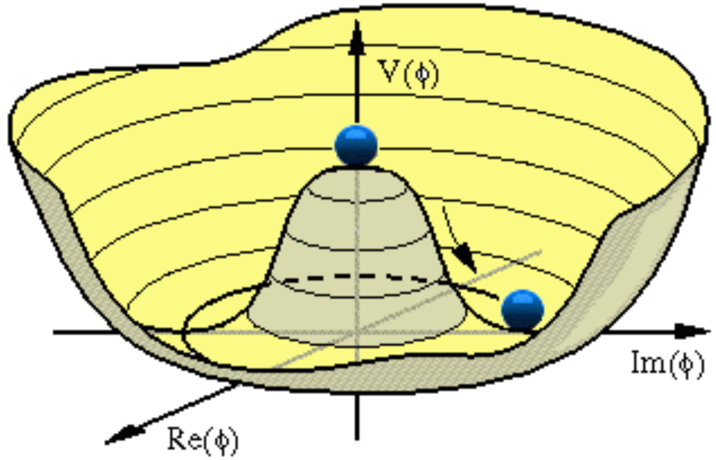
Works well at "low energy", but the Standard Model can't be the fundamental theory of particle interactions at very high energies

Standard Model Higgs

- A simple mechanism for EWSB in the Standard Model: the Higgs
  - weakly-coupled self-interacting fields, with one neutral scalar boson (Higgs)
  - This mechanism can be used to explain the observed $W^{\pm}$ and Z^0 mass
  - Standard Model predicts couplings, not the Higgs mass.
  - W, Z are sensitive to the mass from Higgs loops (logarithmically)
- For SM: $m_H^2 = \frac{1}{2}\lambda v^2$
  - λ relates to the Higgs self-coupling
  - $v \approx 246$ GeV and is set by the scale of the EWSB

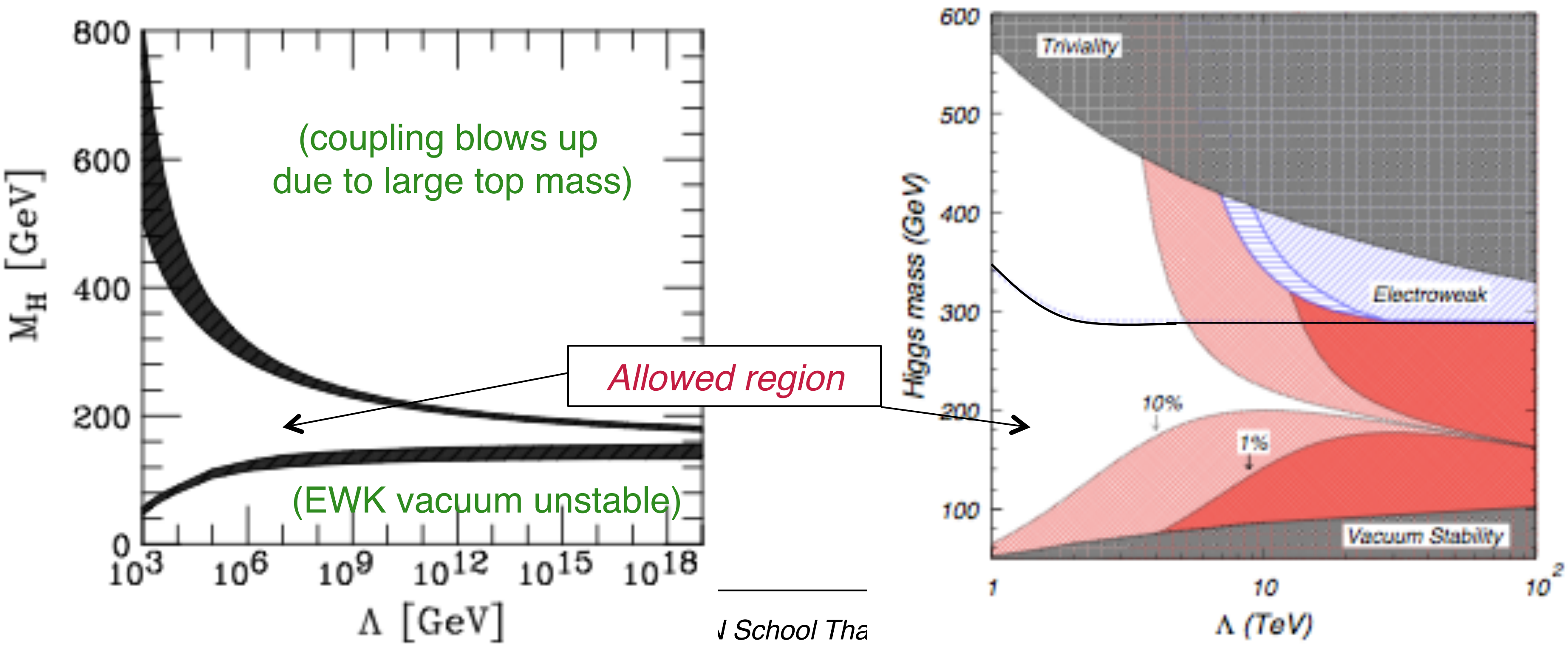






SM Higgs: Constraints from Theory

- For some scale Λ where the Standard Model breaks down, the SM Higgs…
  - cant be too small: can't reproduce observed breaking with v = 246 GeV
  - can't be too big: Higgs self-coupling "blows up"
- Given a scale Λ, can compute the allowed Higgs masses
  - By "naturalness" arguments, Λ ≈ 1 TeV



Argument for 1 TeV EWSB scale

- For an effective field theory, you should be able to calculate the low-energy masses and couplings in terms of parameters at some fundamental scale Λ
  - Scalar squared-masses are quadratically sensitive to Λ
  - All low-energy couplings and fermion masses are logarithmically sensitive to Λ

- Thus at one-loop level the Higgs mass at our energy scale has two parts

$$m_H^2 = (m_H^2)_0 + kg^2\Lambda^2$$

g = the Electroweak coupling

$(m_H^2)_0$ = the "mass" at the fundamental scale

k = constant

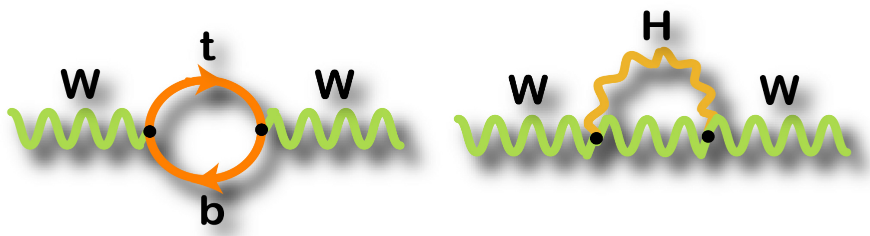
- It seems "unnatural" to have both terms large and (almost) exactly cancelling

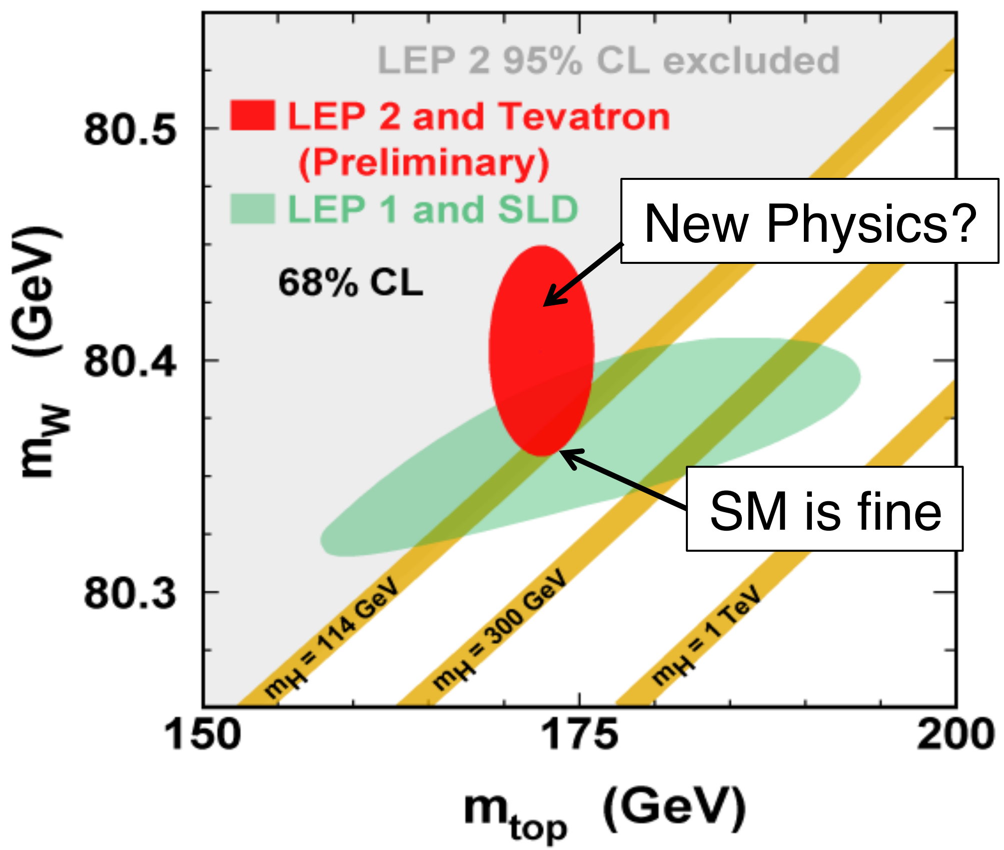
→ *Must be something new at the scale Λ ≈ O(1TeV)*

Indirect limits from W, top, Higgs

- First step in finding the Higgs is to look closely at W, top
- Masses of W, Higgs, and top all related:
  - m_W proportional to m_{top}^2
  - m_W proportional to $\ln(m_H)$
  - Very sensitive to changes in m_{top}
- Relation plotted below
  - If the Standard Model is "right", curves intersect at a point
  - If there are new particles, the relation can change

Already a hint of new phenomena?

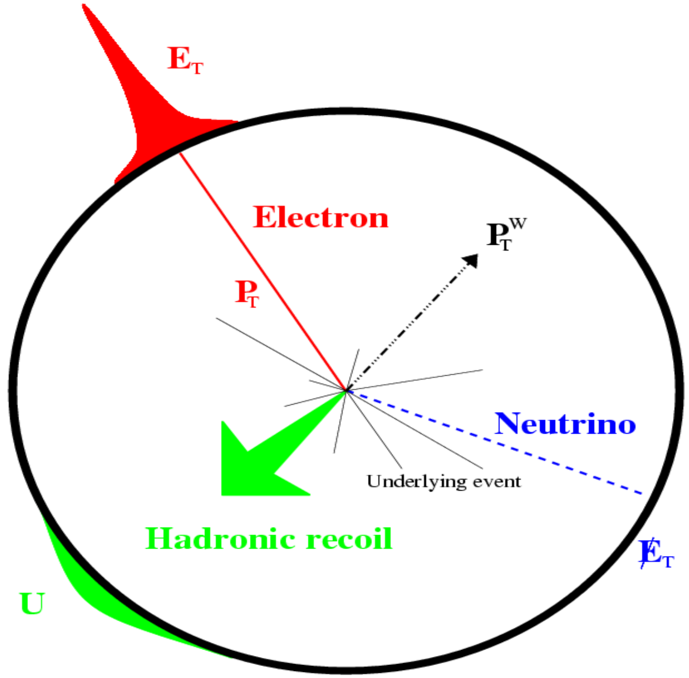




W Boson Mass

- A *precision* measurement:
  - LEP: $m_W = 80.367 \pm 0.033$ GeV/c^2 (0.04%)
  - World Ave: $m_W = 80.399 \pm 0.023$ GeV/c^2 (0.03%)
  - LHC target: 0.01%?

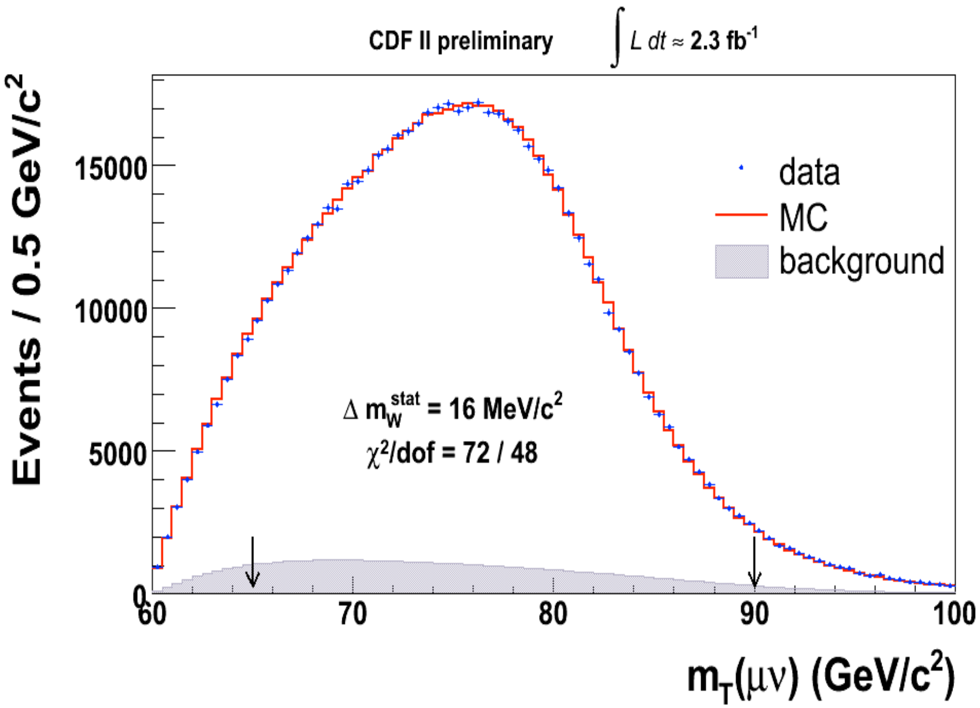
- Experimental challenges
  - Measurement of lepton p_T (tracking)
  - Hadronic recoil (calorimeter)
  - Z → leptons great calibration but limited size
  - Theoretical uncertainties
  - Still dominated by statistics (of Z sample)

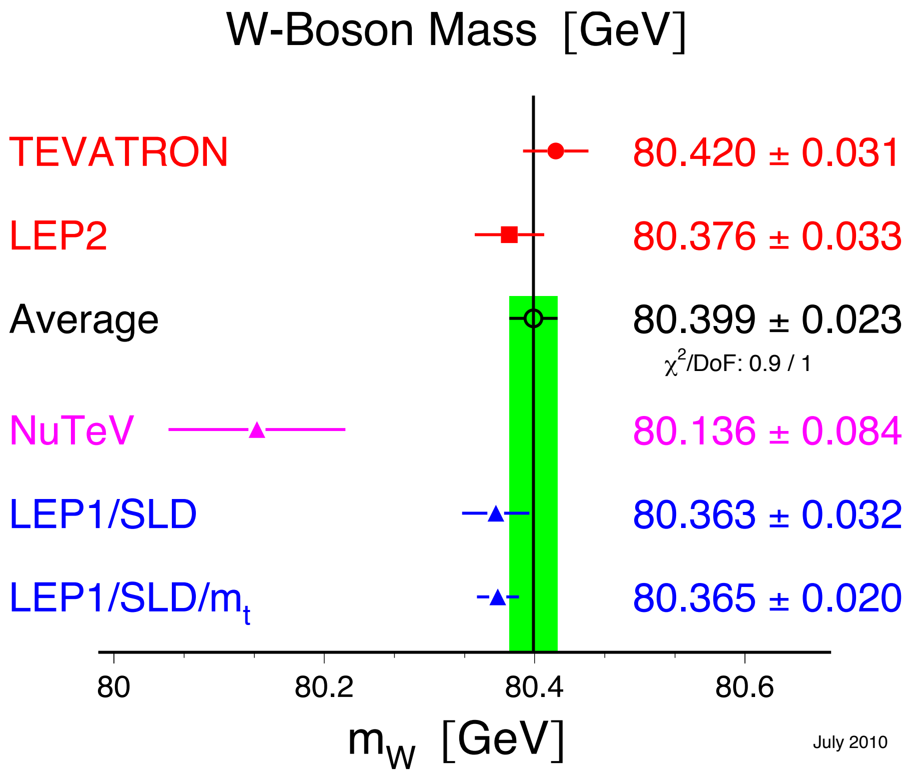


$$\not{p}_T \approx |p_T + u_{||}|$$

$$m_T = \sqrt{2 p_T^l \not{p}_T (1 - \cos\Delta\phi)},$$
$$\approx 2 p_T \sqrt{1 + u_{||}/p_T}$$
$$\approx 2 p_T + u_{||}$$

W Boson Mass

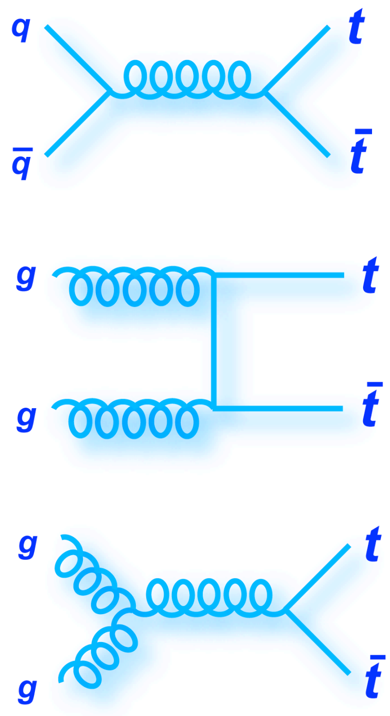




World average: $m_W = 80399 \pm 23$ MeV

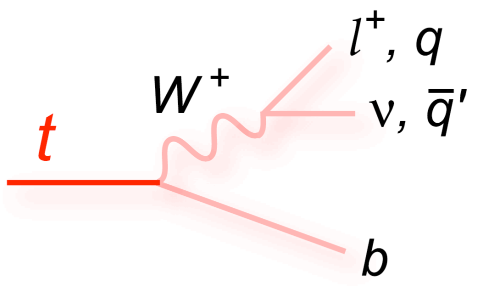
Top Quark Production and Decay

- Top production
  - At Tevatron, mainly produced in pairs via the strong interaction
  - At the LHC, via gluons



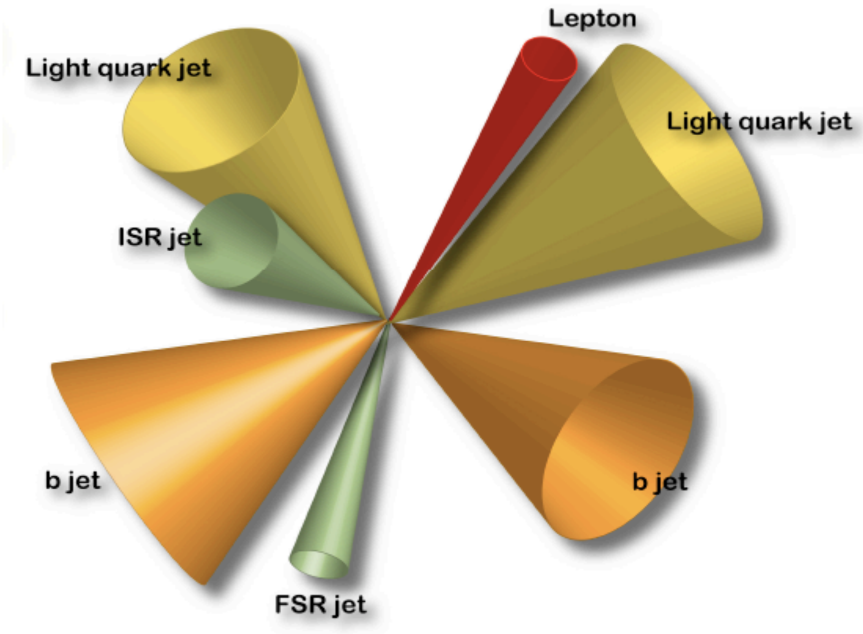
- $t \rightarrow Wb$, with the two W's decaying to hadrons or leptons

- Top decay in three categories:
  - Dilepton $tt \rightarrow ll\nu\nu bb$
  - Lepton+Jet $tt \rightarrow l\nu bb$ + 2 jets
  - All-Hadronic $tt \rightarrow bb$ + 4 jets



- Cross Sections at Tevatron and LHC:
  - Tevatron: 7 pb
  - LHC (7 TeV): 160 pb
  - LHC (14 TeV): 890 pb

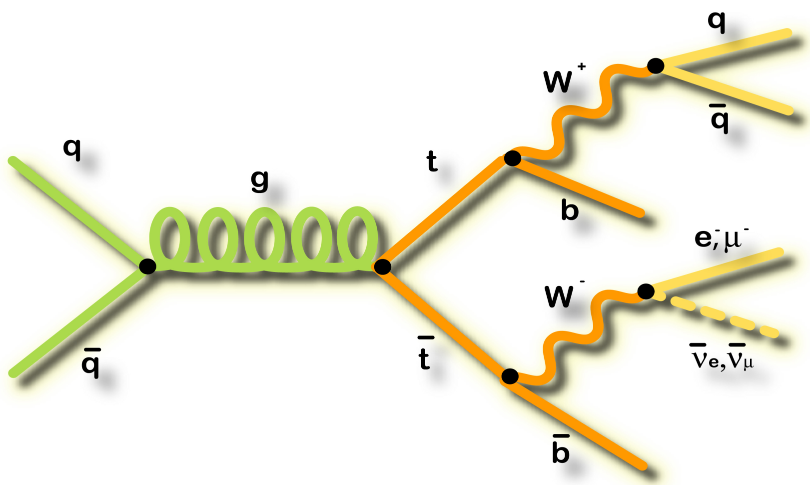
Top Mass Measurement Techniques



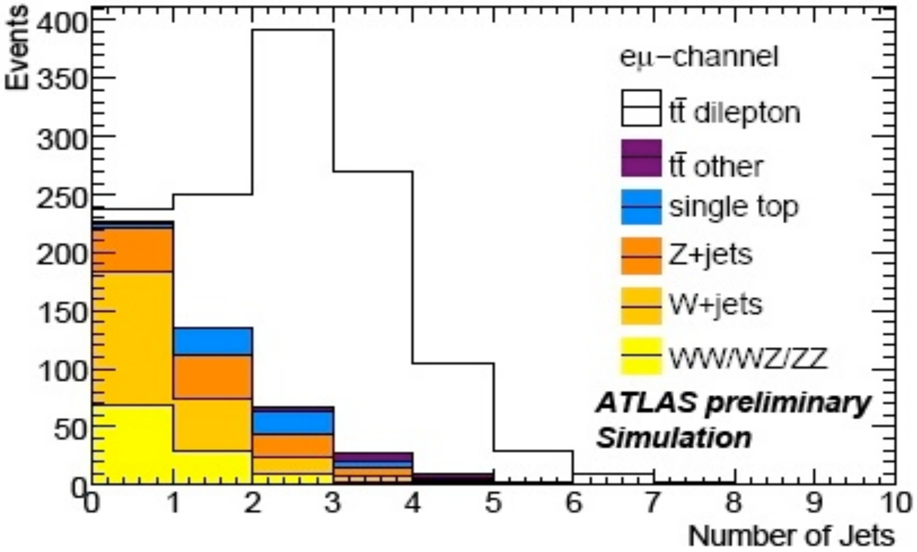
- $t\bar{t} \rightarrow$ lepton + jets: 4 jets, 1 lepton, missing E_T
  - Would like to reconstruct W, b jets
  - many possible combinations possible; what is the right one?
  - B "tagging" helps to greatly reduce possibilities

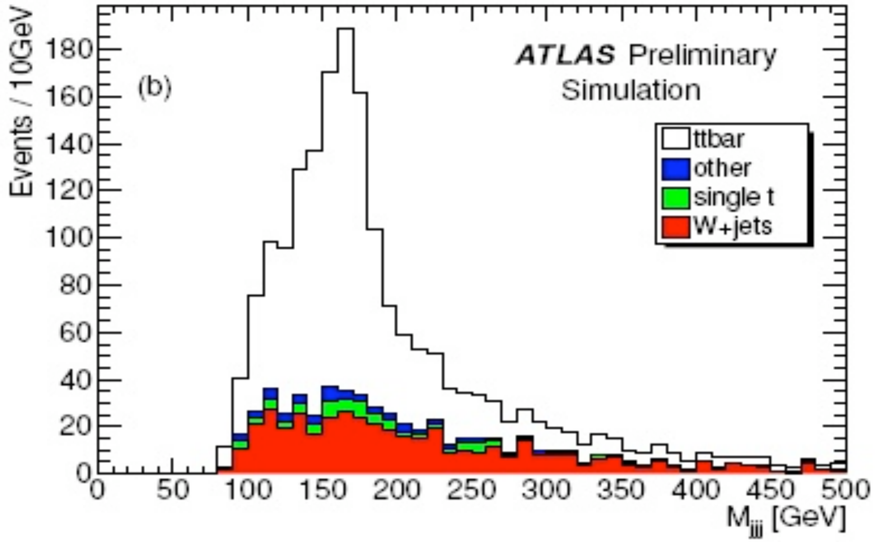
- Template method:
  - Uses "best" combination
  - Chi^2 fit requires two tops with same mass

- Matrix Element method:
  - Uses all combinations
  - Assign probability depending on kinematic consistency with top



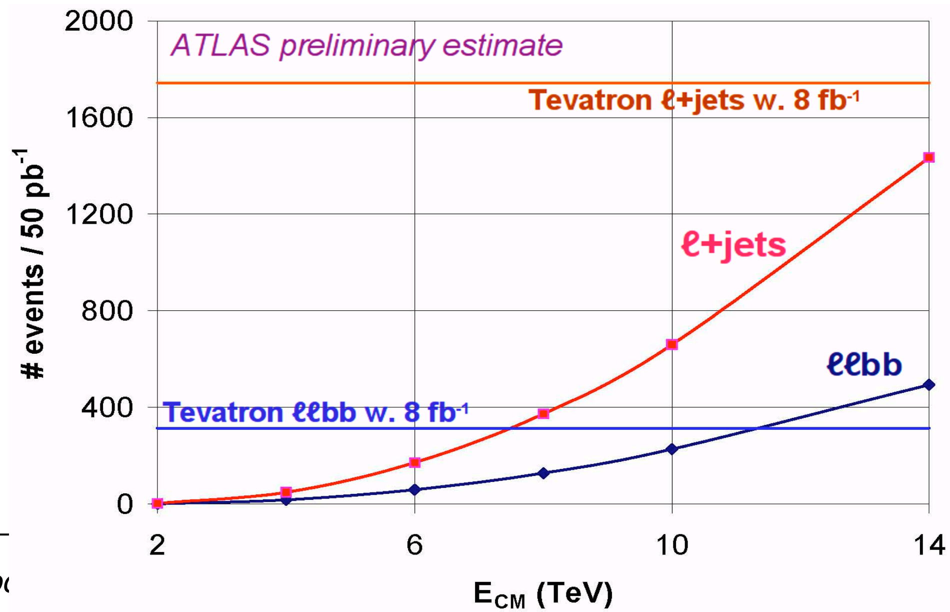
Top at LHC: less background





- For the LHC $\sqrt{s}$=7 TeV
  - About 20 pb^{-1} needed to "rediscover" top (have that ~now)
  - About 200 pb^{-1} surpass Tevatron top sample statistics (next year?)

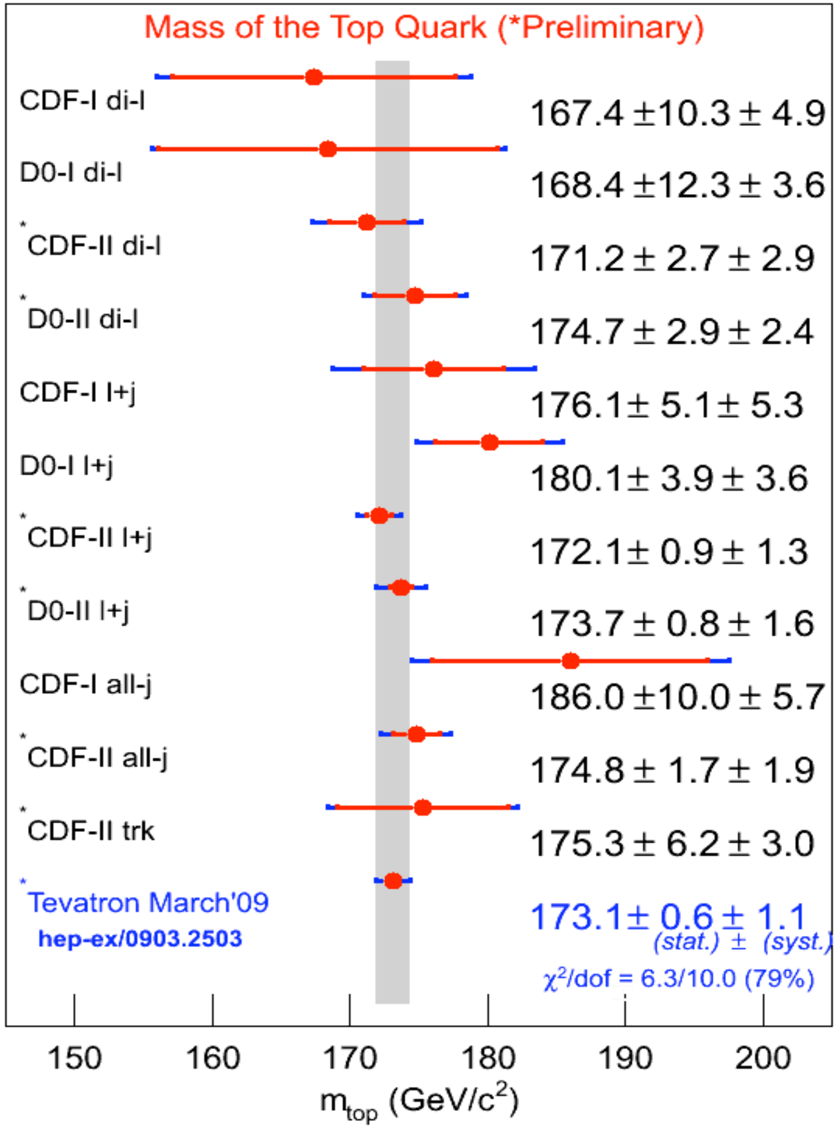
LHC will take the lead soon!



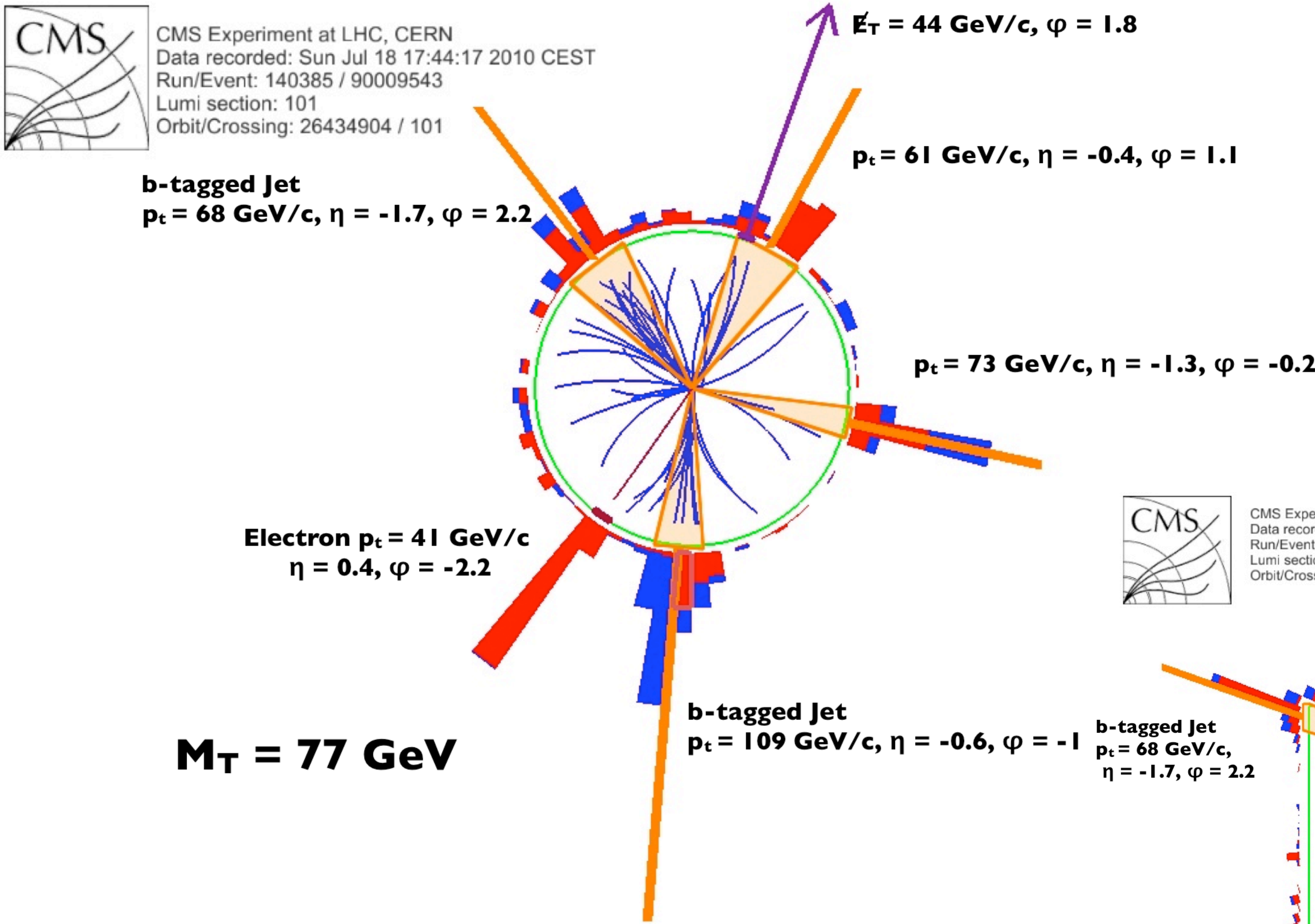
Tevatron Combination of m_{top} Results

- Combine all results to improve precision
  - Correlations taken into account
  - All measurements and channels used: dilepton, lepton+jets, all-hadronic
  - Dominated by systematic uncertainties
- Result: 173.1 ± 0.6 ± 1.1
  - Uncertainty = 1.3 GeV (<1%)
  - Tevatron expects to improve to ~1 GeV

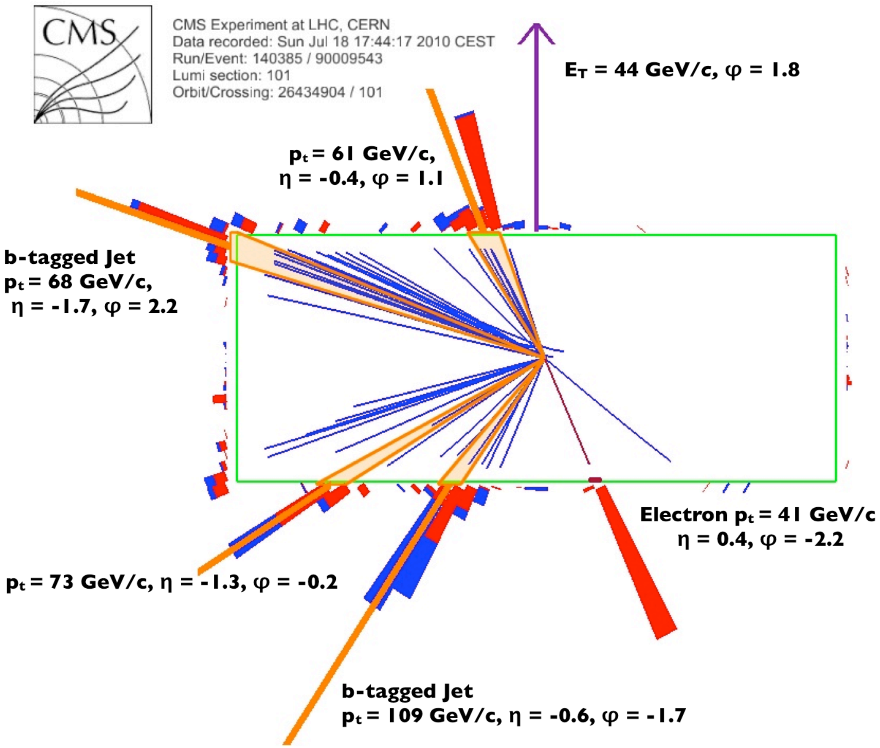
Excellent precision, and still improving



Top at the LHC?

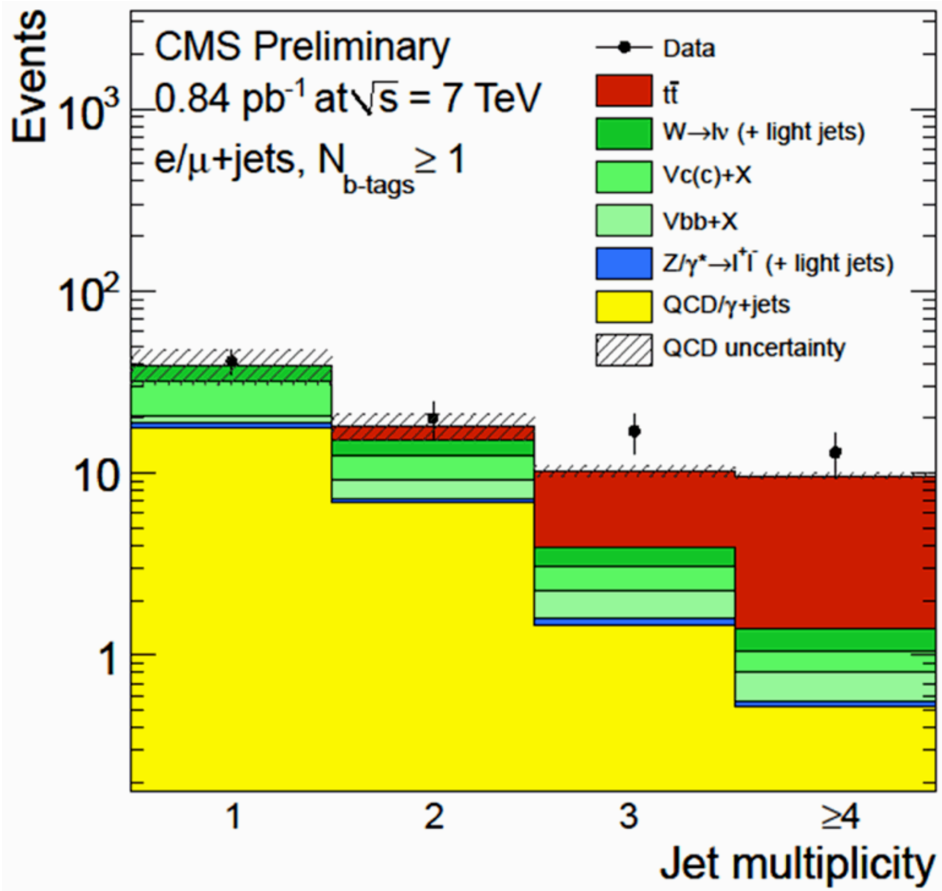


M_T = 77 GeV



LHC is a Top "Factory"

- Top production is underway!
  - Top signatures: lepton+jets or dileptons
  - b-tagging already in use at CMS, ~1% fake
- Look in $N_{jets} \geq 3$ for excess (red in plot)
  - 30 events observed
  - expected 15 + background 5.3
- Top observed with a rate consistent with NLO theory + experimental errors

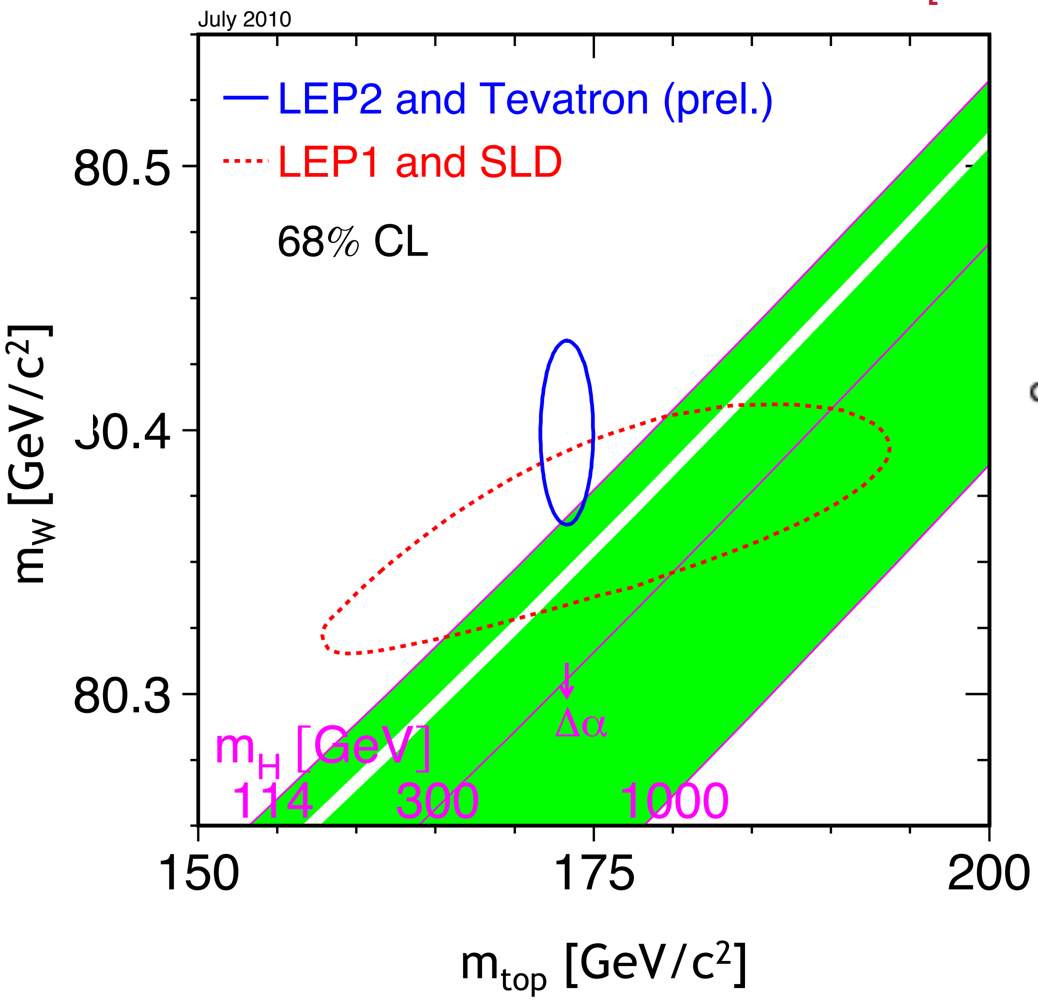


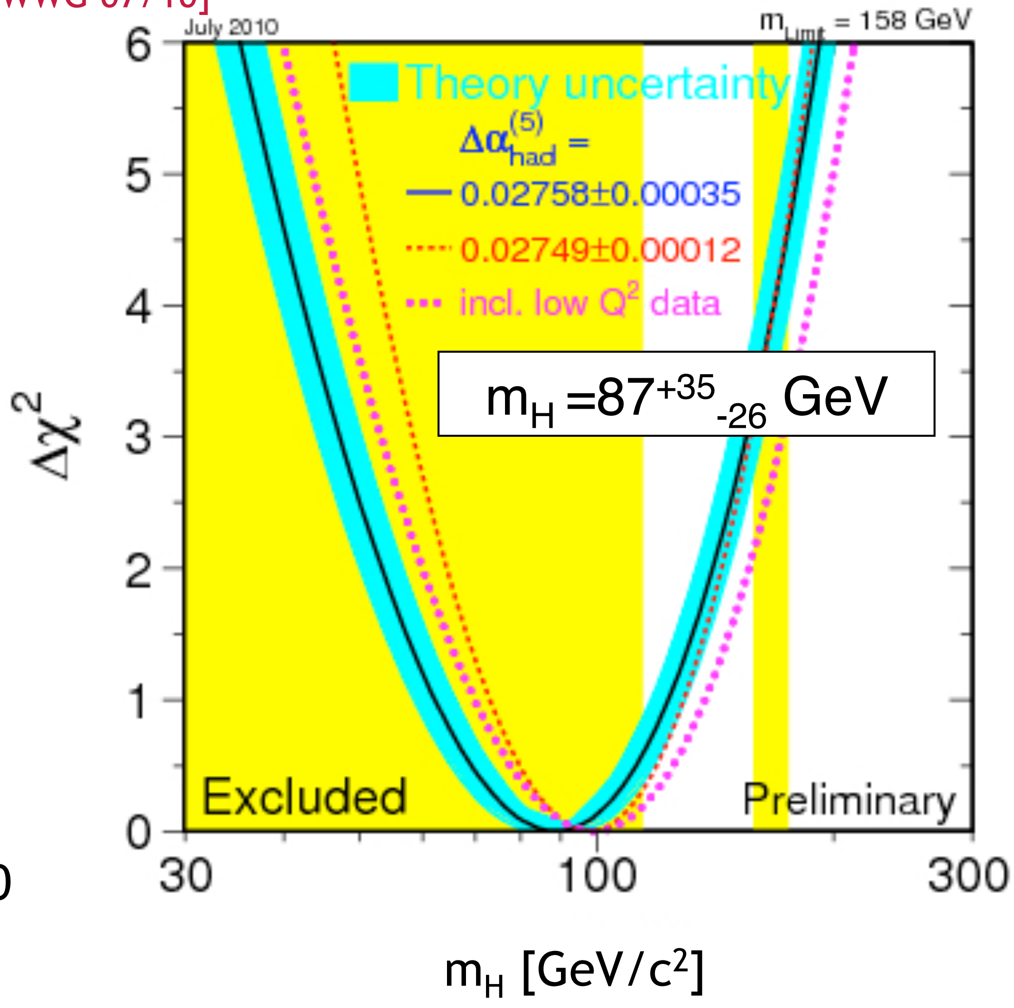
Top can be the gateway to new physics

(See Albert's lectures for more details)

Implications for the Higgs Boson

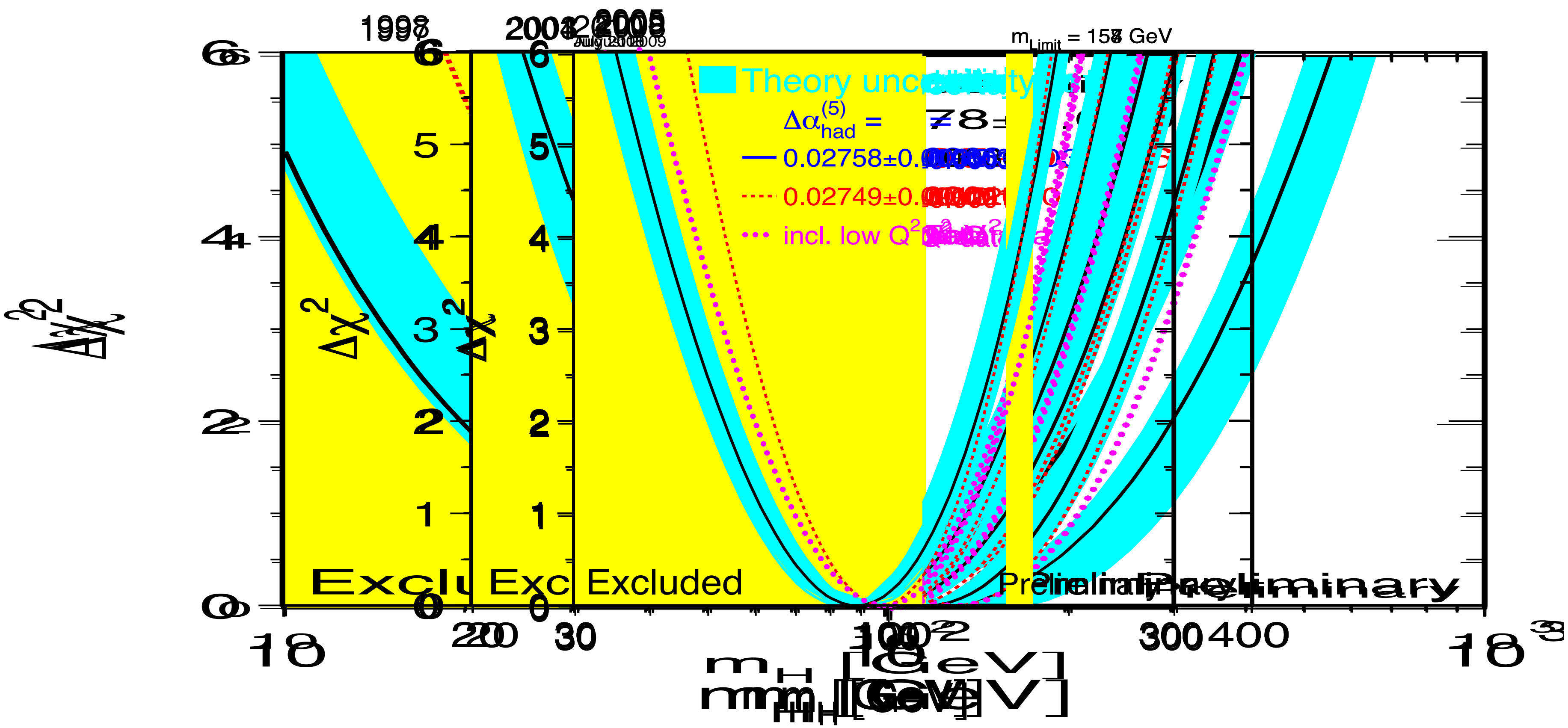
[LEPEWWG 07/10]





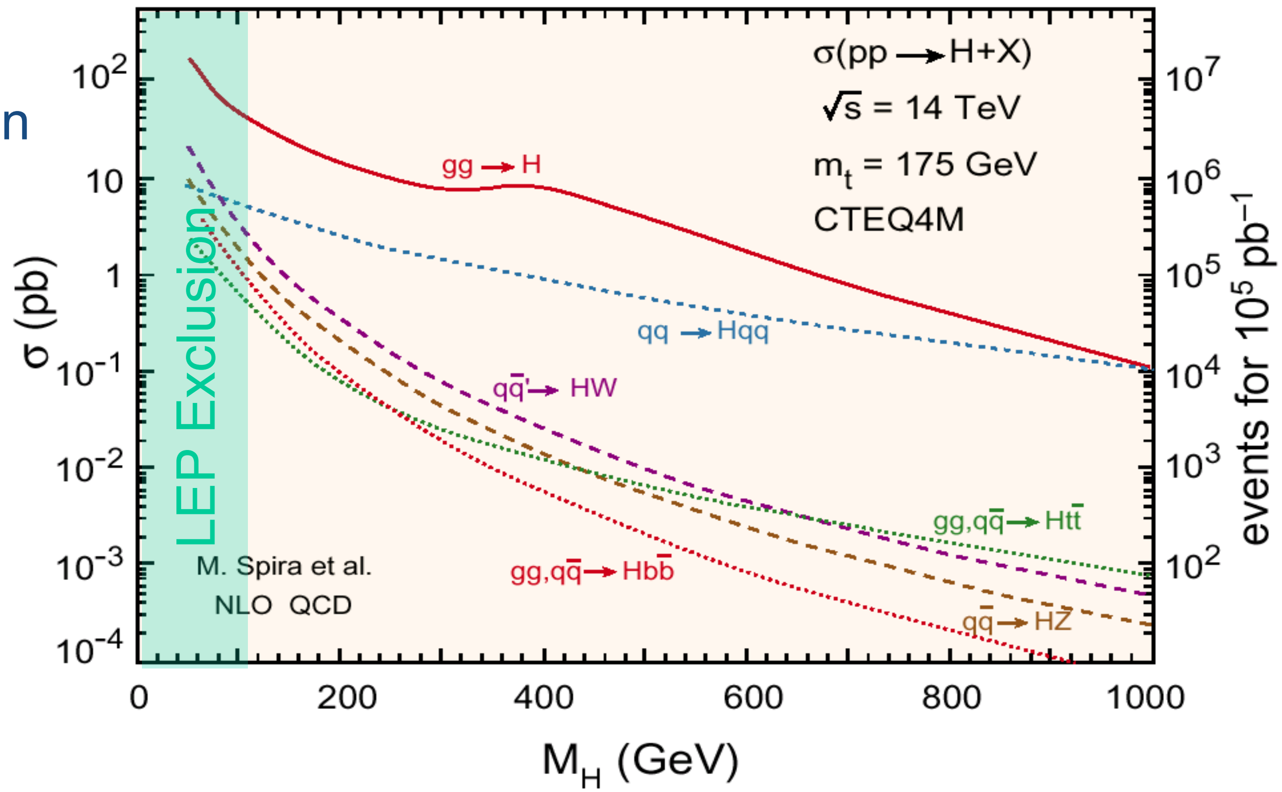
Current constraints: Standard Model m_H<158 GeV @95%CL

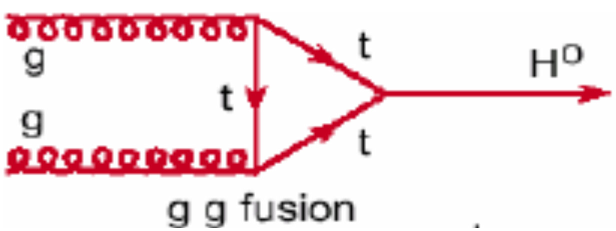
“Narrowing” the search…

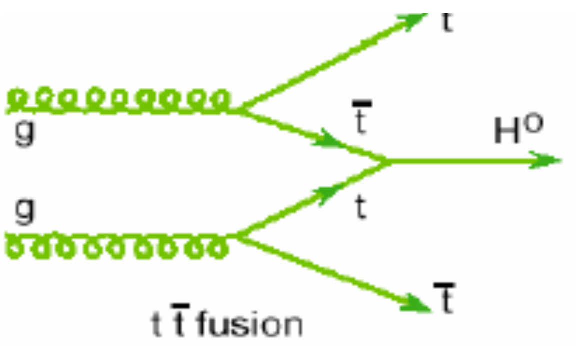


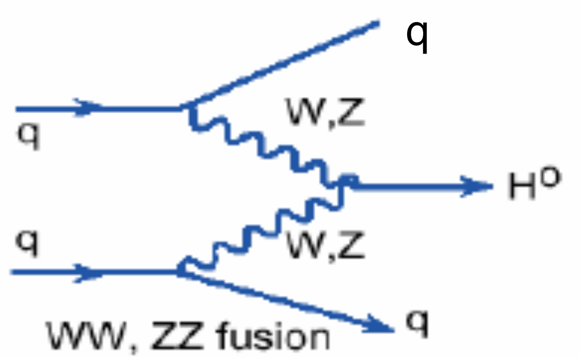
Higgs Production at the LHC

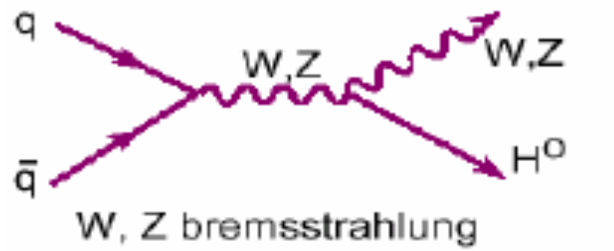
- gg fusion (dominant), VB fusion, associated production
- Cross section > 20 pb for gg in low mass
- Generally "cleaner" than Tevatron qq processes











Higgs: Tevatron vs LHC

- Cross section much larger at LHC compared to the Tevatron (energy)
  - The glue-glue process dominates
- Tevatron vs. the 14 TeV LHC:
  - Factor of 50 higher for low mass H
  - Factor of 100 higher for high mass H
  - Higher backgrounds from qq processes: more backgrounds at Tevatron

mH (GeV)	Tevatron (2 TeV)	LHC (7 TeV)	LHC (14 TeV)
120	1.0	17	54
140	0.7	12	42
160	0.4	9	33
180	0.3	7	26

[Ahrens et al, arXiv:1008.3162]

Higgs: What constitutes a discovery?

- Is our signal inconsistent with background (inconsistent with a fluxuation)?

$$\text{Significance} = \text{signal} / \sqrt{\text{background}}$$
$$= (N_{data} - N_{background}) / \sqrt{N_{background}}$$

Where:

N_{data} = Number of observed data events

$N_{background}$ = Number of estimated background events

- Require typically a "5σ" effect (probability of statistical fluctuation of 5.7×10^{-7})
  - For a "real" signal, significance should increase with luminosity (need lots of data)
  - In practice more complicated than shown above (*eg* with systematic uncertainties)

Higgs has significant backgrounds: need a lot of data and statistical techniques

How might a discovery look for Higgs → γγ?

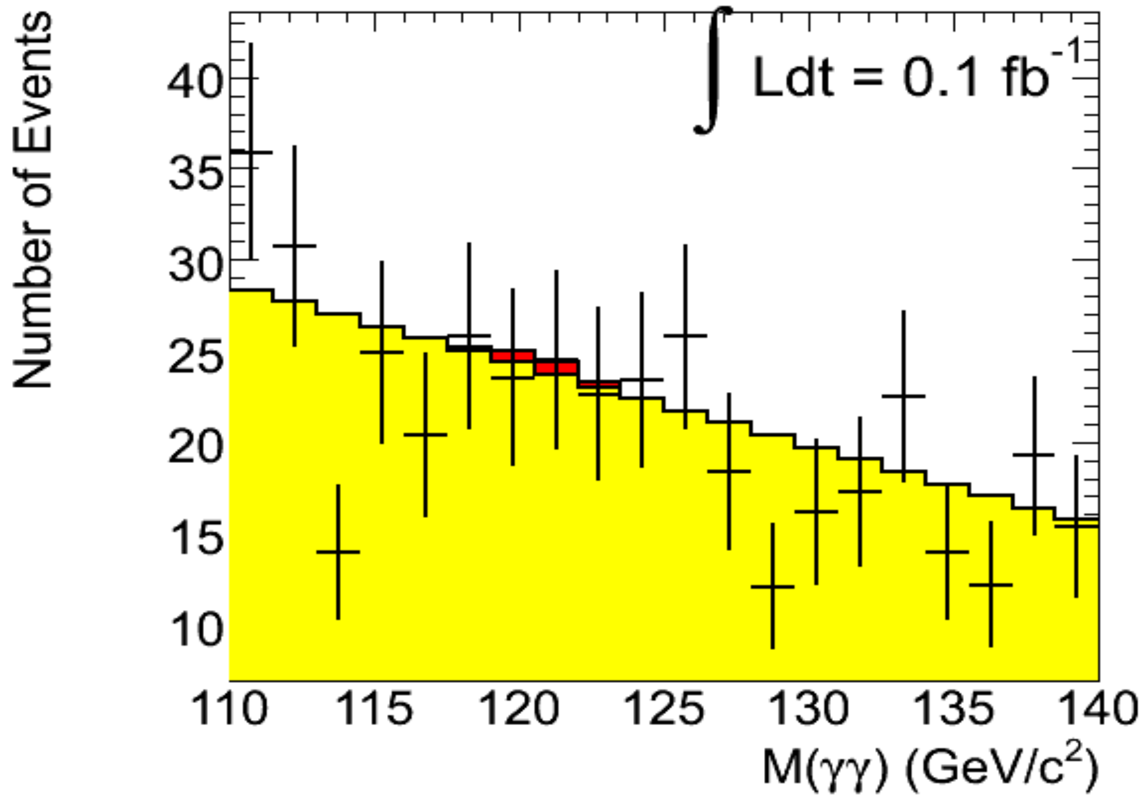
- Expected Events with 100 pb^{-1}

  N_{signal} ≈ 2

  $N_{background}$ = 96 ± 9.8

  S/√B = 0.2

No sensitivity to signal



How might a discovery look for Higgs → γγ?

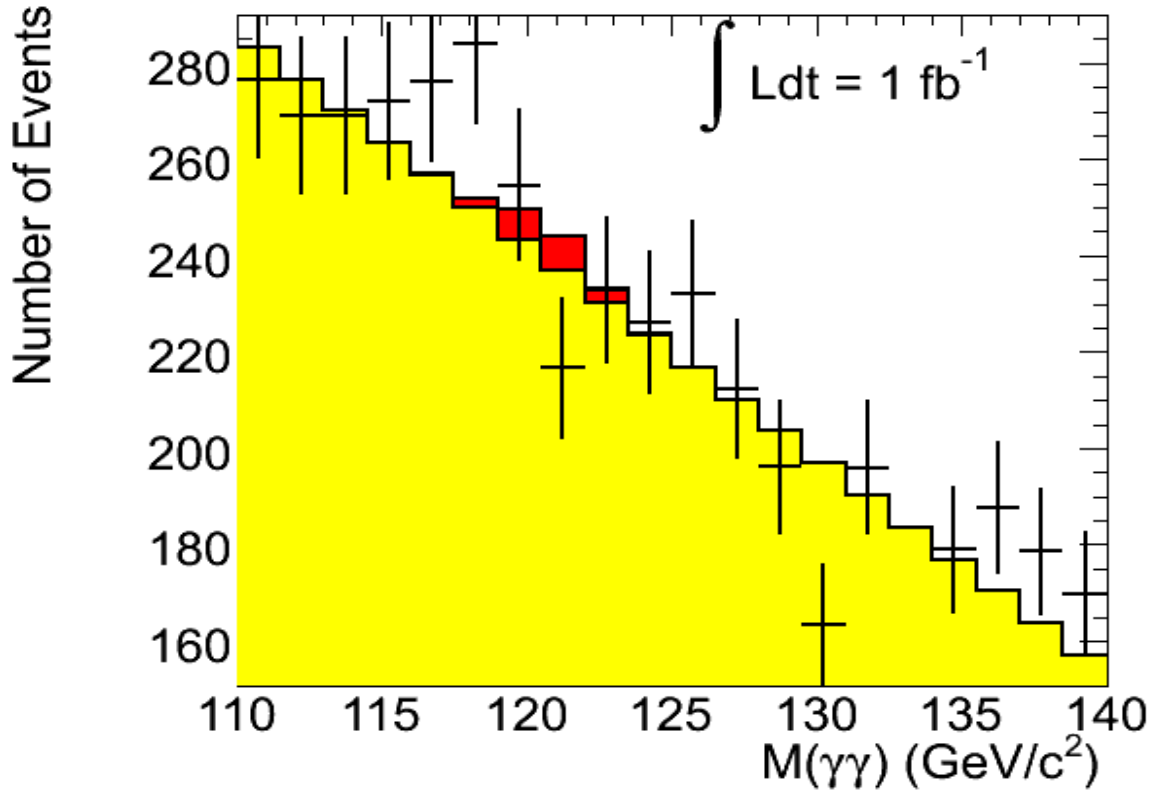
- Expected Events with 1 fb^{-1}

  N_{signal} ≈ 25

  $N_{background}$ = 960 ± 30

  $S/\sqrt{B} = 0.8$

Still not enough sensitivity



How might a discovery look for Higgs → γγ?

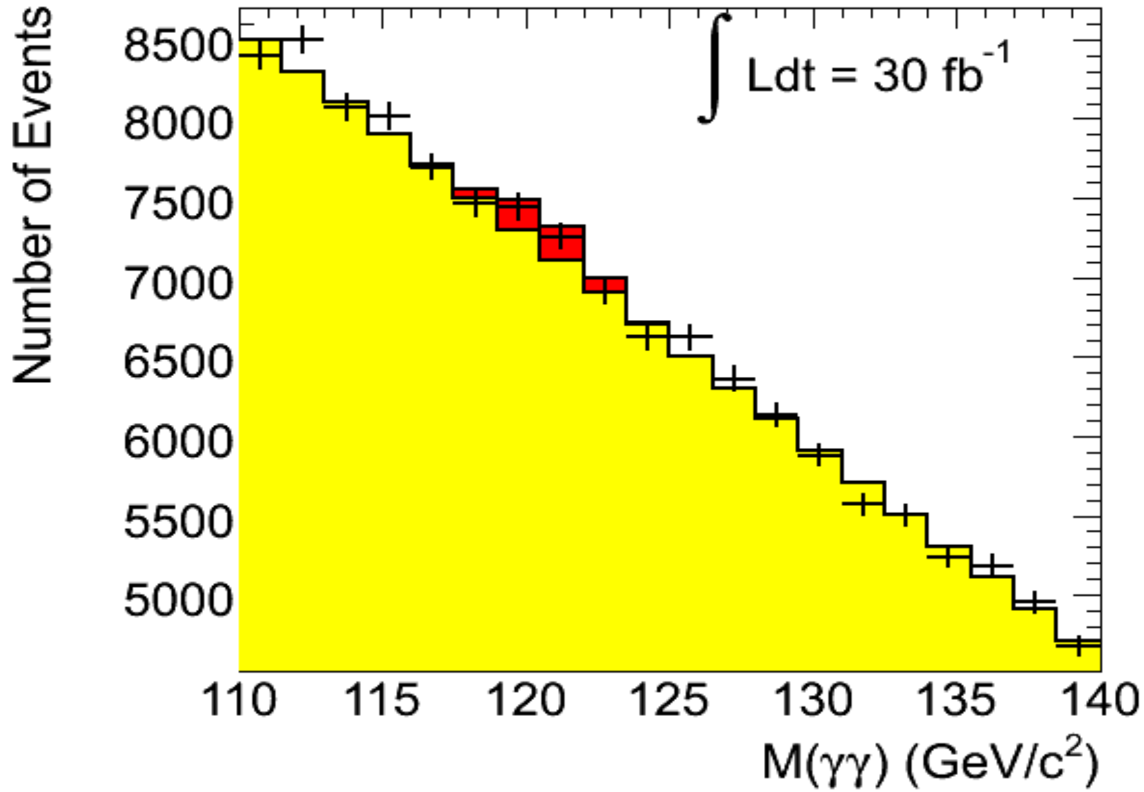
- Expected Events with 30 fb^{-1}

  N_{signal} ≈ 700

  $N_{background}$ = 28700 ± 170

  $S/\sqrt{B} = 4.1$

Something is there!



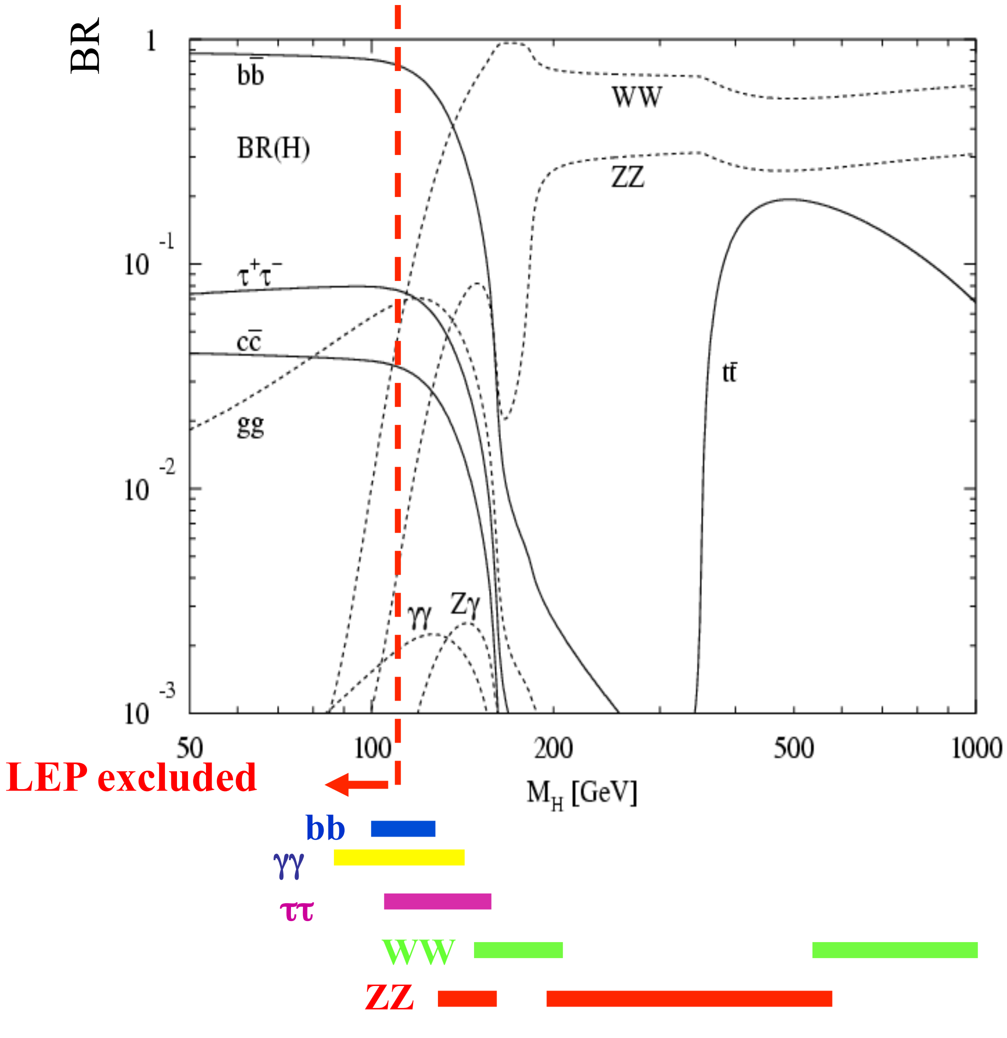
Higgs Decay

- Low mass: $m_H < 130\ GeV/c^2$
  - bb dominant
  - WW and ττ are next
  - γγ small but very useful
  - Tevatron: WH, ZH → bb
  - LHC: gluon fusion

- High mass: $m_H > 140\ GeV/c^2$
  - WW dominant
  - ZZ easiest to use

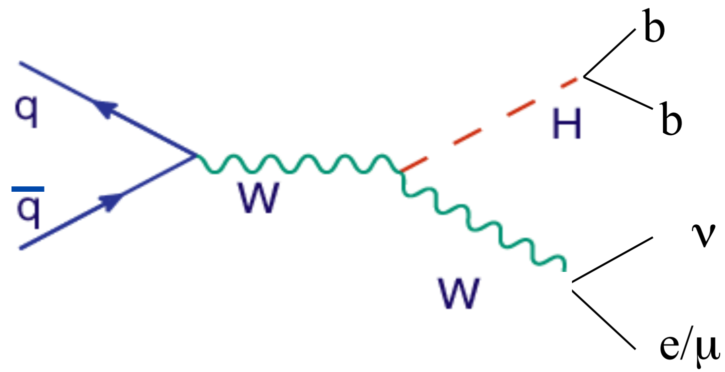
Look in each channel, combine results

Lets look at each one…



Low-mass SM Higgs: WH → bblv

- WH → bblv (Missing E_T)
  - 1 or 2 b-tagged jets
  - electron or muon with p_T > 20 GeV
  - Missing E_T > 20 GeV

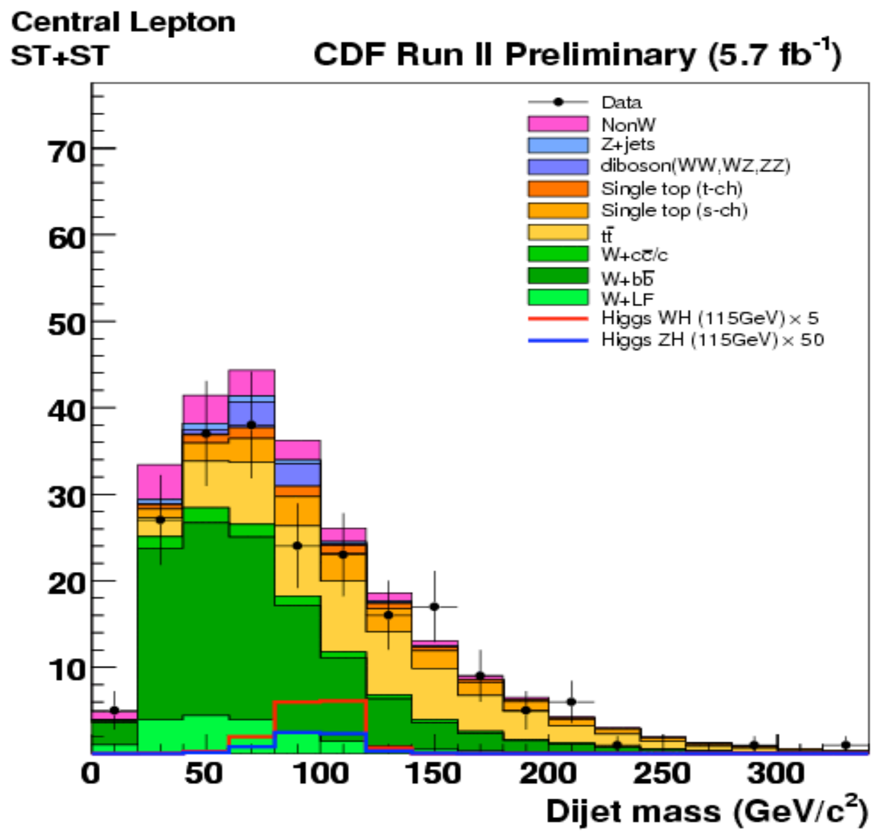


- Several analyses, multiple b-tagging algorithms, Baysean Neural Net, Matrix element technique…

- Set limits on σBr as a ratio to SM expected at m_H = 115 GeV/c^2

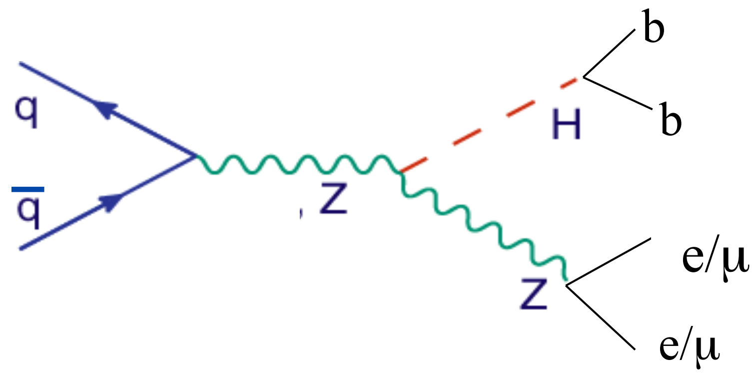
  σBr < 3.5 x SM for CDF (5.7 fb^{-1})

  σBr < 4.8 x SM for D0 (5.3 fb^{-1})



Low-mass SM Higgs: ZH → bbll

- ZH → llbb
  - 1 or 2 b-tagged jets
  - electron or muon with p_T > ~18 GeV

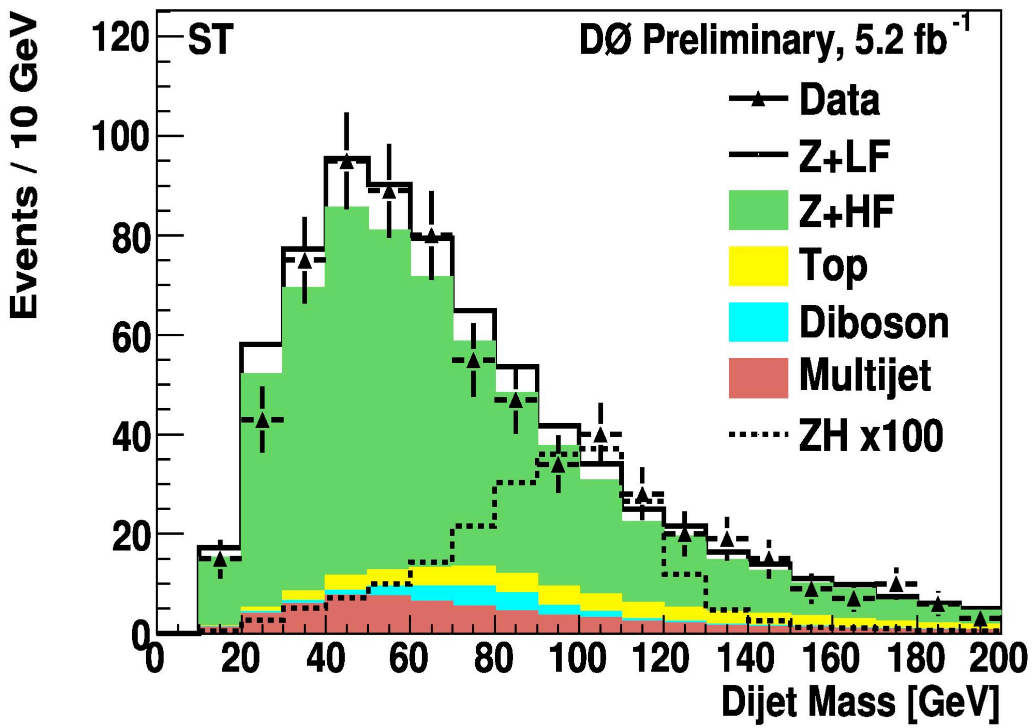


- Again, several analyses and more data being added regularly

- Set limits on σBr as a ratio to SM expected at m_H = 115 GeV/c^2

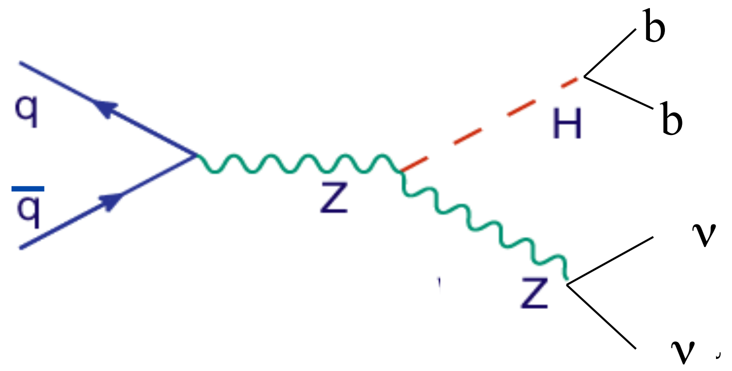
  σBr < 3.5 x SM for CDF (5.7 fb^{-1})

  σBr < 5.7 x SM for D0 (6.2 fb^{-1})



Low-mass SM Higgs: ZH → bbνν

- ZH → bbνν
  - 1 or 2 b-tagged jets
  - Missing E_T

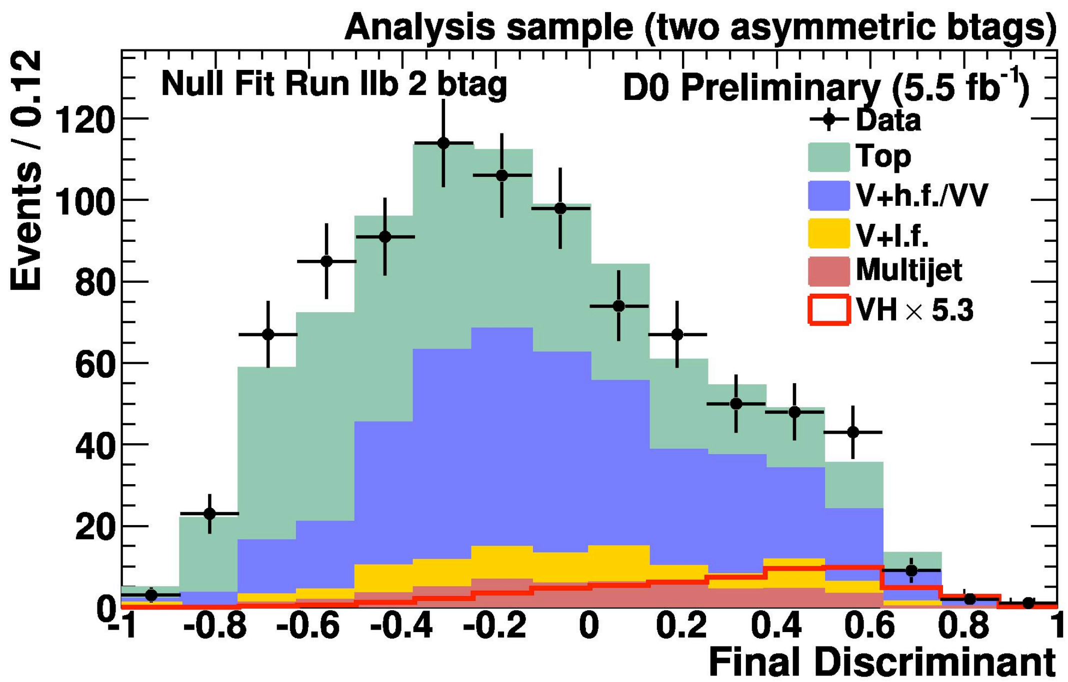


- Set limits on σBr as a ratio to SM expected at m_H = 115 GeV/c²

  σBr < 4.2 x SM for D0 (6.4 fb^{-1})

- Similar for CDF, except VH → bb

  σBr < 4.0 x SM for CDF (6.4 fb^{-1})

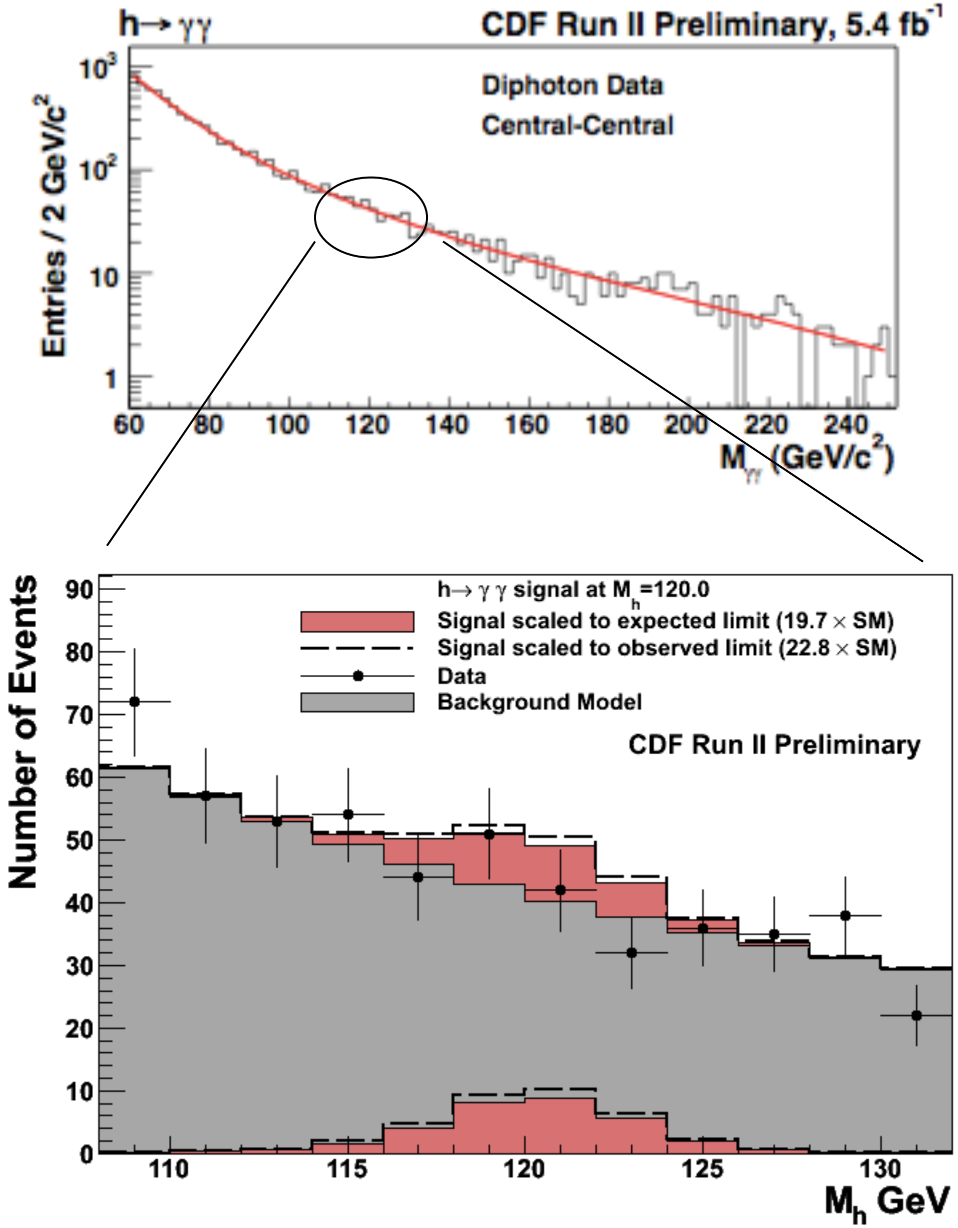


Low-mass SM Higgs: $H \rightarrow \gamma\gamma$

- Higgs $\rightarrow \gamma\gamma$ at the Tevatron
  - Invariant mass of calorimeter E
  - Invariant mass measures m_H
  - Calorimeter resolution important
  - Very small σ, but better $\gamma\gamma$ resolution than dijet
  - Intersting for fermiphobic Higgs, LHC

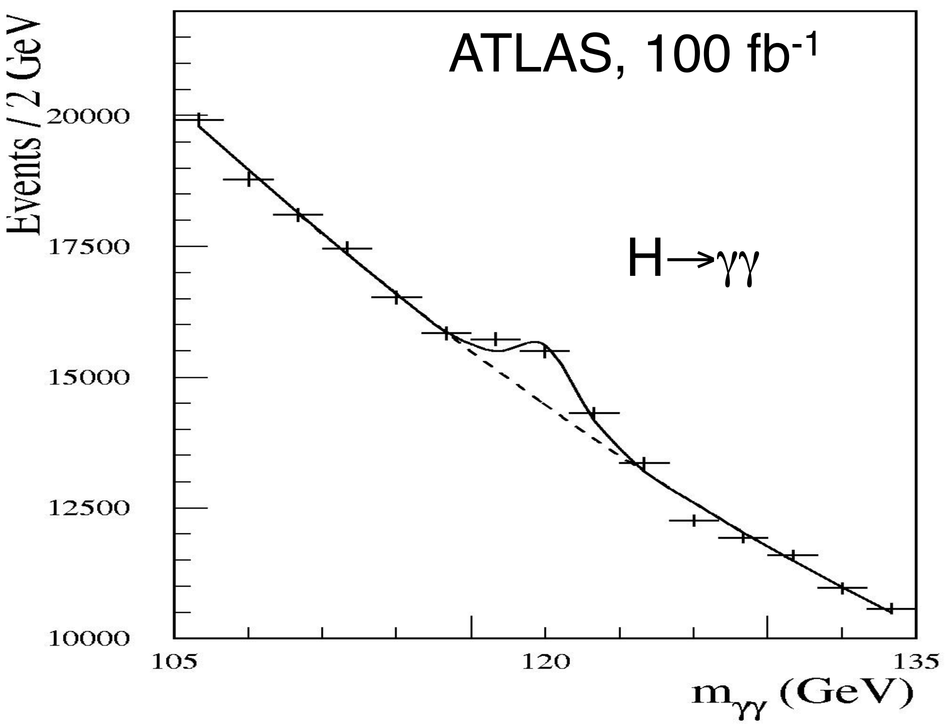
- Set limits on σBr as a ratio to SM expected at m_H = 115 GeV/c^2

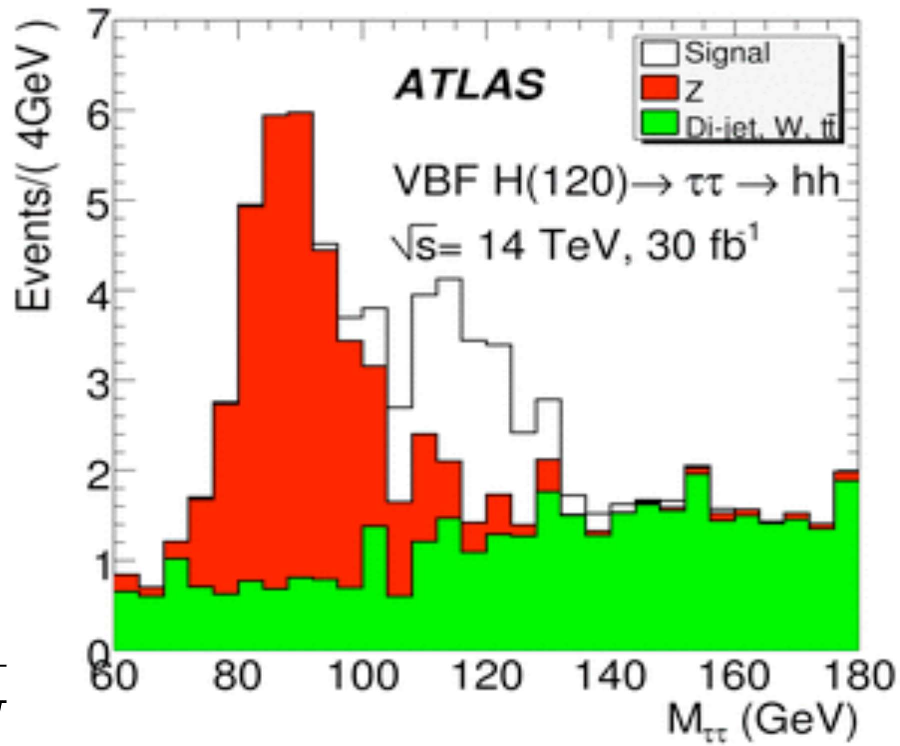
  σBr < 20.8 x SM for CDF (5.4 fb^{-1})



Low-mass SM Higgs at the LHC?

- No results for LHC yet, but how will they look?
- Main Higgs channels at the LHC:
  - $H \rightarrow \gamma\gamma$, ZZ
  - qqH → qq tau tau
- Require O(10 fb^{-1}) integrated luminosity



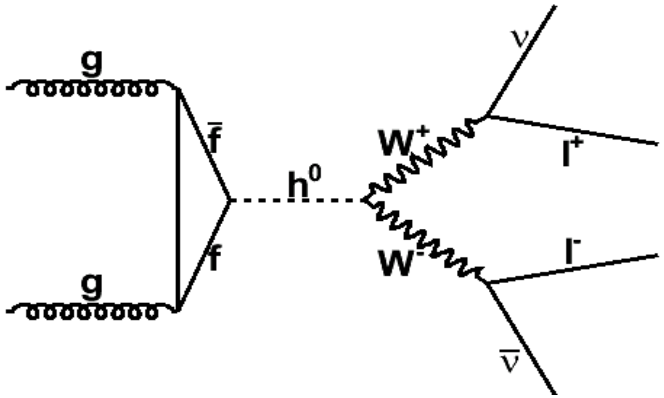


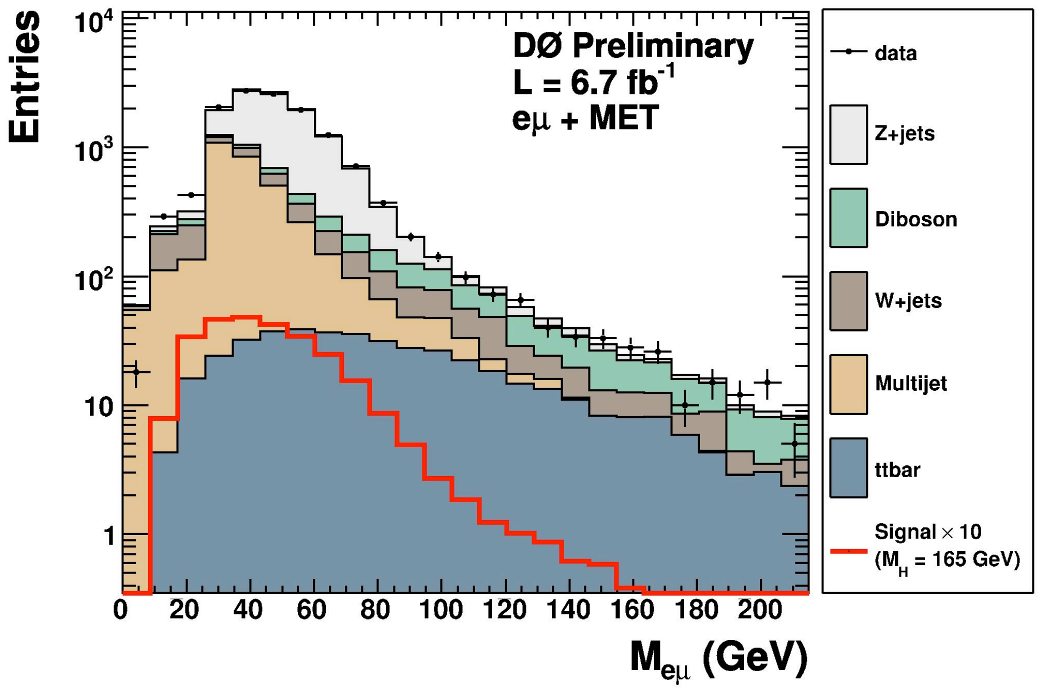
High-mass SM Higgs: H → WW*→ dileptons

- H → WW* or WH → WWW*
  - 2 (or 3) isolated lepton p_T > 15, 10 GeV
  - Missing E_T >20 GeV
  - Veto on Z resonance, energetic jets
- Main backgrounds
  - SM WW production (can suppress by spin correlations; H is scalar)
  - Also Top, Drell-Yan, “fake” leptons
- Again, sophisticated multivariate techniques applied: matrix element or neural nets
- Set limits on σBr as a ratio to SM expected at m_H = 165 GeV/c^2

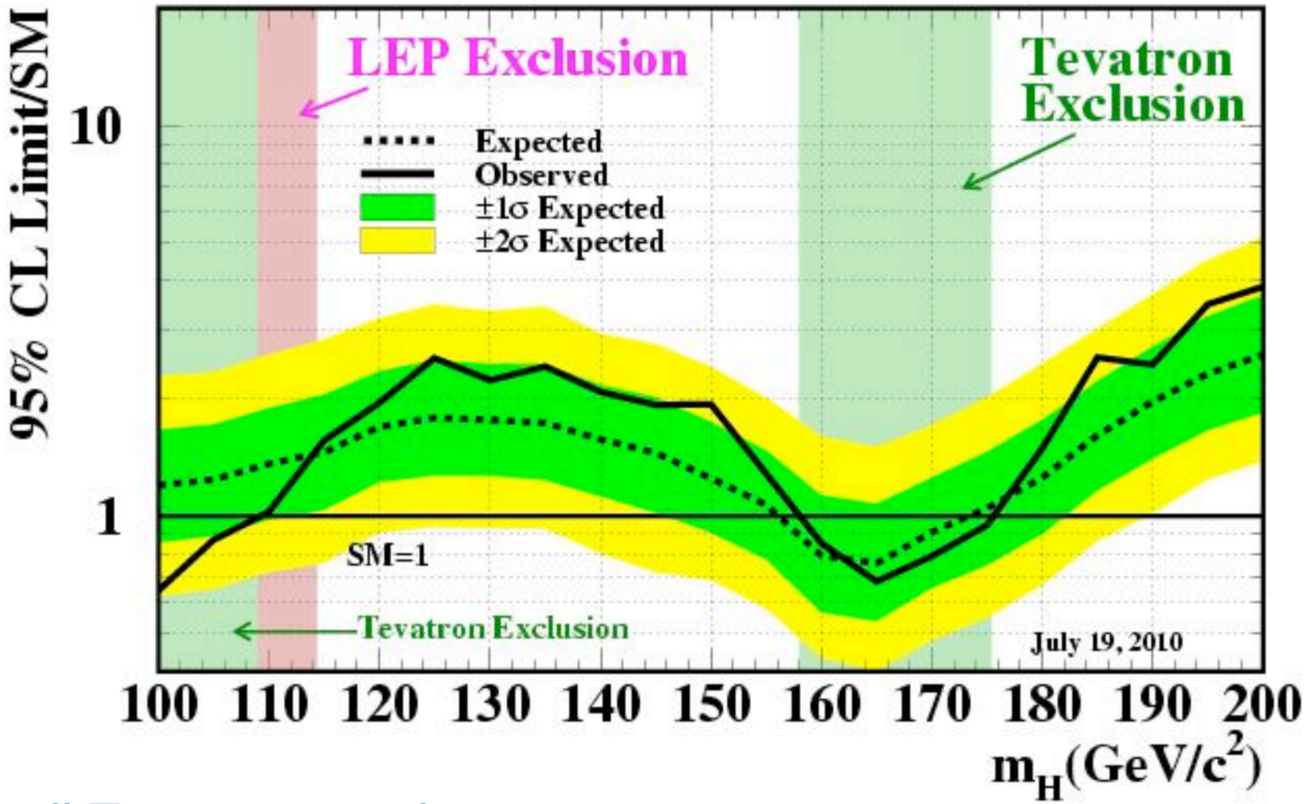
  σBr < 1.0 x SM for CDF (5.9 fb^{-1})

  σBr < 1.35 x SM for D0 (6.7 fb^{-1})





Tevatron SM Higgs Results

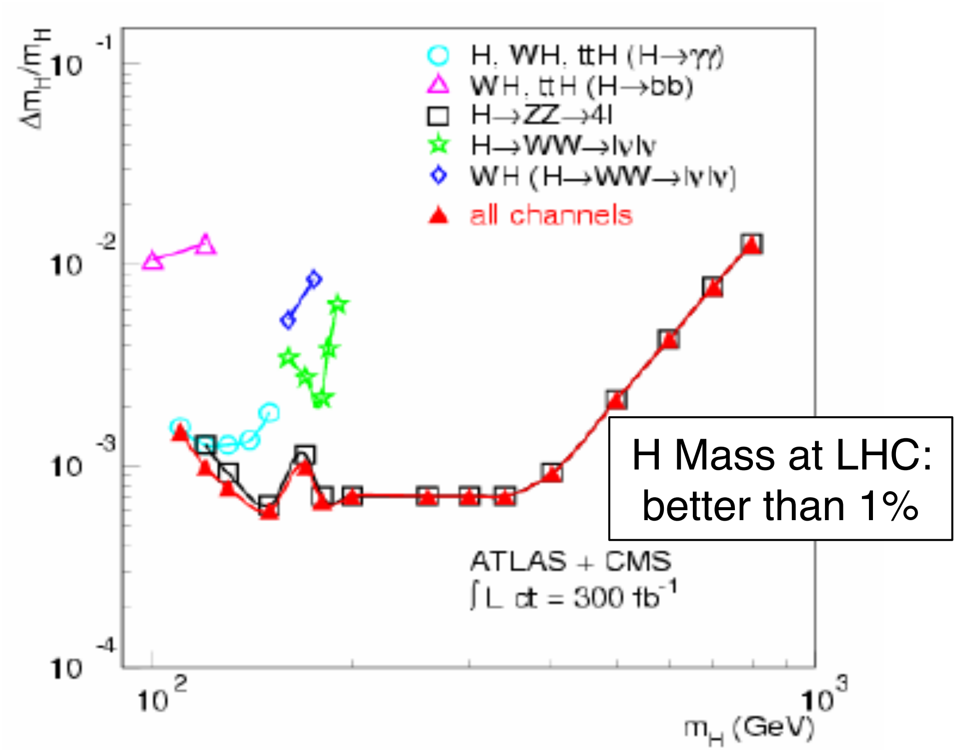


- Combining all Tevatron results:
  - Experimental limits shown measurement divided by theoretical cross section
  - Value of 1 (and below) is excluded at 95% confidence level
  - Recent bickering over errors on theoretical cross sections (H from gg fusion)

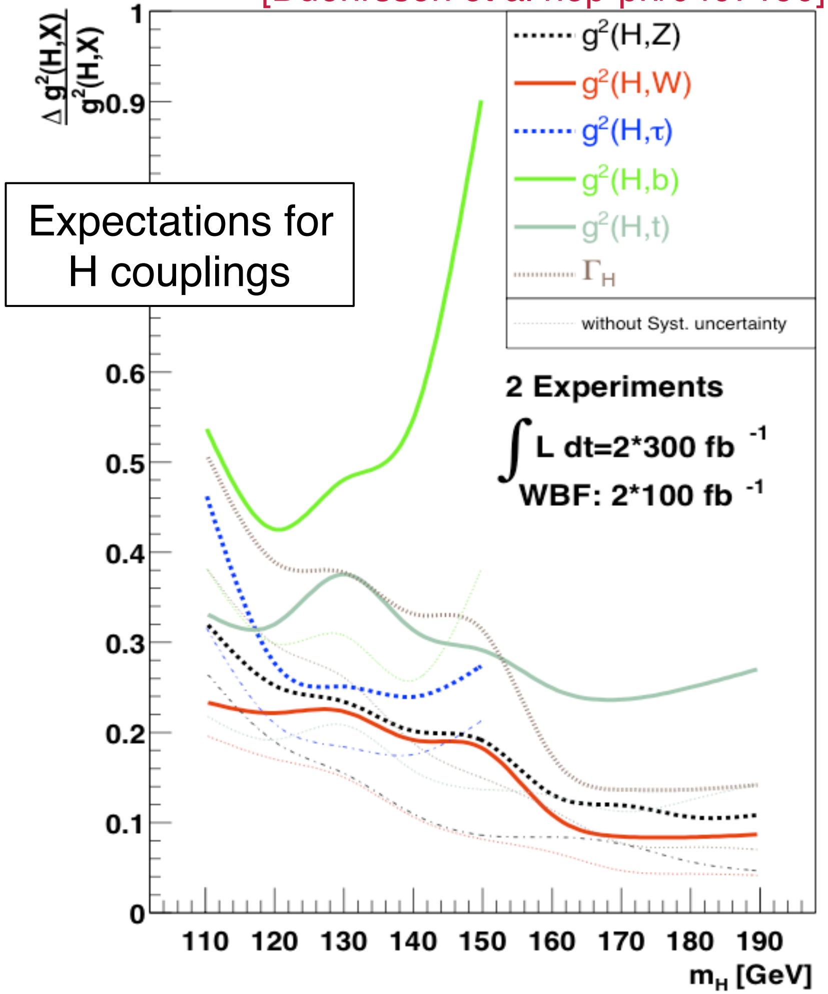
Limits set in new mass regions!

Do we really know it is the Higgs?

- After discovery, start to measure its properties
  - Mass
  - Spin
  - Decays to other particles

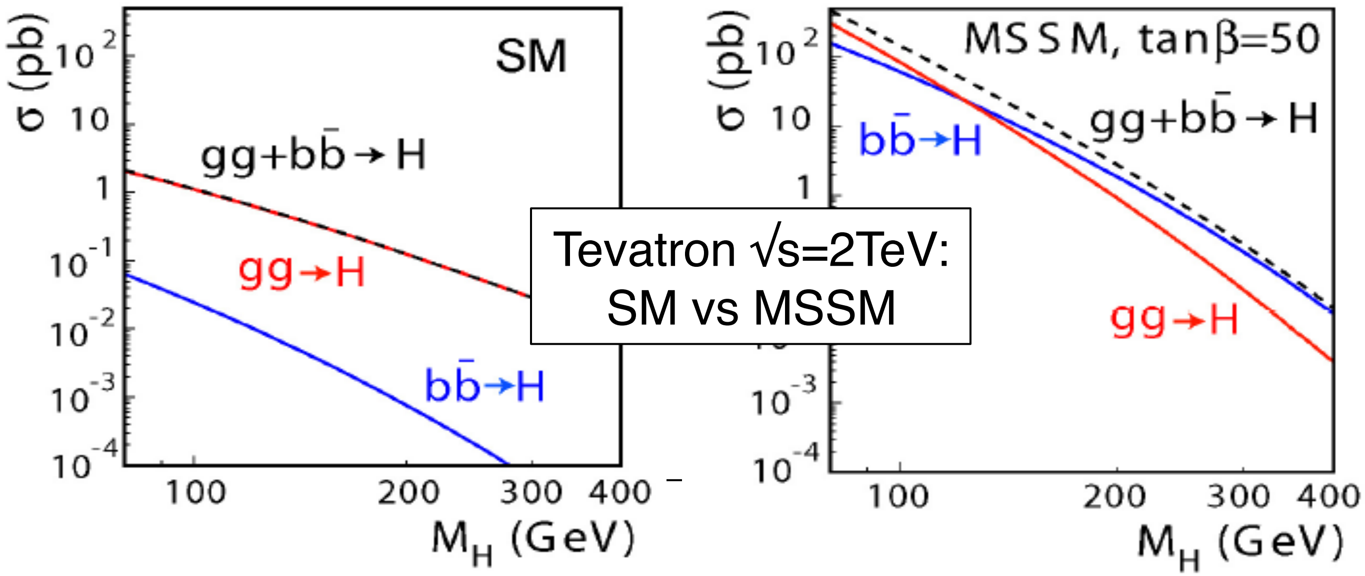


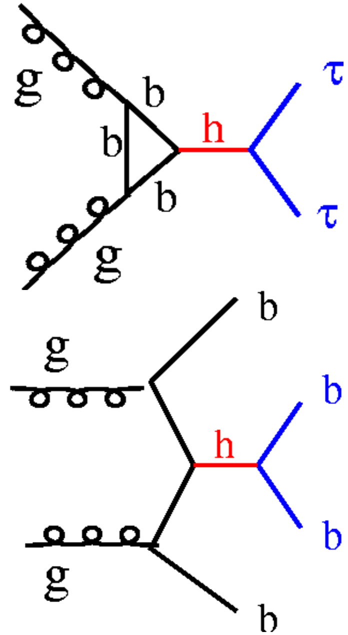
[Duehrssen et al hep-ph/0407190]



Non-SM Higgs?

- Higgs also in Supersymmetry
  - Minimal Supersymmetric Standard Model (MSSM) has two higgs doublets
  - Doublets related by a parameter $\tan\beta = \langle h_u \rangle / \langle h_d \rangle$
  - 5 Higgs bosons: h, H, A, $H^{\pm}$
- Charged and Neutral Higgs Boson:
  - Pseudoscalar A, scalar H, h
  - Lightest (h) is very similar to SM Higgs
- Cross section can be large (depends on tanβ)



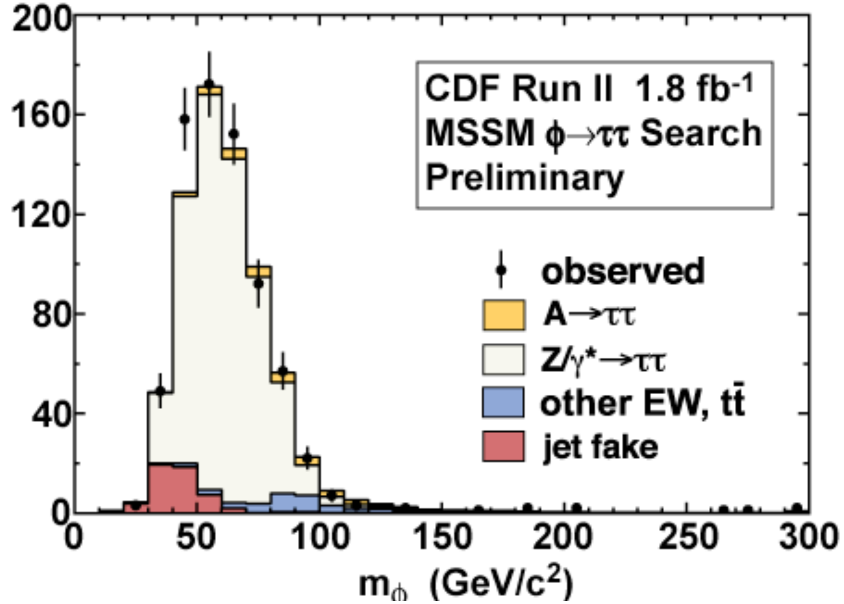


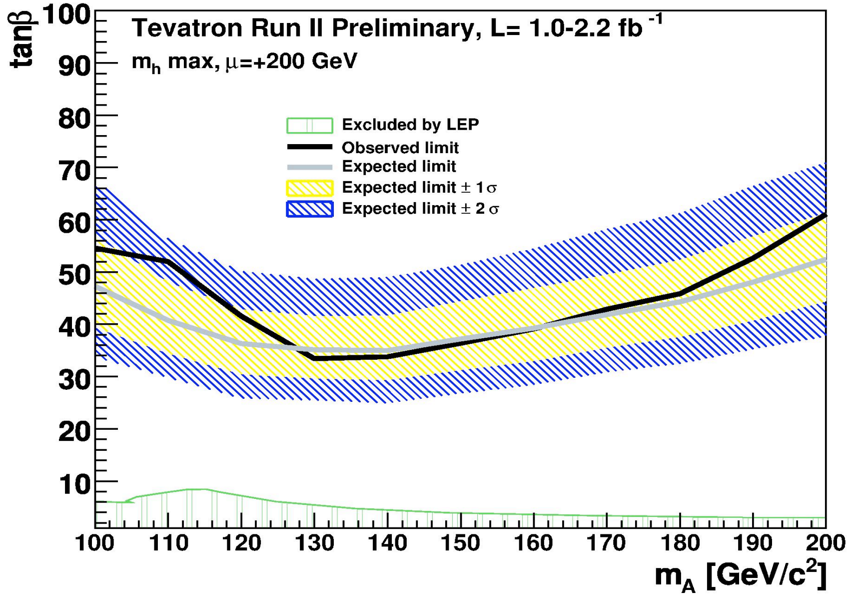
MSSM Higgs: H/A/h → taus

- MSSM H/A/h → taus
  - One tau decays to e or μ
  - Other to hadrons or e/μ
  - Isolation important
  - Tau efficiency ~50%, fake rate <1%

- Reconstruction techniques
  - Two neutrinos: can't form H/A/h mass
  - Use mass-like quantity from visible particles

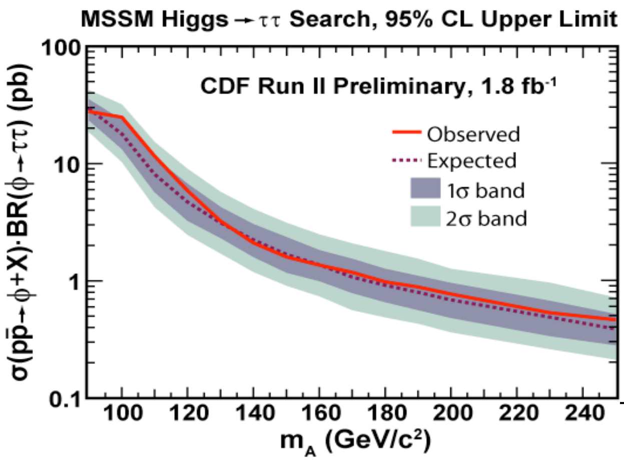
- Set limits on mass versus tanβ:
  - exclude masses up to 200 GeV for tanβ>40 combined CDF+D0 (2.2 fb^{-1})

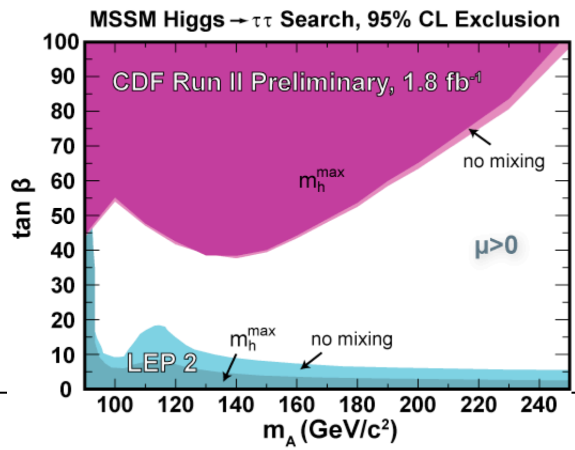


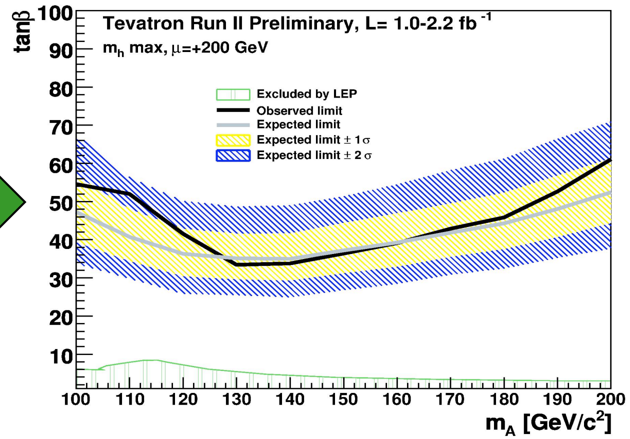


From Measurement to Limit

- Many steps involved in each analysis, each with different efficiency:
  - Select basic quantities (leptons, jets) with lowest possible p_T (triggers crucial!)
  - Reconstruct less-basic quantities: tau, b-tagging
  - Cuts applied on kinematic quantities to reduce backgrounds
  - Typical signal still << backgrounds for Higgs (of order 1:100)
  - Powerful and sophisticated multivariate techniques now the norm
- Interpretation of results also has several steps
  - Use statistical techniques to compare to theory
  - Combine channels and ultimately experiments for "world's best"



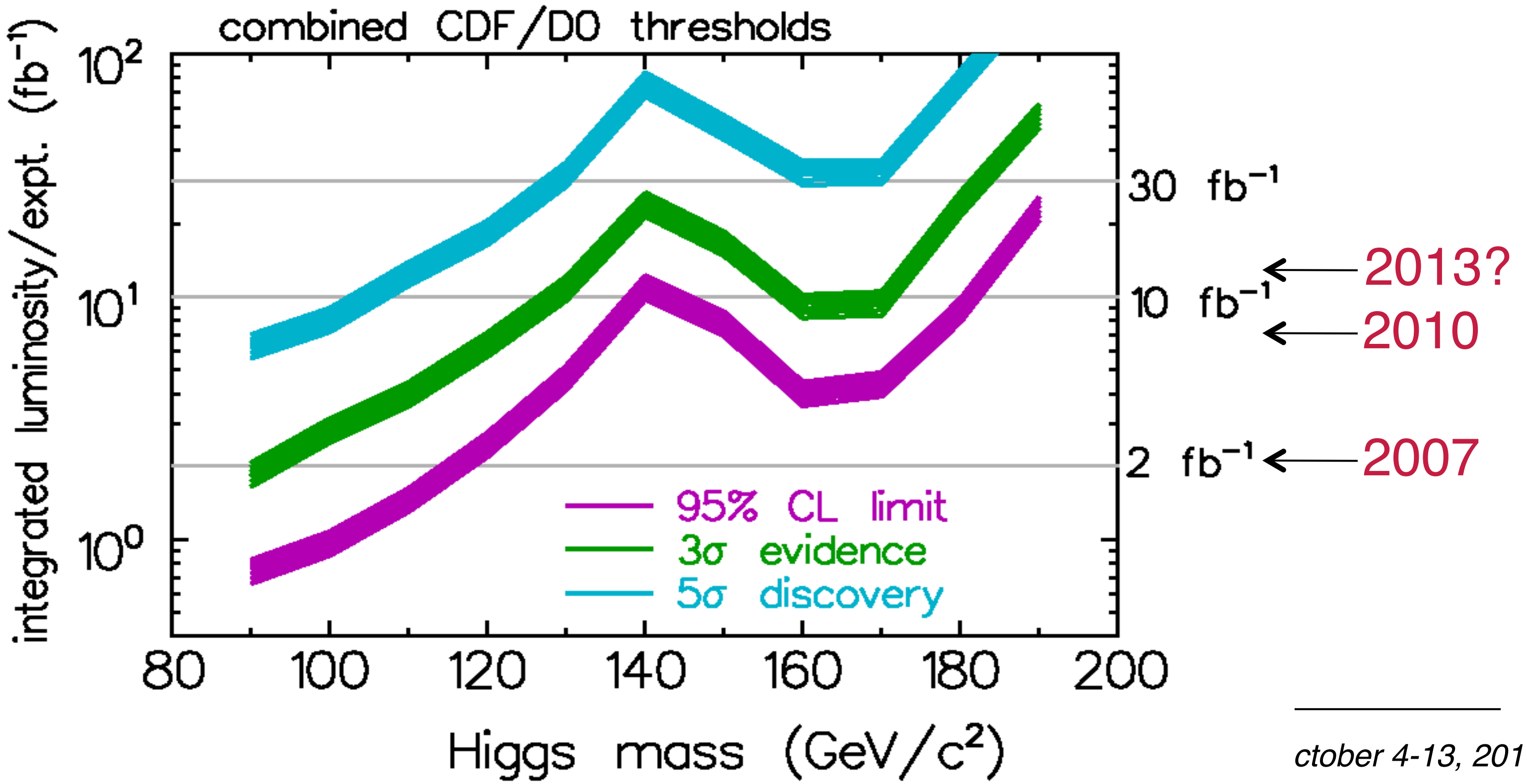




From Limit to 5σ Discovery

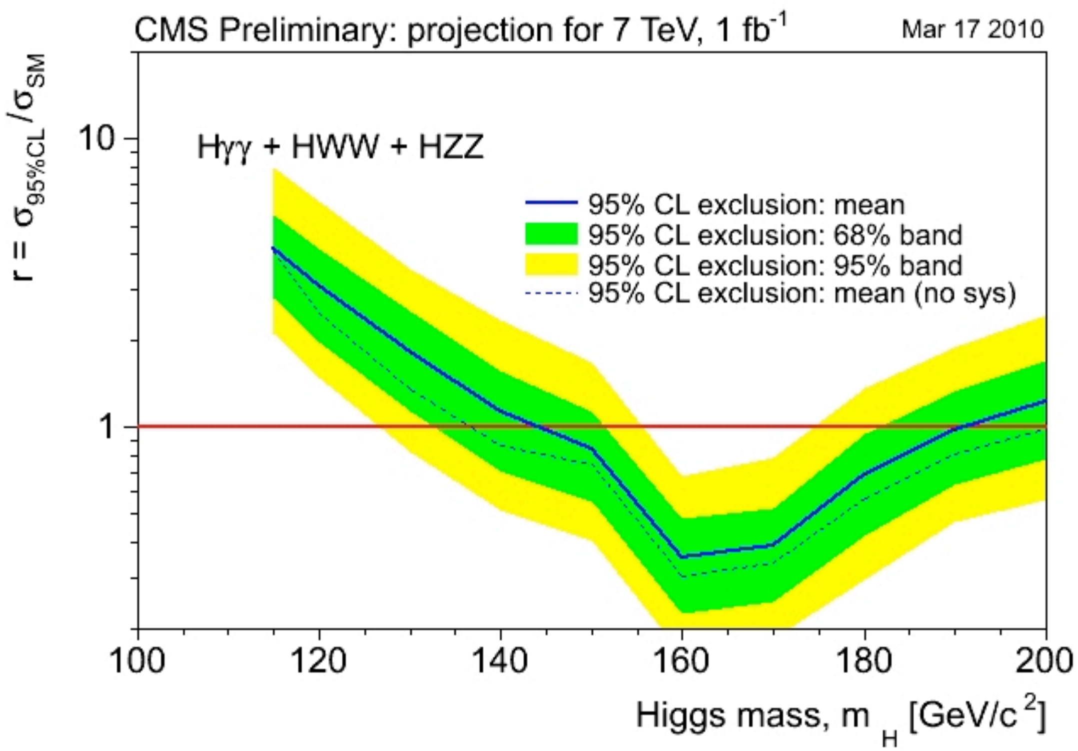
- Tevatron predictions from ~10 years ago shown below
  - CDF+D0 combined estimate, assume improvements including multivariate techniques
  - Not quite right (too optimistic for low-mass H) but good illustration

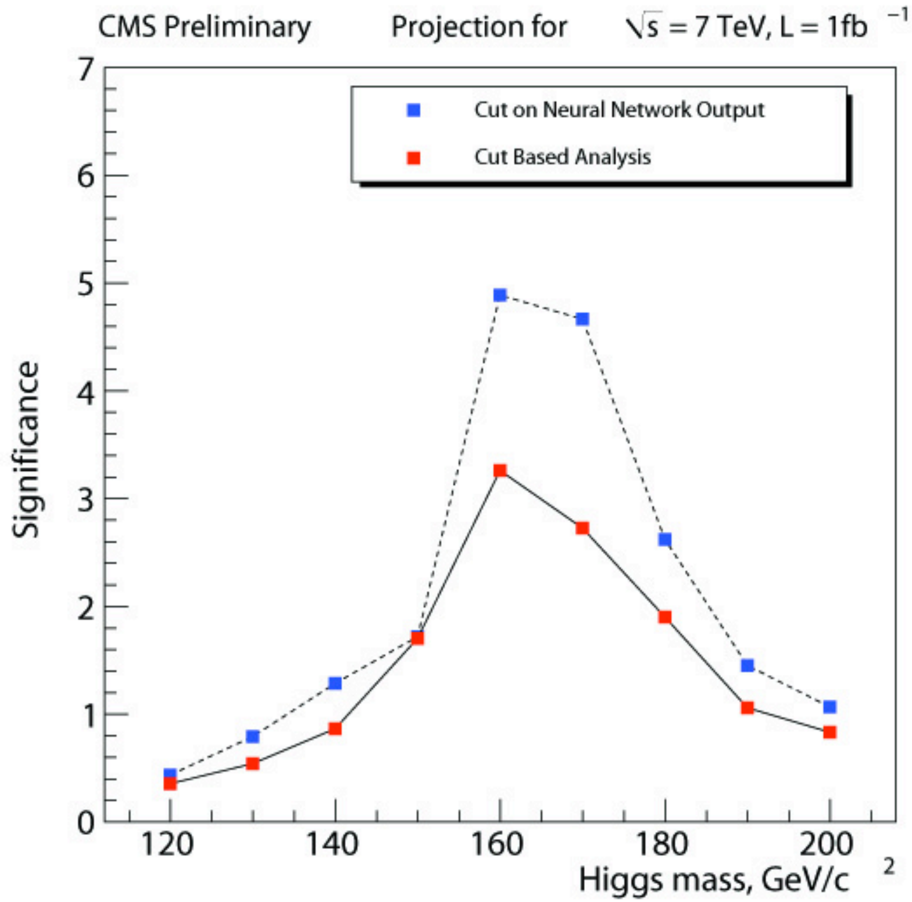
Do you think the Tevatron can"discover" the higgs?



LHC Higgs Discovery Potential

- LHC reach for one experiment at 7 TeV, 1 fb^{-1}
  - Should see an excess growing over the next few years
  - Would really like to increase energy if possible (8 or 9 TeV?)… ultimately 14 TeV
  - LHC will discover the Higgs… or something more exotic (see next lecture!)





Conclusions

- Higgs boson (or something like it) should be found at the LHC!
- Constraints from precision electroweak measurements are important
  - $m_W = 80.399 \pm 0.023$ GeV/c^2
  - $M_{top} = 173.1 \pm 1.3$ GeV/c^2
  - Implies the SM Higgs mass should be between 114 and 157 GeV/c^2
- Direct searches for Higgs boson going at the Tevatron
  - Tevatron excludes wide range of high-mass H based on WW
  - Low mass exclusion nearing the LEP value
  - Not a discovery machine, but many good lessons and experience
- Searches at the LHC are just getting started
  - Cross section higher and channels cleaner
  - Will need ~1 fb^{-1} to really get going